Next Generation HOM-Damping

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Abstract.  
Research and development for superconducting radio-frequency cavities has made enormous progress over the last decades from the understanding of theoretical limitations to the industrial mass fabrication of cavities for large-scale particle accelerators. Key technologies remain hot topics due to continuously growing demands on cavity performance, particularly when in pursuit of high quality beams at higher beam currents or higher luminosities than currently achievable. This relates to Higher Order Mode (HOM) damping requirements. Meeting the desired beam properties implies avoiding coupled multi-bunch or beam break-up instabilities depending on the machine and beam parameters that will set the acceptable cavity impedance thresholds. The use of cavity HOM-dampers is crucial to absorb the wakefields, comprised by all beam-induced cavity Eigenmodes, to beam-dynamically safe levels and to reduce the heat load at cryogenic temperature. Cavity damping concepts may vary, but are principally based on coaxial and waveguide couplers as well as beam line absorbers or any combination. Next generation Energy Recovery Linacs and circular colliders call for cavities with strong HOM-damping that can exceed the state-of-the-art, while the operating mode efficiency shall not be significantly compromised concurrently. This imposes major challenges given the rather limited damping concepts. A detailed survey of established cavities is provided scrutinizing the achieved damping performance, shortcomings, and potential improvements. The scaling of the highest passband mode impedances is numerically evaluated in dependence on the number of cells for a single-cell up to a nine-cell cavity, which reveals the increased probability of trapped modes. This is followed by simulations for single-cell and five-cell cavities, which incorporate multiple damping schemes to assess the most efficient concepts. The usage and viability of on-cell dampers is elucidated for the single-cell cavity since it can push the envelope towards quasi HOM-free operation suited for next generation storage and collider rings. Geometrical end-cell shape alterations for the five-cell cavity with already efficient mode damping are discussed as a possibility to further lower specific high impedance modes. The findings are eventually put into relation with demanding impedance instability thresholds in future collider rings.
1. Introduction

The development of an RF cavity with efficient HOM-damping can take several years from a conceptual idea to an engineering design, followed by prototype fabrication, experimental testing and eventually towards a production unit for use in an accelerator. The acceptable HOM-damper technology depends on the specific machine and its beam parameters. One may raise the question whether existing HOM-damping concepts meet the requirements of future machines - and if not - which improvements can be established to satisfy the demands. This motivated a survey of state-of-the-art HOM-damped superconducting (SC) accelerating cavities. The damping efficiencies are compared with each other by means of computational and experimental data as far as available. It is followed by numerical simulations for single-cell and five-cell SC cavities, which elucidate the most efficient concepts, shortcomings, trade-offs and potential improvements. A section is dedicated to heavily HOM-damped normal-conducting (NC) cavities to demonstrate the efficiency of on-cell dampers. This concept has not been seriously explored in the past for SC accelerating cavities due to the undesired magnetic field enhancement introduced at cavity wall openings. It can yet become a viable option at moderate operating fields. Its feasibility is therefore explored for a single-cell cavity. Main findings will eventually be related to beam impedance instability thresholds for proposed next generation machines. The simulation methods applied are briefly described in the Appendix since these are crucial tools for cavity optimizations that also reveal shortcomings of past designs.

2. Survey of established HOM-damped cavities

HOM-damped cavities have been conceived for operation ranging from rather low-duty cycle to continuous wave (CW) spanning average beam currents from less than 1 mA to the Ampere level. Most of the cavities surveyed are those that have been employed in accelerator facilities. This comprises cavities for e+e- collider rings (CESR) and B-factories (PEP-II, KEKB), the TeV hadron collider ring LHC, the 1 GeV H+ linac for SNS, various medium energy 3rd generation electron storage ring light sources (e.g. ALBA, ESRF, SOLEIL), multi-GeV electron linear accelerators driving Free Electron Lasers (FEL) (e.g. European X-ray FEL, LCLS-II), the multi-pass electron recirculator CEBAF, and the Cornell injector conceived for an Energy Recover Linac (ERL). Some cavities are conceptual, yet well optimized designs for high current (HC) ERLs (e.g. bERLinPro, eRHIC, Cornell ERL). The demands on the HOM-damping requirements are differing considerably among the machines for which the cavities have been conceived. Cavity similarities, differences, and operational experiences related to the HOM-dampers are elaborated.
2.1 Superconducting cavities with coaxial, waveguide, and beam line dampers

Table 1 summarizes relevant operational parameters for SC cavities in sequence of ascending operating frequency, \( f_0 \). The list covers dominantly speed-of-light structures (\( \beta_g = 1 \)), with the exception of the SNS six-cell cavities (\( \beta_g = 0.61, \beta_g = 0.81 \)), and exhibit conventional, high performing elliptically-shaped cell profiles (see Fig. 1). It denotes the number of couplers employed per cavity, \( N_{D} \), associated with the type of dampers, which are divided in three categories as follows:

1. Coaxial (C) dampers (comprising antenna couplers, loop couplers, or a combination of both)
2. Waveguide (WG) dampers
3. Beam pipe/line absorbers (BLA).

When applicable, \( N_{D} \) includes the dampers mutually shared among neighboring cavities in a cryostat such as for cavities linked with each other through large beam tubes, i.e. Cornell ICM, Soleil, and LHC cavities.

Table 1. Relevant parameters of elliptical HOM-damped cavities, \( \beta_g \) = geometrical beta of structure \((v/c_0)\), \( G = Geometry factor (R_s \cdot Q_0)\), \( k_{cc} \) = cell-to-cell coupling

| Cavity          | \( f_0 \)  | \( \beta_g \) | Type | \( N_D \) | \( N_C \) | \( E_{pk}/E_{acc} \) | \( B_{pk}/E_{acc} \) | \( R/Q^* \) | \( G \) | \( k_{cc}^{**} \) |
|-----------------|-----------|--------------|------|---------|---------|------------------|------------------|----------|------|-------------|
| SOLEIL [1]      | 352.2     | 1            | C    | 4       | 1       | 2.0              | 4.5              | 45.0     | -    | -           |
| LHC [2], [3]    | 400.8     | 1            | C    | 4       | 1       | 2.21             | 5.12             | 44.5     | 265.7 | -           |
| CESR [4]        | 500       | 1            | BLA  | 2       | 1       | 2.45             | 5.26             | 44.5     | -    | 251         |
| KEKB [5], [6]   | 508.9     | 1            | BLA  | 2       | 1       | 1.84             | 4.03             | 46.5     | 251   | -           |
| BNL4 HC [7]     | 647       | 1            | W    | 4       | 5       | 2.27             | 4.42             | 251      | 273   | 2.8         |
| BNL3 HC [8]     | 703.79    | 1            | C    | 6       | 5       | 2.46             | 4.27             | 253.2    | 283   | 3.0         |
| JLab HC [9]     | 748.5     | 1            | WG   | 5        | 1       | 2.50             | 4.27             | 262.5    | 276   | 3.2         |
| SNS [10]        | 805       | 0.61         | C    | 2       | 6       | 2.71             | 5.72             | 139.5    | 179   | 1.5         |
| BNL HC [7]      | 805       | 0.81         | C    | 2       | 6       | 2.19             | 4.72             | 241.5    | 260   | 1.5         |
| bERLinPro [11]  | 1300      | 1            | WG   | 5        | 1       | 2.08             | 4.4              | 394      | 273   | n/a         |
| Cornell ICM [12]| 1300      | 1            | BLA  | 2       | 1       | 1.94             | 4.28             | 109      | -     | 0.7         |
| Cornell MLC [13]| 1300      | 1            | BLA  | 2       | 1       | 2.06             | 4.2              | 387      | 270.7 | 2.2         |
| TESLA [14]      | 1300      | 1            | C    | 2       | 9       | 2.0              | 4.26             | 518      | 270   | 1.9         |
| C100 LL [15]    | 1497      | 1            | C    | 2       | 7       | 2.17             | 3.74             | 434.5    | 280.3 | 1.5         |
| C20/50 OC [15]  | 1497      | 1            | WG   | 2        | 5       | 2.56             | 4.56             | 241.3    | 273.8 | 3.3         |
| JLab HG [15]    | 1497      | 1            | C    | 7        | 2       | 2.20             | 4.26             | 391.7    | 265.5 | 1.7         |

\( R/Q = V_{eff}^2/(2 \cdot P_{avg}) \), ** Cell-to-cell coupling factor given by \( k_{cc} = (f_\pi^2 - f_0^2)/(f_\pi^2 + f_0^2) \), when calculating the 0- and \( \pi \)-mode of the TM010 mode (e.g. for cavity dumbbell), *** The JLab HG prototype cavities incorporating four coaxial couplers, but only two were used eventually during beam operation at CEBAF.

The ratios of the surface peak electric, \( E_{pk} \), and surface peak flux density, \( B_{pk} \), to the accelerating field, \( E_{acc} \), should be kept small if high operating fields are being pursued. Both parameters decrease with decreased cavity iris aperture. However, this comes in trade-off with the HOM-damping efficiency as one seeks for a rather large cell-to-cell coupling especially when the number of cavity cells, \( N_C \), increases. At a given cavity iris aperture and for a well-optimized cell shape, \( B_{pk}/E_{acc} \) cannot be further reduced without increasing \( E_{pk}/E_{acc} \) and vice versa. Yet, by transitioning from the given end-cell iris aperture to a larger beam tube diameter, both ratios can be preserved. Larger beam tubes have the benefit to lower the cutoff
frequencies, which can let otherwise trapped HOMs propagate out of the cavity and reduce their quality factors, $Q$.

The type and geometrical layout of a HOM-damper, its location and its orientation with respect to a cavity depend on the broad- or narrowband damping requirements for longitudinal or transverse HOMs, the dissipated power and thus cooling demands and whether or not a rejecting filter is necessary for the accelerating fundamental mode, $FM$. High current machines can generate kW levels of HOM power that cannot be efficiently dissipated at cryogenic temperatures. In contrast, the multi-pass recirculator CEBAF produces HOM power levels of merely a few ten mWatts in CW operation. This is negligible compared to the $FM$ RF surface losses. The original CEBAF (OC) five-cell cavities are therefore equipped with HOM waveguides immersed in the helium bath within the cavity helium vessel. This is a unique concept not employed elsewhere. The absorber loads are broadband, lossy ceramics placed at the end of the waveguides and especially developed to work at 2 Kelvin [16].

**Figure 1.** Examples of established HOM-damped SC cavities with operating frequencies ranging from 352 MHz to 1500 MHz. Figures from top left to bottom right are Soleil cavity pair [17], LHC four-cavity string [18] and LHC single-cell cavity [2], respectively, CESR cavity [19], KEKB cavity [20], BNL ERL cavity prototype [21], JLab High Current cavity (source: JLab), SNS medium-beta and high-beta cavity [10], TESLA-type cavity [22], Cornell injector cryomodule cavity [23], Cornell ERL main linac cavity prototype [24], CEBAF original cavity pair [25], and CEBAF upgrade cavity (source: JLab). Each
The usage of coaxial or waveguide dampers is required when the cavity beam tube diameters are not large enough to let escape longitudinal and transverse HOMs that reside below the corresponding beam tube cutoff and thus exhibit exponentially decaying (evanescent) fields. Typically, this concerns the TE111, TM110 and TM011 modes, which can possess the highest $R/Q$-values among beam-excit able modes. For such modes it is most efficient to place the HOM-dampers as close as practically possible to the cavity end-cell irises. Lowering the external $Q$-value, $Q_{\text{ext}}$, is key since it is the impedance $R/Q \cdot Q_{\text{ext}}$ of the damped mode that needs to be minimized. One may account for the HOM coupling through the FPC line (coaxial or waveguide) as indicated in Table 1. An FPC in fact may considerably contribute to HOM damping if the transmission line including the vacuum RF window(s) together with the power feeding lines allow adequate absorption of the out-coupled fields. This has for instance been taken into account by design for the CEBAF OC cavities since most of the TE111 passband modes resonate below the TE10 HOM waveguide cutoff frequency (~1.9 GHz). Merely the FPC waveguide (TE10 cutoff at 1.1 GHz) can capture these otherwise trapped modes. The coupled fields are transferred to an absorptive filter device ($S_{11} \sim -20 \text{ dB}$) outside the cavity cryomodule. At the same time the filter is designed to represent a very small insertion loss for the incoming wave from the klystron at the $FM$ frequency.

Though the number of coaxial and waveguide couplers is not strictly limited, it comes with a trade-off between the merits of the incremental improvement of HOM-damping and associated costs and complexities. It needs to account for engineering constraints such as space requirements for the Fundamental Power Coupler (FPC) and the mechanical tuner attachment, which also ties in with the engineering rationales for the helium vessel and cryostat design. E.g., an HOM endgroup with one or more dampers can be positioned either inside or outside the helium vessel. The former has the advantage that the endgroup can be very closely joined to a cavity end-cell iris. This yields optimal coupling to evanescent fields. Coaxial HOM couplers are typically placed outside the helium vessel, which allows direct access. This for instance is necessary when tuning of the $FM$ rejection filter is needed, which aims to maximize its $Q_{\text{ext}}$-value to avoid inadvertent damping at the nominal cold operating temperature.

Most existing cavities employ a rather minimum set of two HOM couplers per cavity. Figure 2 depicts different coaxial couplers in use. The housings and antenna probes are typically made from solid niobium to remain superconductive during operation. Otherwise a premature thermal runaway (quench) of the cavity can be caused originating in the endgroup. Compared to the TESLA-type coupler, the LHC couplers have the advantage that the antenna probes are actively cooled via liquid helium circuits. These couplers have been tested up to 800 W HOM power [26]. Most prominently, the TESLA nine-cell cavity [14] - conceived over two decades ago - has been replicated more than 1000 times by industry for use in

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1 The pillbox mode nomenclature is used throughout with the indices $m$, $n$, and $p$, denoting the azimuthal, radial and longitudinal field dependency, respectively. Due to the non-pillbox shape of the SC cavities, the presence of beam tubes and field symmetry-breaking components, not only the transverse magnetic (TM), but also the transverse electrical (TE) modes can possess longitudinal fields on axis and are thus excited by a beam traversing the cavity on axis. Especially for SC cavities with high unloaded $Q_0$-values, the damping of TE-like and TM-like HOMs becomes equally important.

2 Manual rejection filter (notch) tuning is done at room temperature. The procedure requires geometrical deformations at the HOM damper housing to tune the capacitive rejection filter (gap), which must foresee the material contraction upon cool-down. $Q_{\text{ext}}$-values are sometimes measured lower than desired at cryogenic temperature causing excessive damping of the fundamental mode, which necessitates a re-tuning.
multiple small to large-scale electron accelerators. The cavity development required several years of intense experimental and numerical analysis. This included the optimal arrangement of two couplers attached to beam tubes with one coupler positioned on each cavity end close to the end-cells. This concept took into account two differently shaped end half-cells to asymmetrically push out RF fields of parasitic dipole modes to at least one coupler to improve the damping capability [27]. The TESLA cavity has also been selected for the Linac Coherent Light Source upgrade (LCLS-II), particularly after successful 'built-to-print' mass fabrication for the European X-ray FEL at DESY [28]. The HOM-damping is deemed sufficient for both facilities using broadband DESY-type coaxial hook couplers. The design originates from a coupler developed for the four-cell 500 MHz HERA cavity in the 1980s ([29], [30]). A scaled version has then been conceived for the TESLA cavities [31], later adopted for SNS [10], JLab High Gradient (HG) and Low Loss (LL) cavities, respectively.

**Figure 2.** Top row (left to right): Coaxial couplers developed for LHC [26] and Soleil [32], respectively, utilizing narrowband loop couplers for trapped dipole modes (TE111, TM110) and more broadband couplers (antenna or loop) for higher frequency HOMs. Middle row (left to right): Early couplers developed by DESY for HERA with inductive stubs [30], demountable version proposed for TESLA [31] and today’s welded version used for the TESLA cavity. All loop couplers are principally based on an early version for the LEP cavity [33]. Bottom row left to right: JLab’s single-crystal sapphire RF feedthroughs for CW operation of the TESLA-type coupler [34], prototype HOM endgroup as used for JLab HG and LL cavities [34] towards the final CEBAF C100 LL endgroup design [35]. Cavity couplers have been conceived as demountable with vacuum flanges or electron-beam welded to cavity beam tube ports. Each concept has its Pros and Cons as discussed in the past [31]. Each referenced photography or figure falls under the Creative Commons Attribution 3.0 (CC-BY 3.0) license (https://creativecommons.org/licenses/by/3.0/).
Proposed HC cavities for ERLs employ up to six couplers. This implies that existing concepts cannot meet the stability requirements of these machines. However, not only high beam current machines are affected by beam instabilities. Especially in recirculating electron machines regenerative beam break-up instabilities (BBU) can occur at rather low beam currents. For instance, a multi-pass BBU instability has been observed at CEBAF in 2007 at surprisingly low injected beam current of merely 40 µA, which is far below the designed beam current instability threshold [36]. The cause was identified as being a resonant excitation of an inadequately damped dipole mode in a cavity of a then freshly installed prototype cryomodule. The cryomodule accommodated both JLab LL and HG prototype cavities. Each of these prototypes originally conceived the use of four coaxial couplers, two on either side of the cavity. However, the two couplers on the FPC side were blanked off since causing a thermal runaway due to FM heating [34]. Albeit the HOM damping was conceived sufficient with the two remaining couplers [35], several of these cavities exceeded CEBAF’s transverse impedance instability threshold. This has been experimentally verified after cryomodule de-commissioning [37]. The cause of the BBU-inducing cavity could be attributed to fabrication irregularities, particularly for one HG cavity. Note that the TESLA-type HOM couplers were designed for low-duty cycle operation without active cooling. During the CEBAF upgrade prototype development in 2003 it was discovered that cavities could be tested to only a few MV/m in CW operation [38]. The limitation was a thermal runaway originating in the RF feedthrough probe tips of the HOM couplers. To adapt the couplers for high-field CW operation, the feedthroughs were modified by using a single-crystal sapphire RF window instead of alumina, which promotes a direct heat path from the probe tip to a bulk copper sleeve thermally anchored at the outside conductor [34]. This provided adequate heat transfer to operate beyond 20 MV/m in CW mode. In parallel, the HOM couplers were also placed slightly further away from the cavity iris for C100 LL compared to prototype cavities, but re-oriented to satisfy the HOM-damping requirements [35].

For SNS cavities, the scaled TESLA-type couplers are the cause of different operational failures including resonant multipacting [29]. A re-evaluation of the HOM-damping requirements found that the HOM couplers are not needed for stable operation, which is also due to the comparably heavy H+ ions. This led to the decision to remove the RF feedthroughs of the HOM couplers in cryomodules once a cryomodule is taken out of the machine for repairs. Numerical calculations performed after cavity construction could provide evidence of the resonant multipacting in the couplers [39], not only for the modified SNS couplers, but also for the original TESLA-type couplers but less severe and less frequently observed, though experimentally verified [40].

The examples above imply that the usage of an established HOM coupler design at a different cavity frequency or in an unexplored operation regime (e.g. pulsed vs. CW) can impose unforeseen risks with severe consequences. Using numerical tools has become essential to avoid such issues at the design level.

Once HOMs are propagating through a chain of cavities, their Q-values can be lowered by all participating dampers. The interplay of HOMs among cavities can be rather involved since RF fields might be strongly reflected back from neighboring cavities that can act like filters rather than broadband transmission lines. Furthermore, beam pipe dimensions, i.e. tapered or stepping down to smaller diameters, determine up to which frequency modes are reflected. Standing waves with unfavorable field notches at coupler positions can be created [37], but also utilized by design as an advantage to improve the HOM-damping.
Using cavity BLAs in lieu of coaxial or waveguide dampers implies that beam tubes are enlarged such that even the lowest frequency HOM can escape the cavity. This concept has been employed successfully for storage ring cavities to cope with average beam currents in the order of one Ampere. It has first been realized for the CESR and KEKB single-cell cavities, which have since been adopted for various other storage ring-based light sources [41]. These cavities may operate at relatively moderate voltage of a few MV ($E_{\text{acc}}$ is in the order of 10 MV/m). The CESR cavity exhibits a straight beam tube (ID = 240 mm) and one pipe with four flutes (max. ID = 366 mm) that allows the lowest two dipole modes to escape from the cavity, whereas the KEKB cavity employs two straight beam tubes for the same purpose (ID = 220 and ID = 300 mm) [42]. Compared to normal-conducting (NC) cavities, the SC cavities allow enlarging the beam tubes significantly since the reduction of the $F_M$ shunt impedance is not a constraint given the high $Q_0$-value. Thereby the $R/Q$-values of all HOMs are lowered considerably, which relaxes the damping requirements ($Q_{\text{ext}}$). The $R/Q$-value of the $F_M$ is lowered at the same time, which is beneficial to mitigate transient beam loading effects and coupled bunch instabilities that can arise from the $F_M$ itself, especially at high beam current operation. These effects also profit from the higher gap voltage achievable compared to NC cavities [42].

A broadband beam line absorber can be realized by lossy ferrites or ceramic tiles surrounding the beam tube perimeter as depicted in Fig. 3.

![Image](CESR multi-kW cavity beam line absorber)

![Image](KEKB multi-kW cavity beam line absorber)

![Image](Cornell injector beam line absorber for up to 200 W at 80 K temperature)

![Image](DESY inter-cryomodule beam line absorber for 100 W at 70 K temperature)

**Figure 3.** In sequence: Room temperature multi-kW beam line absorber for CESR [43] and KEKB (credit: KEK, e.g. [44]) respectively, 200 W load for 80 K operation at the Cornell injector [45], and DESY 100 W load for 70 K operation between cryomodules employed for the EU X-ray FEL [46] and adapted for LCLS-II. Each referenced photography falls under the Creative Commons Attribution 3.0 (CC-BY 3.0) license (https://creativecommons.org/licenses/by/3.0/).

Yet, BLAs bear implications such as contamination risks from the absorber material in the beam line vacuum and potential electrostatic charge build-up due to the traversing beam that can lead to deflecting fields if the material has no residual DC conductivity or is not properly shielded [47]. Furthermore, absorbers placed between cavities are not desired when seeking to minimize the cryostat real estate length. At a HOM power level of several hundred Watts it can become impractical to incorporate BLAs at cryogenic temperatures. Rather long cold-to-warm beam line transitions are then required. E.g., the ferrite absorbers for CESR and KEKB have to withstand several kW and are therefore water-cooled at room temperature outside the cryostat ([43], [48]). For CESR this led to a ~58 cm long transition from the cavity equator to the absorber flange [42]. Moreover, each of these single cell cavities is housed in its own cryostat, which leads to a comparably long installation length. In storage ring light sources this can be a concern since available straights for the RF cavities are limited (e.g. [49]). In contrast, two or four cavities are linked together via rather large tubes in a single cryostat for SOLEIL ([1], [32]) and LHC cavities.
The beam tubes are tapered at the cryomodule ends terminating in smaller pipes such that cavities may have strong resonant interaction with each other. Instead of BLAs, conventional coaxial antenna and loop couplers are mounted to the large beam tubes (cf. Fig. 2) with their locations optimized according to the standing waves formed by critical HOMs.

The CESR HOM load has been modified for the Cornell ERL injector cryomodule (ICM) [45]. At a HOM power level of up to 200 W (100 mA beam current) the loads operate at 80 K and are placed between the 2 K cavities. The load temperature is a compromise between simplifying the thermal transition and the broadband absorber efficiency taking into account the need to use several materials to span a wide spectral range (6 mm rms bunch length).

The ICM load has also been adopted for the Cornell Main Linac cryomodule (MLC) with slight modifications [51]. BLAs can be placed within the beam line between cryomodules to intercept the traveling HOM power, e.g. at 70 K for EU X-ray FEL cryomodules. Here only a few Watts of power dissipation are expected at low-duty cycle operation, though the design has been outlined for up to 100 W [46].

Most absorbers tend to lose their lossy characteristics at cryogenic temperatures. Therefore JLab collaborated with industry to develop cryogenic absorbers, particularly for CEBAF ([52]), since formerly utilized material [16] is not produced anymore. E.g., a developed lossy AlN-SiC ceramic [53] is now being used for BLAs as well.

Similarly to the LHC and Soleil cavities, the BNL3 HC 704 MHz cavity employs large beam pipes in combination with coaxial couplers but avoiding BLAs for a compact design [16]. The beam tubes taper off on either side of the cavity within a rather short distance to mitigate the crosstalk between individual cavities [54]. Six coaxial dampers are considered for heavy HOM-damping, three placed on either side of the cavity on the large beam tubes. The couplers have been more recently developed to improve the performance of the more established TESLA-type coupler. Hereby, two filter stages are employed to broaden the fundamental mode rejection filter by creating two notches in the transmission spectrum. This aims to mitigate the issue of notch detuning during thermal contraction. The couplers employ a straight antenna probe protruding into the beam tube. The transmission characteristic has been improved compared to a TESLA-type coupler as verified by numerical simulations. Since the beam tubes allow propagation of the HOMs, the couplers are placed further away from the cavity close to the tapered tube sections (see Fig. 4).

![BNL3 HC cavity design for ERL applications](image)

**Figure 4.** BNL3 HC cavity design for ERL applications (left, [21]) and broadband two-stage coaxial coupler (right, [54]).

HOM waveguide couplers have been sparsely used for SC cavities so far, though these are broadband transmission lines with high power capability, while consuming a relatively small beam line space. The static heat leak from room temperature into the cryogenic environment is manageable by appropriate heat
stationing. A major benefit is that a fundamental mode rejection filter is not required since the cutoff frequency provides a natural rejection. Note that no multipacting concerns have been reported in the HOM waveguides of C20/C50 cavities operating since two decades. Compared to coaxial couplers, the waveguides are bulkier and can complicate the Helium vessel and cryomodule design. On the other hand, the fabrication tolerances are rather relaxed. The cavity waveguide endgroups can be produced from deep-drawn sheets like cavity cells and parts be joined by electron-beam-welding (Fig. 5).

**Figure 5.** Deep-drawing of Nb sheet (left) into one half (mid) of a three-folded HOM waveguide endgroup as conceived for JLab’s heavily HOM-damped high current ERL-FEL cavity design [55]. A prototype cavity is shown on the right.

The *JLab HC* five-cell cavity has been specifically designed for heavy HOM-damping suitable for high beam current (Ampere level) ERL and FEL light sources. It is meant to achieve relatively high accelerator fields around 20 MV/m CW [56]. The cavity is packed with two cavity endgroups each utilizing three waveguides on either side of the cavity close to the end-cells. One waveguide serves as an FPC. The cavity possesses only five cells with comparably large aperture \( k_{cc} = 3.2\% \) to enhance the field of trapped/localized modes at the waveguide locations. Three waveguides are spaced symmetrically around the beam tube (120 degrees), which eliminates RF field deflecting fields. This concept is principally an adoption of the waveguide arrangement employed for NC cavities. The waveguides are integrated into the Helium vessel for efficient cooling. They are designed long enough to not damp the fundamental mode. The waveguides are bent and extent to room-temperature, where the absorbers can be water-cooled. Based on a design using lossy SiC ceramic tiles, the HOM power capability is 4 kW per waveguide absorber, which totals 20 kW per cavity. Note that the two HOM endgroups are rotated around the beam axis such that a straight two-phase He return pipe can pass through the structure. Several *JLab HC* cavity prototype cavities have been high-power tested successfully [57]. A conceptual design of the high current cryomodule had been developed as depicted in Fig. 6 [58], but not yet realized for a particular project.
Figure 6. Conceptual cryomodule design for ERL and FELs with a JLab HC cavity pair [58]. Each cavity employs six HOM waveguide dampers with one doing double-duty as an FPC.

Figure 7. The provisional layout of the bERLinPro linac cryomodule (top) housing three seven-cell cavities with HOM waveguide dampers (bottom right), i.e. five waveguides per cavity and one coaxial input coupler. The waveguides are curved so as to allow space for the He gas return pipe as visible in side view (bottom left). The figure is taken from ref. [59].

Yet, the JLab HC HOM-damping concept has remained a viable solution for future high current machines such as for the e- cooler ERL for JLEIC ([60], [61]). The HOM-damping concept has been principally adopted for the main linac seven-cell cavity of the 100 mA bERLinPro demonstration ERL under construction. This cavity combines the strong waveguide damping with the benefit of enlarged beam tubes as in case of the Cornell MLC design. Hereby a coaxial in lieu of a waveguide FPC is employed [11]. A provisional layout of the cryomodule engineering design is shown in Fig. 7 [59]. The HOM power dissipation has been estimated to be only 25 W per absorber.
For the proposed electron-ion collider eRHIC the \textit{BNL4 HC} five-cell cavity has been conceived. It operates at 647 MHz compared to 704 MHz for \textit{BNL3 HC}. Since eRHIC is a multi-pass, high current ERL, BBU instabilities are a concern such that strong HOM damping is required. This lower frequency has been chosen due to beam dynamic reasons [7], but is higher than originally conceived for eRHIC (422 MHz, [62]) mainly due to size and weight restrictions concerning cavity processing and cryomodule engineering. The \textit{BNL4 HC} design is based on the \textit{BNL3 HC} cavity. It exhibits large beam tubes avoiding BLAs by design. The beam tubes step down at a rather short distance away from the cavity. Compared to \textit{BNL3 HC}, HOM waveguides instead of coaxial dampers are employed. Two waveguides are located on either side of the cavity at the far end of the large beam tube. Each tube features thin-walled tapered transitions with a short coaxial line at the ends. This improves coupling to the two waveguides per HOM endgroup. The waveguides are single-ridged with smooth roundings. The HOM endgroups are rotated with respect to each other to eventually capture all mode polarizations. Note that this configuration is still under optimization [63].

\textbf{Figure 8.} \textit{BNL4 HC} 647 MHz five-cell HC cavity with four single-ridged waveguide dampers developed for eRHIC (courtesy of W. Xu). The cross-sectional views reveal the ridges in each of the beam tubes.
2.3 Heavily Damped Normal-Conducting (NC) Cavities

Normal conducting (NC) cavities require small apertures and a re-entrant cell profile to maximize the fundamental mode shunt impedance and thus minimize the power requirements at a given $E_{\text{acc}}$. This reduces the cooling demands of the cavity walls, which otherwise becomes a major limitation at high power operation. Unfortunately, such designs also raise the $R/Q$-values of the HOMs. The voltage achievable in high performing single-cell NC cavities can be close to 1 MV, but cannot fully compete with SC cavities. Therefore, more cavities are required to provide the same voltage, which linearly increases the cavity impedance built into a machine. For storage rings at medium beam energies (few GeV) and beam currents of a few hundred mA, the NC technology is still a viable choice over SC cavities. To cope with the HOM impedance, the cavities must be heavily damped, which can be done by on-cell dampers without major concerns. Table 2 summarizes important parameters of such HOM-damped NC cavities.

| Cavity       | $f_0$ MHz | WG shape | $f_{c,WG}$ MHz | $f_0/f_{c,WG}$ | R/Q* Ohm | Q0 | R MΩ | N.C. | ID b.t. mm | $f_0/f_0^*$ |
|--------------|-----------|----------|----------------|----------------|-----------|----|------|------|------------|------------|
| ESRF [64]    | 352.25    | Round, DR| 452.7          | 1.29           | 72.5      | 33800 | 2.45 | Yes | 100        | 5.0        |
| DAΦNE [65]   | 368.3     | Rect., DR| 492            | 1.34           | 60.6      | 33000 | 2.0  | No  | 242.8 t  | 2.0        |
| PEP-II [66], [67] | 476.3   | Rect.    | 600            | 1.26           | 117.3     | 32469 | 3.81 | Yes | 95.25      | 3.9        |
| EU Cavity [68] | 499.65  | Round, DR| 625            | 1.23           | 117.3**   | 29626 | 3.48 | Yes | 74 t  | 4.7        |

$R/Q = \frac{V_{\text{eff}}^2}{2P_{\text{avg}}}$, *similar to PEP-II as measured for EU cavity production unit for the MLS light source.

| Cavity       | $f_0$ MHz | WG shape | $f_{c,WG}$ MHz | $f_0/f_{c,WG}$ | R/Q* Ohm | Q0 | R MΩ | N.C. | ID b.t. mm | $f_0/f_0^*$ |
|--------------|-----------|----------|----------------|----------------|-----------|----|------|------|------------|------------|
| ESRF [64]    | 352.25    | Round, DR| 452.7          | 1.29           | 72.5      | 33800 | 2.45 | Yes | 100        | 5.0        |
| DAΦNE [65]   | 368.3     | Rect., DR| 492            | 1.34           | 60.6      | 33000 | 2.0  | No  | 242.8 t  | 2.0        |
| PEP-II [66], [67] | 476.3   | Rect.    | 600            | 1.26           | 117.3     | 32469 | 3.81 | Yes | 95.25      | 3.9        |
| EU Cavity [68] | 499.65  | Round, DR| 625            | 1.23           | 117.3**   | 29626 | 3.48 | Yes | 74 t  | 4.7        |

These cavities have been specifically designed for 3rd generation light sources and $e^+e^-$ collider rings and comprise the BESSY/EU cavity (used for ALBA, BESSY-II/HZB, MLS), the DAΦNE cavity (a ~1 GeV phi meson $e^+e^-$ collider), the cavity for the PEP-II $e^+e^-$ B-factory, which has been turned off since 2008, and the ESRF storage ring cavity. Except for the DAΦNE facility operating at comparably low energy, the maximization of the fundamental mode shunt impedance has been important for all other cavities, thus having a re-entrant shape (nose cones) and comparably small iris apertures. This will trap the HOMs with the highest shunt impedances. The similarity among the cavities is the utilization of three broadband on-cell waveguide dampers spaced apart by 120 degrees in azimuth around the cavity (Fig. 9). This assembly allows damping of any dipole polarization by at least one damper and also will efficiently capture quadrupole modes. The DAΦNE [69] and PEP-II cavity [70] were the first to employ this concept followed by the EU cavity [71] and the ESRF cavity [72].
While the DAΦNE and PEP-II cavities utilize rectangular HOM waveguides, the EU and ESRF cavities use round tubes. For DAΦNE a tapered double-ridged waveguide to coaxial transition has been developed to avoid in-vacuum loads [76]. Hereby, the two ridges increase the capacitance to lower the cutoff frequency compared to a waveguide with the same width and height. This reduces the overall size of the waveguide as a benefit. The cutoff is kept constant along the taper for a broad transmission. The external loads can be standard 50 Ω water-cooled absorbers, which are commercially available and can readily withstand power levels of several kW. A similar broadband transition has been developed for a round double-ridged waveguide for the prototype EU cavity [77]. However, for production units it was decided to use straight in lieu of tapered waveguides, which has proven to further lower both the longitudinal and transverse mode impedances [78]. Moreover the waveguide cutoff frequency was reduced - in reasonable trade-off with the TM010 shunt impedance - to capture a persistent mode resonating at the waveguide cutoff with small group velocity. The loads consist of water-cooled ferrite tiles that can handle a few kW of power. The ESRF cavity principally adapted the EU cavity concept and scaled it to the required lower operation frequency with a few modifications [64]. Compared to the PEP-II and DAΦNE cavities, the cavity for the EU cavity is not bell-shaped but pillbox-like. Therefore the couplers point out radially from the straight equator sections, which provides a small real estate length of only 0.5 m (flange to flange) allowing to efficiently stack several units. The advantages of the EU cavity made it attractive to be employed in several modern storage ring light sources (Alba/Spain, BESSY-II/Germany, ESRF/France, MLS/Germany [72]).
3 Comparison of longitudinal and transverse impedance spectra

The figure of merit for beam stability aspects is the shunt impedance $R/Q \cdot Q_l$, and not merely the loaded $Q$-value, $Q_l$, of an HOM. Larger $R/Q$-values will require lower $Q_l$-values and vice versa. Impedance spectra will be reviewed in the following comprising the cavities summarized in Table 3. Experimental and simulation data have been gathered as published and to the best of the author’s knowledge. Data sources taken from third parties are referenced. In some cases, only $Q$-values have been reported, which therefore was not sufficient to determine HOM impedances. In some other cases, no experimental data could be found in literature or only 2D simulation data were reported. The latter are regarded more cautiously since symmetry-breaking components (e.g. FPC coupler, fluted beam tube) may alter results. Several cavities have therefore been modeled in 3D to further support the findings with wakefield and/or Eigenmode computations. These calculations include absorbers with complex material properties for coaxial and waveguide absorbers [79]. The findings for BNL3 HC and BNL4 HC are not included since either not incorporating the details of the coaxial couplers (BNL3) or not deemed fully optimized at the time of writing (BNL4). For SC cavities it is assumed that $Q_l \approx Q_{ext}$, i.e. neglecting RF losses in the superconducting walls if not otherwise mentioned. The focus is on the longitudinal (monopole) and transversely deflecting (dipole) modes since these are most parasitic although in some cases modes with higher transverse order (e.g. quadrupole modes) can become relevant for beam dynamics as well.

**Table 3.** Cavity data collection used for this study as referenced. M = measured data, W = wakefield simulation, E = Eigenmode simulation

| Cavity      | $f_0$ (MHz) | $N_C$ | Data origin and reference                  |
|-------------|-------------|-------|-------------------------------------------|
| SOLEIL      | 352.2       | 1     | M’ [32]                                   |
| PEP-II      | 476.3       | 1     | M + W [67]                                |
| BESSY       | 500         | 1     | M + W + E (author, [68])                  |
| CESR        | 500         | 1     | 2D E** [49] + W (author) + 3D E (author)  |
| KEKB        | 508.9       | 1     | 2D E*** [49]                              |
| JLab HC     | 748.5       | 5     | M + W [57]                                |
| Cornell ICM | 1300        | 2     | 2D E**** [80]                             |
| Cornell MLC | 1300        | 7     | W (author)                                |
| TESLA       | 1300        | 9     | E (author)                                |
| C100 LL     | 1497        | 7     | M (author)                                |
| C20/50 OC   | 1497        | 5     | M + W + E (author)                        |

* Measurement for prototype copper cavity, ** 2D SuperLans calculation for single cavity, *** 2D SuperLans calculation for KEKB cavity pair linked with large beam tube, **** 2D SuperLans for complete Cornell ICM five-cavity string (monopole modes only)

For the longitudinal, $R_l$, and dipole impedance, $R_{tr}$, the following definitions are used:

$$R_l = \frac{R(r=0)}{Q} \cdot Q_l \quad [\Omega] \quad (1)$$

$$R_{tr} = \frac{R(r)}{Q} \cdot Q_l \cdot \frac{1}{k \cdot r^2} \quad \left[\frac{\Omega}{m}\right] \quad (2)$$
Herein $k = \omega/c$ is the wave number and $r$ the radial offset from the cavity axis. The circuit definition $R(r)/Q = V(r)^2/(2Q \cdot P_{\text{avg}}) = V(r)^2/(2\omega U)$ is chosen throughout, wherein $V(r)$ represents the transit-time corrected voltage along the cavity and $P_{\text{avg}}$ and $U$ the average power and cavity stored energy, respectively. Figures 10 and 11 plot the monopole and dipole impedance spectrum, respectively. The lines correspond to wakefield calculations, the symbols represent either measured data or Eigenmode simulations as denoted in Table 3. The frequency data have been scaled to obtain a common accelerating mode (reference) frequency, $f_{\text{ref}}$ of 500 MHz. This allows a quantitatively equal comparison of impedances, while simplifying the graphical comparison for the vast number of cavities. Note that the scaling does not affect the $R_l$-values, however $R_t$ needs to be multiplied by $f_{\text{ref}}/f_0$ due to the denominator $k \cdot r^2$ in eq. (2). All data have then been divided by the number of cavity cells $N_C$ for a fair comparison. These scaled spectra allow identifying certain mode type regimes, which are similar in each cavity, though the correlation becomes more involved at higher frequencies since mode types may change sequence depending on the cavity shape. The TM011-like HOMs typically possesses the largest $R/Q$-values among all monopole modes, but not always the highest HOM impedance. The TE111 and TM110 HOMs are among the most problematic dipole modes, though other HOMs can become critical at higher frequencies, which for instance is true for TM111 modes in the C100 LL cavity.

Figure 10. Monopole mode impedance spectra for various SC and NC cavities as measured and calculated normalized by the number of cavity cells and scaled to a common TM010 acceleration mode frequency of 500 MHz. The broadband coupling impedances (lines) have been calculated by wakefield simulations. The symbols represent either measured data or Eigenmode simulations. Refer to legend and Table 3 for clarification. For the KEKB and Cornell ICL cavity, results were published for 2D computations with two or five cavities, respectively, linked together by large beam tubes including beam line ferrite absorbers between cavities ([49], [80]). This allows for the crosstalk of cavities through propagating waves. In these cases the impedances were divided by the number of cavities as well.
An efficient HOM-damped cavity design should exhibit well-balanced impedances over the full spectrum. This is not necessarily the case for existing designs. The modes with the highest impedances can limit the stable beam current achievable in a machine. These modes are dubbed ‘performance-limiting’ modes in the following.

**Figure 11.** Dipole impedance spectra of various SC and NC cavities as measured and calculated. Refer to Fig. 10 for explanation.
3.1 Discussion of results

Table 4 summarizes the performance-limiting modes for all reviewed cavities to characterize the HOM-damping efficiency more easily. It allows a ranking of cavities by damping performance. Since the data cover a broad spectral range well beyond the first beam tube cutoff frequency, one can assume that no higher monopole or dipole impedances exist. As explained above, all impedances are scaled to \( f_{ref} = 500 \text{ MHz} \) and normalized by the cell number for a fair comparison. The values can be readily scaled to the true cavity operating frequencies and number of cells given Table 4.

| Cavity          | \( f_0 \) MHz | Max. \( R_l/N_C \) kΩ | Max. \( R_{tr}/N_C \) kΩ/m | Max. \( R_l/N_C \cdot f \) kΩ·GHz |
|-----------------|----------------|------------------------|----------------------------|----------------------------------|
| SOLEIL          | 352.2          | 200                    | 885                        | 248 @ 1.24 GHz                   |
| PEP-II (measured)| 476.3          | 2.29                   | 134                        | 3.12 @ 1.36 GHz                 |
| PEP-II (simulated)| 476.3        | 5.57 (W)               | 151 (W)                    | 18.23 @ 3.27 GHz               |
| EU (measured)   | 500            | 10.7                   | 59                         | 7.3 @ 0.680 GHz                |
| EU (simulated)  | 500            | 1.64 (W)               | 53.9 (W)                   | 1.1 @ 0.667 GHz                |
| CESR (2D only*) | 500            | 4.1                    | 21                         | 9.5 @ 2.34 GHz                 |
| CESR (3D**)     | 500            | 12.2 (trapped TE211)   | 83                         | 11.4 @ 0.937 GHz               |
| KEKB            | 508.9          | 1.82 (2D only)         | 7.91                       | 4.24 @ 2.34 GHz                |
| BNL4 HC         | 650            | design not finalized   |                            |                                  |
| BNL3 HC         | 703.79         | details of coaxial couplers not included, damping overestimated |                       |                                  |
| JLab HC         | 748.5          | 75.6                   | 285                        | 106 @ 1.406 GHz                |
| bERLinPro       | 1300           | not yet published or computed in detail |                       |                                  |
| Cornell ICM     | 1300           | 2D only for five-cavity string | dipole modes not computed |                                  |
| Cornell MLC     | 1300           | 5.9                    | 117                        | 8.68 @ 1.47 GHz                |
| TESLA           | 1300           | 707                    | 1205                       | 668 @ 0.950 GHz                |
| C100 LL         | 1497           | 10637                  | 17961                      | 9284 @ 0.870 GHz               |
| C20/50 OC       | 1497           | 108 (TE111 V**)        | 15848                      | 65.3 @ 0.603 GHz***            |

* 2D SuperLans computation with both beam pipes tapered [49], ** 3D CST computation with one beam tube end matched, one beam tube tapered, see Appendix, *** 5.68 kΩ and 5.5 kΩ·GHz at 0.969 GHz for monopole (TM011) mode

A graphical representation of the results is provided in Fig. 12 plotting the maximum longitudinal and transverse impedances as a function of \( N_C \). The findings reveal that the most efficient HOM-damping performance can be achieved with either enlarged beam tubes leading to BLAs or with on-cell dampers. The NC cavities (EU, PEP-II) are therefore among the best ranking HOM-damped cavities yielding impedances even comparable to the CESR and KEKB cavities. The NC cavities exhibit significantly larger \( R/Q \)-values than SC cavities due to the need of a high \( FM \) shunt impedance (small apertures). The \( Q_{ext} \)-values must therefore be appropriately smaller to yield the same impedance, which implies broadband, and high damping efficiency of the on-cell dampers. The benefit of the on-cell dampers arises from the coupling to the resonant modes at the site of their origin within the cavity. The \( EU \) for instance requires no extra real estate length for dampers. For PEP-II and DAΦNE the waveguides point out with a certain angle to the beam axis for best performance. These cavities could still be stacked closely together to save real estate length. On-cell dampers have so far not been explored fully for accelerating SC cavities, whereas BLAs in the cavity-interconnecting region may not be practical for certain machines. The feasibility of using on-cell dampers will be elaborated later. It should be noted that beam tube boundary conditions matter for propagating modes. The 3D wakefield solver computations assume that all
outgoing waves are absorbed at end of beam tubes by matching fields to waveguide modes. Likewise in the complex 3D Eigenmode simulations, the beam tubes are matched with broadband absorbers. This prevents standing wave fields and represents an ideal scenario for HOM-damping unless the location of dampers is specifically optimized depending on standing waves. For the 2D calculations published elsewhere (CESR, KEKB), the beam tubes were equipped with cylindrical absorbers taking into account ferrite material properties. The BLAs have been more realistically resembled for the 3D Eigenmode calculations for the CESR cavity including the fluted beam tube (see Appendix).

Figure 12. Maximum monopole (left) and dipole impedance (right) for various SC and NC cavities as measured (meas.) and simulated (sim.) in dependence on the number of cells.

Not surprisingly, the damping becomes more difficult in multi-cell cavities than in single-cell cavities, though an improper HOM-damping concept may cause unnecessarily high impedances. One difficulty when increasing the cell number ($N_c$) is the higher probability of trapped modes within the cavity. A mode in a single cell theoretically splits into $N_c$ passband modes of the same mode type differentiated by their phase advance ($\varphi_j = j \cdot \pi/N_c$ with $j = 0, 1, ..., N_c$). This naturally yields passband modes with small amplitudes in the end-cells (particularly $1 \pi/N_c$ modes). The situation is illustrated in Fig. 13 by means of a five-cell cavity. The field amplitudes have been derived from lumped circuit theory. Hereby ideal electric (E) and magnetic (M) boundary conditions are resembled at the cavity ends including mixed boundary state. This presupposes that all cells are ringing at the same frequency and that the cell coupling is identical from one cavity to the next. In reality the boundary conditions are not ideal and depend on how a mode couples to the beam tubes. The phase advance can be significantly altered near the end-cells. Deviations from the ideal behavior can cause the existence of additional passband modes, e.g. caused by resonant coupling effects to adjacent coupler/waveguide ports, as well as trapped fields resulting in less than NC passband modes. Fabrication tolerances/errors can further enhance the confinement of modes. Tilted field amplitudes resembling those of the mixed boundary conditions (half integer phase advances) have been observed as well [71]. If HOM-dampers exist only on one side of a cavity, tilted fields to the other side cannot be damped efficiently. This can lead to severe consequences as evidenced by the BBU at CEBAF with a JLab HG prototype cavity.
Figure 13. Field amplitudes (a.u.) of passband modes in a five-cell cavity plotted along the cells number. The amplitudes have been computed utilizing lumped circuit elements to represent a five-cell resonator. Cells couple only to next neighbor cells. End-cells terminate in either electric (E) or magnetic (M) boundary conditions (left/right) as indicated to the right of the figure. Four permutations of boundary conditions are feasible associated with the four rows. The phase advance is denoted for each case. Individual cells are differentiated by colors. Amplitudes may vanish in individual cells. For the purely magnetic boundary conditions (M/M) no 0-mode is possible. For the purely electric boundary conditions (E/E), no π-mode is possible. The phase advances are denoted, which can be half integers for the mixed boundary conditions (M/E, E/M).

Further implications are illustrated in Fig. 14 for the Cornell MLC seven-cell cavity. It plots the computed Q_{ext}-values - due to absorption at the beam tube ends only - over a wide spectral range. Despite the enlarged beam tubes, several modes are trapped since these resonate below the relevant beam tube cutoff (dashed vertical lines). The field confinement is not only experienced for π/7-modes, but also for π-modes since end-cells differ from the mid-cells geometrically. These modes typically exhibit the largest Q_{ext}-values in a passband. For the same reason, some HOMs resonate primarily localized in the end-cells, which mainly concerns modes with higher azimuthal order (m ≥ 2). Monopole (m = 0) and dipole HOMs (m = 1) can more or less escape from the cavity (Q_{ext} < 1e6), but for m ≥ 2 several passband modes are principally undamped.
Figure 14. External $Q$-values as computed for modes up to 3.65 GHz in a bare 1.3 GHz seven-cell cavity with enlarged beam tubes. The beam tubes have been matched on either side at short distance to the end-cells, which determines the $Q_{ext}$-value (no other losses). Modes with similar azimuthal symmetry ($m$) are grouped as denoted in the legend. The passband nomenclature is given. Examples of individual electrical fields corresponding to confined modes are plotted. Beam tube cutoff frequencies are represented by dashed vertical lines.

Trapped modes become critical when the phase velocity, $v_{ph}$, equals the particle velocity, $v_p$, resulting in a comparably high transit time factor, $TTF$, and thus $R/Q$-value. The dispersion relation $f_j(\phi_j)$ ("Brillouin diagram") can be used to illustrate the situation. It is expressed by

$$f_j = \frac{f_0}{\sqrt{1 + k_c \cos \phi_j}}$$

with $\phi_j = j \frac{\pi}{N_c}$, $j = 0, 1, \ldots, N_c - 1, (N_c)$: identical boundaries

$$f_j = \left( j - \frac{1}{2} \right) \frac{\pi}{N_c}$$

with $\phi_j = j, \ldots, N_c$ : mixed boundaries

(3)

with $f_0$ equaling the resonance frequency of the single cell ($\phi = \pi/2$). Figure 15 depicts the Brillouin diagram as calculated for the C100 LL cavity ($\beta_g = 1$). The intersection of the light line ($v_{ph} = c_0 = 2\pi f_0/\phi_j * L_c$, $L_c =$ cell length) and $f_j(\phi_j)$ implies synchronism (large $TTF$-factor) of the beam with the RF field as is the case for the accelerating mode. For HOMs it is important to avoid this situation, particularly for the more confined $\pi/N_c$ and $\pi$ modes. As can be seen in Fig. 15, this has not been achieved for the C100 LL cavity, which exhibits a TM111 dipole pair around 2.9 GHz close to the light line (red star, cf. with Fig. 15). The phase advance of the modes is rather between 0 and $\pi/7$. These TM111 modes are prone to exhibit a tilted field profile - similar to the cases in Fig. 13 for a half integer ($0.5\pi/7$) phase advance - which has been confirmed experimentally [37].
The total impedance built into a machine depends on the number of cavities needed to yield the required accelerating voltage. For medium to large-scale machines it is cost-saving to install multi-cell rather than single-cell cavities to reduce the number of auxiliary components (FPC, tuners etc.). $N_C$ single-cell cavities can be replaced by one cavity with $N_C$ cells\(^3\) that eventually determines the total impedance built into the machine. It is therefore important to understand the scaling of the impedance with the number of cells due to external damping specifically for the most parasitic modes. Due to relation $P_{ext} Q_{ext} = \omega U$ one can theoretically derive that the $Q_{ext}$-value of a given mode scales linearly with $N_C$ ($Q_{ext}(N_C) = N_C Q_{ext}(1)$) to first order if the field amplitudes in all cells are equal (independent of $N_C$) considering that the external losses depend only on the energy leaking out of the beam tubes (proportional to the field amplitudes squared), while neglecting all intrinsic losses. If one assumes further that $v_{ph} = v_p$, then the characteristic shunt impedance closely obeys $R/Q \sim N_C$. The above conditions are for instance well obeyed for the accelerating $\pi$-mode. This implies that $R_l$ and $R_p$ scale with $N_C^2$ to first order for such modes, or $R_l/N_C$ and $R_p/N_C \sim N_C$. In multi-cell cavities it is crucial how confined the modes are (determining $Q_{ext}$), the risk of which increases with $N_C$, and how the $R/Q$-values scale with $N_C$ including cases $v_{ph} \neq v_p$. For this purpose cavities with one up to nine cells ($N_C = 1, 2, \ldots, 9$) have been modelled. The Cornell MCL 1.3 GHz bare cavity design with enlarged beam tubes has been chosen as basis for this study. The end-cells with tubes (endgroups) and mid-cells ring at the same fundamental frequency by design such that the TM010 $\pi$-mode exhibits a ‘flat’ field profile for each cavity. All cavities were created with mirror symmetry with respect to the axial center plane. This aimed to avoid any bias of fields as a prerequisite. The beam tubes have been terminated by broadband absorbers to calculate the $Q_{ext}$-values solely based on the propagating fields avoiding standing waves. In this manner, the mode confinement can be studied purely as a function of $N_C$.

The outcome is depicted in Fig. 16 for the $Q_{ext}$-values of the first four monopole HOM passbands. Typically, $Q_{ext}$-values rise to both spectral ends of a passband as already witnessed in Fig. 16 with a dip more or less pronounced in the passband center. Here the $\pi$-modes exhibit the highest values in any of the monopole passbands shown due to mode confinement. For the TM011 and TM021 modes, the increase is more than two orders of magnitude for the nine-cell cavity from the value in the single cell.

\(^3\) The number of cells usable is eventually limited by the RF power made available or the power capability of the FPC.
Figure 16. External $Q$-values of the first four monopole HOM passbands as computed for 1.3 GHz cavities with one up to nine cells (cf. figure in the legend). The beam tubes are matched by broadband absorbers. The ID of the beam tubes is 110 mm. The TM01 monopole mode cutoff is 2.09 GHz such that already the TM011 modes can propagate out of the cavity.

Yet the mode with the highest Q in a passband does not necessarily possess the highest $R/Q$-value. Consequently the question arises, how the maximum shunt impedance ($R/Q \cdot Q$) in each passband scales with the number of cavity cells. This is shown in Fig. 17. It plots the maximum normalized impedance ($R/Q \cdot Q/N_C^2$) in dependence on $N_C$ found within individual passbands covering the first four monopole (TM011, TM020, TM021, TM012) HOM passbands (left) and the first five dipole (TE111, TM110, TE112, TM111, TE121) passbands (right). Note that for the fundamental TM010 $\pi$-mode not shown, $R/Q \cdot Q/N_C^2$ has been independent of $N_C$ as expected. This is also closely obeyed for the TM011 monopole mode and the TE111 and TM110 dipole modes, respectively.

Figure 17. Maximum monopole (left) and dipole (right) passband shunt impedance for various mode types normalized by $N_C^2$. Values have been computed for 1.3 GHz cavities with enlarged beam tubes (matched) with one up to nine cells.
An efficient HOM-damped cavity should balance all impedances to an equal level. This is not achieved for the high impedance TE112 and TE121 dipole modes. Particularly the TE121 modes are very confined exhibiting $Q_{\text{ext}}$-values $> 1\times 10^6$ for $N_C > 5$. For the even cell numbers $N_C = 6$ and $N_C = 8$ the local maxima are due to relatively high Qs. The TE121 mode for $N_C = 8$ for instance is strongly trapped with $Q_{\text{ext}} \sim 1\times 10^8$ exceeding that in the nine-cell cavity ($Q_{\text{ext}}$ is $\sim 5\times 10^6$).

The findings imply that for a cavity even with enlarged beam tubes (relying on ideal beam line absorbers), the HOM-damping can in fact become inefficient for a large number of cells. The impedance of a cavity with $N_C$ cells may scale with a factor greater than $N_C^2$ compared to a single-cell cavity, even by up to five orders of magnitude (!) for the TE121 mode when using a nine-cell cavity. For some mode types the normalized impedance values also may drop, especially for the TM020 and TM021 modes showing a decrease with $N_C$. The reason is a strong reduction of the $R/Q$-values with $N_C$. Overall, the analysis shows that the maximum shunt impedance found in passband can rise significantly with the number of cells by a factor $> N_C^2$ due to confined modes. While for monopole modes, the $Q_{\text{ext}}$-values can be typically suppressed well below $1\times 10^5$ for cavities up $N_C = 9$, the TE121 dipole modes may exceed $1\times 10^6$ and consequently may possess the highest impedances among dipole modes. The best HOM-damping performance can be achieved for a single-cell cavity, which is therefore the preferred choice for high current storage rings. However, the use of single-cell cavities can become inefficient for high-energy machines. If in parallel the HOM-damping demands are strict, the confined, critical modes must be specifically targeted. Cavity cell modifications such as for end-cells can provide improvements in this respect as elaborated further below. A compromise for $HC$ machines in terms of HOM-damping and required real estate length is $N_C = 5$. This also limits the cavity length at rather low operating frequencies ($\leq 750$ MHz) to practically reasonable values. In the following the focus is therefore on single-cell and five-cell cavities.
4. Single-cell HOM-camped cavity designs
4.1. Overview

A single-cell cavity has been modelled to investigate the HOM-damping efficiency when utilizing different damping concepts. Figure 18 illustrates the four structures conceived in this analysis. The same cavity cell geometry is used throughout to directly compare the damping performance among the various concepts. These comprise the cavity with coaxial (Case A) and waveguide dampers (Case B) attached to one beam tube, the cavity with transitions to enlarged beam tubes (identical on each side) (Case C), and the cavity with on-cell dampers (Case D). The coaxial output ports (Case A) as well the HOM waveguides (Cases B and D) are terminated with broadband absorbers as indicated (brown color). For Case A the JLab-type (A1) and the DESY-type hook coupler (A2) have been employed, respectively, which differentiate by the orientation of the inner hook antenna (“F-part”) with respect to the axis of the cavity. In Case D the three waveguides are angled so as to provide a good balance between the coupling to both monopole and dipole modes as can be seen later. This concept has recently been investigated as a possible choice for the electron storage ring of the proposed JLab Electron Ion Collider in order to cope with a 3 A beam current [83]. The TM010 mode frequency of this cavity is 952.6 MHz and has therefore been chosen for this study, though the findings can be scaled to any frequency. The concept of on-cell dampers is borrowed from the NC cavities. Apart from Case C three coaxial and waveguide dampers have been considered throughout, respectively, for a fair comparison.

Figure 18. Single-cell SRF cavity model with various HOM-damping concepts as explained in the text. The elliptical cavity shape used for each case is depicted in the center.

For Case B the HOM endgroup is as designed for the JLab HC cavity and scaled appropriately to match the size of the beam tube ID. In all cases the couplers are equally spaced by 120 degrees azimuthally. For Cases A and B, the endgroups are joined directly to the cavity iris enabling strong coupling to the evanescent fields of trapped modes, but not without a properly blended transition from the iris to the couplers. Furthermore, the axial distance of the cavity iris to the center of each coaxial HOM can or damping waveguide is the same. This aims to provide the fairest possible comparison for these cases. The beam tube diameter equals the cavity iris diameter (ID = 110 mm) except for Case C. This will trap the TE111, TM110 and TM011 in the cavity such that only the HOM couplers can contribute to the damping. For Case C a smooth transition to the enlarged beam tube (ID = 160 mm) has been modeled. Hereby the lowest resonating HOM (TE111) can escape the cavity. As intended, damping in this case is merely provided via absorption of propagating waves through the beam tubes. Note that for all other cases
the beam tube ends are terminated in a broadband match to avoid undesired reflections. The results for the monopole and dipole mode impedances are plotted in Fig. 19 and Fig. 20 up to 3.2 GHz. This covers the highest impedances among all HOMs. Wakefield and lossy Eigenmode computations have been performed. Complex material properties for broadband absorber loads were utilized to allow for propagating modes in all terminations. This is in lieu of using waveguide modes and provides several advantages. The principal method is described in ref. [79]. Moreover, the impedance extrapolation scheme is used to better resolve the peak impedances, which usually provides excellent agreement of the two independent computational methods. [81]. More details are provided in the Appendix.

![Figure 19. Monopole impedance spectra for the single-cell cavity (f₀ = 952.6 MHz) with various damping concepts (lines = wakefield calculations, symbols = complex Eigenmode computation).](image)

The findings favor the enlarged beam tubes and on-cell dampers, respectively. This is expected from the previous analysis for \( N_C = 1 \). For the coaxial dampers the TM011 mode could not be efficiently captured with either the JLab-type (Case A1) or TESLA-type couplers (Case A2), though the TESLA-type couplers provide better coupling to this HOM than the JLab-type couplers. Its impedance is significantly larger compared to Cases B-D. For the dipole modes (TE111, TM110) however, the coaxial couplers yield a better absorption than waveguide dampers, i.e. less than a factor two for the TM110 mode in Case A1, but significantly better for Case A2. This gain over the waveguide dampers can be attributed to the antennas protruding into the beam tube, which enables capturing the evanescent dipole fields more effectively than the open ports at the beam tube perimeter. There is a limit to what extent the hooks may penetrate into the beam tube, e.g. to provide sufficient clearance for the beam, while avoiding excessive coupling to the fundamental mode. While the JLab-type hook antennas are aligned along the beam tubes - not well capturing the TM110 mode - the TESLA-type hook antennas are angled with respect to the beam axis. This causes a field asymmetry in the horizontal direction (one coupler is directed vertically), such that field amplitudes may be slightly different on the left compared to right side with respect to the vertical plane. Consequently, the dipole spectrum exhibits a ‘leakage’ from the TM010 and TM011 mode, respectively, though these modes have no true dipole character. Overall, the on-cell
dampers are even superior to the cavity with enlarged beam tubes assuming nearly perfectly matched boundary conditions (ideal BLAs).

**Figure 20.** Dipole impedance spectra for the single-cell cavity ($f_0 = 952.6$ MHz) with various damping schemes (lines = wakefield calculations, symbols = complex Eigenmode computations).

Figure 21 demonstrates that the wakefields are decayed within only 10 m for *Case C* and 15 m for *Case D*, whereas in all other cases the wakefields are still ringing well beyond 50 m. For the cavity with on-cell dampers, there is some beating visible in the wake potential since the two dipole modes (TE111, TM110) compete. Yet, the associated peak impedances are both lower than for the cavity with enlarged beam tubes.

**Figure 21.** Dipole wake potentials for four HOM-damped single-cell cavities with different damping concepts as a function of the wake length behind the exciting bunch. The red curve refers to the cavity with three JLab-type couplers (*Case A1*).
The wakefield calculations have been carried out for one dipole mode polarization only. The results do not deviate though significantly for the remaining polarization thanks to the three dampers. This is confirmed by the Eigenmode calculations that typically cover both polarization planes. For Case C the results of course do not depend on the polarization plane. S-Parameter simulations for individual HOM endgroups clarify the dependence of (propagating) wave absorption on mode polarization. Figure 22 plots the quantitative results for four cases as depicted in the legend.

**Figure 22.** S-Parameter calculations performed in frequency domain for the four cases depicted in the legend. The energy absorbed in the dampers is given in percentage of the incident wave, either when launching a TM01 or TE11 waveguide mode, respectively, into the beam tube on one side. The other beam tube is matched. The energy does not account for the energy transmitted from one to the other beam tube. For the TE11 modes, the calculations for case B-D were done separately for the horizontal and vertical polarization. The relevant cutoff frequencies are indicated by the dashed vertical lines.

The HOM endgroups are excited through the nearest port either by the TM01 or the TE11 mode (horizontal and vertical polarization). The opposing beam tube is matched to the outgoing wave. Then the absorption in the dampers is computed as the fraction of the incident energy. The models include the CESR type beam line absorbers accounting for complex material properties of TT2-111 series ferrite [84]. This provides an effective absorption throughout. For BLAs the spectral range of absorption can be improved by employing different materials in series, which becomes important for short bunches. Likewise, broadband load material (e.g. SiC and AlN composite ceramics) is available for use in HOM waveguides covering cryogenic to room temperature application ([52], [53]). Wedge-shaped loads in the waveguide are favorable to smoothly match the impedance from vacuum to a ceramic-filled volume. The waveguide dampers thus can efficiently damp monopole modes particularly at the higher frequency end. The efficiency is also comparable to that of the BLA for the TE11 waveguide modes at the higher
frequency end and almost equivalent for the horizontal and vertical polarization. The coaxial couplers have the disadvantage that the absorption can be either tailored to resonantly couple to HOM frequencies, thus narrowband, or more broadband, but less efficient. The TESLA/JLab-type coaxial dampers therefore yield a smaller energy transmission compared to the other cases for the dominant part of the spectral range and also exhibit a stronger dependency on mode polarization. The energy absorbed in the external coaxial loads can be further constrained by the limited bandwidth of vacuum windows as part of the required RF feedthrough antennas, which have not been allowed for in the models. As discussed above though, the damping to trapped dipole modes might be more efficient than for waveguide couplers and in case couplers are positioned at the same distance away from to the cavity.

4.2 Quantitative and qualitative discussion of results for single-cell cavities

Table 5 lists the performance-limiting modes for all cases analyzed. The findings quantitatively rank the on-cell dampers as most efficient for both monopole and dipole modes. The results can be compared to Table 4 for existing cavity designs, yet referenced to $f_{ref} = 500$ MHz. One may therefore scale the dipole impedances by $f_{ref}/f_0 = 500/952.6$ MHz, while the product $R_l \cdot f$ will also be lower.

### Table 5. Performance-limiting monopole and dipole HOMs for a single-cell cavity ($f_0 = 952.6$ MHz) depending on the damping concept.

| Damping concept       | Case study | Beam tube ID | Max. $R_l$ | Max. $R_{tr}$ | Max. $R_l \cdot f$ |
|-----------------------|------------|--------------|------------|---------------|--------------------|
| Coaxial Dampers       | A1         | 110          | 111        | 554           | 200 @ 1.8 GHz      |
| Coaxial Dampers       | A2         | 110          | 25.0       | 73.3          | 45.1 @ 1.8 GHz     |
| Waveguide Dampers     | B          | 110          | 4.0        | 316           | 7.2 @ 1.8 GHz      |
| Enlarged beam tubes   | C          | 160          | 0.77 @ 1.8 GHz | 16            | 1.7 @ 2.9 GHz     |
| On-cell dampers       | D          | 110          | 0.73       | 8.9           | 1.2 @ 1.7 GHz      |

As expected, Case C and D are superior to the other concepts. At this level of HOM-damping, e.g. with $Q_{er}$-values ranging close to or below 100 for the monopole modes (cf. Fig. 16 for $N_c = 1$), one should further study the influence of fabrication tolerances on the results and explore realistic boundary conditions. The beam tubes have been assumed as nearly perfect absorbing boundaries for all cases. For Case C one can expect that symmetry-breaking components such as an FPC or tapered beam tubes that lead to reflected waves will influence results. For case D, the TE10 HOM waveguide cutoff has a strong impact on those modes that resonate close to the cutoff frequency. Here the group velocity in the waveguide is small, which can lead to so-called persistent modes with comparably high impedance.

Overall, the findings justify conceiving on-cell waveguide dampers for SRF cavities as a viable alternative to established design since comparably compact, while yielding highly- efficient HOM-damping performance without the need of beam line absorbers. The achievable field levels are assessed below.
4.3. RF feasibility study for SRF cavities with on-cell dampers

Opening the cavity walls to attach on-cell waveguide dampers has not been seriously considered in the past for accelerating SRF cavities as it will increase the peak magnetic flux density $B_{pk}$ at the intersection of the waveguide with the cavity wall. The major drawback is the reduced quench field limit that prohibits achieving very high operating fields. The issue arises from the surface current that have to flow around the opening thereby focusing on the narrow side of the waveguide-cavity intersection. Increasing the width of the waveguide in order to lower the cutoff frequency and improve HOM coupling becomes counterproductive as it further focuses the surface currents. On the other hand, the waveguide cutoff must be chosen to capture the lower frequency modes adequately. Therefore a ‘dog-bone’ shaped waveguide is chosen at the intersection tapering up to a rectangular waveguide eventually. The dog-bone principally resembles a double-ridged waveguide as employed in the DAΦNE and EU cavity, but with rounded corners. The narrow height of the dog-bone is utilized to reduce the cutoff frequency (increase of capacitance) without enlarging the waveguide width. A generous rounding blends the waveguide to the cavity wall.

![Figure 23. Single-cell on-cell damper model (left), its mesh representation, RF magnetic and electric field contours and surface currents as denoted.](image)

Figure 23 shows the RF model as utilized in the impedance calculation together with its mesh representation and results, i.e. the surface currents and RF magnetic and electric field contours, respectively. The location of $B_{pk}$ and $E_{pk}$ on the wall is indicated. The waveguide is attached perpendicular to a tangential line at the inner surface that touches the wall at the center of the waveguide. Decreasing the angle between the waveguide and the cavity axis will lower $B_{pk}$, but the angle also comes in trade-off with the damping performance. $E_{pk}$ can potentially be further improved by enlarging the rounding at the broad wall of the waveguide. With the shown design, the accelerator mode parameters as listed in Table 6 are achieved. For conventional speed-of-light cavities, $B_{pk}/E_{acc}$ is typically around 4 mT/(MV/m) (cf. Table 1) compared to a value of $B_{pk}/E_{acc} = 7.84$ mT/(MV/m) for the on-cell damper. This yet depends on the beam tube diameter. Table 6 lists for instance the parameters of the CESR cavity. In comparison, $B_{pk}/E_{acc}$ is 50% higher, and $E_{pk}/E_{acc}$ only 13%. Note that the values listed are well-converged results using a fine tetrahedral mesh. A value of $B_{pk} = 80$ mT can be assumed as a safely achievable field since below the typical onset of the medium-field Q-slope and far below the fundamental quench field limitation of niobium. This relies on conventional surface cleaning and chemical post-processing methods. At this $B_{pk}$-value the cavity would operate at $E_{acc} = 10.2$ MV/m. TESLA nine-cell cavities mass-produced by industry (800+ units) achieved an average usable field in the cryomodules – the usable field is lower than the
maximum field reached - corresponding to \( B_{pk} = 118 \text{ mT} \) or \( E_{acc} = 27.7 \text{ MV/m} \) [28]. These are mean values from two companies. At \( B_{pk} = 118 \text{ mT} \) the cavity would operate at \( E_{acc} = 14.3 \text{ MV/m} \). This for example would exceed the envisioned operational fields in the proposed JLEIC electron and ion collider ring [83].

**Table 6.** Accelerating mode parameters of 952.6 MHz single-cell cavity design with three on-cell dampers. Values are compared to those of the CESR cavity.

| Parameter                      | Unit       | On-cell damper design | CESR cavity         |
|--------------------------------|------------|------------------------|---------------------|
| Frequency                      | MHz        | 952.6                  | 500                 |
| \( R/Q = \frac{V_{eff}^2}{2 \cdot P_{avg}} \) | \( \Omega \) | 52                     | 45.5                |
| \( G \)                        | \( \Omega \) | 219.2                  | 265.7               |
| Beam tube \( \varnothing \)    | mm         | 110                    | 240/366*            |
| \( E_{pk}/E_{acc} \)          |            | 2.76                   | 2.45                |
| \( B_{pk}/E_{acc} \)          | mT/(MV/m)  | 7.84                   | 5.26                |
| Limiting monopole mode        | k\( \Omega \)/k\( \Omega \cdot \text{GHz} \) | 0.73 / 0.65**        | 12.2 / 11.4         |
| Limiting dipole mode          | k\( \Omega \)/m | 4.7                   | 83                  |
| \( E_{acc} \) at \( B_{pk} = 80 \text{ mT} \) | MV/m | 10.2                   | 15.2                |
| \( E_{acc} \) at \( B_{pk} = 112 \text{ mT} \) | MV/m | 14.3                   | 21.3                |

* Maximum dimension with flutes, ** When scaled to \( f_{ref} = 500 \text{ MHz} \) for comparison
5. Five-cell cavities

Similar to section 4, the damping of HOMs in five-cell cavities has been studied utilizing the same HOM endgroups as depicted in Fig. 24. A multi-cell cavity with on-cell dampers has not yet been analyzed. For the numerical setup the same rationales apply as detailed above, except that for Case A and B a coaxial FPC has been added to the side opposing the endgroup, which may provide some additional damping, but deliberately breaks the symmetry in the vertical plane. A fundamental mode frequency of 802 MHz has been chosen, which is of interest for the Large Hadron electron Collider (LHeC) with plans under study for an experimental facility at that frequency [85].

![Figure 24. Five-cell SRF cavity as modelled with various HOM-damping schemes comparable to the one-cell cavity study. The design of the 802 MHz five-cell cavity provides a good balance between FM cell-to-cell coupling \((k_{cc} = 3.2\%)\) and peak field ratios \((E_{pk}/E_{acc} = 2.26, B_{pk}/E_{acc} = 4.2 \text{ mT/(MV/m)}\) by choosing an iris aperture of 130 mm (TE11 cutoff = 1.35 GHz, TM01 cutoff = 1.77 GHz). For Case C the beam tube is enlarged to 200 mm (TE11 cutoff = 0.88 GHz, TM01 cutoff = 1.15 GHz).]

In anticipation of higher \(Q_{ext}\)-values for multi-cell compared to single-cell cavities, the wakefield computations were performed up to 0.5 km throughout. Impedances were extrapolated as usual to better resolve the peak values. Only for Case B additional complex Eigenmode computations have been carried out to demonstrate the achieved agreement with wakefield calculations. The interpretation of the findings principally follows the arguments for the single-cell cavities, e.g. the propagating TM012, TE112 or TE121 may become the performance-limiting modes in principal agreement with the multi-cell analysis above (Fig. 17). The results are shown in figures 25 and 26. Again the coaxial couplers can capture the trapped TE111 and TM110 dipole modes more efficiently than the waveguide dampers, whereas for higher frequencies the waveguide dampers become superior, particularly for the TM111, TE112 and TE121 mode families. Both HOM endgroups – though positioned close to the neighboring cavity end-cell iris (ID = 130 mm) – cannot suppress the impedances of the TM011, TE111 and TM110 modes below the values observed in Case C. The cavity with enlarged beam tubes (ID = 200) therefore still guarantees the best damping performance. Yet at higher frequencies, the waveguide dampers compete well with Case C.
Figure 25. Monopole impedance spectra for a five-cell cavity ($f_0 = 802$ MHz) with three different HOM-damping schemes (lines = wakefield calculations, symbols = complex Eigenmode computation). The sequence for modes types may vary depending on the cavity shape. The TM012 $\pi$-mode appears around 2.25 GHz and is rather confined in the cavity. Therefore its impedance does not significantly depend on the damping scheme.

The impedance of the TM012 $\pi$-mode is hardly affected by the damping schemes since rather confined in the cavity. The $Q_{ext}$-value is in the order of 1e5, which then becomes the highest monopole impedance for Case C. For the dipole modes, the performance-limiting mode in Case B is a TE112 mode (pair).

Figure 26. Dipole impedance spectra (lines = wakefield calculations, symbols = complex Eigenmode computation).
5.1 Impact of end-cell modifications on critical HOMs

It has been mentioned that the end-cells play an important role on how confined a mode can be within a cavity such that even broadband HOM couplers cannot efficiently suppress the $Q_{ext}$-values. Even for propagating modes the damping can be significantly reduced depending on beam pipe boundary conditions, which can influence the RF phase and amplitude within the end-cells and the beam tube where HOM-dampers reside. For a given HOM pattern, the individual mid-cell and end-cell frequencies can vary significantly. This can lead to a strong decoupling of resonant fields from the end-cells which might not be improved by the presence of enlarged beam tubes, though these have the main purpose to let all fields escape. This for instance is the case for the TM012 $\pi$-mode in the five-cell cavities studied above. It exhibits an impedance principally independent of the damping scheme though resonating considerably above the TM01 beam tube cutoff. Its confinement is illustrated in Fig. 27 by means of the RF electric field contours plotted for each case.

Figure 27. Confinement of the propagating TM012 $\pi$-mode at ~ 2.25 GHz for Cases A-C. The RF electric field contours are shown. The field contours are plotted in logarithmic scale comprising four decades. The on axis electrical field changes sign twice per cell (not TM021 mode).

To counteract HOM mode confinement, one can conceive an alteration of the end-cells aiming to enhance the coupling to the beam tubes. This should be done by preserving the flat on-axis field profile of the fundamental mode. Three cases as illustrated in Fig. 28 have been studied to scrutinize their impact on mode confinement.

Figure 28. End-cell shape variations (Case 2 and 3) with the aim to improve the relatively inefficient coupling of the TM021 $\pi$-mode to the beam tubes as experienced in Case 1. At 952.6 MHz the length difference of an end-cell in Case 1 compared to Case 2 and 3 is significant (4.4 mm).

Case 1 represents the original cavity design as used above. It features straight side walls resembling the JLab HC profile. This concept has the benefit that only a single deep-drawing form (die set) is needed
to stamp both the end and mid-cells since the contour of all cells is identical. In order to yield a flat TM010 $\pi$-mode, each endgroup (end-cell plus beam tube) must ring at the same frequency as the mid-cells. This is achieved by trimming each end half-cell equatorial plane so as to raise the endgroup frequency to that of the mid-cells. The end-cells are therefore shorter than mid-cells. In Case 2 and 3 the end-cell length has been made equal to the mid-cell length. In Case 2 the cell equator diameter has been maintained. It leads to a sloped side wall of the end half-cell to retrieve the original frequency of the endgroup. This implies that a second deep-drawing die would be required. Case 3 has been optimized such that the TM021 $\pi$-mode rings with the same frequency in all cells, which is not true in the other cases. To facilitate this, while keeping the mid-cells and end-cells identical in length, the equator diameter of the end-cells must be reduced. Yet, straight side walls have been kept as in the original design. In Case 3 two different deep-drawing die sets would be necessary as in Case 2.

For each of the three cases, the cavity has been equipped with a single waveguide endgroup resembling Case B above. The resulting monopole and dipole impedance spectra are shown in Fig. 29 and Fig. 30, respectively. Compared to the original cavity design, Case 2 reveals a significant suppression of the performance-limiting TM011 mode, but at the same time an increase for the TM012 $\pi$-mode impedance beyond that of the TM011 mode. In Case 3 – with end-cells specifically tuned for the TM012 $\pi$-mode – a significant suppression of its impedance has been achieved, while the impedance of the performance-limiting TM011 mode has been reduced concurrently by as much as one order of magnitude compared to the original design. It is now equally important to study the damping results for the dipole modes. Figure 20 reveals that the findings are diversified.

**Figure 29.** Monopole impedance spectra for 802 MHz cavity shapes as depicted in Fig. 25. Case 3 specifically un-traps the TM012 mode and improves the coupling to the TM011 mode concurrently.
By referring to the highest impedance in the passbands and compared to the original design, the formerly well-damped TM111 mode exhibits an impedance increase for Case 3 by more than an order of magnitude, a minor increase for the TE121 mode impedance, a reduction for the TM120, TM121, and TE121 mode impedances, and most importantly also a reduction of the TM110 mode, which represents the performance-limiting dipole mode. Therefore, Case 3 represents the most efficient HOM-damped design in these cases. Note that cavity has also been designed such that the main beam spectral lines (multiples of \( f_0 \)) are placed at safe distance from HOM frequencies.

The examples show that one can geometrically tweak the cavity end-cells to significantly reduce the highest monopole and dipole impedances in the entire spectrum, while trade-offs need to be taken into account for other, less critical HOMs. One can also consider utilizing two differently shaped end-cells. This produces an axially asymmetric cavity as is the case for the TESLA cavity to bias critical HOMs towards one or the other side of the cavity. It however bears some risk if only one HOM endgroup is employed.

To directly compare the HOM-damping efficiency of Case 3 with the established five-cell JLab HC design, a second HOM-endgroup has been added. For the numerical modelling of each cavity, the HOM endgroups were rotated by 60 degrees with respect to each other. Since the operating frequencies are different, the spectra were scaled to \( f_{ref} = 500 \) MHz and normalized by \( N_C \) as practiced before (Fig. 10 and Fig. 11). The findings are plotted in Fig. 31 and Fig. 32, respectively. Table 7 lists the relevant accelerating mode parameters together with the performance-limiting HOMs. This reveals a factor of six improvement for the maximum monopole mode impedance, and a \(~10\%\) improvement for the maximum dipole mode impedance. For the same cell-to-cell coupling the design also exhibits better surface field enhancement ratios. The parameters for the BNL4 HC cavity have been added to the table at the present status of optimization [63]. Particularly for dipole modes, Case 3 and the JLAB HC cavity show a better damping efficiency.

**Figure 30.** Dipole impedance spectra for 802 MHz cavity shapes as depicted in Fig. 25.
Figure 31. Monopole impedance spectra for the five-cell cavity (Case 3) in comparison to the JLab HC cavity design, both utilizing six waveguide dampers as depicted in the upper figure (wakefield simulations).

Figure 32. Dipole impedance spectra for the five-cell cavity (Case 3) in comparison to the JLab HC cavity design, both utilizing six waveguide dampers (wakefield simulations).
| Parameter                  | Unit   | New HC Design (Case 3) | JLab HC |
|----------------------------|--------|------------------------|---------|
| $R/Q = \frac{V_{eff}^2}{2 \cdot P_{avg}}$ | $\Omega$ | 255.2                  | 262.5   |
| $N_C$                      |        |                        | 5       |
| $G$                        | $\Omega$ | 277.9                  | 276     |
| $k_{cc}$                   | %      | 3.2                    | 3.2     |
| $E_{pk}/E_{acc}$           |        | 2.26                   | 2.50    |
| $B_{pk}/E_{acc}$           | mT/(MV/m) | 4.20                  | 4.27    |
| Max. $R_l^*$               | k$\Omega$ | 63.5                   | 378     |
| Max. $R_l f_{HOM}^*$       | k$\Omega$-GHz | 89.4                  | 531     |
| Max. $R_{tr}^*$            | k$\Omega$/m | 1281                 | 1424    |

* Scaled to $f_{ref} = 500$ MHz for comparison

Table 7. Cavity parameters for the new HC cavity design (Case C) with six waveguide dampers in comparison to the JLab HC with the same number of waveguide dampers.
6. Beam stability threshold demands in next generation e+e- collider rings

Very large circular e+e- collider rings have been proposed in the recent past to operate at the energy frontier with the feasibility to reach over three orders of magnitude higher luminosity than achieved with LEP. This aims to study the Higgs boson discovered at the LHC in more detail, and to allow precise top-quark, W and Z investigations among other new physics. The center-of-mass collision energies are ~90 GeV (Z-pole), ~160 GeV (WW threshold), ~240 GeV (H threshold) and ~350 GeV (tt̄ threshold), respectively. The two main facilities conceived are the Future Circular Collider (FCC) at CERN [87] and the Circular Electron Positron Collider (CEPC) in China [88].

Given the known impedances of a large variety cavities detailed above, one can evaluate their suitability with regard to the impedance requirements in these next generation machines. In a storage/collider ring, coupled bunch instabilities (CBI) due to HOMs can arise due to coherent oscillations of circulating bunches. The beam spectral lines are given by

\[ f_{\text{spec}} = (n + pM) \cdot f_{\text{rev}} + m f_s \]

Herein \( f_{\text{rev}} \) is the revolution frequency and \( f_s \) the synchrotron oscillation frequency. Possible CBI arise when spectral lines coincide with HOM frequencies depending on the damping time taking into account synchrotron radiation losses per turn. The radiation damping time should be smaller than any instability rise time to provide beam stability. Consequently, the threshold impedance, \( Z_{\text{th}} \), beyond which multi-bunch instabilities arise, can be derived by equating the radiation damping time with the respective instability rise time. This yields the following expressions for the longitudinal and transverse impedance thresholds, respectively:

\[ Z_{l_{\text{th}}} = \frac{1}{N_{\text{Cav}}} \cdot \frac{1}{f_{\text{HOM}}} \cdot \frac{2 \cdot E_0 \cdot Q_s}{I_b \alpha \tau_s} \]

\[ Z_{tr(x,y)_{\text{th}}} = \frac{1}{N_{\text{Cav}}} \cdot \frac{1}{f_{\text{rev}} I_b \beta_{x,y} \tau_{x,y}} \]

Herein the assumption is been made that the HOM coincides with an instability-driving beam frequency and that a number of \( N_{\text{Cav}} \) identical cavities are installed \( (E_0 = \text{beam energy}, I_b = \text{average beam current}, Q_s = \text{synchrotron tune}, \alpha = \text{momentum compaction factor}, f_{\text{HOM}} = \text{longitudinal HOM frequency}, \tau_{x,y} = \text{long/ trans. damping time}, \beta_{x,y} = \text{beta functions at the cavity.} \) One can see that \( Z_{l_{\text{th}}} \) is inversely proportional to the mode frequency such that \( Z_{l_{\text{th}}} f_{\text{HOM}} \) becomes the limiting term.
Table 7 summarizes the machine parameters for the FCC-ee physics options [89] and for the CEPC design based on a preliminary conceptual design report (pCDR) [90] to evaluate the corresponding threshold impedances, which are denoted at the bottom of the table. One can see that the envisaged operating fields (CW mode) are rather moderate throughout. For CEPC, 650 MHz five-cell SRF cavities are foreseen with $E_{acc} = 15.6 \text{ MV/m}$, whereas for FCC-ee 400 MHz single-cell cavities are assumed at up to $E_{acc} = 12 \text{ MV/m}$. At higher energies the use of single-cell cavities becomes rather inefficient as the number of cavities increases significantly such that the choice for $N_C$ is still under discussion. The FCC-ee $Z$ physics option presents the most challenging change with $Z_{l}^{th} f_{HOM} < 1 \text{ kΩ·GHz}$ and $Z_{tr}^{th} < 5 \text{ Ω/m}$, respectively, per single-cell cavity.

Table 7. Beam machine parameters for the FCC-ee [89] and CEPC physics options [90] and derived impedance instability thresholds. Note that the FCC-ee collider conceives separate beam pipes for $e^-$ and $e^+$, and CEPC pCDR design a single beam pipe to save costs, though an option with two beam pipes is discussed as well as a larger circumference (100 km). CEPC is also considered to be upgraded to a 70-100 TeV Super Proton-Proton Collider (SPPC) in the same tunnel [90].

| Parameters | Units | CEPC baseline | FCC-ee $Z^*$ | FCC-ee $W$ | FCC-ee $H$ | FCC-ee $t\bar{t}$ |
|------------|-------|---------------|-------------|-----------|-----------|----------------|
| Circumference | km | 54.374 | 100 | 100 | 100 | 100 |
| $f_{RF}$ | MHz | 650 | 400 | 400 | 400 | 400 |
| $E_0$ | GeV | 120.0 | 45.6 | 80.0 | 120.0 | 175.0 |
| $l_b$ | m | 0.0166 | 1.45 | 0.152 | 0.030 | 0.0066 |
| $Q_x$ | | 0.18 | 0.036 | 0.037 | 0.056 | 0.075 |
| $N_{Cav}$ | | 384 | 88 | 180 | 668 | 2224 |
| $N_C$ | | 5 | 1 | 1 | 1 | 1 |
| $f_{rev}$ | Hz | 5475.46 | 2997.92 | 2997.92 | 2997.92 | 2997.92 |
| $\alpha$ | | 3.36e-5 | 7e-5 | 7e-5 | 7e-5 | 7e-5 |
| $\tau_s$ | ms | 7.07 | 440.3 | 81.1 | 24.0 | 7.67 |
| $\tau_x$ | ms | 14.1 | 881 | 162 | 48 | 15 |
| $\beta_x$ | m | 25.6 | 55 | 55 | 55 | 55 |
| Total RF voltage | GV | 6.87 | 0.4 | 0.8 | 3 | 10 |
| $E_{acc}$ | MV/m | 15.6 | 12 | 12 | 12 | 12 |
| $Z_{l}^{th} f_{HOM}$ | kΩ*GHz | 14257 | 0.83 | 38.1 | 399.2 | 3331 |
| $Z_{tr}^{th}$ | kΩ/m | 9500 | 4.92 | 218.9 | 1513 | 9641 |

* Assumption to match $Z_{tr}^{th} = 9.5 \text{ MΩ/m}$ as published [90], ** 30180 bunches, 7.5 ns bunch spacing (a second option is considered using 91500 bunches with 2.5 ns bunch spacing not considered here.)

Figures 33 and 34 depict the monopole and dipole threshold impedances for the CEPC machine, respectively, in comparison to the cavity impedances for the JLab HC, BNL4 HC and the new HC design (Case 3) as described above. In each case the spectra have been scaled to the nominal operating frequency of 650 MHz. Each cavity meets the requirements for the CEPC baseline machine. Note that the number of dampers vary to demonstrate that only three waveguide dampers are necessary for Case 3 to fulfill the HOM-damping demands. For the BNL4 cavity however, the maximum transverse impedance is relatively close to the threshold impedance.
Figure 33. Longitudinal impedance instability threshold for the CEPC machine (dash lines) computed based on Table 7 for a five-cell 650 MHz cavity together with the monopole impedance spectra as calculated for the JLab HC (six waveguides dampers), and the new HC design (Case 3, 3 waveguide dampers), respectively.

Figure 34. Similar to Fig. 33 for dipole impedance instability threshold and cavity impedances.

Similar figures have been created for the FCC-ee physics option (Fig. 35 and 36). Herein, the impedances of the single-cell cavities as studied above with three HOM-dampers (Cases A1, B, C) and the cavity with enlarged tubes and ideal BLAs (Case D) are plotted. This reveals that the damping requirements for FCC-ee $t\bar{t}$ and FCC-ee $H$ can be met with any of the HOM-damping technologies with
a rather large safety margin, but that for $FCC$-$ee$ $W$ and $FCC$-$ee$ $Z$ the requirements become very demanding. For $FCC$-$ee$ $Z$ strictly only the single-cell cavity with on-cell dampers provides acceptable damping longitudinally and transversely without the need of a bunch-to-bunch feedback system ($FS$), though the safety margin is not significant.

**Figure 35.** Longitudinal impedance instability thresholds for the $FCC$-$ee$ physics options (dashed lines) computed based on Table 7 for single-cell 400 MHz cavities together with the monopole impedance spectra as calculated for a single-cell cavity with various HOM-damping concepts (cf. Fig. 17).

**Figure 36.** Similar to Fig. 35 for dipole impedance instability thresholds and cavity impedances.

Feedback systems are routinely used in storage rings for both the longitudinal and transverse plane. Particularly at rather low beam energy the damping due to synchrotron radiation decreases significantly, which can mandate a $FS$ to allow operating stably at the desired beam current.
For the proposed JLEIC electron ion collider for instance, the electron collider ring is conceiving CEBAF as an injector with beam energies ranging from 3 to 10 GeV and up to 3 Ampere average beam current [61]. The design is based on the PEP-II high energy ring lattice and components including magnets, vacuum chambers and RF systems. Therefore the NC PEP-II cavities (476.3 MHz) are considered to be used initially. A limit of 10 kW/m for the synchrotron radiation power is enforced for the PEP-II vacuum chambers. The total RF power has been chosen to not exceed 10 MW, which however limits the stored beam current in the high energy regime. Therefore a decline is taken into account from 5 GeV on [91]. At the low energy regime fewer cavities are needed such that the built-in impedance is reduced. Here however the use of a longitudinal and a transverse FS is required due to the largely reduced synchrotron radiation losses. Since the gain of an FS is limited, the stored beam current at medium energies (5-8 GeV) is constrained by the cavity impedance. This situation is improved by a foreseen later upgrade to 952.6 MHz SC cavities with on-cell dampers as proposed recently [83]. It would also allow utilizing CEBAF at the maximum 12 GeV injection energy. Table 8 summarizes the beam parameters for the electron collider ring with SC single-cell cavities. Given the same 10 MW RF power limit, this will still limit the stored beam current now beyond 7 GeV. Hereby close to 500 kW forward power is necessary per cavity for a maximum of 21 installed cavities. The maximum operating field is $E_{\text{acc}} = 11.25$ MV/m at 12 GeV, which is feasible given the analysis in section 4.3.

### Table 8. Beam machine parameters for the JLEIC e⁻ collider ring at various beam energies when using SC cavities [91] and derived impedance instability thresholds.

| Parameters | Units | JLEIC e⁻ collider ring |
|------------|-------|------------------------|
| $E_0$      | GeV   | 3  4  5  6  7  8  9  10 11 12 |
| $f_{\text{RF}}$ | MHz | 952.6 (SC cavity) |
| Circumference | km | 2.15 |
| $I_0$      | A     | 3  3  3  3  2.95 1.73 1.08 0.71 0.48 0.34 |
| $Q_s$      |       | 0.017 0.022 0.028 0.033 0.039 0.044 0.050 0.056 0.061 0.067 |
| $N_{\text{Cav}}$ |     | 1  3  6  12 21 21 21 21 21 21 |
| $N_C$      |       | 1 |
| $f_{\text{rev}}$ | Hz | 139420 |
| $\alpha$   | ms   | 376.14 158.68 81.25 47.02 29.61 19.84 13.93 10.16 7.63 5.88 |
| $\tau_\alpha$ | ms | 188.07 79.34 40.62 23.51 14.8 9.92 6.97 5.08 3.82 2.94 |
| $\beta_x$  | m    | 25 |
| Fwd. power per cavity | MW | 0.359 0.373 0.455 0.472 0.491 0.491 0.491 0.491 0.480 0.480 |
| $E_{\text{acc}}$ | MV/m | 2.39 1.95 1.99 1.80 1.72 2.70 4.05 5.86 8.23 11.25 |
| $Z_{\text{th}}^{\text{FOM (no FS)}}$ | kΩ*GHz | 0.04 0.06 0.09 0.11 0.14 0.46 1.33 3.45 8.15 17.88 |
| $Z_{\text{th}}^{\text{FOM (no FS)}}$ | kΩ/m | 3.05 3.21 3.92 4.07 4.38 12.74 32.67 75.75 163.91 327.99 |

The impedance instability thresholds at low to medium beam energies cannot be achieved without the use of feedback systems with any existing HOM-damping technology. This is graphically illustrated in Fig. 37 and Fig. 38 for longitudinal and transverse HOMs, respectively. Figure 37 includes the thresholds when using a longitudinal feedback system for 3 GeV and 5 GeV, respectively, and for the latter assuming a low or high FS gain. This implies that a high gain FS is required to provide stable operation at 3 A beam current. Again, single-cell cavities with enlarged tubes plus BLAs or on-cell dampers provide the maximum HOM-damping efficiency, though waveguide dampers could become an alternative. Concerning transverse instabilities however, the conditions are more severe. When assuming a transverse
bunch-to-bunch feedback system with a damping time of 3.2 ms as designed for PEP-II, the most restrictive operation is at 7 GeV with $Z_{th} = 24.6 \, \text{k}\Omega/\text{m}$, which also excludes the cavity with waveguide dampers. Note that for the JLEIC ion collider ring considering protons from 20-100 GeV/u or lead at 40 GeV/u with $I_b = 0.5 \, \text{A}$, the impedance instability thresholds are less severe such that the corresponding analysis is omitted.

Figure 37. Longitudinal impedance instability thresholds for the JLEIC electron collider ring depending on the beam energy without feedback system (grey dashed lines) and with a longitudinal feedback system (black dashes lines at 3 GeV and 5 GeV, respectively) as computed based on Table 8 for 952.6 MHz single cell cavities together with the monopole impedance spectra as calculated for single-cell 952.6 MHz cavities with various HOM-damping concepts (cf. Fig. 17).

Figure 38. Similar to Fig. 37 for impedance instability thresholds and cavity impedances.
6. Conclusion

The HOM-damping performance of prominent operational accelerating SRF cavities and proposed concepts have been quantitatively assessed based on numerically evaluated and/or experimentally available data that covered a broad spectral range for monopole and dipole modes. The data were normalized by the number of cells and scaled to a common accelerating mode frequency (500 MHz) for direct comparison. When plotting the performance-limiting monopole and dipole HOMs as function of the number of cells, the data reveal technical shortcomings for specific cavities. Such shortcomings can be avoided in future designs by a proper choice of the HOM coupler design, location/orientation, and the number of couplers, which should take into account the dependency on mode-polarization and field symmetry-breaking effects relevant for beam dynamics. The capabilities of today’s 3D numerical codes should be employed rigorously to rule out major design issues that might lead to serious operational issues as has been evidenced for several cavities in the past. For instance, numerical tools allow the optimization of the HOM damper geometry particularly important for the rather complex coaxial couplers also with respect to thermal and multipacting issues.

Most existing HOM-damped cavities make use of only a limited number of HOM-couplers for practical and cost reasons, typically two per cavity. A larger number of dampers are conceived for future high current machines such as ERLs and collider rings. The first concept packing a total of six waveguide couplers (three per endgroup), while consuming only a small portion of the beam line space, is the JLab cavity designed for ERL/FEL applications with Ampere-level beam currents [56]. Waveguide dampers typically exhibit a more broadband and efficient transmission to absorbers than coaxial couplers and can be more readily adapted to CW operation and high HOM power levels, while not requiring a fundamental mode rejection filter. It should be mentioned though that in the regime below the beam tube cutoff frequency, coaxial coupler designs can exhibit a better coupling to the trapped cavity modes benefitting from the penetration of the antenna tips into the beam tube.

Considerable efforts went into the optimization of the damping performance of future ERL cavities at various laboratories including more recent works for the bERLinPRo and BNL4 cavities. These cavities favor waveguide couplers, whereas the Cornell main linac cavity concept was based on enlarged beam tubes to damp the HOMs in beam line absorbers. The damping efficiency of cavities with enlarged beam tubes is typically better when compared to coaxial and waveguide couplers as numerically verified for concepts using either three coaxial (TESLA-type or C100 LL-type) or waveguide (JLab HC) couplers; for both single-cell and five-cell cavities. This conclusion is supported by data for the existing single-cell CESR and KEKB as well as two-cell Cornell injector cavities, respectively, which all exhibit very efficient and broadband HOM-damping. Hereby, beam line absorber loads surrounding the beam tube perimeter provide polarization-independent and broadband absorption as numerically evaluated for a detailed CESR-type load modelled in 3D considering realistic material properties. Concerns in the usage of beam line absorbers within the cryostat are linked with the question of practicality, for instance whether the additional beam line length consumed by thermal transitions and absorbers can be accepted and whether the HOM power dissipated within the cryogenic environment is manageable. Associated risks due to the use of the lossy load material within the beam line vacuum and in direct vicinity of the beam must be mitigated by design. This relies on adequate joining techniques of the loads to a metal enclosure and proper surface cleaning procedures to comply with the UHV environment. The Cornell injector cryomodule is an existing example of an operating small-scale facility employing this concept successfully, but not after overcoming a series of technical problems related to the beam line absorbers such as ferrite tiles becoming loose during thermal cool-down, while producing ferrite dust, as well as
charge buildup in the ferrites deflecting the traversing beam [92]. The expenses for beam line absorbers can amount to a considerable fraction of the cavity costs and are therefore not insignificant for large-scale machines.

Rather than using beam line absorbers, the bERLinPro and BNL4 cavity concepts try to make benefit by utilizing enlarged beam tubes in conjunction with waveguide absorbers. The HOM impedance data for these specific cavities were however not yet published as of writing to quantitatively demonstrate potential benefits compared to existing designs. It has to be considered that the usage of beam tubes with varying diameter will generally increase the loss factor of the cavity compared to a cavity with straight beam tubes. Even for cavities with enlarged beam tubes, the likelihood of trapped modes increases drastically with the number of cavity cells as has been assessed quantitatively by means of the maximum impedances for multiple monopole and dipole modes in a single-cell up to a nine-cell cavity. Hereby an impedance increase by several orders of magnitude has been observed for parasitic modes, particularly for dipole modes. This favors a small number of cavity cells for HOM-damping reasons. The restriction to a small number of cells however is not a favorable option for high energy machines. The number of cells must be eventually chosen in trade-off with power requirements and the total cavity impedance that is acceptable to be built into a machine. Except for the Cornell main linac cavity proposal (seven cells), the ERL cavity concepts are therefore rather limited to five cells as a compromise. At low frequency (≤ ~750 MHz) this choice also takes into account the comparably large size of a cavity, which needs to be compatible with surface post-processing tools such as electropolishing machines and high pressure rinse cabinets.

It has been demonstrated that one may significantly enhance the coupling to rather confined cavity HOMs by a geometrical optimization of the end-cells. The aim is to more equalize the individual resonance frequencies for a given HOM in both the cavity mid half-cells and endgroups that otherwise could ring at considerably different frequencies, hence leaving fields confined within the cavity. The end-cell tuning can be facilitated such the flat field of the fundamental accelerating mode is preserved at the same time. A trade-off in the damping between various monopole and dipole mode impedances might be the consequence. However, one can specifically target the performance-limiting mode, which improves the overall damping efficiency in consideration of the impedance instability threshold in a given machine. Applying the end-cell tuning technique exemplarily for a five-cell cavity with waveguide couplers has led to a well-balanced HOM-damping performance for both monopole and dipole modes without sacrificing the accelerating mode efficiency. The cavity for instance fulfills the CEPC pCDR impedance threshold requirements assuming 650 MHz five-cell cavities, while employing a total of three waveguide dampers per cavity rather than six. When utilizing six waveguides, the performance-limiting HOMs have been improved compared to the original JLab HC design (down by ~84% and ~10% for the limiting monopole and dipole mode, respectively) with the same amount of couplers, while fundamental mode parameters \( (E_{ph}/E_{acc}, B_{ph}/E_{acc}) \) have been improved concurrently for the same cavity iris aperture.

In addition to the established HOM-damping concepts, the rather unconventional use of on-cell waveguide dampers for SRF cavities has been explored for a single cell. As known from the experience with normal-conducting cavities (DAΦNE, PEP-II, and EU cavity), the on-cell damping is a very efficient solution to extract HOMs at the site or origin. It has been shown that the HOM-damping efficiency with three on-cell waveguide dampers is equal or even superior to a cavity with enlarged beam-tubes (all HOMs are propagating) assuming ideal absorbing beam tube boundaries. The use of the same number of coaxial and waveguide dampers on the other hand resulted in significantly larger HOM impedances. Similar to a cavity with enlarged beam tubes, the cavity with three on-cell dampers provides
transverse wakefields that are decayed within merely 20 meters behind the exciting bunch implying external \( Q \)-values in the order of a few to a few hundred for the most crucial HOMs. Note that attempts to further improve the damping of the monopole modes were in trade-off with the coupling to transverse modes and vice versa. The cavity yields the minimal longitudinal and transverse impedances achievable among all concepts presented and over the full spectral range, while being a technically feasible concept for moderate accelerating fields. The maximum surface magnetic flux enhancement located at the intersection of the dampers with the cavity wall is slightly below 8 mT/(MV/m), which is about twice the typical value for high-efficient SRF cavity shapes (cf. 4.26 mT/(MV/m) for a TESLA cavity). This promises to achieve usable fields around 15 MV/m with today’s conventional surface preparation methods. It for instance fulfills the desired operational fields in future collider machines, which conceive the use of single-cell SRF cavities such as FCC-ee at CERN (12 MV/m for various physics options) and JLEIC with a maximum operating field of 11.25 MV/m [91]. The evaluation of the impedance instability thresholds for the various FCC-ee physics options shows that the cavity with on-cell dampers would comply with the damping requirements for even the most stringent case (FCC-ee Z). Note that the on-cell damper concept has been recently proposed as an option for JLEIC, specifically to cope with the very strict damping requirements in the 3A electron collider ring [83]. Herein it is apparent that for the lower electron energy range (small synchrotron losses), the use of active transverse and longitudinal bunch-to-bunch feedback systems is inevitable for beam-stability control and thus taken into account by design.
7. Appendix - Numerical computation, merits and enhanced methods

7.1 Impedance extrapolation scheme

Similar to the R&D for superconducting (SC) cavities have computational tools continuously advanced over the course of several decades from rather limited 2D to versatile 3D codes. These enable cavity analyses in frequency and time domain with Eigenmode, beam-induced wakefield, and S-Parameter solvers that can utilize waveguide ports and lossy materials for Higher Order Mode (HOM) absorption. Moreover, coupled multi-physics functionalities allow quantifying the interaction of RF fields with the enclosure for thermal and/or structural analyses such as the RF heat dissipated in a fundamental power coupler (FPC) or HOM coupler/absorber for cooling optimizations as well as wall deformations associated with Lorentz-force detuning. Simulating cavity microphonics due to mechanically induced vibrations is another example for a crucial phenomenon related to the required generator power for stable RF control at desired field levels. Furthermore, tracking and particle-in-cell solvers cover beam-dynamical problems including parasitic electron activities such as resonant multipacting that may occur in cavities, HOM couplers and even curved beam tubes, as well as the evaluation of field-emitted electron trajectories and impact energies on cavity walls, which in turn relate to radiation and material radio-activation phenomena addressable by particle physics codes.

The usage of numerical simulation tools as part of the cavity optimization process has become inevitable proven by numerous examples and lessons learned from experiments. The fabrication of normal-conducting smaller-scaled or full-scaled prototypes as a verification of or complement to a numerical cavity design has been rather common in the past. However, prototyping efforts towards a final design are not insignificant both in time and costs, and measurement methods have their own limitations. These efforts have become more and more obsolete thanks to the precision and capabilities of today’s physics codes also benefitting from the available computational power. This makes feasible studying subtle details that can impact cavity performance, even with superior spatial resolution than can be achieved by fabrication itself. The use of RF computational tools is therefore highly relevant for the development of the next generation HOM-damped cavity as it can precisely forecast the beam-dynamically relevant impedance. It provides a quantitative way to assess the suitability of a HOM-damped cavity for a specific machine given its impedance instability thresholds.

To assess the HOM impedances over a wide spectral range in this paper, 3D wakefield computations have been performed using CST Design Studio [94] complemented by lossy Eigenmode calculations. The wakefield solver has the benefit to yield the broadband coupling impedance spectrum for the monopole and dipole modes each in a single calculation. Ideally, the wake potential has to be truncated at a time/length long enough that the energy is decayed to allow resolving all HOM impedances in the spectrum. This is not always possible if a \( Q \)-value of an HOM exceeds a value that leads to an unreasonable long calculation time, specifically true in SRF cavities, where \( Q \)-values > 1e5 are not uncommon. The simulations have therefore been complemented by Eigenmode calculations that readily provide both the \( R/Q \) and \( Q \)-value of an HOM.

For all computations HOM couplers were equipped with dissipative absorbers. Shape and complex material properties yield a broadband match in each case as verified independently by S-Parameter calculations. Conductive losses are neglected assuming full superconductivity in the whole metallic enclosure such that \( Q_i = Q_{ext} \). In case of the complex Eigenmode computation, the beam tube ends are also equipped with absorbers, whereas for the wakefield solver waveguide modes at the beam tube ends are a requirement to not interfere with the traversing beam and prevent from reflections. The Eigenmode calculations with intrinsic absorbers for broadband matching conditions (\( S11 \sim 0 \)) in lieu of waveguide
modes provide faster computational times and other advantages compared to using waveguide modes to resemble a broadband match. For instance, the $Q$-values are evaluated based on the complex Eigenfrequency of the lossy Eigenmode rather than reconstructed from two standing-wave solutions in case of waveguide modes.

The wakefield simulation utilizes a 1D line current as excitation source. A Gaussian bunch distribution is assumed, but the impedances are normalized by the bunch spectrum eventually. The $Q_{\text{ext}}$-values of HOMs are not known a priori. The energy left by the beam after traversing the cavity decays according to ($e^{-\tau}$) with a mode-dependent time constant $\tau = Q_{\text{ext}}/(2\pi f_{\text{HOM}})$. E.g. at a $Q_{\text{ext}} = 1e5$ and a mode frequency of 2 GHz, this would need a calculation as long as $c_0 \tau = 2.4$ km after which the HOM energy is decayed to $1/e$ of its initial value. This length is usually prohibitively large - depending on the number of mesh cells and related to the bunch length - as it leads to long computational times. The wakefield calculations have typically been truncated after a few hundred meter. This would not allow resolving the peak impedance of such a high-Q mode. However, the impedance extrapolation method has been utilized throughout this paper as described in [81]. It extrapolates the truncated impedance to its value at an infinite wake length and is applicable to the full impedance spectrum at once. Its merits are illustrated in Fig. 39 for a HOM-damped single-cell cavity, for which the wake has been truncated at $\sim 160$ m. The $Q_{\text{ext}}$-values of the peak impedances are denoted. For the TM011 mode this results in $c_0 \tau = 26.5$ m. Its peak impedance is therefore yet underestimated. The extrapolation reveals a factor of $\sim 3$ higher impedance than predicted by the original wakefield solution in excellent agreement with the Eigenmode computation, true also for other peak impedances (green dot).

![Figure 39](image.png)

**Figure 39.** Broadband monopole impedance spectrum as computed for Case A. The wake length is 160 m, which does not fully resolve the impedance of the TM011 and TM020 mode (red line). The extrapolation scheme applied to the full impedance spectrum (green line) guarantees full resolution as verified by Eigenmode calculations (green dots).
The extrapolation scheme however does not work well for nearly undamped modes as is the case for the fundamental mode, but the method can readily identify between resolved and unresolved HOMs. Eigenmode computations deliver the resolved impedances. These computations may then be limited to merely the unresolved modes identified by the impedance extrapolation method. The results from the two independent computations can deviate especially for propagating modes (typically rather low impedance). Hereby the $R/Q$-values as calculated by the Eigenmode solver are computed over a finite length, though the integrated voltage can depend significantly on the path length chosen accounting for the fields in the beam tubes. For propagating modes the integrated voltage however may cancel out on average over a sufficiently long distance. A residual voltage is then rather arbitrarily computed and may cause artificially raised impedances that would not be experienced by a beam in the real machine.

### 7.2 When details matter

Not uncommonly, subtle details may have significant impact on cavity performance. E.g. power and HOM couplers can lead to symmetry-breaking effects with undesired consequences. To study the impact of the FPC, 3D models were created for instance for the CESR cavity and Eigenmode and wakefield computations were performed. The RF model for the CESR cavity is shown in Fig. 40 including the fluted beam tube and ferrite loads. The findings revealed that the first TE211 mode is trapped within the cavity with $Q_{ext} = 3.3 \times 10^7$. Since the waveguide FPC creates an asymmetry in vertical direction, a residual on-axis electrical field is produced. Though the resulting $R/Q$-value on the cavity axis is relatively small ($3.7 \times 10^{-4} \ \Omega$ range), the longitudinal impedance amounts to $R_l = 12.2 \ \text{k\Omega}$. This exceeds the value of the highest monopole impedance. A wakefield simulation for this case confirmed the high peak impedance.

![Figure 40](image.png)

**Figure 40.** 3D model of the 500 MHz CESR cavity as used for lossy Eigenmode calculations. The right view is cut through the beam tube to reveal the details of the absorbers as modelled. Hereby, 16 ferrite tiles placed around the beam tube perimeter each with a 2” length to resemble the BLA. Two rows of ferrites are used per BLA that are attached to a common copper block. The complex material properties for ferrite TT2-111 have been assumed [84] to resemble realistic absorption characteristics.
Figure 41. Trapped TE211 mode in the CESR cavity (f_{HOM} = 937 MHz). The top row shows an RF electrical contour plot. The bottom figure depicts the on-axis electric field that peaks close to the axial location, where the power coupler slot is located.

Furthermore, the beam pipe boundaries can alter results substantially, for instance when standing waves are formed or when cavity fields act resonantly with adjacent HOM couplers. For instance, the CEBAF five-cell OC and upgrade C100 LL seven-cell cavities fall short compared to other designs to effectively damp critical modes. For the CBEAF OC cavities, the HOM endgroup consists of two waveguides with a waveguide stub as shown in Fig. 42. This configuration breaks the symmetry of fields in the transverse plane and yields locally confined modes in the waveguide that exhibit electrical RF field components along the beam axis with rather high R/Q-values. Several of such modes exist as part of the TE111 and TM110 dipole modes. For the TE111 modes, the Q_{ext}-values are in the 1e4 range (verified by measurements) yielding a rather large longitudinal impedance as a consequence. In fact, the FPC (TE10 mode cutoff is 1.1 GHz) has to perform double duty by damping most of the TE111 mode pairs, which actually resonate below the TE10 HOM waveguide cutoff (1.9 GHz). However, the FPC is pointing in horizontal direction and hence the damping is less efficient for vertically than for horizontally polarized modes. The vertically polarized TE111 modes primarily couple to the TE20 waveguide mode, which has a cutoff frequency twice as high as the TE10 mode. This leaves the vertically polarized modes below 1.9 GHz rather trapped. Damping of such modes can merely be facilitated by the exponentially decaying fields leaking into the HOM waveguides towards the loads.

Moreover, the FPC waveguide terminates in a stub, which sets the operational Q_{ext}-value for the fundamental mode given the separation of the FPC to the cavity. However, for both the CEBAF OC and upgrade C100 LL cavities, the stub produces a deflecting field component in horizontal direction for a beam traversing along the axis (Fig. 43). The dipole wakefield computation for the OC cavity (cf. Fig. 11) in fact revealed the leakage of the FM into the dipole impedance spectrum. Overall, due to the high cutoff frequency of the HOM waveguides, the CEABF OC cavity does not fully employ its capability to damp crucial dipole HOMs given the rather large cell-to-cell coupling (k_{cc} = 3.2%) and small number of cavity cells (N_c = 5). The performance-limiting modes have impedances of R/N_c = 108 kΩ (TE111) and R_{tr}/N_c = 17961 kΩ/m (per Table 4, f_{ref} = 500 MHz) due to dipole modes. In comparison, the corresponding mode
impedances in the TESLA cavity ($k_{cc} = 1.9\%, N_C = 9$) are $R_l/N_C = 707 \, \text{k}\Omega$ (TM011) and $R_tr/N_C = 1205 \, \text{k}\Omega/m$.

**Figure 42.** Critical modes in the CEBAF OC cavity as detailed in the text.

Yet, the C100 LL cavities perform least efficient of all cavities reviewed ($R_l/N_C = 10637 \, \text{k}\Omega$ and $R_tr/N_C = 17961 \, \text{k}\Omega/m$). The orientation of the coaxial couplers is not optimal to couple to dipole modes that have longitudinal magnetic fields along the beam pipe wall. Experimental data revealed that the cavity features a critical TM111 dipole pair resonating above the beam tube cutoff. Their $Q_{ext}$-values can vary by up to three orders of magnitude depending on beam tube boundary conditions [37]. With comparably small iris apertures ($k_{cc} = 1.5\%$) and a large number of cells ($N_C = 7$) the HOM field pattern are sensitive to fabrication tolerances. With both coaxial couplers positioned on one side of the cavity only - which is in contrast to the TESLA and SNS cavities - tilted fields towards the FPC side create a risk of insufficient damping. For this reason, the $Q$-values of critical HOMs were routinely checked in all C100 LL before cryomodule installation as part of quality control. This assured that no cavity was built into CEBAF exceeding its BBU impedance instability thresholds for the 12 GeV operation era. Moreover, the FPC waveguide has been optimized to enhance the transmission within the spectral range of the critical modes accounting for both polarizations, and modifications were done for the beam tube ends in cryomodules to enhance the HOM damping [37]. Though the monopole and dipole impedances are the highest among all cavities reviewed, these are still below the multi-pass BBU impedance instability thresholds, i.e. $1.0e7/2.4e7 \, \text{k}\Omega/m$ for deflecting modes ($\sim$100/400 $\mu$A injection current) and $2.7e8 \, \text{k}\Omega$ for monopole modes.

**Figure 43.** Time-averaged RF electric field of traveling fundamental mode in the center plane of the FPC waveguide for the CEBAF OC (left) and C100 LL cavity (right).
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9. References

[1] A. Mosnier, C. Chel, X. Hanus, A. Novokhatski, and G. Flynn, “Design of a Heavily Damped Superconducting Cavity for Soleil”, 7V029, Proceedings of the 1997 Particle Accelerator Conference.

[2] S. Bauer, W. Diete, B. Grieb, M. Peiniger, P. von Stein, S. Calatroni, E. Chiaveri, and R. Losito, “Production of Nb/Cu Sputtered Superconducting Cavities for LHC”, WEP016, Proceedings of the 1999 Workshop on Superconductivity, Santa Fe, New Mexico, USA.

[3] E. Chiaveri, “The CERN Nb/Cu Programme for the LHC and Reduced-Beta Superconductivity Cavities”, WEA003, Proceedings of the 1999 Workshop on RF Superconductivity, Santa Fe, New Mexico, USA.

[4] H. Padamsee et al., “Accelerating Cavity Development for the Cornell B-Factory, CESR-B”, SRF 980612-04, Proceedings of the 1991 Particle Accelerator Conference.

[5] S. Mitsunobu, K. Asano, T. Furuya, Y. Ishi, Y. Kijima, K. Sennyu, T. Tajima, T. Takahashi, and S. Zhao, “Status and Development of Superconducting Cavity for KEKB”, Proceedings of the 1997 Particle Accelerator Conference, Volume 3.

[6] T. Tajima, K. Akai, E. Ezura, T. Furuya, K. Hosoyama, and S. Mitsunobu, “The Superconducting Cavity System for KEKB”, THBL2, Proceedings of 1999 Particle Accelerator Conference, New York.

[7] W. Xu, I. Ben-Zvi, T. Roser, V. Ptitsyn, “Frequency choice of eRHIC SRF linac”, Technical Note, BNL-111776-2016-IR, January 2016.

[8] W. Xu, I. Ben-Zvi, S. Belomestnykh, R. Calaga, H. Hahn, E.C. Johnson, and K. Kewisch, “High Current SRF Cavity Design for SPL and eRHIC”, FROBS6, Proceedings of 2011 Particle Accelerator Conference, New York, USA.

[9] H. Wang, R. Rimmer, and F. Marhauser, “Simulations and Measurements of a Heavily HOM-Damped Multi-Cell SRF Cavity”, WEPMS070, Proceedings of 2007 Particle Accelerator Conference, Albuquerque, New Mexico, USA.

[10] P. Kneisel et al., “Superconducting Prototype Cavities for the Spallation Neutron Source (SNS Project)”, ROAA005, Proceedings of 2001 Particle Accelerator Conference, Chicago, Illinois, USA.

[11] A. Neumann, J. Knobloch, B. Riemann, T. Weis, K. Brackebusch, T. Flisgen, T. Galek, and U. van Rienen, “Final Design for the bERLinPro Main Linac Cavity”, MOPP070, Proceedings of the 2014 Linear Accelerator Conference, Geneva, Switzerland.

[12] R.L. Geng, P. Barnes, M. Liepe, V. Medjizade, H. Padamsee, A. Seaman, J. Sears, N. Sherwood, and V.D. Shemelin, “Progress of the 2-Cell Cavity Fabrication for Cornell ERL Injector”, SRF050608-04, Proceedings of the 2005 Particle Accelerator Conference, Knoxville, Tennessee, May 16-20, 2015.

[13] N. Valles and M. Liepe, “Baseline Cavity Design for Cornell’s Energy Recovery Linac”, THP034, Proceedings of 2010 Linear Accelerator Conference, Tsukuba, Japan.

[14] B. Aune et al., “Superconducting TESLA Cavities”, Physical Review Special Topics – Accelerators and Beams, Volume 3, 092001 (2000).

[15] J. Sekutowicz, G. Ciovati, P. Kneisel, G. Wu, A. Brinkman, W. Hartung, R. Parodi, and S. Zheng, “Cavities for JLab’s 12 GeV Upgrade”, TPAB085, Proceedings of the 2003 Particle Accelerator Conference, Portland, Oregon, USA.

[16] I.E. Campisi, Lynda K. Summers, A. Betto, and B.H. Branson, “Artificial Dielectrics for CEBAF’s Higher-Order-Mode Loads”, Proceedings of the Sixth Workshop on RF Superconductivity, Newport News, Virginia, 1993.

[17] P. Marchand, “Superconducting RF Cavities for Synchrotron Light Sources”, MOYCH03, Proceedings of the 2004 European Particle Accelerator Conference, Lucerne, Switzerland.

[18] LHC Design Report, Vol. 1, The LHC Main Ring, European Organization for Nuclear Research, CERN-2004-003-V-1, 2004.

[19] H. Vogel et al., “Superconducting Accelerator Modules for the Taiwan Light Source”, WEP3A02, Proceedings of the 2004 European Particle Accelerator Conference, Vienna, Austria.
[20] H. Padamsee, “Review of Experience with HOM Damped Cavities”, THX02B, Proceedings of the 1998 European Particle Accelerator Conference, Sweden, Stockholm.

[21] S. Bolomestnykh et al., “Superconducting RF Linac for eRHIC”, MOPB063, Proceedings of the 2012 Linear Accelerator Conference, Tel-Aviv, Israel.

[22] A. Yamamoto, M. Ross, and N. Walter, “Advances in SRF Development for ILC”, MOIOA02, Proceedings of the 2011 Workshop on Superconductivity, Chicago, Illinois, USA.

[23] R.L. Geng et al., “Fabrication and Performance of Superconducting RF Cavities for the Cornell ERL Injector”, WEPM007, Proceedings of the 2007 Particle Accelerator Conference, Albuquerque, USA.

[24] M. Liepe et al., “Progress on Superconducting RF Work for the Cornell ERL“, WEPPC073, Proceedings of the 2012 International Particle Accelerator Conference, New Orleans, Louisiana, USA.

[25] The SRF Department, “RF Superconductivity at CEBAF”, Proceedings of the 5th Workshop on RF Superconductivity, DESY, Hamburg, Germany, 1991.

[26] D. Boussard and T. Linnecar, “The LHC Superconducting RF System”, LHC Project Report 316, 1999.

[27] TESLA, “The Superconducting Electron-Positron Linear Collider with an Integrated X-Ray Laser Laboratory”, Technical Design Report, March 2001, DESY-2001-011, ECFA-2001-209, TESLA-2001-23, TESLA-FEL-2001-05, http://tesla.desy.de/new_pages/TDR_CD/start.html

[28] W. Singer et al., “Production of superconducting 1.3-GHz cavities for the European X-ray Free Electron Laser”, Physical Review Accelerators and Beams 19, 092001 (2016).

[29] M. Howell et al., “History of Cryomodule Repairs at SNS”, THPP109, Proceedings of the 2014 Linear Accelerator Conference, Geneva, Switzerland.

[30] J. Sekutowicz, “HOM Couplers at DESY”, Proceedings of the Third Workshop on Superconductivity, Argonne National Laboratory, Illinois, USA, 1987.

[31] J. Sekutowicz, “Higher Order Mode Coupler for TESLA”, Proceedings of the Sixth Workshop on Superconductivity, CEBAF, Newport News, USA, 1993.

[32] A. Mosnier, S. Chel, X. Hanus, F. Orsini, J. Jacob, and O. Naumann, “HOM Damping in Soleil Superconducting Cavity”, TUPOS5C, Proceedings of the 1998 European Particle Accelerator Conference, Stockholm, Sweden.

[33] Ph. Bernard, E. Chiaveri, E. Haebel, W. Weingarten, and A. Mosnier, “Demountable E/H-Field Higher Order Mode Couplers for the Niobium Sputtered 4-Cell LEP Cavity”, Proceedings of the Fifth Workshop on RF Superconductivity, DESY, Germany, 1991.

[34] C.E. Reece, E. F. Daly, T. Elliott, H. L. Phillips, J. P Ozelis, T. Rothgeb, K. Wilson, and G. Wu, “High Thermal Conductivity Cryogenic RF Feedthroughs for the Higher Order Mode Couplers”, TPPT082, Proceedings of the 2005 Particle Accelerator Conference, Knoxville Tennessee.

[35] C.E. Reece, E.F. Daly, W.R. Hicks, J. Preble, H. Wang, and G. Wu, “Optimization of the SRF Cavity Design for the CEBAF 12 GeV Upgrade”, WEP31, Proceedings of the 13th International Workshop on Superconductivity, Beijing, China, 2007.

[36] R. Kazimi et al., “Observation and Mitigation of Multipass BBU in CEBAF”, WEPP087, Proceedings of the 2008 European Particle Accelerator Conference, Genoa, Italy.

[37] F. Marhauser, J. Henry, and H. Wang, “Critical Dipole Modes in JLab Upgrade Cavities”, THP009, Proceedings of the 2010 Linear Accelerator Conference, Tsukuba, Japan.

[38] P. Kneisel, G. Ciovati, G.R. Myneni and G. Wu, J. Sekutowicz, “Testing of HOM Coupler Designs on a Single Cell Niobium Cavity”, TPPT007, Proceedings of the 2005 Particle Accelerator Conference, Knoxville, Tennessee.

[39] I. Gonin, N. Solyak, J. DeFord, and B. Held, “Multipactor Simulations in Superconducting Cavities”, WEPMN093, Proceedings of the 2007 Particle Accelerator Conference, Albuquerque, USA.

[40] D. Kostin, J. Sekutowicz, W.-D. Moeller, and T. Buettner, “Multipacting in HOM Couplers at the 1.3 GHz 9-Cell Tesla Type SRF Cavity”, THPO003, Proceedings of the 2011 Workshop on Superconductivity, Chicago, Illinois, USA.

[41] S. Belomestnykh, “Superconducting RF in Storage-Ring-Based Light Sources”, SRF071120-03, 13th International Workshop on Superconductivity, Beijing, China, 2007.

[42] J. Kirchgessner, “Review of the Development of RF Cavities for High Current”, SRF 950413-06, Cornell 1995.

[43] E. Chojnacki and W.J. Alton, “Beamline RF Load Development at Cornell”, MOP77, Proceedings of the 1999 Particle Accelerator Conference, New York.

[44] T. Furuya, “Operation Experience of HOM absorbers at KEKB”, Workshop on Higher-Order-Mode Damping in Superconducting RF Cavities, Ithaca, USA, 2010.
V. Shemelin, P. Barnes, B. Gillett, M. Liepe, V. Medjidzade, H. Padamsee, R. Roy, and J. Sears, “Status of HOM Load for the Cornell ERL Injector”, MOPCH177, Proceedings of the 2006 European Particle Accelerator Conference, Edinburg, Scotland.

J. Sekutowicz, N. Mildner, M. Dohlus, and K. Zapfe, “A Beam Line HOM Absorber for the European XFEL Linac”, THP55, Proceedings of the 12th International Workshop on RF Superconductivity, Ithaca, USA, 2005.

M. Liepe et al., “Status of the Cornell Injector SCRF Cryomodule”, TU303, Proceedings of the 2010 Linear Accelerator Conference, Tsukuba, Japan.

T. Tajima et al., “HOM absorbers of Superconducting Cavities for KEKB”, WEP0611, Proceedings of the 1996 European Particle Accelerator Conference.

J. Sekutowicz, N. Mildner, M. Dohlus, and K. Zapfe, “A Beam Line HOM Absorber for the European XFEL Linac”, THP55, Proceedings of the 12th International Workshop on RF Superconductivity, Ithaca, USA, 2005.

T. Tajima et al., “HOM absorbers of Superconducting Cavities for KEKB”, WEP0611, Proceedings of the 1996 European Particle Accelerator Conference.

J. Sekutowicz, N. Mildner, M. Dohlus, and K. Zapfe, “A Beam Line HOM Absorber for the European XFEL Linac”, THP55, Proceedings of the 12th International Workshop on RF Superconductivity, Ithaca, USA, 2005.
S. Bar talucci, R. Boni, A. Gallo, L. Palumbo, R. Parodi, M. Serio, B. Spataro, and G. Vignola, “DAΦNE Accelerating Cavity: R&D”, Proceedings of the 1992 European Particle Accelerator Conference, Berlin, Germany.

R.A. Rimmer, "RF Cavity Development for the PEP-II B Factory", LBL-33360, International Workshop on B-Factories: Accelerators and Experiments, KEK, Tsukuba, Japan, 1992.

F. Marhauser, E. Weihreter, D.M. Dykes, and P. McIntosh, “HOM Damped 500 MHz Cavity Design for 3rd Generation SR Sources”, MPPH033, Proceedings of 2001 Particle Accelerator Conference, Chicago, USA.

N. Guillotin, J. Jacob, and S. Serrière, “Development of HOM damped Copper Cavity for the ESRF”, TUPCH099, Proceedings of the 2006 European Particle Accelerator Conference, Edinburgh, Scotland.

R. Boni, “HOM-free cavities”, TUY01A, Proceedings of the 1996 European Particle Accelerator Conference, Sitges, Barcelona.

J.M. Dorfan, “PEP-II Status Report”, WEY02B, Proceedings of the 1998 European Particle Accelerator Conference, Sweden Stockholm.

F. Perez, B. Bravo, P. Sanchez, and A. Salom, “Commissioning of the Alba Storage Ring RF System”, MOPC045, Proceedings of the 2011 International Particle Accelerator Conference, San Sebastian, Spain.

R. Boni, F. Caspers, A. Gallo, G. Gemme, and R. Parodi, “A Broadband Waveguide to Coaxial Transition for Higher Order Mode Damping in Particle Accelerator RF Cavities”, Particle Accelerators, 1994, Vol. 45, pp. 195-208.

F. Marhauser and E. Weihreter, “First Tests of a HOM-Damped High Power 500 MHz Cavity”, TUPKF011, Proceedings of the 2004 European Particle Accelerator Conference.

F. Marhauser, E. Weihreter, and C. Weber, “Impedance Measurements of a HOM-Damped Low Power Model Cavity”, TPAB005, Proceedings of the 2003 Particle Accelerator Conference.

F. Marhauser, “Calculations for RF Cavities with Dissipative Material”, THPB003, Proceedings of the 2015 Workshop on Superconductivity, Vancouver, Canada.

M. Liepe, “HOM Damping in the Cornell ERL SRF injector module: HOM measurements and high beam current beam operation”, International ICFA Workshop on Higher Order Mode Diagnostic & Suppression in SC Cavities, 2012.

F. Marhauser, R.A. Rimmer, K. Tian, and H. Wang, "Enhanced Method for Cavity Impedance Calculations", FRSPFP094, Proceedings of the 2009 International Particle Accelerator Conference, Vancouver, Canada.

F. Marhauser and H. Wang, “HOM Survey of Low Loss Seven Cell Cavities for the CEBAF 12 GeV Upgrade”, JLab Technical Note JLAB-TN-08-37, 2008.

S. Wang, J. Guo, R. Rimmer, and H. Wang, “JLEIC SRF Cavity RF Design”, WEPMW039, Proceedings of the 2016 International Particle Accelerator Conference, Michigan, USA.

W.H. Hartung, “The Interaction between a Beam and a Layer of Microwave-Absorbing Material”, Thesis, Cornell University, 1996.

Conceptual Design Report, “PERLE, Powerful Energy Recovery Linac Experiments”, CERN, to be published.

S. Belomestnykh, W. Hartung, J. Kirchgessner, D. Moffat, H. Muller, H. Padamsee, and V. Veshcherevich, “Comparison of the Predicted and Measured Loss Factor of the Superconducting Cavity Assembly for the CESR Upgrade”, SRF9504060-04, 1995.

http://fcc.web.cern.ch

FCC, “Future Circular Collider Study Lepton Collider Parameters”, FCC-1401201640-DSC, 2016

The CEPC-SPPC Study Group, “CEPC-SPPC Preliminary Conceptual Design Report”, Vol. II – Accelerator, IHEP-CEPC-DR-2015-01, IHEP-AC-2015-01, March 2015.

R. Rimmer, “Update of the Jefferson EIC SRF Systems”, JLEIC Collaboration Meeting, October 2016.

E. Chojnacki, “Experience with ERL Beamline Load Prototypes”, HOM Workshop 2010, Cornell University, Ithaca, USA.

W. Barry, J. N. Corlett, G. Lambertson, D. Li, J. Fox, and D. Teitelman, “Initial Commissioning Results from the PEP-II Transverse Coupled-Bunch Feedback Systems”, WEP14G, Proceedings of the 1998 European Particle Accelerator Conference, Stockholm, Sweden, 1998.

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