The Summary for Optimization of the Annular Coupled Structure Accelerating Module Physical Design for High Intensity Hadron Linac

V.V. Paramonov *

KEK, Tsukuba, 2013

* - permanent address - Institute for Nuclear Research of the RAS, 117312, Moscow, Russia
Abstract

The normal conducting Annular Coupled Structure (ACS) is applied for 190-400 MeV part of high intensity proton linac for the J-PARC. The ACS operating frequency is 972 MHz. The J-PARC ACS is strongly based on the results of previous investigations, especially results of Japan Hadron Project (JHP) research program in KEK. However, the design was revised and optimized to meet the requirements of reliability, operation efficiency and cost reduction.

The cells shape of accelerating cells was optimized in total energy range to have high shunt impedance value together with the careful matching with the decreased coupling cells. The design of the bridge coupler cells was optimized to simplify mass production and shape of RF input cell together with matching window were optimized for higher operational reliability.

Collected and adjusted all together, these modifications result in the significant effect. The ACS module design doesn’t lose to another possible accelerating structures in RF parameters and dimensions. Previously developed for L-band ACS fabrication technique is applied to 972 MHz ACS construction. The realized solutions have the reserve for ACS module use with very high heat loading during operations with 15% duty factor, the highest heat loading at present time, as compared to accelerating modules with another normal conducting accelerating structures, realized in hadron linacs.

This report contains the descriptions and explanations of changes in the ACS module physical design for the J-PARC linac.
## Contents

1 **Introduction**  
2 **Proven accelerating structures for high energy part of the linac**  
   2.1 The ACS improvements during JHP program  
3 **Optimization of ACS cells. Design parameters.**  
   3.1 Accelerating cells optimization  
   3.2 Coupling cells optimization  
   3.3 Cells adjustment and coupling slots orientation  
   3.4 ACS with the large aperture radius  
   3.5 Thermal-stress analysis  
   3.6 Conclusion for ACS regular cells  
4 **Bridge coupler part optimization**  
   4.1 The coupling coefficients relations in the ACS module  
   4.2 The shape of matching window  
5 **Comparison with SCS in parameters**  
6 **Summary**  
7 **Acknowledgments**  
8 **References**
1 Introduction

In the second part of the 20-th century the development of high intensity normal conducting linacs with the final energy of hydrogen ions up to (600 - 1000) MeV with the average beam current up to (0.5 - 1.0) mA were under development in several countries. The first such linac was constructed in Los Alamos, USA, at the energy 800 MeV, pulse beam current 17 mA and average beam current 1.2 mA, starting with the first beam in 1972. The second such linac, with the designed energy 600 MeV, pulse current 50 mA and average current 0.5 ma, was constructed in USSR, INR of the RAS, starting with the first beam in 1990 and now operating, unfortunately, not with full power.

During development of such linacs, named that time as ‘meson factories’, two important statement for normal conducting accelerating structures in these linacs, were formulated. There are no single accelerating structure, which can overlap the total energy range of such hadron linac.

For high intensity linacs so called compensated accelerating structures should be used, which combine the high RF efficiency with the high stability of accelerating field distribution with respect to errors in manufacturing and tuning, beam loading. The compensated are named structures, in which at operating frequency coincide frequencies of two modes - accelerating mode and coupling mode, with conjugated parity of field distributions, [1]. Another definitions of these structures, used in the literature, are bi-periodical structures or coupled cell structures.

For the initial part of the linacs with the energy up to (50 - 80) MeV the Drift Tube Linac
(DTL), or Alvarez structure, is used with post couplers (for field distribution stabilization) until now without principal changes. In the energy range from 80 MeV to 150 MeV based on DTL structures, Separated DTL (SDTL) or Coupled Cell DTL (CCDTL) can be applied. Anyhow, with the beam energy increasing RF efficiency of DTL-based structures decreases and another accelerating structure should be applied. There were a lot of proposals of such structures for the high energy part of the linac. Most typical are shown schematically in the Fig. 1.

Accelerating structure for the high intensity hadron linac should satisfy to the set of different requirements, which are sometimes contradictory - required RF parameters, operational reliability and stability, vacuum conductivity, technological aspect, including the price of construction. It stimulates research and development for new structures. But very important, decisive points are the level of development and demonstration of the required parameters of the full scale structure at high RF power. It confirms the possibility to create the accelerating system with required parameters.

2 Proven accelerating structures for high energy part of the linac

Figure 2: The SCS structure in the high energy part of the LANSCE linac (left) and the high energy part of the INR linac with DAW structure (right).

The first accelerating structure, realized in the high energy part of the linac, Fig. 2, SCS, invented and investigated in LANL, [2], [3]. Later this structure was used in FNAL injector linac energy upgrade to 400 MeV and also applied in SNS linac in the room temperature part. The schematic view of this structure is shown in Fig. 3b. The structure has a coupling coefficient value $k_c \approx (4 - 5)\%$. Due to position of coupling slots oppositely in diameter, in the field distribution of accelerating cells there is dipole addition and at the beam axis there is not zero transverse field. Due opposite direction in adjacent cells the effect of transverse field for the synchronous particle cancels in the first order in $\delta \beta$, but the second order effects remain. Here $\delta \beta$ is the relative increasing of the particle velocity at one accelerating gap.

In the USSR development program of 'meson facility' linac ACS and DAW were invented, [4], [5]. Both structures were tested at high RF power level, [6], and, due to higher coupling
coefficient $k_c \approx (40 - 50)\%$, the DAW structure, Fig. 3a, was chosen as realized in INR linac, Fig. 2. Together with the high $k_c$ value, DAW has an excellent vacuum conductivity. The washers are connected to disks with L-type supports, in which the cooling channels for water supply in the washer are placed. The structure has a severe High Order Modes (HOM) problem, and HOM’s are placed below, in the vicinity, and above operating frequency. In the structure design the special selective resonant elements - slots (3, in Fig. 3a) were introduced. These slots do not interact with accelerating mode and do not deteriorate operating RF parameters. But, interacting with HOM’s, slots result in the displacement of HOM’s from the vicinity of operating frequency. Another solution for HOM’s displacement was developed later with bi-periodic L-type supports by Y. Iwashita. For this structure there are at least two solutions for RF HOM problem. For the range of particles velocity $\beta = (0.4 \div 0.8)$ from 95% to 80% of the total RF losses are in the washers. For application in linac with the high duty factor value the heat load exceeds in order the value, proven in INR linac. Because water supply can be realized only through thin L-type supports, this problem looks difficult. 

The On axis Coupled Structure, Fig. 3c, is widely used in compact electron linacs. For protons acceleration this structure was considered too, but rejected, due essential reduction of effective shunt impedance $Z_c$ for medium $\beta$ range and possibility of a stable multipactoring in coupling cells.

2.1 The ACS improvements during JHP program

During JHP research and development program in KEK [7], under leadership of Y. Yamazaki, the ACS design for L-band frequency range, Fig. 4, was essentially, in some parameters qualitatively, improved. The number of slot was increased from two to four. It ensures decoupling of accelerating mode with $TM_{110}$ HOM mode, which exists in coupling cells not so far from operating frequency. The tapering, applied near coupling slots, (2 in Fig. 4) allows $k_c$ value $\approx 5\%$ together with significant thickness of the web between accelerating and coupling cells.
The sufficient web thickness allows a placement of cooling channels. Elaborated and effective cooling circuit was developed, ensuring stable ACS operation with high heat loading. The fabrication technique for L-band ACS was developed and tested also. The multi-cell bridge cavity was developed to overlap the space required for focusing elements. In the bridge cavity are placed fast movable tuners for operating frequency fast control. The cooling water is used only for heat removal. The entire cooling system becomes much more simple, as compared to the solution of the frequency control by change of cooling water temperature or flow.

Totally, in JHP research was developed the concept of accelerating module, Fig. 5. Finally, L-band ACS module was successfully tested at the high level of RF power.

Basing on:
- results of comparative estimations for different accelerating structures for high intensity hadron linac;
- proven results of the L-band ACS structure performance and the developed fabrication technique;
accumulated experience for L-band ACS module construction with required parameters;
- proven results of L-band accelerating ACS module and promising expectations and esti-
mations for operating frequency 972 MHz;
the development of accelerating module with ACS structure was chosen as the base line for
normal conducting module for J-PARC linac.

3 Optimization of ACS cells. Design parameters.

The direct scaling from the L-band ACS design is not a solution, because leads to increasing
of transverse dimensions in 1.33 times and structure weight per unit length in 1.75 times.
In this way the developed brazing technique, applied also for SCS in LANL and DAW in
INR, meets strong problems in the uniformity and reliability of brazed joint. After SCS
construction in LANL with $f_{\text{op}} = 805 MHz$, where $f_{\text{op}}$ is the operating frequency, there was
conclusion, that the possibilities of brazing technique limit possible SCS operating frequency
to $f_{\text{op}} > (600 - 700) MHz$. Later, the problems in the construction of SCS module with
$f_{\text{op}} = 704 MHz$ for high RF power test were not the last reasons to change the structure.
In ACS optimization transverse dimensions should be reduced essentially. It are defined in
ACS by diameter of coupling cells. But another points - vacuum ports and connection with
accelerating cell - are also important.
During development the achieved L-band ACS performance should not be lost. Also the
high heat capability should be saved - ACS module should have a possibility for operation
with 15% duty factor.

3.1 Accelerating cells optimization

The procedure and technique of cells optimization is described in [12]. The final choice was
done after several iterations in the mutual adjustment of coupling and accelerating slots and
here mainly reasons, results and conclusions are given.
For the wide range optimization, described in [12] two shapes of accelerating cell, shown in
Fig. 6b and Fig. 6c, were used.
For reference, the shape of L-band ACS was scaled to $f_{\text{op}} = 972 MHz$, Fig. 6a. Two another
shapes differ in outer part. The shape in Fig. 6b has two radii of outer rounding. The shape
in Fig. 6c has the conical part with small adjacent rounding, both for quality factor small
improvement and to provide a smooth surface. The goal of this modifications is to find the
most convenient and effective solution for accelerating cell outer shape for connection with
coupling cell.
The drift tube nose has two radii of rounding, $r_1$ and $r_2$ in Fig. 6c. The maximal electric
field at the surface $E_s$, which determines an electrical strength of the structure and possibil-
ity of breakdowns, takes place at the upper nose part. As the result of applied wide range
study, we can have clear representation about the influence of each geometrical parameter on
structure RF parameters. In Fig. 7a is shown the surface of the effective shunt impedance
$Z_e$ on two variables - the radius of lower rounding $r_1$ and the gap ratio $\alpha$ for another free
parameters being fixed. One can clearly see significant $Z_e$ reduction with $r_1$ increasing, while
$r_1$ increasing affects $E_s$ slightly. We can all time find the relation $r_1$ and $r_2$ to improve $Z_e$
value but to keep $E_s$ below required value.
Figure 6: Considered shapes of the ACS accelerating cell a) - the scaled L-band shape, b) - the shape with two outer rounding, c) - the shape with a conical part, d) - the final choice.

For both shapes under consideration the influence of cell dimensions on RF parameters

Figure 7: The surface $Z_e(r_1, \alpha)$ to illustrate $r_1$ influence (a) and plots of of the total $Z_e$ value for the total ACS system in dependence on $E_a/E_k$ ratio (b).

was considered assuming the total ACS structure for energy range from 190 MeV to 400 MeV, $\beta = (0.556 \div 0.713)$. Some dimensions were fixed, considering ACS RF parameters in relationships with beam dynamics and operational reliability requirements.

Instead of essential $Z_e$ increasing with decreasing the aperture radius $a$, this radius was fixed to $a = 20\,\text{mm}$ for the total ACS system, taking into account beam dynamics conditions, especially taking care for matching with previous linac part.

The total ACS $Z_e$ value also can be increased by $t_w$ reduction - the web thickness between adjacent accelerating cells. But we have to place inside web effective cooling channels and foresee the sufficient thickness of material between cooling cannels and vacuum volume of accelerating cell, taking into account effect of high temperature brazing. The web thickness
was fixed to \(2t_w = 13.7\, mm\) for the entire ACS system. Instead of cooling channels are placed close to the drift tube as possible, the heat evacuation from the drift tube nose, the point with the maximal \(E_s\) value, is due to natural copper heat conductivity only. The drift tube cone angle was fixed to 30° as the compromise between possible \(Z_e\) increasing by angle reduction and heat evacuation conditions without cooling channels inside the drift tube.

In Fig. 7b are shown plot of \(Z_e\) value for the total ACS system in dependence on \(E_s/E_k\) ratio, where \(E_k\) is the Kilpatric threshold value for \(f_{op} = 972\, MHz\). As one can see, plot show saturation with \(E_s/E_k\) increasing. Increasing \(E_s/E_k\) from 1.0 to 1.1, we can expect \(Z_e\) increasing at 25\(\, MOm\), or relative increasing \(\frac{\Delta Z_e}{Z_e}\) < 1%. With increasing of time for conditioning and risk of possible breakdowns during operation we have no adequate compensation in RF efficiency. For the total ACS system the maximal surface electric field was fixed as \(E_s \sim 1.0E_k\).

For another dimension of accelerating cell the RF parameters of the entire ACS system were considered in the option ”all variable” to get the maximal \(Z_e\) value with limitations for \(a, t_w\) and \(E_s\), applied before. After that the fixed parameters for entire ACS system were founded to have the minimal deviation from the optimal \(Z_e\) value. The relative difference was found as 1.2% and for cost reduction in ACS production the dimensions of accelerating cells were fixed, as shown in Fig. 6d. The adjustment of operating frequency for each \(\beta\) is by adjustment of gap length between drift tubes.

As one can see from the plots in Fig. 7b, the price for conical part in the accelerating cell shape is \(Z_e\) reduction at \(\sim 3\%\) as compared to the totally rounded shape. But it is not the final result for the ACS J-PARC structure - it is the intermediate result in 2D, approximation without connection with coupling cell. We have to get the best final result in 3D case.

### 3.2 Coupling cells optimization

To decrease ACS transverse dimension, the ”radial” cell orientation, realized in L-band ACS, Fig. 8a, was changed to the ”longitudinal” one, Fig. 8b.

The shape and dimensions for the lower part of the cell were chosen for better adjustment with accelerating cell, comfortable tool access in surface treatment and for higher, than in upper part, magnetic field density for higher coupling coefficient. The gap length in the cell, Fig. 8b, was reduced slightly, to keep conditions for multipactor discharge in coupling cells as ensured ”not possible”, [13], and do not increase the sensitivity of coupling cell frequency to deviation of gap length during mechanical treatment and brazing.

The vacuum ports are shifted inside the cell, crossing the outer cell part and the cell gap region too. The cells with the modified shape were analyzed for breakdown possibility with cells excitation due to accelerating cells detuning and during transient and the big reserve in the electric strength was detected.

For mass production simplification the dimensions of coupling cells are the same through the total ACS system. Later the cell shape was corrected slightly for further simplification - the outer cell part was modified to flat.

In such design the transverse ACS dimensions are defined by the outer coupling cell radius.
3.3 Cells adjustment and coupling slots orientation

The value of coupling coefficient $k_c$ between accelerating and coupling cell depends on the dimensions, position and mutual orientation of coupling slots. For the structures, coupled with slots for one slot

$$k_c \sim \frac{h_s l_s^3 H_a H_c}{t_s W_a W_c}, \quad (1)$$

where $l_s$ and $h_s$ are the lengths and the height of the slot, $t_s$ is the web thickness between cells in the place of the slot, $H_a, H_c$ are the magnetic field at the slot for accelerating and coupling cells, $W_a, W_c$ are the stored energy in accelerating and coupling cells respectively. Instead of a strong dependence $k_c \sim l_s^3$, the slot length increasing leads to increasing of RF current density at the slot ends and $Z_e$ reduction. At first, the slot height $h_s$ was adjusted to maximal comfortable value and tapering angle was optimized. Finally, the slot dimensions were fixed to $h_s = 27.6 \text{mm}$ and the slot opening angle (from the axis) $33^\circ$

The slot edges from the side of accelerating cell were rounded with $r = 4 \text{mm}$. As compared to sharp $90^\circ$ edges, it results, according simulations, in $k_c$ increasing at $\sim 0.3\%$, (from $5.58\%$ to $5.85\%$, $Q_a$ increasing is several percent’s and thermal stress reduction in the slot region.

(Later, in ACS optimization for mass production, slot rounding was changed to chamfer without degradation of another performances).
If slots at the opposite sides of the cell are placed "face to face", the partial coupling cancellation takes place. The maximal value of coupling coefficient can be achieved when the slots at one side of the cell are placed in between of slots at opposite side of the cell. Such slots orientation was realized in the L-band ACS and the procedure was established to determine cells frequencies for RF tuning before brazing. Such configuration realize complicated symmetry of the structure - simultaneous translation and rotation, [7]. Such structures have no planes of mirror symmetry, where shorting plates can be applied and approximated method of cells detuning was used for frequencies estimations.

The coupling cancellation effect depends on the longitudinal distance between slots. The coupling cell is short enough and "face to face" slots orientation at the opposite sides leads to strong $k_c$ reduction. In the coupling ACS cells slots at one side of the cell are shifted at 45° with respect to slots at the opposite side. In SCS coupling cells "face to face" slots orientation, Fig. 3b, is realized just from necessity and coupling cancellation should be compensated by slots increasing or stronger magnetic field at the slots.

Simulations have shown, [12], that for the worth case of the short accelerating cell $\beta = 0.556$ the difference in $k_c$ value is not so big - $k_c = 6.25\%$ for rotated slot position and $k_c = 6.05\%$ for opposite slots position, for example, with the relative difference $\frac{\Delta k_c}{k_c} \approx 3.3\%$. For the higher $\beta$ values this difference is even smaller. But with opposite slot position we get a plane of mirror symmetry in the middle of accelerating cell and can utilize much simpler procedure for cell frequency measurements during RF tuning. At the plane of mirror symmetry the field of accelerating mode satisfies to electric wall boundary conditions and shorting plate can be used. The measurement of accelerating cells frequency is evident, similar to shown in Fig. 9a or without detuning rods in pumping ports. For coupling mode frequencies measurement non direct method is suggested, [12], because the coupling mode with magnetic wall boundary condition can not be excited. In the assembly with two ACS periods we measure frequencies for 0− and $\pi/2$− mode of the chain from two coupling cells, because accelerating cell is detuned drastically. From the measured values we can extract the frequency for $\pi$− mode, which corresponds to the coupling cell frequency.

All time coupling slots deteriorate the axial symmetry of the cell, resulting in multipole additions in the field distribution. For four slots at each side of the cell this addition starts all time from quadrupole and higher. But for the rotated slot position the quadrupole addition has the even dependence of transverse field components with respect to symmetry plane, and

Figure 9: Schematic sketches for frequency measurements of accelerating mode (a) and coupling mode (b) frequencies. 1) - ACS periods, 2) - shorting plates, 3) - detuning rods for coupling cell, 4) - detuning rod for accelerating mode.
for opposite slot position - the odd dependence with much faster decay of additions from the
slot to the structure axis. It is additional preference of coupled slot structures with mirror
symmetry plane.
Basing on obtained results for not so big $k_c$ decreasing and practical preference of opposite
slot position at opposite sides of accelerating cell, this configuration is chosen for J-PARC
ACS.
Normally in the slot coupled structures the coupling coefficient value can be achieved at the
expense of $Z_e$ reduction with the rate $\sim (1 - 2\%)$ reduction in $Z_e$ for 1%$k_c$ increasing. For
the slot coupled structures with the rounded outer part of accelerating cell the adjustment
with coupling cell is not convenient. One can see the complicated surface in the connecting
region for SCS, Fig. 3b. During SCS cells production for SNS linac additional mechanical
treatment was required to remove sharp edges and provide tolerable slot shape, [14].
With the conical part in the shape of accelerating cell, Fig. 6c, we get a strong mechanical
design, with controllable slot shape and reduced slot length. For the shorter slot the density
of RF current near slot ends is lower and in the total 3D structure we recover the reduced
at 3.3% in 2D case $Z_e$ value. Comparative 3D simulations have shown, that for the same $k_c$
value and the same modified coupling cell the structures with rounded accelerating cell, Fig.
6b, and the structure with conical part in accelerating cell, Fig. 6c, differ in $Z_e$ at < 1%.
In ACS $k_c$ depends also on the thickness of the web between coupling and accelerating cells.

![Figure 10: The final configuration of the J-PARC ACS period.](image)

| $\beta$ | $k_c, \%$ | $Q_a$ | $Z_e, \frac{\text{MOM}}{m}$ | $T$ | $\frac{Z_e}{Q_a, \text{KOM}}$ | $E_{\text{max}}$ | $E_o/T$ |
|--------|------------|-------|-----------------|------|---------------------|-------------|--------|
| 0.5583 | 5.86       | 16190 | 28.1            | 0.8366 | 1.735               | 7.385     |
| 0.6427 | 5.58       | 18720 | 33.64           | 0.8313 | 1.797               | 7.691     |
| 0.7085 | 5.32       | 20690 | 37.64           | 0.82574 | 1.820              | 7.381     |

For web thickness 12mm $k_c \approx 7.2\%$ is possible. But in this web should be placed cooling
channels to supply fluid for cooling of the accelerating cell. The web thickness is chosen
16mm, which is comfortable and reliable for placing of cooling channels 7mm in diameter.
With modification of mutual slot positions in accelerating cells the cooling circuit is modified slightly in the directions of cooling fluid, \[12\], but without decreasing of cooling ability. Developed with all modifications, described above, the configuration of ACS for J-PARC linac is shown in Fig. 10.

Calculated in 3D approximation RF parameters, \[12\] are illustrated in the Table 1, where \(Q_a\) is the quality factor for accelerating mode, \(T\) is the transit time factor value. For 2D approximation more result one can find in \[12\].

### 3.4 ACS with the large aperture radius

For beam parameters matching between the linac and RGS special cavities - debunchers - with essentially increased aperture radius \(a\) are required. The general study of different accelerating structures for strongly increased aperture has been performed and described in \[15\]. Results shown, that \(Z_e\) reduction with \(a\) increasing takes place in different structures with the same scale. In ACS structure the deterioration of dispersion curve due to increasing of neighbor coupling between accelerating cells, starts after \(2a > 100mm\). No reasons were found to use for debuncher another structure. After mutual consideration of contradictory requirements of beam dynamics and ACS RF parameters, the aperture diameter was fixed to \(2a = 70mm\) for Debuncher 1 and \(2a = 85mm\) for Debuncher 2. The maximal possible value of \(Z_e\) is required all time at least to relax RF power requirement.

For the highest \(Z_e\) value the optimal value of accelerating gap ratio \(\alpha\) depends on \(\beta\) and \(a\) values. For \(\beta = 0.7131\) the dependence \(Z_e(\alpha)\) was studied for accelerating cells with increased aperture first in 2D approximation, but at the frequency 995\(MHz\), taking into account future frequency decreasing by coupling slots. After that several options were considered in 3D simulations.

To realize the optimal \(\alpha\) value, we have to adjust accelerating cell radius \(R_c\). But the dependence \(Z_e(\alpha)\) is smooth near point of maximum and some deviation from optimal point are possible. For Debuncher 1 application of the same cell radius, as for regular ACS cell, \(R_c = 111.6mm\), results in relative \(Z_e\) reduction only at 2\% and is not significant. For this cavity the outer part, including coupling cell, should be the same as for regular ACS.

Figure 11: ACS structure, regular cells, \(2a = 40mm\) (a), cell for Debuncher 1, \(2a = 70mm\) (b) and cell for Debuncher 2 (\(2a=85\) mm) (c).
For Debuncher 2 realization of \( r_c = 111.6\, mm \) leads to relative \( Z_e \) reduction at 6.3% with respect to optimal value. But optimal \( \alpha \) value results in \( R_c = 119.6\, mm \) and also requires rearrangement of coupling cell dimensions \((R_cC)\) and increasing of outer diameter. It is not a problem in simulations, but can lead to additional set of axillary tools in cavity construction. The schematic pictures for ACS cells for debunching cavities are shown in Fig. 11 in comparison with regular cell. The calculated results for debunching cavities are listed in the Table 3. After consideration of the total set of sequences, the Debuncher 2(a) option was selected for realization.

Table 2: The calculated parameters of debunching cavities.

| Parameter          | Debuncer 1 | Debuncer 2(a) | Debuncer 2(b) |
|--------------------|------------|---------------|---------------|
| \( \beta \)        | 0.7131     | 0.7131        | 0.7131        |
| \( 2a, mm \)       | 70         | 85            | 85            |
| \( \alpha \)       | 0.5214     | 0.5025        | 0.6306        |
| \( R_c, mm \)      | 111.6      | 111.6         | 119.6         |
| \( R_{cc}, mm \)   | 194.5      | 194.5         | 202.0         |
| \( k_{c}, \% \)    | 5.38       | 5.61          | 6.07          |
| \( Z_e, \frac{\text{MOm}}{m} \) | 22.54     | 15.57         | 16.61         |
| \( Q_a \)          | 20170      | 18560         | 21050         |

### 3.5 Thermal-stress analysis

The thermal-stress analysis for ACS cells has been performed both assuming moderate cooling conditions - the water flow velocity \( \leq 2\, m/s \), input temperature \( 27^\circ C \) and the heat exchange coefficient of \( \approx 9500\, W/m^2\, ^\circ C \). For the initial \((\beta = 0.508)\) and the final \((\beta = 0.708)\) ACS cell the heat loading corresponding both to 3% and 15% duty factor operation was considered, \[16, 17\]. In Fig. 12 the temperature and displacement distributions are shown for \( \beta = 0.508 \) assuming 15% duty factor operation. Numerical results are listed in the Table 3.

As one see from the Fig. 12 and the Table 3, even for very high heat loading \( P_h \) the temperature of the drift tube nose \( \delta T_{\text{max}} \) is significant, but not drastically. The cooling channels come closer to the drift tube, as possible, and the tube shape results in sufficient heat removal due to copper conductivity. It supports the decision about drift tube cone angle in the ACS accelerating cell optimization. As one can see from Fig. 12a, the temperature distribution at the surface of accelerating cell (except drift tube nose and near slot region) is rather uniform. The shift of accelerating mode frequency \( \delta f_a \) is equivalent to the average heating of accelerating cell at \((12 - 13)^\circ C \). This value can be reduced by increasing of water
flow velocity in the safe limits and corresponding increasing of the heat exchange coefficient. To compensate this frequency shift for the total ACS module the tuning ability of tuners in the bride cavity is sufficient. Specially should be pointed out the very small in a value and opposite sign for low and high $\beta$, the frequency shift for the coupling mode $\delta f_c$, even for 15% duty factor operation. It means, that there will be no stop band width increasing and strong deterioration of accelerating field distribution in operation with very high heat loading. The second hot spot in the temperature distribution is at the coupling slot ends. It is common to slot coupled structures and takes place due to higher density of RF currents. As compared to another structures, in the current ACS design this effect is reduced as possible by the slot shape adjustment and cooling channels choice. But the bottom slot corners are the regions with maximal stress value and for 15% duty factor operation the maximal stress value comes close to the yield stress of the copper material. It is one of limiting points for possibility of operation even with higher heat loading.

3.6 Conclusion for ACS regular cells

As the result of ACS cells optimization the transverse dimensions of ACS at operating frequency $972\,MHz$ are the same as for the L-band ACS. And the weight per unit length is even lower, because we withdraw more material from cylinder. It allows reliable application of the previously developed fabrication technique, based on brazing with high temperature silver alloys.

The previously achieved ACS performances are not lost and even improved slightly in $k_c$ value, resulting in improvement of uniformity and stability of accelerating field distribution. The mechanical cells design is also sufficiently strong to ensure stability both in construction and during long term stability.

In the J-PARC ACS cells neither highest possible $Z_e$ nor $E_a$ values are realized. The goal was to create the counterbalanced structure design, when there are no bright achievements in one point at the expense of significant reduction in another parameters, but also there...
are no extra reserve in one point, which allow significant improvement of the total set of parameters.

4 Bridge coupler part optimization

The multi cell Bridge Cavity (BC), developed for L-band ACS module, consists from similar simple cells, excited in $\pi/2$ mode. The schematic sketch of two BC cells together with field distribution, is shown in Fig. 16. For ACS module the 9 cells BC is applied. In the excited BC cells the tuners are installed for operating frequency control. Distinguishing from coupling coefficient value for regular ACS structure $k_c$, let us denote the coupling coefficient for BC cells as $k_b$. To the ACS tanks with the regular ACS structure BC is connected with intermediate coupling cells, which have not symmetrical coupling $k_1$ to ACS tanks and $k_2$ to BC, $k_2 > k_1$.

![Figure 13: Schematic sketch for two regular BC cells with field distribution.](image)

4.1 The coupling coefficients relations in the ACS module

The ratio $k_2/k_1$ defines the relative level of the field in excited BC cells with respect to the field in regular ACS cells. With $k_2/k_1$ increasing we reduce field in BC cells, reduce RF power, dissipated in BC, but simultaneously reduce tuning rate for tuners and increase the value for coupling correction for matching window in RF input cell. For the L-band ACS the ratio $k_2/k_1 = 2$ was proven in the high RF power test. No reasons were found in additional consideration to change it and for J-PARC ACS $k_2/k_1 = 2$ is adopted as the reasonable, safe compromise.

To avoid frequency spectrum deterioration and field stability reduction, in the ACS module should be fulfilled condition $k_1 \geq k_c$.

The intermediate coupling cell - this case it is a side coupled cell with respect ACS accelerating cell - was changed from circular to more complicated shape to fit with modified ACS accelerating cell. The required $k_1$ value is achieved by increased slot opening to 49.8°. The value of another coupling coefficient $k_2$ depends on the distance between BC axis and intermediate cell nose axis, which defines the insertion of intermediate cell into the first BC cell.
Figure 14: Left - the ACS module modes spectrum for different $k_b$ values. $k_c = 6\%, k1 = 6\%, k2 = 12\%, C1) - k_b = 6\%, C3) - k_b = 12\%, C4) - k_b = 18\%$. Right - the amplitude distribution along the ACS cavity for distinct modes.

The coupling coefficient $k_b$ for BC cells is not fixed so rigidly. As one can see from BC cell sketch, Fig. 13, for the fixed length of the BC cell $L_{cb}$ we have three variables - the cell radius $R_c$, the aperture radius $r_a$ and the disk thickness $t_w$. But the rigid requirement is just one - operating frequency 972MHz. Additionally we have to provide sufficient coupling coefficient, frequency separation with the nearest $TE_{11n}$ passband and BC vacuum conductivity. In the BC cavity for L-band ACS the concept $t_w = const$ was suggested, resulting in the high $k_b \approx 18\%$ value and sufficient separation with $TE_{11n}$ passband.

For the case $k_b \gg k_c$ in the modes spectrum of ACS module arise distinct modes, which are placed enough far outside from ACS passband, Fig. 14 (left). The field for such modes is concentrated in BC cells and do not penetrate in ACS tanks, Fig. 14 (right). Such modes do not improve the field stability in ACS module, which is defined by coupling coefficient of regular ACS cells. From this point of view, very big $k_b$ value is an extra reserve and do not improve significantly ACS module parameters.

For mass production looks attractive to fix the cell radius $R_c$ for all BC’s in the system. Additionally, the distance from the BC axis to the beam axis will be constant over entire ACS system, for more standard in connections.

In the BC’s for J-PARC ACS the concept of ’constant cell volume’ is realized. If we need in adjustment for two dimensions (for $L_{cb}$ increasing with $\beta$) , $t_w$ and $r_a$, let us connect the disk thickness as $L_{cb} - t_w = 80.0mm$. This case for low $\beta$ we have sufficient for rigidity disk thickness $2t_w = 12.72mm$ and $k_b \approx 12\%$, (depending on $R_c$ choice). With this condition the volume of the field in BC cell remains approximately the same for all $\beta$. It results in ’nearly the same’ tuning rate for tuners over entire ACS system and in ’nearly the same’ $k_2$ value in BC coupling with intermediate cell. Such solution significantly decreases the possible spread in tuning rate and transverse dimensions between different module’s in ACS system. The
frequency separation with the nearest $TE_{11n}$ passband in BC cells even improves - the cells becomes shorter for high $\beta$ region.

The BC’s cell radius was chosen to have $14.9\% > k_b > 7.8\%$ and frequency separation between ACS passband and $TE_{11n}$ passband is $> 60 MHz$ over entire ACS system. Because the aperture radius $r_a$ rises with $\beta$, simultaneously with $2t_w$ rise, the vacuum conductivity of BC is not deteriorated. For BC’s cells in ACS module is the fixed value $R_c = 132.2 mm$.

The schematic sketch for BC cavity design, adopted for J-PARC ACS module, is shown in

Figure 15: Schematic sketches bridge cavity design (a) and bridge cavities with variable coupling cells (b).

Fig. 15a.

In optimization for mass production, due to the request of producer, the additional possibility was considered. Following to $\beta$ increasing, the total BC length should increases. It can be realized by changing the length of all cells in BC simultaneously. But we can do it by changing length just for several cells and keeping the length of another cells as constant for different BC’s cavities. This case all BC cavities should be reasonably separated in several groups. In each group BC have the cells with the constant, inside the group, length, and one or two cells with variable length, specific for each BC. Subdivision in groups is required, because the possibility in cell length change is limited by RF parameters. For cell length decreasing we have increasing of the cell frequencies for operating $TM_{010}$ mode, both for the cell under change and for neighbor cells. For cell length increasing we have decreasing of $TE_{11n}$ modes frequencies and also decreasing for operating mode frequencies, both for the cell and for neighbors.

The most convenient choice for cells with variable length is two not excited cells near the middle BC cell with RF input. This case the own frequency for the variable cell can be adjusted by cell radius $R_c'$, which becomes specific for each variable cell. The distortion of frequency for neighbor cells, which are excited and equipped with tuners, is of $\approx 0.5 MHz$ and can be corrected by tuners. The variation of $k_b$ value is not significant $\delta k_b/k_b < 7\%$ and passband separation with $TE_{11n}$ modes is $> 50 MHz$. Such solution leads to decreasing in
the set of BC dimensions in mass production, but requires the individual tuning of variable cells and individual tuners adjustment for neighbor cells in ACS operation. This solution was not accepted for ACS.

4.2 The shape of matching window

The vicinity of matching window between driving waveguide and input cell in the bridge cavity was modified as shown in Fig. 16. The initial window configuration is shown in Fig. 16a and has not the best cooling conditions. Together with increased density of RF current near edges, it can result in the temperature rise.

The idea of tapering near window, similar to tapering in ACS coupling cells, was applied, Fig. 16b. The width of the window (in the beam axis direction for ACS module) is limited for low $\beta$ by the length of input cell in bridge cavity. The tapering was applied for the window length. Additional tapering in perpendicular direction is not effective, because leads to the coupling reduction. With the tapering near modified window the same coupling is obtained with shorter window, resulting in reduction of RF current density, which is reduced additionally by edges rounding. In this design the space is sufficient to place V-like cooling channel close to window, providing better conditions for matching window cooling.

5 Comparison with SCS in parameters

After all modifications, the ACS cell were compared in parameters with SCS cells. SCS structure is mostly distributed in hadron linacs and can be considered as the reference one. But SCS is applied at the frequency $f_{op} = 805 MHz$, sometimes with special requirements, such as high accelerating gradient in the FNAL linac. We have to compare the structures at other equal conditions - frequency, aperture radius and so on. For this purpose we considered for the SCS the ACS-like accelerating cell in the dimensions of drift tube and web thickness - it were chosen taking into account J-PARC linac requirements at the frequency 972 MHz. But for SCS we accept the outer cell rounding, Fig. 2b, Fig. 17a, even supposing an initial
preference in $Z_e$ for SCS. The conical part in the shape of SCS cell is not required. For coupling cells formation was accepted concept, realized for SNS coupled cell linac \[14\]. The direct scaling of SCS coupling slots from SNS design results in $k_c = 4.32\%$, compared to $k_c = 5.86\%$ in ACS for $\beta = 0.556$. Structures should be considered at the same $k_c$ value.

In SCS the coupling coefficient value $k_c$ can be increased by coupling cell length $L_c$ increasing, together with more deep coupling cell insertion into accelerating one, see Fig. 1a. It leads to strong increasing in coupling slot dimensions, rise in direct coupling coefficient $k_c$ value. But simultaneously much faster rises the coefficient of neighbor coupling $k_{aa}$, resulting in the distortion of dispersion curve. The limiting case of coupling cell insertion is shown in Fig. 17a (right) and is limited by crossing with 'drift tube' in coupling cell. Further insertion of coupling cell into accelerating cells does not results in $k_c$ increasing. With the single SCS slot against four ACS slots we have no freedom in $k_c$ increasing and should go to not comfortable mechanical design of the slot region. Anyhow, adjusting $k_c = 5.57\%$ for $\beta = 0.556$, we apply, according procedure of the SNS coupled cell linac, the same coupling cell to the total $\beta$ range. Examples of the obtained SCS are illustrated in Fig. 17b. Results of comparative simulations are listed in the Table 4.

As one can see from the Table 4, even for lower $k_c$ value, for the same conditions, SCS has

| $\beta$ | 0.56 | 0.64 | 0.71 |
|---------|------|------|------|
| $Z_e$ SCS | 5.57/5.86 | 5.18/5.58 | 4.90/5.32 |
| $Z_e$ ACS | 0.970 | 0.993 | 1.005 |
| $k_{aa}$ SCS | 0.75/0.01 | 0.66/0.01 | 0.60/0.01 |
| $k_{aa}$ ACS | 0.01/0.63 | 0.01/0.31 | 0.01/0.2 |

no preference in RF efficiency. And initial preference due to rounded cell shape in cancelled
by not comfortable connections of the cells. In the shape distortions for dispersion curve, the structures are nearly the same - there is neighbor coupling between ACS coupling cells and similar coupling between SCS accelerating cells.

More comparison is in results of thermal-structural analysis. For SNS the operational duty factor is of 6%. The results of such SCS thermal analysis are described in [18]. Comparing results for SCS and ACS, one will see less uniform temperature distribution for SCS and higher stress values near slot, even for adopted coupling cell for SCS design, which leads to lower $k_c$ value for J-PARC conditions.

The J-PARC ACS accelerating module has much more reserve for operation with the enlarged duty factor value.

6 Summary

Proposals for the Annular Coupled Structure modification to improve ACS advantages for 972 MHz option are described in this report. Mainly these improvements are directed to simplify mass production and mass tuning process. But each modification should not deteriorate (only improve) ACS parameters achieved before. For this purpose all modifications were strongly investigated with different methods, available in the design of accelerating structures, discussed and revised for possible sequences. Only if in the reference ACS design there was extra reserve in some parameters, these reserves were decreased to conservative, proven in another structures, values, leading to improvements in another parameters. Each modification separately is not a big achievement. But collected and adjusted all together, these modifications have enough significant effect - proposed ACS design doesn’t lose to reference design in rf parameters but has advantage of smaller transverse dimensions and strongly reduced weight, allowing application of fabrication technique similar to L-band ACS option.

During JHP research program very robust concept of the accelerating tank was developed and tested - reasonably effective accelerating structure with very effective cooling circuit, added with bridge coupling cavities, equipped with fast movable tuners. Together with latest improvements in ACS design and follow the concept of the total cavity, ACS looks now as the mostly promising cost-effective solution for normal conducting accelerating structure for high intensity proton linac with high duty factor operation. The present ACS 972 MHz design has the possibility to operate with the average heat loading up to $80kW/m$ during 15% duty factor linac operation.

7 Acknowledgments

This report presents one part of the 972 MHz ACS development, mainly results of RF parameters study, which was under way in KEK (and later JAEA) ACS group. All results were discussed in ACS meetings - nice trial field to protect and improve proposals in the atmosphere of creative research, large experience and high responsibility for final result - high intensity linac.

The author warmly thanks all participants of ACS meetings - Y. Yamazaki, H. Ao, M. Ikegami, F. Naito, T. Kato, N. Hayashizaki, S.C. Joshi, A. Ueno, for providing creative
atmosphere of the joint work, discussions, recommendations, reasonable objections and all time - warm human relations.

References

[1] G.Dome, Review and survey of accelerating structures. in Linear Accelerators, ed. P. Lapostolle.- Ams. North-Holland Publ. Co., 1970

[2] E.A. Knapp et al., Standing wave accelerating structures for high energy linacs. Rev. Sci. Instr., v. 39, n. 7, p. 31, 1968.

[3] E.A. Knapp et al., Coupled resonator model for standing wave accelerators tanks. Rev. Sci. Instr., v. 38, n. 11, p. 22, 1967

[4] V.G. Kulman et al., Accelerating structure with annular coupling cells. Instruments and Experimental Techniques, v. 4, p. 56, 1970

[5] V.G. Andreev, Structure with alternating accelerating field. Journal of Technical Physics, n. 41, p. 788, 1971

[6] B.P. Murin ed., Linear ion accelerators, Atomizdat, Moscow, 1978, (in Russian).

[7] Report of the Design Study on the Proton Linac of the Japanese Hadron Project [II], JHP 14, KEK 90-16, KEK, 1990

[8] K. Yoshino et al., Studies on water cooling of an ACS high power model (in Japanese). Proc. 1991 Linac Meeting in Japan. Tokyo, p.242, 1991.

[9] K. Yamasu et al., Fabrication technique of ACS cavity. Proc. Linac 1990, p.150, 1990.

[10] Y. Morozumi et al., Multi-cell Bridge Coupler. Proc. Linac 1990, p.153, 1990.

[11] T. Kageyama et al., A high-power model of the ACS cavity. Proc. Linac 1990, p.47, 1990.

[12] V. Paramonov, The Annular Coupled Structure Optimization for JAERI/KEK Joint Project for High Intensity Proton Accelerator. KEK report 2001-14, 2001

[13] V. Paramonov, S. Tarasov, The possibility of multipactoring discharge in coupling cells of coupled cells accelerating structures. Proc. Linac 1998, p.971, 1998.

[14] Spallation Neutron Source (SNS) Coupled-Cavity Linac Hot Model. LA-13945, (SNS 101020000-TR0001-R00), Los Alamos, 2001

[15] V. Paramonov, The Coupled Cell Structures Parameters for the Large Bore Hole Diameter, KEK report 2002-5A, KEK, 2002

[16] V. Paramonov, N. Hayashizaki, Y. Yamazaki. Power-handling capability of the Annular Coupled Structure linac for the JAERI/KEK Project. Proc. Linac 1992, p. 752, 2002
[17] S.C. Joshi, RF-thermal-structural analysis of ACS structure, KEK Internal, 2001-6, 2001

[18] S. Konecni, N. Bultman. Analysis of the Slot Heating of the Coupled Cavity Linac. Proc, PAC 2001, p. 900, 2001