Dual-mode cavity design for advanced continuous-wave electron injector

Citation for published version (APA):
Rajabi, A., Toonen, W. F., van den Berg, R. G. W., Stragier, X. F. D., Mutsaers, P. H. A., Smorenburg, P. W., & Luiten, O. J. (2021). Dual-mode cavity design for advanced continuous-wave electron injector. Nuclear Instruments and Methods in Physics Research. Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, 1019, [165843]. https://doi.org/10.1016/j.nima.2021.165843

Document license:
CC BY

DOI:
10.1016/j.nima.2021.165843

Document status and date:
Published: 11/12/2021

Document Version:
Publisher’s PDF, also known as Version of Record (includes final page, issue and volume numbers)

Please check the document version of this publication:
• A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher’s website.
• The final author version and the galley proof are versions of the publication after peer review.
• The final published version features the final layout of the paper including the volume, issue and page numbers.
Link to publication

General rights
Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.
• Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
• You may not further distribute the material or use it for any profit-making activity or commercial gain.
• You may freely distribute the URL identifying the publication in the public portal.

If the publication is distributed under the terms of Article 25fa of the Dutch Copyright Act, indicated by the “Taverne” license above, please follow below link for the End User Agreement:
www.tue.nl/taverne

Take down policy
If you believe that this document breaches copyright please contact us at:
openaccess@tue.nl
providing details and we will investigate your claim.
Dual-mode cavity design for advanced continuous-wave electron injector

A. Rajabi a,∗, W.F. Toonen a, R.G.W. van den Berg a, X.F.D. Stragier a, P.H.A. Mutsaers a, P.W. Smorenburg b, O.J. Luiten a,∗

a Department of Applied Physics, Coherence and Quantum Technology Group, Eindhoven University of Technology, P.O. Box 513, 5600 MB Eindhoven, The Netherlands
b ASML Netherlands B.V., De Run 6501, 5504 DR Veldhoven, The Netherlands

A R T I C L E I N F O
Keywords:
RF cavity
High average current
High repetition rate
Train of bunches

A B S T R A C T
The Advanced Continuous-wave Electron (ACE) injector group at the Coherence and Quantum Technology (CQT) group of the Eindhoven University of Technology is developing a GHz repetition-rate electron injector where a low emittance and high repetition-rate are simultaneously required. The injector is based on a high-quality DC thermionic gun and two normal conducting RF cavities utilizing dual-mode resonance frequencies in the 1.5–3 GHz range. In the first phase, the installation and commissioning of ACE’s electron gun were completed. In this next phase, two dual modes RF cavities are designed for chopping and compressing of a DC electron beam. This paper focuses on the RF design and measurements of these cavities, demonstrating the claimed quality and performance.

In this article, we present a new dual-mode RF cavity design which can be used for both chopper and compressor cavities in the ACE injector. This injector is designed to provide up to 70 pC electron bunches at a 1.5 GHz repetition rate resulting in a high average current. The properties of this gun are significantly different from conventional guns, so that various applications may exist [3,21,22].

It is well known in the ICS theory that the quality of the internal structure of a bunched beam dominates the X-ray production. In order to saturate ICS interaction, the bunch length, size and emittance should be very low [23–26]. The ACE injector consists of three separate stages. First, a continuous electron beam up to 10 mA with a custom-designed 100 kV thermionic DC gun will be generated [19]. By operating at a 100 kV, which is significantly lower than other electron sources (e.g., 300–500 kV [27,28]), the gun remains compact while a field gradient of 10 MV/m at the cathode minimizes space-charge effects. Next, a dual-mode RF deflecting cavity chops the beam into separate bunches. Finally, a bunch compressor cavity containing two modes longitudinally compresses each bunch to picosecond pulse lengths. Based on these classifications, the setup was divided into three main parts depicted in Fig. 1.

With the DC gun already operational [20], Section 2 details the design and characterization of the chopping section. Section 3 compares the RF measurements of the chopping cavity with its simulation results. In Section 4, the design of the compressor cavity will be explained. Finally, the particle simulation of the whole system based on these designs will be discussed in Section 5.

1. Introduction

The performance of any electron accelerator crucially depends on the abilities of its electron source. A wide variety of electron beam-based applications requires electron sources capable of generating a beam with low transverse emittance, short bunch length, and low energy spread [1–3]. Such beams can be used in ultrafast electron diffraction [4,5] and microscopy [6], free electron lasers [7] and other light sources [8]. The exact required beam properties depend on the particular application. However, in all cases, the ideal performance requires the lowest possible transverse emittance and the highest quality in the longitudinal phase space, including bunch length and energy spread. Generally, an ideal electron injector would provide high-quality electron bunches at both high peak and high average current. In recent years, electron injectors capable of creating high-quality electron bunches with a high peak current were studied and constructed [9–11]. High average current electron injectors, however, are not widely available. Several sources aim to achieve these higher currents, with a few reaching that in the past years [12,13] due to advancements in cathode research [14] and the use of specialized lasers [15].

In particular, the usefulness of compact light sources with intrinsically low conversion efficiency such as Inverse Compton Scattering (ICS) Sources [16–18] critically depends on the availability of sufficiently high-current electron beams. The Advanced Continuous-wave Electron (ACE) injector at Eindhoven University of Technology [19,20] has been designed to create such a semi-continuous high average current electron beam based on a CW operation of a thermionic cathode.
2. Chopping section

The continuous beam from the DC thermionic gun is cut into bunches in the chopping section, consisting of a dual-mode RF cavity and a high-precision aperture. The transverse magnetic component of the RF fields deflects the beam periodically, after which after which a knife-edge aperture slices the beam into a train of electron bunches. The knife-edge has a hole with a 1.5 mm radius at the center and is designed to handle a continuous 1 kW power dissipation on its walls. To maximize the duty cycle and consequently the charge per bunch, a dual mode chopper cavity with an additional static magnetic field is used. This results in an on-axis magnetic field given by Eq. (1) where $B_1$ is the amplitude of the magnetic field for the first mode, $\zeta = B_1/B_2$ is the ratio between the amplitude of the two modes, and $\phi_1$ and $\phi_2$ are the angular frequencies and the phases of first and second mode respectively [19]. The on-axis transverse magnetic field then can be obtained as

$$B_x(t) = B_1 \left( \sin (\omega_1 t + \phi_1) + \frac{1}{\zeta} \sin (\omega_2 t + \phi_2) \right). \quad (1)$$

As discussed in [19], among all higher harmonics, adding the second mode (TM$_{120}$) to the first mode (TM$_{120}$) leads to the highest duty cycle and, with proper tuning, the required flat top in the electron beam trajectory as shown in Fig. 2. This leads to more electrons passing through the aperture, meaning a higher charge per bunch.

The RF fields of TM$_{klm}$ modes, with $k$, $l$, and $m$ the number of antinodes, are required to obtain the appropriate transverse magnetic field on the axis. To achieve a high duty cycle without losing the beam quality, the magnetic field applied on the electrons should remain constant for as long as possible. For experimental feasibility, we only included two modes in the cavity. This results in an on-axis magnetic field given by Eq. (1) where $B_1$ is the amplitude of the magnetic field for the first mode, $\zeta = B_1/B_2$ is the ratio between the amplitude of the two modes, and $\phi_1$ and $\phi_2$ are the angular frequencies and the phases of first and second mode respectively [19].

The most straightforward choice for a dual mode operation is a rectangular cavity, as it is easy to construct. However, these cavities have several disadvantages. The field pattern of a rectangular cavity is very sensitive to the position of the tuning plungers and antennas. Moreover, the frequency of the TM$_{120}$ mode is within 1 MHz of the TM$_{120}$ mode, resulting in a mode competition. Furthermore, RF simulations of the rectangular cavity show that the on-axis magnetic field of the second mode is relatively weak at the center, as can be seen in Fig. 4. This means more RF power is needed to achieve a field strength comparable to the first mode. Model optimization revealed that increasing the curvature of the cavity walls increases the concentration of the magnetic field lines at the center. Accordingly, combining these two facts resulted in a new cavity design with an elliptical cross-section called the “Elliptobox” cavity. Figs. 3 and 4 show the magnetic field patterns in the rectangular and Elliptobox cavities. In Table 1 the properties of these two cavities are compared.

![Fig. 1. Schematic view of the ACE injector consisting of, (1) DC thermionic Gun, (2) Chopping section, (3) Compression section. The electrons are deflected by the magnetic field in the chopper cavity, cut with the slit, and finally compressed in the compressor cavity.](image1)

![Fig. 2. The time-dependent magnetic field in the center of the chopping cavity. The green circle represents the field probed by the electrons that will pass through the aperture. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)](image2)
Fig. 3. Field patterns of the TM_{120} mode in the (a) rectangular cavity; (b) Elliptobox cavity. These cavities were designed and optimized in CST Microwave Studio [31]. The beam travels on-axis in the z-direction, outside the plane of paper.

Fig. 4. Field patterns of the TM_{320} mode in the (a) rectangular cavity; (b) Elliptobox cavity. The beam travels on-axis in the z-direction, outside the plane of paper.

Table 1
RF Properties of the Rectangular and Elliptobox cavities. Powers are calculated based on a maximum magnetic field of 0.5 mT for the First mode (FM) and 0.27 mT for the second mode (SM).

|                | Rectangular | Elliptobox | Unit   |
|----------------|-------------|------------|--------|
| Frequency (FM) | 1.499275    | 1.499275   | GHz    |
| Frequency (SM) | 2.998550    | 2.998550   | GHz    |
| Frequency (TM_{420}) | 2.99907 | 3.09885 | GHz |
| Q (FM)         | 15100       | 14133      | –      |
| Q (SM)         | 20260       | 19426      | –      |
| Power (FM)     | 36.80       | 32.92      | W      |
| Power (SM)     | 65.04       | 16.61      | W      |

Fig. 5. Design of the Elliptobox cavity including the loop antennas for power coupling between the coax lines and the cavity. The electron beam hole radii are 5 mm.

Table 2
The dipole magnet and shields characteristics.

|                | Value     | Unit |
|----------------|-----------|------|
| Dipole Gap     | 272       | mm   |
| Dipole width   | 40        | mm   |
| Coil No. of turns | 700   | –    |
| Coil current   | 2         | A    |
| Shield material| Mu-Metal  | –    |
| Shield distance| 100      | mm   |

To an inter-coupling between them. This problem can be solved by correctly and precisely positioning the antennas in the node of the other mode and using a band-pass filter. Using a rod antenna instead of a loop antenna is also possible, but the coupling of the antennas to the cavity modes depends on the antenna length. This length, in turn, affects the resonance frequencies of the modes, increasing the difficulty of tuning the cavity.

As mentioned before, a constant magnetic field is required to keep the flattops in electron trajectory on-axis. For this purpose, a C-type dipole magnet was designed. There are three locations that the dipole magnet can be mounted: in front of, behind, or around the cavity. The disadvantage of putting the dipole magnet in front of or behind the cavity is that the beam gets deflected from the axis. Because of the particular shape of the beam between the chopper cavity and slit, a pair of correction coils cannot be used to return the beam to the axis. After the slit, however, the beam immediately enters the solenoid. So, returning the beam to the axis then is also not possible. Therefore, the dipole magnet should be placed around the cavity. This choice results in a wide-gap dipole magnet, leading to a wide magnetic field. Electrons will feel the magnetic field early in the beamline. Accordingly, the electrons will be deflected from the axis before even reaching the chopper cavity. This can be solved by utilizing a pair of magnetic shields around the cavity. Fig. 6 shows the configuration of the cavity with the dipole and shields, whose characteristics are given in Table 2.
3. Chopper cavity characterization

In this section, the operational characteristics of an aluminum version of the Elliptobox cavity are tested in air and compared with the simulation results. Section 3.1 presents the RF coupling for each mode, inter-coupling between antennas, and the quality factor of the cavity. In Section 3.2, the on-axis transverse magnetic field profiles for both modes are evaluated with simulation results.

3.1. Power reflection and transmission

Two normal modes in the Elliptobox cavity can be excited using loop antennas as coaxial couplers. A loop antenna can create a magnetic dipole with an intensity proportional to the loop area and the input power. The amplitude of a normal mode is proportional to the scalar product between the magnetic dipole and the magnetic field of that mode in the loop region. Based on Maxwell’s equations, the normal modes inside the standing wave cavity are given by

\[
\begin{align*}
\mathbf{E} \exp(j\omega t) &= \sum_{n=0}^{\infty} E_n \mathbf{E}_n \exp(j\omega_n t), \\
\mathbf{H} \exp(j\omega t) &= \sum_{n=0}^{\infty} h_n \mathbf{H}_n \exp(j\omega_n t),
\end{align*}
\] (2)

where \(E_n\) and \(h_n\) are the electric and magnetic fields of the \(n\)th normal mode and \(\omega_n\) is the angular frequency of the \(n\)th normal mode. The electric field \(\mathbf{E}_n\) and magnetic field \(\mathbf{H}_n\) consist of the electric field \(\mathbf{E}_n\) and magnetic field \(\mathbf{H}_n\) of the normal mode, respectively. For a loop antenna with sufficiently small area one can obtain these coefficients as

\[
\begin{align*}
h_n &\approx \frac{k^2 M H_n}{k_n^2 - k^2 \left(1 + \frac{1}{Q_{in}}\right)} \\
e_n &\approx \frac{j \omega_n \mu_0 h_n M H_n}{k_n^2 - k^2 \left(1 + \frac{1}{Q_{in}}\right)},
\end{align*}
\] (3)

where \(Q_{in}\) is the quality factor related to the normal mode in the cavity, \(k\) is the wavenumber and \(M\) is the dipole moment. In general, solving Eq. (3) is very hard and adding a second antenna to the cavity makes it even more difficult. According to Eq. (3), changing the angle between the loop and the local magnetic field can increase the coupling to the source. These angles can also affect the inter-coupling between two antennas.

However, aside from the leakage of power from one antenna to the other, adding the second antenna can also change the resonance frequencies. An equivalent circuit can provide insight into what can happen to the resonance frequencies in the presence of a second antenna. If the antennas are put in the nodes of the other mode, the inter-coupling between antennas is expected to be negligible. However, based on the field maps in Figs. 3 and 4, the first mode only has nodes where the second mode does as well. Consequently, the antenna of the second mode also couples to the field of the first mode. This inter-coupling increases the \(L\) and \(C\) of the cavity (Fig. 7) to \(L'\) and \(C'\). Therefore, the quality factor \(Q_{in} = R \sqrt{C'/L'}\) and resonance frequency \(\omega = 1/\sqrt{L'C'}\) of the first mode will be changed. Whereas the 1.5 GHz antenna is placed in the node of the 3 GHz mode. This means no inter-coupling happens between them and therefore the frequency for the second mode remains unchanged.

To prevent the RF power of the first mode leaking to the second mode amplifier, a high-power bandpass filter is used (Table 3). However, the connection and the cable between the cavity and the bandpass filter can still alter the \(L\) and \(C\) of the cavity. For RF measurements, a Network Vector Analyzer was used and all measurements were done at a surrounding temperature of \(T = (21.5 \pm 0.5)°C\). As shown in Fig. 8, the coupling of the RF powers from the amplifiers to the cavity occurs pretty well. The bandpass filter on the 3 GHz antenna (Port II) prevents leaking the power to the 3 GHz amplifier and the 1.5 GHz antenna (Port I) in the node of the 3 GHz mode, prevent inter-coupling between the second mode and port-I. Based on Fig. 8, one can see that the quality factor of the second harmonic in the prototype is lower than the simulation results, while the measurement of the fundamental mode matches the simulation more closely. This difference is mainly due to the fact that the prototype was not vacuum brazed, leading to an increased electric resistance of the walls. Since the frequency of the second mode is double the first mode, the 3 GHz mode shows more deviation from the simulation results. This problem will be solved in the final vacuum brazed cavity.

3.2. Field profile

In order to measure the field profile along the \(z\)-axis, the “bead-pull” method is used, based on the perturbation theorem of Maier...
Fig. 8. Power reflection and transmission of the Elliptobox cavity as a function of frequency, measured at a temperature of $T = (21.5 \pm 0.5)$°C. The $S_{11}$ is simulated by CST (red) and compared to the measurements (Blue). The measurement of the transmitted power from one antenna to the other antenna (with bandpass filter connected) is shown in black. Port I and Port II are the connections for the 1.5 GHz and the 3 GHz antennas, respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Fig. 9. On-axis transverse magnetic field profile of the Elliptobox cavity as calculated with CST (black) and as measured with the perturbation method (red), (a) first mode $TM_{120}$, (b) second mode $TM_{320}$. Since the size of the “bead” was comparable to the beam holes, at $Z<9$ mm and $Z>50$ mm the resolution of the network analyzer was reached. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

and Slater [32], in which a small bead introduces a field perturbation leading to a frequency shift. This shift results in a change in the cavity stored energy, which can be converted to the cavity field strength at the location of the bead. For the case of a small spherical bead with volume $V$, where the unperturbed field may be considered uniform over a region larger than the bead, it can be shown that:

$$\frac{\Delta \omega}{\omega} = -\frac{\omega V}{PQ} \left[ c_j \frac{\epsilon_j - 1}{\epsilon_j + 2} E_0^2 + \frac{\rho_0}{\mu_j} + \frac{1}{2} H_0^2 \right].$$

(4)

where $P$ and $Q$ are the power dissipation in the cavity and quality factor, respectively. For a metal bead with $c_j \to \infty$ and $\mu_j \to 0$, this relation reduces to:

$$\frac{\Delta \omega}{\omega} = -\frac{\omega V}{PQ} \left[ c_0 E_0^2 - \frac{\rho_0}{2} H_0^2 \right].$$

(5)

In the case of the $TM_{120}$ and $TM_{120}$ modes, the electric field amplitude is negligible on the $z$-axis. Only in the vicinity of the entrance and exit holes does it become slightly more powerful. As such, the contribution of the electric field to the frequency shift is neglected. Fig. 9 shows the bead-pull measurement results in the prototype cavity, which is in good agreement with the simulation results. As the size of the bead is comparable to that of the beam hole size, no accurate measurements can be performed near the cavity entry and exit.

3.3. Tuning plungers

Simultaneous tuning of the two frequencies is achieved by rotating the antennas simultaneously to obtain best match of the antennas to the cavity and using two metallic tuning plungers on the major and minor axes of the Elliptobox to fine-tune the frequencies. Because of the low RF power operation, the heat load is not an issue and a water cooling system with $\sim 3$ mK temperature stability will ensure a stable operation of the cavity. Based on the simulation model, the Tuning plunger (X) (see Fig. 5) should change only the first mode frequency, while the Tuning plunger (Y) should alter only the second mode. Fig. 10 shows the effect of tuning plungers on each mode compared to the simulation results. The effect of each designated tuning plunger on the corresponding mode is in the MHz range, while it is in the kHz range for the non-corresponding mode. Although the experimental results are slightly different from the simulation results, the overall behaviors remain the same. Based on the measurement results, each mode can be tuned separately by a maximum of $\Delta f \approx 1.8$ MHz.
4. Compression section

It was demonstrated that an RF cavity with an on-axis longitudinal electric field component could longitudinally compress low energy electron bunches [33]. Electrons in this electric field experience a force solely in the propagation direction, causing them to be accelerated or decelerated depending on the RF phase. Due to the time dependence of the field, different parts of an electron bunch will gain or lose different amounts of energy. By setting the RF phase so that the center of the bunch passes the center of the cavity when the electric field goes through its zero-crossing, the electrons at the head of the bunch will then be decelerated while those at the tail will be accelerated, initiating a ballistic compression.

This compression method uses the fact that the electric field around the zero-crossing is approximately linear, leading to a linear velocity chirp. This approximation is no longer valid for a long electron bunch in a cavity operating only at the fundamental mode. To allow longer bunches to be effectively compressed, a second harmonic can be added to linearize the waveform, as shown in Fig. 11. Similarly to the chopping section, an Elliptobox cavity is considered for the compressor cavity. While the dimensions and positions of the antennas and tuning plungers differ slightly from the chopper cavity, the concept is the same. Hence, as the simulations show it is possible to couple and tune the desired modes, it was not deemed necessary to build a prototype for the compressor cavity. Fig. 12 shows the compressor cavity layout and Fig. 13 displays the magnetic fields in the compressor cavity. One of the advantages of using an Elliptobox cavity...
Table 4
RF Properties of the Elliptobox compressor cavity. Powers are calculated based on a maximum 0.42 MV/m electric field required for bunch compression to 1.2 ps.

| Elliptobox       | unit  |
|------------------|-------|
| Frequency (FM)   | 1.499275 GHz |
| Frequency (SM) [GHz] | 2.99855 GHz |
| Q (FM)           | 12708 – |
| Q (SM)           | 18441 – |
| Power (FM)       | 92.52 W |
| Power (SM)       | 79.25 W |

Fig. 12. Design of the compressor cavity including the loop antennas. The antennas are positioned on the node of the other mode. The electron beam hole radii are 5 mm.

5. Particle tracking simulation

The electron gun of the ACE injector is capable of generating a 10 mA electron beam, with a normalized rms emittance of 49 nm-rad in both the x- and y-direction [20]. The complete injector, including all beam line elements, is simulated using General Particle Tracer (GPT) [34]. Both the electrostatic field of the electron gun and the RF fields of the chopper and compressor cavities described in Sections 2 and 4 are simulated in CST and used in the particle tracking simulations.

The electron beam is generated at $t = 0$ and $z = 0$ and immediately accelerated to 100 keV within a 10 mm cathode–anode interval by a field strength of 10 MV/m. In the simulations, a 10 mA electron beam with a diameter of 0.3 mm is considered. Since GPT cannot simulate a continuous beam, an initial beam with a bunch length of 2 ns is considered. The beam then travels through a focusing solenoid and eventually enters the chopping cavity at $z = 0.23$ m. The distance between the solenoid and cavity is chosen to have enough space for the solenoid to collimate the beam and to prevent penetration of the fringe field of the solenoid inside the chopper cavity. The RF phases in the Elliptobox cavity are set to extract the electron bunch from the middle part of the initial 2 ns electron beam, as this part behaves similarly to a section created from a continuous beam. 17 cm after the chopper cavity, a slit blocks most of the beam creating mustache-shaped bunches, as shown in Fig. 14.

After the slit, the RF compressor cavity imposes a negative velocity chirp and initiates the bunch compression. The electron bunches then ballistically compress while passing through a second solenoid and drifting for a total of about 50 cm towards a screen. The bunch evolution is shown in Fig. 15.

6. Conclusions

In summary, we present the design of two new dual-mode RF cavities with elliptical cross-sections for electron deflection and compression as well as the low RF power measurements of the prototype.
of one them. Simulations show that by using these cavities, the ACE injector can create ultra-short electron bunches at energies suitable for injection into a booster or for direct use in different applications requiring high average current. The concept is based on the deflection of a DC electron beam by a dual-mode Elliptobox cavity and cutting the beam with an aperture. A figure of merit of the Elliptobox cavity is the low power consumption for TM_{20} modes. As the cavity operates at two modes simultaneously, accurately tuning the frequencies and thus accurately controlling the temperature is imperative. With less power required to operate the Elliptobox at a specific field strength, the difficulty of temperature control is decreased. Furthermore, due to the high stability of the field patterns in the presence of the tuning plungers, tuning the modes independently is feasible.

Since the compressor Elliptobox cavity uses the same concept of antenna mounting and coupling as the chopper Elliptobox cavity, similar RF behavior is expected for the compressor. With a custom-design thermionic DC gun, together with the Elliptobox cavities and a high precision aperture, the simulation results confirm that an electron beam with a repetition rate of 1.5 GHz, a charge of ~2 pC per bunch, an rms bunch length of 1.2 ps, and a normalized emittance of 0.15 μm-rad with a peak current of 0.28 A can be obtained. With such a high repetition rate beam, burst mode operation for accelerator-based photon sources such as SmartLight is possible.

Acknowledgment

The authors would like to thank Eddy Rietman and Harry van Doorn for their invaluable technical support in the mechanical and electrical design of the thermionic gun. This research is part of the High Tech Systems and Materials programme of the Netherlands Organization for Scientific Research (NWO-AES) and is supported by ASML, Netherlands.

References

[1] W. Graves, J. Bennuille, P. Brown, S. Carboje, V. Dolgachev, K.-H. Hong, E. Ihloff, B. Khaykovich, H. Lim, K. Murari, et al., Compact x-ray source based on burst-mode inverse compton scattering at 100 kHz, Phys. Rev. Special Top.-Accelerators Beams 17 (12) (2014) 120701.
[2] T. van Oudheusden, Electron source for sub-relativistic single-shot femtosecond diffraction, (Ph.D. thesis), Eindhoven University of Technology, 2010.
[3] J. Corlett, K. Baptiste, J. Byrd, P. Dienes, R. Falcone, J. Kirz, W. McCurdy, H. Padmore, G. Penn, J. Qiang, et al., Design Studies for a VUV-Soft X-ray Free-Electron Laser Array, Taylor & Francis, 2009.
[4] R. Srinivasan, V.A. Lobastov, C.-Y. Ruan, A.H. Zewail, Ultrashort electron diffraction (UED) a new development for the 4d determination of transient molecular structures, Helv. Chim. Acta 86 (6) (2003) 1761–1799.
[5] M. Dantus, S.B. Kim, J.C. Williamson, A.H. Zewail, Ultrashort electron diffraction. 5. Experimental time resolution and applications, J. Phys. Chem. 98 (11) (1994) 2782–2796.
[6] O. Bostanjoglo, High-speed electron microscopy, in: Advances in Imaging and Electron Physics, Vol. 121, Elsevier, 2002, pp. 1–51.
[7] Z. Huang, K.-J. Kim, Review of x-ray free-electron laser theory, Phys. Rev. Special Top.-Accelerators Beams 10 (3) (2007) 034801.
[8] D.H. Bilderback, P. Elleaume, E. Weckert, Review of third and next generation synchrotron light sources, J. Phys. B: At. Mol. Opt. Phys. 38 (9) (2005) S773.
[9] M. De Loos, S. Van der Geer, F. Kiewiet, O. Luiten, M. van der Wiel, A high brightness pre-accelerated RF-Photo Injector, in: Proc. EPAC 2002, 2002, pp. 1831–1833.
[10] R.L. Sheffield, Photocathode rf guns, in: AIP Conference Proceedings, Vol. 184, (2) American Institute of Physics, 1989, pp. 1500–1531.
[11] R. Xiang, J. Teichert, Photocathodes for high brightness photo injectors, Physics Procedia 77 (2015) 58–65.
[12] B. Dunham, J. Barley, A. Bartnik, I. Bazarov, L. Cultrera, J. Dobbins, G. Hoffstaetter, B. Johnson, R. Kaplan, S. Karkare, et al., First operation of a photocathode radio frequency gun injector at high duty factor, Appl. Phys. Lett. 63 (15) (1993) 2035–2037.
[14] T. Rao, D.H. Dowell, An engineering guide to photoinjectors, 2014, arXiv preprint arXiv:1403.7539.
[15] D. Dowell, I. Bazarov, B. Dunham, K. Harkay, C. Hernandez-Garcia, R. Legg, H. Padmore, T. Rao, J. Smedley, W. Wan, Cathode R&D for future light sources, Nucl. Instrum. Methods Phys. Res. A 622 (3) (2010) 685–697.
[16] B. Hornberger, J. Kasahara, M. Gifford, R. Ruth, R. Loewen, A compact light source providing high-flux, quasi-monochromatic, tunable X-rays in the laboratory, in: Advances in Laboratory-Based X-Ray Sources, Optics, and Applications VII, Vol. 11110, International Society for Optics and Photonics, 2019, 1111003.
[17] F.C. Jones, Inverse compton scattering of cosmic-ray electrons, Phys. Rev. 137 (5B) (1965) B1306.
[18] A. Ovodenko, R. Agustsson, M. Babzien, T. Campese, M. Fedurin, A. Murokh, I. Pogorelsky, M. Polyanskiy, J. Rosenzweig, Y. Sakai, et al., High duty cycle inverse compton scattering X-ray source, Appl. Phys. Lett. 109 (25) (2016) 253504.
[19] W. Toonen, X. Stragier, P. Mutsaers, O. Luiten, Gigahertz repetition rate thermionic electron gun concept, Phys. Rev. Accelerators Beams 22 (12) (2019) 123401.
[20] W. Toonen, A. Rajabi, R. van den Berg, X. Stragier, P. Mutsaers, P. Smorenburg, O. Luiten, Development of a low-emittance high-current continuous electron source, Nucl. Instrum. Methods Phys. Res. A (2021) 165678.
[21] S. Bettoni, M. Pedrozzi, S. Reiche, Low emittance injector design for free electron lasers, Phys. Rev. Special Top.-Accelerators Beams 18 (12) (2015) 123403.
[22] B. Dunham, et al., Erl2011 summaries of working group 1, 2011.
[23] O. Luiten, KNAW Agenda Large-Scale Research Facilities: Smart*Light: A Dutch Table-Top Synchrotron Light Source, Royal Netherlands Academy of Arts and Sciences (KNAW), 2016.
[24] X. Stragier, P. Mutsaers, O. Luiten, Smart*light: A tabletop, high brilliance, monochromatic and tunable hard X-ray source for imaging and analysis., Microsc. Microanal. 24 (S2) (2018) 310–311.
[25] D. Seipt, A. Surzhykov, S. Fritzsch, Structured x-ray beams from twisted electrons by inverse compton scattering of laser light, Phys. Rev. A 90 (1) (2014) 012118.
[26] K. Chouffani, D. Wells, F. Harmon, J. Jones, G. Lancaster, Laser-compton scattering from a 20 MeV electron beam, Nucl. Instrum. Methods Phys. Res. A 495 (2) (2002) 95–106.
[27] Y. Wang, Development of a 300 kV dc high voltage photogun and beam based studies of alkali antimonide photocathodes, 2018.
[28] N. Nishimori, R. Nagai, H. Iijima, R. Hajima, M. Yamamoto, T. Muto, Y. Honda, T. Miyajima, M. Kuriki, M. Kuwahara, et al., Development of a 500-kV photocathode DC gun for the ERL light sources in Japan, in: Proc. of ERL09, Liverpool, UK, 2009, p. 277.
[29] Y. Wang, T. Emoto, M. Nomura, et al., A novel chopper system with very little emittance growth, in: Proceedings of the 4th European Particle Accelerator Conference, in London, 1994.
[30] M.S. Grbić, Modes of an elliptical cylindrical resonant cavity—analytical solution, J. Appl. Phys. 125 (22) (2019) 224501.
[31] D. Systemes, Cst microwave studio, 2019, [Computer Program] Available At: http://www.cst.com.
[32] L.C. Maier Jr., J. Slater, Field strength measurements in resonant cavities, J. Appl. Phys. 23 (1) (1952) 68–77.
[33] T. Van Oudheusden, P. Pasmans, S. Van Der Geer, M. De Loos, M. Van Der Wiel, O. Luiten, Compression of subrelativistic space-charge-dominated electron bunches for single-shot femtosecond electron diffraction, Phys. Rev. Lett. 105 (26) (2010) 264801.
[34] S. van der Geer, M. de Loos, Pulsar physics, general particle tracer, 2020, Available at: www.pulsar.nl/gpt.