ISBN: 978-3-95450-184-7 doi:10.18429/JACoW-IPAC2018-THPMF089

DESIGN OF A RADIAL RF ELECTRON GUN*

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Abstract

Most electron beam sources generate beams that propagate away from the source in a single primary direction, with the overall envelope being either pencil-like or sheet-like. We present the design of a radial RF electron gun, intended to produce electron beams propagating radially inward, with the overall envelope being that of a contracting annulus when the beam reaches its intended target. Such a source has several potential advantages for materials processing, and may also be useful as the basis for unique optical elements for hadron machines.

INTRODUCTION

In June 2017, the US Department of Energy Accelerator Stewardship Program [1] released its "FY2017 Research Opportunities in Accelerator Stewardship" [2], including a call for design studies of four types of high-power electron accelerators for energy and environmental applications. Table 1 lists the target performance for the "Type 1" and "Type 2" accelerators in this call.

Table 1: Desired Parameters for Type 1 & 2 Accelerators

	Type 1 Demo/Small Scale	**Type 2 Medium Scale Low Energy**
Electron Beam Energy	0.5 – 1.5 MeV	1 – 2 MeV
Electron Beam Power (CW)	> 0.5 MW	> 1 MW
Wallplug Efficiency	> 50%	> 50%
Target Capital Cost[1]	< \$10/W	< \$10/W
Target Operating Cost[2]	< 1.0 M\$/yr	< 1.5 M\$/yr

[1] Including all supporting systems, e.g. power, cooling.
[2] Including all labor, supplies, repair, electricity, etc.

Several high-power DC- and RF-based sources designed for applications such as FEL drivers can approach these requirements [3], but all take on the same basic form of a linear accelerator, generating a "pencil" beam along an axis. While this is ideal from the standpoint of injecting a beam into a higher-energy accelerator, it poses several issues regarding the use of the beam for waste stream processing. Los Alamos National Laboratory (LANL) and the Air Force Research Laboratory (AFRL) have developed a concept for a "radial" RF-driven electron beam source, with an annular RF cavity delivering a beam towards the axis of the annulus; Figure 1 shows our initial concept. We believe such a design has significant advantages for waste-stream processing.

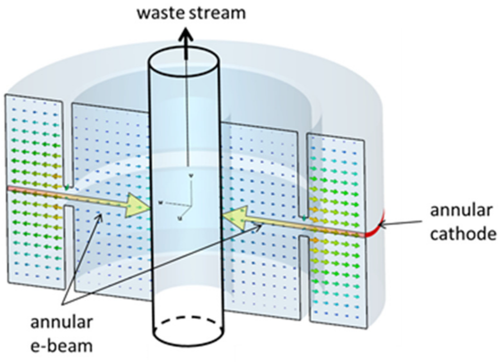
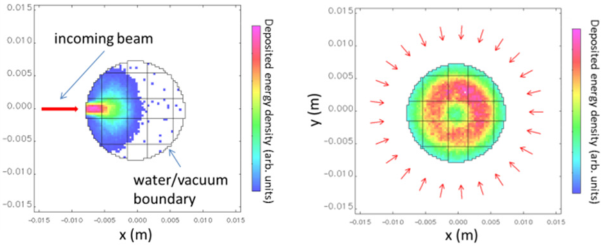


Figure 1: Initial concept for a radial RF gun.

Figure 2 encapsulates the comparison between a linear and radial beam source for waste stream processing. In short, a linear beam source requires overpenetration of the waste stream to deliver dose to all portions of the stream, wasting beam power, and waste stream cross-sectional area scales linearly with the beam energy. A radial beam source, in contrast, can be designed such that all of the waste stream can receive dose while completely absorbing the beam within the stream, and the waste-stream area scales with the square of the beam energy. (Two opposing linear beam sources with rastering systems could capture several of these advantages, but with significantly increased complexity.)



(a) (b)

Figure 2: Contour map of deposited energy density within a cylinder of water 1.5 cm in diameter, being impacted by 1.75-MeV (kinetic) electron beams in (a) pencil and (b) radial configurations. The black grid lines are artifacts of the plotting program. Calculations were performed with **shower** [4].

The energy ranges given in Table 1 suggest the use of an RF, rather than DC, accelerator; the efficiency requirements suggest superconducting RF. Therefore, our design centers around the use of "SC-compatible" RF cavity shapes.

We note that our design bears considerable resemblance to the Rhodotron [5], which also makes use of a coaxial $\lambda/2$ resonator. However, Rhodotrons are typically intended to operate in the 3 – 10 MeV range, with beam powers

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* Work supported by the US Department of Energy Accelerator Stewardship Program LA-UR-18-23364
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to several hundred kW, so are higher-voltage, lower-current machines compared to our design. Also, the Rhodotron directs the beam through multiple transits of the coaxial resonator to obtain the desired beam energy. Since our design is intended to have a target along the axis of the resonator, we cannot make use of this elegant approach.

FUNDAMENTAL CONCEPTS

We selected an operating frequency of 350 MHz, as MW-class CW klystrons at this frequency are commercially available and in service in storage rings.

Cavity Design

The basic form of the cavity is a half-wavelength coaxial resonator with length L_{cav}, and inner (outer) radii $r_{i(o)}$. The mode of interest has electric fields $E_z = E_\phi = 0$, and

$$E_r(r,z,t) = \frac{E_n}{r}cos\left(\frac{\pi}{L_{cav}}z\right)cos(2\pi f_o t + \varphi) \qquad (1)$$

for $|z| < L_{cav} / 2$ and $r_i \leq r \leq r_o$, E_n is the magnitude of the field at unit radius, $f_o = {}^{c}/_{2L_{cav}}$ is the resonant frequency, and φ is a constant phase offset.

The notional cavity shown in Fig. 1 is a 2-cell coupled-cavity coaxial resonator, the radial RF gun equivalent of a 1.6-cell photoinjector cavity. In practice, while we found it possible to generate such a coupled cavity design, as in the 1.6-cell photoinjector the field balance between the cells is quite sensitive to the details of the geometry. Therefore, we decided to focus upon the use of either single cavities, or multiple cavities that are independently powered and phased.

Electron Source

The conceptual design shown in Fig. 1 shows an annular cathode. While ideal in concept, in practice it does not appear practical. Rather, we consider using N cathodes spaced at 360/N degrees around the equator of the cavity as the beam source. For N ≥ 6 we should have a reasonable approximation of an annular beam by the time the beams reach the target at the axis of the cavity.

As the eventual goal is the design of an industrial beam source, we wish to use thermionic cathodes rather than photocathodes. Given that the RF cavities are to be superconducting, however, we require both thermal isolation, and short emission windows (relative to the RF period) to minimize "tails" and beam loss inside the cavity. To that end we have also developed a conceptual design for a relatively low-voltage (~25 kV) DC gun based around a gridded cathode.

If the total beam current is to be on the order of 1 A, then each cathode must supply on the order of 0.1 – 0.2 A. At 25 kV, this corresponds to an electron gun power on the order of 5 kW, well within the range of commercial power supplies.

Per-cathode beam currents of 0.1 – 0.2 A correspond to bunch charges of 0.3 – 0.6 nC. We wish to have bunches shorter than about 40° relative to the cavity RF period to help control energy spread and differential focusing, corresponding, at 350 MHz, to 300 ps, or peak beam currents of around 1-2 A.

Operating at this voltage allows us to drift the beam from the gun through a reasonable distance to the cavity entrance, allowing for thermal isolation, and access to the cathode from outside of the cryogenic enclosure for easier maintenance.

SIMULATIONS

Cavity

We chose elliptical toroids for our basic cavity design, similar in cross-section to linear superconducting cavities. Our initial design has both an inner and an outer toroid, each with six beam tubes. Figure 3 shows a 3-d perspective view; Fig. 4 shows the fields in cross-sectional slices, and Fig. 5 shows the normalized radial field, $E_r(r)$, along one of the beam tubes. CST Microwave Studio [6] was used to perform the cavity modeling.

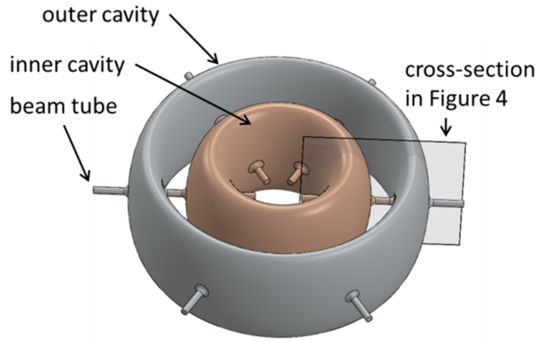


Figure 3: Perspective view of the 2-cavity radial RF gun.

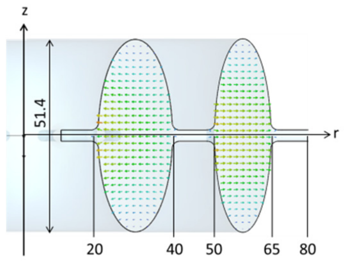


Figure 4: Cross-sectional view; all dimensions are in cm.

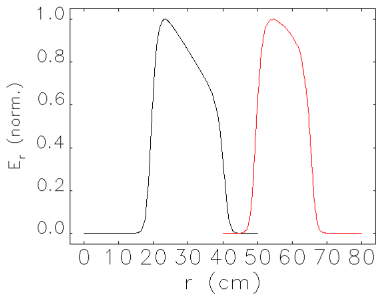


Figure 5: Radial field as a function of position along the beam tube for inner (black) and outer (red) cavities, normalized to the peak field along the beam tube axis.

The cavities' lengths were individually optimized to have their fundamental modes resonant at 350 MHz. The cavity radial separation is shown as 10 cm; the separation could be increased to accommodate a small inter-cavity solenoid, or to increase cavity-to-cavity RF isolation. The radial dependence of E_r is clearly visible in Fig. 5.

Finally, while the cavity shown in Fig. 3 has six beam tubes, the cavity could readily support up to at least 12-15 ports; doing so trades off a lower per-cathode beam current, versus greater heat leakage from outside the cryostat.

Electron Source and Initial Transport

The cathode emission parameters are described above. Our initial source design is based around the use of a Pierce-like 25-kV DC gun, plus a small solenoid to aid transport prior to beam injection into the outer cavity.

The gun, simulated using Poisson [7], has a cathode/anode cone angle of 50° (measured from the axis), a 1-cm accelerating gap, and an 0.56-cm radius cathode located at r = 80 cm. The solenoid is 2 cm long, and centered at r = 72.5 cm.

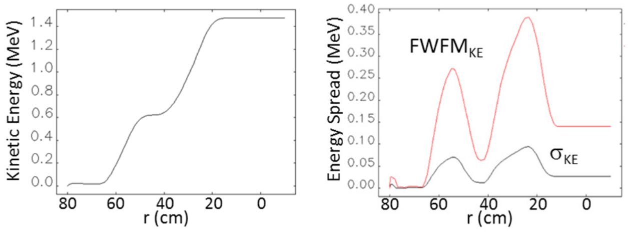
For comparison, commercial products such as the Model HWEG-1228 e-gun from HeatWave Labs [8] exhibit comparable performance in terms of duty factor, voltage, and perveance,

Beam Dynamics

The General Particle Tracer (GPT) code [9] was used to perform beam dynamics modeling from the cathode grid at r=80 to r=0, using 300-pC bunches and 300-ps emission times, and a 25-kV DC gun voltage. This corresponds to a per-gun peak (average) current of 1 A (0.105 A). The gun solenoid had a peak field of 225 gauss; the on-axis field at r=65 cm (boundary of the outer cavity) was approximately 10 gauss. The peak on-axis fields in the outer and inner cavities were 4.5 MV/m and 4.8 MV/m, respectively, and were phased for maximum beam energy gain. The results shown were generated by tracking 50k particles, using GPT's 3-d space charge routine and the fields calculated with CST and Poisson for the cavities and DC gun, respectively. GPT's **`bzsolenoid`** element was used to approximate the gun solenoid. (Simulations with 0.6-nC bunches also show acceptable transport.)

In Figures 6 and 7 below, the beam is propagating from left to right, and properties are plotted vs. the radial coordinate axis in Fig. 4.

Figure 6 shows the beam energy and fractional energy spread as a function of radial position.



(a) (b)

Figure 6: (a) Beam energy and (b) RMS (black) and FWFM (red) energy spread as functions of radial position.

The beam envelope is plotted in Fig. 7 using a local Cartesian coordinate system aligned with one beam tube. In both the horizontal (perpendicular to z-r plane in Fig. 4) and vertical (parallel to the z axis in Fig. 4) local directions the beam core is well confined; the full beam radius does not exceed the nominal beam pipe radius of 1.5 cm. The inner cavity ends at r=20 cm, so, if required, an additional solenoid could be placed before the exit window to spread the beam for a more uniform dose delivery.

This 2-cell design can easily meet the requirements of either a Type 1 or Type 2 source from Table 1; it appears likely a 1-cell design could also meet the Type 1 requirements.

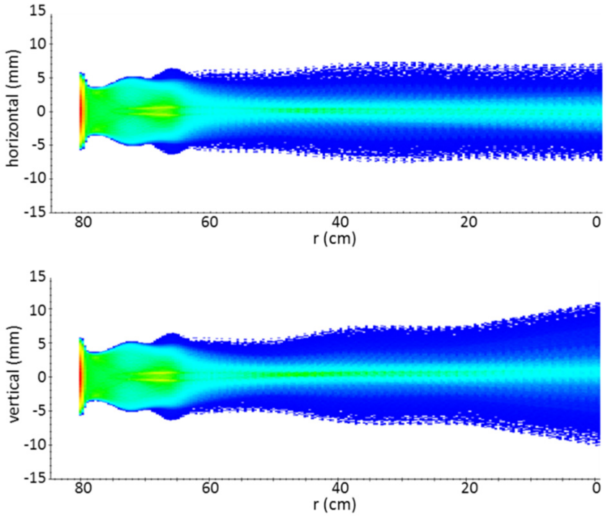


Figure 7: Beam envelope in "horizontal" (top) and "vertical" (bottom) local planes as a function of radial position. "Scalloping" is from histogrammed timestep output.

FUTURE PLANS

Going forward, our focus will switch to preliminary design of the RF power couplers, thermal analysis of the electron gun, cavity structure and exit window materials, modeling irradiation of notional target materials, and developing estimates for capital and operating costs. We will also construct a cold-test model of the inner cavity to verify our predictions as to field profile and frequency.

CONCLUSION

We are performing a conceptual design of a radial RF beam source for applications such as sterilization, flue gas and waste-water treatments. The design is based around the use of superconducting coaxial-resonator-like cavities, coupled with gridded DC guns operating at low voltage. Initial beam dynamics are very promising, and we now turn to power coupling design, thermal modeling, and cost estimation.

ACKNOWLEDGEMENTS

Thanks to Patrick McChesney for useful and interesting discussions related to the Rhodotron and other topics.

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