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NOVEL HIGH POWER SOURCES FOR THE PHYSICS OF IONOSPHERIC MODIFICATION*

B.L. Beaudoin, T.M. Antonsen Jr., I. Haber, T.W. Koeth, A.H. Narayan, G. Nusinovich, K. Ruisard,
Institute for Research in Electronics & Applied Physics,
University of Maryland, College Park, MD 20742-3511, USA
J.C. Rodgers, U.S. Naval Research Laboratory, SW Washington, DC 20375, USA

Abstract

The ionosphere plays a controlling role in the performance of critical civilian and DoD systems including the ELF-ULF communications, radars, navigation (including GPS) and geo-location systems. Ionospheric Modification (IM) is a complementary approach to passively studying the ionosphere that has intensified over the last 30 years with the construction of the High-Frequency Active Auroral Research Program (HAARP). The objective of IM is to control and exploit triggered ionospheric and magnetospheric processes to improve the performance of trans-ionospheric Command, Control, Communications and Intelligence (C3I) systems and to develop new applications that take advantage of the ionosphere as an active plasma medium. A key instrument in IM is the Ionospheric Heater (IH), a powerful High Frequency transmitter that modifies the properties of the ionospheric plasma by modulating the electron temperature at preselected altitudes.

A major reason for the development of a Mobile IH source (MIHs) is that it would allow investigators to conduct the needed research at different latitudes without building permanent installations. As part of a multi-university research initiative (MURI), UMD will develop a powerful RF source utilizing Inductive Output Tube (IOT) technology running in class-D amplifier mode. This technology was chosen because it has the potential to operate at high efficiencies. Some of the technical challenges presented in this paper will include: a gun design that minimizes intercepted current, a compact tunable hybrid cavity operating in the 1-10 MHz range, and an efficient modulator system capable of modulating a high power electron beam.

MAGNETRON INJECTION GUN (MIG) IOT DESIGN

A major concern with the gridded class-D operation of an IOT device is the heating of the grid due to intercepted electrons. A design using a MIG-type cathode that produces a hollow beam avoids this complication, as a small mod-anode local to the thin annular cathode can be used to bias the beam on and off without intercepting any electrons. We already possess a MIG-type cathode with a negative injection angle for this purpose. The proposed source with a Pierce-type geometry has been characterized with the Michelle code [1] with 2D axisymmetric geometry as shown in Fig. 1a. Steady state electrostatic PIC simulations show that for 60 kV on the anode and 200 V on the mod-anode, we can expect approximately 2 A of beam current from a 4.7 cm^2 emitter. The magnetic field design was identified by using Maxwell 2D (axisymmetric geometry) code to simulate solenoid coils/pole piece geometries. Iterations over several geometries maximized the dot product of the field lines with the unmagnetized beam trajectory (to minimize conversion of longitudinal to transverse momentum). The most recent iteration is shown below in Fig. 1b. The field lines follow the unmagnetized beam trajectory closely, except near the cathode surface. An additional set of coils or iron field shapers behind the cathode may be used to adjust the field lines in this region. As seen in simulation (Fig. 1b), with a 1.4 kGauss field (shown in Fig. 1c), the beam ripple due to transverse energy gain is minimal. This field simulation assumes ideal iron.

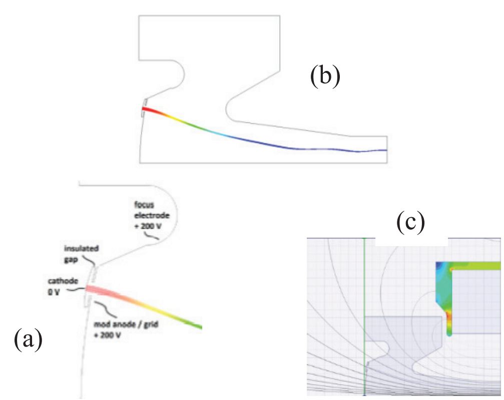

Figure 1: (a) Geometry of cathode, focusing electrode and mod-anode of a MIG-type gun and the particle trajectories. (b) Beam trajectory with field from a solenoid (c), with a peak on-axis field of 1.4 kGauss.

Steady state Michelle simulations were used to estimate the capacitance seen by the grid driver due to the focus electrode-mod anode spacing in the vicinity of the cathode. Calculations were done with and without beam in a 2D axisymmetric Michelle simulation, and the no-beam case was verified against a Maxwell 3D model of the gun assembly. Michelle and Maxwell measurements agreed to within 2 %, with the most likely discrepancy being a difference in mesh density. Additional comparisons of Michelle simulations with and without beam, predicts a 1 % increase in capacitance due to beam loading. We predict that the capacitance due to the inner surface of the mod-anode is 15.6 pF, requiring the grid driver to pull 2 A for a 5 ns rise time on a 600 V swing.

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However, this estimate does not account for capacitance in the transfer line, which may be considerable.

We have also used the Michelle electrostatic time domain solver to probe MIG IOT performance in pulsed operation. In this mode, we obtained the cathode-grid I-V curve by allowing the grid voltage to slowly ramp (12 V/ns) at a fixed anode voltage 60 kV. The extracted perveance in the cathode-mod anode gap was fitted to be 17.7 μPervs with a turn-on voltage of -308 V.

LIMITING CURRENT OF AN ELECTRON BEAM IN A GAP

The development of high current accelerators in the late 1960's-early 1970's initiated an active study of limiting currents of charged particle beams that can be transported through metallic pipes in vacuum and/or plasma (see, for example, textbooks [2-4]) and references therein. The simplest case which allows for an analytical study of limitations due to the space charge effects is the case when a beam of charged particles (electrons or ions) are guided by an infinitely strong external focusing magnetic field through a uniform metallic pipe. Below we summarize the results of such a beam propagating in the presence of a gap.

Consider a system schematically shown in Fig. 2. Here a cylindrical electron beam of an arbitrary cross-section (pencil-like or an annular one) propagates through a pipe being guided by an infinitely strong guiding magnetic field; so electrons perform a 1D motion in the z-direction.

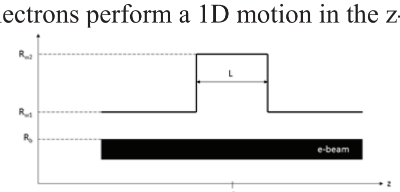


Figure 2: Geometry of a beam propagating in a pipe with a gap.

The limiting current dependence on the beam voltage (shown in Eqn. 1) at low voltages ($\hat{V} = eV / mc^2 << 1$) is plotted below in Fig. 3 for a gap length of 7 mm and beam radius of 2.5 mm.

$$I_{\max} = \frac{mc^3}{e}\frac{1}{3}\sqrt{\frac{2}{3}}\pi\left(R_b / L\right)\frac{K_1\left(\pi\left(R_b / L\right)\right)}{K_0\left(\pi\left(R_b / L\right)\right)}\left(\hat{V}\right)^{3/2} \quad (1)$$

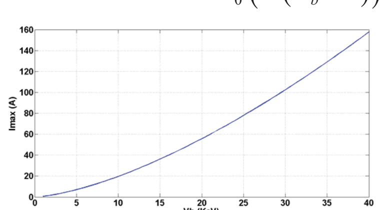
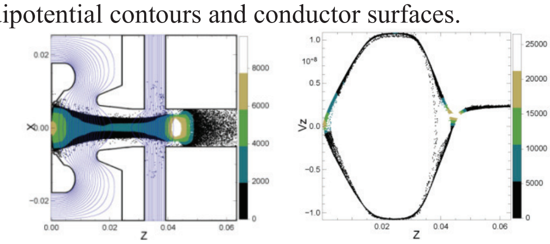


Figure 3: Limiting current dependence on beam voltage.

SIMULATIONS OF REFLECTED PARTICLES IN A GAP

A preliminary series of axisymmetric electrostatic WARP [5] PIC simulations has been conducted to examine beam behavior resulting from the application of a decelerating voltage that is a large fraction of the beam energy. The practical limits on the retarding voltage are an important factor limiting IOT efficiency. It is therefore desirable to approach these limits without generating reflected particles capable of intercepting the device walls and limiting device lifetime.

The configuration examined here is a standard Pierce gun diode with a 0.25 in radius cupped cathode structure, operating at 37 kV and the nominal 3.28A space-charge-limited current. A 7 mm wide 35 kV retarding gap in the ~5 cm radius wall is inserted 32 mm downstream from cathode. Fig. 4a is the x-z configuration space particle plot after 5 ns, compared to a transit time of approximately 1 ns. Also plotted on the same axes are equipotential contours and conductor surfaces.



(a) (b)

Figure 4: (a) Particle plot of x-z configuration space and equipotential contours for a 3.28 A electron beam accelerated to 37 keV and then decelerated by 35.5 kV. (b) v_z-z phase-space plot from the same simulation.

From Fig. 4a it is evident that a population of the reflected particles is outside the main beam body and that these particles can hit the conducting surface. Some of these particles (shown in Fig. 4b) can acquire significant energy as they traverse the decelerating gap in the negative direction. Particles that hit the conductive walls will have adverse consequences to the device lifetime. Immersing the beam in a longitudinal magnetic field will mitigate the dispersal of reflected particles outside the beam body. However, imposing a strong constant longitudinal field will maintain the beam at a constant beam radius. Because the cathode radius is greater than the anode aperture radius, this has the undesired result that the outer portions of the beam intercept the anode conductor. The anode geometry was therefore modified by simply increasing the radius of the anode aperture from 0.2 in to 0.3 in. In this way, particles that are emitted from the edges of the cathode and guided by the magnetic field, that travel at a near constant radius, will remain inside the radius of the anode aperture.

PROTOTYPING TEST-STAND

HeatWave Labs Gridded Gun

An off-the-shelf gridded gun is being procured from HeatWave Labs for various prototyping studies, including the fast RF modulator and tunable constant impedance cavity circuits. Though the gun is gridded, it will allow us to bench mark codes and calculations against a beam in the appropriate parameter range. The HeatWave Labs

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gridded gun model HWEG-101225, is capable of 5.7 A at 20 kV [6]. The gun will be mounted to beam pipe with a gap for deceleration studies and also surrounded by a solenoid (shown in Fig. 5a) for transverse containment. A Michelle simulation (shown in Fig. 5b) illustrates the particle trajectories as well as those particles being decelerated by a 16 kV DC gap immersed in the guide field.

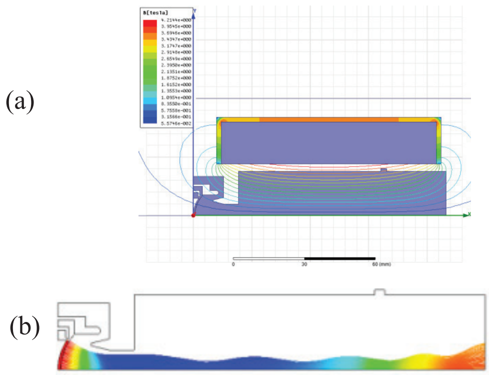

Figure 5: (a) Magnetic field from solenoid. (b) Beam trajectory with field from the solenoid traversing a gap with a 16 kV retarding potential.

Fast RF Modulator

Michelle simulations of the MIG gun mod anode indicate that the required voltages to bring the gun from cutoff to saturation are approximately 600-700 V. We may operate the gun at higher beam currents which will as a result demand higher mod anode voltages. The modulator (an inductive summer) will drive the grid in burst mode at 1-10 MHz with pulse widths of 50-150 ns at low repetition rates.

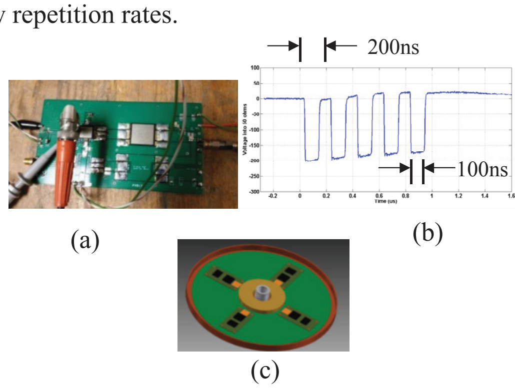

Figure 6: (a) Prototype RF power MOSFETs and gate drivers. (b) Circuit output into 50Ω. (c) CAD drawing of the complete modulator mounted onto the HeatWave Labs gun.

A prototyping circuit (6a) is used to test the low-side driver and RF power MOSFETs from IXYS into 50 Ω. The MOSFETs are capable of peak voltages of 1 kV and currents of 20 A switching within 5 ns where the driver can handle a maximum switching frequency of 45 MHz [7].

Constant Impedance Cavity

The cavity we will use for the test-stand can be modelled using a parallel LC resonant circuit (shown in Fig. 7a) where the capacitor of the resonant circuit is on the beam side.

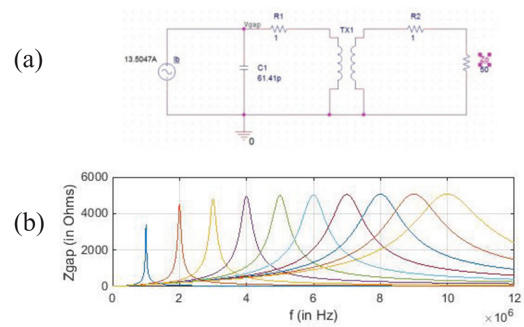

Figure 7: (a) Parallel LC resonant circuit. (b) Gap impedances for different resonant frequencies

The cavity will operate at approximately 1-2 MW at 1-10 MHz. With this design requirement in mind, we assume a total pulsed beam current (I_b) of 30 A active only during 1/4th of an RF period and potential difference of approximately 70kV across the gap. The resonant frequency is given by $\omega_c = 1/\sqrt{N^2 L C_1}$ where L is inductance per turn, the quality factor is given by $Q = Z_o/\omega_c L M^2$ and the gap impedance at resonant frequency is given by $Z_{gap} = Z_o (N/M)^2$. There is no flexibility in the choice of capacitance once the gap impedance, resonant frequency and quality factor are chosen. Hence, if the inductor and the number of turns are to remain constant, then the quality factor will have to vary when the resonant frequency varies (as shown in Fig. 7b).

CONCLUSION

As part of a MURI, UMD is underway in designing and prototyping for a powerful RF source that will utilize IOT technology running in class-D amplifier mode. As mentioned, the ultimate goal is to design a 1-2 MW source. This will require, among other things, designing a higher perveance gun, or possibly a multiple beam version of the MIG-type gun discussed above. The preliminary calculations presented in this paper suggest that the design of such an efficient source is feasible. The general concept of a Class D anode-modulated annular beam, combined with a depressed collector and a constant impedance cavity should yield maximum efficiency. Efficiency is considered critical, as a mobile IM antenna array of dimensions 30m by 40m would require a total source power of 100 NW to achieve the same radiated power density in the ionosphere as HAARP. However, many technical challenges remain.

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[6] http://www.cathode.com

[7] http://www.ixys.com