

DEVELOPMENT OF HIGH-AVERAGE-CURRENT RF INJECTORS*

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Abstract

A key component of the high-average-power FEL is a low-emittance, high-average-current RF photoinjector. High average current requires high bunch charge and high duty factor. While the accelerating gradient can exceed 100 MV/m in a pulsed normal conducting RF (NCRF) injector, it is significantly lower in a cw or high-duty RF injector. Emittance compensation has been achieved in NCRF injectors with an axial solenoid magnetic field near the photocathode to produce normalized rms emittance on the order of a few microns. The use of emittance compensation eliminates the need for very high accelerating gradients, thereby minimizing ohmic heating in a high duty RF photoinjector. Three high-duty NCRF photoinjectors have been designed with one being tested. Two superconducting RF photoinjectors with different emittance compensation techniques have been designed and are being either fabricated or tested. This paper reviews the development of normal-conducting and superconducting RF photoinjectors leading to high average current.

INTRODUCTION

Low-emittance RF photoinjectors have been an area of active research in the past two decades. These high brightness RF injectors have produced nanocoulomb bunch charge and micron rms emittance, albeit at low duty factor. Large single-pass gains have been demonstrated in self-amplified spontaneous emission FEL driven by RF photoinjectors [1, 2]. RF photoinjectors are presently used to drive short-wavelength and x-ray FEL. Up to now, RF photoinjector designs have been largely based on high gradient acceleration at the cathode to mitigate space-charge induced emittance growth. Recent progress in high-average-power FEL has rekindled interest in high-average-current RF photoinjectors that operate at high bunch charge and high duty factor. The design of high-average-current RF injectors differs significantly from that of low-duty RF injectors. In high-duty operations where RF power is applied continuously on the injector cavity, cavity heating due to ohmic losses becomes an important issue. Since ohmic losses scale with the square of the accelerating gradient, and heat removal requires access to the RF surface area, high-duty-factor injectors tend to operate at reduced gradients and at lower frequency than their low-duty counterparts. A new design approach is needed to deliver electron beam's performance similar to those of the low duty RF injectors, but with reduced gradients, improved thermal and vacuum management, long photocathode lifetime and good stability over long periods of operation.

A schematic of the RF photoinjector is shown in Fig. 1. The RF photoinjector typically consists of a high gradient

structure with integer-and-a-half RF cells. The cathode is located on the wall of the first half cell where a high accelerating gradient is applied to quickly accelerate electrons to relativistic velocities. Other sub-components of the RF photoinjector include a high-power klystron, a photocathode capable of withstanding high accelerating fields, and a modelocked drive laser with frequency conversion. For emittance compensation, a solenoid producing an axial magnetic field is placed either at the exit of the photoinjector or near the photocathode.

The design of high-duty RF must take into account the strength and weakness of the injector sub-components and the interaction between these sub-components. For instance, low-loss cavity shapes reduce ohmic losses and increase RF efficiency but their small apertures reduce the vacuum conductance and thus affect the operational lifetime of photocathodes. Ultra high gradients provide suitable beam dynamics for low emittance at the expense of high ohmic losses. High gradients also require the use of metal cathodes with low quantum efficiency and thus complicate the design of the photocathode drive laser. Switching to superconducting cavities allows one to operate at a higher gradient, but these cavities do not support an external magnetic field for emittance compensation. The design of high-average-current injector thus requires one to make compromises among opposing requirements. A look at the history of RF injector developments reveals how RF photoinjectors have evolved toward high-duty-factor designs.

RF PHOTOINJECTOR DEVELOPMENT

The RF photoinjector was invented by Fraser et al. [3] at LANL in 1985 as a high brightness electron source for the high-power Free-Electron Laser program. In the early days of RF injector development, the LANL researchers made a surprising discovery: the electron beam's rms emittance was getting smaller as the beam propagated away from the cathode, an apparent violation of Liouville's theorem. Upon further investigation, Carlsten discovered that the transverse phase space ellipses of different axial "slices" of the electron bunch rotated in the $x'-x$ (or $y'-y$) plane under different space charge forces but the direction of this phase space rotation was reversed by the axial focusing magnetic field and, at a point downstream of the cathode, different transverse ellipses corresponding to different axial slices re-aligned in phase space. The re-alignment of these phase-space ellipses decreased the area that they projected onto the $x'-x$ phase space and gave rise to the apparent reduction in rms emittance. This reduction of normalized emittance is known as emittance compensation [4]. Emittance compensation has been used extensively to achieve low rms emittance in space-charge dominated electron beams.

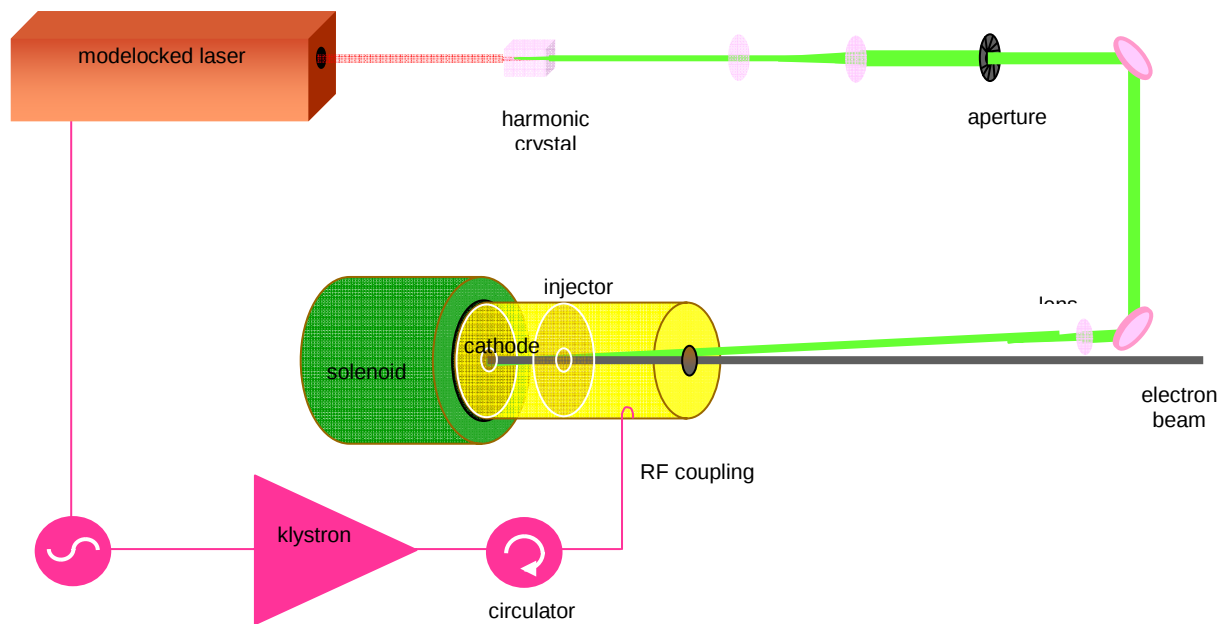


Figure 1: Schematic of a normal-conducting RF photoinjector with a solenoid magnet for emittance compensation.

Low-duty-factor Integrated Photoinjectors

The first integrated RF photoinjector designed with emittance compensation was Carlsten's $5\frac{1}{2}$ -cell gun called the HIBAF photoinjector [5]. The HIBAF photoinjector used magnetic coupling via coupling slots on the cavity walls, a solenoid magnetic field for emittance compensation, and a bucking coil to null the axial magnetic field at the cathode. This last step was necessary to avoid introducing an angular momentum in the generated electron beams, which would lead to an intrinsic emittance. The measured rms emittance of the electron beams exiting the HIBAF photoinjector using a K_2CsSb photocathode was less than 10 microns at bunch charge up to 6 nC [6]. However, the HIBAF photoinjector suffered from a cumulative quadrupole field as its magnetic coupling slots were all oriented in the same direction. As the solenoid field mixed the x and y emittance of the electron beam, this quadrupole field caused an emittance growth. At the time, LANL was assembling another integrated, $10\frac{1}{2}$ -cell photoinjector designed for the Advanced FEL project (Fig. 2) [7]. Upon discovery of the HIBAF quadrupole field problem, the AFEL coupling slots were alternated in x and y to cancel the quadrupole field. With this modification, the AFEL photoinjector was able to produce normalized rms emittance of 1.6 microns at 1 nC (Fig. 3) [8]. Due to heating at the high-current paths around the magnetic coupling slots, the AFEL injector's duty factor was limited to 10^{-4} . The AFEL photoinjector can deliver electron beam energies up to 20 MeV in a relative compact design. However, this design offers little flexibility for placement of additional accelerator cavities

at their optimum locations to damp out the transverse plasma oscillation and obtain higher beam brightness.

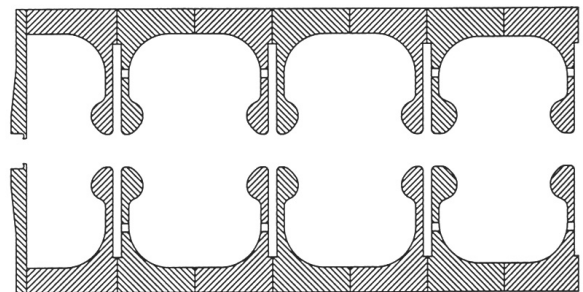


Figure 2: Cutaway view of the first $3\frac{1}{2}$ cells of the LANL Advanced FEL integrated photoinjector, showing the coupling cells and coupling slots.

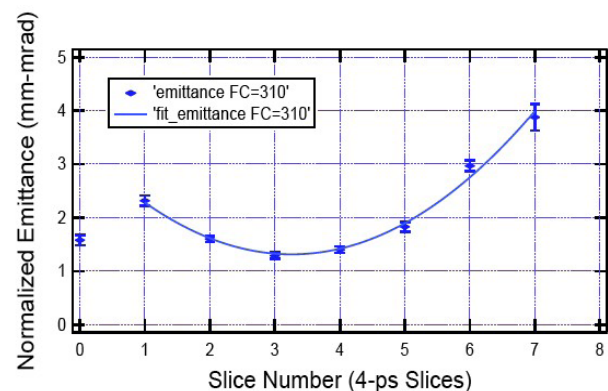


Figure 3: Measured normalized rms and slice emittance of the AFEL photoinjector.

High-duty-factor NCRF photoinjectors

The next logical step after achieving high peak brightness is to increase the average brightness by increasing the photoinjector duty cycle. The first high-duty-cycle RF photoinjector was the Boeing normal-conducting RF injector at 433 MHz. Similar to the very first LANL RF injector design, the Boeing 433 MHz gun had re-entrant cavity walls and was made out of oxygen-free electrolytic copper (Fig. 4) [9]. Unlike the LANL emittance compensation solenoid design, the Boeing gun uses a small solenoid coil near the beam pipe for emittance compensation. At 25% duty factor, the Boeing gun delivered 32 mA, the highest average current for any electron injectors. The measured rms emittance was 5-10 microns for bunch charge between 1 and 10 nC. At duty factor between 1% and 25%, the average photocathode lifetime was 2.3 hours. The cathode lifetime correlated with partial pressure of water, which was caused by water-to-vacuum leaks in the copper braze joints. The vacuum in the Boeing gun was also limited by low vacuum conductance due to small apertures in the cavities and the electron beam line.

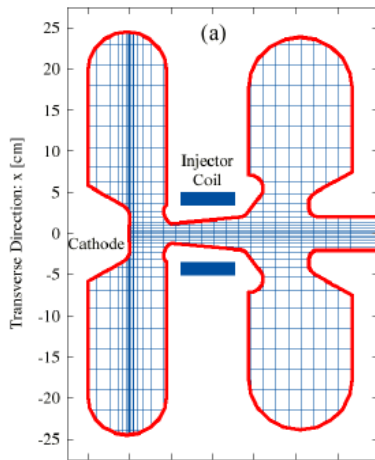


Figure 4: The Boeing 433-MHz re-entrant RF injector cavity design.

Three other NCRF injectors have been designed, two of which have already been fabricated and will soon be tested. These are the Los Alamos National Lab/Advanced Energy System (LANL/AES) NCRF photoinjector, the high-average-power RF gun for the BESSY soft x-ray FEL in Germany, and the AES/JLab re-entrant NCRF injector. The LANL/AES NCRF injector is a 100% duty, 2½-cell 700 MHz gun (Fig. 5) that relies on magnetic solenoid emittance compensation, instead of high accelerating gradient at the cathode, to achieve normalized emittance on the order of a few microns [10]. The NCRF injector uses on-axis electric field coupling (instead of magnetic coupling in the early LANL designs) and cavity with flat walls for ease of cooling. The beam apertures are enlarged to increase cell-to-cell coupling

and vacuum conductance between the non-resonant vacuum cell and the injector active cells (Fig. 6).

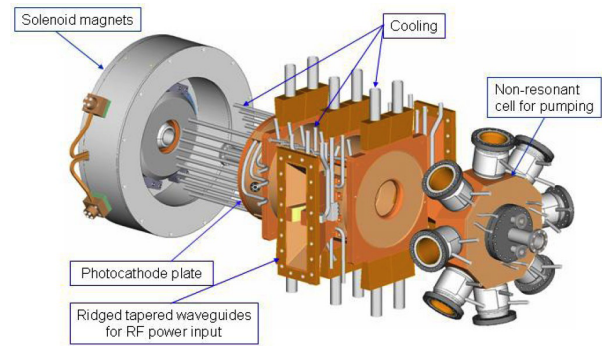


Figure 5: The LANL/AES 2½-cell cw NCRF injector.

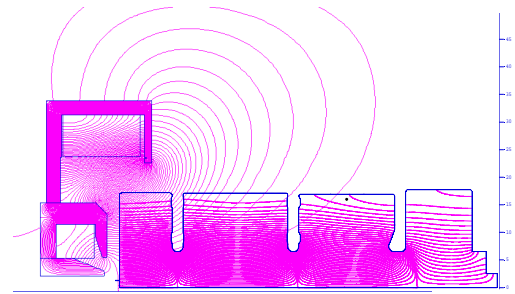


Figure 6: SUPERFISH design of the cw NCRF injector.

The BESSY FEL injector is a 2.5% duty, 1½-cell 1.3-GHz gun (Fig. 7) designed to operate with accelerating gradient of 60 MV/m [11]. High power RF conditioning at the Photo Injector Test Facility at DESY in Zeuthen (PITZ) has recently been performed up to 47 kW average power and a peak electric field of 53 MV/m. The AES/JLab NCRF injector is an all copper RF gun (Fig. 8) that can be operated at 100% duty factor without excessive stresses and with low RF power induced frequency shifts. The AES/JLab gun can operate with cathode fields greater than 20 MV/m and is expected to produce 1 μm normalized rms emittance at 1 nC [12].

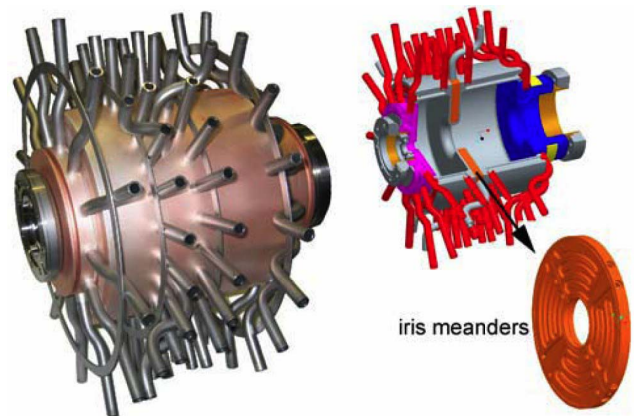


Figure 7: The BESSY 1½-cell NCRF injector.

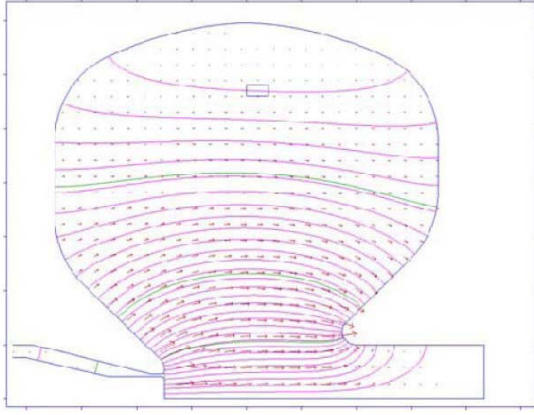


Figure 8: SUPERFISH design of the AES/JLab all-copper NCRF injector.

Gradient versus Duty Cycle

There exists a trade-off between accelerating gradient and duty cycle. The equation governing the beam envelope evolution is given below.

$$\sigma'' + \sigma' \left(\frac{\gamma'}{\beta^2 \gamma} \right) + K_r \sigma - \frac{\kappa_s}{\beta^3 \gamma^3 \sigma} - \frac{\epsilon_n^2}{\beta^2 \gamma^2 \sigma^3} = 0 \quad (1)$$

The second term in Eq. 1 denotes damping of the beam envelope as a result of accelerating gradient and the third term denotes external radial focusing from a solenoid magnetic field or RF field (or both). At low duty factors, RF injectors can achieve gradients in excess of 100 MV/m, providing low-emittance beams. This high gradient requires the development of metal cathodes that can survive the high electric field. However, metal cathodes have low quantum efficiencies (QE) and the drive laser becomes exceedingly complex. For high-average-current applications, it is necessary to operate at a lower gradient and to employ high QE semiconductor photocathodes. One thus has to rely on radial focusing (third term of Eq. 1) and emittance compensation to achieve low-emittance beams. As a rule of thumb, the gradient only has to be larger than twice the electric field created by space charge at the cathode (Gauss law).

$$E_{sc} = \frac{q}{\epsilon_0 \pi r^2} \quad (2)$$

Here, q is the bunch charge and r is the photoemission radius. At increasing duty cycle, the accelerating gradient has to be reduced to keep ohmic heating on the cavity walls at manageable levels, since heating will lead to thermal stress, cavity deformation and consequently a shift in the cavity resonant frequency. The resonance frequency shift causes RF power to be reflected and the injector will fail to establish the necessary cavity field. RF heating in a photoinjector is proportional to the square of cavity accelerating gradient, as given by

$$P_{RF} = \frac{E_0^2 L_c}{Z_s} \quad (3)$$

where L_c is the cavity length and Z_s is its shunt impedance. Heat is not distributed evenly on the cavity walls. In a standard pillbox cavity, most of the heat is on the walls of the cavity equator. The highest heat flux is at the location of highest magnetic field on the septum plates and decreases as we approach the beam apertures. As such, pillbox cavities are relatively straightforward to cool but they have lower shunt impedance compared to re-entrant cavities. Re-entrant cavities consume less RF power and concentrate the field lines near the beam axis, thereby minimizing space charge effects. The re-entrant design, however, increases the heat flux on the cavity septum plates especially near the beam apertures where there is less surface area to cool. Although having less ohmic losses, the re-entrant design is more challenging to manage thermally. Also, the cavity shunt impedance can be improved by reducing the beam aperture, at the expense of vacuum conductance

Photocathode versus Drive Laser

Ohmic heating not only complicates the mechanical and cooling system designs but also degrades the vacuum in the cathode cell. A typical vacuum in the NCRF injector during operation is about 10^{-9} torr with approximately 10^{-10} torr partial pressure of water. Under this condition, the cesiated potassium antimonide (CsK_2Sb) cathodes are expected to have 1/e lifetime of a few hours. To compensate for this rapid decay, one will have to design a drive laser that can operate with a QE of less than 1%. For photocathodes that respond to light at 530 nm, the required laser power has to be more than 23 watts of green light to generate 100 mA. With typical 50% conversion efficiency from IR to green, this means the modelocked drive laser has to put out more than 46 watts of IR light. Progress in diode-pumped solid-state laser could eventually lead to the use of other UV sensitive photocathodes (e.g. Cs_2Te) that are more rugged than the CsK_2Sb cathodes.

Superconducting RF Photoinjectors

An obvious solution to the ohmic heating is to use superconducting RF cavities which offer the benefit of low RF power consumption at relatively high gradients and exceptional vacuum. Having a good vacuum also helps maintain the QE of semiconductor photocathodes. However, superconducting cavities cannot operate with a magnetic field (other than the RF field) and thus new techniques of emittance compensation need to be developed. So far, the highest average current that has been achieved with SRF injectors is 0.5 mA, significantly less than that of an NCRF injector.

The first employment of photocathodes in a superconducting RF cavity was done in 1988 by Michalke at the University of Wuppertal [13]. Different layers of

Cs_3Sb photocathode were deposited on the end wall of a $\frac{1}{2}$ -cell S-band superconducting niobium cavity. These layers showed strong RF losses and field emission at gradients around 2-3 MV/m. During cathode testing, the low- Q_0 superconducting cavity gradient was limited to 5-7 MV/m. The QE of Cs_3Sb at cryogenic temperatures was measured between 1.5 and 2% on niobium substrates and up to 5% on copper substrates, with photocathode lifetime of several days. The second demonstration of photocathode inside a superconducting cavity, though it was called the first SRF gun demonstration, was done more recently by Janssen and co-workers at Forschungszentrum Dresden Rossendorf [14]. Driving a Cs_2Te cathode inside a $\frac{1}{2}$ -cell SRF gun at 4.2K with a modelocked UV laser at a pulse frequency of 26 MHz, they measured a maximum bunch charge of 20 pC, corresponding to an average current of 0.5 mA. At 22 MV/m accelerating gradient, the exiting beam energy was only 900 keV. Surprisingly, the QE of Cs_2Te cathode at 77K was only 0.25%, in contrast to its room temperature QE of $\sim 10\%$.

FZD Rossendorf has completed a new design of SRF injector with emittance compensation techniques. The first technique uses RF focusing at the cathode wall, but this turns out to be rather weak. The second technique is to excite a magnetic RF mode (e.g., TE_{021} mode) to serve as an RF substitute for the solenoid magnetic field (Fig. 9) [15]. With emittance compensation and top-hat laser pulses, the Rossendorf SRF photoinjector is expected to achieve normalized rms emittance of $\sim 1 \mu\text{m}$ at 2.5 nC [16]. In the US, a high-average current SRF injector is being developed at Brookhaven in collaboration with AES. The BNL/AES is a $\frac{1}{2}$ -cell niobium cavity at 703.75 MHz [17]. The BNL/AES SRF gun uses a high T_c superconducting solenoid to achieve emittance compensation (Fig. 10). Several candidates of photocathodes have been proposed for the SRF injector: metals (Nb, Pb), multi-alkali (CsK_2Sb) and diamond amplifier. It remains to be seen whether SRF injectors can deliver the promised high bunch charge at high repetition rates and still maintain the low rms emittance, as there are several questions about the compatibility of the photocathodes operating at high current inside a superconducting cavity and the efficacy of emittance compensation after the electron beams have exited the cavity at high energies.

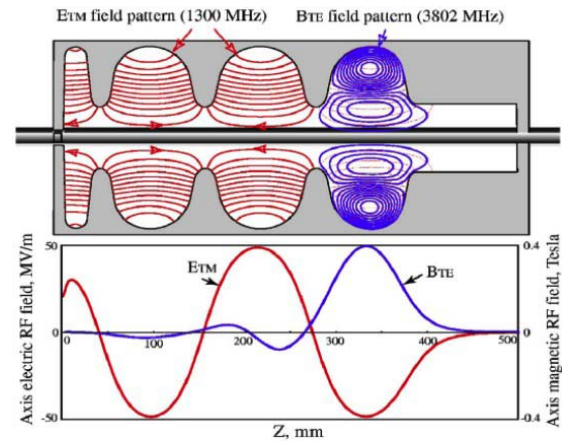


Figure 9: Field patterns of the fundamental and magnetic modes of the new ELBE $3\frac{1}{2}$ -cell SRF injector.

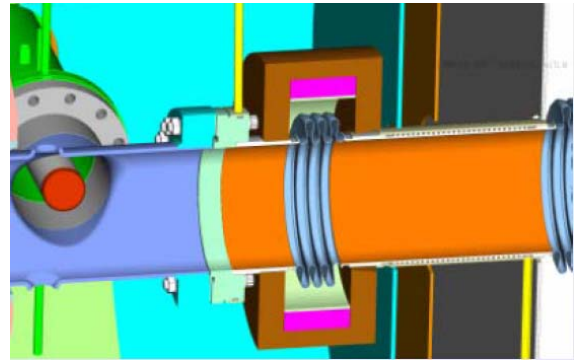


Figure 10: High- T_c solenoid magnet for the BNL/AES superconducting RF injector.

CONCLUSIONS

RF photoinjectors have revolutionized the way high-brightness electron beams are generated to drive high-gain and short-wavelength free-electron lasers. High bunch charge, low emittance beams are now routinely produced to drive a new class of FEL amplifiers. The push for high average brightness has led to the designs of both normal-conducting and superconducting RF photoinjectors operating at very high duty factors or even continuously. Some of these injectors have already built while others have been designed. Each of these injector designs has its unique advantages and disadvantages. These injectors will be tested and data are expected shortly. It is anticipated that the next milestone of high average current ($>100 \text{ mA}$) will be demonstrated in a not too distant future.

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