AMPERE AVERAGE CURRENT PHOTOINJECTOR AND ENERGY RECOVERY LINAC*

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Abstract

High-power Free-Electron Lasers were made possible by advances in superconducting linacs operated in energy-recovery mode. In order to get to very high power levels, say a fraction of a megawatt average power, many technological barriers are yet to be broken. We describe work on CW, high-current and high-brightness electron beams. This will include descriptions of a superconductinglaser-photocathode RF gun employing a new secondary-emission multiplying cathode and a superconducting accelerator cavity, both capable of producing of the order of one ampere average current, as well asand plans for an ERL based on these units.

INTRODUCTION

A frontier of very high power Free-Electron Lasers (FEL) is opening up. The Energy Recovery Linac (ERL) based FEL at Jefferson Laboratory [1,2] demonstrated the potential of ERL- based FELs to obtain kilowatts of average power, with a record of 10 kW recently achieved in the JLAB ERL upgrade, operating with an average current of the order of 10 mA and energy of the order of 100 MeV, or a beam power of the order of one megawatt. However, much higher FEL powers are possible with the right technology; hundreds of kilowatts should be possible. An ERL current of the order of one ampere is desirable with reasonably good emittance, of the order of a few microns normalized RMS. This level of high-brightness, high-power beam performance does not yet exist. The purpose of this paper is to describe work carried out at Brookhaven National Laboratory in collaboration with industry (Advanced Energy Systems, Inc.) and Jefferson Laboratory to push the frontier of high-brightness ERLs. There are three main elements in this effort:

1. Development of an electron source providing CW, ampere-class electron beams with low emittance.
2. Development of an ampere-class linac structure
3. Demonstration of an ampere-class ERL.

We define ampere-class current refers to currents of between a few hundred mA to one ampere micron-class emittance refers to normalized RMS emittances of one to a few microns.

While beam optics and dynamics also play an important role in the systems under discussion, this paper will not cover these subjects for reasons of compactness.

AMPERE-CLASS CURRENT, MICRON-CLASS EMITTANCE ELECTRON GUN

There are two aspects that must be considered in order to obtain ampere-class currents and micron-class emittance in CW gun operation. First is the attainable RF field needed for accelerating high-charge low–emittance electron bunches. Second is a cathode capable of generating high charge electron bunches at the right repetition rate. As we will se later, these aspects are closely related.

The RF gun

A simple argument can be made to narrow down the range of technological possibilities for ampere-class, micron-class electron sources. Since the accelerator is necessarily an RF linac at the frequency range of the order of one giga-Hertz, (say from 0.7 GHz to 1.5 GHz), and the electron bunches must occupy no more than a few degrees of RF phase, the bunch-length in the linac must be of the order of 10 picoseconds. A much longer bunch would lead to distortions of the longitudinal phase-space that would be difficult to correct even with cavity harmonics. The transverse emittance is also increased due to time dependent RF forces. A much shorter bunch would lead to increased wake fields and High-Order Mode (HOM) power, as well as other potential problems such as coherent synchrotron radiation (CSR). It is well known from the experience of developing and operating electron guns with space-charge related emittance growth, that high electric fields are essential for obtaining a good emittance at a reasonable bunch charge. High bunch charge of the order of one or more nano-Coulomb with short bunches of the order of a few pico-seconds to a few tens of pico-second have been demonstrated only with photocathode RF guns. At low duty factors it is possible to achieve accelerating fields of a few tens to slightly over 100 megavolts per meter. Using these accelerating gradients laser-photocathode RF guns achieved

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spectacular successes with sub-micron emittance at a bunch charge of about half a nano-Coulomb [3], and a few microns for bunch charges of one to a few nano-Coulomb. The problem is to combine high fields with CW operation. The best performance to-date of nearly CW RF gun (to be precise, 25% duty factor) has been demonstrated with the Boeing photoinjector [4]. Los Alamos and AES are developing a CW photoinjector [5]. It is clear that even with a large fraction of a megawatt spent on maintaining the field in a copper cavity, the field is limited to under 10 MV/m.

Since it is clear that the ERL will be based on Superconducting Radio Frequency (SRF) technology based on considerations of efficiency and sheer size, it is natural also to seek an SRF photoinjector. A SRF photoinjector will convert all the input RF power (which is to be on the order of one or two mega-Watts) into beam power and permit an accelerating field significantly larger than 10 MV/m. Why has this obvious solution been playing catch-up to other gun technologies? To understand this we have to look into the cathode issue.

The Collider-Accelerator Department at Brookhaven National Laboratory, in collaboration with Advanced Energy Systems and Jefferson Laboratory, is developing a superconducting gun that will accept a high-quantum efficiency photocathode. As a first step we are testing a 1.3 GHz superconducting photoinjector that is used for photocathode development. The initial development has been done by using the niobium as the photocathode. Following that we plan to install a high quantum-efficiency cathode package and test it in the gun. Following that, we are working on the development of a 703.75 MHz half-cell gun with a demountable cathode and couplers for megawatt power. The megawatt CW RF power system, shielding and cryogenics are being installed at BNL.

The performance requirements of this gun are:

1. A frequency of 703.75 MHz to match a RHIC revolution harmonic and the ERL cryomodule frequency (see below)

2. Achieve coupling of 1 MW into the half-cell (with possible upgrade to twice this power) using two opposed input couplers

3. Deliver a current of 0.5 ampere (example: 1.42 nC at 351.87 MHz), requiring a high quantum efficiency cathode insertion

4. Provide a high average accelerating field of about 20 MV/m.

Figure 1 shows the electric field lines of a half-cell gun cavity with a cathode insertion using a double choke-joint. This design allows the cathode itself to be at liquid nitrogen temperature while the gun cavity is at liquid helium temperature. The cathode stalk is slightly recessed to provide RF focusing for the emerging electrons. The beam port is large to allow High-Order Modes (HOM) to escape the cavity to be dumped by a ferrite beam-pipe HOM absorber. Not shown are the input coupling ports, which are a non-trivial part of the gun package, since the amount of CW power required to accelerate the beam is extremely high.

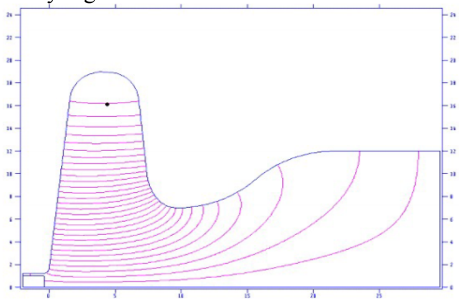

Figure 1. Superfish simulation of a half-cell gun cavity showing part of a choke-joint for the photocathode. The cathode surface is slightly recessed to provide focusing of the electrons.

The photocathode and laser

The photocathode is an enabling technology for the high-current accelerator system. The list of photocathodes that can produce ampere-class average current is short to begin with, and has much to do with laser technology. Without going into details, one must understand that mode-locked lasers operating in CW mode are limited to a few tens of watts in the near IR or visible range of the spectrum, and take a huge penalty (in terms of the number of photons per pulse) when converted to UV. Even a 30 watt average power visible laser is a complicated and expensive device, costing over $0.5M. The higher quantum efficiency photocathodes such as multi-alkaline and cesiated gallium arsenide are short lived unless provided with an ultra-high vacuum, and have volatile materials that are not compatible with superconducting RF technology, since even minute quantities of a material like cesium would lead to field emission and multipactoring in a superconducting cavity by lowering the work function of the niobium. An additional problem with gallium arsenide is non-prompt emission of the photoelectrons. There is a critical requirement for a photocathode that will have the following properties:

1. It should be compatible with a superconducting gun, the only gun that can provide the high accelerating fields to preserve emittance.

2. It should have high quantum efficiency to make the drive laser reasonably feasible.

3. It should have long life, to provide a usable MTBF (mean time between failures).

4. It should have prompt emission, to avoid blowup of longitudinal and transverse phase-space.

5. It would be advantageous to have a sealed cathode capsule that can be exposed to air yet not lose its other properties, to simplify servicing the photoinjector.

6. It would be also advantageous in some cases to have a low thermal emittance.

The last requirement, low thermal emittance, is important only for very low bunch charge, much lower than a nano-Coulomb, since at higher charge the emittance is dominated by collective effects and non-linearities.

Single stage photocathodes simply do not possess these properties. A solution to this problem was recently proposed [6] and R&D on the system is in progress. The basic concept is shown in Figure 2. The idea is to use secondary emission to amplify by a large factor (between one and two orders of magnitude) the emission from a photocathode. A thin (of the order of 20 micrometers) diamond window is positioned between a photocathode (taken to be cesium potassium antimonite in the figure) and the gun (not shown, above the capsule). The primary electrons are generated in the photocathode by the laser (shown coming in on the left), accelerated in the gap between the photocathode and the diamond and strike the diamond with 5 to 10 KeV. The accelerating field is provided by the gun cavity field that penetrates the diamond window. The primary electrons produce a large shower of secondary electrons (up to 100 secondaries per primary, depending on the primary energy). The secondary electrons drift through the diamond, thermalizing to a small fraction of an electron volt in the process and exit the diamond to the gun. A critical element here is endowing the diamond side facing the gun with a negative electron affinity, by bonding hydrogen to the diamond's dangling bonds.

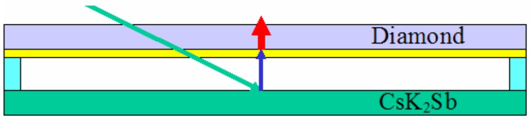

Figure 2. A schematic diagram of an encapsulated diamond amplified photocathode. The diamond is coated with a very thin gold layer on the primary injection side, the one facing the CsK_2Sb photocathode.

Starting with the quantum efficiency of cesium potassium antimonite, which is typically 5 to 10 percent for visible photons, the effective quantum efficiency of the amplified cathode is a few hundred percent. The diamond window protects the superconductor from the cathode materials and the cathode from poisoning by back-streaming contaminants. The emission is prompt and has very low thermal energy. The diamond properties are such that the heat generated by the various processes (mainly the primary energy deposition, RF heating of the gold and the heat generated by the transport of the secondaries through the diamond) is conducted efficiently to the walls with an insignificant temperature gradient. In addition, the mechanical strength of the diamond promises that the capsule may hold atmospheric pressure for transporting the evacuated photocathode.

AMPERE-CLASS ERL SUPERCONDUCTING CAVITY

ERLs need a specially designed cavity for best performance. Until now, cavities used in ERLs have been developed as a non-energy-recovering linac structures. To achieve ampere-class currents it is clear that a dedicated design must be done.

Higher order modes are one of the dominating factors influencing the design of high current cavities. These modes give rise to two limits on the performance and operation of a cavity:

- Multi-pass, multi-bunch instabilities driven by high impedance dipole modes resulting in beam-breakup.
- Power loss into the HOMs which must be removed safely from the cavity and the cryogenic system.

We designed a 5-cell linac cavity optimized for most efficient removal of HOM power. The cavity has been described in detail in various conferences [7,8]. The shape of the cavity is shown in Figure 3.

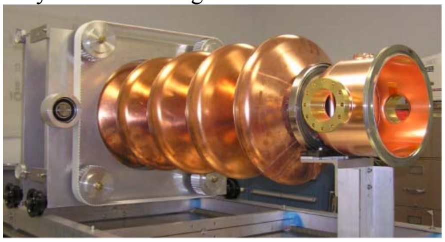

Figure 3. The 5-cell ERL cavity copper model in its tuner. Note the large iris and beam pipe diameters, designed for removal of HOM power to ferrite absorbers.

The main performance measures of the cavity are given in Table 1.

Table 1: Electric properties of the ERL 5-cell cavity

Property	Units	Value
Frequency	MHz	703.75
E_p/E_a	-	2.0
H_p/E_a	mT/(MV/m)	5.8
R/Q	Ω	807
Geometrical factor	Ω	225
Cell-to-cell coupling	%	3
Expected unloaded Q	-	$2x10^{10}$
Dynamic power loss	Watt	22
External Q	-	$2x10^{7}$
Max. amplifier power	kW	50
1^{st} Mechanical resonance	Hz	96
Lorentz detuning	$Hz/(MV/m)^2$	1.5
Loss factor	V/pC	1.2

Ep/a is the peak surface electric field to accelerating field ratio; Hp/Ea is the peak surface magnetic field to accelerating field ratio; R/Q is the shunt impedance normalized to the Q. The number given for the expected

Q is assuming a total surface resistance of 10 nΩ. The dynamic power loss assumes this surface resistance and a field of 20 MV/m (or 20 MV acceleration, given that the length is 1 meter). Non-linear Q droop at this field may make this figure worse, however the Tesla experience shows that at this field the droop may be negligible.

The assembled cryomodule is shown in Figure 4.

The cavity has been extensively simulated using the MAFIA FEA code and the results were reported elsewhere [7,8]. The simulations show that the HOMs are very effectively damped, leading to loaded Q of the HOMs that range from 10^2 to a few times 10^3 in the worst case. No trapped modes were found. Using the calculated values of the Q and R/Q of the HOMs, we used the TDBBU code to estimate the beam breakup (BBU) threshold current for a 4 cavity ERL and found a BBU threshold of about 1.5 (+/-0.2) amperes based on a Gaussian distribution of 3 (+/- 2) MHz of the HOMs.

Using the ABCI code we find that the longitudinal loss factor of the cavity is 1.2 volts per pico-Coulomb (just the bare cavity, not including other beam line elements such as ferrites, valves etc.). This is an excellent value, about a factor of 6 or more lower than the TESLA cavity. We can conclude that we have designed a cavity that has a very high BBU threshold current and which generated significantly less HOM power than previous linac cavities, making it ideal for ampere-class ERL service.

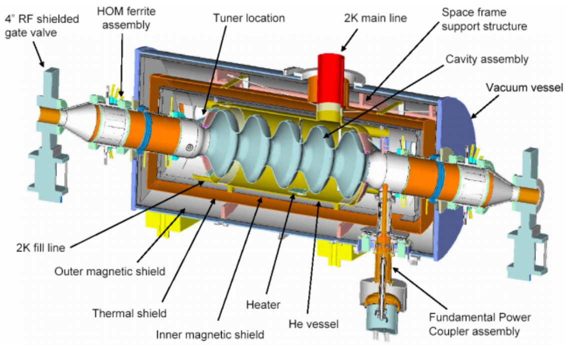

Figure 4. The cryomodule assembly configuration.

AMPERE-CLASS ERL

The only way to prove the performance of the photoinjector and linac cavity as a platform to produce high-brightness, ampere-class CW current is to use them in an energy recovery linac. For this purpose we are moving forward with the construction of such an accelerator. The superconducting gun described in section 2 will be combined with the accelerating structure described in section 3 to form an energy recovery linac. A schematic layout of this ERL is shown in Figure 5.

The return loop of the prototype ERL includes all necessary controls for studying the electron beam dynamics in ERLs: the arcs are achromatic with tunable longitudinal dispersion (R_{56}) and the lattice provides for full control of the phase advances and the optics in both x and y directions.

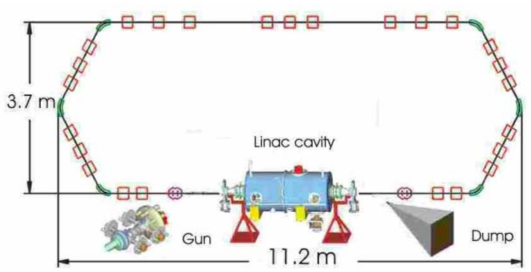

Figure 5. Schematic layout of the ERL-prototype based on 5-cell SRF linac. Details of the gun and dump beam optics and high-energy beam separation are left out.

The circumference of the entire ERL loop will be about 20 meters and will be determined after the final lattice design is frozen. It is important that the time of flight of electron from the exit of the SRF cavity till its entrance must be equal to an exact integer number and a half of RF cycles – this insures that after passing through the re-circulating loop the accelerated beam returns in the decelerating field with exactly same amplitude (but with opposite sign).

Each arc has an achromatic lattice, which comprises of three bending magnets and up to six quadrupoles (the number of quadrupoles is to be finalized later). This structure provides adjustable longitudinal dispersion (so-called R_{56}, where R is the transport matrix of the system) while remaining achromatic. A preliminary simulation shows that β and D functions can be kept under 5 and 0.6 m, respectively.

The straight section will have from six to twelve quadrupoles, which will provide for complete control of the elements of the one turn matrix, including the elements R_{12} and R_{34}, which will determine threshold of the transverse beam break-up instability.

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