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Review of various approaches to address high currents in SRF electron linacs ☆

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Abstract

The combination of high-brightness electron sources and high-current SRF Energy Recovery Linacs (ERL) leads to a new emerging technology: high-power, high-brightness electron beams. This technology enables extremely high average power free-electron lasers, a new generation of extreme brightness light sources, electron coolers of high-energy hadron storage rings, polarized electron–hadron colliders of very high luminosity, compact Thomson scattering X-ray sources, terahertz radiation generators and much more. What is typical for many of these applications is the need for very high current, defined here as over 100 mA average current, and high brightness, which is charge dependent, but needs to be in the emittance range of between submicron up to perhaps 50 μm, usually the lower – the better. Suffice it to say that while there are a number of projects aiming at this level of performance, none is anywhere near it. This work will review the problems associated with the achievement of such performance and the various approaches taken in a number of laboratories around the world to address the issues.

Keywords: SRF; ERL; High current; HOM

1. Introduction

In the past few years we are witnessing the growth of a new class of particle accelerators, that of high-power, high-brightness electron beams. This emerging technology, which is the subject of this paper, is enabled by the combination of high-brightness electron sources and high-current SRF Energy Recovery Linacs (ERL). While the current state-of-the-art is at about 10 mA current [1] (the Jefferson Laboratory FEL upgrade), there is interest in much higher currents, in the range of 0.1–1 A CW, with emittances that are of the order of under one to a few tens microns normalized rms, depending on the application, in particular on the bunch charge.

What are the applications driving this interest? First, as the Jefferson Laboratory example suggests, high power free-electron lasers (FELs) are one candidate. The high-brightness is required for the lasing conditions at near IR or shorter wavelength, and ampere-class currents are desirable for the highest power FELs [2]. The energy required for such applications is not very high, in the range of 100 MeV to less than 1 GeV for UV high-power FELs.

The next application is also for the production of electromagnetic radiation, but for mostly spontaneous emission. This is the ERL based light sources [3,4]. For this application the current may be in the range of 100 mA, less for the extremely high brightness X-ray radiation or higher for flux domination applications. The required energy is between 3 and 10 GeV.

Another application is in an altogether different field, electron ion colliders [5]. In this type of machine a current of electrons or polarized electrons is needed at energy of up to 10 or 20 GeV.

A somewhat specialized application is electron cooling of hadron storage rings, in particular heavy ion beams

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[6]. This application may require magnetized (angular momentum dominated) electron beams at currents of up to 0.2 A but relatively low energies of under 100 MeV. Finally, there is a host of other applications that are have been demonstrated but are still under development: X-ray sources via Thomson scattering of laser on the electron beam and terahertz radiation.

It is appropriate to mention at this point that high currents have been accelerated in SRF structures in a context that is not in the scope of this paper which is dedicated to linacs. These are single-cell cavities in electron storage rings. Examples are the Cornell collider and the KEK-B factory. The currents in these machines are in the high range of what is desired now in linear accelerators.

In this paper we will look at the technology and challenges confronting the developer of high-current, high-brightness electron beams and describe the approach taken by the few laboratories which are actively developing this technology: Brookhaven National Laboratory, Cornell University, Thomas Jefferson National Accelerator Facility and KEK High Energy Accelerator Research Organization. To the best knowledge of the author, while there is significant interest in this application (e.g. Daresbury's 4GLS [7]), no other laboratory is currently engaged in actual design and construction of elements of such accelerators, but apologies if such a project went unacknowledged.

2. Considerations for high-current SRF electron linacs

What is required by way of technology in order to get a high average current with a reasonable gradient? The high average current necessitates CW operation of the machine, thus SRF is required. Furthermore, currents of a fraction of an ampere at hundreds of MeV have hundreds of megawatt beam power, therefore high average current also requires energy recovery to be practical.

Some immediate consequences of this is that no high-power input couplers necessary in the energy recovered structures of the linac (although certainly there are always parts of the accelerator that are not energy recovered, and thus require high power input couplers). Another consequence is that high Q_{ext} operation is desirable to minimize RF power requirements. This brings up issues such as stability against microphonics, but relieves us of the issue of pulsed Lorentz force due to the CW operation. The control issues are also complicated by the very high reactive power of the beam and call for significant efforts in the stability of the machine and advanced feedback circuits. The issues of microphonics, stability of the RF control system and high Q_{ext} are beyond the scope of this review paper, but must be considered in the context of ERL linacs, including high-current ones. Suffice it to say that recent progress has been made in this area [8], where the Cornell new digital cavity control system was tested at the JLab ERL at a current of 5 mA and external Q of 1.2×10^{8}, achieving an amplitude stability of about 10^{-4} and phase stability of 0.02 °.

CW operation also means that the dynamic load on the helium refrigerator will be a dominant cost issue. The optimization of a CW machine in terms of capital and operating costs will push the optimal gradient to a low level; say of the order of 20 MV/m. That is good news considering the current excellent field performance of SRF structures, since we may expect to operate below the onset level of field emission. On the other hand the residual resistivity of the niobium becomes much more important than in typical pulsed, high-gradient linacs. More about this aspect below.

Now we must consider the most challenging item for a high-current ERL: higher order mode (HOM) power generation and beam breakup. The amount of HOM power generated by a cavity in an ERL (including the return current) is determined by the expression

$$P_{\text{HOM}} = 2Iqk_{\text{l}}$$

where I is the beam current, q is the bunch charge and k_{l} is the longitudinal loss factor, which is given approximately by

$$k_{\text{l}} \approx \frac{\Gamma(0.25)Z_0 c}{4\pi^{2.5}}\frac{1}{a}\sqrt{\frac{dN}{\sigma}}$$

where a is the aperture radius, d is the cell length and N is the number of cells per cavity, Z_0 is the impedance of vacuum and c the speed of light.

The amount of HOM power can be extremely high, particularly for high current and high charge operation, as can be seen from the Fig. 1, reproduced from the work of Ram Calaga [9].

This figure shows various ERL cavity HOM power normalized for a loss factor of 1 V/p. Due to this normalization, the location of the markers of various ERLs signifies only the planned bunch charge and current and not the actual power. To get the corresponding HOM power one has to move the point towards higher power or lower power, depending on the loss factor for the cavity in question. The loss factor varies considerably from under 1 V/p up to 10 V/pC, depending on the structure's frequency (the lower the frequency the better), the degree to which the cavity aperture has been maximized (possibly sacrificing some other parameter) and the number of cell (the fewer the better). Note that the beam properties enter in three places: the HOM power is proportional to the average current and the bunch charge, and is proportional to the square root of the pulse length.

As can be seen from Fig. 1, some ERLs (in particular the BNL projects of electron cooling and eRHIC) require care in the generation and handling of HOM power. This is due to the combination of high bunch charge and high average current. For that matter the loss factor of the BNL cavity (excluding the fundamental mode) is about 0.6 V/pC, less than the normalization of the figure.

Another aspect of HOMs is the multi-bunch, multi-pass beam breakup. In this case damping of the higher order modes is essential for getting a high threshold current for the beam break up (BBU). The current generation of