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 transverse emittance range of between sub micron up to perhaps 50 microns, 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.

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 ampere to over 1 ampere CW, with emittances that are of the order of under 1 to a few 10's microns normalized rms, depending n 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 [6]. This application may require magnetized (angular momentum dominated) electron beams at currents of up to 0.2 amperes 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 his 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 un-acknowledged.

*) Work performed under the auspices of the U.S. Department of Energy.

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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 Qext 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 $1.2{\cdot}10^8$, achieving an amplitude stability of about 10^{-4} and phase stability of 0.02 degrees.

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

$$P_{HOM} = 2Iqk_l$$

Where I is the beam current, q is the bunch charge and k_l is the longitudinal loss factor, which is given approximately by

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

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/pC. 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/pC 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 3 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 SRF linac structures is not stable or just marginally stable in ERLs with currents over ~100 to ~200 mA, certainly not for one ampere. The main issue here is damping of the dipole modes, but going to a lower frequency also helps. This subject was recently treated extremely well [10]. The following approximate equation shows the main parameters that affect the BBU threshold:

$$I_{th} \approx \frac{-2c^2}{e(R/Q)_m Q_m \omega_m T_{12} \sin(\omega_m t)}$$

The dependence of the BBU threshold on frequency and the shunt impedance of the HOMs is clear, and the message is clear: Good damping of the HOMs is essential for high threshold currents. As we shall see in the next section, there are a few projects aimed at the development of high current ERL cavities, and all take extra care to have large irises and beam tube apertures, and there are various efforts to develop new approaches for coupling out the HOM power and dump it out of the liquid helium environment. The highest current cavities are also aiming at a lower frequency.

Another aspect of CW linacs is the refrigeration load mentioned above. The surface resistance is given by the sum of the BCS surface resistance and the residual surface resistance. For a magnetically well shielded cavity it is possible to get a residual resistance of one nΩ or less. It is practical to work at temperatures of about 1.8K to 2K. However, temperatures significantly below 1.8K become problematic, requiring overly massive helium pumps and bringing about loss of thermal conductivity of the niobium, which plunges rapidly below about 1.8K.

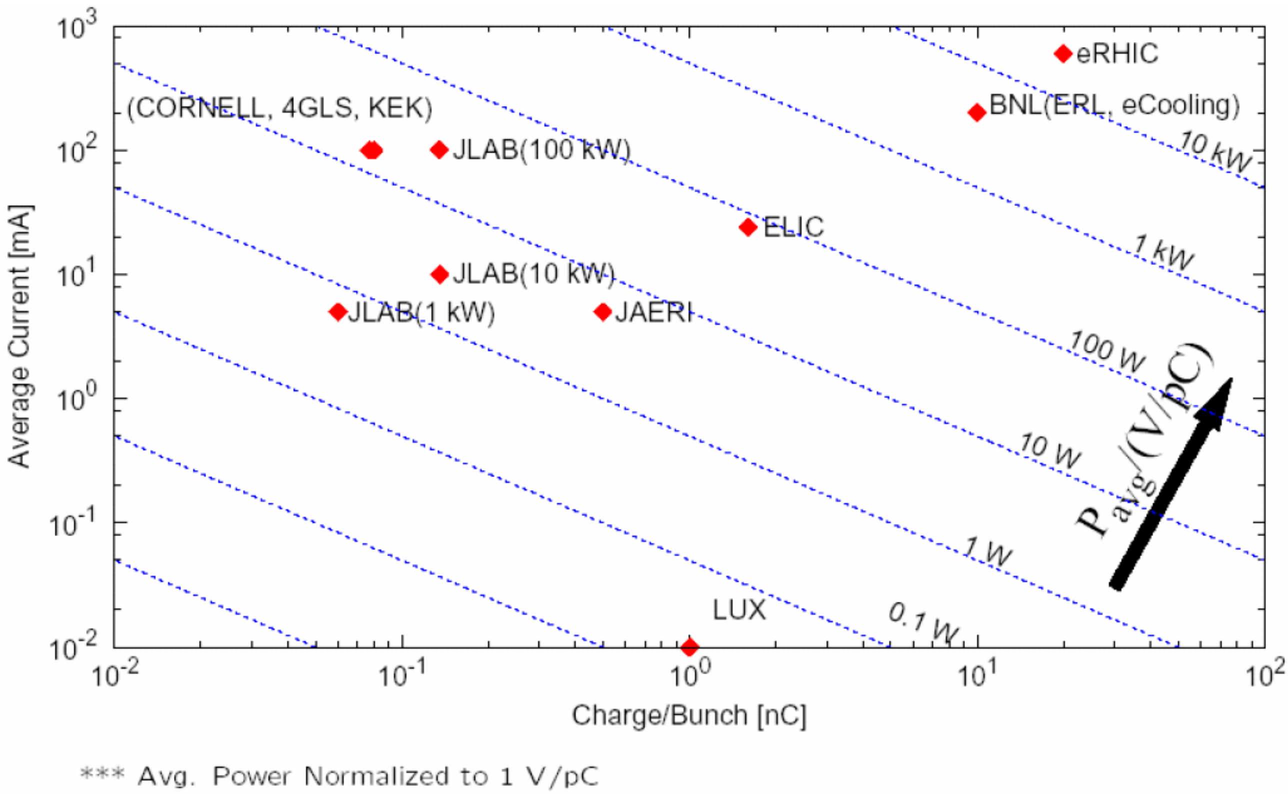

Fig. 1. HOM power as a function of bunch charge and current for a linac cavity having a loss factor of 1 V/pC.

Thus we would like to minimize the BCS surface resistance of the niobium as long as it is above 1 nΩ, using temperatures in the 1.8 to 2K range. From the well known expression for the BCS surface resistance:

$$R_{BCS} = 89.9 \cdot 10^{-6} \frac{1}{T} f(GHz)^2 \exp\left(-\frac{17.76}{T}\right)$$

We find that at 1.8K the BCS surface resistance is slightly above 1 nΩ at 700 MHz, but more than four times that much at 1.3 GHz.. That means that the refrigeration load of the linac is significantly reduced at 700 MHz relative to 1.3 GHz, even after taking account of the reduced R/Q of the fundamental mode, which is proportional to the frequency. Thus, given a residual resistance of 1 nΩ or less, there is a strong motivation to design CW ERLs at a low frequency, well under 1 GHz, to reduce the cryogenic load.

It is very helpful to see the range of ERL main linac parameters in a tabulated form. The following table is borrowed from the outstanding survey work done by Matthias Liepe [11].

Some of the material presented by Liepe is reproduced in Table 1, the main linac parameter space. It is important to note that this table covers various ERLs, both under constructions and planned or proposed, and it covers both lower current ERLs and high current ERLs. Thus the indicated ranges are not necessarily self consistent. For example, one should not expect to find a 10 GeV ERL with 1 ampere beam current and 2 ps bunch length. It should also be noted that the bunch repetition frequency covers a wide range, from a few 10's of MHz to 1.3 GHz.

The entries of two cells in Table 1 have been updated relative to Liepe's original table, to reflect a higher bunch charge of the BNL electron cooler of RHIC and the eRHIC linac-ring version. These values are marked by ($^{\#}$).

Table 1. Main linac parameter space.

Parameter	Minimum value	Maximum value
Linac energy gain	20 MeV	10 GeV #
Average current	10 mA	1 A
Bunch charge	10 pC	20 nC #
Bunch length	2 ps	100 ps
Cavity frequency	700 MHz	1.5 GHz
Cells per cavity	5	9
Accelerating gradient	12 MV/m	20 MV/m
Unloaded Q_0	$8\cdot10^9$	$2\cdot10^{10}$
Loaded Q	$2\cdot10^7$	$1\cdot10^8$?
HOM power per cavity	some 10 W	>1 kW
HOM spectrum, 95% upper freq.	1 GHz	60 GHz
Amplitude/phase stability	10^{-3} / 0.1 deg	10^{-4} / 0.02 deg
Average / peak RF power per cavity	0.5 kW/1 kW	25 kW / 50 kW

#) These values in M. Liepe's original table were changed. The original bunch charge was 1.5 nC, and the maximum linac energy was 5 GeV. The changes were made to include parameters planned for RHIC electron cooling ERL and eRHIC.

NEW HIGH-CURRENT SRF ERL CAVITIES

There are four research efforts currently under way to develop high current ERL cavities.

- Brookhaven National Laboratory (BNL), Upton NY USA:
  - Construction of 5-cell, 703.75 MHz cavity.
- Cornell University, Ithaca NY USA:
  - Construction of a 2-cell, 1300 MHz injector cavities.
  - Design of cavities and cold HOM damping of 1.3 GHz, 7-cell cavities
- Jefferson National Accelerator Facility (JLab), Newport News, VA USA:
  - Design of a 5-cell, 748 MHz cavity,
  - SRF booster under construction.
- High Energy Accelerator Research Organization (KEK) Tsukuba, Japan
  - Development of radial damping scheme for TESLA type ERL cavity.

The electron sources and test facilities will be discussed in the next section. In this section we will look at the linac structures.

The BNL 5-cell ampere-class cavity [12, 13] is being constructed in collaboration with AES and JLab for the purpose of electron cooling of RHIC and for the eRHIC electron-ion collider. The cavity's 3-D drawing is shown in Figure 2. The BNL design aims to address the most extreme HOM conditions (as seen in Figure 1 above).

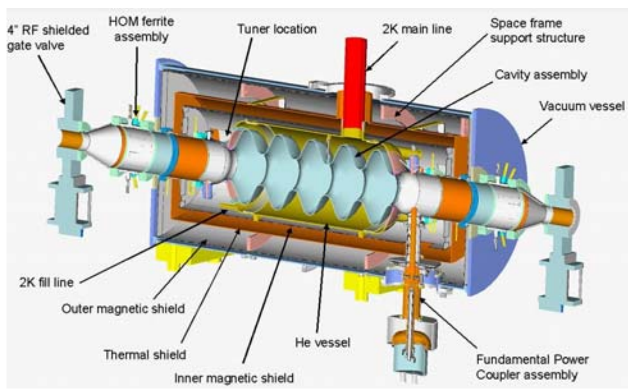

Fig. 2. The BNL ampere-class 703.75 MHz 5-cell cavity in its cryostat.

The main features of this design are a low frequency of 703.75 MHz, very large cavity irises (17 cm diameter) and extremely large beam pipe, 24 cm in diameter. The beam pipe is large enough to propagate all the HOMs to the ferrite HOM load, which is at room temperature on either side of the cavity. As a result of these design features the cavity is a "single mode" cavity, all HOMs are strongly coupled to the HOM damper, and the loss factor is very low. The cell shape also enhances mechanical stability.

This cavity has been first constructed as copper prototypes (two of them) and HOM measurements were made and compared with MAFIA simulation then the niobium cavity was constructed. Some of the notable features of this cavity are an extremely low longitudinal loss factor, about 0.6 V/pC (excluding the fundamental and for a bunch length of 1 cm), and a very high mechanical resonance frequency of about 100 Hz. The peak surface electric field to accelerating field ratio is 1.97 and the magnetic field ratio is 5.78 mT/MV/m. The Lorentz detuning coefficient is 1.2 Hz/(MV/m)^2. The welded niobium cavity on the tuning device is shown in Fig. 3.

The measured R/Q of the monopole modes (copper cavity equipped with a HOM damper) are shown in Fig. 4 and those of the dipole modes in Fig. 5, compared with the MAFIA simulations in both cases. In these figures as well as in the other impedance figures to follow, the impedance is given in the circuit definition.

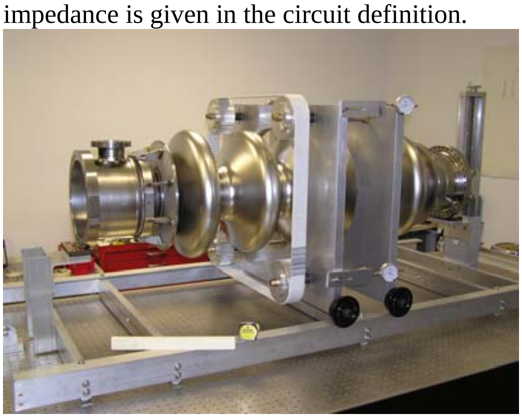

Fig. 3. The BNL niobium cavity being tuned.

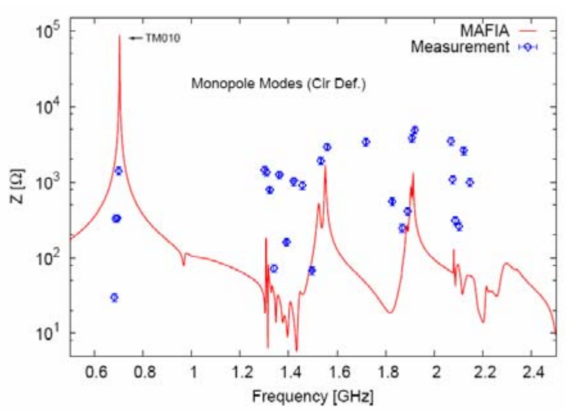

Fig. 4. The monopole modes of the BNL cavity. Blue points - measured values, red line - MAFIA simulation.

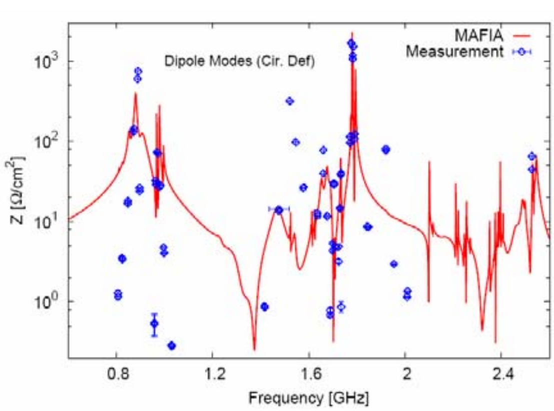

Fig. 5. The dipole modes of the BNL cavity. Blue points - measured values, red line - MAFIA simulation.

The Cornell University development is aimed at the development of a 5 GeV ERL light source [4]. This application is planned for a current of up to 100 mA, thus at the low end of the current range under discussion in this paper. The cavity being designed for this ERL [14] is a 7-cell, 1.3 GHz cavity as shown in Fig. 6.

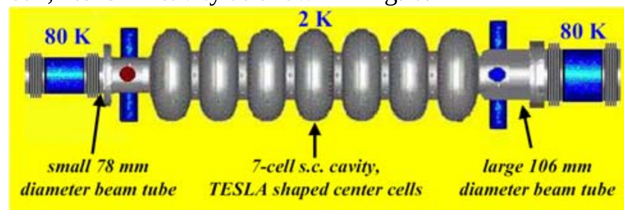

Fig. 6. The Cornell 1.3 GHz, 7-cell cavity.

The cell shape in this cavity follows the TESLA cavity design. The cavity has an asymmetry with beam pipes that are 10.6 and 7.8 cm in diameter. The purpose of this arrangement is to shift "trapped modes" from the cavity center towards the cavity ends, thus "detrap" some modes. Another use of this shape is to propagate all TM monopole modes and most dipole modes out of the larger diameter side while maintain a high shunt impedance of the fundamental mode by keeping the other side at a smaller diameter. Damping is achieved by the use of a combination of TESLA style coaxial HOM dampers (8 per cavity) and cryogenic broadband ferrite rings at 80K. The number of cells was chosen to be 7 as a compromise between cost effectiveness (which increases with the length of the cavity, thus with the number of cells) and the R/Q of modes, that tend to get trapped (or increase in R/Q) with a large number of cells.

The impedance of the monopole and dipole modes of this cavity are shown in Fig. 7 and Fig. 8, respectively.

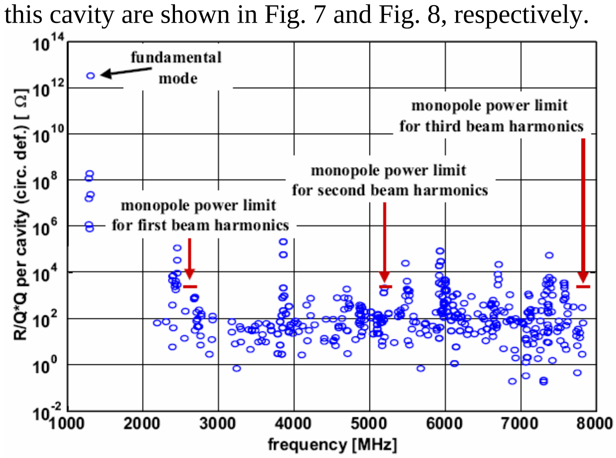

Fig. 7. The monopole modes of the Cornell cavity.

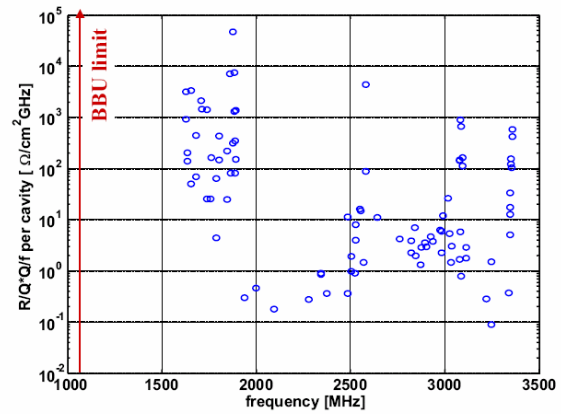

Fig.8. The dipole modes impedance multiplied by the mode frequency in GHz for the Cornell cavity.

Thomas Jefferson National Accelerator Facility is designing a cavity aimed at a very high-power FEL. This cavity, like the BNL cavity, is design for ampere-class currents. As a result, there are similarities but also differences in the design. The JLab requirements include real-estate gradient of at least 10 MV/m and very strong HOM damping to push BBU thresholds up by two or more orders of magnitude compared to existing designs. Cavity considerations include a large iris for beam halo, low-RF losses, HOM frequencies and Q's, low peak surface fields, field flatness and microphonics. Thus the design adopted a low frequency of 750 MHz, 5-cell cavity with a beam aperture of 76.2mm.

The cell shape is optimized in terms of peak surface field ratio, and is shown in Fig. 9.

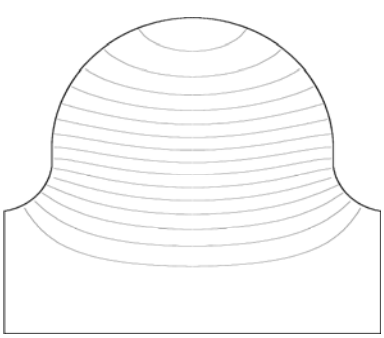

Fig. 9. The cell shape of the JLab 750 MHz 5-cell cavity.

The R/Q for this shape at 750 MHz is 103Ω per cell and the peak surface electric field to accelerating field ratio is excellent at 1.86. Thus, this design is more aggressive in terms of SRF cavity performance (relative to the similar BNL cavity) at a cost of smaller beam pipe apertures, leading to a slightly higher HOM impedances. The estimated HOM power per cavity is 20 kW. The HOM damping is based on waveguide coupling, placed very close to the cavity (to overcome the fact that some HOMs do not propagate in the beam pipe). The designed cavity shape with the HOM couplers is shown in Fig. 10.

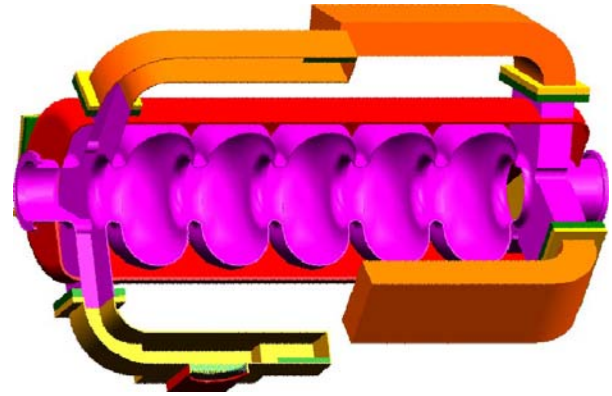

Fig. 10. The JLab ampere-class 750 MHz 5-cell cavity.

Note the 3-fold symmetric layout of the 6 HOM waveguide couplers. This arrangements practically eliminates RF kicks from the couplers.

The calculated monopole and dipole mode impedance of this cavity are shown in Fig. 11 and Fig. 12, respectively.

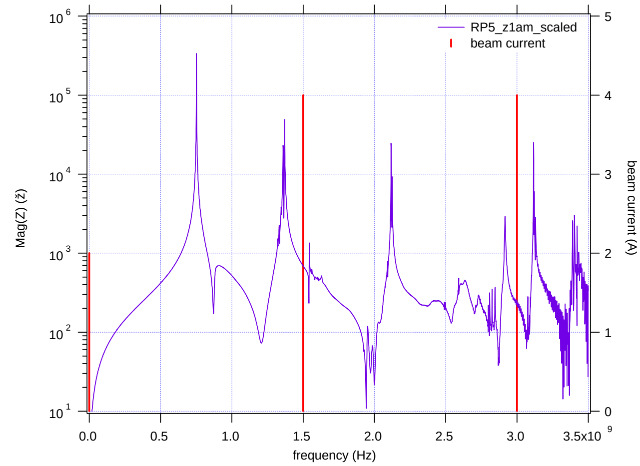

Fig. 11. The monopole modes impedance for the JLab 750 MHz, 5-cell cavity.

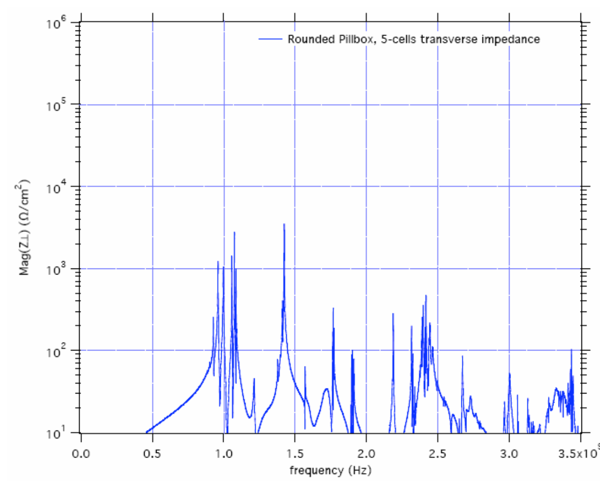

Fig. 12. The dipole modes impedance for the JLab 750 MHz, 5-cell cavity.

The last cavity to be discussed is for the KEK ERL program. The objective of KEK is to move towards a 5 GeV 100 mA ERL based light source [15]. A research program has been initiated on this subject. There is not much one need to say about the cavity, since the KEK project is planning to use the well known TESLA 9-cell, 1.3 GHz cavity. Recognizing the fact that the TESLA cavity is not optimized for ERL service, the research is targeted at improving the HOM damping of the TESLA cavity.

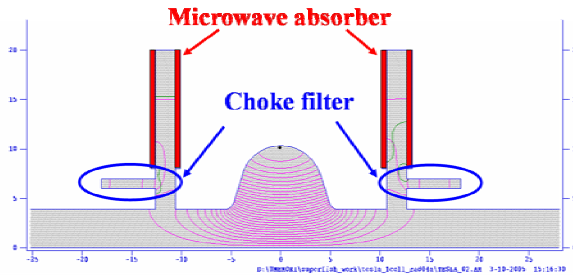

Fig. 13. A radial transmission line HOM damper applied to a single cell cavity, with a choke joint to isolate the fundamental mode.

The idea for the KEK HOM damper is very interesting. It will use a radial transmission line [16], as shown in Fig. 13 schematically applied to a single cell. The radial damper has a few advantages. It consumes very little space along the beam line and it can be mounted very close to the cavity. The last advantage is important, since the TESLA cavity beam pipe does not propagate the HOMs, thus the coupler must be placed very close to the cavity for effective damping. It also has some disadvantages, in particular the fact that it propagates all modes, including the fundamental mode. Thus the design must include a choke joint to block absorption of the fundamental mode by the damper. Fig. 14 shows a radial damper assembled onto a copper model of the 9-cell cavity for microwave measurements.

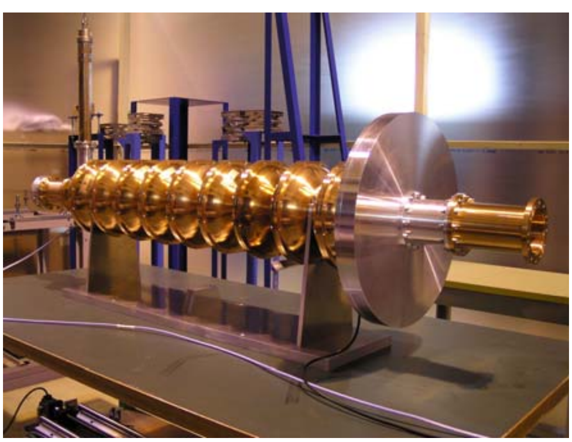

Fig.14. The KEK radial HOM damper assembled on a 9-cell 1.3 GHz cavity.

The effectiveness of this HOM damping technique depends on how close to the cavity one can place the HOM damper. This is clearly seen in Fig. 15.

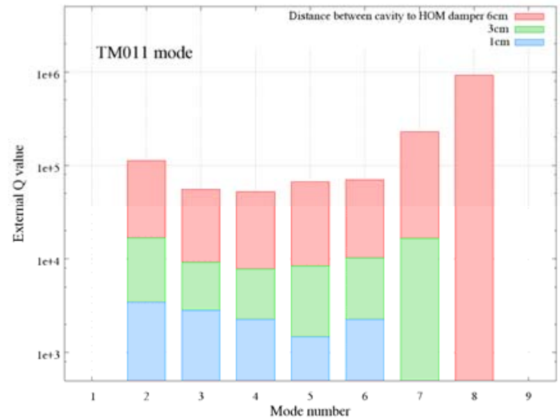

Fig. 15. Loaded Q of the TM011 mode pass-band.

In Fig. 15, The measured external Q value is plotted against mode number for 3 positions of the damper relative to the cavity, 1, 3 and 6 cm. Two of the modes were too weak to measure. Clearly the mode Q changes by as much as two orders on magnitude as the position of the radial line is moved by 5 cm.

SOURCES AND TEST FACILITIES

The discussion of addressing issues of high current in electron linacs would not be complete if one did not address the generation of the high-current, high-brightness beams and plans for the construction of prototype machines in this class. All four institutions working in this area plan to use electron guns based on a laser photocathode. One (BNL) plans to use a superconducting RF gun, the others plan to use a DC gun, followed by superconducting booster (pre-accelerator) cavities. The main difference between the two approaches is the charge to be extracted per bunch. For the extraction of large charge (over 1 nC) at a good emittance (below 2 microns normalized rms) the higher field on the cathode possible with a superconducting gun is important.

BNL has a 20 MV, 0.5 ampere demonstration ERL under construction, including the SRF gun and linac [17]. Cornell is constructing the injector system (including DC gun and SRF booster cavities) as part of a plan to construct a 100 MeV, 100 mA test facility [18]. JLab has a similar plans and also has the gun and booster cavities under advanced stages of construction [1]. KEK has plans for a 100 mA, 200 MeV test facility [19].

The technology of the high-current, high-brightness electron injector is critical to the success of the high-current ERL, and the challenges there are as great or even greater than in building the high-current ERL. This subject has been recently reviewed by Alan Todd [20] and the

SUMMARY

We discussed the issues and various approaches to address high beam currents in electron linacs, where high currents were defined as 0.1 ampere to over 1 ampere. We concluded that the only way to generate this much current at multi MeV to GeV energy levels is through the use of superconducting energy recovery linacs. We identified the following issues:

- Generating the electron beam: Gun and booster.
- Reducing the amount of HOM power generated by the SRF structure.
- Extracting the HOM power out of the cavity.
- Overcoming multi-pass beam breakup.
- Mechanical vibration stability at high Qext, low steady state Lorentz detuning, low microphonics.
- Phase / amplitude control at high Qext, high reactive beam power.
- Lowering surface resistivity and avoiding field emission.
- Very high gradient is NOT an issue (limited by refrigeration), 20 MV/m but low loss is highly desirable.

We observed the various projects engaged in the development of high current SRF ERLs at Brookhaven National Laboratory, Cornell University, Jefferson Laboratory and KEK in Tsukuba, Japan. All of these laboratories approach the challenge of removal of a large quantity of HOM power from the cavity by adopting new HOM dampers located in the beam line, however each laboratory approaches this task in a different way. All of these institutions plan an injector to achieve the high current, and all plan to demonstrate the new systems by building a test facility.

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