BEAM BREAK-UP ESTIMATES FOR THE ERL AT BNL*

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Abstract

A prototype Ampere-class superconducting energy recovery linac (ERL) is under advanced construction at BNL. The ERL facility is comprised of a five-cell SC Linac plus a half-cell SC photo-injector RF electron gun, both operating at 703.75 MHz. The facility is designed for either a high-current mode of operation up to 0.5 A at 703.75 MHz or a high-bunch-charge mode of 5 nC at 10 MHz bunch frequency. The R&D facility serves a test bed for an envisioned electron-hadron collider, eRHIC. The high-current, high-charge operating parameters make effective higher-order-mode (HOM) damping mandatory, and requires the determination of HOM tolerances for a cavity upgrade. The niobium cavity has been tested at superconducting temperatures and has provided measured quality factors (Q) for a large number of modes. These numbers were used for the estimate of the beam breakup instability (BBU). The facility will be assembled with a highly flexible lattice covering a vast operational parameter space for verification of the estimates and to serve as a test bed for the concepts directed at future projects.

HOW TO DETERMINE HOM DAMPING

Beam breakup (BBU) is a critical issue for high-current Energy Recovery Linacs (ERL), and it could get particularly difficult for multi-pass ERLs [1]. The eRHIC collider [2,3] is aimed at a current of 50 mA, energy up to 20 GeV and 4 passes at full current. The Research and Development (R&D) towards this machine includes benchmarking of cavities and Higher Order Mode (HOM) damping in a R&D linac and the development of new highly damped cavities and HOM dampers.

The R&D ERL is based on a "single mode" 5-cell cavity at 703.75 MHz. This cavity [4] couples all the HOMs through the beam pipes to ferrite lined HOM absorbers, which are located at room temperature. The design has a cavity-transition section that allows lossless propagation of all HOMs while attenuating the fundamental mode. Sufficient length of a beam pipe is required to attenuate the fundamental to an acceptable power load in the HOM loads and the non-superconducting section. Of course the cavity design is important to provide good coupling of HOMs to the beam pipe and avoid trapped modes. This has proven to be a very successful approach for the R&D ERL. This ERL [5] is designed for a high average current and high brightness at 0.5 A at a normalized rms emittance of less than 5 mm·mrad, a high charge per bunch ranging from 0.7 to 5 nC, a large energy acceptance due to its low dispersion and large aperture. Most important it is designed with an adjustable transverse phase advance for beam break up instability study, adjustable longitudinal dispersion and the ability to operate at two-pass acceleration thanks to a variable path length, as shown in Figure 1.

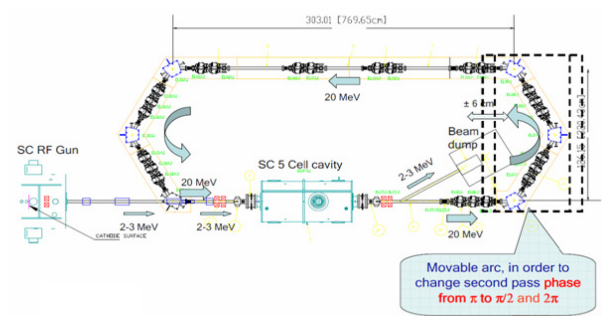

Figure 1: Layout of the R&D ERL, showing the movable arc (right).

The lattice of the ERL loop controls the parameters of a symplectic transport matrix, which affect the stability and operation conditions of the ERL. The lattice of the loop is intentionally chosen to be very flexible for the R&D ERL to be a test-bed of new Ampere-range of beam currents in ERL technology. The adjustable part of the lattice has two arcs and a straight section. Each arc is an achromatic with adjustable longitudinal dispersion. Quadrupoles in the dispersion-free straight section provide for matching of the β-function and for choosing the desirable phase advances independently in horizontal and vertical planes.

MAXIMUM ALLOWABLE Q VALUES

For the calculation of the BBU threshold the computer code GBBU [6] was used. The code tracks bunches through the accelerator and computes their interaction with the dipole modes of the cavities. If the transverse displacement of a bunch at the exit of the accelerator exceeds a limit, then the configuration is considered instable.

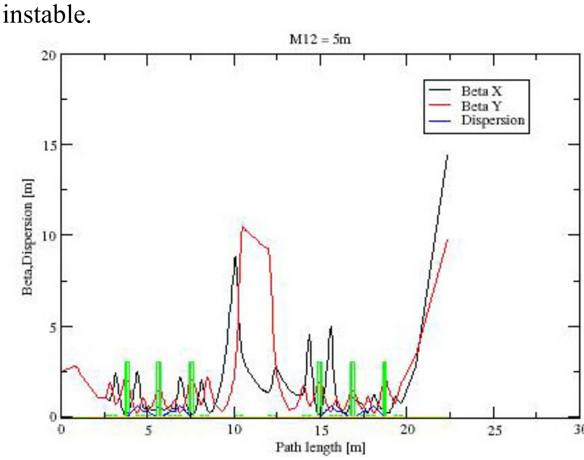

Figure 2: R&D ERL optics with M12=5m

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The optics of the ERL is flexible and allows changing the betatron phase advance by changing the gradient of the quadrupoles in the straight section. In order to provide a test of the BBU simulations, we can try to cause instability in the R&D ERL. We will use two sets of optics: one where the M_{12} element of the beam transport between the cavities is zero. For this optics there is no beam breakup expected even at the highest currents.

The other optics, shown in Fig. 2, has a M_{12} element of 5 meters, which is as large as achievable without significantly increasing the beam size in the cavity. Besides the optics of the linac the program needs as input the beam current and the Q and R/Q for each mode. Using bracketing the maximum stable beam current can be found. In our calculations we tried to answer the opposite question: With a given beam current and R/Q, what is the maximum stable Q? This will tell us how efficient do the HOM dampers have to be to allow the beam current without break up. This is done for each mode separately. In all calculations we found that the break up threshold for all modes combined is close to the breakup threshold for the worst single mode.

Figure 3 shows the result of investigating 146 dipole modes in the range from 750 to 3100 MHz with a beam current of 0.5 A in the R&D ERL. Since we lack the tools to measure the R/Q the number is obtained by simulation with the Microwave Studio (MWS) program suite. No HOM damper was included in this calculation. Only modes with a maximum stable Q of less than 10^7 are displayed as black stars.

We compare those Q with values actually measured in the R&D ERL at 2 degree K including the ferrite dampers (red squares). Since the first set of data originates from an ideal model of the cavity and the second from a real cavity with manufacturing tolerances and dampers, we do not expect a perfect agreement of the mode structure. However, we can use these data to predict the possibility of beam breakup.

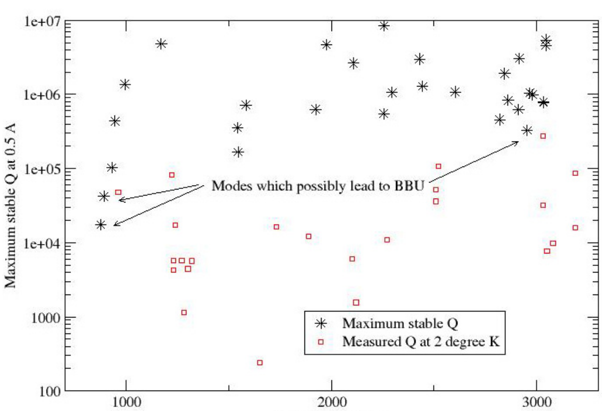

Figure 3: The maximum stable Q of dipole HOMs for the R&D ERL, calculated from MWS and Q values measured in the R&D ERL at 2 degrees K with ferrite dampers.

The concept of computing the beam breakup threshold for each mode separately can be used to grade the optics of ERLs with respect to their resistance to beam breakup. As an example a scan for the proposed MeRHIC accelerator is shown Figure 4. This machine would have 3+3 passes of the beam through 72 cavities. The frequency of a single mode with R/Q=100Ω, which is present in all cavities, is scanned in steps of 1 MHz. One can easily read from the figure that the cavities must be equipped with dampers that limit the Q to $2 \cdot 10^3$ and that, as expected, an optics that minimizes the betatron function in the cavities and allows larger betas in the quadrupoles performs better than one that minimizes the beta function everywhere.

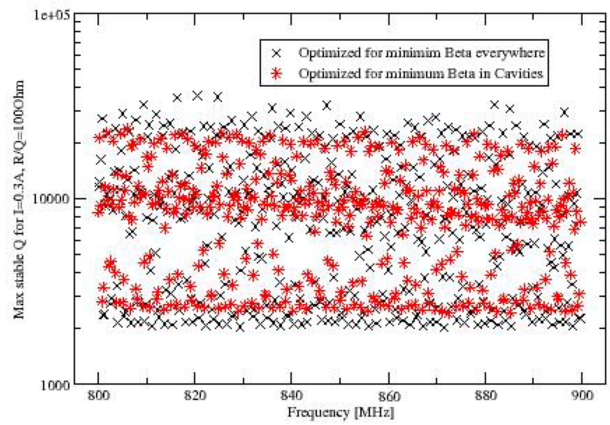

Figure 4: Scan of the maximum stable Q in MeRHIC a beam current of 0.3 Ampere and a single dipole HOM with R/Q=100 Ω. These numbers are arbitrarily selected to demonstrate the application of the beam breakup code.

DESIGN OF NEW ERL CAVITY

We learned quite a lot from the design of the ERL cavity. Symmetric, lossy ferrites are robust and simple in high current linacs, however, the use of HOM loops should be sufficient for damping requirements for eRHIC (see next section). The ultra-clean environment and compact layout w/o cold-to-warm transitions beg for HOM loops. The new cavity design improves the ratio of peak surface magnetic field to accelerating field, reduces the power dissipation for a given field as well as improves the mechanical design of the cavity. We examine the replacement of the ferrite dampers with compact antenna style probes close to the cavity, yet use the principle that the beam pipe acts as a filter, attenuating the fundamental mode. However, given the aim to achieve a compact design, we plan to share the required attenuation of the fundamental between the beam pipe and band-stop filters located on the HOM probes.

The procedure that we adopted is as follows:

- Determine the maximum fundamental power allowed to propagate in each HOM damper. This has to do with the power carrying capacity and cryogenic loss of coax lines leading from room temperature to the probes.
- Design a well-damped cavity with small fundamental load into the beam pipe.
- Design band-stop filters integral to HOM probes and determine the ratio of damping of the

fundamental to that of the HOMs and the external Q of the HOMs.
- Calculate the HOM modes of the cavity, their frequencies and R/Q value.
- Use the calculated HOM modes in a Beam breakup program to establish the maximum Q allowed (for a particular ERL design) at each mode.
- Compare the Q achievable with the designed probes and their HOM band-stop filters to the allowable Qs.

Additional task related to this program are the use of the R&D ERL to benchmark the various codes we use, microwave measurements on prototype cavities and measurements of prototype HOM probes and their filters. This program is making progress but is not complete yet. However, we can already present here some of the results we got.

The work described above serves as guidance to the design of new cavities, which are suitable for high-current ERL (or straight linac) service. One such 704 MHz, 5-cell cavity is being developed at BNL, based on the experience gained from the R&D ERL cavity. Fig. 5 shows this cavity in cross section. The asymmetry in the beam pipe is to allow space for the Fundamental Mode Coupler (FPC). The reduced diameter is meant to reduce cavity-to-cavity coupling.

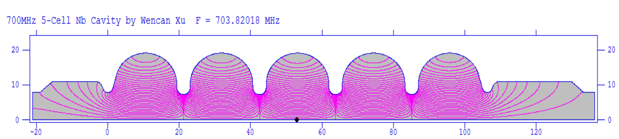

Figure 5: Cross section of the new high-current cavity, showing field lines derived from simulations.

This cavity's shape is optimized to improve the $G*R/Q$, which determines the cryogenic dissipation for a given surface resistance, minimize the normalized peak surface magnetic field, allow excellent HOM damping and improved mechanical design to tenability. The value of $G*R/Q$~28786 is improved by nearly 60%, and the peak surface magnetic field, at 0.00426 T/MV/m is reduced by about 36%.

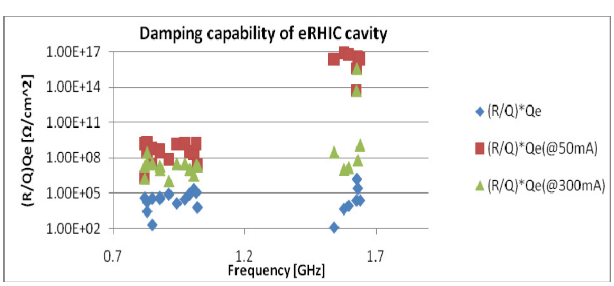

Figure 6: Comparison of the $R/Q*Qe$ obtained by the R/Q corresponding to the eRHIC cavity design (blue diamonds) with the requirement for 50 mA (red squares) and 300 mA (green triangles) in 3 passes through the ERL.

Most importantly, the BBU threshold, as can be seen in Fig. 6, exceeds the requirements of the MeRHIC 4 GeV 3 pass ERL even at 300 mA. We find that we can use electric field probes to couple to the HOMs and damp the HOM power through coaxial transmission lines at room temperature. The probes deliver the external Q required by the HOM calculations described above. However, the isolation of the fundamental mode provided by the beam tube is not quite enough in this compact design (about 1.6 m long cavity center to cavity center). This would lead to excessive fundamental power loading in the coax lines. The solution is to use band-pass filters in the probes. We are developing a compact and robust design, however there is not enough space in this document to include this work.

SUMMARY

We are constructing a 0.5 ampere average current ERL at BNL. The ERL uses a 703.75 MHz 5-cell SRF accelerating cavity. We described results of HOM measurements and simulations on this cavity and plans to use the ERL for code benchmarking. We further describe our BBU simulations on a large multi-pass ERL and how these simulations are used to specify the necessary damping of HOMs. Finally we describe the design of a new cavity, with improved SRF parameters and excellent BBU threshold using electric probe HOM damping.

REFERENCES

[1] Georg H. Hoffstaetter and Ivan V. Bazarov Beam-breakup instability theory for energy recovery linacs, Phys. Rev. ST Accel. Beams **7**, 054401 (2004)

[2] Ben-Zvi, I. Kewisch, J. Murphy and S. Peggs, Accelerator Physics Issues in eRHIC, Nuclear Instruments and Methods in Physics Research **A463**, 94 (2001),

[3] eRHIC Conceptual Design, V. Ptitsyn, et al, Proceedings of Hadron Beam 2008, Nashville, Tennessee, http://cern.ch/AccelConf/HB2008/papers/wge01.pdf

[4] R. Calaga, et al, Ampere class linacs: status report on the BNL cryomodules, proceedings Energy Recovery Linac Workshop, Newport News, Va, USA, March 19 - 23, 2005. Nuclear Instruments and Methods in Physics Research **A557** (2006) 243

[5] Status of High Current R&D Energy Recovery Linac at Brookhaven National Laboratory, D. Kayran, et al, Proceedings of LINAC08, Victoria, BC, Canada, http://cern.ch/AccelConf/LINAC08/papers/tup028.pdf

[6] E. Pozdeyev, Phys. Rev. ST Accel. Beams 8, 054401