CONCEPTUAL LAYOUT OF THE CAVITY STRING OF THE CORNELL ERL MAIN LINAC CRYOMODULE*

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Abstract

Cornell University, in collaboration with Jefferson Laboratory, has proposed the construction of a prototype energy-recovery linac (ERL) to study the energy recovery concept with high current, low emittance beams [1, 2]. In the main linac of this machine two beams, with a beam current of up to 100 mA each, will excite significant higher-order-mode (HOM) power in the superconducting RF cavities. Cost efficiency requires the use of multicell cavities, which is challenging along with the storage-ring like beam current. In this paper we present a promising layout of the cavity string in the main linac module and discuss the HOM damping concept.

THE CORNELL ERL

Cornell University is exploring the potential of a Synchrotron Radiation User Facility based on a 5 GeV, low emittance, Energy Recovery Linac (ERL) with up to 100 mA beam current. To study and resolve the accelerator challenges of such a machine, Cornell University, in collaboration with Jefferson Laboratory, has proposed the construction of a 100 MeV, 100 mA cw ERL prototype. One of the main components of the ERL light source is the superconducting main linac with an end-energy of 5 GeV. Two 100 mA beams will pass through this linac: While the electron bunches of the first beam are accelerated, the bunches of the second beam are decelerated to recover the energy from the beam. The resulting beam has a bunch repetition rate of 2.6 GHz with a bunch charge of 77 pC and a bunch length of about 2 ps (600 μm). The beam harmonics have significant amplitudes even above a frequency of 50 GHz and could excite higher-order-modes excessively if the modes are not strongly damped. Using multi-cell cavities in the ERL main linac is a must for cost efficiency, and so is the operation at high cw fields of about 20 MV/m.

MAIN LINAC CAVITY DESIGN

The main linac of the Cornell ERL will accelerate a beam with up to 100 mA and 2 ps bunch length to an energy of 5 GeV. This combination of beam parameters is far beyond the parameter space of any s.c. cavity installation presently in operation. Storage ring cavities accelerate beams with high average currents well above 100 mA. However, the bunch length in storage rings is significantly longer and only low frequency higher-order-modes can be excited in the cavities by the beam. On the other hand, s.c. linacs like the CEBAF linac do accelerate beams with short bunches, however only with a moderate beam current.

In the following we will discuss the design goals for the Cornell ERL main linac cavities. We will present a cavity layout designed to match these goals. This layout is a hybrid of present storage ring cavities and linac cavities.

Design Goals

The design of the Cornell ERL main linac cavity is driven by a list of requirements, some of which are essential, others are desirable. A desirable goal is to minimize both construction and operational cost. A cavity field of about 20 MV/m and minimized cryogenic losses at this field are therefore wanted. An essential design goal is to reduce emittance growth in the main linac. For this small or vanishing transverse kick-fields are required. Further the main linac has to accelerate / decelerate two 100 mA beams without causing beam instability. Beam-break-up (BBU) can be a result of beam excitation of dipole or quadrupole higher-order-modes, since these modes have transverse fields. Simulations have been done, resulting in the following requirements for beam stability above 100 mA [3]: Dipole modes have to be damped to (circuit definition for R/Q)

$$\left(\frac{R}{Q}\right)\frac{Q}{f} < 1.4\cdot 10^5 \quad \frac{\Omega}{\mathrm{cm^2 GHz}} \quad , \tag{1}$$

where R/Q is the ratio of shunt impedance and quality factor of a dipole mode, f its frequency and Q its quality factor. Is a similar way, for quadrupole modes

$$\left(\frac{R}{Q}\right)\frac{Q}{f} < 4\cdot 10^6 \quad \frac{\Omega}{\mathrm{cm^4 GHz}} \tag{2}$$

is required. For the monopole modes the required damping is determined by the possibility of resonant HOM excitation. The cavity to cavity frequency variation of a higher-order-mode is in the MHz regime. Therefore the potential for resonant excitation exists for all modes with average frequencies within some MHz to a beam harmonics. In the Cornell ERL with its two beams, the beam harmonics are multiple of 2.6 GHz. The power transferred by a beam into a monopole mode in resonant excitation is given by (circuit definition for R/Q)

$$P = 2\left(\frac{R}{Q}\right)QI_b^2 \quad . \tag{3}$$

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For a total beam current of $I_b = 200$ mA and assuming an upper power limit of 200 W per mode and cavity, we result in the requirement

$$\left(\frac{R}{Q}\right) Q < 2500 \ \ \Omega \tag{4}$$

for the modes close to the $N \cdot 1.3$ GHz beam harmonics.
In *average*, the power transferred from the beam to the monopoles of a cavity is given by the single bunch loss times the bunch repetition rate f_b

$$P_{\|} = k_{\|} Q_b^2 f_b = k_{\|} Q_b I_b \ \ , \tag{5}$$

where $k_{\|}$ is the longitudinal loss factor of the cavity and Q_b is the bunch charge. Note that this *average* HOM monopole power is independent of the strength of the HOM damping. For a multicell structure, more than 100 W per cavity have to be intercepted at a temperature with good cryogenic efficiency, e.g. 80 K.

Frequency

Scaling the Nb surface resistance according to BCS theory and assuming a moderate residual resistance of 10 n Ω, the AC power to intercept the dynamic cavity head load for a 5 GeV, 100 mA linac has been calculated as function of the cavity eigenfrequency, see Figure 1. At low frequencies the large size of the cavities increases the power consumption, whereas at high frequencies the growth in BCS resistance causes increased losses. In addition the likelihood of surface defects and field emission increases with surface area. Because of this presently only cavities with a frequency above 1 GHz reach fields higher than 15 MV/m at a reasonable Q_0.
The longitudinal wakefield decreases with decreasing cavity frequency f_c, $k_{\|} \propto f_c^2$. However, this benefit is partly compensated by the fact, that the bunch charge has to increase if f_c gets smaller, assuming that the beam current is constant and that every bucket is filled. Figure 1 shows the power required to intercept the monopole HOM power for 100 mA beam current and its resulting linear increase with f_c. For our machine parameters the minimum of the sum of the dynamic cavity load and the HOM load is at a cavity fundamental frequency of about 1.1 GHz.
This optimum gets shifted to higher frequencies by two reasons: The cost of a linac section increases with decreasing f_c, since the cavities and the cryostats are getting larger. Secondly, as mentioned before, the bunch charge has to increase if f_c decreases. This will result in a increased beam emittance in the ERL injector, where space charge is dominating the emittance. A low emittance is of great importance for an ERL light source. We concluded from this that 1.3 GHz is a good choice for out machine parameters, where also the well established TESLA technology is available.

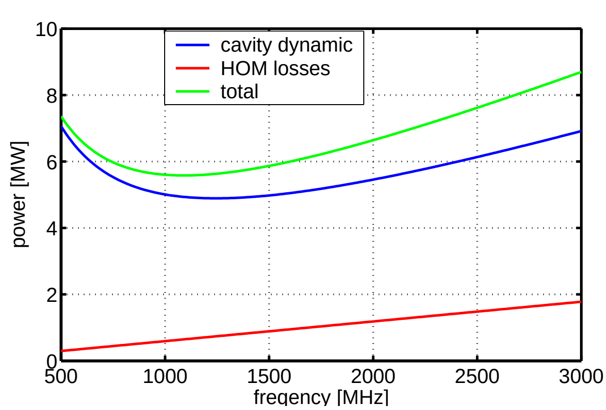

Figure 1: Required AC power as function of cavity frequency for a 5 GeV ERL main linac to intercept the dynamic head load from fundamental mode (20 MV/m) at 2 K, and to intercept the absorbed HOM power (100 mA beam current, every bucket filled) at 80 K. Also shown is the sum of both.

Cell Shape

The shape of the cavity cells is a tradeoff between the goal to reduce the loss factor and the wish to minimize cryogenic losses at a given accelerating gradient. The longitudinal loss factor scales as $k_{\|} \propto r_{ir}^{-2}$, where r_{ir} is the iris radius of the cell. Thus a large iris opening is preferable. In addition, the peak electric surface field decreases with increasing iris diameter. Since the ERL main linac cavities will be operated at 15 to 20 MV/m and low dark current is a critical issue for an ERL, low electric peak fields are desirable. However, the power dissipated in the walls of a cell is given by[1]

$$P_{dis} = \frac{V_{acc}^2}{2\frac{R}{Q}G} R_s \tag{6}$$

and the factor $(R/Q) \cdot G$ gets smaller with increasing iris diameter; see for example [4]. Therefore, a small iris diameter is preferable to minimize cryogenic losses and to reduce operating cost.
The TESLA cavity cell shape [5] appears to us as a good compromise and has the advantage of a well proven high gradient performance. In a later state of optimization we might consider small shape changes to further increase the $(R/Q) \cdot G$ factor.

Number of Cells

Since the effective beam loading in an ERL cavity is close to zero, the required RF power per cell is small (less than 1 kW). Thus a large number of cells could be driven via one input coupler. Multicell cavities with a large number of cells would also improve the ratio of active linac length to total length, thereby further reducing the cost of

[1] V_{acc} is the accelerating voltage in the cell, R/Q is the ratio of shunt impedance and quality factor for the accelerating mode, G is the geometry factor of the cell and R_s is the surface resistance of the cavity wall.

the ERL linac. However, as discussed above, strong HOM damping is essential because of the high beam current. The mode damping in cavities with five, seven and nine cells has been simulated and compared. The 7-cell structure was found to fulfill the requirements for an 100 mA ERL, see results below. The mode damping in a 9-cell cavity is critical with respect to the Cornell ERL beam parameters.

End Cells

In a long multicell cavity some higher-order modes are confined to the inner cavity cells and have low field amplitudes in the beam tubes. Therefore they are weakly damped by the HOM couplers and absorbers mounted on the beam tubes. These ”trapped modes” with high quality factors may cause beam instability and excessive losses. This potential risk can be reduced by using multicell cavities with a small number of cells and by making the cavity asymmetric. End cells with different shapes will give such an asymmetry and shift ”trapped modes” from the cavity center towards the cavity ends. Since this increases the field in one end of the cavity, HOM couplers and absorbers mounted on this side become more effective and the mode damping increases.

One way to get different end cell shapes is having beam tubes with different diameters at the two cavity ends. While we kept the TESLA beam pipe diameter of 78 mm on one side, on the other cavity end we increased the tube diameter to 106 mm, see Figure 2. This way the main linac cavities have the same end-tubes and end-half cells as the Cornell ERL injector cavities [6]. Beside causing asymmetry, the advantage of an increased tube diameter is a lower cut-off frequency for HOMs. Thus more parasitic cavity modes propagate through the tube and can very efficiently be damped by the beam pipe absorbers, see discussed below. As in the Cornell ERL injector cavities, the end-cell iris on the large beam tube side is reduced to 39 mm to maximize the R/Q factor for the accelerating cavity mode.

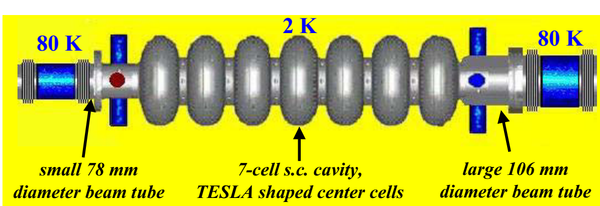

Figure 2: Sketch of a 7 cell cavity for the Cornell ERL main linac.

HOM Damping

The damping concept we envision to use in the main linac of the Cornell ERL is shown schematically in Figure 2 and Figure 3. The enlarged beam tube on one side of each cavity allows propagating all TM monopole modes and most dipole modes. Ferrite broadband ring-absorbers are located at 80 K between the cavities and damp the propagating modes very efficiently. In average each ring absorber has to intercept 140 W of HOM monopole power. This is moderate compared to the ferrite ring-absorbers at storage ring cavities, which have to intercept several kW of RF power. However, since in the ERL the ferrite absorbers are located in a long cavity string at cryogenic temperatures, also the absorbers are at a low temperature to simplify thermal transitions. Intercepting the HOM power at 80 K will give a sufficiently good cryogenic efficiency. A total of six HOM loop couplers per cavity will be mounted on the beam tubes to damp quadrupole modes reliable. Two couplers each are placed at an 180° angle to have symmetric HOM coupler sections. This symmetry reduces transverse kick fields and thus emittance growth. Simulations have been started to study if one input coupler gives a tolerable small transverse field on the cavity axis or if two couplers at an 180° angle are needed to minimize emittance growth.

MAIN LINAC CAVITY STRING

We envision having a string out of eight to ten 7-cell cavities per cryo-module. Between the cavities and at the ends of the cavity string short tube sections with ferrite HOM ring-absorbers and bellows are placed. Figure 3 shows a section of this cavity string with the positions of the input couplers, HOM loop couplers and ring-absorbers. Magnets will be placed between the eight to ten cavity string sections for beam focusing and steering. At an accelerating gradient of 20 MV/m, 31 to 38 cryo-modules are required for a total energy gain of 5 GeV.

HOM DAMPING SIMULATUIONS

The HOM damping by the ferrite HOM ring-absorbers has been studied by numerical simulations with the finite element code CLANS. CLANS uses a complex eigen solver to calculate modes in a RF structure in the presence of a RF absorbing material. The complex permeability and permittivity of ferrite (type TT2-111R from Trans-Tech [7]) have been measured at 80 K [8] and the obtained data where used in the CLANS calculations. Figure 4 shows the CLANS cavity string model with two 7-cell cavities and three ferrite HOM ring-absorbers. The calculated mode damping factors are summarized in Figure 5, Figure 6 and Figure 7 for monopole, dipole and quadrupole modes respectively.

As intended, the fundamental mode passband is not prop-

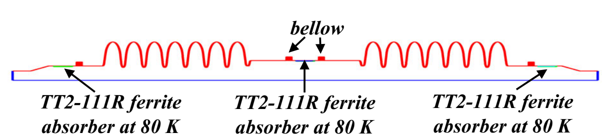

Figure 4: CLANS model with two 7-cell cavities and three ferrite HOM ring-absorbers.

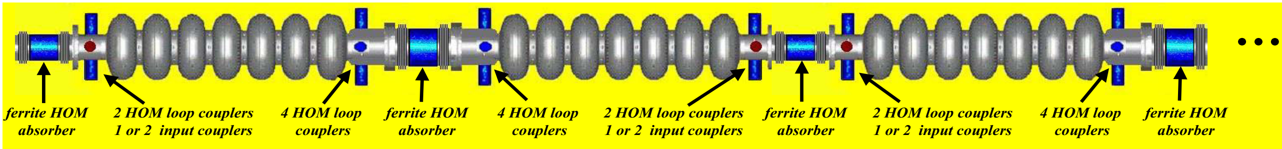

Figure 3: Sketch of the cavity string for the Cornell ERL main linac.

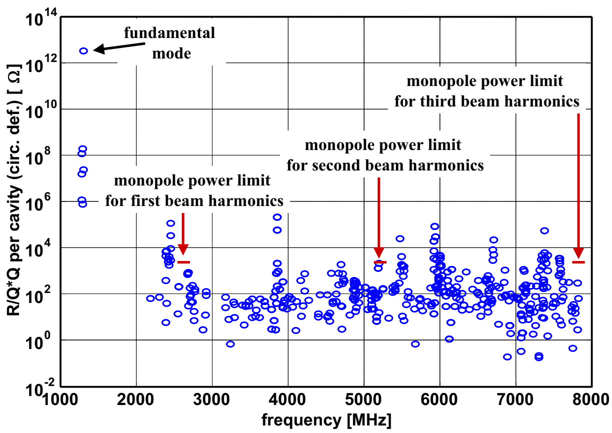

Figure 5: Calculated damping of TM monopole modes by the three ferrite HOM ring-absorbers in the cavity string shown in Figure 4. The damping is represented by the mode impedances $Z = (R/Q) \cdot Q_{ferrite}$, with $Q_{ferrite}$ being the mode quality factor caused by the losses in the ferrites.

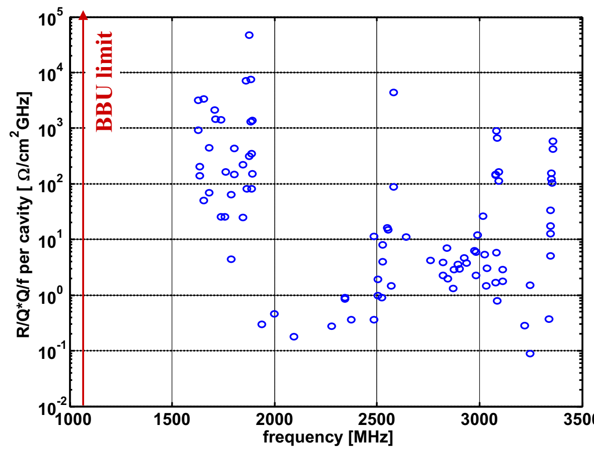

Figure 6: Calculated damping of dipole modes by the three ferrite HOM ring-absorbers in the cavity string shown in Figure 4. The damping is represented by the BBU factor $(R/Q) \cdot Q_{ferrite}/f$, with $Q_{ferrite}$ being the mode quality factor caused by the losses in the ferrites.

agating through the tubes, thus the fields at the absorbers are small and these modes are not significant damped by the ferrites. However, all other TM monopole modes have frequencies above the TM01 cut-off of 2.16 GHz and are propagating. The resulting strong damping by the absorber material is reflected in the small impedances of these modes. All modes with frequencies close to beam harmonics are sufficiently damped with $Z < 2500\ \Omega$.

All dipole modes above 1.66 GHz propagate in the large beam tube and are sufficiently damped by the ferrite absorbers. Even modes below the cut-off have enough field at the ferrite absorbers to be damped below the limit for 100 mA beam current . The loop couplers will further increase the damping of the lower frequency modes, thus increasing the safety-factor towards BBU.

Above 2.75 GHz all quadrupole modes start to propagate in the large beam tube and are efficiently damped by the ferrite absorbers. The loop couplers will damp the non-propagating quadrupole modes to guarantee beam stability. Only weak damping with $Q < 10^7$ is required for this.

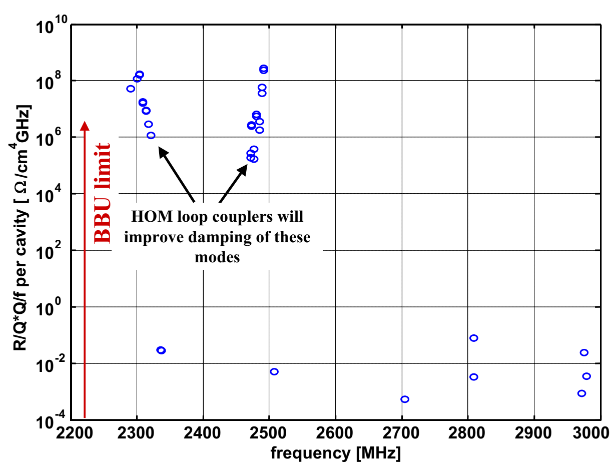

Figure 7: Calculated damping of quadrupole modes by the three ferrite HOM ring-absorbers in the cavity string shown in Figure 4. The damping is represented by the BBU factor $(R/Q) \cdot Q_{ferrite}/f$, with $Q_{ferrite}$ being the mode quality factor caused by the losses in the ferrites.

OUTLOOK

We will continue to optimize the shape of the 7-cell ERL main linac cavity with the goal to further increase the HOM damping and to lower the cryogenic losses at a given energy gain. Microwave studio calculations have been started to study the mode damping by the HOM loop couplers. In order to verify the numerical results measurements on copper models are planed .

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