WAKE FIELDS IN THE CORNELL ERL INJECTOR *

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Abstract

Cornell University is currently commissioning a novel, 100 mA electron injector for an energy-recovery linac based X-ray light source. Substantial wake fields will be generated by the short bunch, high current beam when it passes through the injector cryomodule, hosting five superconducting microwave cavities together with six broadband beam pipe microwave absorbers. In this paper we present wake field and loss factor calculations for all components inside this cryomodule, including RF cavities, microwave absorbers, flanges, gate valves, and beam pipe radius transitions. The dependence on bunch length is discussed as well as a comparison of results from different numerical wake field codes.

INTRODUCTION

Cornell University is proposing the construction of a new hard x-ray light source driven by an Energy-Recovery Linac (ERL) [1]. The x-ray performance and the scientific potential of such a light source would be transformational, greatly surpassing any existing storage-ring based x-ray source [2]. One of the key technological challenges of an ERL based x-ray light source is the production of a high current (100 mA), very low emittance beam in its injector ($< 1 \times 10^{-6}$ m rad at a bunch charge of 77 pC). In order to demonstrate the feasibility of such an electron injector, Cornell University has developed and set up a prototype of this injector, which is currently under commissioning and extensive testing [3].

One of the main components of the ERL injector is its energy booster cryomodule, hosting five superconducting RF (SRF) 2-cell cavities (1.3 GHz fundamental mode frequency). Each of these cavities will be transferring up to 100 kW of RF power to the electron beam to increase its energy from a few 100 kV after the DC electron gun to over 5 MeV at the exit of the booster cryomodule. The parameter space of the beam passing through the SRF injector cryomodule is far outside what has been achieved previously, and the resulting challenges are manifold.

One of these challenges is the excitation of substantial electromagnetic fields by the 100 mA bunched electron beam while it passes through the SRF injector cryomodule. These so-called wake fields can cause emittance increase, beam instability and significant heating of sections of the walls of the beam line elements. Detailed qualitative and quantitative understanding of the excitation of the wake fields in the injector cryomodule is therefor a must.

The *average* power transfered from the beam to electromagnetic fields while the beam passes on axis through a beam line element (e.g. a SRF cavity, gate valve...) is given by [4]

$$\Delta P = k_{||} I q \quad , \tag{1}$$

where I is the average beam current, q the charge per bunch, and $k_{||}$ is the longitudinal loss factor of the given beam line element. The loss factor itself depends on the geometry of the beam line element, as well as on the length σ of the particle bunches. It can be computed from the wake potential $W_{||}(s)$ via the integral

$$k_{||} = \int_{-\infty}^{\infty} W_{||}(s)\lambda(s)ds \quad , \tag{2}$$

where s is the spatial coordinate along the beam axis, and $\lambda(s)$ the longitudinal charge distribution function of the bunch. The wake potential generated by a particle bunch itself also depends on the bunch length, and can be computed numerically for a given geometry of a beam line element.

In this paper we use two wake field computation codes to calculate the wake potentials and resulting longitudinal loss factors for the ERL injector beam line. The focus here is on

- comparing the relative contributions of the different elements in the injector module beam line to the total loss factor of the injector cryomodule,
- studying the dependence of the loss factors on bunch length,
- exploring the potential reduction of the loss factor per length for the somewhat periodic beam line in the injector module, and
- comparing the numerical results from two different wake field codes.

In the following we will first give an overview of the numerical codes used to calculate the wake potentials, followed by an overview of the ERL injector beam line. We then present and discuss results from these codes for the Cornell ERL injector cryomodule.

COMPUTATIONAL DETAILS

For this study, two programs where used to simulate the wake fields trailing the bunches passing through the ERL injector module beam line and to compute loss factors.

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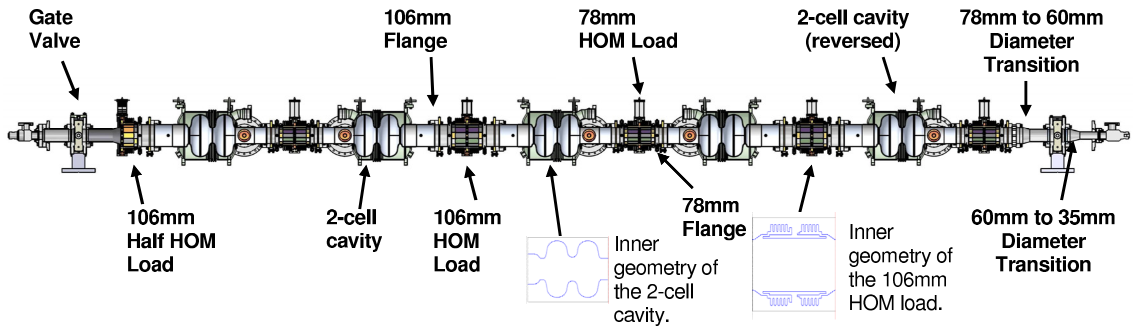

Figure 1: CAD model view of the Cornell ERL injector cryomodule beam line. Beam line components from left (beam entrance) to right (beam exit): gate valve; 106 mm half HOM load; first SRF cavity; 78 mm HOM load; second SRF cavity; 106 mm HOM load; third SRF cavity; 78 mm HOM load; fourth SRF cavity; 106 mm HOM load; fifth SRF cavity; 78 mm HOM load; 78 mm to 60 mm diameter transition; gate valve; 60 mm to 35 mm diameter transition.

These were NOVO, written by Alexandre Novokhatski [5], and ABCI (Azimuthal Beam Cavity Interaction), written by Yong Ho Chin [6]. This allowed for verification of results by comparing the outputs of the two programs, especially at short bunch lengths where small spacial resolution becomes critical. Both programs assume axial symmetry, and use finite difference algorithms to compute the fields generated by a bunch traveling through the input geometry, and from there compute wake potentials and loss factors.

ERL INJECTOR MODULE BEAMLINE

Figure 1 shows a CAD model view of the ERL injector module beam line. It consists of the following beam line elements, connected by conflat type flanges:

- 2-cell SRF cavities (neglecting the two input coupler ports on one end of the cavity), facing in two opposite directions, with 78 mm diameter beam pipes on one end and 106 mm diameter pipes on the other end;
- two types of full Higher-Order-Mode (HOM) loads, one at 78 mm diameter and one at 106 mm;
- one 106 mm diameter "half" load at the beam entrance side of the cryomodule, which includes a transition from 60 mm to 106 mm diameter;
- two beam pipe diameter transitions, one from 78 mm to 60 mm and a second from 60 mm to 35 mm;
- and RF shielded gate valves on either end of the module.

Wake fields and loss factors have been first computed individually for each of these element types, including the different diameter conflat flanges used. Then, the entire beam line has been simulated.

ANALYSIS OF INDIVIDUAL COMPONENTS

For each type of element in the beam line of the ERL injector cryomodule the wake potential and the resulting

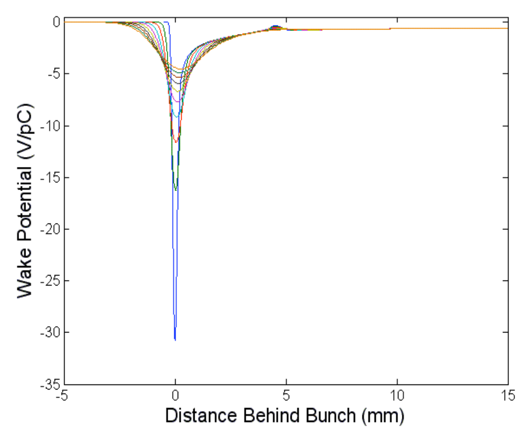

Figure 2: (color) Wake potential computed by ABCI for the 2-cell cavity at bunch lengths ranging from 0.1 mm to 1.0 mm. Shorter bunches result in a deeper potential well.

longitudinal loss factor where calculated for bunch lengths between 0.1 mm and 1 mm. The nominal bunch length in the ERL injector (after compression) is 0.6 mm. Figure 2 for example shows the wake potential of the 2-cell cavity for this range of bunch lengths. The obtained longitudinal loss factors for the individual beam line elements as function of bunch length are summarized in Figure 3 (as computed by ABCI) and Figure 4 (as computed by NOVO). The mesh sizes used where 0.05 mm to 0.1 mm for NOVO (denser meshes are not supported by the version of NOVO used here) and 0.01 mm to 0.05 mm for ABCI. The ratio of the results by ABCI and NOVO for given bunch length and geometry are shown in Figure 5 for relative comparison of the two wake field programs. With two exceptions, the results from the two programs agree well within a few percent for bunch lengths of 0.2 mm and greater. The reason for the $\approx$7% difference in the loss factors of the cavities and the significant $\approx$20% lower loss factors from ABCI for the half HOM load are unclear and warrent further studies. Descrepancies at 0.1 mm bunch length might results from the relative corse mesh used in NOVO.

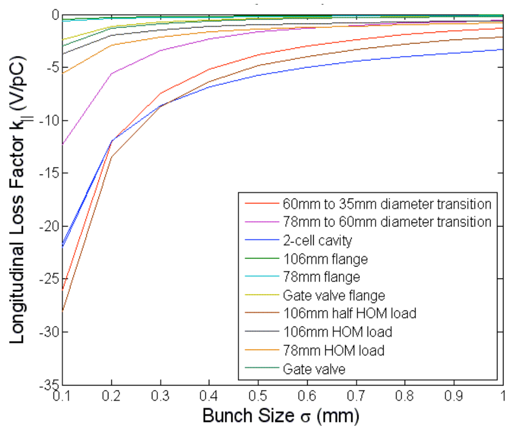

Figure 3: (color) Loss Factors for individual components as a function of bunch length as computed by ABCI.

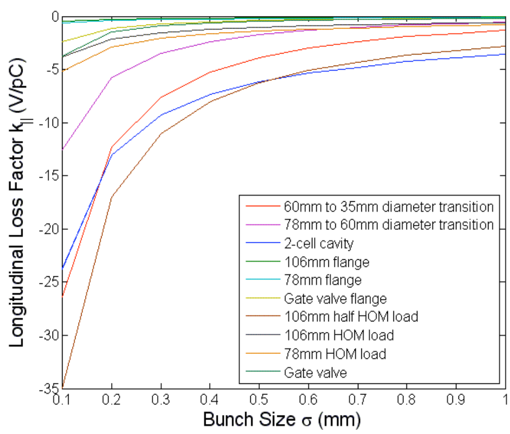

Figure 4: (color) Loss Factors for individual components as a function of bunch length as computed by NOVO.

The SRF cavities and the beam diameter transitions (note that the half HOM load includes a pipe diameter transition from 60 mm to 78 mm) have the largest loss factors, which increase rapidly for shorter bunch lengths. Note that even though the SRF cavities are the primary component in the injector cryomodule, they nevertheless contribute only ≈50% to the total loss factor of the entire beam line. The loss factor of the HOM loads is comparible small (≈1 V/pC at 0.6 mm bunch length), so that they contribute only ≈10% to the total loss factor. This demonstrates the effective shielding of the bellow sections in the HOM loads by the absorber support plates; see Figure 1. As expected, the flanges and gate valves with their relatively small changes in tube radius contribute to the total loss factor only on the few percent scale.

ANALYSIS OF THE FULL INJECTOR MODULE

For long bunches, the single-element approximation can be used to calculate the total wake potential and loss factor of the entire beam line in the injector cryomodule. In this approximation it is assumed that the bunch keeps the same field pattern in its vicinity before and after it traveled through the beam line element (for the longer bunch, the electric force lines are almost radial after passing the element, as they were at entering it). The excitation of wake fields is then identical in each element of given type, i.e. independent of its relative longitudinal position in the beam line and the total energy loss of the beam is simply the sum of the energy loss in the individual beam line elements. Figure 7 and 8 show the total wake potential of the beam line in the ERL injector cryomodule as obtained from the wake potentials of the individual elements under this long bunch approximation. The total longitudinal loss factor of the entire beam line obtained this way is shown in Figure 9.

However, for short bunches, the field pattern changes significantly after passage through a section of the beam line, and the single-element approximation is no more valid; see also Figure 6. For periodic or quasi-periodic beam lines (like long chains of identical cavities) it has been found that this effect can lead to a significant reduction in the loss

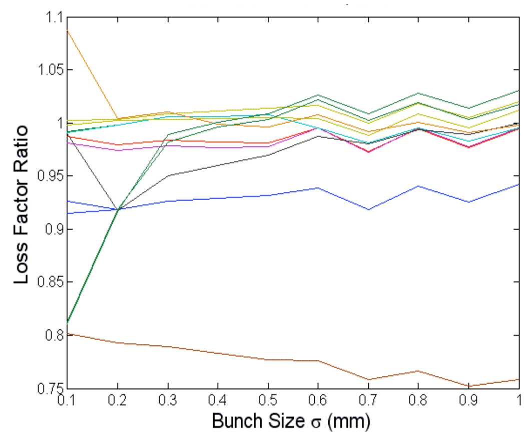

Figure 5: (color) Ratio of the loss factors calculated by ABCI and NOVO (k_{ABCI}/k_{NOVO}). At shorter bunches, there is more discrepancy between the two programs. The legend is the same as in Figure 3 and 4.

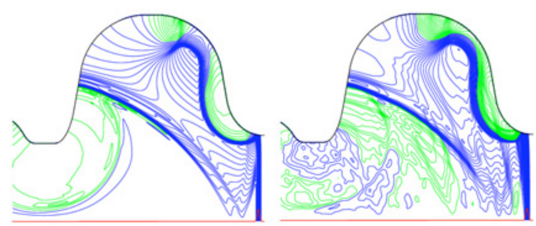

Figure 6: Comparison of electric force lines computed by NOVO for a bunch entering the two-cell cavity after also traveling through the beam entrance section of the cryomodule (left) and after just traveling though the 2-cell cavity in isolation (right).

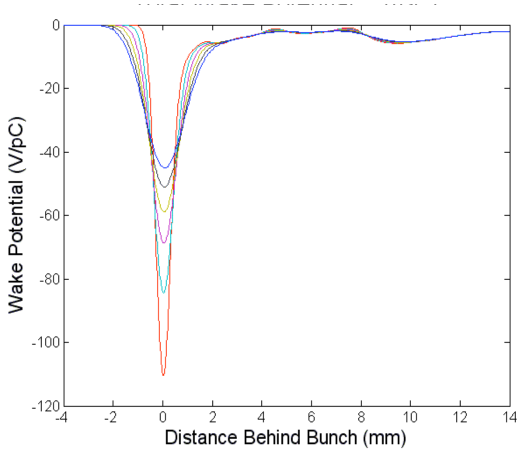

Figure 7: (color) Total wake potential the entire beam line of the injector cryomodule, as computed by adding individual wake potentials for each component, as computed by ABCI, for bunch sizes ranging from 0.1mm to 0.8mm.

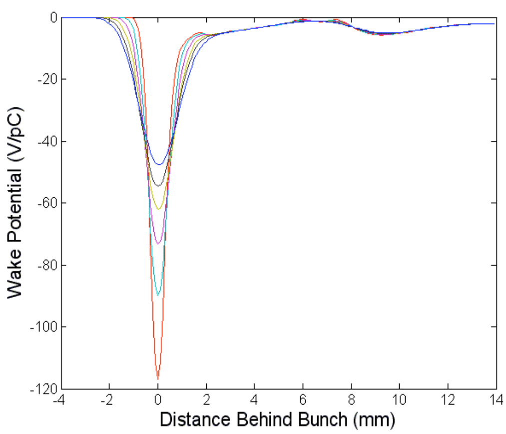

Figure 8: (color) Total wake potential the entire beam line of the injector cryomodule, as computed by adding individual wake potentials for each component, as computed by NOVO, for bunch sizes ranging from 0.1mm to 0.8mm.

factor per length of beam line [7]. In order to explore if this reduction by periodicity at short bunch lengths is still significant for the case of the injector module beam line, the loss factor of the entire beam line has been calculated by ABCI for different bunch lengths; see Figure 9. As can be seen, the loss factor at 0.2 mm bunch length is only half of the sum of the loss factors of the individual elements. This is remarkable, since the beam line in the injector cryomodule has many breaks in periodicity.

At the nominal bunch length of 0.6 mm, the total loss factor computed is about 30 V/pC, which results in a total average power loss of 230 W for a 100 mA beam with 77 pC bunch charge.

CONCLUSIONS AND OUTLOOK

Detail numerical studies of the wake fields excited in the Cornell ERL injector cryomodule have been done. The two numerical wake field programs ABCI and NOVO show mostly good agreement in their computations of wake potentials and loss factors. A significant reduction in the loss factor of the entire beam line at short bunch lengths has been found as compared to the sum of the loss factors of individual beam line components. Although the loss factor of individual components may be small, they can add considerably for a large number of elements. Even though the most significant loss is due to the SRF cavities, they contribute only about 50% to the total loss factor of the entire beam line in the ERL injector cryomodule.

During the next year we plan detailed measurements of the loss factor vs. bunch length at the Cornell ERL injector to test these numerical results.

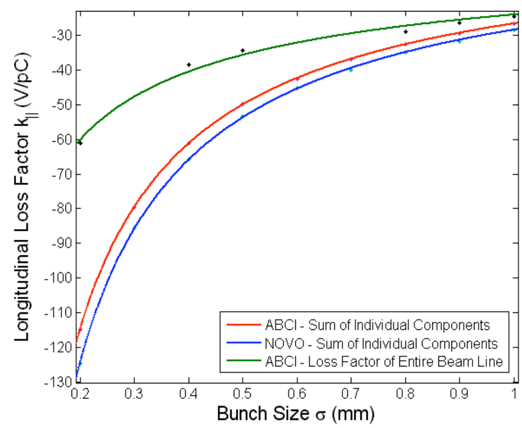

Figure 9: Total loss factor in the injector beamline as a function of bunch length. Notice that summing up the loss factors of the individual components overestimates the total loss factor, especially at shot bunch lengths.

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