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THE HOMEN MODEL: AN ESTIMATOR OF HIGH ORDER MODES EVOLUTION IN AN ENERGY RECOVERY LINAC

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Abstract

Energy recovery linacs represent the new frontier of energy sustainability in the field of particle accelerators while providing remarkable performance in terms of high average current and average brightness. Operating superconducting radio-frequency cavities in continuous wave make high repetition rates (GHz-class) affordable and allow the construction of light sources such as FEL or Compton based characterized by high flux. This study originates in the context of the design study of BriXSinO, an ERL based on the two-pass two-way scheme à la Maury Tigner in which the cavities are traveled by the beam in both directions, the first time in the accelerating phase and the second time in the decelerating phase. The code HOMEN was conceived as a model to simulate the evolution of high order modes on long time scales in high Q cavities of machines of this kind and monitor their effects on the beam.

INTRODUCTION

After 57 years of being discovered, Energy-recovery linacs (ERLs) became one of the most convenient technologies for electron accelerators, due to their ability to generate high-average current beams by operating in continuous wave (CW) mode with high brightness and small emittance at small cost [1–3]. The idea of the mechanism behind the ERL belongs to Maury Tigner. He had it while looking for an advanced way to boost the current in a collider for high energy physics at Cornell university [4].

ERL technology allows to recover more than 90% of the energy during the deceleration process. This energy will then be used as a power source for the next accelerated beam so that the electron bunch will be re-injected into the linac at the appropriate time and phase for deceleration. This mechanism avoids to dump a fully energetic beam, which is a huge loss of power in case of traditional linear accelerators.

Going back in history, ERL was first developed in order to drive high power Free electron laser (FEL) for providing high peak power and allowing an emission of coherent radiation from a high energy electron beam [5].

ERL's role now is expanded to cover more applications involving short pulse radiation sources, fixed target experiments, electron cooling instruments and many others.

The type of ERL studied in this paper is a two-pass two-way (TPTW) scheme based on SRF (Superconducting radio-frequency) technology able to drive an Inverse Compton Scattering and FEL sources. Another interesting point is that the machine is also conceived to be both a demonstrator of the double acceleration scheme based on TPTW of MariX and of the TPTW ERL of BriXS [6–13]. In this work we first introduce the theory of our model for evaluating the impact of High Order Modes (HOM) in long time-scale on beam dynamics, and the approaches behind our simulations. The second part describes in detail the stabilization of the fundamental mode in both accelerating and decelerating phases, followed by an example of the effects of HOM on the particle beam inside a multi-cell cavity.

HOMEN MODEL

The idea of HOMEN (High Order Mode evolution based on Energy budget) was born mainly to investigate the effect of HOMs on beam dynamics (BD) in a long-time scale generally in superconducting (SC) cavities and precisely in BriXSinO [14, 15]. Another relevant point of our model is the possibility to check the beam stability considering also the high repetition rate and high average current in the machine.

A set of coupled differential equations were developed to study neatly the propagation of an electron bunch inside the cavity. We represent the electric field on the cavity axis as a composition of normal orthogonal modes. Here, for our cavity model with an even number of gaps, it is convenient to write the time dependence of the longitudinal electric field equation using the sine in preference to the cosine:

$$E_n(z,t) = A_n(t)\ e_n(z)\ \sin(\omega_n t + \phi_{n,i}) \qquad (1)$$

where n and i are the RF mode and the bunch number respectively. We classically model the bunches as N point-like charges propagating along the cavity axis. A_n is the mode oscillation amplitude and e_n is the spatial field distribution calculated by POISSON/SUPERFISH code [16].

The system of coordinates is chosen to have the beam trajectory along the positive z cavity axis (beam axis). To evaluate the fields triggered off by the electron bunch while crossing the cavity, we compute the stored energy in each individual mode since all modes can be treated separately. Our model is based on energy budget. We considered the variation of the stored energy as the sum of the following power contributions:

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Klystron Power For the accelerating cavity mode, the required RF power is evaluated considering the amount of power lost both into the cavity walls and to accelerate the electron bunches and also the variation of energy gain during the acceleration process. At this stage, taking into account only the forward direction (acceleration phase), the power source P_s was simulated in order to provide energy only to the TM_{010} mode, as indicated below by Dirac delta $\delta_{1,n}$. The final Klystron power is represented as follows:

$$P_{\mathrm{Kly}} = \delta_{1,n}|P_s|$$

Dissipated Power The dissipated power on the cavity walls is calculated using the following expression:

$$P_{\mathrm{diss}} = \frac{\omega_n U_n}{Q_{L,n}}$$

where ω_n is the resonant angular frequency, $Q_{L,n}$ is, for the fundamental mode, the loaded quality factor and for n > 1 it represents the damped quality factors, and U_n is the stored energy of the resonant mode n.

Average Power By average power, in this paper, we refer to the amount of power transferred to accelerate the electron bunch. It is expressed as:

$$P_{\mathrm{av}} = \frac{qV_{\mathrm{acc,n}}}{\tau_{\mathrm{cav}}}$$

where q is the bunch charge, V_{acc} is the overall accelerating voltage of the cavity system and $\tau_{\mathrm{cav}} = \frac{L_{\mathrm{cav}}}{\beta c}$ is the time of flight of the electron bunch through the cavity.

HOM Power During the bunch passage inside the cavity, the beam transfers a quantity of power in the form of wakefield to the HOMs according the loss factor parameter $K_{\mathrm{loss,n}}$ for each individual mode. This power is expressed as follows:

$$P_{\mathrm{HOM}} = \frac{q^2 K_{\mathrm{loss,n}}}{\tau_{\mathrm{cav}}}$$

The stored energy in the $\mathrm{n^{th}}$ mode can be then represented by the following expression:

$$\frac{dU_n}{dt} = P_{\mathrm{Kly}} - P_{\mathrm{diss}} - P_{\mathrm{av}} + P_{\mathrm{HOM}} \tag{2}$$

The reader must pay attention to the signs represented in Eq. 2, they depend on how different quantities have been defined in simulation. For example, the accelerating voltage of the cavity changes sign depending on the electric field. According to the Slowly Varying Envelope Approximation (SVEA) i.e. $dA_n/dt \ll \omega_n A_n$, we can express the variation of the mode oscillation amplitude as function of stored energy:

$$\frac{dA_n}{dt} = \frac{A_n}{2U_n}\frac{dU_n}{dt} \tag{3}$$

The variation of both stored energy and mode amplitude have to be studied together with the variation of the energy gain of the bunch when passing through the cavity, during the interaction with the RF field. The bunch energy gain, γ, is given in terms of the accelerating potential and the rest energy, by:

$$\frac{d\gamma}{dt} = \frac{e}{m_e c^2 \tau_{\mathrm{cav}}} \sum_{n=1}^{N_{\mathrm{RF}}} V_{\mathrm{acc,n}} \tag{4}$$

where e is the elementary charge, m_e is the electron rest mass and N_{RF} is the RF mode number.

FUNDAMENTAL MODE STABILITY

To clarify the approach followed in this study, we describe the environment of our calculations. We used HOMEN for the BD study in one of the SC cavities of BriXSinO ERL main linac. The resonator is a standing wave 7-cell cavity operating at 1.3 GHz with a high average current (5 mA) and high repetition rate of 100 MHz.

A point charge traveling along the beam axis excites all modes inside the cavity resonator. Supposing that the charge passes precisely on axis only monopole modes are excited. Since all modes are orthogonal to each other, they can be treated separately. For this reason we analyze the fundamental mode separately in this section. Firstly, we face the problem of stabilizing the interactions inside the cavity in both acceleration and deceleration directions, next we discuss briefly one of the ways to handle this type of interactions.

Acceleration Direction

Starting with 1 J of initial stored energy, we inject about 100 electron bunches (50 pC bunch charge) at an initial phase granting the maximum acceleration in order to analyze the beam interaction. The bunches are spaced in time by 10.8 ns, the stored energy will constantly decreases of few J during the acceleration process while the bunch energy increases. This operation is stabilized in time, as shown in Fig. 1: the value of γ remains unchanged from the entrance to the exit of the cavity. The main parameters used to simulate this effect are listed in Table 1.

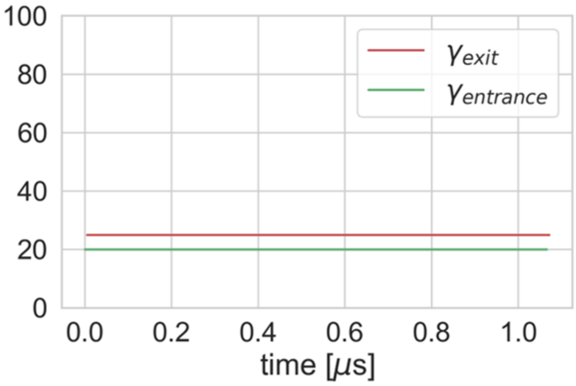

Figure 1: Energy gain variation at the entrance and exit of the cavity during acceleration.

Table 1: Frequency and Quality Factor of Modes

	f (GHz)	Q_0
Fundamental mode	1.298	2.894×10^{10}
1^{st} HOM	2.437	3.147×10^{10}

Deceleration Direction

Starting with ≈ 1 J of initial stored energy, we re-inject the beam with the same parameters used for the acceleration mode but in the opposite direction. We multiply the power lost by the beam P_{HOM} in Eq. 2 by a factor 2 taking into account the double passage of the beam.

We attain a stability of the beam similar to the previous section, this implies that the system of equations and approaches followed in this work are tolerable for a TPTW ERL scheme proposed for BriXSinO.

The stability of the bunch energy gain was verified for a longer time period (over 3×10^6 bunch) for both acceleration and deceleration phases.

IMPACT OF MONOPOLE HOMS ON BEAM DYNAMICS

HOMs in high current CW configuration may be parasitically excited and have to be studied in detail. These modes are turned on in a wide spectrum after the passage of a particle beam through the accelerating cavity. The consequence of this passage is a wakefield left behind by the beam itself. These modes are dangerous as they may turn to be a source of longitudinal beam instability, increase the beam energy spread or lead to additional heat load in the cavity. Particularly in ERLs, HOMs resonate for long time (multiple turns), thus considered undesired and need to be dumped by extracting the stored energy with HOM couplers settled up in the beam pipe sections of the cavity. The SC cavity has no external HOM dampers installed, therefore the HOMs energy can be damped only in the two beam pipes.

The energy transferred to HOM is proportional to the loss factor k_{loss} presented in the first section. For a point-like charge, this factor is estimated and it is proportional to the frequency and the ratio between the shunt impedance and the quality factor of each individual mode.

We consider a bunch train with 10 MeV of initial energy and evaluate the stored energy in the first HOM for a first rough value of the loss factor (0.9 V/pC), as shown in Fig. 2. The stored energy increases in time due to the k_{loss} value, and will reach an equilibrium after few milliseconds. The fluctuations in energy variation are caused by the phase injection instability from bunch to bunch, since for the HOM, each new bunch arrives with a different phase. The frequency and quality factor of the corresponding mode are reported in Table 1.

The presence of HOMs will increase the bunch energy spread at the cavity exit with a consequent effect on the following application, as the injection into the FEL. To analyze this, we varied k_{loss} of the first HOM from 0.5 until 4 V/pC to evaluate the maximum beam energy spread. Figure 3 shows the distribution of bunch energy at the cavity exit as function of k_{loss}. The strong dependence on k_{loss} of U_n reveals that higher is k_{loss}, the higher is the energy stored in the corresponding mode, underlying the necessity to damp it. The characteristic shape of the graph (Fig. 3) is due to the fact that we are projecting in position the energy gain of the bunch, which distributes over the sinusoidal variation of the HOM each time with a different phase. In other words, these fluctuations are a harmonic oscillations that has an impact on the beam quality. The relative energy spread of the bunch in the beam induced by the first HOM is 2.5×10^{-3} for a $k_{loss} = 0.9$ V/pC. This value can be considered suitable for our application, and as far as we know, will not introduce crucial effects on the quality of the radiation produced by BriXSinO.

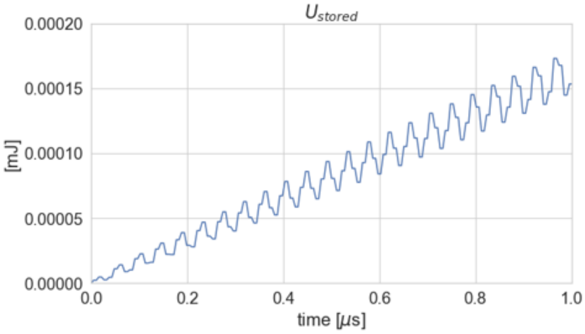

Figure 2: Stored energy as a function of time for the 1^{st} HOM at $k_{loss} = 0.9$ V/pC.

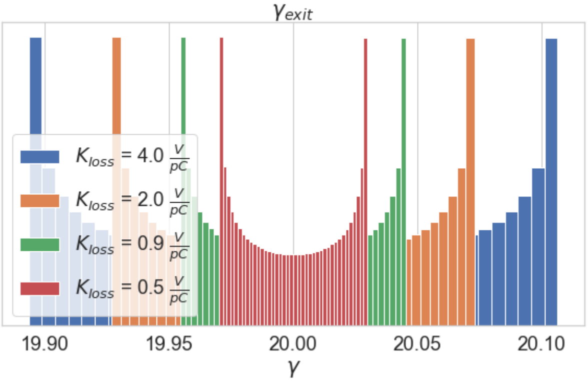

Figure 3: Distribution of the bunch energy at the cavity exit.

CONCLUSION

We used a new method to evaluate the impact of HOM in long time-scale on BD for ERL, mainly to study the relative energy spread of the beam. For BriXSinO, this study is still in progress. The preliminary obtained results predict an energy spread due to HOMs in the order of 10^{-3} which is considered tolerable for FEL's injection. More investigations are foreseen in future work.

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