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MODELING CHALLENGES FOR ENERGY RECOVERY LINACS WITH LONG, HIGH CHARGE BUNCHES*

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Abstract

Historically, nearly all energy recovery linacs (ERLs) built and operated were used to drive a free-electron laser (FEL). The requirement for high peak current bunches necessitates bunch compression and handling the attendant beam dynamical challenges. In recent years, ERLs have turned from being drivers of light sources toward applications for nuclear physics experiments, Compton backscattering sources and strong electron cooling. Unlike an FEL, these latter uses require long, high charge bunches with small energy spread. The electron bunch must maintain a small projected energy spread and therefore must avoid gross distortion due to CSR and longitudinal space charge over a single (or multiple) recirculations. Accurately modeling the relevant collective effects in the system – space charge, microbunching instability, CSR and the effect of shielding – in addition to beam dynamical processes such as halo, presents a formidable challenge. Absent a code that models all of these effects, we outline an approach towards the design, analysis and optimization of the high-energy electron cooler for the Jefferson Lab Electron-Ion Collider and survey widely used codes and their capabilities.

INTRODUCTION

There has been a recent shift in ERL applications from driving FELs to long bunch applications. Where once a short bunch length was the key performance metric, now there is a premium on maintaining a small correlated energy spread (with a commensurately long bunch). Here we consider some of the challenges in modeling these machines, whose parameters often put them in a unique region of parameter space where their performance is difficult to assess via a single code. As a particular example we will consider the bunched-beam electron cooler for the Jefferson Laboratory Electron-Ion Collider (JLEIC) which shares many of the challenges of other long bunch, high charge ERL applications [1].

The paper is arranged in the following way; after a brief introduction to the electron cooler, we describe some of the physics processes that are relevant in the parameter space in which it lives. A brief survey of the simulation codes used at Jefferson Laboratory is given, followed by the simulation protocol for evaluating system performance. Finally, we present some results for a recirculation arc design used in the cooler complex.

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JLEIC ELECTRON COOLER

In order to achieve the luminosity requirements of JLEIC, several stages of electron beam cooling must be utilized. The most challenging is the high energy, bunched-beam cooler designed to cool 100 GeV protons. This requires the generation, transport and preservation of very high-charge (3.2 nC), long (2 cm full) magnetized bunches, acceleration of the bunches in an ERL and transfer of these bunches to the circulating cooler ring (CCR) for 11 passes though the cooling channel before being transferred back to the ERL for energy recovery (see Fig. 1). Given the amount of bending – 360° in the ERL and (11×360)° in the CCR – the recirculation arcs represent a particular challenge due to the confluence of collective effects such as coherent synchrotron radiation (CSR), microbunching instability (μBI) and space charge.

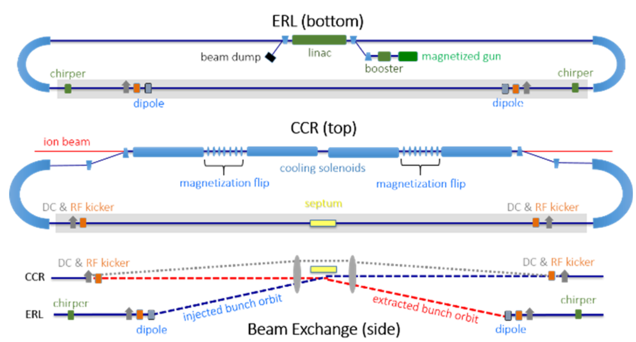

Figure 1: Schematic of the JLEIC bunched-beam electron cooler. The ERL (top) generates and transports beam to the CCR (middle) via a beam exchange region (bottom) where bunches make 11 recirculations before returning to the ERL for recovery.

RELEVANT PHYSICS

A brief survey of the effects most likely to cause beam degradation in the kind of systems we are considering are described below:

space charge: The aggressive bunch charge coupled with the relatively low final energy (55 MeV) means that space charge – both transverse and longitudinal – will not only need to be managed during the beam formation process, but throughout the entirety of the system.

CSR: There has been much progress in recent years to undo the effects of CSR in the bend plane with an appropriate choice of beam optics [2]. Though possible to control the transverse emittance growth, it is more difficult to undo the gross longitudinal distortion caused by the CSR wake – particularly in applications where the intrinsic energy spread is small and/or where the effect can accumulate over

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multiple recirculations. One possible mitigation is shielding of the CSR wake from the beam pipe. Therefore a proper treatment of both CSR and shielding in the codes is essential.

μBI: The amount of bending alone raises concern about the microbunching instability developing. The situation, however, is further aggravated by the necessarily small intrinsic energy spread ($3{\times}10^{-4}$ rms, for the cooler). Having the ability to quickly assess the microbunching gain without relying on time-consuming particle pushing codes is paramount.

halo: It is well known that halo represents one of the most difficult operational challenges for ERLs [3]. To adequately assess the impact of halo particles requires simulating initial distributions that are as realistic as possible and pushing large numbers of particles. For instance, in a 1M particle distribution even a single rogue particle represents significant beam power. Processes that may generate halo particles include intrabeam, Touschek and beam/gas scattering. All of which must be taken into account.

Additional effects such as beam breakup, ion trapping and the ability to model collimation schemes must also be appropriately accounted for.

CODE SURVEY

This is not intended to be an exhaustive survey, but represents the current suite of codes in use at Jefferson Laboratory. Each code offers unique insight into the behaviour of the system. Absent a single "do-it-all" code, the challenge is to establish a self-consistent model based on the analysis from a variety of codes.

DIMAD is a no-frills lattice design code which is efficient and is well-established having been instrumental in the design of the Continuous Electron Beam Accelerator Facility (CEBAF) and three ERL-driven FELs [4].

elegant is a widely used code in the accelerator community which has the ability to track large numbers of particles, has an ultra-relativistic 1D CSR model and allows for streamlined post-run analysis with the associated SDDS Toolkit [5]. A parallelized version (Pelegant) is also available making it well suited for pushing large distributions in start-to-end simulations.

Bmad is an open source code for simulating relativistic charged-particle dynamics which was developed at Cornell University in the 1990s. In addition to a 1D CSR model, Bmad is the only code which also includes CSR shielding [6]. An idealized "high energy" space charge model is also available.

TStep is a particle tracking code which is best suited to model space charge dominated regions of a machine (i.e. injector, merger, linac) [7]. The documentation lists the option to include CSR, but results have shown this to be an unphysical model.

General Particle Tracer (GPT) is a code for studying 3D charged-particle dynamics in electromagnetic fields [8]. Because it is fundamentally based on fields, it can be difficult to translate lattice descriptions designed in conventional matrix-based codes (e.g. DIMAD, elegant, Bmad). On the other hand, it provides the framework to simulate 1D CSR and space charge more rigorously. The code is also highly customizable, one example being a CSR shielding module that was developed [9].

Vlasov-solver is a code that was developed recently at Jefferson Laboratory to study microbunching [10]. Studying the microbunching instability in the time-domain (i.e. via particle tracking) is a computational burden so that it becomes difficult to exercise parametric studies and/or model an entire accelerator complex. On the other hand, a semi-analytical Vlasov-solver that works in the frequency-domain and models relevant collective effects such as LSC, CSR and linac geometric effects using analytic impedance expressions has led to insights on lattice constraints for control of the microbunching instability [11].

MODELING STRATEGY

An outline of the modeling strategy for a generic beam transport is given below:

1. Design an initial lattice in DIMAD.
2. Translate the deck to elegant.
   a. Use the Vlasov-solver to evaluate microbunching gain. If unacceptable redesign lattice (Step 1).
3. Perform initial check of lattice in elegant with CSR. If system performance is unacceptable:
   a. Translate lattice to Bmad and check efficacy of CSR shielding. If system performance still suffers:
   b. Modify optics and start over from Step 2.
4. Translate deck to GPT, include both space charge and CSR and evaluate system performance.
5. Push a large number of particles to evaluate halo, making sure to include the most egregious (but perhaps not all) collective effects using the appropriate code.

RESULTS FOR A SIMPLE ARC

We consider an isochronous arc design for the JLEIC CCR [12] and apply the protocol from the previous section. The arc was intentionally designed to be simple, in the sense that it does not have high periodicity (it only has 4 dipoles) nor does it try to maintain local axial symmetry throughout (though it is globally axially symmetric). A schematic is shown in Fig. 2.

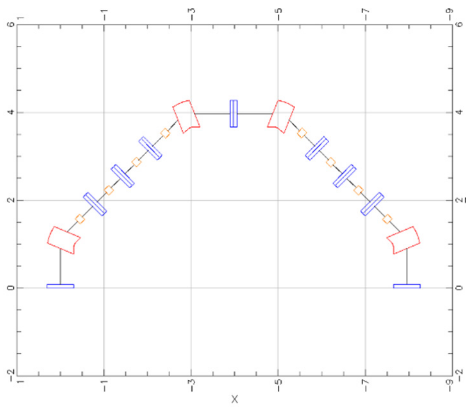

Figure 2: Floor plan of a simple isochronous arc. Red markers denote dipoles, blue markers denote quadrupoles and orange markers denote sextupoles.

The ability to control microbunching is critical. Even modest microbunching gains, if they are above unity, are unacceptable in systems where multiple recirculations are required since the total gain goes as the gain for a single pass raised to the number of passes. An example is shown in Fig. 3 where an arc with modest gain (1.5) is used in a CCR and modeled for 10 turns. Fortunately, the simple arc example exhibits good control of microbunching.

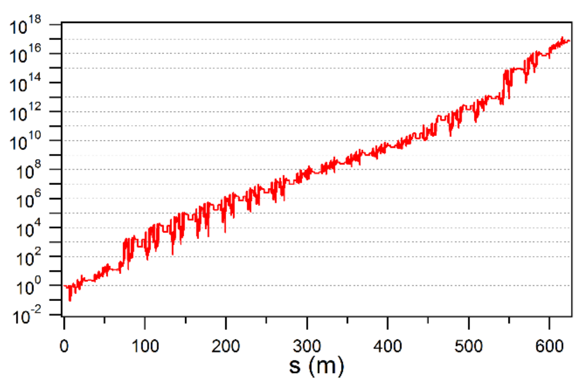

Figure 3: Even an arc with a modest gain (1.5) will lead to unacceptably large microbunching gain over many turns.

Much effort was made to compare the results of pushing a 1M particle distribution through the arc in elegant (CSR only), Bmad (CSR with 2” beam pipe shielding) and GPT (CSR and space charge). The results are summarized in Figs. 4 and 5. In general the transverse emittance is well preserved, however, the CSR wake causes an energy gradient along the length of the bunch and results in a decrease in centroid energy. Some of the effect is ameliorated by the CSR shielding. For multiple recirculations active compensation is needed, namely using an RF cavity run far off-crest to restore energy lost by CSR and to remove the energy chirp. We also find that space charge is not a major concern in the arc proper.

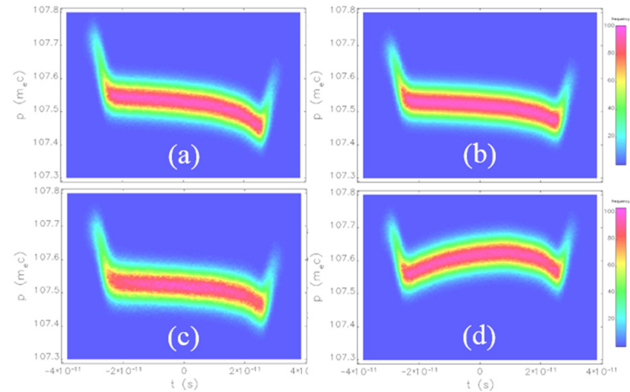

Figure 4: Longitudinal phase space at the exit of the simple arc simulating CSR with (a) elegant (b) GPT (c) GPT including space charge (d) Bmad including the effects of shielding from a 2” full aperture.

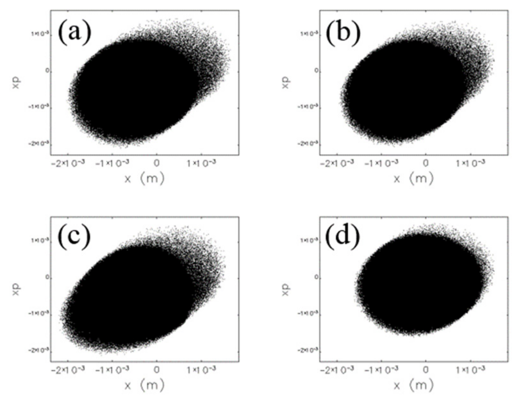

Figure 5: Horizontal phase space at the exit of the simple arc simulating CSR with (a) elegant (b) GPT (c) GPT including space charge (d) Bmad including the effects of shielding from a 2” full aperture.

SUMMARY

Naively, there is a desire for a single code that can do it all. In reality the best solution is not simply to put every conceivable feature into a single code. There exist clear needs for lattice design and optimization codes versus codes that can efficiently push large numbers of particles with a specific subset of collective effects versus codes catered to careful analysis of multiple collective effects at once. It is simply a matter of judiciously using the tools that currently exist.

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