WG SUMMARY: BEAM DYNAMICS AND INSTRUMENTATION*

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Abstract

Ten presentations were given within the Beam Dynamics and Instrumentation Working Group at the ERL 2022 Workshop, covering topics ranging from design studies for future accelerators and reports on experiences with existing machines, to ideas for novel accelerators and analytical approaches to beam dynamics problems. Here we summarize the main points of these presentations.

SUMMARY

Filling pattern and beam line topology have significant impact on the stability and performance of an Energy Recovery Linac (ERL). Studies on the fundamental accelerating mode show a clear optimal solution for sequence preserving schemes. For studies of BBU threshold current, comprehensive studies are required, as the optimum solution is strongly dependent on the machine parameters. In order to perform comprehensive studies, one needs to be able to determine all combinations of filling pattern and transition sets. A mathematical formalism was developed to solve this problem for any number of ERL turns [1]. This formalism can also be used for other related applications, such as the optimization of the arc lengths for PERLE.

PERLE lattice design includes two experimental areas with low beta insertions. Single and multi-bunch tracking studies have been performed for the PERLE facility, aiming to deliver an intense 500 MeV electron beam to the two experimental areas before performing energy recovery [2]. The studies include Coherent Synchrotron Radiation (CSR) emission and short and long range wakefields in the superconducting radio-frequency structures of the linacs. Start-to-end tracking studies including CSR at nominal current with a reduced bunch length showed perfect transmission, hence there should be margin with the nominal bunch length. A larger initial energy spread appears to reduce the longitudinal nonlinearities caused by CSR, corroborating the results obtained with the use of a laser heater in free-electron lasers. Multi-bunch tracking studies show a stable operation at nominal current, and the optimisation of the bunch filling pattern provides stable operation up to 10 times the nominal current as opposed to the original filling pattern for which High-order modes become unstable. Besides the bunch intensity, the beam breakup threshold is also influenced by the bunch recombination pattern in the linacs, which is directly related to the linac-to-linac path-length.

An energy recovery linac must have a self-consistent match in longitudinal phase space. An overview of the possible longitudinal solutions for any multi-pass ERL using a semi-analytical method was presented [3]. This method is applied in collider scenarios (minimizing energy spread) and in FEL scenarios (embodying a compressive match). Additionally, the differences between common transport and separate transport topologies, as well as the impact of energy loss due to synchrotron radiation, were explored. Solutions can be obtained in all scenarios that do not require SR energy compensation. However, if SR energy compensation is required, only separate transport configurations can reliably provide adequate solutions.

In August 2021, the S-DALINAC has been realized as an SRF multi-turn ERL. This was a special challenge due to the common beam transport design. In this design, the once-accelerated and the once-decelerated beam have to share the same recirculation beamline. Here, beam tuning influences both beams simultaneously, so a proper setup had to be found prior to beam tuning using sophisticated beam dynamics simulations. These studies used low injector momenta to investigate an influence on the efficiency, and therefore it was necessary to take phase slippage into account by field map tracking. From the results of these simulations, a setup to realize the twofold ERL mode at S-DALINAC was found [4]. By comparing the beam loading of the twofold ERL mode with the beam loading of the conventional twofold acceleration mode, the efficiency of a SRF multi-turn ERL has been shown for the first time. Here, an efficiency of up to 87% was achieved.

The baseline scheme for hadron beam cooling in the Electron Ion Collider (EIC) calls for Coherent electron Cooling (CeC) of the hadrons with 150 MeV, 1 nC bunches, and 100 mA of average current provided by an ERL. Physicists and engineers at Xelera Research, working with colleagues at BNL, Jefferson Lab, and Cornell University, are working on a complete design of a system capable of satisfying these requirements and have produced an initial closed lattice design [5]. This design includes simulation of the injector, merger, multi-pass Linac, merger into the cooling section, demerger into the return line (which includes 180-degree arcs), and final extraction of the energy-recovered beam. Xelera is currently working on incorporating a precooling system into this design, as well as further studies such as beam breakup, tolerance investigations, start-to-end simulations, and beam halo studies.

Polynomial Chaos Expansion (PCE) is a method for representing a random variable in terms of a series of polynomials, where the polynomials are functions of other random variables. It can be used to determine uncertainty in parametric systems. Solenoid misalignment leads to a highly non-linear and highly coupled dependence of the trajectory and the beam size on the solenoid field. Therefore, a beam-based procedure to determine solenoid misalignment is needed

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for the commissioning of bERLinPro [6]. Distributions of solenoid misalignments can be created in the machine or as tracking input. When they are mapped to the corresponding beam positions and beam sizes on a screen behind the gun, the data can be used to set up a PCE surrogate model predicting the screen results for arbitrary misalignments. The same data can be used to reverse the process and predict the misalignments of the solenoid from the data on the screen. In this case, the polynomial series is expanded for the distributions of the positions and beam sizes on the screen. 100 data points are sufficient to predict the according offsets or angular misalignments of the solenoid to a few microns or micro radians. The uncertainty of the results can be estimated by Sobol's indices, which can be analytically determined from the polynomial expansions. They reveal that the accuracy of the results is primarily dependent on the accuracy of the determination of the beam sizes.

IR-SASE-FEL light has been demonstrated at the compact ERL for proof of concept of the EUV-FEL project [7]. The energy chirp phase was systematically surveyed for the bunch compression to find the best parameters for IR-FEL. It was found that the longitudinal space charge effects are severe compared to CSR wake. Beam tuning for maximizing IR-FEL intensity was performed using AI, which makes the beam tuning highly efficient because 3 to 6 parameters are optimized simultaneously. Energy recovery was demonstrated after installing the undulator, and high current operation with 0.25 mA was successful with radiation level kept low by collimating the halo and tail at low energy.

CBETA is a 4-pass ERL constructed at Cornell University in Ithaca, NY and commissioned in December 2019, with beam energy accelerating from 6 MeV to 150 MeV and decelerating back down to 6 MeV. This novel machine was a collaboration between Brookhaven National Lab and Cornell University, funded by New York State Energy Research and Development Authority (NYSERDA). The primary beam instrumentation devices used for commissioning the machine include view screens, beam position monitors (BPM), phase measurement bunch arrival monitors (BAMs), slow loss monitors and fast loss monitors. Details of these devices were presented, with a focus on the challenges of BPM measurements of up to 8 different beams (4 accelerating and 4 decelerating) coexisting in the same beam pipe [8]. A selection of additional beam dynamics issues from CBETA, including semi-empirical and full response matrix, 4-turn measured vs. model tunes, accelerating vs. decelerating splitter orbits, and more was also presented [9].

The Ghost Collider is a new concept for a high-energy, high-luminosity e+e- collider. Accelerating electrons and decelerating positrons in the same bucket eliminates higher order mode excitation. Interestingly, this means that there is no need for large aperture SRF cavities and high-power HOM couplers. The Ghost Collider adds the concept of four-beam collisions to remove beam-beam interactions and disruption [10]. This concept brings up a series of new beam dynamics problems which make optimization of the parameters difficult, but exciting.

REFERENCES

[1] R. Apsimon, "Implications of beam filling patterns on the design of recirculating energy recovery linacs", presented at ERL'22, Ithaca, New York, USA, October 2022, this conference.

[2] K. Andre, "Beam Dynamics and Performance Studies of PERLE", presented at ERL'22, Ithaca, New York, USA, October 2022, this conference.

[3] G. Perez-Segurana, "Multi-pass ERL Driven FELs and Light Sources", presented at ERL'22, Ithaca, New York, USA, October 2022, this conference.

[4] F. Schliessmann, "Challenges of a Twice-Recirculating ERL Mode", presented at ERL'22, Ithaca, New York, USA, October 2022, this conference.

[5] C. Gulliford, "Energy Recovery Linac Design and Studies for Electron Cooling of EIC Hadron Beams", presented at ERL'22, Ithaca, New York, USA, October 2022, this conference.

[6] B. Kuske, "Using Polynomial Chaos Expansion to determine solenoid misalignment during bERLinPro commissioning", presented at ERL'22, Ithaca, New York, USA, October 2022, this conference.

[7] M. Shimada, "Beam tuning for IR-FEL and industrial application at the compact ERL", presented at ERL'22, Ithaca, New York, USA, October 2022, this conference.

[8] R. Michnoff, "CBETA Instrumentation: From Beam Diagnostics to Machine Protection", presented at ERL'22, Ithaca, New York, USA, October 2022, this conference.

[9] S. Brooks, "Multi-Turn Performance Studies and Beam Dynamics Issues", presented at ERL'22, Ithaca, New York, USA, October 2022, this conference.

[10] A. Hutton, "Beam Dynamics Challenges of a Far-Future ERL-Based Collider - The Ghost Collider", presented at ERL'22, Ithaca, New York, USA, October 2022, this conference.