

# ERL BEAM DYNAMICS AND OPTICS: A SUMMARY OF WORKING GROUP 2 AT THE ERL WORKSHOP 2015

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## Abstract

The 45<sup>th</sup> Advanced Beam Dynamics Workshop on Energy Recovery Linacs, hosted by the Brookhaven National Laboratory, was held at the Stony Brook University Campus, June 7-12, 2015. It was the sixth in the series of international workshops covering accelerator physics and technology of Energy Recovery Linacs.

The workshop was organized into five working groups. Working group 2 (WG2) covered beam dynamics and optics issues of ERLs in operation as well as of proposed and future ones. Key aspects of some representatively selected talks together with the outcome of the working group discussion are summarized in this report.

## INTRODUCTION

Energy recovery linacs enable the generation of high current beams with ultimate brilliance - lowest transverse emittance at very short pulse lengths. Several ERL demonstrator facilities have been operated so far as well as a few one, that are or had been used for light generation: ALICE [1], NovoFEL [2] and JLab FEL [3], where the latter delivered the highest ever reached average photon flux and power in the near IR. ERL operation at higher energies and highest currents (as available in 3rd generation and ultimate storage rings or required for collider experiments) still needs to be demonstrated. On this route various physical and technological problems still must be overcome to fully benefit from the potential performance of ERLs.

The ERL workshops provide the ideal stage for presentation and discussion of latest results in the community. The 45<sup>th</sup> Advanced Beam Dynamics Workshop on Energy Recovery Linacs, hosted by the Brookhaven National Laboratory, was held at the Stony Brook University Campus, June 7-12, 2015. It was the sixth in the series of international ERL workshops, proceedings of previous workshops are available [4]. Five working groups have been established for the ERL2015:

- WG1 Injectors: Injector Performance, Electron Guns, Cathodes and Lasers
- WG2 Beam Dynamics and Optics: Collective Effects, Multi-Pass Effects and Halo Simulations
- WG3 Beam Instrumentation, Controls, Beam Losses and Halo Management
- WG4 ERL and SRF: SRF System Performance, Field Stability, Synchronization, Special Requirements and HOM Damping
- WG5 Applications

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For WG2, on those activities we report here, the charge has been defined in advance of the workshop as follows:

"WG2 will address the optics and beam dynamics challenges in ERLs. It will include lessons learnt from past and present ERL operation as well as issues arising during the design work on future ERL facilities. The group scope includes design approaches for one-pass and multi-pass ERL lattices, error tolerances, preserving longitudinal and transverse beam emittances during beam transport, simulation tools suitable for ERL modelling. We also will look at beam instabilities and collective effects as well as at mechanisms defining halo formation and beam losses"

Beside the plenary session with two talks assigned to WG2, three (split) sessions were dedicated to the WG2 topics. In addition there were a joint session with WG4 (SRF) and the poster session with four WG2 related posters.

A large variety of interesting and important topics has been presented in the 12 talks of the WG2 sessions. Just from the number of contribution we identified 4 "hot topics":

1. ERLs & FFAG beam transport: eRHIC (BNL),  $C\beta$  (Cornell/BNL), LHeC (CERN)
2. Microbunching Instability: simulations and  $\mu$ B-enhanced radiation generation
3. Beam Break Up: MESA (Mainz, Germany), KEK
4. CSR effect on the beam

on which we will focus on in the following. At the end we will recapitulate a fruitful discussion on beam losses and halo formation & control, triggered by the presentation of recent measurement results from cERL (KEK).

## ERLS & FFAG BEAM TRANSPORT

Recent results from BNL ERL Test Facility have been reported in Plenary talk by DMITRY KAYRAN (BNL), "STATUS AND COMMISSIONING RESULTS OF THE R&D ERL AT BNL". The first photocurrent from the ERL SRF gun has been observed in Nov. 2014 (1 uA per 500 msec RF pulse). During the spring 2015 new "multipactor free" Ta tip cathode stalks were prepared and conditioned, demonstrating 4% QE at room temperature and 1% QE in the gun. First beam test with the new cathode achieved the maximum average current of 4.5  $\mu$ A per 3 msec RF pulse. In a mode with rare bunch pulses, the maximum bunch charge of 0.55 nC has been demonstrated. The beam parameters, such as the energy and emittance have been measured. The commissioning of beam instrumentation is underway.

The progress on the lattice development and simulations for future ERL-based collider LHeC [5] was reported by ALEX BOGACZ (JEFFERSON LAB) AND DARIO PELLEGRINI (CERN), "ERL – DESIGN AND BEAM DYNAMICS ISSUES".

The lattice of all major components of recirculating passes has been worked out and optimized. It includes isochronous arcs, detector bypasses, spreader/recombiners and SR compensation sections. The major goal of lattice optimization was the emittance preservation during the beam transport. The interaction region still needs to be integrated to complete the lattice integration. PLACET2 code is being used for beam dynamics simulations, including synchrotron radiation, beam-beam effects, cavity misalignments and long range wakefields. The importance of combined consideration of BBU and beam-beam interaction was pointed out. In near plans are studies of ion cloud effects.

Several talks were dedicated to the studies of FFAG (Fixed-Field Alternating Gradient) lattice which is considered for application in multiturn ERL-based collider eRHIC [6]. STEPHEN BROOKS (BNL), "eRHIC: AN EFFICIENT MULTI-PASS ERL BASED ON FFAG RETURN ARCS" described all major features of FFAG lattice in eRHIC, where 32 of total recirculations are planned by using only two FFAG beam lines. The elementary FFAG cell contains two quadrupoles which centers are offset. Proper arrangement of the offset between quadrupole centers allows to realize various FFAG lattice components, arcs, straights, matching sections and detector bypasses. The lattice optimization was done to minimize synchrotron radiation, as well as other important values (pathlength difference, orbit spread, ...). The FFAG lattice can be realized with permanent magnets. The design of permanent magnets for eRHIC FFAG beam lines was presented

Since the beam of multiple different energies propagating through the same FFAG beam line, the subject of the orbit control is of large importance. It was reported by CHUYU LIU (BNL), "CORRECTION METHODS FOR MULTI-PASS ERHIC LATTICE WITH LARGE CHROMATICITY" who concluded that the large chromaticity, intrinsically present at lower energies in the FFAG beam line, had to be included in the correction algorithm to warranty the successful orbit correction. It may require measuring orbit response modified by large chromaticity during machine commissioning or operation. The SVD-based orbit correction algorithm includes the orbit measurements taken from several turns, with the quality of the orbit correction quickly converging with the number of turns used.

NICHOLAUS TSOUPAS (BNL), "THE OPTICS OF THE ERHIC LOW ENERGY FFAG CELL WITH REALISTIC FIELD MAPS" showed the eRHIC simulations done with 3D-field maps of FFAG cell magnets. The field maps were calculated for Halbach-type permanent magnets. The field measurements done for short length prototypes of this magnet agreed with field calculations very well. The results for the beam transport through the FFAG beam line of low energy FFAG satisfied the machine requirement.

Simulations of beam transport in eRHIC FFAG arcs, including beam polarization, were shown by FRANCOIS MEOT (BNL), "BEAM AND POLARIZATION DYNAMICS IN ELECTRON FFAG LATTICES". The ray-tracing code ZGOUBI was used for these studies. The effect of synchrotron radiation leads

to small deterioration (3%) of beam polarization. The simulations with different kind of magnetic errors would help to establish the tolerances on the magnetic field errors. The effect of emittance dilution due to the orbit errors in the lattice with high chromaticity has been also studied.

Longitudinal dynamics studies for eRHIC using ELEGANT code has been presented by YUE HAO (BNL), "ASPECTS OF ERHIC LONGITUDINAL DYNAMICS". eRHIC design uses additional RF systems to compensate for energy losses caused by synchrotron radiation and to reduce the beam energy spread. In addition the proper choice of the pathlength and  $R_{56}$  parameters is required in order to minimize the energy spread of decelerated beam. Further optimization of longitudinal parameters is planned to ensure better energy recovery efficiency.

Two talks were devoted to another ERL that will use the FFAG lattice for beam recirculations. In the Plenary talk GEORG HOFFSTAETTER (CORNELL UNIVERSITY), "A FFAG-ERL AT CORNELL, A BNL/CORNELL COLLABORATION" described the future  $C\beta$  ERL-facility at Cornell University planned in a collaboration with BNL [7]. The few hundred MeV facility can be used to verify various aspects of FFAG technology applications for ERLs as well as to carry out nuclear physics experiments with an internal target. It takes an advantage of existing Cornell high-current injector and a Linac Cryomodule. The detail of lattice components for this Cornell/BNL ERL were shown by CHRISTOPHER MAYES (CORNELL UNIVERSITY), "OPTICS CONSIDERATIONS FOR THE CORNELL-BNL FFAG-ERL TEST ACCELERATOR". It included the optics for all passes through the FFAG beam line, as well as for spreader/merger and main linac. The longitudinal transport was optimized to reduce the energy spread of decelerated beam. Studies of various beam dynamics effects as well as orbit/optics correction are ongoing.

## MICROBUNCHING INSTABILITY

Initial small longitudinal density modulation (even random noise) can cause momentum variations by interact with the various wakes fields in the beam pipe. On the other hand such a micro-bunching itself can drive the generation of strong wakes (e.g. SC or CSR). Under certain circumstances the momentum modulation leads to an enhanced density modulation and a resonant feedback loop - the micro bunching instability ( $\mu$ BI) - can build up. The density modulation is described by the Fourier-components of the longitudinal density distribution: the bunching factor  $b(k)$ . Its wavelength depending amplification passing a given accelerator is calculated as the bunching gain  $G(k)$ .  $\mu$ BI have been observed on linacs with strong compression but also on storage rings operating bunches with high peak current. A series of  $\mu$ BI dedicated workshops have been held in the past [8].

Two talks were related to  $\mu$ BI on the ERL2015: ATOOSA MESECK (HZB), MICROBUNCHING INSTABILITY IN ERLs - A BLESSING OR A CURSE": The  $\mu$ BI at bERLinPro [9] has been studied, using analytical formulas as well as the sim-

ulation code ASTRA. Amplification of initial shot noise due to LSC has been simulated, showing the most pronounced impact in the wavelength range from 1  $\mu\text{m}$  to 1 mm, as expected from the applied impedance spectrum for analytical calculations. However, the longitudinal machine dispersion ( $R_{56}$ ), leads to damping (instead of amplification) of the shot noise for almost the entire wavelength range. As result of the simulations no significant gain and thus  $\mu\text{BI}$  is expected for bERLinPro's standard mode of operation. Additional analytical 1D estimations including CSR impedance give no indication for  $\mu\text{BI}$  too.

As an example a test beam line including a Compact FODO Channel (CFC) has been optimized to drive the  $\mu\text{BI}$ : significant gains can be reached, potentially allowing the generation of at least partly coherent radiation in the EUV. Next studies will consider  $\mu\text{BI}$  in bERLinPro's short pulse mode and further investigations on  $\mu\text{BI}$  supported radiation generation.

CHENG-YING TSAI (VIRGINIA POLYTECHNIC INSTITUTE AND STATE UNIVERSITY), "LINEAR MICROBUNCHING GAIN ESTIMATION INCLUDING CSR AND LSC IMPEDANCES IN RECIRCULATION MACHINES": to investigate  $\mu\text{BI}$  on the CCR (Circular Cooler Ring) of JLab's proposed Medium Energy Electron Ion Collider MEIC [10], a new program, based on an extended Vlasov solver, has been written. Main program features are the implementation of horizontal & vertical bending magnets (need for spreaders and recombiners in ERLs), non ultra-relativistic, transient and steady state CSR as well as 1D LSC. The semi-analytical program uses elegant generated input and calculates gain curves for a given lattice. Calculation times for the whole gain curve correspond to those of a single elegant run. Application to a high energy arc for code testing showed very good agreement to elegant, both for a lattice developing a strong  $\mu\text{BI}$  as well as for one tuned to minimize the overall gain. Gain curves for MEIC CCR have been presented, indicating high gains with peak values in the order of  $10^8$  at 350  $\mu\text{m}$  wavelength, where LSC caused even higher gains compared to CSR. Implementation of further impedance models, energy changes in the beam line and benchmarking with experiments are planned.

## BEAM BREAK UP

A bunch passing a cavity off-axis excites higher order dipole modes (HOMs), where the amount of transferred energy depends on the off-axis amplitude. At the same time an already existing cavity HOM field kicks the bunch, thus changing its downstream trajectory. If the bunch's total energy transfer into the cavity HOM from all turns is not damped until the next bunch passes, a resonant loop can be formed. Especially in super conducting cavities with high quality factors, HOM amplitudes can get high enough to cause beam loss. The so called Beam Break Up (BBU) occurs in various forms - transverse and longitudinal, single and multi pass - and can severely limit the maximum machine current. The instability has been observed on many

machines since the 1960ies and needs to be carefully considered in the design of high current accelerators.

In WG2 two BBU dedicated talks were given: THORSTEN KUERZEDER (TU DARMSTADT), "INVESTIGATIONS ON TRANSVERSE BEAM BREAK UP USING A RECIRCULATED ELECTRON BEAM": observation of current limitations at the S-DALINAC facility [11] were introduced and related to the transverse BBU instability. While planning for a maximum of 20  $\mu\text{A}$  no currents higher than 8  $\mu\text{A}$  have been reached so far. A BBU instability, caused by the eight 3 GHz cavities, is supposed. In the design of these 1 m long, 20 cell cavities neither minimized HOMs nor HOM absorber had been considered. Several proposals to increase the BBU threshold are considered: beside the optimization of transverse tunes, 3 skew quadrupoles have been inserted into the new, second recirculation line, enabling a complete transverse phase space exchange. First test will be start in July 2015. Another approach is a massive increase of chromaticity: for large values with  $|\xi \Delta E/E| \gg 1$  a significantly increased BBU threshold current is expected. With  $\Delta E/E 10^{-3}$  the natural chromaticity is one order of magnitude too low. 12 sextupole magnets with an integrated sextupole strength of 10 T/m have been fabricated and will be placed at highest dispersion positions inside the arcs. Detailed BBU studies are planned for 2015/16.

SI CHEN (KEK), "HOM-BBU SIMULATION FOR KEK ERL LIGHT SOURCE": The ERL driven photon factory [12], proposed at KEK, is planned to operate with up to 100 mA beam current. Results of latest BBU simulations, using a new 3.4 GeV lattice design together with the new HOM optimized "Model II" cavities, have been presented and compared to former calculation with the 3.0 GeV lattice and TESLA like resonators. Recirculation phase scans yields threshold currents between 220 and 300 mA, where BBU simulations for single cavities indicate lower thresholds when placed in low energy sections. Based on an FFT analysis of the simulated transverse beam motion the dominant mode at  $f = 4.011$  GHz could be identified and excellently agrees with the input HOM parameter set. As expected, HOM frequency randomization studies for the 224 cavities yield higher thresholds: the average value for 1000 sets of Gaussian distributed HOM frequency shifts is 640 mA ( $\sigma_f = 1$  MHz). Variation of the frequency shift showed an almost linear threshold increase from the shift-free case ( $\sigma_f = 0$  MHz, 220 mA) to 940 mA at  $\sigma_f = 2$  MHz. Further lattice and cavity optimization work is planned for the next time.

## CSR EFFECT ON THE BEAM

Two talks were devoted to studies related with Coherent Synchrotron Radiation. CHRISTOPHER HALL (COLORADO STATE UNIVERSITY), "STUDY OF CSR IMPACT ON ELECTRON BEAM IN THE JLAB ERL", presented results of measurements which used controllable bunch compression in two locations of the JLab ERL. The resulting beam energy distribution, impacted by CSR-induced energy loss, was measured in the downstream arc. The fragmentation of the energy spectrum,

enhanced by longitudinal space charge, was observed. All measured results show good qualitative agreement to 1-D CSR simulations. It was also concluded that CSR in drifts after a bunch compressor can have a large impact on the energy distribution.

SIMONE DI MITRI (ELETTRA - SINCROTRONE TRIESTE), "TRANSVERSE EMITTANCE PRESERVING ARC COMPRESSOR: SENSITIVITY TO BEAM OPTICS, CHARGE AND ENERGY" extended the theory of CSR kick-optics balance to the case of varying bunch length. The optimal optics is based on a principle of canceling successive CSR-induced kicks to minimize CSR-induced emittance growth. The theoretical and simulation studies were presented for the arc compressor, based on DBA cells that has properly balanced optics.

## BEAM LOSSES & HALO

Much of the discussion time was devoted to the topic of the beam halo and related slow beam loss. PAVEL EVTUSHENKO (JEFFERSON LAB) listed the major halo sources in JLab FEL injector. They include a limited extinction ratio of drive laser, stray laser light and its reflections hitting the cathode and elsewhere, and space charge dominated beam transport. There is no intentional collimation implemented in JLab ERL, but minor collimation of bunch tails is done naturally by the vacuum chamber.

cERL, which is under commissioning in KEK (Japan), carried out initial collimation studies, mentioned in the Plenary talk by SHOGO SAKANAKA (KEK), "SUCCESSFUL RESULT OF THE COMMISSIONING ON cERL IN KEK". The collimated portion of beam was up to 0.1% of total beam current, but the efficiency of the collimation with respect to the radiation levels seen in recirculating arc was not very clear. It was pointed out that the collimation system has not yet been optimized, since it is not necessary at the present beam current levels ( $<100 \mu\text{A}$ ). Thus, much of interest will be the further experience with the collimation system at cERL, as the beam current increases. For simulation of collimation the GPT code was used with  $10^5 - 10^6$  particles. It was noted that 2012 an "Unwanted Beam" workshop took place in Berlin, devoted to the topic of the beam halo, dark current and beam loss control.

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