MAGNET OPTICS AND BEAM DYNAMICS OF B*ERL*inPro

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Abstract

The Helmholtz-Zentrum Berlin für Materialien und Energie GmbH is proposing to build an Energy Recovery Linac prototype, called B*ERL*inPro, at its site in Berlin Adlershof. In this paper we introduce the recirculator part of the ERL and discuss the ERL requirements to the magnet optics. The current design of the magnet lattice will be described and main parameters and simulation results presented. Since B*ERL*inPro aims to demonstrate high current operation with short pulses according optics aspects will be also discussed. The focus here will be on longitudinal phase space manipulations and lattice layout options, suppressing the BBU instability and increasing its threshold currents.

INTRODUCTION

After almost 30 years of successful storage ring operation the Helmholtz-Zentrum Berlin für Materialien und Energie GmbH (HZB, previously BESSY) is presently developing a design for a future multi-user light source as a possible successor to BESSY II to enable "next-generation" experiments. This facility will be based on the energy-recovery-linac (ERL) principle. To demonstrate the ERL's high current and low emittance operation capabilities and to bring ERL technology to maturity HZB is proposing to build B*ERL*inPro [1], a 100 MeV prototype ERL facility.
B*ERL*inPro's main components will be the superconducting rf accelerating structures: a photo-injector gun, a booster and a main linac module. These accelerating sections are connected by beam transport lines: a merger, a recirculator and a splitter with the beam dump line. A test stand for a superconducting RF gun is already under construction [2]. A machine draft is shown in Fig. 1, the main parameters of B*ERL*inPro are summarized in Table 1.

Table 1: Main Parameters of B*ERL*inPro

maximum beam energy	100 MeV
maximum beam current	100 mA
nominal bunch charge	77 pC
maximum repetition rate	1.3 GHz
normalized emittance	$<$ 1 mm mrad

Although the main task of the recirculator is to transport the beam back to the linac for energy recovery, there are a lot of other requirements that have to be considered in the recirculator design. Most important demands on the recirculator's beam transport properties are discussed in this paper: the magnet lattice layout and its linear and nonlinear properties, options for re-linearizing corrections and finally optics adjustments, aiming to counteract the Beam BreakUp (BBU) instability.

RECIRCULATOR OPTICS

Path Length

To recover the energy on the second linac passage the beam has to enter the linac with a phase shift of $\Delta\phi = \pi$ which corresponds to a reciculator circumference (including the linac) of $C_R = (N + 1/2)\lambda_{RF}$, adjusted by the reference orbit length (λ_{RF}: RF wavelength, N: arbitrary integer number). Due to limits in the alignment accuracy a tool for minor path length adjustments will be needed. Three options are in discussion:

- dipole chicane in a straight section: separated device but needs extra space,
- dipole chicane integrated in the arc, using one of the arc's bending magnets: only few extra space required but coupled function,
- mechanical shifting of a whole arc (one large girder): accuracy in the micrometer range can be reached and is fully sufficient, large changes possible.

In order to have maximal flexibility for a prototype test facility we currently favor the last option.

Magnet Lattice

The simplest and most compact design of an ERL recirculator will have a racetrack shape, where merger, linac and splitter are placed in the first straight section while the second one will be available for experiments e.g. ID tests. For the two $180°$ arcs basically two symmetric and achromatic options exist: a Triple Bend Achromat (TBA), using three bends, either identical $60°$ magnets (ERLP/ALICE [3]) or with a stronger middle dipole ($45°$-$90°$-$45°$) (Japan Test ERL [4]). The second type is a so called Bates Arc [5], made up from four smaller bends together with a large $180°$ magnet (JLab IRFEL Driver ERL [6]). In principle also a double DBA (Double Bend Achromat) can be considered but for its most compact form with no space between the DBA segments one ends up with the TBA. A detailed comparison of TBA and Bates arc has been done for the ERLP design [7], concluding very similar properties for both options. Preference is given to the TBA there due to its good momentum acceptance. For that reason we also decided to use a TBA structure in the B*ERL*inPro recirculator arcs, with all magnets of equal length, field and angle ($\phi = 60°, \rho = 1.0$ m). Two quadrupole magnet families

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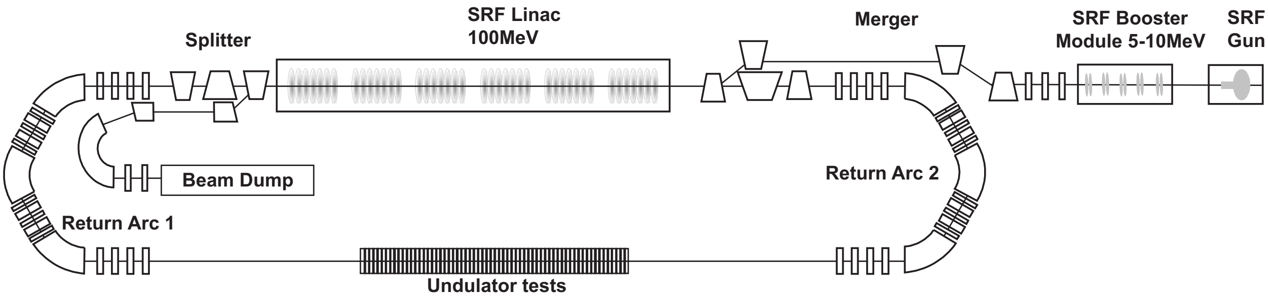

Figure 1: B*ERL*inPro: schematics of the ERL prototype.

inside each arc allow to keep the arcs achromatic and to control the first order dispersion and thus the matrix element R_{56} independently. In order to be able to modify the nonlinear terms of the longitudinal as well as of the transverse beam dynamics two sextupole and one octupole magnet family per arc are used. Up to four quadrupole magnets before and after each arc allow for a proper beta matching into and out of the arcs.

Linear Optics

The Twiss-parameter for the B*ERL*inPro recirculator have been set to meet various criteria:

- small transverse beam size: since only very few losses can be tolerated the beam should only fill a small fraction of the available vacuum aperture. To reach this the arc is achromatically operated, giving dispersion free straight sections and the maximum dispersion value in the arc is kept small,
- depending on the operational mode a vanishing R_{56} (normal mode) or a moderate R_{56} of varying sign (short pulse mode) can be adjusted,
- suitable beta functions in the multipole magnets for an effective operation of those,
- suitable transverse beam size for a possible (ID) experiment,

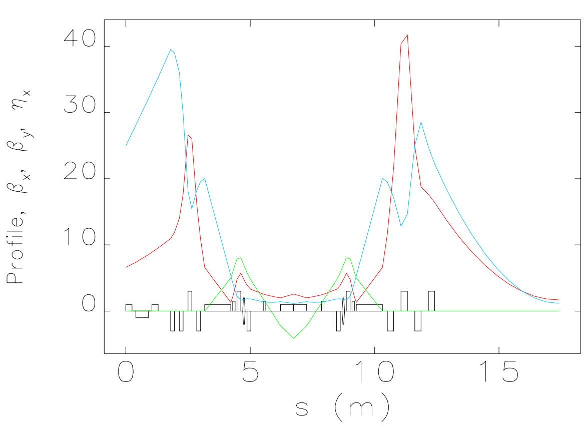

Figure 2: Magnet lattice and Twiss-parameter for the first half of the B*ERL*inPro recirculator in "Normal Operation" ($R_{56} = 0$ m). red: β_x, blue: β_y, green: $\eta_x \cdot 10$.

- suitable betatron phase advance to maximize BBU limited current thresholds.

In Fig. 2 the magnet lattice and the Twiss-parameter for the first half of the recirculator are shown. Since Twiss-parameter out of the linac are not yet known some exemplary values have been used here.

Nonlinear Optics

Two modes are foreseen for the B*ERL*inPro operation: a main, high current, low emittance mode with moderate bunch length ($I = 100$ mA, $\varepsilon_{x,y} = 1$ mm mrad, $\sigma_t = 2$ ps) and a lower current, short pulse mode with ultimate bunch lengths of 100 fs and below. Although due to diverse reasons the use of multipole magnets is essential for operation in each of the modes.

Normal mode: even with on crest acceleration the RF induced energy spread of longer bunches can cause significant chromatic effects e.g. an emittance growth. Multipole magnets in the first arc will be used to counteract these effects and ensure preservation of the low emittance. In the second arc the multipoles are set to reproduce the longitudinal phase space out of the linac, minimizing the energy spread of the decelerated beam.

Short pulse mode: to reach shortest pulses bunch compression is required. This is done by passing the linac off crest generating an energy ramp $E(s) = E_0 \cos(s \cdot 2\pi/\lambda - \phi_0)$ and sending the beam through a non-isochronous section $\Delta L = R_{56}\delta + T_{566}\delta^2 + U_{5666}\delta^3 + \mathcal{O}(\delta^4)$ afterwards, with $\delta(s) = (E(s) - E(0))/E(0)$. Ultimate compression can only be reached without any nonlinearities in $E(s)$ and $\Delta L(\delta)$ or if they can be adjusted to cancel out each other. Since the first case never happens in reality we are dealing with case two. For the non-isochronous section we use the arcs instead of extra dipole chicanes and adjust for a moderate R_{56} of changing sign in both arcs: $R_{56}^{A1} = -R_{56}^{A2} = 20$ cm. Two sextupole and one octupole family per arc allow to optimize the higher order matrix elements T_{566} and U_{5666} so that they can cancel out with the RF induced nonlinearities. Numerically the matrix values can be derived from a Taylor expansion of the inverse function: $f^{-1}(\delta(s)) = s(\delta)$.
In Fig. 3 the longitudinal phase space of compressed

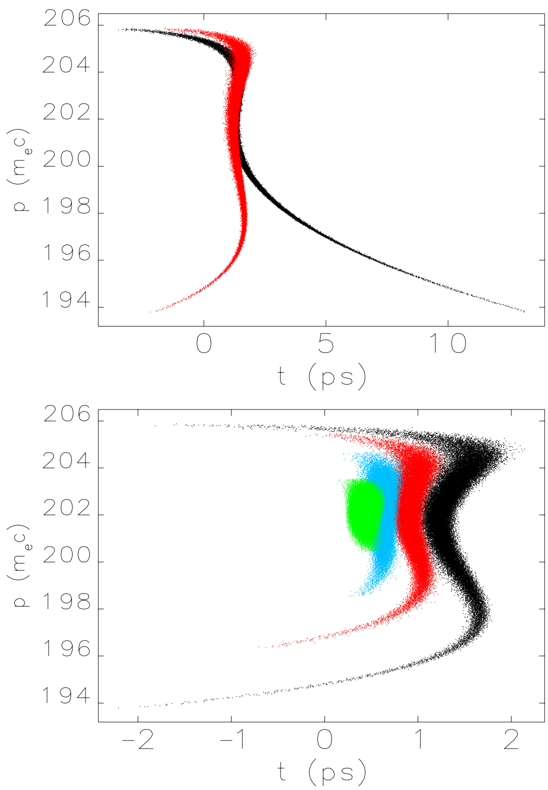

Figure 3: Short pulse mode: top) long. phase space without (black) and with (red) multipoles, ($\sigma_{l,i} = 2.0$ mm); bottom) long. phase space for bunches of minimized length starting with various initial pulse lengths out of the linac: $\sigma_{l,i} = 2.0$ (black) / 1.5 (red) / 1.0 (blue) / 0.5 (green) mm $\longrightarrow \sigma_{l,f} = 73/34/21/20\ \mu$m.

bunches is plotted: the upper graph shows the effect of multipoles, the lower one pulses of varying initial length, with multipoles individually optimized to reach shortest pulses. For initially longer pulses the nonlinear tails determine the bunch length, while starting with shorter pulses the initial energy spread ($\sigma_E = 0.1$ % assumed at linac entry) dominates the final bunch length.

BEAM BREAKUP INSTABILITY

BBU is one of the beam instabilities that can limit the current in an ERL. BBU mechanisms are well understood and there are a number of codes to simulate it. We modeled the BBU threshold current with a gbbu code [8]. The threshold current depends on the frequency f and quality factor Q of the dipole HOMs in the cavity. The distribution of the measured f and Q in Tesla cavities is quite wide; Q can differ by a factor of 3, f can have up to 10 MHz separation. This leads to a definite uncertainty in the threshold current prediction. In this model we tried to find the optimal betatron phase advance in the ERL recirculator without focusing optics between the accelerating cavities. We assumed two sets of Q's: one according to DESY measurements [9] and another one, measured on a Tesla type cavity with TDR HOM couplers in HoBiCat [10].

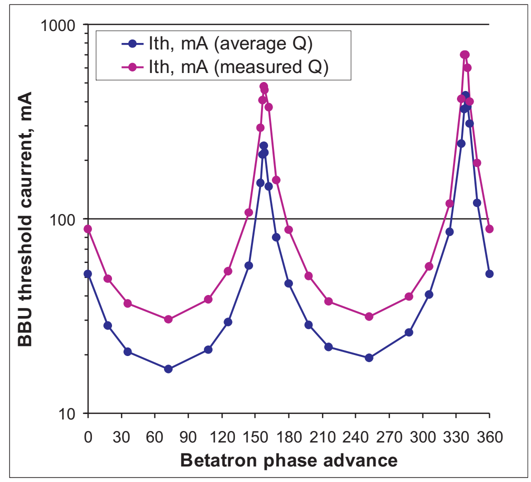

Figure 4: B*ERL*inPro: BBU threshold currents vs recirculator phase advance for two HOM sets.

The HOM frequencies are taken to be equidistant with $\Delta f = 1$ MHz from cavity to cavity. The separation between polarizations is set to 0.1 MHz for all modes. 11 modes with the highest $(R/Q) \cdot Q$ parameter and frequencies up to 3 GHz are taken into account for each of the 6 cavities. In Fig. 4 the BBU threshold currents as function of the betatron phase advance in the recirculation loop are shown, indicating that the 100 mA target current can be reached with the assumptions we made.

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