FEASIBILITY STUDY OF AN ERL-BASED GEV-SCALE MULTI-TURN LIGHT SOURCE*

Y. Petenev#, T. Atkinson, A.V. Bondarenko, A.N. Matveenko, HZB, Berlin, Germany

Abstract

A new generation of particle accelerators based on an Energy Recovery Linac (ERL) is a promising tool for a number of new applications. These include high brilliance light sources in a wide range of photon energies, electron cooling of ion beam and ERL-based electron-hadron colliders. Helmholtz-Zentrum Berlin started a feasibility study of GeV-scale multi-turn ERL-based light source (LS). This LS will work in diffraction limited regime in X-rays and with a short length of a light pulse in femtosecond region. The average and peak brightness will be at least an order of magnitude higher than synchrotron-based LS. In this work an overview of the future multi-turn light source is given. Estimations of the Beam Break Up instability are presented.

INTRODUCTION

In this document we present a design of a new 3 pass ERL-based LS with 6 GeV maximum energy of electron beam. This future facility is named Femto-Science Factory (FSF). The design was optimised to achieve advantages in the average and peak brilliance. The schematic layout of the facility is presented in Fig. 1. A beam is created in 1.3 GHz SRF gun with photo cathode. The problem of high brilliance SRF injectors is being deliberately investigated as the injectors promise to deliver extremely low emittance bunches needed for the future linac-based light sources. We consider an SRF injector with similar parameters to the B*ERL*inPro injector under development at HZB [1, 2]. Then it passes a 100 MeV Linac and is accelerated to 6 GeV after passing 3 times through each of two 1 GeV main Linac's. In the arcs between the acceleration stages it is assumed to have undulators with periods of 1000 and in the long straight section (see Fig. 1) a long undulator with 5000 periods is assumed.

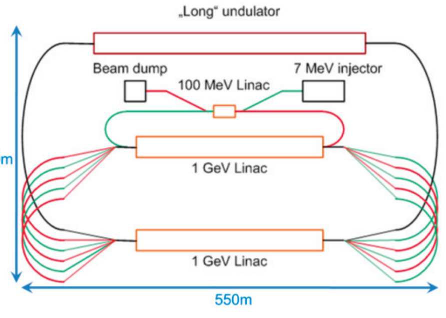

Figure 1: The scheme of FSF.

To reach the proposed wavelength of 1 Å, undulators require a period d=2 cm and K=0.8.

$$\lambda = \frac{d}{2\gamma^2}(1+\frac{K^2}{2}) \approx 1\mathring{A}\,, \qquad (1)$$

for a 6 GeV beam. Therefore to work in diffraction limited regime a normalized emittance ε_n should be below 0.1 μm:

$$\varepsilon_n \approx \gamma\frac{\lambda}{4\pi} \approx 0.1\mu\mathrm{m}\,. \qquad (2)$$

To achieve the record parameters it is planned to have two operation modes. The 1st mode will be optimized to provide a high brilliance beam. Another option is short bunch mode with a final beam minimal bunch length of around 10 fs.

The main design parameters of FSF are presented in Table 1.

Table 1: Main design parameters of FSF

Parameter	**High brilliance mode**	**Short bunch mode**
E, GeV	6	6
<I>, mA	20	5
Q, pC	15	4
τ, fs	200-1000	~10
<B>, ph/s/mm2/mrad2/0.1%	$8\cdot10^{22}$	$\sim4\cdot10^{21}$
B_{peak}, ph/s/mm2/mrad2/0.1%	10^{26}	$\sim10^{26}$
Accelerating gradient, MV/m	17	
Energy gain per linac, GeV	1	
f, GHz	1.3	

Peak and Average Brilliance

For an undulator of N=1000 periods in a diffraction limited regime, the average brilliance B_{av} is given by the beam size σ and the phonon flux through the solid angle Ω.

$$\sigma \approx \frac{Nd}{2\gamma}\sqrt{\frac{1+0.5K^2}{2N}} \approx 22\mu m\,, \qquad (3)$$

where a period of undulator d=2 cm and undulator parameter K=0.8 were taken for this estimation.

The 22 micron-sized 20 mA beam produces a spatial

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#yuriy.petenev@helmholtz-berlin.de

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flux for the *i*-th harmonic which can be approximated in the forward direction [3].

$$\left.\frac{d\dot{N}}{d\Omega}\right|_i = 1.746\cdot 10^{23} E[GeV]^2 I[A] N_p^2 \frac{\Delta\omega}{\omega} f_i(K) \approx_{i=1} 4\cdot 10^{19}\frac{ph}{s\cdot mrad^2\cdot 0.1\%}, \quad (4)$$

where $f_i(k)$ – are the amplitudes of the harmonics and $f_l(0.8) \sim 0.3$.

An average brilliance is given by:

$$B_{av} = \frac{d\dot{N}}{d\Omega}\frac{1}{\sigma^2} \approx 8\cdot 10^{22}\frac{ph}{s\cdot mm^2\cdot mrad^2\cdot 0.1\%}, \quad (5)$$

that is higher than for the 3rd generation light sources.

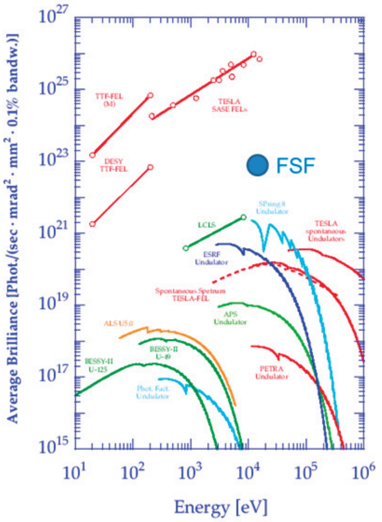

Figure 2: Average brilliance.

Bunch compression is required to achieve high peak brilliance. The compression is subtle as not to spoil the emittance. With an average current of 20 mA, longitudinal size of 200 fs and peak current is 30 A one can likewise approximate the peak brilliance B_p.

$$\left.\frac{d\dot{N}}{d\Omega}\right|_{i=1} \approx 6\cdot 10^{22}\frac{ph}{s\cdot mrad^2\cdot 0.1\%}, \quad (6)$$

$$B_p \approx 10^{26}\frac{ph}{s\cdot 0.1\%\cdot mm^2\cdot mrad^2}, \quad (7)$$

A comparison between average brilliance of 3rd generation light sources and Free Electron Lasers and FSF is presented in Fig. 2.

Short Bunch Mode

Single pass machines do not suffer the same fate as storage rings as equilibrium is never reached. Here first design considerations, based on linear uncoupled optic, help address a proof-of-principle for the short pulse mode.

In this regime the combination of the linac chirps and the R56 in the arcs are described as a simple focusing lens. The shortest pulse achievable is from a multi-turn isochronous structure with full compression in the final arc. This is however at the expense of a correlated energy spread, shown in Fig. 3 blue.

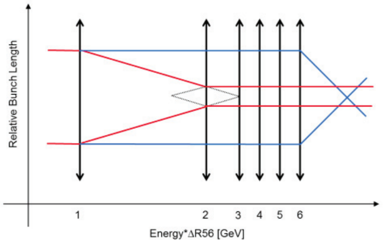

Figure 3: Longitudinal focusing.

In order to conserve the uncorrelated energy spread and still produce a short pulse an alternative solution is based on a telescopic lattice. Implementing the first two arcs as achromats and accelerating off-crest in both main linacs, the two "lenses" can share the same focal plane, just like in a telescope, to maximize the magnification and conserve the energy correlation properties, in Fig. 3 red.

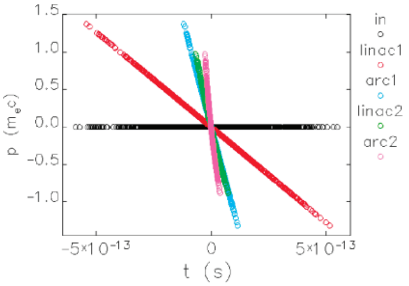

Figure 4: Longitudinal phase space plot of two stage scheme towards full compression.

Large cumulative distortions due to radiation effects are not envisaged in this two stage process to achieve full compression as the energy after the first main linac is 1 GeV and the bunch charge is reduced for the short pulse mode.

The minimal bunch length of the final beam into the long undulators, assuming longitudinal emittance is conserved, is restricted by the requirement of an rms energy spread of ~ 1/UndulatorPeriods ~ 10^{-4}, to be around 10 fs. The beam properties at the injector exit of BerlinPRO [2] will be used as a starting point for future simulations, and compared to the linear optic case above.

Linac Optics Design

In this part we design a 1 GeV linac for the FSF. The linac is planned to be based on the BERLinPro[2] 7-cell cavities. To reach 1 GeV in the Linac we took 72 cavities and distributed them over 9 cryomodules. The cryomodule is schematically presented in Fig. 5.

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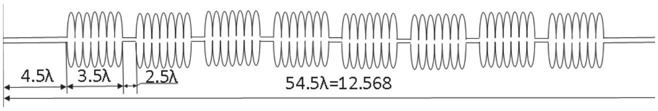

Figure 5: The scheme of FSF cryomodule.

Triplets of quadrupoles are planned to be in between the cryomodules in the linac. The full length of the linac is then about 140 m. Optics for all three passes through the first 1 GeV linac is presented in Fig. 6. It will be discussed in the last paragraph of this paper that one serious limitation on the beam current for ERL-based machines is a Beam Break Up instability which will develop in the 1-st linac for the FSF. Therefore the strengths of the quadrupoles were optimized to have the minimum of the beta functions on the 1-st pass through the 1-st linac.

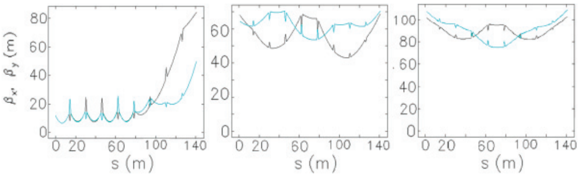

Figure 6: Optics design of the first 1 GeV linac. 3 passes with 1, 3 and 5 GeV beam energy after the pass from left to right correspondingly.

Also the optics was designed for the second 1 GeV Linac and it is presented in Fig. 7.

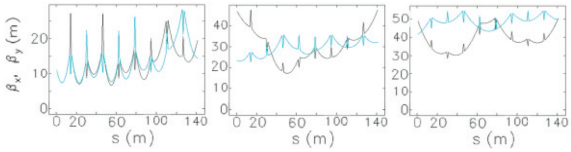

Figure 7: Optics design of the second 1 GeV linac. 3 passes with 2, 4 and 6 GeV beam energy after the pass from left to right correspondingly.

In both linacs the optic is assumed to have mirror symmetry at the middle of the 5-th cryomodule. Optic for deceleration is then shown from right to left in Figs. 6, 7.

Design of the Arc

We consider the ring consisting of 20 triple bend achromats. The magnetic length of a bend L=1.4 m, the bending angle α=6° and bending magnetic field B=1.5 T.

The arcs for all passes are vertically spread and proportionally adjusted to match the energy. The optic design of one TBA cell is presented in Fig. 8.

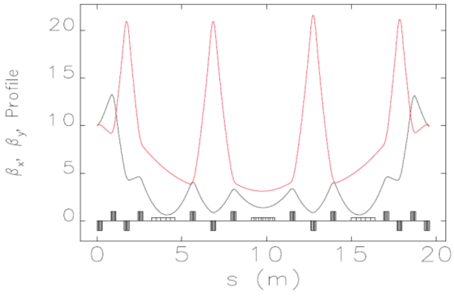

Figure 8: Beta function in a triple bend achromat cell with matching section.

Between TBA sections it is assumed to have an undulator with N=1000.

To achieve 10 m beta functions after an undulator we put a triplet in the middle as it is shown in Fig. 9.

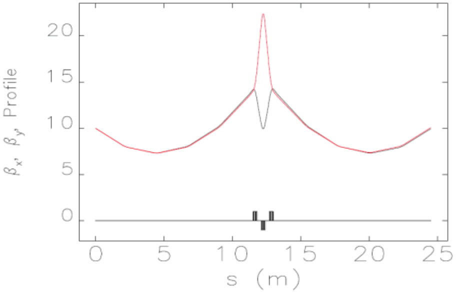

Figure 9: Beta function in an undulator.

The length of one TBA section is 20 m and the length of the undulator section is 25 m, so a perimeter of a 6 GeV ring without linacs is 20·(20m+25m)≈900 m.

Estimations of BBU Instability Threshold

One of the main problems of modern superconducting ERLs is the Beam Break Up instability. A theory of BBU instability in ERLs was presented in [4]. If an electron bunch passes through an accelerating cavity it interacts with dipole modes (e.g. TM110) in the cavity. First, it exchanges energy with the mode; second, it is deflected by the electro-magnetic field of the mode. After recirculation the deflected bunch interacts with the same mode in the cavity again which constitutes the feedback. If net energy transfer from the beam to the mode is larger than energy loss due to the mode damping the beam becomes unstable.

One can roughly estimate the BBU threshold current for multipass ERL with one mode in one cavity using [4, 5]:

$$I_b = -\frac{2pc^2}{e\omega R_d m_{12}\sin(\omega T)}\frac{1}{N(2N-1)}, \qquad (8)$$

and with $R_d=6\cdot 10^5$, $\omega=2\pi\cdot 2\cdot 10^9$, $\sin(\omega T)=1$, $m_{12}=\beta$ gives $I_{th}\sim 0.8\ A$ for $E=10\ MeV$ and $\beta=1\ m$ and $I_{th}\sim 0.05\ A$ for $E=110\ MeV$ and $\beta=12\ m$, this means that the instability will develop in the 1st 1 GeV Linac.

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