FEASIBILITY STUDY OF SHORT PULSE MODE OPERATION FOR MULTI-TURN ERL LIGHT SOURCE*

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Abstract

The optic and simulation group at HZB are designing a light source based on the emerging Energy Recovery Linac superconducting technology, the Femto-Science-Factory (FSF) will provide its users with ultra-bright photons of angstrom wavelength at 6 GeV. The FSF is intended to be a multi-user facility and offer a wide variety of operation modes. A low emittance $\sim 0.1\,\mu$m rad mode will operate in conjunction with a short-pulse $\sim$10 fs mode.

INTRODUCTION

This paper continues on from a recent introductory study[1] and highlights the physical limitations when trying to offer interchangeable modes and preserve beam quality. The paper concentrates on the short bunch mode, introducing the multi stage compression schemes in a general manner and presents the first results of the start-to-end beam simulations.
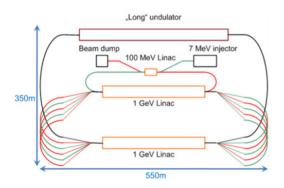

Figure 1: Schematic of the FSF Multi-Turn ERL.

The main design parameters of the FSF are listed in Table 1 and Fig. 1 shows the layout of the light source.

A SRF injector based on the design parameters of the BERLinPro[2] project delivers the 100 MeV electron beam into the main accelerator. Here two 1 GeV linacs are continually traversed until 6 GeV beam energy is reached. Each Arc contains straight sections for undulators and the final energy Arc permits a long straight section for 5000 period undulators.

The beam quality delivered to the long undulators and

Table 1: Main design parameters of FSF

Parameter	High Brilliance Mode	Short Bunch Mode
Energy (GeV)	6	6
Charge (pC)	15	4
Bunch Length (fs)	>200	$\sim$10
<B> (ph/s/mm²/mrad²/0.1%)	10^{22}	10^{21}
B_{peak} (ph/s/mm²/mrad²/0.1%)	10^{26}	10^{26}

hence the photon brilliance attainable depends on the machine operating mode.

SHORT BUNCH MODE

Single pass machines do not suffer the same fate as storage rings as equilibrium is never reached. A design based on linear uncoupled optic, helps address a proof-of-principle for the short pulse mode, which is later then tested using a realistic input beam distribution from the BERLin-Pro injector project.

Compression in the Injector

Producing a femto-second pulse of low energy spread starts at the Gun, Table 2. Here the longitudinal electron beam properties are restricted by the photo-injector laser pulse and the superconducting RF acceleration. The primary subtle compression in the Merger between the Booster and linac minimizes transverse emittance growth.

Table 2: Injector ASTRA[3] simulations

Component	Bunch Length (mm)	Emittance (keV mm)	Energy (MeV)
Gun	0.7	0.3	1.8
Booster	1.0	2	6.6
Linac	0.45	2.2	50

The injector Arc is then used to prepare the beam for the main accelerator. The combination of a second linac to increase the beam energy to 100 MeV and the R_{56} in the Arc compress the beam to $\sigma_t \sim 660\,fs$ with a correlated energy spread of $\Delta E/E \sim 1.5 \cdot 10^{-4}$.

Telescopic Compression

The main acceleration stage uses a scheme based on telescopic compression. In this regime the combination of the linac chirps and the R_{56} in the Arcs are described as a simple focusing (F) and defocussing (f) lens, Eq. 1. The shortest pulse achievable from a multi-turn isochronous structure is with full compression in the final arc. This is however at the expense of a correlated energy spread, blue in Fig. 2.

$$\begin{pmatrix} z \\ \Delta E/E \end{pmatrix}_1 = \begin{pmatrix} f/F & F-f \\ 0 & F/f \end{pmatrix} \begin{pmatrix} z \\ \Delta E/E \end{pmatrix}_0 \quad (1)$$
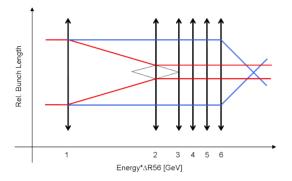

Figure 2: Telescopic bunch compression to preserve energy spread.

In order to remove the correlated energy spread and still produce a short pulse consider an alternative solution based on a telescopic lattice, red in Fig. 2. Implementing the first two arcs as achromats and accelerating either side of on-crest in each linac, the two "lenses" can share the same focal plane, just like in a telescope, to maximize the magnification and recover the energy correlation properties of the injector.

The minimal bunch length of the final beam into the long undulators is restricted by the requirement of an rms energy spread given by $\Delta E/E \sim 1/UndulatorPeriods \sim 10^{-4}$, to be $\sigma_t \sim 10\,fs$ when implementing purely linear optic.

Simulation Codes

Starting from previous calculations using ASTRA[4] up until the $50\,MeV$ injector linac exit, the beam distribution was converted and tracked onwards through the FSF using Elegant[5].

Short Bunch Simulations

The first $50\,m$ shown in Fig. 3 is the initial bunch compression in the injector Arc to prepare the beam for the first $1\,GeV$ FSF linac of phase $\phi_1 = +8\,°$ off crest . What follows this a step like bunch compression in the first Arc with $R_{56} = 20\,cm$ till the second $1\,GeV$ linac at $\phi_2 = -20\,°$ (placed at $s \sim 500\,m$). The second Arc of $R_{56} = 5\,cm$
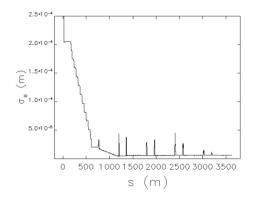
Figure 3: Bunch length variations in the FSF.

then completes the full bunch compression. These longitudinal bunch parameters are then preserved in the remaining isochronous Arcs, with some "spiking" shown due the vertical spreaders.

With the present optic a bunch length $\sigma_t \sim 20\,fs$ and energy spread $\Delta E/E \sim 1 \cdot 10^{-4}$ is achievable at the long undulator entrance Fig. 4.
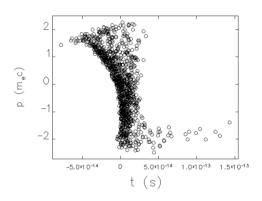

Figure 4: Phase space at long undulator entrance.

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.

LONGITUDINAL EMITTANCE

The longitudinal emittance can be described as an ellipse occupying a density of particles in $(c\Delta t, \delta)$ phase space. The non-linear properties of RF curvature acceleration can alter the phase distributions varying the normalized emittance.

2nd Order Aberrations

An emittance compensation scheme using higher order magnetic terms created in the Arcs is described here.

Using the linacs relative energy Eq. 2 and the Arcs bunch length Eq. 3 variations respectively one can calculate the emittance variation across the two stages as follows.

$$LINAC$$
$$\delta_1 = \delta_0 + R_{65}c\Delta t_0 + T_{655}(c\Delta t_0)^2 \quad (2)$$
$$c\Delta t_1 = c\Delta t_0$$

$$+ARC$$
$$\delta_2 = \delta_1$$
$$c\Delta t_2 = c\Delta t_1 + R_{56}\delta_1 + T_{566}\delta_1^2 \quad (3)$$

Keeping only second order terms, assuming $\delta_0 = 0$ and substituting Eq. 2 and Eq. 3 the emittance can be approximated as Eq. 4

$$\epsilon^2 = <(c\Delta t_2)^2><\delta_2^2> - <(c\Delta t_2\delta_2>^2 \quad (4)$$
$$\epsilon^2 \simeq <(c\Delta t_0)^4><(c\Delta t_0)^2>\left(T_{566}R_{65}^3 - T_{655}\right)^2$$

Emittance Correction

One can interpret Eq. 4 as a useful tool to control the normalized emittance. The accelerating phase determines both the R_{65} and T_{655} terms and sextupoles in the Arc can adjust T_{566} to compensate for them.
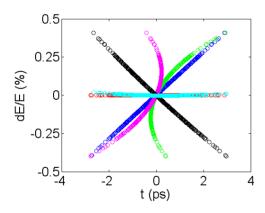

Figure 5: Correction of the 2nd order aberrations.

Fig. 5 demonstrates this concept, showing anticlockwise the variation of the beam phase space from an uncorrelated low emittance flat beam (red) through a non-linear RF chirp (blue). Then the introduction of first and second order magnetic correction, rotating and deforming the phase space (green - magenta - black) before finally a second linac is used to approximately recover the original distribution (cyan).

Emittance Correction Simulations

This scheme was adapted for the two stage telescopic bunch compression in the FSF machine simulations Fig. 6.

The second order terms from the off-crest RF acceleration for the short bunch mode were optimized so that they would be fully compensated for by the T_{566} term created in the dipoles in the achromat Arcs.
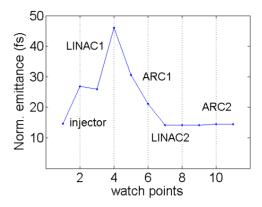

Figure 6: Recovering the injector properties.

Additional correction using sextupoles will be considered for future calculations as an essential tool for the recovery of the injectors longitudinal beam properties.

CONCLUSION

A two stage linear bunch compression scheme for the FSF light source has been presented and simulated using realistic beam parameters from the BERLinPro injector. A compensation scheme to recover the normalized emittance of the injector has been proposed.

REFERENCES

[1] Y. Petenev et al., "Feasibility Study of an ERL-Based GeV-scale Multi-turn Light Source", IPAC2012, New Orleans, USA.

[2] T. Kamps, et al., Journal of Physics: Conference Series 298 (2011) 012009.

[3] ASTRA code, A Space Charge Tracking Algorithm, http://tesla.desy.de/ meykopff/ 2012.

[4] J. Knobloch et al., Status of the BERLinPro Energy Recovery Linac Project, IPAC 2012, New Orleans, July 2012.

[5] M. Borland, "elegant: A Flexible SDDS-Compliant Code for Accelerator Simulation," Advanced Photon Source LS-287, September 2000.