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


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 $\sim 0.1 \mu m \text{ rad}$ mode will operate in conjunction with a short-pulse $\sim 10 \text{ fs}$ 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 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 1: Main design parameters of FSF

<table>
<thead>
<tr>
<th>Parameter</th>
<th>High Brilliance Mode</th>
<th>Short Bunch Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy (GeV)</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>Charge (pC)</td>
<td>15</td>
<td>4</td>
</tr>
<tr>
<td>Bunch Length (fs)</td>
<td>$&gt;200$</td>
<td>$\sim 10$</td>
</tr>
<tr>
<td>$&lt;B&gt;$ (ph/s/mm$^2$/mrad$^2$/0.1%)</td>
<td>$10^{22}$</td>
<td>$10^{21}$</td>
</tr>
<tr>
<td>$B_{\text{peak}}$ (ph/s/mm$^2$/mrad$^2$/0.1%)</td>
<td>$10^{26}$</td>
<td>$10^{26}$</td>
</tr>
</tbody>
</table>

Table 2: Injector ASTRA[3] simulations

<table>
<thead>
<tr>
<th>Component</th>
<th>Bunch Length (mm)</th>
<th>Emittance (keV mm)</th>
<th>Energy (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gun</td>
<td>0.7</td>
<td>0.3</td>
<td>1.8</td>
</tr>
<tr>
<td>Booster</td>
<td>1.0</td>
<td>2</td>
<td>6.6</td>
</tr>
<tr>
<td>Linac</td>
<td>0.45</td>
<td>2.2</td>
<td>50</td>
</tr>
</tbody>
</table>

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 $R_{50}$ in the Arc compress the beam to $\sigma_t \sim 660 \text{ fs}$ with a correlated energy spread of $\Delta E/E \sim 1.5 \cdot 10^{-4}$.

01 Electron Accelerators and Applications

1B Energy Recovery Linacs
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 defocusing ($f$) 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.

$$
\left( \frac{z}{\Delta E/E} \right)_1 = \left( \begin{array}{cc} f/F & F-f \\ 0 & F/f \end{array} \right) \left( \frac{z}{\Delta E/E} \right)_0
$$

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 $\Delta E/E \sim 1/\text{Undulator Periods} \sim 10^{-4}$, to be $\sigma_t \sim 10\text{ fs}$ 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 $\phi_1 = +8^\circ$ off crest. What follows this a step like bunch compression in the first Arc with $R_{56} = 20\text{ cm}$ till the second 1 GeV linac at $\phi_2 = -20^\circ$ (placed at $s \sim 500\text{ m}$). The second Arc of $R_{56} = 5\text{ cm}$ 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 $\sigma_t \sim 20\text{ fs}$ and energy spread $\Delta E/E \sim 1 \cdot 10^{-4}$ is achievable at the long undulator entrance Fig. 4.

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 EMMITTANCE

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.

\[ \begin{align*}
\delta_1 &= \delta_0 + R_{65} c \Delta t_0 + T_{655} (c \Delta t_0)^2 \\
\delta_1 &= \delta_0 + R_{56} \delta_1 + T_{566} \delta_1^2 
\end{align*} \tag{2} \]

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

\[ \begin{align*}
\varepsilon^2 &= \langle (c \Delta t_2)^2 \rangle - \langle (c \Delta t_2 \delta_2)^2 \rangle \\
\varepsilon^2 &\approx \langle (c \Delta t_0)^4 \rangle - \langle (c \Delta t_0)^2 \rangle (T_{566} R_{65}^2 - T_{655}^2) 
\end{align*} \tag{4} \]

**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.

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**


