THE FEMTO-SCIENCE FACTORY: A MULTI-TURN ERL BASED LIGHT SOURCE*

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Abstract

A conceptual design study for a future multi-turn ERL based light source at HZB is completed and presently under internal review. The Femto-Science-Factory (FSF) is a candidate for a 4th generation diffraction limited synchrotron light source. It 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. Presented in this paper is an overview of the conceptual design with respect to the facility layout, operation modes and the expectations of the beam parameters from the start-to-end simulations.

INTRODUCTION

This paper continues on from a recent feasibility study [1] for multi-turn ERL based light sources. The most recent additions to the optic are the numerous matching sections needed to geometrically optimize the machine layout into a single tunnel and the final deceleration recovery stage to dump the beam at 10 MeV.

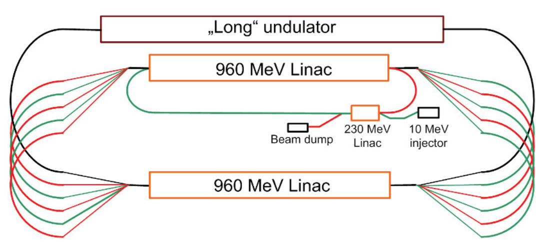

Figure 1: Schematic of the FSF. Green lines - acceleration, red - deceleration and black - 6 GeV final beam.

Figure 1 shows the layout of the light source and Table 1 summarizes the main parameters.

The difference in the two modes with regards to the lattice design occurs in the low energy section of the machine. For the High Brilliance Mode (HBM) a beam of higher charge is accelerated on crest in all of the linacs and circulates round isochronous arcs. The Short Pulse Mode (SPM) however relies on achromatic arcs for the telescopic compression technique removing the correlated energy spread due to the off-crest acceleration. The modes share common high energy arcs where radiation effects play an important role in emittance growth.

The vertical spreaders geometry has been designed so that the total length of the structure is restricted to 25 m.

Table 1: Main Parameters of the FSF Multi-turn ERL

Parameter	HBM	SPM
Energy (GeV)	6	6
⟨I⟩ (mA)	20	5
Q (pC)	15	4
ε_n (mm mrad)	0.1	0.5
σ_t (fs)	2000	10
$\langle B \rangle$ (ph/(s mm^2 mrad^2 0.1%))	$8{\cdot}10^{22}$	$4{\cdot}10^{21}$
B_{peak} (ph/(s mm^2 mrad^2 0.1%))	10^{26}	10^{26}

The optic is isochronous, contains sextupoles to correct the second order for high energy spread beams, and the beta functions are minimized throughout. Due to these heavy demands, the 4 and 6 GeV spreaders bend in both transversal planes.

TWO STAGE INJECTION

The beam parameters achieved in the injector is essential for ultimate brilliance in both modes of the FSF. The 0.1 mm mrad goal of the transverse emittance is challenging and compensation techniques up to 50 MeV where space charge still dominates are required to preserve emittance. A Space Charge Optimizer (SCO) [2] program was used to numerically solve the Kapchinsky-Vladimirsky equations repetitively and to find the optimal setting for the quadrupoles for minimum emittance growth (2D emittance compensation). Modeling of the injector is comprehensively described in [3]. ASTRA was used to produce a realistic bunch starting simulations from the cathode, as shown in Fig. 2 which could be converted to Elegant and tracked onwards.

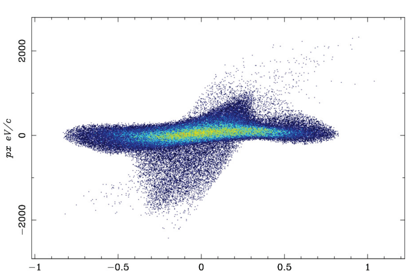

Figure 2: Typical beam distribution on injector exit.

The 230 MeV linac and the respective arc in the injection scheme are used to further accelerate the beam and provide intermediate bunch compression to 2 ps in both modes. In addition, energy staging considerations, transversal beam

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break-up and micro-bunching instability studies have all contributed to the inclusion and layout of this two stage injection process.

HIGH BRILLIANCE MODE

The transverse emittance growth is kept to a minimum throughout the whole 8 km machine, to utilize the undulator radiation in all acceleration and deceleration sections in order to maximize user potential. Shown in Fig. 3 is the spectral brightness expectations of the FSF using the start-to-end beam parameters.

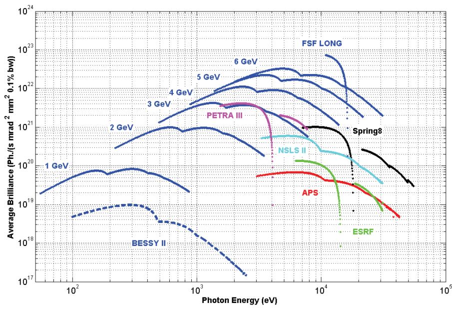

Figure 3: Comparison of the spectral brightness for the FSF and present 3rd generation light sources.

The average brilliance expectations of the FSF from 1 to 6 GeV plotted in blue, cover a broad wavelength and are a magnitude larger than present 3rd generation light sources. The comparison is made using realistic undulator parameters and common operational modes.

For the high brilliance mode, with all the suppression techniques described in place, the transversal emittance mainly grows due to incoherent radiation effects and can be analytically estimated in the 6 GeV arc as 0.04 mm mrad.

Table 2 summarizes the main beam dynamic parameters at various stages across the machine. The bunch is of great quality regarding minimal emittance from the 1st to the final user station on recovery.

Table 2: Start-to-end Beam Parameters for the 15 pC HBM

Pos.	ε_{nx} (mm mrad)	ε_{ny} (mm mrad)	σ_t (ps)	σ_E (10^{-3})	Energy (MeV)
Input	0.13	0.09	3.09	2.93	50
1st user	0.14	0.08	2.13	0.21	1000
Undulator	0.20	0.08	2.13	0.18	6000
Final user	0.28	0.09	2.13	0.66	1000
Dumpline	1.24	0.11	3.60	72.56	10

The 7.3 ‰ output energy spread is foreseen as unproblematic for the future beam dump design.

SHORT PULSE MODE

Each off-crest acceleration followed by achromatic arcs constitute the telescopic compression scheme in the lower energy acceleration sections. The first two arcs up to a beam energy of 2 GeV have $\phi_1 = +10\,°$, $\phi_2 = -20\,°$ and positive $R56_1 = 20$ cm and $R56_2 = 8$ cm values. On recovery the linac phase is shifted $\phi_{1,2} \rightarrow \phi_{1,2} + 180\,°$ (ERL process) and the arcs have the corresponding symmetric negative $R56$ values. This telescopic scheme not only has the potential to produce ultra short bunch lengths but also helps remove the correlated energy spread from RF on acceleration. Figure 4 shows the SPM to have a larger relative energy spread compared with the HBM (Low Emittance Mode LEM).

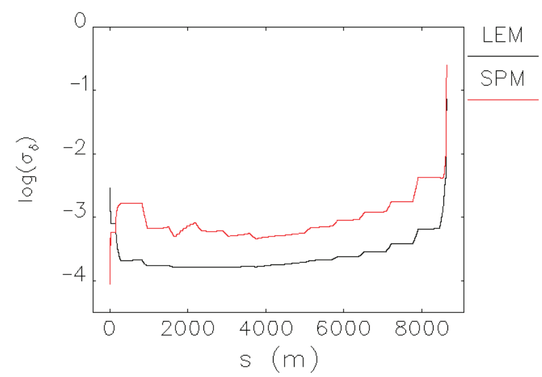

Figure 4: Log plot of the evolution of the energy spread throughout the FSF for both modes.

Sextupoles are required to combat the transverse emittance growth due to chromatic aberrations due to the high energy spread on recovery $s > 6$ km. As an alternative to computationally expensive particle tracking, key 2nd order terms were analytically found to reduce the transverse emittance growth.

$$\varepsilon_1^2 = \langle {x_1}^2\rangle\langle x'^2_1\rangle - \langle x_1 x'_1\rangle^2 \quad (1)$$

$$\varepsilon_1^2 = (T_{161}T_{262} - T_{162}T_{261})^2(\langle\delta_0^2 x_0^2\rangle\langle\delta_0^2 x'^2_0\rangle - \langle\delta_0^2 x_0 x'_0\rangle^2)$$

Suitable optic can be found where $T_{161}T_{262} = T_{162}T_{261}$ in a few seconds rather than the usual time scales associated with dedicated particle tracking codes. Without these additional corrections the beam degradation on recovery is too large and results in energy spreads far above the specification at the dump.

To complement this analytic 2nd order technique, a longitudinal emittance compensation scheme uses the higher order magnetic terms created in the arc Eq. 3 and the linac off-crest acceleration Eq. 2 to recover the longitudinal emittance of the injector Eq. 4.

$$\begin{aligned} \text{LINAC: } c\Delta t_1 &= c\Delta t_0 \\ \delta_1 &= \delta_0 + R_{65}c\Delta t_0 + T_{655}(c\Delta t_0)^2 \end{aligned} \quad (2)$$

$$\begin{aligned} \text{ARC: } c\Delta t_2 &= c\Delta t_1 + R_{56}\delta_1 + T_{566}\delta_1^2 \\ \delta_2 &= \delta_1 \end{aligned} \quad (3)$$

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$$\varepsilon_2^2 = (T_{566}R_{65}^3 - T_{655})^2 \langle (c\Delta t_0)^4 \rangle \langle (c\Delta t_0)^2 \rangle \quad (4)$$

Figure 5 shows the positive implications of this method adapted for the two stage telescopic bunch compression, the vertical scale is logarithmic ($\log 10^{-14} \rightarrow 10$ fs). The longitudinal emittance, black line, is recovered after the first arc at 1 km. This allows the full potential for further compression in the following arc resulting in a 10 fs long bunch length shown in red. The longitudinal emittance then grows due to CSR effects producing unwanted energy spread. The bunch length at 2 GeV also increases to 25 fs at the entrance to the long undulator section at 6 GeV. On recovery the bunch is actively decompressed in preparation for the dump.

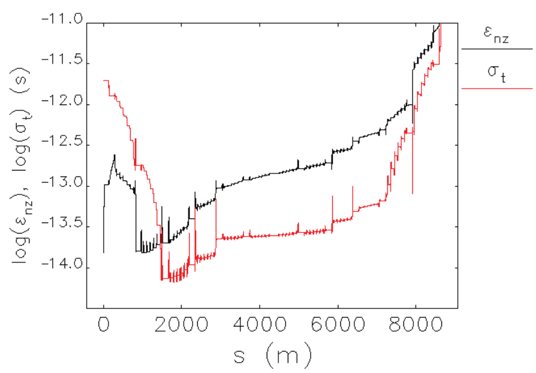

Figure 5: Normalized longitudinal emittance and bunch length in the FSF.

If one assumes that the compression scheme represents a limit for any given bunch charge, then the zero-charge bunch length can be deduced from the rectangular bunch model and the data (red crosses) from start-to-end simulations to be 5.6 fs. As the SPM is heavily dependent on CSR, this notion is extrapolated in Fig. 6 to form a boundary for feasible operation in the FSF. Bunch lengths below the boundary will induce distortions due to CSR that will be too large to recover the beam at 10 MeV.

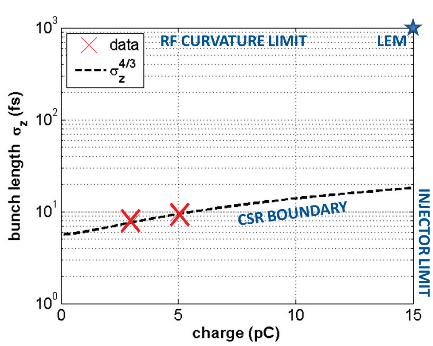

Figure 6: Boundary of minimum bunch length due to CSR effects in the FSF.

Above the boundary all machine settings are possible. The upper charge boundary of 15 pC is the limit from the injector studies for low emittance. The 1 ps long bunch extremity on the top of the figure is seen as a value that will not produce excessive longitudinal emittance growth during acceleration. Notably the LEM results would exist in the top right hand corner of the figure suggesting that the operation mode is well above the CSR limit and further bunch compression is possible, but will reduce the average brilliance.

Bunches of 1, 3 and 5 pC were used in the SPM start-to-end simulations. Table 3 summarizes the results for the 3 pC case. The bunch length remains below 50 fs throughout the user stages Low and High Energy Arcs (LEA and HEA) and the corresponding expectations of the peak brilliance is shown in Fig. 7.

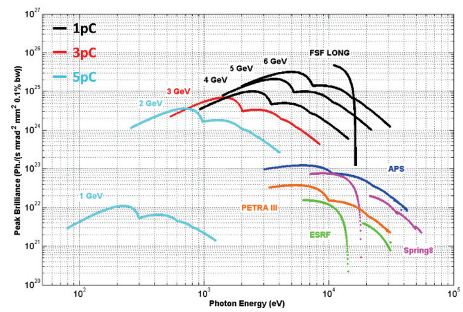

Figure 7: Comparison of the peak brilliance for the FSF and present 3rd generation light sources.

As the energy increases and the beam distortions grow depending on the bunch charge and length, the beam properties rise beyond the diffraction limit. This is apparent in Fig. 7 as the ultimate peak brilliance favors lower bunch charges at the final beam energy of 6 GeV.

Table 3: Start-to-end Beam Parameters for the 3 pC SPM

Pos.	ε_{nx} (mm mrad)	ε_{ny} (mm mrad)	σ_t (fs)	σ_E (10^{-3})	Energy (MeV)
Input	0.11	0.06	1990.09	0.46	50
LEA	0.18	0.06	7.39	0.71	2000
HEA	0.30	0.08	22.59	0.62	4000
Undulator	0.49	0.10	24.73	0.52	6000
HEA	1.00	0.23	48.70	0.92	4000
LEA	2.52	0.49	452.22	1.77	2000
Dumpline	32.88	0.64	4430.29	14.66 %	10

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