MULTI-TURN ERL BASED LIGHT SOURCE: ANALYSIS OF INJECTION AND RECOVERY SCHEMES*

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Abstract

The optics simulation group at HZB is designing a multi-turn energy recovery linac -based light source. Using the superconducting Linac technology, the Femto-Science-Factory (FSF) [1] will provide its users with ultra-bright photon beams of angstrom wavelength. The FSF is intended to be a multi-user facility and offer a variety of operation modes. The driver of the facility is a 6 GeV multiturn energy recovery linac with split linacs. In this paper we compare different schemes of beam acceleration: a direct injection scheme with acceleration in a 6 GeV linac, a two-stage injection with acceleration in a 6 GeV linac, and a multi-turn (3-turn) scheme with a two-stage injection with two main 1 GeV linacs as proposed for FSF. The key characteristic of comparison is the beam breakup (BBU) instability threshold current.

INTRODUCTION

One potential weakness of the ERLs is transverse beam breakup (BBU) instability, which may severely limit a beam current. If an electron bunch passes through an accelerating cavity it interacts with dipole modes (e.g. TM_{110}) 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.

In this document we compare different schemes of acceleration for FSF. Optics in the linacs is presented. BBU threshold currents are estimated.

Direct Injection Scheme

In this scheme the beam after an injector section goes directly to the main linac (see Fig. 1), where it is accelerated up to 6 GeV and used for experiments and after the recirculation turn it decelerated and the beam then goes to the dump.

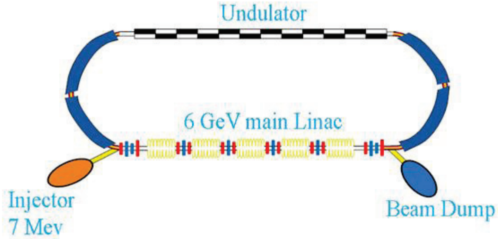

Figure 1: Direct injection scheme.

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The linac is planned to be based on the BERLinPro [2] 7-cell cavities. To reach 6 GeV in the linac we took 464 cavities with an accelerating gradient of about 16 MeV/m and distributed them over 58 cryomodules. The cryomodule is schematically presented in Fig. 2, where λ~0.231 m is the wavelength of the accelerating mode.

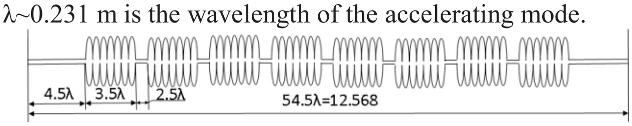

Figure 2: The scheme of FSF cryomodule.

Triplets of quadrupoles are planned to be in between the cryomodules in the linac and were optimized in such a way that the BBU instability should develop similarly for all the cavities in the linac. In this case the highest threshold current can be achieved. The threshold current for the transverse beam breakup may be estimated for the case of a single cavity and single mode for a multipass ERL in the form [3]:

$$I_{th} \approx I_0 \frac{\lambdabar^2}{Q_a L_{eff} \sqrt{\sum_{m=1}^{2N-1} \sum_{n=m+1}^{2N} \frac{\beta_m \beta_n}{\gamma_m \gamma_n}}}, \quad (1)$$

where I_0- Alfven current, Q_a is the quality factor of HOM, $\lambdabar = \lambda/2\pi$, λ is the wavelength corresponding to the resonant frequency of the TM_{110} mode, γ_m is the relativistic factor at the m-th pass through the cavity, β_m – is the Twiss parameter, L_{eff} – is the effective length of the cavity, N is the number of passes during acceleration.

One can see from (1) that the threshold current is higher when the square root in the denominator is minimized. We will use this eq. to find the best optic solution assuming the HOM nature is predictable. The most dangerous for the BBU stability are the cavities where the beam has the lower energies. Therefore the initial Twiss parameters before the linac were optimized to minimize the beta functions in the first cryomodule. In this cryomodule the energy is increased from 7 to 110 MeV, where RF focusing, which was described in [4], plays a vital role.

We can transfer the beta function through the 1st cryomodule as:

$$\beta_1 = \frac{\gamma_1}{\gamma_0}(\beta_0 m_{11}^2 - 2\alpha_0 m_{11} m_{12} + \frac{1+\alpha_0^2}{\beta_0} m_{12}^2), \quad (2)$$

where m_{11} and m_{12} - the coefficients of the transfer matrix of the cryomodule, which can be founded for

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example in Elegant [5] program. Now we just have to minimize β_1 in Eq. (2) for the initial Twiss parameter α_0, that gives:

$$\alpha_0 = \frac{m_{11}}{m_{12}} \beta_0 . \qquad (3)$$

We also want to keep constant the value of β/γ, so the threshold current is the same for all cavities and the solution is given by: $\beta_0 = m_{12}$, $\alpha_0 = m_{11}$ and $\beta_1 = \gamma_1 m_{12}/\gamma_2$.

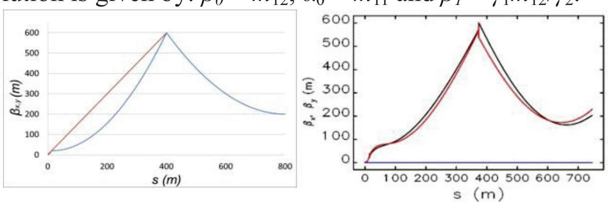

Figure 3: Theoretical (left) and calculated in Elegant program optics design of the beta-functions in the main linac for the direct injection scheme.

The preferable theoretical BBU stability optic is shown in Fig. 3 (left). The red line shows the values with a constant $\beta/\gamma \sim 0.1$ m, and the values below this line will give a higher threshold current. Optics, calculated in Elegant using this pattern is presented in the same Fig. (right).

It should be noted that we used only 5 triplets (between 1st and 2nd, between 8th and 9th and cryomodules (and symmetrically on the other half of the linac) and in the middle of the linac. The length of the linac is then about 750 m.

The main disadvantage of this scheme is the high ratio between the injection energy E_{in} = 7 MeV and the final energy E_{fin} = 6 GeV: $E_{in}/E_{fin} \sim 850$. This complicates the focusing in the main linac, because the triplets which focus a beam at the beginning of the linac will not affect the beam on the deceleration phase. For a given optics in Fig. 3 (right) one can estimate the value of the threshold current using: $I_{th} = 10^{-6}E/4\pi\beta \sim 400$ mA for the middle point of the linac. For the estimations we took a mode with $(R/Q)_d \cdot Q_d = 6\cdot 10^5\ \Omega$, $\omega = 2\pi\cdot 2\cdot 10^9$ Hz.

Two Stage Injection Scheme

In this part we discuss an improved scheme of ERL based light source, which is presented in Fig. 4.

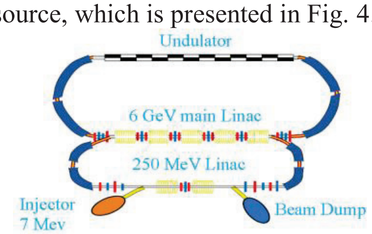

Figure 4: Two stage injection scheme.

The main improvement is that now a beam after an injector passes through a short linac, where it is accelerated up to 250 MeV, then round the first arc and comes to the main linac where it accelerated up to 6 GeV. After that it might be used as a light source before returning back on the deceleration phase. Our goal again will be to find the optimum optic solution for the beam break up stability in the both linacs. But first let us discuss the stability in the preinjection linac.

Preinjector

For the preinjection linac we suggest to use two cryomodules with a triplet of quadrupole magnets in between. The role of the triplet is to change the sign of α_1 of the beam. Let us find the initial Twiss parameters to have the equal threshold currents for the beginning and for the middle of the linac.

Changing the sign of α in (2) and introducing t_{11} and t_{12} as the transport elements of the second cryomodule, the beta function at the end of the linac can be found as:

$$\beta_2 = \frac{\gamma_2}{\gamma_1}(\beta_1 t_{11}^2 + 2\alpha_1 t_{11} t_{12} + \frac{1+\alpha_1^2}{\beta_1} t_{12}^2) . \qquad (4)$$

The minimum of $\beta_2 = \gamma_2 (t_{12})^2/\gamma_1\beta_1$ is given, when $\alpha_1 = -\beta_1 t_{11}/L$. Now we can proceed with using Eq. (1):

$$\sqrt{\frac{\beta_0\beta_2}{\gamma_0\gamma_2}} = \frac{\beta_1}{\gamma_1} . \qquad (5)$$

Now we can find the initial beta-function:

$$\beta_0 = \frac{\gamma_0}{\gamma_1}\frac{\beta_1^3}{t_{12}^2} . \qquad (6)$$

And after the minimization of Eq. (2) over α_0 we get:

$$\beta_0 = \sqrt{\frac{\gamma_1}{\gamma_0}\frac{\mathrm{m}_{12}^3}{t_{12}}} , \ \alpha_0 = m_{11}\sqrt{\frac{\gamma_1}{\gamma_0}\frac{m_{12}}{t_{12}}} . \qquad (7)$$

Using Elegant program we can find the matrix elements of the cryomodules: m_{11}= -0.835, m_{12}= 1.62 m. and t_{12}= 7.261 m. Finally we get the initial parameters: α_0 = -1.421 and β_0= 2.757 m. It should be noted that the initial parameters we found are located at the entrance to the cavity but not to the cryomodule (where it is about 1 m of a free drift Fig. 2), so an offset is required. The final optic is presented in Fig. 5.

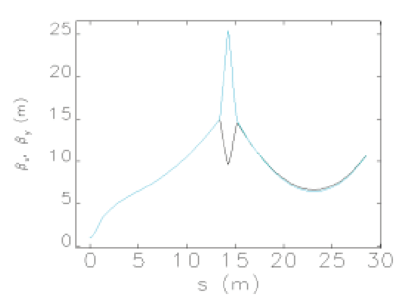

Figure 5: Optics design of the preinjection linac.

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The value of the threshold current for the same mode as previously described is I_{th} = 1.64 A. Our goal was to have the same values of the threshold currents for all cavities in the linac, but our model assumed the same values for the first and the last cavity of the cryomodule. The threshold current in the middle of the cryomodule is higher (one can see this already from the Fig. 5) - about 2.5 A. In the next part we discuss the optics in the main Linac.

Main Linac

The main difference for the optic design between two schemes with direct injection and with a preinjector is that in the scheme with two stage injection the initial energy in the main linac is 250 MeV instead of 7 MeV in the scheme with a direct injection. This strongly improves the optics, because the quadrupole magnets which focus the beam at low energies (>250 MeV) will also focus the beam at high energies (<6 GeV). We calculate the optic in the following way: for the first half of the linac we adjust the triplets between the cryomodules in such a way that the beam will go like in a free drift with initial/final beta-functions about the length of the cryomodule (Fig. 6). We assume symmetrical optics for deceleration, which is given from right to left in Fig. 6.

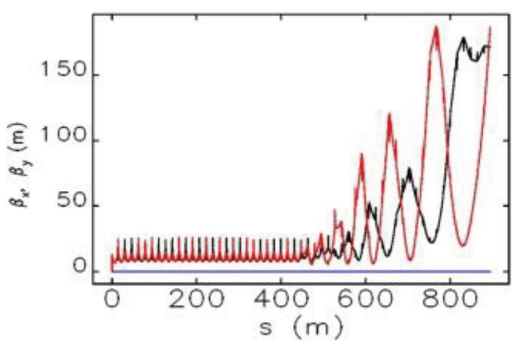

Figure 6: Optics design of the main 6 GeV linac for the two stage injection scheme.

For the first/last cavities estimations give the threshold current about 4 A and about 35 A for the middle of the linac for the same mode parameters as we used before.

Scalable Scheme with Preinjector and 3 Passes

In this part we present an upgrade of the acceleration scheme of the FSF which was presented at [6]. In this scheme the acceleration in the preinjector and in two main linacs is assumed to be scalable. The final energy of a beam $E_{fin} = (E_0 + E_{preinj})(1+2Nk)$ = 6 GeV, where E_0 = 10 MeV is the energy after booster, E_{preinj} is the energy gain in the preinjector, N is the number of passes during acceleration and constant k = 4. Therefore we got E_{preinj} = 230 MeV and E_{linac} = 960 MeV. So our main scheme of FSF is now looks like it presented in Fig. 7.

This change for the scalable facility was made because of the spreader design. A design of the spreader for 6 arcs is complicated and if the energy is changed due to unforeseen circumstances we could change field gradients of cavities in a proportional way to use the same spreader.

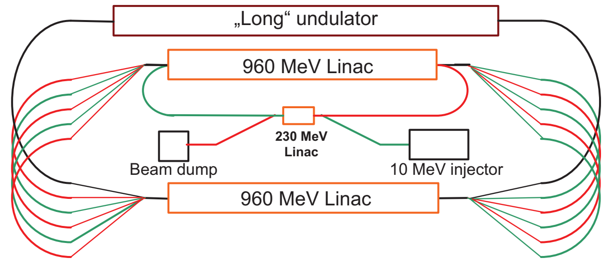

Figure 7: New scheme of a scalable FSF.

Optic in the preinjector was optimized in the same way as it described earlier.

The strengths of the quadrupoles were optimized to

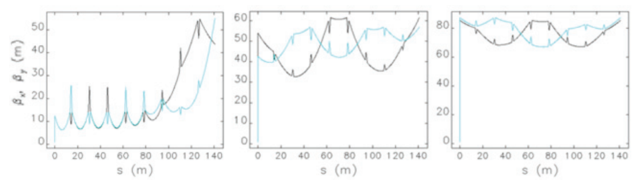

Figure 8: Optics design of the first 0.96 GeV linac. 3 passes on acceleration are presented from left to right.

have the minimum of the beta functions on the 1-st pass. Optics for the 3 passes through the first and the second main linacs is presented in Figs. 8, 9. In both linacs, the optic is assumed to have mirror symmetry at the middle of the 5-th cryomodule.

The threshold currents for the optics presented in Figs. 8, 9 can be estimated using the Eq. (1) and for a mode which we always used one could get for the beginning of the first linac I_{th} = 0.73 A and for the second I_{th} = 2.34 A, when for the preinjector it is about 1.14 A. What means the instability should develop in the first main linac.

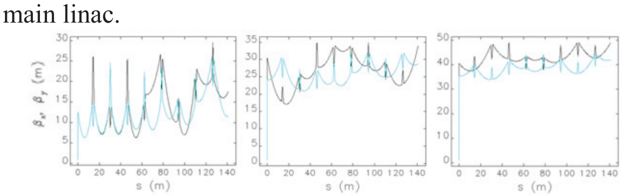

Figure 9: Optics design of the second 0.96 GeV linac. 3 passes on acceleration are presented from left to right.

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