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ELECTRON BEAM TRANSFER LINE FOR DEMONSTRATION OF LASER PLASMA BASED FREE ELECTRON LASER AMPLIFICATION

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Abstract

One direction towards compact Free Electron Lasers (FEL) is to replace the conventional linac by a laser plasma driven beam, provided proper electron beam manipulation to handle the value of the energy spread and of the divergence is done. Applying seeding techniques enables also to reduce the required undulator length. The rapidly developing LWFA are already able to generate synchrotron radiation. With an electron divergence of typically 1 mrad and an energy spread of the order of 1 %, an adequate beam manipulation through the transport to the undulator is needed for FEL amplification. A test experiment for the demonstration of FEL amplification with a LWFA is under preparation in the frame of the COXINEL ERC contract. A specific design of electron beam transfer line following different steps with strong focusing variable strength permanent magnet quadrupoles, an energy de-mixing chicane with conventional dipoles and second set of quadrupoles for further dedicated focusing in the undulator has been investigated. Beam transfer simulations and expected FEL power in the XUV will be presented.

INTRODUCTION

FEL based fourth generation light sources [1-2] presently offer femtosecond tunable radiation in the X–ray domain. Besides the preparation of additional FEL light sources for users around the world, new schemes are also under investigation. In view of the fifth generation light sources [3] several approaches are considered. One direction goes towards the improvement of FEL performance in a wide spectral range and with versatile properties and flexibility for users. Another one aims at reducing the size either by exploring further seeding and / or by replacing the conventional linear accelerator by a compact alternative one. Indeed, the rapidly developing Laser WakeField Accelerator (LWFA) [4-5] are now able to generate synchrotron radiation. With an electron divergence of typically 1 mrad and an energy spread of the order of few percent, an adequate beam manipulation through the transport to the undulator is required for FEL amplification. Different strategies have been proposed, such as a decompression chicane [6], a transverse gradient undulator [7] and lastly a dedicated chromatic matching [8-9]. The studies presented here take place in the context of the LUNEX5 (free electron Laser Using a New accelerator for the Exploitation of X-ray radiation of 5th generation) [10] collaboration, aiming at investigating the production of short, intense, coherent pulses in the 40-4 nm spectral range with a 400 MeV superconducting linac and a LWFA both connected to a single FEL for advanced seeding configurations. The LWFA has first to be qualified by the FEL application. In this frame, beam transfer simulation of longitudinal and transverse manipulation of a LWFA electron beam showing that theoretical amplification is possible, a test experiment is under preparation, with the support of different grants.

BEAM MANIPULATION

The electron different trajectories through the refocusing stage, according to their energy, span the trace phase space distribution adding the chromatic emittance. From phase space geometry, the initial divergence drastically increases this effect. The slice energy sorting of the chicane will then transfer the chromatic emittance into mismatch from slice to slice along the undulator and spoil the FEL process efficiency. Up to second order, a general quadrupole transfer using the usual TRANSPORT notation limited to the horizontal plane is given by:

$$\begin{pmatrix} x \\ xp \end{pmatrix} = \left[\begin{pmatrix} r_{11} & r_{12}=0 \\ r_{21} & r_{22} \end{pmatrix} + \delta \begin{pmatrix} r_{116} & r_{126} \\ r_{216} & r_{226}=0 \end{pmatrix} \right] \begin{pmatrix} x_0 \\ xp_0 \end{pmatrix}$$

with (x xp) the position-angle coordinates and δ the energy deviation. In addition, cancelling the chromatic term r_{226}, the 3 rms associated image momenta according to their relative energy deviation are approximated by:

$$\sigma_x^2(\delta) = r_{11}^2 \sigma_0^2 + r_{126}^2 \sigma_{xp0}^2 \delta^2$$
$$\sigma_{xxp}(\delta) = r_{126} \sigma_{xp0} \delta / r_{11}$$
$$\sigma_{xp}^2(\delta) = \sigma_{xp0}^2 / r_{11}^2$$

with the $(\sigma_{x0}\ \sigma_{xp0})$ initial rms beam size and divergence. The energy slice geometrical emittance are given by $\epsilon_0 = \sigma_{x0}\ \sigma_{xp0}$ and the total geometrical emittance integrated over the energy deviation, is given by:

$$\epsilon_t^2 = \epsilon_0^2 + \epsilon_{chrom}^2 = \epsilon_0^2 + \left(\frac{r_{126}}{r_{11}} \sigma_{xp0}^2 \sigma_\delta\right)^2$$

The second term of the right hand side is the chromatic emittance that is drastically enhanced by the initial divergence to the square.

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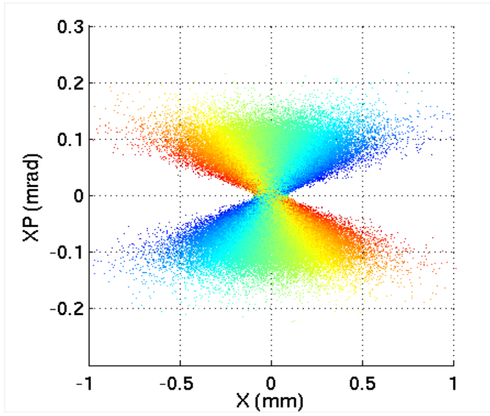

Figure 1: Horizontal phase space at undulator centre. Colours according to the energy deviation.

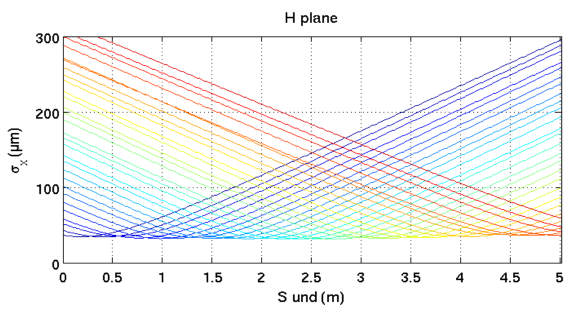

Figure 2: Horizontal slice beam envelops along 5 m of undulator. Colours according to the energy deviation as figure 1.

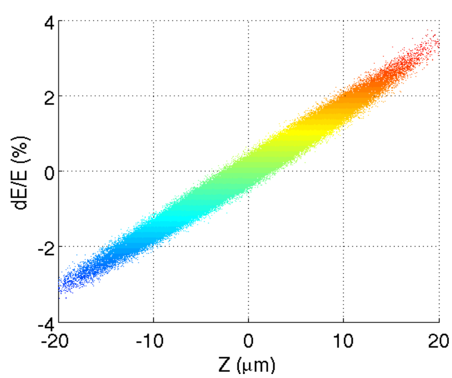

Figure 3: Decompressed longitudinal phase space. Colours according to the energy deviation as figure 1.

They present a set of up-righted ellipses (Fig. 1) and, according to the energy deviation, they reach the minimum size σ_{xmin} progressively (Fig. 2) along the propagation direction : $S_{und}(\delta)=-r_{11}r_{126}\delta$.

The bunch decompression of the chicane correlates the longitudinal position of the particles according to their energy (Fig. 3) such as the minimum beam size (or the waist) is propagating from the tail to the head of the bunch. It is then possible to synchronize the FEL optical wave propagation with the electron beam waist and improving the amplification process. The synchronization is then simply given by [8] :

$$r_{56}=\frac{-r_{11}r_{126}}{3}\frac{\lambda_{photon}}{\lambda_{undulator}}$$

with r_{56} the chicane strength, r_{11} the focusing magnification, r_{126} the chromatic emittance driving term, $(\lambda_{photon}\ \lambda_{undulator})$ the FEL wave length and the undulator period, and according to the FEL wave speed.

To operate this chromatic focusing slippage, in both horizontal and vertical planes, at least an additional triplet of quadrupoles is mandatory. A set of four quadrupoles gives more flexibility to also control both magnifications. To summarize, including the vertical plane referenced by the indexes 3 and 4 following the usual transport notation, the set of seven matrix transport conditions from the source to the undulator centre are:

- set $r_{12}=r_{34}=0$ to have a linear imaging,
- fix $r_{11}=r_{33}=M$ to set a round beam and fix the synchronized r_{56},
- set $r_{226}=r_{446}=0$ to apply the focusing slippage,
- fix $r_{126}=r_{346}$ to equilibrate both horizontal and vertical chromatic emittance.

The two terms, r_{126} and r_{346}, drive the chromatic emittances. They cannot be cancelled or reduced together by means of quadrupoles.

FEL SIMULATIONS

With typical electron beam parameter [11-16] listed in table 1 and for an energy of 400 MeV beam transfer and FEL simulations has been carried out.

Table 1: Initial Bunch rms Parameters for 34 pC Charge (4 kA peak)

E	Emittance	Divergence	Length	E-spread
MeV	$\pi.mm.mrad$	mrad	μm	%
400	1	1	1	1

The electron beam transfer simulations are done in two steps: a first pass with the BETA code [17] fitting the first and a second order matching to fix the quadrupole strength followed by a sympletic 6D tracking pass based on perfect hard edge model magnets from the source to the undulator exit. These trackings include second and every higher order optic aberrations that do not exhibit sensitive alteration to former beam manipulations limited to second order. Both radial emittances are increased from 1 to about 5 $\pi mm.mrad$ in the earlier stage of the refocusing where the divergence is still high. This increases are induced by the chromatic emittances and the first refocusing triplet is also tuned to get an equilibrate ratio between both horizontal and the vertical planes. Once the divergences are reduced, the emittances are kept constant.

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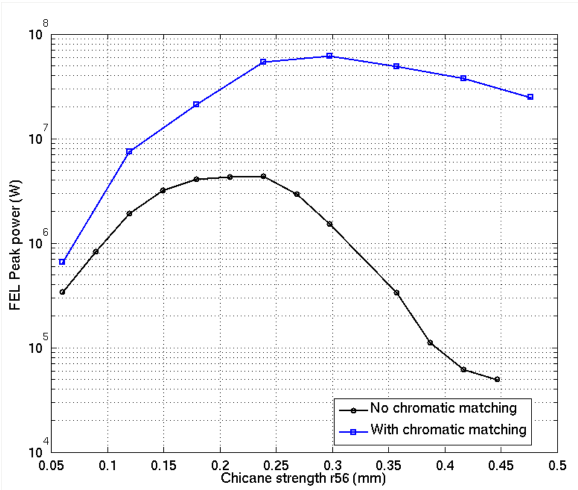

Figure 4: Output FEL peak power comparison versus chicane strength.

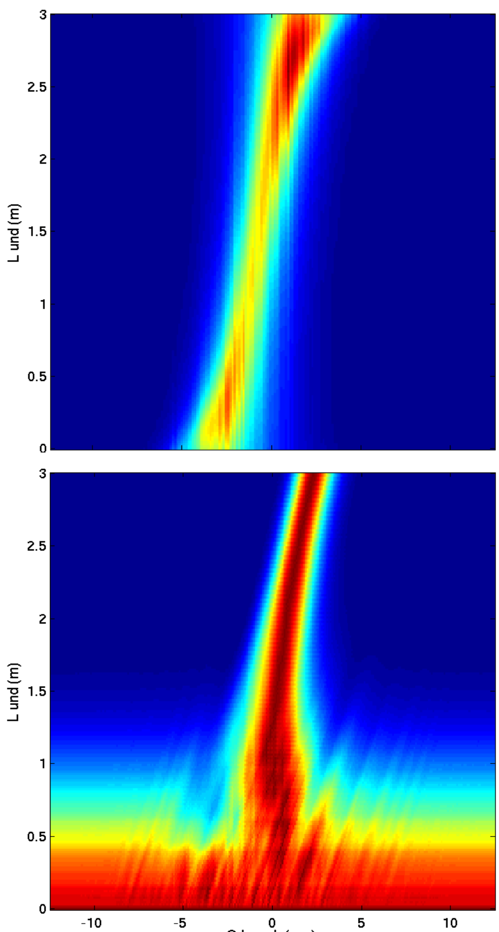

Figure 5: Example of transverse electron density (up) and according FEL peak power (down) along the 3 m undulator with the chromatic matching.

The FEL simulations (GENESIS [18]) for 40 nm wavelength (U15, 1.5 T, 3 m, 200 periods) are plotted in figure 4 where with and without operating the chromatic matching. When adding the four additional quadrupoles, the FEL peak power exhibits an increase of about one decade reaching an effective amplification toward a few ten of MW peak power in seeded mode (10 kW). The optimum chicane strengths, where the FEL is synchronized with the maximum radial bunch density are around r_{56}=0.3 m as plotted in figure 5 where the FEL peak power is superposed over the maximum beam transverse density. The chicane tuning is not sensitive and its focusing effect are almost negligible. The FEL enhancement of the chromatic matching is naturally linked to the undulator length, typically a factor of 2, 10 and 100 respectively for 2, 3 and 5 m length at 40 nm with the previous beam configuration.

COXINEL

For this purpose, a transfer line has been designed to be as compact as possible with an overall length of about 11 m [19]. It comports a first set of strong permanent magnet based variable quadrupoles to handle the large electron beam divergence, a chicane with four dipoles for the electron beam decompression, a second set of four standard electromagnetic quadrupoles to handle the chromatic matching, an undulator, a beam dump dipole, and a series of diagnostics.

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REFERENCES

[1] D.A.G. Deacon et al., Phys. Rev. Let. 38, 892-894 (1977).
[2] M. E. Couprie, J. M. Filhol, Compte-Rendus Physique, 9, 5-6, 487-506 (2008).
[3] ICFA-sponsored workshop series on Physics and Applications of High Brightness Beams, March 25-28, 2013, San Juan, Puerto Rico.
[4] T. Tajima and J. M. Dawson, Phys. Rev. Lett. 43, 267 (1979)
[5] V. Malka et al., Nature Physics 7, 219 (2011)
[6] A. R. Maier et al. Phys. Rev. X 2, 031019 (2012)
[7] Z. Huang et al., Phys. Rev. Lett. 109, 204801 (2012)
[8] A . Loulergue et al. New J. Phys. 17 023028, (2015)
[9] ME. Couprie et al. J. Phys. B : At., Mol., Opt. Phys. 47(2014)
[10] LUNEX5 http://www.lunex5.com
[11] J. Faure et al. Nature, 431:541, 2004.
[12] O. Lundh et al. Nat. Phys, 7:219, 2011.
[13] W.P. Leemans et al. Nature Phys., 2:696, 2006.
[14] J. Faure et al. Nature, 444:737, 2006.
[15] C. Rechatin et al. Phys. Rev. Lett., 102:164801, 2009.
[16] C. Fritzler et al. Phys. Rev. Lett., 92:165006, 2004.
[17] J. Payet. Beta Code, CEA, SACLAY.
[18] S. Reiche. Nucl. Instrum. Methods Phys. Res. Sect. A, A 429:243, (1999).
[19] ME Couprie, et al. “Progress in the LUNEX5 project”, IPAC 2015, TUPWA011, these proceeding.