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TOWARDS A FREE ELECTRON LASER USING LASER PLASMA ACCELERATION

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Abstract

The ERC Advanced Grant COXINEL aims at demonstrating the free electron laser (FEL) amplification, based on the Laser Plasma Accelerator (LPA). To handle the inherent large energy spread and divergence with respect to conventional accelerators, a 10 m long transport line was designed to manipulate such beam. A first triplet of permanent magnet variable gradient quadrupoles (QUAPEVA) with strong gradient located close to the source refocuses the large beam divergence. The bunch lengthening and according slice energy spread reduction is then performed by a magnetic chicane. Finally, a set of electromagnetic quadrupoles provides a dedicated chromatic focusing in the downstream 2 m in-vacuum low gap undulator. Electrons injected in the line, were produced by the LPA using ionization assisted self-injection and show a broad energy spectra up to ~220 MeV and few mrad divergence. The target energy is 176 MeV enabling an FEL wavelength of 200 nm. Beam position and dispersion, from screen imaging, are controlled thanks to specific beam based alignment method using displacement of the QUAPEVA magnetic center. The energy range was also controlled using a slit inserted in the chicane. Experimental results and according numerical simulations are in correct agreement [1].

INTRODUCTION

Since the first FEL [2] in the infra-red in Stanford on MARK III, followed by the ACO FEL in Orsay [3] in the visible and harmonic generation [4] in the VUV, X ray base FEL light sources are actively developed around the word [5-8]. Besides, laser wakefield acceleration (LWFA) [9] can now generate very high electric fields (of the order of hundreds of GeV/m) [10-12] associated to the intense plasma waves, exceeding what can be achieved on conventional accelerators by several orders of magnitude. Such beams are considered for undulator synchrotron radiation [13] and Free Electron Lasers [14]. LWFA can now provide few GeVs range electron beams with hundreds pC charge, percent energy spread and mrad divergence, even though all these characteristics are not achieved all together. While conventional accelerators deliver µrad divergence and per mille of energy spread beams, the LWFA large energy spread and divergence require to mitigate chromatic effects [15-17], that leads to a dramatic growth in emittance and consequently beam quality degradation in the transfer lines.

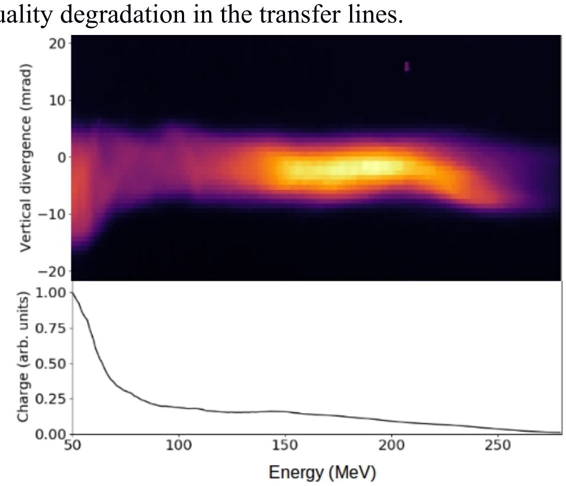

Figure 1: Typical energy and divergence profile of the electron beam at the exit of the plasma.

The COXINEL [18-22] transfer line is designed to handle the large divergence of LPA electrons thanks to strong permanent magnet quadrupoles, a magnetic chicane [21, 23] permits to reduce the slice energy spread and a chromatic focusing in the undulator is implemented to improve FEL performance [24].

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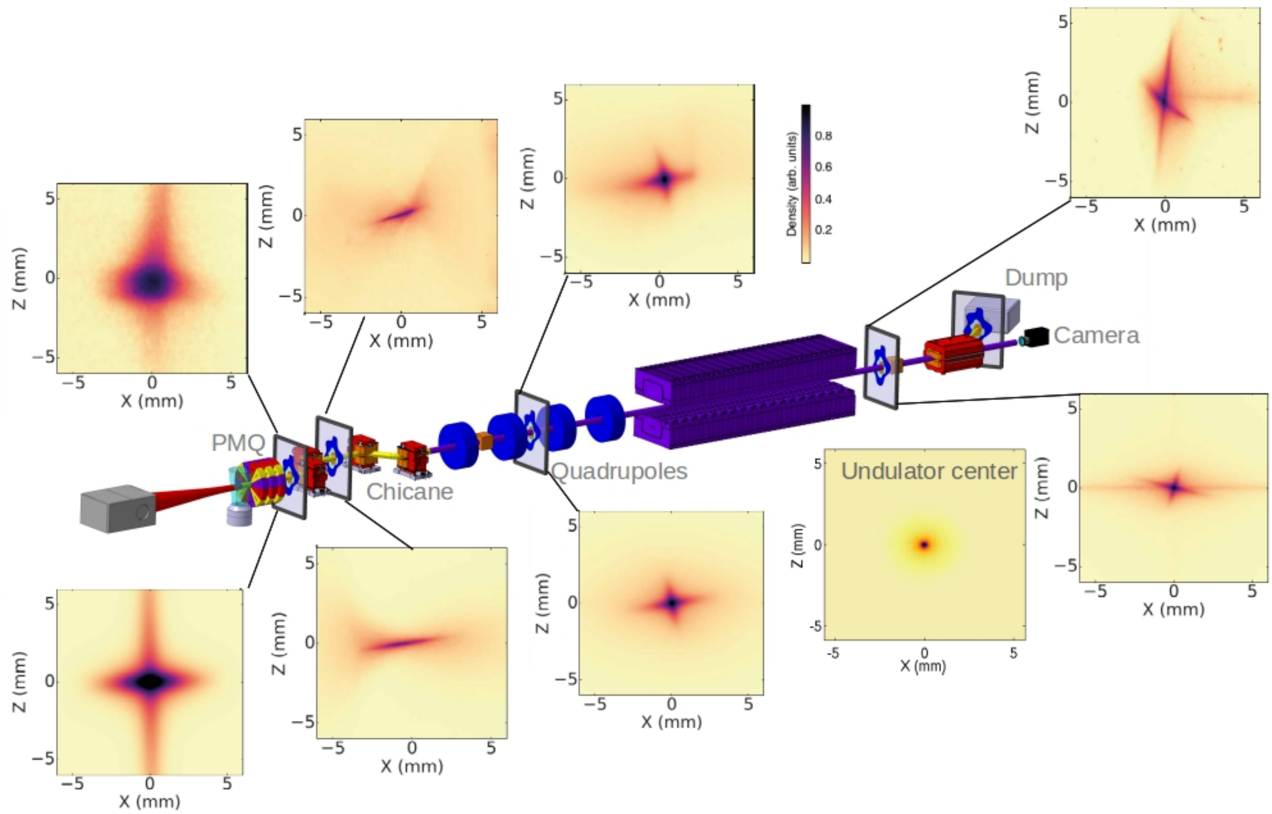

Figure 2: Scheme of the COXINEL manipulation line with screens for electron beam imagers. Measured (top) and simulated (down) electron beam transverse profiles (horizontal: x and vertical: z direction) along the line.

ELECTRON BEAM PRODUCTION

The laser system for the Laboratoire d'Optique Appliquée (Salle Jaune) delivers 1.5 J, 30 fs full width at half-maximum (FWHM) pulse that when focused properly into the gas jet provides the electron beam.The beam is first characterised with a spectrometer. Electrons are accelerated over a large energy spectrum ranging from few tens up to ~250 MeV (Fig 1). They present few mrad divergence (vertical divergence of 4.5 mrad-RMS with a standard deviation of 0.3 mrad over 20 shots. The slice divergence in the energy range of 176 ± 5 MeV is 3.5 mrad-RMS with a standard deviation of 0.2 mrad over 20 shots.

ELECTRON BEAM TRANSFER

A sketch of the manipulation line developed at Synchrotron SOLEIL is shown in Fig. 2. This large divergence is rapidly reduced via strong focusing of the variable permanent magnet quadrupoles (QUAPEVA) [25-26], located 50 mm downstream from the gas jet. The electron beam is then sorted in energy by means of a magnetic chicane. In parallel, the energy range of interest can be selected via a removable and adjustable slit mounted in the middle of the chicane. The four following electro-magnetic quadrupoles match the beam inside an cryo-ready in-vacuum undulator having a periodic magnetic field of 18 mm over 2 meters long [27]. Several scintillator screens are located along the line to image the electron beam in the transverse plane. The electron beam transverse distribution measured on the first screen (Fig. 2) tends to provide larger averaged divergence resulting from the low energy electrons that are not captured by the first spectrometer. In the same energy region of interest, typical horizontal divergence values of 5 mrad-RMS can be estimated. Significant pointing fluctuations (2.2 mrad-RMS) from intrinsic features of the LWFA source are measured.

With the QUAPEVA triplet inserted, the beam then refocused for the down-stream line. The transfer line pipe naturally filters the low energy electrons. While the QUAPEVAs provide a strong focusing, they also permit to freeze the total-emittance growth at the exit of the triplet. The emittance around 176 MeV over ±5 MeV slice is typically increased from 1 to ~90 (in H) and ~30 π.mm.mrad (in V). The emittance is then dominated by the chromatic emittance component due to the large initial divergence (quadratic dependency) and remains then unaffected along the line. The focused beam, both measured and simulated, also exhibits a cross-like shape which results from these chromatic effects (Fig. 2).

The alignment of the LWFA electron beam in the line is non-trivial. First, the transfer line components and LWFA laser are aligned within ±100 μm on the same reference axis using a laser tracker. Still, remaining QUAPEVA misalignment and/or systematic shifts or drift of the electron beam pointing can induce large orbit deviations and dispersion, that have to be reduced to minimise the beam distortions in the undulator. A specific beam

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pointing alignment compensation (BPAC) strategy has been developed. It relies on the transfer matric method: The horizontal and vertical response matrices of the system, at a position s along the line, that links the beam position and dispersion to the transverse offset of the magnetic centre of the three QUAPEVAs, are solved. Taking advantage of the motorised translations, the positions of the magnetic centres are adjusted to independently minimise the transverse offset and the dispersion according to the required correction on a given screen in both planes (Fig. 3). Finally, the QUAPEVA variable gradient is slightly varied (at the percent level) for the fine tuning of the electron beam focusing. A correct agreement versus simulation profile is obtained, as shown in Fig. 2.

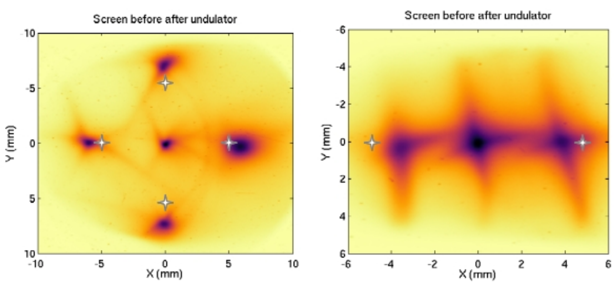

Figure 3: Beam pointing alignment compensation alignment illustration over different screens.

The electron beam transfer is then suitable for the observation of the undulator synchrotron radiation with a camera installed under vacuum at the end of the line (Fig 1). Figures 4a and b) display the transverse profiles of the radiation measured and simulated without the slit: they are similar in terms of both signal level and profile shape.

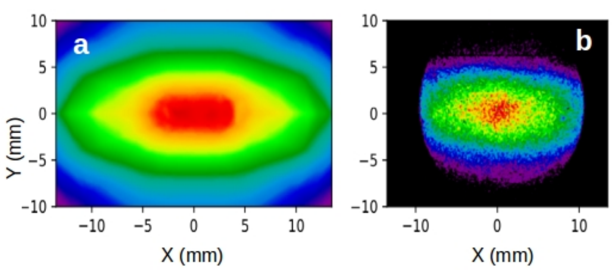

Figure 4: Undulator radiation observation (a) simulation, (b) experiment.

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