ELECTRON BEAM DIAGNOSTICS FOR COXINEL

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Abstract

On the path towards more compact free electron lasers (FELs), the project COXINEL was recently funded: a transfer line will be installed to adapt a plasma accelerated beam (from LOA) into an in-vacuum undulator built by SOLEIL. This experiment should enable to demonstrate the first FEL based on a plasma accelerator. Because plasma beams are intrinsically very different from RF acceletor beams (much shorter, divergent and smaller with a higher energy spread and energy jitter), their transport and matching in the undulator is critical if willing to obtain a significant amplification. This is why special care has to be taken in the design of the beam diagnostics to be able to measure the transverse beam sizes, energy spread and jitter, emittance and bunch length. For these purposes, several diagnostics will be implemented from the plasma accelerator exit down to the undulator exit. In each station, several screen types will be available and associated to high resolution imaging screens. In this paper, we present the experimental layout and associated simulation of the diagnostics performances.

COXINEL LAYOUT

COXINEL project [1] was recently funded by the European Research Council. This project aims at demonstrating the operation of a plasma accelerator based Free Electron Laser. The key concept relies on an innovative electron beam longitudinal and transverse manipulation in between the plasma accelerator and the undulator. Indeed, typical plasma accelerator beams exhibit percent level energy spread which intrinsicly disables any FEL amplification. The very small transverse dimensions and very large divergence of those beams also tend to dramatically spoil the initial emittance along the transport to the undulator. We proposed to use a "demixing" chicane to sort the electrons in energy and reduce the slice energy spread from 1 % to 0.1 %. Following the chicane, a set of quadrupoles is used to maintain the transverse density seen by the FEL radiation constant all along the undulator.

The COXINEL layout is illustrated in Figure 1. COXINEL will use the plasma accelerator of the Laboratoire d'Optique Appliquée (Palaiseau, France). The downstream equipements are under preparation at Synchrotron SOLEIL. They consist, following the electron beam path, in a triplet of quadrupoles, a demixing four dipoles chicane, a second set of quadrupoles, an undulator and a final beam dump. The expected electron beam and FEL parameters are summarized in Table 1. The targetted wavelength is 200 nm in first phase and 40 nm in second phase. The FEL will be operated in seeded mode.

Table 1: COXINEL Expected Parameters. (*) At the plasma accelerator exit.

Parameter	**Value**
Electron beam	
Energy	400 MeV
Energy spread (*)	1 %
Charge	10 pC
Peak current (*)	500 A
Electron beam duration in ID	15 fs-FWHM
Undulator	
Period	20 mm
Length	2 m
Peak magnetic field	0.9 T

Since the experiment relies on a refine manipulation of the electron beam phase space, beam diagnostics are vital on this project. Their location is indicated in Figure 1.

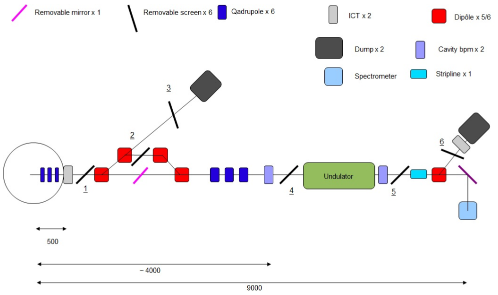

Figure 1: COXINEL layout.

DIAGNOSTICS STATIONS

Six diagnostics stations (DS) will be implemented on COXINEL. They are all designed on the same principle to ease their operation and reduce their cost. The fisrt one will be installed just after the first triplet, the second one in the demixing chicane, the third one on the first beam dump, the fourth and fifth at entrance and exit of the undulator and the last one will be on the final beam dump. They consist in:

- a motorized tree than can position on the beam axis three different targets at 45^o (see Figure 2),
- three targets: OTR screen, YAG:Ce or LYSO:Ce screen and calibration grid,
- an extraction viewport,
- an optical system to image the targets' surface,

- a ccd camera for image acquisition.

Those stations enable position, transverse dimensions, energy, energy spread and emittance measurements.

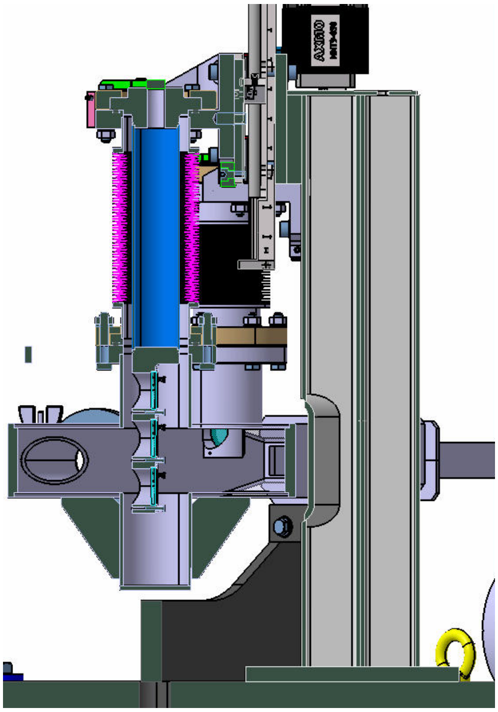

Figure 2: Motorized tree for the insertion of the diagnostics station screens.

Position and Transverse Size Measurement

To measure the electron beam position and transverse dimensions, a screen is inserted on the electron beam path at 45^o incidence. OTR, YAG:Ce or LYSO:Ce screens can be used. The screen surface is then imaged thanks to an optical system on to a CCD camera. All diagnostics stations are identical and all mounted screens are 1” diameter. The imagers specifications are summarized in Table 2.

To be imaged on a 4 mm large CCD, a field of 20 mm has to be reduced by a factor 5. Assuming standard pixel size of 7 μm, this would give a resolution of 35 μm in the image plane. To satisfy the requirements both in terms of field and resolution, we decided to equip the optical system with two possible magnifications, swapping one to the other using a translation stage. In each case, the system consists of a set of four focussing lenses of fixed focal length. The distance between the second and the third lens is simply changed to adapt the magnification. The final performances of the systems are summarized in Table 3.

But the imaging of electron beams using OTR or scintillator screens can be compromised when the electron beam (or some internal structures) becomes typically as long as optical wavelengths. In such cases, coherent OTR (COTR) is emitted with an intensity far above the incoherent OTR or the fluorescence in the case of the scintillator screens, and with a transverse distribution which no longer corresponds to the initial electron beam one. Such effects have been extensively observed on several machines [2,3].

On COXINEL, the electorn beam duration will vary from a few fs at the source up to ≈ 20 fs inside the undulator, corresponding to a spectral range of 300 nm up to 10 μm, allowing strong coherence effects in the visible range. First simulations of the COTR electric field distribution imaged on the CCD are presented in Figure 3, revealing the presence of a ring.

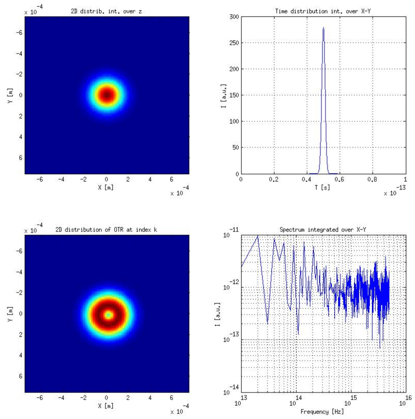

Figure 3: Calculation of the 3D OTR electric field in the image plane using [3]. Electron beam parameters are those of Table 1. Beam duration: 1 fs-rms.

For accurate transverse size measurements, COTR has to be mitigated. Several methods have been proposed, relying on spectral, temporal or spatial separation. We will test spectral and spatial selection and compare their efficiency.

But we will also use the COTR emitted for other electron beam diagnostic. Measuring the COTR spectrum or performing autocorrelation will provide some information on the electron bunch length. COTR measurement in the far field could also be an other way to measure the electorn beam energy.

Energy Measurement

The electron beam energy and energy spread will be measured at DS2, DS3 and DS6. Indeed, those three DS are located in a dispersive section of the transport beam line. In all DSs, the electron beam deviation is ensured by the same type of dipole magnets. The maximum available field is 1 T while the nominal field is 0.53 T in the demixing chicane i.e. before DS2 and DS3 and XX T before DS6. Basic equations of electron beam deviation in a magnetic field enable to simulate the electron beam distribution expected at DS2, DS3 and DS6 and therefore to predict the measurable energy range as illustrated in Figure 4.

With the nominal field in DS2, the measurable energy range is 330 - 520 MeV with a resolution of 0.32 MeV to 0.1 MeV depending on the zoom which is used.

Table 2: COXINEL Imagers Specifications. *: horizontal x vertical plane. ?: last imagers specifications are not defined yet.

Imager	1	2	3	4/5	6
σ_x [mm - rms]	0.4	0.35	0-20	0.15	?
σ_z [mm - rms]	0.2	0.2	0.2	0.15	?
Field [mm]*	15x15	20x20	20x20	20x20	20x20
Res. [μm - rms]	40	5	5	10	10
f_{acq} [Hz]	10	10	10	10	10
Charge min [pC]	10	10	10	10	10
Charge max [pC]	100	100	100	100	100

Table 3: COXINEL Imagers Expected Performances. Res. is the resolution in μm.

Imager	1	2	3	4/5	6
Zoom 1					
M	0.18	0.18	0.18	0.18	0.18
Field [mm]	20	20	20	20	20
Res. [μm]	41	41	41	41	41
Zoom 2					
M	-	1.5	1.5	0.74	0.74
Field [mm]	-	2.4	2.4	4.9	4.9
Res. [μm]		5	5	10	10

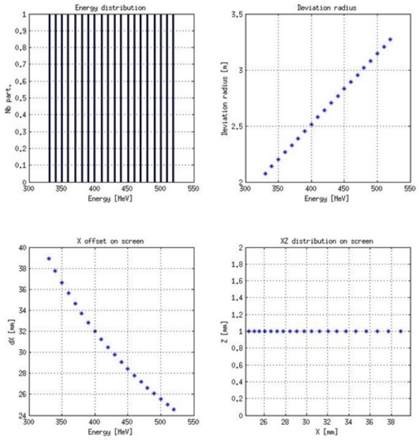

Figure 4: Calculation of the electron beam distribution on the target plane at DS2, DS3 and DS6 as a function of energy.

OTHER ELECTRON BEAM DIAGNOSTICS

Charge Measurement

The electron beam charge will be measured just after the first triplet, i.e. close to the plasma source, and at the undulator exit. We will use commercial Integrated Current Transformer from Bergoz, which allow accurate measurement even at the low expected charge of 10 pC.

Beam Position Measurement

The beam position can be measured on the diagnostics stations but not on-line. This is why other diagnstics are used for this purpose: cavity Beam Position Monitors (cBPM) and a stripline.

Two cBPM will be installed at the entrance and exit of the undulator, to ensure accurate orbit measurement and control where the amplification will occur. Both are systems provided by the Paul Sherrer Institute [4] which will be first tested on the SOLEIL's linac. The expected resolution is below 1 μm even at low charge.

The stripline is designed at SOLEIL as illustrated in Figure 5. The expected resolution is higher, 30 μm at 1 pC but more simple of operation. It will be installed at the exit of the undulator.

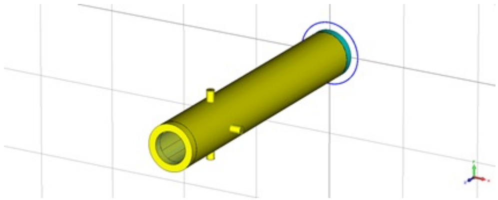

Figure 5: 3D modeling of the COXINEL stripline. Courtesy M. El Ajjouri.

DIAGNOSTICS FOR SEEDING

Because of space constraints, one single undulator will be used for the experiment. So that to see some amplification, the FEL has to be operated in seeded configuration. The seed will be generated via Harmonic Generation in gas using a leak of the drive laser used for plasma acceleration. It will be injected via a viewport using a mirror located in the middle of the chicane (where the electron beam deviation is the largest: few 30 mm).

Seeding requires accurent alignment of the seed on the electron beam in the spatial, temporal and spectral domain.

Spatial Alignment

The seed will be aligned on the electron beam trajectory using DS4 and DS5. Indeed, the electron beam position can be recorded at these two locations and then used as reference to steer the seed. The screens reflectivity at the seed wavelength (200 nm) has been measured and any type of screen could be used.

Temporal Alignment

Temporal alignment is a more serious issue. Both electron beam and seed will be ≈ 10 fs long, requiring a few fs temporal diagnostic. One way could be to make an autocorrelation between the two infra-red lasers generating the electron beam and the seed at the exit of DS4 or 5. In this case, an appropriate setup has to be implemented to allow propagation of the drive laser through out DS4. An other way could be to use a streak camera at DS4 or 5. The temporal resolution could be 300 fs-fwhm meaning that a final scanning will be required to find the synchronism condition.

Spectral Alignment

The spectral alignment will be done using a spectrometer located at the undulator exit. We plan to install a commercial system with a spectral range of 300 - 30 nm at least. The device will then enable to visualize both the seed and the synchrotron radiation spectra. Again, space constraints require the use of a short focal length spectrometer, but resolution below 0.1 % could still be reached.

CONCLUSION

The COXINEL project aims at demonstrating FEL amplification on a plasma accelerator, relying on a refine manipulation of the electron beam phase space. The experiment will take place at Laboratoire d'Optique Appliquée which provides the plasma source. SOLEIL is preparing the downstream equipments: essentially magnets, undulator and diagnostics. The electron beam will be characterized all along the FEL line in terms of charge, position, transverse dimensions, emittance, energy and energy spread. Installation and first experiments are scheduled in 2015.

REFERENCES

[1] M.E. Couprie et al., “Progress of the LUNEX5 project”, IPAC'2014, Dresde, Germany, May 2014, THPRO003(2014).

[2] S. Matsubara et al., “Improvement of screen monitor with suppression of coherent-OTR effect for SACLA”, IBIC'2012, Tsukuba, Japan, Septembre 2012, MOCC04 (2012).

[3] H. Loos et al., “Observation of coherent optical transition radiation in the LCLS linac”, FEL'08, Gyeongju, Korea, August 2008, THBAU01 (2008).

[4] B. Keil et al., “Design of the Swiss FEL BPM system”, IBIC'2013, Oxfoord, UK, Septembre 2013, TUPC25 (2013).

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