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PLASMA ACCELERATION-INDUCED BETATRON RADIATION: A POTENTIAL SEED FOR FREE ELECTRON LASERS

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Abstract

Betatron radiation produced in the plasma acceleration process could be used as seed for Free Electron Laser (FEL). A broadband radiation in the X-ray spectral region is produced by the strong transverse electron oscillation in the plasma channel driven by particle or laser wakefield acceleration. Selecting the betatron radiation wavelength matched with FEL resonance, with proper synchronization of the electron and photon pulses in the undulator, the FEL emission will be stimulated. In this paper, the scheme that could be adopted in EuPRAXIA@SPARC-LAB facility as well as the betatron and FEL emission simulations are presented.

INTRODUCTION

The Free Electron Laser (FEL) radiation produced by electron accelerated in the plasma accelerator driven by a particle wakefield (PWFA) has been recently demonstrated [1, 2].

The EuPRAXIA project, recently entered in the European Strategy Forum on Research Infrastructure (ESFRI) roadmap, aims to develop FEL facilities adopting laser wakefield acceleration (LWFA) and PWFA techniques.

The research infrastructure that will use the PWFA to generate FEL radiation in X-rays region will be built in the INFN Frascati Laboratories [3].

To increase the efficiency and extend the emitted radiation spectrum, the use of betatron radiation, produced by electrons during PWFA, as FEL seed is proposed.

Two bunches of electrons, one of high charge and one of low charge (driver and witness) are generated by a low emittance photoinjector followed by a linac operating with X-band radiofrequency and a plasma acceleration stage. The electrons of the bunch oscillate due to the intense transverse forces generating a wide bandwidth radiation in the X-ray: the betatron radiation.

This radiation, suitably selected in spectrum and temporally overlapped to the witness beam, separated from the driver after crossing the chicane, enters the undulator stage act as seed of the FEL emission as shown in Fig.1[4]. The seeding scheme with photons matched with the EuPRAXIA undulator fundamental wavelength (4nm) enhances the number of photons per pulse generated and the shot-to-shot temporal stability as in the self-seeding scheme [5].

The seeding with the betatron radiation can also extend the EuPRAXIA FEL frequencies maintaining the designed output parameters, while generally, to do so the undulator gap should be opened but the gain drops and the saturation is not reached in the case of pure SASE

The reported simulations show that injecting the betatron radiation, matched with the open undulator, it is possible to saturate also at higher frequencies.

SEEDING SCHEME

In the electron PWFA scheme a high charge bunch, called driver, passing through a gas-filled capillary generates the plasma wakefield losing energy and a following low charge one, the witness, is accelerated.

A magnetic chicane, composed by four dipole magnets, is placed before the FEL undulator to separate the driver and witness, due to the different energy, in order to stop the driver and send the witness in the undulator.

The proposed seeding scheme is shown in Fig.1

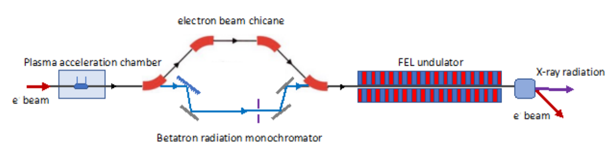

Figure 1: Betatron radiation seeding FEL scheme.

As soon as the electron bunches is deflected in the chicane the betatron radiation, that in the first magnet of the chicane propagates straight, is deflected by the first optical element of the monochromator that act also as delay line. The betatron radiation is then selected in bandwidth in order to match the FEL frequency and sent in the undulator direction overlapping the electrons in the first part of the undulator.

A fs-level synchronization between the electron bunch and the seeding photons at the entrance of the undulator is requested. However, the betatron radiation is automatically synchronized because is generated by the same electron beam in the plasma and to overlap the electron and photon pulses is only necessary that the trajectory of the photons in the monochromator is such as to compensate for the delay of the electrons in the chicane

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BETATRON RADIATION

Betatron radiation is the radiation emitted by electrons accelerated in plasma channels. We have studied the betatron radiation spectrum of the witness bunch of Eupraxia, for a possible future FEL seeding experiment, and of the driver bunch of the SPARC Linac for the feasibility study of a test at SPARC_LAB.

Radiation from the EUPRAXIA Witness Bunch

The target parameters of the witness bunch in Eupraxia are resumed in the table below.

Table 1: Eupraxia Witness Beam Parameters

	In	Out
Charge	30 pC	30 pC
Beam size (transverse, rms)	2 µm	2 µm
Beam size (longitudinal, rms)	7 µm	7 µm
Normalized rms emittance	0.6 mm*mrad	0.6 mm*mrad
Relative energy spread, rms)	0.05 %	0.05 %
Peak current	1.8 kA	1.8 kA
Beam energy (mean)	500 MeV	1 GeV

For the simulation of the radiated betatron spectrum we have assumed a linear energy gain, with initial value ~ 1000 and final value ~ 2000 at 0.4 m. Furthermore, we consider a gaussian beam and the background electron plasma density is $n_e = 3 \times 10^{16} cm^{-3}$. The result of the simulation, based on the same formulas in [6] and on the data reported in Table 1, is shown in Fig. 2.

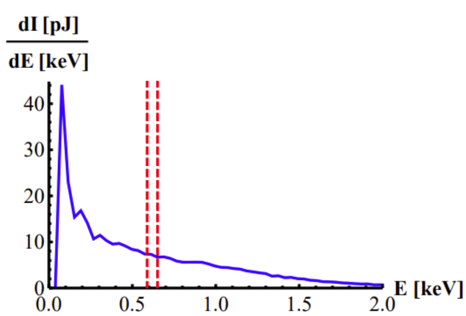

Figure 2: Simulated betatron radiation spectrum emitted by the Eupraxia witness bunch. 10% bandwidth at 620 eV is shown.

From Fig. 2 is possible to infer the number of emitted photons, after integration over E. In particular, the number of photons emitted at 620 eV (2 nm), within a bandwidth of 10 %, is 8.9×10^6, while the number of photons emitted at 310 eV (4 nm) within a bandwidth of 10 %, is 1.4×10^7. Reducing the bandwidth to 1 %, we get 1.4×10^6 at 4 nm and 8.9×10^5at 2 nm.

Radiation from the SPARC Driver Bunch

For SPARC we have considered the driver bunch instead of the witness, due to the fact that the radiation from the witness would be not enough for a seeding experiment. For the simulation of the radiated betatron spectrum we have considered the electron and plasma parameters of Ref. [1]. The result of the simulation is shown in Fig. 3.

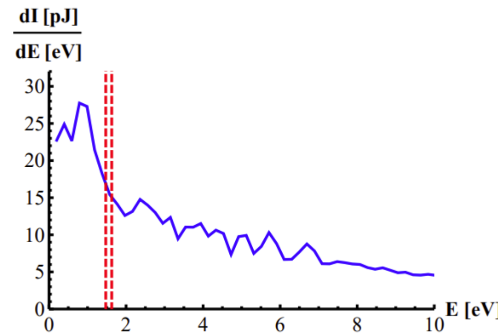

Fig. 3: Simulated betatron radiation spectrum emitted by the SPARC driver bunch. 10% bandwidth at 1.55 eV is shown.

From Fig. 3 is possible to infer the number of emitted photons, after integration over E. In particular, the number of photons emitted at *1.55 eV (800 nm),* within a bandwidth of *10 %*, is 2×10^7, corresponding to 5 pJ pulse energy.

SEEDED FEL SIMULATIONS

The betatron radiation has been used as seed for the FEL emission generated by the witness electron beam.
The undulator is the EuPRAXIA high-energy line AQUA [7], with 10 modules with period λ_w=1.8 cm for a total length of about 25 m. The initial longitudinal power distribution of the seed has been prepared with random spikes and random phase structure so as to mimic the incoherent structure of the betatron pulse. The witness beam has been matched to the undulator with transverse dimensions σ_x=69 µm and σ_y=44 µm. The SASE simulation, made with GENESIS 1.3 [8] at 4 nm (Fig. 4, blue curve) shows that the radiation in 25 m is still in the exponential stage, achieving at the undulator end 5.3 µJ of energy, corresponding to 10^{11} photons /shot. Starting with the seed, instead, allows the radiation to reach saturation within 20-22 m, arriving to an energy of 20 µJ, corresponding to 4 10^{11} photons/shot (red curves). The stability of the pulse is moreover increased.

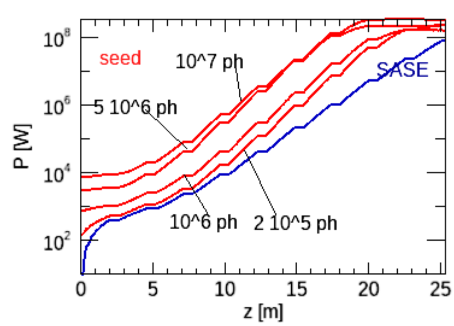

Figure 4: Growth of the FEL radiation at 4 nm along z(m) for the SASE case (blue curve) and various seed values (red curves)

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At 3.2 nm, the use of the betatron radiation as a seed appears even more advantageous, provided to seed the FEL with at least 2/3 106 photons. In this case, shown in fig. 5, the SASE provides 3 109 photons, vs 1011 of the seeded operation. Table 2 summarizes the data.

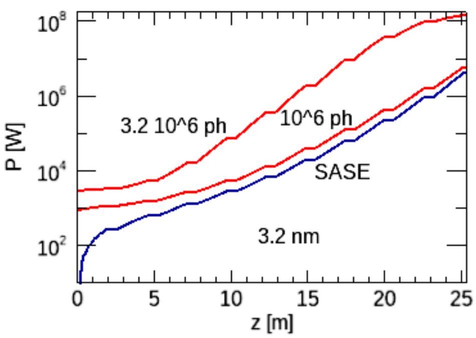

Figure 5: Growth of the FEL radiation at 3.2 nm along z(m) for the SASE case (blue curve) and various seed values (red curves).

Table 2: Number of photons for different wavelength

λ_{rad}	N_{seed} ph.	N_{rad} ph.	BW
4 nm	0	10^{11}	0.08%
4 nm	10^6	$3\ 10^{11}$	0.12 %
4 nm	$5\ 10^6$	$4\ 10^{11}$	0.12%
3.2 nm	0	$3\ 10^9$	0.1%
3.2 nm	10^6	$5\ 10^9$	0.09%
3.2 nm	$2\ 10^6$	10^{11}	0.09%

TEST AT SPARC

Waiting for the realization of the EuPRAXIA facility, a proof-of-principle in the near infrared wavelength range could be done on the SPARC accelerator in Frascati. The idea is to collect the betatron radiation produced by the electrons of the driver bunch, to focus and delay it appropriately and superimpose it in the first part of the undulator on the witness beam accelerated by the plasma itself. Instead of using a traditional delay line with mirrors in order to synchronize the photons generated by the driver in the plasma with the witness electrons at the input of the undulator, a proper lens will be used which will have the dual purpose of both refocusing and slowing down the photons with respect to the electrons.The radiation will act as seed for the FEL emission.

The calculated power and spectrum of betatron radiation is shown in Fig. 3, while the effect of the radiation in the effective bandwidth coupled with the FEL is shown in Fig. 6 where the growth of the FEL emitted radiation without (SASE) and with the seeding are compared for reasonable values of the seeding divergence. The emitted power grows more rapidly if seeded. A significant effect consisting in the power radiation one order of magnitude more intense could be measured at the 3rd and 4th undulators.

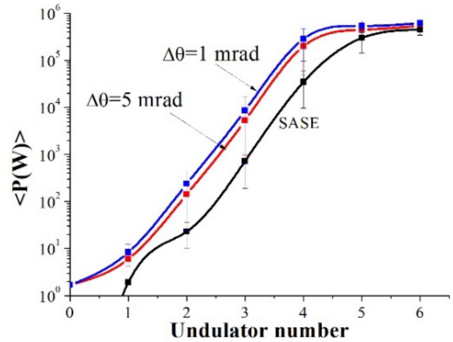

Figure 6: Growth of the FEL radiation in the case of SPARC vs. the undulator number. The emitted power has been averaged over 20 shots. In black: SASE case, in red divergence of the seed Δθ=5 mrad, in blue Δθ=1 mrad.

CONCLUSION

In the X-FEL driven by plasma-accelerated electrons, the betatron radiation, produced during the acceleration process, can be used as seeding in a wavelength region where there are no laser sources available with the advantage of being synchronized to femtosecond levels.

This seeding configuration could be adopted in all the FEL driven by LWFA/PWFA accelerated electron bunches. Next studies will be focused on the simulations of the 3D effects in betatron radiation emission and on the betatron radiation stimulating the FEL emission on the higher harmonics range.

A proof-of-principle SPARC experiment is being proposed in the near-infrared region.

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