SHORT PULSES THz FEL FOR THE OXFORD ACCELERATOR SCIENCE LABORATORY

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Abstract

The Accelerator Science Laboratory (ASL) is under development at the John Adams Institute in Oxford with the aim of fostering advanced accelerator concepts and applications. The option to install a short pulse THz FEL based on a conventional RF accelerator driven by a RF photocathode gun is being investigated. This report presents the concept of the facility, the accelerator physics and FEL studies and engineering integration in the University physics department.

INTRODUCTION

Tuneable, wideband long-wavelength and THz sources, are receiving growing interest because they enable the exploration of many rotation and vibration modes of molecules with different experimental techniques like imaging and spectroscopy in a wide range of applications: medical science, biology, security [1], beyond the usual electron beam diagnostics [2]. Several facilities are explicitly targeting accelerator based THz sources and free electron laser (FEL), which has a potential to generate high power short pulses THz radiation [3]. This work describes the compact THz FEL light source that is under consideration for the Accelerator Science Lab (ASL). This is one of the options proposed by the John Adams Institute (JAI), for the construction of a university-scale accelerator laboratory at the University of Oxford.

S2E SIMULATION

The Linac driven THz FEL comprises a S-band cavity 3 m long, an X-band cavity 0.6 m long, a four dipoles magnetic chicane and a 6-m planar undulator. The machine layout is shown in Fig. 1. The final beam energy can reach 20 MeV. In order to study a Linac for the THz FEL, full start-to-end (S2E) simulation has been done from a RF photocathode gun to an undulator. The simulation is divided into three sections. The first section studies the beam injector which consists of a 1.6-cell S-band RF gun and S-band cavity. This section has been studied with ASTRA [4]. The second section consists of an X-band harmonic cavity followed by a four dipole chicane bunch compressor. The beam dynamics in this part has been simulated with ELEGANT [5]. We assume that space charge effects are negligible after the S-band cavity and defer the investigation of this aspect to forthcoming studies. The last section is the FEL study in a planar undulator by using GENESIS [6].

Injector

We considered a laser profile at the photocathode with a flat-top of 6 ps (FWHM) length and 0.8 ps rising and falling time with 0.5 nC bunch charge. The electrons from the cathode are injected by the RF gun. Two solenoids are used: next to the RF gun and in front of the S-band cavity. The gradient of the RF gun, the magnetic field of the first solenoid, and the position of S-band cavity have been optimized in order to satisfy the conditions for the invariant envelope for compensating the emittance growth due to the space charge force in a drift between the gun and the cavity. The second solenoid is used to control the beam optics in the cavity. At the end of S-band cavity, a 20-MeV beam has the emittance lower than 1 mm-mrad and energy spread of 1%. The parameters in each component are listed in Table 1. Note that the beam is accelerated off-crest in the S-band cavity to embed an energy chirp which is required for the bunch compression at the later stage.

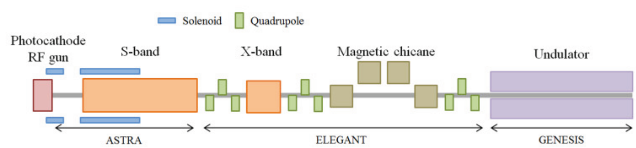

Figure 1: THz FEL linac for the ASL.

Bunch Compression

In this section, the beam passes through a beamline consisting of an X-band cavity and magnetic chicane to compress the bunch length. The X-band cavity is used in order to linearize the longitudinal phase space giving a better control of the bunch compression. The beam is then dispersed in the chicane. Particles of different energy traverse different path lengths. The longitudinal phase space is then rotated; therefore, the bunch is longitudinally compressed across the chicane. The gradient of the X-band cavity and the bending angle of the chicane have been optimized to ease the compression. The optimized parameters are listed in Table 1. Although the bunch length is not at the minimum, this configuration copes with the transverse emittance growth due to the longitudinal space charge force and the coherent synchrotron radiation (CSR). By minimizing the horizontal beta function at the last bending magnet in the chicane, the CSR effect is alleviated. At the end of this section, the bunch length can be reduced to about 0.7 ps with the peak current of 0.5 kA. The phase spaces before and after the chicane are shown in Fig. 2.

FEL Study

The distribution of the compressed beam is passed into the undulator to study the generation of FEL radiation. The study is based on the FEL under Self-Amplified Spontaneous Emission (SASE) mode and no external seed sources have been considered. In order to get the THz radiation from the beam with energy of about 18 MeV, we consider a hybrid undulator with a period of 3.5 cm and a gap of 1.2 cm having an undulator parameter K = 2.06. The FEL parameter is $\rho \approx 1.8\times10^{-2}$. Figure 3 shows the simulated FEL power about the resonance wavelength of 46.4 μm (6.47 THz). The FEL power saturates within 4 m with the saturation power of about 1 MW. A single-shot spectrum of the radiation is shown in Fig. 4.

Table 1: Parameters in injection section (ASTRA) and bunch compression section (ELEGANT)

Parameter	Value	Unit
Injector		
Bunch charge	0.5	nC
Gun and S-band cavity frequency	2.856	GHz
Gun cell number	1.6	cell
rms spot size on cathode	0.4162	mm
Laser pulse length (FWHM)	6.0	ps
Laser rising and falling time	0.8	ps
Norm. emittance on cathode	1.36	mm-mrad
Gun max. gradient	120.2	MV/m
Gun RF phase	-3.939	Degree
Gun solenoid max. long. field	0.2797	T
S-band accelerating gradient	3	MV/m
S-band RF phase	-27.22	degree
After S-band		
Beam energy	20	MeV
Norm. emittance	1.01	mm-mrad
rms energy spread	1.042	%
Bunch compression		
X-band accelerating gradient	4	MV/m
X-band RF phase	-180	degree
Chicane bending angle	12	degree
Beam energy after X-band	17.52	MeV
Before chicane		
rms bunch duration	1.799	ps
Norm. emittance	0.99/1.01	mm-mrad
rms energy spread	0.605	%
Peak current	80	A
After chicane		
rms bunch duration	0.722	ps
Norm. emittance	6.50/1.01	mm-mrad
rms energy spread	0.638	%
Peak current	500	A

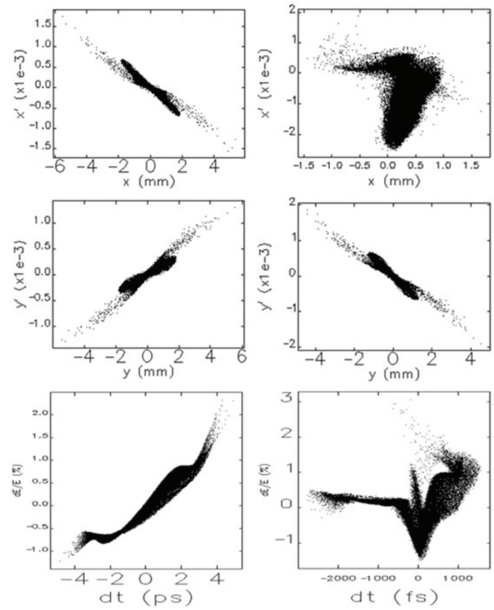

Figure 2: Horizontal (top), vertical (middle) and longitudinal (bottom) phase spaces before (left) and after (right) the magnetic chicane.

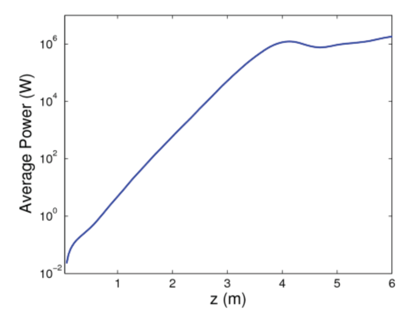

Figure 3: Average FEL power versus the distance (z) in the undulator.

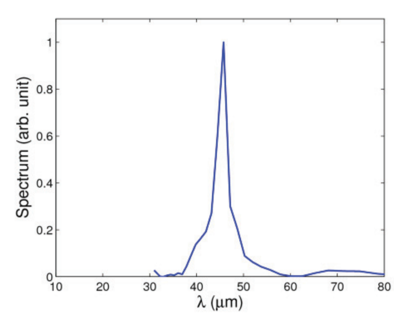

Figure 4: Spectrum of the FEL radiation at the distance 6 m in the undulator.

RADIATION SHIELDING SIMULATION

The radiation shielding of the ASL is also included in our study. The study is done with FLUKA [7]. In view of future upgrades, to an LPWA-based light source the beam is assumed to have an energy of 1 GeV. The shielding components in the study are concrete walls in the basement of the Denys Wilkinson Building (DWB) of the Department of Physics and a beam dump with the local

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shielding around it. The FLUKA simulations are based on the 1-GeV electron beam with a bunch charge of 1 nC and repetition rate of 10 Hz.

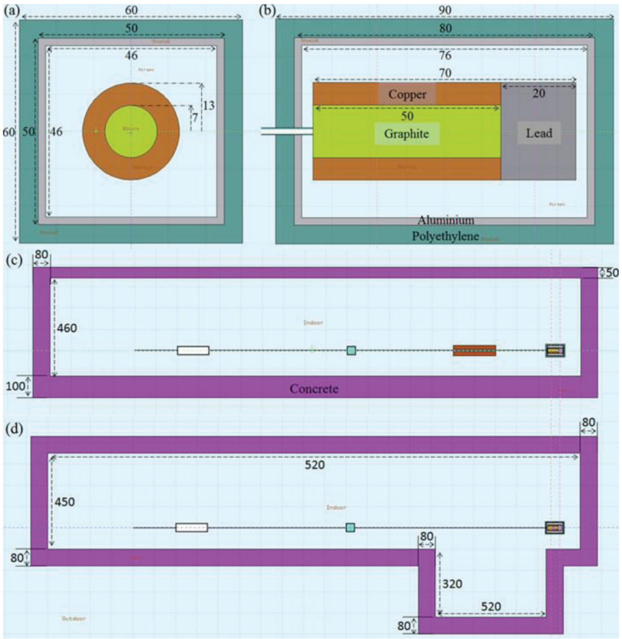

Figure 5: Front view (a) and side view (b) of the beam dump and the shielding. Side view (c) and top view (d) of the FLUKA simulation region. All the dimension is in cm.

The beam dump is modelled in a cylindrical shape corresponding to the beam symmetry. The optimized model of the dump consists of three components: graphite core, copper shell, and lead backstop. The dimension of the dump is shown in Fig. 5(a) and 5(b). It is designed to absorb 99% of the beam energy. The shielding around the dump has two components: inner aluminium box and outer polyethylene box. The dump shielding is used to ensure the radiation safety within the accelerator room. The space between the dump and the shielding is reserved for mechanical structures and for an ease of maintenance. Figure 5(c) and 5(d) show side and top views of simulation region for the ASL accelerator room, which is proposed to be located in the basement of the Departmemt of Physics, Oxford University.

Radiation during beam operation (prompt radiation) and radiation after the beam operation (residual radiation) have been calculated with FLUKA with different irradiation profiles and time durations after the beam is terminated. Criteria for radiation protection are based on CERN standard [8] and annual working hours is estimated as 2000 hours. The prompt dose equivalent rate in the public area outside of the concrete walls stays well below the dose limit for non-occupationally exposed person of 0.5 μSv/h as shown in Fig. 6. In case of the residual radiation, the dose rate in the experimental area outside of the dump shielding is below the dose limit for occupationally exposed person of 10 μSv/h after the beam is switched off.

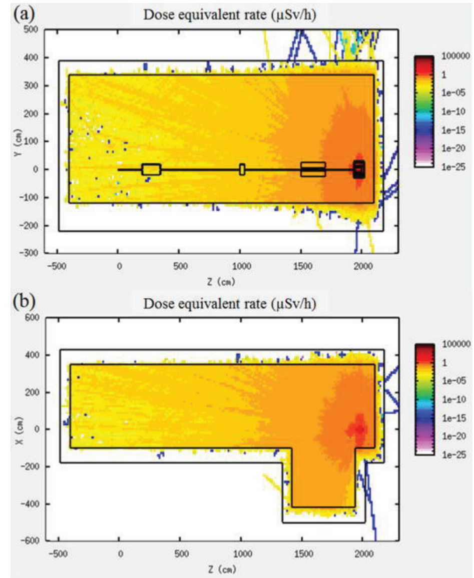

Figure 6: Dose equivalent during the beam time from FLUKA simulation in (a) side view and (b) top view.

CONCLUSION

We studied the performance of a Linac based THz FEL as a candidate for the ASL. The study has been done by S2E simulation starting from RF photocathode gun to the undulator divided into three sections. The first section uses the ASTRA code to study the injection of a 0.5-nC electron bunch from the RF gun through the S-band cavity. The beam at the end of this section has energy of 20 MeV, emittance of 1 mm-mrad and energy spread of 1% with energy chirp embedded by accelerating the beam off-crest in the S-band cavity. The bunch compression was studied in the second section with the ELEGANT code. The bunch duration is compressed from 1.8 ps to 0.7 ps across a magnetic chicane with bending angle of 12°. The third section is for the FEL study using GENESIS code. The radiation in SASE mode at about 6.5 THz with the power of 1 MW was obtained within 4 m in the undulator.

The structures for radiation shielding of the ASL were also investigated, using the FLUKA code. The beam dump and the local shielding around the dump were designed to absorb the energy from a 1-GeV electron beam. Our simulation shows that the dump and the concrete walls can provide acceptable radiation safety in terms of both prompt radiation and residual radiation.

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