ISBN: 978-3-95450-168-7 doi:10.18429/JACoW-IPAC2015-TUPJE060

DEVELOPMENT OF ADVANCED FOURTH GENERATION LIGHT SOURCES FOR THE ACCELERATOR SCIENCE LABORATORY

T. Chanwattana[1], R. Bartolini[1,2], A. Seryi[1], E. Tsesmelis[3]
[1]John Adams Institute, University of Oxford, OX1 3RH, UK
[2]Diamond Light Source Ltd, Oxfordshire, OX11 0QX, UK and
[3]CERN, Geneva, Switzerland

Abstract

The John Adams Institute for Accelerator Science (JAI) has proposed the realisation of the Accelerator Science Laboratory (ASL) at the University of Oxford as a facility for the development of advanced compact light sources enabling accelerator science research and applications. The installation of a compact light source in the ASL is planned with two options for the accelerating technologies. Firstly, a conventional RF based accelerator is considered to be a driver for a short pulse THz coherent synchrotron radiation (CSR). The other option focusses on the radiation produced by a Laser Plasma Accelerator (LPA) advanced accelerator technique that will provide the possibility to shorten the length of the beamline. This paper presents results of the studies on beam dynamics for both options of compact light sources in the ASL.

INTRODUCTION

Compact advanced fourth generation light sources enable advanced research and experiments in a wide range of applications in small-scale facilities, especially at universities. The John Adams Institute for Accelerator Science (JAI) at the University of Oxford has been studying the possibility of establishing the Accelerator Science Laboratory (ASL) as an accelerator laboratory dedicated to advanced research with compact light sources. Many facilities worldwide aim to generate terahertz (THz) radiation, which is required in numerous scientific experiments and applications, such as imaging and spectroscopy of molecules, disease diagnostics and organism detection, electron beam diagnostics, safety non-destructive monitoring and weapons inspection. The THz radiation can be produced by various schemes, such as solid state oscillators, gas and quantum cascade lasers, coherent synchrotron radiation (CSR) and free electron lasers (FELs). Currently, the ASL aims at producing short pulse THz CSR from a dipole magnet with two options of acceleration technologies. The first option is based on the acceleration of electron beams with a conventional RF linac and shortening of the electron bunch length by a magnetic chicane bunch compression. The other is to utilize the electron beam with extremely short bunch length produced from laser plasma accelerator (LPA) in a bubble regime to produce the coherent radiation. This paper presents beam dynamics studies of the THz radiation source for the ASL in both options after [1] and the assessment of the achievable performance.

RF-DRIVEN RADIATION SOURCE

Beam Dynamics

A beamline of the THz radiation source based on the RF linac consists of a 1.6-cell S-band photocathode gun, an S-band cavity, an X-band harmonic cavity and a four-dipole magnetic chicane as shown in Fig.1. An electron beam emerges from a cathode in the RF gun. The S-band cavity accelerates the beam to reach the desired energy and employs the emittance compensation process to increase beam brightness. The X-band harmonic cavity is used for linearization of the beam longitudinal phase space, which offers better control of bunch length compression in the magnetic chicane. The synchrotron radiation is generated at the last dipole magnet of the chicane.

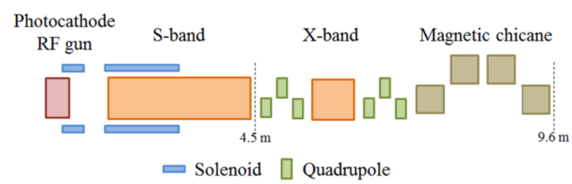

Figure 1: Layout of the RF-driven radiation source.

Beam dynamics of this RF-based radiation source has been studied with start-to-end (S2E) simulations starting from the beam at the photocathode gun to the generation of CSR. The simulation is separated into two parts: the injector, comprising the RF-gun and the S-band cavity and the second part comprising the X-band cavity, the bunch compressor and its matching section. Low bunch charge is considered in order to get short bunch length leading to our target to generate the short pulse THz radiation. Hence, the simulations were done based on two choices of bunch charge: 100 pC and 500 pC.

Injector

The first part of the S2E, from the photocathode gun to the end of the S-band cavity, was simulated with ASTRA [2] because of the dominance of the space charge effect on a low energy beam. RF frequency of both components is 2.856 GHz. A flat-top laser profile is considered in both 100 pC bunch and 500 pC bunch. After the gun, the electron beam is focussed by a solenoid to get the minimum beam waist at a position where the S-band cavity is located at in order to compensate emittance growth by using an appropriate accelerating gradient. The S-band cavity accelerates the beam to about 55 MeV and also operates off-crest in order to introduce a

ISBN: 978-3-95450-168-7 doi:10.18429/JACoW-IPAC2015-TUPJE060

longitudinal-correlated energy modulation (energy chirp) required for bunch length compression process in the next part. Another solenoid is located at a position along the cavity to control beam optics obtained at the end of the section. The optimized parameters are shown in Table 1. The electron beams simulated with both bunch charge values have the emittance of below 0.8 mm-mrad with the energy spread of a few percent.

Table 1: Parameters in Injector Simulation

Parameter	**Value**		**Unit**
Bunch charge	100	500	pC
Laser pulse length	3.0	6.0	ps
Laser rise/fall time	0.1	0.1	ps
Spot size on cathode	0.50	0.54	mm
Gun acc. gradient	120.0	120.2	MV/m
Gun RF phase	-1.395	-4.050	degree
1st solenoid field	0.279	0.276	T
S-band acc. gradient	25.34	25.46	MV/m
S-band RF phase	-30	-30	degree
2nd solenoid field	-0.162	-0.140	T
Beam energy	54.82	55.28	MeV
Norm. emittance	0.63	0.76	mm-mrad
Energy spread	0.71	1.54	%

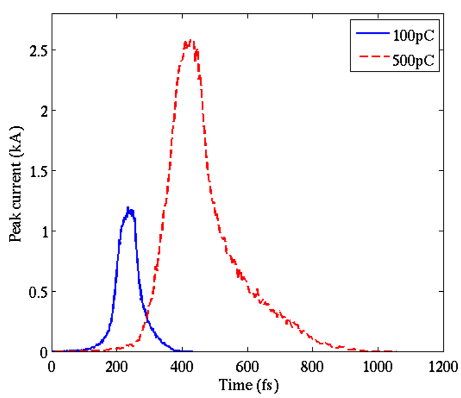

Figure 2: Current distribution of 100 pC bunch and 500 pC bunch at the end of injector at 55 MeV.

Bunch Compressor

The 55-MeV beam from the S-band cavity traverses the X-band harmonic cavity operating at the decelerate phase to linearize the energy chirp. After that the magnetic chicane provides different path lengths for electrons with different energies to compress the bunch. The electrons with higher energy follow a longer path and vice versa leading to the rotation of the longitudinal phase space and hence the bunch length is compressed. The simulation in this part was done with ELEGANT [3] with the assumption that space charge forces are already negligible in the range of charge and energy under analysis. The gradient of the X-band cavity and the bending angle of chicane magnets were optimized for getting the minimum bunch length targeting in the range of 100 fs. The minimum achievable bunch length for 100 pC and 500 pC are 40 fs and 114 fs with the peak current of 1.2 kA and 2.5 kA, respectively. The compressed bunch profiles are shown in Fig. 2. Table 2 lists optimized parameters for getting the minimum bunch lengths.

Synchrotron Radiation from a Dipole Magnet

The longitudinal bunch profiles ($\rho(z)$) from the simulation are fitted with multi-Gaussian distribution. The distribution is then used to calculate the form factor $f(\omega) = \left|\int \rho(z) e^{i\omega\hbar z/c}\, dz\right|^2$ and the spectral intensity of the radiation of the electron bunch is calculated from the number of electrons in a bunch (n_e), the form factor ($f(\omega)$), and the spectral intensity of each single electron as following [4]:

$$\left(\frac{d^2I}{d\omega d\Omega}\right)_{bunch} = [n_e + f(\omega) n_e (n_e - 1)] \left(\frac{d^2I}{d\omega d\Omega}\right)_e$$

in which the first term corresponds to incoherent radiation, and the second corresponds to coherent radiation. The resulting spectra of both bunch charge choices are shown in Fig. 3 using a 0.3-m-long dipole magnet with bending radius of 1.7 m. The CSR spectra of 100 pC and 500 pC extend up to approximately 80 THz and 35 THz respectively, corresponding to the shorter length of the 100 pC bunch. The spectrum of the 500 pC bunch at 0.01 THz is higher than the spectrum of 100 pC bunch by factor of 25. This dependence of n_e^2 confirms that the radiation is coherent. As the spectra in Fig. 3 show, the CSR gain up to a frequency of 100 THz is substantial, and the machine parameters proposed are appropriate for the operation of the RF-driven linac to deliver the THz radiation. Considering the frequency range of 0.01-1000 THz, the peak power is 3.8 GW (100 pC) and 8.8 GW (500 pC), whereas the average power is 15 mW (100 pC) and 100 mW (500 pC) assuming a 100 Hz repetition rate.

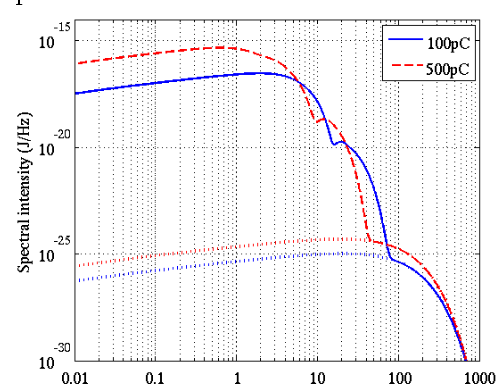

Figure 3: Spectra of radiation from a dipole magnet of 100 pC bunch and 500 pC bunch.

LPA-BASED RADIATION SOURCE

Laser Plasma Accelerators (LPAs) are the object of a large R&D effort in the plasma and accelerators

ISBN: 978-3-95450-168-7 doi:10.18429/JACoW-IPAC2015-TUPJE060

communities for their extremely high accelerating gradient that may potentially allow the construction of table top compact light source. LPAs not only provide a high-accelerating gradient, but they also generate beams with ultra-short bunch length on the femtosecond scale which is an essential property in view of our application to the production of short-pulse radiation. For this purpose, we performed S2E simulations with the 2D particle-in-cell EPOCH [5] to characterize the radiation source driven by an ultra-short self-injected electron bunch generated by a LPA in the bubble regime.

Table 2: Parameters in Bunch Compressor Simulation

Parameter	**Value**		**Unit**
Bunch charge	100	500	pC
X-band acc. gradient	1	4	MV/m
X-band RF phase	-180	-180	degree
Chicane bending angle	9.5	9.3	degree
Beam energy	54.24	52.52	MeV
Pre-compression			
Bunch length	863	1723	fs
Norm. emittance	0.64(h) 0.63(v)	0.82(h) 0.78(v)	mm-mrad
Energy spread	0.66	1.39	%
Peak current	34	80	A
Post-compression			
Bunch length	40	114	fs
Norm. emittance	2.30(h) 0.63(v)	7.00(h) 0.80(v)	mm-mrad
Energy spread	0.69	1.61	%
Peak current	1.2	2.5	kA

EPOCH Simulation

The EPOCH simulation was done by using a 20 fs 10 TW laser with wavelength of 800 nm and spot size of 15 µm interacting with uniform plasma of density 4×10^{18} cm^{-3}. The result shows that the self-injected bunch, at 7 ps after the laser pulse enters the plasma as shown in Fig. 4, has the normalized transverse emittance of 1.2 mm-mrad and the bunch length of 4.4 fs with the energy of 219 MeV and the energy spread of 2.8%. The charge of the injected bunch can be calculated by the wavelength of the laser and the plasma density [6]. In this simulation, the estimated bunch charge is 120 pC.

Synchrotron Radiation from a Dipole Magnet

The radiation spectrum from a dipole magnet of the injected bunch profile from EPOCH simulation is shown in Fig. 5. The CSR from the 4 fs bunch dominates up to about 1000 THz. This result and the spectrum of 100 pC bunch from the RF-based light source are in agreement with the upper limit for the CSR frequency being inversely proportional to the bunch length. The peak power is 0.9 TW. Due to limits on the high-power laser technology, the LPAs will operate at a substantially reduced repetition rate, at for example 10 Hz. Hence, the average power is 40 mW.

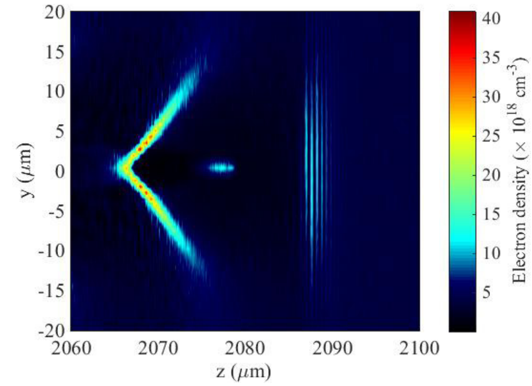

Figure 4: Electron density of the plasma at 7 ps after the laser pulse travelled in the plasma.

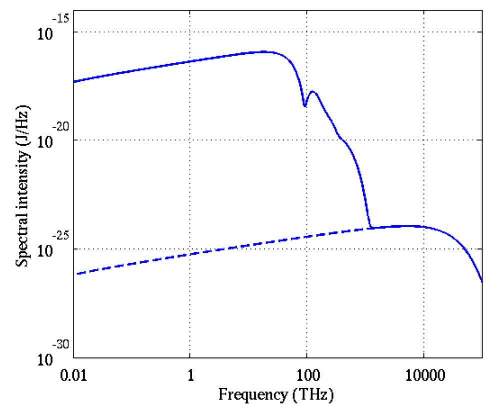

Figure 5: Spectrum of radiation from a dipole magnet of 120 pC bunch driven by LPA.

CONCLUSION

The beam dynamics studies of short pulse THz radiation source for the ASL were done considering the electron beam driven by the RF linac and the LPA. The S2E simulation of the RF-driven source was done using bunch charges of 100 pC and 500 pC and show that high peak power ultra-short THz pulse can be obtained in both cases. For the LPA-based source, the 2D EPOCH simulation was done to produce a self-injected electron bunch with ultra-short bunch length. We obtained a 219-MeV bunch of 1.19 mm-mrad normalized emittance and 4.4 fs bunch length. The upper limit of the CSR spectrum extends to about 1000 THz.

This study demonstrates the great potential of the ASL in providing short pulse THz radiation for advanced research at the University of Oxford.

REFERENCES

[1] T. Chanwattana *et al.*, p. 2934, THPRO031, IPAC14.
[2] K. Flottmann, in http://www.desy.de/~mpyflo
[3] M. Borland, elegant, APS LS-287, (2000).
[4] M. Schwarz *et al.*, p.568, MOPPP003, IPAC12.
[5] http://ccpforge.cse.rl.ac.uk/gf/project/epoch/
[6] W. Lu *et al.*, p. 3050, THPMS023, PAC07.