A COMPACT EUV LIGHT SOURCE USING A mm-WAVE UNDULATOR*

F. Toufexis†[1], C. Limborg-Deprey, V.A. Dolgashev, S.G. Tantawi,
SLAC, Menlo Park, CA 94025, USA
[1]Also at Department of Electrical Engineering, Stanford University, Stanford, CA 94305, USA

Abstract

We are building an Extreme Ultra Violet (EUV) light source based on a 1.75 mm period RF undulator. We will use a thermionic X-Band injector which utilizes RF bunch compression. The beam is accelerated using an X-Band traveling wave accelerating structure followed by a high shunt impedance standing wave accelerating structure up to 129 MeV. The beam then goes through a 91.392 GHz RF undulator with a period of 1.75 mm, producing EUV radiation around 13.5 nm. The RF undulator is powered by a 91.392 GHz decelerating structure, which extracts the RF power from the spent electron beam. The length of the entire beam line from the cathode to the beam dump is approximately 6 m. We describe the design and projected operating parameters for this EUV light source.

INTRODUCTION

EUV and Soft X-ray radiation has several important applications in semiconductor manufacturing, material science, and biology. Light of 13.5 nm wavelength is required for actinic mask inspection of EUV photomasks [1–4]. Currently EUV mask inspection tools use a beamline of synchrotron light sources because they require high brilliance, on the order of 100 W mm^{-2} sr^{-1} [5]. Soft X-ray radiation is used to study magnetic materials [6]. Radiation in the water window – 2.33 nm to 4.36 nm – is used to image biological structures [7]. Soft X-ray microscopy enables visualization of protein structures with resolution down to 30 nm [8, 9]. Soft X-ray tomography generates 3-D views of cells with 60 nm resolution [10]. Most of these experiments are performed in synchrotron light sources because of the high source brilliance required.

We are developing a 13.5 nm EUV light source based on an RF undulator operating at 91.392 GHz [11, 12]. Figure 1 shows an overview of this light source. For this source we will reuse most of the existing infrastructure of the SLAC X-Band test accelerator [13]. We will replace the existing RF photo-gun with a new injector, consisting of a 11.424 GHz thermionic RF gun, an accelerating structure, and a quadrupole-free TM_{01} mode launcher, which feeds both the gun and the accelerating structure [14]. The electron bunches will be accelerated in a 11.424 GHz booster linac downstream of the injector, and 91.392 GHz RF power will be extracted from the bunches in a decelerating structure. This extracted RF power will feed the RF undulator. EUV light around 13.5 nm is generated from the interaction of the electron beam with the RF fields inside the RF undulator.

The RF undulator cavity has a loaded quality factor of approximately 12,700 [11] and a filling time of 22 ns. To reach steady state fields inside the undulator, an input RF pulse length that is several times the filling time of the undulator is required. A decelerating structure at 91.392 GHz has a loaded quality factor of only 1,700 and a filling time of approximately 3 ns. Therefore, to generate sufficient pulse length to fill the RF undulator we will use a 11.424 GHz multi-bunch beam. To generate this multi-bunch beam we developed a thermionic RF injector. We need bunches with a small 6-D emittance because we will compress them to a small fraction of the wavelength at 91.392 GHz and focus them transversely into the small aperture of the decelerating structure. We considered high-voltage and low-voltage DC injectors with subharmonic bunching. A high-voltage low emittance thermionic DC injector using a small CeB_6 cathode has been developed for a Free Electron Laser [15–17]; however, the fact that it requires a DC voltage of approximately 500 kV and a complex bunching system makes it large and expensive. A low voltage DC injector with subharmonic bunching cannot satisfy the small 6-D emittance requirement.

Here we report a preliminary design of our light source and its beam dynamics simulations. We also report the design of the 91.392 GHz decelerating structure. The RF pulse length of the accelerator is 250 ns with a repetition rate of up to 120 Hz.

LIGHT SOURCE DESIGN

Figure 1 shows the schematic of the beamline. A train of electron bunches is generated in a 3.5-cell thermionic

Table 1: Bunch parameters at the undulator entrance z = 5.08 m. The notation in this table is described in [14].

	80 %	50 %	20 %
E (MeV)	129.67	129.62	129.64
Q (pC)	4.376	2.618	1.263
I_{bunch} (A)	15.84	25.77	18.17
$B_n \left(\frac{A}{\mathrm{mm^2 mrad^2}}\right)$	4.72	23.52	59.48
σ_x(µm)	118.58	69.71	37.13
σ_y(µm)	97.56	65.67	35.37
σ_z (fs)	69.05	25.40	17.38
$\epsilon_{x,n}$ (mm · mrad)	2.60	1.32	0.71
$\epsilon_{y,n}$ (mm · mrad)	2.58	1.65	0.86
ΔE_{rms} (%)	0.091	0.044	0.032

* This project was funded by U.S. Department of Energy under Contract No. DE-AC02-76SF00515, and the National Science Foundation under Contract No. PHY-1415437.

† ftouf@stanford.edu

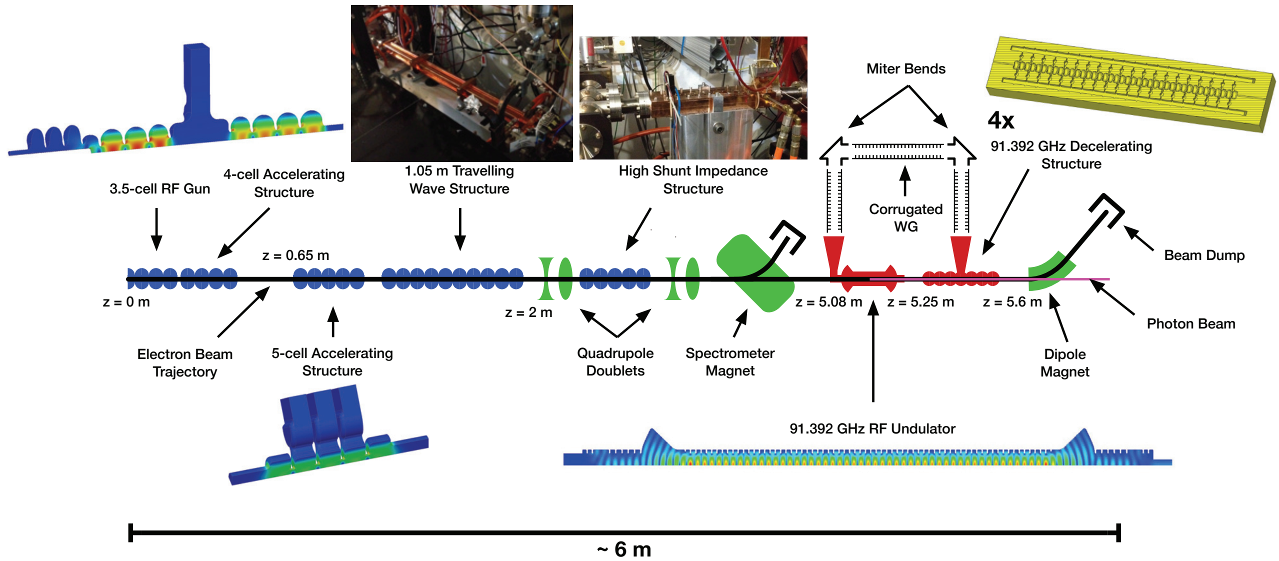
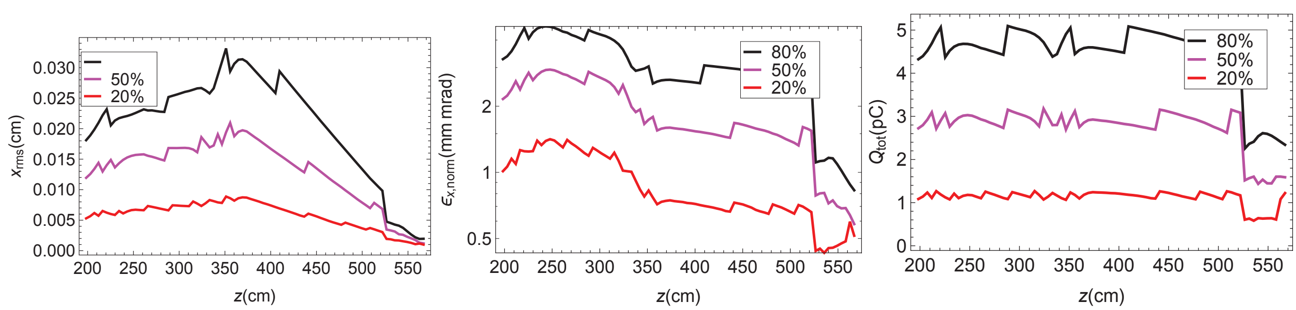


Figure 1: EUV Light Source Beamline. The 91.392 GHz undulator is positioned at $z = 5.08$ m. The 91.392 GHz decelerating structure is positioned between $z = 5.25$ m and $z = 5.6$ m and has an aperture of 340 µm.

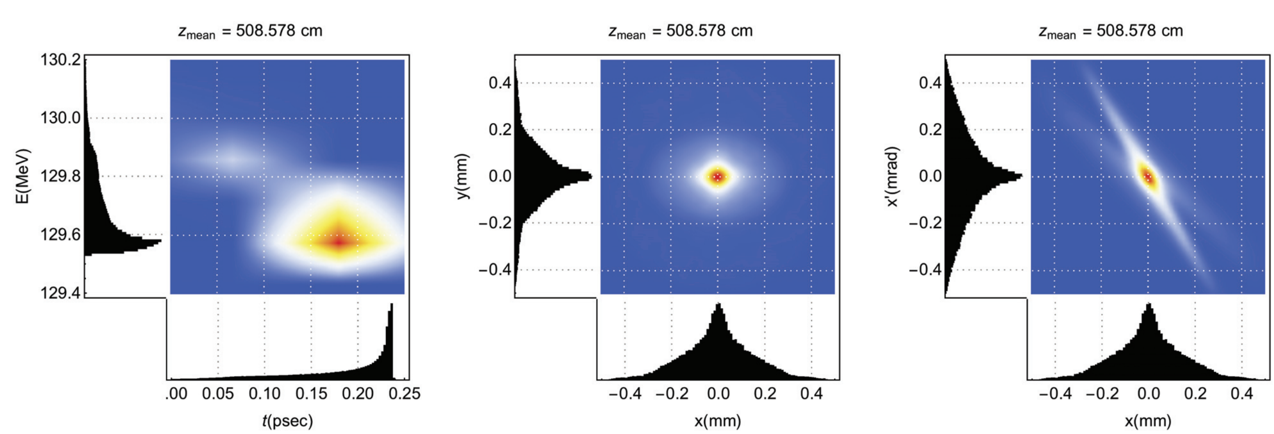


(a) RMS bunch size vs distance.

(b) Normalized Transverse Emittance vs distance.

(c) Bunch charge vs distance.

Figure 2: Beam dynamics simulation results. In this plots $z = 2$ m is the entrance of the first quadrupole doublet. A substantial part of the beam is collimated at the aperture of the decelerating structure $z = 5.25$ m.



(a) Long. phase space.

(b) Bunch cross-section.

(c) x-coordinate trans. phase space.

Figure 3: Phase Space at the entrance of the RF undulator $z = 5.08$ m.

ISBN 978-3-95450-182-3

RF gun, and a 4-cell accelerating structure induces energy chirp on the bunches for their further ballistic compression. The design of the injector is reported in [14]. We define the z axis along the beam trajectory, where $z = 0$ m is the cathode surface. At $z = 0.65$ m – the point of maximum bunch compression – a 5-cell standing wave accelerating structure is used to remove the correlated energy spread induced by the injector. The bunches then enter the traveling wave accelerating structure where they are accelerated to 110 MeV. Then, a high shunt impedance standing wave accelerating structure further accelerates the beam to its final energy of 129 MeV. Two quadrupole doublets focus the electron beam. A dipole magnet will allow us to measure the energy spread. The electron beam interacts with the RF undulator producing EUV light. The spent beam goes through the decelerating structure to extract RF power at the frequency of the RF undulator. This 91.392 GHz RF power is transported to the undulator through low-loss corrugated waveguides and miter bends.

In this paper we report beam dynamics simulations using Astra [18] for the entire beamline from the end of the injector at $z = 0.5$ m up to the beam dump. For the initial particle distribution we used the middle bunch of the simulation reported in [14]. The relative RF phases of the accelerating structures and quadrupole strengths were optimized to achieve minimum waist and minimum bunch length at the middle of the decelerating structure. Figure 2 shows the results of the beam dynamics simulation. Figure 3 shows the bunch phase space at the entrance of the undulator $z = 5.08$ m. Table 1 summarizes the bunch parameters at the same position.

DECELERATING STRUCTURE

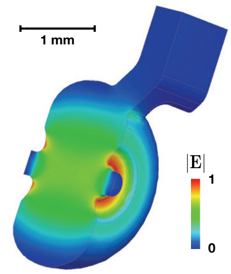
For power extraction at 91.392 GHz we will use 4 standing wave parallel coupled structures, each consisting of 40 reentrant cavities. The beam pipe diameter of these cavities is 340 μm. The exact shape of the cavities has been optimized to maximize the shunt impedance while minimizing surface fields. The results of the optimization are: shunt impedance 444 MΩ m^{-1} and peak surface electric field to accelerating gradient ratio 2.64. The decelerating cavity is shown in Fig. 4. For 10 kW of power in one cell the peak surface electric and magnetic fields are 137.26 MV m^{-1} and 283.86 kA m^{-1}, respectively. The peak surface magnetic field is at the coupling iris. From [19] the peak pulsed surface heating for 250 ns RF pulses is 49 °C, which is considered safe for copper [20]. Forty cavities are power combined through two waveguide manifolds [21] as shown in Fig. 5.

The power extracted from a decelerating structure when driven by a multi-bunch beam having an average current I_b during the RF pulse is given by

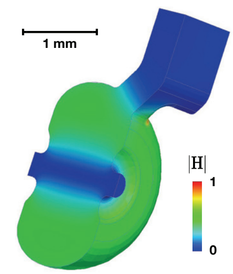
$$P_{out} = \frac{\beta}{(\beta+1)^2} I_b^2 R_{sh} l, \quad (1)$$

where β is the coupling coefficient, R_{sh} is the shunt impedance, and l is the total length of the structure. The maximum power is obtain for $\beta = 1$

$$P_{out} = \frac{1}{4} I_b^2 R_{sh} l. \quad (2)$$



(a) Electric Field.



(b) Magnetic Field.

Figure 4: Surface fields of the decelerating cavity. For 10 kW of power in one cell the peak surface electric and magnetic fields are 137.26 MV m^{-1} and 283.86 kA m^{-1}, respectively.

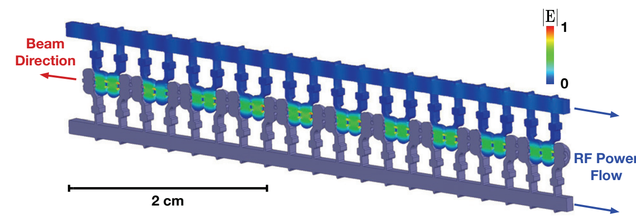


Figure 5: HFSS model of one half of the decelerating structure.

As seen in Table 1, the beam size is higher than the aperture of the decelerating structure. As a result, a substantial part of the beam is collimated. The charge per bunch transported through the decelerating structure is 2.3 pC. From (2) this charge corresponds to 20 kW of extracted RF power. This power generates an equivalent undulator strength of K = 0.012 [22]. This bunch charge has been calculated assuming a 10 A cm^{-2} emission current density [14], which is considered the maximum for a dispenser cathode in a DC gun. We speculate that we could run at higher current density than 10 A cm^{-2} with a different cathode material. If the charge transported through the decelerating structure is increased by a factor of 8.4 utilizing a combination of higher cathode current density and better optics, then the extracted RF power becomes 1.4 MW, which generates an equivalent undulator strength of K = 0.1.

CONCLUSION

We presented a preliminary design of the beamline for a compact EUV light source. This light source is based on an RF undulator operating at 91.392 GHz [11, 12]. We also presented the design of a decelerating structure at 91.392 GHz, which extracts energy from the spent electron beam and feeds the RF undulator. In our end-to-end simulations, the charge per bunch transported through the decelerating structure is 2.3 pC. This charge generates 20 kW of RF power in the decelerating structure. With this RF power, the undulator strength is K = 0.012.

REFERENCES

[1] Y. Liu *et al.*, "A dual-mode actinic EUV mask inspection tool," in *Proc. SPIE , Emerging Lithographic Technologies IX*. International Society for Optics and Photonics, 2005, pp. 660–669.

[2] T. Terasawa *et al.*, "Development of actinic full-field EUV mask blank inspection tool at MIRAI-Selete," in *Proc. SPIE , Alternative Lithographic Technologies*. International Society for Optics and Photonics, 2009, pp. 727 122–727 128.

[3] T. Harada *et al.*, "The coherent EUV scatterometry microscope for actinic mask inspection and metrology," in *Proc. SPIE , Photomask and Next-Generation Lithography Mask Technology XVIII*. International Society for Optics and Photonics, 2011, pp. 80 810K–9.

[4] Z. J. Qi, J. H. Rankin, M. Lawliss, K. D. Badger, and C. Turley, "Toward defect-free fabrication of extreme ultraviolet photomasks," *Journal of Micro/Nanolithography, MEMS, and MOEMS*, vol. 15, no. 2, pp. 023 502–023 502, 2016.

[5] S. F. Horne *et al.*, "High brightness electrodeless Z-Pinch EUV source for mask inspection tools," in *Proc. SPIE , Extreme Ultraviolet EUV Lithography III*. International Society for Optics and Photonics, 2012, pp. 83 222M–9.

[6] G. van der Laan, "Soft X-ray resonant magnetic scattering of magnetic nanostructures," *Comptes Rendus Physique*, vol. 9, no. 5, pp. 570–584, 2008.

[7] R. B. Hoover *et al.*, "Development of the water window imaging x-ray microscope utilizing normal incidence multilayer optics," *Optical Engineering*, vol. 30, no. 8, pp. 1086–1093, 1991.

[8] G. Schneider, "Cryo X-ray microscopy with high spatial resolution in amplitude and phase contrast," *Ultramicroscopy*, vol. 75, no. 2, pp. 85–104, 1998.

[9] D. Weiß *et al.*, "Computed tomography of cryogenic biological specimens based on X-ray microscopic images," *Ultramicroscopy*, vol. 84, no. 3–4, pp. 185–197, 2000.

[10] C. A. Larabell, "X-ray Tomography Generates 3-D Reconstructions of the Yeast, Saccharomyces cerevisiae, at 60-nm Resolution," *Molecular Biology of the Cell*, vol. 15, no. 3, pp. 957–962, Dec. 2003.

[11] F. Toufexis and S. G. Tantawi, "A 1.75 mm Period RF-Driven Undulator," in *Proc. of International Particle Accelerator Conference (IPAC'17), Copenhagen, Denmark, May 14-19, 2017*, May 2017.

[12] F. Toufexis, J. Neilson, and S. G. Tantawi, "Coupling and Polarization Control in a mm-wave Undulator," in *Proc. of International Particle Accelerator Conference (IPAC'17), Copenhagen, Denmark, May 14-19, 2017*, May 2017.

[13] C. Limborg-Deprey *et al.*, "Performance of a first generation X-band photoelectron rf gun," *Phys. Rev. Accel. Beams*, vol. 19, no. 5, p. 053401, May 2016.

[14] F. Toufexis, V. A. Dolgashev, C. Limborg, and S. G. Tantawi, "A Compact Thermionic RF Injector with RF Bunch Compression and a Quadrupole-Free Mode Launcher," in *Proc. of International Particle Accelerator Conference (IPAC'17), Kopenhagen, Denmark, May 14-19, 2017*, May 2017.

[15] T. Shintake *et al.*, "A compact free-electron laser for generating coherent radiation in the extreme ultraviolet region," *Nature Photonics*, vol. 2, no. 9, pp. 555–559, Jul. 2008.

[16] K. Togawa *et al.*, "CeB_6 electron gun for low-emittance injector," *Phys. Rev. ST Accel. Beams*, vol. 10, no. 2, p. 020703, Feb. 2007.

[17] T. Shintake *et al.*, "Stable operation of a self-amplified spontaneous-emission free-electron laser in the extremely ultraviolet region," *Phys. Rev. ST Accel. Beams*, vol. 12, no. 7, p. 070701, Jul. 2009.

[18] K. Floettmann, *ASTRA*, Deutsches Elektronen-Synchrotron, Hamburg, Germany. [Online]. Available: www.desy.de/~mpyflo/Astra_manual/Astra-Manual_V3.1.pdf

[19] V. A. Dolgashev, "High magnetic fields in couplers of X-band accelerating structures," in *Proceedings of the 2003 Particle Accelerator Conference*, May 2003, pp. 1267–1269 Vol.2.

[20] L. Laurent *et al.*, "Experimental study of rf pulsed heating," *Phys. Rev. ST Accel. Beams*, vol. 14, no. 4, p. 041001, Apr. 2011.

[21] S. G. Tantawi, Z. Li, and P. Borchard, "Distributed coupling and multi-frequency microwave accelerators," Patent US 9,386,682, 2016.

[22] M. Shumail and S. G. Tantawi, "Theory of electromagnetic insertion devices and the corresponding synchrotron radiation," *Phys. Rev. Accel. Beams*, vol. 19, no. 7, p. 074001, Jul. 2016.

ISBN 978-3-95450-182-3