THE MIT BATES X-RAY LASER PROJECT

T. Zwart, M. Farkhondeh, W. S. Graves, F. Kaertner, R. Milner, D.E. Moncton, C. Tschalaer, J. B. van der Laan, F. Wang, A. Zolfaghari, MIT Bates, Middleton MA 01949, USA

Abstract

MIT and the Bates Linear Accelerator Center are exploring the construction of an x-ray free electron laser user facility. It will be based on a superconducting linac of 4-8 GeV energy, and produce XUV light in the 0.3-100nm range at kilohertz repetition rates. The facility will be a full user facility incorporating up to 30 beamlines. Conventional lasers that produce the electron beam, seed the FEL and execute pump-probe experiments are carefully integrated. The current design of the facility is discussed.

INTRODUCTION

Recent advances in accelerator, laser and undulator technology [1] [2] have created the possibility of constructing a national user facility based on an intense free-electron laser at extreme ultraviolet and x-ray wavelengths. MIT is exploring the construction of such a facility at its Bates Laboratory site. The facility would produce x-ray beams with peak brilliance some ten orders of magnitude greater than are available from today's synchrotron sources, and pulse durations from 100 femtoseconds to less than 1 femtosecond. The wavelengths produced will range from 0.3 nm to 100 nm in the fundamental, with substantial power in the x-ray 3rd harmonic at 0.1 nm. The possibility of future upgrades to even shorter wavelengths will be preserved in the design. Based on a superconducting linac (with energy above 4 GeV) incorporating a number of extraction points, the complex will include the potential for 30 undulators and x-ray beamlines.

EXPERIMENTAL PROGRAM

The characteristics of the proposed x-ray laser source will enable a class of experiments that are beyond the reach of today's technology. For the first time, this source will combine short pulses, high power and coherence in the range between 100-0.1 nm. The science that is foreseen spans many disciplines including atomic and fundamental physics, condensed matter physics and materials sciences, femtochemistry, structural biology and various fields of engineering. The x-ray laser proposal [3] includes eight contributions from scientists at MIT, Brandeis, Yale, Argonne, and the Stanford Synchrotron radiation Laboratory. In some instances the techniques of the proposed experiments will require fundamentally new approaches and may have more similarity with experiments performed using table top lasers than those using synchrotron sources.

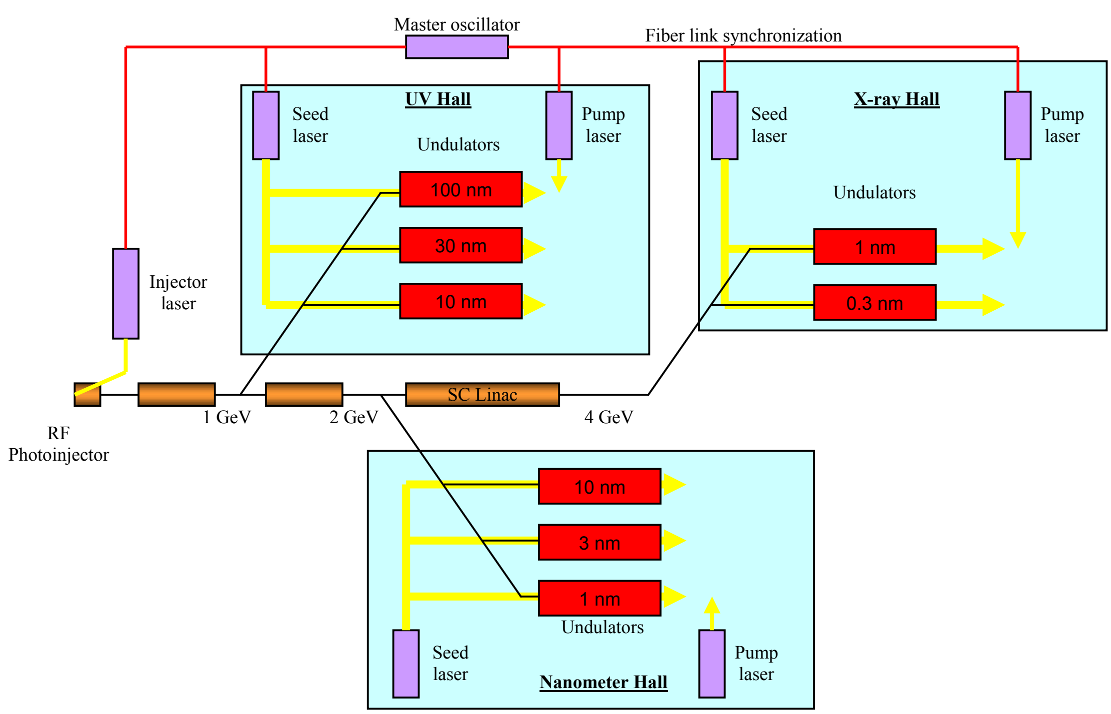

Figure 1: Layout of the MIT x-ray laser facility.

PRELIMINARY FACILITY DESIGN

While detailed design of the x-ray laser user facility will require additional resources, considerations of initial facility parameters and how best to integrate the various systems have already begun. Figure 1 shows a schematic layout of the facility and table 1 lists many of the accelerator parameters.

Table 1: Facility Parameters

Injector:	
Structure	1.3 GHz Copper 2 ½ Cell Independent Phasing
Repetition rate	1-10 kHz
Duty factor	2 %
Bunch charge	100-500 pC
Transverse emittance	0.5-2 um
Linac:	1.3 GHz TESLA structure
Gradient	20 MV/m
Active length	200 m
Total length	300 m
Linac duty factor	10%-CW
2K Dynamic heat load	<10 kW
RF coupling (Q_{ext})	$2 \cdot 10^7$
RF power/cavity	15 kW
Total Facility Power	<15 MW
Electron beam switches	1-10 kHz RF separators or Fast Ferrite Magnets TBD
Undulators:	
Undulator Beamlines	10-30
Undulator Periods	15-50 mm
Saturation Lengths	5-50 m
Rep. Rate/Undulator	~1 kHz
Total facility length	500 m

A room temperature RF photoinjector produces moderate charge, bright electron bunches at multi-kilohertz repletion rates. These bunches are accelerated in a superconducting 1.3 GHz TESLA-style linac [4] to energies up to ~4 GeV. The distortion of ~20 ps bunches in longitudinal phase space is linearized with a 3rd harmonic 3.9 GHz RF structure and compressed to sub-picosecond lengths at two bunch compressors located in the early stages of the accelerator. Three extraction points serviced by either RF separators or fast ferrite deflecting magnets deliver the bunches to the three experimental halls (VUV, nanometer and x-ray). In the baseline concept, each extraction point feeds 3-6 undulator lines, with each undulator receiving kHz repetition rates, and each capable of supporting multiple x-ray beamlines. As can be seen in the figure, conventional laser systems are tightly integrated into the design.

LASER PERFORMANCE

Advanced laser technology will be used throughout the proposed facility. Laser systems will provide an extremely stable base clock for the RF master oscillators and all other facility timing systems. Picosecond, UV lasers operating at kHz rates are now available which will meet the requirements of the RF photoinjector. Conventional laser systems will also be present in all experimental halls for use as either pumps or probes in conjunction with the FEL x-ray beams and to generate seed pulses.

In order to produce beams of the highest quality, various methods of seeding the electron beam with high harmonics of laboratory lasers are currently under investigation, as is lasing by self-amplification of spontaneous emission (SASE). A number of these methods will be exploited to produce radiation sources to match experimental needs. The spectral and timing characteristics of both SASE and seeded beams have been modeled using the GINGER FEL simulation code and are reported in reference [5]. Seeding opens the possibility of creating diffraction limited FEL beams which can be tailored either for short pulse length (τ~1 fs) or narrow bandwidth ($\Delta E/E<10^{-5}$). Table 2 shows how the parameters of the proposed MIT x-ray laser compare with existing synchrotron sources and several other proposed FEL facilities. The peak brilliance is ten orders of magnitude greater than is available at today's 3rd generation synchrotron sources, and is comparable to the peak brilliance expected at other propsed FEL facilities. While the peak brilliance is one of the strong suits of the proposed machine, it's time averaged flux is still comparable to the synchrotron sources.

EFFICIENT UPGRADE PATHS

The proposed facility allows several efficient paths for later upgrades. The use of a high duty factor, possibly CW, superconducting linac will support additional beamlines, to a maximum of 30 in the present concept. The development of shorter period (λ~10mm) high field (B~1T) undulators could be used with the 4 GeV beam to reach x-ray wavelengths shorter than 0.3 nm in the fundamental. The development of substantially brighter injectors, with transverse emittance < 1 um, will reduce saturation lengths and thus undulator costs. Finally, the 1.2 km Bates site allows for the extension of the linac to higher energies which would also extend the reach of the facility to shorter wavelengths. This energy upgrade would be possible while the proposed machine was operational, a vital consideration for a user facility.

Table 2: FEL Beam Properties

	APS	MIT Bates			BESSY	LCLS	TESLA	Cornell
	Und. A	**SASE FEL**	**Min bandwidth seeded FEL**	**Min pulse length seeded FEL**	**FEL**	**FEL**	**FEL**	**ERL**
X-rays per pulse (0.1% max BW)	1.E+08	3.E+11	3.E+11	6.E+09	1.E+13	2.E+12	2.E+12	1.E+07
Peak power (GW)	3.E-06	4.0	4.0	4.0	7.0	8.0	20.0	7.E-05
Peak brilliance (p/s/0.1%/mm2)	3.E+22	1.E+33	3.E+35	7.E+33	5.E+32	1.E+34	3.E+34	3.E+25
Peak flux (p/s/0.1%)	1.E+18	6.E+24	6.E+24	1.E+23	5.E+25	7.E+24	1.E+25	4.E+19
Peak trans. coh. flux (p/s/0.1%)	4.E+14	6.E+24	6.E+24	1.E+23	5.E+25	7.E+24	1.E+25	2.E+17
Avg. flux (p/s/0.1%)	7.E+14	3.E+14	3.E+14	6.E+12	8.E+16	2.E+14	5.E+15	2.E+16
Average brilliance (p/s/0.1%/mm2)	4.E+19	5.E+22	1.E+25	3.E+23	1.E+24	4.E+23	1.E+25	1.E+22
Average coherent flux (p/s/0.1%)	2.E+11	3.E+14	3.E+14	6.E+12	8.E+16	2.E+14	5.E+15	8.E+13
Trans. coh. fract. (%)	0.03	100	100	100	100	100	100	0.5
Degeneracy parameter	0.03	4.E+09	3.E+11	6.E+09	8.E+11	4.E+09	1.E+08	100
Pulse length (fs)	73000	50	50	1	200	230	200	300
Photon beamlines	34	10-30	10-30	10-30	3	1	5	~20
Wavelength (nm)	0.015 - .4	0.3 - 100	0.3 - 100	0.3 - 100	1.2 - 60	0.15 - 1.5	0.1 - 1.5	0.03 - .5
Pulse frequency (Hz)	7.E+06	1000	1000	1000	8000	120	2300	1.30E+09

CONCLUSIONS

The proposed MIT x-ray laser user facility seeks to capitalize on the recent advances in accelerator FEL technology. Use of the latest low emittance RF photoinjectors, TESLA SRF linac structures, and hybrid permanent magnet undulators will allow the facilty to serve multiple users with 100-0.3 nm beams of unprecedented brilliance and coherence. The careful integration of conventional laser systems in the design from the outset will allow the facility to exploit both the ultrafast or narrow bandwidth x-ray beams that will be available with the successful implementation of seeding.

The MIT team and its collaborators have produced a three year design study proposal that is now before the National Science Foundation. An accelerator review committee is being assembled and will convene in Fall 2003. A series of workshops on the science that would be possible with such a facility will also begin in Fall 2003 on the MIT campus. A major goal of the proposed study is to prepare the facility design to sufficient maturity such that construction of the x-ray laser could begin in 2007.

REFERENCES

[1] S.V.Milton et al., "Exponential gain and saturation of a self-amplified spontaneous emission free-electron laser," Science **292,** 2037 (2001).

[2] V. Ayvazyan et al. "Generation of GW radiation pulses from a VUV free-electron laser operating in the femtosecond regime," Phys. Rev. Lett. **88**, 104802 (2002).

[3] http://mitbates.mit.edu/xfel

[4] TESLA Technical Design Report, http://tesla.desy.de/ ew_pages/TDR_CD/start.html

[5] W.S. Graves, "Simulations of an x-ray FEL seeded with attosecond pulses," these proceedings.