

CONSIDERATIONS ON FERMILAB'S SUPERCONDUCTING TEST LINAC FOR AN EUV/SOFT X-RAY SASE FEL

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Abstract

A superconducting (SC) RF Test Accelerator at the New Muon Lab (NML) is currently under construction at Fermilab. Its design goals include the demonstration of the 9-mA pulse train proscribed for the International Linear Collider (ILC) and operations with this prototypic beam of the base RF unit which consists of three SCRF cryomodules. An RF photoelectric gun based on the DESY design will generate the beam. The selected gun has an emittance of about 1 pi mm mrad when run at 1 nC or less per micropulse based on tests at Zeuthen with an almost identical gun design. This beam quality is sufficient, when properly bunch compressed, to provide the driving beam for an extreme ultraviolet (EUV) and soft x-ray (SXR) self-amplified spontaneous emission (SASE) free-electron laser (FEL) or seeded FEL. Estimates for the gain length and output power have been calculated for wavelengths from 80 to 12 nm (at 1.5 GeV) using a simple scaling formula of M. Xie.

INTRODUCTION

A new superconducting radiofrequency (SCRF) linac is currently under construction at the Fermilab New Muon Lab (NML) building. The primary design goals include the replication of the pulse train proscribed for the International Linear Collider (ILC) and to demonstrate operation with this prototypic beam of the base RF unit which consists of three SCRF cryomodules [1, 2]. At 3.2 nC per micropulse and with 3000 micropulses per macropulse at a 5-Hz rate and at 810 MeV, 40-kW average beam power is generated. An RF photoelectric gun will generate the "ILC-like" beam. However, the selected gun has a lower emittance of 1 mm mrad when run at 1 nC or less per micropulse [3,4]. This beam quality is sufficient when properly bunch compressed to provide the driving beam for an extreme ultraviolet (EUV) and soft x-ray (SXR) self-amplified spontaneous emission (SASE) free-electron laser (FEL). Gun, injector, SCRF accelerator and infrastructure would be a significant part of any FEL facility investment, and would constitute a unique opportunity for government agency funding leveraging. The large number of micropulses would open the possibility for beamline switching so several user beamlines could run concurrently. Also this wavelength regime with 200-fs bunch lengths would complement the hard x-ray SASE FEL Linear Coherent

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Light Source (LCLS) project at SLAC and would provide USA scientists the same opportunities that are developing in Europe and Asia as exemplified by FLASH [5,6].

The original ~70-m-long NML building could not accommodate the ILC test accelerator with gun, injector and bunch-compressor, 3 SCRF cryomodules, diagnostics beamline and beam dump. An extension with a tunnel section and a separate building is currently under construction that will double the length of the beamline. This will allow a test of the full ILC RF unit as well as other advanced accelerator R&D experiments [7]. A second bunch compressor (BC) has been proposed as indicated to allow a more gradual compression when combined with BC1 to limit emittance growth. The possibilities for SASE-FEL R&D will be discussed here as indicated schematically in the extended mode in Fig. 1, where an undulator string could be added after BC2 for generation of EUV or SXR photons. The schematic indicates three cryomodules before BC2, but additional ILC-type cryomodules could be added after BC2.

INITIAL TECHNICAL FEASIBILITY CONSIDERATIONS

The rf photocathode (PC) gun, booster cavities, and three cryomodules (one ILC RF unit) are scheduled for operation in 2012, assuming an adequate funding profile. This will provide an estimated 810-MeV beam energy if the cavity gradients are achieved as proposed. On the RF PC gun side, the basic design from DESY in Germany will be used with some minor modifications. In ILC-TA mode, the emittance should be 4.5 pi mm mrad for a 3.2-nC uncompressed micropulse, but an almost identical gun was tested at DESY-Zeuthen with 1.2 mm mrad at 1nC as reported in the FEL07 Conference [3] and more recently as 0.76 mm mrad [4]. As will be shown in the following tables, the beam energies and emittance indicate operational wavelengths comparable to the currently operating FLASH facility in Hamburg [6].

For a planar undulator, the FEL process is governed by the resonance condition $\lambda = \lambda_u (1 + K^2/2)/2\gamma^2$, where λ is the FEL wavelength, λ_u is the undulator period, K is the undulator field strength parameter, and γ is the relativistic Lorentz factor. Table 1 shows the range of wavelengths that might be possible just by using the same undulator parameters as used in the APS LEUTL SASE FEL project [8]. In this case the undulators were 2.4 m long with a

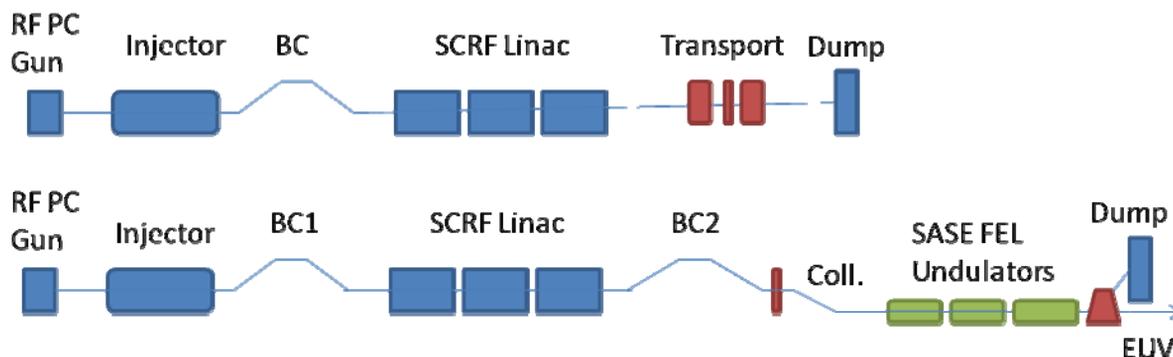


Fig. 1: Schematics of the NML layouts in base mode (upper) and the proposed extended mode for a combined ILC-TA and SASE FEL facility (lower). One might also add additional ILC rf cryomodules after the BC2.

period of 3.3 cm and the K value of 3.1 peak. The first two cases cited are for wavelengths obtained in SASE operations at APS with energies available there and modest rf PC gun beam quality. The rest of the cases invoke the energies anticipated at NML with up to two ILC RF units (6 cryomodules). Wavelengths considered are from 80 to 12 nm with the third harmonic operation invoked for the 4-nm case. In this case the undulators are 2.4 m long with a period of 3.3 cm and the K value of 3.1 peak.

In Table 2, we add the requirements of basic beam quality of normalized rms emittance, $\epsilon_n = 2 \pi \text{ mm mrad}$ (allowing for some degradation in compression) and peak current, $I_p = 1 \text{ kA}$ with $\beta = 5 \text{ m}$ in the undulators. The FEL scaling formulation of M. Xie [9] was used to calculate key performance parameters of a SASE FEL for gain length, saturated length, and saturated power under these conditions. All cases show output peak powers of more than 1 GW, similar to the FLASH operations. The large number of micropulses gives average power comparable to FLASH.

Table 1. Summary of possible SASE FEL wavelengths based on the energies and parameters in the previous ANL SASE FEL VUV undulators. These were not optimized for the EUV regime.

Energy (GeV)	Facility	Harmonic #	Wavelength (nm)
0.220	APS	1	540
0.408	APS	1	157
0.570	NML	1	80
0.750	NML	1	46
1.000	NML	1	26
1.500	NML	1	12
1.500	NML	3	4

One additional example, with improved emittance and peak current of $1.5 \pi \text{ mm mrad}$ and 2 kA, respectively, is shown in the last row for the 12-nm case. A dramatic improvement in gain length is obtained that would benefit operations at the shorter wavelengths and keep the saturated length under 30 m. Also we note that FLASH has a shorter undulator period at 2.7 cm and lower K at 0.81 (rms) than LEUTL to reach shorter wavelengths for a given beam energy [10]. They have recently reached 6 nm with only a 1-GeV beam. Additionally, the interest in lower charges with even lower emittances could lead to even shorter saturation lengths at these wavelengths [11].

Table 2. Summary of the results of the FEL scaling calculations using M. Xie's formulation showing the gamma, output wavelength, 3D gain length, saturated length, natural β function, and saturated output power.

Gamma	Lambda (nm)	3D Gain length (m)	Sat. length (m)	Natural β (m)	Sat. Power (GW)
430	540	0.29	6.8	1.00	1.4
798	157	0.45	10.0	1.86	1.6
1115	80	0.58	12.8	2.60	1.7
1467	46	0.71	15.7	3.44	1.7
1957	26	0.95	20.0	4.58	1.6
2935	12	1.46	29.6	6.71	1.3
2935*	12	0.83	17.6	6.7	5.9

CONTEXT AND USA EUV GAP

Figure 2 gives an overview of synchrotron light facilities (operating, under construction, and planned) in terms of photon peak brilliance versus photon energy and wavelength, presented at a past FEL conference by A. Oppelt (PSI) [12]. The SASE FELs offer orders of magnitude more peak brilliance than the operating third generation x-ray synchrotron radiation sources. The LCLS with a normal conducting RF linac will operate from 15 to 1.5 Angstroms, and the proposed European X-ray facility with its SCRF linac will exceed it in brilliance when it becomes operational. The FLASH facility is based on a SCRF linac and is currently operating now down to 6 nm for users. Both the Japanese SCSS/XFEL project and the PSI XFEL proposal would reach the hard x-ray regime. There are several other projects evolving in the EUV and soft x-ray regime in Europe, but none as yet funded in the USA. We have marked the USA EUV gap by the blue rectangle in the plot, and it is this regime that the FEL at NML would address for USA science. Besides the fact that the FLASH facility is oversubscribed by about a factor of three now, the science cases have also been made within the recent WiFEL Workshop for this wavelength regime [13]. It is clear that the already large investment in the SCRF linac at Fermilab can be leveraged to cost-effectively address this USA light source need.

STATUS OF THE PROJECT

The installations in the NML building are ongoing. The low energy end will use the RF gun plus two SCRF booster cavities to reach about 40 MeV. Booster cavity 2 is in place as shown in Fig. 3. It has reached a gradient of 24 MV/m. A SCRF 3.9 GHz cavity for longitudinal phase space linearization is eventually planned. The first tests of 40 MeV beam are scheduled for FY12. The beam from this section will be injected into the cryomodule string. The first cryomodule is in place on the girder, and commissioning is underway. The installed cryomodule is shown in Fig. 4. It is a type TTF III+ unit with approximately 250 MeV of acceleration. The next two cryomodules are due in the next two years. The new rf PC gun, PC preparation chamber, PC transport chamber, and the PC transfer chamber are in hand and are being tested. The PC chambers were fabricated at INFN Milano under the direction of D. Sertore. The extension of the NML building to allow space for up to six cryomodules is in civil construction with completion expected in by the end of CY10.

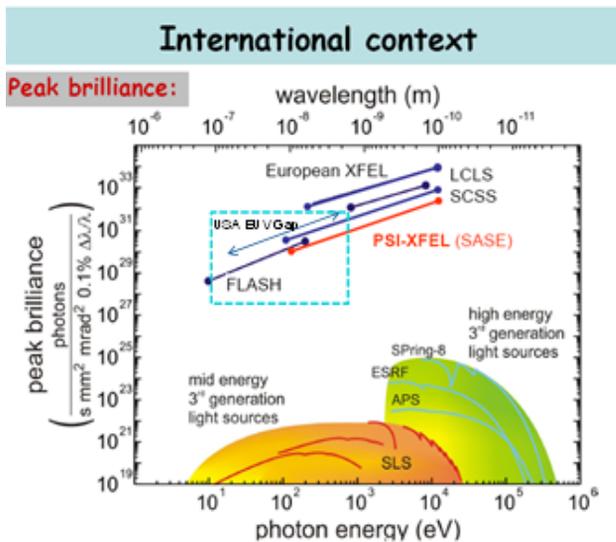


Fig. 2. A summary of emerging and proposed SASE FEL projects in the EUV and x-ray regimes compared to existing light sources. The figure is revised from ref. 12. The USA EUV-soft x-ray facility gap is indicated in the blue rectangle. Essentially one could complement the LCLS wavelength regime for US scientific research.



Fig. 3. Booster cavity 2 (from DESY and Saclay) has been installed in the NML facility and has a gradient of 24 MV/m.



Fig. 4: Cryomodule 1 of type TTF III+ from DESY has been installed on its girder in the NML facility and commissioning will proceed in the coming months.

SUMMARY

In summary, the ILC-TA project at NML has defined a path to build a world-class superconducting linac close to the GeV beam energy level. Besides the ILC-like beam pattern, the gun could be operated in FEL mode at lower charge and improved emittance. Preservation of the lower beam emittance in bunch compression stages to kA levels would provide sufficient beam quality for SASE operations in the 80-4 nm regime with about a 30-m long undulator with 3-cm period. Although there are several projects in Europe and Asia underway, there is no funded project in the USA for this wavelength regime in ultrafast science that would uniquely complement the hard x-ray facility at LCLS. The additional paths of using seeding or even much lower charges than 0.5 nC with concomitantly lower emittances and shorter saturation lengths may extend the useful operating range of the FEL.

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