A DESIGN STUDY OF A FIR/THZ FEL FOR HIGH MAGNETIC FIELD RESEARCH

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Abstract

Presently a conceptual design for a NIR-FIR FEL system at the National High Magnetic Field Lab. - Florida State University (NHMFL-FSU) is being undertaken in collaboration with the FEL group at the Thomas Jefferson Laboratory. The system is expected to combine high magnetic field research with an intense, tuneable photon source spanning the spectral region ~ 2 - 1100 microns. Here, a design study involving the FIR/THz part of the NHMFL-FEL design proposal is presented. The suggested long-wavelength FEL encompasses in the first phase a thermionic injector with a ~2 mA average current and a ~10 MeV superconducting rf linac module operating at 1.3 GHz. The broadband outcoupling over the envisaged FIR/THz spectral range (100 - 1100 microns) can be accomplished by adopting a variable-outcoupler scheme in a waveguided cavity. Besides the performance predictions of the suggested long wave-length FEL, techniques for the generation of high peak power, nanoseconds long THz pulses (for magnetic resonance applications) are also briefly discussed.

Table 1:FIR FEL Specifications

PARAMETER	FIR FEL	UNITS
Wavelength	*100 to 1100*	µm
Micropulse Energy	*1 to 3*	µJ
Micropulse-width	*~ 5 to 60*	ps
Fract. bandwidth	*~ 0.3 - 5%*	
Resonator	*pp- waveguide, ~ 5.8*	m
Outcoupling	*Variable (others?)*	
Pulse rep. rate	*26 (13)*	MHz
Macropulse-width	*100µs to CW*	
Beam energy	*10 - 11*	MeV
Wiggler period	*70 (hybrid.)*	mm
Wiggler K	*0.6-3.5*	
Periods	*40*	

INTRODUCTION

In the framework of the NHMFL FEL initiative the design efforts for the construction of FIR/THz FEL radiation sources are twofold; the main effort is directed towards the generation of high peak power micropulses for time resolved measurements in the (tens of) picoseconds range. The planned rf-linac based system relies on relatively mature technologies developed at FELIX (FOM), Stanford, Jefferson Lab. and FZ-Rossendorf. The use of superconductive rf-linac cavities enables quasi-cw operation with the associated higher average THz radiation power levels (tens of Watts) and offers the possibility of an extension to an energy recovery linac (ERL) system (considered for the NIR-MIR FELs) as well. The second part of the FEL effort focuses on the development of techniques in producing relatively long ((sub-) nanoseconds), kW - level tuneable (sub-)millimetre wave pulses, in order to generate spin excitations at high magnetic fields and for possible pulsed magnetic resonance applications. While it has been shown that the FIR-FEL technology developed by the TeraHertz Center at UCSB with an electrostatic accelerator (EA) [1,2], this long wavelength range at the envisioned power levels have not yet been achieved with a rf linac system.

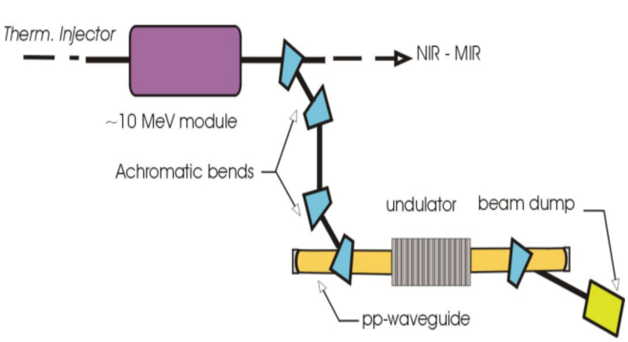

Figure 1: Layout of the FIR-FEL beamline option.

Here, we give an overview of the studied outcoupler design options and report on the simulated performance of a rf-linac driven waveguide FIR-FEL based on specified system settings. Finally, we discuss briefly on the current status of search for methods that would allow us to extend the inherently short pulse durations in the studied sc rf linac driven FIR FEL configuration into the ns range.

RF LINAC-FIR FEL DESIGN ISSUES

In the current design , the beam energy for the FIR FEL is provided by the first cryomodule (~10 MeV, operating at 1.3 GHz) which constitutes, along with the thermionic injector, the injector section of the NIR-MIR FELs. The thermionic injector system (a grid modulated DC gun followed by subharmonic and fundamental

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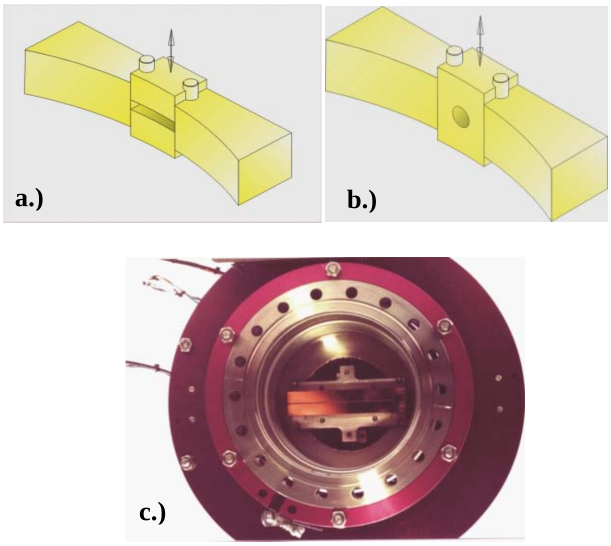

Figure 2 a-c: The lateral dimension of the outcoupler mirrors shown in a.) , b.) amounts to ~14 cm. The radius of curvature is ~3.5 m. The outcoupler mirror shown in c.) is constructed for an FIR FEL operating at ~230-650 µm.

bunchers) [3] is similar to the ones in use at FZ-Rossendorf and Stanford University. It is planned to provide ~2 mA average current at 26 MHz repetition rate. The NHMFL FIR-FEL is being designed to cover a large portion of the THz spectrum while employing a single wiggler, (possibly) a single cylindrical outcoupler mirror along with a waveguide structure that extends over the entire cavity (~5.8 meters). The latter option reduces the diffraction losses inherent in this long wavelength spectral region and avoids oversized cavity mirrors and mirror vacuum chambers. It requires the injection of the beam into the parallel-plate waveguide cavity (gap:10 mm) prior matching the beam into the undulator. After leaving the interaction section, the spent beam is directed into a beam dump. The design specifications along with the major system parameters are listed in Table 1.

The continuous tunability offered by the FEL over the envisaged large spectral range ideally would incorporate a broad-band feedback/outcoupling which can be accomplished by adopting a variable outcoupler scheme on one of the cylindrical metal-mirrors. The outcoupler option illustrated in Fig. 2a is a modified version of the variable height outcoupler (Fig. 2c) studied and realized in [4,5]. Adjusting the slot aperture in the vertical dimension between 0. – 3.0 mm continuously, the power output can be optimised over the entire 100 - 1100 microns. Hereby, the use of inserts with different lateral sizes (1.5mm, 3.0mm) allows one to keep the ratio of horizontal to vertical dimensions of the aperture < ~1.5 , at any slot aperture/wavelength configuration. In the second option, depicted in Fig. 2b, the middle insert (thus the centre of the hole aperture) is displaced in the vertical, sampling different areas of the hybrid waveguide mode on the mirror surface. The latter scheme covers the targeted wavelength range using max. three different hole apertures (or, alternatively, three cylindrical mirrors that could be moved up and down in the vertical, each having a different hole aperture). The optical beam transport accounts for the small (max. ~ 2 - 3 mm) off-axis displacement of the optical beam centre behind the outcoupler. Other variable outcoupler options such as FPI-meshes are being considered (as far as they remain operational at cw multi-kW level intracavity power), particularly for wavelengths above 500 microns.

The performance modelling of the FIR-FEL system is based on electron beam parameters (bunch charge, norm. transverse emittance, longitudinal emittance, energy spread) that are similar to those implemented at FZ-Rossendorf FEL, with the exception of an increase in the electron bunch repetition frequency up to 26 MHz, the latter being relevant in determining the resonator length and the average radiation power. Using the waveguide FEL code described in [5,6], that models the physics of a rf-linac driven, highly slippage dominated short pulse THz-FEL oscillator, the FEL performance for various

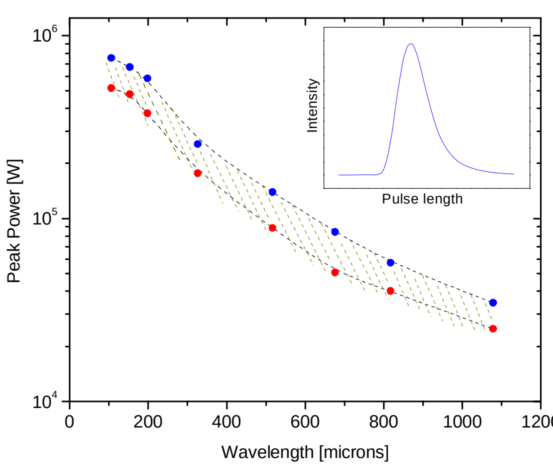

Figure 3: The upper peak power values (blue dots) are obtained at the peak of the detuning curve whereas the lower data points at cav. Detuning ~ -0.4·λ.

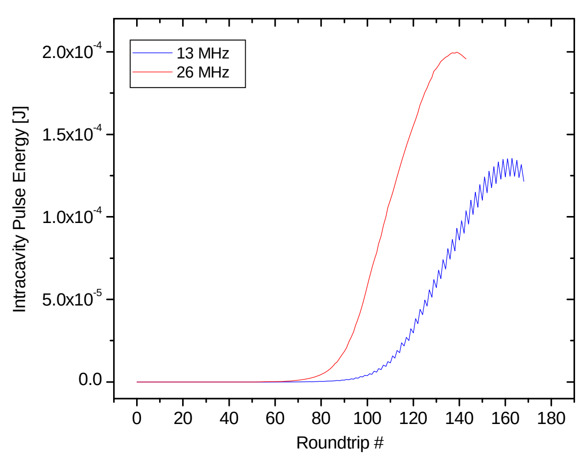

Figure 4: FEL operation at 13 MHz and 26 MHz pulse rep. rates with ~5.8 m cavity length , λ ~ 155 µm.

wavelength/wiggler settings (assuming a FEL operating at a fixed beam energy of 10.8 MeV) and outcoupling ratios (optimised by using the transmission characteristics of the scheme shown in Fig. 2a) are studied. An aspect that affects strongly the intracavity radiation build-up process and the evolution of the optical pulse structure is the use of ps-short electron bunches for the generation of (for rf-linac based systems unusually) long wavelength radiation in a waveguided propagation medium. Fig.3 shows the predicted (approximate) peak power levels achievable in the generated THz micropulses. The inset illustrates the simulated pulse shape whose leading edge exhibits a distinct exponential decay deviating from the Gaussian.

Another possible operational mode is driving the FIR FEL with 13 MHz rep. rate (limiting the average current to ~1mA), while keeping the waveguide resonator length 5.8 meters. In this case, the optical pulse interacts with the electron beam every other roundtrip, thus experiencing nearly twice as much cavity losses for each amplifying pass. The simulated evolution of the intra-cavity micropulse energy up to the saturation is shown in Fig. 4 at 155 microns (as an example) for both, 13 MHz and 26 MHz rep. rates. In the '13 MHz case' the outcoupling ratio is set to ~ 0.6 % (optimised to obtain the highest pulse energy coupled out), while the '26 MHz case' employs ~ 3.0 %. The calculated outcoupled pulse energies at different wavelengths indicate that 13 MHz rep. rate in combination with 5.8 m resonator length does not lead to a satisfying FEL operation. It results in a significant reduction in the pulse energies obtained. In addition, the micropulse energy fluctuations in subsequent roundtrips (by an amount defined by the cavity losses) may not be tolerable in many applications. In the following, simulated pulse energies are given for the '13 MHz and 26 MHz repetition rates' at two different wavelengths, 155 microns and 1080 microns respectively:

- '13 MHz 'case:

- outcoupled max. pulse energy ~0.7 μJ (@155 μm)
- outcoupled max. pulse energy ~0.3 μJ (@1080 μm)

- '26 MHz' case:

- outcoupled max. pulse energy ~3.1 μJ (@ ~155 μm)
- outcoupled max. pulse energy ~1.6 μJ (@ ~1080 μm)

GENERATION OF (SUB-) NS PULSES

For pulsed magnetic resonance excitations, the pulse length condition is given by $\gamma B_1 \tau \approx 0.5$ in which γ is 28 GHz/Tesla, B_1 is the amplitude of the oscillating magnetic field, and τ is the FIR pulse length. For the envisioned time resolution and the available power, the pulse length is of the order of 1 ns. At the present design stage, having optical pulse rep. rates of max. 26 MHz, the planned superconductive rf-linac FIR FEL configuration is not suitable for the implementation of interpulse phase-locking techniques described in [7] to generate narrow bandwidth, ns - long pulses. On the other hand, the

Table 2: Grating Stretcher specifications

λ [μm]	*d* [μm]	*m*	*Z* [m]	*Initial* [ps]	*Final* [ns]
100	80	1	3.0	5.0	1.5
100	80	3	1.34	5.0	3.1
500	400	1	3.0	25.0	1.6
500	400	3	0.57	25.0	3.1
1000	800	1	3.0	65.0	1.2
1000	800	3	0.78	65.0	3.1

flexibility offered by the variation of cavity desynchronization on modifying the pulse durations (thus the Fourier transform limited spectral bandwidth) falls short of providing the pulse lengthening effect that would be necessary to meet the requirements posed on the pulse durations and the associated spectral bandwidths. A possible (standard-) solution to lengthen the (rf-linac generated) picoseconds long optical pulses with sufficiently broad bandwidths is the use of grating stretchers [8], ending up with frequency chirped pulses of ns-duration. However, due to the introduced time frequency correlation within the pulse and the still existent broad bandwidth (not Fourier transform limited pulses), frequency chirped pulses remain restricted in their applications in the area of pulsed magnetic resonance experiments. Table 2 illustrates the parameters of a grating stretcher and the stretching factors achievable upon application of the device on the outcoupled FIR FEL pulses specified in Table 1. In Table 2, parameters *d, m, Z* denote the groove spacing of the blazed grating, the order at which the grating is used and the variable distance between the grating and the telescope mirror used in the setup, respectively.

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