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THE FHI FEL UPGRADE DESIGN

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Abstract

Since coming on-line in November 2013, the Fritz-Haber-Institut (FHI) der Max-Planck-Gesellschaft (MPG) Free-Electron Laser (FEL) has provided intense, tunable infrared radiation to FHI user groups. It has enabled experiments in diverse fields ranging from bio-molecular spectroscopy to studies of clusters and nanoparticles, nonlinear solid-state spectroscopy, and surface science, resulting in more than 55 peer- reviewed publications so far. A significant upgrade to the original FHI FEL has been funded and is presented here.

A second short Rayleigh range undulator FEL beamline is being added. It will permit lasing from < 5 µm to > 160 µm. Additionally, a 500 MHz kicker cavity will permit simultaneous two-colour operation of the FEL from both FEL beamlines over an optical range of 5 to 50 microns by deflecting alternate 1 GHz pulses into each of the two undulators. We describe the upgraded FHI FEL physics and engineering design and present the plans for two-colour FEL operations by the end of 2020.

FEL LAYOUT & DESIGN PARAMETERS

The layout of the original and proposed FHI FEL Upgrade beamlines is shown in Fig. 1. The existing design consists of the accelerator section, the MIR beamline and a diagnostic beamline. The design performance parameters and physics design [1], the engineering design [2], first lasing [3], and subsequent user performance [4] for the existing FEL have been described.

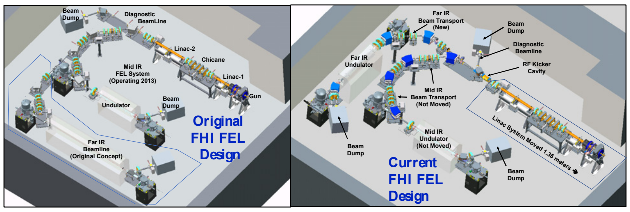

Figure 1: Original (left) and Current (right) FHI MIR and FIR FEL Designs.

The FEL consists of a 50 MeV accelerator driven by a gridded thermionic gun with a beam transport system that feeds two undulators and a diagnostic beamline. The first normal-conducting 2.998 GHz linac accelerates the electron bunches to a nominal energy of 20 MeV, while the second one accelerates or decelerates the electrons to deliver any final energy between 15 and 50 MeV. A chicane between the structures allows for adjustment of the bunch length as required. Originally, the Mid-IR and Far-IR undulators were planned to be parallel to each other directed 180 degrees from the accelerator axis [Refs. 1, 2]. However, we have now selected a single achromat for the Far-IR FEL which is now at 90 degrees to the accelerator axis. The accelerator section has been moved back 1.35 m to allow insertion of an RF kicker cavity, and the diagnostic beamline has been relocated. The principal subject of this paper is the design and fabrication of the Far-IR beamline and FEL, and the changes in configuration from the original design that we have adopted.

MID-IR FEL PERFORMANCE

The generated IR radiation forms ps-long micro-pulses at a pulse repetition rate of 1 GHz. Up to 10,000 consecutive micro-pulses form a pulse train, referred to as the macro-pulse that are repeated at a rate of 10 Hz. Figure 2 shows tuning curves of the macro-pulse energies for 6 different electron energies ranging from 18 to 44 MeV. For any given electron energy, the IR wavelength can be tuned continuously by a factor of 2 to 3 by changing the undulator gap. The data plotted in Fig. 2 has been observed for a relatively narrow FEL line spectrum with $\Delta\lambda / \lambda \sim 0.4$, where λ is the central wavelength and $\Delta\lambda$ denotes the full width at half maximum (FWHM) of the spectral distribution that is monitored with a grating spectrometer. Best performance in terms of macro-pulse energy is found for $\lambda \sim 7.5$ µm. Even more pulse energy (and pulse peak power) can be achieved by fine adjustment of the FEL cavity length (5.4 m nominal length) at the cost of an increased spectral line width. The latter corresponds to shorter mid-IR radiation pulses. This way, pulses as short as 500 fs can be generated.

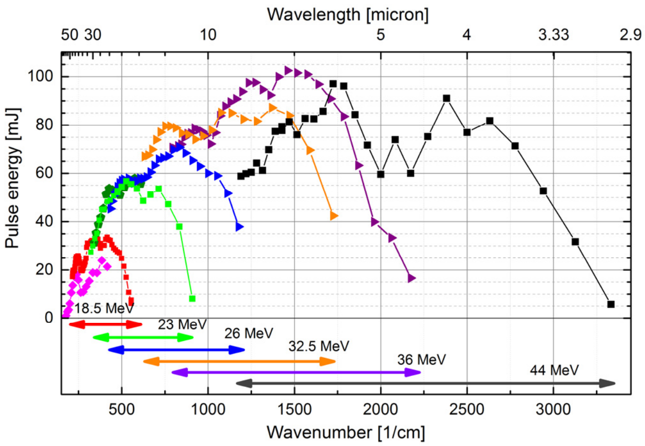

Figure 2: Macro-pulse energy measured at the FHI FEL Mid-IR system which has been in user operation since 2013. Each curve is measured by an undulator gap scan for the electron energies indicated at the bottom.

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[1] Consultants to the Fritz-Haber-Institut

FAR-IR BEAMLINE DESIGN

In addition to completing a Far-IR beamline capable of generating wavelengths greater than 150 µm, a key feature of the revised FHI FEL upgrade was a desire for simultaneous two-colour operation across the 3 µm to > 150 µm range. Users insisted that both beamlines be capable of operating simultaneously at the same 5 to 50 µm. Pulse picking requirements forced the two optical cavities to be the same length. We have chosen a short Rayleigh range Far-IR undulator that is not a waveguide, which we believe should resolve the wavelength holes observed on Flare [5].

In order to do this, we will separate the existing system after the linacs, leaving the Mid-IR arc in place. The electron gun, sub-harmonic buncher, linacs and chicane will be moved back 1.35 m to allow the insertion of a 500 MHz RF kicker cavity powered by a 65 kW solid-state amplifier.

Initial beam dynamics analysis revealed that emittance growth along the long back leg of the original Far-IR beamline was unacceptable. This realization occurred at the final design review setting a furious redesign effort in motion. Fortunately, we were quickly able to find a solution with excellent performance by instituting a bypass line and single achromat on the Far-IR beamline, as shown in Fig. 1. This design is not completely achromatic and isochronous, but is sufficiently close that performance is not negatively impacted. An additional benefit is a large reduction in parts count and hence, all-important cost. The diagnostic beamline has had to be relocated, but is still capable of performing the required measurements in the new location.

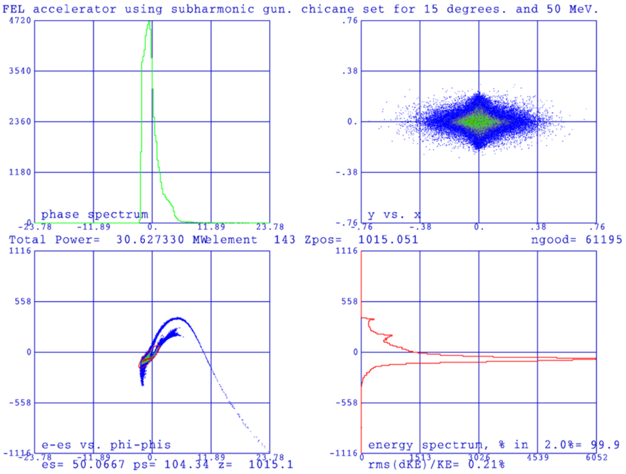

Figure 3: 50 MeV end-to-end TStep simulation at the exit of the Far-IR achromat.

Figure 3 shows the phase space after the Far-IR achromat for a 50 MeV electron beam with the chicane set for 15 degrees. The resultant rms energy spread of 0.21% and the FWHM bunch length of 2.5 ps were used in the FEL physics simulations described below.

Figure 4 shows an 18 MeV Trace3D simulation from the exit of linac 2 (left) to the Far-IR beam dump (right). The horizontal (blue) and vertical (red) $5\varepsilon_{\rm rms}$ beam envelopes can be seen to be well matched into the undulator (elements 54 and 55). The dispersion (gold) is well controlled at entry to the undulator. $K_{\rm rms}$ is 2.15 for this case yielding a radiation wavelength of 150 µm.

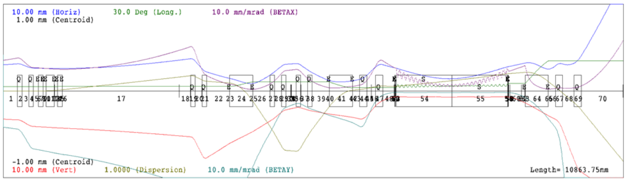

Figure 4: Trace3D simulation of the Far-IR beamline from the linac 2 exit (left) to the beam dump (right).

A key component of the update engineering design, shown in Fig. 5, is the new 500 MHz kicker cavity which operates in a dipole mode using the electric field between the vanes to deflect the beam. The cavity is capable of deflecting the 50 MeV electron beam through ±2 degrees. It is surrounded by two small 2 degree rectangular dipole magnets. For two-color operation, the beam is alternatively bent -1, -2, -1 => - 4 degrees by the dipole-kicker-dipole combination into the Far-IR line and -1, +2, -1 => 0 degrees for the Mid-IR beamline. For single-color operation, the kicker is not used and the dipoles are off for the Mid-IR and at -2, -2 => -4 for the Far-IR. A more detailed view of this region showing the kicker beam box and dipoles is shown in Fig. 6.

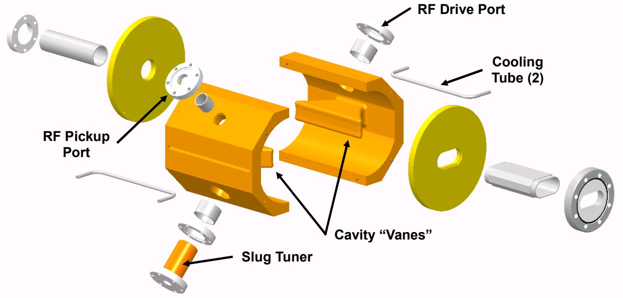

Figure 5: Exploded view of the 500 MHz RF kicker cavity showing the vanes.

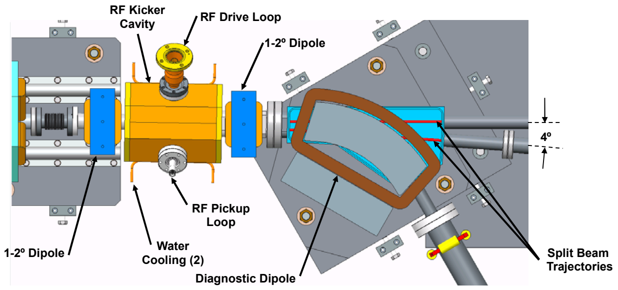

Figure 6: Detail of the RF kicker region

FEL PHYSICS DESIGN

No significant change is anticipated in the performance of the Mid-IR beamline. The anticipated performance of the Far-IR beamline will deliver 2.5 ps pulses at 50 MeV with bunch charge of 200 pC. This is sufficient to deliver the 5 µm radiation demanded by users. Shorter bunches

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should be possible with more aggressive chicane settings and hence increased IR power.

At long wavelengths, the optical mode is wide due to increased diffraction, and requires a relatively large resonator mirror diameter of 7.2 cm. The outer radius of the gold mirrors is designed to control the optical mode shape with 96% of the power in the fundamental mode. Hole out-coupling is used on the downstream mirror. This unique FIR FEL open resonator design enables continuous tunability over the largest wavelength range of any laser of any kind.

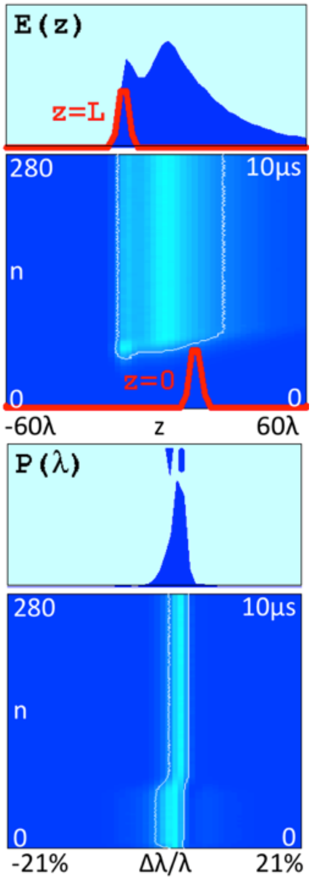

Figure 7: Final, steady-state optical pulse shape E(z) (blue-top left) for 120 λ, with the electron pulse (red) superimposed at z = L. The relative positions at z = 0 (bottom left) shows the electron pulse a full 30 λ ahead of the optical pulse. The intensity (bottom left) and spectral (bottom right) evolution of the optical pulse shape (light blue) is shown over the n = 280 amplification passes of the 10 µs macropulse. The final optical spectrum P(λ) has an ~2.5% width (top right).

The slippage distance of the optical pulse is more than six times longer than the short 2.5 ps (FWHM) long electron pulse, but provides sufficient single-pass gain to reach saturation in strong optical fields in 2.4 µs. Figure 7 shows the final steady-state optical pulse and spectrum.

FAR-IR UNDULATOR DESIGN

The parameters for the Far-IR undulator have been selected. The period is 68 mm, there are 30 spectrally active periods and the minimum gap is 3.2 cm, corresponding to a root-mean-square (*rms*) undulator parameter $K_{\mathrm{rms}} \sim 2.29$. The Far-IR FEL cavity will be 5.4 m long, as is the existing Mid-IR cavity. However, the former will have a smaller Rayleigh range of just 1/3.

Because of the diameter of the long wavelength optical modes, the 6.5 cm gap of the dipoles at each end of the undulator is very large to avoid mode scrapping, and thus these beam boxes provide a significant engineering challenge.

STATUS OF FAR-IR FABRICATION

We have already begun the fabrication process for the FHI FEL Upgrade. Tenders have been issued for the dipole magnets, kicker cavity, and solid-state-amplifier. Diagnostics, steerers, quadrupole magnets, magnet power supplies, and other components have been issued and the first components are already beginning to be delivered. We anticipate having all critical components in hand by summer 2020. The goal is to complete all upgrade activities by the end of 2020.

UPGRADES TO THE MIR-BEAMLINE

In the process of developing the FHI FEL upgrade design, and partially due to the analysis of the upgrade, we have uncovered a number of deficiencies in the existing system that have been remedied. These include movement and reorientation of the achromat dipole magnets based upon vault location surveys. We have also adjusted the tuning of the linac 1 bunching cavity. This resulted in shorter bunches, a nearly 3-fold increase in the optical power delivered to 400 mJ per macropulse, and reduced vault radiation levels that allow operation at higher PRF. New bipolar relay circuitry will eliminate hysteresis effects in the rarely-used chicane dipoles, allowing the achievement of higher undulator peak current. Similarly, an improved RF arc protection system and higher gun voltage (40 kV with a target of 45 kV) have already extended operations towards 50 MeV and should enable extension of the macropulse length beyond the typical value of 10 µs.

CONCLUSIONS

The physics design for the FHI FEL has been completed and the engineering design is ongoing. Major tenders have been issued and POs are being let for many other key systems. The plan is to start installation of all ex-vault components ahead of user shutdown. Two-colour operation is scheduled to be available before the end of 2020.

REFERENCES

[1] H. P. Bluem *et al.*, “The Fritz Haber Institute THz FEL Status,” in *Proc. FEL’10*, Malmo, Sweden, August 2010, paper MOPA09.

[2] A. M. M. Todd *et al.*, “Commissioning Status of the Fritz Haber Institute THz FEL,” in *Proc. IPAC’11*, San Sebastian, Spain, September 2011, paper THPC106.

[3] W. Schöllkopf *et al.*, “First Lasing of the IR FEL at the Fritz-Haber-Institut Berlin,” in *Proc. FEL’12,* Nara, Japan, August 2012, paper MOOB01.

[4] W. Schöllkopf *et al.*, “The new IR and THz FEL Facility at the Fritz Haber Institute in Berlin,” Advances in X-ray Free-Electron Lasers Instrumentation III, Sandra G. Biedron, Editor, *Proc. of SPIE*, vol. 9512, 95121L (2015). `doi:10.1117/12.2182284`

[5] D. Arslanov, R. Jongma, L. van der Meer *et al.*, “Scanning Problems of FLARE, a THz-FEL with a waveguide,” in *Proc. FEL’14*, Basel, Switzerland, August 2014, paper TUP065.