ANALYSES SUPPORTING THE TWO-COLOR UPGRADE TO THE IR FEL AT FHI, BERLIN*

A. M. M. Todd†, AMMTodd Consulting, Princeton Junction, USA ; W. B. Colson, WBC Physics, Carmel, USA ; D. H. Dowell, SLAC, Menlo Park, USA : S. C. Gottschalk, STI-Magnetics, Woodinville, WA, USA ; J. W. Rathke, JW Rathke Engineering Services, Centerport, USA ; T. J. Schultheiss, TJS Technologies, Commack, USA; L. M. Young, LMY Technology, Lincolnton, GA, USA; W. Schöllkopf, M. De Pas, S. Gewinner, H. Junkes, G. Meijer, G. von Helden, FHI, Berlin, Germany

Abstract

This paper provides a summary of the analyses that led to the definition of the 2-color upgrade of the IR FEL at the Fritz-Haber-Institut (FHI), Berlin. We briefly cover several different aspects of the design, beginning with the beam dynamics of the second far-IR (FIR) beamline, engineering considerations of that physics design, and the FEL physics that defined the short-Rayleigh-range undulator, as well as aspects of the undulator design itself. Additionally, we touch on the approach to 2-color operation and considerations for the FIR optical transport to users. The status of commissioning is described in a parallel paper [1].

INTRODUCTION

The FHI mid-IR (MIR) FEL first lased on February 14, 2012 [2]. Since November 2013, it has provided continuous 3 to 60µm radiation service to users, resulting in more than 80 peer-reviewed publications [3].

In 2018, FHI embarked upon an ambitious upgrade project to add a FIR FEL beamline that could deliver radiation from 5 to 166µm. By adding a 2-degree deflecting cavity right after the second linac, alternately, 2-color, 500MHz pump-probe radiation can be delivered to experiments on the MIR and FIR beamlines, which are separated by 4 degrees, when the new FEL is commissioned.

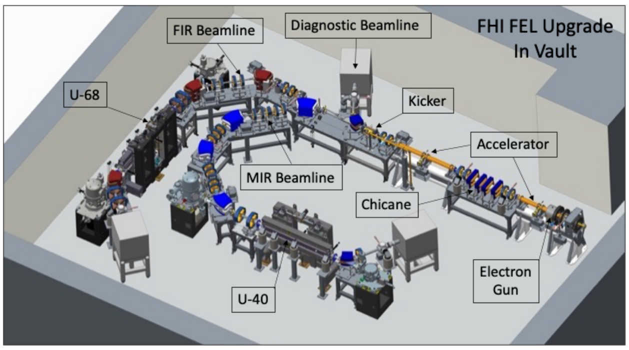

Figure 1: Engineering schematic showing the FHI FEL MIR and FIR electron beamlines in the vault.

This paper describes the analysis that underpinned the FIR FEL physics and engineering design illustrated in Fig 1. It touches on the beam dynamics and engineering analyses of the electron beamline, the undulator FEL physics and engineering, the FIR optical transport and scanner magnet calibration measurements used in the beam dynamics calculations.

BEAM DYNAMICS

We concentrate on the most difficult 18MeV energy operation at the longest wavelengths (166µm with the minimum 32mm undulator gap). Fig. 2 shows a TRACE3D [4] plot for the FIR electron beamline beginning after the accelerator at the left edge to the beam dump at the right edge. Note that the dispersion trace (gold) goes to zero at the center of the U-68 undulator indicating that the 94-degree pre-undulator FIR bend is achromatic. The horizontal U-68 match has a waist in mid-undulator, while the near constant vertical trace illustrates the proper match in the vertically focusing undulator.

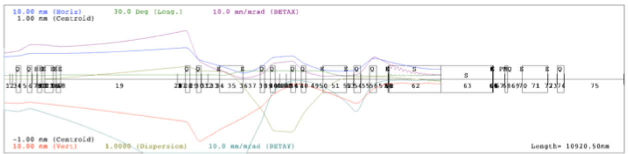

Figure 2: TRACE3D 5ε beam envelope simulation of the FIR electron beamline with achromaticity in the center of the undulator (gold trace) and an excellent match (horizontal/blue - vertical/red) to the U-68 undulator (62 and 63).

Using identical post-linac parameters, the corresponding Fig. 3 TSTEP [5] simulation for this case shows the revised FIR achromat delivers a 2.5ps, 100keV FWHM beam to the FIR undulator for FEL physics analysis.

The most difficult operating scenario will occur for 2-color FEL operation where, for any given beam energy, we are short of beam matching variables on the U-68 beamline. Our plan is to utilize quadrupoles QB05 and QB06 after linac 2, and QC04 and QC05 ahead of U-68, to produce waists in the middle and the near constant matched vertical beam size through U-68, at the longest wavelength. For the MIR beamline, we use the matched FIR values for the two magnets after linac 2, adjusting QC01 and QC02, ahead of U-40 and two of the MIR mid-achromat triplet magnets, to provide a similar match for U-40 at the minimum gap yielding 50µm radiation.

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† ammtodd@fhi-berlin.mpg.de

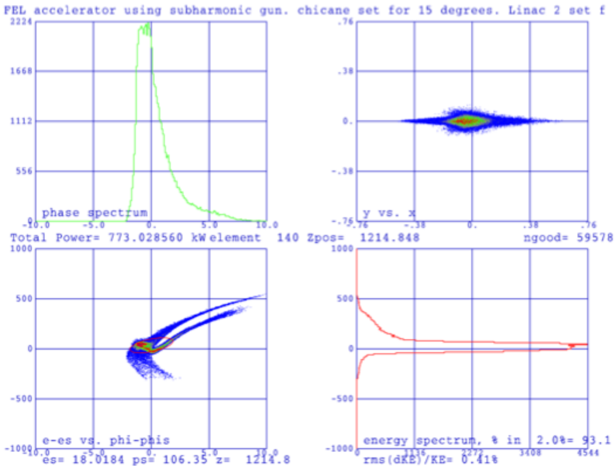

Figure 3: TSTEP simulation of the FIR electron beamline showing the 2.5ps, 100keV beam at the entry to U-68.

As shown in Fig. 4, given there is no undulator horizontal focusing, the horizontal beam remains well matched during a gap scan, but the vertical beam starts to exhibit betatron oscillations as the undulator opens. At maximum FIR gap for 31µm radiation, the vertical match has deteriorated significantly, but the maximum vertical beam size is still less than 2mm rms, which still fits nicely inside the larger FIR optical mode and should lase adequately. If necessary, we will have the control system vary the key focusing quadrupole magnets with gap size to maintain the focus in the two undulators, though we are reluctant to introduce this added complexity.

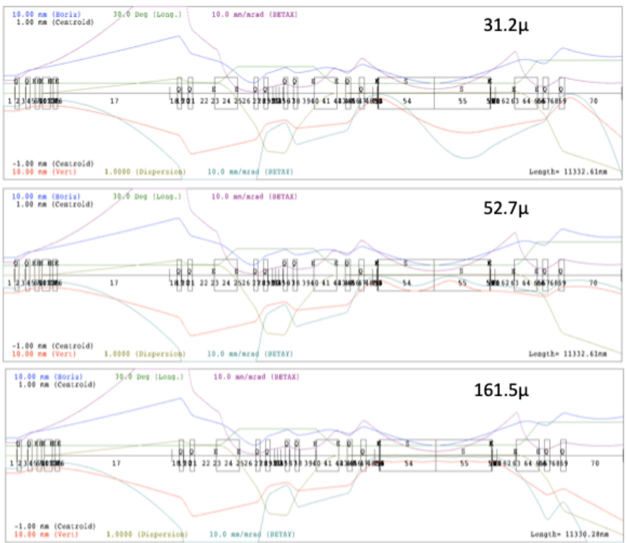

Figure 4: TRACE3D 5ε beam envelope simulation of the FIR electron beamline during a gap scan at 18MeV showing the loss of vertical focusing (red trace) as the U-68 gap opens from bottom to top.

BEAMLINE ENGINEERING ANALYSIS

The major FIR engineering issues cantered on the performance of the deflector cavity, the design of the very large gap DF dipole magnets because of the large, short Rayleigh range oscillator FIR optical beam envelope on each side of U-68, and the output FIR beam dump window. Fig. 5 shows the axial deflecting electric field and thermal analysis for the cavity which was fabricated by Research Instruments GmbH. All potential issues were addressed in the analysis and fabrication, so we are confident that these components will deliver their required performance.

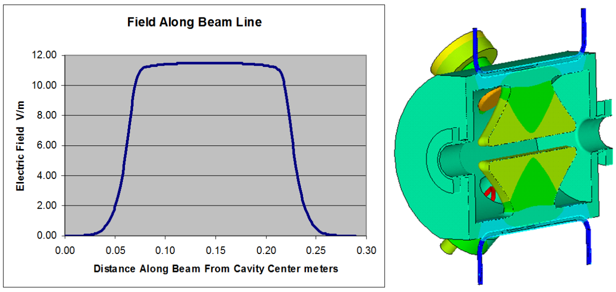

Figure 5: Flat deflecting cavity transverse electric field (left) and thermal analysis of the cavity indicating the predicted small temperature variation of the design (right).

U-68 UNDULATOR ANALYSIS

The undulator design challenge was to provide a nominally non-steering, non-offset, gap-tapered end design to reduce scraping of the 166µm optical mode at a gap of 32mm for the 18MeV electron beam energy. Simultaneously, the entry needed to have a minimal gap dependence to keep the trajectory straight enough that the 40 turn upstream electromagnetic (EM) coils could turn the beam to maintain good optical mode overlap under all operating conditions. A radiation resistant, wedged-pole hybrid with grain boundary diffusion was chosen.

Signature-based finite element analysis (FEA) with metaheuristic, genetic optimization was performed. The heights of the first three poles and the first two magnets were varied and confirmatory, non-signature, multi-gap, full 3D FEA was performed as shown in Fig. 6. Mechanical design of the ends imposed added constraints and requirements. The FEA model illustrates the range of pole and magnet heights with the first pole 5.65mm shorter than the center poles. Features like steel strongbacks, EM and clamping bolt holes, pole clamp ears and the nominal 0.3mm air gap between poles and magnets were included.

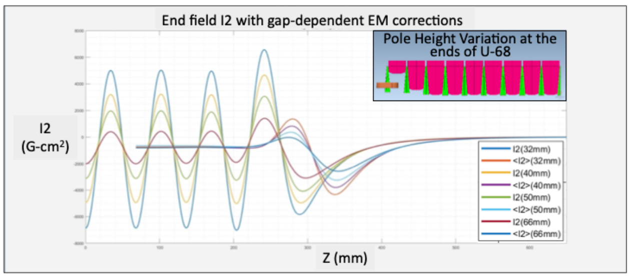

Figure 6: Field integral, I2, from FEA with gap-dependent EM correction for the entry to U-68. The inset shows the pole height variation.

FEL PHYSICS

We have designed a short 68cm Rayleigh range oscillator undulator to deliver FIR radiation from 5 to 166µm. The 2.5ps beam in the 30 period, 68mm undulator delivers the 166µm radiation at the minimum gap of 32mm for 18MeV operation. The mode is large at the 8cm diameter optical cavity mirrors but has 96% of the radiation in the fundamental mode and optimizes to a 6mm diameter outcoupling hole under these conditions. For the shortest wavelengths, a 1mm diameter outcoupling hole is preferred.

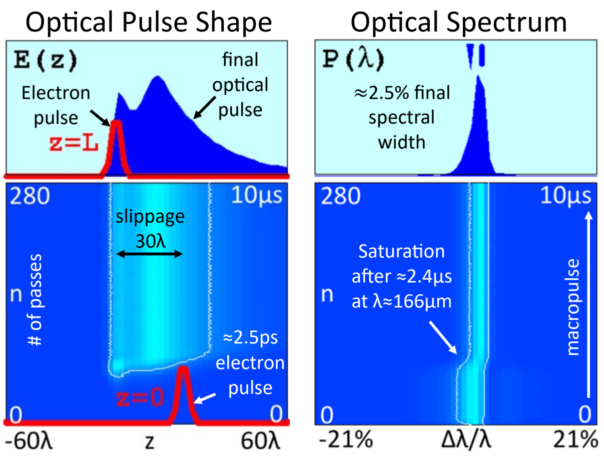

Figure 7: FIR output radiation performance at 166µm.

Fig. 7 shows the optical pulse shape and the spectrum for this 166µm operation point. Saturation occurs in 2.4µs and the final spectral width is 2.5%. Thus, we are very encouraged by these FEL physics simulations.

OPTICAL TRANSPORT

The first experimental FIR target will be the so-called "X4" location upstairs in the FHI user center. The revised MIR optical transport is already successfully in operation.

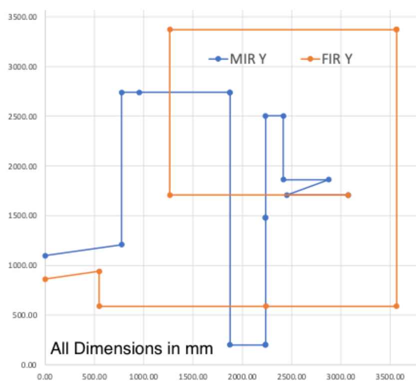

Figure 8: MIR and FIR optical transport in the optical diagnostic room and the upstairs X4 experiment.

We have defined an FIR optical transport solution but are waiting for the X4 users to finalize their requirements for optical waist size, pump-probe timing and target orientation. The baseline geometry from the entrance to the optical diagnostic room and onward upstairs to X4 is shown in Fig. 8 for the MIR (blue) and FIR (orange) optical transport lines. A trombone on the FIR beam line may have to be added to control arrival times between the two lines for pump-probe experiments.

The existing MIR and baseline FIR optical transport is shown in Fig. 9, illustrating the waists in the optical diagnostic room and at the X4 target. Both 3.5w waists at the X4 target are less than 2.5cm.

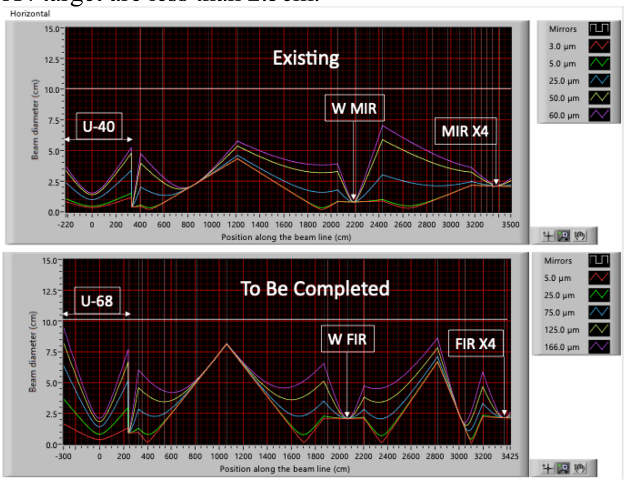

Figure 9: MIR and FIR 3.5w optical transport IR beam envelope transport to the X4 experimental target.

CONCLUSIONS

The design and analysis of the FHI far-IR (FIR) electron and optical beamlines has been completed with all key components delivered and installed.

The redesigned single-achromat FIR beamline has improved emittance delivery at the U-68 undulator for effective FIR lasing. The kicker performance has been verified. Magnetic measurement of key magnets was completed using the magnet scanner system installed at FHI.

Excellent user FIR power performance from 5 - 166µm is predicted for the FIR beamline in stand-alone and 2-color operation. MIR optical transport to the user X4 target is in operation and the FIR design that will permit 2-color FEL operation is completed awaiting user confirmation and procurement.

The existing mid-IR (MIR) has been recommissioned and regular user operations are ongoing.

REFERENCES

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[4] TRACE3D, https://laacg.lanl.gov/laacg/services/traceman.pdf

[5] TSTEP, https://tstep.lmytechnology.com