UCLA SEEDED THz FEL UNDULATOR BUNCHER DESIGN

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UCLA is planning to build a THz user facility. One is a seeded THz FEL tunable in the range of 0.5 - 3 THz or even 3-9 THz in an optical klystron configuration [1]. Another [2] relies on microbunching at 340 μ using a 3.3-cm undulator or even driving the FEL with an electron beam from a laser-plasma accelerator. These FELs make use of a 2.1-m-long pre-buncher, chicane and shorter, 110-cm-long radiator. Chicane requirements are modest. A round copper waveguide with 4.8-mm ID will be used. We will describe the magnetic design and measured performance of the gap tunable undulators, mechanical design of the entire system, vacuum boxes, waveguides, and expected operational approaches. Both undulators have 33-mm periods and curved poles for two-plane focusing. Discussions will be included on issues associated with fabricating, sorting and shimming curved pole undulators. A new optimization method will be described that was used to meet magnetic requirements with a minimum volume of magnetic material.

INTRODUCTION AND BACKGROUND

The UCLA Neptune lab and STI Optronics have collaborated on undulators for THz operation in the 0.5-9 THz range as well as a potential future FEL based on Laser Wakefield Acceleration [1,2]. Planned first experiments [2] will use a ~kilowatt, 340-μm seed generated by nonlinear difference frequency generation in GaAs using 10.3-μm and 10.6-μm CO_2 lines. A round copper waveguide is used to preserve linear polarization. After passing thru a 1-m undulator, the FEL power is expected to be 300kW. A chicane, or a drift of 1-1.5 meters suffice to convert energy modulation to spatial bunching which will be measured in an X-band RF deflector cavity with a resolution <200 fs.

Future experiments in the THz regime will use an 8- to 14-MeV electron beam from the Neptune photoinjector in a variety of configurations [2]. From 0.5-1.5 THz a 2-m-long, 3.3-cm period undulator would be seeded with a ~1-kw seed laser to reach 2- to10-MW power at saturation. From 1.5-3.0 THz the system would operate as an optical klystron where the first undulator, ~2-m long, is seeded with a 10-100 W laser and then the energy modulation is converted to spatial bunching inside a chicane prior to entering a 1-m long radiator. A third mode is to use HGHG wherein the beam is modulated at 1-3 THz inside a 2-m undulator and then sent into a 1-m radiator tuned to the 3^{rd} harmonic to generate 3-9 THz. All of these situations have been modeled using Genesis 1.3 and confirm the feasibility of multi-MW power output [3]. The UCLA team has built and fully characterized a kW power seed source tunable in the range of 0.5-3 THz [4].

Undulators have been delivered to UCLA after tests at STI. Vacuum boxes, custom optical tables and waveguides have also been delivered to UCLA.

SYSTEM OVERVIEW

The layout for seeded FEL operation in the 1.5 to 3.0-THz wavelength regime is shown in Fig. 1. Both undulators, CAD model of one of the vacuum boxes and kinematic feet hardware are shown. A closeup of the curved poles on the 2-m undulator is in the upper left corner. The 2.1-m long undulator is mounted on kinematic feet and has a motorized gap adjustment with a control system GUI, which is operated by a laptop computer. The 1-m undulator has a manually adjusted gap. It uses 1-μm resolution half-gap micrometers.

The round copper waveguide also has adjusters for x, y, z to help straighten and align the tube. STI designed the waveguide sub-system with UCLA guidance, review and approval of drawings. The UCLA machine shop fabricated it.

UCLA designed the vacuum boxes and STI generated production drawings which were reviewed and approved by UCLA prior to fabrication. Vacuum boxes shown on the right side have vertical and differential micrometer translators for alignment. An off-axis paraboloid reflector with tip, tilt, translation adjusters is used to introduce the seed laser and outcouple the THz radiation. Electron beam passes thru a hole in the center of the paraboloid. Pop-in targets are moved into position with a pneumatic actuator and viewed thru side windows.

MAGNETIC DESIGN

Curved poles with sextupolar focusing [5] are used to minimize the possibility of synchrotron-betatron resonance and provide horizontal focusing in addition to natural vertical wiggler focusing. Unlike an earlier undulator, [6], these two undulators use a more standard approach of changing the gap rather than retracting magnets. For both approaches the focusing depends on gap. This means that the e-beam matching will need to be adjusted as the gap changes and the beam will be elliptical, rather than circular.

When shaping the poles used in the 2-m undulator, we took advantage of the fact that the inner diameter of the round copper waveguide is 4.8 mm. This is a significant issue for 2-m undulator because it means that wide poles are not needed, modest shaping is sufficient and existing spare poles from CHESS could be used. Forces were about 2X lower, which reduced moment loads on linear bearings and required less motor torque. Field quality was

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not impacted. Poles on the 2-m undulator were 25.5-mm (x) x 17.65 mm (y) x 5.93mm (z). CHESS poles that were used to make these poles were 62.24 mm (x) x 31.74 mm (y) x 5.93 mm (z). We made two poles from a single CHESS pole. The 110-cm-long undulator used APS Undulator A wedged poles. Its pole curvature is the same as the straight pole, so we only describe the straight pole design.

Optimization varied pole width, height, step depth, step width, step polynomial coefficients, pole transverse chamfers, and magnet overhangs. OptiNet was used and custom scripts employed to shape poles, calculate focusing, and determine K_{rms}. Field was maximized subject to constraints on deviations from sextupolar focusing. The original klystron design [1] was optimized for a period of 2.7 cm, K_{rms}=2.015, γ = 16.2 and saturation occurred in 1.8 m with microbunching after a drift length of 4 m. When the period was increased to 3.3 cm, the same performance was achieved with K_{rms}=1.772. During pole shaping, the minimum magnetic field at a gap of 8 mm had K_{rms}=1.772. Final K_{rms} was 1.795. Deviations

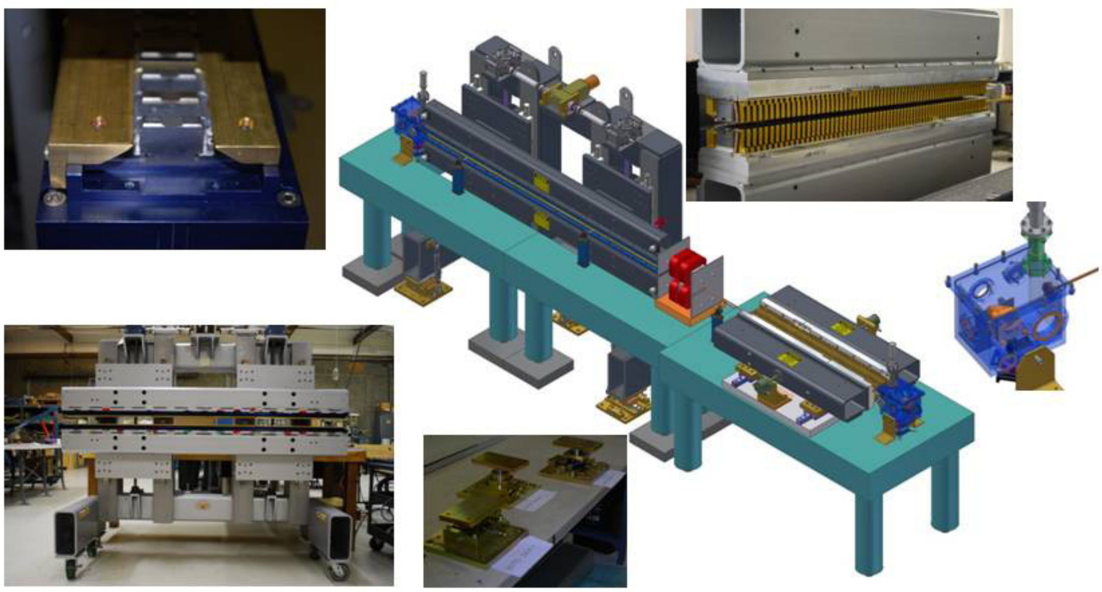

Figure 1: UCLA Neptune THz FEL - Optical Klystron configuration shown.

from analytic sextupolar fields [3] were <2% over a quarter period long, 4-mm diameter circular region.

Like the earlier device [6], equal two-plane focusing was not possible without losing ~40% in K_{rms} or reducing the gap. For the 2-m undulator equal two-plane focusing would require a gap of about 3 mm. The reason for such a small gap is simple: the flat part of the poles has a lower reluctance than the curved part, so as the curvature is increased to boost the focusing, the gap in the flat region must decrease disproportionately to compensate for leakage. Therefore, we allowed unequal sextupolar focusing, which is shown in the lower left part of Fig. 2. Genesis 1.3 simulations showed that this will not significantly degrade FEL performance.

The FEA model, pole shape and focusing fields after optimization are shown in Fig. 2. Magnet clamping chamfers were added later. Upper left is an isometric picture of the geometry and B field. Upper right is the B field at the midplane. Lower left is the sextupolar B-field profile and the lower right is the pole profile. Sixth order poles achieved the best focusing. We left space between the waveguide and poles to allow for vacuum tube imperfections.

Curved Pole Undulator Issues

Curved poles required modifications to fabrication, alignment and tuning. For fabrication we used wire EDM and inspected 10% of the poles with CMM. The peak-to-peak profile errors were 15 μm and rms profile errors were 4 μm. Curved poles must create very large sextupoles and they must precisely cancel out for every period or a net sextupole will be generated. On these devices the required sextupole was 3300 G/cm^2 and the rms deviation was 3% or 100 G/cm^2. We think that this is mainly a concern for ERLs, which must satisfy stringent beam dynamics requirements. For these seeded FELs, the pole-by-pole sextupole fluctuation should only change matching quadrupole settings. For future undulators of this type, random sextupole errors can be reduced.

End fields produced the desired zero steering and zero entrance angle, but they were not zero sextupole. Since the design was anti-symmetric, this was not an issue. A better approach would be to change the curvature of end poles so that they have zero integrated sextupole after several periods.

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Alignment made use of the 3D B-field shape using $\cosh(k_w x)$ fitting for each pole. This was used to adjust pole alignment on multi-period modules. It agreed with direct mechanical measurements made with digital micrometers attached to the Hall probe stage.

Trajectory and phase shimming had to deal with sextupoles created by shims in addition to the usual dipole. The approach we used was to vary the transverse widths of shims as well as allowing two-part shims, which is more commoly used for skew tuning. Sextupole shims were also used to simultaneously straighten off-axis trajectories. Special purpose spread sheets were written for this purpose because most undulators do not need normal sextupole tuning.

PERFORMANCE

After assembly we compared measured and predicted off-axis B fields. The STI scanner uses Senis YM12 probes, which do not have planar or tensor Hall effects [7,8]. We confirmed this by comparing normal and skew multipoles off the midplane as well as examining $B_y(y)$ for tensor Hall effects caused by the $\sinh(k_w y)\sin(k_w z)$ dependence of $B_z(y)$. The average $B_x(x,y,z_{pole})$ and $B_y(x,y,z_{pole})$ over central poles was compared with FEA. Measured and predicted magnetic field profiles agreed to 0.1% for |x| and |y| < 2mm. Phase error was < 4.2° at all gaps. Genesis simulations indicate 10° is sufficient. Fig. 3 shows 1st and 2nd integrals of the field at x = -1 mm, 0 mm and +1 mm. A non-zero, slowly varying sextupole is the most notable feature.

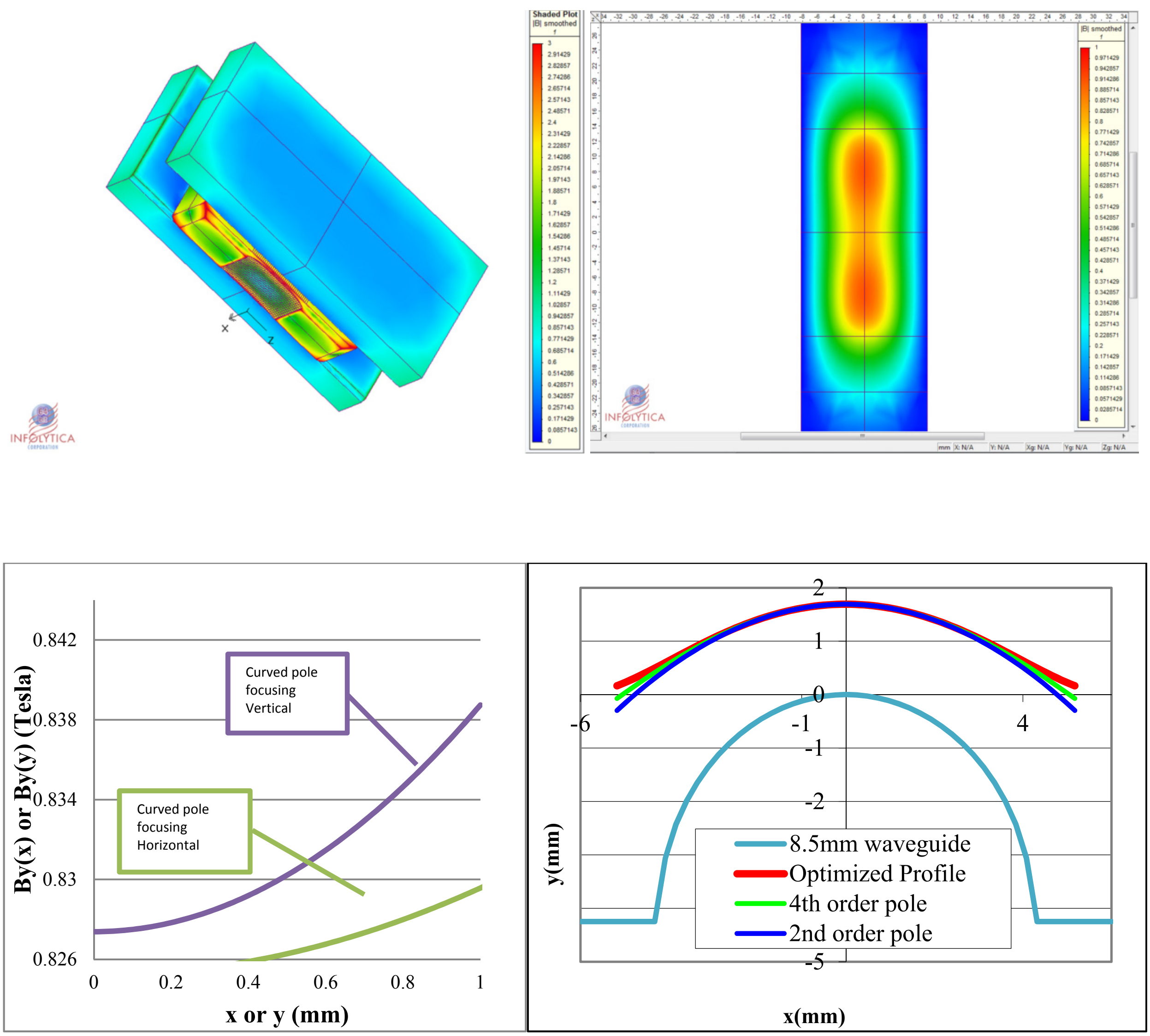

Figure 2: Curved pole design, fields and profile.

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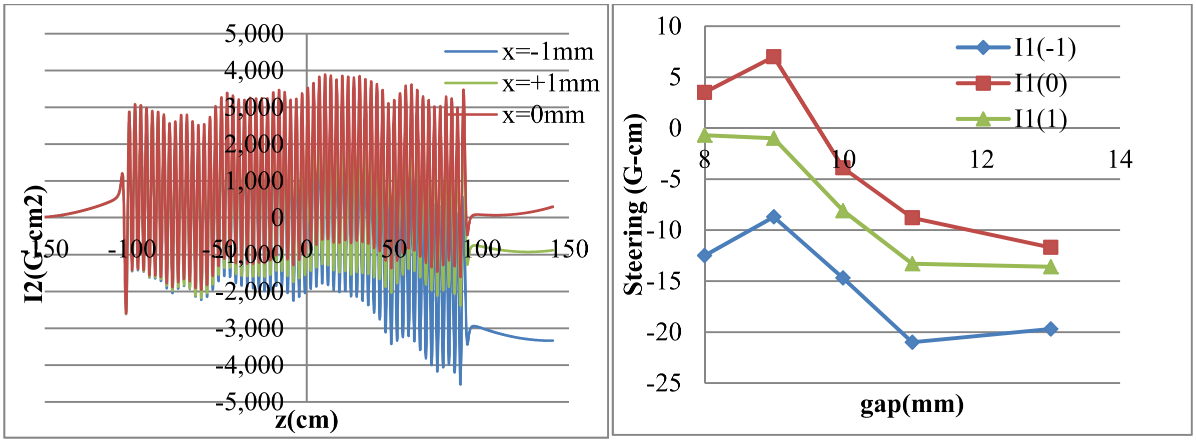

Figure 3: 1st and 2nd integrals for the 2-m undulator.

CONCLUSION

We have described the design and performance of undulators for the UCLA THz at Neptune Lab FEL. The undulators meet requirements. The next step is to use them in FEL experiments.

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