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FABRICATION & COLD TESTS OF A MILLIMETER-PERIOD RF UNDULATOR*

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Abstract

To reduce the linac energy required for an FEL radiating at a given wavelength, and hence its size, a smaller undulator period with sufficient field strength is needed. Previous work from our group successfully demonstrated a microwave undulator at 11.424 GHz, using a corrugated cylindrical waveguide operating at the HE_{11} modes. We have designed, built, and cold-tested a mm-wave undulator cavity at 91.392 GHz with an equivalent undulator period of 1.75 mm. This undulator requires 1.4 MW for sub microsecond pulses for an equivalent K value of 0.1. In this work we report the mechanical design and fabrication of this 91.392 GHz RF undulator, as well as preliminary cold test data.

INTRODUCTION

Free-Electron Lasers (FELs) are tunable sources of high-power, coherent electromagnetic radiation from microwave frequencies all the way to hard X-rays. In biology and material science, SLAC's Linac Coherent Light Source (LCLS) [1] – the first operational hard X-ray FEL – has revealed the structure of key biomolecules [2] and catalysts and their interactions [3]. However, hard X-Ray FELs are very large and expensive. The European XFEL is 3.4 km long, and produces 0.1 nm photons. It costed €1.1B to build, while operational expenses are estimated at €83M/year [4]. Developing a technology that reduces the size and cost of X-Ray FELs, and makes them accessible to more scientists, will have tremendous impact in advancing science.

Traditionally, coherent emission of short wavelength electromagnetic radiation employed undulators – devices that generate a periodic magnetic field – made of permanent magnets. Such undulators present several limitations on the shortness of their period while maintaining reasonable field strength and beam aperture. In order to shrink an FEL, a smaller linac, and therefore lower beam energy, is required. This means that a smaller undulator period is required while sufficient field strength is maintained. However, the undulator wavelength cannot be too small – for example using directly a laser beam [5, 6] – because the emittance requirements make it infeasible for the beam to lase. Alternatives to traditional undulators are in-vacuum and superconducting magnet-based undulators [7–9], crystalline undulators [10, 11], short-period electromagnet-based undulators [12], microfabricated permanent magnet undulators [13], microfabricated electromagnet undulators [14, 15], laser-driven undulators [16–19], and microwave undulators [20, 21]. In-vacuum undulators, short-period electromagnet-based undulators, microfabricated permanent magnet undulators and microfabricated electromagnet undulators are all limited by the beam aperture being smaller than their period in order to maintain high fields. Laser-driven undulators are also limited by small beam apertures. Superconducting undulators are very expensive and present several reliability issues in high-energy beams. Crystalline undulators are still in their infancy and are not suitable for high-current beams. Previous work in our group on microwave undulators investigated several overmoded waveguide systems [22, 23] and concluded that corrugated cylindrical waveguides operating in the HE_{11} mode had the lowest resistive losses and peak surface fields for the same K. Such an undulator has been successfully demonstrated at 11.424 GHz [21]. Scaling this undulator into the mm-wave/terahertz regime could dramatically reduce the size and cost of an FEL.

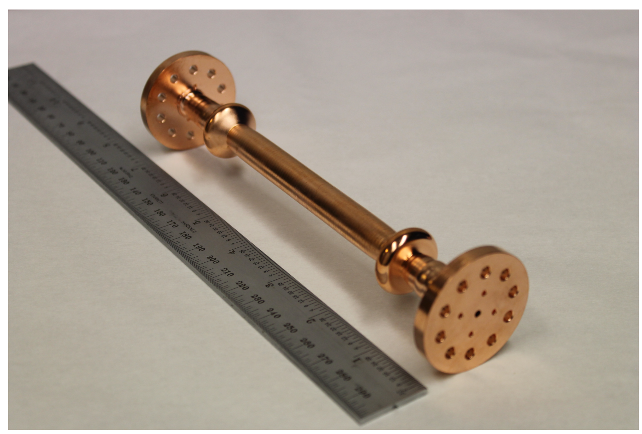

Figure 1: Manufactured 1.75 mm-period RF Undulator operating at 91.392 GHz. The length of this structure is 18.55 cm. The picture shows the input RF cylindrical waveguide and beam pipe as well as the flange for connecting to a network analyzer or coupler. The input beam pipe diameter shown in this picture is 2.375 mm. The output beam pipe diameter on the other side of the structure is 4.92 mm.

We have designed, built, and cold-tested an RF undulator cavity – shown in Figure 1 – that operates at 91.392 GHz with an equivalent undulator period of 1.75 mm and 2.375 mm/4.92 mm input/output beam apertures. Figure 2 shows the RF model of the undulator cavity. The RF power required for $K = 0.1$ is 1.4 MW. Since this cavity is axisymmetric, it supports two degenerate eigenmodes and allows fast control of the polarization of the light simply by changing the excitation of the cavity. The RF design of this RF undulator has been reported in [24, 25]. In this work we report the mechanical design and fabrication of the RF

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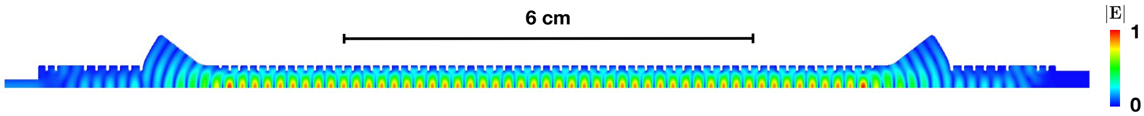
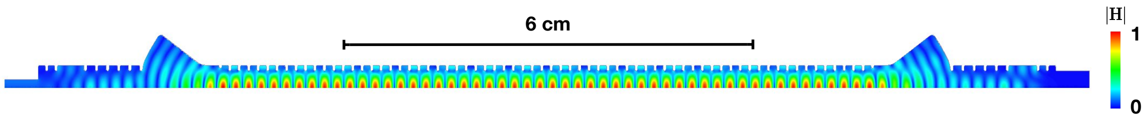


(a) Electric field profile.



(b) Magnetic field profile.

Figure 2: Undulator Cavity RF Model, adapted from Toufexis *et al* [24].

undulator cavity. We further report preliminary cold test results showing good agreement with the design.

MECHANICAL DESIGN & FABRICATION

Figure 3 shows the mechanical design of the RF undulator. To fabricate this undulator, a mandrel of aluminum 6061-T6 was machined on a lathe to recreate the shape of the vacuum envelope. Figure 4 shows the vacuum model of the RF undulator. Figure 5 shows the three machined mandrels. As shown in Figure 3, two copper flanges, machined separately, are attached on each mandrel. These flanges have the alignment hole pattern of the standard mm-wave rectangular waveguide in order to both align the structure with the coupler and also allow for a direct cold-test with a Vector Network Analyzer (VNA). The flanges are covered with plastic pieces – also shown in Figure 5 – and the assembly is platted with copper. The plastic covers are removed and the aluminum is etched away. Three RF undulators were manufactured.

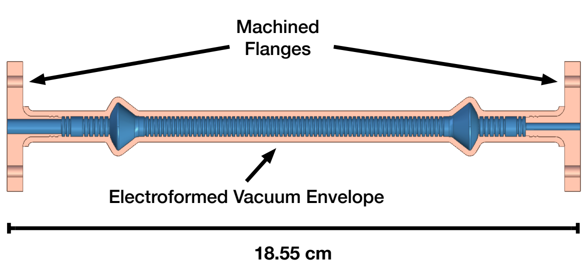


Figure 3: Mechanical Design of the RF Undulator.

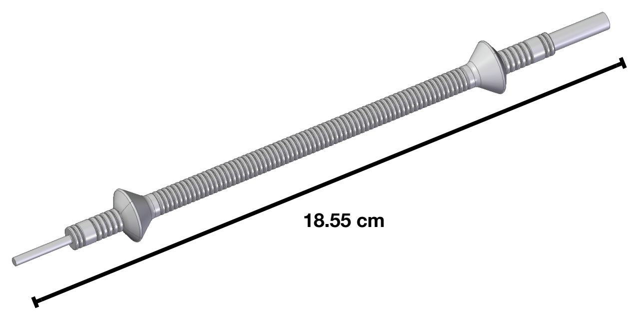


Figure 4: Vacuum Model of the RF Undulator.

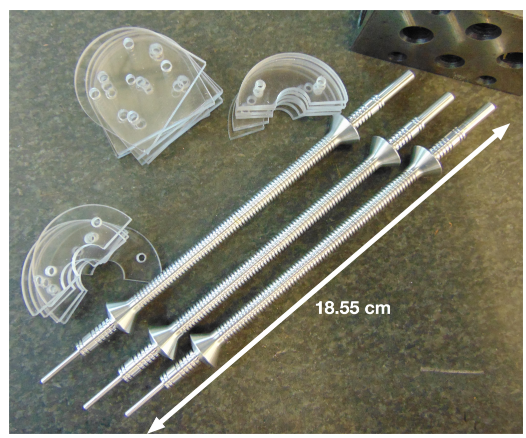


Figure 5: Manufactured Mandrels.

COLD TESTS

The three manufactured RF undulators were cold-tested using a VNA (HP 8510C with an HP 85105A Millimeter-Wave Controller) and VNA Extenders having a WR10 waveguide interface. A Thru, Reflect, Line (TRL) calibration was performed between 91.365 GHz and 91.4 GHz with 801 points – the maximum this VNA could provide. At the time of this writing the mode converter from WR10 waveguide to the cylindrical input of the RF undulator was not yet manufactured and hence the WR10 waveguide of the two VNA Extenders was connected directly to the two ends of the undulator, as shown in Figure 6. Port 1 of the VNA was connected to the input beam pipe/cylindrical waveguide of the RF undulator and port 2 to the output beam pipe. In an HFSS [26] simulation, the transition from WR10 to 2.375 mm cylindrical waveguide, also assuming a 100 µm gap, has an $S_{21} = 0.89$, which was considered adequate to get the resonance frequency and a very good estimate of the quality factor and coupling coefficient.

RF undulator #1 showed very good agreement with the design and results from it are further reported. RF undulator #2 showed no resonance within 100 MHz of the design frequency; at this point we suspect that the aluminum was

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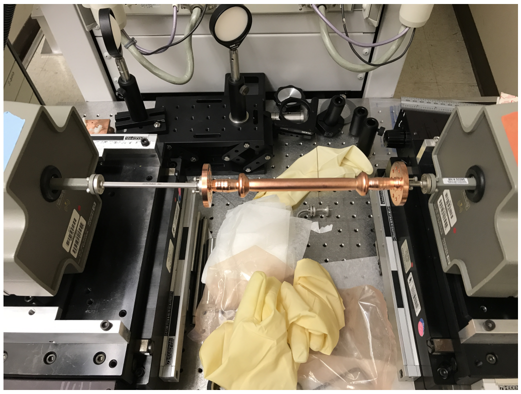

Figure 6: Experimental Setup for Cold Tests.

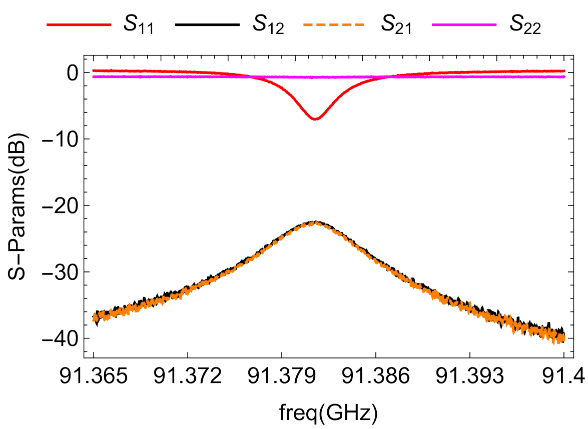

Figure 7: Measured S-Parameters for the Horizontal Polarization.

not fully etched at the end sections and, as a result, they no longer act as RF short-circuits. RF undulator #3 seemed to have a resonance slightly below the initial calibration range and at that point had issues recalibrating the VNA. Hence we do not report data from RF undulators #2 and #3.

Figure 7 shows the measured S-Parameters of RF undulator #1 for the horizontal polarization. There is a clear resonance near the design frequency in S_{11}. S_{22} seems to behave as a short-circuit and both S_{21} and S_{12} are very low – as designed. To calculate the resonance frequency f_0, intrinsic quality factor Q_0, and coupling coefficient β_c, the following cavity circuit model was fit on the S_{11} data:

$$\Gamma(f; f_0, Q_0, \beta_c) = \frac{1 + jQ_0\delta(f; f_0) - \beta_c}{1 + jQ_0\delta(f; f_0) + \beta_c}, \quad (1)$$

where

$$\delta(f; f_0) = \frac{f}{f_0} - \frac{f_0}{f}. \quad (2)$$

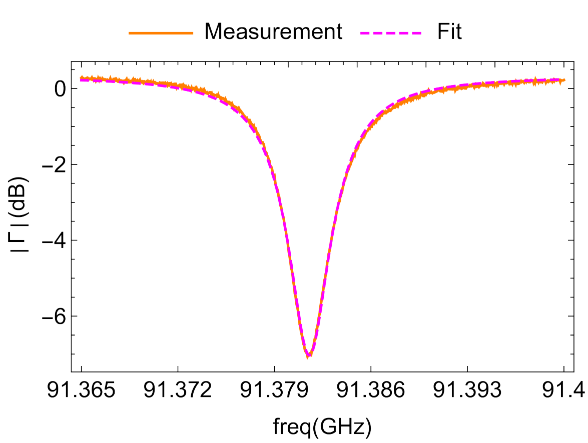

Figure 8: Reflection Measurement vs Fit for the Horizontal Polarization.

Figure 8 shows the measurement versus fit for the horizontal polarization. The results of the fit for the two polarizations of RF undulator #1 are summarized in Table 1 along with the design parameters. For both polarizations the frequency deviation from the design is only 11 MHz, while the intrinsic quality factor is reasonably close to the design value. The reduction in Q_0 can be explained by a combination of poor surface finish as a result of the chemical etch process and an incomplete etch leaving a thin layer of aluminum behind. The poor surface finish could potentially be improved by either thermal annealing or RF processing. The coupling coefficient β_c is almost half of the design value, potentially due to tolerance issues at the end features of the coupling end section.

Table 1: RF Undulator #1 Parameters Design versus Measurement Summary

	f_0 (GHz)	Q_0	β_c	Q_t
Designed	91.3920	25,200	1.0	12,700
Meas. Horizontal	91.3815	21,700	0.4	15,500
Meas. Vertical	91.3794	21,800	0.4	15,600

CONCLUSION

We have designed, built, and cold-tested an RF undulator operating at 91.392 GHz with an equivalent undulator period of 1.75 mm and 2.375 mm/4.92 mm input/output beam apertures. To fabricate the undulator, a mandrel of aluminum 6061-T6 was machined on a lathe, platted with copper, and subsequently etched away. Preliminary cold-test data show that for both polarization the frequency deviation from the design is only 11 MHz, while the intrinsic quality factor is reasonably close to the design value given the manufacturing process. The coupling coefficient β_c was sensitive to the manufacturing process and further analysis and fine-tuning of the process is required.

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