# A COHERENT COMPTON BACKSCATTERING HIGH GAIN FEL USING AN X-BAND MICROWAVE UNDULATOR

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*Abstract*

High power microwave sources at X-Band, delivering 400 to 500 of megawatts for about 400 ns, have been recently developed. These sources can power a microwave undulator with short period and large gap, and can be used in short wavelength FELs reaching the nm region at a beam energy of about 1 GeV. We present here an experiment designed to demonstrate that microwave undulators have the field quality needed for high gain FELs.

## INTRODUCTION

We describe a proposed high-gain SASE-FEL using an X-band microwave undulator and operating at a wavelength of 1 μm. Microwave undulator at X-band have a period of about 1.5 cm and a gap of about 2 cm, and can be used in short wavelength FELs reaching the nm region at a beam energy of about 1 GeV [1] The experiment is designed to demonstrate that microwave undulators have the field strength and quality to be used for high gain FELs without gain degradation.

The proposed FEL uses a 50 MeV electron beam produced by the NLCTA X-band linac at SLAC. The electron source is an S-band high-brightness photoinjector. The undulator consists of a circular waveguide with an rf wave counter-propagating with respect to the electron beam. The undulator is powered with high-power X band klystrons and a dual-moded pulse compressor recently developed at SLAC[2]. This system is capable of delivering flat-top rf pulses of up to 400 ns and 400 to 500 MW. The equivalent undulator period is 1.7 cm, the radius of the circular pipe is 0.9 cm, and the undulator parameter is about 0.4 for a helical undulator configuration, obtained using two cross-polarized TE modes, or larger for a planar configuration, using one rf polarization. The undulator is four meters long. The FEL will reach saturation within this distance when operated in a SASE mode.

We describe the FEL performance parameters, the undulator characteristics and tolerances, and the RF system powering the undulator. The main goal of the experiment is to demonstrate that a microwave undulator has the field quality required by a high gain FEL.

## RF UNDULATOR-BASED FEL DESIGN

The initial choice for the undulator geometry is a waveguide with a circular cross-section and the parameters given in Table 1. For beam diagnostics in the undulator and easier tapering of the waveguide to compensate RF power losses, it might be convenient to have an open waveguide geometry, as will be discussed later in the paper. However the initial FEL calculations are based on a circular cross-section waveguide.

The undulator is powered by two transverse electric modes, shifted in the time phase by π/2. The resulting electron trajectory is a helix. The waveguide radius has been chosen to reduce the RF power attenuation due to losses in the walls, while having a short period. The RF wave group velocity is about half the speed of light. The required RF pulse length is the sum of the time needed to fill the waveguide and the electron transit time, and is about 40 ns.

Table 1 RFR undulator parameters.

| | |
|---|---|
| RF frequency, GHz | 11.4 |
| Radius, cm | 0.9 |
| Input power per mode, MW | 200 |
| Cut-off frequency, GHz | 9.8 |
| Magnetic field, T | 0.28 |
| Undulator parameter | 0.4 |
| Attenuation, 1/m | 0.0093 |
| Period, cm | 1.736 |
| Group velocity/c | 0.52 |
| Defocusing e-length, m | -1.189 |

The RF force on the electrons has two terms, one producing the wiggling motion, while the other is a nonlinear defocusing term. The equation of motion in one of the transverse directions is

$$\frac{d\beta_x}{dz} = -\frac{2\pi\beta_z K}{\gamma\lambda_U}\sin\frac{2\pi z}{\lambda_u} + (\Omega_{rf}^2 - \Omega_B^2)x \qquad (1)$$

where the undulator parameter $K=eB_0Rc/2\alpha'_{11}mc^2$, R is the waveguide radius, $\alpha'_{11}$ is the first root of the derivative of the first order Bessel function, $\lambda_U$ is the helix and undulator period, $\Omega_{rf}=\pi K/\sqrt{2}\, R\gamma$ is the defocusing force strength. An external focusing force, $\Omega_B$, has been added to produce the focusing needed to transport the beam and optimize the gain

Table 2 Electron beam characteristics

| | |
|---|---|
| Beam energy, MeV | 50 |
| Peak current, A | 200 |
| Normalized emittance, mm mrad | 2 |
| Relative energy spread, | $5\text{x}10^{-4}$ |

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The electron beam characteristics are given in **Table 2**. The resulting FEL characteristics are given in **Table 3**.

The effect of power losses in the waveguide walls is to change the undulator parameter value and the radiation wavelength. To avoid FEL gain reduction we can taper the undulator radius.

Table 3 FEL characteristics.

| | |
|---|---|
| Radiation wavelength, micrometer | 1 |
| FEL parameter | 6.8x10$^{-3}$ |
| Gain Length, m | 0.2 |
| Saturation length, m | 4 |
| Saturation power, MW | 37 |
| Beta function in undulator, m | 0.3 |

Waveguide tapering. The power changes as

$$P = P_0 \exp(-2\beta_{att} z) \qquad (2\ \ )$$

where $\beta_{att}$ is the attenuation coefficient for one of the two RF modes. For the waveguide radius tapering, a profile of the form

$$R = R_0 \exp(-\alpha\beta_{att} z) \qquad (3)$$

would be appropriate for a linear approximation. This is shown in **Figure 1** and **Figure 2**.

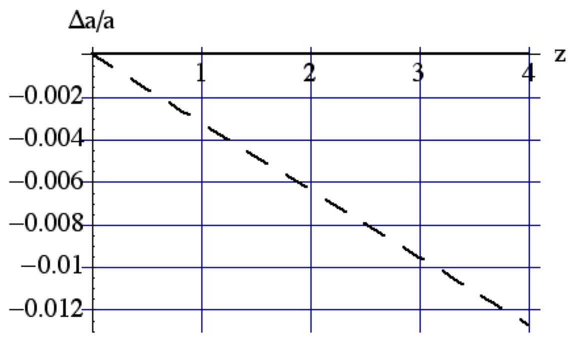


Figure 1 Effect of power losses: Relative radius change for constant radius, solid line, and tapered undulator, dotted line. In the last case α=0.175. Frequency 11.4 GHZ, Power per mode 200 MW.

To avoid gain reduction the relative wavelength change due to to power losses or other sources must be smaller than the gain bandwidth, which is of the order of the FEL parameter $\rho \cong 7\times10^{-3}$. As Figure 2 shows with our choice of tapering the relative wavelength change is much smaller than the gain bandwidth. Of course other effects, like RF voltage and phase fluctuations or mechanical tolerances in the waveguide geometry, can also produce a waveguide change. Some of these effects are discussed later. To demonstrate that all tolerances required to avoid a gain reduction can be met is the main goal of the experiment.

The average $\beta$-function needed for the desired beam density inside of the undulator is approximately 30 cm, which in the foreseen energy range is strikingly similar to that provided by the VISA undulator [3]. In the VISA device, the external quadrupole focusing is provided by a FODO permanent magnet system. The component magnets allow the required 33 T/m fields to generated while maintaining a relatively open geometry, and at low cost. As the gap between the magnet pieces is over 1 cm in the VISA undulator, integration with the waveguide assembly is possible with relatively small changes in the previously demonstrated geometry.

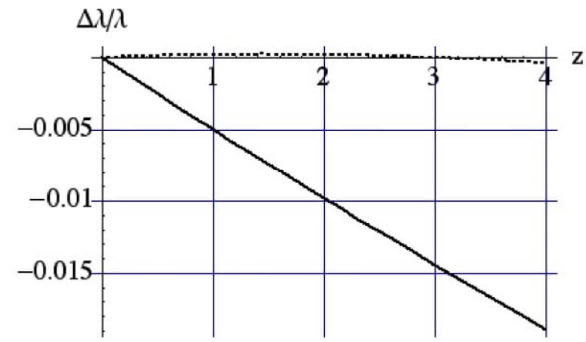


Figure 2 Effect of power losses: Relative wavelength change for constant radius, solid line, and tapered undulator, dotted line. In the last case α=0.175, and the relative change is multiplied by 10.

Electron beam diagnostics require an open waveguide geometry, allowing insertion at a number of points along the undulator. With the high power RF off, beam monitors based on OTR will yield the centroid and profile information needed for tuning. In the absence of the undulator field, the tuning procedure should be more straightforward. When the undulator RF is turned on, however, insertions are excluded, and so one may not consider measuring the FEL light characteristics within the undulator itself.

In the post-undulator region, a number of FEL diagnostics are foreseen. These include CCD cameras that give spatially-resolved intensity information in both the near- and far-field, and wavelength spectrometers. More sophisticated diagnostics to be employed include a newly developed double-differential (wavelength and angle) spectrum monitor [4] as well as GRENOUILLE measurement [5] of the time-resolved wavelength spectrum.

## THE RF SYSTEM

The layout of our system is pictured in Figure 1. The four klystrons incorporated in the system, powered from a common solid state modulator and driven through TWT's, offer a nominal 200 MW input at a pulse width of 1.6 µs. The outputs of these klystrons are combined in pairs through planar hybrids [6]. The fourth port of each of these brings misphased/mismatched power into a high power load [7] WR90 waveguide carries the combined rf from each of these klystron pairs to a port of the dual-mode combiner. This combiner is a three-port device, whose third port launches power from the single-moded inputs into overmoded circular waveguide in either the $TE_{11}$ or $TE_{01}$ mode, depending on the relative phase of the inputs.

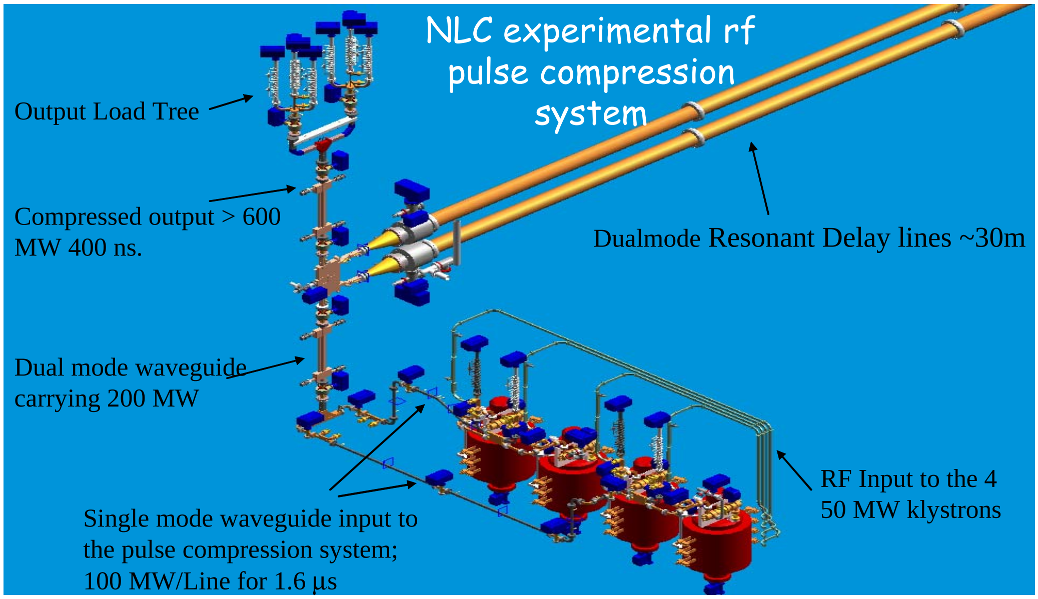


Figure 3: The RF system used to generate the undulator pulsed power

The total combined power is fed into the SLED Head, a "cross potent"-type [8] device. With the klystron pairs phased to launch $TE_{01}$ into the system, power is directed through the dual-moded SLED-II pulse compressor. By the opposite phasing, power is directed around an alternate path to the same dual-mode output port. Thus, the system can be run in compressed ($TE_{01}$) or uncompressed ($TE_{11}$) mode. Before and after the SLED Head are dual-mode directional couplers in circular waveguide for monitoring the power in each operating mode.

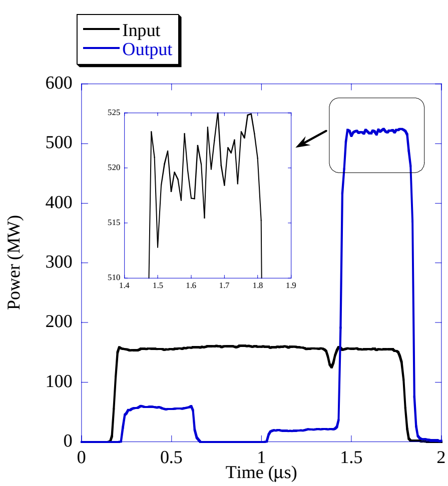


Figure. 4 A typical output wave form from the rf system.

A typical output from this system is shown in Figure such this system is shown in Fig. 4. The flat top is obtained through an ad hoc feed forward system. The variations shown at the flat top was deemed adequate for collider applications however it is not sufficient for our purpose. It is our believe that a slightly more sophisticated feed forward system can reduce the amplitude variations to the desired levels. For further detailed discussion of the this system the reader is referred to [2]

## RF UNDULATOR WAVEGUIDE SYSTEM

Several waveguide systems are possible for this undulator. The main issues associated with this type of system are: Power handling capability, machining tolerances, tapering for power loss compensation, and mode launchers for producing the correct modes.

### *Power Handling Capabilities of the Undulator Waveguide*

Power handling capabilities of waveguides have been studied experimentally for applications associated with future linear colliders [9]. Breakdown phenomenon in vacuum copper waveguide is complicated and there is no clear theoretical understanding of it to date. The limits of peak power or peak fields depends on the waveguide geometry and pulse length. From the studies done [9-10-2] on rectangular waveguides at x-band, the limit of 50 MV/m at 400 ns pulse width with more than 500 MW of pulsed power is relatively conservative number as evident by the robust operation of our RF system[2]. A surface field of 28 MV/m at 1.6 µs pulse width with a power level close to 100 MW is inadequate as evident by the difficulty of running WR90 waveguide at these parameters [2]. At a diameter of 0.9 cm and 200 MW of power the peak surface field at the wall of a circular waveguide carrying the $TE_{11}$ mode is 30.9 MV/m. At a pulse length < 100 ns this waveguide undulator should be able to run reliably. At this level the wiggler parameter is ~ 0.4. One could imagine increasing this factor to ~1 by pushing the waveguide power up to 1.26 GW. The peak surface field in that case is 77.5 MV/m. At short pulse lengths < 100 ns this may be adequate, however, this remains to be tested. Also, the use of other materials, such as stainless steel, could be increase the power handling capabilities of the waveguide [9]. To increase the power level to the undulator one can compress the power by a greater factor using shorter delay lines and producing shorter pulses. Also, one could have the waveguide undulator as a part of a resonant ring.

### *Waveguide Construction and Tapering*

To reduce the spectrum spread of the microwave undulator-based FEL, the field level of the undulator and hence the K factor need to be kept constant over the length of the undulator. Because the power $P \sim a^2 B^2$ for a constant field $B$ the waveguide radius $a$ needs to vary as $P^{1/2}$. Based on a 0.9 cm diameter copper circular waveguide carrying the $TE_{11}$ mode, over 4 meter of length the diameter have to drop by about 1.2% as shown in **Figure 1**.

Of course the waveguide radius need not exactly follow the exponential drop in power; as shown above, a linear taper would be sufficient. Nonetheless, machining such taper to the length of 4 mater is not simple. One could use x-band accelerator structure building techniques to construct this waveguide[11]. Alternatively, one could use open waveguides. The electric field lines of an elliptical waveguide carrying the $sTE_{12}$ mode is shown in Fig. 5.

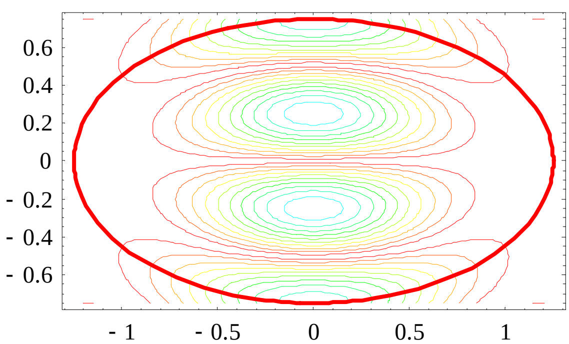


Figure 5. Electric field lines for the $sTE_{12}$ mode.

This waveguide could by cut from either side without perturbing the field patterns. Having the waveguide as two mechanically detached elliptical shells, allows us to taper it by tuning it over a movable stage. Using overmoded waveguide has also a very important advantage; the ratio of the peak surface field to the field in the center is better. For our example of using $TE_{11}$ mode in a circular guide the center field is 1.58 times bigger than the surface field. For the $TE_{12}$ mode this ratio is 7.7. In the case of the elliptical waveguide shown this ratio is ~5.

For the cross polarization in elliptical waveguides the $cTM_{12}$ have similar properties to that of the s $TE_{12}$ mode, that is, the waveguide could be cut in either side without perturbing the mode.

Finally, one can have a precisely machined straight waveguide. The tapering of the rf field could be achieved temporally. The power at the beginning of the pulse could be increased and then dropped lineally, and since the e-beam counter propagates against the RF signal it will only see near constant RF fields.

### *Mode Launchers*

If one is to launch the fundamental $TE_{11}$ mode in the circular guide this could be done by direct abrupt junctions similar to accelerator structure couplers [12]. The power handling capabilities of these have been tested and one could imagine that stretching them to 200 MW at short pulse length should be reasonable.

However, if one need to launch a higher order mode such the TE12 mode in circular guide or the equivalent mode in elliptical guides, it is not possible to use this kind of abrupt junctions. One possibility is the periodic of continuous coupling from a fundamental waveguide running in parallel to the undulator waveguide. For a discussion of this type of mode couplers the reader is referred to [2] and the references cited therein.

It is also possible to use an abrupt junction to a fundamental mode waveguide and then taper and mode convert to the desired mode in a larger diameter . waveguide

## CONCLUSIONS

The X-band power source existing at SLAC can be used to power a 4 m long microwave undulator to operate a high gain SASE FEL at 1 μm. The experiment would test the control of the microwave field, including wall losses, the waveguide mechanical tolerances, and other issues important for high gain FELs.

## REFERENCES


[1] C. Pellegrini, "RF Undulators for FELs and Undulator Radiation Sources", Proceedings of this conference.

[2] S. Tantawi et. al, Phys. Rev. ST Accel. Beams 8, 042002 (2005) [19 pages].

[3] R. Carr, et al., Phys. Rev. ST Accel Beams **4**, 122402 (2001).

[4]G. Andonian, et. al. Phys. Rev Lett. 95, 054801 (2005).

[5]Patrick O'Shea, et. al., Optics Letters, 26, 932 (2001).

[6]S. G. Tantawi et. al., in Proceedings of the 1999 Particle Accelerator Conference (PAC'99), New York.

[7] Sami G. Tantawi et. al., in *Proceedings of the 1995 Particle Accelerator Conference (PAC'95), Dallas, TX* (IEEE, Piscataway, NJ, 1996).

[8] Christopher D. Nantista et. al, IEEE Microwave Guided Wave Lett. 10, 520 (2000).

[9] V. Dolgashev, et. al., Proc. 8th European Particle Accelerator Conference (EPAC 2002), Paris, France, (2002), 2139.

[10] Sami G. Tantawi et al., IEEE Trans. Microwave Theory Tech. 47, 2539 (1999)

[11]J. W Wang et. al. in Proceedings of the 1999 Particle Accelerator Conference (PAC'99), New York, 3423

[12] C. Nantista et. al., physical review special topics - accelerators and beams, volume 7, 072001 (2004)