OBSERVATION OF COHERENT MICROWAVE TRANSITION RADIATION IN THE APS LINAC*

G. Decker, X. Sun
Argonne National Laboratory
Argonne, IL 60439, USA

Abstract

The APS injector includes a conventional S-band linear accelerator with three separate electron sources. Two electron guns are used as primary and secondary sources for injection into the APS 7-GeV storage ring, while a separate laser photocathode gun is available for free-electron laser (FEL) research. We report here the results of the dependence of 30-GHz coherent microwave transition radiation on electron bunch length. Sensitivity to pulses as short as 200 to 300 femtoseconds has been demonstrated.

BACKGROUND

As part of upgrade efforts to generate very short (< 1 ps) bunches in the APS linac to support FEL research, a bunch compressor was installed in CY2000-2001. The APS linac is used 75% of the time for routine top-up injection to the storage ring every two minutes, with the balance of 25% of the time reserved for injector studies, operator training, and FEL studies. A bunch compressor is installed in linac sector three, where the electron beam energy is approximately 150 MeV.

A diagnostic station including an infrared Michelson interferometer [1,2] is located immediately downstream of the bunch compressor. It consists of a vacuum cube with two ports in-line with the electron beam and one port devoted to an actuator with an insertable mirror inclined at a 45 degree angle. A separate port has a commercial-grade fused silica window providing the optical path to the interferometer. This interferometer is sensitive to coherent transition radiation generated by the electron beam striking the mirror.

For the duration of the summer 2002 APS operating period, a Ka-band microwave detector, shown in Figure 1, was installed in the optical path of this diagnostic station, "looking" directly into the aforementioned window. For this measurement, the waveguide H-plane was oriented vertically, and the mirror orientation was such as to deflect the radiation in the horizontal plane. Figure 2 represents a plan view of the measurement geometry.

SIMULATION RESULTS

Simulation results [3] showed the potential for the generation of electron bunches as short as 10 to 20 fs rms, provided that reasonable improvements in linac rf system stability were made. In actual fact, recent experiments indicate that the minimum attainable bunch length using the present linac hardware is somewhere in the range of 200 to 250 fs rms using the laser photocathode gun (PC gun) [4], and 250 to 300 fs using thermionic rf gun 2.

The PC gun emits a single pulse of electrons at up to a 6-Hz duty cycle, with the temporal profile defined by the laser pulse. In contrast, rf gun 2 emits an 8-nanosecond-long train of pulses separated by 350 ps, with the pulse train duty cycle being as high as 30 Hz.

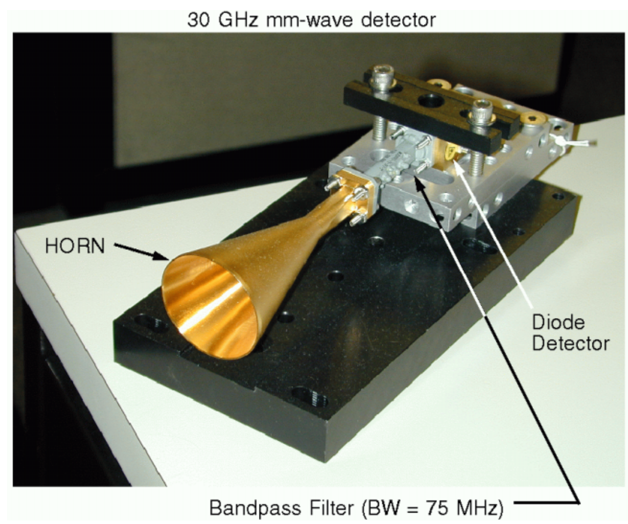

Figure 1: Microwave horn / detector assembly used to detect coherent transition radiation.

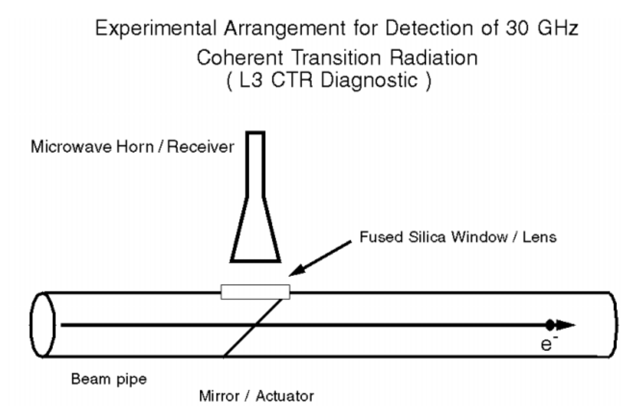

Figure 2: Microwave horn / detector arrangement used to detect coherent transition radiation. Plan view.

Shown in Figure 3 is the geometry used in a MAFIA simulation to determine the output of the microwave horn resulting from the collision of a Gaussian line charge with the mirror. Here, the beam is traveling in the positive Z

*Work supported by U.S. Department of Energy, Office of Basic Energy Sciences, under Contract No. W-31-109-ENG-38.

direction, with the Y axis corresponding to the vertical coordinate–the H-plane of the WR-28 waveguide. The circular beam openings upstream and downstream of the mirror, and the waveguide horn output were constrained by waveguide boundary conditions in the MAFIA simulation.

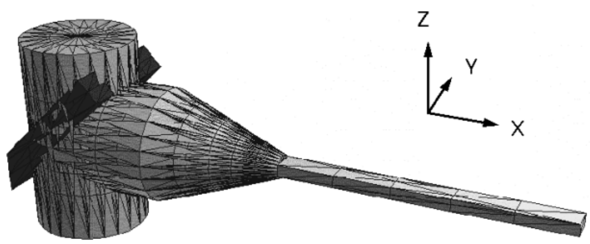

Figure 3: Microwave horn geometry used in MAFIA simulation.

Results of the simulation at the waveguide output are shown in Figure 4.

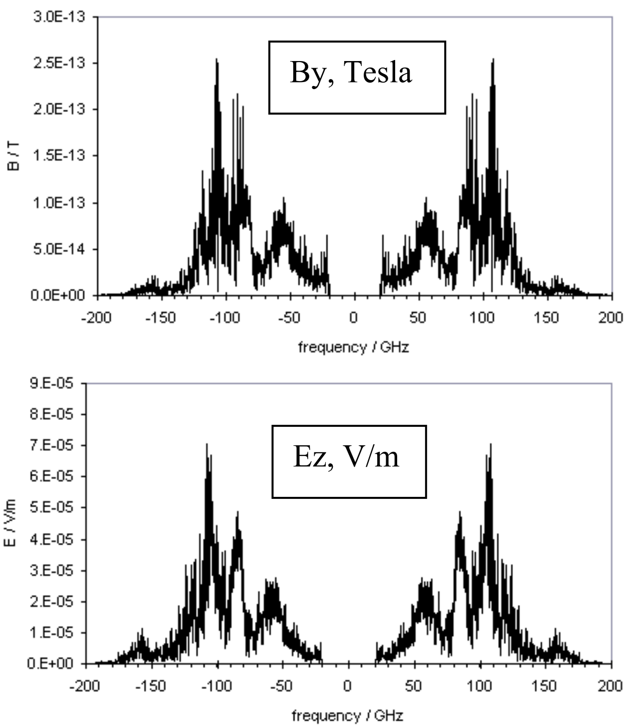

Figure 4: Magnetic and electric field vs. frequency for 0.7-ps rms, 0.75-nC line charge striking a mirror inclined at 45 degrees.

While all six components of the electromagnetic field were calculated, only those corresponding to the lowest propagating waveguide mode (WR-28) are displayed. This mode has a cutoff frequency of 21.1 GHz, consistent with the MAFIA result.

The MAFIA simulation was performed after actual experimental results using the detector of Figure 1 were in hand, so it was somewhat of a surprise to see relatively little predicted signal strength near 30 GHz, where the detector was designed to be most sensitive. The remaining electromagnetic field components had strengths comparable to those shown in Figure 3; however, E_x shows a cutoff near 45 GHz, and E_y shows cutoff-type behavior near 70 GHz. Since the bunch spectrum extends out to a few hundred GHz, it should be no surprise that these higher-order waveguide modes are excited.

In fact, you can do a simple calculation using the method of images to convince yourself that you ought to have seen no signal in the 26.5-40 GHz waveguide passband, by symmetry. Shown in Figure 5 is a contour plot showing the scalar potential shortly after a 150-MeV point charge has passed through a mirror inclined at 45 degrees relative to the direction of motion.

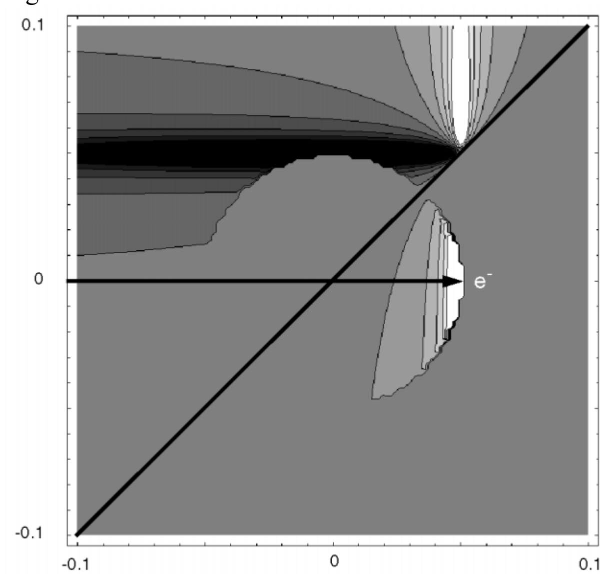

Figure 5: Scalar potential of an electron passing through an infinite mirror, indicated by the diagonal line. The arrow indicates the trajectory of the electron.

It is interesting to see the Coulomb field of the particle and its image annihilate each other at the instant that they strike the mirror. On the other side, you can see the Coulomb field reassembling itself. The sphere centered on the point of impact is the light cone. Points inside of it above the mirror think there aren't any charges anywhere, and similarly points outside the sphere below the mirror also think there are no charges anywhere, i.e., the scalar potential is zero. Given that one part of the electric field can be written as the gradient of the scalar potential, the step change in potential at the light cone will contribute a large, radially polarized electric field, consistent with known properties of transition radiation [1].

It appears that, by symmetry, we expect that the lowest TE_{10} waveguide mode would not be excited at all. Being good experimentalists, and prior to realizing this, we installed a 30-GHz microwave horn anyway, as described above, basically to "see what happens."

EXPERIMENTAL RESULTS

Lo and behold, using the device shown in Figure 1 with its passive, nonlinear detector (i.e., a diode) driving a

50-ohm line (Andrews FSJ1-50), the oscilloscope traces of Figure 6 were collected.

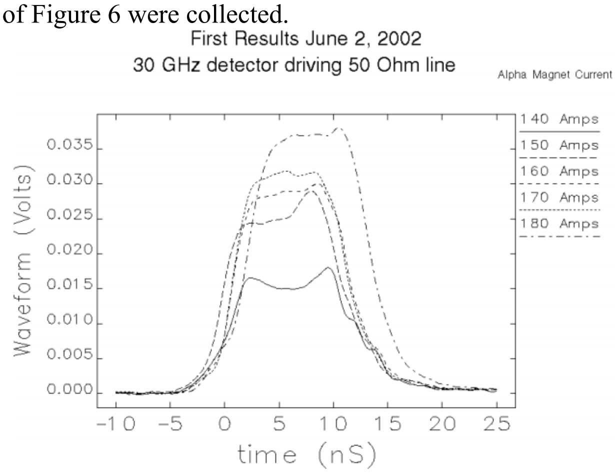

Figure 6: Microwave horn / detector signal from 8-ns, S-band-modulated, 150-MeV beam striking a mirror.

The different traces correspond to changes in the rf gun 2 alpha-magnet setting, which had the effect of changing the bunch length. An attempt was made to keep the macropulse charge constant at approximately 0.5 nC. In fact, at the extreme of short bunch length, the transmitted charge actually decreased, but this resulted in the largest signal from the detector.

Shown in Figure 7 are data collected with the addition of an in-tunnel transimpedance amplifier, since the microwave detector was never designed to drive a 50-ohm line. The tradeoff is signal strength vs. speed, as can be seen from the long signal decay time.

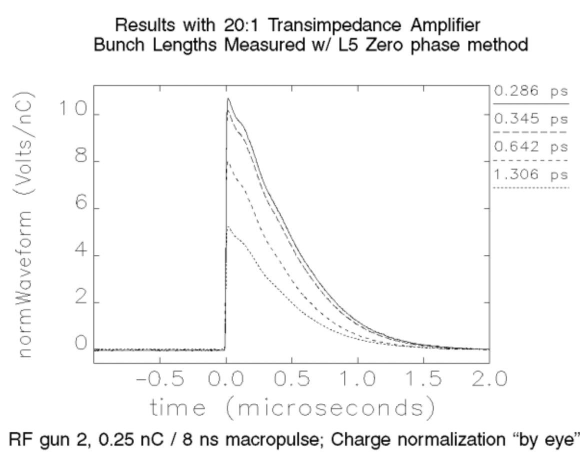

Figure 7: Normalized detector signal vs. bunch length.

The data are roughly normalized by noting the beam current reading from a nearby current monitor. In this case, a careful rms bunch length measurement at each alpha-magnet setting was performed [4], as indicated in the legend.

One last data set (Figure 8) was collected prior to removal of the device, but this time a careful charge normalization was performed by collecting a nearby BPM's intensity signal using the same oscillosope. In this case, the linac wasn't behaving itself very well, and we were unable to get the rms bunch length much below 500 femtoseconds. The data set does fill in the gaps for longer bunch length, and shows some peculiar differences in decay time that are not well understood.

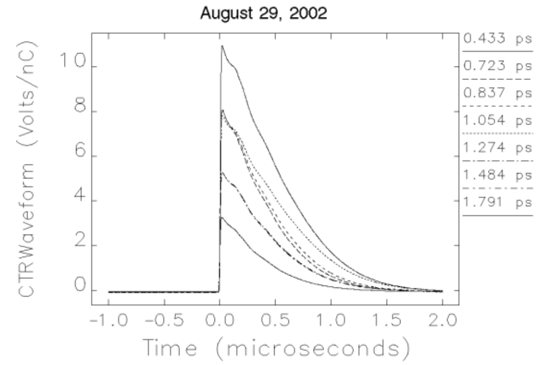

Figure 8: Accurately normalized signal vs. bunch length.

CONCLUSIONS

One final observation was that the 30-GHz center frequency, 75-MHz bandwidth bandpass filter shown in Figure 1 is not a very good filter for frequencies above about 45 GHz. Using the APS Diagnostics Group's 50-GHz network analyzer, it is clear that things are going awry as we push to higher frequencies. It is reasonable to suppose that the really high frequency junk seen in Figure 4 is bleeding through to the detector. This is a likely explanation as to why this device is such a good bunch length detector, even down below 300 femtoseconds (that's 3 degrees of phase at 30 GHz).

A second possibility is simply that alignment is critical, and the nulling effect described earlier only applies to the condition where the waveguide is accurately aligned on the image charge trajectory as it approaches the mirror. In any case, it was very gratifying that it was so easy to build a bunch-length monitor that is sensitive to short bunches appropriate for free-electron lasers in spite of not understanding what we were doing at the time.

ACKNOWLEDGEMENTS

Michael Borland's assistance in performing the careful independent bunch-length measurements was absolutely crucial to this work.

REFERENCES

[1] U. Happek, E.B. Blum, A.J. Sievers, Phys. Rev. Lett. **67** (1991) 2962.

[2] A.H. Lumpkin et al., Nucl. Instrum. Meth. **A** 475 (2001), 476.

[3] M. Borland, "Potential Production of Ultrashort Electron Bunches with the Advanced Photon Source Linac," PAC'01, Chicago, IL, p. 2209 (2001).

[4] M. Borland, J. Lewellen, "Initial Characterization of Coherent Synchrotron Radiation Effects in the APS Bunch Compressor," PAC'01, Chicago, IL, p. 2839 (2001).