MM-Wave Source Development at Los Alamos National Laboratory

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Summary

- Motivation for planar geometries.
- Goal – 95 GHz sheet beam traveling wave tube (TWT).
- “Conventional” planar RF structures we have designed and tested.
- Dielectric photonic band gap (PBG) structures that may replace our conventional copper circuits.
- Sheet beam generation and transport.
- Beam cooling as a path to very high frequency devices (~300 GHz).

Motivation

Possible Applications for a High-Power, 95 GHz (or higher) RF Source

- Communications.
- High resolution radar.
- Remote sensing.
- Accelerators.
- Lot's of other stuff

Why Planar Geometries is a Natural Approach to High-Power, High-Frequency Microwave Tubes

RMS Envelope Equations

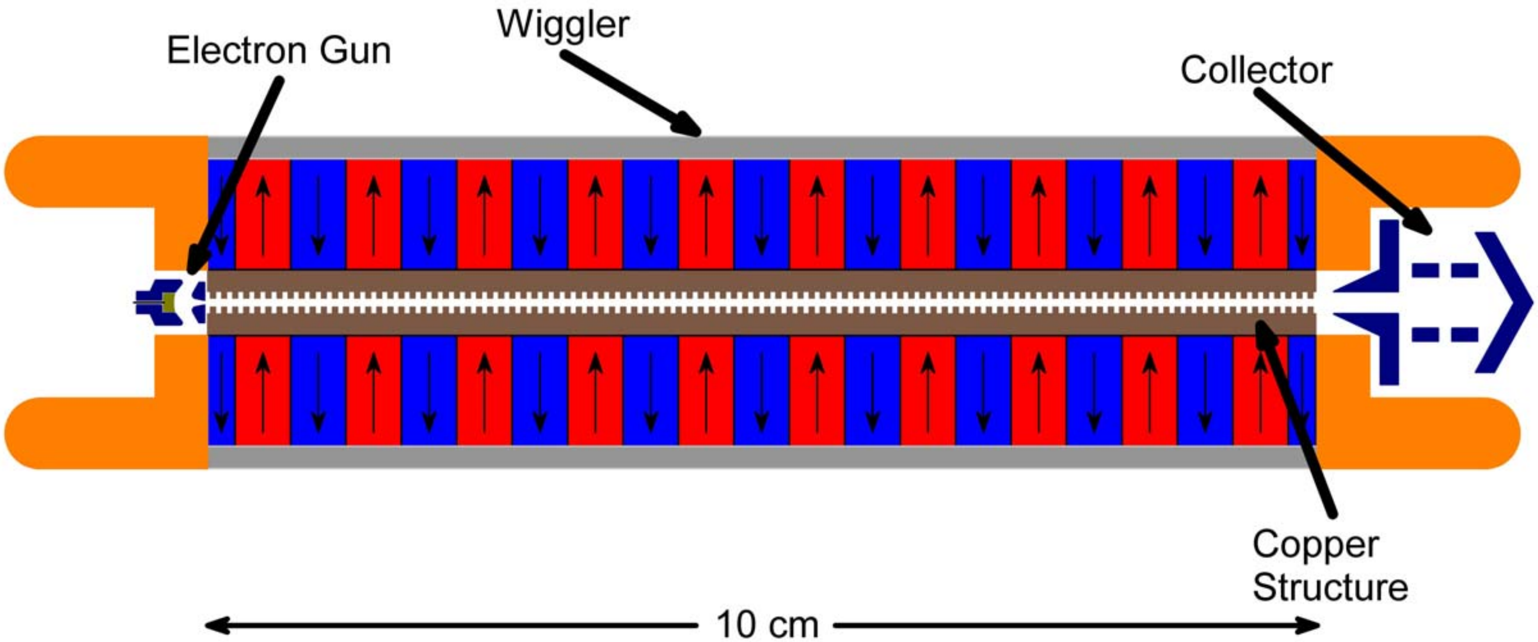
$$\frac{d^2}{dz^2}x_{RMS} + k_x x_{RMS} - \frac{\varepsilon_x^2}{x_{RMS}^3} - \frac{K}{2\left(x_{RMS} + y_{RMS}\right)} = 0$$

$$\frac{d^2}{dz^2}y_{RMS} + k_y y_{RMS} - \frac{\varepsilon_y^2}{y_{RMS}^3} - \frac{K}{2\left(x_{RMS} + y_{RMS}\right)} = 0$$

- Planar RF structures lend themselves well to established micro-fabrication techniques.
- By spreading the electron beam in one dimension, we can transport a high net beam current, enabling very high power devices.

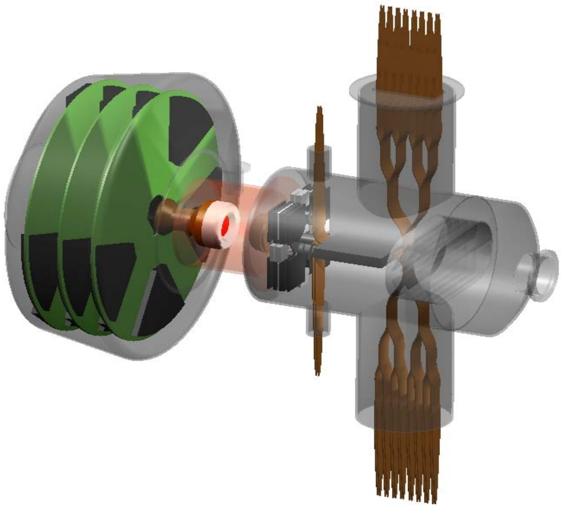
Our Goal

Cross Section Schematic of Planar 95 GHz TWT

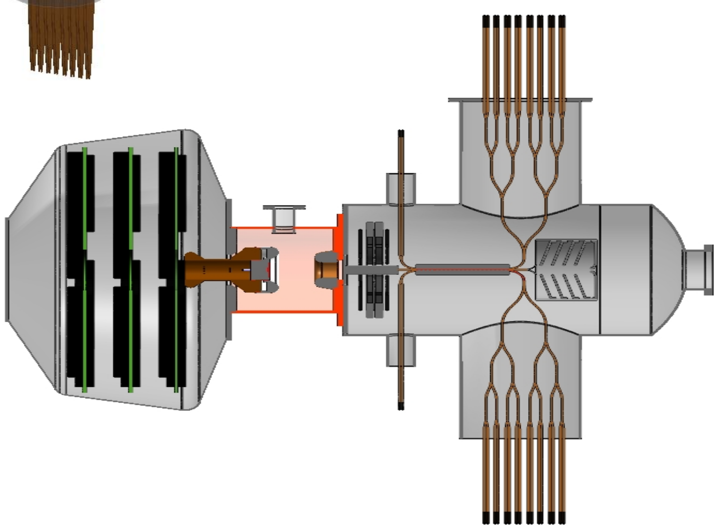


LANL 95 GHz Planar TWT Concept

3D View



Side View

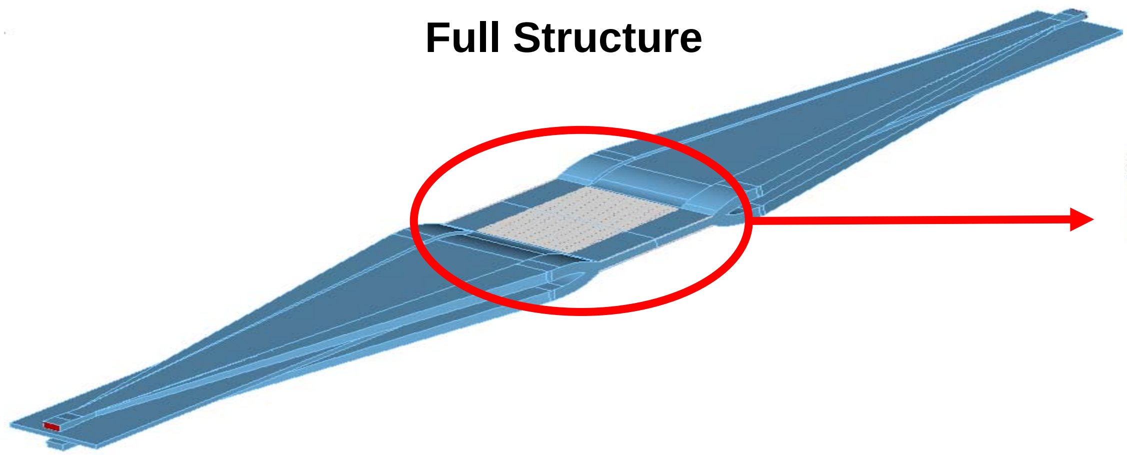


- High gain (40-60 dB)
- High efficiency (50% with depressed collector)
- High bandwidth (10s of GHz)
- High peak power (500 kW)
- High average power (1-10 kW)
- Small size (about 1 gallon with power modulator)

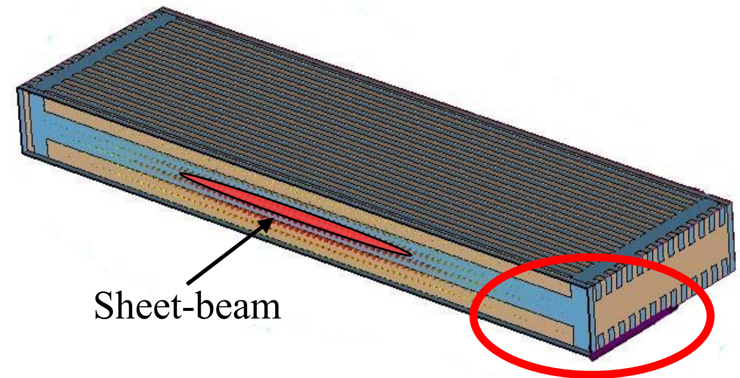
Planar RF Structures

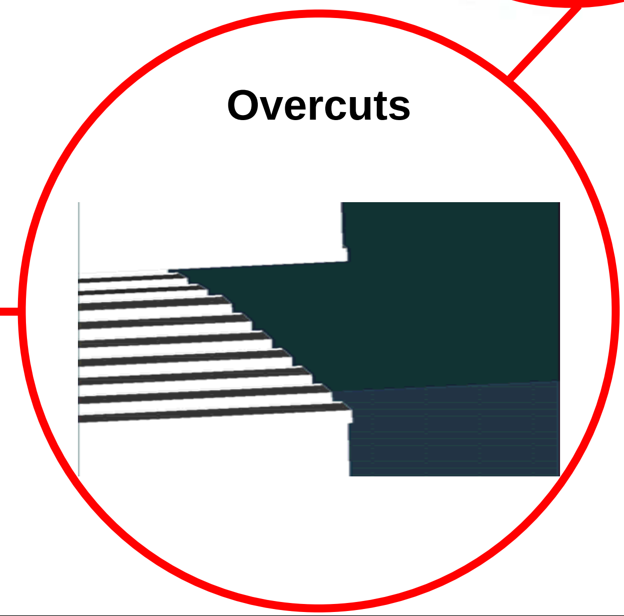
Wide Planar RF Structure Concept

Full Structure

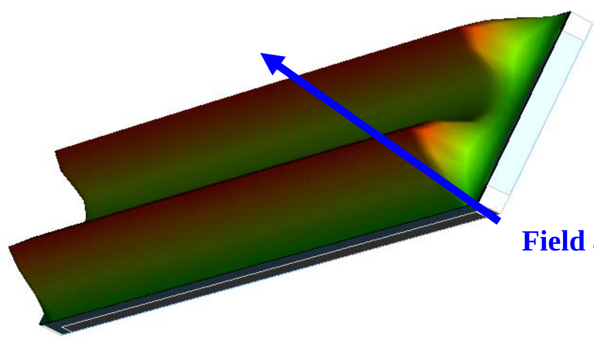


Wide RF Structure





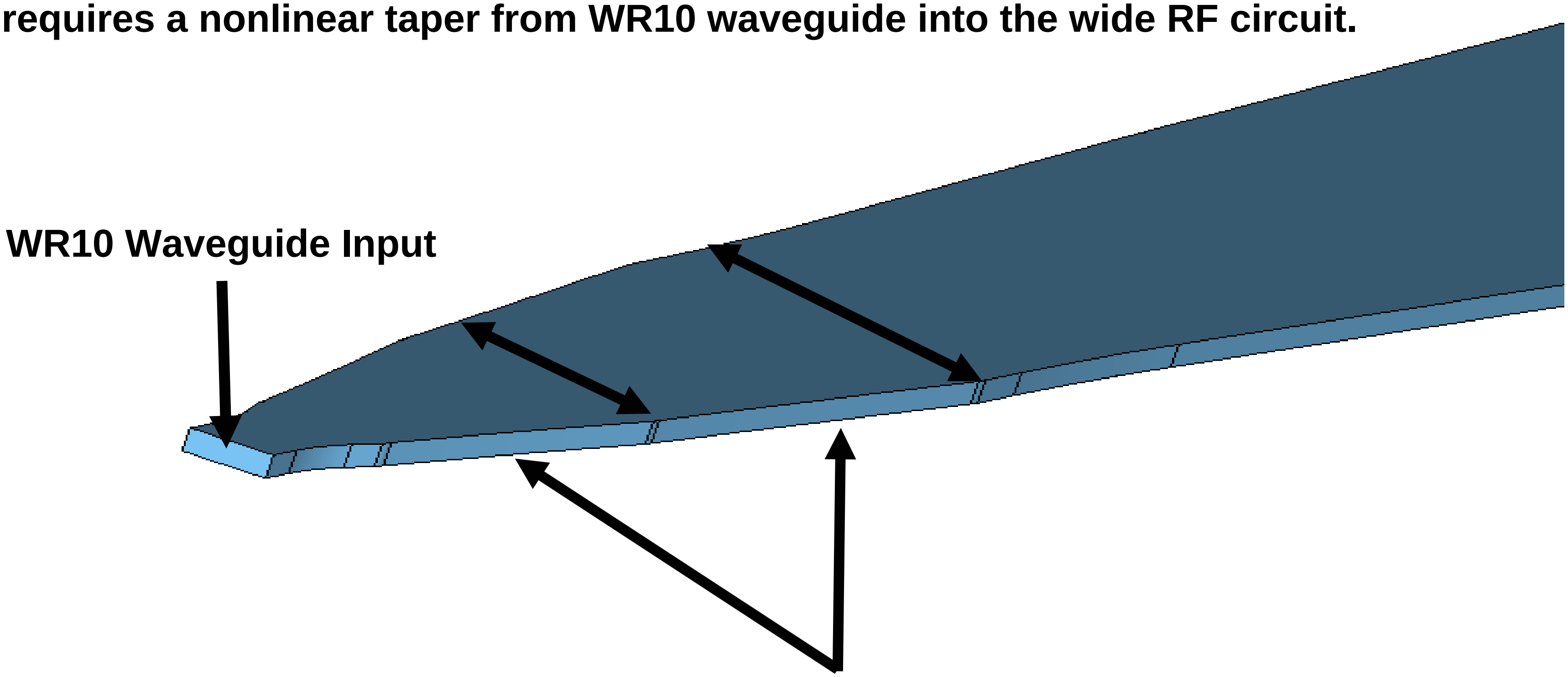
Overcuts flatten field



Field amplitude

Planar Structure RF Converter

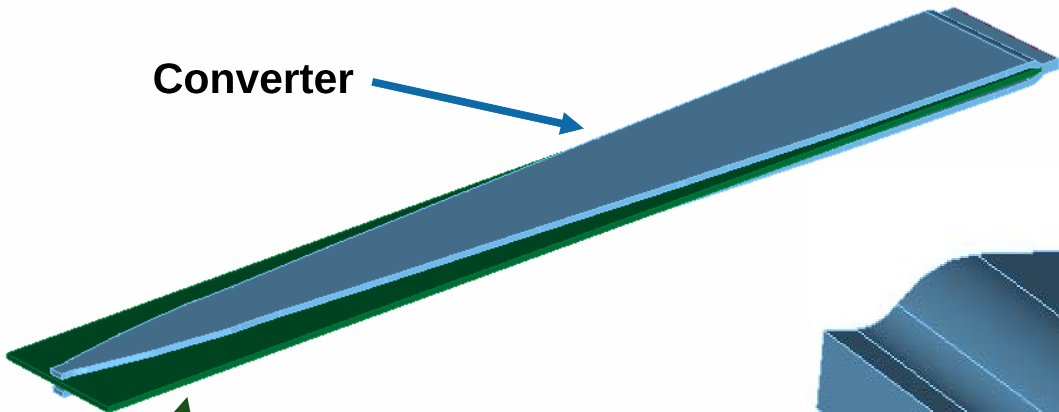
Inputting RF into the planar structure is a complicated design problem. It requires a nonlinear taper from WR10 waveguide into the wide RF circuit.

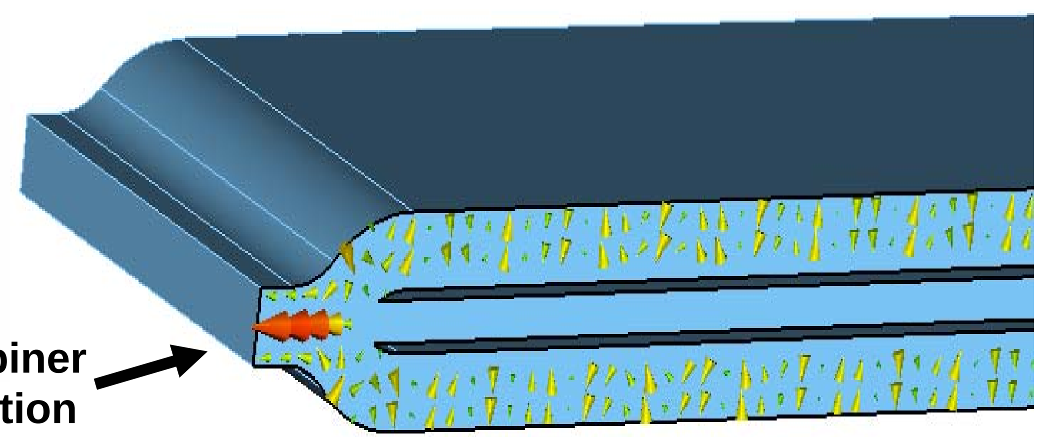


Curved segments connect straight pieces whose width is given by their mode-carrying capabilities

Two Converters are Combined by 45° Waveguide Sweeps

Using two converters allows us to launch the proper mode in the highly over-moded wide RF structure.

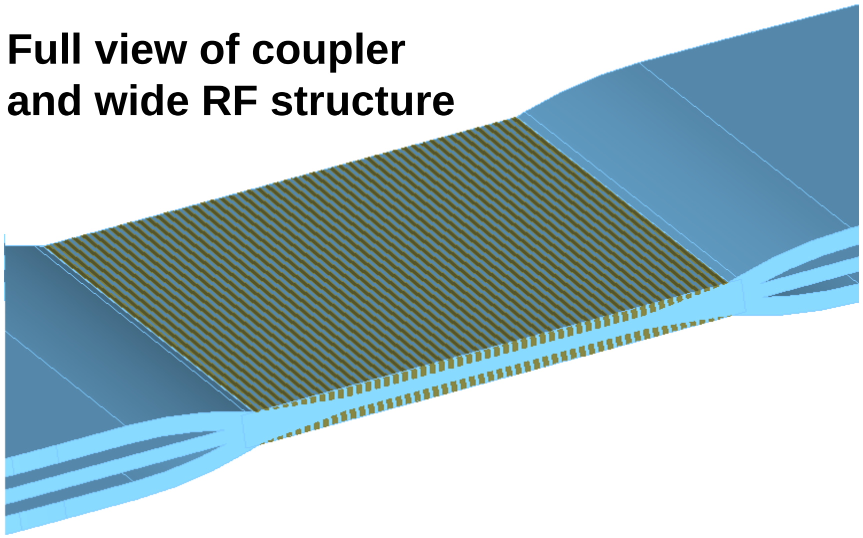




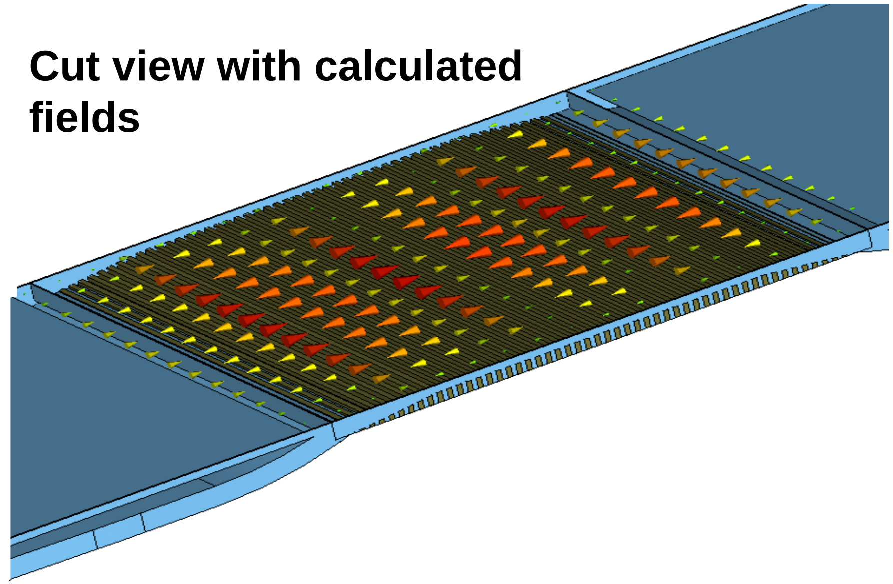
The two converters are combined by 45 degree waveguide sweeps in which the TE mode is converted to a TM mode.

Full Model of Coupler Matched into Wide RF Structure with Tapered Vanes

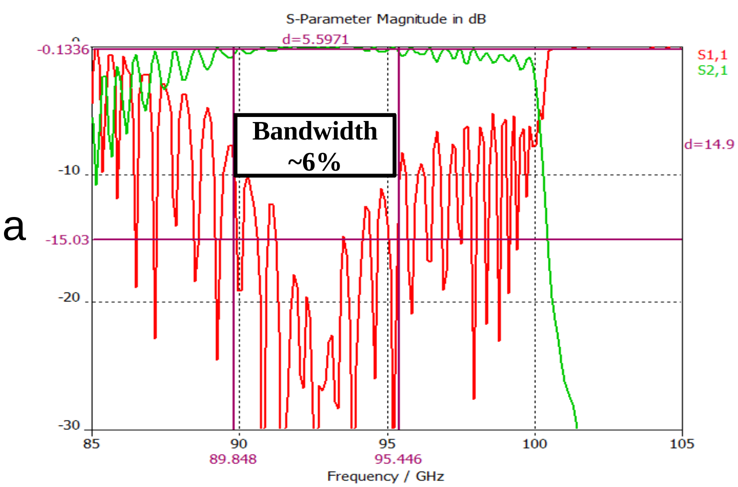
Full view of coupler and wide RF structure



Cut view with calculated fields

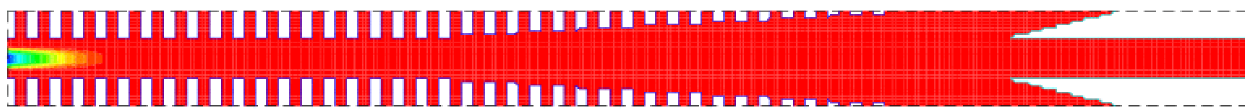


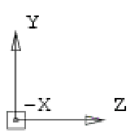
Calculation of the S parameter shows a bandwidth of approximately 6% at 94 GHz.



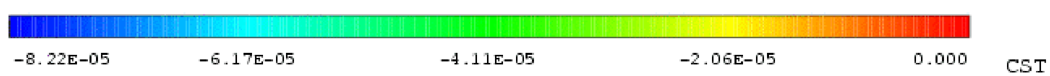
We Simulate the Beam Interacting with the RF Structure using MAFIA

Beam interaction with structure showing beam bunching. View is cross section of simulation at x = 0.



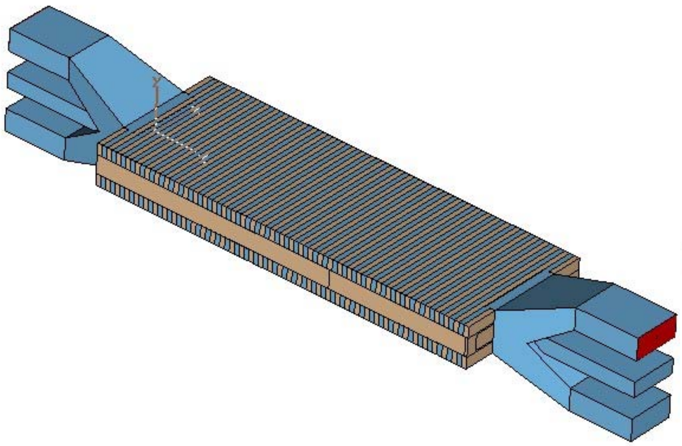


Beam density scale (arbitrary units).

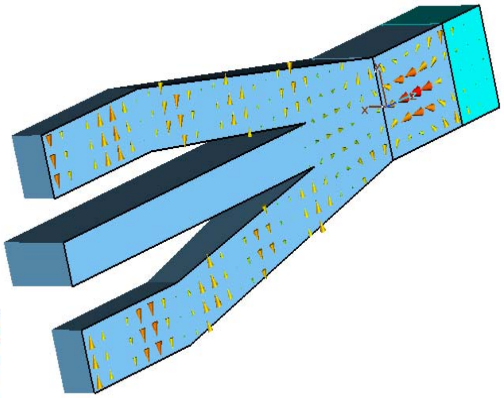


We Built a Narrow Planar Structure for a Proof-of-Principle Experiment

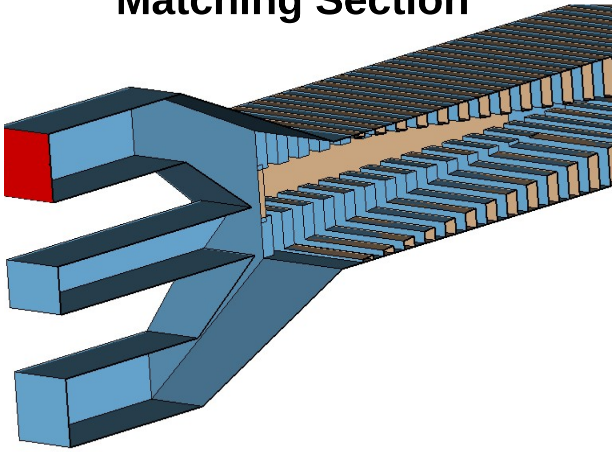
Full Narrow Structure



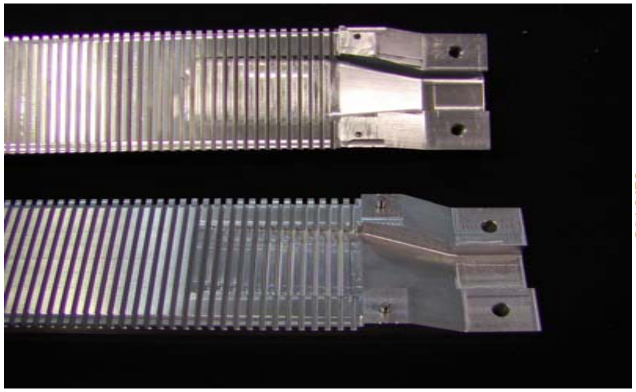
Combiners

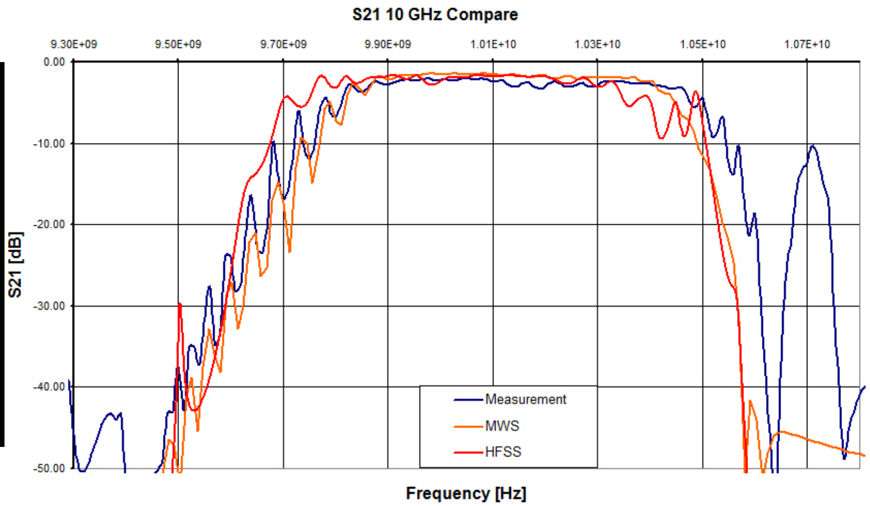


Combiners with Tapered Matching Section

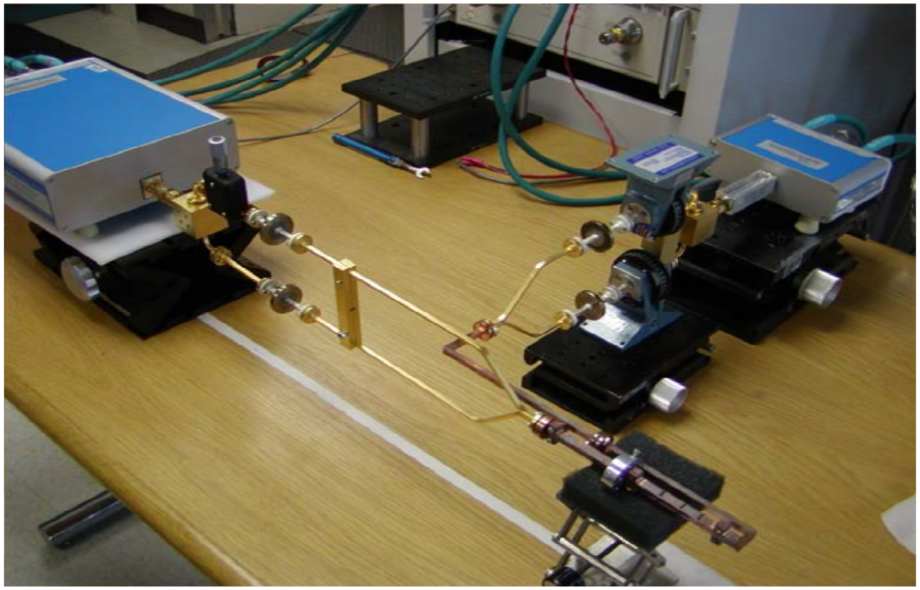


10 GHz aluminum cold model matched simulations very well.

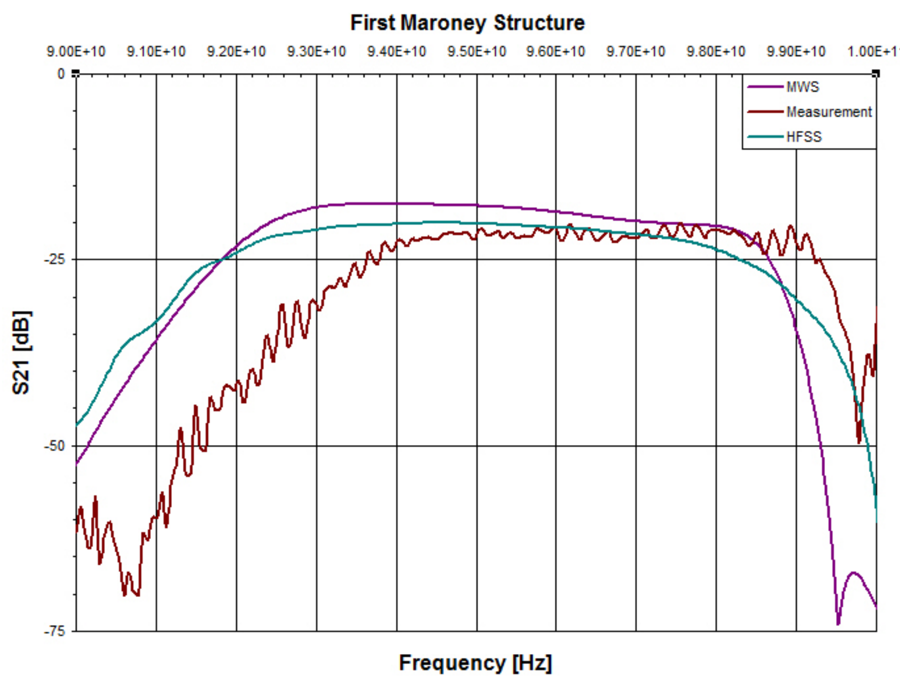




Network Analyzer Measurements of a 94 GHz Copper Structure Agreed well with Simulations

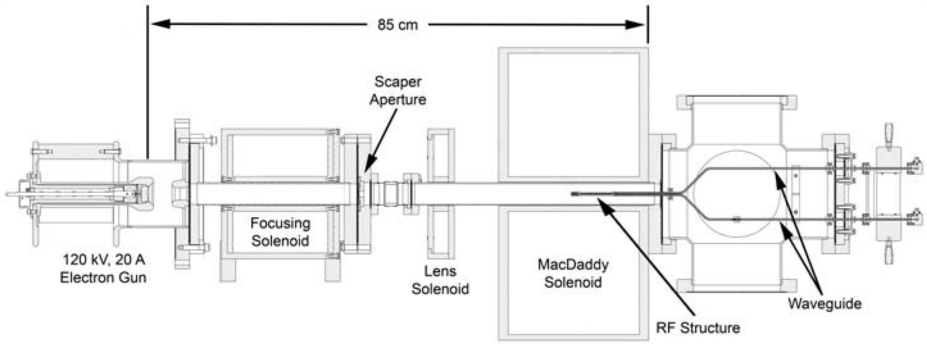


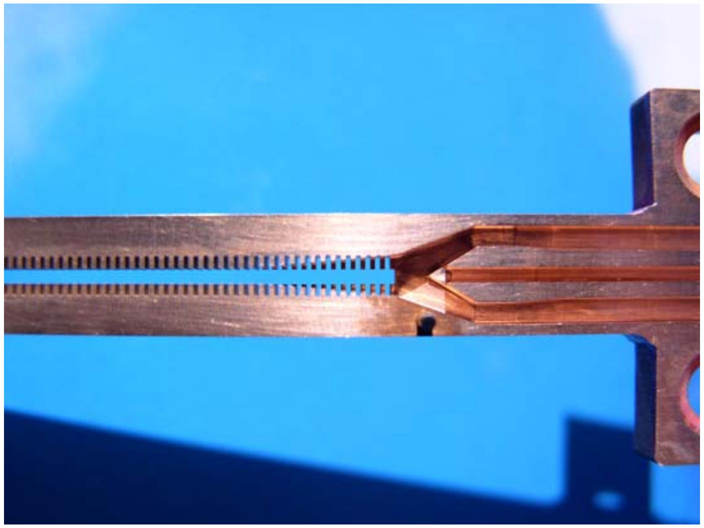
Agreement between measurement and simulations using HFSS and Microwave Studio were very good.

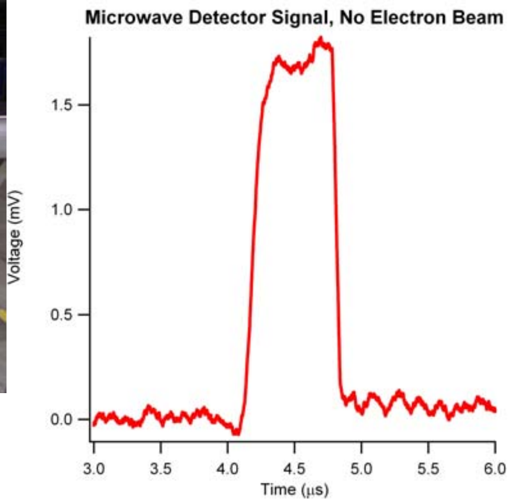


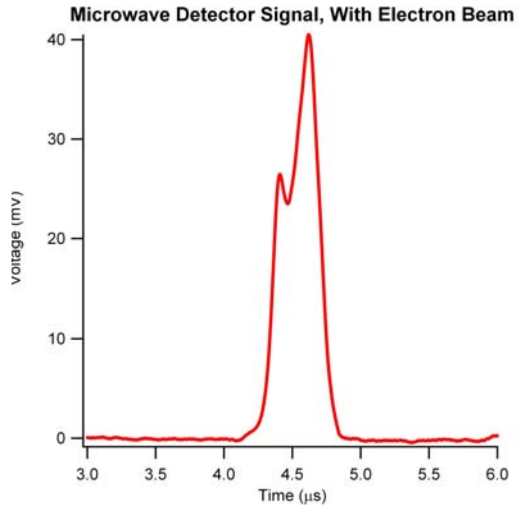
94 GHz copper narrow planar structure built by Maroney Company using wire EDM being tested with network analyzer.

We Tested the 94 GHz Copper Structure with a 120 kV, 2A Pencil Beam and Showed RF Gain





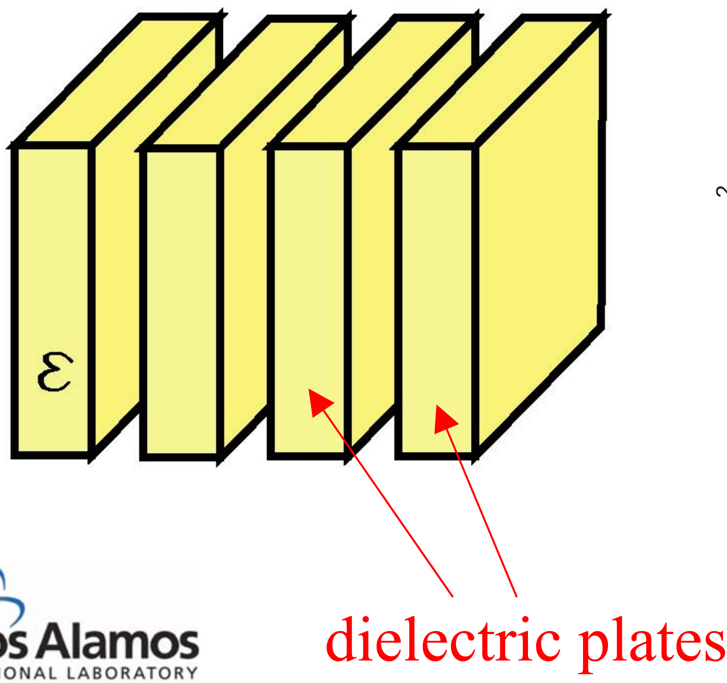


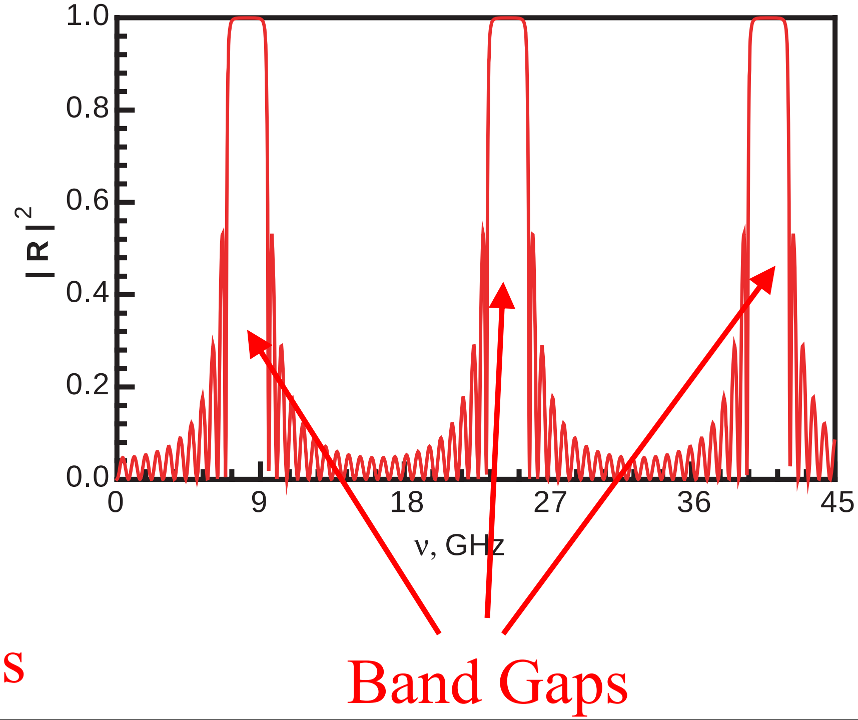


PBG Slow Wave Structures (Omniguide)

Bragg Filters

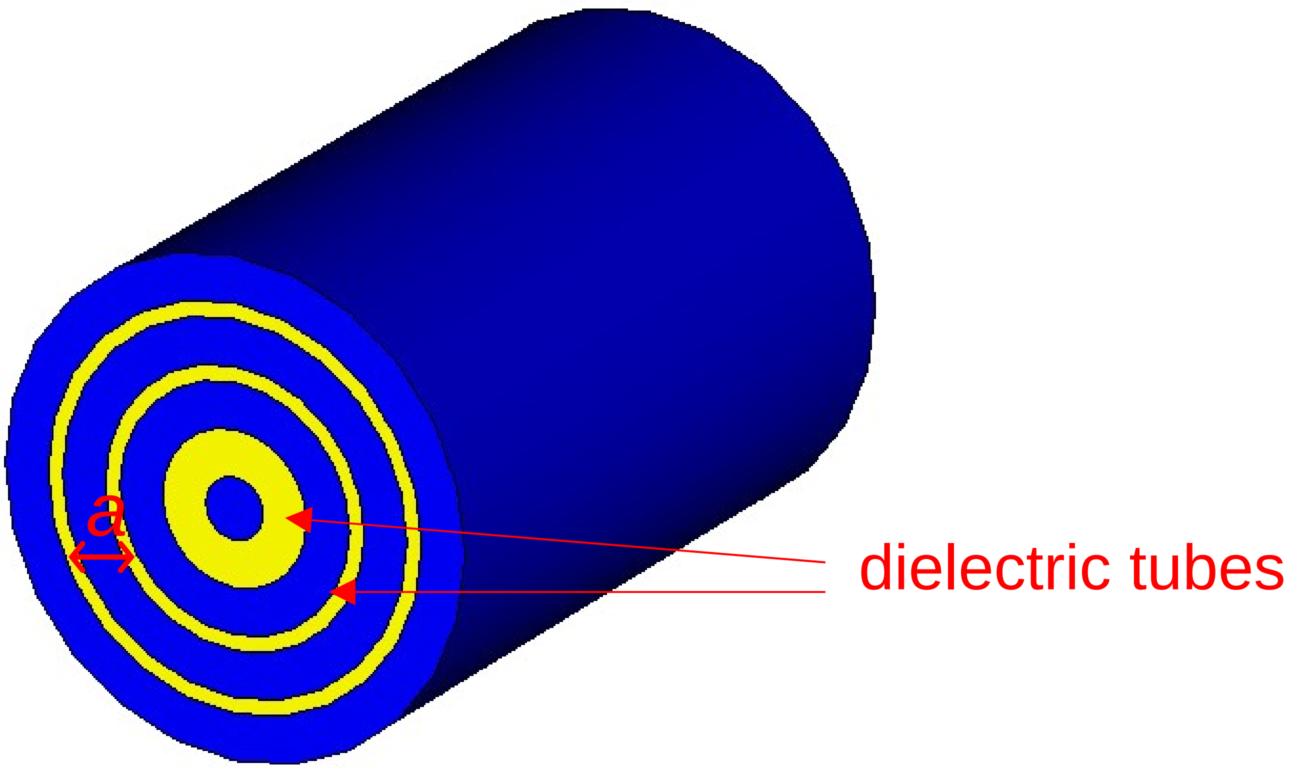
Bragg filter is a particular one dimensional version of the photonic band gap (PBG) structure. Bragg filters allow waves of certain frequencies to pass through while reflecting the waves of other frequencies.





Omniguides*

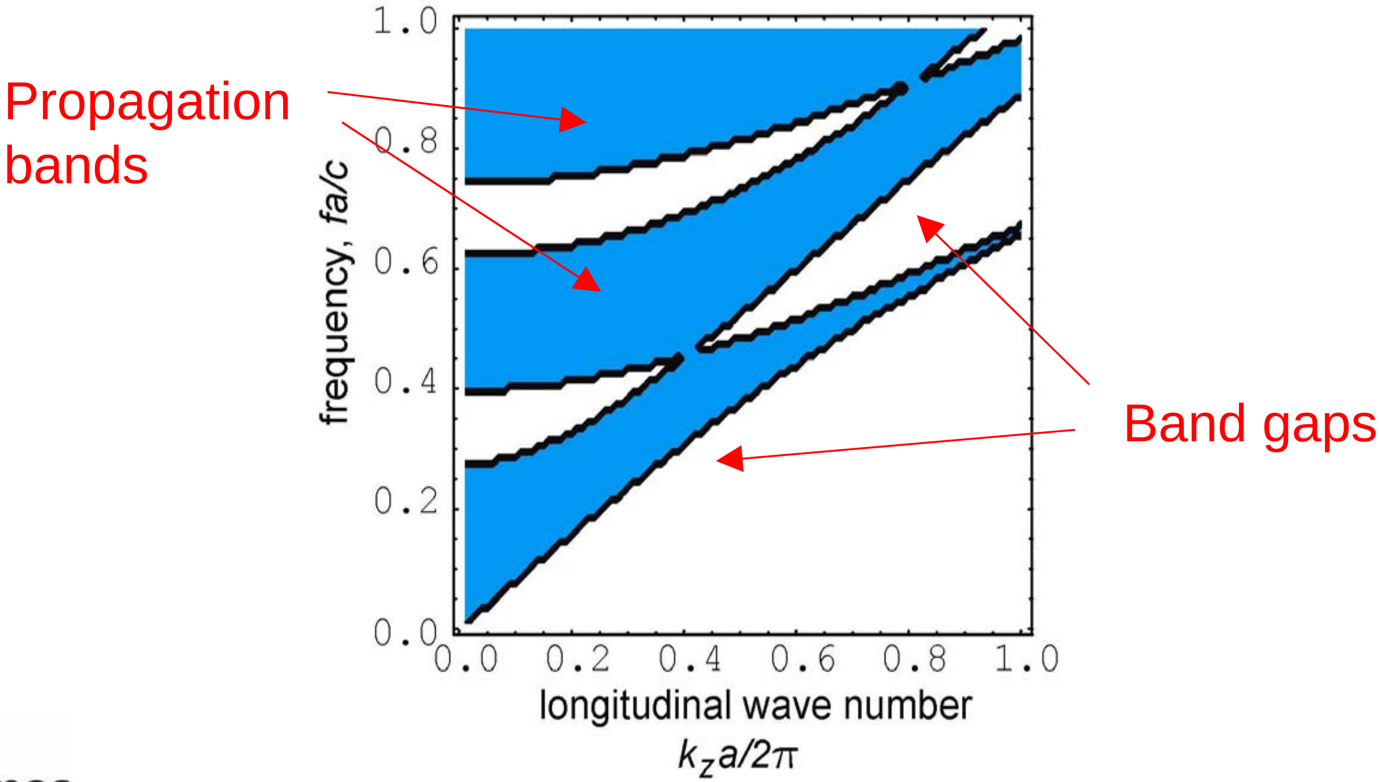
An omniguide is a cylindrically symmetric version of a Bragg filter representing a periodic system of concentric dielectric tubes.



*Y. Fink, et al., J. of Lightwave Tech., **17**, 2039-2041, 1999.

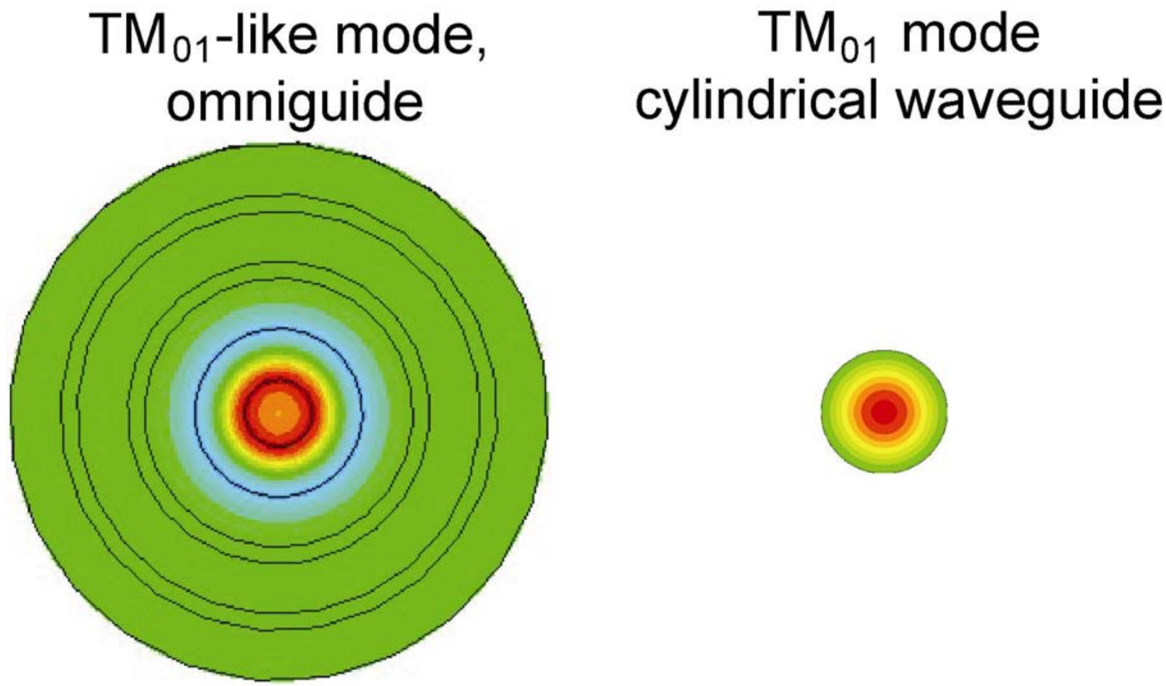
Band Gaps in Omniguides

Certain frequencies are confined by the periodic structure and can only propagate along the omniguide. The bands of the confined frequencies are called "band gaps."



Modes in Omniguides

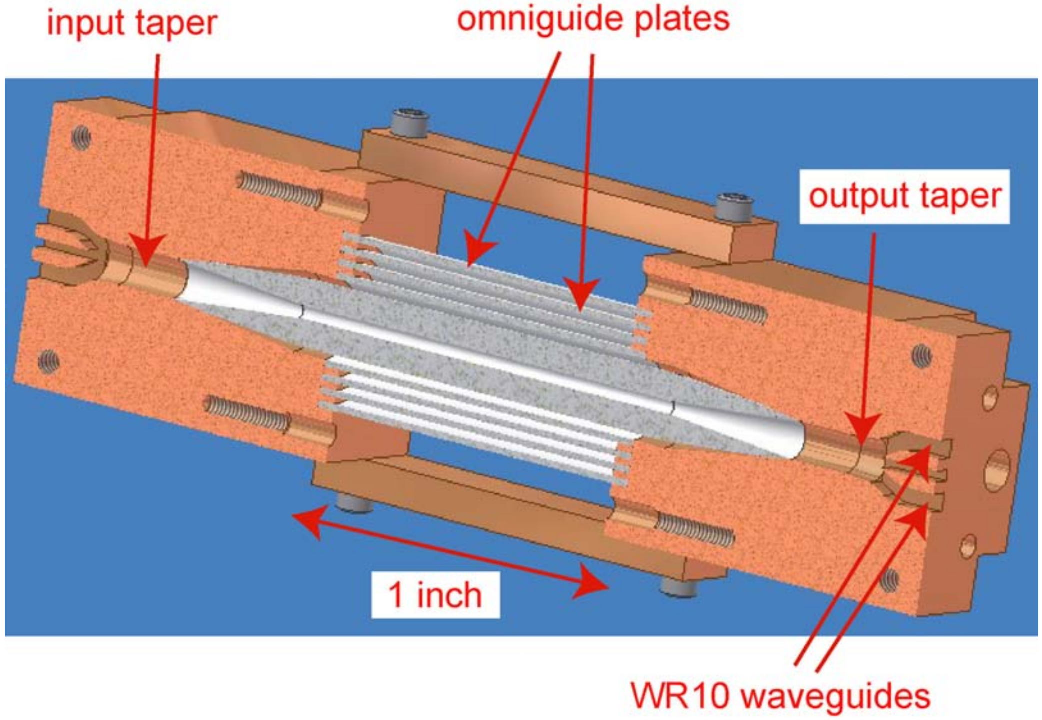
The frequencies which are confined by an omniguide form eigenmodes. The eigenmode of an omniguide resembles the TM_{01}-mode of a cylindrical waveguide, and can be employed as the operating mode in a TWT.



A Silica TWT Test Structure is Being Fabricated Right Now

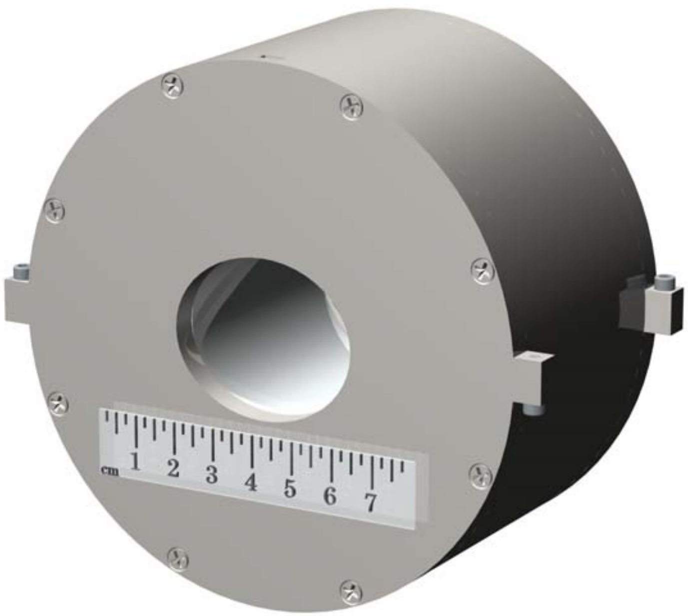
Fabrication of an omniguide test structure from fused silica is being performed by Specialty Glass Products, Inc. in Willow Grove, PA. We use a similar coupling scheme as for our copper TWT structures.

Frequency	100 GHz
Spacing between the tubes, *a*	0.45 mm
Thickness of the tube, *t*	0.45 mm
Length	25.4 mm



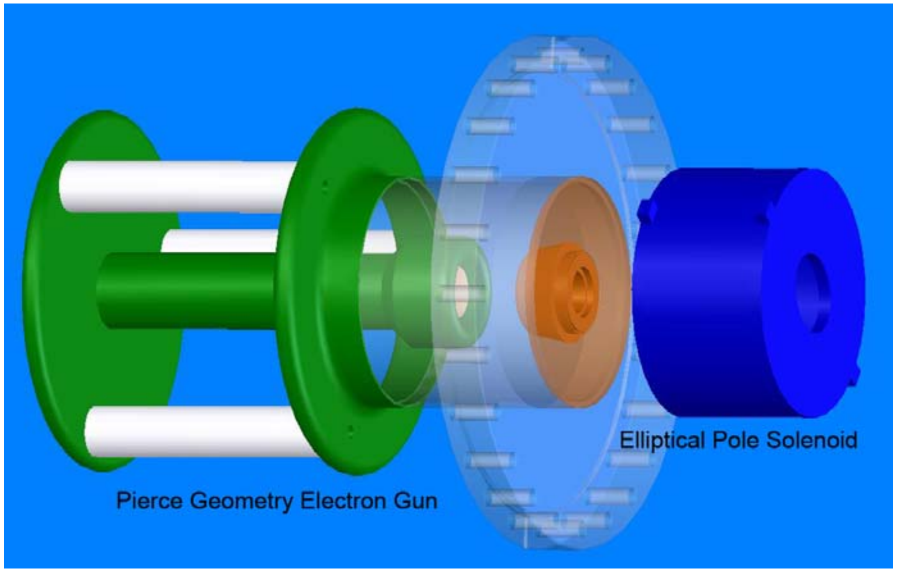
Sheet Beam Generation and Transport

We Currently Generate our Sheet Electron Beam with an Elliptical Pole Solenoid



The solenoid is placed downstream from a standard Pierce geometry 120 kV, 20 A electron gun, transforming an initially round beam to form an elliptical sheet beam.

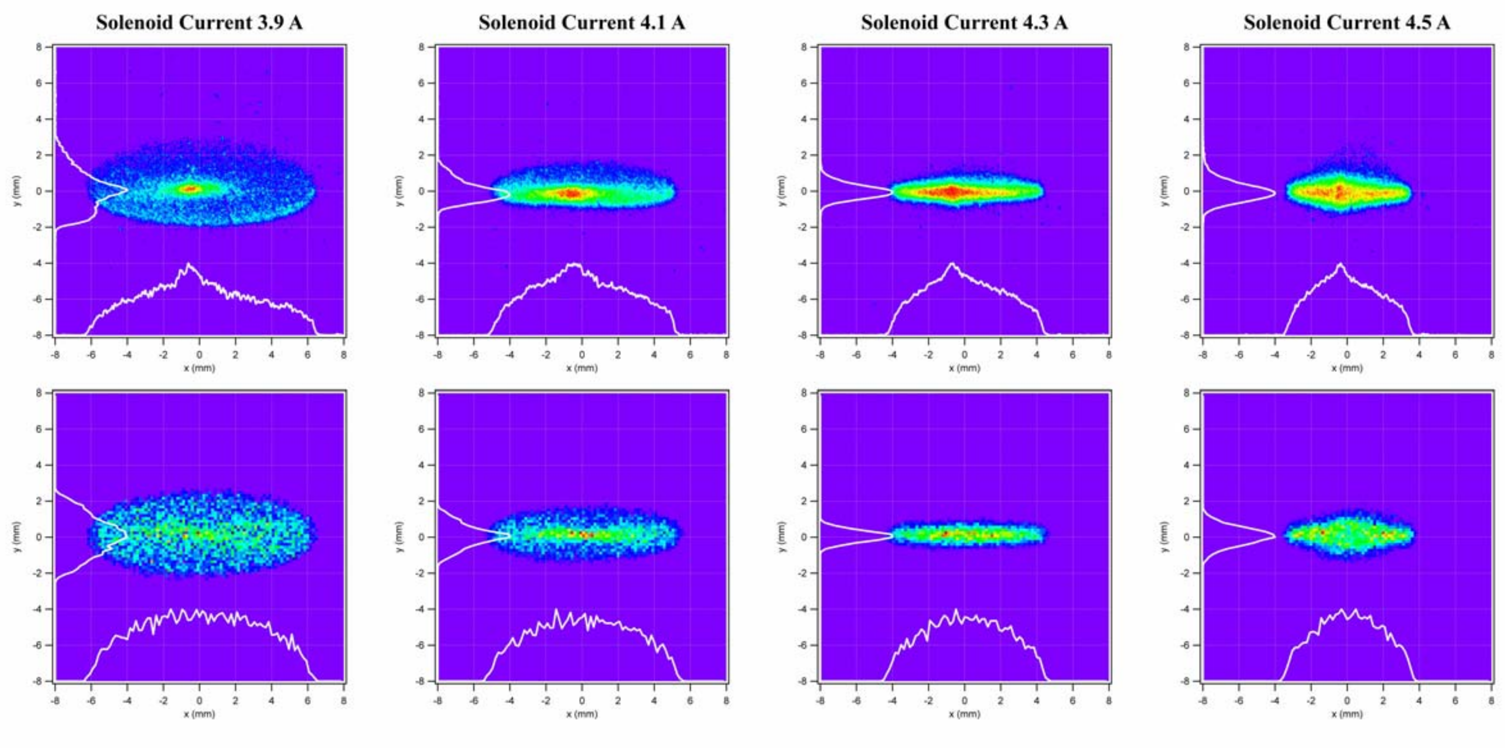
Our elliptical pole solenoid is 2.75 inches long and has an elliptical aperture with a horizontal semi-axis radius of 0.866 inches and a vertical semi-axis radius of 0.716 inches.



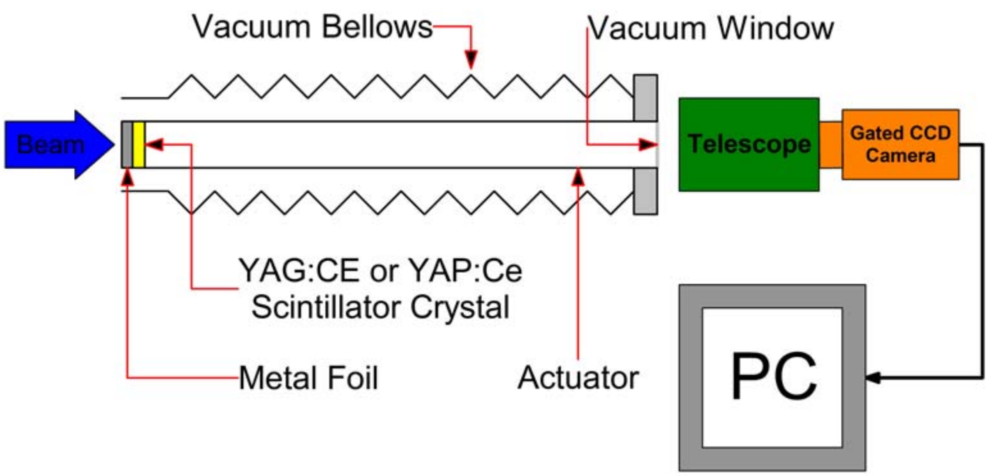
Demonstration of Sheet Beam Formation with Elliptical Solenoid at 20 kV, 1.42 A

Measurement

Simulation
(OmniTrak)

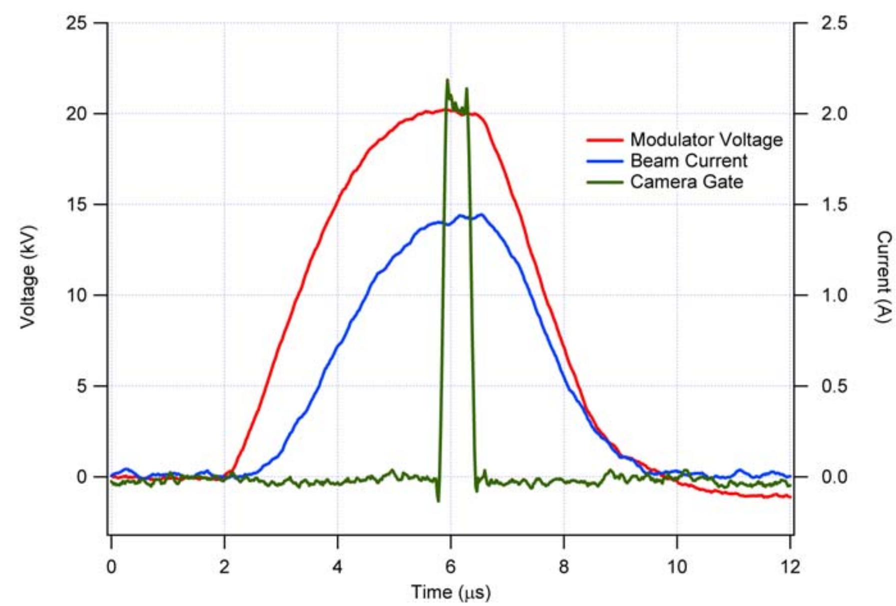


Our Beam Diagnostic uses a Gated Camera to Sample a Single Beam Energy



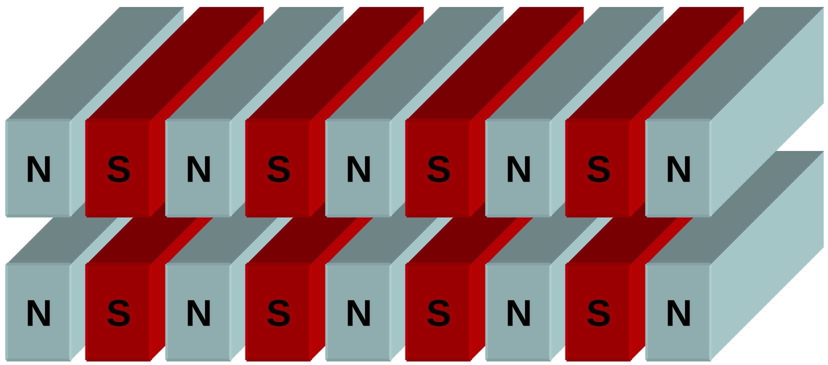
Schematic of optical diagnostic.

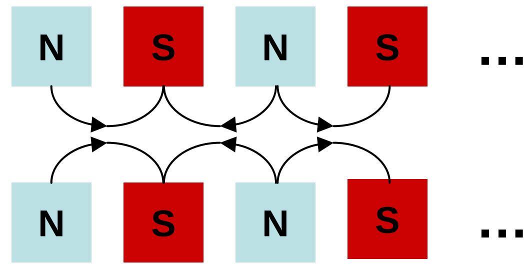
Gun pulse showing overlaid camera gate



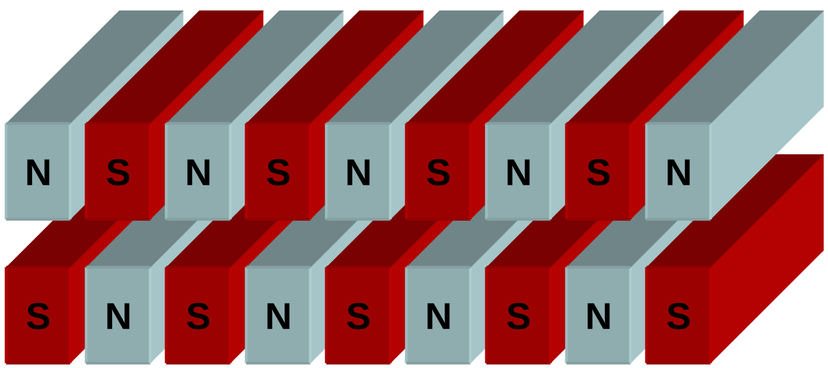
Once Formed, the Sheet Beam is Transported in a PCM Array or Wiggler Array

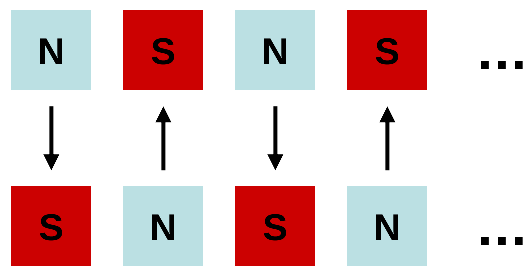
Periodic Cusped Magnetic (PCM) Array





Wiggler Array





PCMs and Wigglers Provide the Same Focusing Force, but have Different Stability Requirements

Required Field Magnitude

$$B_{mag} = \frac{\sqrt{2}\gamma m_e v_b}{e}\left(\frac{K}{2y_{RMS}\left(x_{RMS}+y_{RMS}\right)}+\frac{\varepsilon_y^2}{y_{RMS}^4}\right)^{\frac{1}{2}}$$

Stable Transport Places Constraints on the Array Period

Wiggler

Period is limited by magnet length needed to turn electrons around

$$\lambda_{max} = \frac{\sqrt{2}\pi\beta\gamma c^2}{\varepsilon_{ny} 576 f_{RF}^2}$$

PCM

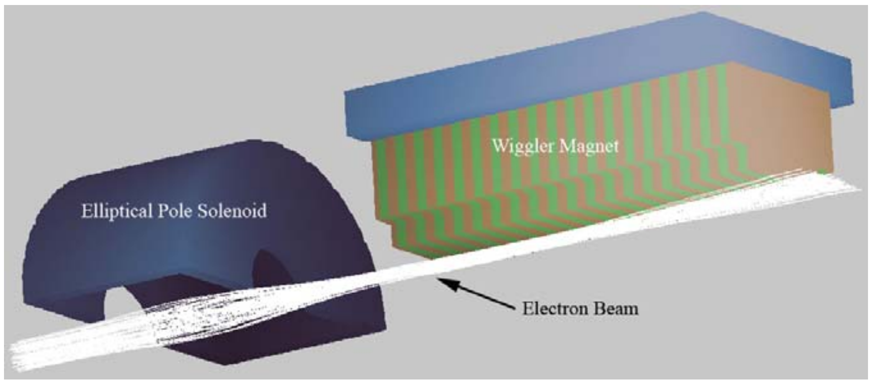
Period is governed by Mathieu's equation (assuming emittance dominated beam)

$$\lambda_{max} = \frac{\sqrt{0.66}2\pi\beta\gamma c^2}{\varepsilon_{ny} 576 f_{RF}^2}$$

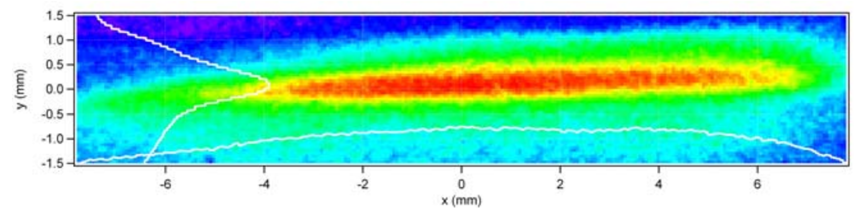
B. E. Carlsten, L. M. Earley, F. L. Krawczyk, S. J. Russell, J. M. Potter, P. Ferguson and S. Humphries, "Stable two-plane focusing for emittance-dominated sheet-beam transport," *PR-STAB*, **8**, 062002 (2005).

Original Sheet Beam Experiment with Single Plane Focusing Wiggler

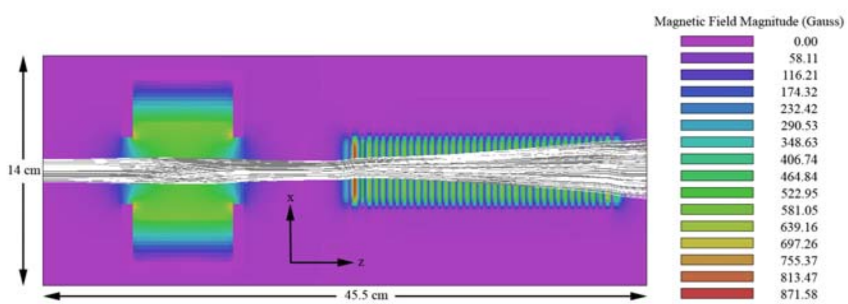
3D OmniTrak Simulation

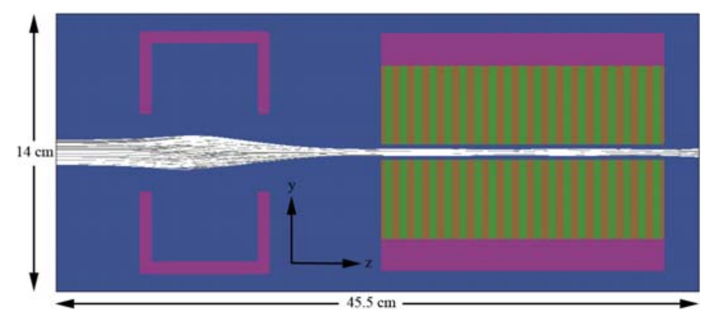


Measured Beam 6.4 cm Inside Wiggler (30 kV, 2.6 A)



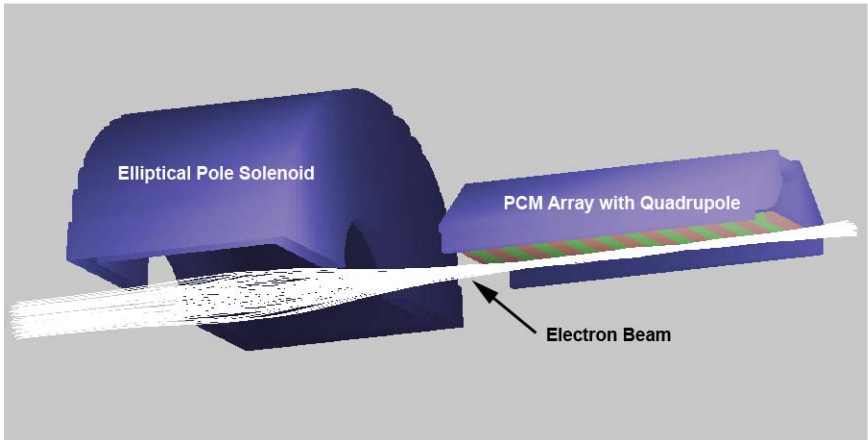
Horizontal and Vertical Projections of OmniTrak Simulation





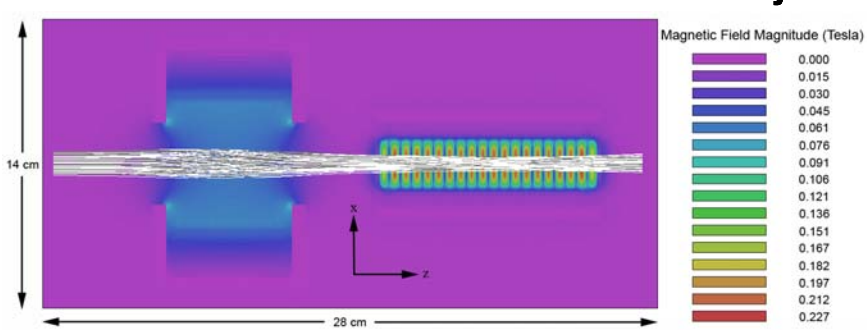
PCM/Quad Hybrid Dual Plane Focusing Experiment

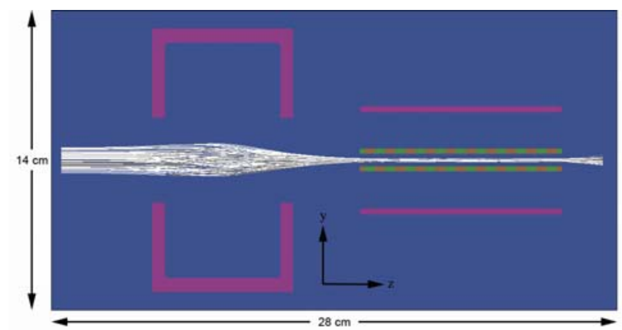
3D OmniTrak Simulation



The PCM/Quad hybrid dual plane focusing experiment superimposes a quadrupole field on a planar PCM structure to achieve focusing in both planes. This experiment has been designed and is currently being fabricated.

Horizontal and Vertical Projections of OmniTrak Simulation





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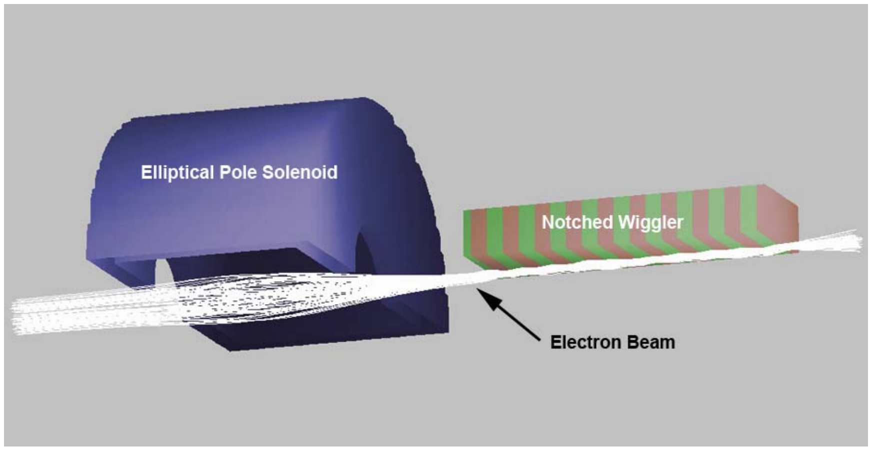
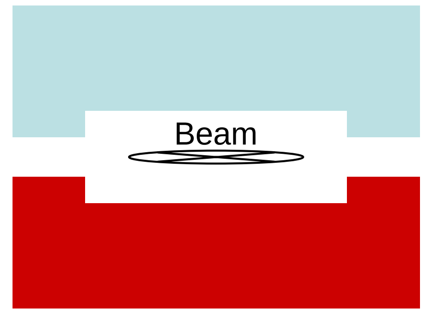
Notched Wiggler Dual Plane Focusing Experiment

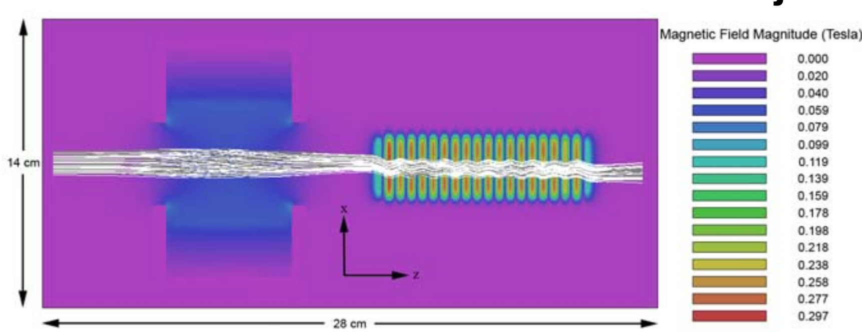
3D OmniTrak Simulation

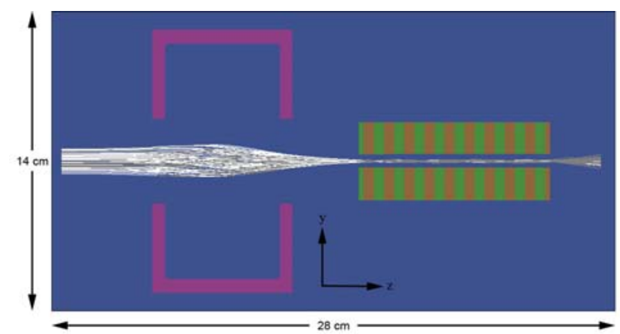


Notched magnets leads to linear vertical focusing and nonlinear horizontal focusing (notch is exaggerated).



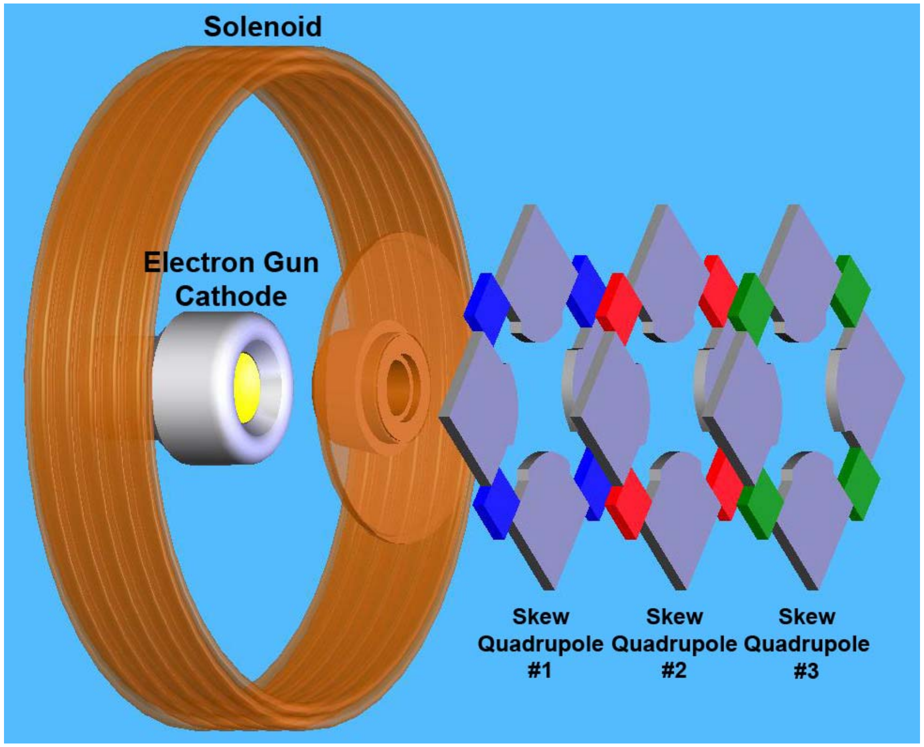
Horizontal and Vertical Projections of OmniTrak Simulation





Beam Cooling for High Frequency (~300 GHz)

We See Emittance Cooling as Providing a Path to Very High Frequency TWTs (~300 GHz)



With proper placements and strengths of quadrupoles (rotated 45°), we can transfer emittance from one transverse plane to the other.

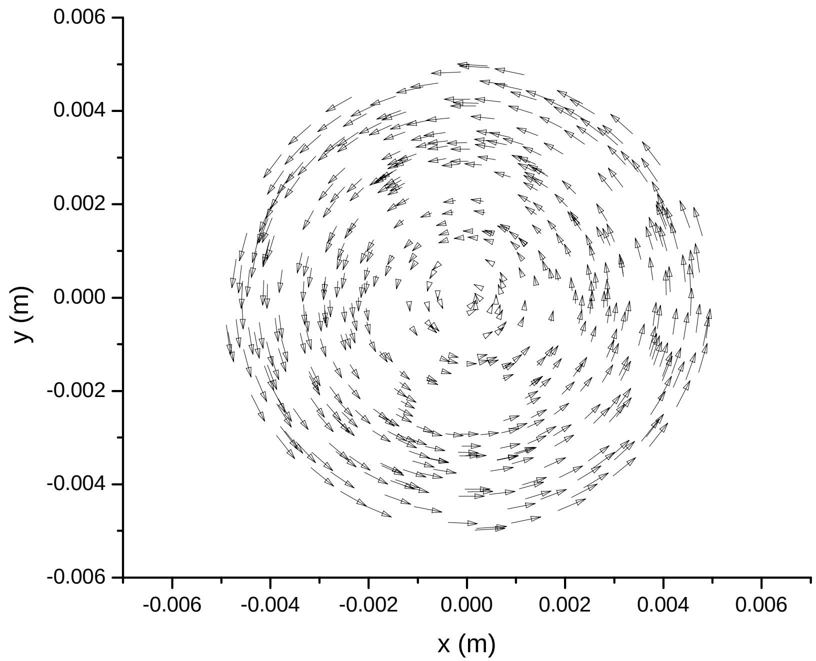
$$\frac{\varepsilon_{\text{larger}}}{\varepsilon_{\text{smaller}}} \approx \left(\frac{2\mathbf{L}}{\varepsilon_{\text{intrinsic}}}\right)^2$$

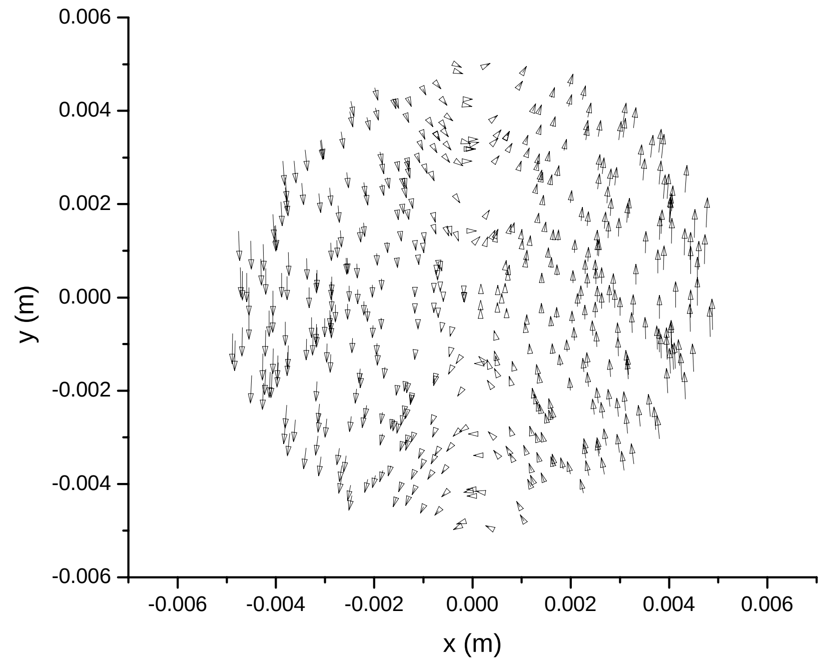
$$\mathbf{L} = \frac{eB_{\text{cath}}\pi R_{\text{cath}}^2}{16 m_e c}$$

The intrinsic emittance is the thermal emittance of the beam (assuming gun is well designed).

R. Brinkman, Ya. Derbenev, and K. Floettmann, *Phys. Rev. ST – Accel. and Beams*, **4**, 053501 (2001).

After the First Quadrupole, the Beam Shears Vertically on Either Side of the x = 0 Axis

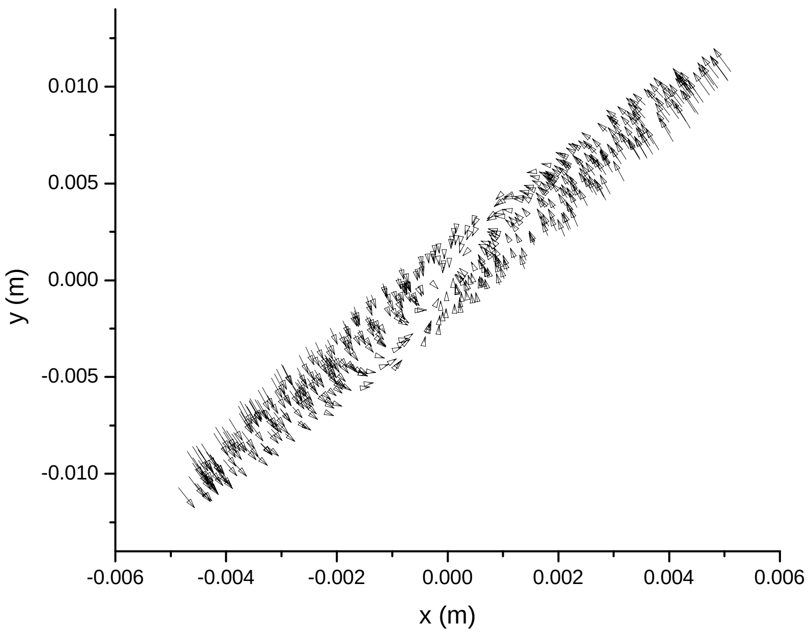


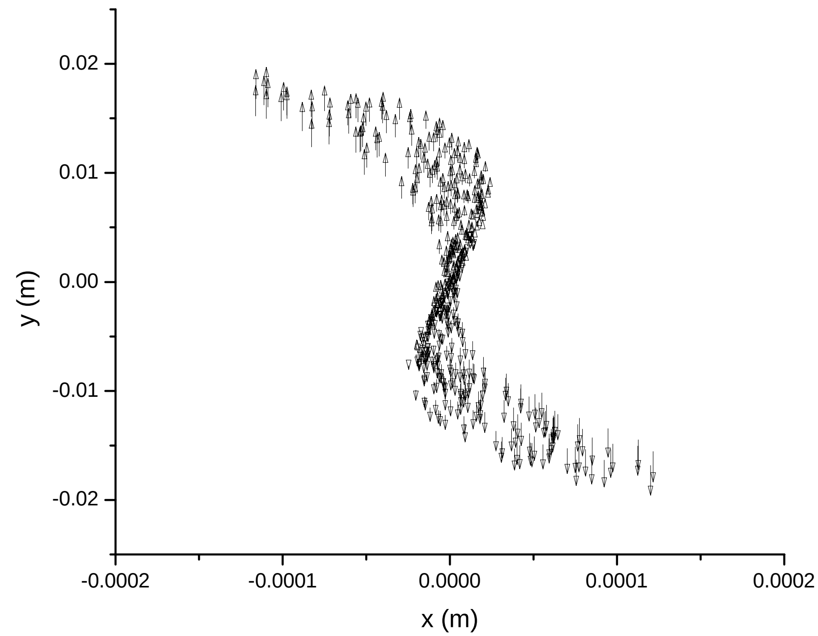


The beam exits the electron gun with angular momentum due to the solenoid field on the cathode.

The first skewed quadrupole stops much of the horizontal motion of the beam electrons, leading to vertical beam shear about the x = 0 axis.

Quadrupoles Two and Three Complete the Process of Removing Horizontal Beam Motion



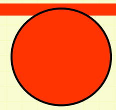
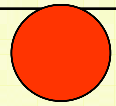


After the second skewed quadrupole, the beam is again spinning but now has a highly elliptically shape.

The final skewed quadrupole, like the first, stops the horizontal motion of the beam. This completes the transfer of horizontal motion to the vertical direction. The result is a sheet beam that is very "cold" in the horizontal plane.

At 300 GHz, Emittance Cooling Allows for Practical Transport Magnet Parameters

The following table gives the important parameters for a PCM or Wiggler array used to focus a 120 kV, 2A, 1 cm wide sheet electron beam in a 300 GHz TWT. The calculations assume different initial sources for the electron beam and assume no contribution to the beam emittance due to aberrations in focusing magnets upstream from the sheet beam transport array. All cathodes emit with a 4A/cm^2 current density and have an applied field of 433 Gauss.

	Cathode Shape	Cathode Width	Cathode Height	Required Beam Final Height	Normalized Emittance Lower Bound in Narrow Plane (Theory)	Required Magnitude of PCM or Wiggler Field	Maximum Stable PCM Period	Maximum Stable Wiggler Period
Conventional Gun		0.80 cm	0.80 cm	0.17 mm	0.95 μm (thermal emittance)	1.32 T	0.68 cm	0.59 cm
Elliptical Gun		1.00 cm	0.64 cm	0.17 mm	0.76 μm (thermal emittance)	1.06 T	0.85 cm	0.73 cm
Sheet Beam Gun with Rectangular Cathode		1.00 cm	0.50 cm	0.17 mm	0.69 μm (thermal emittance)	0.96 T	0.93 cm	0.81 cm
Conventional Gun with Emittance Converter		0.80 cm	0.80 cm	0.17 mm	0.006 μm	0.10 T	113 cm	8.2 cm

Future Plans

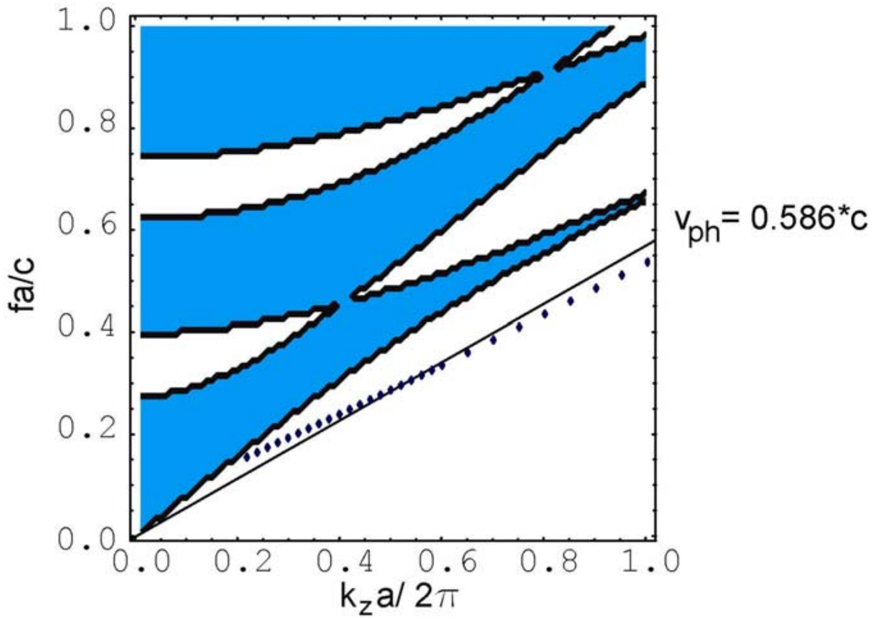
- Dual plane sheet beam focusing experiment is planned for later this summer.
- Emittance cooling experiment is in design phase and planned for late summer/early fall (Bishofberger).
- We plan on testing our silica TWT this fall (Smirnova).
- Starting in October, we will begin design an experiment to test a wide RF structure with a sheet electron beam.

Conclusion: Great Fun and Great Progress Happening at Los Alamos!

Properties of Silica TWT

Fused silica (SiO_2) is widely used in optics. Dielectric properties of silica at 100 GHz are the following: ε = 3.8, tan δ = 0.0001.

Band Gaps with Phase Velocity Overlaid for Silica TWT



Interaction Impedance of Silica TWT