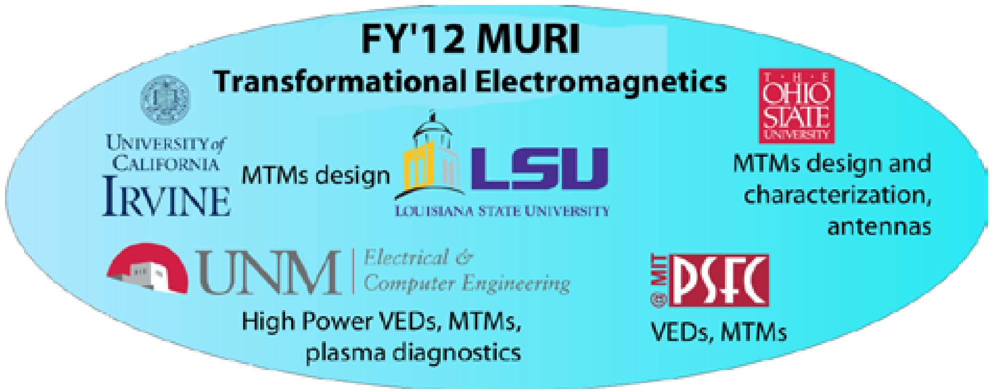
# Innovative Use of Metamaterials in Confining, Controlling, and Radiating Intense Microwave Pulses

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MIT Dept. of Physics
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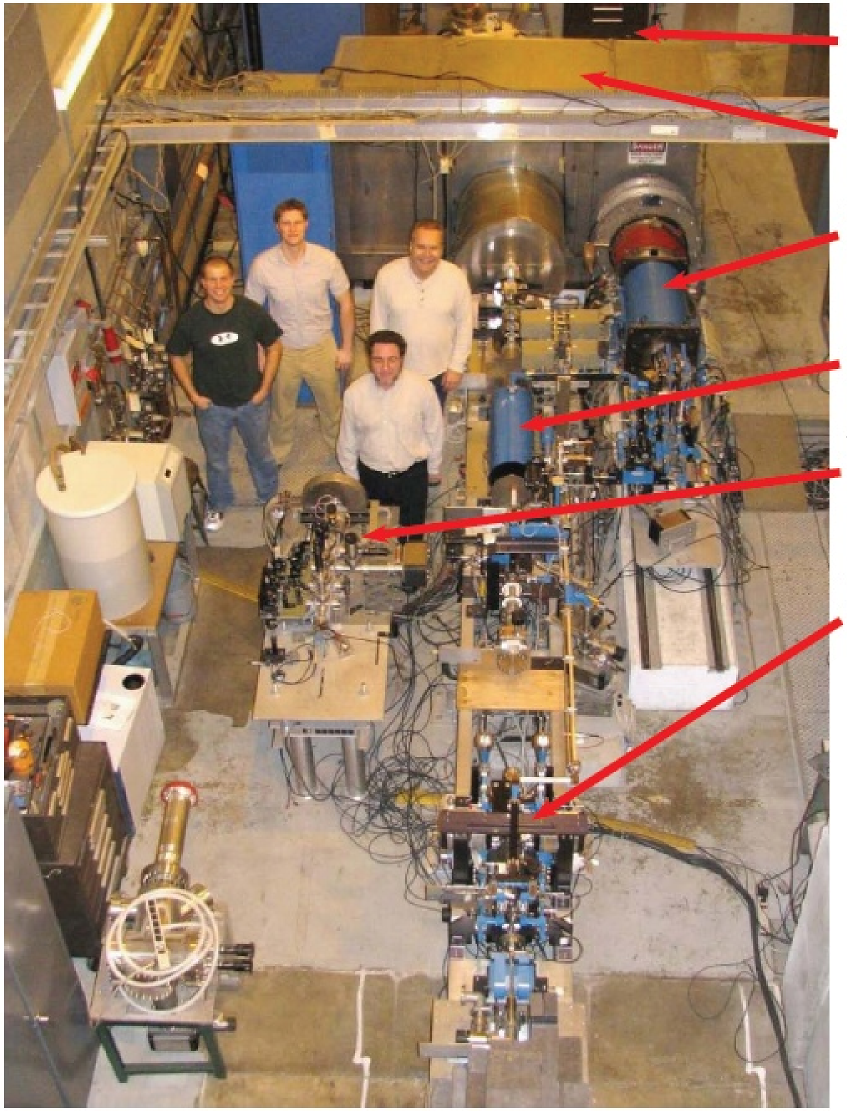
MURI Kickoff at Univ. New Mexico
August 21, 2012

# Outline

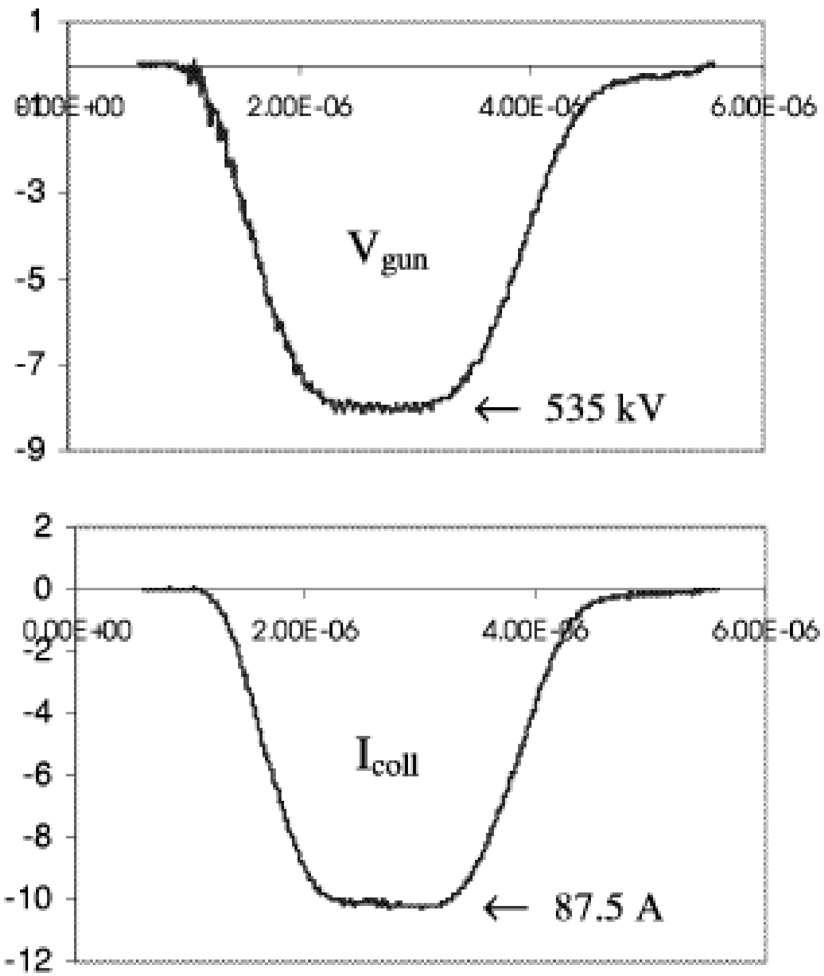
- **MIT HPM Research Capabilities**
- MTM HPM Amplifier Design
- S-Band MTM Amplifier Experiment – First Design
- Summary

# MIT Accelerator and HPM Lab

| MIT Accelerator Parameters | |
|---|---|
| Klystron Power | 25 MW |
| RF Frequency | 17.14 GHz |
| Linac Energy | 25 MeV |
| Linac Length | 0.5m, 94 cells |
| Test Stand Power | 4 MW |



# 700 kV Modulator




Modulator V, I Waveforms

| MIT Modulator Parameters | |
|---|---|
| **Modulator Voltage** | **700 kV** |
| **Modulator Pulsed Power** | **500 MW** |
| **Beam Current** | **780 A** |
| **Modulator Pulse Length** | **1.0 ms Flat-top** |
| **Klystron Power** | **25 MW** |

Features of Long Pulses

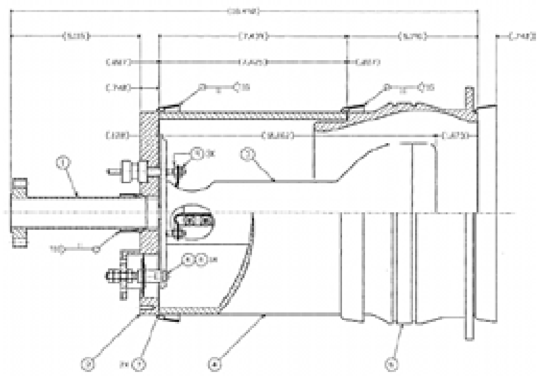
- High Energy
- Equilibrium
- For Q~5000 and ω ~ 3 GHz, Q/ω ~300 ns

# Previous MIT HPM Experiments

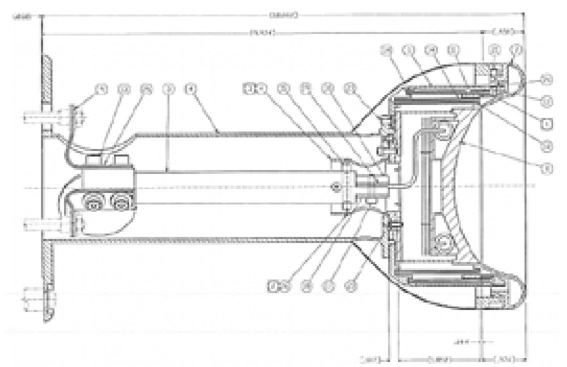
- Injection locked 3.3 GHz Magnetron, 30 MW, 400 ns
- Cyclotron Autoresonance Maser (CARM) oscillator, 1.9 MW, 28 GHz in 1 μs pulses; 450 kV, 80 A, 5.2% efficiency
- Free Electron Laser Oscillator, 1 MW, 27 GHz in 1 μs pulses at 10% efficiency; 320 kV and 30A
- Haimson Research Corp. 17.1 GHz Klystron; 525 kV, 100A
  - First version: 25 MW with 50 dB of gain
  - Second version: 25 MW with 71 dB of gain

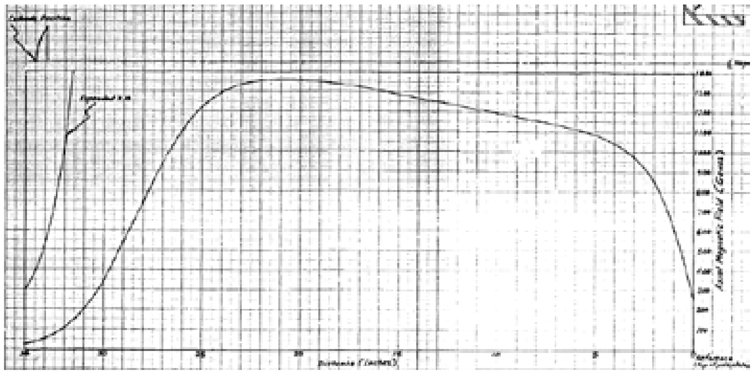
# SLAC 5045 Electron Gun

- SLAC 5045 Klystron Gun built for MIT



- 350 kV
- 414 A
- Perveance 2 μP
- E Beam Power 145 MW
- Microwave P = 65 MW



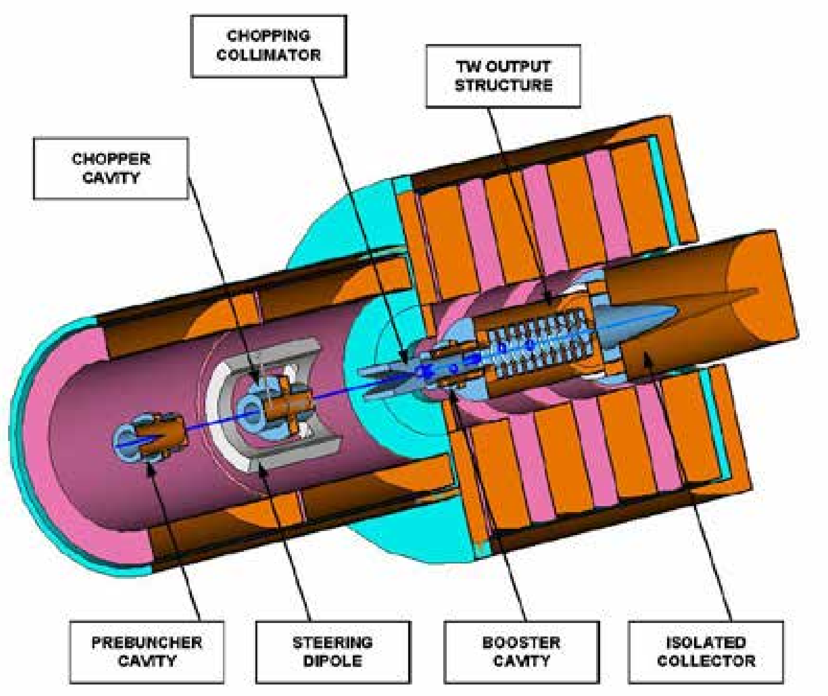


Magnetic Field Profile ~ 1.4 kG

SLAC 5045 Klystron

# Haimson Research Choppertron

- Test of Choppertron

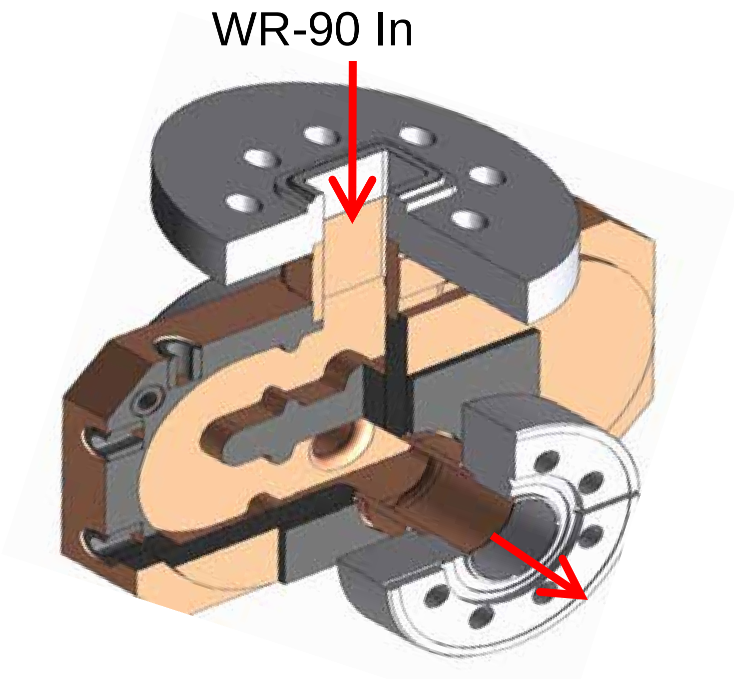


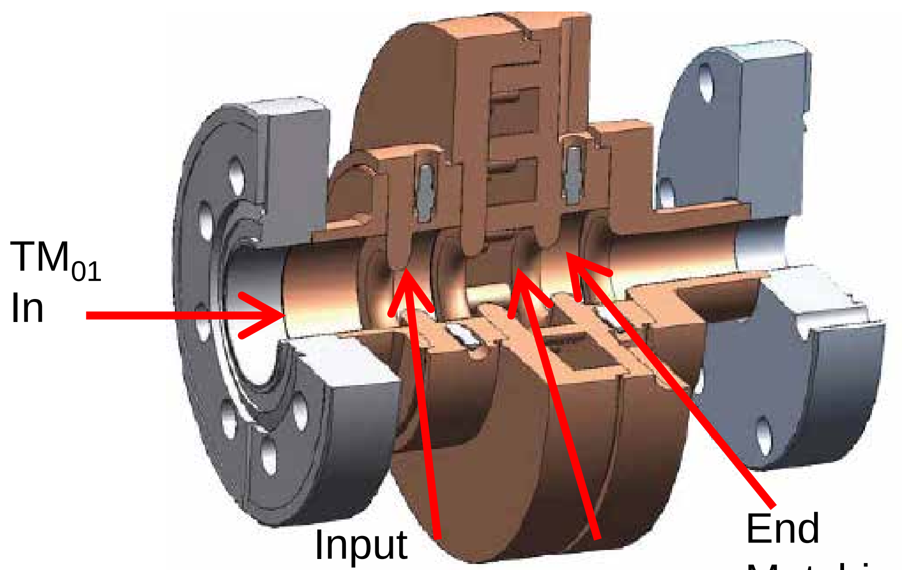

Choppertron Schematic

Choppertron Gun
500 kV, 80A
Electron Beam diameter 4 mm

# MIT RF Breakdown Research at 11.4 GHz

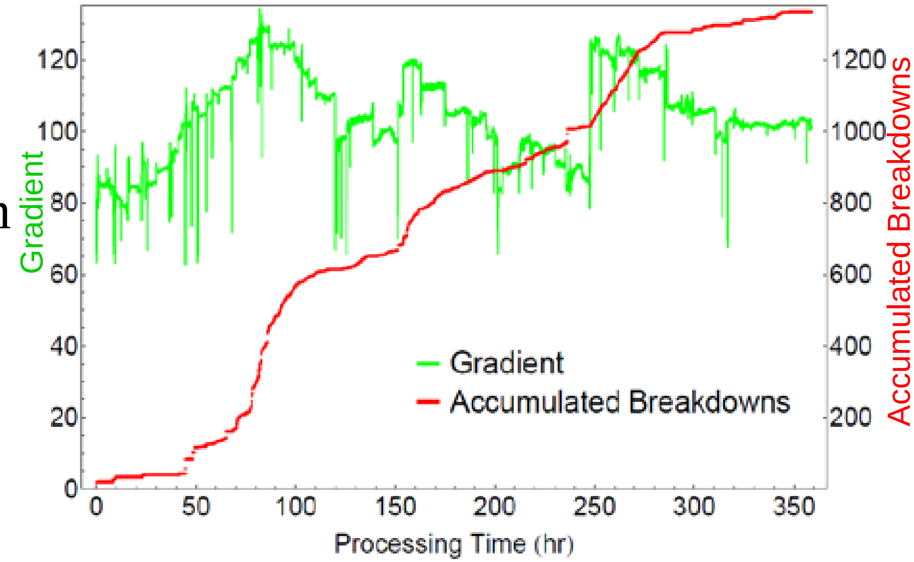
- RF breakdown could be a major issue for MTM structures
- Standing wave Photonic Bandgap structures with half field in each of 2 coupling cells and full field in test cell
  - Designed at MIT, built and tested at SLAC

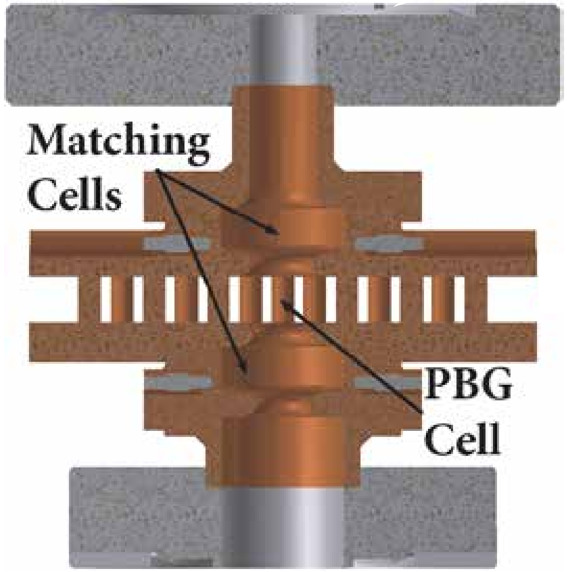


# Metallic PBG Structures

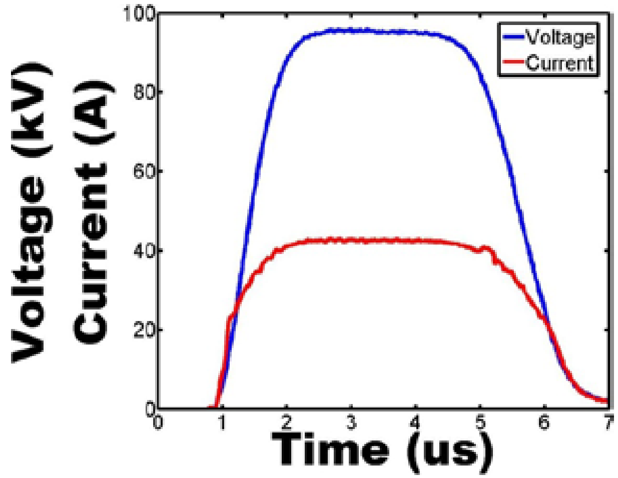
- Achieved high gradient and low breakdown rate at 11.4 GHz
  - 3.6 * 10^-3 /pulse/m @128 MV/m
  - Surface field is about 250 MV/m
- Breakdown testing will begin at MIT at 17.1 GHz in 2012



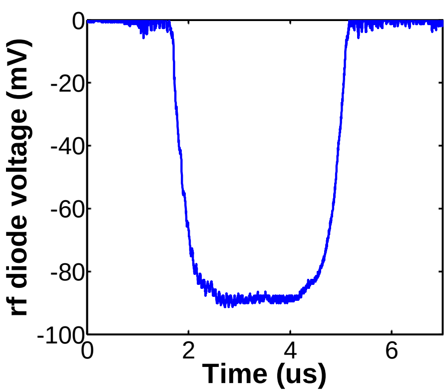



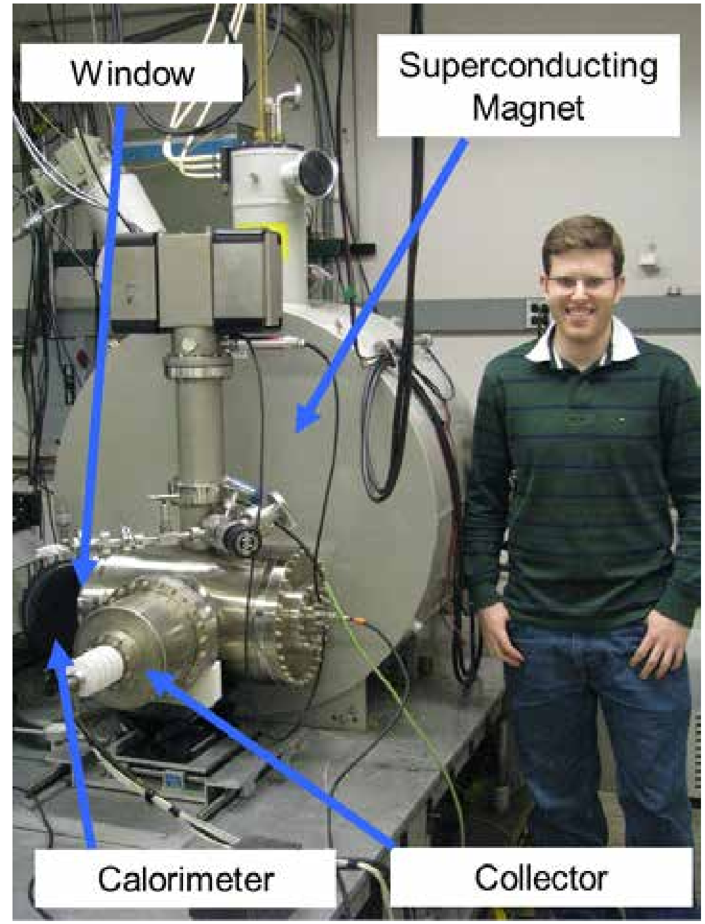
# Gyrotron and TWT Research Lab

- Two experiments operate from a single power supply
  - 100 kV, 120 A, 2 ms flat-top



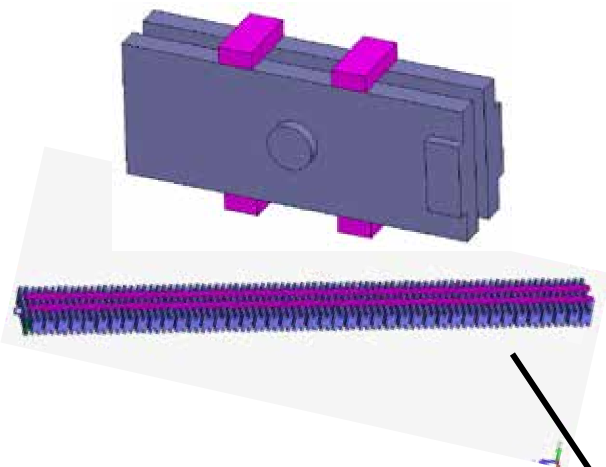

Output Power

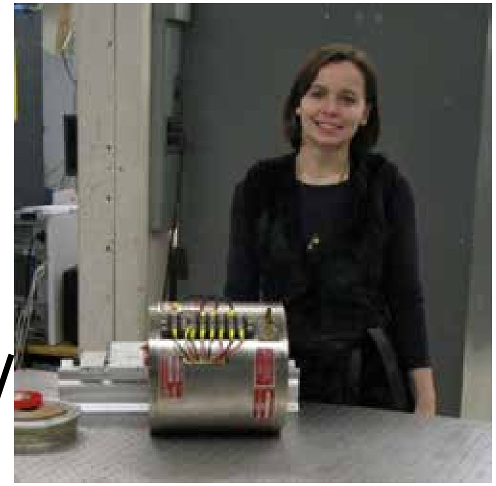


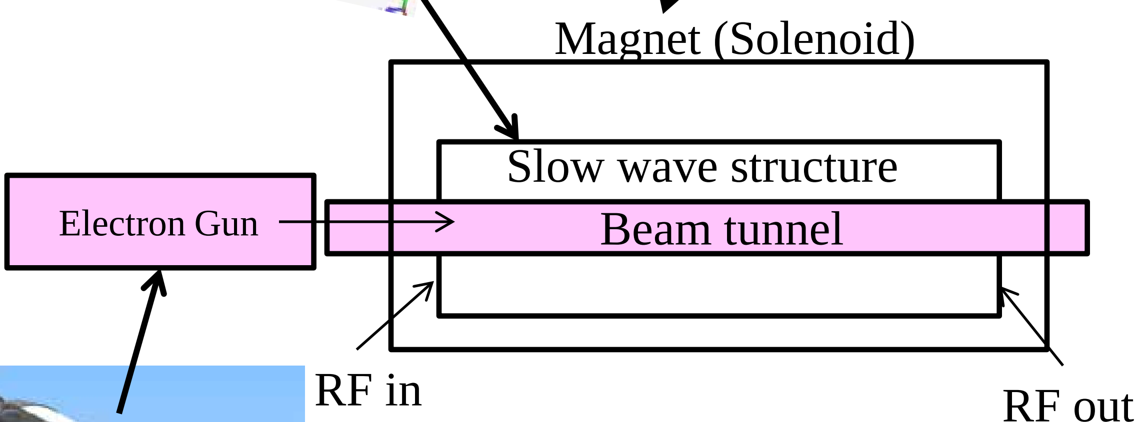



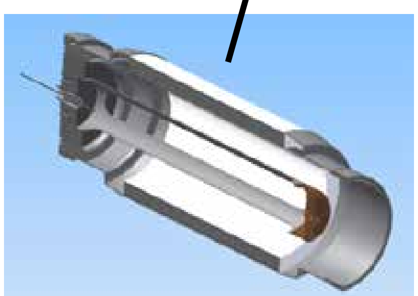

1.5 MW 110 GHz Gyrotron
96 kV, 42 A

# 94 GHz TWT Experimental Design



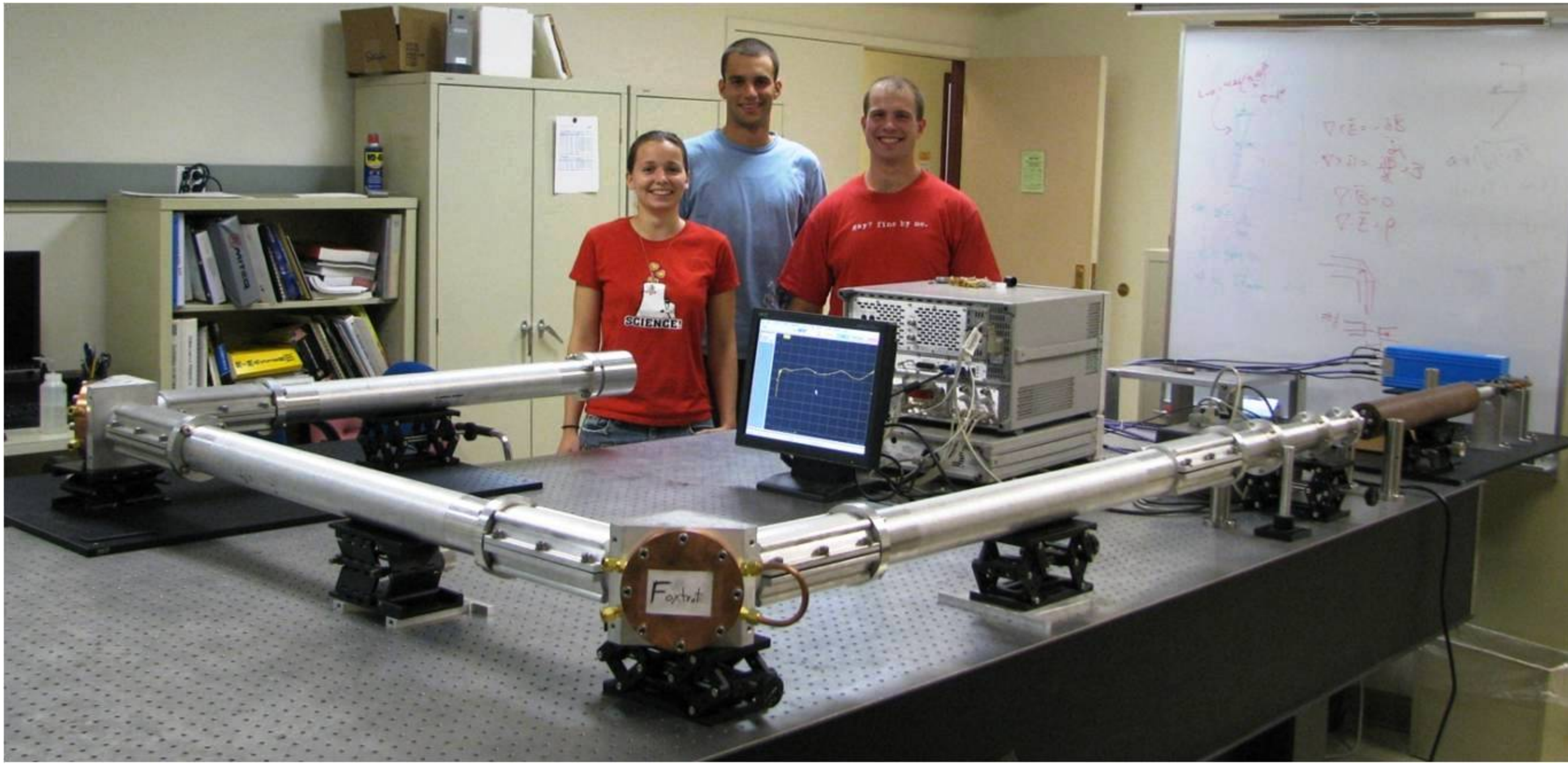




| Operation Parameters | |
|---|---|
| Frequency | 94 GHz |
| $V_0$ | 31.1 kV |
| Current | 330 mA |
| Kinetic Spread | 0.1% |
| Beam radius | 0.3 mm |
| Cavities | 86 |
| Length | 6.88 cm |
| K at 94GHz | 2.8 Ohms |
| Cold Circuit Bandwidth | 4 GHz |
| Magnetic Field | 2.5 kG |

# Cold Test Laboratory




- Vector Network Analyzer for frequencies of 10 MHz to 325 GHz

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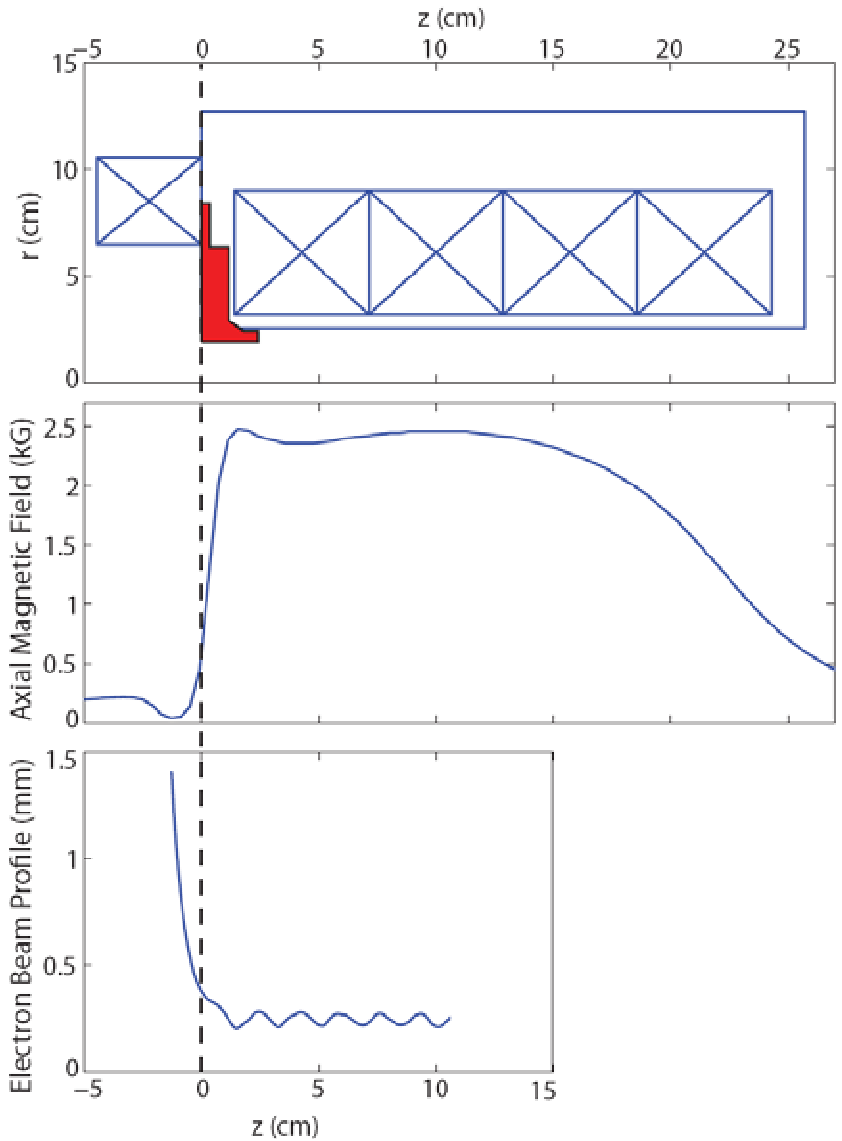
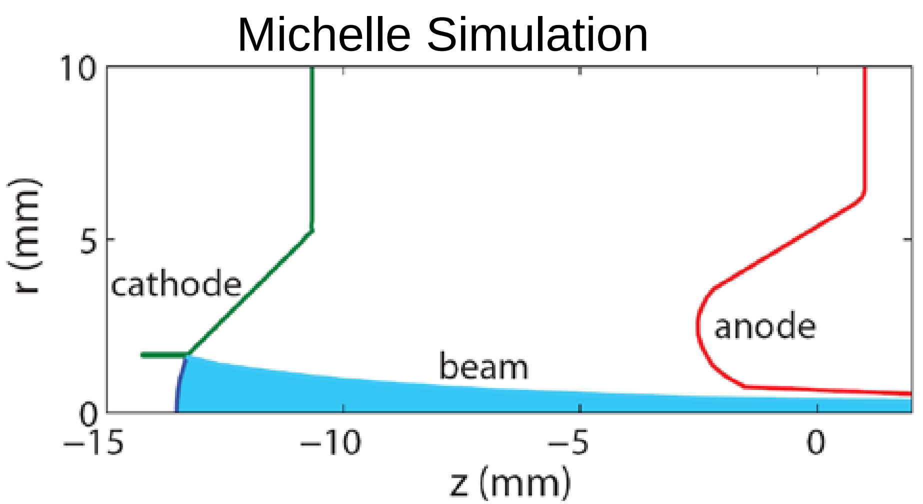
# Theory Overview

- MTM amplifier will be based on an electron beam from a Pierce gun with solenoidal magnet focusing and transport through a MTM structure
- Design procedure will be similar to conventional TWT designs
  - First: design an electron beam system and magnet
  - Second: design the amplifier circuit, estimate linear gain
  - Third: calculate the saturated gain using CST particle studio
- We have a preliminary (first) MTM structure design
  - We would like to try other designs suggested by other team members

# 94 GHz Electron Gun Design

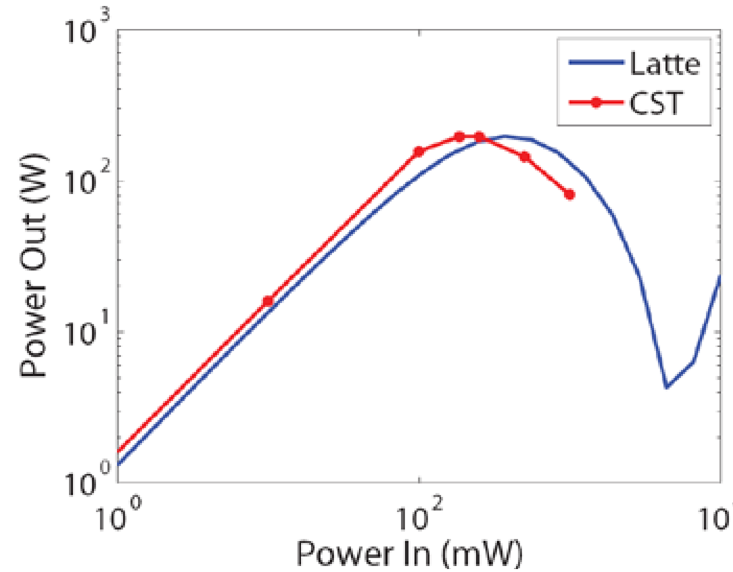


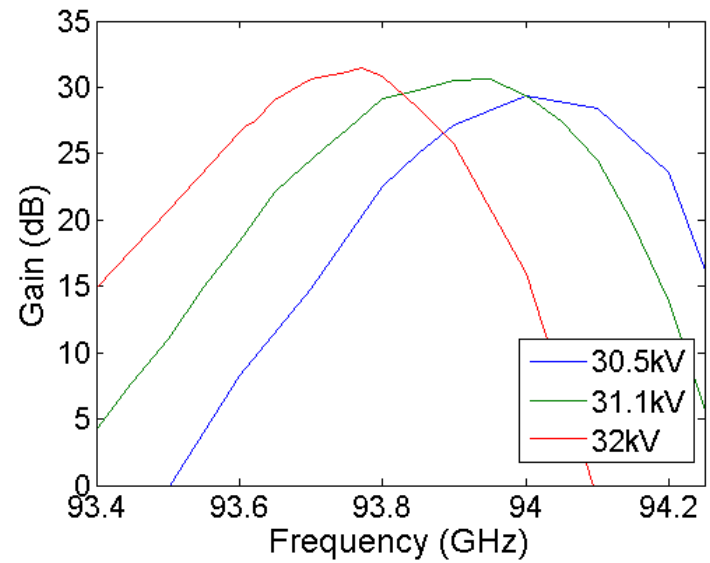

- Pierce electron gun designed with Michelle (SAIC) for operation at: 31 kV, 330 mA, 0.25 mm beam radius
- 4 A/cm$^2$ at cathode; 1.63 mm/0.25mm compression ratio

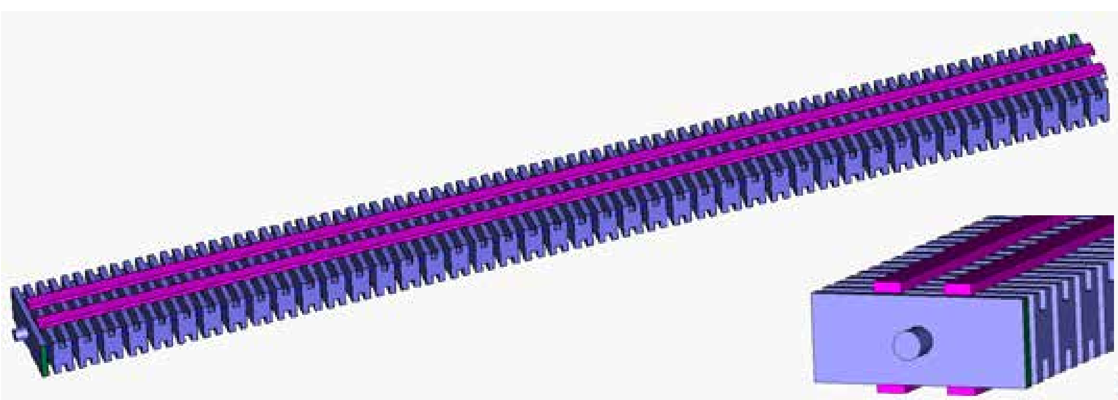


# CST and Latte Simulations

- CST Particle Studio (3D PIC code) simulations with 86 cavity (6.88 cm long) structure at 94GHz
- Results show 32 dB gain with 300 W peak output power and 200 MHz bandwidth
- 3D CST results agree with 1D LMSuite Latte Simulations with 4 dB/cm loss and 3 Ω coupling impedance



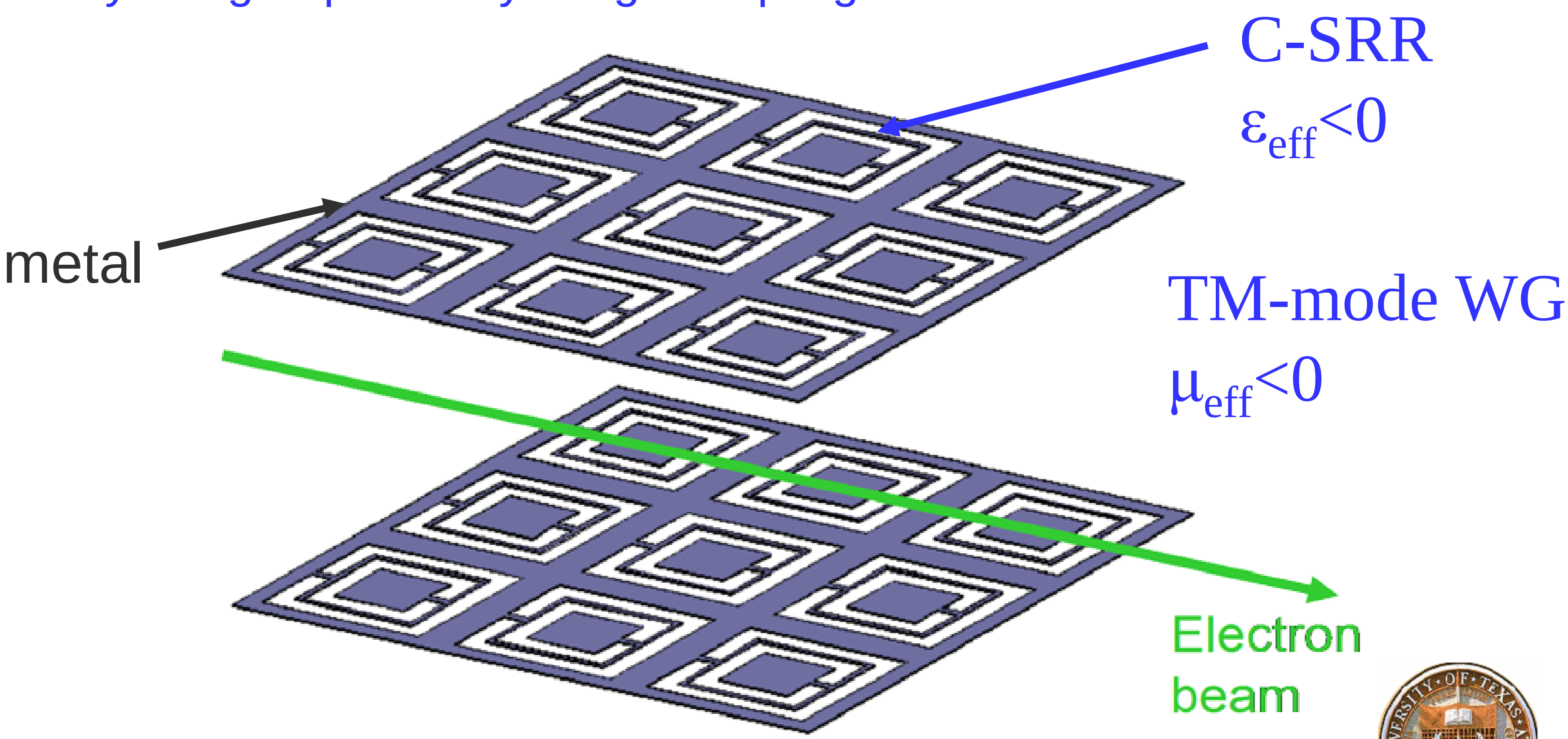



# Beam-powered Negative Index Complementary Metamaterial

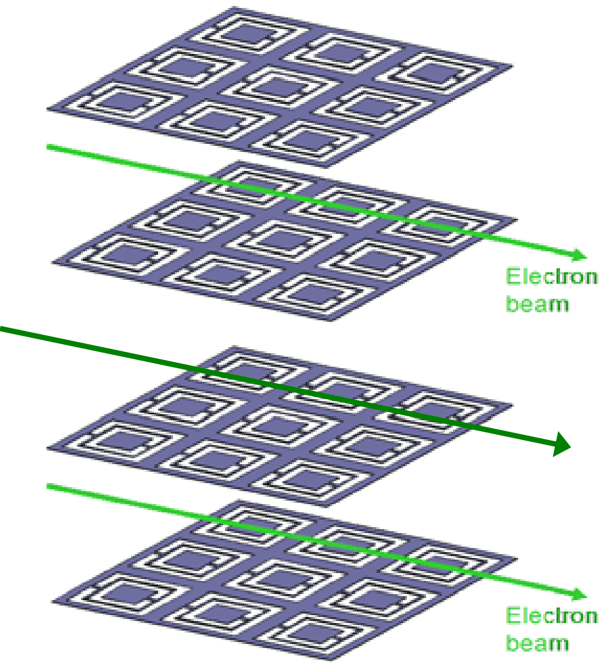
Beam-driven power source:

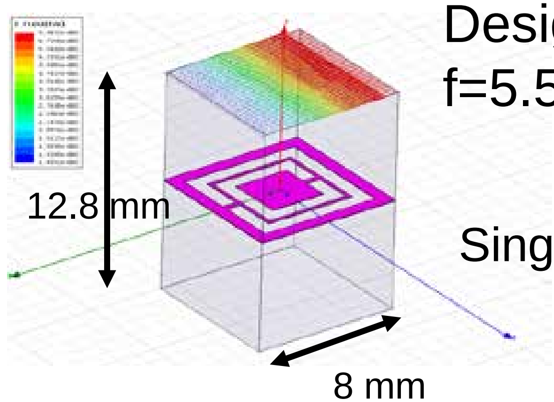
- Waveguide with perforated walls is used
- TM mode interacts with electron beam
- Very low group velocity – high coupling to electron beam




***Collaboration with UT-Austin (G. Shvets group)***

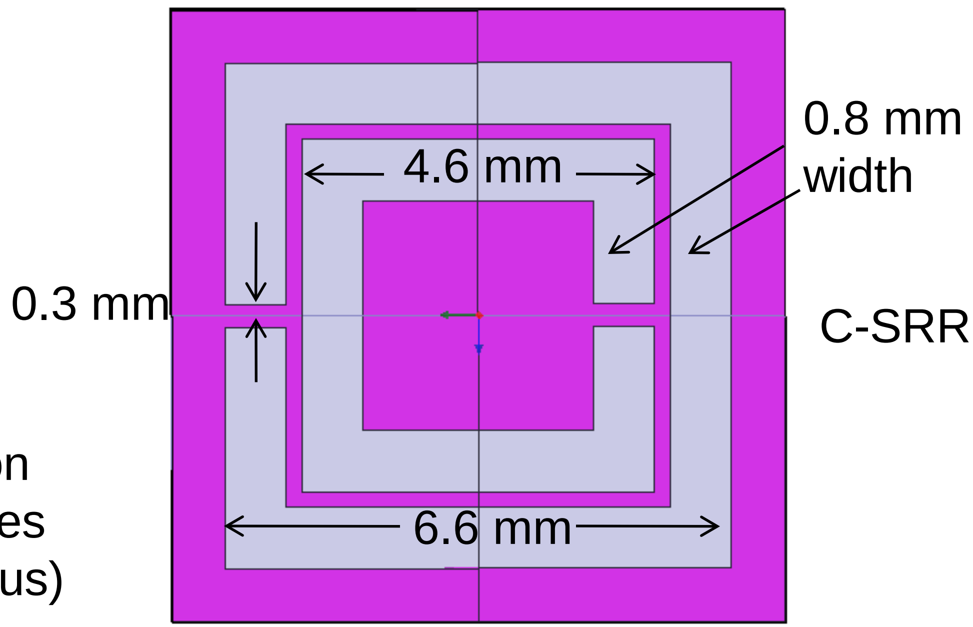
# Negative Index Complementary Metamaterial




Design at f=5.5 GHz

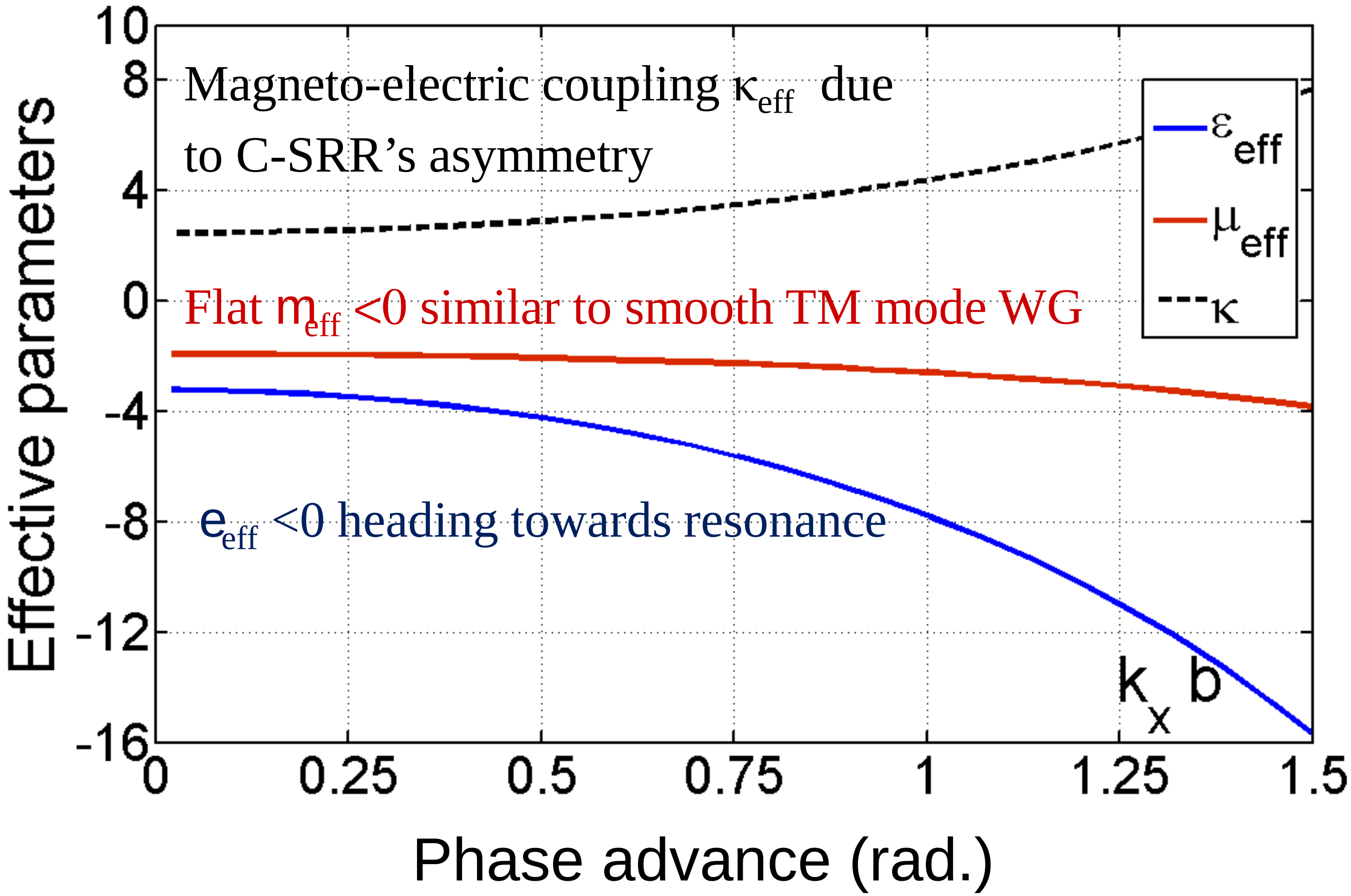
Single cell HFSS simulation




C-SRR dimensions

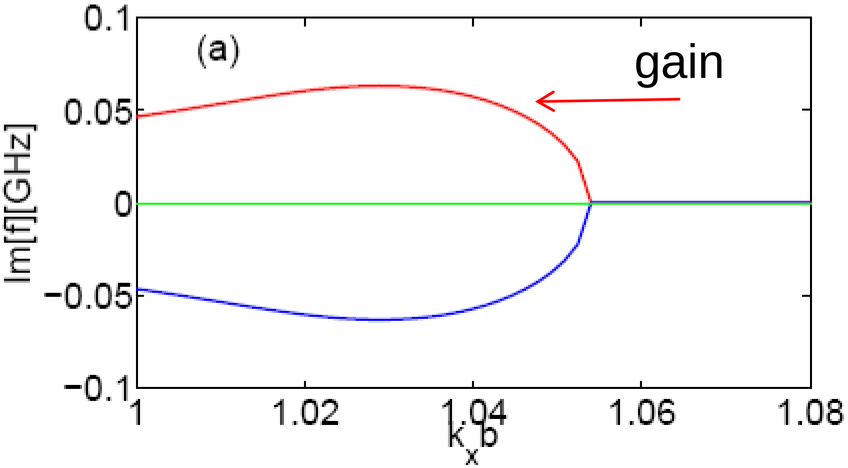
C-MTM model:
- infinite in transverse direction
- wave propagates along plates
- multiple beams (or continuous)

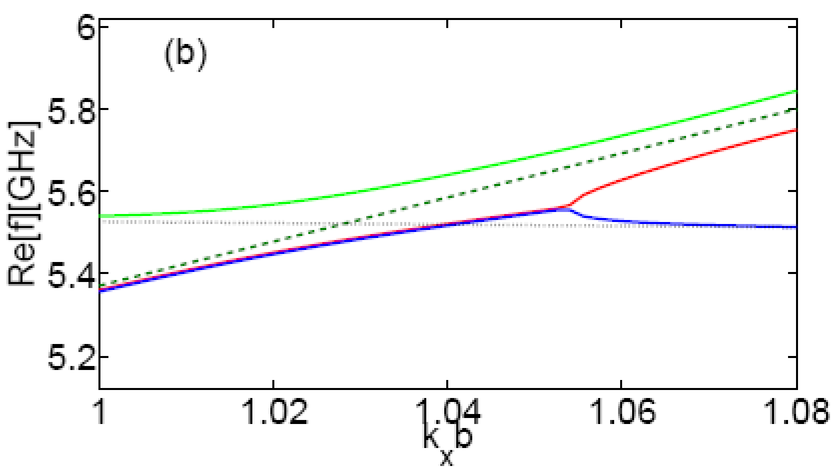
# Extracted effective parameters




COMSOL simulation

# Beam-NIM instability




$$\left(k_x^2 - \frac{\omega^2}{c^2}\left(\varepsilon_{eff}\,\mu_{eff} - k_{eff}^2\right)\right)(\omega - k_x v_b)^2 = \frac{\omega^2}{c^2}(\mu_{eff} - 1)\varepsilon_{eff}\,\omega_b^2$$

Dispersion equation is analogous to TWT equation:
three waves – growing, decaying, and neutral

Beam plasma frequency $\omega_b$

Maximum gain:

$$g_{\max} = \frac{\sqrt{3}}{2}\left(\frac{1}{2}\frac{v_b^2}{c^2}(\mu_{eff} - 1)\varepsilon_{eff}\,\omega\omega_b^2\right)^{1/3}$$

*M. A. Shapiro et al., "Active Negative-index metamaterial powered by an electron beam" to be published in PRB 2012*

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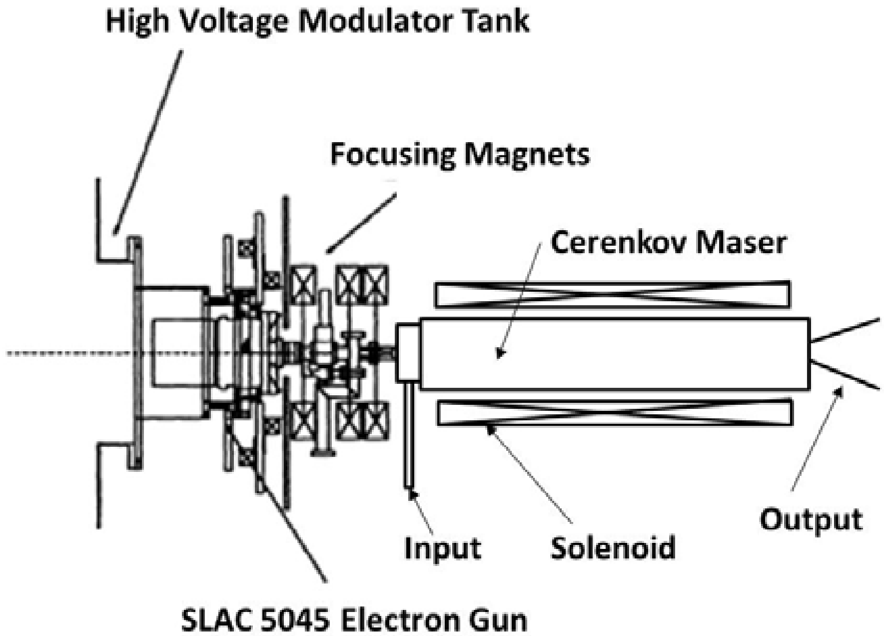
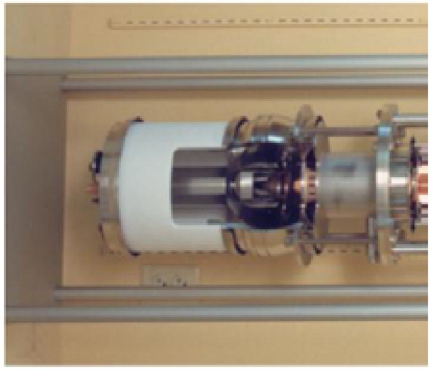
# S-Band MTM Amplifier Experiment

- S-Band (2 -4 GHz) amplifier
  - Wavelength of 10 cm
  - Structure size and breakdown field more manageable
- Input power ~ 100 kW; about 10 to 100 MW output, so we will need 20 to 30 dB of saturated gain
- Plan A is to use SLAC 5045 electron gun: 350 kV, 414A
  - Beam size about 24 mm in diameter, equal to about l /4
  - Magnetic field requirement is 1.4 kG over 0.75 m length
- Plan B is to use Haimson Research Choppertron gun: 500 kV, 80 A, 4 mm beam diameter
  - Already mounted to MIT modulator tank

# Schematic of MTM Amplifier



- Schematic is based on previous implementation of SLAC 5045 electron gun on MIT modulator tank
- SLAC gun shown on right for comparison

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