ECH Program Update

Watt's Happening in ECH Technology

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On behalf of the ECH Technology Program

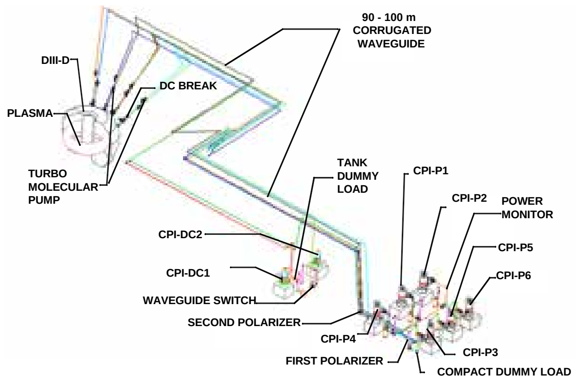
August 15, 2012

VLT
Virtual Laboratory for Technology
For Fusion Energy Science

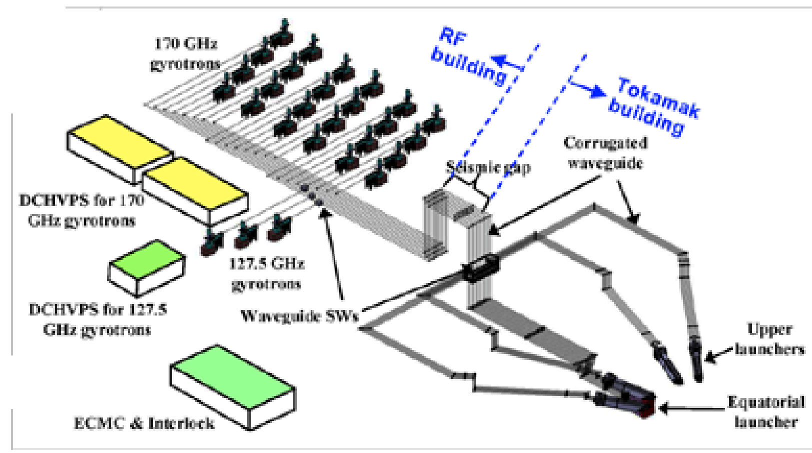
OUTLINE

- **Introduction and Recent Accomplishments**
- **New Experimental Results on Mode Competition in Megawatt Gyrotrons**

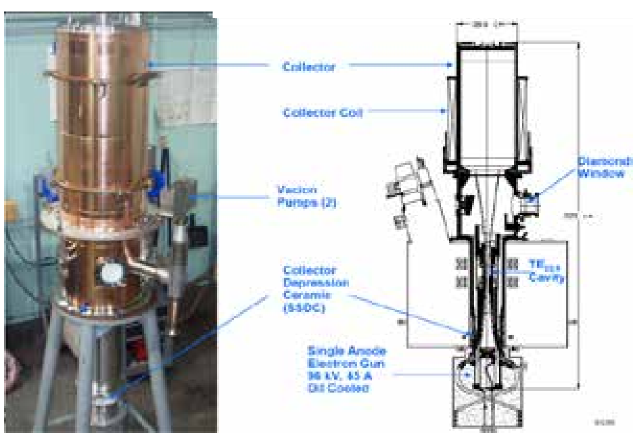
ECH Technology Goals



- Upgrade of DIII-D to 12 MW



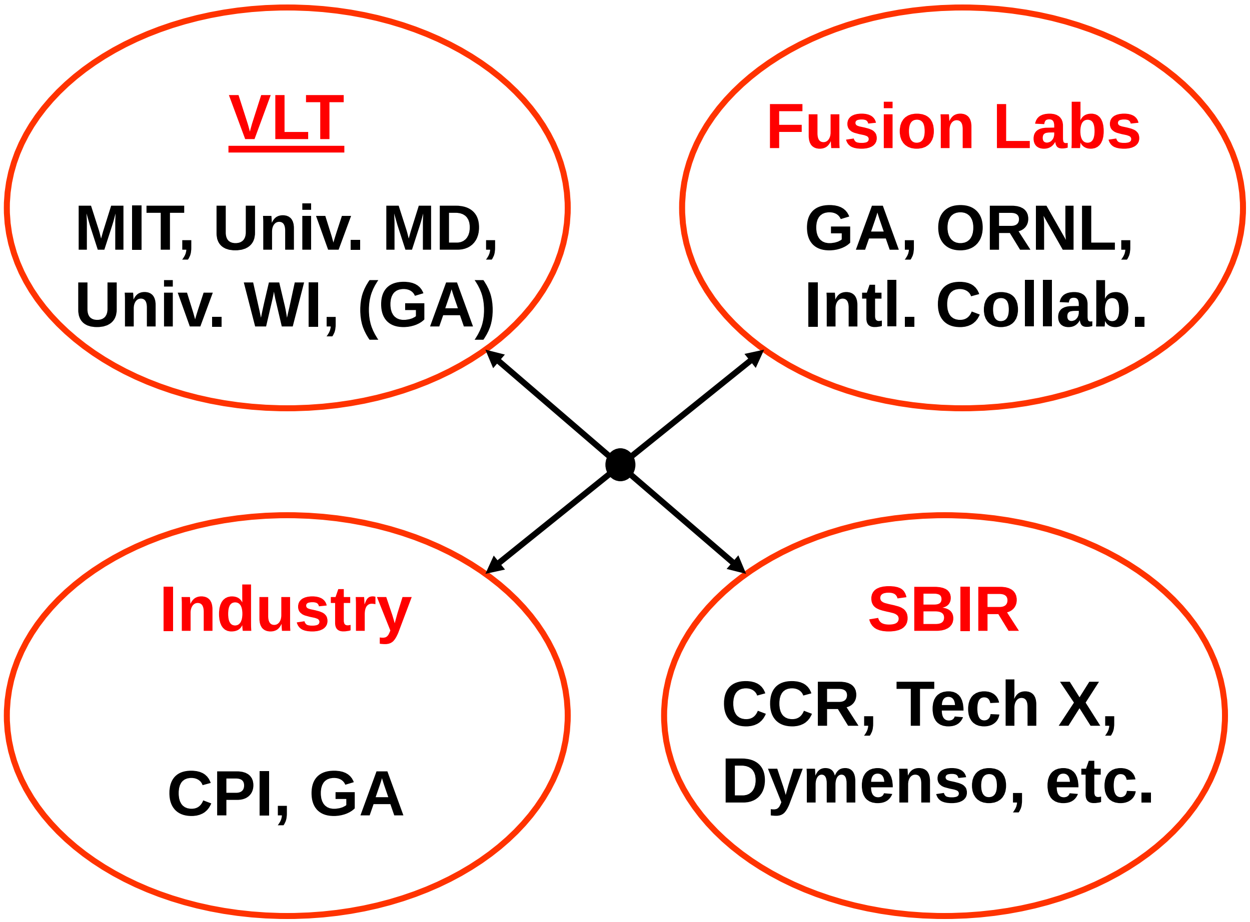
- Support ITER Project /
  ORNL ECH Program



- Support future needs of US fusion program including
  - DEMO
  - Other Machines

- Support industrial gyrotron development

ECH Technology Participants



Recent Accomplishments

- **VLT**
  - **Experimental and theoretical study of mode competition**
  - Demonstration of Smooth Mirror internal mode converter
  - Basic theory of High Order Modes of ITER ECH Transmission Lines

- **Fusion Labs**
  - GA: Upgrade of ECH system to 7.2 MW
  - ORNL: Complete design of ITER ECH Transmission Line System

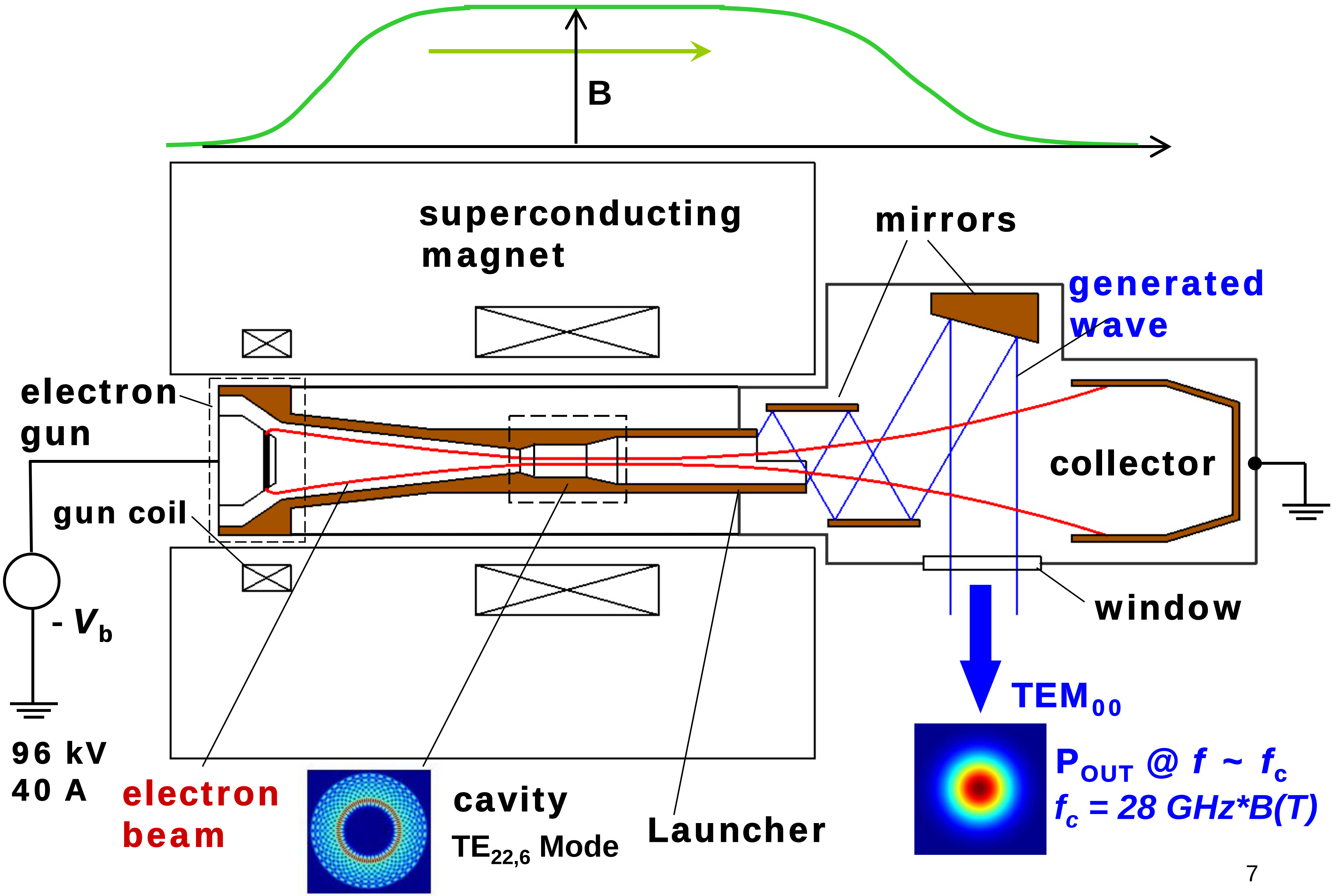
- **Industry**
  - CPI: Fabrication of 1.2 MW, 110 GHz gyrotron for GA;
    Fabrication of 0.5 MW, 170 GHz gyrotron for ORNL ITER Project
  - GA: Fabrication of components for ITER ECH transmission lines

- **Small Businesses**
  - Calabazas Creek Research: Test of novel internal mode converter
  - Tech X: Computer code for calculating gyrotron beam/wave interaction
  - Dymenso: New microwave load for ITER Project

OUTLINE

- **Introduction**
- **New Experimental Results on Mode Competition in Megawatt Gyrotrons**

Gyrotron Schematic



Industrial CPI Gyrotron at DIIID

Gyrotron

SC Magnet

Corrugated Waveguide

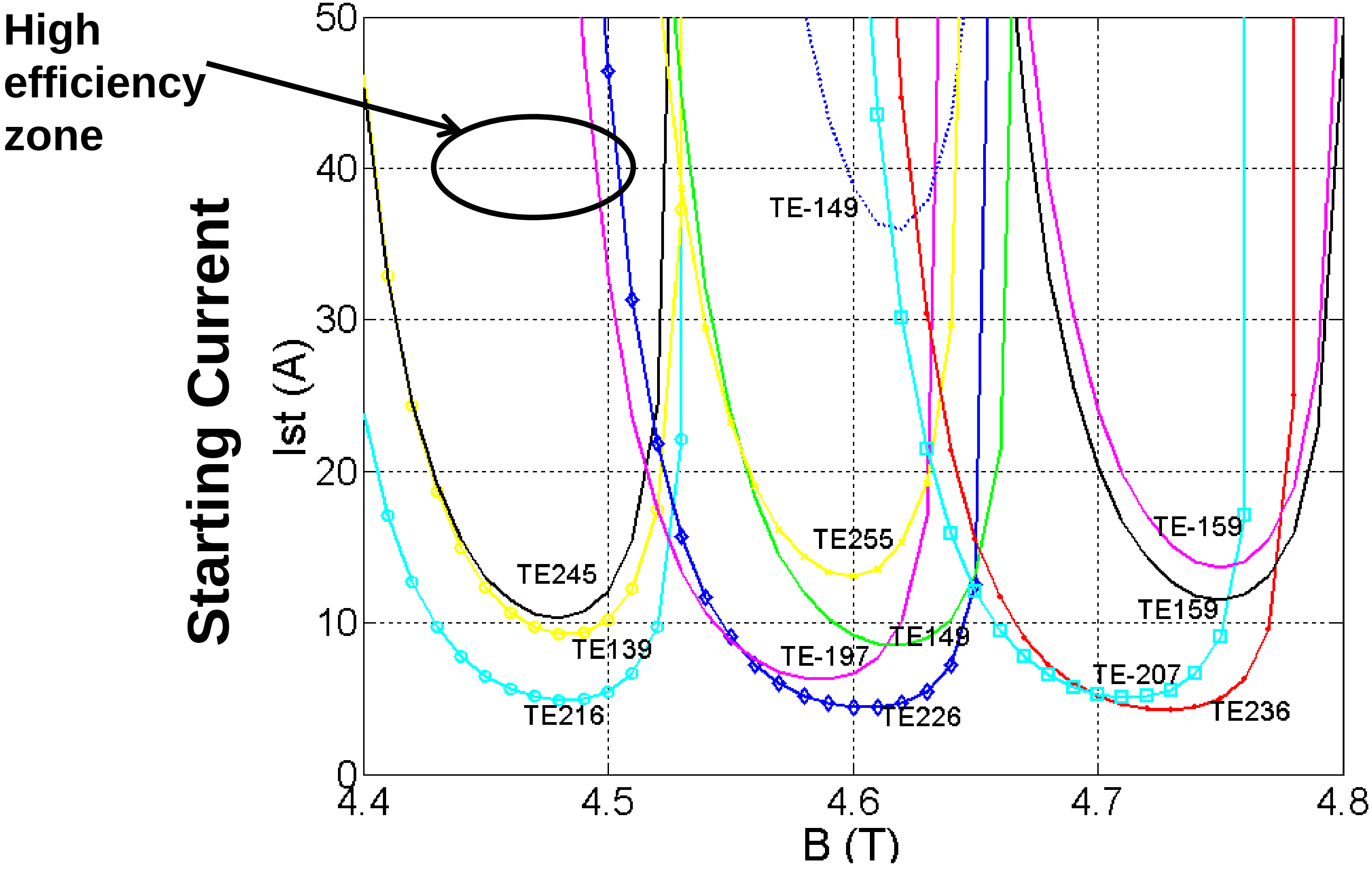
- **1 MW, 110 GHz, 10 sec**

CPI Communications & Power Industries

GENERAL ATOMICS

Gyrotron Mode Competition

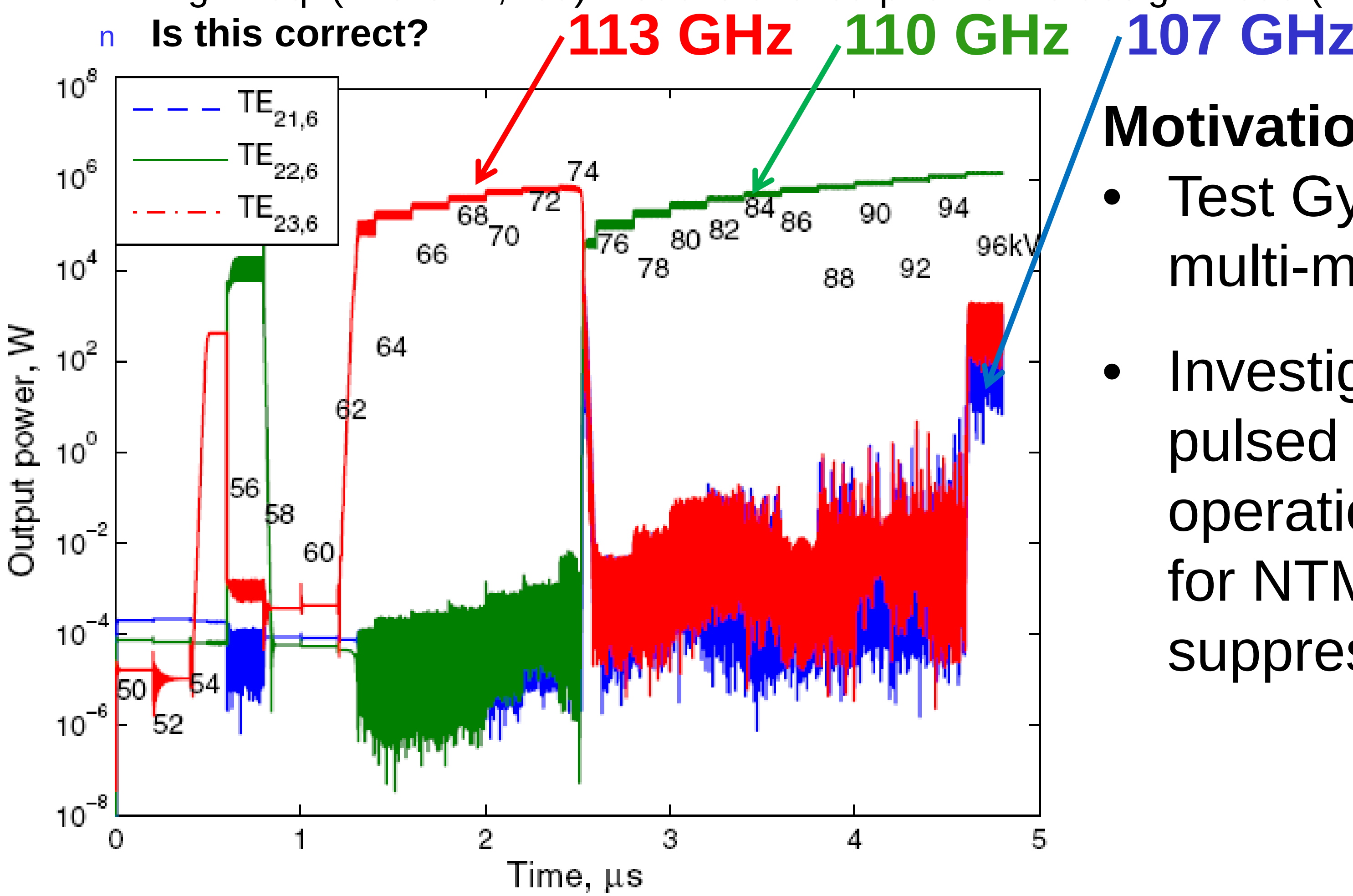
- **Minimum current required for oscillations to grow**



Mode competition leads to reduced efficiency and possible operation in the wrong mode

Motivation for Start-Up Study

- Gyrotron nonlinear multi-mode simulation code (MAGY, MD & NRL) of voltage rise from 50 to 96 kV shows:
  - High freq. (113 GHz, red) mode is excited prior to the design mode (110 GHz, green).
  - **Is this correct?**

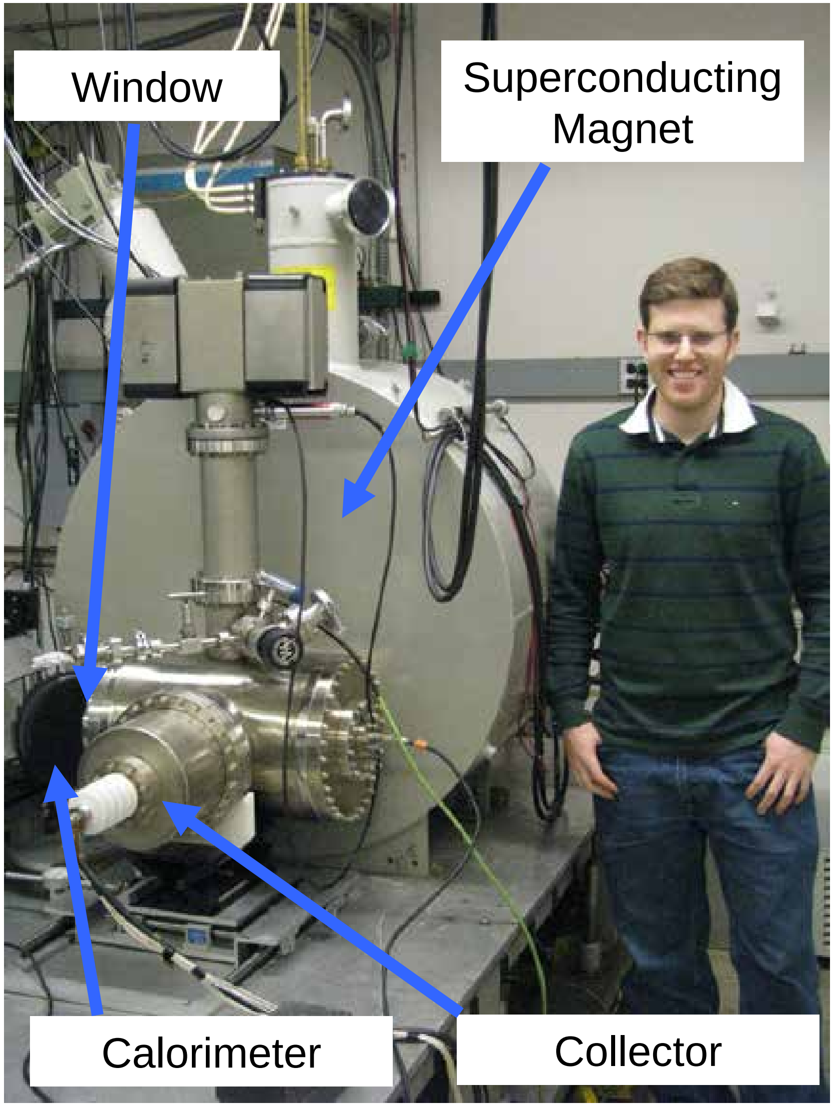


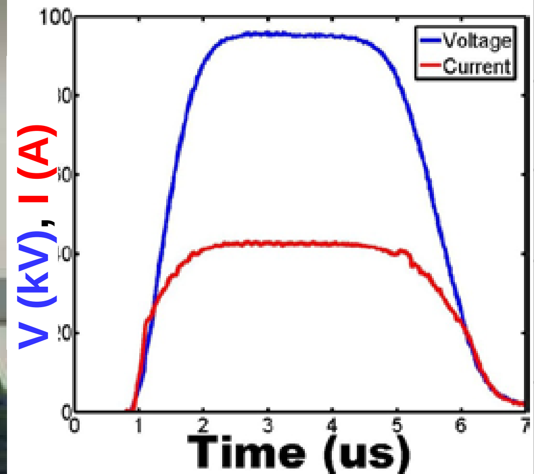
Motivation:

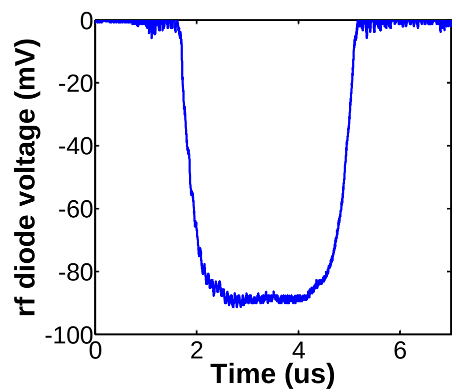
- Test Gyrotron multi-mode theory
- Investigate pulsed gyrotron operation needed for NTM suppression

* G. S. Nusinovich et al Phys Rev Lett Vol. 96 125101 (2006).

MIT Gyrotron

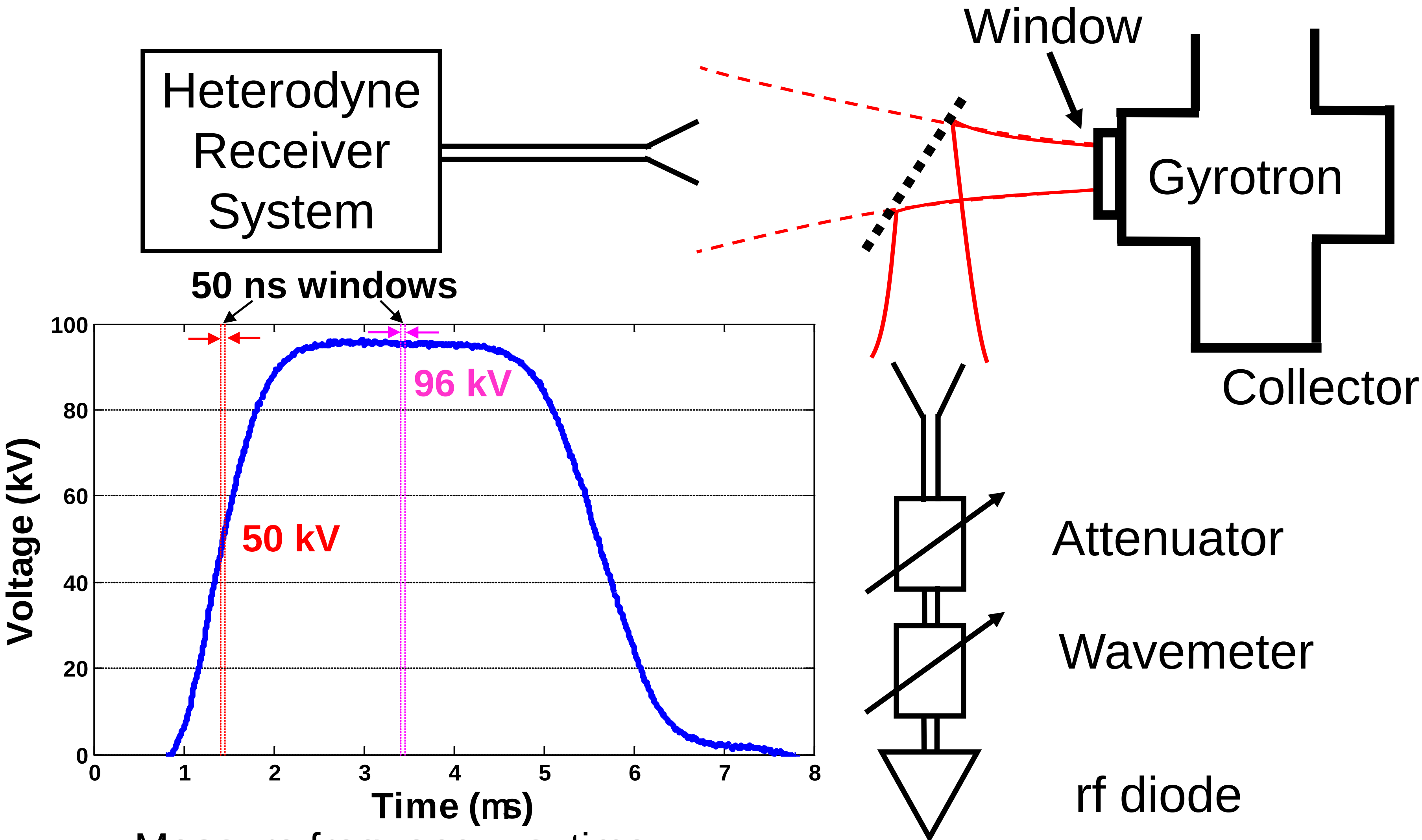






Frequency	110 GHz
Power	1.5 MW
Voltage	96 kV
Current	40 A
Operating Mode	$TE_{22,6}$
Pulse Length	3 μs
Magnetic Field	4.3 T
Efficiency (w/o Depr. Col.) (w/ Depr. Col.)	40 % > 50 %

Power and Frequency Measurement



- Measure frequency vs. time
  - same as frequency vs. voltage

Mode Map

- 2 operating points have been examined in detail:

"**High power**"

P ~ 1.2 MW

B_0 = 4.38 T

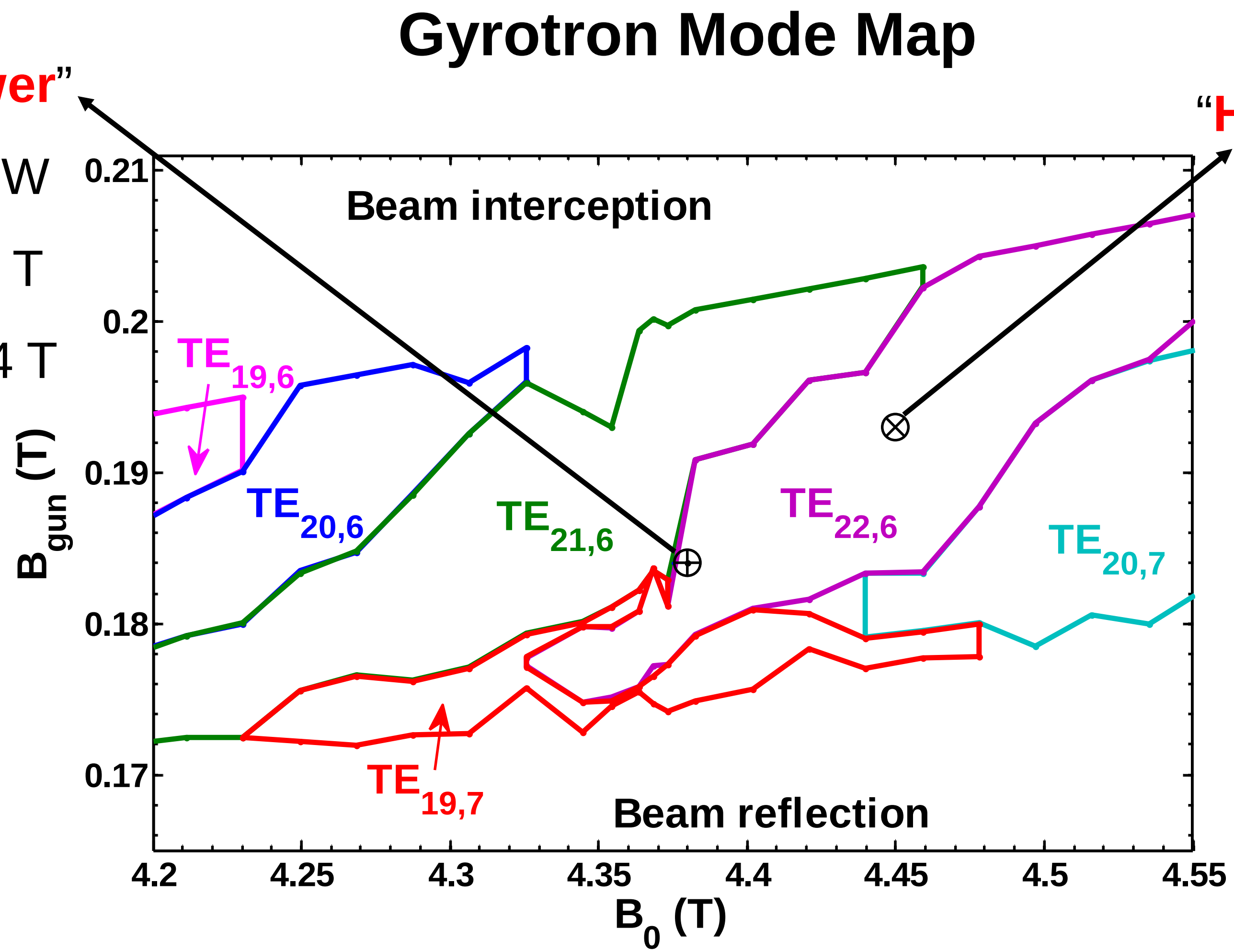
B_g = 0.184 T

"**Highly stable**"

P ~ 600 kW

B_0 = 4.45 T

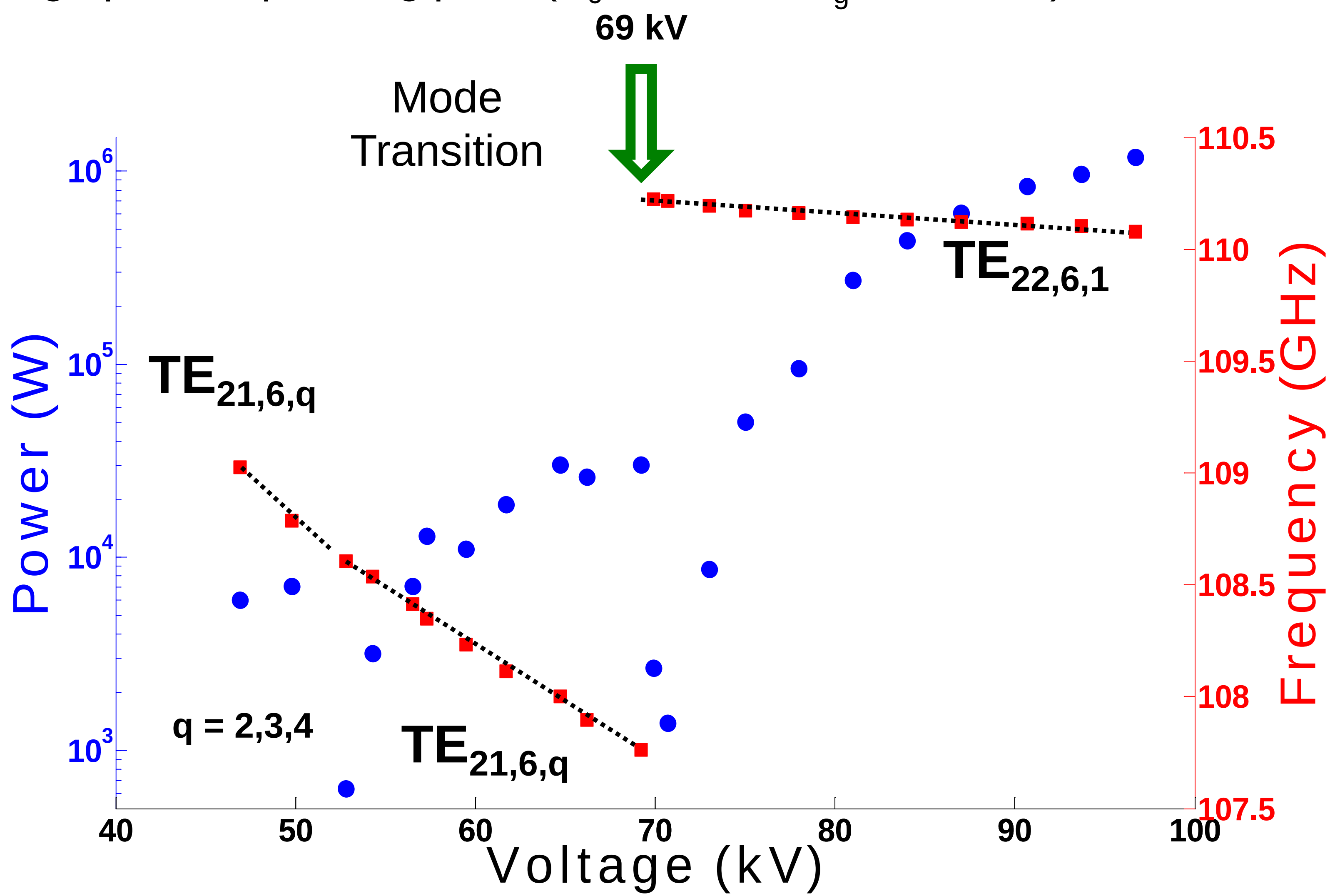
B_g = 0.193 T



V_k = 97 kV, I_{coll} = 42 A

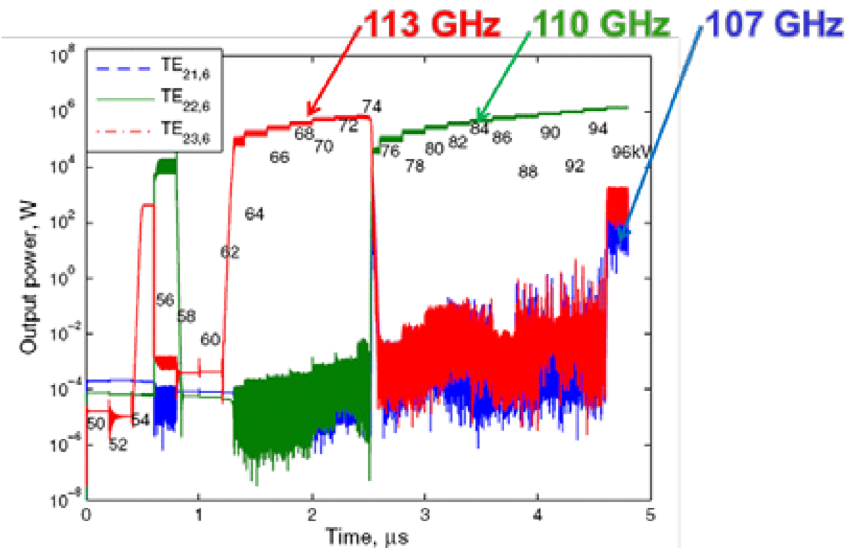
Power & Frequency vs. V @ B=4.38T

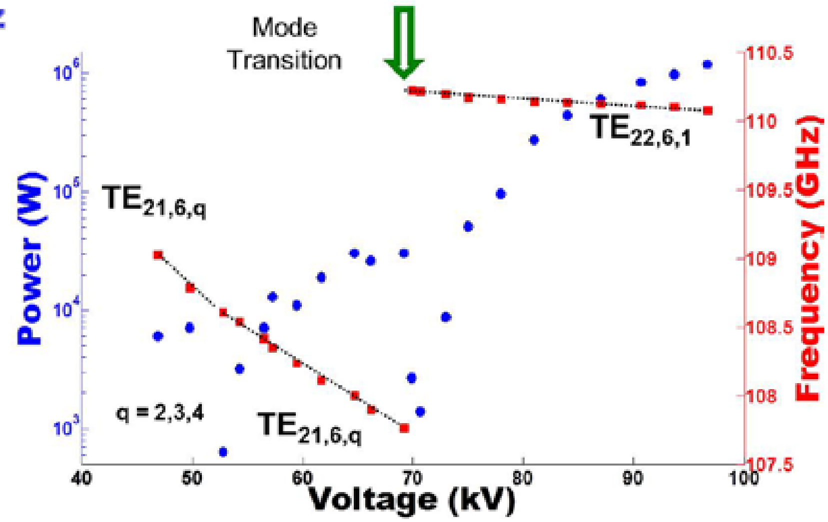
- High power operating point (B_0 = 4.38 T, B_g = 0.184 T):



Theory vs. Experiment

- Theory predicts competition from high frequency modes (113 GHz)
- Experiment finds competition from lower frequency modes (108 GHz)





Theory
Predicts 113 GHz Mode

Experiment
Finds 108 GHz Mode

Dispersion Relation

- Uncoupled dispersion relation indicates that the modes seen at low voltages are backward waves with large axial k_z (far from cutoff):

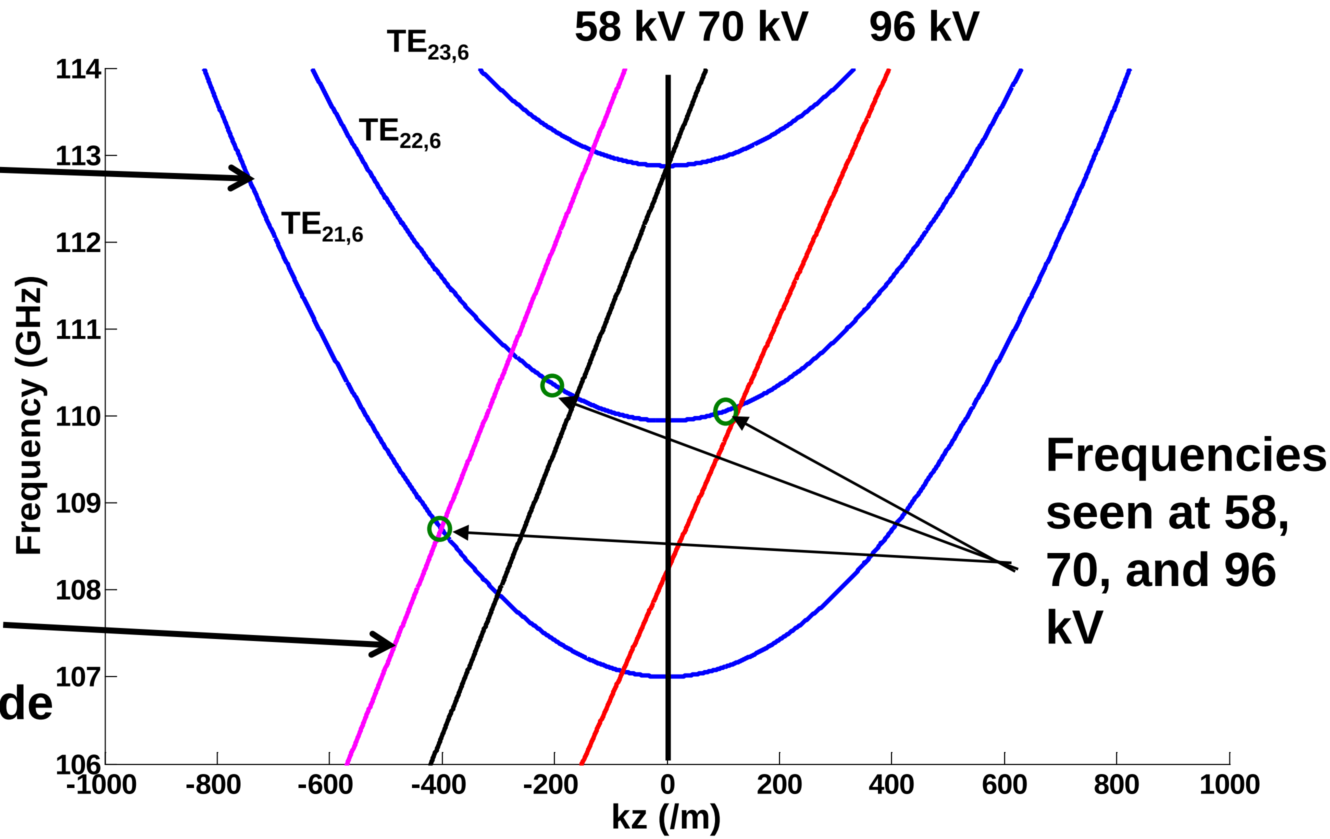
Waveguide Mode

$$\frac{\omega^2}{c^2} = k_\perp^2 + k_z^2$$

$$\omega - k_z v_z = \omega_c / \gamma$$

$$\gamma = 1 + V_b / 511kV$$

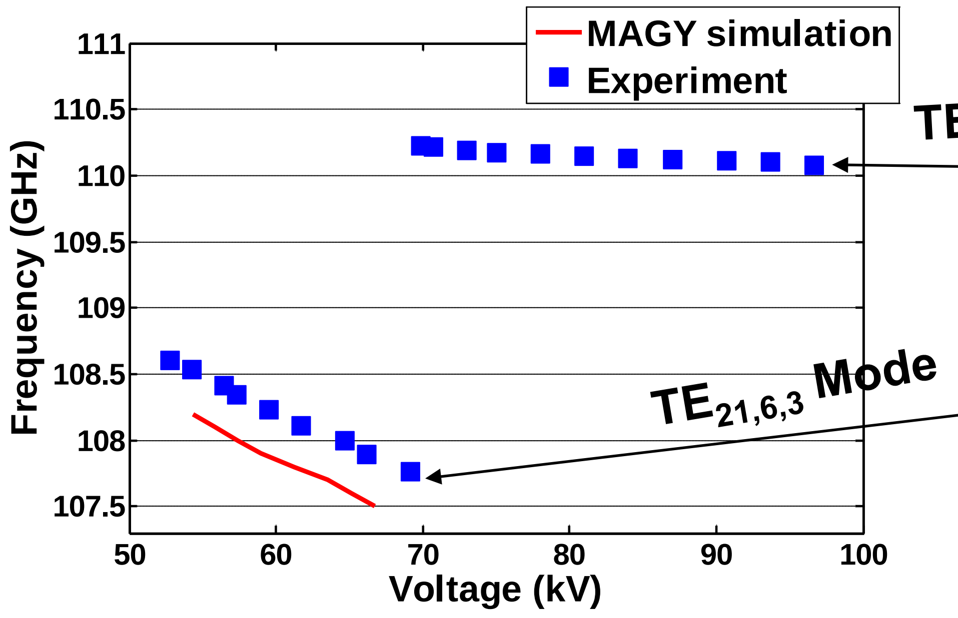
Beam Cyclotron Mode



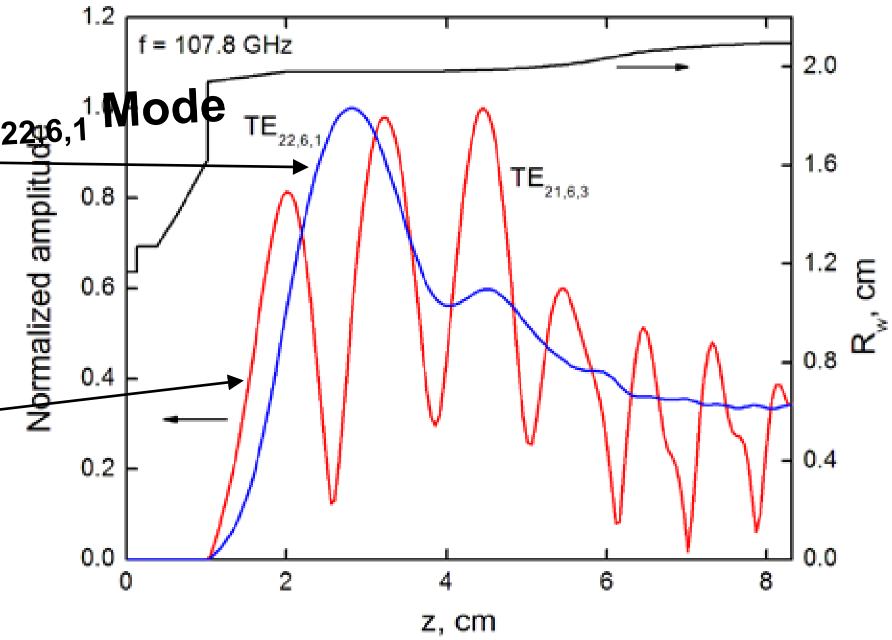
MAGY Simulations

- MAGY simulations identify the excitation of $TE_{21,6,q}$ (q > 1) modes during voltage rise:

Observed Frequencies



Axial Field Profile



MAGY simulations by O. Sinitsyn (U MD)

Conclusions

- VLT ECH Program continues to make major progress in support of FES program needs
  - Many recent accomplishments

- Mode excitation during Voltage Rise of the Gyrotron has been studied theoretically and experimentally
  - Multi-mode nonlinear code MAGY predicts high frequency mode competition
  - Experiments show lower frequency modes are excited
  - New simulations with MAGY identify the low frequency modes and their frequencies vs. voltage

- Future Plans
  - Two frequency gyrotron research: 110 and 124 GHz
  - Efficiency improvement in depressed collector gyrotrons

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