Really, Really Efficient ECH Heating Systems

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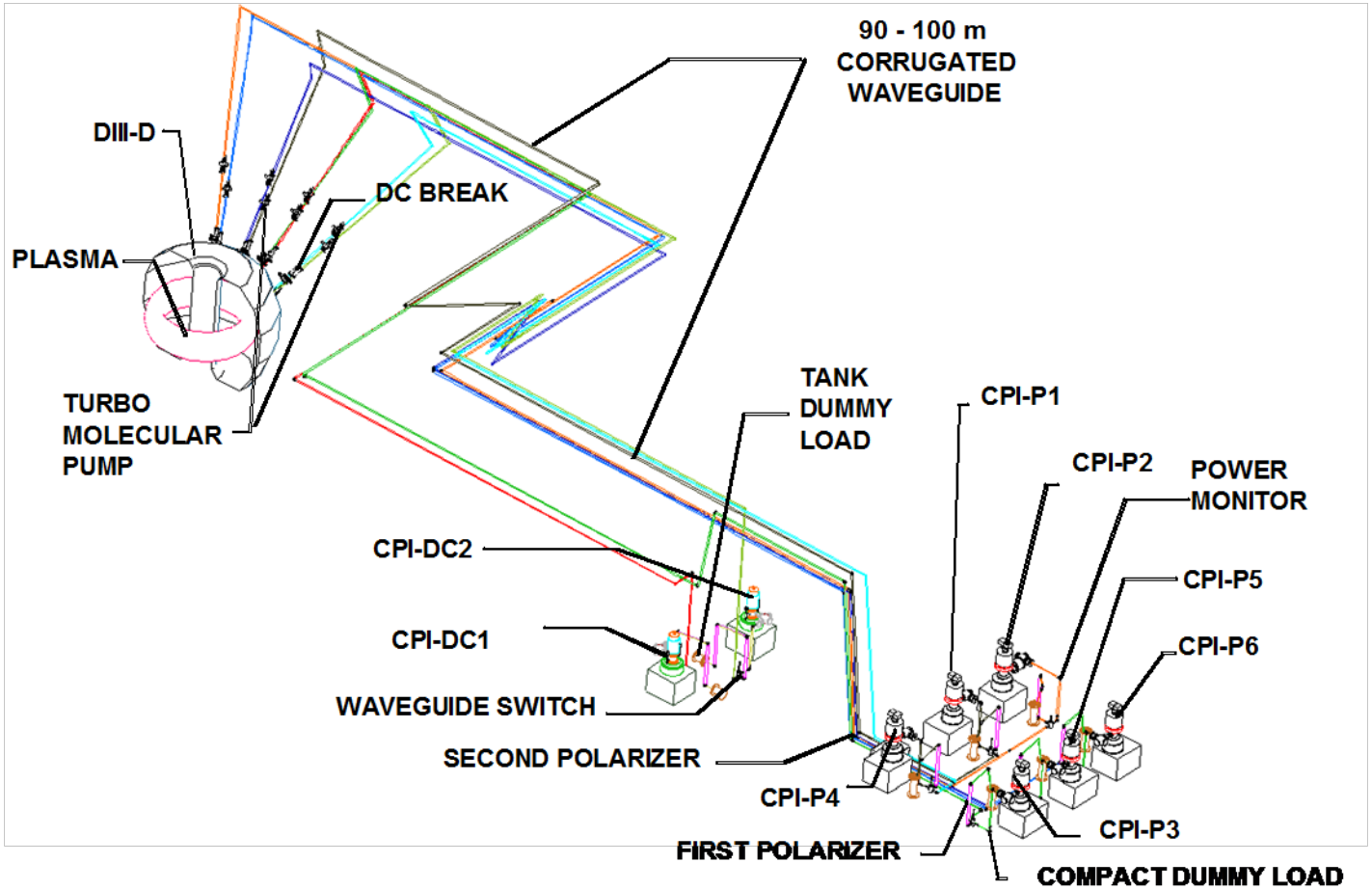
VLT Conference Call
October 17, 2007

Topics

- Challenges / Opportunities for ECH Technology
  - DIII-D ECH Upgrade
  - ITER
- Recent Advances for Higher Efficiency
  - **Internal Mode Converters**
  - **Depressed Collector**
  - Gyrotron Cavities
  - Transmission Lines
- Efficiency 30 → 40 → 50 → 60 → 70% (?)

6 MW ECH System at DIII-D

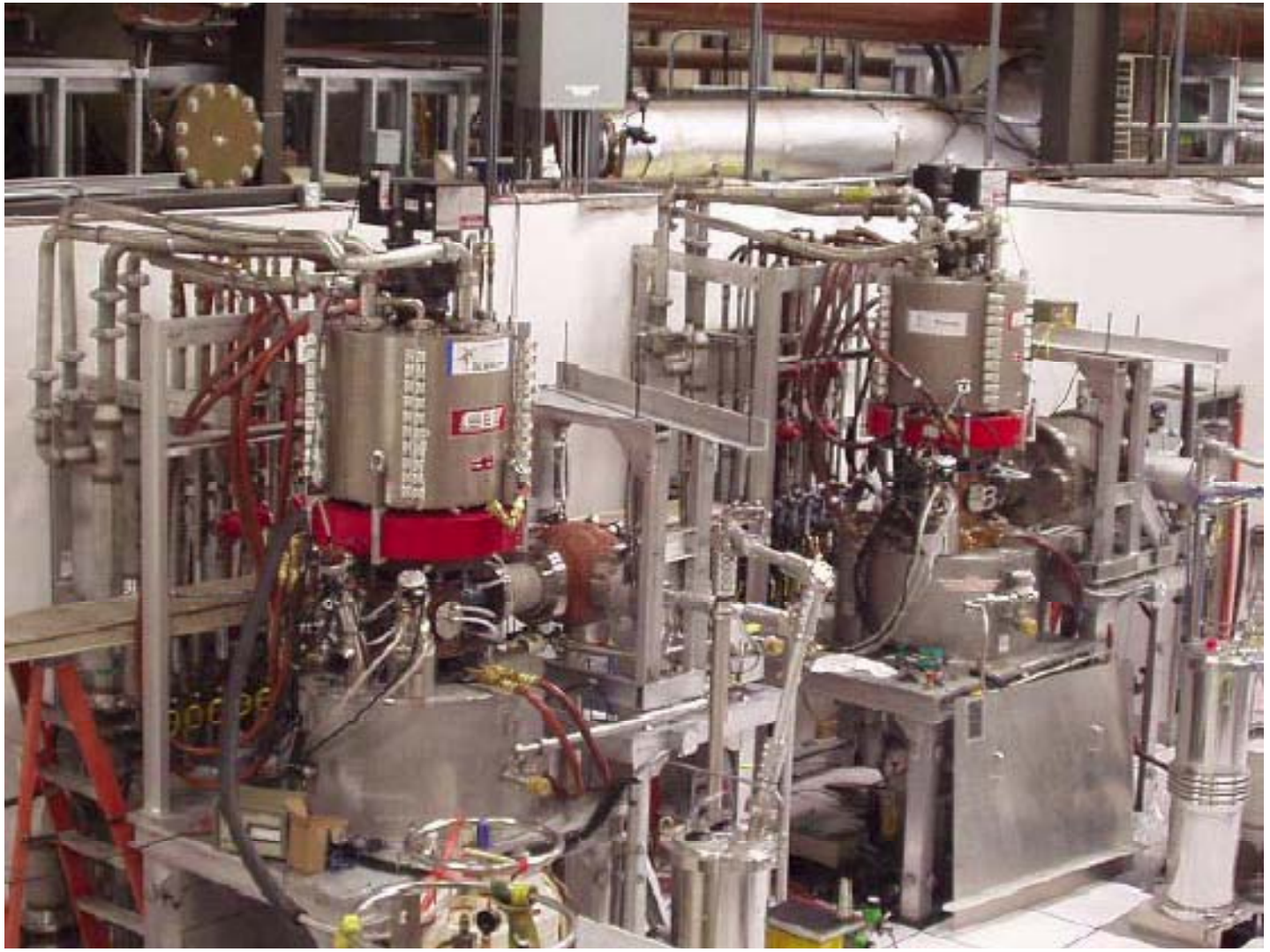


Achieved:

- 1 MW
- 110 GHz
- 10 sec

Planned Upgrade to 12 MW using 1.5 MW gyrotrons by 2012

DIII-D ECH System

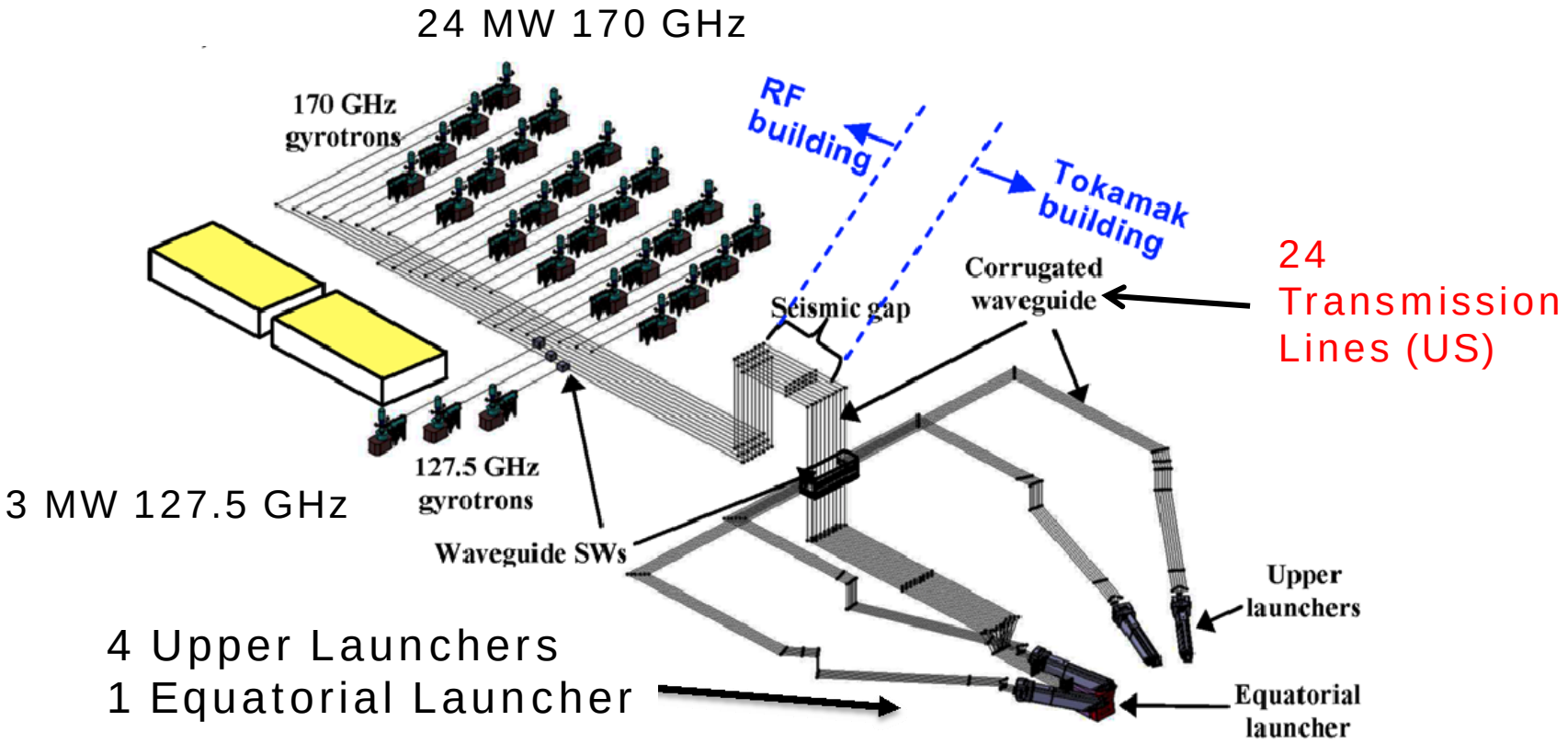


- Two of the six 1 MW, 110 GHz gyrotrons

Motivation

- The efficiency of 1 MW CW gyrotrons can be low.
  - CPI 1 MW, 140 GHz gyrotron efficiency is < 40%.
  - But CPI 100 kW, 95 GHz gyrotron efficiency > 50%.
  - Why? Physics is not yet fully understood.
- Higher efficiency means:
  - Lower heat loading on the collector.
  - Smaller power supplies.
  - Reduced water flow.
  - Lower Cost.

ECH/ECCD System for ITER



- US supplies all transmission lines
  - Can we improve the efficiency of the lines?

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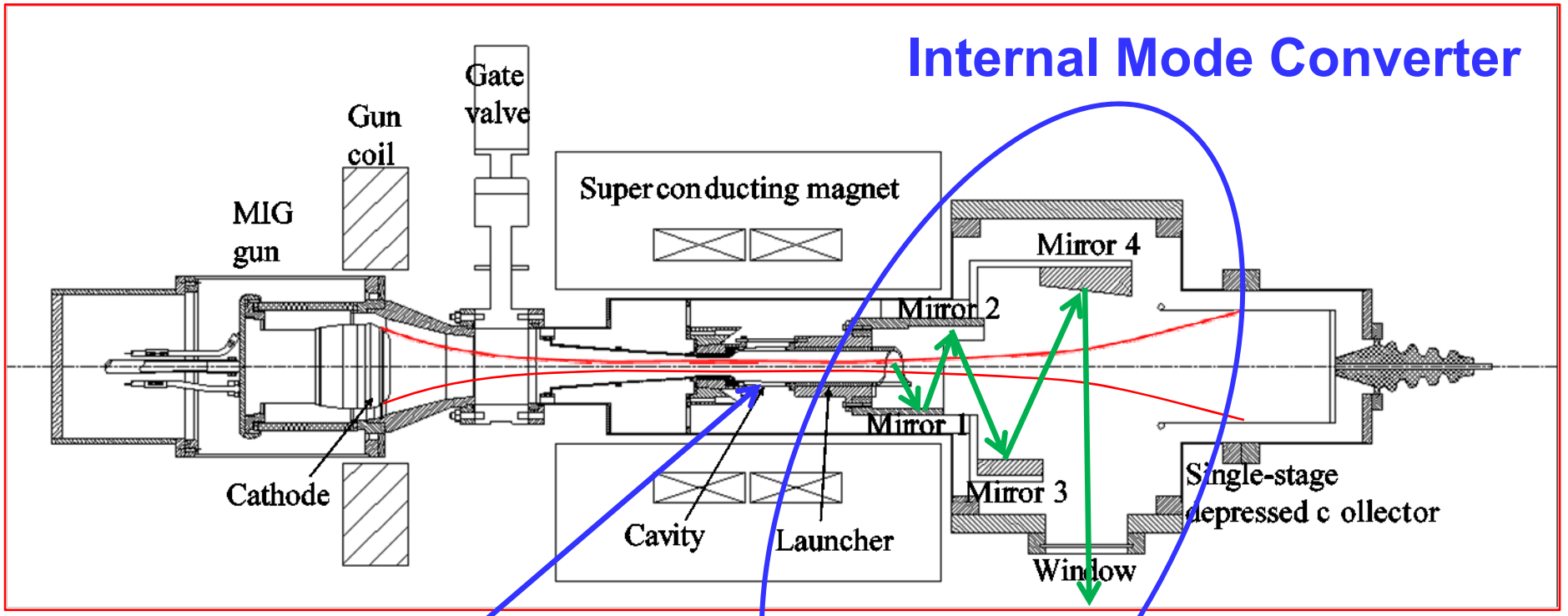
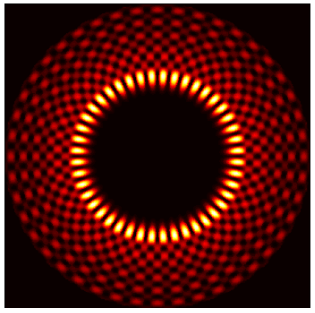
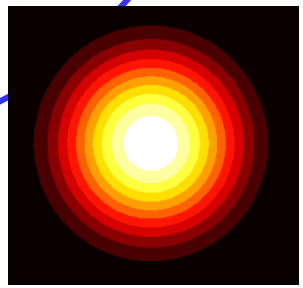
Gyrotron Schematic



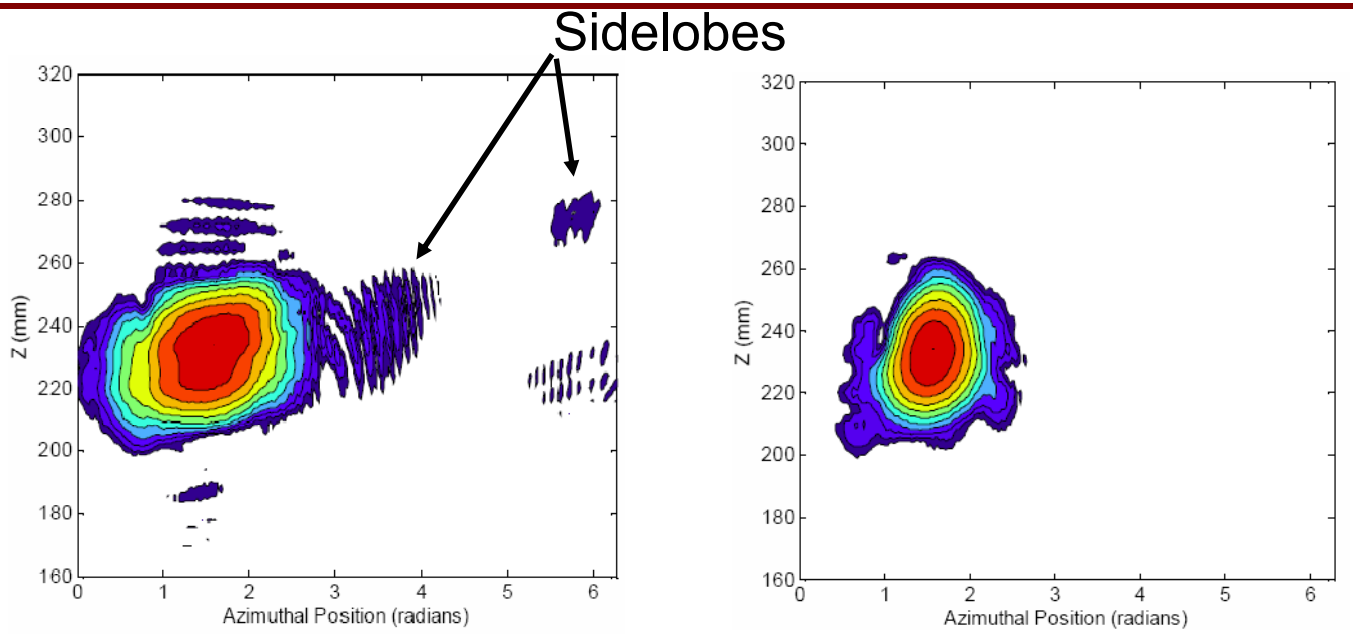


$TE_{22,6}$ Mode

Gaussian Output Beam



New Internal Mode Converter Code



Old Design

New Design

- New Launcher Design produces excellent, near-Gaussian microwave beam
- Improves internal mode converter efficiency from 92% to > 98%; critical advance
- In use in US, Europe, Japan

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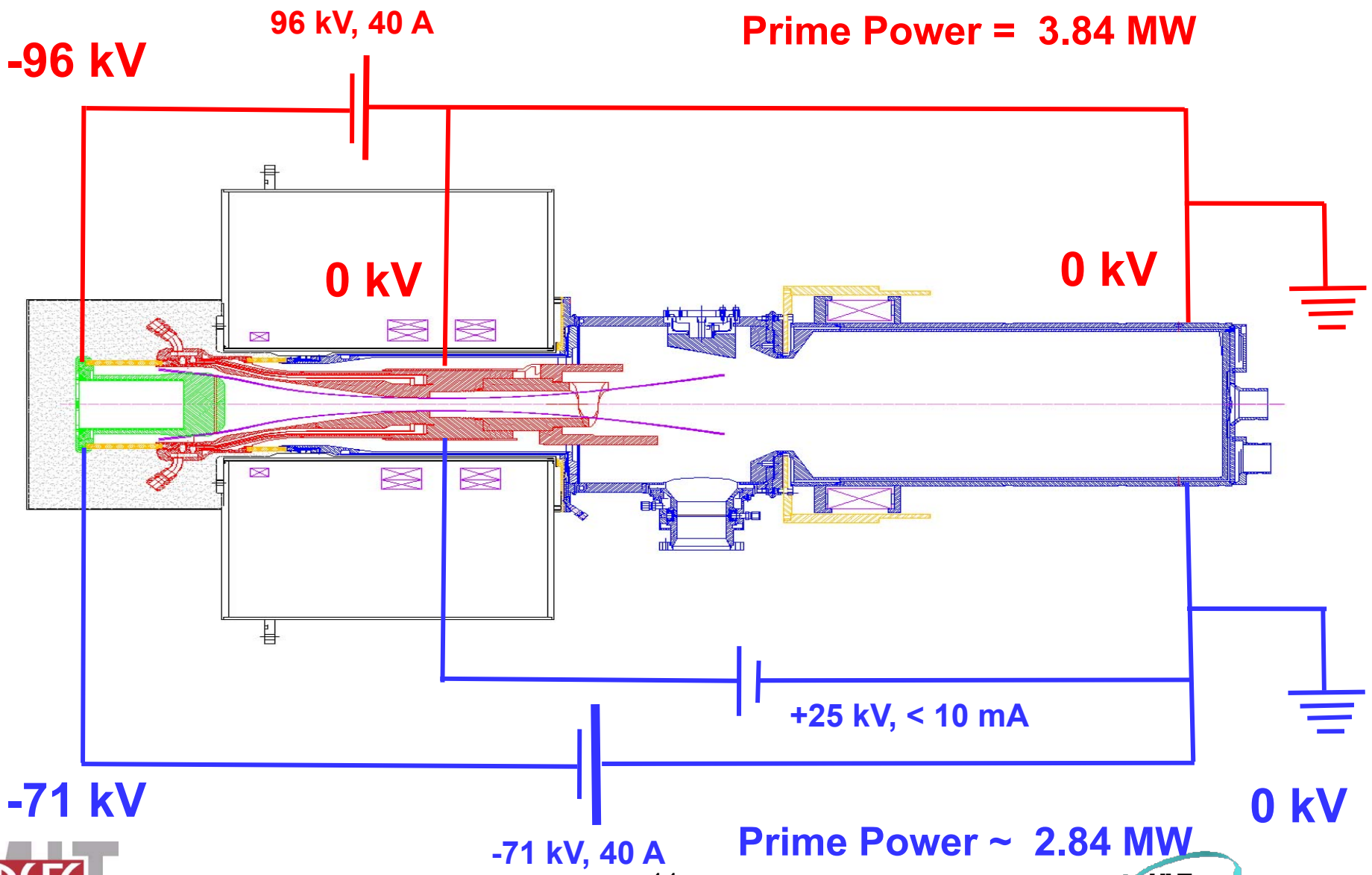
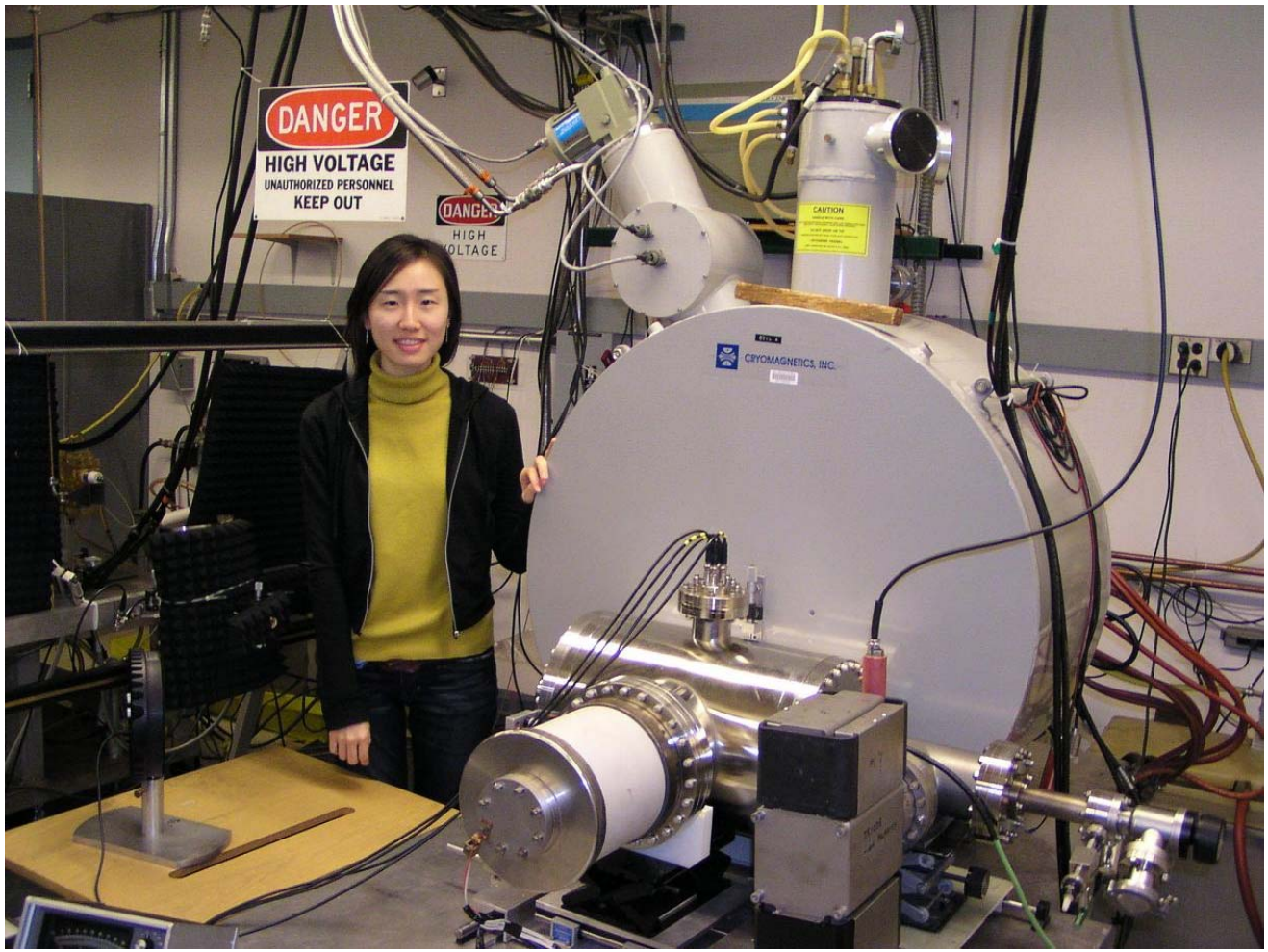
Depressed Collector

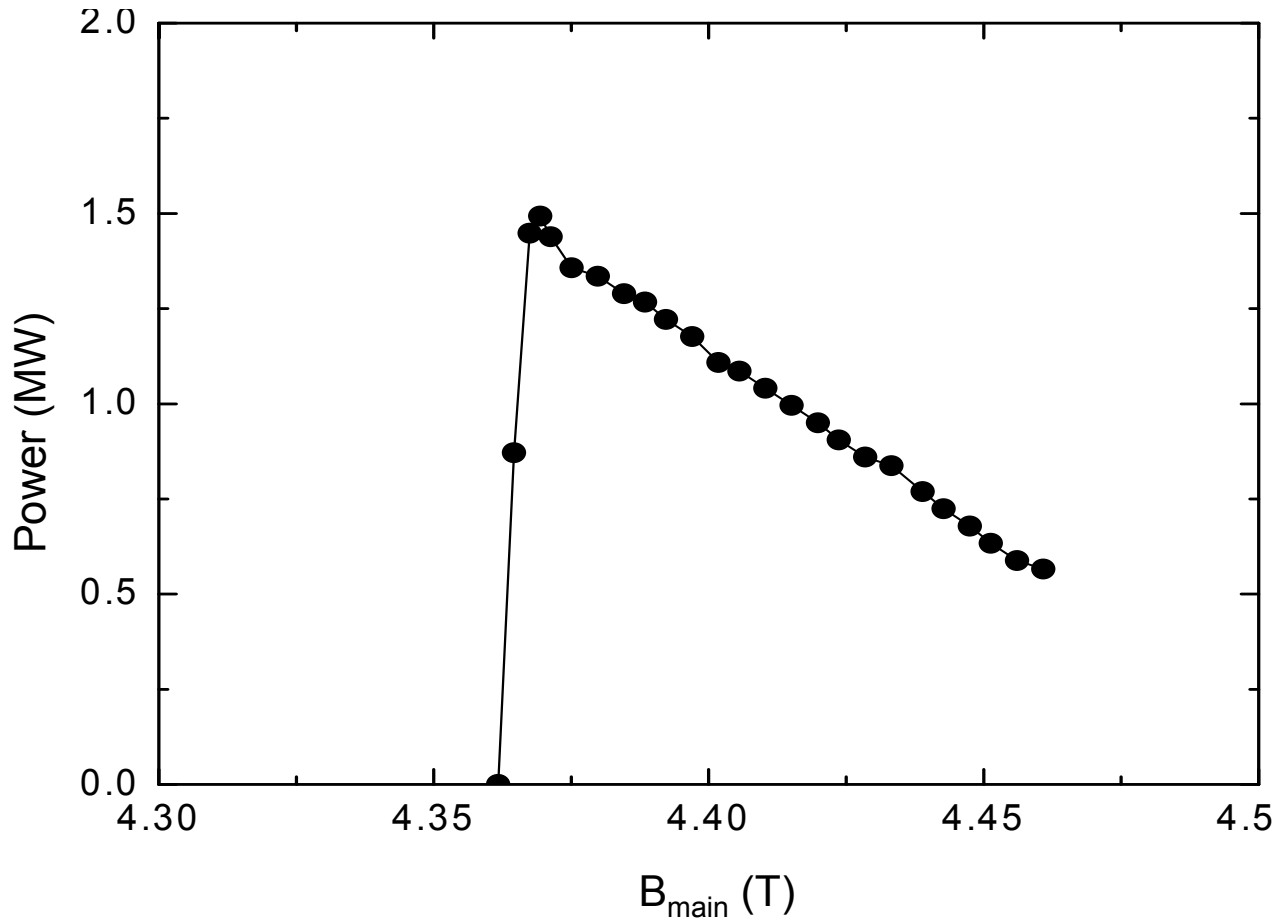


Experimental Setup



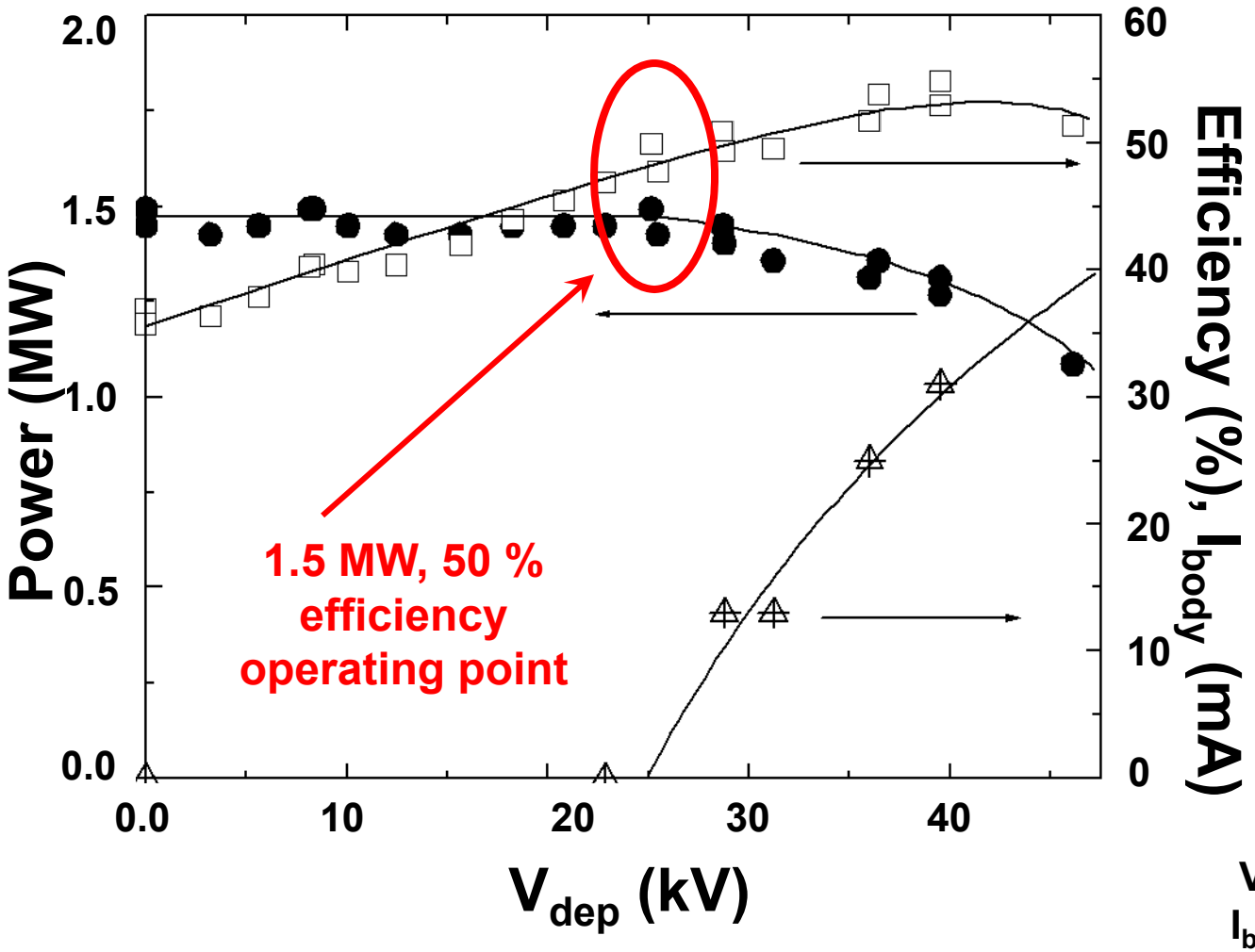
Frequency	110 GHz
Power	1.5 MW
Voltage	96 kV
Current	40 A
Operating Mode	$TE_{22,6}$
Pulse Length	3 μs
Magnetic Field	4.3 T
Efficiency (w/o Depr. Col.)	40 %
(w/ Depr. Col.)	> 50 %

Power vs. Magnetic Field



- Max. power of 1.5 MW obtained at 96 kV, 42 A.

Depressed Collector Operation

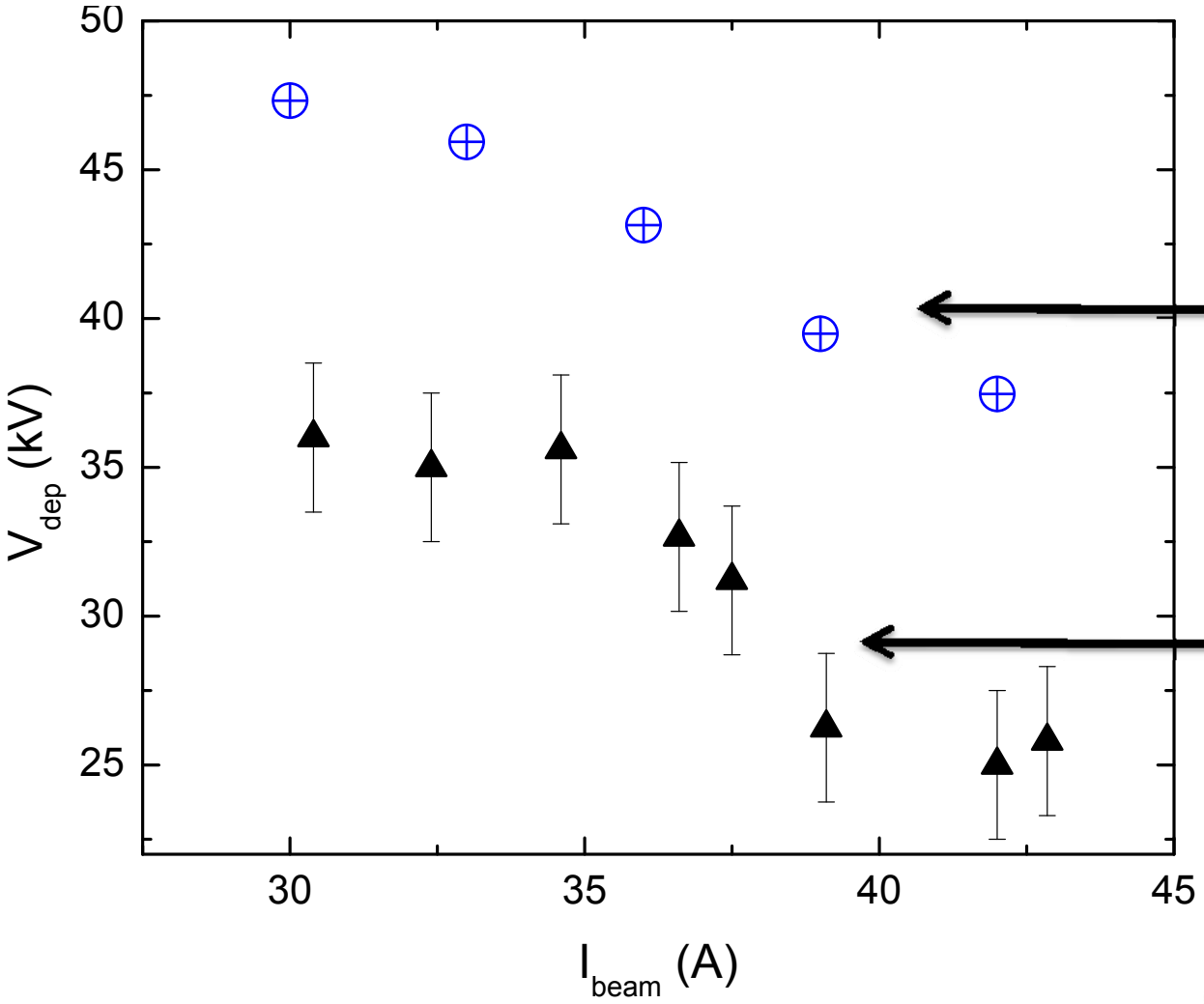


V_k = 96 kV
I_{beam} = 42 A

- V_{dep} is limited to ≤ 25 kV by the onset of body current.

Theory and Experiment

- What about theoretically predicted collector depression?



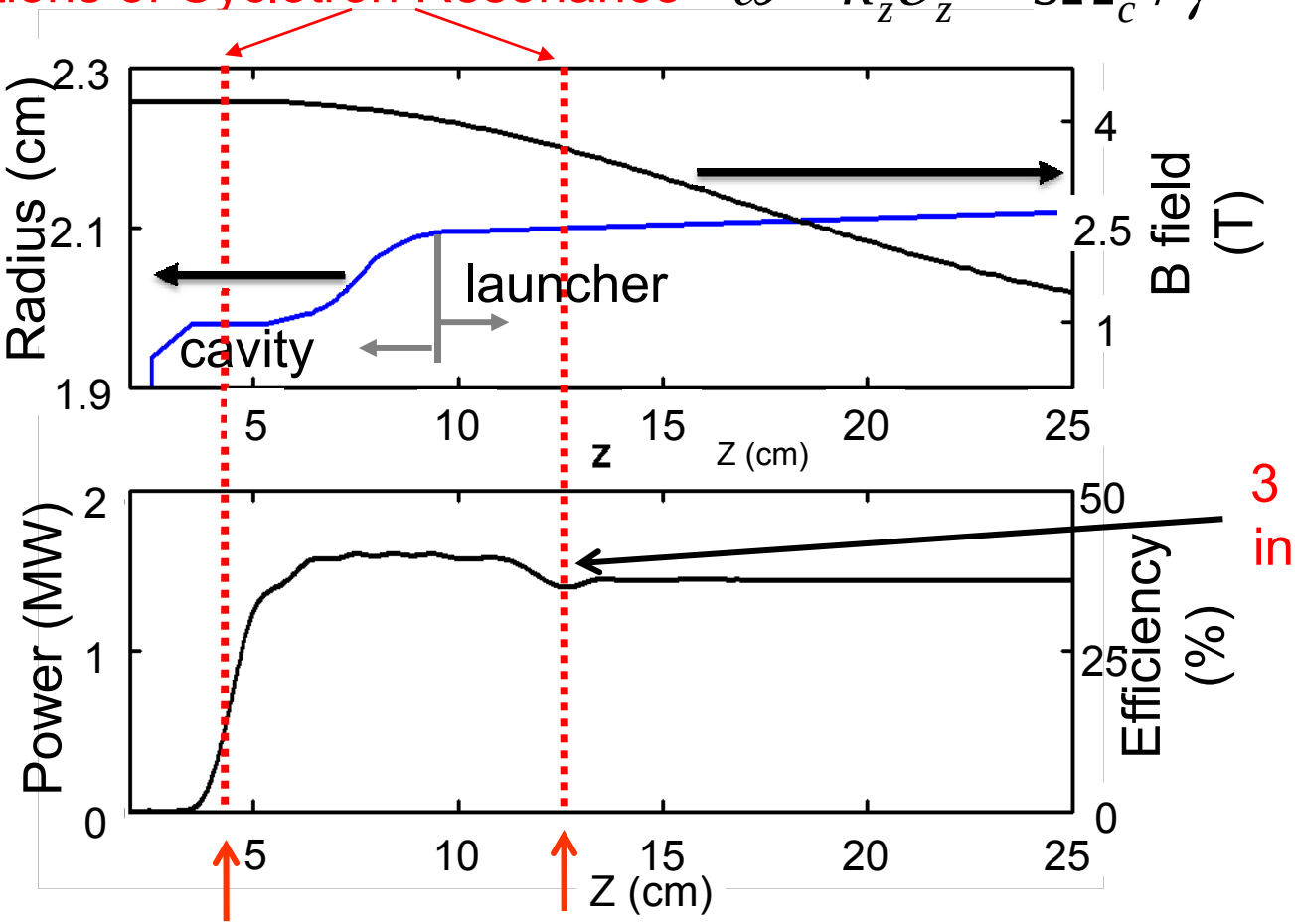
MAGY Prediction

Experimental Results

V_k = 96 kV

After Cavity Interaction

Locations of Cyclotron Resonance $\omega - k_z \upsilon_z \approx s\Omega_c / \gamma$

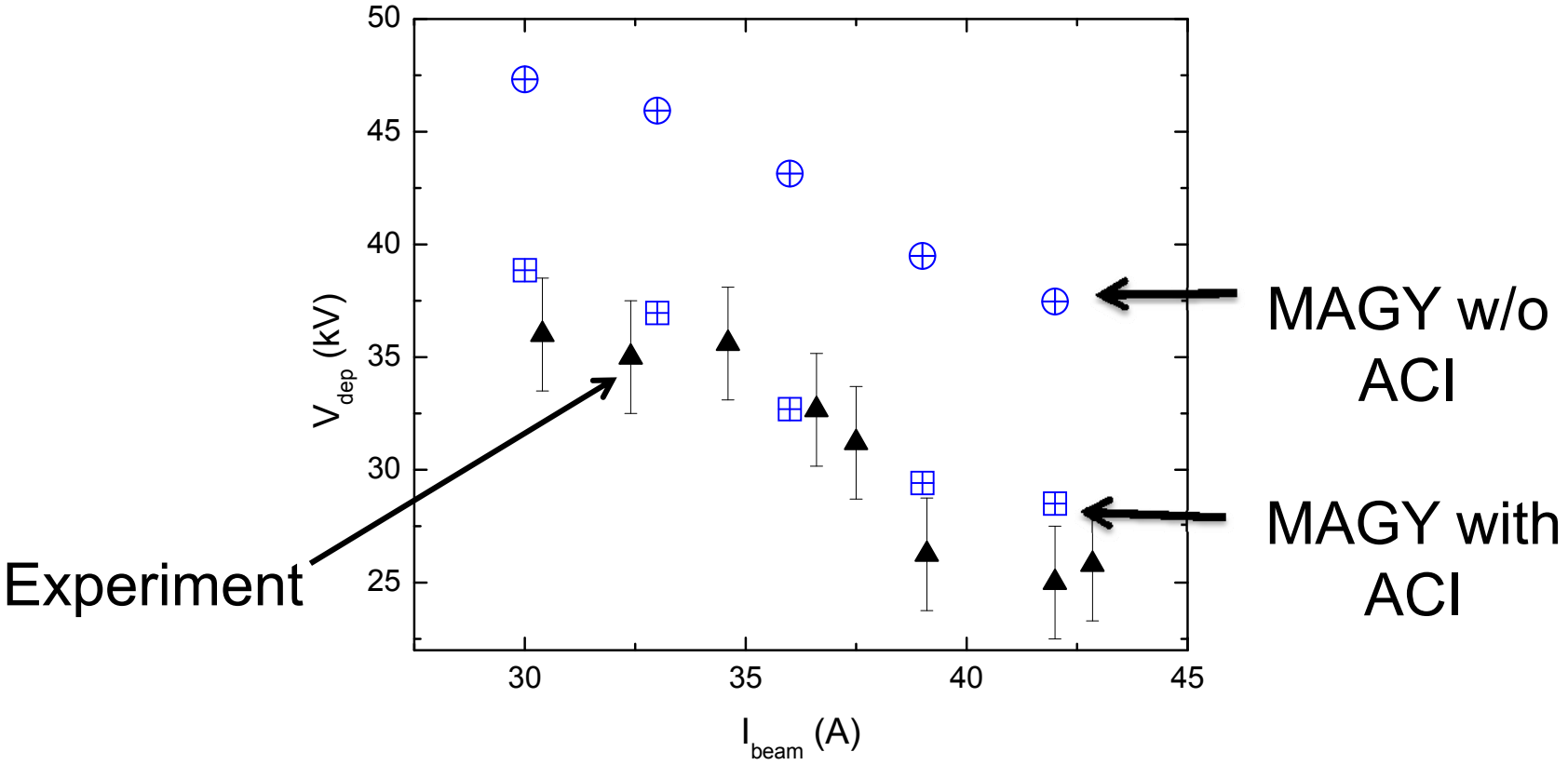


3 % drop in Power

Power Generated in Cavity

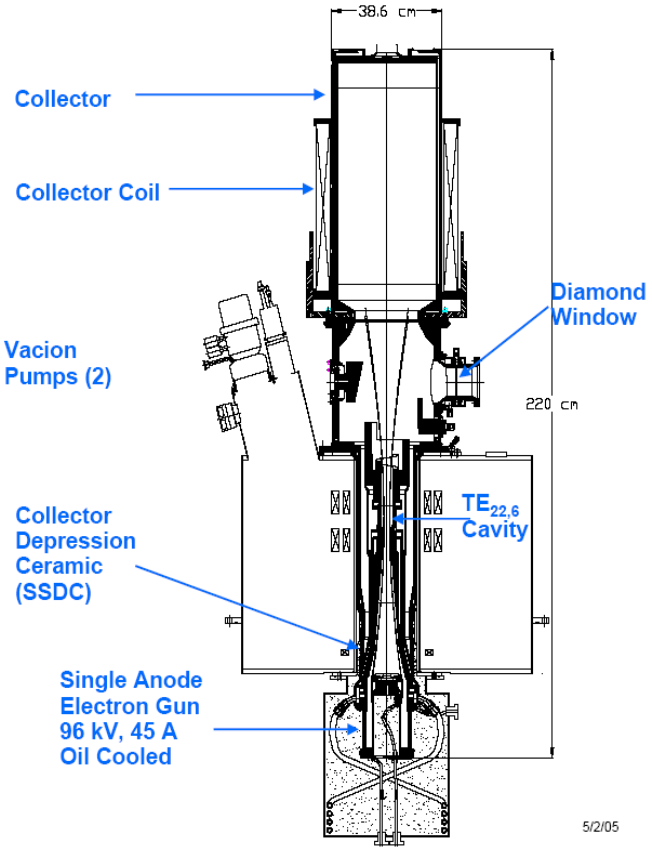
Unwanted power loss after cavity

Theory and Experiment



- Good agreement between experiment and simulation when After Cavity Interaction is included
- Future Work: New gyrotron cavity and waveguide system to eliminate this effect!

110 GHz, 1.5 MW CPI Gyrotron



Achieved

- **1.3 MW at 96 kV, 40 A (ms pulses)**
- **0.5 MW, 10 s at 25 A**
- **Efficiency = 42 %**

- **Sent to DIII-D for test but failed due to vacuum leak**
- **Rebuild could incorporate these new ideas for high efficiency operation.**

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Acknowledgments

- Gyrotron Development Program – National Consortium within VLT

Communications & Power Industries

GENERAL ATOMICS

Users

Industry

MIT PSFC

UNIVERSITY of WISCONSIN MADISON

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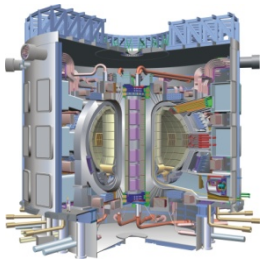
Universities

VLT Virtual Laboratory for Technology For Fusion Energy Science



- ITER ECH Technology (ORNL)
- MIT Group: M. Shapiro, J. Sirigiri, S. T. Han, Y. Hidaka, I. Mastovsky, A. Cerfon, E. M. Choi, E. N. Comfoltey, D. Tax