VLT
Virtual Laboratory for Technology
For Fusion Energy Science

ITER ECH System and US ECH Program for ITER

R. Vernon, R. Temkin, R. Callis, K. Felch, T. V. George, G. Nusinovich, M. Shapiro, and the US ITER ECH Team

16th TOFE, Madison, Wisconsin

Wednesday, September 15, 2004

Participating US Groups

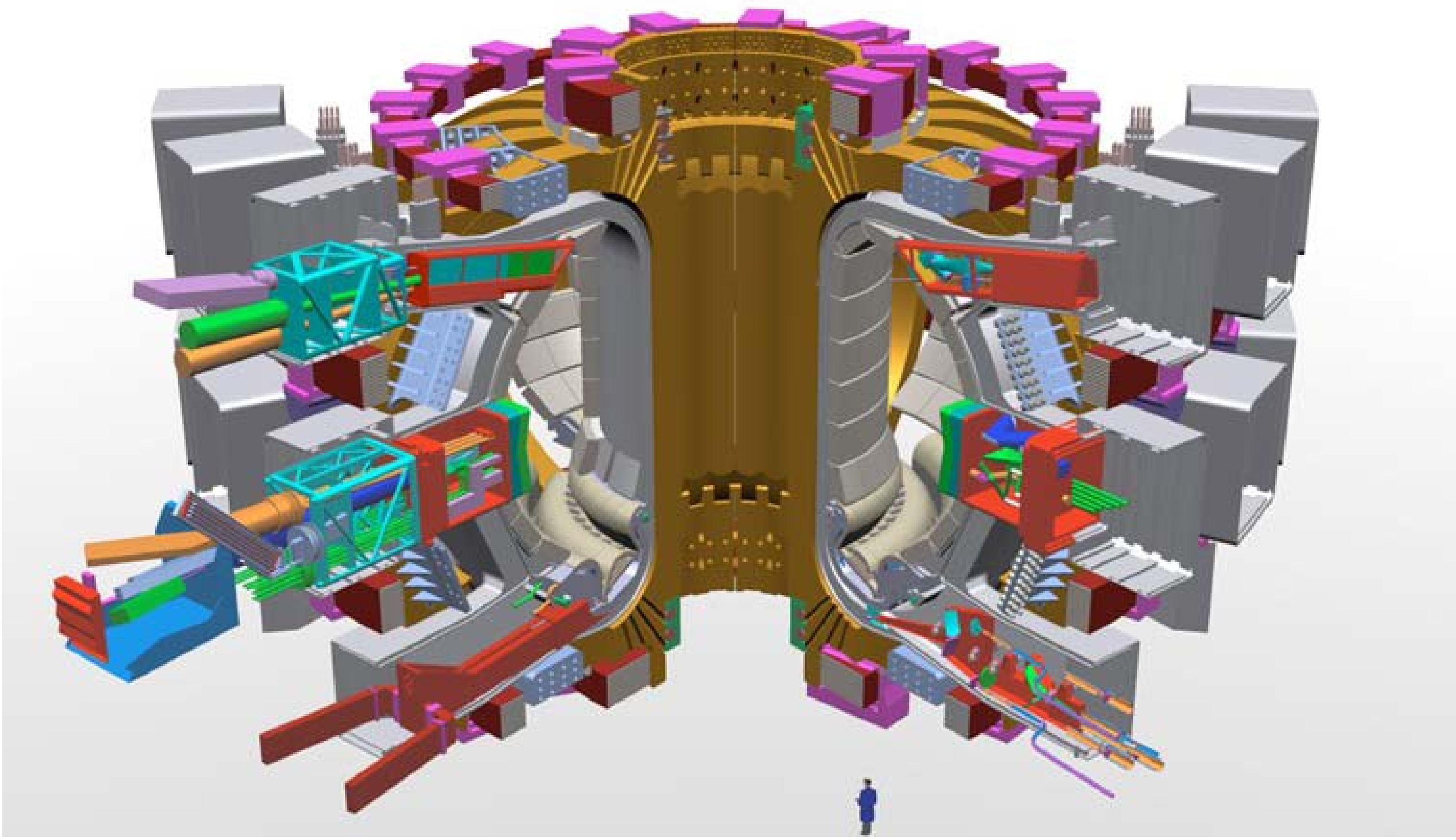
- MIT - Rick Temkin, Michael Shapiro
- General Atomics - Rich Callis
- CPI - Kevin Felch
- Univ. of Maryland - Gregory Nusinovich
- Univ. of Wisconsin - Ron Vernon
- CCR - Lawrence Ives, Jeff Neilson

Topics

VLT
Virtual Laboratory for Technology
For Fusion Energy Science

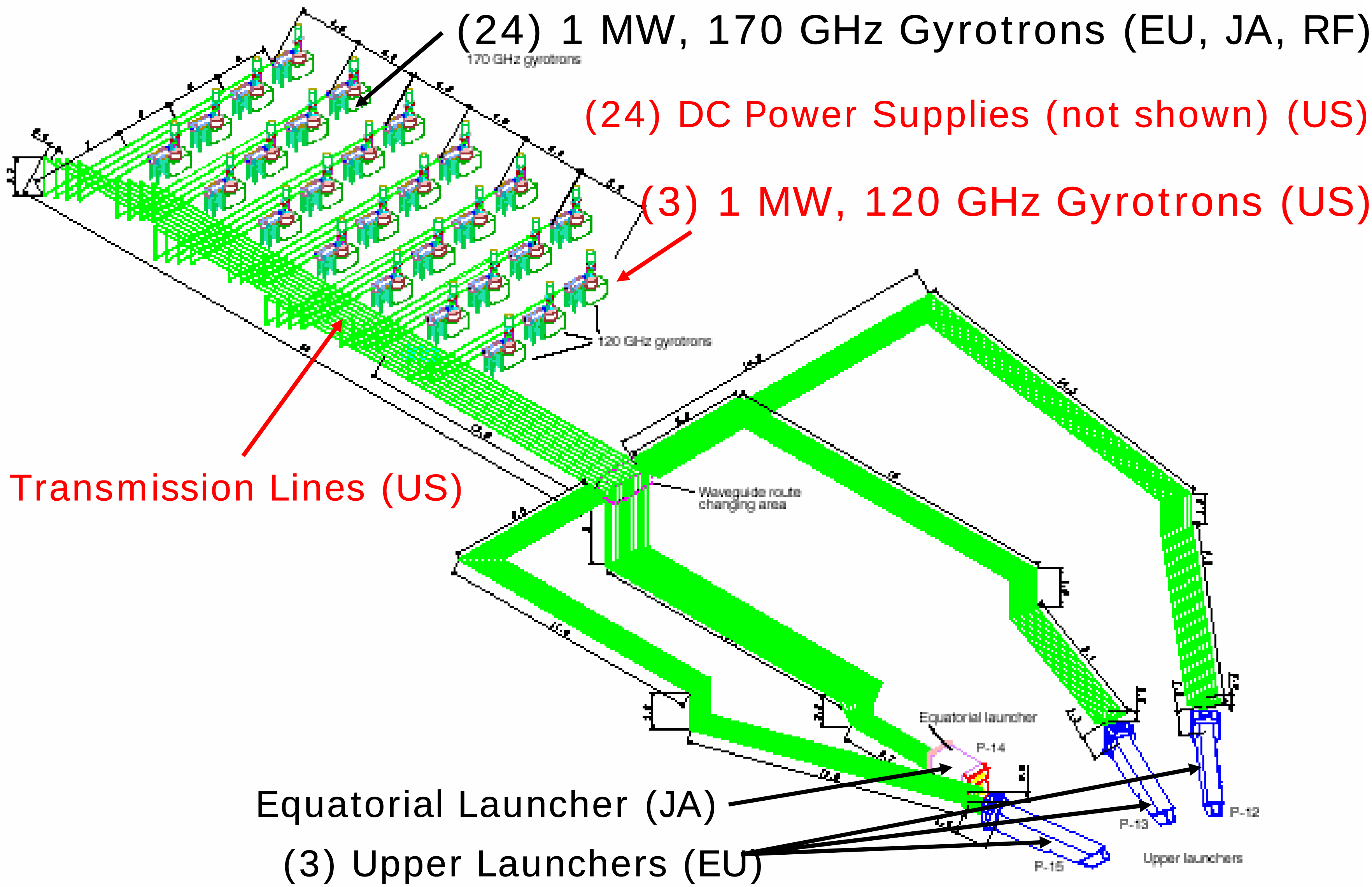
- ITER ECH System
- US ECH Technology Program R&D
- VLT Program Plan for ITER ECH
- ITER Project Program Plan for ITER ECH
- Conclusions

ECH on ITER



- EC Current Drive (ECCD), off-axis.
- EC Heating (ECH), including start-up.
- Neoclassical Tearing Mode (NTM) stabilization.

ECH System / Allocations



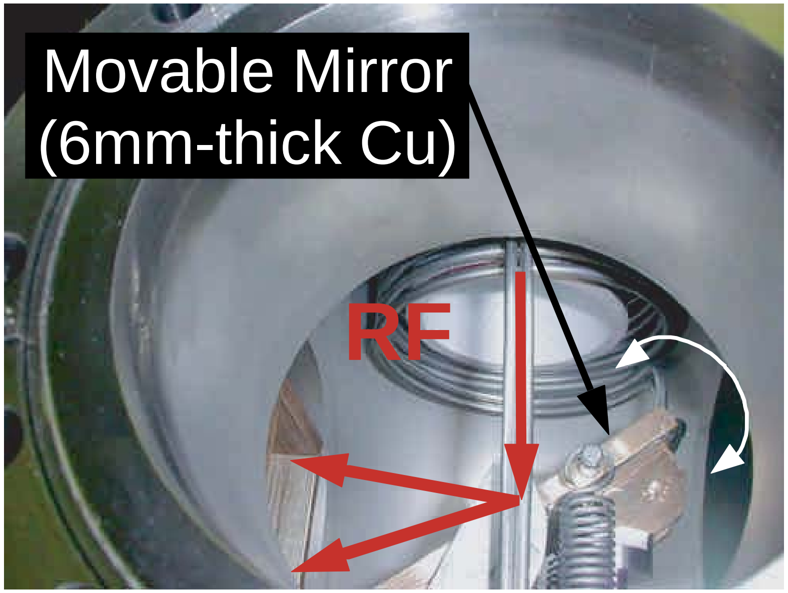
Topics

VLT
Virtual Laboratory for Technology
For Fusion Energy Science

- ITER ECH System
- US ECH Technology Program R&D
- VLT Program Plan for ITER ECH
- ITER Project Program Plan for ITER ECH
- Conclusions

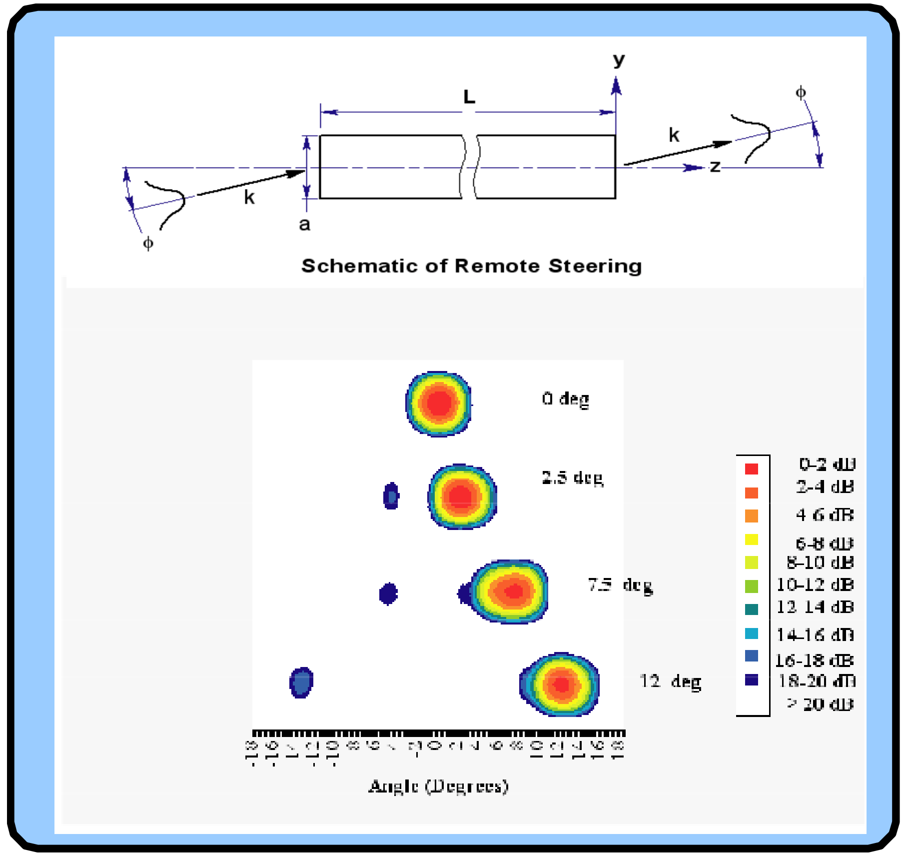
ECH Technology Advances

VLT Virtual Laboratory for Technology
For Fusion Energy Science



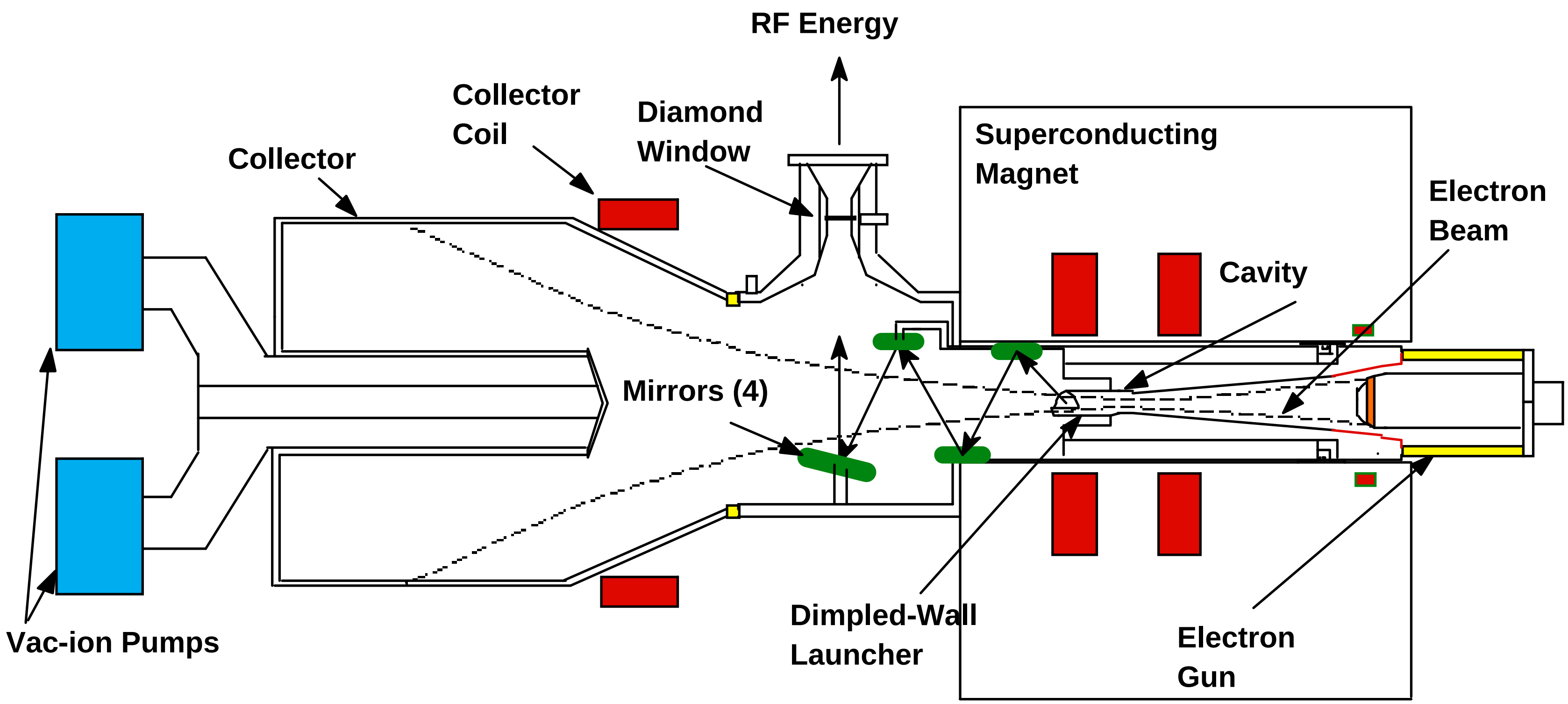
Steering section

Steering Mirror for Remote Launcher (from K. Takahashi of JAERI)



Remote Steerable Launcher for ITER (GA, Japan collaboration)

Schematic Diagram of a CPI Gyrotron



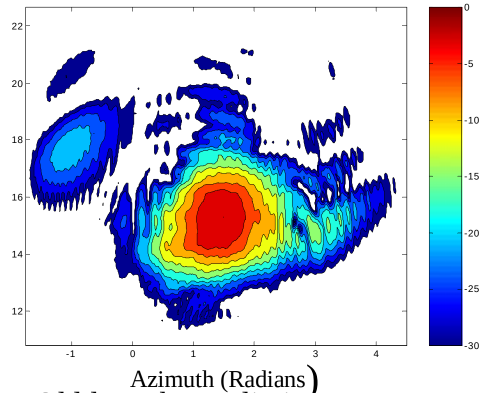
This schematic is for a depressed collector gyrotron with four mirrors and a diamond window.

Improved Launcher Design

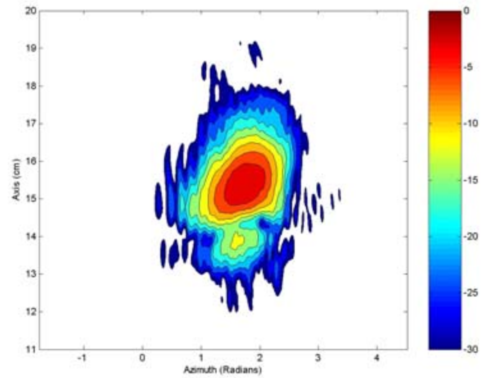
VLT Virtual Laboratory for Technology For Fusion Energy Science

- The launcher that radiates the cavity mode to the first mirror has recently been improved with a new CCR design.
- The upper figure shows the measured pattern of an old launcher.
- The lower figure shows the measured pattern of the new launcher which was used in the new CPI 1.5 MW gyrotron.

Launcher radiation patterns measured at UW.



Old launcher radiation pattern.



New launcher radiation pattern.

(The contours are from -3 dB to -30 dB in 3 dB increments.)

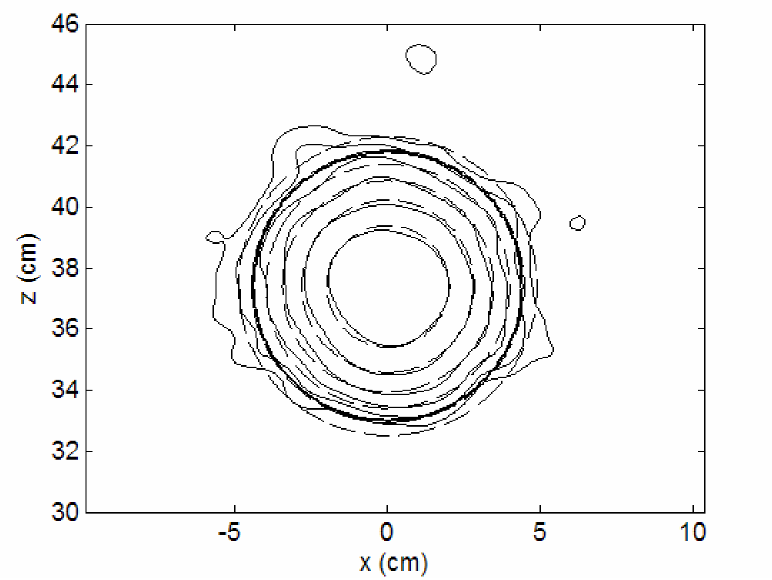
Improved Internal Converter for a CPI Gyrotron

VLT
Virtual Laboratory for Technology
For Fusion Energy Science

Table of System Efficiencies for UW Mirror System Design

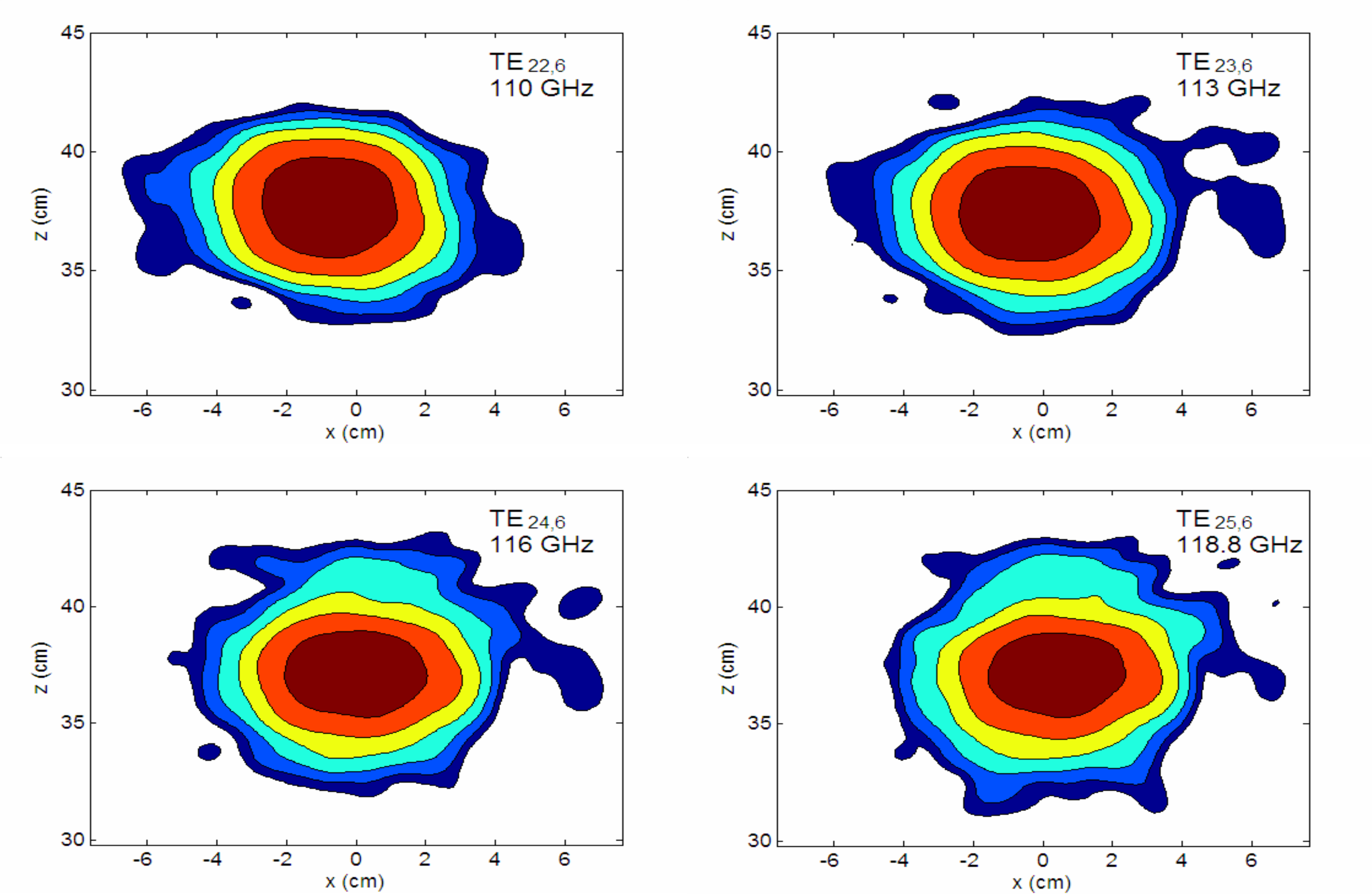
	Old Launcher-Mirror System	New Launcher-Mirror System
Percent of power from launcher hitting M1	95.9 %	99.3 %
Percent of power radiated from launcher passing through window	93.0 %	98.1 %
Percent of power coupled to target Gaussian beam (using complex amplitude)	98.2 %	99.0%
Overall system efficiency (Coupling to target)	91.3 %	97.0 %

Output at the Window Plane



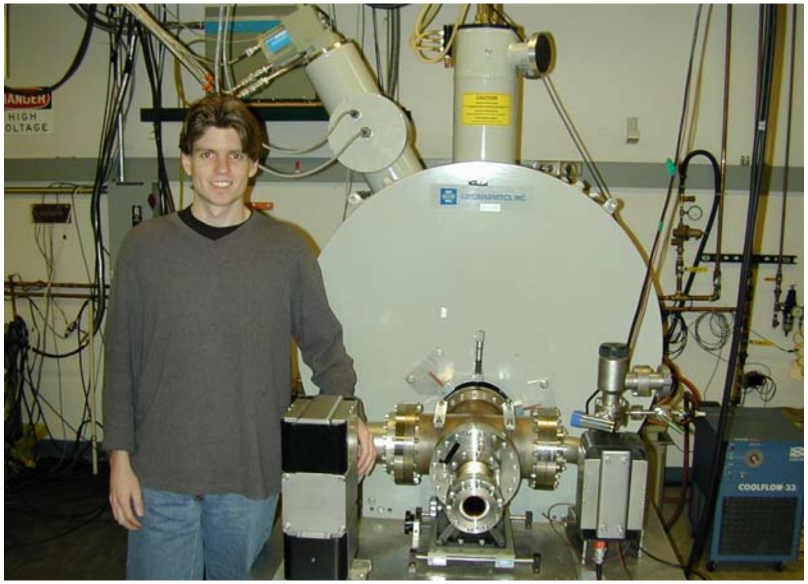
Measured cold-test (solid) and ideal target (dashed) amplitude patterns of E_X at the window. The dark circle is the aperture of output window. The contours are from -5 dB to -30 dB in 5 dB increments.

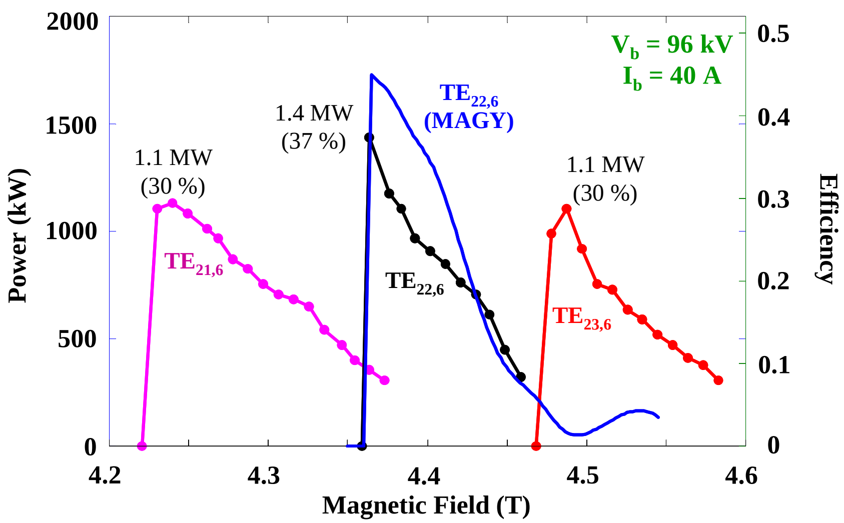
Step Tunable Frequency Capability at UW



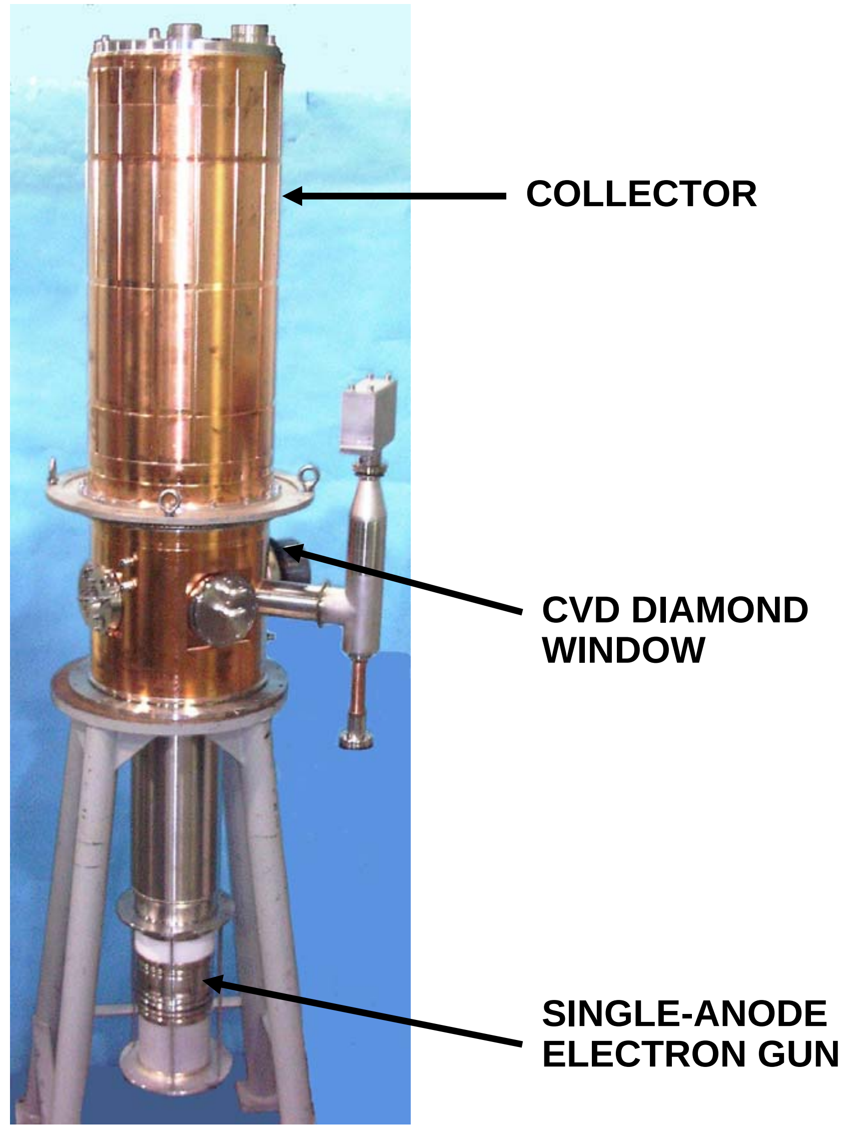
Computed output at window. The contours are from -5 dB to -30 dB in 5 dB increments.

1.5 MW, 110 GHz Gyrotron





Demonstration of 1.4 MW at Short Pulse Lengths (MIT)



CW Tube will operate in 2004 at CPI

1.5 MW, 110 GHz Gyrotron Research Status

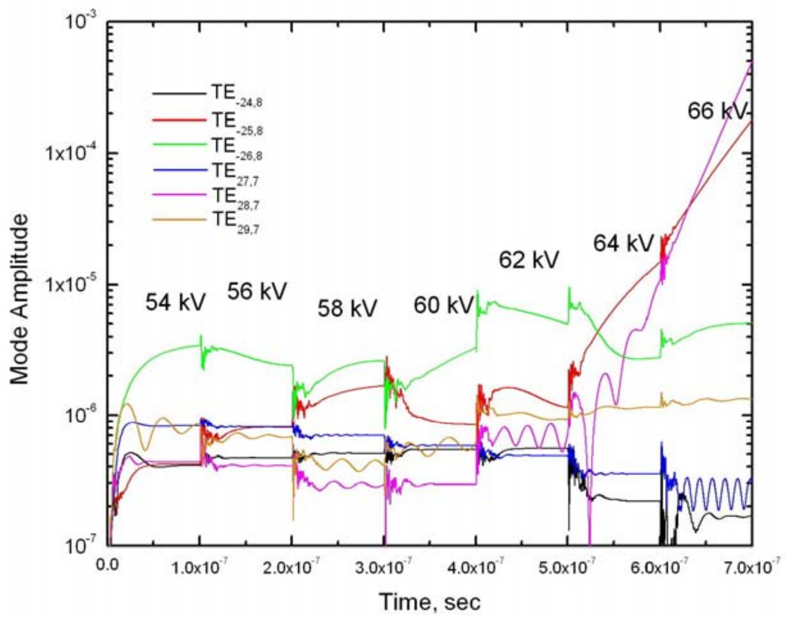
VLT
Virtual Laboratory for Technology
For Fusion Energy Science

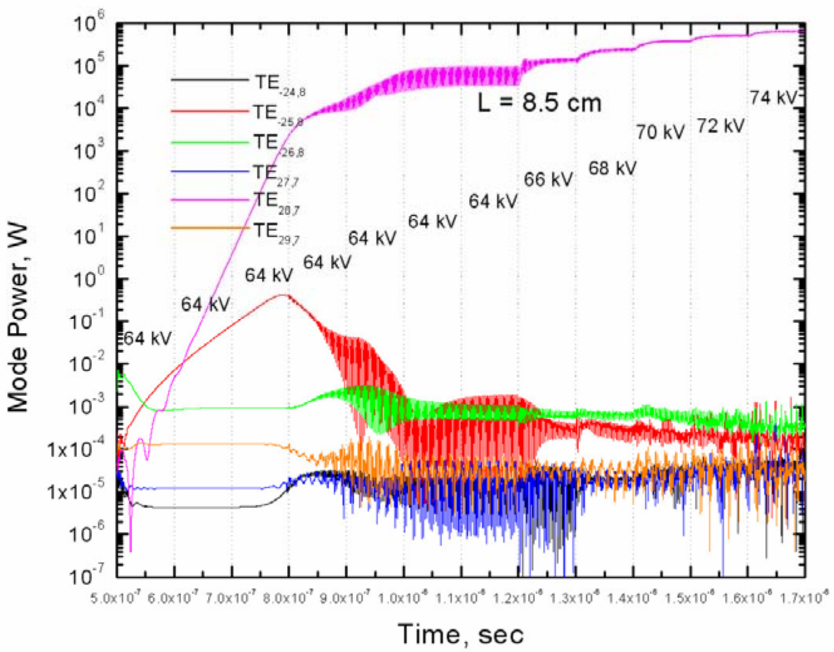
- **Short Pulse Prototype Research at MIT**
  - Up to 1.4 MW at 37% efficiency obtained in 3 microsecond pulsed operation in the $TE_{22,6}$ mode at 96 kV and 40A.
  - Good agreement with MAGY code simulations.
- **Industrial Gyrotron Development at CPI.**
  - Tube fully constructed and baked out.
  - Ready for testing at CPI; testing limited to about 600 kW.
  - Tube has a depressed collector.
- **Two Stage Depressed Collector**
  - Developed by Calabazas Creek Research.
- **Depressed Collector Power Supply**
  - Developed by Diversified Technologies Inc.
- **Final Testing at General Atomics**
  - Final testing to 10 s pulse length at 1.5 MW power level will be conducted at GA in late 2004.
- **Development of 1.5 MW, 110 GHz gyrotron will pave the way for ITER 120 GHz gyrotron development.**

Start-Up Scenario in MW-Class Gyrotrons

VLT Virtual Laboratory for Technology For Fusion Energy Science

Gyrotron operation at very high-order modes with a dense frequency spectrum requires a careful analysis of the start-up scenario.
Example: start-up scenario in a 1-MW, 140 GHz, CPI gyrotron; MAGY runs by Univ. Maryland





Topics

- ITER ECH System
- US ECH Technology Program R&D
- VLT Program Plan for ITER ECH
- ITER Project Program Plan for ITER ECH
- Conclusions

VLT Program Plans for ITER

- **Design Study of 120 GHz, Start-Up Gyrotrons**
  - 1 MW, 120 GHz gyrotron needed; gyrotron operating at up to 2 MW would be useful for both ITER and DIII-D.
  - Milestone: Complete design by September, 2005.
- **Advances in remotely steerable launcher design** will be made to permit steering at larger angles and with the incorporation of miter bends in the line at GA.
  - Now part of design for ITER ECH antennas.
- **Industrial 120 GHz Gyrotron for ITER**
  - Useful for both ITER and DIII-D.
  - Milestone: complete engineering design and fabricate long lead time components by September, 2006.
- **Testing of Short Pulse Prototype of 2 MW, 120 GHz Gyrotron at MIT.**
- **These tasks will be supported by the US VLT Enabling Technology program for ECH.**

Topics

Virtual Laboratory for Technology
For Fusion Energy Science

- ITER ECH System
- US ECH Technology Program R&D
- VLT Program Plan for ITER ECH
- ITER Project Program Plan for ITER ECH
- Conclusions

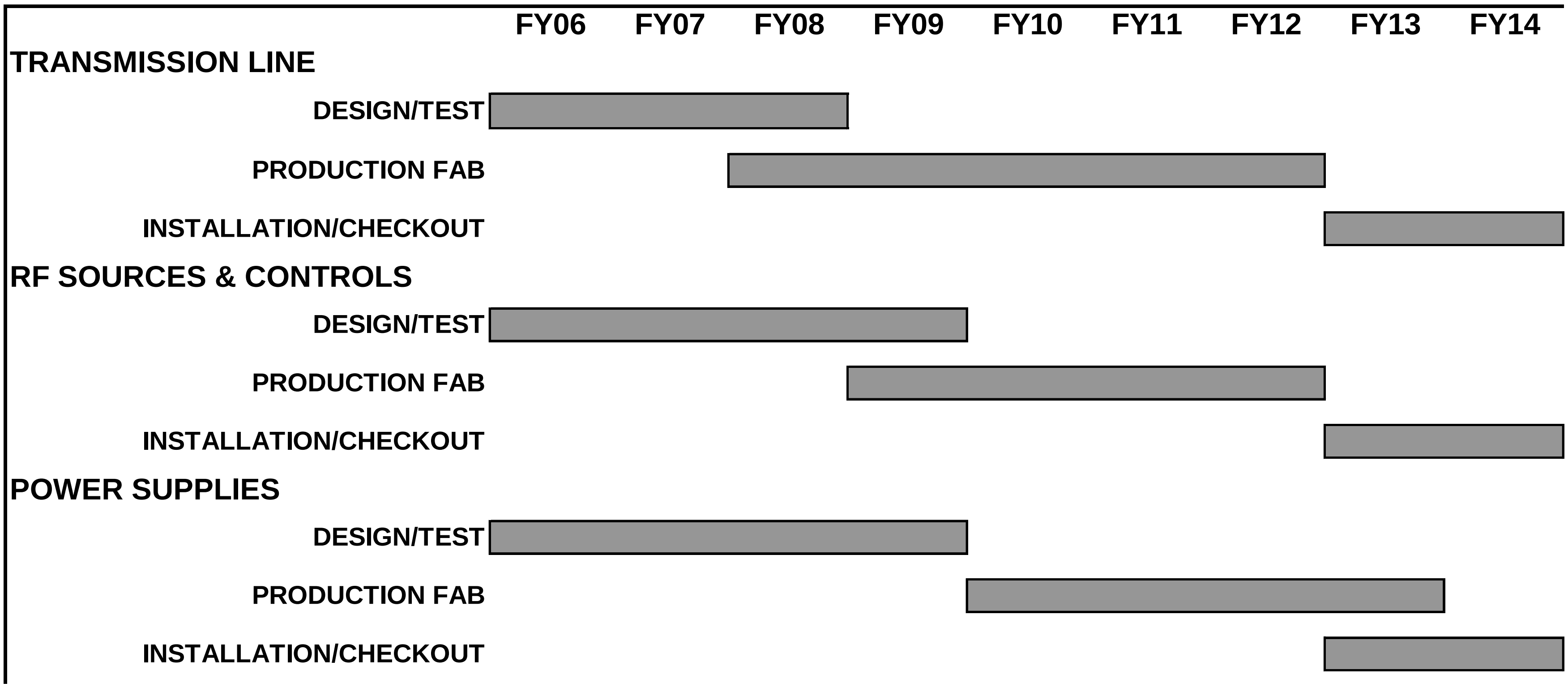
Proposed 2006 ITER Project Tasks

VLT
Virtual Laboratory for Technology
For Fusion Energy Science

- **These tasks will have direct support from the US ITER Project.**
- **TRANSMISSION LINES**
  - Design of transmission line components completed.
  - Start fabrication of new cw prototype components.
  - Perform proof of principle tests on new components.
- **RF SOURCES & CONTROLS**
  - Complete the design of a 120 GHz gyrotron.
  - Complete the design of the gyrotron control system.
  - Complete the design of the gyrotron support system.
  - Order long lead items for prototype system.
- **POWER SUPPLIES**
  - Complete the system conceptual design.

US ITER ECH Project Plan

VLT
Virtual Laboratory for Technology
For Fusion Energy Science



This project plan was developed by GA.

ITER ECH TRANSMISSION LINES

- **The new requirement of ITER is for ECH transmission line components to operate at 1-2 MW cw**
  - Components now being designed by GA for 170 and 120 GHz 1-2 MW cw operation in 63.5 mm diameter include
    - Cooling clamps for aluminum waveguides
    - Miter bends with water cooling of miter bend arms and enhanced mirror cooling
    - DC breaks
    - Waveguide bellows
    - In-line power monitors
  - Such components are being fabricated for high power long pulse experiments at CRPP using the European 2 MW coaxial gyrotron
- **Additional components needing further development include dummy loads, MOUs/L-boxes, gate valves, and stainless steel waveguides with water cooling**
- **Integrated testing of prototypical components is needed before components are fabricated for ITER**

ITER ECH POWER SUPPLY ISSUES

VLT Virtual Laboratory for Technology
For Fusion Energy Science

- **During the ITER EDA phase, two gyrotron power supply configurations were proposed.**
  - A Pulse Step Modulation concept, which has 2 transformers with 58 secondary windings, each feeding an IGBT power module. The power modules are stacked in series and give a voltage resolution of 1400 volts
  - A thyristor converter with series IGBT switch
- **Neither concept provided individual control of a gyrotron**
- **Neither concept provided fine control of the accel voltage that is required for optimum control**
- **The US is proposing a concept that uses 2 large transformer rectifier sets with individual IGBT Pulse Width Modulated power modules. A High-Voltage Power Amplifier provides the fine high voltage control needed.**
  - The IGBT PWM power modules are the only element that needs development. Presently there is a SBIR funded program in this area in the US.

ITER REMOTE STEERING LAUNCHER

- **Remote steering launcher for ITER is under development by GA in collaboration with JAERI and more recently with FOM**
  - High power 170 GHz prototype at JAERI demonstrated excellent steering over ± 12° steering range
    - Theoretical radiation pattern in excellent agreement with experiment
    - Additional experiments with miter bends planned; improved miter bend design under investigation to improve performance at large steering angles
    - Calculation of heat deposition profile in waveguide is underway for comparison with JAERI measurements
- **GA presently fabricating square corrugated waveguide for prototype ITER launcher at FOM**
  - Rounded rather than sharp corrugations to reduce chance of breakdown at 2 MW operation
  - Corrugation geometry designed to have same phase velocity for E parallel or perpendicular to plane of steering

Topics

VLT
Virtual Laboratory for Technology
For Fusion Energy Science

- ITER ECH System
- US ECH Technology Program R&D
- VLT Program Plan for ITER ECH
- ITER Project Program Plan for ITER ECH
- Conclusions

Conclusions

- FY05 and FY06 ECH Technology program plans provide strong support for Heating and Current Drive Physics research both in the US program and for ITER .
- FY06 ECH ITER program should initiate all three areas – Gyrotrons, Transmission Lines and ECH DC Power Supplies.
- Early start to technology development essential to reducing total cost and risk!