High Frequency Gyrotrons and Their Applications

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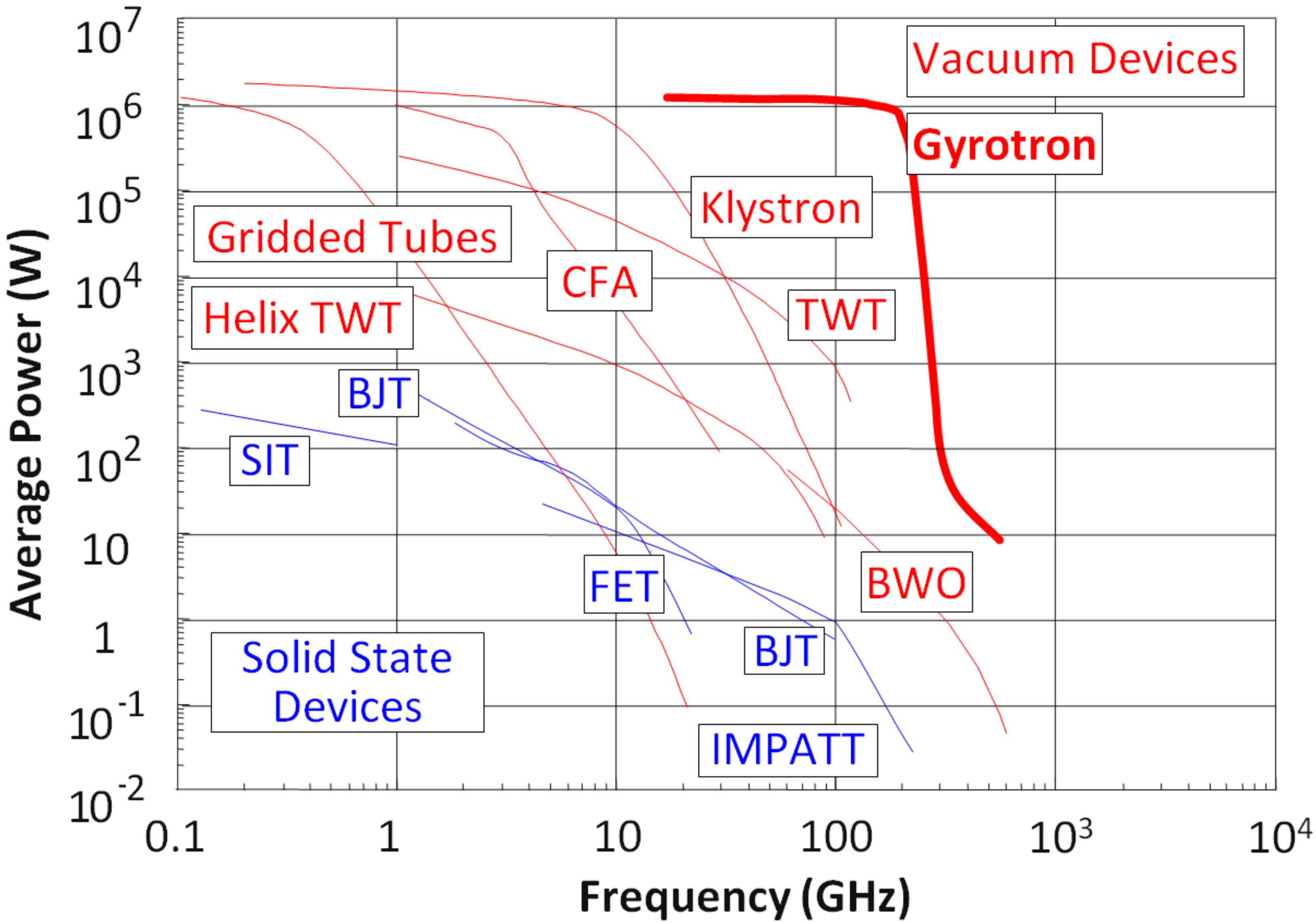
Plasma Physics Colloquium
Applied Physics and Applied Math Dept.
Columbia University
February 28, 2014

Topics

- **Introduction to Gyrotrons**
- Gyrotron Physics and Technology
- High Power Gyrotrons
- Applications

Gyrotrons

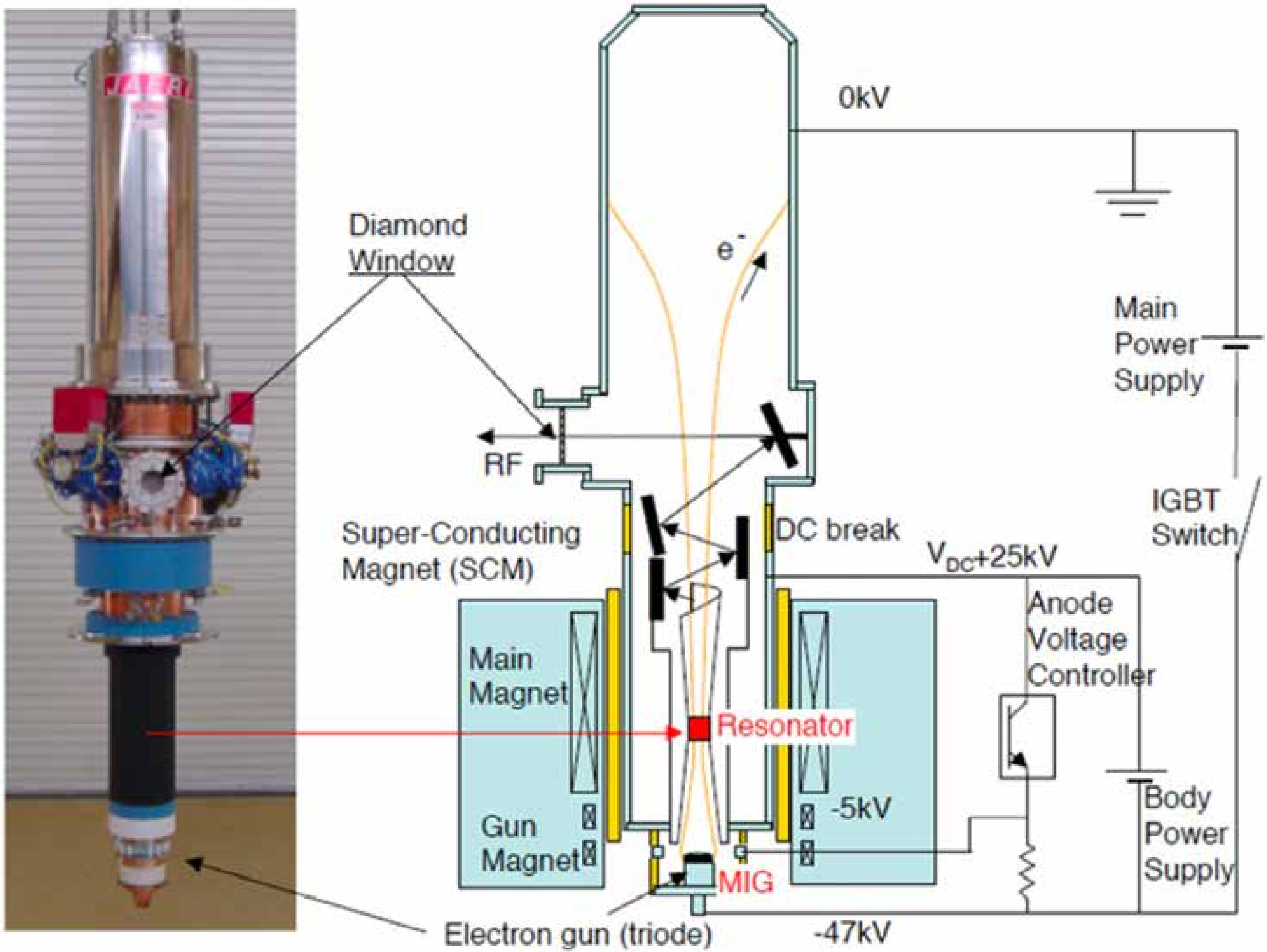
Gyrotrons - most powerful MM wave and THz sources



Updated from Granatstein et al. Proc. IEEE 1999

Gyrotron Concept

- MW gyrotron for plasma heating and current drive



JAEA ITER 1 MW, 170 GHz gyrotron

K. Sakamoto et al., Nucl. Fus. (2009)

Electron Cyclotron Maser Dispersion Relation

- Gyrotron is an electron cyclotron resonance maser

Waveguide Mode:

$$\omega^2 - k_z^2 c^2 - k_\perp^2 c^2 = 0$$

Cyclotron Mode:

$$\omega - s\Omega/\gamma - k_z v_z = 0$$

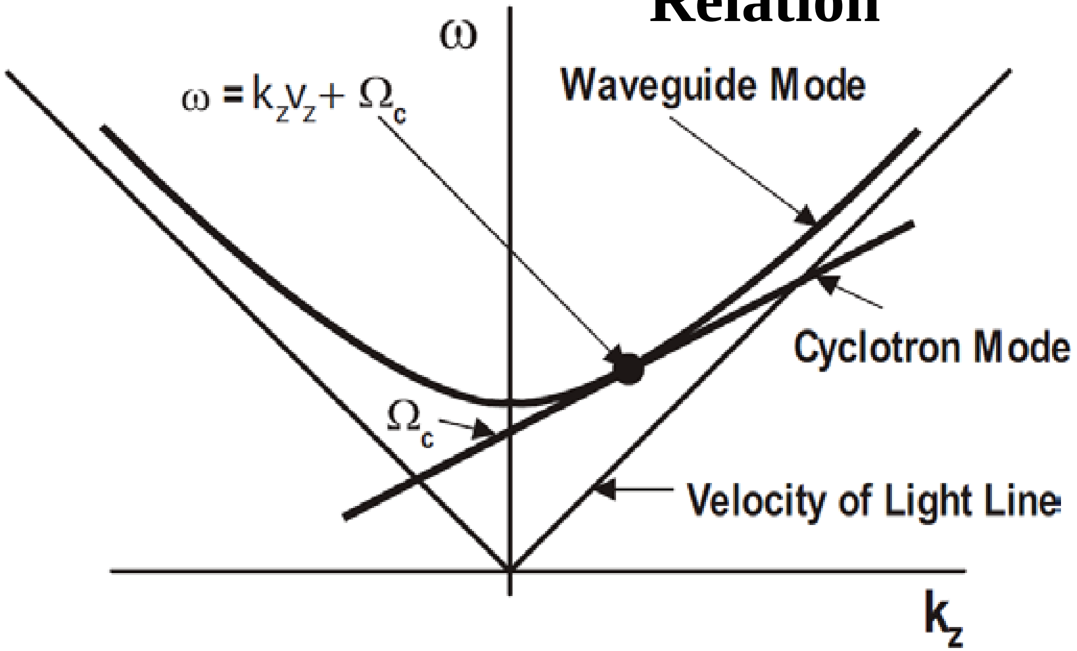
$\Omega = eB_0/m_e$ **~ 28 GHz/T**

s = harmonic number

$$\gamma = (1 - v^2/c^2)^{-1/2}$$

Lorentz Factor – Relativity

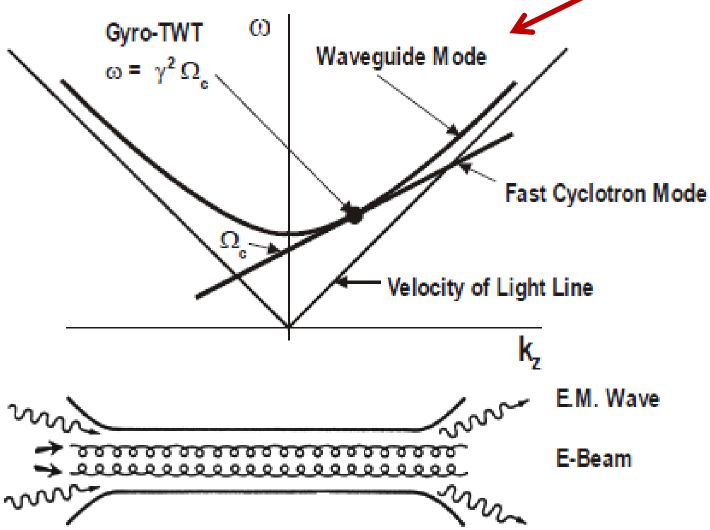
Dispersion Relation

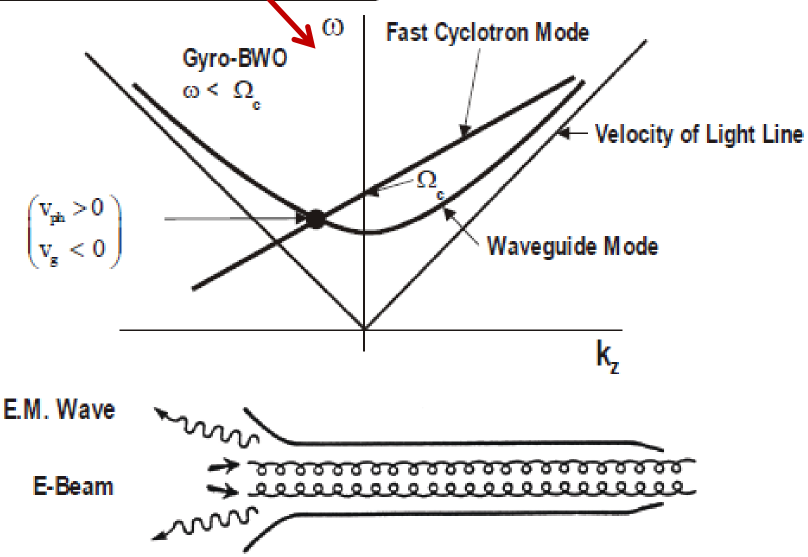


Gyrotron Devices

"0" TYP DEVICES	MONOTRON	KLYSTRON	TWT	TWYSTRON	BWO
TYPE OF GYRO-DEVICE	GYRO-MONOTRON	GYRO-KLYSTRON	GYRO-TWT	GYRO-TWYSTRON	GYRO BWO
MODEL RF-FIELD STRUCTURE					
MODEL ORBITAL EFFICIENCY	0.42	0.34	0.7	0.6	0.2

Flyagin IEEE MTT 1977





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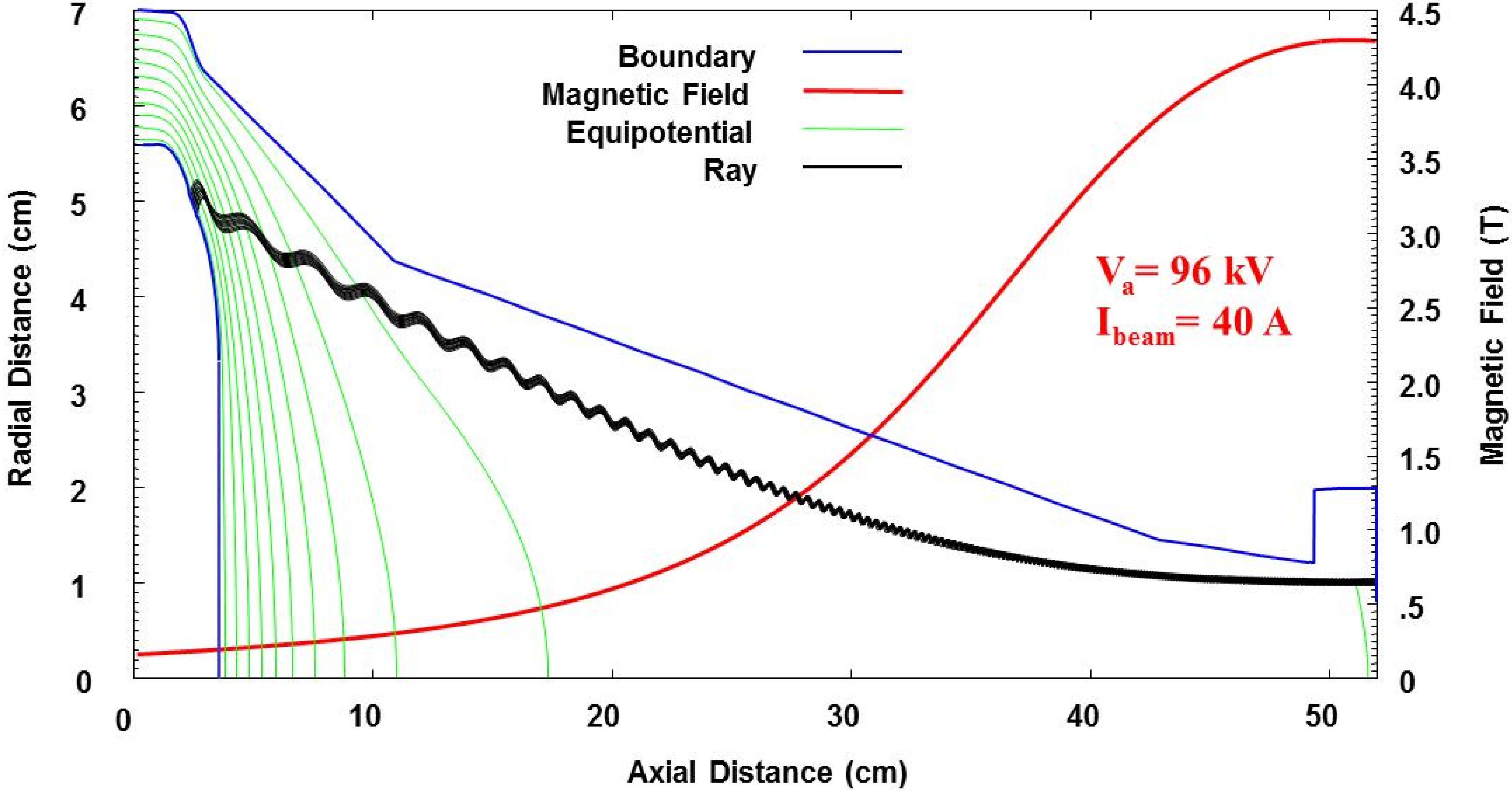
- **Gyrotron Physics and Technology**
- High Power Gyrotrons
- Applications

Electron Gun

Diode Magnetron Injection Gun for a 110 GHz Gyrotron

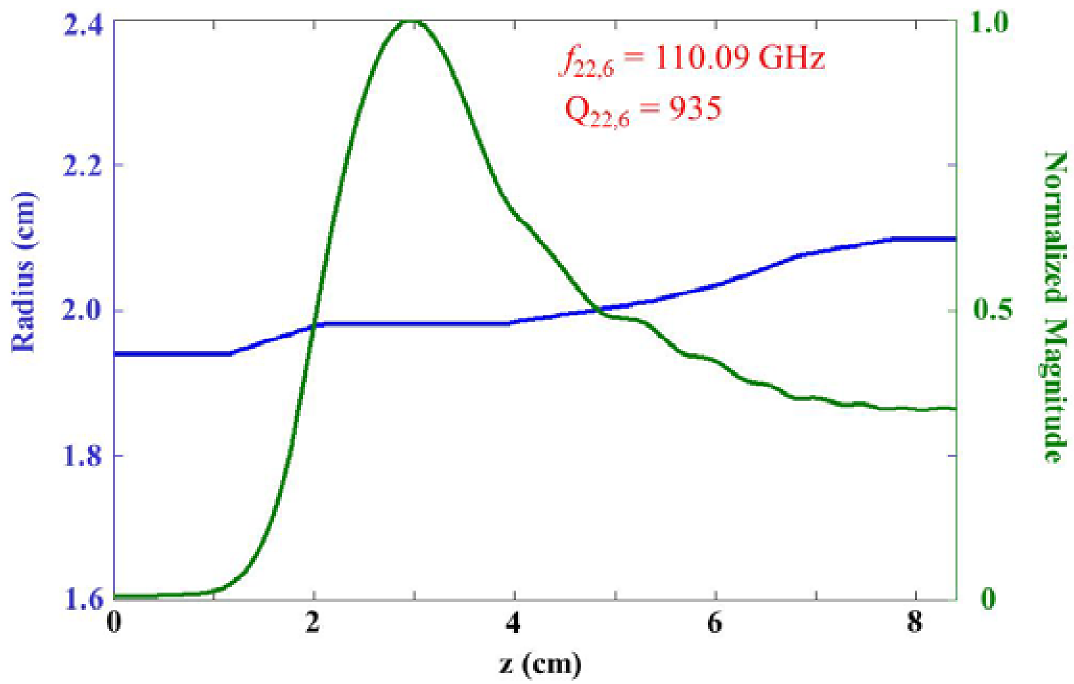


- Adiabatic compression of annular electron beam from the cathode to the resonator
  - Conservation of $v_{\perp}^2 / B$; increase of $v_{\perp}$
- Low velocity spread required

Interaction Structure

- Open Resonator with cutoff towards the electron gun
- Beam radius is optimized to interact with the desired mode

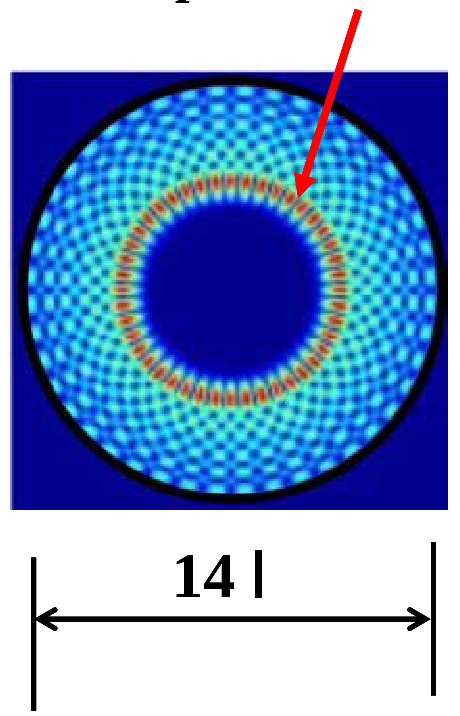
$TE_{22,6,1}$ Cavity at 110 GHz



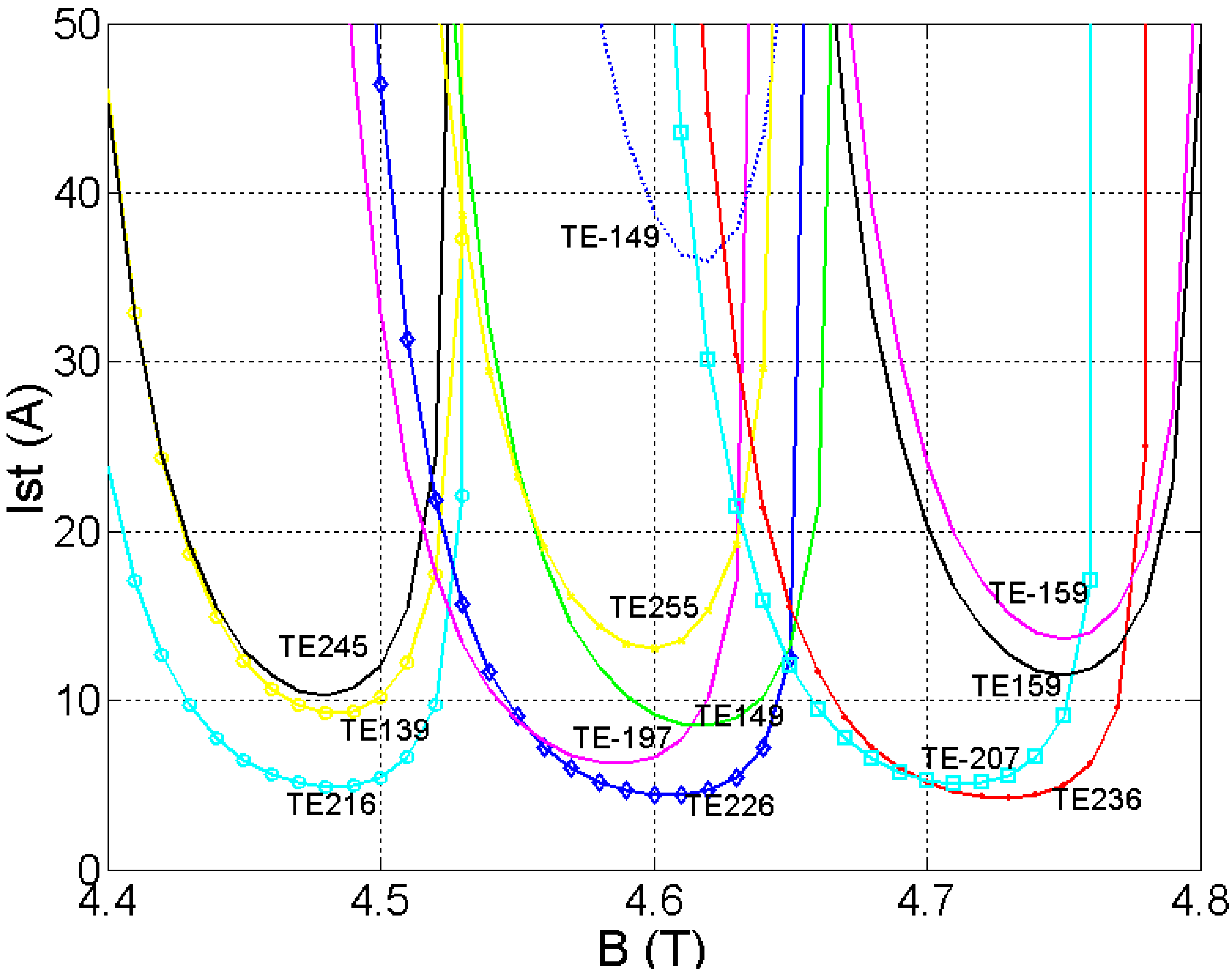
- There are 282 modes at lower frequency than the $TE_{22,6}$ mode!

High Order Modes

Optimal electron beam position



Linear Theory: Starting Current and Mode Competition



Nonlinear Theory - Efficiency

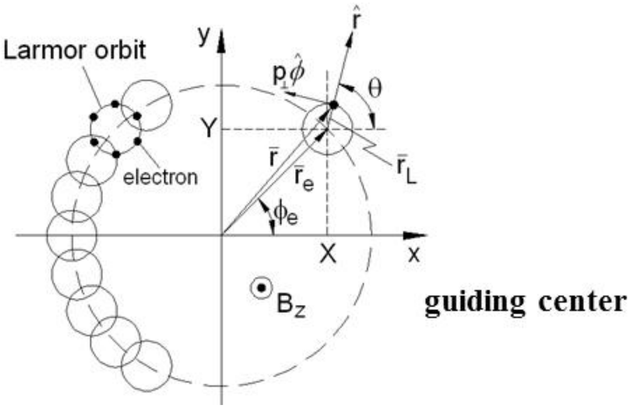
The equations of motion of an electron

$$\frac{d\varepsilon}{dt} = -e\vec{u}\times\vec{E}$$

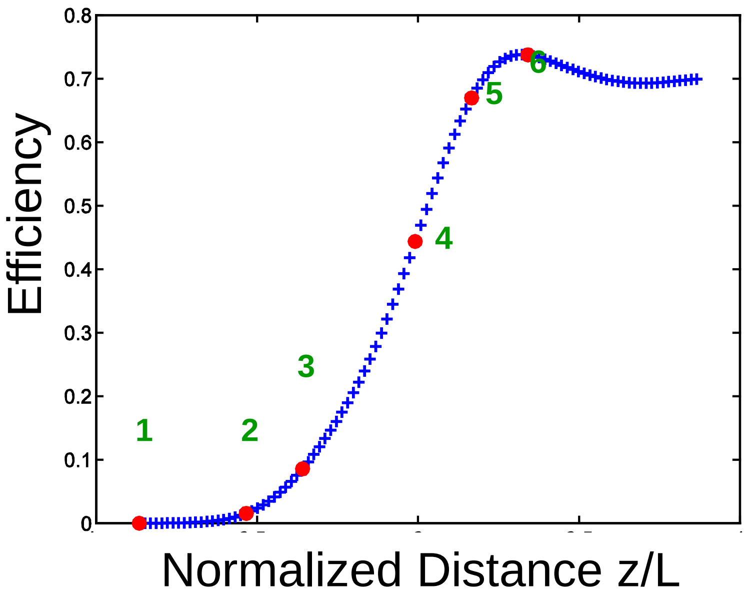
$$\frac{d\vec{p}}{dt} = -e\vec{E} - e\vec{u}\times\vec{B}$$

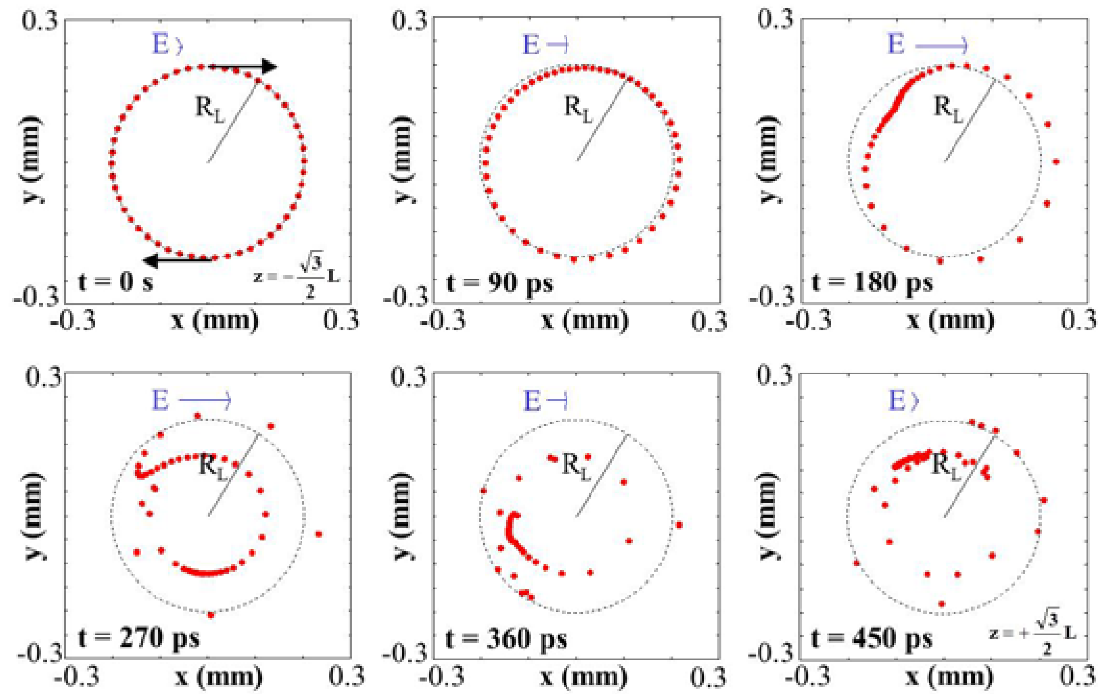
$$r_{\perp} = \frac{v_{\perp}}{\Omega_c}$$

$$\Omega_c = \frac{eB}{\gamma m_e}$$

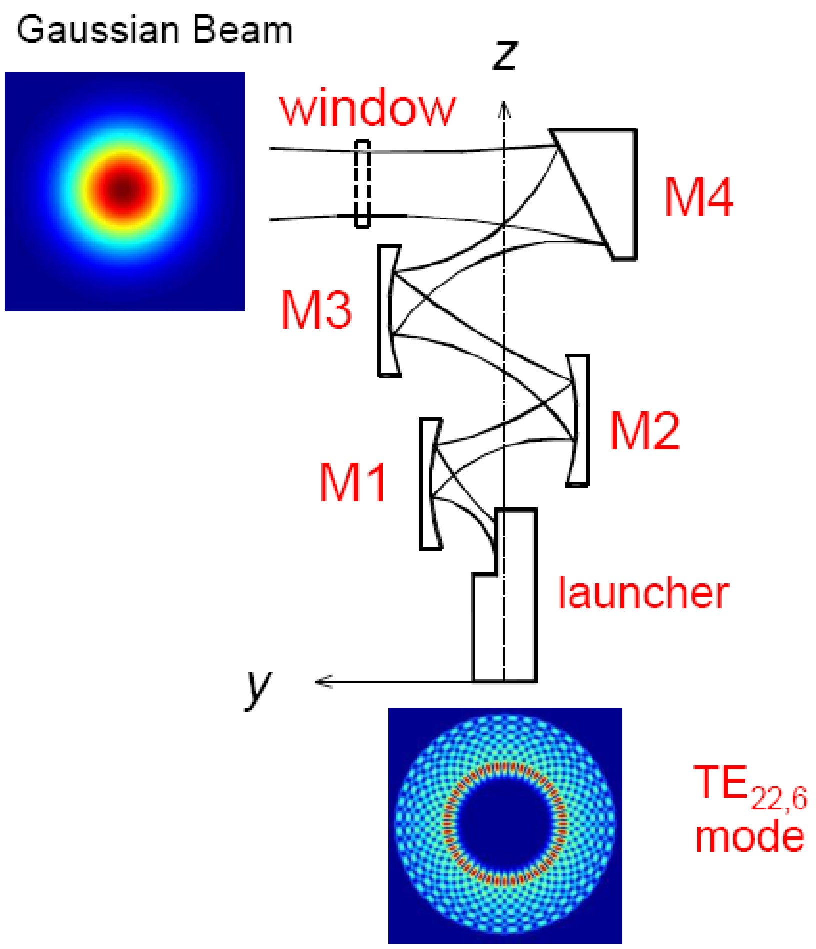


Efficiency plot



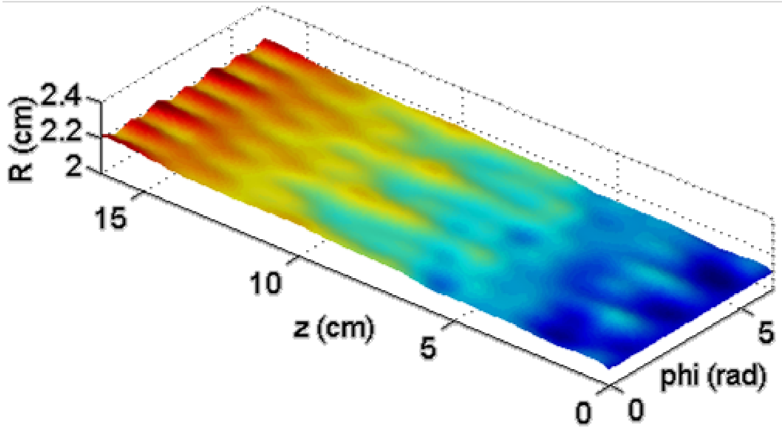


Output Coupler



110 GHz Gyrotron Mode Converter

- Internal Mode Converter (IMC) converts the cavity mode into a Gaussian Beam
- Launcher is a waveguide section with profiled walls designed to generate a mode mixture resulting in a Gaussian-like pattern on the surface



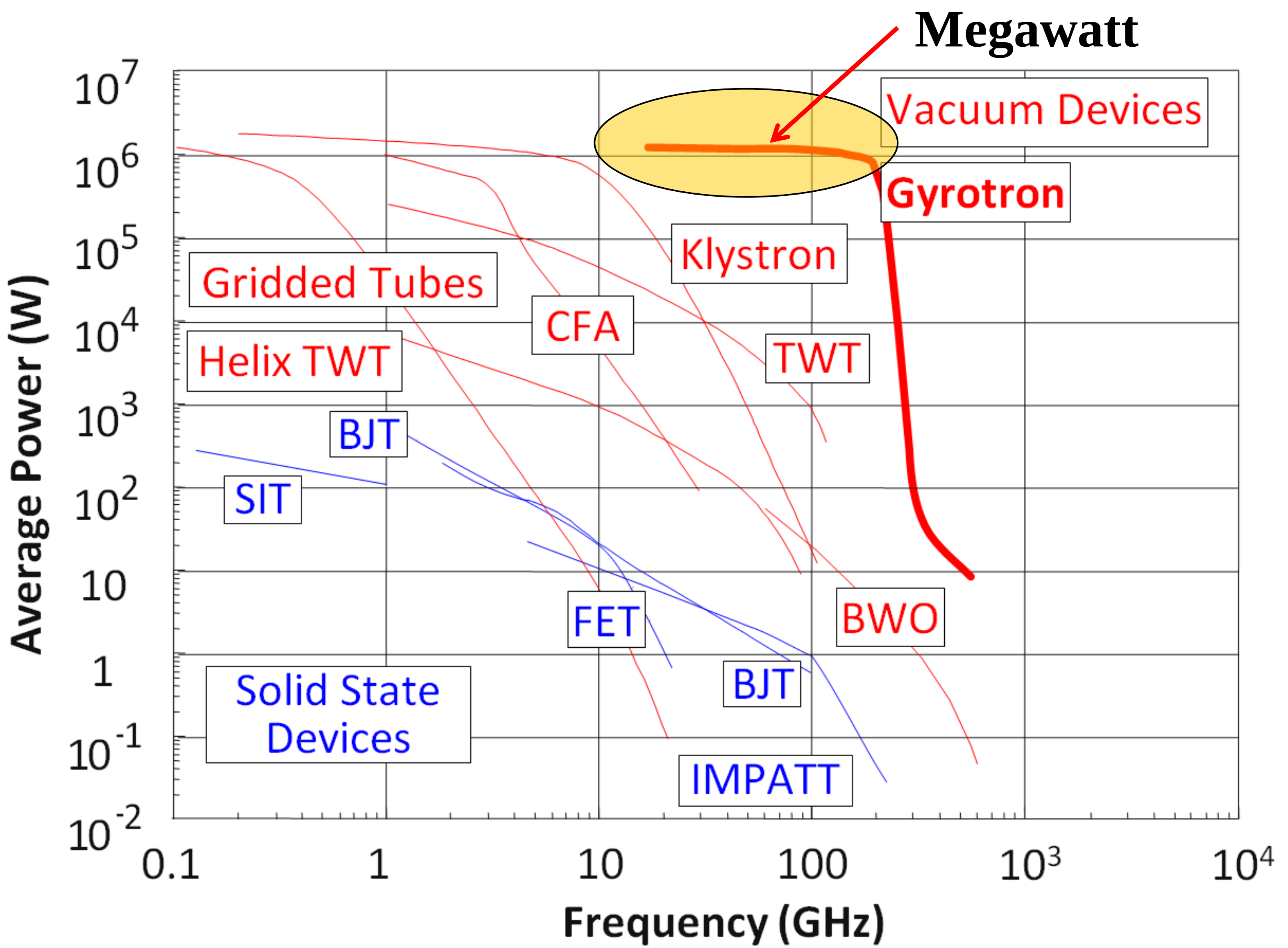
Launcher designed using code LOT

J. Neilson, JIMT (2006)

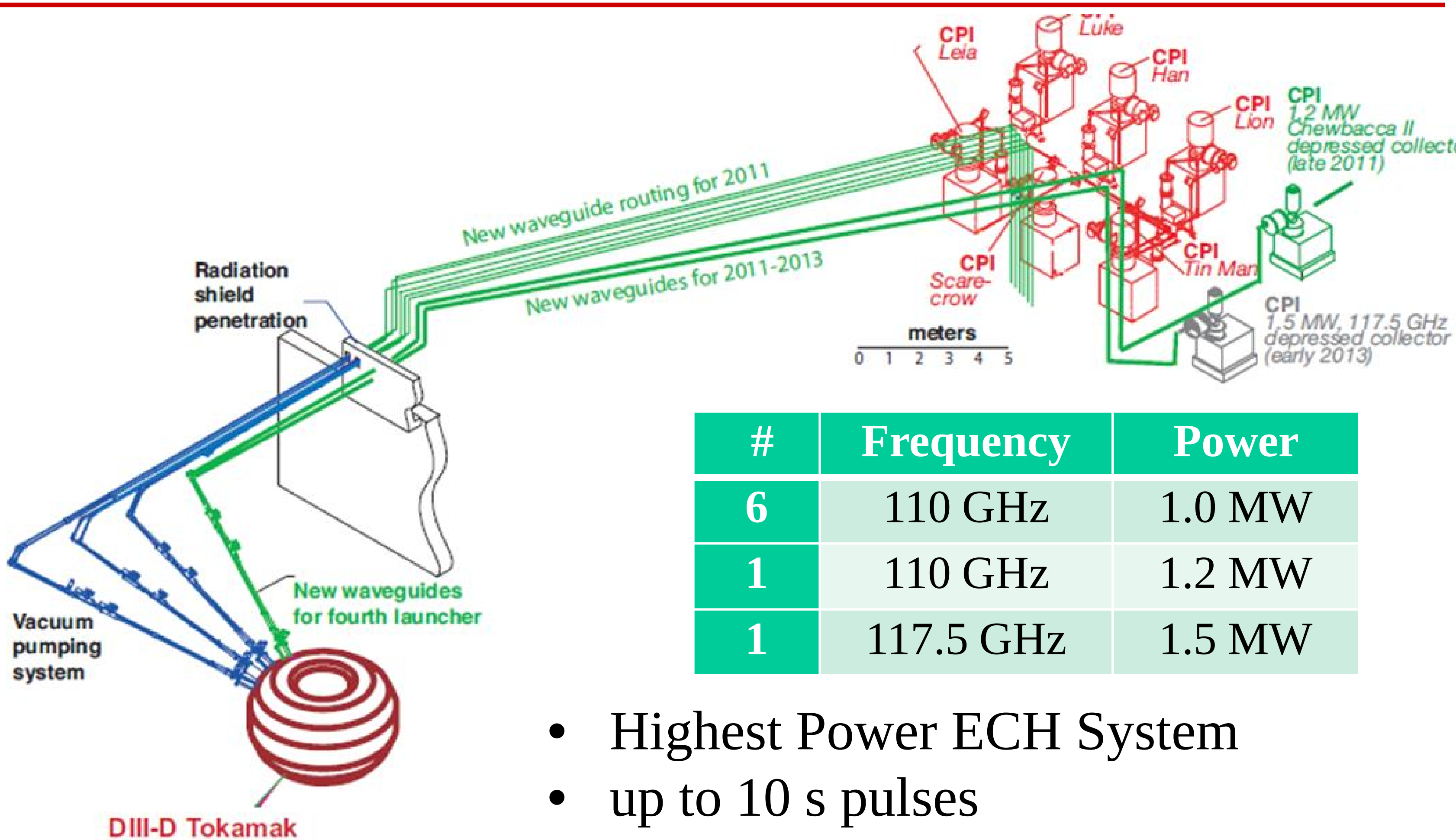
Topics

- Introduction to Gyrotrons
- Gyrotron Physics and Technology
- **High Power Gyrotrons and Applications**
  - **Plasma Heating with Megawatt Gyrotrons**
  - **Spectroscopy with THz Gyrotrons**
  - **Materials Processing**
  - **Novel and Future Applications**

Megawatt Gyrotrons



D-IIID 110 GHz ECH System

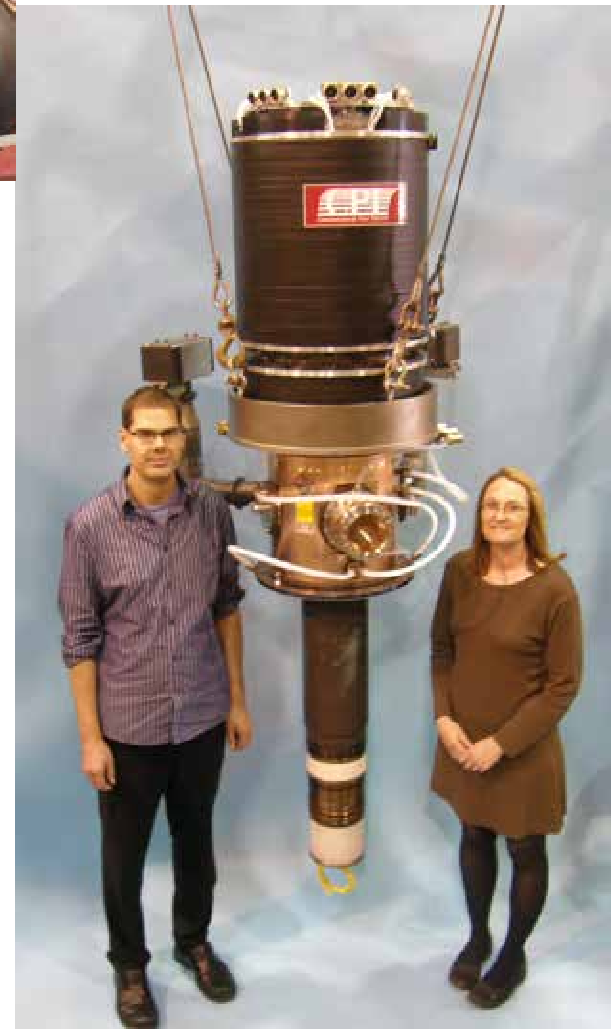


#	Frequency	Power
6	110 GHz	1.0 MW
1	110 GHz	1.2 MW
1	117.5 GHz	1.5 MW

- Highest Power ECH System
- up to 10 s pulses
- Corrugated aluminum transmission lines propagate HE_{11} mode with low loss

J. Lohr, General Atomics, 2012

Megawatt Gyrotrons at DIII-D

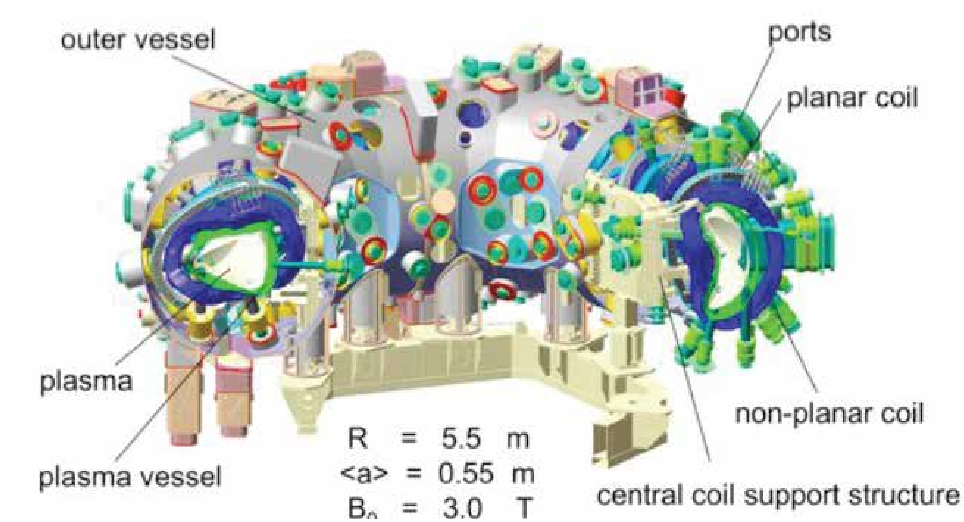


- 1MW, 110 GHz gyrotron installed in SC Magnet

- 1.2 MW, 110 GHz Gyrotron

K. Felch, EPJ Conf. Web, 2012

W7-X Stellarator Germany



10 MW, 140 GHz ECH System

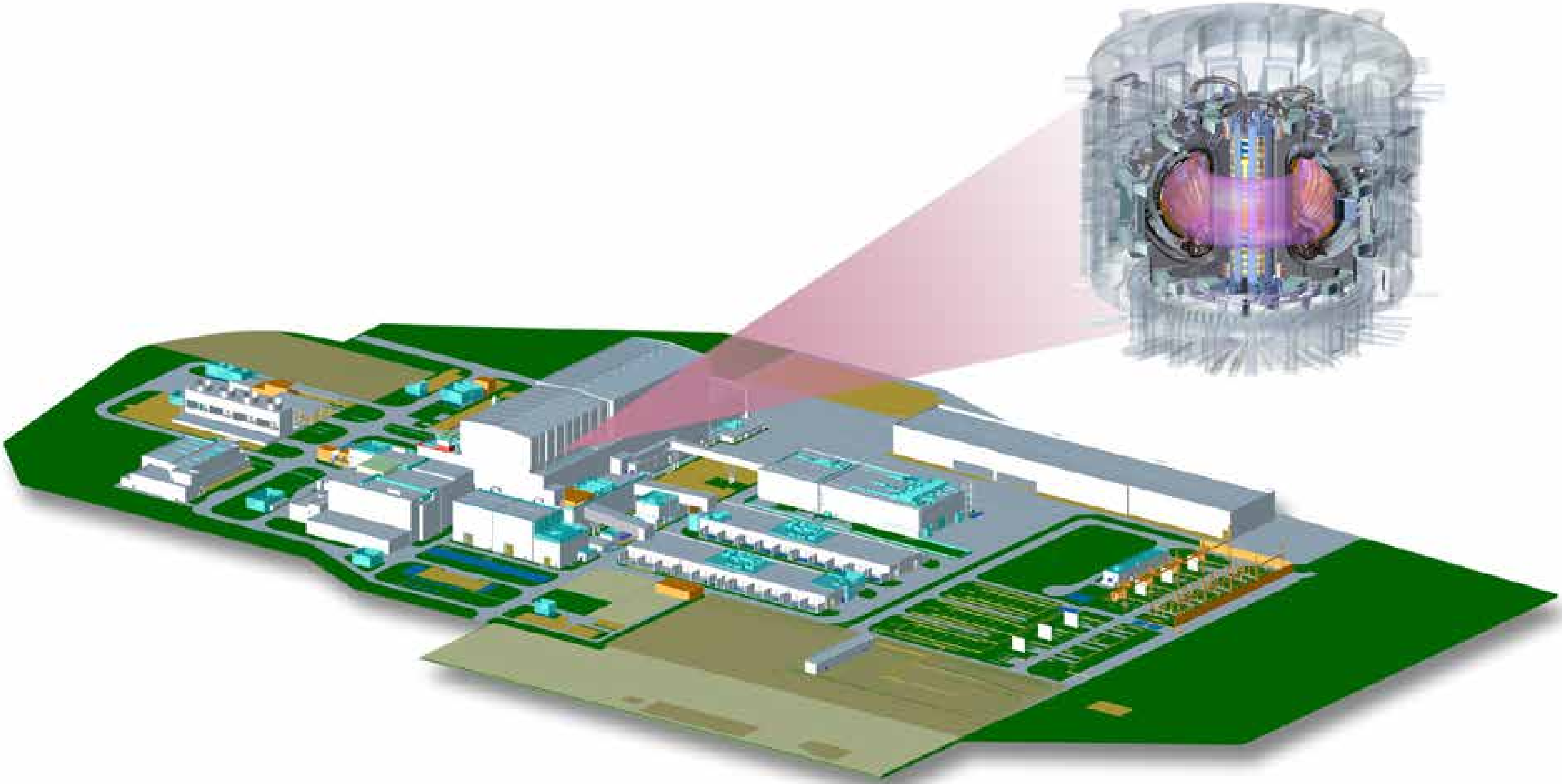
FZK, CRPP, THALES
(0.92 MW, 1800 s)

US/CPI (0.9 MW, 1800 s)

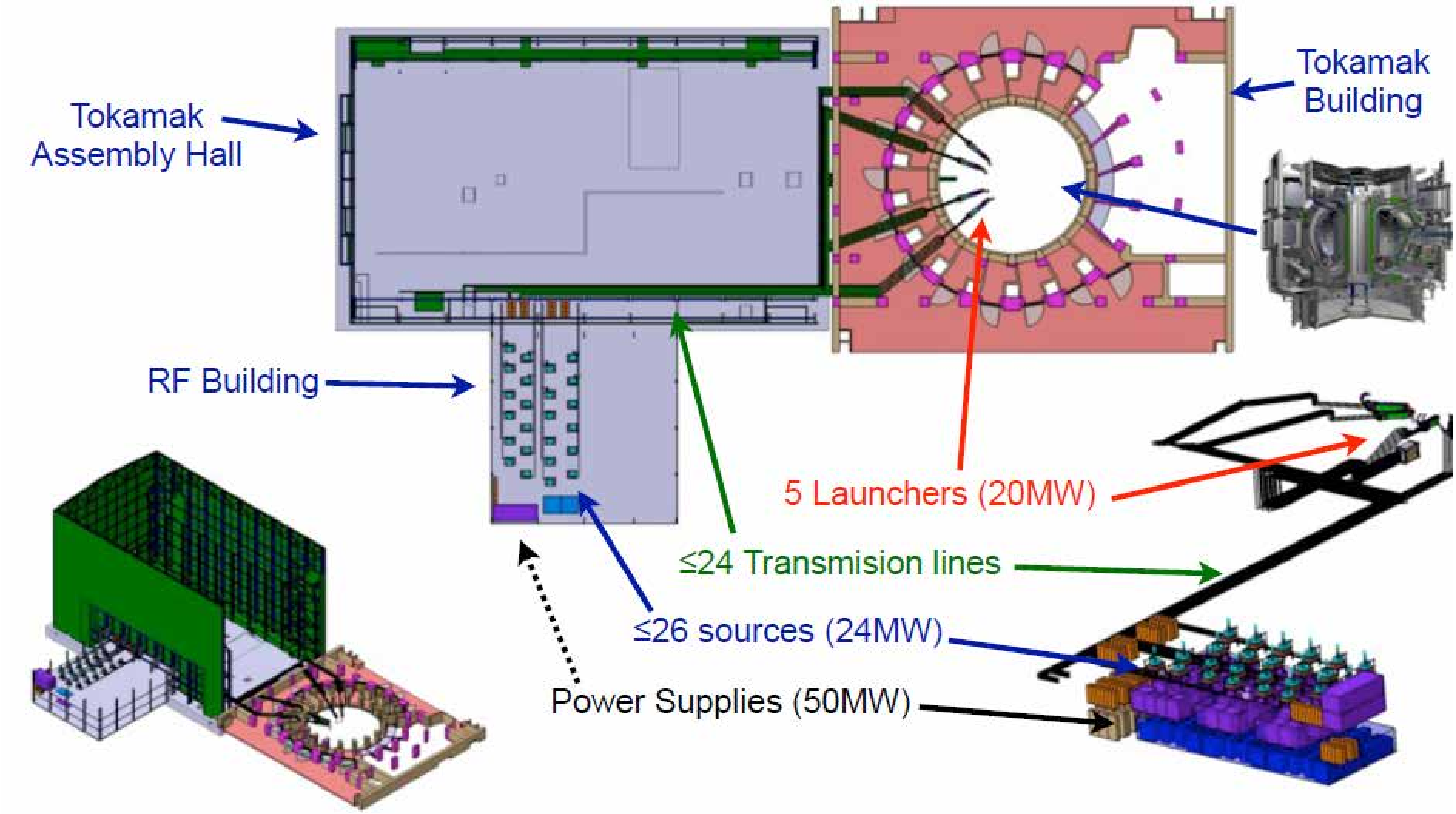
(cryo-free magnets)

V. Erckmann, W7-X, 2012

ITER

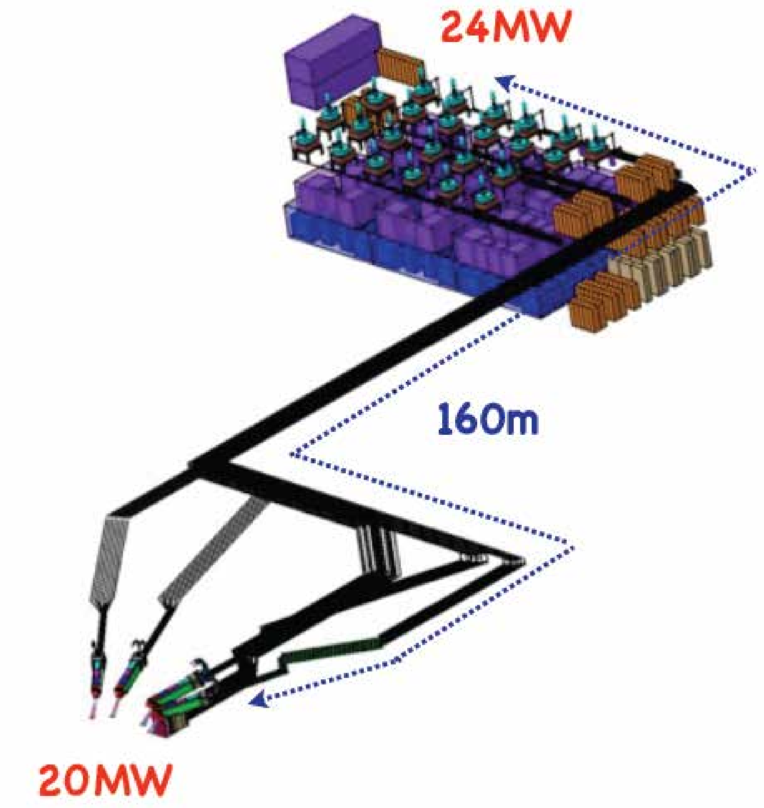


ITER ECH System

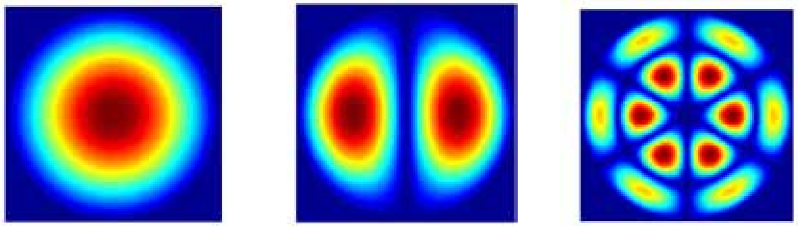


M. Henderson, ITER, 2012

Low Loss Transmission Lines



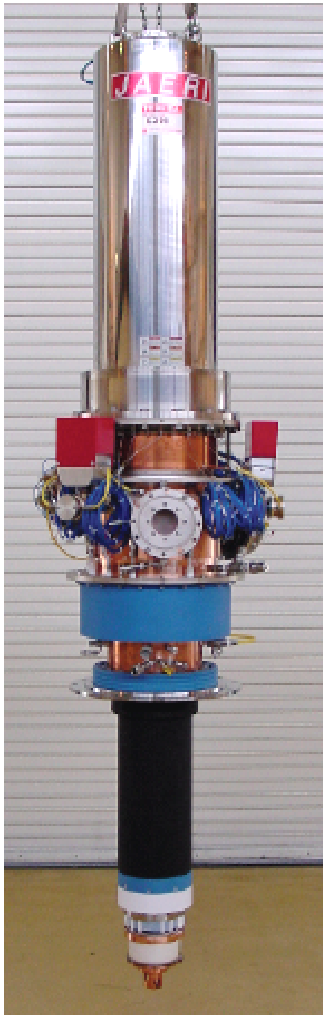
- 24 MW of gyrotron power at 170 GHz; 20 MW at the plasma
  - Gyrotron Gaussian Beam mode purity >95%
  - Loss budget <17%
- 63.5 mm diameter corrugated Al waveguides transport the HE_{11} mode
- Losses occur due to both ohmic loss and mode conversion loss to non-HE_{11} modes
- US responsible for supplying the transmission lines



HE11 **LP11** **LP32**

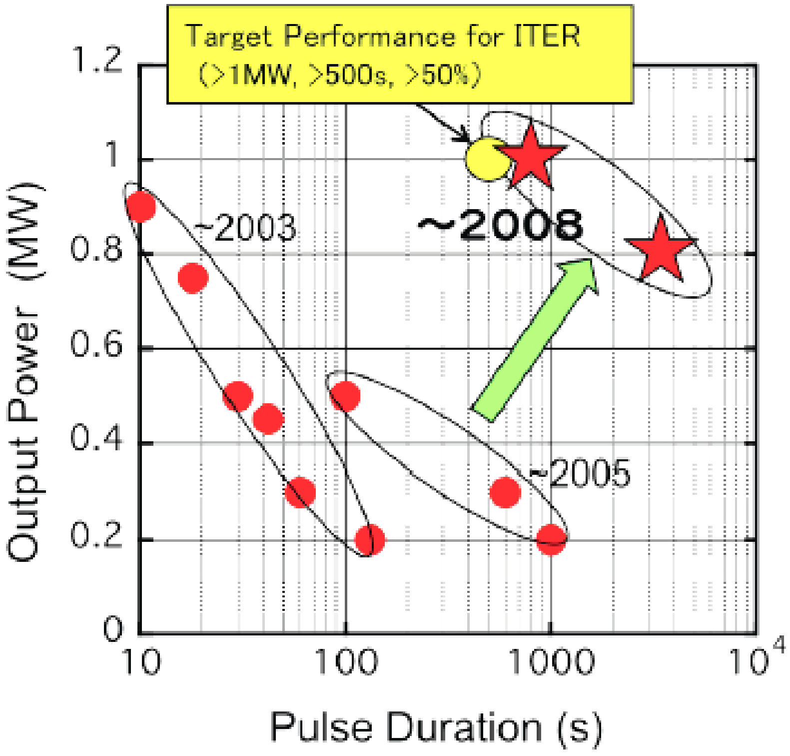
E. Kowalski, IEEE MTT, 2010
M. Shapiro, FS&T, 2010
D. Rasmussen, US ITER, 2012

170 GHz, 1 MW JAEA Gyrotron



JAEA gyrotron

Previous results



TE31,8 mode gyrotron

- 1MW/800s
- 0.8MW/1hr operation
- Max. efficiency: ~60%
- Total output energy: >250GJ

↓

- **Higher power**
- **Modulation**
- **Multi-frequnecy**

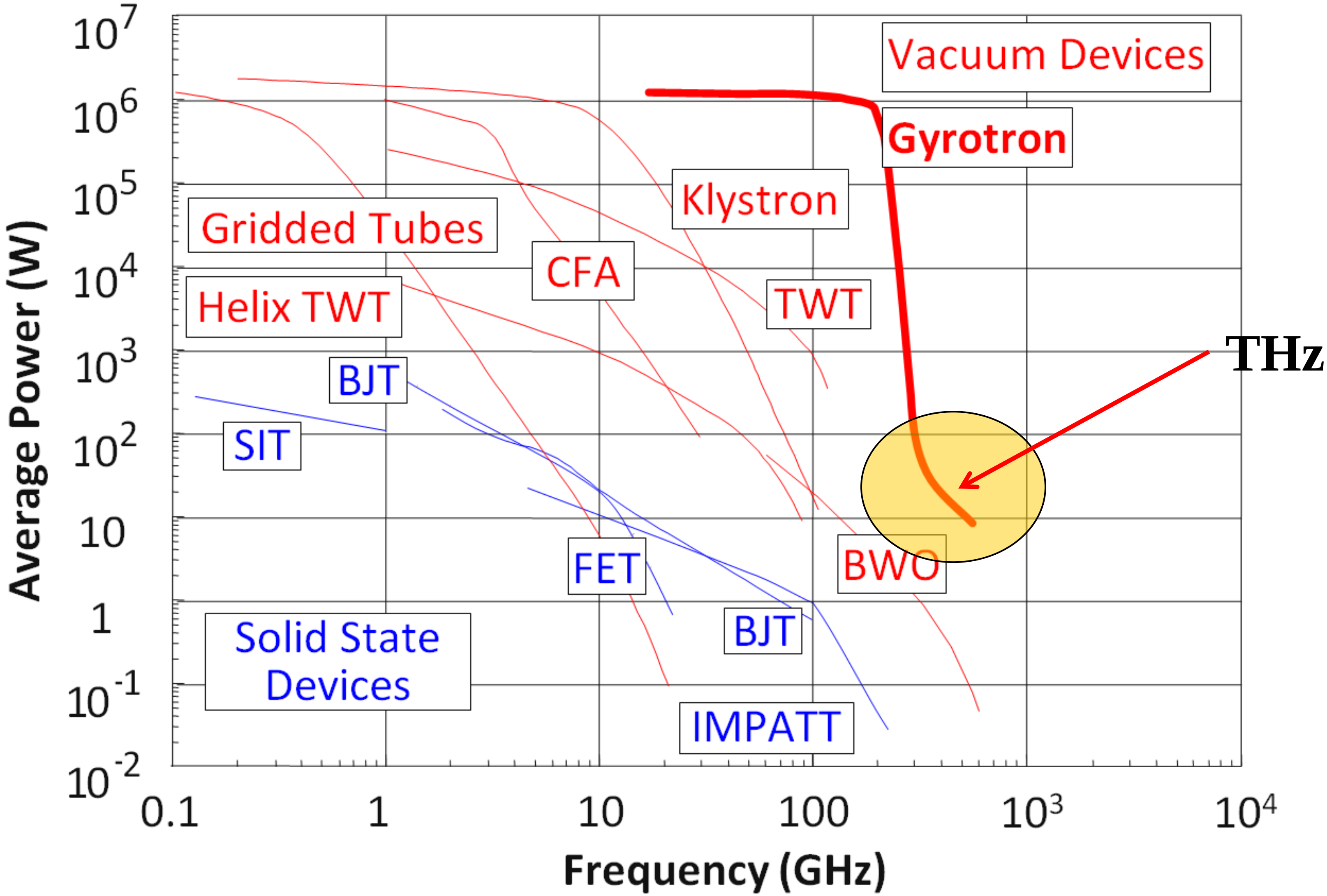
K. Sakamoto, 2012

170 GHz, 1 MW Gyrotron - Russia

- $TE_{25,10}$ Mode Gyrotron
  - 70kV, 45 A
  - 0.96 MW
  - 55% efficiency
  - 1000 seconds

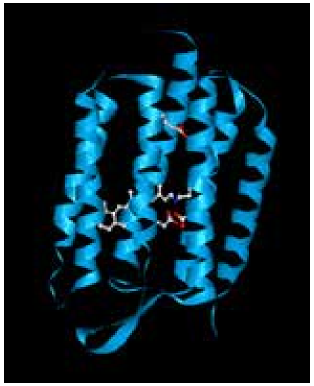
G. Denisov, IVEC 2013

THz Gyrotrons



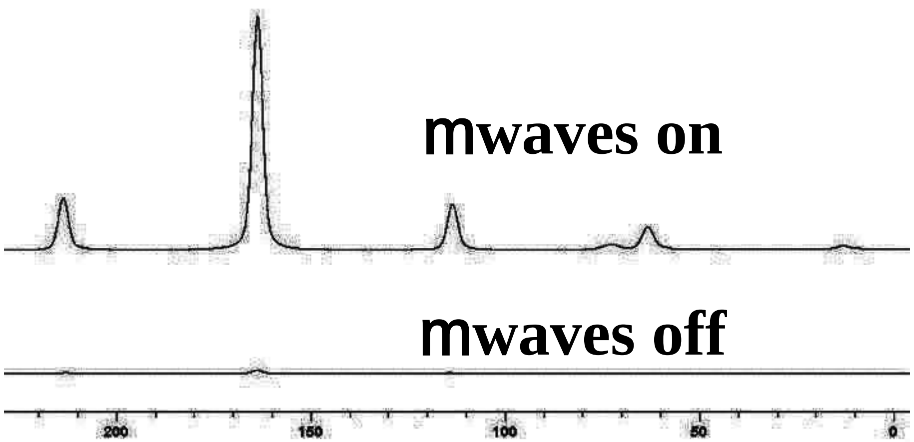
- **High power at THz freq. is tens to hundreds of Watts**

THz Gyrotrons for DNP/NMR



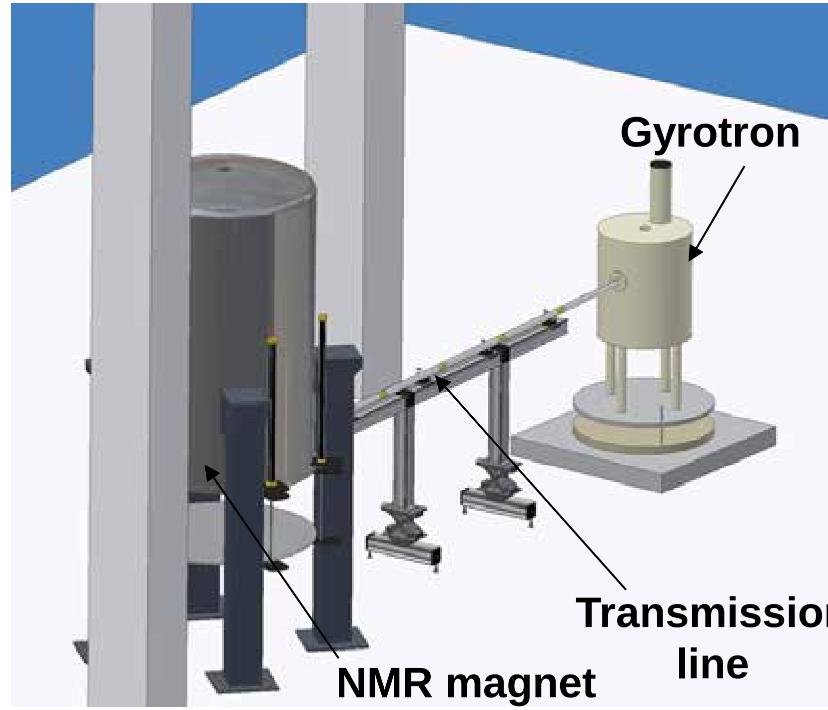
- Transfer of e^- spin polarization to nuclear spin polarization

DNP signal enhancement = 80



^{13}C Chemical Shift (ppm)

20 mM TOTAPOL in frozen glycerol/water with 2 M ^{13}C Urea



Frequency	140-600 GHz
Tuning range	~ 1 to 2 GHz
Power	10 – 100 W (CW)
Power stability	1% for 24 hours
Frequency stability	1 MHz

L. R. Becerra et al. Phys Rev Lett (1993)

250 GHz Gyrotron for DNP/NMR

- 250 GHz / 380 MHz

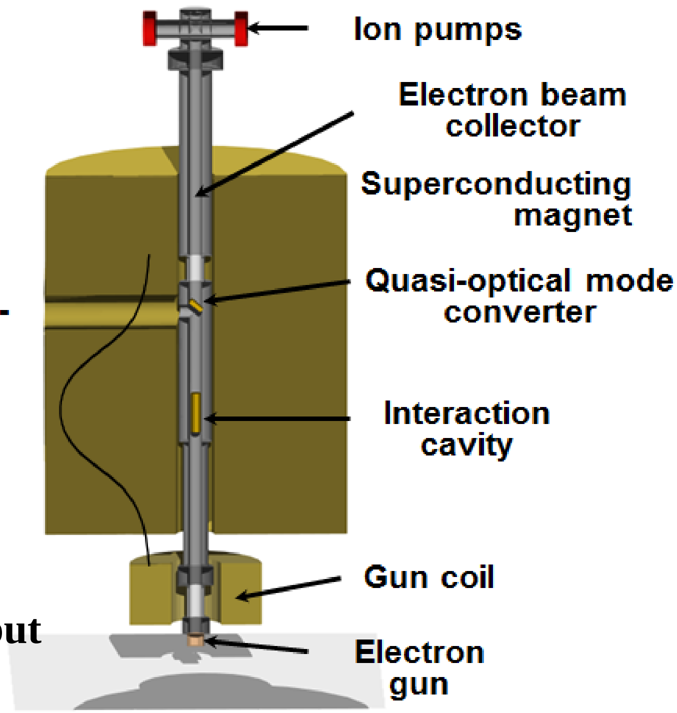
Operation Voltage, V_0 (kV)	12
Beam Current, I_0 (mA)	180
Operating Mode	TE_{521}
Gyrotron Tube Output Mode	HE_{11}
Magnetic Field, B_0(T)	9.0
Cyclotron Harmonic Number	1
Output Power (W)	30

- Dynamic Nuclear Polarization NMR yields signal increase up to 600!
- Gyrotron has 3 GHz tuning range

K. E. Kreischer et al., Proc. IR MM Waves Conf. (1999)

V. S. Bajaj et al., Journal of Magnetic Resonance Vol. 189 (2007)

Moving to Second Harmonic: 460 GHz



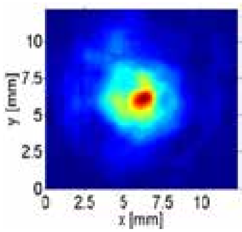
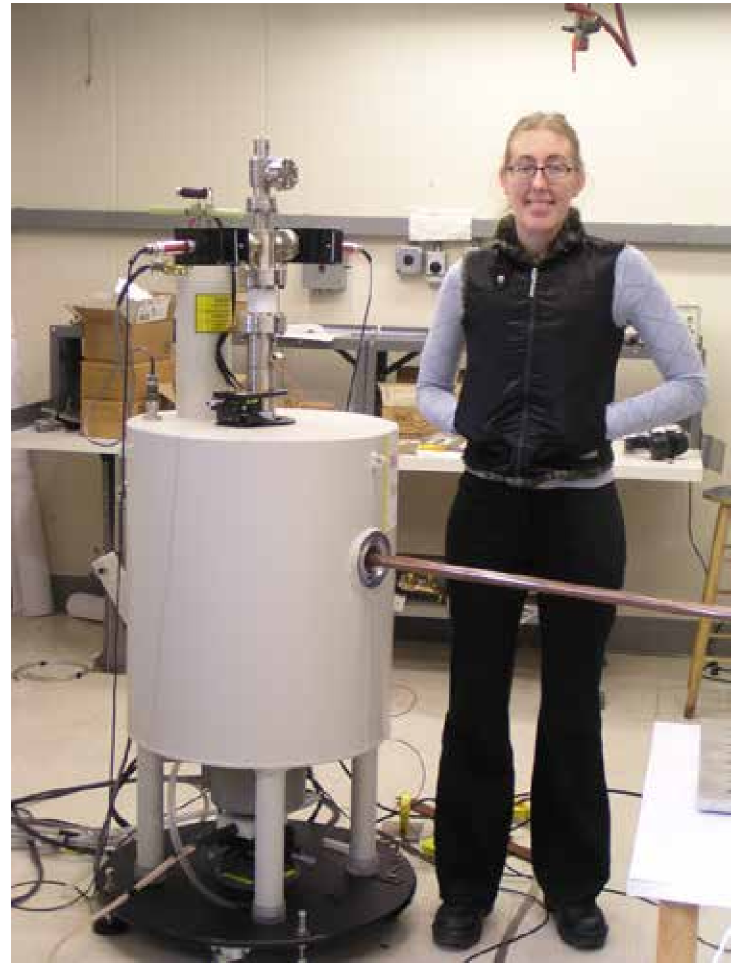


Image of output beam

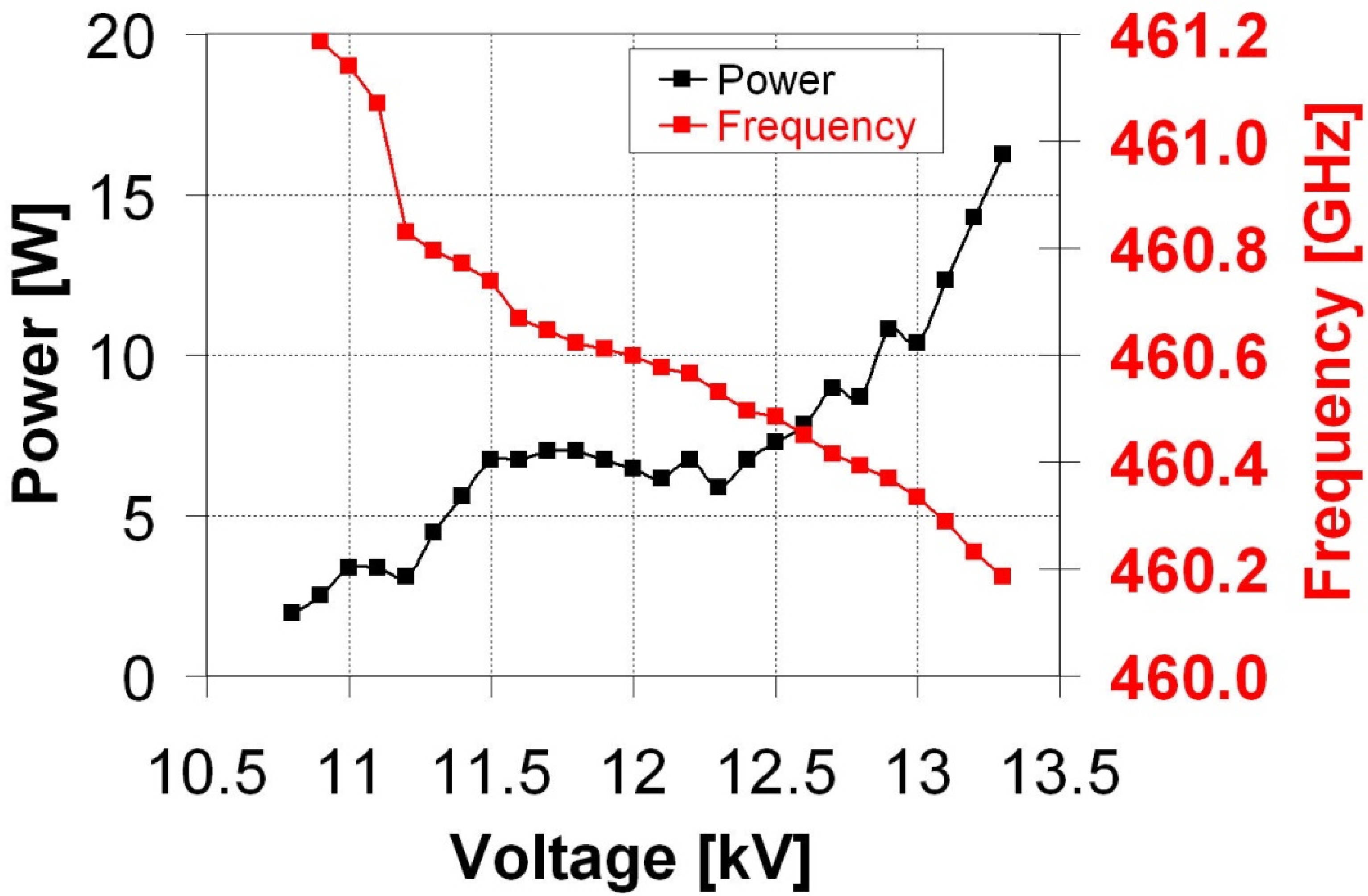


- $w@2w_c$ second harmonic
- Gain ~ $(v_{\wedge}/c)^{2n}$
- $(v_{\wedge}/c)^2 = 0.04$ at 12 kV

M. K. Hornstein et al., IEEE Trans. Elec. Devices (2005)
A. C. Torrezan et al. IEEE Trans. Plasma Sci. 2010

460 GHz gyrotron – Voltage Tuning

- **Broadband frequency tuning @ 2w_c: 1 GHz**

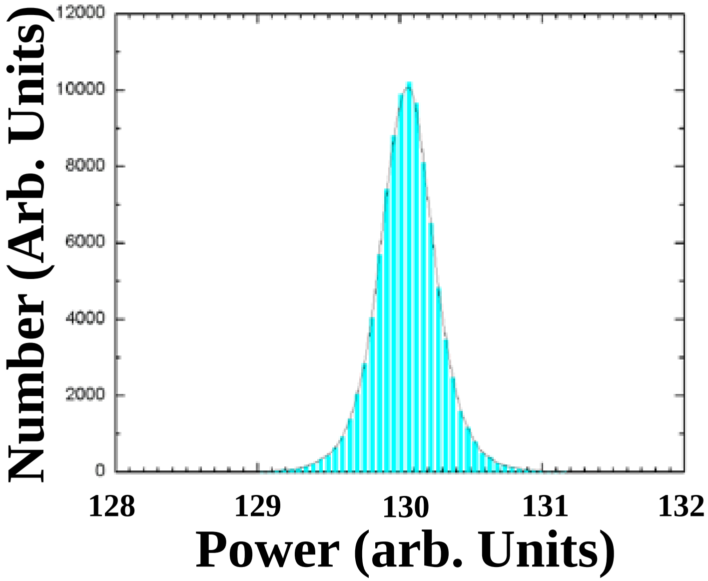


B_o = 8.43 T, I_b = 100 mA

A. C. Torrezan et al. IEEE Trans. Plasma Sci. 2010

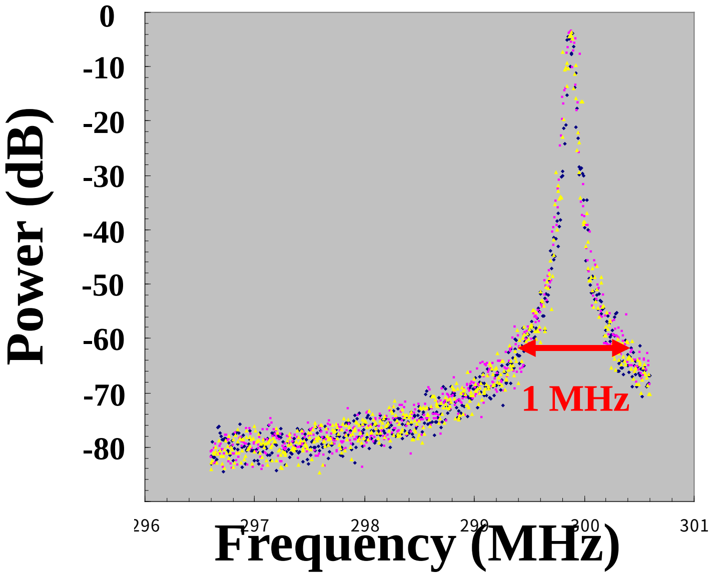
Gyrotron Stability

Stability



- 24 hour run at 460 GHz; output power stable to ± 0.5 %

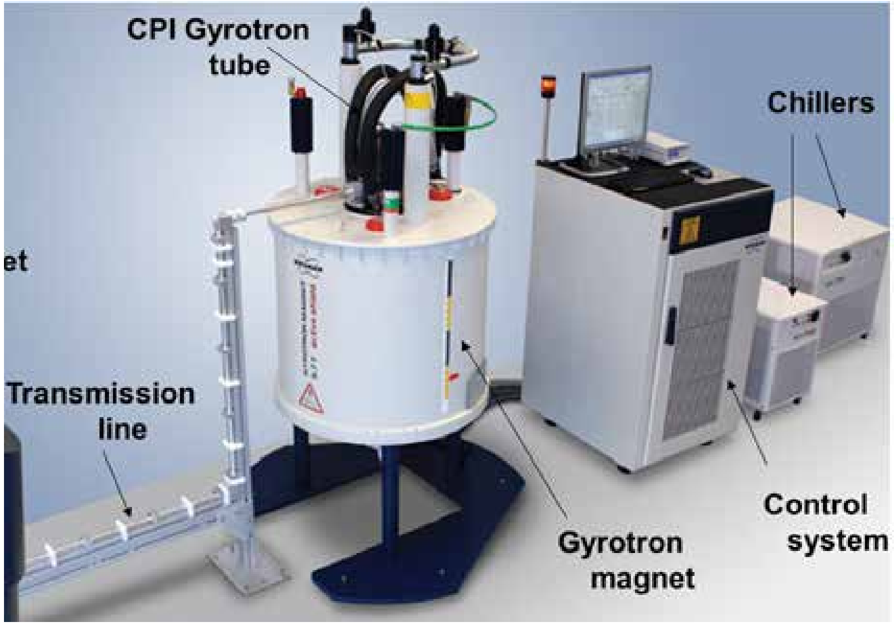
Bandwidth



- 140 GHz oscillator bandwidth < 1 MHz

S-T Han et al., IEEE Trans Plasma Sci 2007

Bruker DNP/NMR Systems

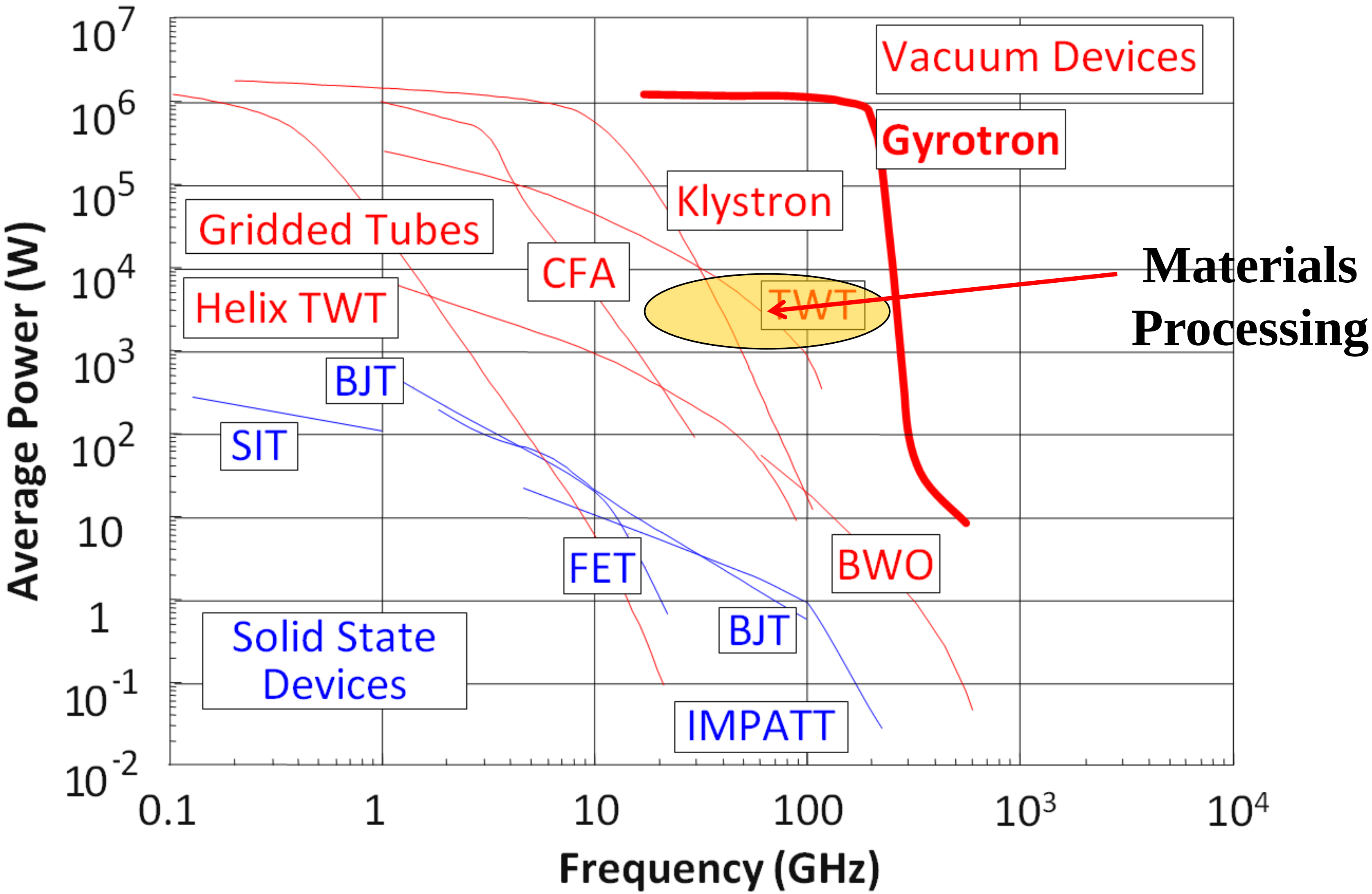


263 GHz for 400 MHz NMR

527 GHz for 800 MHz NMR

http://www.bruker.com/products/mr/nmr/dnp-nmr/overview.html

Materials Processing Gyrotrons

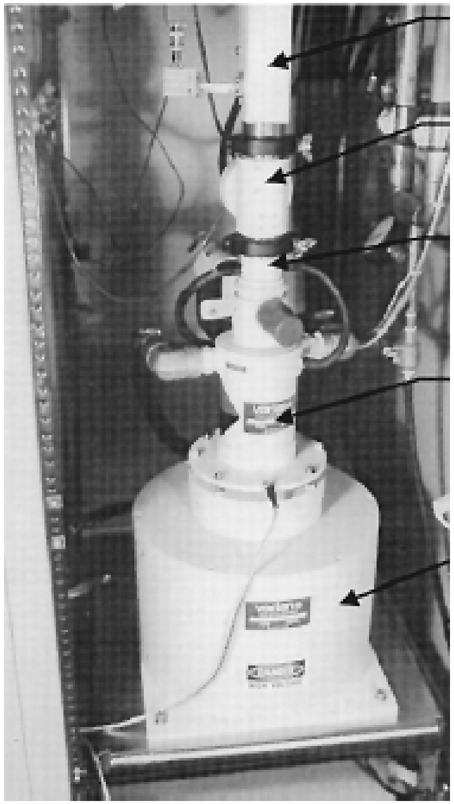


Materials Processing

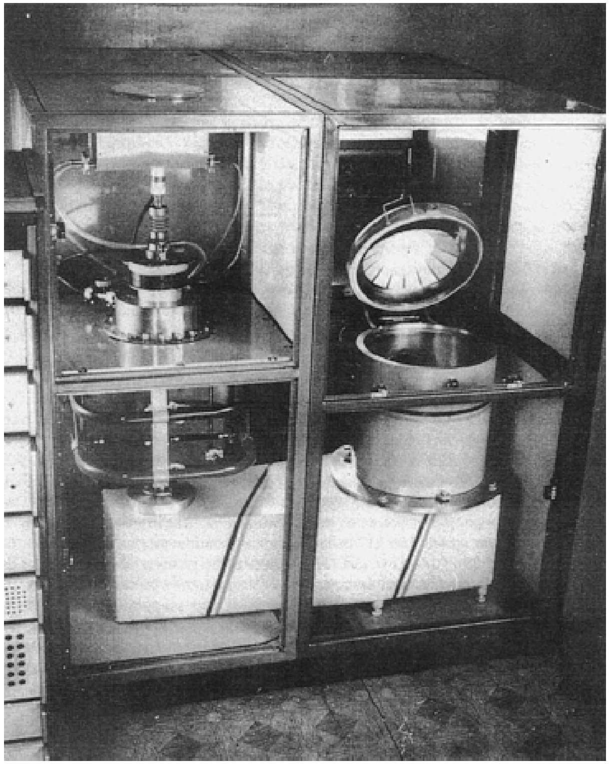
- Non-contact, rapid heating of ceramics, glass, semiconductors

- Power ~ 1 - 20 kW
  - Frequencies ~ 24 to 84 GHz
- Used with materials of low loss tangent at lower frequencies – power absorption increases with frequency

- Large scale applications?



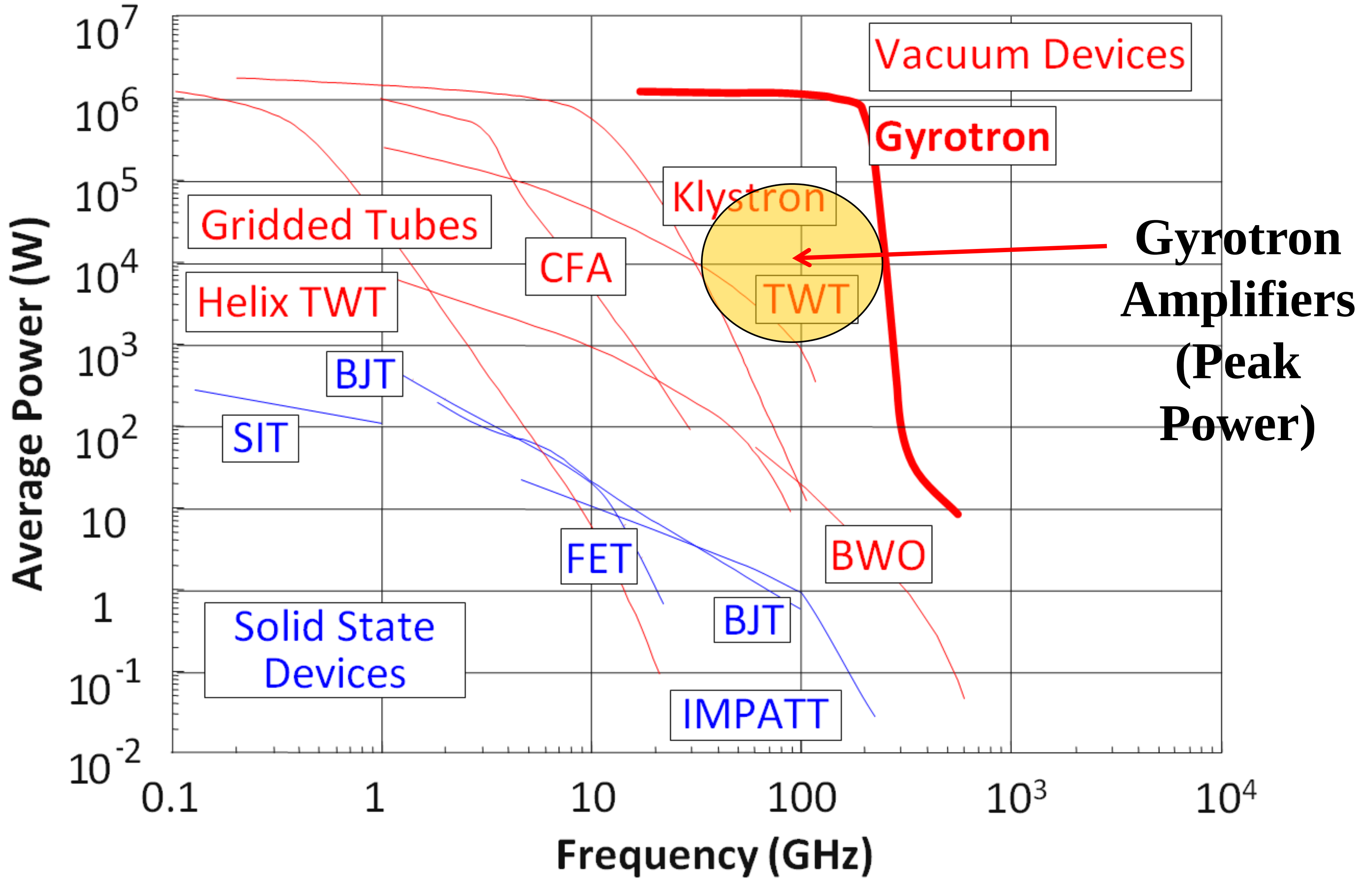
CPI 28 GHz 10 kW Industrial Gyrotron



Gycom 30 GHz Gyrotron and Applicator

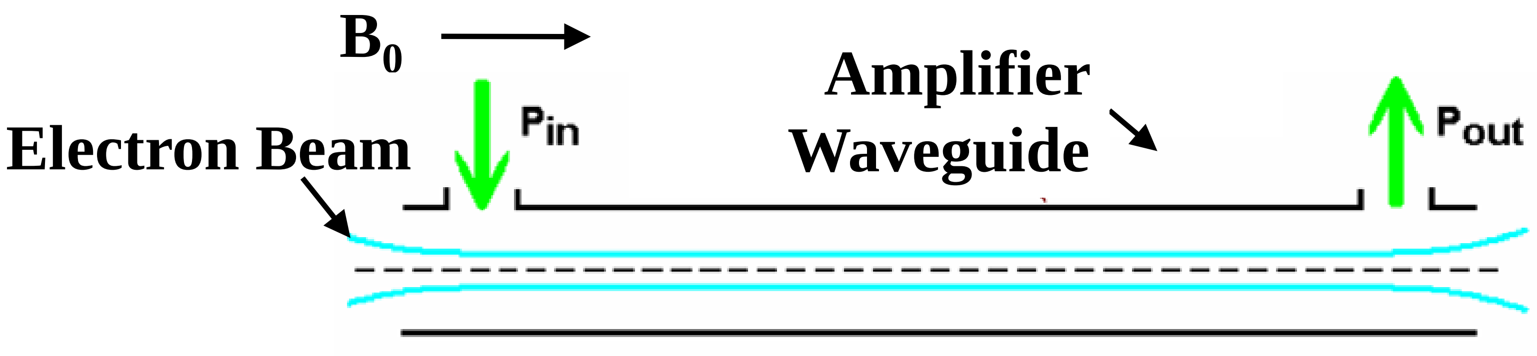
Gyrotron Amplifiers

- Applications: radar, spectroscopy



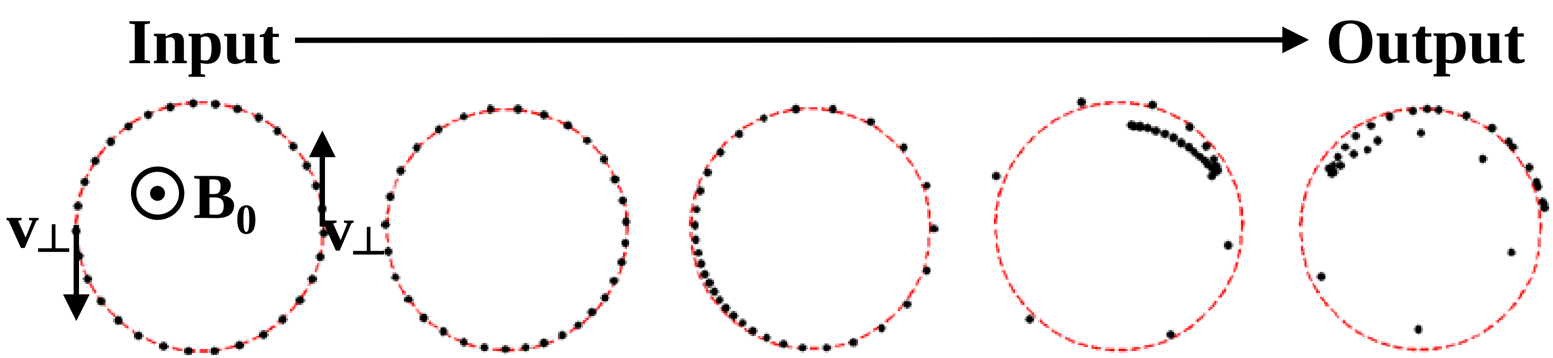
Interaction Region

- Amplifiers have new physics challenges:
  - Instabilities; single pass gain; role of velocity spread



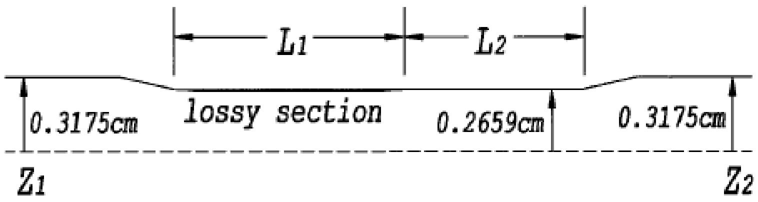
$$\frac{\partial \vec{p}}{\partial t} = -e\vec{v} \times \vec{B}_0 - e\vec{E}_{RF} \qquad \omega_c = \frac{eB}{\gamma m_e}$$

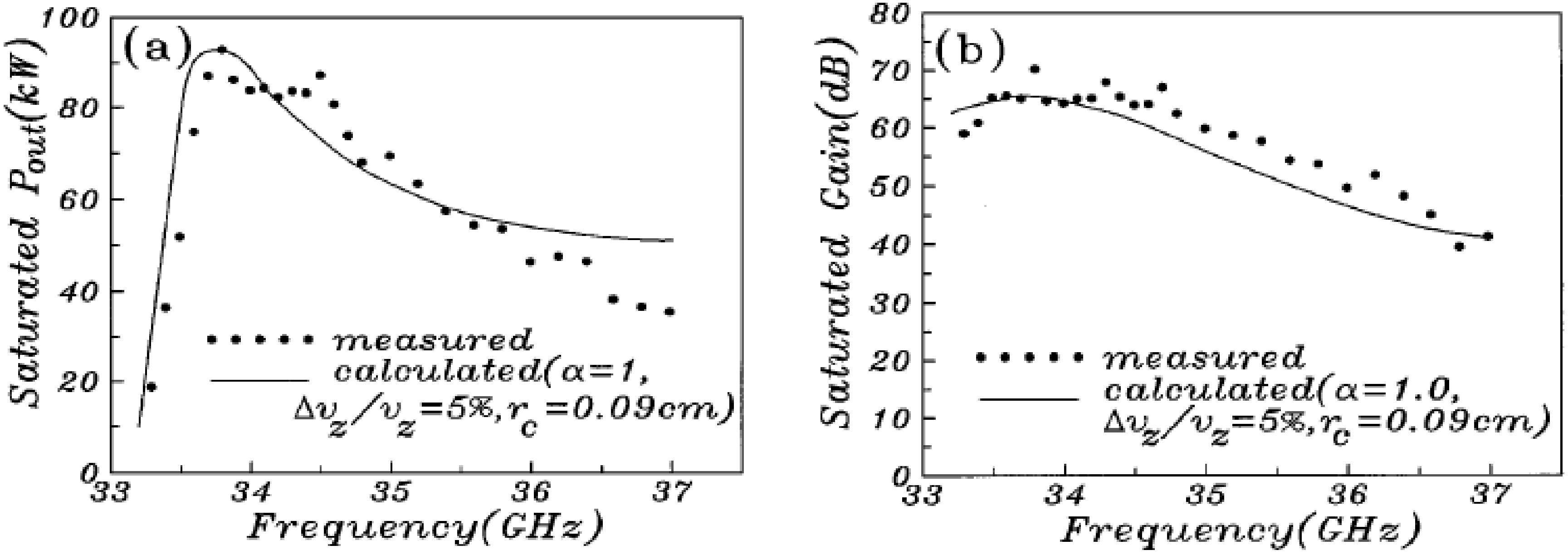
Note: $\omega_c \propto \frac{1}{\gamma}$



Ultra High Gain Gyro-TWT

- Instability stopped by highly lossy circuit
- 93 kW, 70 dB gain at 35 GHz, with 3 GHz Bandwidth



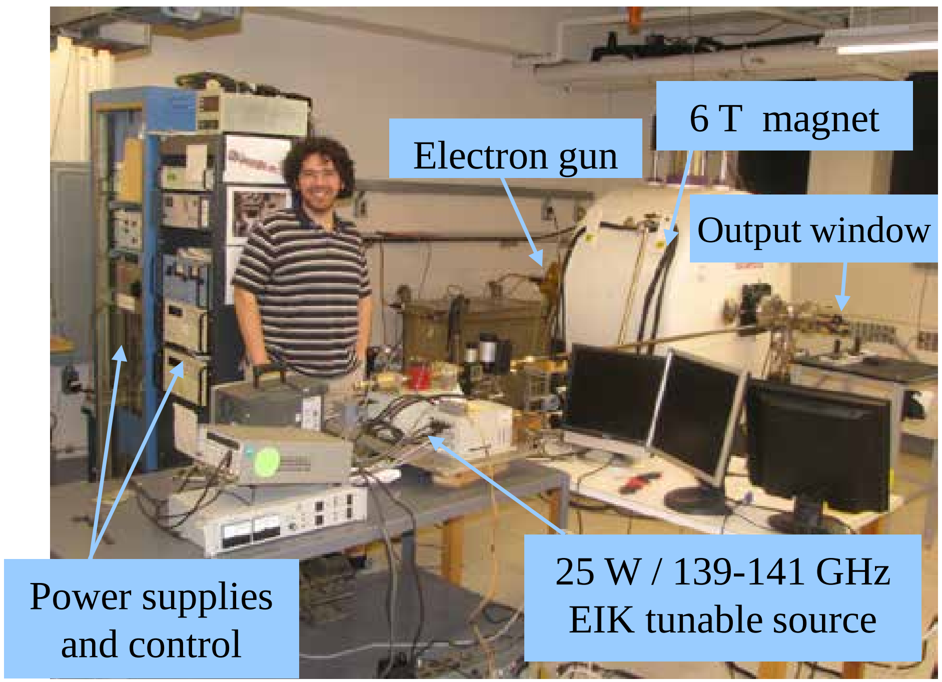


K. R. Chu et al, PRL (1998)

Gyrotron Amplifier Research at MIT

- High power microwave amplifiers for time-domain DNP NMR spectroscopy based on novel structures

140 GHz Gyrotron Amplifier
Confocal Structure
34 dB Gain, 820 W

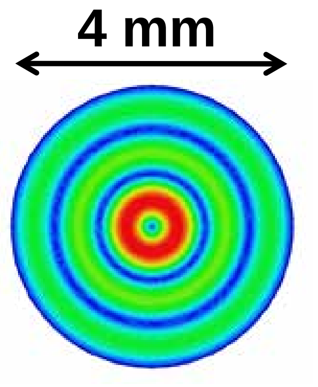


250 GHz Gyrotron Amplifier
Photonic Band Gap Structure
38 dB Gain, 45 W

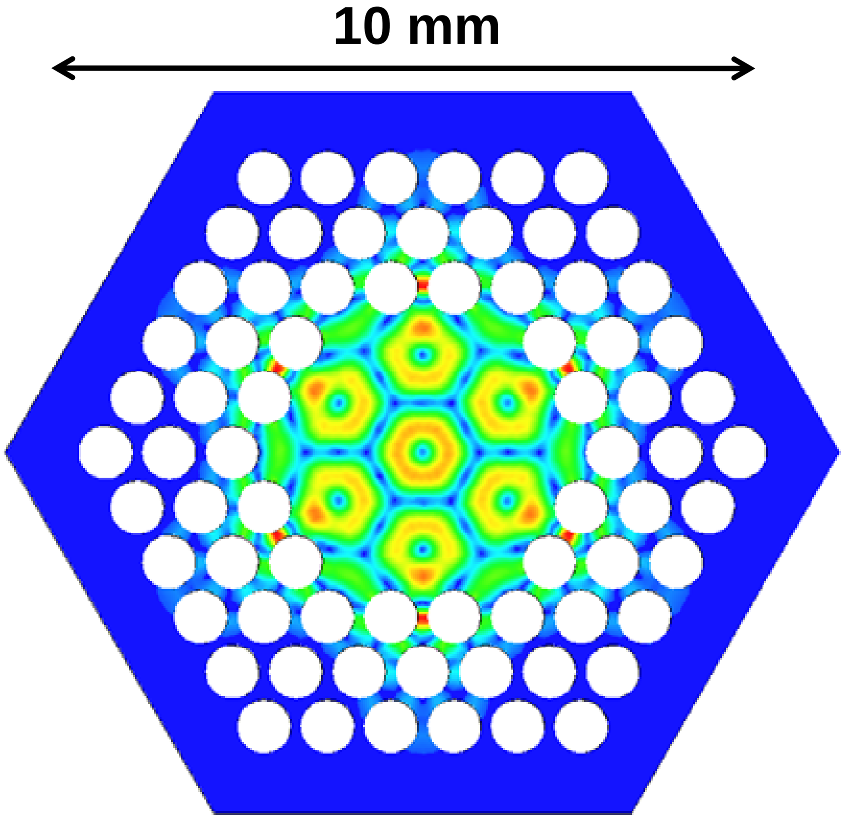
TE_{03}-Like Mode

- Defect region in photonic structure confines waveguide mode

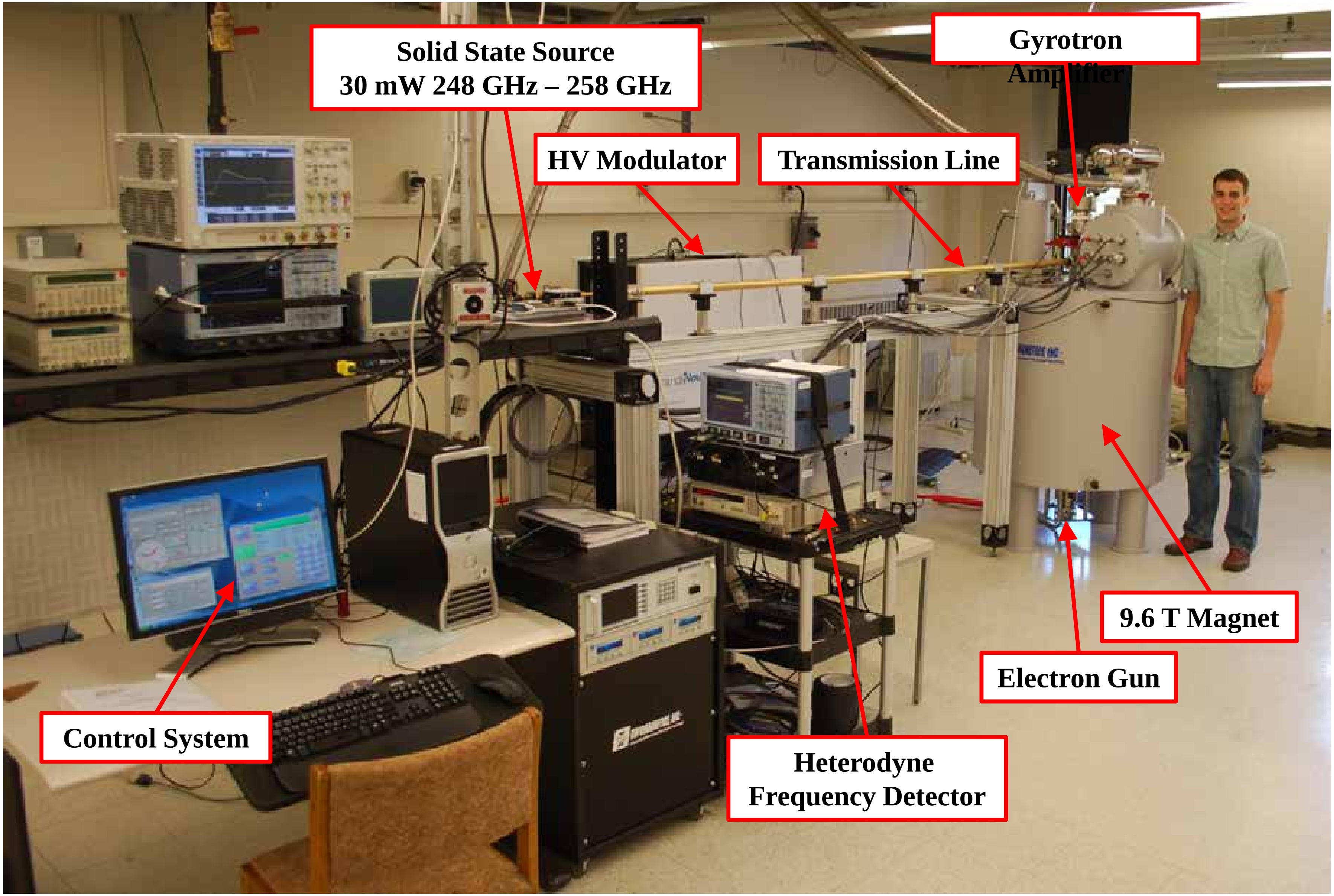
Circular Waveguide: TE_{03} Mode



PBG Waveguide: TE_{03}-like Mode



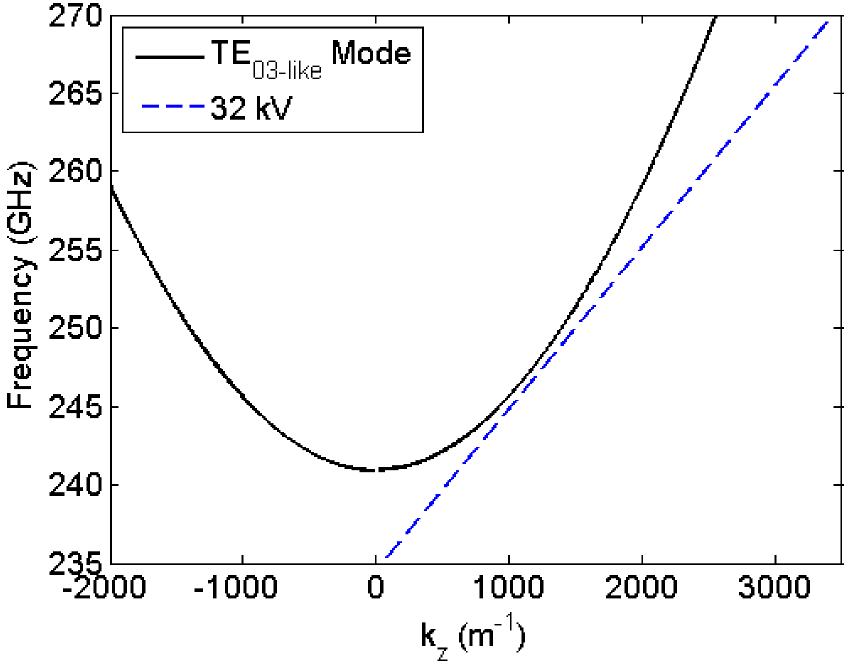
Experimental Setup

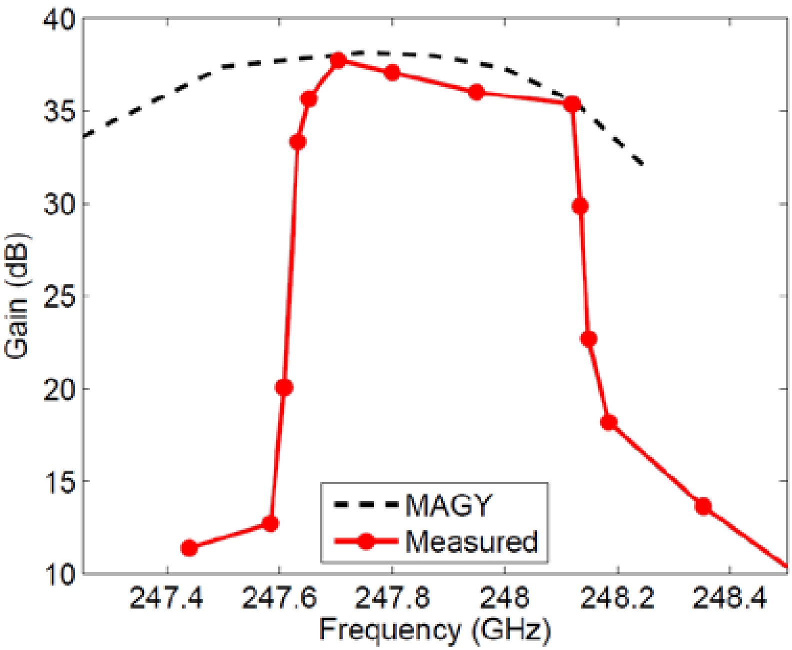


Peak Power and Gain

- 7.5 mW Input Power (after isolator)
- 45 W Output Power
- 37.8 dB Gain (50 dB Circuit Gain)
- Bandwidth = 400 MHz, limited by input coupler

f = 247.7 GHz
V_k = 32 kV
I_b = 0.345 A
α = 1.12
B_0 = 8.90 T

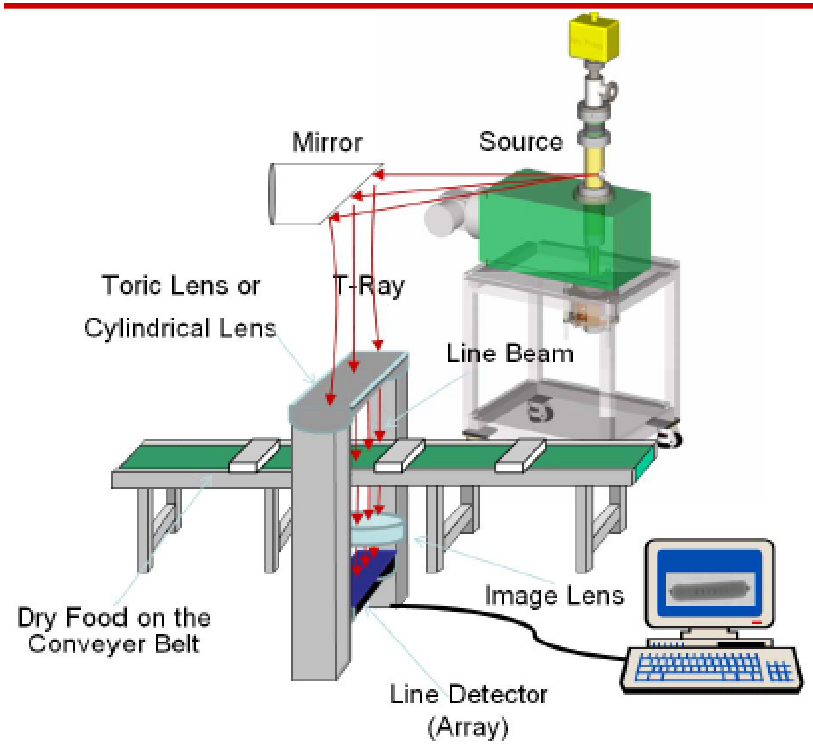


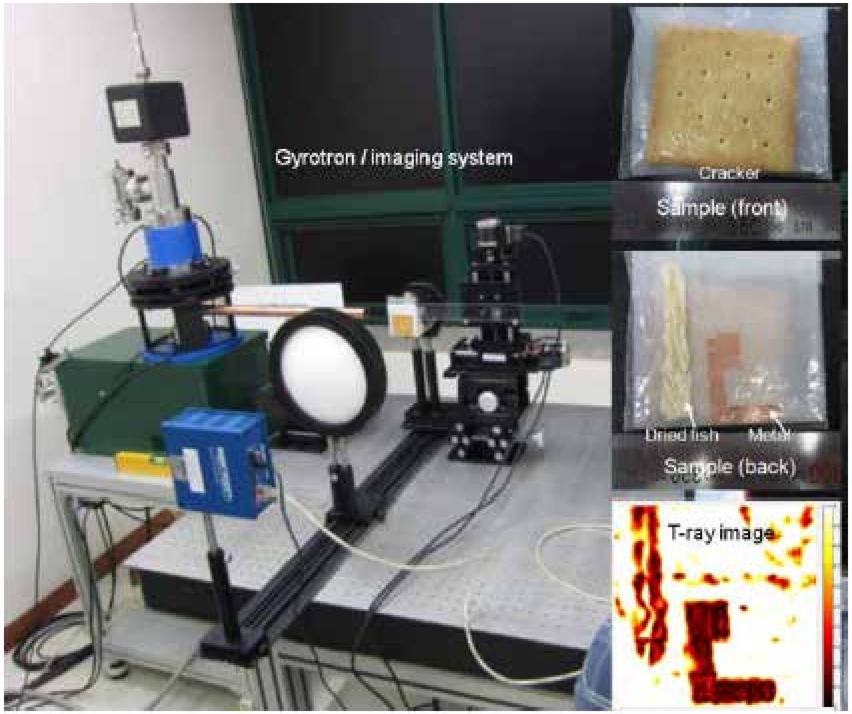


E. Nanni et al. Phys Rev Lett 2013

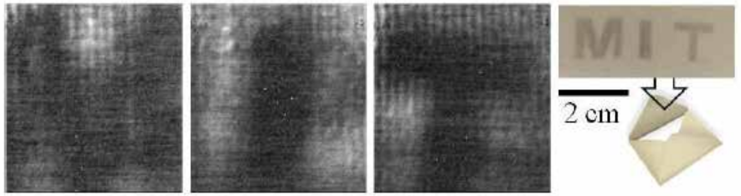
Novel Applications

Imaging and Inspection





- 200 – 400 GHz gyrotron radiation images material on a conveyor belt
  - Application to the food industry
- Metal or other foreign objects are identified



S-T Han, J. Phys. Soc. Korea 2012

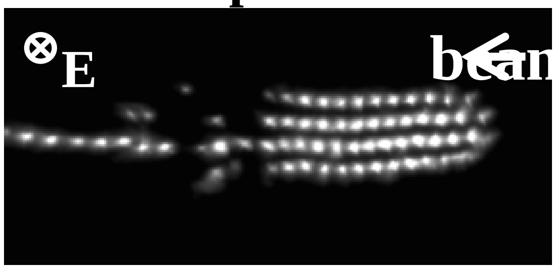
S-T Han, IRMMW-THz Conf. 2011, 2012

MIT Study of Air Breakdown

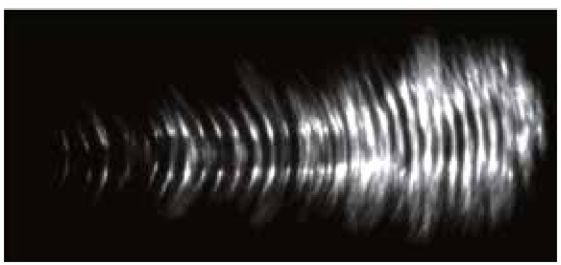
- Air breakdown using 1 MW, 110 GHz pulsed (3 μs) gyrotron

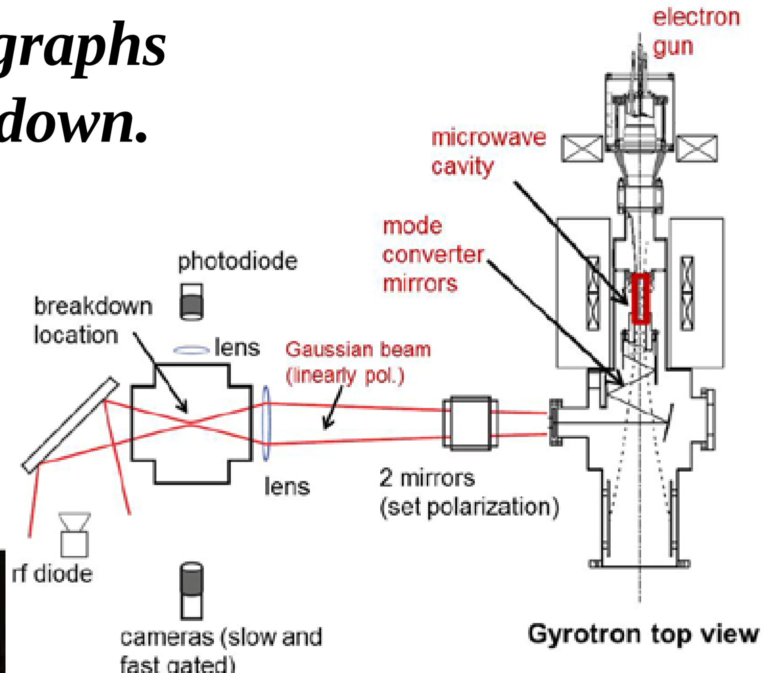
Open-shutter photographs of free-space breakdown.

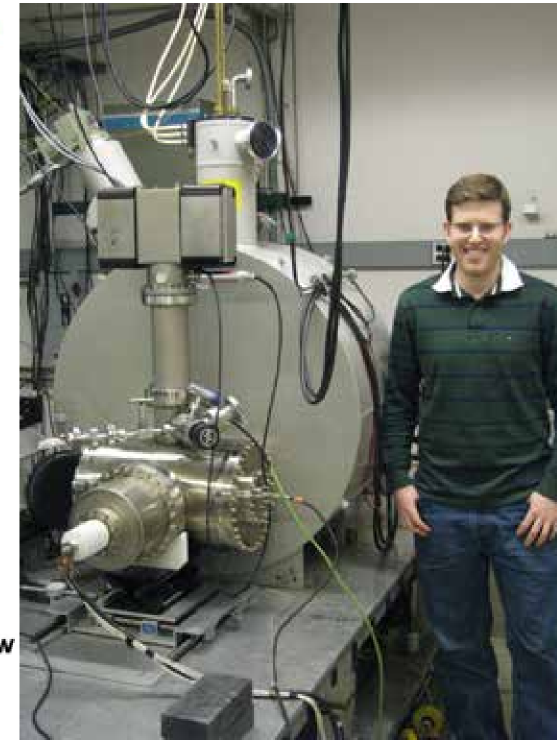
Top View



Side View



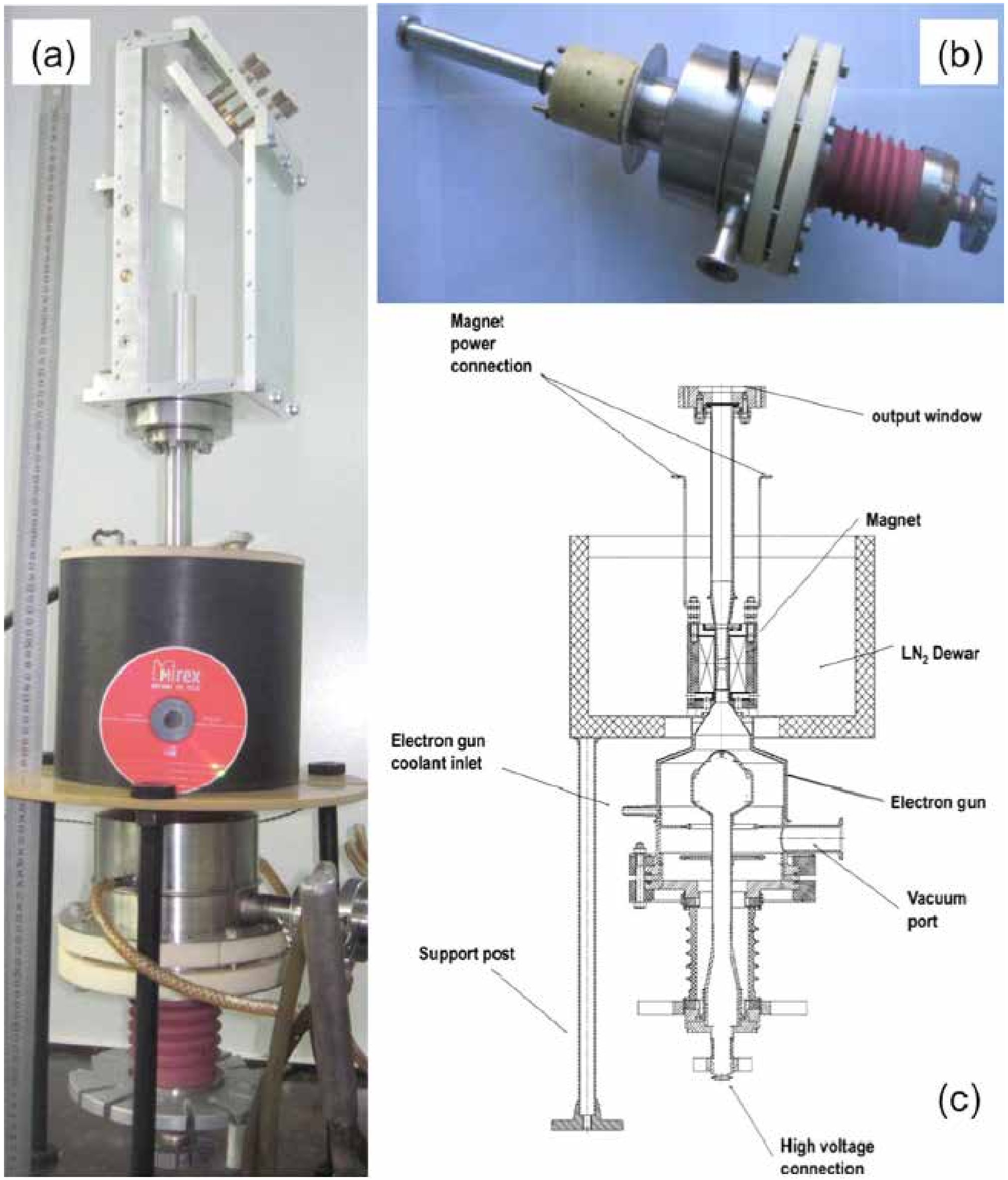




- 2D arrays, 50-100 filaments
- Quarter-wavelength separation
  - $\lambda/4 \sim 0.68$ mm

Y. Hidaka, PRL, 2008
J. Hummelt, PoP, 2012

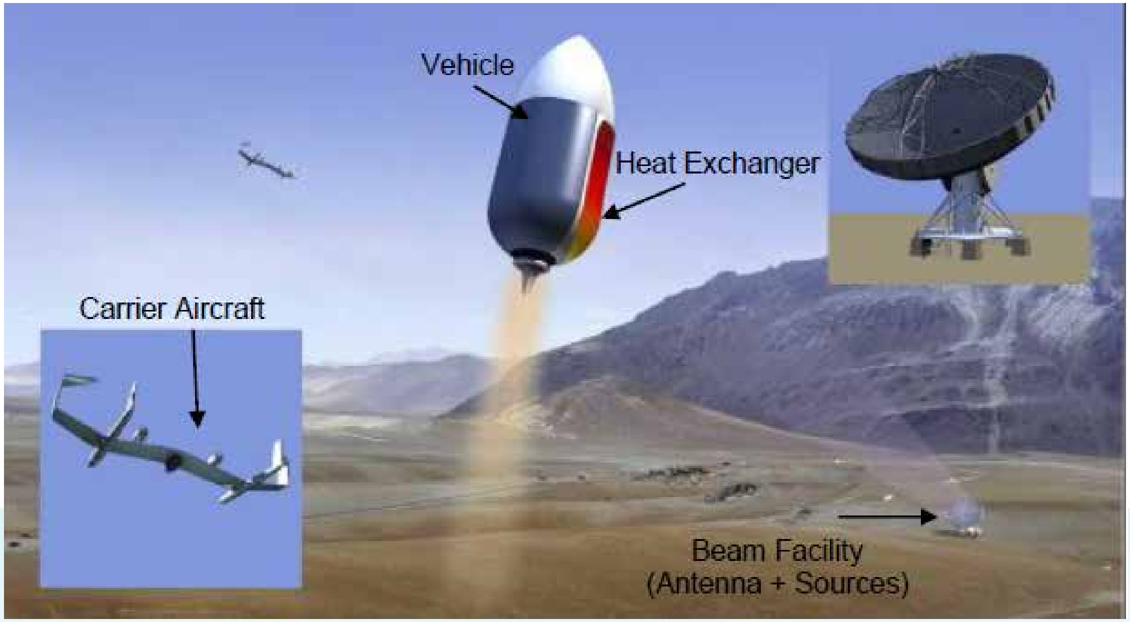
Radioactive Material Detection



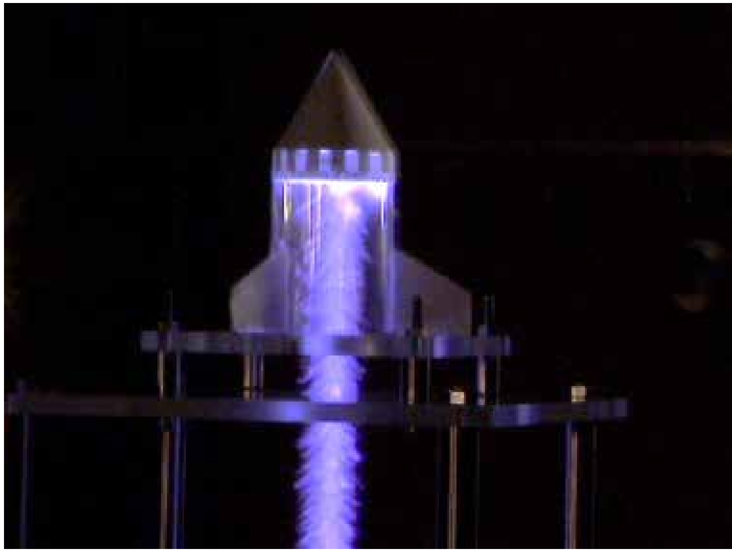
- 210 kW, 670 GHz gyrotron built with a pulsed solenoid
- Remote detection of radioactive materials
- Seed electrons produced by radioactivity will allow air breakdown by the THz radiation, leading to detection

G. Nusinovich, JIMT, 2011
M. Glyavin, APL, 2012

Rocket Launcher

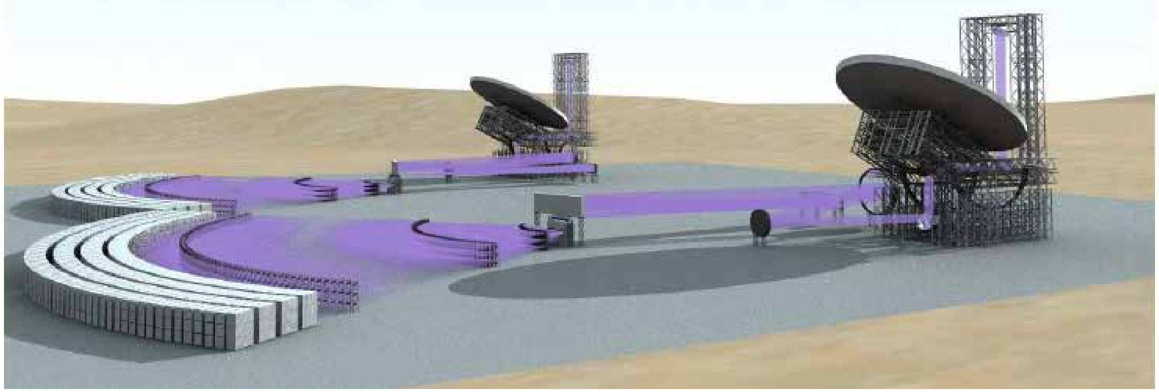


Beamed Energy Propulsion Concept



Lab test of rocket at JAEA by Univ. Tokyo team

J. Oda, JAEA, 2012



Rocket Launch – Artist's Concept, NASA

A. Murakami, AIAA, 2012

Conclusions

- Gyrotrons are the most powerful sources of radiation in the millimeter wave and the Terahertz regions
- Gyrotron oscillators have three major applications
  - Plasma Heating
  - Materials Processing
  - Spectroscopy including DNP/NMR
- Gyrotron amplifiers are less well developed but have significant applications
  - Radar, Spectroscopy
- High power gyrotrons and applications have a promising future!

Acknowledgements

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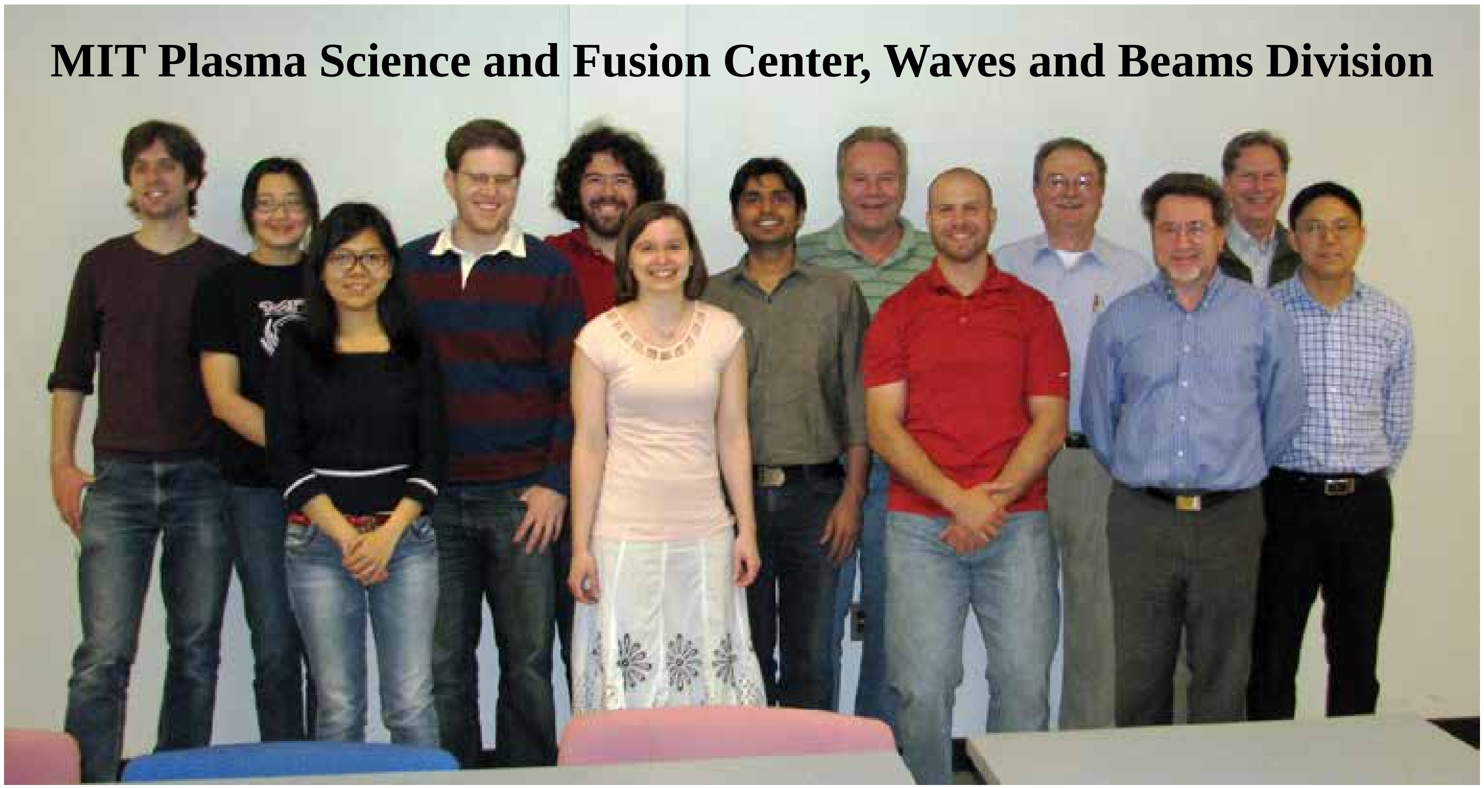

MIT Plasma Science and Fusion Center, Waves and Beams Division