ECH Technology for Burning Plasma Experiments

Burning Plasma Science Workshop II

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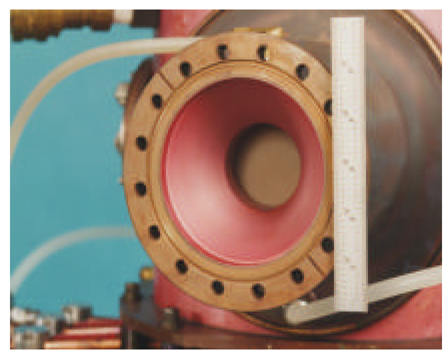
Outline

- *Where are we today?*
  - **Intensive research leading to many advances worldwide.**
- *What do we need to develop for a Burning Plasma Experiment?*
  - **JET, ITER FEAT, FIRE, IGNITOR, others?**
- *What are the prospects for Development?*
  - **Gyrotron development is the key issue.**
- *Conclusions*
  - **We can do it!**

ECH Technology Program: US Program

1 MW gyrotron system at GA

- 1MW, 110 GHz gyrotrons, with CVD diamond window, built by CPI.
- Three tubes must operate this year at 1 MW power level at GA to meet ECH system milestone:
  - Scarecrow; Tinman; Lion
- Factory acceptance test at CPI to 0.6 MW, 10s (limited by power supply).
- Final acceptance test at GA to 1 MW, 10s.



CVD diamond window

Spectacular Worldwide Progress in ECH Technology!

- ***Europe – FZK, Lausanne, Thomson***
  - **Gyrotrons for Wendelstein VIIX: 1 MW, 140 GHz gyrotrons**
    - **1.0 MW, 10 s pulsed operation achieved in April, 2001**
      - **47% efficiency with a depressed collector.**
    - **0.86 MW for 40s; 0.64 MW for 140s**
  - **Gyrotron development for JET, 1 MW at 110 or 113 GHz**
    - **Considered to be within the state-of-the-art.**
- ***Japan – JAERI / Toshiba***
  - **Gyrotron Development for ITER FEAT: 1 MW at 170 GHz**
    - **1 MW, 2s pulsed operation at 170 GHz achieved in 2001.**
      - **Longer pulses at lower power.**
  - **Gyrotron development for JT60-U**
    - **1 MW, 2s pulsed operation achieved at 110 GHz**
- ***Russia – IAP, N. Novgorod, Kurchatov, GYCOM***
  - **Gyrotron development at 110, 140 and 170 GHz.**
  - **1 MW, 110 GHz gyrotron with 2 s pulsed operation.**

What do we need to develop?

- *Main issue is gyrotron development.*
  - **Good news: all machines can be heated at the fundamental.**
  - **Large savings in development costs, increased feasibility and reliability.**

Machine	B(T)	Cyclotron Frequency (GHz)	$N_e(0)$ ($10^{20}m^{-3}$)	$(w_p/w_c)^2$
ITER FEAT	5.3	150 - 170	1.1	0.4
FIRE	10	280	6.8	0.7
IGNITOR	13	364	9.5	0.6

280 GHz Gyrotrons for FIRE

- *Gyrotron R&D proceeds in two steps:*
  - *Basic research on the prototype (at MIT in short pulse operation) ; Industrial development (CPI).*
- *Basic Research on a 280 GHz Gyrotron*
  - **MIT conducted R&D in support of BPX; MW power level gyrotron operation was demonstrated in the 200 – 300 GHz band.**

Frequency (GHz)	TE Mode	Power (MW)
202	35,4	0.9
229	34,6	1.0
280	25,13	0.8
292	41,8	0.9
303	27,14	0.3

Reference: T. L. Grimm et al., Phys. Fluids B, Vol. 5, pp. 4135-4143 (1993).

The Grimm Results

•Results were obtained at magnetic fields up to 14T.

•Electron beam of 90 kV, 50 A.

•Single mode operation achieved.

•Efficiency was low, about 20%.

- •Concern about cathode emission uniformity.

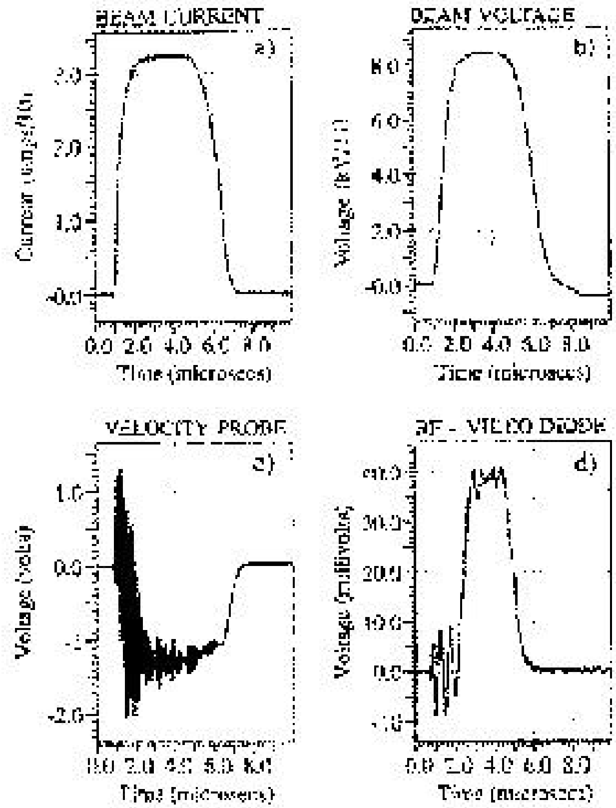
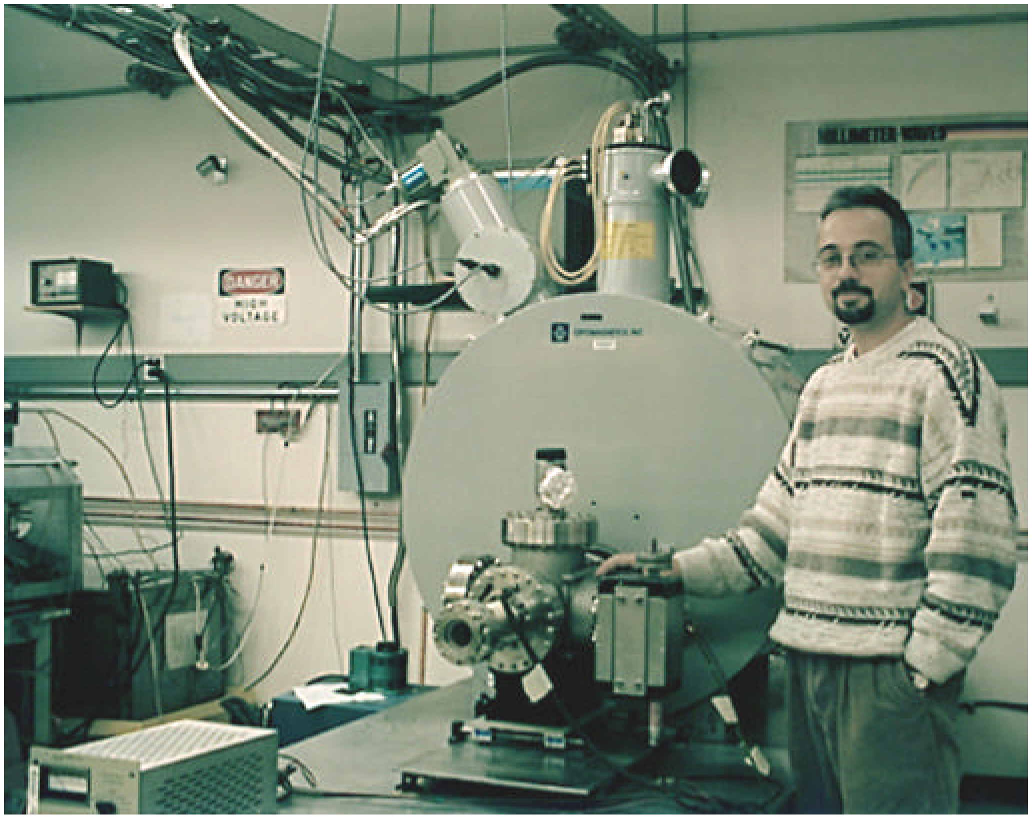


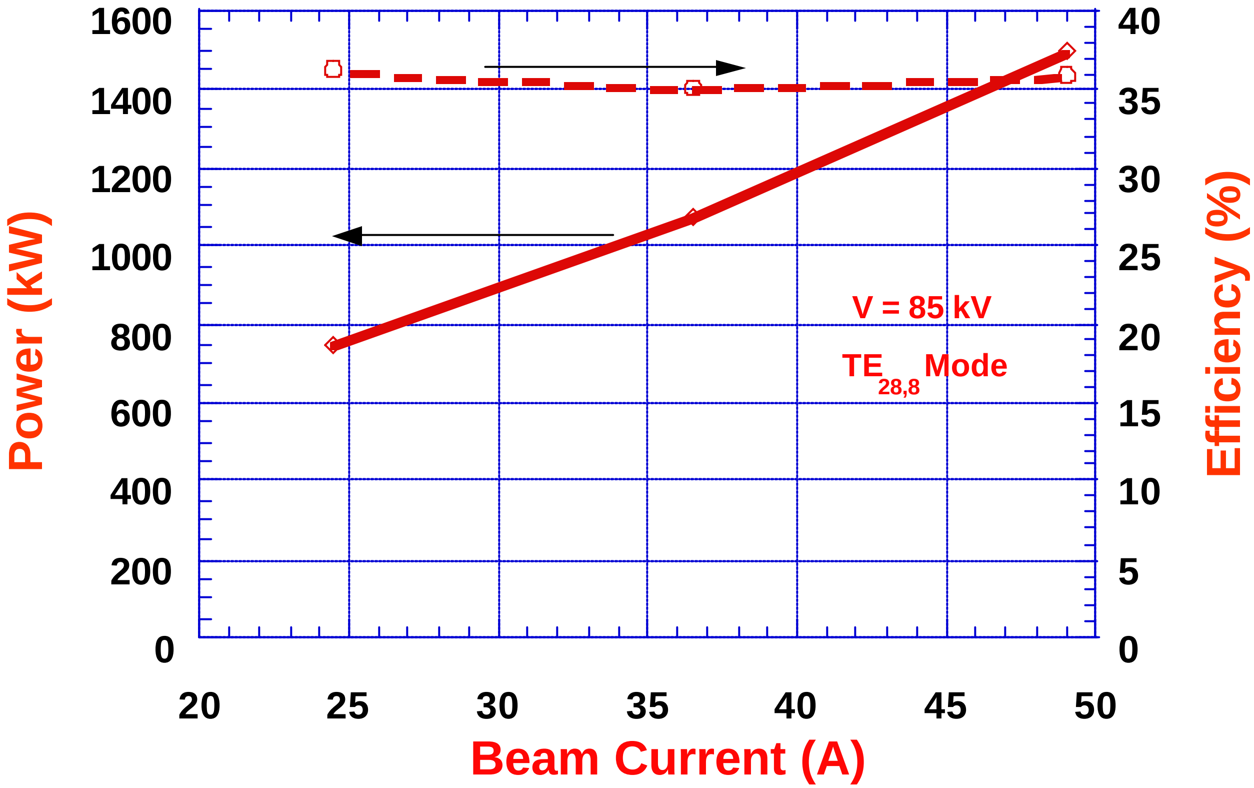
FIG. 3. Experimental data; (a) beam current (32.5 A), (b) beam voltage (95 kV), (c) capacitive probe (proportional to the beam's axial density), and (d) microwave power using a high-frequency video diode.

MIT 1MW Gyrotron Research



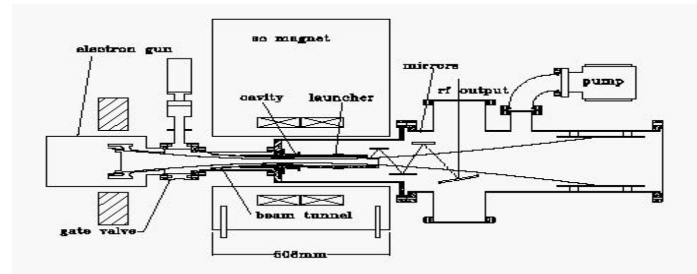
- 110 - 170 GHz gyrotrons operate at up to 85 kV and 50 A with output power of > 1.5 MW at over 35% efficiency.
- Gyrotron is operated in 3 μs pulses.
- Gyrotron is a prototype of a continuous wave source which could be developed by industry.

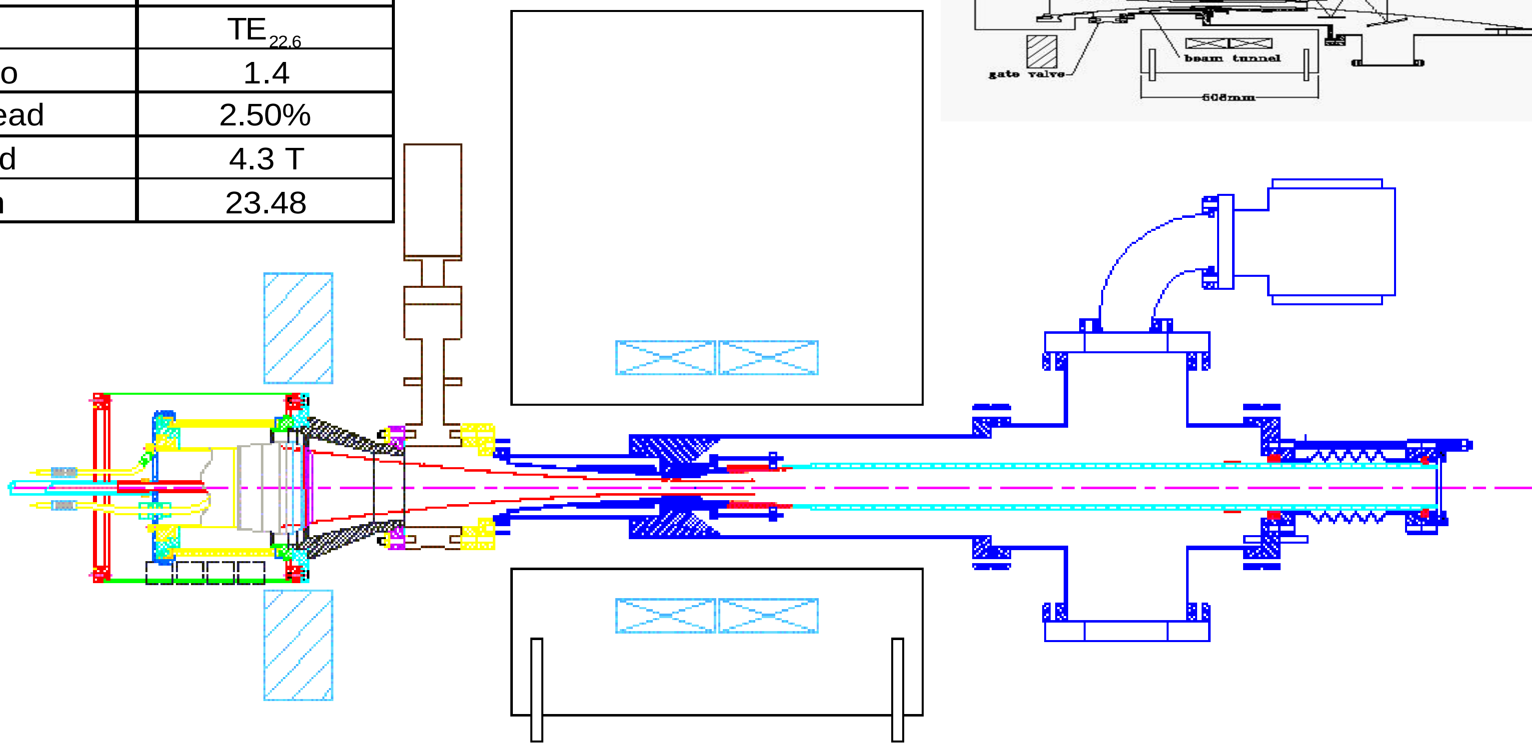
Measured Power from MIT 170 GHz Gyrotron



1.5MW 110 GHz Experiment

Frequency	110 GHz
Output Power	1.5 MW
Beam Voltage	96 kV
Beam Current	40 A
Mode	$TE_{22,6}$
Velocity Ratio	1.4
Velocity Spread	2.50%
Cavity B Field	4.3 T
Compression	23.48





•Experiment is under construction.

•Expected to operate at > 1.5 MW of output power at 110 GHz.

Gyrotron Development, 280 GHz Gyrotrons

- Previous results at 280 GHz indicate that we can have confidence in developing 1 MW, 280 GHz gyrotrons.
  - Additional (low cost) prototype research would be required to demonstrate:
    - high efficiency operation, efficiency > 50% with a depressed collector.
    - internal mode converter.
- Industrial development could be carried out on the time scale to meet the FIRE schedule.
- Gyrotron system costs are low.
  - Most costs comparable to lower frequency gyrotrons after completion of development.
  - Magnet costs will be high.
- IGNITOR Gyrotron Development is not so clear; high frequency is a challenge at high power.
  - MIT is currently developing a 100 W, 460 GHz CW gyrotron for spectroscopy.

100W, 250 GHz Gyrotron for EPR Spectroscopy

- **Gyrotron system operates at 250 GHz for Electron Paramagnetic Resonance (EPR) of solids at 9T.**
- **Dynamic Nuclear Polarization (DNP) spectroscopy at extremely high resolution; EPR system is used with 380 MHz NMR system.**
- **Gyrotron CW operation at 25W is stable to better than 150 kHz.**
- **Future research at 460 GHz.**

Conclusions

- **Present state-of-the-art in ECH technology is very promising for ECH of Burning Plasmas, at least up to 10T.**
  - **Gyrotron development in the worldwide fusion community has produced strong results at the 1 MW, 110 to 170 GHz.**
- **Burning Plasma Experiments allow heating at the fundamental, $w_p = w_c$, simplifying the gyrotron R&D.**
- **Previous results at short pulse at MIT at 280 GHz indicate that the 280 GHZ gyrotrons needed for FIRE can be built.**
- **A development program would obviously be needed to develop CW gyrotrons at 280 GHz.**
- **Other components such as transmission lines and launchers could also be developed; lower risk.**
- **Future research at higher frequency may allow us to develop gyrotrons to heat plasmas at 13 T.**