# Electron Cyclotron heating and current drive technology

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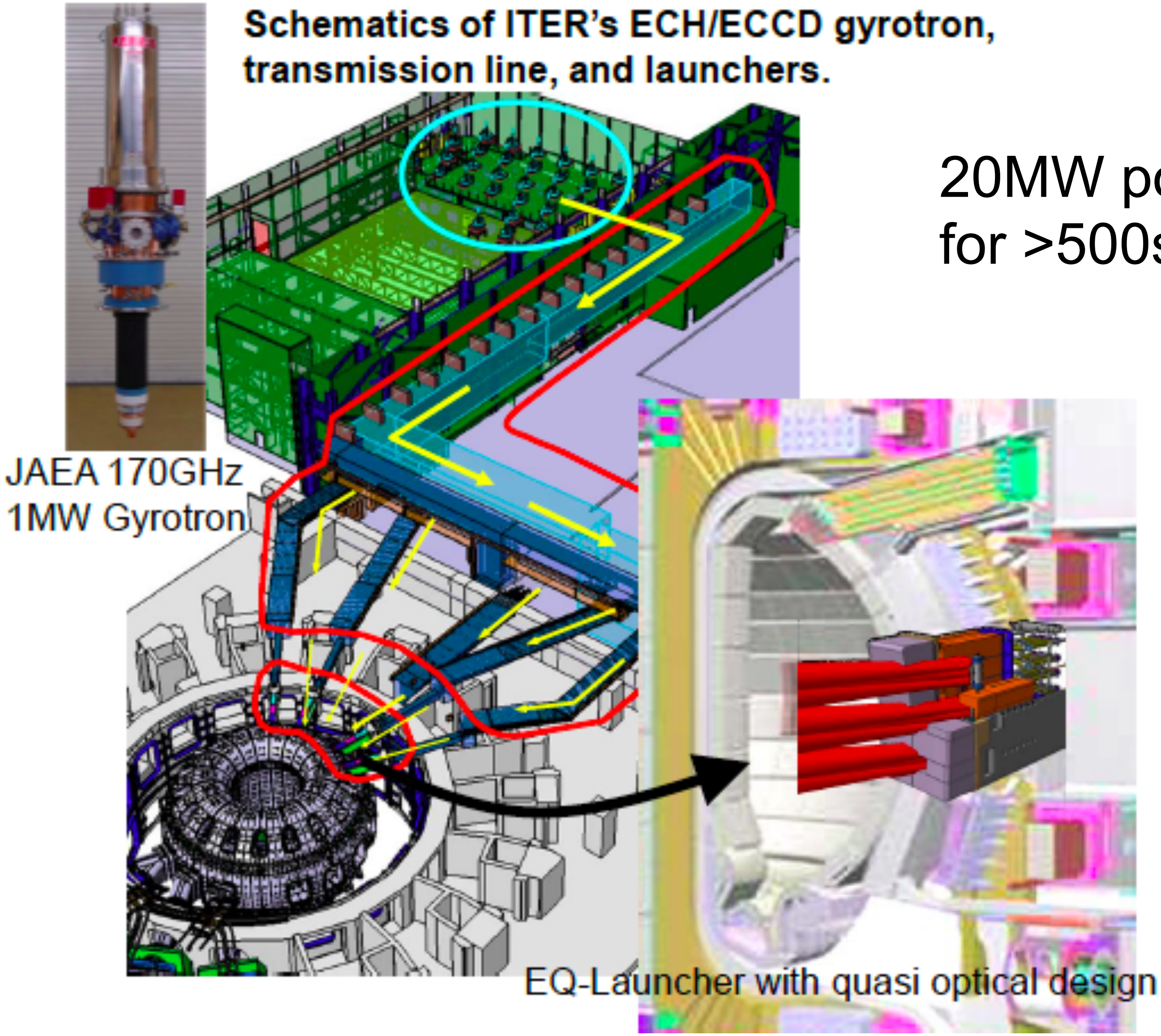
Japan Atomic Energy Agency

# Contents

- Power source (Gyrotron)
- ITER EC system (transmission line launcher)
- Others

# EC Heating & Current Drive System on ITER

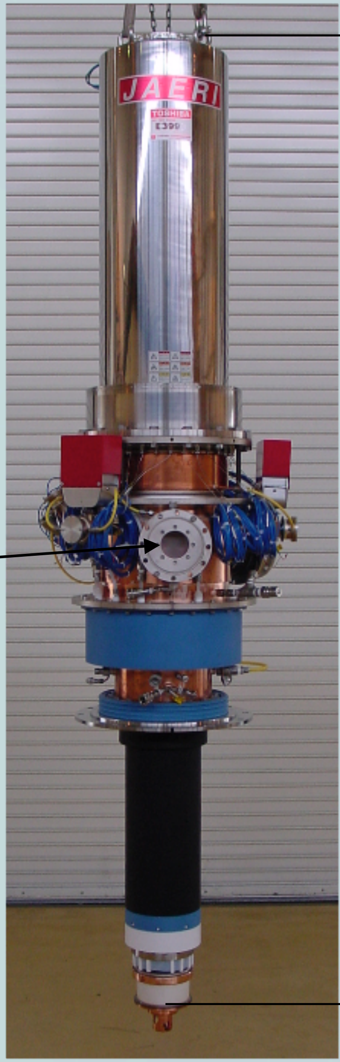



20MW power Injection
for >500s (burn experiment).

ITER:
$B_t$=5.3T
I=15MA
R=6.2m

500MW output

# Gyrotron



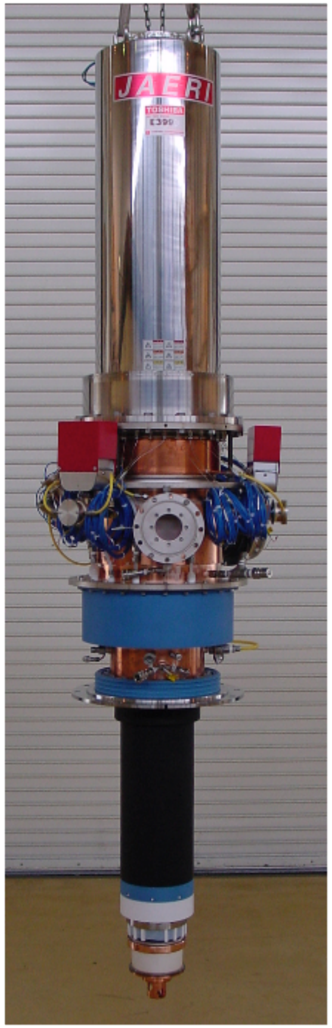
Output
window)

3m

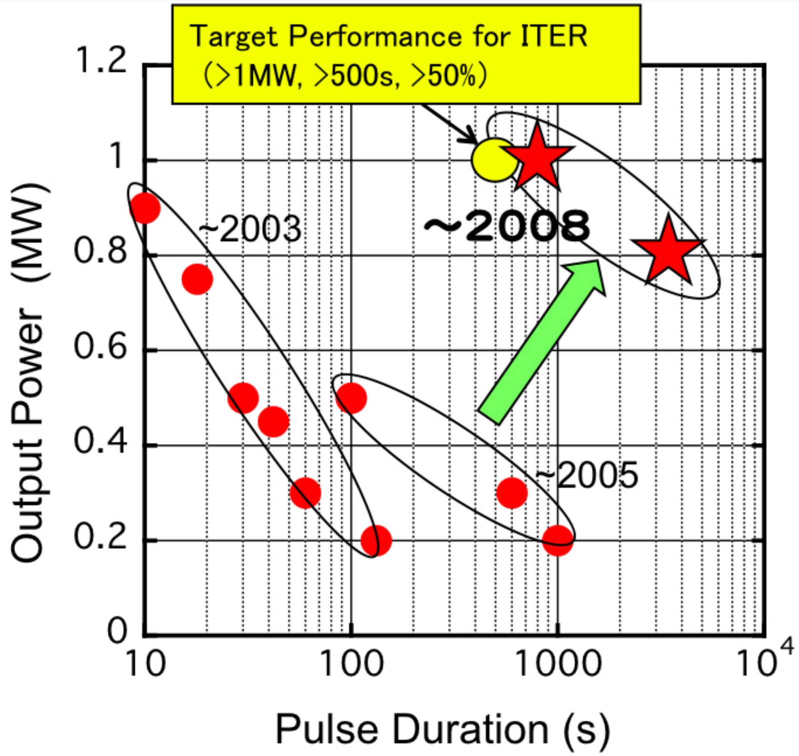
800kg

ITER Gyrotron (JA)

# 170GHz Gyrotron (TE31,8 mode)

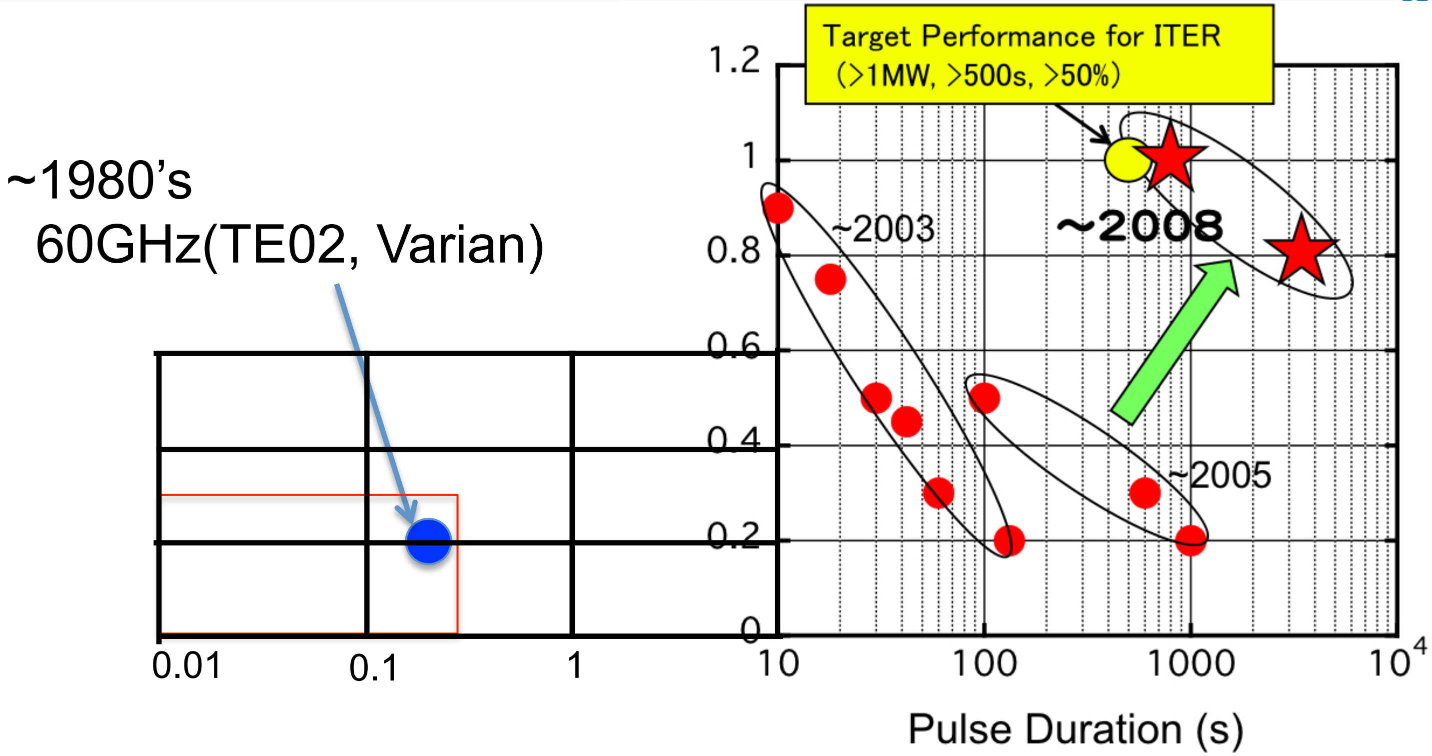



ITER-J5M2




- ITER basic requirement (1MW/800s)
- Maximum Efficiency=60 % (0.6MW, CW mode)
- Repetitive operation : 0.8MW/600s (every 30min)
- 5kHz full power Modulation at 1.1MW (60s)
- Output Energy>250GJ

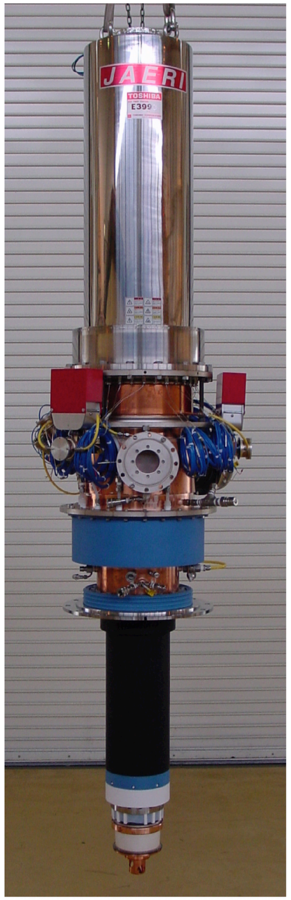
# 170GHz Gyrotron (TE31,8 mode)

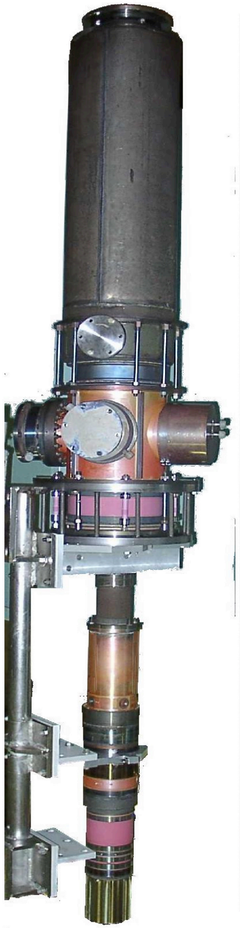


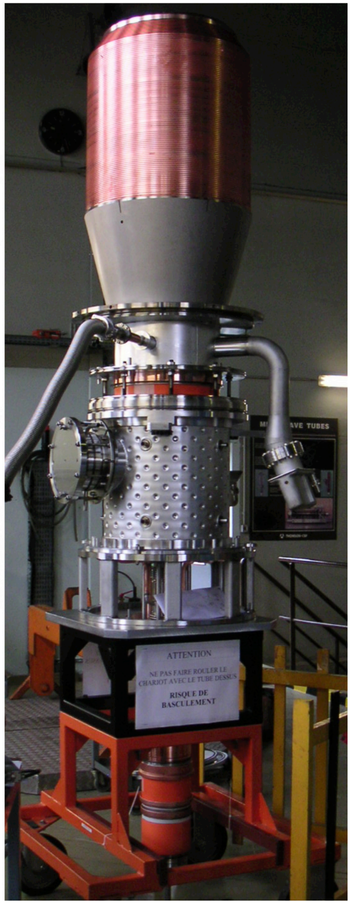

In ITER/EDA phase (1992-2000), some innovations were obtained in the gyrotron development.

EDA (Engineering Design Activities)

# 170GHz Gyrotrons for ITER





**Japan Russia EU**

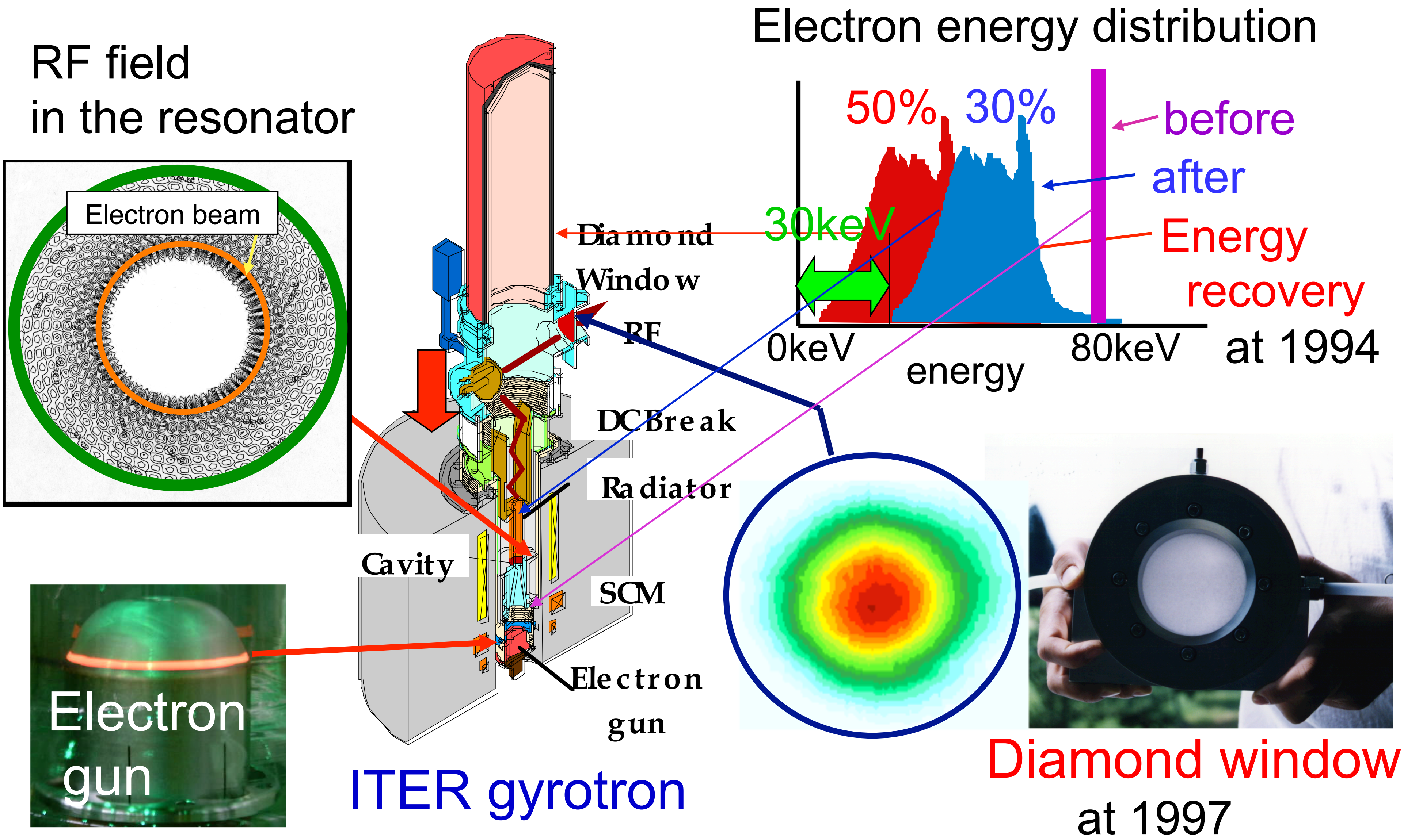
# Deficit & Innovations on gyrotron

Criticism at early 1990 was:

- Low efficiency (20~30%) → Innovations
  - Energy recovery : 30%->50% (depressed collector)
  - Oper. in hard excitation region
- Low power, short pulse (~0.2MW, 0,2s) →
  - High order mode oscillation
  - Advanced mode converter (reduction of stray RF in tube)
- No output window → Diamond window
- Low cost performance

EC will show highest cost performance on ITER.

# Key technologies for gyrotron



# Electron in Magnetic Filed

Cyclotron Frequency: $$\omega_{ce} = \frac{eB}{m_e \gamma}$$

B : Magnetic field
e : electron charge
$m_e$: electron rest mass

Relativistic factor: $$\gamma = 1 + \frac{E}{mc^2}$$

E: Electron energy

As electron energy higher,
Cyclotron frequency decreases
(Relativistic Effect)

Example : at B=5T

E～0eV : $\omega_{ce}/2\pi$=140GHz

E～80keV : $\omega_{ce}/2\pi$=121GHz

# Electron Cyclotron Resonance Maser (CRM)

## Oscillation Principle of Gyrotron：
## Electron Cyclotron Resonance Maser

Maser: Microwave Amplification by Stimulated Emission of Radiation

1958: Twiss（astrophysics ）

1959: Gaponov , Schnider（CRM）

Schneider: stimulated emission is possible when the electron interaction time is long enough: $\omega T \frac{E}{mc^2} > 1$

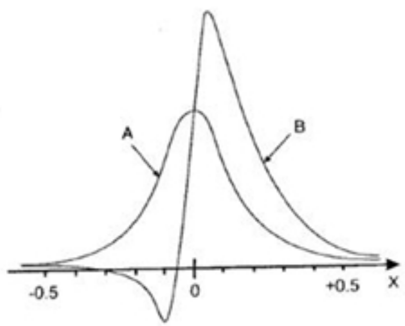



Figure 1. Cyclotron resonance absorption of a non-relativistic (A) and a relativistic (B) electron. The kinetic electron energy in the latter case is 76 eV. The interaction time is close to 1600 wave periods.

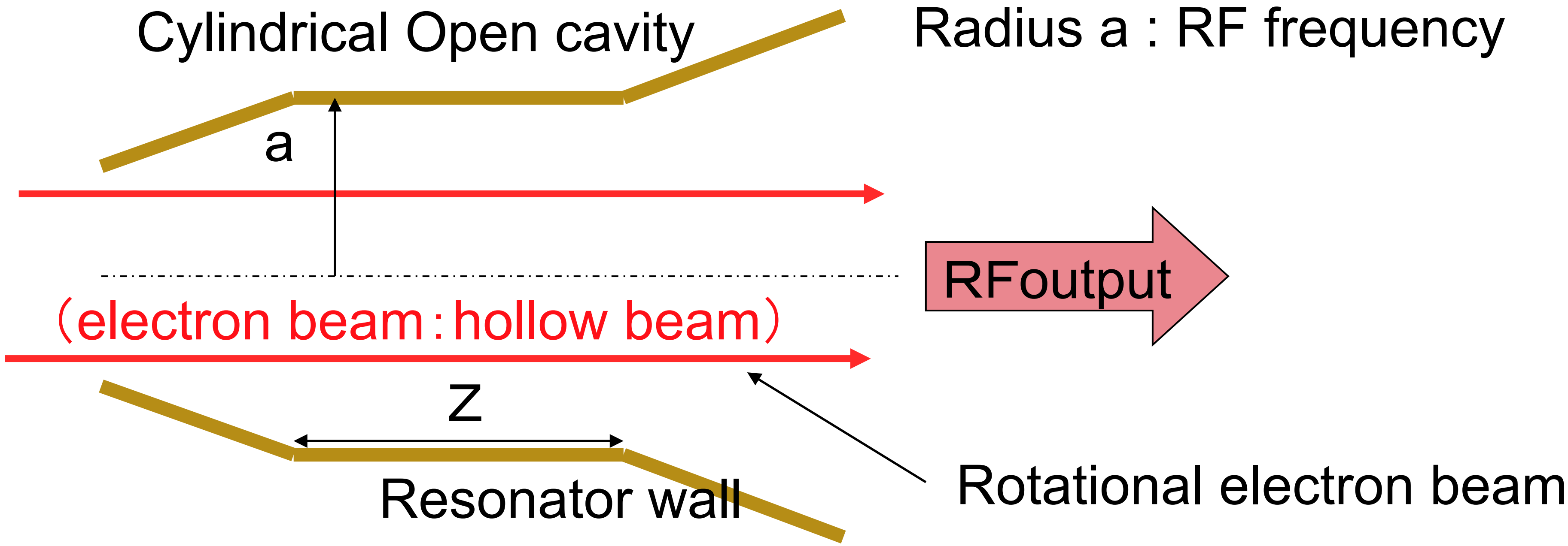
J.Hirshfield (CRM experiment)

↓

Gyrotron by USSR (Russia) group

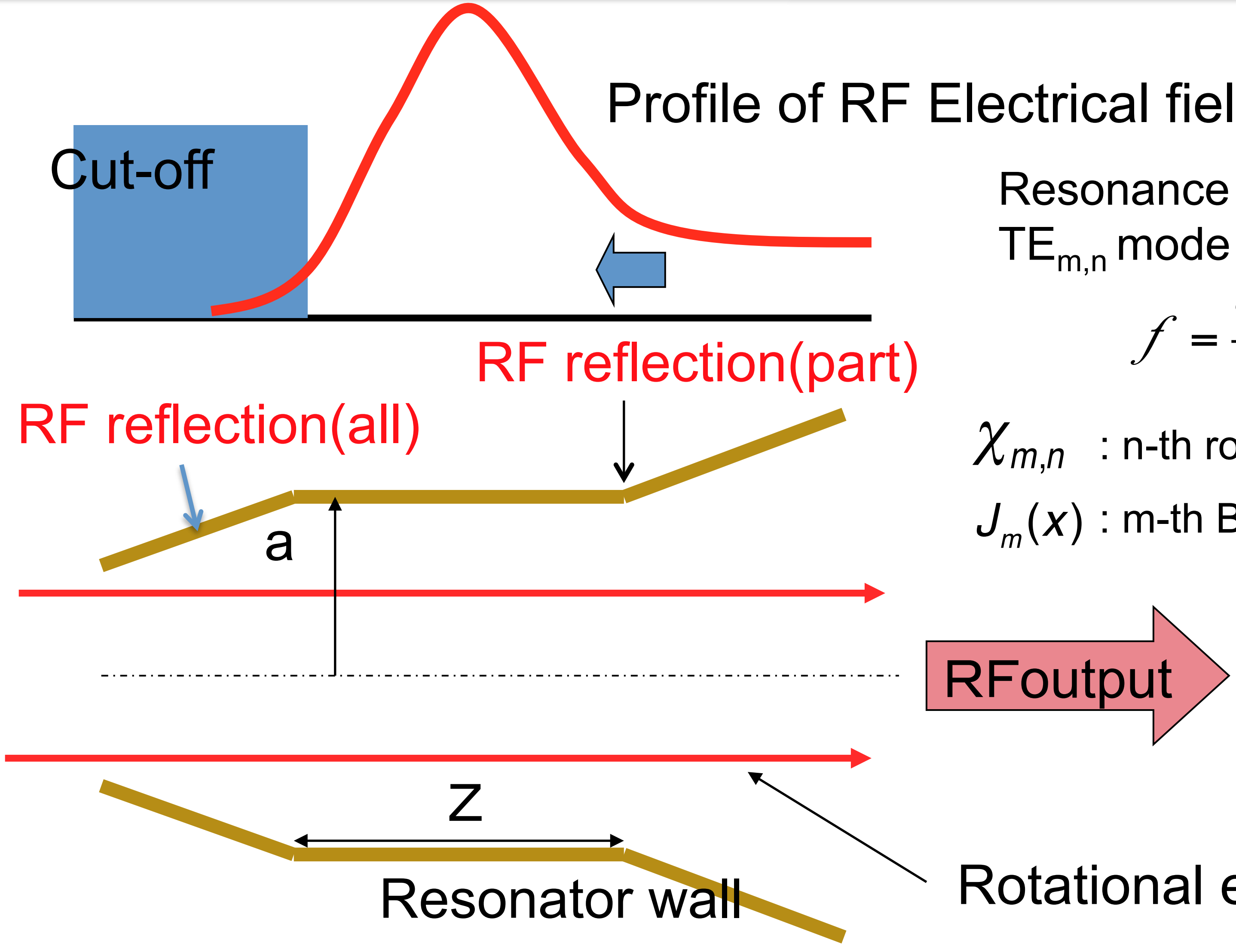
Role of Resonator：Enhance the interaction between the RF and electrons

Length z： Interaction length
Radius a : RF frequency




Gyrotron resonator

# Open Resonator




Resonance frequency of $TE_{m,n}$ mode $f$ :

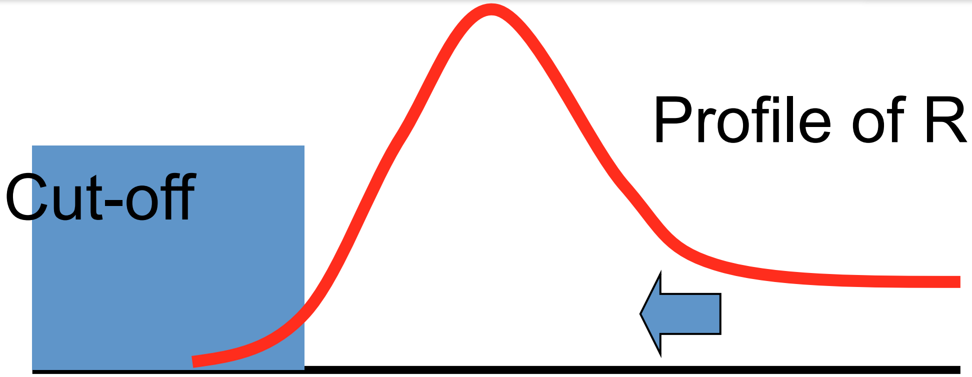
$$f = \frac{c\chi_{m,n}}{2\pi a}$$

$\chi_{m,n}$ : n-th root of $\frac{d}{dx}J_m(x) = 0$

$J_m(x)$ : m-th Bessel function

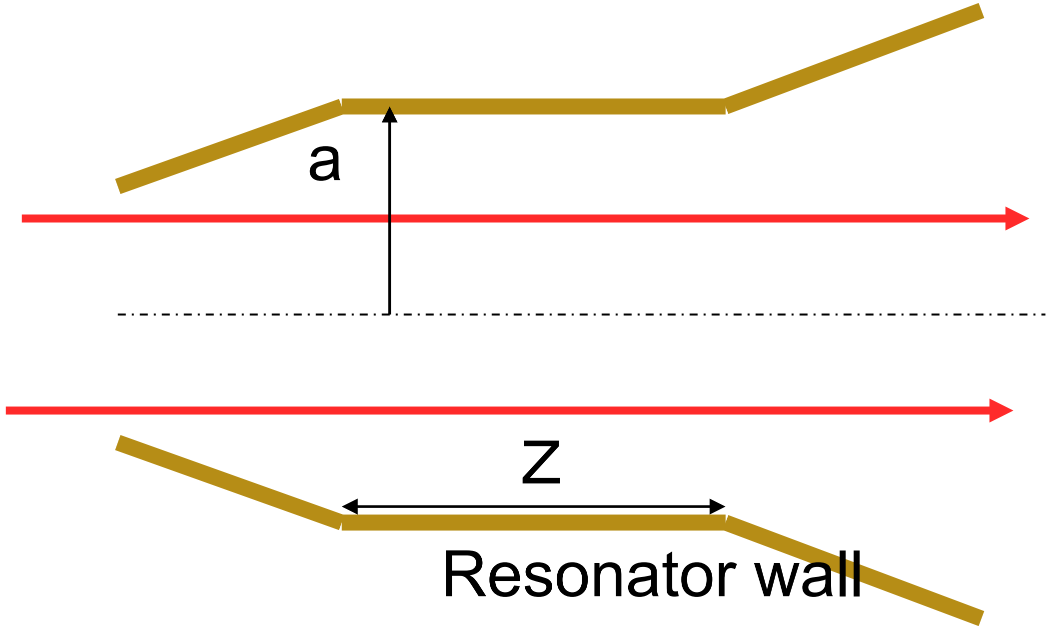
<u>Configuration of gyrotron resonator</u>

# Open Resonator




Resonance frequency:

$$f = \frac{c\chi_{m,n}}{2\pi a}$$




Example: TE31,8 mode

$\chi_{31,8} = 63.7675$

a=17.9mm

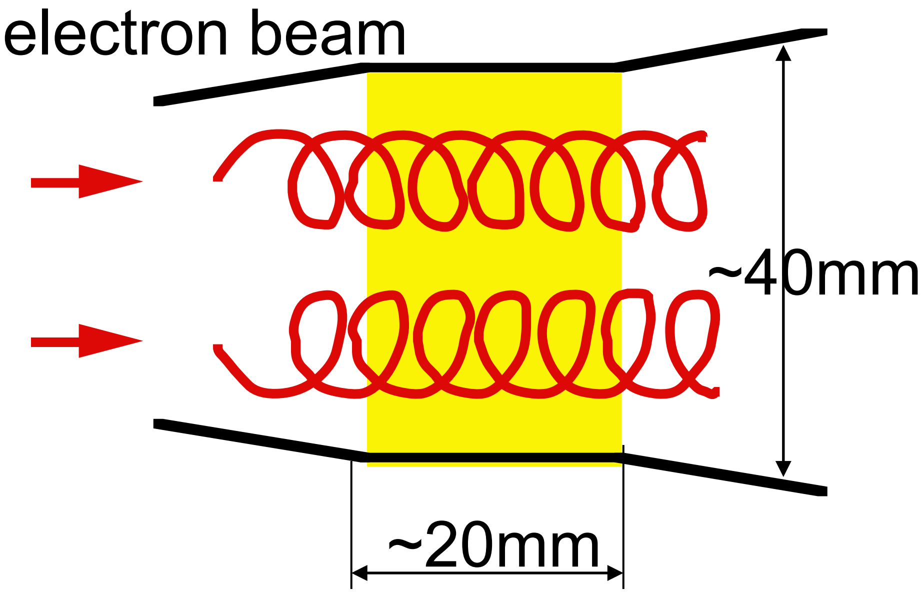
f=170GHz

Higher mode -> large radius

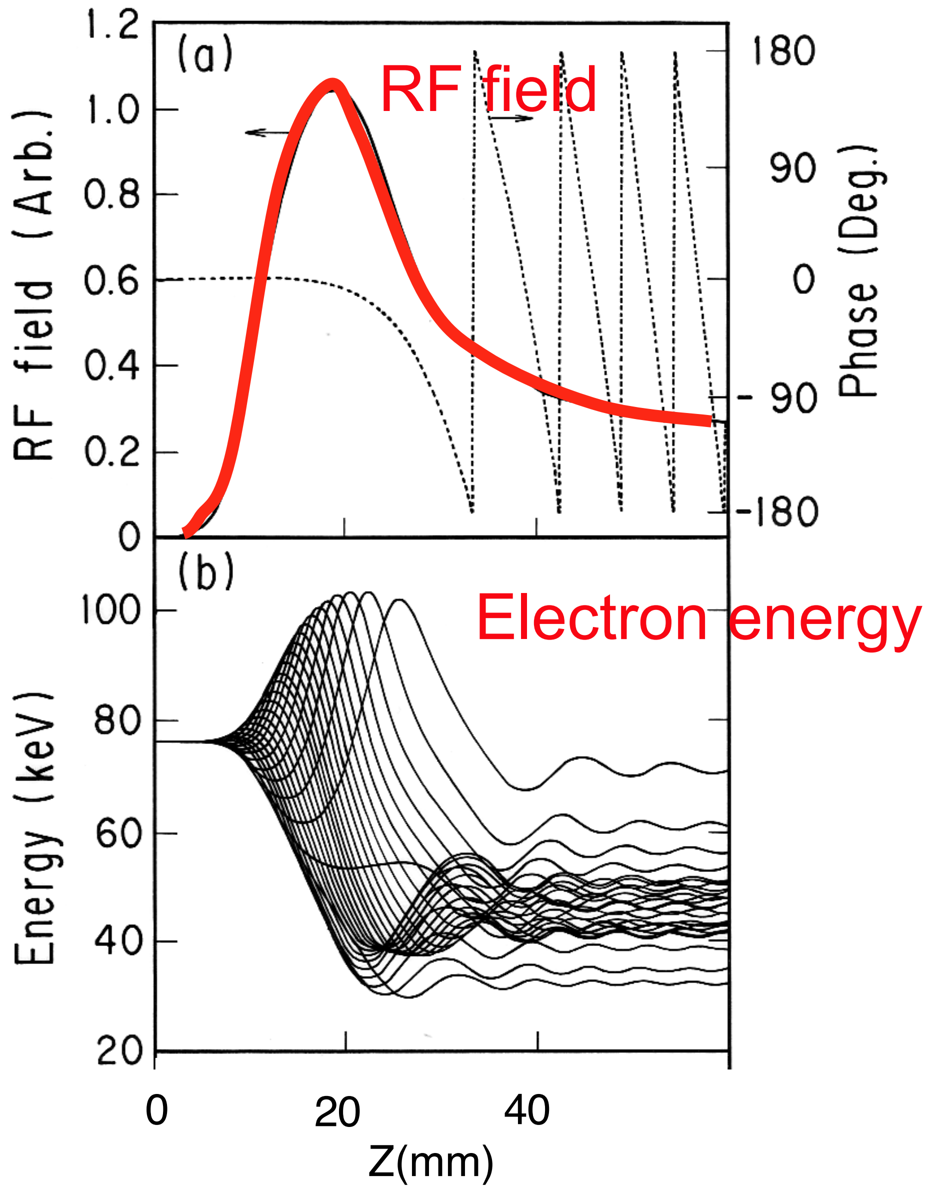
$a \propto f^{-1}$

Configuration of gyrotron resonator

# Behaviors of electron energies in the resonator



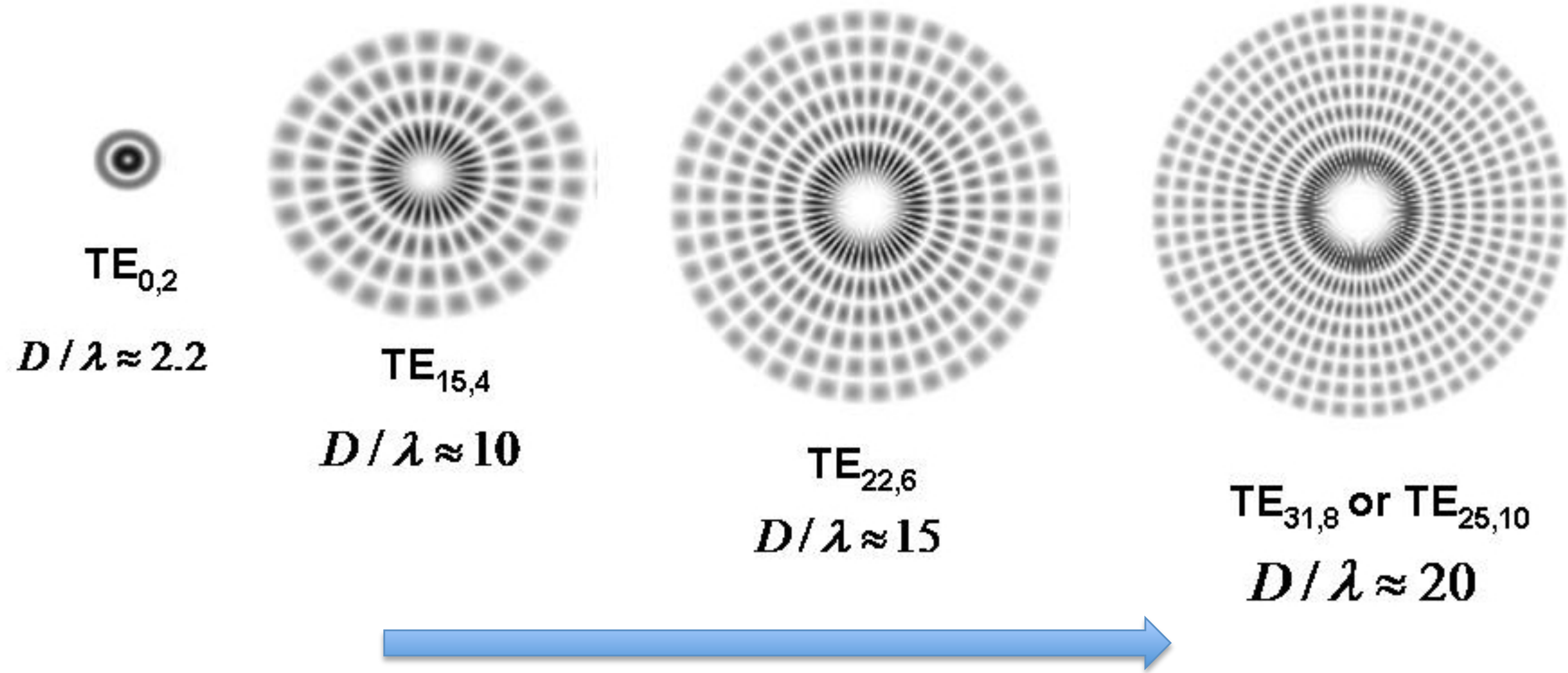

Resonator




Electrons pass through
the resonator within 1nsec.

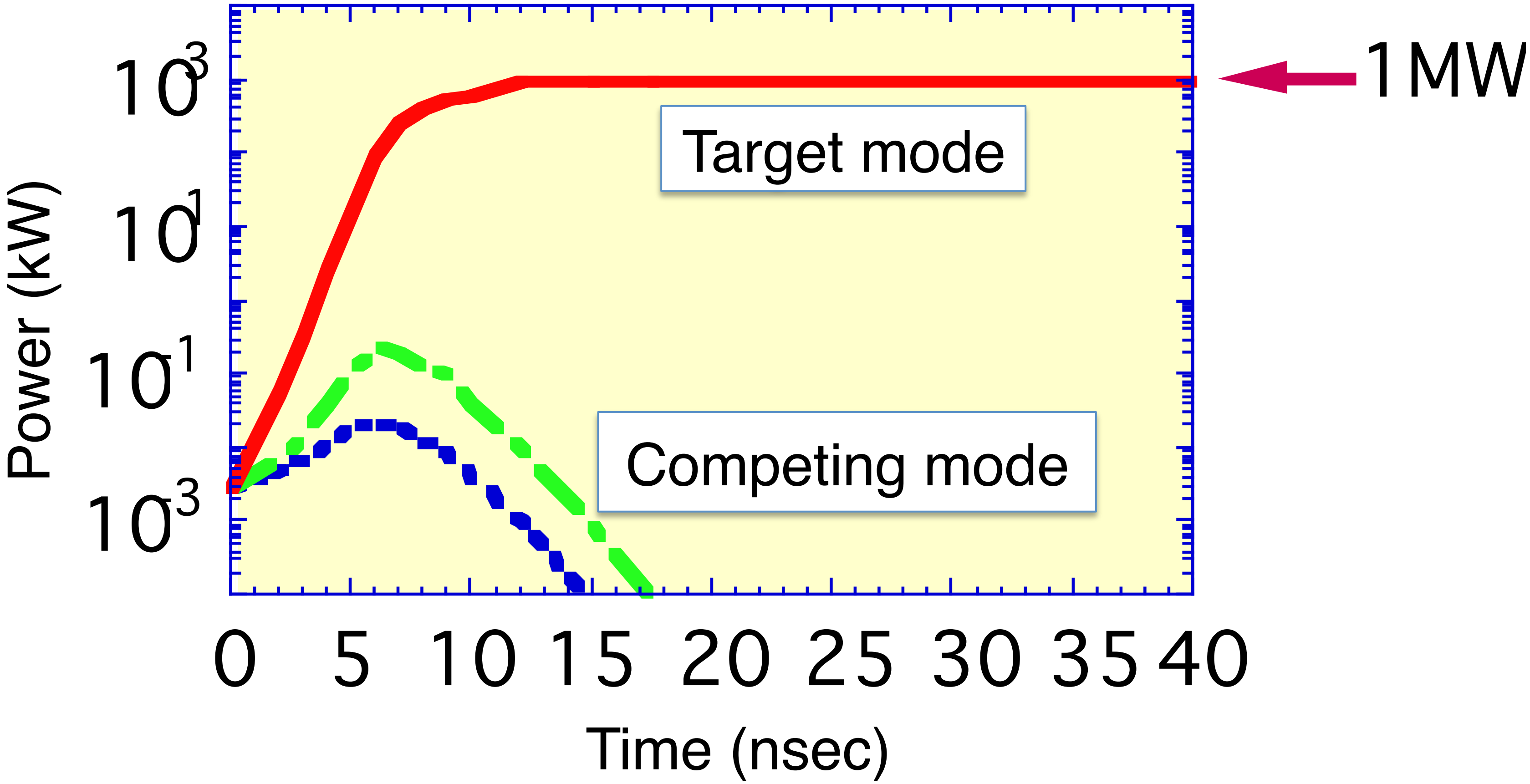
(set $\omega_{RF} > \omega_{ce} / \gamma$ initially)

# Evolution of operating modes



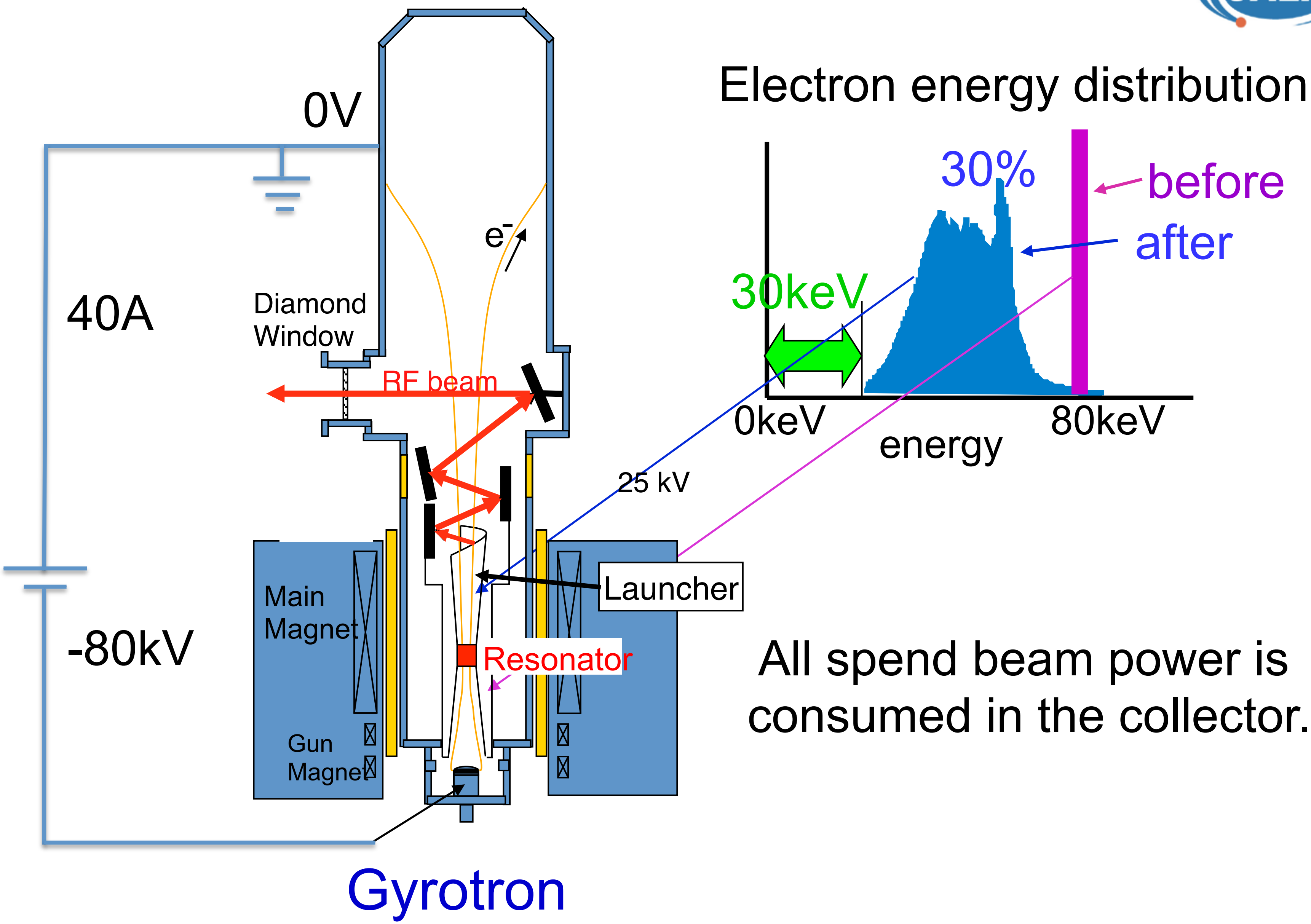

Suitable for higher power, higher frequency.
But, concern of competition with other oscillation modes.

# Start-up phase of oscillation



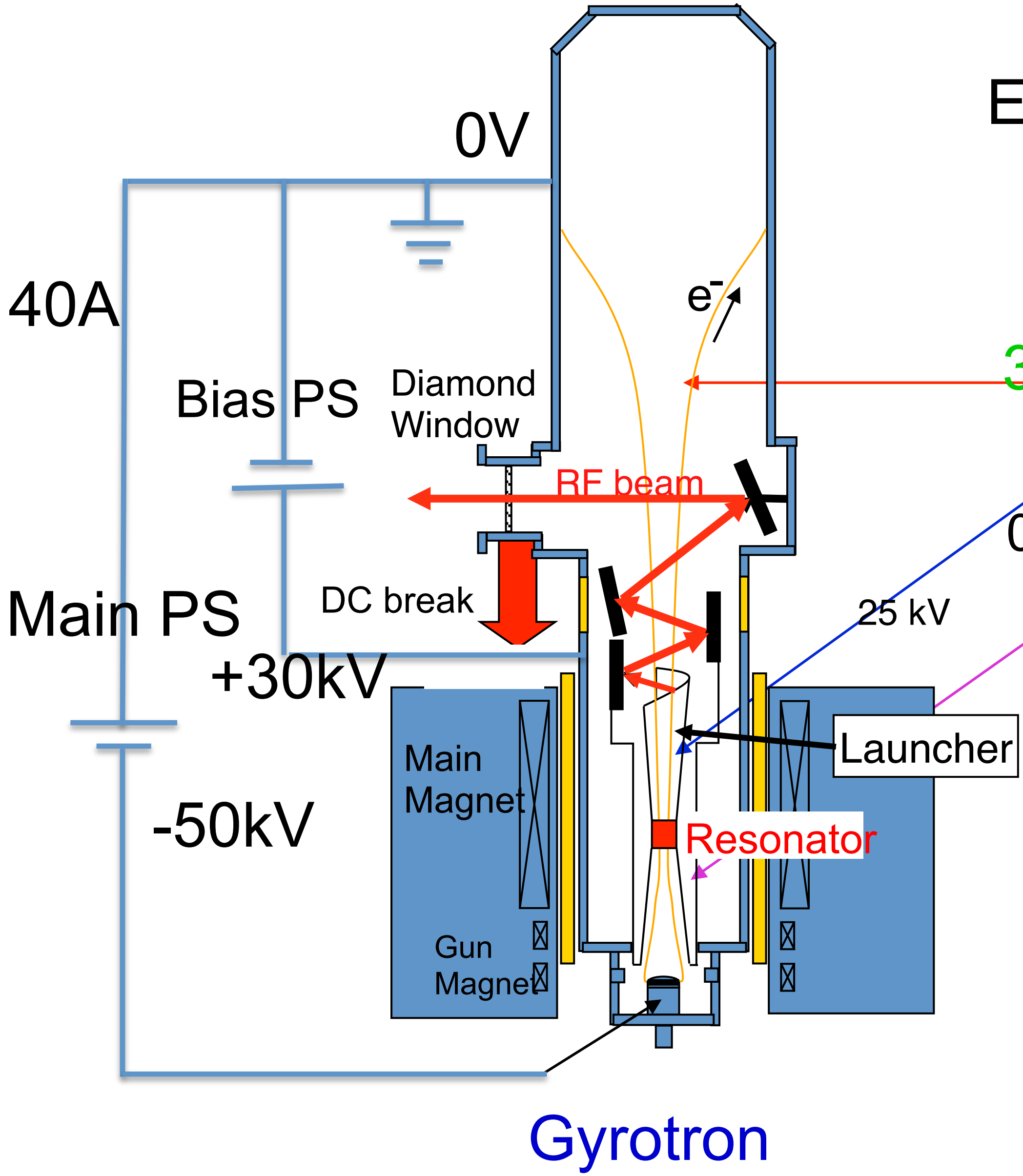

Single mode oscillation is possible at higher mode.
(at least at TE31,8 level.)
-> High power, high frequency oscillation is available

# Depressed collector (1)

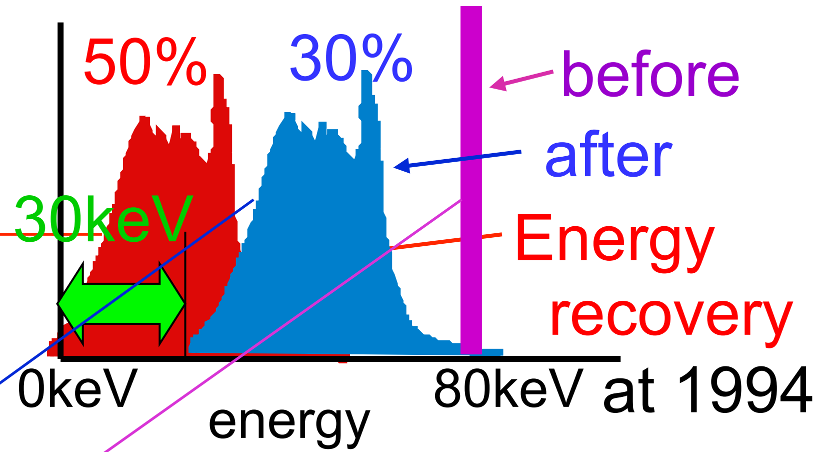



All spend beam power is consumed in the collector.

# Depressed Collector




Electron energy distribution

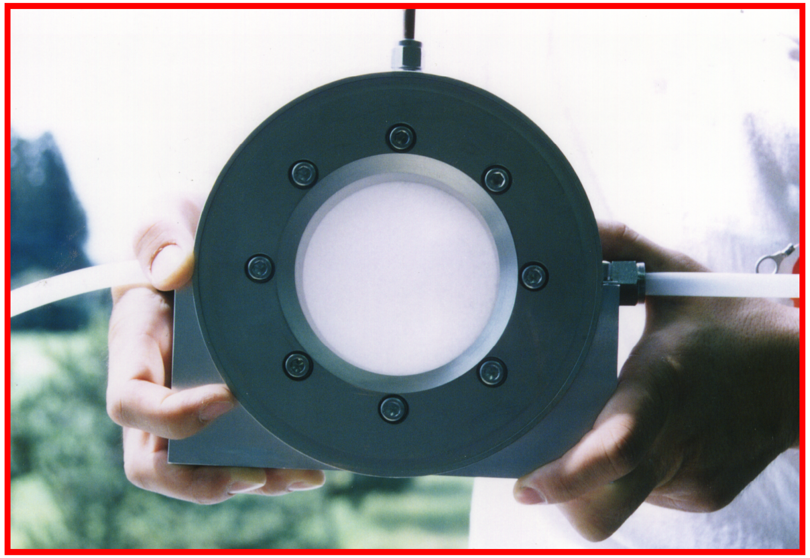



Spend beam is decelerated by 30kV.
(1.2MW power saving)

Big merits

- large efficiency improvement
- smaller collector size
- smaller power supply, cooling
- smaller x-ray generation

# Diamond window

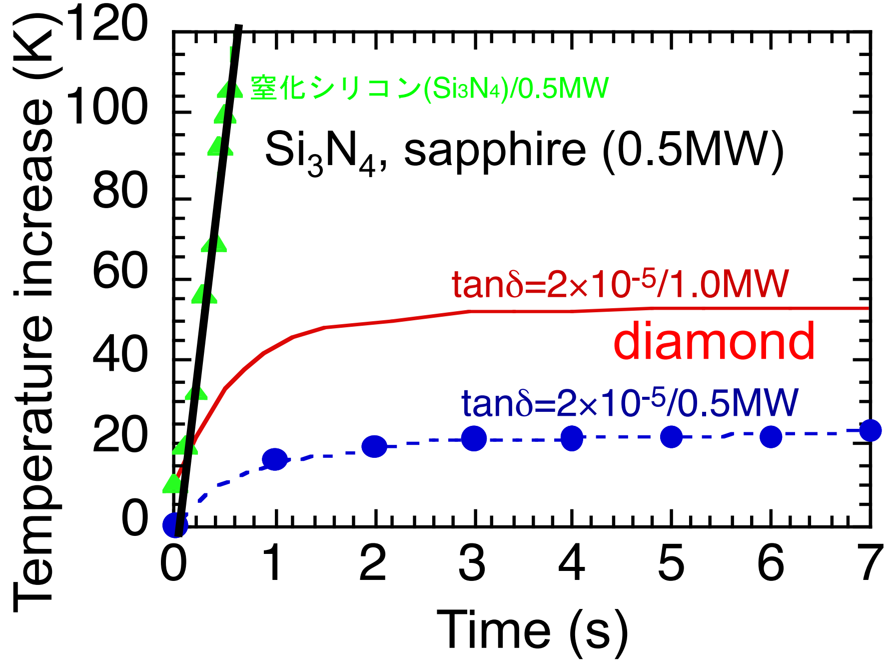


diameter: 100mm
thickness:  1.853mm

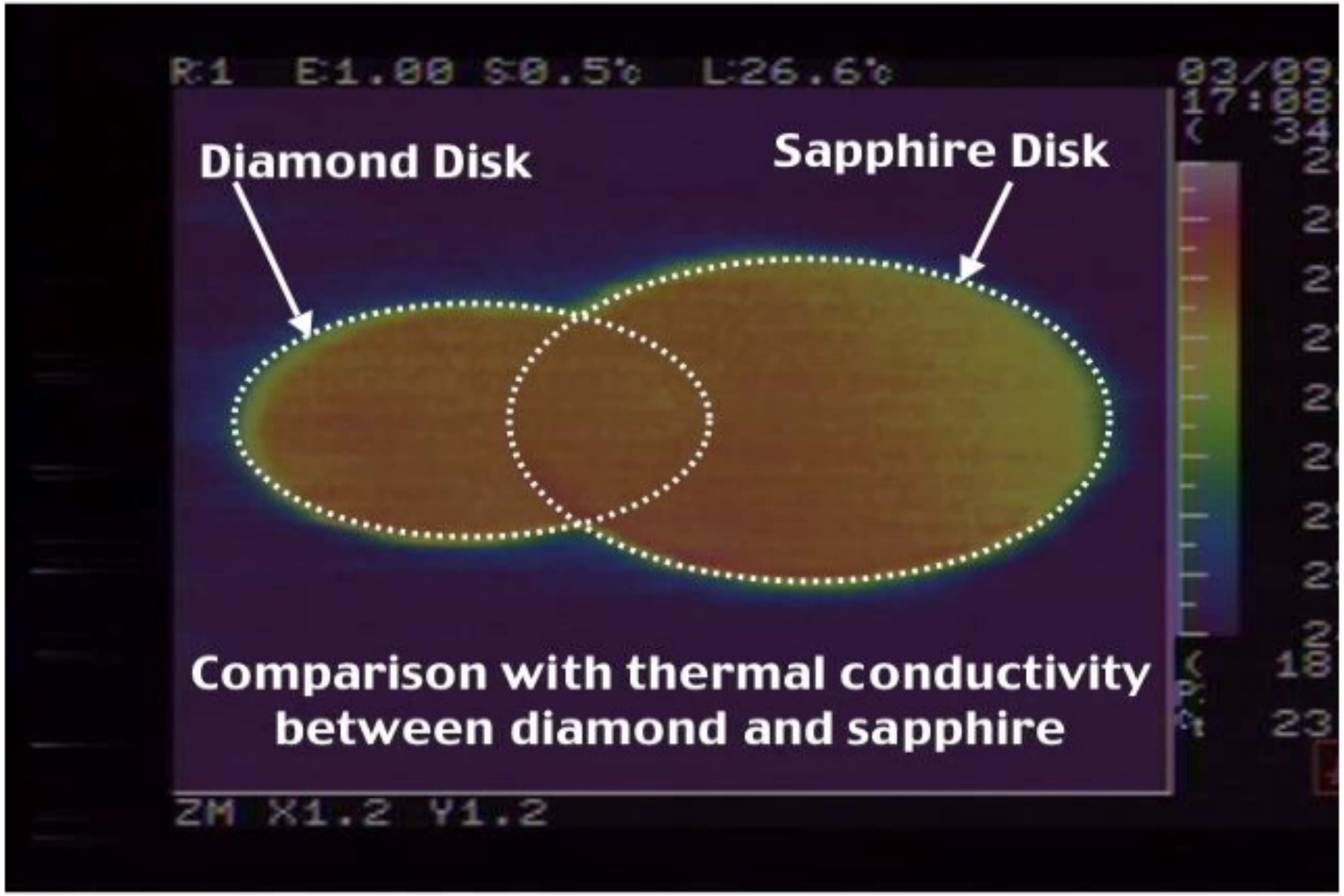
Diamond disk@1996

Long pulse operation was available.

・$\tan\delta$= 2x10$^{-5}$ ( <10$^{-5}$ at present)
(<1/10 of standard window material )
・thermal conductivity=2000W/m/K
(5 time higher than Cu.)



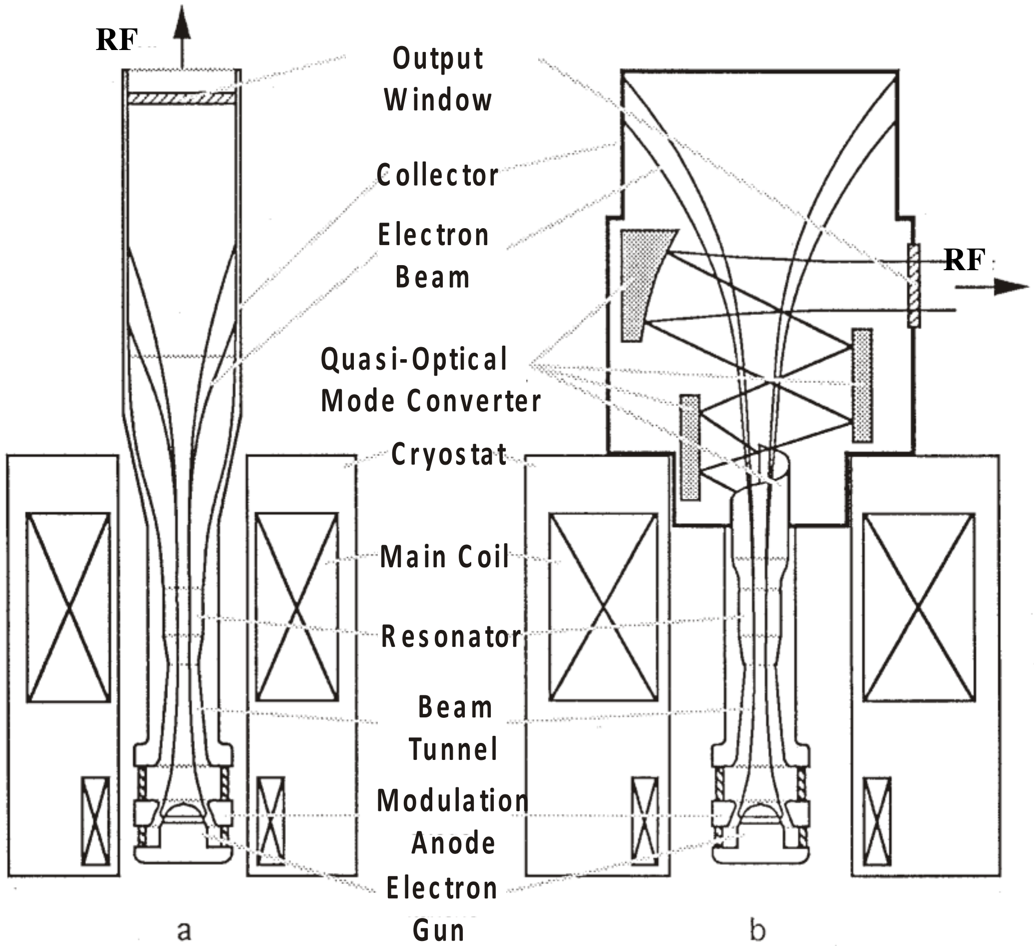
# Temperature of the diamond disk



# Built-in Mode Converter

Convert the oscillation mode to Gaussian beam

# Quasi-Optical Output Couplers for High-Power Gyrotrons (1975 Russia)




**Axial Output Coupling through Oversized Circular Waveguide e.g. $TE_{03}$**

**Advantages :**

- **Isolator for Reflections**
- **Optimum Mode for Transmission**
- **Free Choice of Collector Design**

**Radial Output Coupling through Optical Elements $TEM_{00}$ (Gaussian Beam)**

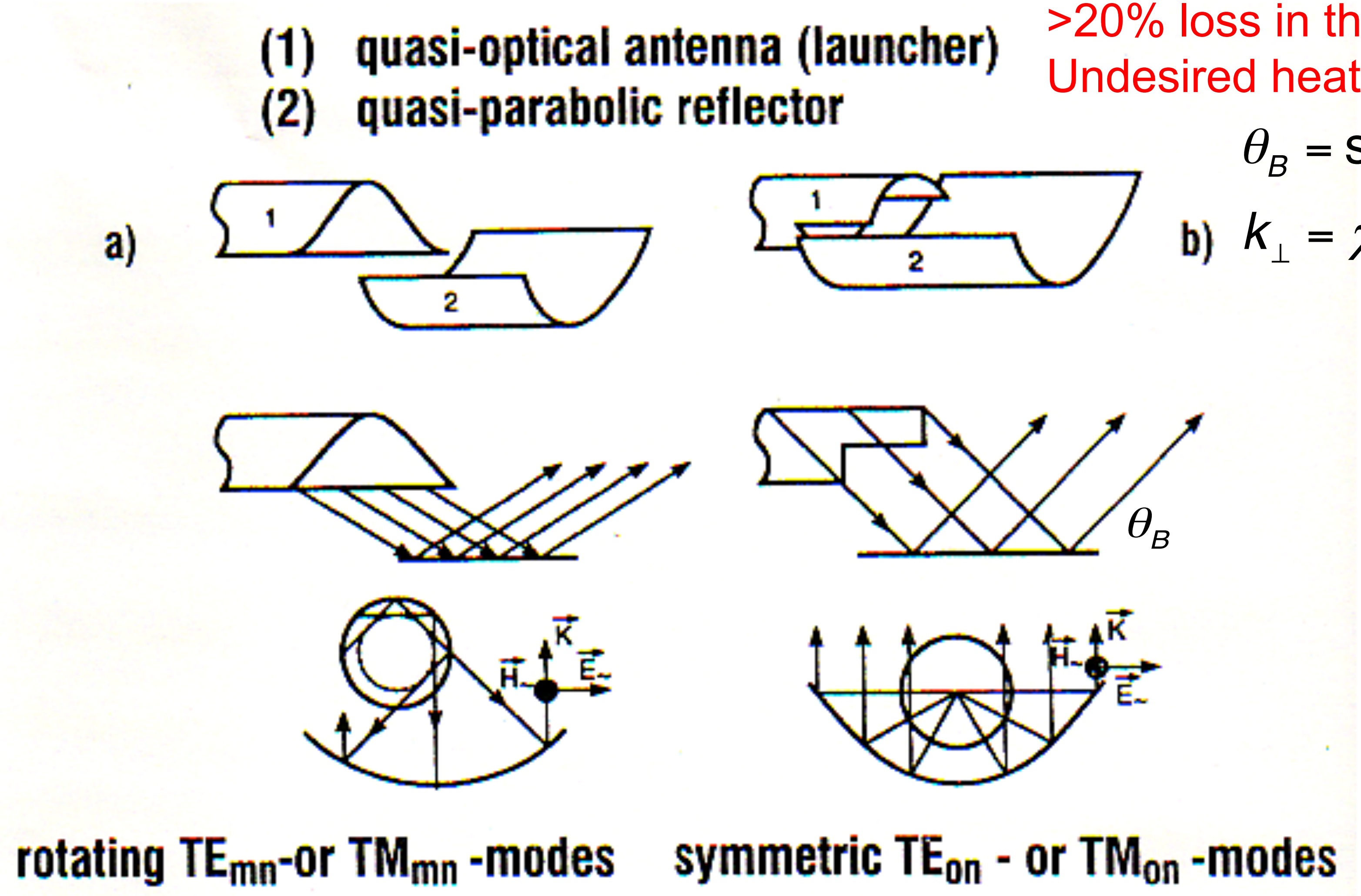
## Vlasov converter ( until early stage of 1990's)

Convert the $TE_{mn}$ mode to parallel beam quasi-optically
(80% conversion efficiency to Gaussian beam)

>20% loss in the gyrotron.
Undesired heating inside.

$$\theta_B = \sin^{-1}(k_\perp / k)$$

$$k_\perp = \chi_{mn} / r_w$$

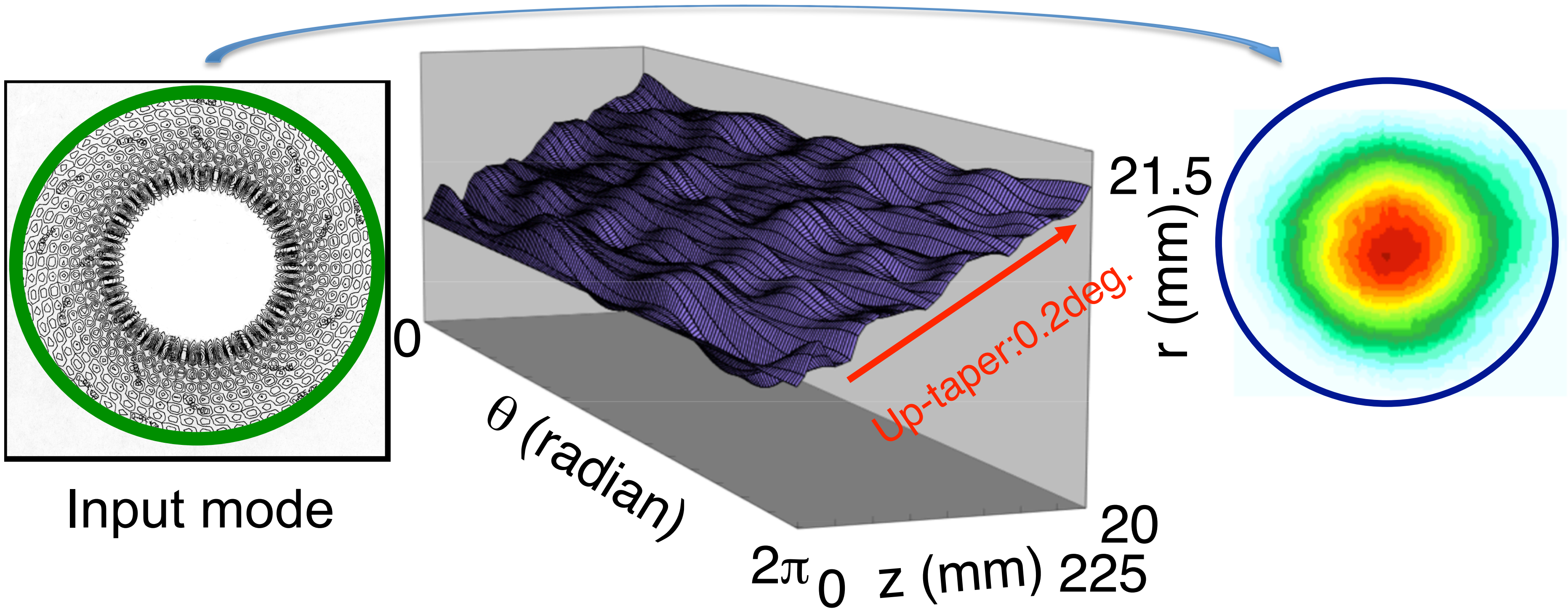


# Mode converter : from waveguide mode to Gaussian beam

Generate the Gaussian beam power profile at the converter end.

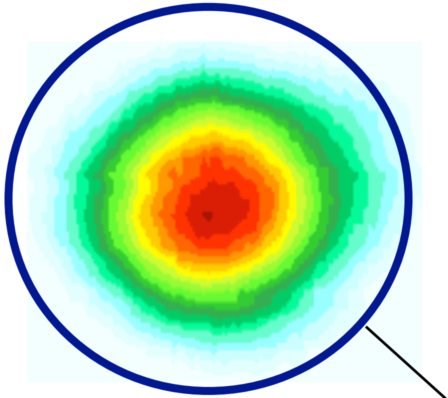
$$r(\phi,z) = r_0 + \alpha z + \sum_l \left[ a_l(z)\cos(l\phi) + b_l(z)\sin(l\phi) \right] \qquad \text{(CCR-LOT )}$$

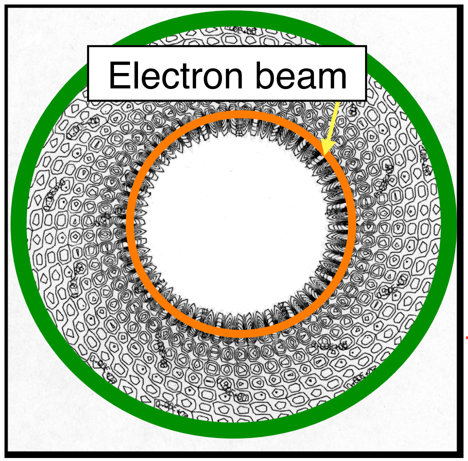
$r_0$=20.7 mm  α=0.0035  l=1,2,3,6




Development of inner surface of mode converter (magnified) : inner surface of the waveguide is perturbed.

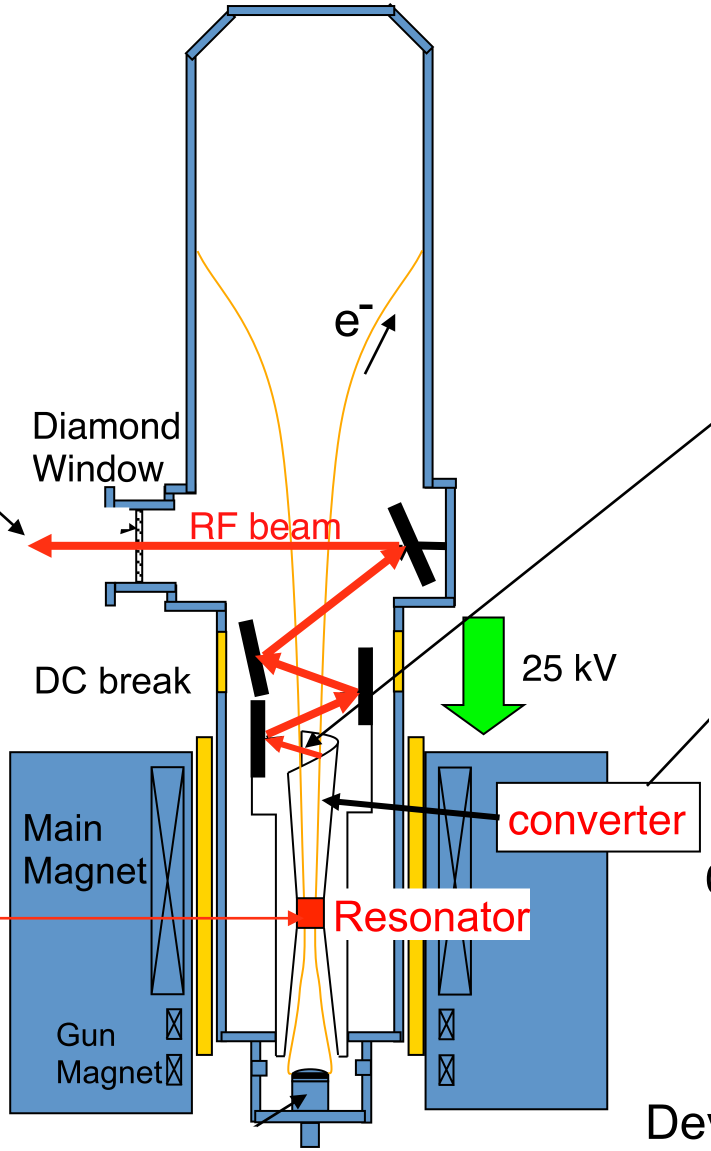
# Built-in mode converter (conversion efficiency ~99%)

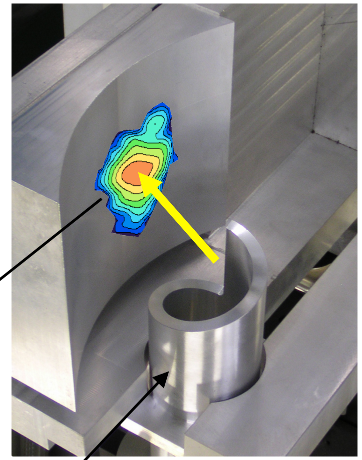


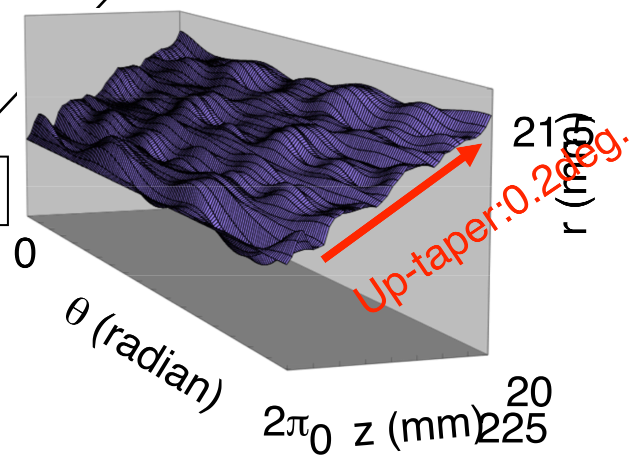



RF power profile

TE31,8 mode





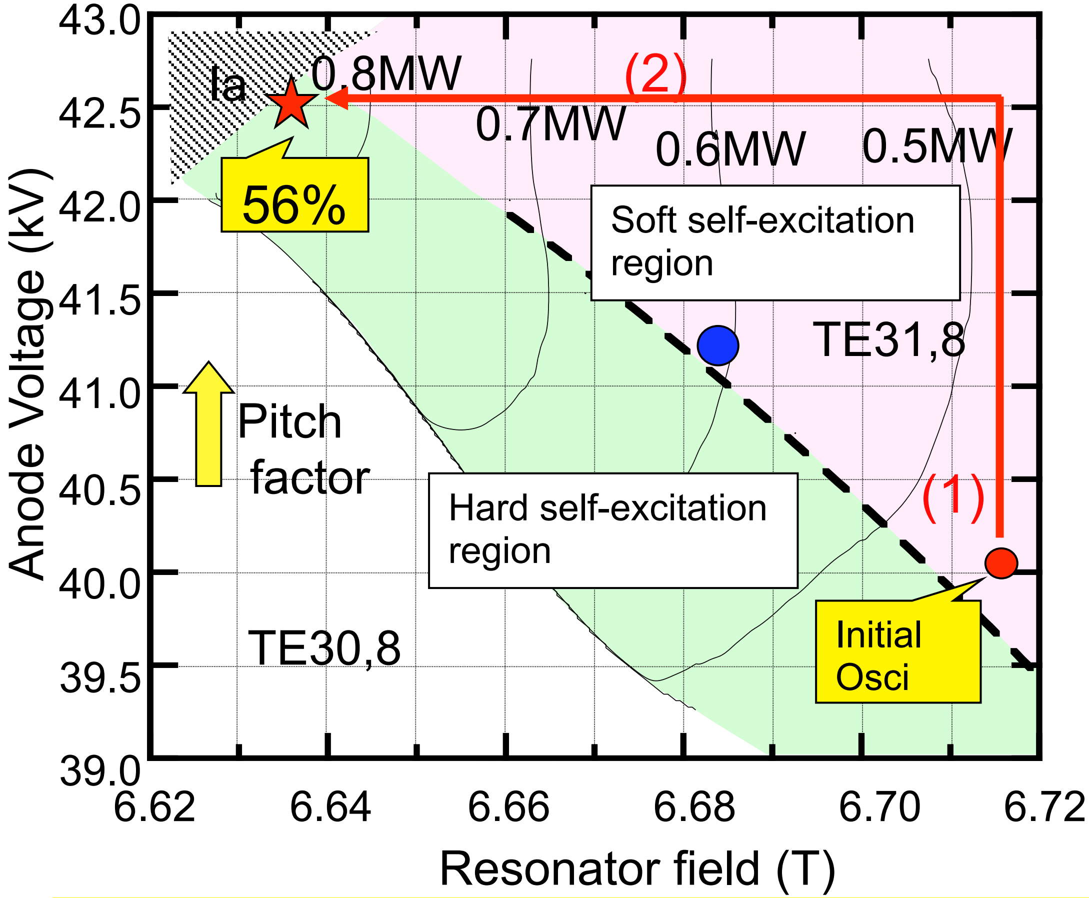

Development of inner surface of mode converter

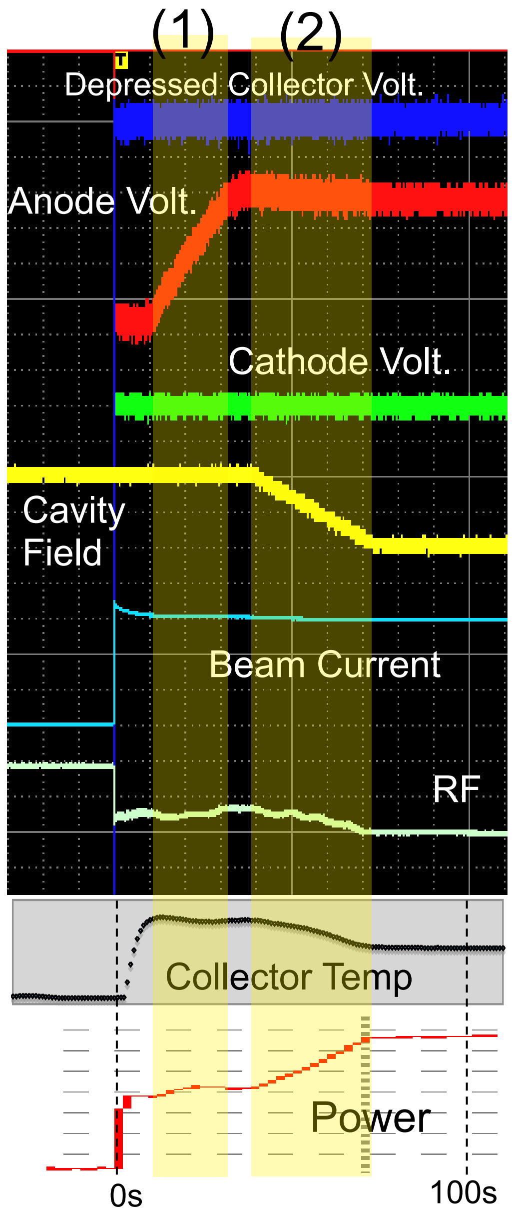
Operation in the highest efficiency point
in hard excitation region

(nonlinear excitation)

# A scenario for High Efficiency Operation

(1) Increase of anode voltage ($\alpha$)
(2) Decrease of cavity field




It is proved accessibility to maximum theoretical efficiency by active control.

# Oscillation in Hard self-excitation region (4)

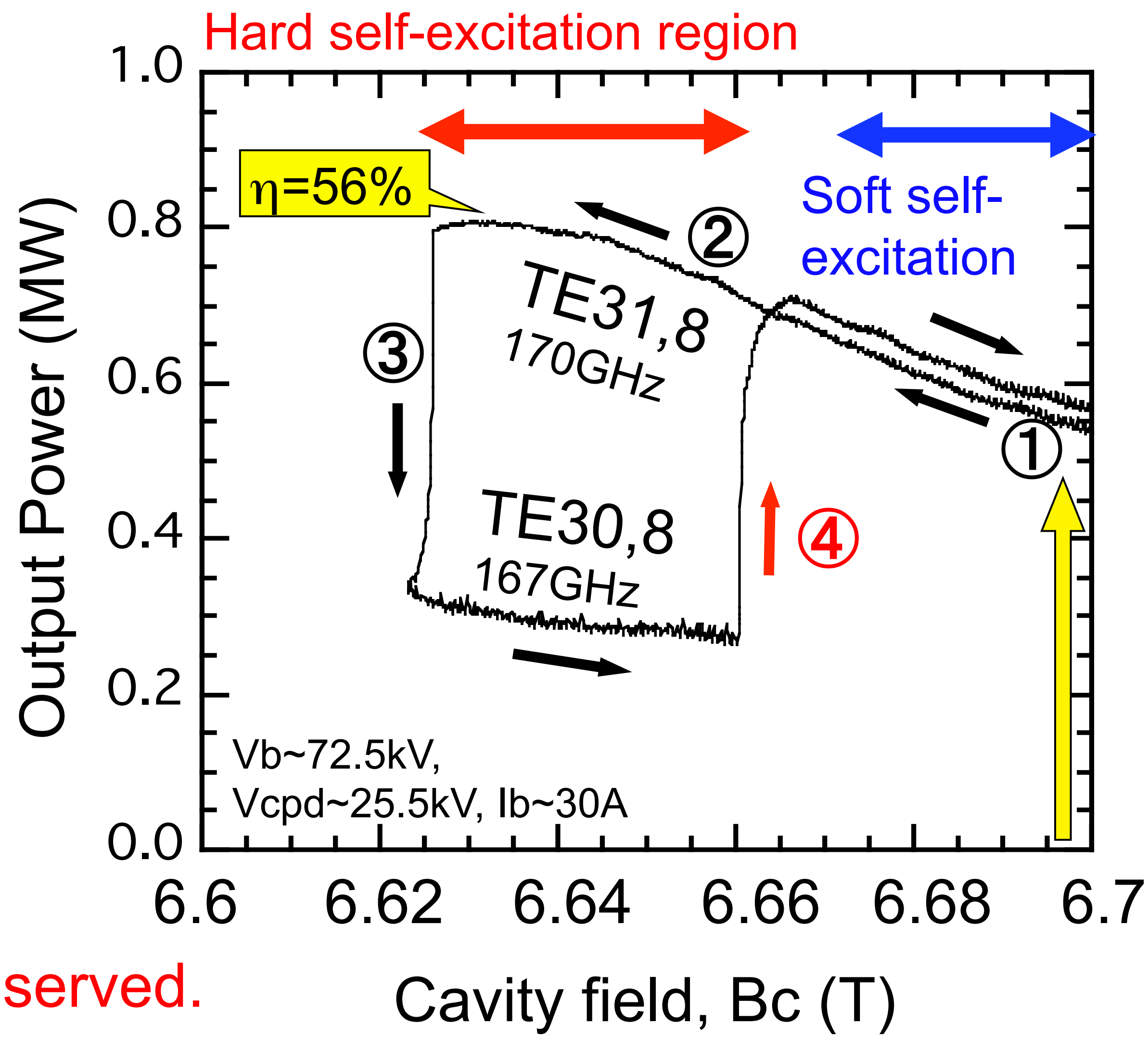
① Oscillation Start-up
Pitch factor increase
(Raise the control anode voltage)

② By decreasing Bc with keeping oscillation

Hard self-excitation region (High Efficiency)

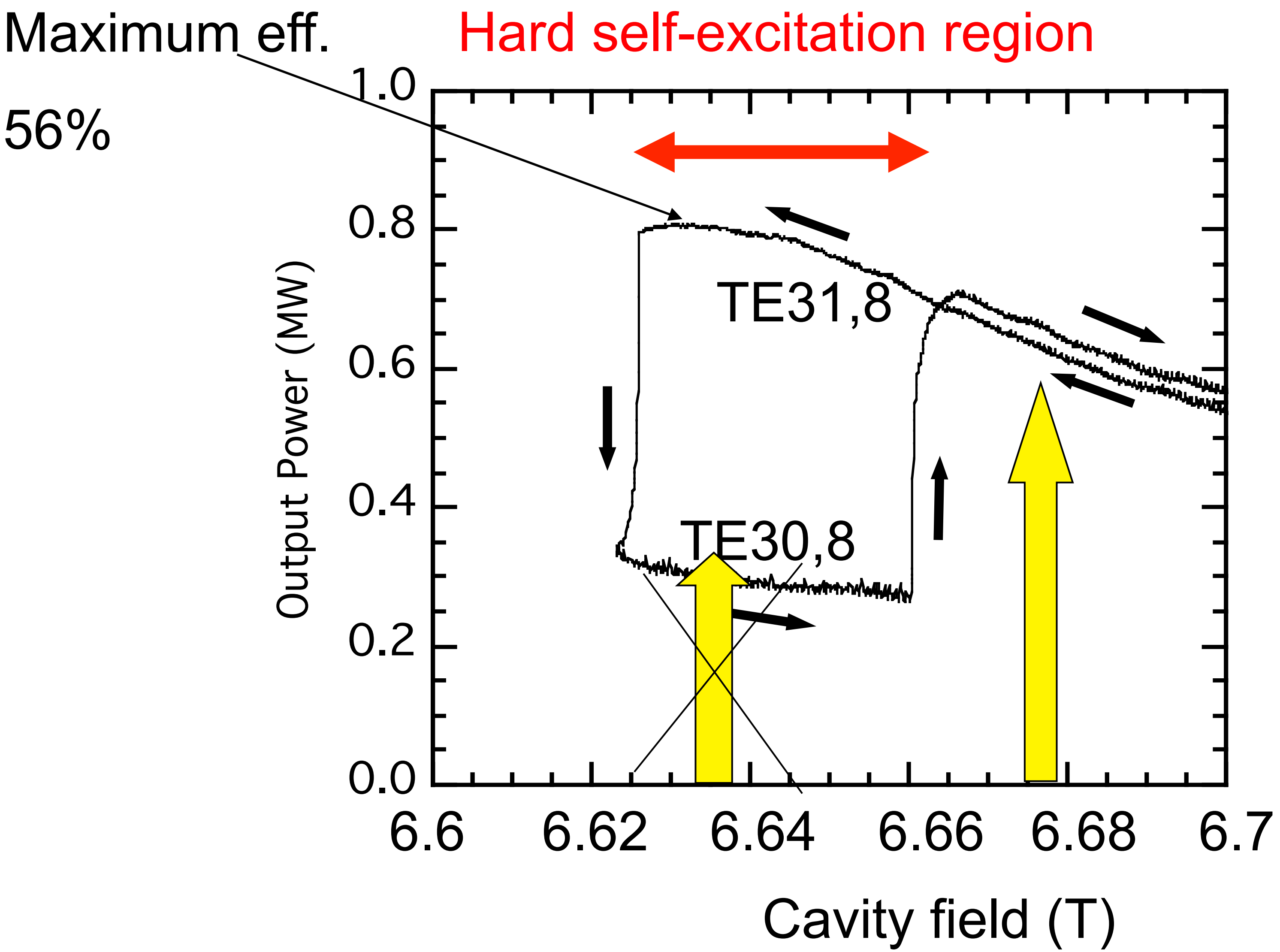
③ Mode change from TE31,8 to TE30,8

④ Returned to TE31,8

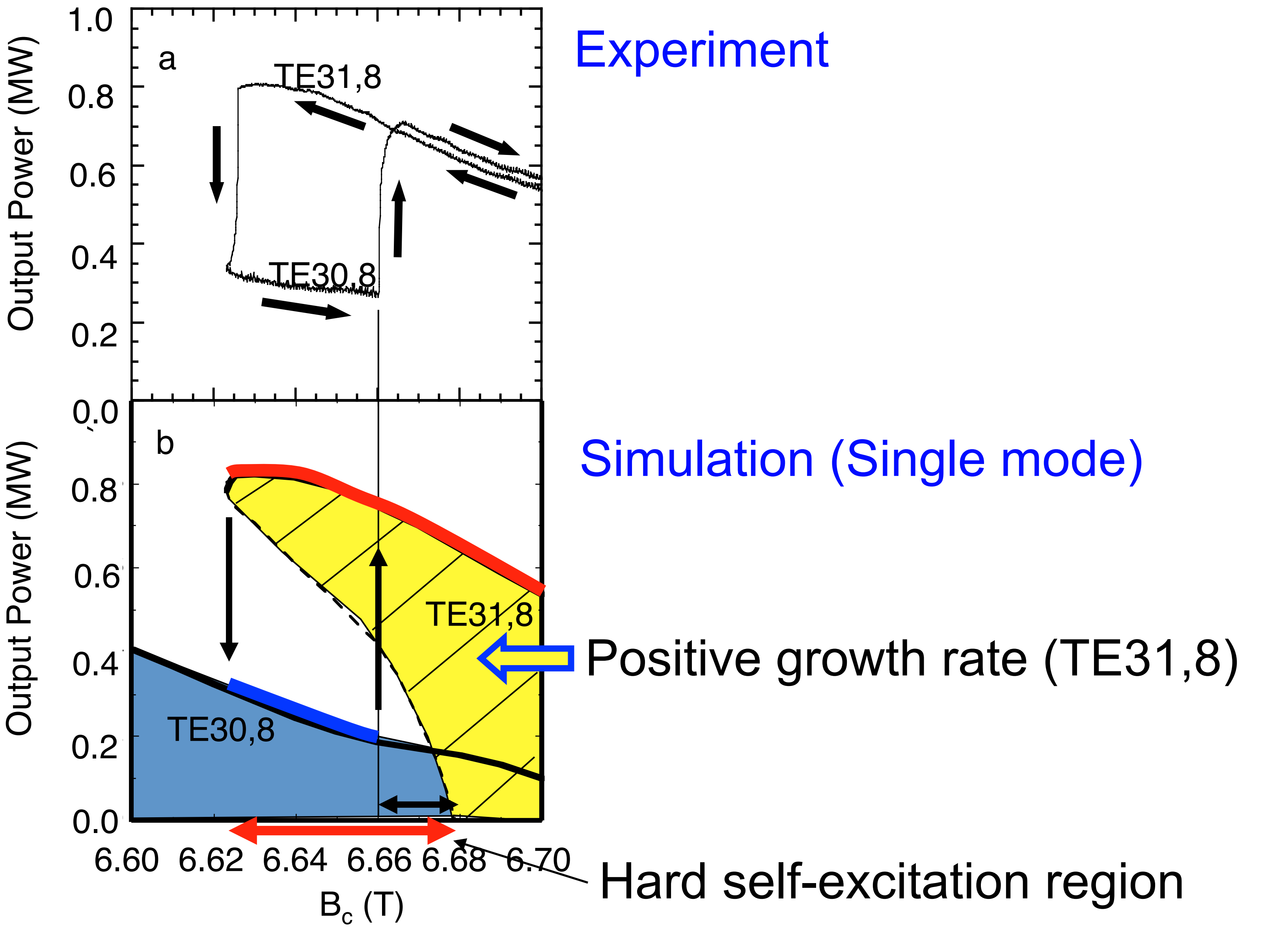



Clear hysteresis was observed.

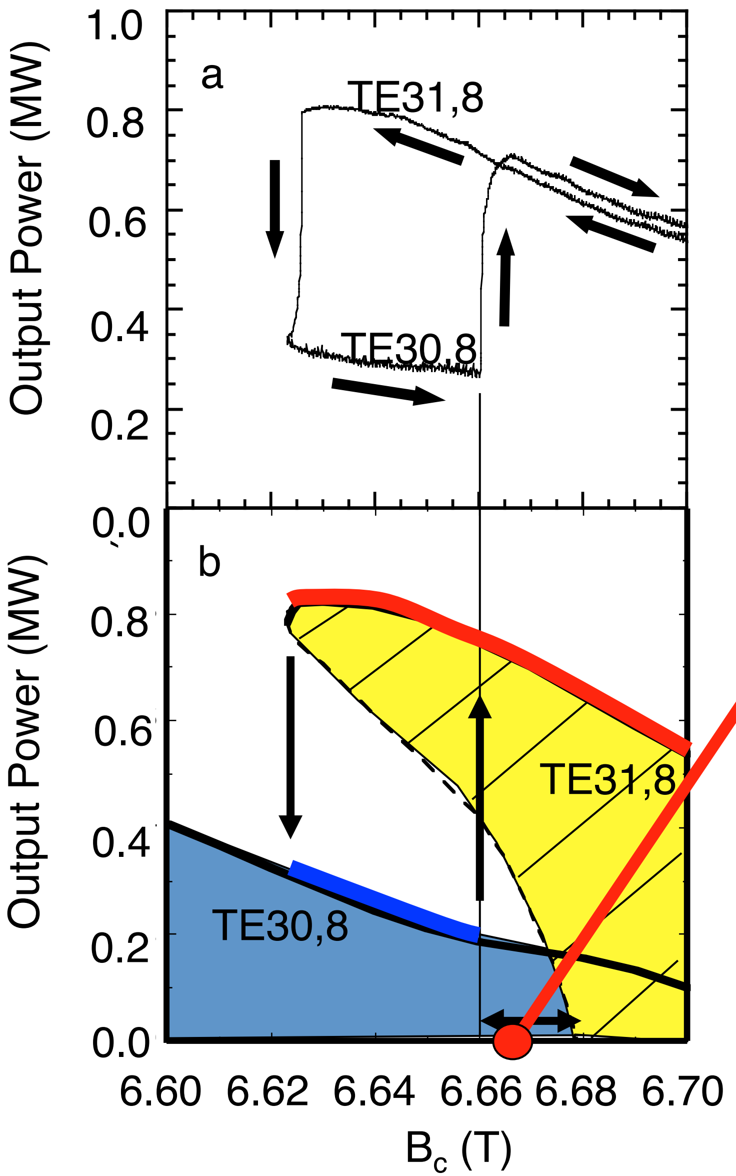
# Oscillation in Hard self-excitation region (5)

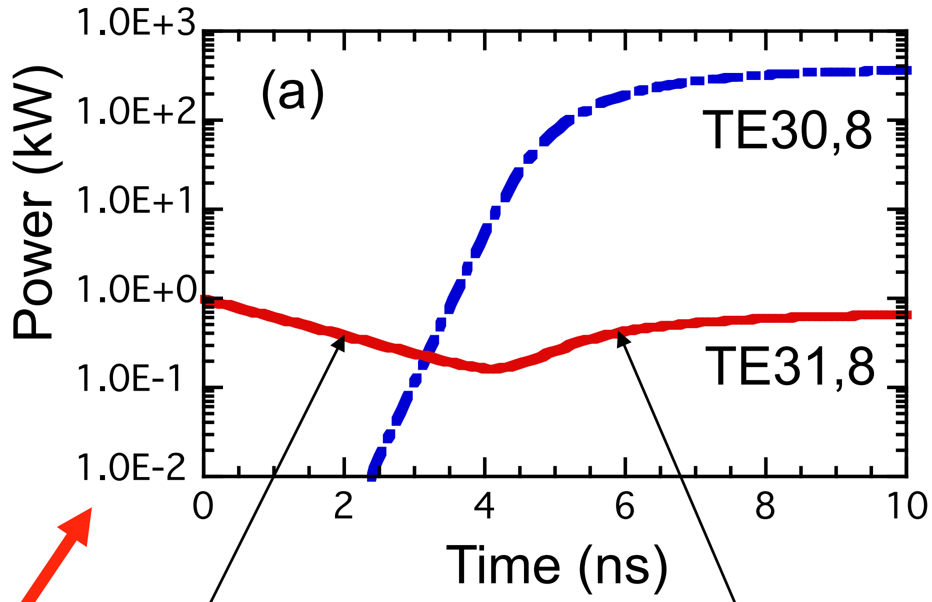


# Experiment vs. Simulation (Single mode analysis)



# Nonlinear Excitation (2) (Two-modes simulation)

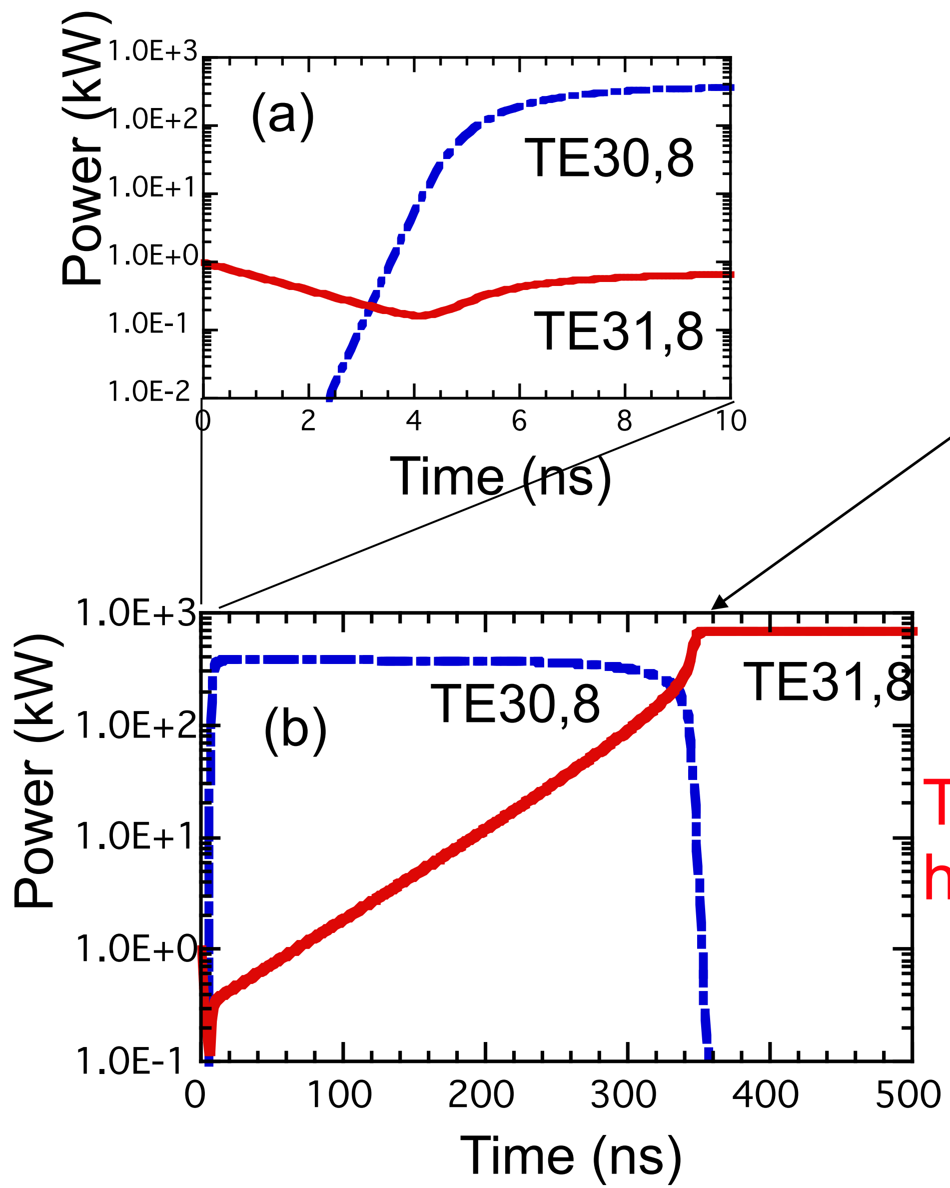



TE31,8 dumps

When TE30,8 exist,
TE31,8 can grow.

# Nonlinear Excitation (4)




TE31,8 grows as a parasitic mode of TE30,8.

TE31,8 suppress TE30,8.

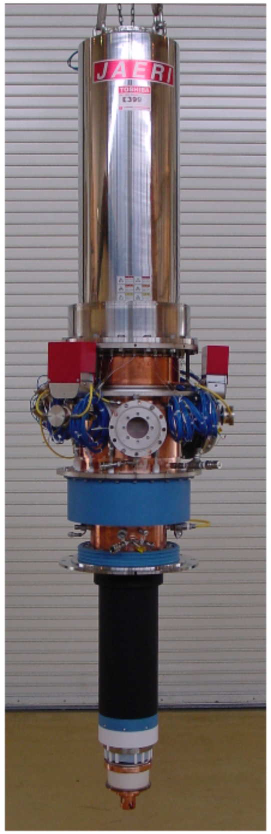
Single mode oscillation of TE31,8 is attained.

TE31,8 mode is robust in the hard self-excitation region.

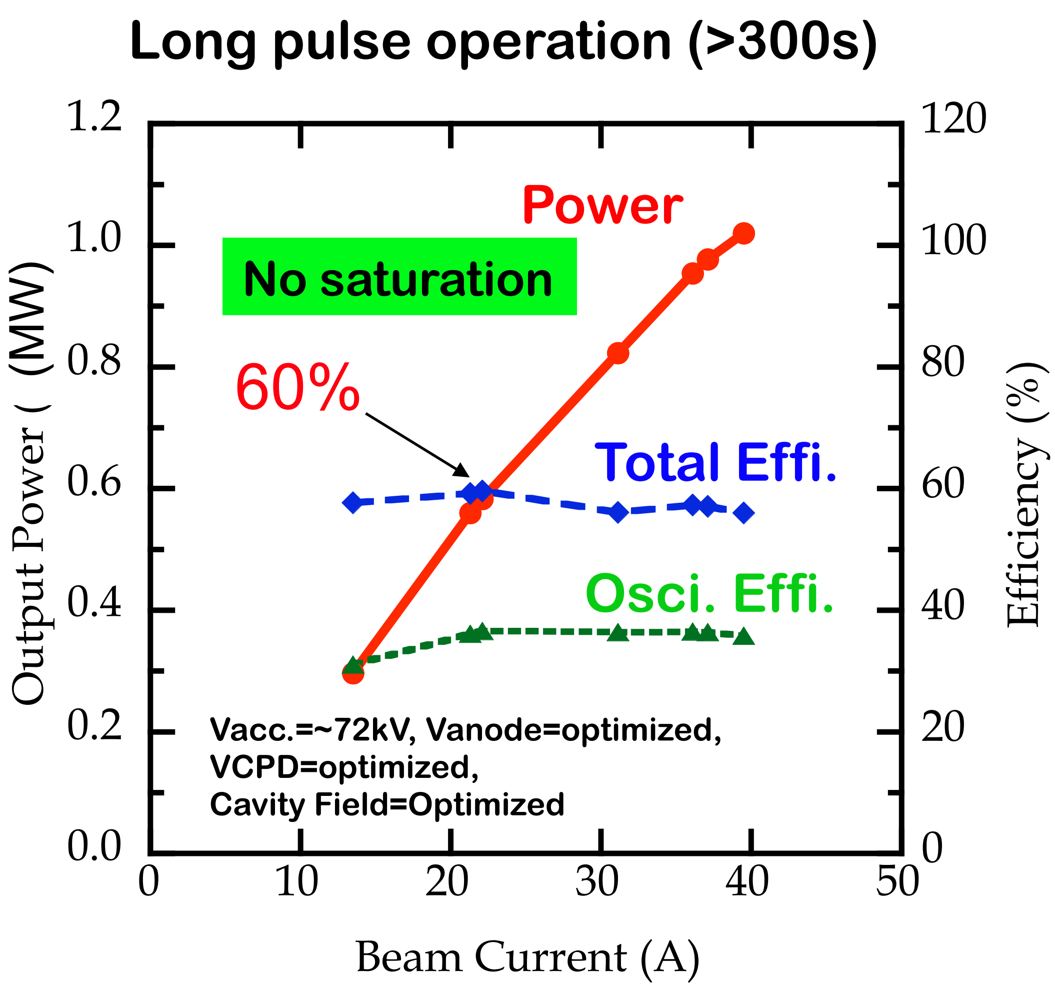
High Efficiency, stable operation is expected.

# Output power, Efficiency v.s. Beam Current

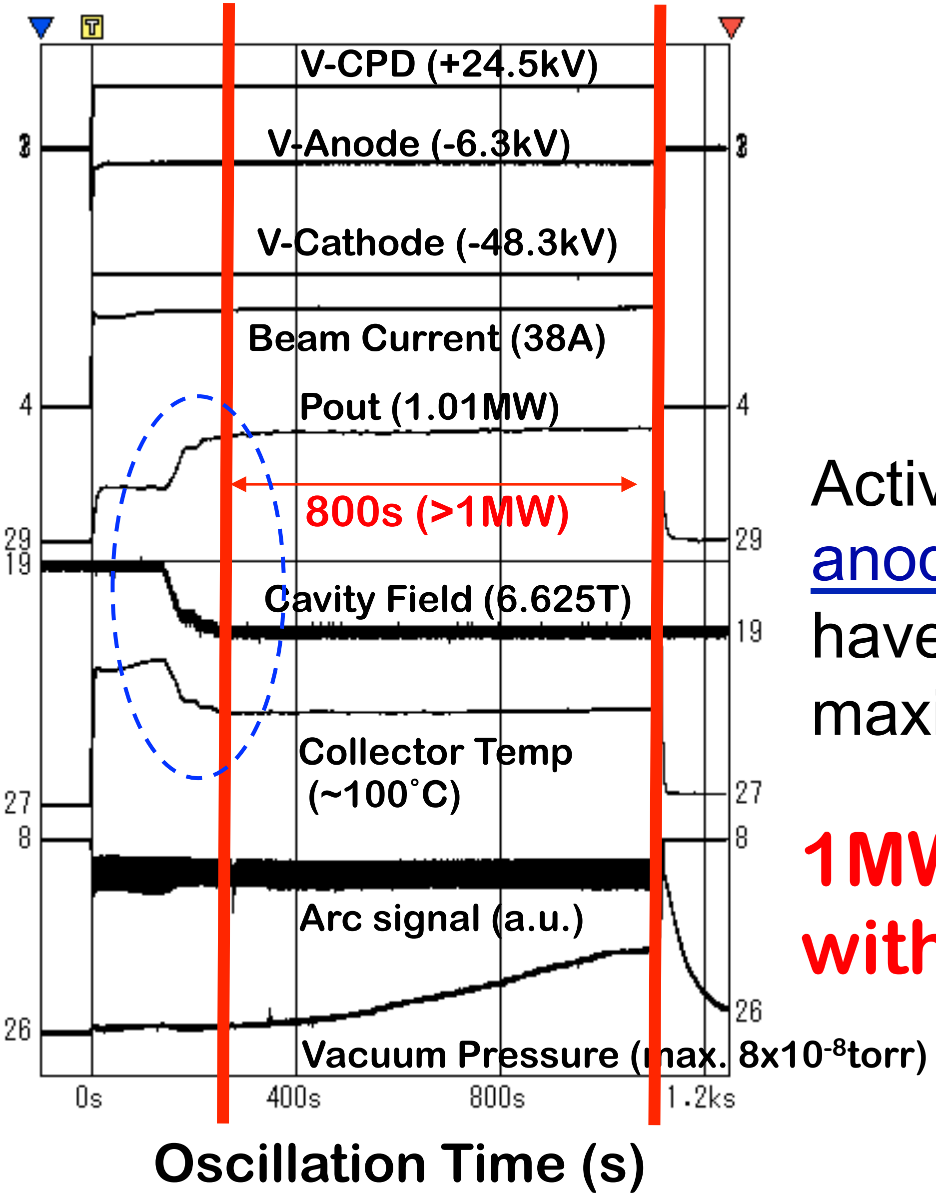
Hard excitation region



J5
(TE31,8)



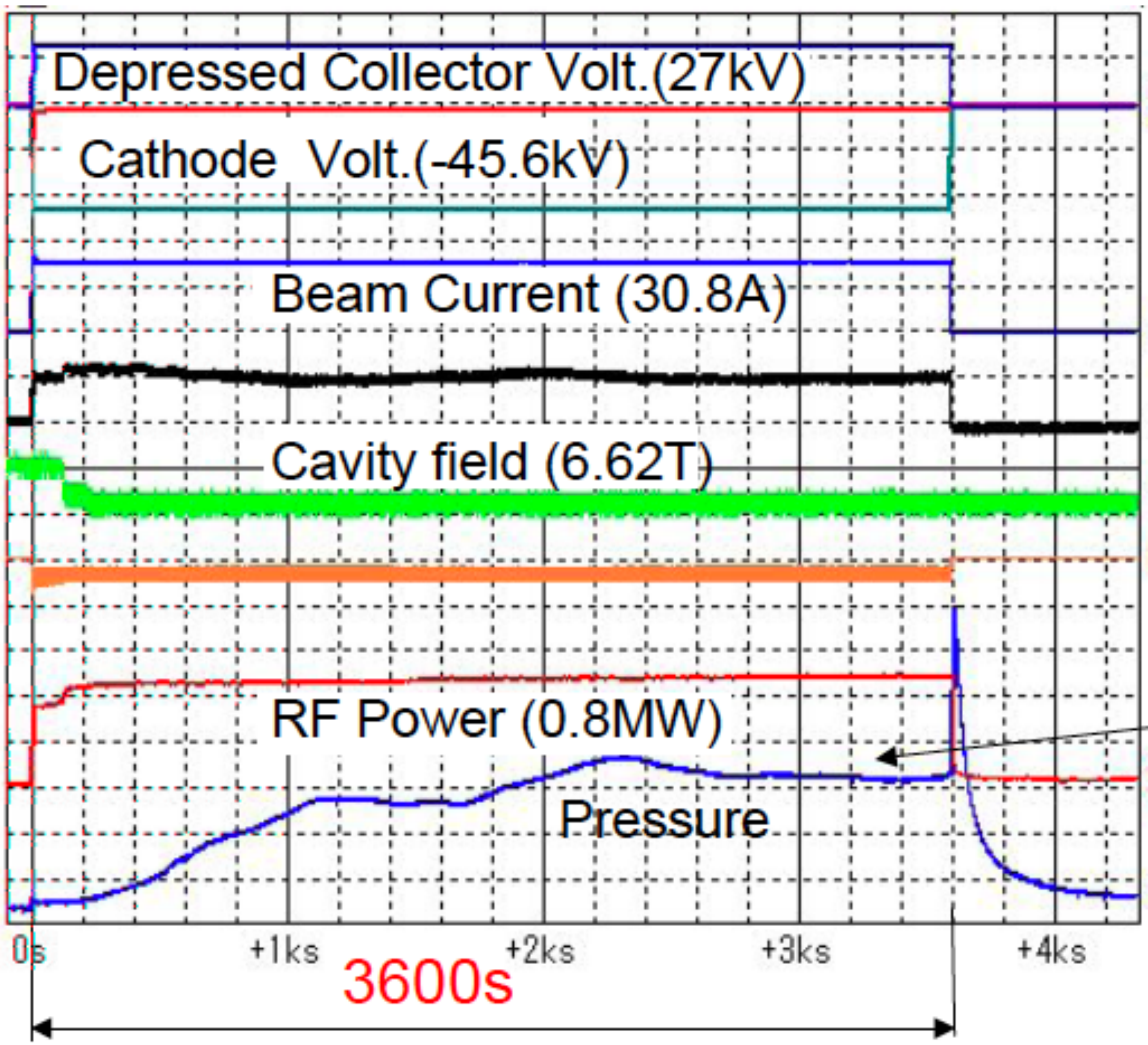
# 1MW/800s/55% operation




Active control of resonator field, anode voltage,heater power have been controlled to access maximum point at hard excitation.

**1MW/800s/55% attained with triode operation.**

# Demonstration of 1hr operation at 0.8MW




Power : 0.8 MW
Pulse : 1hr
Eff. : 57 %

Cooling water for
Input : 42 deg.C

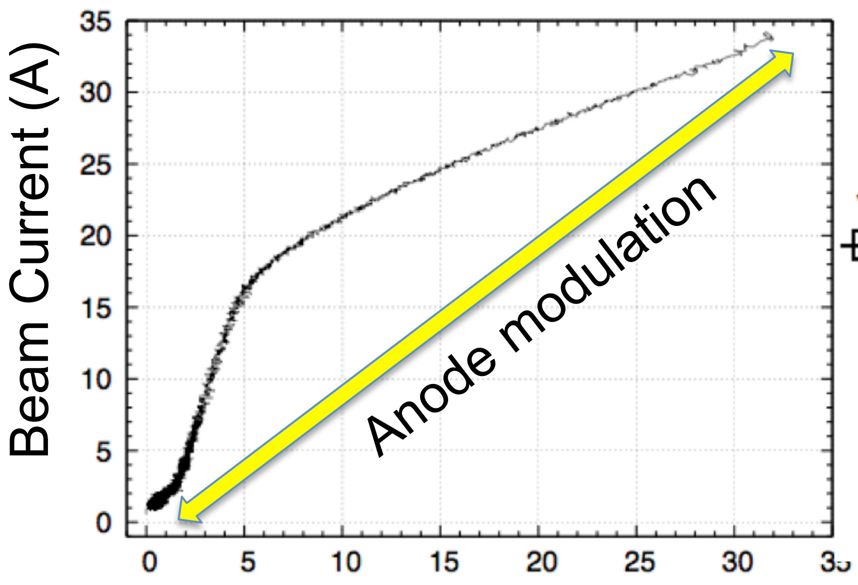
p~1.5x10$^{-7}$torr

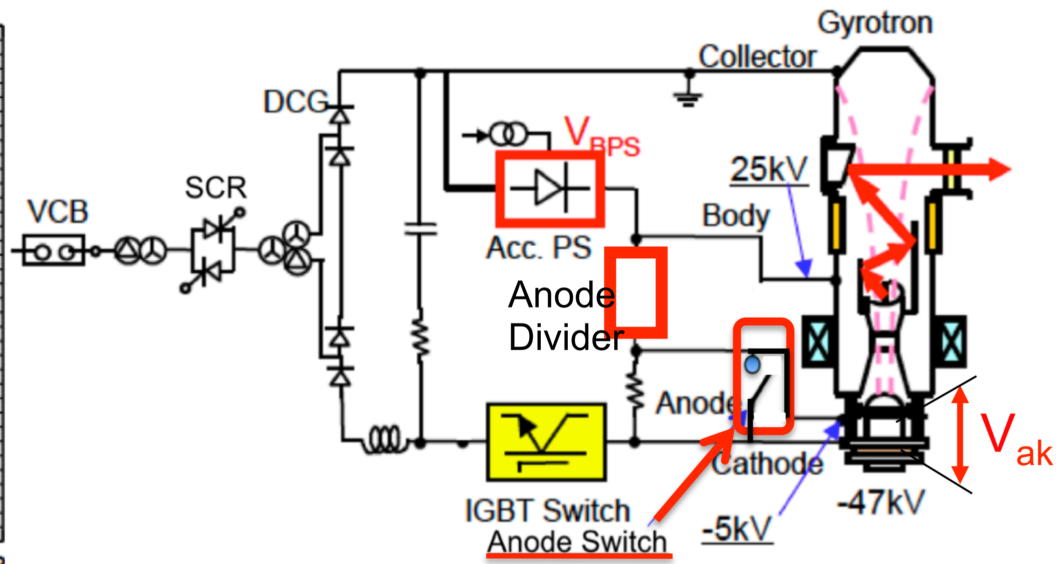
Stable 1hr operation at 0.8MW at 57%

High Frequency Power Modulation
for NTM suppression

# High Frequency Beam current Modulation

Beam Current vs Anode voltage



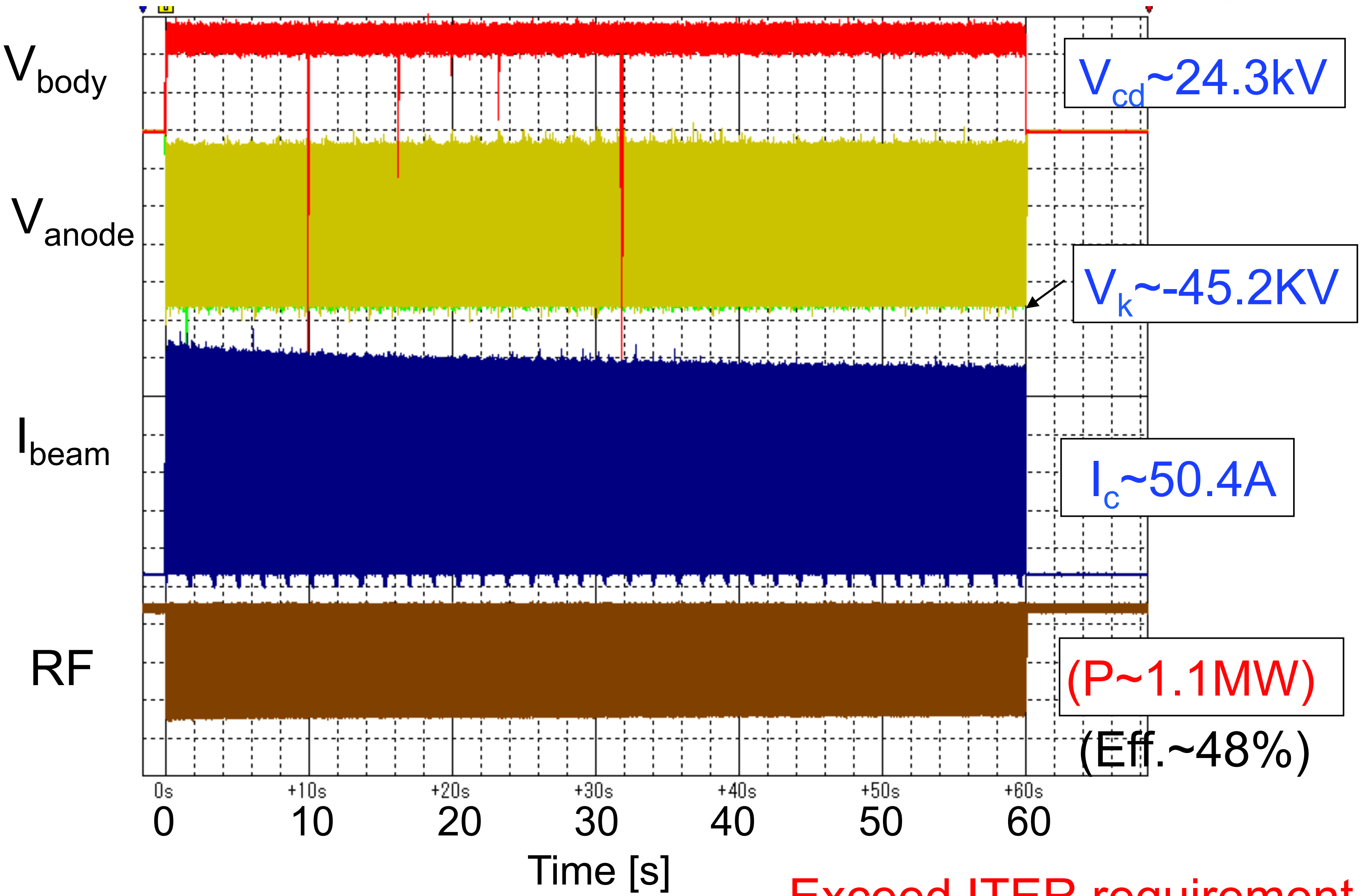




$V_{ak}$(kV)

Beam current modulation is available by anode modulation in Triode MIG.

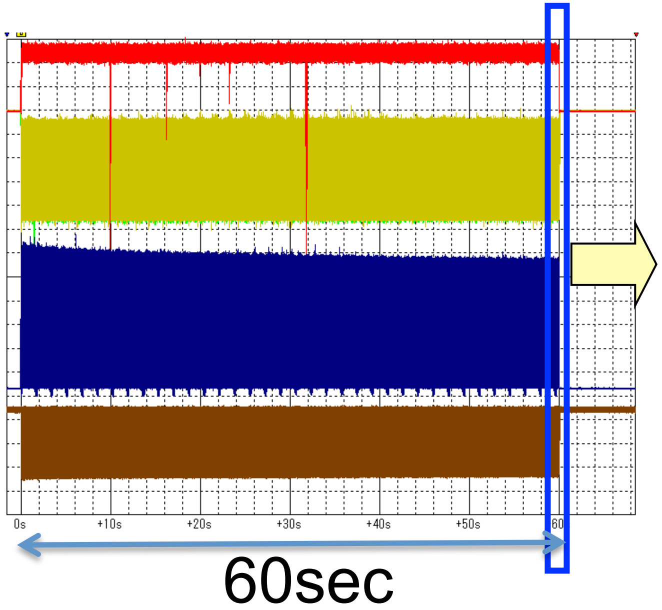
➡ Minimize a collector heat load.
Increase the total efficiency.

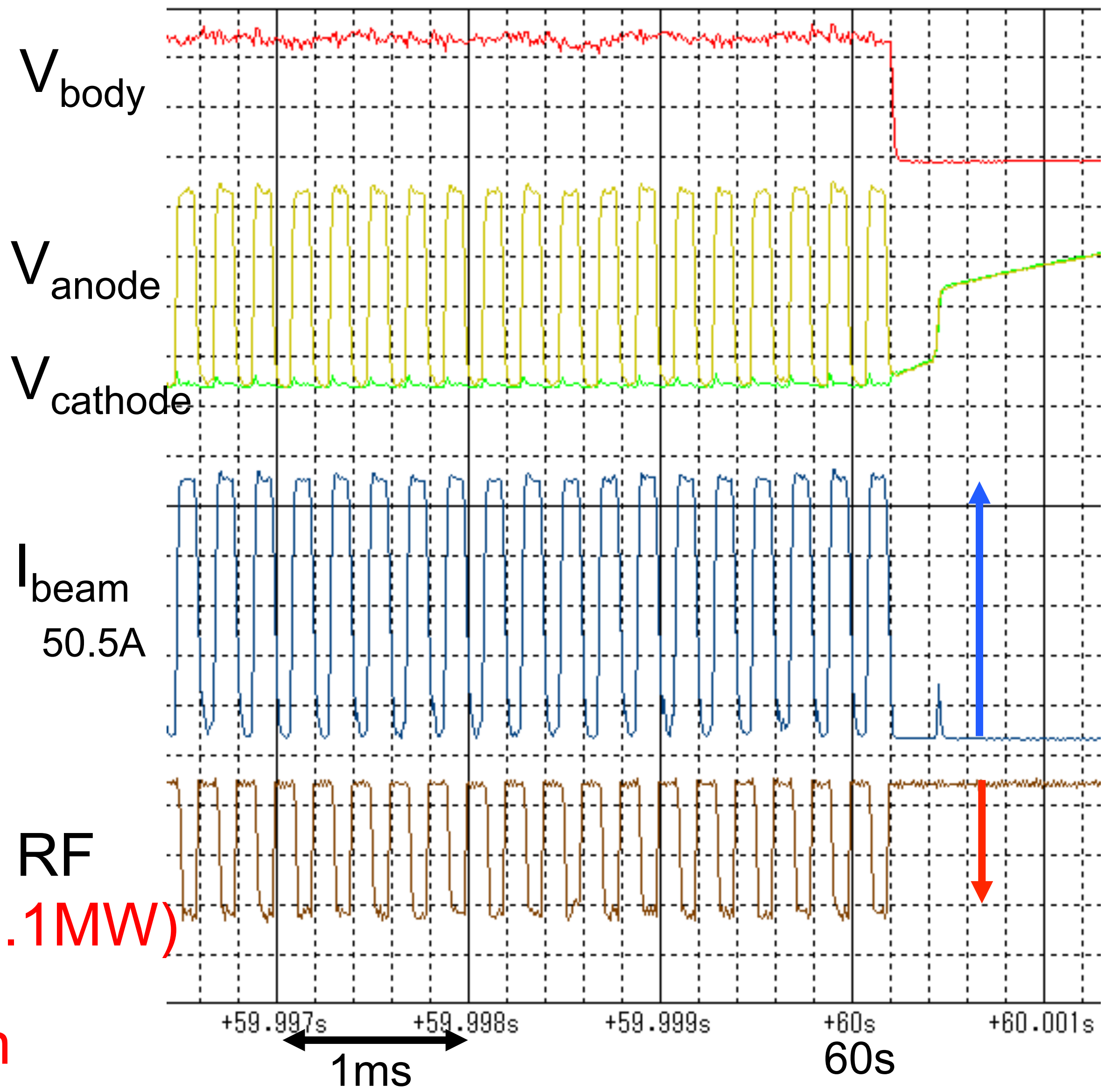
# 5 kHz full power modulation (60s) for NTM suppression




Exceed ITER requirement

# 5 kHz power modulation (anode modulation)




<u>ITER target</u>

5kHz/50s

(0.5MW-1MW) mod.

<u>Attained</u>

5kHz/60s

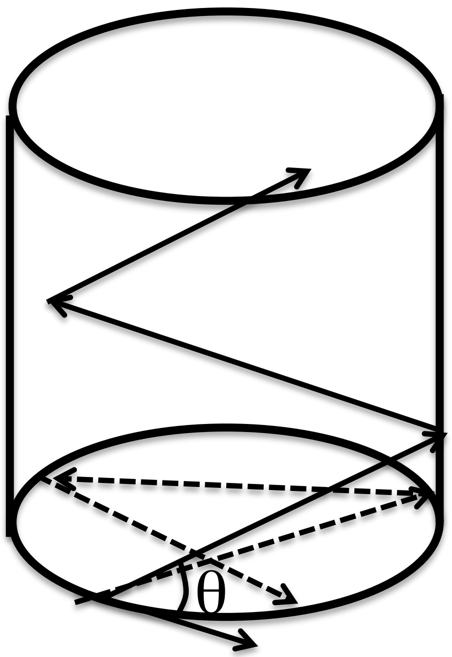
Full 1.1MW modulation

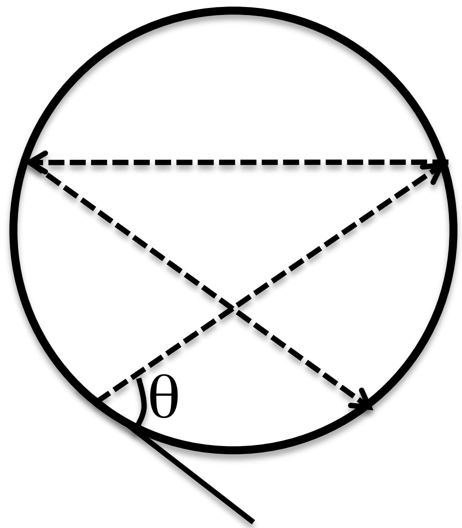
# Multi-Frequency Gyrotron

# Multi-Frequency Gyrotron (Mode selection)

- Window (1.853mm diamond): 170GHz/136GHz/102GHz
- Launcher : Select similar θ for both mode

$$\theta = \cos^{-1}(m/\chi_{m,n})$$



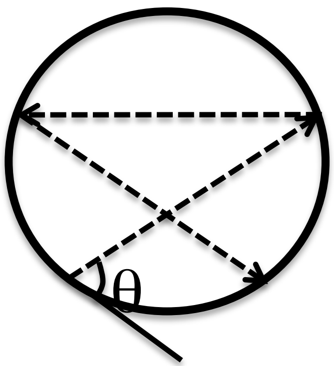
# Multi-Frequency Gyrotron (Mode selection)

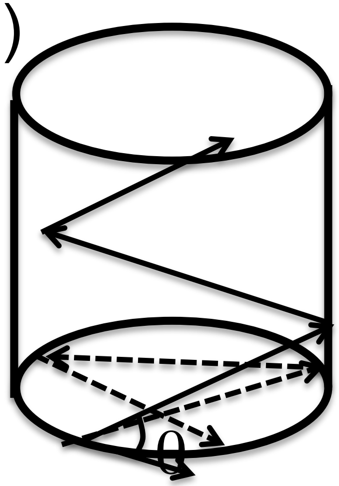
(single window disk is available:1.853mm)

| TE(m,n) | Frequency | θ(deg) | Window transparent f. |
|---|---|---|---|
| (37,13) | 203GHz | 65.3665 | 204GHz |
| (31,11) | 170GHz | 65.3492 | 170GHz |
| (25,9) | 137GHz | 65.3235 | 136GHz |
| (19,7) | 104GHz | 65.3003 | 102GHz |

Very Similar!

$\theta = \cos^{-1}(m/\chi_{m,n})$




Same angle θ:
Mode converter act similarly for all modes.
High efficiency is expected for all modes.

# Design of Oscillation at Multi-Frequency gyrotron (J7)

Beam voltage =72kV, Beam current=40A

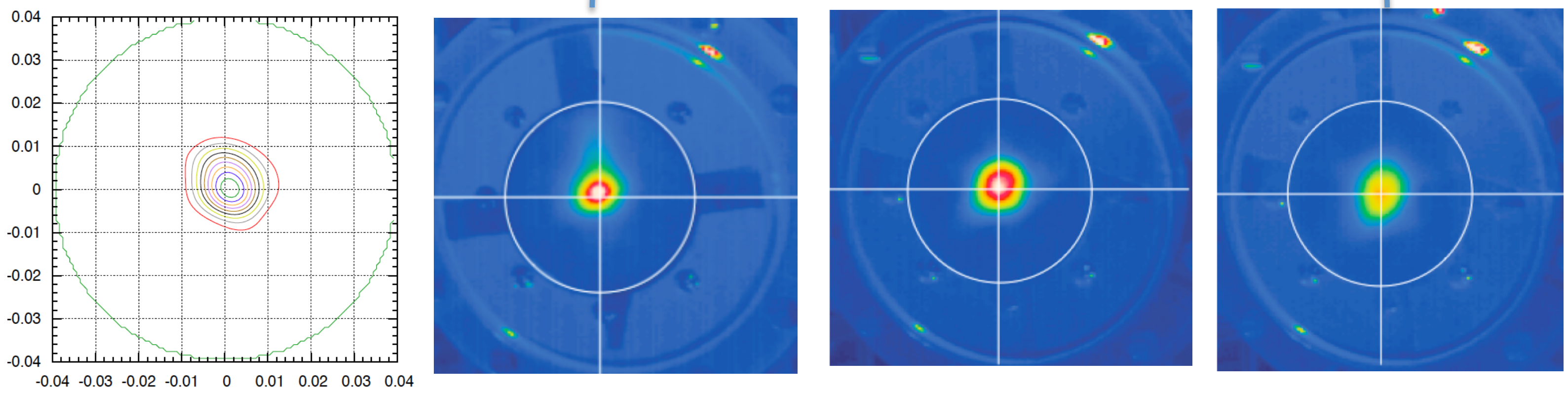
| Mode | 203.1GHz | 170.0GHz | 137GHz | 104GHz |
|---|---|---|---|---|
| Frequency | TE37,13 | TE31,11 | TE25,9 | TE19,7 |
| Cavity Field | 7.98T | 6.63T | 5.32T | 4.08T |
| Gun Field | 0.31T | 0.28T | 0.21T | 0.172T |
| Beam radius | 9.10mm | 9.13mm | 9.19mm | 9.25mm |
| Anode voltage | 50kV | 42kV | 36kV | 28kV |
| Pitch factor | 1.35 | 1.35 | 1.35 | 1.32 |
| Oscillation Power | 1.3MW | 1.3MW | 1.26MW | 1.12MW |
| | | | | |
| | | | | |

# Multi- Frequency Gyrotron

## RF power profiles at output window

Calculation

Experimental Result




203GHz 170GHz 137GHz 104GHz

Four frequency power generation is available, and
RF beams of four frequencies pass through
the center of the window at same direction.

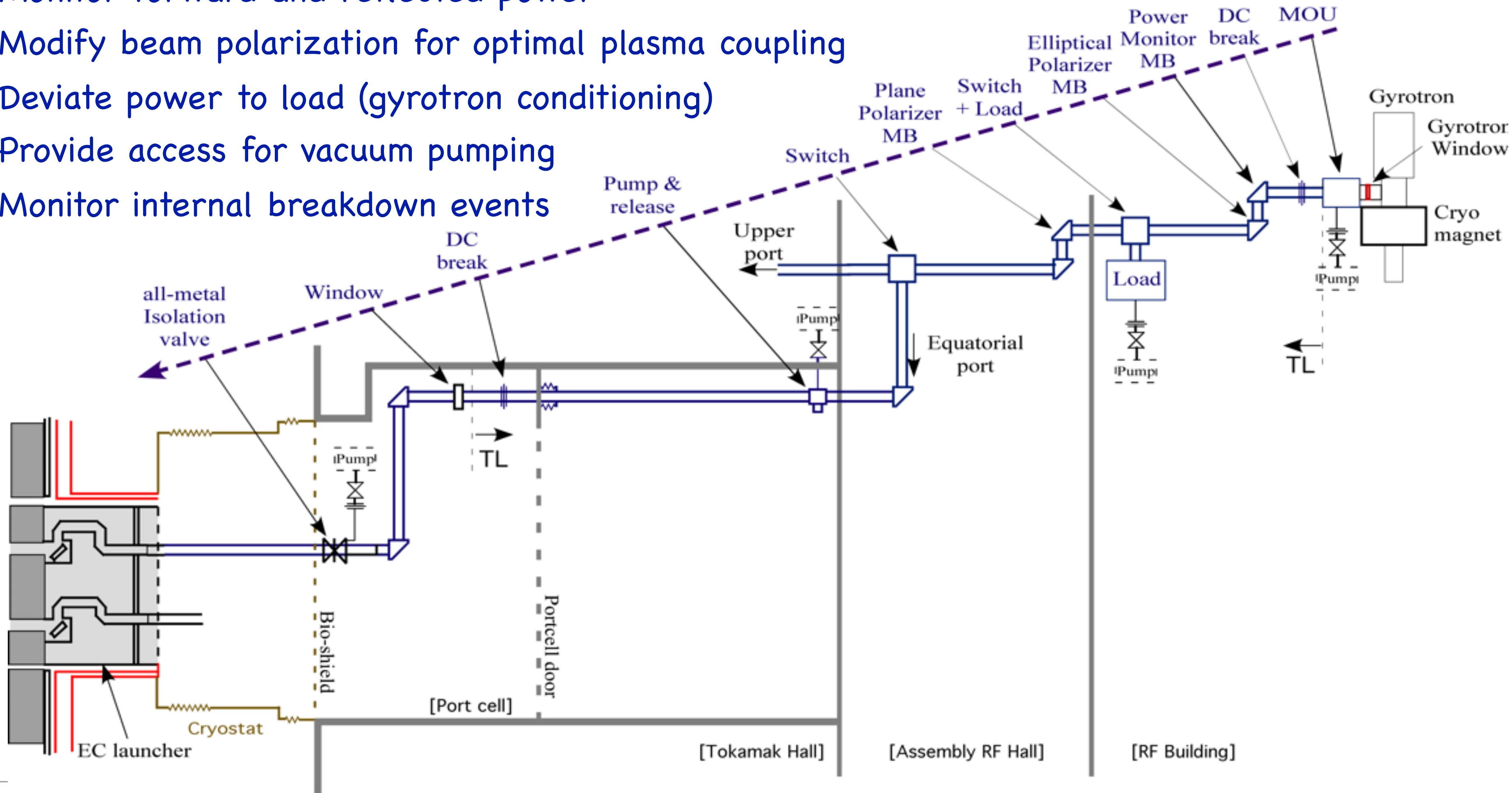
-> High efficiency power transmission to the plasma.

# Power Transmission

# Transmission line (ITER)

## In addition to power transmission, the TL provides:

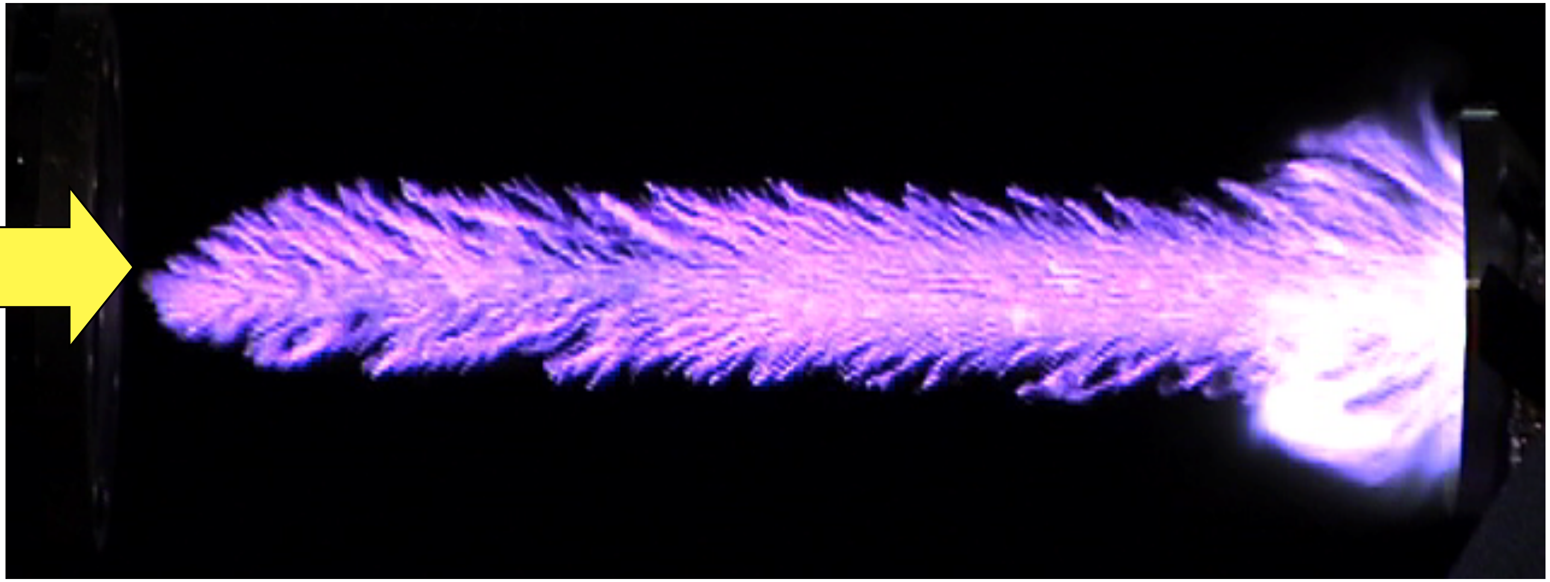
- DC isolation at gyrotron and tokamak
- Monitor forward and reflected power
- Modify beam polarization for optimal plasma coupling
- Deviate power to load (gyrotron conditioning)
- Provide access for vacuum pumping
- Monitor internal breakdown events



# RF Discharge

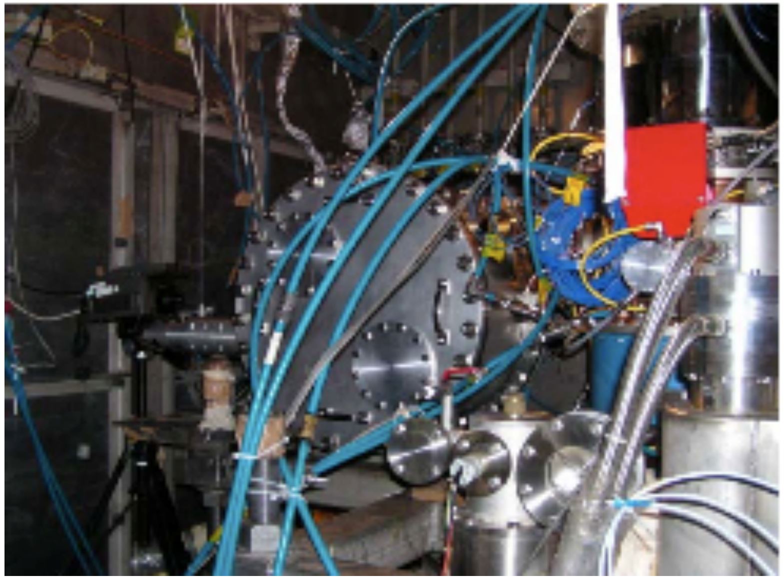
Discharge proceed toward the source.

Transmission line should be evacuated.

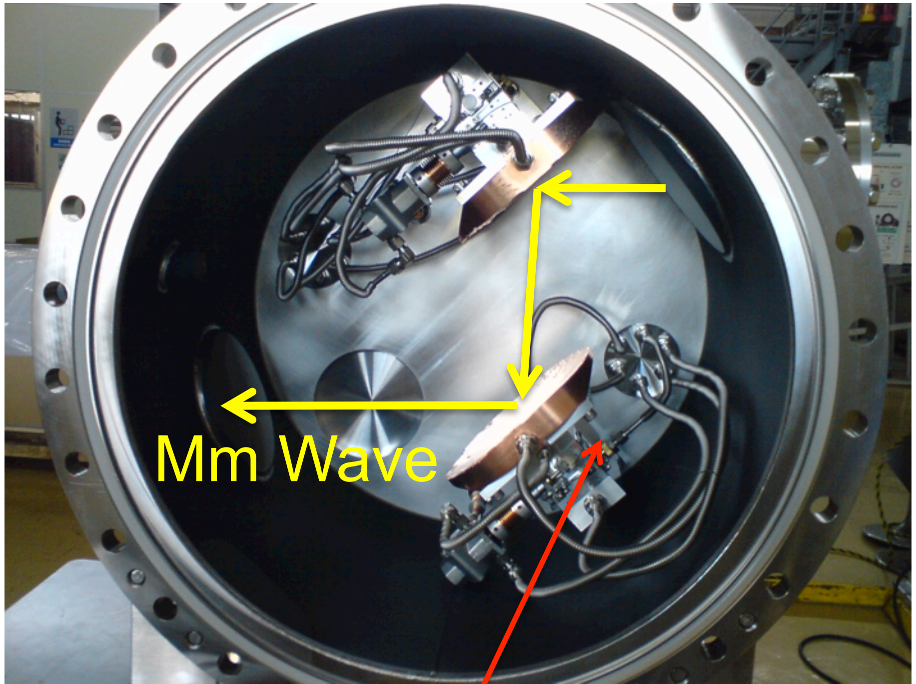


RF beam

# MOU and transmission line



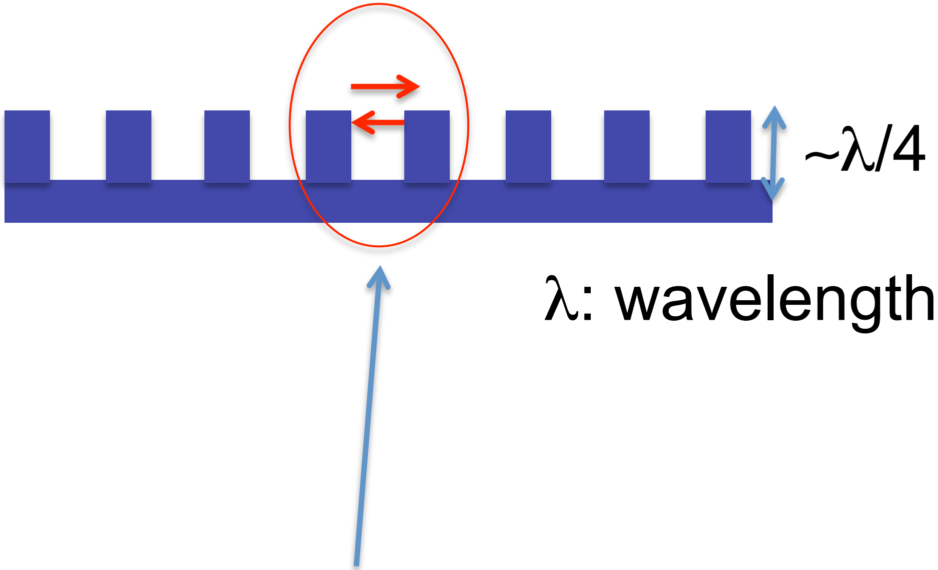
Matching Optics Unit

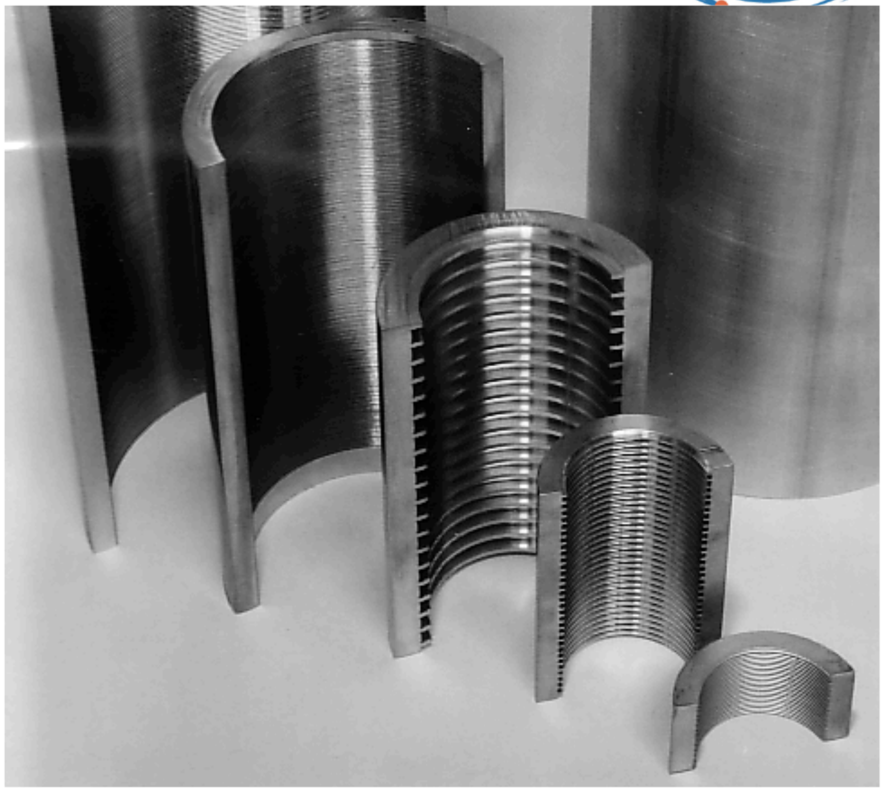



Adjustment of mirror

# Corrugate waveguide

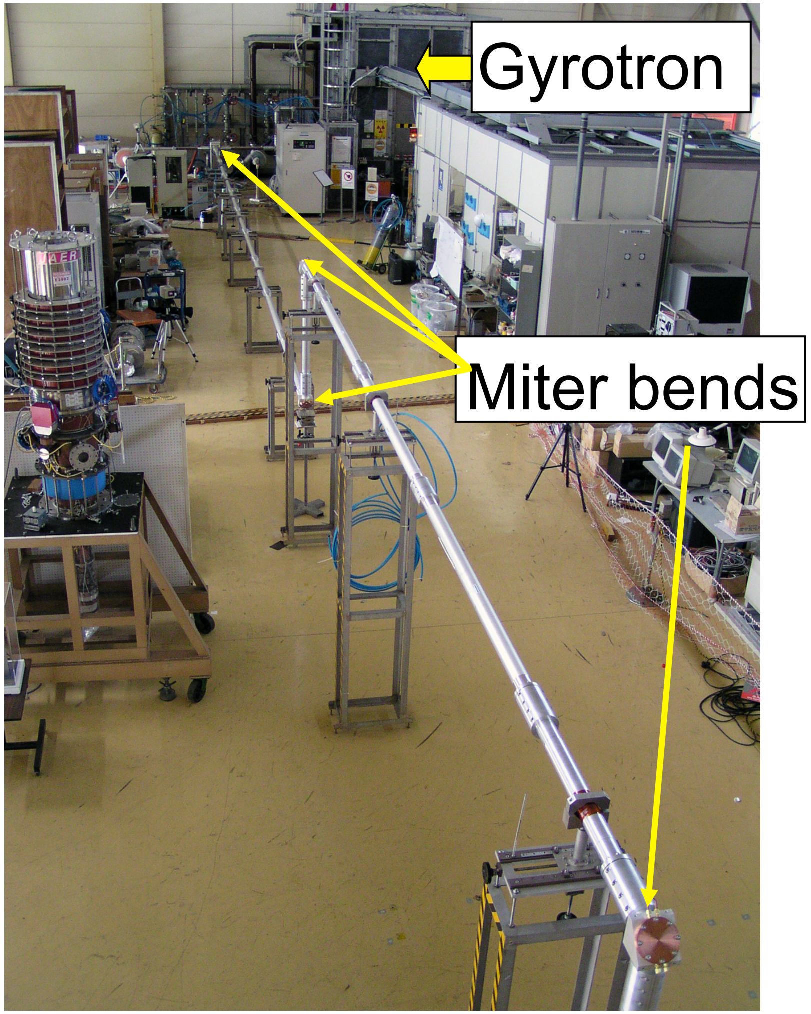
## Corrugate on the inner surface



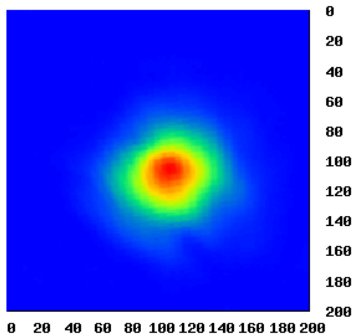
Surface RF current of the waveguide wall vanish,
as a result, low loss transmission is realized.

# ITER simulated Transmission line (63.5mm dia.)




40mWaveguide +7 bends

At present, 92 % transmission from gyrotron window to the dummy load (after 40m).

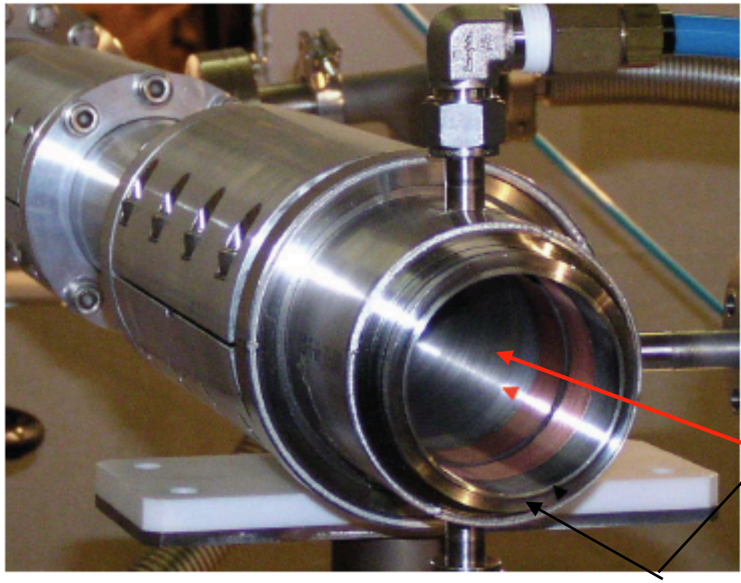


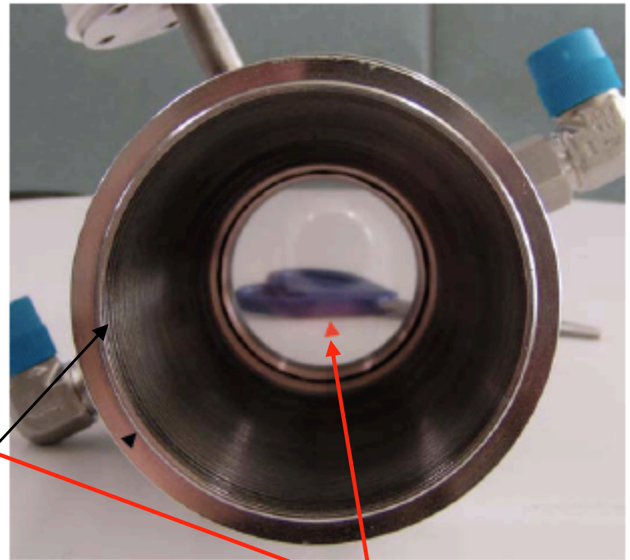

30cm from W/G

(HE11: ~92%.)

# Torus window for Tritium Shielding

## Torus window for ITER (EU-JA Collaboration)



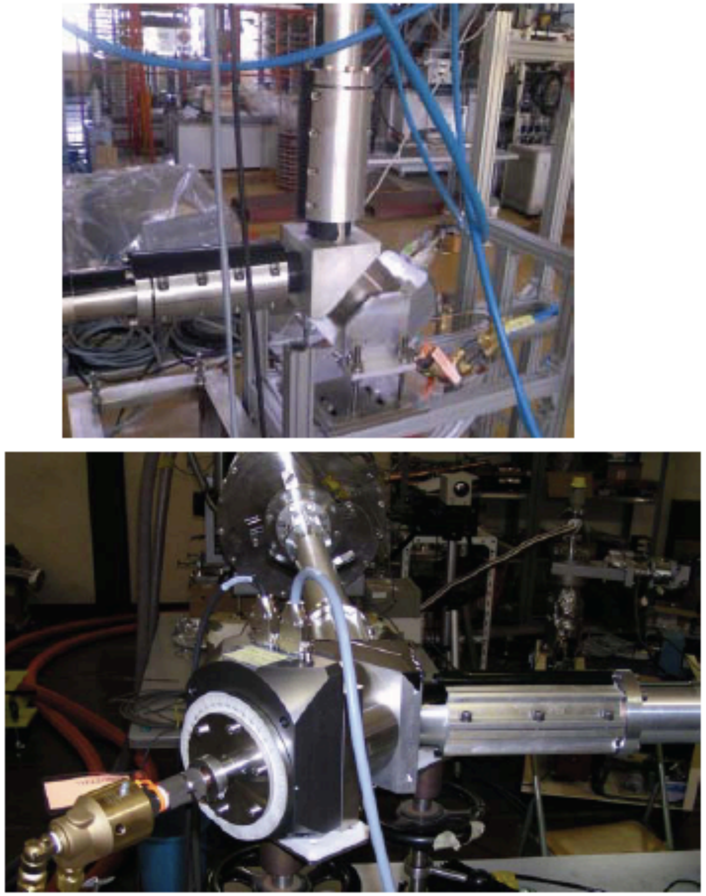


Waveguide

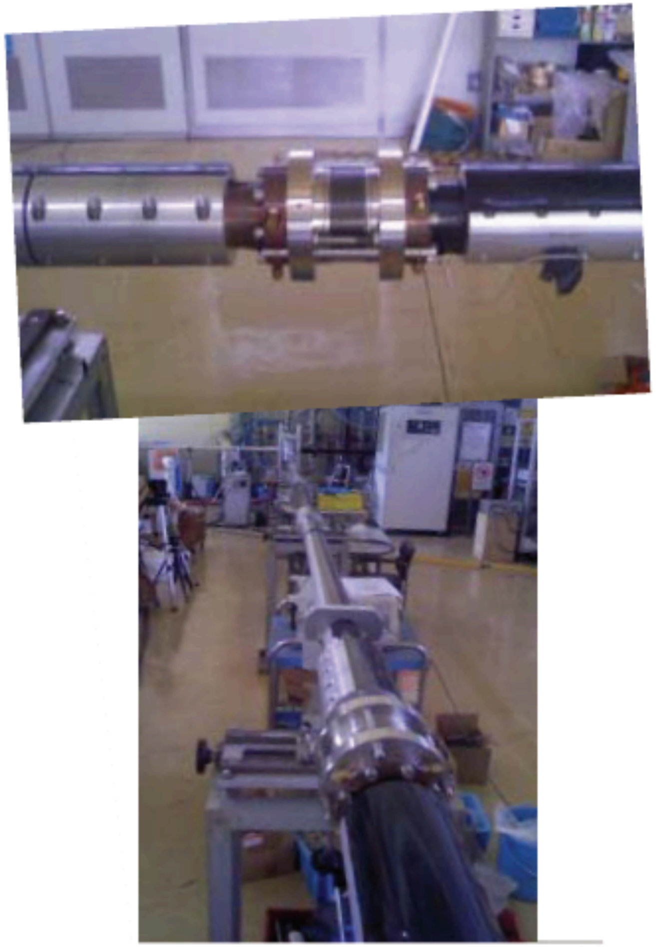
Diamond window
1.12mm

KIT (T.Scherer, et al.)

## Transmission Components (Collaboration with GA)



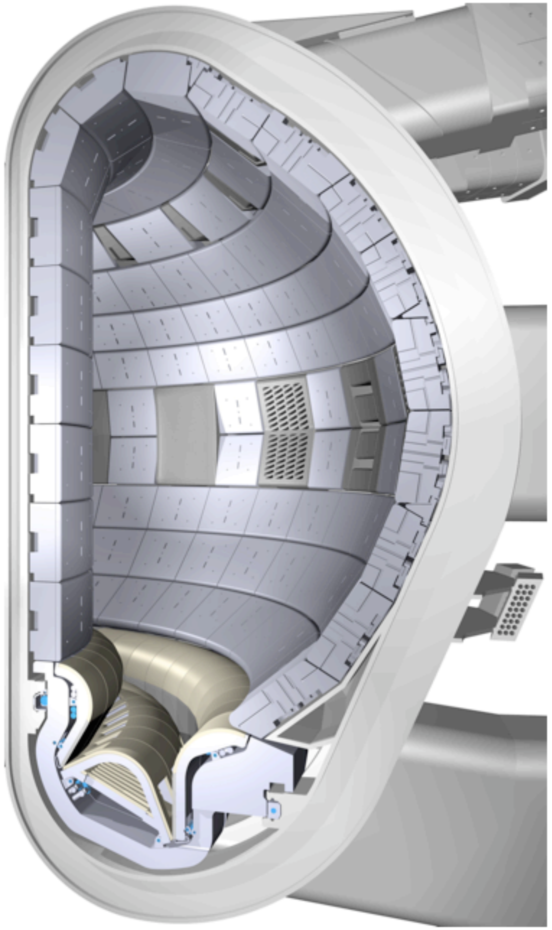
Polarizer

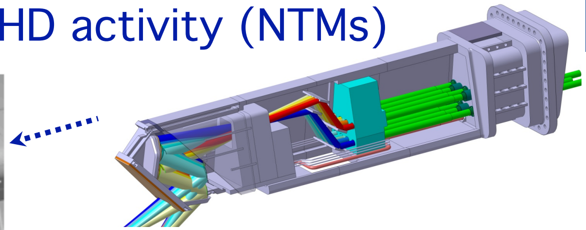


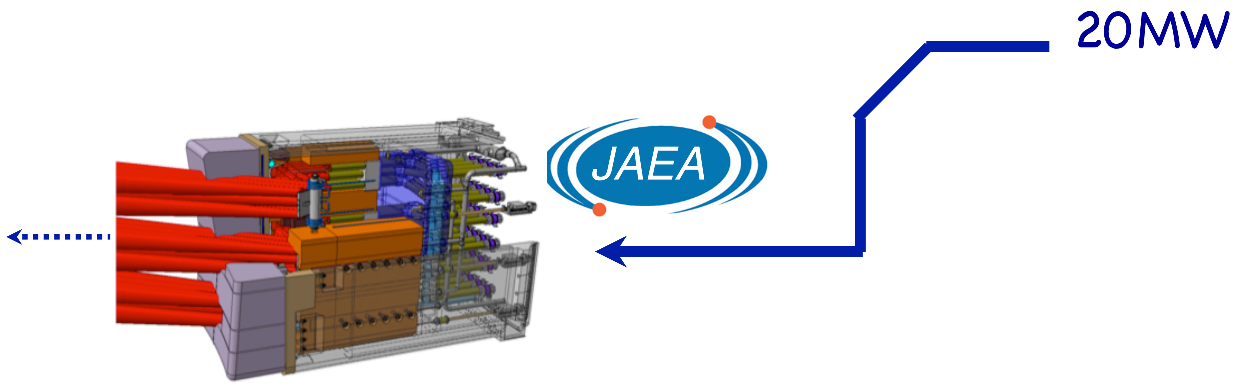
Waveguide Expander

# ITER has Two types of launchers

## Upper launcher
- 4 ports, 8 entries each
- Control of MHD activity (NTMs)

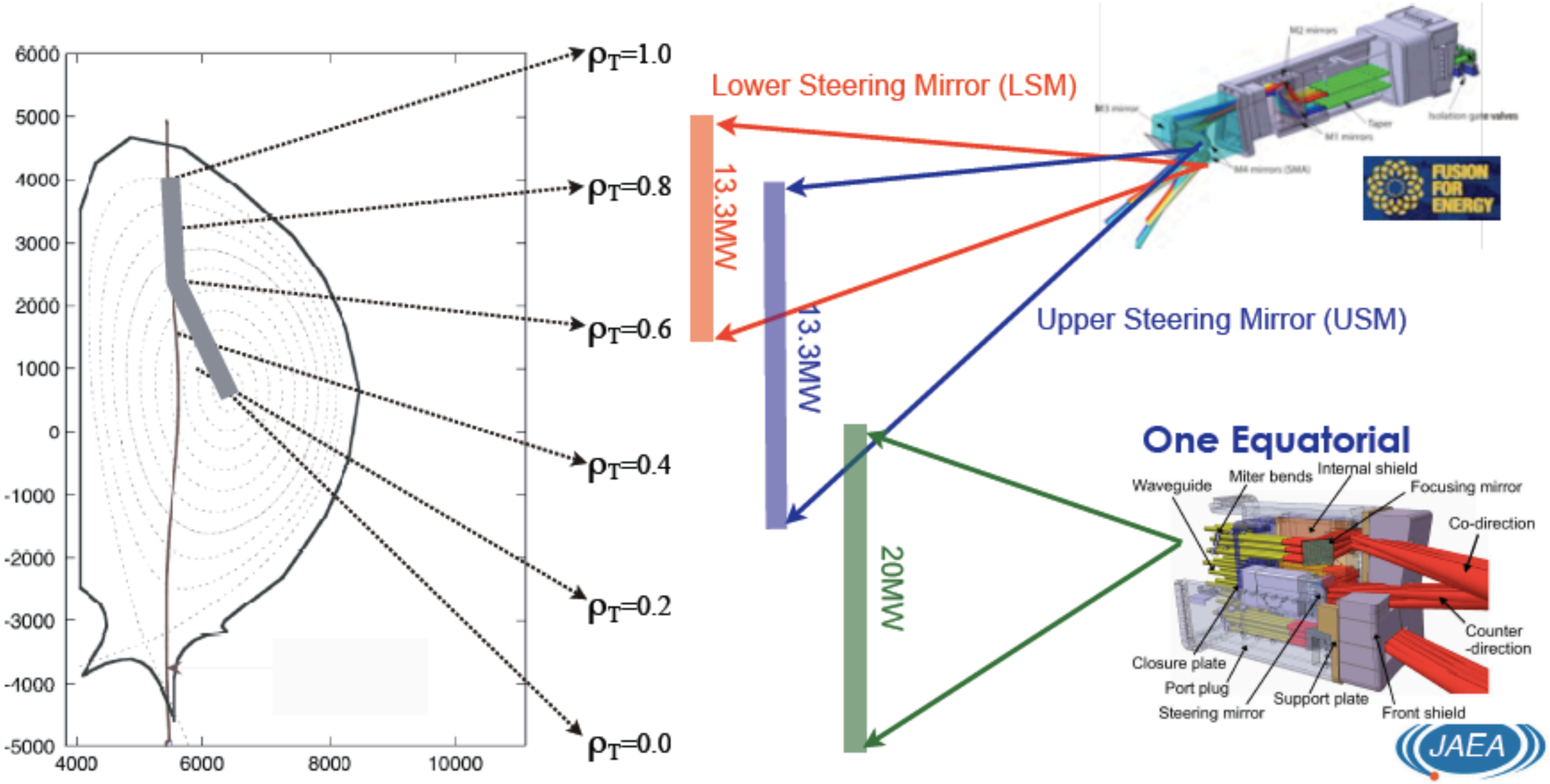




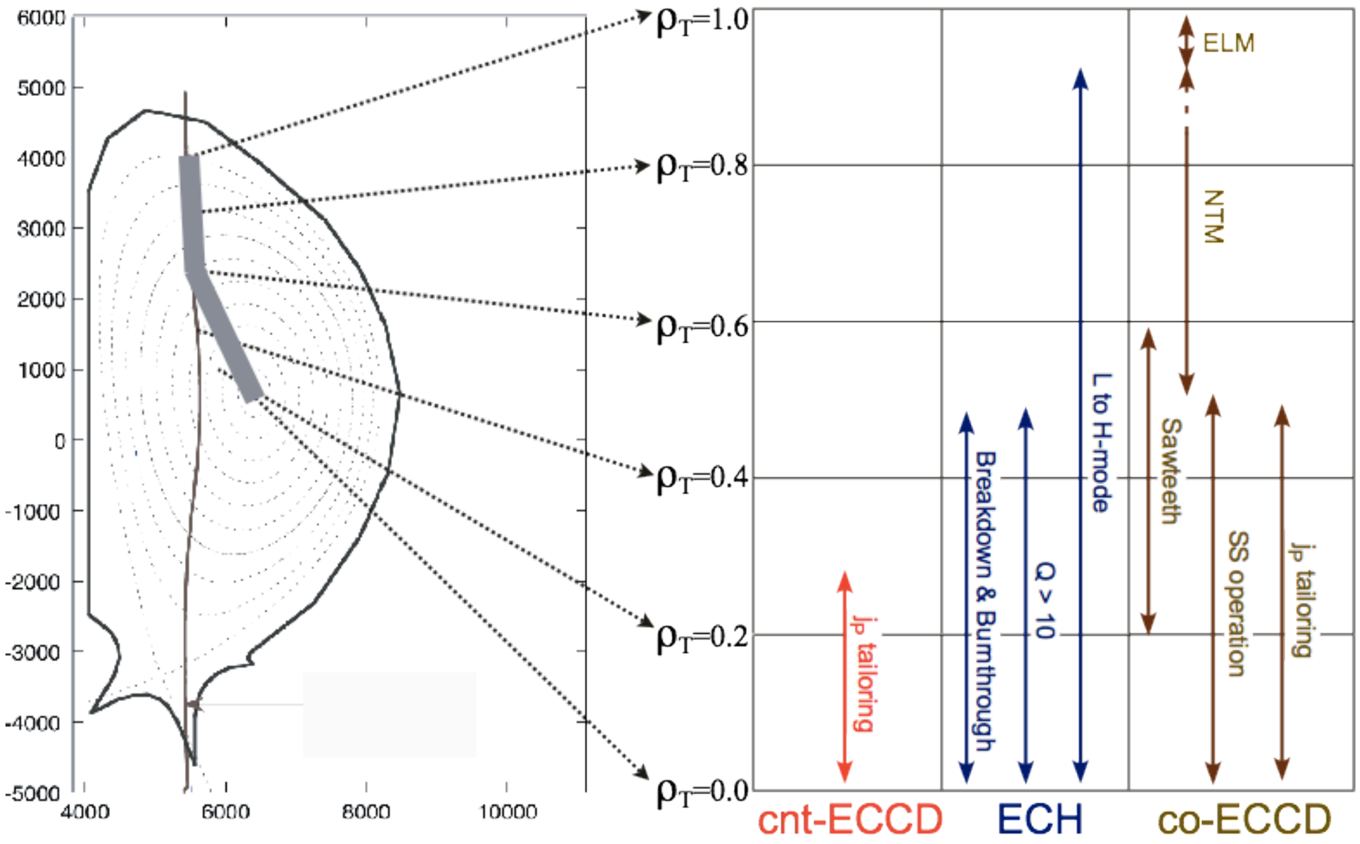



## Equatorial launcher:
- 1 Port, 24 entries
- Central heating and current drive

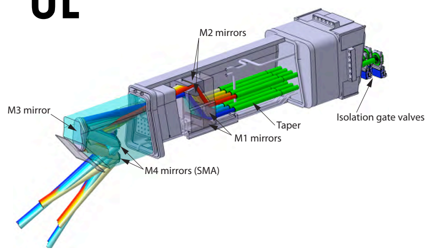
- Access range in Plasma



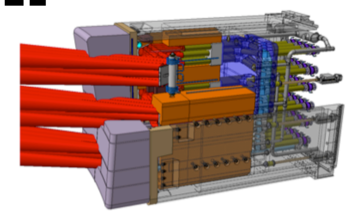

- EL has 13.3MW in co-ECCD and 6.7MW in Counter ECCD (Decouples heating and current drive capabilities (Independent control of $T_e$ and $j_P$)




**UL**




**EL**





M.Henderson

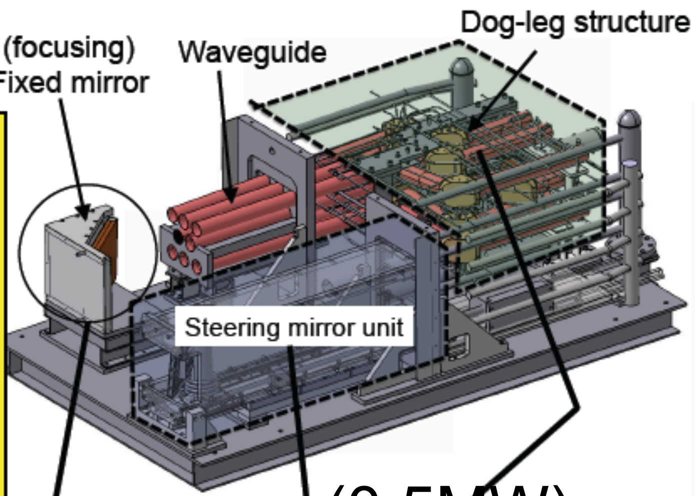
# Equatorial Launcher Mock-up

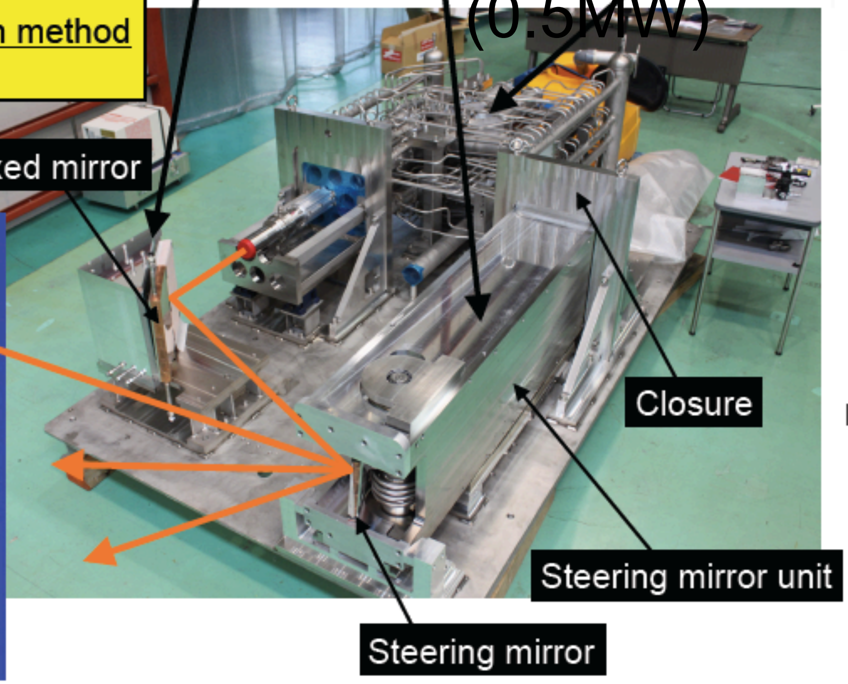
## EL mock-up

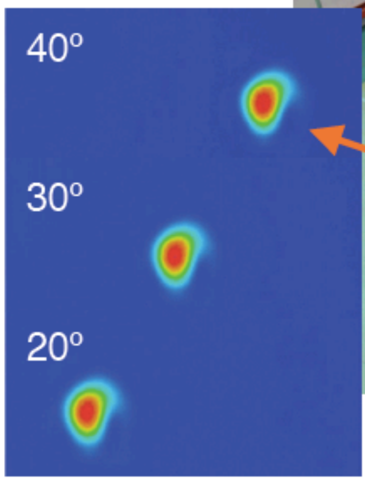
Fabrication
- MM wave transmission :
  1/3 unit
  Dog-leg structure (cooling incl.)
- Fixed mirror : 20cm recess
- Modularized steering mirror unit
- Interface with closure :
  Steering mirror unit } Flange
  Waveguide unit

⬇

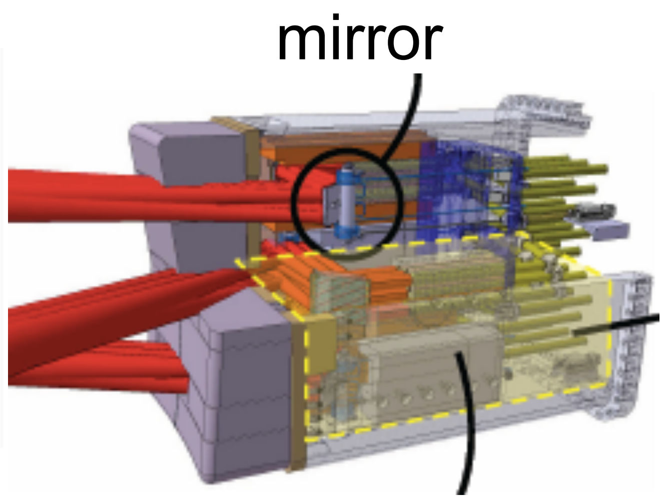
Prospect of fabrication method was obtained.




Beam profile at 1.5m from steering mirror (High power test)



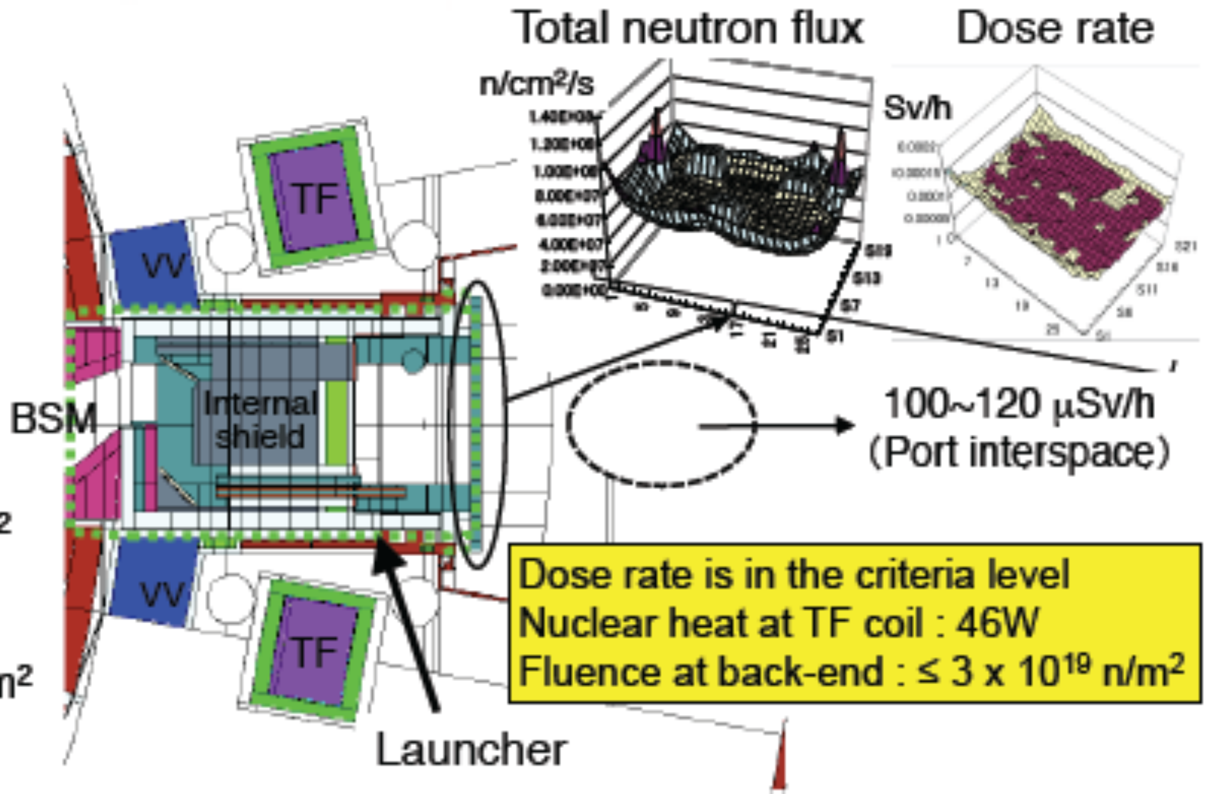

K.Takahashi, et al.,IAEA FEC 2012

# Neutronics for Launcher

## Nuclear shielding

del : CATIA --> MCNP
VV : B-Lite (provided by IO)
EL : CATIA --> MCNP

- Analysis code : MCNP 1.51
- Analysis condition
  Fusion power : 500MW
  Neutron fluence @FW : 0.3MW•a/m$^2$
  Accumulated operation time : 4600h
- Shield criteria
  Fluence @ EL back-end : ≤ $10^{20}$ n/m$^2$
  Shut-down dose rate : ≤ 100 μSv/h




Neutron fluence is well below the critical value.
Shut-down dose rate by Gamma-ray will be
within acceptable level.

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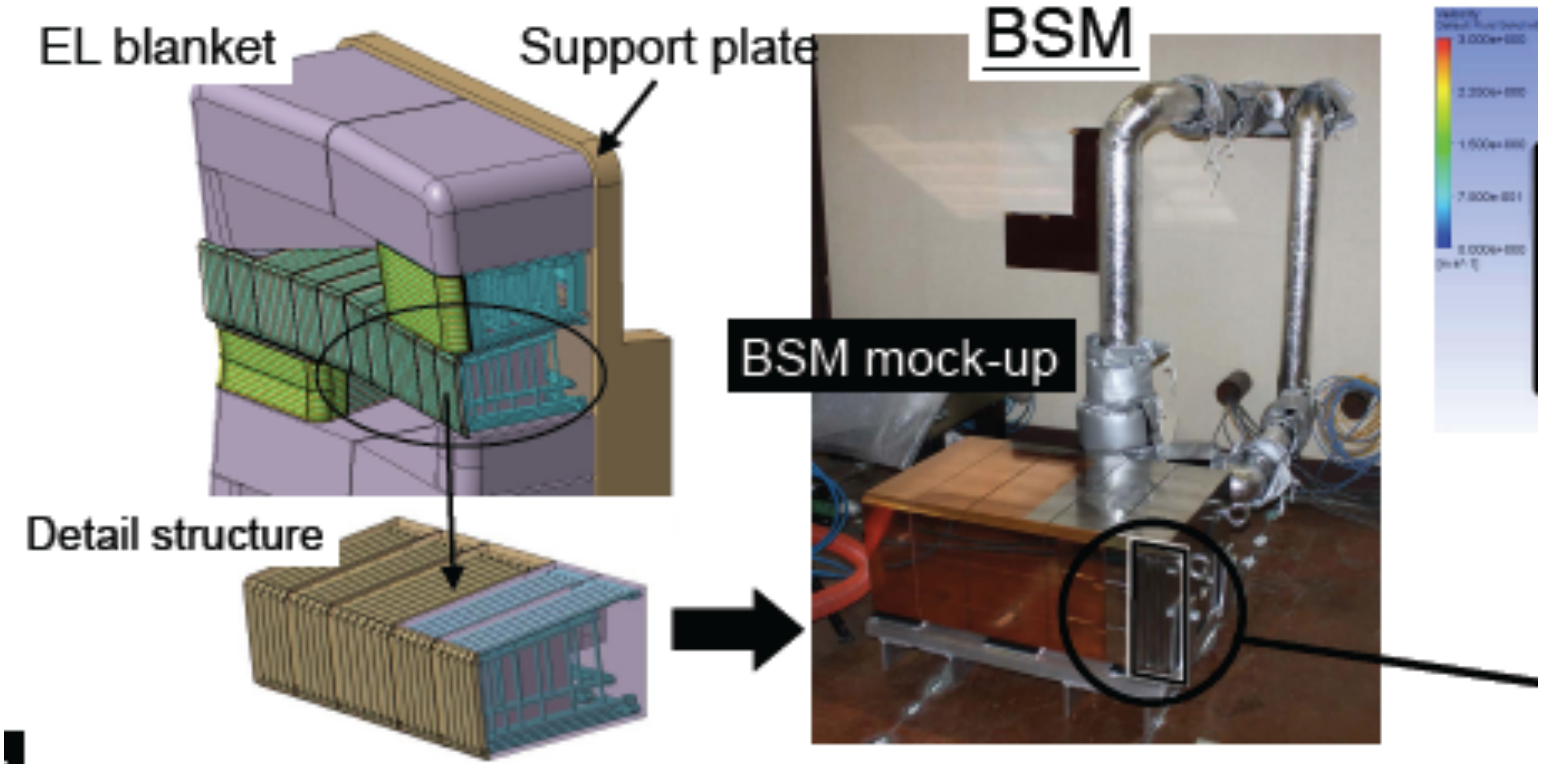
# Shield Blanket Module at the top of the launcher




BSM mock-up was fabricated based on the detail design.
FW : CuCrZr + SS (HIP), Heat treatment considering Be joint
Preliminary result of flow test : 1.4~1.5m/s @ FW

K.Takahashi, et al.,IAEA FEC 2012

# Conclusion/perspective

- Significant progress has been obtained in EC technology.
- International collaboration was effective.
  (ITER/Engineering Design Phase)
- Further progress is expected.
- Present EC technology will be available for DEMO as it is.