Present Status of 28 GHz Gyrotron Test System in NFRI

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Motivation

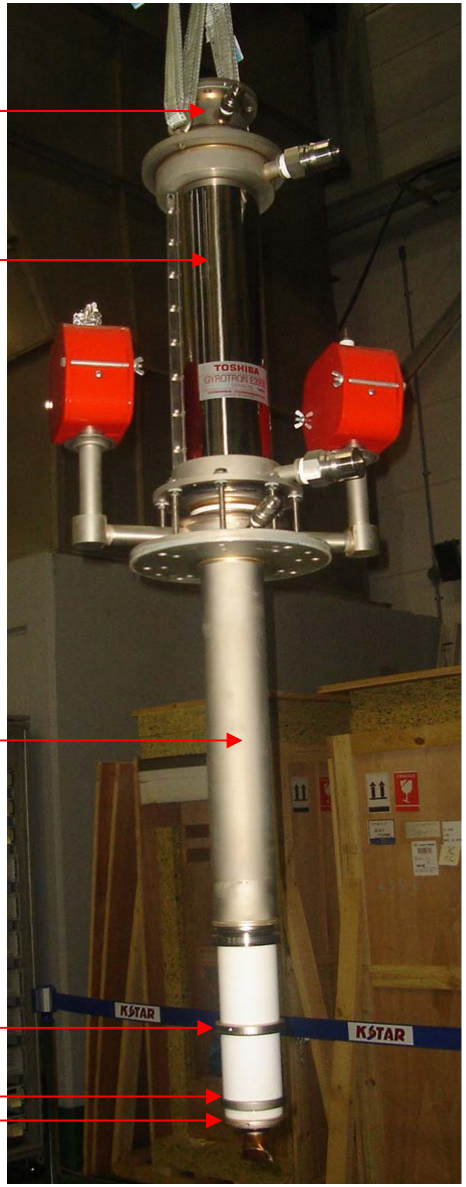
NFRI ←— collaboration —→ 筑波大学 University of Tsukuba

Two Toshiba gyrotron tubes (without their magnet systems) had been provided by Tsukuba university, Japan in June, 2006.

This gyrotron was used for 28 GHz ECH system for Gamma10 Tandem mirror device in Plasma Research Center (PRC), Tsukuba University.

In 2007, 28 GHz gyrotron test system was set up using NFRI superconducting magnet which was used for 28 GHz gyro-klystron system in Hanbit mirror device.

28 GHz gyrotron (Toshiba E3955D)

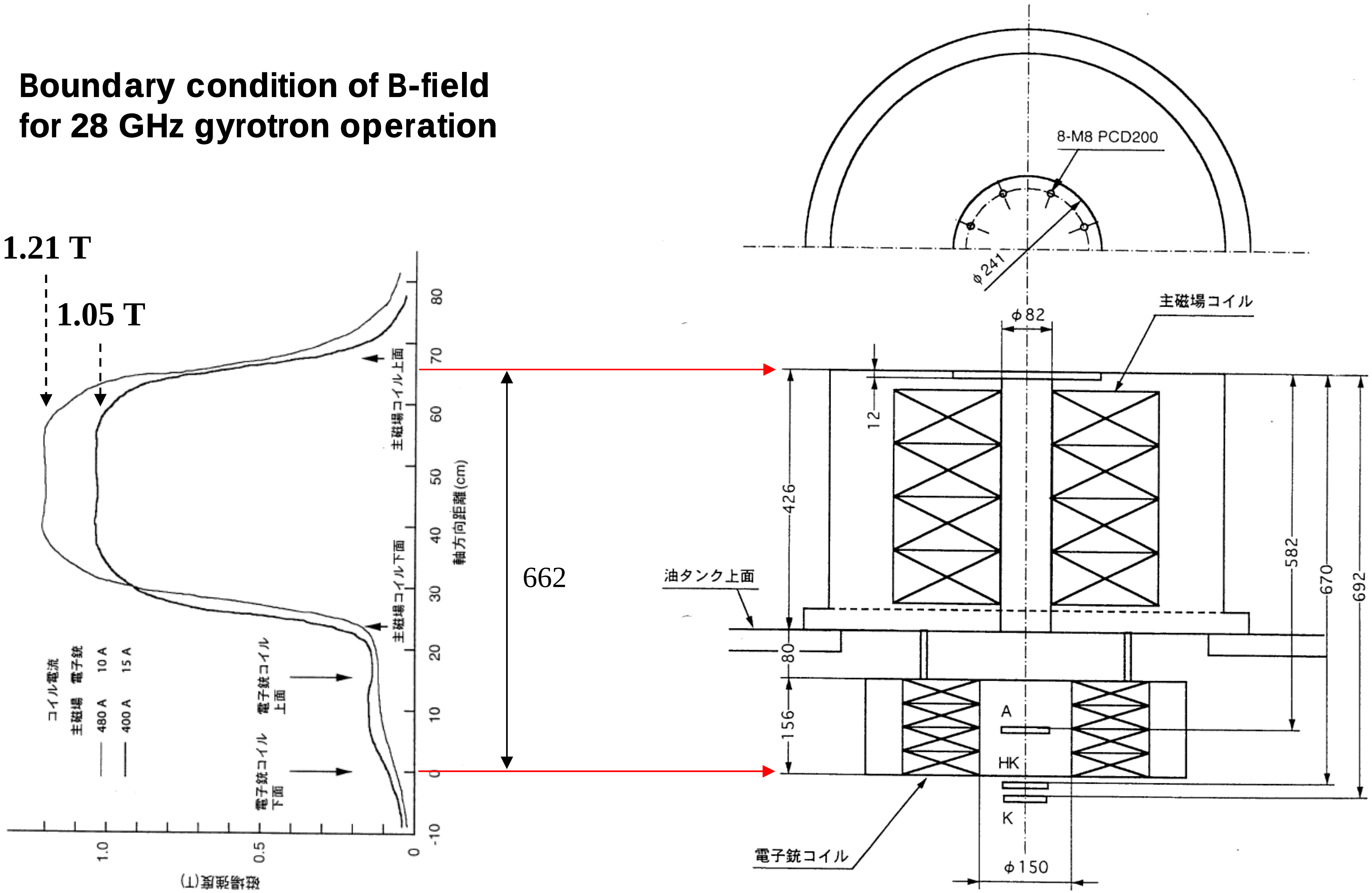


Specification of 28 GHz gyrotron

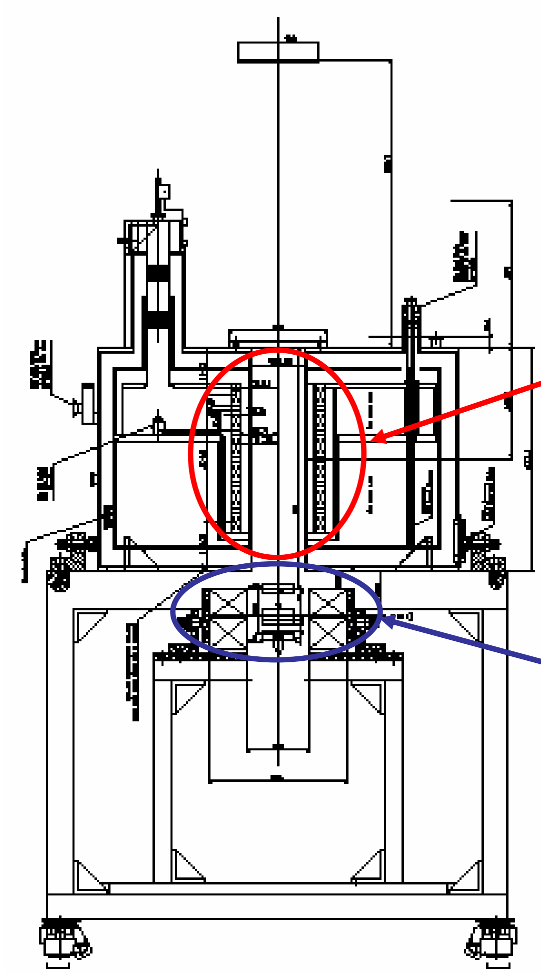
Parameter	Maximum	Nominal data	unit
Beam voltage	90	75	kV
Beam current	9	8	A
Anode voltage	35	28.8	kV
Heater voltage	13	7.8	Vdc
Heater current	9	5.8	Adc
Cavity magnetic flux density	1.35	1.1	T
Cathode magnetic flux density	0.17	0.11	T
Output power(TE_{02} mode)	211	205	kW
Efficiency		34.2	%
Pulse width	75	1	ms
Duty factor	0.005	0.002	

Tsukuba magnet system

Boundary condition of B-field for 28 GHz gyrotron operation

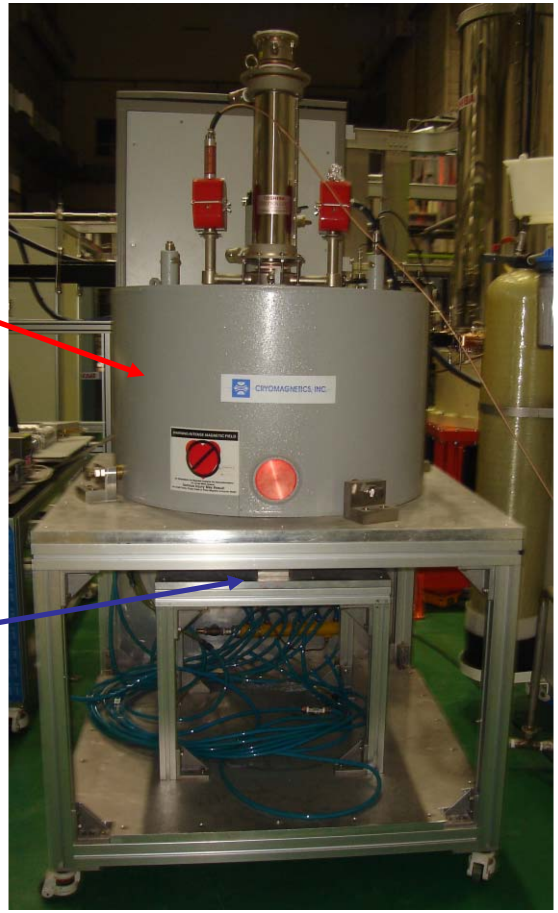


NFRI magnet system

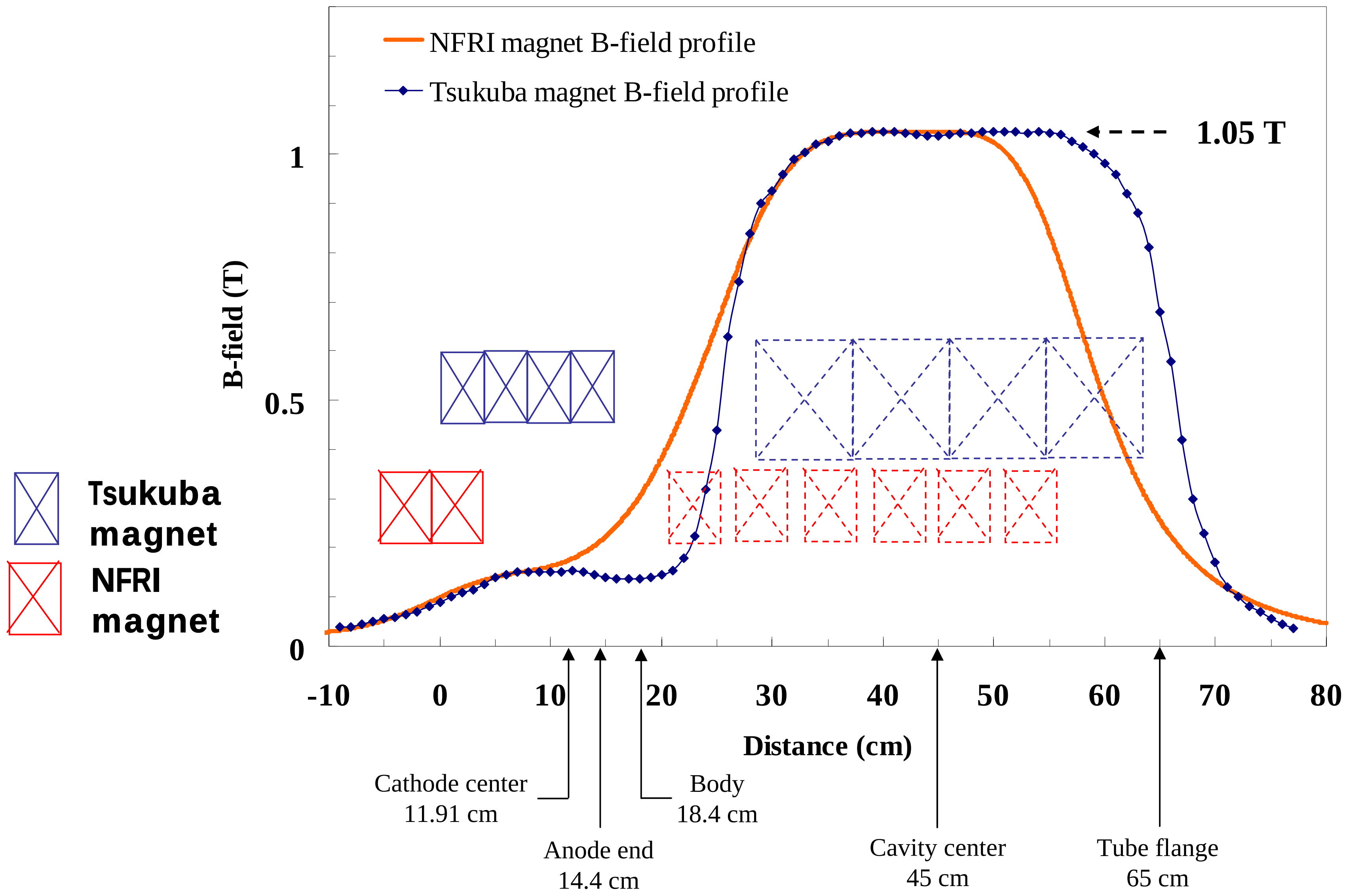


Main coil:
Superconducting
magnets

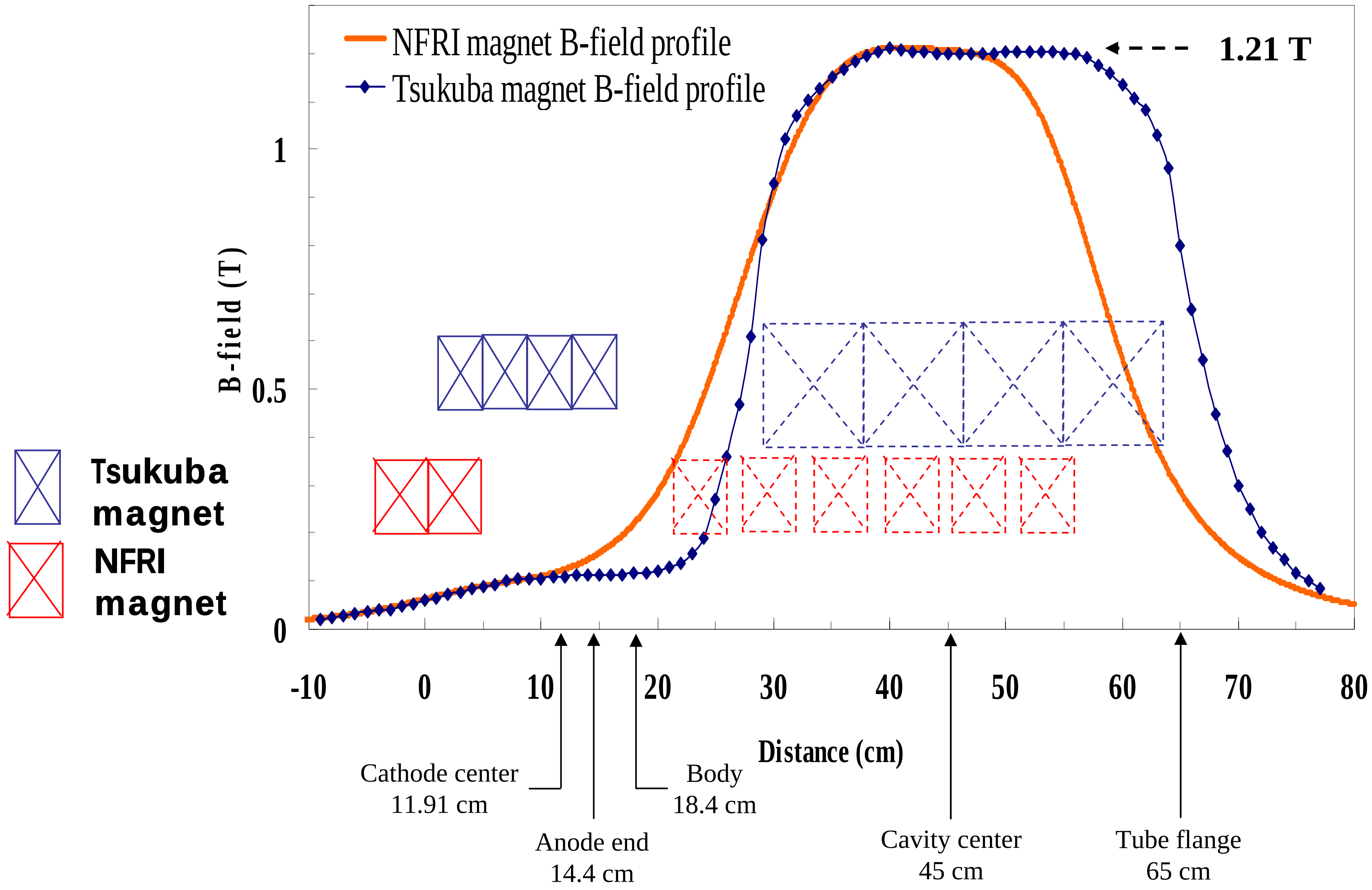
Gun coil:
Normal
conducting
magnets



Comparison of B-field profile at 1.05 T



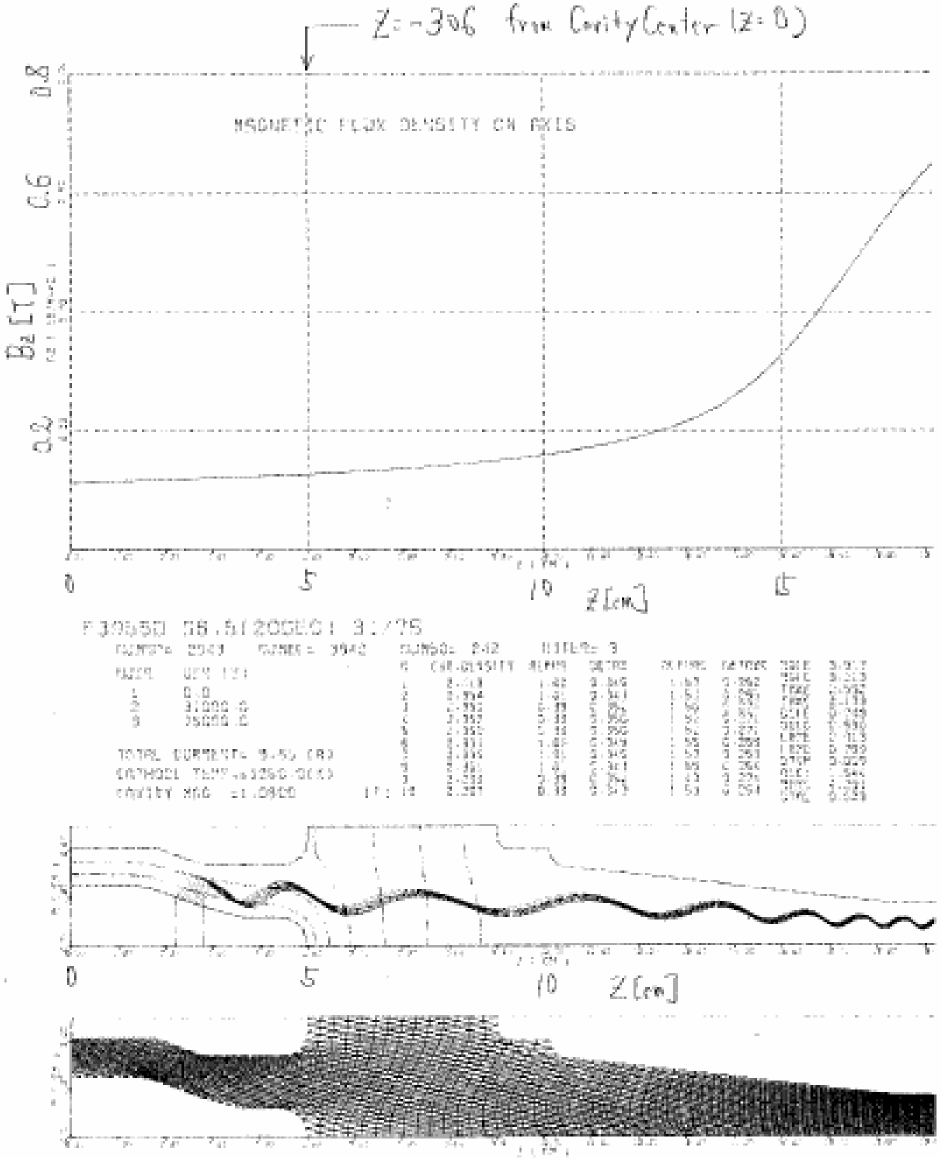
Comparison of B-field profile at 1.21 T



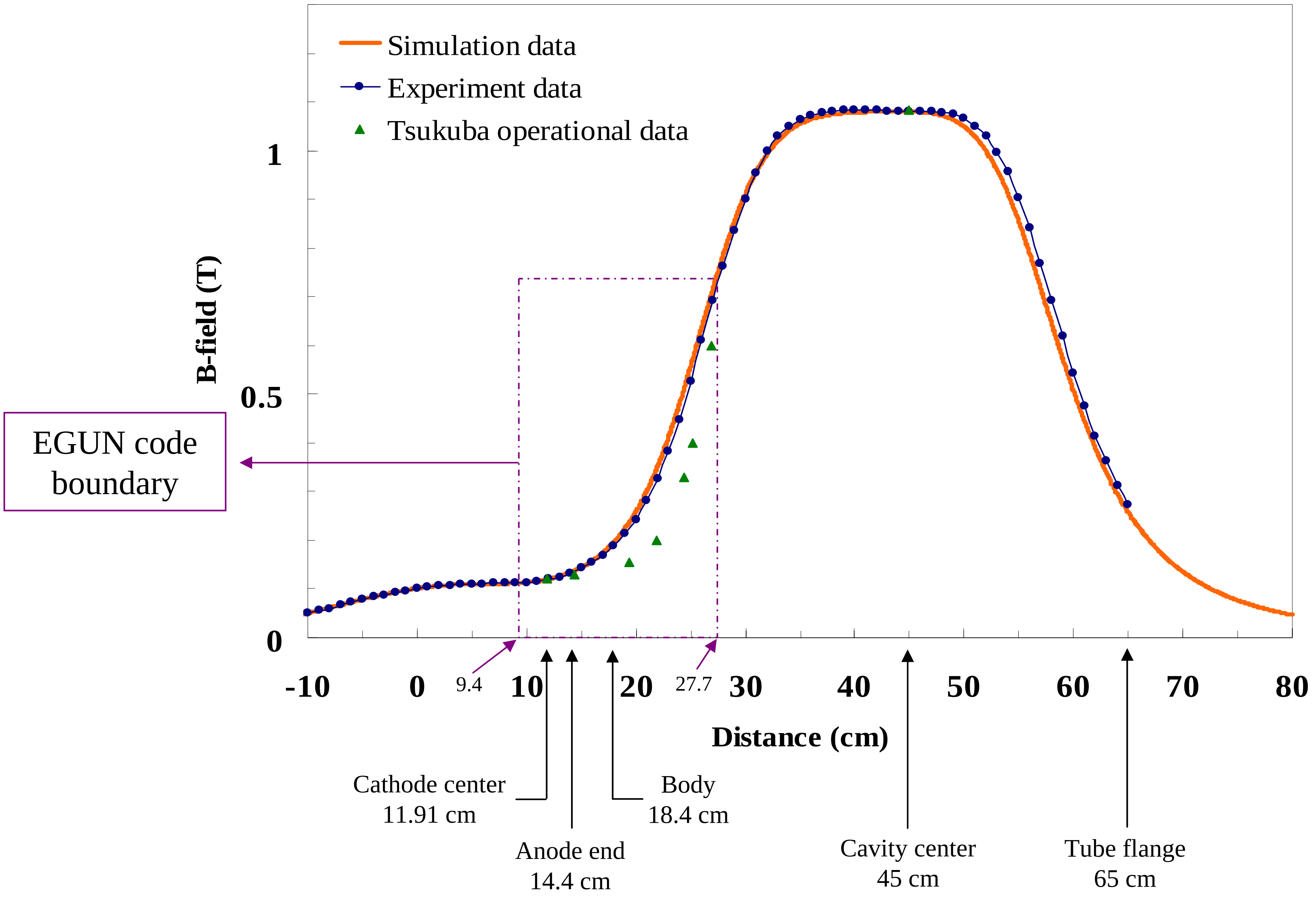
Actual operation data

B-field at cathode center(11.91 cm) = 0.12 T

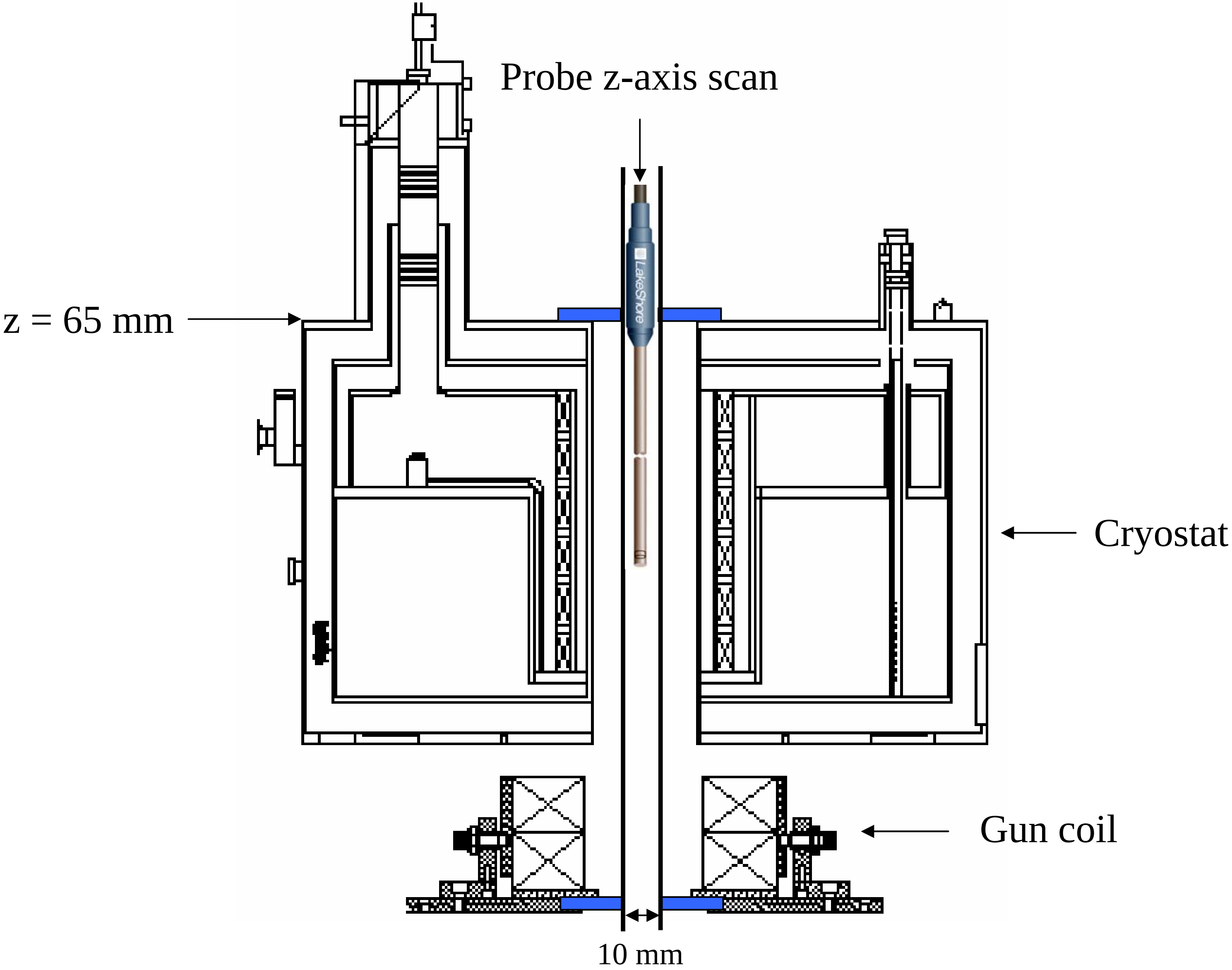
B-field at cavity center(45 cm) = 1.08 T



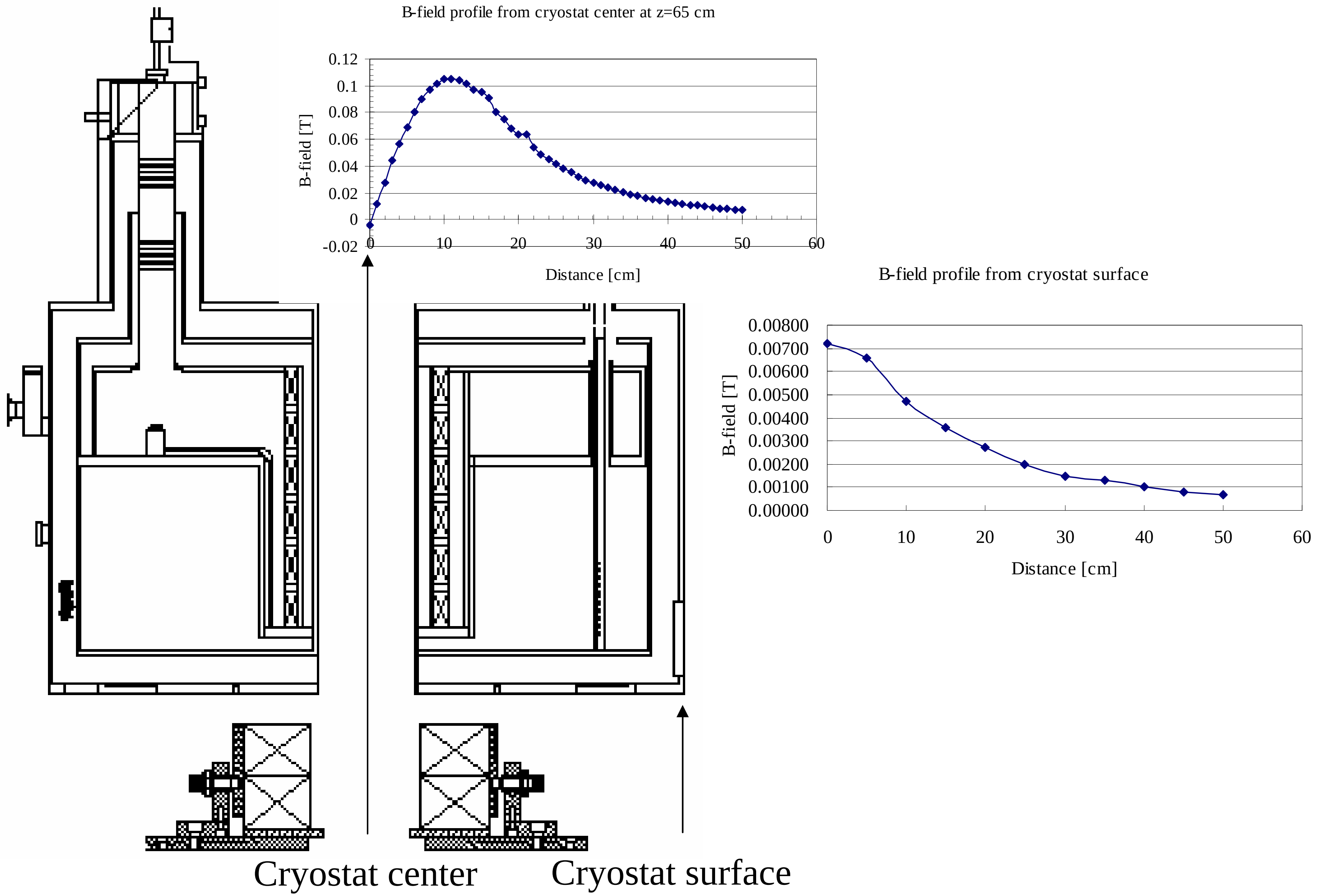
NFRI magnet B-field profile for 28 GHz gyrotron



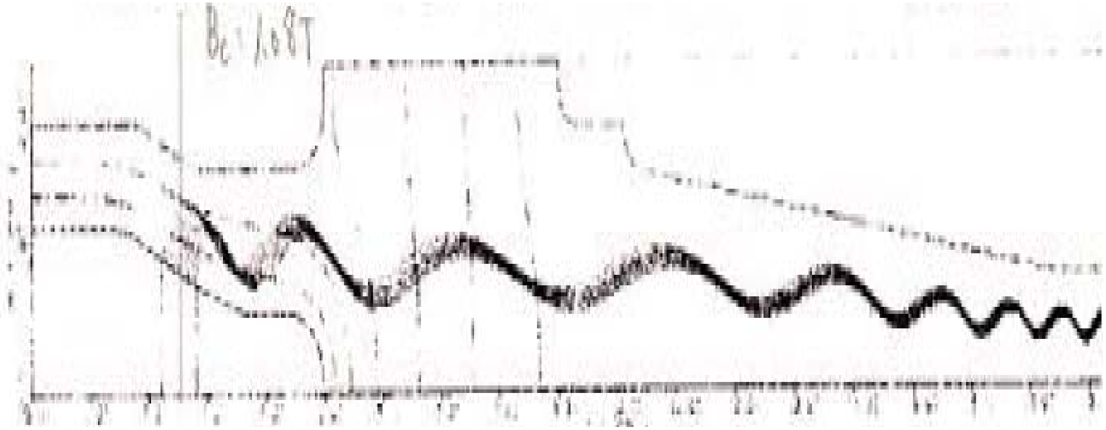
Set-up for B-field measurement



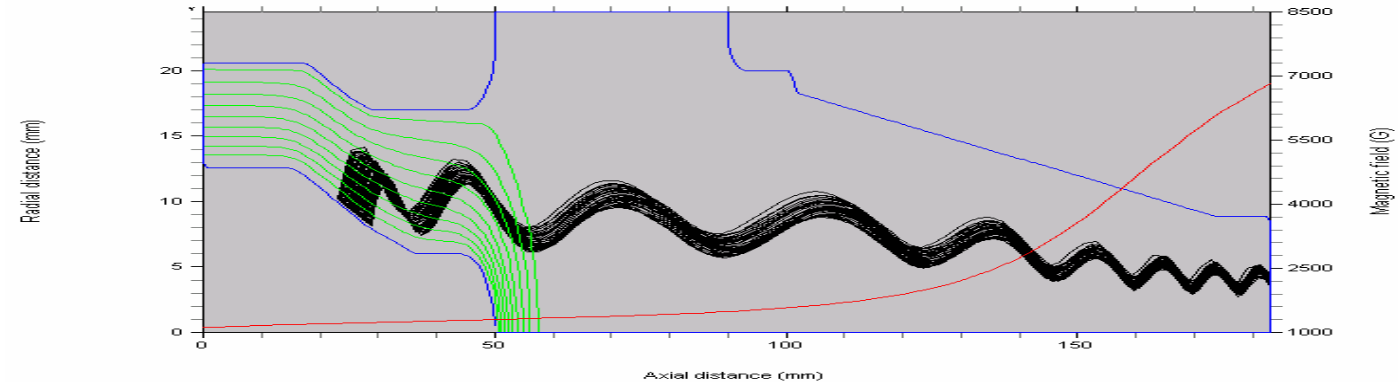
B_r field measurement



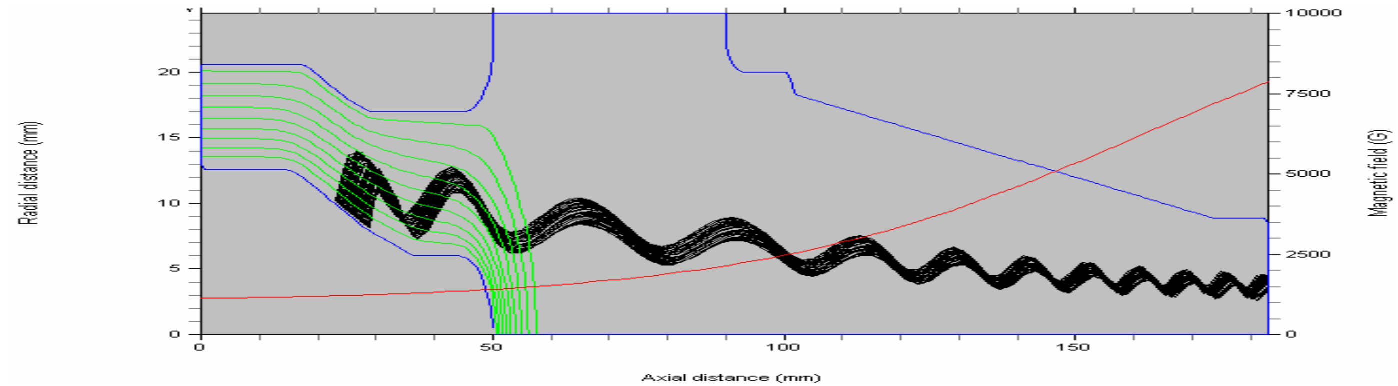
Comparison of E-beam trajectories by EGUN code



Under Tsukuba magnet B-field profile



Under Revival Tsukuba magnet B-field profile



Under NFRI magnet B-field profile

Beam data comparison

	Tsukuba data	NFRI simulation data	unit
Emittance	497	2610	pi-mm-mrad
Normalized emittance	278	1460	pi-mm-mrad
$\langle \gamma \rangle$	1.1459	1.1459	
Energy	74.5454	74.5391	keV
Gamma difference	0.02	0.03	%
Voltage difference	0.17	0.27	%
$\langle r \rangle$	3.957	4.145	mm
$\langle \beta_z \rangle$	0.3799	0.4012	
$\langle \beta_t \rangle$	0.3066	0.2776	
$\langle \beta_t \rangle / \langle \beta_z \rangle$	0.8070	0.6919	
Average pitch factor, $\langle \beta_t / \beta_z \rangle$	0.8073	0.6936	

Operation cavity mode and beam radius

28 GHz corresponds to a wavelength of 10.71mm.

For operation in the $TE_{n,m}$ mode, the cavity radius is related to λ by $R_0 = x'_{n,m}\lambda / 2\pi$

where $x'_{n,m}$ is the mth root of $J'_n(x)$.

Cavity radius : $R_0 = 11.96\,mm$ (TE_{02} mode, 28 GHz)

For operation at the first harmonic the optimum beam radius is given by

Beam radius : $R_e = x_{n\pm1,i} R_o / x_{n,m}\ (i = 1\, or\ 2)$

In general, the corotating mode (with the lower sign) is chosen, since this provides better coupling of the beam to the RF field.

Beam radius : $R_e = \dfrac{1.8412}{7.0156} \times 11.96\,mm \cong 3.14\,mm$

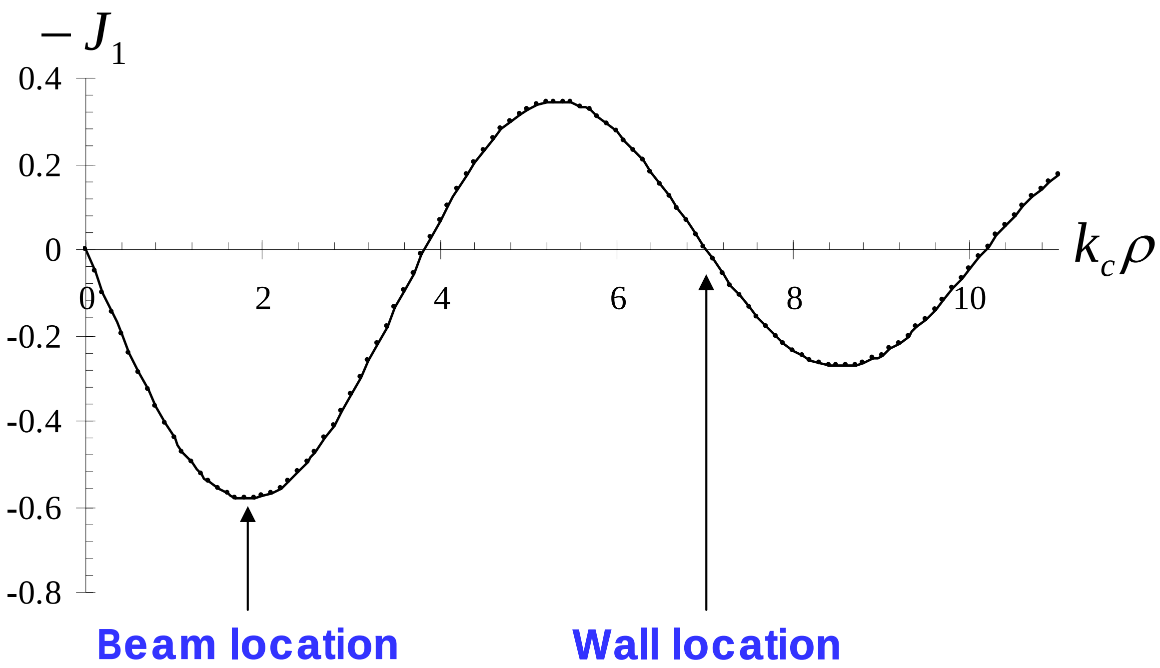
Operation cavity mode and beam radius

TE_{02} mode in circular waveguide

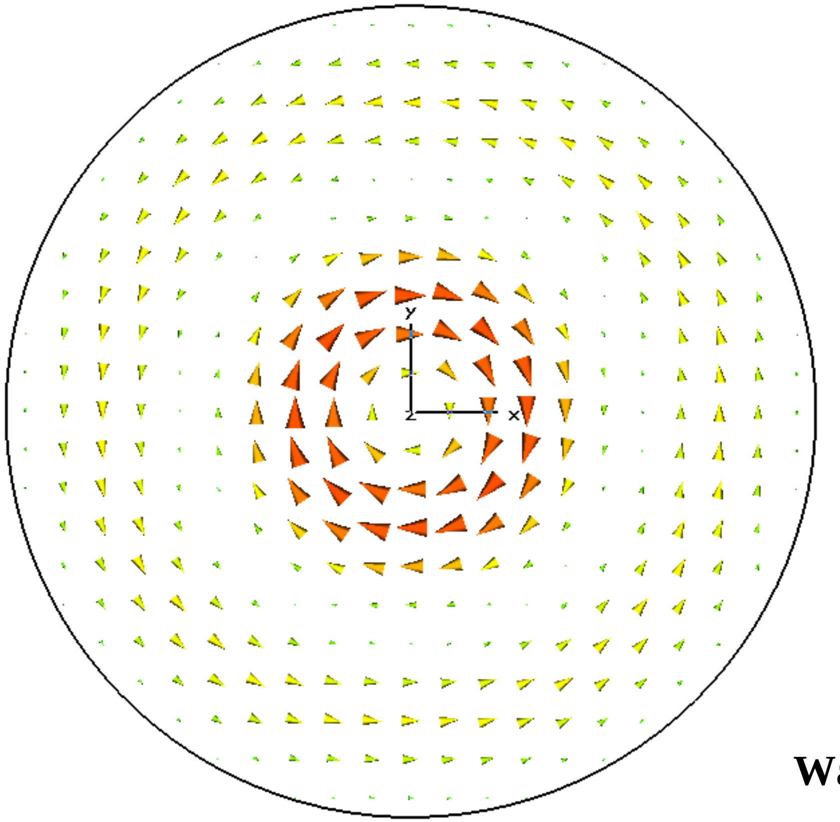
$e^{-jk_z z}$ propagation bas been assumed. ($\because k_c^2 = k^2 - k_z^2$)

$E_\rho(\rho, \phi, z) = 0$

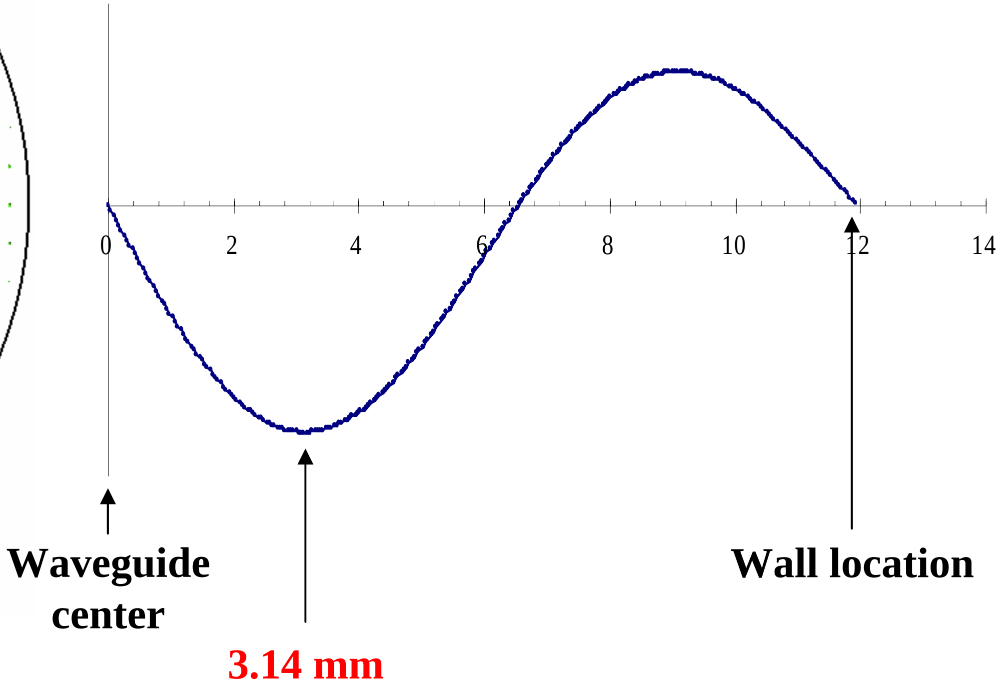
$E_\phi(\rho, \phi, z) \sim J_0^{'}(k_c \rho) = -J_1(k_c \rho)$



Operation cavity mode and beam radius

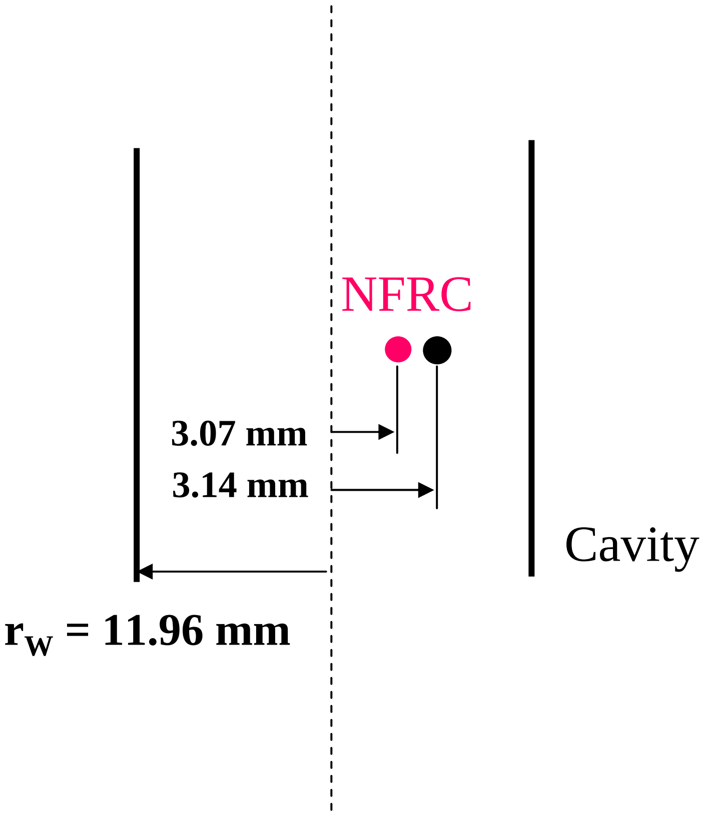


TE$_{02}$ mode result by MWS



x-axis versus E-field (arb. amplitude)

Calculation of beam radius by mirror ratio



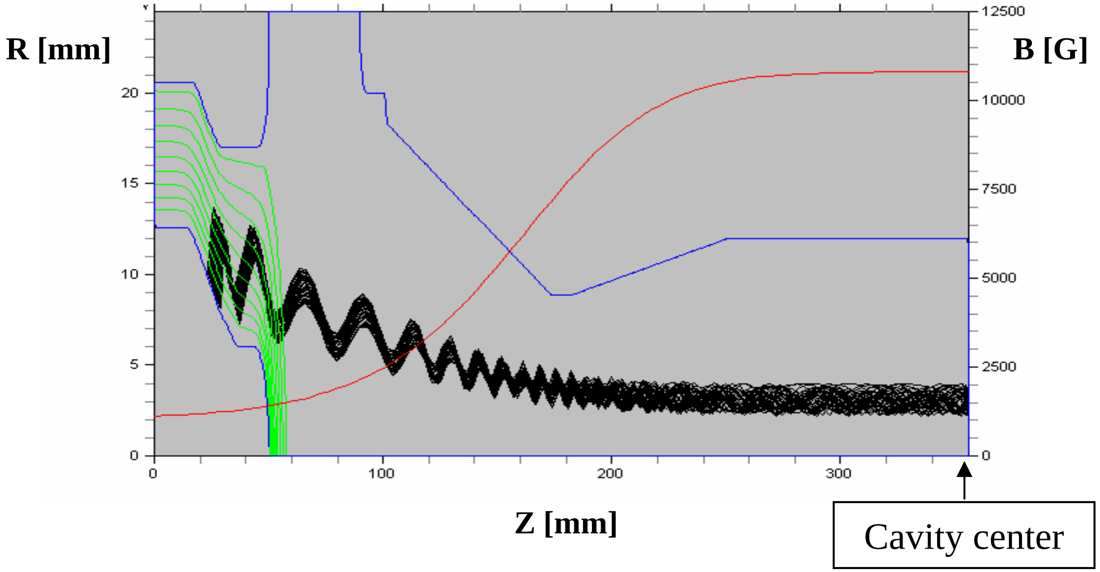
Conservation of Magnetic Moment
$\mu = 1/2mv^2/B$ = const.
$\rightarrow B_G r_G^2 = B_C r_C^2$

Where, B_G and B_C are the B-fields at cathode center and cavity center, respectively, and r_G and r_C are the beam radii at the cathode center and cavity center, respectively.

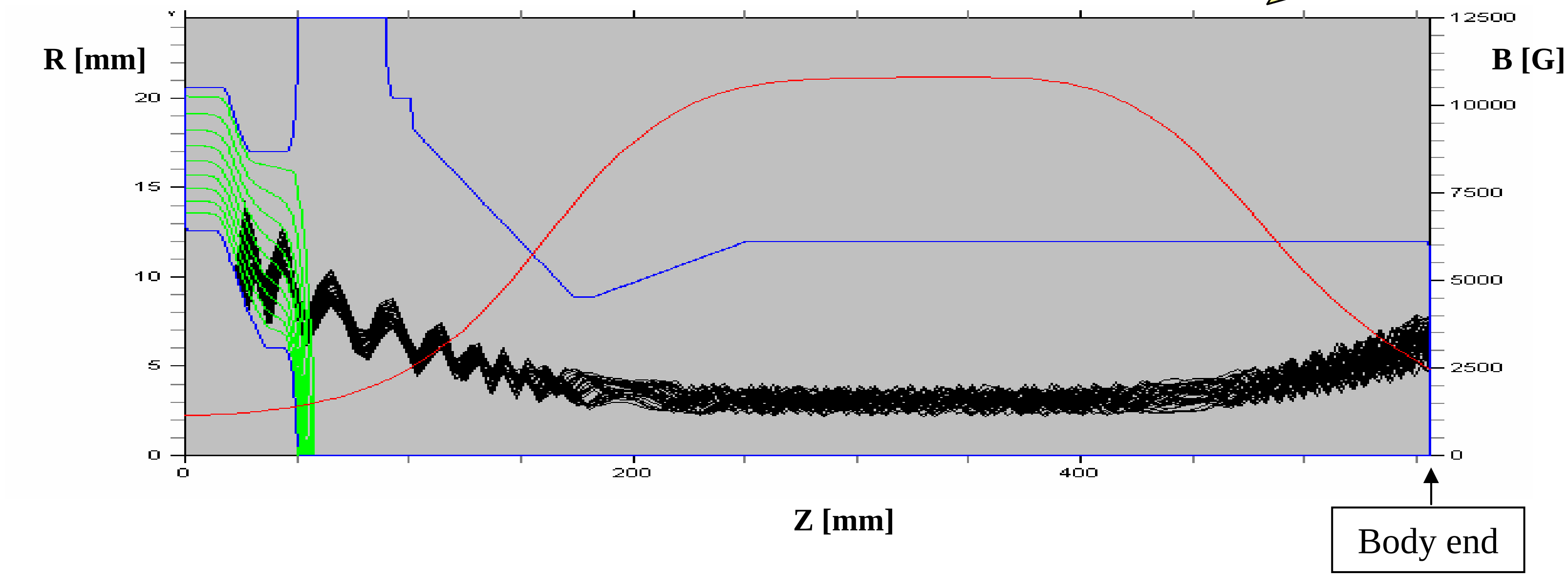
For r_G = 9.21 mm,
Mirror ratio, $R = B_C/B_G = r_G^2/r_C^2 = 9.21^2/3.14^2 = 8.6$

For NFRC B-field profile,
$R = 1.08/0.12 = 9$
$r_C = (9.21^2/9)^{1/2} = 3.07$ mm

E-beam trajectories under NFRI magnet B-field



E-beam does not collide with gyrotron body.

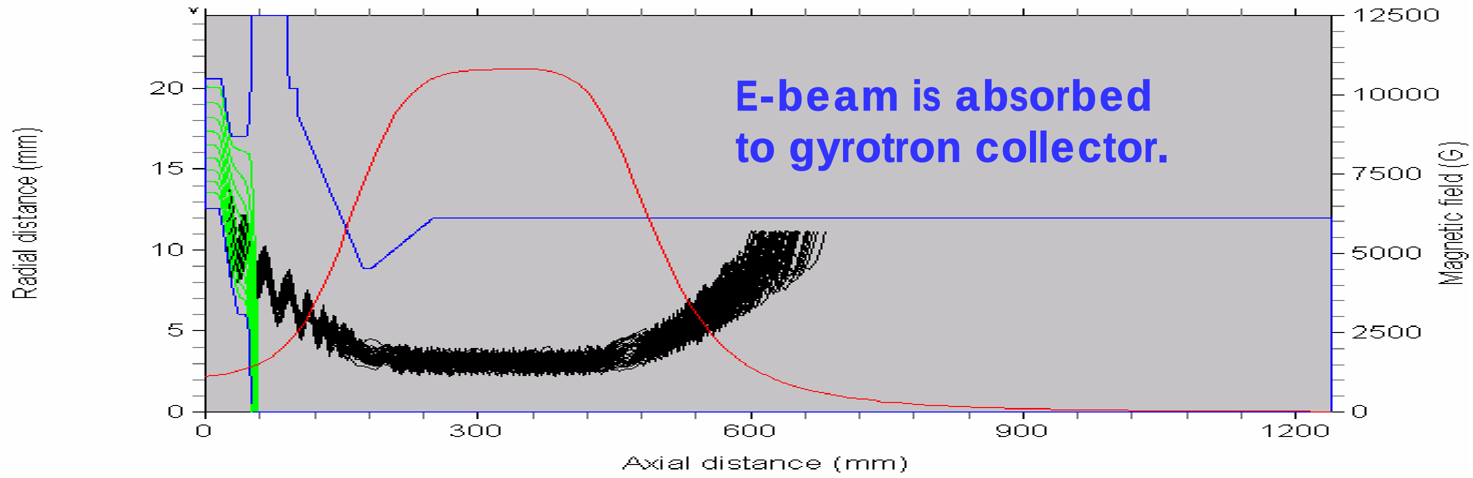


Beam data under NFRI magnet B-field

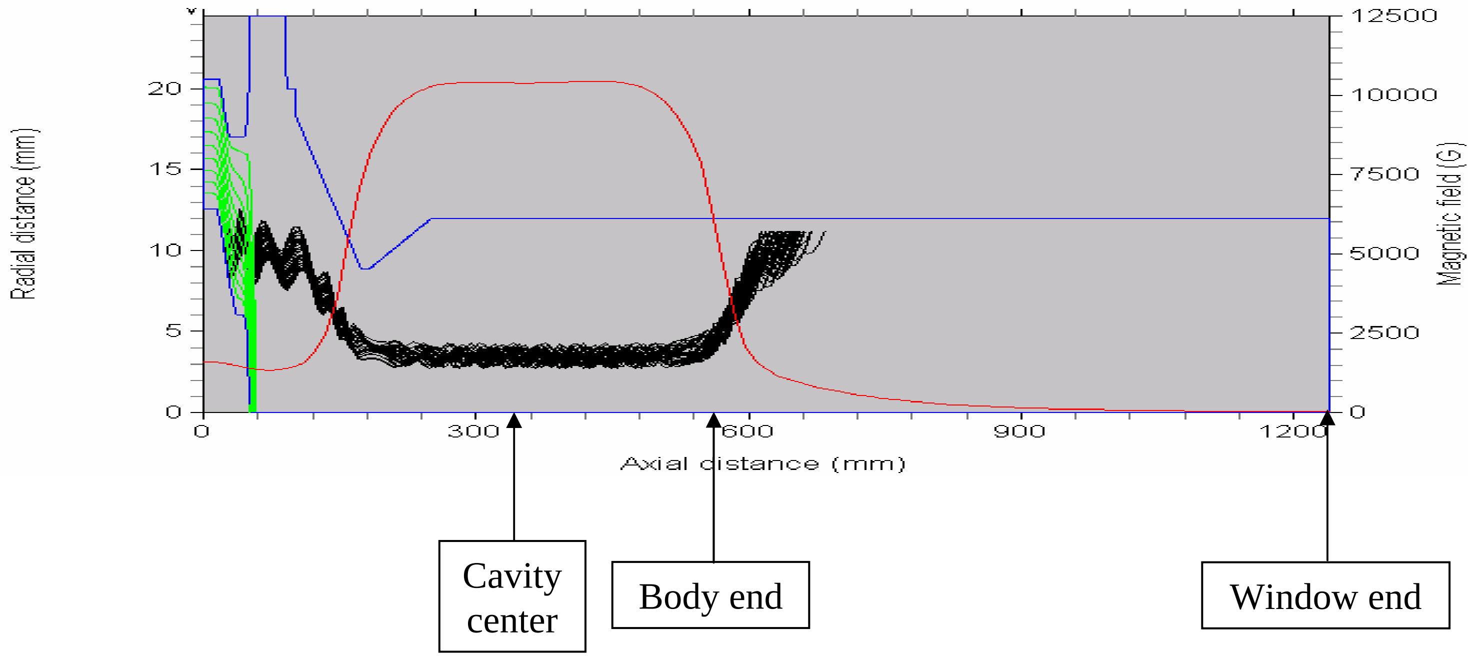
	Cavity center	Body end	unit
Emittance	3550	2810	pi-mm-mrad
Normalized emittance	1980	1580	pi-mm-mrad
$<\gamma>$	1.1450	1.1462	
Energy	74.0878	74.6981	keV
Gamma difference	0.07	0.07	%
Voltage difference	0.52	0.54	%
$<r>$	3.096	6.358	mm
$< \beta_z >$	0.3622	0.4641	
$< \beta_t >$	0.3249	0.1520	
$<\beta_t>/<\beta_z>$	0.8971	0.3276	
Average pitch factor, $<\beta_t/\beta_z>$	0.9004	0.3280	

Beam radius r=3.096 mm by E-gun simulation is similar r=3.14 mm calculated by operation theory.

E-beam trajectories under NFRI & Tsukuba B-field

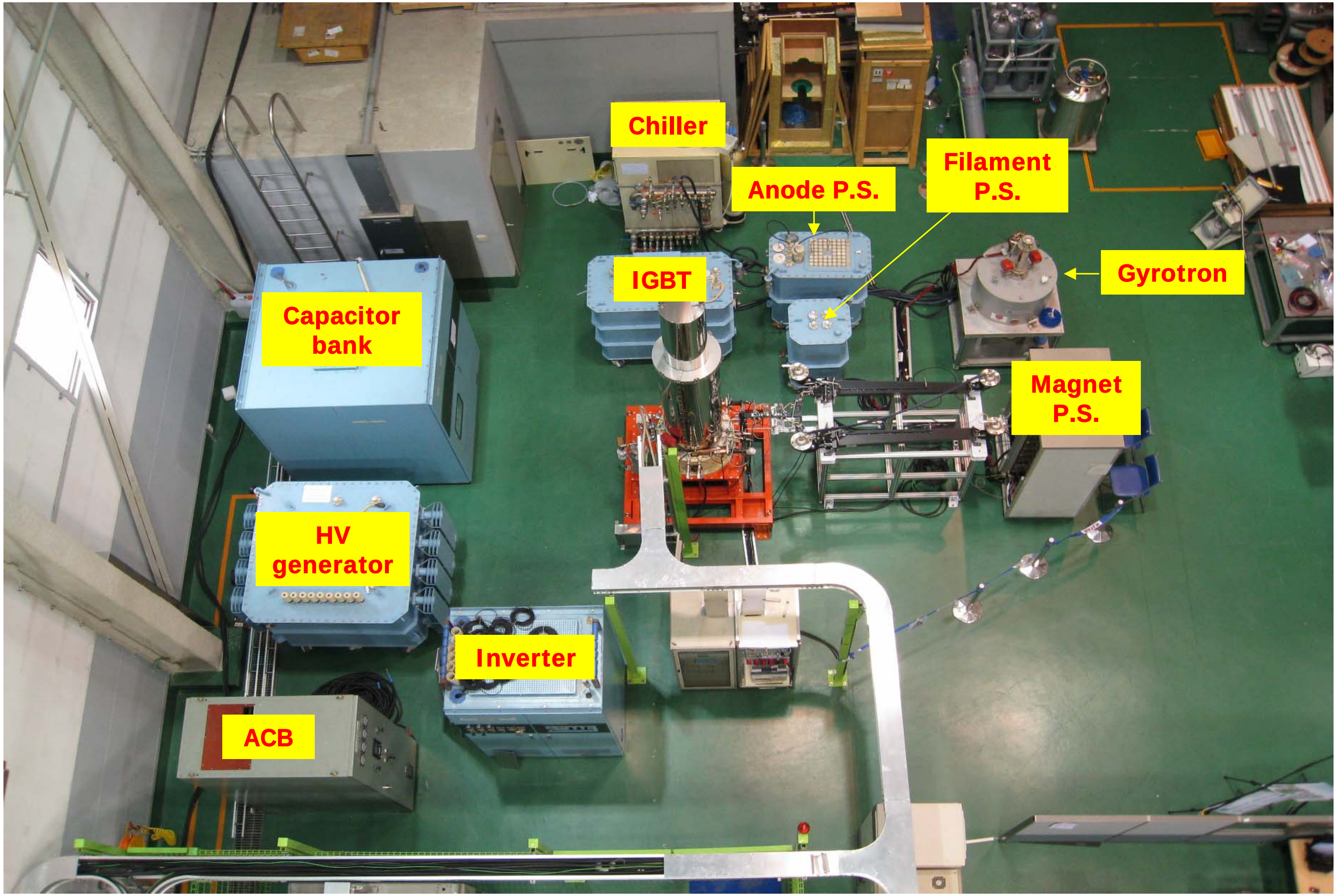


Under NFRI magnet B-field profile

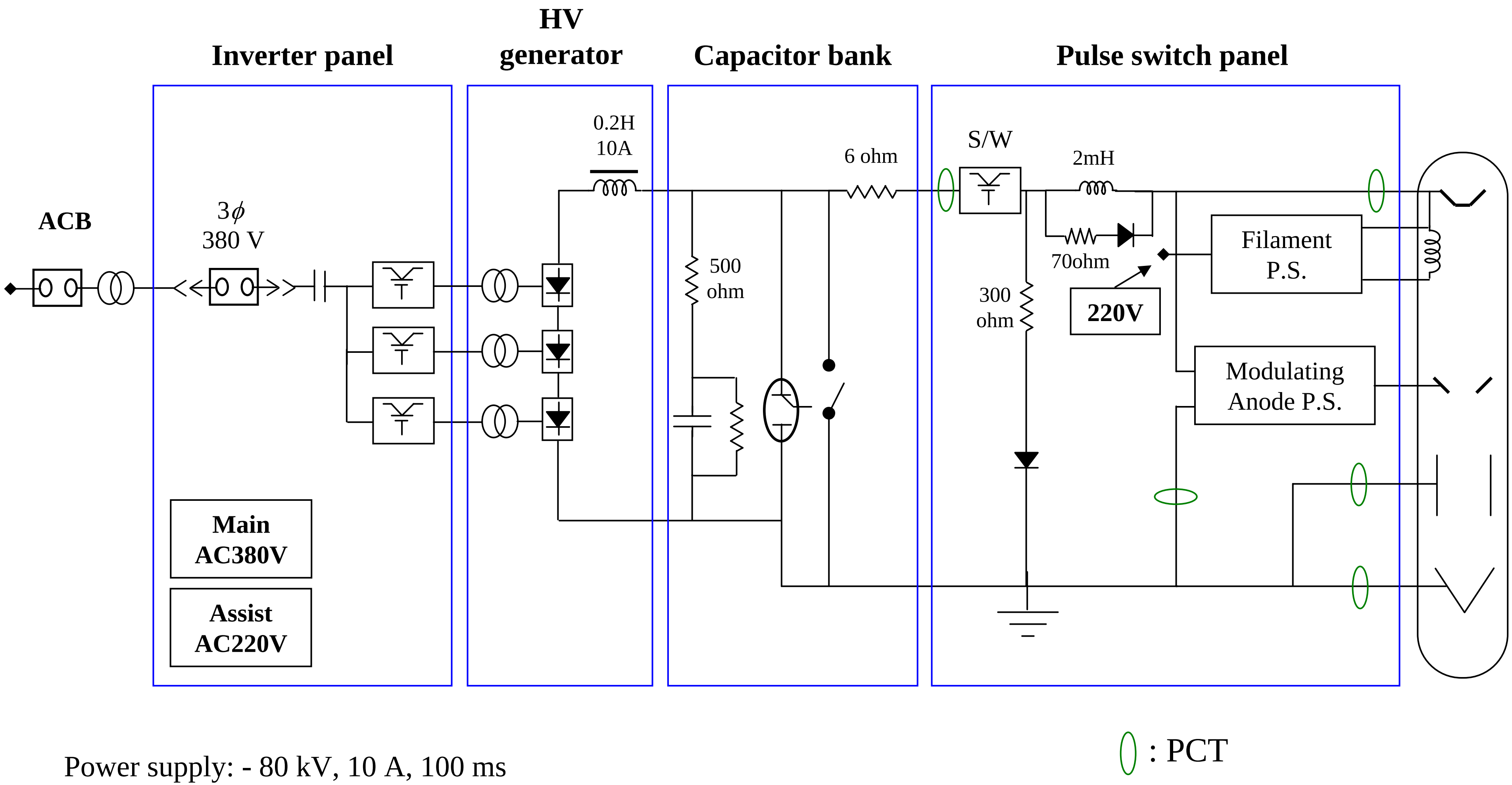


Under Tsukuba magnet B-field profile

Power supply for 28 GHz gyrotron (Repairing)



Schematics of NFRI power supply

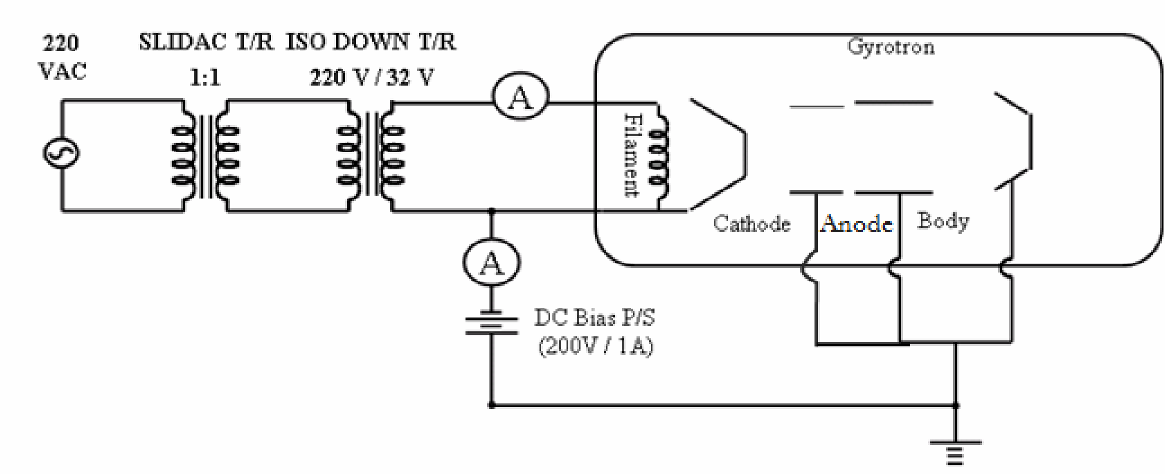


Power supply: - 80 kV, 10 A, 100 ms

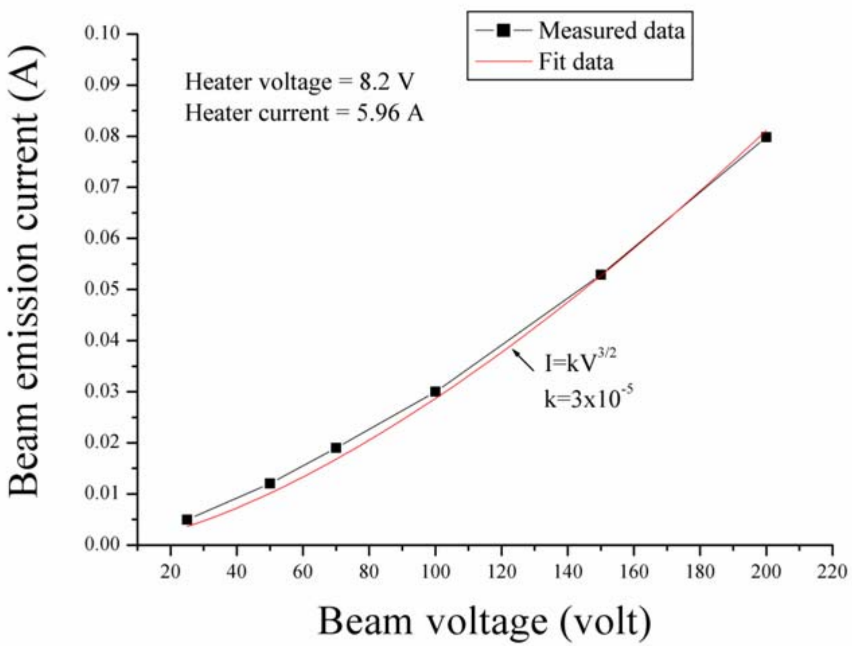
Modulating anode power supply: - 40 kV ~ - 60 kV

Filament power supply: 20 V, 20 A

Gun activation



Schematics of gyrotron gun activation experiment

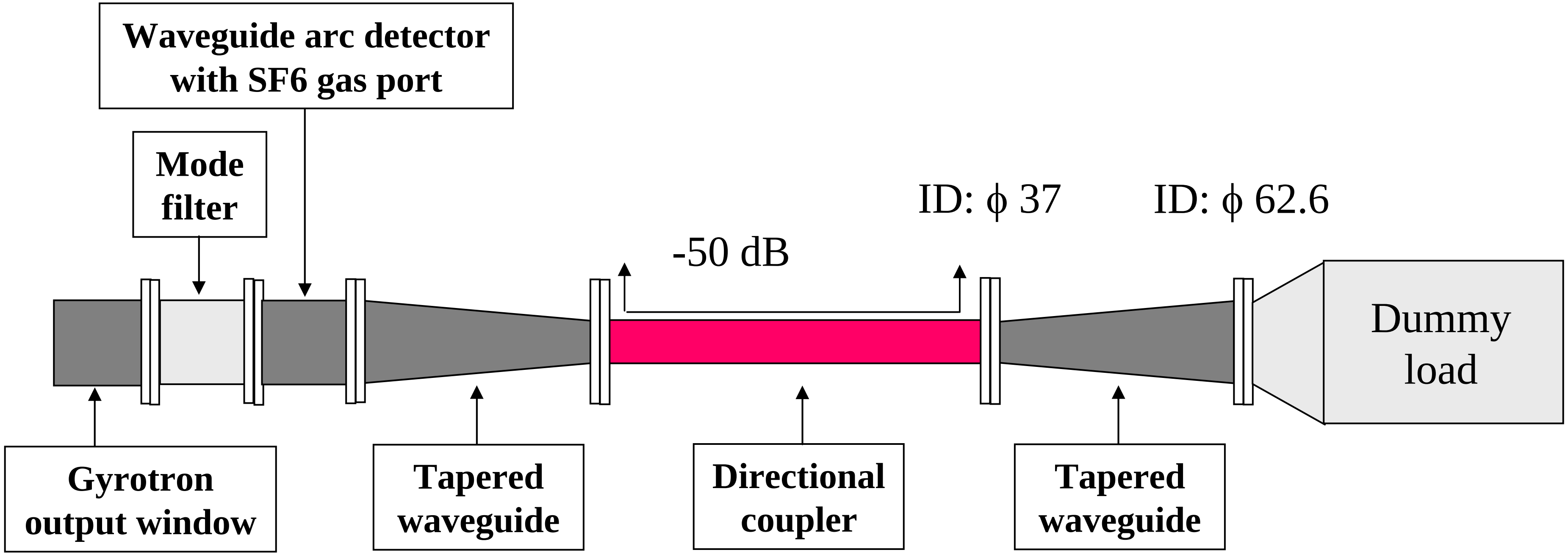


Operation regulation of heater:

8.2 V, 5.96 A

This experiment result is fit with $I=kV^{3/2}$.

RF power and frequency measurement



Directional coupler: RF power and frequency measurement using power meter

Dummy load: RF power measurement with calorimetric method

Summary

1. The development of 28 GHz gyrotron system was promoted at National Fusion Research Institute (NFRI).
2. We obtained the required B-field: 1.08 T at cavity center and 0.12 T at cathode center using NFRI magnet system.
3. By E-gun simulation, the e-beam trajectory shows the possibility to operate 28 GHz gyrotron under NFRI magnet B-field profile.
4. These results are also fit to 28 GHz, TE_{02} mode gyrotron operational theory.
5. We are now preparing power supply, RF waveguide components and gun socket for high voltage wiring.
6. 28 GHz gyrotron will be capable to generate the RF beam with 150 kW, 50 ms at NFRI system.