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Design and Optimization of a Diode–Type Magnetron Injection Gun for a Triple-Frequency Gyrotron

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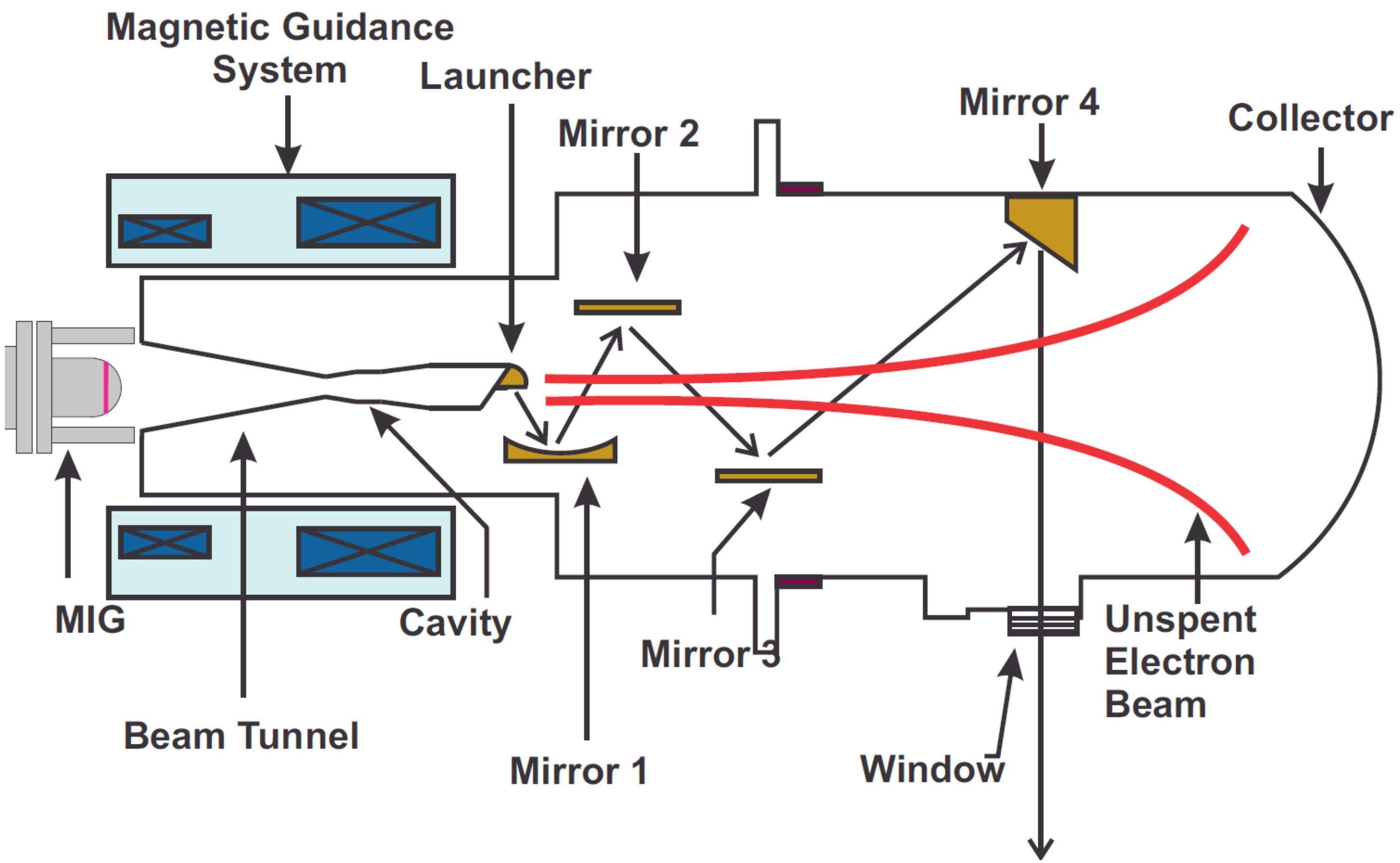
CONTENTS

Gyrotron schematic



Need for a Multi-frequency Gyrotron

At a given Thermonuclear fusion facility, **several** Gyrotrons are used in various operations such as plasma startup, heating, current drive, instability suppression etc., all operating at different frequencies

As these operations are not simultaneous, a **single** Multi-Frequency Gyrotron can be used

A single Multi-Frequency Gyrotron is capable of operating at any of the several (designed) frequencies **without** any change in the physical parameters

Frequency switching is accomplished by external electrical parameters, such as **voltages and currents**

Triple Frequency Gyrotron – Choice of Frequencies

Single frequency Gyrotron designs exist for 42 GHZ, 84 GHz and 95 GHz

Dual frequency Gyrotron designs exist for 42/84 GHz

Triple frequency Gyrotron design for 42/84/95 GHz with output power range of 100 kW – 200 kW is a novel extension

Design Goals and Specifications

Parameter	Value
Frequency	42/84/95 GHz
Output power	200 – 500 kW
Beam Energy	60 – 70 kV
Beam Current	10 A
Magnetic field at interaction	1.6/3.2/3.62 T
Velocity ratio (α)	1.3 – 1.4
Total output efficiency	45 %

Selection of a Operating Mode-Triplet

Criterion:

Electron gun parameters depend on the parameters of cavity, which in-turn depend on the parameters of the output system

For the common mode converter and launcher, for the $TE_{m,p}$ mode of operation, the ratio

$$m/\chi_{m,p}$$

should be approximately same for all the desired modes (frequencies),

where

m - azimuthal index

p - radial index

$\chi_{m,p}$- p^{th} *zero of the* m^{th} *order derivative Bessel function,* $J'_m(x)$

Frequency (GHz)	Mode (m,p)	Eigenvalue ($\chi_{m,p}$)	Cavity radius (mm)	$m/\chi_{m,p}$	$\Delta\phi = 2\arccos(m/\chi_{m,p})$ (deg)
42	6, 2	11.73	13.34	0.51	118.67
84	10, 4	23.76	13.34	0.42	130.33
95	12, 4	26.24	13.34	0.46	125.23

Cavity parameters needed for Gun design

The beam radius, R_b, the average *radial position* of guiding centre for the gyrating electron

$$R_b = \chi_{m\pm1,1}\ \lambda/2\pi$$

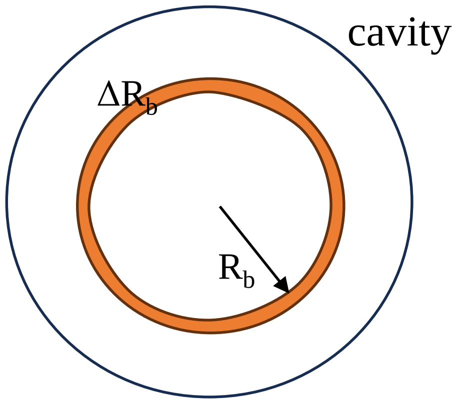
The Larmour radius, $r_{L0,}$ of the electron orbit around the guiding centre

$$r_{L0} = v_{\perp 0}/\omega_{c0}$$

The (maximum) thickness of the beam, ΔR_b , which is given as,

$$\Delta R_b \approx \lambda/4 + 2r_{L0}$$

The magnetic field strength, B_0



Cathode Design – Emitter Strip

The average radius (R_c) of the **conical** emitter ring is related to the beam radius (R_b) in the cavity by

$$R_c = \sqrt{b}\, R_b$$

where

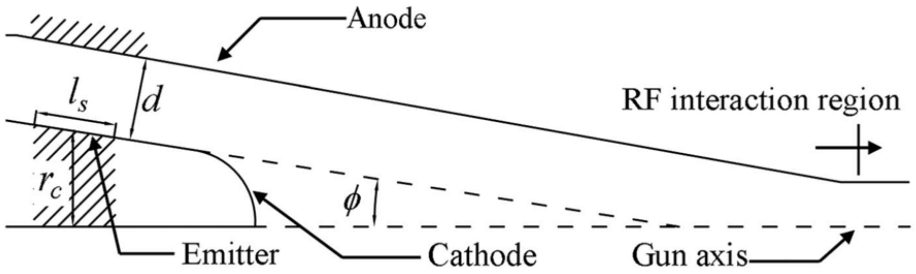
$'b'$ is the magnetic compression factor (B_0 / B_c)

The **axial length** of the emitter is given by

$$(2\pi R_c l_a) * J_c = I_0$$

where

I_0 - specified beam current, (A)
J_c - selected current density (A/cm^2)
l_a - axial length of the emitter, (cm)



The **slant length** of the emitter is given by

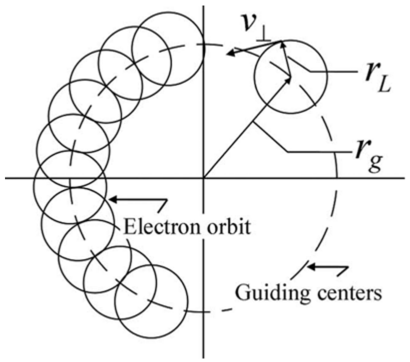
$$\Delta R_c = l_s \sin \emptyset_c = \sqrt{b}\, \Delta R_b$$

where

ΔR_c – height of the emitter strip
ϕ_c – elevation angle of the emitter strip
ΔR_b – Guiding centre radii spread in the cavity

Anode Design

Cathode – Anode distance, $\mathbf{d_{ac}}$

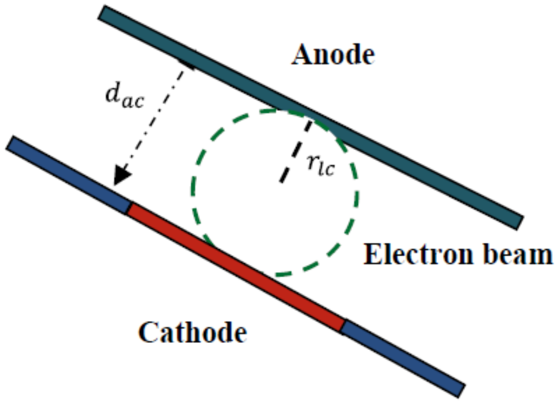


Minimum distance is dictated by **Two** factors

Larmour radius: It should be at least twice the Larmour radius at the cathode, r_{Lc}

$$r_{Lc} = \sqrt{b}\, r_{L0}$$

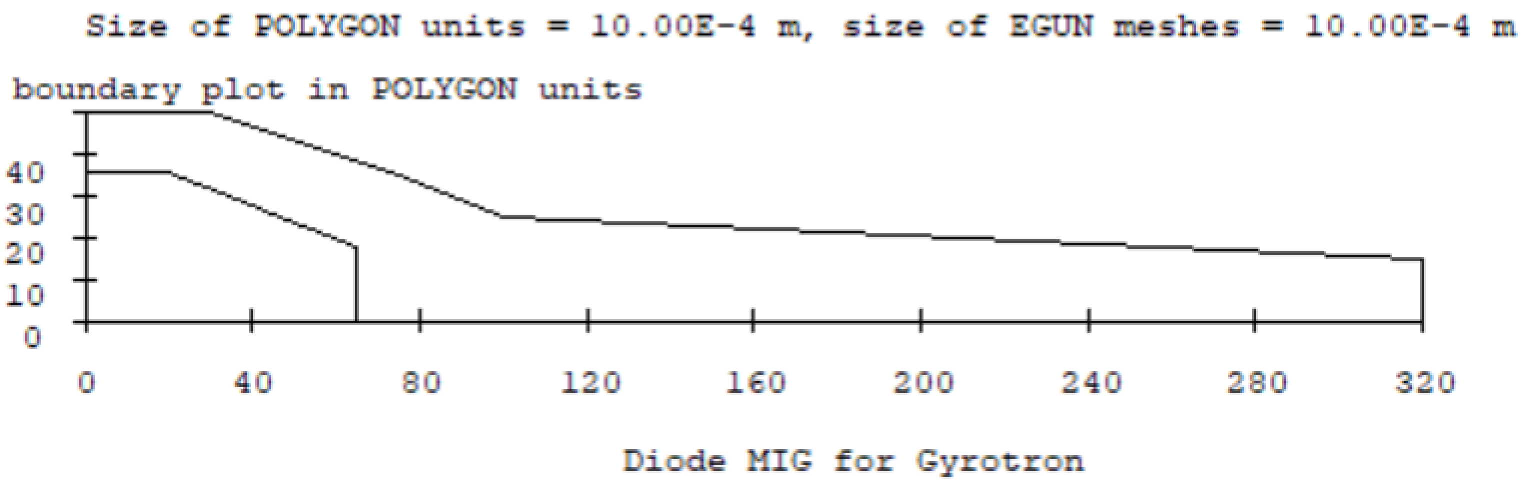
Peak electric field strength: Should not exceed 7 kV/mm



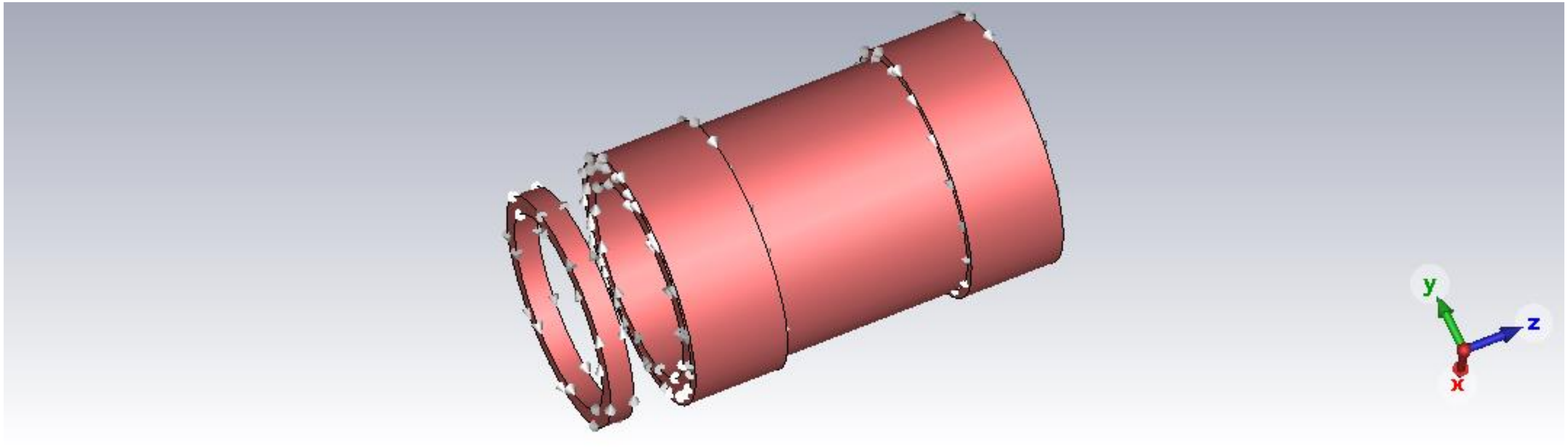
Maximum distance is governed by the size of the tube

MIG - Geometry

Beam radius	7.28 mm
Compression ratio	14
Emitter radius	26.71 mm
Beam current	9 A
Emitter current density	1.1 A/cm^2
Axial length of Emitter	4.9 mm
Slope angle	22.5^o
Slant length of emitter	5.3 mm
Cathode – Anode spacing	10 mm

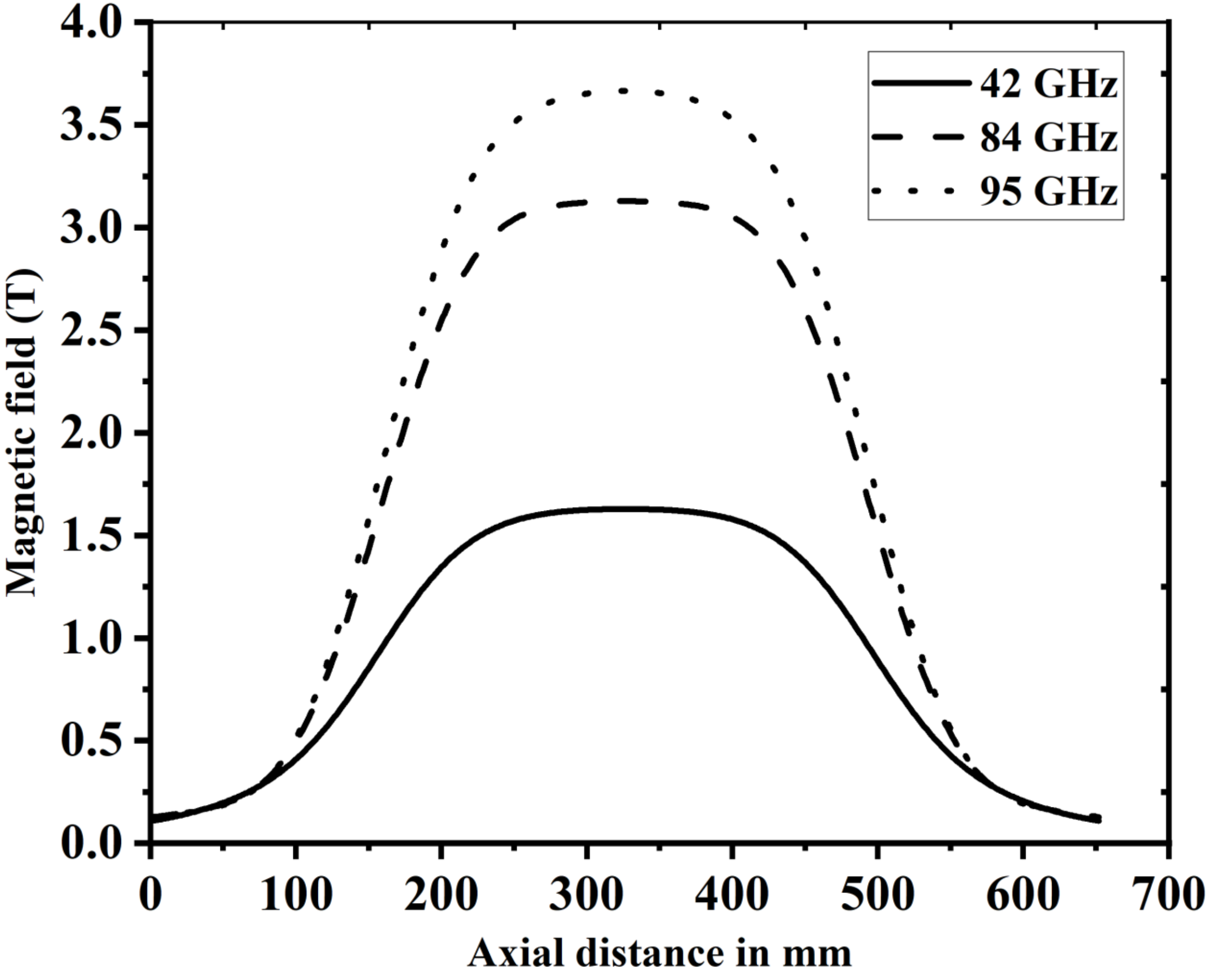


Magnetic field - Coil

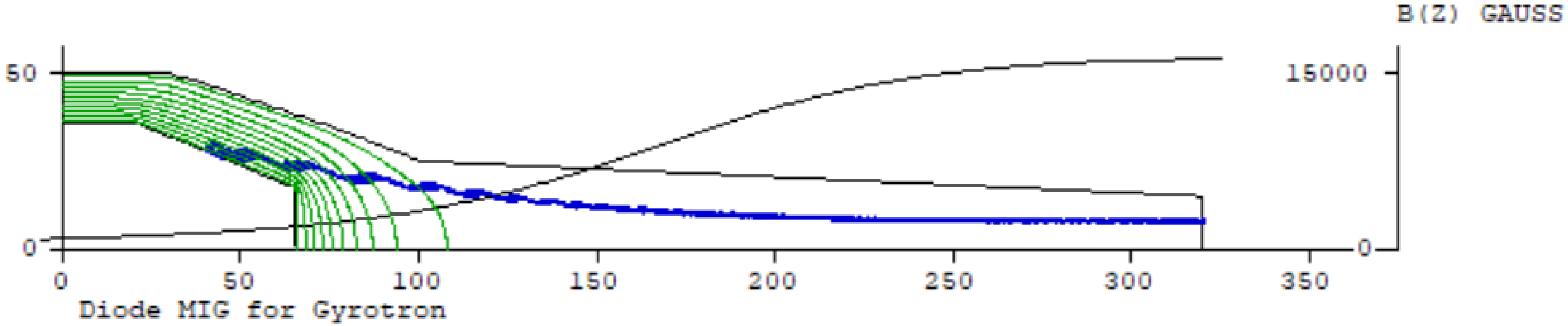


Coil	Axial Position (mm)	Radial Position (mm)	Width (mm)	Height (mm)
Main	320	90	320	15
Aux. Coil-1	200	101.25	80	7.5
Aux. Coil-2	440	101.25	80	7.5
Gun Coil	100	90	20	15

Magnetic field profile



MIG Performance: Simulation at 42 GHz

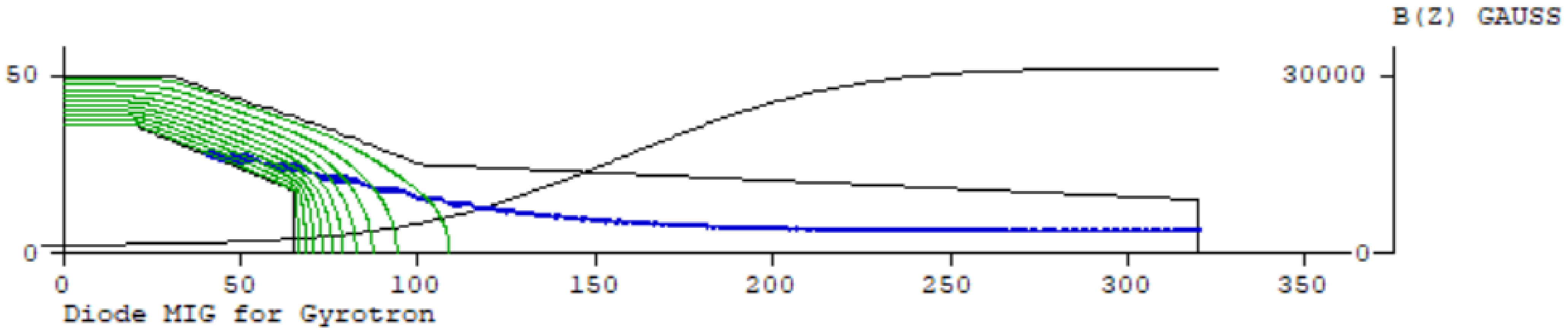


ray	guide cntr	alpha
1	7.712	1.012
2	7.748	1.080
3	7.783	1.150
4	7.818	1.220
5	7.853	1.290
6	7.887	1.376
7	7.921	1.462
8	7.955	1.553
9	7.989	1.635
10	8.022	1.731
11	8.055	1.808

Z	R	W	H	I
320	90	300	15	99
200	101.25	80	7.5	7
440	101.25	80	7.5	7
100	90	20	15	-10

Perpendicular velocity spread	6.5 %
Average alpha	1.39

MIG Performance: Simulation at 84 GHz

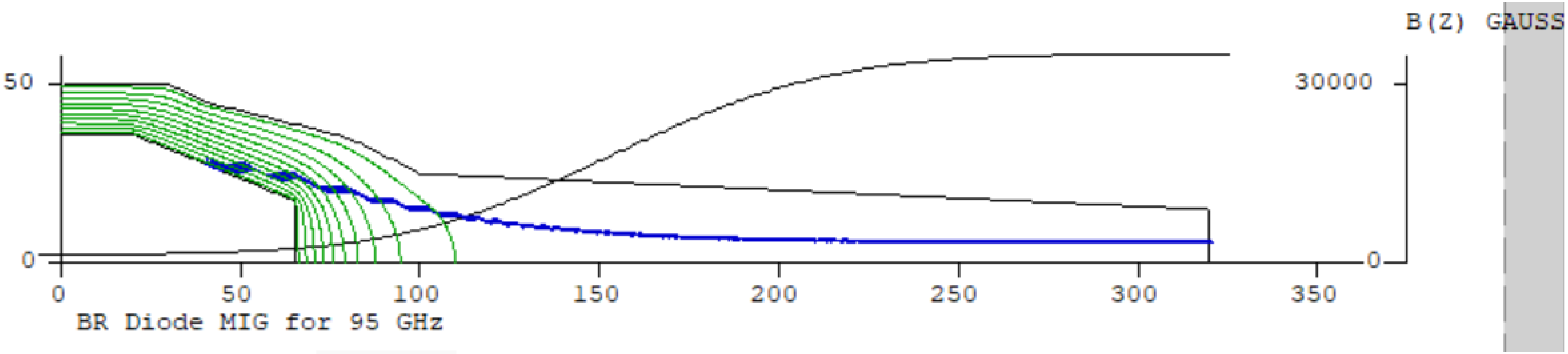


ray	guide center	alpha
1	6.046	1.262
2	6.077	1.281
3	6.109	1.296
4	6.140	1.304
5	6.171	1.331
6	6.202	1.356
7	6.233	1.387
8	6.265	1.418
9	6.296	1.450
10	6.327	1.499
11	6.358	1.536

Z	R	W	H	I
320	90	300	15	175
200	101.25	80	7.5	150
440	101.25	80	7.5	150
100	90	20	15	-153

Perpendicular velocity spread	2.14 %
Average alpha	1.375

MIG Performance: Simulation at 95 GHz

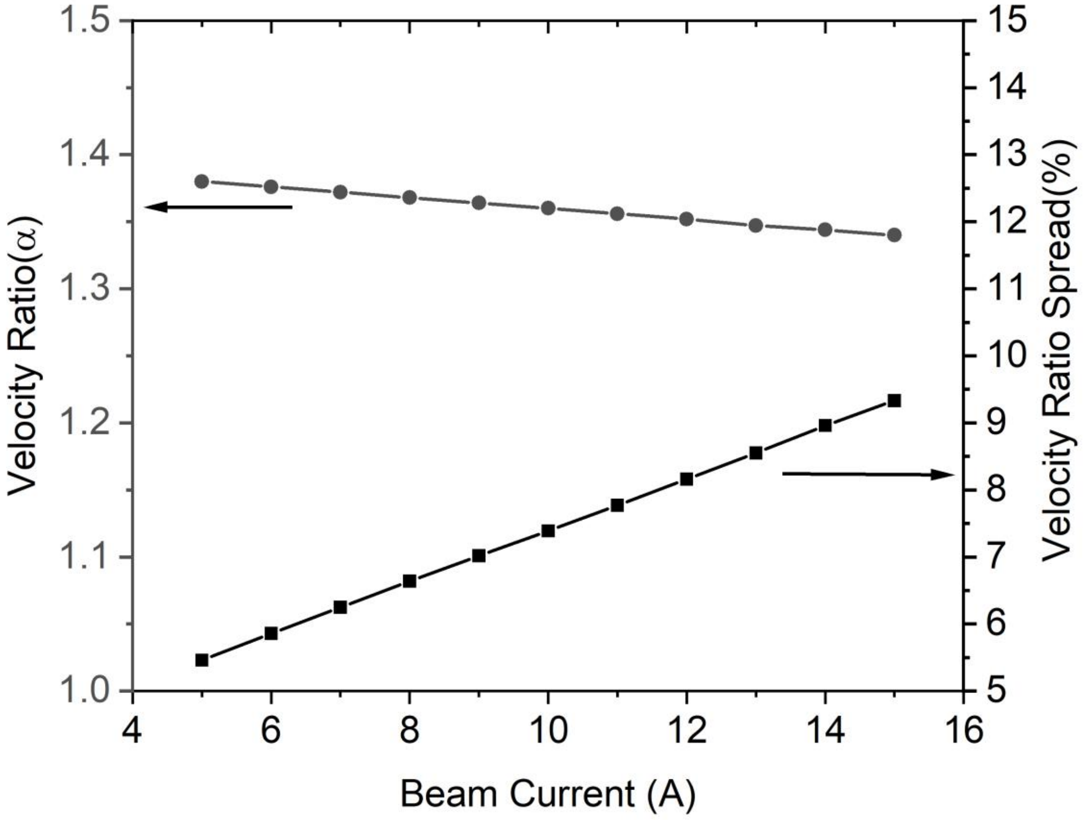


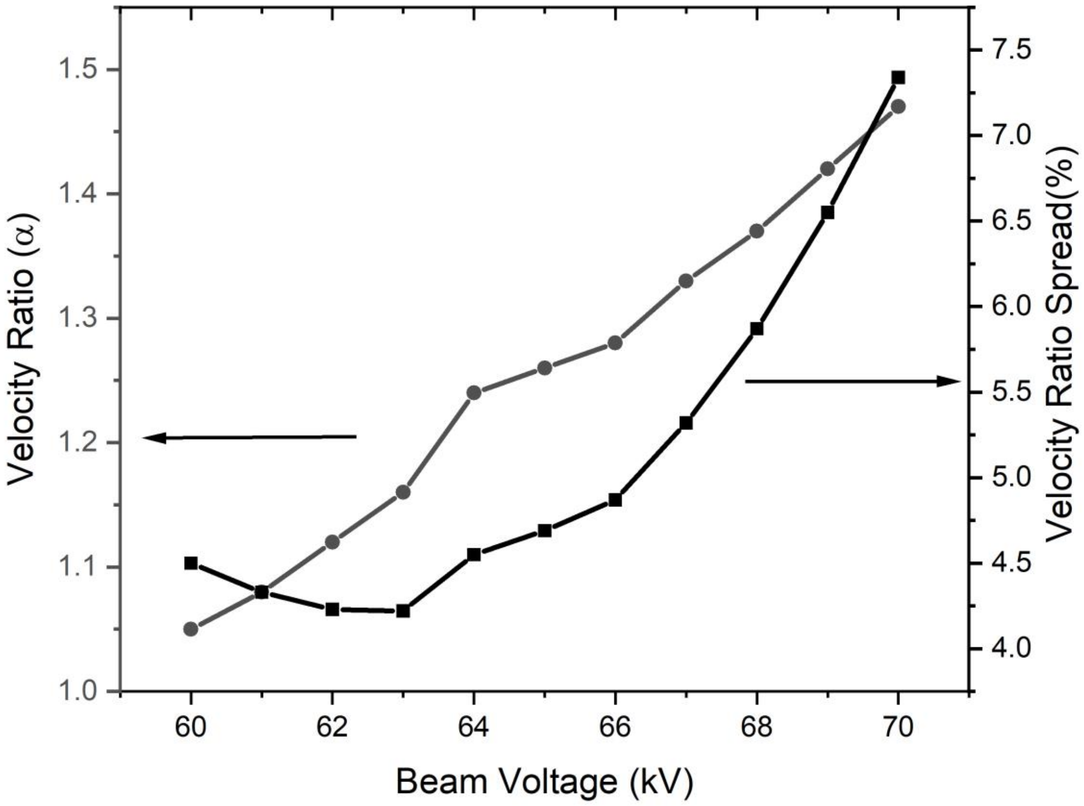
ray	guide cntr	alpha
1	5.852	1.289
2	5.883	1.301
3	5.913	1.312
4	5.944	1.317
5	5.974	1.341
6	6.005	1.363
7	6.035	1.392
8	6.066	1.423
9	6.097	1.454
10	6.127	1.503
11	6.158	1.541

Z	R	W	H	I
320	90	300	15	195
200	101.25	80	7.5	153
440	101.25	80	7.5	153
100	90	20	15	-209.5

Perpendicular velocity spread	1.94 %
Average alpha	1.385

MIG – Parametric Study





Conclusion and Future Scope

A Magnetron Injection Gun of Diode type has been designed for Triple frequency Gyrotron operating at 42/84 /95 GHz

The compression and positioning of the annular beam at the desired radial position in the cavity is achieved by Magnetic filed profiling

Generation of annular electron beam of specified beam parameters is presented

Application of Machine learning/Reinforcement learning for magnetic field profile optimization

extention of the design to one more frequency 30/60/75 GHz

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