Magnets for charge particle beams

Sanjay Malhotra

Bhabha Atomic Research Centre

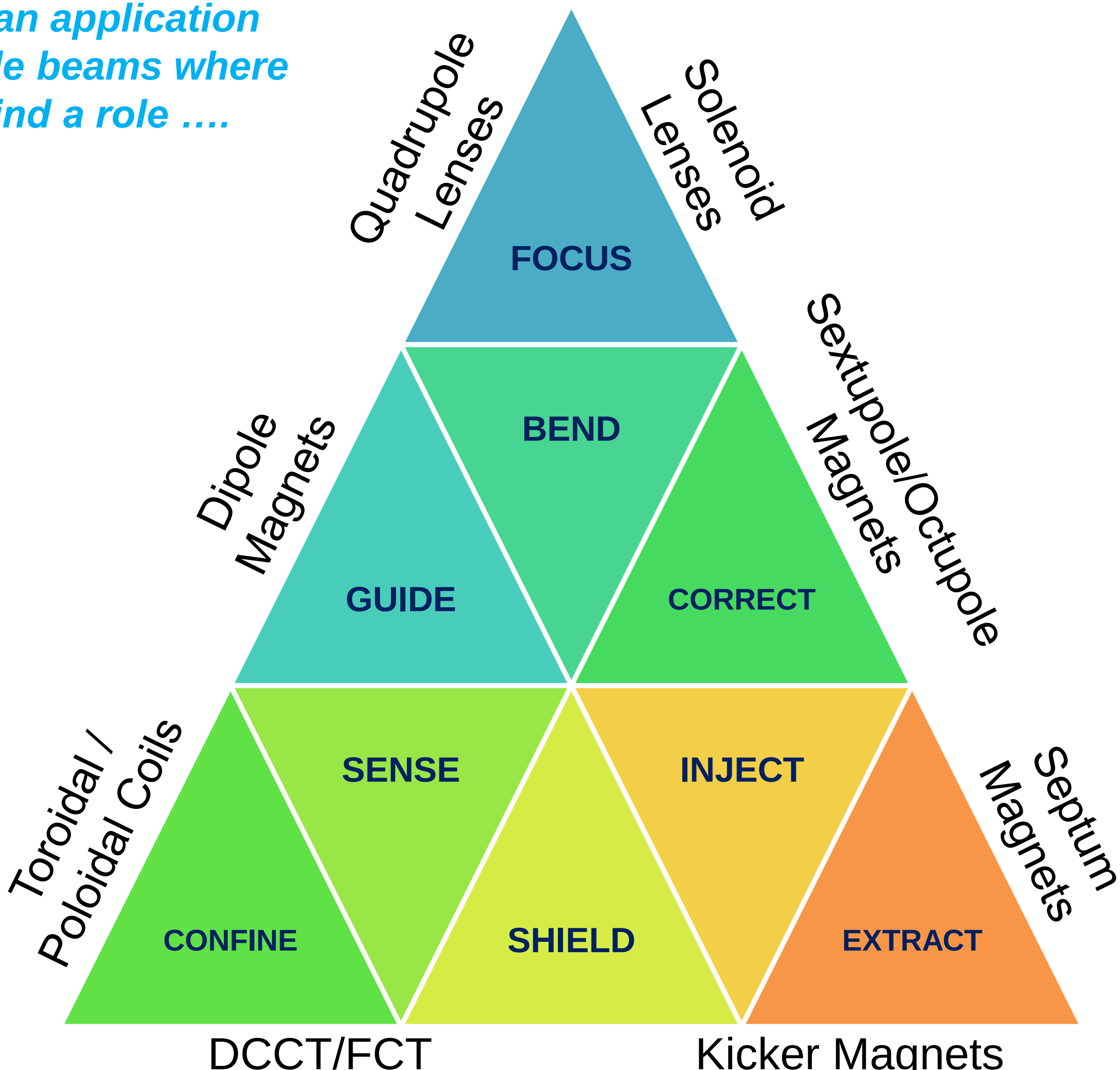
Commemoration of 30 Years of ADITYA Tokamak, IPR, Gandhinagar

Outline of the presentation

- **Introduction**
- **Accelerator beam line magnets**
  - *Drift tube Linac (10-20 MeV) & PMQs*
  - *Linac Magnets for PIP-II*
  - *Magnets for Delhi Light Source*
  - *Synchrotron beam line magnets*
- **Electromagnetic isotope Separation**
- **Magnets for RF Devices**
  - *PM magnet for miniature Klystron*
  - *Hybrid Magnet for S-Band Klystron*
  - *PM magnet for X-Band RBWO*
  - *Cavity Magnet for 42GHz Gyrotron*
  - *Pulsed Electromagnet for high frequency Gyrotron*
- **Superconducting magnet technology**
  - *300mm RT Bore liquid helium cooled superconducting magnet*
  - *300 mm RT Bore Conduction cooled superconducting magnet*
  - *130 mm RT bore 4T conduction cooled magnet assembly*

Roles that magnet plays

It is rare to find an application of charge particle beams where magnets don't find a role ….



Application Areas

Accelerator (Linear/Cyclotron/ Synhcrotron)

Medical (MRI, NMR)

Fusion Experiments

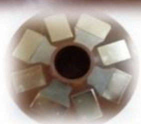
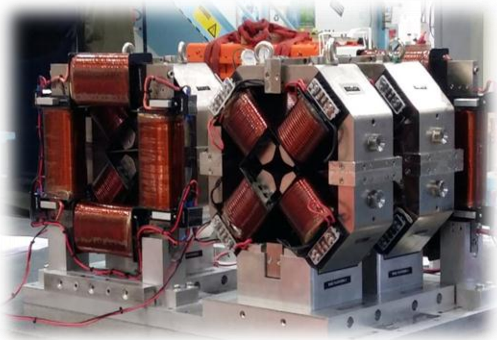
Mass spectrometers

RF Devices (Klystron, Gyrotron, BWO)

Agriculture

Sensors (SQUIDS/Fluxgates/ GMR/Faraday rotation)

Contributing to an ever-expanding magnet compass

Accelerator Magnets
(Focusing & Steering Magnets)


Magnets for MHD Experiments

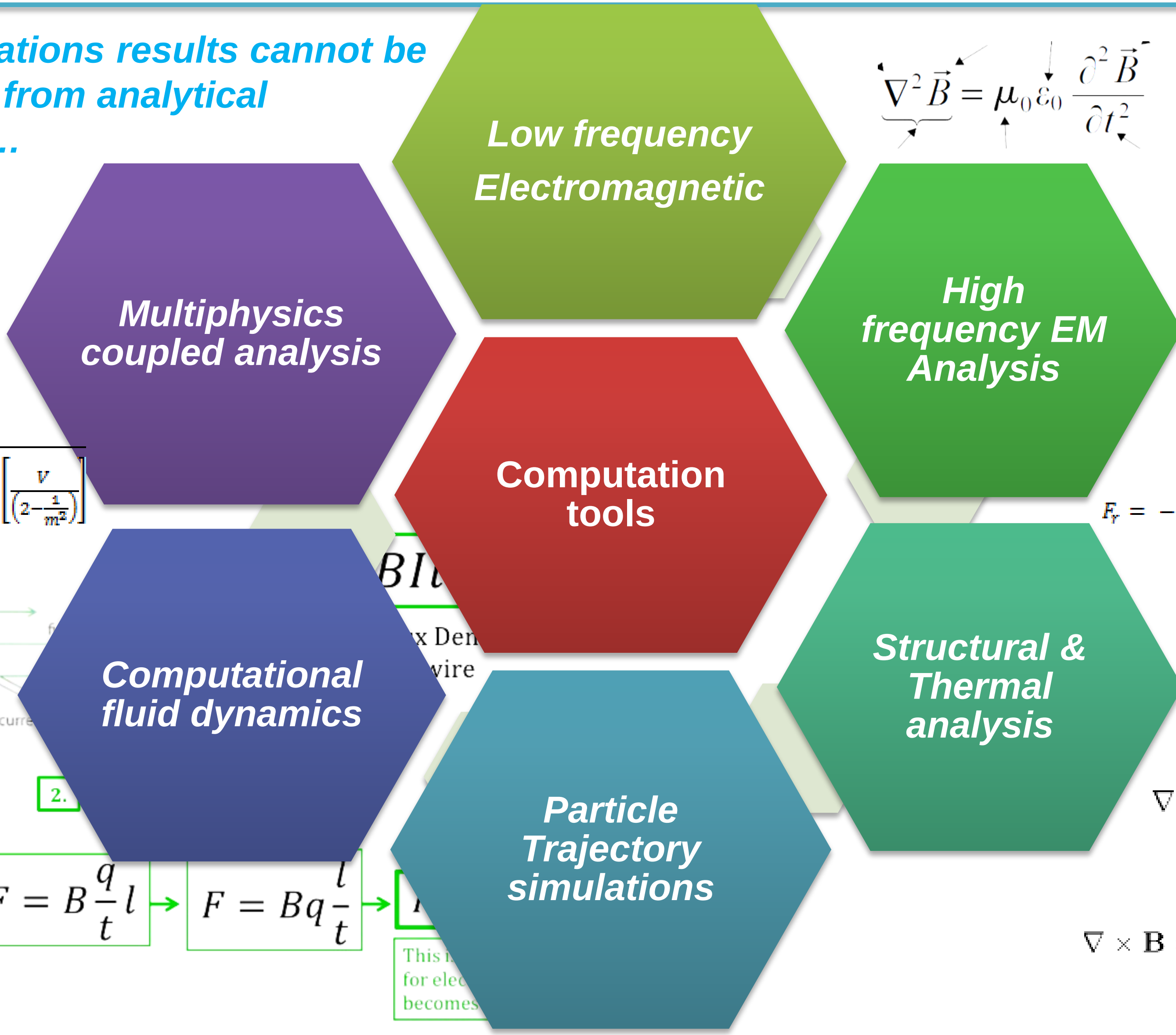
Electromagnetic Isotope separator magnet


Focussing Lenses for Vacuum tubes


Synchrotron Beam Line Magnets

Design capabilities for end to end magnet design

In real life situations results cannot be solely derived from analytical expressions ….



$$\nabla^2 \vec{B} = \mu_0 \varepsilon_0 \frac{\partial^2 \vec{B}}{\partial t^2}$$

$$\lambda_s = \frac{0.030\, x\, 10^{-3}}{B} * m \sqrt{\left[\frac{V}{\left(2-\frac{1}{m^2}\right)}\right]}$$

$$F_r = -\frac{1}{4}\frac{e^2}{m} B^2 m \left(1 - \frac{\Psi_k^2}{B^2 \pi^2 r^4}\right)$$

$$\nabla \cdot \mathbf{E} = \frac{\rho}{\varepsilon_0}$$

$$\nabla \cdot \mathbf{B} = 0$$

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

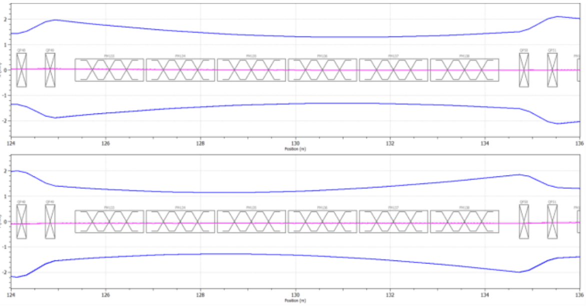
$$\nabla \times \mathbf{B} = \mu_0 \left(\mathbf{J} + \varepsilon_0 \frac{\partial \mathbf{E}}{\partial t}\right)$$

1. $I = \frac{q}{t}$ $F = BIl$

2. $F = B\frac{q}{t}l$ → $F = Bq\frac{l}{t}$

What goes into developing a magnet…

1. Beam Dynamics Simulations



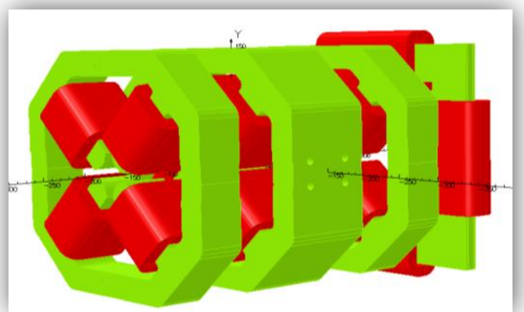
2. Functional Requirement

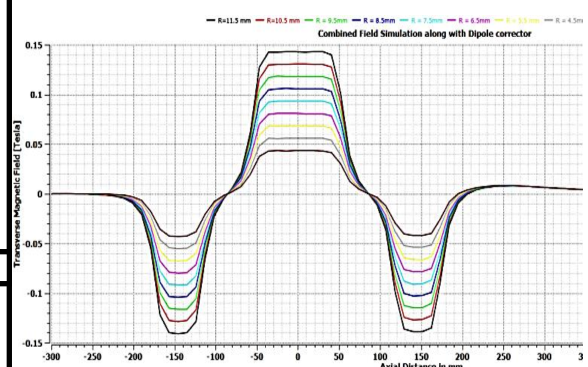
- Application
- Physics requirement

3. Engineering Requirements

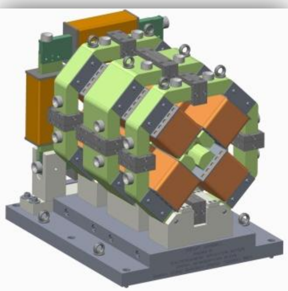
- Size/power consumption
- Seamless Interfaces
- QA & Acceptance

4. Electromagnetic design





5. Engineering design



6. Series Fabrication

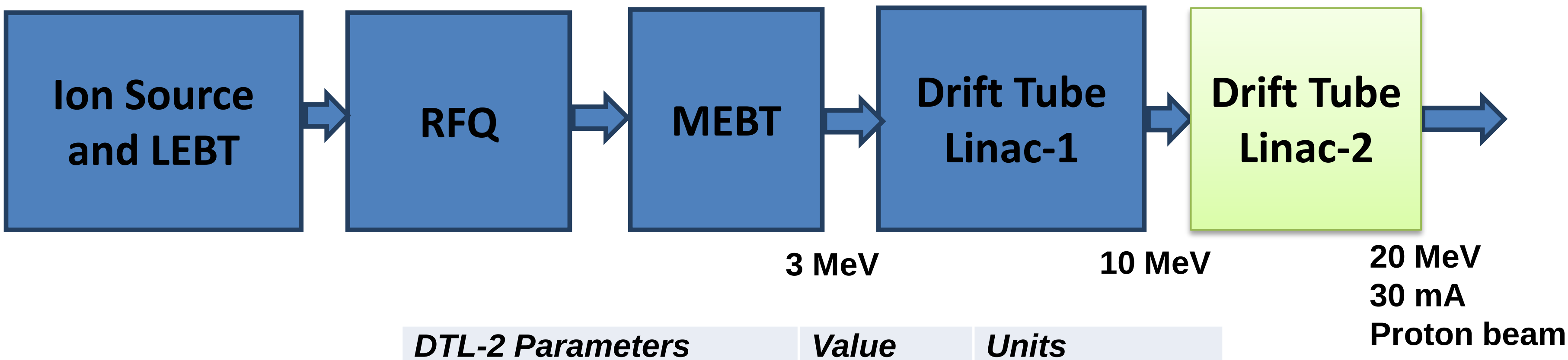
7. Qualification

8. Integration in beamlines

Accelerator beam line magnets

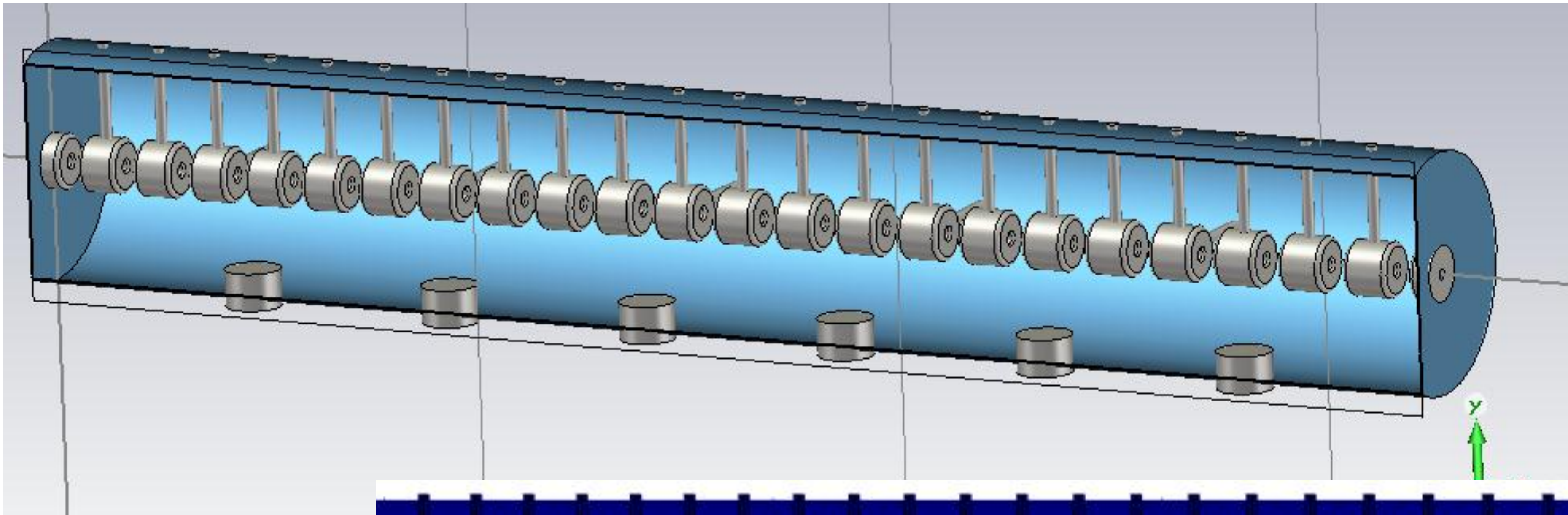
- Drift tube Linac (10-20 MeV) & PMQs (H^+ Beam)
- Linac Magnets for PIP-II (H^- Beam)
- Magnets for Delhi Light Source (e^- Beam)
- Synchrotron beam line magnets (e^- Beam)

Low Energy High Intensity Proton Accelerator

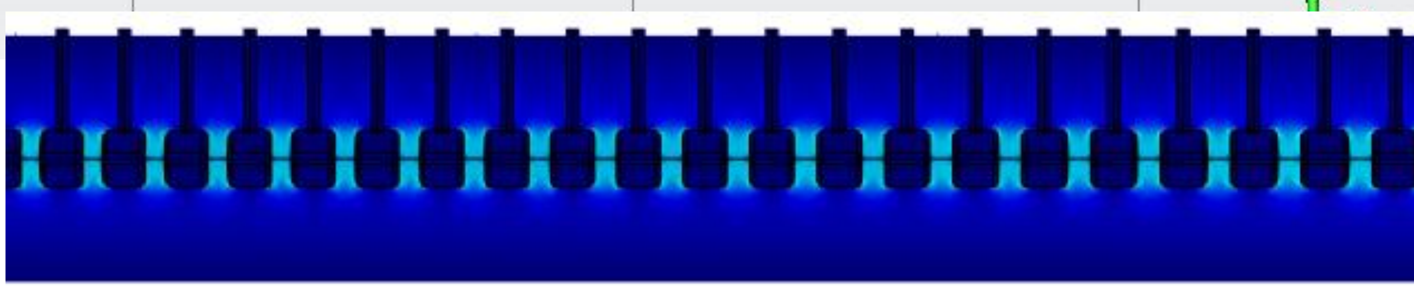


DTL-2 Parameters	***Value***	***Units***
I/O energy	10/20	MeV
Frequency	352.21	MHz
Current	30	mA
No. of Tanks	2	
Total length	~ 6	m
Total RF power	1	MW
Type of quadrupole	PMQ	
Focussing Lattice	FFDD	
Norm.RMS emittance	0.021	π cm-mrad

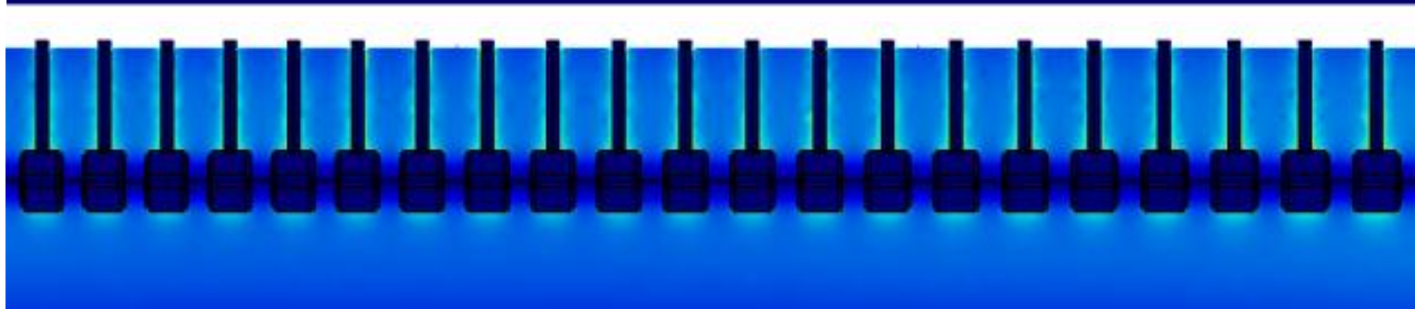
Sectional view of Drift Tube Linac



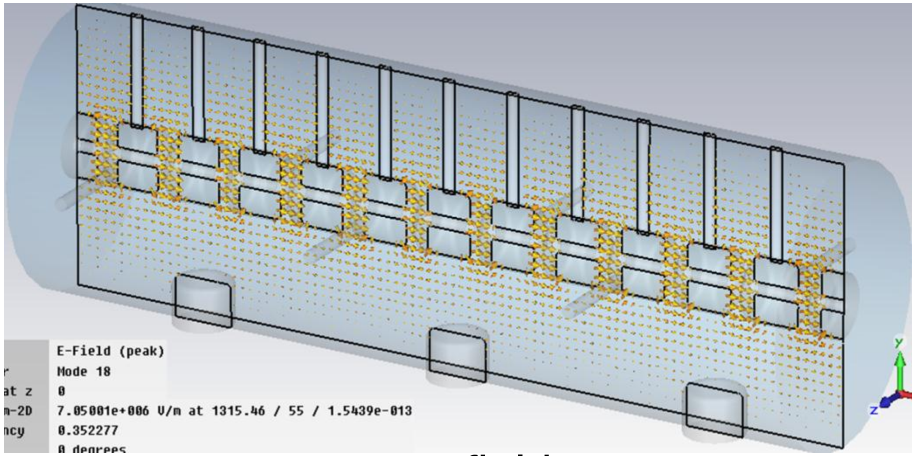
E-field distribution



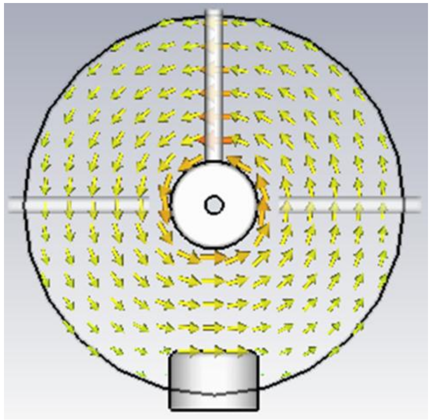
H-field distribution



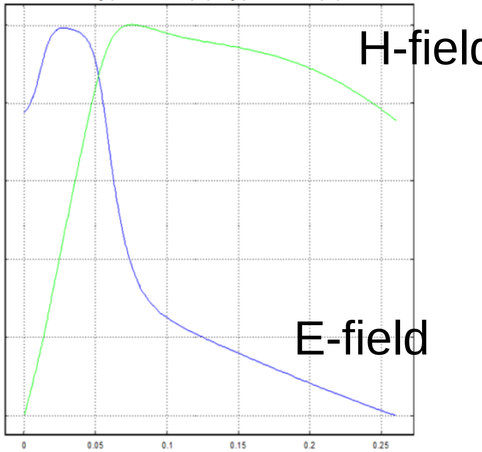
EM Field distribution in DTL

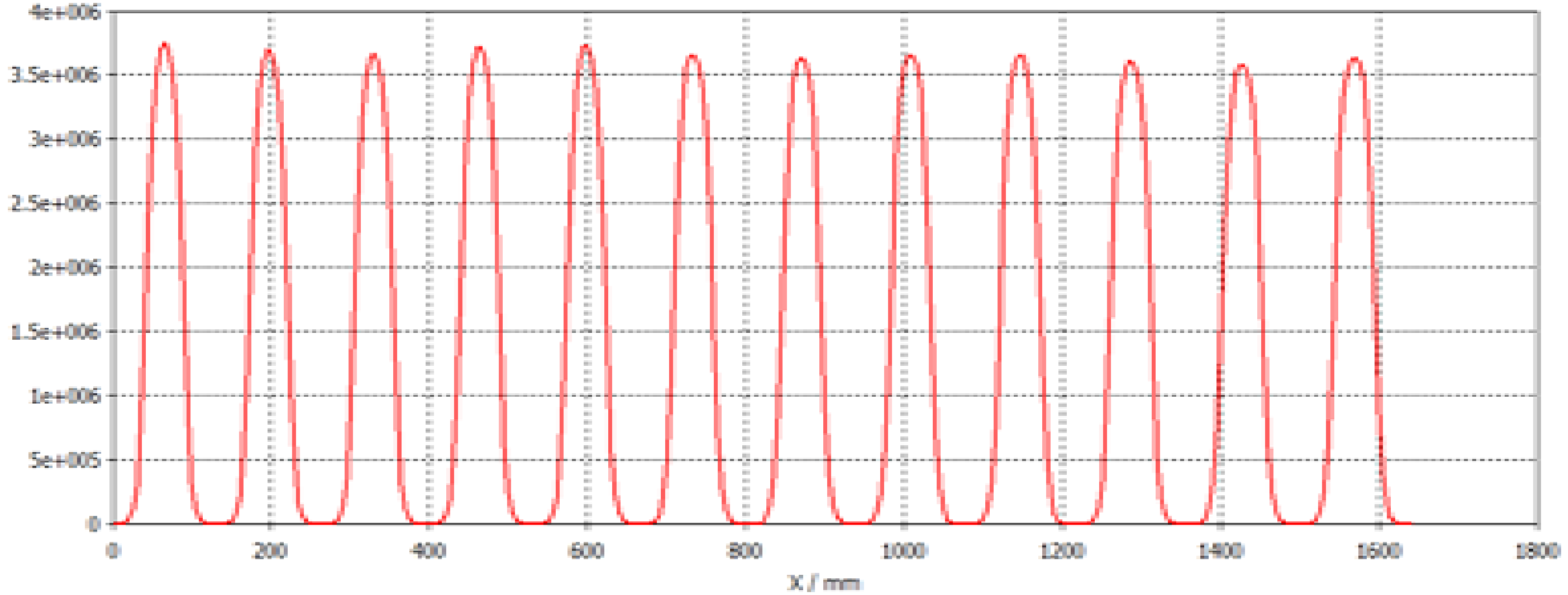


E-field



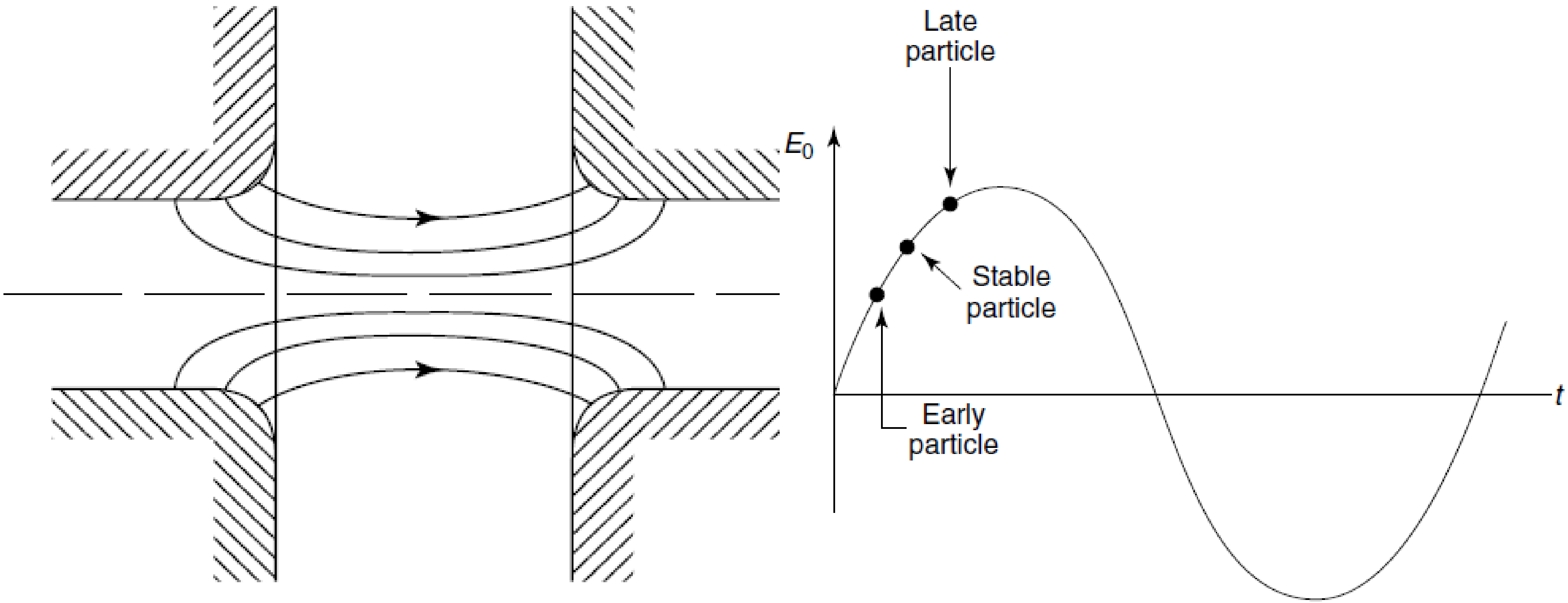
H-field





E-field profile along the beam axis

RF defocusing force- Incompatibility theorem

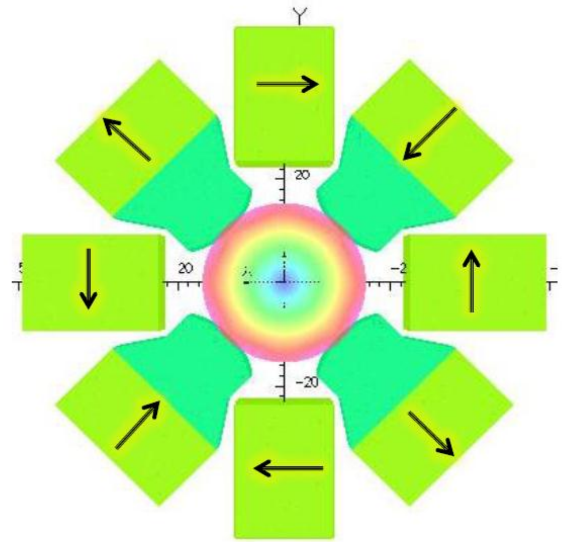


Ref: RF Linear accelerators
Thomas P. Wangler

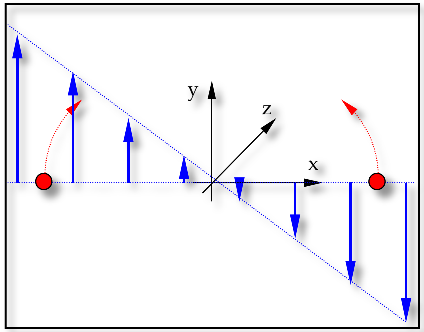
The Quadrupole configuration

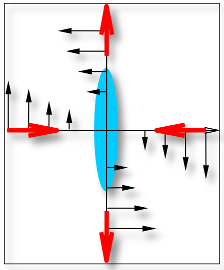
The Permanent magnet Quadrupoles

- Field Gradient in the aperture α $1/r^2$
- Rare Earth Permanent magnets for high air gap flu density
- Smaller diameter leads to smaller drift tubes , henc higher shunt impedance
- Absence of Power supplies / high capacity coolin systems lead to greater reliability

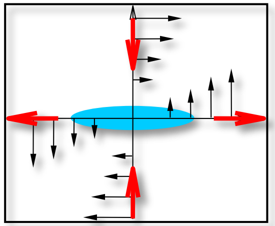


Gradient field (quadrupole)

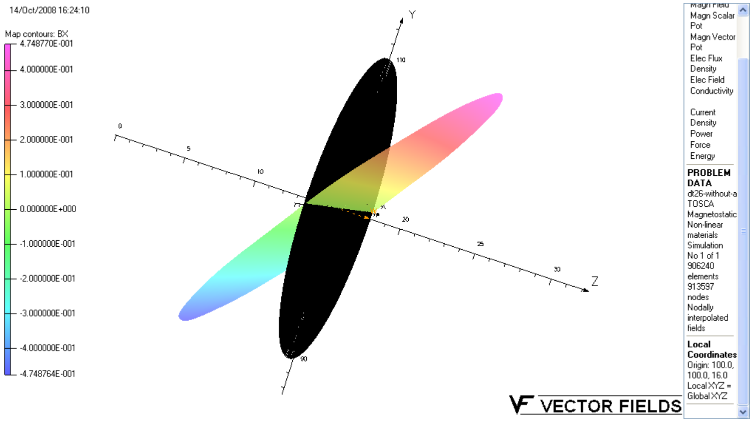




Focusing

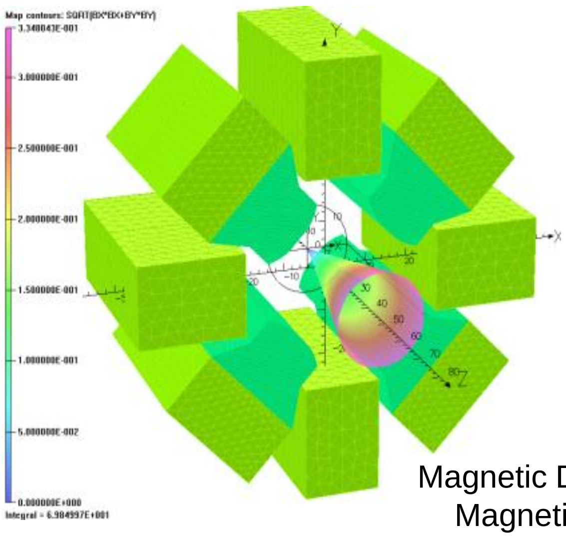


De-focusing



Field gradient in aperture

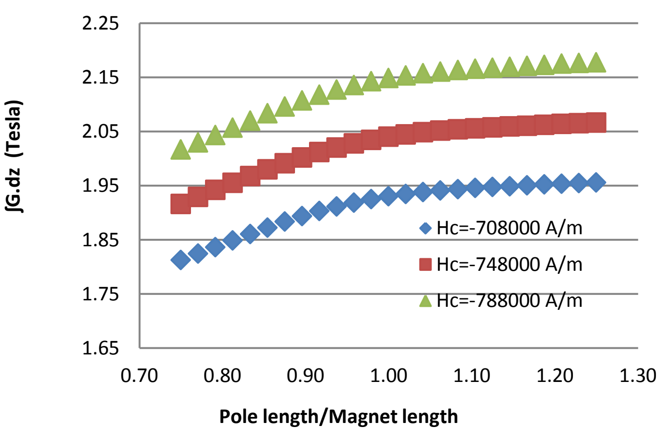
Magnetic Design of Permanent Magnet Quadrupoles



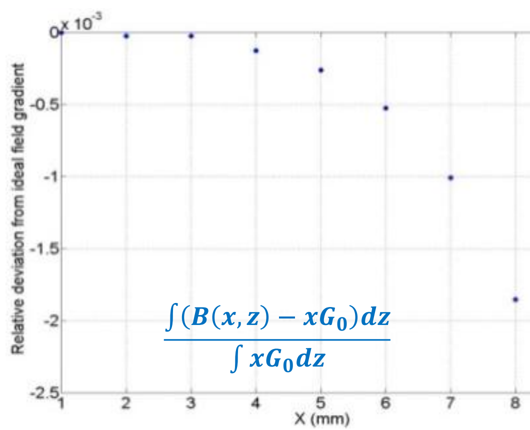
Magnetic Design of PMQ with Magnetic field histogram

Independent measurements carried out at BARC, RRCAT and Danfysik using different measurement methods matched within 0.1%.

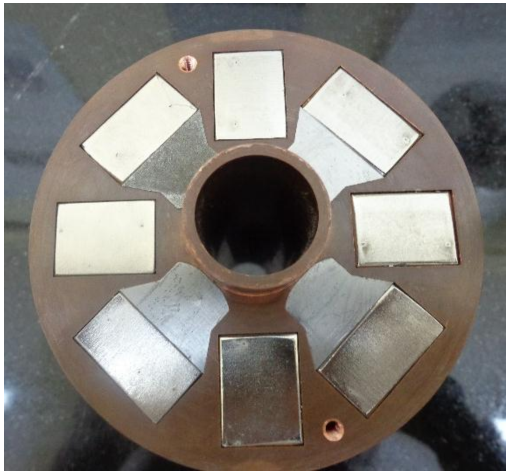
At BARC (Hall probe): 2.053 Tesla	At RRCAT, Indore (Rotating Coil) 2.051 Tesla
At BARC (Stretch Wire bench) 2.048 Tesla	



Tuning curves for different magnet strength

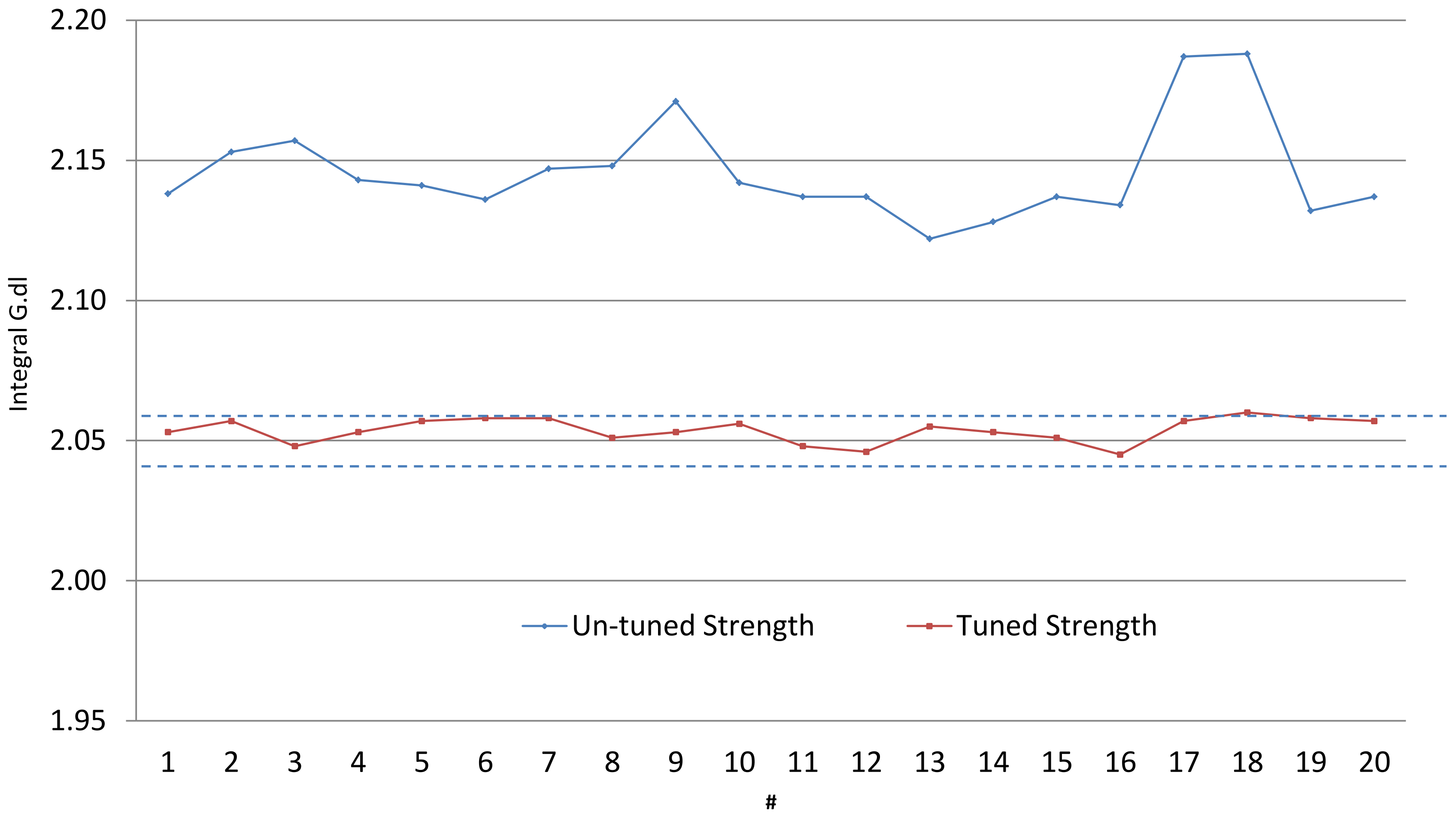


Uniformity of ∫G.dl



PMQ Assembly

Tuning of Permanent Magnet Quadrupoles



The DTL Engineering

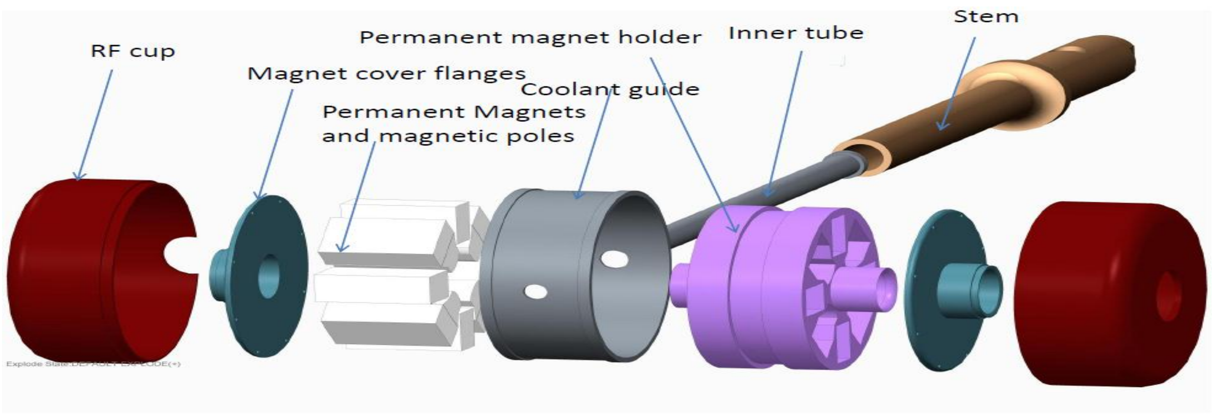
- *Beam Physics* defines the accelerator structure requirement in terms of EM Field distributions
- The *RF and mechanical Engineering* address the practical realization of physics design
- Basic RF properties of the structure are resonant frequency, the RF power losses , the coupling to the RF source and the structure tuning
- Mechanical properties include the vacuum , cooling , alignment and structure integrity
- Properties to be maintained in spite of aging of components with thermal and vacuum cycling
- Sources of frequency errors in the DTL include machining tolerances of tank I.D and Drift tubes and the inaccuracies in estimating perturbations due to D.T stem and vacuum pump out slots
- Hierarchical tuning mechanism to achieve correct frequency
- Post coupled DTL structure allows for a good approximation of the physics design with readily realizable construction tolerances

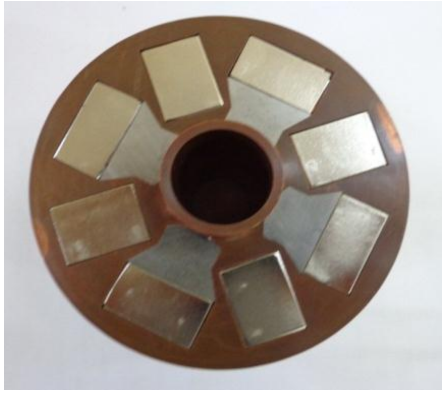
Alvarez Drift Tube Linac

Developed Drift Tubes Linac cavity with assembled Drift Tubes

Drift Tubes aligned concentrically along the DTL cavity axis

Drift Tube





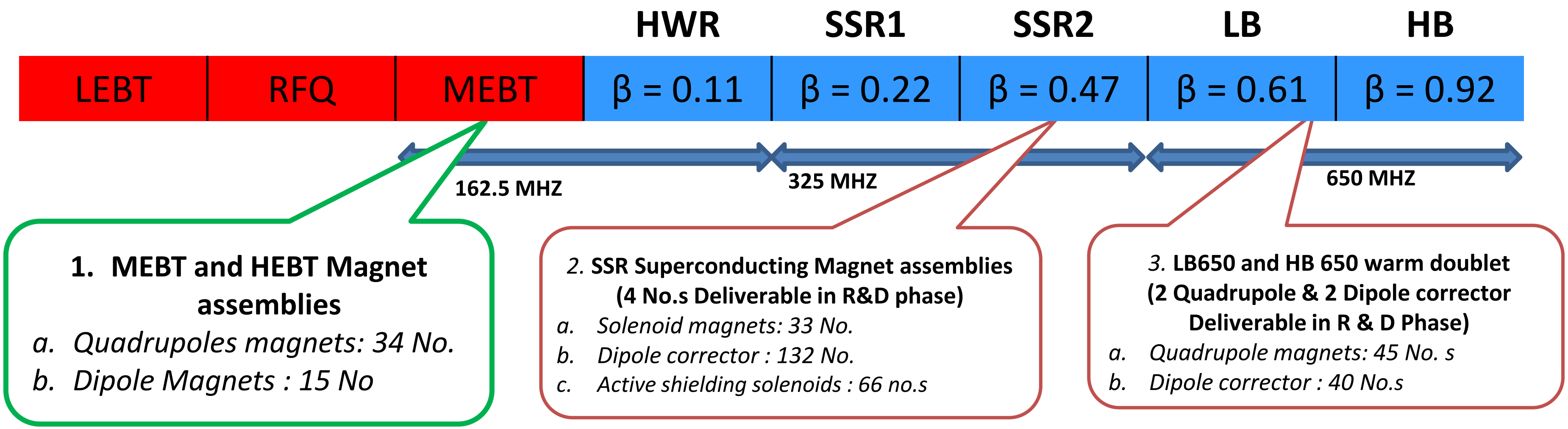
Permanent Magnet Quadrupole

20 MeV Alvarez DTL developed at BARC

20 MeV Alvarez DTL – RF input view

Drift Tubes located aperiodically inside DTL

LINAC magnets for PIP-II



Beam Commissioned

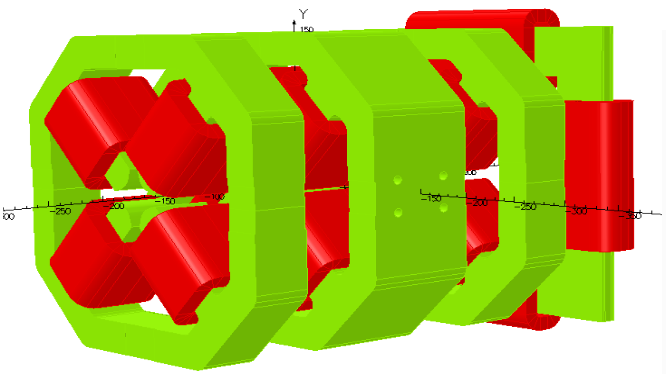
"Magnets" shown in PIP-II Technology Map

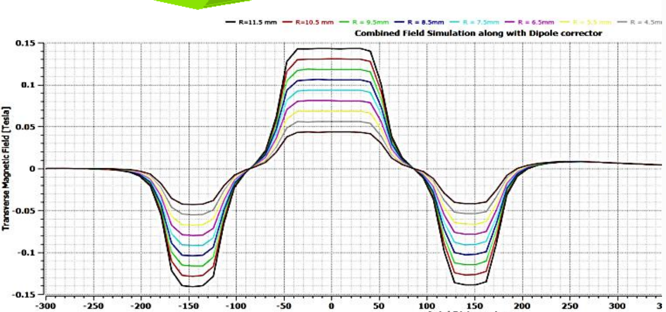
- 49 Nos of BARC developed MEBT magnets (34 Quads + 15 H/V Dipole corrector) commissioned in PIP2IT beamline, FNAL.
- Design and engineering development of bath cooled superconducting focussing lenses. Cryogenic Qualifications @ 2.1K proves efficacy of BARC design to meet beam optics and engineering requirements.
- Design and Engineering development of LB/HB650 warm doublet (Quads and Dipole corrector).

Design and Development of Focusing lenses for MEBT

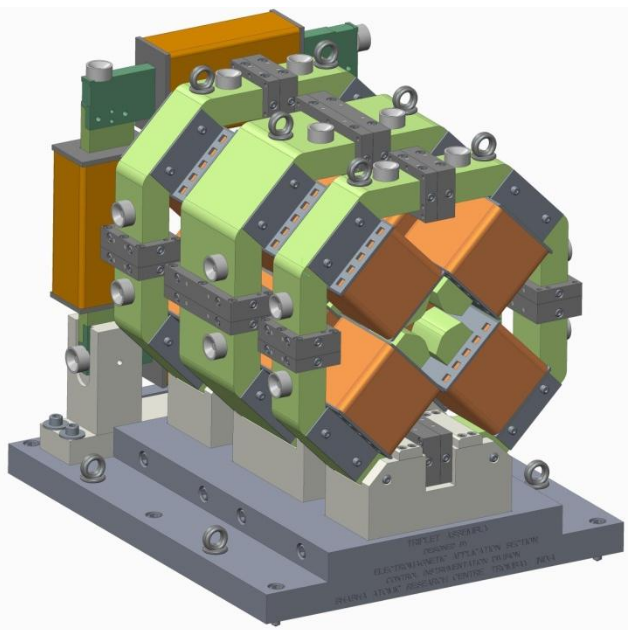
Stages of development at BARC:

1.Electromagnetic design of lenses - Quadrupole Focussing Magnets and dipole correctors
2. Engineering design
3. Development drawings
4. Fabrication and Geometrical inspection
5. Magnetic measurements (integral fields)
6. Quality checks and traveller
7. Qualification tests with H^+ beam at 2.5 MeV

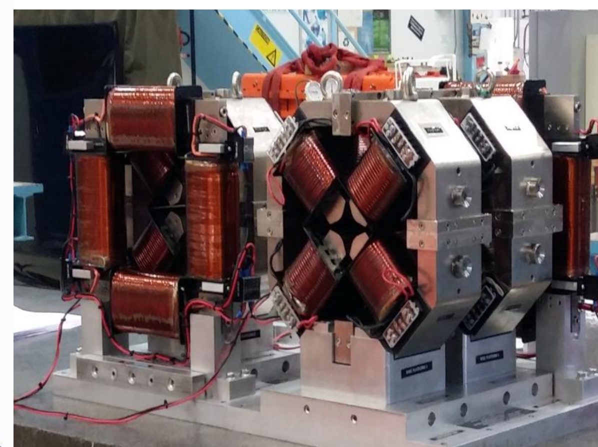




Electromagnetic Simulation



Mechanical Design



Developed Magnets

Summary of magnetic measurements at FNAL

Quadrupole

SN	Parameter	Requirement	Designed for	Measured	Unit	Remarks
1.	∫ G.dl	1.44	1.44	1.44	T	Meets Req.
2.	Magnetic Centre (X axis)	Within ± 100	0	45 to -30	um	Meets Req.
3.	Magnetic Centre (Y axis)	Within ± 100	0	30 to -40	um	Meets Req.
4.	Integrated Magnetic field uniformity (up to n=10)	<1	0.30	<0.5	%	Meets Req.
5.	Magnetic centre as function of current	50	0	<20	um	Meets Req.
6.	Transfer function stab.	0.30	0.20	<0.5	%	Meets Req.
7.	Higher Order Multipoles	<1	0.20	<0.3	%	Meets Req.
8.	Skew Components	0.2	0.05	<0.1	%	Meets Req.

Dipole Corrector

S. No	Parameter	Specified	Achieved	Remarks
1.	Magnetic field integral	2.1 mT-m	2.4mT-m	Meets requirements
2.	Field tilt -Deviation of X and Y field from perpendicular	$<3^0$	Negligible	No evidence of tilt in the orthogonal field
3.	Integrated field uniformity	5%	Highly uniform	Acceptable even at 25mm radius, well beyond requirement level

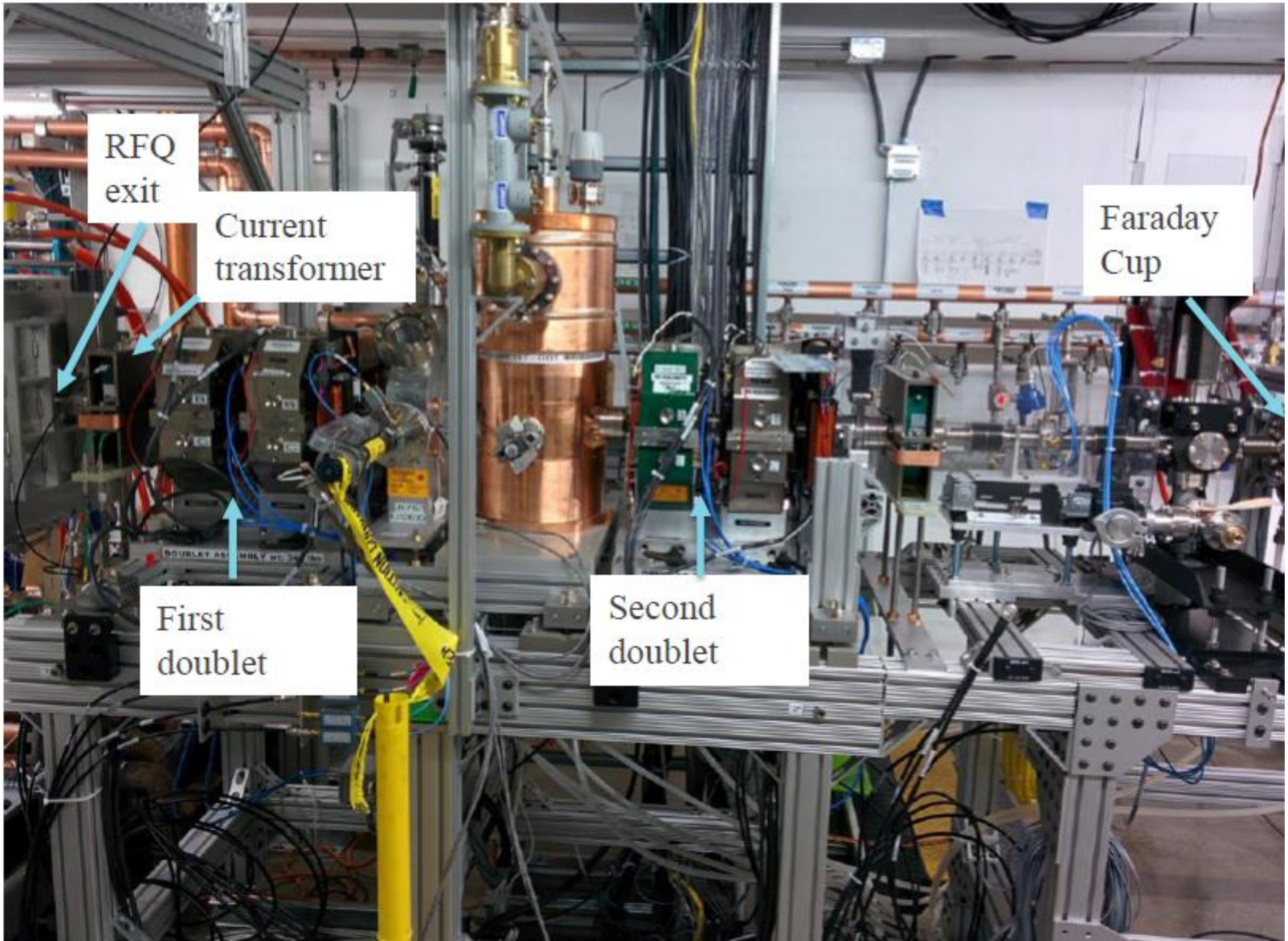
Memo generated by FNAL after magnetic qualifications of pre-series magnets

To:	Dr. Shekhar Mishra
From:	Dr. Michael Tartaglia, PXIE Magnet SPM, Tech. Division Test & Instrumentation Department Head
Subject:	Qualification of PXIE MEBT Pre-series Magnets from BARC

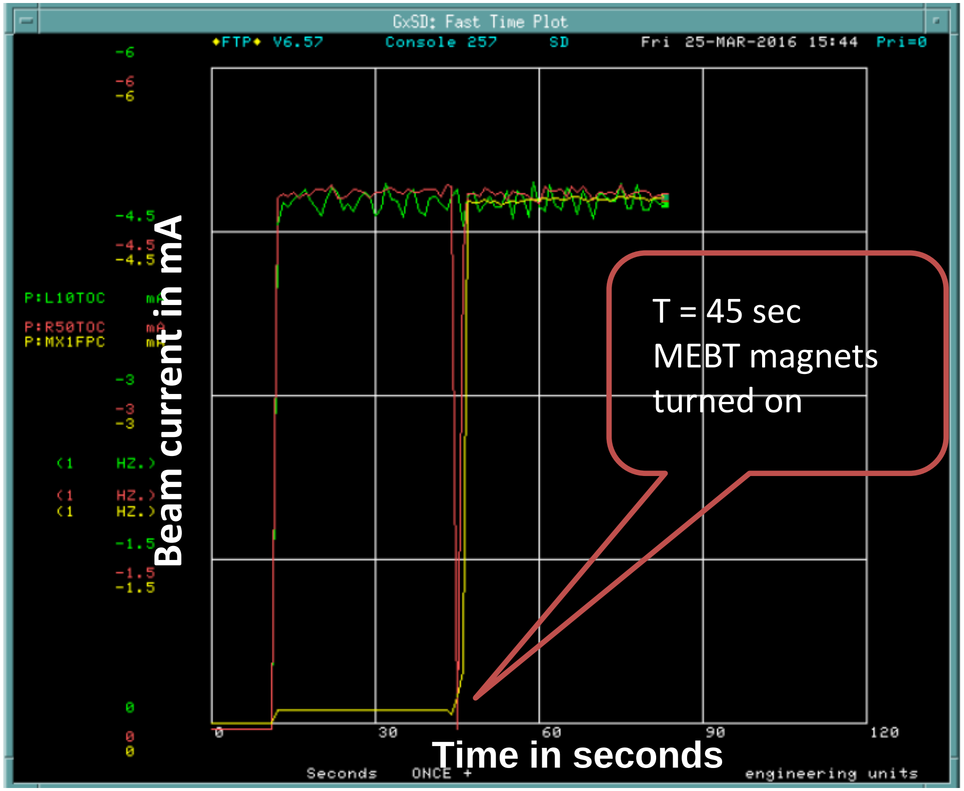
As part of the Indian Institutions and Fermilab Collaboration, the Electromagnetic Applications Section at the Bhabha Atomic Research Centre (BARC) has delivered to Fermilab a set of pre-series magnets suitable for use in the MEBT section of the PXIE beamline. The deliverables included three F-Quadrupoles (PXQF), two Corrector Dipoles (PXD), and two “doublet” frames, used for mounting two PXQF and one PXD into one “doublet” assembly. No design changes have occurred in the PXQF magnets, and some minor changes were introduced for the PXD magnets, since the first two prototype magnets were accepted one year ago. These BARC-designed magnets were built by industry in India according to drawings provided by BARC, and came complete with travelers documenting the components, fabrication and tests.

Upon delivery the magnets were electrically inspected and measured at the Fermilab Magnet Test Facility to verify that they achieved the required magnetic performance as documented in the Technical Requirement Specifications (Teamcenter ED0003467). The results of these measurements have been reviewed by Dr. A. Shemyakin (PXIE Warm Front End Manager), C. Baffes (PXIE Warm Front End Engineer), and me. I am pleased to say that these magnets meet the required performance in terms of physical aperture and length, maximum operating current, integrated magnetic strength, field uniformity, stability of the quad magnetic center, and dipole field angle perpendicularity. These pre-series magnets are ready for integration into the PXIE beam line. Based upon the successful fabrication and test performance of these pre-series magnets it is recommended that approval be given to BARC to proceed as soon as possible with fabrication of production quantities of the PXQF, PXQD, and PXD magnets.

PXIE Beam line integration of MEBT (2 Doublets) (Feb' 2016)



Transport through the MEBT 1.1 line (March , 2016)



The MEBT magnets were turned on at T=45 sec.

Green - beam current at the entrance of RFQ.

Red - beam current at the exit of RFQ.

Yellow - beam current in the Faraday Cup.

Vertical axis –beam current, 1.5 mA/div.

Horizontal axis –time, 30 sec/div.

5 mA, 20 μs, 10 Hz

With quadrupoles and dipole correctors tuned, most of the beam goes into the Faraday Cup at the end of the beam line at the nominal current of 5 mA.

Mail from Steve Holmes on BARC magnets performance

From: owner-iifc@listserv.fnal.gov [mailto:owner-iifc@listserv.fnal.gov]
On Behalf Of Stephen D Holmes Sent: Wednesday, March 23, 2016 4:45 PM

To: iifc <iifc@fnal.gov> Cc: Nigel S. Lockyer <lockyer@fnal.gov>

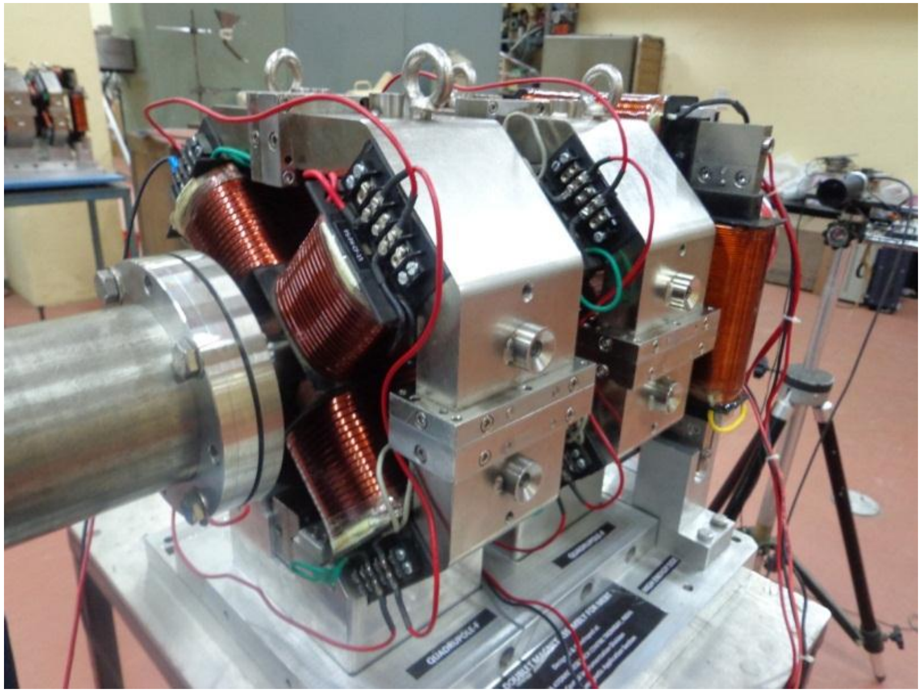
Subject: Beam through the PXIE RFQ

Dear Colleagues,
It is a pleasure to tell you that today we successfully accelerated beam through the RFQ at PXIE. Following the exit of the linac are four quadrupoles and two correction dipoles manufactured at BARC. Once the quadrupoles were energized beam transmission to the Faraday Cup downstream of the magnets approached 100%.

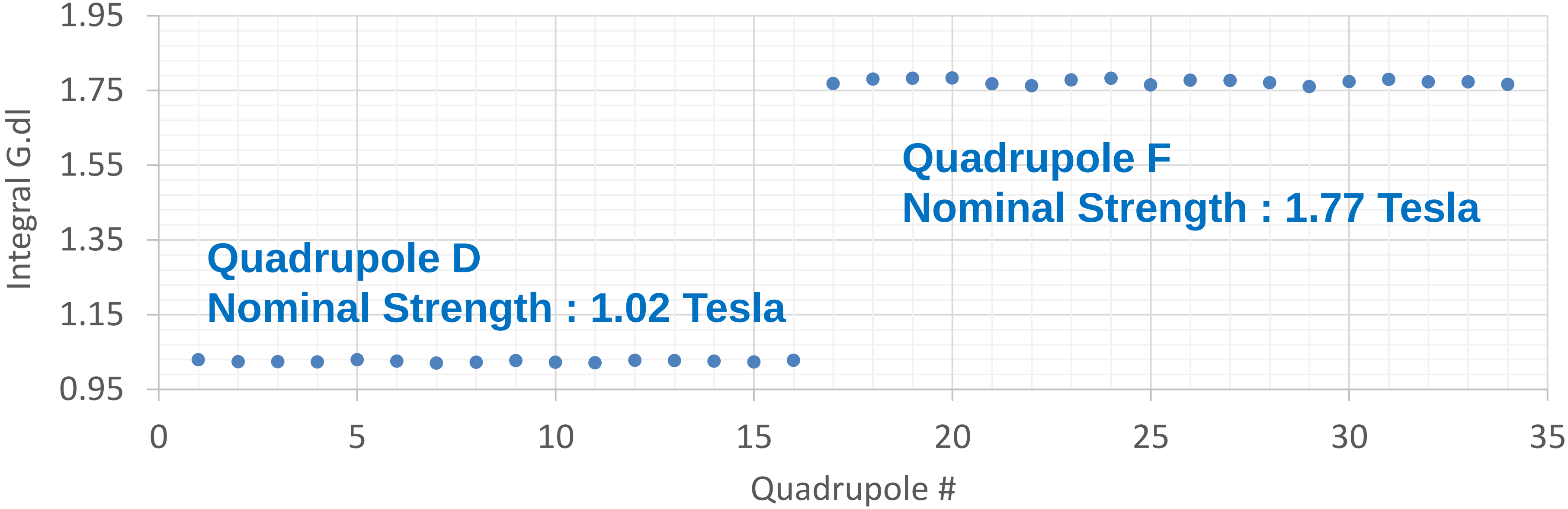
For those of you at Fermilab we will be congregating at the Users Center tomorrow (Thursday) at 5:00 for a little celebration.

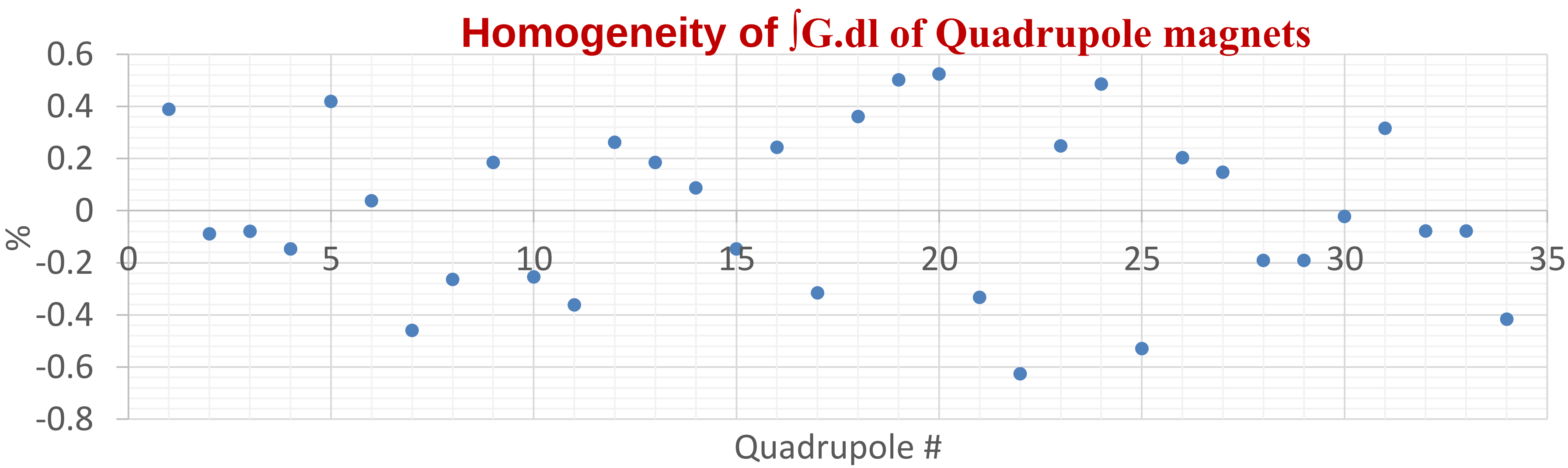
Best Regards,
Steve

MEBT Quadrupole Triplets & Doublets for PIP2-IT (IIFC)

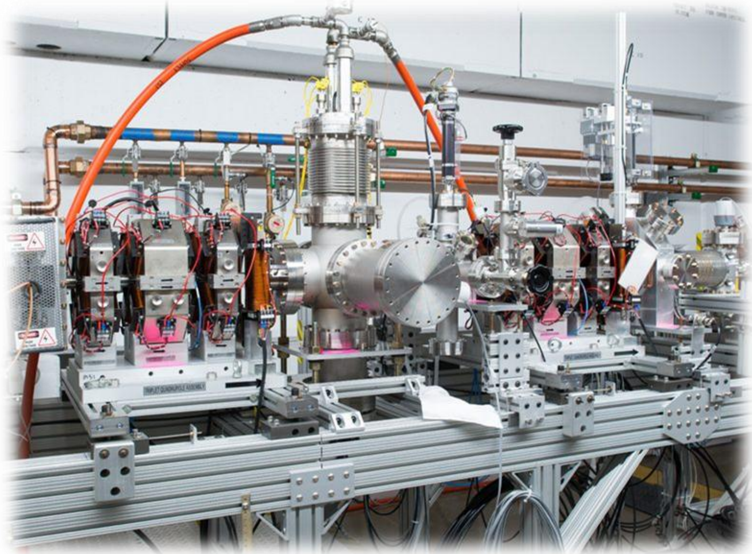


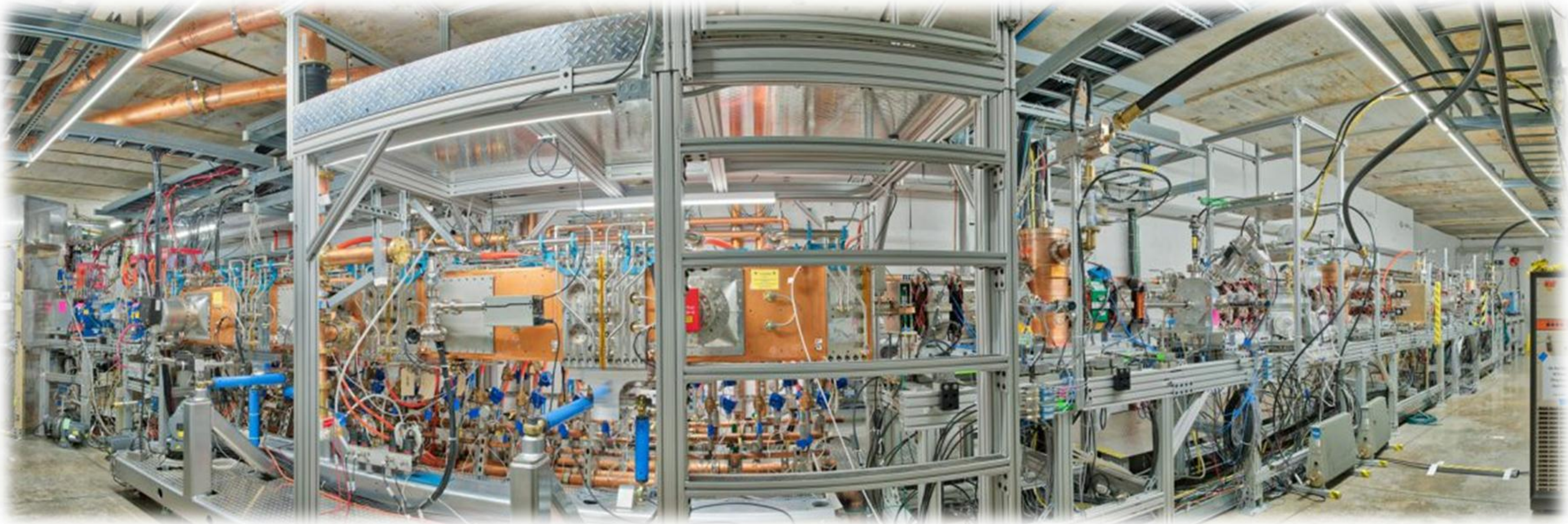
Integral Magnetic Field Gradient of series Quadrupole Magnets



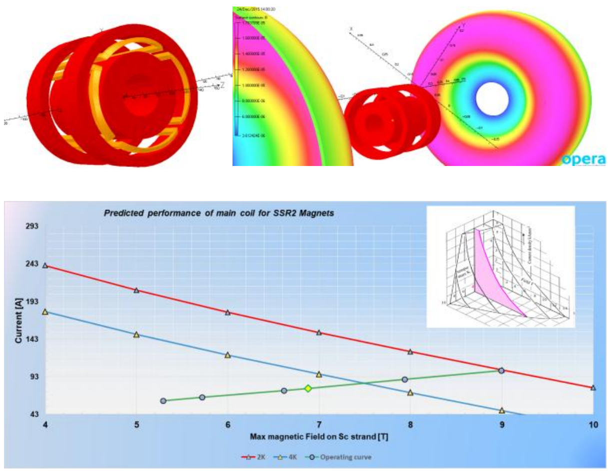


Magnets Commissioned in P2IT beam line at FNAL

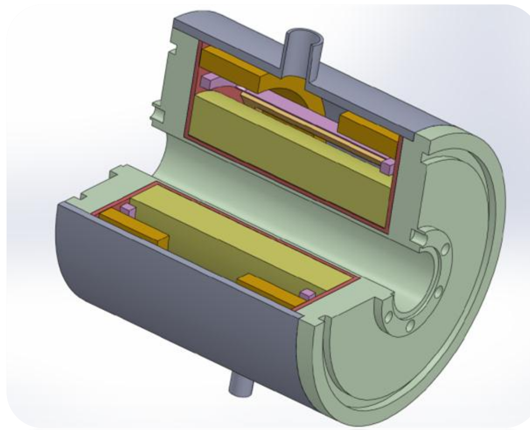




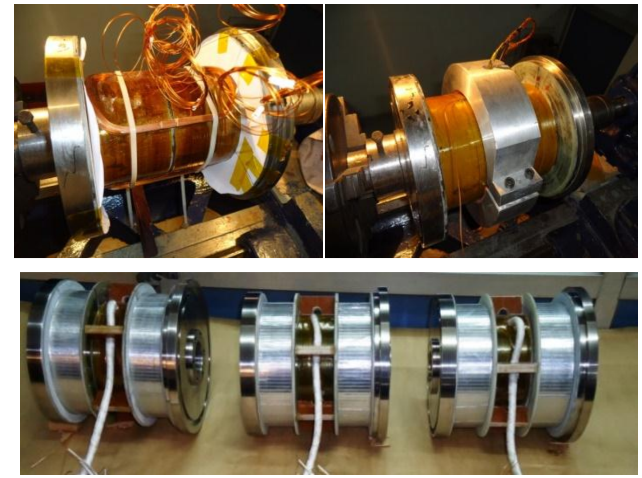
SSR superconducting magnet assemblies



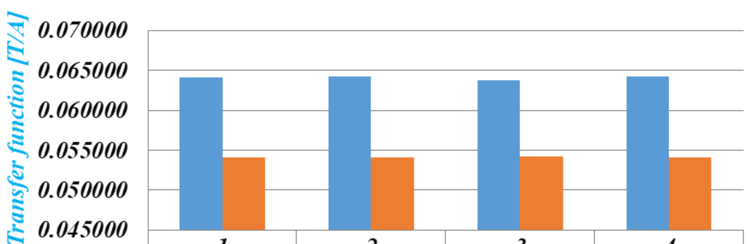
Electromagnetic & Thermal (Quench Design)



Engineering Design

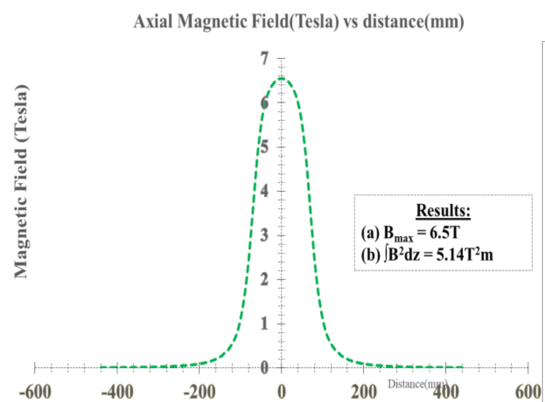


Engineering Development

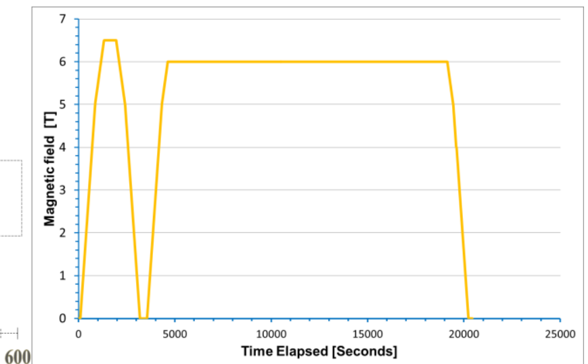


	1	2	3	4
MC	0.064155	0.064227	0.063746	0.064250
MC+BC	0.054070	0.054104	0.054173	0.054141

Warm Magnetic Qualifications



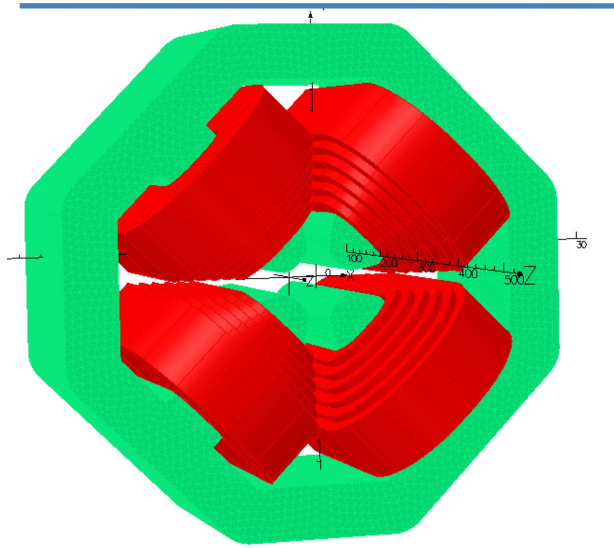
Axial field mapping at 4.2K



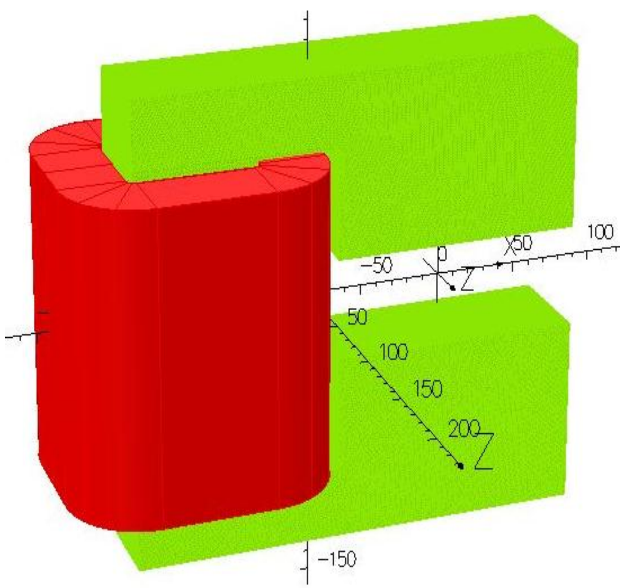
Power Tests & Quench Qualifications

Cold Magnetic Qualifications

Quadrupole Magnets for LB/HB 650 PIP-II

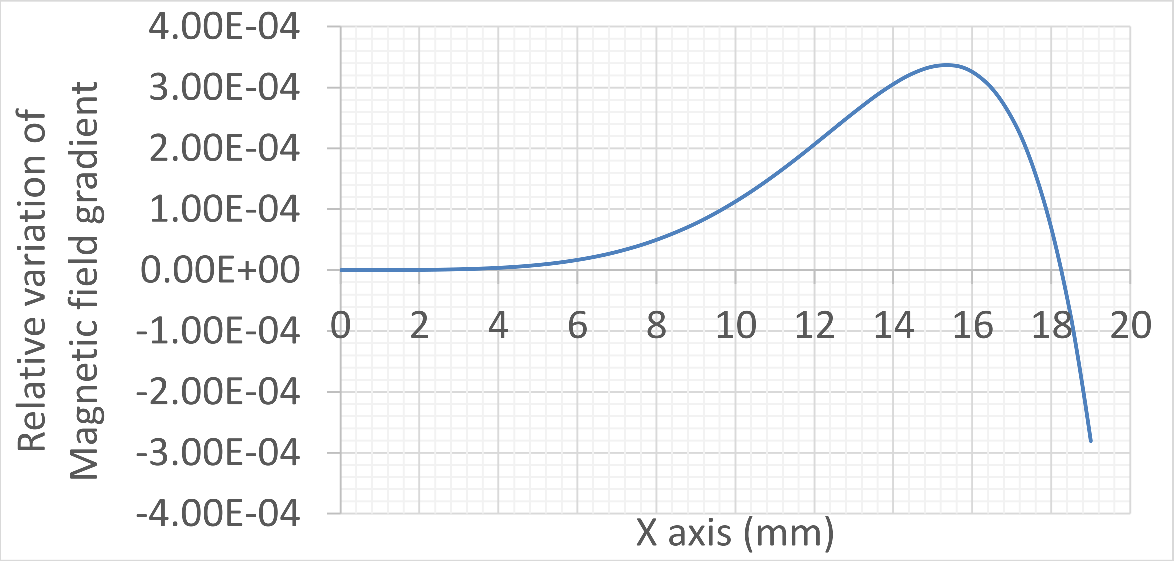


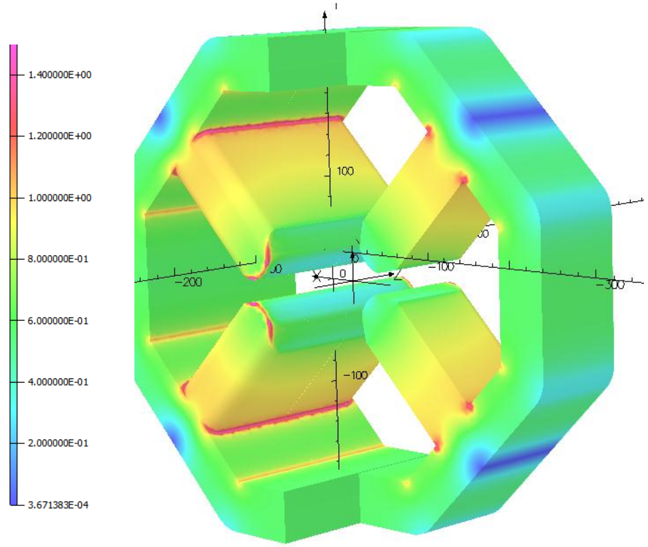
Parameters	Required	Achieved in design	Unit
Integral magnetic field gradient (∫G.dl)	3.0	3.0	(T/m).m
MMF	3600	3555	At
Magnetic field gradient	13.5	12.8	T/m
Aperture	52	52	mm
Good field region aperture	26	26	mm
Uniformity of ∫G.dz in GFR	0.100	0.007	%
Physical length	200	200	mm
Maximum transverse dimensions	600	425	mm

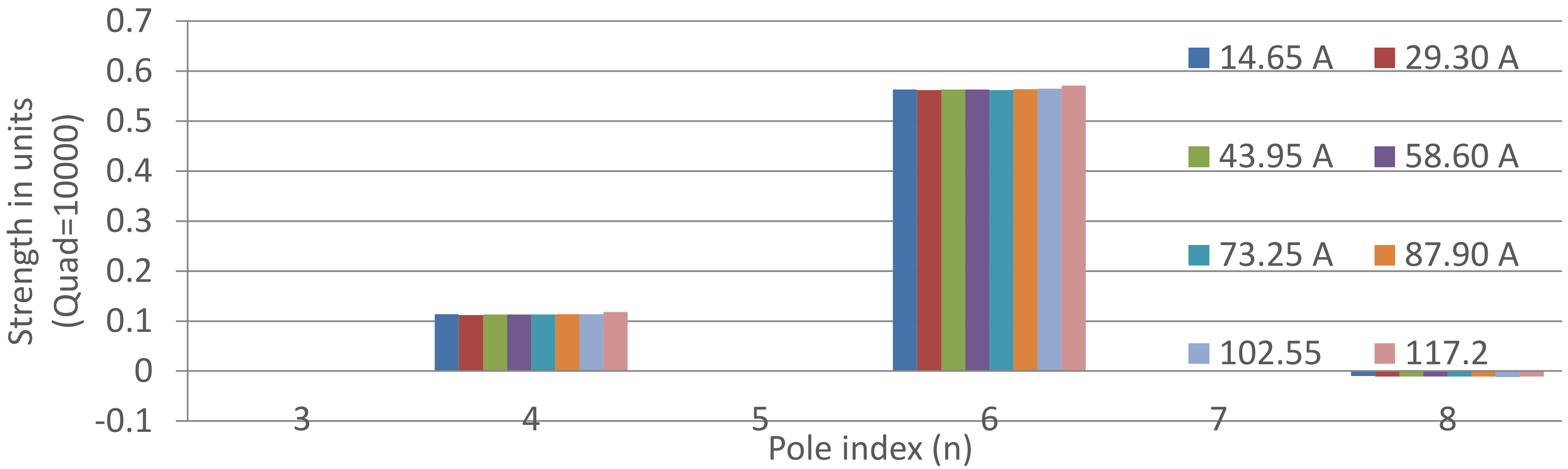


Parameter	Required	Achieved in design	Units
Integral Magnetic field	10	10	mT.m
Pole tip to pole tip gap	52	52	mm
Good Field region	Ø 26	Ø 26	mm
Uniformity in GFR	1	0.58	%
Maximum transverse dimensions	600	275	mm
Maximum longitudinal dimensions	180	130	mm
Power supply preference (I)	<15	9.2	A
Power supply preference (V)	<30	2.5	V

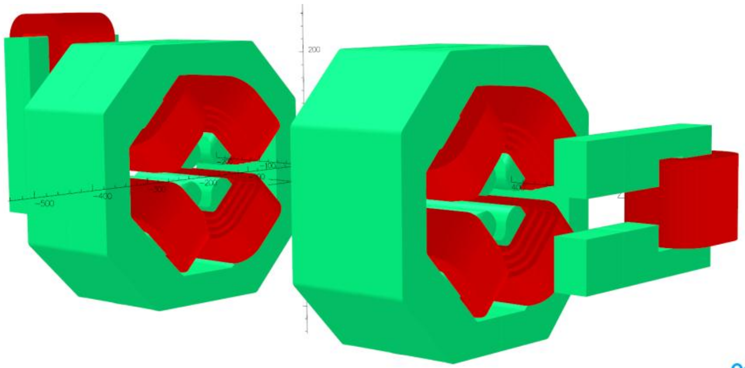
Magnetic design of Quadrupole Magnets for LB/HB650



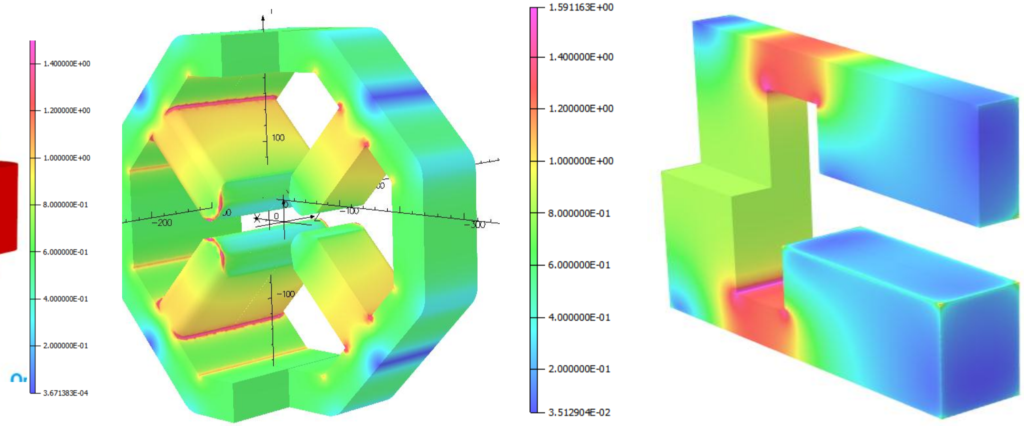




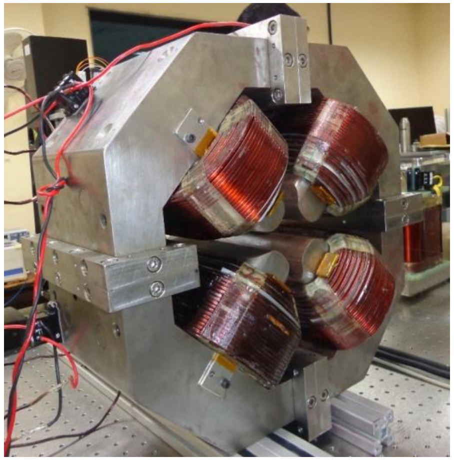
Doublets for LB/HB 650 MHz section of PIP-II

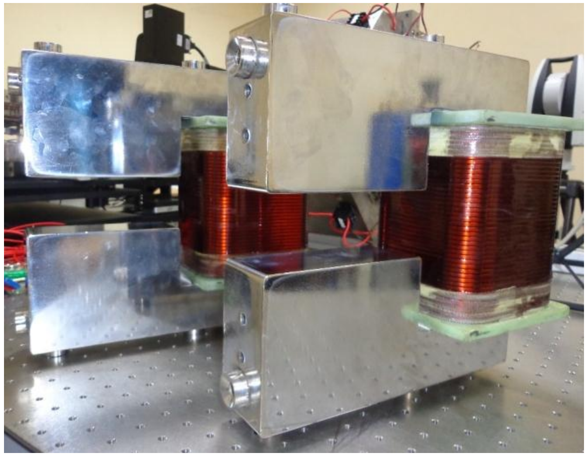


3D Model for LB/HB650 Warm doublet

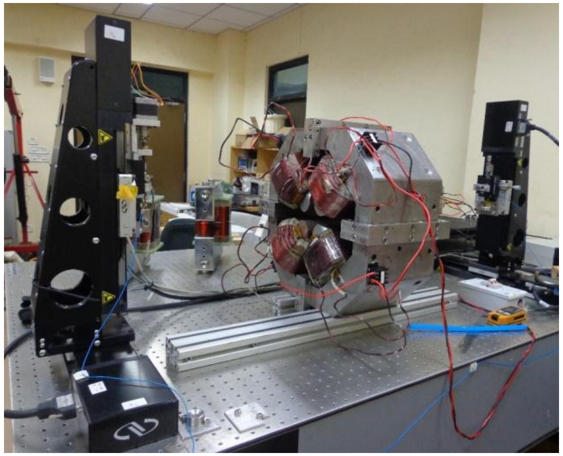


Electromagnetic Design





Developed Quadrupole & Dipole Magnet Assemblies



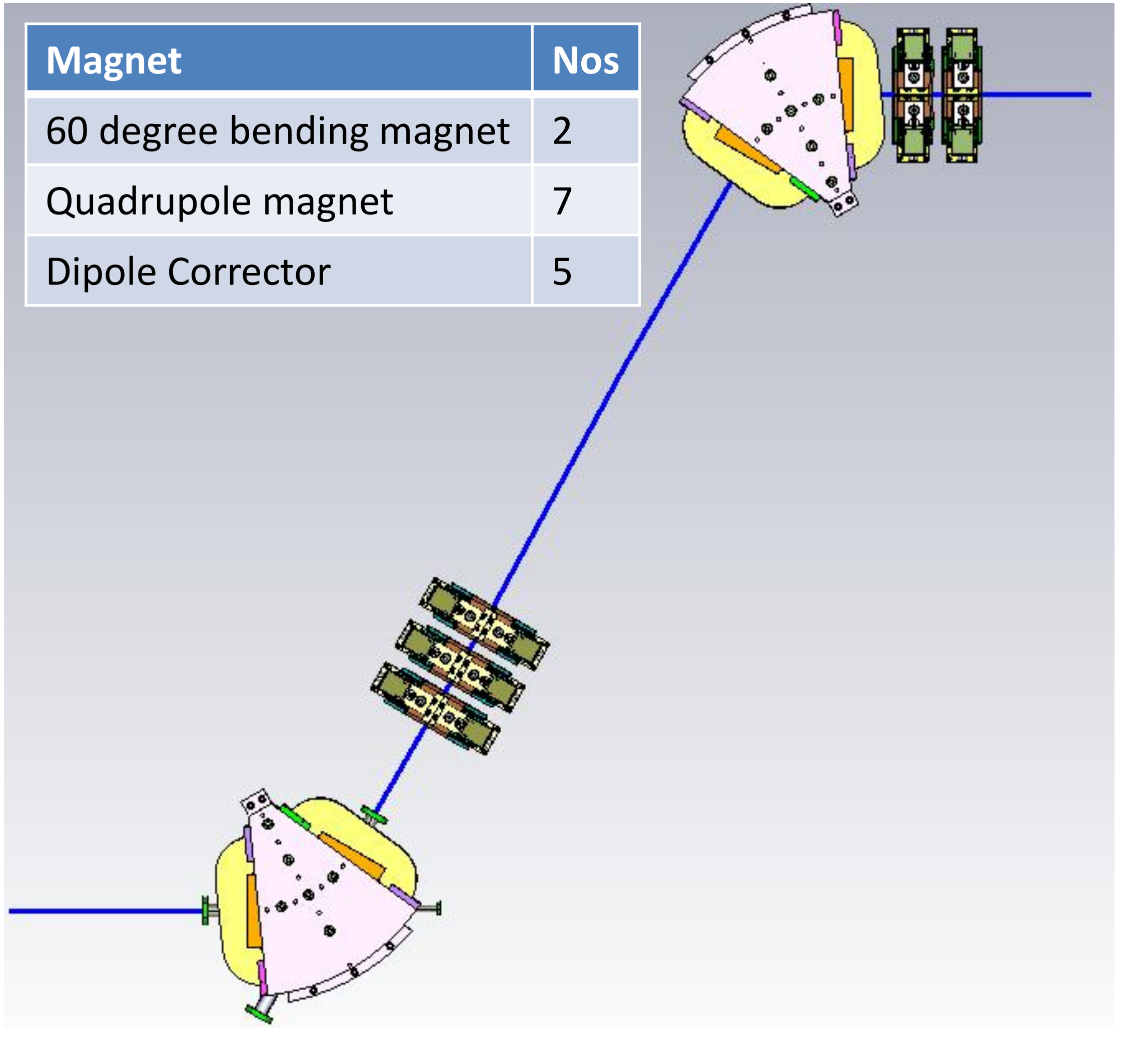
Magnetic Qualification bench

Magnets for Delhi Light Source (DLS) (Electron beam)

Magnet layout and specifications

Bending Magnet

SN	Parameter	Value	Unit
1.	θ	60 ± 0.5°	°
2.	R	300 ± 1	mm
3.	Pole gap	40 ± 0.1	mm
4.	B_0	1200	G
5.	Entry and exit angle	6 ± 0.1°	°
6.	Homogeneity of B field	500	ppm
7.	Good field region	± 16 (Z) ± 40 (R)	mm

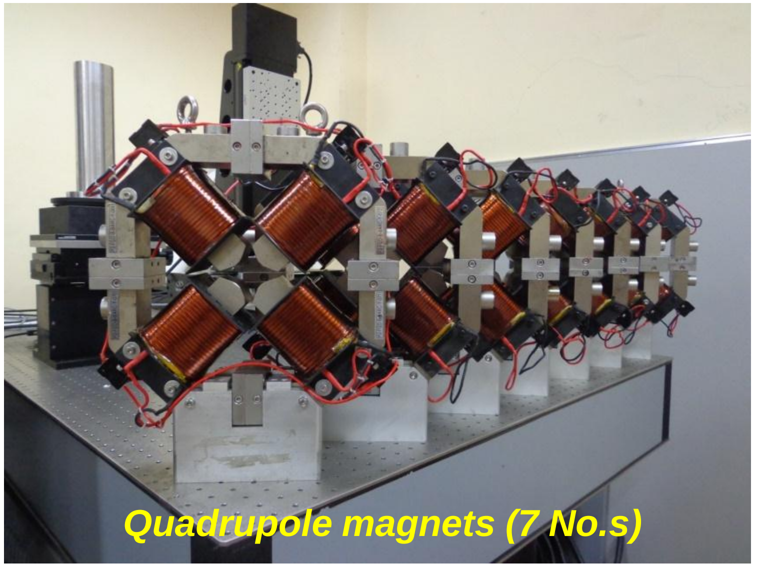


Magnet	Nos
60 degree bending magnet	2
Quadrupole magnet	7
Dipole Corrector	5

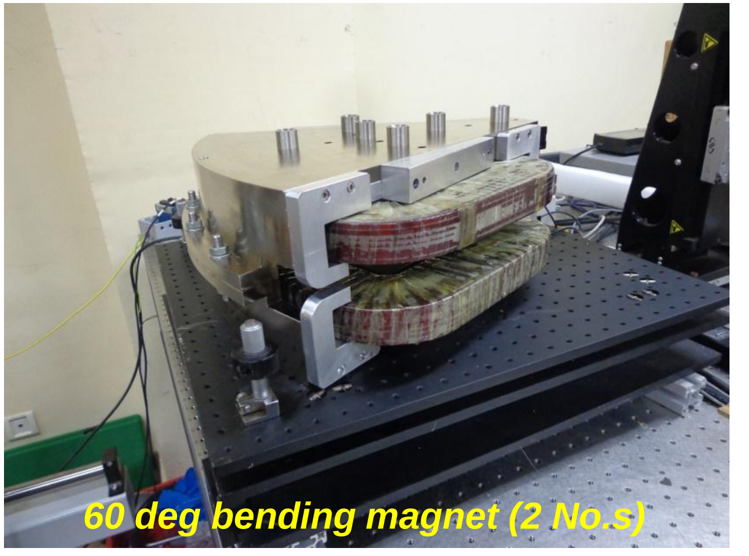
Quadrupole Magnet

SN	Parameter	Value	Unit
1.	G	11.5	T/m
2.	Aperture	34	mm
3.	GFR	23	mm
4.	Homogeneity in GFR	<0.5	%
5.	Effective length	71	mm
6.	Roll angle	<3 mrad	ppm

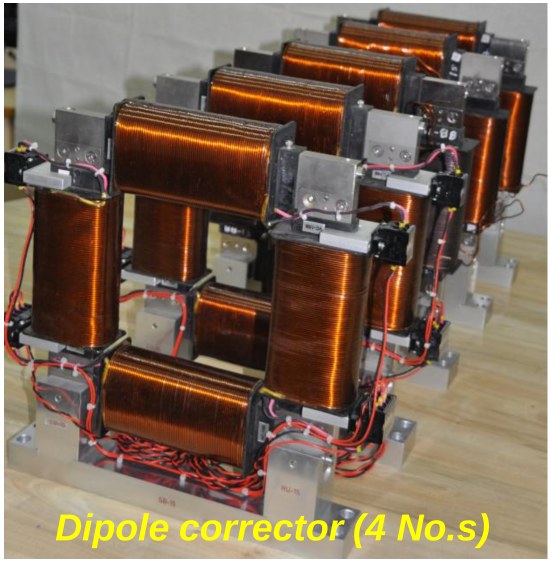
Magnets for DLS



Quadrupole magnets (7 No.s)



60 deg bending magnet (2 No.s)



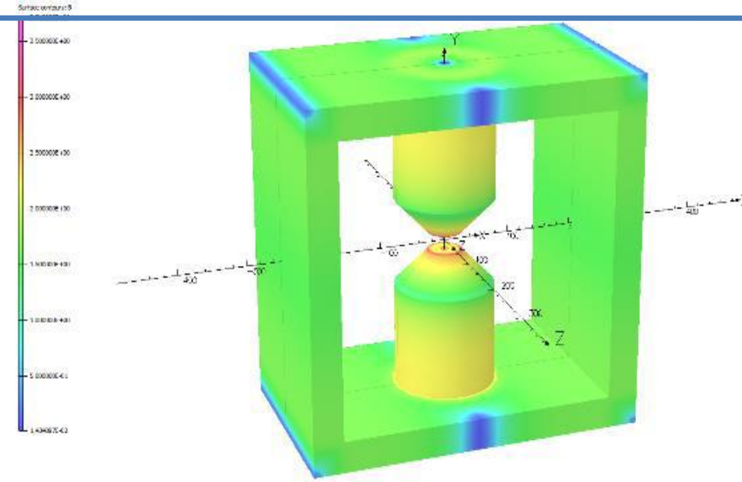
Dipole corrector (4 No.s)

Synchrotron Beamline Magnets

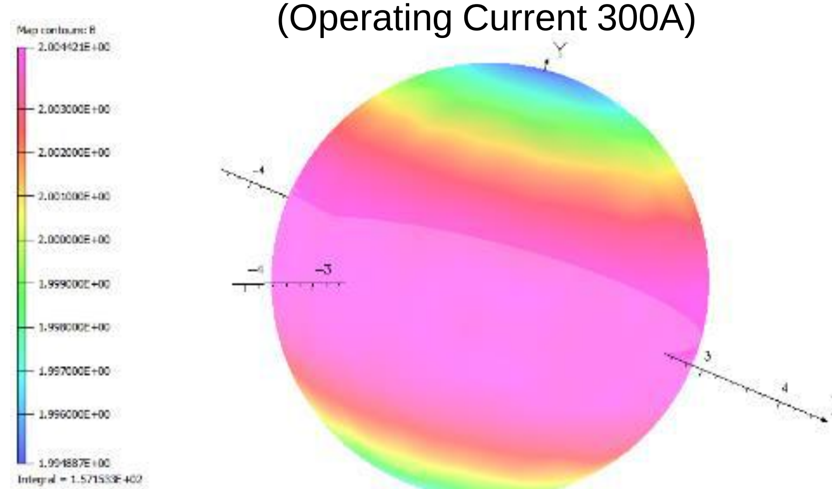
Dipole Magnet for XMCD Measurements (BL-08)

Technical specification of the Electromagnet for XMCD measurements

Parameter	Values
Central Magnetic field	2 Tesla
Pole Air gap	25 mm
Max Sample size Area	5 mm × 5 mm
DSV	5 mm
Magnetic field uniformity	100 ppm
Magnet Shape	H Dipole
Magnet outer dimensions Restrictions	500 mm×500 mm ×400 mm
10 mm diameter central hole through the magnet for the X-ray beam to pass through	



EM Design of the electromagnet (Operating Current 300A)



Central Magnetic Field (2 Tesla)

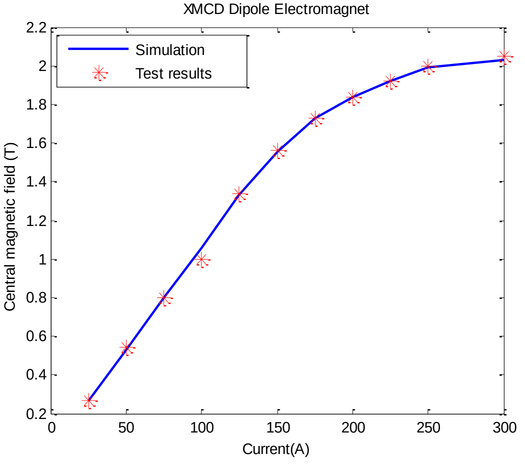
Magnetic field uniformity (DSV: 5 mm) (Better than 100 ppm)

XMCD Magnet measurements

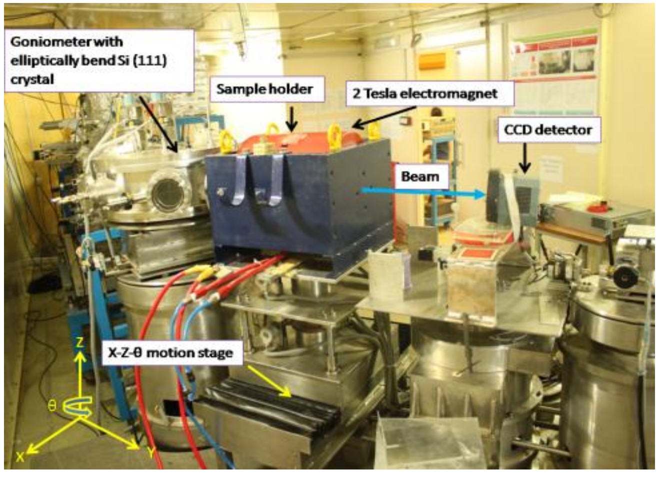
Jig for winding 12mm × 12mm hollow conductor

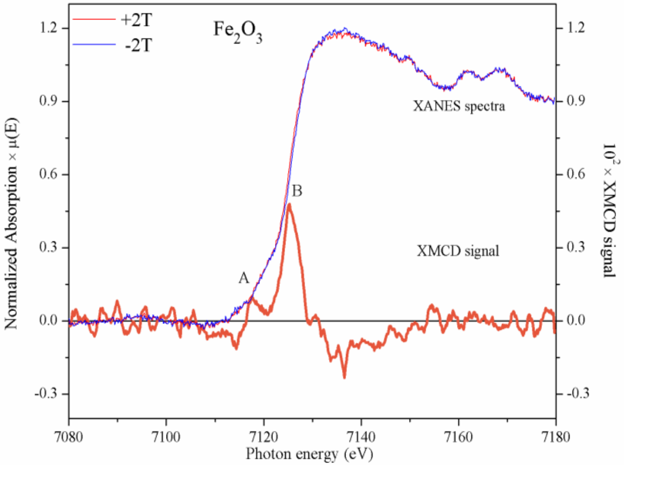
X-Z-θ motion stages which can carry 500 Kg max load

Electromagnet with hydraulic and Electrical connections



Simulated and measured B-Field in center of air-gap

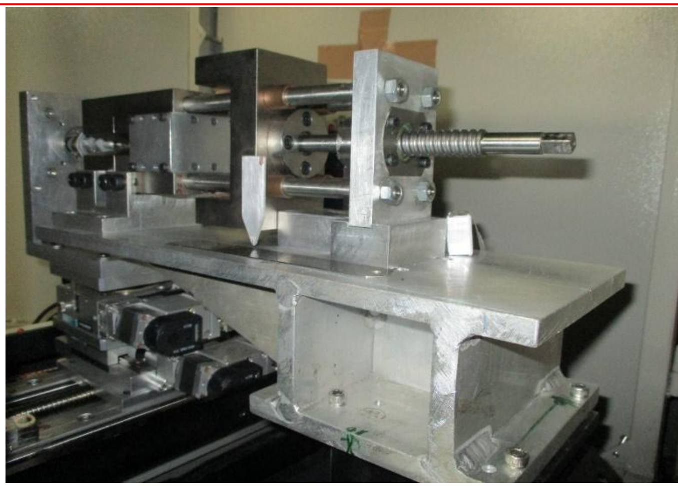




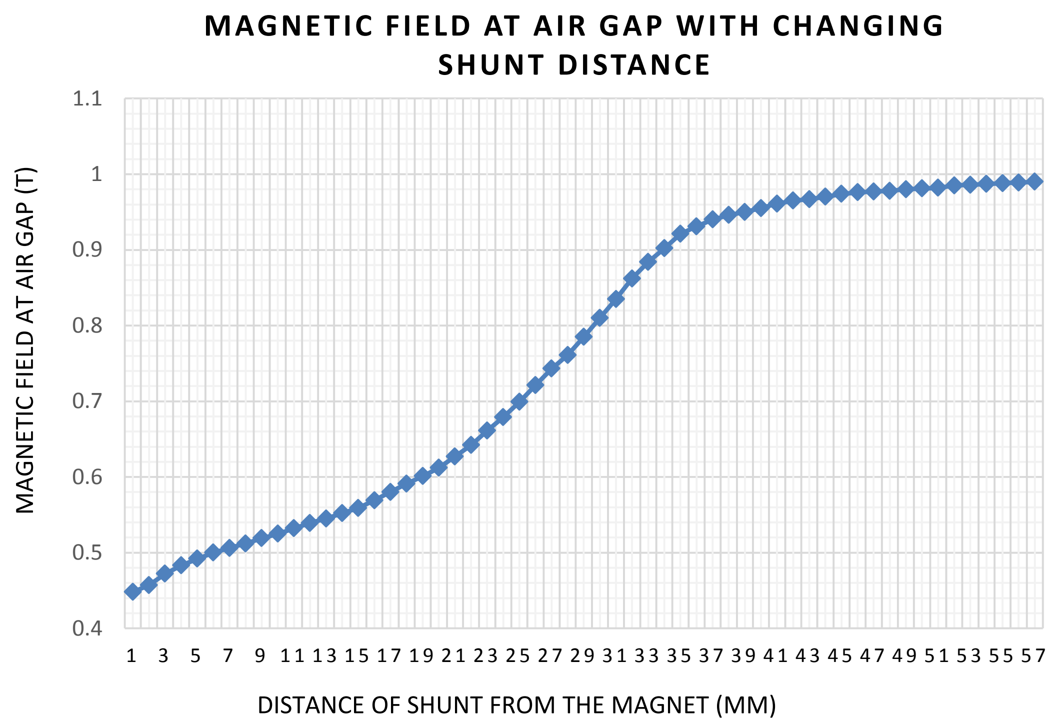
Photograph of the Energy Dispersive EXAFS beamline along with the magnet in BL-08 at Indus-2 Synchrotron

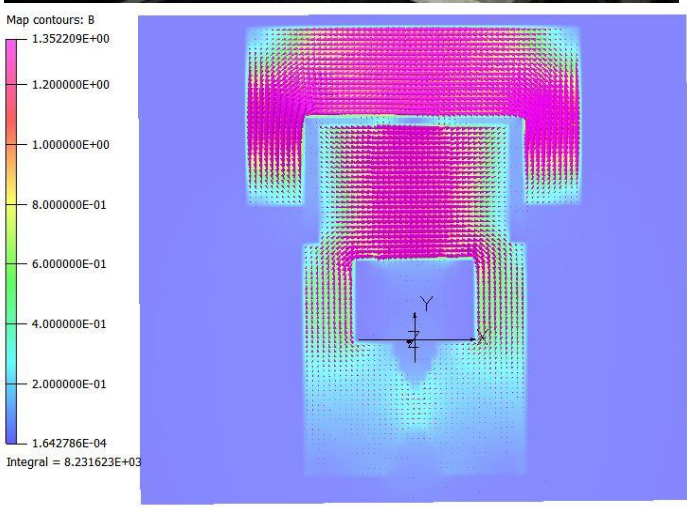
Variable field Permanent Magnet Dipole

- To understand the magneto-structural transitions in magneto-caloric materials at room temperature, x-ray diffraction studies have to be done in the presence of magnetic field.
- These studies are done at Beamline-11 of INDUS-II at RRCAT, Indore
- 1 T tunable permanent magnet based dipole was developed. Tuning of the magnetic field was achieved using a shunt soft iron plate.



Magnet installed at BL-11, INDUS-II

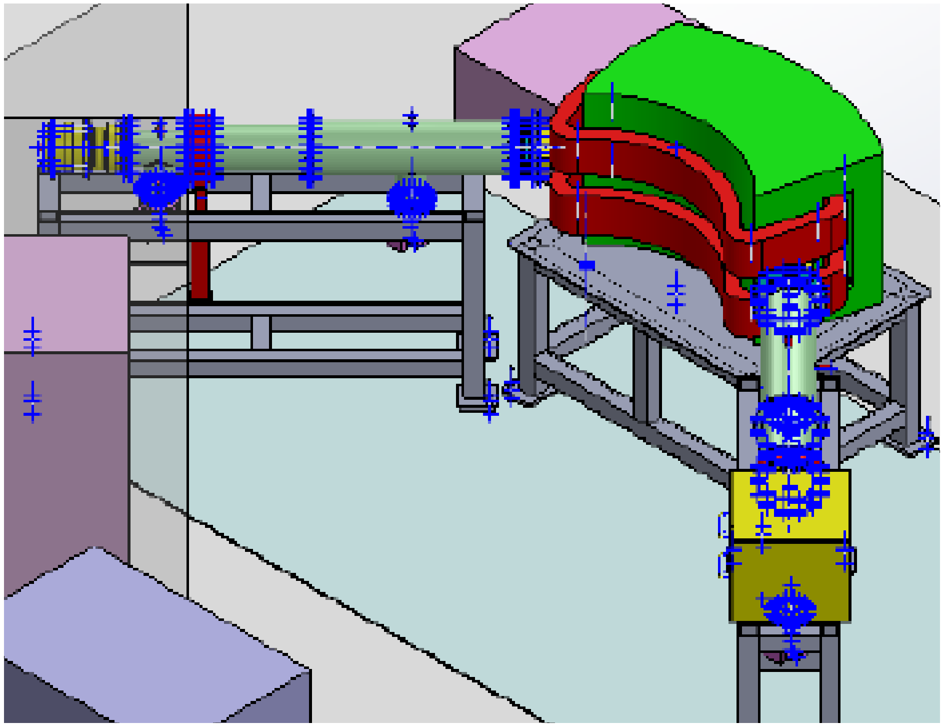




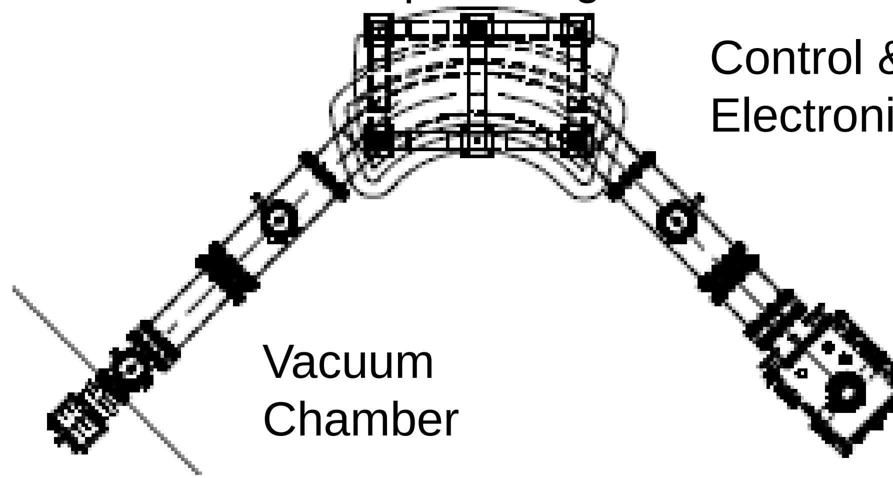
Magnetic flux being shunted by soft iron plate

- **Electromagnetic isotope Separation**

Layout of EMIS facility

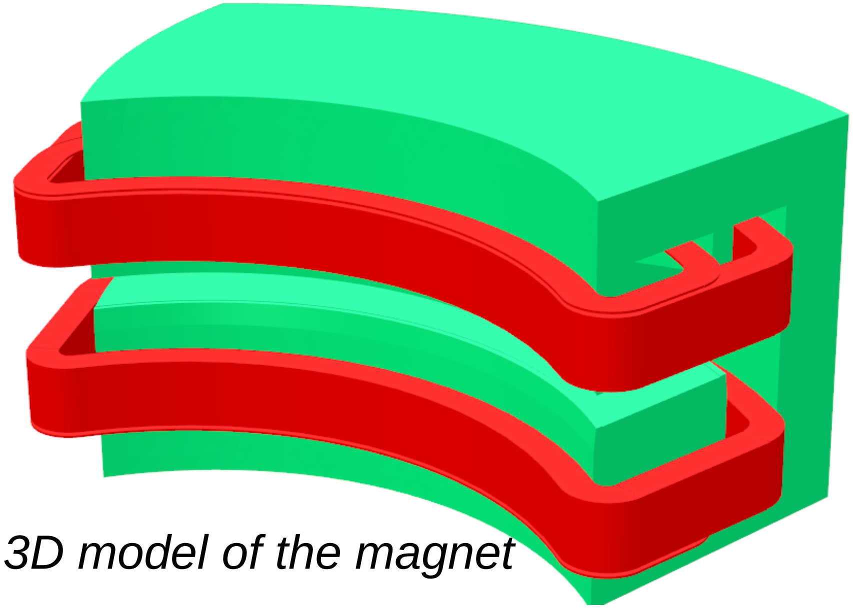


EMIS facility can be utilized to enrich other therapeutic radiopharmaceuticals

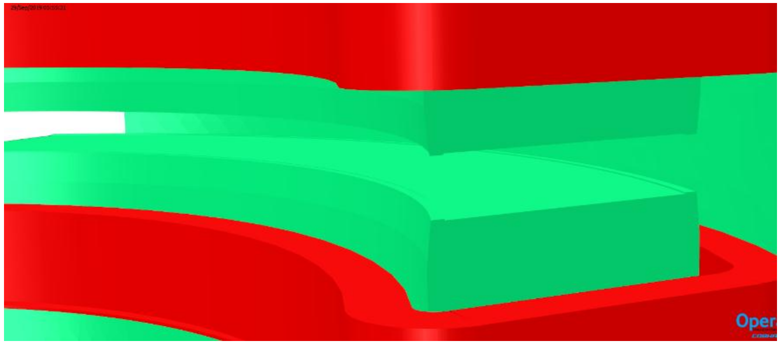


- Present requirement of Lu-177 is 100 mg per annum which will double in next couple of years.
- Natural Lutetium consists of about 2.5 % Lu-176
- 1 mg Lu-176 required to be produced every day
- 1 mA Lu beam required per day, assuming 8 hours operations.

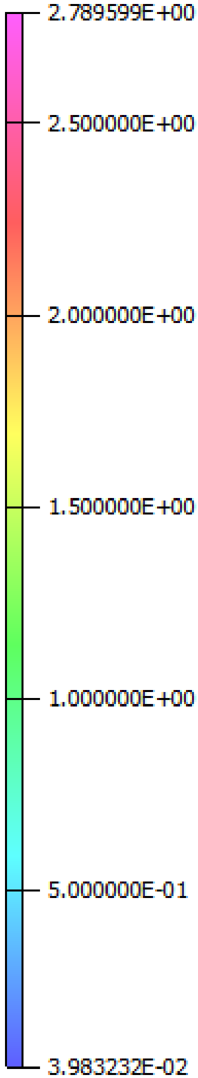
Magnetic Design

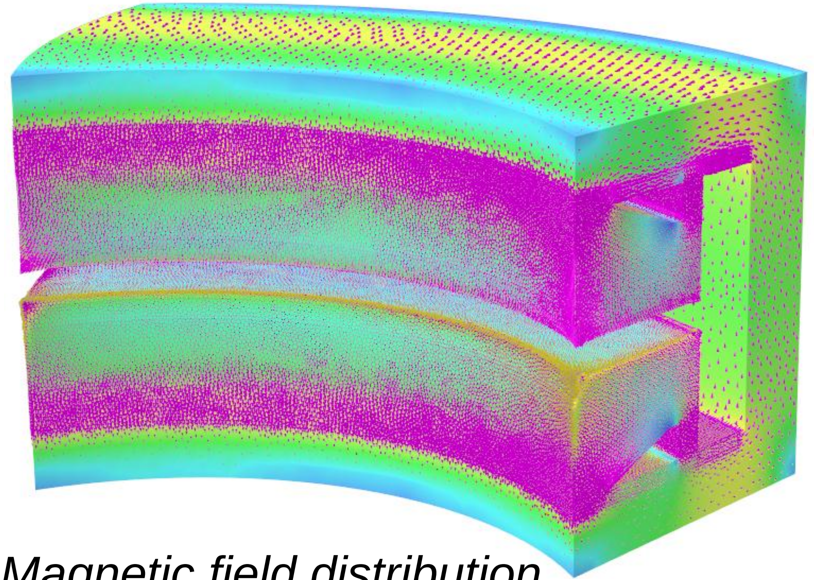


3D model of the magnet

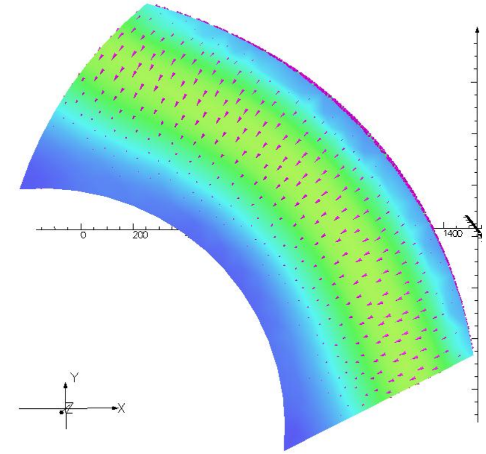


Pole shim design to achieve desired magnetic field homogeneity



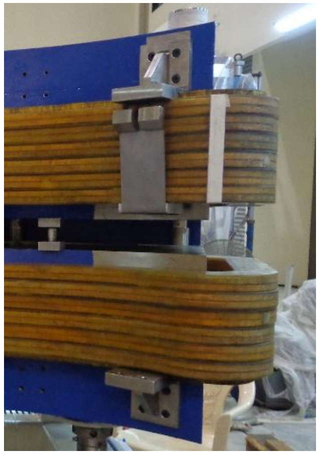


Magnetic field distribution in the magnet yoke and poles



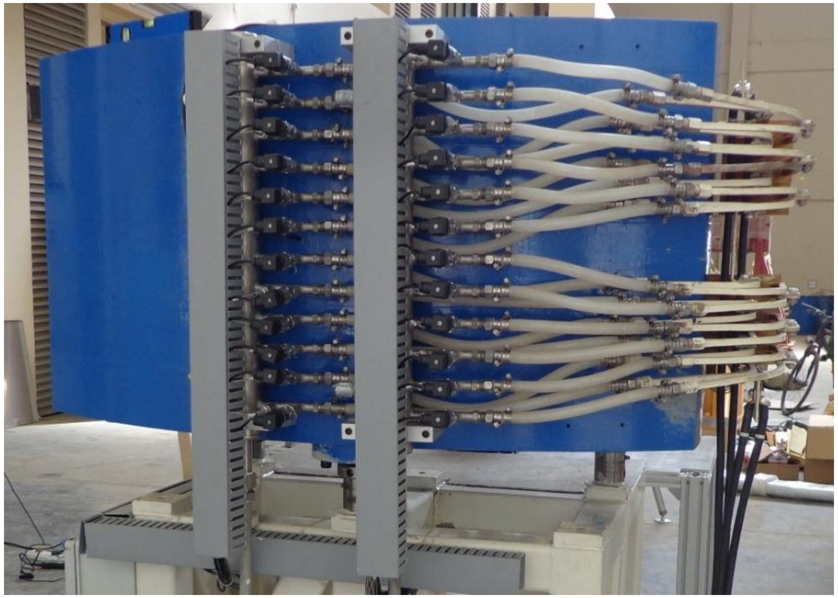
The developed Electromagnet

Magnet installed at Engineering Hall-11



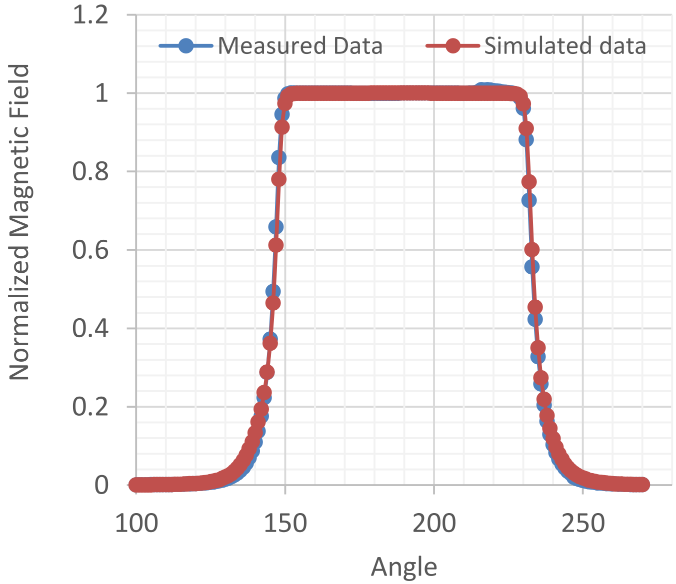
Rotatable poles

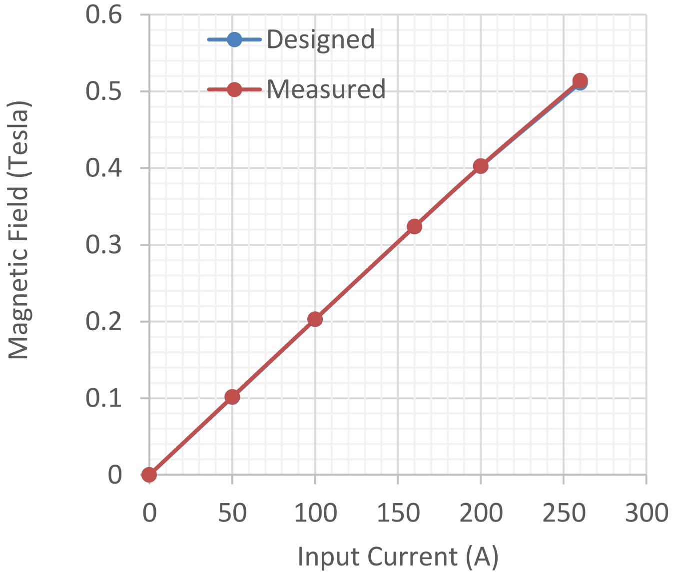
Pole gap region



Headers for coils heat removal

Magnetic Measurement Results



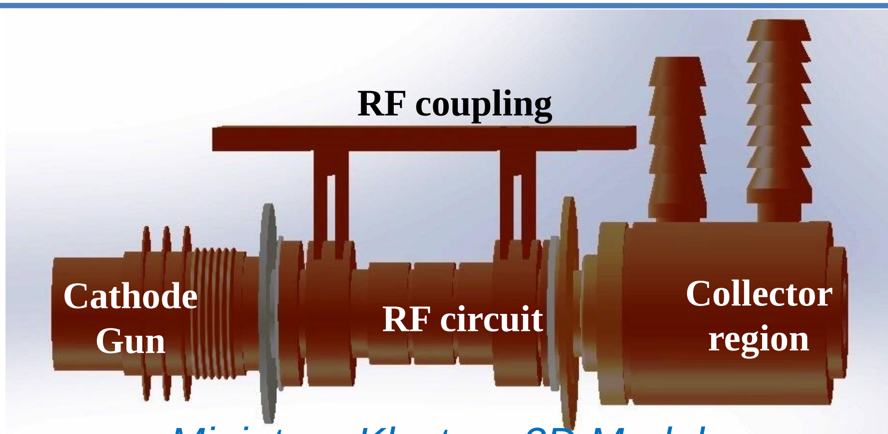


- **Magnets for RF Devices** ***(Electron beam)***
    - *PM magnet for miniature Klystron*
    - *Hybrid Magnet for S-Band Klystron*
    - *PM magnet for X-Band RBWO*
    - *Cavity Magnet for 42GHz Gyrotron*
    - *Pulsed Electromagnet for high frequency Gyrotron*

Magnetic Field Requirements and challenges for RF Devices

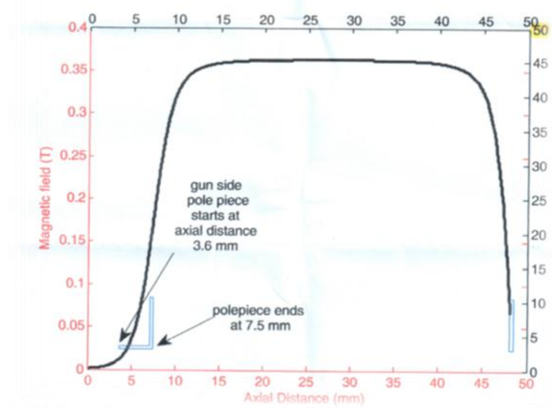
Axial magnetic Field ***(High Space Charge beam)***	• *High Magnetic field requirement for single beam Klystrons and Gyrotrons*
Rise of field	• Transition from zero axial field to full field (2 decades) over very short axial distance.
Field Uniformity	• Highly uniform field is required for beam focusing.
Cathode gun shielding (Confined Flow)	• An optimum field level of field is required for maximum beam transmission in Klystrons and Gyrotrons
Collector field requirement	• Optimum Level of field for adiabatic beam expansion in collector region
Asymmetry ***(RF Ports/Waveguides)***	• Asymmetries in the magnet design interferes with optimum performance of the tube in output cavity region.

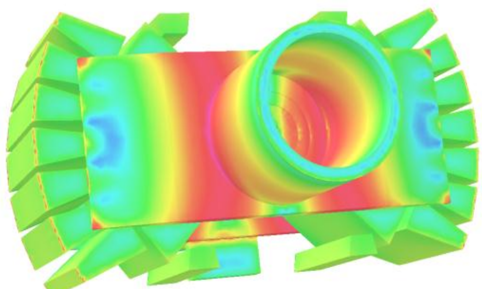
0.35T Permanent Magnet for Miniature High Frequency Klystron



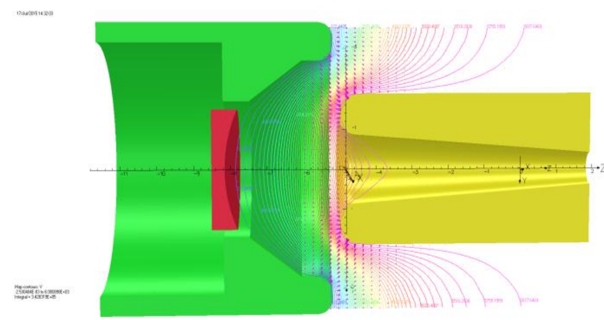
Miniature Klystron 3D Model

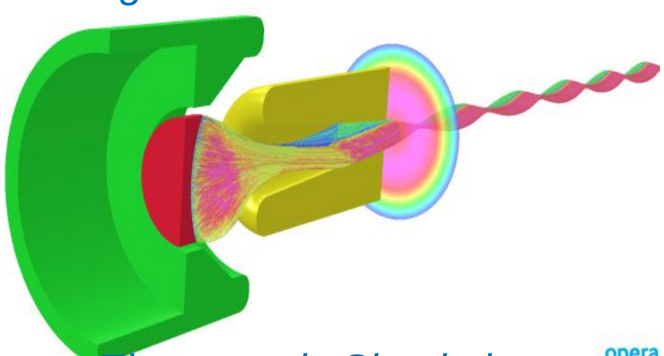
Beam optics requirement



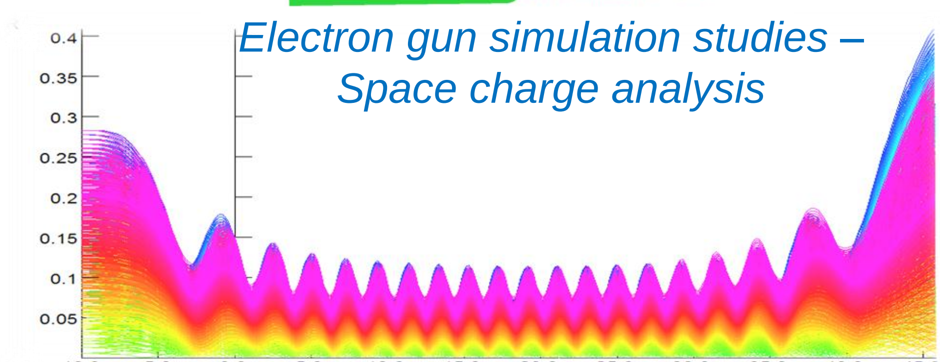


Magnetostatic Simulation



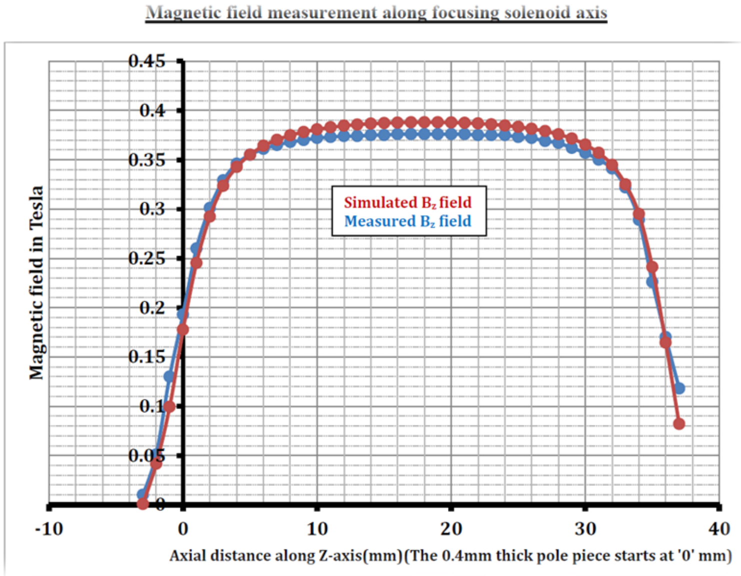


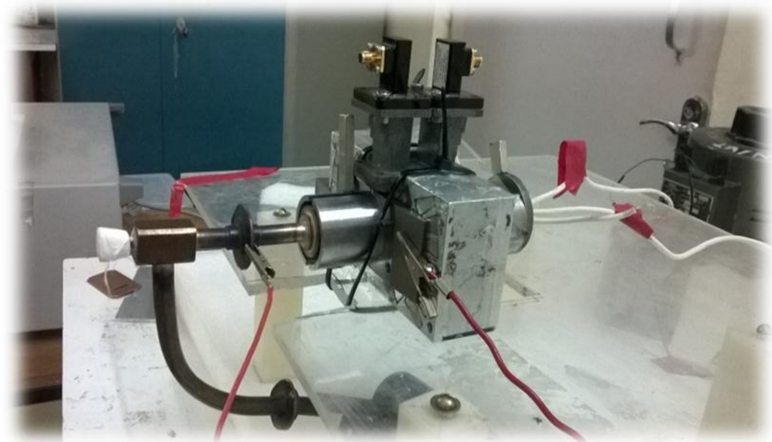
Electrostatic Simulation



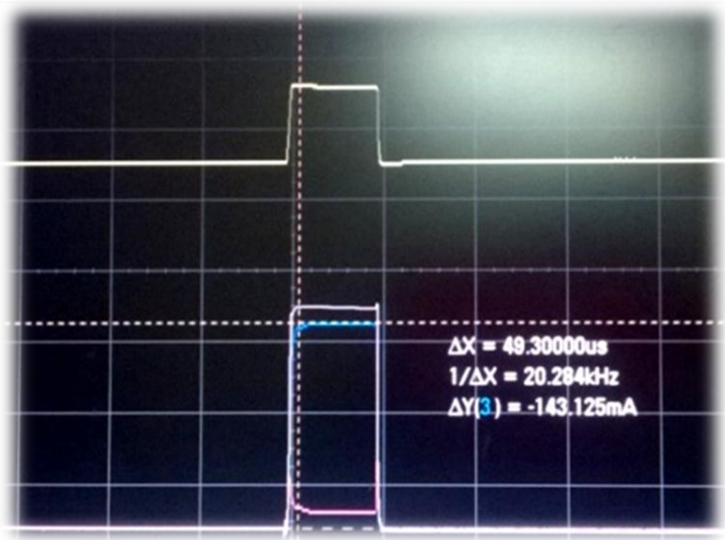
Electron gun simulation studies – Space charge analysis

0.35T Permanent Magnet for Miniature High Frequency Klystron

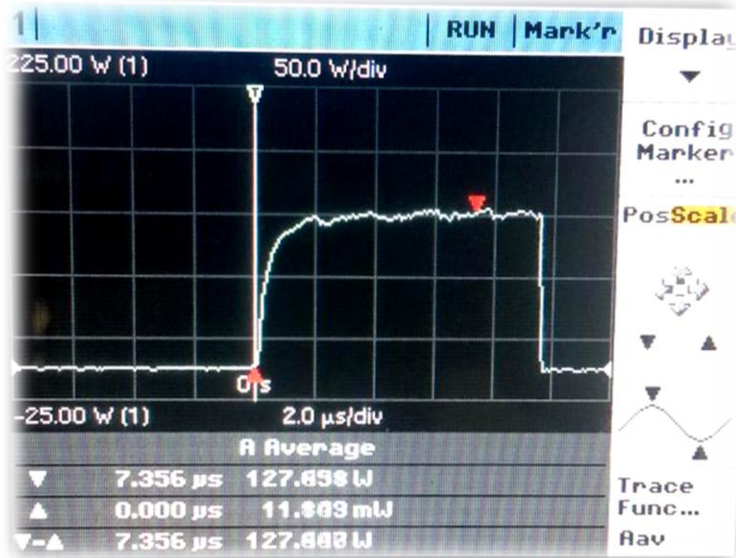




Magnet integrated with the klystron tube



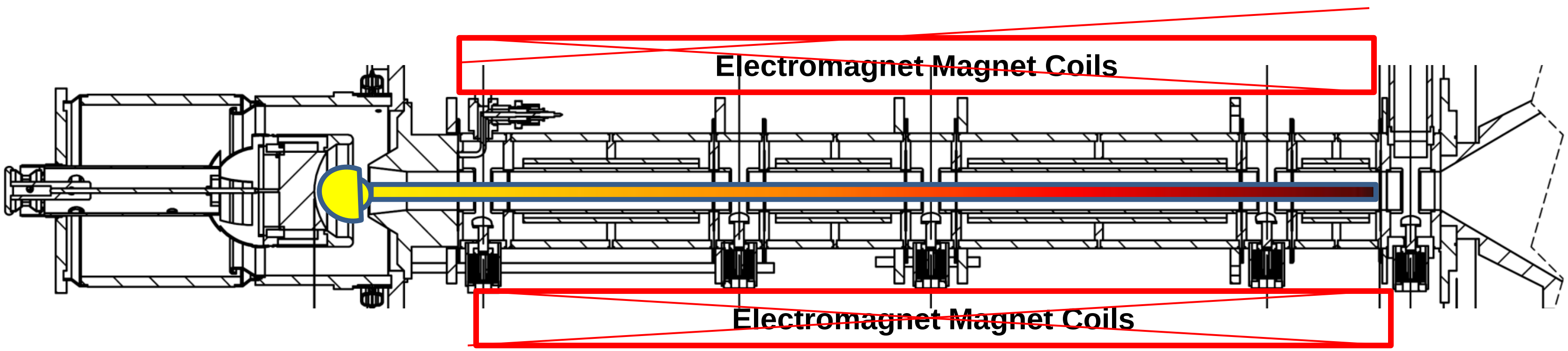
Beam transmission results



RF Power Measurement (125W)

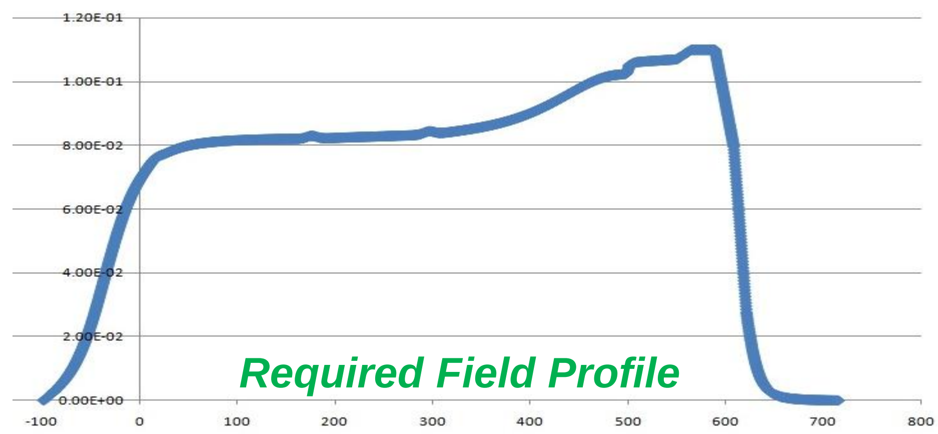
Hybrid Magnet Assembly for S-Band Klystron

5 MW, 2856 MHz S-Band klystron is being developed by CSIR-CEERI for 10MeV RF Linear Accelerator.



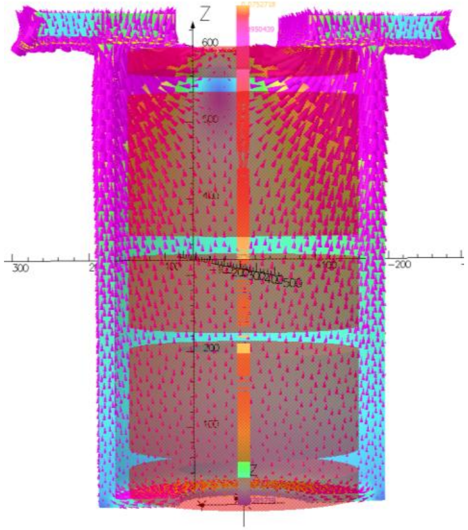
Cathode Gun **Beam-Wave Interaction Region** **Collector**

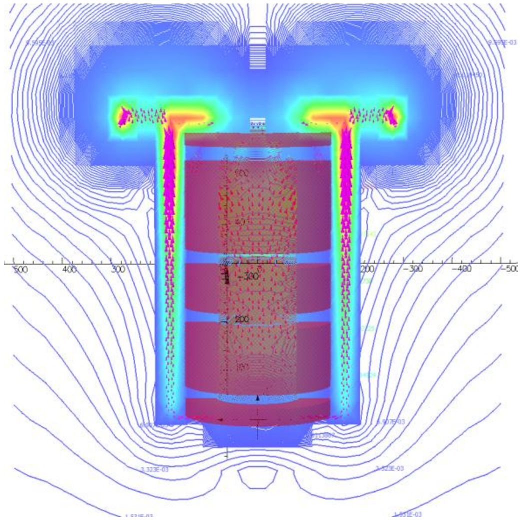
Parameter	Value
Frequency	2856 MHz
Output power	20KW (Average) /5 MW Peak
Beam Voltage	135 KV
Beam Current	116 A
PRF	300Hz



Development of Focusing lens to confine the electron beam with high spatial charge density was a major bottleneck in the Klystron development.

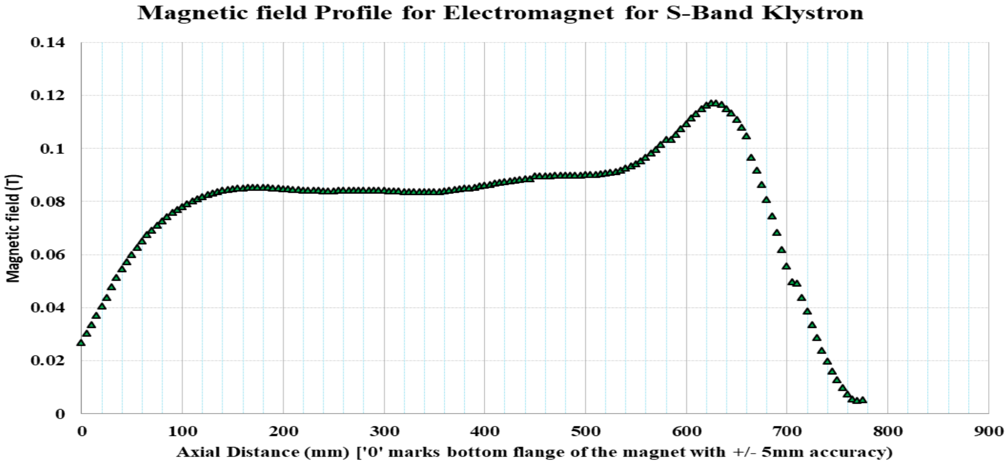
Hybrid Magnet Assembly for S-Band Klystron





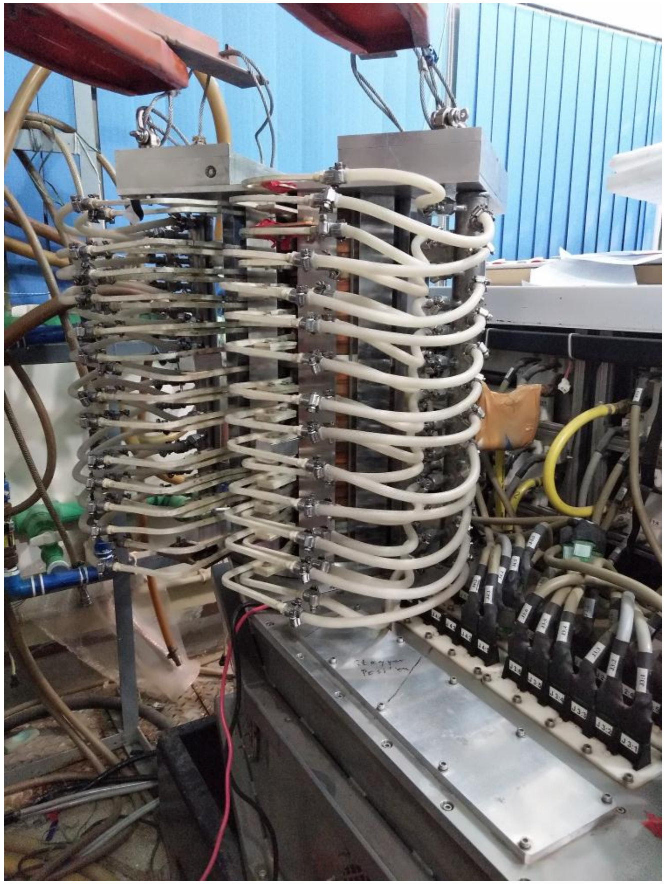
S-band Klystron assembly

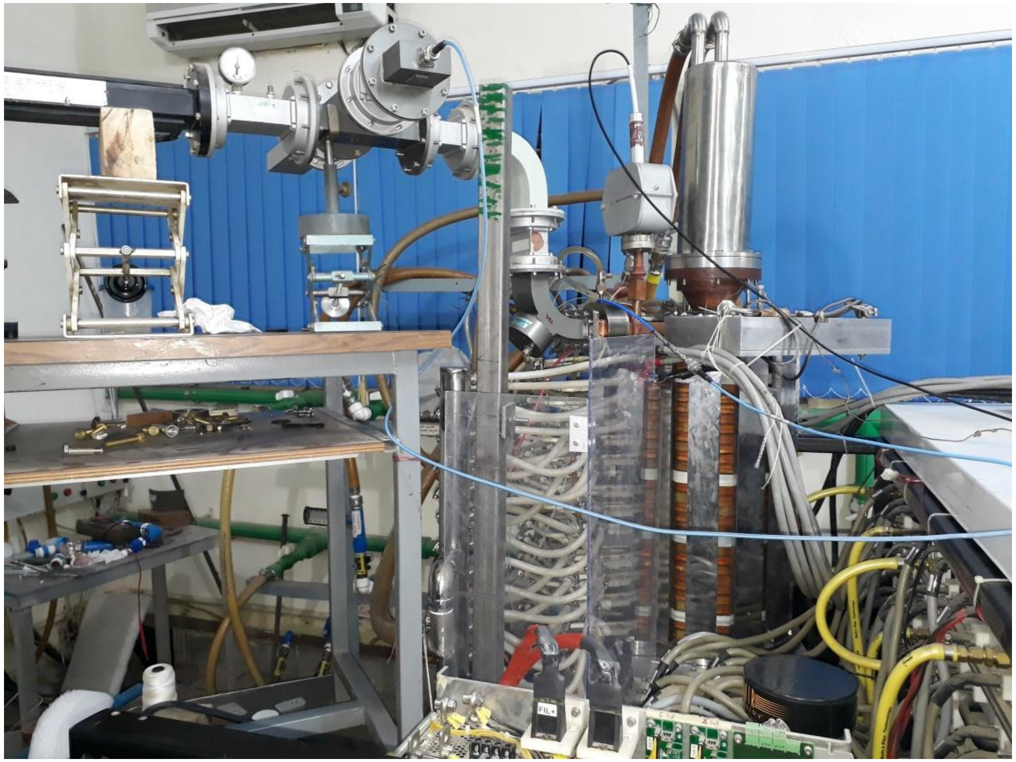
Electromagnetic design



Field profile Hybrid Electromagnet Assembly

Integration & assembly

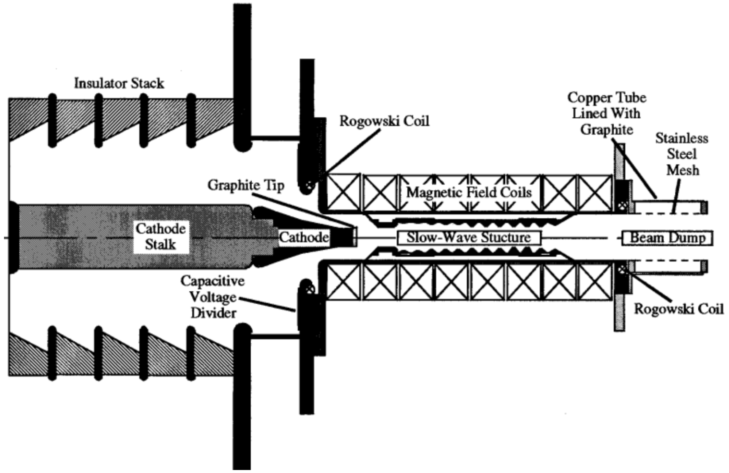




Magnet has been integrated with S- Band Klystron Tube assembly at CSIR-CEERI & RF Trials are in progress.

Magnets for high power Backward wave Oscillators

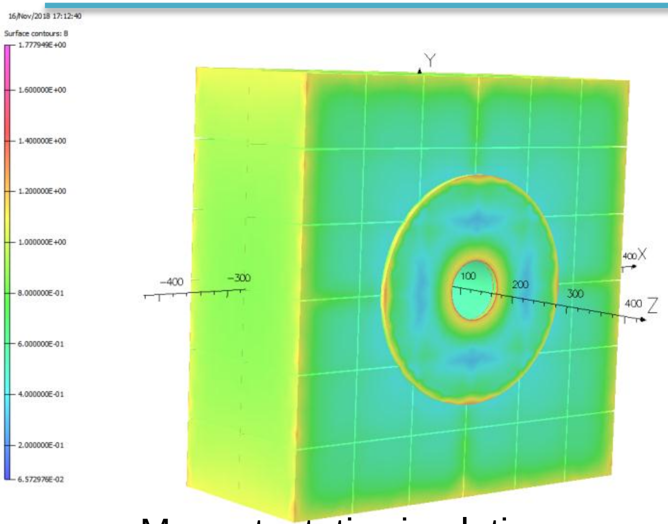
Backward wave oscillators (BWOs) are *Cerenkov radiation b*ased, high power microwave sources. These find application in plasma science, electronic warfare (Active Denial System- ADS), high power radar (Nanosecond Gigawatt Radar-NaGiRa system) and electronic system susceptance and vulnerability testing.



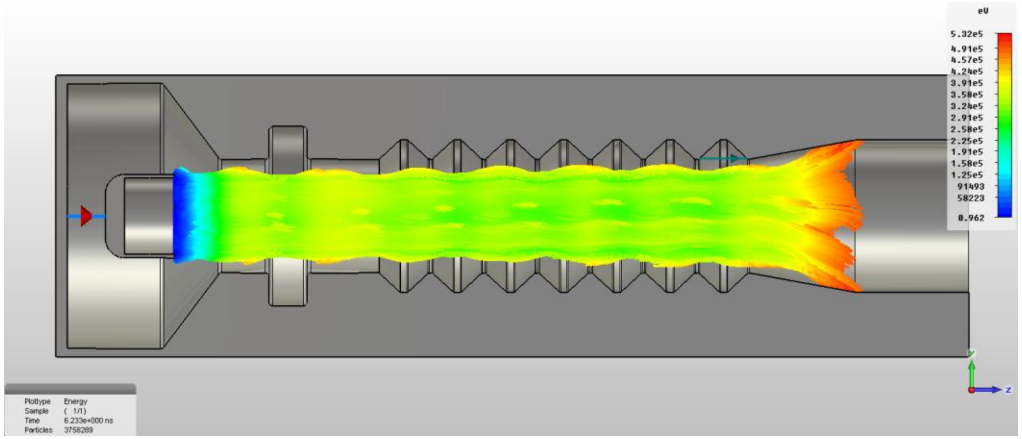
Schematic drawing of backward wave oscillator.

Slow Wave Structures (SWSs) are an essential component of the BWO system since they guide the electromagnetic mode while concurrently matching wave velocity to the electron beam velocity.

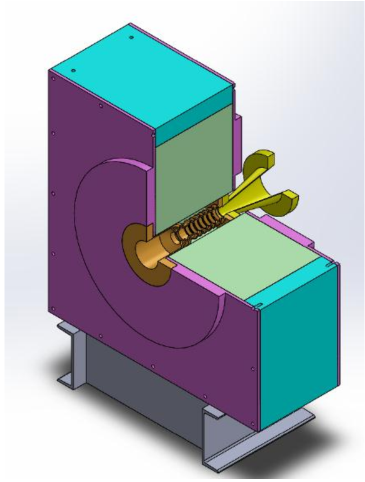
Permanent Magnet Design For X-Band RBWO



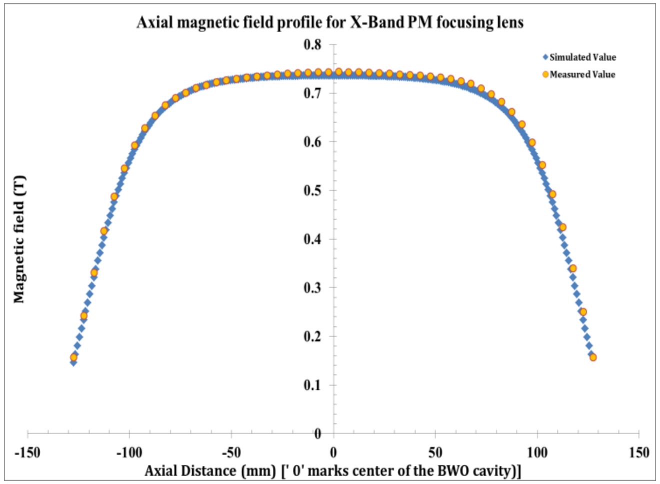
Magnetostatic simulation



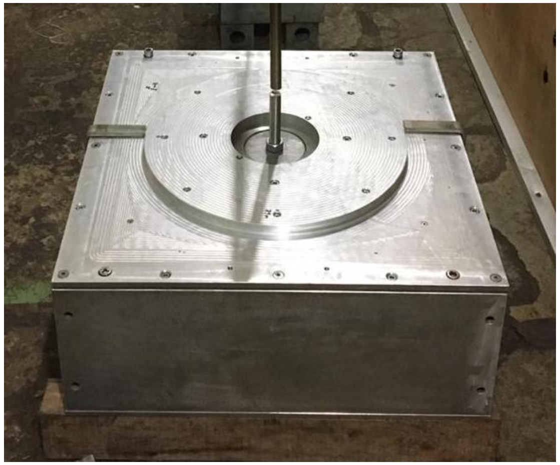
Beam transmission through the RBWO tube



Engineering Model of magnet assembly and tube



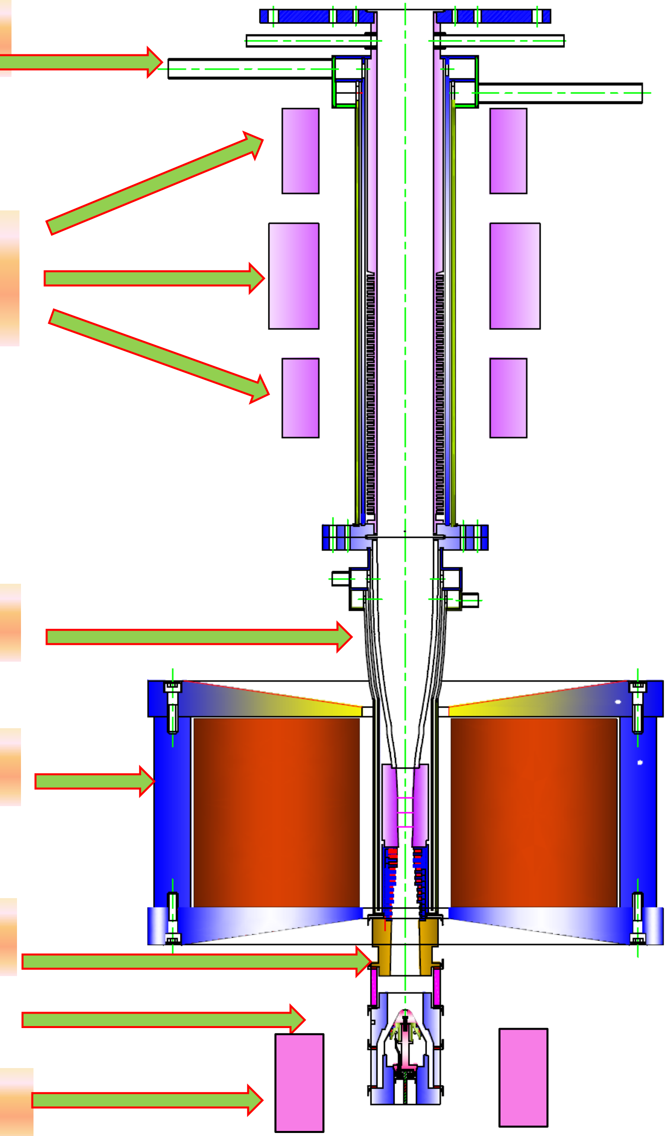
Magnetic measurement result



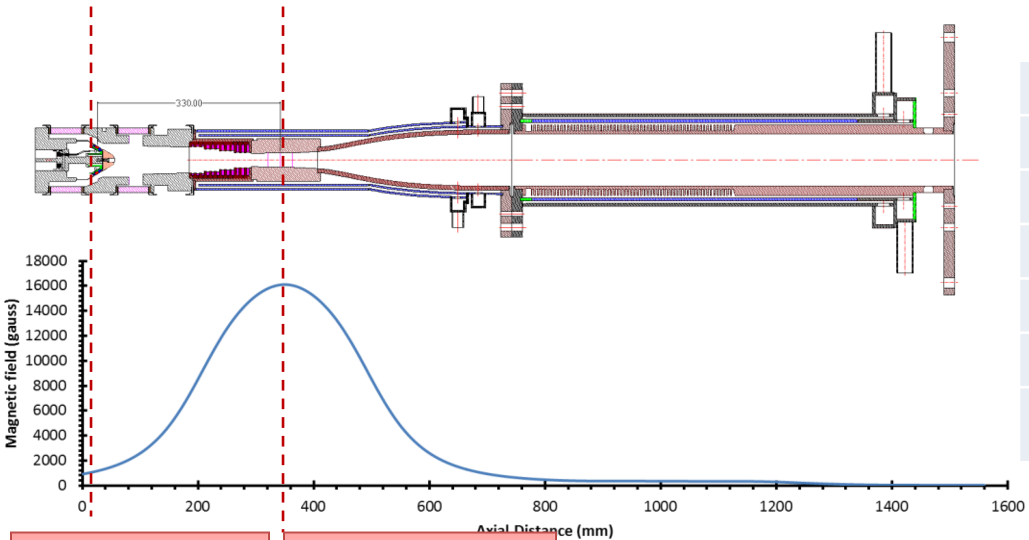
Developed Magnet Assembly

42 GHz, 200 kW Gyrotron for Indian TOKAMAK system

- DST sponsored multi-institutional research project.
- First indigenous high power Gyrotron tube development
- ***Development of Focusing lens to confine the electron beam with high spatial charge density was a major bottleneck in the Gyrotron development.***



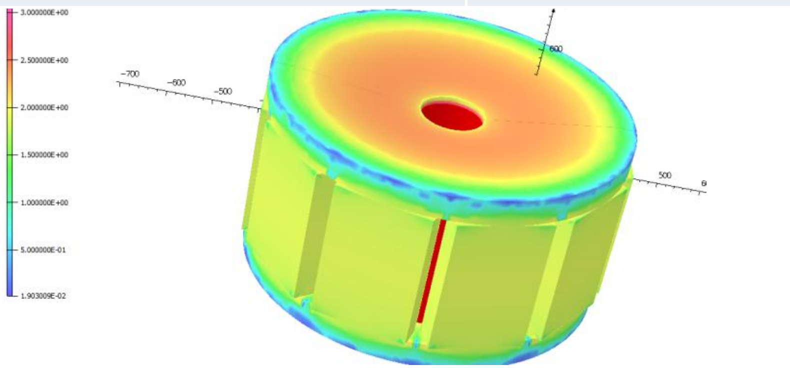
Field Requirements & Simulation studies



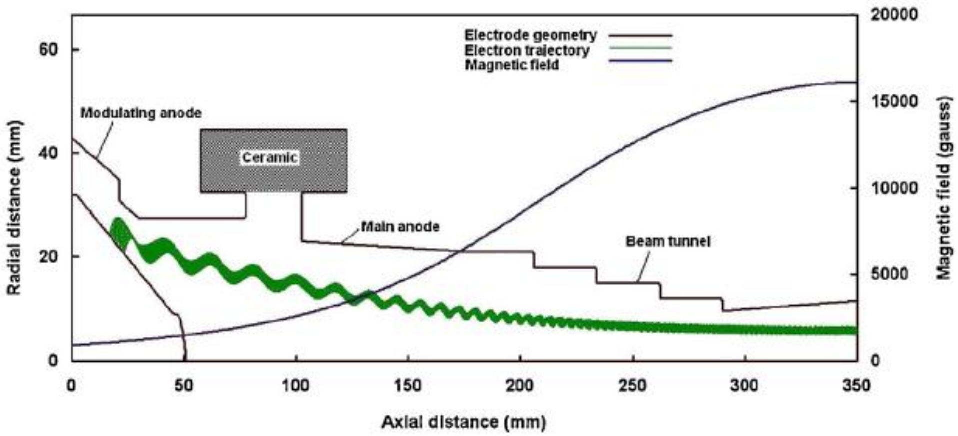
Cathode center:
0.11 T

Cavity center:
1.611 T

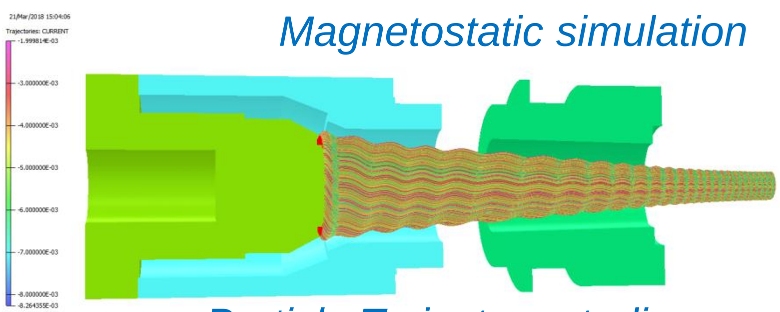
Frequency	42GHz
Output power	200kW(CW)
Beam Voltage	60-70kV
Beam Current	10A
Beam Velocity ratio (α)	1.35
Total conversion efficiency	>30%
Oscillating Mode	TE_{03}



Magnetostatic simulation



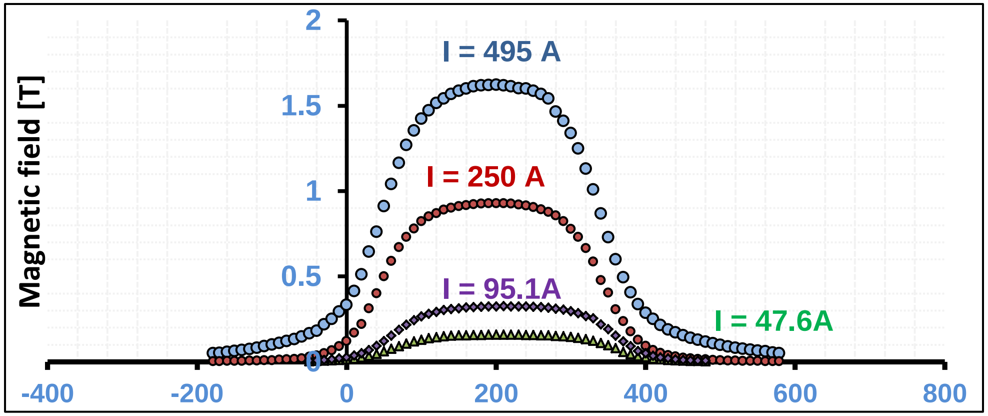
Axial beam Compression



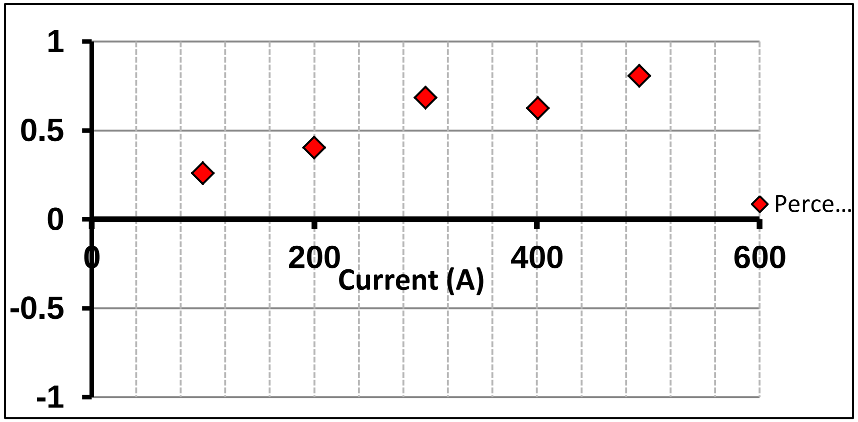
Particle Trajectory studies

Summary of test results

S No	Parameter	Measured	Designed
1	Magnetic field at cavity center	1.612T	1.611T
2	Magnetic field at MIG gun	0.1030 T	0.1036T
3	Hydraulic Pressure drop	9.5 bar @ 37 LPM	9 bar @ 36 LPM
4	Maximum temperature rise	45ºC	44ºC
5	Voltage across coil @ 495A	240V	235V



Measured axial field at various currents

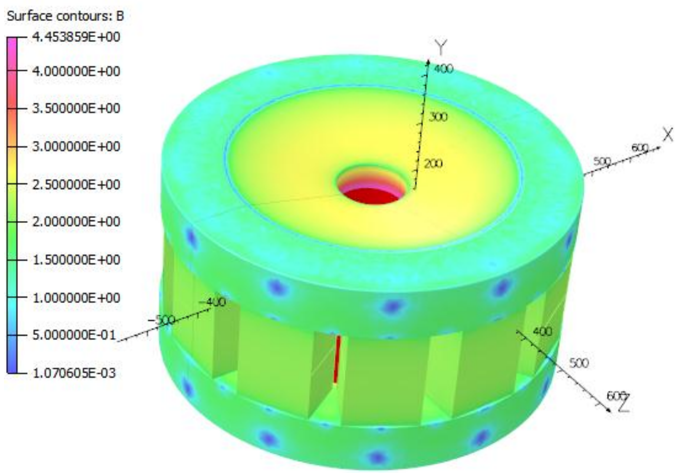


% Error plot in simulated Vs Measured data

Installation at IPR

- Design initiated in Jan’2017; Magnet delivered to IPR in Nov,2017
- Installed and commissioned at IPR Jan’ 2018
- Integrated with the Gyrotron tube on second week of February
- Beam successfully transmitted through the Gyrotron
- 125 KW of RF power extracted.

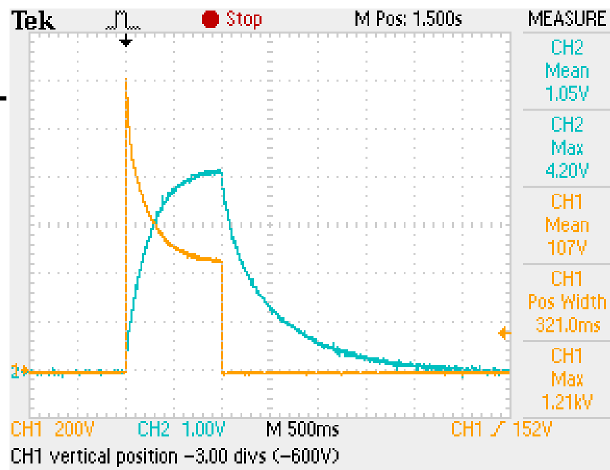
Pulsed Electromagnet for high frequency Gyrotron



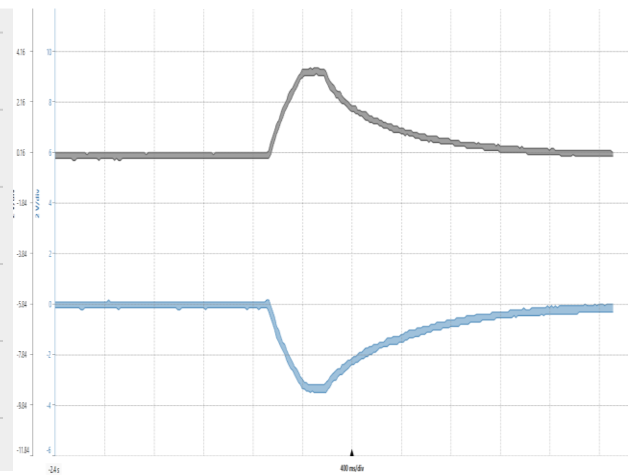
3D EM Design Model

Developed magnet assembly

Ampere turns required : 850 KAT
Bcavity : 3.665T
Field Uniformity : ± 0.1%
B $_{Cathode}$: 0.1875 T
Stored Energy : 114 KJ
Inductance : 0.27 H



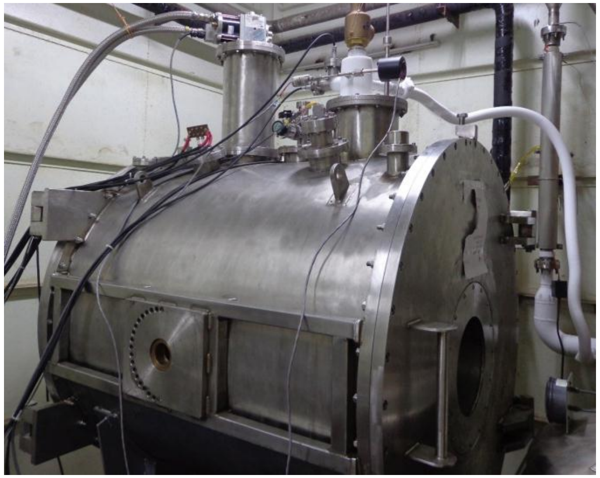
PS Current and voltage plot



Current and magnetic field plot

- **Superconducting magnet technology**
  - *300mm RT Bore liquid helium cooled superconducting magnet*
  - *300 mm RT Bore Conduction cooled superconducting magnet*
  - *130 mm RT bore 4T conduction cooled magnet assembly*

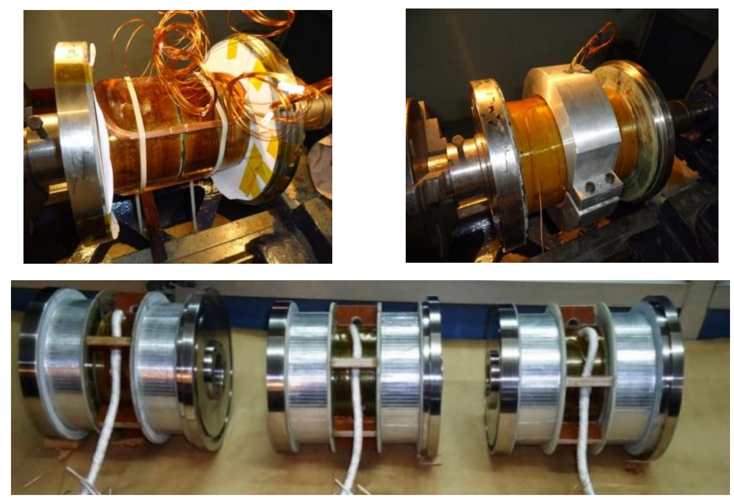
Superconducting Magnet Technology



300mm LHe cooled SC magnet for MHD experiments

130 mm warm bore cryogen free SC magnet for High Frequency RF device

300mm cryogen free SC magnet for MHD experiments

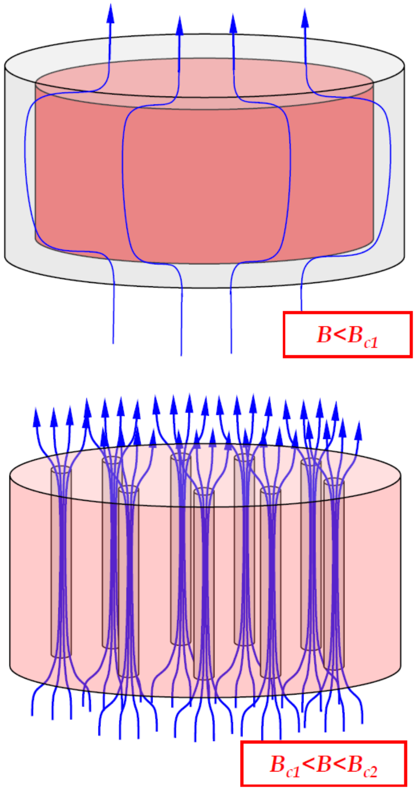


Cold bore SC magnet for SSR Cryomodule under IIFC

Introduction to superconducting magnet technology

Superconducting magnet design is a multidisciplinary field:

Material Science	Superconducting material
Quantum Physics	Key mechanism of superconductivity
Classical Electrodynamics	Magnet Design
Mechanical Engineering	Support Structures
Electrical Engineering	Powering & Quench protection
Cryogenic & Thermal	To maintain cryogenic temperatures



Flux Pinning in Type II SC magnets

Quench Phenomenon in SC magnets

Conductor limited quench

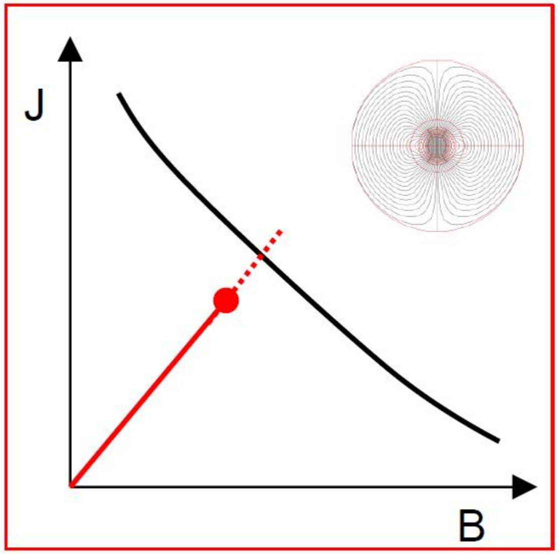
Critical surface is crossed due to an increase in I (or B)

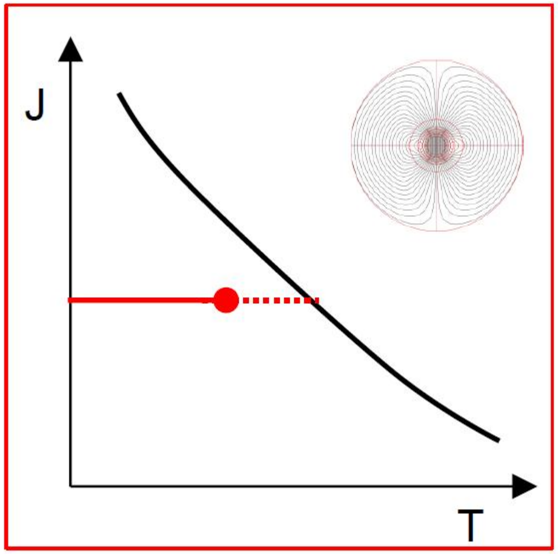
Taken care in magnet design by choosing the load line of the magnet so as to operate at nearly 80% of the critical current

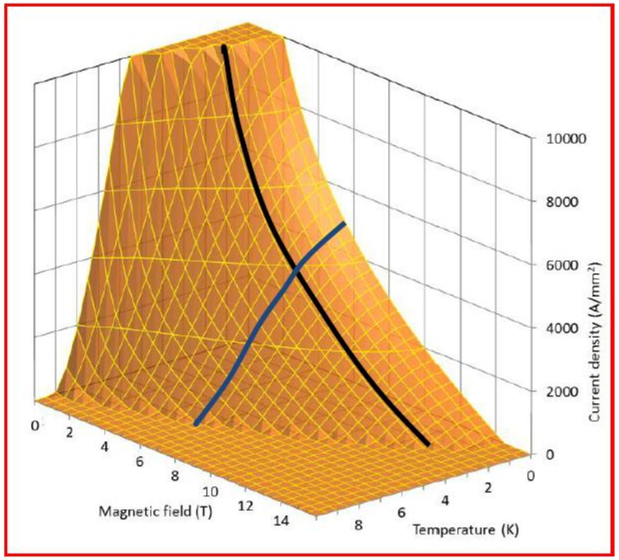
Energy- deposited or premature Quenches

Critical surface is crossed due to an increase in T

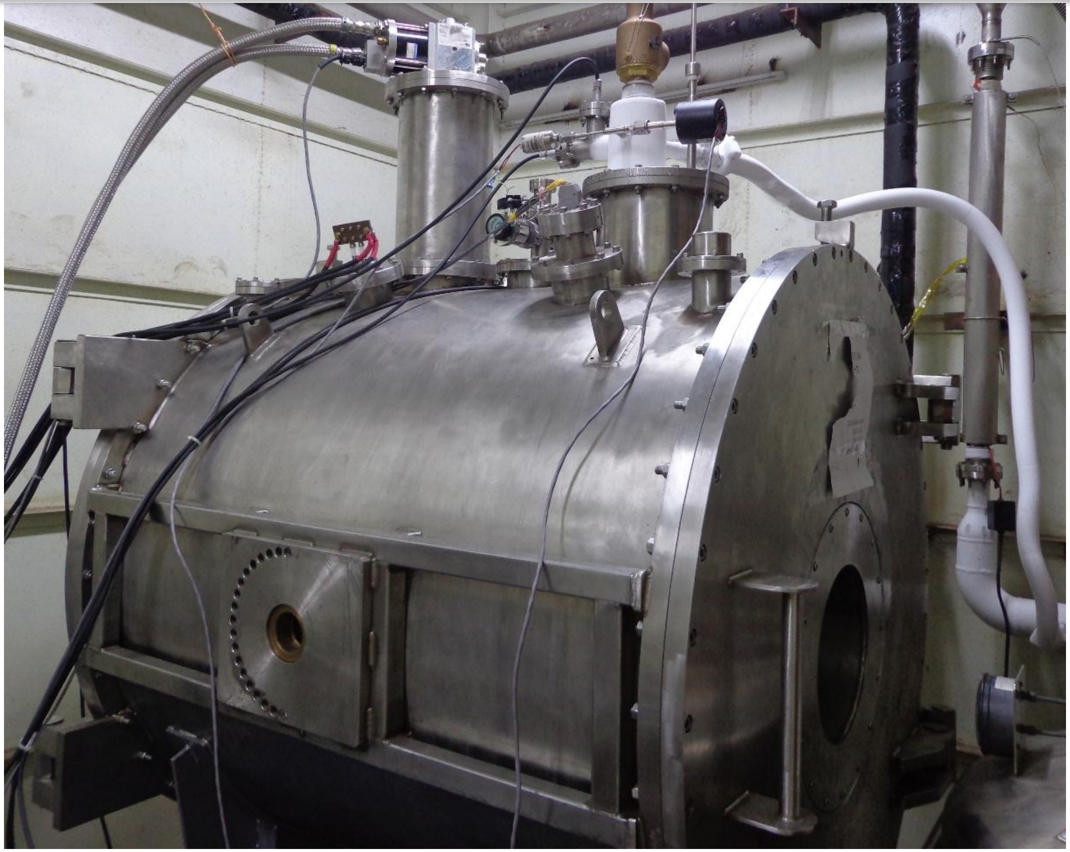
Taken care in magnet thermal design & magnet fabrication by pre-stress to avoid epoxy cracks during powering of the magnet





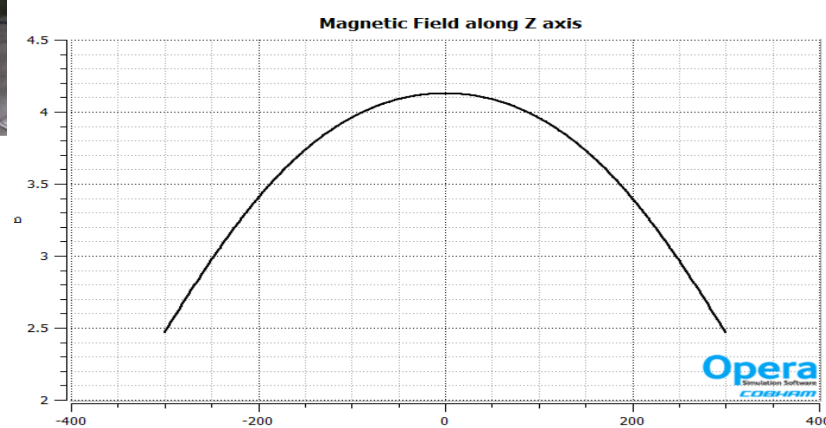


Warm Bore LHe cooled SC Solenoid magnet for MHD experimental Studies



Liquid Helium Cooled 4 Tesla 300mm diameter room temperature bore Superconducting Solenoid magnet

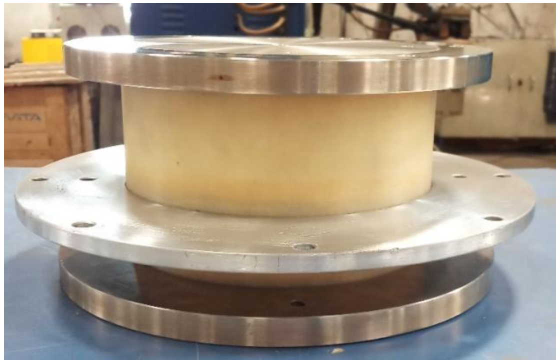
Technical specifications	
Central Magnetic field	4 Tesla
Operating current	300 A
Magnet stored energy	930 KJ
Room Temperature Bore	300mm
Thermal shield	50K
Cooled by Closed Cycle GM Cryocooler	
Operating Vacuum level	10^{-6} Torr
Helium evaporation rate	< 1 LPH



Warm Bore Conduction cooled SC Solenoid magnet for MHD induced experimental corrosion studies

Technical specifications	
Central Magnetic field	4 Tesla
Operating current	200 A
Magnet stored energy	1025 KJ
Room Temperature Bore	300mm
Thermal shield	50K
Cooled by Closed Cycle GM Cryocooler	
Operating Vacuum level	10^{-6} Torr

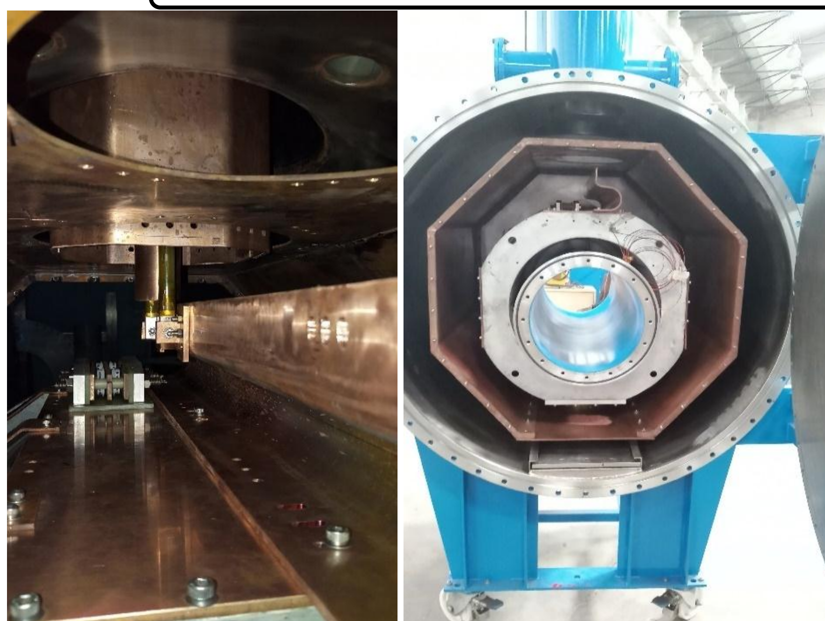
Conduction Cooled Superconducting Solenoid magnet Development and testing



Compression Post

Compression Post and Current Lead Heat Load measurement setup

SC Magnet Thermalisation using OFHC copper



Final Magnet Assembly ready for MLI wrapping and cold testing


Strive for self reliance
P2-FQD-B-BARC-Y-069
P2-FQD-B-BARC-Y-072
P2-FQD-B-BARC-Y-070
P2-FQD-B-BARC-Y-071
Thank you for your kind attention

Back –up slides

Magnetic Measurement Techniques for qualification of accelerator magnets

SN	Method	Measurable Quantity
1.	Solid State Sensors : Hall Probes	(a) Integral Magnetic field gradient (b) Higher order multipoles : Normal and skew Components (c) Magnetic centre
2.	Harmonic Coil Measurements	(a) Higher order multipoles measurements (b) Magnetic Centre (c) Integral magnetic field gradient
3.	Stretch Wire Magnetometer	(a) Integral magnetic Field measurements (b) Magnetic centre (c) Higher Order Multipoles

Facilities at BARC

6 axis Magnetic Field Mapping system

Volume of scanning : 1200 (mm) X 300(mm) X 300(mm) X 360^0 X 360^0 X 5^0

Magnetic field sensor: Hall probes (better than 0.1% accuracy) and induction coils

Maximum weight of magnet : 1000 Kg

Stretch Wire bench

Maximum aperture measurement : 300 mm

Accuracy : better than 0.5 %

Maximum weight of the magnet : No limit

Magnetic measurement sensors

Hall probes, GMR, Flux Gate sensors, NMR magnetometer, AMR magnetometer