Indigenous Development of Accelerator Magnets at RRCAT, Indore



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On behalf of

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Outline of talk

- Introduction
- Technical issues of Synchrotron magnets
  - Magnet design, Engineering & Characterization
- Development of magnets for various projects
- Technical facilities for development of magnets
- Conclusion & Acknowledgement

INTRODUCTION

AMTD, RRCAT designed, developed & characterized the large number of conventional magnets (~ 600 Nos.) for various Accelerator Projects, since 1988. These include:

- Magnets for Indus Accelerators (Indus-1 & Indus-2)
- Up-gradation of magnets for Booster Synchrotron
- Recent development of magnets for Indus-2 improvements
- Magnets for other projects
  - IRFEL , ARPF,BARC, photon beam line experiments etc.
- Magnets for CERN, Swiss

Considerable expertise has been developed in the field of conventional electro-magnets and pulsed magnets.

CONVENTIONAL MAGNETS

- **Low and medium energy circular accelerators (Bρ ~ few 10s of T-m)**
  => Conventional (iron dominated) magnets.

- ***Requirement of long beam lifetime in a synchrotron radiation source***
  => High quality (typical field quality ~ 5x10^{-4}) magnets.

- **Main Magnets for Synchrotrons:**
  Bending Magnet **=> guide the beam to a complete circular path.**
  Quadrupole Magnet **=> control the beam size.**
  Sextupole Magnet **=> chromaticity correction.**
  Corrector magnets => minor vertical and horizontal steering of beam.

- ***Specialized magnets (e.g. septum, kicker magnets) for beam injection/extraction.***

Magnet types →
- **D.C or Slowly varying magnets (1 – 2H_z)**
- **Low frequency magnets (few Hz – several 100Hz)**
- **Pulsed magnets (≥ 1 kHz)**

Technical Issues of Synchrotron magnets

Prerequisites for design of magnets:

Beam dynamic requirements:

- **Required B or g & its variation in GFR ($\Delta B/B$ or $\Delta g/g$ ~ 10^{-4}).**

  In general, field quality for Dipole magnets: 0.05 %
  Quadrupole magnets: 0.05 – 0.1 %
  Sextupole magnets: 0.1 %
  Steering magnets: 0.5 - 1 %

- **Magnetic lengths & variation in a group of magnets**

- **Positioning tolerances of magnets in X, Y & Z Axes**

  - Translations (< 0.1 mm) & Rotational Axes (0.2 – 2 mrad)

Synchrotron Magnet design steps

- **Design of magnets as per beam dynamic requirements.**

- Selection of core geometry (BL passage) & Materials

  ➢ *Laminated (ramped magnets, dB/dt) / solid core (constant field magnets)*

- Optimization of core & coil sections with field distribution.

❖ Finite element codes **(2D & 3D)** for predicting field distributions between poles and at the magnet ends.

- Magnetic field quality **(ΔB/B or Δg/g)**

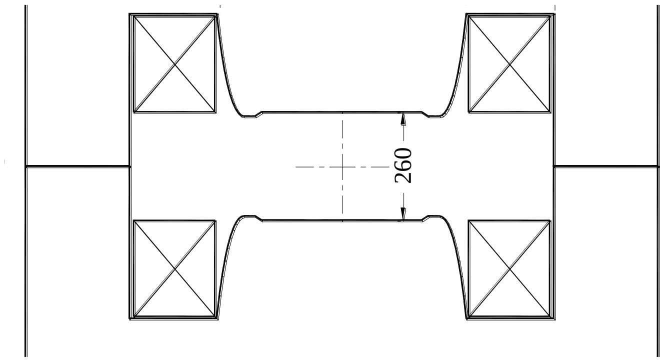


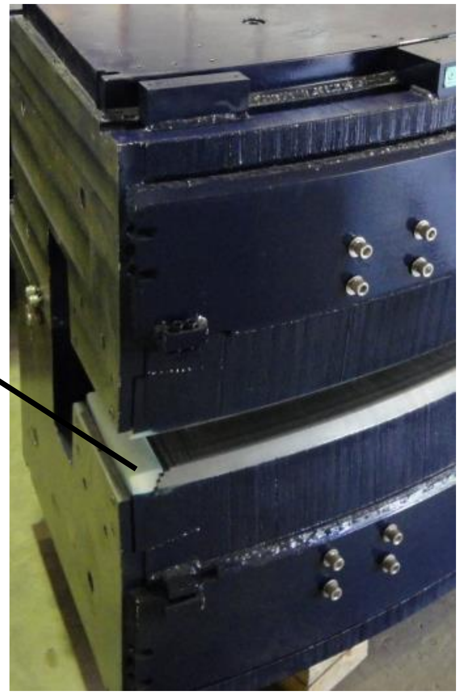
Fig. : Tapering & Shimming of poles to improve field uniformity.

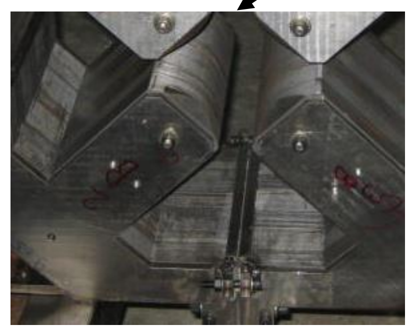
Magnet coils:

➢ *Air cooled (solid wire or strip) / water cooled (hollow sections)*

- Based on current density (j)

❑ Finalization of physical length of cores
- Optimization of entry-exit profiles





➢ to reduce systematic 12 pole and 20 pole, end chamfer size of 9 x 9 mm used for QP magnets of Indus-2.

❖ Finalization of magnet power supply specifications

- High current, low voltage supplies

- Current stability (ΔI/I), Setting resolution & Reproducibility ~ (± 5.0 x 10^{-5})

Magnetic field quality of SR magnets depends on:

- Degree of optimization of magnet parameters at design stage.
- Uniformity in the magnetic properties of steel used
  - Chemical composition & processing
  - Shuffling / mixing of laminations(laminated magnets)
    - To minimize magnet to magnet variation
- Geometrical accuracy of magnet construction.
  - Magnet pole-gap size variation & dimensional stability.
- Stability / Reproducibility of magnet power supply.

Stages involved in development of magnets

- Engineering design of magnet components - Magnet core, coils, assembly parts, support system & their integration
- Selection of manufacturing processes
- Preparation of engg. drawings & technical specifications
- Procurement of materials as per specs.
- Prototyping & finalization of specifications for series magnets
- Series production
- Quality control & acceptance at every stage of production

Engineering design considerations

- *Magnetic forces, Gravity loads*

  - 2D/3D Simulations (Magnetic & structural analyses)

- *Stability and repeatability of magnet assembly*

  - Open type magnets are more critical than close type assemblies
  - Achieving small error between physical & magnetic centers

- *Selection of materials for magnet assembly components*

  - Non magnetic materials

- *Selection magnet coil insulation*

  - Based on magnet powering requirements

- *Reliability of magnets during machine operation*

  - Good workmanship

Engineering design simulations

Dipole magnet:

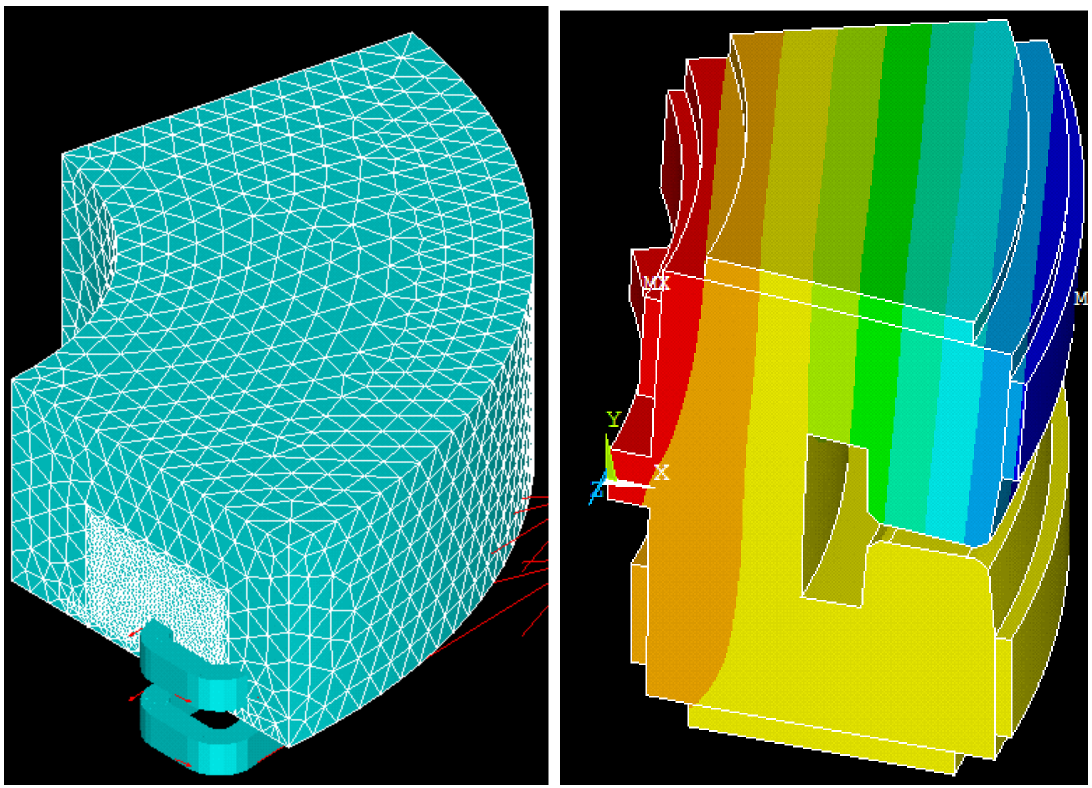
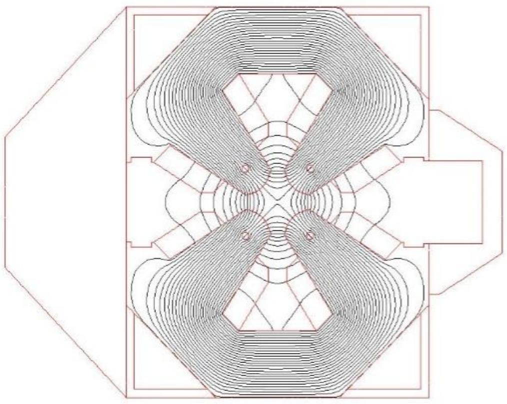


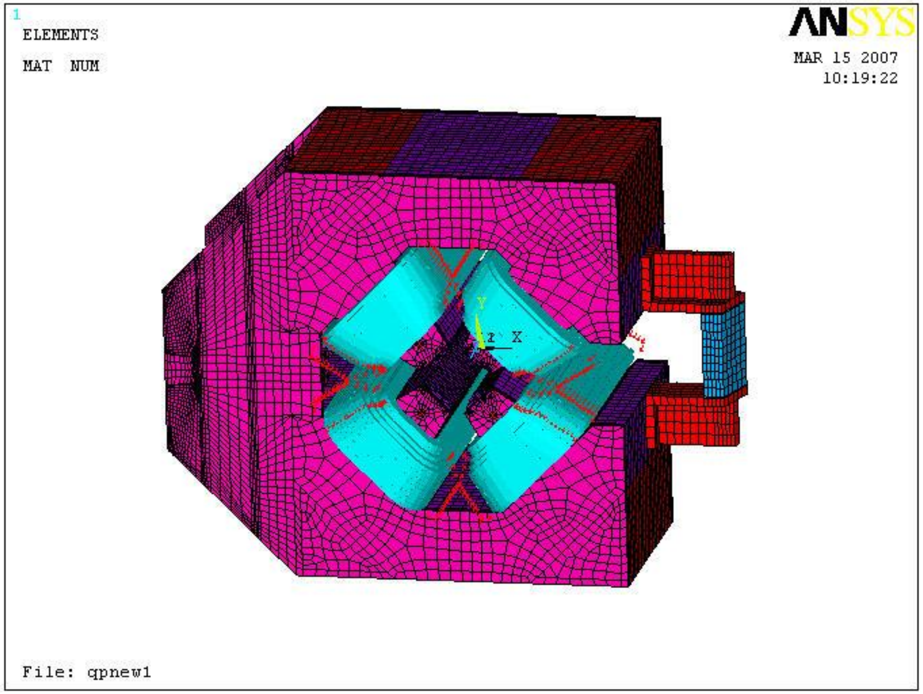
Fig. : Half DP magnet geometry 3-D FE model (L) & vertical volumetric deformation of full dipole core (R).

- Design based on stiffness is followed for critical magnet components those control the deformation (≤ 0.02 mm) of magnet poles.

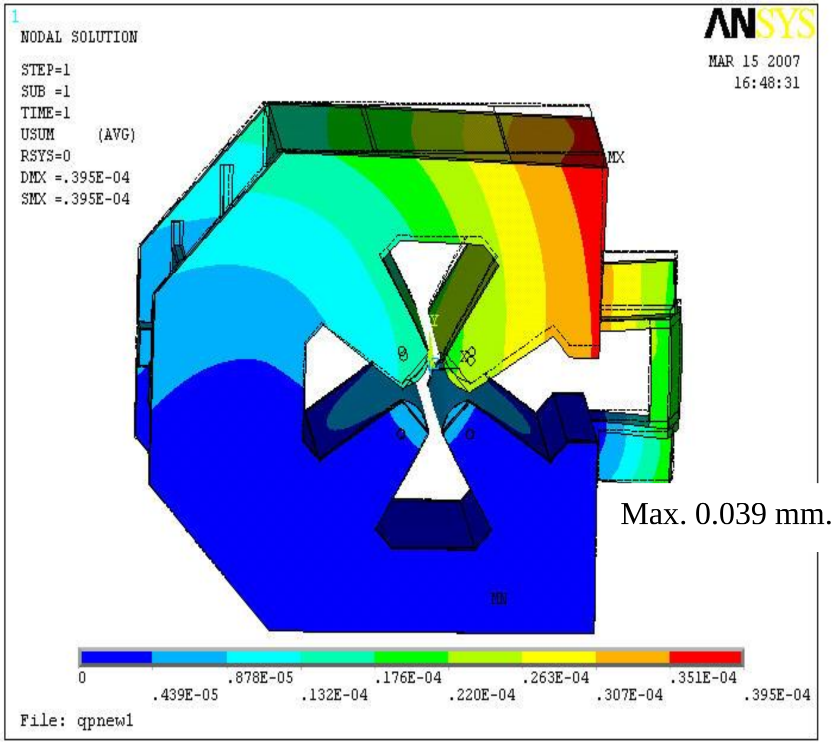
- Design based on strength is followed for other magnet components (eg. Magnet coil holding brackets), where the induced deformation (> 0.1 mm) is not critical.

Quadrupole magnet simulations





FE Model of magnet showing racetrack coil on poles for static magnetic analysis.



Vector sum of displacement plot

Manufacturing considerations of magnets

Tolerances on magnet geometry

- Magnet pole profile (≤ 0.02 mm)
- Pole gap size variation (± 0.02mm to ± 0.05 mm)

Selection of manufacturing techniques

- *Gluing, Bolting, & Welding techniques & combination – laminated cores*
- *Shuffling of steel for uniformity in magnetic properties*
- *Winding & Insulation - Magnet coils*

Quality control

- Mechanical geometry
- Mechanical & Electrical testings

Materials for construction SR magnets

Magnet cores: Soft magnetic materials

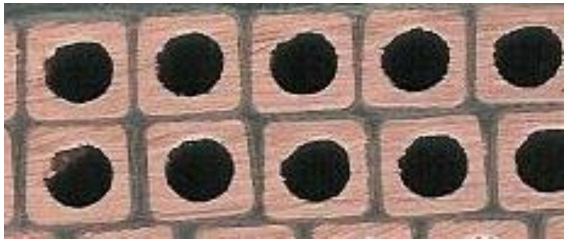
- Decarburized steels, Electrical steels (Si steel)

- *Magnetic properties*
  - High permeability & saturation induction
- *Mechanical properties*
  - Strength , Hardness

Magnet coils:

- OF Copper tubes, Enameled ETP copper wires

- Pure Aluminum conductors



Water cooled coil section

Current density: $j = NI/A_{conductor}$

j : < 1.5 A/mm^2 for air-cooled & 5 – 8 A/mm^2 for water cooled coils.

Use of hollow conductor: High current density, compact magnet, prevent excessive heating, reduce effects on material property.

Magnet coil insulation:

- Inorganic tapes – kepton, adhesive and glass fibre tapes – For turn insulation.

- Epoxy resins – For coil impregnation & encapsulation.

Insulation of Magnet Coils (except pulsed magnets)

Most of the magnet coils of Indus magnets are subjected to moderate voltages (< 100 V) except the coils of following magnets:

(a) Main Dipole magnets of Booster Synchrotron (1500 V)
(b) Indus-2 Series Quadrupole magnets: Q4 (800V) & Q5 (408 V)
(c) Indus-2 Series Sextupole magnets (300V)

All the water cooled coils of Indus magnets were inter-turn insulated with glass tape followed by epoxy-resin impregnation & encapsulation under vacuum. The thermal class of insulation is F Class (155° C).

All the air cooled coils of Indus magnets were made from enamelled copper wire/strip with thermal class of insulation to F Class (155° C) / H Class (180°C).

Insulation of Pulsed Magnet Coils

Septum coils: Insulated with high purity alumina (250 – 300 μ-m / side) coating with low porosity. It provides high insulation resistance (> 20 MΩ) between magnet core & coil which enable it to with stand high voltage (> 2KV).

Kicker coils: Indus-1 coils were insulated with kapton tape and Indus-2 kicker magnet coils were insulated with high purity alumina (250 – 300 μ-m / side).

Cooling of magnet coils

Demineralsed (DM) water is used for cooling accelerator water cooled magnet coils due to following reasons:

- To avoid leakage currents, electrical short-circuiting & scaling problems.

Electrical Conductivity of cooling water: < 1 μs/cm

Design parameters for cooling of magnet coils:

- Limiting value of temperature rise (Δ T) of magnet coils $\leq$ 20°C.
- Velocity of flow in magnet coils $\leq$ 3 m/sec.
- Pressure-drop (Δ P) in magnet coils $\leq$ 5bar.

Protection systems with magnets:

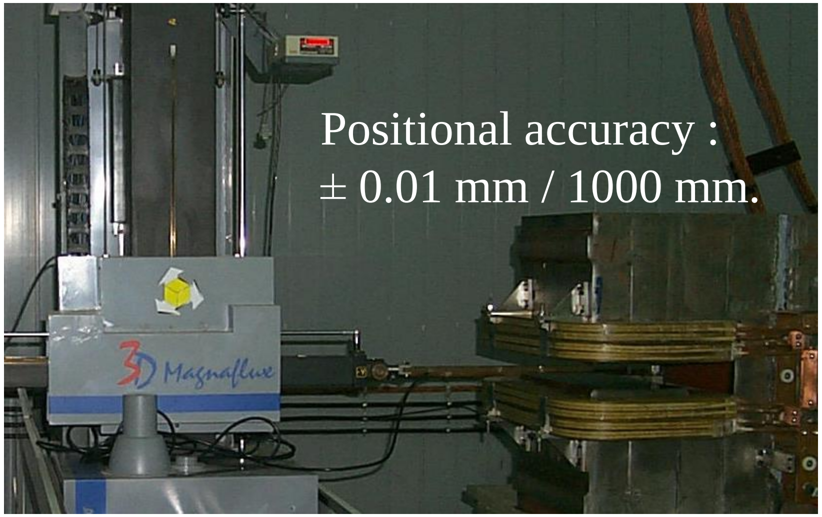
Protection through magnet power supplies by:

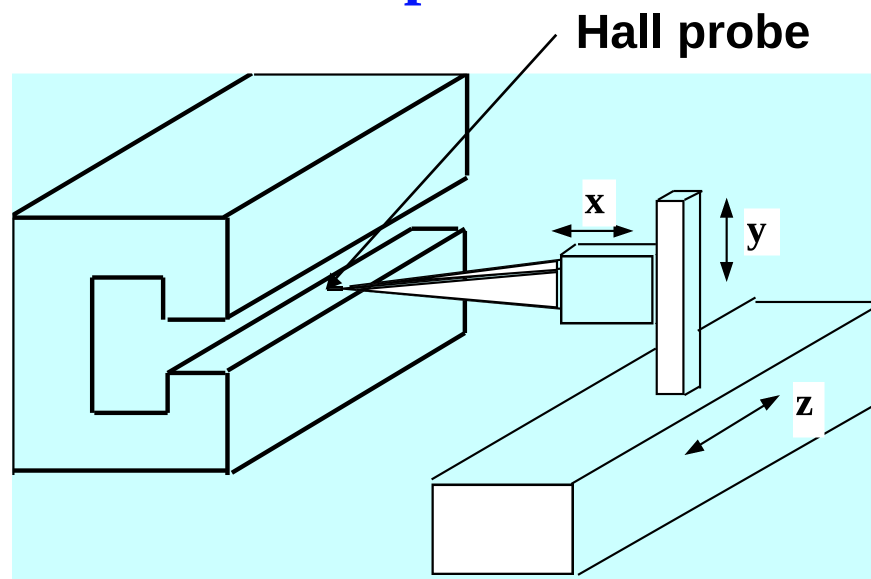
- Over current & voltage protections
- Low water flow and high temperature interlocks in the power supply circuits.

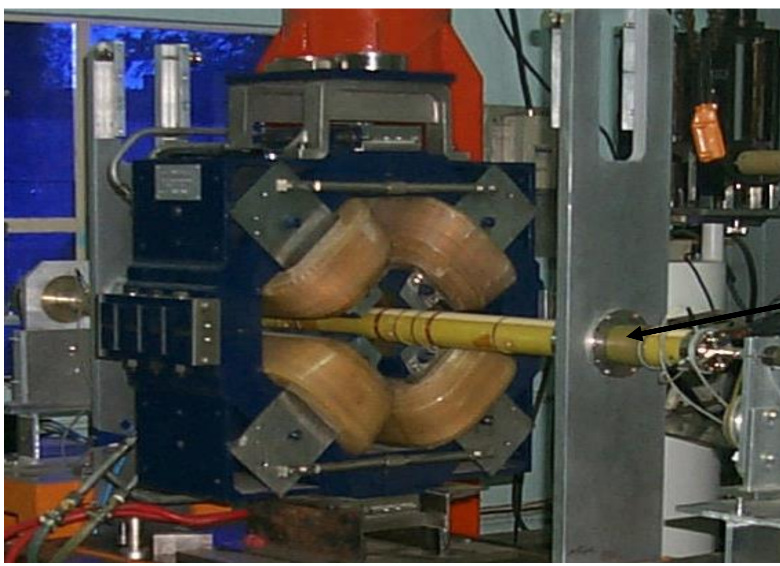
Fixing of thermal switches on outlet terminals of magnet coils.

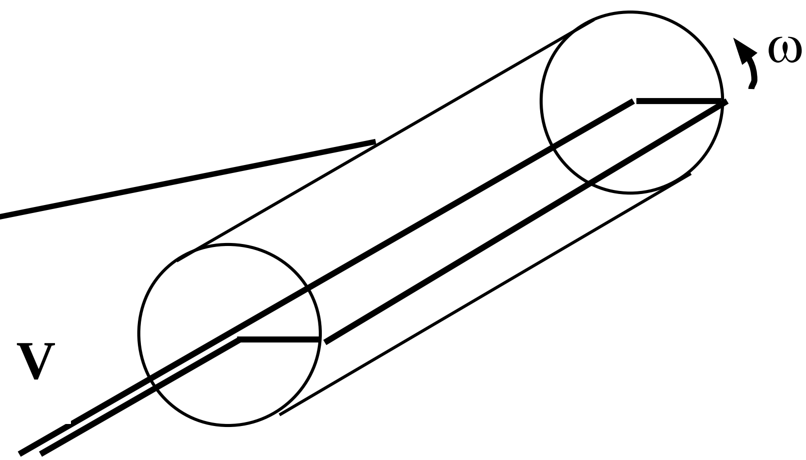
Characterization of magnets

Dipole magnet field measurement with Hall probe



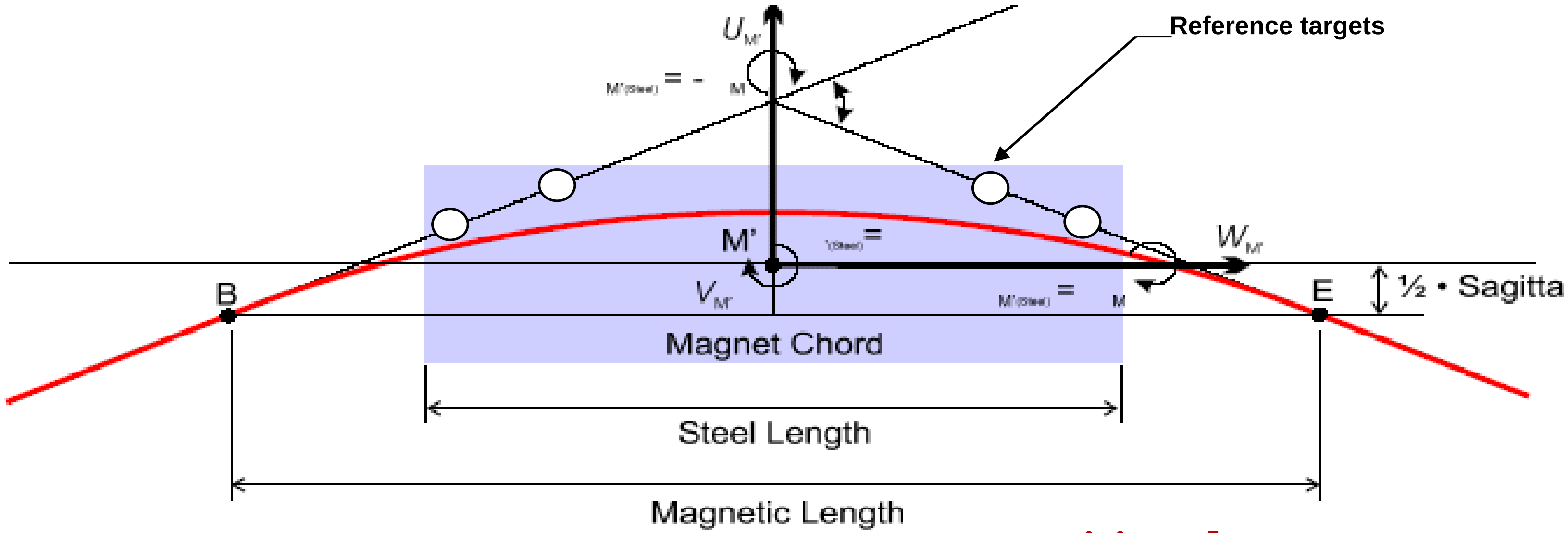






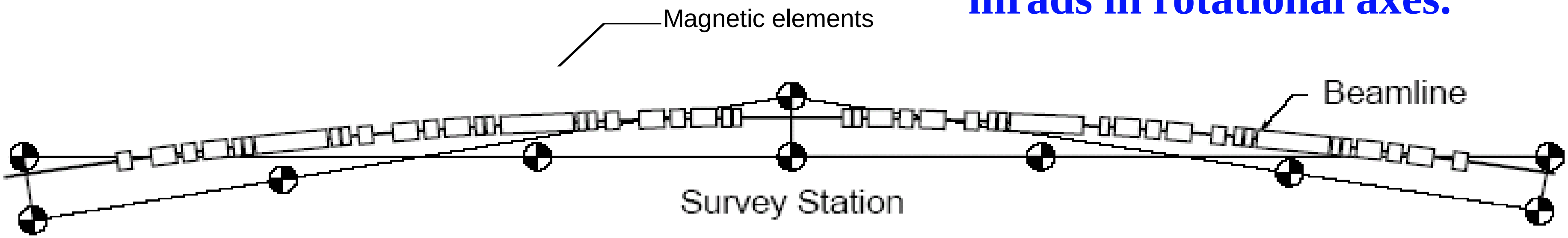
QP / SP magnet pole field measurements with Rotating coil

Positioning of magnets in Indus accelerators



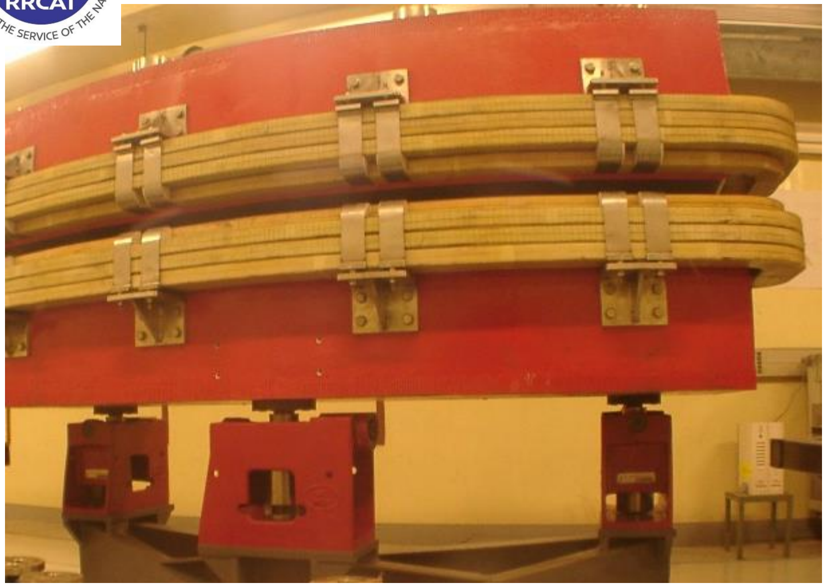
Magnet coordinate system

Positional accuracy:
0.1 mm in linear and 0.2 mrads in rotational axes.

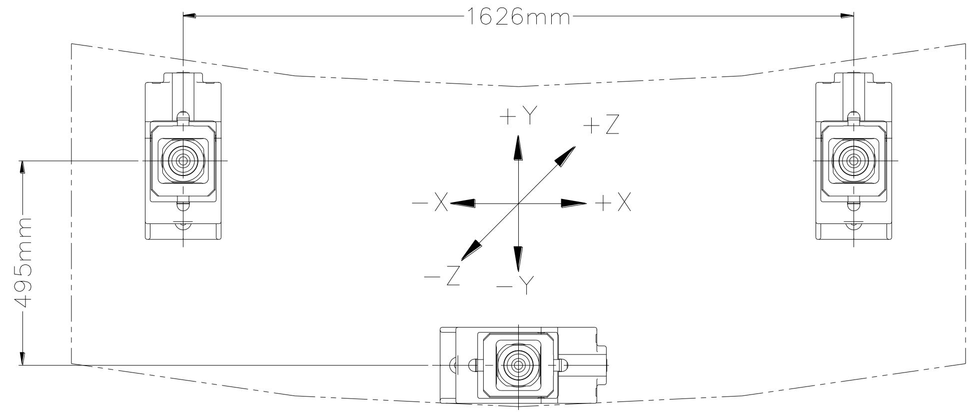


Typical Accelerator tunnel network layout and placement of magnets.

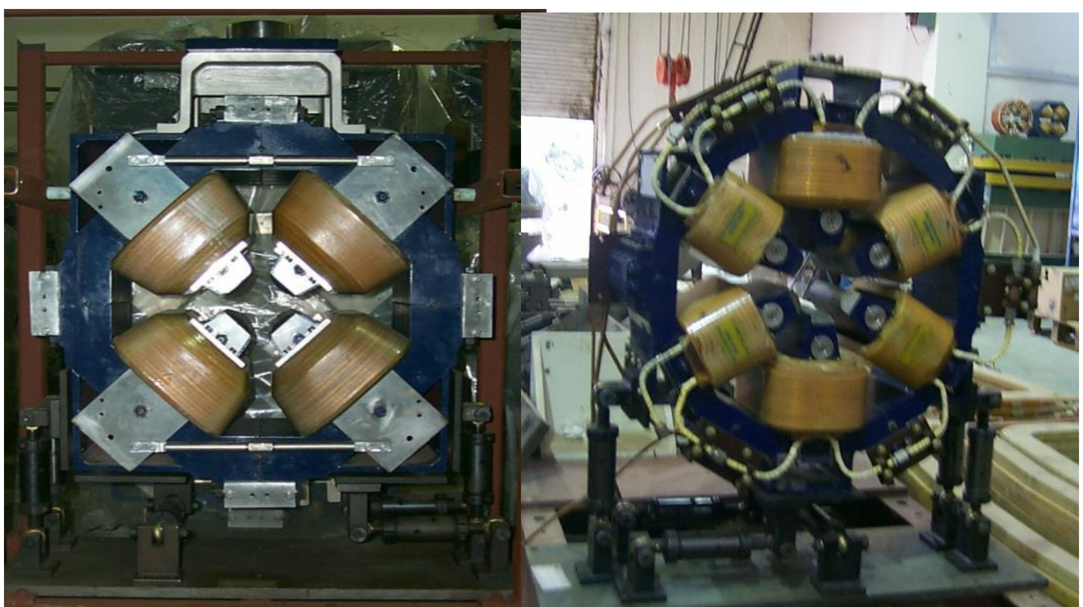
Support system for positioning of magnets



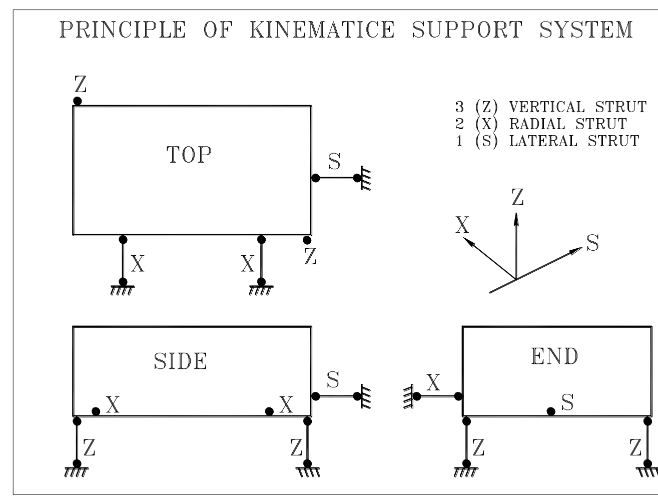
Support system mounted below the Dipole magnet



Layout of support system of Dipole magnet



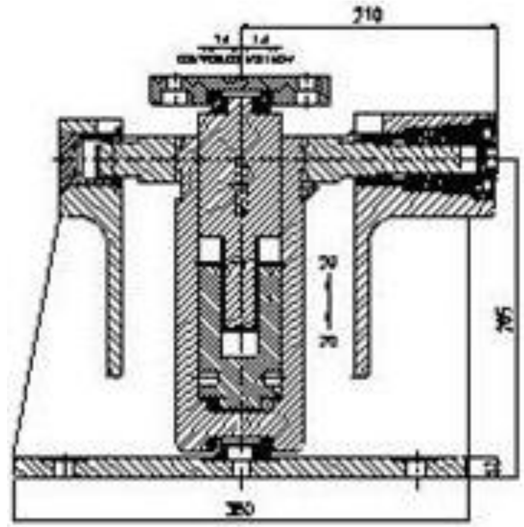
Kinematic support system mounted below QP & SP magnets

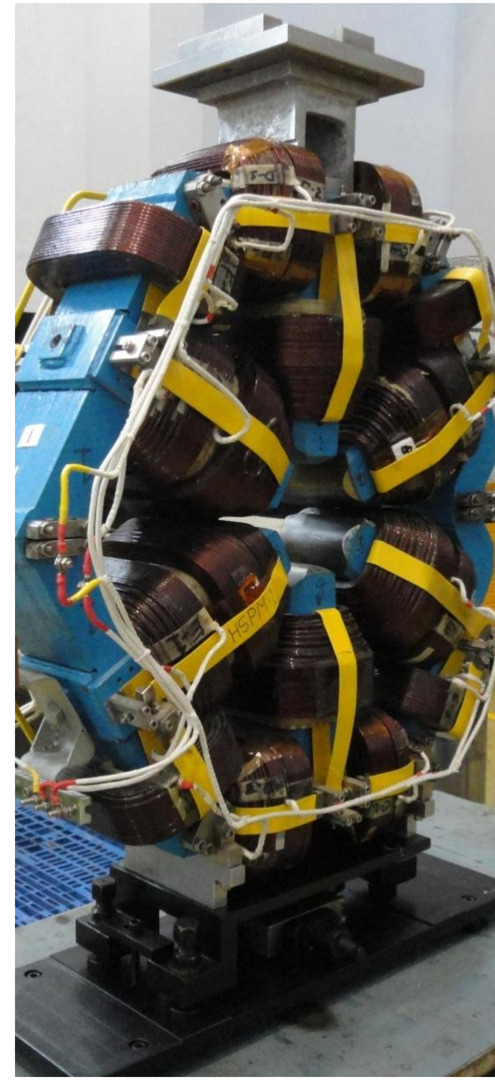


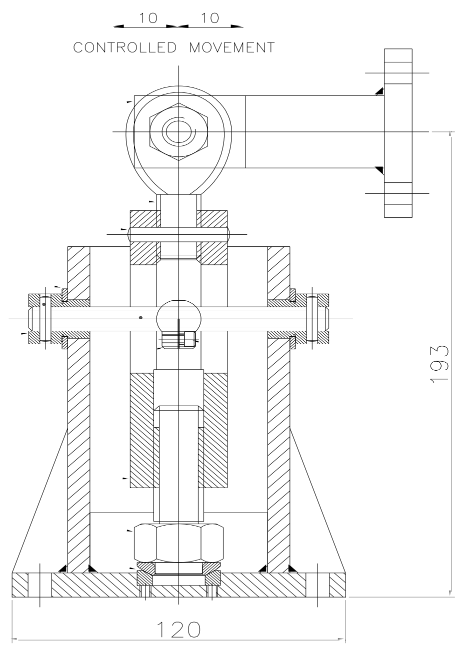
Precision movement system for Indus-2 (contd.)

Precision movement system mounted below short SS girder

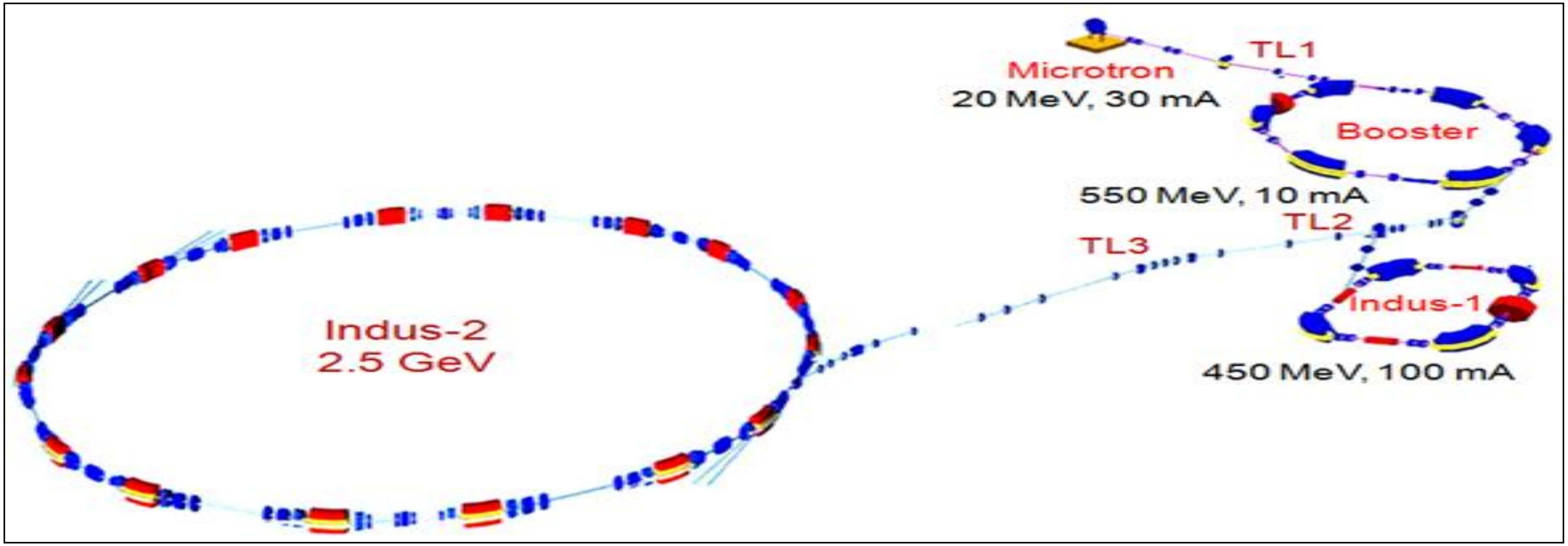
Jacks of magnet support system







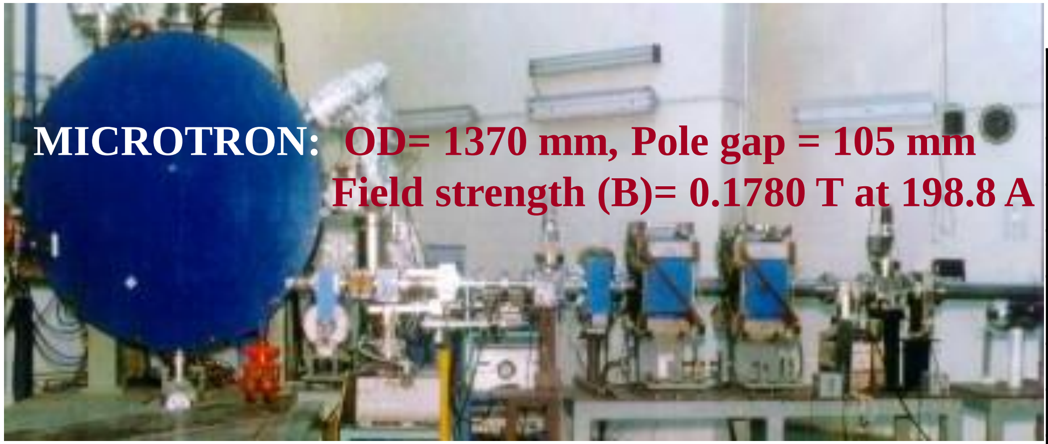
Magnets for Indus Accelerators



Dipole magnets	: 33 Nos.
Quadrupole magnets	: 132 Nos.
Sextupole magnets	: 40 Nos.
Steering/Corrector magnets	: 109 Nos.
Kicker magnets	: 09 Nos.
Septum magnets	: 05 Nos.

ALL THESE MAGNETS ARE OF CONVENTIONAL TYPE AND INDIGENOUSLY DEVELOPED BY AMTD.

Microtron, Booster and Transfer line magnets



Microtron and TL-1 Magnets

550 MeV Booster Synchrotron

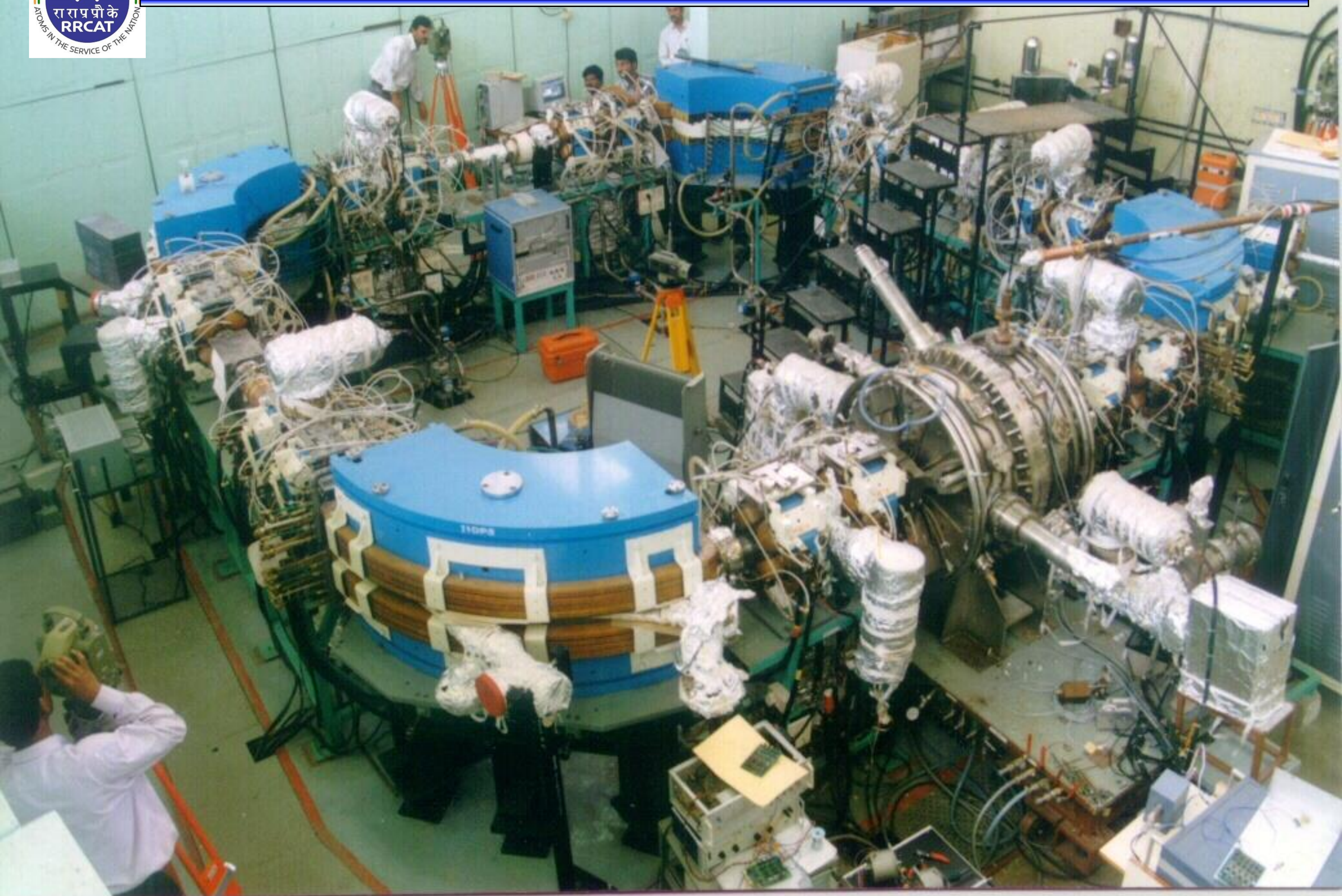
Made in 1989 - 1992

S. No.	TYPE OF MAGNETS	STRENGTH (B, g/k, θ)	QUANTITY (Numbers)
I	**TRANSFER LINE (TL – 1) MAGNETS**		
a)	Quadrupole magnets	2.5 m^{-2}	06
b)	15^0 Bending magnet	0.075 T	01
c)	Corrector dipole magnets	± 5 to ± 10 mrad	08
II	**550 MeV BOOSTER SYNCHROTRON**		
a)	Injection Septum magnet	0.22 T, 15^0	01
b)	Injection Kicker magnets	0.045 T, 20 mrad	03
c)	60^0 Bending magnets	1.3 T	06
d)	Quadrupole magnets	8 T/m	12
e)	Corrector dipole magnets	± 2 mrad	06
f)	Extraction Septum magnet	0.877 T, 16^0	01
g)	Extraction Kicker magnet	0.08 T, 12 mrad	01
III	**TRANSFER LINE (TL – 2) MAGNETS**		
a)	Bending magnets	1.17 T / 0.75 T	02
b)	Quadrupole magnets	6 m^{-2}	08
c)	Steering magnets	± 5 mrad	15

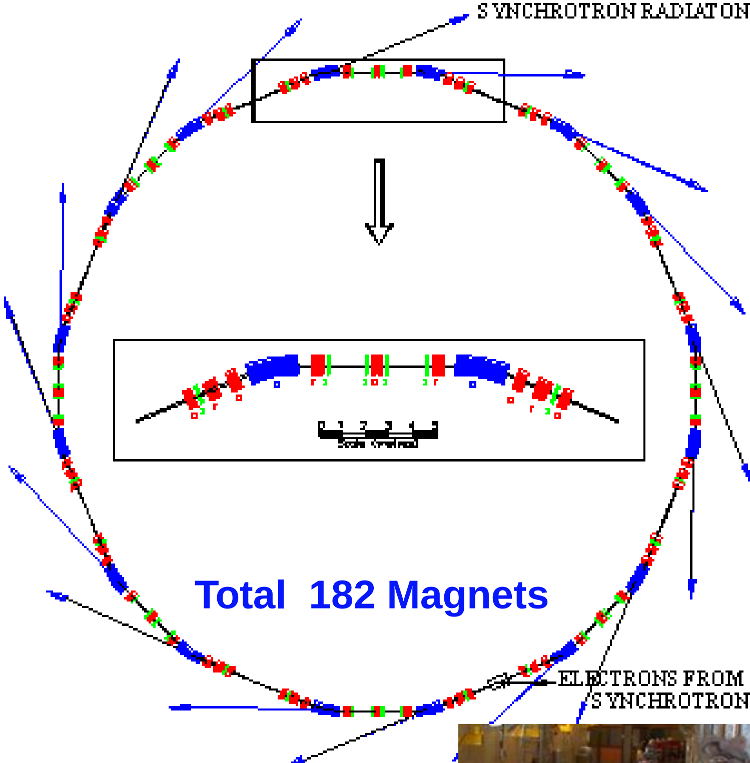
Indus-1 Storage ring magnets

S. No.	TYPE OF MAGNETS	STRENGTH (B, g / k, θ)	QUANTITY (Numbers)
IV	450 MeV INDUS – 1 MAGNETS		
a)	Injection Septum magnet	0.8377 T, 18.3^0	01
b)	Injection Kicker magnet	0.08 T, 3 – 16 mrad	01
c)	90^0 Bending magnets	1.5 T	04
d)	Quadrupole magnets	$6\ m^{-2}$ / $13.5\ m^{-2}$	16
e)	Sextupole magnets	$4\ m^{-2}$ (k.l)	08

450 MeV Indus-1 Synchrotron



S. No.	TYPE OF MAGNETS	STRENGTH (B, g / k, θ)	QUANTITY (Numbers)
V	TRANSFER LINE (TL –3) MAGNETS		
a)	Quadrupole magnets	8 T/m	18
b)	Bending magnets	0.65 T	03
c)	Corrector dipole magnets	5 mrad	24
VI	2.5 GeV INDUS – 2 MAGNETS		
a)	Thin Septum magnet	0.5 T, 2^0 & 3^0	01
b)	Thick Septum magnet	0.9 T, 19^0	01
c)	Kicker magnets	0.22 T, 25 mrad	04
d)	22.5^0 Bending magnets	1.5 T	16
e)	Quadrupole magnets	16 T/m	72
f)	Sextupole magnets	400 T/m^2	32
g)	Corrector dipole magnets	1.3 mrad / 1.5 mrad	56



Magnetic Layout of Indus-2 ring

T L - 3 Magnets

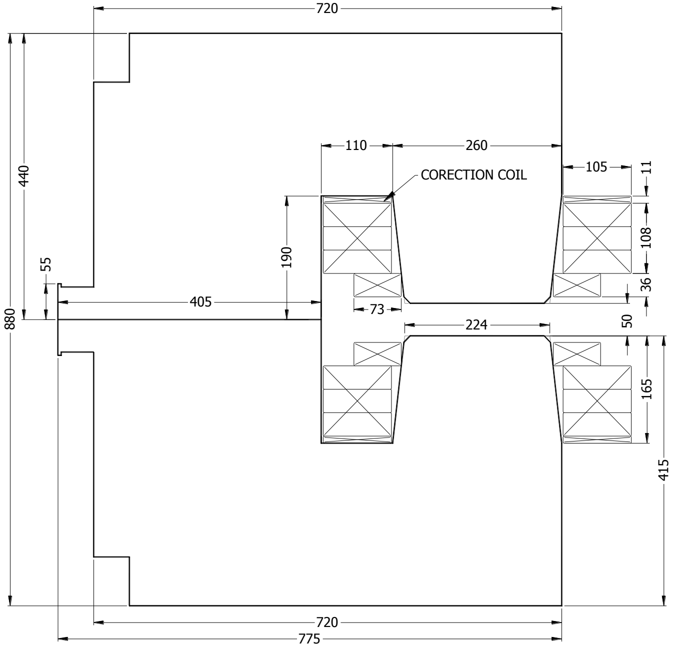
Magnets for Indus-2 (2.5 GeV Synchrotron)

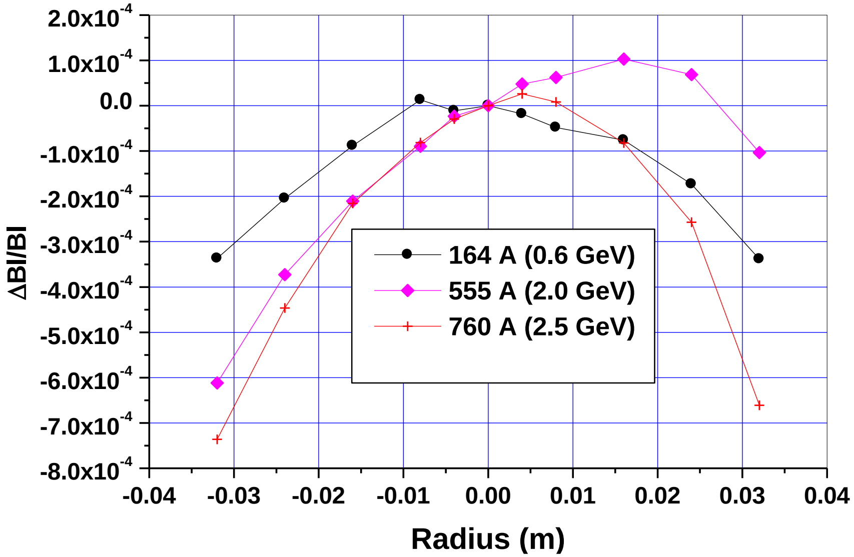
Dipole Magnets, Qty.: 16 Nos.

Magnet ends are rolled off along the vertical direction (z) following the relation z = ± g/2*cosh(s/g) to minimize the variation of magnetic length with excitations and get better field quality in the transverse plane.

Back leg width is determined taking into account the **pulling force of 45 Tons** at 1.5 T.

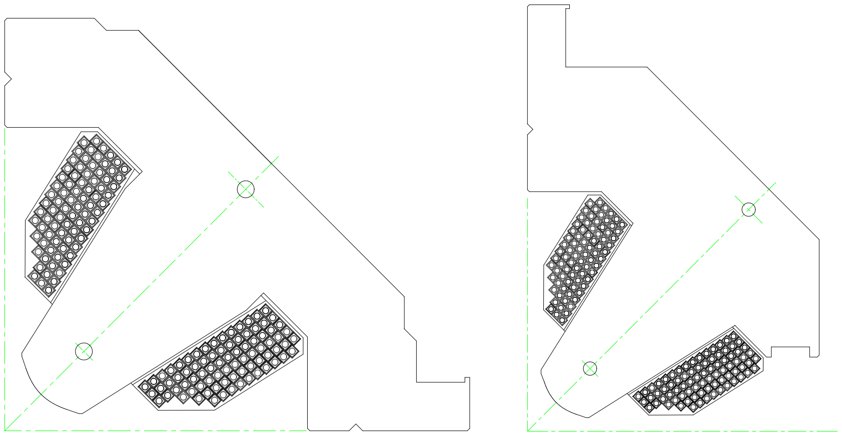
Slow ramp rate (~300s) => 5.8 mm thick low carbon steel laminations as core material.



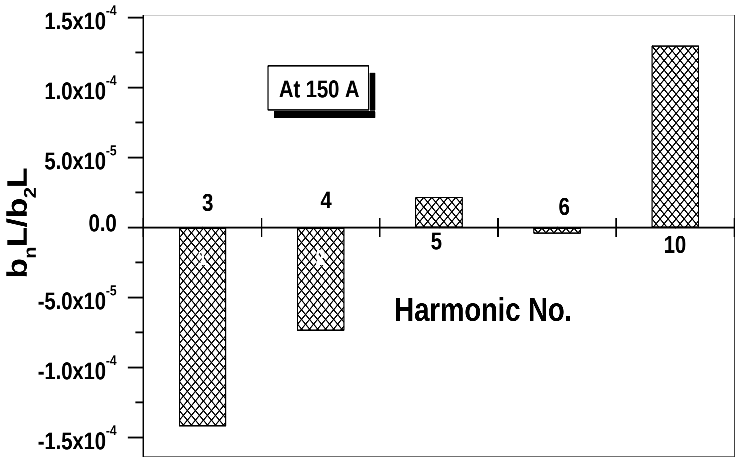


Measured integrated field uniformity in the GFR (± 0.032 m).

Indus-2 Quadrupole Magnets (16 T/m), Qty.: 72 Nos.



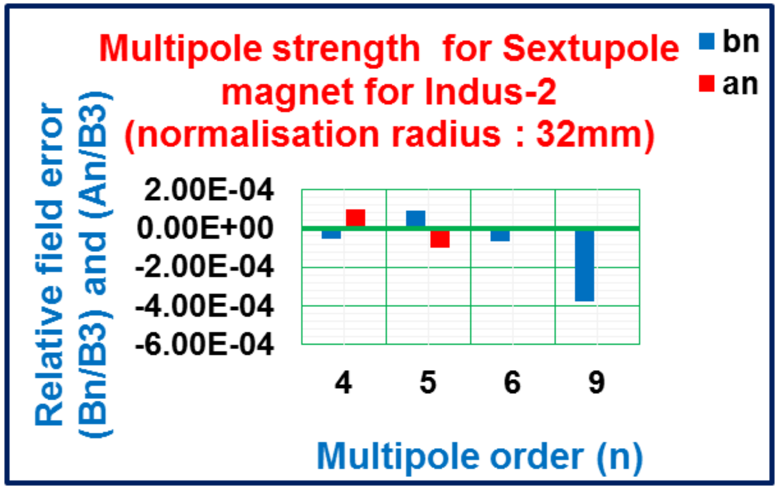
Lamination C/S (0.5 mm thk. CRNGO Si steel) of close-type & Lamination C/S (1.5 mm thk. low carbon steel) of open-type QP magnets.



Measured higher order harmonics of Q2 type magnet.

Indus-2 Sextupole Magnets (400T/m^2), Qty.: 32 Nos.

Indus-2 sextupole magnets (Wt. ~ 0.6 MT) with support/positioning system (Right).

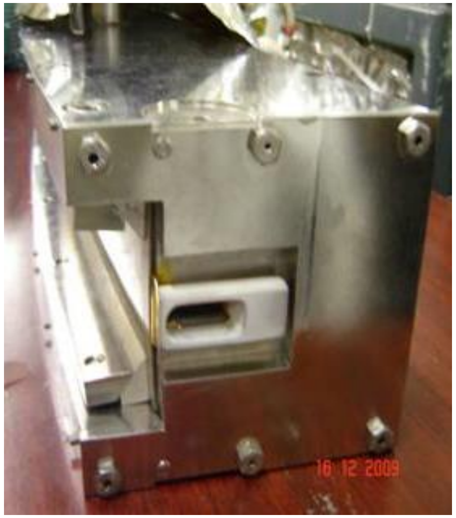


Measured higher order harmonics in SP magnet.

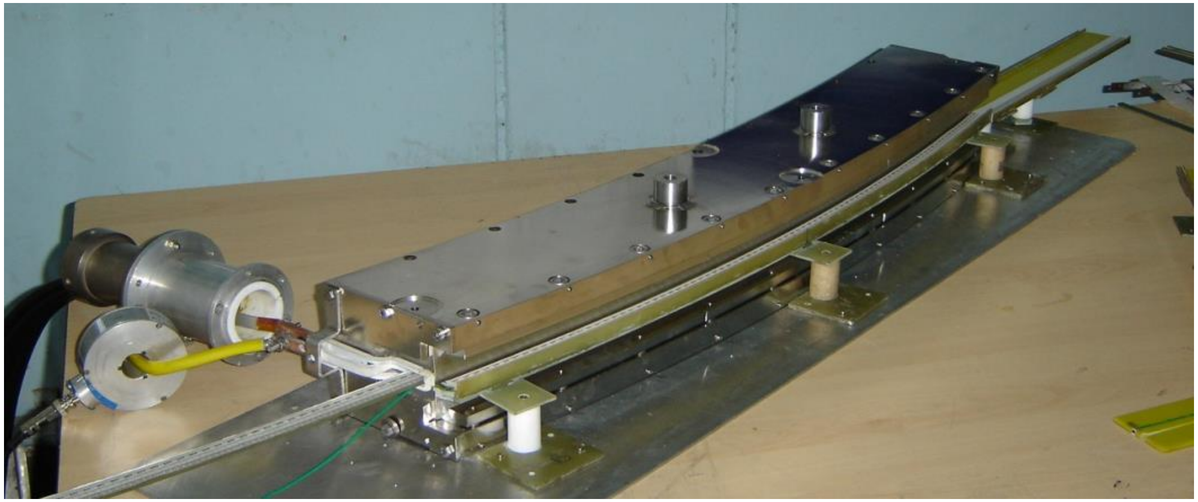
Cores (200 mm) were made from 0.5 mm thick CRNGO Si steel laminations and the coils from hollow OF Copper conductors.

Pulsed Magnets for Indus Accelerators

❖ Septum Magnets (Beam injection & extraction).

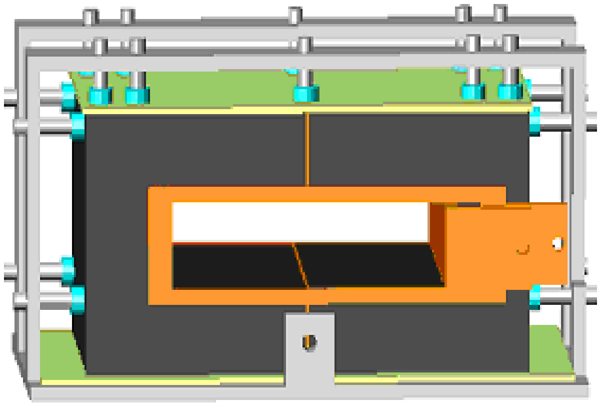


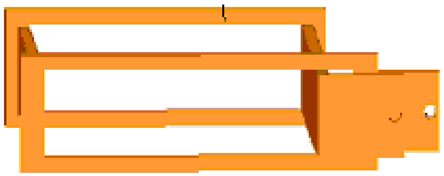
0.1 mm thick Ni-Fe Laminated magnet core and
Alumina coated OF copper coil.

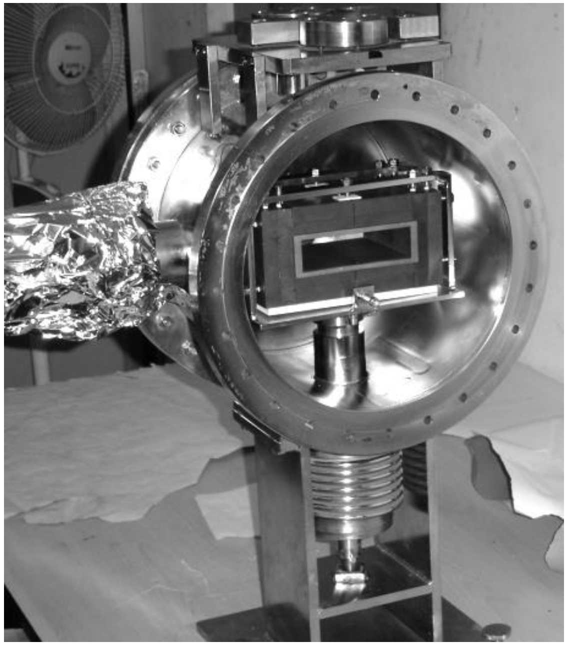


Injection Septum magnet assembly for Indus-2.

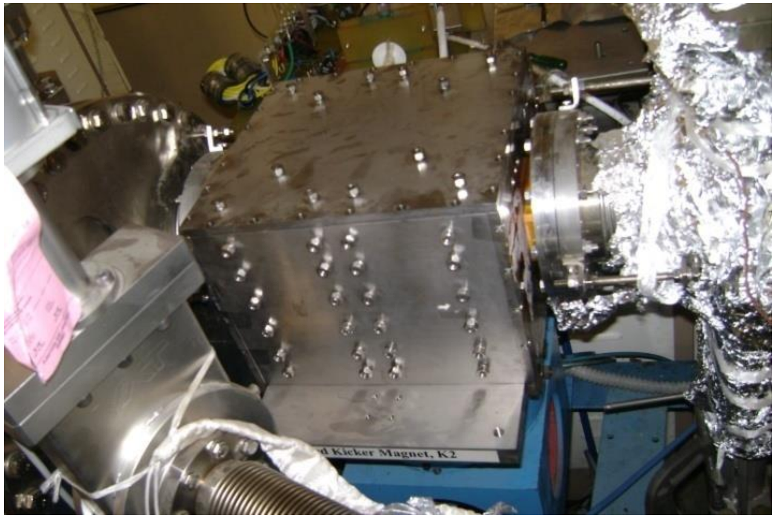
❖Kicker Magnets (Beam injection & extraction).





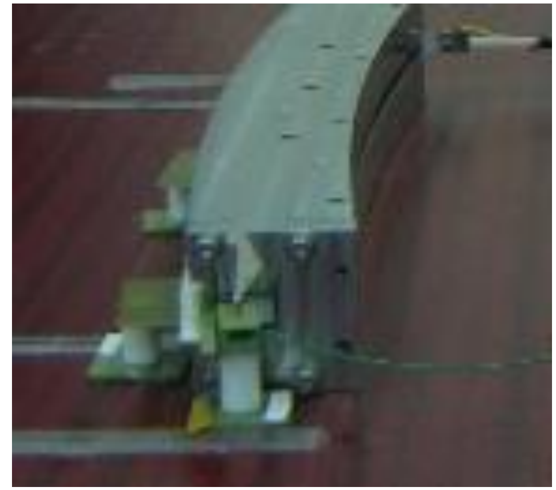


Kicker magnet assembly for Booster Synchrotron.

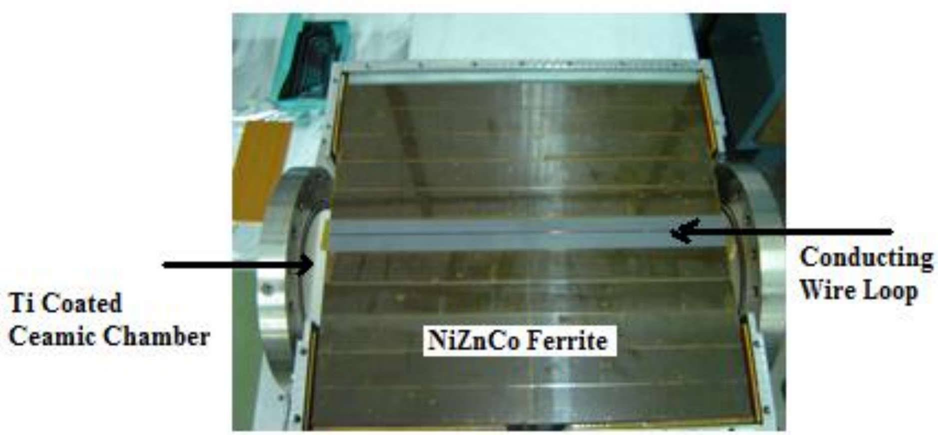


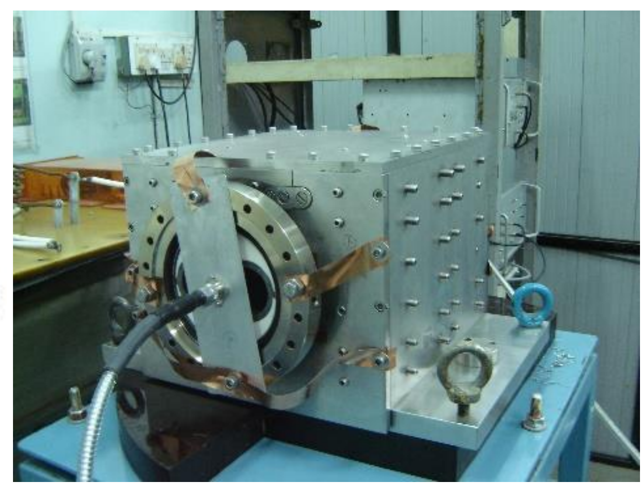
Up-Graded pulsed magnets

- New septum magnets were developed for improved electron beam injection and extraction for Booster Synchrotron. The achieved stray field is < 2 G-m and uniformity is better than 6 $\times 10^{-4}$.



Improved injection and extraction septum magnets.



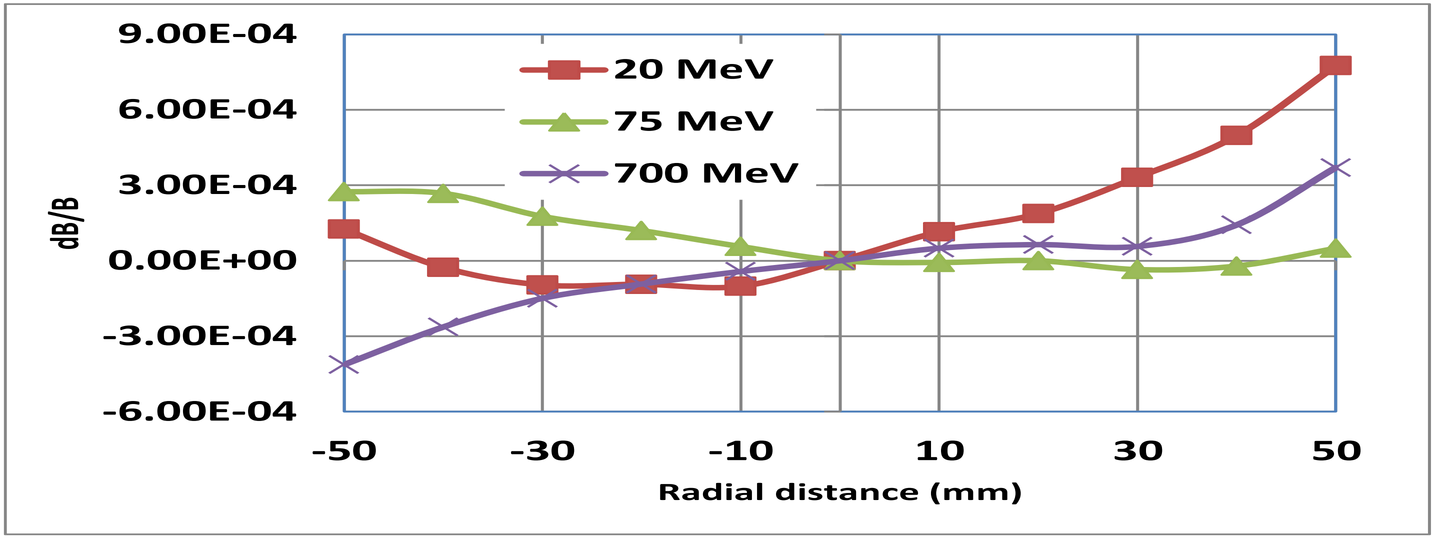


Low coupling impedance kicker magnet for Indus-2.

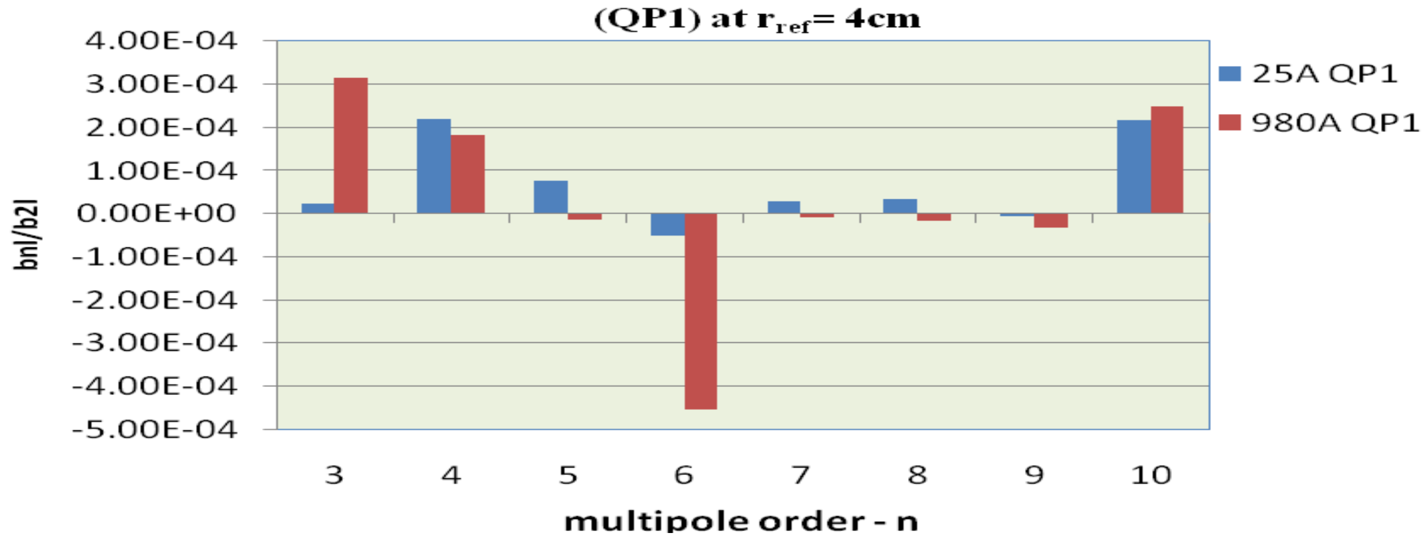
Up-Gradation of magnets for Booster Synchrotron

Upgraded new dipole and combined function quadrupole magnets were developed to operate the booster synchrotron at 700 MeV energy.

Parameter	Dipole Magnet	Quadrupole Magnet
Field strength/Gradient	0.037T @ 20 MeV 1.3 T@ 700 MeV	0.268 T/m @ 20 MeV 9.32T/m@ 700 MeV
Total Amp-turns	60,000	40,000
Pole gap/Aperture	52 mm at the centre	50 mm (Aperture radius)
Good field region	± 40mm (horizontal) ± 17 mm (vertical)	± 40 mm radius
Field uniformity	± 0.05 %	± 0.05 %
Effective length	1.88705 m	250 mm
Core material	1.5 mm thk. Low carbon steel	0.5 mm thk. Si steel
Quantity in numbers	6	12



Measured field quality of upgraded Booster Dipole magnet.

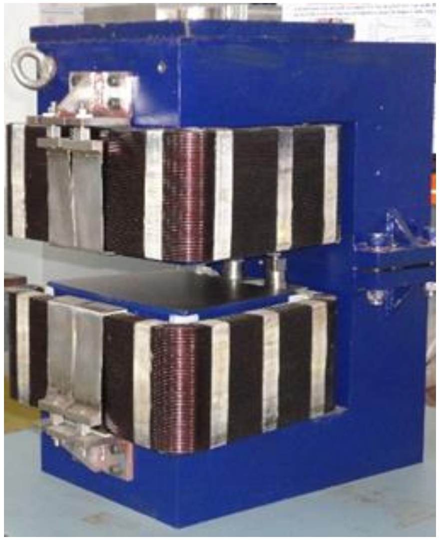


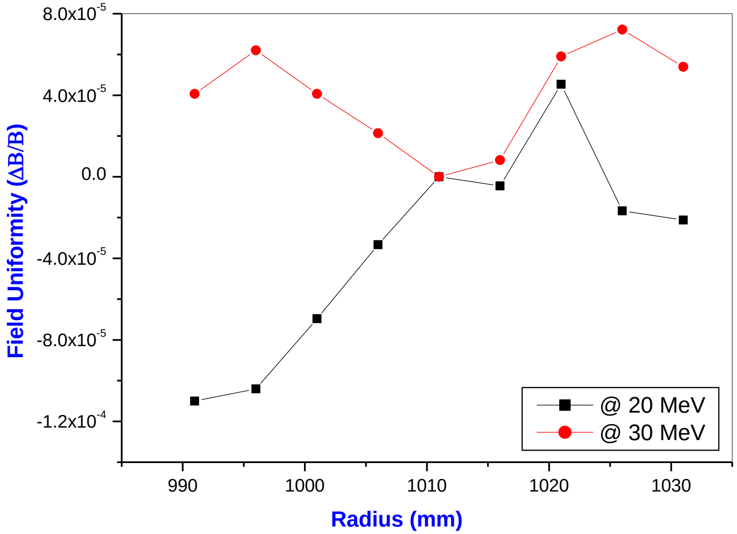
Measured higher order harmonics of upgraded Booster Quadrupole magnet.

New 30 MeV Booster Linac transfer line magnets

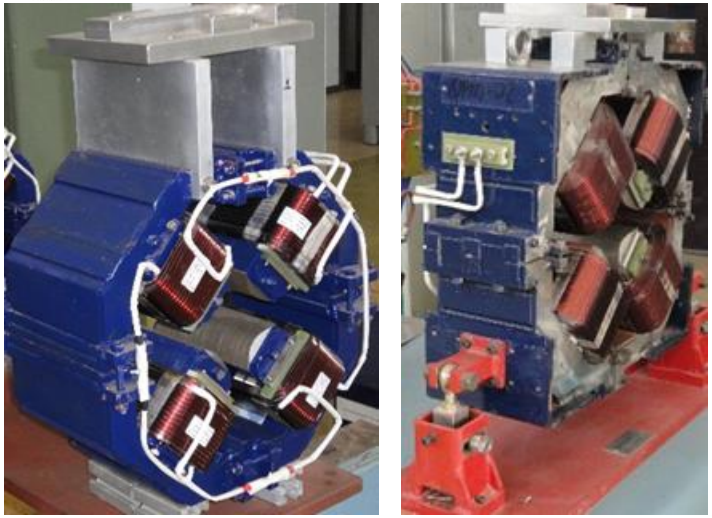
A set of dipole, quadrupole and steering magnets were developed to connect new 20 - 30 MeV Linac to the Booster Synchrotron

Parameter	**Dipole magnets**	**Quadrupole magnets** (QP-80)	(QP-100)	**Combined function steering magnets**
Pole gap/Aperture	50 mm	80 mm Dia.	100 mm Dia.	94 mm
Peak field/Gradient	0.17 T	2.5 T/m	1 T/m	60 Gauss
NI/Pole in AT (Max.)	2640	960	3500	400
Bending angle	17°	--	--	± 6 mrad
Overall length	479 mm	236 mm	246 mm	100 mm
Core material	Low carbon steel	0.5 mm thick CRNGO Silicon steel		Low carbon steel
Quantity	1 No.	2 Nos.	4 Nos.	5 Nos.

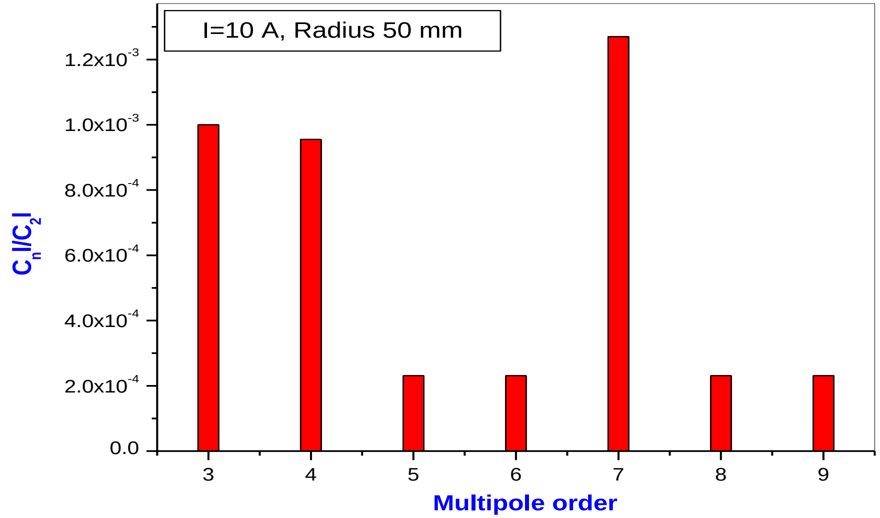




Measured field quality in DP magnet.

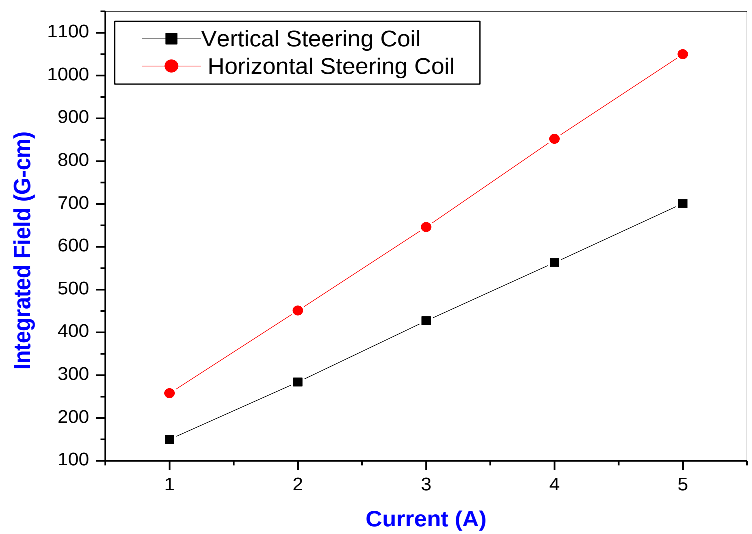


QP-80 and QP-100 Magnets.



Measured higher order harmonics in QP-100.

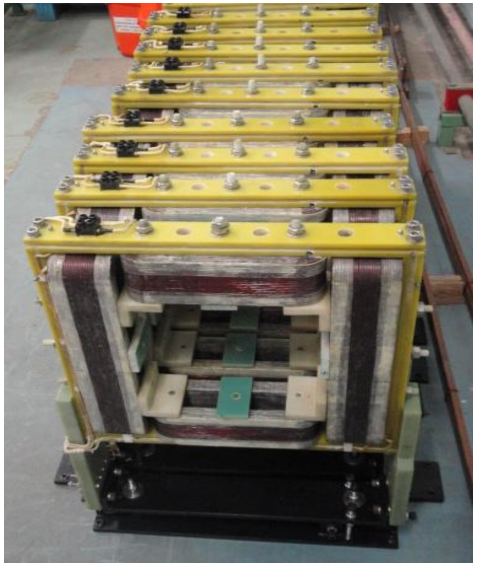
Steering Magnets.



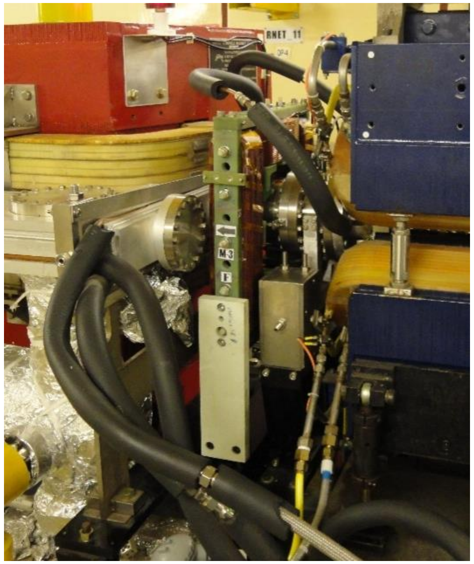
Measured Current vs integrated field in steering magnets.

Recent development of magnets for Indus-2 improvements

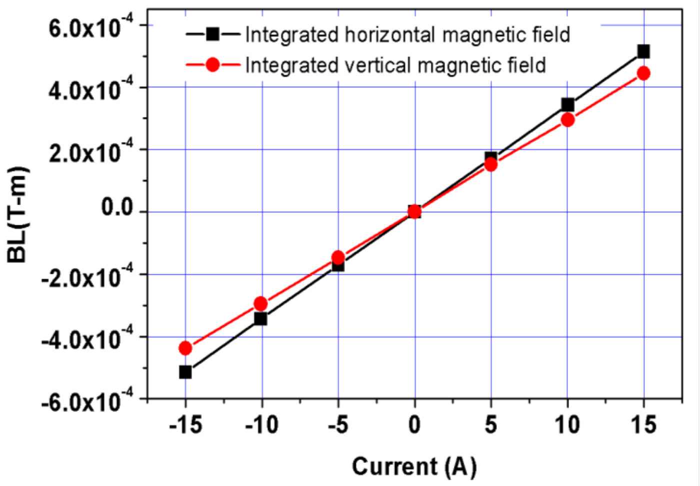
- Typical requirement of beam position stability is ≤ 10 % of the r.m.s size of electron beam. So, Indus-2 needs (40 correctors) correction of beam orbit disturbances in the range from DC to 100 Hz.



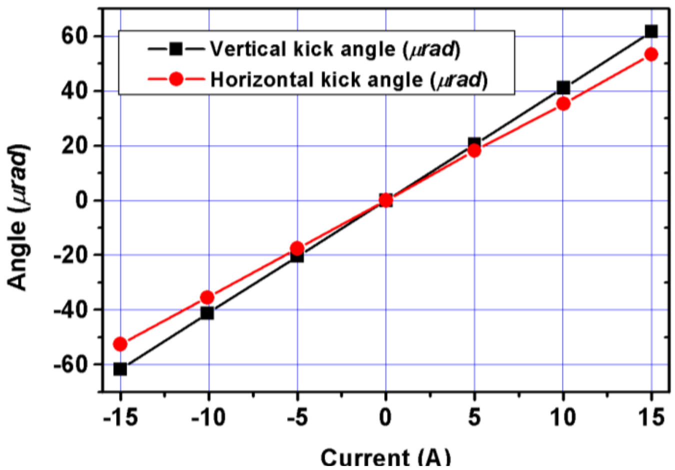
Fast Correctors magnets for Indus-2.



Installed fast corrector at Indus-2 .



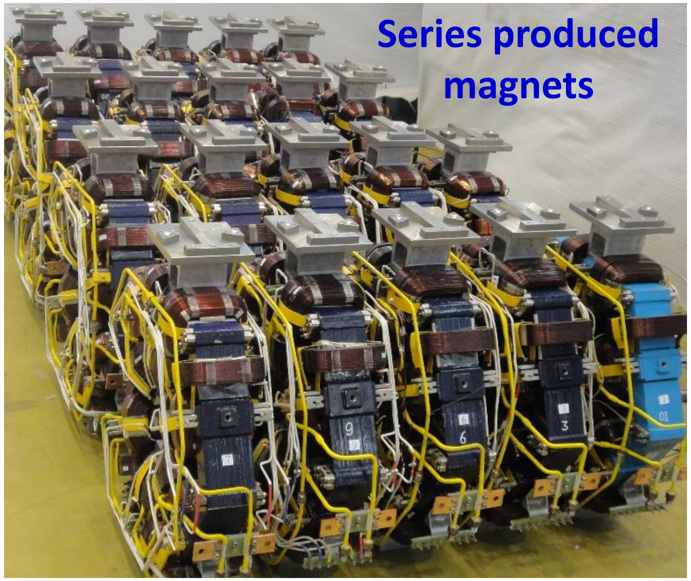
Integral field strengths (DC) with current.



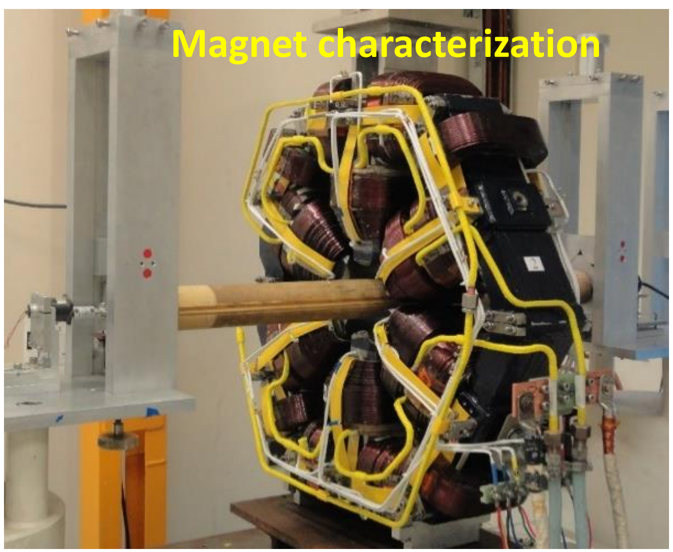
Angular kick strengths (DC) with current.

Initial fast orbit local correction results orbit variation within 3 μm in both the planes.

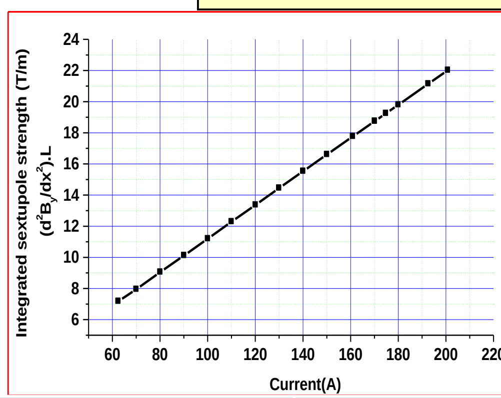
Development of harmonic sextupole magnets with skew quadrupole and steering coils for Indus-2

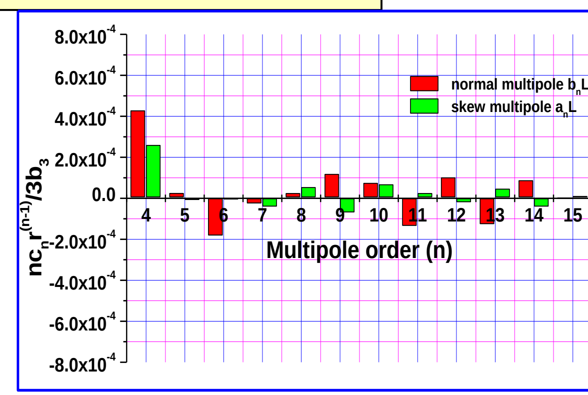


32 Combined function harmonic sextupole magnets (aperture radius: 60 mm & overall length: 250 mm) were developed to improve the dynamic aperture in Indus-2 . Each combined function magnet has harmonic sextupole field strength of 17 T/m (G'.L); skew quadrupole strength of 0.1 T (G.L) and horizontal & vertical dipole strength (By.L & Bx.L) of 0.0133T-m for1.6 mrad kick in both the planes. The magnet yokes were made from low carbon steel plates and the coils were from copper conductors.



Magnetic field measurement results

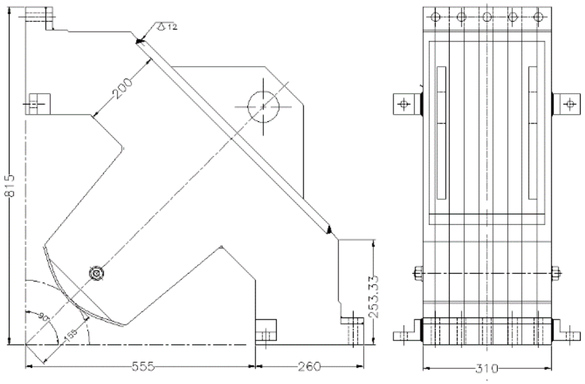




Field component	Current (A)	Integrated strength at r=32mm
Sextupole	170.15	17.58 T/m
Skew QP	-10.0	0.1036 T
Horizontal Steering	-9.872	-1.44E-02T-m (1.72 m rad at 2.5 GeV)
Vertical Steering	-10.0	1.39E-02 T-m (1.668 m rad at 2.5 GeV)

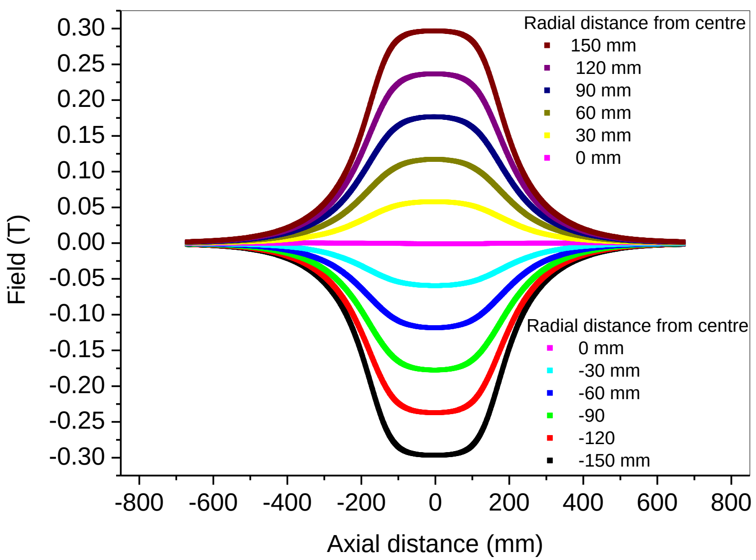
Measurement results satisfy the beam dynamics requirements of integrated field strengths and quality.

Large bore Quadrupole magnet for characterization of rotating coils

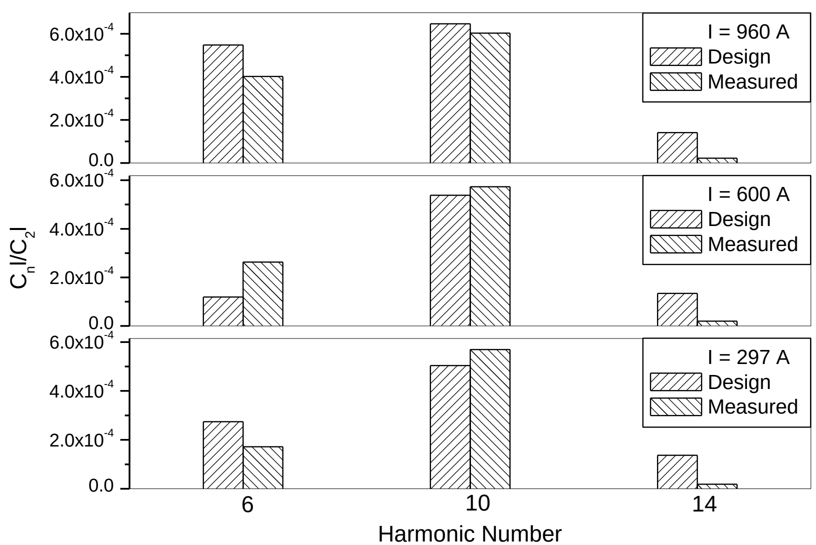


Magnet Parameter	Value
Aperture radius	155 mm
Gradient	3.2 T/m
Magnet Weight	~ 6000 Kg

Magnet core quadrant details.

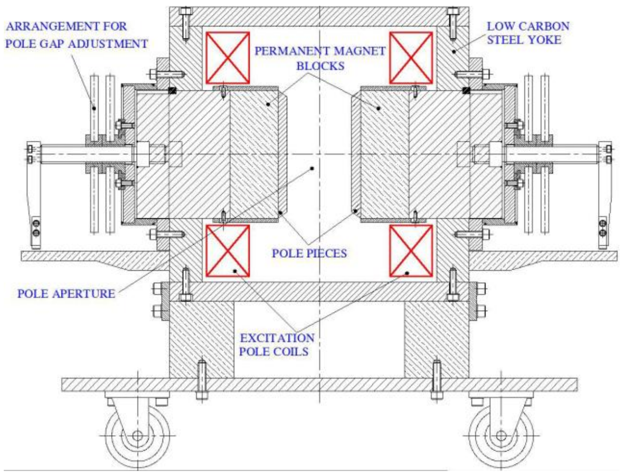


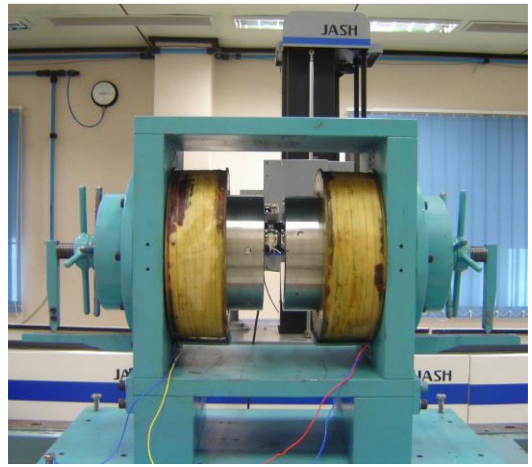
Measured magnetic field pattern along axial direction at various radial distances.

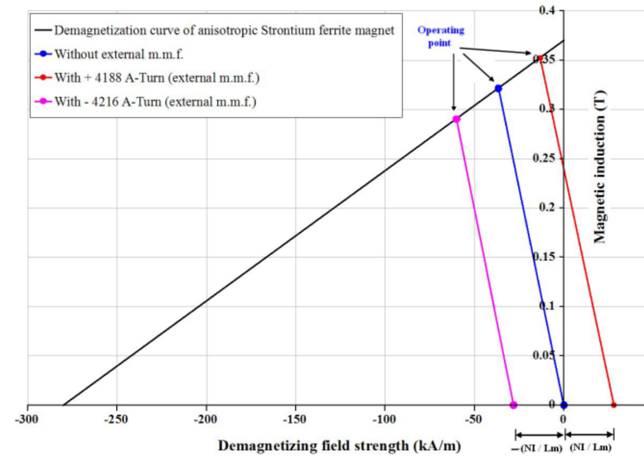


Measured higher order harmonics.

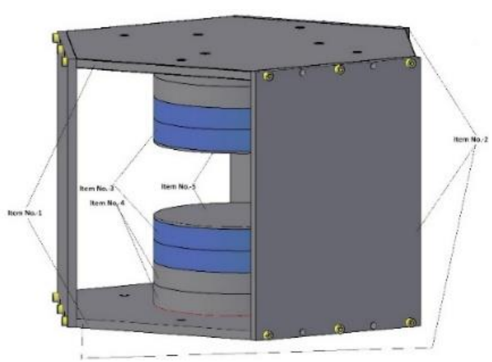
Composite magnets for indigenous circulator development at 505.8 MHz & 650 MHz

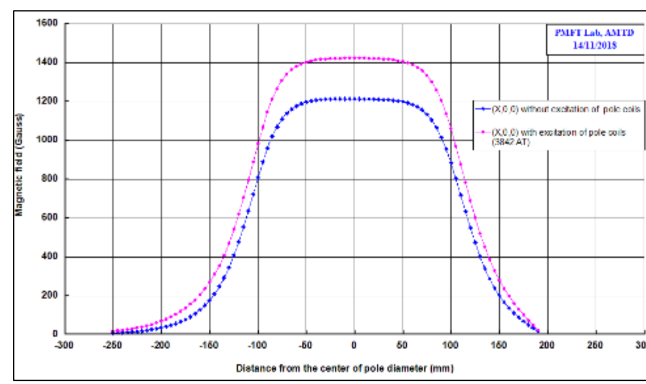






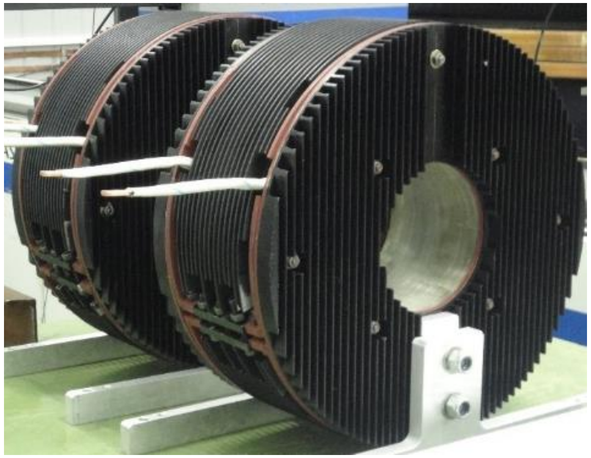
- Designed and developed for biasing of 60 kW, 505 MHz power ferrite circulator at RRCAT.





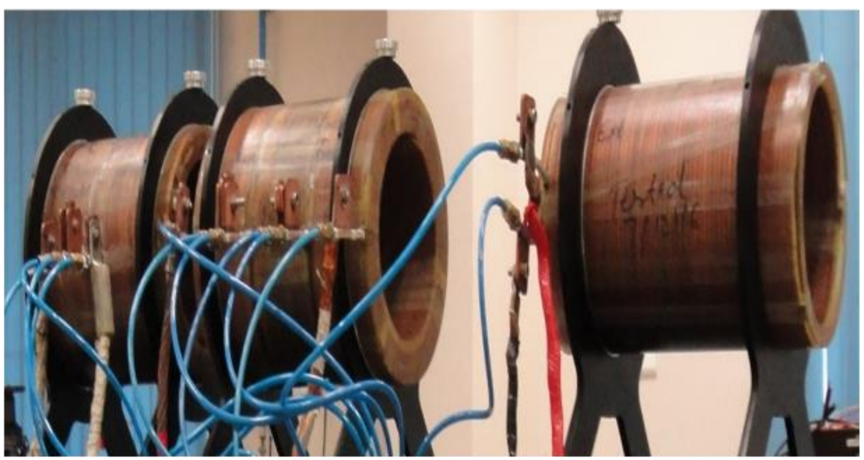
- Developed for biasing of Ferrite resonator used in 50 kW CW circulator at 650 MHz.

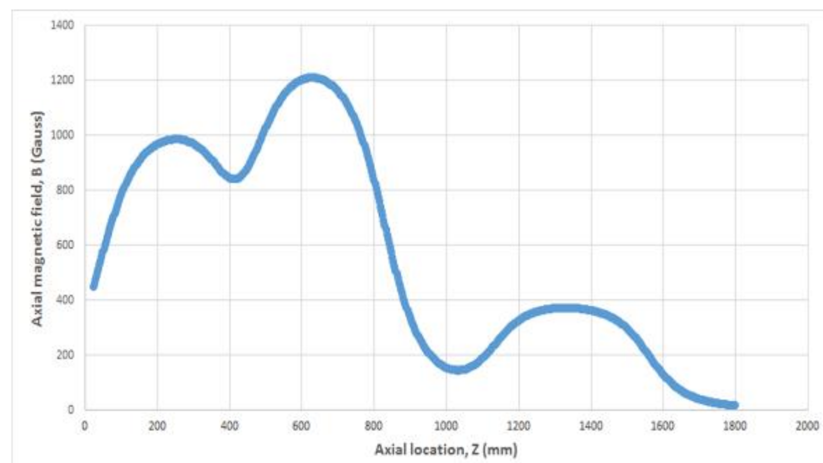
Magnets for Agriculture Radiation Processing Facility (ARPF)



Air cooled Solenoids.

Parameter	Value
Magnetic field	500 Gauss
Ampere Turns	8640 AT
Operating current	40 A (Max.)
Size: ID x OD x L	132 x 316 x 175 mm
Coil conductor	10 x 4 mm copper strip
Power dissipation	0.12 kW



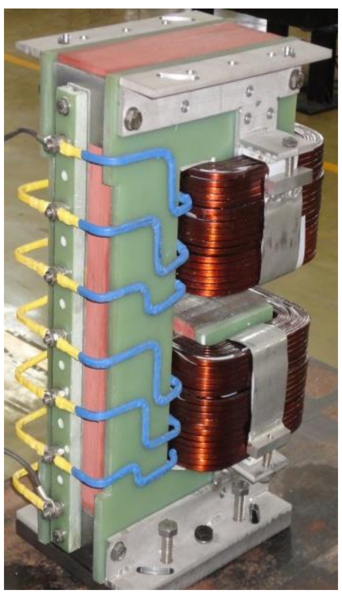


A set of three water cooled solenoids (L) and their combined field profile (R).

(ARPF Magnets contd.)

Scanning magnet

Parameter	Value
Integrated field	86,300 G-mm.
Magnetic length	205 mm
Bending angle	± 15 Degrees
Ampere Turns	2000 AT
Operating current	9 A (Max.)
Size: L x W x H	420 x 220 x 110mm
Core material	0.5 mm thk. CRNGO Si steel.
Coil conductor	SWG 10 Copper wire.



Pulse selector magnet

Parameter	Value
Magnetic field in its pole gap of 34 mm	0.17 Tesla.
Magnetic length	104.72 mm.
Bending angle	30 Degrees.
Bending radius	200 mm.
Ampere Turns/pole	2300 AT.
Operating current	15 A (Max.)
Size: L x W x H	170 x 255 x 480 mm.
Core material	0.23 mm thk. Si. Steel.
Coil conductor	3 x 5 mm copper strips.

Parameter	Value
Magnetic field	0.17 Tesla
Magnetic length	314.16 mm
Bending angle	90^{o}
Bending radius	200 mm
Amp. Turns/pole	2300 AT
Operating current	15 A (Max.)
Size: L x W x H	700 x 530 x 524 mm.
Core material	Low carbon steel.
Coil conductor	3 x 5 mm copper

Energy analyser bending magnet.

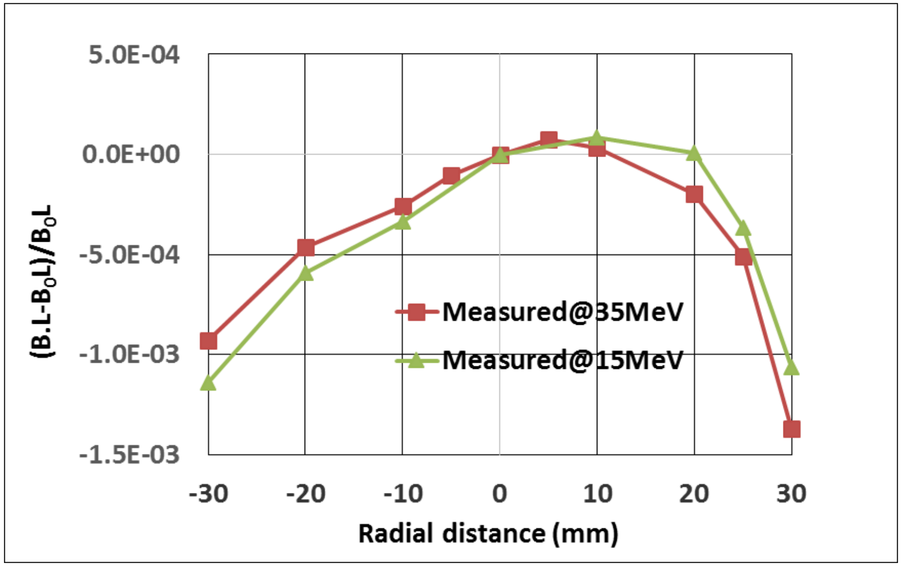
Parameter	Value
Integrated field strength (B.L)	666 G-cm
Bending angle	20 m rad

Steering magnets.

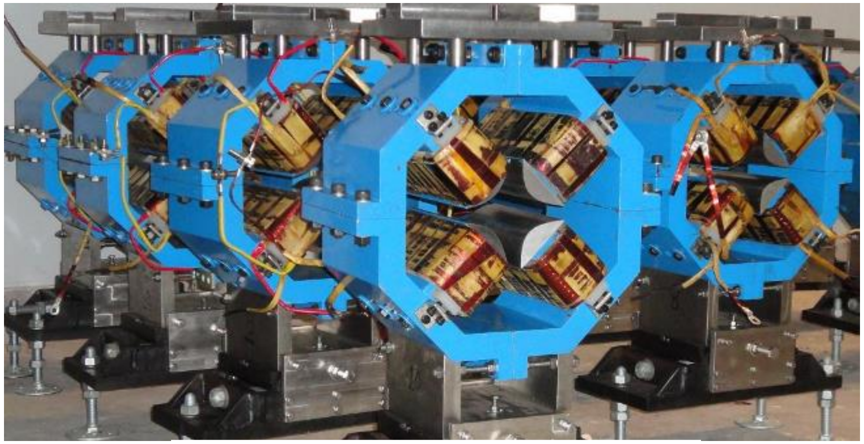
Transfer line Magnets for Infra-Red Free Electron Laser (IRFEL)

Parameter	Dipole magnets	Quadrupole magnets	Water cooled solenoids
Pole gap/Aperture	42 mm	Dia.: 60 mm	Dia.: 278 mm
Peak field/Gradient	0.23 T	2.5 T/m	B.L: 71.18 G-cm
Bending angle	22.5°	--	--
Magnetic length	198 mm	204 mm	--
Core material	Low carbon steel		
Quantity	3 Nos.	12 Nos.	20 Nos.

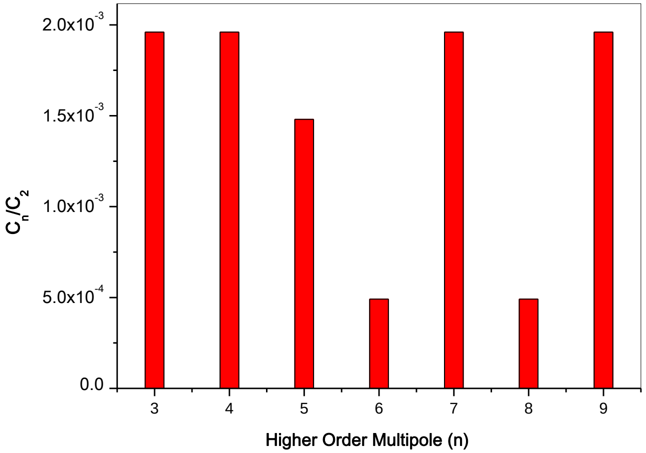
Dipole magnets in measurement bench.



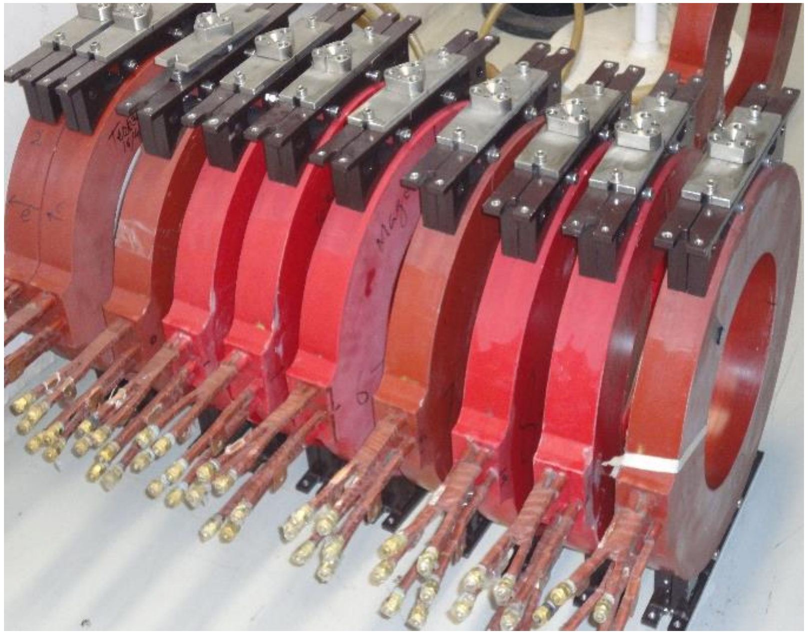
Measured integrated field uniformity.



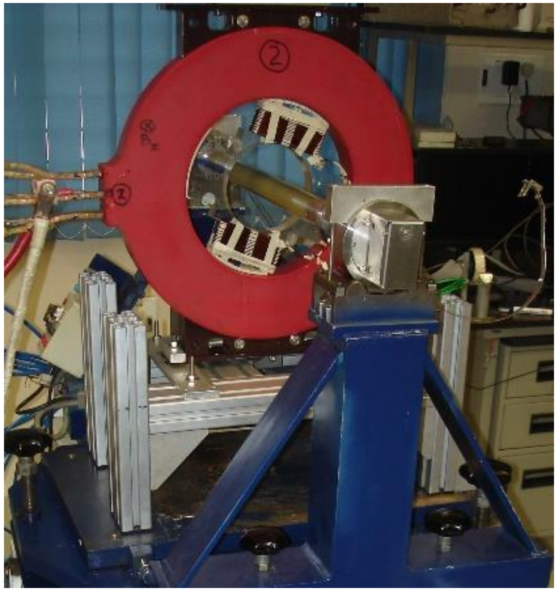
Quadrupole magnets.



Measured higher order harmonics in a Quadrupole magnet.



Water cooled solenoids.



Solenoids in measurement bench.

Mass Spectroscopy Analyser Magnets for BARC

- For isotope ratio measurements of nuclear materials. AMTD designed and developed 10 mass spectrometer analyzer dipole magnets and delivered to Technical Physics Division (TPD), BARC.

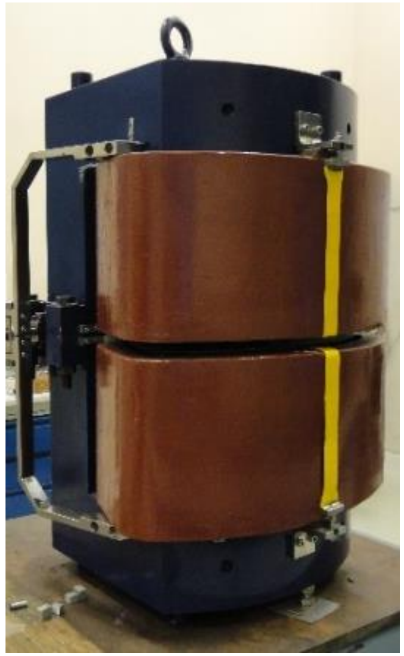
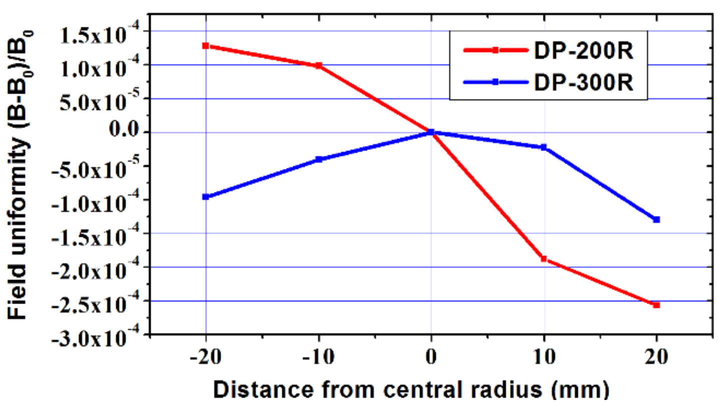


Table : Specifications of dipole magnets

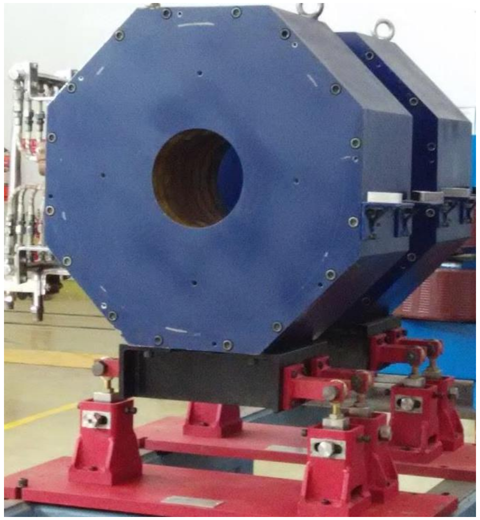
Description	DP-200R	DP-300R
Max. Magnetic field	0.8 tesla	0.7 tesla
Pole gap	14 mm	16.5 mm
Bending radius	200 mm	300 mm
Bending angle	90 degree	
Entry angle	26.5 degree	
Exit angle	26.5 (± 5°)	
Required Pole exit angle adjustment	± 5 ° with step size of 0.5 °	
Radial magnetic field homogeneity	300 ppm in ± 20 mm from central radius.	



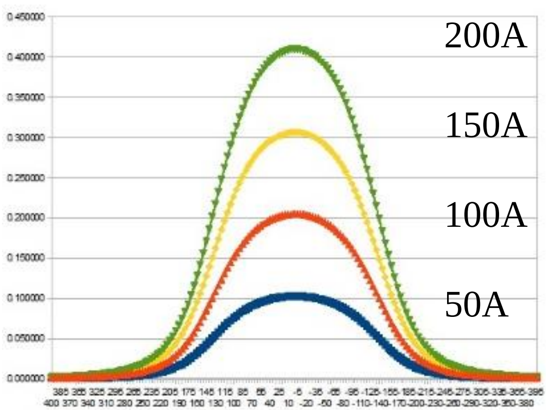
Measured radial field quality in Dipole magnets.

Magnets for LEBT of Proton Linac

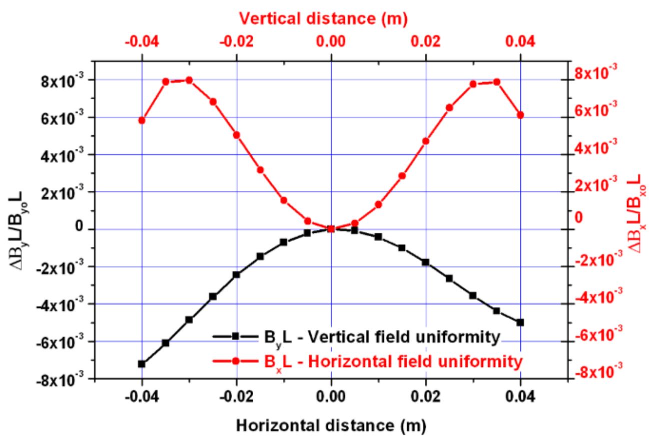
- Solenoids and steering magnets were developed for Low Energy Beam Transport (LEBT), 1 GeV Proton linac, RRCAT.



Measured results of Solenoid.				
Current (A)	Field (T)	Effective length (mm)	$\int_{-\infty}^{+\infty} B_z^2\, dz$ (T^2-mm)	Spherical aberration C1 (/m^2)
50	0.1025	280.434	2.25	23.8
100	0.2050	280.451	8.99	23.7
150	0.3064	280.999	20.11	23.7
200	0.4094	280.733	35.82	23.7



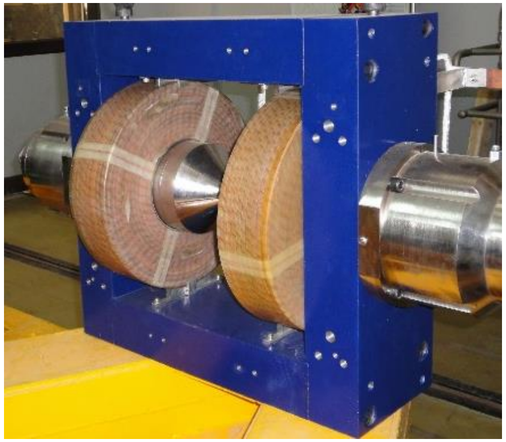
Measured longitudinal field profile in solenoid.



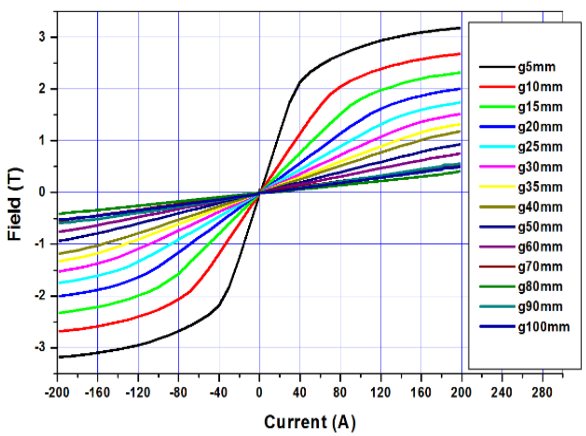
Measured integrated field quality in steering magnet.

Dipole magnets for (SR) beam line experiments

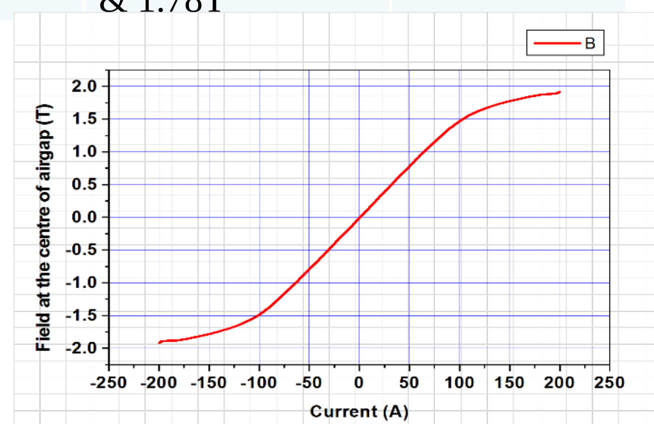
❖ Two magnets one with fixed pole gap and other with variable pole gap dipole magnets were developed .



Parameter	Variable-pole gap magnet	Fixed-pole gap magnet
Pole gap (mm)	0-100	30
Pole diameter (mm)	150	200
Steel length (mm)	200	200
Amp-turns/coil	22000	37000
Nominal current (A)	183	110
Nominal field (T)	2.6@ 183A	1.5 @ 115A
Max. current (A)	200A	200A
Maximum field (T)	**3.2** (5mm gap)	**1.9**
Field uniformity over 1cm^3 (%)	± 0.2 % & ±0.37% at 0.6 T & 1.78T	0.17%



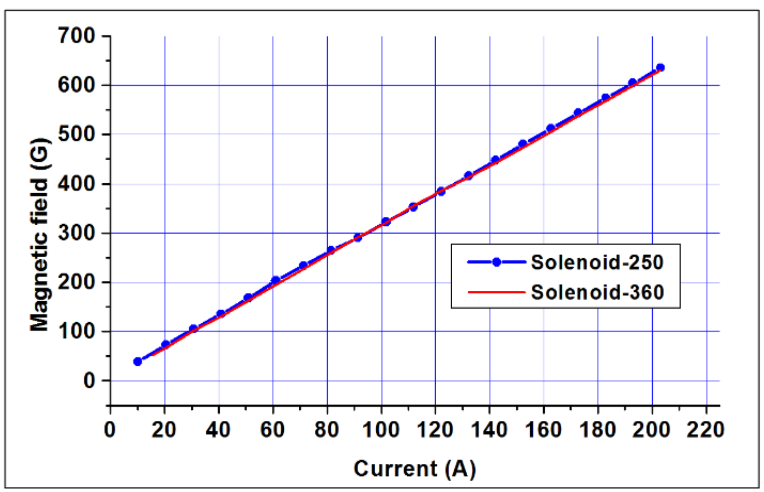
Excitation current vs field in variable-pole gap dipole magnet.



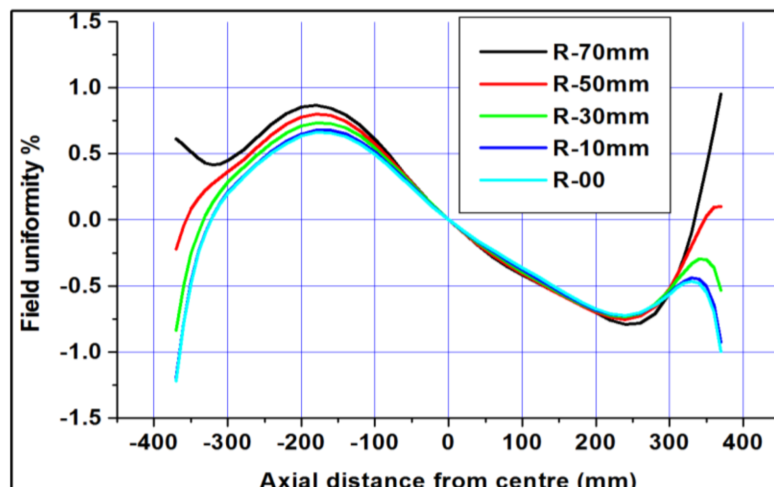
Excitation current vs field in fixed-pole gap dipole magnet.

Solenoids for NEG coating facility, RRCAT

Parameters	Solenoid-360		Solenoid-250	
	Main coil	Trim coil	Main coil	Trim coil
Bore diameter	360 mm		250 mm	
NI (A-turns)	43400	3680	43400	2800
N (Turns)	248	21	248	16
I (A)	175		175	
Length (mm)	1000	88	1000	72
ΔB/B (%) at central axis	± 1 % (L ~ 800 mm)		-1.56% (L ~800 mm)	
Central field, Bz	535 Gauss		512 Gauss	
Power loss (kW)	6.59		5	



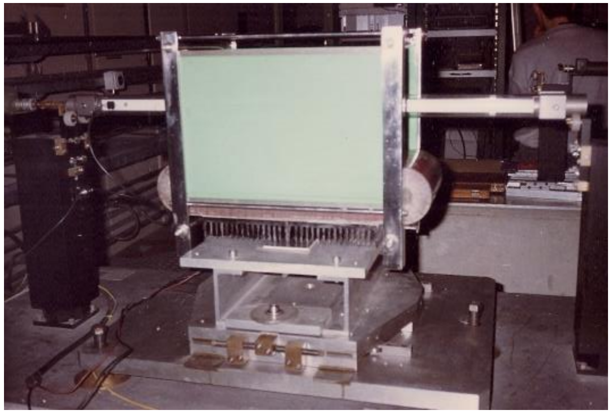
Excitation current vs measured axial magnetic field in the solenoids.



Measured field uniformity in solenoid-250.

Magnets for CERN, Switzerland

❖ 80 Vertical beam orbit corrector magnets (MCVs) for LEP Collider and 5 H-type dipole magnets for CLIC test facility were developed for CERN.



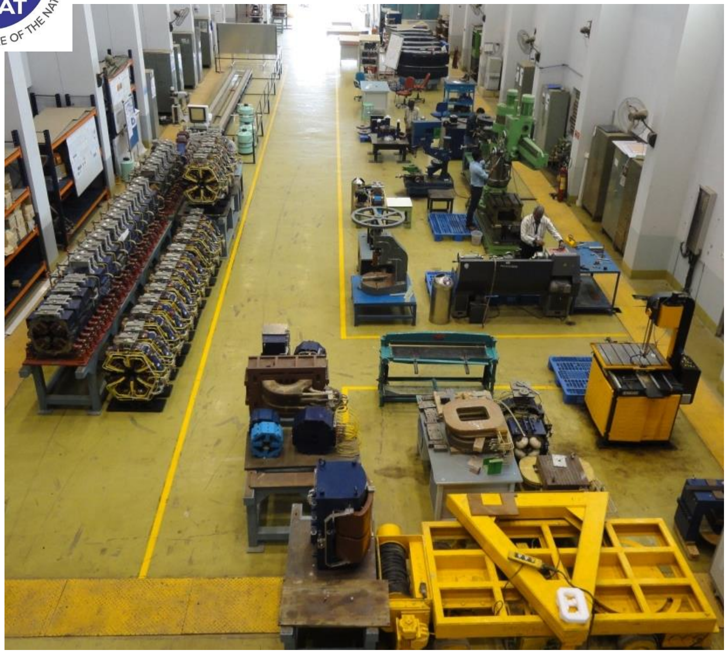
MCVs developed for CERN.

Parameter	Value
Magnetic field	0.038 T
Pole gap	200 mm
Yoke length	400 mm
Coil turns (N)	2420 Nos.
Current (I)	2.5 A (Max.)
Magnet mass	~ 110 kg
Power dissipation	160 W

Parameter	Value
Magnetic field	1.3 T
Pole gap	45 mm
Yoke length	465 & 235 mm
Magnetic length	518 & 268 mm

H-type Dipole magnets for CLIC test facility, CERN.

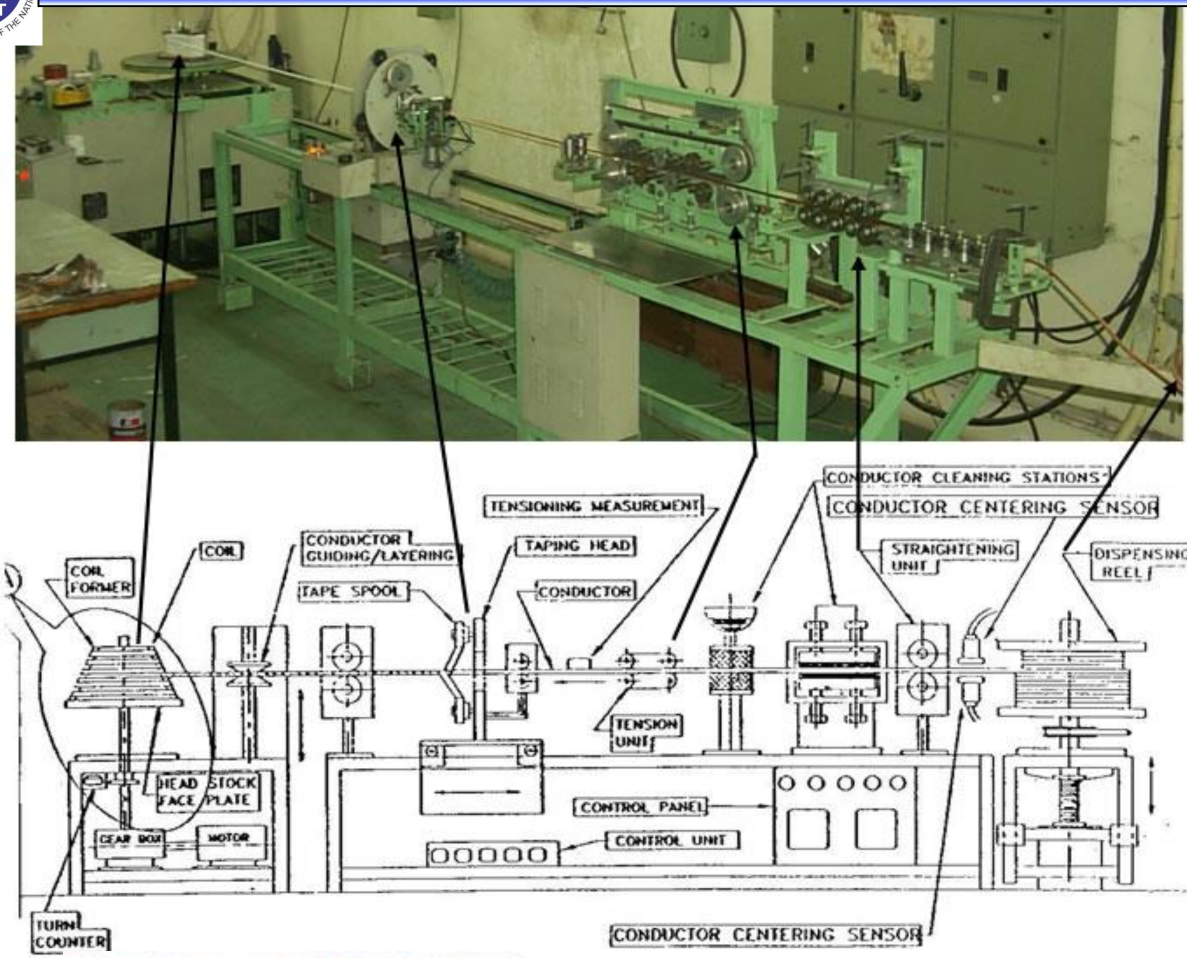
Major in-house magnet development and testing facilities



General machinery for magnet development and installed 50 ton EOT Crane .

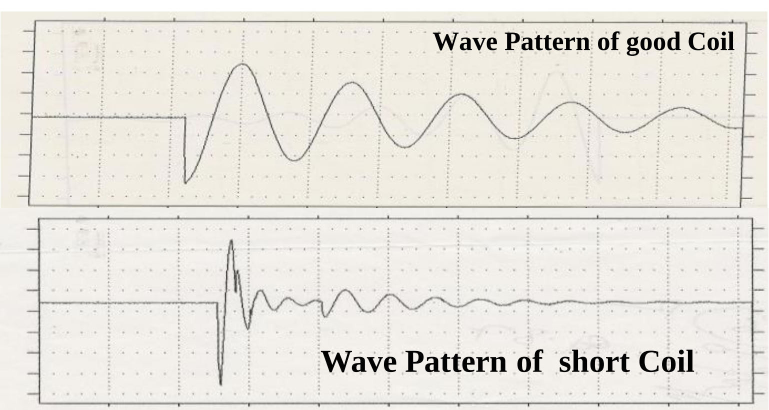
Dipole magnet coil winding machine and epoxy-resin encapsulated coils .

Quadrupole & Sextupole magnet coil fabrication facility



Inspection/testing facility

Electrical test set-up for magnet coils



Inspection of core laminations on co-ordinate measuring machine

Hydraulic-Pneumatic test set-up for water-cooled QP magnet coils

LCW PLANT

Outside view of LCW Plant.

(700 kW, 650 LPM & 10 bar pressure)

Process machinery inside LCW Plant.

Soft ferrites development facilities

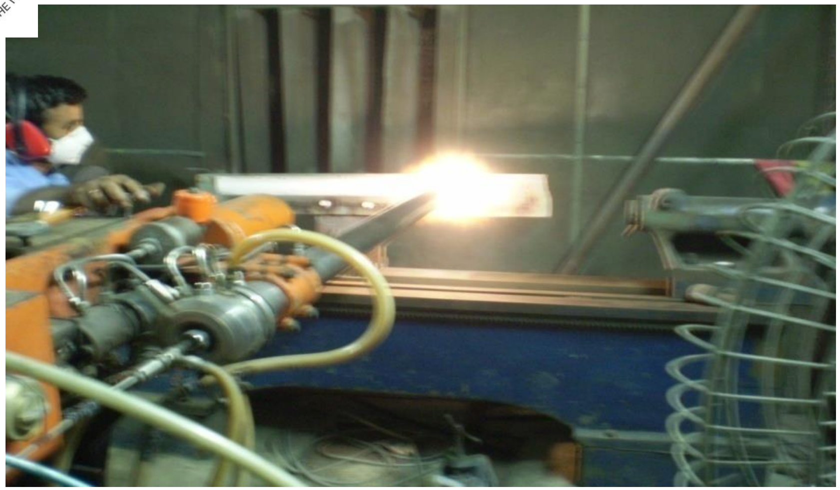
- ❖ Planetary ball mills;
- ➢ Mechanical & Hydraulic Presses;
- ❖ Furnaces (sintering and hydrogen annealing furnaces);
- ➢ Microwave digestion system;
- ❖ Lapping and polishing machines;
- ➢ Precision slicing machine;
- ❖ Surface grinding machine;
- ➢ Thermal spray alumina coating system.

Hydrogen Annealing facility

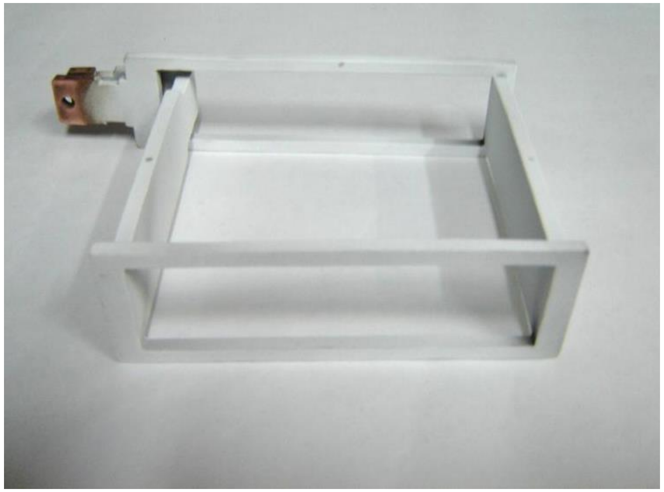
A bell type hydrogen annealing furnace is indigenously developed for thermal annealing of Soft magnet cores –Nickel Iron (0.1 mm thick laminations).

Septum magnet laminations were annealed at 1180 ^{0}C under hydrogen atmosphere to relive internal stresses for restoring magnetic properties in order to satisfactorily operate the magnet in high field pulsed condition .

Thermal Spray Coating facility



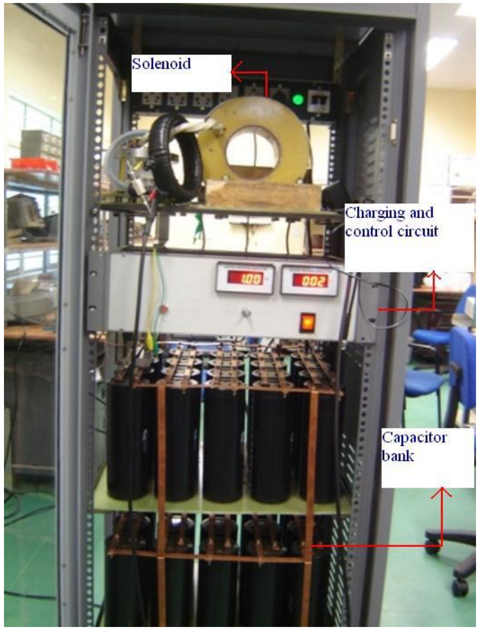
- This facility is developed for alumina – high voltage (~ 10 kV) insulation on the surfaces of copper coils used in Pulsed magnets of Indus Accelerators.



Alumina coated copper coil for kicker magnet.

5Tesla Pulsed magnetizer

- Developed magnetization of large size ceramic and NdFeB magnets (90mm diameter). This is a capacitor discharge type magnetizer that generates a unidirectional pulse of magnetic field with a peak value of about 5T in the cylindrical fixture.



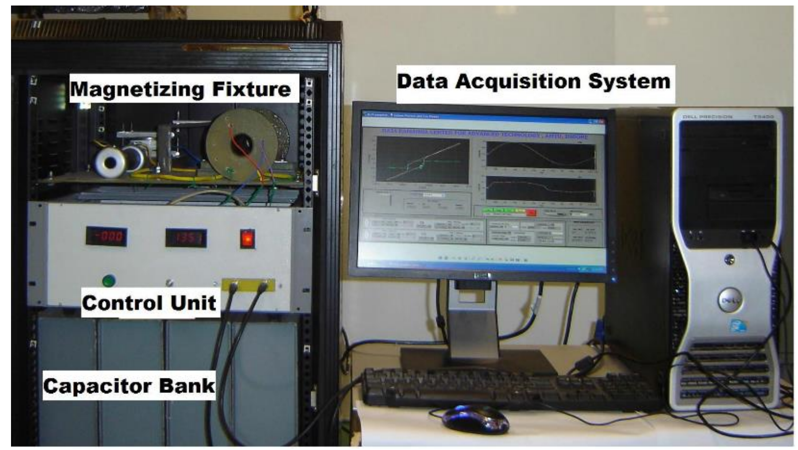
5Tesla Pulsed Demagnetizer

- Developed for demagnetization of ceramic and high energy NdFeB magnets of disc shape (up to 25 mm diameter and thickness 15 mm) .

Magnetic material characterization facilities

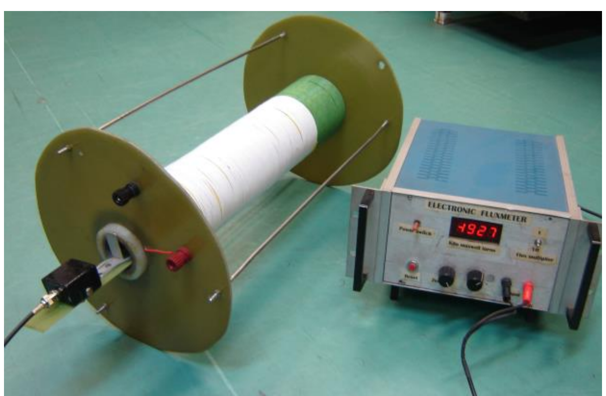
DC Permeameter system for B-H loop of soft magnetic materials

- Plotting of DC B-H loop of soft magnetic materials at 0.05 Hz.



M-H loop tracer system for characterization of high energy rare earth magnets

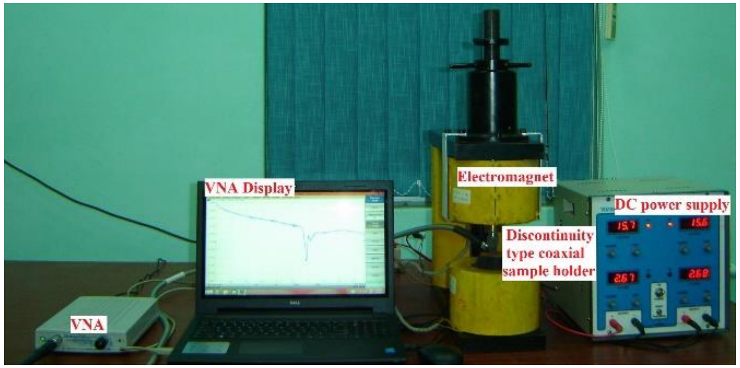
Magnetization system of 5 T field was developed for measurement of demagnetization curve, operating points of magnet in second quadrant & recoil permeability measurement of permanent magnets.



Measurement set up for characterization of feebly magnetic materials

- Based on the measurement of the magnetization (M) of the material under an increasing external field H.

Ferrite characterization benches



FMR measurement setup using RF Sweeping technique

- Measurement of resonance line width of microwave ferrites.

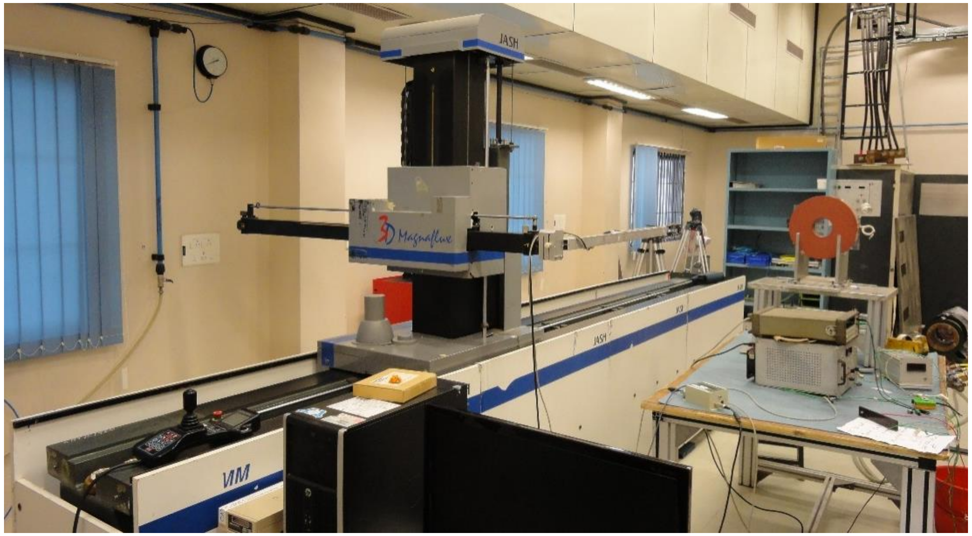
Wide Band Complex Permeability Measurement set up

- Based on transmission Line techniques (Transmission/Reflection parameter) and used for wide frequency range, thus satisfying both the high frequency and wide band criteria of characterization.

Spin wave line width measurement system

For Microwave ferrite & garnets for 7 MW circulator (2856 MHz) development at RRCAT.

Magnetic field measurement facilities



3-D Magnaflux field mapping machine for dipole magnets.

(X, Y & Z: 3m x 0.8m x 0.6m, positional accuracy : ± 0.01 mm / 1000 mm.)

Rotating coil measurement system (Danfysik make)

(Accuracy of integrated main harmonics: ± 3×10^{-4})

Basic specification of Coordinate Measureing Machine (CMM)

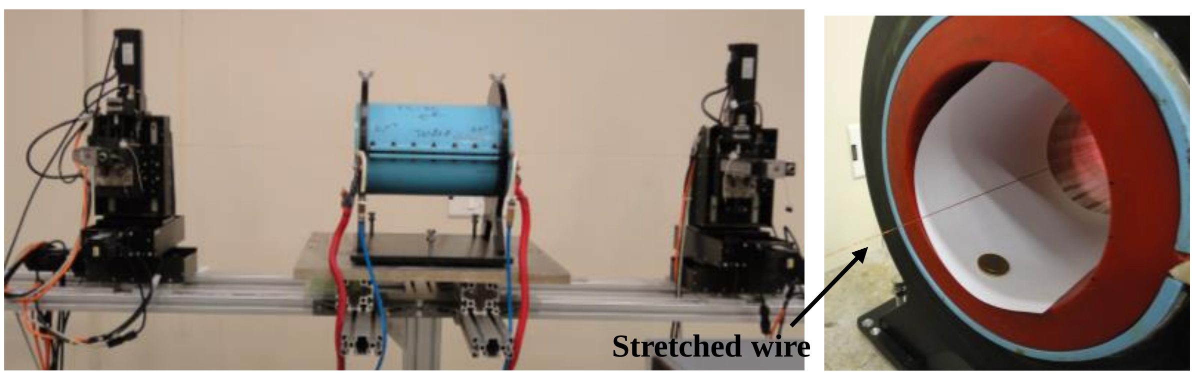
X Axis (mm) Y axis (mm) Z axis (mm)	3000 800 600
Resolution of feed back mechanism (mm)	0.0005
Positional Accuracy fo X , Y and Z (Non cumulative with compensation)	±0.01 mm/1000 mm

Tesla meter (Group3 make DTM151)

Field Range	0.3-3.0 T
Accuracy	±0.01 % of reading and ±0.006 % of full scale
Temperature Stability	±10 ppm of reading / ^{o}C max.
Time Stability	±0.1 % max over 1 year
Calibration	NMR

Magnetic field measurement facilities

Indigenous Rotating coil measurement system



Stretched wire measurement setup for measurement of magnetic axis of a solenoid (L);
Enlarged view of stretched wire passing through the aperture of the solenoid (R).

Conclusion

Accelerator Magnet Technology Division (AMTD), RRCAT has developed in-house technology and dedicated equipment for engineering of various accelerator magnets.

Acknowledgement

We acknowledge the efforts of all AMTD colleagues in the development of magnet technology and equipment for engineering of various accelerator magnets.

Thanks for your kind attention