T.1: Development of pulsed magnets for Indus Accelerators at RRCAT

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Abstract:

Injection and extraction system of Indus Accelerator is crucial, challenging & sophisticated for electron injection into 700 MeV Booster synchrotron, extraction of electron bunches then injection into 450 MeV storage ring and 2.5 GeV Storage ring. This is carried out by precision pulsed septum and kicker magnets consisting of low & high frequency magnets operating at high magnetization rates (up to 5 T/microsecond).Pulsed magnets are operated for a short duration ranging from nano seconds to tens of micro seconds during beam injection and extraction.

This article provides brief review of pulsed septum and kicker magnet development strategy, technical challenges involved, pulse characterization of magnet cores-Ni-Fe lamination and Ni-Zn-Co ferrites at high magnetization rates, special measurement benches & future upgradation pulsed magnets for improved e beam injection and extraction.

1. Introduction

Pulsed magnets are used in the synchrotron source injection and extraction system to transfer the electron beaminto (injection) and out of (extraction) from one accelerator to the other. The design of the injection and extraction systems aims to minimize beam loss, place the newly injected or extracted particles onto the correct trajectory. In general, the injection and extraction systems of accelerators require pulsed kicker and septum magnets.These are pulsed dipoles used to capture the beam in a circular accelerator, either in the booster or in the storage ring. They are installed in the magnetic lattice of the accelerators

In this report, a brief overview of various pulsed magnet development for injection and extraction of electrons into Indus Accelerators are described.

1.1 Pulsed kicker magnets

The kicker magnets are used for the temporary, very rapid displacement of the closed orbit that is needed, either to accept a newly injected beam into a stable, unobstructed orbit, or to move the beam close to the final extraction element at the end of the acceleration process, prior to extraction. These magnets provide fast field rise- and fall-times. These requirements are best met by the standard window frame dipole design is shown in Fig. T.1.1, with the magnet placed outside the accelerator vacuum system, to minimize effect of outgassing of magnet cores on vacuum quality. Lumped type kicker magnets are used for generation of half sine magnetic fields with rise time of 50 ns, whereas transmission line kickers are used for generation of magnetic field waveform with rise of tens of ns & flatness of 0.1 % for extraction of electrons from the synchrotron into storage ring.

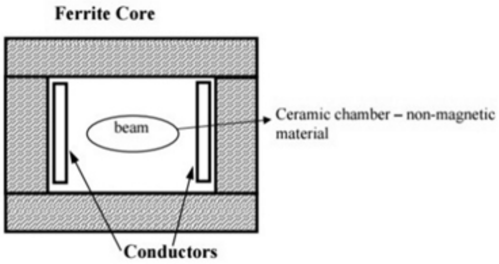


Fig.T.1.1: Window frame kicker magnet

1.2 Pulsed Septum magnets

The change of closed orbit produced by the kicker magnets moves the beam path into the field of a septum magnet which provides the necessary deflection to the incoming or outgoing beam to match the angle of the beam transfer line to the accelerator orbit. A single septum conductor is used to separate the gap field from the zero field external region. The space between these two regions is occupied by a thin conductor (the septa) and hence beam entering this area strikes the septum and is lost. It is therefore the aim of the designer to minimize this unusable region. To facilitate merging of the injected and stored beams, the septum conductor is designed to be as thin as possible without compromising its mechanical, thermal,electrical,or magnetic shielding performance.

Septum magnet is usually located inside the machine vacuum and deflects the incoming or out-going beam. The simple C core yoke has the coil placed in the plane of the beam as shown in Fig. T.1.2.

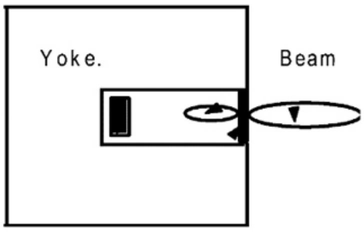


Fig.T.1.2: C type septum magnet

The other conductor (thick section), placed inside the throat of the magnet, is not subject to any dimensional constraints. The outer conductor (thin section) of the coil forms the septum and must therefore be as thin as possible (< 2 mm). This is the required the circulating beam is to the right of the septum, with the injected or extracted component receiving a deflection inside the magnet.

2. Pulsed magnets for Indus Accelerator

Electron Synchrotron facility at RRCAT Indore consists of 20 MeV microtron, 700 MeV Booster Synchrotron, 450 MeV storage ring (Indus-1) and2.5 GeV storage ring (Indus-2). Pulsed Injection and extraction system of Indus Accelerator is crucial, challenging & sophisticated for electron injection into 700 MeV Booster Synchrotron, 450 MeV and 2.5 GeV storage ring& extraction of e from Booster Synchrotron. This has been carried out by combination of pulsed septum & kicker magnets.

Various low frequency (septum) and high frequency (kicker)magnets have been indigenously developed, now in use in routine round the clock Indus operation. Further they have been upgraded for large aperture with improved field uniformity aperture, low stray fields < 1 G-m ease of assembly for preventive maintenance & high voltage insulation Detail of pulsed magnets installed in Indus Accelerators are listed in Table T.1.1.

Table T.1.1: List of Pulsed magnets in Indus-Accelerators

Pulsed Magnets	Purpose
Pulsed injection kicker magnets	20 MeV e beam injection intoBooster ring
Pulsed injection septum magnet	20 MeV e beam injection into Booster ring
Fastrise extraction Kicker magnet	550MeV e bunches extraction from Booster to Transfer line -2
Pulsed extraction septum magnet	550 MeV e bunches extraction from Booster to Tl-2
Fast decay type magnet with decay τ < 150 ns	450 MeV e beam injection into in to Indus1 ring
Pulsed- injection thin & thick septum magnet and kicker magnets	550 MeVe beam injection into the 2.5 GeV Storage ring

3. Requirement of magnetic cores for pulsed magnets

Soft magnetic materials are the limiting factor in pulse magnet systems operating at high magnetic amplitudes & in high frequency applications in accelerator subsystem. Soft magnetic cores with high value of knee of magnetization, low corecivity, low remeance, low magnetic losses & high pulse permeability are required for development of high performance, efficient pulsed magnets of Indus Accelerators.

3.1 Soft magnetic Ni-Fe cores for Pulsed septum magnets

Soft magnetic lamination (Ni-Fe) with thickness 0.1 mm thickness chosen for penetration of pulse field of 100 µs width into material (order of skin depth), low remeance, high values of Bkneeand pulse permeability,10-50 KHz frequency response, compatible in UHV and bakeble up to 250^0C. Soft magnetic Ni-Fe was selected and fabricated from Midhani. These cores are fast switching core materials for pulsed magnets involving magnetization rates of ~1 Tesla/microsecond and magnetization reversal of the order of tens of microsecond.

3.2 Ni-Zn-Co ferrite materials for fast pulsed kicker magnets

Fast switching magnets are used for e beam injection / extraction. The function of the ferrite in a kicker magnets is to efficiently guide magnetic energy into a vacuum gap. While the steady state magnetic field is dominated by an airgap and the transient field is dominated by the magnetization of the ferrite. The magnetization must increase to the required value as rapidly as possible to reduce the impedance mismatch between the source and the magnet because that mismatch degrades the rise time. The response of the ferrite is therefore a limiting factor in the rise time of the magnetic field. Ni-Zn Co ferrite materials with low remeance (< 900 Gauss),lowcorecivity (< 0.3 Oe),large pulse permeability at 200 mT (~ 1000)& high frequency response (~ 100 MHz) have been selected & developed in-house for fast kicker magnets .

4. Development strategy of Pulsed magnets

Pulsed magnets are operated for few nano seconds to tens of micro seconds during beam injection and extraction. It was a challenging task to design and develop the magnets for the required magnetic field uniformity ($\Delta B/B < 1 \times 10^{-3}$, fast pulse response at high magnetization rates, low stray fields & negligible residual fields. To achieve this, Septum magnets have been developed using NiFe laminations (0.1 mm thick) with stringent properties, thermal annealing in hydrogen to remove stresses induced during core fabrication,10 micron thick oxidised insulation on both surfaces laminations, and complex single turn coil with 200 micron alumina coating for high voltage insulation between core & coil and assembly of magnet within 50 micron tolerances with pole gap better than 10 micron. Thermally sprayed alumina coating for high voltage insulation in the pulsed magnet have been developed at Industries.

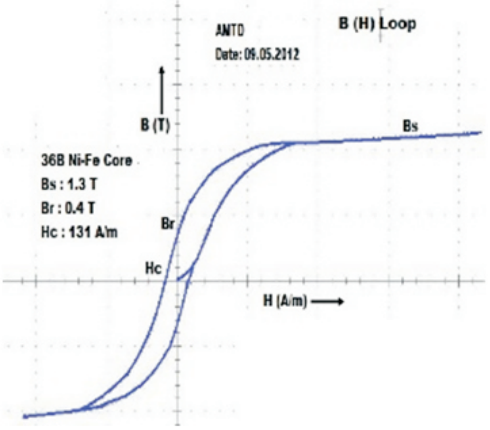
The kicker magnets are operated for relatively shorter duration and were fabricated from different types of NiZnCo ferrite blocks developed indigenously. The fastest kicker magnet is the booster extraction kicker which produces a magnetic field with a rise time of ~50 ns.The special ferrites was not available locally, import cost was very high, and therefore, we have developed large ferrite blocks in collaboration with private industries. This exercise saved not only huge foreign exchange but also generated skill manpower for future projects in DAE.

5. Pulse magnetic characterization of magnet cores

Soft magnetic materials are the limiting factor for high performance efficient pulsed magnets which are operating at high rates of magnetization used in accelerator subsystem. High magnetization rates in magnet cores are associated with magnetic losses due to induced eddy current in magnetic alloys & spin relaxation-damping loss in ferrites. Losses not only reduce efficiency, but also result in increase in core temperature, which ultimately limit the maximum frequency or rise time at which magnetic materials are used. The magnetization behavior of magnetic materials at dc is entirely different from dynamic/pulsed conditions. Therefore, the dynamic studies of magnetic materials have been carried out to know how the magnetic cores behaves when its magnetization reverses in the order of 100 ns.

5.1. Characterization of nickel iron core materials for pulsed septum magnets

Magnet performance greatly depends on pulse magnetization behavior of Ni-Fe cores.C shape core fabricated from 36B Midhani lamination. Pulse magnetic properties particularly knee of magnetization, pulsepermeability and coercivity are degraded in the great extent (about 30%) during cold work-fabrication into C shape. Thermal stress reliving process has been optimized to restore original magnetic properties.



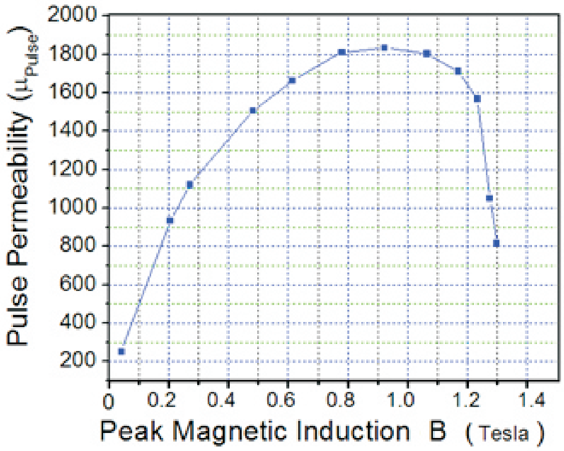


Fig. T.1.3: Pulse BH loop of NiFe lamination and pulse permeability as a function of B_{peak}

A set of the laminations were annealed at different temperatures in hydrogen atmosphere followed by surface oxidation at 400ºC in air atmosphere. Measured pulsed magnetic permeability of these laminations are of the order of 2000 at a peak magnetic induction of 0.9 Tesla and pulsed magnetic field homogeneity of the order of ~ 5×10^{-4} is shown in Fig. T.1.3.A special pulse apparatus has been in-house developed to characterize NiFe laminations at magnetization rates up to 1 Tesla/microsecond.

5.2 Pulse characteristics of ferrite at high rates magnetization for fast kicker magnets

Ni-Zn-Co and Ni-Zn-Cu are indigenously developed for fast switching magnetic devices like fast rise kicker magnets and FCTs for accelerator sub-systems. The magnetization rates are involved up to 5 T / s & magnetization reverses in the order of tens of nano-second. A pulse test bench was in-house developed to measure the response of ferrite to fast, high rates of magnetization (~ 5T / s) so that these test results directly applied to the design of high speed magnetic devices like fast switching magnets & magnetic switches for lasers and accelerators. The measured dynamic magnetization curves were used in the development of fast kicker magnet & FCTs.

Snokes limit in the ferrite & garnet for onset of resonances has been accurately estimated from the complex permeability spectrum. These results have been found useful in the evaluation of field propagation time through ferrite cell for development of Transmission line kicker magnets & Wide band Fast Current Transformers (FCTs).

6. Pulsed magnets for Booster Synchrotron

A 20 MeV electrons are injected into the Booster synchrotron by adopting a multi-turn injection scheme using 1 µs long electron beam pulse from the Microtron at a repetition rate of 1 Hz. A compensated bump producing maximum amplitude near the injection septum is produced using three injection kicker magnets. Injection is carried using the de excitation of the kicker .The field fall linearly to zero in the duration of 1 µs. During this period about 11 turns are injected using three kickers.

6.1 Pulsed injection kicker magnets

Kicker magnet technology development involves magnetic designs, ferrite fabrication, pulse magnetic testing, high voltage coils, HV insulations, mechanical structures & their assembly. A lumped type kicker magnet chosen to meet fast response & power supply simplicity. Due to limitation of space, the section of yoke, conductors, and macor insulations has been designed to avoid dimensional resonance & magnetic force resonance. Window frame type configuration chosen on the basis of good field spatial homogeneity, low circuit leakages, and simplicity construction. Electrically lumped type magnet is selected & its layout is shown in Fig. T.1.4.

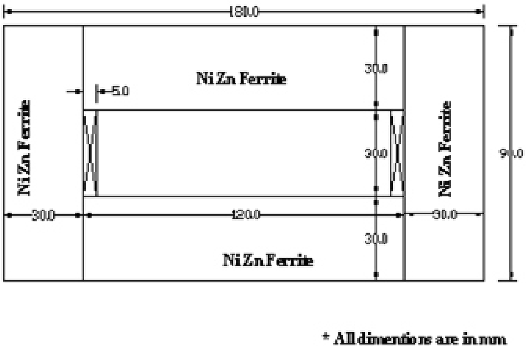


Fig. T.1.4: Cross sectional view of Kicker magnet – Window frame type

6.1.1 Up-gradation of injection kicker magnets

Pulsed injection kickers were commissioned in the year 1996.Consequent to successful operation in Booster synchrotron, further they have been up-graded for reduced coupling impedance. A copper wire loop (0.5 mm diameter) has been optimized for minimal effect on field distribution but reduction of Impedance from ferrite to beam in great extent. A kicker with conductor windings around the ferrite in top & bottom along beam path showed a significant reduction of longitudinal coupling impedance without affecting kicker field pulse shape & its distribution. Copper wire loop has been inserted around ferrite block in top & bottom poles which is shown in Fig. T.1.5.

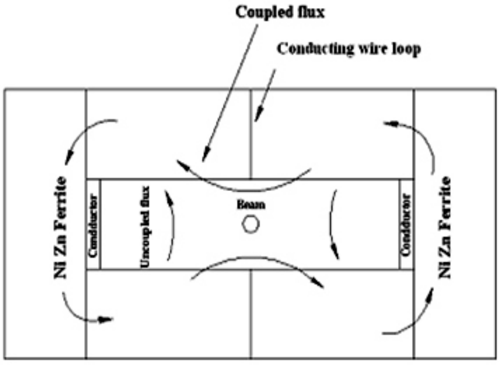


Fig. T.1.5: Reduction in coupling impedance of Injection kicker magnet

Longitudinal coupling impedance of kicker magnets was measured using coaxial bench in-house developed. The real part of the impedance has a peak value of about 6-7 ohms around 10 MHz The imaginary part of the impedance is inductive within the test frequency. A new resonance model of ferrite assembly for window frame kicker magnet has been developed. Experimentally observed results were compared with values obtained from New Resonance model. A close agreement between them has been observed.

Measured pulsed magnetic field homogeneity (~ 10^{-3}) and up graded injection kicker magnet installed in the vacuum chamber isshown in Fig. T.1.6 &T.1.7 respectively.

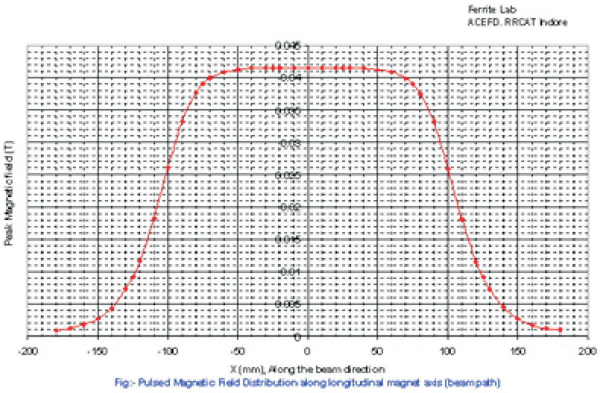


Fig. T.1.6: Pulsed magnetic field distribution along longitudinal axis (beam path)

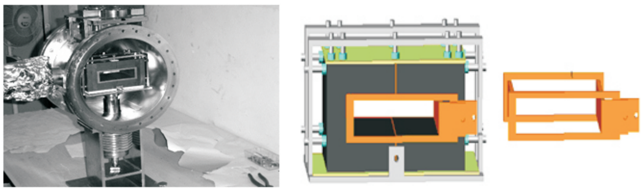


Fig. T.1.7: Upgraded injection kicker installed in the vacuum chamber

Pulsed kicker magnets are working satisfactorily in injection of 20 MeV electrons into Booster Synchrotron during accelerator operations. They are found to work efficiently and reliably.

6.2. Fast rise extraction kicker magnet

Booster orbit time of 100 ns and a maximum of 3 electrons bunch, spaced at 30 ns. These electron bunches are required to be extracted from Booster synchrotron at a repetition rate of 1–2 Hz for injection into 450 MeV & 2.5 GeV storage ring. The kicker system required generating a pulse magnetic field with a rise time (<30 ns) and flat-top (100 ns). With this three electron bunches are to be extracted.

Kicker magnet is electrically lumped type with a full aperture. The magnet have been constructed in C shape in two half cells using various Ni-Zn ferrite blocks. The two halves of magnet are positioned in the top and bottom thereby giving a well-defined mechanical center. Their assembly details are shown in Fig. T.1.8.

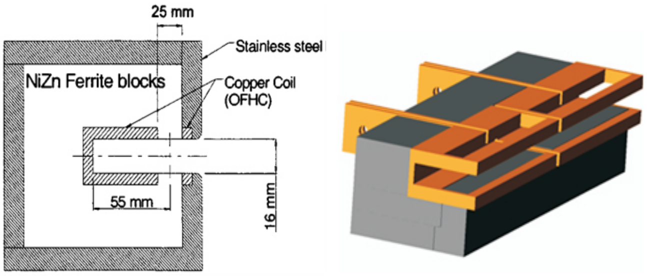


Fig. T.1.8: Sectional view of fast rise kicker magnet

A fast extraction kicker magnet has been developed & tested A pulsed magnetic field of 624 G with a rise time of 45 ns and duration of 75 ns was obtained.

The magnet has been operated at 30 kV (at 800 A) and now in routine operation for e beam extraction. During routine Indus operations, the kicker system show an excellent performance by extracting two electron bunches from the Booster. The extracted electron bunches time structure is shown in Fig. T.1.9.

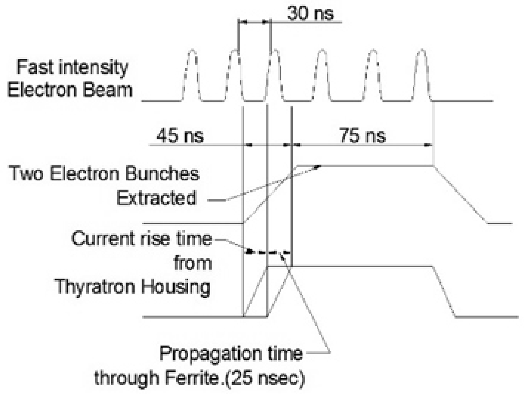


Fig. T.1.9: Time profile of extracted ebunches show bunch spacing and kicker rise time.

6.2.1 Up-gradation of fast rise kicker magnet for improved electron bunch extraction

Existing lumped kicker magnet extracting two electron bunches from booster synchrotron and subsequently injected into Indus 2.

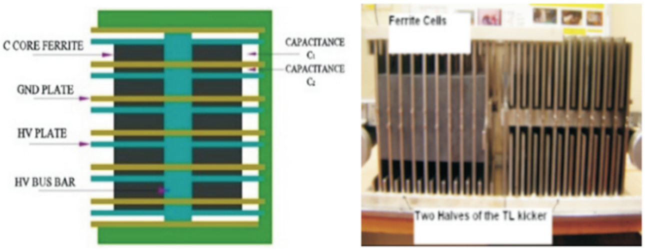


Fig. T.1.10: Tr line kicker magnet with NiZnCo ferrite

For injection of three electron bunches into Indus-1 & Indus-2, a kicker magnet system with rise time (~ 20-25 ns) & longer flattop (~ 75 ns) with stability of 0.1% is required. To meet these requirements, Prototype transmission line kicker magnet (five cell) with 25 ohm characteristics has been developed for design studies of kicking pulse transmission through ferrite. The kicker magnet was split into several ferrite cells of low inductance (54 nH). Ferrite yoke is sandwiched between two HV plates and each is connected to ground by decoupling capacitor (84 pF) as shown in Fig. T.1.10.

A transmission line kicker magnet using Ni-Zn-Co frames have been fabricated & tested. A fast magnetic field rise time (~ 28 nsec), 100 nsec flat top with 1 % flatness stability has been obtained during low power testing. Experimentally observed results are well agreed with modeled response. This study has been found useful in the development of actual transmission line kicker magnet.Pulsed BH loop of NiZnCo ferrite-CAT 3/2 & measured pulse waveforms of magnetic field and current are shown in Fig. T.1.11.

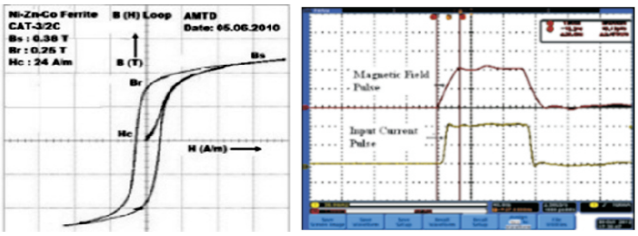


Fig. T.1.11: Pulse BH loop of NiZnCo ferrite cell & measured pulse wave form of Tr line kicker

6.3 Development of upgraded pulsed injection and extraction septum magnets

The aperture (5.3 mm x 8 mm) of existing extraction septum magnet does not have sufficient clearance for electron beam in the booster synchrotron. To reduce the electron beam loss and to increase the extraction efficiency from booster, new extraction septum magnet with 10 mm x 15 mm aperture has been developed. The thickness of septum has been reduced from 5 mm to 3 mm with reduced leakage field. The thickness of septum (~ 3 mm) for both the septum magnets have been optimized for high radial field homogeneity near the septa & low leakage fields outside the septum edge. Modified injection & extraction septum magnets with a large aperture have been developed as shown in Fig. T.1.12. Field homogeneity of the order of 1×10^{-4} inside the septa edge & low stray fields of the order of less than 2 Gm have been achieved. The obtained results are found satisfactory.

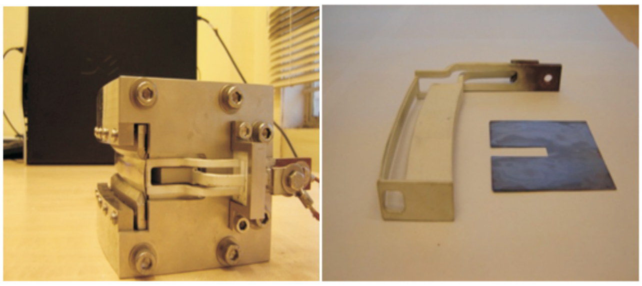


Fig. T.1.12: Injection septum magnet, coil & Core

7. Fast Decay Kicker magnet for Indus-1

The Indus-1 Synchrotron radiation facility consists of a 20 MeV microtron injector, 700 MeV Booster synchrotron & 450 MeV storage ring provides the radiation in the VUV region of the electromagnetic spectrum. In single mode operation, two electron bunches spaced at 30 ns are required to inject into storage ring (orbit time 63 ns). The kicker magnet required to produce kicker field with a rise time (1.2 µs) and exponentially fall ($B_z \geq B_0 e^{-t/\tau}$) with a decay constant (τ) < 150 ns. Window frame configuration chosen on the basis of good field spatial homogeneity, low circuit leakages, and simplicity construction and easy setting over the ceramic chamber as magnet is outside the vacuum (Fig. T.1.13).

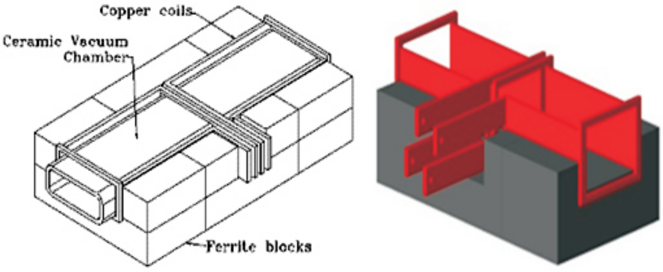


Fig. T.1.13: Assembly of Fast decay kicker Magnet

Kicker was made in two ferrite halves for fast response (Fig. T.1.14). The magnet was excited by a pulse current with a rise time of 1.2 µs and exponential fall decay with a constant < 150 ns. A pulsed magnetic field of 800 G with a rise time of 1.2 µs and exponential decay of 125-130 ns was obtained. The observed rise time was 1.2 µs (0-100%), which is within acceptance value, fall decay with constant 125-130 ns has been observed. The field quality ($\Delta B/B$) ~ 1×10^{-3} has been achieved over magnet aperture of 80 mm (H) x 25 mm (V).

The magnet operated at 30 KV at 2500 A in routine Indus operation. The fast decay magnet system showed the desired stability, reliability & field homogeneity

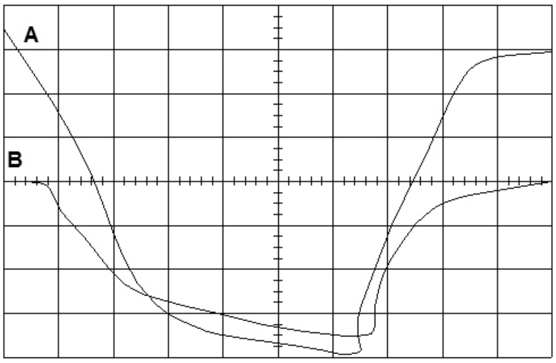


Fig. T.1.14: Pulse magnetic field waveforms; Trace A: Pulse current at 2500 A and Trace B: Pulse magnetic field, B_{pk} curve

8. Pulsed magnets for 2.5 GeV Storage ring

Booster synchrotron provides two electron benches each around 2 ns long & separated from each other by nearly 30 ns at 700 MeV energy(PRF of 1-2 Hz). Injection system consists of pulsed thin & thick septum magnets & four kicker magnets. Injection of 600 MeV electrons into the Storage ring in the horizontal plane is carried out by combination of these pulsed magnets. The maximum kick angle produced by kicker magnets is 25 mrad, which produce an orbit bump of 20 mm and beam in injected thru septum magnet into Indus-2 ring.

8.1 Pulsed septum magnet system

Pulsed septum magnets which have two field regions. High magnetic field region- generate high uniform magnetic field (ΔB/B ~ 10^{-4}) in the aperture for providing uniform beam deflection to the incoming e beam. Whears zero field region (low field) through which the circulating beam pass without suffering unacceptable deflection or orbit distortion.
The space between two regions occupied by thin conductor and hence beams entering thin area strikes the septum & is lost tolerable stray field ~ 2 G meter. Septum magnets operated in pulsed mode to reduce the average power loss on a thin septum sheet.

Table T.1.2: Main Parameters of Septum magnet (600 MeV)

Parameters	Thin Septum	Thick Septum
1. Max magnetic field	4.190 KG	7.720 KG
2. Radius of Curvature	7162 mm	2594 mm
3. Deflection angle	2 Δ	19 Δ
4.Effective magnet length	250 mm	860 mm
5. Magnetic field pulse shape	Half sine wave (50 Δs)	Half sine wave (100 Δs)
6. Effective Septum thickness	3 mm	3.50 mm
7. Peak Current (Amp.)	3330	6140
8. Magnetic field uniformity, (ΔB/B)	~ 5 x 10^{-4}	~ 5 x 10^{-4}

Main parameters of thin and thick septum magnets is shown in Table-T.1.2.

The coil fabricated from OFH copper conductor & insulated with thermally sprayed alumina by detonation process. The cross section of the septum magnet is shown in Fig. T.1.15. Pulsed septum magnet was excited by half sine current (100 μs & 50 μs base width) with 10 kA peak current (Thick septum) and 5 kA (Thin septum). The main and stray magnetic fields measured with integrated coil & point coils. 14 bit digitizer magnetic measurement system (3 axes) was developed for pulse magnetic characterization of septum and kicker magnets. Magnetic field uniformity with 100 ppm accuracy was measured using this system. Pulsed field uniformity for thick septum is shown in Fig. T.1.16.

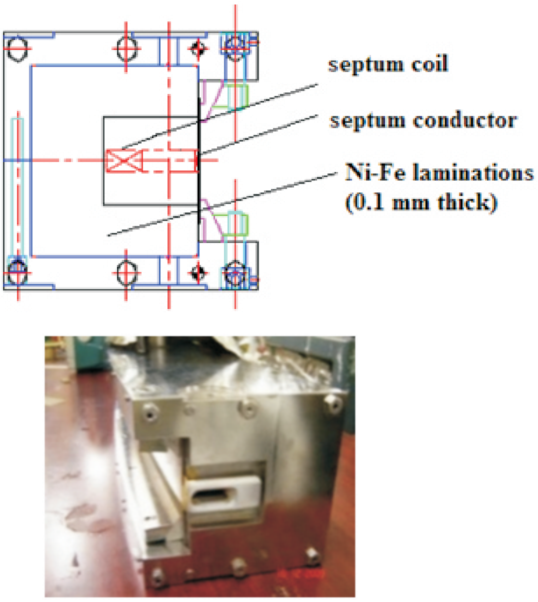


Fig. T.1.15: Cross sectional view of septum magnet

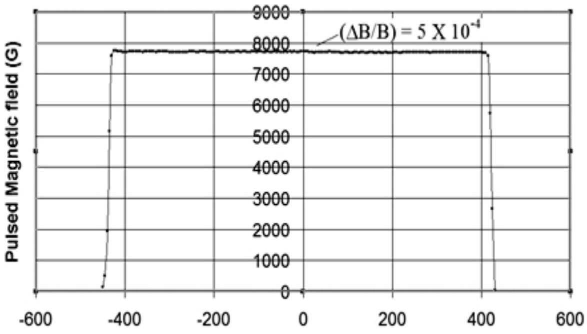


Fig. T.1.16: Pulsed field uniformity along beam path

The stray field at the edge of the septum to the outside region where circulating beam travels is shown in Fig. T.1.17.

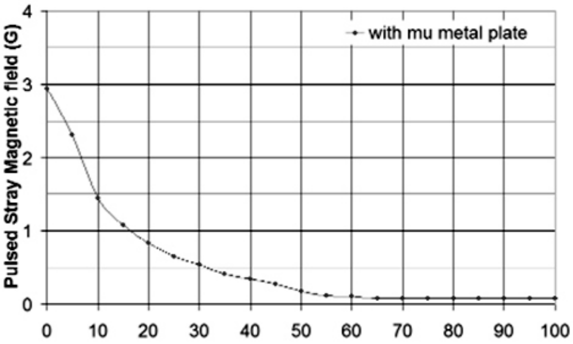


Fig. T.1.17: Distribution of stray field outside of the septum towards beam circulating orbit

Pulsed field stability$\Delta B/B \sim 10^{-3}$ at 600 MeV have been observed for both septum magnets over period of 12 hrs.

8.1.1 Development of upgraded thin and thick septum magnet

The electrical short of thick septum coil with core was detected in Aug 2009.It was also noticed that along with the coils, the C- cores were also damaged. Subsequently new coils with 90corner were fabricated & alumina coated. New septum magnets with these modified coils were made and characterized. Stray B field of the order of 0.6 G-m has been measured on beam circulating orbit. Both upgraded septum magnets are working satisfactorily during Indus operation since 2010 till date.

8.1.2. Prototype development of Eddy current septum for improved injection into Indus-2

Technologies for an eddy current septum magnet are intricate, complex which involves severe engineering and technical challenges in fabrication of coils, cores with special profile and mumetal shield. An eddy current septum magnet with the blackleg winding & force free thin septa (2 mm) has been developed as shown in Fig. T.1.18.

Eddy current septum magnet was excited using 50 µs half sine wave for field homogeneity & stray fields.The integrated transverse field uniformity better than 1 x 10^{-3} near the injection plane & low stray fields less than 2 G-m has been obtained. The measured waveforms of stray field well agree with the simulation results. This will not only reduce impedance to electron beam but also improve electron injection efficiency into Indus-2 storage ring.

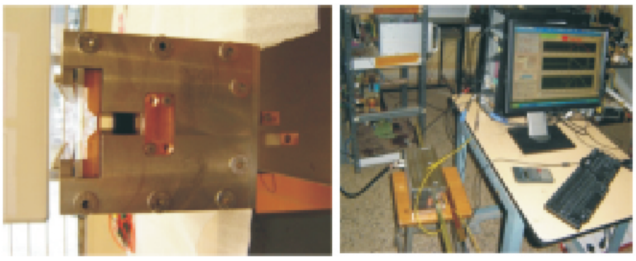


Fig. T.1.18: Prototype eddy current septum

8.2 Pulsed lumped kicker magnet

Window type, electrically lumped kicker magnets are chosen on the basis of good field spatial homogeneity, low circuit leakages, magnet fabrication & power supply simplicity.

Design simulation was carried out using transient flux 2D. The dimensions have been optimized to generate half sine wave (3µs width), 0.2T Peak magnetic field with high homogeneity (ÅB/ B ~ 10^{-3}) operation below the knee of magnetization of B (H) curve. Each magnet has been constructed in window frame, single turn coil with Ni-Zn-Co ferrites mounted around ceramic chamber their assembly details are shown in Fig. T.1.19.

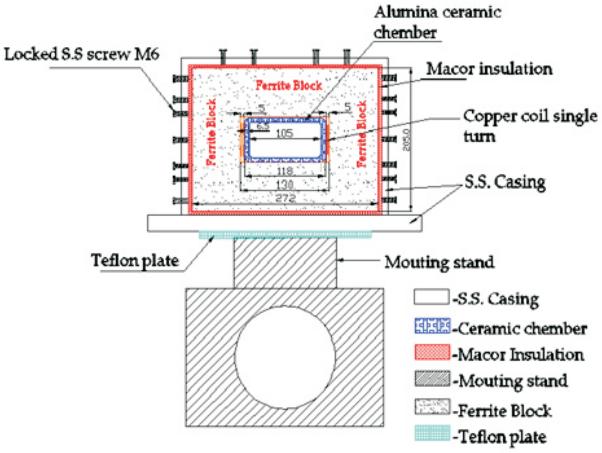


Fig. T.1.19: Sectional view of Kicker magnet

A special coaxial test bench is developed for coupling impedance measurement in our Lab. The measurement was performed transforming the kicker magnet with Ti coated ceramic chamber under test (DUT) to a coaxial line structure with a characteristics impedance of about 155 Ω.The longitudinal coupling impedance of a kicker magnet with Ti coated ceramic chamber has been measured from 0.3 to 100 MHz using RF network Analyzer. The real part of the impedance has a peak value of about 1Ω around 30 MHz, then decreases monotonously when the frequency increases. Measured longitudinal coupling impedance has been compared with calculated values from Resonance model developed in-house at Ferrite lab. The agreement between two is reasonably good that validates our experimentation method.

8.2.1 Characterization of Ti coated ceramic chambers with ferrite kicker magnet

Ceramic chambers have been used in the pulsed kicker to avoid shielding of a fast-changing external magnetic field by metallic chamber walls and to reduce eddy current heating. The inner surfaces of the ceramic chamber has been coated with 1 micron Ti conductive layer to reduce the beam coupling impedance, provide passage for beam image current and to reduce the secondary electron yields. Cross sectional view of ceramic chamber is shown in Fig.T.1.20.

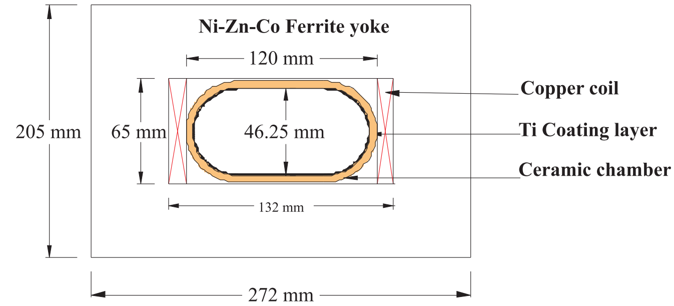


Fig. T.1.20: Ti coated ceramic chamber

Ti coating thickness & its distribution on inner surface of ceramic chambers have been measured using Co-centric circular & Eddy current probes developed in house at Ferrite lab as shown in Fig. T.1.21.

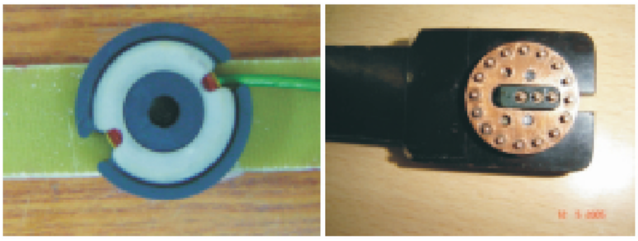


Fig. T.1.21: Co-centric circular & Eddy current probes

Ti coating thickness has been measured by both methods are in goodagreement. Experimentally measured kicker field attenuation of 1-2 % & 10-30ns time delay are an excellent agreement with modeled results. Four Ti coated ceramic chambers have been assembled in the kicker magnets and tested for field uniformity & coupling impedances.

We have also analytically calculated the field attenuation and time delay for different Ti coating thickness is shown in Figs. T.1.22 and T.1.23.

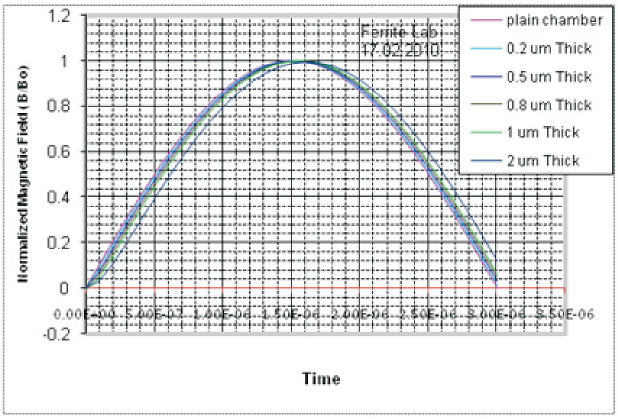


Fig: T.1.22: Analytically estimated time delay

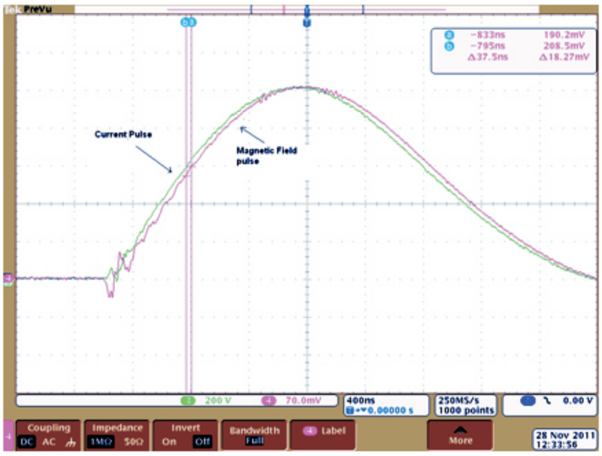


Fig: T.1.23:Experimentally observed kicker delay

Experimentally measured magnetic attenuation (1 – 2 %) & phase delay of kicker field pulse (60 -80 ns) is well agreement with analytically simulated model. have been measured. Field uniformity in the order of (ΔB/Bo) $\sim 5 \times 10^{-3}$ has been observed. Magnetic field distribution in kicker aperture along longitudinal axis (beam path) is shown in Fig. T.1.24.

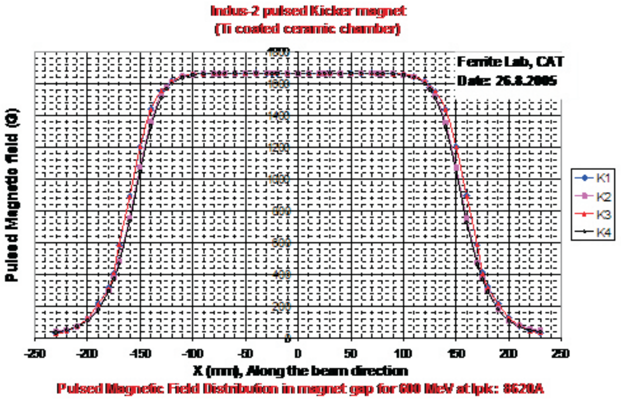


Fig.T.1.24: Magnetic field distribution in gap along magnet length

Kicker body was kept open (floated) so as to keep low voltage across ferrite yoke**.** Kicker field stability about 0.2 % with floated body at 30 KV/10 KA has been observed. Pulsed kicker magnets are working satisfactorily in injection of 550-600 MeV electrons into 2.5 GeV Storage ring during Indus operations. They are found to work efficiently and reliably during round the clock Indus-2 operation.

8.2.2 Development of low coupling impedance kickermagnets

Pulsed injection kicker magnets of Indus-2 were commissioned in the year 2005. Longitudinal coupling impedance of the existing pulsed injection kicker magnet is about 5 ohm. It needs to be reduced further for improved electron beam injection & beam stability at high current for round the clock operation of Indus-2.Consequent to successful operation in Indus-2, further they were up-graded for reduced coupling impedance for better beam stability.

Impedance of kicker magnets in a storage ring is one of the most important reasons causes beam instabilities. In order to facilitate improved injection & beam stability, low coupling impedance kicker magnets (Fig. T.1.25) have been developed by optimizing the 0.5 mm eddy current wire inserting around the ferrite symmetrically in the top & bottom poles of magnet along beam path without affecting the field homogeneity and pulse response.

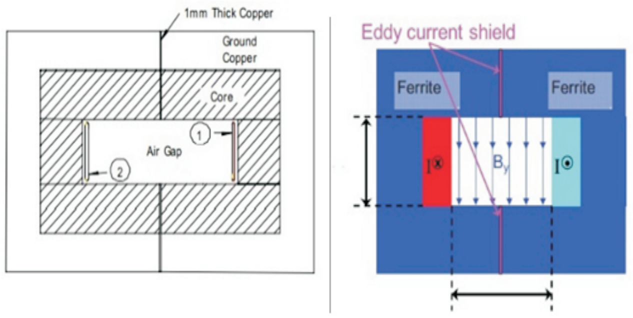


Fig. T.1.25: Low coupling impedance kicker magnet with eddy current strip

The longitudinal and transverse coupling impedances of a kicker magnet with Ti coated ceramic chamber have been measured by coaxial wire and twin wire method from 0.3 to 2000 MHz using RF network Analyzer (Fig. T.1.26). The real part of the longitudinal coupling impedance less than 0.5 ohm whereas transverse coupling impedance 2 kOhm up 500 MHz have been observed.

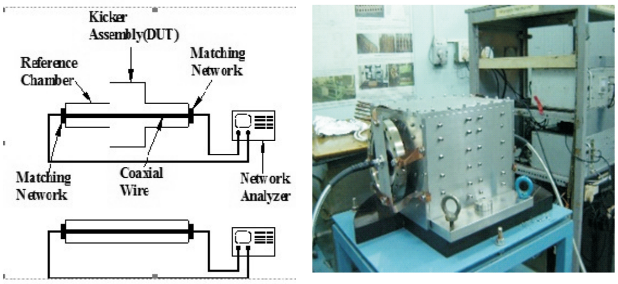


Fig. T.1.26: Coupling impedance measurement setup

A resonance model was developed to estimate the coupling impedances offered by kicker magnet to the circulating beam. Modeled results have been compared with the experimentally observed results and found excellent close agreement. Pulsed field uniformity of the order of 5 x 10^{-4} has been observed with no distortion in the magnetic field distribution along beam path is shown in Fig. T.1.27.

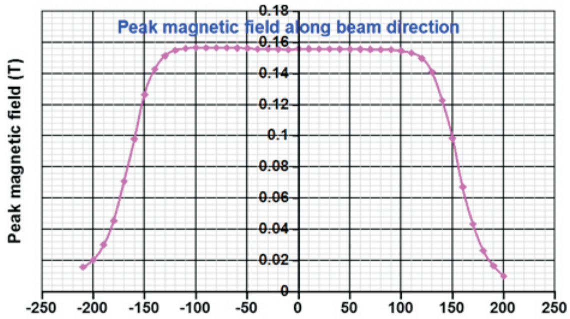
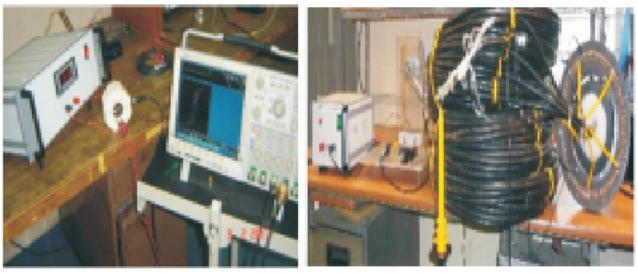


Fig. T.1.27: Magnetic field uniformity along beam path

Subsequently, four new ceramic chambers with Ti coating (1 μm) on inner surface optimized for minimum attenuation of kicker field (< 1%) and low impedance seen by the beam (< 0.5 ohm), characterized and installed in the ring. This has not only facilitates improved e injection into Indus 2 ring but also achieved beam current above 200 mA at beam injection by reducing the beam oscillation. It is observed that it helps to reduce the beam injection time.

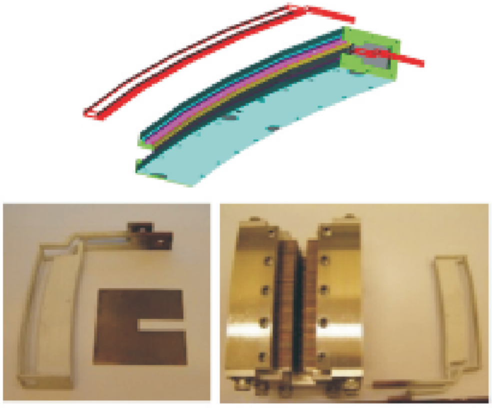
Photographs of Pulsed magnets and Test facilities



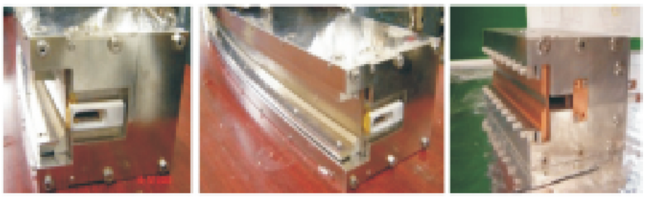
Pulse Magnetization at high dB/dt measurement of ferrite & Ni-Fe laminations

Pulsed Magnet field & coupling impedance measurement systems in-house developed at Pulse Magnet Lab.

Pulsed kicker magnets installed in the Indus-2 and Booster Synchrotron ring.



Septum magnet coils



Thin Thick Eddy current

Pulsed septum magnets

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