DAE-DOE
Discovery Science Collaboration

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On Behalf Indian Institutions and Fermilab Collaboration

U.S. DEPARTMENT OF ENERGY

Fermilab

Introduction

- Fermilab has proposed the construction of
  - High Intensity Superconducting Proton Accelerator (HISPA) (aka PIP-II)
  - Long Baseline Neutrino Facility (LBNF)
- DAE laboratories have proposed the construction of
  - Indian Spallation Neutron Source at RRCAT, Indore
  - Accelerator for Medical, Energy and Industrial applications at BARC
- HISPA R&D phase collaboration
  - Fermilab, BARC, Mumbai, IUAC, New Delhi, RRCAT, Indore and VECC, Kolkata
- Intensity Frontier Neutrino Experiment (IFNE) R&D phase collaboration
  - Fermilab, 15 Indian institutions funded by DAE and DST for Neutrino Collaboration
- HISPA and IFNE construction phase negotiation is in final stage between India-DAE and US-DOE.
  - Project Annex I & II to the DAE-DOE Implementing Agreement to the US-India S&T Agreement

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Indian Institutions and Fermilab Collaboration

- **The collaboration signed MOU to collaborate on**
  - **High Intensity Superconducting Proton Accelerator for the respective domestic programs**
    - **Concept of "Total Project Collaboration" on Accelerator**
  - **Intensity Frontier Neutrino Experiments (MINOS, NOvA and LBNF)**
    - **Develop LBNF-ND physics and Detector Technology**

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Technical work under MOU

1. Collaboration on ILC Main Linac SRF Accelerator Technology R&D" (October 2, 2007)
2. Collaboration on ILC RF Power Sources and Beam Dump Design R&D" (December 3, 2007)
3. Collaboration on High Intensity Proton Accelerator and SRF Infrastructure Development" (February 10, 2009)
4. Collaboration on Neutrino Physics, Related Experiments and Detector Development (Nov 2009)
5. Collaboration on RF Power (325 MHz) Development for High Intensity Proton Accelerator" (August 22, 2011)
6. Collaboration on RF Power (650 MHz) Development for High Intensity Proton Accelerator" (Aug 22,2011)
7. Collaboration on Instrumentation and Control for High Intensity Proton Accelerator" (Aug 22, 2011)
8. Collaboration on Accelerator Physics issues for High Intensity Proton Accelerator" (Aug 22, 2011)

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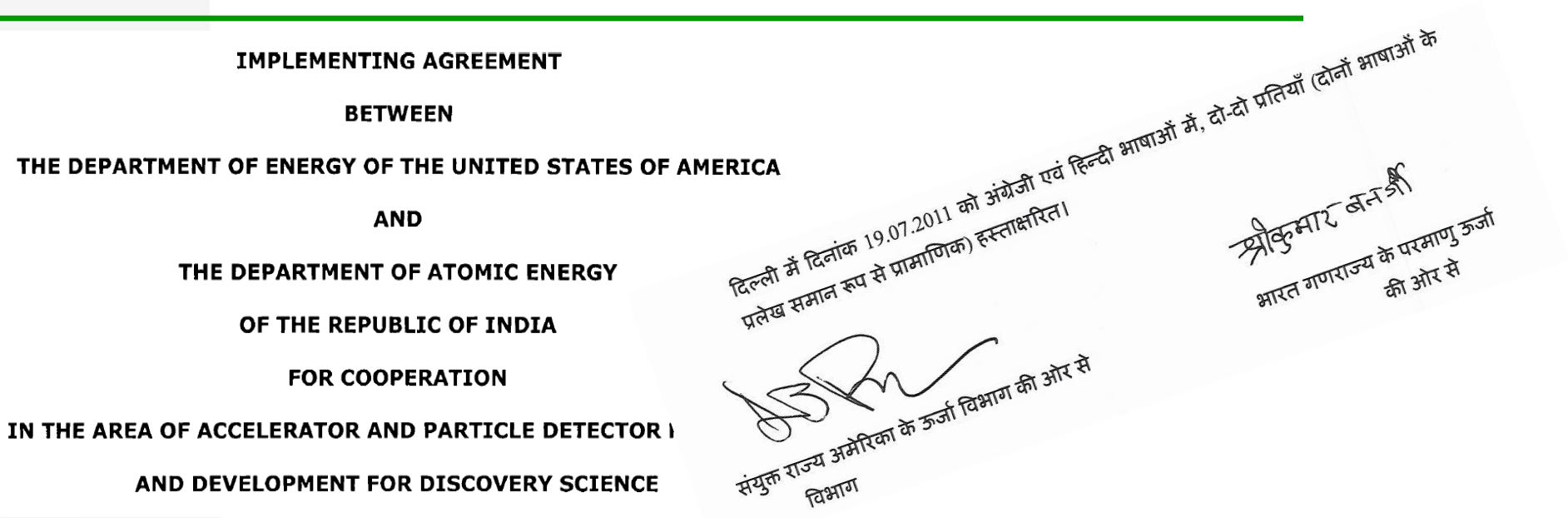
2010: DAE-DOE Discussions

- **Jan 2010, Dr. Dennis Kovar, Associate Director, US-DOE-HEP visited DAE**
  - **Idea of three Phase Collaboration Developed**
    - **Phase 1 (SRF)**
    - **Phase 2 (no-SRF)**
    - **Phase 3 (Construction)**
- **May 2010, Secretary, DAE, requested US-DOE a Road Map for the Fermilab collaboration on High Intensity Proton Accelerator**
  - **Mr. Poneman, Deputy Secretary, DOE and Dr. Banerjee agreed to develop a DOE-DAE agreement**
    - **The concept of "Discovery Science" collaboration emerged**
- **Fermilab and Indian-DAE established working groups to develop plans for**
  - **Accelerator Programs**
  - **Indian Collaboration in Fermilab physics program**

DOE-DAE Implementing Agreement



IMPLEMENTING AGREEMENT

BETWEEN

THE DEPARTMENT OF ENERGY OF THE UNITED STATES OF AMERICA

AND

THE DEPARTMENT OF ATOMIC ENERGY

OF THE REPUBLIC OF INDIA

FOR COOPERATION

IN THE AREA OF ACCELERATOR AND PARTICLE DETECTOR

AND DEVELOPMENT FOR DISCOVERY SCIENCE

दिल्ली में दिनांक 19.07.2011 को अंग्रेजी एवं हिन्दी भाषाओं में, दो-दो प्रतियाँ (दोनों भाषाओं के प्रलेख समान रूप से प्रामाणिक) हस्ताक्षरित।

संयुक्त राज्य अमेरिका के ऊर्जा विभाग की ओर से

विभाग

भारत गणराज्य के परमाणु ऊर्जा की ओर से

Discovery Science: The United States' Department of Energy and India's Department of Atomic Energy signed an Implementing Agreement on Discovery Science that provides the framework for India's participation in the next generation particle accelerator facility at Fermilab. (US State Department Press)

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US-India Strategic Dialogue

SCIENCE & TECHNOLOGY DIALOGUE, WASHINGTON, DC ///

MEET THE CATALYST

June 11, 2012

At the end, the Joint Commission recommended several new directions of cooperation including research in the areas of high energy particle physics and gravitational wave detection under the 'Discovery Science Agreement' between Department of Atomic Energy and U.S. DOE. In Basic and Applied sciences — materials research, computer sciences and neurosciences have been identified as potential areas of future engagement.

Accelerator and Physics Programs Technical Collaboration are No 1 deliverables to the Joint US-India Science Working Group

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DAE-DOE Project Annexes

- **Jan 2012**
  - **DOE submitted DRAFT Project Annex I (Accelerator) and Project Annex II (Intensity Frontier Neutrino Experiment) to DAE**
    - **DOE has received initial approval to proceed for US Agencies**
- **July 2012 – Feb 2013**
  - **DAE, DOE and US Government Agencies worked to finalize the agreement and froze the language of Annex I and II.**
    - **DAE initiated internal India approval process**
- **May - Aug 2013**
  - **Final deliverable document for Annex I was agreed by DAE-DOE**
  - **Collaboration also forwarded a Detailed Project Reports for Annex I & II**
- **Aug 2013**
  - **The Atomic Energy Commission(AEC) of India Recommended Annex I for approval from the Government of India**
    - **It is awaiting the final approval of the Indian Government.**
  - **The DAE has given in principle approval to Annex II.**
    - **Funding for R&D phase has been approved by DAE and DST**
    - **DAE is working to finalize the approvals**

Indian Institutions at Fermilab

Before 2006

Dzero Experiment

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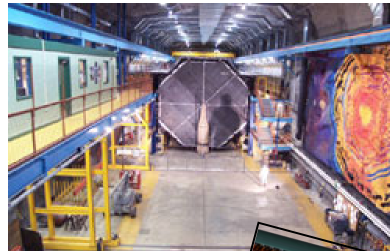
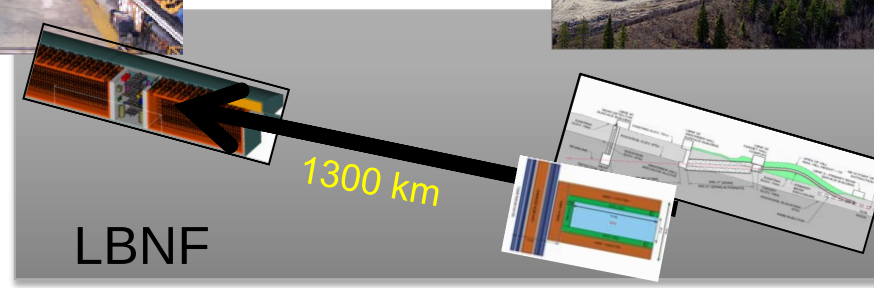
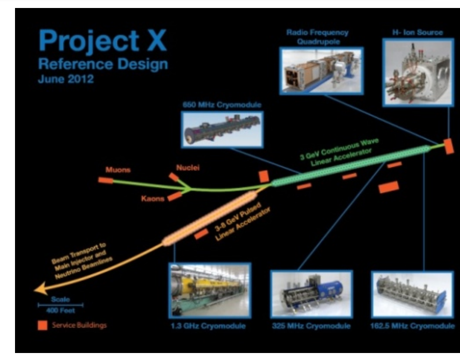
Now







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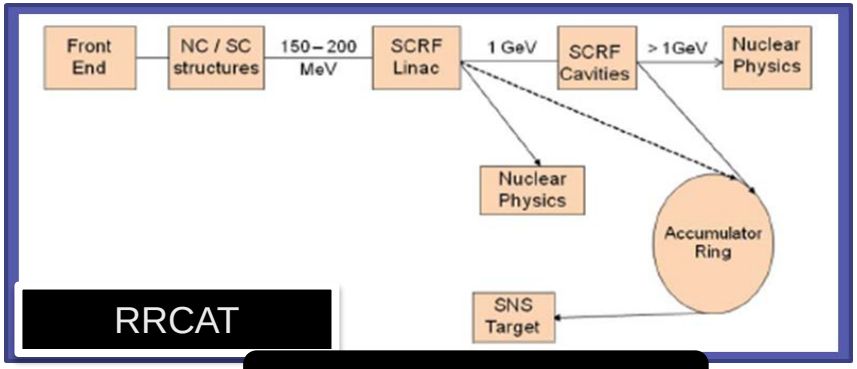
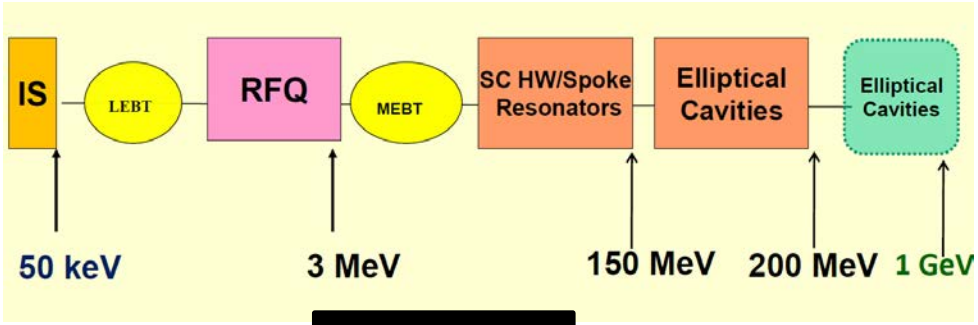
Indian Institutions and Fermilab R&D Collaboration

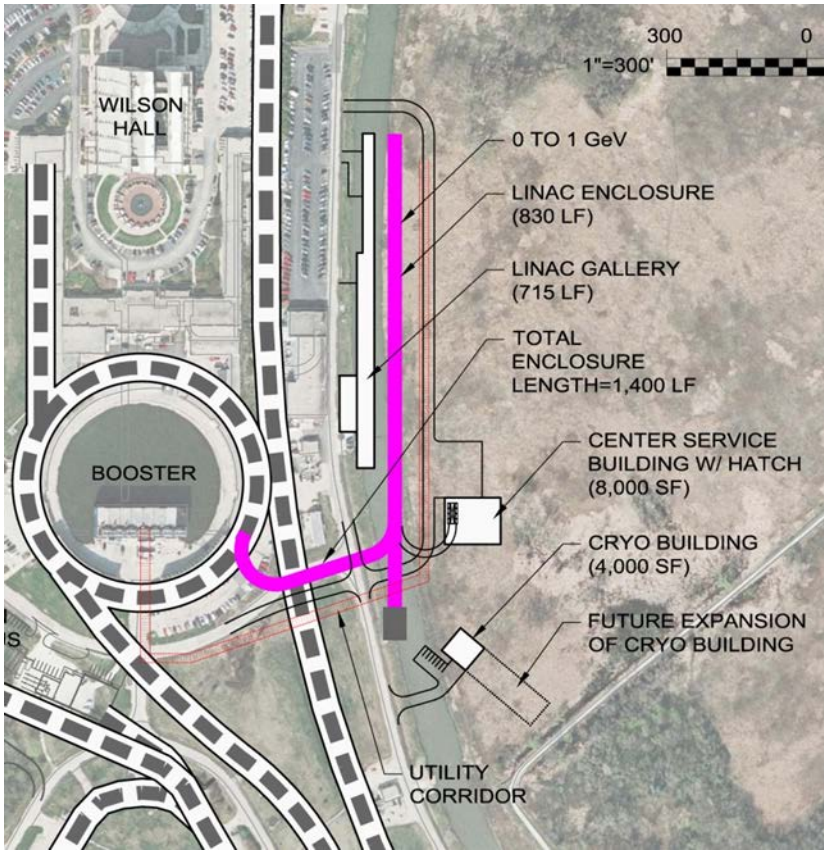
- **Signed its first institutions level MOU in 2006. Eight addendum MOUs (2007-12)**
  - **Covering all aspects of SRF linac and Neutrino Collaboration**
- **Since Jan 2012, Collaboration operates under the DAE-DOE Discovery Science Implementing Agreement to US-India Science and Technology Agreement**
  - **In the 12th and 13th plan of India**





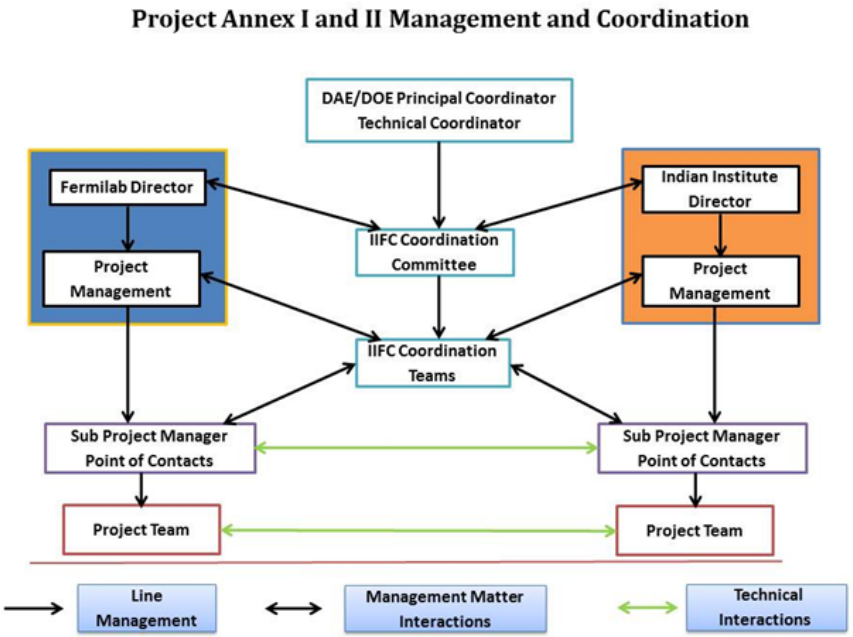
Fermilab: HISPA (aka PIP-II)

- **High Intensity Superconducting Proton Accelerator (HISPA) (aka PIP-II) is a ~1 GeV Linac.**
  - **The design of this machine is similar to the two Indian accelerators.**
  - **It is design to provide 1.2 MW of beam for LBNF on day one of its operation.**
  - **It is upgradable.**
- **PIP-II will be build with significant "In-Kind" contributions of accelerator components from foreign countries.**
  - **India is a significant contributor**



Fermilab

Collaboration

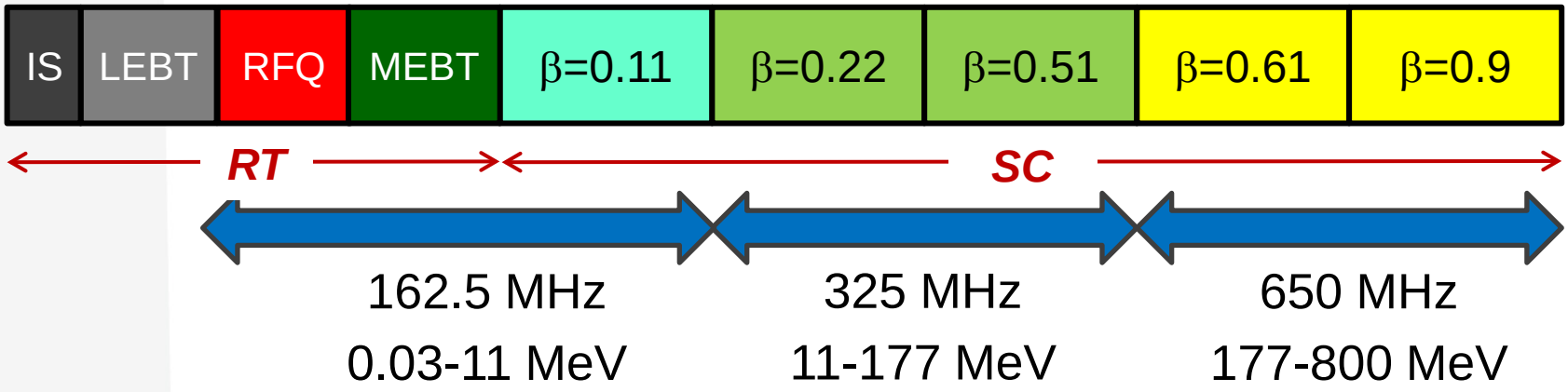


Areas of collaboration

- HISPA Design
- High Intensity Particle Source
- Radio Frequency Quadrupole
- Superconducting Radio Frequency Cavities and cryomodule
- Cavity Helium Vessel and Tuner
- Radio Frequency Power
- High Power Radio Frequency Coupler
- Distribution, monitoring and control of High Power Radio Frequency
- Normal and Superconducting Solenoid, Dipole and Quadrupole magnets
- Beam Instrumentation
- HISPA Control
- Cryogenic Plant, distribution and control

- **All the technical work are being carried out by the Project Teams at Fermilab and the collaborating Indian laboratories.**
  - Under the supervision of the Sub Project Mangers (SPM) and Point of Contacts (POC)
- **SPM working with the PIP-II Project Management**
  - Develop a Functional Specification Document for each component.
- **SPM-Fermilab working with their Indian counterpart**
  - Develop a Technical Specification for the work to be perform.
- **SPM (POC) and Project teams meet weekly or as needed to discuss progress and technical issues.**
- **Fermilab maintains a Share Point Database for all the documents, drawings produced and shared by IIFC.**

IIFC: Accelerator



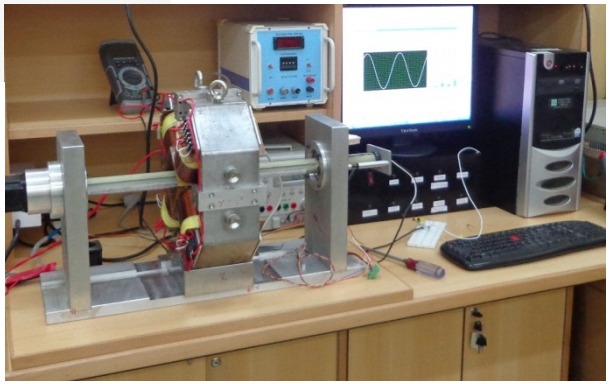
- **Basic design of the three SRF machines are exactly the same**
  - **DAE laboratories and Fermilab are jointly doing Research, Design and Development of the accelerators and infrastructure**
- **Fermilab HISPA (aka Project X or PIP-II)**
  - **Phase I: 0.8-1 GeV (Pulsed and CW, maximum current 2 mA)**
  - **Phase II: 1-3 GeV (Pulsed and CW, maximum current 1 mA)**
  - **Phase III: 3-8 GeV (Pulsed, maximum current 1 mA)**
- **BARC**
  - **1 GeV (CW, maximum current 10 mA)**
- **RRCAT**
  - **1-1.5 GeV (Pulsed, maximum current 1 mA)**

MEBT Magnet Specifications

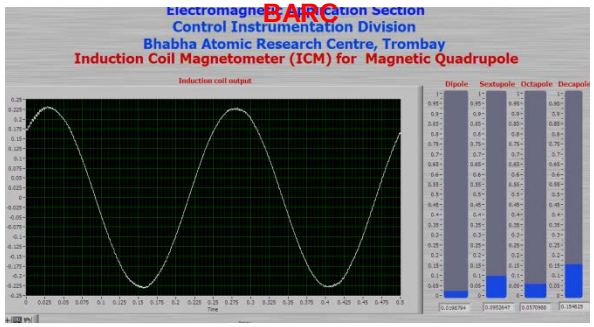
S. no	Type	Qty.	Integrated Gradient / integrated field	Field homogeneity in GFR of 23 mm	Longitudinal space
1	Quadrupole F (QF)	18	1.5 T	1%	100mm
2	Quadrupole D (QD)	16	0.85 T	1%	50mm
3	H/V Dipole corrector	15	2.1 mT*m	5%	55mm

Magnetic Measurements and beam line Qualification of Quad F

Summary of magnetic measurements



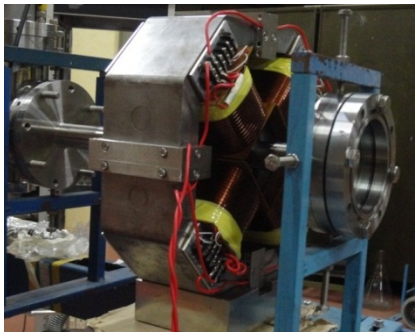
Magnetic measurement set-up comprising of Induction coil, flip coil and Hall probe at

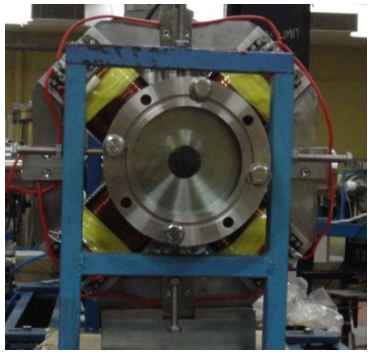


Magnetic field and its higher order multipoles measured using induction coil

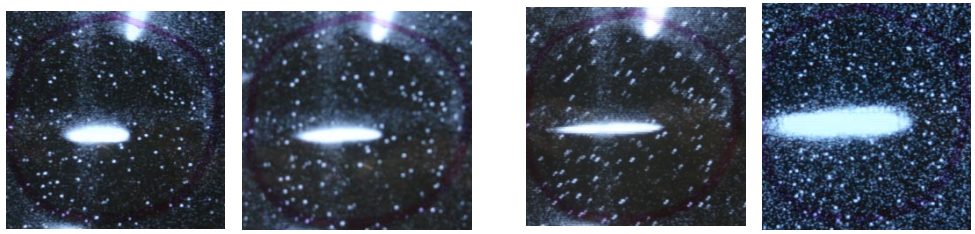
Parameter	Simulated	Achieved	Unit
Input MMF	1500	1500	AT
∫G.dl	1.533	1.59	Tesla
Magnetic Flux/pole	8.91	8.95	kmax

Summary of Beam line Qualification of Quad-F with 2.5 MeV H+ beam



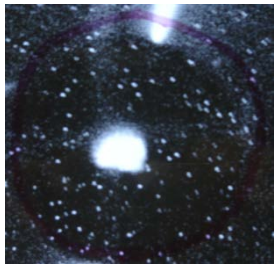


Quad-F assembly installed in FOTIA beam line

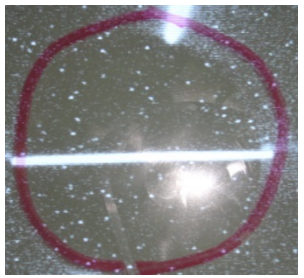


Focusing snap shots at different currents,

Beam focuses as current of Quad increases, and it tends to de-focus when focused beyond focal point



Beam snap shot (Quadrupole off)



Beam snap shots (Quadrupole on)

BARC Magnet at Fermilab

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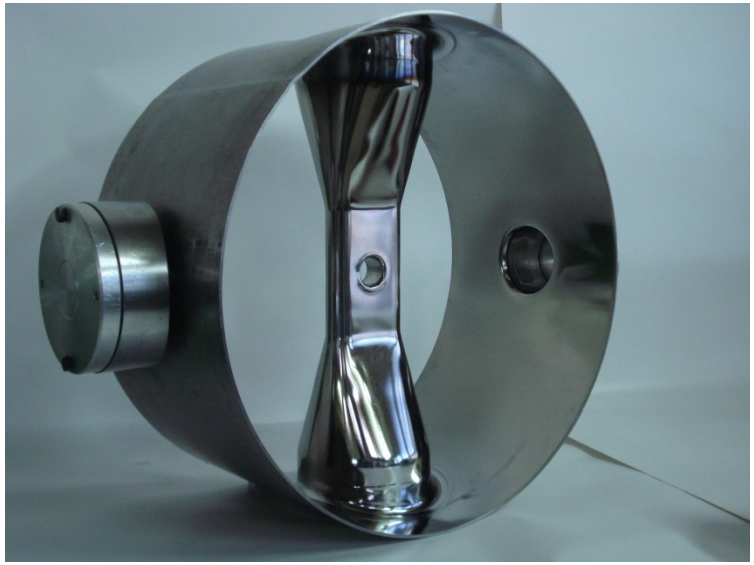
IUAC: SSR1

- **Inter University Accelerator Center, New Delhi is working of the fabrication of SSR1.**

Spoke assembly after electropolishing.



Spoke assembly with Outer Shell

IUAC plans to finish the first two SSR1 by end of Oct 2014.

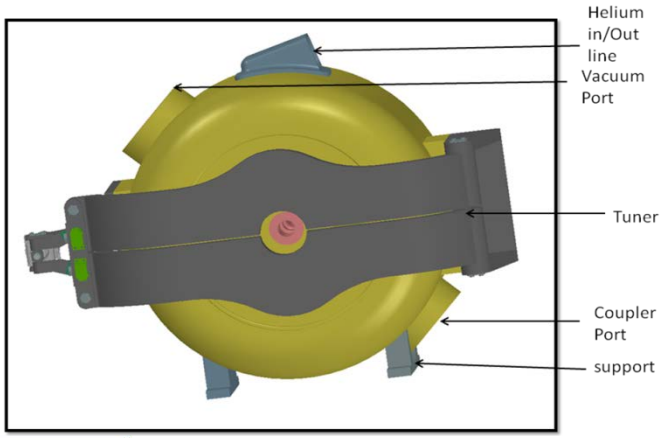
Next Step for SSR1

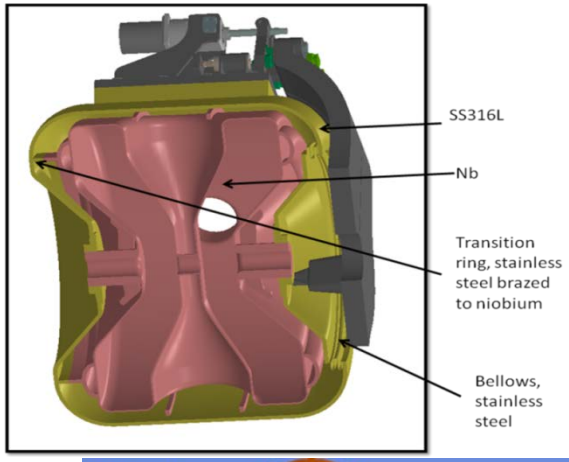
The next step is to tune the resonators and attach the End Walls to the Outer Shells. All the four End Wall assemblies are ready.

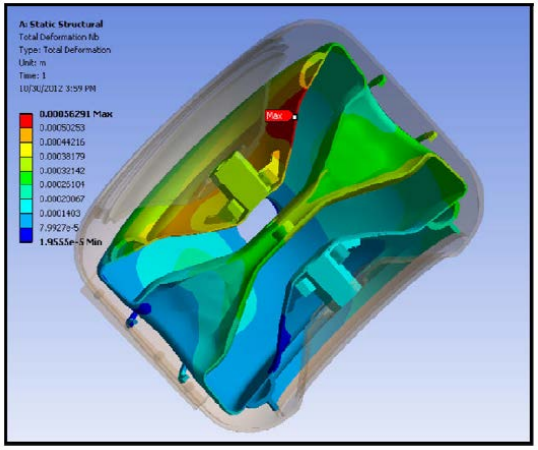
All the 4 End Walls (left), and electropolished RF side of an End Wall (right).

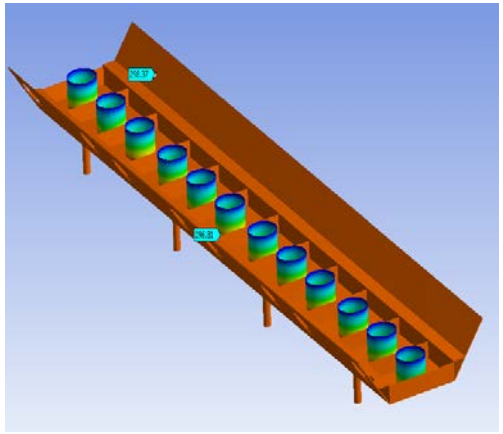
VECC: SSR1 CM

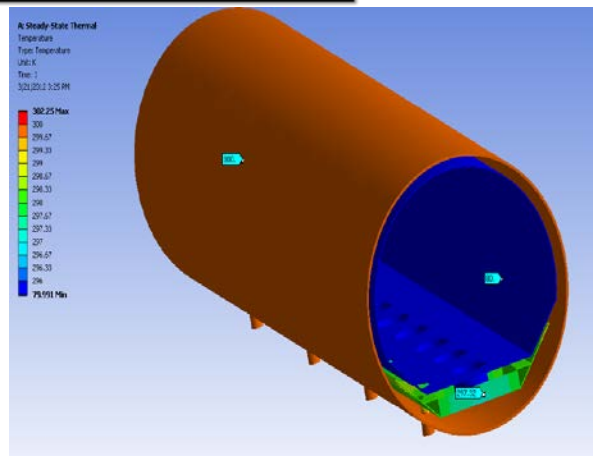
- **VECC is working on the Helium Vessel, Tuner for SSR1 and design of SSR1/SSR2 CM.**
- **VECC engineers work on specific mechanical engineering tasks that are integrated in the Fermilab design.**











BARC: 325 MHz, 10 kW RF

- **VECC has done a complete design of a 325 MHz Solid State RF system that meets the Functional Specification Requirements provided by Fermilab.**

Prototype testing of 3 kW RF amplifier

Fully assembled 3 kW whole Unit

65% efficiency has been achieved for one unit

- **325 MHz, 7 kW Solid State RF Power Amplifier has also been bench tested for its design values**

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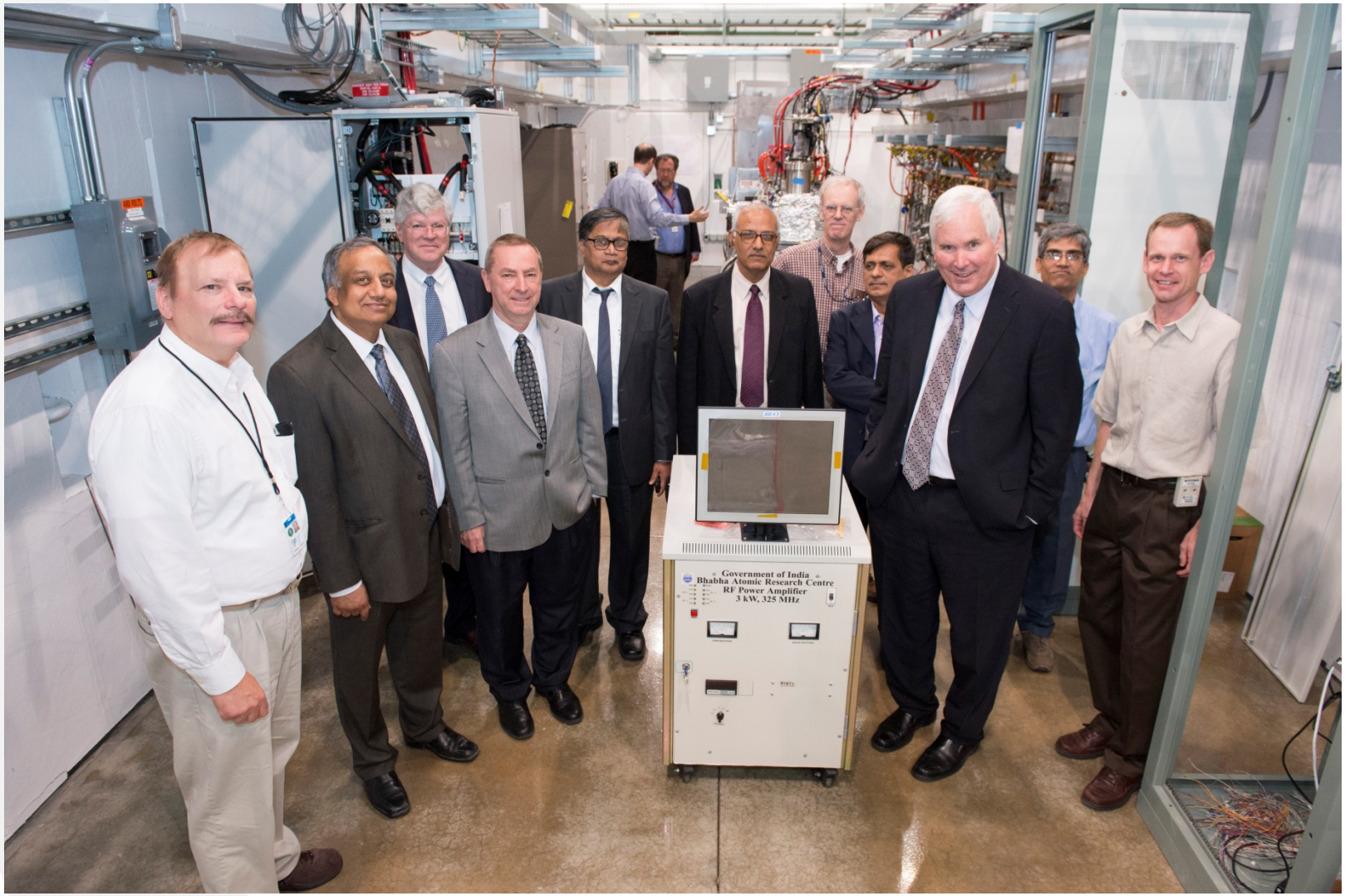
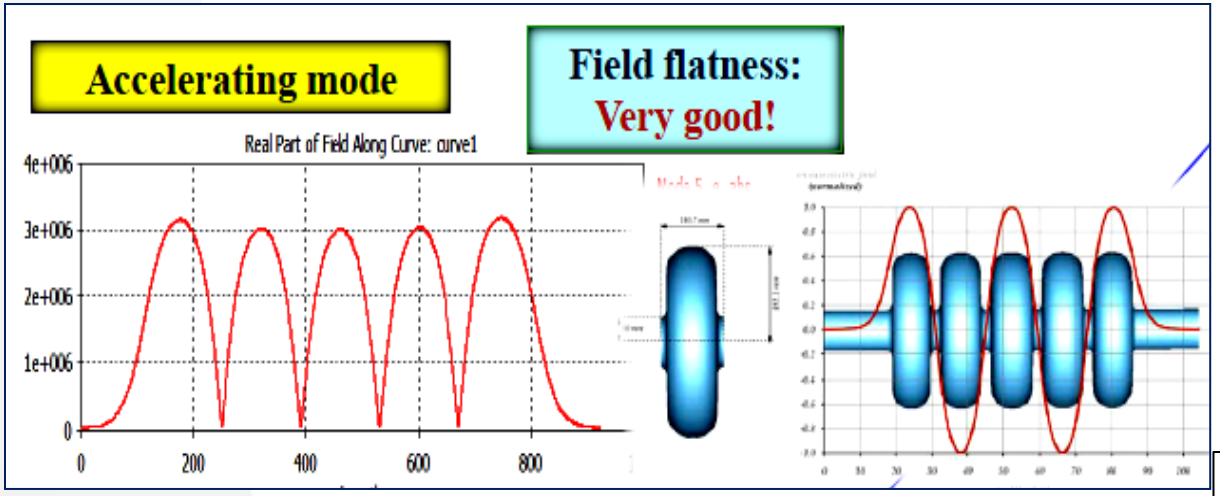
BARC: 325 MHz, 3 kW RF at Fermilab

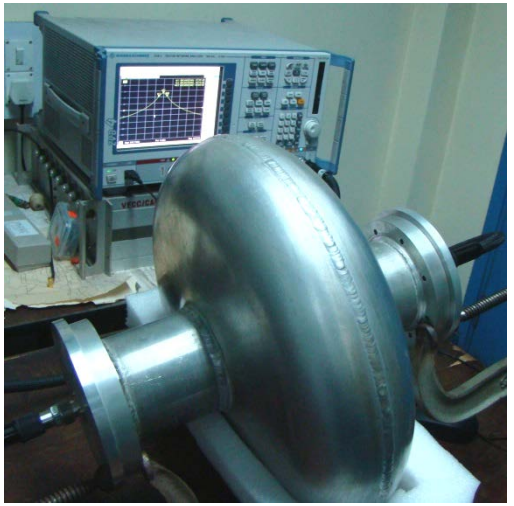


BARC: Assembled and wired unit of 7 kW

VECC:650 MHz β=0.61 Cavity

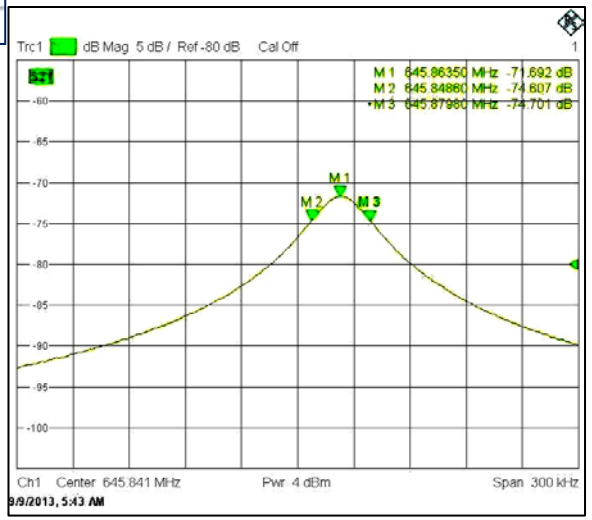
- **VECC has done a complete design of a 5-cell, β=0.61, cavity that meets the Functional Specification Requirements provided by Fermilab.**





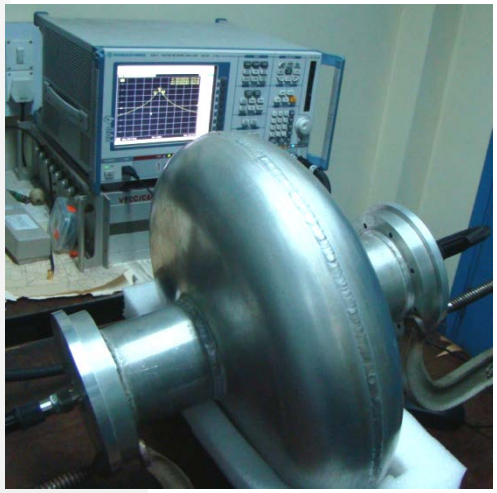
Nb Half Call

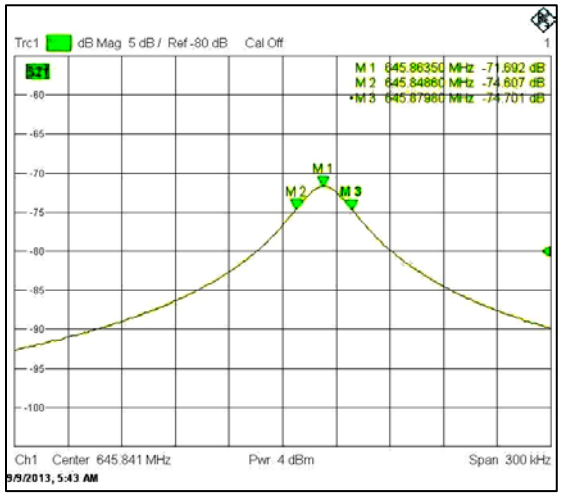
1-Cell Cavity to be welded at IUAC



VECC:650 MHz β=0.61 Cavity

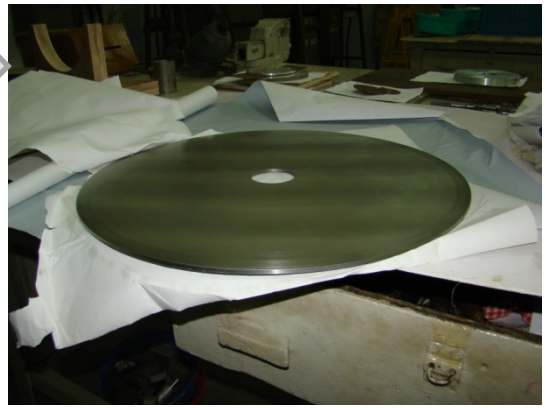
- **For Prototype Aluminum Cavity measurement (VNA):**
  - **Resonant frequency, f_0 = 645.86350 MHz.**
  - **Half power (–3dB) Bandwidth, $\Delta f = f_2 - f_1$ = 31.2 kHz.**
    - **[f_1 = 645.84860 MHz; f_2 = 645.87980 MHz]**
      - **Q = $f_0 / \Delta f$ = 20700.**





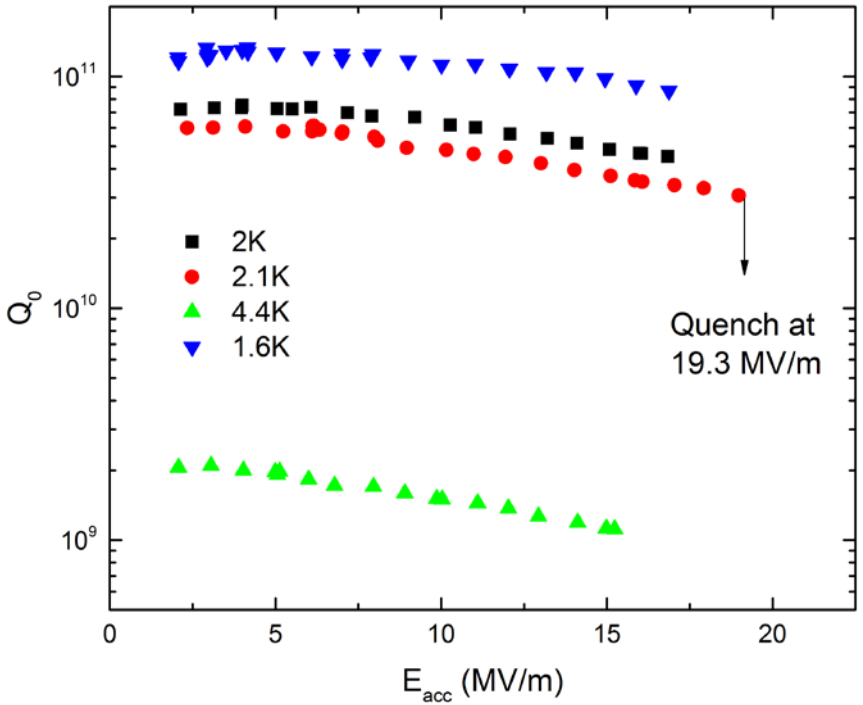
VECC:650 MHz β=0.61 Cavity

- **Fabrication of Niobium Half Cell**



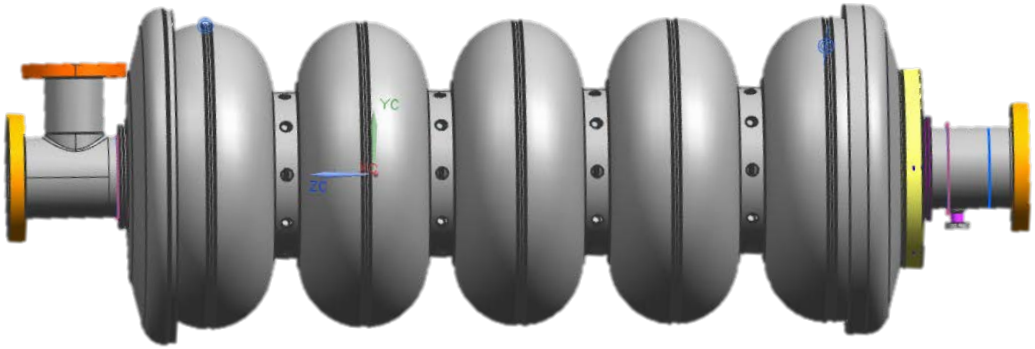
RRCAT: 650 MHz β=0.9 1-cell cavity

- **First 650 MHz single-cell niobium cavity fabricated by RRCAT and IUAC was processed and tested at Fermilab during Dec-2013 and January 2014.**
  - **Cavity reached E_{acc} of 19.3 MV/m and Q_o of of $7x10^{10}$ at 2K. This performance exceeds the design parameters.**



RRCAT:650 MHz β=0.92 five-cell Cavity

- **RRCAT has received a new e-beam welding machine, it is under commissioning.**
- **RRCAT with IUAC build a 5-cell, 1.3 GeV cavity.**



650 MHz five-cell SCRF cavity 3-D model

- Drawing received from Fermilab : Dec 2013
- Development of forming tools : June 2014
- Forming of half cell+ Machining +RF qualification : Sept 2014
- Fabrication and testing of single-cell cavity : Dec 2014
- Fab. and qualification of dumbbells+ End groups : Mar 2015
- Fabrication of 1st 650 MHz 5 cell cavity : June 2015

Fermilab

RRCAT: 650 MHz He Vessel

- **Two trial vessels of titanium, grade-2 (similar in shape & size for 650 MHz cavity) have been manufactured in industry to understand the fabrication process.**

Titanium vessels fabricated at M/s TITAN, Chennai

Preparation for Welding (back purging and trailing shield arrangement)

Welding in progress

- **The actual fabrication of helium vessel for 650 MHz cavity will be taken up once the design is finalized between Fermilab and RRCAT.**

Fermilab

RRCAT: 650 MHz Cryomodule

Capability Exists for Design of Subsystems - Significant ground Covered

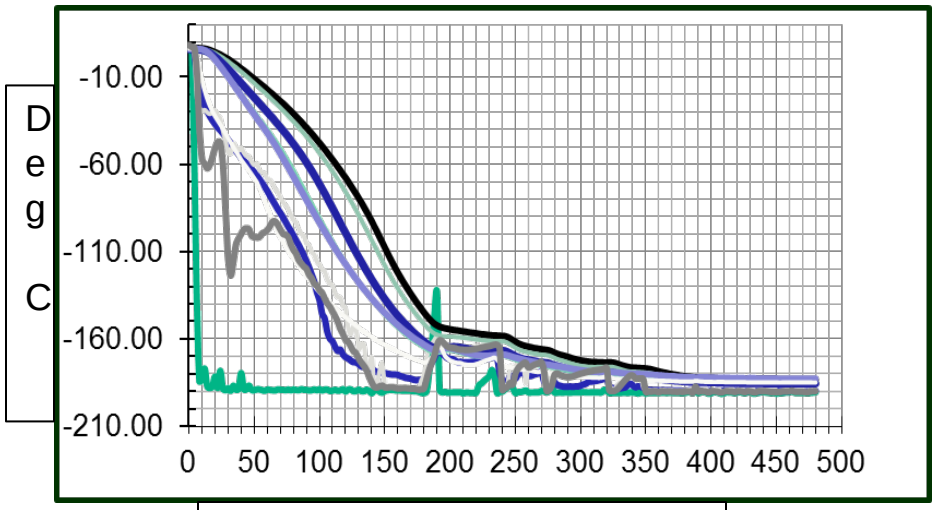
- **RRCAT proposed 5 options. FNAL selected Tesla type configuration.**
- **Design of vacuum vessel, cavity support system ,thermal shield completed**
- **3-D model completed .**

Cross-sectional view

RRCAT: 650 MHz Cryomodule

- **Design of cryomodule subsystems was started from scratch. 5 Initial configurations were proposed.**
  - **Fermilab selected Tesla type configuration.**
  - **3-D model of 650 MHz cryomodule completed.**
- **Design of vacuum vessel, cavity support system, and thermal shield completed and tested in CM Test Rig**

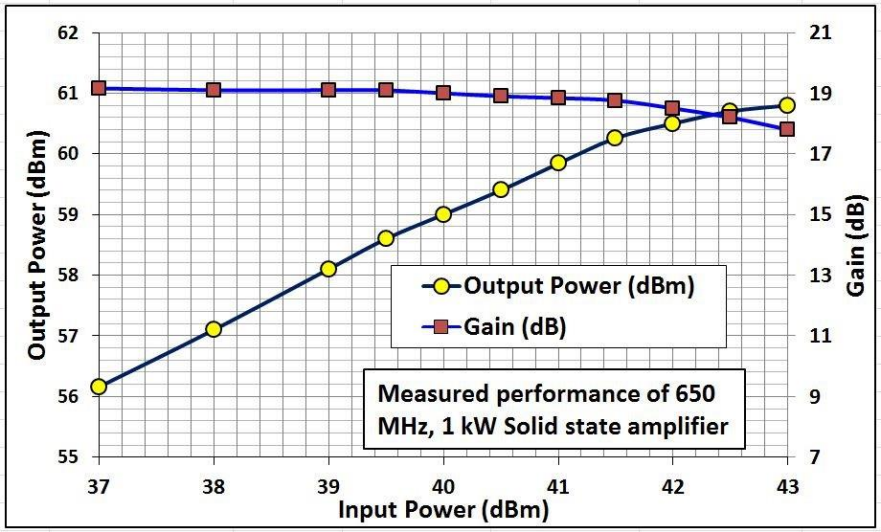
Cryomodule component test rig



Experiment result of thermal shield cool down

RRCAT: 650 MHz Solid State Amplifier

- **A 12 kW unit has been assembled and is under testing. Three such units will be housed in a single euro rack with 32 amplifier modules per unit, each amplifier is LDMOS giving output RF power of 500 W.**
  - **Operating frequency: 650 MHz**
  - **Output Power: 12 kW CW**
  - **Gain: 60 dB**
  - **Bias Voltage: 50 V DC**
  - **Input Mains supply: 3 Phase**



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RRCAT: Cavity Processing and Assembly Hall

E-beam welder installed and Commissioned

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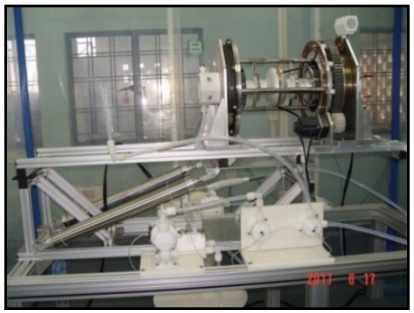
RRCAT: Infrastructure for SCRF Cavity Fabrication, Processing and Characterization

Cavity forming facility



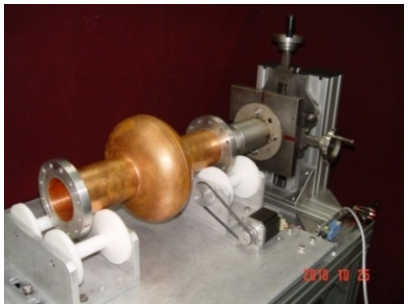
Electro-polishing setup

Centrifugal barrel polishing machine

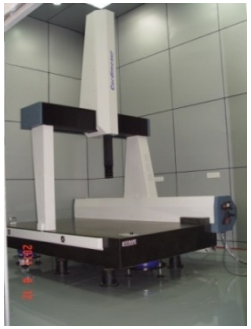
High pressure rinsing Set up

15 kW e-beam welding machine

SIMS setup



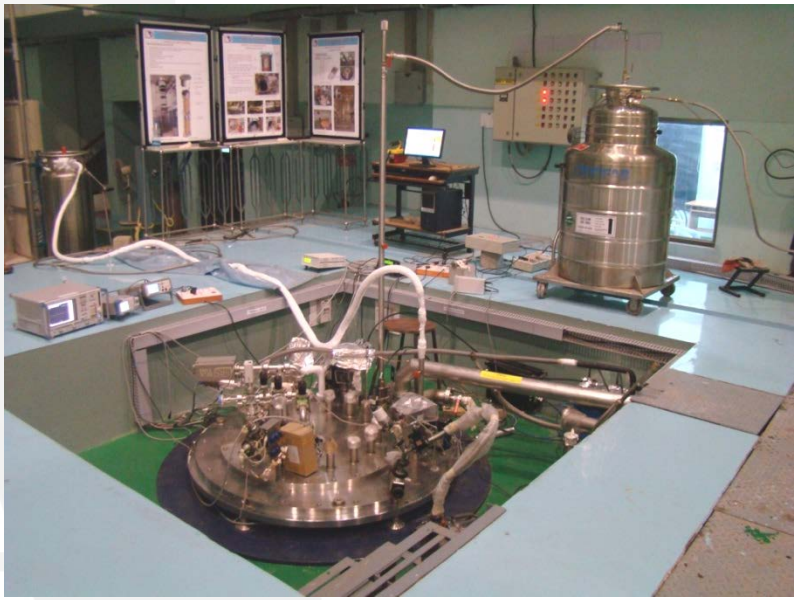
Optical bench setup



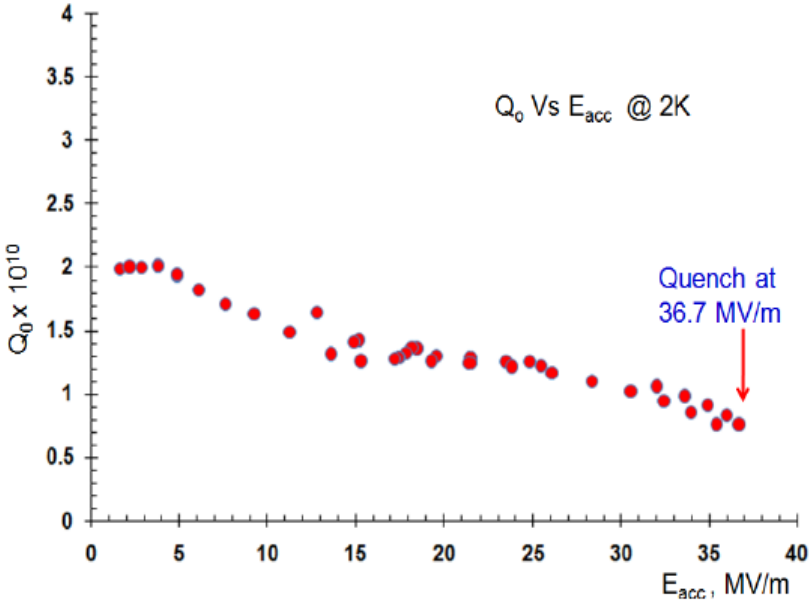
3D CMM

RRCAT: Vertical Test Stand

- **A Jointly design and Fabricated Vertical Test facility for RF characterization of SCRF cavities at 2 K has been commissioned.**
  - **A single-cell 1.3 GHz cavity has been successfully tested using the facility.**



Transfer of liquid helium in the VTS cryostat



Testing of single-cell 1.3 GHz SCRF cavity in the VTS facility at RRCAT

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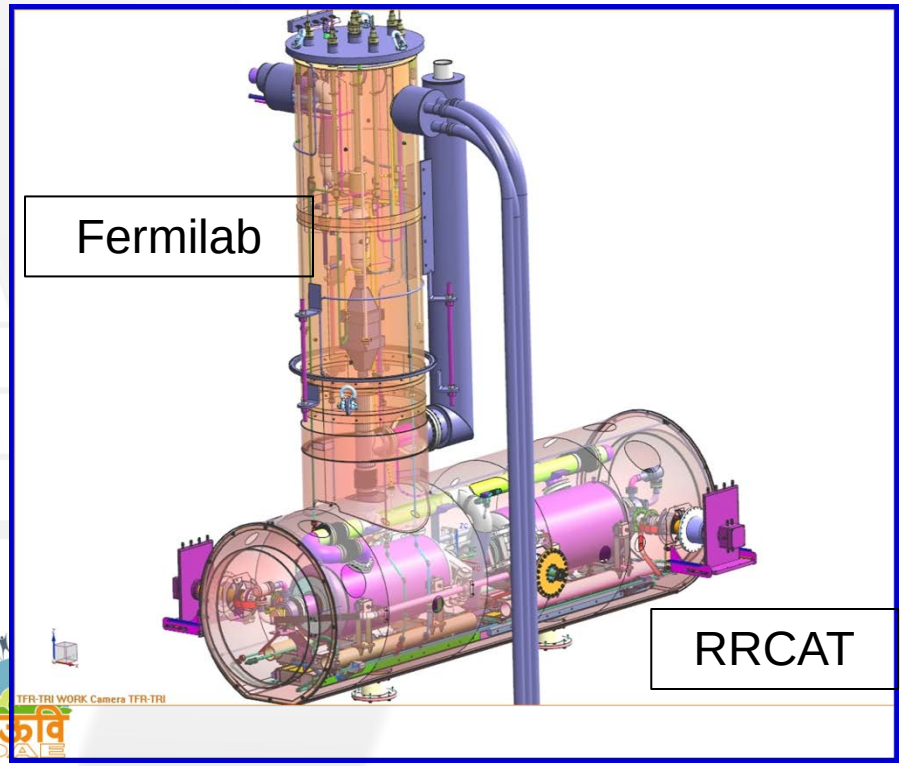
RRCAT: Horizontal Test Stand

- **HTS-2 is being jointly designed to individually test two fully dressed 650 MHz cavities in single cycle under conditions similar to those in a cryomodule.**
  - **Design and 3-D model has been completed.**
  - **Design report on sub-systems finished.**
    - **A joint design review is expected by March2014.**
- **RRCAT will fabricate this for Fermilab and India DAE**



- **Status:**
  - **Prototype of cryogenic support post completed and tested in CCTR.**
  - **Scaled-down frame bridge prototype completed.**
    - **It will be tested in CCTR by March 2104.**
  - **Prototype of thermal shield completed.**
    - **Along with frame bridge and rolling cart it will be tested shortly in cryomodule component test rig (CCTR).**

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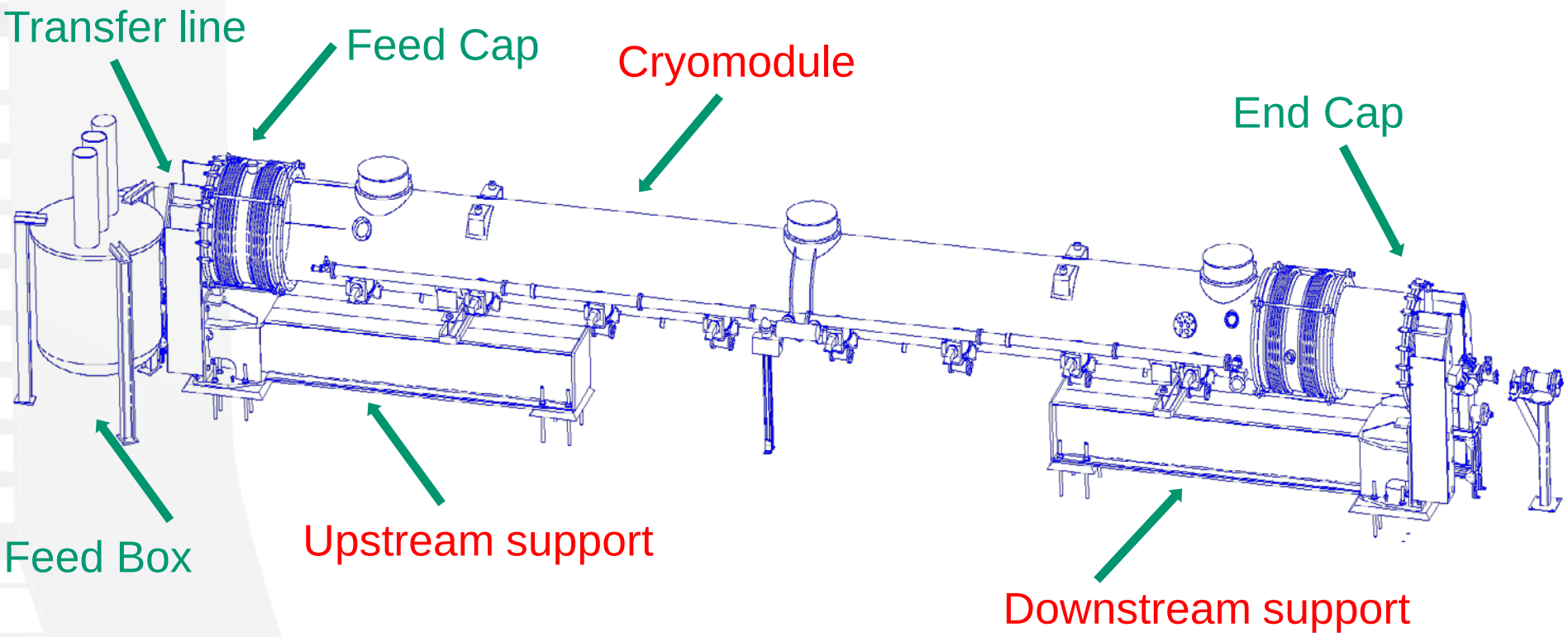
BARC: Cryomodule Test Facility



- **Under IIFC 1.3 GHz Cryomodule Test Facility is being built for FNAL.**
- **BARC will design, manufacture and supply Feed Box, Transfer Lines, Feed Cap and End Cap.(Items shown in green).**
- **Items shown in red are under scope of FNAL**

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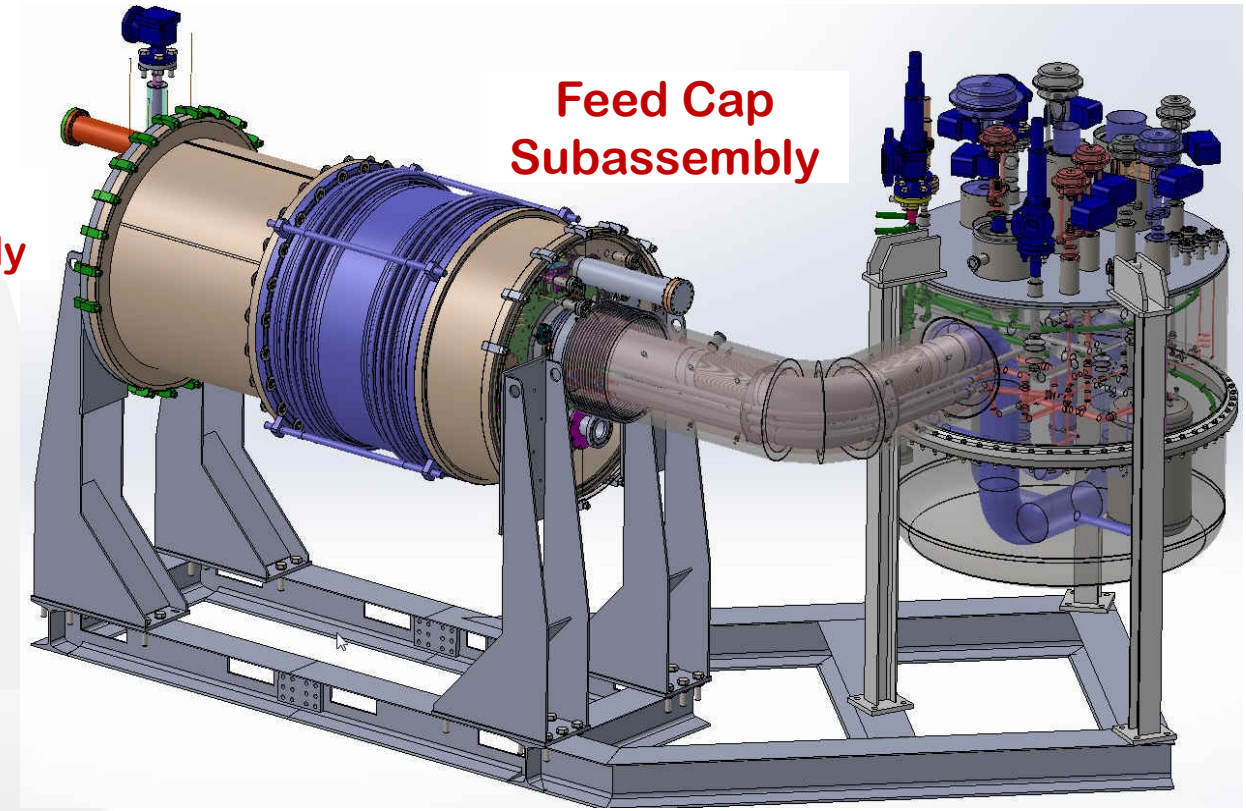
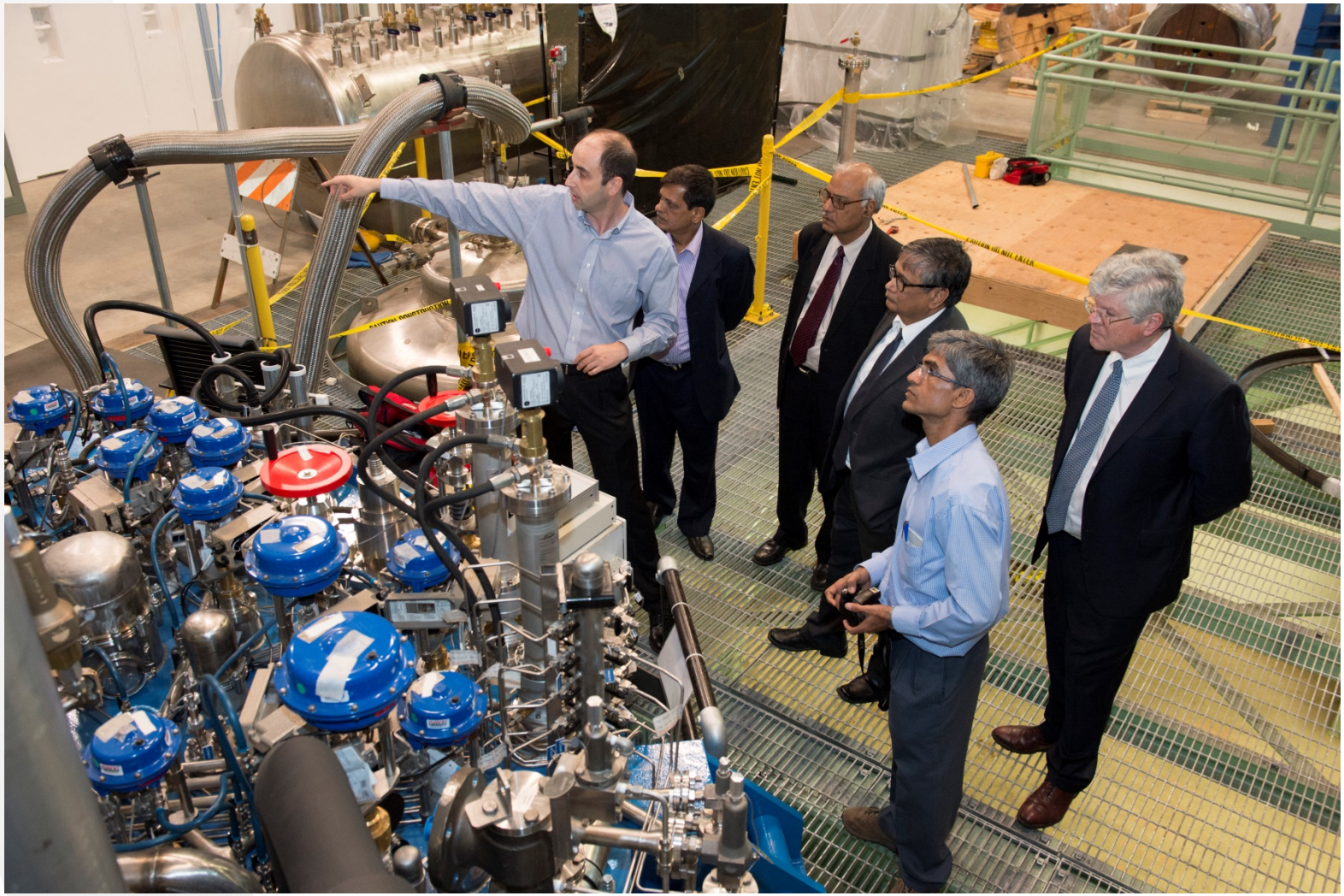
BARC: CMTS

- Fermilab and BARC Engineering team are working jointly in developing the design of a new 1.3 GHz CMTS
- Experience gained from this unit will be applicable to 650 MHz CMTF, which is a fully integrated system, with CMTS, RF, Instrumentation and Control.



Cryogenics at Fermilab



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Control and Instrumentation Systems

Following systems are part of the collaboration

- **RF Protection Interlock (RFPI) System**
- **Beam Position Monitor (BPM) system**
- **Low Level RF (LLRF) system**
- **Integrated Control System for CMTS**

In the first phase work has got initiated on RF Protection Interlock system

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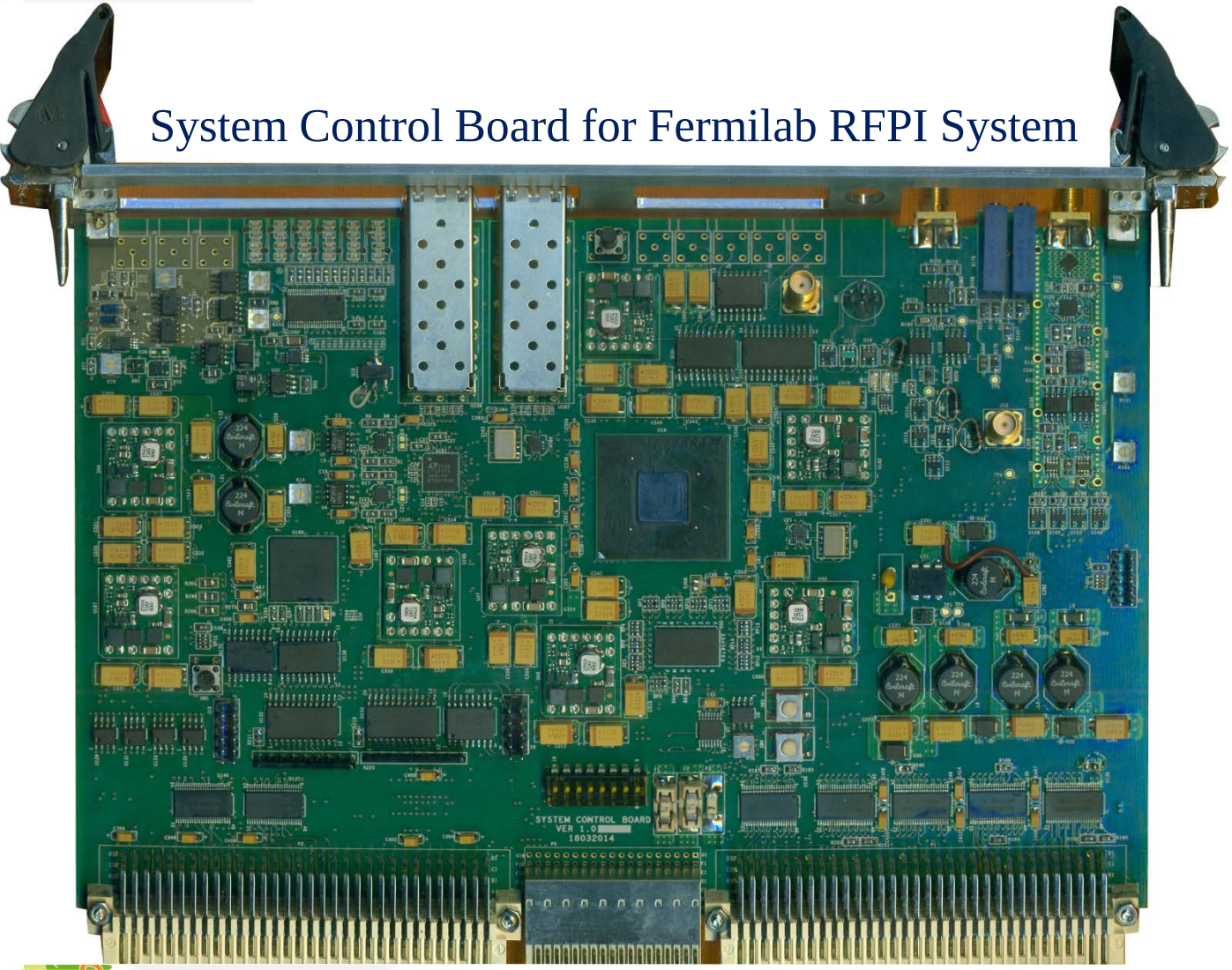
RF Protection Interlock System - Status

1. System control Board designed and fabricated, presently under testing

System Control Board for Fermilab RFPI System



Features:

- VME-64x Interface
- 2 High Speed Serial transceivers @ 3.125 GbPS
- 4x PCIe interface
- One channel for Photo Multiplier Tube monitoring
- One channel for RF leakage Monitoring
- Four channel 80MSPS 14 bit ADC
- 256MB DDR3 RAM for 1 sec circular buffer on each channel

पऊवे DAE

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Indian Industry

Visit to Electronics Corporation of India Ltd.

Solid State RF and Electronics could be built by ECIL

Fermilab R&D Linac

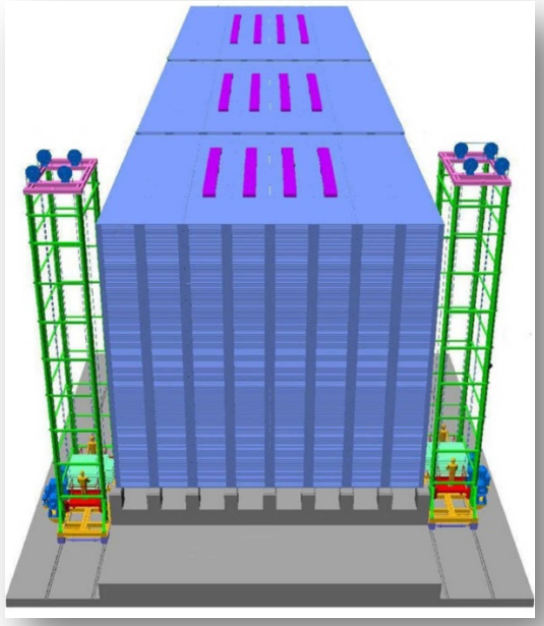
Fermilab

DAE and PXIE

- **Collaborating DAE laboratories are already working on the Research, Design and Development of almost all hardware of the High Intensity Superconducting Proton Accelerator.**
- **BARC has also proposed to develop similar 50 MeV linac.**
- **IIFC is already working on the following that would be used for PXIE**
  - **MEBT Magnets**
  - **SSR1 Cavity and CM**
  - **325 MHz Solid State RF Amplifiers,**
  - **RF Protection system**
  - **LLRF System**
- **DAE has proposed to send scientific and engineering staff to participate in PXIE construction, installation and commissioning.**
  - **DAE propose to take a leading role in jointly developing an integrated SSR1 CM (Cavity to RF). It is part of Project Annex I.**

India Based Neutrino Observatory

- **Create experimental facility in the country where we can carry out front ranking experiments in the field of particle & astro-particle physics**
  - **Frontline neutrino issues e.g., mass parameters and other properties, will be explored in a manner complementary to ongoing efforts worldwide**
  - **Will support several other experiments when operational: Neutrino-less Double Beta Decay and Dark Matter Search experiments foreseen in the immediate future.**



50 kton magnetized Iron calorimeter

IIFC – νP Collaboration

- Eight Indian Institutions have joined the Fermilab Neutrino Physics Program.
  - MINOS, MINOS+
  - NOvA
  - LBNF
- We are expecting a total of 20-100 Ph.D. students from India under this program.
  - 50% funded by the Indian Governments.
  - Faculties participation and infrastructure in India fully funded by India
- This collaboration is growing
  - Indian Infrastructure Development
  - We continue to include more institutions and
  - Recruiting faculties and postdoctoral fellows.

पऊवि DAE

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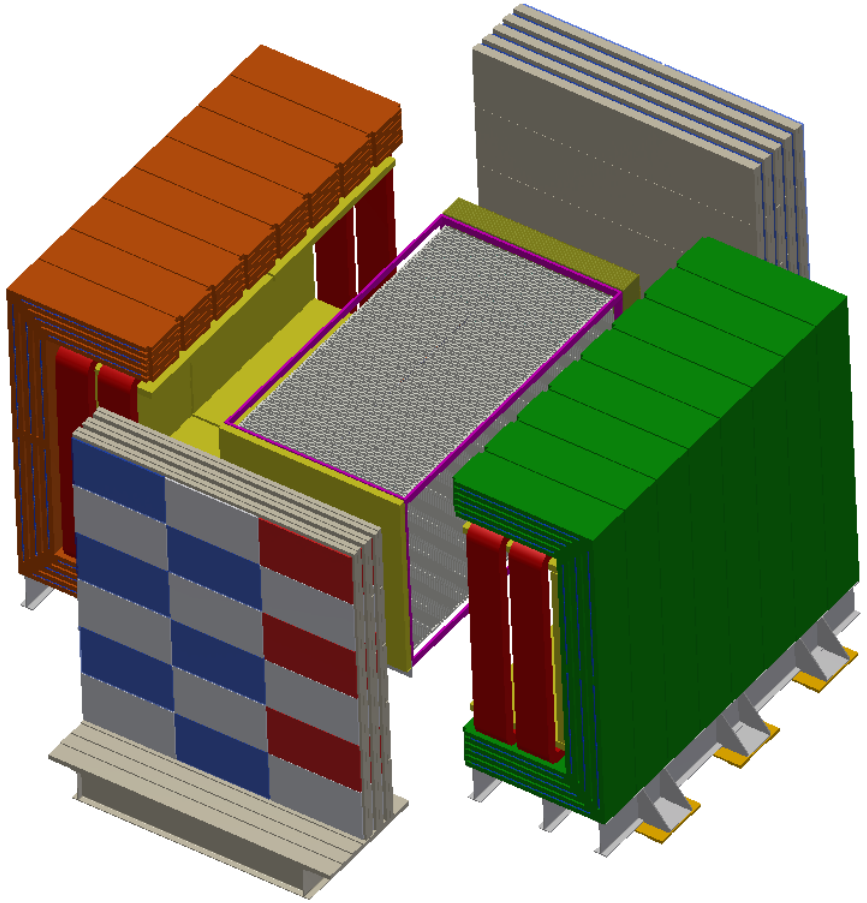
IIFC: LBNF-ND Detector

- **The details of how the collaboration will develop LBNF-ND is under discussion.**
  - **DOE-DAE-DST-Fermilab-India Institutions**
- **Major Subsystems with Indian expertise**
  - **Straw Tube**
  - **Muon ID**
  - **ECAL**
  - **Magnet**
  - **Instrumentation and DAQ**
- **Proposed Schedule**
  - **Conceptual Design CY14**
  - **Preliminary Design CY 15**
  - **Final Design and Prototype CY16**
  - **Infrastructure Development CY16-17**
  - **Prototype Construction CY16-17**



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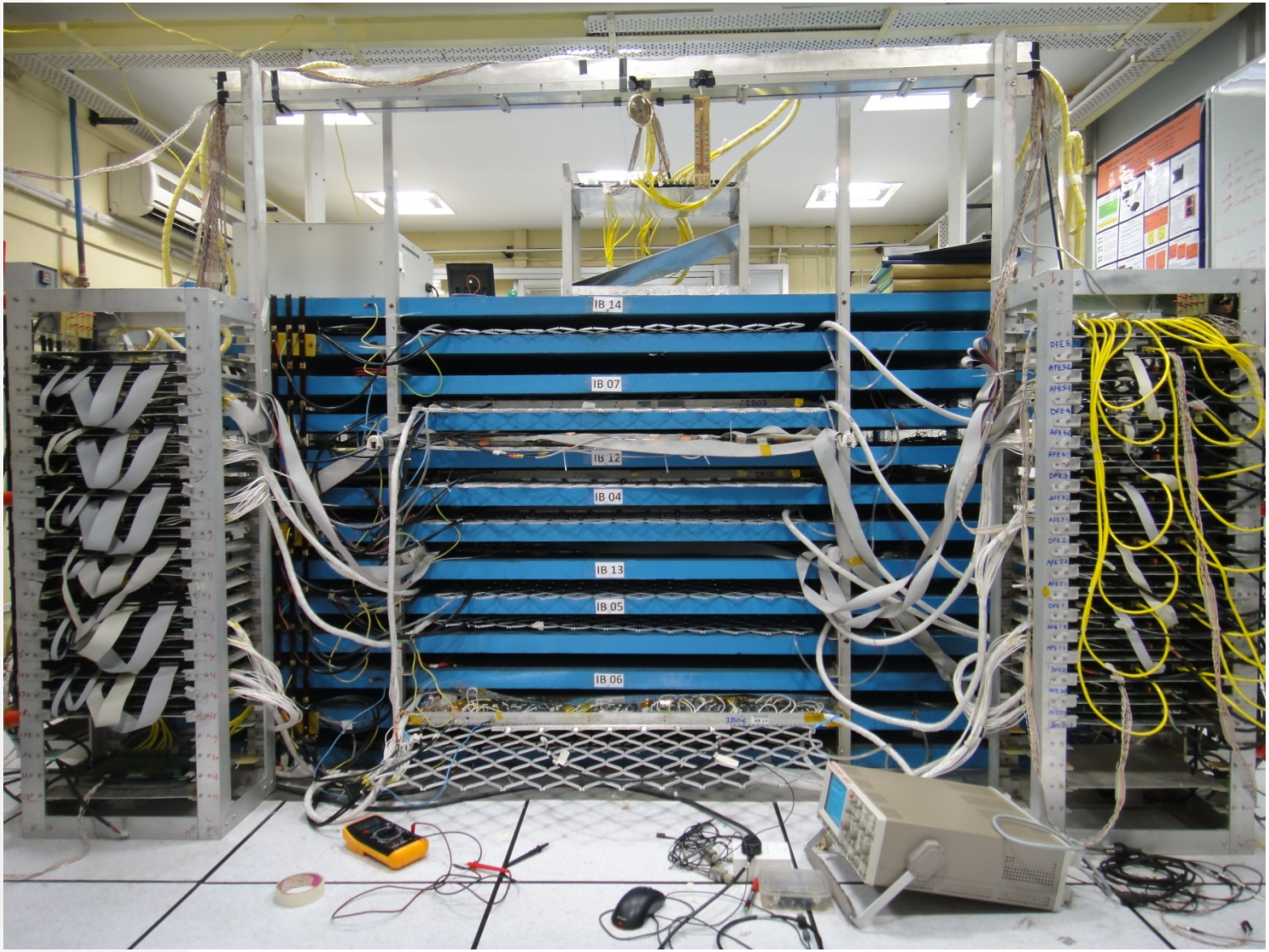
PU: STT Prototype

- **Straw Chamber Received from Dubna operating at PU**
  - **Experience**
- **Purchased 50 Kapton straws for R&D**
- **Establishing infrastructure for fabrication**

VECC: RPC Prototype



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IIT-G: Computing Infrastructure

- **Supported by DAE-DST Apex grant for the IIFC-nuP collaboration ($2M)**
  - **250 cores High Performance Computing cluster**
  - **500 GB RAM**
  - **15 TB storage**
- **LBNF Simulation work of the collaboration**
  - **LBNF-ND Geant 4 simulation in ART framework.**

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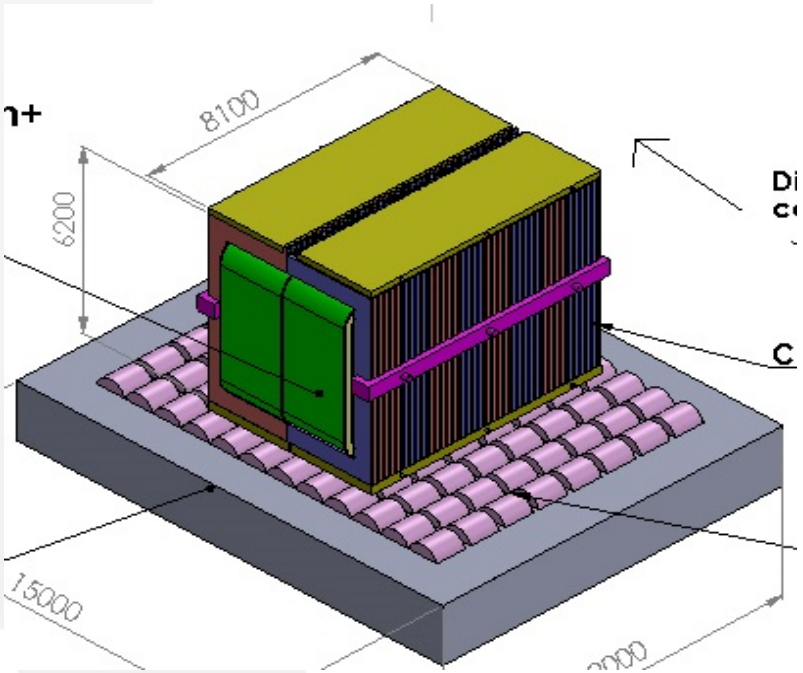
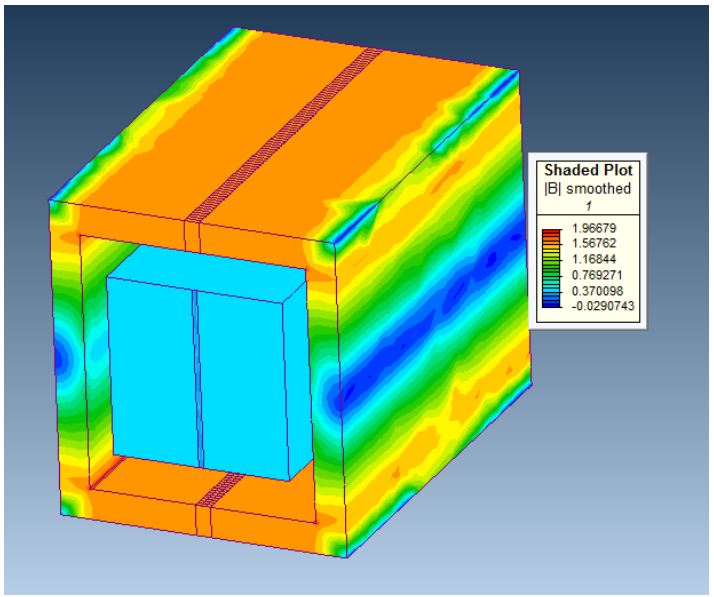
BARC: LBNF-ND Dipole

- **LBNF-ND Tracking detectors and ECAL Modules will reside in 0.4T dipole magnetic field volume with inner dimensions 4.5m*4.5m*8.1m.The magnet needs to support and anchor the detectors**





Volumetric Magnet field plot

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Fermilab: LBNF-Near Detector

LBNF-India proposal is for the US and Indian to jointly build the LBNF Near Detector with India as a leading partner.

IIFC Message

- **DAE-DOE Discovery Science Collaboration jointly initiated by the Indian Institutions and Fermilab provides an excellent and unprecedented opportunity for both countries.**
  - **US-India Strategic Dialogue (Cooperation on Basic Science)**
- **Accelerator**
  - **DAE laboratory's (BARC and RRCAT) and Fermilab accelerator designs, components and infrastructures are being developed jointly.**
    - **Total Project Collaboration**
  - **Indian domestic interest is in a CW SRF Accelerator**
    - **We would be a significant collaborator in the Fermilab HISPA development**
    - **DAE laboratories would work with Fermilab in the construction of PIP-II**
  - **DAE support the concept that initially the 1 GeV linac will be operated in a pulsed mode to start, as soon as possible, the Long Baseline Neutrino Facility (LBNF) at > 1 MW beam power.**
- **Physics**
  - **Indian Institutions are collaborating on LBNF**
    - **We are interested in the proposed neutrino physics program**
    - **We are jointly developing the LBNF Near Detector**
  - **Fermilab physics program is also of interest for**
    - **Indian universities infrastructure development**
    - **Indian human resources development**

Summary

- **Since 2009, the Indian Institutions and Fermilab Collaboration has made considerable technical progress in jointly developing SRF technology for proton accelerator**
  - **At present almost every component of SRF accelerator is under prototyping at Indian laboratories.**
  - **DAE laboratories have developed significant infrastructure to support construction projects**
- **Indian Institutions have joined MINOS, NOvA and LBNF.**
  - **Playing a major role in the development of LBNF-ND**
- **IIFC is looking forward to the conclusion of the legal agreement phase with DOE by the signing of the Project Annex I and II.**
  - **Under the agreement DAE-DOE will jointly develop technology for the SRF accelerators for respective domestic programs**
  - **DAE is positioned to make significant contribution to Fermilab program HISPA**
  - **DAE and DST will also make "In-Kind" contributions to LBNF**