# Indian Institutions and Fermilab Collaboration: A Road We Travel Together

**Shekhar Mishra**

**Project-X,**

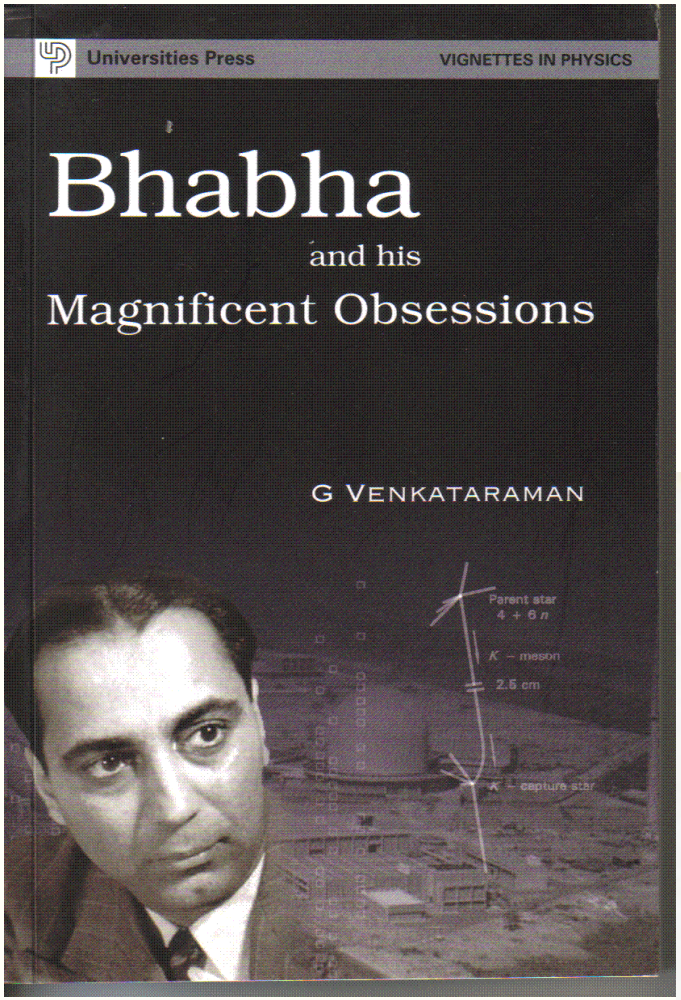
**International Collaboration Coordinator**

**Fermilab**

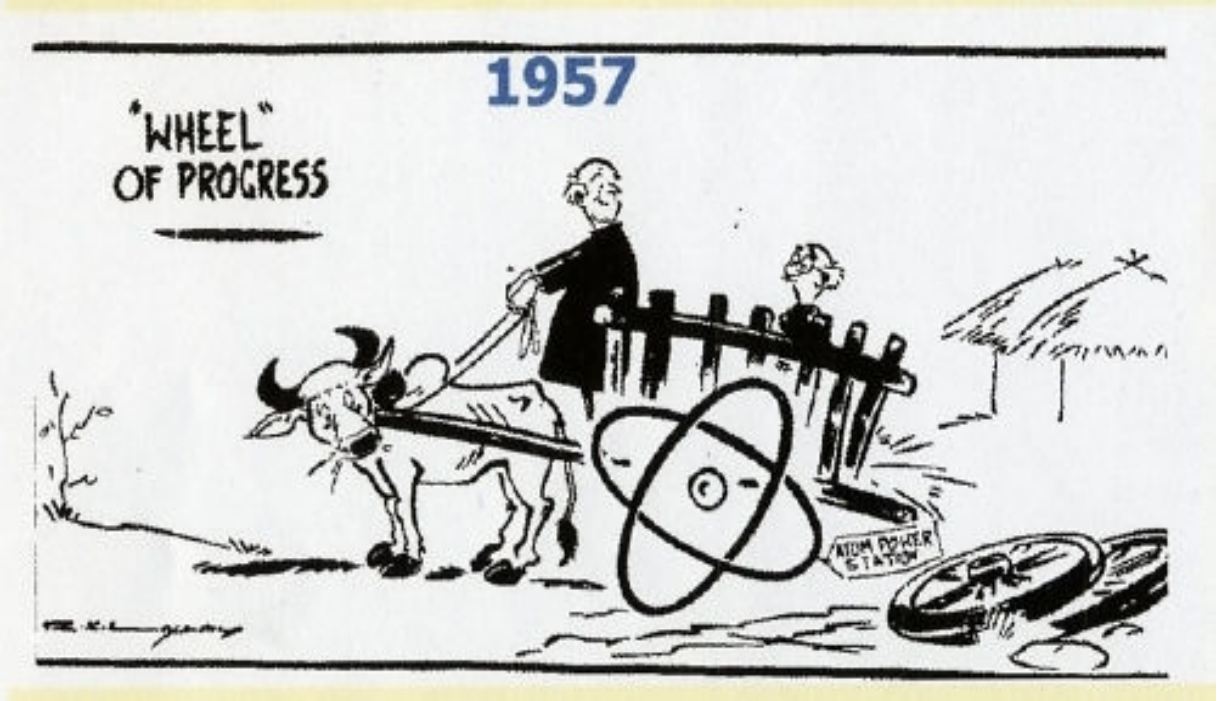
# Thoughts

- **Till 2003, Indian Science Program was foreign to me.**
  - **Indian economy was growing very fast. India had established collaboration in many areas with US (NIH, NASA, IT Industries)**
  - **I made it a mission to extend Indian physics collaboration in US**
    - **It started with my initial role in International Linear Collider**
  - **Today this collaboration with India has taken a magnitude that I myself had not contemplated**

# Vision of Nuclear India




**"The introduction of atomic energy in India in the early 1950s was not purely for the sake of introducing atomic power, but essentially for the introduction of new technologies dependent on basic sciences generated within" Bhabha to Ramanna**

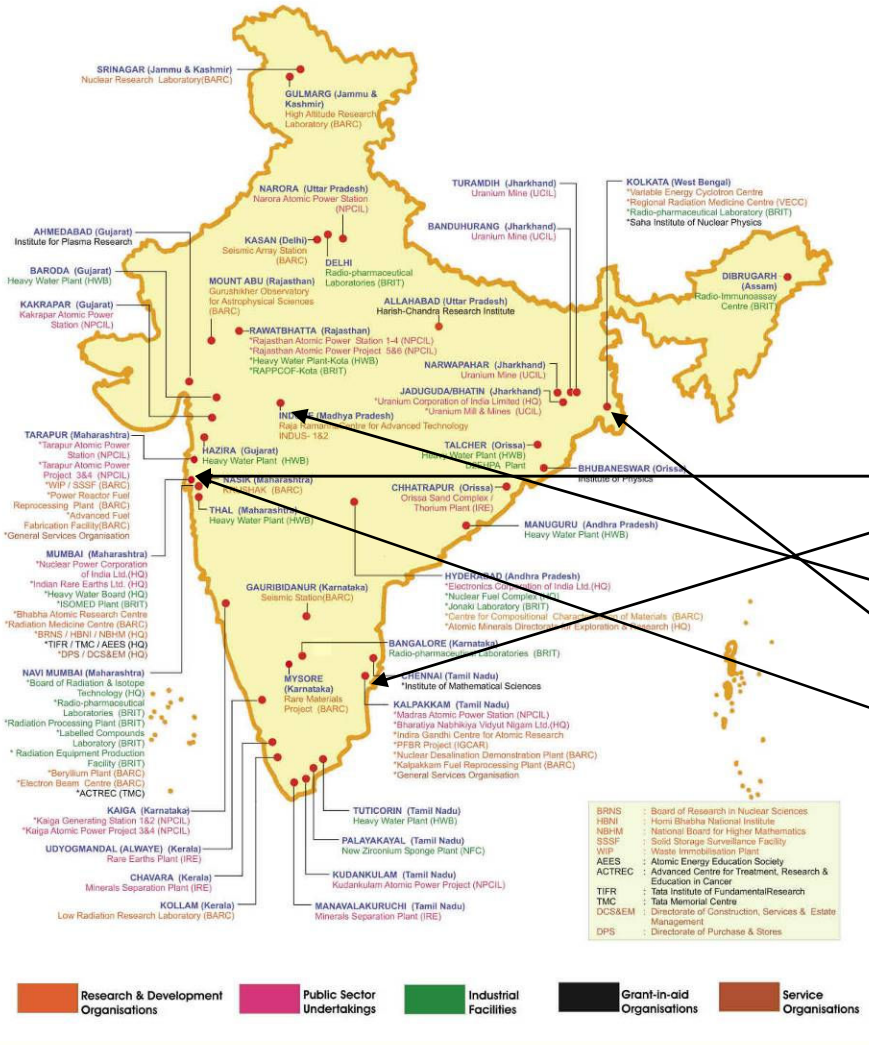


# How did this new effort start ?

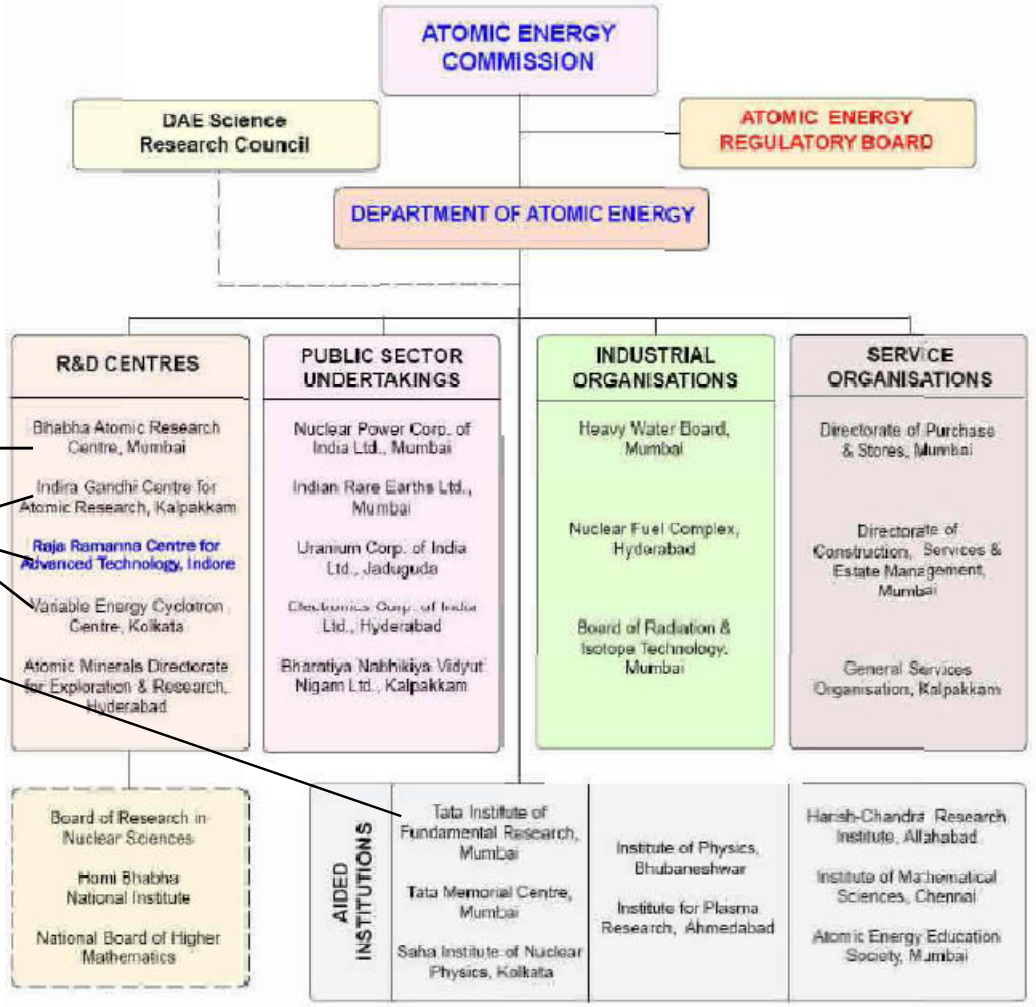
- Physicists from Indian Institutions have been collaborating at Fermilab since 1986.
- In 2002, LHC expected start and ILC were the talk of the town.
- India HEP was thinking of packing its bag from Fermilab and moving to CERN
  - D0 → CMS
- In Fall of 2002, with the help of Indian scientists collaborating at Fermilab, I met with Prof. V. S. Ramamurthy, Secretary, Department of Science and Technology (NSF) and Dr. Anil Kakodkar. Secretary, Department of Atomic Energy (DOE).
  - Message I got: "Get our scientists excited about the science and show that there are mutual benefits to both sides."
  - A working group was formed to develop this collaboration
- Since that meeting, We have been to India several times
  - First just to talk about Indian program, understand what Indian scientists want
  - Understand how we can work together.
  - Work with Indian scientists in developing a accelerator R&D program
  - Today we have one MOU and four Addendums in Accelerator and Neutrino
  - We are discussing significant "In-Kind" contribution from India for Project-X

# Indian DAE

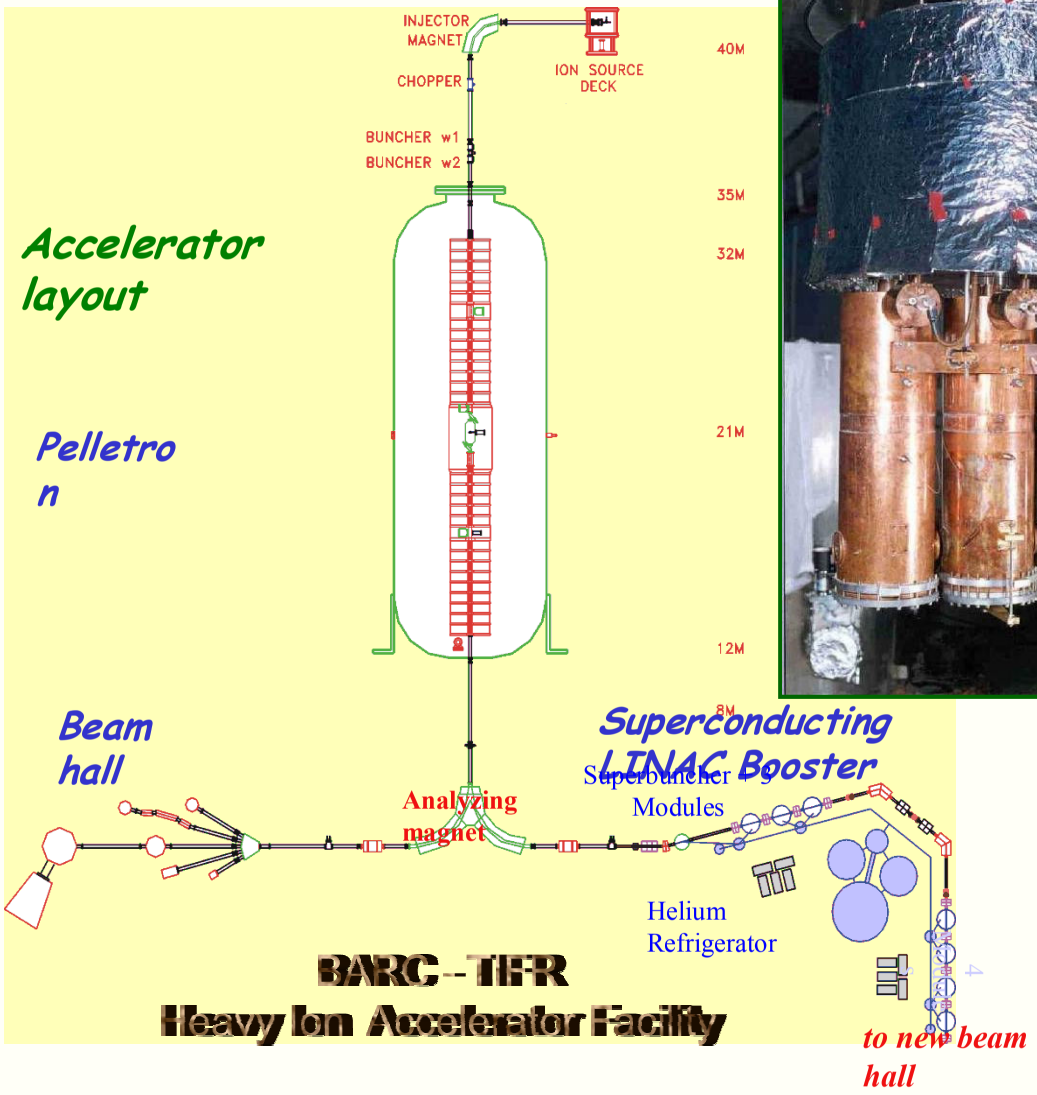
## Atomic Energy Establishments in India

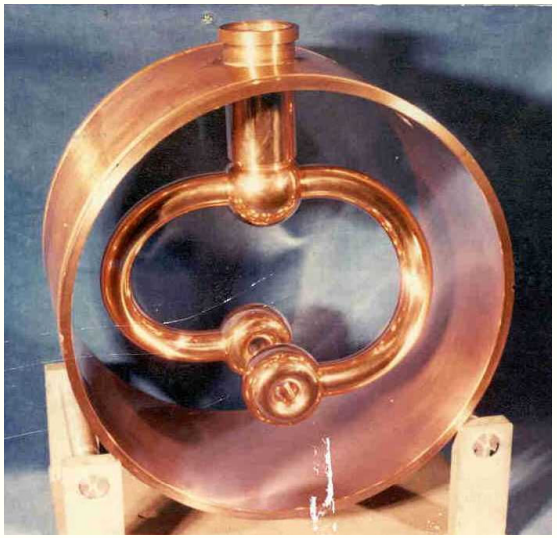


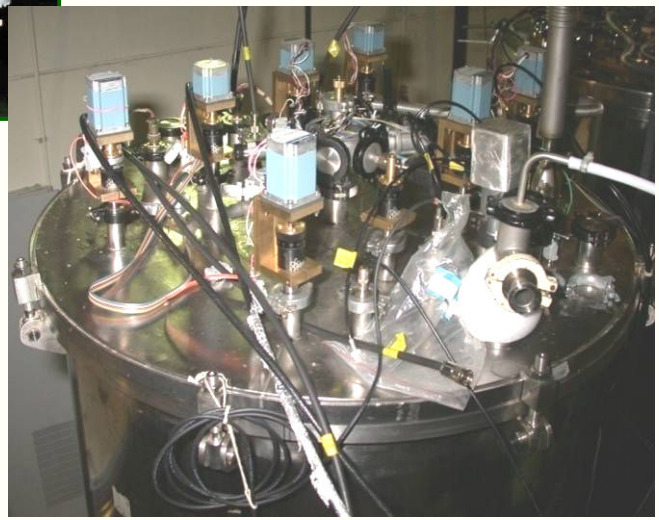

## DAE Organisational Chart



# BARC-TIFR Heavy Ion Accelerator







# Accelerator Development for ADS

Normal Conducting

Phase III

High current injector 20 MeV, 30 mA

Proton IS 50 keV → RFQ 3 MeV → DTL 20 MeV

Phase 1

DTL/ CCDTL

Phase II

Super-conducting

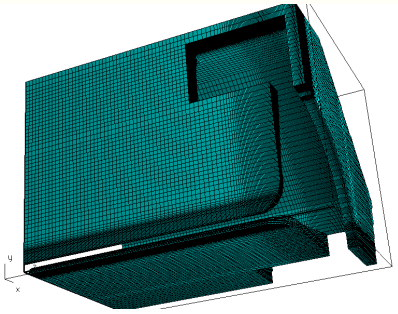
100 MeV → SC Linac → 1 GeV

Proton beam from high power accelerator

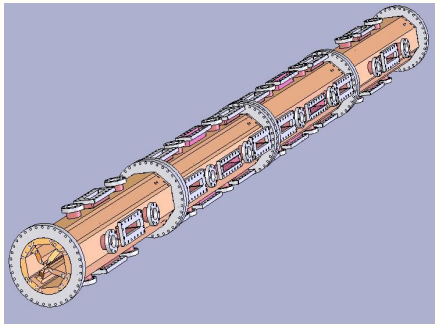
Design completed and fabrication is in progress

ECR Ion Source

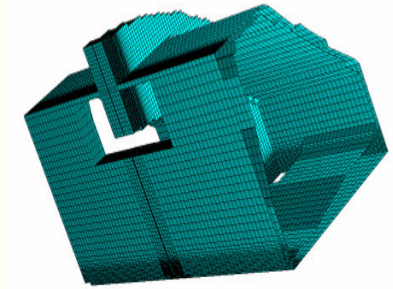
Beginning/End Cell



RFQ

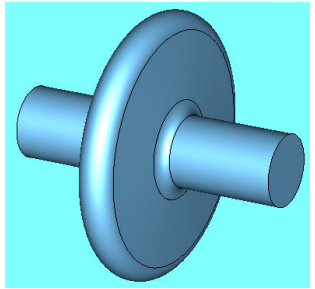


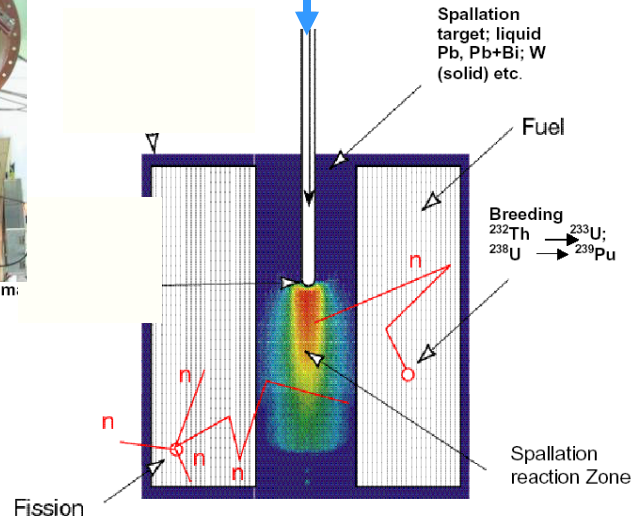
Coupling Cell



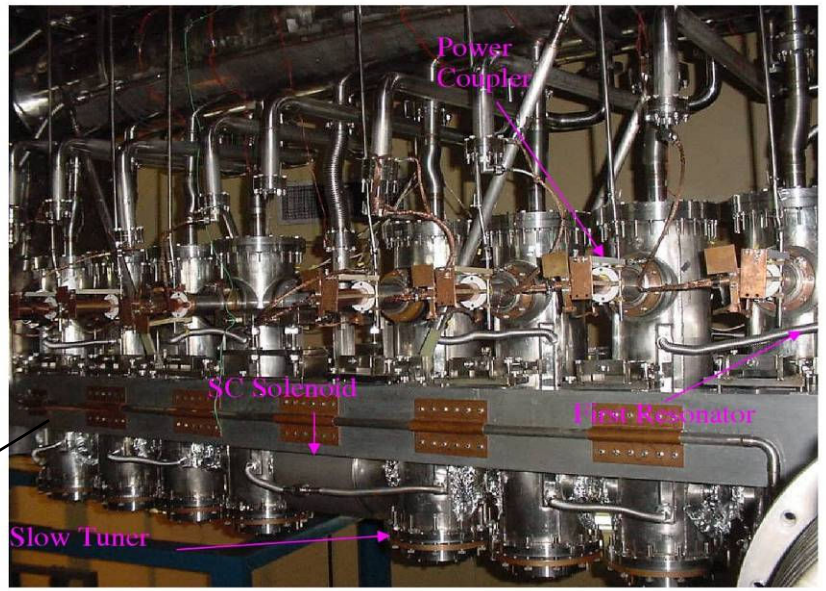
DTL

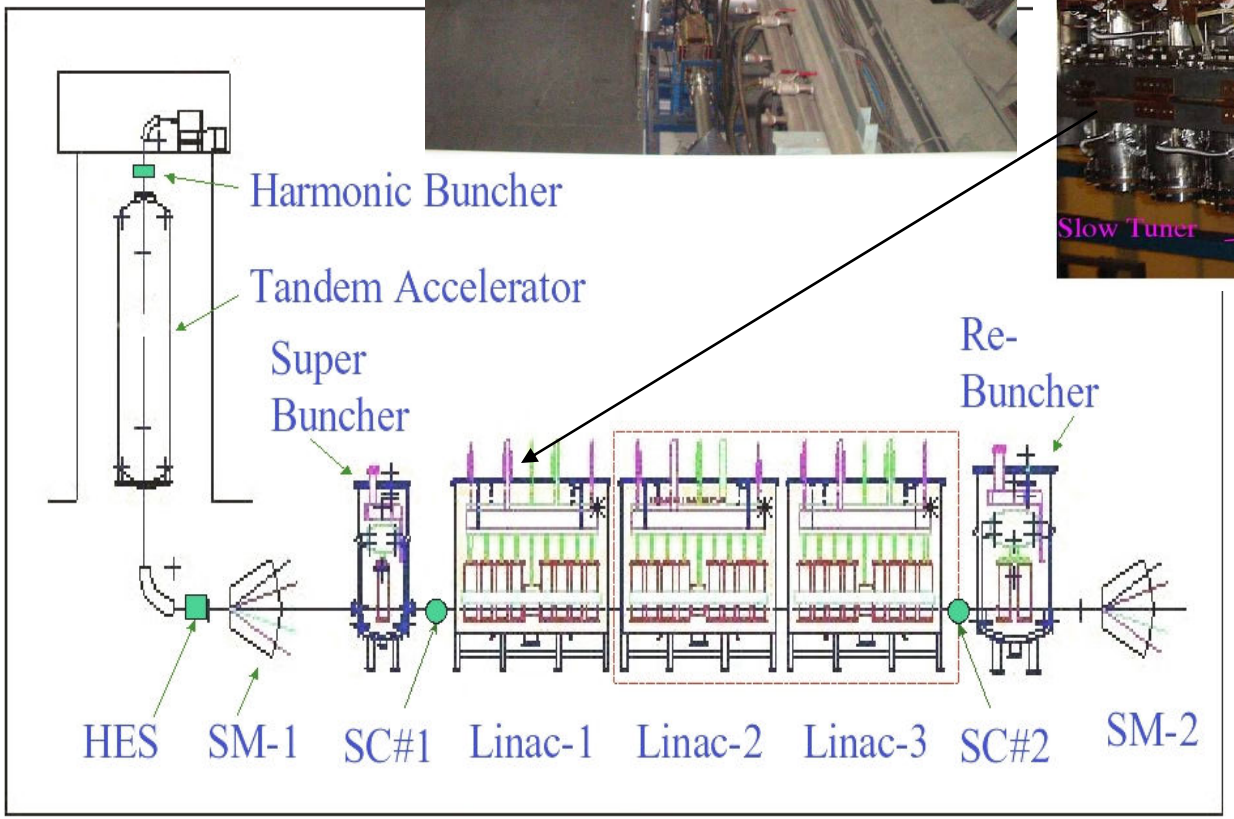
Elliptical SC Cavity





# IUAC: Pelletron and SRF Linac




Upgrade to ECR based High Current Injector

# IUAC: SRF Infrastructure

Fume hood

Electron Beam Welding

Oven

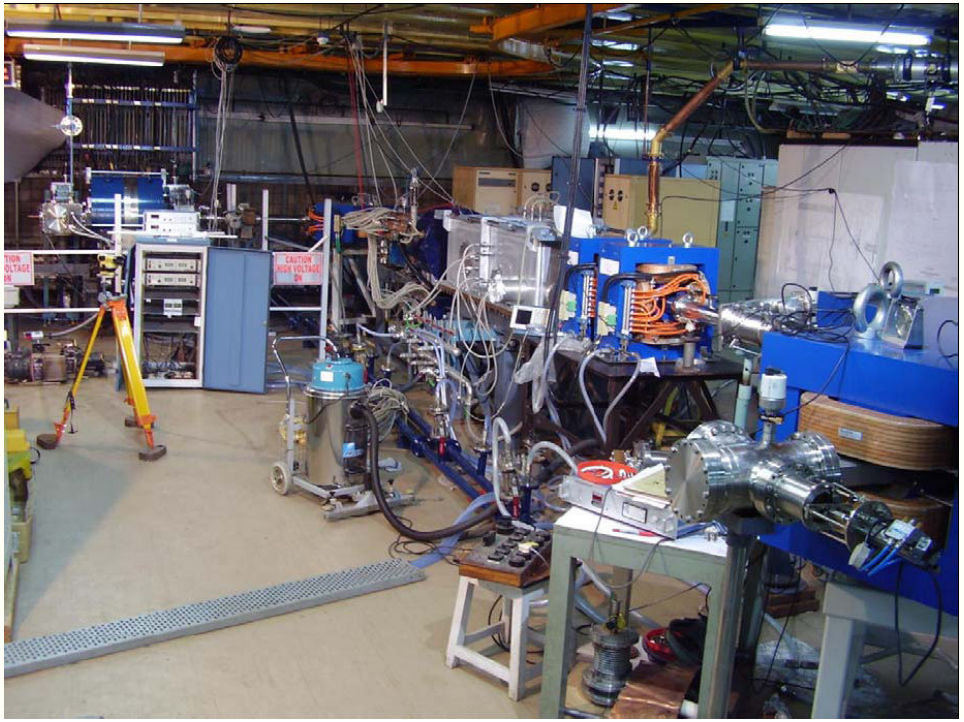
Surface Preparation

High Pressure Rinse

Vertical Test Stand

# VECC: Nuclear Physics

- Superconducting Cyclotron
- Radioactive Ion Beam Facilty
- R&D on Superconducting RF Linac
- Strength
  - Cryogenic
  - Mechanical Engineering
  - RF Power



# RRCAT: Indus-II

Indus-2 Ring in the Tunnel

RF Cavities installed in Indus-2 Ring

Long Straight Section LS-6 Assembly

Transport Line-3 Joining on to Indus-2

# India: LHC Accelerator

7080 Nos. Magnet Positioning System Jacks

MCS (1146 Units) & MCDO (616 Units)

Magnetic measurements teams- ~100 Man-years

5500 Nos. Quench Heater Power supplies( QHPS)

1435 Nos. Local Protection Units

A part of DAE's contributions installed in LHC Tunnel at CERN

# Nuclear Power Reactor

KUDANKULAM
ATOMIC POWER PROJECT

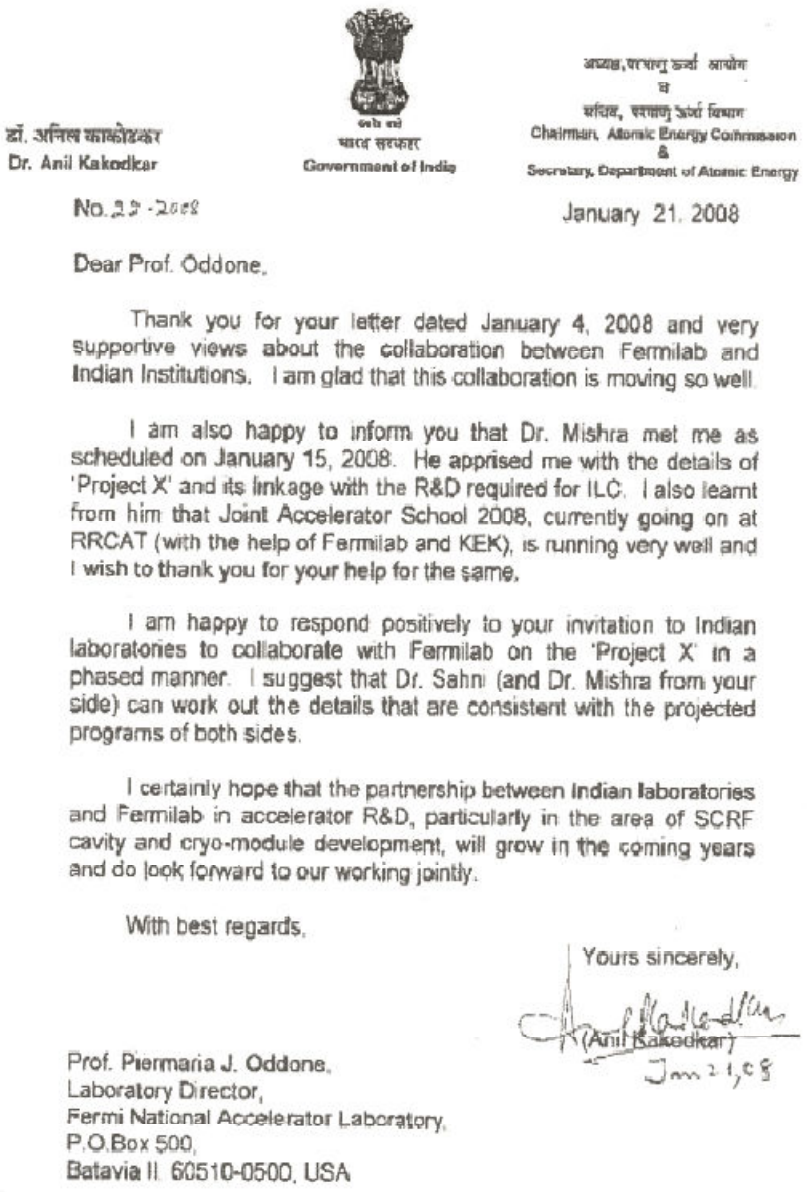
RAJASTHAN
ATOMIC POWER PROJECT

KAIGA
ATOMIC POWER PROJECT

CD-3 to CD-4 in Five yrs.

Indo-US Nuclear Treaty

# It takes a lot of time



डॉ. अनिल काकोडकर
Dr. Anil Kakodkar

भारत सरकार
Government of India

अध्यक्ष, परमाणु ऊर्जा आयोग
व
सचिव, परमाणु ऊर्जा विभाग
Chairman, Atomic Energy Commission
&
Secretary, Department of Atomic Energy

No. 23 -2008

January 21, 2008

Dear Prof. Oddone,

Thank you for your letter dated January 4, 2008 and very supportive views about the collaboration between Fermilab and Indian Institutions. I am glad that this collaboration is moving so well.

I am also happy to inform you that Dr. Mishra met me as scheduled on January 15, 2008. He apprised me with the details of 'Project X' and its linkage with the R&D required for ILC. I also learnt from him that Joint Accelerator School 2008, currently going on at RRCAT (with the help of Fermilab and KEK), is running very well and I wish to thank you for your help for the same.

I am happy to respond positively to your invitation to Indian laboratories to collaborate with Fermilab on the 'Project X' in a phased manner. I suggest that Dr. Sahni (and Dr. Mishra from your side) can work out the details that are consistent with the projected programs of both sides.

I certainly hope that the partnership between Indian laboratories and Fermilab in accelerator R&D, particularly in the area of SCRF cavity and cryo-module development, will grow in the coming years and do look forward to our working jointly.

With best regards,

Yours sincerely,

(Anil Kakodkar)
Jan 21, 08

Prof. Piermaria J. Oddone,
Laboratory Director,
Fermi National Accelerator Laboratory,
P.O.Box 500,
Batavia Il 60510-0500, USA

- **Summer 2006 to Jan 2008:**
  - **Initial Interaction and visit by Indian**
  - **ILC R&D funding**
  - **Project-X**
- **Jan 2008 to Jan 2009, it took one year and several trips to get the Addendum MOU III signed.**
  - **Fermilab**
  - **Indian Laboratories**
  - **DOE & DAE**
  - **Management structure**
  - **Funding**
    - **No $ leaving boundaries**
  - **Laws and Lawyers**
    - **Export Controls**
    - **IPR**
    - **Sensitive Country**
  - **US Industries**

# Developing US Collaboration With India

# Jan 2009: Addendum MOU III

- Initial two Fermilab and SLAC Addendums were focused on ILC Cavity and RF Power.
- Addendum III includes All SRF aspects of
  - High Intensity Proton Accelerator.
  - SRF infrastructure
  - Personnel exchange and Training of manpower
  - Indian Industries involvement

Mishra, Fermilab and Dr. Vinod C. Sahni, India serve as the Collaboration Coordinators.

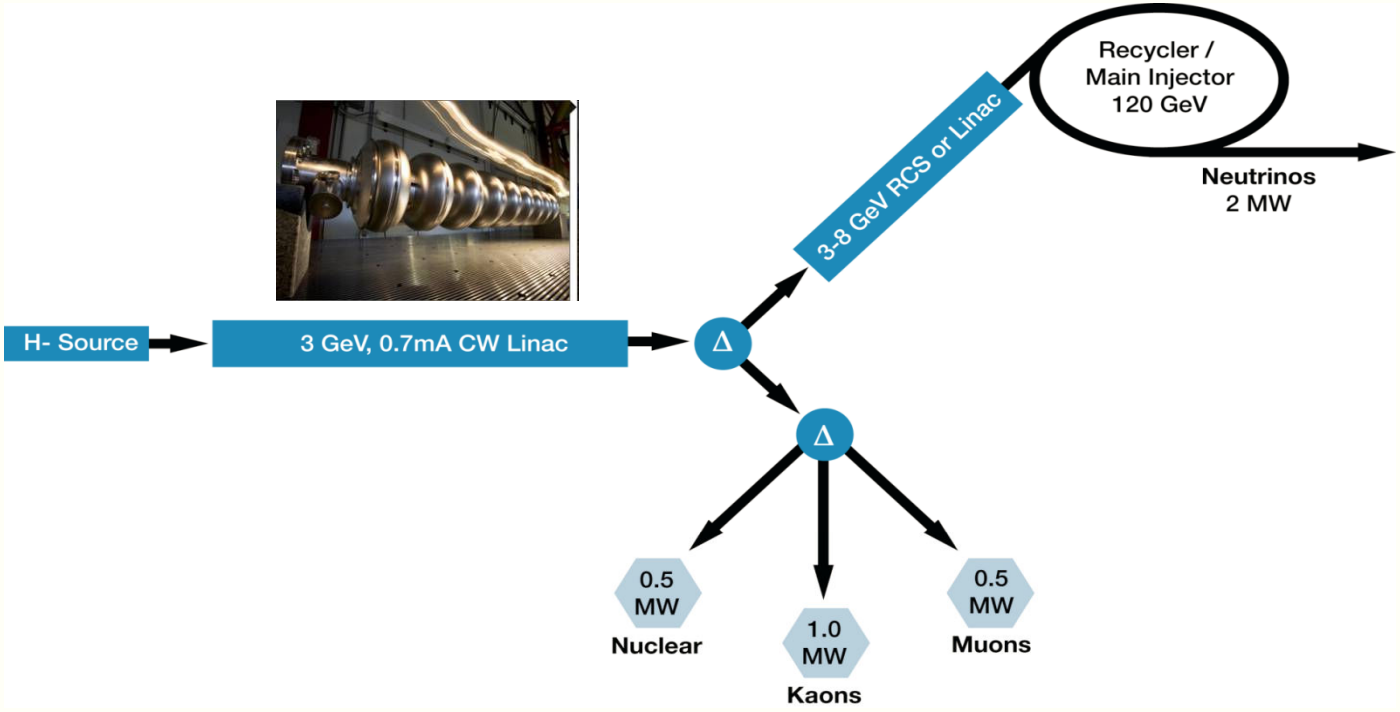
The following concur on the terms of this Memorandum of Understanding Addendum:

| | | | |
|---|---|---|---|
| Dr Vinod C. Sahni, Director, RRCAT | Date | Dr. Piermaria Oddone Director, FNAL | Date |
| Dr Srikumar Banerjee, Director, BARC | Date | Dr Amit Roy, Director, IUAC | Date |
| Dr Bikash Sinha, Director, VECC | Date | | |

# MOU: US and Indian Laboratories

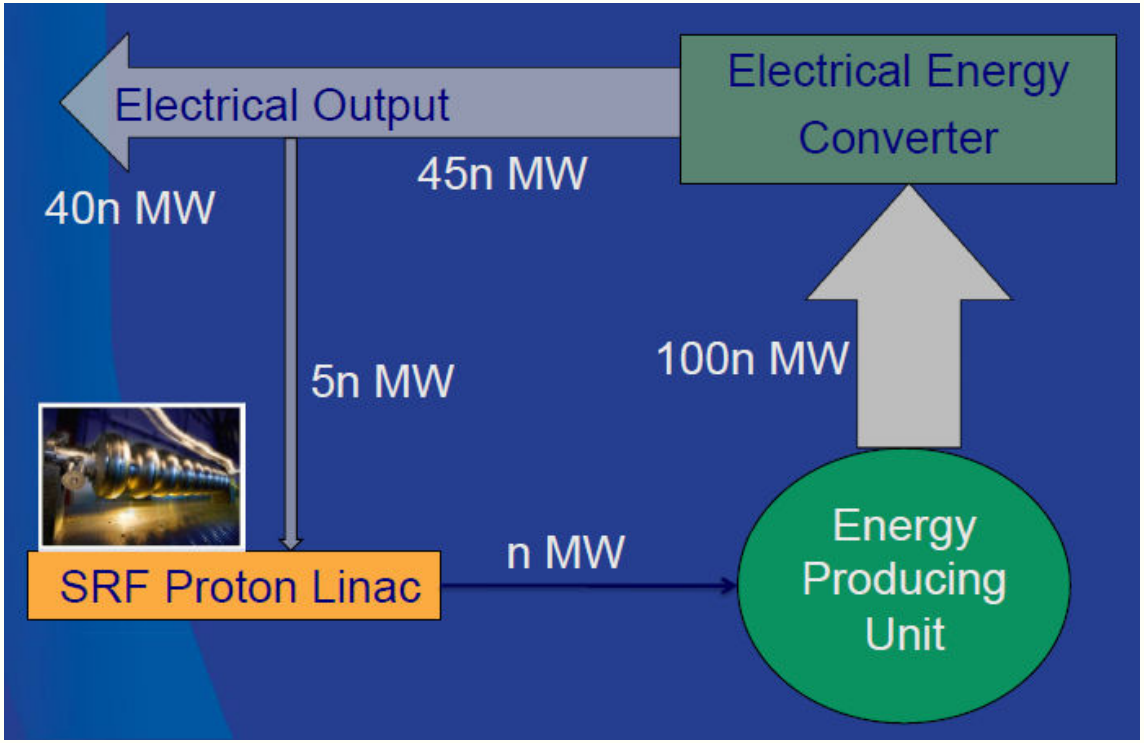
- On Jan 9, 2006, US (Fermilab, SLAC, Jlab, Cornell) and Indian Institutions (BARC, RRCAT, VECC, IUAC, DU) signed an MOU to collaborate on Accelerator and High Energy Physics
- We are collaborating under four addendums to the MOU (http://iifc.fnal.gov)
  1. Fermilab, RRCAT, BARC, IUAC and VECC Collaboration on ILC Main Linac SRF Accelerator Technology R&D
  2. SLAC, RRCAT, BARC, IUAC and VECC Collaboration on ILC RF Power Sources and Beam Dump Design R&D
  3. Fermilab and Indian Accelerator Laboratories Collaboration on High Intensity Proton Accelerator and SRF Infrastructure Development (Phase I)
  4. US and Indian Institutions Collaboration on Neutrino Physics, Related Experiments and Detector Development.

# Fermilab Next 10 yrs Strategy




- **A multi-MW Proton Source, Project-X, is the main part of Fermilab's strategy for future development of the accelerator complex.**
  - **Project-X is designed to provide flexibility in evolving Fermilab program in response to research results from the LHC**

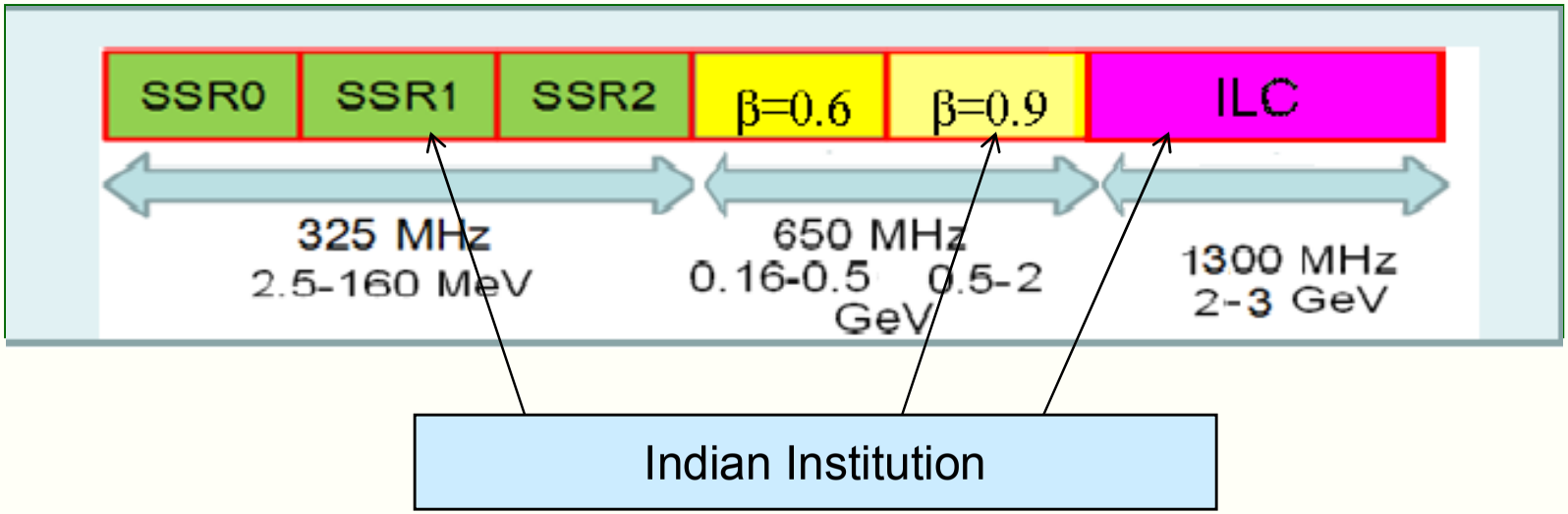
# Indian Next 10-15 yrs Strategy




- **A multi-MW Proton Source is one of part of 3rd stage**
  - **Multi MW CW beam at 1-2 GeV (similar to Fermilab Project-X) could be the accelerator technology demonstration project corresponding to 10s of MW electrical power if applied to a suitable Accelerator Driven Subcritical Reactor.**

# Phase I: R&D Indian Institutions

- **Fermilab is developing HIPA (Project-X) as a national project with International participation.**
  - **Indian DAE laboratories are 1st international partner.**
- **Indian Accelerator Program for Nuclear Energy and Fermilab High Intensity Proton Accelerator program are aligned in design.**

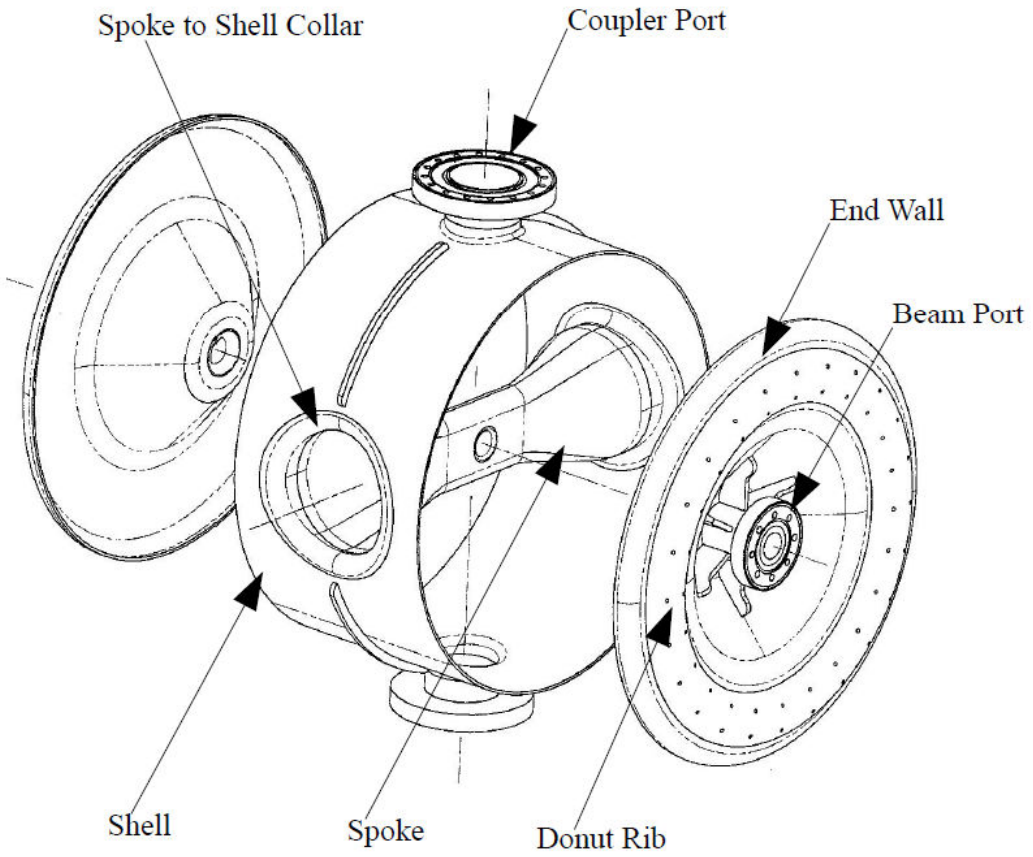


# Phase 1: Deliverable

- SSR1 Cavity
- 650 MHz, $\beta$ = 0.9 cavity design, prototype and fabrication
- 650 MHz Cryomodule design
  - He Vessel
  - Blade Tuner
- SRF Infrastructure
  - Vertical Test Stand design
  - Horizontal Test Stand design and cryostat
  - Cryomodule Test Stand design and cryostat

# IUAC: Fabrication of SSR1

- **Two SSR1 cavities are under fabrication at IUAC**

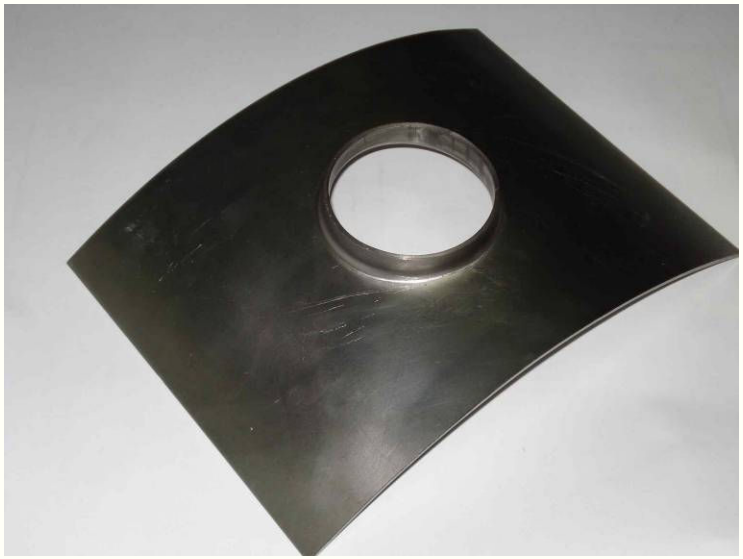



Major components of SSR1 – β = 0.22, f = 325 MHz

# Spoke – Forming & EBW

# Shell – Rolling & EBW

# End Wall - Forming



Niobium Coupler Port pullout

Power Coupler Port - Tubes

# Elliptical Cavity: Forming and Machining

**Developed forming tooling & process for 1.3 GHz SCRF cavity.**

Forming

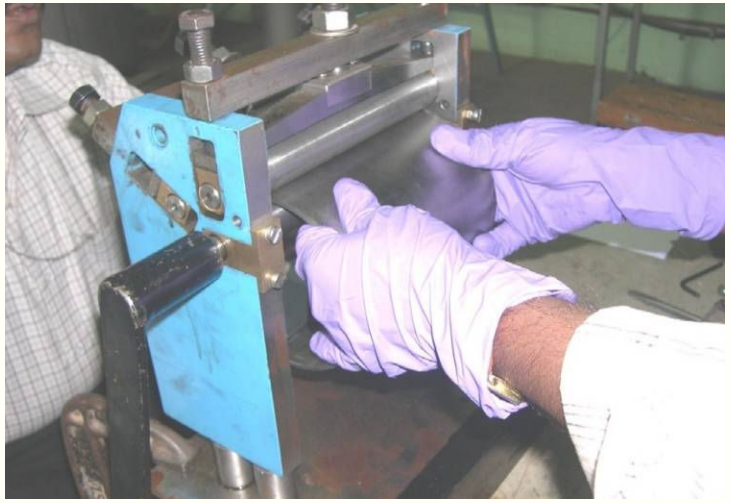
Inspection

120 T - HYDRAULIC PRESS

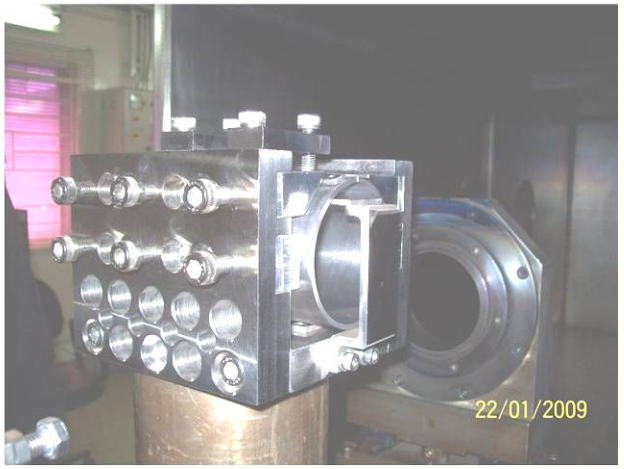
Machining

Formed Niobium Half cell

# Manufacturing of Beam Pipe



This compact & dedicated machine it is suitable for clean room application required for the rolling Niobium sheet.




**Beam pipe welding**

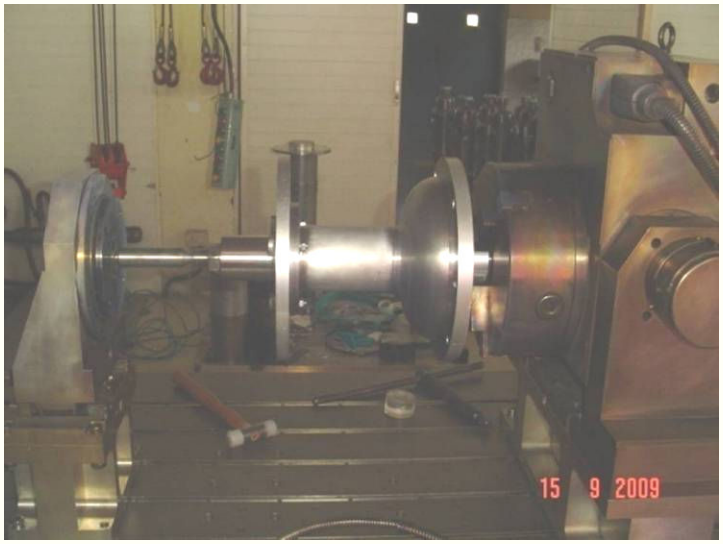
**Beam pipe machining**

# Welding of Components

Pre weld Etching

Cleaning and assembly of pipe-Flange

Pipe-Flange welding




Outside Iris welding Half cell assly

Inside Iris welding Half cell assly

# Trimming , frequency and mechanical measurements

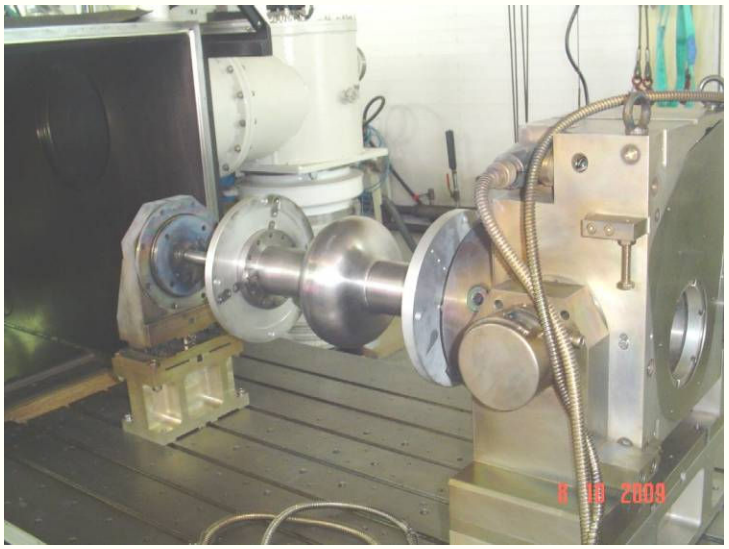
| Half cell assembly | Before length (mm) | Before Frequency (MHz) | After length (mm) | After frequency (MHz) | Sensitivity MHz/mm |
|---|---|---|---|---|---|
| AL -132 | 199.02 | 1286.5080 | 197.5 | 1289.7635 | 2.17 |
| AL-133 | 198.82 | 1288.6623 | 197.92 | 1293.3215 | 5.17 |

Equator trimming

Frequency Measurement

Mechanical inspection

# Equator Welding



Setting inside IUAC EBW Chamber

Frequency measurement

Mechanical inspection

This work was carried out by RRCAT in collaboration with Fermilab and IUAC.

Significant input was provided by DESY and US Company AES

# Leak testing (Stage wise + Final)

Leak testing of Niobium half cell

Leak testing of Single cell cavity

**Leak testing at 300 K and 77 K,**
**Qualified for leak rate of 1 x 10 $^{-10}$ mbar.l/sec .**

# RF measurement ( at FNAL)

| Frequency | TE1CAT001 | TE1CAT002 | |
|---|---|---|---|
| FNAL (23 C) | 1297.031 | 1296.793 | dF= -238 KHz ( between two cavities) |
| RRCAT (27 C) | 1296.926 | 1296.675 | dF = -251 KHz ( between two cavities) |

| 'Q' factor | | |
|---|---|---|
| FNAL (23 C) | 9960.53 | 9917.766 |
| RRCAT (27 C) | 9076 | 9328 |

The frequency measurement data match well between RRCAT & FNAL measurement.

A basic shift in frequency can be attributed to difference in measurement temperature.

The offset between two cavities is very close {~ 13 KHz}.

# Cavity assembly in to VTS (FNAL)

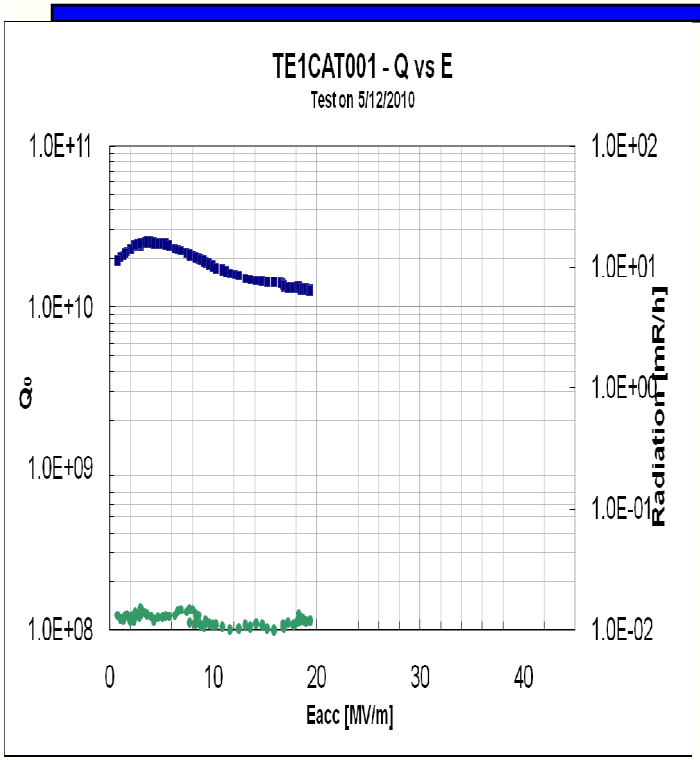
- The cavity was processed at ANL using the standard procedure and baked at Jlab.

Mounted on the VTS

Connecting to VTS inside clean room

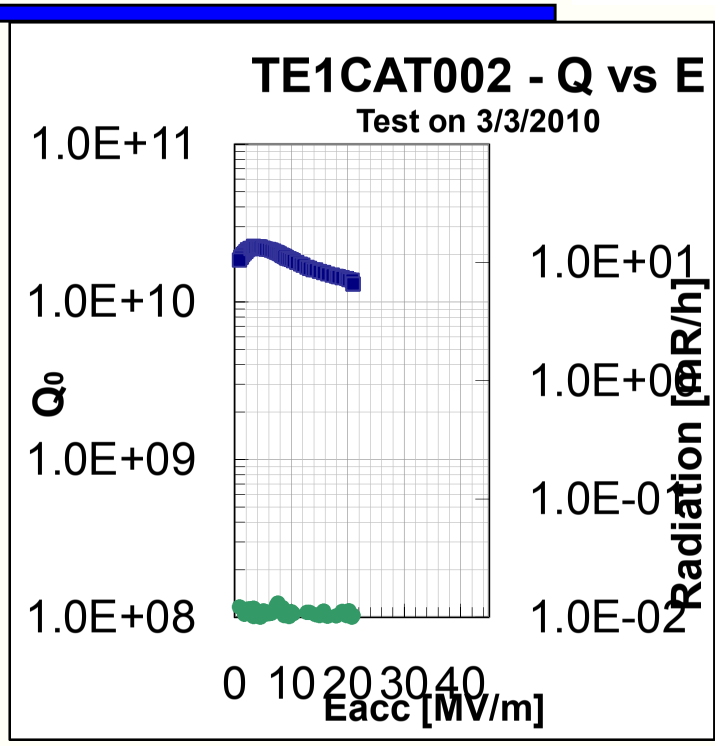
Lowering in to Dewar

# 1-cell Cavity 2 K VTS test result




No Field Emission

Quench at Equator




The equator weld is a suspect. Welding procedure.

These cavities have been barrel polished at Fermilab and awaits further processing and testing.

RRCAT in collaboration with IUAC will fabricate 2, 7 cell, 1300 MHz cavities to validate their procedure and infrastructure.

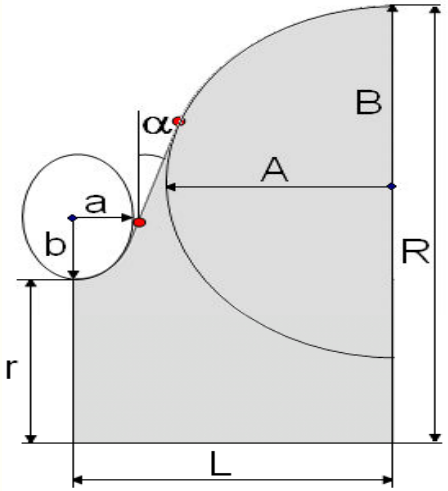
# END Group R&D

- High RRR End Group under machining from a Single Billet .
- The Three Major suggestions that have been incorporated are
  - All flanges will be NbTi and not NbTi ring embedded in Nb flange .
  - HOM port length kept same but location of joint changed.
  - Some minor modifications on flange thickness

# 650 MHz Cavity Design

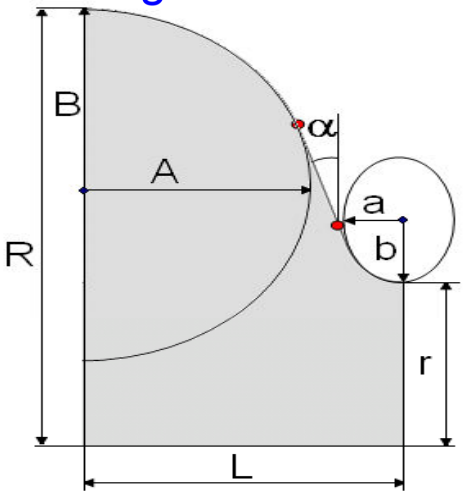
- **Fermilab, DU, RRCAT and VECC are collaborating on 650 MHz elliptical cavity design.**

Left cell



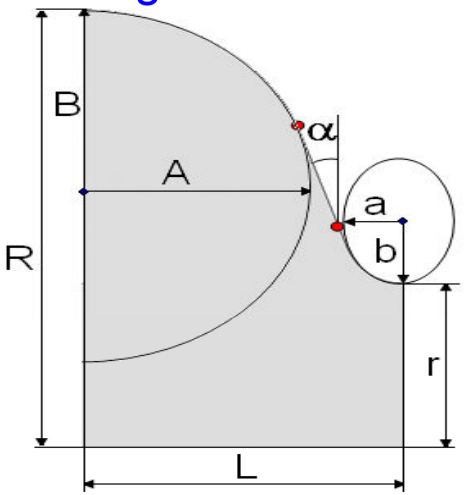

| | |
|---|---|
| r | 50 |
| R | 200.277 |
| L | 106.974 |
| A | 82.5 |
| B | 84.5 |
| a | 20 |
| b | 39.5 |
| α | 7.02 |

Regular cell




| | |
|---|---|
| r | 50 |
| R | 200.277 |
| L | 103.75 |
| A | 82.5 |
| B | 84 |
| a | 18 |
| b | 38 |
| α | 5.2° |

Right cell



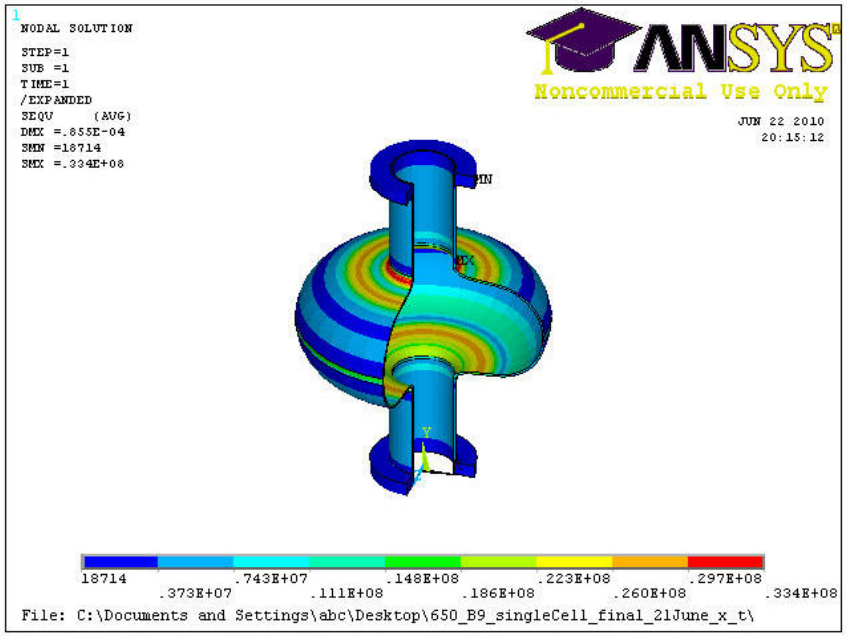

| | |
|---|---|
| r | 50 |
| R | 200.277 |
| L | 106.974 |
| A | 82.5 |
| B | 84.5 |
| a | 20 |
| b | 39.5 |
| α | 7.02 |

All dimensions are in mm.

# 650 MHz, 1-cell development

- **Calculation of Mechanical Deformation for beta 0.90 single cell cavity**

## Both ends fixed

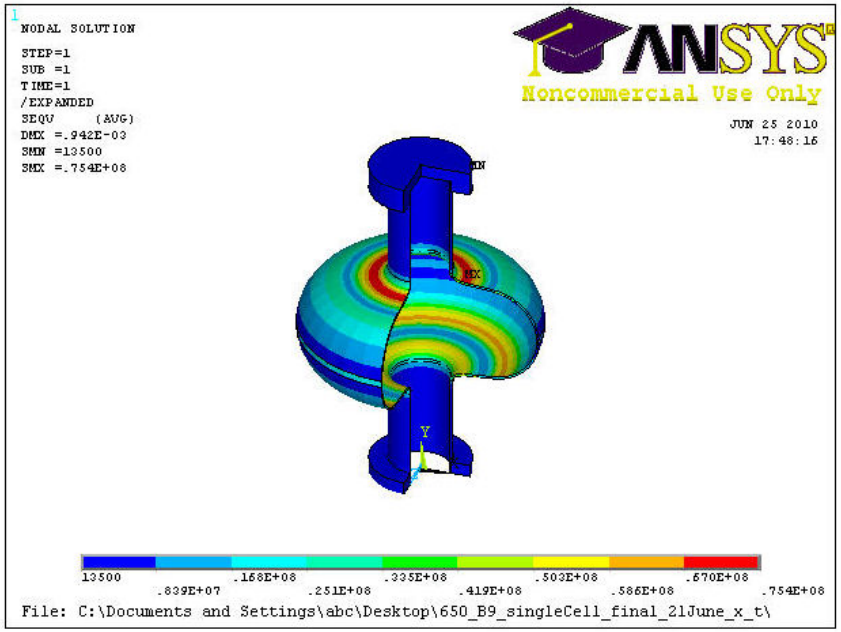



Applied Pressure= 2 Bar

Max stress = 33.4 MPa

Max Displacement= 85.5 um

## One end open




Applied Pressure =2 bar

Max stress = 75.4 MPa

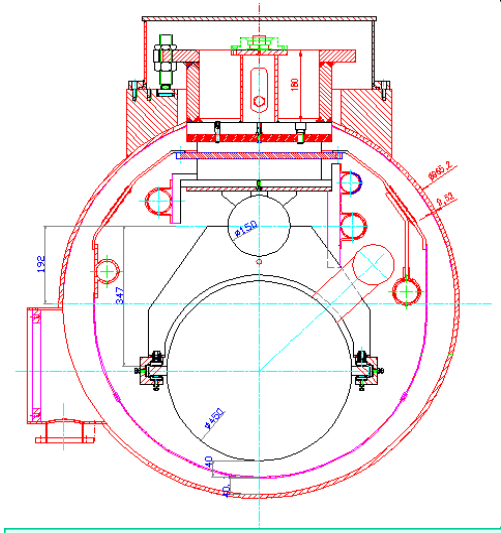
Max Displacement= 0.942 um

# 650 MHz, β = 0.6 cavity design

- VECC has been working on 704 MHz, b = 0.6 cavity design, prototype and testing.
- Recently under IIFC discussions VECC have decided to switch their frequency to 650 MHz
  - Despite having significant infrastructure for 704 MHz

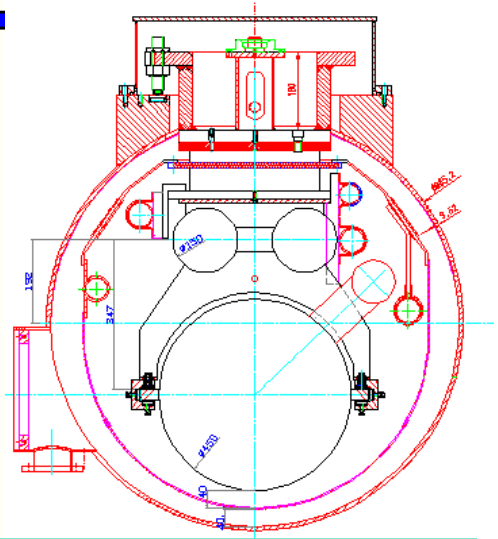
| | $\frac{A}{B}$ mm./ mm. | $\frac{a}{b}$ mm./ mm. | Equator radius R mm. | Iris radius r mm. | Half-cell L (inner) mm. | $\frac{R}{Q}$ Ω | Energy (Joule) | $E_{acc}$ MV/m | $\frac{E_p}{E_{acc}}$ | $\frac{B_p}{E_{acc}}$ | $f_{0-mode}$ MHz | $f_{\pi-mode}$ MHz | $\%k_{cc}$ (calculated) | Remarks |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| FERMILAB RESULTS | As per the following data provided by FERMILAB | | | | | 378 | ? NOT given | 17 | 2.25 | 4.21 | 645.5 | 650 | 0.695 | Code used: ? (Not known) |
| | 54/58 | 14/25 | 194.95 | 41.5 | 70.34 | | | | | | | | | |
| VECC RESULTS1 | 54/58 | 14/25 | 194.95 | 41.5 | 70.34 | 373 | 93.63 | 16.93 | 2.667 | 4.5 | 651.773 | 656.187 | 0.675 | Code used: HFSS |
| VECC RESULTS2 | 54/58 | 14/25 | 194.95 | 41.5 | 70.34 | 300 | 93.63 | 15.19 | 3.817 | 7.519 | 649.955 | 655.687 | 0.878 | Code used: CST |
| VECC RESULTS3 | Data generated by VECC | | | | | 324 | 93.63 | 15.81 | 3.512 | 6.401 | 645.663 | 649.992 | 0.668 | Code used: HFSS [a/b_end cell = 12.4/15] |
| | 45/47 | 15/15 | 200.8 | 43.5 | 70.38 | | | | | | | | | |

# Internal Configuration of Cryomodule for 650 MHz Cavity



**Possible Options & their evaluation**

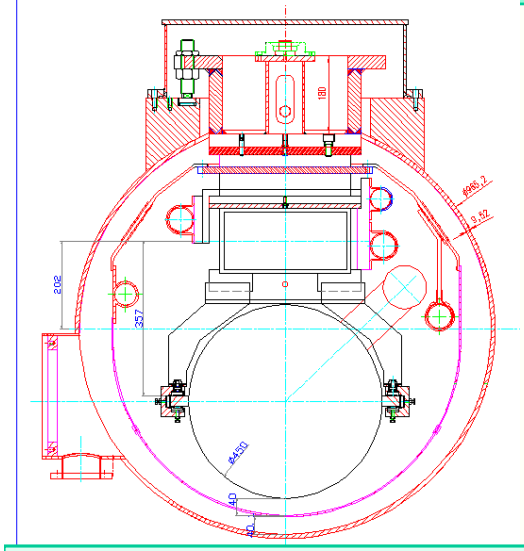
**Goal** :Use Popular T4CM Cryomodule design for Fermilab Project X
-(Although cavity size is up by a factor of 2)

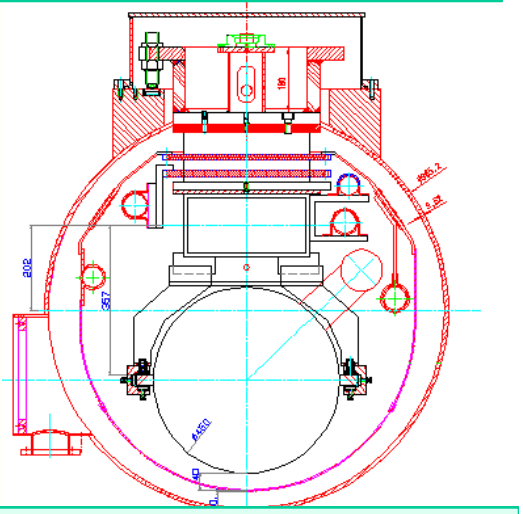


**Option A- Single Pipe support**

**Evaluation Based on:**
- Static heat leaks (approx)
- Pressure drop in HGR pipe
- Stiffness of the system (approx)
- Availability of pipes
- General Mech. Engineering issues

**Option B- Support on two pipes**

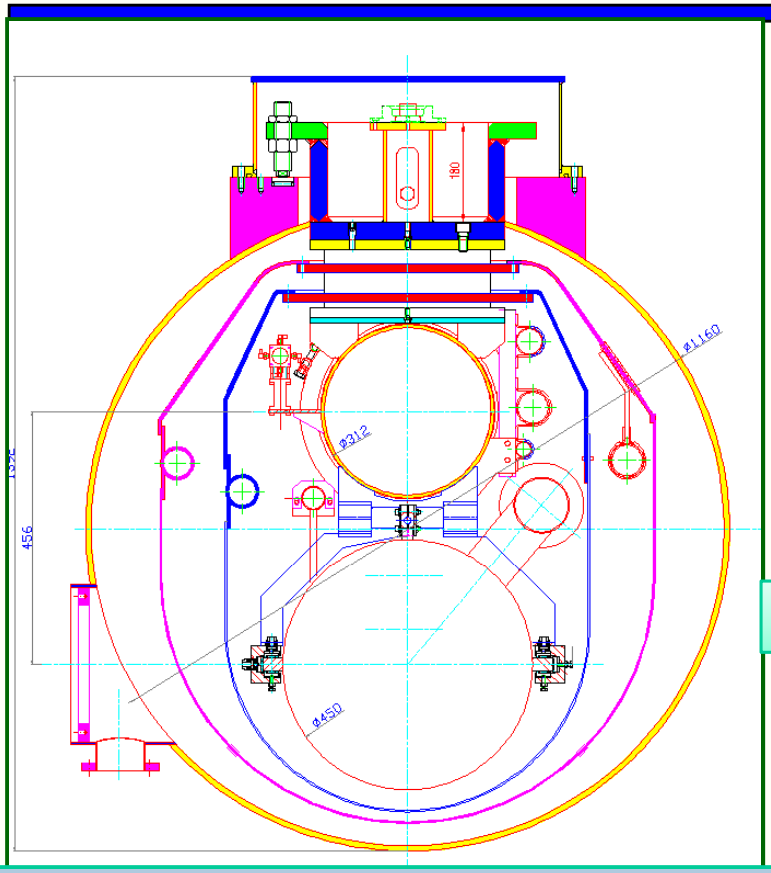




**Option C- Rectangular Duct support**

**Option D- Rectangular Duct support with interception flange**

# Option Chosen for Detailed Analysis



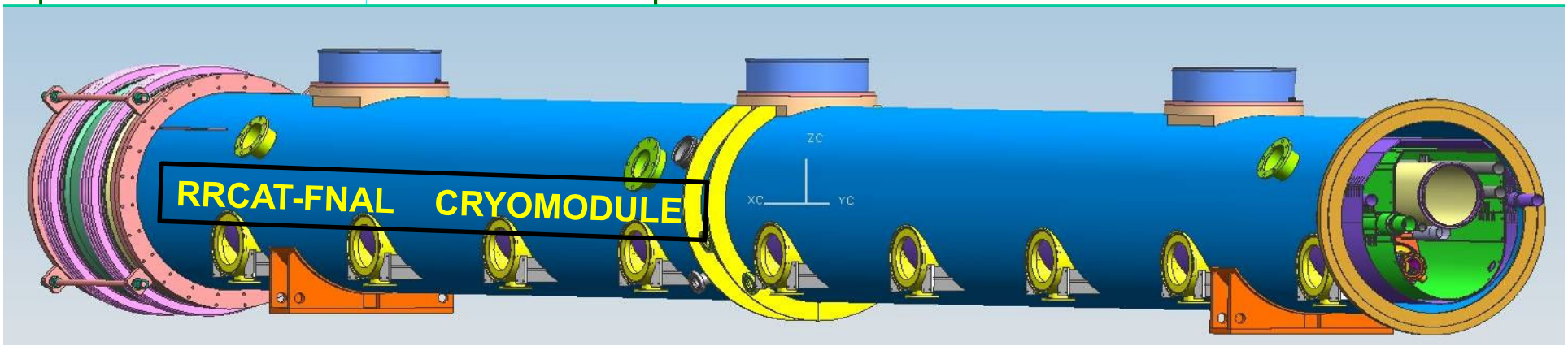

**Option E-**
**Vacuum Vessel with Dia 46inches.**

✓Retaining essential features of T4CM design.

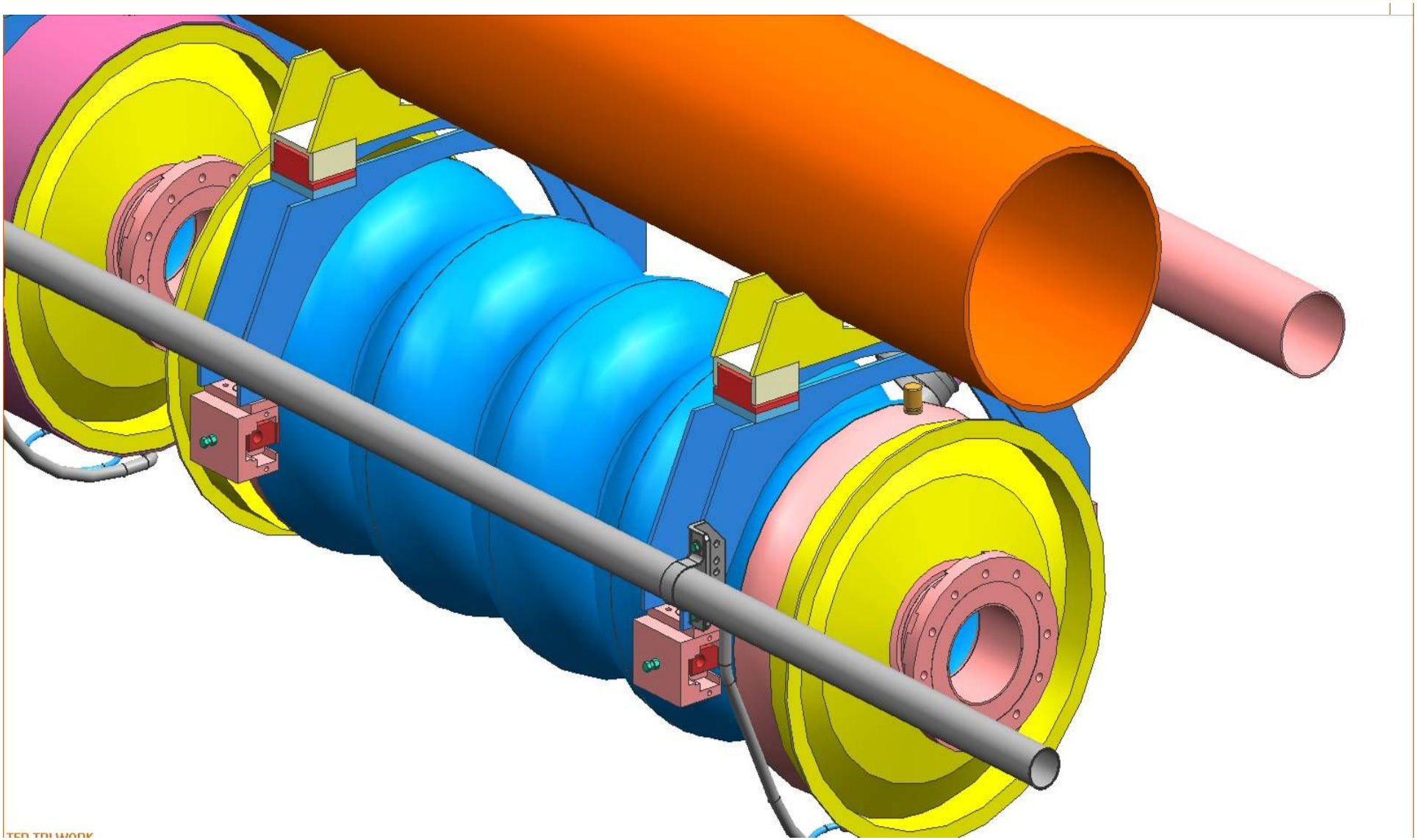
✓ But incorporating Value Engineering Changes.

The Cross section

The 3-D Model (Under designing)

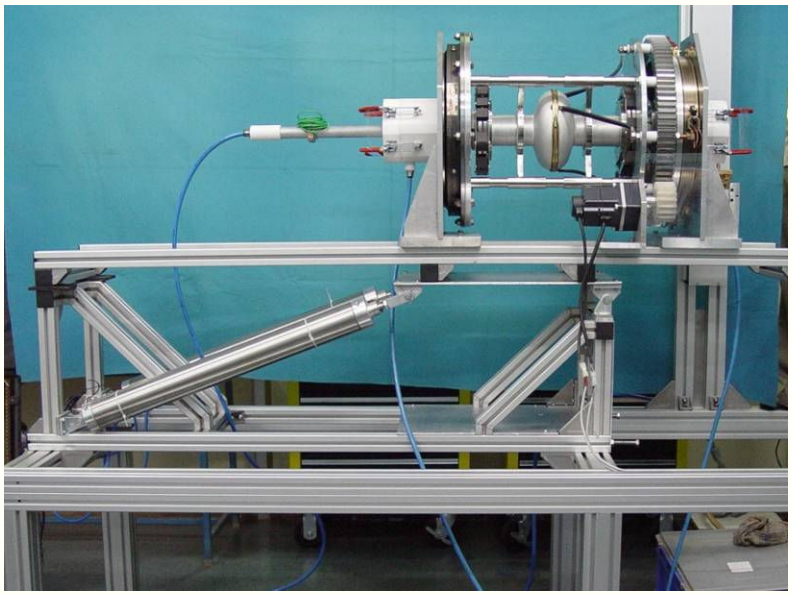


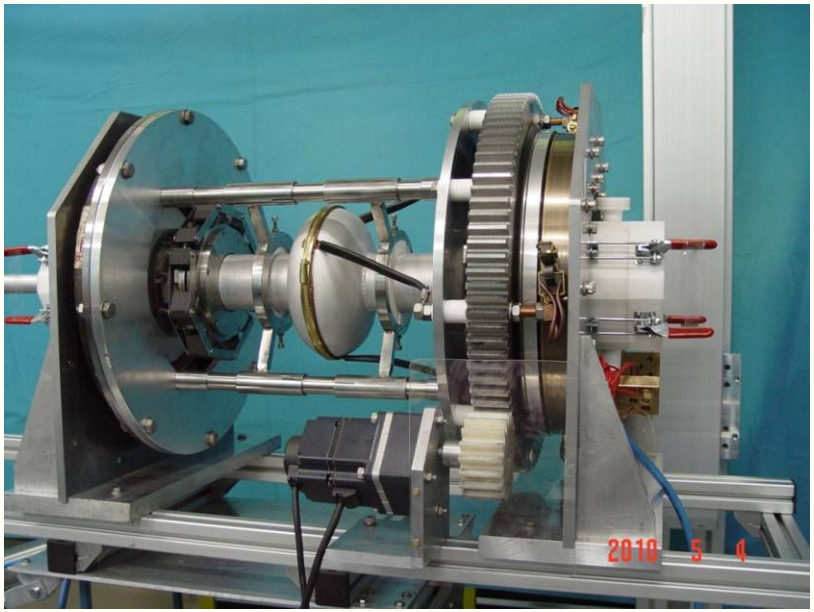
# The 650MHz cavity



# RRCAT: SRF Infrastructure

- Similar to ANL design bench for electro-polishing of SCRF cavity has been developed, it can process up to nine cell cavity. The stand is capable of :
  - Rotating the cavity at 2-10 rpm.
  - Holding the cavity in horizontal position during processing & in vertical position during draining/ rinsing and for loading the cathode
  - Slip ring with 4 carbon brushes to connect power supply.
  - The flow circuit has been tested with water.
  - Acid pumps, valves & plumbing have been procured.
  - 25V – 1000A DC Power supply has been procured.





# RRCAT: SRF Infrastructure

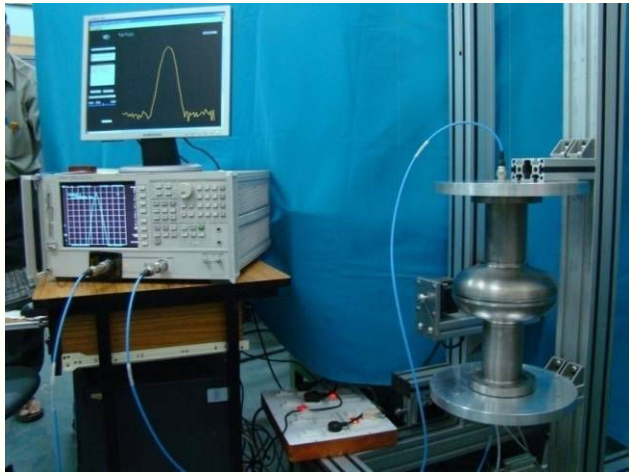
## High Pressure Rinsing Setup

High Pressure Rinsing Set up in Clean enclosure (Class 100)

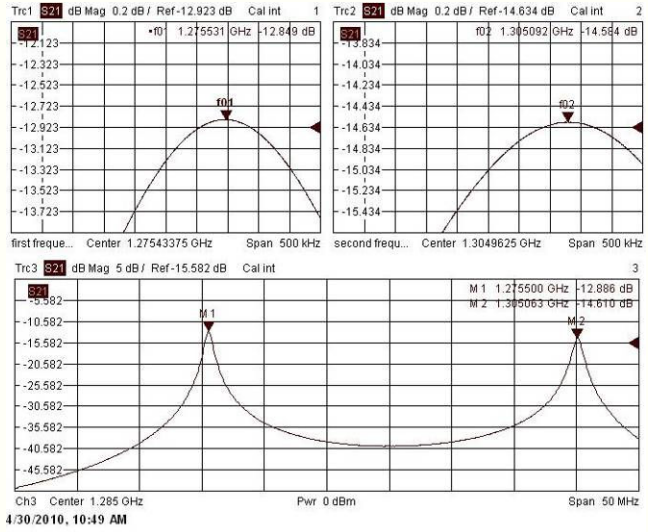
Ultra Pure Water Plant

# RRCAT: Cavity RF Measurement

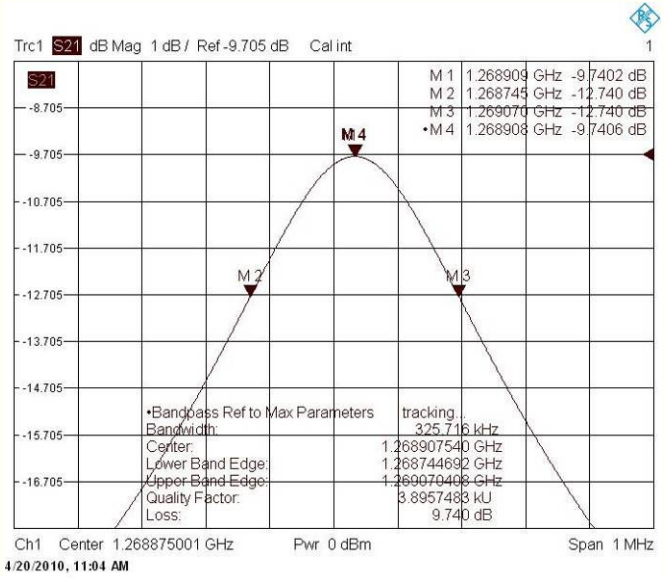
PNEUMATICALLY OPERATED RF FREQUENCY MEASUREMENT SETUP



RF MEASUREMENT SET UP FOR FREQUENCY AND FIELD DISTRIBUTION




RF FREQUENCY PEAKS OF DUMB-BELL

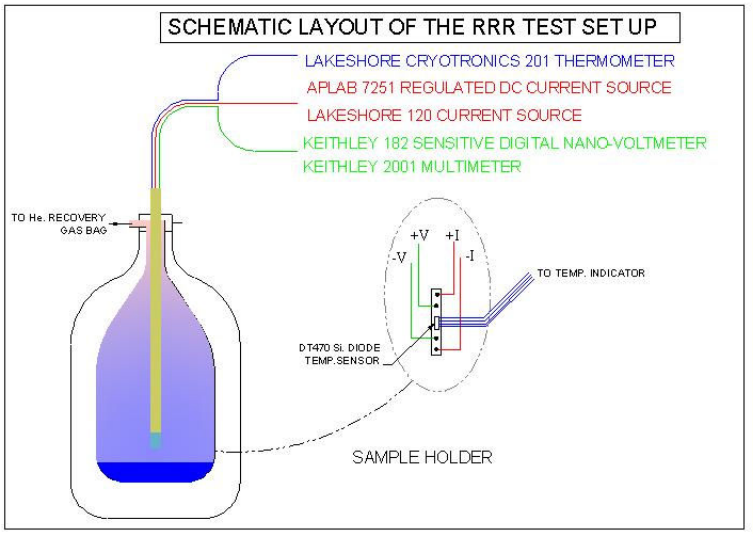



RF FREQUENCY PEAKS OF SINGLE CELL CAVITY

# Indigenous Development of Nb

NFC, Hyderabad (materials development)

RRCAT, Indore ( electrical and superconducting properties, elemental analysis)




| *SUMMARY & COMPARISION OF TEST RESULTS* | | | |
|---|---|---|---|
| **S.No.** | **Source** | **Sample ID** | **RRCAT RRR Results** |
| Measurement results | | | |
| **1** | **NFC** | ***Nb/NFC/I80Nb III/U/B*** | 96 ( 20.03.09) |
| **2** | **NFC** | ***Nb/NFC/IU1/Ti clad expt*** | 98 ( 06.04.09) |

# Building for SCRF Cavity Development

**Cavity Processing Building** (Expected to be ready by mid of 2011)

• The building will house clean rooms, Electron Beam welding machine. High Vacuum Annealing Furnace, Electro-polishing setup, Centrifugal barrel polishing machine etc.

**SCRF Lab Building (**Expected to be ready by mid of 2011)

• The building will house Cavity forming facility, machining facilities, CMM, SIMS, material testing facility etc

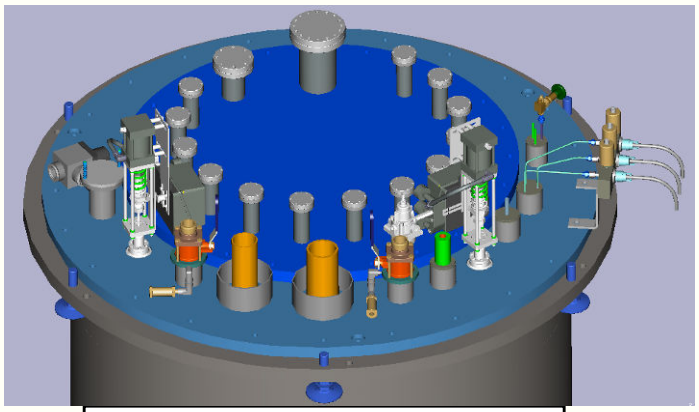
Fermilab has shared infrastructure information with RRCAT.

Bid for Electron Beam Welder with specifications similar to AES is out.

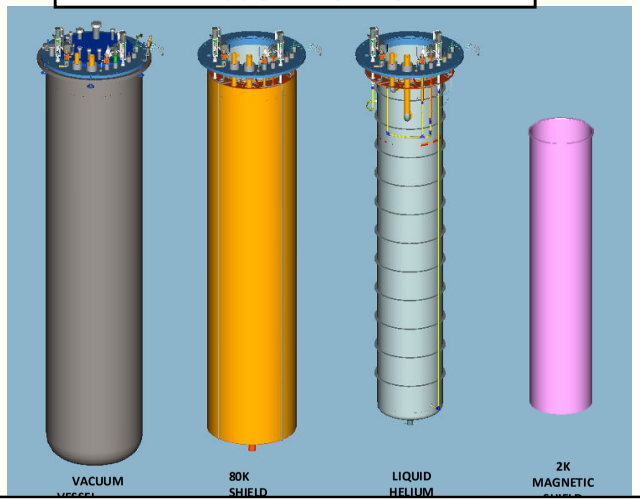
AES has agreed to collaborate with RRCAT on some of these development.

# Vertical Test Stand Design

- **Indian Institutions have provided engineering resources to design an upgraded Vertical Test Stand for Fermilab.**
  - **It is being fabricated by a US vendor using ARRA funds**
  - **RRCAT also purchased one**



VTS-2 TOP PLATE – CRYOGENIC & VACUUM INSERTS




3-D MODELS OF VTS-2 VESSELS

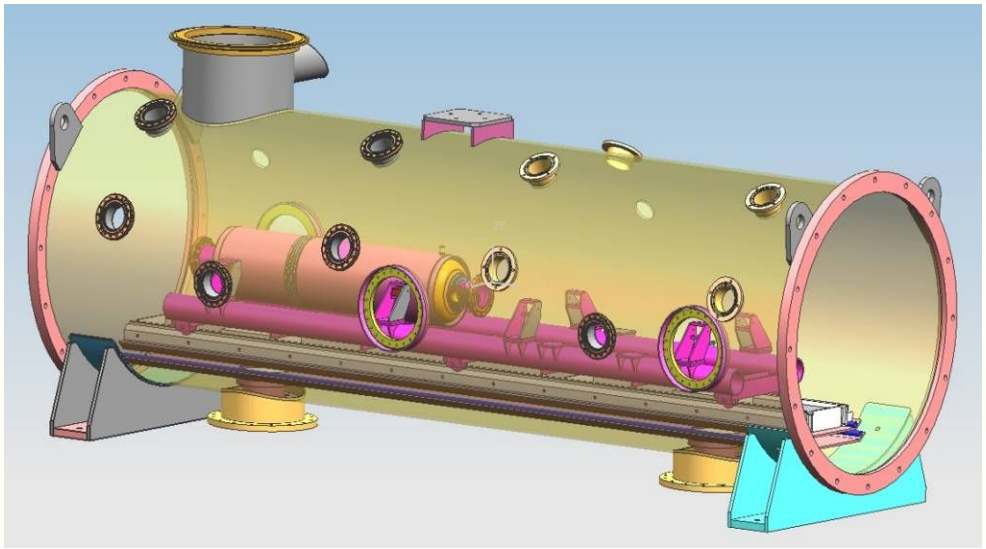
- **RRCAT has carried out design of the following:**
  - **Liquid Helium Vessel Shell**
  - **Liquid Helium Vessel Top Flange**
  - **Vacuum Vessel Shell**
  - **Vacuum Vessel Flange**
  - **Top Insert Plate**

- **RRCAT has also verified the design of following by Analysis**
  - **Assembly of LHe Vessel Top Flange, Weld Rim**
  - **Top Insert Plate**
  - **Assembly of Vacuum Vessel Flange, LHe Vessel Flange, Top Plate, Support Pads**
  - **Magnetic Shield design – 300K & 2K**

# Horizontal Test Stand (HTS-2)

- **Fermilab has fabricated and is operating the first US Horizontal Test Stand for 1.3 GHz elliptical cavities.**
- **Indian collaboration is designing an upgraded Horizontal Test Stand for Fermilab and RRCAT.**
  - **Test a combination of two cavities and/or magnet**
  - **650 MHz and 1300 MHz cavities**
  - **CW or pulse mode testing of cavities**
  - **Incorporating modifications based on operational experience of HTS-1**

**A 3-D model of the HTS-2 being designed**

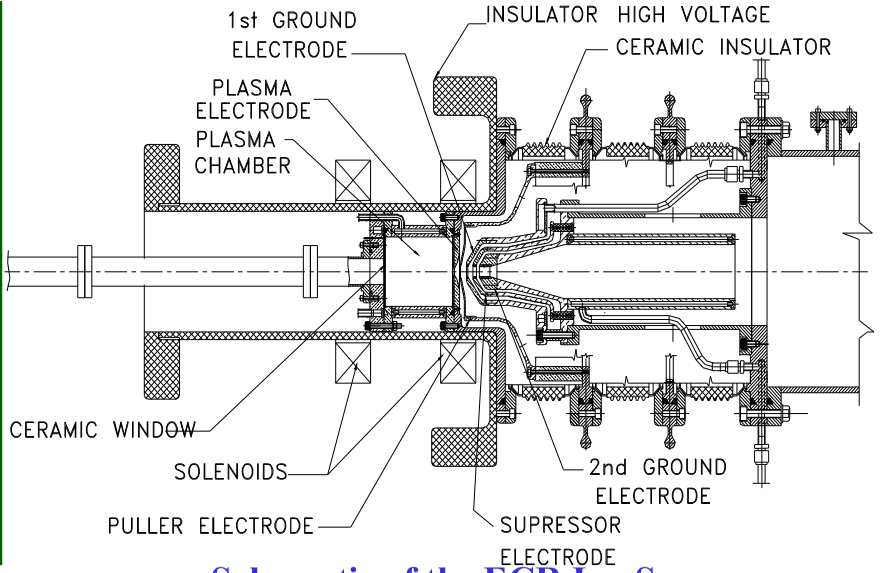


# Phase II: Discussions

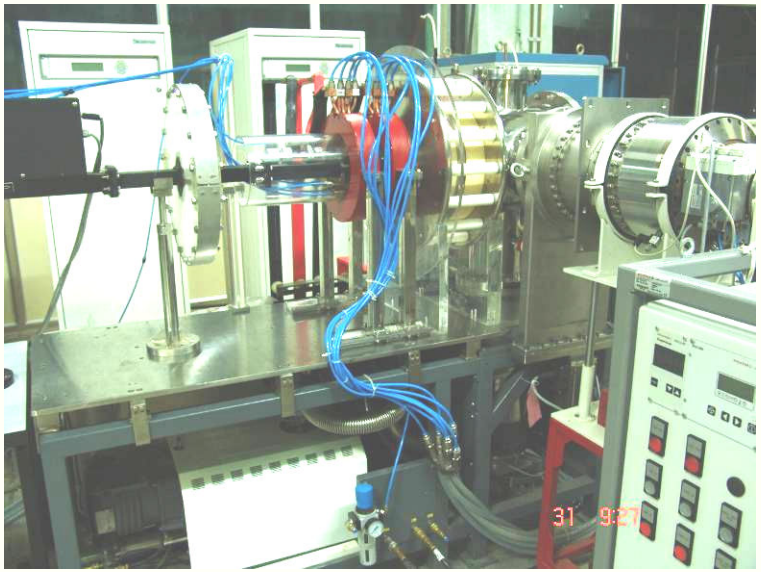
- The Phase II of this collaboration is under discussion. It is expected to expand the collaboration to all non SRF areas of Project-X
  - But it would be tied to the Phase III (construction of Project-X at Fermilab)
- Elements of Phase II: (Very Preliminary)
  - Front End: Source and RFQ
  - 325 MHz RF Power
  - Instrumentations and Controls
  - Superconducting Magnet
  - Cryogenics

# BARC: ECR Ion Source

- Five electrodes
- 2.45 GHz
- 50 keV
- 50 mA
- 0.02 π cm-mrad




Schematic of the ECR Ion Source

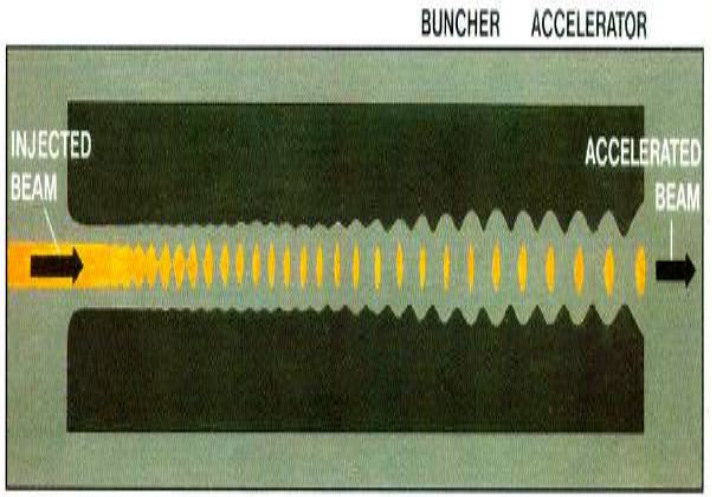


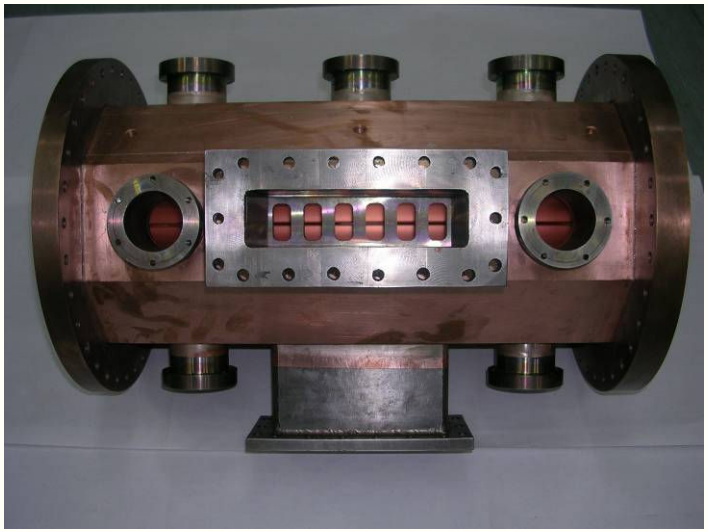
Ion source with 3 electrode extraction system made & Testing is in progress

# RFQ Parameters

1. Bunching 2. Focusing 3. Acceleration

| | |
|---|---|
| **Frequency** | **352.21 MHz** |
| **Energy** | **50 keV/ 3 MeV** |
| **Input current** | **30 mA** |
| **Vane voltage** | **80 kV** |
| **Avg. Aperture $R_0$** | **3.63-4.53 mm** |
| **Length** | **4 m** |
| **Total RF power** | **500 kW** |
| Transmission | 98% |



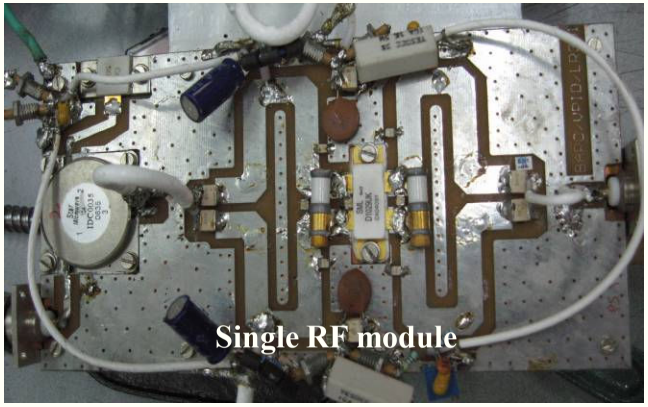
- **Design of a 325 MHz RFQ has started**

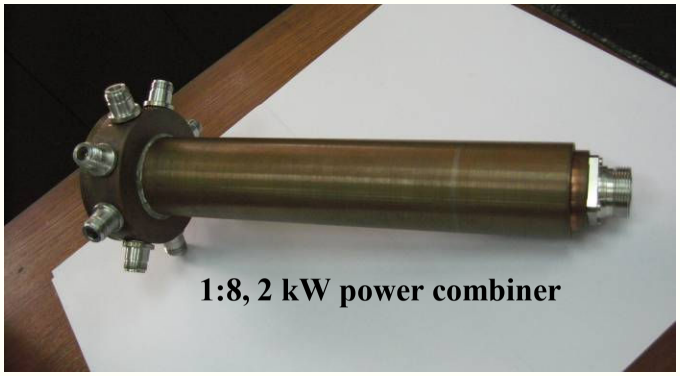
# BARC: 350 MHz, 700 W Solid-state Amplifier

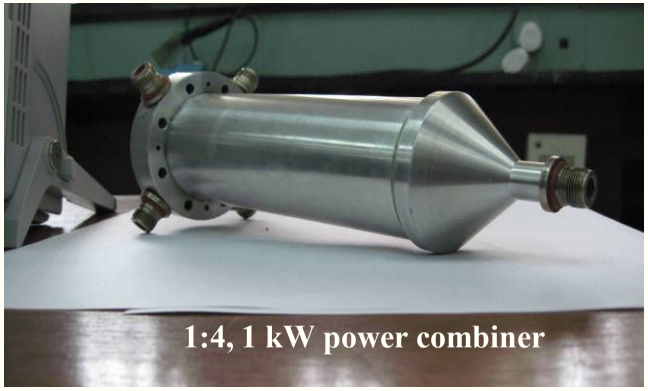
- **Total Power Gain : 20 dB**
- **3dB Band width : 10 MHz**
- **No. of modules : 4 plus 1 drive module**
- **Efficiency : 50%**
- **Devices LR301, DMD1029**
- **VSWR of each Module & Total amplifier : <1.2**

RF amplifier set up

- Wilkinson designed based power combiners /splitters at 2KW (1:8) and 1KW (1:4) power levels
- At 1KW, with transmission loss of < 7%.
- Return Loss :> 20dB at combining port and >13 dB at dividing ports
- Isolation >28 dB
- 8 modules test set-up for 2.5 kW is underway

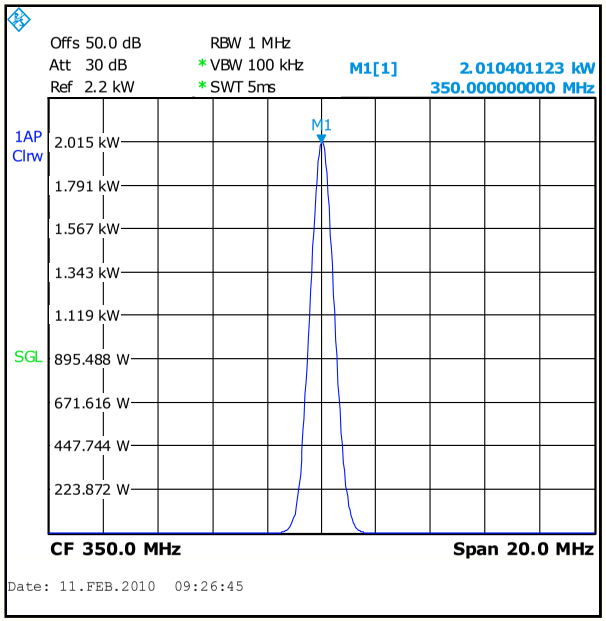

Single RF module


1:8, 2 kW power combiner


1:4, 1 kW power combiner

# New RF Driver: 350 MHz, 2.5 kW (CW and pulse mode) for 60 kW RF system

A new RF driver for 60 kW RF system has been developed based on tetrode TH 393. Efforts are being made to test it at $3^{+}$ kW (CW) level.



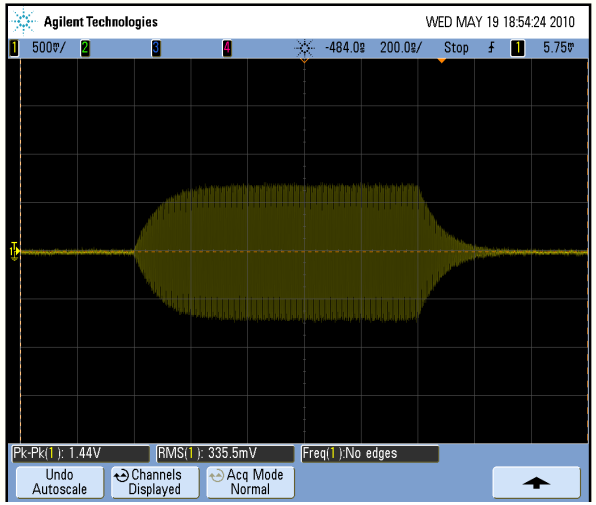

CW mode results:

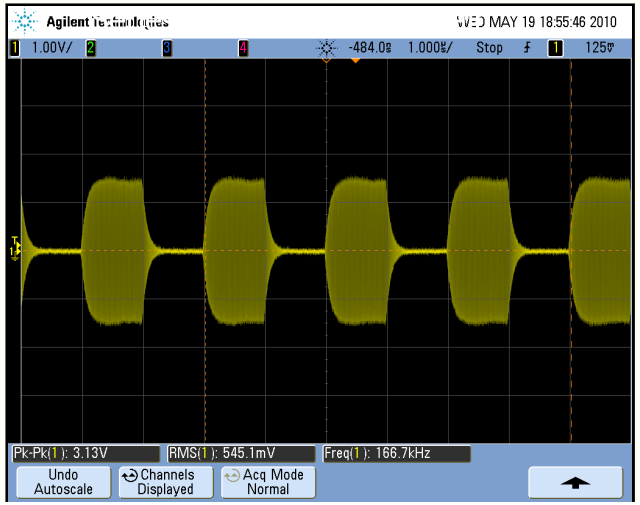
- Frequency: 350 MHz
- Power: 2000 $^{+}$ Watt (CW)
- Gain: 15 dB
- Efficiency: 56 %
- Class A
- Device: TH 393

The amplifier has been tested in pulse mode also.

**Pulsed Mode Results:**

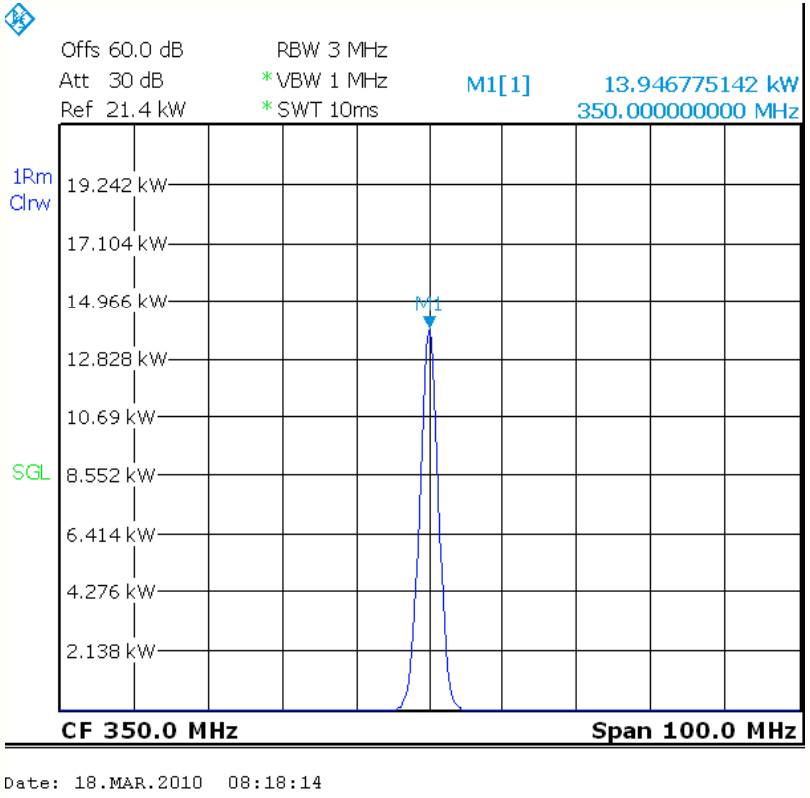
1. Center frequency: 350 MHz
2. Pulse width:1 mS
3. Pulse repetition rate: 100 Hz
4. Pulse power (pk):4 kW



# 350 MHz, 60 kW RF system for deuterium 400 KeV RFQ

**For 400 KeV ($D^+$) radio frequency quadrupole (RFQ) accelerator based Neutron Generator (pilot ADS project), the RF system has been tested upto 14 kW and efforts are in progress for 60 kW testing.**




**RF Power waveform on spectrum Analyzer**

**RF system set up (14 kW @ 350 MHz)**

# Collaboration on High Energy Physics

- **Indian institutions have been collaborating on Fermilab based High Energy Physics experiments since 1986.**
  - **Several students have received PhD from Indian universities while working on Fermilab experiments.**
- **Recently we have established a Neutrino Physics collaboration with India (Addendum IV)**
  - **Indian Institutions have joined MINOS, MIPP and LBNE**
  - **Students and faculties are contributing to the analysis**
    - **Several PhD thesis**
  - **Faculty and engineering staff are getting involved in design of future experiments.**
- **On the request of Indian DAE/DST**
  - **We are holding a joint interaction meeting in Jan 2011 to discuss collaboration on all aspect of Project-X Physics**
  - **Tie Accelerator contribution to physics participation**

# What Next

- **The magnitude of the Phase III is very large and the regulations are very complicated.**
  - **DOE and DAE are negotiating this**

We are the US we …

Critical Technology

Non-precertification

Inspection

Making a Bridge

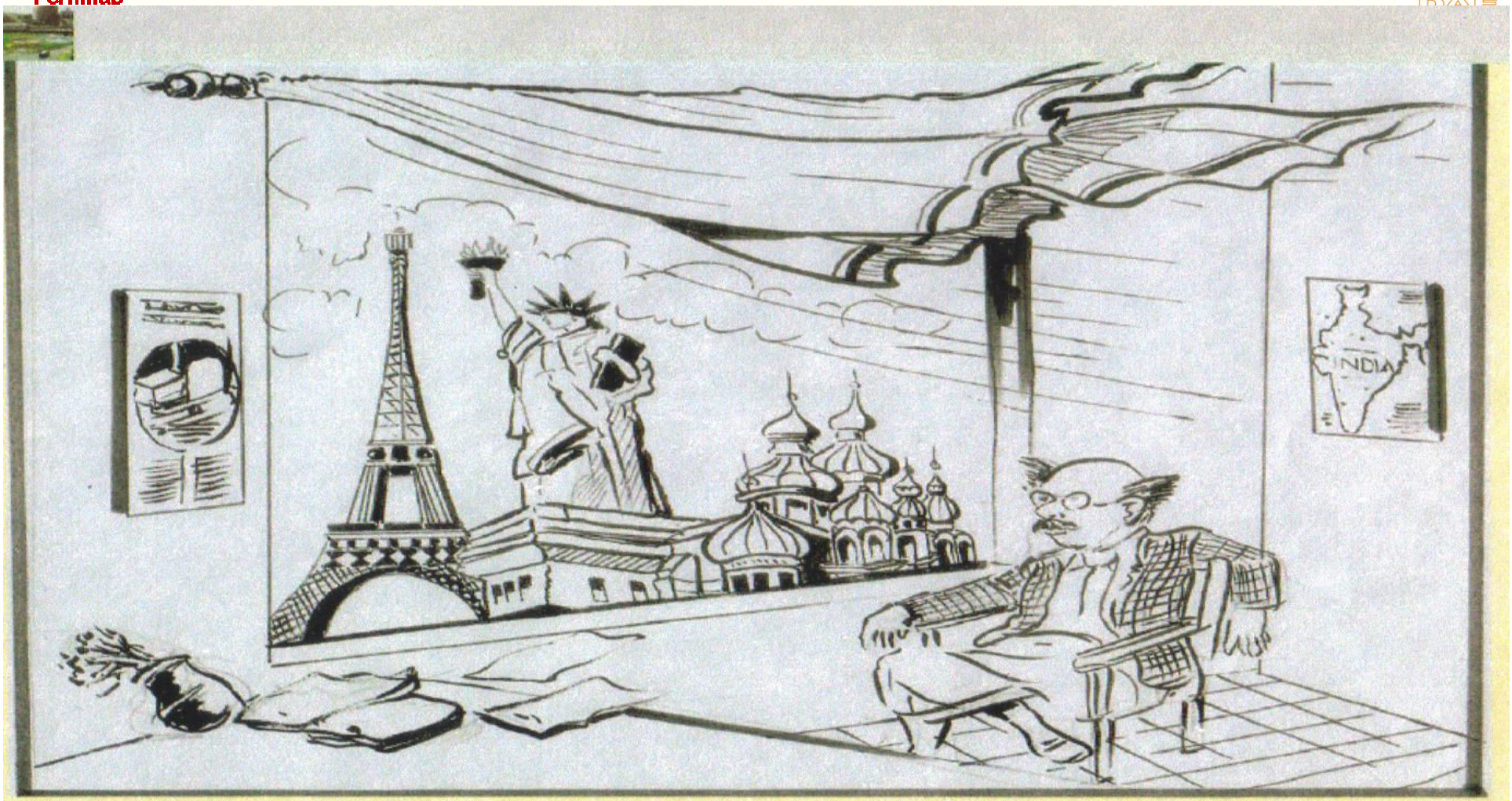
Will you follow through

CERN/DESY

Our records are clean

Strategic R&D center

# Wind of Change




*I do not want my house to be walled in on all sides and my windows to be stuffed. I want the cultures of all the lands to be blown about my house as freely as possible. But I refuse to be blown off my feet by any.*

*- Mahatma Gandhi*