

The New Frontier: India-Fermilab

Shekhar Mishra
International Collaboration Coordinator



U.S. DEPARTMENT OF
ENERGY

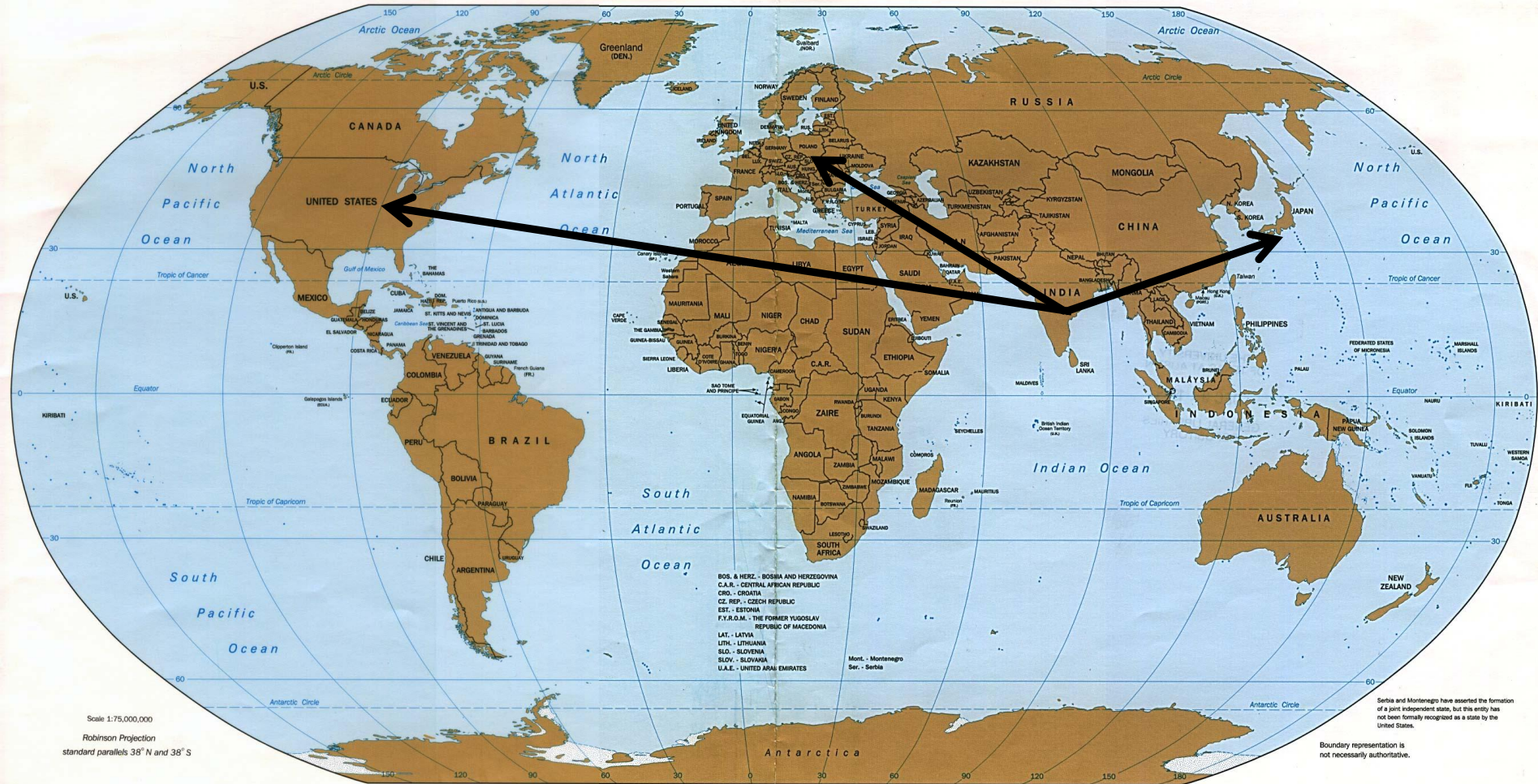


 **Fermilab**



India and the HEP/NP World

Political Map of the World



Indian Institutions Collaborates with
International Laboratories



The International Laboratory



India



Fermilab Accelerator Complex: Vision





Message



Get Our scientists excited

Collaboration must
leapfrog Indian program
and Interest

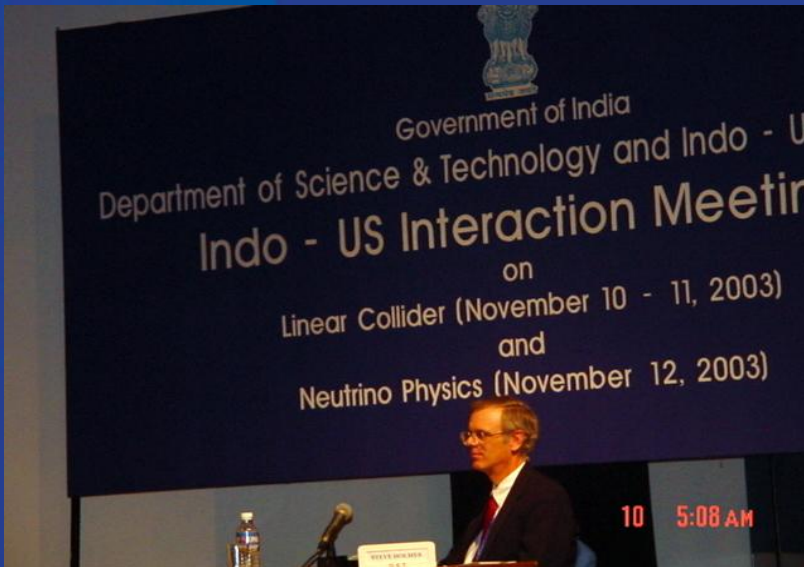


Training of future
scientist is a must



1st Indo-US Interaction Meeting

- 1st Indo-US Interaction meeting, Nov. 2003, New Delhi.
 - Supported by High level Indian and US government & management
 - 19 US physicists and 70+ Indian Scientists participated.
 - US-India discussed accelerator and neutrino physics collaboration
 - Working group formed to develop collaboration
- Outcome:
 - Indian science management and Fermilab agreed to develop a new collaboration in HEP

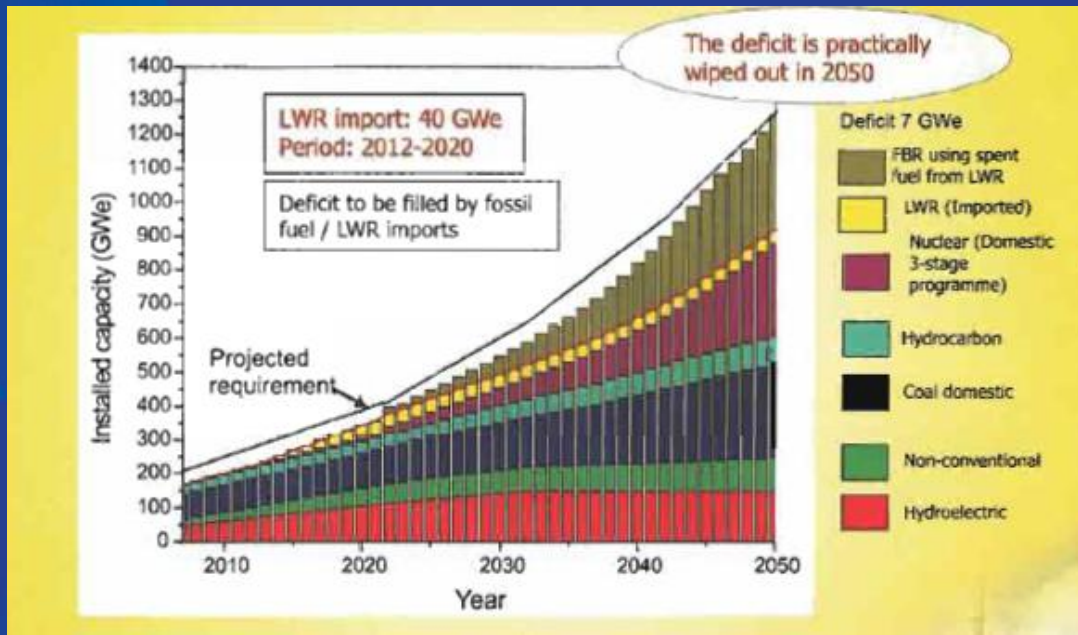


2003-06: Indian and Fermilab scientists visited institutions to understand and evaluate strengths



Indian Interest in Fermilab

- In 1950's Bhabha presented a vision that included a 3 Stage Domestic Nuclear Program for India.
 - High Intensity CW Proton Accelerator
- The current growth in Indian economy and its technical strength provides an **“Opportunity”** for realizing this vision.
 - But India needs efficient accelerator technology
- Physics experiments at Fermilab
 - Training of technical manpower

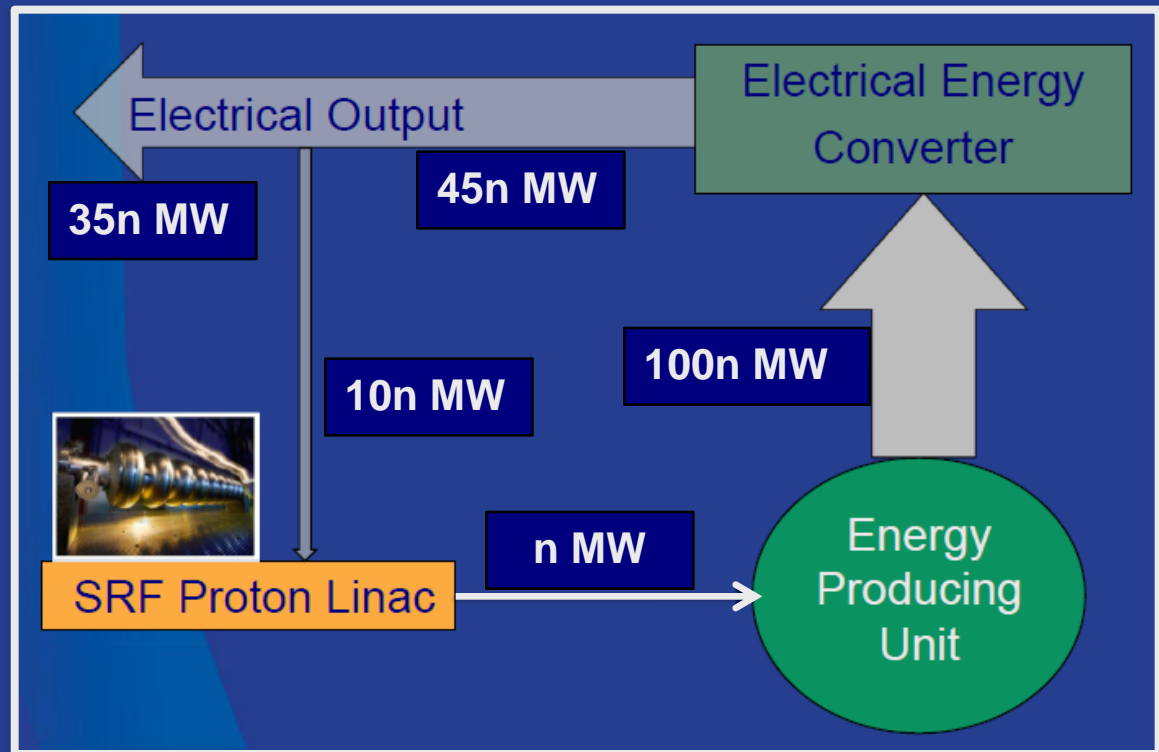


Indian Energy Vision



Indian Next 15+ yrs Strategy

1 GeV,
Continuous Wave,
High Intensity, Proton,
Superconducting
Radio Frequency,
Accelerator:
Fermilab



- A multi-MW Proton Source:
 - 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.

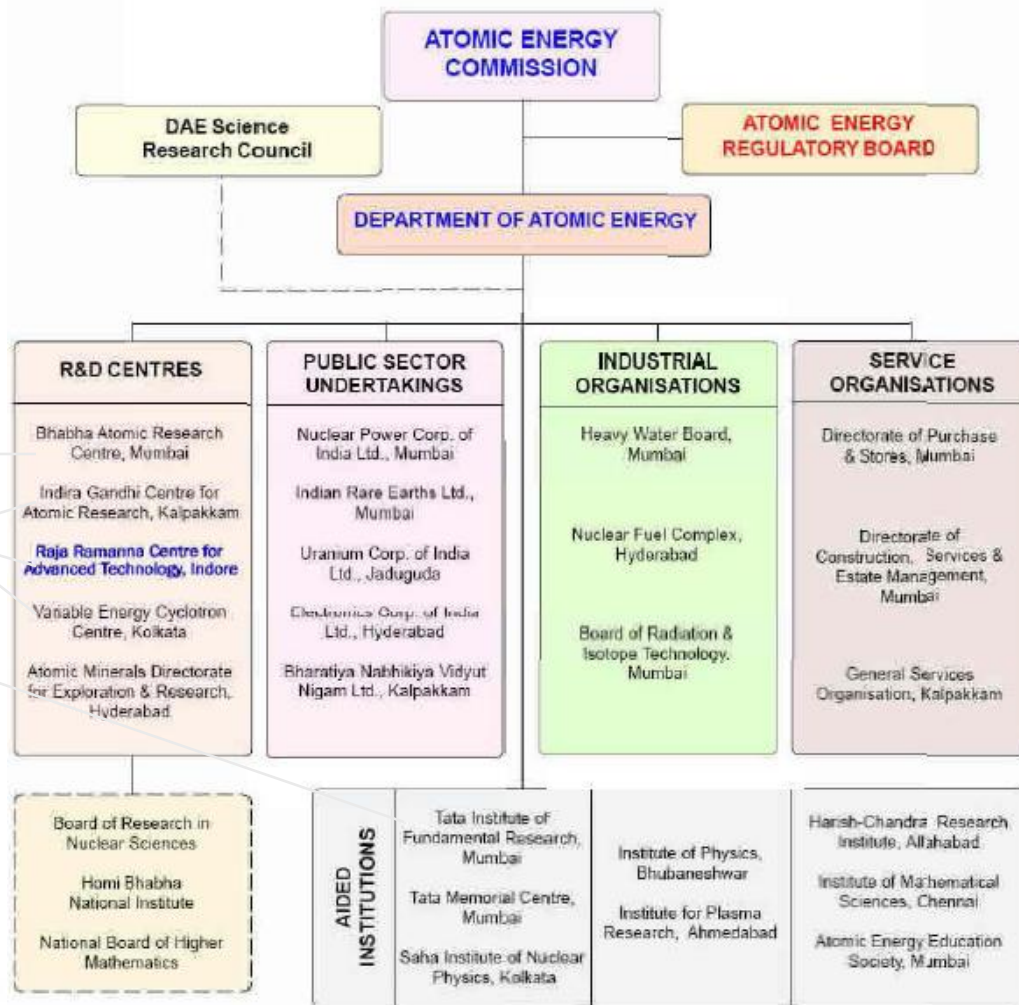


Indian DAE

Atomic Energy Establishments in India

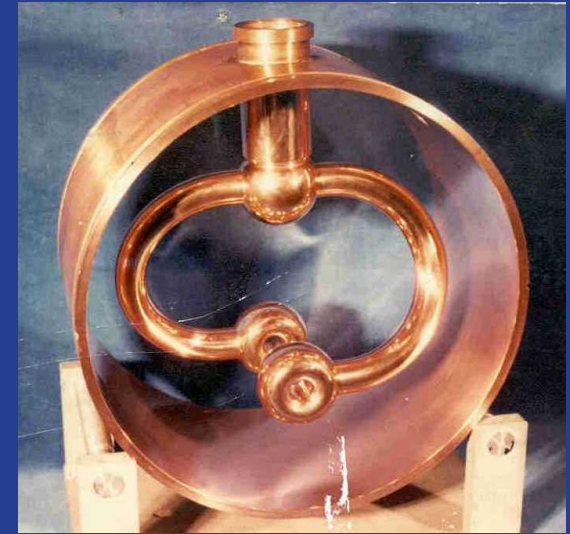
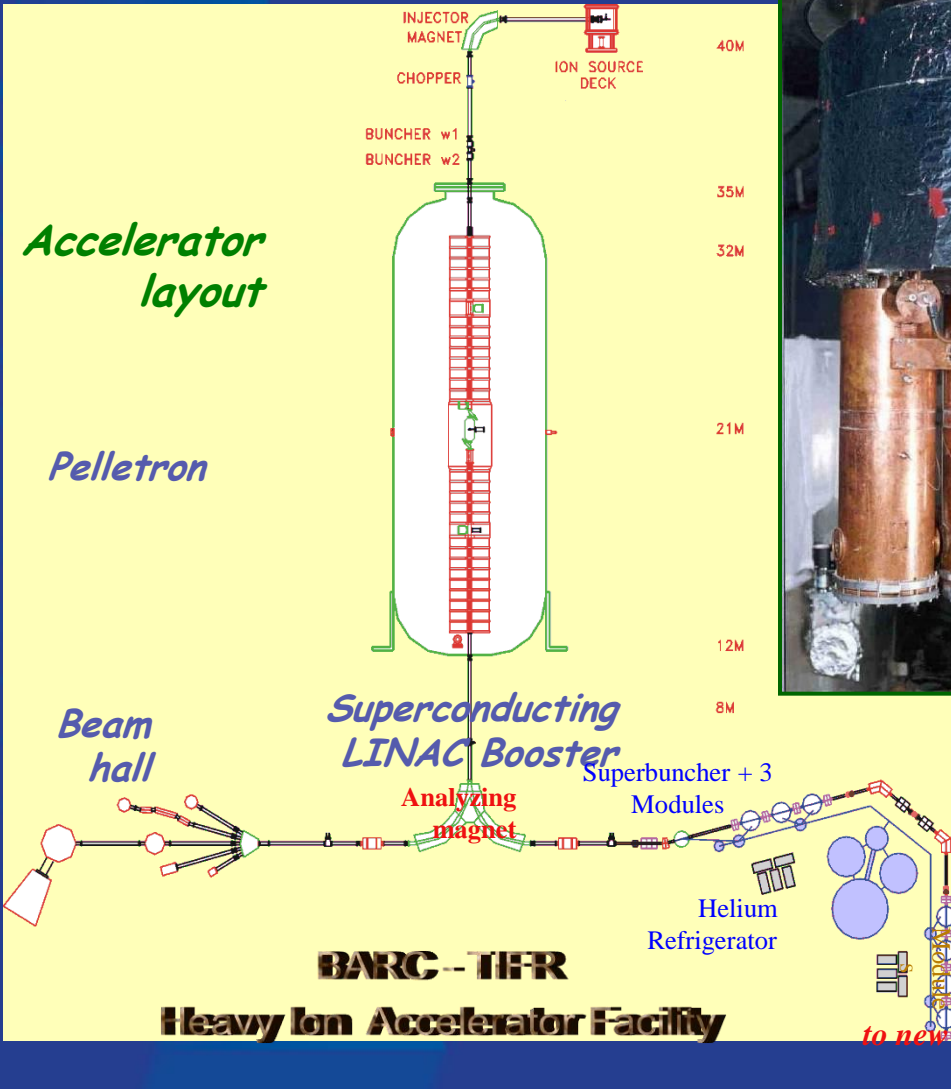


DAE Organisational Chart





BARC-TIFR: Heavy Ion Accelerator





BARC: Accelerator Development for NE

High current injector 20 MeV, 30 mA

Proton IS
50 keV

RFQ
3 MeV

DTL
20 MeV

Phase I

Normal Conducting

DTL/
CCDTL

Phase II

Super-
conducting

100 MeV

Phase III

SC
Linac

1 GeV

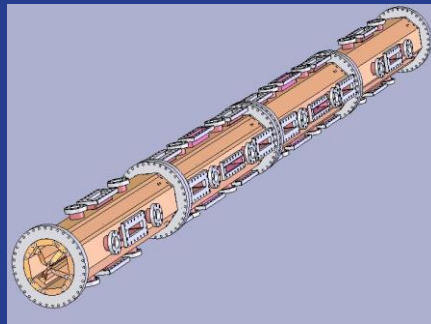
Proton beam from
high power
accelerator

Design completed and fabrication is in progress

ECR Ion Source

RFQ

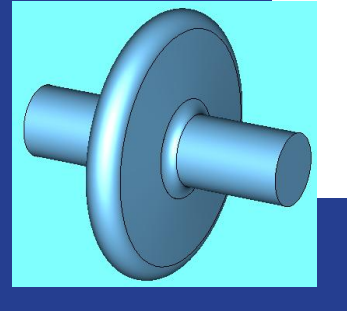
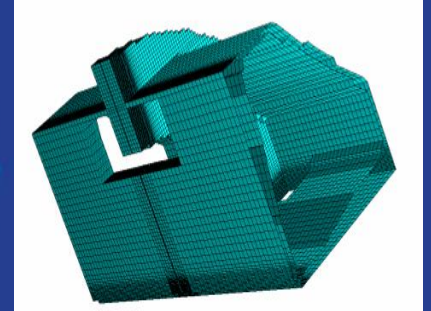
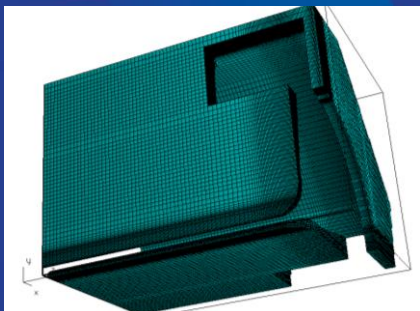
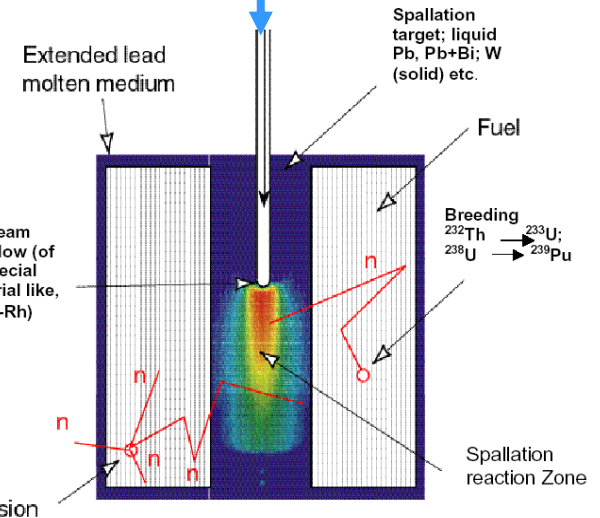
DTL



Beginning/End Cell

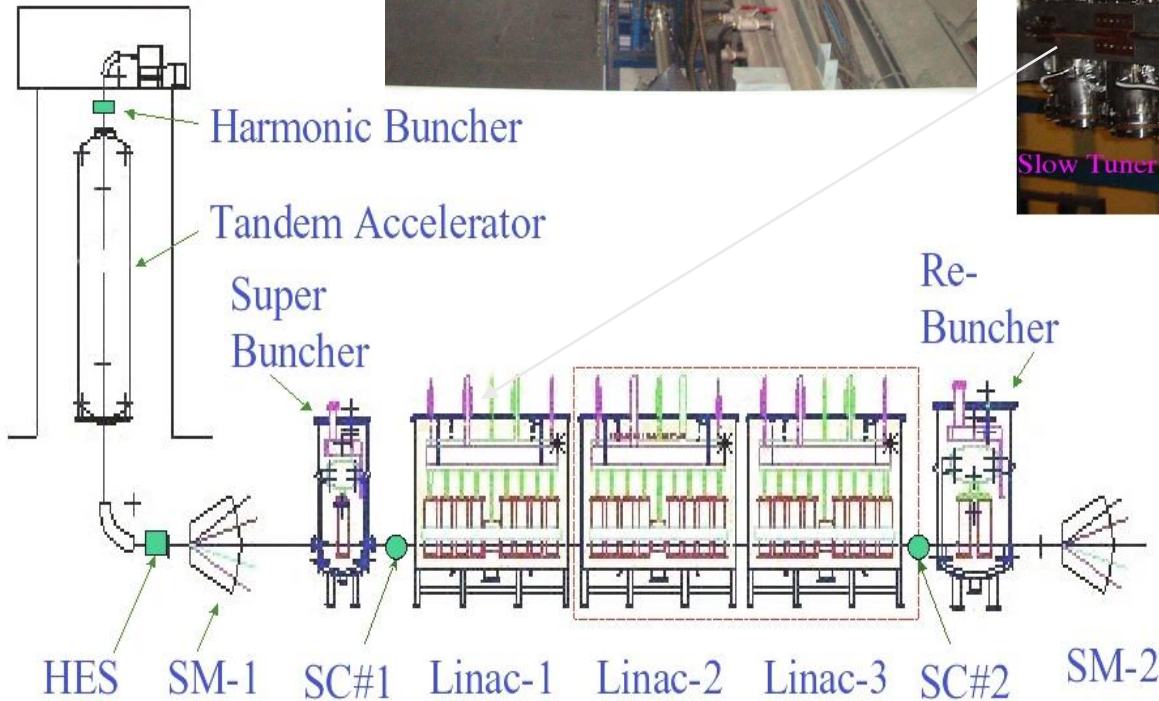
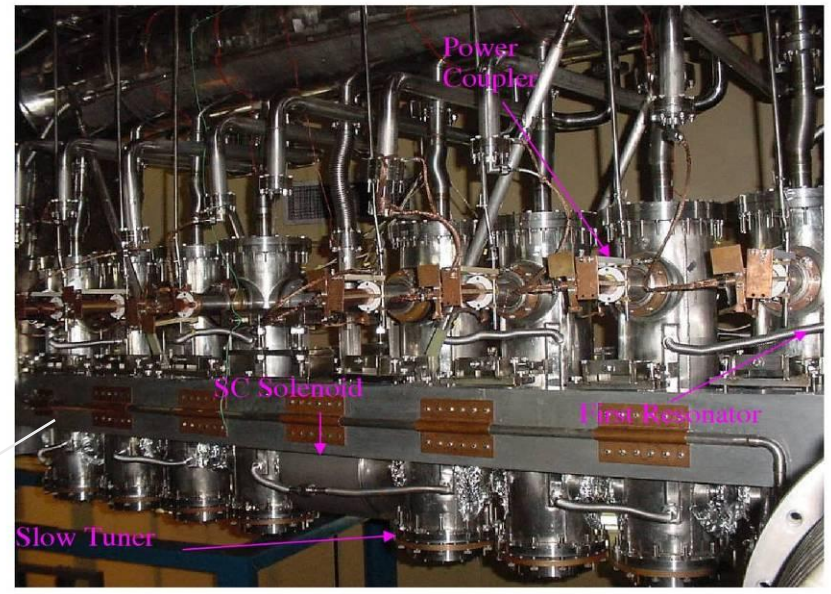
Coupling Cell

Elliptical SC Cavity





IUAC: Pelletron and SRF Linac

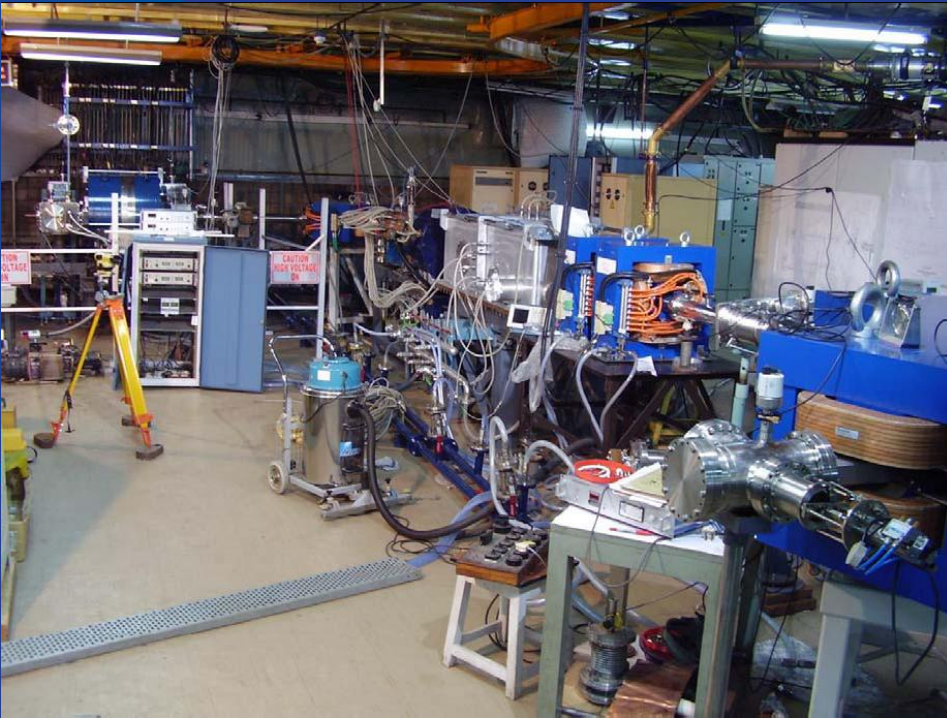


Upgrade to ECR
based High Current
Injector



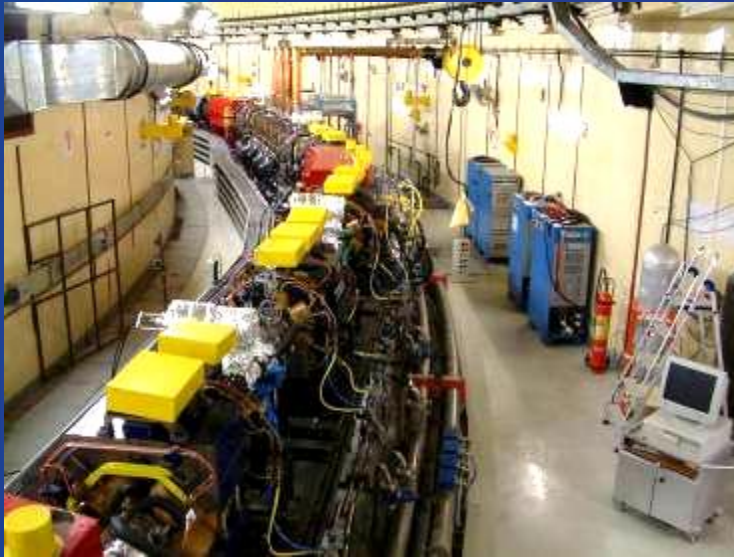
VECC: Nuclear Physics

- Superconducting Cyclotron
- Radioactive Ion Beam Facility
- 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



Institutes to Institutes MOU: Jan 2006

Memorandum of Understanding

between

US Universities & Accelerator Laboratories

and

Indian Universities & Accelerator Laboratories

concerning

Collaboration on R&D for Various Accelerator Physics and High Energy Physics Projects

January 9, 2006

The following concur on the terms of the original MOU and outlined in the extension of the Memorandum of Understanding.

T. R. Sinha
Dr. Ratan Kumar Sinha
Director, BARC
Date: 30-01-2012

R. B. Bhandari
Dr. Rakesh Kumar Bhandari
Director, VECC
Date: 24/3/2012

P. D. Gupta
Dr. P. D. Gupta
Director, RRCAT
Date: 30-01-2012

M. Barma
Prof. Mustansir Barma
Director, TIFR
Date: 2/3/2012

M. Sanyal
Dr. Milan Sanyal
Director, SINP
Date: 23/3/2012

Piermaria Oddone
Dr. Piermaria Oddone
Director, FNAL
Date: 1/19/12

S. Mishra
Dr. Shekhar Mishra
Project-X, Co-Chair IIFC
Fermilab
Date: 1/19/12



4.2 Approvals

The following concur in the terms of this Memorandum of Understanding:

Piermaria Oddone
Piermaria Oddone, Director, FNAL

Date: 1/9/05

Jonathon Dorfman
Jonathon Dorfman, Director, SLAC

Date: 1/23/06

Christoph Lee
Christoph Lee, Director, TJNAJ

Date: 1/18/06

Maury Tigner
Maury Tigner, Director, Newman Lab

Date:

Date:

Date:

Date:

Date:

Date:

Vinod C. Sahni
Vinod C. Sahni, Director, CAT

Date: March 8, 2006

Bikash Sinha
Bikash Sinha, Director, VECC

Date: March 9, 2006

Amit Roy
Amit Roy, Director, IUAC

Date: March 9, 2006

S. Bhattacharya
S. Bhattacharya, Director, TIFR

Date: April 17, 2006

Srikanth Banerjee
S. Banerjee, Director, BARC

Date: March 14, 2006

Deepak Pental
Deepak Pental, Vice Chancellor, DU

Date: April 10, 2006

Date:



2006-7: Technical Work

- BARC and RRCAT physicists and engineers visited Fermilab to discuss details of technical collaboration.

Focused on Cavity Development Accelerator Physics

ADDENDUM

to the

Memorandum of Understanding

between

US Universities & Accelerator Laboratories

and

Indian Universities & Accelerator Laboratories

concerning

Collaboration on R&D for Accelerator Physics and High Energy Physics
Projects

Addendum I: "Fermilab, RRCAT, BARC, IUAC and VECC Collaboration
on ILC Main Linac SRF Accelerator Technology R&D"

October 2, 2007

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

Dr Vinod C. Sahni,
Director, RRCAT

Oct 2, 2007
Date

Dr. Piermaria Oddone
Director, FNAL

10/2/07
Date

Dr. Shekhar Mishra
Deputy ILC Program Director, FNAL





2008: Fermilab ↔ India



Fermi National Accelerator Laboratory
P.O.Box 500 • Batavia, IL • 60510-0500
630-840-3211 FAX 630-840-2900

Director's Office

January 4, 2008
(By E-Mail and Facsimile)

Dr. Anil Kakodkar
Chairman, Atomic Energy Commission of India
Secretary, Department of Atomic Energy
Anushakti Bhavan
CSM Marg
Mumbai – 400001, India

Dr. Pier Oddone, in a letter to Dr. Anil Kakodkar, Secretary, DAE invited India to collaborate on High Intensity Proton Accelerator: **Project X**

Fermilab that would provide discovery opportunities in the next two to three decades. The

I have asked Shekhar Mishra to provide you with additional technical details on the present collaborative efforts, Project-X R&D and its commonality with Indian accelerator programs, when he meets you on Jan 15th.

Sincerely,

Piermaria J. Oddone,
Laboratory Director



सर्वे भद्राणि सुकुरुते
भारत सरकार
Government of India

डॉ. अनिल काकोडकर
Dr. Anil Kakodkar

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

No. 22 -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

Dr. Kakodkar sent a very positive response: Requesting development of a "Phased Collaboration Plan"

With best regards,

Yours sincerely,

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





2009: Indian Institutions and Fermilab

- Jan 2009, During the signing of the Addendum MOU III at Indore, Dr. Kakodkar and Dr. Oddone agreed on the
 - Concept of “Total Project Collaboration”
 - Fermilab changed the HIPA design to CW



- Indian Institutions and Fermilab Collaboration also established MOUs to join Neutrino Physics experiments at Fermilab
 - MINOS/MINOS+
 - NOvA
 - LBNE



Banerjee: Discovery Science

- Dr. Banerjee in May 2010, charged the IIFC to prepare a plan that would expand the accelerator collaboration to include physics collaboration with Fermilab.
 - The program should be rich in Physics
 - Indian contribution should be significant and DAE-DST Ownership
 - Contribution should have synergy with interest and expertise in India
 - Development of Indian manpower, laboratory and industrial infrastructure
- The collaboration has developed such a program and was submitted to DAE in 2011.



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 R&D

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।

श्रीकुमार बनर्जी
भारत गणराज्य के परमाणु ऊर्जा की ओर से

संयुक्त राज्य अमेरिका के ऊर्जा विभाग की ओर से
विभाग

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.**

<http://www.state.gov/r/pa/prs/ps/2011/07/168740.htm>





Technical work under MOU

Covering all aspects of Project X, Indian Accelerators and Fermilab Neutrino Program

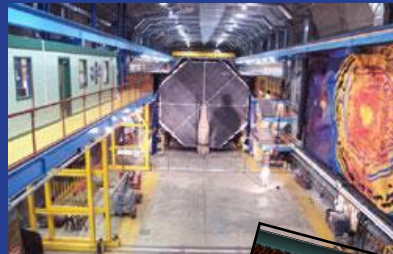
1. "Fermilab and Indian Accelerator Laboratories Collaboration on Neutrino Physics, Related Experiments and Detector Development" (Signed on: November 2008)
2. "SLAC and Indian Accelerator Laboratories Collaboration on Neutrino Physics, Related Experiments and Detector Development" (Signed on: November 2008)
3. "Fermilab and Indian Accelerator Laboratories Collaboration on Neutrino Physics, Related Experiments and Detector Development" (Signed on: November 2008)
4. "US and Indian Institutions Collaboration on Neutrino Physics, Related Experiments and Detector Development" (Signed on: November 2008)
5. "Fermilab and Indian Accelerator Laboratories High Intensity Proton Accelerator" (Signed on: August 2011)
6. "Fermilab and Indian Accelerator Laboratories High Intensity Proton Accelerator" (Signed on: August 2011)
7. "Fermilab and Indian Accelerator Laboratories High Intensity Proton Accelerator" (Signed on: August 2011)
8. "Fermilab and Indian Accelerator Laboratories High Intensity Proton Accelerator" (Signed on: August 2011)





Indian Institutions at Fermilab

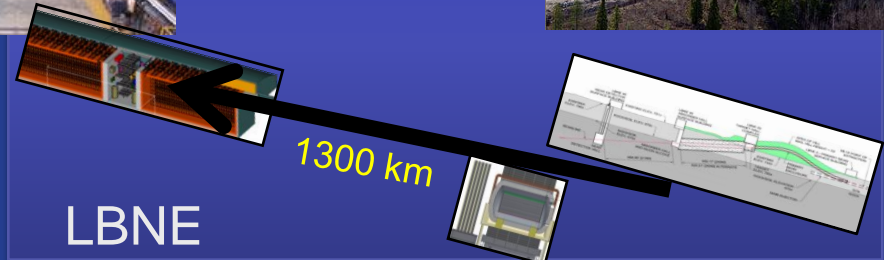
Before 2006



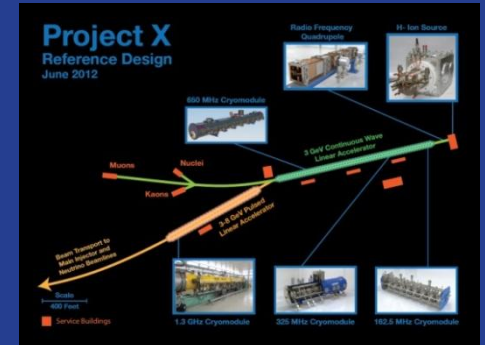
Now



+



LBNE



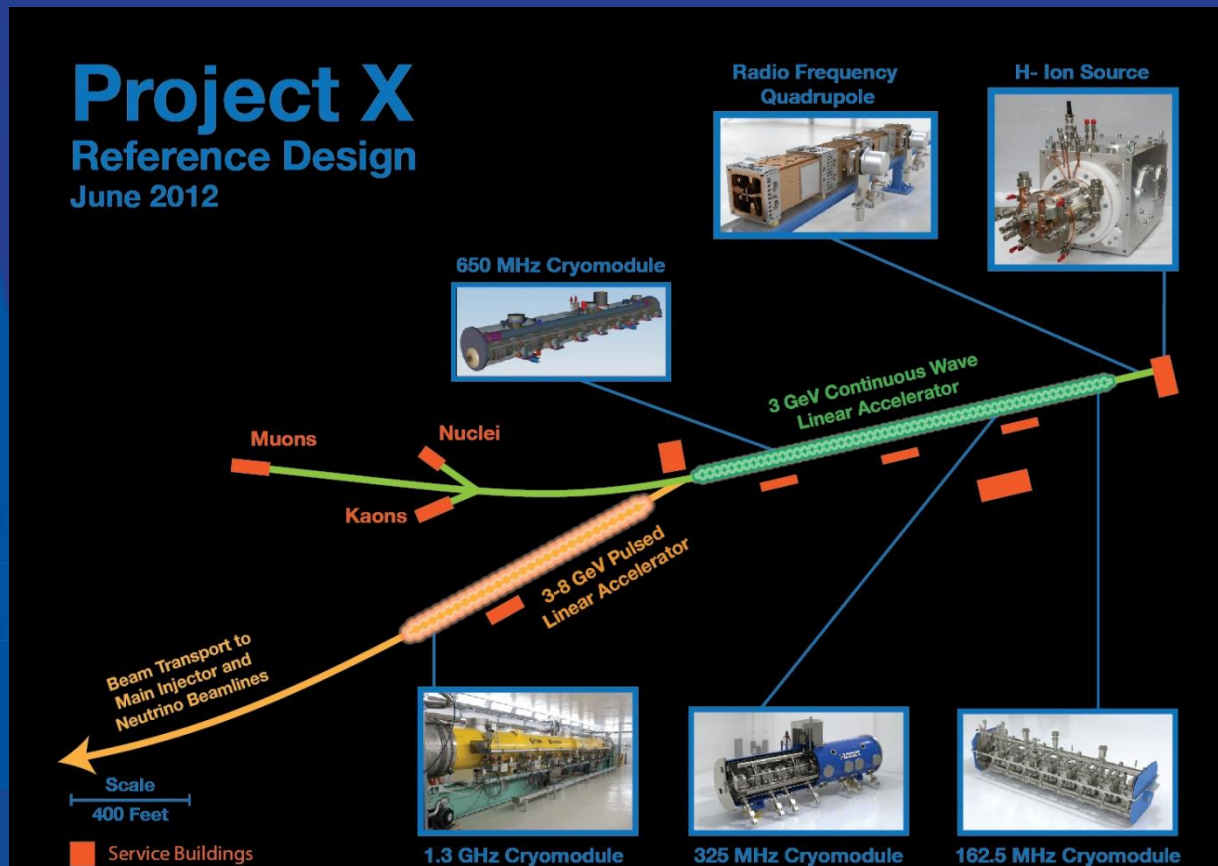
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DOE: Fermilab Project X

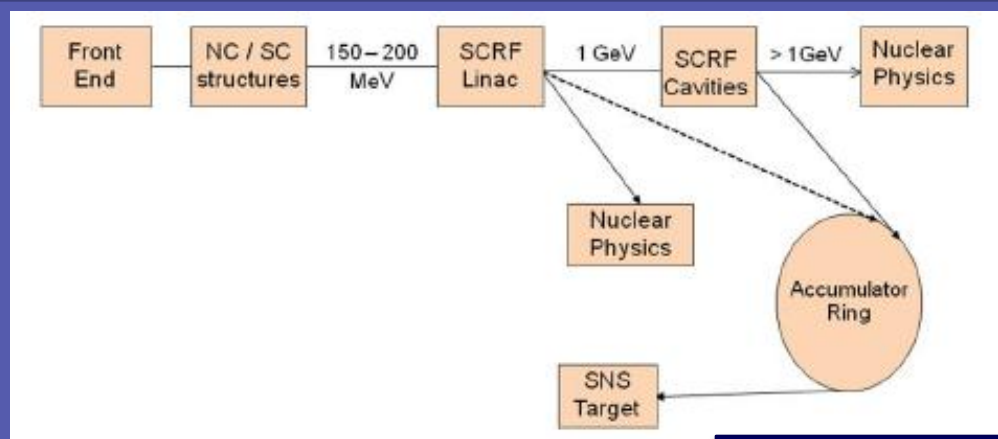
- Fermilab has proposed the construction of a Superconducting Radio Frequency linac to support the High Intensity Physics mission of the US-DOE
 - Indian DAE laboratories are collaborating in this program





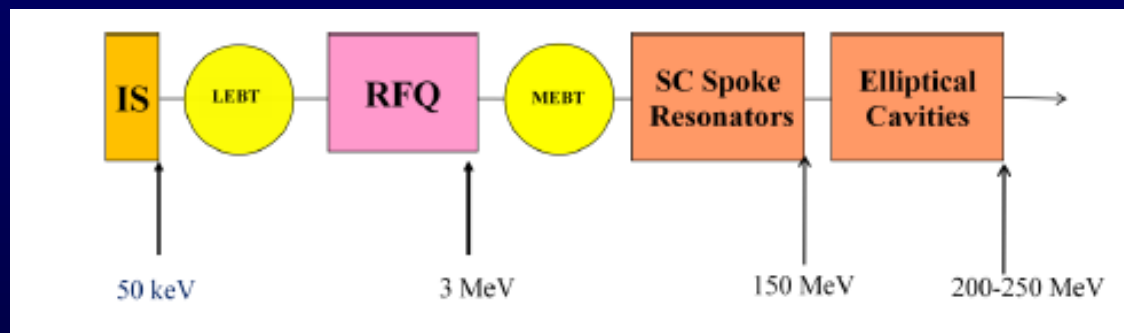
DAE: BARC & RRCAT

- DAE laboratories (RRCAT and BARC) in collaboration with other DAE laboratories and Fermilab have proposed
 - Physics Studies and Enabling Technology Development for Ion Accelerators, a CW SRF Linac
 - High Power Proton LINAC Based Spallation Neutron Source



RRCAT

BARC





Fermilab – DAE Laboratories R&D

- Indian DAE laboratories are now working on all major components of 3 GeV CW linac.
 - In some cases they are leading the R&D with Fermilab specifications.

IUAC:

- SSR1

VECC:

- SSR1 Dressing,
- 325 MHz CM components
 $\beta=0.6$, 650 MHz, Cavity
Dressing, Magnet etc

BARC:

- SSR2 and CM components

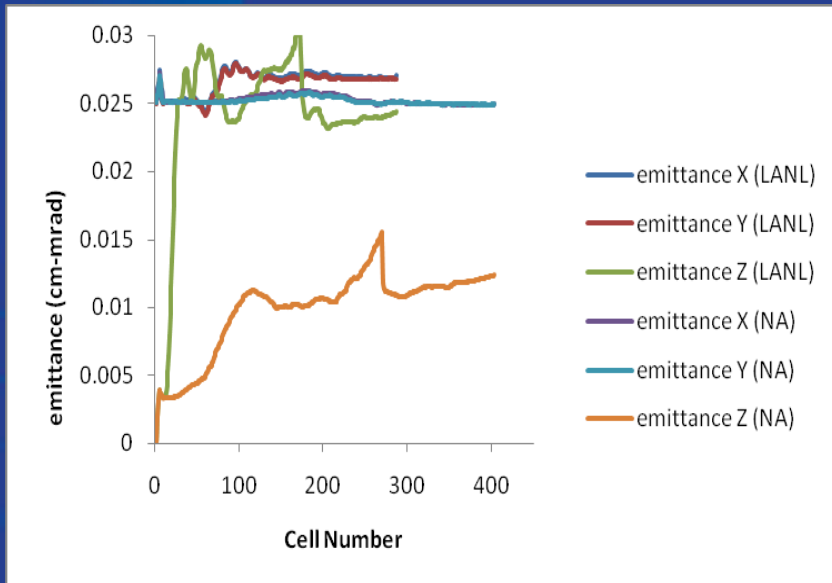
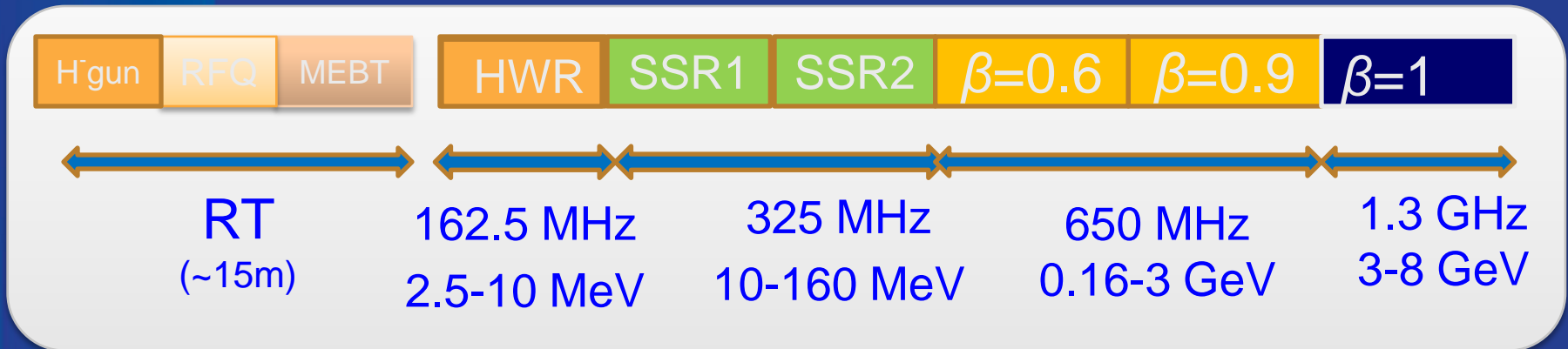
- 325 MHz RF Power
- 325 MHz power coupler
- BPM, LLRF
- Controls

RRCAT:

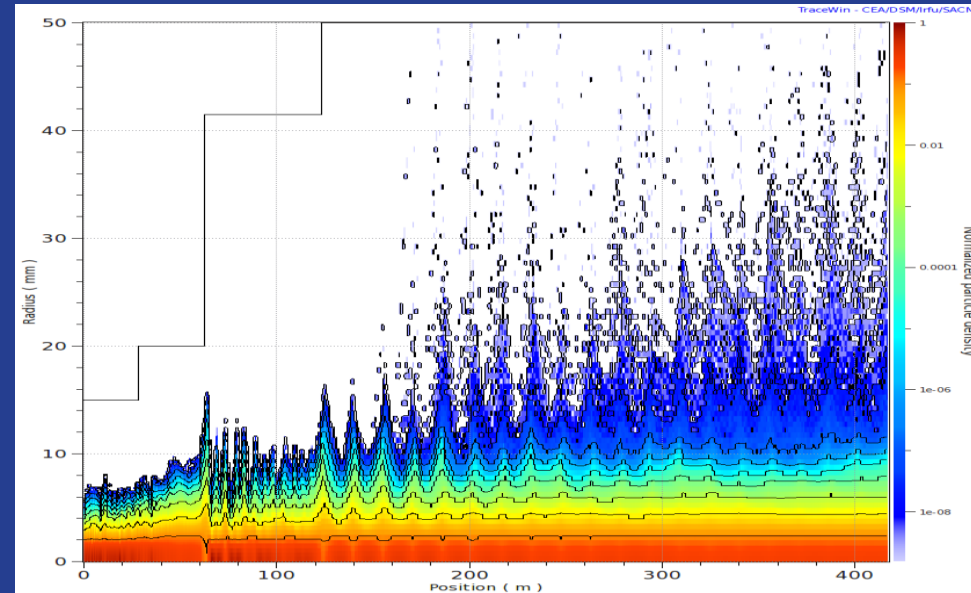
- $\beta=0.9$, 650 MHz Cavity
Dressing, Magnet etc
- 650 MHz RF Power



Project X: IFC Accelerator Design



Evolution of emittances RFQ

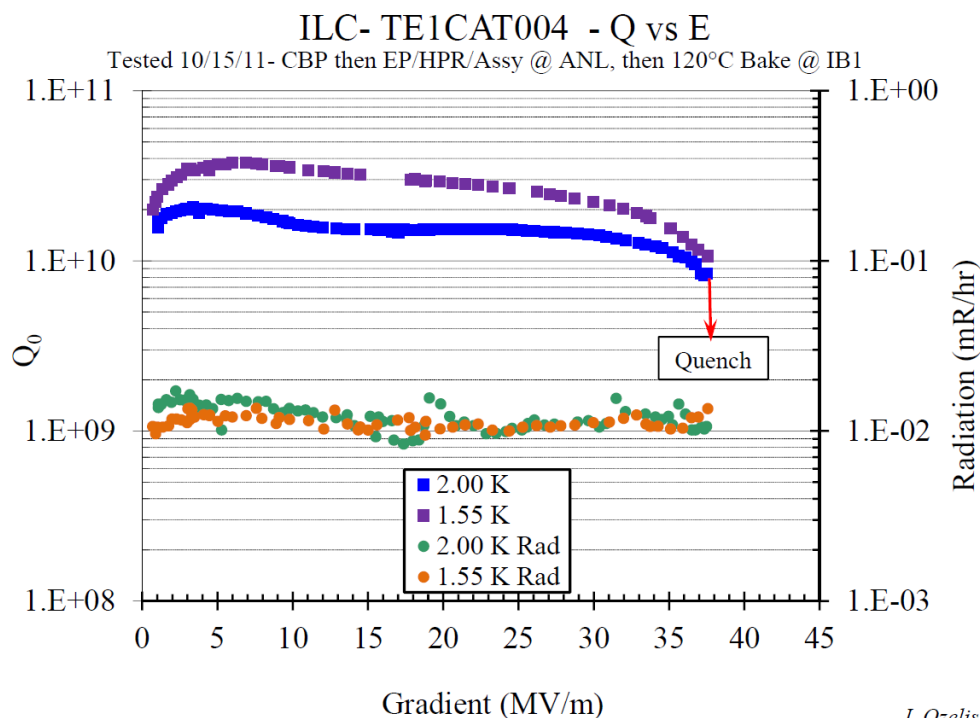
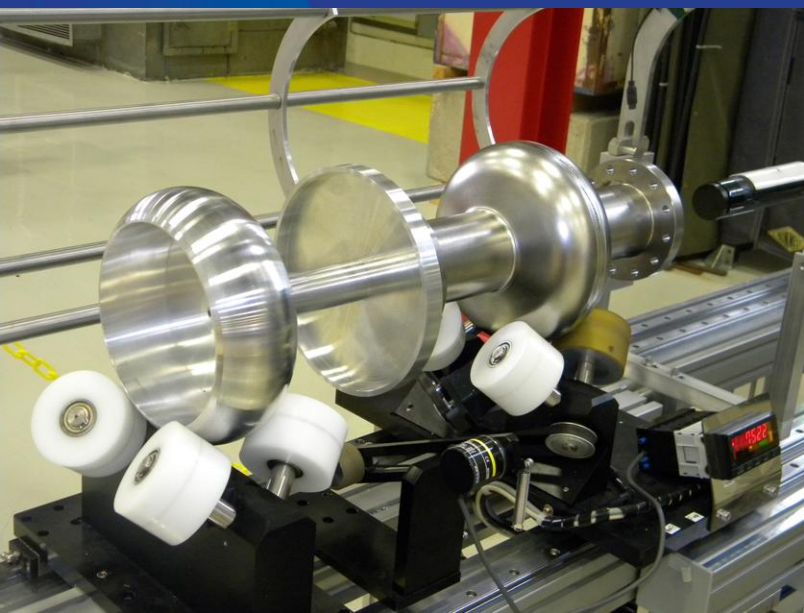
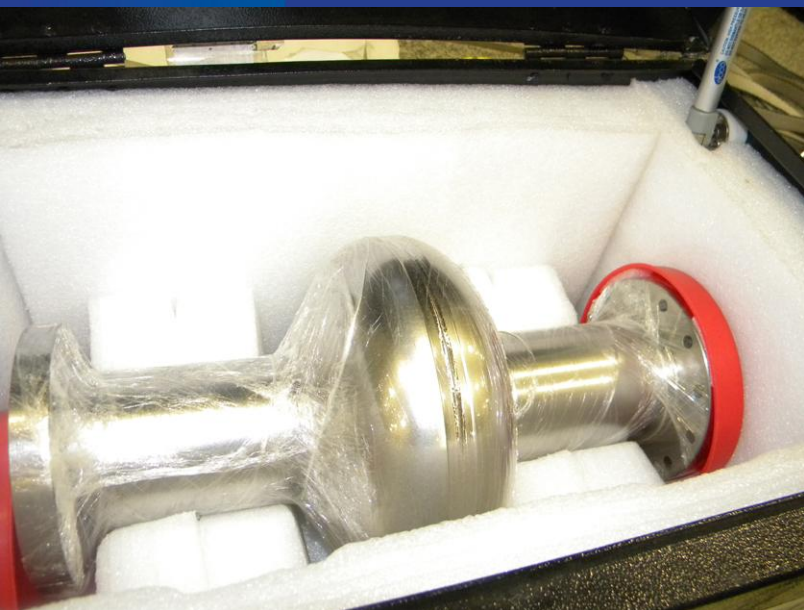


Beam envelope 2x all errors



1.3 GHz Cavity Development

- Fabrication of cavity at RRCAT in collaboration with IUAC
- Processing and testing at FNAL/ANL





325 MHz, SSR1 Cavity IUAC

- IUAC, New Delhi has developed tooling for the fabrication of SSR1 cavities. The built to print cavity drawings were provided by Fermilab.

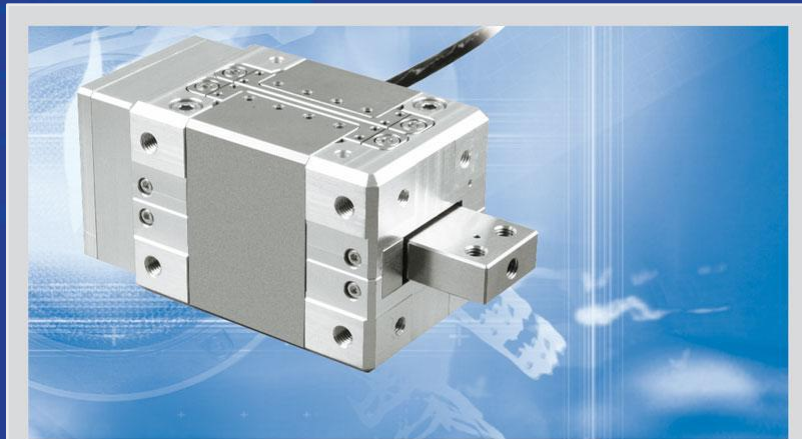
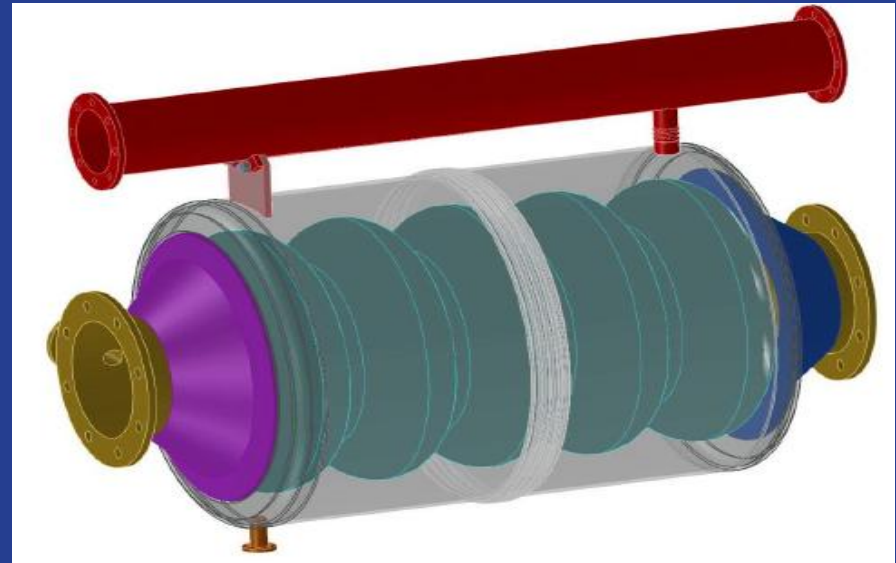


BARC has initiated work on SSR2



$\beta=0.6$, 650 MHz Cavity

- VECC, Kolkata is working on design, fabrication and testing of $\beta = 0.6$ cavity for Project-X.





$\beta=0.9$, 650 MHz RRCAT Progress

- 650 MHz $\beta=0.9$ 1-cell and 5-cell cavities to be built, based on experienced gained from 1.3 GHz work at RRCAT and IUAC.



Die- Punch Set at RRCAT



Aluminum blank, 3mm thickness



Die-Punch Set mounted on Press at RRCAT



Beginning of forming trials with  Fermilab



e-beam → Laser Welding

- RRCAT has significant expertise in laser. They have proposed to use laser to weld Nb cavities, replacing very delicate and expensive e-beam



Indigenously developed Laser System
By SSRL, RRCAT for this task



Laser welded half cells of SC Cavity
at CMEL, RRCAT



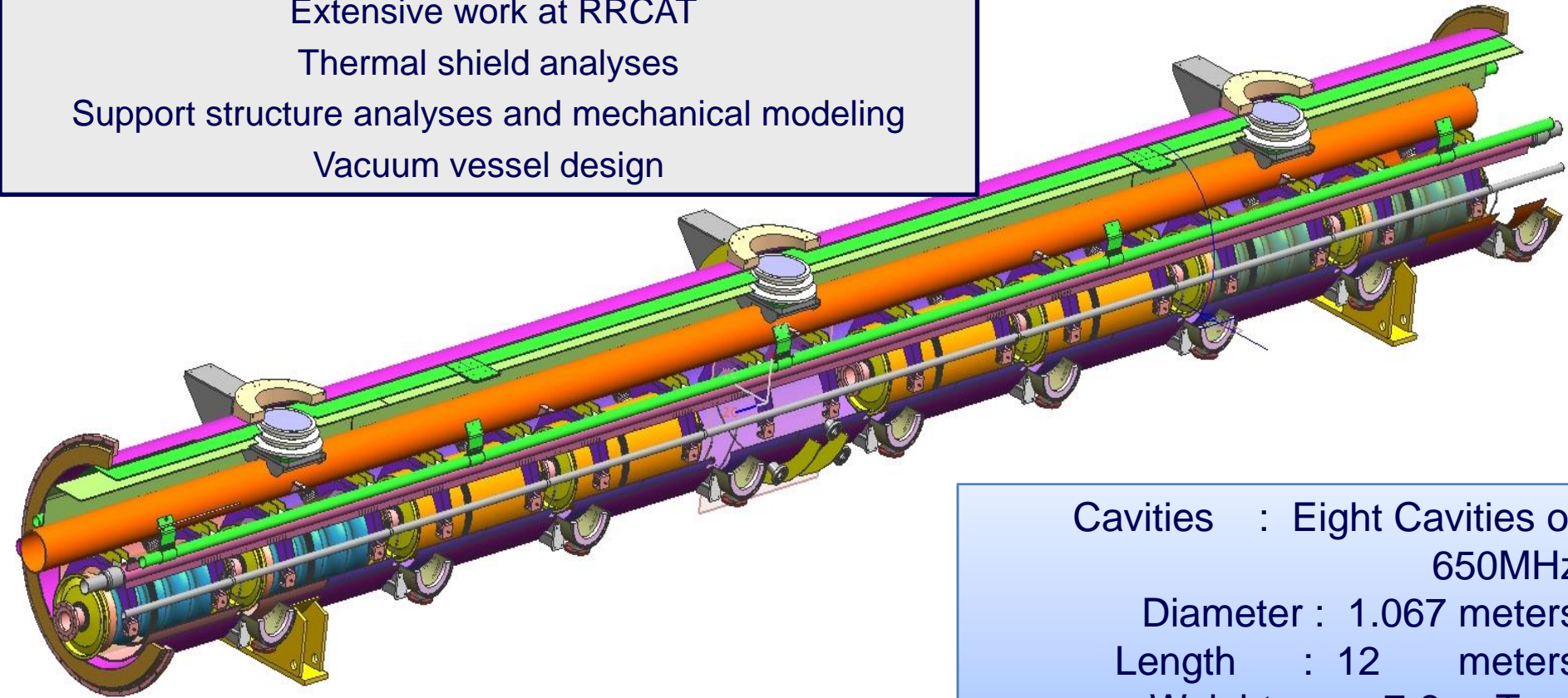
RRCAT: 650 MHz Cryomodule

Extensive work at RRCAT

Thermal shield analyses

Support structure analyses and mechanical modeling

Vacuum vessel design



Cavities : Eight Cavities of
650MHz

Diameter : 1.067 meters

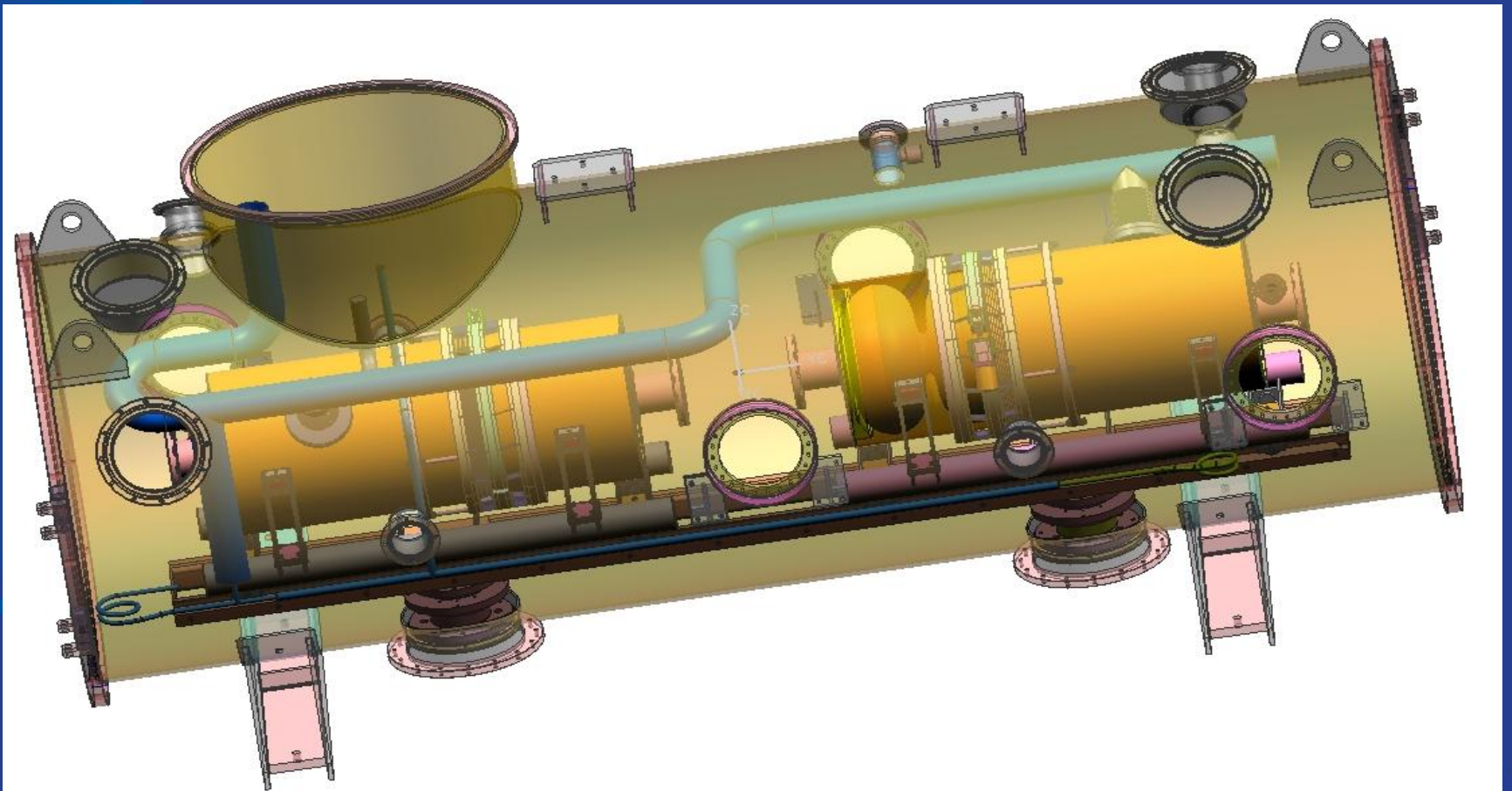
Length : 12 meters

Weight : 7-8 Tons



RRCAT: Horizontal Test Stand

- In collaboration with Fermilab RRCAT is developing a multipurpose CW, Horizontal Test Stand for Fermilab and DAE.





RRCAT: SRF Facility

- RRCAT in collaboration with Fermilab and TTC is developing a complete SRF cavity facility under one roof.
- It is design to take Nb Sheet to fully processed, dressed and tested cavities





Fermilab/DAE SRF Infrastructure



All of these infrastructures were focused on 1.3 GHz.

With India Collaboration we are upgrading them to 325 and 650 MHz



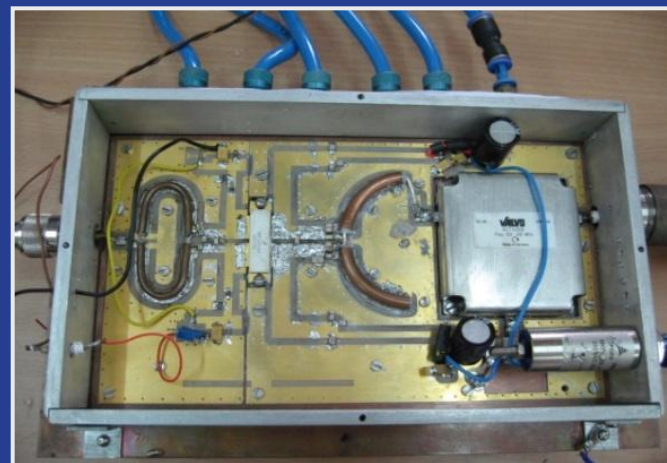
Solid-state Amplifiers at 325 MHz

- BARC using the specifications provided by Fermilab is developing 325 MHz RF source for Project X.
- **Similar development is underway at RRCAT for 650 MHz**



Preliminary test results

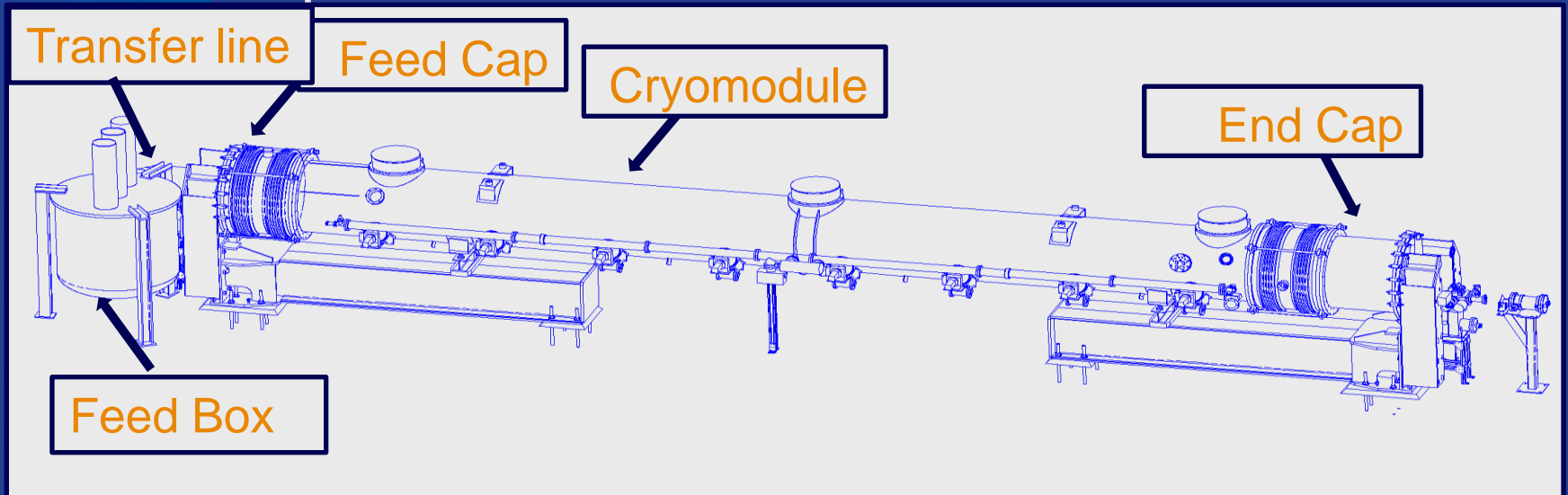
1. Center frequency : 325 MHz
2. Power output (CW) : 834 W
3. Gain : 22.2dB
4. Cooling : Water Cooled
5. Efficiency (Total) : 69.7%





BARC: Cryomodule Test Stand

- Conceptual Arrangement of Feed Box, Feed Cap, End Cap & Transfer Lines.



- **Status: Design & Drawing of all three sub assemblies is taken up. Ready to order material.**
- **CMTF (FY16): 650 MHz CW Test Stands for Project X**
 - Install shielding, RF, cryo for PX test stands
 - 1300 MHz (pulsed) CM test stand (with India)
 - 650 MHz (CW) CM Test Facility (with India) ← Integrated System



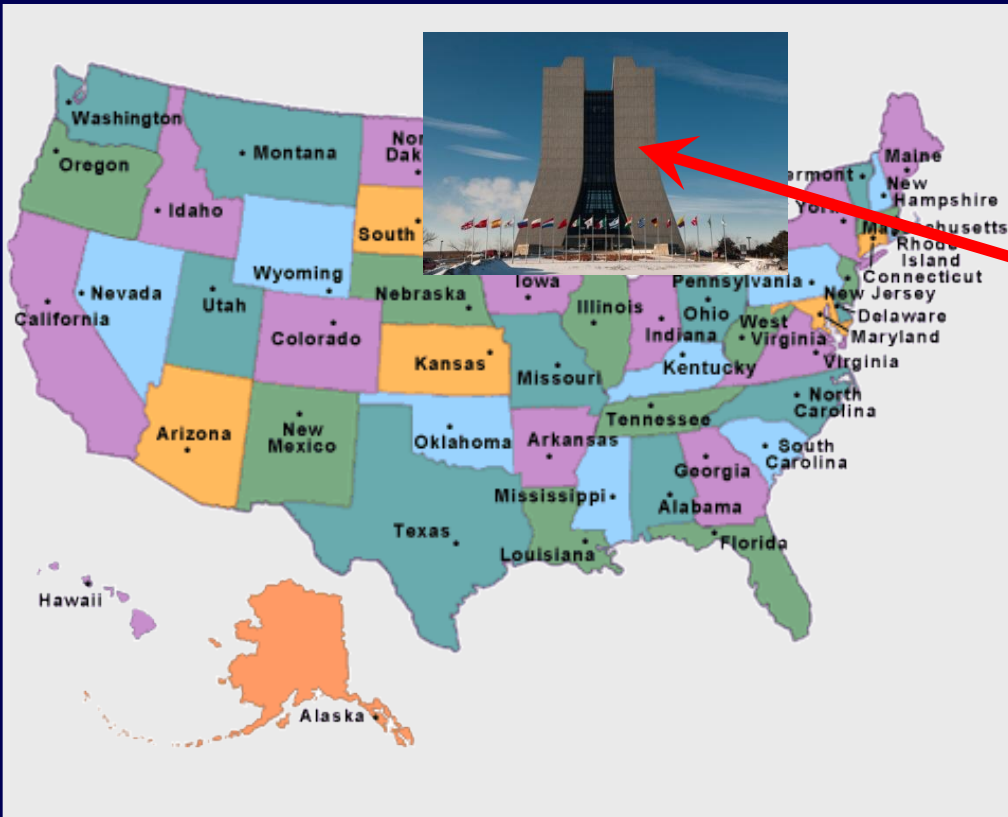
IIFC – Accelerator 2010



Technical people in
India ~100



The New Frontier: India-Fermilab



Indian Institutions and Fermilab Collaboration is jointly building infrastructure, accelerator and physics program(s) **in India and at Fermilab** for the programs of vital interest to both countries.



Project X and Its Physics Program

S1&2:

Next generation muon-to-electron conversion experiment

S1&2:

$K^+ \rightarrow \pi^+ \nu \nu$: >1000 events, Precision rate and form factor

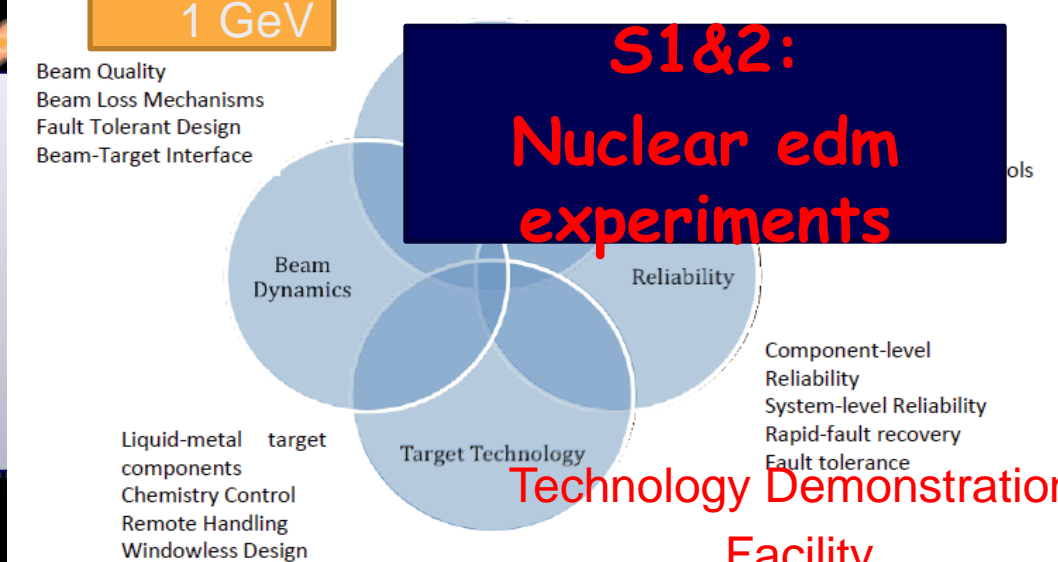
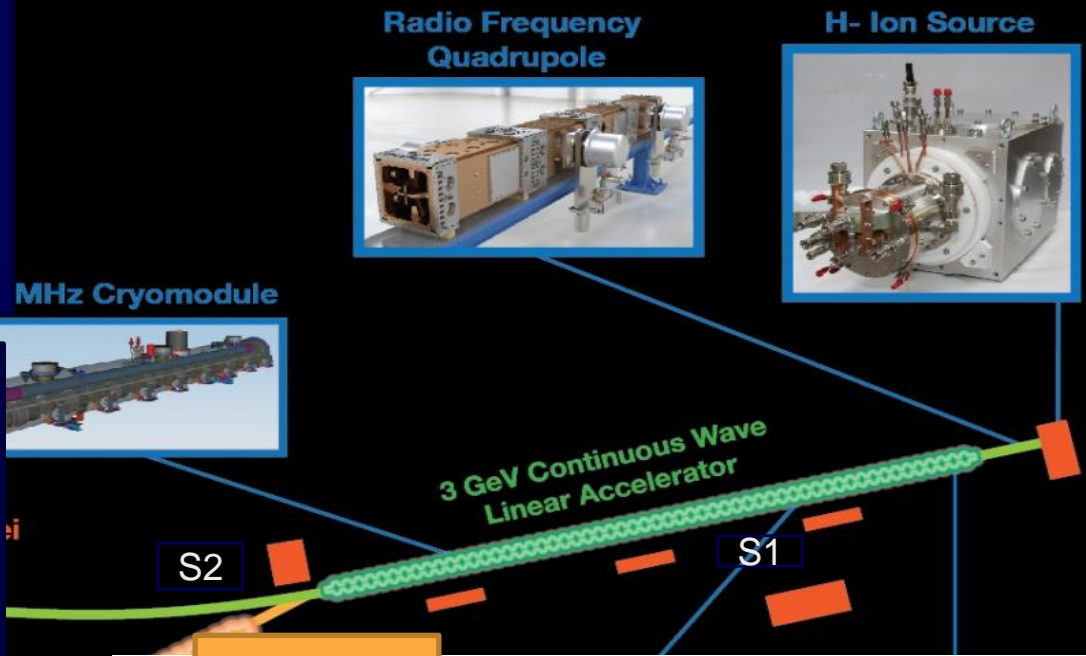
Stage 1-3:

Neutrino Physics:

➤ **Mass Hierarchy**

➤ **CP violation**

➤ **Precision measurement**



S1&2:
Nuclear edm experiments



Fermilab Timeline

Opportunities for Discovery 2011–2030

Legend

- R&D
- Construction
- Operation

'11

'20

'30

Intensity Frontier

Neutrinos

MiniBooNE

MINOS/MINOS+

MINERvA

MicroBooNE

NOvA

LBNE

Neutrino Factory

Muons

Muon g-2

Mu2e

Nuclear Physics

SeaQuest


Project X

Project X Accelerator Facilities and Experiments



IIFC – v P

- Eight Indian Institutions have joined the Fermilab Neutrino Physics Program.
 - MINOS, MINOS+
 - LBNE
 - NOvA
- We are expecting a total of 20 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
 - We continue to include more institutions and
 - Recruiting faculties and postdoctoral fellows.



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Neutrino Physics Program

- Fermilab and the Indian Institutions within the “Discovery Science” collaboration are jointly working on physics research program at Fermilab and at the Indian laboratories,
 - Focus on neutrino physics (MINOS, NO_νA, LBNE)

Indian Institutions:
MINOS, NO_νA,
LBNE





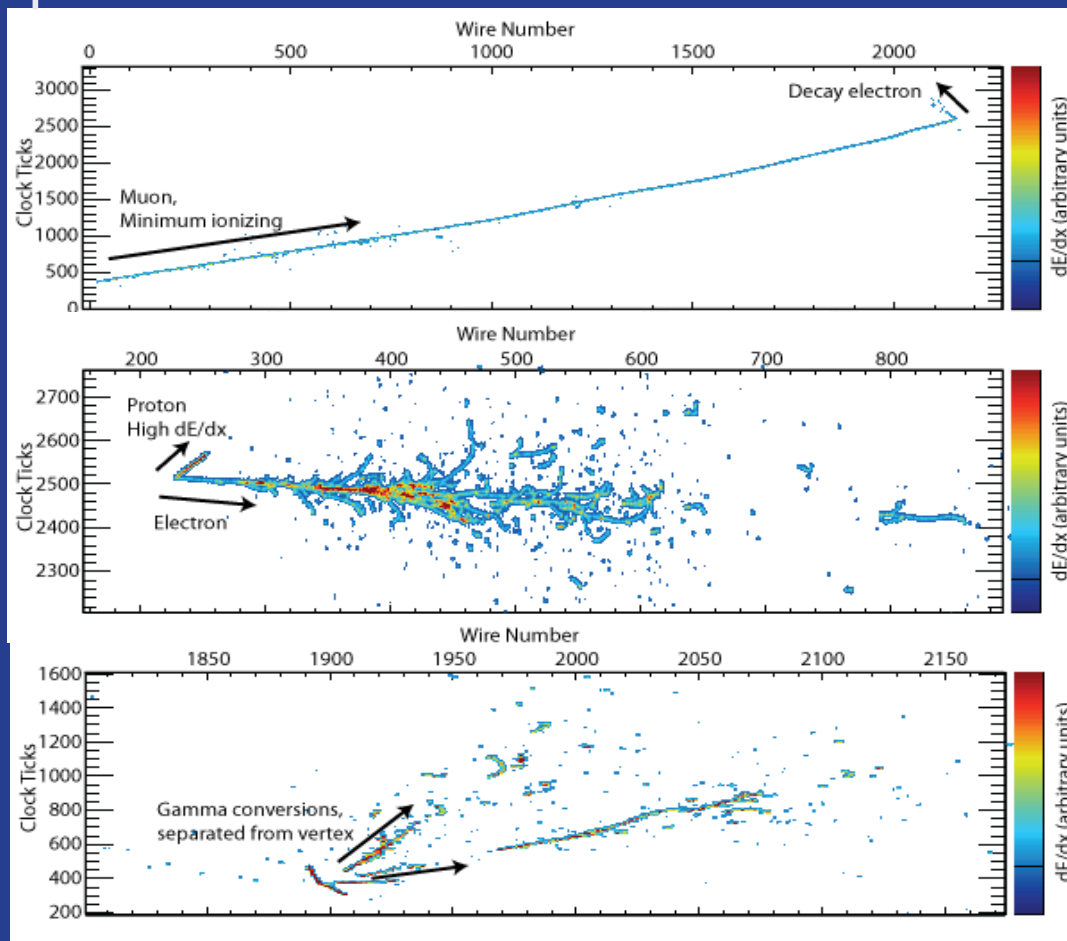
Detector Technology: LAr

Liquid Argon TPC based on its excellent performance in particle identification

ν_μ CC event w/
 μ decay

ν_e QE event

NC event w/
 $\pi^0 \rightarrow \gamma\gamma$

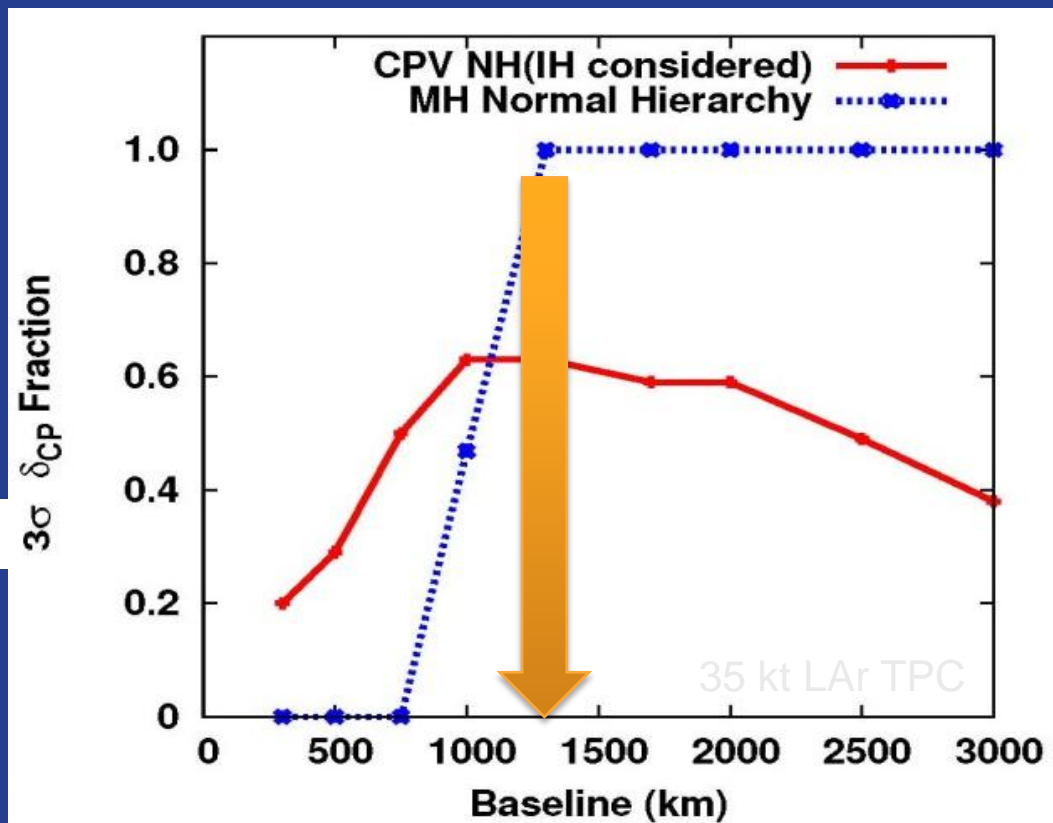


Exquisite 3D event information!



Large θ_{13} (March 8, 2012)

Mass hierarchy and CP sensitivity vs. Baseline



~1,300 km is nearly optimal for a combined sensitivity of CP and mass hierarchy measurements.



Material Science

- Fermilab Project X CW proton beam at 1 MW, 1 GeV would be the only proposed facility in the world.
- High temperature irradiations carried with the Project X proton beam would result in swelling, irradiation induced hardening and embrittlement.
- The “Material Science” facility at Fermilab would help design materials with tailored microstructures and compositions.
 - To obtain optimal value of swelling and irradiation induced mechanical properties.
- Measurement of neutron cross section of some of the minor actinides.
 - $^{93}\text{Np-238}$, $^{95}\text{Am-241}$, $^{95}\text{Am-242}$ and $^{96}\text{Cm-242}$



Particle Physics with Nucleon and Nuclei

- Near Term future (next 20 years) is on Intensity Frontier
 - Neutrino Physics (MINOS, MINOS+, NOvA, LBNE, MicroBonne, MINERvA)
 - Material Science
 - $\mu \rightarrow e$
 - g-2
 - Rare Kaon Decay
 - $n \rightarrow n(\text{bar})$ oscillation
 - Particle Production
 - Hyper-Nuclei



Human Resource Development

- Under the DAE-DST funding we are in the 1st phase of the HRD development
 - Mandate to admit 20 Ph.D. students in 3 yrs (2012-2014)
 - Develop infrastructure at collaborating institutions, including Punjab University
- The collaboration has proposed an expanded HRD development program jointly carried out by US and Indian scientists
 - To support the growing need to trained technical and scientific manpower
 - We proposed to establish institute(s) with initial infrastructure for the development of the RD&D and construction of LBNE-ND
- This would require significant support from the collaborating institutions in
 - Building and related infrastructure
 - Students and flexibility in programs



Summary

- Fermilab along with its US and Indian collaboration is making significant R&D, infrastructure and industrial progress that could lead to
 - The Neutrino and Material Science Experiment
 - Project X construction at Fermilab.
 - Construction of two vital accelerators in India
 - Training of next generation of scientists
- We have set the foundation of a very strong technical collaboration with Indian Institutions.
 - US-DOE and Indian DAE are working to finalize two project Annexes for the funding of Fermilab and Indian-DAE programs
 - Support of all collaborating institutions for this unique collaboration is very strong
 - Working with DOE/DAE-DST in making developing the next stage of this program.

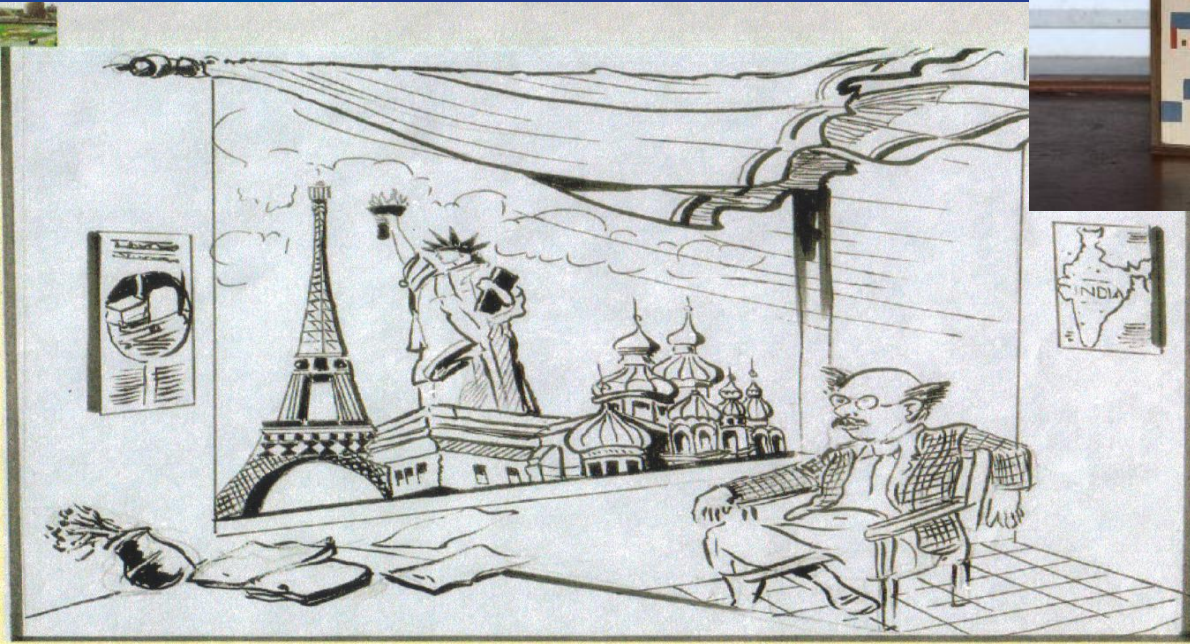


Thanks to All who helped





Wind of Change and Friend



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