Fermilab

पऊवि
DAE

Development of Indian High Intensity Proton Accelerator

(In Collaboration with Fermilab Project-X)

Shekhar Mishra

Project-X, Fermilab

International Collaboration Coordinator

Talk Given at BARC/DAE March 22nd, 2011

My Background

- Ph.D., Experimental Nuclear Physics, University of South Carolina and Los Alamos National Laboratory (LANL) (1987)
- Research Associate, LANL, 87-89
  - Principle Investigator of 3 experiments at LANL
- Research Associate, Fermilab, 89-91
  - Lead Author and only RA on experimental proposal E789
- Staff Scientist Fermilab, 91-Present (Scientist-II)
  - Physicist in Charge, Fermilab Experiment E789, 1992-93
  - Main Injector Department
    - Main Injector and Recycler Accelerator Physics Team 1991-2003
    - Member of the Fermilab Run Coordinator team, 1994-95
    - Head of the Main Injector Commissioning, Fermilab, 1998-99
    - Head, Main Injector Department, Fermilab, 1999- 2003
      - Head of the Recycler Ring Commissioning, 2001-03
  - Program Leader, ILC R&D at Fermilab, 2003-2005.
  - Deputy ILC/SRF Program Director, Fermilab, 2005-2010
  - Project-X, International Collaboration Coordinator, 2010-Present
- Adjunct Professor, University of Delhi
  - Supervise Ph.D. student, Chair Ph.D. Thesis committee

My Laboratory: Fermilab

The Fermilab Tevatron has now passed on the energy frontier to LHC, following 25 years as the highest energy particle collider in the world.

Fermilab operates the highest power long baseline neutrino beam in the world. But will face stiff competition from J-PARC

India Collaboration Development

- In 2002, International Linear Collider
  - Discussed collaboration with Prof. V. S. Ramamurthy
  - Nov. 2003 Indian and US Institutions Interaction meeting
    - 19 US Scientists and mangers came to this meeting and site visit
  - 2004 DAE and DST formed a working group to develop collaboration, all DAE lab directors were member
  - 2004, SRF was chosen as the technology for ILC
  - 2006 Umbrella MOU signed
  - 2007 an Addendum to collaborate on SRF was signed
    - Pitamber Singh and Jishnu Dewedi visited Fermilab
- In 2008, Fermilab and US attention shifted from ILC to High Intensity Proton Accelerator
  - Dr. Pier Oddone, Director, Fermilab, wrote a letter to Dr. Anil Kakodkar, Secretary, DAE inviting India to collaborate on High Intensity Proton Accelerator
  - Dr. Kakodkar sent a very positive response
  - Jan 2009, During the signing of the Addendum MOU III at Indore, Dr. Kakodkar and Dr. Oddone met privately
    - Concept of "Total Project Collaboration" emerged
    - Fermilab changed the HIPA design from Pulsed to CW
    - Supplement I to Addendum MOU III was developed
    - Oct 2009, Dr. Banerjee, Dr. Bhandari and Dr. Sahni, visited Fermilab
    - Jan 2010, Dr. Dennis Kovar, Assistant Secretary, US-DOE-HEP visited DAE
      - Idea of three Phase Collaboration Developed
    - Brinkman, Director, US-DOE-OS met with Dr. Banerjee and Dr. Grover several time

Status: MOU and Agreement

- In Feb 2010, Shekhar Mishra made first US government presentation on behalf of DOE at DAE-OYC
  - US-India Civil Nuclear Working Group
- May 2010, Dr. Banerjee requested US-DOE for a Road Map for this collaboration
  - Mr. Dennial Poneman Deputy Secretary, Dr. Brinkman, Dr. Miller, Dr. Banerjee and Ms. Meera Shankar, Indian Ambassador met in Washington to discuss this Road Map
  - Supplement I to Addendum MOU III and additional MOUs were discussed
  - Dr. Poneman and Dr. Banerjee agreed to develop DOE-DAE agreement
- Oct 2010 IIFC meeting to discuss these documents in detail
  - Dr. Banerjee gave IIFC action items for Indian XII Plan.
- US-DOE and Indian-DAE are working on the text of an agreement for the Phase III of this collaboration.
  - US-DOE has obtained Circular-175 for this collaboration
    - The Circular 175 procedure seeks to confirm that the making of treaties and other international agreements by the United States is carried out within constitutional and other legal limitations, with due consideration of the agreement's foreign policy implications, and with appropriate involvement by the State Department.
  - Fermilab, US-DOE, US-SD,… has gone over this collaboration with India
    - A high level agreement document is with DAE at present
    - As soon as that is signed, we will develop addendums to this agreement for Phase-III
      - Dr. Kakodkar and Dr. Banerjee has already discussed the high level contents with Dr. Oddone, Dr. Kovar and Dr. Brinkman

Indian Management of IIFC

- In Summer 2010, Dr. Srikumar Banerjee, Secretary, Department of Atomic Energy, India, has formed two Indian committee for the Indian side of IIFC management.
  - DAE-ACFAP (Apex Committee to Formulate Action Plan)
    - Dr S. Banerjee- Chairman
    - Dr. S. Kailas, Convener
  - IC-IIFC (Internal Committee for Indian Institutions & Fermilab Collaboration (IC-IIFC) with participating institutions
    - Bhabha Atomic Research Centre
    - Raja Ramanna Centre for Advanced Technology
    - Variable Energy Cyclotron Centre
    - Inter-University Accelerator Centre
    - Indira Gandhi Centre for Atomic Research
      - Dr. R. K. Bhandari, Chairman
      - Dr. V. C. Sahni, Convener
      - Dr. P. Singh, Member-Secretary
- IC-IIFC to develop the technical part of this collaboration
    - Working with IC-IIFC we have developed several documents, 3 additional Addendum MOUs and Project Documents

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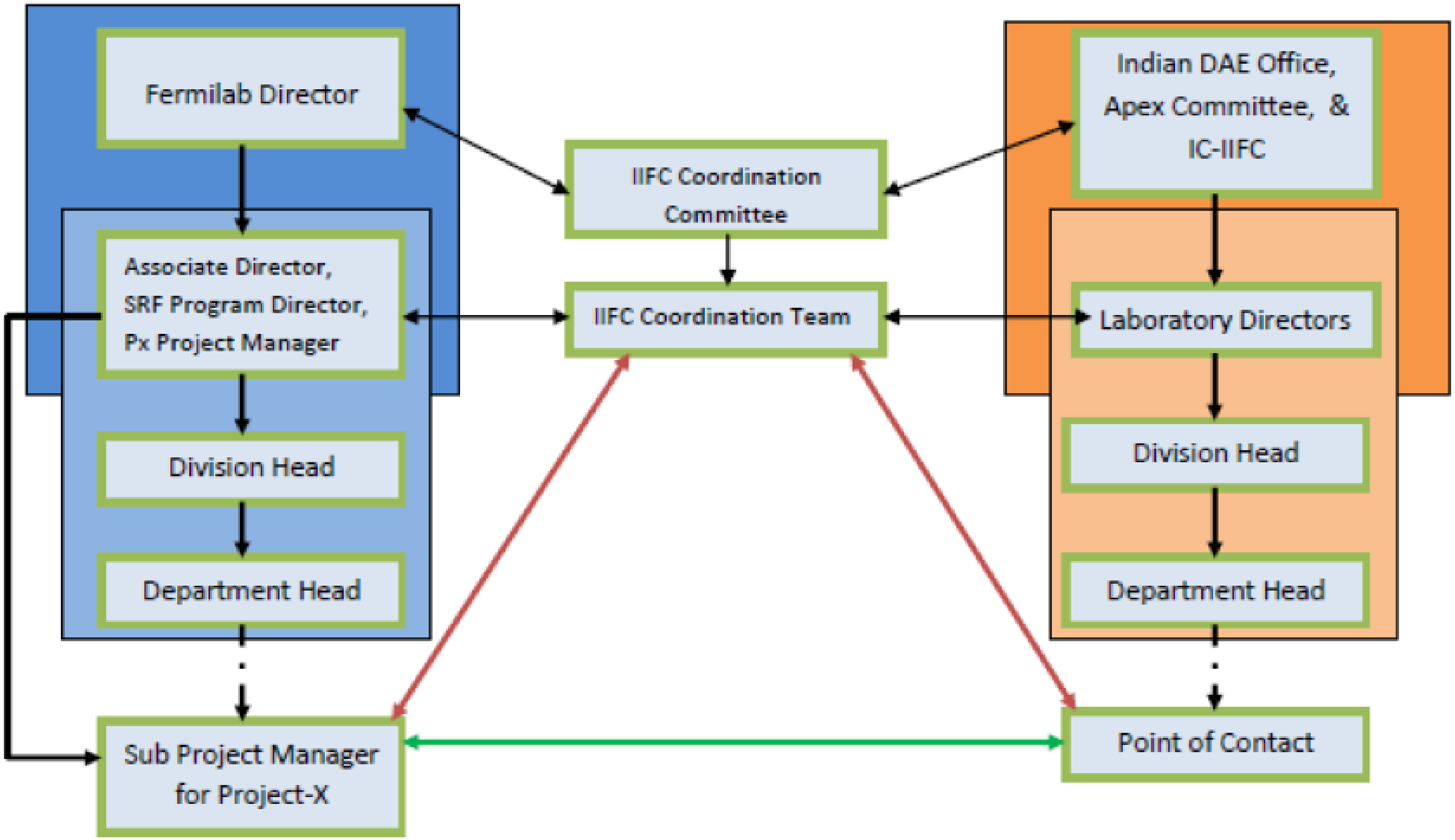
IIFC Joint Management



Fermilab Director

Associate Director,
SRF Program Director,
Px Project Manager

Division Head

Department Head

Sub Project Manager for Project-X

IIFC Coordination Committee

IIFC Coordination Team

Indian DAE Office, Apex Committee, & IC-IIFC

Laboratory Directors

Division Head

Department Head

Point of Contact

↔ Management Matter Interaction

↔ Oversight and Coordination

↔ Direct Technical Interaction

→ Line Management

- · - · → Line Management oversight

Iifc.fnal.gov

Px: Collaboration Plan

- A multi-institutional collaboration has been established to execute the Project X RD&D Program.
  - Being organized as a “national project with international participation”.
    - Fermilab as lead laboratory with ultimate responsibility
    - International participation via “in-kind” contributions, established through bi-lateral MOUs.
    - Collaborators assume responsibility for components and sub-system design, development, and construction.
  - National Collaboration

MOU signatories:

ANL
BNL
Cornell
Fermilab
LBNL

ORNL/SNS
MSU
TJNAF
SLAC
ILC/ART

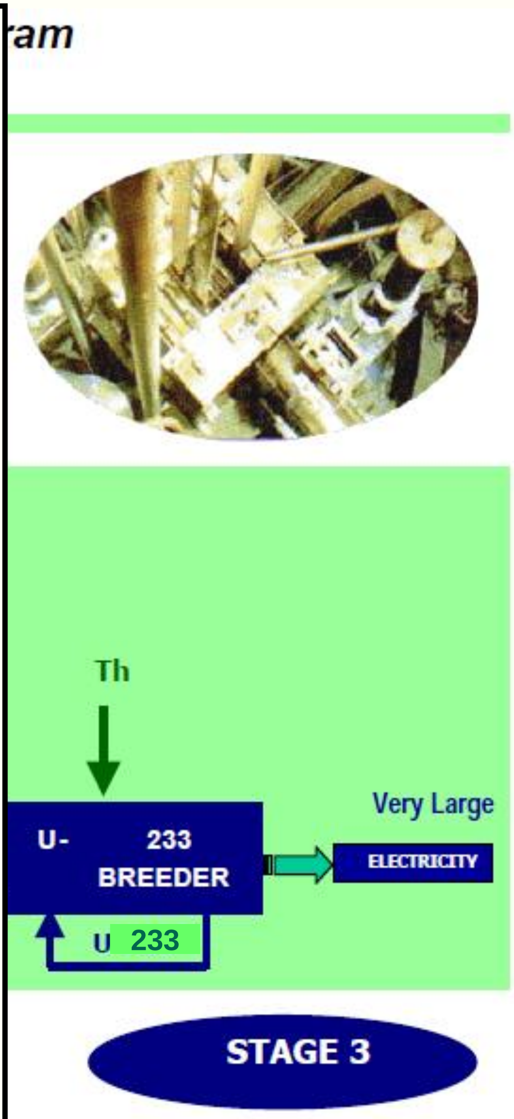
- International Collaboration MOU

Indian Institutions:

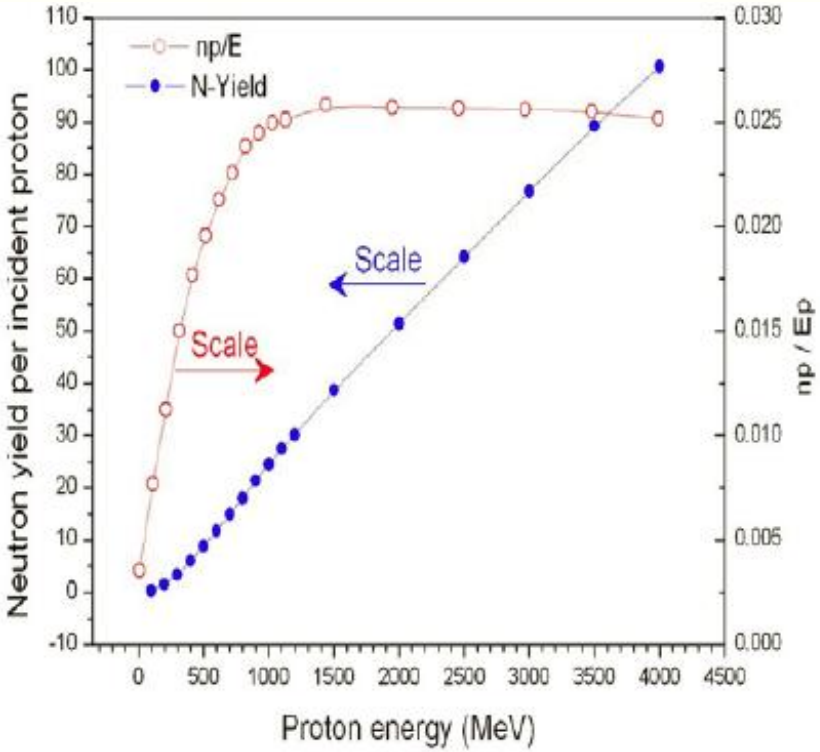
BARC/Mumbai
IUAC/Delhi
RRCAT/Indore
VECC/Kolkata

Indian Nuclear Program

- Indian 3rd Stage program focuses on utilization of thorium.
- Paths of converting Thorium into fissile material:
  - Fast Breeder Reactor
  - AHWR
  - Accelerator Driven System
- ADS is the only system that could remove the Indian dependence on foreign Uranium.
- In ADS high-energy proton beam generates neutrons directly through spallation reaction.
  - Efficient Accelerator
  - Accelerator → Spallation Target
  - Reactor



Beam Energy and Power

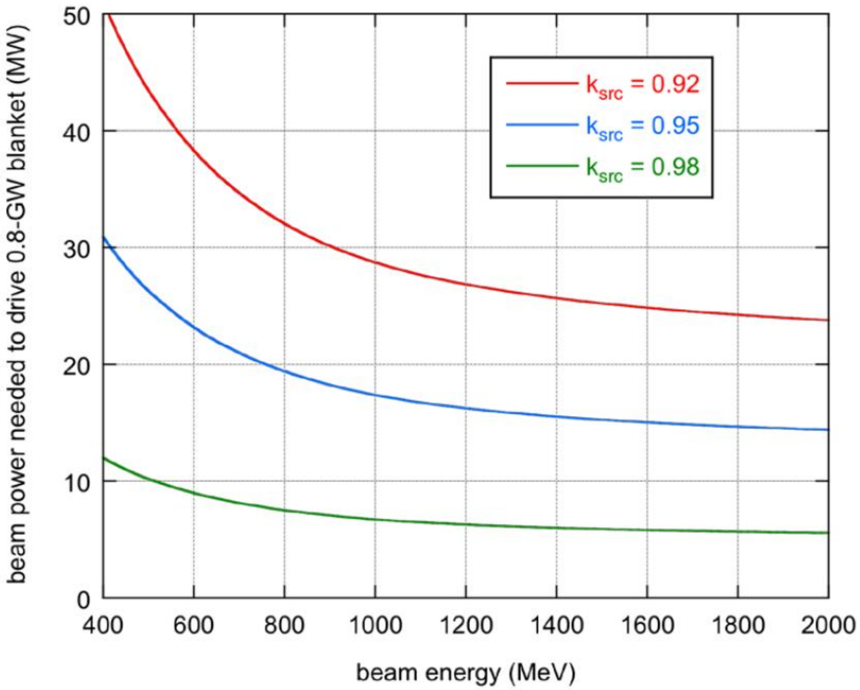


Neutron yield as a function of proton energy for one set of target and moderator condition

Beam Energy 1-2 GeV

Beam power needed to drive a 0.8 GW ADS sub-critical core as a function of k_{src}, the effective neutron multiplication factor.

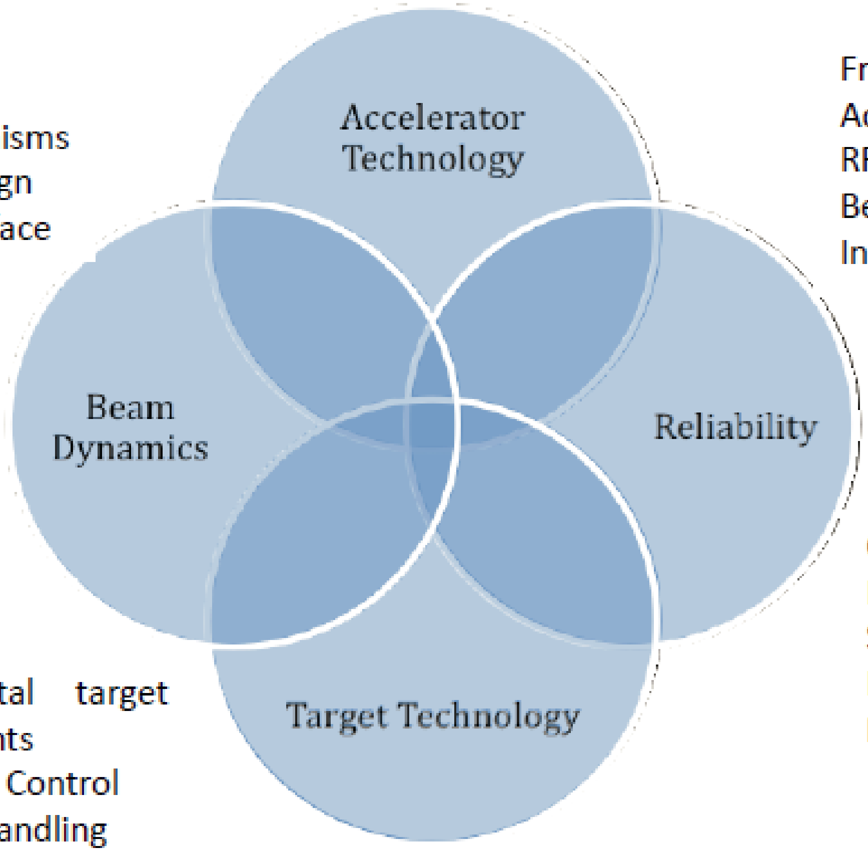
Beam Power → 1-2 MW



Accelerator Requirements

Beam Parameter	Parameter value or range for the Nuclear Energy Demonstration Experiment
Beam Power	1-2 MW
Beam Energy	1-2 GeV
Beam Time Structure	Continuous Wave
Beam trips (1<t<10 Sec)	< 5000 per year
Beam trips (10 sec < t < 5 mins)	< 2500 per year
Beam trips (t > 5 mins)	< 50 per year
Availability	➢ 50%

Key Technology Issues



- Beam Quality
- Beam Loss Mechanisms
- Fault Tolerant Design
- Beam-Target Interface

- Front-end
- Acceleration Section
- RF Plant
- Beam Delivery System
- Instrumentation and Controls

- Liquid-metal target components
- Chemistry Control
- Remote Handling
- Windowless Design

- Component-level Reliability
- System-level Reliability
- Rapid-fault recovery
- Fault tolerance

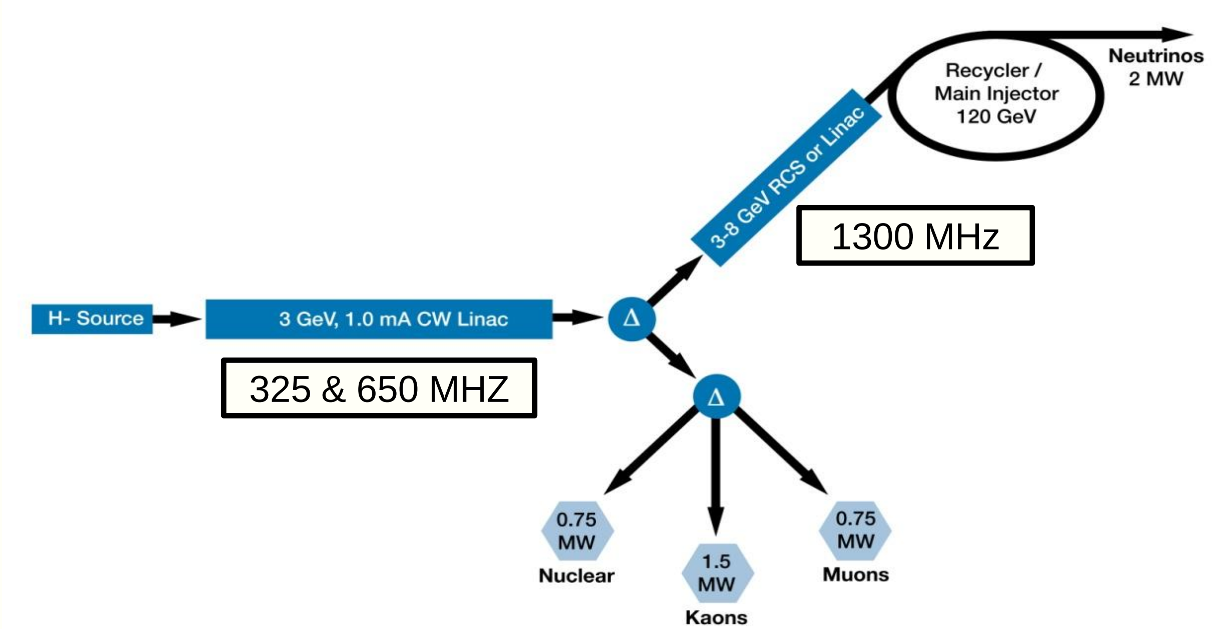
Technology Demonstration Facility

Technology Demonstration

		Transmutation Demonstration	Industrial-Scale Transmutation	Power Generation
Front-End System	Performance	🟩	🟩	🟩
	Reliability	🟨	🟨	🟥
Accelerating System	RF Structure Development and Performance	🟩	🟩	🟩
	Linac Cost Optimization	🟩	🟨	🟨
	Reliability	🟨	🟨	🟨
RF Plant	Performance	🟩	🟩	🟩
	Cost Optimization	🟩	🟨	🟨
	Reliability	🟨	🟨	🟥
Beam Delivery	Performance	🟩	🟩	🟩
Target Systems	Performance	🟩	🟨	🟨
	Reliability	🟨	🟨	🟨
Instrumentation and Control	Performance	🟩	🟨	🟨
Beam Dynamics	Emittance/halo growth/beamloss	🟩	🟨	🟨
	Lattice design	🟩	🟨	🟨
Reliability	Rapid SCL Fault Recovery	🟨	🟥	🟥
	System Reliability Engineering Analysis	🟨	🟥	🟥

Green: Ready, Yellow: May be ready, Red: More R&D

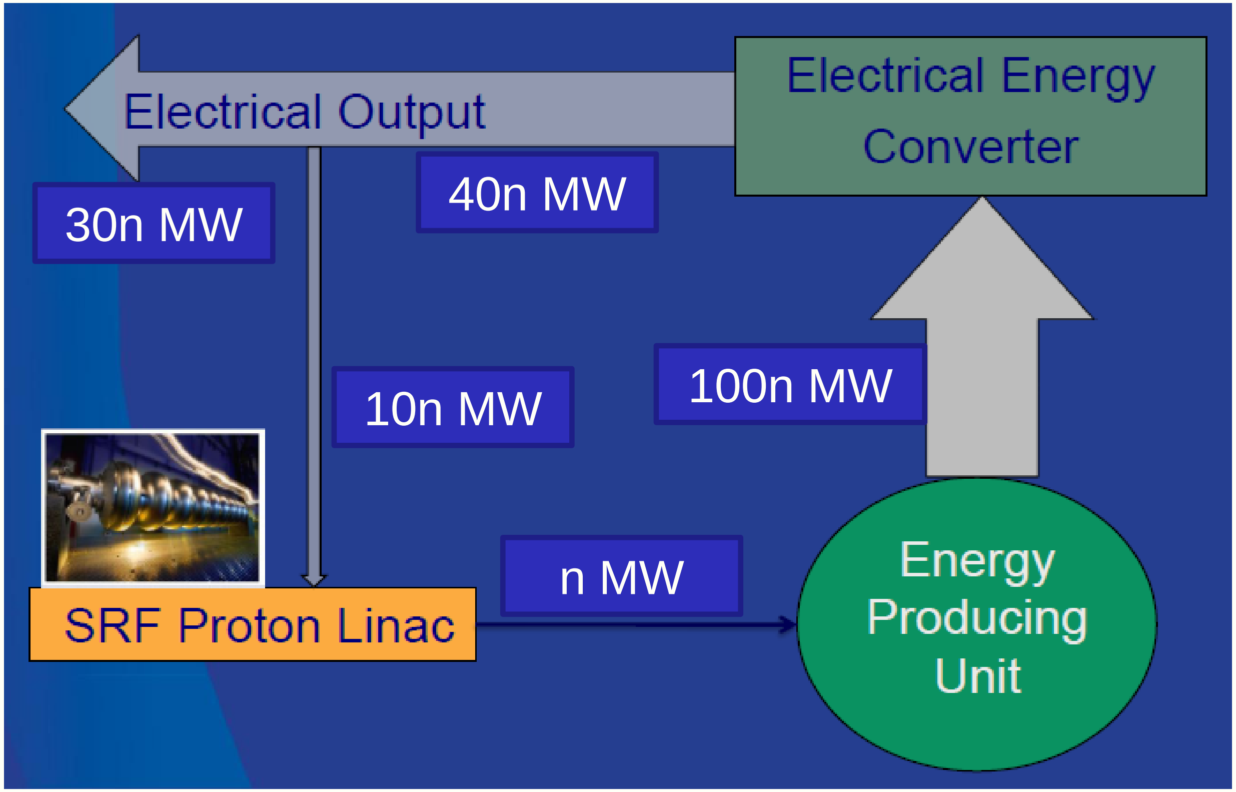
Px: Reference Design Configuration



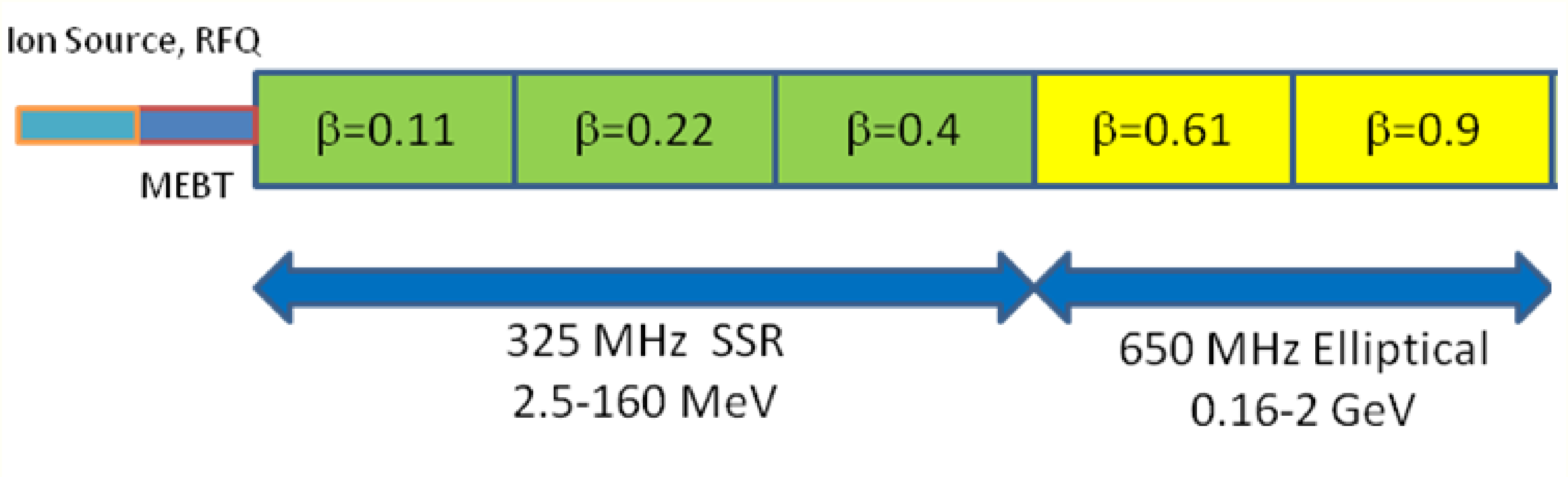
- **3-GeV, 1-mA, CW linac, 325 and 650 MHz, provides beam for rare processes, nuclear and energy programs**
  - **~3 MW; flexible provision for beam requirements supporting multiple users**
  - **< 5% of beam is sent to the Main Injector**
- **Reference Design for 3-8 GeV acceleration: pulsed linac**
  - **Linac would be 1300 MHz with <5% duty cycle**

Next 10-15 yrs Strategy

- A multi-MW Proton Source with 1-2 GeV, ~2MW, CW proton beam could be the accelerator, spallation target, and accelerator, target and reactor interface, technology demonstration project corresponding to 10s of MW electrical power production.



SRF Accelerator Design



Ion Source, RFQ

MEBT

β=0.11

β=0.22

β=0.4

β=0.61

β=0.9

325 MHz SSR
2.5-160 MeV

650 MHz Elliptical
0.16-2 GeV

- Ion source
- Radio Frequency Quadrupole
- Medium Energy Beam Transport (MEBT), including the bunching cavities
- Three accelerating sections based on 325 MHz Single-Spoke Resonators (SSR),
- Two accelerating sections of 650 MHz elliptical cavities.

Radio Frequency Quadrupole

- The Radio Frequency Quadrupole is placed after the ion source for simultaneous
  - focusing, bunching and accelerating the low energy ion beams with high transmission and good beam quality (low emittance).
- The Beam dynamics of 2.5 RFQ accelerator for HIPA has been studied for operating frequencies of 325 and 162.5 MHz using the codes PARMTEQM/TOUTATIS. (Rao, BARC)
  - The simulations have been done using two different techniques: LANL technique and Non-adiabatique technique.

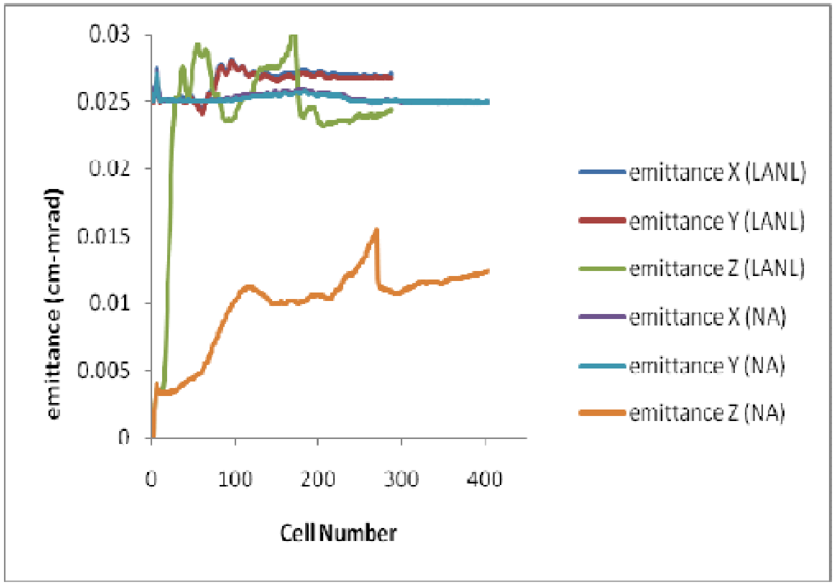
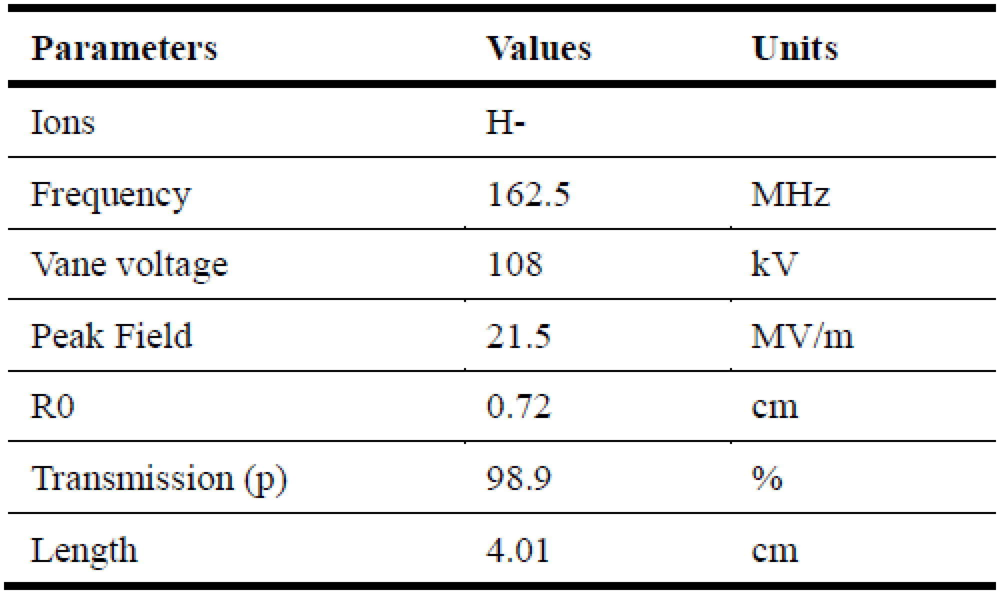


Figure 4: Evolution of emittances along RFQ.

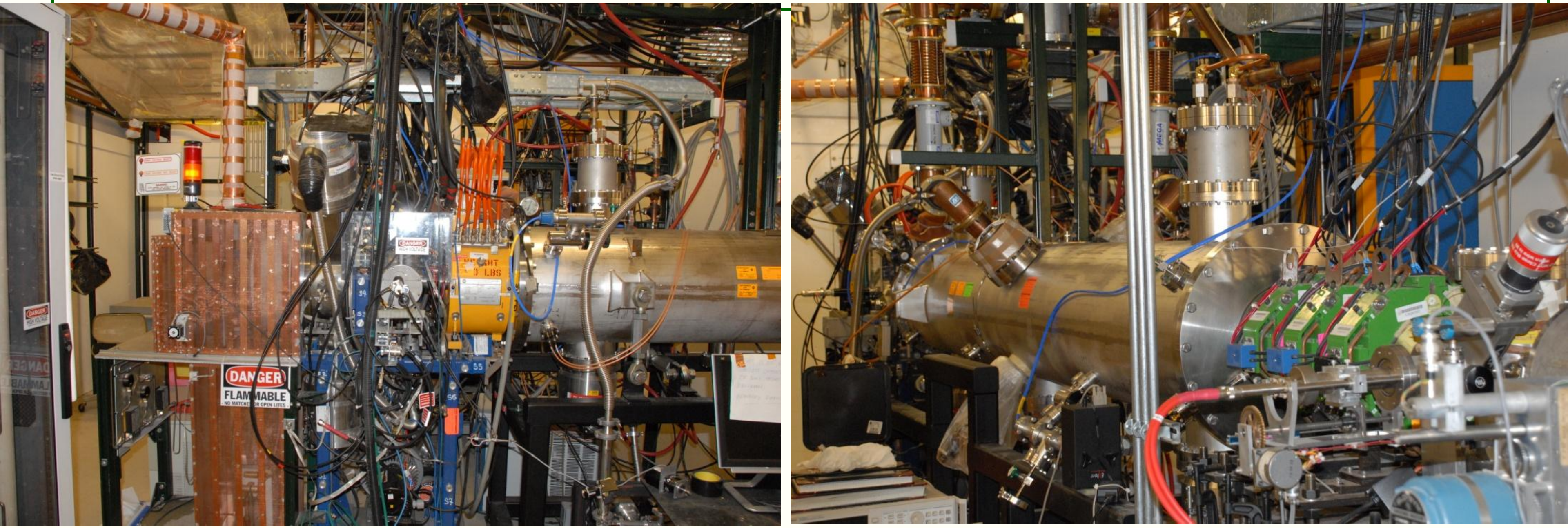
Table 3: Parameters of 162.5 MHz RFQ



Parameters	Values	Units
Ions	H-	
Frequency	162.5	MHz
Vane voltage	108	kV
Peak Field	21.5	MV/m
R0	0.72	cm
Transmission (p)	98.9	%
Length	4.01	cm

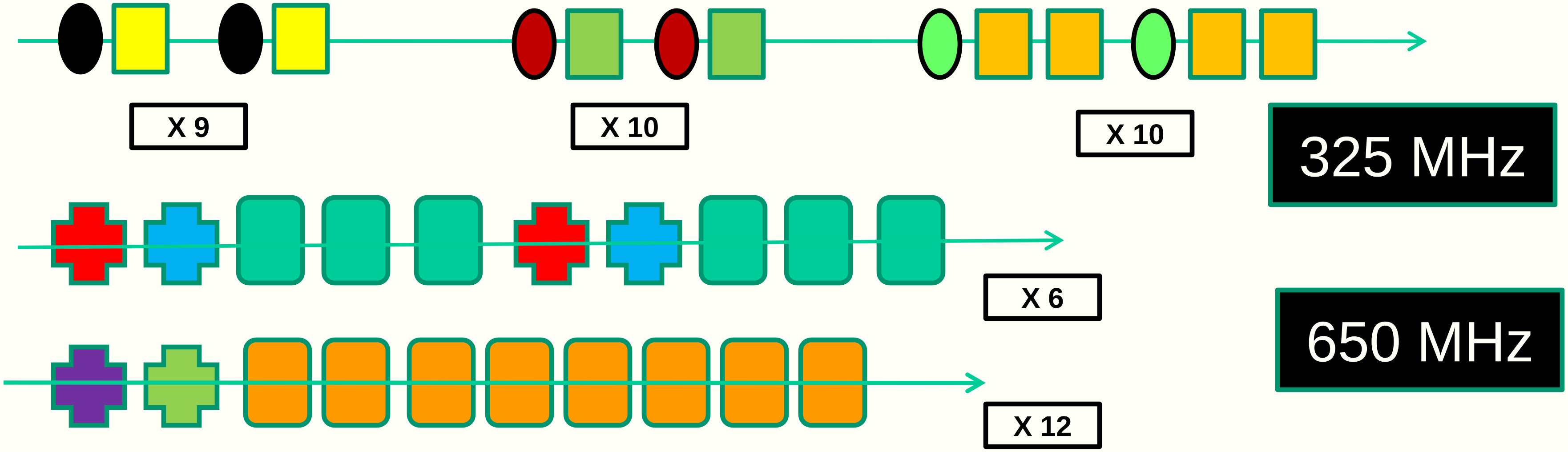
RFQ at Fermilab

- **Fermilab is developing a High Intensity Front End Test Facility for HIPA.**
  - **Indian colleagues (BARC) are participating in this activity.**



- **BARC could propose to fabricate two CW-RFQ of the design that is being developed in collaboration with Fermilab.**
  - **Send one to Fermilab and test it with beam**

SRF HIPA Accelerator Layout



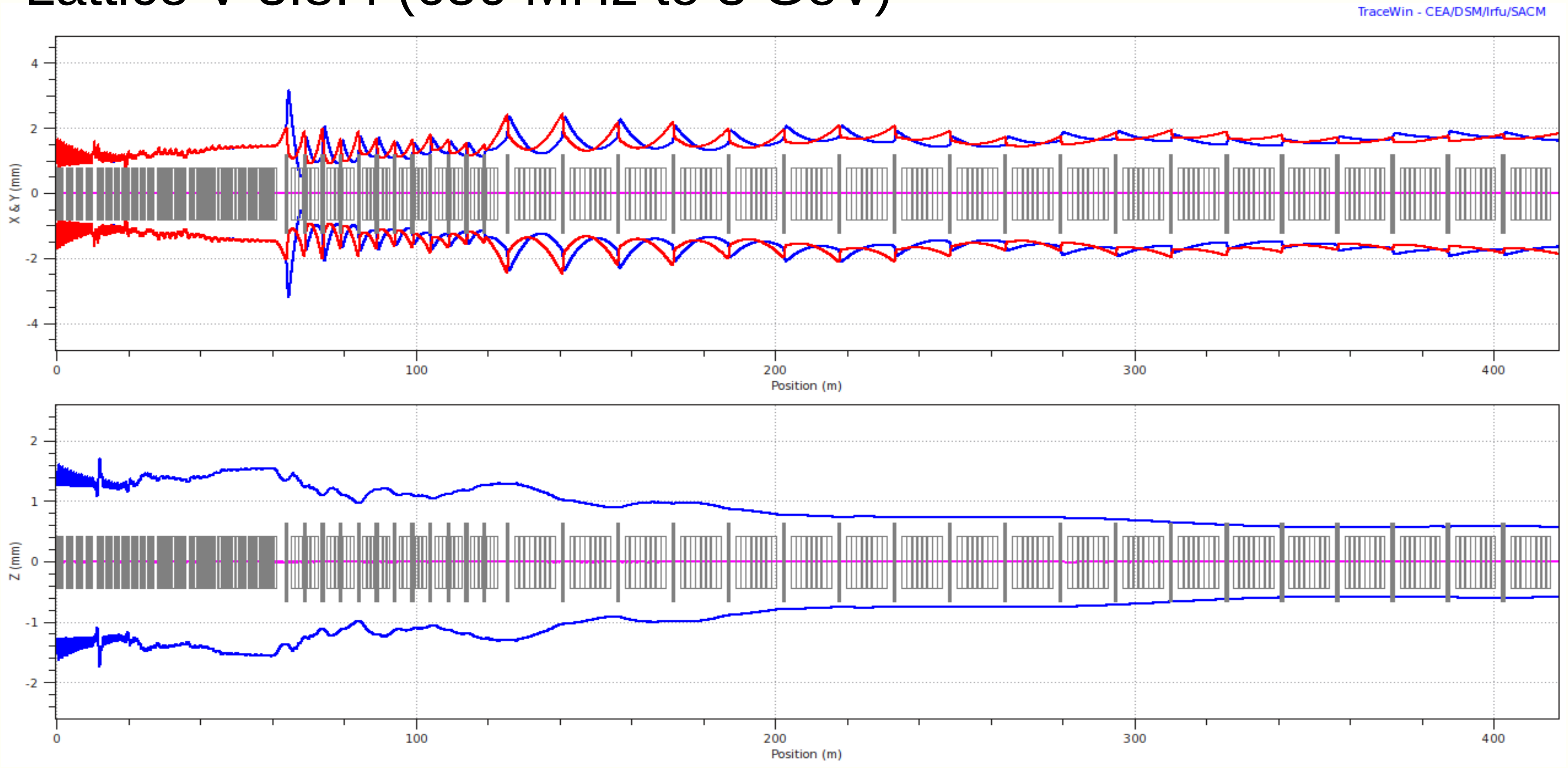
- **Extensive design of the SRF accelerator layout and beam optics has been carried using five families of cavities**
  - **Increase the acceleration efficiency**
    - **Minimize the cost**
  - **Reduce the beam loss**
    - **Operation at higher intensity**

HIPA Design and Beam Dynamics

- Accelerator design and its interplay with engineering:
  - The SC linac lattice is independent of beam current, wave numbers (phase advance per unit period length) of transverse and longitudinal oscillations should be smooth through the SC linac and should change only gradually in order to avoid possible mismatch.
  - Longitudinal phase advance (under zero beam condition) is smooth without discontinuities throughout the SC linac to avoid halo excitation.
  - Length of the focusing period is kept short, especially in the low energy section where space charge dominates.
  - Matching between each cryomodule is smooth to avoid halo generation and emittance growth.
    - Beam matching is achieved by adjusting the gradients and phases of the outermost elements of each side of the transition.

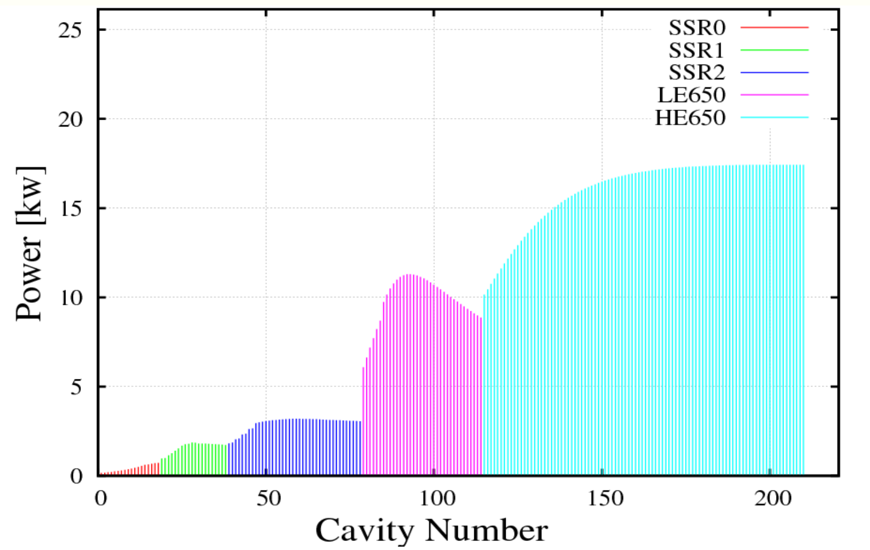
CW Linac (RMS) Beam Envelopes

Lattice V 3.8.4 (650 MHz to 3 GeV)

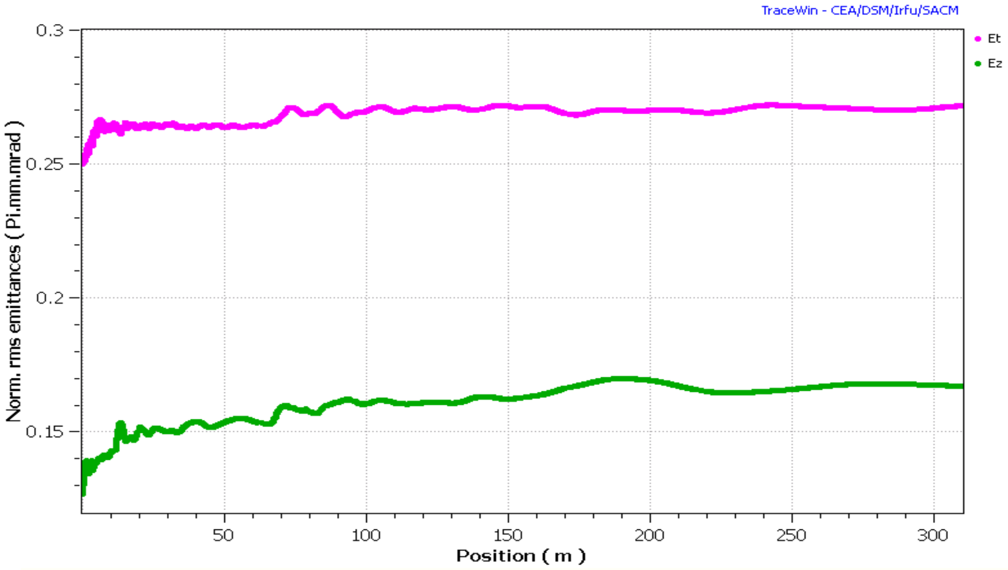


TOP: **Transverse horizontal and vertical envelopes**
BOTTOM: Longitudinal envelope

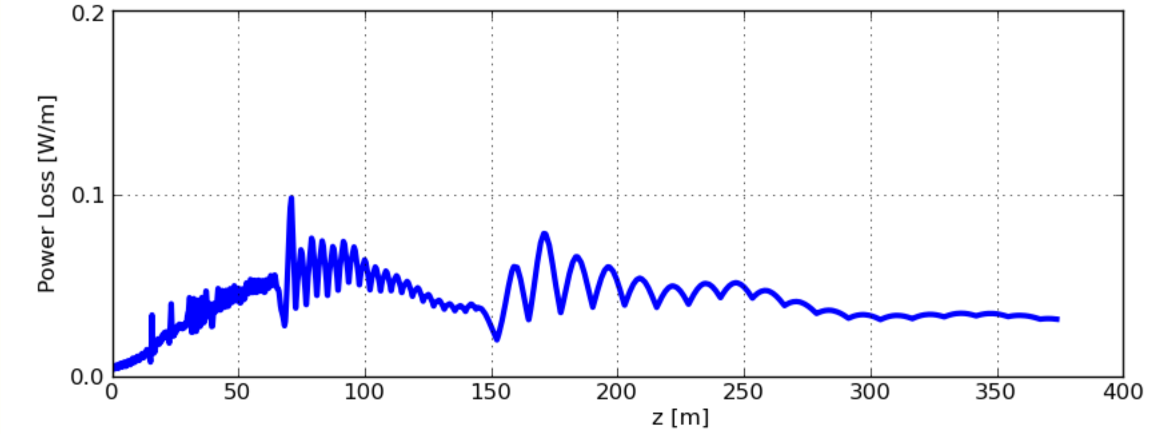
Beam Dynamics



RF power consumption per cavity



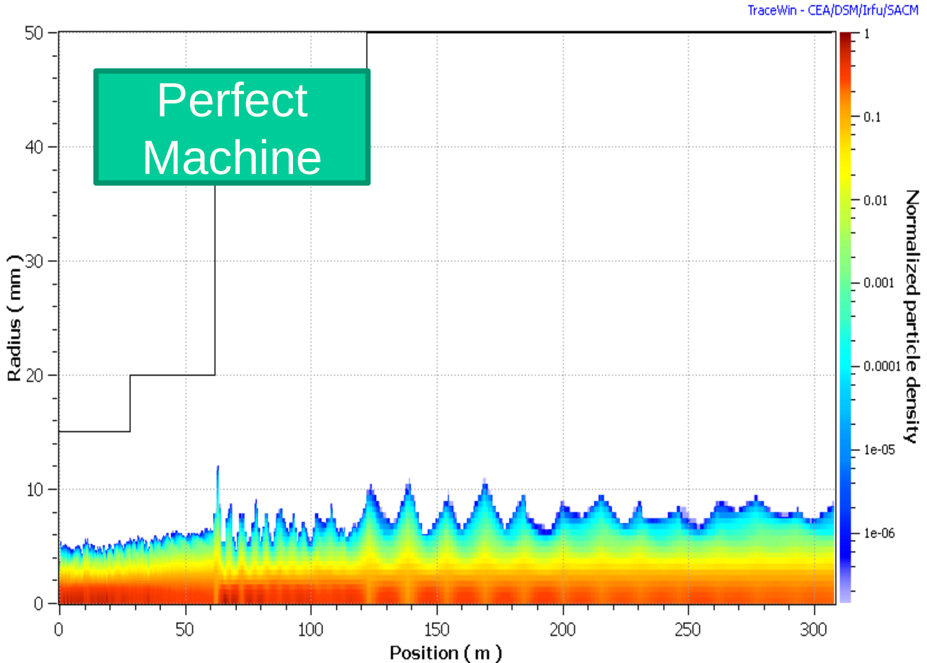
Normalized transverse (magenta) and longitudinal (green) emittances

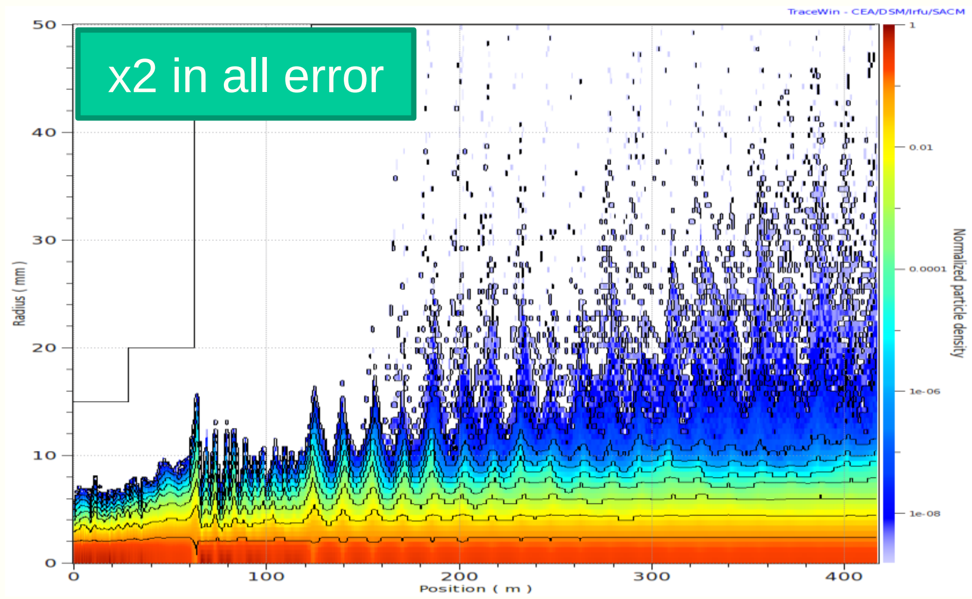


Beam power losses per unit length caused by intra-beam stripping

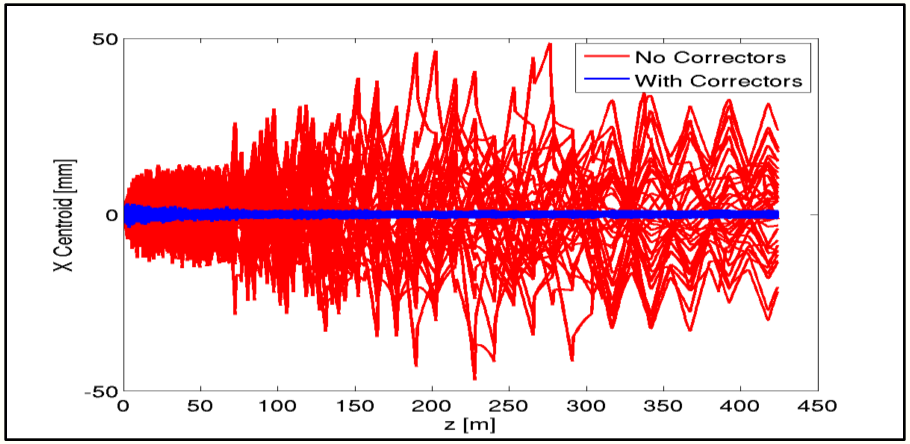
Accelerator Design and Beam Dynamics

- Matching between each cryomodule is smooth to avoid halo generation and emittance growth.
  - Beam matching is achieved by adjusting the gradients and phases of the outermost elements of each side of the transition.
- Lattice design is robust to allow for spread in designed parameters
  - Spread in cavity gradient, operation of linac with failed beam line elements, misalignments etc.

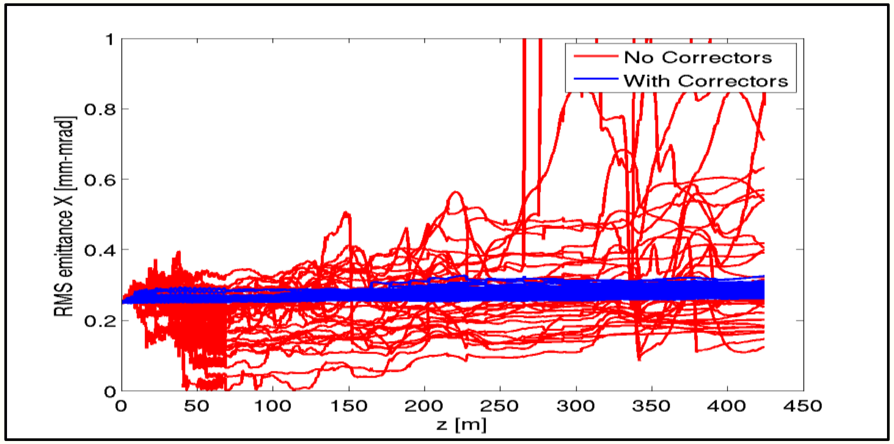




Steering Error Correction



Beam Centroid Position



Transverse Emittance

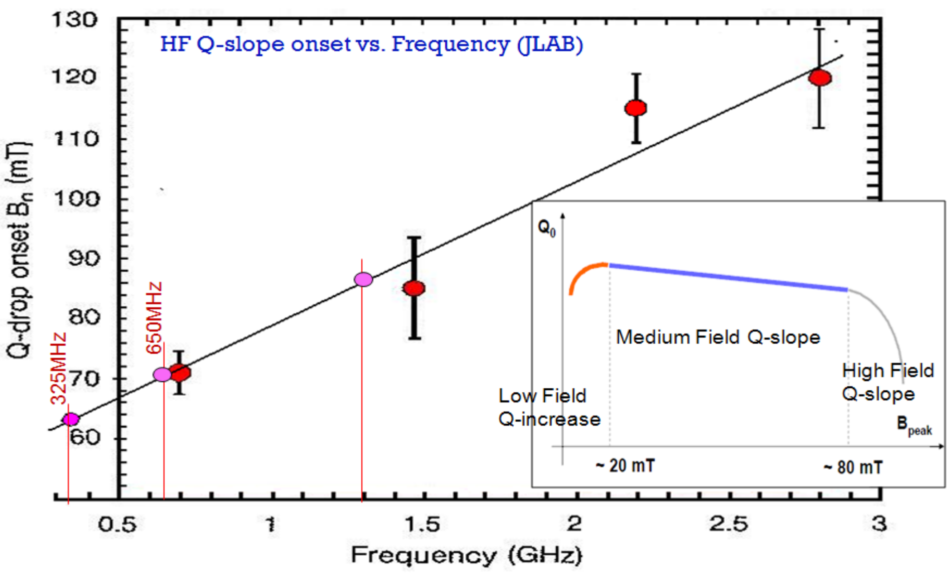
RED: steering correction **OFF**

BLUE: steering correction **ON**

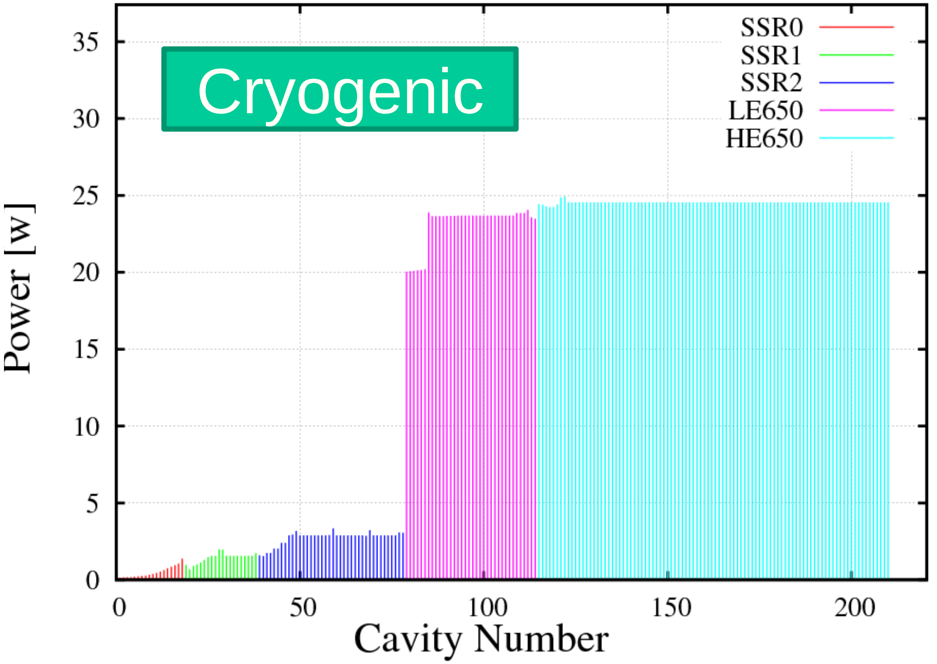
- **Misalignments ±1 mm for all elements (specification ±0.5 mm)**
- **RF jitter of 0.5 ° x 0.5 % in the front-end & 1 ° x 1% RF jitter in the high-energy part was implemented.**
- **100 seeds and 1 million macro-particles per seed.**
- **1 corrector,+ 1 BPM per solenoid/doublet/quad; BPM resolution = 30 µm**
- **Beam centroid is corrected to ± 1mm; Emittance increase < 20%.**
- **The uncorrected seeds predict losses above 100 W/m; corrected – no losses**

Accelerator Design and Beam Dynamics

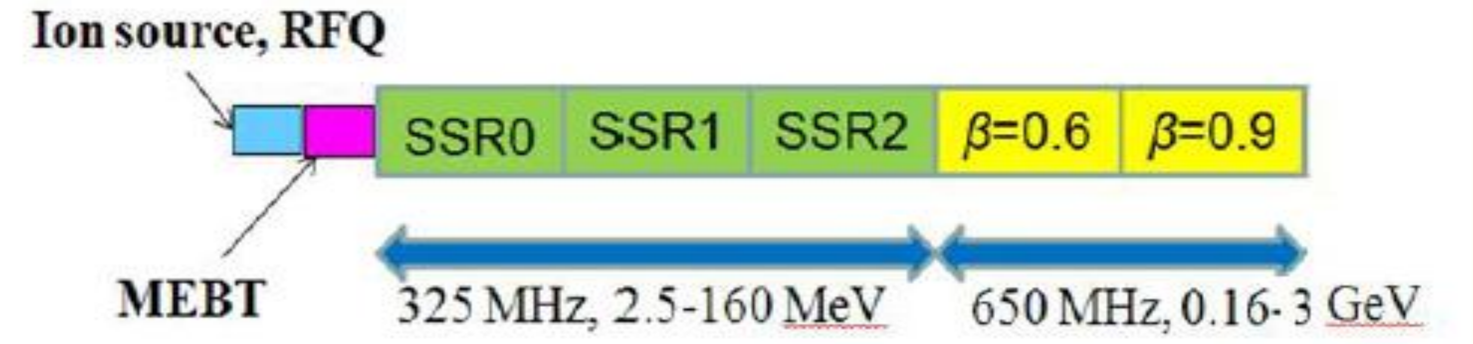
- **Working gradient of the cavities are limited by the peak surface magnetic field & cryogenic losses.**
  - **Maximum surface field which is chosen to protect the RF cavity from quenching.**
    - **60 mT for all the 325 MHz cavities**
    - **70 mT for all the 650 MHz cavities.**
  - **Cryogenic losses per cavity should be less than 25 W.**



High field Q-slope versus frequency



Baseline Design of HIPA



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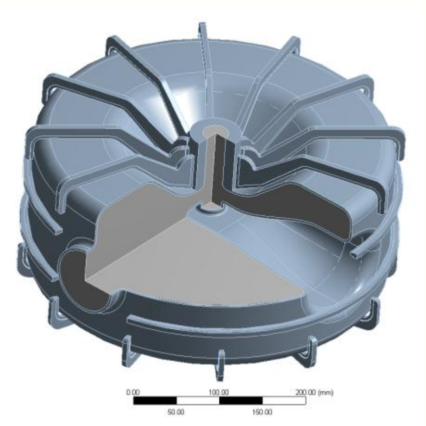
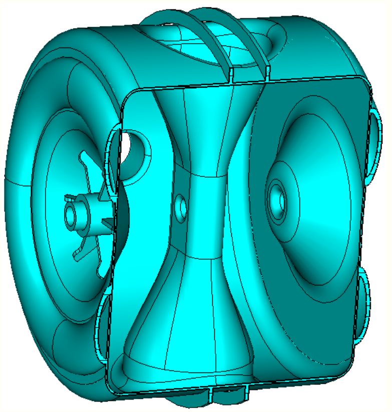
	SSR0	SSR1	SSR2	LE	HE	HE (2-3Gev)
# Cavities	18	20	40	36	96	56
# Solenoids	18	20	20	0	0	0
# Quadrupoles	0	0	0	24	24	14
# Cryomodules	1	2	4	6	12	7
Length (m)	11.38	16.8	34.86	61.93	184.8	107.8
Position (m)	0	11.38	28.18	63.04	124.97	309.77
Period Length (m)	0.61	0.8	1.6	5	15.4	15.4
# periods	18	20	20	12	12	7
Transition Ene (MeV)	10.18	42.57	160.53	515.38	2056	3028
Transition β	0.146	0.291	0.52	0.763	0.95	0.97

325 MHz spoke cavities family



SSR0 - design

SSR1 – prototyping, testing

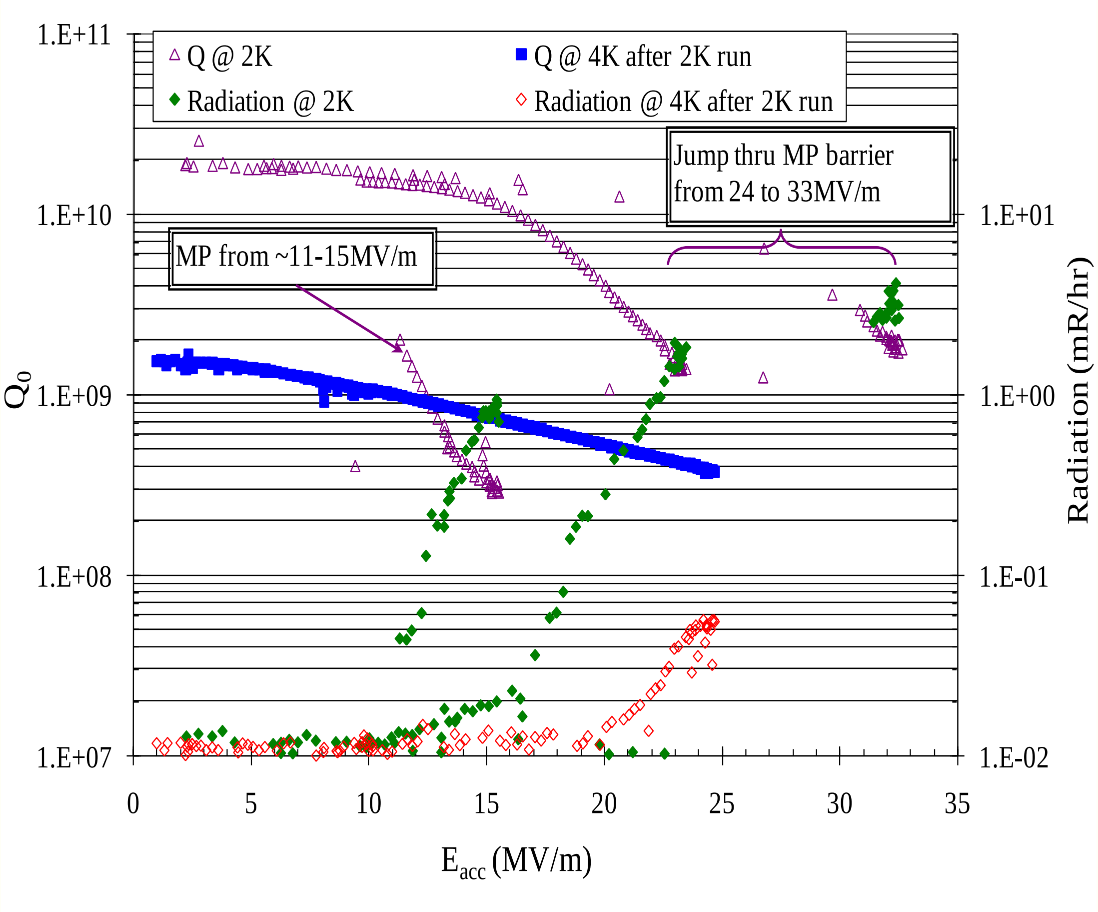


SSR2 - design

Parameters of the Single-Spoke Resonator cavities

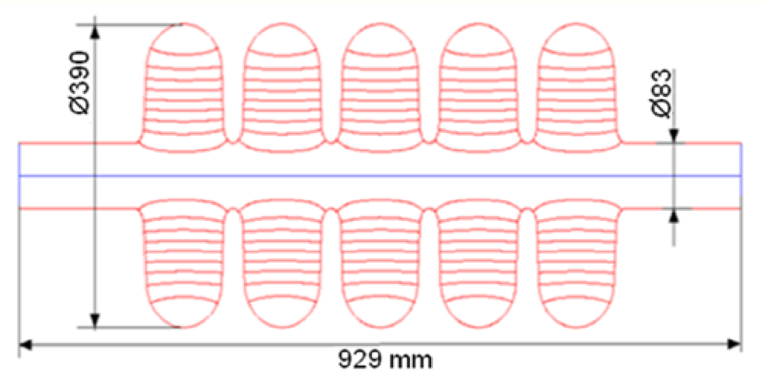
cavity type	β G	Freq MHz	**Beam pipe ø, mm**	$V_{a,\max}$ MeV	$E_{\max}$ MV/m	$B_{\max}$ mT	R/Q, Ω	G, Ω	$^*Q_{0,2K}$ $\times 10^9$	$P_{\max,2K}$ W
SSR0	β=0.114	325	30	0.6	32	39	108	50	6.5	0.5
SSR1	β=0.215	325	30	1.47	28	43	242	84	11.0	0.8
SSR2	β=0.42	325	40	3.34	32	60	292	109	13.0	2.9

325 MHz Cavity Result

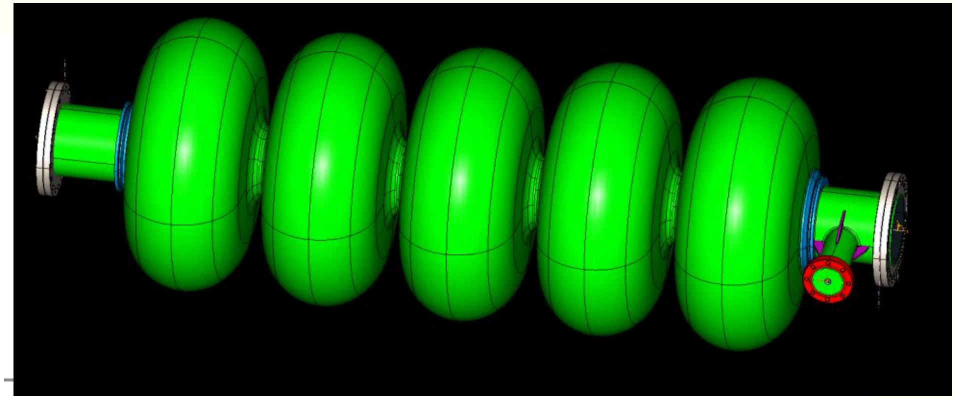


Eacc > 15 MV/m for Q > 1e10
HIPA Design needs < 10 MV/m

650 MHz Cavity Design Parameters



650 MHz: β=0.61



650 MHz: β=0.9

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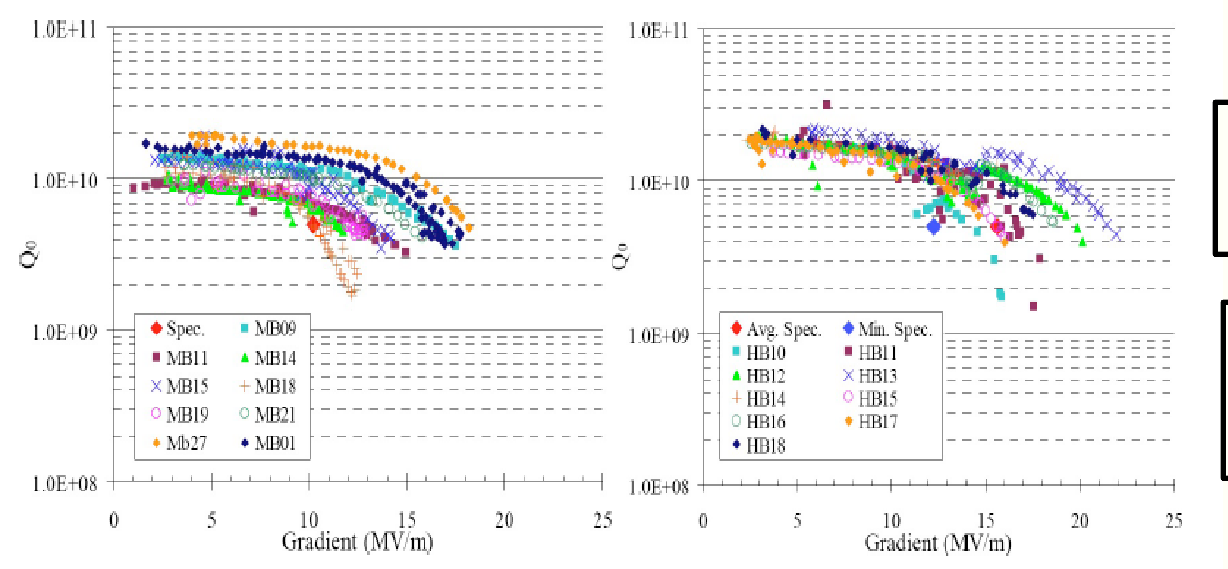
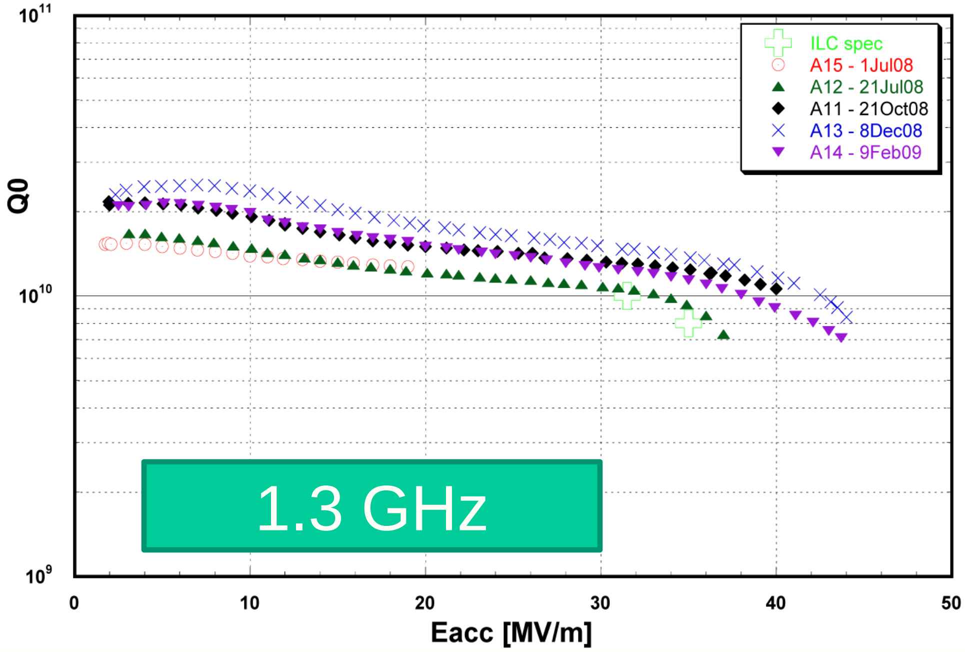
β	0.61	0.9
R/Q, Ohm	378	638
G-factor, Ohm	191	255
Max. gain per cavity, MeV (on crest)	11.3	19.9
Gradient, MeV/m	16.1	19.2
Max. Surface electric field, MV/m	36.4	37.3
E_{pk}/E_{acc}	2.26	2
Max surf magnetic field, mT	68	72
B_{pk}/E_{acc}	4.21	3.75

Cavity Accelerating Gradient

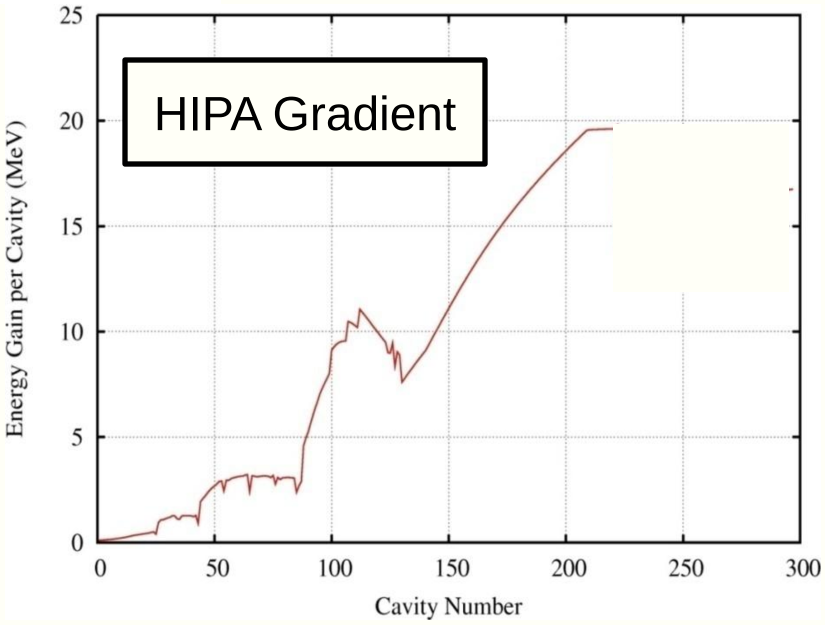


SNS Cavity Result

Cavity Technology Improved in last 10 yrs



1.3 GHz

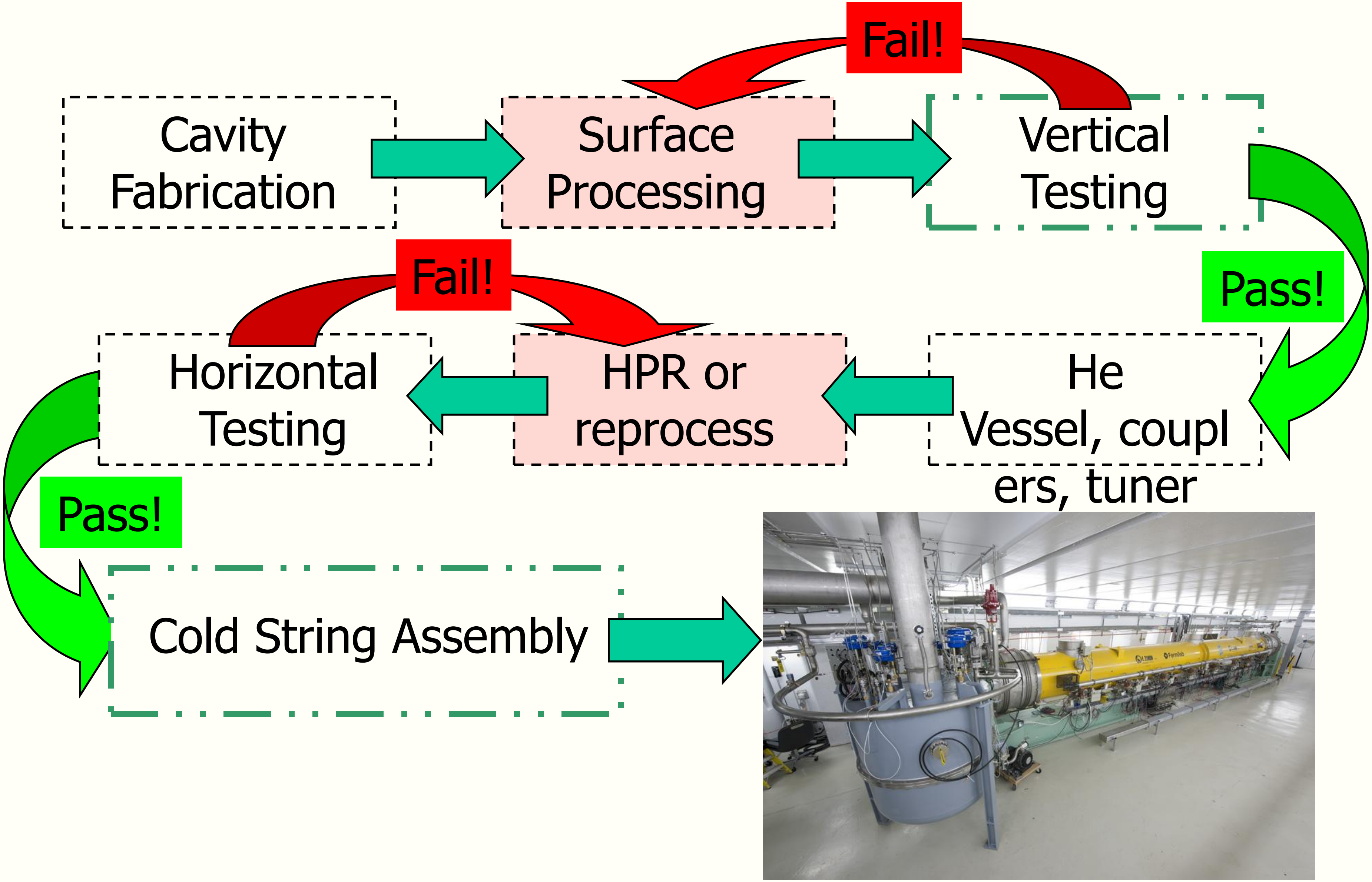


HIPA Gradient

Niobium → Cryomodule

- Cavity Design and Fabrication:
  - Niobium purchased from Industry
  - Nb QA/QC at Laboratory
  - Cavity Fabricated by lab/Industry
  - Cavity QA/QC at Laboratory
- Cavity Process and low power test at Laboratory
  - Bulk processing at lab/industry
  - Fine processing, assembly
  - Vertical Test Stand at laboratory
- Dressed Cavity (He vessel, Tuner, Coupler) at Lab
  - Start at lab but work to transfer this technology to industry
- High Power Test of Dressed Cavity at Lab
  - Horizontal Test Stand
- Cavity String and Cryomodule Fabrication at Laboratory
- Cryomodule Testing at Full Power at lab
  - Cryomodule Test Stand

Cavity & Cryomodule Fabrication



Cavity Fabrication

Surface Processing

Fail!

Vertical Testing

Pass!

He Vessel, couplers, tuner

HPR or reprocess

Fail!

Horizontal Testing

Pass!

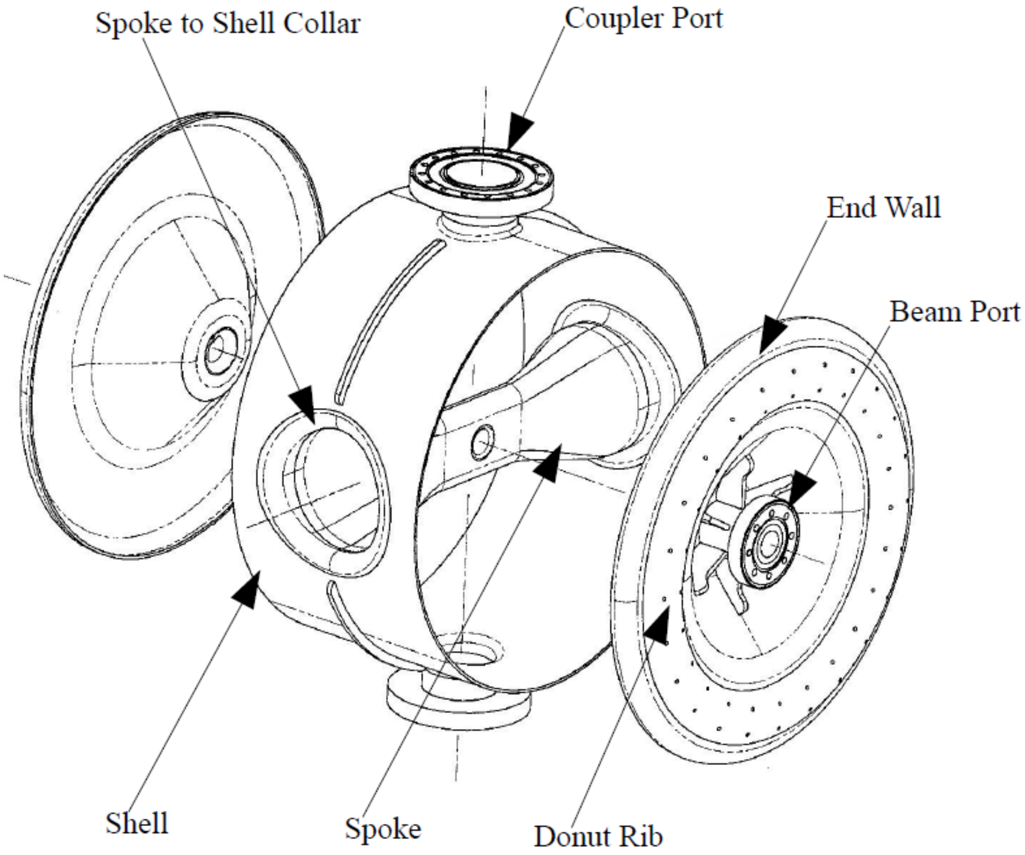
Cold String Assembly

Cavity Fabrication

- **Under the Addendum MOU III and its Supplement I, Indian Institute and Fermilab Collaboration are jointly developing the design and fabrication of Cavity in India.**
  - **SSR1 Cavity is under fabrication at IUAC**
    - **Fermilab transferred all the drawings and tooling information to IUAC.**
    - **IUAC with a local industry has developed all the infrastructure for this cavity fabrication**
    - **First two prototype fabrication is progress. These two will be processed and tested at Fermilab.**
    - **Future processing and testing in India.**
    - **These will be also dressed (VECC) and 325 MHz power coupler attached in India (BARC).**
  - **Elliptical Cavities are under fabrication at RRCAT and VECC**
    - **RRCAT engineering have made many visits to Fermilab and US industries for the development of the cavity fabrication infrastructure in India.**
    - **Development of cavity fabrication technology using 1.3 GHz cavity**
    - **Excellent prototype results.**

Fabrication of SSR1

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



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

Figure 6: Electron beam welding setups showing, (a) above – outer shell, (b) below – spoke halves.

1.3 GHz Elliptical Cavity

- RRCAT in collaboration with IUAC is developing elliptical 1.3 GHz cavities
  - Indian engineers were trained at Fermilab and US industry
- Three 1-cell 1.3 GHz (β=1) cavities have been built by RRCAT, in collaboration with IUAC
  - Two 1-cells were inspected, processed and tested at Fermilab
    - TE1CAT001: Quench at 19 MV/m, Q0 at max gradient > 1.5 E+10
    - TE1CAT002: Quench at 21 MV/m, Q0 at max gradient > 1.0 E+10
    - TE1CAT002 : 2nd test after CBP Quench at 23 MV/m, Q0 > 1.5 E+10
  - A third has recently been built using improved weld parameters and handling, based on feedback received, and will be processed and tested at Fermilab
- A fourth 1.3 GHz 1-cell and one 1.3 GHz 5-cell Cavity with straight end tubes to be built later this year; to be processed and tested at FNAL

1300 MHz Cavity: Forming and Machining

RRCAT: Developed forming tooling & process for 1.3 GHz SCRF cavity.

Forming

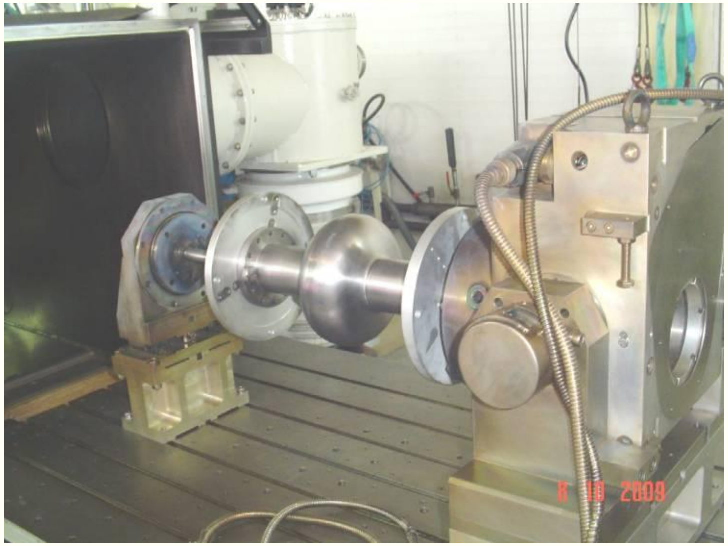
Inspection

120 T - HYDRAULIC PRESS

Machining

Formed Niobium Half cell

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

IIFC Collaborative work

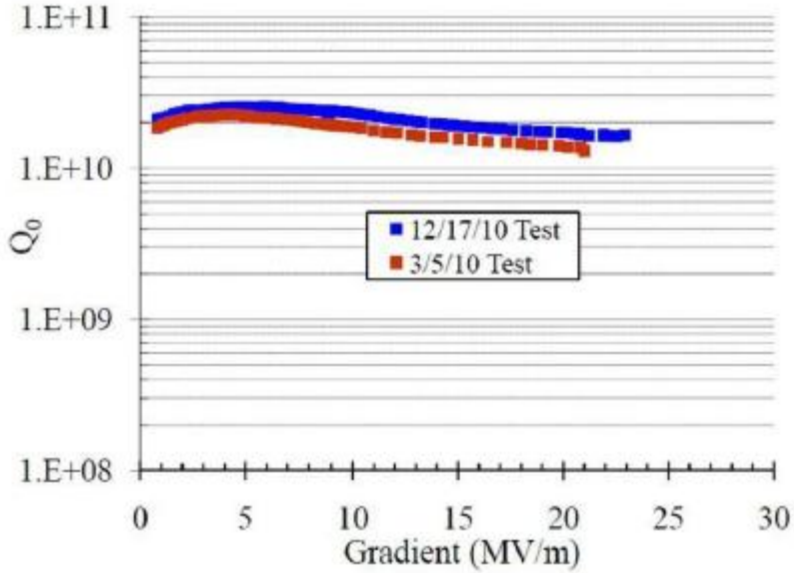


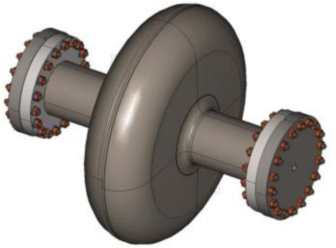
Figure 8: Quality factor Q_0 as a function of accelerating gradient at 2 K, on the second 1.3 GHz single cell cavity.

TE1CAT003 with RRCAT-IUAC & FNAL team members

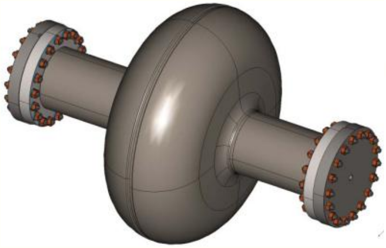
650 MHz FNAL progress

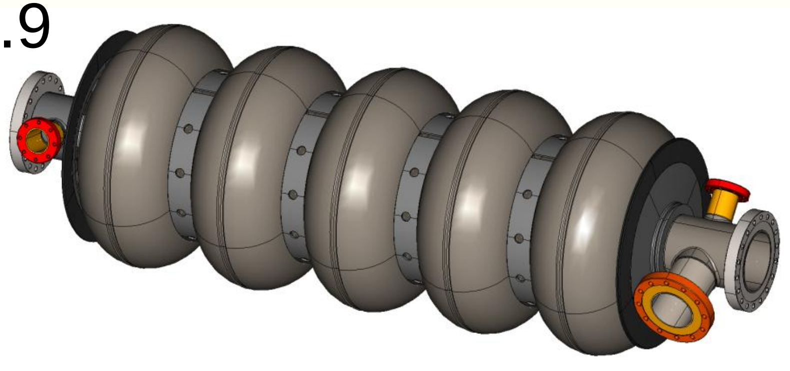
- **Preliminary 1-cell design for both betas was presented at LINAC10** **(MOP099 by S. Barbanotti et al.)**
- **5-cell β=0.9 cavity design nearly final**

β=0.61



β=0.9



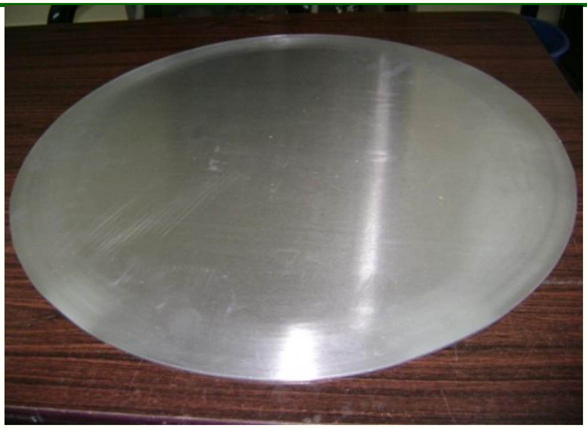


- **Cavity fabrication**
  - **Ordered six prototype β=0.9 1-cells from industry (AES), first two expected July 2011**
  - **Will order 2 prototype β=0.9 5-cells soon**
- **Cavity infrastructure development for process and test in progress**

650 MHz IIFC Progress

- **650 MHz β=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



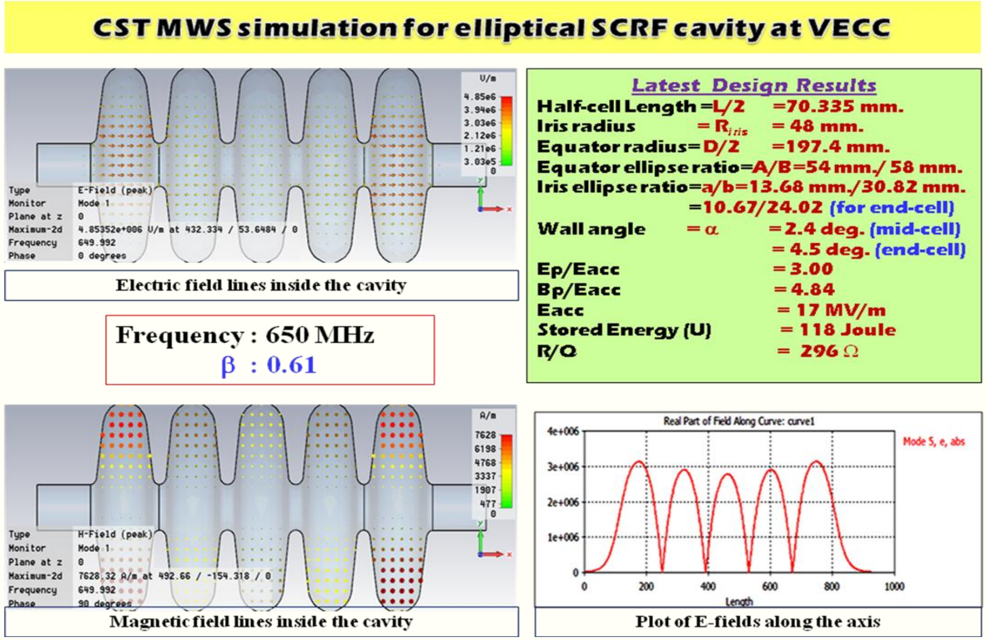
Aluminum blank, 3mm thickness

Die-Punch Set mounted on Press at RRCAT

Beginning of forming trials with aluminum

650 MHz IIFC Progress

- **Simulations of 650 MHz β=0.61 5-cell cavity at VECC**
  - **Design comparison using FNAL design input: 2D-SLANS [FNAL], 3D-HFSS [VECC], 3D-CST [VECC], 2D-SUPERFISH [VECC]**
  - **Some modifications to FNAL design also simulated in 3D-HFSS**
  - **Fruitful interactions of VECC staff with Fermilab and JLab RF designers have occurred**



CST MWS simulation for elliptical SCRF cavity at VECC

```
Type           E-Field (peak)
Monitor        Mode 1
Plane at z     0
Maximum-2d     4.85352e+006 U/m at 432.334 / 53.6484 / 0
Frequency      649.992
Phase          0 degrees
```

Electric field lines inside the cavity

Frequency : 650 MHz
β : 0.61

Latest Design Results

Half-cell Length = L/2 = 70.335 mm.
Iris radius = R_{iris} = 48 mm.
Equator radius = D/2 = 197.4 mm.
Equator ellipse ratio = A/B = 54 mm./ 58 mm.
Iris ellipse ratio = a/b = 13.68 mm./30.82 mm.
= 10.67/24.02 (for end-cell)
Wall angle = α = 2.4 deg. (mid-cell)
= 4.5 deg. (end-cell)
Ep/Eacc = 3.00
Bp/Eacc = 4.84
Eacc = 17 MV/m
Stored Energy (U) = 118 Joule
R/Q = 296 Ω

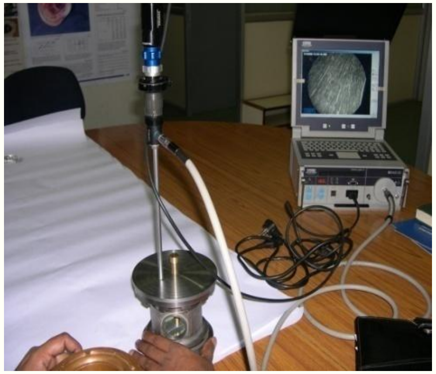
```
Type           H-Field (peak)
Monitor        Mode 1
Plane at z     0
Maximum-2d     7628.32 A/m at 492.66 / -154.318 / 0
Frequency      649.992
Phase          90 degrees
```

Magnetic field lines inside the cavity

Plot of E-fields along the axis

End Group Development (RRCAT)

Development of prototype in Low RRR Nb completed at Workshop, RRCAT.



Baroscopic examination

High RRR end group Machining in progress

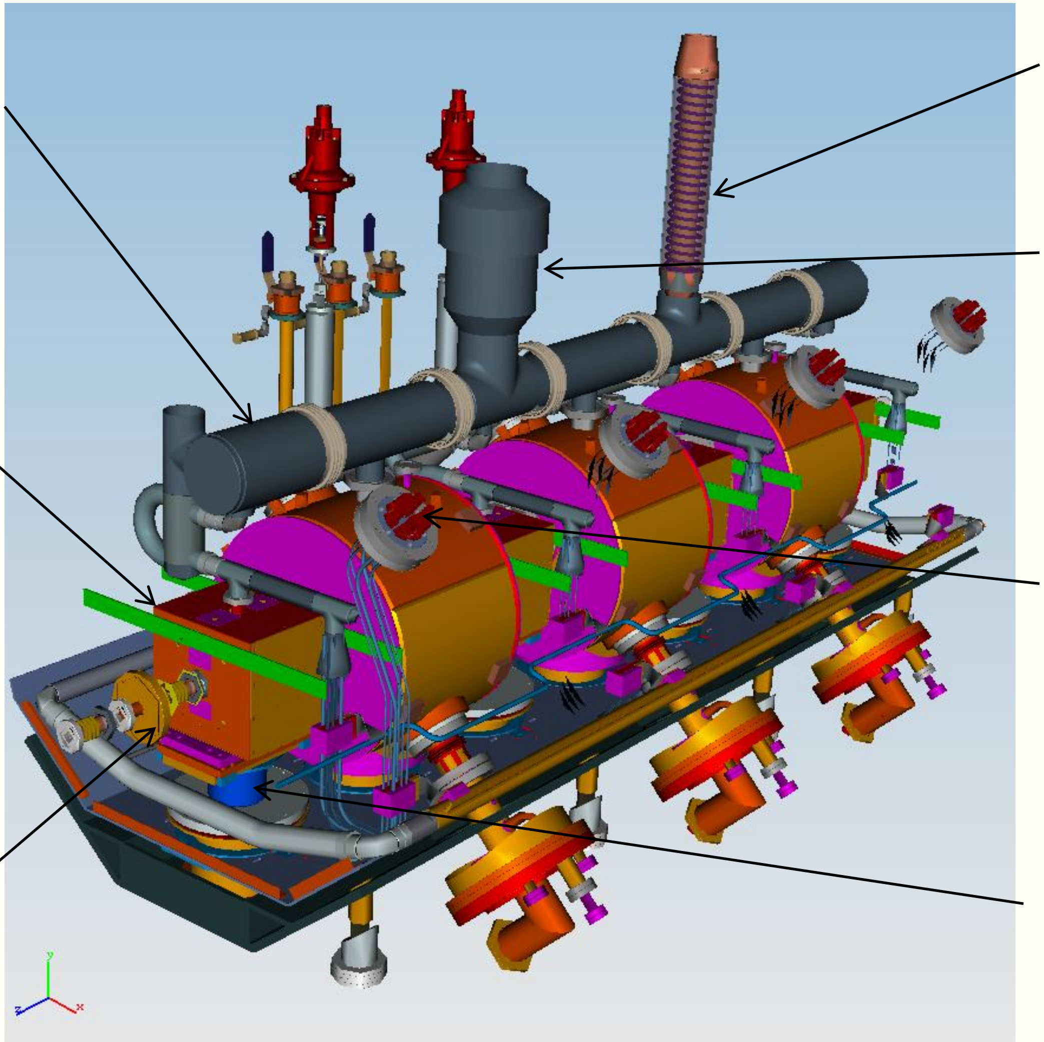
Concept

- Machine out entire end group from a single billet of Nb. Billet is cheaper.
- Material from bore used for making HOM coupler and Form teil.

Advantages

1. **Easy manufacturing, Less Fabrication time.**
2. **Just 6 EB weld Joints instead of 13.**
3. **Pre Weld Etching reduced.**
4. **No pull out operations.**
5. **Machining operations. Better control on tolerances.**
6. **Rejections go down. Error in later welding stages causes complete rejection of job.**
7. **LOWER COST: $16500 per end group $27000. (Machining costs in India)**

Spoke Resonator Cryomodule



2-phase header

Solenoid
and shield

C/W transition

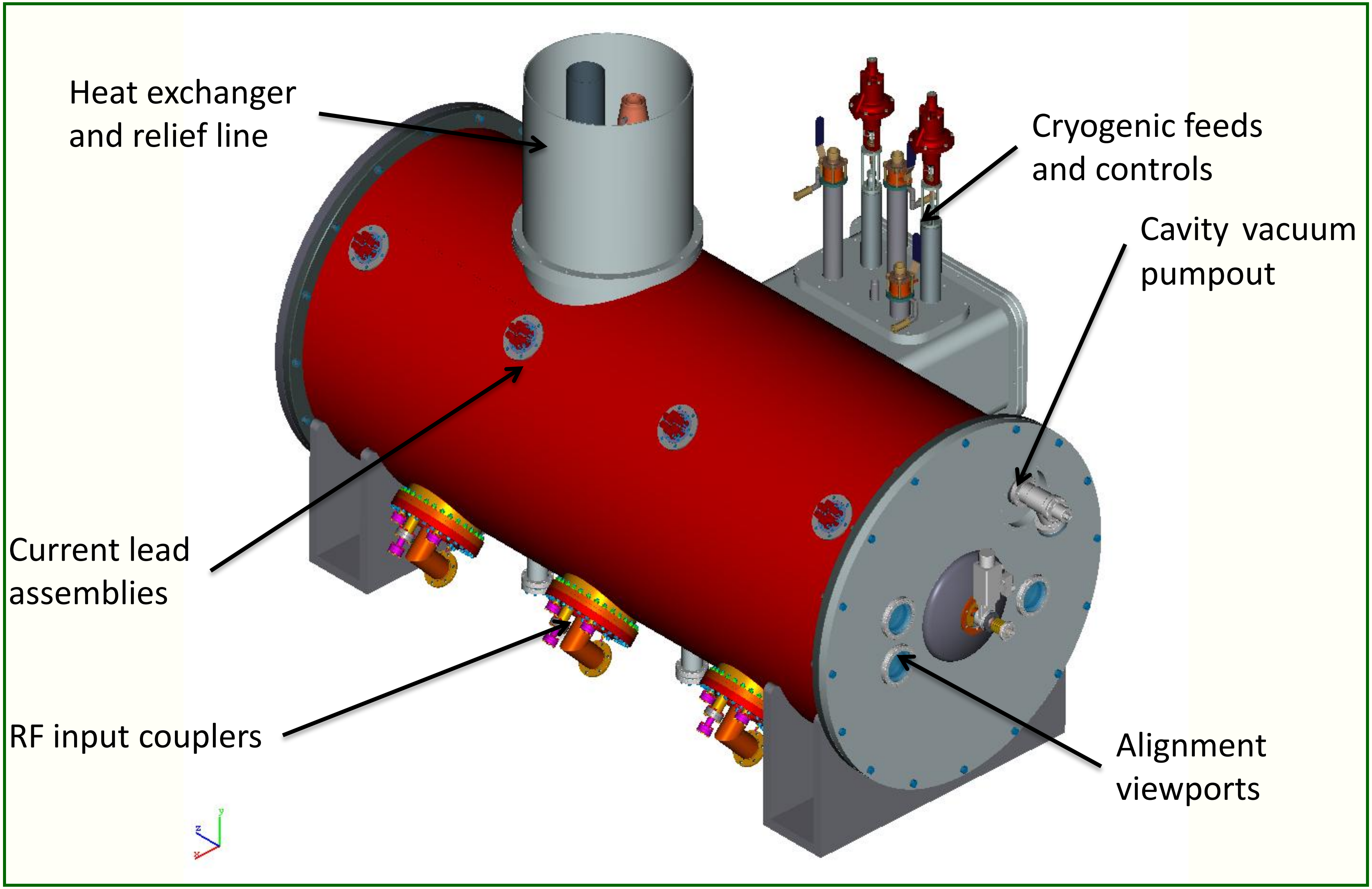
Heat exchanger

Check valve (may omit)

Current lead assembly

Solenoid pedestal

Prototype SSR cryomodule



Heat exchanger and relief line

Cryogenic feeds and controls

Cavity vacuum pumpout

Current lead assemblies

RF input couplers

Alignment viewports

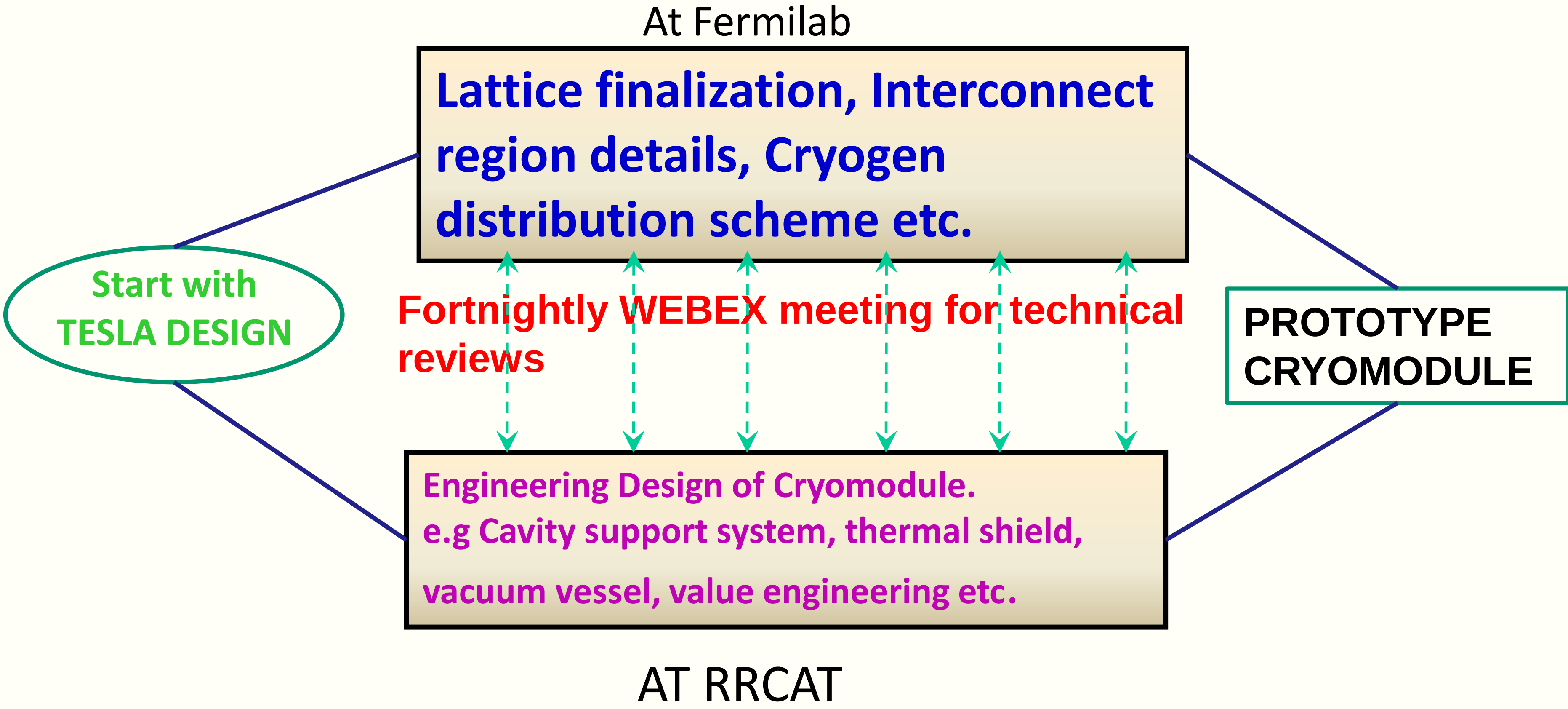
Development of Cryomodule

Initiated 650 MHz Cryomodule (CW type)

- **650 MHz cryomodule team**
  - Design Effort is spearheaded by Tom Peterson (Sub Proj.Manager FNAL)
  - Prashant Khare, (with 4 engineers from RRCAT) is leading Indian effort . (Acts as point of contact for Indian Institutions)
  - Yuriy Orlov (Fermilab point of contact)
- **Design status**
  - Completed Cross Cultural study of designs prevalent at other accelerator laboratories (Jointly by RRCAT and Fermilab)
  - Finalized the Overall mechanical and thermal design. A closed-ended cryomodule similar to TESLA-Type selected as an initial baseline .

    Despite Choosing the Tesla Type as a baseline
    - Designs differ due to various kinds of requirements as this will be a CW cryomodule
    - Generally means adapting but not copying design concepts for Project X
  - Completed the design of Vacuum vessel, Thermal Shields and concurrent prototyping of cavity support system is in progress.
  - Value engineering of entire cryomodule forms a significant part of the effort.

The Approach



At Fermilab

Lattice finalization, Interconnect region details, Cryogen distribution scheme etc.

Start with TESLA DESIGN

Fortnightly WEBEX meeting for technical reviews

PROTOTYPE CRYOMODULE

Engineering Design of Cryomodule.
e.g Cavity support system, thermal shield,
vacuum vessel, value engineering etc.

AT RRCAT

Unique Features:- As compared to conventional Tesla type Cryomodule.

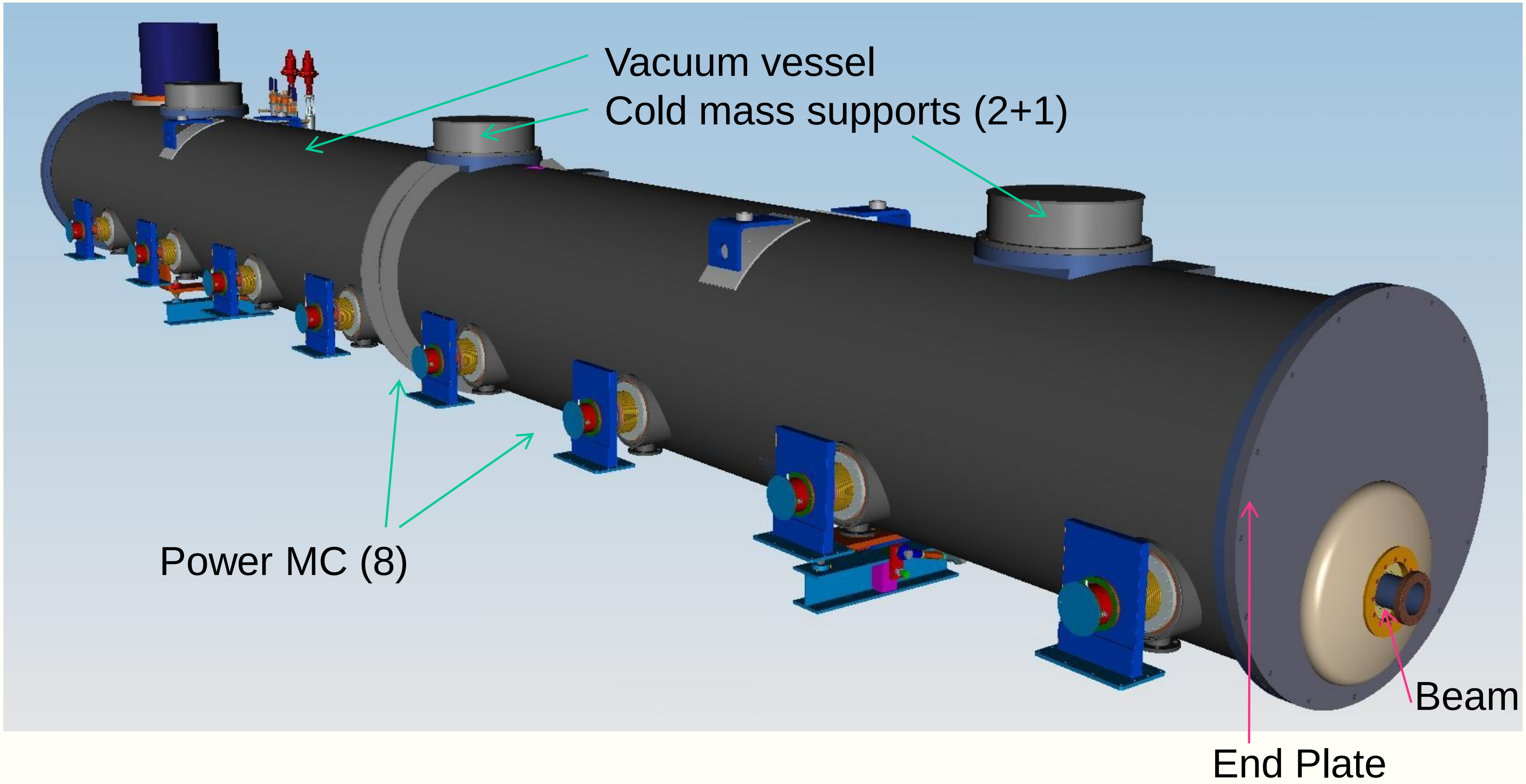
- ❖650 MHz Cryomodule has a heat load of 25 W/cavity as it operates in CW mode. Earlier it was 0.9 W/cavity.
- ❖The size of the cavity is almost two times i.e. 400mm dia.

Design Status

- Various cryomodule designs from laboratories around the world have been reviewed by Fermilab and RRCAT to understand "the state of the art" and to supplement our design concepts
  - Designs differ due to various kinds of requirements
  - Generally means adapting but not copying design concepts for Project X
- Overall mechanical and thermal design based on a closed-ended TESLA-style cryomodule has been selected as an initial baseline
  - Design incorporates unique features for high dynamic heat loads at 2 K (~25 W/cavity)
  - CW operation and RF power tightly constrain cavity tune and microphonics

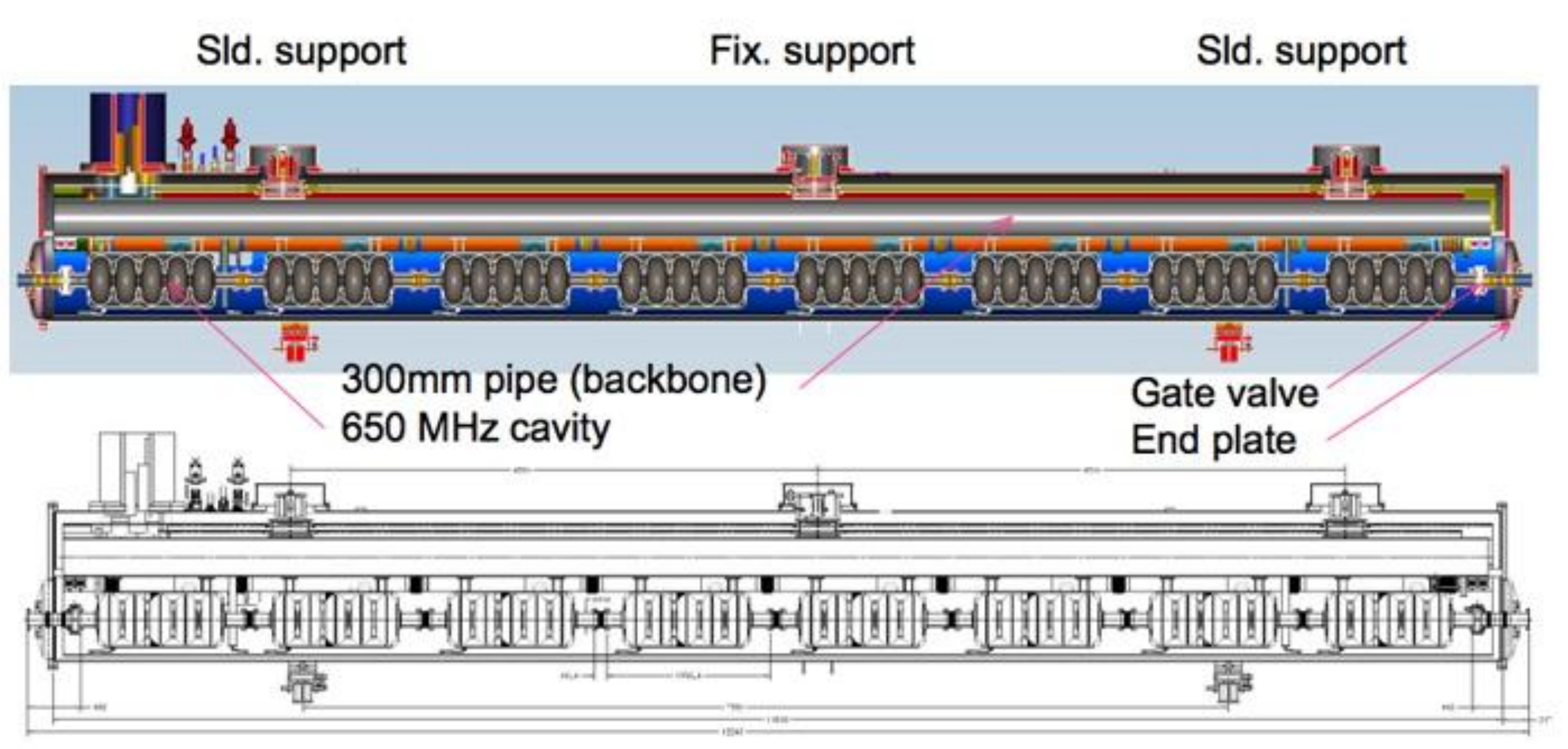
650 MHz Cryomodule

(Tesla Style-Stand Alone Concept Fermilab)



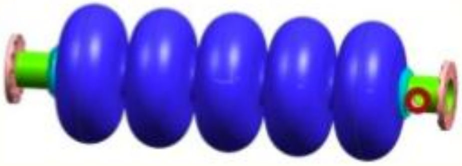
650 MHz Cryomodule

Tesla Style Concept Cross-section Fermilab



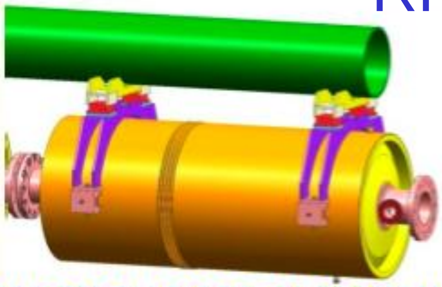
650 MHz CRYOMODULE & ITS SUBSYSTEMS

RRCAT

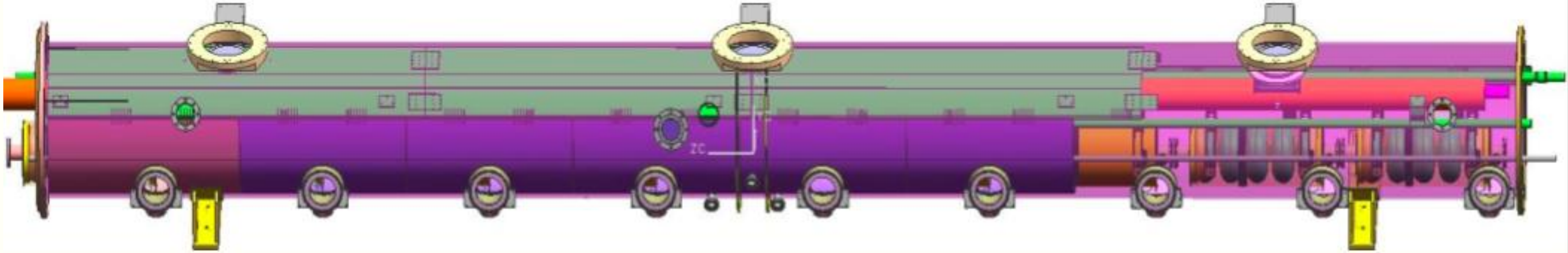


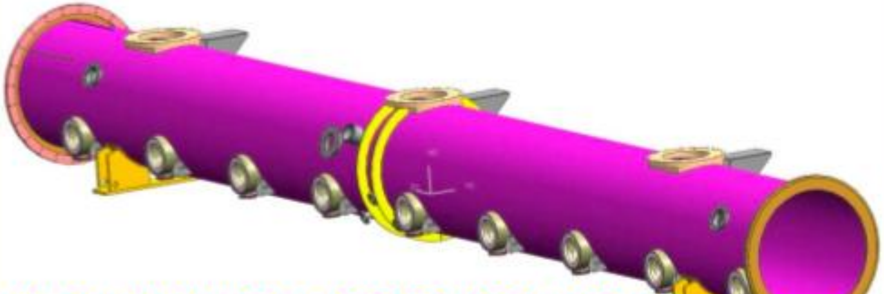
650 MHz SCRF CAVITY-UNDER FABRICATION AT RRCAT

He VESSEL to be fabricated

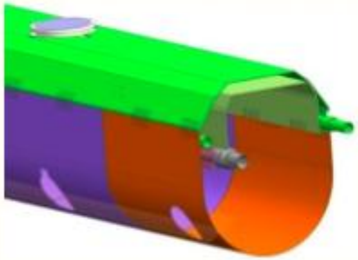


CAVITY SUPORT SYSTEM UNDER PROTOTYPING AT RRCAT

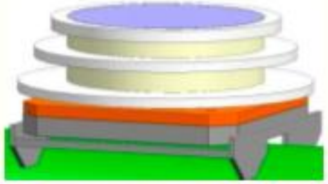




VACUUM VESSEL FOR CRYOMODULE UNDER DESIGNING AT RRCAT



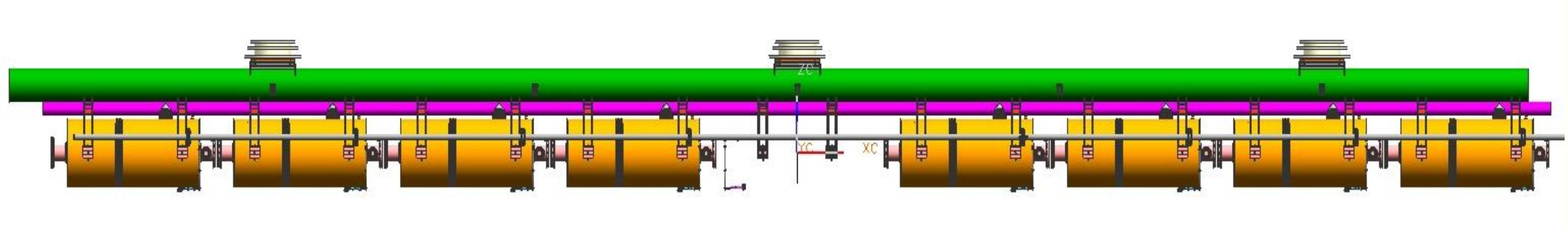
THERMAL SHIELD UNDER DESIGNING AT RRCAT



CRYOGENIC SUPPORT POST UNDER PROTOTYPING AT RRCAT

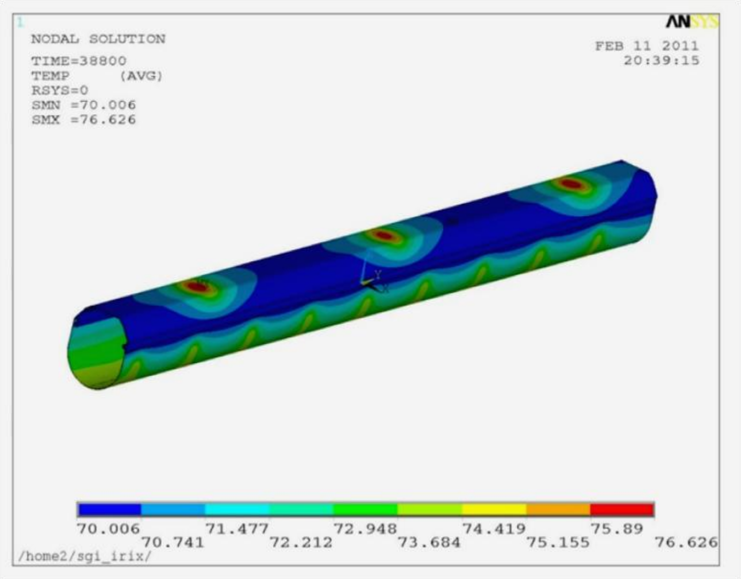
Glimpses of 650 MHz CM 3-D Model (more from RRCAT contd…)

SCRF Cavity supported on HGR pipe

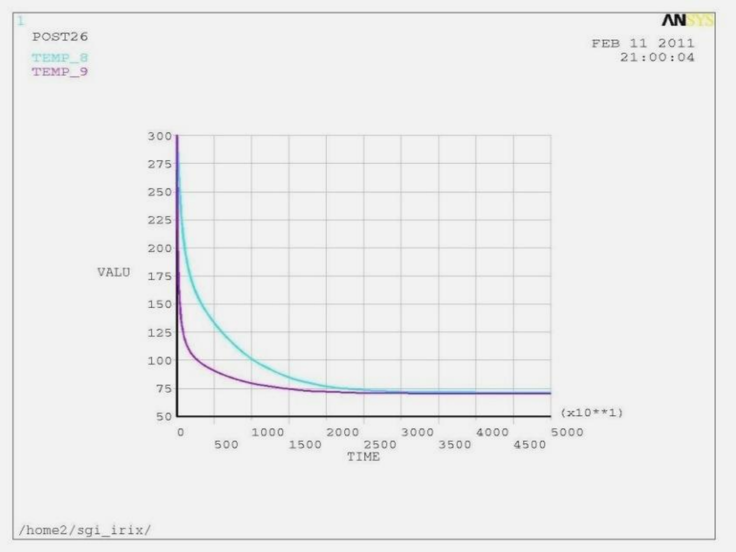


- The model incorporates a modified Cavity support system.
- 2K helium supply line includes a bellow in vertical configuration

Steady State & Transient Thermal Analysis



1. Mass flow rate- 24 gm/sec
2. Convection heat transfer coefficient- 200 W/m2K
3. Heat load:
   Through support post: 10 watt per support post
   Through coupler input: 2 watt per coupler input

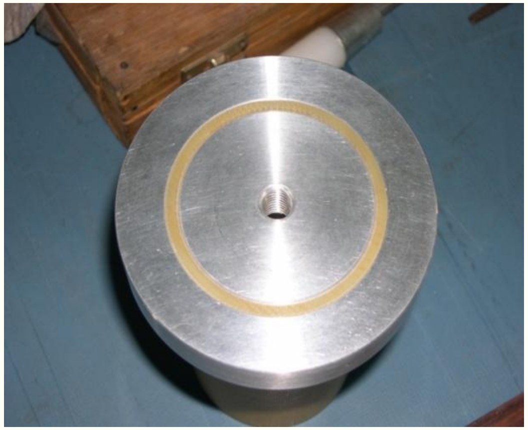


A. Cool down reached in 10.7 Hour

B. Max temperature gradient is found to be less than 40 K at finger weld region

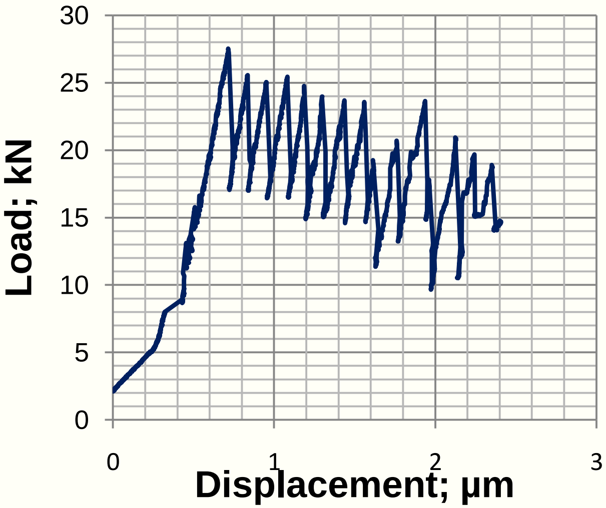
C. Fig. shows the temperature plot of 70 K thermal shield after 10.7 hours

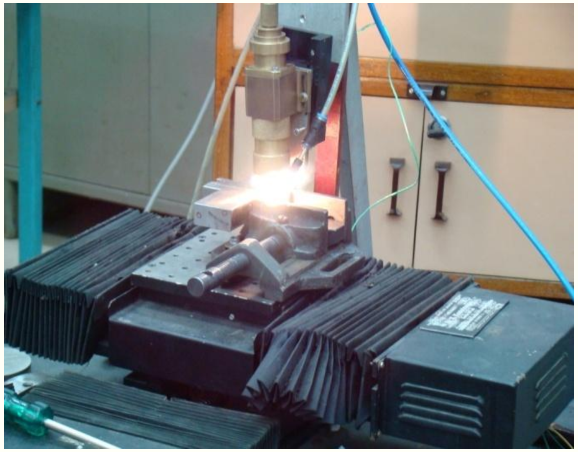
Snippets of Prototyping & Testing



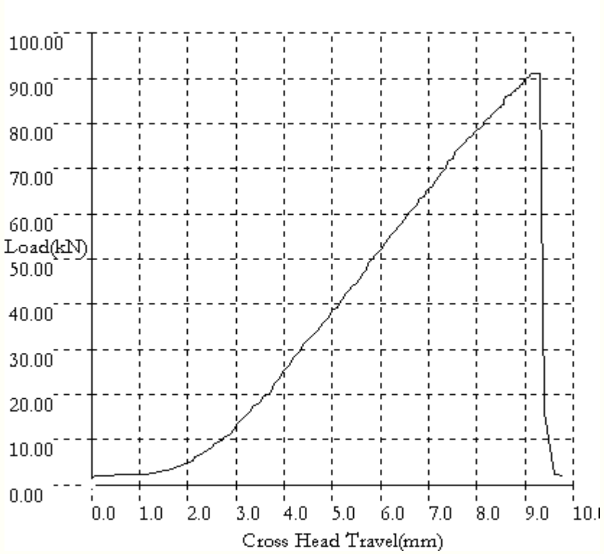
Cryogenic Support Post

Load Testing of Cryogenic Support Post prototype at RRCAT



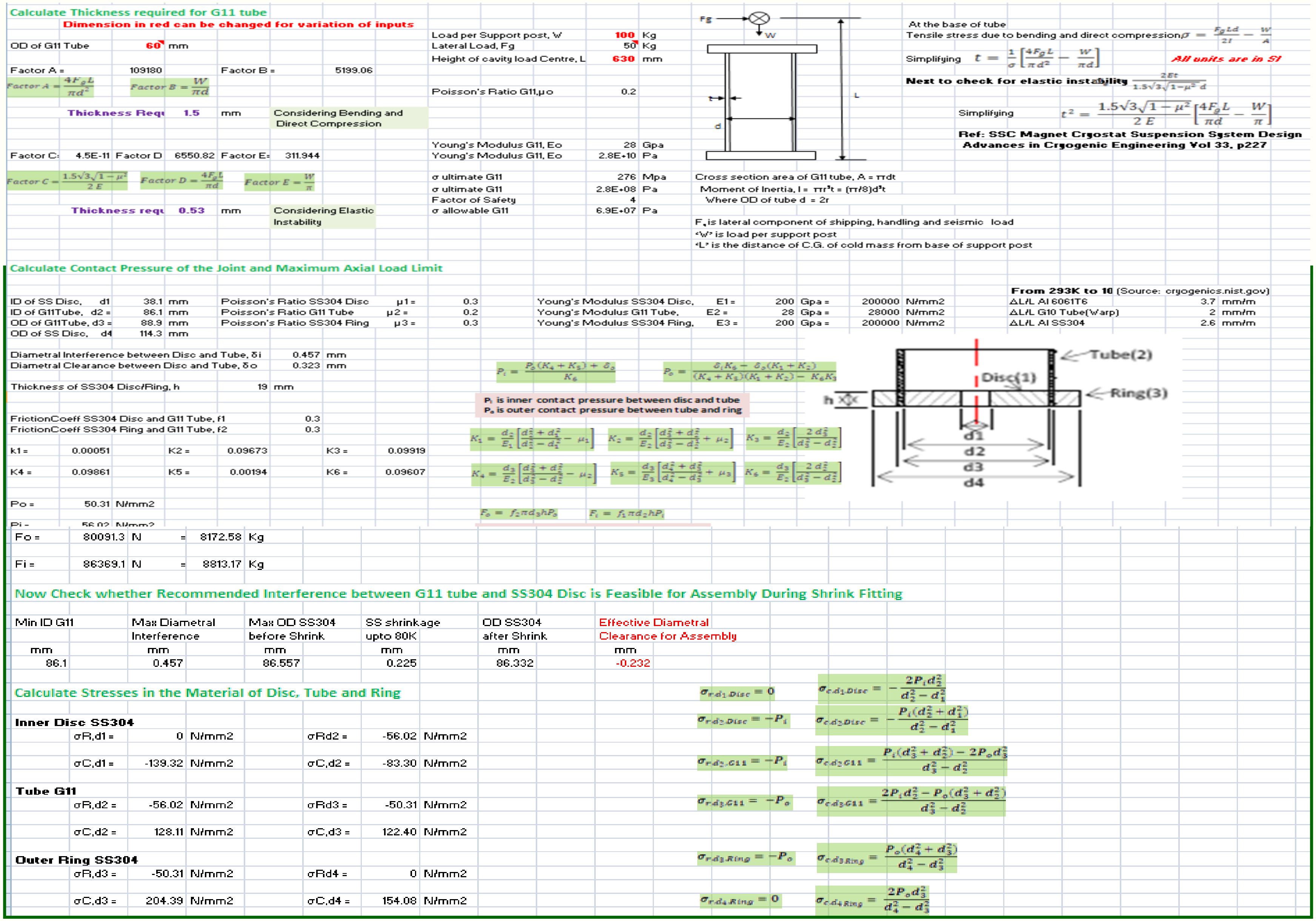


Laser welding of Cavity Support system at RRCAT



Load Testing of Cavity Support System

All calculations done on Spreadsheet (to Facilitate Any Change)



Calculate Thickness required for G11 tube

Dimension in red can be changed for variation of inputs

OD of G11 Tube	60	mm	
Factor A =	109180	Factor B =	5199.06

$Factor\ A = \frac{4F_gL}{\pi d^2}$ $Factor\ B = \frac{W}{\pi d}$

Thickness Requ 1.5 mm — Considering Bending and Direct Compression

Factor C:	4.5E-11	Factor D	6550.82	Factor E:	311.944

$Factor\ C = \frac{1.5\sqrt{3}\sqrt{1-\mu^2}}{2\ E}$ $Factor\ D = \frac{4F_gL}{\pi d}$ $Factor\ E = \frac{W}{\pi}$

Thickness requ 0.53 mm — Considering Elastic Instability

Load per Support post, W	100	Kg
Lateral Load, Fg	50	Kg
Height of cavity load Centre, L	630	mm
Poisson's Ratio G11,μo	0.2	
Young's Modulus G11, Eo	28	Gpa
Young's Modulus G11, Eo	2.8E+10	Pa
σ ultimate G11	276	Mpa
σ ultimate G11	2.8E+08	Pa
Factor of Safety	4	
σ allowable G11	6.9E+07	Pa

At the base of tube

Tensile stress due to bending and direct compression $\sigma = \frac{F_gLd}{2I} - \frac{W}{A}$

Simplifying $t = \frac{1}{\sigma}\left[\frac{4F_gL}{\pi d^2} - \frac{W}{\pi d}\right]$

All units are in SI

Next to check for elastic instability $\frac{2Et}{1.5\sqrt{3}\sqrt{1-\mu^2}\ d}$

Simplifying $t^2 = \frac{1.5\sqrt{3}\sqrt{1-\mu^2}}{2\ E}\left[\frac{4F_gL}{\pi d} - \frac{W}{\pi}\right]$

Ref: SSC Magnet Cryostat Suspension System Design
Advances in Cryogenic Engineering Vol 33, p227

Cross section area of G11 tube, A = πdt
Moment of Inertia, I = πr³t = (π/8)d³t
Where OD of tube d = 2r

F_g is lateral component of shipping, handling and seismic load
'W' is load per support post
'L' is the distance of C.G. of cold mass from base of support post

Calculate Contact Pressure of the Joint and Maximum Axial Load Limit

ID of SS Disc, d1	38.1	mm	Poisson's Ratio SS304 Disc	μ1 =	0.3
ID of G11Tube, d2 =	86.1	mm	Poisson's Ratio G11 Tube	μ2 =	0.2
OD of G11Tube, d3 =	88.9	mm	Poisson's Ratio SS304 Ring	μ3 =	0.3
OD of SS Disc, d4	114.3	mm			

Young's Modulus SS304 Disc,	E1 =	200	Gpa =	200000	N/mm2
Young's Modulus G11 Tube,	E2 =	28	Gpa =	28000	N/mm2
Young's Modulus SS304 Ring,	E3 =	200	Gpa =	200000	N/mm2

From 293K to 10 (Source: cryogenics.nist.gov)

ΔL/L Al 6061T6	3.7	mm/m
ΔL/L G10 Tube(Warp)	2	mm/m
ΔL/L Al SS304	2.6	mm/m

Diametral Interference between Disc and Tube, δi	0.457	mm
Diametral Clearance between Disc and Tube, δo	0.323	mm
Thickness of SS304 Disc/Ring, h	19	mm
FrictionCoeff SS304 Disc and G11 Tube, f1	0.3	
FrictionCoeff SS304 Ring and G11 Tube, f2	0.3	

$P_i = \frac{P_o(K_4+K_5)+\delta_o}{K_6}$ $P_o = \frac{\delta_i K_6 - \delta_o(K_1+K_2)}{(K_4+K_5)(K_1+K_2) - K_6K_3}$

P_i is inner contact pressure between disc and tube
P_o is outer contact pressure between tube and ring

$K_1 = \frac{d_2}{E_1}\left[\frac{d_2^2+d_1^2}{d_2^2-d_1^2} - \mu_1\right]$ $K_2 = \frac{d_2}{E_2}\left[\frac{d_3^2+d_2^2}{d_3^2-d_2^2} + \mu_2\right]$ $K_3 = \frac{d_2}{E_2}\left[\frac{2\ d_3^2}{d_3^2-d_2^2}\right]$

$K_4 = \frac{d_3}{E_2}\left[\frac{d_3^2+d_2^2}{d_3^2-d_2^2} - \mu_2\right]$ $K_5 = \frac{d_3}{E_3}\left[\frac{d_4^2+d_3^2}{d_4^2-d_3^2} + \mu_3\right]$ $K_6 = \frac{d_3}{E_2}\left[\frac{2\ d_2^2}{d_3^2-d_2^2}\right]$

k1 =	0.00051	K2 =	0.09673	K3 =	0.09919
K4 =	0.09861	K5 =	0.00194	K6 =	0.09607

Po =	50.31	N/mm2
Pi =	56.02	N/mm2

$F_o = f_2\pi d_3hP_o$ $F_i = f_1\pi d_2hP_i$

Fo =	80091.3	N	=	8172.58	Kg
Fi =	86369.1	N	=	8813.17	Kg

Now Check whether Recommended Interference between G11 tube and SS304 Disc is Feasible for Assembly During Shrink Fitting

Min ID G11 mm	Max Diametral Interference mm	Max OD SS304 before Shrink mm	SS shrinkage upto 80K mm	OD SS304 after Shrink mm	Effective Diametral Clearance for Assembly mm
86.1	0.457	86.557	0.225	86.332	-0.232

Calculate Stresses in the Material of Disc, Tube and Ring

Inner Disc SS304

σR,d1 =	0	N/mm2	σRd2 =	-56.02	N/mm2
σC,d1 =	-139.32	N/mm2	σC,d2 =	-83.30	N/mm2

Tube G11

σR,d2 =	-56.02	N/mm2	σRd3 =	-50.31	N/mm2
σC,d2 =	128.11	N/mm2	σC,d3 =	122.40	N/mm2

Outer Ring SS304

σR,d3 =	-50.31	N/mm2	σRd4 =	0	N/mm2
σC,d3 =	204.39	N/mm2	σC,d4 =	154.08	N/mm2

$\sigma_{r\text{-}d_1.Disc} = 0$ $\sigma_{c\text{-}d_1.Disc} = -\frac{2P_id_2^2}{d_2^2-d_1^2}$

$\sigma_{r\text{-}d_2.Disc} = -P_i$ $\sigma_{c\text{-}d_2.Disc} = -\frac{P_i(d_2^2+d_1^2)}{d_2^2-d_1^2}$

$\sigma_{r\text{-}d_2.G11} = -P_i$ $\sigma_{c\text{-}d_2G11} = \frac{P_i(d_3^2+d_2^2)-2P_od_3^2}{d_3^2-d_2^2}$

$\sigma_{r\text{-}d_3.G11} = -P_o$ $\sigma_{c\text{-}d_3G11} = \frac{2P_id_2^2-P_o(d_3^2+d_2^2)}{d_3^2-d_2^2}$

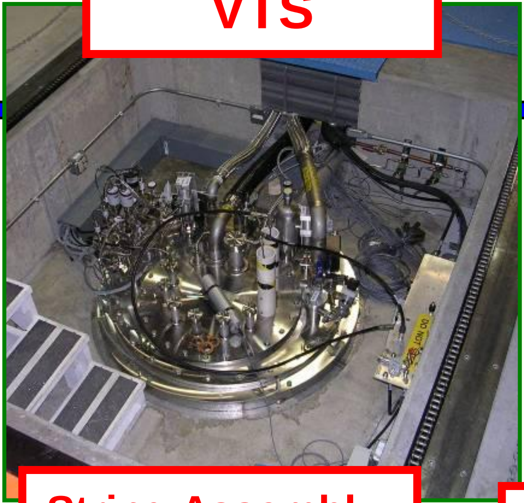
$\sigma_{r\text{-}d_3.Ring} = -P_o$ $\sigma_{c\text{-}d_3.Ring} = \frac{P_o(d_4^2+d_3^2)}{d_4^2-d_3^2}$

$\sigma_{r\text{-}d_4.Ring} = 0$ $\sigma_{c\text{-}d_4.Ring} = \frac{2P_od_3^2}{d_4^2-d_3^2}$

Remarks on Cryomodule Development

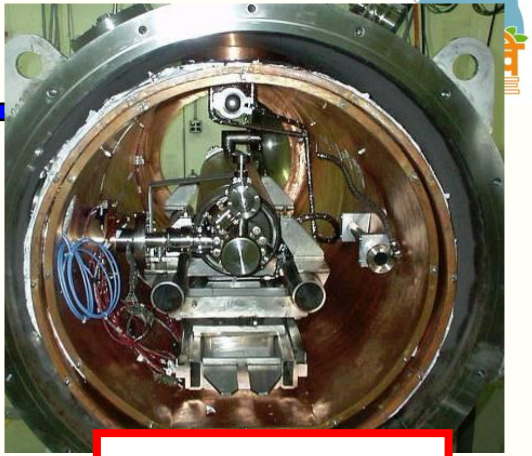
- Many very good ideas and much work have already gone into cryomodule design by various laboratories around the world .
- Fermilab and RRCAT are building upon the experience from these laboratories as well as continuing our own analysis & design work in developing a cryomodule design for the unique requirements of 650 MHz, CW section of the Project X linac.
- Tesla type of cryomodule has been taken as the baseline and this design is being modified to accommodate the requirements of the project .
- A major value engineering exercise has been taken up .
- Very close interaction through fortnightly WEBEX meetings has resulted in covering a lot of ground.

VTS



VTS

ANL/FNAL EP



String Assembly

MP9 Clean Room

HTS

Final Assembly

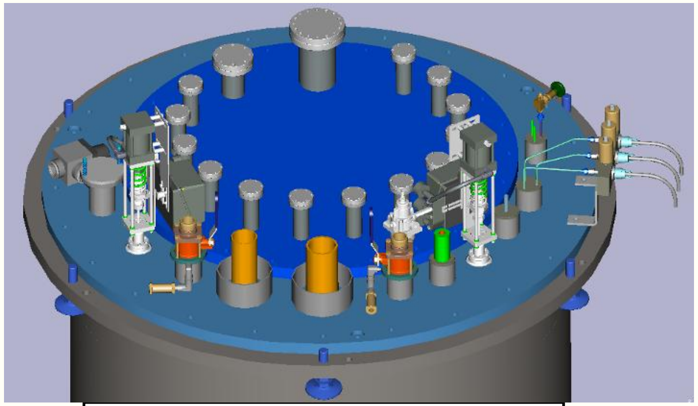
1st U.S. built ILC/PX Cryomodule

1st Dressed Cavity

Fermilab Vertical Test Stand

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**



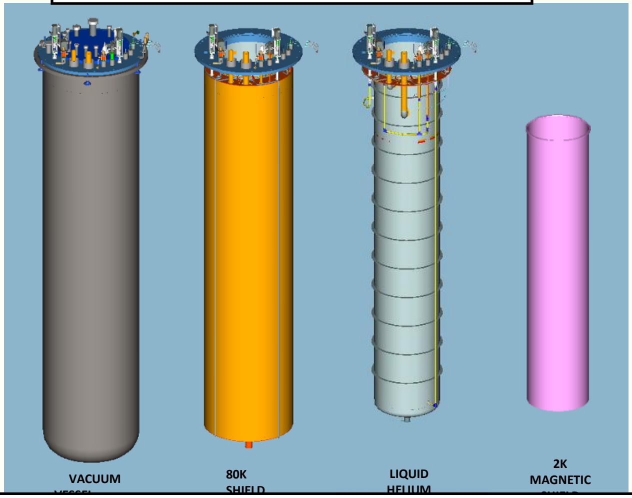
VTS-2 TOP PLATE – CRYOGENIC & VACUUM INSERTS

- **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

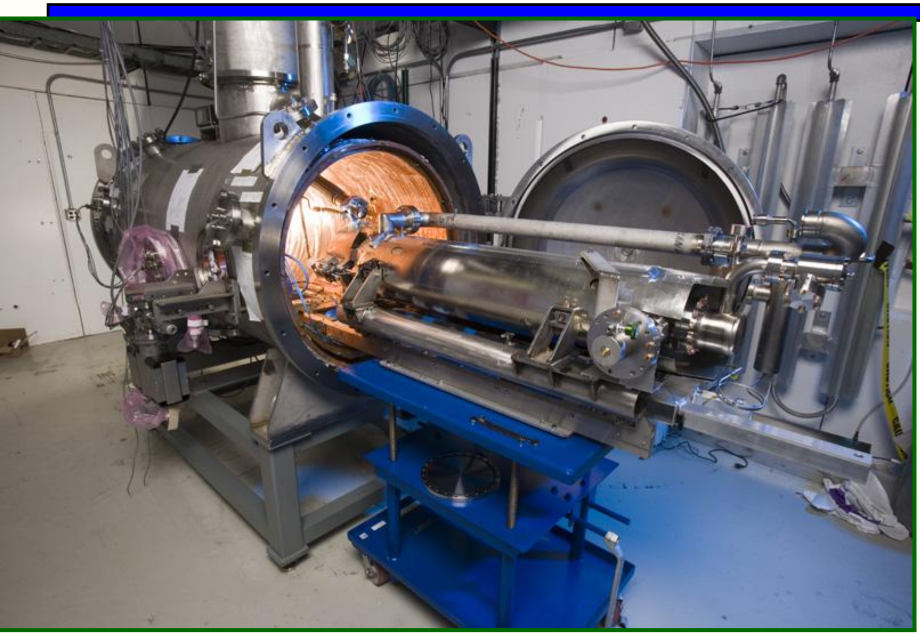
- **RRCAT has also verified the design of following by Analysis**

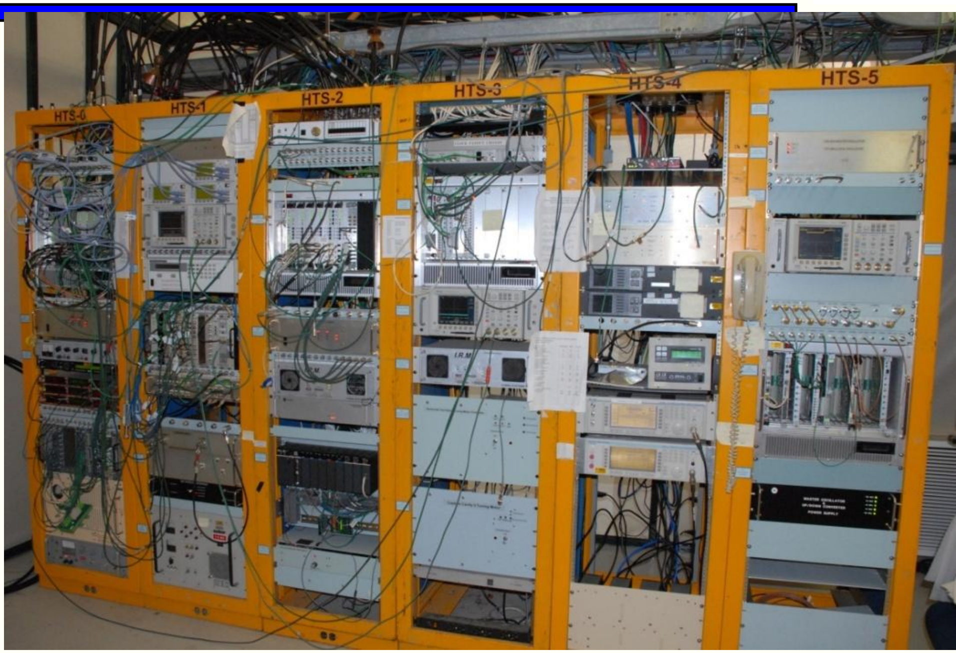
– Assembly of LHe Vessel Top Flange, Weld Rim
– Top Insert Plate
– Assembly of Vacuum Vessel Flange, LHe Vessel Flange, Top Plate, Support Pads
– Magnetic Shield design – 300K & 2K



3-D MODELS OF VTS-2 VESSELS

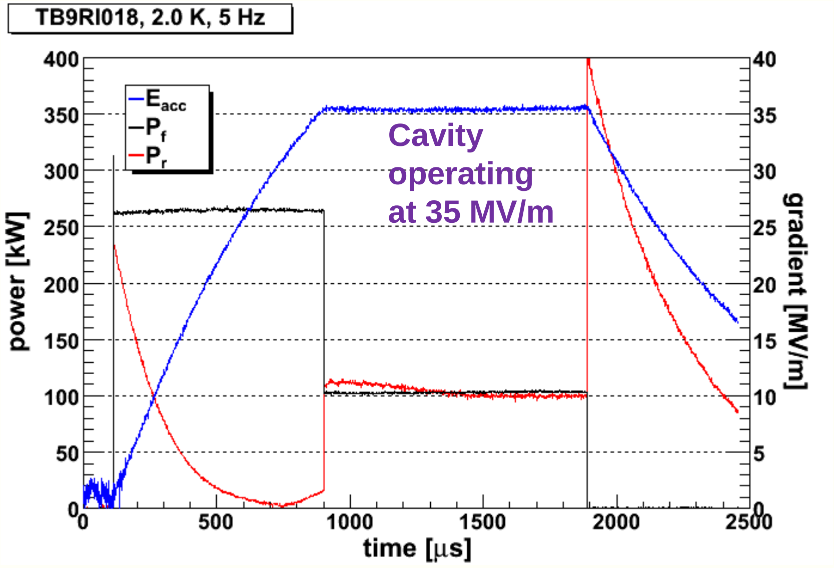
Horizontal Test Stand (HTS)



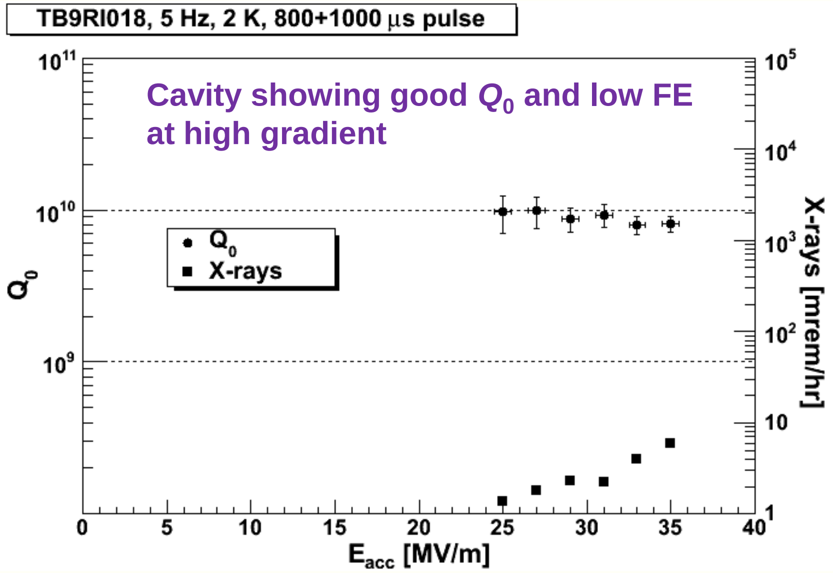


- Purpose: high power tests of dressed cavities
  - “high power” = tens to hundreds of kW of input power
  - “dressed” = LHe vessel, high power input coupler, mechanical tuners, HOM couplers
- Test goal 1: qualify cavities for CM assembly based on Q_0, E_{acc}, field emission
- Test goal 2: verify functionality of auxiliary components

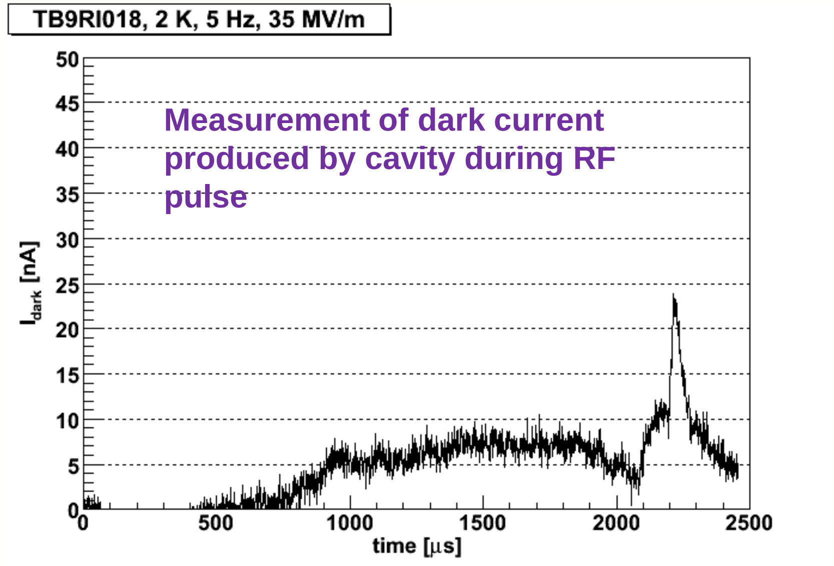
HTS data: examples


TB9RI018, 2.0 K, 5 Hz

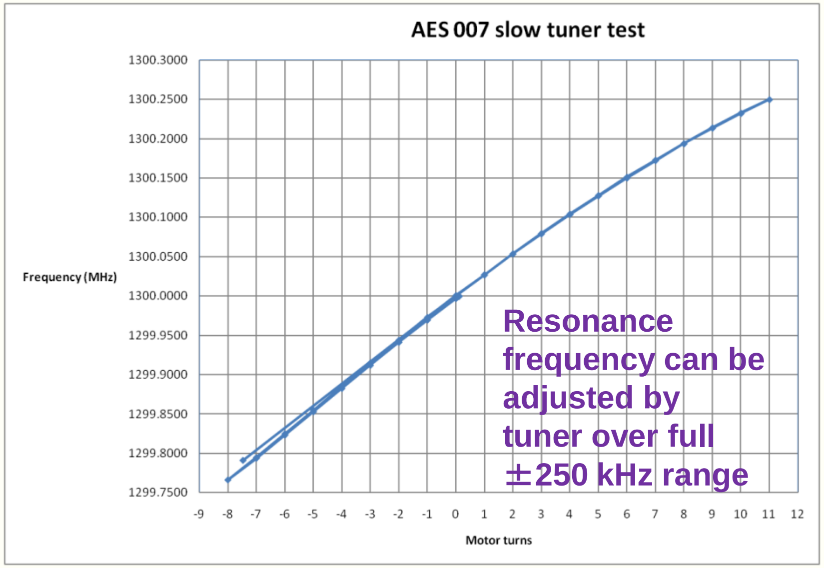
Cavity operating at 35 MV/m


TB9RI018, 5 Hz, 2 K, 800+1000 µs pulse

Cavity showing good Q_0 and low FE at high gradient


TB9RI018, 2 K, 5 Hz, 35 MV/m

Measurement of dark current produced by cavity during RF pulse

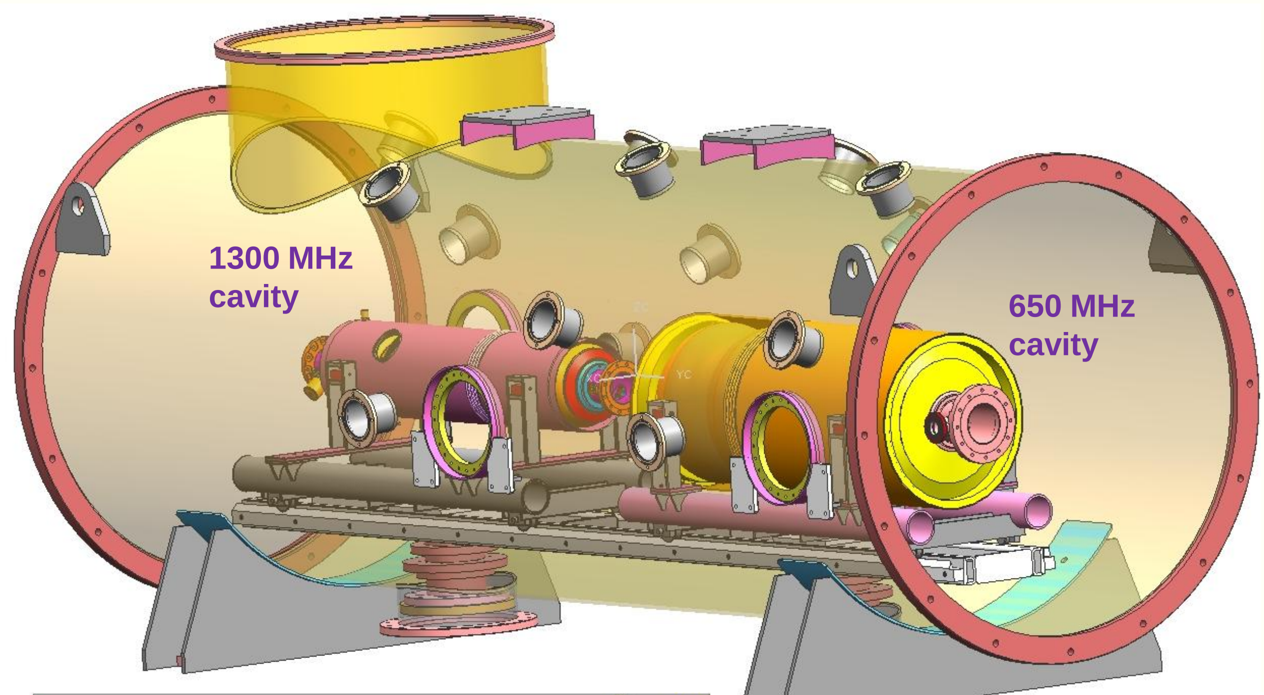

AES 007 slow tuner test

Resonance frequency can be adjusted by tuner over full ±250 kHz range

HTS-2

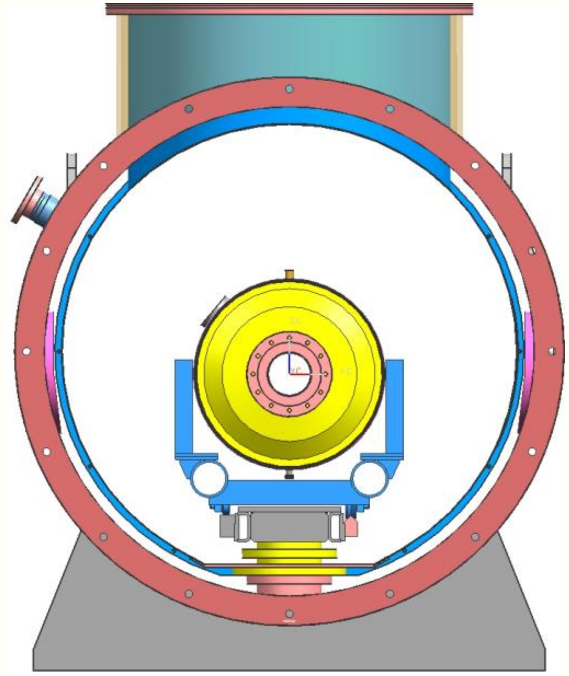
- **HTS-2 is a facility similar to HTS but with expanded capabilities**
  - **Cool down of two cavities simultaneously**
    - **Doubles the number of tests that can be done per thermal cycle**
  - **Testing of either 650 or 1300 MHz cavities**
  - **CW testing as well as pulsed**
  - **Testing a cavity + magnet package**
- **An IIFC project**
  - **India will design and procure the cryostat and its cryogenic feed box, including J-T heat exchanger**
  - **Fermilab will assemble RF system and other test infrastructure**
  - **Similar facility to be built in India based on HTS-2 experience**

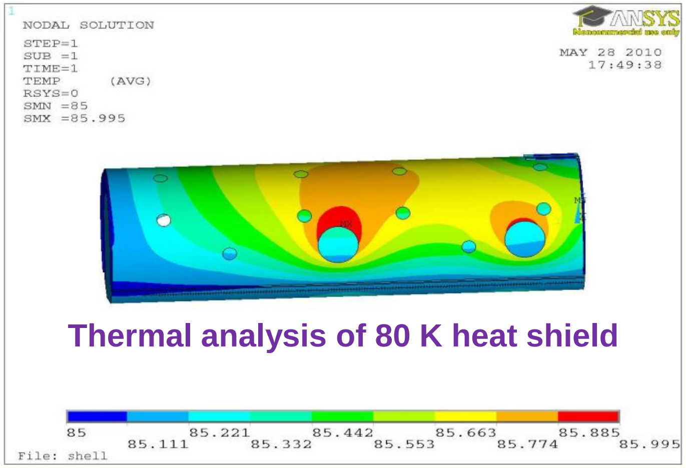
HTS-2 cryostat design at RRCAT



1300 MHz cavity

650 MHz cavity



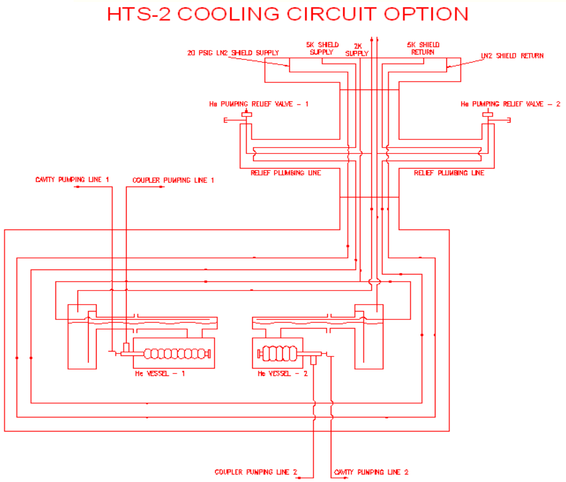


```
NODAL SOLUTION

STEP=1
SUB =1
TIME=1
TEMP       (AVG)
RSYS=0
SMN =85
SMX =85.995
```

Thermal analysis of 80 K heat shield

Preliminary cooling circuit design



325 MHz Spoke Cavity Processing at ANL

- Chemical polishing, high-pressure rinsing in G150 by Argonne and Fermilab SRF staff
- Cold testing performed at Fermilab
- Both cavities have achieved world leading performance

Cryomodule Assembly at Fermilab

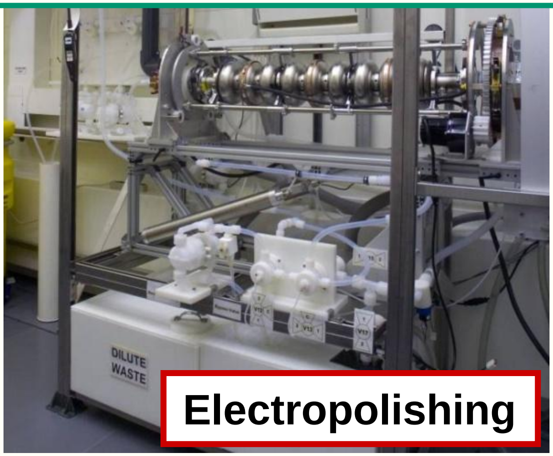
- Extensive infrastructure completed for CM assembly

String Assembly in Class 10 area of MP9 Clean Room

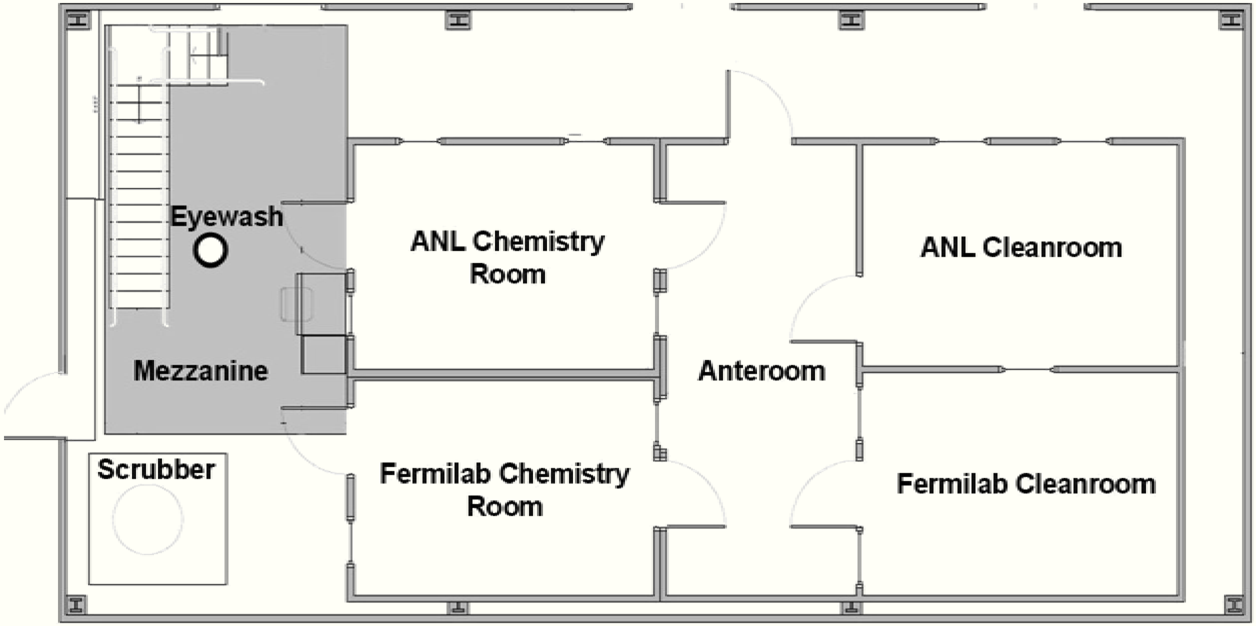
Exterior of MP9 Clean Room

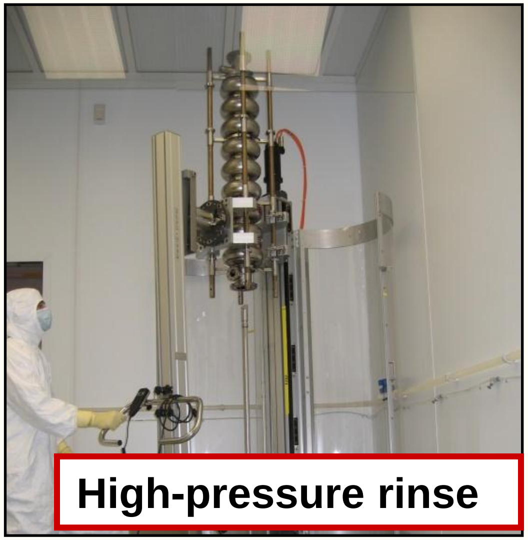
SRF Infrastructure at ANL

- ▪Joint facility built by ANL/FNAL collaboration
- ▪EP processing of 1300 MHz 9-cells
- ▪Together with Jlab, ANL/FNAL facility represents state-of-the-art cavity processing facilities for ILC or Project X
- ▪Adding 650 MHz processing infrastructure


Electropolishing


Ultrasonic Cleaning



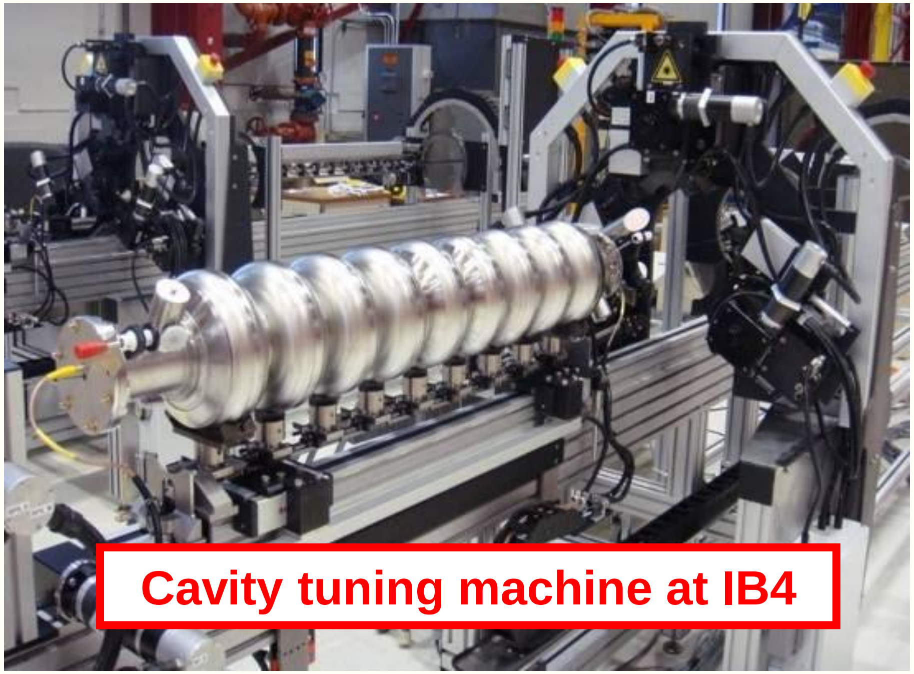

High-pressure rinse

SRF Infrastructure at Fermilab

- KEK/Kyoto optical inspection system, commissioned in 2009
- In routine use examining cavities after each step of processing

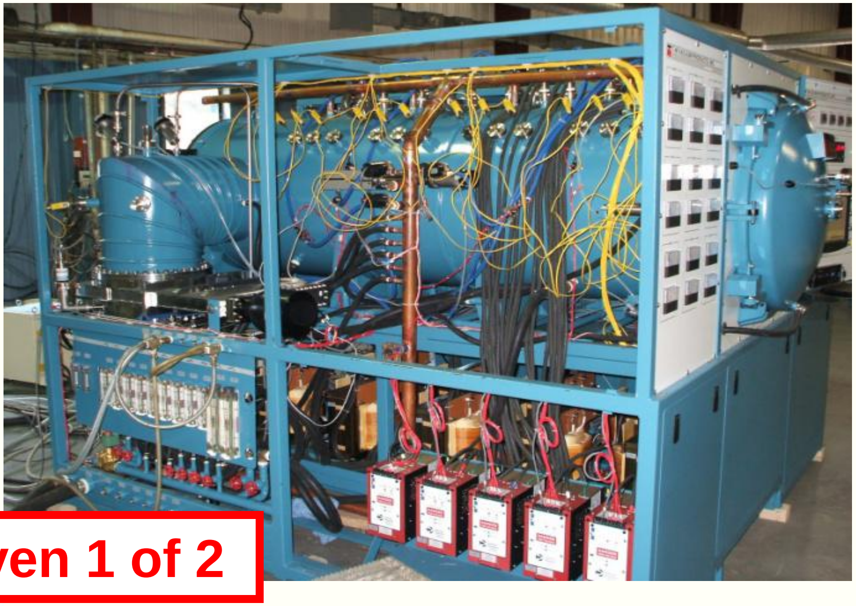
- Automated Cavity tuning machine
- DESY/FNAL/KEK collaboration
- 2 machines at DESY, one at KEK
- FNAL machine in routine use

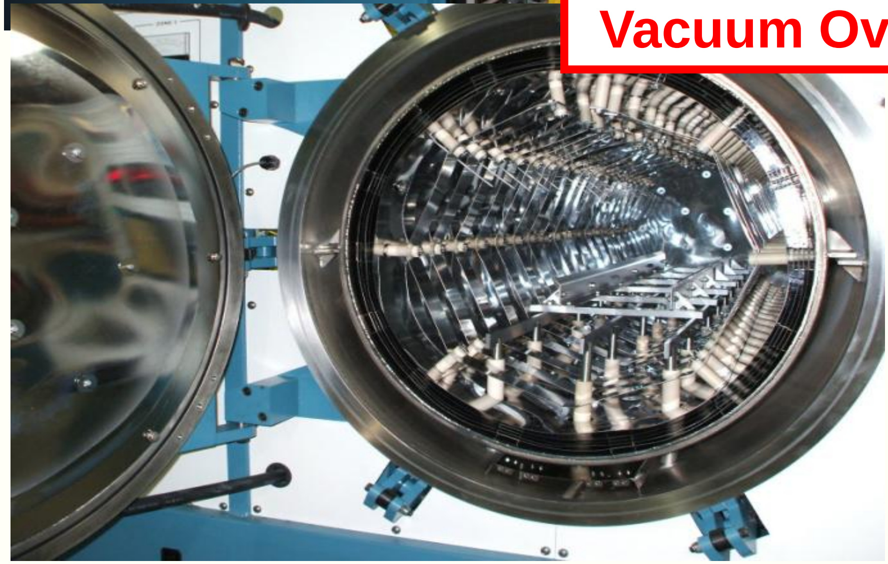
Optical Inspection Machine at ICB



Cavity tuning machine at IB4

SRF Infrastructure at Fermilab





Vacuum Oven 1 of 2

- **Removes H_2 introduced during surface treatment**
- **Key to high Q operation at high gradient**

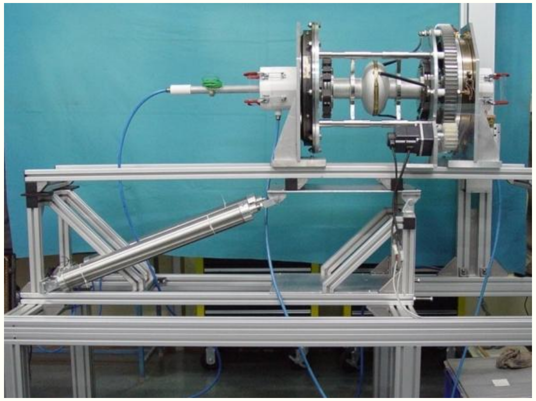
Fermilab is helping RRCAT purchase this from US vendor

Infrastructure for Cavity Development

Infrastructure installed at RRCAT in Collaboration with Fermilab

- Electro-polishing setup
- Centrifugal barrel polishing machine
- High pressure rinsing
- Cavity forming facility

Cavity forming facility



Electro-polishing setup

Centrifugal barrel polishing machine

High pressure rinsing Set up

Infrastructural Work In Progress

Large scale SRF Infrastructure being set up at RRCAT in collaboration with Fermilab.

- Clean room (class 10000 to 10)
  - Fermilab Design
- Electron beam welding machine
  - US Vendor
- High vacuum annealing furnace
- Cavity machining facilities
- CMM, SIMS etc
- Building under construction (area 70m x 20m)

Building expected to be ready by mid - 2011

SRF Test Linac Project Overview

- **Overall Goals**
  - **Build a RF Unit Test Facility at the New Muon Lab (NML)**
    - **ILC RF Unit = 3 cryomodules**
    - **10-MW RF system**
    - **Beam with ILC parameters (3.2 nC/bunch @3 MHz, Up to 3000 bunches @ 5Hz, 300-µm rms bunch length)**
  - **Build a RF Unit for Project X (like ILC but 4 cryomodules @25 MV/M)**
  - **Build Test facilities for Project-X cryomodules**

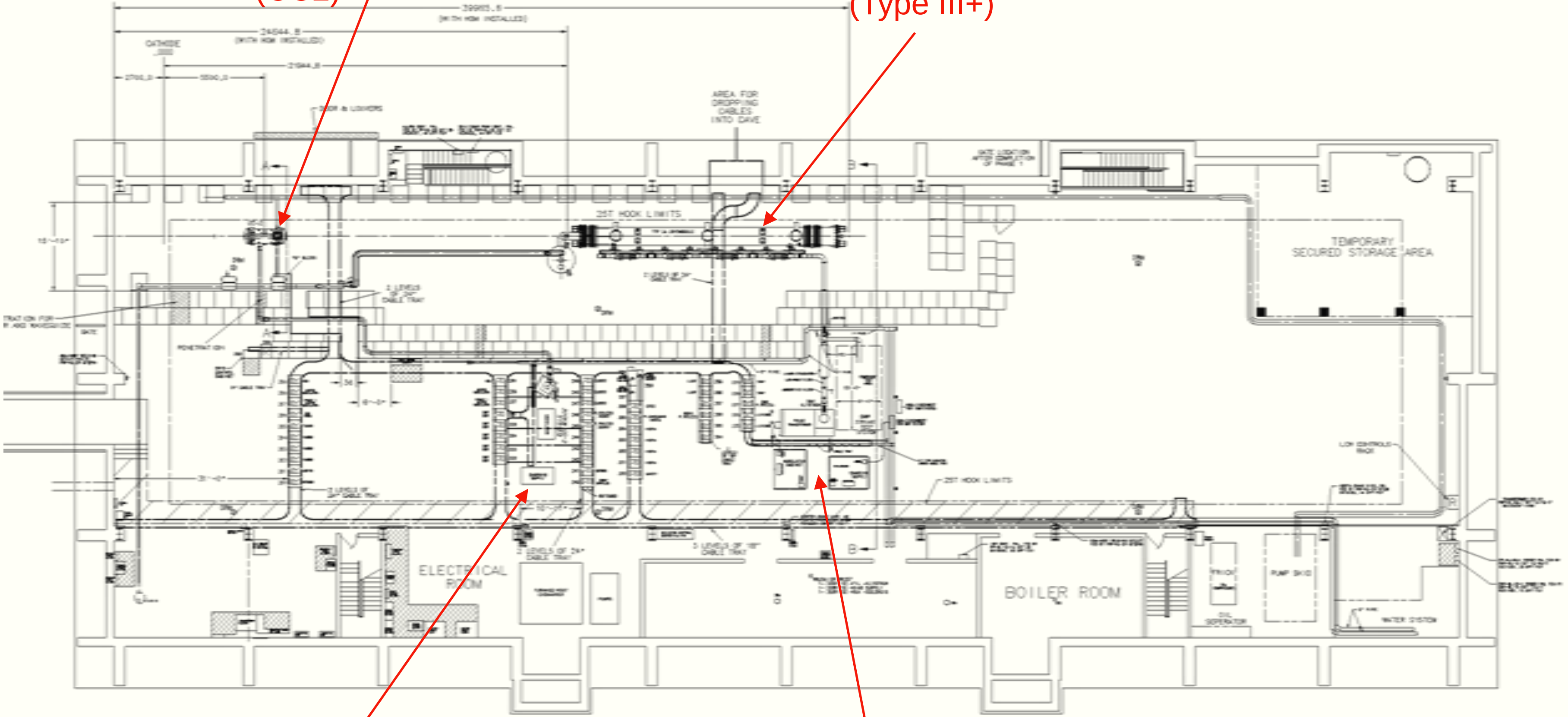
- **Phase-1 (FY07 – FY10) (Completed Dec. 2010)**
  - **Prepare facility for testing first cryomodule (CM1) without beam**
    - **Infrastructure, RF power, cryogenics (Tevatron satellite refrigerators #1 & #2)**
    - **Install first cryomodule (CM1) and Capture Cavity-2 (CC2), cooldown, and begin RF testing**
    - **New tunnel civil construction (capability for 2 RF units)**

SRF Test Linac Project Overview

- **Phase-2 (FY11 – FY12)**
  - Prepare for First Beam
    - Civil construction for new cryoplant and test stands
    - Move parts from FNPL photo-injector to NML
    - Install new gun, injector, Test beamlines, and beam dump
    - Swap CM1 with second cryomodule (CM2) - (S1)
    - Commission gun – generate first beam
    - Accelerate beam through single cryomodule

- **Phase-3 (FY12 – FY14)**
  - Complete RF Unit
    - Upgrade RF system to 10 MW
    - Install RF Unit (3 cryomodules)
    - Commission new Cryogenic Plant
    - Operate full RF Unit with beam - (S2)

Phase-1 Layout of SRF Test Linac



Capture Cavity 2 (CC2)

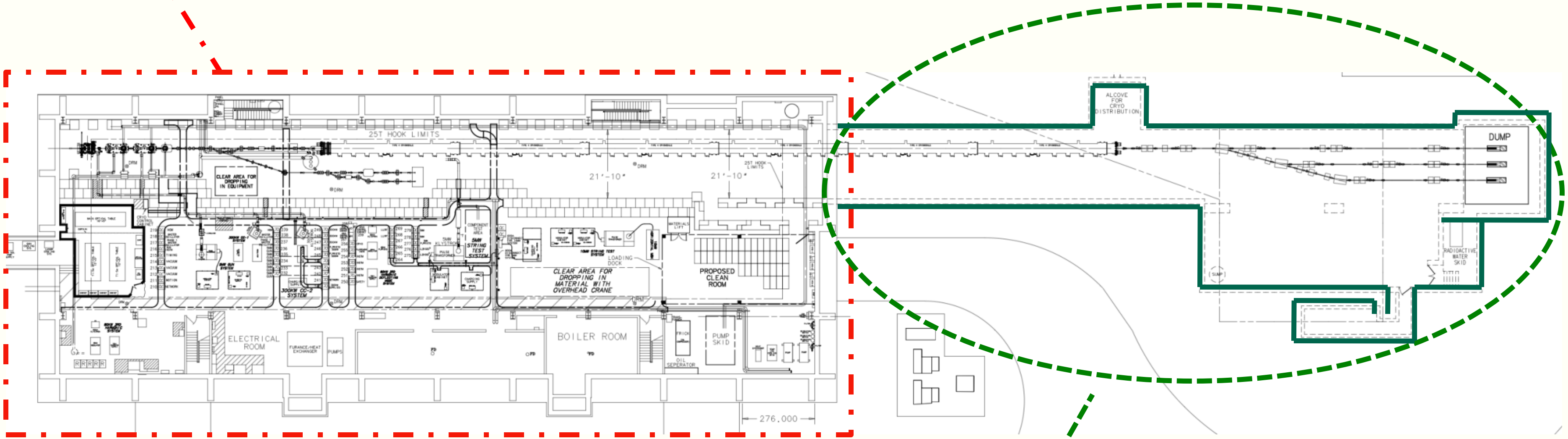
Cryomodule-1 (CM1) (Type III+)

CC2 RF System

5 MW RF System for CM1

Phase-1 Civil Construction

Funded by ARRA

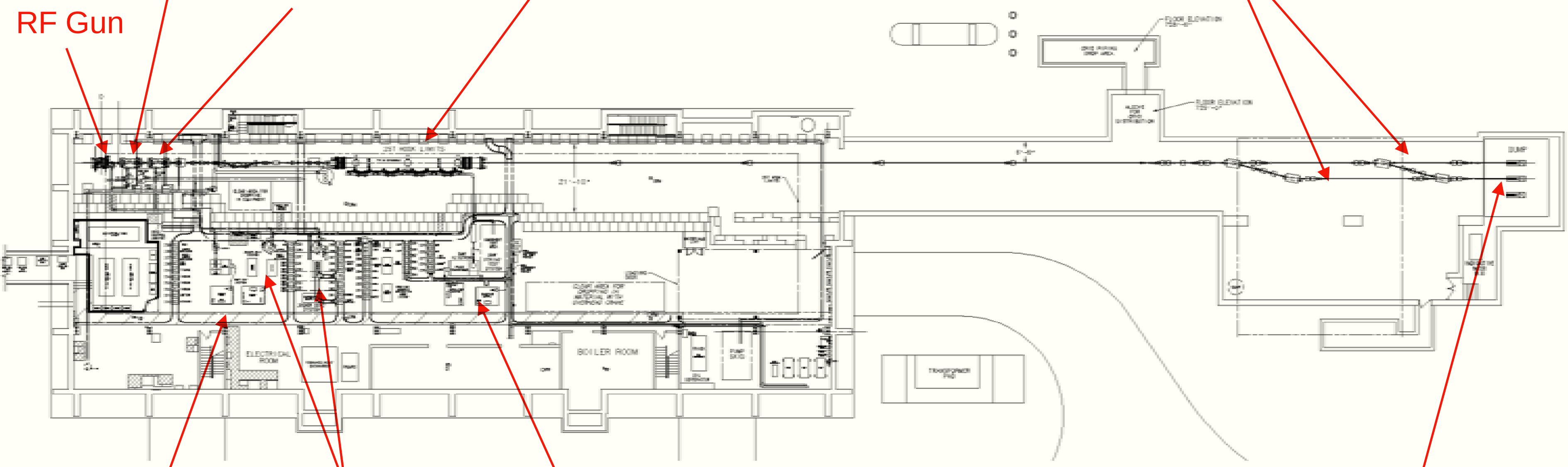


Existing NML Building

New Underground Tunnel Expansion

(Space for 6 Cryomodules (2 RF Units), AARD Test Beam Lines)

Phase-2 Layout of SRF Test Linac



Capture Cavity 1 (CC1)

Cryomodule

Test Beam Lines

CC2

RF Gun

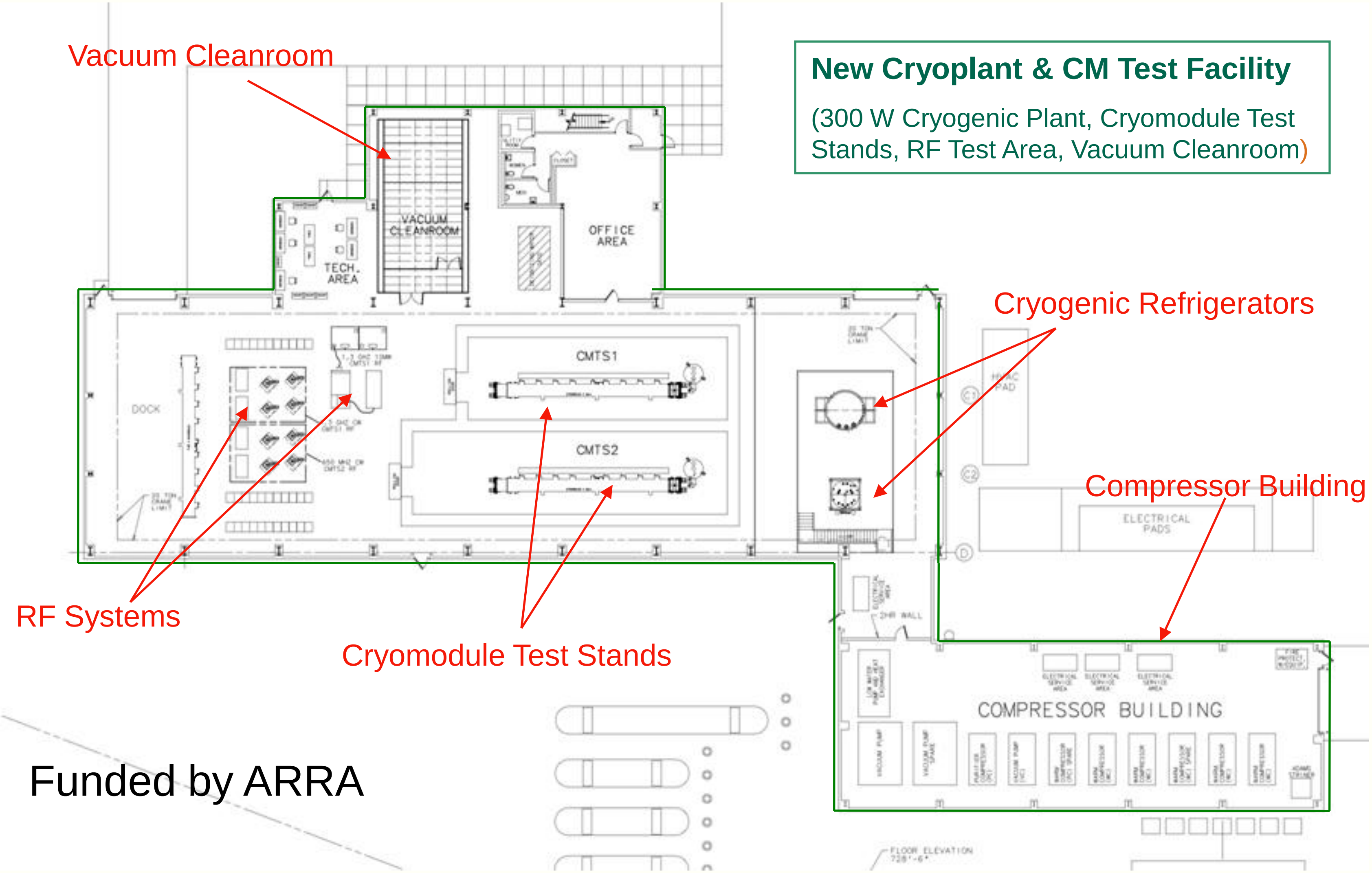
High Energy Beam Absorber

CC1 & CC2 RF Systems

10MW RF System for Cryomodules

5MW RF System for Gun

Phase-2 Civil Construction



Vacuum Cleanroom

New Cryoplant & CM Test Facility

(300 W Cryogenic Plant, Cryomodule Test Stands, RF Test Area, Vacuum Cleanroom)

Cryogenic Refrigerators

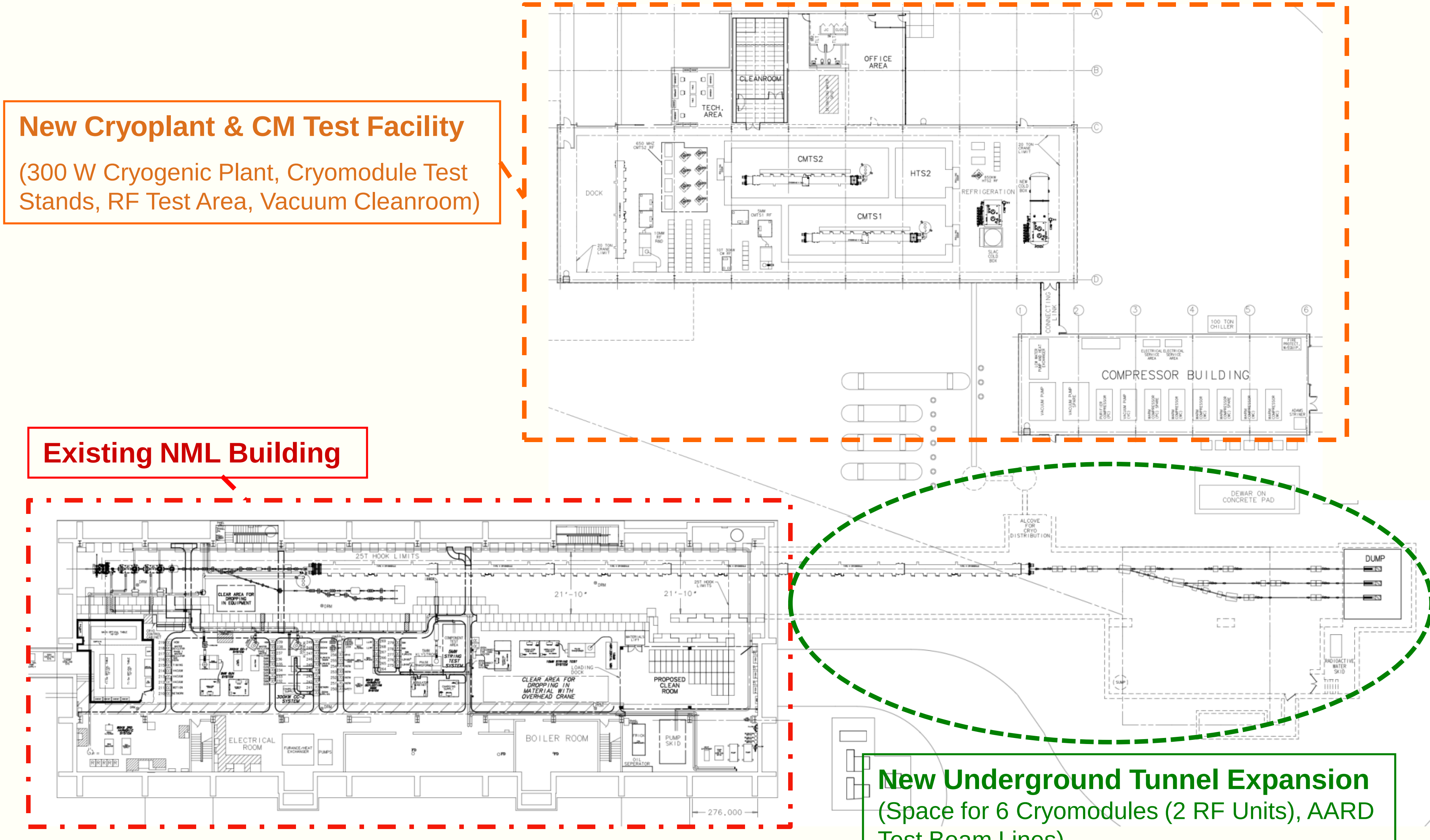
Compressor Building

RF Systems

Cryomodule Test Stands

Funded by ARRA

Phase-3 of SRF Test Linac and CMTF



New Cryoplant & CM Test Facility

(300 W Cryogenic Plant, Cryomodule Test Stands, RF Test Area, Vacuum Cleanroom)

Existing NML Building

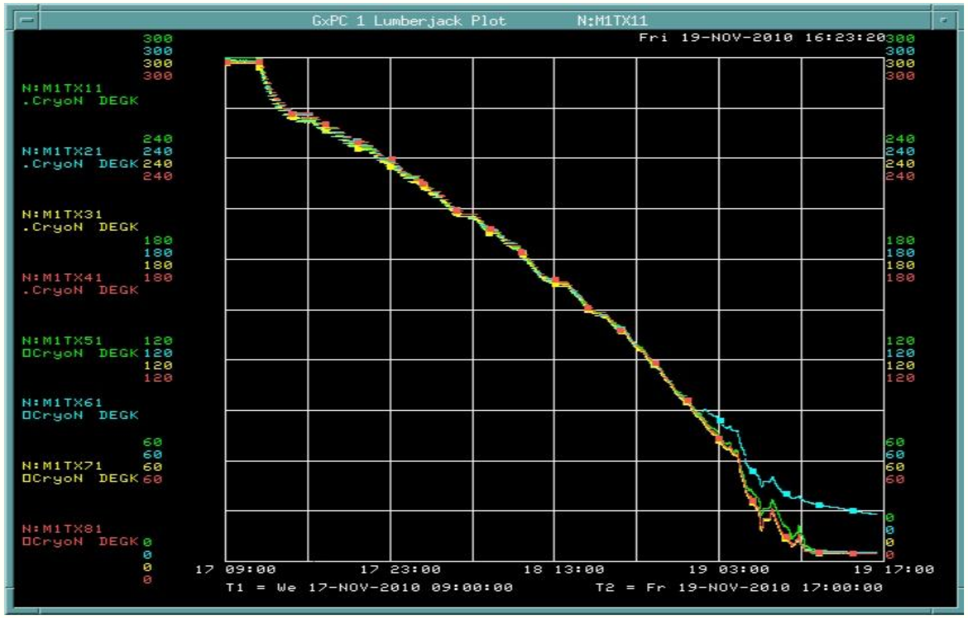
New Underground Tunnel Expansion

(Space for 6 Cryomodules (2 RF Units), AARD Test Beam Lines)

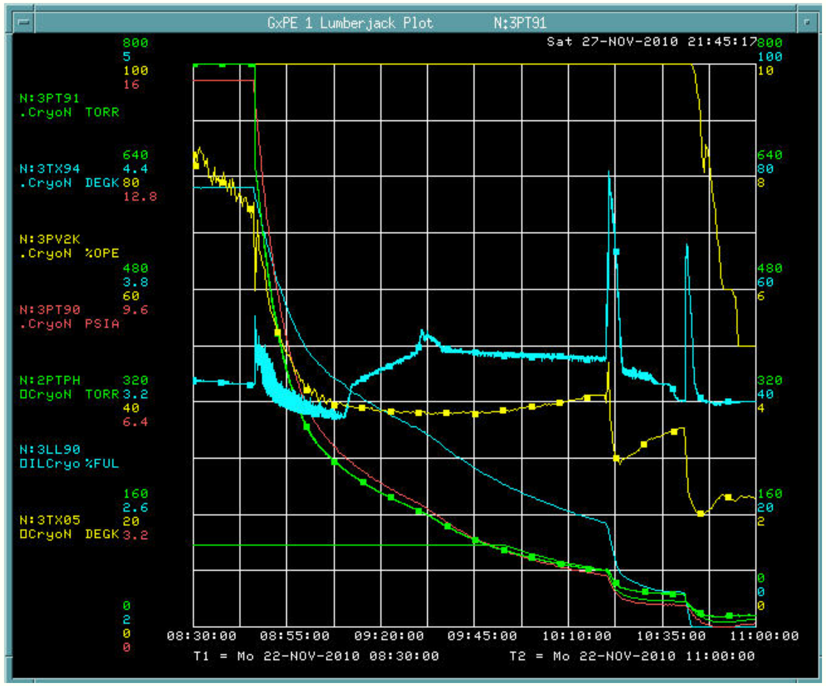
Future NML Complex

Cryomodule-1 (CM1)

Cool down of CM1



Cool down to 4.5 Kelvin
(2+ days)



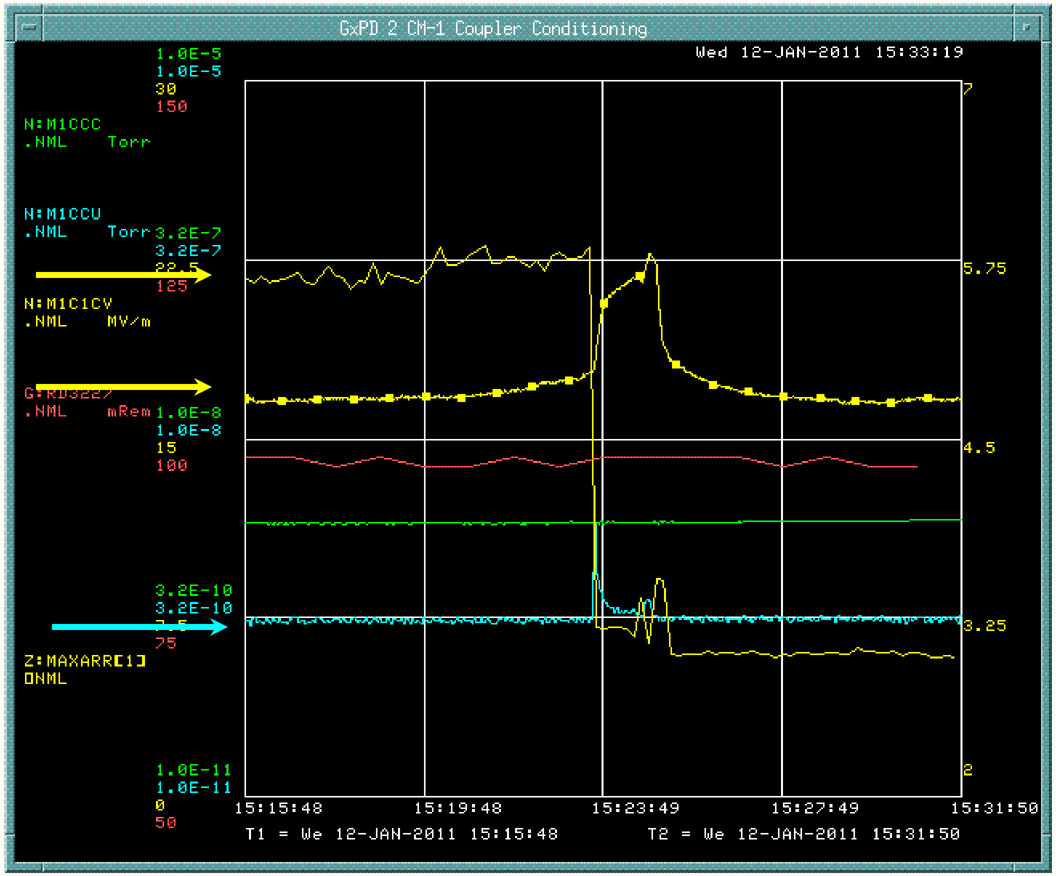
Cool down to 2 Kelvin
(~2 hours)

Cavity #1 Performance

Gradient (22 MV/m)

HOM temperature

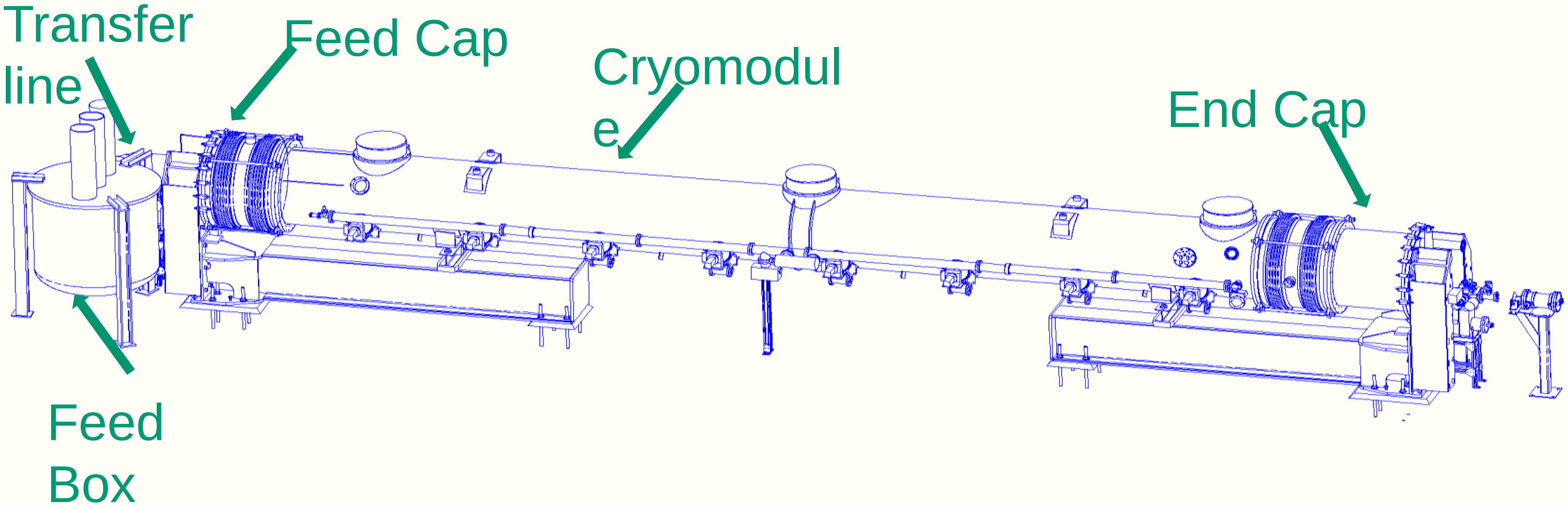
Cavity vacuum



Fast Thermometry response during a possible quench

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.**

- **CMTF (FY15):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 stand (with India)**

Accelerator Unit Test Status

- Injector
  - Detailed Lattice designed
  - New gun system being installed
    - Collaboration with DESY, KEK & INFN
  - CC2 (single 9-cell cavity) operational - 10/09
- Accelerator
  - CM1 installed, aligned, and under vacuum
  - Cooled, Under RF Power

Phase II: R&D

- **The Phase II of this collaboration would expand the present R&D collaboration to all non SRF areas of Project-X**

- **Elements of Phase II: R&D**
  - **Front End: Source and RFQ**
  - **325 MHz RF Power**
  - **650 MHz RF Power**
  - **Power Coupler**
  - **Instrumentations and Controls**
  - **Superconducting Magnet**
  - **Cryogenics**

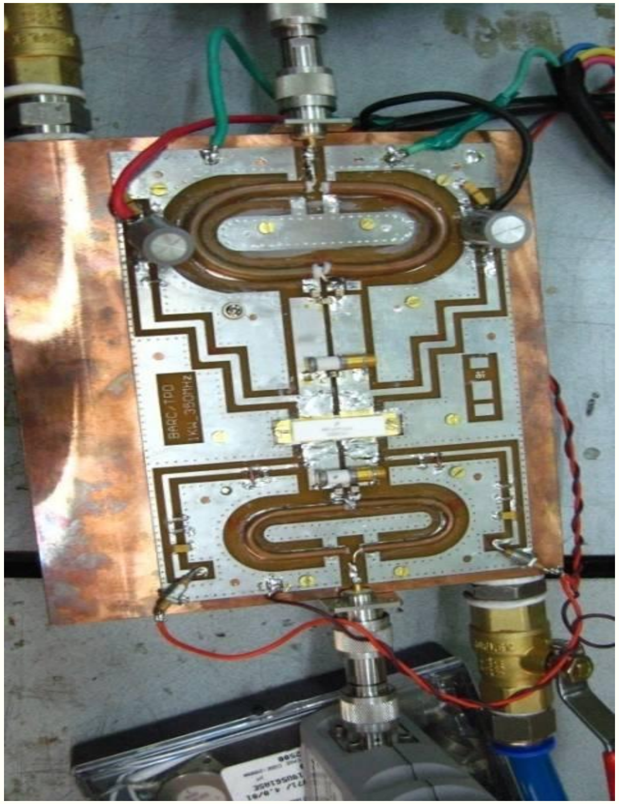
- **The technical discussions have already started**
  - **This meeting will outline these areas of collaboration**

BARC: Solid State Amplifiers at 325 MHz

- 1 kW (2 nos.) and 5 kW (1 No.) Solid-state amplifiers

Specifications from Fermilab:

- Center frequency : 325 MHz
- Bandwidth (3 dB) : 10 MHz
- Power output (1 dB), CW : 1 kW and 5 kW
- Gain (1 dB), minimum   : 50 dB
- Gain Stability : +/-0.5 dB
- Stability : Un conditionally Stable
- Cooling : Water Cooled
- Harmonics & Spurious : <30 dBc
- Efficiency (Total) : > 50%
- Gain Stabilization with in +/- 0.5 dB

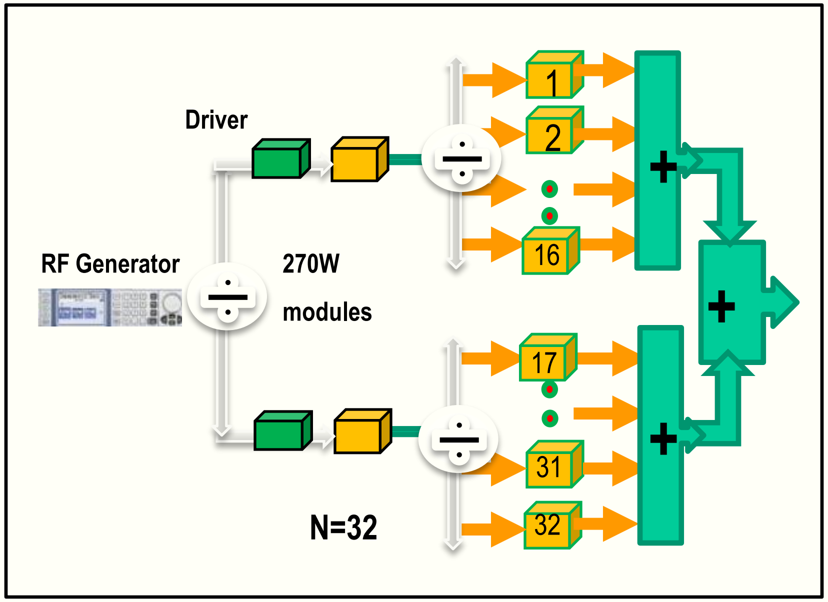


1 kW solid state module under testing at BARC

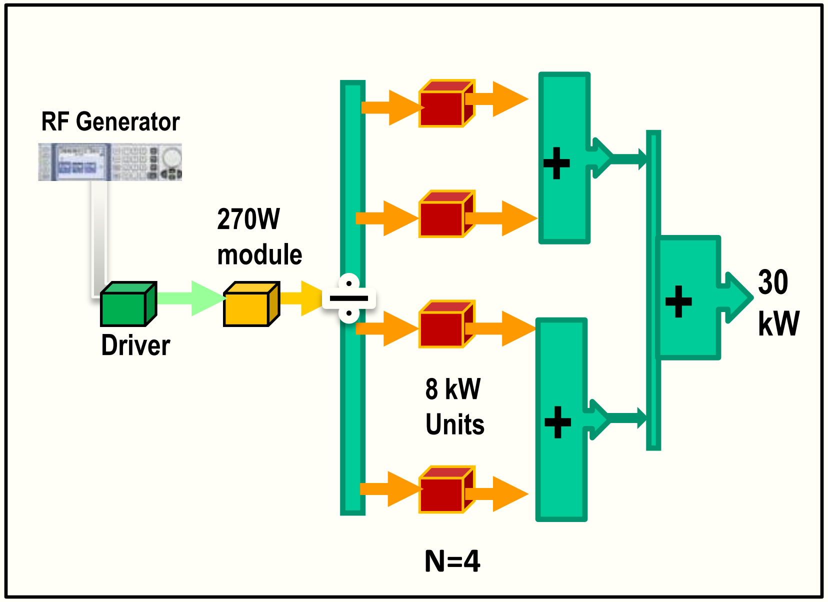
Solid State Amplifier Development 650 MHz

- RRCAT has taken up development of 30 kW CW 650 MHz solid state amplifiers for energizing SCRF cavities

8kW Amplifier Scheme

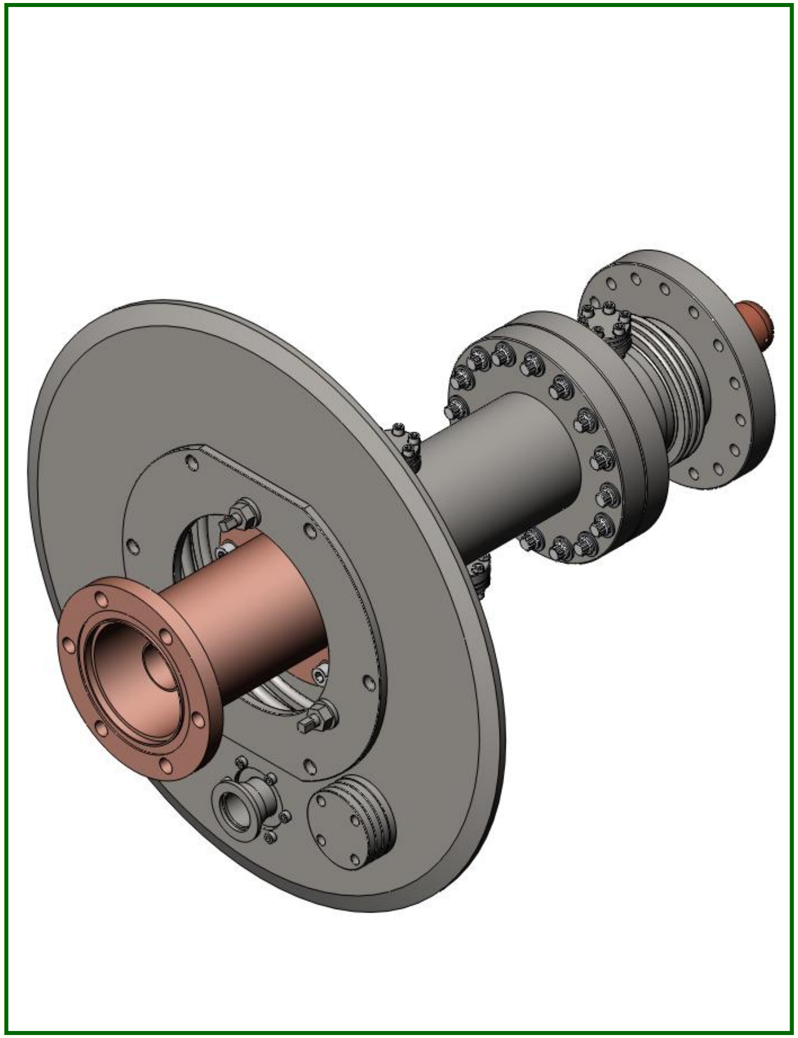


30kW Amplifier Scheme

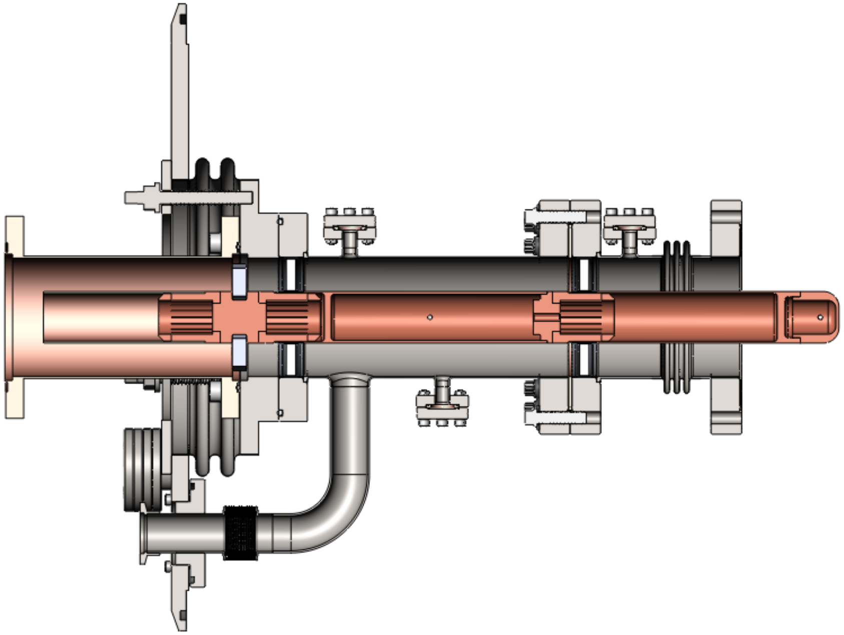


- 32 Nos. of 270 W RF modules are used with suitable combiners and dividers to make a 8 kW RF amplifier module. Four such modules will be combined to obtain 30 kW RF power output.

Input coupler



Coaxial design, adjustable, 76.9 mm outer/33.4 mm inner, two disk-type ceramic windows.



3 couplers are in-house and tested. One currently installed in test cryostat. Design modifications in-process to reduce weight.

Phase III: Project-X

- Fermilab and DAE accelerator laboratories have proposed to jointly work
  - On the construction and commissioning of the Project-X accelerator at Fermilab
  - Development of Indian capabilities and industrial infrastructure that could lead the construction of HIPA in India.
- India is expected to make significant In-Kind contributions
  - US will share accelerator technology and knowledge
- The Accelerator collaboration started in 2006 and has now gone into the 3rd stage
  1. Component level → Scientists to Scientists
  2. System Level → Laboratories to Laboratories
  3. Facility Level → Agency to Agency
     - i. Fermilab has worked with US DOE in developing a DOE-DAE agreement based on IIFC discussion to date)
     - ii. At present the US-DOE and DAE are working to negotiate the language and high level details of DOE-DAE agreement.

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**
  - **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.**
- **We held a joint workshop in Jan 2011 to discuss collaboration on all aspect of High Energy Physics, Nuclear Physics and Energy**
  - **Support is overwhelming**
  - **We are developing a set of proposal for XII plan.**

Colleagues at Fermilab under IIFC

Accelerator: 5+1 (1 Student), HEP: 6+2 (5+2 Students)

IIFC Developing Indian Technical Expertise

Summary

- **Indian Institutions and Fermilab have established an excellent working relationship and are collaborating on SRF part of the High Power Linac for HIPA.**
  - Progress is being made on several fronts.
- **We are proceeding to expand this R&D collaboration to all non-SRF aspect of the accelerator.**
- **Fermilab has proposed to build a 3 GeV CW, ~3 MW SRF linac (followed by 3-8 GeV Pulsed SRF Linac) for its High Energy Physics program.**
  - The design of this SRF linac is aligned with Indian 3rd Stage Nuclear program.
- **This is an unprecedented opportunity for both Indian and US Institutions, and agencies to collaborate on jointly developing accelerators for its domestic program.**
  - Total Project Collaboration
- **During this meeting**
  - we need to make significant technical progress on Phase I and II
  - Discuss steps that could be taken to make a plan for Phase III