Laser Welding For Fabrication of SCRF Cavities & Design of 650 MHz Cryomodule

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Outline

A. Laser Beam Welding For Fabrication of SCRF Cavity

1. Introduction to Laser Beam Welding (LBW) Technology for SCRF Cavities
2. Roadmap followed for development of LBW of SCRF cavities
3. Results of first laser welded SCRF cavity
4. Advantages of LBW technology for fabrication of SCRF cavities
5. Fabrication of world’s first laser welded multi –cell SCRF cavity
6. Summary

Outline

B. Design and Development of Cryomodules

1. Introduction
2. Design Path Followed for Cryomodule
3. Design Efforts for Cryomodule and HTS (mini cryomodule)
4. Tasks Undertaken
   - A. Design of HTS
   - B. Design of 650MHz cryomodule (Tesla Type)
   - C. Design of 650MHz, Beta=0.92, cryomodule
   - D. Design of 650MHz Beta=0.61 cryomodule
5. Design of cryomodule components (couple of example)
6. Future Plan

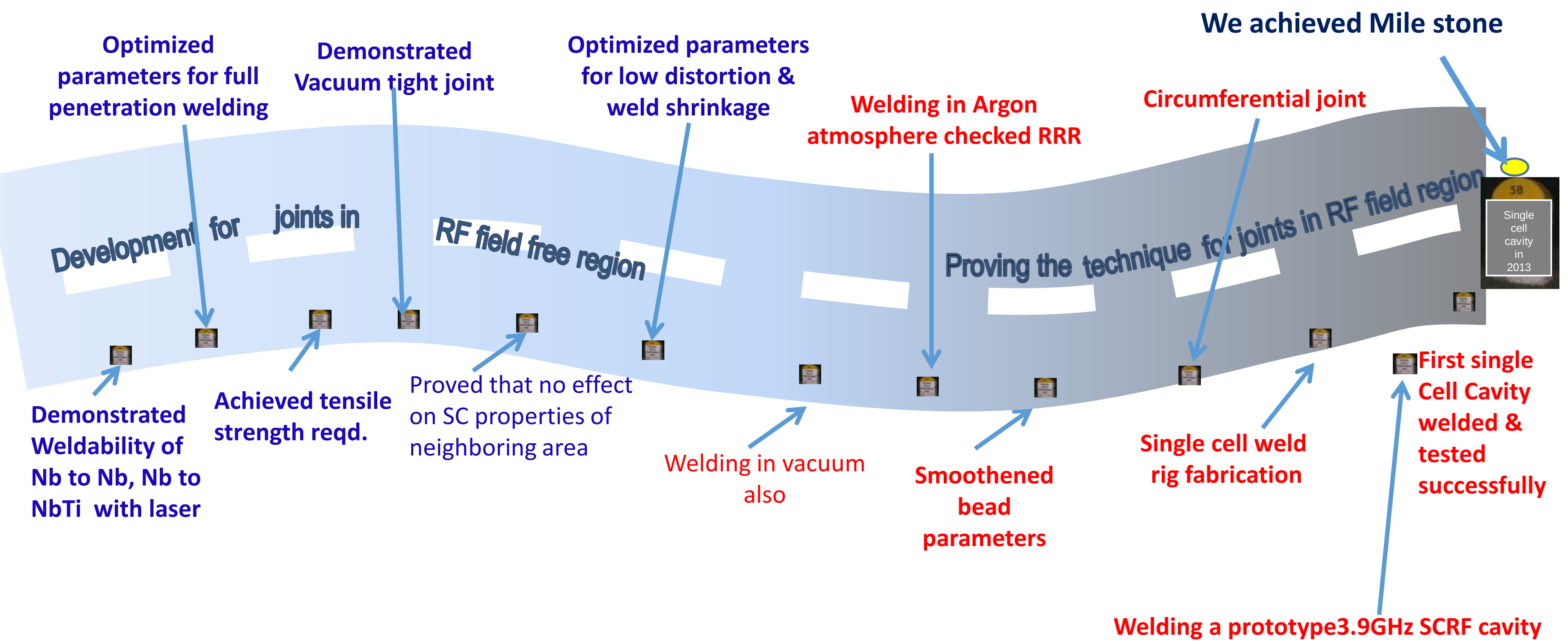
Outline

A. Laser Beam Welding For Fabrication of SCRF Cavity

1. Introduction to LBW Technology for SCRF Cavities

- SCRF cavities are the heart of particle accelerators built with this technology and probably where most R&D effort has gone into.
- Traditionally these are fabricated with Electron Beam Technology.
- At RRCAT we have developed this technology because of some advantages that we could perceive.
- RRCAT has very significant strength in Laser technology.
- A systematic path was pursued for development of laser beam welding technology for SCRF cavities. World's first laser welded SCRF cavity was tested and it gave very good performance.
- We are developing this technology further by developing multi-cell cavity.
- Intellectual property rights have been secured.
- Patents have been granted by USA, Europe and Japan patent offices.

2. Developmental Path Traversed So Far



More than 180 experiments carried out till date

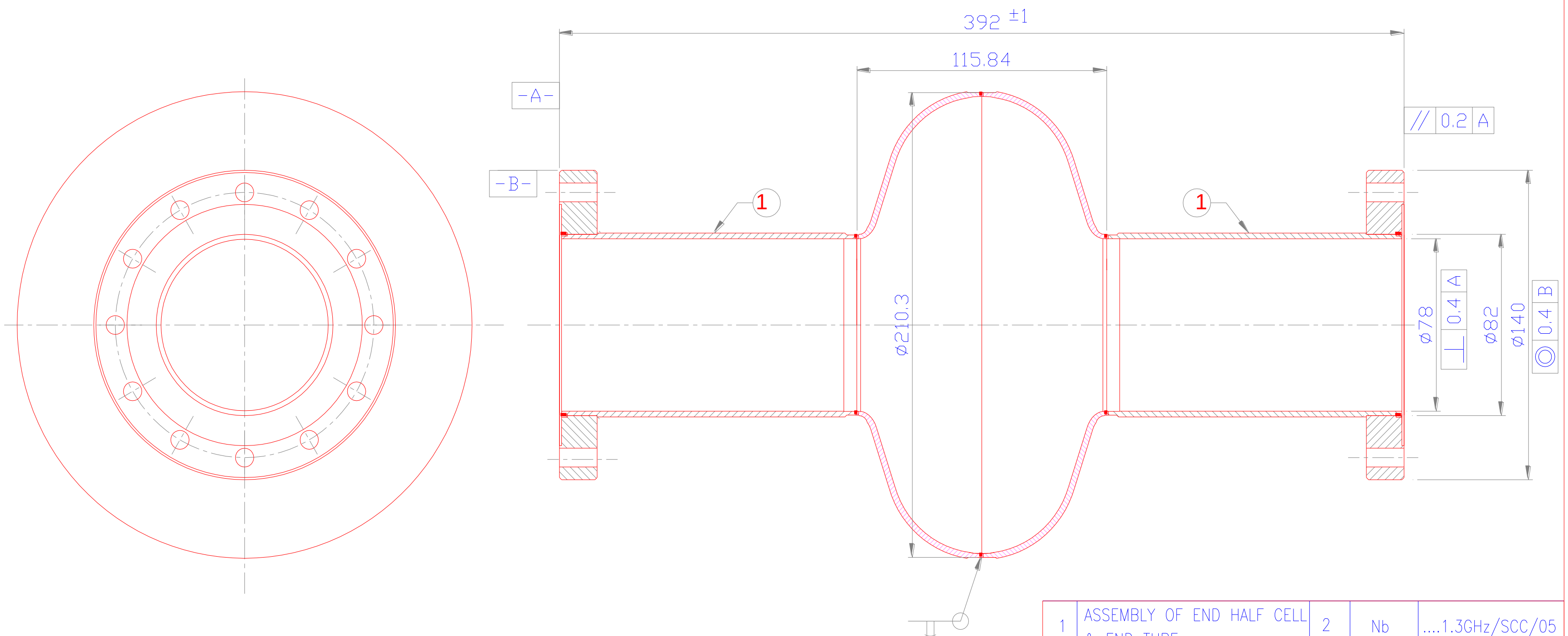
Next Target → **Multi-cell cavity By end 2015**

2. Infrastructure Created

- An experimental welding rig was established for the purpose.
- Development of target maneuvering system (capable of weld tacking, giving precise movement, displaying length welded etc).
- Development of a tailor made Laser System for SCRF cavity fabrication.

Specially Developed Nd:YAG Laser 500W(avg)

Laser Welding rig



1	ASSEMBLY OF END HALF CELL & END TUBE	2	Nb	....1.3GHz/SCC/05
PART No.	DESCRIPTION	QTY.	MATL.	REMARKS

BILL OF MATERIAL

ACAD REF: BUTT JOINT CELL

NOTES:-

1. ASSEMBLY TO BE VACCUM TIGHT. No LEAK SHALL BE DETECTABLE ON THE MOST SENSITIVE SCALE OF A HELIUM MASS SPECTROMETER LEAK DETECTOR WITH A MINIMUM SENSITIVITY OF 2×10^{-10} mbar l/SEC FOR HELIUM.
2. ASSEMBLY TO BE CLEANED AND PACKAGED SO AS TO ASSURE NO CONTAMINATION FROM FORIENGN MATERIALS, METAL CHIPS OR OTHER CONTAMINATES.
3. ALL ASSEMBLY AND HANDLING IS TO CONFORM TO STANDARD ULTRA HIGH VACUUM PRACTICES.
4. PROTECT THE SEALING SURFACE DURING HANDLING.

GOVERNMENT OF INDIA

RAJA RAMANNA CENTRE FOR ADVANCED TECHNOLOGY

ACCELERATOR PROGRAMME

TITLE

CAVITY ASSEMBLY

(1.3 GHz SINGLE CELL ScRF CAVITY)

DESD	DATE	CHKD	DATE	SCALE
P.KHARE		P.KHARE		NTS
DRN	DATE	APPD	DATE	
A.L.Narayanan		P.K.KUSH		
ORIGINATING SECTION / GROUP		CRYO ENGG. AND CRYOMODULE DEV. DIVISION		

GENERAL TOLERANCES	
LINEAR	: ±0.1
ANGULAR	: ±0.1°
SURFACE FINISH	: 1.6

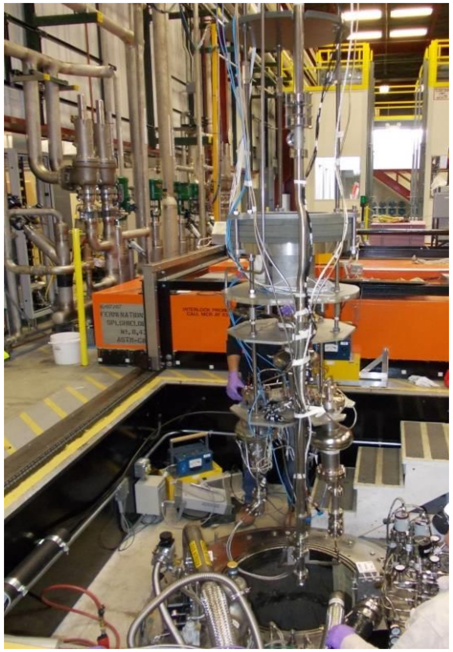
ROUND OFF ALL SHARP CORNERS TO 0.2 UNLESS OTHERWISE SPECIFIED

DRG No. RRCAT/CMEL/1.3GHz/SCC/06 — SIZE A3 — SHEET 1 OF 1

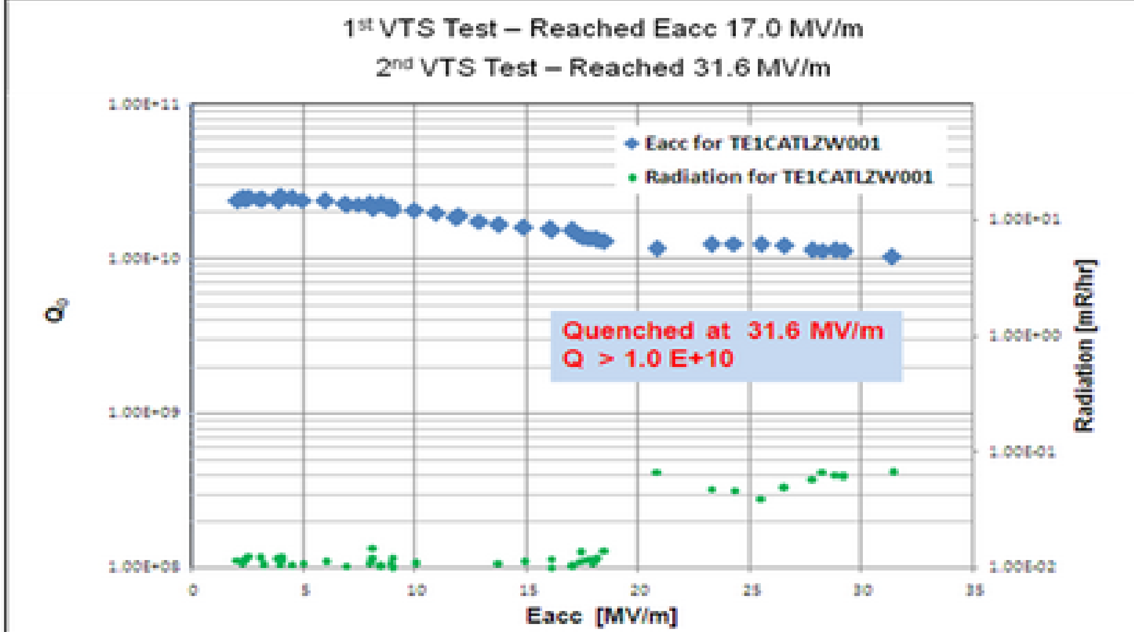
REV NO	LOCATION	DESCRIPTION	DATE	APPD

REVISIONS

3. Results of First Laser welded SCRF cavity



The cavity being lowered inside VTS at FNAL



Q_0 v/s E_{acc} Plot of Laser Welding Single Cell 1.3 GHz Cavity Tested on 17/09/2013

Novelty

Use of Laser instead of Electron Beam welding
Use of inert gas environment instead of high vacuum

The very first 1.3 GHz SCRF cavity developed at RRCAT with this technique showed E_{acc} of 31.6 MV/m with a quality factor (Q_0) of 1.0 x 10^{10} at 2 Kelvin.

4. Advantages of this technique

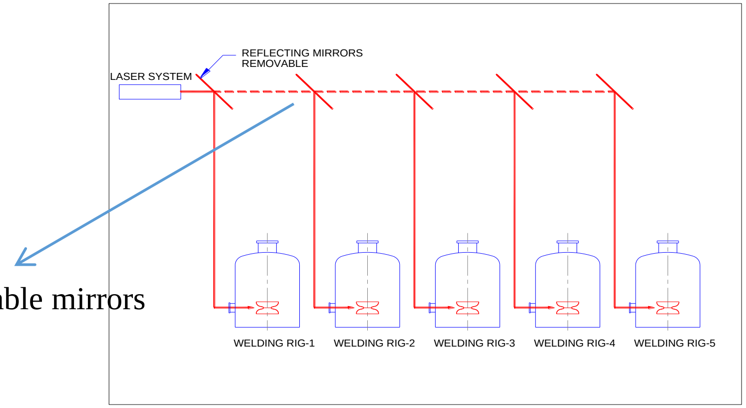
ECONOMICS

- **A. Lower capital cost 20- 25** times less (cost of fixtures & welding rig accounted)
- **B. Operating Cost is less** (laser welding is $39 per hour, EBW is ~ $250/hr).

  Just 10 KW of electric power flash lamp which lasts 1 million shots
- **C. Manufacturing time will be very less as**

  1. Laser travels through optical fiber so many joints can be made in a single setting.

  2. One LASER System can drive operations in 4-5 chambers (Weld preparation in second chamber by the time welding is over in the first one (see Fig below).



Removable mirrors

4 to 5 chambers can work with a single laser. Cost of chamber and fixtures is very less so it is a significant advantage.

4. Advantages of this technique

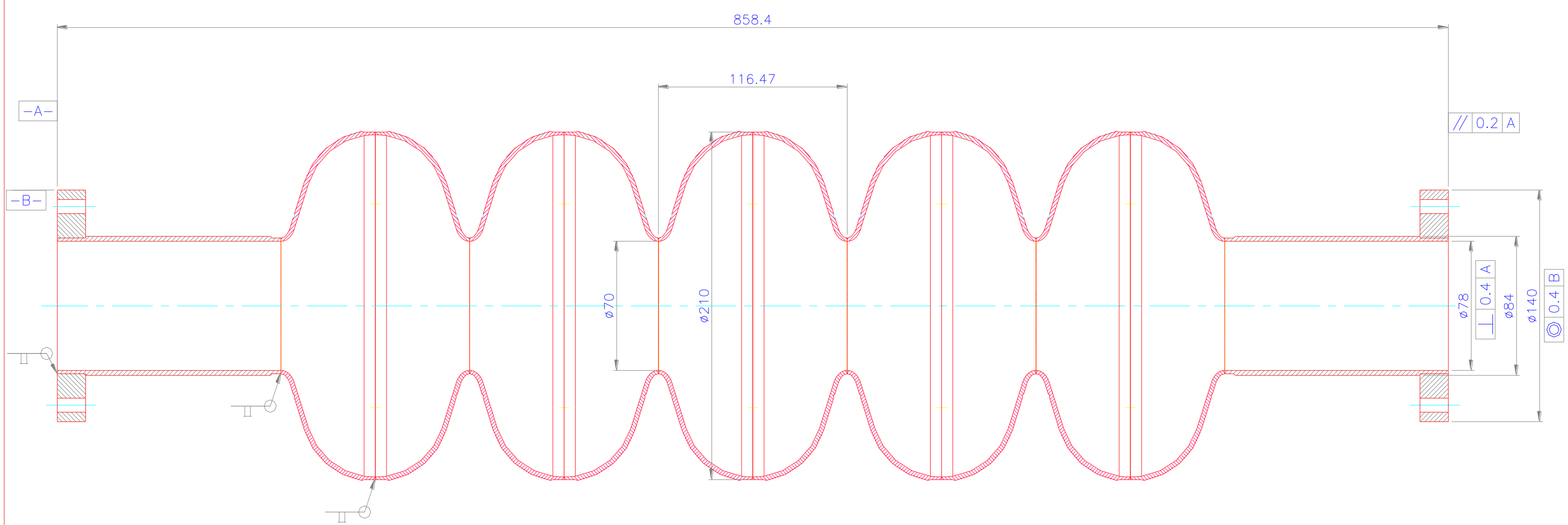
Factors effecting performance

- Lower HAZ . With rigorous parameter optimization we could bring it to 0.5mm
- Energy deposition is 5-6 times less hence very less shrinkage and distortion.
- Predictability of shrinkage . These are very predictable with a variation of less than 10%. Maybe a right amount of allowance would mitigate the requirement of intermittent machining.
- Inert gas jet can drive away metal vapors, spatter etc, thus protecting the inner cavity surface
- As laser can also weld / repair /smoothen from inside a very smooth surface can be obtained.
- Similarly while welding stiffening ring there is no "swelling" on the inside surface.

4. Advantages of this technique

Intangible Benefits

- May provide flexibility to designers. Possible to join components along complicated seam.
- May be helpful in reducing contamination and thereby reduce chemical processing.
- May be useful for low beta cavities with complicated shapes.



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ACAD REF : LONG END HALF CELL

GOVERNMENT OF INDIA
RAJA RAMANNA CENTRE
FOR ADVANCED TECHNOLOGY
ACCELERATOR PROGRAMME

TITLE
5 CELL ASSEMBLY
(5 CELL 1.3GHz SCRF LASER WELDED CAVITY)

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SURFACE FINISH	: 1.6
ROUND OFF ALL SHARP CORNERS TO 0.2 UNLESS OTHERWISE SPECIFIED	

DESD	DATE	CHKD	DATE	SCALE
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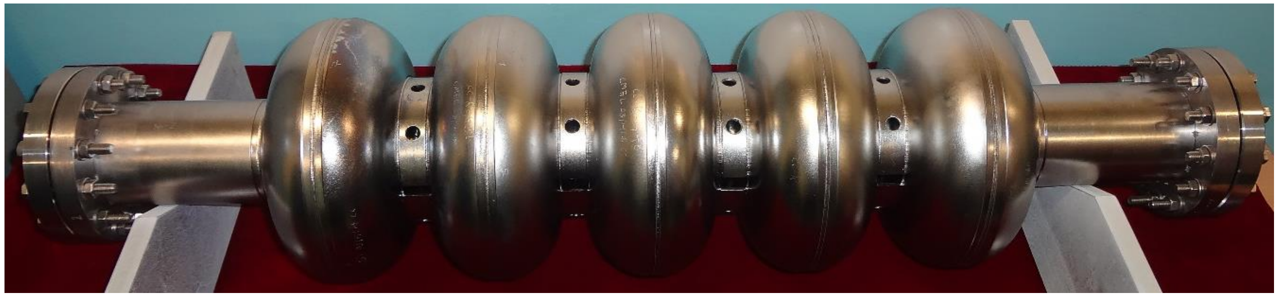
A..L.Narayanan	12.03.14	P.Khare		
ORIGINATING SECTION / GROUP		CRYO ENGG. AND CRYO MOUDLE DEV.SECTION		

DRG No. RRCAT/CCDS/CEML/1009-003 | SIZE A3 | SHEET 1 OF 1

4. World's first multi-cell laser welded SCRF cavity

May 2016



After successful fabrication and testing of laser welded single cell 1.3GHz SCRF cavity , FIVE Cell laser welded cavity has been fabricated at RRCAT

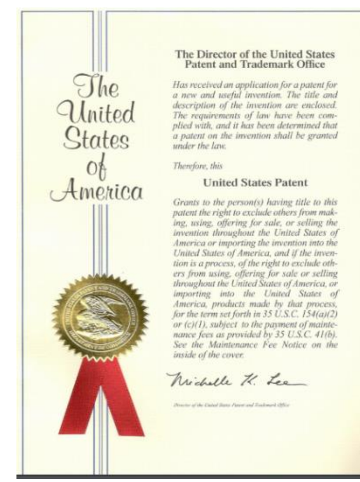
Japanese Patent

Patent No. JP5632924
grant date 17 Oct 2014

Patent referenced By:

Citing Patent	Filing date	Publication date	Applicant	Title
US8872446 *	10 Feb 2011	28 Oct 2014	Mitsubishi Heavy Industries, Ltd.	Welding method and superconducting accelerator
US9055659 *	24 Mar 2011	9 Jun 2015	Mitsubishi Heavy Industries, Ltd.	Method for manufacturing outer conductor
US20120256563 *	10 Feb 2011	11 Oct 2012	Shuho Tsubota	Welding method and superconducting accelerator
US20130008021 *	24 Mar 2011	10 Jan 2013	Haruki Hitomi	Method for manufacturing outer conductor

* Cited by examiner



US Patent

Patent No. US 9352416 B2
grant date May 31, 2016

Optimization was the key to the development of this techniq

Parameters Optimized

- Minimization of energy, and still achieve full depth of penetration.
- Parameter optimization for smoothening of bead.
- Parameter Optimization for HAZ and shrinkage reduction.
- Gas Flow optimization so that debris is dislodged, cooling is good & weld pool is un-disturbed

Result With Optimized Parameters

A. Tensile test

Cleared

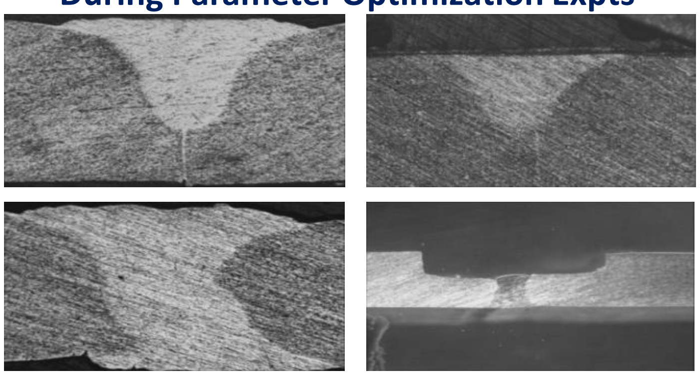
B. Vacuum test

Leak rate was of the order of 1 X 10^{-10} mbar l/s

C. RRR measurement

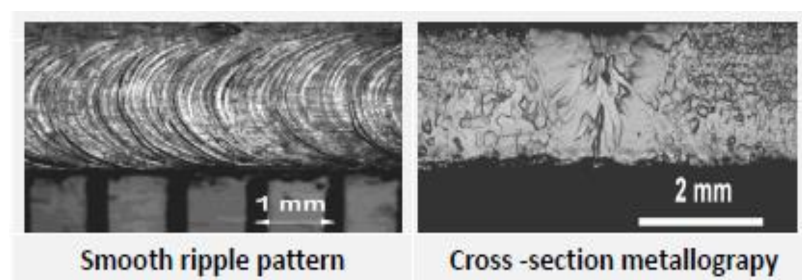
Welded in Argon Environment (99.9999 %) RRR value reduced from 314 to 296 (~6%)

During Parameter Optimization Expts



Metallographic Images of Niobium samples during parameter optimization

Metallographic Images with final parameters



- 2.5 mm weld bead, smooth ripple pattern
- No defect seen in cross sectional examination
- Very narrow HAZ ~ 500 µm

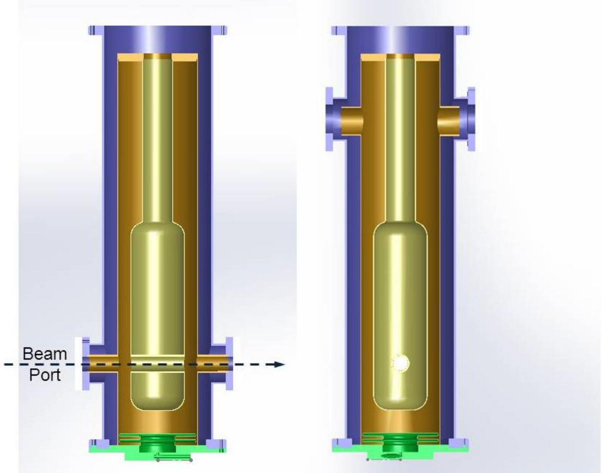
Our Experience

- LBW process is quite versatile and forgiving . This latter aspect is specially helpful when we are dealing with components made from a costly material like niobium.
- There is high repeatability in this process. The amount of shrinkage , penetration depth, spread of HAZ etc are identical with similar parameters. Will benefit SCRF cavity fabrication.
- LBW process has many variables ex pulse energy, pulse duration, repetition rate, focal spot size, pulse shaping, scan speed of the job, gas jet velocity , nozzle shape, flow rate etc.
- Careful selection of the parameters can give us enough flexibility.

Summary & Future Plan

- This technique has shown technical feasibility and financial viability can be easily assessed. We have taken up two projects shown below.
- The new technique may simplify the fabrication process and open up some new avenues too.
- RRCAT has a strong Laser Program and we are putting efforts in developing this technology for future projects.

1. 650MHz Single cell SCRF Cavity

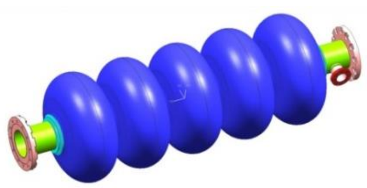


Cut away views of IUAC QWR, cut in two perpendicular planes.

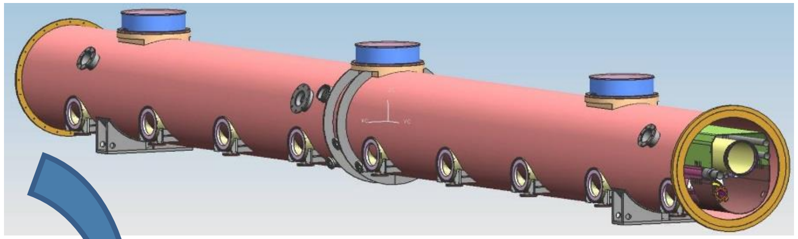
2. QWR cavity in collaboration with IUAC

Outline

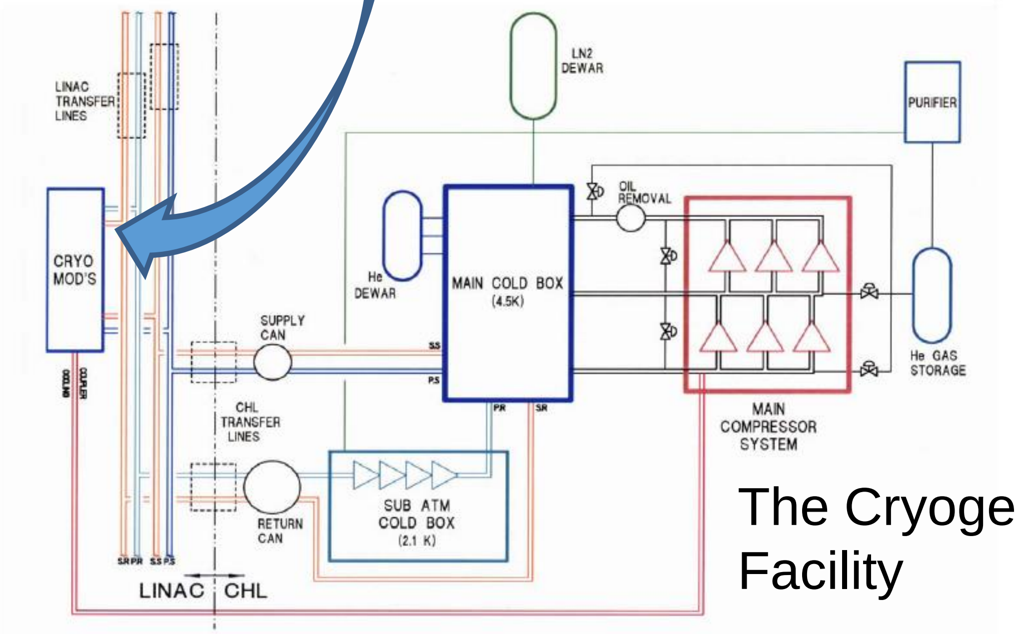
B. Design of 650MHz Cryomodules
(In Collaboration with Fermilab under IIFC)



The SCRF Cavity



& It’s Cryomodule



The Cryogenic Facility

1.Need For Cryogenics & Cryomodule

- The SCRF cavities need to maintained at cryogenic temperatures.

- This requires that the cavities be "packaged" inside an enclosure that can maintain them at low temperatures, and fulfill other requirements related to alignment, shipping ,availability for maintenance etc.
  This enclosure is the cryomodule.

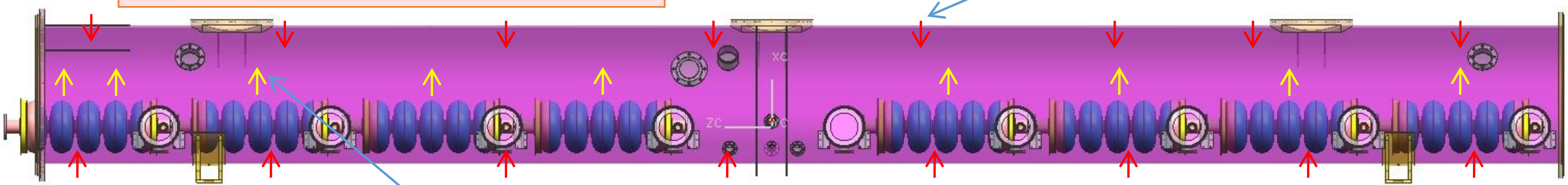
- An elaborate mechanism is required to take out the heat produced inside the cavity (dynamic heat load) and the static heat load. This mechanism consists of transfer lines, helium refrigerators and many other auxiliary systems referred here as the "Cryogenic System"

- In this talk I will deal with the first part i.e. "The cryomodule"

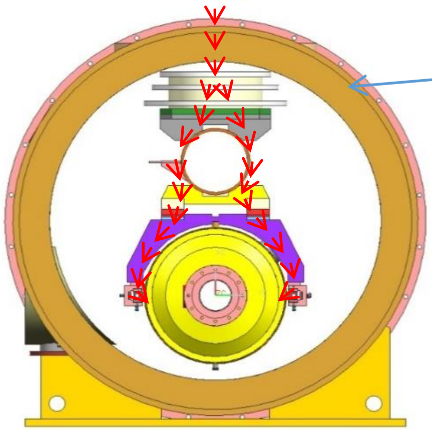
1.Location of heat generation and its removal

Locations of Heat Source

B. THERMAL RADIATION - STATIC



A. GENERATION OF HEAT - DYNAMIC

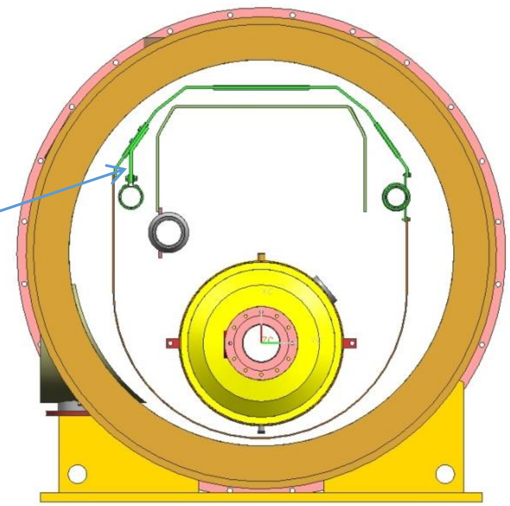


Conduction (STATIC)

MAJOR HEAT SOURCES:
A. CAVITY LOAD (DYN)
B. THERMAL RADIATION (STATIC)

END VIEW OF CRYOMODULE

Removal of Heat



THERMAL SHIELDS COOLED BY HELIUM GAS AT 80K

HELIUM VESSEL WITH SUPER FLUID HELIUM AT 2K

END VIEW OF CRYOMODULE

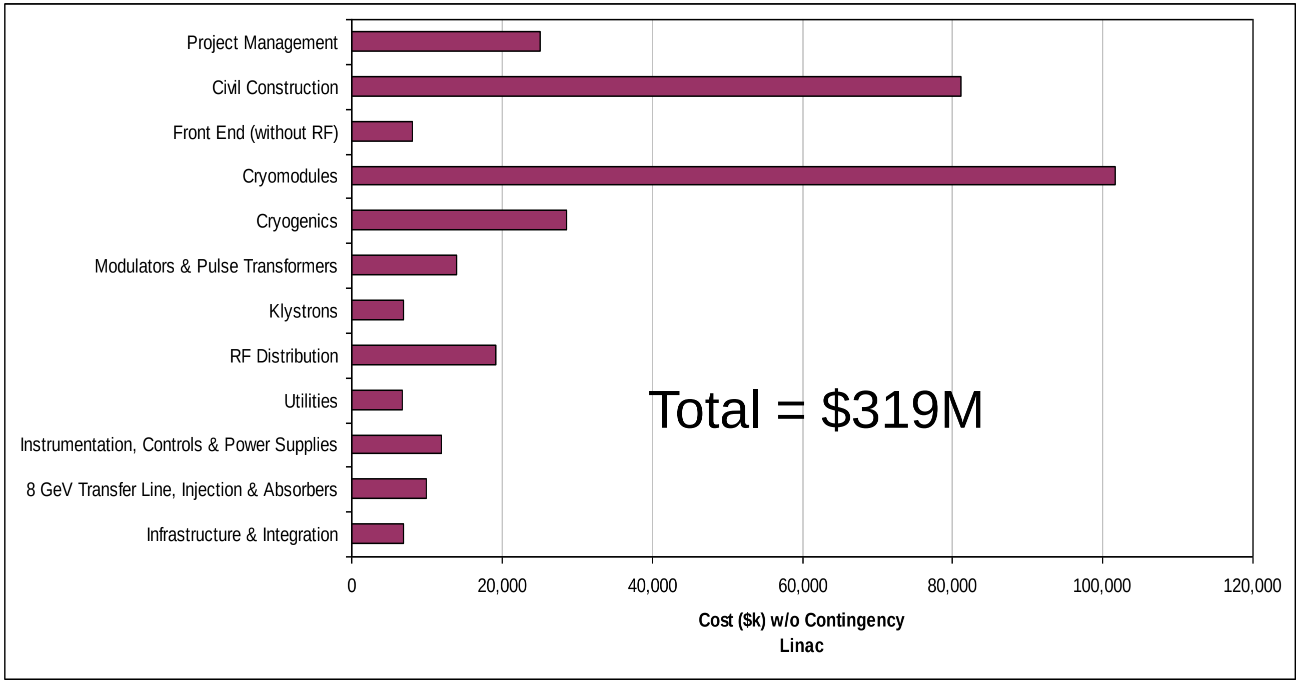
1.Functions of a Cryomodule

- Cryomodule is the building block of an accelerator based on SCRF Technology.
- Cryomodule is an enclosure that supports and houses SCRF cavities and fulfills requirements such as

  - Providing cryogenic environment for SCRF cavities and magnets which operate at temperatures of 2K or 4K.
  - Keeps cavities in good alignment with respect to the designed beam line.Typically within 0.5 mm of ideal beam axis, even after cool down.
  - Provides an interface for feeding RF power generated at room temperature to cavities, which operate at temperature of 2 K.
  - Allows cool-down and warm-up of limited-length strings for repair.

1.Cryomodule –The Major Cost Driver of LINAC

- Cryomodule components & assembly costs, constitute the major part of LINAC price tag.
- A survey of Linear Accelerator (0.5MW)in 2005 to show relative costs of subsystems.

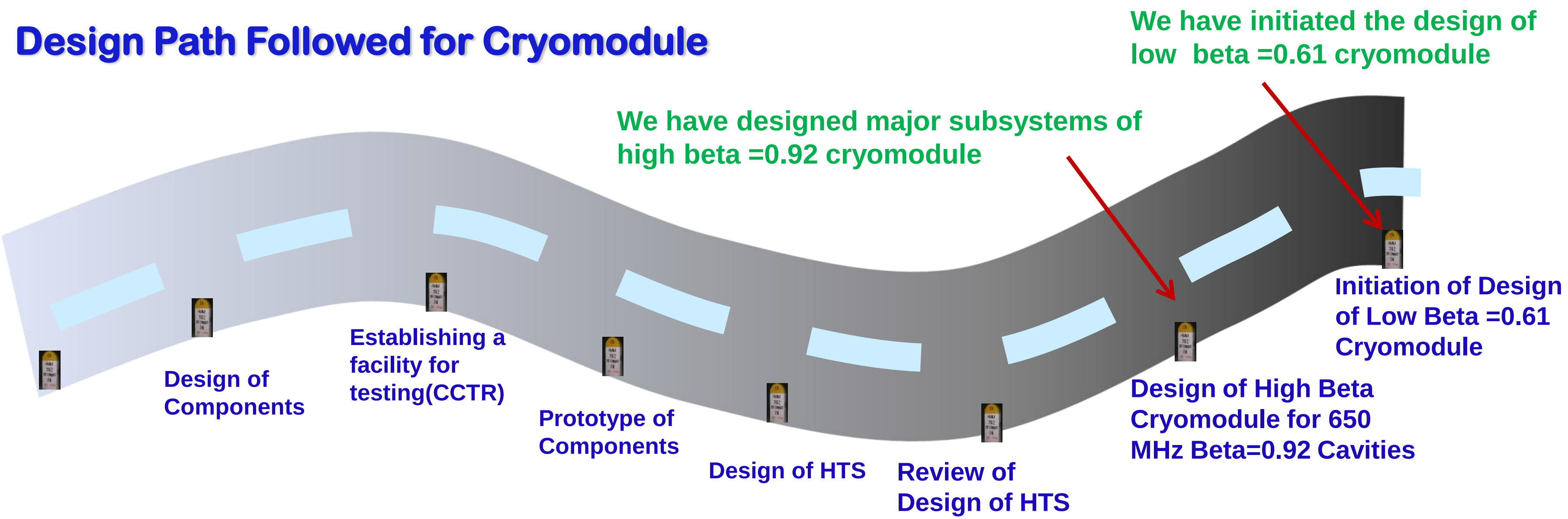


➢A Tesla type cryomodule today costs about $2.2 Mn without SC cavities.

Cost Drivers are the Cryomodules (with cavities), Civil Construction and Cryogenics. A very concerted effort will have to be made to economize cryomodules.

2. Roadmap for 650 MHz Cryomodule Design

Design Path Followed for Cryomodule



- Development of Cryomodule Technology is a time taking process
- Final lattice design is the beginning of this design process
- The subsystems have to be carefully designed and evaluation of their performance at cryogenic temperatures is a very important step.
- Infrastructural requirements are high (large halls for assembly, huge fixtures etc)

3.Design Efforts for 650 MHz Cryomodule at RRCAT

Design activities Completed

1. Design of Cryostat for Horizontal Test Stand .
   a. Design completed and reviewed by FermiLab & RRCAT Experts
   b. Procurement in progress
2 Design of 650MHz Beta=0.92 was performed earlier (Tesla concept)

Work in Progress

3. Design work on stand alone Beta=0.92, 650 MHz cryomodule
   (FermiLab to lead design effort and share with DAE)
4. Design work on stand alone Beta=0.61, 650 MHz cryomodule.
   (RRCAT to lead and Fermilab to review it).

3.Features of 650 MHz Cryomodule

Unique Features of 650MHz Cryomodule

▪Thermal load of 250 W/cryomodule as compared to ~10W at 2K for Tesla cryomodule.

▪Physical size (dia.400mm) of the cavity: ~ two times that of 1.3GHz Tesla type cavity.

▪Stand alone cryomodule for ease of accessibility for repairs.

▪Beta=0.92 Cryomodule to have 6 SCRF cavities and Beta =0.61 cryomodule to have 3 SCRF cavities

▪There will be just one thermal shield .

3.The Approach Adopted

Developing a 3-D Model based on information available ex. Dressed SCRF cavity

Designing subsystems like Vacuum vessel, thermal shield, cryogenic support post , cavity support system etc.

Update 3-D model

Developing a scaled down model using Buckingham PI theorem

Verify results

Fabricating the scaled down model

Testing the model in cryomodule component test Rig

Design review

Finalize the Design

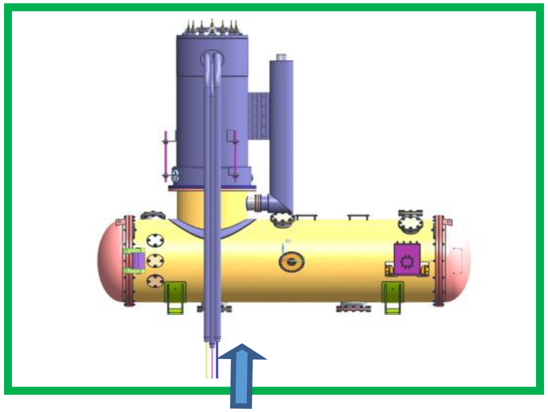
First Task :Horizontal Test Stand Cryostat -A Mini Cryomodule

- Horizontal Test Cryostat is a cryostat for testing two 650 MHz dressed SCRF cavities at 2 K, individually, but in single test cycle to qualify them for assembly into cryomodule.
- RRCAT & Fermi National Accelerator Laboratory (FNAL) have jointly designed the cryostat.
- Operating experience of Horizontal Test Stand-1 at FNAL has been taken into account.
- Design was reviewed by FNAL & RRCAT review committee and approved for fabrication.

HOBICAT, BESSY

Operational Bi-Cavity Horizontal Test Facility

FREIA
Facility for REsearch Instrumentation & Accelerator Development, Sweden
Uppsala University, Sweden ,installed in 2014



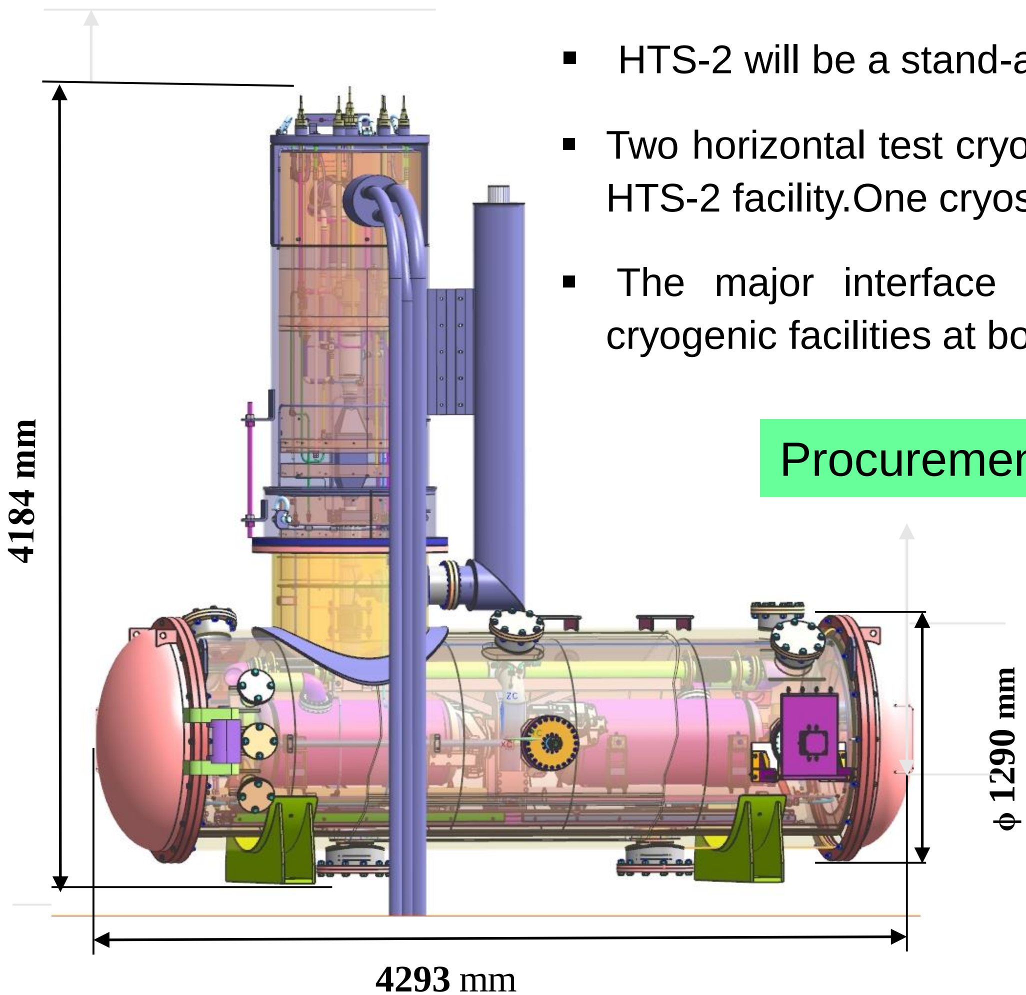
RRCAT

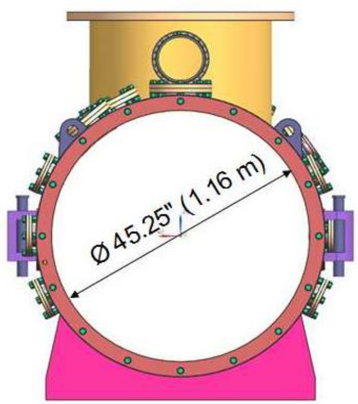
Will be Third such facility in world

3-D model of HTS-2

- HTS-2 will be a stand-alone facility.
- Two horizontal test cryostats are being fabricated as the main part of HTS-2 facility.One cryostat for RRCAT and other for FNAL.
- The major interface of the cryostats will be to the upgraded cryogenic facilities at both institutions (Fermilab and RRCAT).

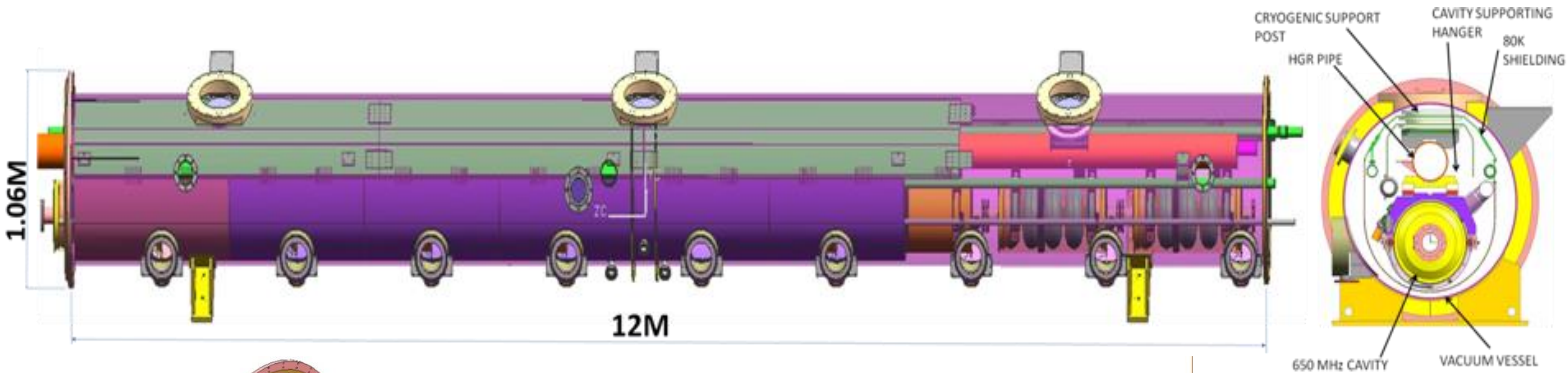
Procurement process nearly complete

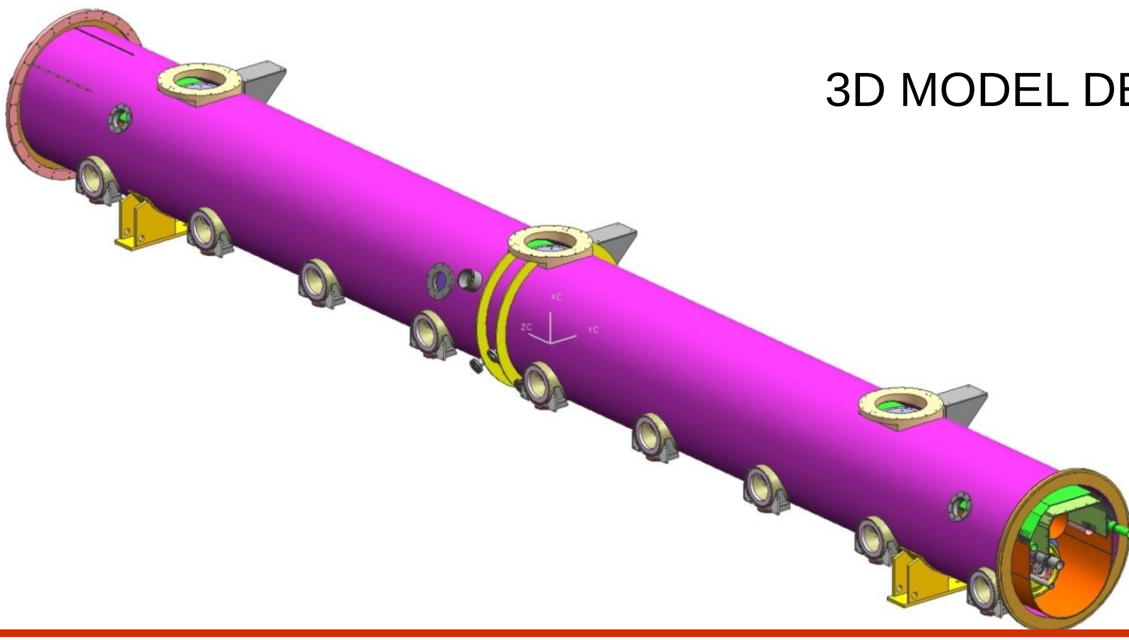




3-D MODEL OF HORIZONTAL TEST CRYOSTAT-2 WITH FEEDCAN

Second Task: 650 MHz Beta =0.92 cryomodule -Tesla Type Design

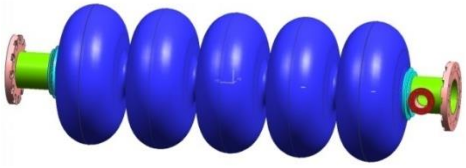




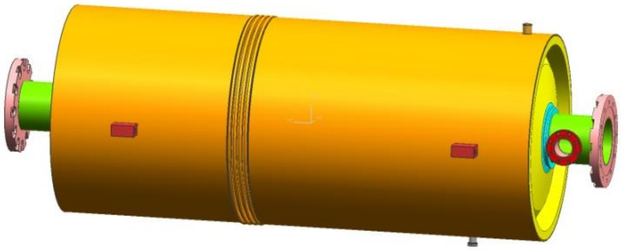
3D MODEL DEVELOPED AT RRCAT

But IT IS TESLA TYPE DESIGN

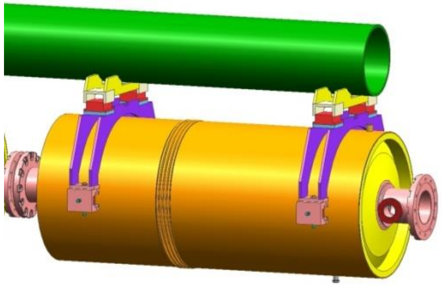
Second Task: 650 MHz Beta 0.92 Subsystems



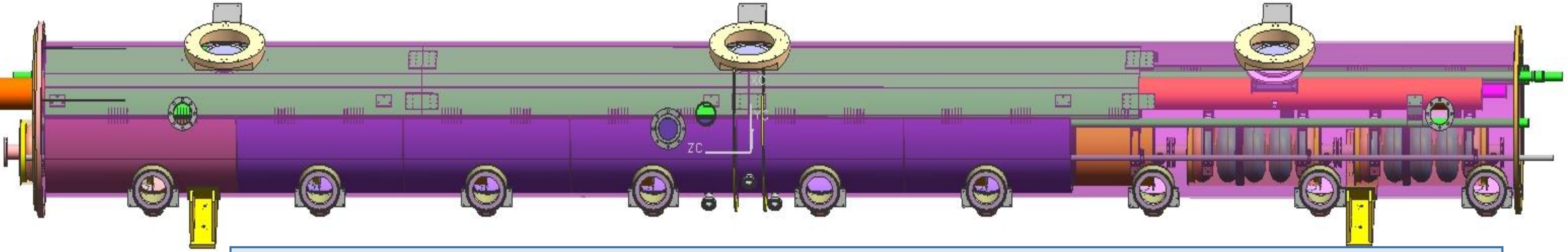
SCRF CAVITY



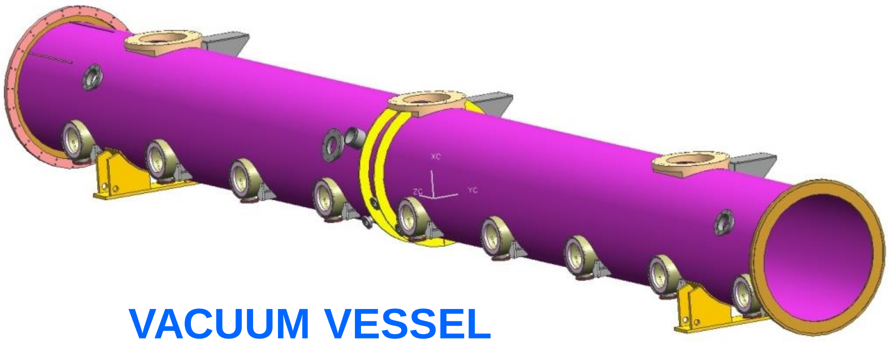
HELIUM VESSEL



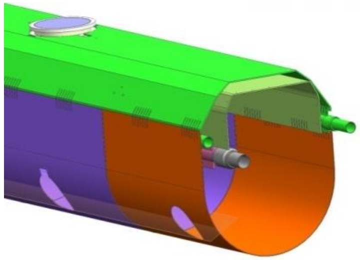
CAVITY SUPORT SYSTEM



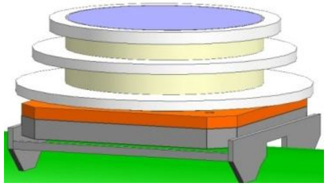
3-D Model of top supported 650 MHz cryomodule



VACUUM VESSEL

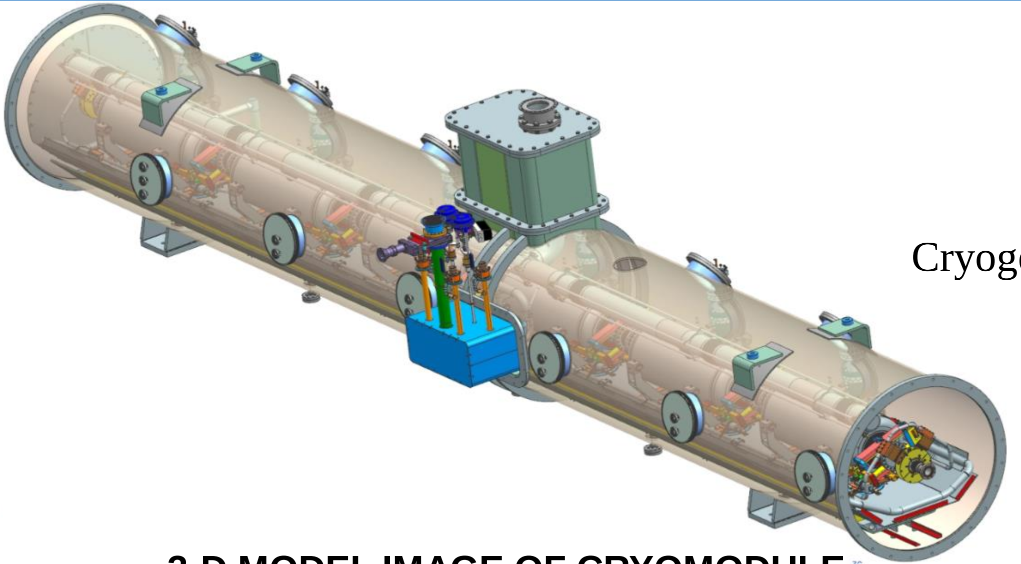


THERMAL SHIELD

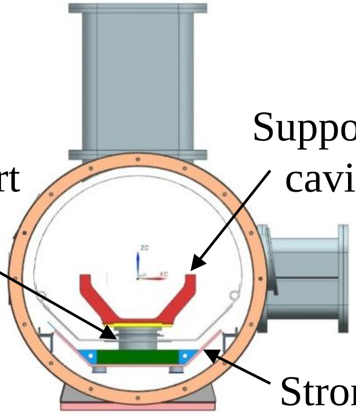


CRYOGENIC SUPPORT POST

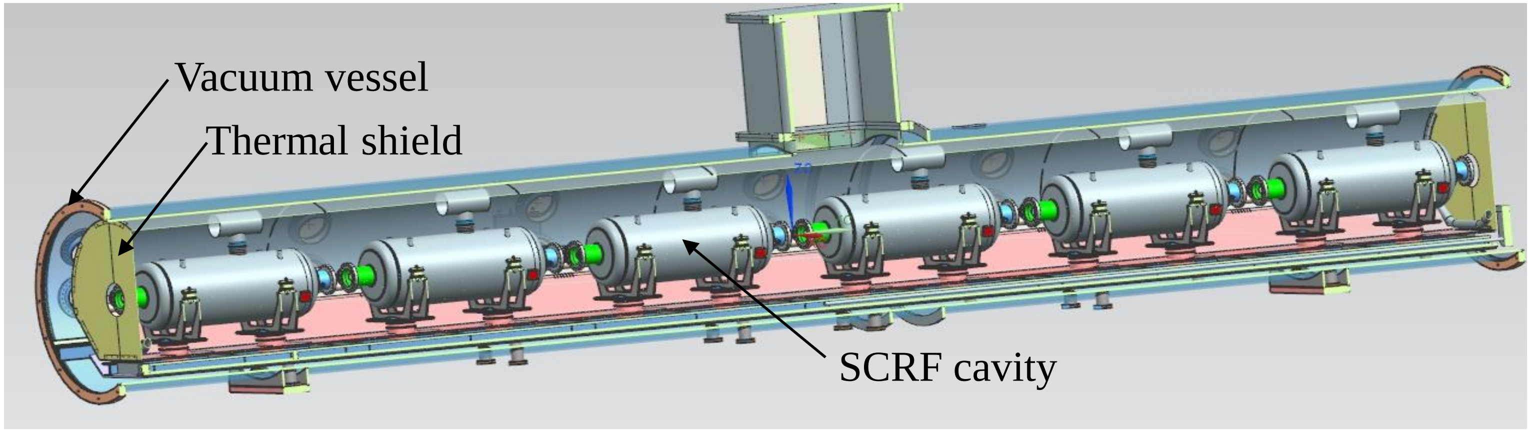
Third Task: 650 MHz Beta 0.92 cryomodule - Bottom Supported Design



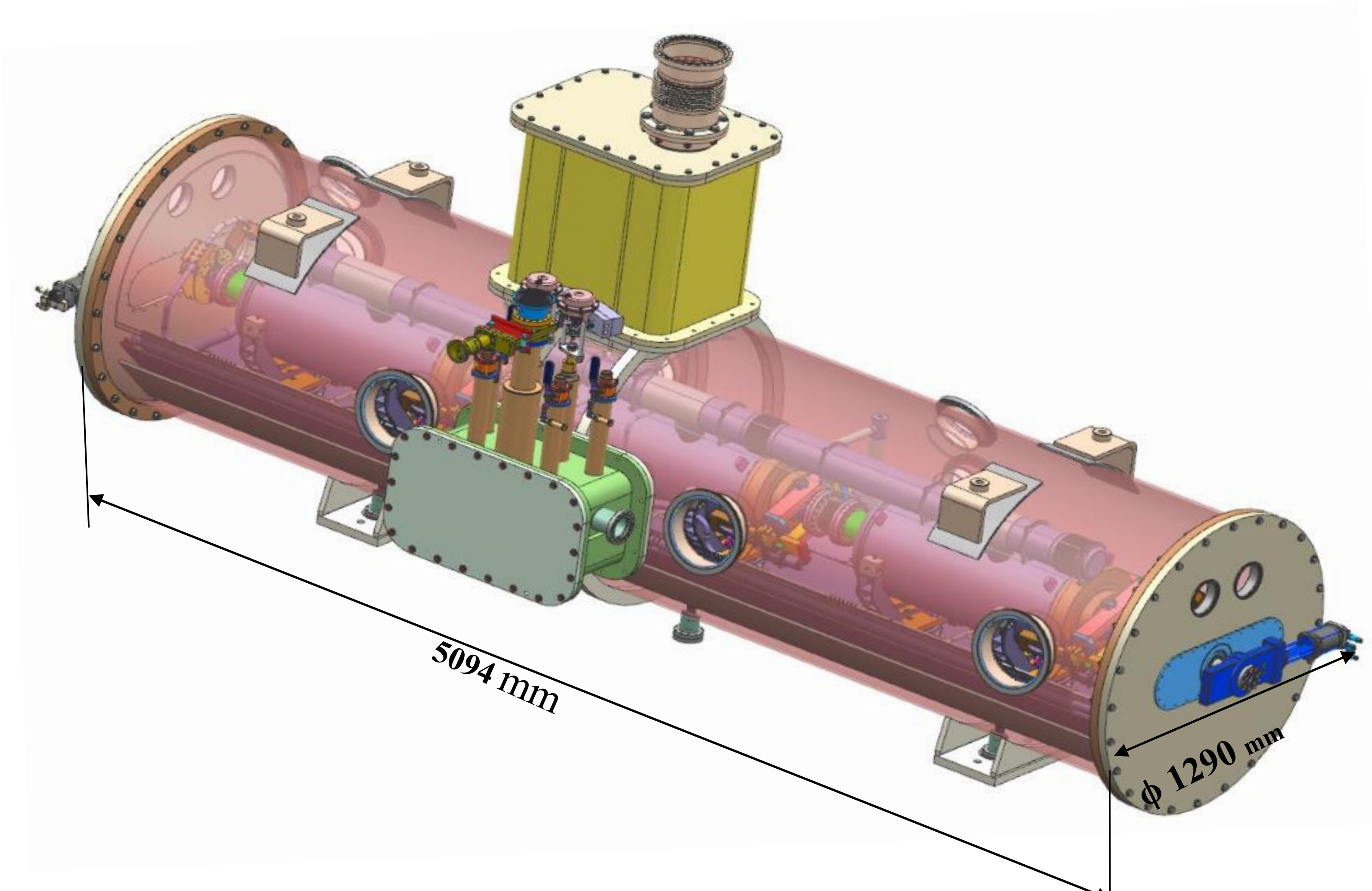
3-D MODEL IMAGE OF CRYOMODULE
(Showing major sub-systems in Cryomodule w/o piping)



CROSS SECTION

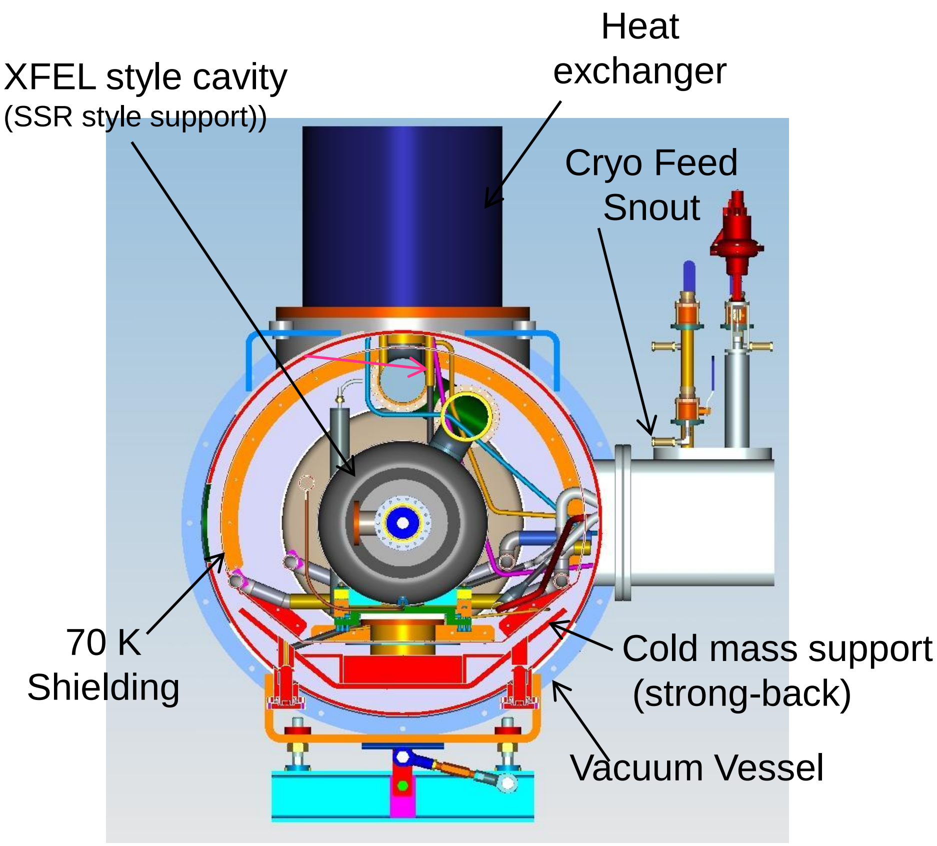


Fourth Task: Bottom Supported Cryomodule Beta=0.6



3-D model of 650 MHz Cryomodule Beta=0.61

Configuration of 650 MHz Cryomodules (similar to SSR configuration)



CROSS SECTION OF CRYOMODULE

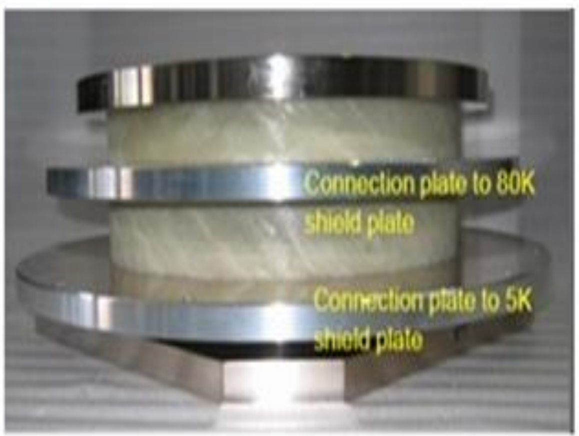
Courtesy: Tom Peterson and Tom Nicol, FNAL

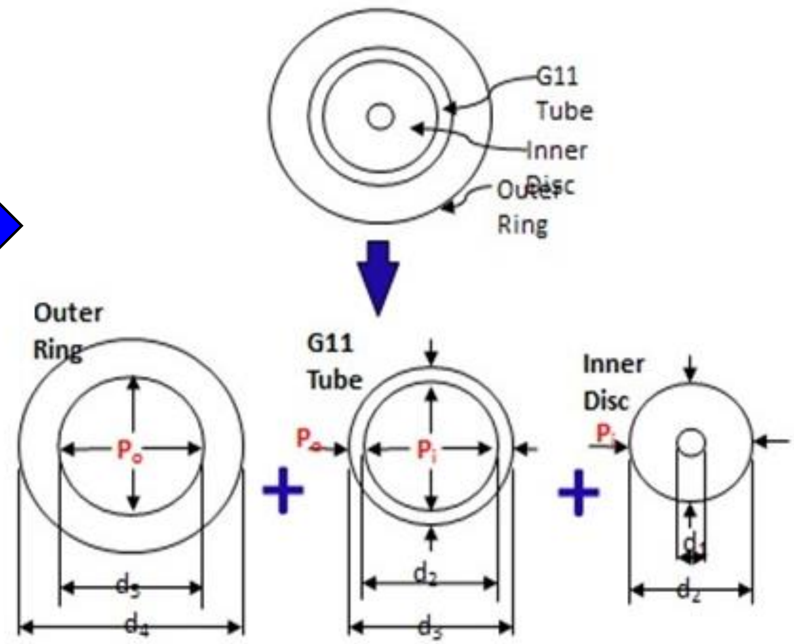
- Standalone cryomodule for β=0.61, 650 MHz SCRF cavities.
- Own vacuum envelope isolated from vacuum envelope of other cryomodules.
- Individually interfaced with main cryogenic transfer line.
- Only beam tube is common (with vacuum isolation valves at ends)

Cryomodule Components design examples

Design of Subsystems:
1. Cryogenic support post

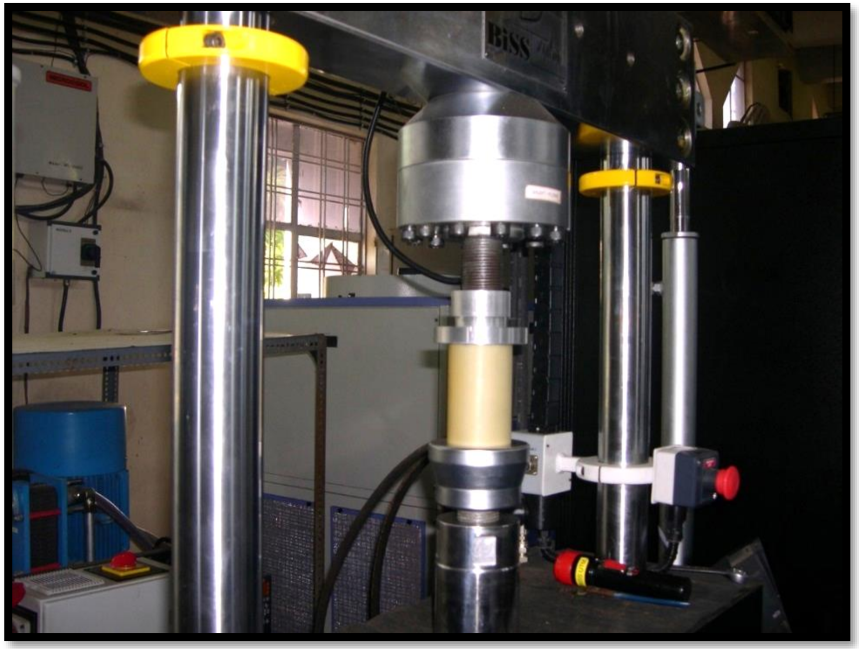
- Structurally transfers cold mass weight to strongback structure
- Thermally isolates cold mass from room temperature environment
- Generally made by shrink fitting SS discs and rings on G-11 tube

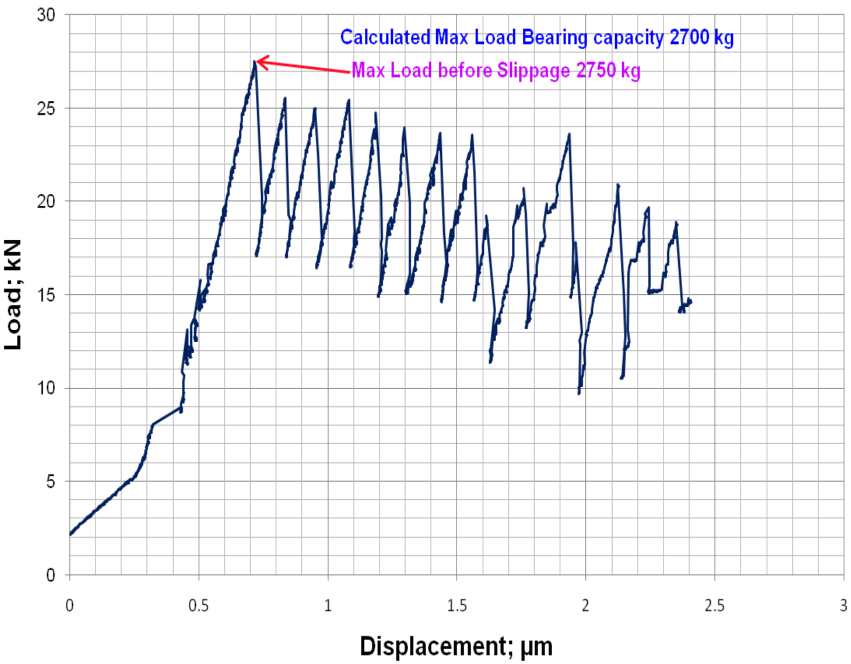




Stress formulae for thick cylinders have been used to find out stress and interference/clearance fits.

Testing of cryogenic support post



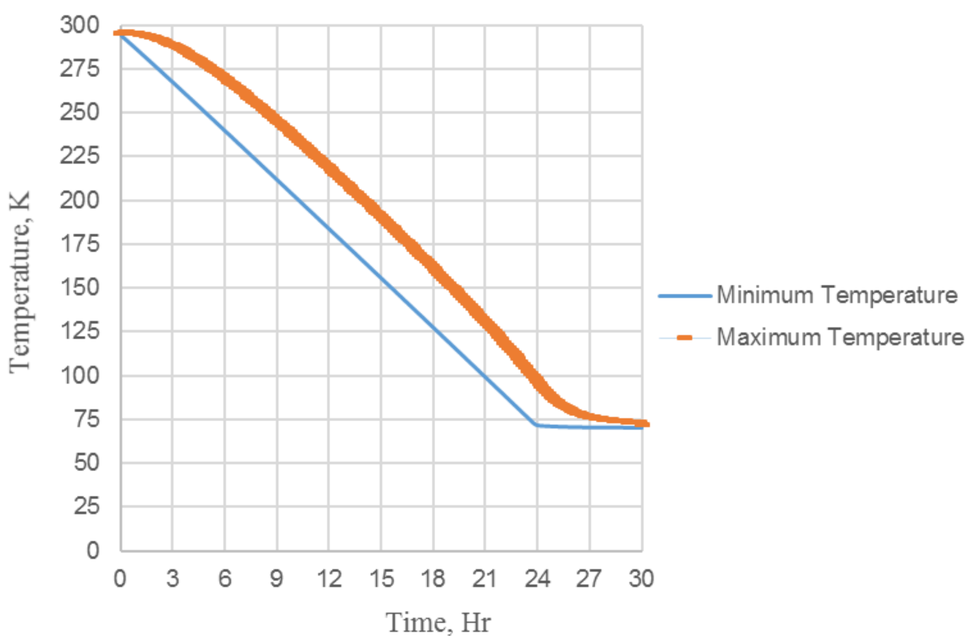


Load Testing of Inner Joint

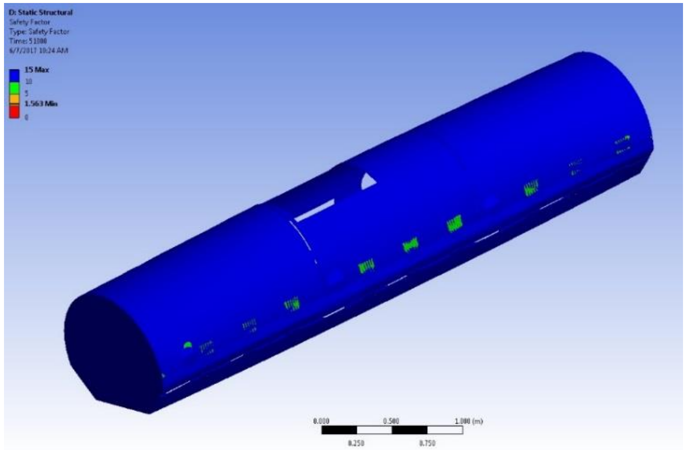
Load bearing capacity of support post is found to be ~2700 kg, which matches with calculated values.

Design of subsystems:
70 K thermal shield

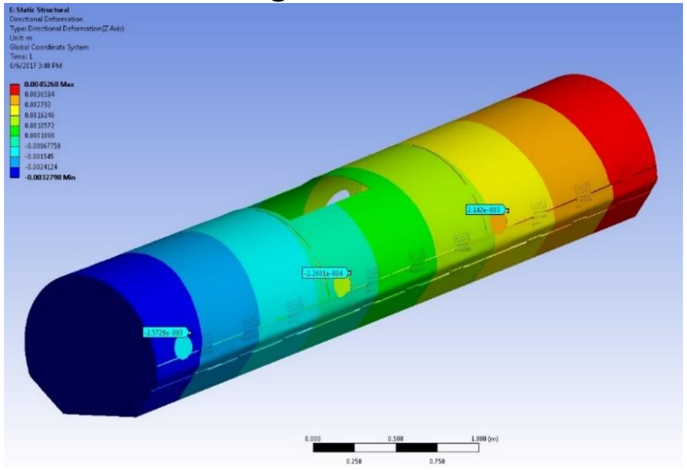
- Linear cool down has been assumed
- Structural analysis is also carried out at maximum gradient.



Max. and Min. temperature with time



Structural analysis at maximum gradient



Axial deformation after cool down

Testing of 70 K thermal shield of cryomodule (using scaled down model)

Buckingham Pi-theorem: Consider 'n' number of independent variables for a physical option: $f(q_1, q_2, q_3 \ldots\ldots q_n) = 0$ or $q_1 = g(q_2, q_3\ldots\ldots q_n)$

Then as per this theorem, one can form (n-3) independent dimensionless groups $\pi_1, \pi_2, \pi_3 \ldots\ldots \pi_{n-3}$, so that $h(\pi_1, \pi_2, \pi_3\ldots\ldots\pi_{n-3}) = 0$

Dimensionless numbers:

1. $\frac{h*L}{k}$
2. $\frac{L*Q_{Rad}}{k*T}$
3. $\frac{L*Q_S}{k*T}$ & $\frac{L*Q_C}{k*T}$
4. $\frac{T_S}{T_f}$ & $\frac{T_S}{T_a}$
5. $\frac{\alpha*t}{L^2}$
6. $\frac{C}{k*L*t}$

Summary of dimensional analysis:

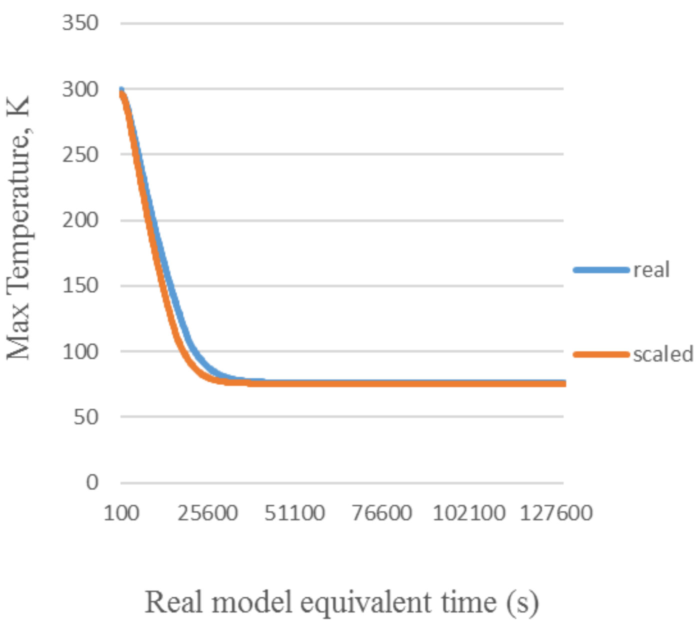
- Reduce all dimensions by a factor of n.
- Reduce time, t by factor of n^2.
- Increase all heat fluxes, Q by a factor of n.
- Increase heat transfer coefficient, h by a factor of n.

Material for model and prototype are same

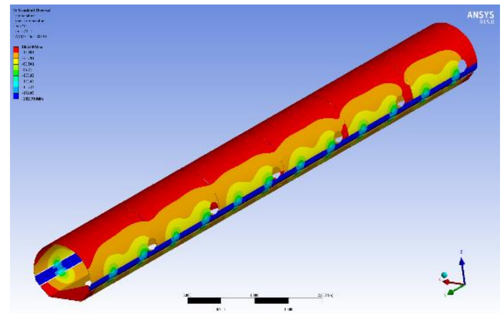
We have reduced model by one fourth, for FEA.

Courtesy: *HBNI M.Tech. thesis of* ***Mr. Ankit Tiwari***

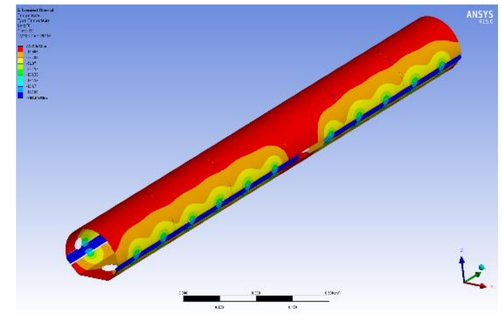
FEA verification of dimensional analysis



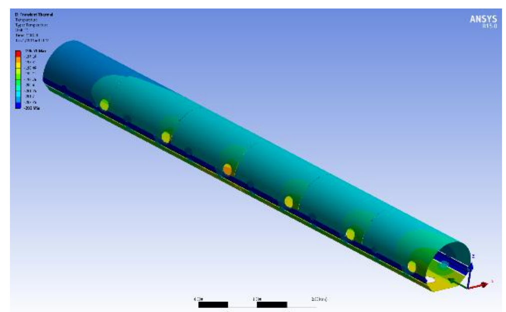
HB cryomodule shield used for verification



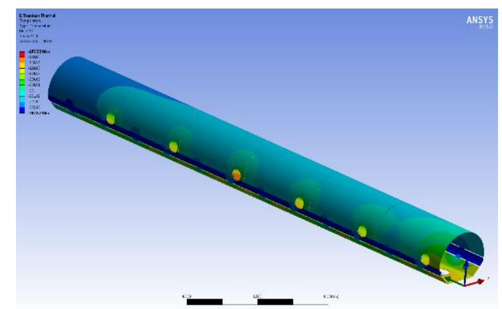
Time = 2400 sec



Eq. Time = 2400 sec



Time = 118400 sec



Eq. Time = 118400 sec

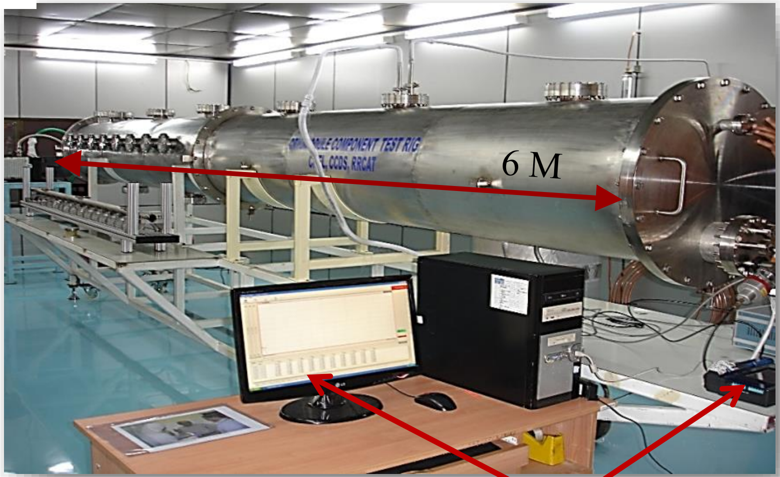
Real model results

Scaled model results

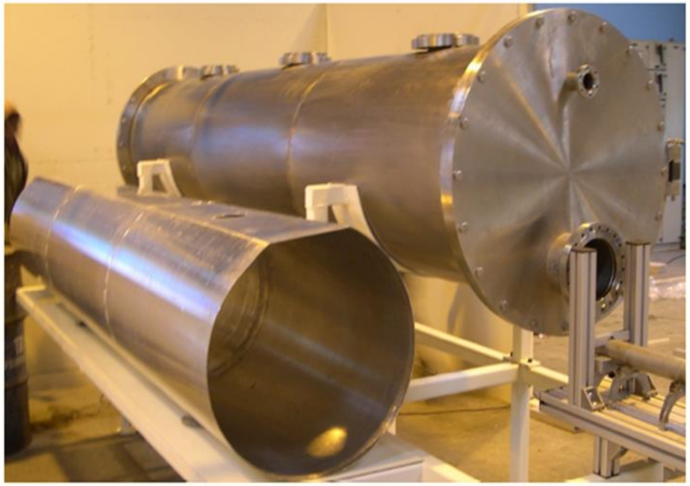
- ✓ *Above Figures show correlation between real and scaled model so, scaled down model of thermal shield can be used for experimental verification of thermal shield.*

Courtesy: *HBNI M.Tech. thesis of* ***Mr. Ankit Tiwari***

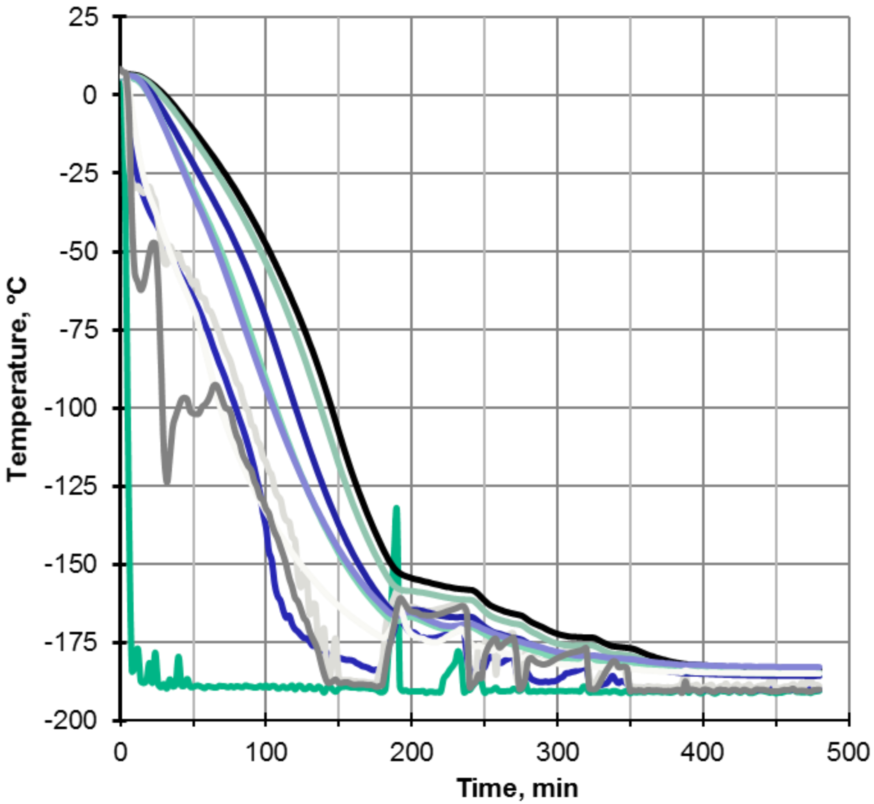
Validation in CCTR



Data acquisition from temperature sensors during cool-down of liquid nitrogen cooled thermal shield



Shield tested in CCTR



Temperature data recorded for shield experiment in CCTR

THANKS

Heat load estimate of the PIP-II cryogenic system for CW mode.

	No. of CM	2K static heat load per CM (W)	2K dynamic heat load per CM (W)	Total 2K heat load (W)	5K[a] heat load per CM (W)	Total 5K heat load (W)	70K[b] heat load per CM (W)	T
	1	37	23.5	60.5	60	60	250	
	2	12	23.1	70.2	88	176	166	
	7	9	52.3	429.1	62	434	126	
	11	2	55.5	632.5	16	176	48	
	4	4	129.8	535.2	32	128	86	
				1727.5		974		
				129.3		77.8		
				1856.8		1051.8		
ty margin				2101		1367.4		

Heat load estimate of the PIP-II cryogenic system for pulsed mode.

	No. of CM	2K static heat load per CM (W)	2K dynamic heat load per CM (W)	Total 2K heat load (W)	5K[a] heat load per CM (W)	Total 5K heat load (W)	70K[b] heat load per CM (W)	T
	1	37	23.5	60.5	60	60	250	
	2	12	0.89	25.8	88	176	166	
	7	9	2.8	82.6	62	434	126	
	11	2	2.9	53.9	16	176	48	
	4	4	6.8	43.2	32	128	86	
				266		974		
				129.3		77.8		
				395.3		1051.8		
ty margin				493		1367.4		

loads, [b] Includes the intercept loads as well as 45 – 80K thermal shield loads
urced from PIP-II CDR

Results and Discussion

2K helium flow in the cryomodules vary from 96.7 g/s to 15.1 g/s from the CW to the pulsed modes of operation.

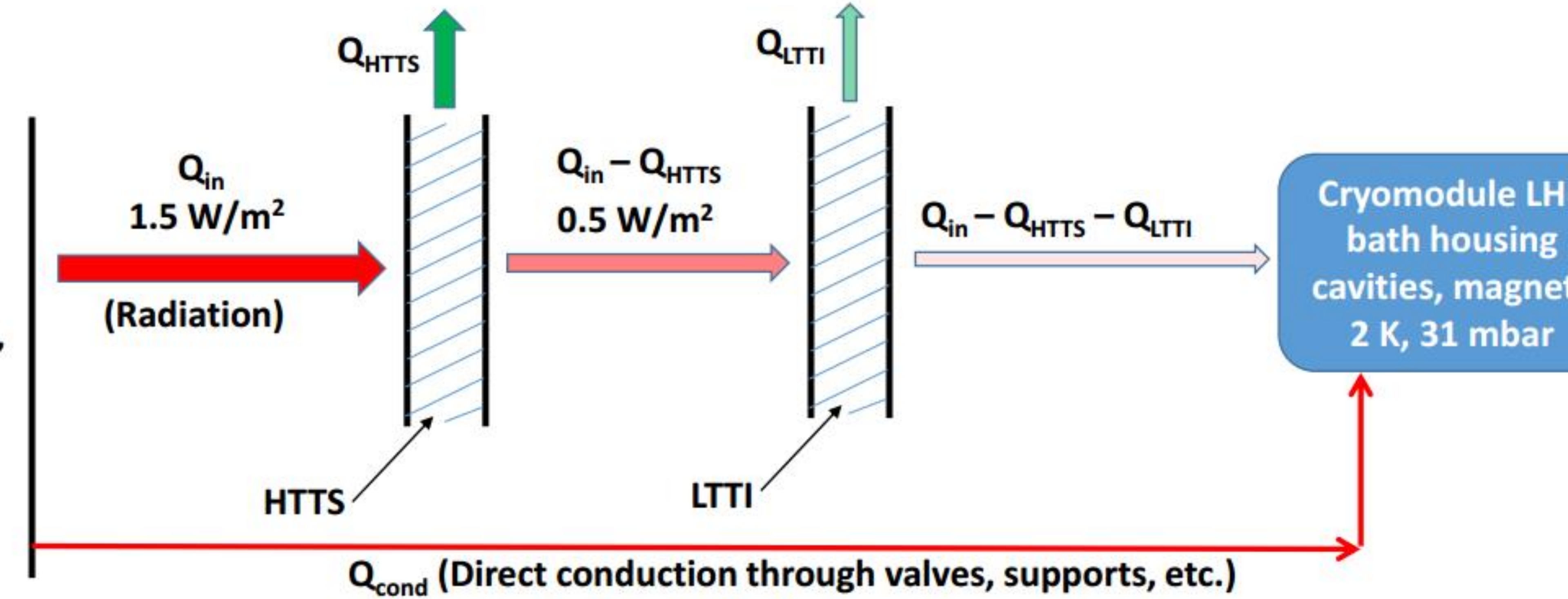
Spread of pumped down mass flow rate that the cold compressor (CC) train needs to handle (a ratio in excess of 6) is much higher than that reported in literature.

Return line B temperature at the exit of the CDS varies from about 3.7K for the CW mode to about 5.6K for the pulsed mode.

CC operation is limited by its surge and choking limits which restricts the spread of inlet process parameters and mass flow rate.

One solution for pulsed mode may be to source 4.5K helium stream from line C and mix with line B to maintain required process conditions for CC; however not likely to bring significant saving to process compressor power requirements.

Static heat loads*



HTTS: High temperature thermal shield and intercepts (35 K – 80 K)

LTTI: Low temperature thermal intercepts (4.5 K – 9 K)

ejas Rane will talk on the computation of static heat loads of a prototype cryomodule

Features of 650 MHz Cryomodule

Unique Features of 650MHz Cryomodule

- Thermal load of 250W/cryomodule as compared to ~10W at 2K for Tesla cryomodule.
- Physical size (dia.400mm) of the cavity: ~ two times that of 1.3GHzTesla type cavity.
- Stand alone cryomodule for ease of accessibility for repairs.
- Bottom supported design
- Cryo-system pressure stability at 2K ~ 0.1 mbar (RMS)
- Cavity alignment error (RMS) ~ 0.5 mm
- Physical beam aperture 118 mm
- Warm MAWP at 2K ~ 2 bar
- Cold MAWP at 2K ~ 4 bar

Courtesy: FRS HB 650 MHz Cryomodule, FNAL

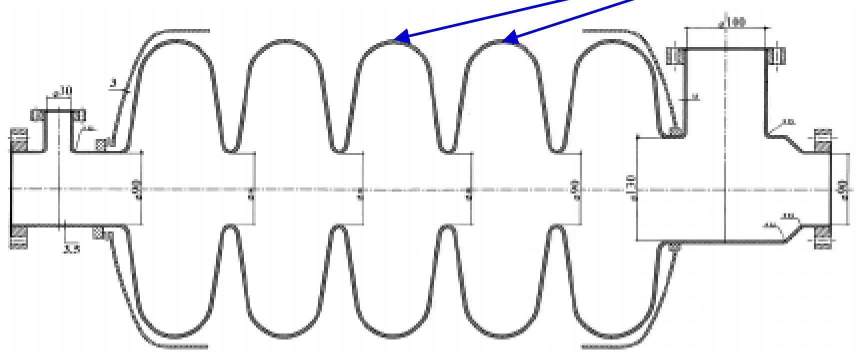
5. Field flatness of fabricated 5-cell cavity

Flatness of multi cell cavity is defined as:

$$field\ flatness[\%] = \left(1 - \frac{E_{c\max} - E_{c\min}}{\frac{1}{N}\sum E_{ci}}\right) \times 100\%$$

- Where
- E_{ci} is the peak axial electric field of ith cell.
- E_{cmax} (E_{cmin}) is the maximum (minimum) filed among N cells.
- N is a number of cell.

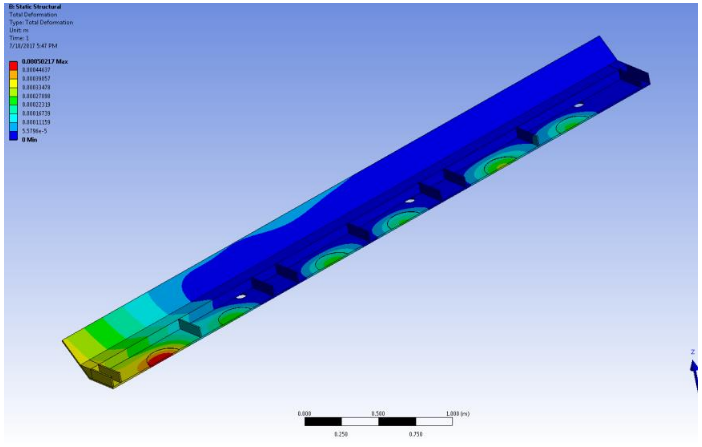
Energy stored in all cells is equal then, flatness = 100%



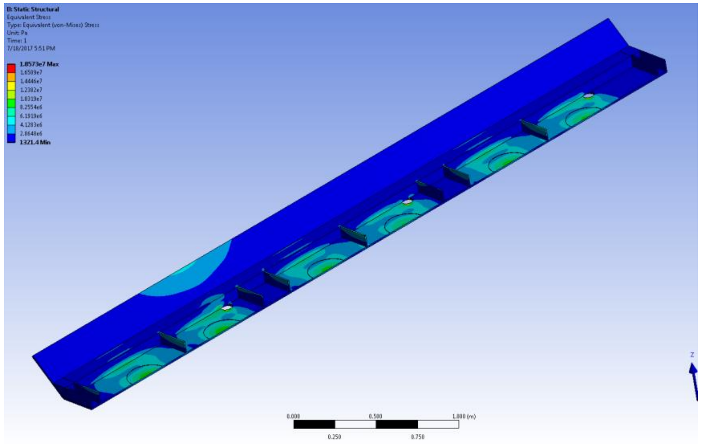
Field flatness of multi cell cavity made by laser welding was found to be 85%.

Design of Subsystems: Strongback

- Design of cavity support system for LB 650 MHz cryomodule is currently under progress.
- Design of strongback for LB 650 is similar to HB 650 MHz cryomodule strongback structure.
- Supports loads of three 650 MHz cavities.
- Heat transfer calculations has been carried out to find temperature of strongback.
- Temperature of strongback is found to remain at near room temperature (as expected).



Max. deformation ~ 0.5mm

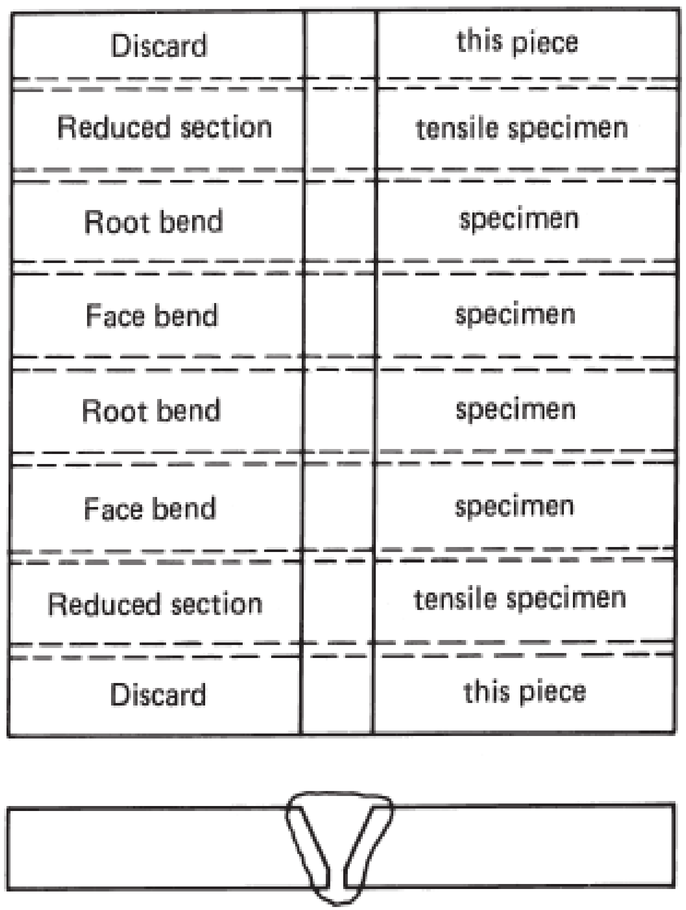


Max. Stress ~ 19 MPa

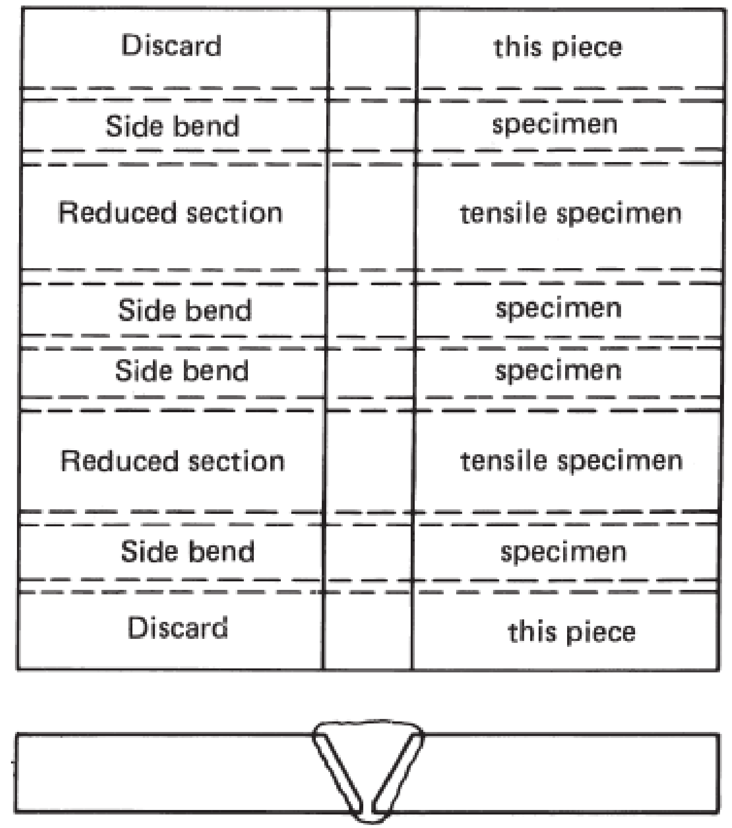
Qualification tests:

- Tension Test
- Bending Test
- Radiography Inspection (NDT)
- Ultrasonic Testing (NDT)
- RRR Measurement Test

QW-463.1(a) PLATES — LESS THAN $^3/_4$ in. (19 mm) THICKNESS PROCEDURE QUALIFICATION [1]



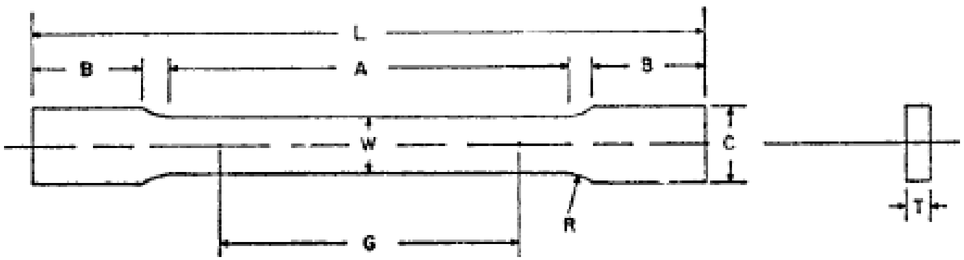
QW-463.1(b) PLATES — $^3/_4$ in. (19 mm) AND OVER THICKNESS AND ALTERNATE FROM $^3/_8$ in. (10 mm) BUT LESS THAN $^3/_4$ in. (19 mm) THICKNESS PROCEDURE QUALIFICATION [1]



Sample preparation

Tensile test specimen

E8/E8M – 09



Dimensions			
	Standard Specimens		Subsize Specimen
	Plate-Type, 40 mm [1.500 in.] Wide	Sheet-Type, 12.5 mm [0.500 in.] Wide	6 mm [0.250 in.] Wide
	mm [in.]	mm [in.]	mm [in.]
G—Gage length (Note 1 and Note 2)	200.0 ± 0.2 [8.00 ± 0.01]	50.0 ± 0.1 [2.000 ± 0.005]	25.0 ± 0.1 [1.000 ± 0.003]
W—Width (Note 3 and Note 4)	40.0 ± 2.0 [1.500 ± 0.125, -0.250]	12.5 ± 0.2 [0.500 ± 0.010]	6.0 ± 0.1 [0.250 ± 0.005]
T—Thickness (Note 5)		thickness of material	
R—Radius of fillet, min (Note 6)	25 [1]	12.5 [0.500]	6 [0.250]
L—Overall length, min (Note 2, Note 7, and Note 8)	450 [18]	200 [8]	100 [4]
A—Length of reduced section, min	225 [9]	57 [2.25]	32 [1.25]
B—Length of grip section, min (Note 9)	75 [3]	50 [2]	30 [1.25]
C—Width of grip section, approximate (Note 4 and Note 9)	50 [2]	20 [0.750]	10 [0.375]

FIG. 1 Rectangular Tension Test Specimens[2],[3],[4],[5],[6],[7]

Bend Test

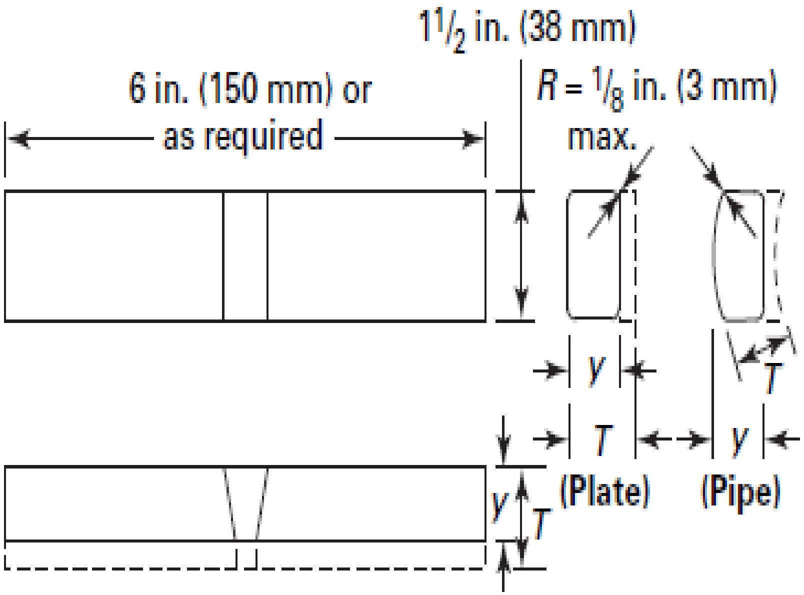
The bend test is a simple and inexpensive qualitative test that can be used to evaluate both the ductility and soundness of a material. It is often used as a quality control test for butt-welded joints, having the advantage of simplicity of both test piece and equipment.

Guided bend test specimen shall be prepared by cutting the test plate to form specimen of rectangular cross section.

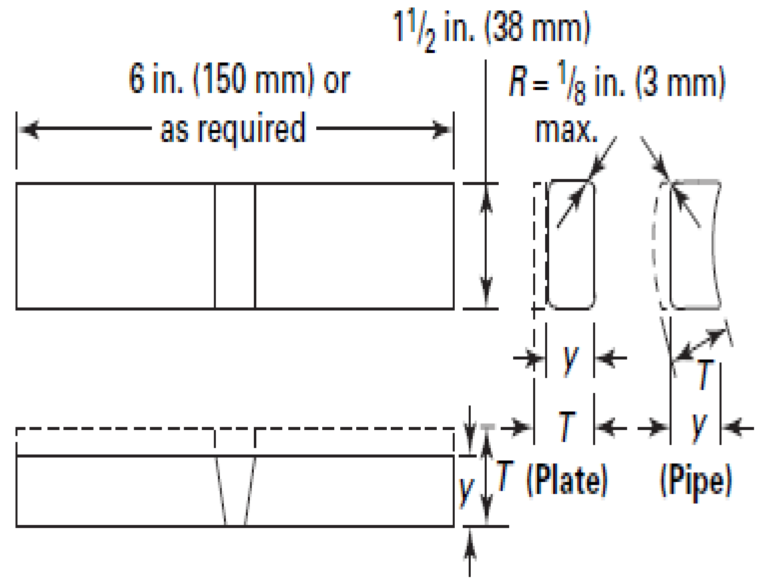
Guided-bend specimens are of five types, depending on whether the axis of the weld is transverse or parallel to the longitudinal axis of the specimen, and which surface (side, face, or root) is on the convex (outer) side of bent specimen. The five types are defined as follows.

Transverse Side Bend
Transverse Face Bend
Transverse Root Bend
Longitudinal Side Bend
Longitudinal Face Bend
Longitudinal Root Bend

Bend Test



Face-Bend Specimen — Plate and Pipe



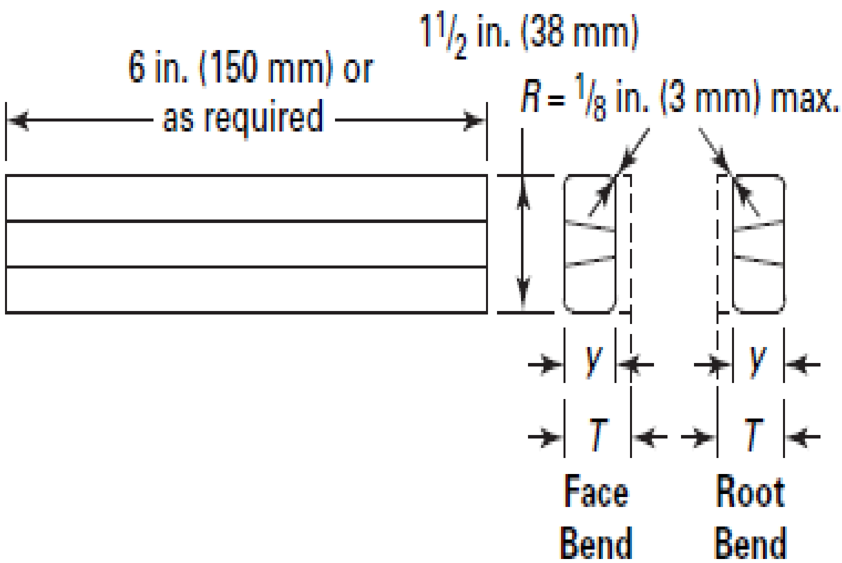
Root-Bend Specimen — Plate and Pipe

	Y, in. (mm)	
T, in. (mm)	P-No. 23, F-No. 23, or P-No. 35	All Other Metals
1/16 < 1/8 (1.5 < 3)	T	T
1/8–3/8 (3–10)	1/8 (3)	T
>3/8 (10)	1/8 (3)	3/8 (10)

QW-462.3(a) FACE AND ROOT BENDS —**TRANSVERSE** [1]

Cont….

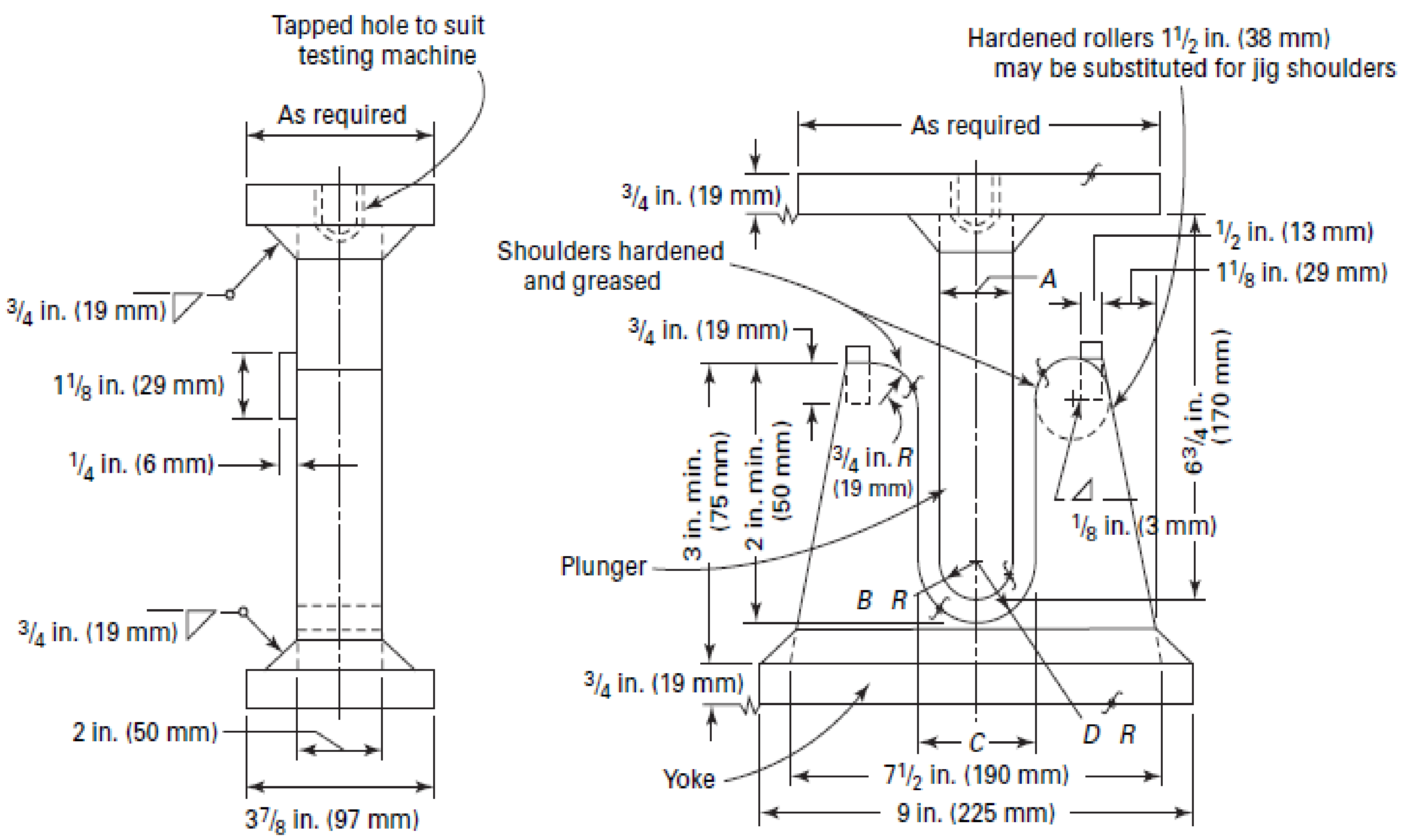
QW-462.3(b) FACE AND ROOT BENDS — LONGITUDINAL



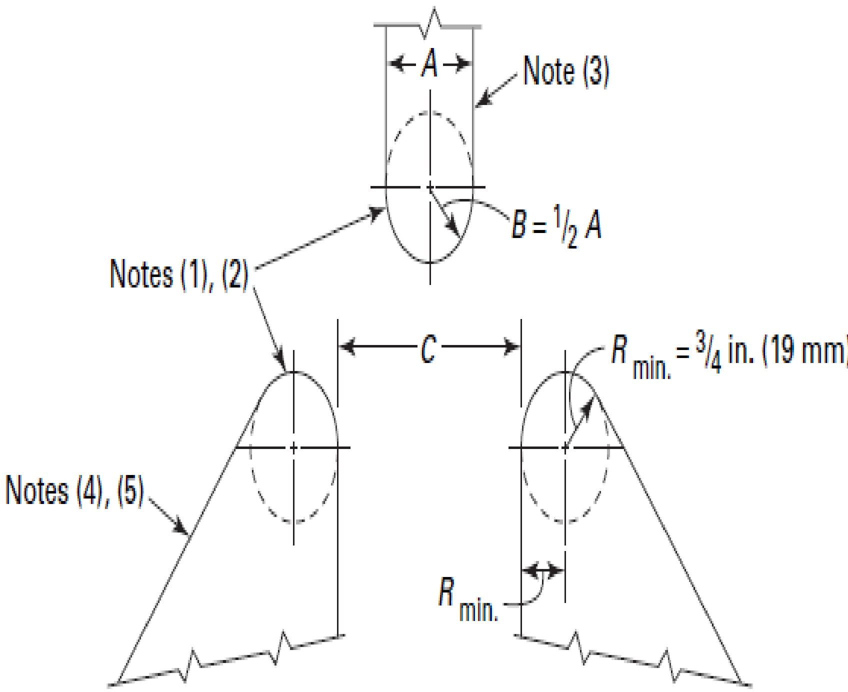
T, in. (mm)	Y, in. (mm) P-No. 23, F-No. 23, or P-No. 35	Y, in. (mm) All Other Metals
$\frac{1}{16} < \frac{1}{8}$ (1.5 < 3)	T	T
$\frac{1}{8}$–$\frac{3}{8}$ (3–10)	$\frac{1}{8}$ (3)	T
$>\frac{3}{8}$ (10)	$\frac{1}{8}$ (3)	$\frac{3}{8}$ (10)

QW-462.3(a) FACE AND ROOT BENDS —**LOGITUDINAL** [1]

QW-466.1 TEST JIG DIMENSIONS [1]

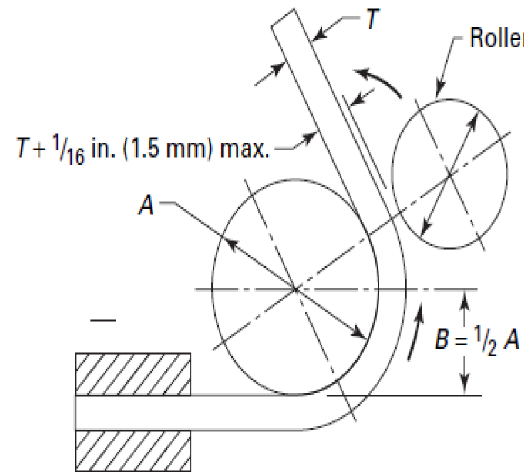


QW-466.2 GUIDED-BEND ROLLER JIG [1]



GENERAL NOTE: See QW-466.1 for jig dimensions and general notes.

QW-466.3 GUIDED-BEND WRAP AROUND JIG [1]



GENERAL NOTES:
(a) See QW-466.1 for jig dimensions and other general notes.
(b) Dimensions not shown are the option of the designer. The essential consideration is to have adequate rigidity so that the jig parts will not spring.
(c) The specimen shall be firmly clamped on one end so that there is no sliding of the specimen during the bending operation.
(d) Test specimens shall be removed from the jig when the outer roll has been removed 180 deg from the starting point.

Acceptance Criteria — Bend Tests

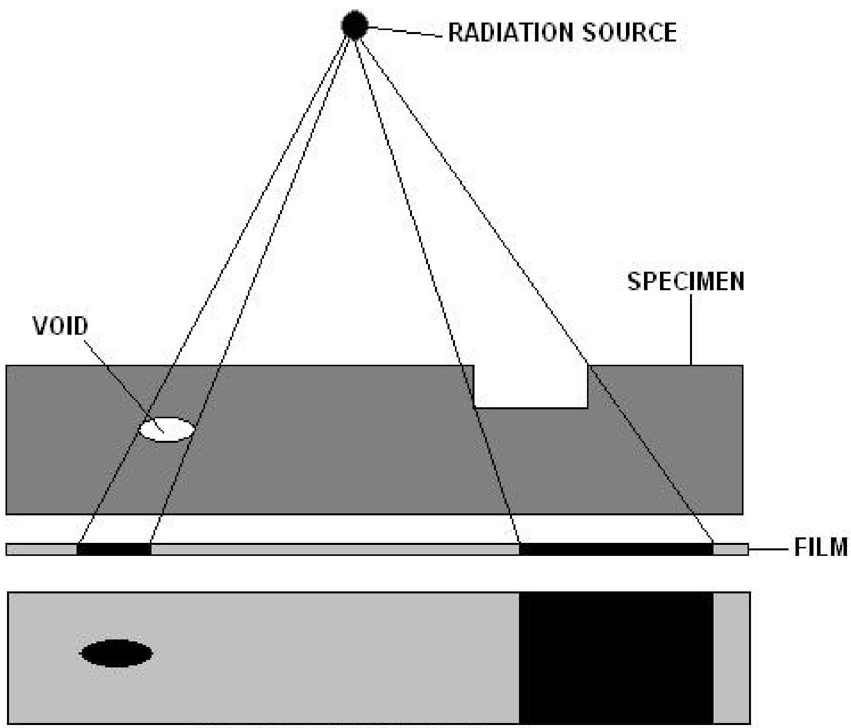
The weld and heat-affected zone of a transverse weldbend specimen shall be completely within the bent portion of the specimen after testing.

The guided-bend specimens shall have no open discontinuity in the weld or heat-affected zone exceeding 1⁄8 in. (3 mm), measured in any direction on the convex surface of the specimen after bending.

Open discontinuities occurring on the corners of the specimen during testing shall not be considered unless there is definite evidence that they result from lack of fusion, slag inclusions, or other internal discontinuities.

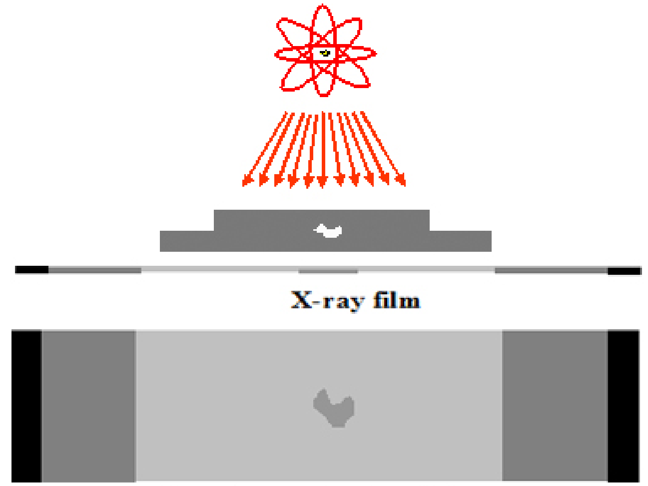
Radiography Inspection (NDT)

- It is a method of inspecting materials for hidden flaws by using the ability of short X-rays and gamma rays to penetrate various materials.
- In Radiography Testing the test-part is placed between the radiation source and film (or detector).
- The material density and thickness differences of the test-part will attenuate (i.e. reduce) the penetrating radiation through interaction processes involving scattering and/or absorption.
- The differences in absorption are then recorded on film(s) or through an electronic means.
- There are two different radioactive sources available for industrial use; X-ray and Gamma-ray. These radiation sources use higher energy level, i.e. shorter wavelength, versions of the electromagnetic waves.



PLAN VIEW OF THE FILM

DARKER AREAS (AFTER PROCESSING)



Top view of developed film

The film darkness (density) will vary with the amount of radiation reaching the film through the test object

= less exposure

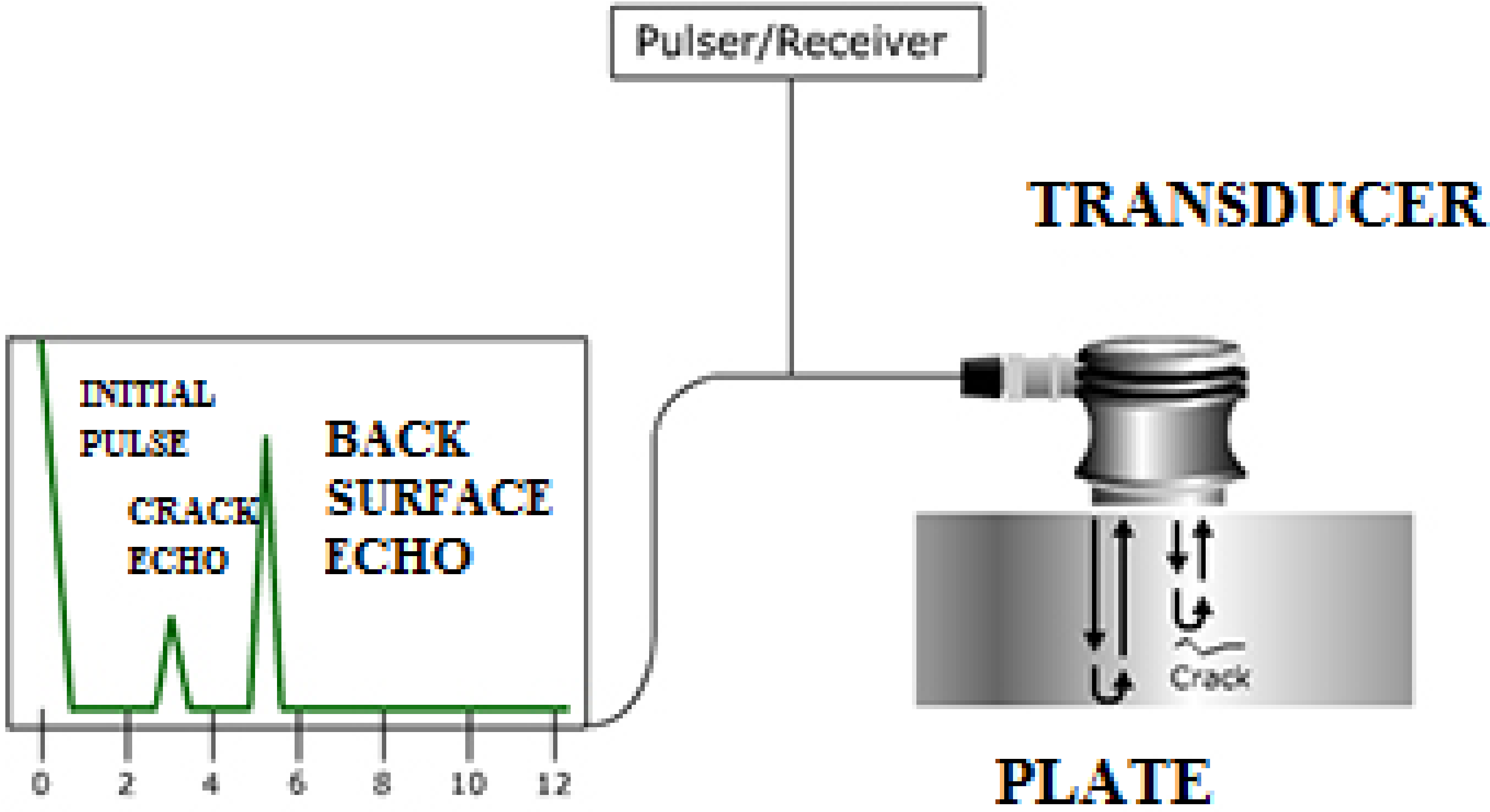
= more exposure

Ultrasonic Testing (NDT)

Basic Idea of Ultrasonic Testing using EPOCH –XT Flaw Detector

- This method works on the principle of Reflection. Whenever the Ultrasound waves reach the boundary of the medium, some part of it is transmitted to the other medium and maximum part is reflected back.
- As we incident the ultrasound waves to the materials to be tested or the test piece, the wave travels through the material (medium) of the test piece. The wave is reflected back from the boundary of the test piece.
- A defect can be in any form like crack, inhomogenity, hole, discontinuity, etc. So the incident wave will be reflected by the boundary as well as the defect. But, the wave reflected by the defect would be received earlier than the wave reflected by the boundary.
- Now in the basic way, if there is a Crack echo waveform on the screen, which proves that, there is some defect.
- Now, in the flaw detector machine, we can find the depth of the defect on the screen. It is calculated with the simple concept of time and distance.

$$\left(Depth = velocityofwave \times \frac{TimeofFlight}{2} \right)$$



EXPERIMENTAL SETUP FOR ULTRA SONIC TESTING

RRR MEASUREMENT

- RRR is defined as the ratio of the resistance of sample at room temperature (300K) and resistance at temperature just before its superconducting transition (~10K for Nb) [8].
- Lower Value of RRR indicates greater concentration of imperfection.
- The result drops abruptly to zero if the material enters at superconducting state at a critical temperature “T_c”.
- The value of RRR indicate, purity and low temerature thermal conductivity. The thermal breakdown happened at higher field level.
- The RRR gives information about the total impurity content and allow a rough estimation of the thermal conductivity.

Methodology

- In our system, RRR is measured using temperature method, which is simpler and becomes feasible with the use of a thermostatic tank (standard liquid helium Dewar) with almost negligible consumption of liquid helium.(Figure-1)
- RRR is defined as the ratio of the resistance of sample at room temperature (300K) and resistance at temperature just before its superconducting transition (~10K for Nb)
- The resistance measurement is performed using a standard four-probe method.
- Current is fed by a stable **DC source** (Keithley 2611 source meter) and voltage is read through Keithley 2182 **voltmeter** (resolution of 1n-volt). Temperature is sensed using DT-470 **silicon diode** and is monitored through Lakeshore 218s **temperature monitor**.
- A four-channel DAQ (Data Acquisition) system is developed to acquire current, voltage drop and temperature at both ends of the sample under test to ensure uniformity of temperature.
- The complete data acquisition activity is programmed using LabVIEW software.