Manufacturing of SCRF cavity related Components/Sub assemblies

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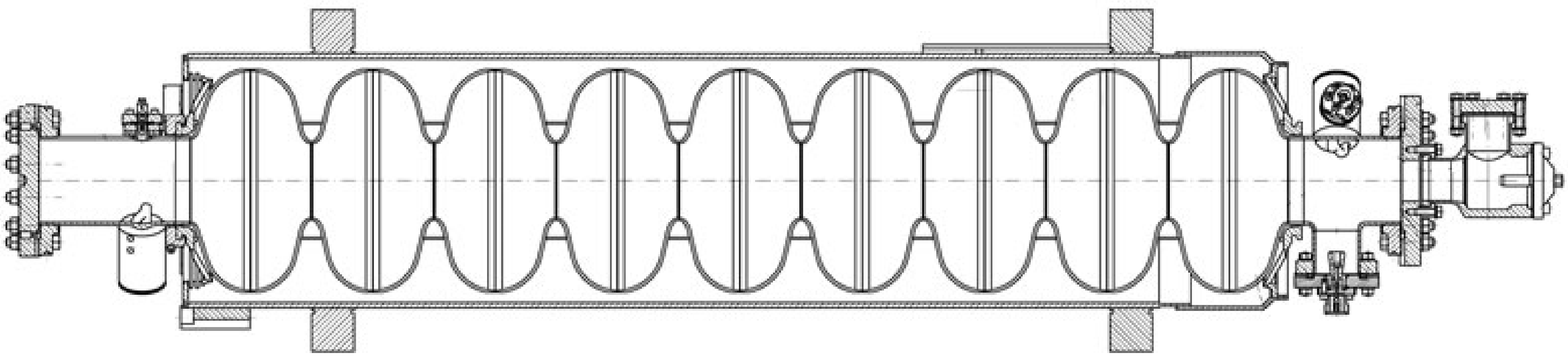
Out line of the lecture

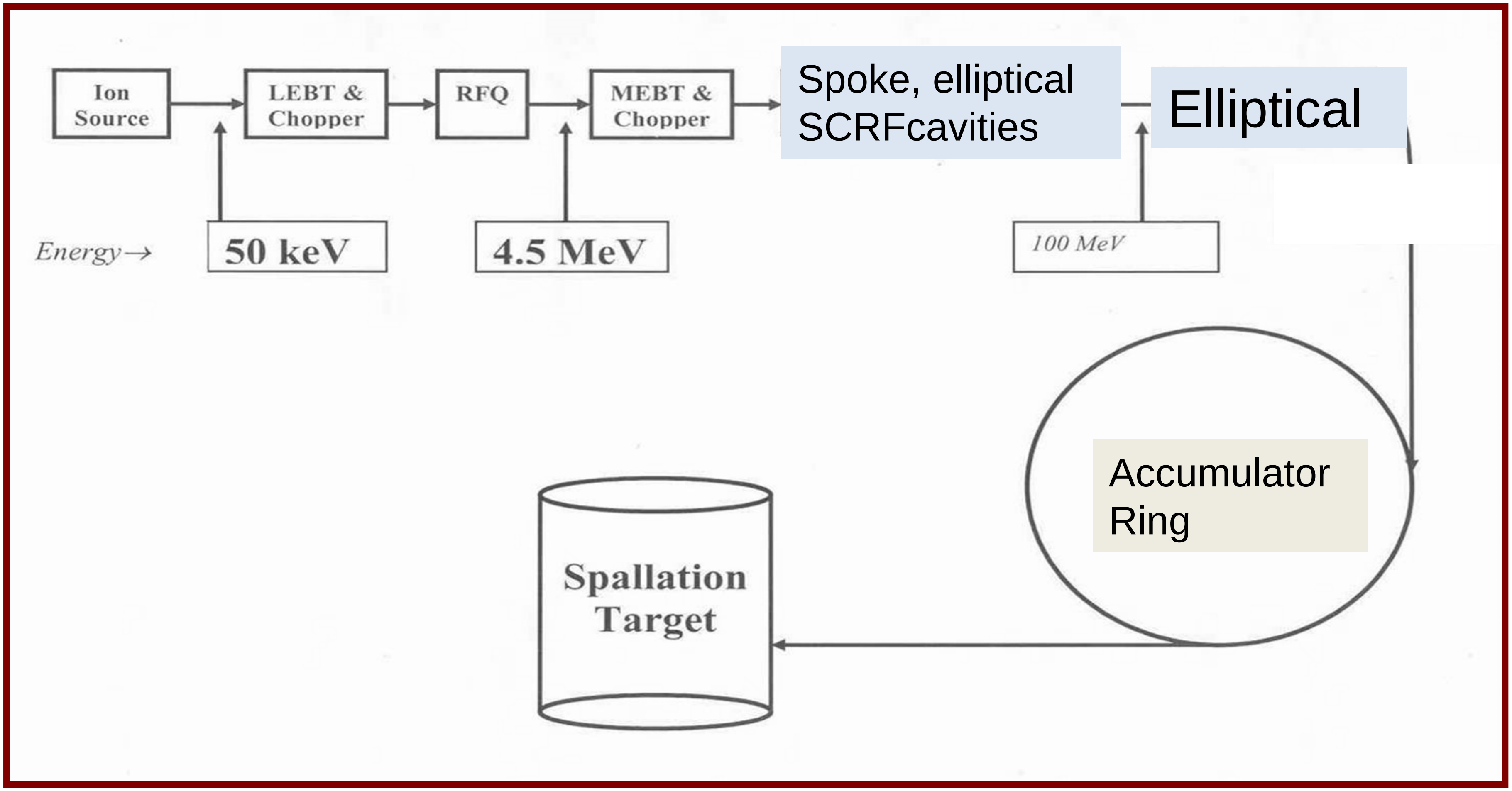
- Common materials of construction for superconducting technology
- Typical components and subassembly manufacturing.
- Various techniques for SCRF cavity manufacturing.
- General conventional and unconventional machines , equipments used for SCRF cavity manufacturing.
- Common issues in machining of Nb, Titanium, and NiTi etc.
- Manufacturing of components and subassemblies like (Tuners, He vessel, cavity half cells, dumbbells, end-group, beam pipe and flange, Nb-SS transition joints etc.)
- Components related to forming tooling.
- Metrology and inspection during machining/forming.
- Conclusion.
- References and Acknowledgement

The most common material used in SCRF accelerator are

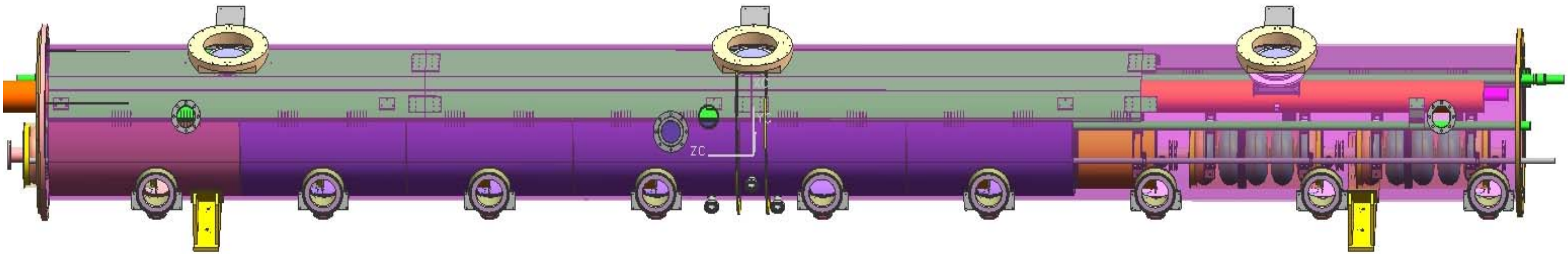
- Niobium (for SCRF cavity)
- Titanium (For He vessel, Tuner)
- Ni-Ti (for connecting Nb cavity to Ti Helium vessel)
- Stainless steel (preferable grades are 304L and 316L) (for He vessel and Tuner)
- SS to Nb Transition Joint



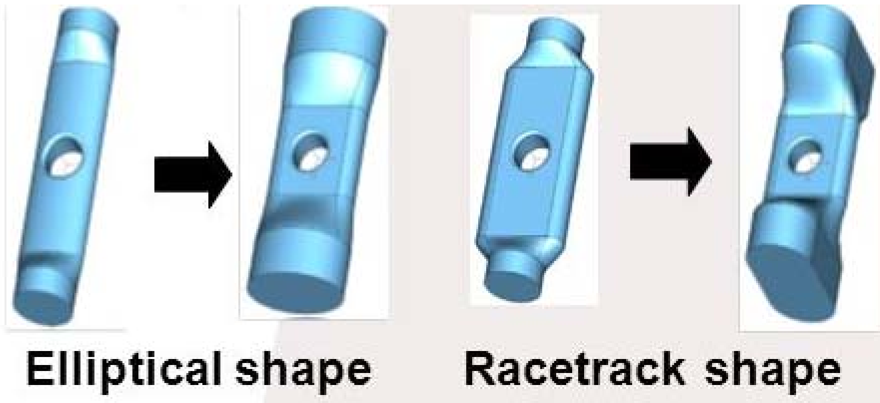
Typical SCRF Linac consists of

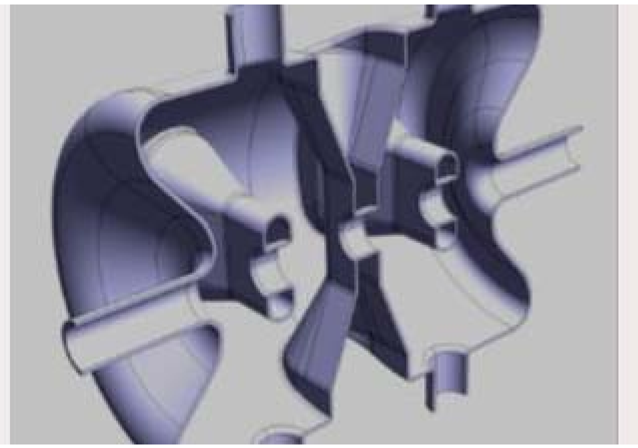


Cryomodule assembly



Spoke cavity (machining requirements)



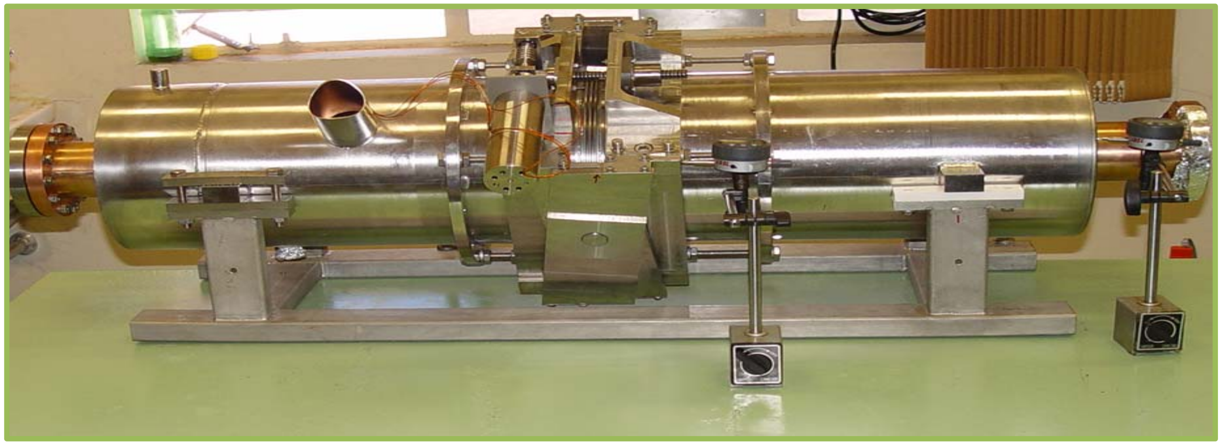


Nb Blank machining
Forming tooling machining
Formed spoke machining
He vessel /Cavuty port opening

Typical spoke cavity

Dressed cavity and components

A dressed cavity consists of a cavity assembly assembled with Helium vessel and tuner



Many type of tuners (Inline and End tuners)
Inline tuners
(1) Blade tuners

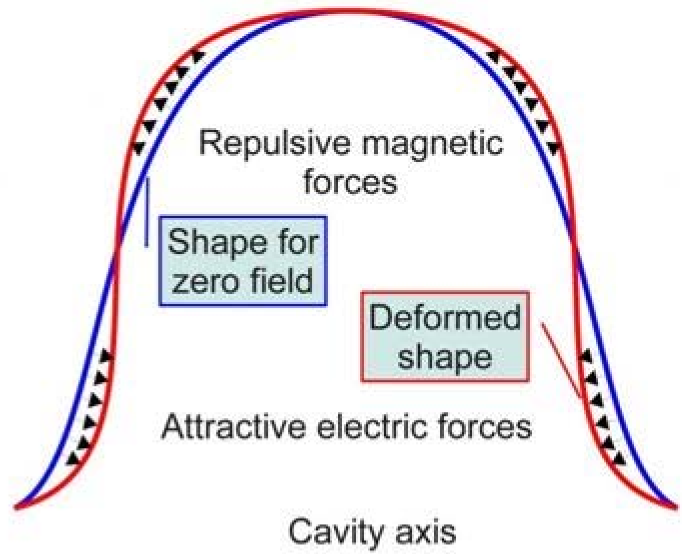
(2) Scissors tuners

(3) Wedge tuners

End tuners
(1) Frame type tuner
(2) Liver tuner

Cavity Detuning

- SC cavities
  - Operate with very narrow bandwidths
  - Manufactured from thin sheets of niobium to allow cooling
  - Resonance frequency sensitive to mechanical distortions of cavity walls
- Tuner needed to
  - Tune cavity resonance to RF frequency following cool-down
  - Compensate for dynamic detuning
    - Lorentz force
    - Helium pressure variations
    - Microphonics
  - Tune cavities off resonance in case of failure

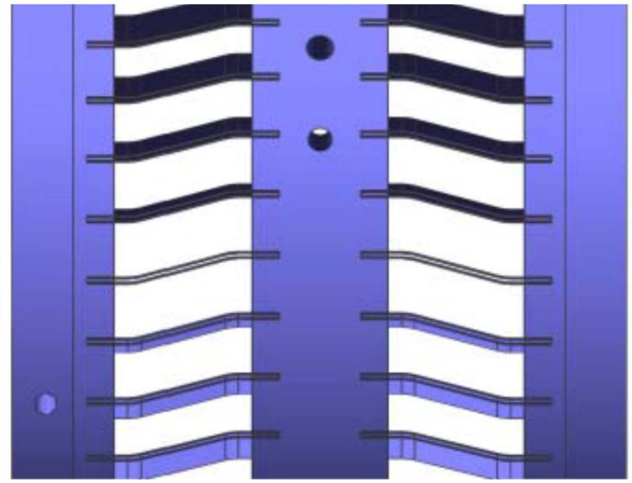


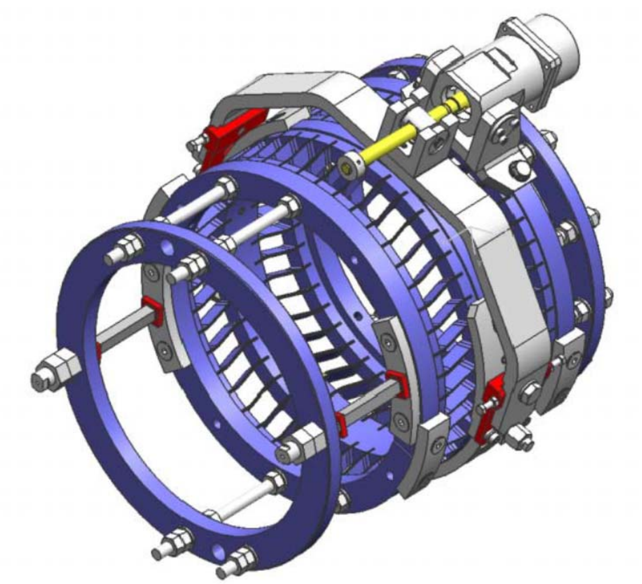
$$P_s = \frac{1}{4}(\mu|\vec{H}|^2 - \varepsilon_0|\vec{E}|^2)$$

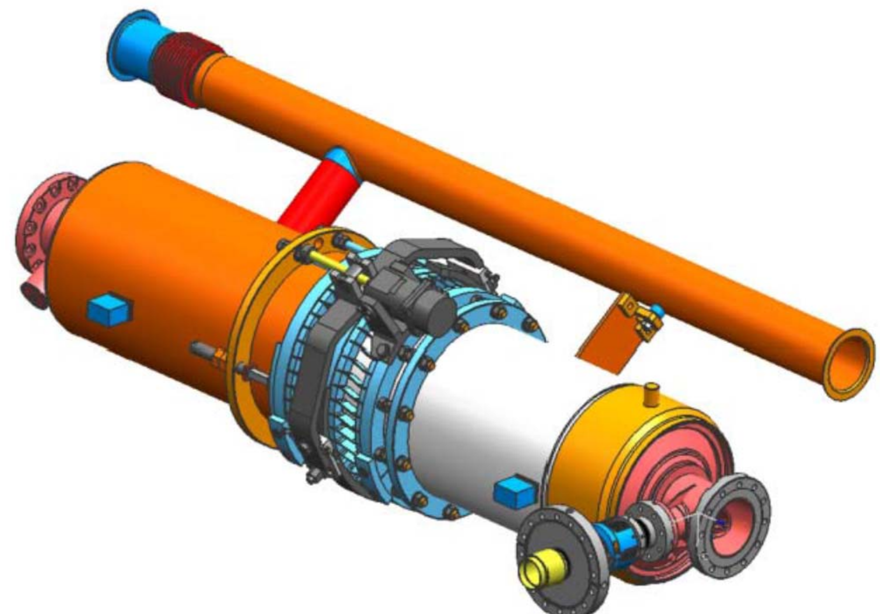
$$\Delta f_0 = (f_0)_2 - (f_0)_1 = -K\, E_{acc}^2$$

Image: Maurisz Grecki

Blade tuner





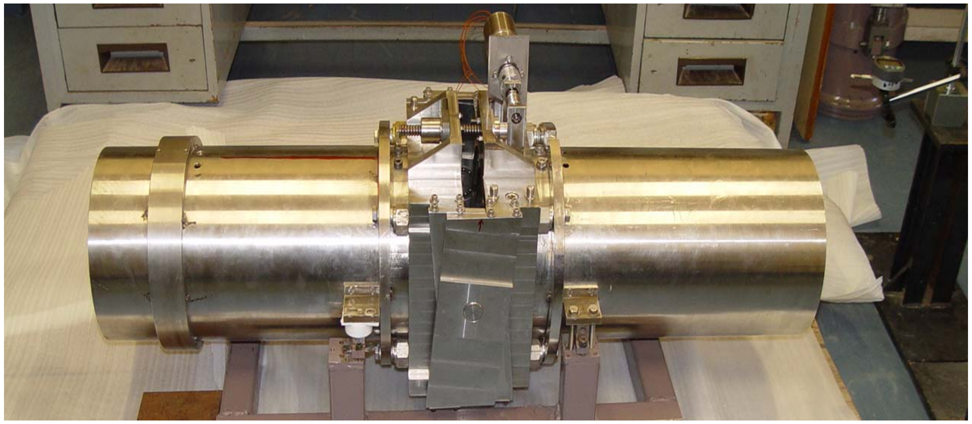


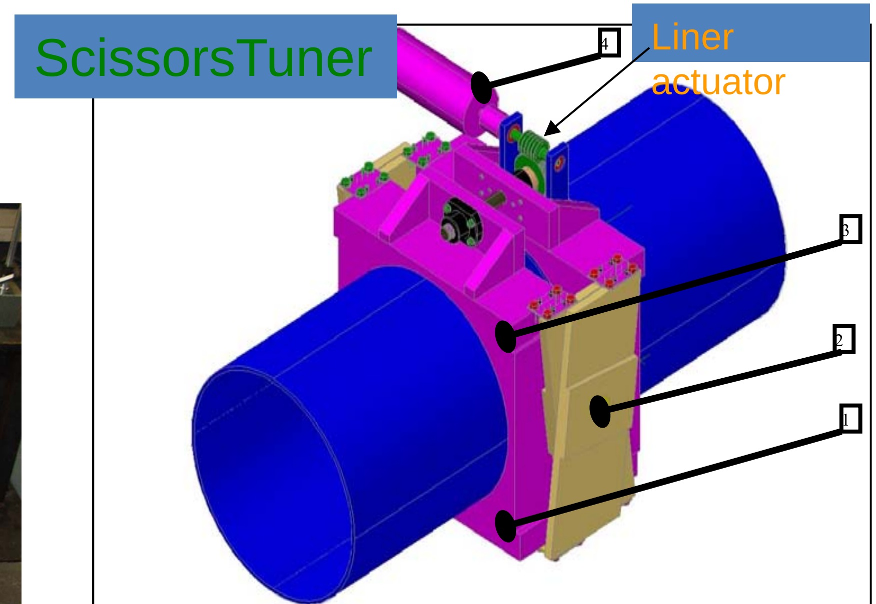
Wedge Tuner Mock up Assembly at CDM

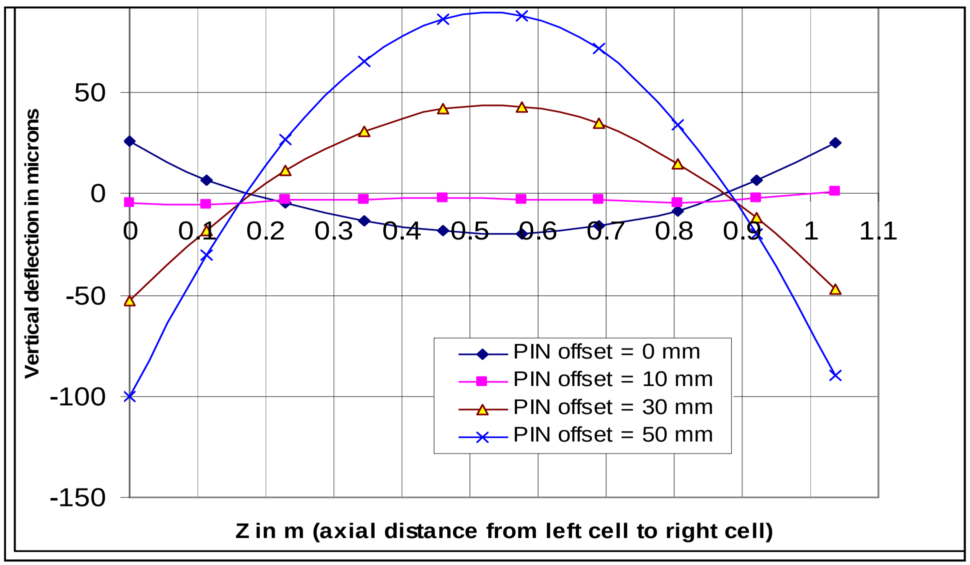
Prototype Tuner for β=1 cavity

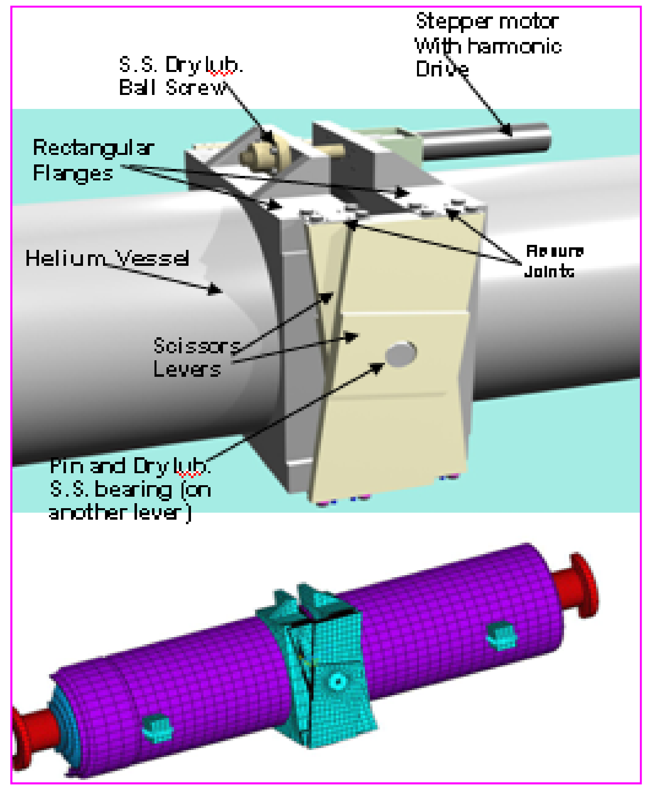
Vinay Mishra CDM, BARC

Scissors Tuner

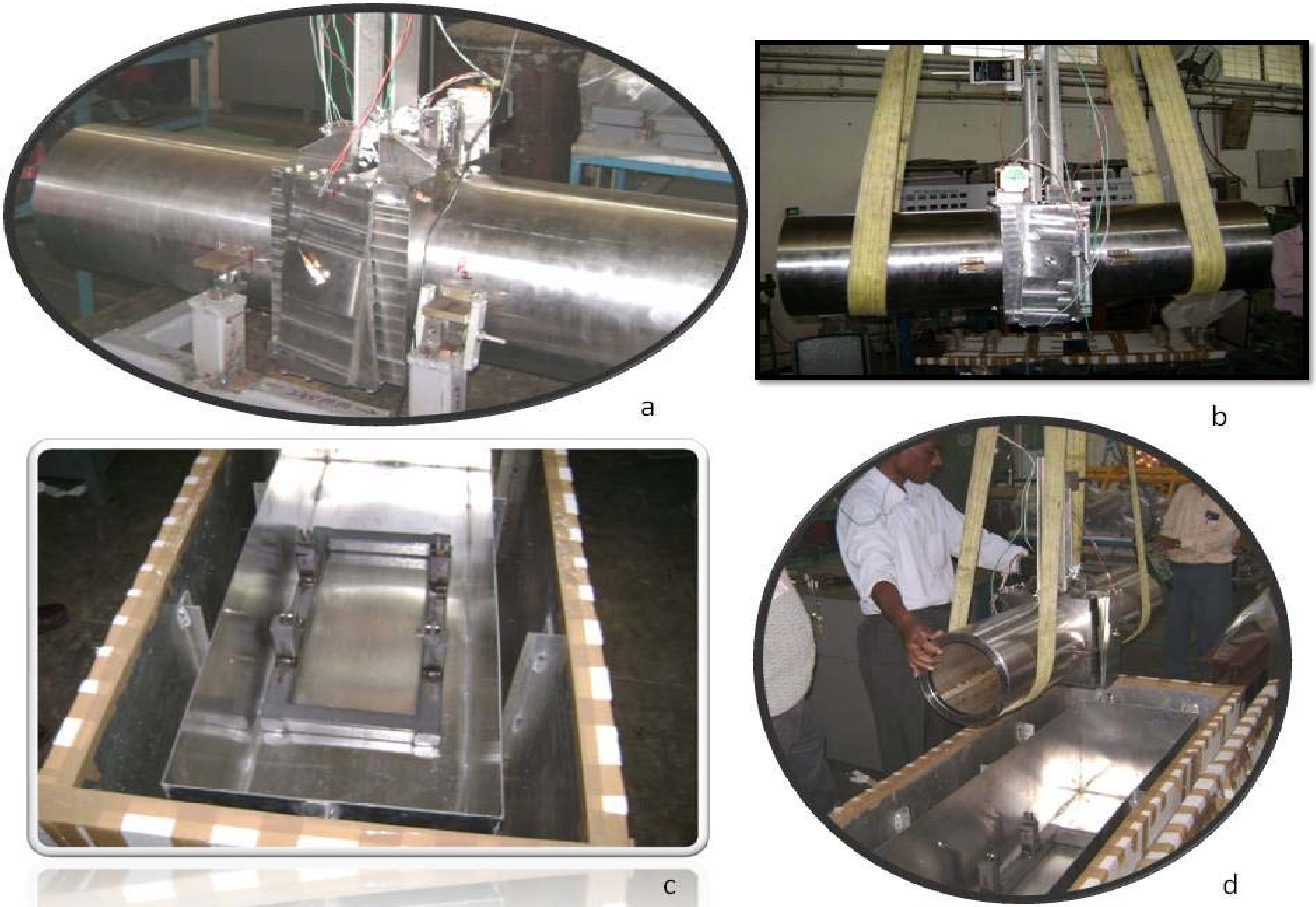






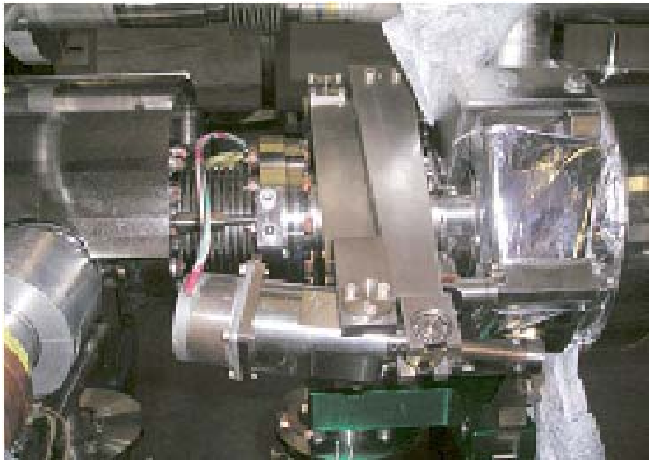


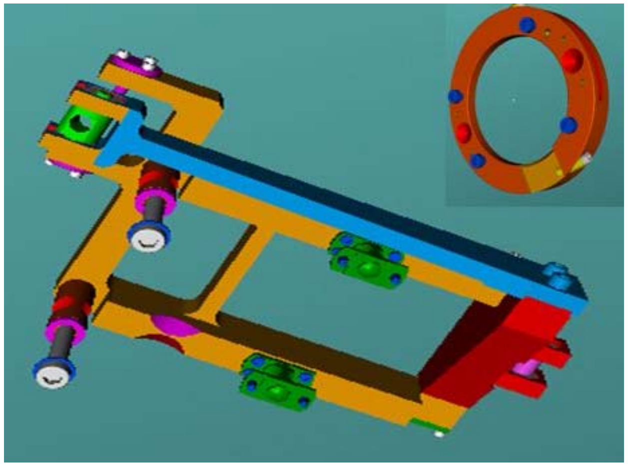
Scissors tuner prototype shown on a test setup.

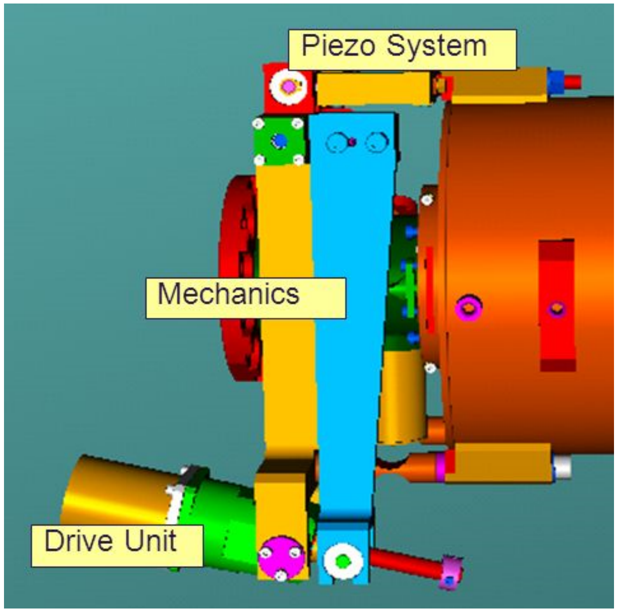


Testing of scissors tuner at LN_2 temperature was performed (motor/ actuator is also at LN_2 temperature)

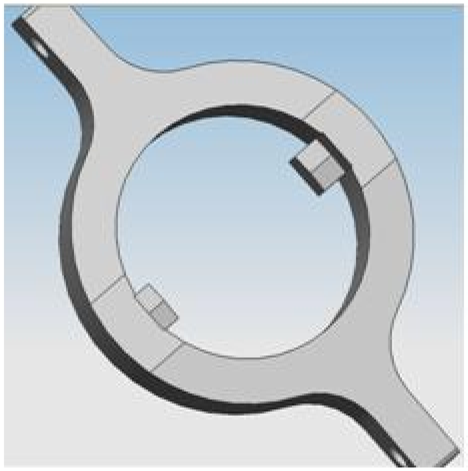
End tuners (Machining of SS or Titanium)



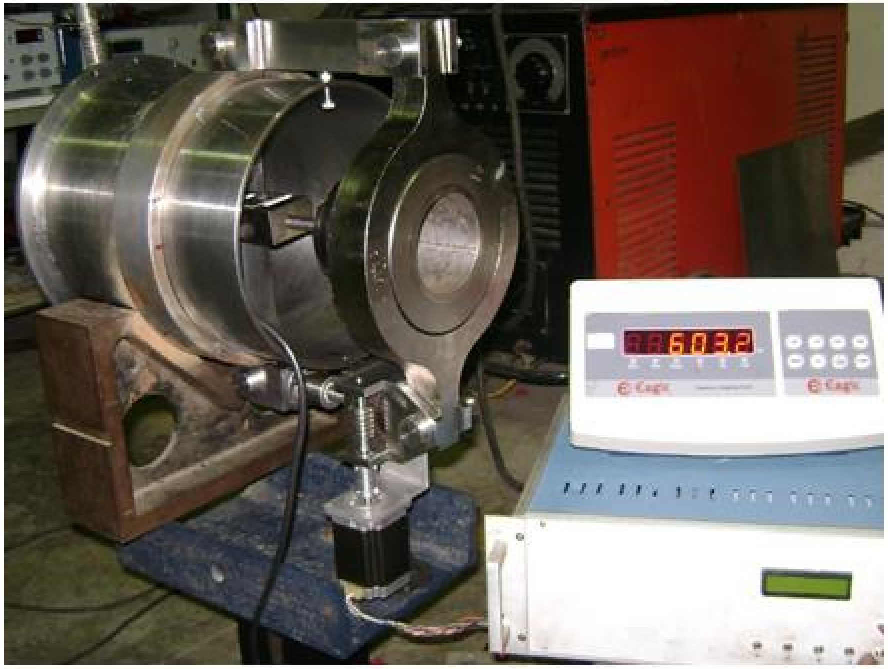


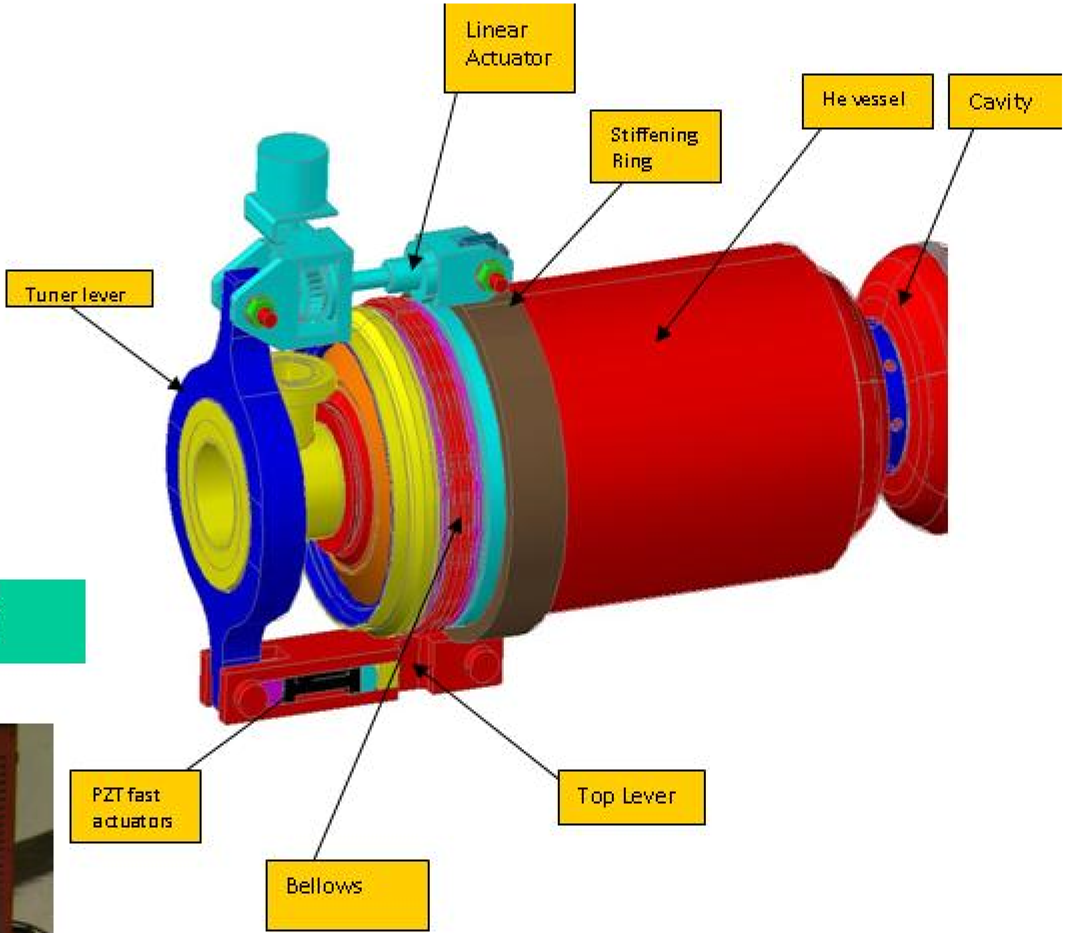


Frame type end tuner



Lever Tuner Prototype testing at RT





Lever Tuner assembled on the Cavity

(The tuner assembly can be at any orientation)

Actuators for Tuners

What is an actuator:

What is a tuner

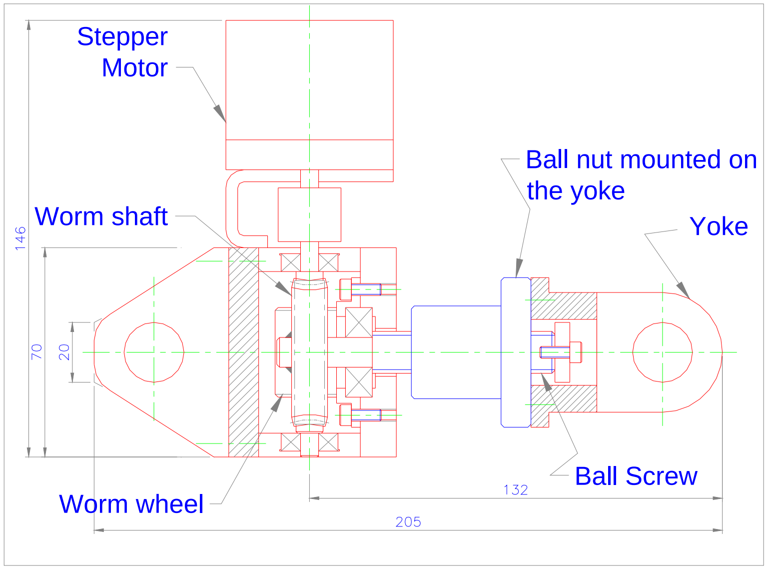
- *Mechanical tuners for in-situ (at LHe temp.) tuning. The cavity is pressed or stretched along the axis within elastic limit. Linear movements up to few mm and the tuning range up to few hundreds of kHz (max.)*
- *To overcome the detuning due to thermal and beam loading effects on the structures.*

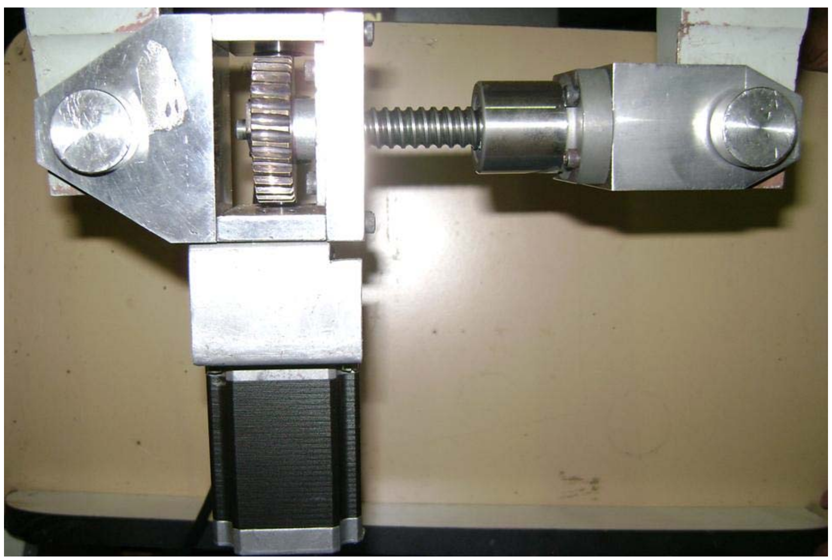
Actuator

- *One of the main parts of any tuner mechanism assembly is linear actuator. These tuner mechanisms need a backlash free linear actuator which can provide desired force, movement and resolution to the cavity. The function of linear actuator is to provide linear movement (hence force) to a mechanism which in turn presses /stretches the cavity, along the axis and hence leads to frequency change / tuning.*

- *Linear actuators are driven by stepper motor/linear stepper motor or DC motors*

Design and fabrication of a linear actuator





- The linear motion is achieved by a ball screw driven by stepper motor through a specially designed worm and wheel reduction gearing.
- The indigenously designed and developed worm and wheel based reduction gear.
- Blade tuner and other tuners use Harmonic reduction gear drive, which is very costly

The components of tuners to be coated for lubrication at cryo-temperature

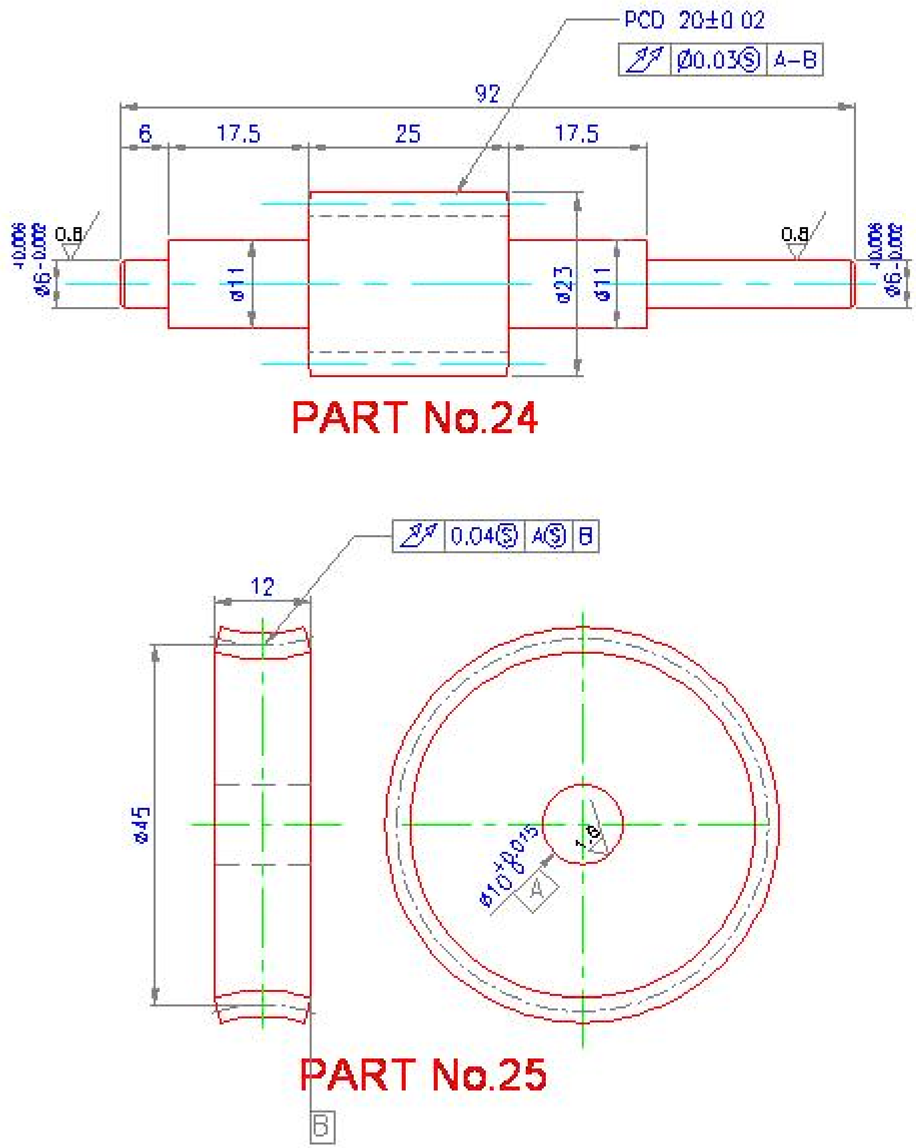
- All the machine elements like worm wheel gear assembly, ball bearings, thrust bearing, and ball screws were ultrasonically cleaned

- WS2 Dry lubricant was applied by PVD technique (Dr. Chandrachur Mukherjee)

- WS2 (Dicronite^{TM}) and MoS2 are among few solid lubricants which are used in application like this "liquid helium temperature and UH vacuum" [4][5]

[4] GNIRS Gemini near infrared spectro graph. SDN 0015 internal report on testing of cold motors.
http://www.noao.edu/ets/gnirs/SDN0015.htm
[5] Dicronite \DicroniteTM Dry Film Lubricant Process.htm site.

The parts are to be machine with calculated tolerance and fit to ensure non intereferance at Cryotemperatures.



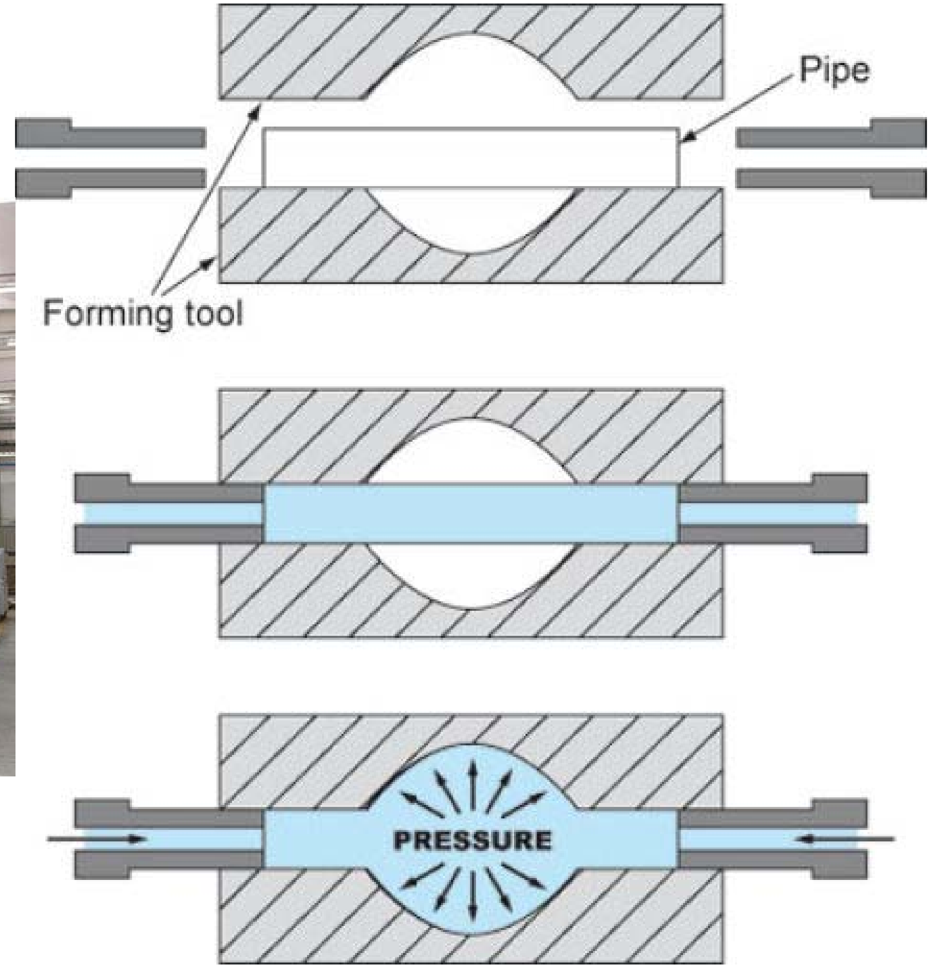
	WORM	WORM WHEEL
MODULE	1.5	1.5
OD	23	49.5
PCD	20	45
No.OF TEETH	--	30
No. OF START	1	--

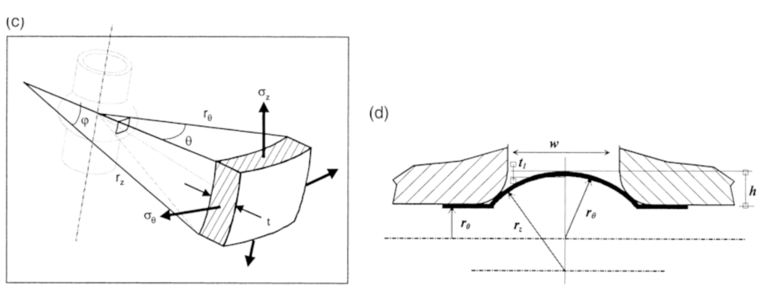
Note:
The components shall be machined as per BIS721 IS 3734
tooth to tooth pitch error less than 5 microns
Cumulative pitch error lessthan 15 micron

SCRF Cavity manufacturing

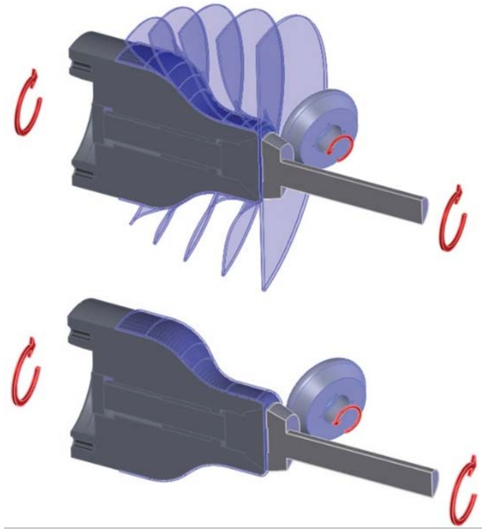
- Hydro forming
- Spinning/Flow forming
- Deep drawing machining and welding (most common)

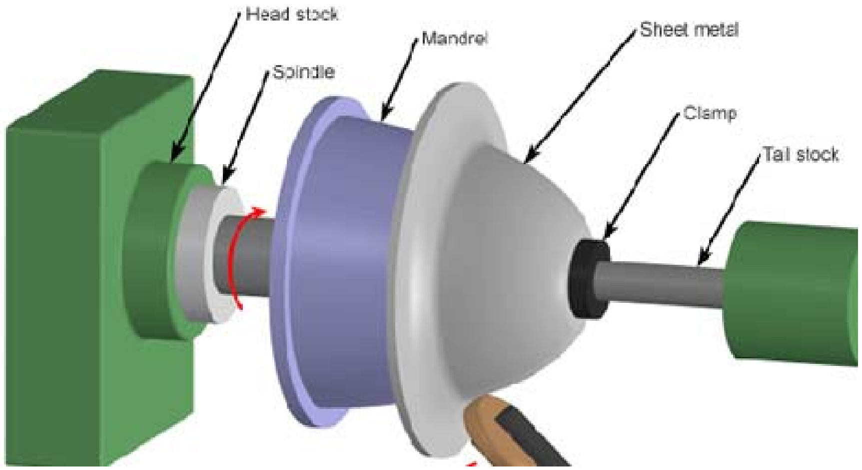
Hydroforming

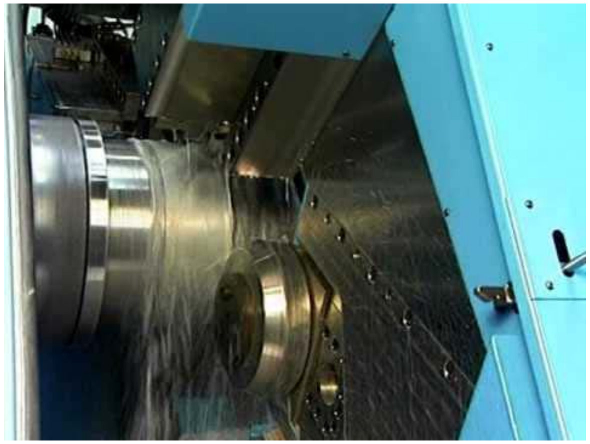


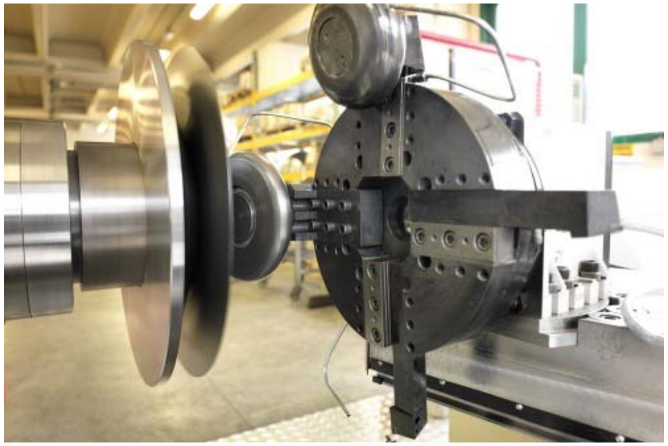


Spin and flow forming of half cells





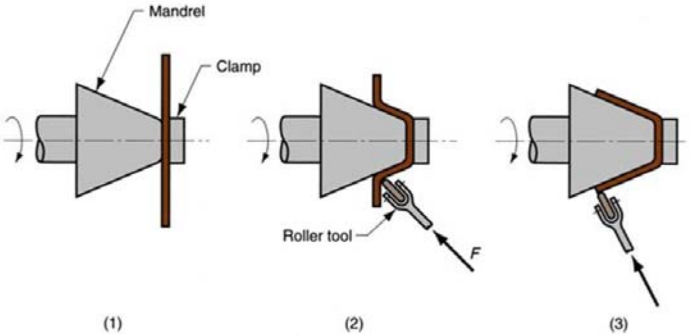




- Need of intermediate annealing
- Very poor reproducibility

Spin forming

Metal forming process in which an axially symmetric part is gradually shaped over a rotating mandrel using a rounded tool or roller



Conventional spinning: (1) setup at start of process; (2) during spinning; and (3) completion of process

Hydroforming and spinning contd.

Hydro-forming

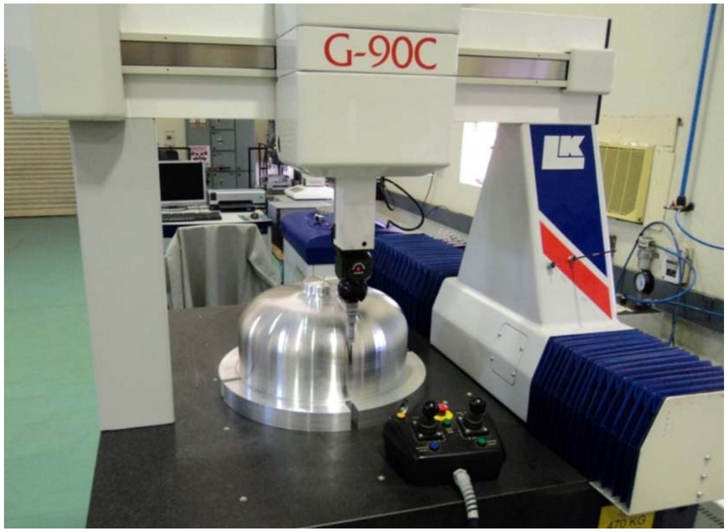
(Singer-DESY, KEK)

Spinning

(Palmieri-INFN)

Machining of forming tooling for Nb half cells

Nb being soft material (like copper) the forming tooling are machined from Aluminum alloy like AA 7075 T6 or Beryllium copper, AMPCO etc. (Steel or Tungsten Carbide are not used because they gall (friction weld with Nb)



Nb blank machining

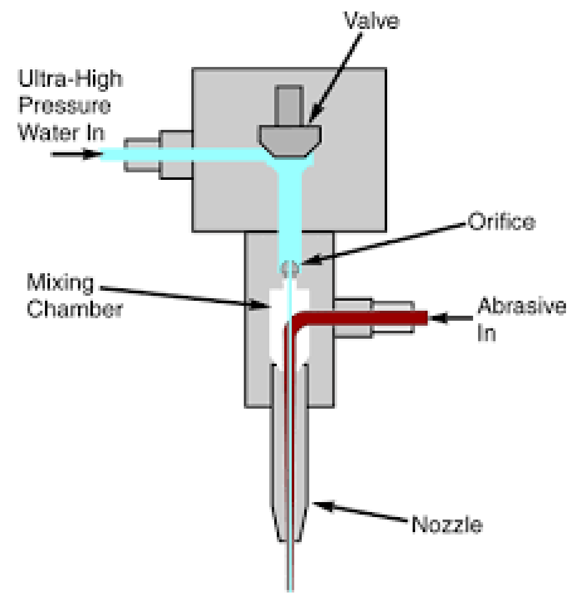
The blanks are cur from high purity fine grain rolled Nb sheets by precision machined at ID and OD. The blank machining is done by

- EDM wire cut
- Water jet cutting machine

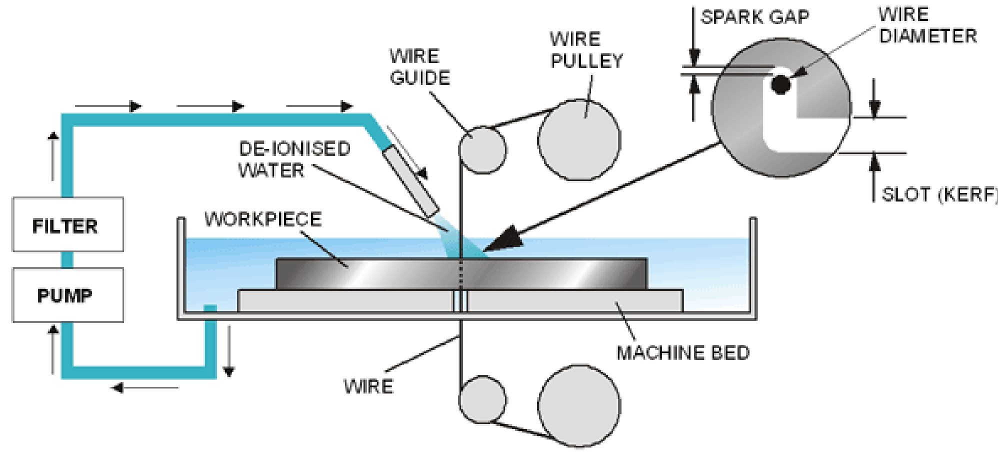
Water jet cutting machine

The main advantages of water jet cutting machine are

- Very fast cutting compared to EDM wire cutting
- No heat affected zone, as cold cutting
- Can cut any material (metal non metal, conducting non conducting, hard and soft)



EDM wirecut



Advantage

Very precise
Very good surface finish
Very large thickness can also be cut
No burr on the cut edge

CNC EDM Submersed and Flush Type Wire Cut Machines
X,Y & Z strokes-600, 400 & 400 mm Accuracies - ± 10 μm

Half cells forming at RRCAT

Loading arrangement of dies on the 200 Ton Hydraulic Press at RRCAT

Blank Loading for Forming

Half cups of finally formed parts of cavity

Machining of Cavity components

SCRF cavity consist of various components such as Niobium half-cell, end flanges, beam pipes made of high RRR Niobium material.

The performance of super conductive RF cavities is seriously affected by any contamination of other metal chips and surface finish of machined components.

MACHINING CHARACTERISTICS of Nb

- Nb being pyrophoric material, special care is to be taken, being potential fire hazards.

  (No chip accumulation in the machine, Hand held fire extinguisher is to be kept ready, Fast evaporative cooling effect coolant, No fire load shall get accumulated in the machine.)

- High RRR niobium material is very soft and behaves like soft copper.

- Niobium while machining is difficult to machine. Chips during machining has tendency to seize to tool and gives the problem of BUE.

- Sharp tools which high surface finish and with high rake angle gives better result.

- We at our machining facility are using diamond polished uncoated tungsten carbide inserts with high rake angle and nose radius of 0.2 mm for machining of niobium components.

The precautions which are to be observed during machining Nb

- Suitable hand gloves are used while handling Nb material so as to avoid any fingerprint marks on the component.
- These fingerprint marks cannot be easily removed even after chemical cleaning.
- Machining are kept in isolated clean room away from other machines.
- To avoid contamination machines are thoroughly cleaned before machining operations.
- A new set of cutting tools/inserts is used for machining of Niobium components and are preserved safely and are not allowed to be used for other material.
- The SCRF cavities require a very high quality interior surface without any defect or impurities embedded on it.

Nb Machining Contd…

- Compare to data provided in literature, speed must be increased by a large factor when dealing with high RRR material.

- While machining niobium on a lathe, important points are:

  (1) Always keep tools sharp

  (2) Use manual feed (rate at operator’s discretion) to remove niobium chips away from the part as rapidly as possible

  (3) Employ high cutting speeds.

- Typical cutting speed is 250 – 270 rpm. This translates to a range of approximately 80 – 200 ft /min

- A very sharp carbide insert is used for weld prepping half-cell equators. Cutting speeds are in the range of 350 – 400 rpm (280 – 320 ft/min).

The tools are ground by hand. Typical tool geometry is shown below

Machining parameters optimizations for Nb

The optimum machining parameters is to be found by Response Surface Methodology (RSM) in dry machining condition.
The main machining parameters are speed, feed and depth of cut under dry machining condition

Feed, Speed
Depth of cut

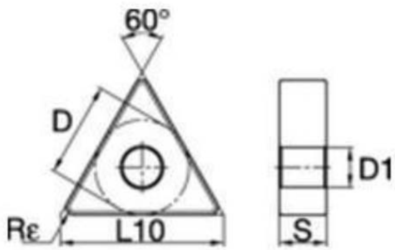
→ Machining of Nb → Cutting temperature

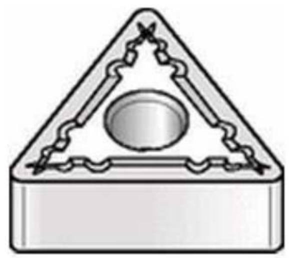
Cutting speed is main influencing factor on cutting temperature.

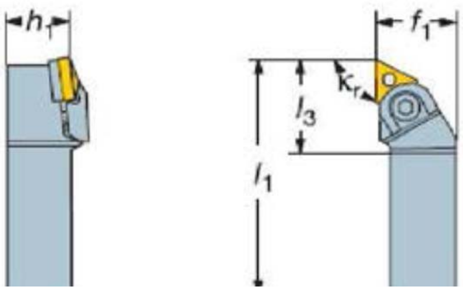
Optimum value of parameters to minimize the value of Cutting Temperature is (Nb Alloy)1(reference)

Cutting speed =80.00m/min, Feed = 0.08 mm/rev & Depth of cut = 0.60 mm

Cutting force optimization:







Four component dynamometer

- The highest influence on cutting force is exerted by the depth of cut. Cutting force increase with increase in the depth of cut.

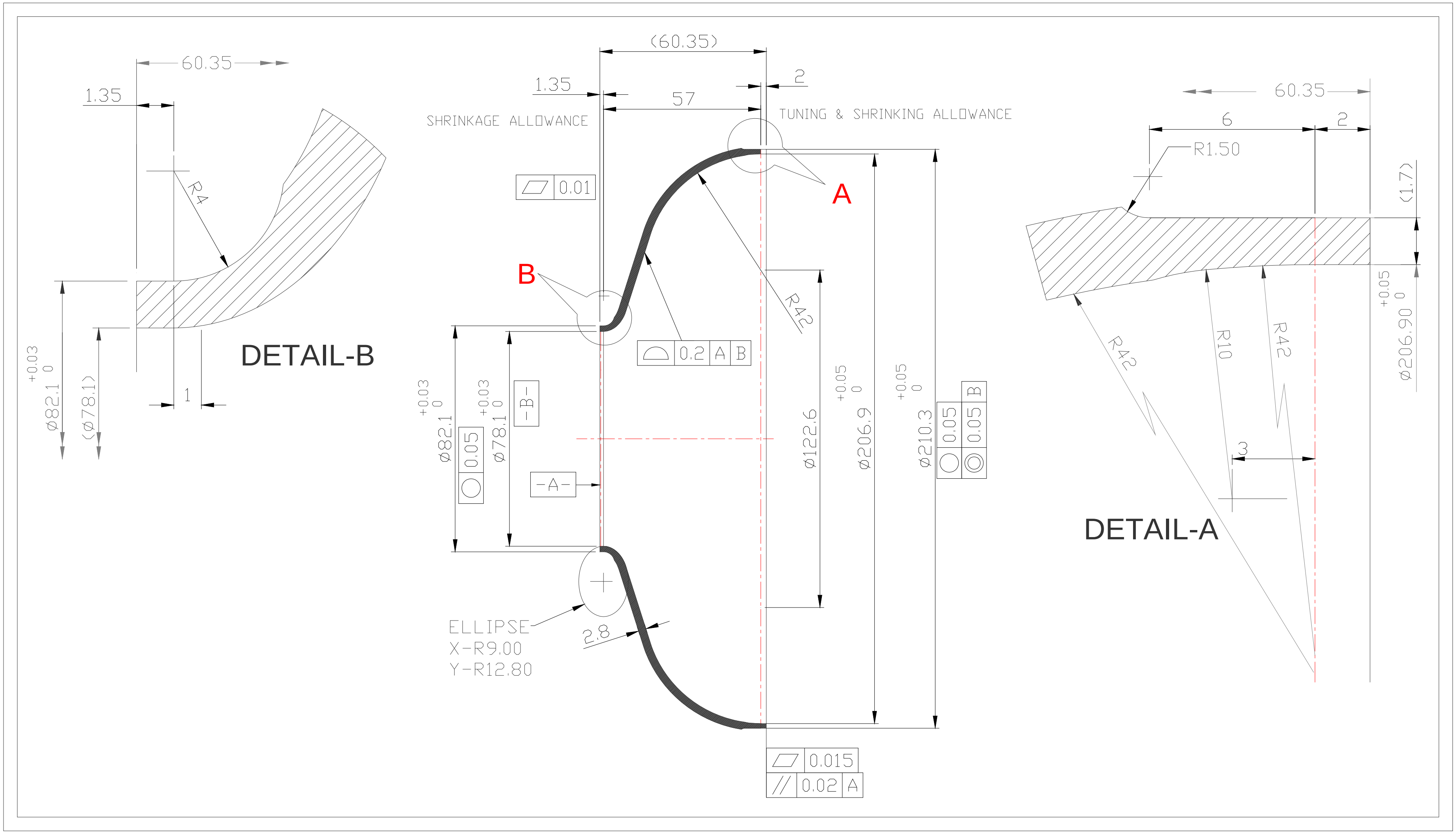
- The optimum cutting parameters to minimize the cutting force are cutting(Nb alloy) 1 reference

speed =84.32 m/min, feed = 0.15 mm/rev & depth of cut = 0.37mm.

Coolant to be used

- Conventional cutting oil/coolant shall not be used.
- Silicon type of oils and coolant containing sulphur are prohibited, as it is very difficult to eliminate.
- Alcohol/ Propanol is used which gives noticeable good results. With this particle contamination issue is also solved.

Half cell drawing of SCRF cavity



Machining of SCRF cavity components contd…

- The main challenge/requirement of half cell machining apart from

(i) Machining of high purity Nb (ii) Cleanliness of machine, tool, fixtures & Handling (iii) Machining for repetitiveness.

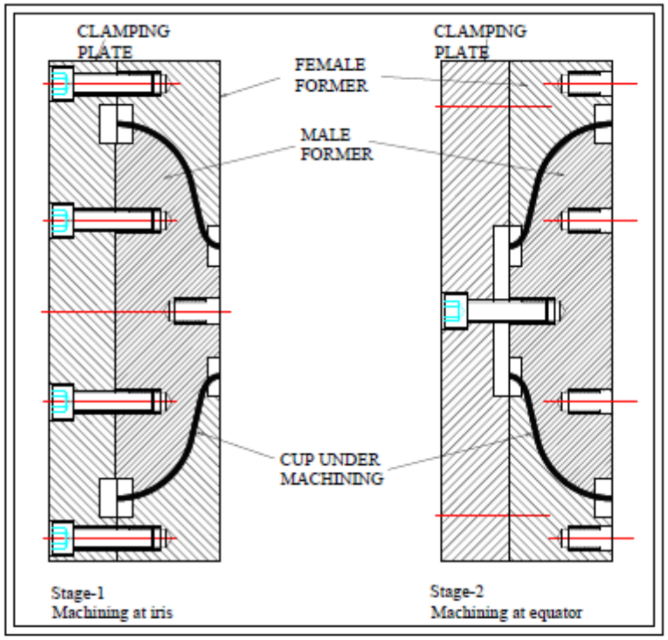
- The flexibility of half cell, being very thin structure.

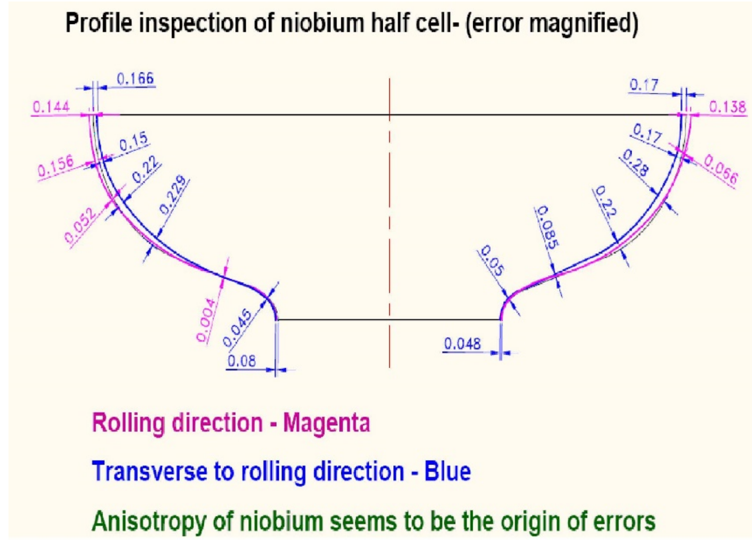
- The problem in machining 650MHz half cell is multifold as the flexibility increases in cubic order.

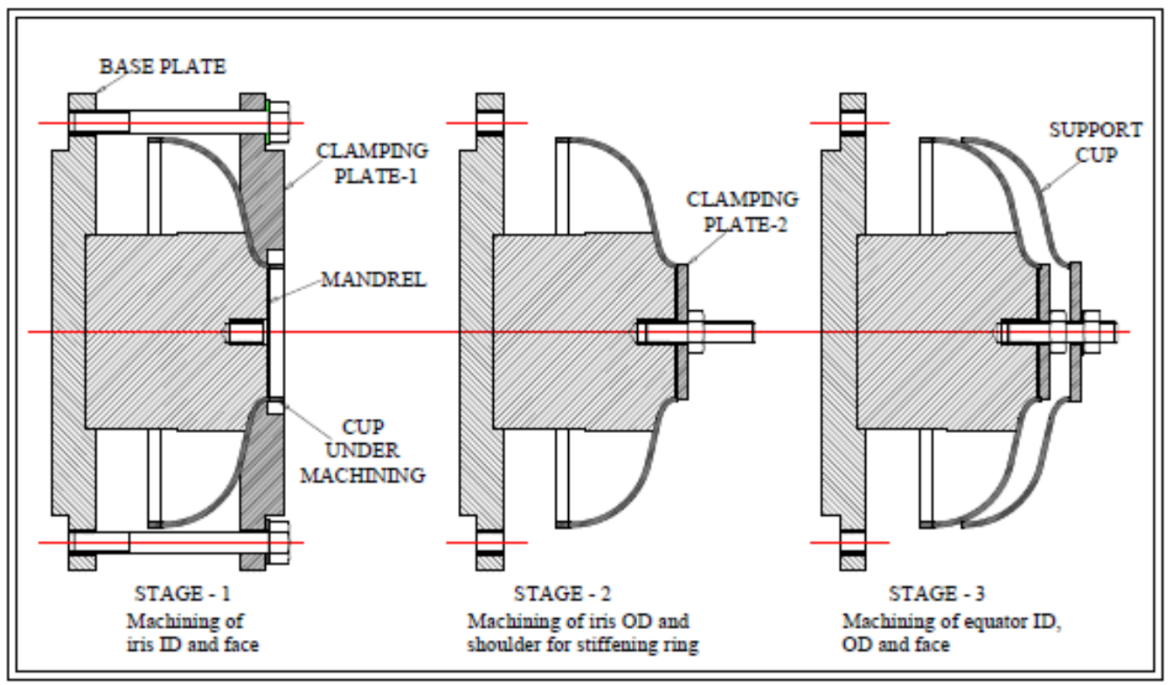
- Machining fixtures were developed and machining parameters were established overcome machining problems

- large number of formed half cells machined at equator, iris and shoulder for stiffening ring to facilitate EB welding .

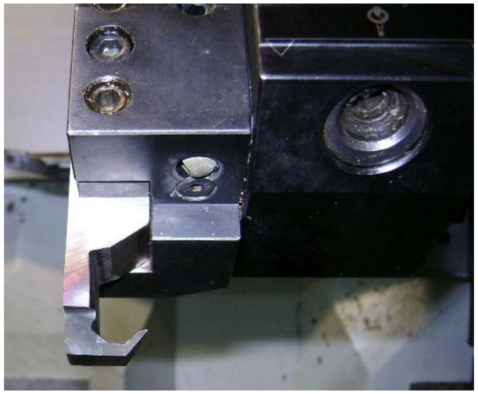
Fixture development for half-cell machining







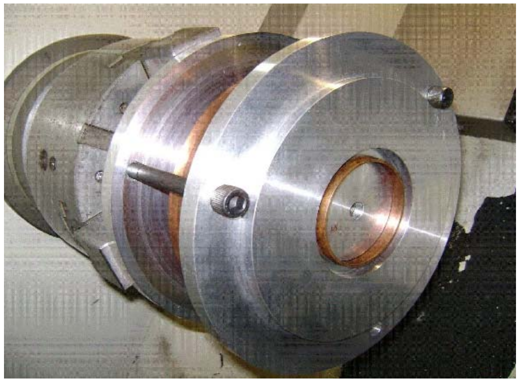
Machining of half cell-contd…



HSS tool for machining ID & face of equator

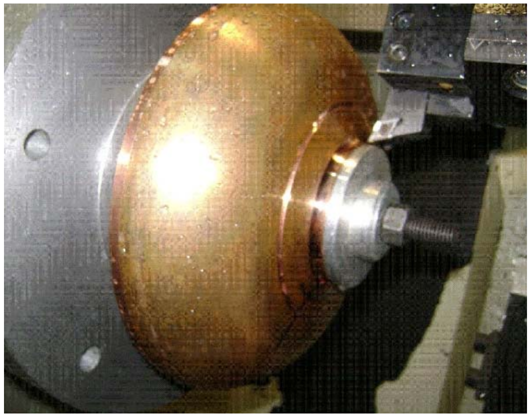
Carbide tool for machining ID of equator

Mandrel and clamping plate of new fixture



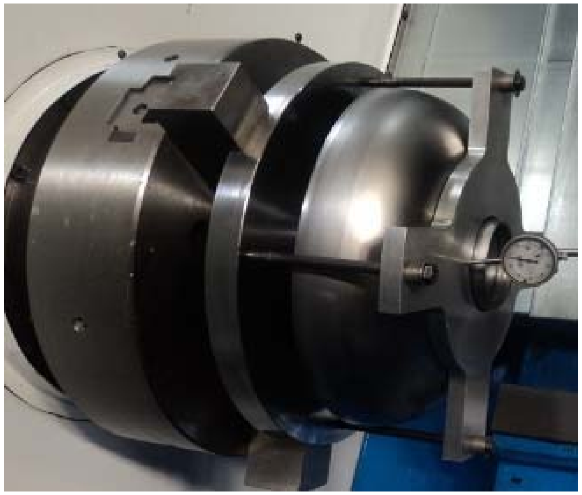
Machining of iris face and ID

Machining of iris OD and shoulder



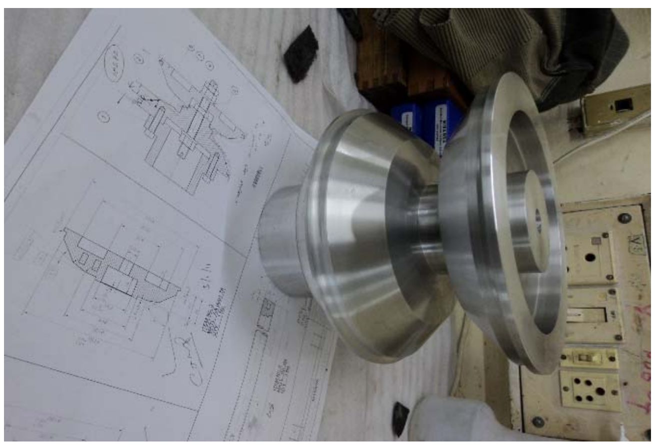
Machining of equator OD face and ID

Machining of cavity components contd…



Alignment of Fixture on machine

Machined half cells of 9 cell SCRF cavity



Dumbell Machining fixture development

Machining of dumbells on precision lathe

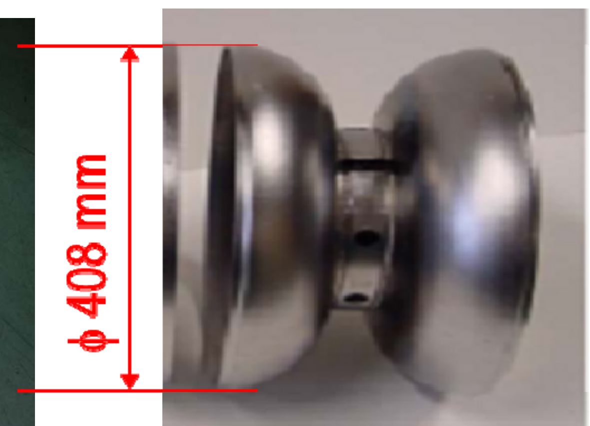
Results with new fixture:

Diametric tolerances: DIA 78.1+0.03, DIA 82.1+0.03 DIA 206.9+0.05 DIA 210.3+0.05

Inspection on CMM and results

Parameter	***Value mentioned in the drawing***	***Value measured on machined half cells***
Flatness on iris surface	0.02mm	0.01mm
Flatness on equator surface	0.02mm	0.015mm
Parallelism of equator surface wrt iris surface	0.02mm	0.03mm
Surface finish	1.6 microns	0.8micron
Roundness on equator	ID0.05mm	0.03mm
Roundness on equator OD	0.05mm	0.02mm
Roundness on iris OD	0.05mm	0.01mm

Product Identification Number



Machined dumb bells

G. Mundra Technology Development of Superconducting RF Cavities Date 19-7-2017

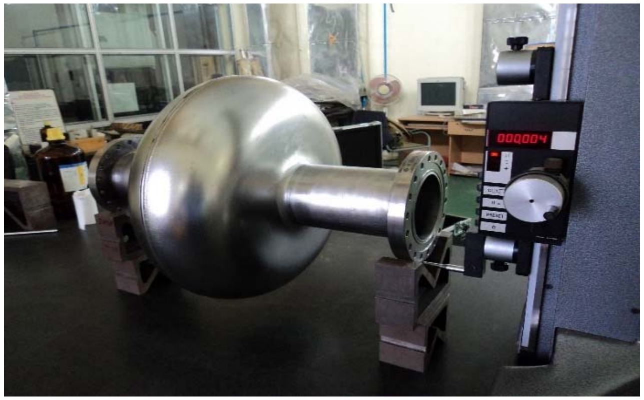
Machinning of Endgroup components

Single cell-cavity end flange

Multi-cell end group components

End pipe machining

SCRF cavities after EB and Laser welding-at RRCAT

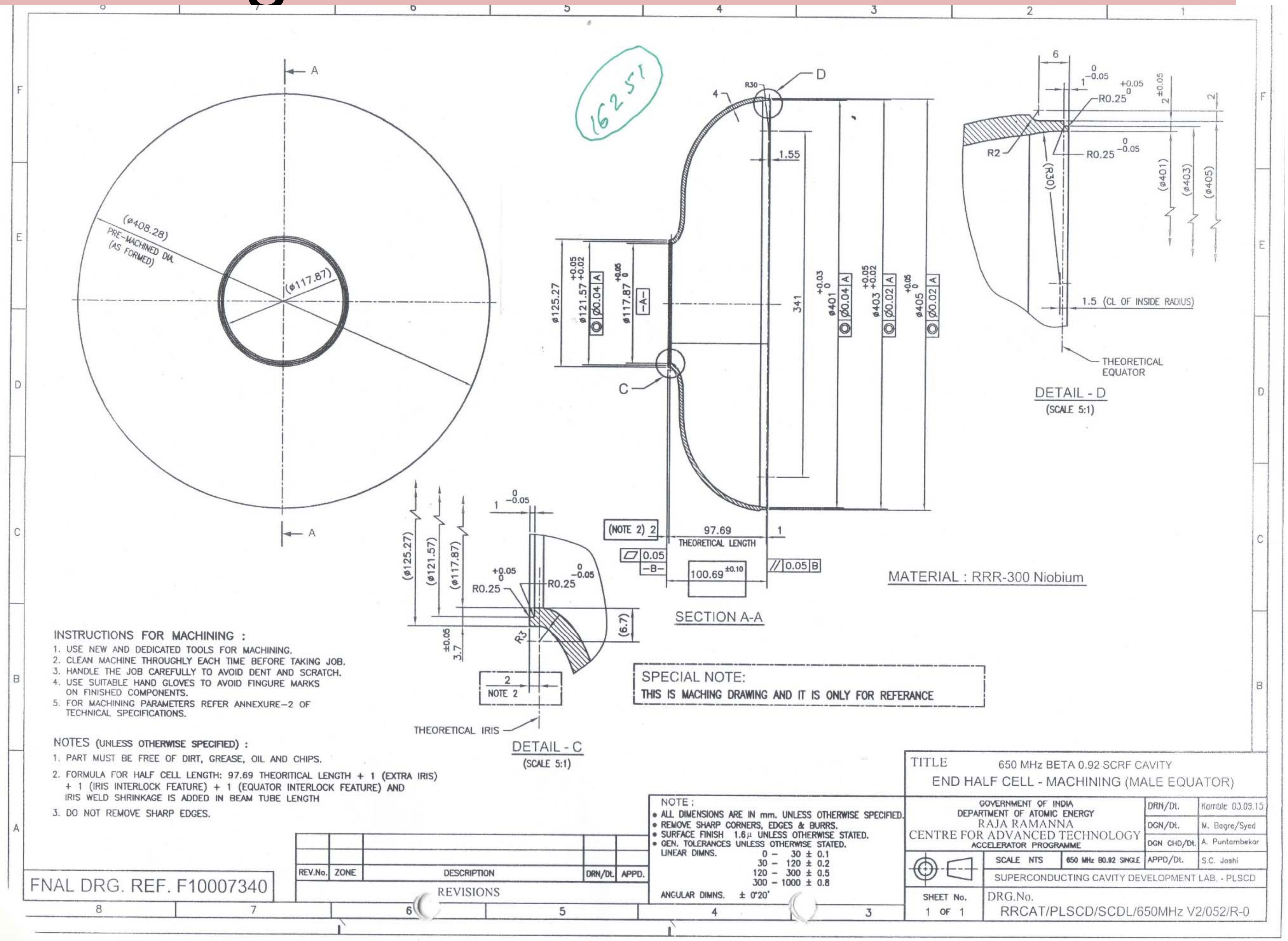


Laser welded single cell SCRF cavity Under inspection

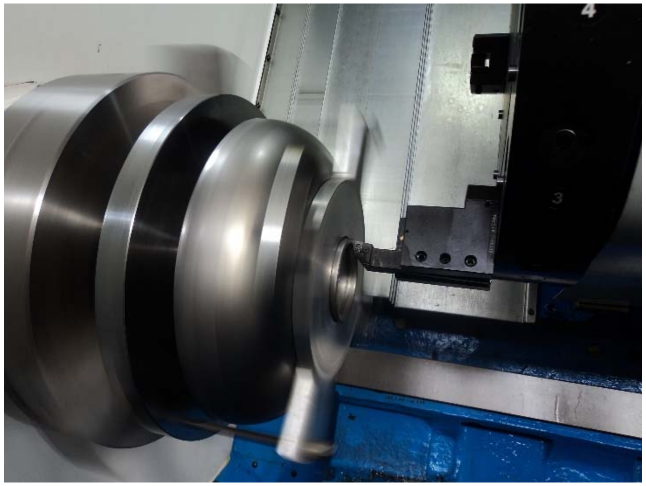
SCRF 1.3 GHz 9 cell cavity

5 Cell Cavity

Drawings of 650 MHz Half cell



Machining of 650MHz Components



Hollow Spindle CNC Lathe
With Fanuc 0TD Controller
M/s Miven, Hubli, Make,
Model- WSU-40x1.5m
Spindle Through Bore- 210mm
X stroke -485mm
Z stroke - 1500mm
Accuracies - 10 μm

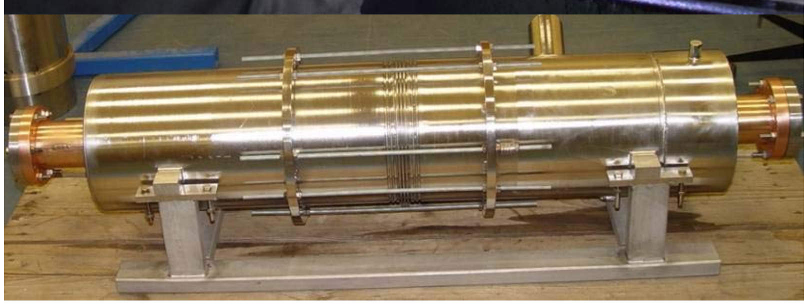
Prototype Helium vessel manufacturing

Development of Open atmosphere welding process for titanium vacuum vessel

- problem occurs in welding titanium in open atmosphere.
- Indigenously developed trail shields were used.
- Titanium grade 2 material confirming to ASTM B863 & welding filler wire confirming to AWS A 5.16 was used to fabricate this chamber
- The vacuum chamber has been vacuum leak checked at $2x10^{-10}$mbar liters/sec.
- Use of XL grade argon and welding in controlled atmosphere (RH less than 40%) helps a lot to make a quality weld joint .

Plate bending machine

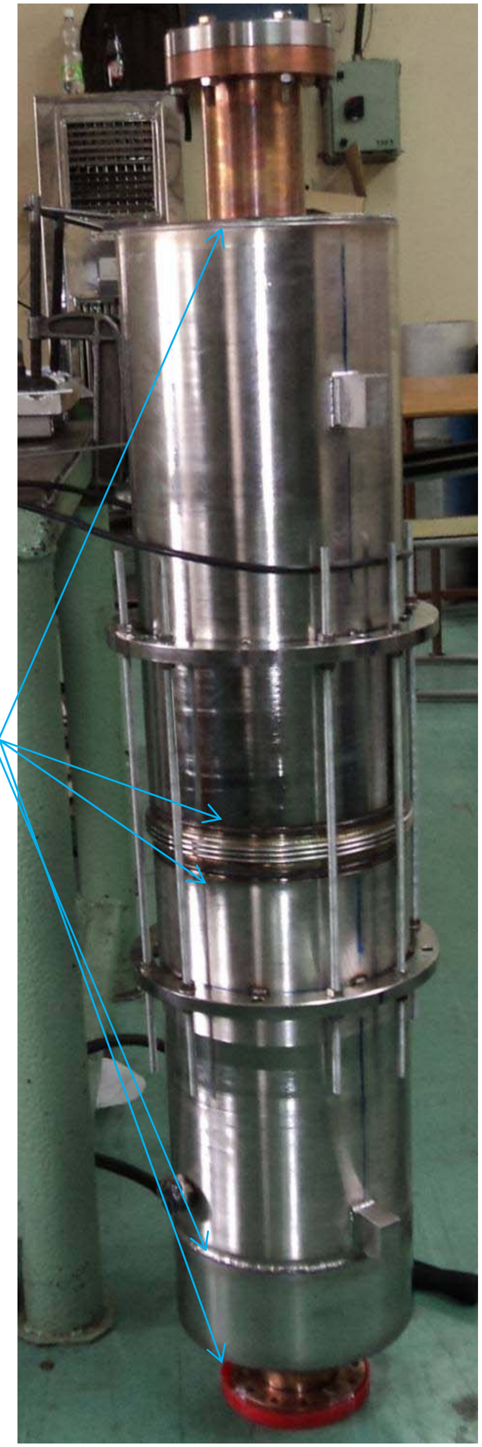
He vessel under He leak testing



Prototype Dressed Cavity:-

TIG Welding of Helium Vessel with 9 Cell Copper cavity

Circumferential Joints



Machining of Titanium

Titanium is difficult to machine mainly because
(1) Low thermal conductivity causes concentration of heat on the tool cutting edge and face, reduces tool life.

(2) Reactivity with cutting tool material causes galling, smearing and chipping of the work piece surface and rapid tool wear.

(3) Surface hardening by formation of hard solid solution due to internal diffusion of oxygen and nitrogen cause decrease of the fatigue strength of machined surface and increase of tool wear.

(4) Low elastic modulus allows deflection of slender work piece under tool pressure, inducing chatter and tolerance problems.

(5) The high temperature strength and hardness of titanium alloys require high cutting forces which results in deformation of the cutting tool during cutting process.

(6)High dynamic shear strength during cutting process induces abrasive saw-tooth edges, generating tool notching.

Main techniques for cutting improvement.

Flood cooling: With this method the coolant is delivered with a low pressure pump and flooded in general cutting area, which is effective when machining at low cutting speed.

The use of water vapor: This is environmentally friendly and reduce cutting force and extend tool life. Water removes heat 2.5 times faster than oil do and is encouraging when mixed with soluble oils because this provides better lubrication also.

Cryogenic cooling is based on directing liquid nitrogen, under pressure and at low temperature, into the cutting zone, and is an efficient way to maintain the cutting temperature well below the softening temperature of the tool material.

Cold-air method use compressed refrigerated gas with small amount of oil, which is directed to the cutting zone. Mixing air with oil gives better performance.

Solid lubricants In the form of dry powder, the graphite and MoS2 are the most common materials used as solid lubricants. Performance of solid lubricants is better at higher cutting speed.

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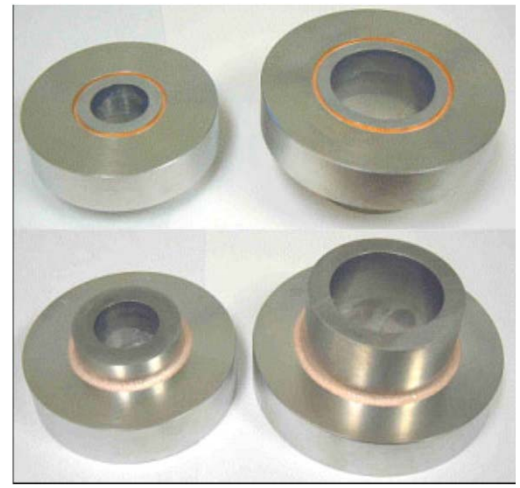
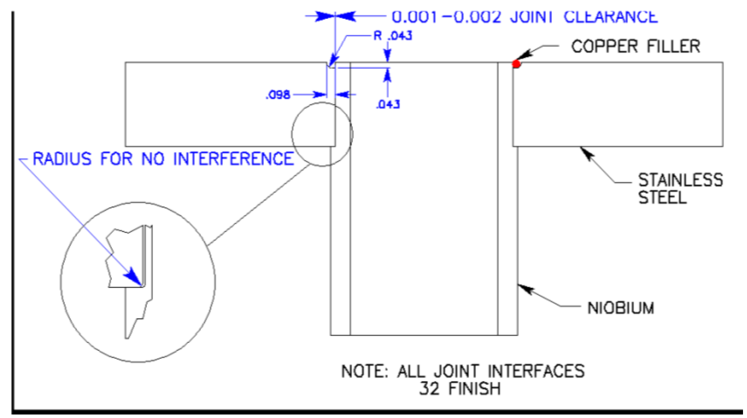
Thank you

Nb-SS brazed transition joint:

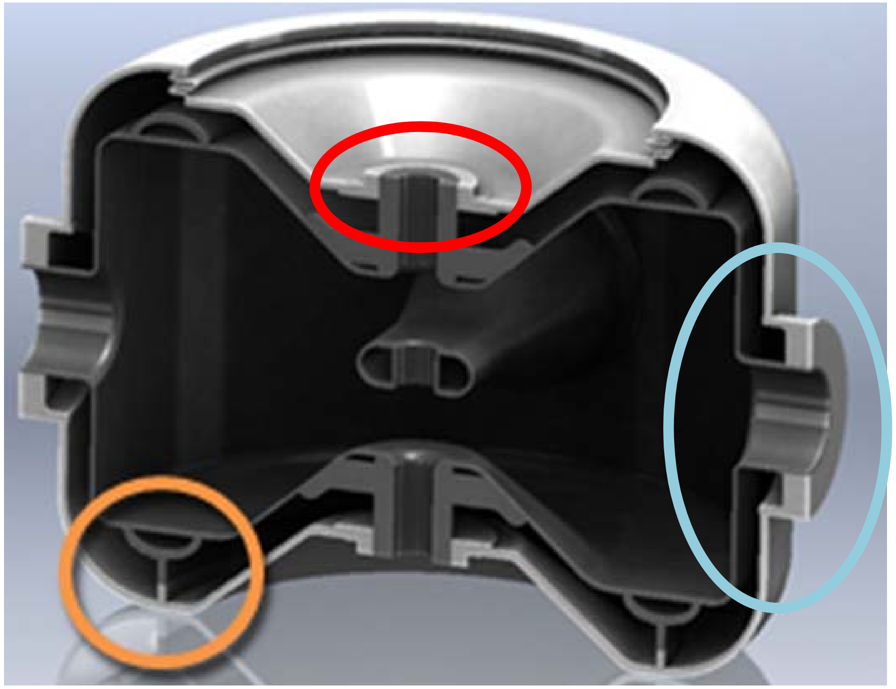
- Develop a reliable cryogenic leak-tight, copper-brazed transition between niobium and stainless steel for use in superconducting niobium cavities.
- Helium container that houses a niobium cavity of stainless steel rather than titanium both for (i) Ease of fabrication and also for (ii) low cost.
- Aim is, a very robust, void-free, and leak tight joint, withstands mechanical load, repeated thermal cycles, and can tolerate subsequent EBW of niobium within a few cm of the braze joint.
- Very high precision machining of SS and Nb components is required (both in terms of size and geometry is required to ensure capillary flow of brazing alloy





Motivation for Nb-SS joining development

- Stainless steel helium vessel offers ease of fabrication along with increased stiffness.
- Stainless steel is already chosen as helium vessel material for spoke type cavities.
- Efforts are underway to replace titanium with stainless steel for elliptic cavities also.



* There two major areas in which a transition joint between niobium and stainless steel will be required:
  * Cavity stiffeners
  * Cavity end flange

Journal Publications:

(1) 1 research paper in ASM's Material Engineering and Performance.

(2) 1 research paper in prestigious Welding Journal of AWS.

(3) 1 design innovation paper for the unique design for manufacture and assembly in The Transaction of ASME: Manufacturing Science and Engineering.

Awards:

(1) Non-ferrous category: Panthaki Memorial Award - 2014 by Indian Institute of Welding at International Congress.

(2) Stainless Steel Category: Venus Wire Award – 2016 by Indian Institute of Welding at National Welding Seminar.

Controlled atmosphere vacuum brazing furnace

Maximum Job Size : 500 mm dia. and 1500m length with 500 Kg. Job weight

Vacuum condition

Cold Vacuum – 5 x 10-7 mbar

Temp. range – 500 - 1200 Deg C,

Temperature uniformity : ± *5 °C*

pumping system (Clean and Dry)
2 x 10,000 lps Cryopumps, 1 x 2400 lps TMP backed by 230 lps roots (1) + screw pumps (1).

Gas mode operation : High Purity Argon @ 0.5 mbar (abs)