Cavity Manufacturing Techniques II
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"From Sheets to Fields"

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Advanced Technology Equipment and Turn-Key System Supplier for Research, Industry and Medical worldwide

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RI Research Instruments GmbH is continuing the accelerator and special manufacturing business of the former ACCEL Instruments GmbH from April 01, 2009.

- Linear Accelerators
- RF Cavities, Couplers, Auxiliaries
- Superconducting Accelerator Modules
- Electron and Ion Sources
- Beam Diagnostic Elements and
- Particle Beam Lines
- Accelerator Equipment for Particle Therapy
- Specialized Manufacturing Projects

Content and Overview

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In this overview we concentrate on the manufacturing of superconducting rf (srf) cavities (and related auxiliaries) and show the process from the source of niobium material until the final installation of srf accelerating modules.

- Production of niobium for srf cavities
- Forming niobium into shape
- Assembly and electron beam welding
- RF-control measurements
- Completion of a cavity / helium vessel
- Final RF-adjustments
- Surface preparation
- Cold rf test
- Auxiliary components, coupler, tuner, cryostat
- Assembly of a srf module
- Delivery and installation
- Technical variants
- Acknowledgements

Some important properties of Niobium

Columbit (Fe, Mn)(Nb, Ta)$_2$O$_6$

- Niobium is a rare, soft, malleable, ductile, gray-white metal.
- The metal is inert to acids
- It tends to react with oxygen, carbon, the halogens, nitrogen, and sulfur at low temperatures (<200°C)
- Melting point: 2410 °C
- Critical temperature: 9,2 K (at atmospheric pressure, the highest critical temperature of the elemental superconductors)

General Use:

- Niobium is used for the production of high-temperature acid resistant alloys and special stainless steels. Small amounts of niobium impart greater strength to other metals.

- Niobium-tin and niobium-titanium alloys are used as wires for superconducting magnets.

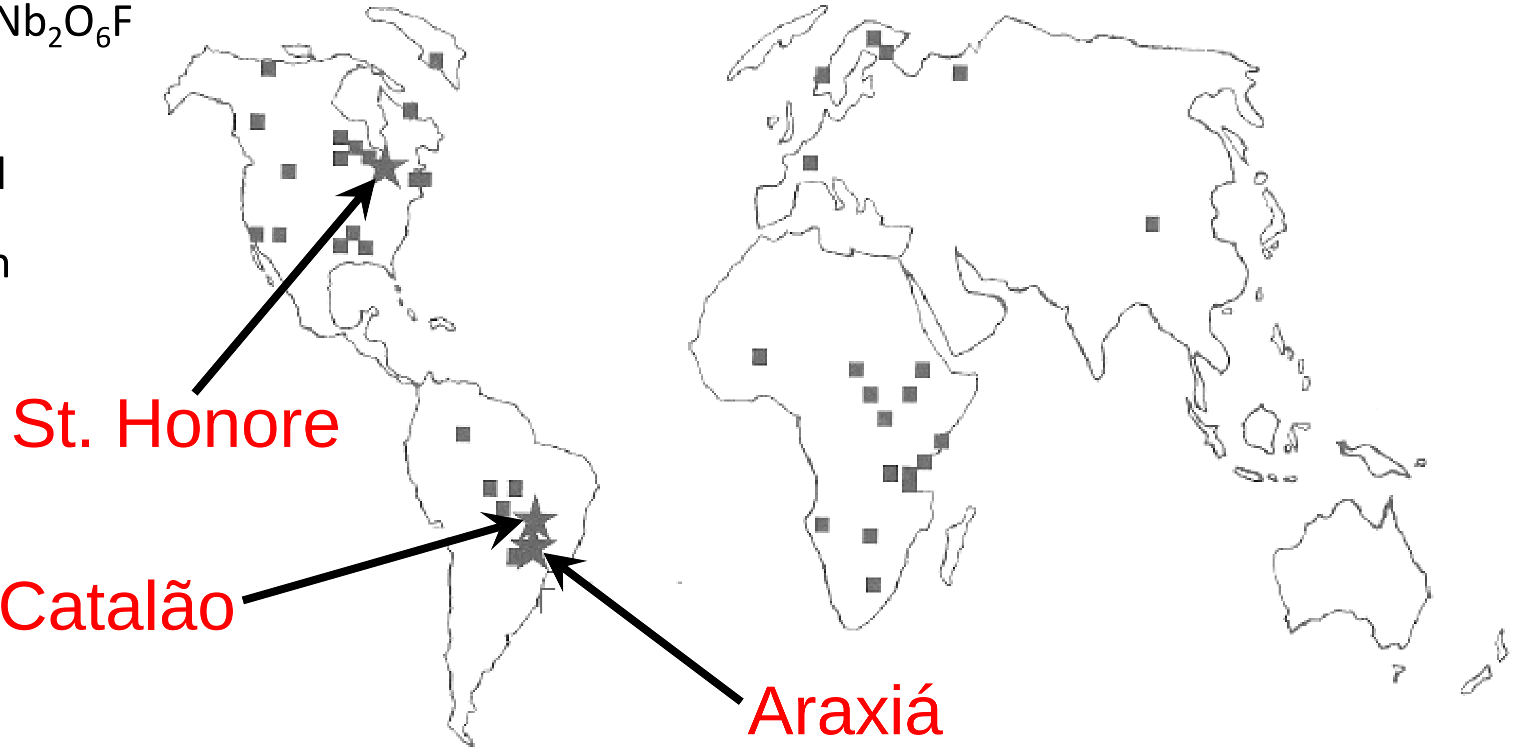
Special Use:

For accelerator cavities is its highest purity form

Nb mines worldwide

- Tantalite (Fe, Mn)(Nb,Ta)$_2$O$_6$
- Columbite (Fe, Mn)(Nb,Ta)$_2$O$_6$
- Pyrochlore (Ca,Na)$_2$Nb$_2$O$_6$F

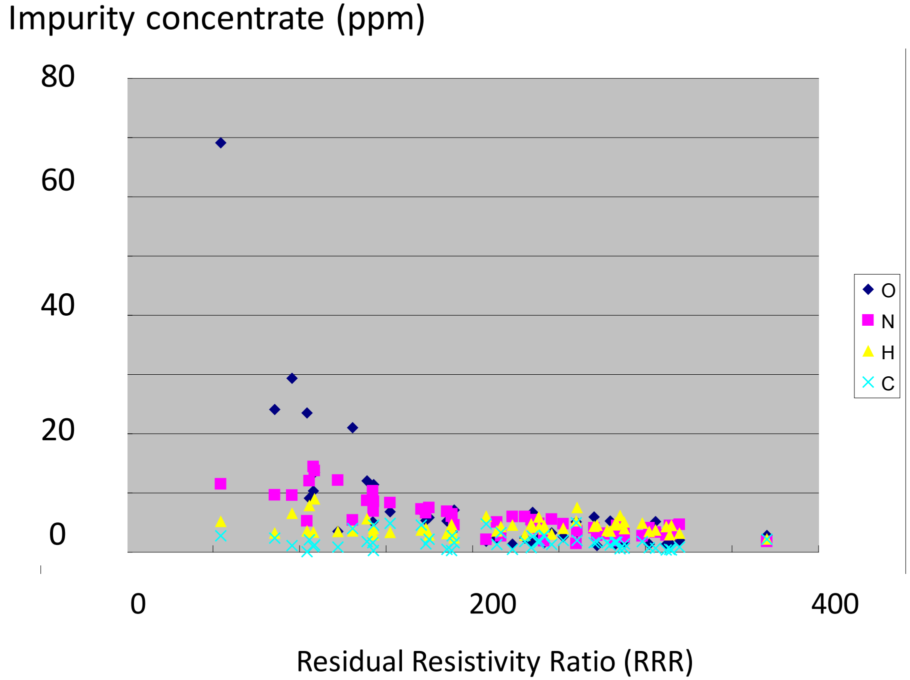
Pyrochlore is mostly used for the generation of high purity niobium due to its low TA-content



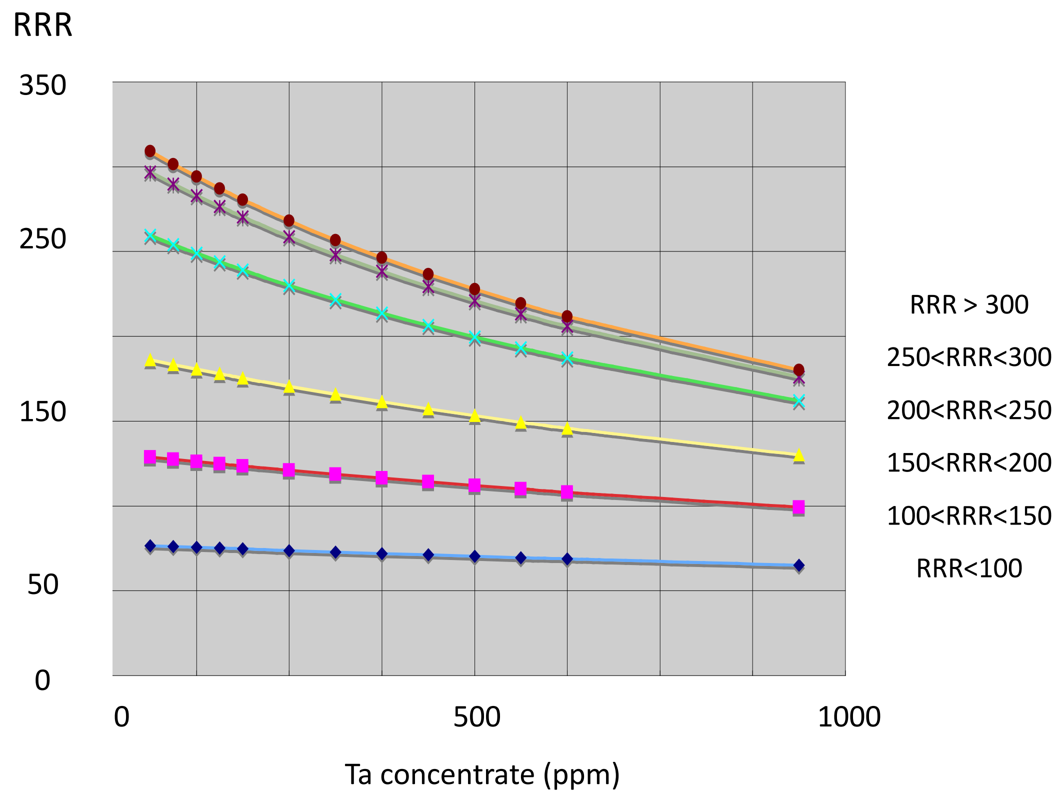
Imagumbai, et al: "Resource, production volume & manufacturing technology of niobium" Material Science & Technology Vol.72(2002)No.3 pp204-210

High Purity Niobium

The Residual Resistivity Ratio (RRR) is the main parameter for characterization for the purity of Niobium



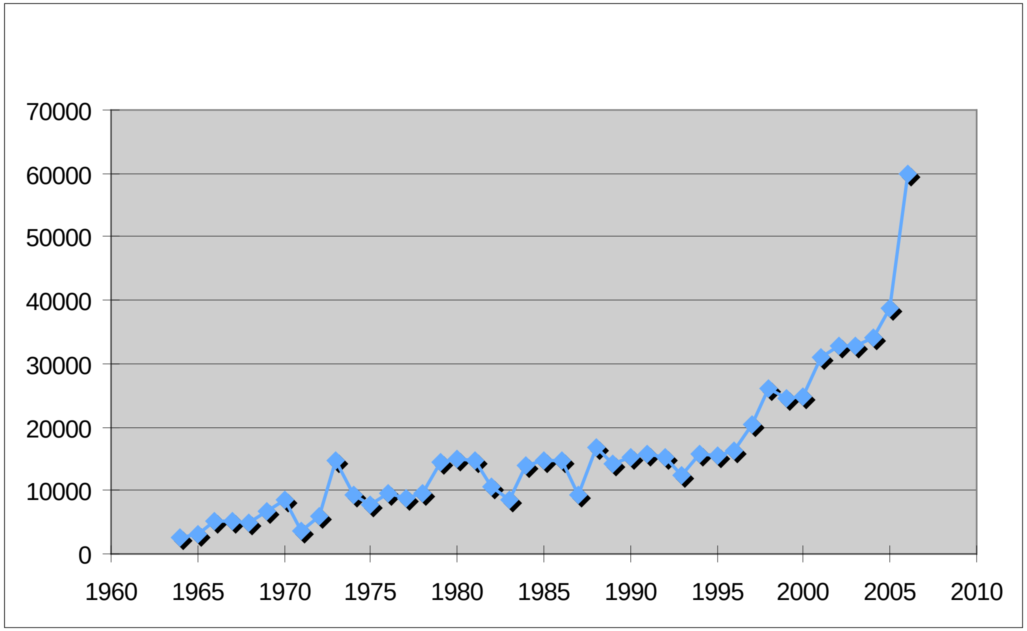
Relationship between RRR and interstitial impurities (O, N, H, C)



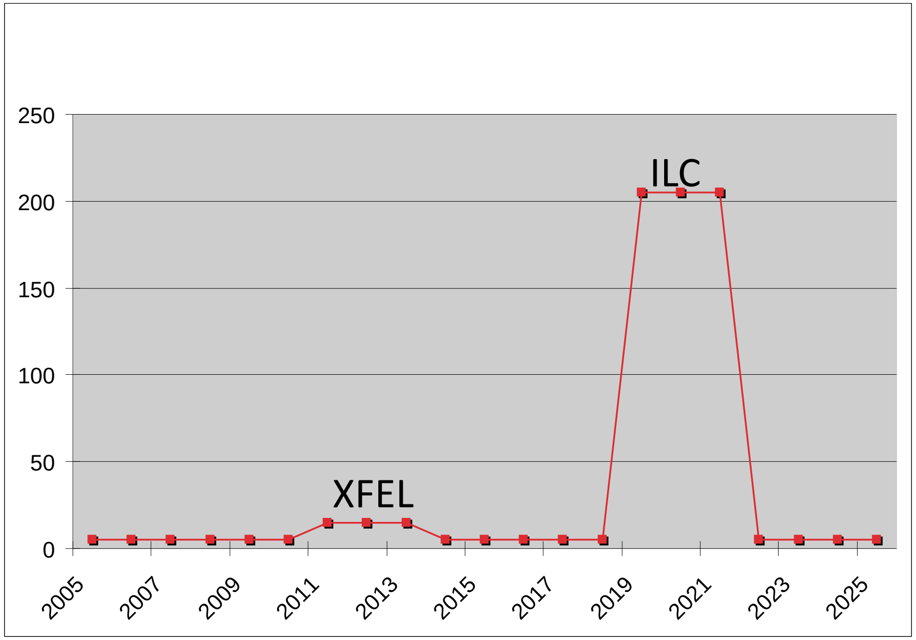
Relationship between RRR and Tantalum content for various states of purity (RRR)

SRF Cavity production needs Nb with RRR between **250 and 300 RRR** (besides specific mechanical properties)

Production of niobium worldwide and high purity niobium consumption for accelerator manufacturing



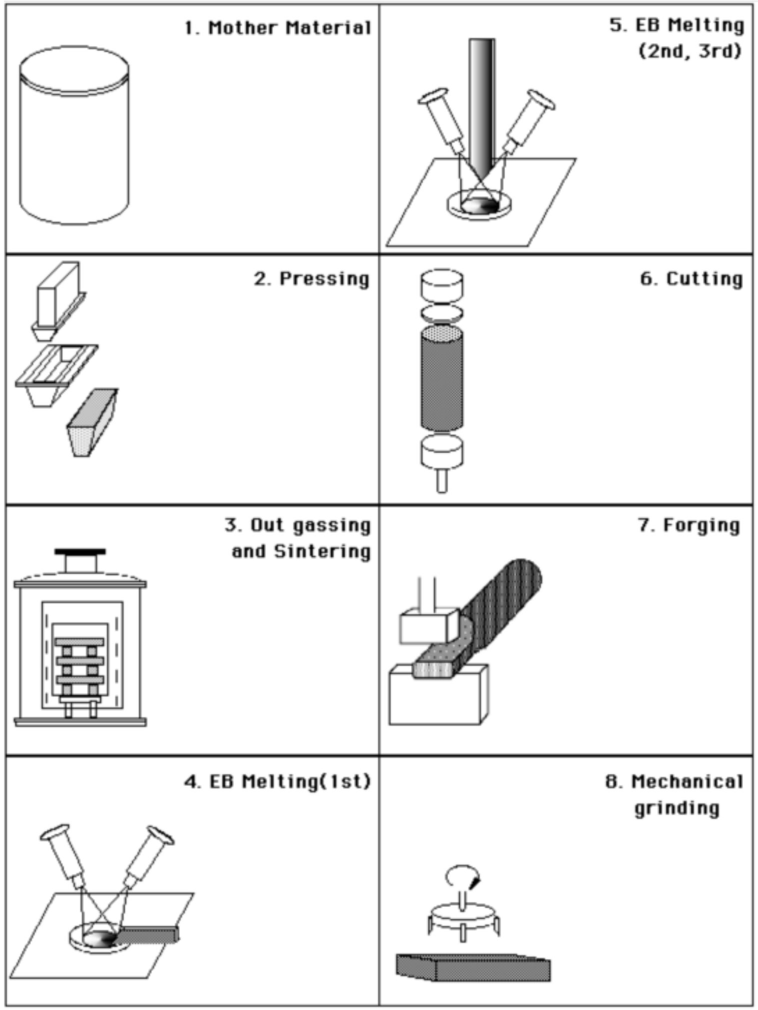
world mine production (ton)

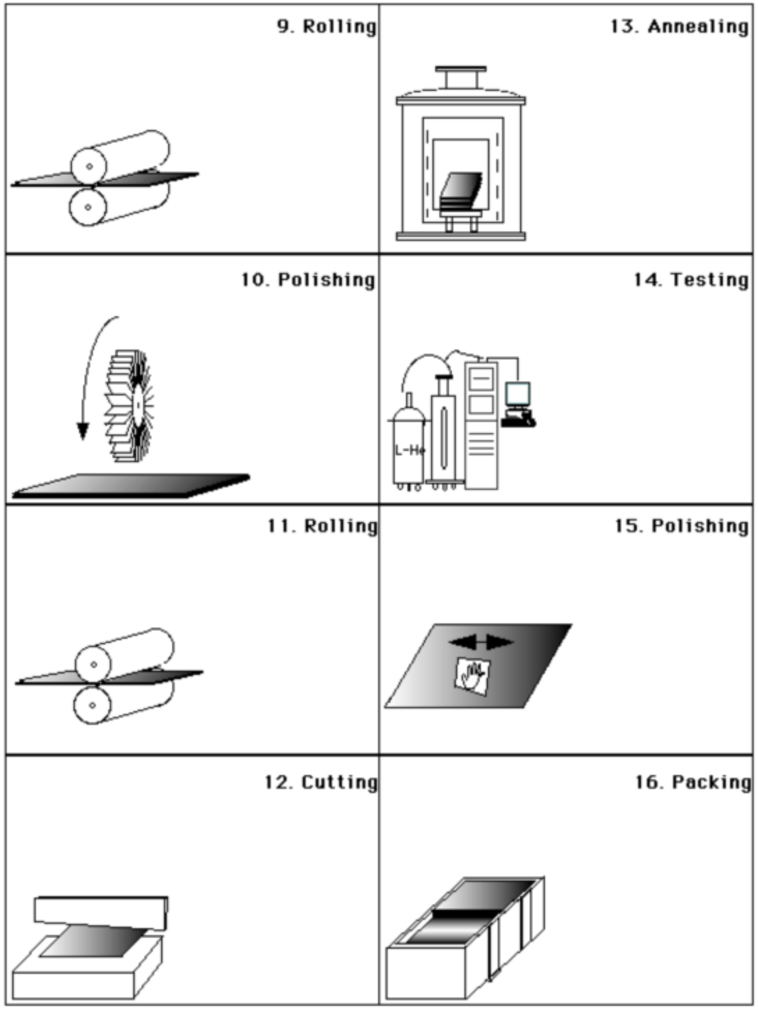


word demand high purity (estimated) Nb (ton)

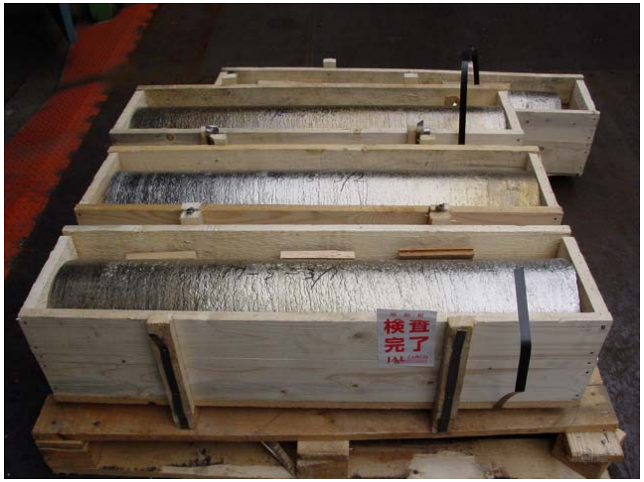
Even large scale srf projects should be easily supplied with high purity Nb in relation with the world mine production

Fabrication process of Nb sheets for superconducting cavities (1)



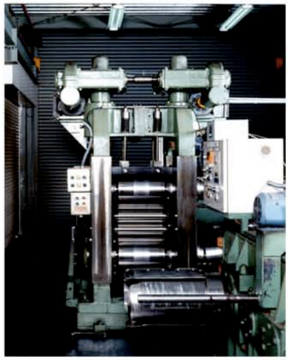


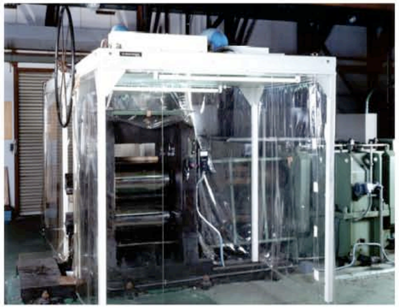
Fabrication process of Nb sheets for superconducting cavities (2)



Nb ingot after refining by multiple electron beam welding in vaccum*

Nb sheets ready for cavity production*



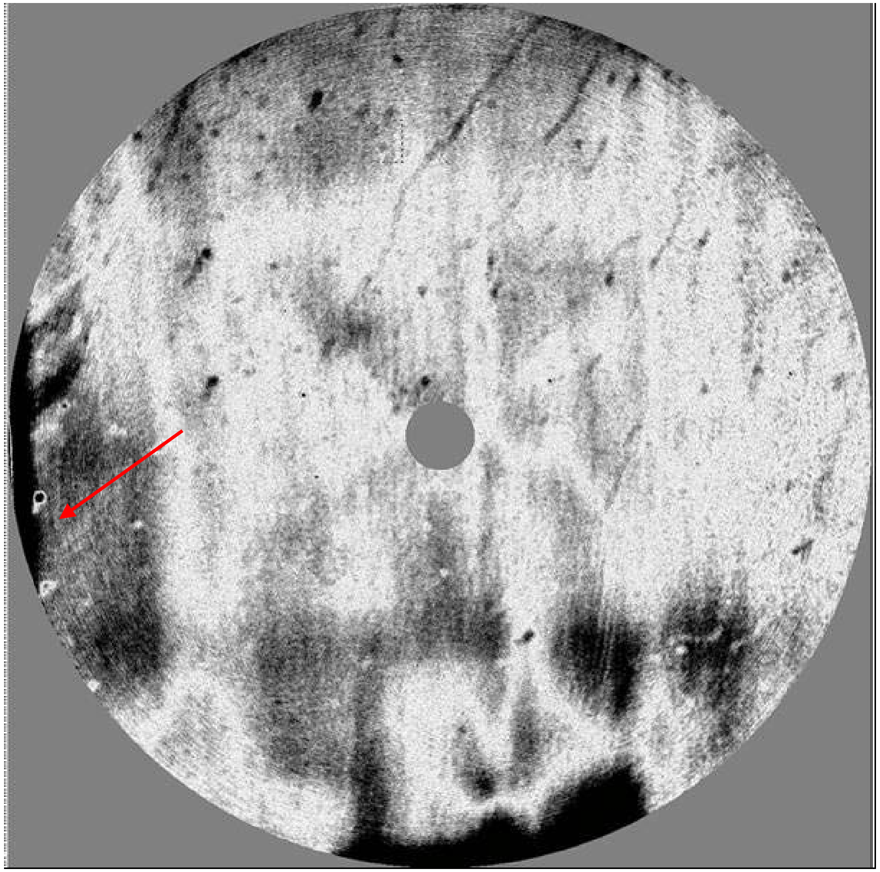


Name	Roll Size		Motor	Specific Sheet Size	
	Diameter	Width		Thickness	Width
Two High Rougher Mill	500 mm ø	1,000 mm	300 kW	60–8 mm	
Two High Finishing Mill	500 mm ø	1,100 mm		8–0.8 mm	900 mm
Two High Rougher Mill	460 mm ø	800 mm	75 kW	8–3 mm	
Two High Finishing Mill	420 mm ø	800 mm		3–0.1 mm	500 mm
Four High Mill	390/130 mm ø	450 mm	37 kW	1–0.1 mm	350 mm
Four High Mill	300/145 mm ø	300 mm	37 kW	0.3–0.08 mm	200 mm
Six High Mill	40/105 mm ø	150 mm	5.5 kW	0.3–0.05 mm	100 mm

sheet rolling installation*

* Courtesy by Tokyo Denkai Co Ltd.

Quality control for niobium sheets



Eddy current scanning is a method developed at DESY for Nb sheet investigation on foreign material inclusion defects etc.

* Courtesy DESY

Forming of single parts for cavities (1)

7Cell cavity for Jefferson Laboratory

Cavity cells and waveguide coupler parts and flanges are made from NB sheet

two half of a waveguide coupler

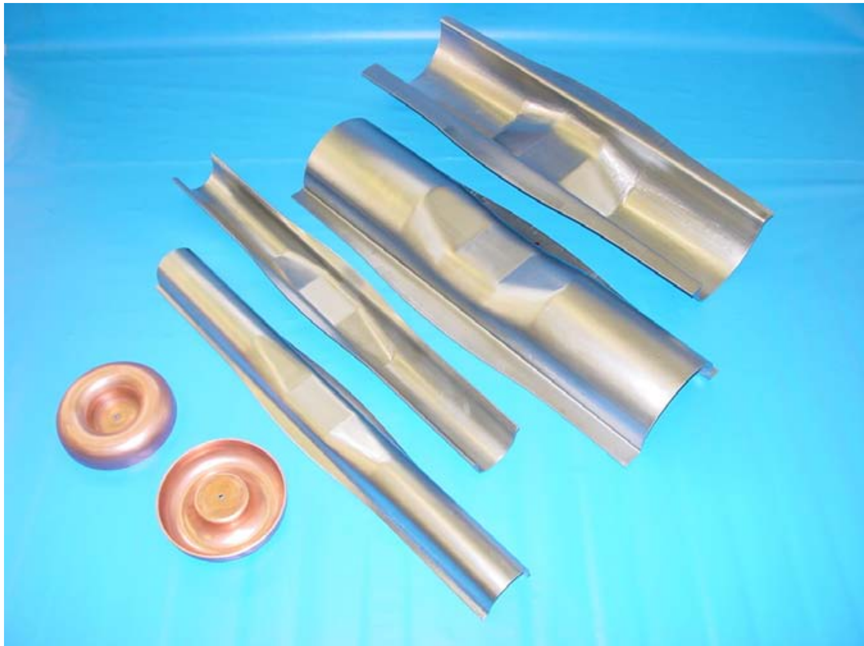
Half cells (cups)

Forming of single parts for cavities (2)

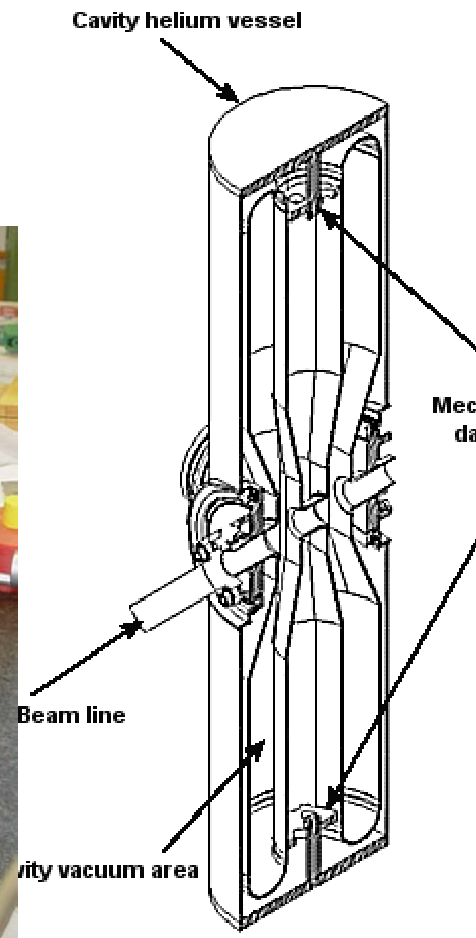
Oak Ridge Spallation Neutron Source (SNS) high β cavity

Beam tubes made from a single sheet

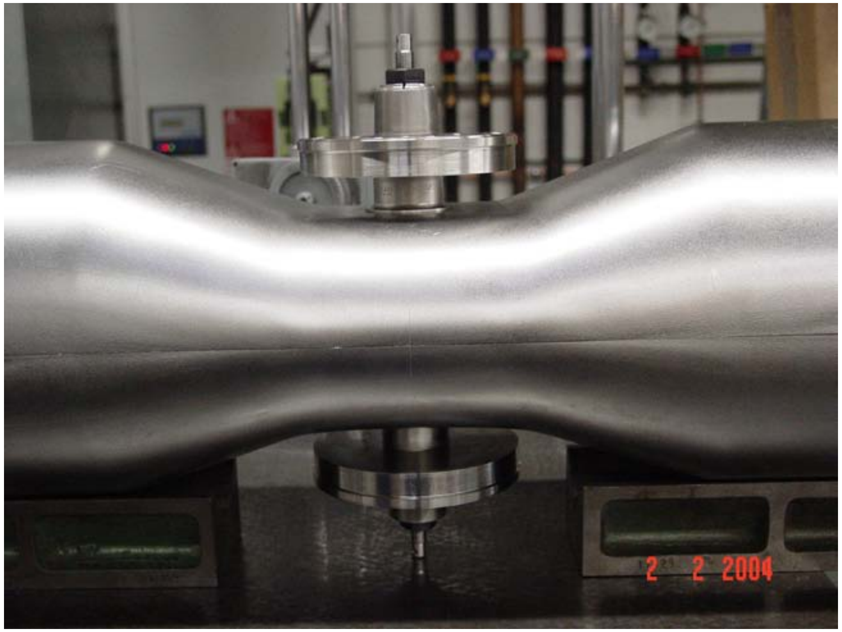
Forming of a single parts for cavities (3)

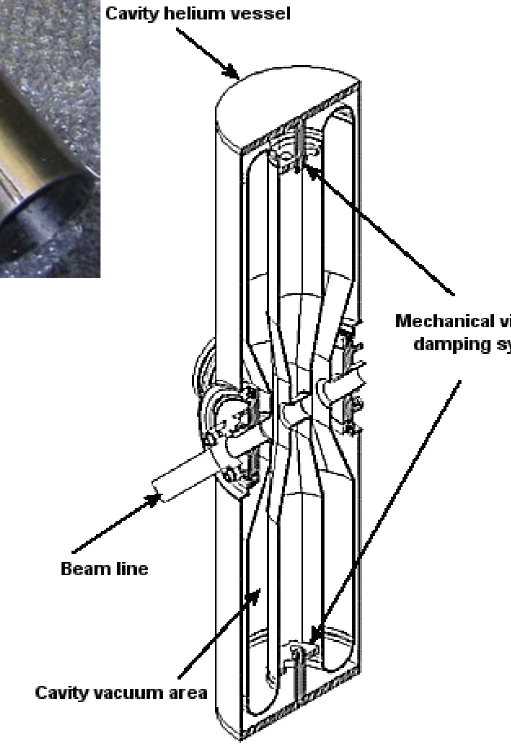


Half Wave Resonator (176 MHz) developed by RI for the 2 mA cw proton/deuteron linear accelerator at SOREQ (Yavne, Israel)



Forming of a single parts for cavities (4)



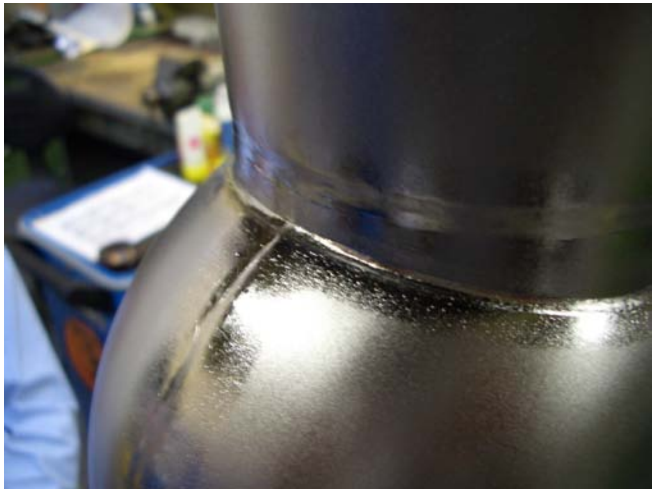


176 MHz Half Wave Resonator

Assembly and electron beam welding

Due to the high purity of the Niobium and the requirement to maintain this high purity, electron beam welding in vacuum (< 5×10^{-5}mbar) is the established reliable joining technology for accelerator cavity production

Assembly of the centre conductor of a quarter wave resonator



Eb-welds in quarter weld resonator

A view into a Quarter Wave Resonator

RF control measurements

Each pair of half-cells (dumbbell) is checked for its frequency assembled in a special tool

RF control measurements

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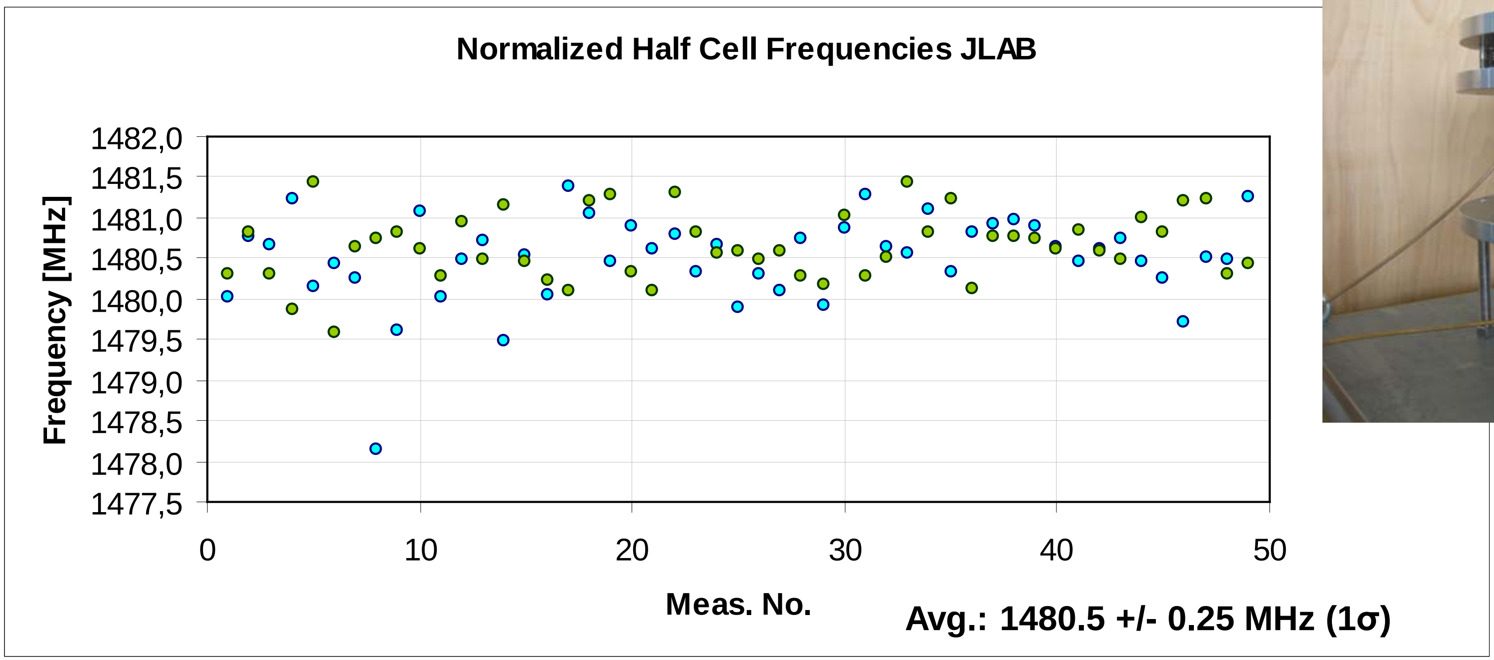
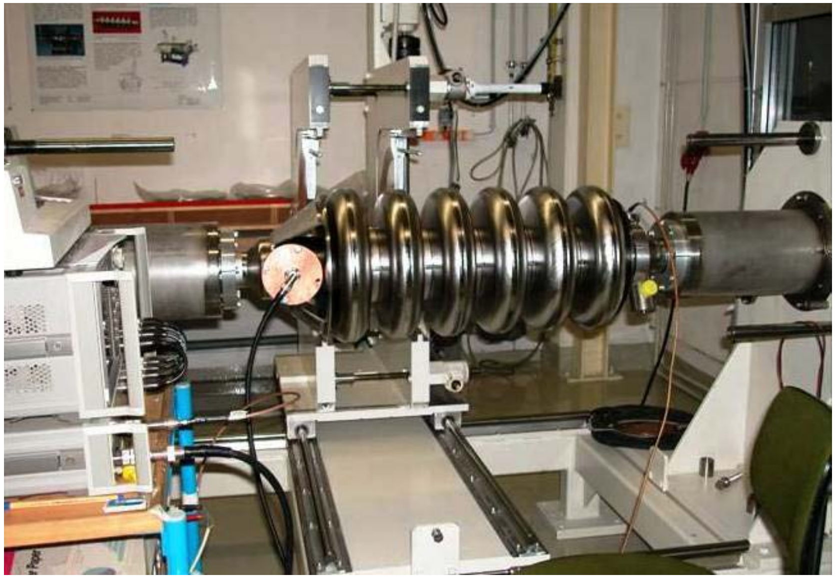


Frequency measurements are used for:

- Quality control of preceding manufacturing steps
- Statistical analysis of the manufacturing process
- Prediction of subsequent machining operations to determine correct frequency and length of the multi cell cavity (Dumbbells have a specific extra length that will be machined to size calculated from the measured frequency)

Final RF adjustment

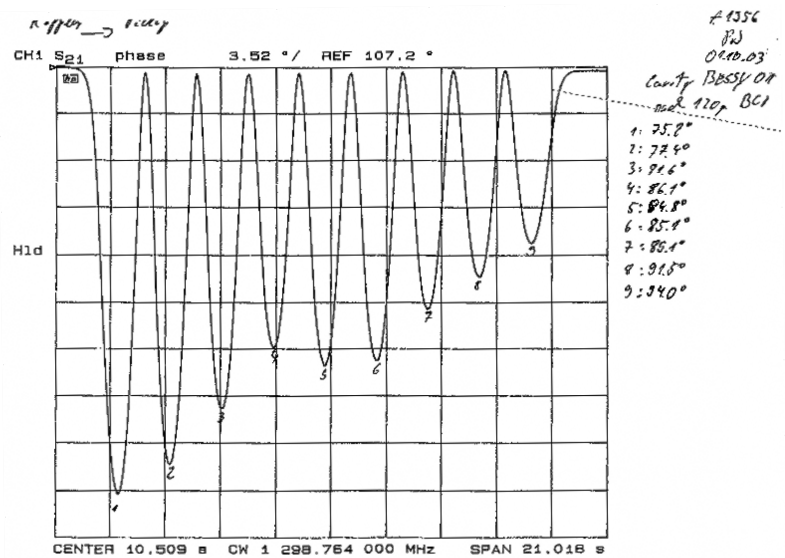
Operating frequency and the uniformity of the field profile of multi cell cavities are controlled and adjusted by a small precision mechanical deformation of each cell (Tuning)

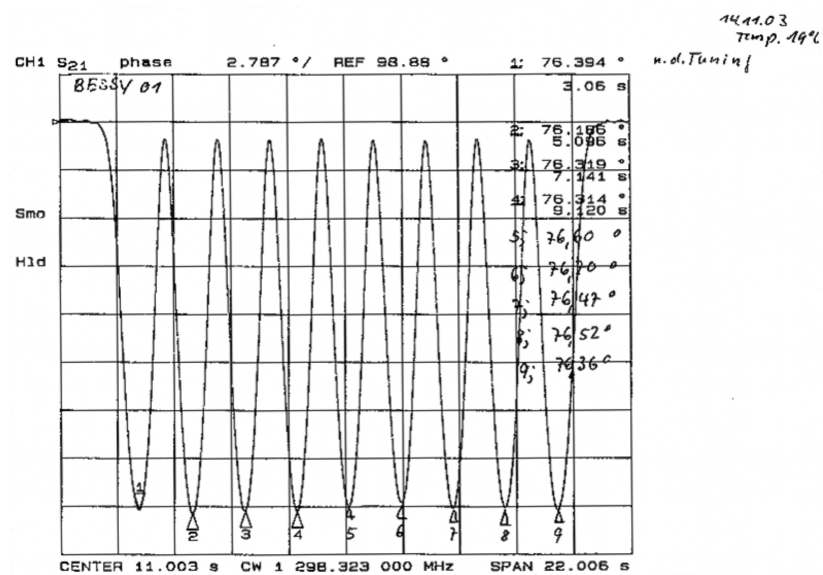


SNS medium β cavity (6 cell) during the tuning process

Final RF adjustment

The uniformity of the "field profile" (value of the accelerating gradient in each Cell), here for a 9 cell XFEL Cavity is adjusted by mechanical, plastic





The field strength (accelerating gradient) is measured in the resonator by method of "bead pull measurement"

Completion of a cavity

XFEL 9-cell cavity with/without He-vessel and He-gas pipe (all produced from titanium)

He-vessels are generally made from titanium or stainless steel using the following joining techniques:

- EB-welding Nb with Titanium by means of an intermedate sheet of an Niobium Titanium alloy and two welds: Nb to Nb/Ti and Nb/Ti to Ti
- Brazing Nb to SS

Surface Preparation of srf Cavities (1)

Surface preparation is used mainly for two purposes

1) Coarse treatment (100 to 150 µm of inner surface to remove the damage layer, which is to be understood as the first (50 to 100 µm material layer affected by the manufacturing process (forming, milling, grinding,…)

2) Final treatment: 20 to 40 µm preferably inside a clean room environment with immediately following High Pressure Water Rinse (HPWR, 100 bar, some hours, ultrapure, demineralized, particel filtered 0,01µm, class 10 , resp. ISO 4)

Three procedures for chemical surface preparation have been established

1) Buffered chemical polishing: HF (40%) / HNO_3 (65%) / H_3PO_4 (85%) 1/1/2

(state of the art process)

2) Electropolishing: HF (48%) /H_2SO_4 (96%) 1/9 under application of voltage (17Volt) and a current density about 350 A/m^2 cavity surface (state of the art process)

3) Barrel-polishing (rarely applied)

Surface Preparation of srf Cavities (2)

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Closed loop BCP

HPR

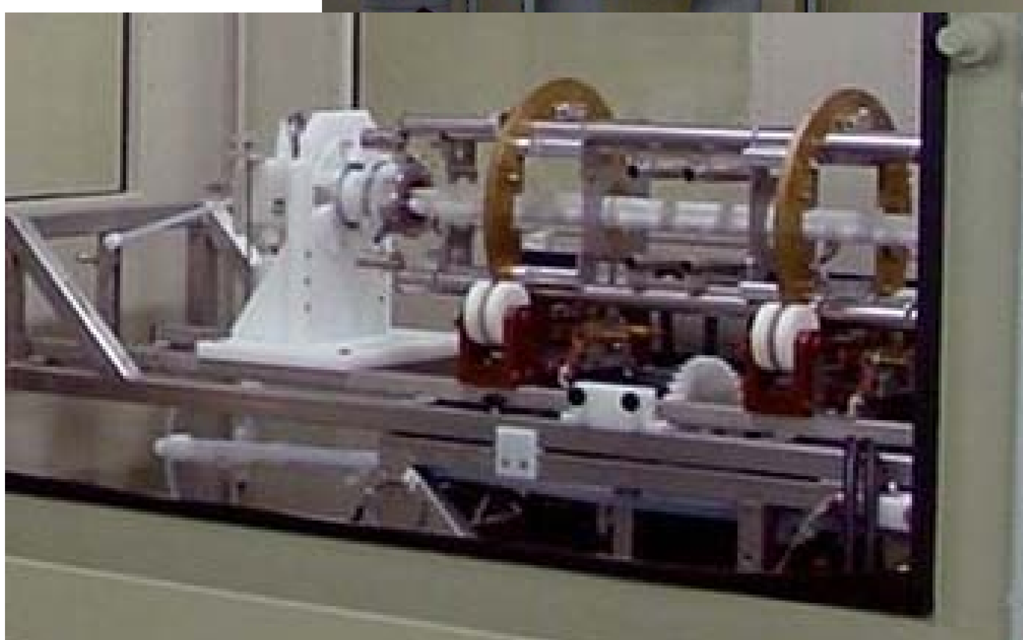
Assembly in clean room

Packing and shipping for vertical test

Surface Preparation of srf Cavities (3)

Electropolishing:

a cavity is half filled with the electrolyte (HF (48%) /H_2SO_4 (96%)) with a cathode placed “on axis” and rotating while 17 Volt and a current density 0f 350 A/m² are applied.



Cold rf testing of cavities (1)

Cold rf testing of cavities is generally done with the individual cavity after surface preparation to show performance (cold frequency, quality factor, maximum achievable accelerating gradients)

Test-installations are established in Research Institutes and used within the frame of cooperation agreements. Some installations are found in industry

A XFEL Cavity (9 Cell, 1,3 GHz) under final rf control measurement completed with the cryogenic equipment ready to go into a cryostat for cold rf testing (2,0 K)

Cold rf testing of cavities (2)

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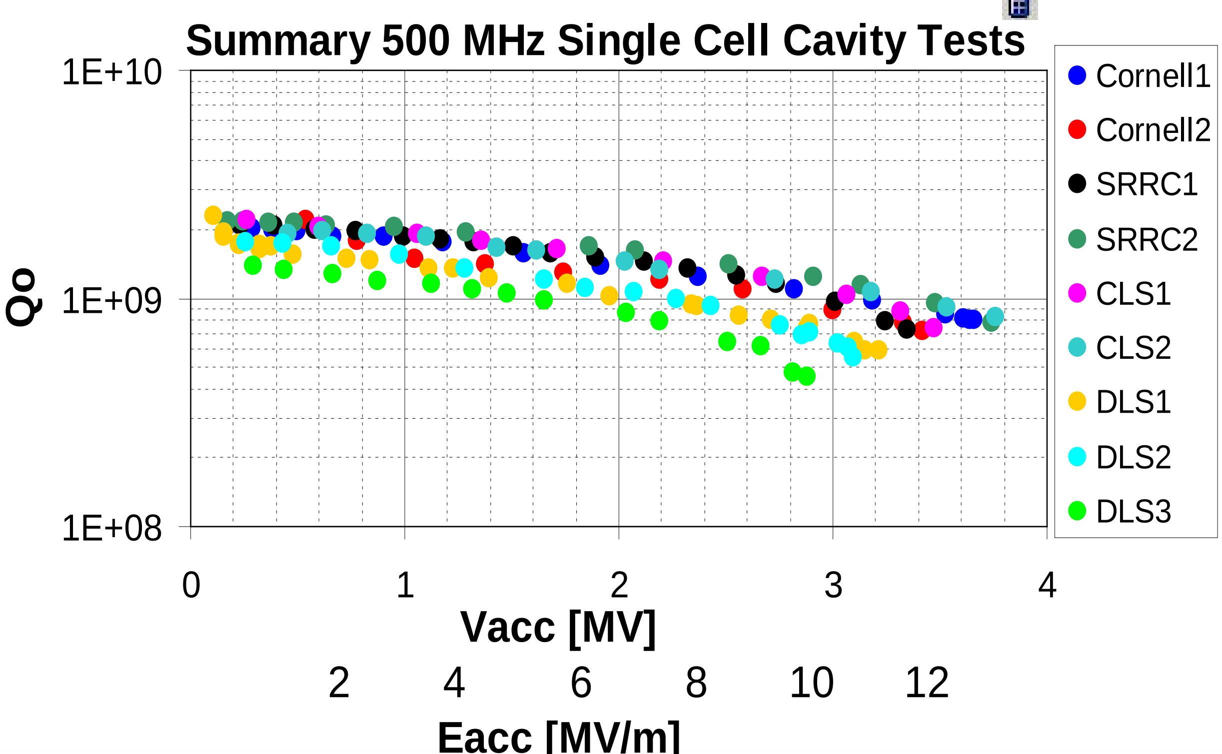

typical preparation is done at RI as follows:

- Degreasing
- Buffered chemical polishing (1:1:2), in closed loop chemistry, acid actively cooled to temperatures below 15 °C
- Water Rising > 17 MOhmcm
- High pressure water rinsing (100 bar)
- Drying by pumping
- Assembly in class 100 clean room

- All test results achieved in consecutive preparations / tests
- All field values limited by available RF power

Cold rf testing of cavities (3)

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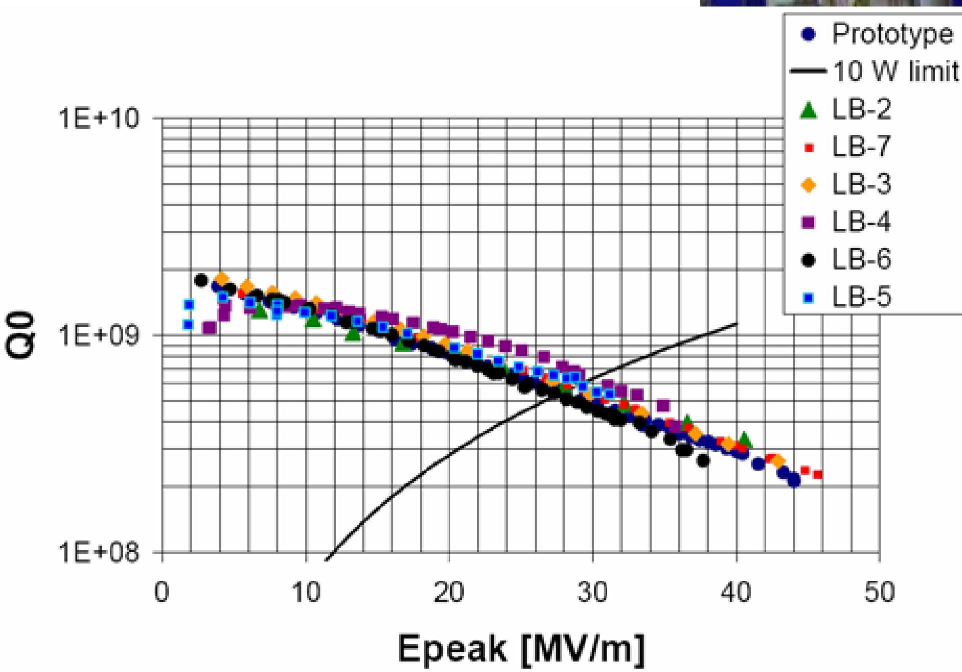

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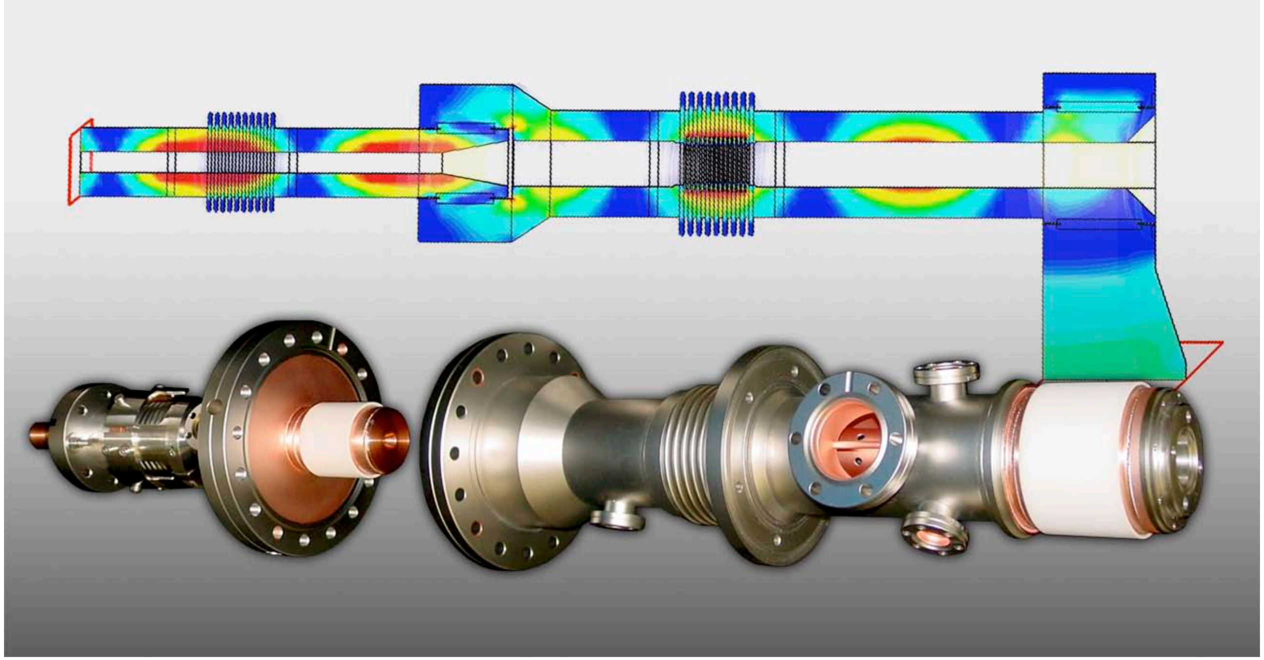
Auxiliary components/Power couplers (1)



XFEL Power Coupler:

Coaxial type with two ceramic windows ("cold and warm")

Besides other components power couplers are the main auxiliary component for a srf module.

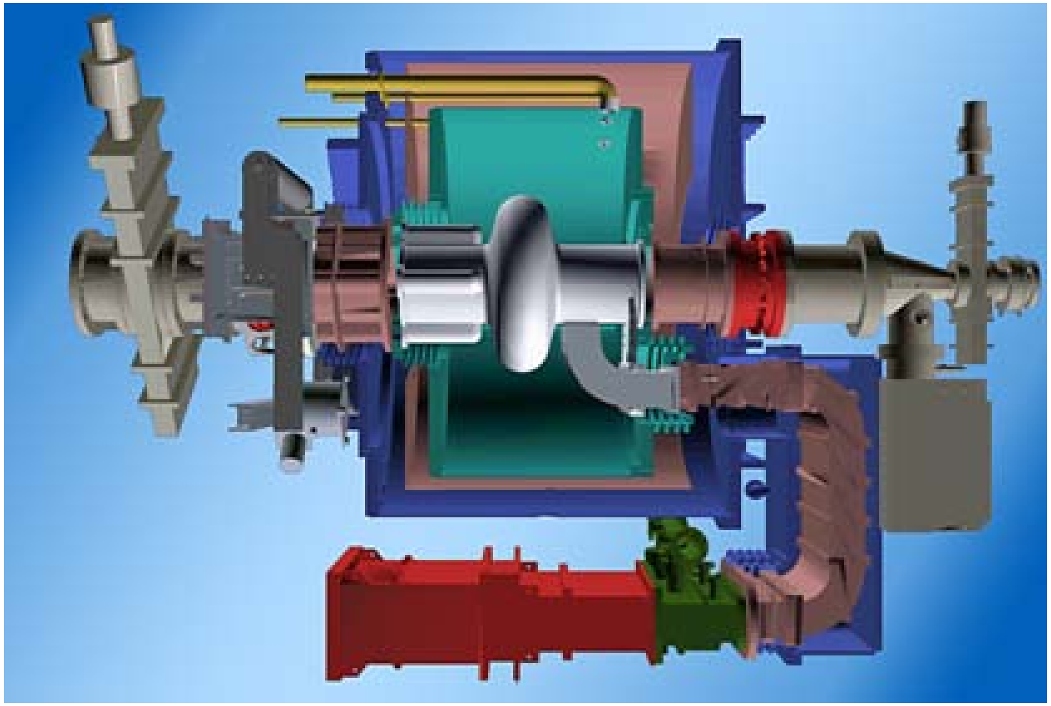
Power couplers:

- transfer the rf power from the amplifier to the cavity
- provide the vacuum barrier to the cavity
- provide the warm cold transition (room temperature to 2 or 4K)

Power Couplers are of two main designs:

Coaxial or waveguide

Auxiliary components/Cryostat (1)



Artist view of a CORNELL srf module
500 Mhz, single cell

Main components of a srf module:

- cavity
- He-Vessel
- Heat shield (at intermediate temperature)
- Vacuum Vessel
- Power coupler
- Cryogenics supply
- Tuning system
- Vacuum system

Auxiliary components/Cryostat (2)

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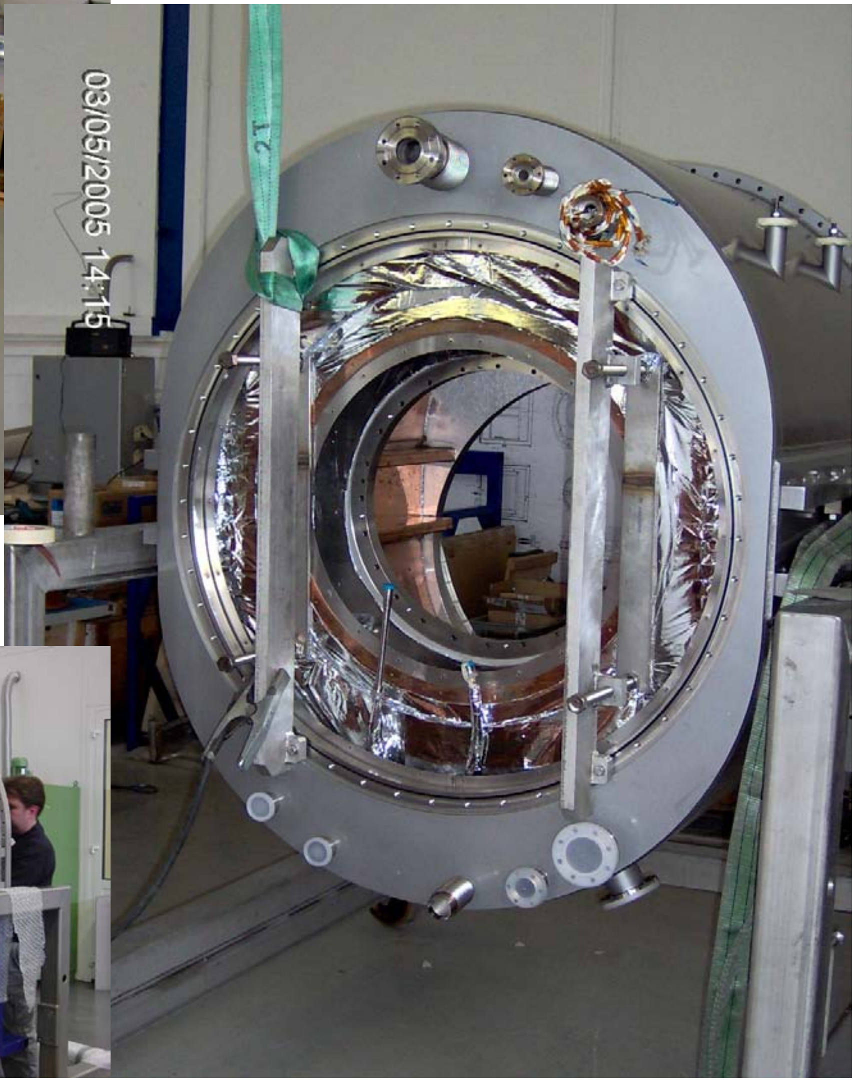
Heat Shield with cryogenic piping (LN2 cooling) and superinsulation foil



Vacuum vessel with preassembled heat shield of a 500 MHz module (CORNELL desing)

Assembly of srf cavities

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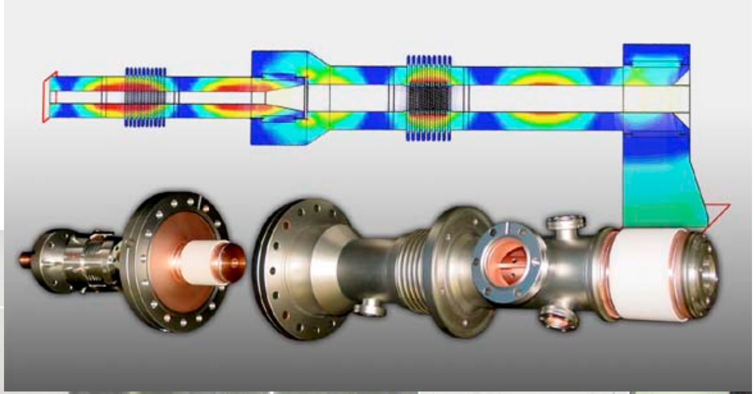
Steps

- completion of auxiliary parts to the cavity (e.g. power couple)
- connection of several cavities and beam tubes
- quality control (rf-tests, leak-tests)



leak testing of a XFEL string

String assembly of 8 cavities for an XFEL module

Assembly of srf modules (1)

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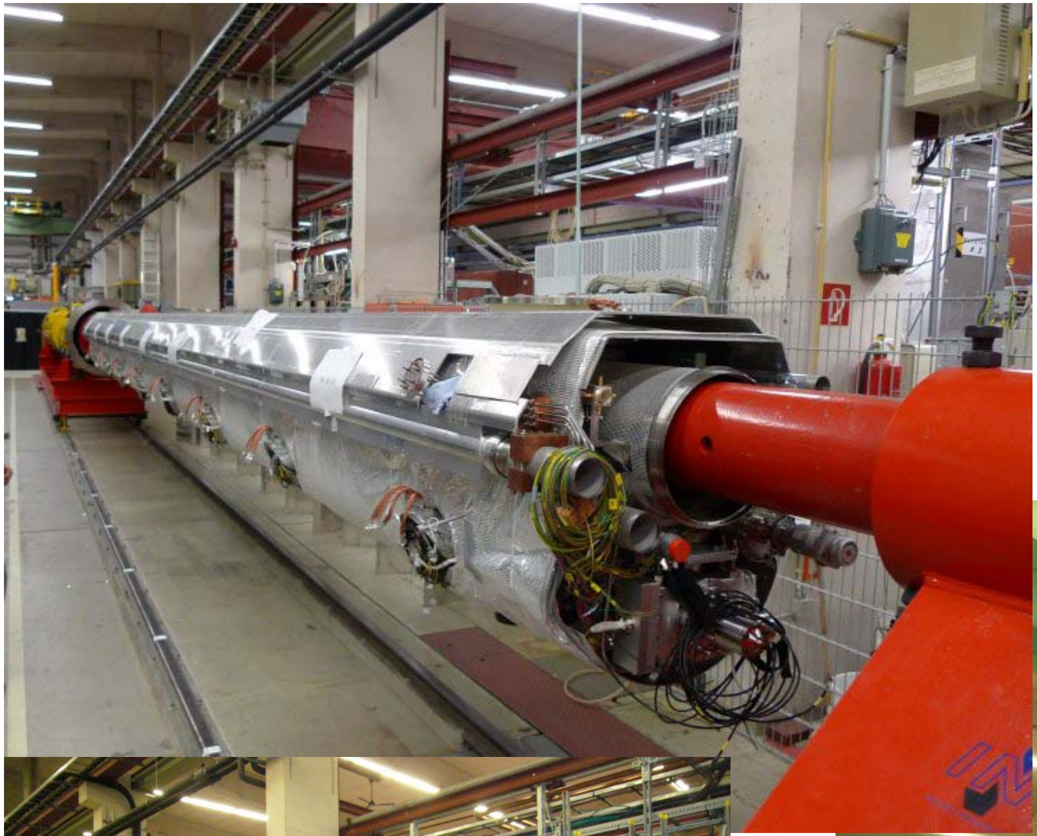
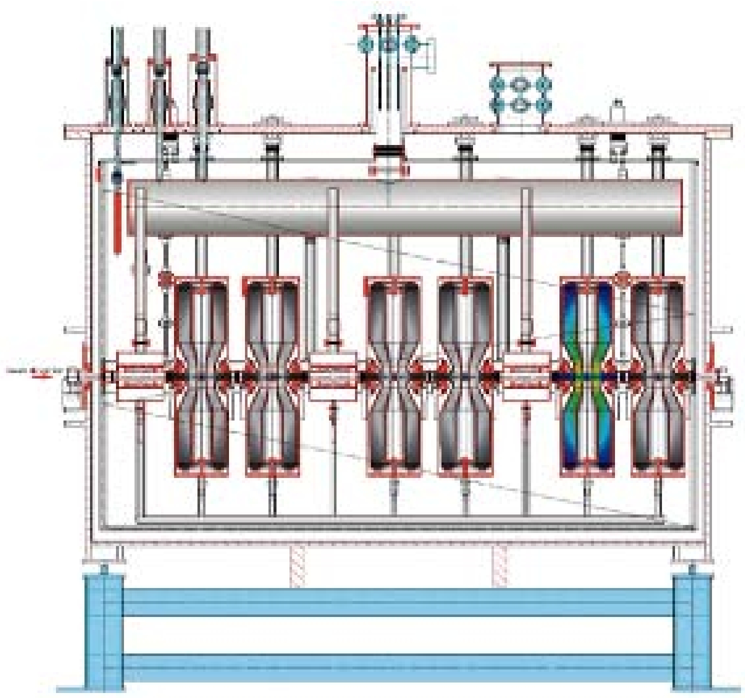


Completion of the XFEL srf accelerator module

Assembly of srf modules (2)

Completion of a srf accelerator module consisting out of 6 Half Wave Resonators, 3 sc Solenoids, and auxiliaries all assembled below a “top-plate” (ready to be moved into a vacuum vessel)



Transport of srf modules

Overseas transport by air freight

Land transport by truck with the srf module mounted to a special shock absorbing transport frame

Delivery and Installation

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A 500 MHz Module to be placed at its final position in a storage ring

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Technical Variants for SRF Cavity production: Nb on copper technology: LEP, LHC, Cornell, SOLEIL

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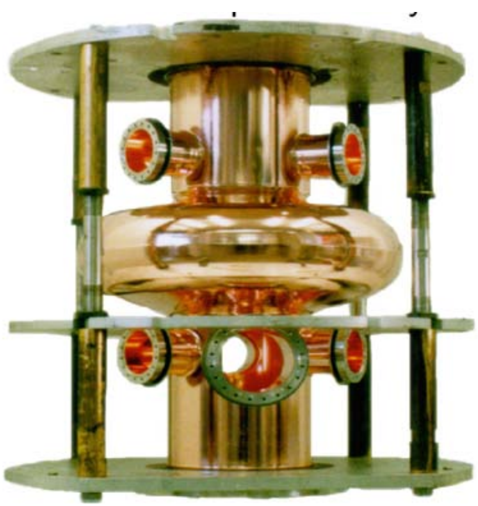
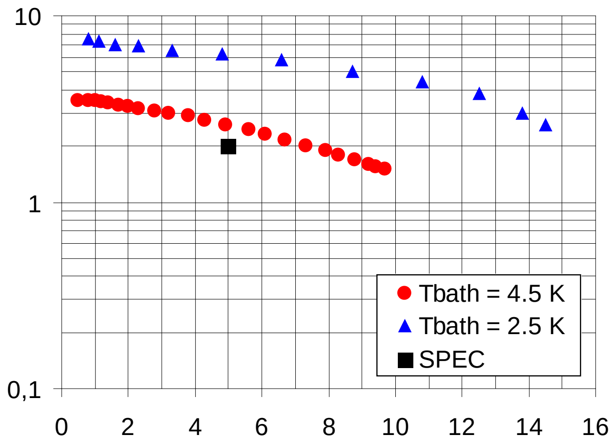


Assembly of the Niobium Cathode into a Copper cavity on the cavity axis



srf cavities are produced by coating the inner surface of a copper cavity with a 1 to 2 µm niobium layer by magnetron sputtering.

By application of a magnetic field and a superposed electric dc field niobium is evaporated from the cathode and “condenses” on the copper surface.

Technical Variants for SRF Cavity production: Nb on copper technology: LEP, LHC, Cornell, SOLEIL

13 Meter Modules for LEP housing 4 350 MHz cavities produced by sputtering Niobium on Copper cavities during final assembly of the modules

Technical Variants for SRF Cavity production: Nb on copper technology: LEP, LHC, Cornell, SOLEIL

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13 Meter Modules, turn key: Cavities, HOM-Couplers, Power Couplers, Tuners, Cryogenic Piping, assembly, low power tests, transport, guaranteed performance

Acknowlegements

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- Our colleagues at RI Research Instruments

Thank you for
your attention!