Course of RF for Accelerators


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ADVANCING
CAVITY
TECHNOLOGY

Neutrinos for peace
Feebly interacting particles
ALICE's dark side

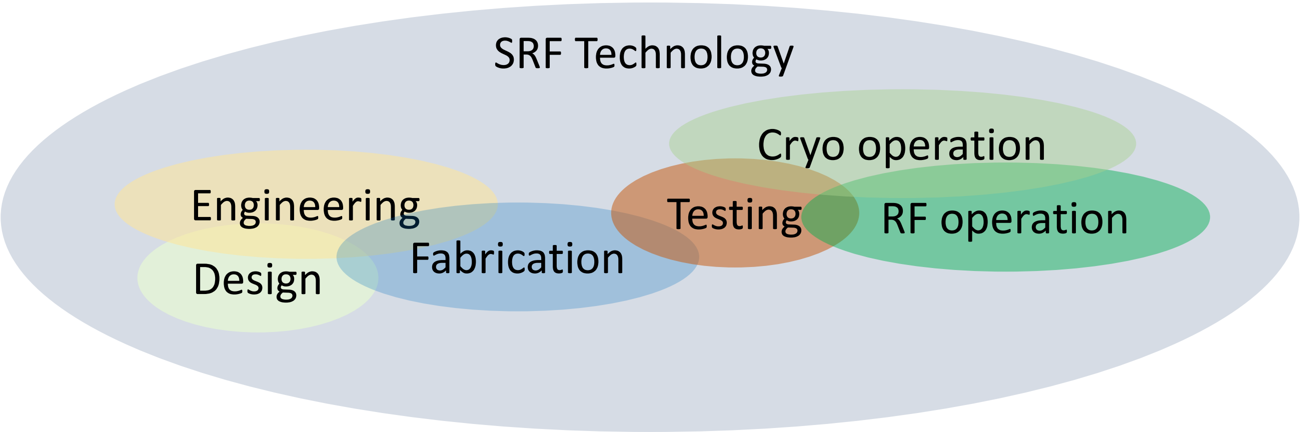
SRF Cavities

[Mostly about Technology]

Paolo Pierini, ESS

This week:

Theory of EM fields I-II
Overview Cavities I-II
RF measurements I-II
EM simulations I-II


SRF Technology
Cryo operation
Engineering
Testing
RF operation
Fabrication
Design

Next week:

LLRF I-III
Beam Loading
Power coupling

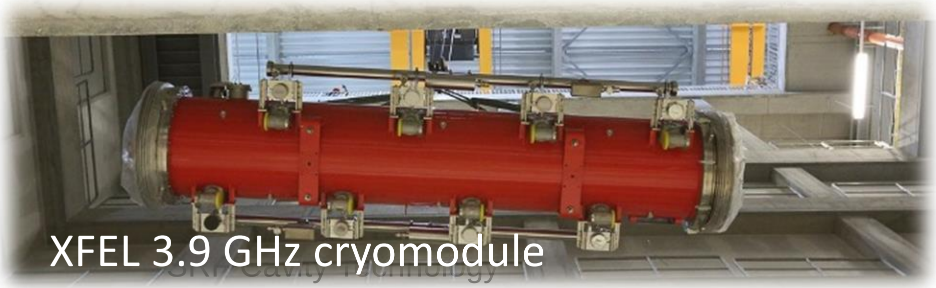
Multipacting
HOM

Me, in short

- Places
  - 1989-2015 INFN Milano/LASA - Inkind contribution to XFEL (TESLA/ILC)
  - 2015-2017 DESY - Visiting Scientist during XFEL commissioning
  - 2017-now ESS - Section Leader SRF / SCL Machine Section Coordinator
- Work
  - Free Electron Laser theorist (~10y)
  - Particle accelerator physicist, SRF linac technology
    - SRF cavities and cryomodules
      - from design, engineering, assembly, to commissioning/operation

ESS Linac

XFEL 3.9 GHz cavities



XFEL 3.9 GHz cryomodule

Outline

- Part I
  - Why SRF?
    - Surface resistance
    - Choice of temperature & thermodynamics aspects
  - From Design to Fabrication & Preparation
    - Material
    - Fabrication
    - Surface preparation (chemical processing) and preservation
    - Cavity ancillaries (tuners, couplers, …)
- Part II
  - The Environment: Cryomodule fundamentals
    - Carnot cycle & efficiency, cryoplants and cryomodules
    - Cooling, heat loads, mass flows
- Part III
  - Testing & operation of Cryomodules

Courtesy INFN LASA & EZ

Why SRF?

Why Superconductivity in RF linacs?

- *In normal conducting linacs a large amount of power is deposited in the copper structure*, in the form of heat, that needs to be removed by water cooling (in order not to melt the structures)
  - Dissipated power can be much higher than the power transferred into the beam for acceleration
- Superconductivity - at the expenses of higher complexity - drastically reduces the dissipated power on the structure and *the cavities transfer more efficiently the RF power to the beam*
- In short:
  - NC linac: lower capital cost, but high operational cost
  - SC linac: higher capital cost, but low operational cost

The role of surface resistance in P_{diss}

- In a good but not perfect conductor, the fields and currents penetrate in a small layer at the cavity surface (the skin depth)
- Therefore it is possible to define a surface resistance (inverse of the conductivity divided by the skin depth) and evaluate the *average power dissipated on the cavity surface* S

$$P_{diss} = \frac{R_s}{2} \int_S H^2 dS$$

- The dependency of the surface resistance from the frequency and the operating temperature of superconducting materials allows to understand the benefits of the use of superconductivity

Which temperature?

	T_c
Hg Mercury	4.2 K
Pb Lead	7.2 K
Nb Niobium	9.2 K
NbTi	10 K

- Devices (magnets and cavities) need to operate below the critical temperature of the material
  - Practically only 1 coolant possible
    - either P_{atm} LHe (4.2 K)
    - or subatm LHe (2.0 K, superfluid!)
- **CONSEQUENCES**
  - **FUNDAMENTAL:** Power is deposited at cold
    - can’t beat thermal cycle efficiency!
  - **TECHNOLOGICAL:** A cryogenic environment needs to be provided
    - handling of cryo fluids & cryostats
    - mechanical environment at extremely low temperatures
    - complex thermomechanical analysis

See G. Ciovati, CAS Superconductivity 2013

Estimates of Rs

- For bulk Nb (with a critical temperature of 9.2 K):

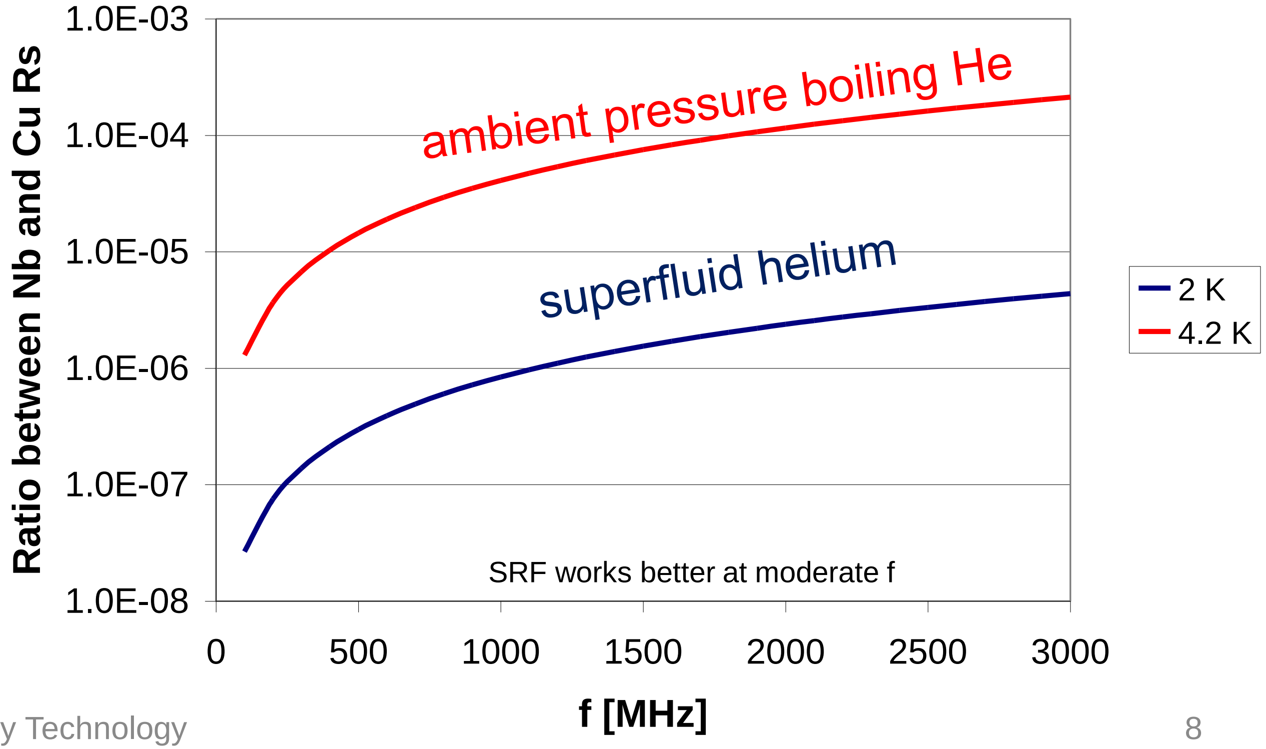
$$R_s[\mathrm{n\Omega}] = 9 \times 10^4 \frac{f^2[\mathrm{GHz}]}{T[\mathrm{K}]} \exp\left(-\frac{17.664}{T[\mathrm{K}]}\right)$$

- The surface resistance of room temperature copper is:

$$R_s[\mathrm{m\Omega}] = 7.8\, f^{\frac{1}{2}}[\mathrm{GHz}]$$

- With RF fields, a SC cavity still dissipates power, since not all e- are in Cooper pairs

Q: Good, are we going to gain 6 order of magnitudes?



A: No!

- Power is deposited at the operating temperature – 2 K
- What price we pay?
  - A thermal “machine” performs work at room temperature to extract the heat deposited at cold
    - We can’t beat Carnot cycle! (lucky if we get to 20-30%...)
    - Overall, 1 W @ 2 K ⇒ ~800 W @ 300 K
- Further considerations:
  - Material & procedure issues to preserve good R_s
  - Special precautions to maintain the 2 K environment
    - Technological complication: cryogenic infrastructure

Take into account Carnot & cycle efficiency

- The power is deposited in the cold bath: this means a power in the refrigerator that, at least, has to compensate for the overall thermal cycle efficiency:

$$\eta_C = \frac{T_2}{T_1 - T_2} = \begin{cases} 1/70 \text{ for } T_1 = 300\text{K}, T_2 = 4.2\text{K} \\ 1/150 \text{ for } T_1 = 300\text{K}, T_2 = 2\text{K} \end{cases} \qquad \eta_{th} = \begin{cases} 25-30\% \text{ at } T = 4.2\text{K} \\ 15-20\% \text{ at } T = 2\text{K} \end{cases}$$

$$\eta_{tot} = \eta_C \eta_{th} \approx \begin{cases} 250\text{W at } 300\text{K for } 1\text{W at } T = 4.2\text{K} \\ 800\text{W at } 300\text{K for } 1\text{W at } T = 2\text{K} \end{cases}$$

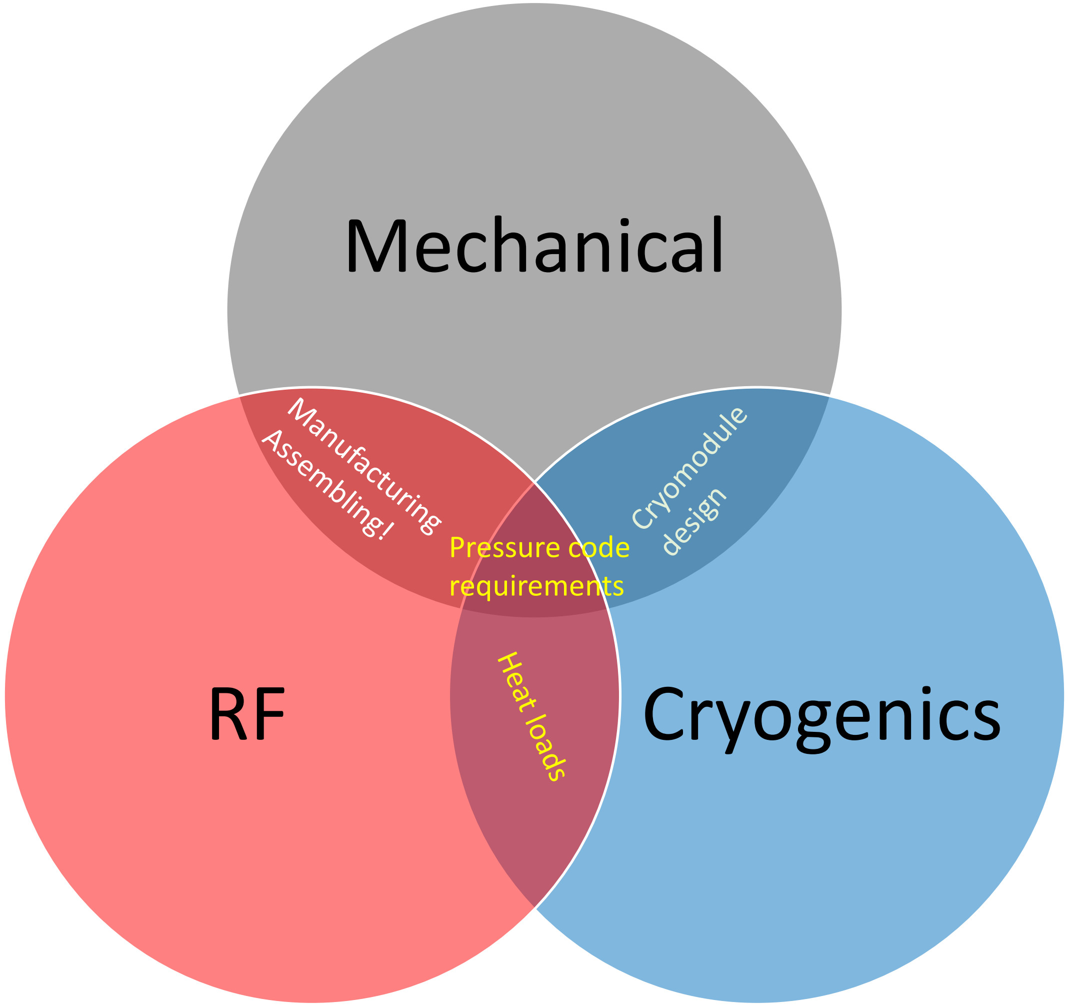
- Of course, life is generally worse than that, since here we neglected (at least):
  - Static (spurious) heat in the He bath (power flowing directly in the He)
  - Material impurities which degrade R_s (higher dissipation)
- Still, a wide frequency range favors superconductivity

Design

Mostly showing elliptical cavities, this is not a cavity design primer, but more an introduction of the SRF technology

Course of RF for Accelerators

There does not exist a unique solution



- Depending on the **application** the right balance needs to be found, to address the challenges at the boundary
- Project/Machine design set the scene
  - Large/Compact machine
  - CW/pulsed
  - Particle type (e-,p,ions,…)
  - High current/low current
  - High gradient/High reliability
  - Licensing/Code conformance
  - …

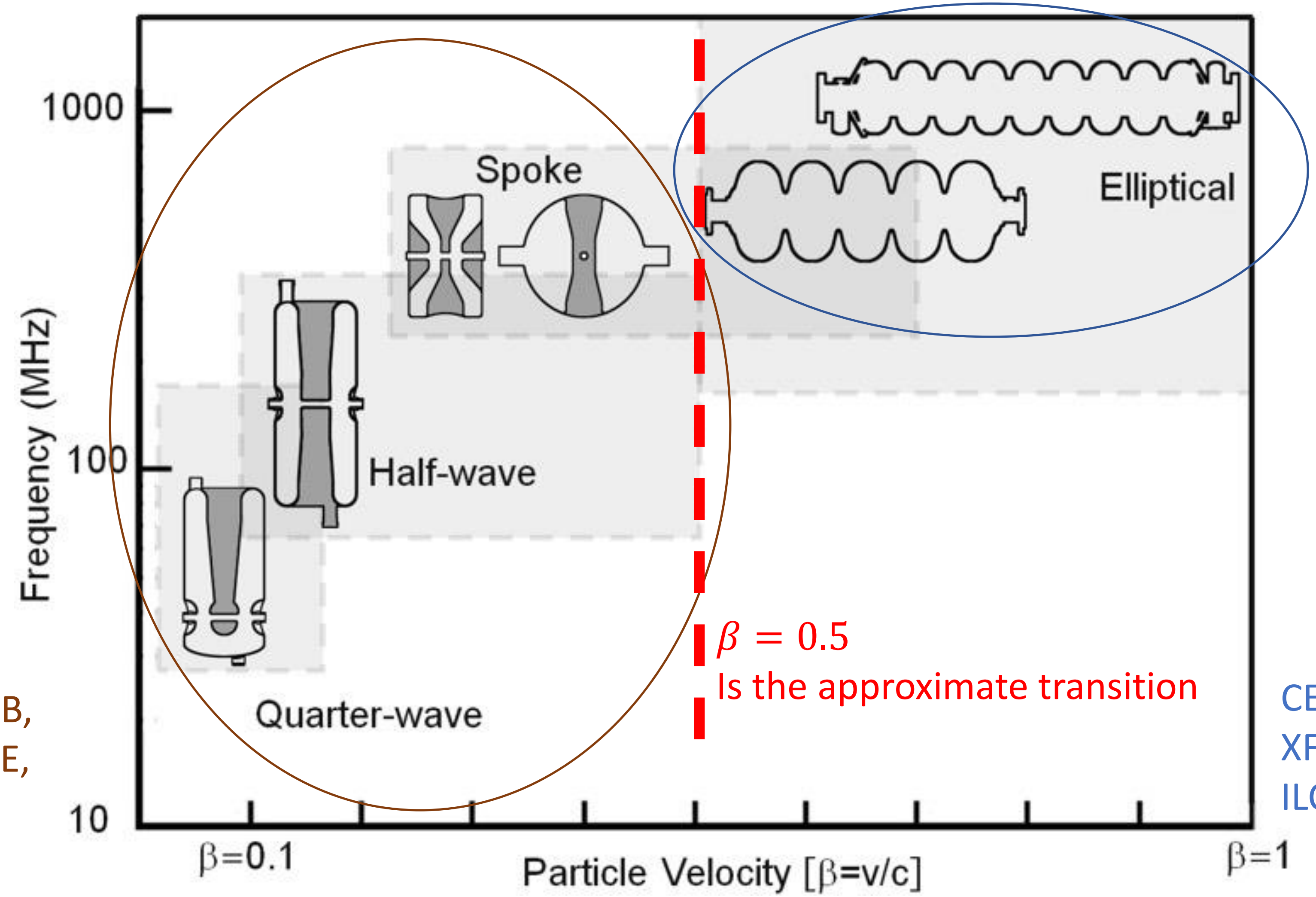
Two main families of cavities

TEM Cavities: Several shapes, suited for particles that travel with velocities (much) smaller than the speed of light

- Protons at low energies
- Ion beams

ATLAS, TRIUMF, FRIB, EURISOL, HE-ISOLDE, SPIRAL2, …

Credit: S. Belomestnykh: SRF Tutorials 2021



$\beta = 0.5$
Is the approximate transition

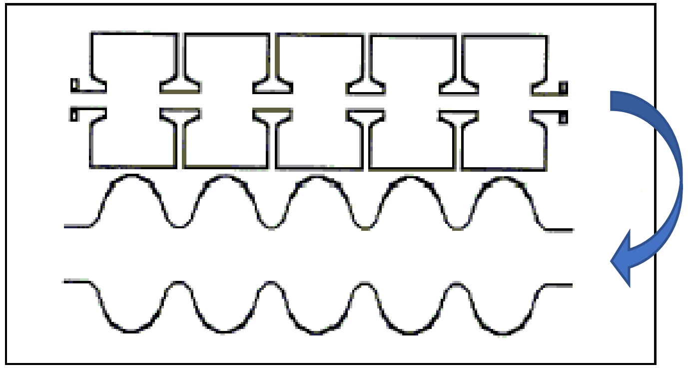
TM Cavities Elliptical shape, suited for particles that travel close to the speed of light

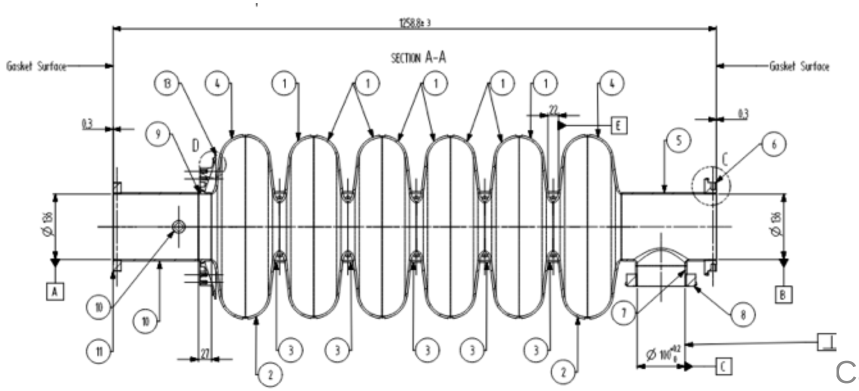
- Electrons
- Protons at energies above ~100 MeV

CEBAF, LHC, ERLs, XFEL/FLASH, ESS, SNS, ILC…

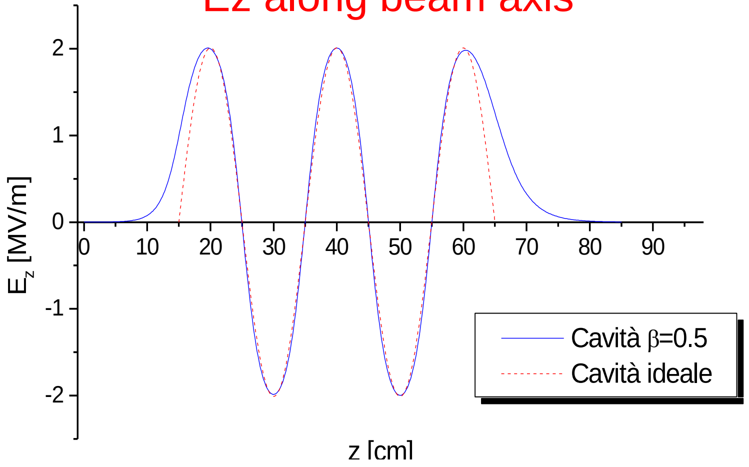
Realistic SC cavity geometries

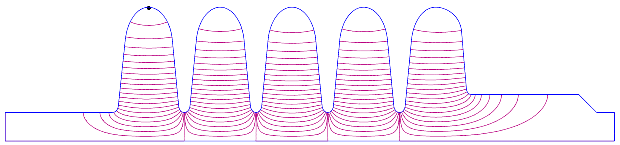
- Simplest geometry: Pillbox (‘Analytical’ TM cavity found in all primers)
    - the presence of resonant electron trajectories at the cavity “flat-top” and between the “vertical walls”, which are seeded by electron emission (multipacting)
- A smoother cavity geometry is used to mitigate the multipacting phenomenon



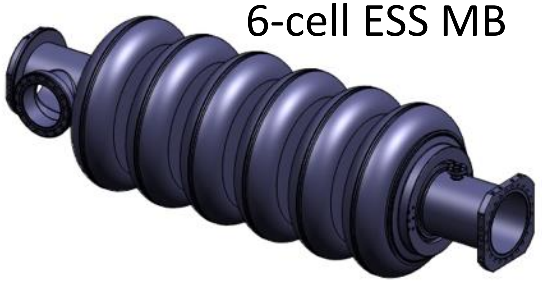


Ez along beam axis





Axisymmetric computational model (beta=0.5 5-cell elliptical cavity)



6-cell ESS MB

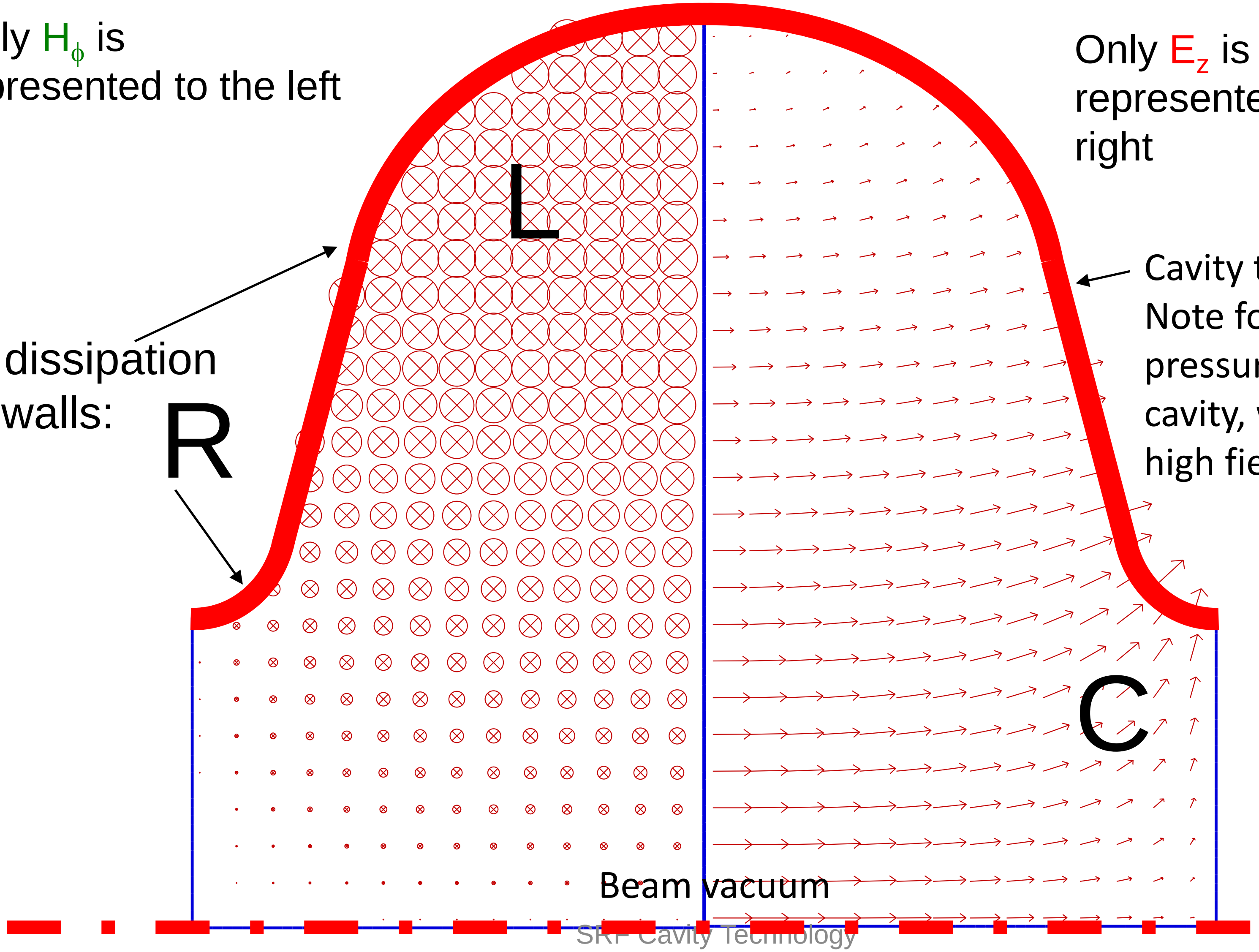
General observation: all SRF cavities are **thin-walled structures**, built bending and welding metal sheets (cfr NC structures)

Fields in the cavity cell (TM$_{010}$)

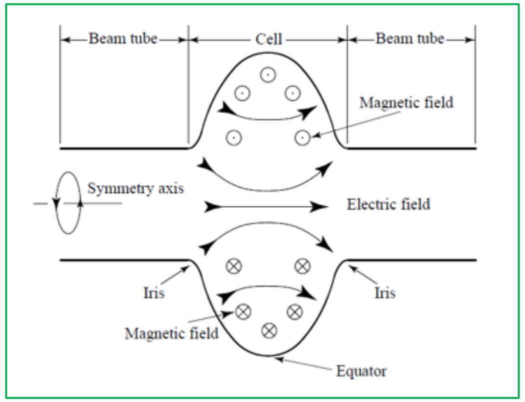
Only H_ϕ is
represented to the left

Only E_z is
represented to the right

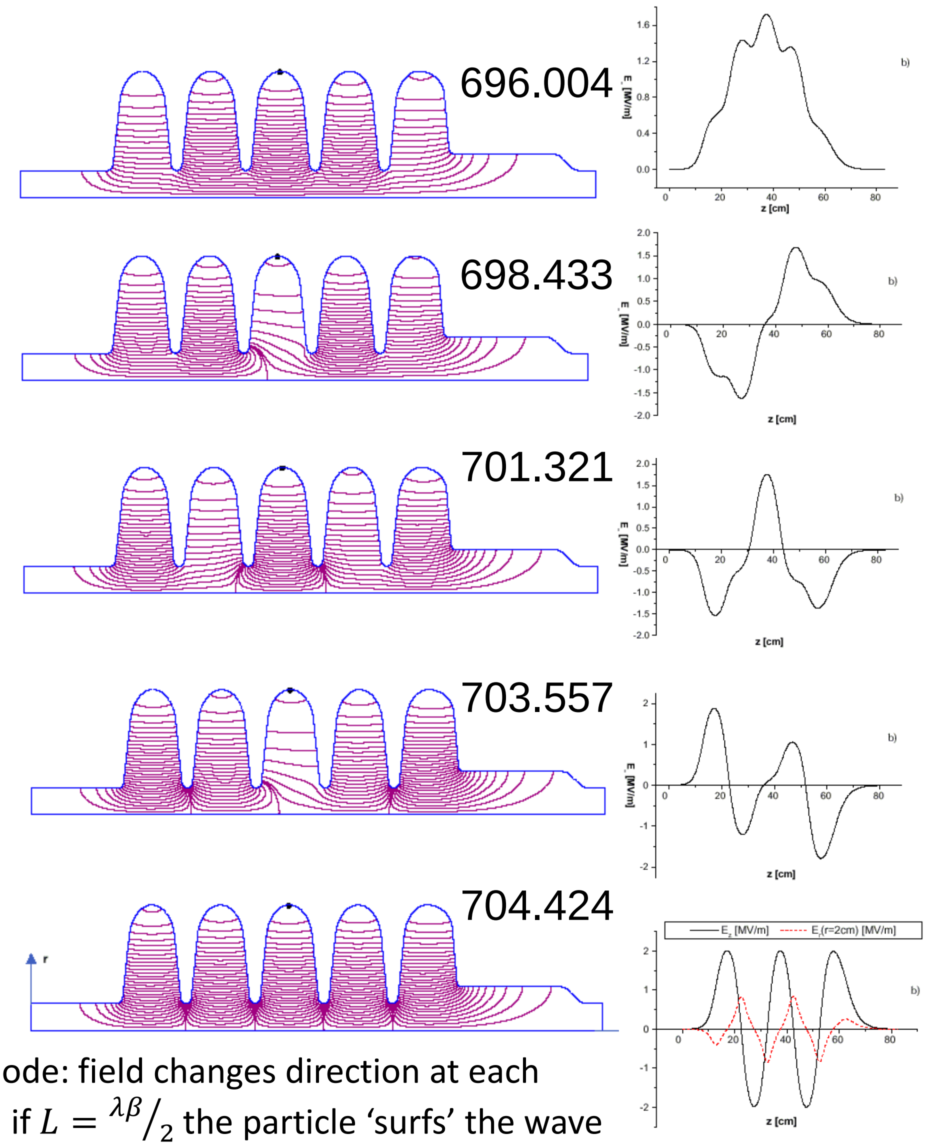
Power dissipation
on the walls:



Cavity thin wall.
Note for later: EM radiation carries a pressure acting on the walls of the cavity, which are able to deform it at high fields



Modes of a multicell cavity

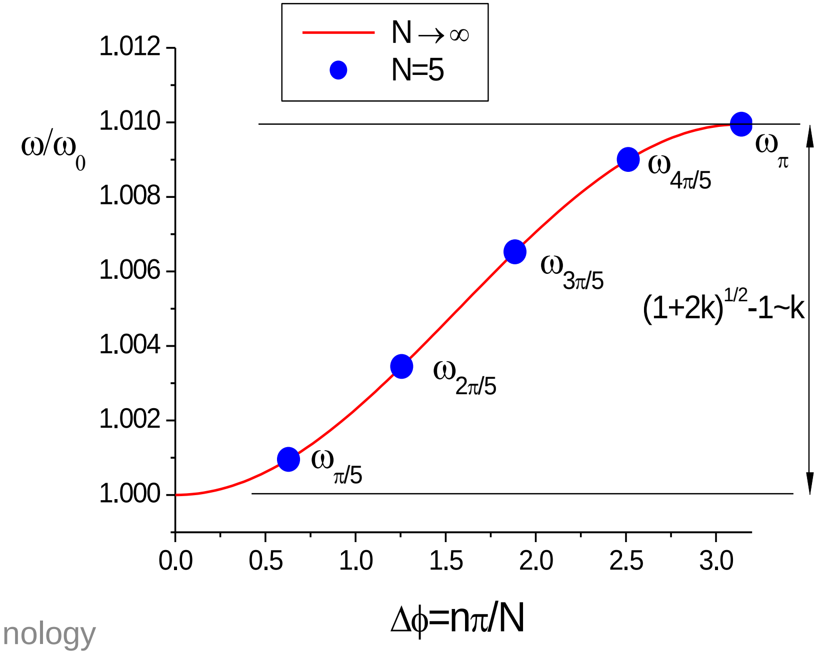


π mode: field changes direction at each cell: if $L = {}^{\lambda\beta}/_2$ the particle 'surfs' the wave

- A coupled system of N resonant oscillators at ω_0 can oscillate in N normal modes with eigenfrequencies close to ω_0

$$\omega_n = \omega_0\sqrt{1+k\left[1-\cos\left(\frac{n\pi}{N}\right)\right]}$$

- Where k is the coupling coefficient



Some figure of merits of a cavity

i.e. how many cycles are required to deplete the cavity

- Quality factor: (as high as possible) → $\frac{\text{Energy in cavity}}{\text{Energy loss per cycle}}$

$$Q = \frac{\omega U}{P_{diss}}$$

Where U is the energy stored in the cavity and P_{diss} the power dissipated along the surface, typ. 10^9-10^{11} (Cu – 10^3-10^5)

Gives also the frequency bandwidth of the cavity

- Geometry factor:

$$Q = \frac{G}{R_s}$$

G is a geometrical factor and R_s the surface resistance

- Shunt impedance: (as high as possible, NC)

$$r = \frac{(\Delta V)^2}{P_{diss}}$$

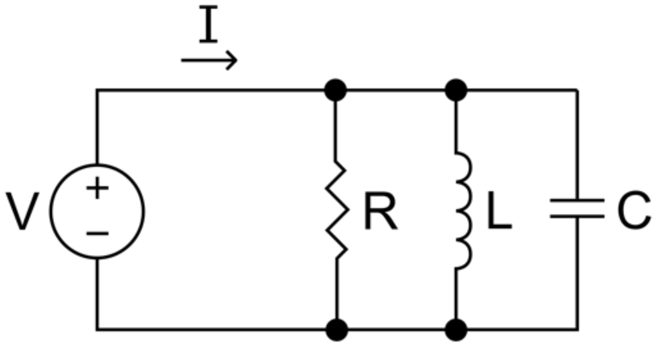
Where ΔV is the voltage seen by the beam

- “r over Q”: (as high as possible)

$$\frac{r}{Q} = \frac{(\Delta V)^2}{\omega U}$$

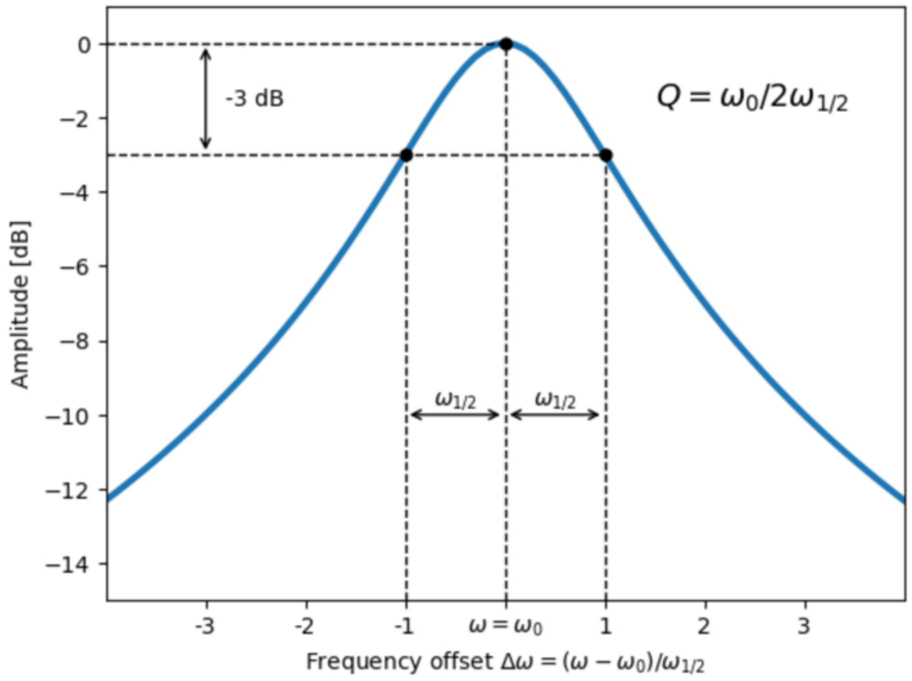
Depends only on the geometry and not from the surface properties

Lumped circuit model of a resonator



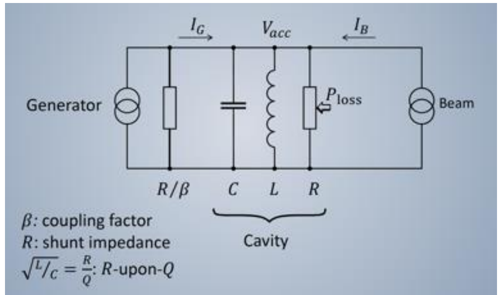
- All the cavity parameters have their exact equivalent in a lumped resonant circuit model

$$\omega_0 = \frac{1}{\sqrt{LC}} \qquad Q = \omega_0 RC$$



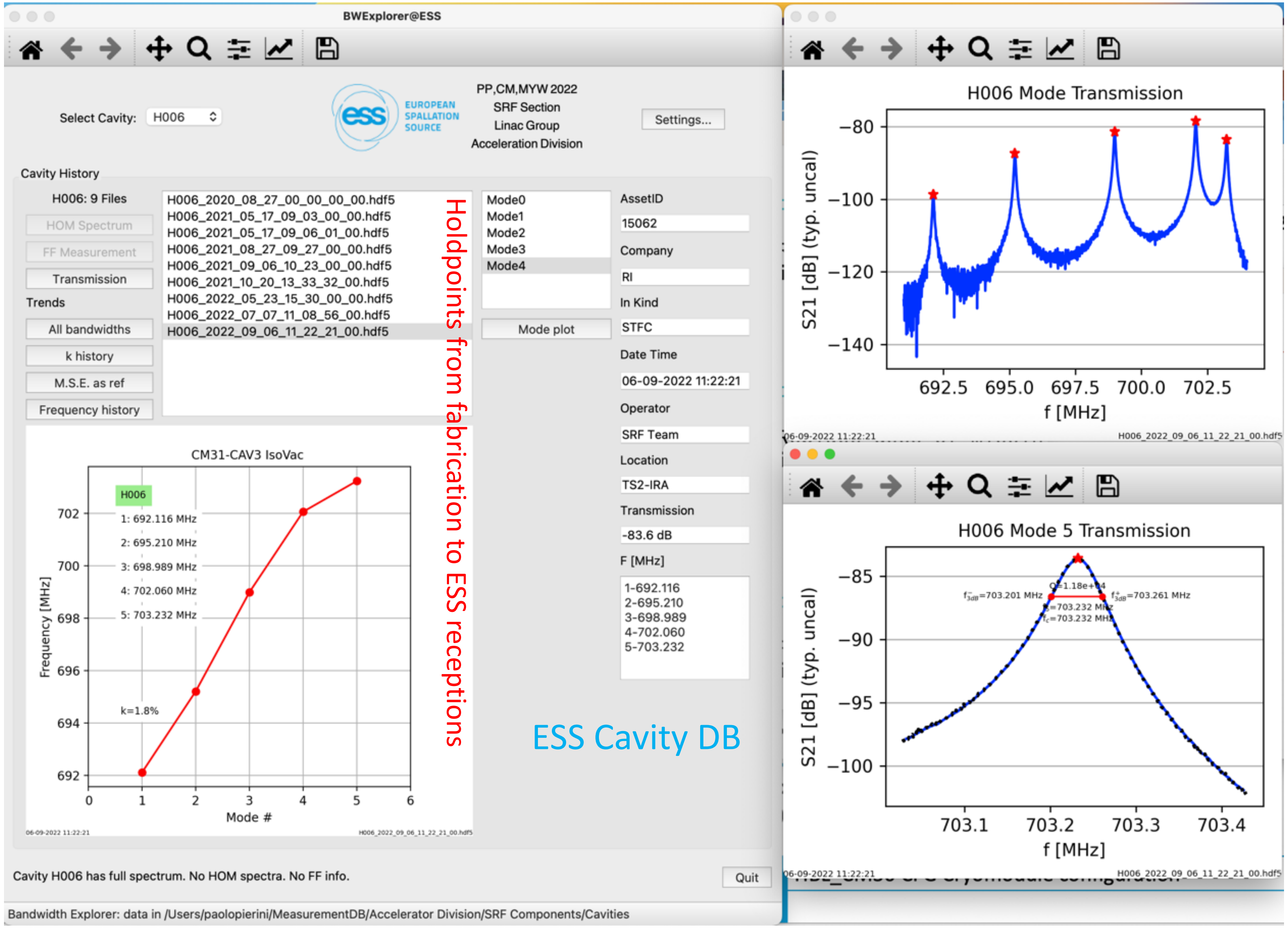
- The lumped circuit model is a very convenient way
  - to analyze and describe a multicell cavity with either inductive or capacitive coupling between the cells and
  - to describe, by conveniently extending it, to the coupling to the RF generator (+beam)

Credit: E.Jensen
SRF Tutorials 2019



+
Power Coupling
Next Week

Bandwidth control is a standard tool



Holdpoints from fabrication to ESS receptions

ESS Cavity DB

BWExplorer@ESS

Select Cavity: H006

PP,CM,MYW 2022
SRF Section
Linac Group
Acceleration Division

Cavity History

H006: 9 Files

H006_2020_08_27_00_00_00_00.hdf5
H006_2021_05_17_09_03_00_00.hdf5
H006_2021_05_17_09_06_01_00.hdf5
H006_2021_08_27_09_27_00_00.hdf5
H006_2021_09_06_10_23_00_00.hdf5
H006_2021_10_20_13_33_32_00.hdf5
H006_2022_05_23_15_30_00_00.hdf5
H006_2022_07_07_11_08_56_00.hdf5
H006_2022_09_06_11_22_21_00.hdf5

Mode0
Mode1
Mode2
Mode3
Mode4

AssetID: 15062
Company: RI
In Kind: STFC
Date Time: 06-09-2022 11:22:21
Operator: SRF Team
Location: TS2-IRA
Transmission: -83.6 dB
F [MHz]:
1-692.116
2-695.210
3-698.989
4-702.060
5-703.232

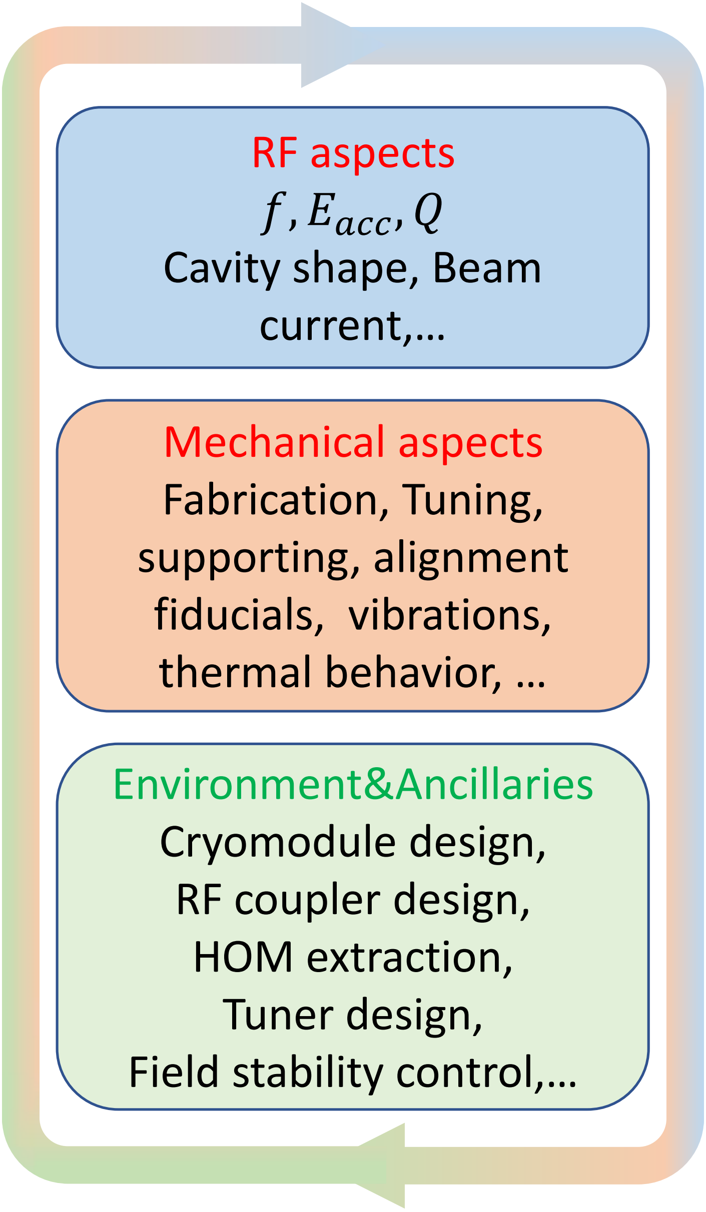
Cavity H006 has full spectrum. No HOM spectra. No FF info.

Bandwidth Explorer: data in /Users/paolopierini/MeasurementDB/Accelerator Division/SRF Components/Cavities

- Allows followup from cavity fabrication to vertical testing, cryomodule assembly and ultimately to operation in order to detect major exceptions
  - Tuner assembly
  - Damage during transports
  - For elliptical cavities: mean spectral error to assess uneven deformations

Cavity design process

- SRF Cavity design is always an **iterative process** across several disciplines and subcomponents, in order to meet goals typically set by projects
- EM design is (only) the starting point. The RF geometry needs soon to be expressed in a drawing package and the fabrication details considered in order to **produce cavities at the right frequency with the right length**
  - Weld shrinkages, shape tolerances, stress handling due to pressure and tuning forces, dynamic Lorenz force detuning, He circuitry choices, inclusions of RF ports for probes and couplers, ….



RF aspects
f, E_{acc}, Q
Cavity shape, Beam current,…

Mechanical aspects
Fabrication, Tuning, supporting, alignment fiducials, vibrations, thermal behavior, …

Environment&Ancillaries
Cryomodule design,
RF coupler design,
HOM extraction,
Tuner design,
Field stability control,…

Coupling of the mechanical and RF domain

- Mechanical behavior is strongly related to RF characteristics
  - Material removal from the surfaces affect the frequency
    - Need to be accounted beforeheand to reach the fabrication goal
  - Cavity is surrounded by He (either at 1 bar for 4 K operation or at ~30 mbar for 2 K)
    - Variation of pressure can deform the thin walls (Pressure sensitivity)
  - The EM field in pulsed operation acts as a time varying pressure on the thin walls (through the Poynting vector),
    - A.k.a. dynamic Lorenz Force Detuning (LFD) in pulsed linacs
  - The frequency of the cavity can't be usually met by tolerances
    - Needs to be finely adjusted with an active deformation of the cavity length, by the mechanical tuners
- Most of the above imply very small variations of the cavity shape, that have no significance in the mechanical domain…
- …however, effect on the cavity frequency can be relevant, due to strong sensitivity to the geometry and the relative narrow bandwidth, and could limit operation at the fixed frequency of the RF sources if not handled correctly

Slater theorem comes useful

- Sensitivity to small geometrical perturbations
  - Fabrication tolerances/ Field flatness
  - Tuning/Pressure sensitivity/LFD

Microwave Electronics

By
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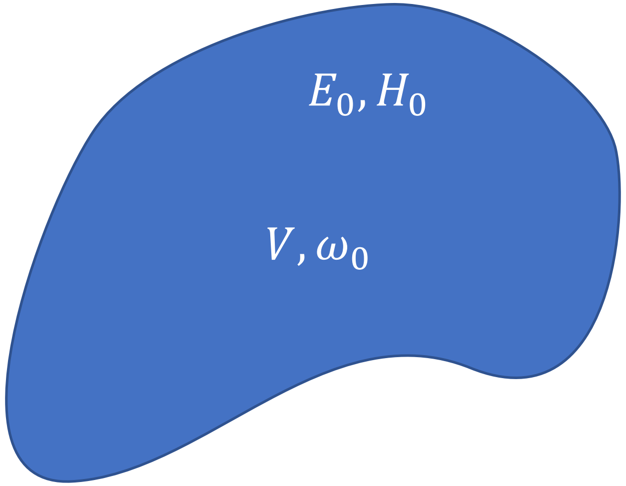
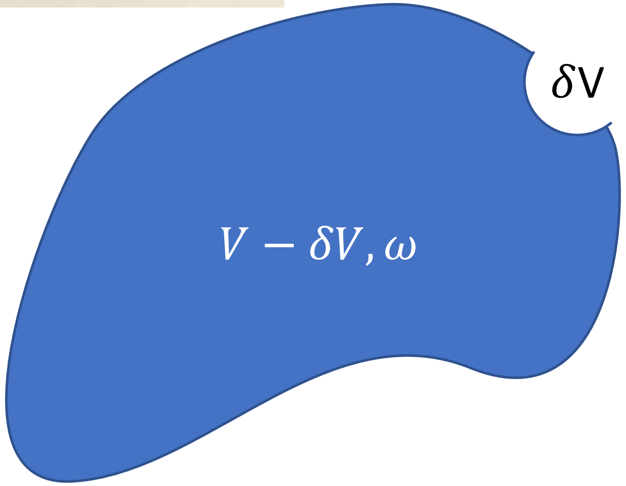


$$\frac{\omega - \omega_0}{\omega_0} = \frac{\iiint_{\delta V} (\mu_0 |H_0|^2 - \epsilon_0 |E_0|^2) dV}{\iiint_V (\mu_0 |H_0|^2 + \epsilon_0 |E_0|^2) dV}$$

Stored energy



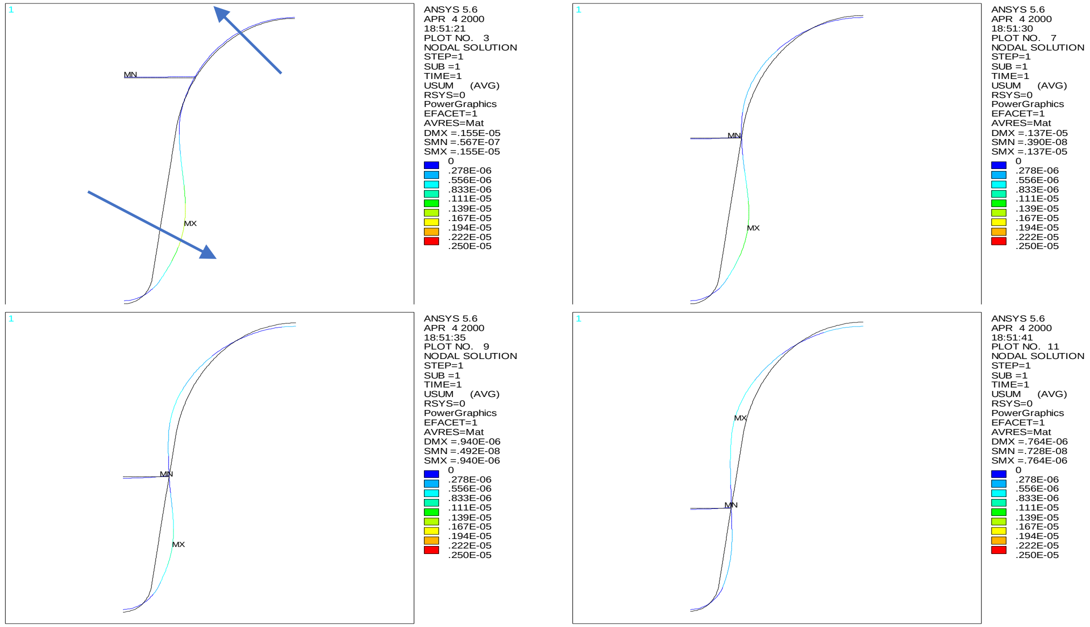
- Powerful tool to avoid “brute force” detuning calculations by using a perturbation tecnique

Lorentz Force Detuning

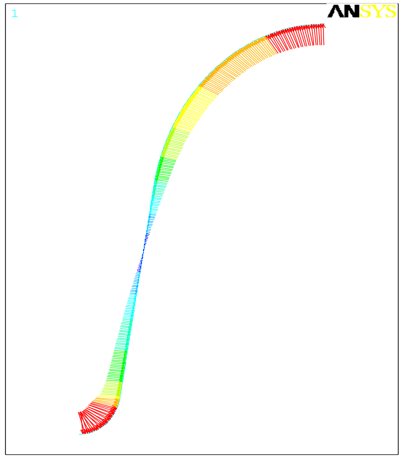
- High magnetic field and high currents on cavity surface

$$\vec{F}_{em} = \vec{F}_{Lorentz} = \frac{d\vec{p}}{dt} = q\,(\vec{E} + \vec{v} \times \vec{B}) = \vec{F}_{el} + \vec{F}_{mag}$$

- At each RF power pulse this force produces a cavity deformation at the micrometer level
  - Cavity Stiffening rings



Pressure on the cavity surface: Cavity deformation for different stiffening ring radial position



Slater coefficients, i.e. local sensitivity to small deformations. Integrating this along the deformed surface we can derive the overall frequency shift

The cavity is detuned during filling by this effect and due to the high Q (small frequency band) can be brought off-resonance ($\Delta f \sim E_{acc}^2$)

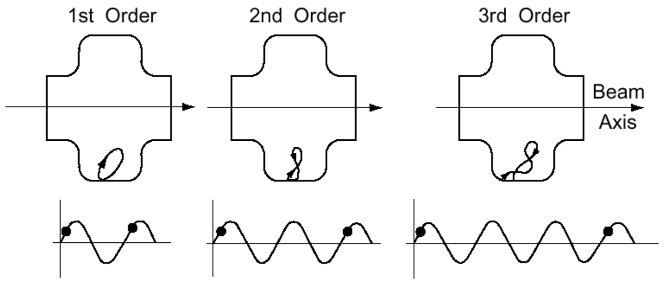
What happens after design?

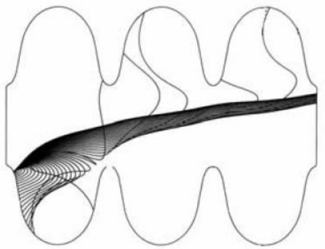
Care needs to be take for the surfaces to sustain the RF fields

- Material Selection
  - Bulk Nb
    - High RRR (200-300)
    - *[Frequently QA techniques: scanning for foreign inclusions]*
- Material and Surface Treatments
  - 600-800°C Temperature treatments
    - Stress annealing / hydrogen degassing
  - Deep (0.1-0.2 mm) chemical etching or EP in elliptical cavities at ultimate performances
    - Remove damage layer and contaminants from the SRF surfaces
  - High Pressure Water Rinsing
    - Ultra Pure Water
  - [optional] Doping and Baking treatments for state-of-art high Q cavities
    - Open the path for improved performances
      - 120 C bake of EP cavities
      - surface tailoring, e.g. N doping
- Handling
  - Clean room assembly operations. Particle-free environment

Limiting factors during early SRF times

- Poor material properties
  - Moderate Nb purity (Niobium from the Tantalum production)
  - Low Residual Resistance Ratio → Low thermal conductivity
  - Normal Conducting inclusions
    - Quench at moderate field
- Poor cavity treatments and cleanness
  - Cavity design and preparation procedures still at the R&D stage
  - Rinsing and clean room assembly not yet introduced
    - Multipacting
      - Major limit for linacs to ~80s
      - Issues related to geometry and surface status
    - Field Emission
      - Poor cleaning of the surfaces, geometrical field enhancement

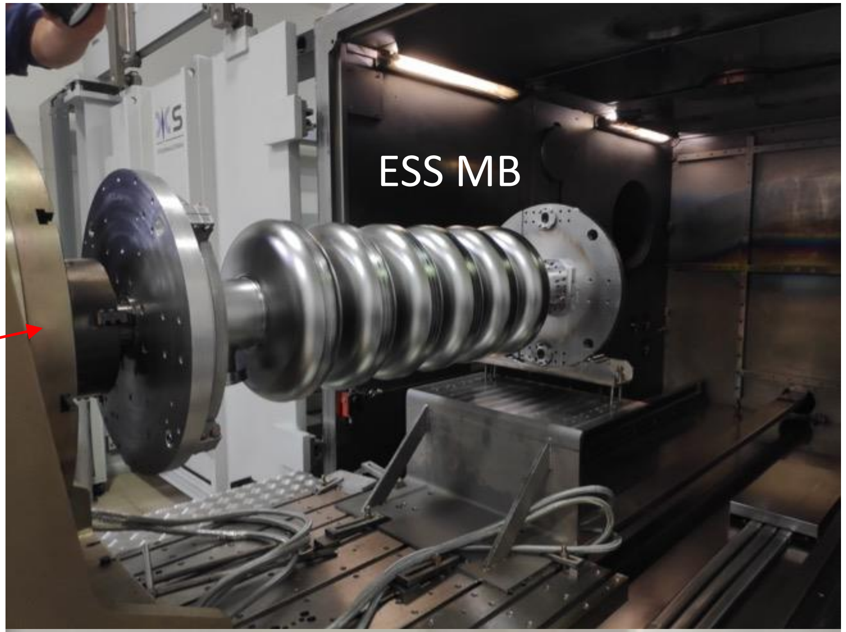




And how they were addressed

Courtesy D.Sertore, INFN

- Use of the best niobium
- QA/QC procedures during industrial fabrication of cavity subcomponents
- Fabrication of cavities via Electron Beam Welding in clean vacuum conditions (to avoid inclusion in welds)
- Etching by closed loop chemistry setup with precisely specified and controlled process parameters
- Thorough cleaning with ultra pure water (>18MΩcm)
- Cavity preparation in Class 10 Clean Room
  - Particularly for final cleaning and drying
  - Integration of cavity ancillaries



In short, tighter Quality Control

Course of RF for Accelerators

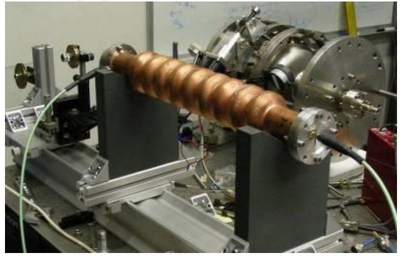
Fabrication

Mostly showing elliptical cavities, this is not a cavity design primer, but more an introduction of the SRF technology

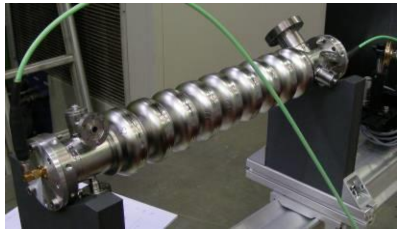
Setting of fabrication/treatment procedures

RF “parts”

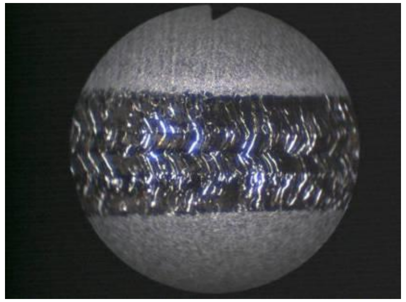
Copper mockup



Full Nb mockup

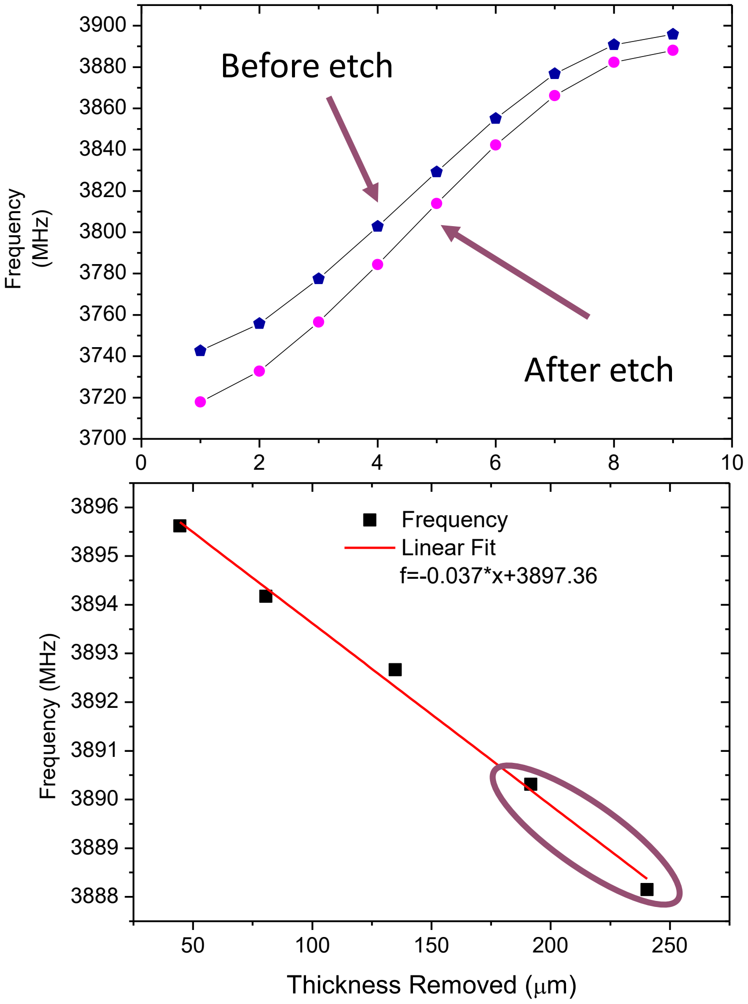


Inspections



Etching

Analysis, derivation of sensitivity coefficients and comparison with calculations



3.9 GHz Cavity at the XFEL injector

See: P. Kneisel, ILC School 2006, W. Singer, CAS 2013 Superconductivity

Material: Niobium

- Niobium is the elemental superconductor with the highest critical temperature and the highest critical field

- Chemically Inert material
- Formability like OFHC copper (deep-drawing, spinning)
- Available in different grades of purity (RRR > 250) in bulk form (rod/sheet)
- Can be further purified by UHV heat treatment or solid state gettering

- High affinity to interstitial impurities like H, C, N, O
- Joining by electron beam welding (expensive, not widely available)
- Metallurgy not so easy
- Hydrogen can readily be absorbed and can lead to Q-degradation in cavities

Niobium: Material quality

Quality/purity of niobium used for accelerator application is specified by the RRR ratio

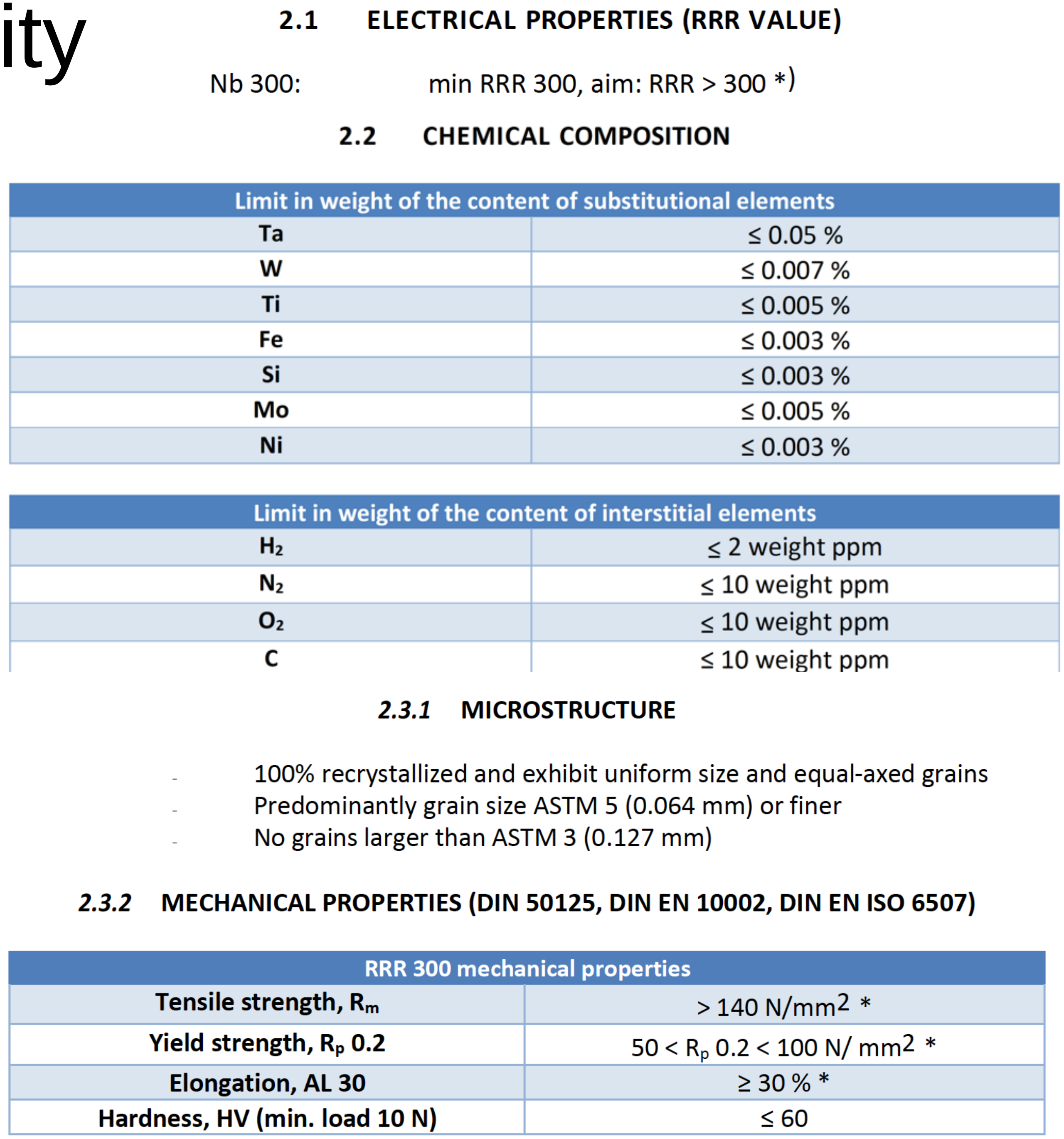
$RRR = R(300)/[R(10) + \Sigma\, \delta R_i/\delta C_i\,]$

$\delta R_i/\delta C_i$ are the contributions by interstitial impurities such as H,C,N,O and Ta

H:	0.8×10^{-10} Ωcm/at ppm
C:	4.3×10^{-10} Ωcm/at ppm
N:	5.2×10^{-10} Ωcm/at ppm
O:	4.5×10^{-10} Ωcm/at ppm
Ta:	0.25×10^{-10} Ωcm/at ppm

K.Schulze, Journal of Metals, 33 (1981), p. 33ff

ESS Nb Specs



2.1 ELECTRICAL PROPERTIES (RRR VALUE)

Nb 300: min RRR 300, aim: RRR > 300 *)

2.2 CHEMICAL COMPOSITION

Limit in weight of the content of substitutional elements	
Ta	≤ 0.05 %
W	≤ 0.007 %
Ti	≤ 0.005 %
Fe	≤ 0.003 %
Si	≤ 0.003 %
Mo	≤ 0.005 %
Ni	≤ 0.003 %

Limit in weight of the content of interstitial elements	
H_2	≤ 2 weight ppm
N_2	≤ 10 weight ppm
O_2	≤ 10 weight ppm
C	≤ 10 weight ppm

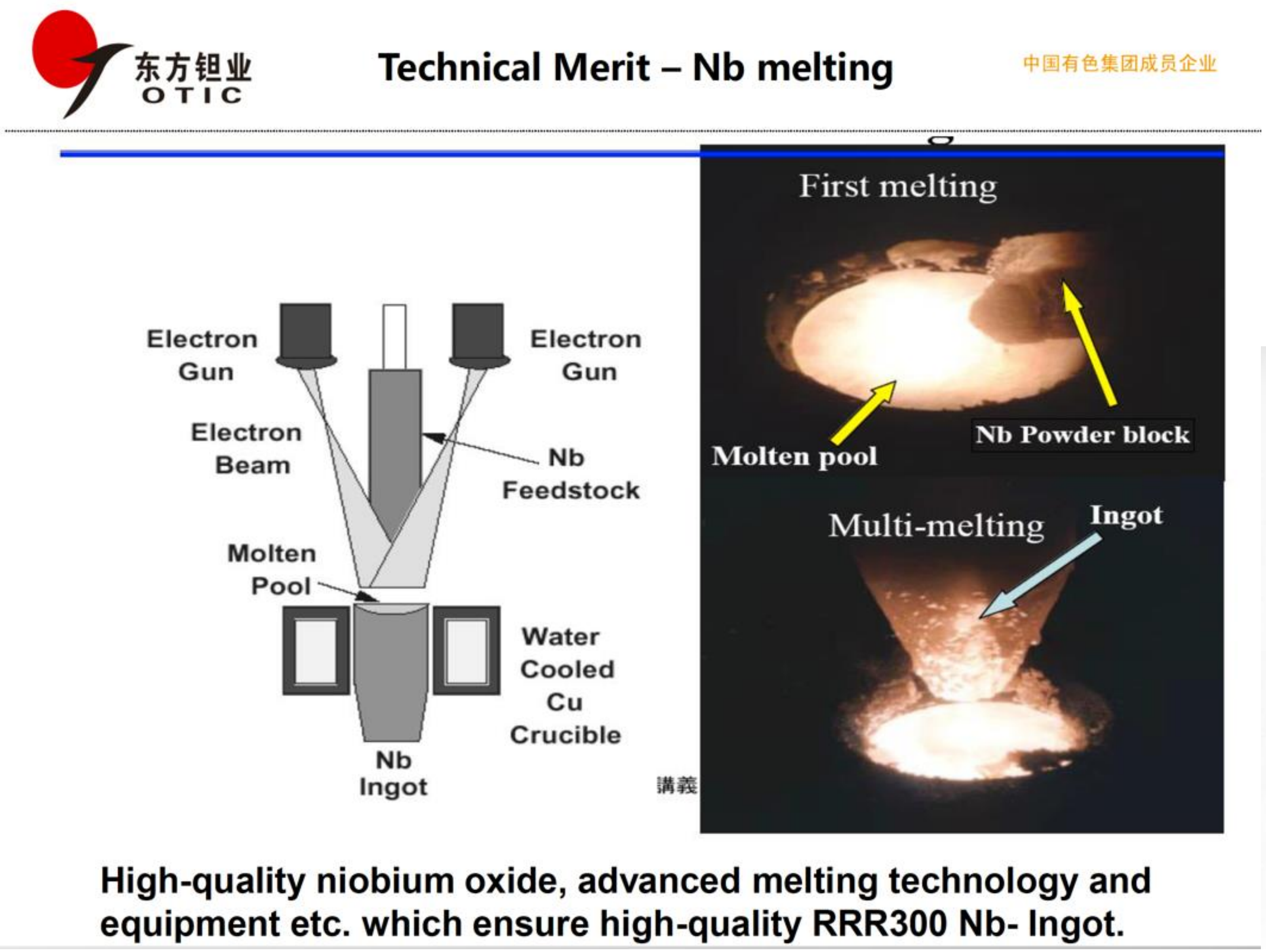
2.3.1 **MICROSTRUCTURE**

- 100% recrystallized and exhibit uniform size and equal-axed grains
- Predominantly grain size ASTM 5 (0.064 mm) or finer
- No grains larger than ASTM 3 (0.127 mm)

2.3.2 **MECHANICAL PROPERTIES (DIN 50125, DIN EN 10002, DIN EN ISO 6507)**

RRR 300 mechanical properties	
Tensile strength, R_m	> 140 N/mm^2 *
Yield strength, R_p 0.2	50 < R_p 0.2 < 100 N/mm^2 *
Elongation, AL 30	≥ 30 % *
Hardness, HV (min. load 10 N)	≤ 60

Nb industrial production…



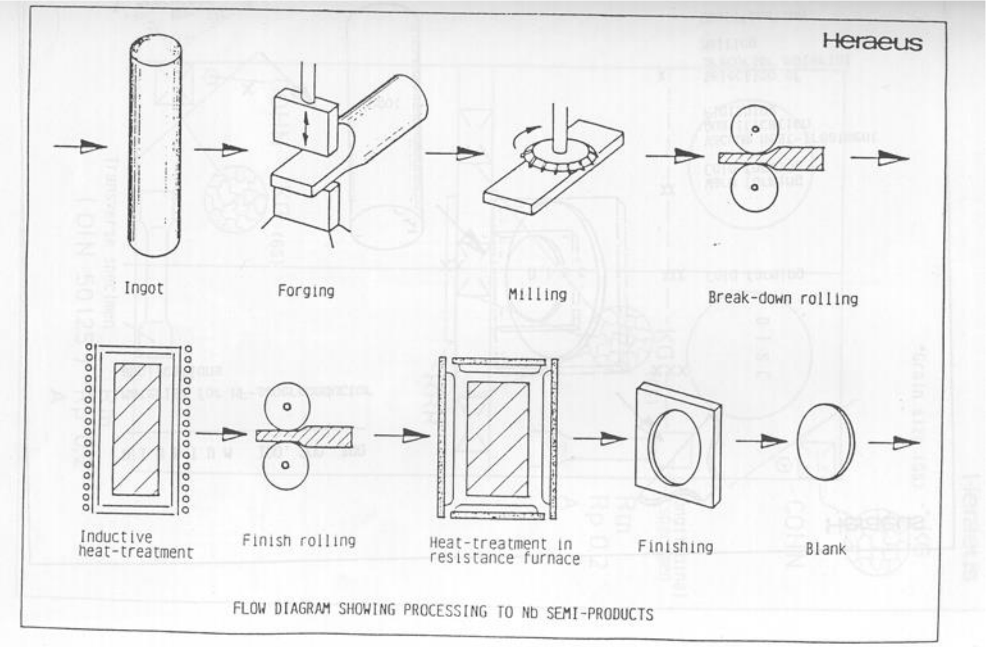
东方钽业 OTIC

Technical Merit – Nb melting

中国有色集团成员企业

High-quality niobium oxide, advanced melting technology and equipment etc. which ensure high-quality RRR300 Nb- Ingot.

- Start with pure oxides and melt/purify with EB furnaces to produce the initial ingots



… within strict QA/QC

- Furnaces, rolling mills, presses, annealing ovens…
- Then metallurgic analysis
  - Chemical analysis (spectrometers)
  - Mechanical analysis (hardness, grain size, tensile, …)

东方钽业 OTIC **Technical Merit –Main Equipment** 中国有色集团成员企业

Main Equipment for RRR Nb Material

1200KW EB furnace

1000X1250mm twin rolling mill

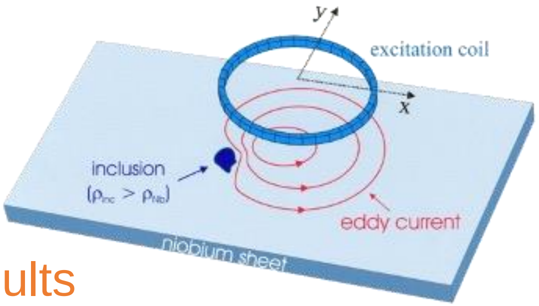
东方钽业 OTIC **Technical Merit –Main Equipment** 中国有色集团成员企业

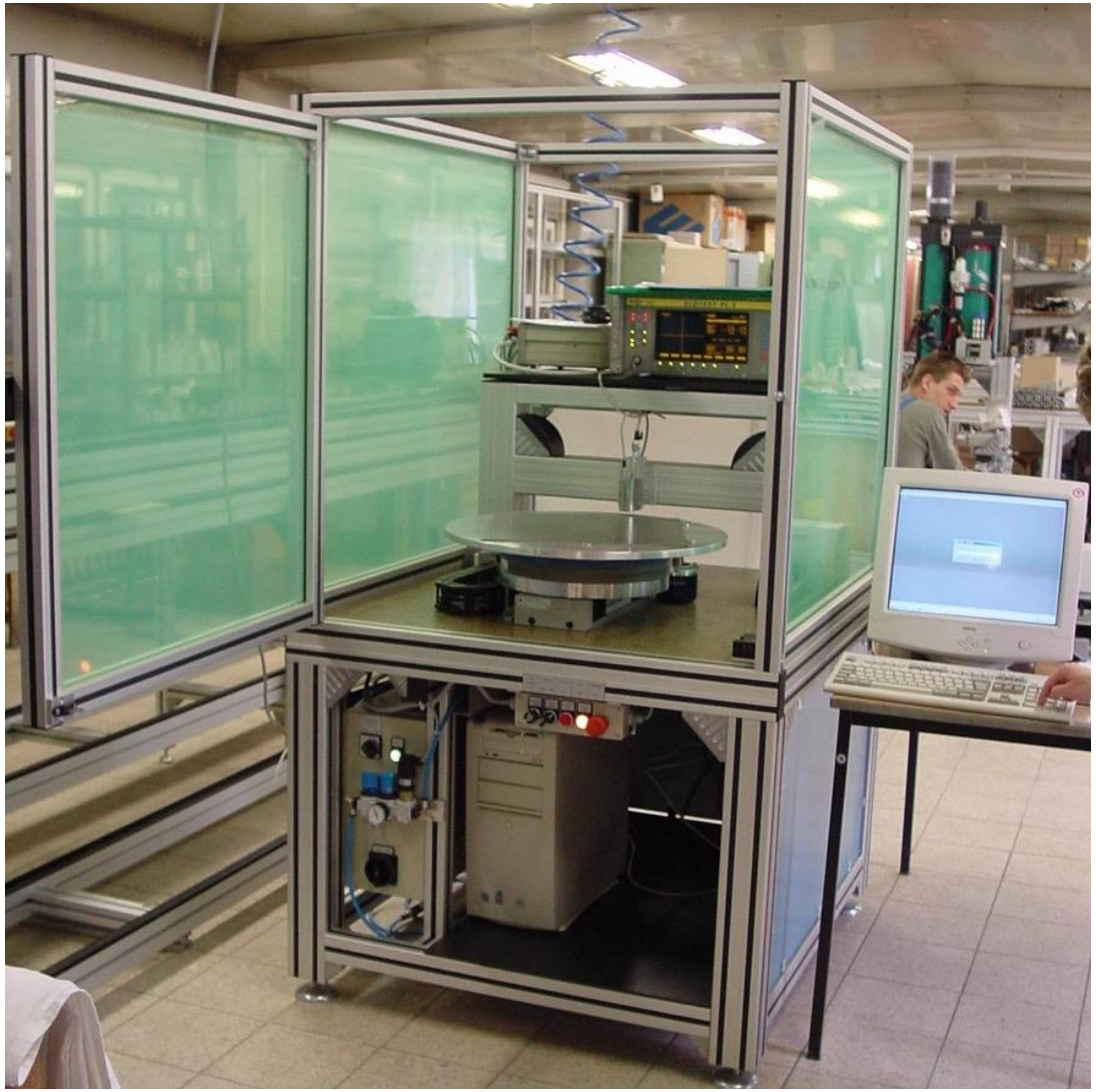
Main Equipment for RRR Nb Material

10000T hydraulic press equipment

2500X1050 vacuum annealing furnace

Eddy Current Scanner for Nb Sheets





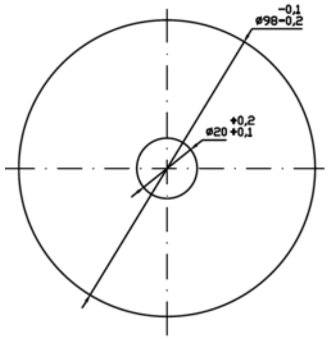
Scanning results

- Material quality control
- Rolling marks and defects are visible on a niobium disk to be used to print a cavity half-cell.
- Surface analysis is then required to identify the inclusions

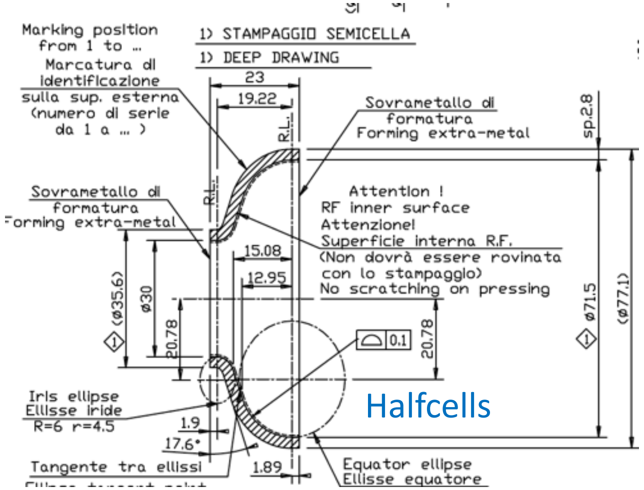
Fabrication workflow, with RF holdpoints

Example here:
XFEL 3.9 GHz

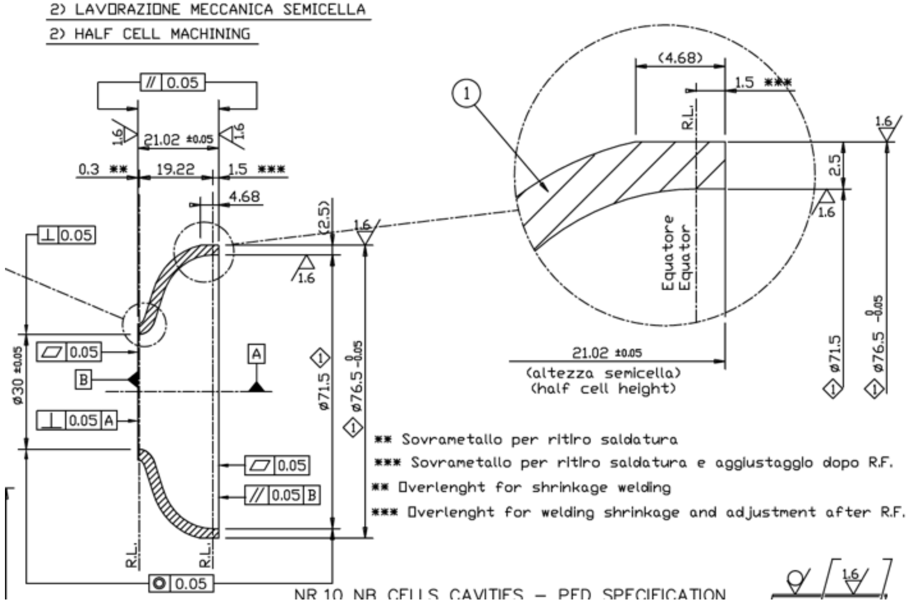
Base Nb material
(after QA)



Forming: foresee overlengths



Halfcells

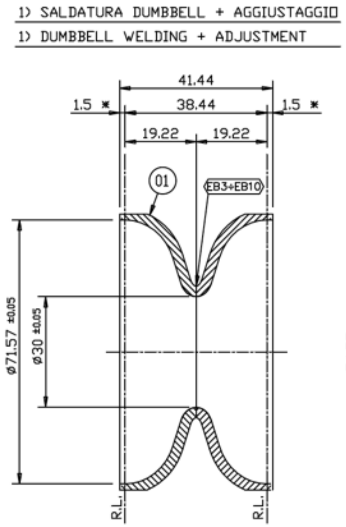


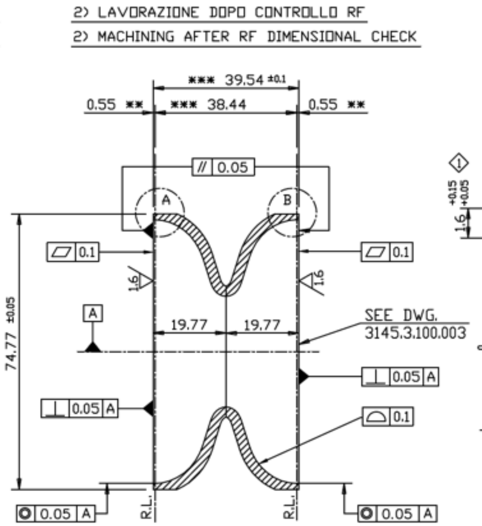
Include shape and geometrical tolerances

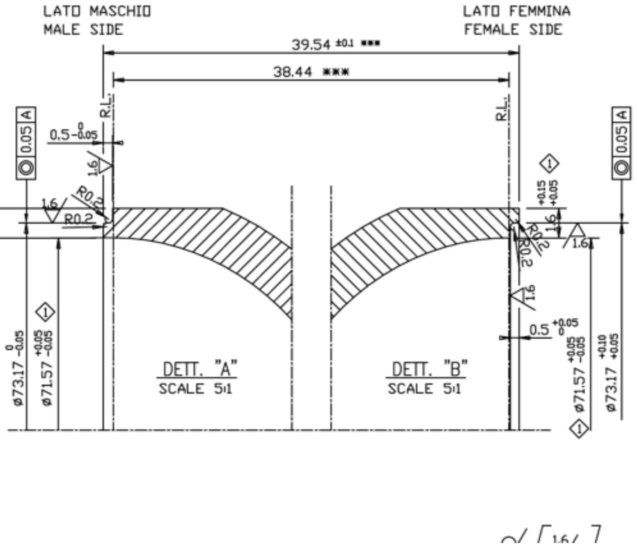
Foresee overlengths for weld shrinkages, and for the next phases of RF-based length adjustments

Sub-weldments
(Dumbells)

RF controls on parts to determine trimming







Need to master:

- Metallurgical aspects (cold forming, machining)
- Welding aspects (e.g. joint preparation)
- RF holdpoints to guide fabrication process

Not a unique domain: Mechanical aspects need always to be coupled with RF

RF activities at all stages

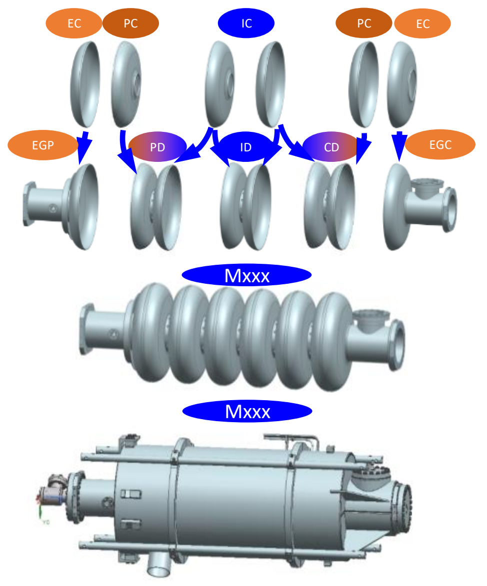
All pics courtesy of INFN/LASA

Always coupled with mechanical surveys to achieve length and frequency within tolerances

ESS Deepdrawing

Dimensional controls

CU mockups



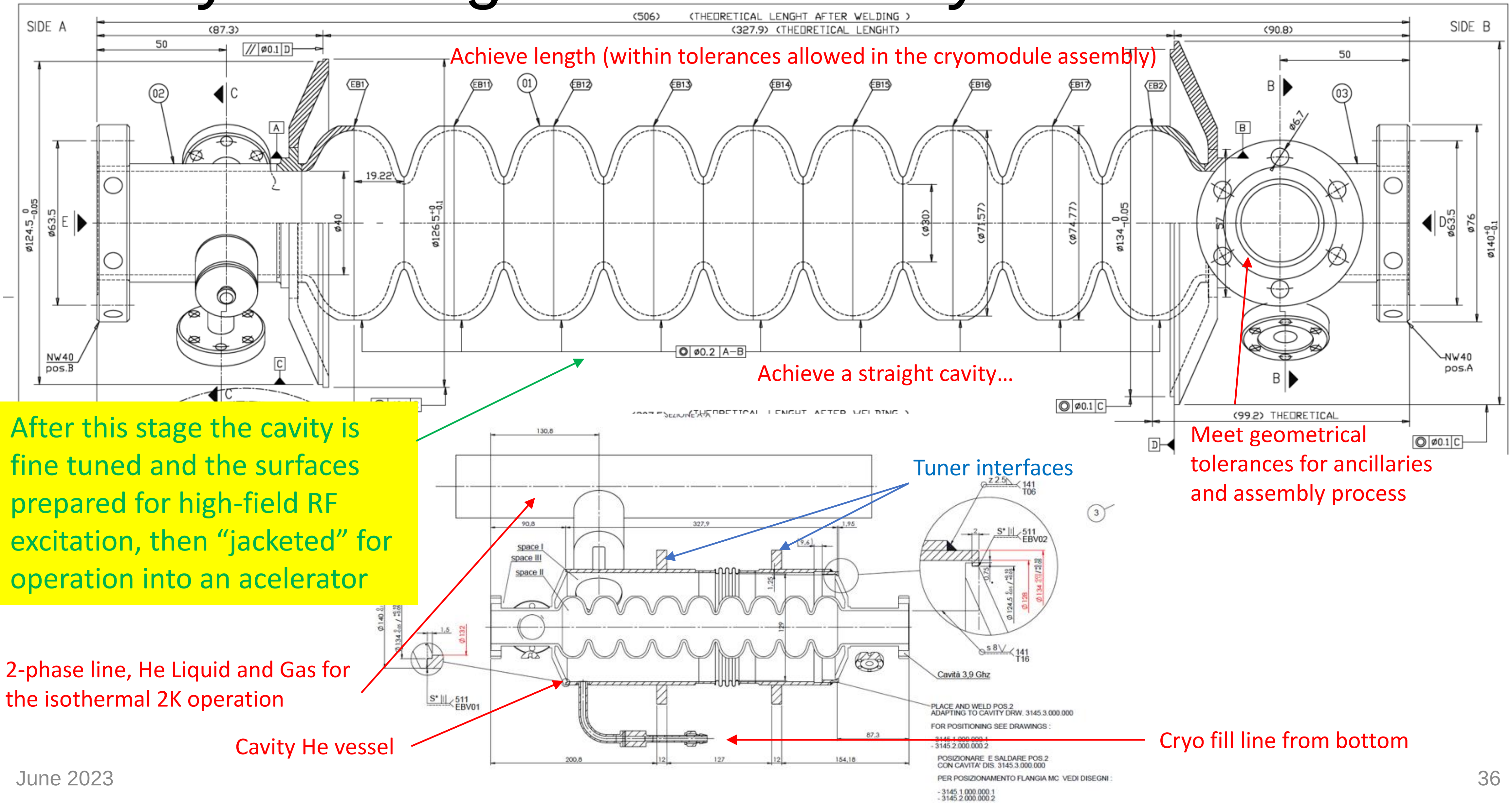
ESS CU mockup

Use of templates

RF measurement of 3.9 GHz HC/DB

RF measurement of ESS EG

Cavity for integration into a cryomodule



Achieve length (within tolerances allowed in the cryomodule assembly)

Achieve a straight cavity…

After this stage the cavity is fine tuned and the surfaces prepared for high-field RF excitation, then “jacketed” for operation into an acelerator

Tuner interfaces

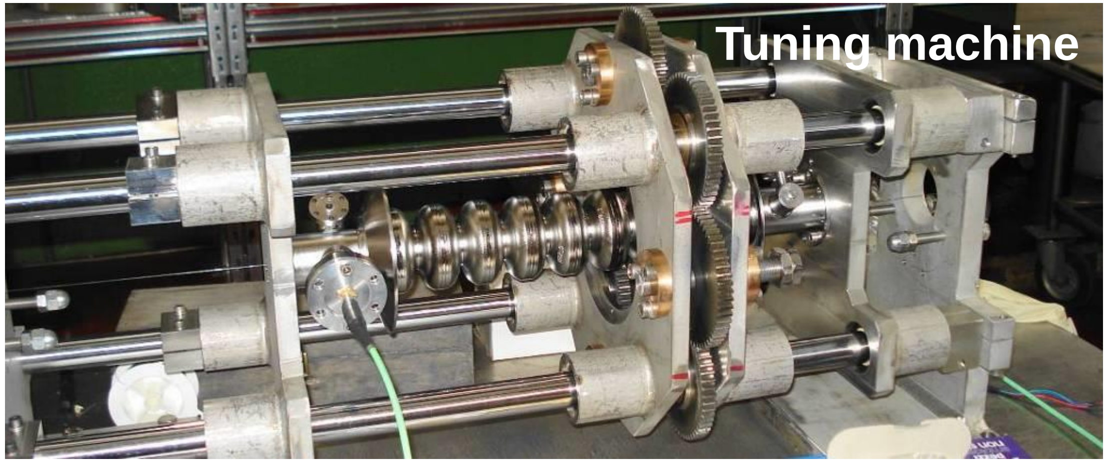
Meet geometrical tolerances for ancillaries and assembly process

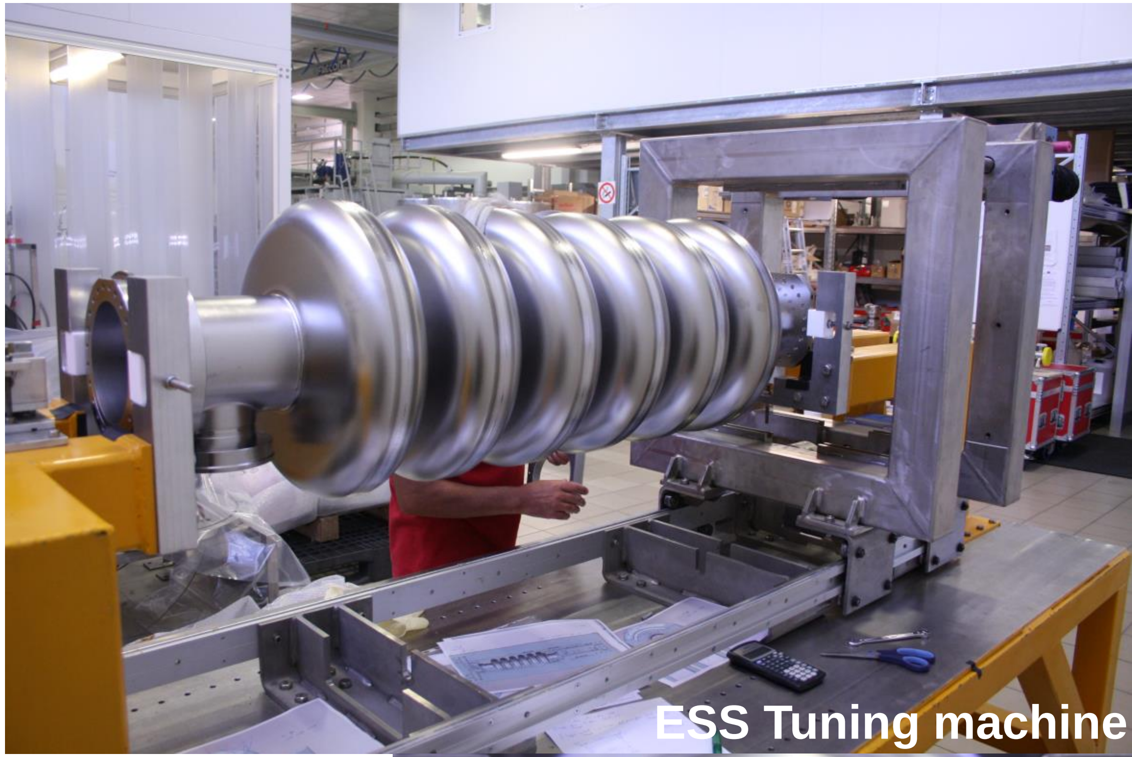
2-phase line, He Liquid and Gas for the isothermal 2K operation

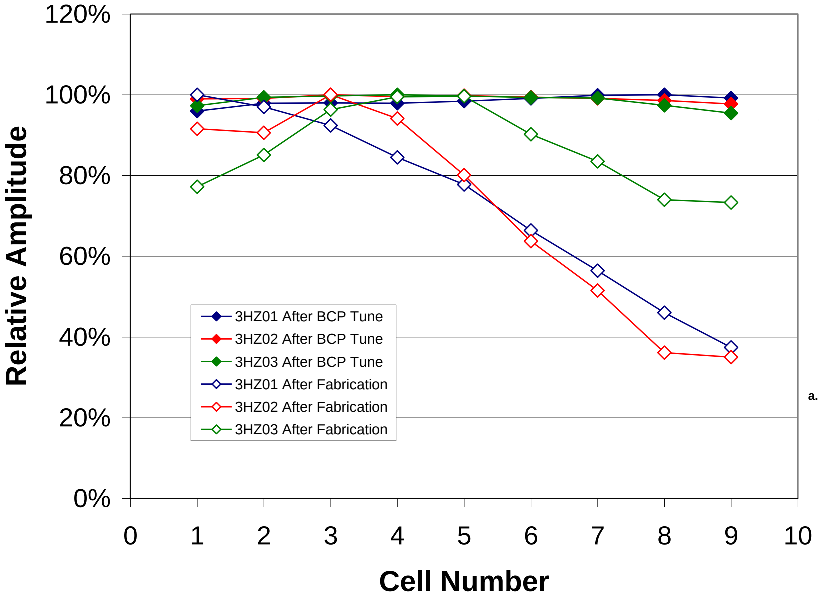
Cavity He vessel

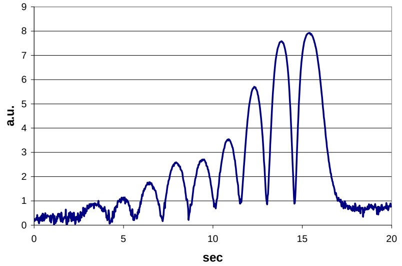
Cryo fill line from bottom

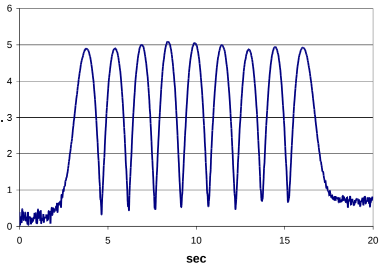
Field flatness Tuning

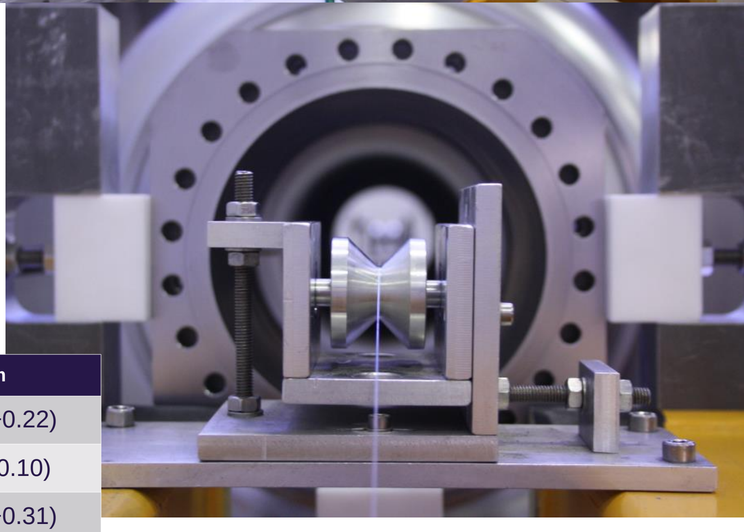








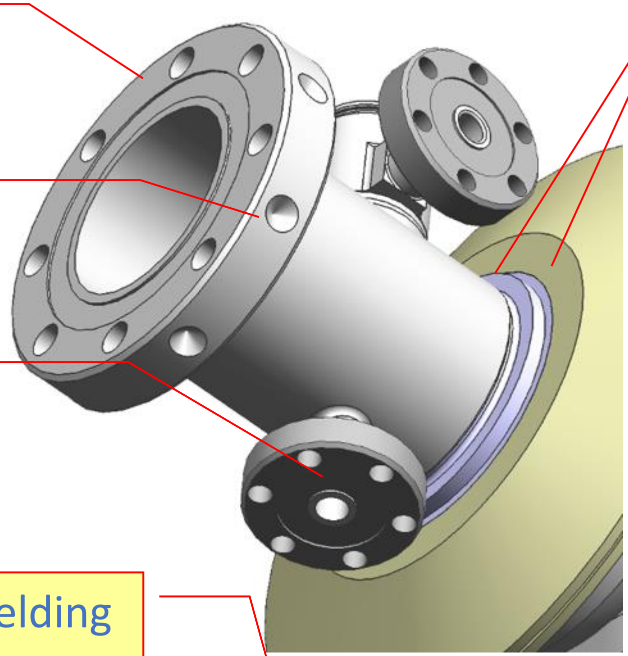




	Frequency, MHz	Length, mm
3HZ01	3894.033	506.20 (+0.22)
3HZ02	3893.965	505.88 (-0.10)
3HZ03	3894.199	506.30 (+0.31)

More: Flanges/Reference Ring/Welds

XFEL 3.9 GHz



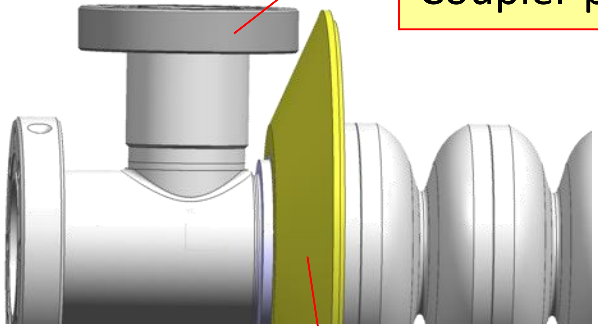
Flat flange,
Al diamond seal

Alignment boreholes/fiducials

PU flange, Al “diamond” seal

Machined surfaces for **geometrical referencing**

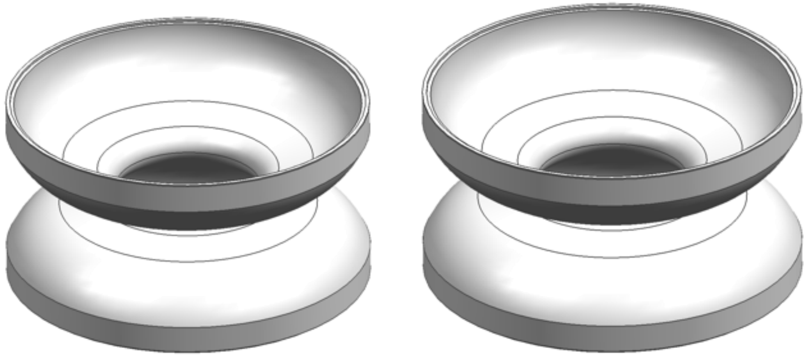
How can we relate RF axis to external geometry to position along beam path?

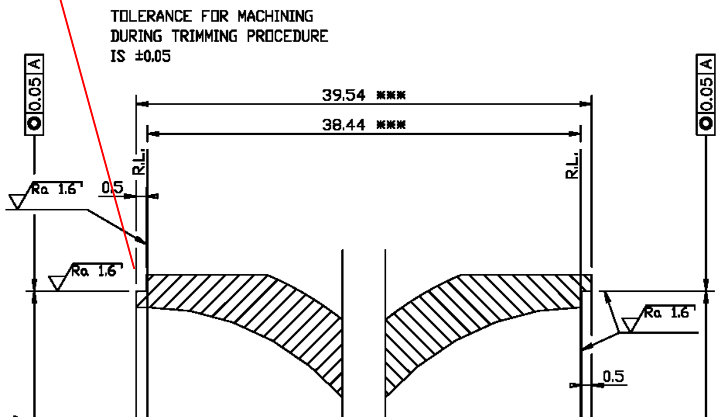


Coupler port

Endcone geometry, designed for weld access

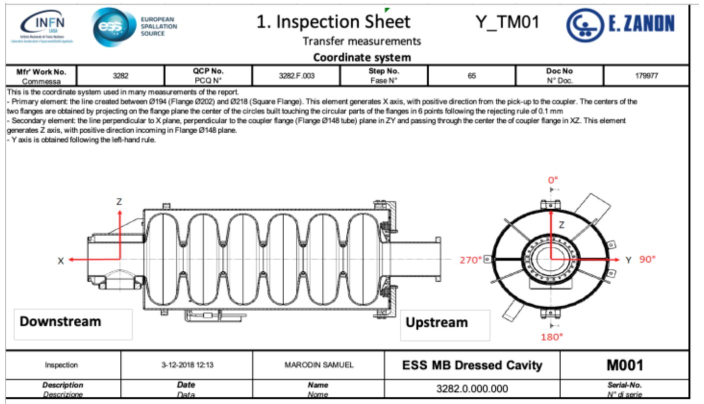
Eq weld preparation, easing welding operations





Referencing and fiducialization

- The cavity fabrication procedure needs to provide means to align cavities to the beam axis of the accelerator
  - Definition of a reference system
  - Accessible fiducials during critical alignment procedures
  - Transfer measurement to determine the cavity position from the fiducials



1. Inspection Sheet Y_TM01

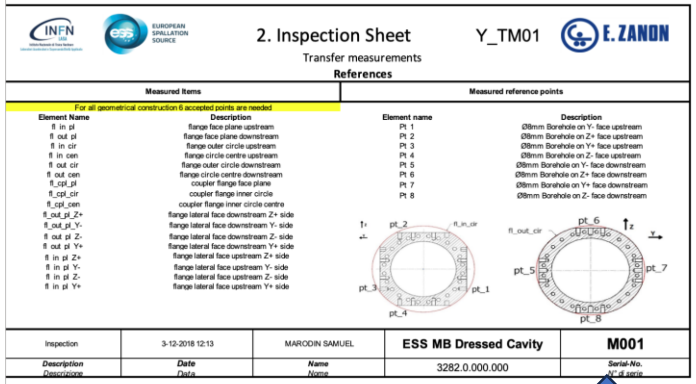
Transfer measurements

Coordinate system

Mfr' Work No. Commessa	3282	**QCP No.** PCQ N°	3282.F.003	**Step No.** Fase N°	65	**Doc No** N° Doc.	179977

This is the coordinate system used in many measurements of the report.
- Primary element: the line created between Ø194 (Flange Ø202) and Ø218 (Square Flange). This element generates X axis, with positive direction from the pick-up to the coupler. The centers of the two flanges are obtained by projecting on the flange plane the center of the circles built touching the circular parts of the flanges in 6 points following the rejecting rule of 0.1 mm
- Secondary element: the line perpendicular to X plane, perpendicular to the coupler flange (Flange Ø148 tube) plane in ZY and passing through the center the of coupler flange in XZ. This element generates Z axis, with positive direction incoming in Flange Ø148 plane.
- Y axis is obtained following the left-hand rule.

Inspection	3-12-2018 12:13	MARODIN SAMUEL	**ESS MB Dressed Cavity**	**M001**
Description *Descrizione*	***Date*** *Data*	***Name*** *Nome*	3282.0.000.000	***Serial-No.*** *N° di serie*



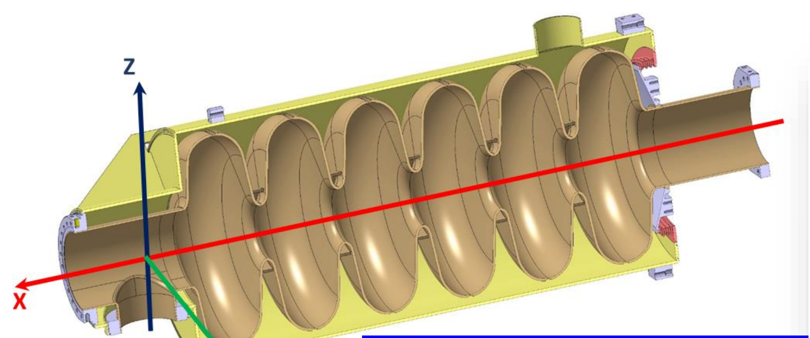
2. Inspection Sheet Y_TM01

Transfer measurements

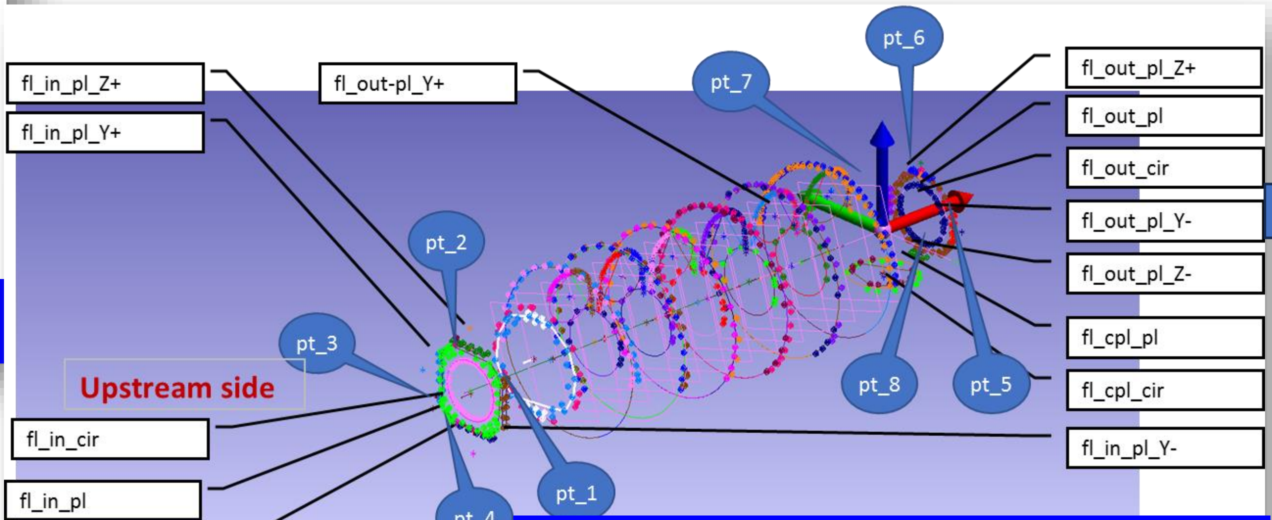
References

Measured Items		Measured reference points	
For all geometrical construction 6 accepted points are needed			
Element Name	**Description**	**Element name**	**Description**
fl in pl	flange face plane upstream	Pt 1	Ø8mm Borehole on Y- face upstream
fl out pl	flange face plane downstream	Pt 2	Ø8mm Borehole on Z+ face upstream
fl in cir	flange outer circle upstream	Pt 3	Ø8mm Borehole on Y+ face upstream
fl in cen	flange circle centre upstream	Pt 4	Ø8mm Borehole on Z- face upstream
fl out cir	flange outer circle downstream	Pt 5	Ø8mm Borehole on Y- face downstream
fl out cen	flange circle centre downstream	Pt 6	Ø8mm Borehole on Z+ face downstream
fl_cpl_pl	coupler flange face plane	Pt 7	Ø8mm Borehole on Y+ face downstream
fl_cpl_cir	coupler flange inner circle	Pt 8	Ø8mm Borehole on Z- face downstream
fl_cpl_cen	coupler flange inner circle centre		
fl_out_pl_Z+	flange lateral face downstream Z+ side		
fl_out_pl_Y-	flange lateral face downstream Y- side		
fl out pl Z-	flange lateral face downstream Z- side		
fl out pl Y+	flange lateral face downstream Y+ side		
fl in pl Z+	flange lateral face upstream Z+ side		
fl in pl Y-	flange lateral face upstream Y- side		
fl in pl Z-	flange lateral face upstream Z- side		
fl in pl Y+	flange lateral face upstream Y+ side		

Inspection	3-12-2018 12:13	MARODIN SAMUEL	**ESS MB Dressed Cavity**	**M001**
Description *Descrizione*	***Date*** *Data*	***Name*** *Nome*	3282.0.000.000	***Serial-No.*** *N° di serie*

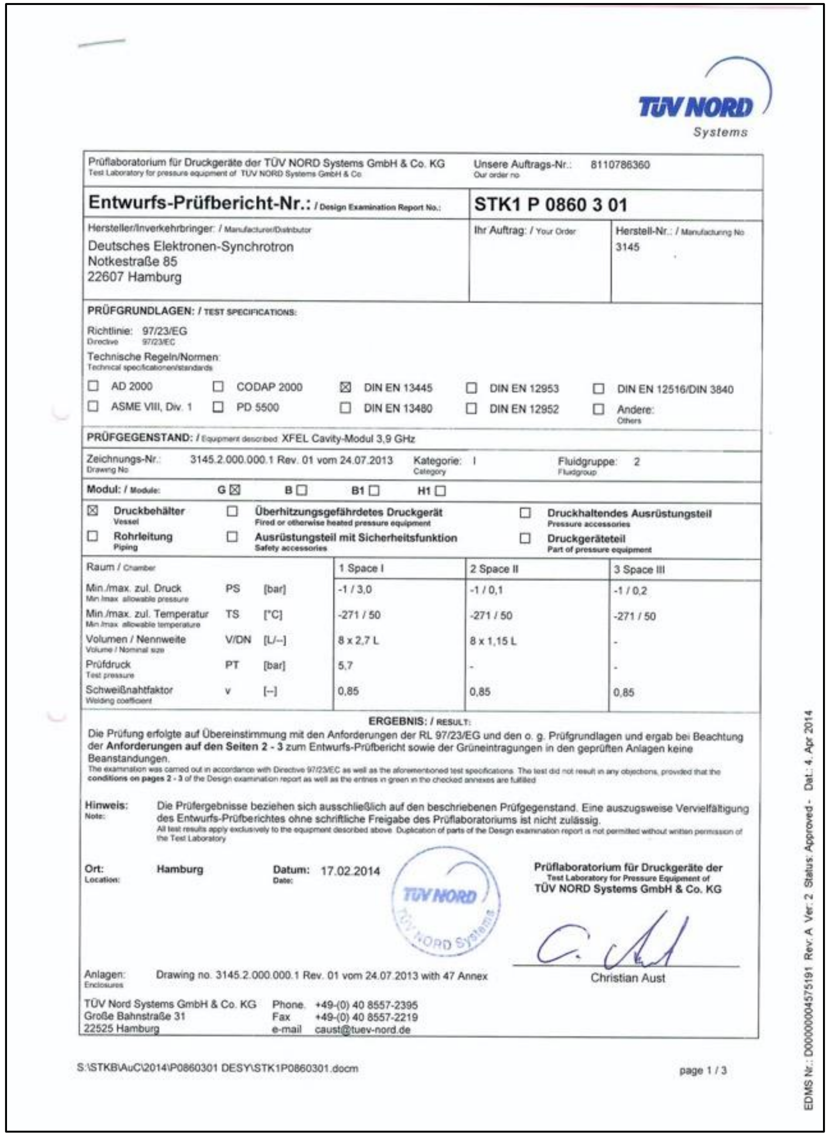


Reference system



Geometrical items descriptions

Licensing aspects: PED Compliance



TÜV NORD
Systems

Prüflaboratorium für Druckgeräte der TÜV NORD Systems GmbH & Co. KG
Test Laboratory for pressure equipment of TÜV NORD Systems GmbH & Co

Unsere Auftrags-Nr.: / Our order no: 8110786360

Entwurfs-Prüfbericht-Nr.: / Design Examination Report No.: **STK1 P 0860 3 01**

Hersteller/Inverkehrbringer: / Manufacturer/Distributor
Deutsches Elektronen-Synchrotron
Notkestraße 85
22607 Hamburg

Ihr Auftrag: / Your Order

Herstell-Nr.: / Manufacturing No: 3145

PRÜFGRUNDLAGEN: / TEST SPECIFICATIONS:

Richtlinie: / Directive: 97/23/EG / 97/23/EC

Technische Regeln/Normen: / Technical specifications/standards

☐ AD 2000 ☐ CODAP 2000 ☒ DIN EN 13445 ☐ DIN EN 12953 ☐ DIN EN 12516/DIN 3840
☐ ASME VIII, Div. 1 ☐ PD 5500 ☐ DIN EN 13480 ☐ DIN EN 12952 ☐ Andere: / Others

PRÜFGEGENSTAND: / Equipment described: XFEL Cavity-Modul 3,9 GHz

Zeichnungs-Nr.: / Drawing No: 3145.2.000.000.1 Rev. 01 vom 24.07.2013 Kategorie: / Category: I Fluidgruppe: / Fluidgroup: 2

Modul: / Module: G ☒ B ☐ B1 ☐ H1 ☐

☒ **Druckbehälter** / Vessel
☐ **Überhitzungsgefährdetes Druckgerät** / Fired or otherwise heated pressure equipment
☐ **Druckhaltendes Ausrüstungsteil** / Pressure accessories
☐ **Rohrleitung** / Piping
☐ **Ausrüstungsteil mit Sicherheitsfunktion** / Safety accessories
☐ **Druckgeräteteil** / Part of pressure equipment

Raum / Chamber			1 Space I	2 Space II	3 Space III
Min./max. zul. Druck Min./max. allowable pressure	PS	[bar]	-1 / 3,0	-1 / 0,1	-1 / 0,2
Min./max. zul. Temperatur Min./max. allowable temperature	TS	[°C]	-271 / 50	-271 / 50	-271 / 50
Volumen / Nennweite Volume / Nominal size	V/DN	[L/--]	8 x 2,7 L	8 x 1,15 L	-
Prüfdruck Test pressure	PT	[bar]	5,7	-	-
Schweißnahtfaktor Welding coefficient	v	[--]	0,85	0,85	0,85

ERGEBNIS: / RESULT:

Die Prüfung erfolgte auf Übereinstimmung mit den Anforderungen der RL 97/23/EG und den o. g. Prüfgrundlagen und ergab bei Beachtung der **Anforderungen auf den Seiten 2 - 3** zum Entwurfs-Prüfbericht sowie der Grüneintragungen in den geprüften Anlagen keine Beanstandungen.
The examination was carried out in accordance with Directive 97/23/EC as well as the aforementioned test specifications. The test did not result in any objections, provided that the **conditions on pages 2 - 3** of the Design examination report as well as the entries in green in the checked annexes are fulfilled.

Hinweis: / Note: Die Prüfergebnisse beziehen sich ausschließlich auf den beschriebenen Prüfgegenstand. Eine auszugsweise Vervielfältigung des Entwurfs-Prüfberichtes ohne schriftliche Freigabe des Prüflaboratoriums ist nicht zulässig.
All test results apply exclusively to the equipment described above. Duplication of parts of the Design examination report is not permitted without written permission of the Test Laboratory.

Ort: / Location: **Hamburg** **Datum:** / Date: 17.02.2014

Prüflaboratorium für Druckgeräte der
Test Laboratory for Pressure Equipment of
TÜV NORD Systems GmbH & Co. KG

C. Aust
Christian Aust

Anlagen: / Enclosures: Drawing no. 3145.2.000.000.1 Rev. 01 vom 24.07.2013 with 47 Annex

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e-mail caust@tuev-nord.de

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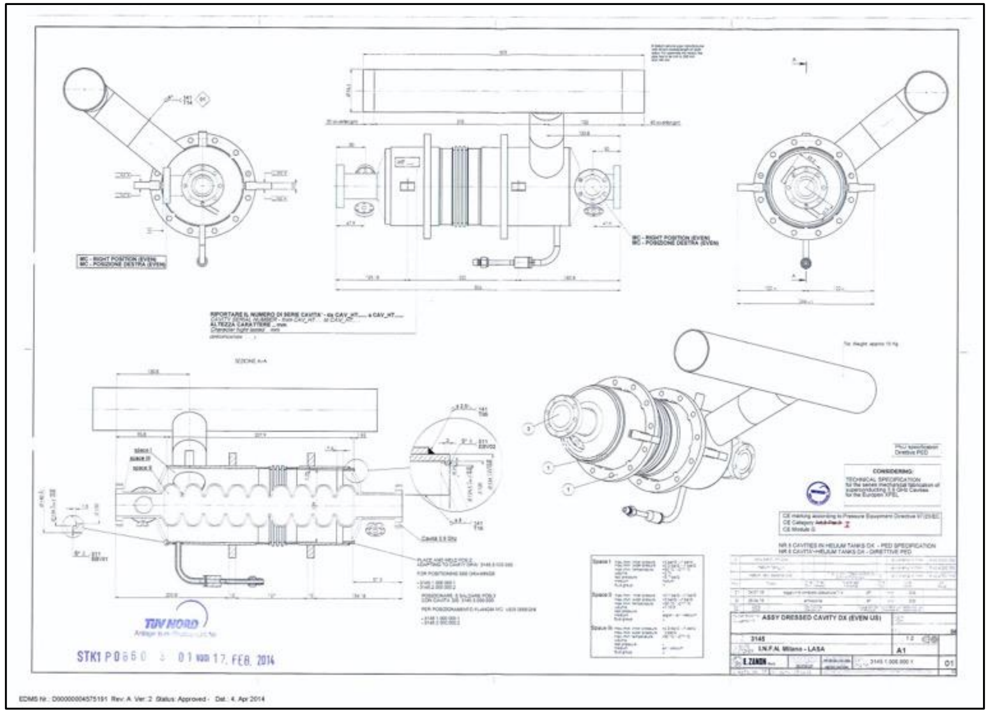
page 1 / 3

EDMS Nr.: D000000004575191 Rev. A Ver. 2 Status: Approved - Dat.: 4. Apr 2014

Project environment may require compliance to norms, e.g. the harmonized Pressure Equipment Directive for pressure bearing components

- Fabrication may be subject to third-party (notified body) scrutiny and foresee followup of strict procedures and hold points (weld samples, pressure tests)

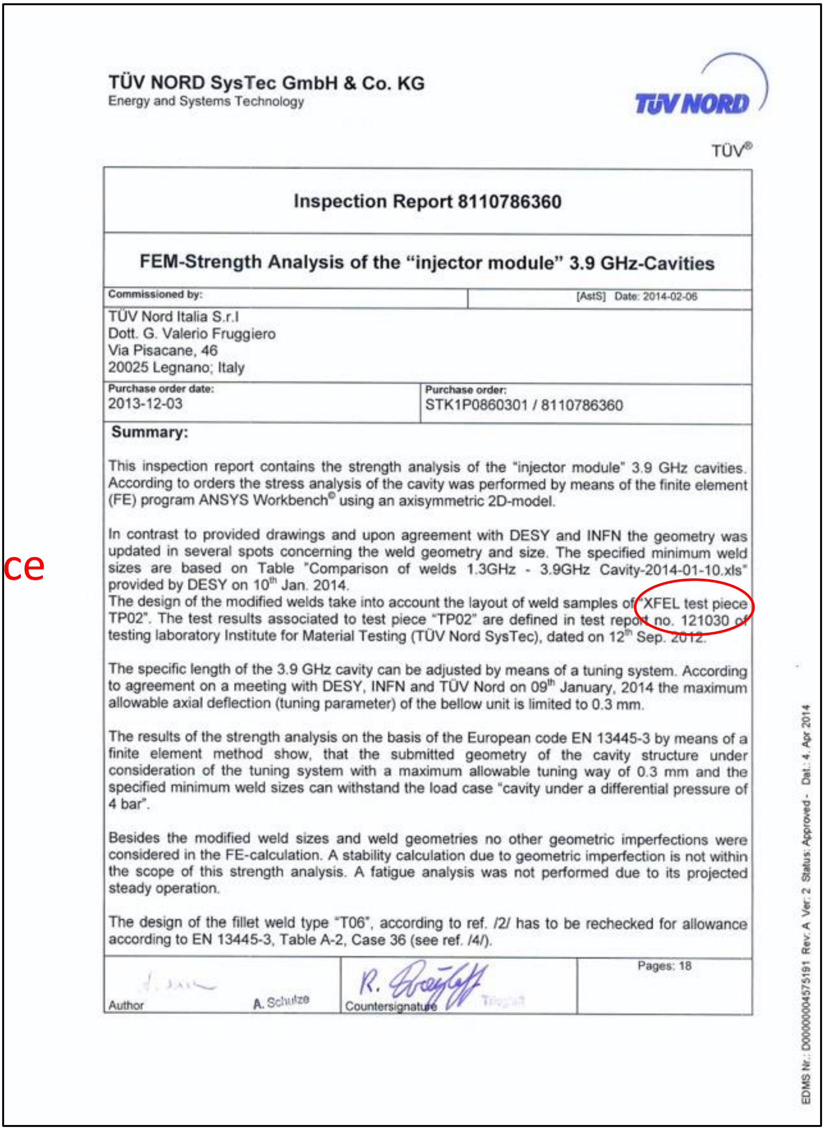
[Remember 1 l of Lhe evaporates into 700 l of gas]



FEM Analysis with severe weld depth reduction

Course of RF for Accelerators

Test piece



TÜV NORD SysTec GmbH & Co. KG
Energy and Systems Technology

TÜV NORD

TÜV®

Inspection Report 8110786360

FEM-Strength Analysis of the "injector module" 3.9 GHz-Cavities

Commissioned by:	[AstS] Date: 2014-02-06
TÜV Nord Italia S.r.l Dott. G. Valerio Fruggiero Via Pisacane, 46 20025 Legnano; Italy	
Purchase order date: 2013-12-03	**Purchase order:** STK1P0860301 / 8110786360

Summary:

This inspection report contains the strength analysis of the "injector module" 3.9 GHz cavities. According to orders the stress analysis of the cavity was performed by means of the finite element (FE) program ANSYS Workbench© using an axisymmetric 2D-model.

In contrast to provided drawings and upon agreement with DESY and INFN the geometry was updated in several spots concerning the weld geometry and size. The specified minimum weld sizes are based on Table "Comparison of welds 1.3GHz - 3.9GHz Cavity-2014-01-10.xls" provided by DESY on 10th Jan. 2014.
The design of the modified welds take into account the layout of weld samples of "XFEL test piece TP02". The test results associated to test piece "TP02" are defined in test report no. 121030 of testing laboratory Institute for Material Testing (TÜV Nord SysTec), dated on 12th Sep. 2012.

The specific length of the 3.9 GHz cavity can be adjusted by means of a tuning system. According to agreement on a meeting with DESY, INFN and TÜV Nord on 09th January, 2014 the maximum allowable axial deflection (tuning parameter) of the bellow unit is limited to 0.3 mm.

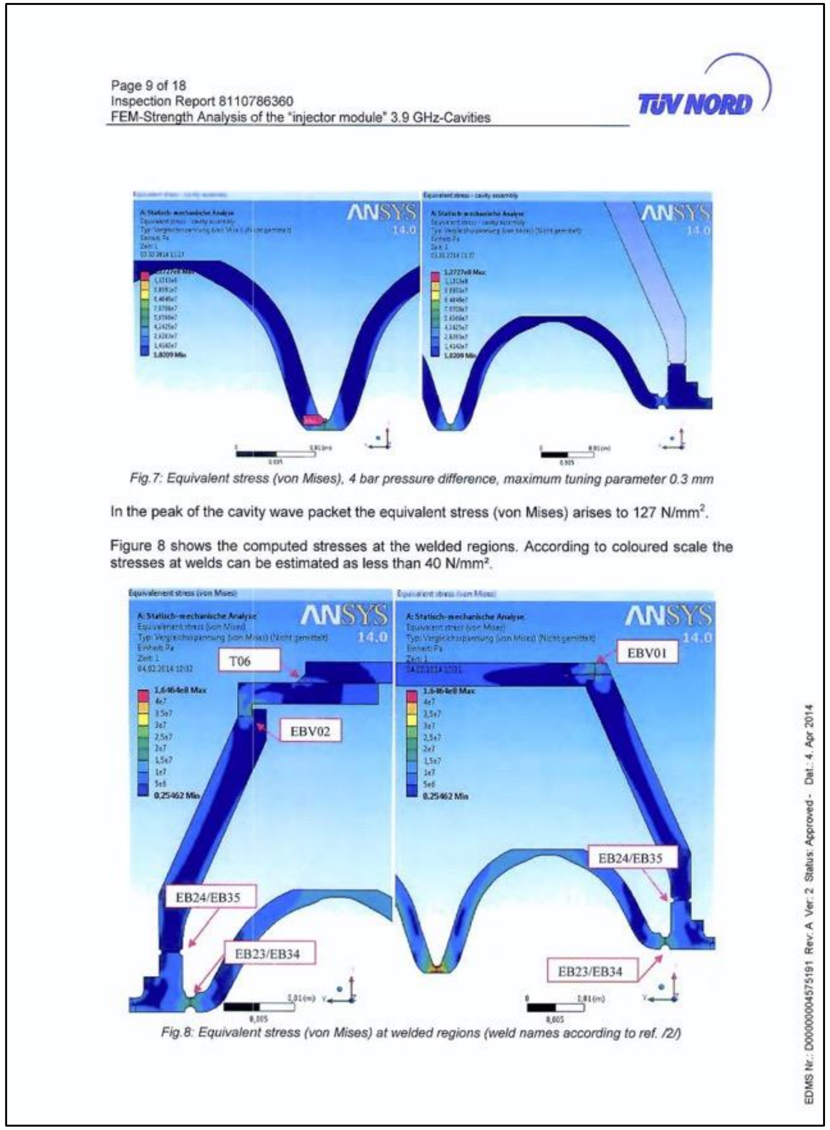
The results of the strength analysis on the basis of the European code EN 13445-3 by means of a finite element method show, that the submitted geometry of the cavity structure under consideration of the tuning system with a maximum allowable tuning way of 0.3 mm and the specified minimum weld sizes can withstand the load case "cavity under a differential pressure of 4 bar".

Besides the modified weld sizes and weld geometries no other geometric imperfections were considered in the FE-calculation. A stability calculation due to geometric imperfection is not within the scope of this strength analysis. A fatigue analysis was not performed due to its projected steady operation.

The design of the fillet weld type "T06", according to ref. /2/ has to be rechecked for allowance according to EN 13445-3, Table A-2, Case 36 (see ref. /4/).

Author A. Schutze	R. Countersignature	Pages: 18

EDMS Nr.: D00000004575191 Rev: A Ver: 2 Status: Approved - Dat.: 4. Apr 2014



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Inspection Report 8110786360
FEM-Strength Analysis of the "injector module" 3.9 GHz-Cavities

TÜV NORD

Fig.7: Equivalent stress (von Mises), 4 bar pressure difference, maximum tuning parameter 0.3 mm

In the peak of the cavity wave packet the equivalent stress (von Mises) arises to 127 N/mm^2.

Figure 8 shows the computed stresses at the welded regions. According to coloured scale the stresses at welds can be estimated as less than 40 N/mm².

Fig.8: Equivalent stress (von Mises) at welded regions (weld names according to ref. /2/)

EDMS Nr.: D00000004575191 Rev: A Ver: 2 Status: Approved - Dat.: 4. Apr 2014

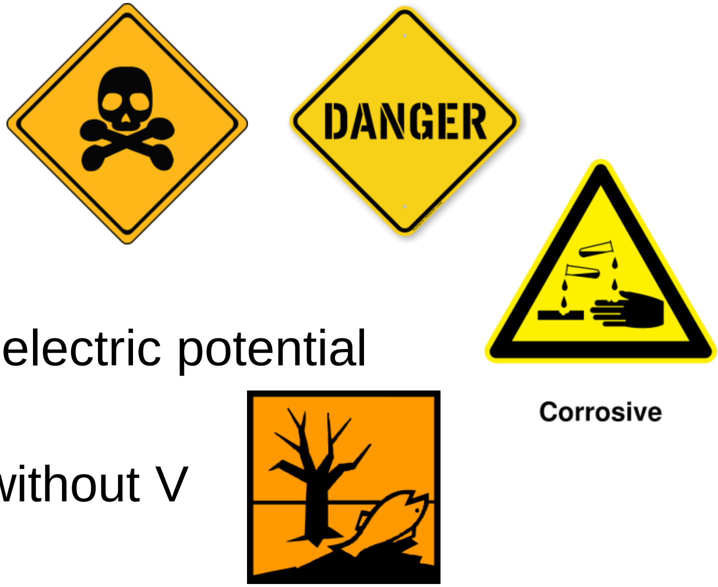
Preparation

Mostly showing elliptical cavities, this is not a cavity design primer, but more an introduction of the SRF technology

Damage layer removal

See C. Antoine, CAS 2013 Superconductivity

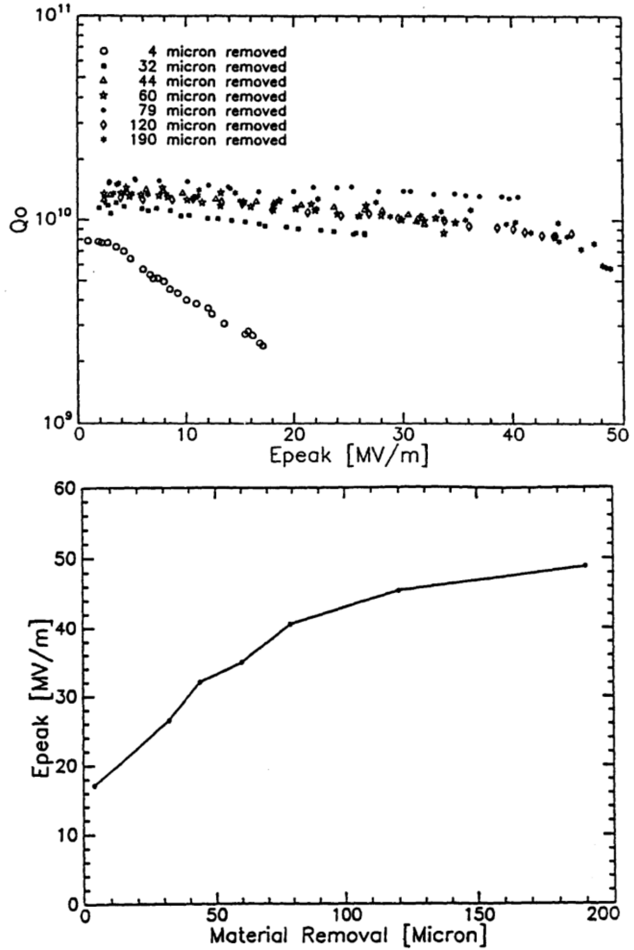
- The cavity fabrication processes (rolling, forming, machining) creates a damage layer on the surface
  - Contamination, foreign material inclusion, dust, scratches, residual strain, grain irregularities, small geometrical “features”
  - **CONSEQUENCE**: Cavity as fabricated **NOT CAPABLE** to sustain high fields
- Remove 100-200 um on the cavity surface (and predict its RF effect!)
  - Chemical etching (BCP) ~ 1 um/min (@20 C)
    - 2:1:1 H_3PO_4 buffer, HNO_3 oxidant, HF to dissolve oxide
    - Strong exothermal reaction: need cooling
    - Preserve the surface roughness
  - Electropolishing ~ 0.5 um/min (@20 C)
    - 9:1 H_2SO_4 buffer, HF to dissolve the oxide formed due to the electric potential
    - Obtain smoother surfaces (potential for higher field reach)
    - Tighter control of process parameters needed, but no effect without V



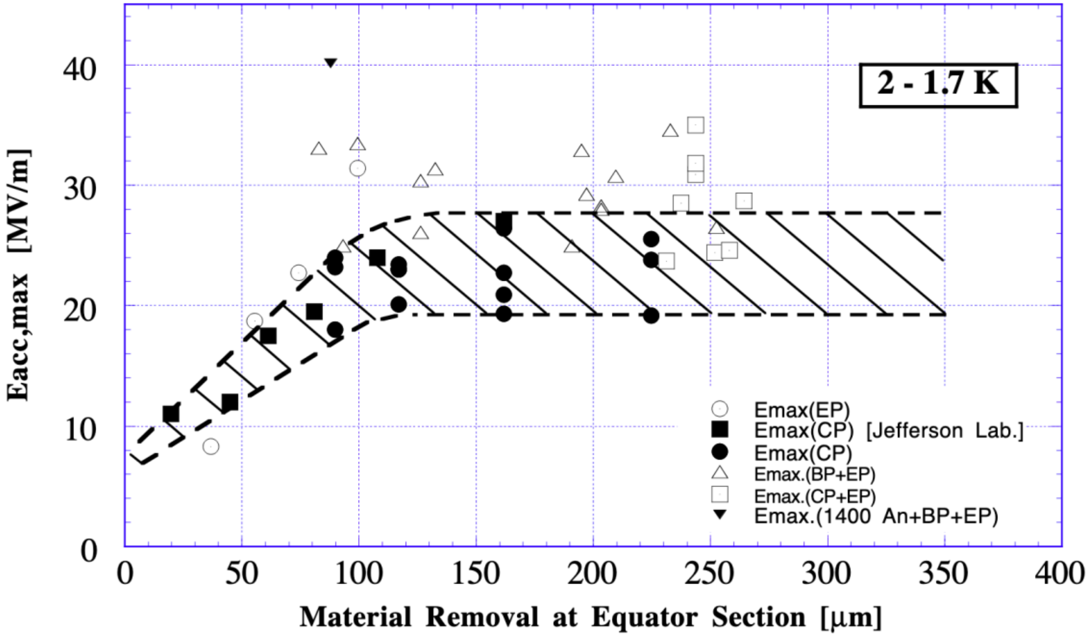
Q vs Eacc and surface removal

- High field performances can be obtained only after removal of a sufficient layer of the cavity surface

From P. Kneisel, SRF Workshop 1993



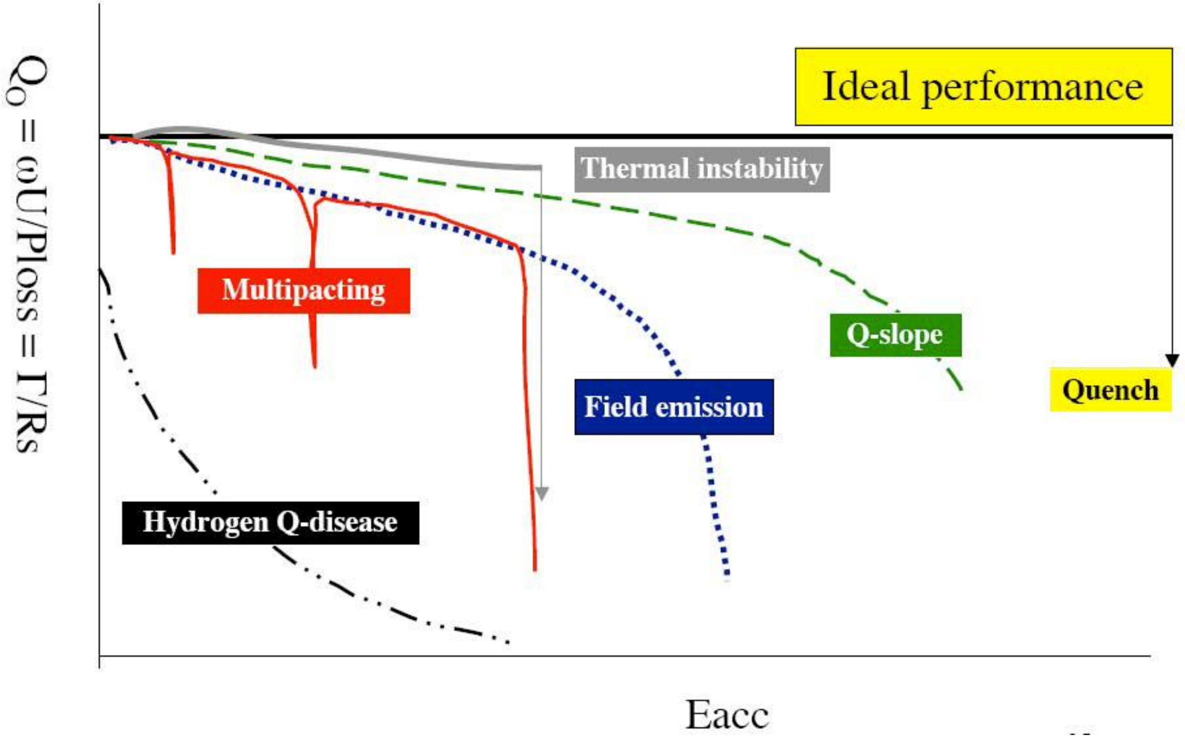
From K. Saito, SRF Workshop, 1997



Other limits

- Several other fundamental and technological limits
  - Magnetic field limit (~200 mT)
  - Magnetic flux trapping
    - Screen from ambient field
  - Field emission from particulate deposited during assembly operations
  - Geometrical field enhacements, residues, grain boundaries
  - Hydrides formation (Q-disease)
  - Multipacting phenomena
  - Thermal instability & runaway
    - Local resistive defects
    - Limited thermal conductivity
    - Kapitza resistance at He/Nb interface

From D. Reschke, SRF Tutorials, 2007



Each has specific “signature” in QvsE curve

Huge literature, very hard to cover properly

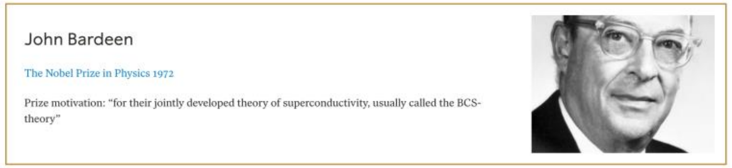
Rs again

See G. Ciovati, CAS Superconductivity 2013

- For bulk Nb (with a critical temperature of 9.2 K):

$$R_s[\mathrm{n\Omega}] = \underbrace{9 \times 10^4 \frac{f^2[\mathrm{GHz}]}{T[\mathrm{K}]} \exp\left(-\frac{17.664}{T[\mathrm{K}]}\right)}_{\substack{\text{Theory} \\ \text{(given here in an approximate engineering formula)}}} \underbrace{+R_{res}}_{\text{Reality}}$$

B



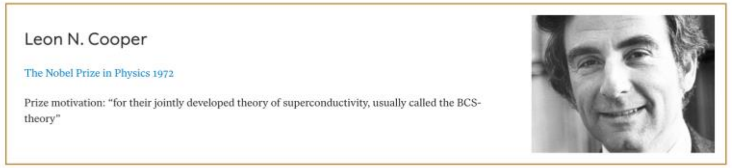
John Bardeen

The Nobel Prize in Physics 1972

Prize motivation: “for their jointly developed theory of superconductivity, usually called the BCS-theory”

(x2)

C

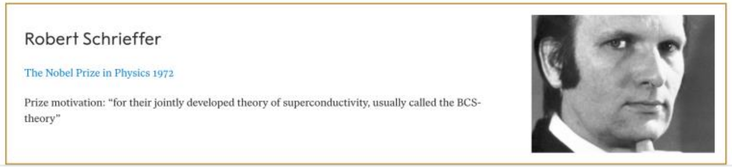


Leon N. Cooper

The Nobel Prize in Physics 1972

Prize motivation: “for their jointly developed theory of superconductivity, usually called the BCS-theory”

S



Robert Schrieffer

The Nobel Prize in Physics 1972

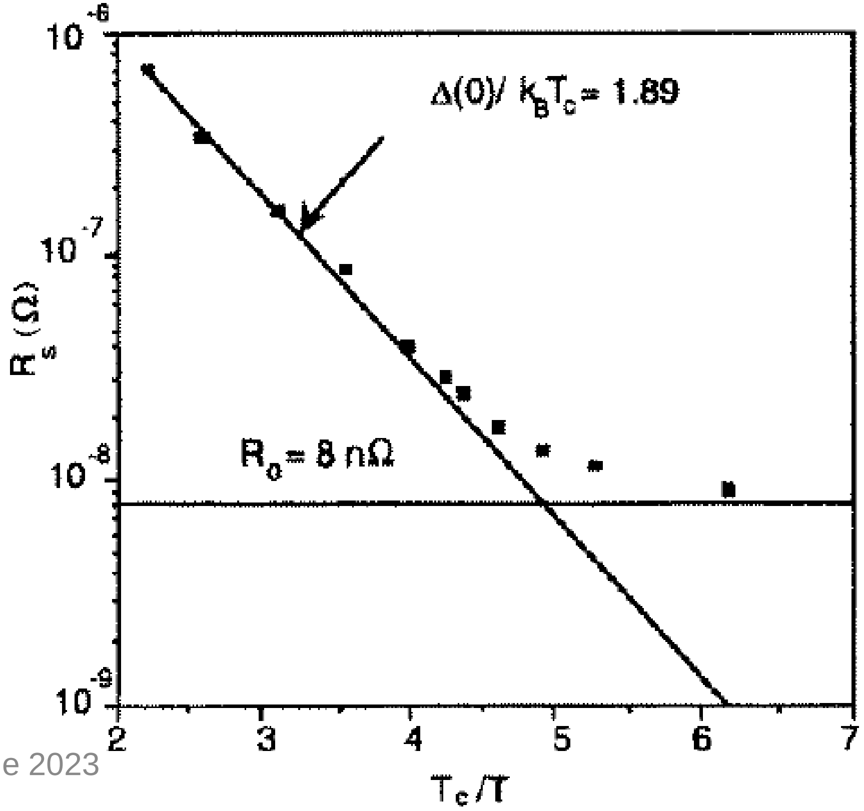
Prize motivation: “for their jointly developed theory of superconductivity, usually called the BCS-theory”

Surface Resistance - Reprise

- In general

$$R_s = R_{BCS}(f, T, \ldots) + R_{res}$$

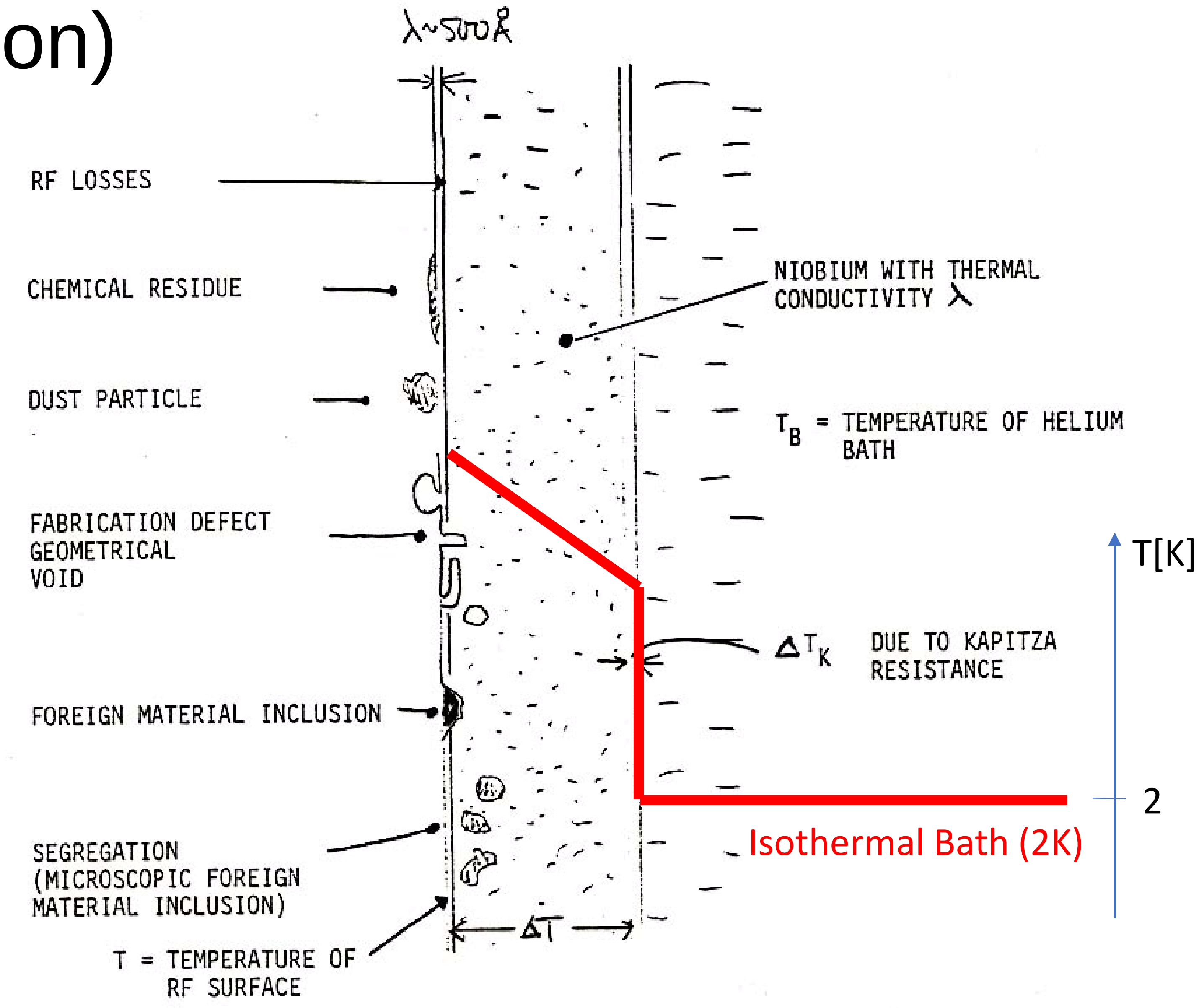
H. Padamsee et al.,
RF Superconductivity for Accelerators,
J.Wiley, 1998



- The first component is described by the BCS theory
- The second is the residual resistance, that comes from :
  - Trapped magnetic flux
  - Impurities and defects
  - Resistive precipitates (hydrides)
  - (…)
- Both can have field dependence
  - Key to new surface tailoring for higher Q & Field
    - See Grassellino, 2021 SRF Tutorials

Cavity Surface (Cartoon)

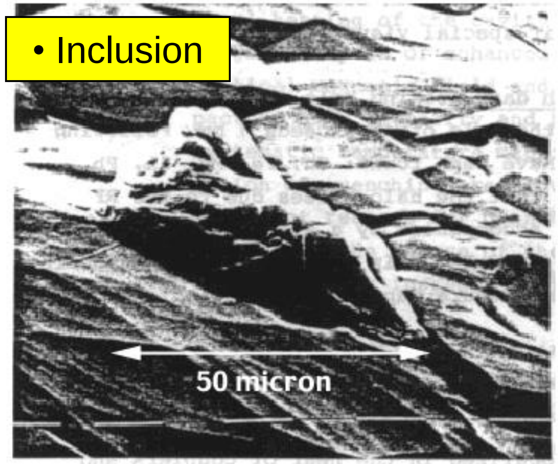
- Based on Temperature maps and inspection of the cavity surface different possible sources of localized losses have been identified:
  - Geometrical irregularities leading to field enhancement
  - Accumulation of foreign material, of resistive type
  - These defects generate additional heat loss, heat up the region and eventually cause a thermal instability, if locally $T > T_C$

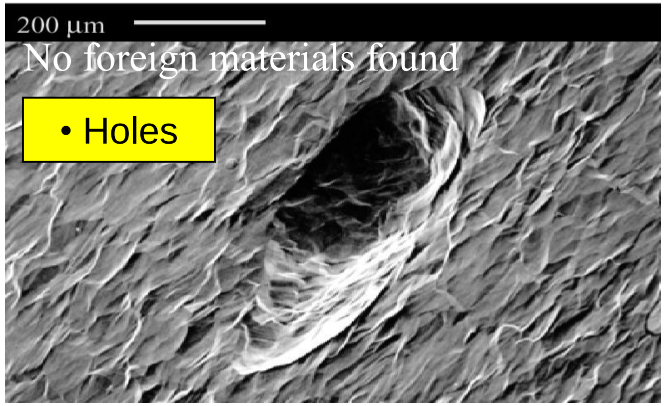


$$T = \Delta T_{Cond} + \Delta T_K + T_B < T_C$$

Surface Defects Examples

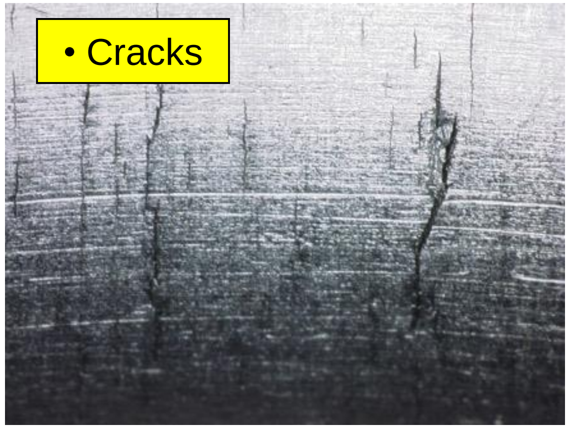
- Originally Niobium was a by-product of Tantalum production
  - Strong limitation in the technology

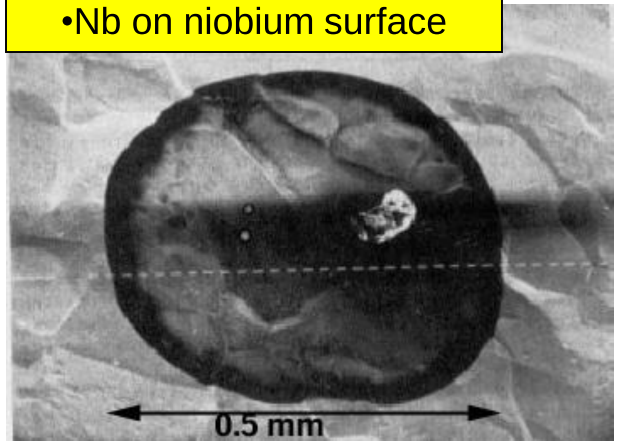

- Inclusion

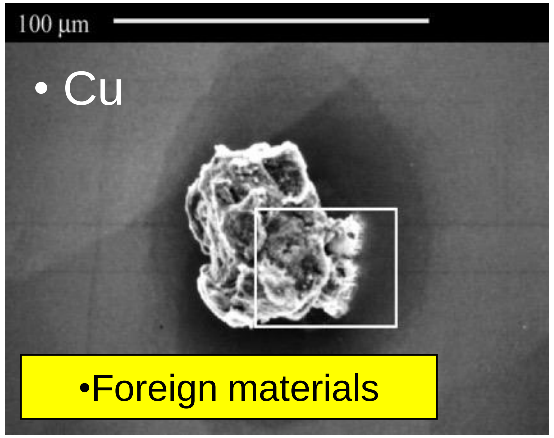


- Holes

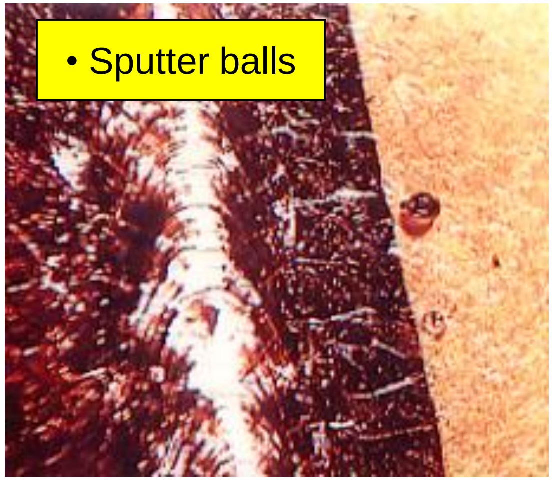
Surface defects, holes can also cause TB


- Cracks


- Nb on niobium surface



- Cu
- Foreign materials


- Sputter balls

Preparation procedures

Even removing the damage layer cavity performance is affected by:

- Defects and contamination (grease, residues)
  - (leads to field emission)
- All preparation procedures need to address the control of contamination
  - Use the controlled environment of a clean room
- Level of contamination depends on the facilities, and the tools
  - Most important factor are the operators: Training
  - Proper choice of hardware (e.g. nuts and bolt)
- Labs and projects usually develop strict procedures to manage preparation workflow (see L. Popielarski, SRF Tutorial 2021)

Contamination

- Sources
  - Processing Chemicals (filtered!)
  - High Purity Water (>18 MΩcm, <0.02 mm filter)
  - Clean Room environment (typically ISO4 for cavity handling)
  - Particulates on equipment, tooling, hardware, clothing, gloves…
- Remedies
  - Stringent control of processes and procedures
  - In-line monitoring of particulate levels in air and liquids
  - Scheduled maintenance
  - “Blow-off” of all equipment with filtered N2, monitored by particle counter
  - Use of appropriate hardware (e.g. screw/bolts of different material)
  - Good component designs (e.g. gaskets, clamp rings, fixtures, cobots…)
  - Enforce “best practices” through whole assembly process

Cleanroom Technology

- Use of standard CR practices (Semiconductor)
  - HVAC (Heating Ventilation Air Conditioning) Systems
  - Filtration of Air/gases and Liquids
  - All processes under “clean” conditions,
    - e.g. Vacuum-, Temperature- and Wet-
  - Personal: Clothing and Behaviour
  - CR-compatible equipment and tooling
  - Equipment layout to preserve laminar flow
  - Cleaning Processes of CR and equipment
    - daily wiping, filter change, on-line monitoring of air quality..
- Dedicated equipment for SRF
  - Ultrasonic cleaning
  - BCP/EP: etching, electropolishing
  - HPR: High Pressure rinsing
  - Leak check and controlled pumping/venting equipment with no particulate movement
  - Tooling for handling and assembly, e.g. lift carts, bench

Preparation is a key factor

High Pressure Water Rinsing

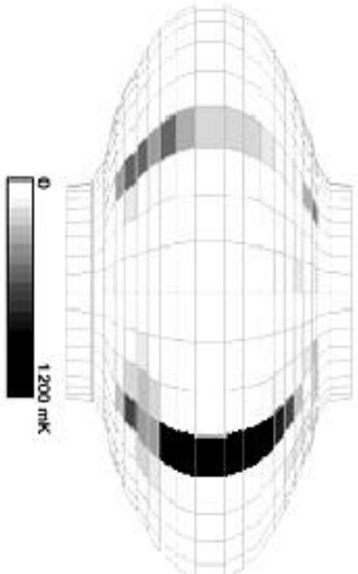
- It is universally used as last step in surface preparation, to remove particulate on the surfaces by a high pressure clean water jet
  - Ultrapure water, with resistivity > 18 MΩcm
  - Pressure: ~ 100 bar
  - Nozzle configuration: avoid material erosion, typically use sapphire
- Surface cleaning needs to adapted to cavity geometry
  - single or multiple sweeps,
  - continuous rotation + up/down
- Additional HPR after attachment of auxiliary components

HPWR crucial to cure Field Emission

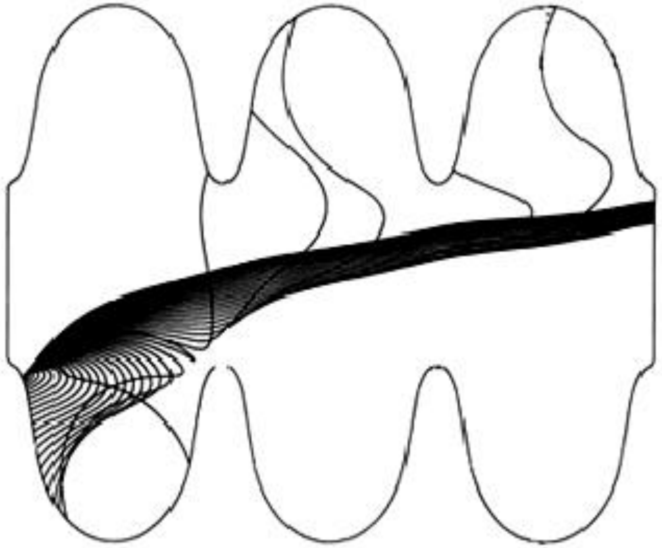
Field emission is normally caused by foreign particle contamination

- Emitted electron current grows exponentially with field
- Reaching the surface accelerated electrons produce cryo-losses and quenches
- Part of the electrons reaches high energies: Dark Current

Particle causing field emission



Temperature map of a field emitter



Simulation of electron trajectories in a cavity

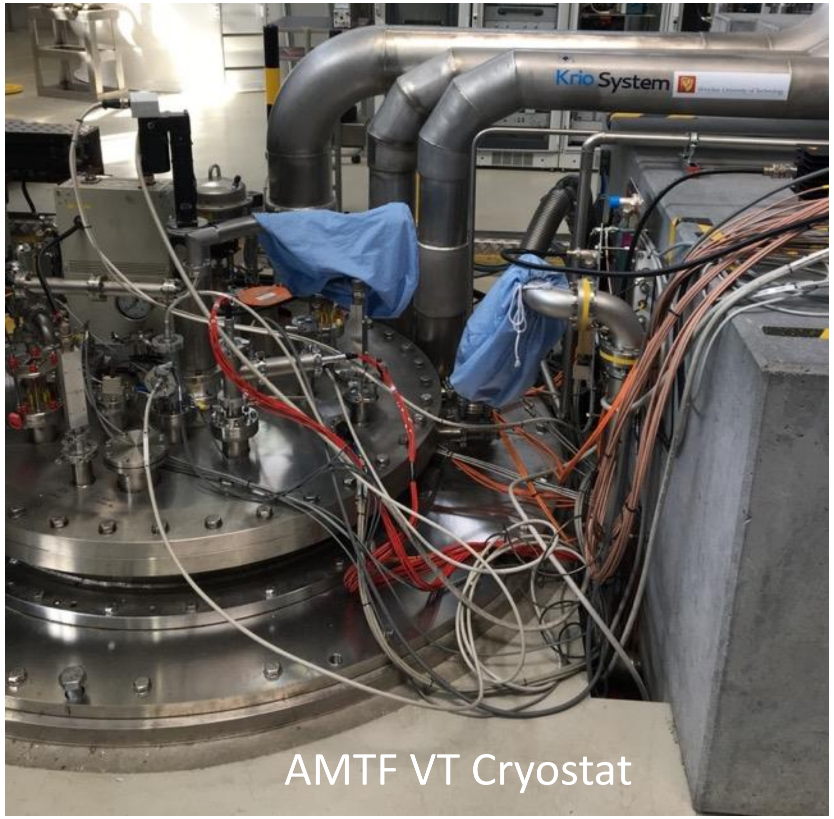
Pictures taken from: H. Padamsee, Supercond. Sci. Technol., 14 (2001), R28 –R51

Cavity Vertical Test


XFEL Cavities


ESS MB Cavity

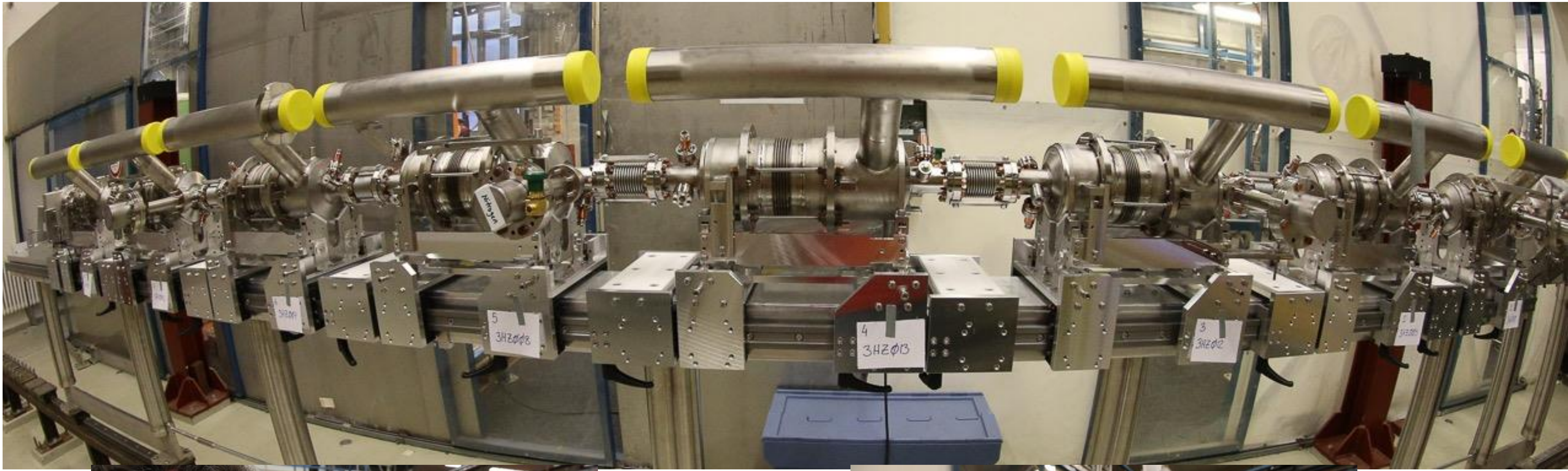
- The cavity is in a isothermal superfluid He bath at 2 K
- High power coupler and tuner are not installed
  - High Q antenna for nearly critical coupling
- RF test are performed in CW


AMTF VT Cryostat

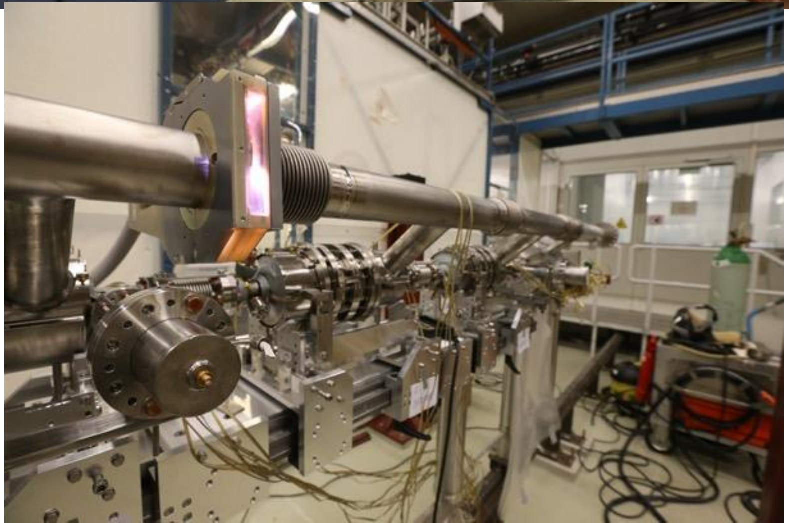
The ancillaries

The cavity needs to be completed with a set of ancillaries to operate

Cavity string out of Clean Room



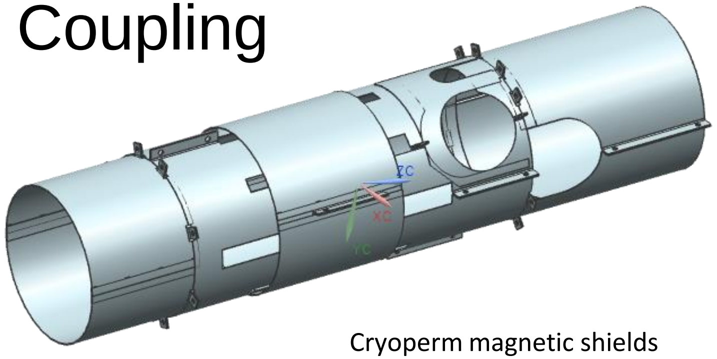
Tuner assembly, connection of linear actuator



Ti welds to complete cryogenic circuit of cavities

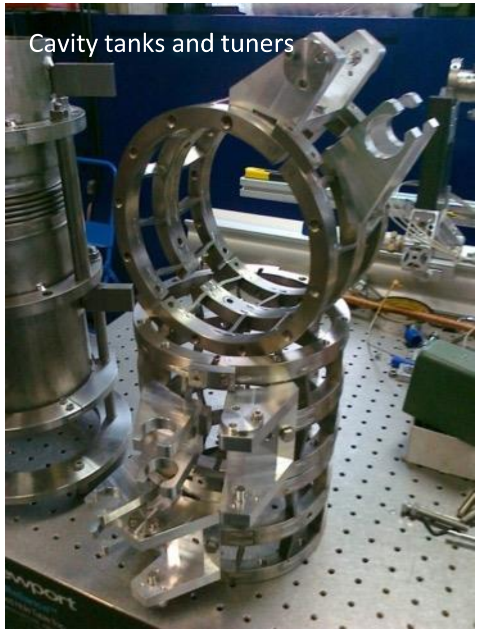
Ancillaries

- Several ancillary components need to be assembled either in clean conditions or on the cavities
  - Antennas for Field probe, HOM removal and Power Coupling
  - Intercavity components
  - Cavity tuners



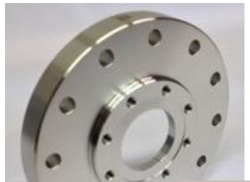
Cryoperm magnetic shields

PU and HOMs



Cavity tanks and tuners

Tank&Tuner characterization



Beamline transition flanges

(etc...)

Intercavity bellows (prototype)

Fundamental Power Couplers(1)

G. Burt, next Thu

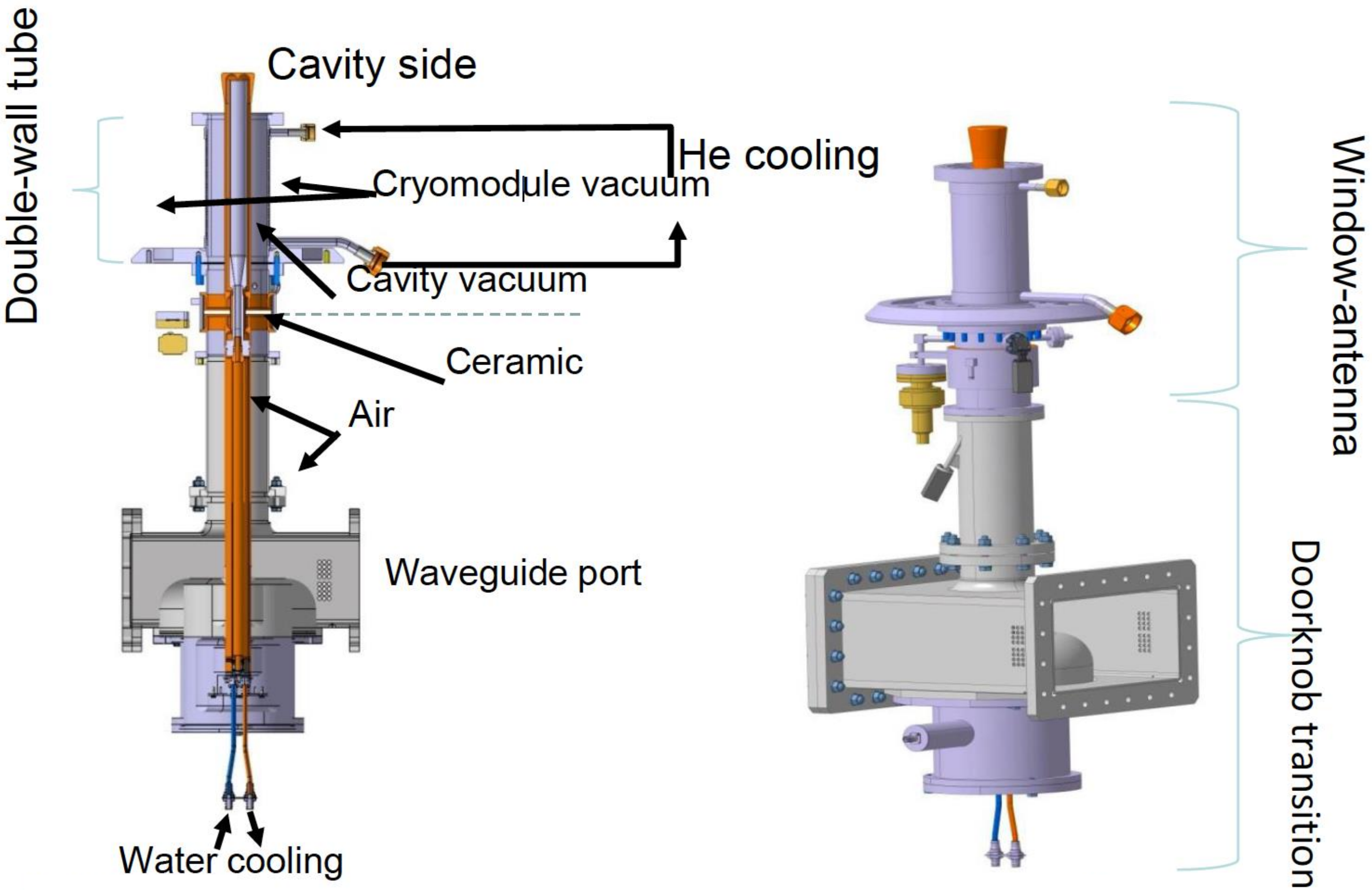
- A coupler provides the proper rate of energy transfer to a resonator: characterized by Q_{ext}
- For SC cavities a power coupler
  - Establishes the electromagnetic fields in the cavity
    - Antenna penetration can be adjusted for optimal coupling (or not)
  - Has to support the thermal gradients (300K to 2K) with minimal heat loads to 2K
    - Intercept direct conduction, use proper choice of material
  - Has to provide a vacuum barrier
    - Ceramic window(2)
  - Has to prevent contamination
    - Follows similar processes in CR as cavities
  - Must not deteriorate cavity performance
- Requirements on couplers are becoming increasingly more demanding:
  - Higher gradients require more standing wave power
  - Higher beam currents: more traveling wave power
  - Pulsed power: transient conditions, transient gas loads

Fundamental Power Couplers (2)

- Power couplers for superconducting cavities are very complicated structures, which must perform at the limit of several technologies:
    - Brazing,
    - Welding,
    - Coating (copper on SS parts),
    - Coating (TiN, anti-multipacting),
    - Vacuum (proper design and leak rate),
    - RF power,
    - Cleaning, compatible with cavity environment
    - testing/conditioning (interlocks for arcing, electrons)…
- In general, couplers are at least as delicate, vulnerable and as expensive as niobium cavities

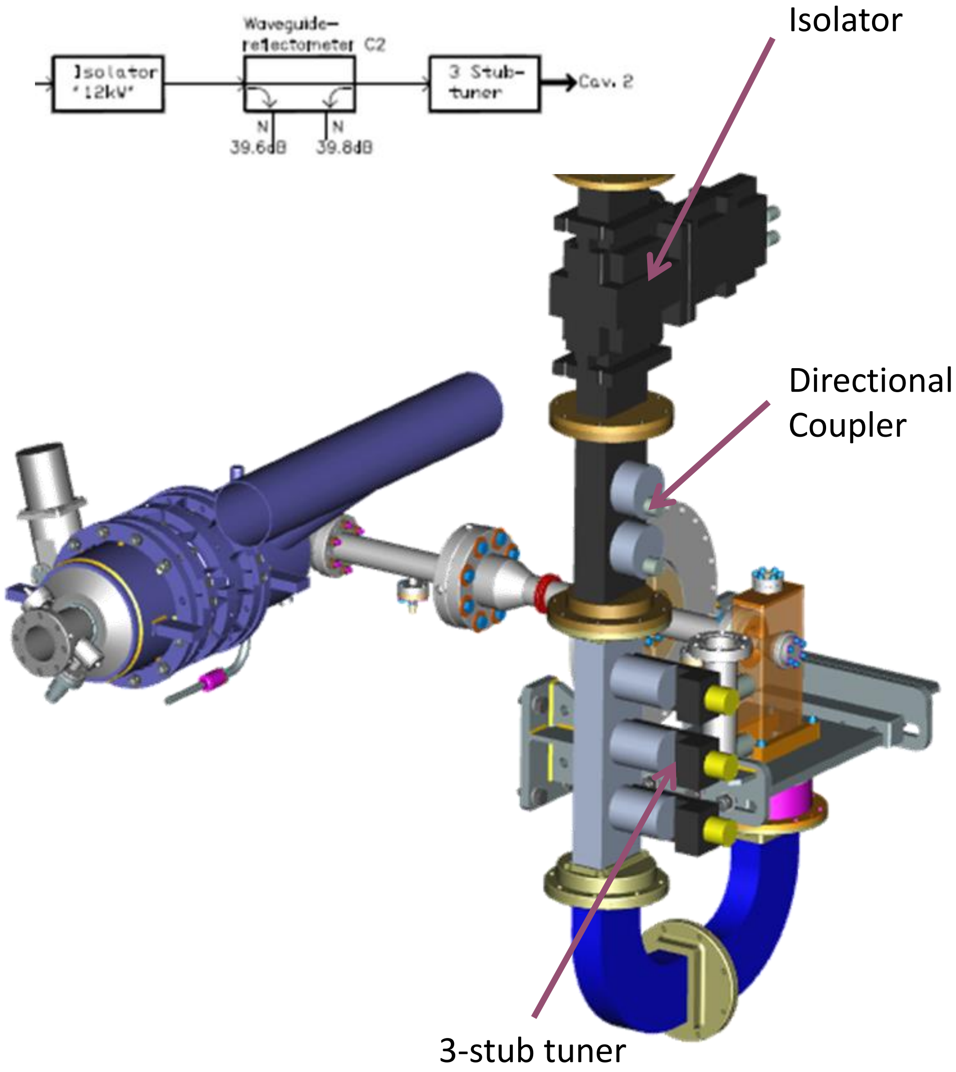
Example: 1.2 MW Peak ESS FPC (CEA)

- WG to coax matched transition
- Fixed coupling
    - ESS is 1:1 RF-Cav
- He cooling on outer conductor within the cryomodule to limit conductive load
- Single (TiN coated) window
- Antenna water cooling
- Diagnostics (Arc,e-)



XFEL 3.9 with Phasing and QL adjustment

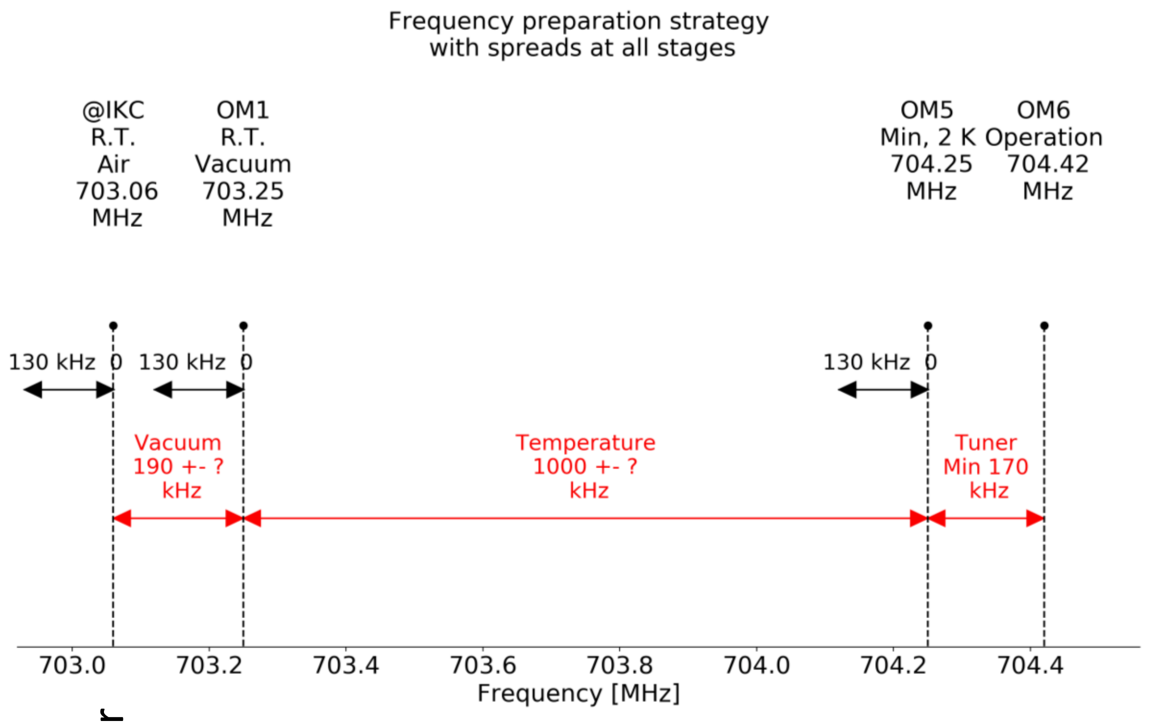
- Fixed coupler design
- WG distribution with splitters to provide RF power to cavities
  - May include phase shifters
  - Flexible waveguide sections
- Use 3-stub tuners to achieve the desired QL adjustment and cavity phasing with a fixed coupler and no phase shifters



The cavity tuner

- The tuner adjusts the cavity frequency to the Master Oscillator of the RF systems
- Usually it shortens or lengthens the cavity to use ($\partial f/\partial z$)
    - Tuning is generally a “slow” process (~Hz/s)
    - A Fast (piezo-based) tuning action can be added to compensate dynamic cavity behavior
        - LFD, microphonics
- Need to work in a well defined mechanical situation
    - Avoid “inversion points”

Cavity fabrication need to set a goal frequency to account for cavity tunability



As fabricated, in air

$f \sim 1/\sqrt{\varepsilon_r}$

$\partial f/\partial z \sim 210\ \mathrm{kHz/mm}$

$\Delta f/f = -\Delta\ell/\ell$

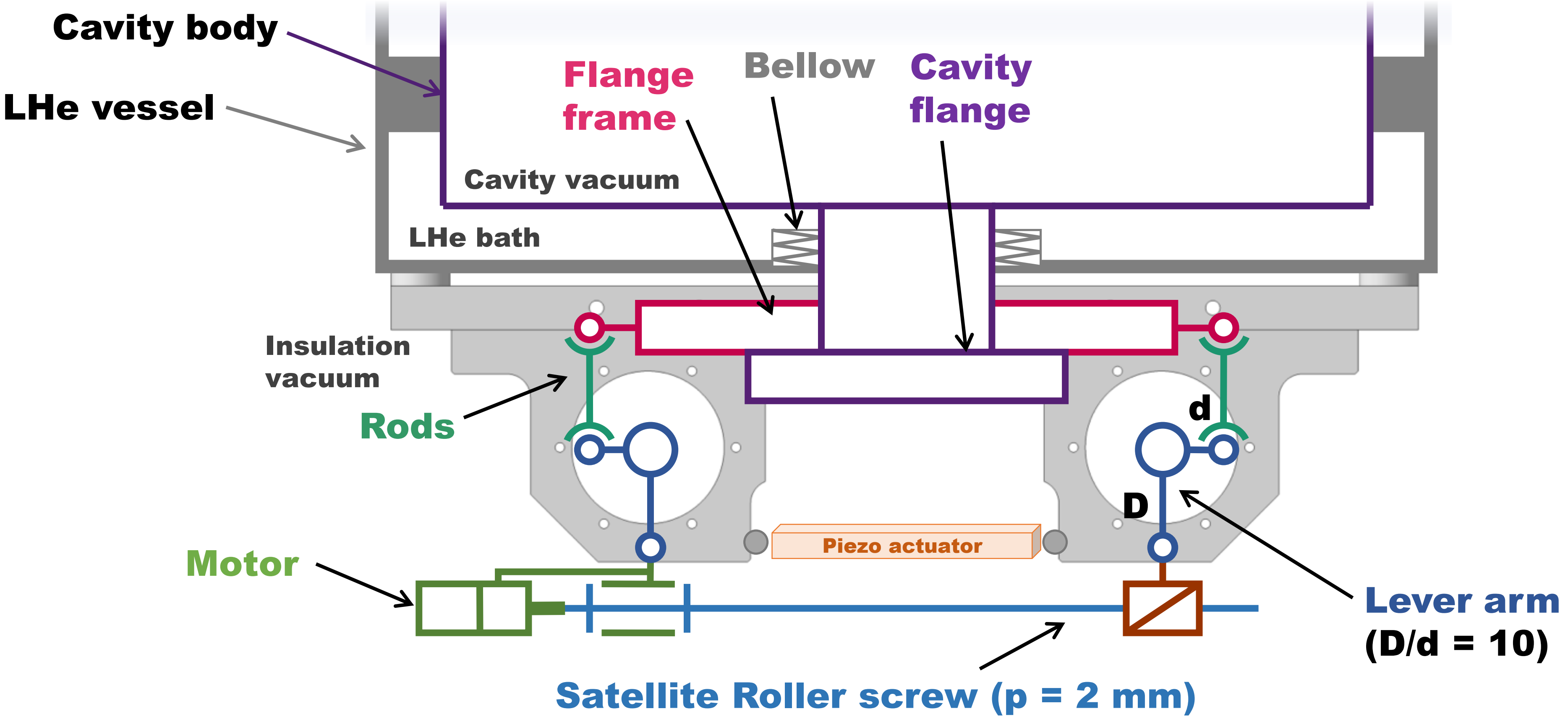
OPERATION

ESS ELL criteria

The ESS SPK Tuner

A satellite roller screw system driven by a stepper motor acts on a double lever arm mechanism to provide a significantly reduced displacement of the cavity flange along the beam axis

Courtesy N. Gandolfo, IJCLAB



Course of RF for Accelerators

End of Part I

Why SRF, from Design to Cavities

References

- Hasan Padamsee books on SRF Technology by Wiley
- CAS Proceedings
  - 2013 Superconductivity
  - 2011 High Power Hadron Machines
  - 2010 RF for accelerators
  - ...
- Tutorials before SRF Conferences (since 2007)
- International SRF Conference proceedings (every odd year)
- International collaboration meetings
  - TTC, SLHIPP