Congresso Nazionale SIF 2021 - Milano

Superconducting RF cavities activities at INFN LASA

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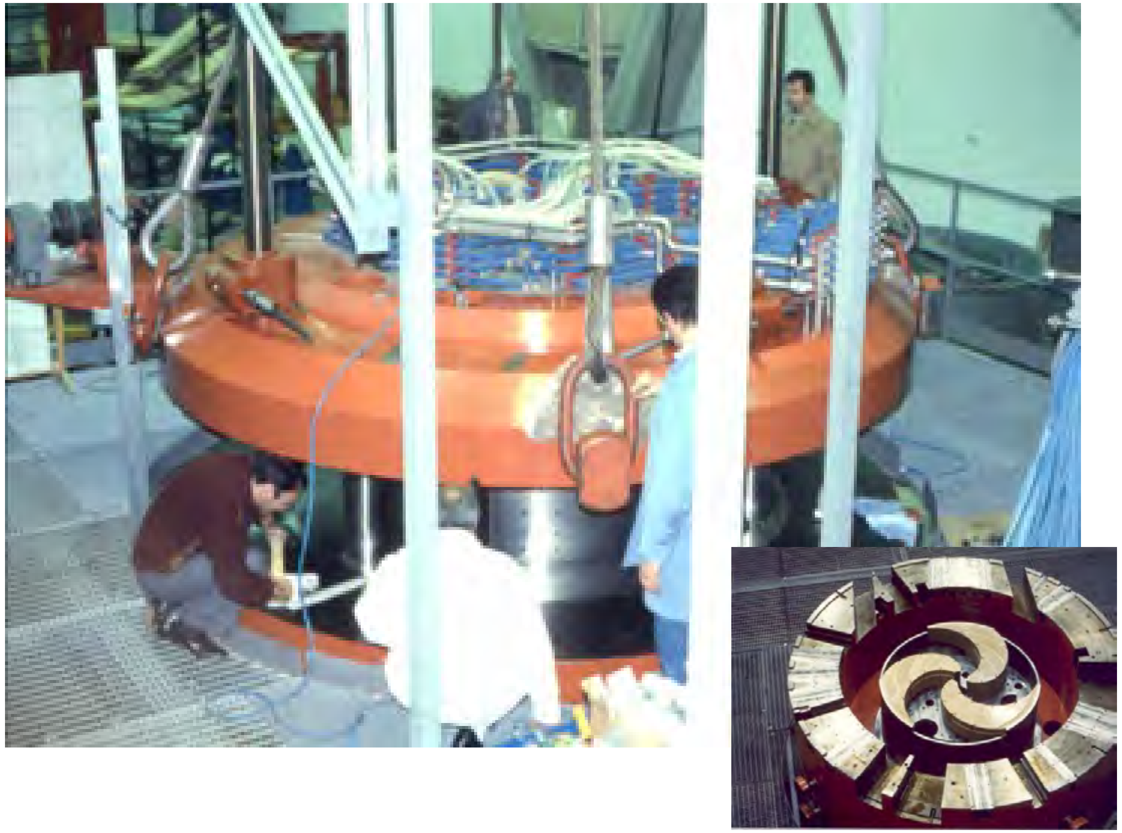
INFN Milano - LASA

The Superconductivity path in Milano

- LASA is an INFN lab hosted by Universita' degli Studi di Milano
- LASA (**L**aboraotorio **A**cceleratori e **S**uperconduttività **A**pplicata) was built in the '80 to realize a K800 SC Cyclotron, the first in Europe and the third worldwide.
- Designed, built and tested in Milano, it is in operation since 1994 at LNS in Catania



It is now a **center of excellence** at an international level in the field of advanced technology for particle accelerators.

The **main mission** of LASA currently is the development of **radiofrequency superconducting resonators** for particle beam acceleration and **superconducting magnets** for particle beam orbit and focusing.

Today LASA main assets

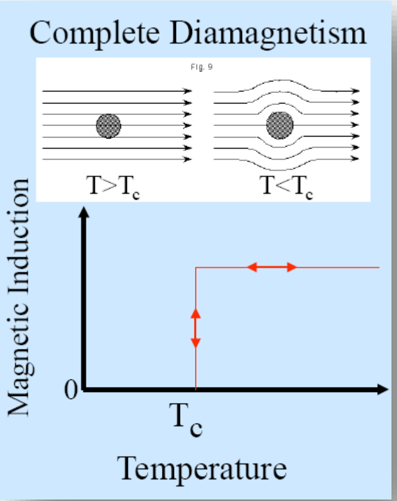
- **Experience, competences, capabilities for design, prototyping, testing, industrialization and series production** of accelerator components for High Energy and Applied Physics.
  - **Superconducting (SC) RF accelerating cavities**, cryostat and ancillaries for electron and protons accelerator
  - **High intensity Superconducting magnets** for accelerator and detectors
  - **Photocathodes** for High Brightness Electron Sources (RF Gun)
- Our competences on several projects as **European XFEL, ESS, LHC-HiLumi, PIP II, etc.**
- **Long tradition of LASA** for working in collaboration with industries, since the time of the Superconducting Cyclotron, the LEP cavities, the LHC dipoles: ASG (ex ANSALDO), Ettore Zanon, SAES GETTERS, RIAL VACUUM, etc.
- **Specific M.o.U's** have been signed with many international laboratories and organization as CERN, DESY, FNAL, JLAB, KEK, GSI, LBNL, DOE, SHINE, etc.

- Further activities
  - **Accelerators for medical application: LIBO and ACLIP** (CNS5)
  - **Laser light ion acceleration** (CNS5 L3IA)
  - **Radionuclides** production and separation, nuclear medicine and environmental fields (CNS5, several experiments)
  - **Neutron dosimetry**
  - **Training and Third Mission**
    - *University Courses*
    - *Professional Courses* for internal and external users
    - *Dissemination* of scientific themes for schools and public

Superconducting Radio Frequency

Superconductivity

- The 3 Hallmarks of Superconductivity
  - Complete diamagnetism "Meissner effect"



Meissner

and

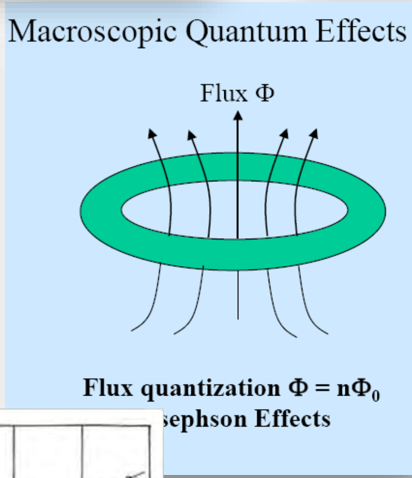
Ochsenfeld

1933

  - Macroscopic Quantum Effects
    - Flux quantization

$$\Phi = n\, \Phi_0$$

$$\Phi_0 = \frac{h}{2\, e} \approx 2.068\ 10^{15} Tm^2$$



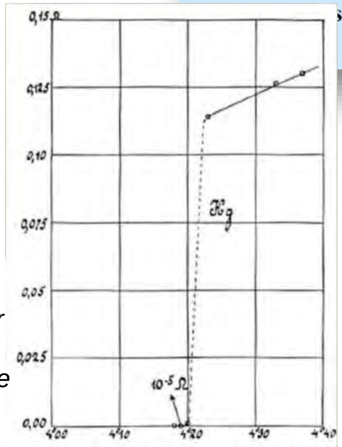
Deaver

and

Fairbank

1961

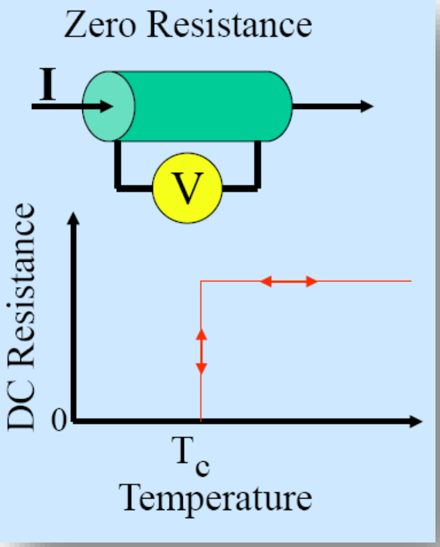
  - Zero resistance



Historic plot *of resistance (ohms) versus temperature (kelvin) for mercury from the 26 October 1911 experiment shows the superconducting transition at 4.20 K. Within 0.01 K, the resistance jumps from unmeasurably small (less than 10^{-6} Ω) to 0.1 Ω.*

Kammerlingh-Onnes

1911



RF Losses in NC and SC Cavities

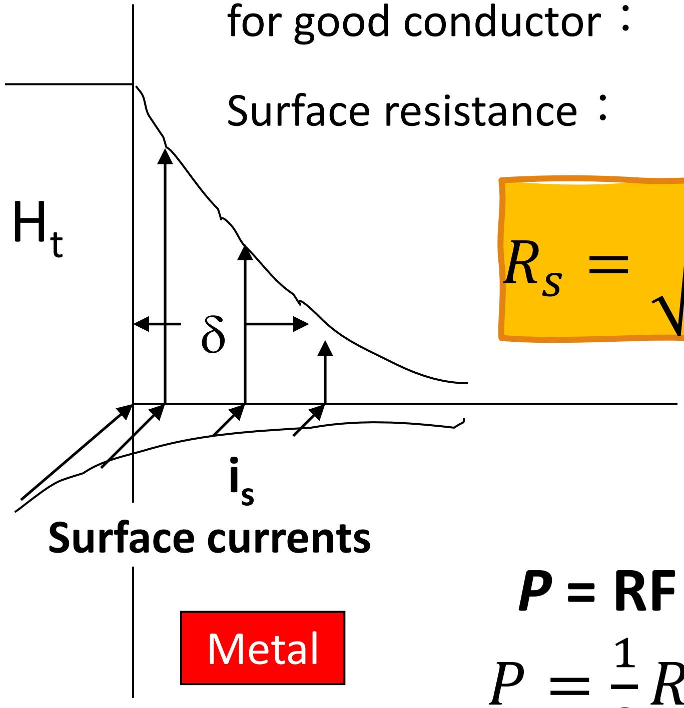
Normal conducting

δ = skin depth of microwave

for good conductor : $\frac{\sigma}{\omega\epsilon} \gg 1$

Surface resistance :

$$R_s = \sqrt{\frac{\mu\omega}{2\,\sigma}} = \frac{1}{\sigma\delta}$$



***P* = RF losses**

$$P = \frac{1}{2} R_s \int H_s^2 ds$$

Superconducting

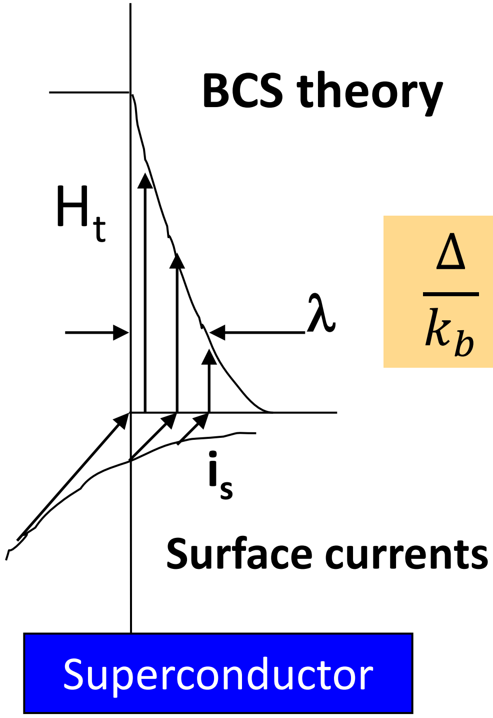
λ = London penetration depth

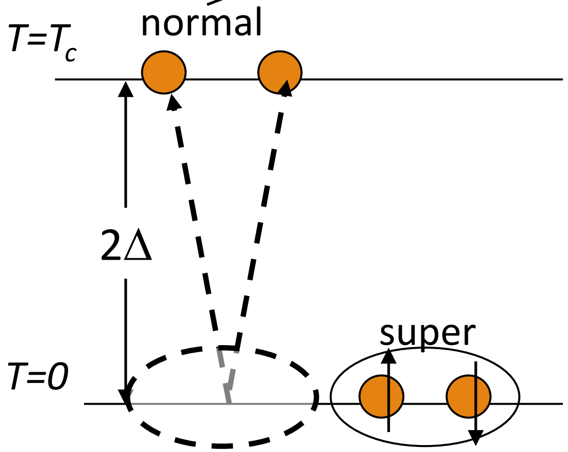
BCS theory

$$R_s \propto \frac{\omega^2}{T} e^{-\frac{\Delta}{k_B T}}$$

$$\frac{\Delta}{k_b} = 1.76\,T_c$$

$$e^{-\frac{\Delta}{k_B T}}$$





$$Q_0 = \frac{\omega U}{P} = \frac{G}{R_s}$$

Why Superconductivity in RF linacs?

- In normal conducting linacs a huge 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 and:
  - cavities transfer **more efficiently** the RF power to the beam.
  - it allows large bore radius (**less beam losses**)
  - **CW** or **high duty** cycle operation.

- In short:
  - NC linac: lower capital cost, but high operational cost
  - SC linac: higher capital cost, but low operational cost

Estimates of Rs

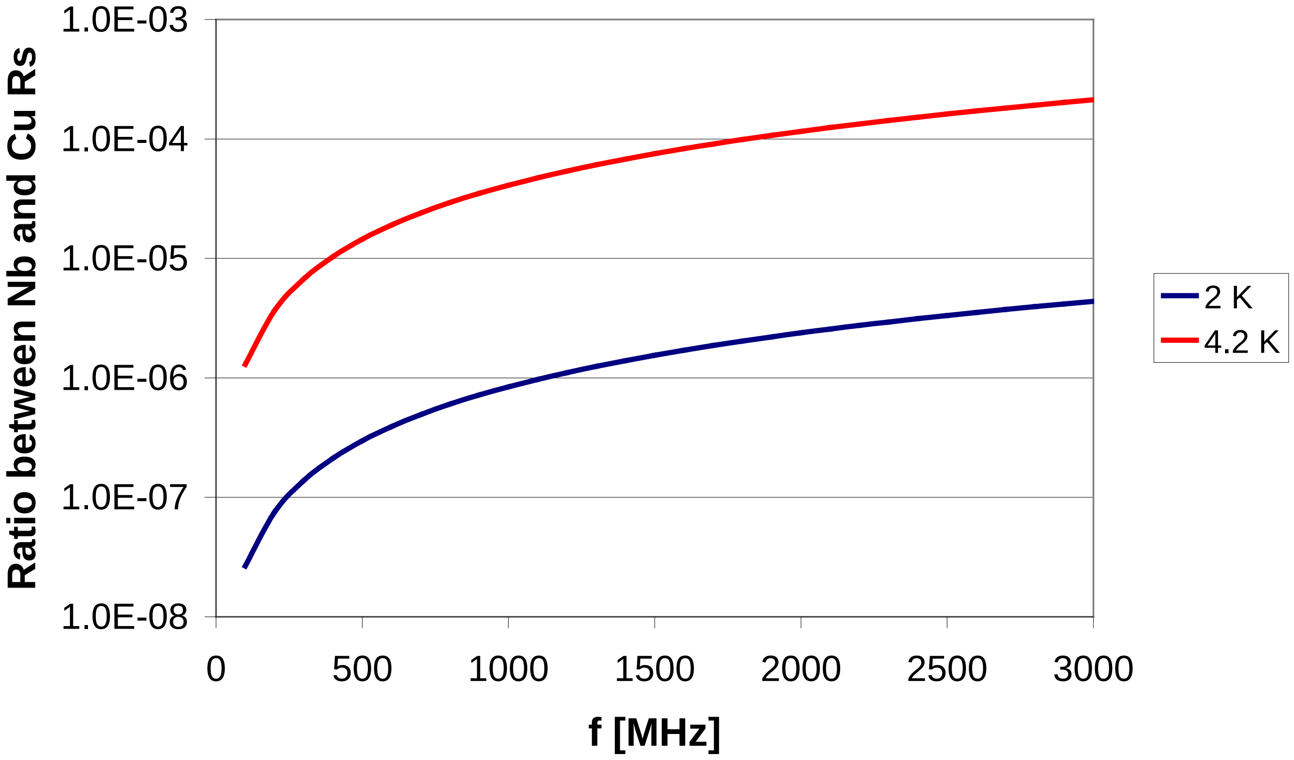
- With RF fields, a SC cavity still dissipates power, since not all e⁻ are in Cooper pairs.

- For bulk Nb (with a critical temperature of 9.2 K), the temperature dependent surface resistance can be approximated by:

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

- The surface resistance of room temperature copper is:

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



But... Take into account Carnot

- The R_s predicts a factor 10^5-10^6 of reduction in losses, but we need to keep in mind that in the SC case, this 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:

$$\eta_C = \frac{T_2}{T_1 - T_2} = \begin{cases} 1/70 \text{ for } T_1 = 300\text{K}, T_2 = 4.2\text{K} \\ 1/150 \text{ for } T_1 = 300\text{K}, T_2 = 2\text{K} \end{cases}$$

$$\eta_{th} = \begin{cases} 25-30\% \text{ at } T = 4.2\text{K} \\ 15-20\% \text{ at } T = 2\text{K} \end{cases}$$

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

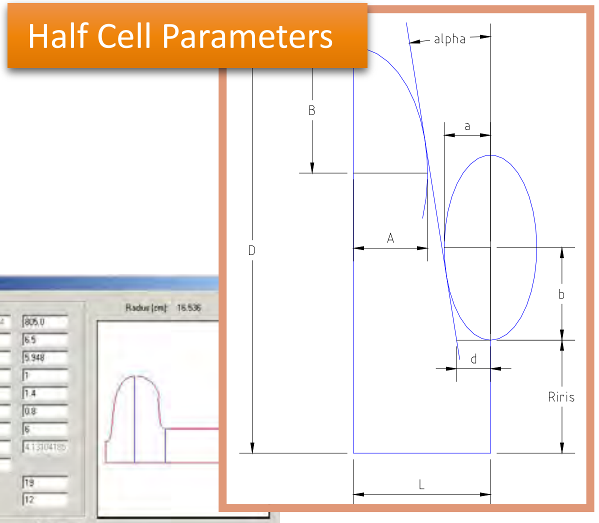
- Of course, life is generally worse than that, since here we neglected (at least):
  - Static power losses in the He bath (power directly in the He)
  - Material impurities which increase R_s (higher dissipation)
- Still, a wide frequency range favours superconductivity

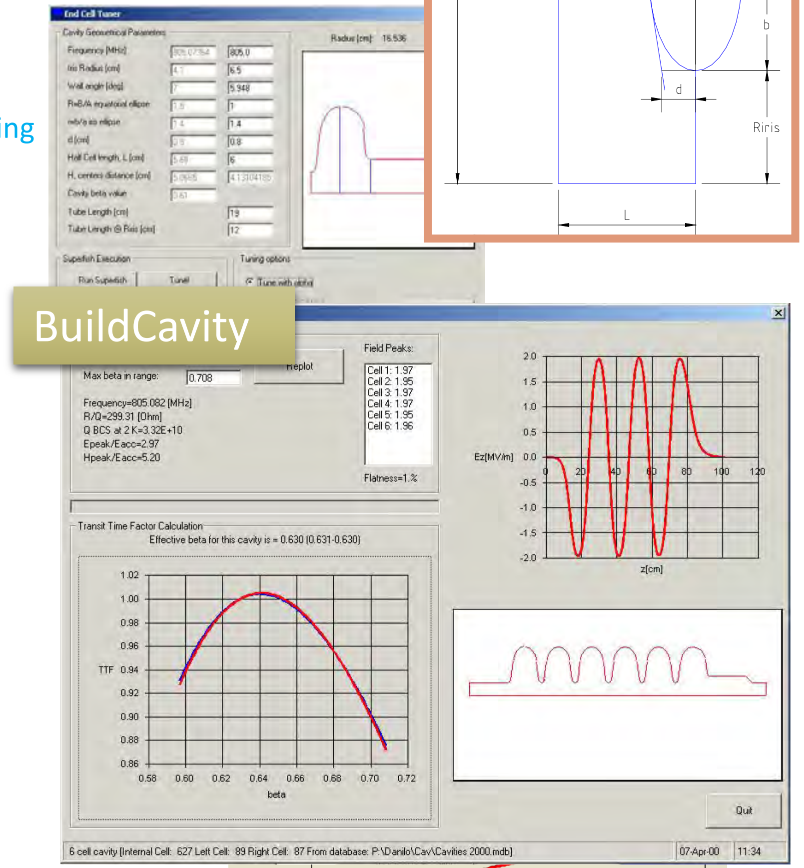
SRF Elliptical Cavities and related components

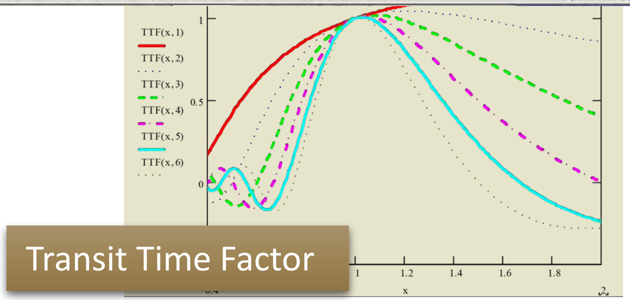
Cavity – Electromagnetic Design

- Full parametric model in terms of 7 geometrical parameters:
  - Ellipse ratio at the equator (R=B/A) Ruled by Mechanics
  - Ellipse ratio at the iris (r=b/a) E_{peak}
  - Side wall inclination (α) and position (d) E_{peak} vs. B_{peak} tradeoff and $k_{coupling}$
  - Cavity iris radius R_{iris} $k_{coupling}$
  - Cavity Length L Geometrical β
  - Cavity radius D Frequency tuning

- We built a parametric tool for the analysis of the cavity shape on the electromagnetic (and mechanical) parameters
  - All RF computations are handled by SUPERFISH
  - Inner cell tuning is performed through the cell diameter, all the characteristic cell parameters stay constant: R, r, α, d, L, R_{iris}
  - End cell tuning is performed through the wall angle inclination, α, or distance, d. R, L and R_{iris} are independently settable.
- All e.m. cavity results are stored in a database for futher parametric investigations.
- A multicell cavity is then built to minimize Field Flatness, compute β and TTF as well as final performances.







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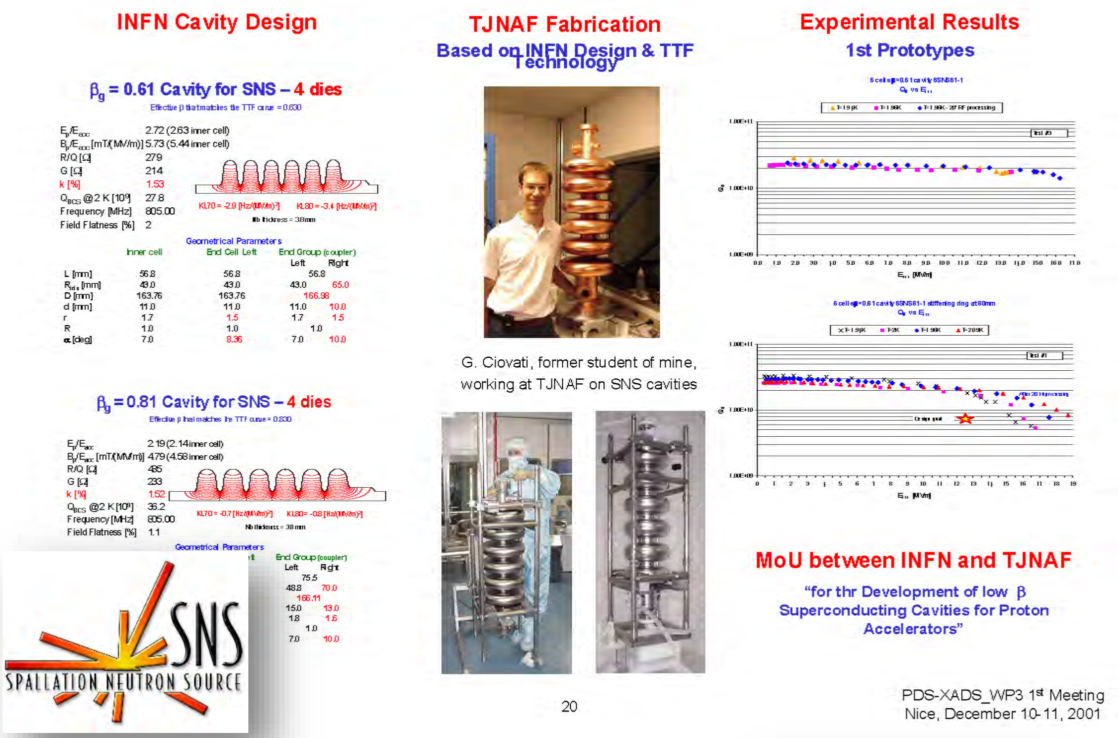
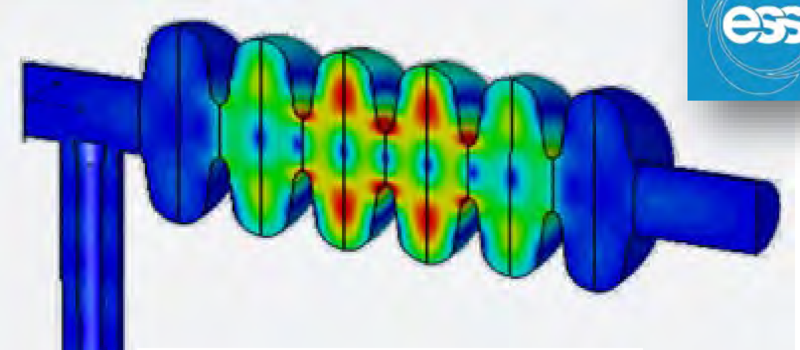
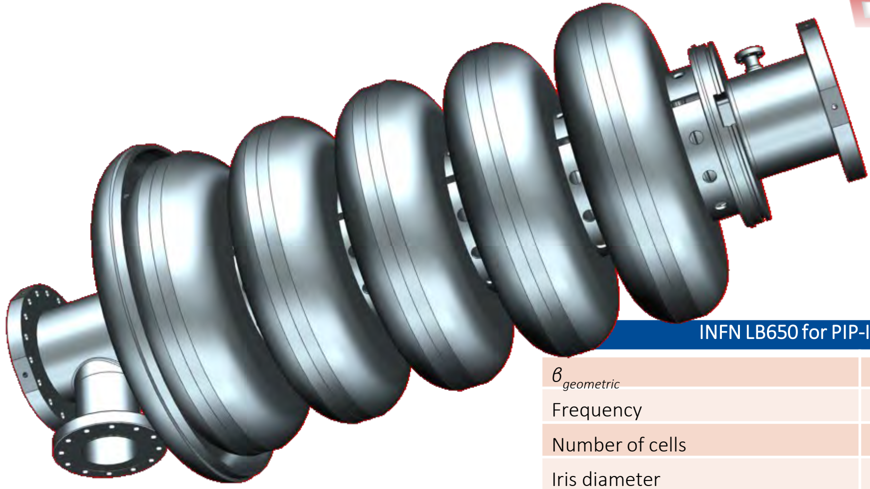
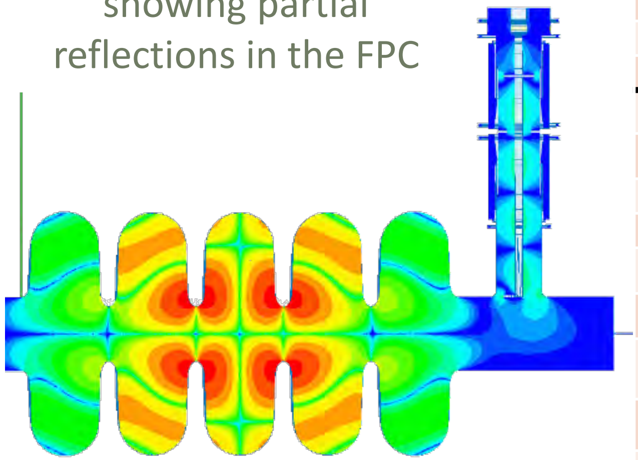
Cavity – Electromagnetic Design Examples





ESS MB Cavity: Example of **EM analyses performed**: Dipole HOM at 1742.47 MHz



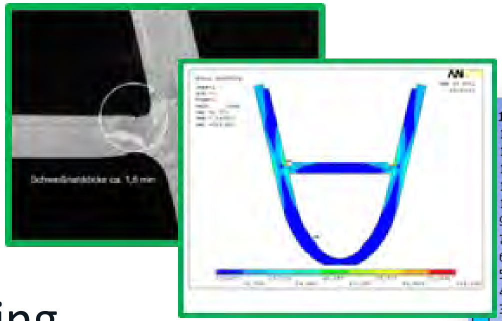


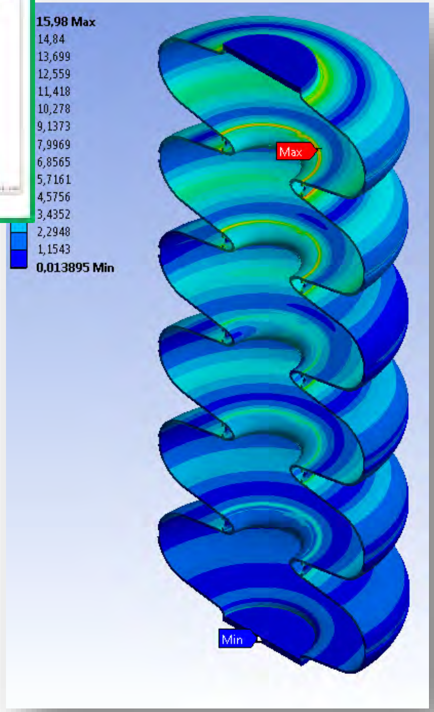
PIP-II LB Cavity: Example of **EM analyses performed**: Dipole HOM at 1678 MHz showing partial reflections in the FPC

INFN LB650 for PIP-II, cold cavity	
$\beta_{geometric}$	0.61
Frequency	650 MHz
Number of cells	5
Iris diameter	88 mm
Cell-to-cell coupling, k_{cc}	0.95 %
Frequency separation π-4π/5	0.57 MHz
Eq. diameter - IC	389.8 mm
Eq. diameter - EC	392.1 mm
Wall angle – Inner & End cells	2 °
Effective length (10*L_{hc})	704 mm
Optimum beta β_{opt}	0.65
E_{peak}/E_{acc} @ β_{opt}	2.40
B_{peak}/E_{acc} @ β_{opt}	4.48 mT/(MV/m)
R/Q @ β_{opt}	340 Ω
G @ β_{opt}	193 Ω
Inner cells stiffening radius	90 mm
External cells stiffening radius	90 mm
Wall thickness	4.2 mm
Longitudinal stiffness	1.8 kN/mm
Longitudinal frequency sensitivity	250 kHz/mm
LFD coefficient k_{ext} *at 40 kN/mm*	-1.4 Hz/(MV/m)^2
Pressure sensitivity k_{ext} *at 40 kN/mm*	-11 Hz/mbar
Maximum Pressure *VM stress at 50 MPa*	2.9 bar
Maximum Displacement *VM stress at 50 MPa*	1.5 mm

Cavity – Mechanical Design

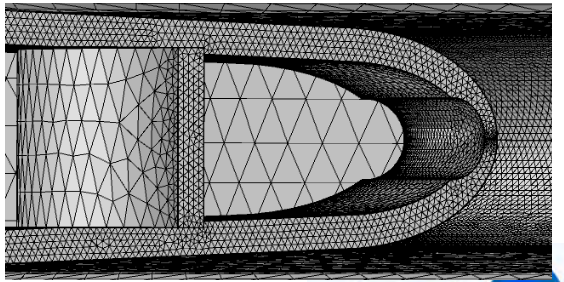
- The EM design is transfer to mechanical analysis (loop) for estimating critical parameters as:
  - Ring radius
  - Stiffness
  - Tuning sensitivity
  - Vacuum sensitivity
  - Lorentz Force Detuning
  - PED compliance
- Developed a specific tool

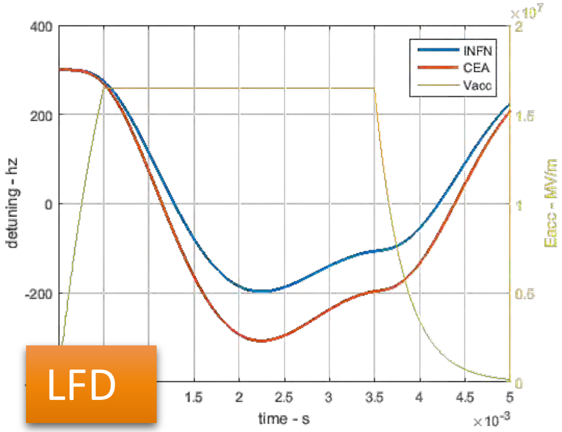




Mechanical Parameters	INFN design
Cavity wall thickness (mm)	4.2
Stiffening ring radius (mm)	70
Internal volume (l)	69
Cavity internal surface (m^2)	1.8
Stiffness (kN/mm)	1.7
Tuning sensitivity K_T (kHz/mm)	205
Vacuum sensitivity K_V - k_{ext} ~ 21 kN/mm (Hz/mbar) -	-8
LFD coefficient K_L - k_{ext} ~ 21 kN/mm (Hz/(MV/m)^2) -	-1.8

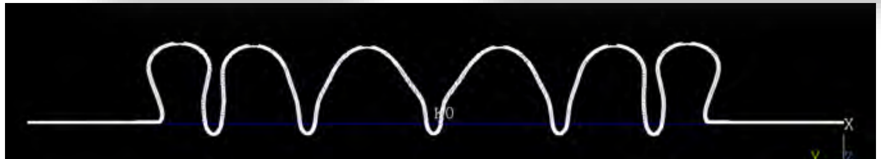
MECHAVITY





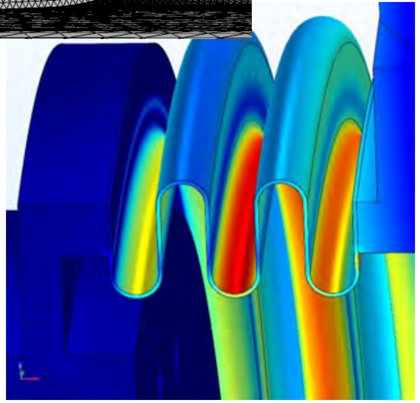
LFD

EUROPEAN SPALLATION SOURCE



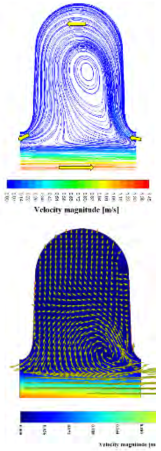
Dynamical analyses: natural modes

PIP-II

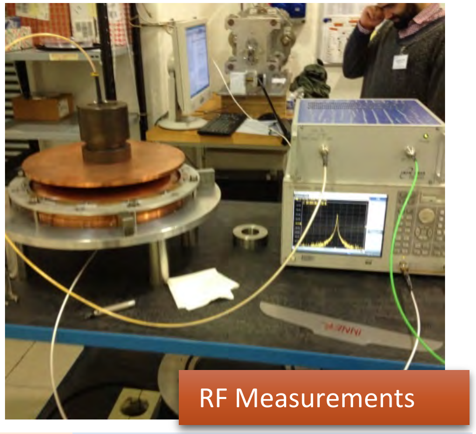


Cavitiy - Towards production -> Prototypes

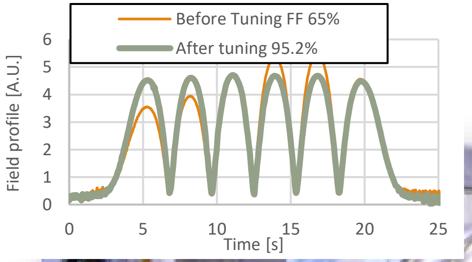
- A key element of our expertise consists also in the transfer of the em-mechanical design to production:
  - RF procedures from sheets to cavity
  - Define production cycle to guarantee final length and frequency
  - Define appropriate treatment (BCP, EP, etc.)
  - Mechanical and RF measurement and control plan
  - Test of defined scheme on prototypes
  - 2 K test for final acceptance

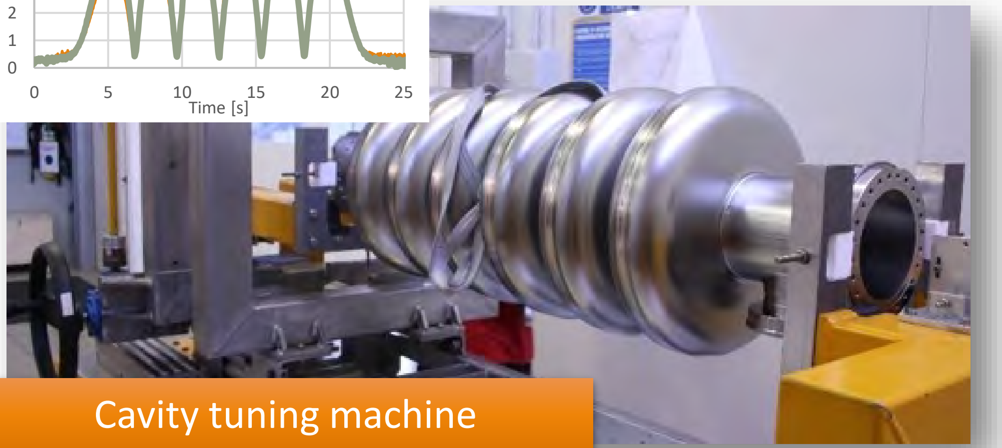


Simulated (sx) vs. Measured (dx) velocity field during etching

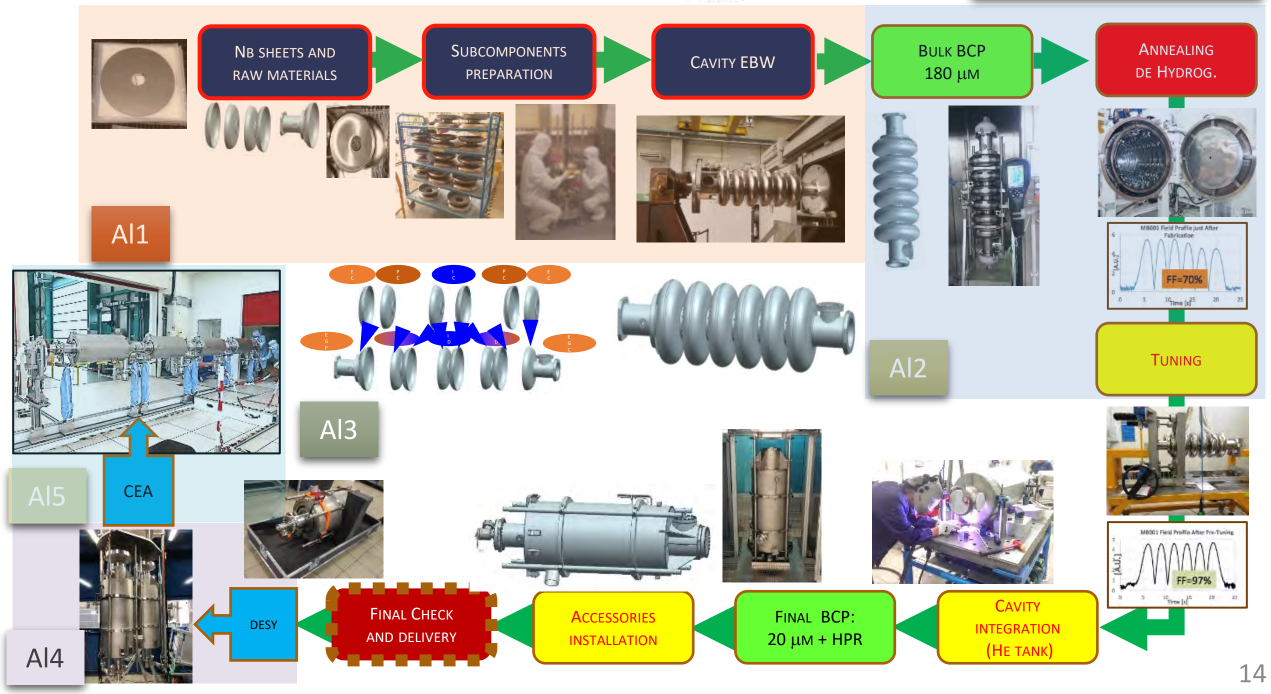


RF Measurements



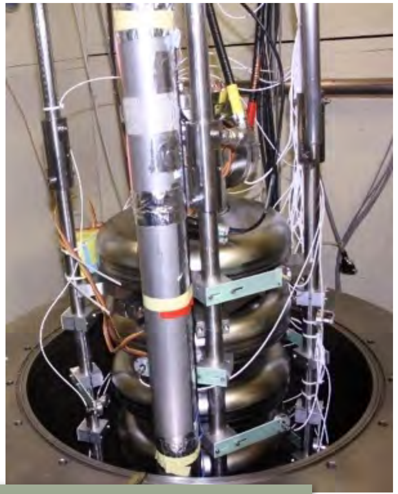


Cavity tuning machine

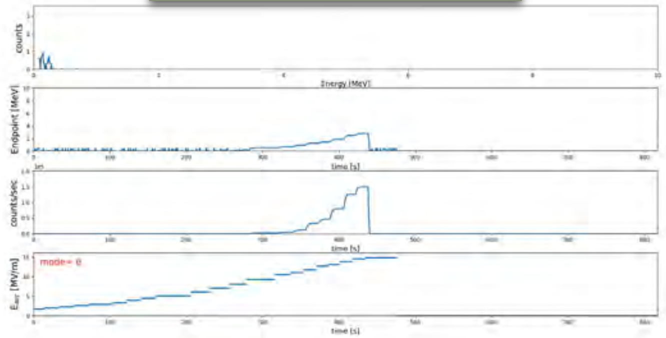


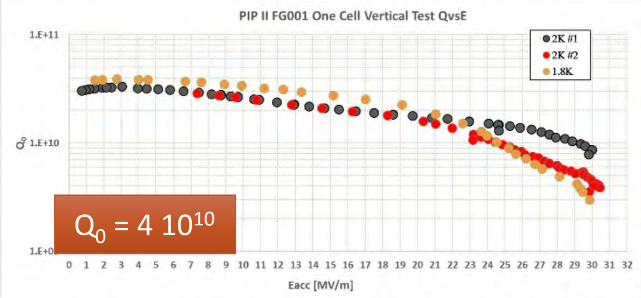
Cavity – Cold test @ LASA

- **Clean Room and UPW**
  - Ultra Pure Water plant
  - ISO4/7 clean room, HPR system
  - Qualified Slow Pumping Slow Venting system
- **Cryostat**: ϕ 700 mm, 4.5 m length, **losses < 1 W @ 4 K**
- **Residual magnetic field**: < **8 mG** (single shield).
  Single μmetal external shield, second cryogenic shield (Cryoperm) just installed and measurement in progress.
- **Sub-cooling system**:
  - Cooling power: ~ **70 W @ 2 K**
  - Lowest temperature **1.5 K**.
  - Soon capability of **direct filling at 2 K**
- **RF** capability (500 to 3900 MHz)
- Dedicated inserts with several diagnostics: **second sound** detectors for quench localization, **cryogenic photodiodes**, **fast thermometry, flux gate**.
- **X-ray counter** and **X-ray NaI spectrometer** available.

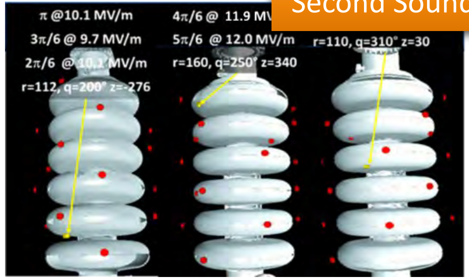


Real-time Scintillator





Second Sound

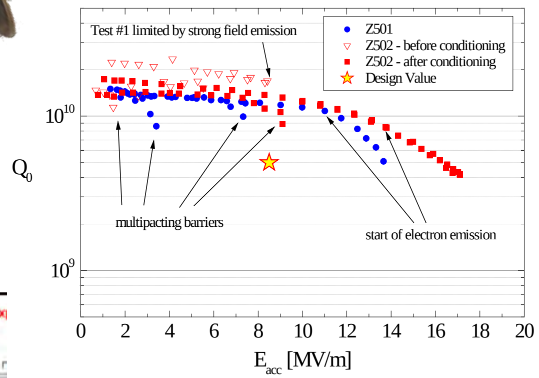


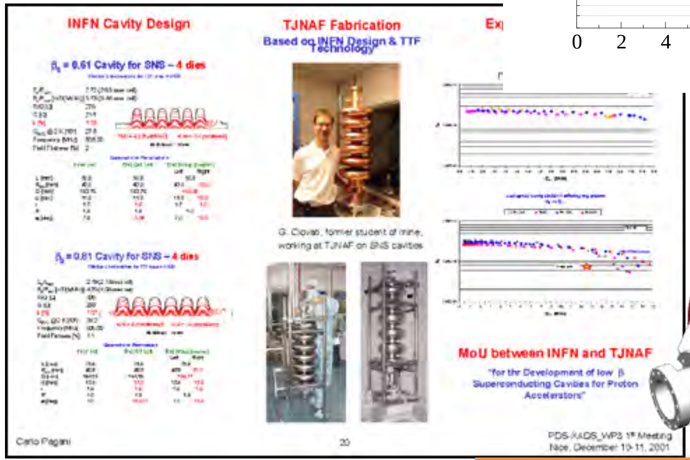
Internal Magnetic Shield

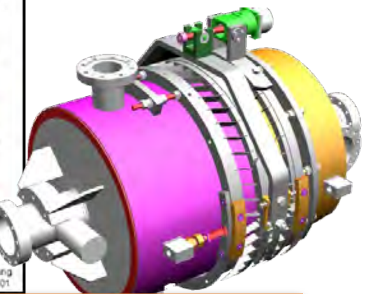
SC RF for high intensity proton linacs

- In the past there have been several **activities** in collaboration with different labs, **in the framework of national and international programs**, on high intensity SC proton linac projects (TRASCO, ADS, SNS, PDS-XADS, MAX, MYRRHA).
  Cavity design, prototypes, cryomodule production, etc. …

TRASCO Cavity

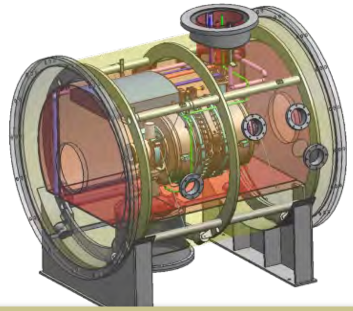




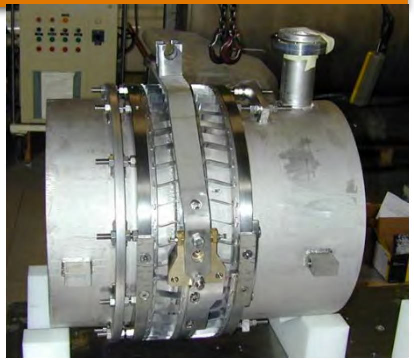


HIPPI: Tuner & He tank

MYRRHA ACCELERATOR EXPERIMENT
RESEARCH & DEVELOPMENT PROGRAMME



EUROTRANS Cryomodule



Cavity – Series Production

- INFN LASA has a long experience on **cavity design, fabrication and qualification** of SC cavities.
- We shared with DESY the production of the **800 cavities** at **1.3 GHz** for European-XFEL cavity production with European companies.
- Afterwards, we have been in charge of the design, production and test of the **20 cavities for the 3.9 GHz** module for European-XFEL.
- We are now involved in the ESS project as responsible for the Italian In-Kind contribution to the Medium Beta Section of the Superconducting Linac with **36 cavities** at **704.4 MHz**.
- We are also starting our activities towards the production of the **36 Low Beta cavities** at **650 MHz** for the PIP-II accelerator of the LBNS at FNAL.

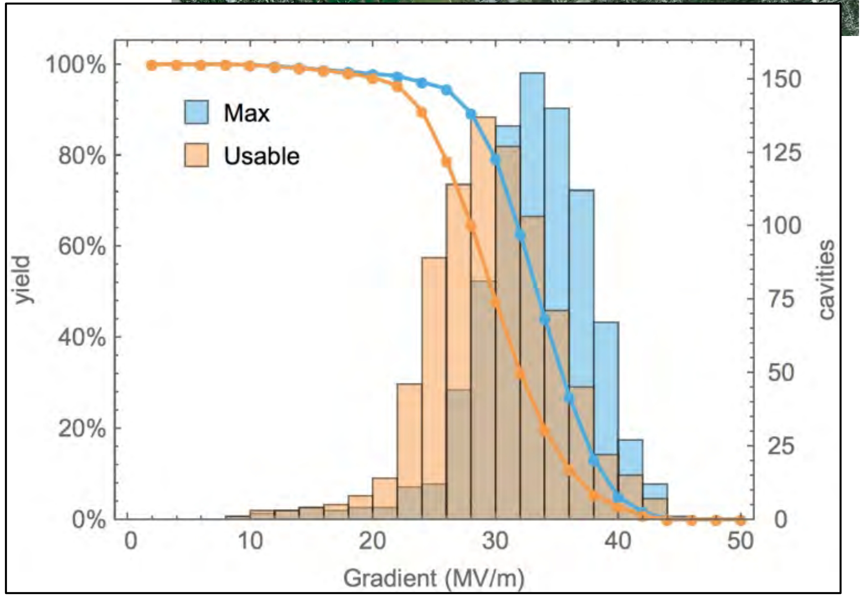
European XFEL: 1.3 GHz SC cavities results

Objective:

- 800 SC cavities
- average usable E-XFEL gradient 23.6 MV/m @ $Q_0=1x10^{10}$, X-Rays <$1x10^{-2}$ Gy/min
- Delivery rate: about 8 CVs/week

Results:

- **Accepted Cavities** as Delivered: **≈ 75% (over 800)**
- **Rejected Cavities** (replaced by companies): **8 (1%)**
- After Additional Treatments: **all cavities accepted**



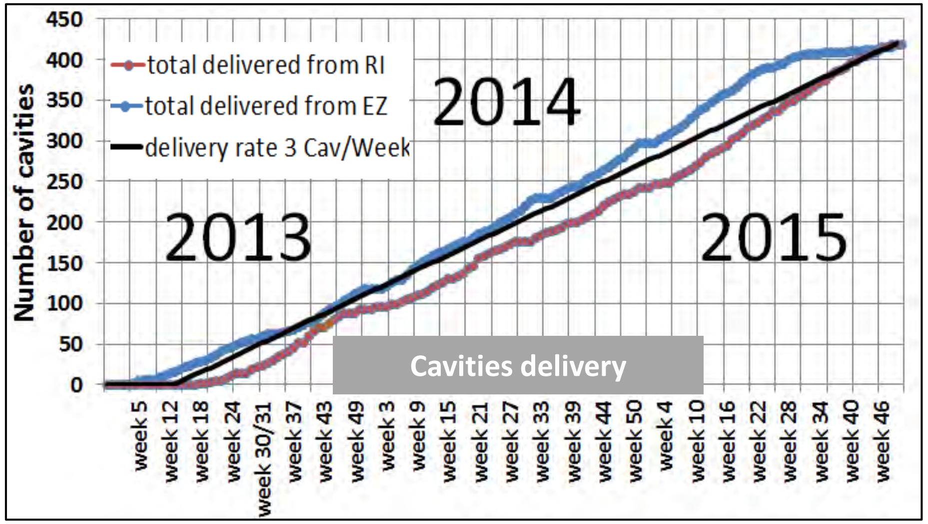
Final Performances

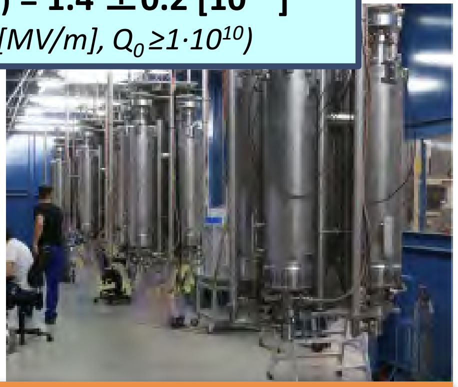
E_{max} = 33.0 ±4.8 [MV/m]

E_{usable} = 29.8 ±5.1 [MV/m]

Q_0 (23.6MV/m) = 1.4 ±0.2 [10^{10}]

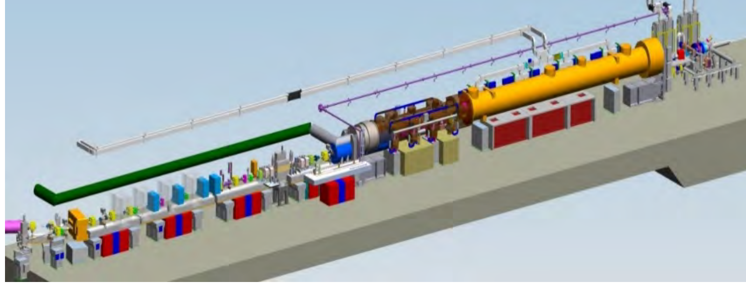
(E_{goal} = 23.6 [MV/m], $Q_0 \geq 1 \cdot 10^{10}$)





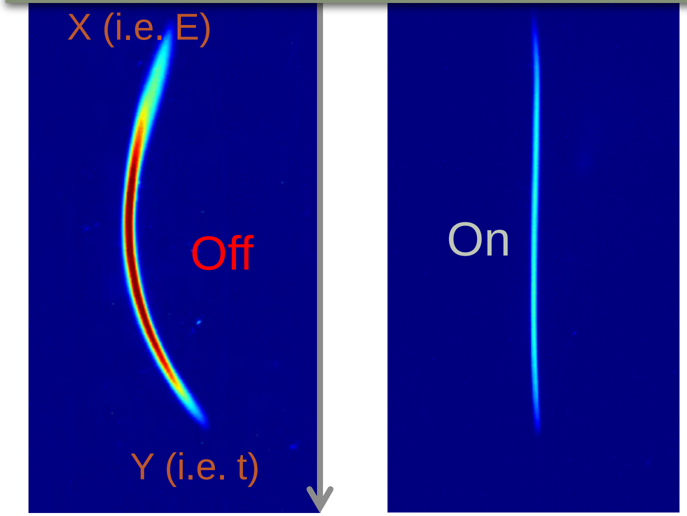
Cavities ready for the cold test

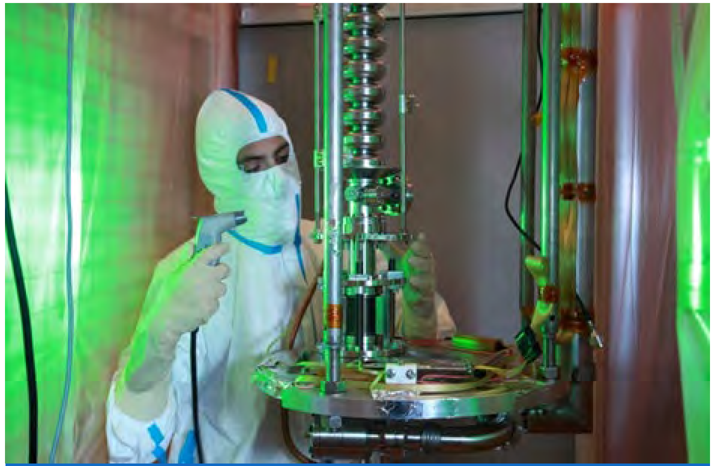
European XFEL 3.9 GHz series production



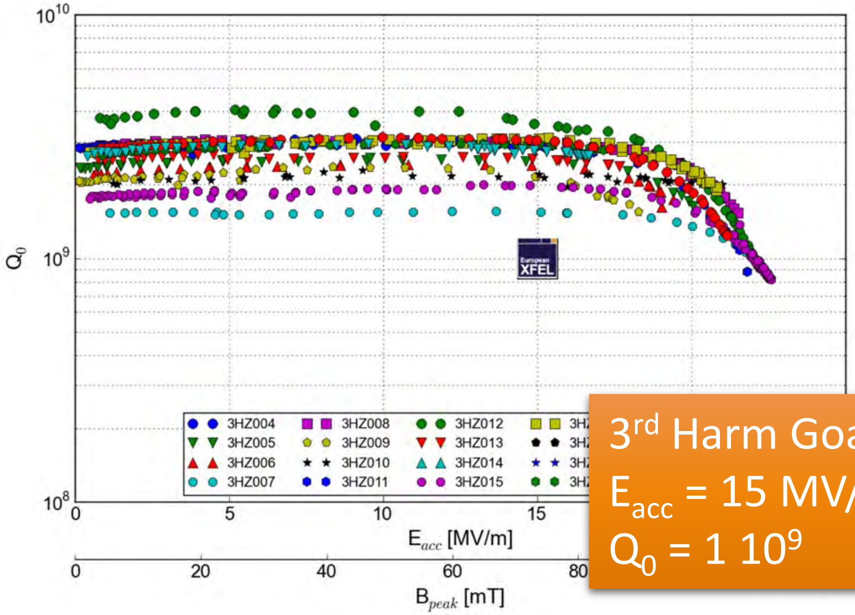
- **Linearization** of phase space to improve FEL performances
- All 20 cavities **overcome** the requests!
- Improvement of the QC (based on the 1.3 GHz experience)
  - **Inner visual inspection** after bulk BCP and annealing (check of the surface quality)
- 3 prototypes lessons learnt
  - **Adaptation** of the 1.3 GHz infrastructures for BCP treatment to the smaller dimensions of the 3.9 GHz cavities was tricky

RF Curvature Linearization by AH1



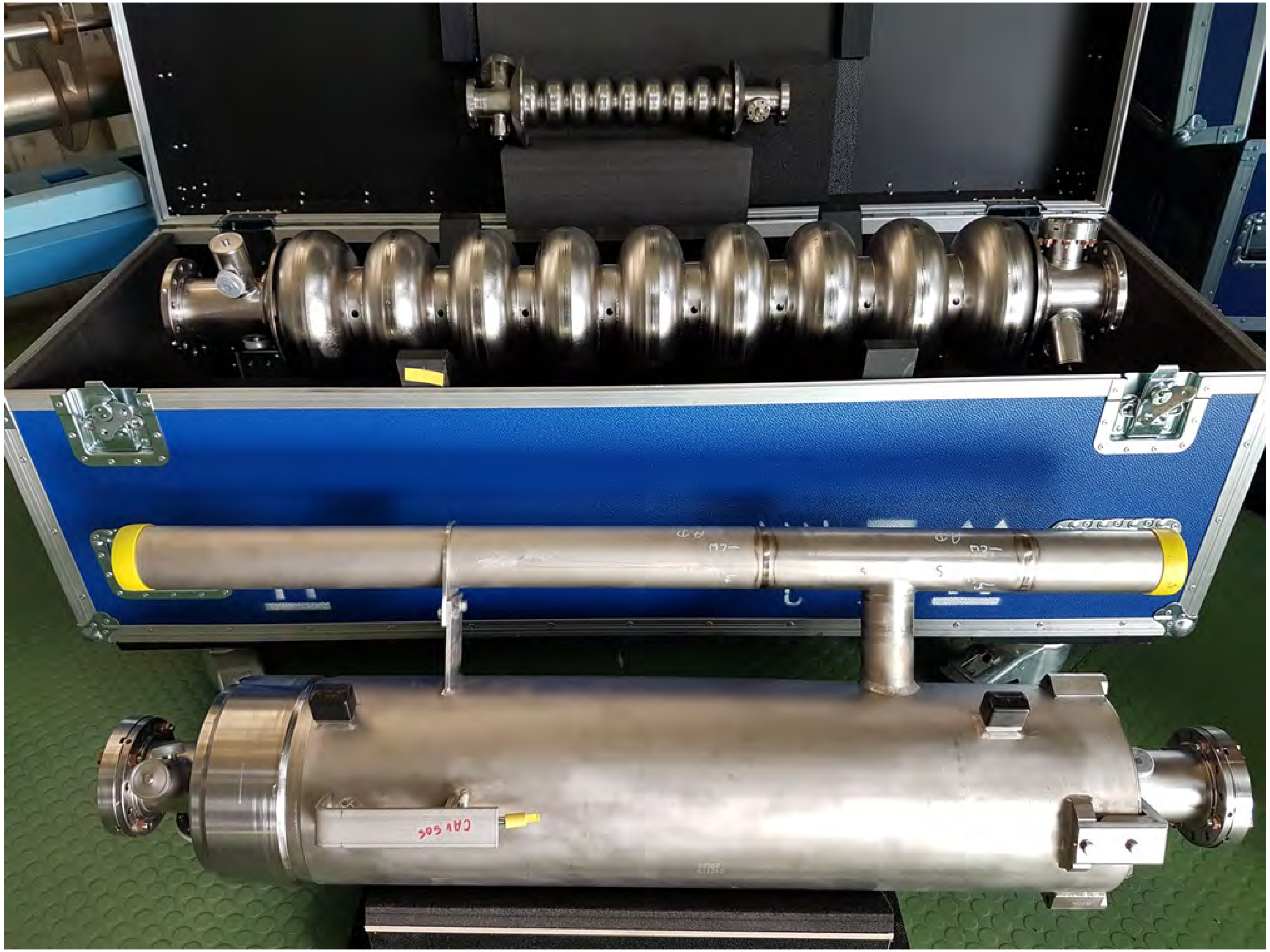


Preparation for VT at LASA clean room

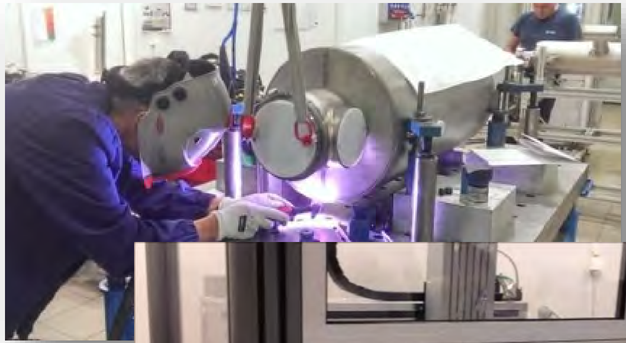


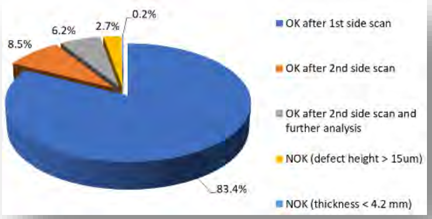
3[rd] Harm Goal
E_{acc} = 15 MV/m
Q_0 = 1 10^9

INFN LASA Cavities for the Euroepan XFEL

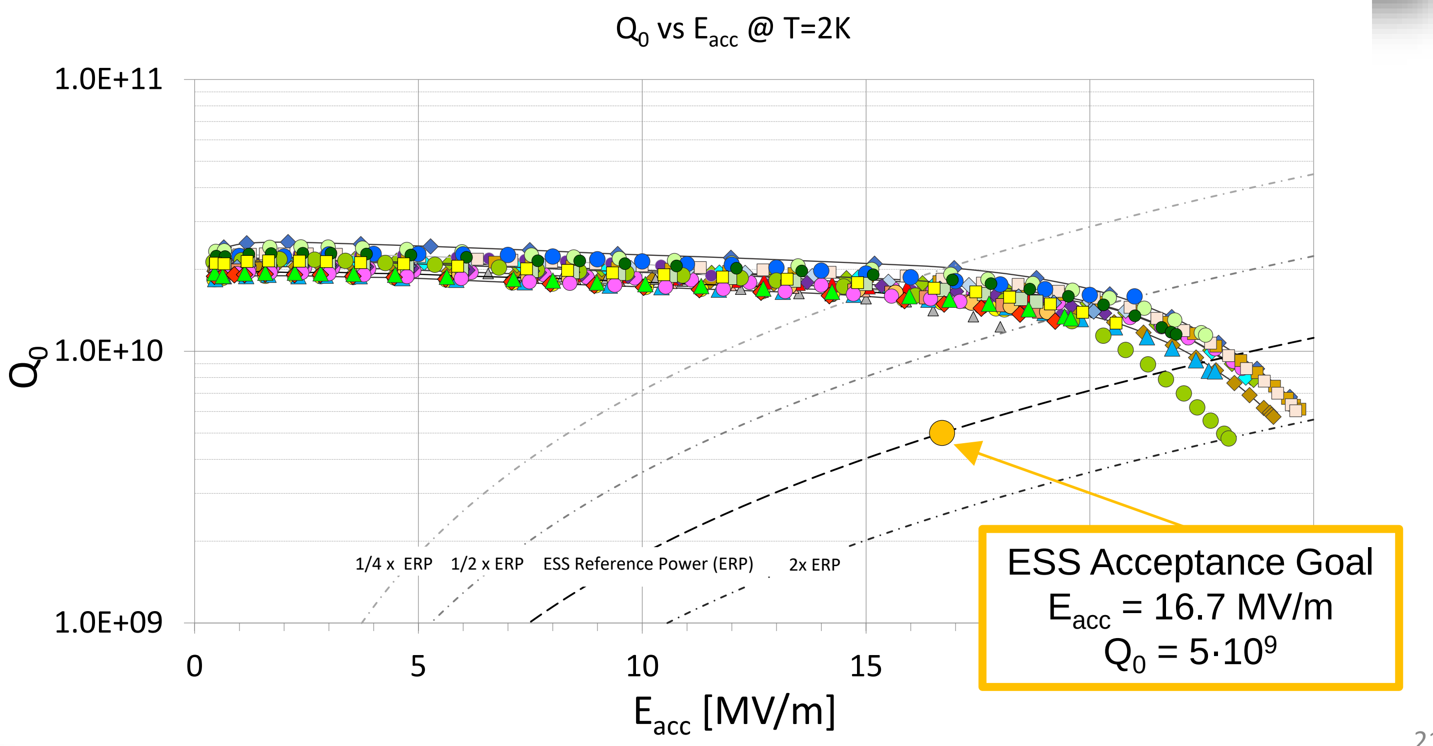


ESS Medium Beta Results



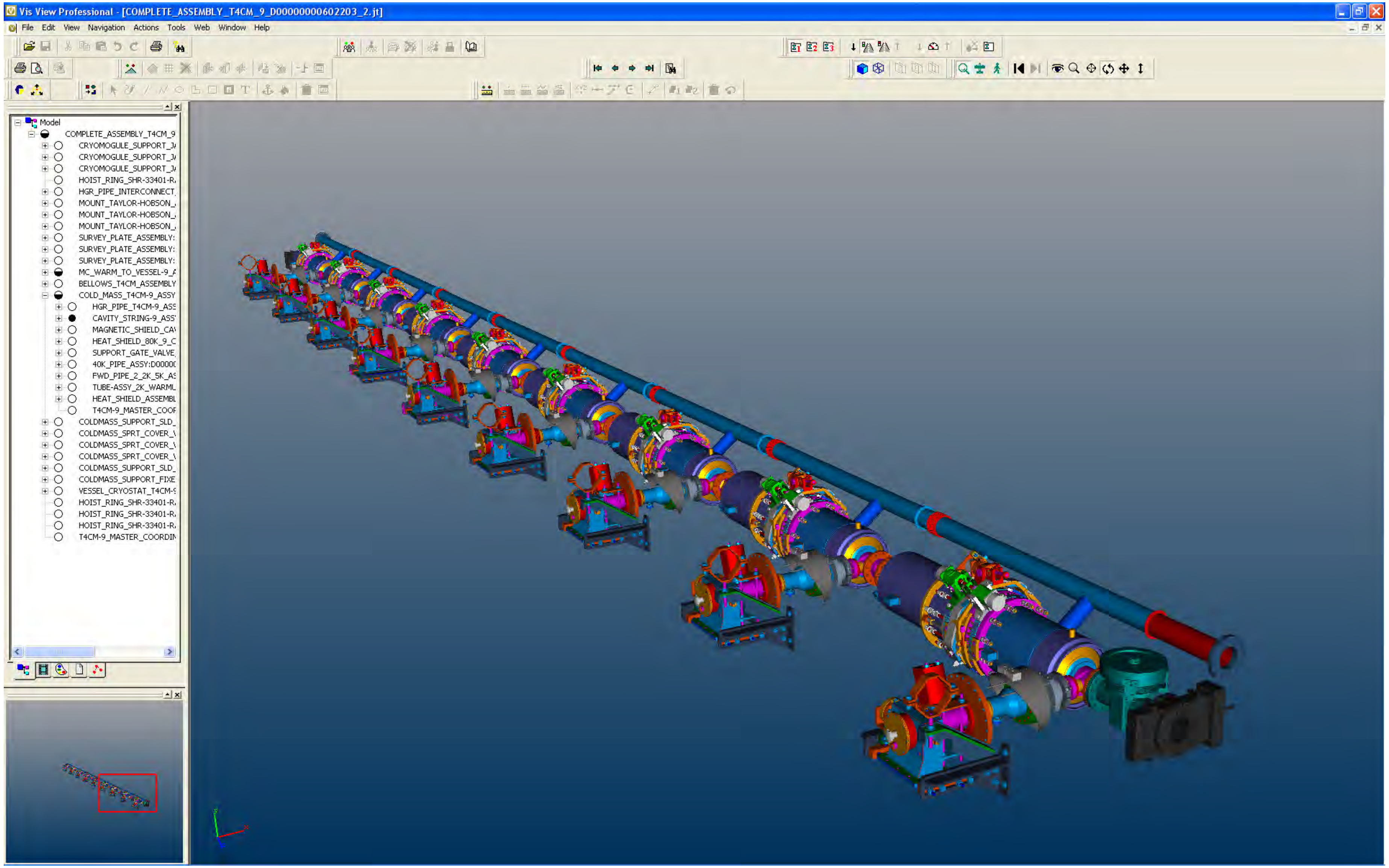


- 36 cavities production is **on going**
- **Prototypes** used:
  - To setup production
  - To prepare test infrastructure at LASA and DESY
  - To debug module assembly
  - To finalize QA/QC
- **Lessons** learnt:
  - Niobium inspection on vendor site to limit delays
  - Cross-check between different sites (incoming-outgoing documents)



EUROPEAN SPALLATION SOURCE

The TESLA/European XFEL/ILC Cryomodule



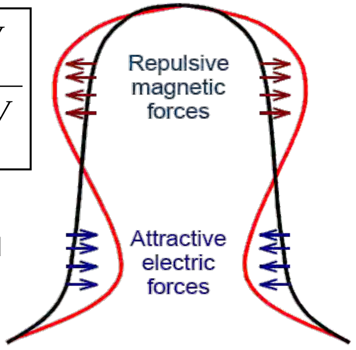
Tuners and Blade Tuner

- Each SRF cavity must be equipped with a cryogenic tuning device, **Cold Tuner**, to set the cavity **resonant frequency** to the project value during operation. Tuners must also **compensate detuning**.
- Among detuning sources:
  - **Lorentz forces** on cavity walls shielding currents induced by electromagnetic fields
  - **Microphonics** and stochastic noise, strongly correlated to helium bath pressure fluctuations
- Tuners control **static frequency value** (slow action, scale of second to minutes) and suppress dynamic detuning (fast action, scale of milliseconds).
- At INFN LASA we **designed, developed** and **experimentally qualified tuners** and their **control systems** for many international projects!

Cavity *Detuning*: $\Delta\omega \equiv \omega_{RF} - \omega_0$

$$\frac{\Delta f}{f} \propto \frac{\int_{\Delta V} (\varepsilon_0 E^2 - \mu_0 H^2)dV}{\int_{V_{CAVITA'}} (\varepsilon_0 E^2 + \mu_0 H^2)dV}$$

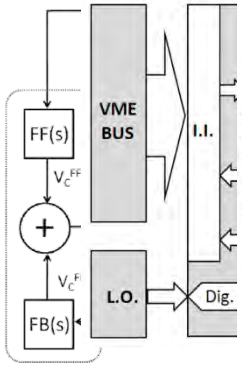
Slater's theorem:
detuning rises with the square of field

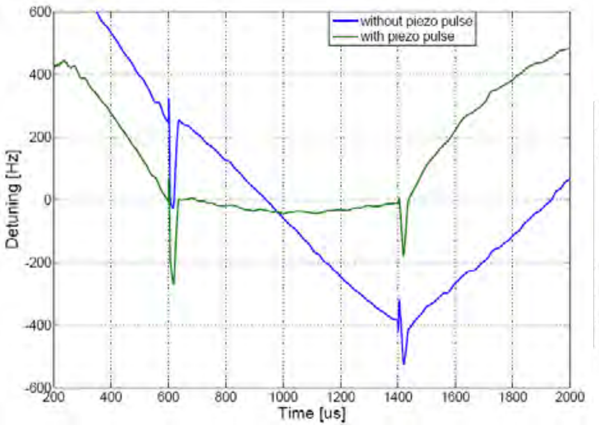


Lorentz Force detuning

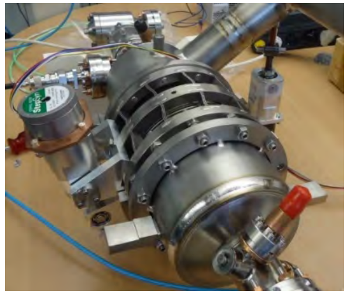
$$P = V_{acc} I_b \left(1 + \frac{1}{4} \left(\frac{\Delta f}{f_{FWHM}} \right)^2 \right)$$

Required power rises with the square of detuning!

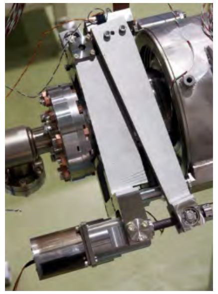




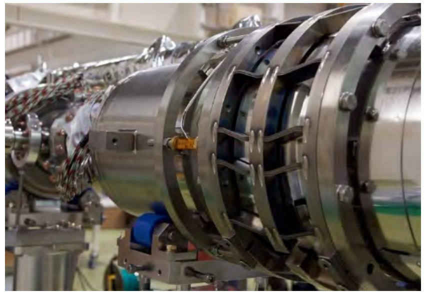
INFN Blade Tuner for
E-XFEL, DESY, **Germany**



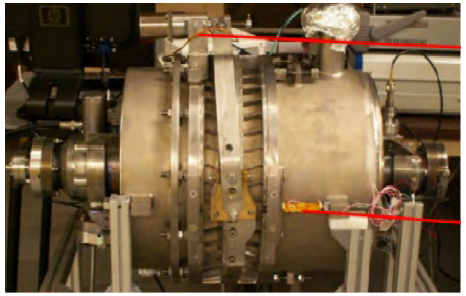
E-XFEL Main
Linac Tuner



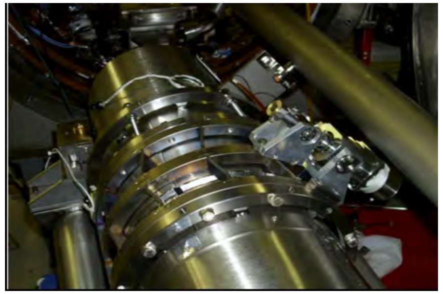
INFN Blade Tuner at S1-Global
KEK, **Japan**



INFN Tuner for the ADS cryomodule
at IPN-Orsay, **France**

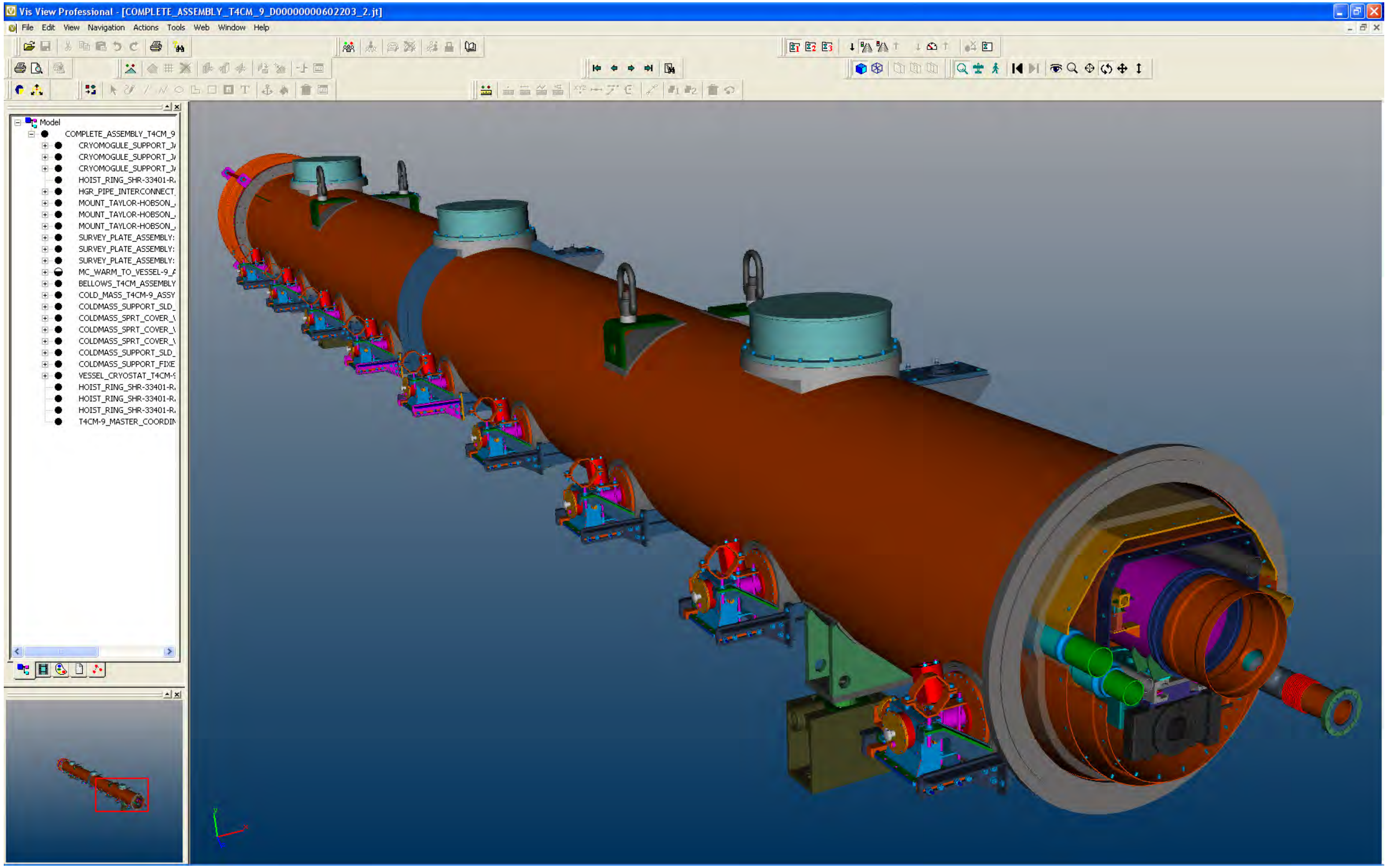


INFN Tuner for the ILC cryomodule
at Fermilab, **USA**



Piezoelectric actuators for
fast tuning, E-XFEL, DESY

The TESLA/European XFEL/ILC Cryomodule



Cryomodule: TESLA →XFEL→ILC design criteria

High filling factor

- maximize real estate gradient/cavity gradient
  - long cryomodules/cryo-units, short connections

Moderate cost per unit length

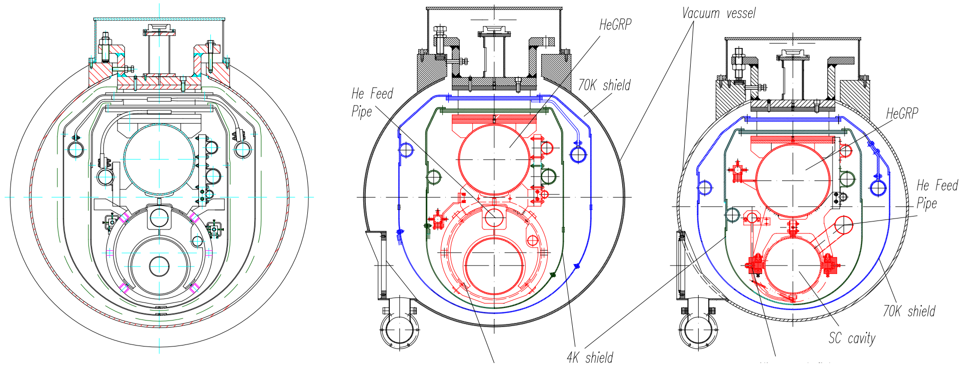
- simple design, based on reliable technologies
- low static heat losses in operation

Effective cold mass alignment strategy

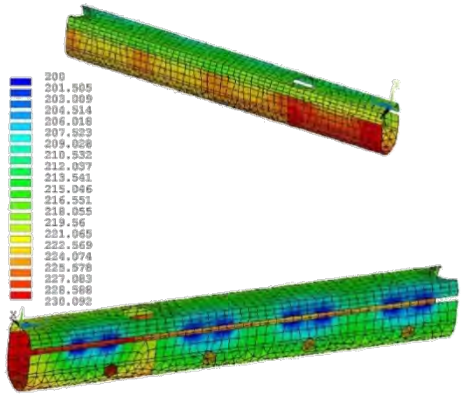
- room temperature alignment preserved at cold

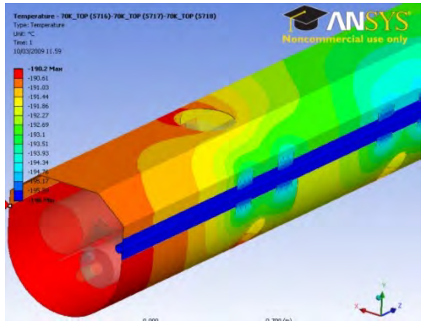
Effective/reproducible assembling procedure

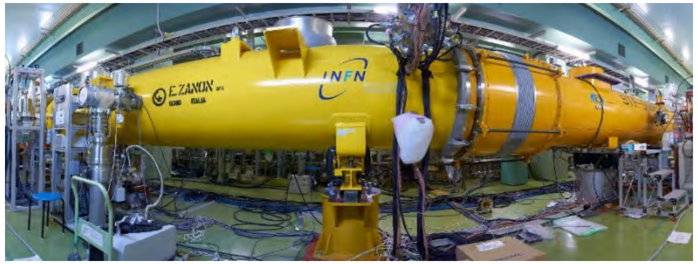
- clean room assembly just for the cavity string
- minimize time consuming operations (cost /reliability)

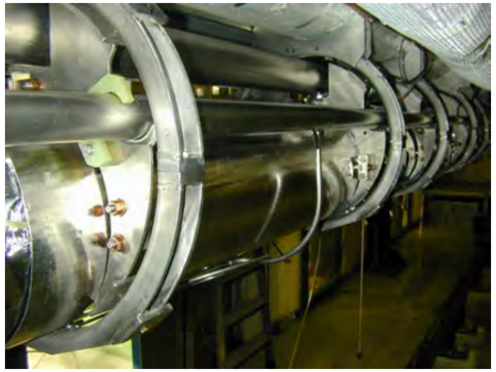


Module 1 Module 2 & 3 Module 4+

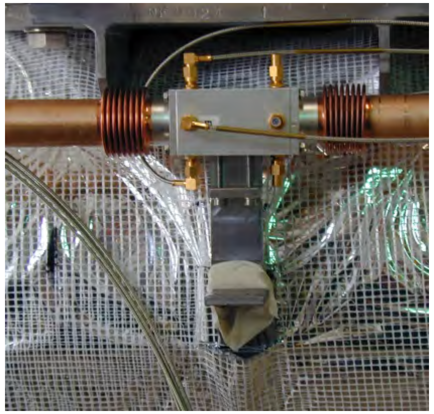


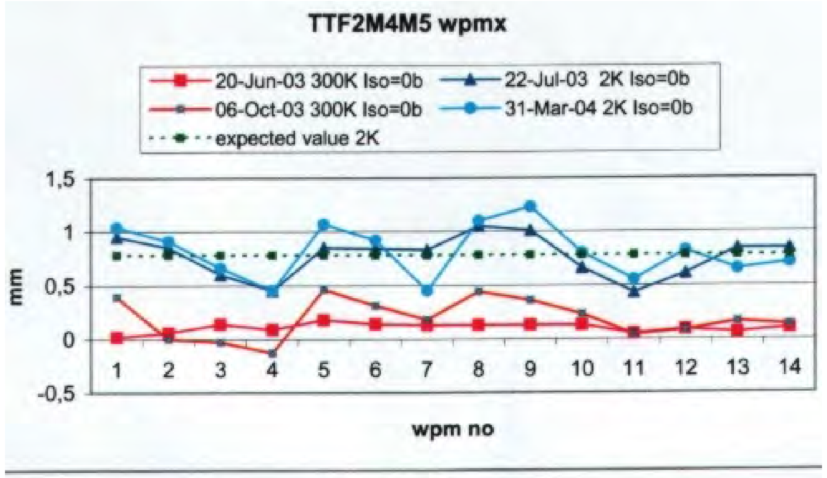






Cryomodule Diagnostic Tool – Wire Position Monitor





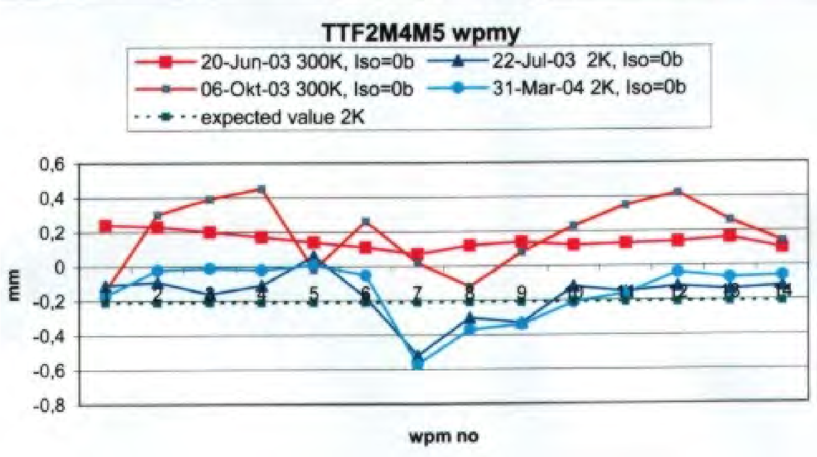
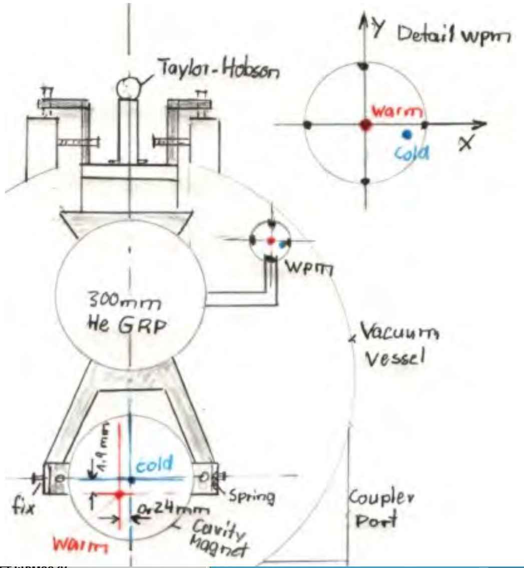
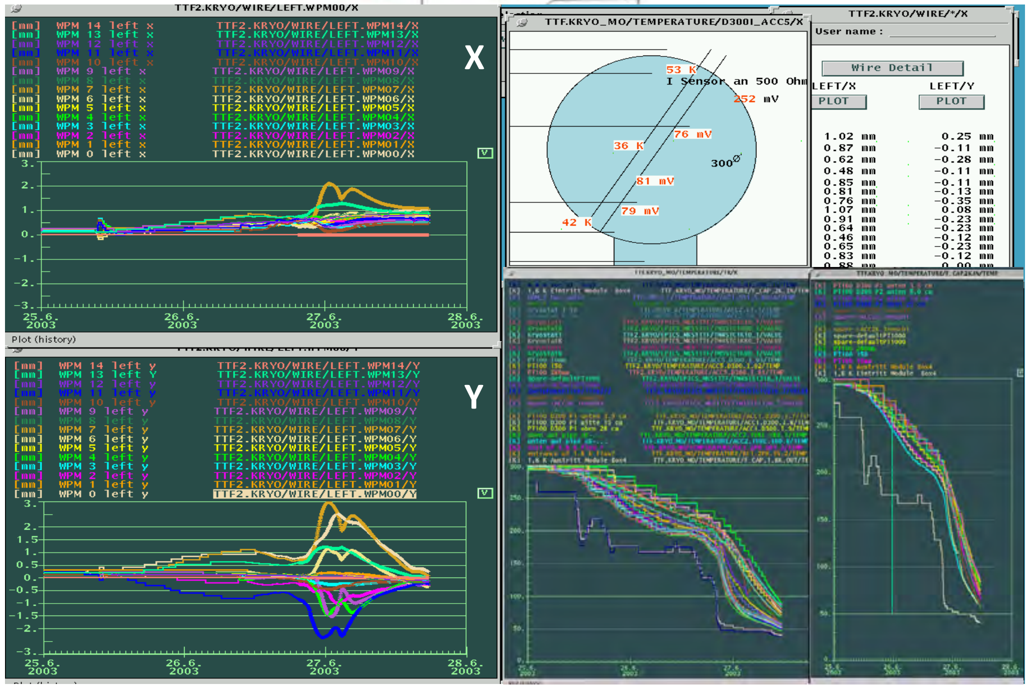


Table 1: Result Summary

TDR Specifications (rms)		
Cavities	x/y	± 0.5 mm
Quadrupoles	x/y	± 0.3 mm
WPM results (peak)		
Cavities	x	+ 0.35/- 0.27 mm
	y	+ 0.18/- 0.35 mm
Quadrupoles	x	+ 0.2/- 0.1 mm
	y	+ 0.35/- 0.1 mm





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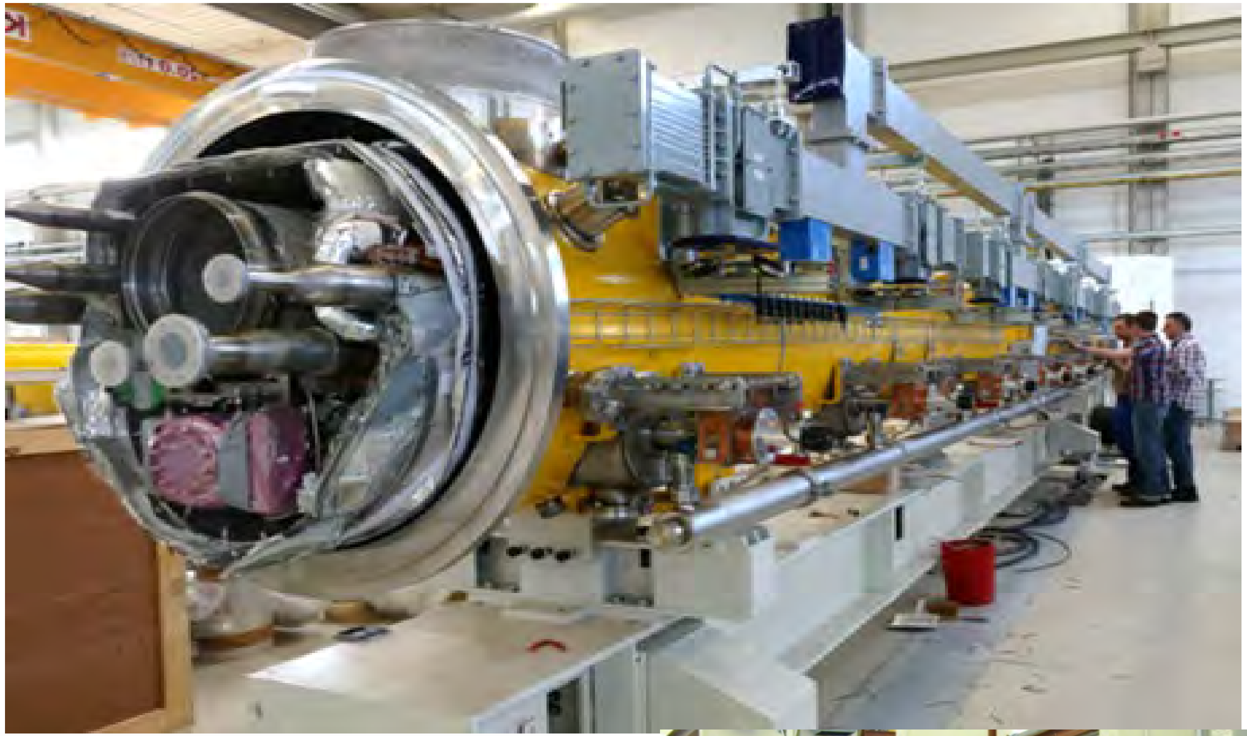
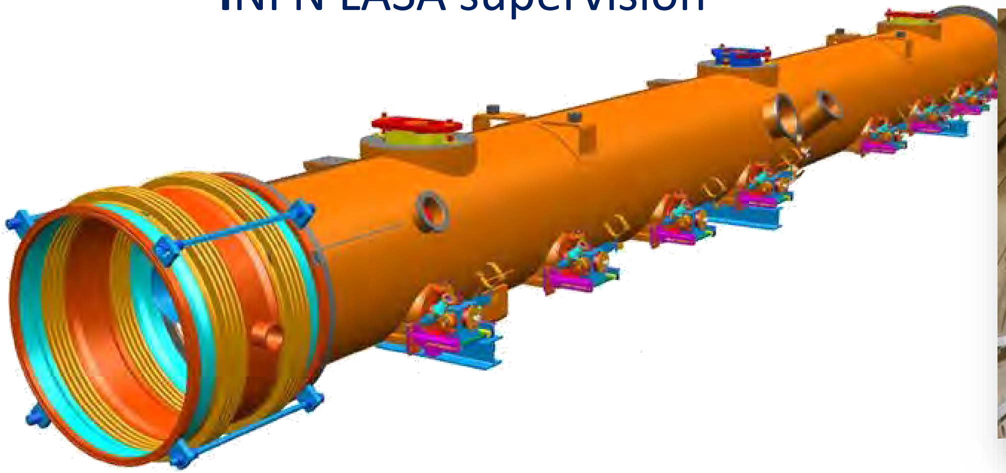
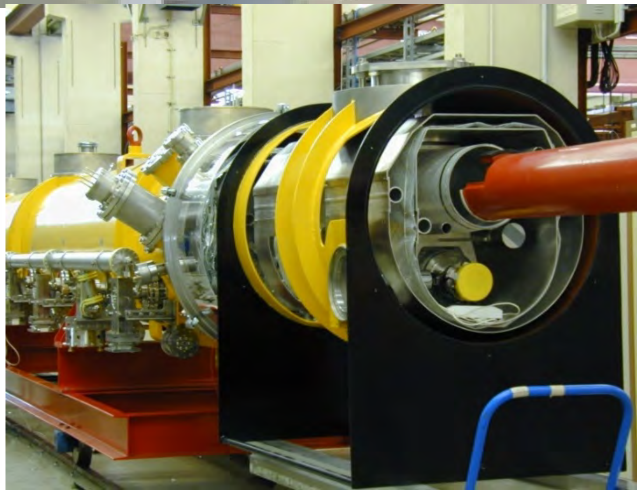
European XFEL: INFN LASA 1.3 GHz Cryomodule

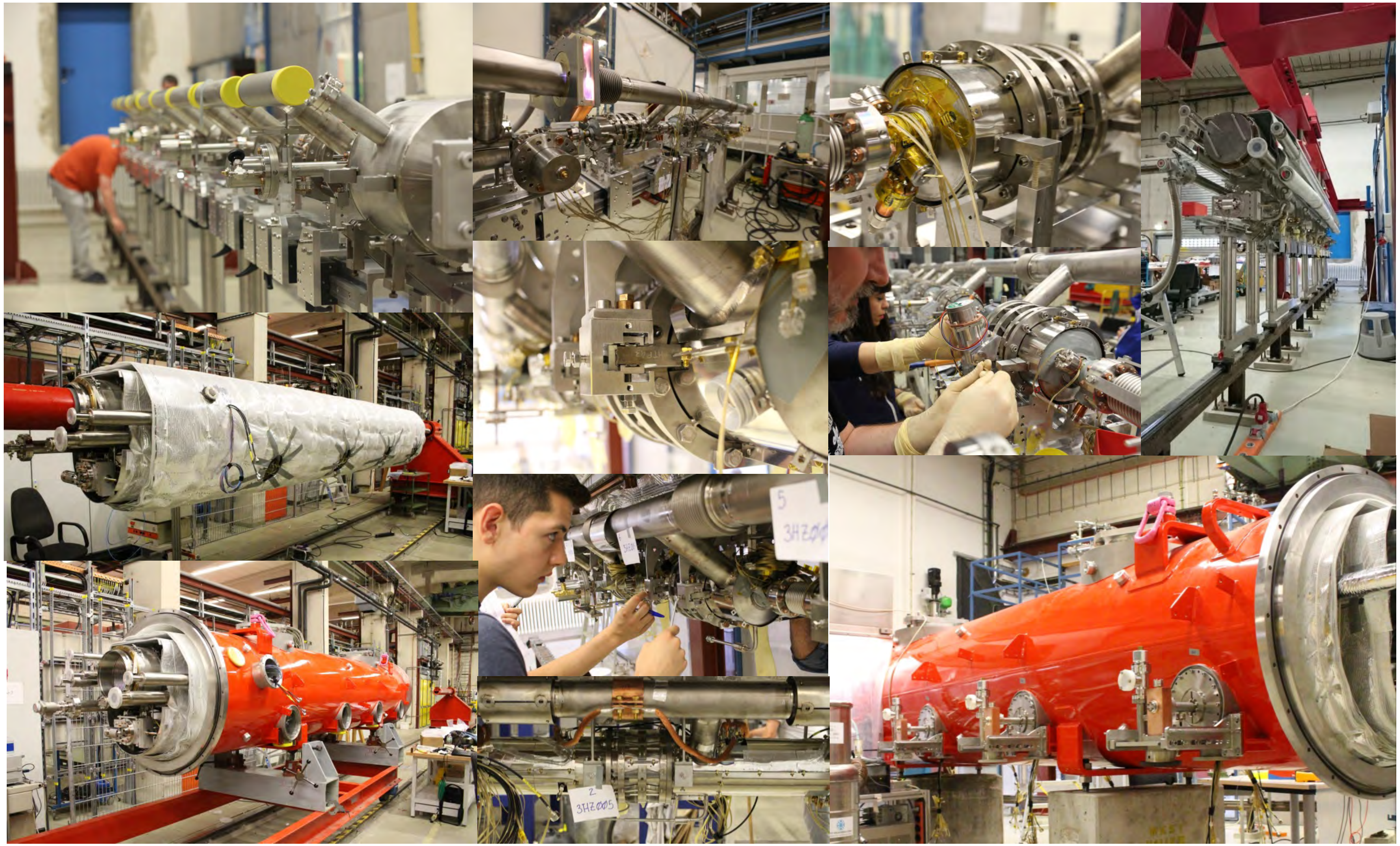
- **INFN LASA Design, generation 3**
  - Increased performances
  - Simplified assembly
  - **Cost reduction**
  - **Performance validated** on first 3 module by **WPM**
- **45 cryomodules over 101 …**
  - Cold masses, thermal shield
  - Vacuum chambers
- **… Produced by Italian industry**
  - INFN LASA supervision



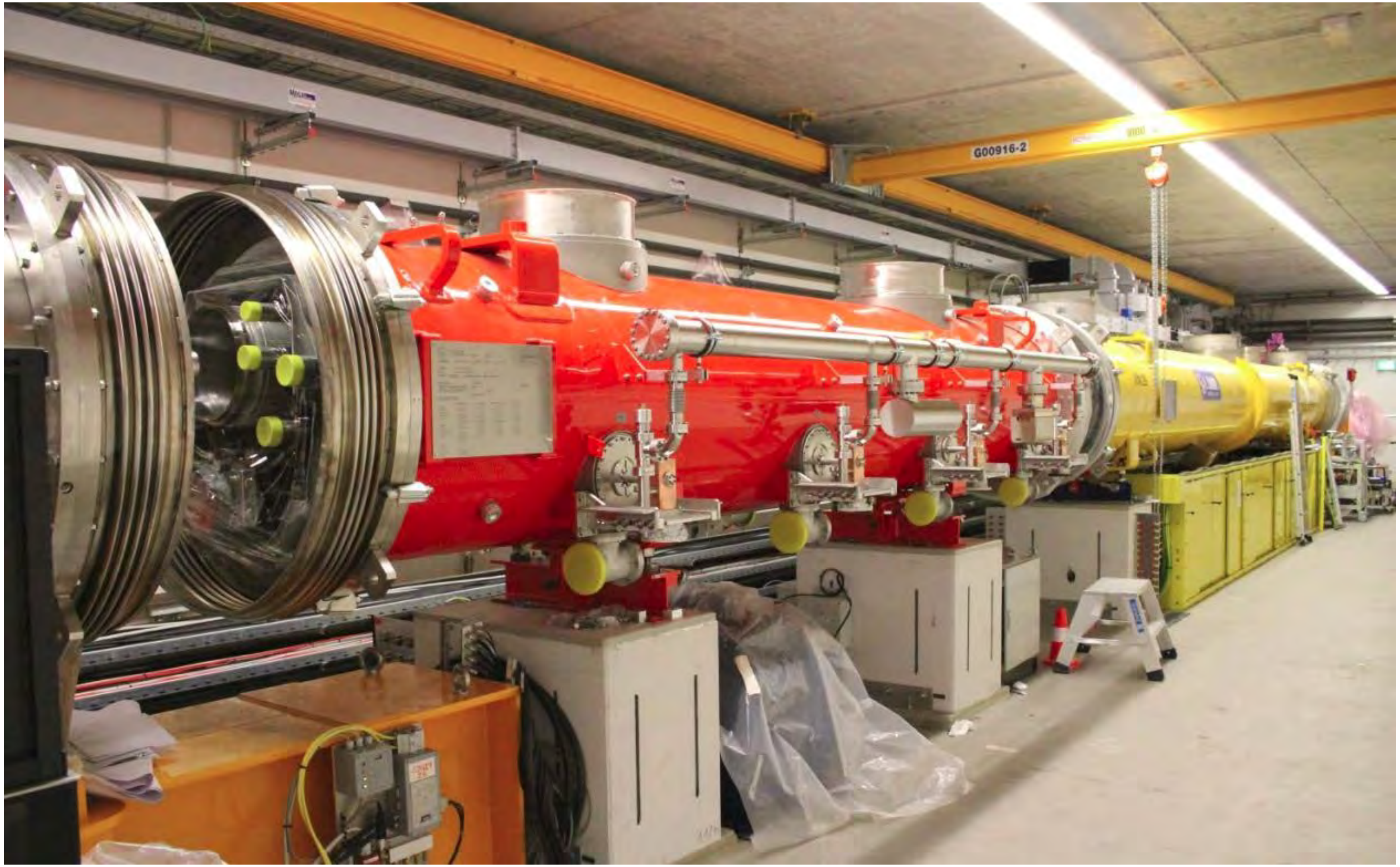




3.9 GHz Cryomodule Assembly by INFN at DESY



INFN LASA and European XFEL Cryomodule Family



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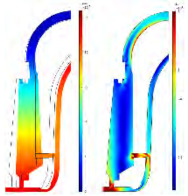
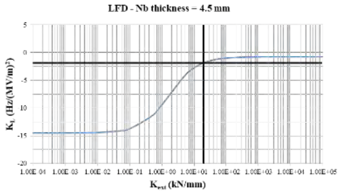
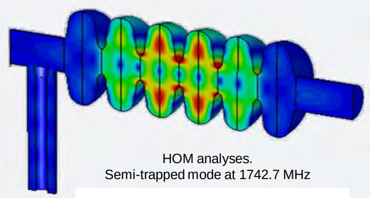
SRF@ INFN LASA

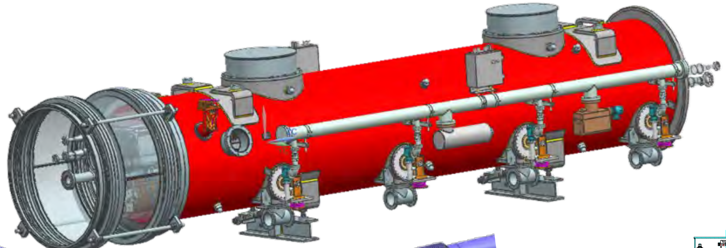
- Design
  - Cavities
  - Cryomodules
  - Ancillaries
- Qualification
  - Cavities
  - SRF Ancillaries
- Facilities
  - RF Test Stand (500 to 3900 MHz)
  - ISO4-7 Clean Room (HPR, UPW, etc.)
  - Large Vertical Cryostat and advanced quench diagnostic
- With Industry
  - Fabrication of cavities and cryomodules
  - Mass Production of European XFEL cavities and cryomodules (1.3 and 3.9 GHz)
    - QA/QC
    - Technology Transfer (within XFEL contract)
  - Large Production of ESS Medium Beta Cavities
  - Upcoming Production of PIP-II LB650 Cavities

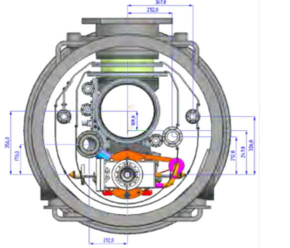


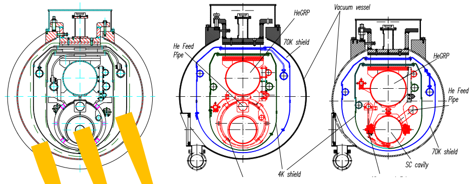


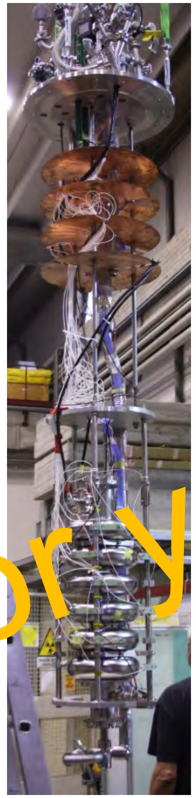


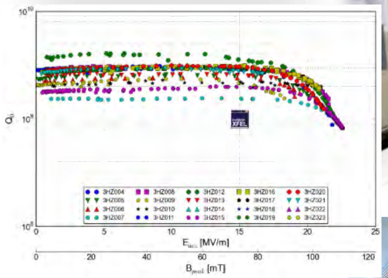
FEM analysis of the spool transition ring exhibiting about 60 kN/mm stiffness

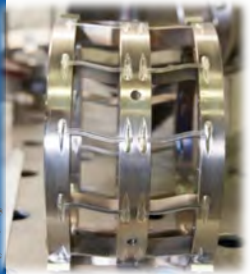


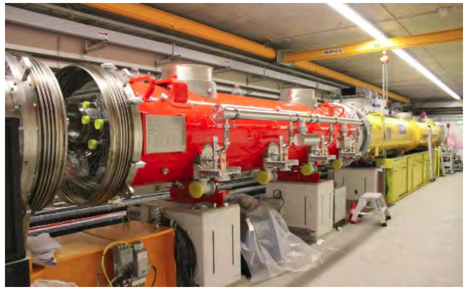


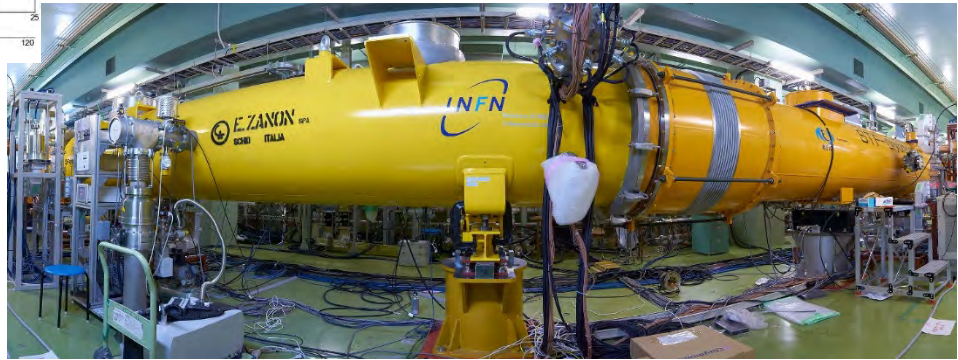












Thanks for your attention!!!

For any further information

daniele.sertore@mi.infn.it