SRF activities in INFN

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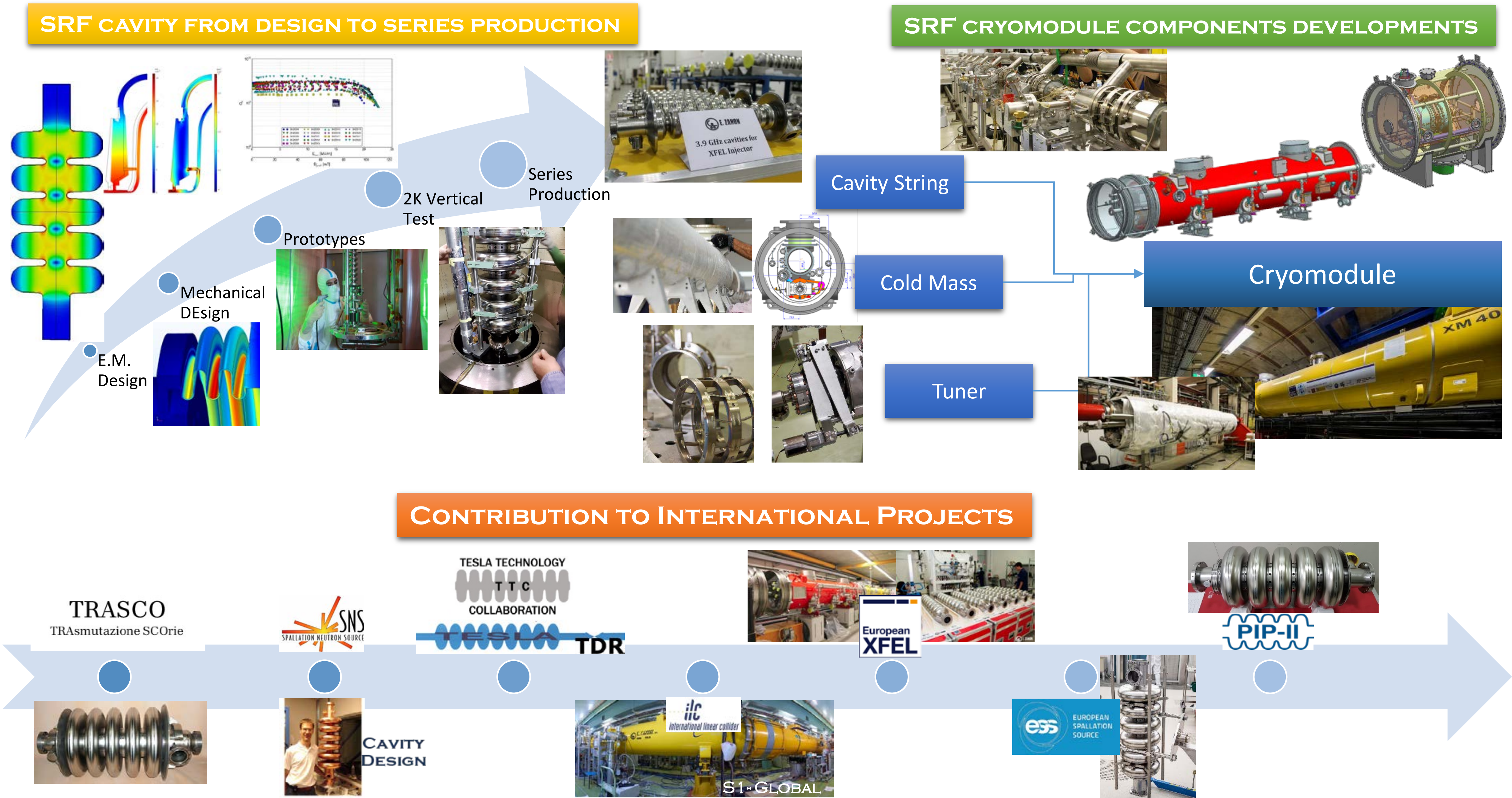
INFN Milano – LASA

Outline

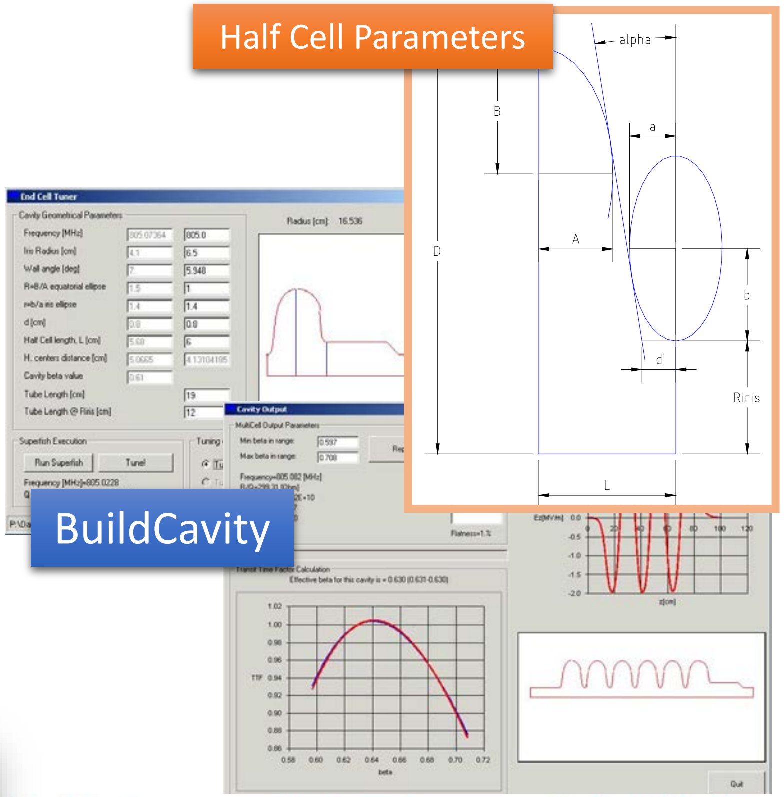
- History of LASA-INFN activites
- LASA expertises:
  - Electromagnetic and mechanical design, surface treatments, prototype production, cavity test and diagnostics, series production. Cryomodules, tuners, magnetic shields
- Main projects:
  - The past: E-XFEL
  - The present: ESS
  - The future: PIP-II
- R&D activities:
  - high Q/high G
  - New criostat design

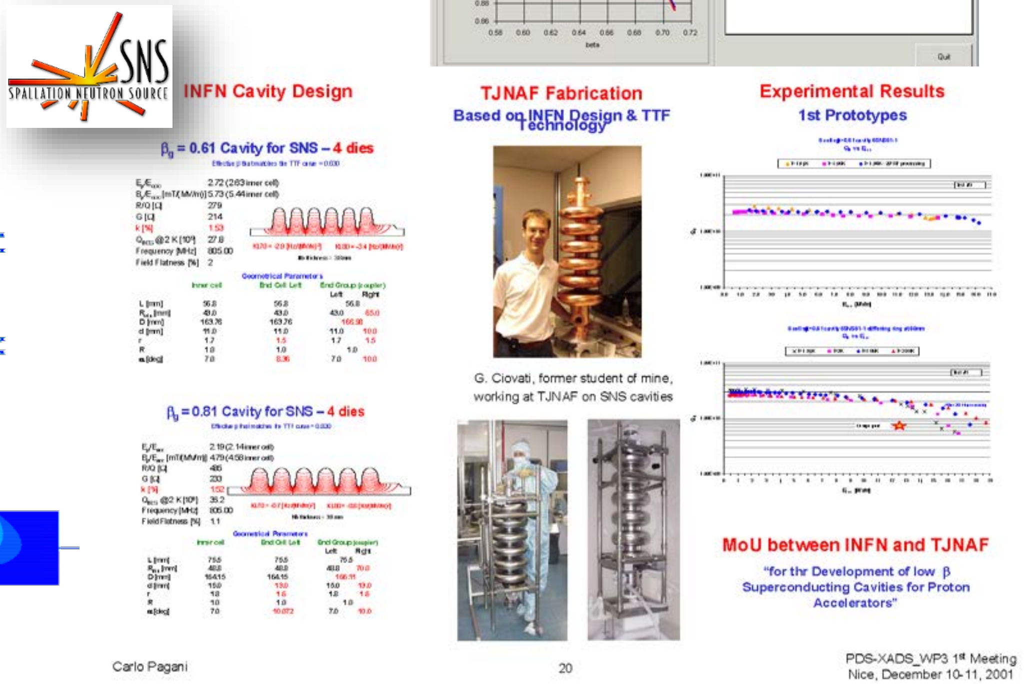
LASA SRF Group: expertise and experience in SRF

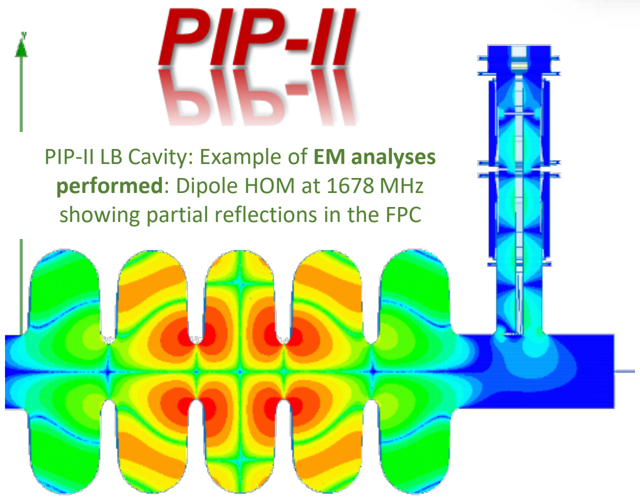


Cavity – Electromagnetic Design

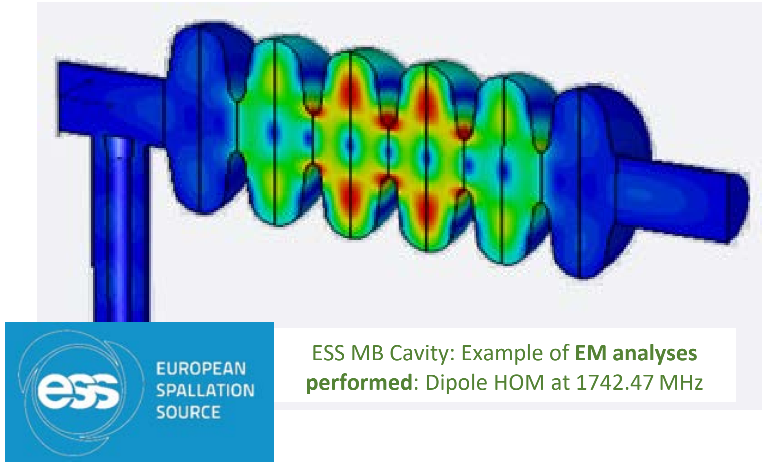
- Full parametric model in terms of **7 geometrical parameters**
- We built a **2D parametric tool** BuildCavity for the analysis of the cavity shape on the **electromagnetic** parameters based on SUPERFISH
- **A multicell cavity is then built** minimizing Field Flatness error, compute β and TTF as well as final performances
- The **2D model** constitutes the **basis for further 3D simulations** (HFSS, CST) for HOMs, multipacting, field emission considerations







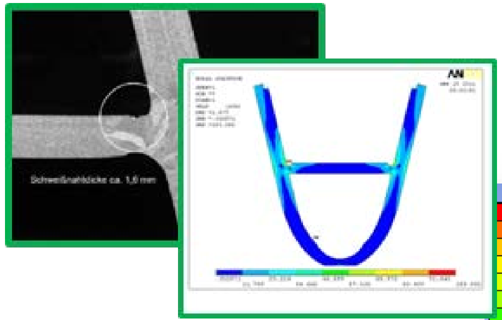
PIP-II LB Cavity: Example of **EM analyses performed**: Dipole HOM at 1678 MHz showing partial reflections in the FPC



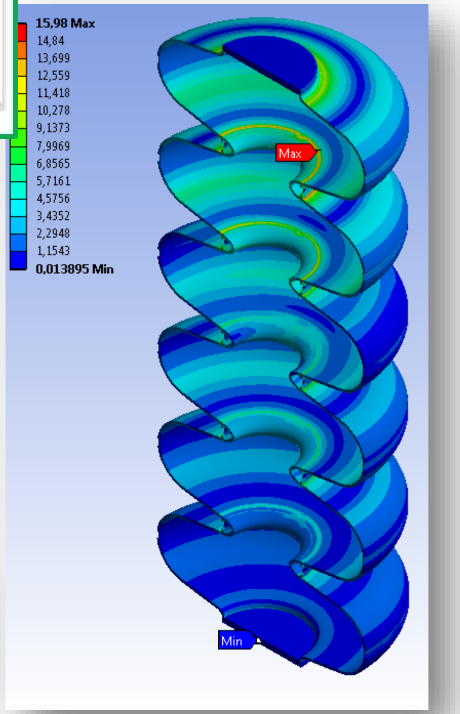
ESS MB Cavity: Example of **EM analyses performed**: Dipole HOM at 1742.47 MHz

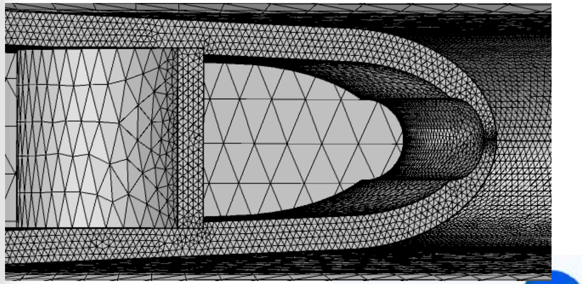
Cavity – Mechanical Design

- The **EM design** is **transferred** to **mechanical analysis** (iterative loop) for estimating critical parameters as:
  - Ring radius
  - Stiffness
  - Tuning sensitivity
  - Vacuum sensitivity
  - Lorentz Force Detuning (LFD)
  - PED, ASME compliance

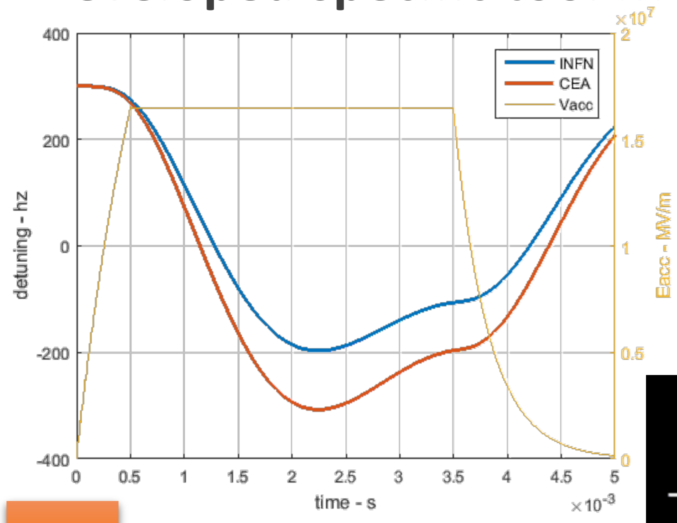


Mechanical Parameters	INFN design
Cavity wall thickness (mm)	4.2
Stiffening ring radius (mm)	70
Internal volume (l)	69
Cavity internal surface (m^2)	1.8
Stiffness (kN/mm)	1.7
Tuning sensitivity K_T (kHz/mm)	205
Vacuum sensitivity K_V - k_{ext} ~ 21 kN/mm (Hz/mbar) -	-8
LFD coefficient K_L - k_{ext} ~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



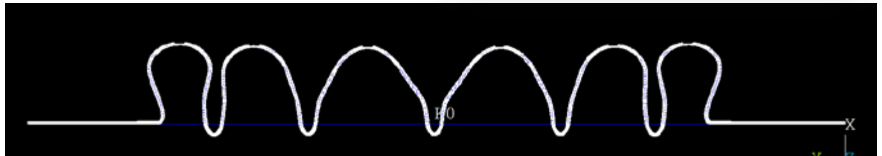


- **Developed specific tool Mecavity**



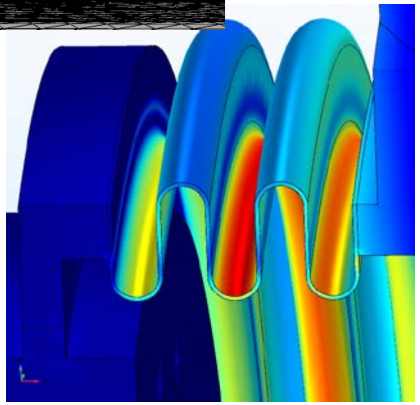
LFD

EUROPEAN SPALLATION SOURCE



Dynamical analyses: natural modes

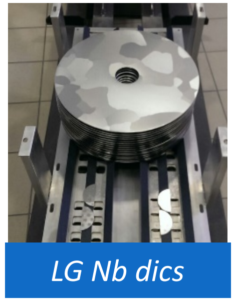
PIP-II

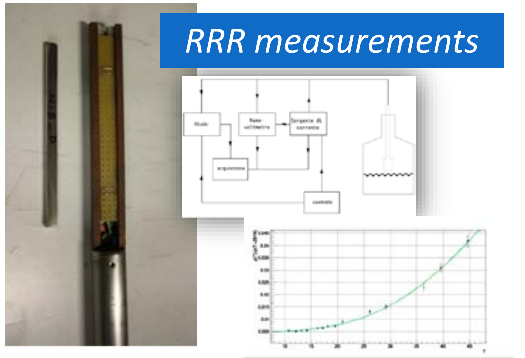


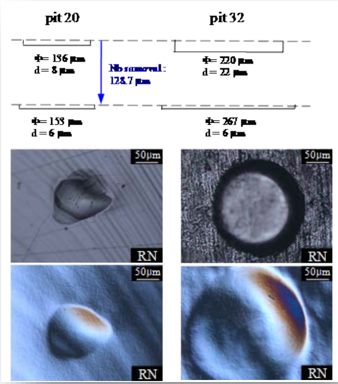
Cavity – Nb studies and characterization

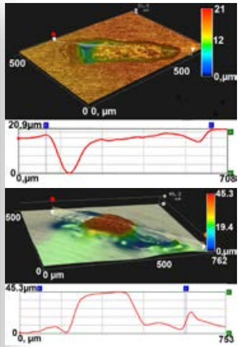
- **Nb quality is critical** for the final cavity performances:
  - **Mechanical** properties (grain size, hardness, thickness, etc.)
  - **Chemical** composition (elements and gas contents)
  - **RRR** (Residual Resistance Ratio)
  - **Surface defects** (scratches, marks, grease, etc.)
  - **Foreign materials** (ECS – Eddy Current Scanning)
  - **Traceability** (pressure vessel code)

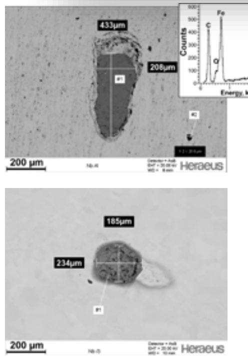
- **Studies and tools developed**:
  - Treatment studies (BCP/EP) of **defect evolution** on Nb samples
  - **Final roughness** (Ra) of Nb surface
  - **RRR measurements** set-up
  - Experience on **FG and LG Nb**
  - **EBW** (Electron Beam Welding) **studies**

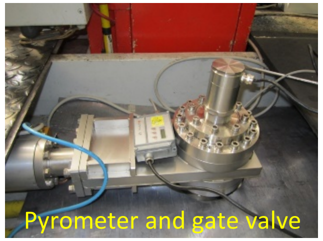


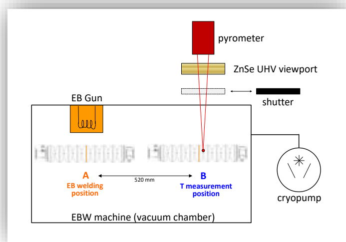


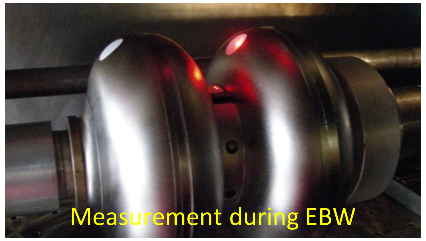


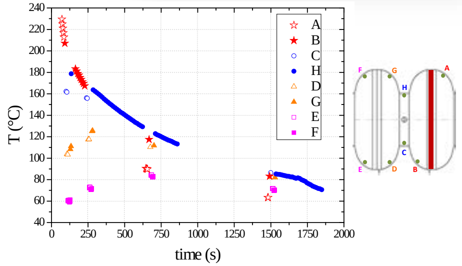


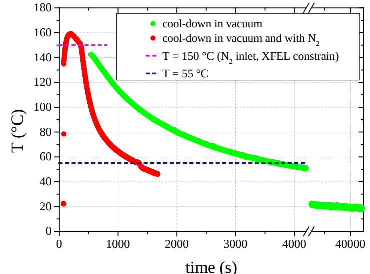








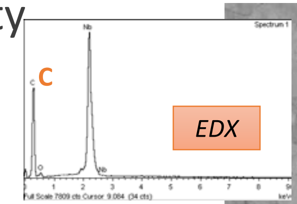


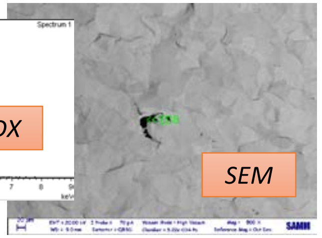


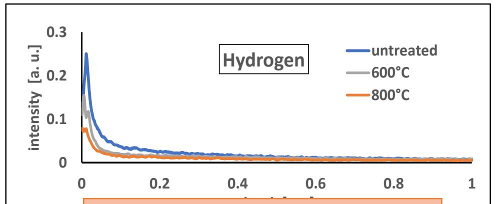
Cavity – Thermal and Surface treatments

- Once the mechanical production is complete, **thermal** and **surface treatments** play a crucial role in the **cavity preparation** to reach the **final performances.**
- Thermal treatments for **stress release**, **de-hydrogenation**, **performance improvement:**
  - Vacuum quality (RGA - Residual Gas Analysis), pressure and temperature control, RRR
- Surface treatments for **proper finishing** and **cleaning** of the inner **surface exposed to RF**:
  - **BCP** (Buffered Chemical Polishing) and **EP** (Electro Polishing)
- **Studies and tools developed**:
  - **Depth profile** and SEM/EDX for process optimization and quality
  - Acid flow **simulation** and **test bench** for process improvement
  - **Temperature** and **thickness** evolution **during BCP/EP**
  - **Inner visual inspection** set-up for surface finishing check
  - **X-ray fluorescence** set-up for foreign materials analysis (non-destructive diag.)

Annealing cycle



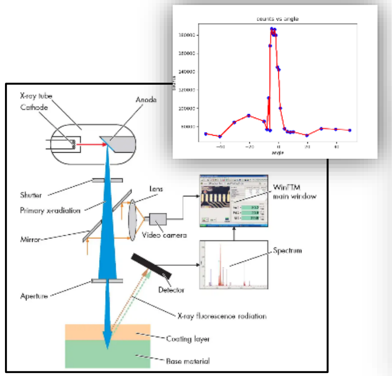


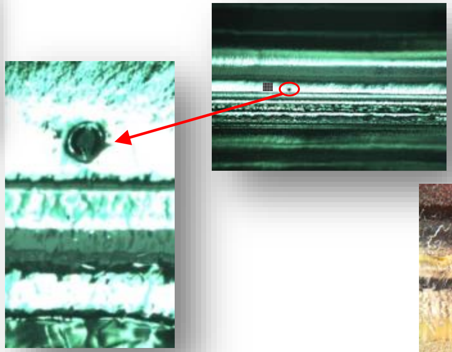


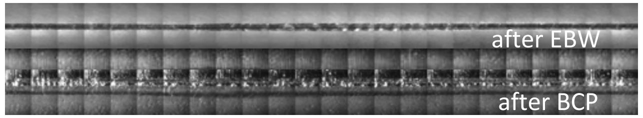
Depth profile on Nb samples

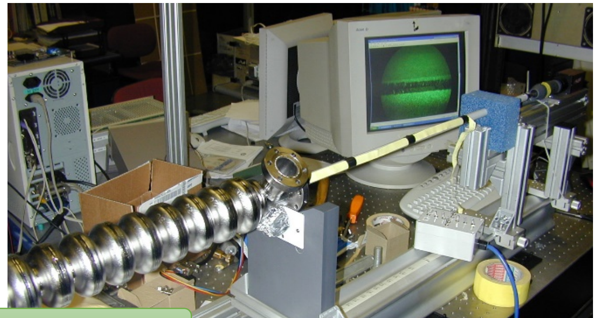
X-ray fluorescence system and Inner optical inspection

ESS cavity





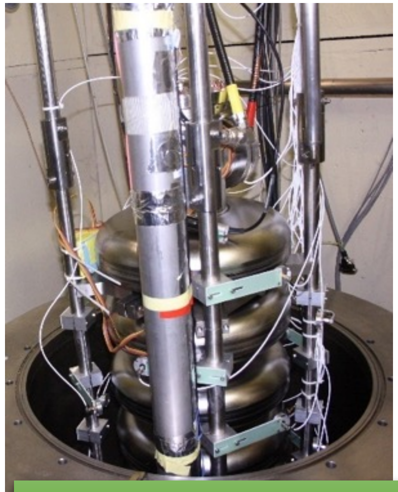


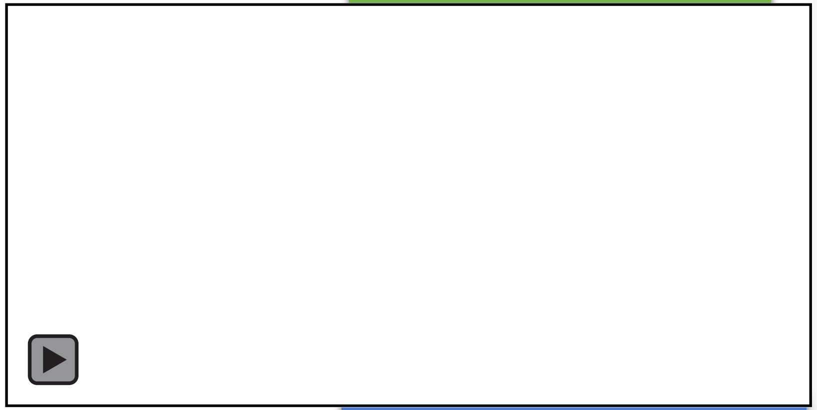


E-XFEL 3.9 GHz cavity

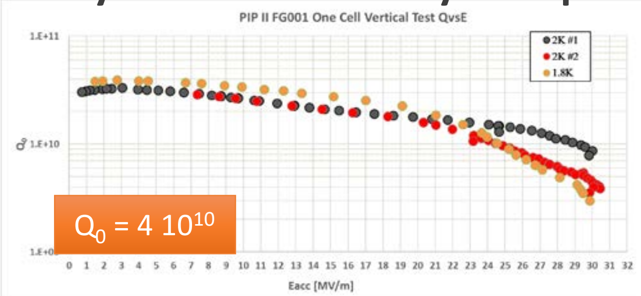
Cavity – Cold VT at LASA

- **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 @ 2 K
- **Residual magnetic field**: < 8 mG (single shield)
  - Single μmetal external shield and, second cryogenic shield (Cryoperm) installed
- **Sub-cooling system**:
  - Cooling power: ~ 60 W @ 2 K
  - Lowest temperature 1.5 K.
  - Direct filling at 2 K
- **RF capability:** 500 to 3900 MHz
- **Dedicated inserts with several diagnostics**:
  - 2nd sound detectors for quench localization
  - cryogenic photodiodes
  - fast thermometry
  - fluxgates/AMR sensors for magnetic mapping
- **X-ray counter and X-ray NaI spectrometer**

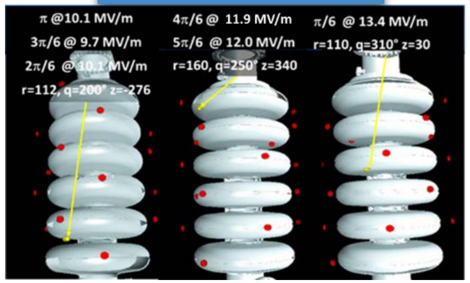




Internal Magnetic Shield



Second Sound



From prototypes to series production

- **Large projects requirements**:
  - **Large number** of **components** (cavities, cryomodule, ancillaries), **massive number** of **high quality Nb** sheets
  - **Process optimization** (**industrialization**) for **high reproducibility** and **reliability**
  - **High production rate**

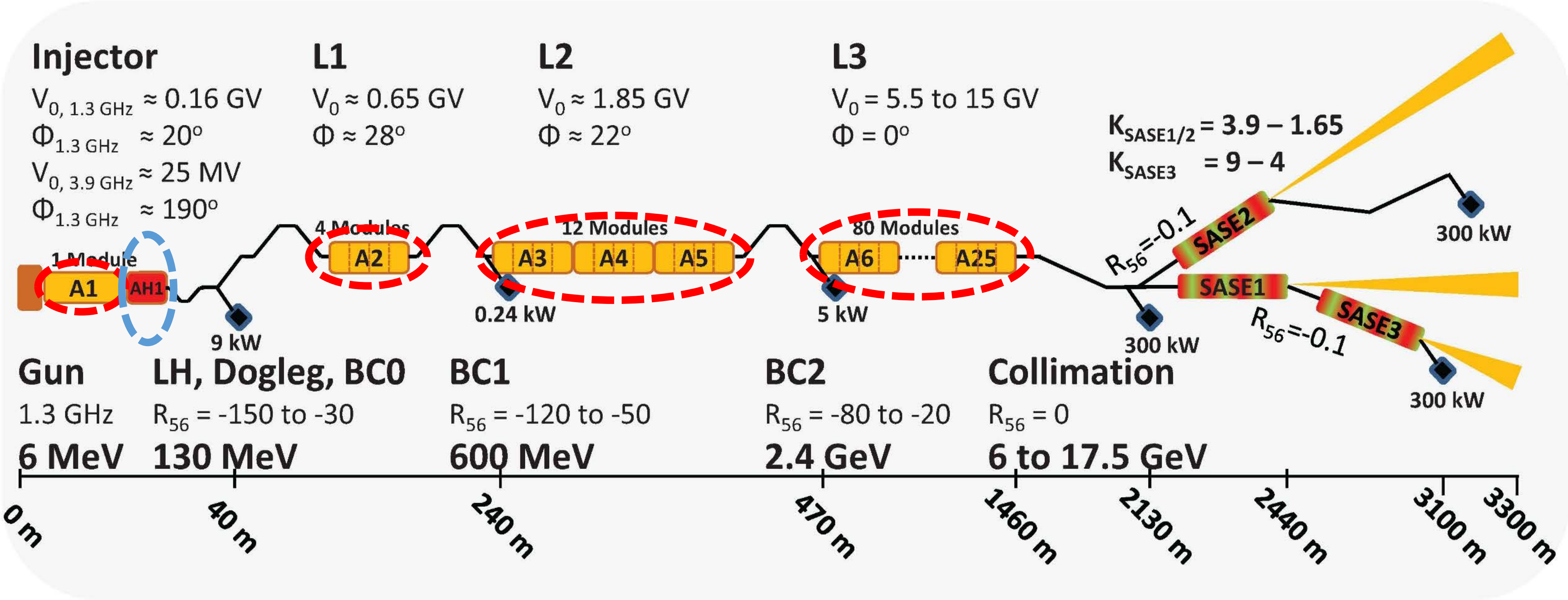
- **Laboratory resources**:
  - **not able to manage** large numbers in term of quality, man-power, optimized cost, scheduling respect, infrastructures, etc.

- **Criticalities**, **warnings** **(mainly for cavities):**
  - **Optimization of components design**: feasible for the production and for repairing action
  - **Stable and feasible preparation process**: **no R&D** during series production -> **high risk of delays!**
  - **Long production cycle**: from mechanical production to final steps some months -> **risk** of several **defective cavities** and a **long and expensive recovery process**
  - **High Quality Control (QA/QC plan) is a must**: diagnostic of large number of parameters during all production steps (failures mitigation)
  - **Preventive maintenance on plants**: mitigation of possible faults

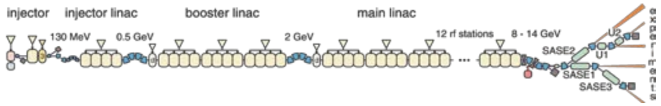
European XFEL

Italian in-kind contribution:

- 1.3 GHz: 320 cavities, 42 cryomodules, QC 800 tuners
- 3.9 GHz: 1 cryomodule, 20 cavities (blade tuners, He-tanks, magnetic shields)



European XFEL: 1.3 GHz series cavity



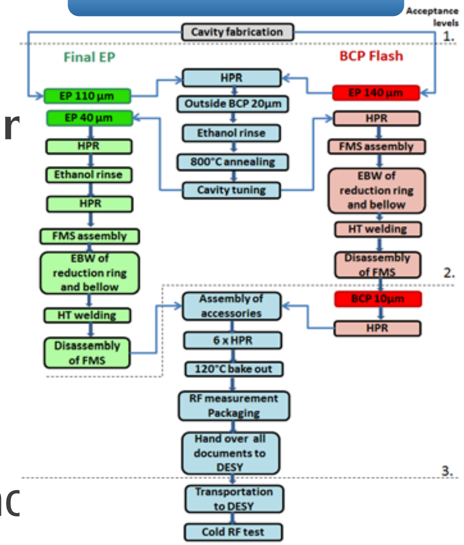
Purposes:

- **800** SC cavities, **3 Nb suppliers**, **2 industries**, **2 recipes** (**Final EP**/ **Flash BCP**)
- Average usable E-XFEL gradient
  - **Q_0=1x10^{10} @ 23.6 MV/m, X-Rays <1x10^{-2} mGy/mir**
- Delivery rate about **8 CVs/week**

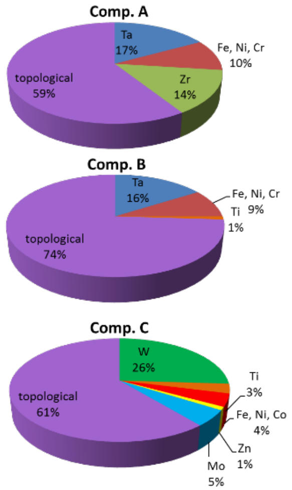
How it worked:

- **Materials** and **vendors qualification** (Nb)
- **Definition of production specs** (2 recipes), **PED 4.3** compliant (prototypes, TESLA experienc
- **Cavity producers qualification** (mechanical)
- **Technology transfer to industries**
- **Grown** and **qualification of insfrastrucutes**
- **Qualification of the transferred technology**
- **Set-up** of the «external» **QA/QC at industries**
- **Series cavities production: continuos monitorin of key parameters**
- **Prompt feedback of the production quality** (analysis of VT vs. key parameters)

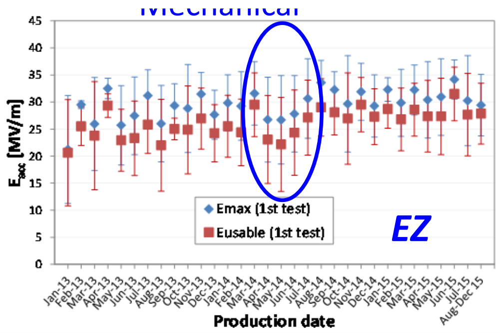
Final EP / Flash BCP

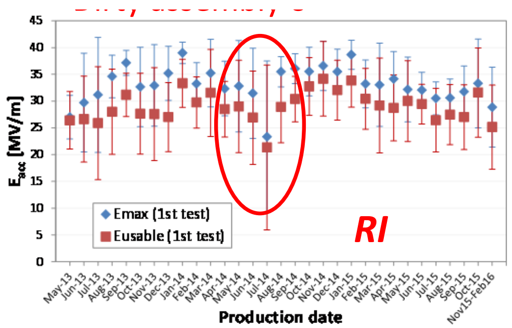


Inclusions in Nb sheets



Analysis VT @ 2 K vs. running production quality





120 °C baking system (EZ)

HPR cabinet (RI)

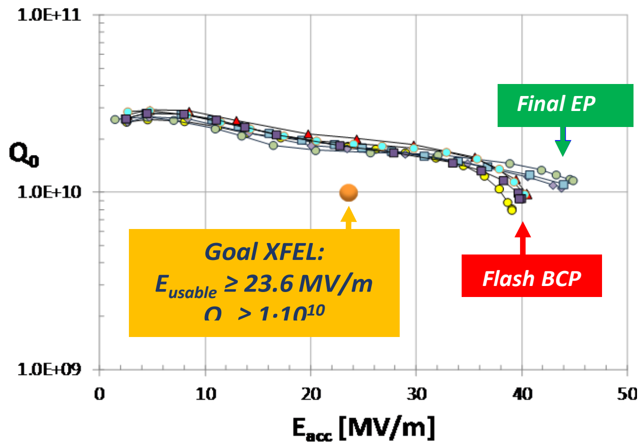
EBW (EZ)

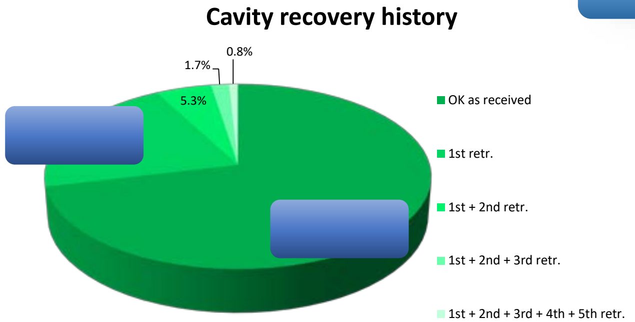
European XFEL: 1.3 GHz series cavity results

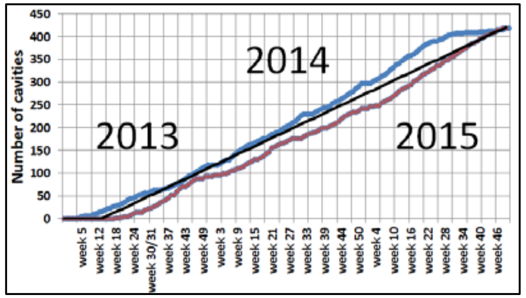
Results:

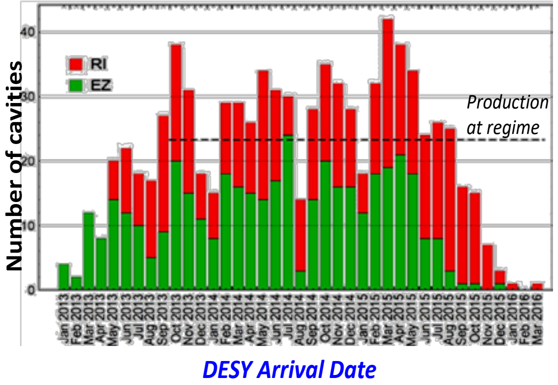
- **Accepted Cavities as Delivered: ≈ 70% (over 800)**
- After Additional Treatments (**mainly HPR**): all cavities accepted
- **Rejected Cavities** (replaced by companies)**: 8 (1%)**
- In total **3 years** (2013-2015)

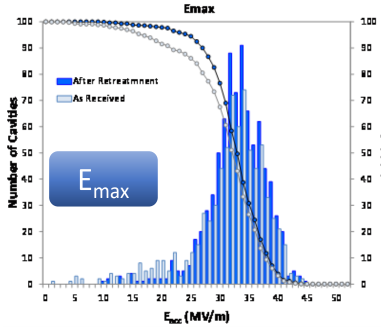
Cavities ready for the cold test at AMTF (DESY)

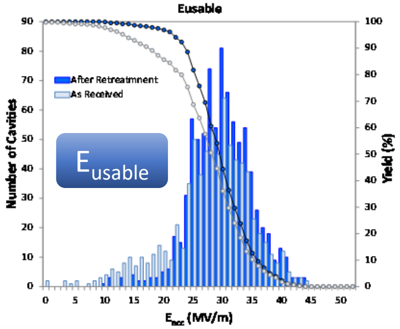






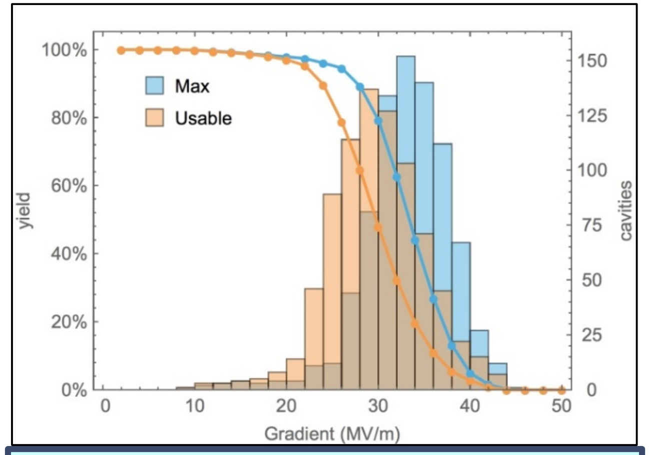






After 33.0 ± 4.8 [MV/m]
Before 31.4 ± 6.8 [MV/m]

After 29.8 ± 5.1 [MV/m]
Before 27.7 ± 7.2 [MV/m]



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}]

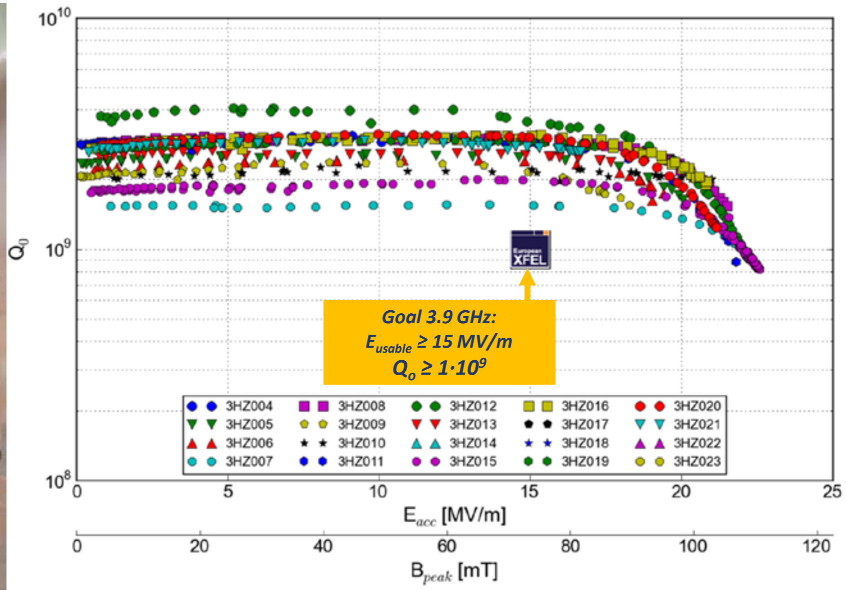
(E_{goal} = 23.6 [MV/m], $Q_0 \geq 1 \cdot 10^{10}$)

European XFEL: 3.9 GHz cavity and cryomodule results

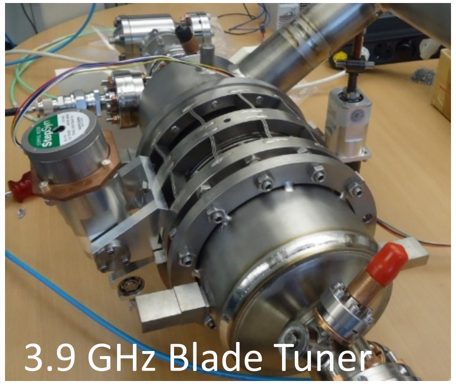
Results:

- **Accepted Cavities as Delivered: 85% of 20 overall**
- After Additional Treatments (**only HPR**): **all accepted**
- **Rejected Cavities: none**
- Delivery rate: **2 cavs/3 weeks**

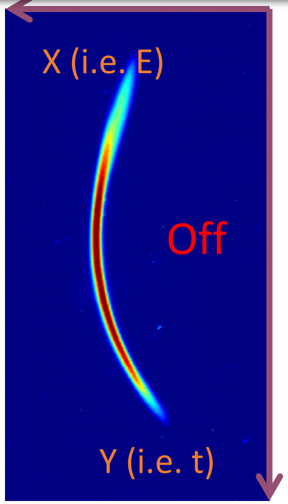

3.9 GHz cavities on LASA VT insert

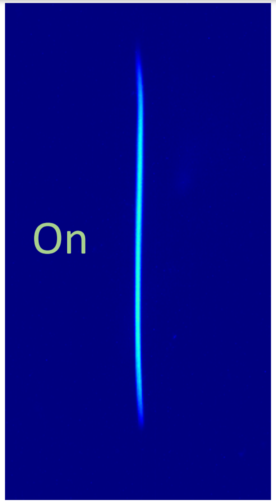


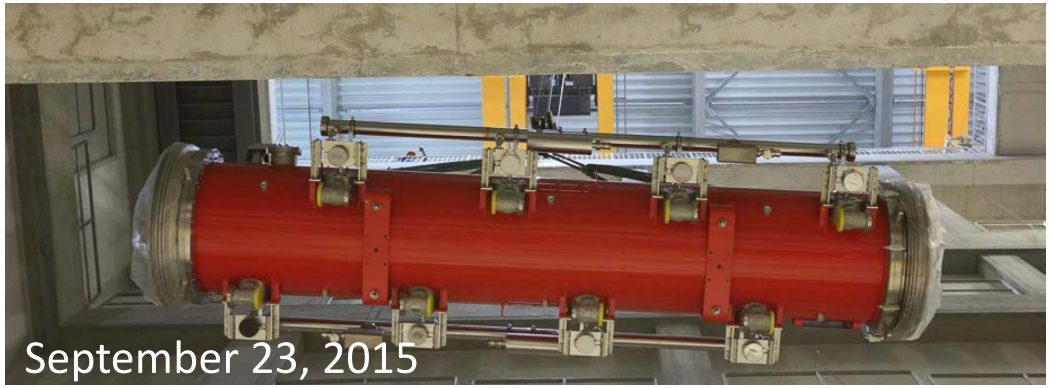

String Assembly (DESY)

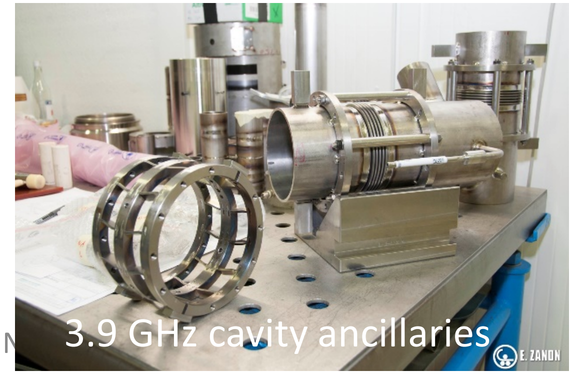

3.9 GHz Blade Tuner

RF Curvature Linearization by AH1





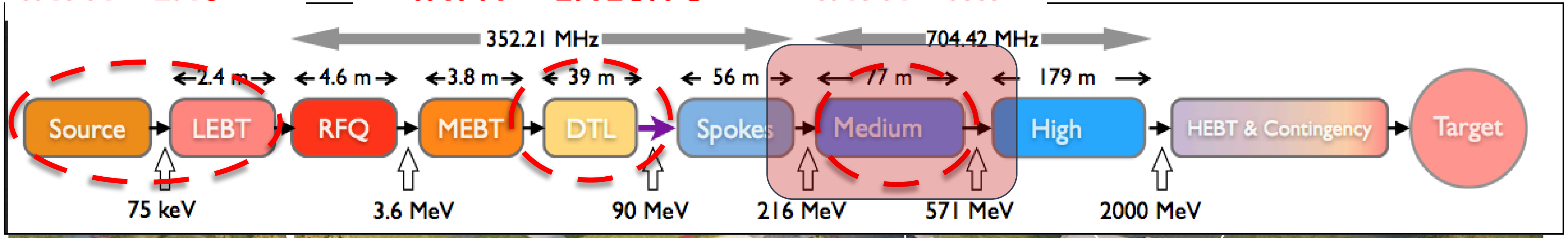

September 23, 2015

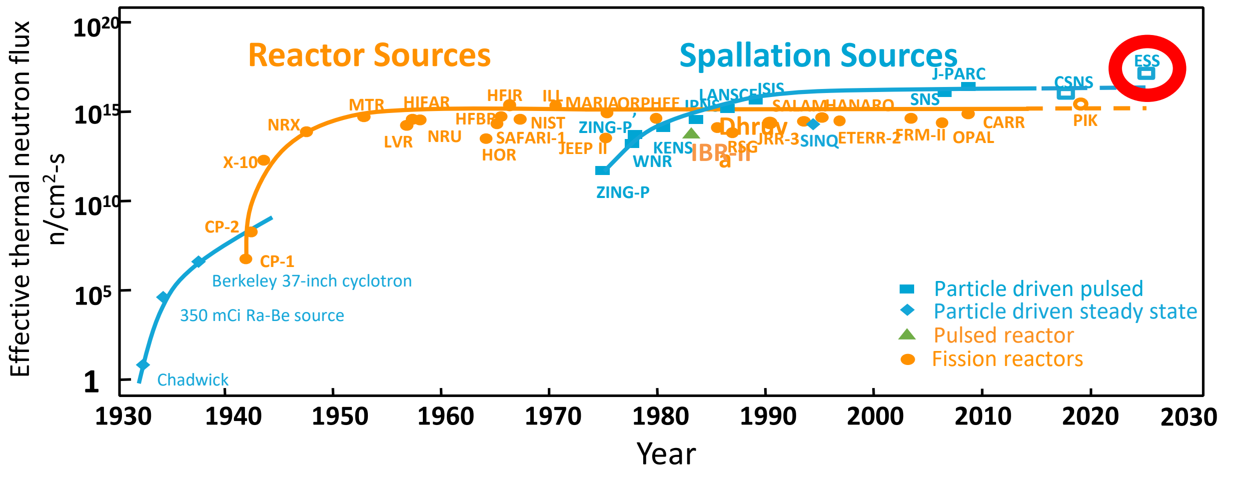

3.9 GHz cavity ancillaries

European Spallation Source

EUROPEAN SPALLATION SOURCE

INFN - LNS INFN – LNL&TO INFN - MI





(Updated from *Neutron Scattering*, K. Skold and D. L. Price, eds., Academic Press, 1986)

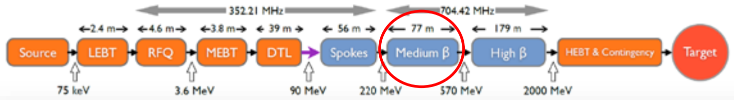
16 Instruments in Construction budget

Committed to deliver 22 instruments by 2028

Peak flux ~30-100 brighter than the Institute Laue-Langevin

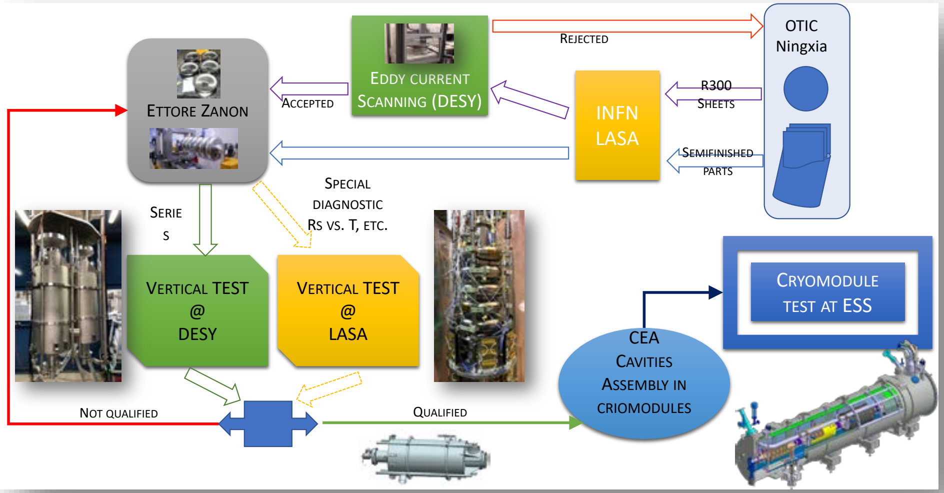
Total cost: 1843 MEuros$_{2013}$

ESS: 704.4 MHz series cavity



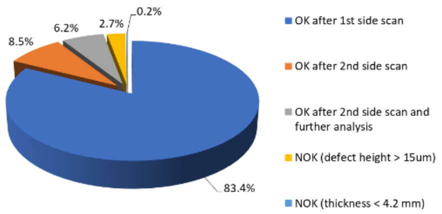
Purposes:

- **36** (+2) SC cavities, **1 Nb suppliers**, **1 industry**, **1 recipe (BCP)**
- ESS medium β (0.67) $\mathbf{Q_0 = 5{\cdot}10^9}$ **@ 16.7 MV/m**

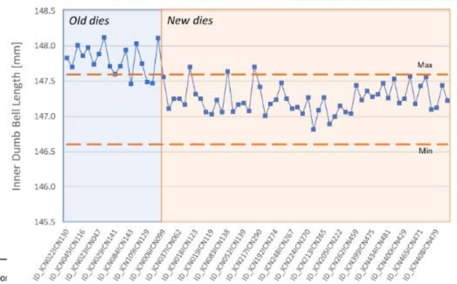


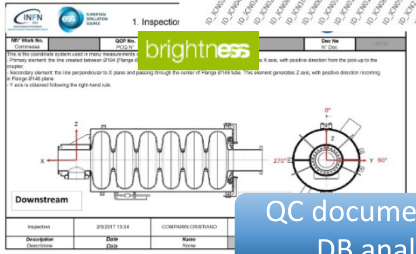
How it is working:

ECS Nb sheets (DESY)

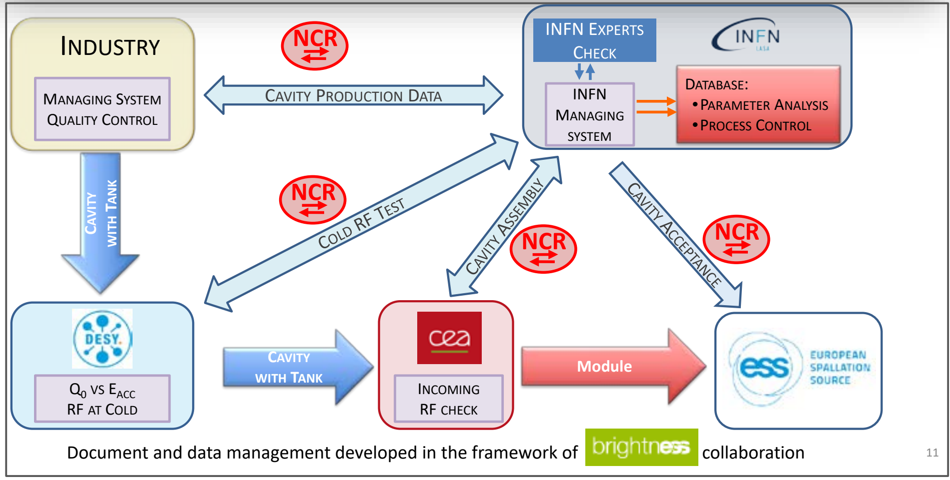


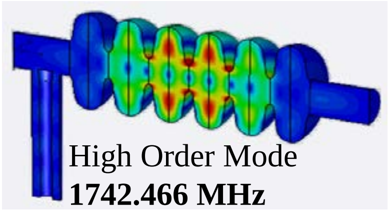
- **Definition of Nb specs** and **QC** (inspection at **Nb** vendor, **ECS** at **DESY)**
- **Optimization** of the **RF** and **mechanical design**
- **Definition of detailed production specs** (1 recipe), **PED sound engineering practice** compliant (3 prototypes)
- **Infrastructures adapted** to **704.4 MHz larger geometry** and **qualified** (BCP treatment, new HPR head geometry, new inner inspection system, EP treatment, tuning machine)
- **Definition of the QC plan** -> **QC improved** for the **interfaces between all partners** (INFN-Industry-DESY-CEA-ESS)
- **Management** of all documentation (INFN Alfresco based) and **database** developed for **analysis of key production parameters**
- **Cold VT at LASA** for «special» cavities (more diagnostics available)

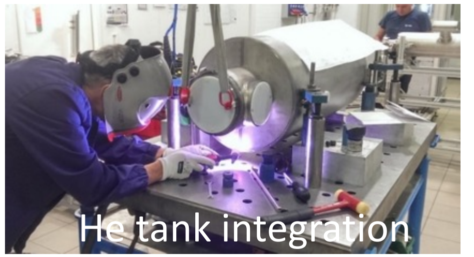




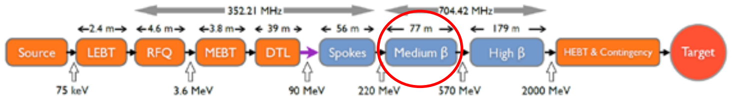
QC documents and DB analysis





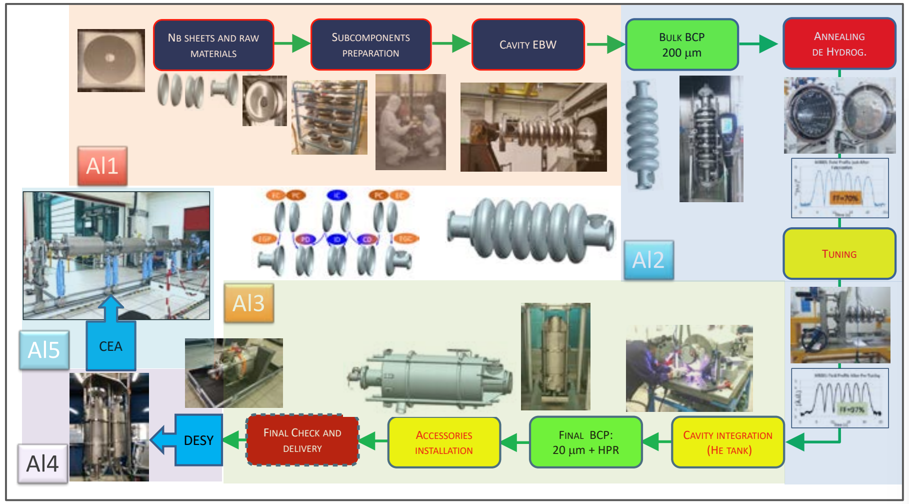


ESS: 704.4 MHz series cavity results



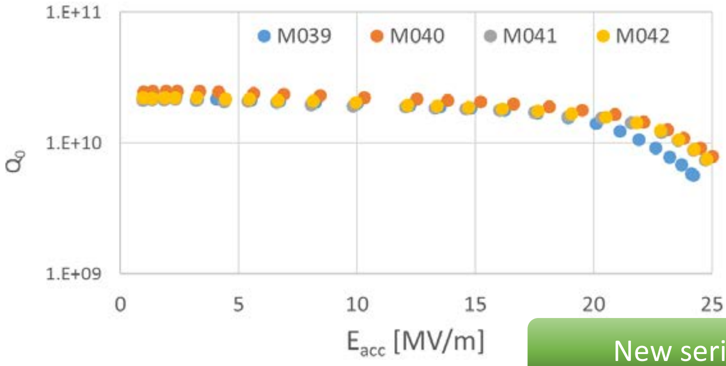
Results:

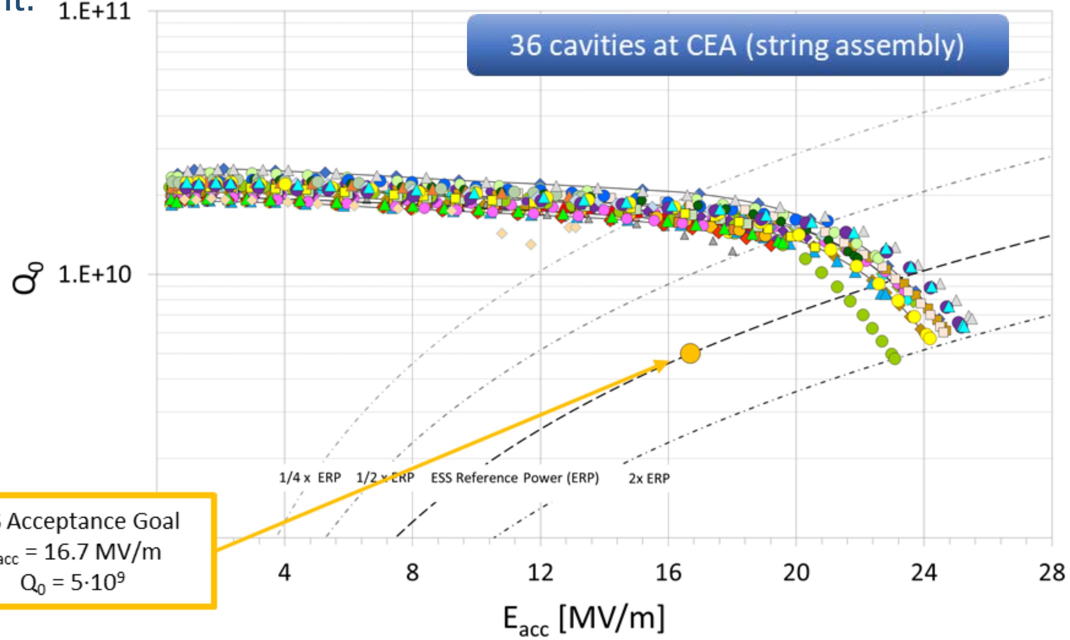
- **Cavities at CEA for string assembly (cryomodule): 36 (+1 spare)**
- **Accepted Cavities as Delivered: 27**
- Recovered after Additional Treatments
  - **HPR**: **3**; **EP**: **3**
- Further 4 cavities produced (**EP cycle**):
  - **Now integrated in cryomodule 9 @ ESS**
- **Cavities in quarantine: 5**



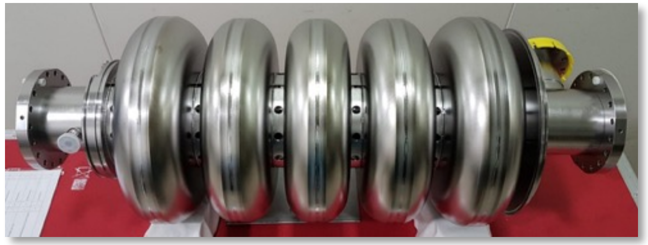
Recovery strategy:

- **HPR improved** to better fit the **cell shape** (new head), **EP** adapted to ESS shape for surface treatment: -> **performance improvement of MP/FE limited cavities**
- **rotating BCP** on integrated cavities**:** -> **some performance improvement**
- **Risk mitigation with 4 new cavities** produced: -> **all** cavities **overcome ESS goal** (EP process)





INFN in-kind contribution to PIP-II



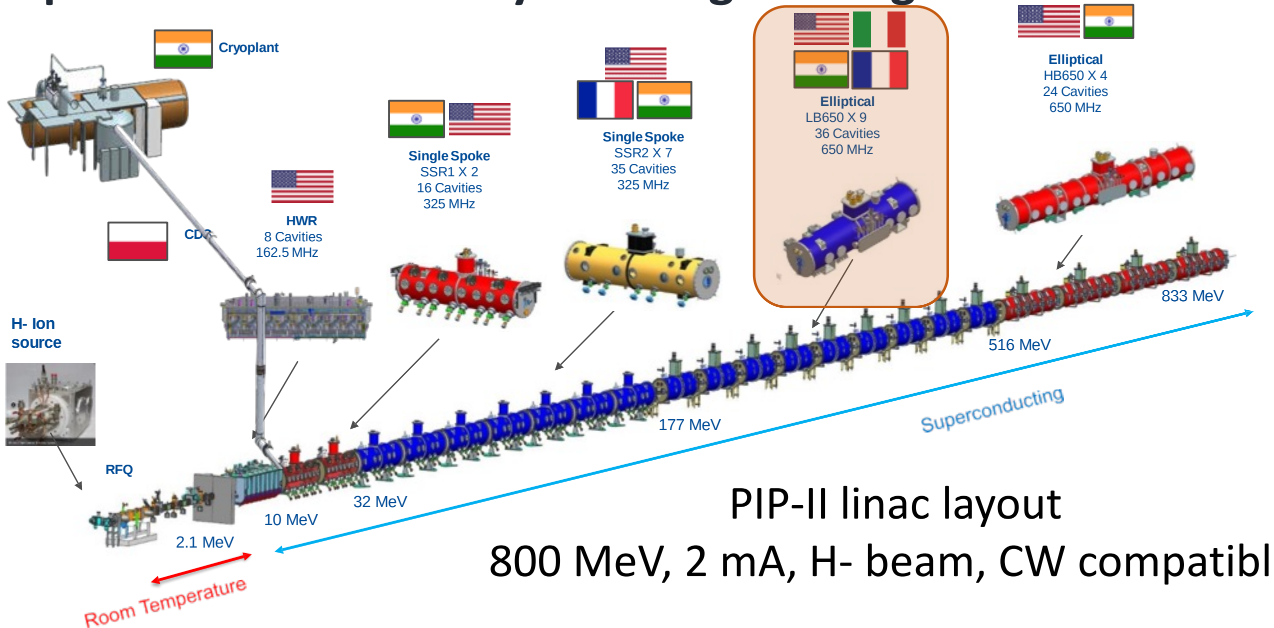
INFN LASA provided a ***novel RF design for the LB650 cavities***, compliant to Fermilab technical interfaces and specifications (outstanding Q_0 requirements).

PIP-II LB650 Project Specifications	
Acc. Gradient	**16.9 MV/m**
Q_0	**$2.4\ 10^{10}$**
RF rep rate	20 Hz to CW
Beta	0.61

INFN-LASA contribution will cover the needs of LB650 section:

- **2 proto cavities** to validate processing and tech. transfer
- **38 SC cavities** required to equip 9 cryomodules with 2 spares, delivered **as ready for string assembly**.
- **Qualification** via vertical cold-test provided by INFN through a **qualified cold-testing infrastructure** acting as a subcontractor
- **Compliance** to the **PIP-II System Engineering Plan**

INFN Deliverable Components	Acceptance Early Date
LB Jacketed Cavities (Batch 1 - Qty 4) and Pre-Series (Qty 2)	Jun-2025
LB Jacketed Cavities (Batch 2 - Qty 4)	Aug-2025
LB Jacketed Cavities (Batch 3 - Qty 4)	Oct-2025
LB Jacketed Cavities (Batch 4 - Qty 4)	Dec-2025
LB Jacketed Cavities (Batch 5 - Qty 4)	Feb-2026
LB Jacketed Cavities (Batch 6 - Qty 4)	Apr-2026
LB Jacketed Cavities (Batch 7 - Qty 4)	Jun-2026
LB Jacketed Cavities (Batch 8 - Qty 4)	Sep-2026
LB Jacketed Cavities (Batch 9 - Qty 4)	Oct-2026



PIP-II linac layout

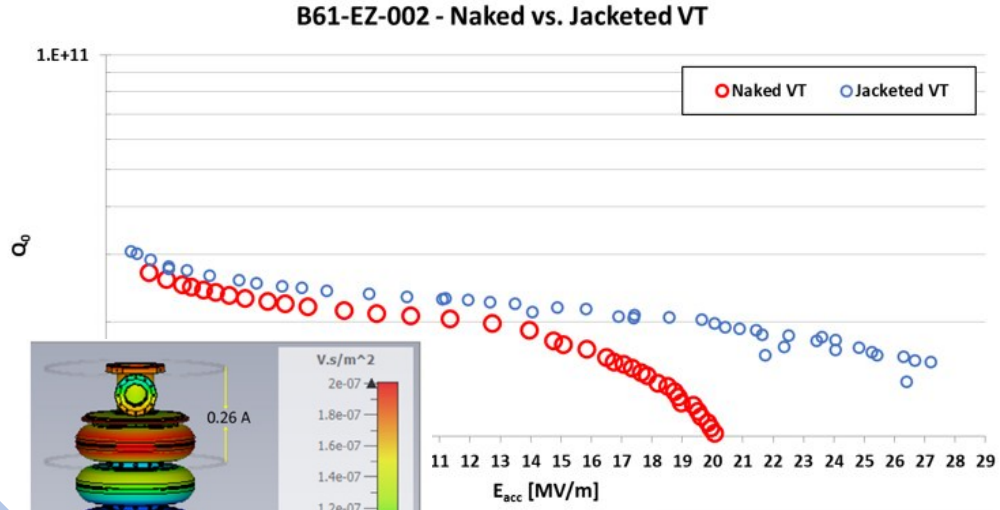
800 MeV, 2 mA, H- beam, CW compatible

PIP-II

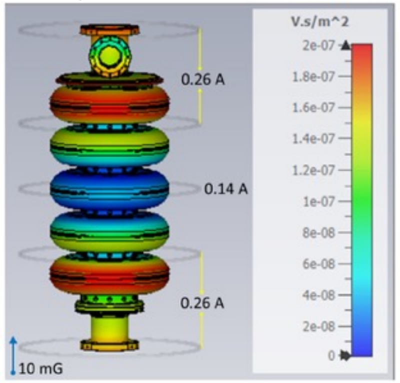
LB650 on-going activities at INFN

R&D towards high Q_0 and **preparation for transfer to industry**

- Prototypes to **develop proper surface treatments**
  - B61-EZ-001 jacketed and tested at FNAL
  - B61-EZ-002 jacketed and tested at LASA
  - B61S-EZ-001 single cell treated and tested at FNAL
  - B61S-EZ-002 treated, jacketed and tested at LASA
  - B61S-EZ-003 single cell processed and tested at LASA



- **Develop diagnostic** for process control
- Analytical Field-Emission model
- **Cavity transport boxes** developed; prototypes built
- Prepare **LASA test station** for **high Q_0** measurements
  - Lower residual magnetic field, Helmholtz coils
  - Faster cool-down rate across SC transition



Main procurements in view of the series production

- **RRR300 Nb** tender: 1st batch inspected in Oct. 23 and delivered, next Eddy Current Scanning.
- Agreement with DESY in progress for **Eddy current scanning** and **series cavity vertical tests**
- **Cavity manufacturing, treatment and preparation**: CFT and selection closed, waiting for final awarding.

INFN High-Q/High-G R&D activities

Foreseen activity (3 years):

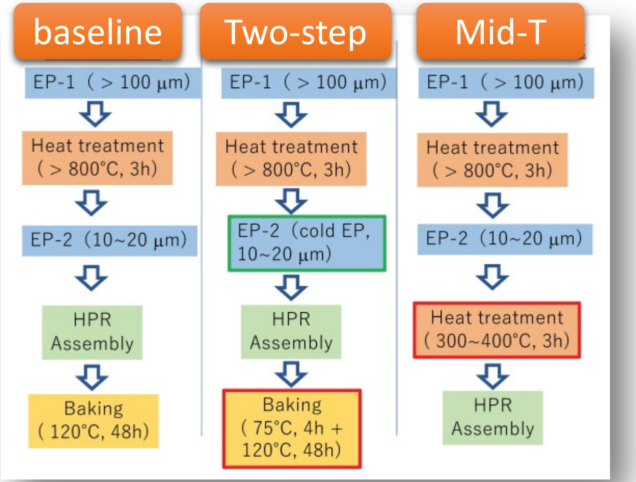
- **Surface treatments** development for reaching High-Q/High-G perfomances (single-cells)
- **Industrialization**: from single to multicell cavity
- **R&D on cavity ancillaries** (tuner, magnetic shield, etc,)

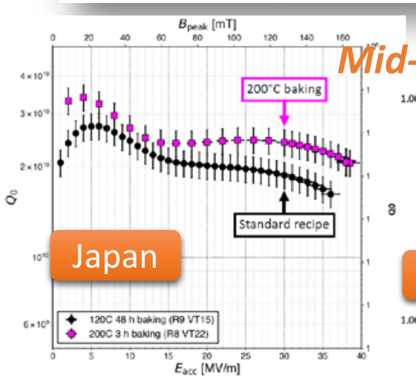
R&D for High-Q/High-G cavities :

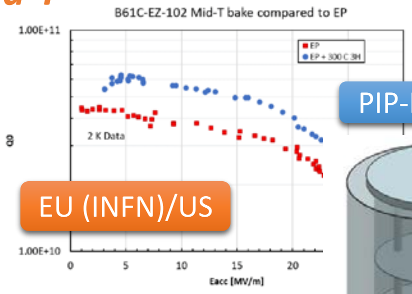
- 1-cells 1.3 GHz: **surface** and **thermal treatments** development & qualification
  - E-XEFL (baseline), Mid-T , two-step baking
  - Cold VT (qualification) at LASA and in other labs (results validation)
- 9-cells 1.3 GHz: **industrialization** (9-cells) of the developed process

Upgrade of LASA VT system:

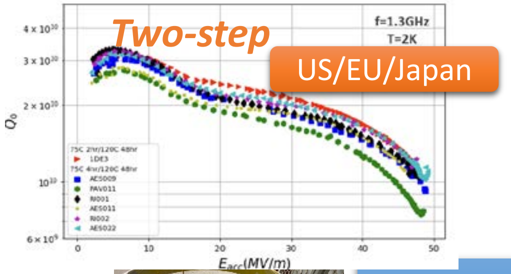
- **New cryostat dedicated to R&D**:
  - Design specifically for R&D on TESLA type single- and multi-cell cavities
  - Much faster overall work cycle compared to main cryostat
  - Active B-field compensation by design

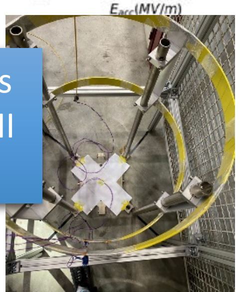






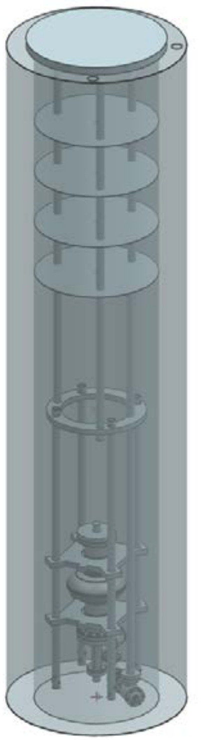
PIP-II





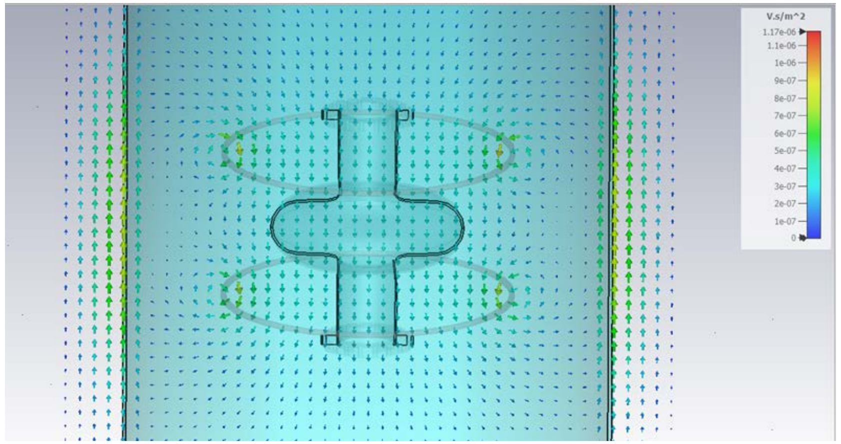
Helmholtz coils (based on PIP-II experience)

Sketch of R&D cryostat and insert

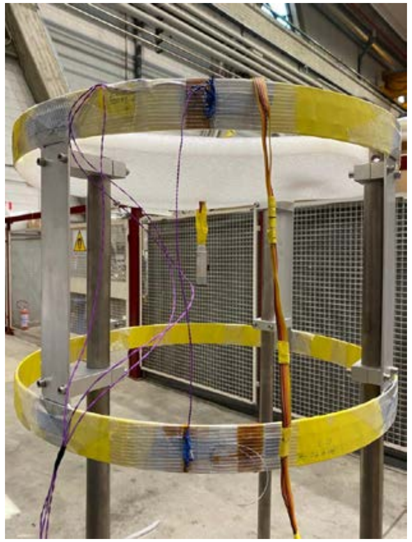


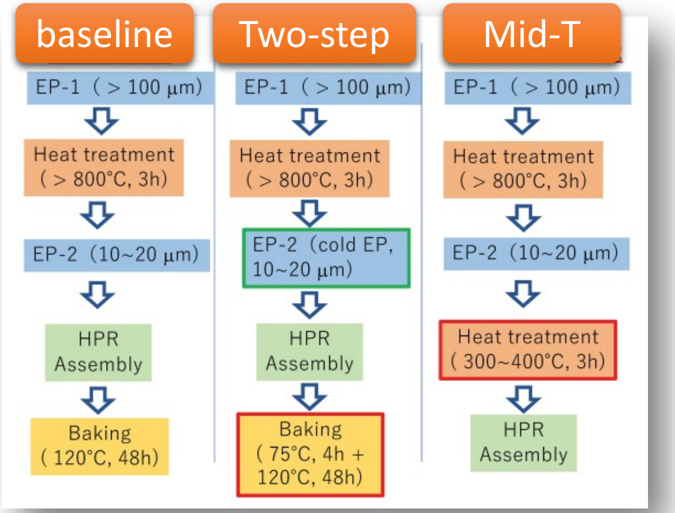
INFN High-Q/High-G R&D: experience on PIP-II LB650 single-cells

- The same recipes foreseen for the 1.3 GHz cavities are currently carried out on the PIP-II LB650 single cell prototypes
- This allows a real-time optimization of treatment parameters (EP, furnace for baking, HPR,….)



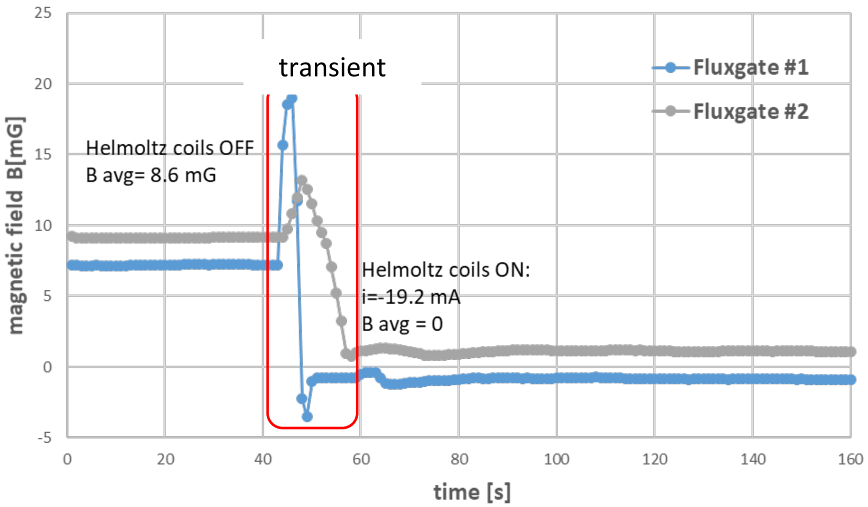
Coil field + residual field CST simulation



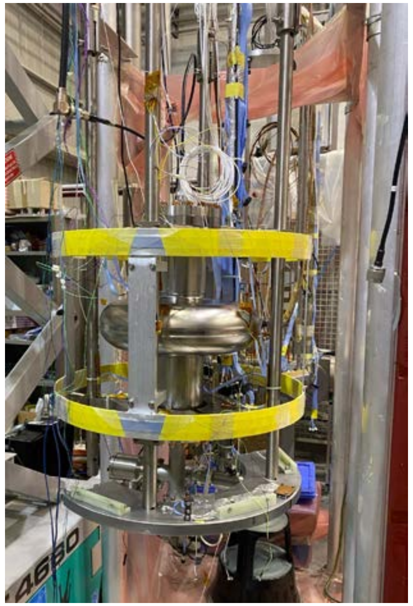


Done To be done Done

Field cancellation during cooldown



PIP-II Vertical insert with Helmoltz coils



Sinergies: ITN e EAJADE

- ## ILC Technology Network (ITN), 2-4 years

  derived from ILC IDT (ILC International Development Team) to support pre-lab technological priorities as identified by the International Expert Panel

  - March '23: budget approved by Japan; KEK-CERN agreement: signed in July 2023
  - **INFN Milano LASA** involved in ILC SRF activities (R&D and industrialization of 1.3 GHz cavities)
  - **Activities foreseen in 2023-2026**
    - Treatments targeted to ILC goal (single and 9-cell cavities) towards industrialization with qualified vendors
    - Harmonization of pressure vessel codes (PED/ASME/HPGS)
    - Fine Grain and Mid Grain Nb studies for single and 9-cell cavities -> in view of the cost reduction
    - Assembly at KEK of an ILC cryomodule with 1 EU cavity, 1 US cavity and 6 Japan cavities

Item	Parameters
C.M. Energy	250 GeV
Length	20km
Luminosity	1.35 x10^{34} cm^{-2}s^{-1}
Repetition	5 Hz
Beam Pulse Period	0.73 ms
Beam Current	5.8 mA (in pulse)
Beam size (y) at FF	7.7 nm@250GeV
SRF Cavity G. Q_0	31.5 MV/m (35 MV/m) Q_0 = 1x10 ^{10}

ILC cavity Goal

- ## EAJADE, 4 years

  European Commission | *Marie Skłodowska-Curie Actions Staff Exchanges*

  Staff exchange network for accelerator R&D within elementary particle physics

  - Exchange between:
    - EU labs/univerisity and US-Japan labs/universities
    - EU labs/univeristy and EU industries
  - started in March 2023, 4 years duration
  - Six WPs

  EAJADE
  Europe-America-Japan Accelerator Development Exchange Programme

- **INFN responsibility**:
  - WP2 lead beneficiary L. Monaco (*State-of-the-art high-gradient, high-efficiency, reduced-cost radio-frequency structures and power Sources)*

Conclusive remarks

- LASA is involved since several years in the field of SRF
  - Cavity design (EM and mechanical), prototyping, study of material and surface treatments, vertical test in the LASA facility. Beyond cavities: cryomodule installation, tuner, magnetic shields,...
- LASA contributes to the series production of cavities for acceleration of electrons (E-XFEL) and protons (ESS, PIP-II)
- LASA is devoted to R&D activities for the development of surface treatments for high-Q/high-G performances in view of future colliders
  - Study and industrialization of cutting-edge surface recipes
  - Project and development of a cryostat for prototypes with high magnetic hygiene and dedicated diagnostics to investigate possible performance limitations.