First FCC-Italy Workshop
Roma 21-22 marzo 2022

Superconducting RF: INFN participation in large projects

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INFN Milano – LASA

On behalf of the LASA SRF Group

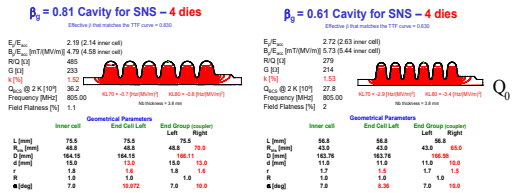
Outline

- **Intro**
- **Large Projects challenge**:
  - From Lab to Industry
  - Reason for industrialization
- **Our contribution to**:
  - European-XFEL
  - European Spallation Source (ESS)
  - Proton Improvement Plan-II (PIP-II)

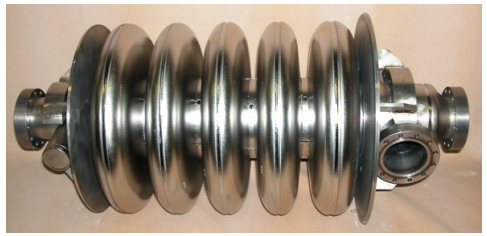
Introduction

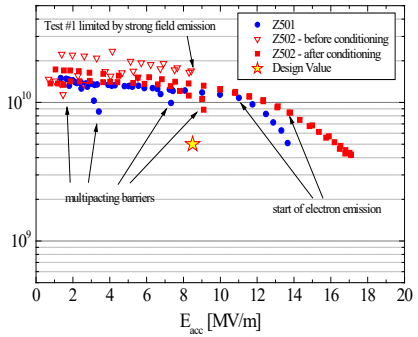
- **INFN LASA SRF group** has a long experience on **design, fabrication and qualification** of **SC cavities**, cavity **ancillaries** (tuner, magnetic shield, etc.) and **cryomodules** (cold mass, etc.) started in the framework of the **TESLA Collaboration**

RF design for SNS

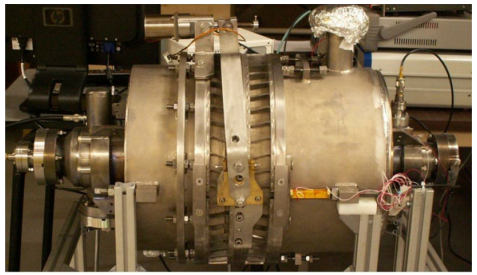


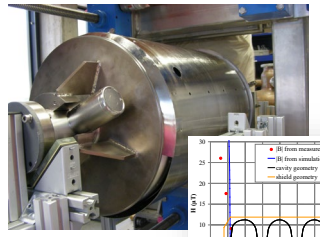
RF and mech. design, fabrication and VT (TRASCO)

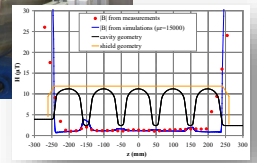


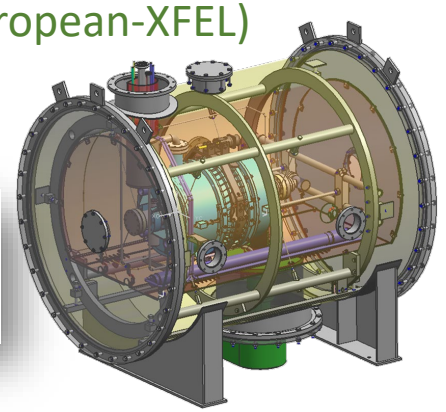


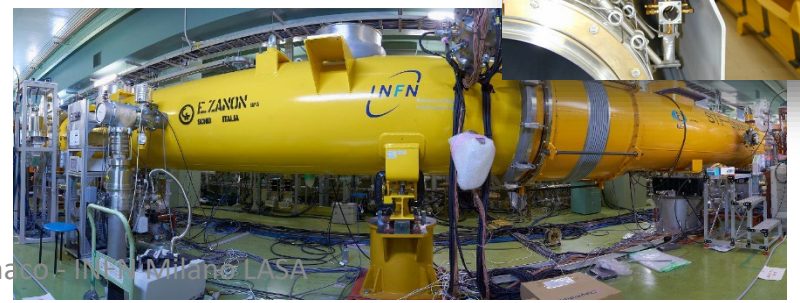
Design, fabrication and qualification of cavities and cryomodule ancillaries (HIPPI, EUROTRANS, TTF, FLASH, European-XFEL)

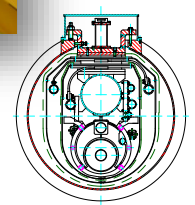




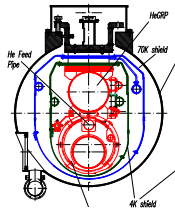




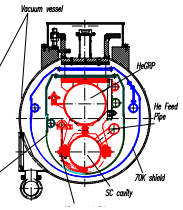




Module 1



Module 2 & 3

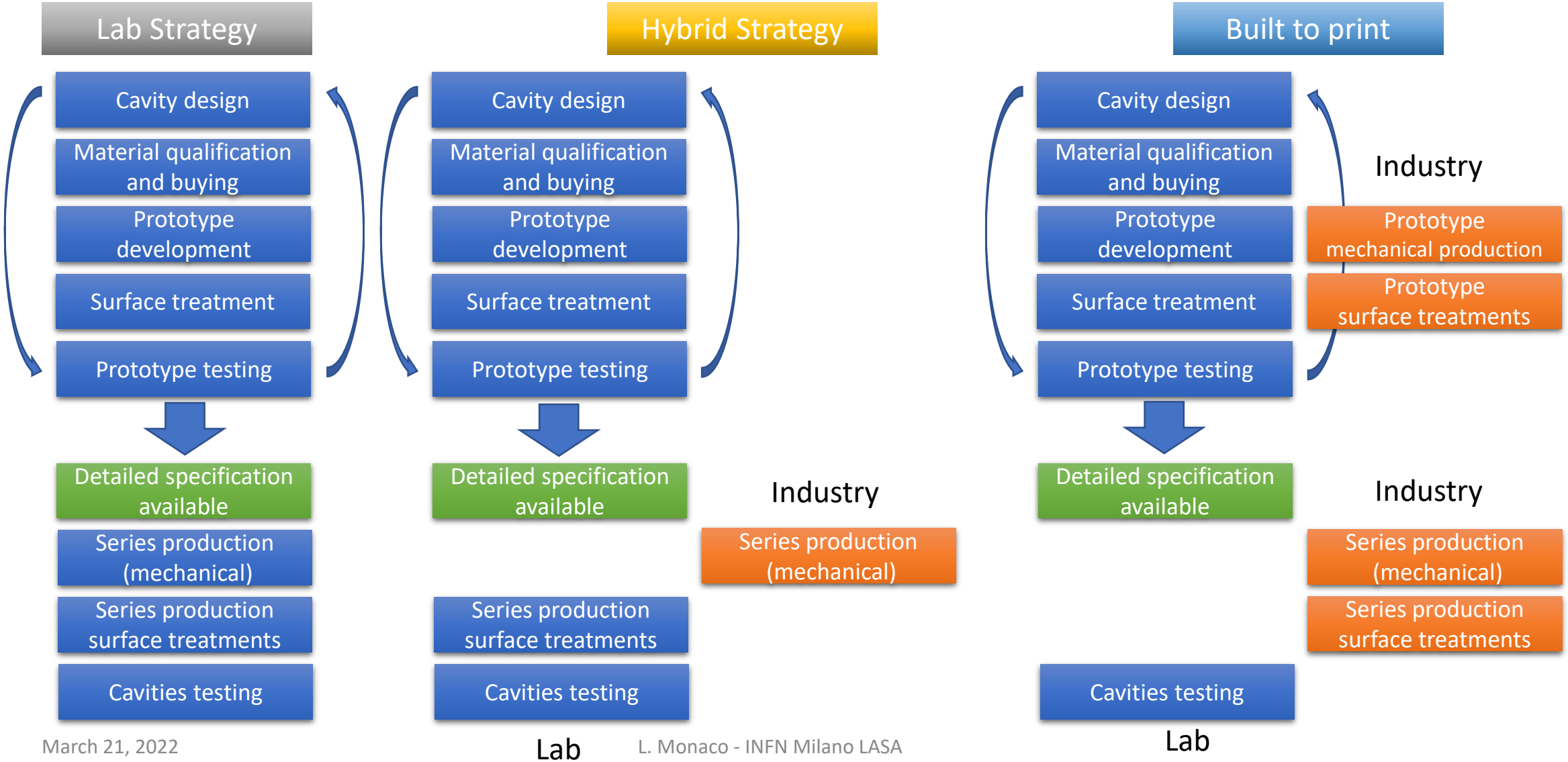


Module 4+

Introduction

- INFN LASA SRF group has a long experience on design, fabrication and qualification of SC cavities, cavity ancillaries (tuner, magnetic shield, etc.) and cryomodules (cold mass, etc.) started in the framework of the TESLA Collaboration
- For the **European-XFEL**, we shared with DESY the production of the **1.3 GHz 800 cavities** with European companies. We produced **42 cryomodules** and did the **QC** of the **800 tuners**.
- Moreover, we have been in charge of the design, production and test of the **20 3.9 GHz cavities** and **ancillaries** (blade tuner, magnetic shield, etc.), of the **3.9 GHz cryomodule** (design, production and cavity assembly) 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 **36 704.4 MHz cavities**.
- We are also starting our activities towards the production of the **38 650 MHz Low Beta cavities** for the **PIP-II** accelerator of the LBNS at FNAL.

From lab to industry production



Reason for industrialization, critical aspects

Large projects requires:

- **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**

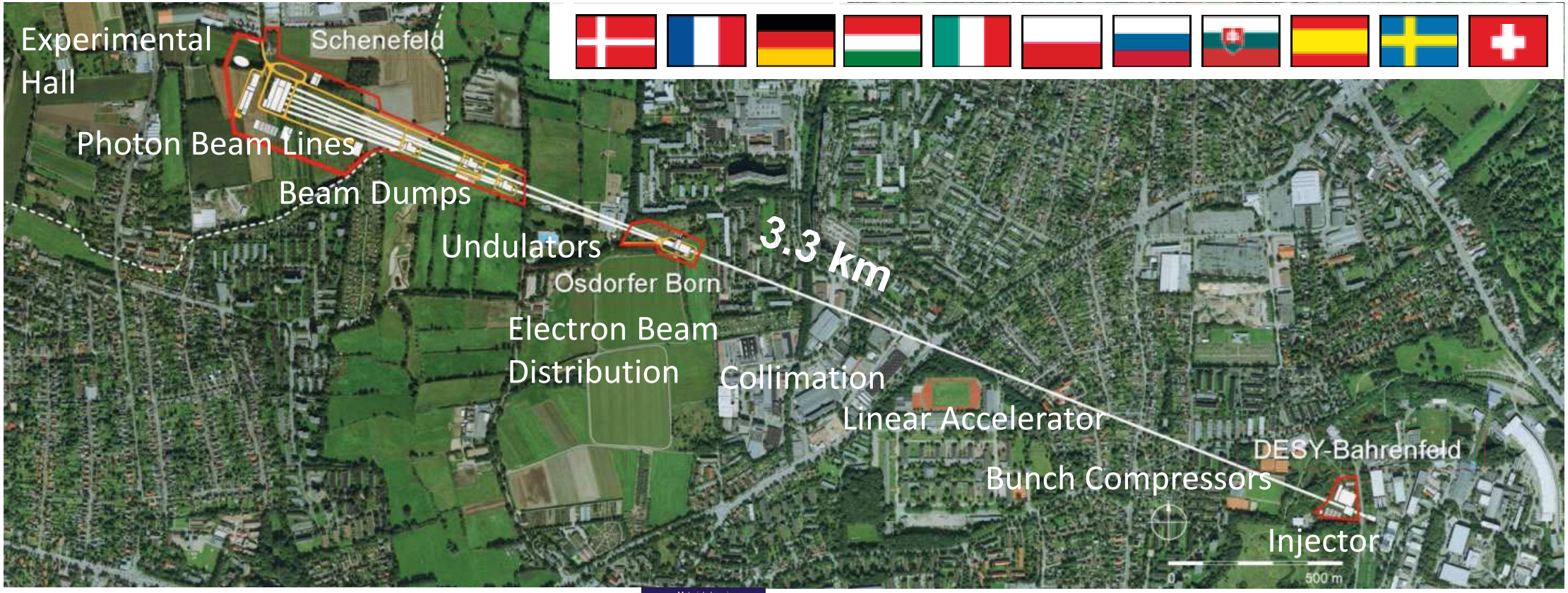
Laboratory resources:

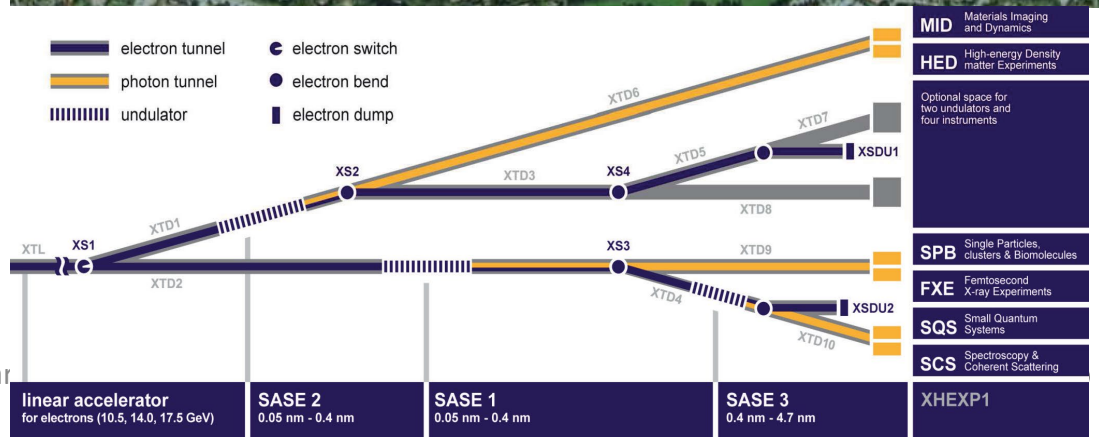
- **not able to manage large numbers** in term of quality, man-power, optimized cost, scheduling respect, infrastructures, etc.

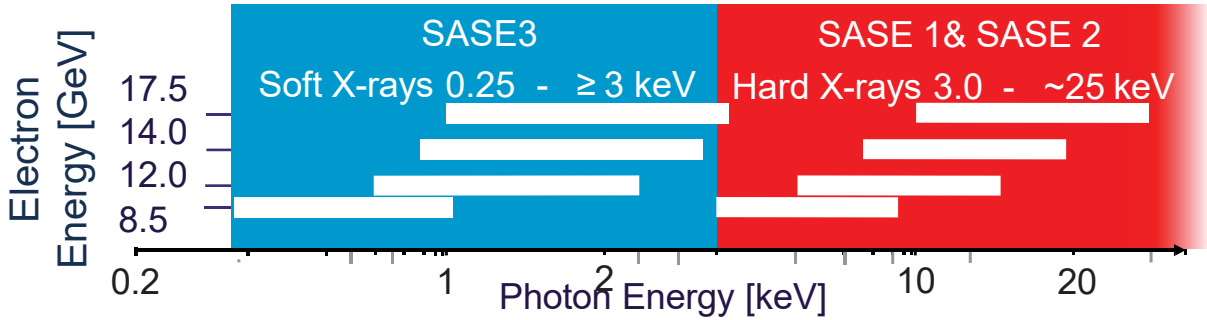
Criticalities, warnings (mainly for cavities):

- 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 for 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



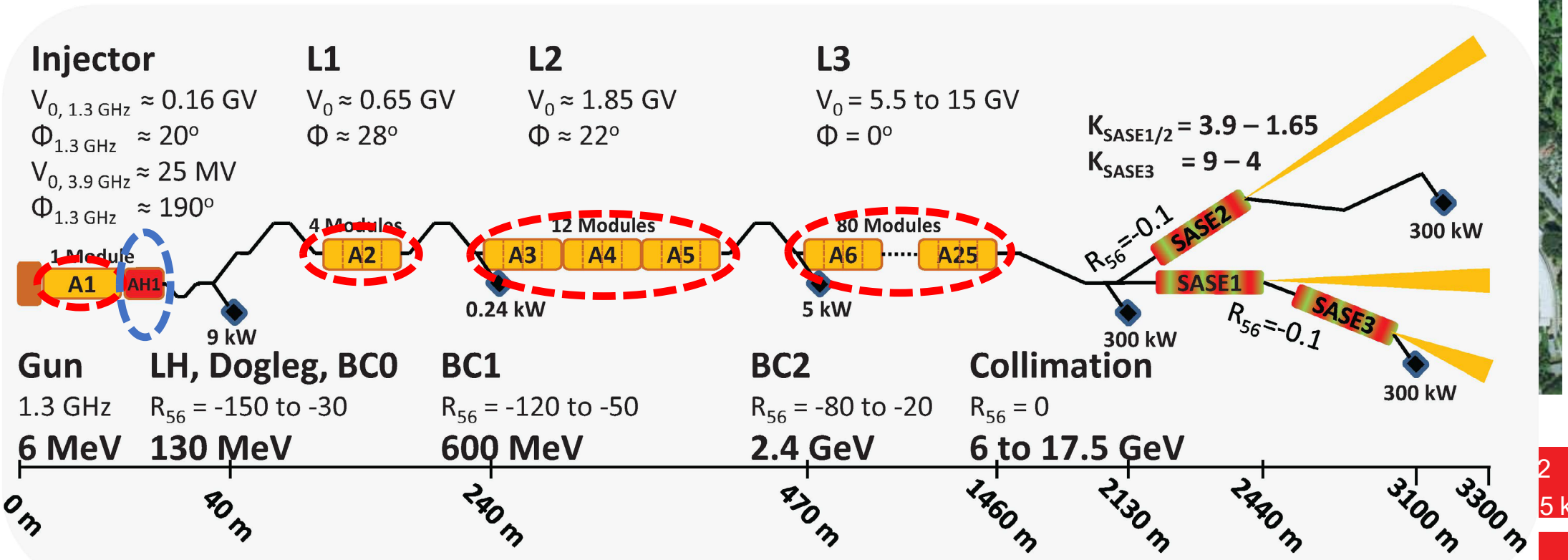


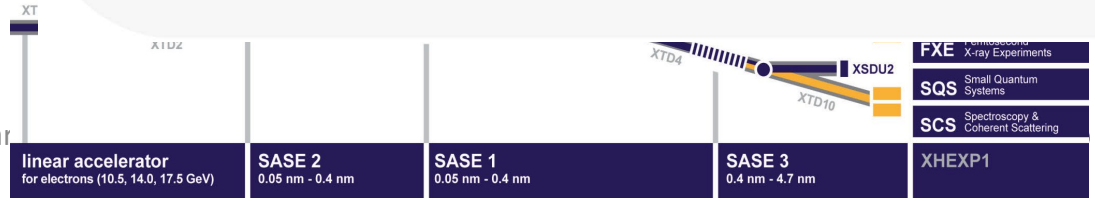


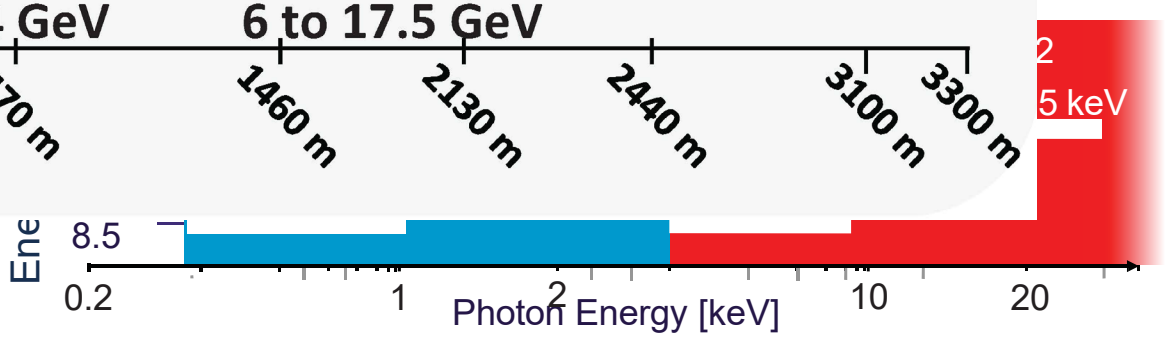
European XFEL

Italian in-kind contribution:

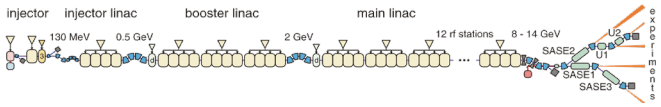
- **1.3 GHz: 320 cavities, 42 cryomodules, QC 800 tuners**
- **3.9 GHz: 1 cryomodule, 20 cavities (blade tuners, He-tanks, magnetic shields)**







European-XFEL 1.3 GHz Cavities



Eu-XFEL 1.3 GHz cavity series production: strategy

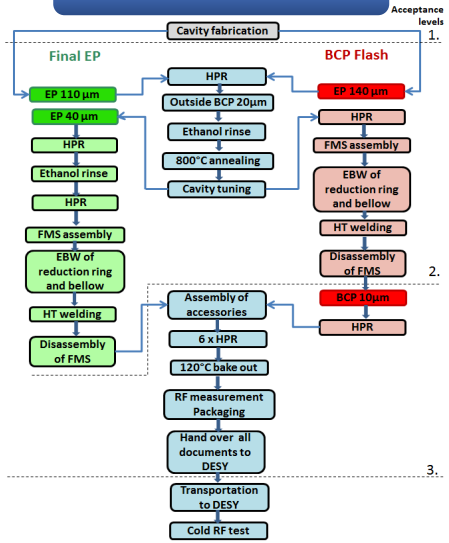
Purposes:

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

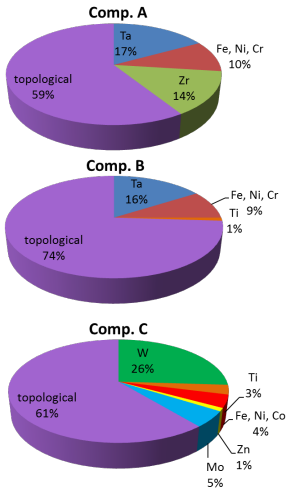
How it worked:

- Materials and vendors qualification (Nb)
- Definition of detailed production specs (2 recipes), PED 4.3 compliant (prototypes, TESLA experience)
- 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 monitoring of key parameters
- Prompt feedback of the running production quality (analysis of VT vs. key parameters)

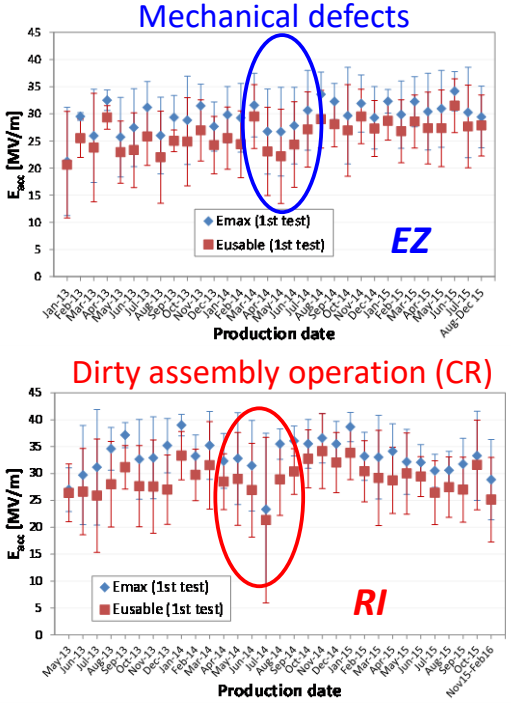
Final EP / Flash BCP



Inclusions in Nb sheets

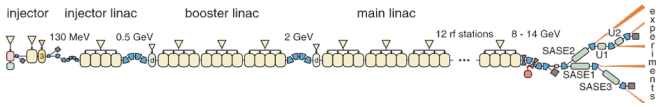


Analysis VT @ 2 K vs. running production quality



120 °C baking system (EZ)

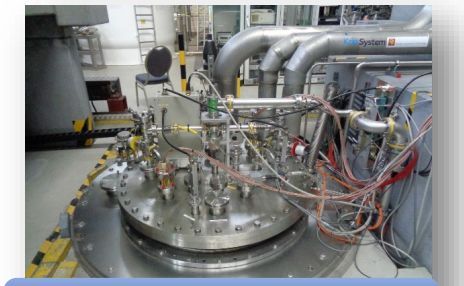
HPR cabinet (RI)



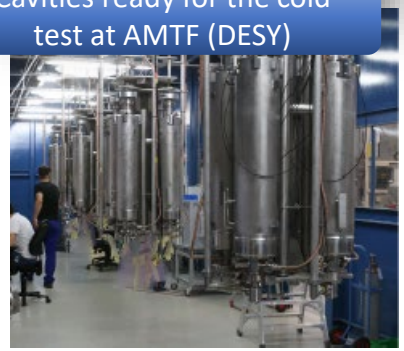
Eu-XFEL 1.3 GHz cavity series production: results

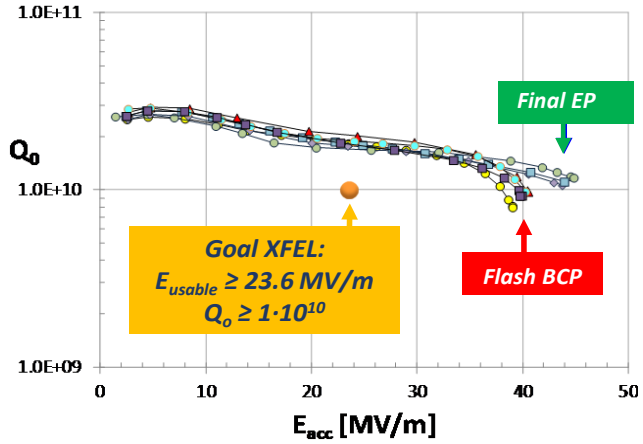
Results:

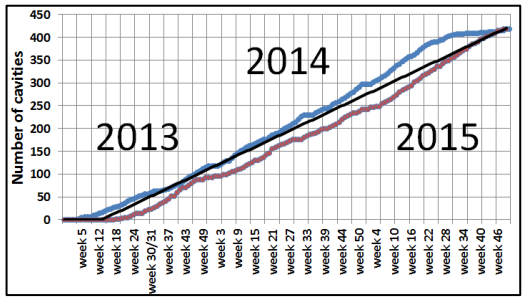
- Accepted Cavities as Delivered: ≈ 70% (over 800)
- After Additional Treatments (**mainly HPR**): all cavities accepted
- Rejected Cavities (replaced by companies): 8 (1%)
- In total **3 years** (2013-2015)

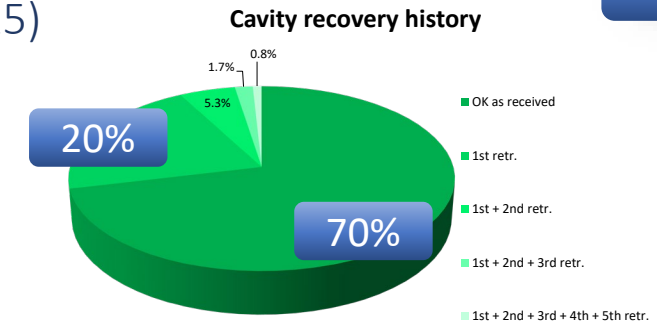


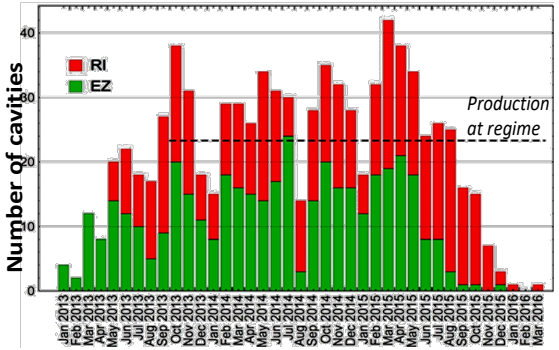
Cavities ready for the cold test at AMTF (DESY)



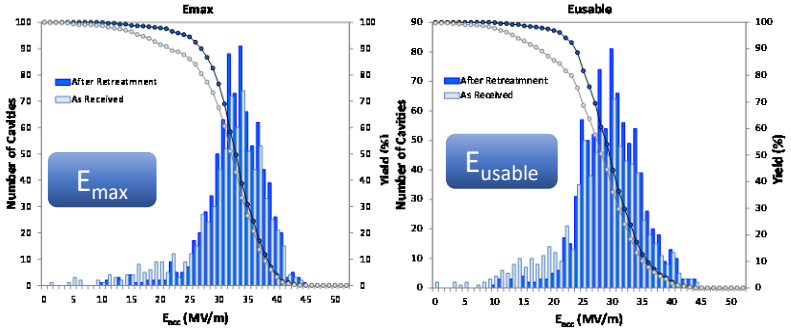






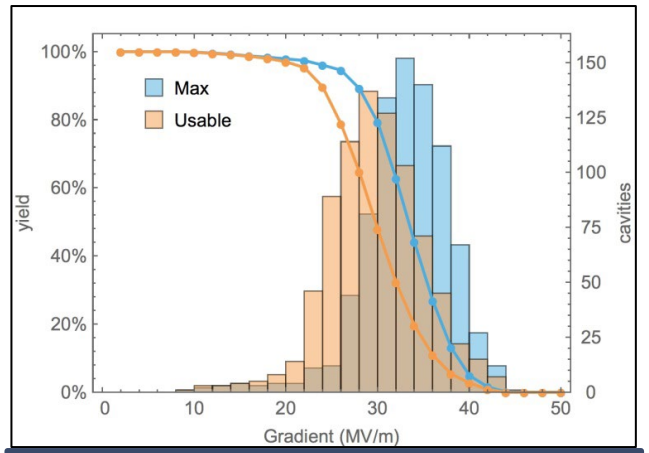


DESY Arrival Date



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

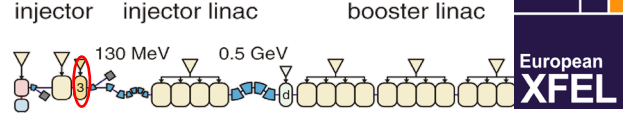
After 29.8 ± 5.1 [MV/m]
Before 27.7 ± 7.2 [MV/m]



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 Module



Eu-XFEL 3.9 GHz cavity series production: strategy

Purposes:

- 10+10 Cavities, 1 Nb supplier, 1 industry, 1 recipe (BCP)
- 3.9 GHz E-XFEL gradient 15 MV/m @ Q_0=1x10^9
- **Cavity ancillaries:** Blade Tuners, magnetic shields, He-tank, etc.
- **Cryomodule:** cold mass, thermal shielding, etc.

How it worked:

- **RF and mechanical design** of cavity
- **Recipe** developed also in collaboration with industry using **three prototypes, PED 4.3** compliant
- Industry and LASA **infrastructures adapted to 3.9 GHz geometry** (smaller) and **qualified** (BCP treatment, new HPR set-up, inner optical inspection system)
- **QC at industry and at LASA -> QC improved** (based on 1.3 GHz experience)
- **Production shared between Industry and LASA** (final steps in LASA clean room)
- **Cold VT (performance qualification) all done at LASA**

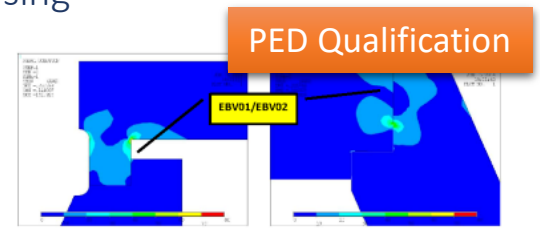
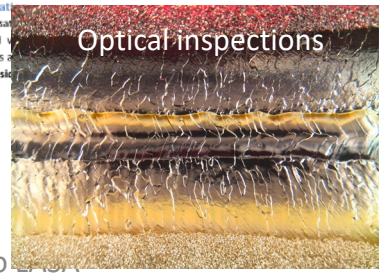
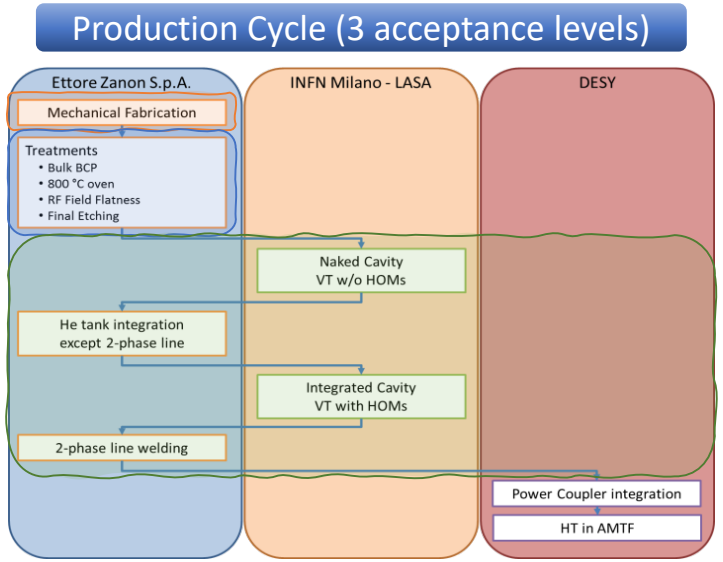
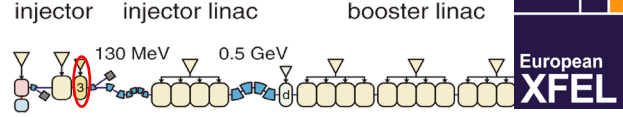


Figure 11: Equivalent Von Mises stress at the regions of welds EBV02 (left) and EBV01 (right).

1.2.3 Stress linearization and stress categorizat
Since the most stressed regions are the Ti1 compensa
sections the stress linearization, categorization and
EN13445-3 will be performed only in the two regions
and in particular T04/T05 and EBV02, it was consi



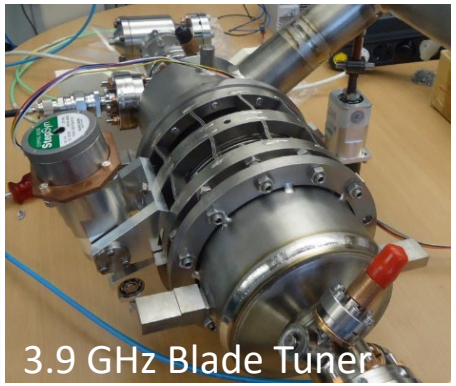


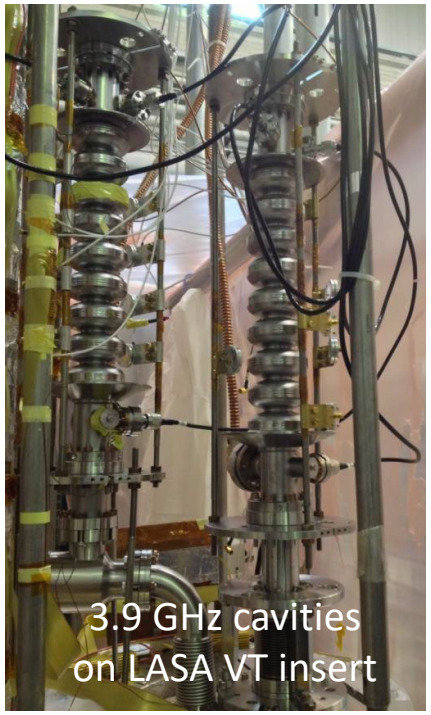


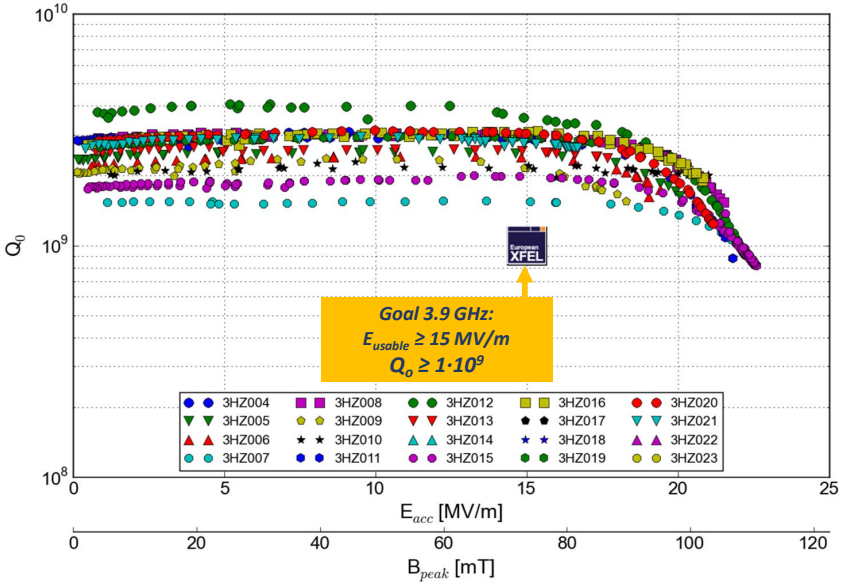
Eu-XFEL 3.9 GHz: cavity and cryomodule results

Results:

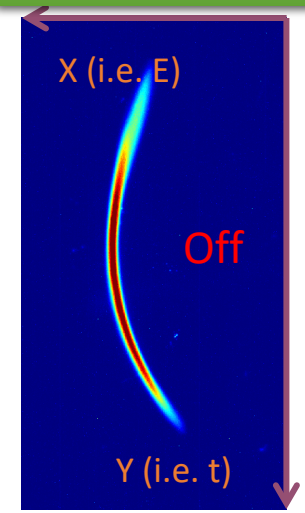
- Accepted Cavities as Delivered: ≈ 85% (over 20)
- After Additional Treatments (only HPR): all accepted
- Rejected Cavities: none
- Delivery rate: 2 cavs/3 weeks

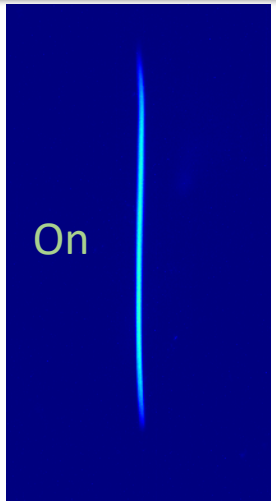


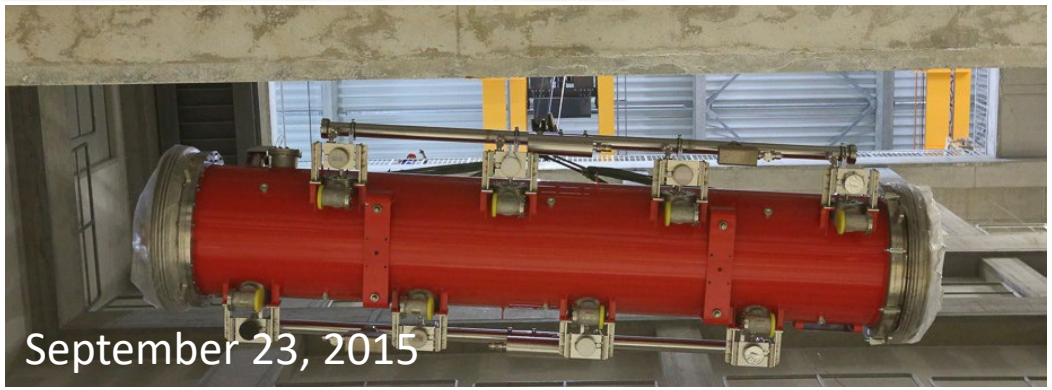




RF Curvature Linearization by AH1



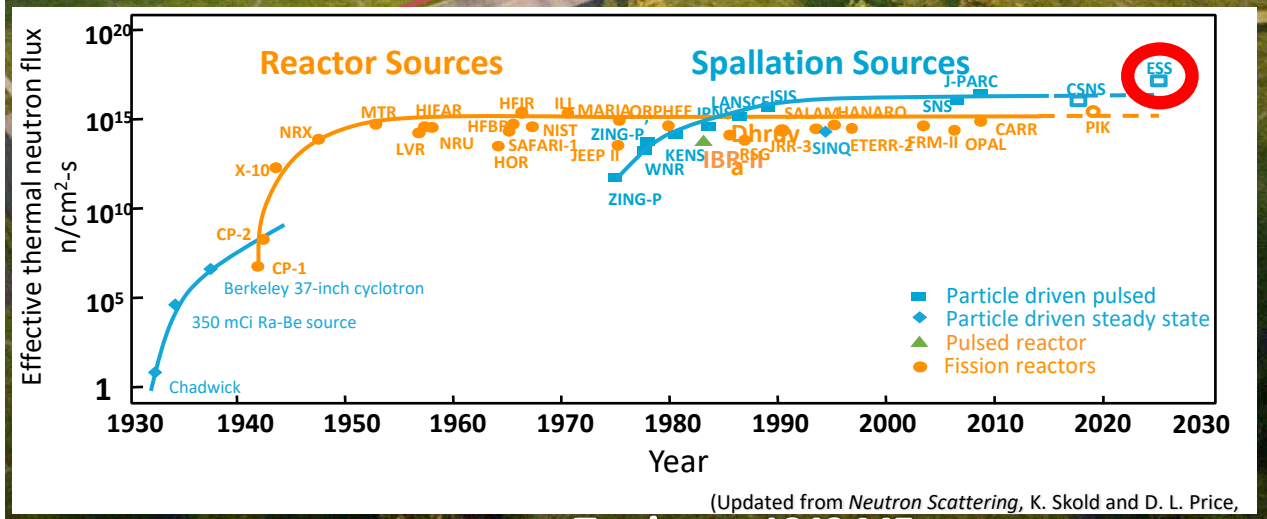




European Spallation Source

High Power Linear Accelerator:
- Energy: 2 GeV
- Rep. Rate: 14 Hz
- Current: 62.5 mA

Target Station:
- He-gas cooled rotating W-target (5MW average power)
- 42 beam ports



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

16 Instruments in Construction budget

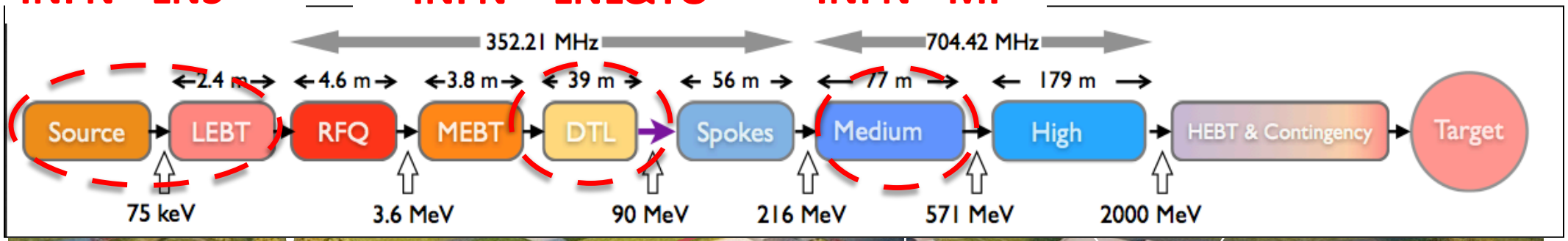
Committed to deliver 22 instruments by 2028

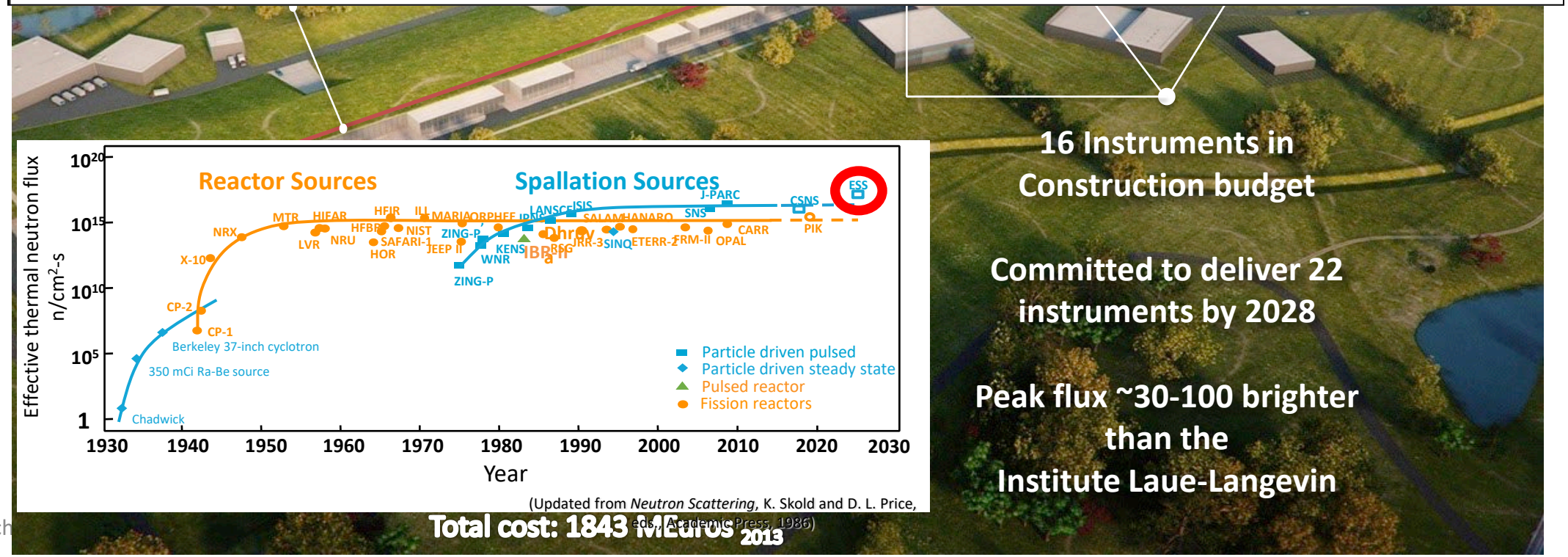
Peak flux ~30-100 brighter than the Institute Laue-Langevin

Total cost: 1843 MEuros 2013

European Spallation Source

INFN - LNS **INFN – LNL&TO** **INFN - MI**





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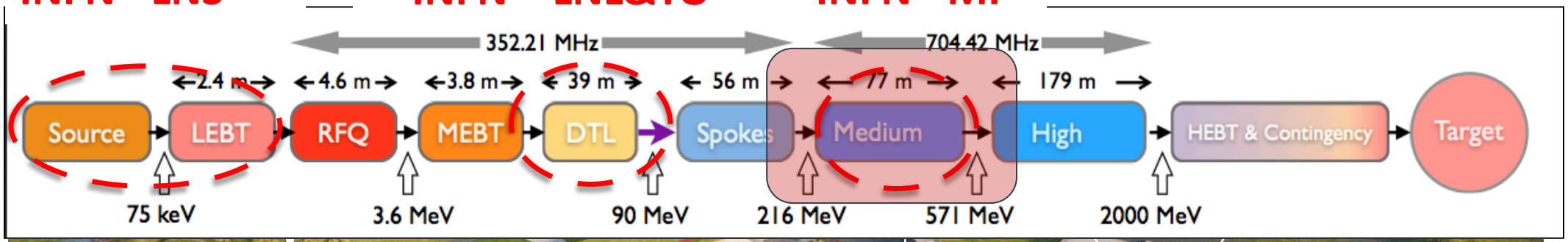
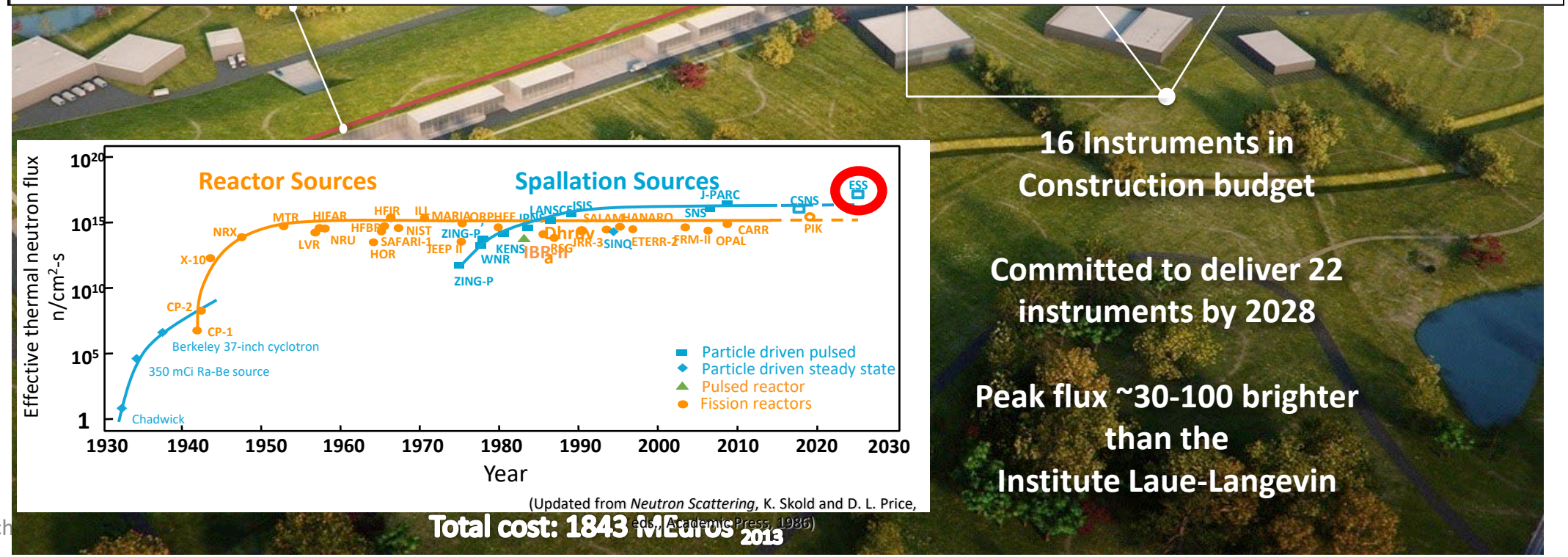
European Spallation Source

INFN - LNS **INFN – LNL&TO** **INFN - MI**





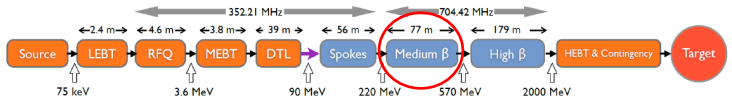
16 Instruments in Construction budget

Committed to deliver 22 instruments by 2028

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

Total cost: 1843 MEuros 2013

ESS Medium Beta Cavities



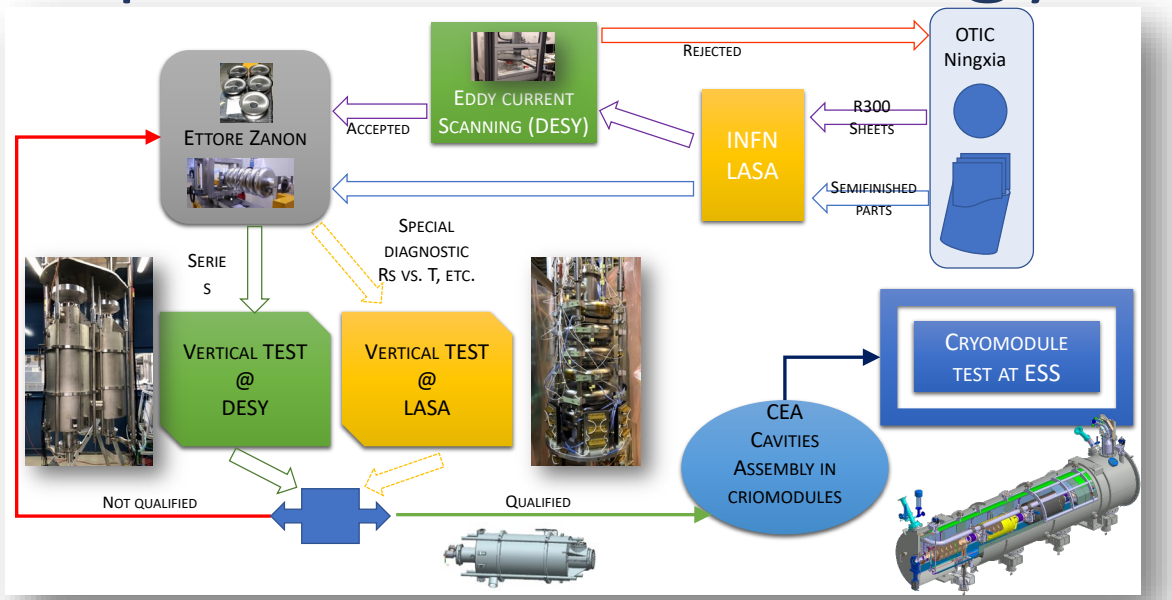
ESS 704.4 MHZ cavity series production: strategy

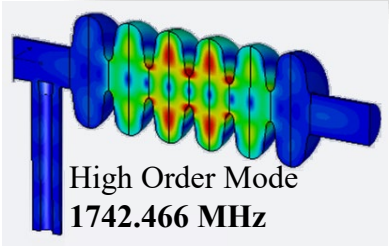
Purposes:

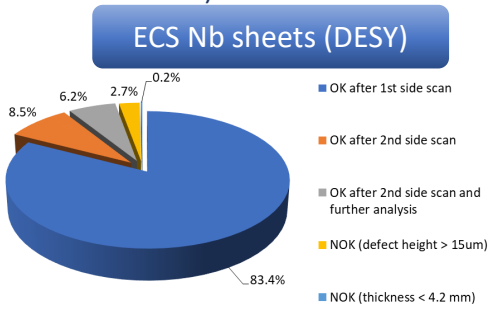
- **36** (+2) SC cavities, **1 Nb suppliers**, **1 industry**, **1 recipe** (BCP)
- ESS medium β (0.67) $E_{acc} \geq 16.7$ MV/m @ $Q_0 \geq 5x10^9$

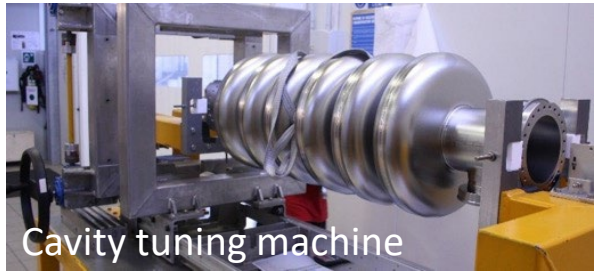
How it is working:

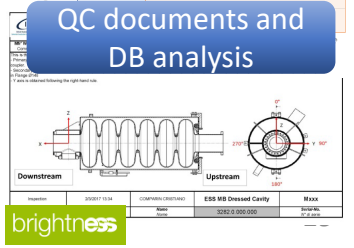
- **Definition of Nb specs** and **QC** (inspection at **Nb** vendor, **ECS** at **DESY)**
- **Optimization** of the **RF** and **mechanical design**
- **Definition of detailed production specs** (1 recipe), **PED sound engineering practice** compliant (3 prototypes)
- **Infrastructures adapted** to **704.4 MHz geometry** (larger) 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)

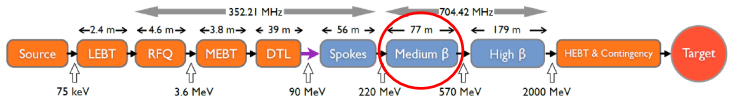










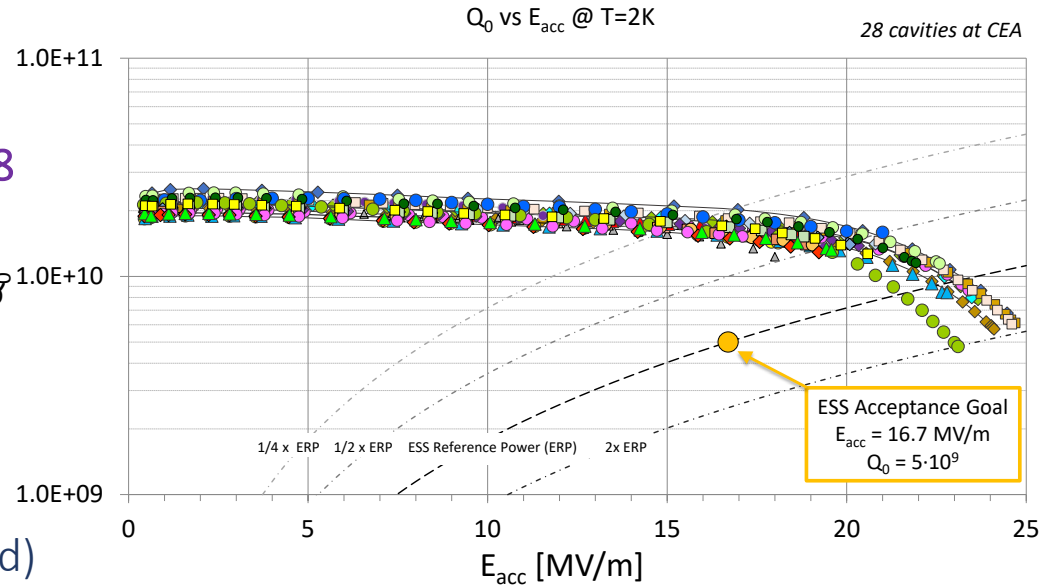


ESS 704.4 MHZ cavity series production: results

The production is still running!

Results:

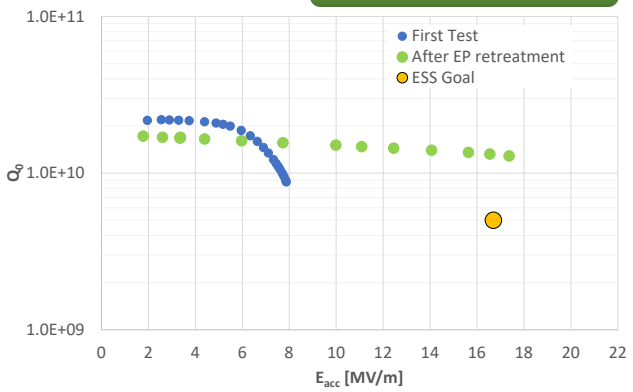
- Cavities at CEA for string assembly (cryomodule): 28
- Accepted Cavities as Delivered: 25
- After Additional Treatments (**HPR**): 3 recovered
- Cavities in quarantine (under retreatment): 10



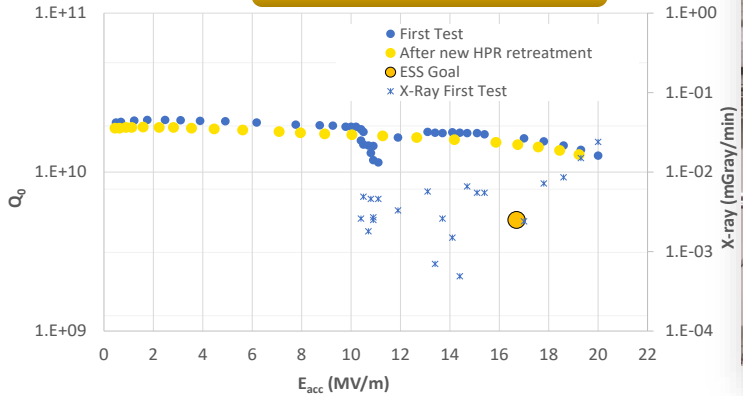
Recovery strategy:

- **HPR improved** to better fit the **cell shape** (new head)
- **ElectroPolishing (EP)** adapted to ESS shape for surface treatment -> **recovered the first low performance cavity after EP**
- One low performance cavity **treated with the new rotating BCP** -> test will be done in April
- **4 new cavities** are in production for risk mitigation

EP retreatment



New HPR retreatment



PIPII - INFN contribution

The **PIP-II** particle accelerator will be the new heart of Fermilab, featuring a brand-new, **800-MeV, leading-edge superconducting linear accelerator**.

INFN firstly provided a **novel RF design for the LB650 cavities**, fully plug compatible with the technical interfaces and performances specifications of the DOE **Long-Baseline Neutrino Facility** at Fermilab.

- **Cavity design meets the CW RF performance requirements**


December 4th, 2018, the U.S. DOE and Italy's MIUR agreement signed

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INFN contribution aims to cover the needs of **LB650 section**, and this includes:

- **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** and **Technical Interfaces**.

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assembly.

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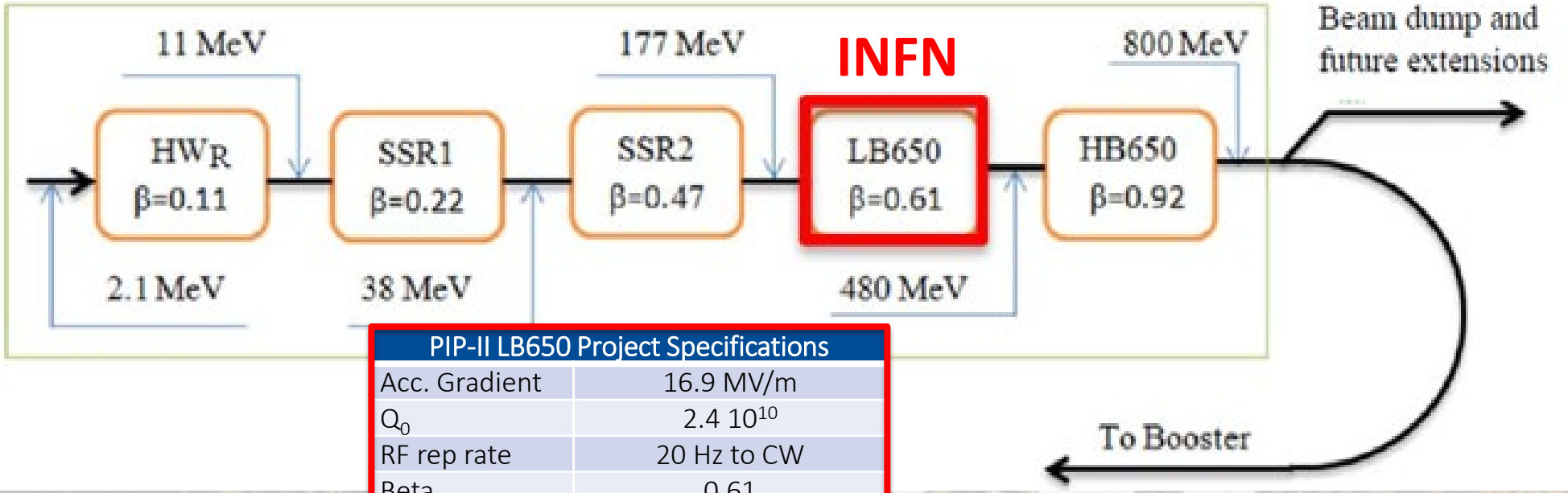
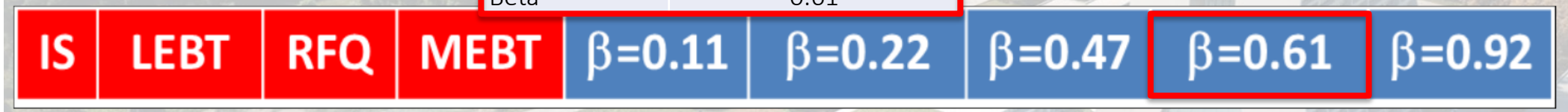


PIP-II LB650 Project Specifications	
Acc. Gradient	16.9 MV/m
Q_0	2.4 10^{10}
RF rep rate	20 Hz to CW
Beta	0.61



RT

SC

PIP-II LB650 MHz

PIP-II 650 MHZ cavity series production: strategy

We are now in the procurement phase

Purposes:

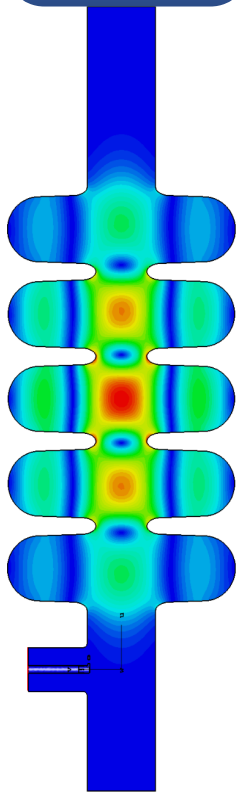
- **38** SC cavities, **1 Nb suppliers**, **1 industry**, **1 recipe** (EP + N-doping/MidT baking)
- PIP-II Low β (0.61) gradient ≥ **16.9 MV/m @ Q_0 2.4x10^{10}**, 20 Hz to **CW**

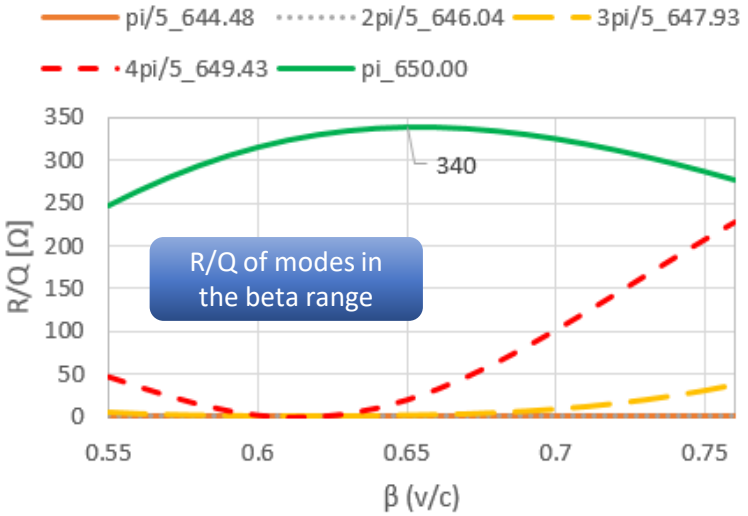
PIP-II LB650 challenges:

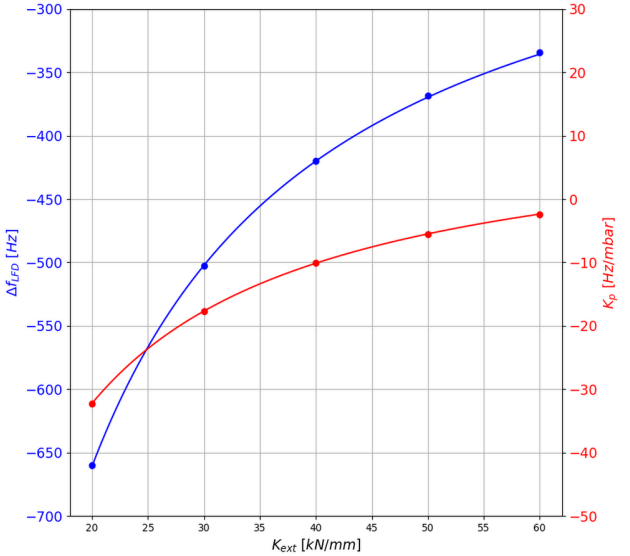
LB650 cavities are among the **key scientifical challenges of the project**, requiring:

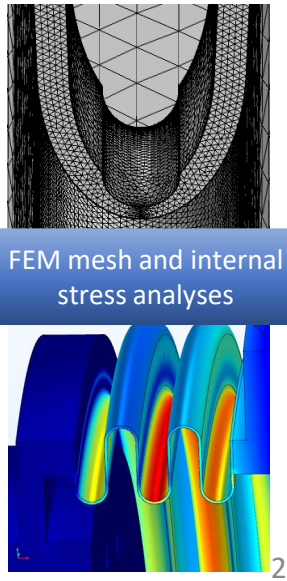
- An **unprecedented quality factor** for these resonators
- **High-Order Modes** risks have been assessed so that neither instabilities nor additional cryogenic losses are critical issues.
- PIP-II is heavily demanding **in terms of detuning control,** requiring deep understanding of Lorentz Force detuning, pressure sensitivity and mechanical leading parameters as rigidities, yield limits, stresses.
- Extensive finite element analysis to evaluate the **challenging mutual compliancy to both PED and ASME codes**, a first-time for an accelerator project.

Last mode in 2nd monopole passband, +8 MHz away from 9th ML









FEM mesh and internal stress analyses

PIP-II 650 MHZ cavity series production: strategy

INFN LASA High-Q activities:

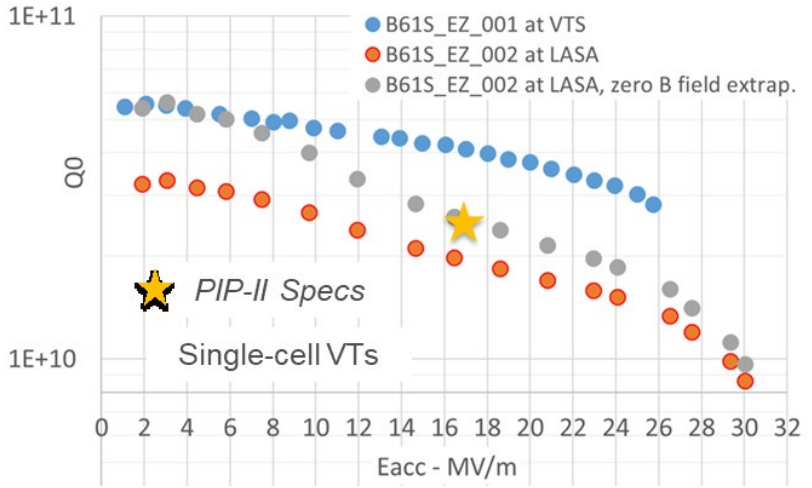
A total of **7 cavities have already been produced**, 3 of them shared with Fermilab in a joint effort.

Single-cells prototypes:

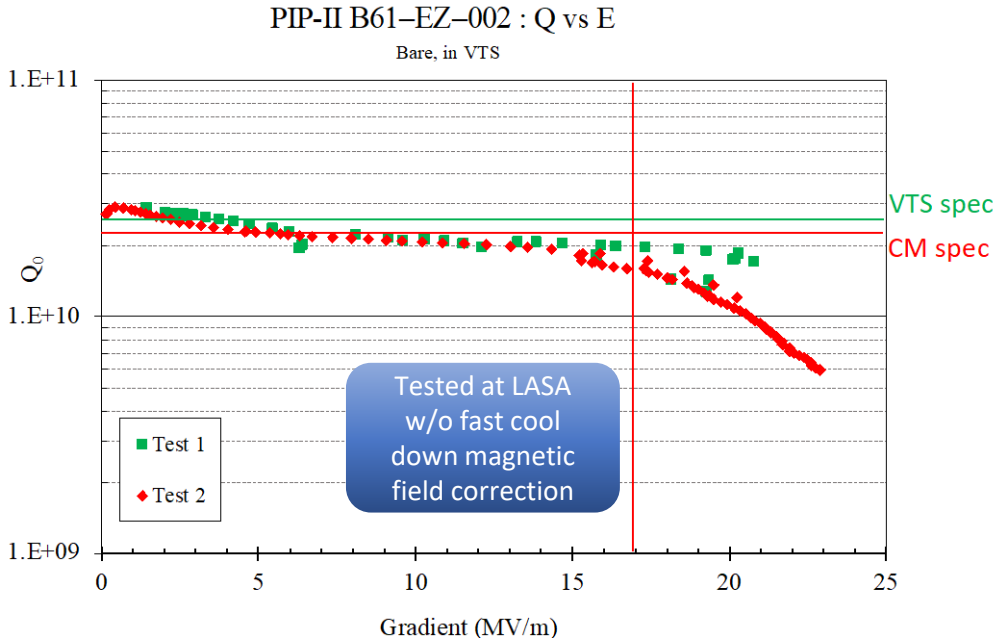
- B61S-EZ-002 with baseline recipe qualified at LASA:
  - *200 μm bulk EP + 800˚C HT + final EP + 120˚C*
  - ***High-Q treatment and re-test coming in 2022***
- B61S-EZ-001 with high-Q recipe treated at FNAL:
  - *180 μm bulk EP + 900˚C HT +N-Doping + final EP*
  - Test at Fermilab-VTS, project goals met
- **B61S-EZ-003 to be prepared by INFN in 2022**
  - Target recipe is **mid-T baking (300 °C)**

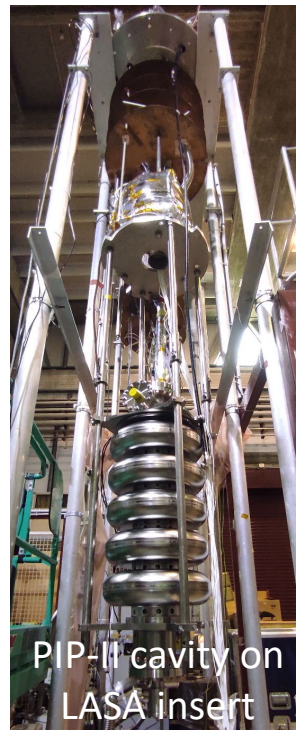
5-cells prototypes:

- **B61-EZ-001 successfully qualified at Fermilab** VTS both **naked** and **jacketed** at Fermilab
  - Accepted for title transfer by Fermilab
- **B61-EZ-002 successful VT at LASA in October**:
  - *150 μm bulk EP + 800˚C HT +final cold EP + 300˚C HT*
  - now targeted for **jacketing in industry from April 2022**



LB650 single-cell during Electro-Polishing





PIP-II cavity on LASA insert

Pre-production to 2021, production to 2025

A total of **7 LB650 prototype cavities produced and shared** for a joint development effort.

Electro-polishing (EP) surface treatment developed and proved with novel diagnostic tools for a LB650 single-cell. Ongoing extension for multi-cell.

LASA SRF infrastructure upgrade for lower remnant magnetic field, higher cryogenic refrigeration power and faster temperature rate at Niobium transition in order to align to state-of-the-art vertical cold test facilities. In progress.

Test bench for chemical surface etching (EP and BCP) **validation of fluid-dynamics simulation** through Particle Image Velocimetry camera technique in collaboration with *Politecnico di Milano*.

Overview of High-Q activity at INFN	
Pre-production cavities, Nb order placed	Jan 19
Pre-production cavities, order placed	Jan 19
Pre-production cavities, Nb delivered	Jun 19
Acceptance of pre-production cavities at vendor	Mar 20
BCAV#2 tuned for frequency and field-flatness	May 20
Transport and acceptance of BCAV#1 at FNAL	Jun 20
BCAV#1 surface treated at FNAL	Jan 21
BCAV#1 qualified in VTS FNAL	Jun 21
BCAV#2 surface treated with novel EP	Jul 21
BCAV#2 qualified at cold at LASA	Oct 21
BCAV#1 jacketing at FNAL	Nov 21
JCAV#1 qualified as jacketed at VTS FNAL	Dec 21
JCAV#1 qualified as dressed in HTC FNAL	Apr 22
BCAV#2 jacketing at INFN	Apr 22
High-Q recipes optimization with single-cells	May 22
Dressed cavity Final Design Review close-out	May 22
JCAV#2 qualified at LASA	Jul 22
High-Q single-cells qualified at LASA	Sep 22

Conclusions

- INFN LASA SRF group has long-term experience in several areas related to SRF components, from the design to the fabrication and performances qualification.
- Since the last 15 years, LASA is working on large scale SRF projects managing complex production processes not only of cavities but also of cryomodules and related ancillaries.
- The conclusion of the ESS contribution and the launch of the PIP-II project are our commitment for the coming years.
- In parallel, we continue also our R&D programs, mainly devoted to address the challenging requirements in term of High Q_0 /High E_{acc} to be prepared for new future projects.

Thanks for your attention!