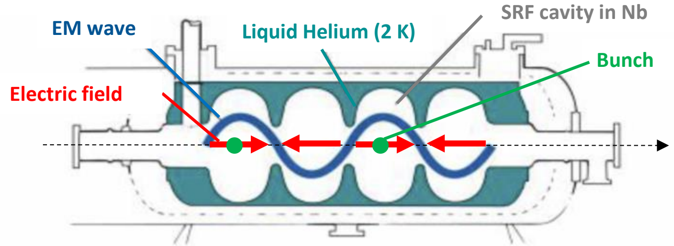
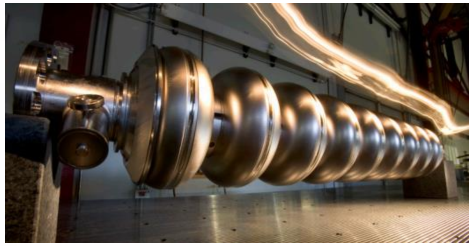
Bulk SRF Nb cavities overview (WG1)

- **Bulk niobium (Nb) for superconducting radiofrequency (SRF) cavities**
  - Under optimization for the last 50 years
  - Today, **still main operational technology** for **future large SRF accelerators**
  - Operational temperature **2 K**



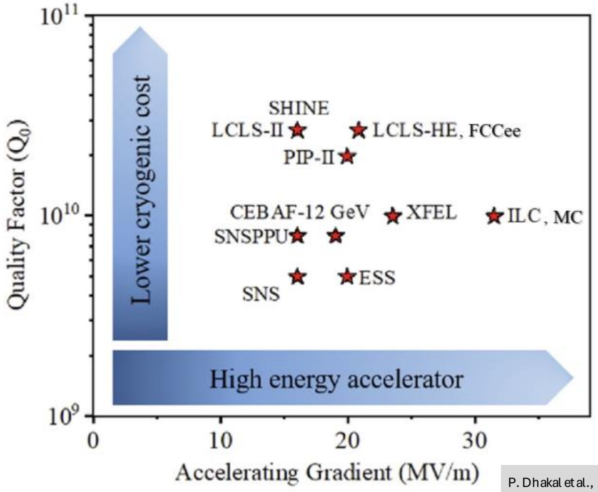


- **Requirements on sustainability and cost reduction push R&D SRF Nb bulk activities to improve cavity performances:**

Goals : reach higher quality factor Q_0 and field E_{max}, with surface treatments, in a reproducible way

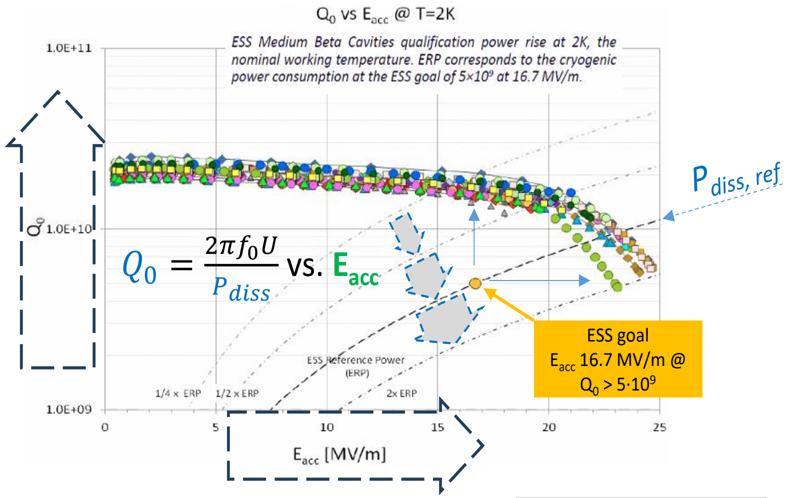
- **Higher E_{max}** ➔ energy reached with less cavities at higher gradient (Energy gain ∝ E_{acc} L_{acc}) ➔ reduced machine length
- **Higher Q_0** ➔ less loss in cavities (loss ∝ $1/Q_0$) ➔ minimize cryogenic power
- **Minimizing field emission** (FE) ➔ increase reliability

RF Cavities: reduce operational cost (Q_0 ↑) and capital cost (E_{acc} ↑)



P. Dhakal et al., https://doi.org/10.1016/j.physo.2020.100034

Sustainability & Cost Reduction



D. Sertore et al., SRF23, doi:10.18429/JACoW-SRF2023-TUPTB061

Higher E_{acc}

ILC – higher E_{acc} ⇒ **smaller linac** (= lower capital **cost**)
MC – **quick acceleration** (vs μ-lifetime)
FCC – **fewer cavities** ⇒ smaller RF installation

Higher Q_0

FCC, ERL, ILC – lower RF losses, **cryogenic power minimised.**

Others: Reproducibility, cost, industrial manufacturing

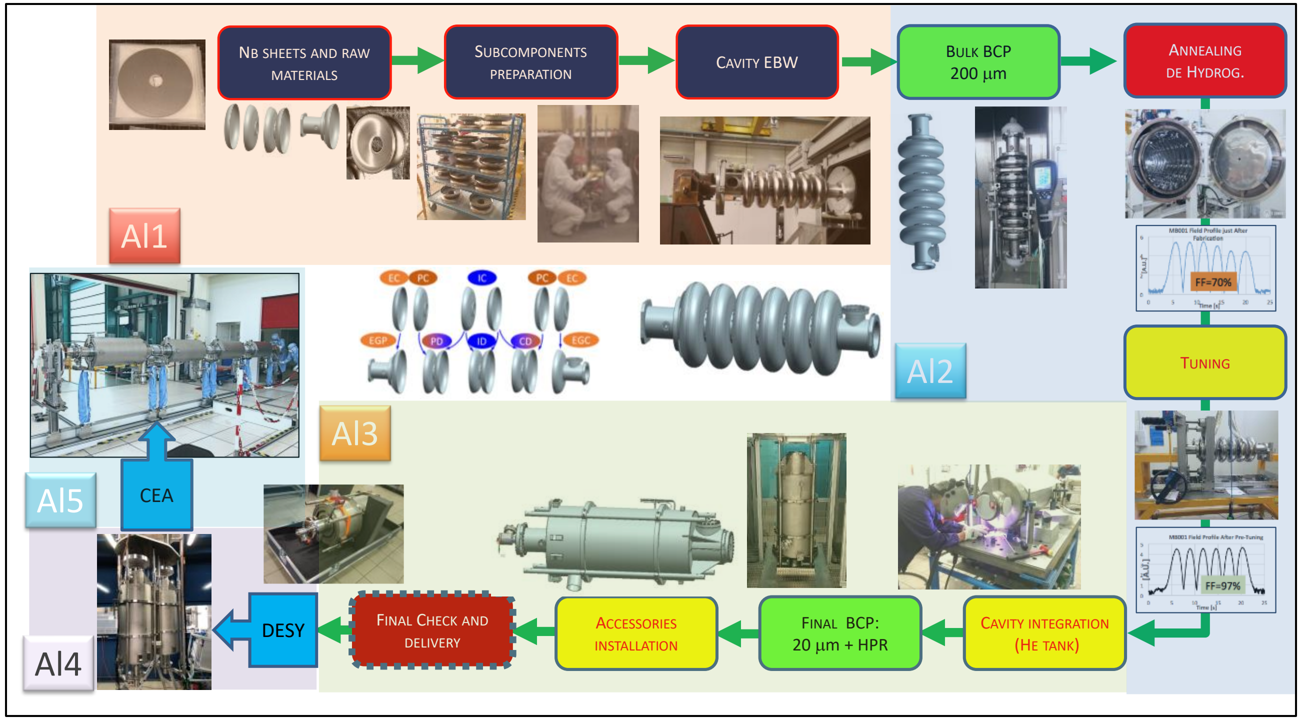
G. Bisoffi et al., Community Report on Accelerators Roadmap, 12-13 Jul 2023, INFN LNF, IT

R&D for performance improvements (WG1)

➢ **Performances (Q_0, Emax) of cavities (electrons & hadrons) improves dramatically over time thanks to R&D efforts on**

- **RF and mechanical shape optimization**
- **Surface and thermal treatments**
  - **Surface cleaning**
    - Ultra-Sonic cleaning
    - High-Pressure Rinsing (HPR)
    - Buffered Chemical Polishing (BCP)
  - **Vacuum**
    - Slow Pumping Slow Venting (SPSV)
    - Residual Gas Analyzer (RGA)
  - **Surface polishing**
    - Electro-polishing (EP)
  - **Surface treatment**
    - N2 doping and N2 infusion
  - **Heat treatment**
    - Hydrogen degassing
    - low-T baking, 2-step baking, mid-T baking
- **Contamination reduction during assembly**
  - **Robots in clean room** to minimize contamination
  - **In-situ plasma processing** to recover from contamination

ESS Medium Beta Cavity production cycle

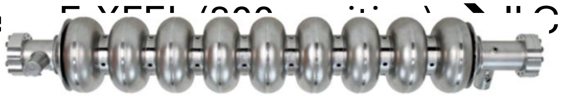


Specifications for cavities in operational conditions (at 2 K)

Project	Frequency	Cavity type	E_{max} (MV/m)	Q_0
FCC-ee	**800 MHz**	**5-cell**	**20**	**$3 \cdot 10^{10}$**
ILC, pulsed	**1.3 GHz**	**9-cell**	**31.5**	**$1 \cdot 10^{10}$**
muon collider (base scenario), pulsed	**1.3 GHz**	**9-cell**	**30**	
E-XFEL pulsed / CW	1.3 GHz	9-cell	23.6 / 17	$1 \cdot 10^{10}$ / $2 \cdot 10^{10}$
PIP-II (low β) from 20Hz to CW	650 MHz	5-cell	16.7	$2.4 \cdot 10^{10}$
LCLS-II (CW) / LCLS-II-HE (CW)	1.3 GHz	9-cell	16 / 23	$2.7 \cdot 10^{10}$ / $2.5 \cdot 10^{10}$ (@21)

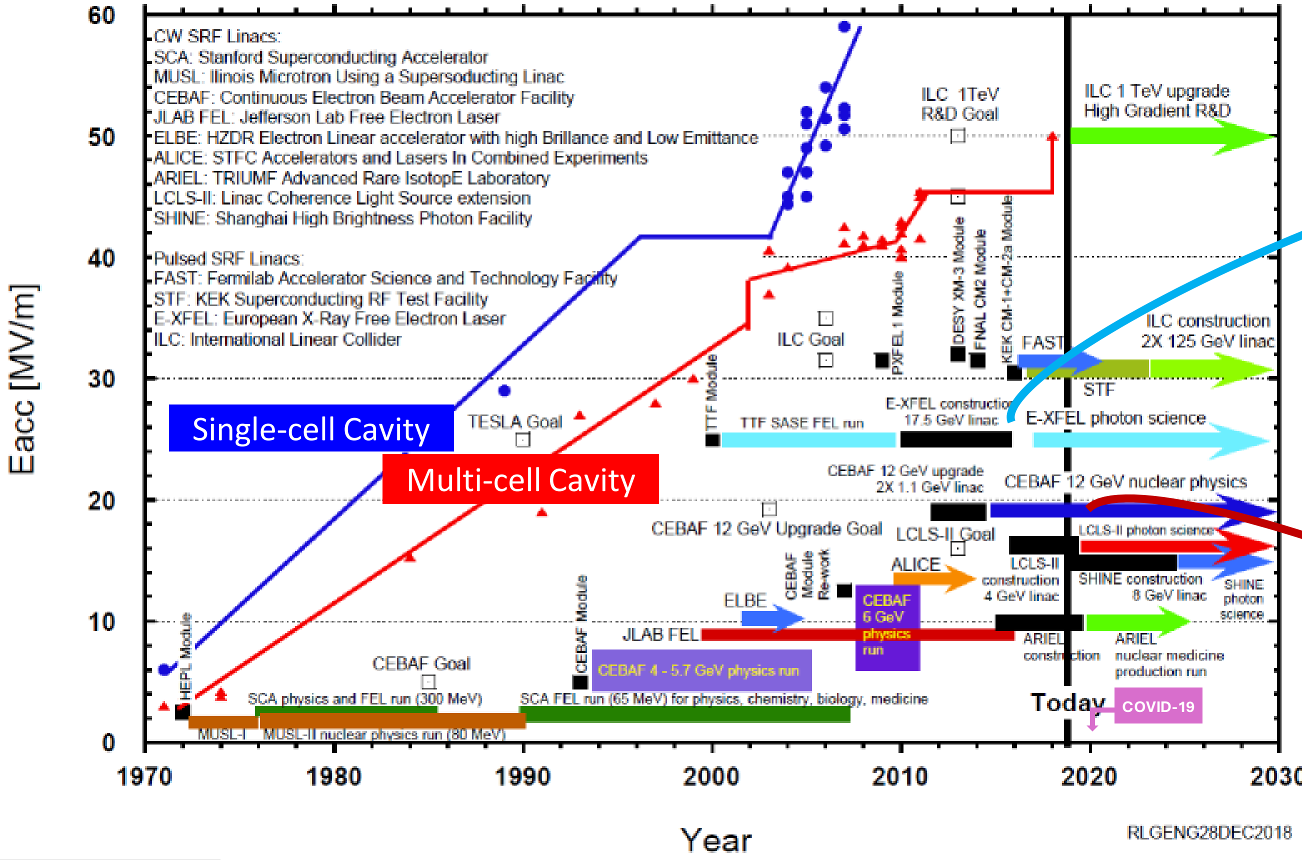
R&D results versus large series performances (WG1)

- **From R&D to industrialization : for large series of cavities, performance reproducibility and reliability are compulsory**
  - Results on single and multi-cell cavities must be **migrated to a series production** (large number of components) ➔ **yield and reliability**
  - Some example … E-XFEL (800 cavities) ➔ ILC (8000 cavities) ; LCLS-II (280 cavities)



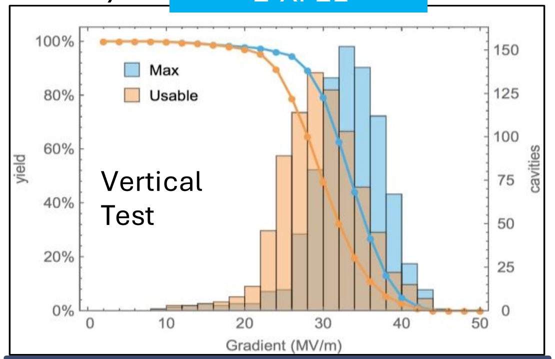
L-band SRF Linear Accelerator Technology

Impact to Nuclear, Elementary Particle, and Photon Sciences and Medical Applications



R.L. Geng et al., SRF19, doi:10.18429/JACoW-SRF2019-MOP064

E-XFEL



D. Reschke et al., doi:10.1103/PhysRevAccelBeams.20.042004

Final Performances

E_{max} = 33.0 ±4.8 [MV/m]

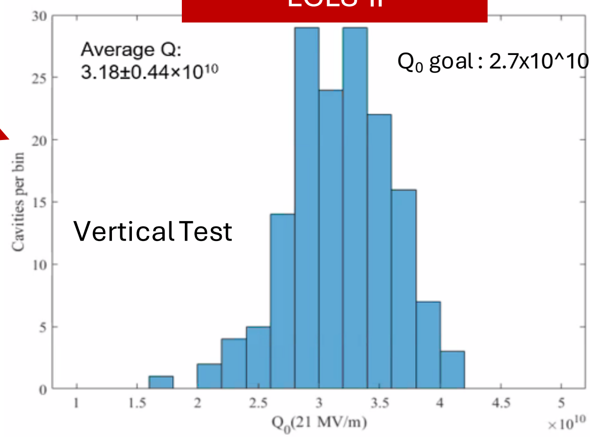
E_{usable} = 29.8 ±5.1 [MV/m]

Q_0 (23.6MV/m) = 1.4 ±0.2 [10^{10}]

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

Reproducibility over large series cavities

LCLS-II



M. Checchin, oral presentation at SRF2023

Other goals and specifications for Bulk Nb R&D (WG1)

➢ Cost reduction of Nb material by increasing Nb grain size (from fine grain (FG), presently used)

- **R&D** on Mid and Large grain Nb (MG and LG) materials **still required to validate performances** and their possible **use in accelerators** (pressure vessel compliance)
- **Cost reduction for the cells of 1.3 GHz 9-cell cavities** estimated using medium grain (MG) :

➔ **From FG to MG: cells-materials 35% cheaper, full-cavity materials 5% cheaper**

Grain size < 50µm

Grain size < 1mm
(200-300 µm)

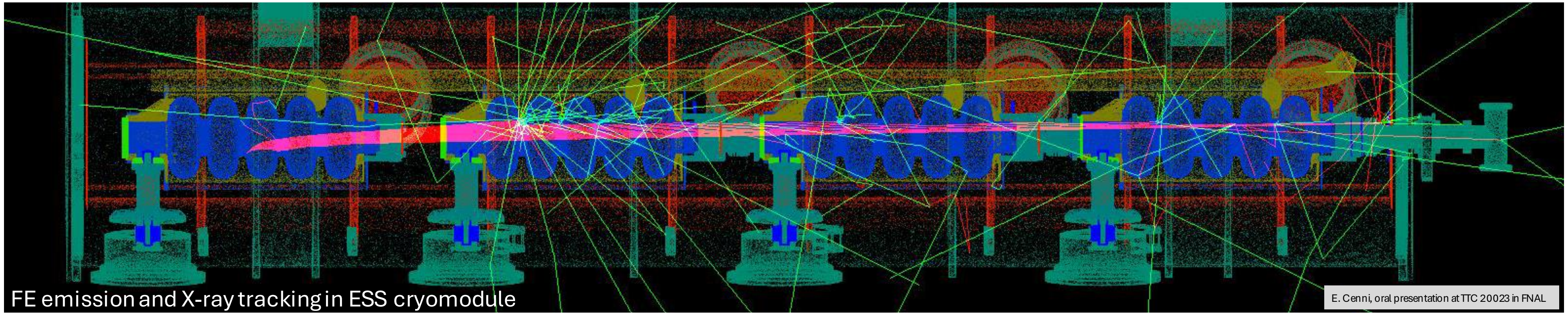
Grain size > 1cm

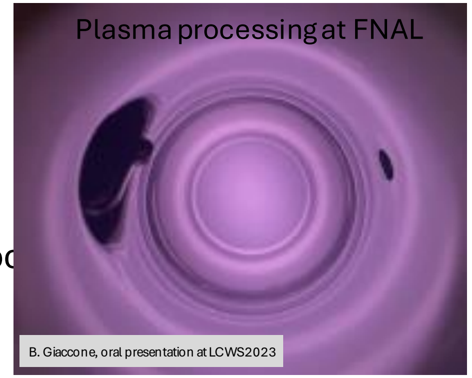
A. Kumar et al., SRF23, doi:10.18429/JACoW-SRF2023-WEIXA04

➢ Increase reliability by reducing field emission (FE), both for bulk Nb and thin fil

- **Minimize contamination in clean room by robots assisted cavity preparation and string assembly**
- Improve **diagnostics on FE** for cavity vertical tests, and in cryomodules (also during operation)
- Implement techniques to **recover from cavity FE as in-situ plasma processing**

➔ FE reduction and in-situ recovery for cavity performances reproducibility and cryomodule operation reliability





➢ R&D studies for cavity production cost reduction and environmental footprint

- **3D-printed cavities** via additive manufacturing (AM) aim to reduce both cost and environmental footprints, via enhanced coo
- **Plasma Electrolytic Polishing (PEP)** with a diluted water solution

R&D landscape of bulk Nb cavities in Europe and criticalities/hints (WG1)

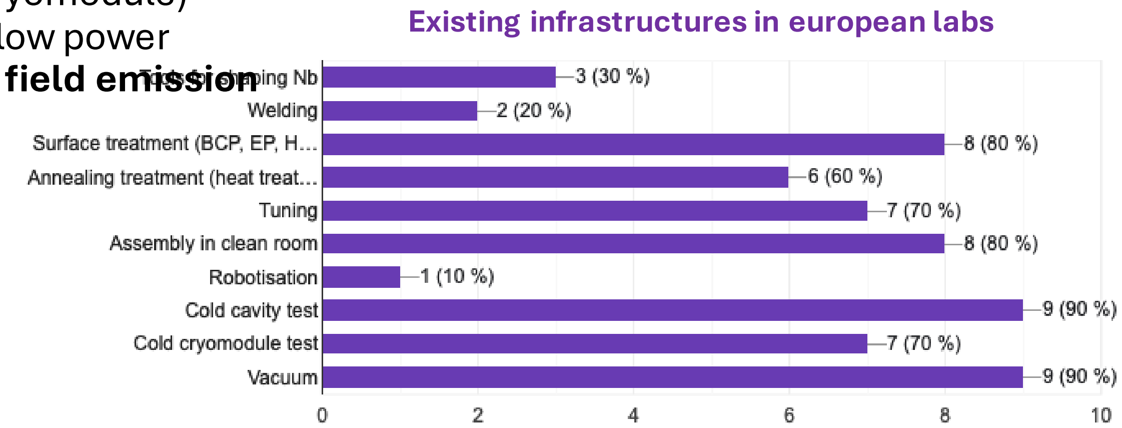
➢ Survey of R&D on bulk Nb cavities in Europe

About **10 labs:** CEA, CERN, CNRS-IJCLab, DESY, ESS, HZB, INFN (LASA, LNF), STFC, U. Hamburg, U. Uppsala

Cavity Frequencies (and harmonics): 1.3 GHz (325 MHz, 650 MHz, 3.9 GHz), 802 MHz (401 MHz), 704 MHz (352 MHz)

Most **R&D on elliptical cavities**: **single-cell** to develop the **preparation procedure, to be** further **applied on multi-cells**

- **Preparation protocol for cavity production require a wide variety of techniques** in labs and also industry (surface and heat treatment ...)
- **Heavy infrastructures required,** existing in several labs:
  - **ISO4 clean rooms** for **cavity preparation** and **cavity string assembly** (cryomodule)
  - Infrastructures of **vertical test (VT) for cavity qualification at 2 K** and at low power
  - **Diagnostics** used **during cold tests to characterize performances and field emission**
- **Aspirational infrastructures:**
  - Eddy Current Scanning **(ECS)** for **Nb material Quality Control**
  - **Ovens** for **heat treatments (High-T, Mid-T)**
  - **Robots** for **clean rooms, in-situ plasma processing**
  - **New/upgrade VT infrastructures**
  - **Cryomodule assembly facilities**



➢ How to speed up existing R&D

- **SRF R&D is costly so more money (& HR)** could help speed up some R&Ds considering present large cost uncertainty (materials, electricity and fluids)
- To speed up R&D, **introduce and/or extend collaborations with experts outside of accelerators**, for example:
  - Robotisation in clean room for cavity preparation ➔ robotics experts
  - Plasma processing for FE recovery ➔ chemistry experts

➢ Criticalities and hints

- **Risk of losing manufacturing capability**
  - Few Nb suppliers (1 in China, 2 in Japan/USA)
  - Few cavity suppliers (2 European-XFEL qualified in Europe, 2-3 in China, 1 in Japan)
- **For future machines, SRF technology skills must be maintained both in laboratories & industries**
- **Investment in industrial processes for large series cavity production are needed**