SRF programs towards High-Q/High-G cavities in IJCLab

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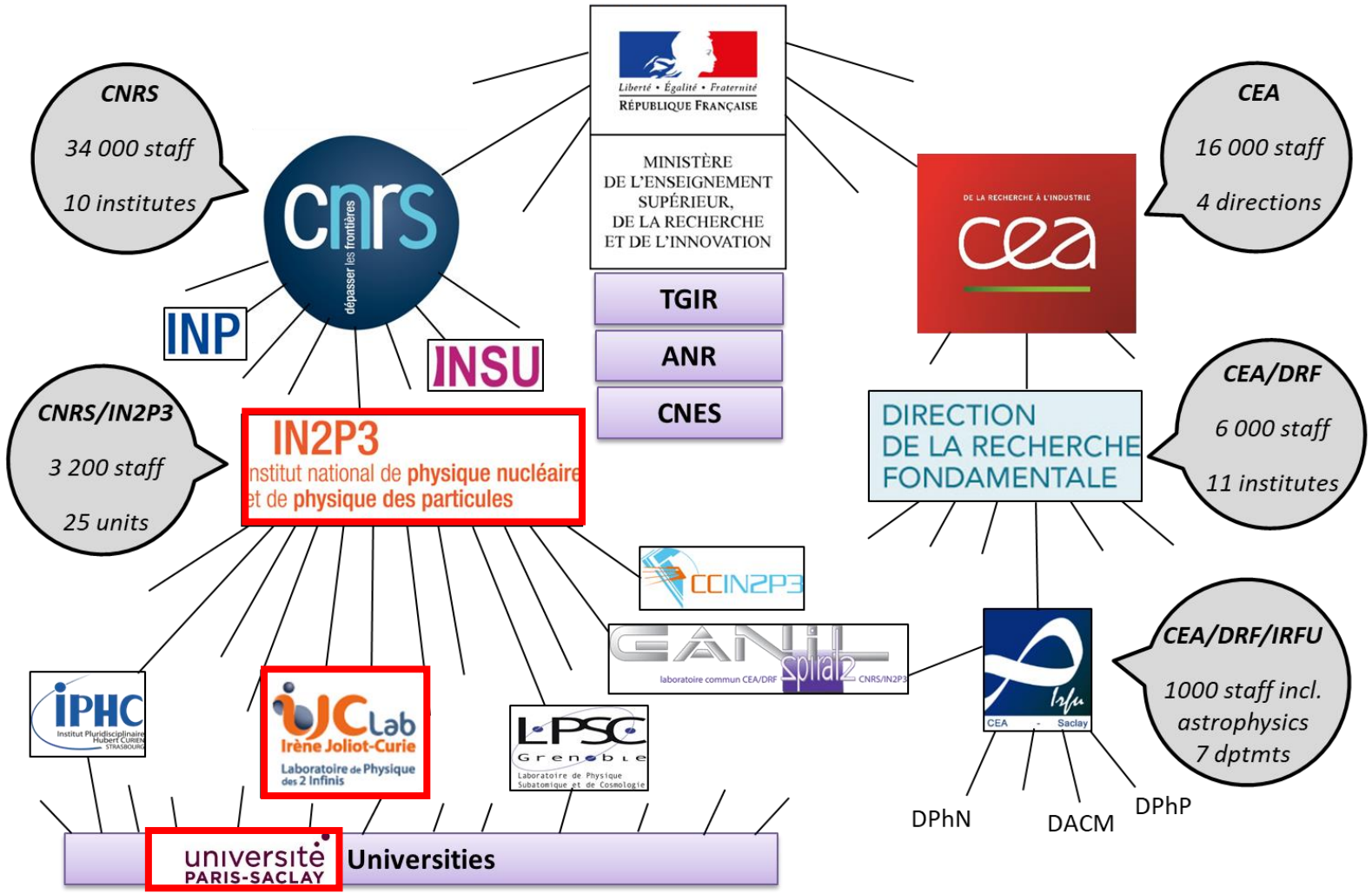
Introduction : Instances around SUPRATech



Credits :
J.L. Biarrotte

Introduction : History summary and series production

Prototyping Phase | Series production | R&D

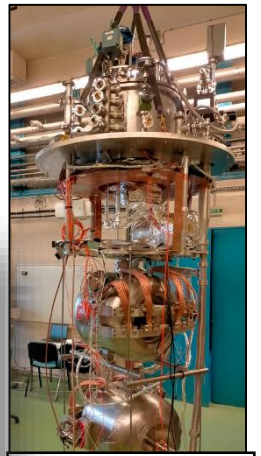
Spiral2 : Integration and test of 7 cryomodules

ESS : - preparation & testing of cavities, couplers and tuners
- Integration of 14 cryomodules

LHC : Calibration of all Cernox thermal sensors (> 6000 units)

EU-XFEL : Preparation and power testing of 800 couplers

MYRRHA : - preparation & testing of 60 couplers and tuners



PIP-II : Testing of 33 Spoke cavities

Calibration Station (2000)
Vertical cryostat (CV800)
Clean-room for cryomodule (2007)
Chemical facility (2008)
He Liquefier (2008)
Furnace (2016)
Klystron (2017)
Upgrade CV800 (2018)
New Assembly Hall (2020)

LHC | SPIRAL2 | SPIRAL2 | ESS | ESS
EURISOL | MAX | MYRTE | MYRRHA | MYRRHA
TTF3 | EU-XFEL | PIP2 | PIP2

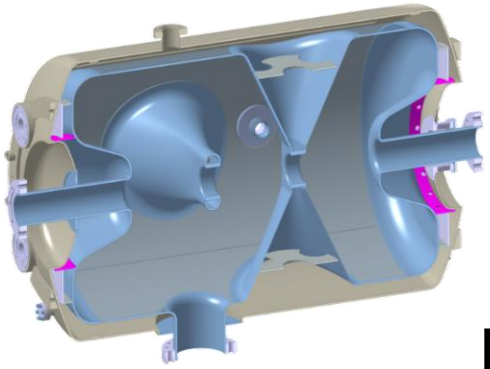
1995 | 2000 | 2005 | 2010 | 2015 | 2020 | 2025

First cryogenic test of a Spoke resonator in Europe (2002)
Supratech Platform is created (2004)
First cryogenic test of a cryomodule at Supratech (2007)
Supratech Platform is officially recognized by IN2P3 (2017)
Creation of IJCLab, merging of equipment from LAL and IPNO in Supratech (2020)

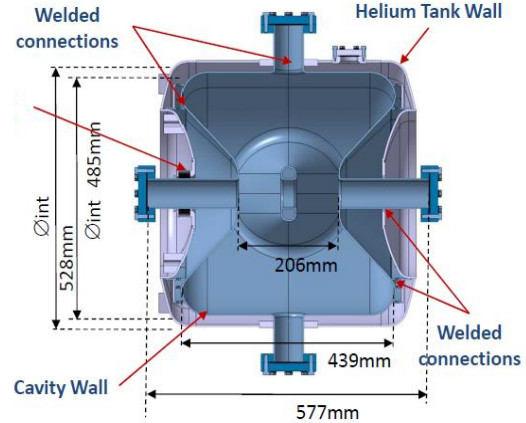
Low-β cavities for protons & heavy ions→ collider cavities

88 MHz

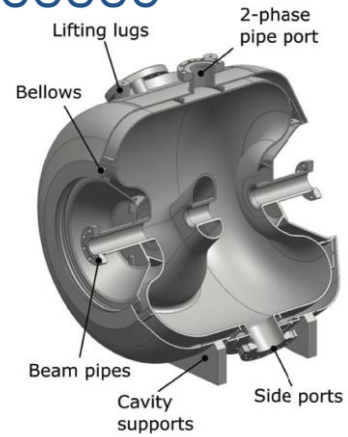
352 MHz



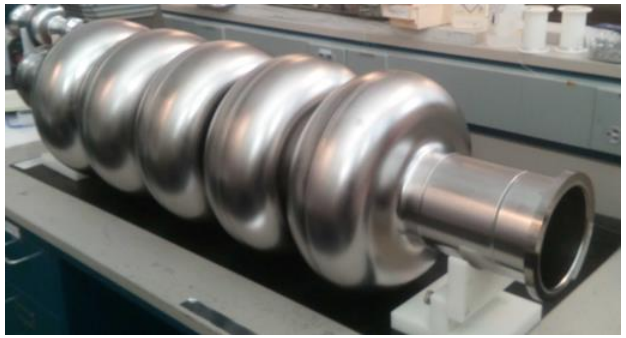
352 MHz



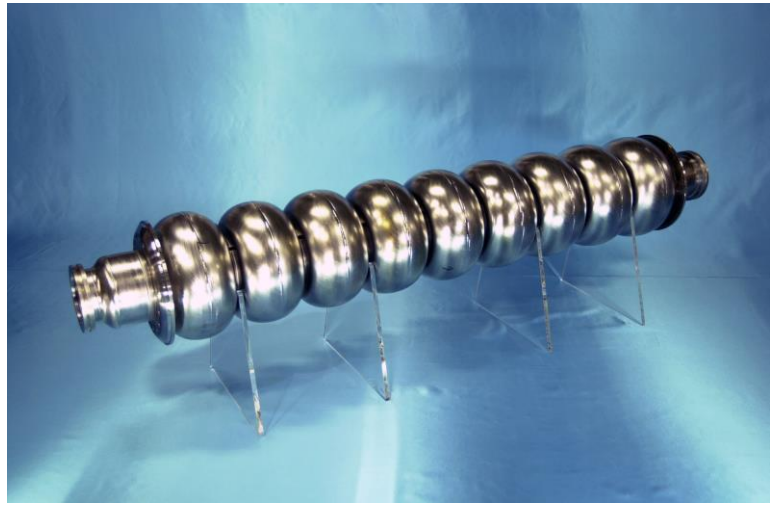
325 MHz



FCC/PERLE cavities (800 MHz)

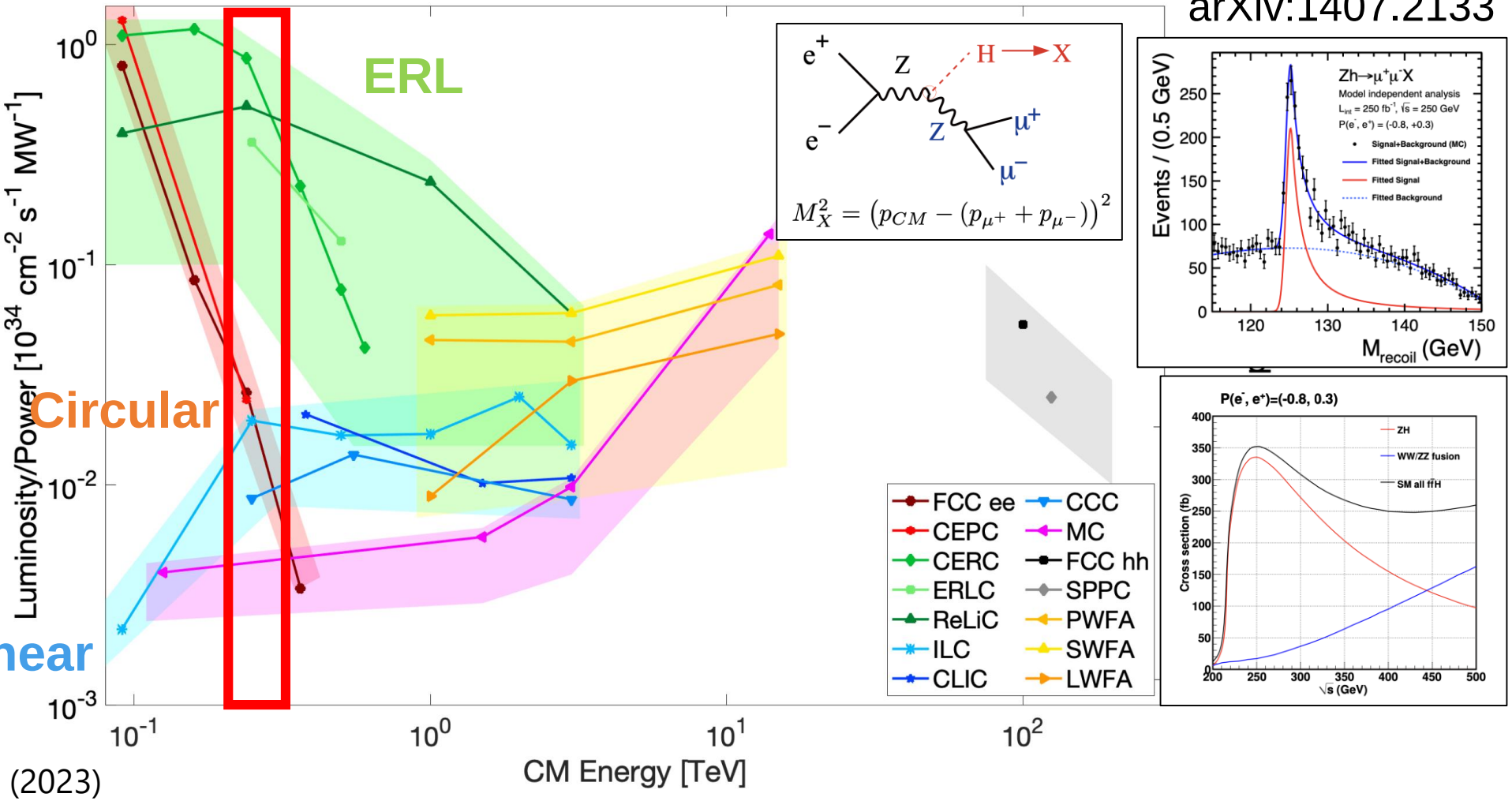


ILC cavities (1.3 GHz)



Next future colliders: priority in Higgs boson

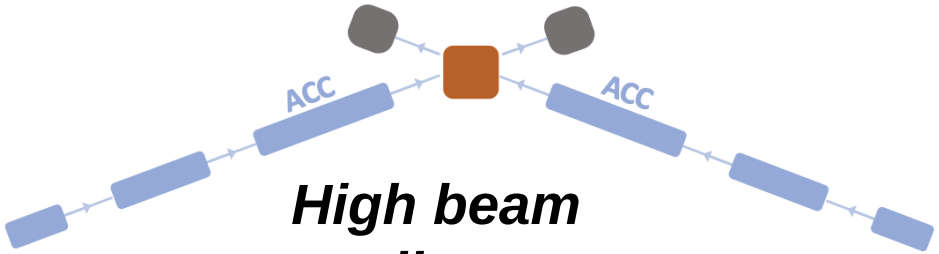
arXiv:1407.2133



JINST 18 P05018 (2023)

Energy Recovery Linac (ERL)

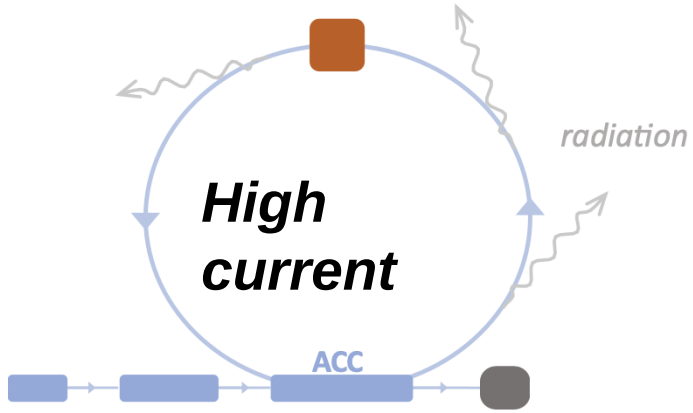
Linear colliders



High beam quality

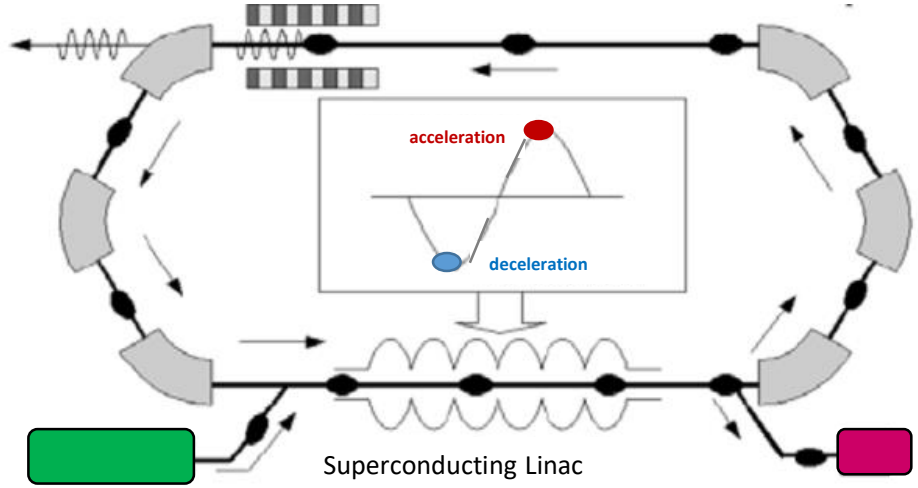
+

Circular colliders



High current

ERL Loop



Injector

Superconducting Linac

Beam dump

	FCCee/CEPC	ILC	HE ILC	CCC	HE CCC	CLIC	HE CLIC	CERC	ReLiC	HE ReLiC	ERLC	XCC	LHeC/FCCeh
RF Systems													
Cryomodules													
HOM detuning/damp													
High energy ERL													
Positron source													
Arc&booster magnets													
Inj./extr. kickers													
Two-beam acceleration													
Damping rings													
Emitt. preservation													
IP spot size/stability													
High power XFEL													
e^- bunch compression													
High brightness e^- gun													
IR SR and asymm.quads													

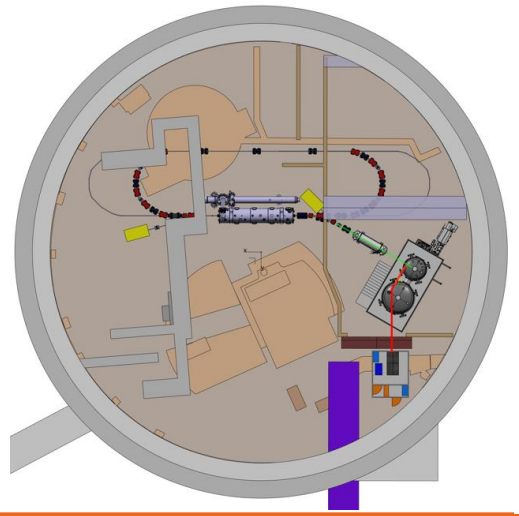
JINST 18 P05018 (2023)

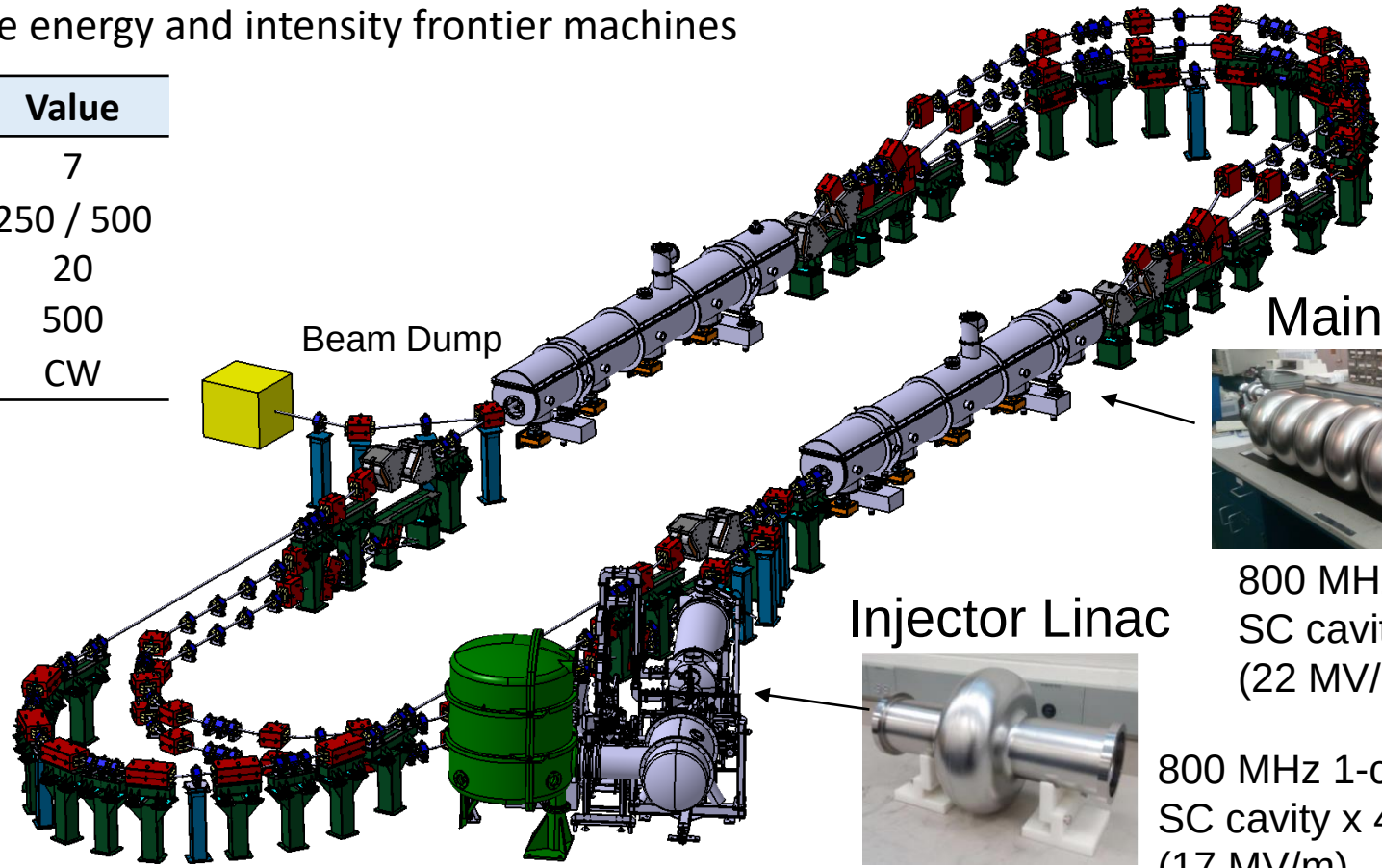
PERLE project at IN2P3/IJCLab

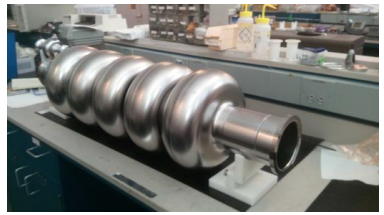
Ultimate goal of PERLE: first multi-turn ERL designed to operate at 10 MW (20 mA, 87→250→500 MeV)

→ A hub to explore a broad range of accelerator phenomena and to validate technical choices improving accelerators for future energy and intensity frontier machines

Target Parameter	Unit	Value
Injection energy	MeV	7
Electron beam energy	MeV	250 / 500
Average beam current	mA	20
Bunch charge	pC	500
Duty factor		CW







800 MHz 5-cell
SC cavity x 4
(22 MV/m)

800 MHz 1-cell
SC cavity x 4
(17 MV/m)

R &D targets

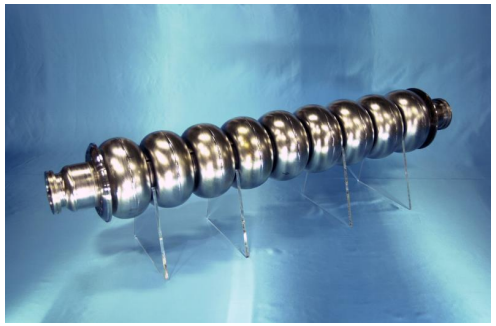
For FCC/PERLE

Duty cycle
=100%

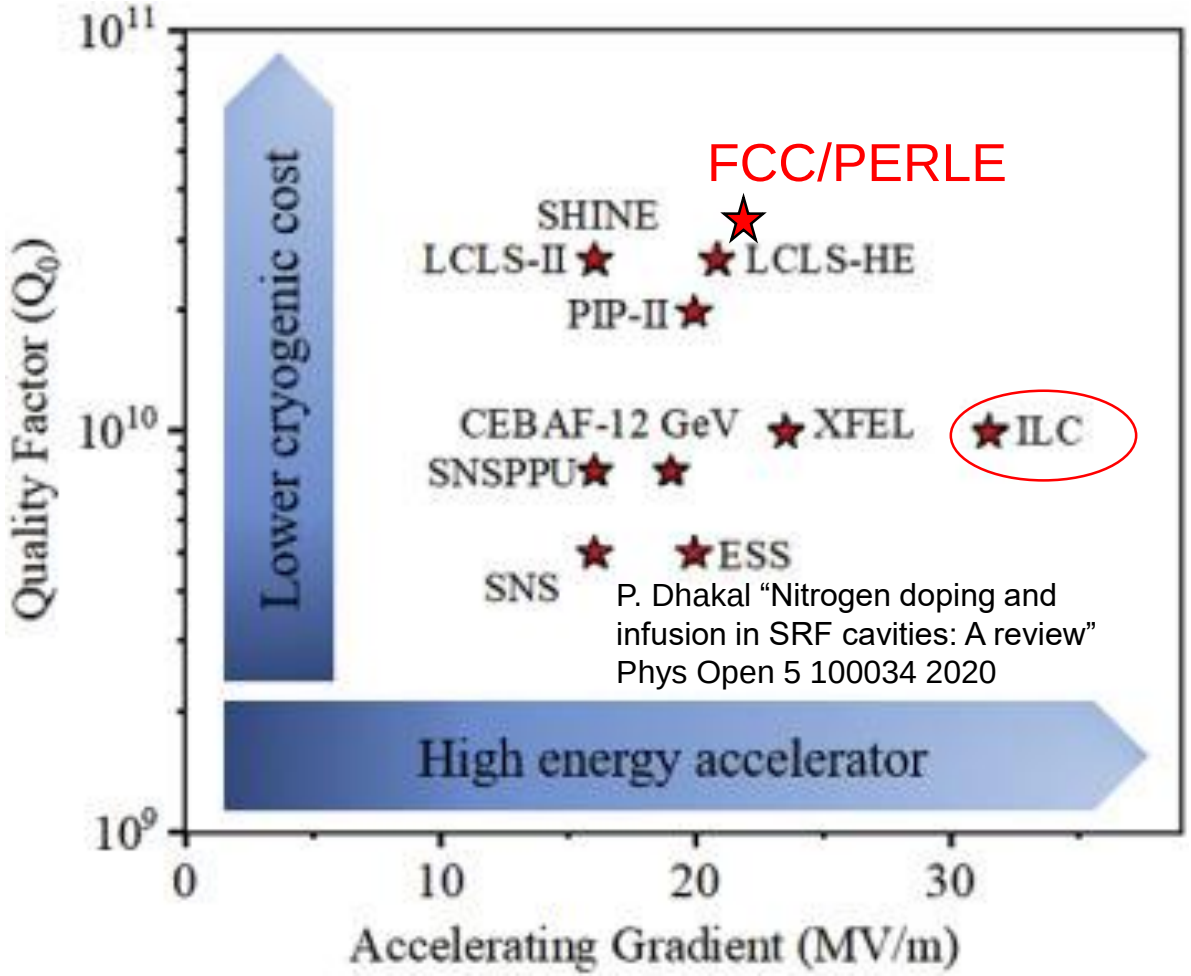
Extremely high-Q at relatively high gradient in large cavities (800 MHz)

For ILC250

Duty cycle
<1%



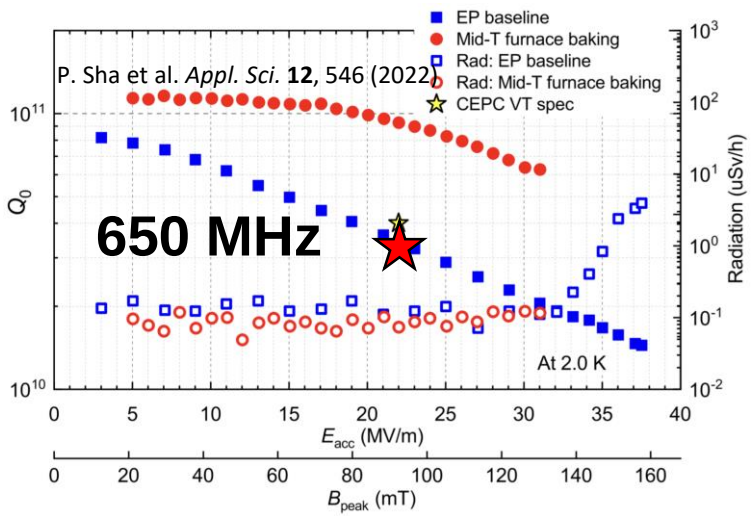
Extremely high gradient with relatively high-Q in a large # of cavities (~8000)



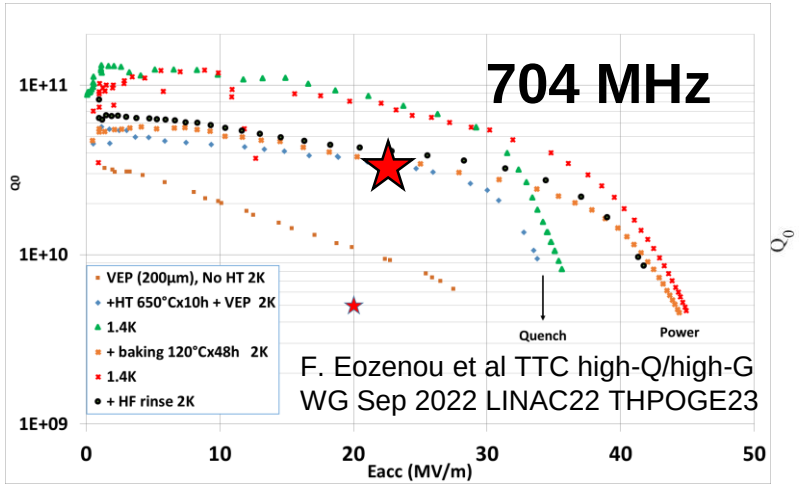
P. Dhakal "Nitrogen doping and infusion in SRF cavities: A review" Phys Open 5 100034 2020

high-Q / high-G cavities in the world

300C baking @ IHEP

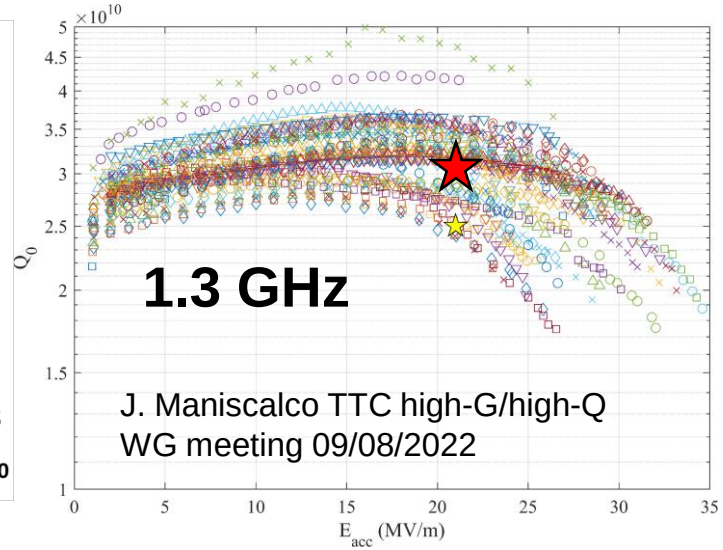


120C baking @ CEA-Saclay



F. Eozenou et al TTC high-Q/high-G WG Sep 2022 LINAC22 THPOGE23

2N0 doping at 800C @ LCLSII

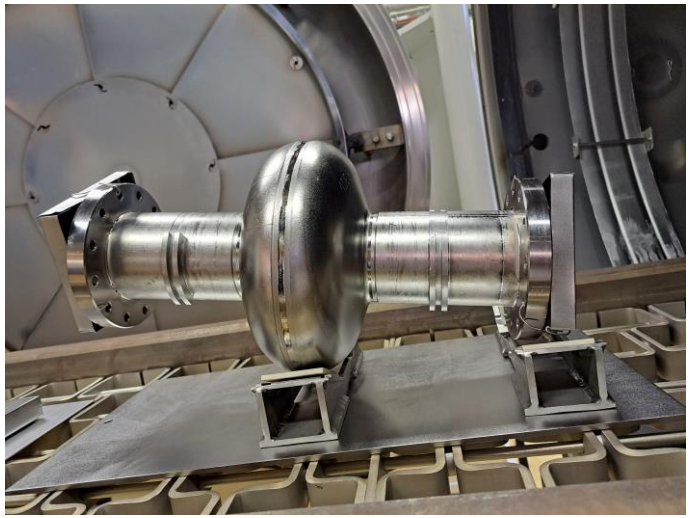


J. Maniscalco TTC high-G/high-Q WG meeting 09/08/2022

- 300C baking or N-doping seems like the best option for FCC/PERLE
- 120C or 2-step baking for higher gradient → ILC

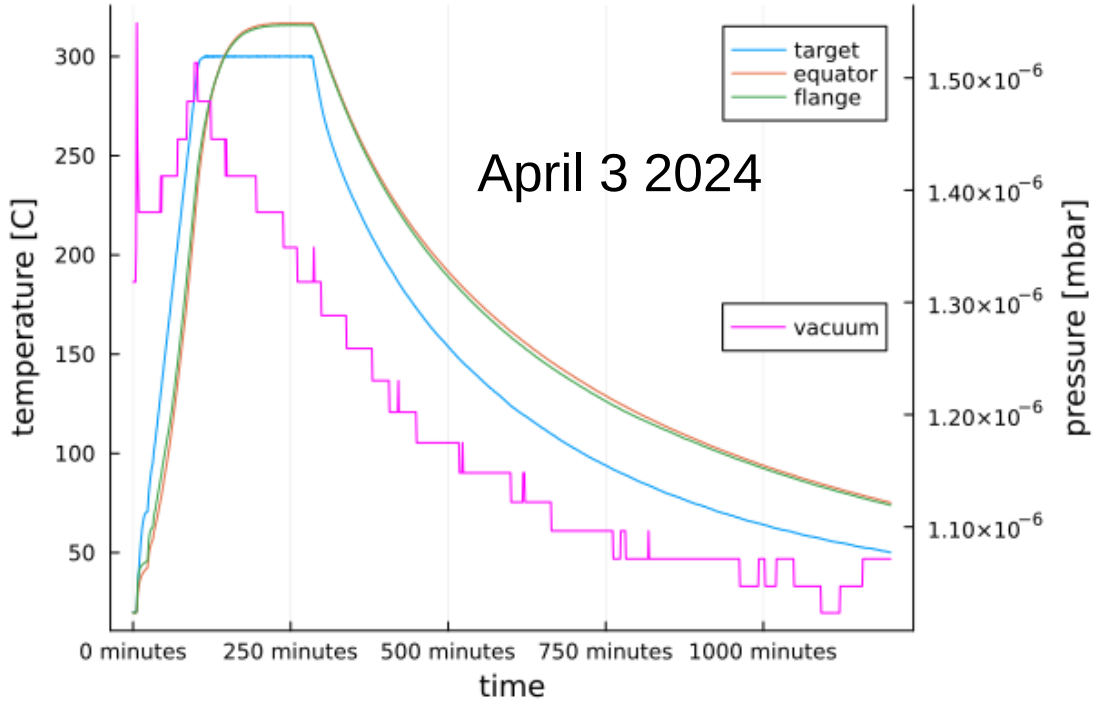
- **Clean vacuum baking furnace** is key in this research domain

300C baking in IN2P3/IJCLab

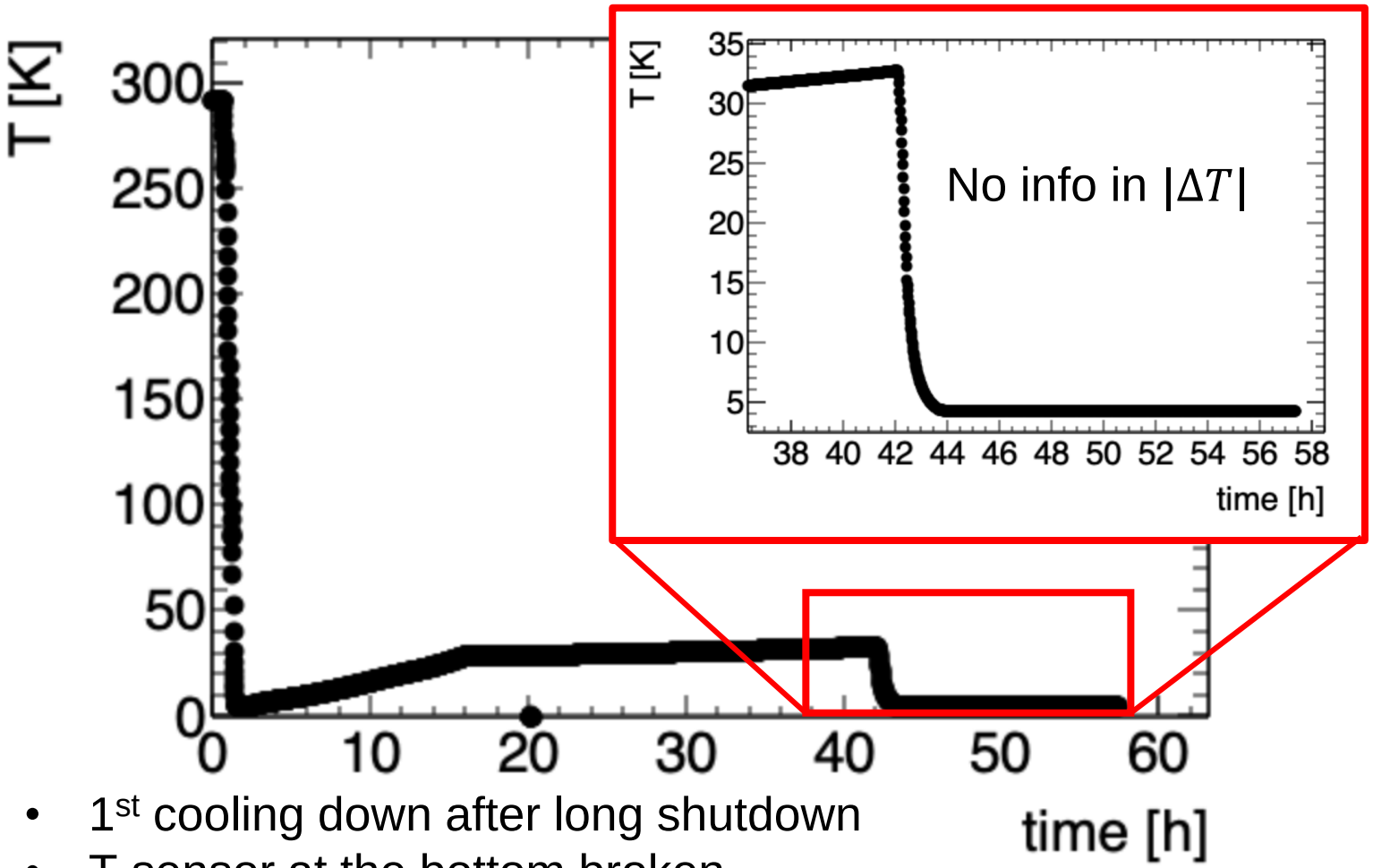


- Vacuum furnace originally used for 600C annealing of ESS spoke cavities
- A cryogenic pump, pure Ar for purging etc
- New R&D with DESY 1.3 GHz cavities

M. Fouaidy et al., IEEE Transactions on Applied Superconductivity, vol. 28, no. 4, pp. 1-6 (2018)

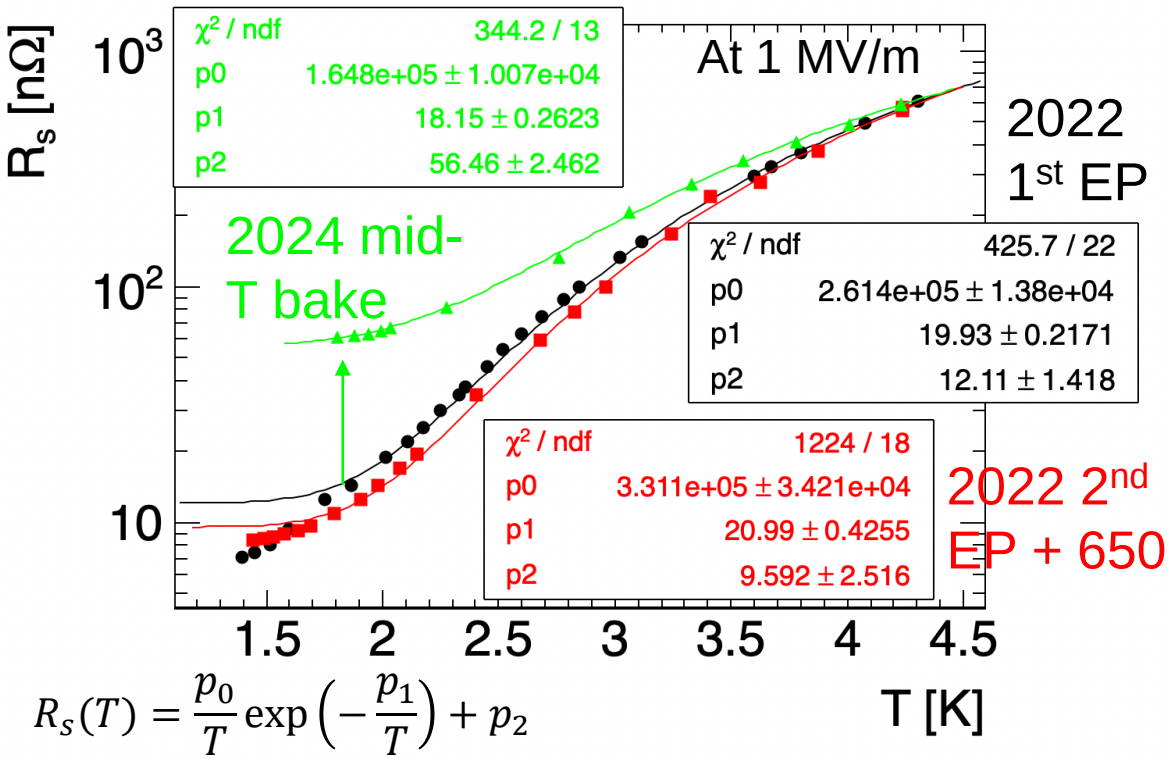


1st test is always far from ideal (CV1 at CEA Saclay on June 18 2024)

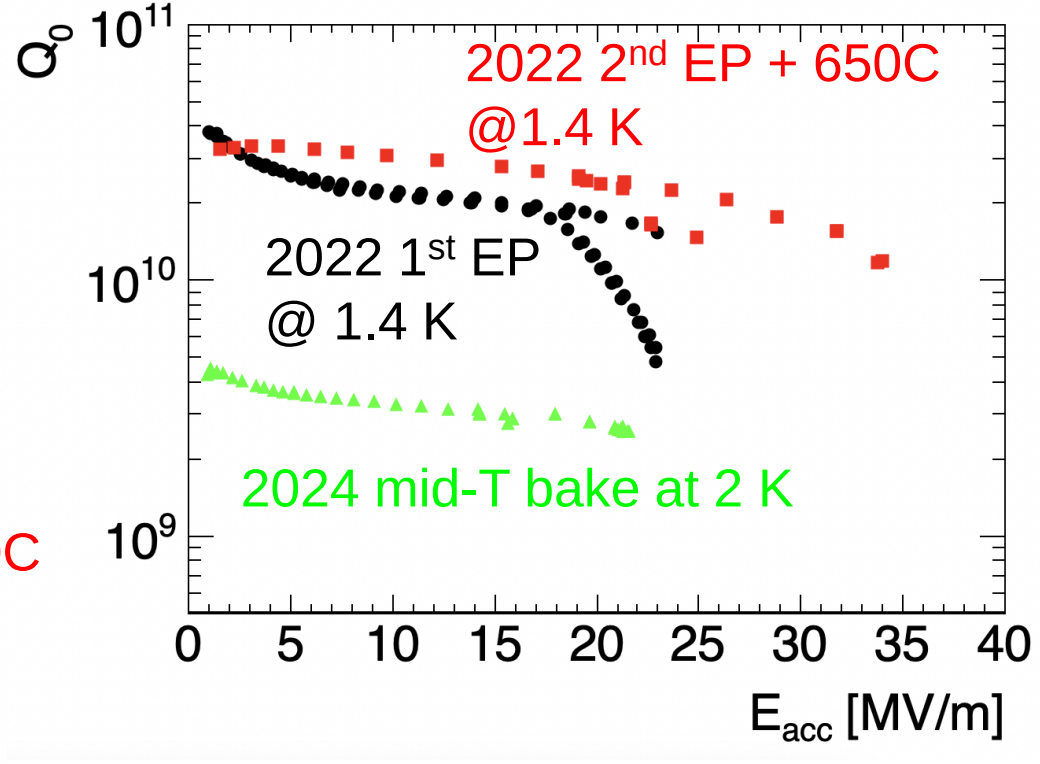


- 1st cooling down after long shutdown
- T-sensor at the bottom broken

1st test results



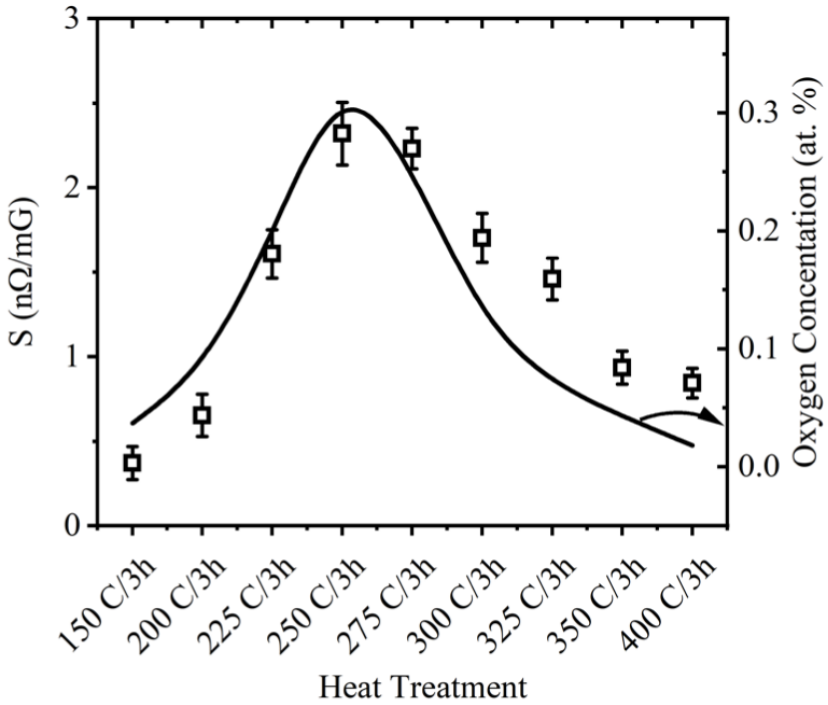
$$R_s(T) = \frac{p_0}{T}\exp\left(-\frac{p_1}{T}\right) + p_2$$



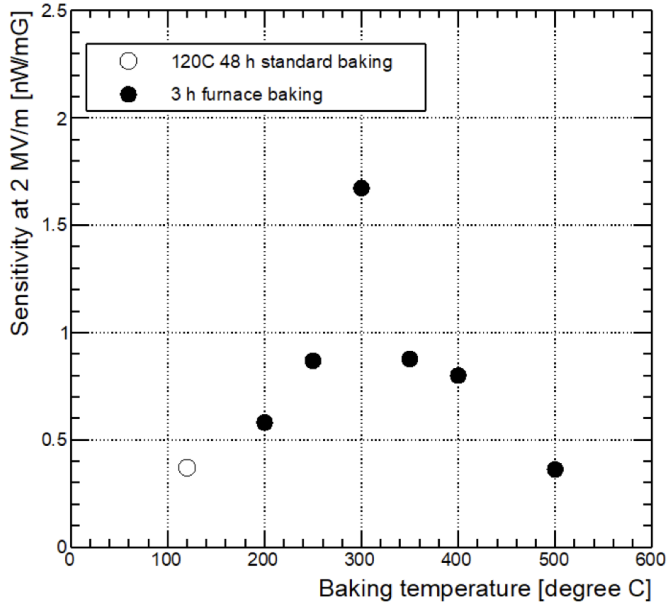
- The mid-T baked cavity showed significantly high residual resistance $\Delta R_{res} > 46\ n\Omega$
  → Is it due to contamination of furnace/cavity or magnetic field effect?

Magnetic field sensitivity (1.3 GHz cavities)

JLab



KEK



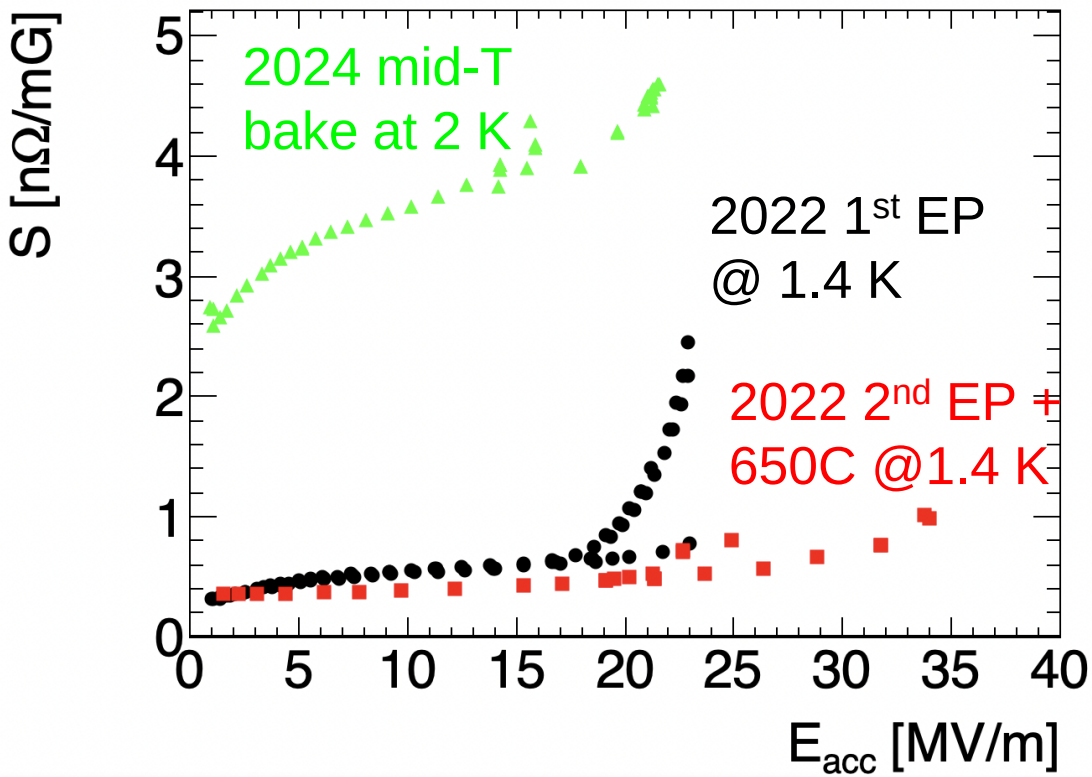
$H_{ext} \sim 25\ \mathrm{mG} = 2.5\ \mu\mathrm{T}$

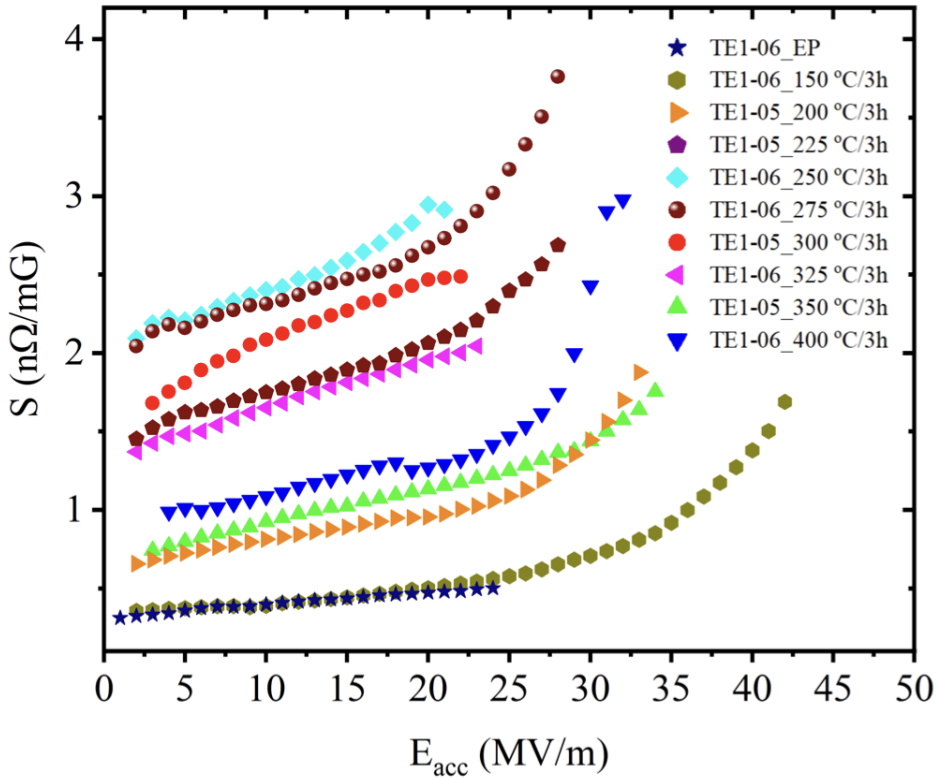
Not yet optimized

$S \sim 2\ \mathrm{n\Omega/mG}$

$\rightarrow \Delta R_{res} \sim S H_{ext} = 50\ n\Omega$

Compare to JLAB result at 2 K: 25 mG case



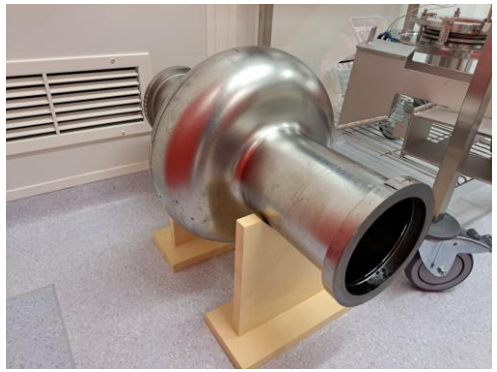


- We could explain the degradation of Q due to non-optimized magnetic shield and high sensitivity to trapped flux in mid-T baked cavities

→ Improving magnetic shield and installing magnetic field mapping at CEA after summer

Conclusions

- IJCLab has been a world-leading laboratory of SRF cavities for proton / heavy ion linear accelerators
  - R&D of Spiral2, ESS, MYRRHA, PIPII cavities are coming to the final phase
  - Contributions to collider projects has been in beam dynamics and nanobeams (ATF), RF couplers (Eu-XFEL), temperature sensors (LHC), etc
- IJCLab is expanding R&D activities of SRF cavities towards future colliders
  - FCC / PERLE 800 MHz cavities: super high-Q
  - ILC 1.3 GHz cavities: super high-G
- Advanced heat treatment is the key R&D subject
  - IJCLab is equipped with a clean vacuum furnace originally used for the ESS spoke cavity project
  - Mid-T baking for super high-Q
  - 1st mid-T baked results in 1.3 GHz cavity → studies on-going
- Future prospects
  - 2nd test with improved magnetic field at CEA (July 18), test at STF in KEK (October)
  - Heat treatment of the 800 MHz prototype cavity
- Collaborations
  - ERL collaboration with KEK via FJPPL
  - FCC: collaboration with CERN/FNAL
  - PERLE: collaboration with CERN/JLAB



backup

Open questions

- Magnetic field sensitivity
  - N-doping/mid-T bake makes cavities sensitive to trapped magnetic fields
  - Factor 10 better magnetic shield may be necessary
  - Flux expulsion technique with higher thermal gradient
  - Advantage of mid-T baking is based on a compromise between ultimately high-Q and realistic trapped flux level in a cryomodule
- EP vs BCP
  - EP + mid-T bake has been studied intensively
  - EP is mandatory for very high gradient but may not be for high-Q at decent field
  - BCP is simpler and less expensive
  - The limited number of tests have been performed for BCP + mid-T baking → results are somewhat contradictory
- Low-T bake could also be an option for FCC/PERLE
  - Not enough margin even in the best case but probably more conservative

List of the different recipes

xNy doping

- High temperature degassing 800 °C (~ 3hours) in UHV
- Nitrogen injection at the end of process (~ 25 mTorr) hold for 'x' mins
- Evacuate furnace and temperature hold for 'y' mins
- Furnace cooldown to room temperature in UHV
- Electropolishing (5-10 µm)
- High Pressure Rinse (HPR), clean room asselbly and rf test

N-infusion

- HPR and Nb caps installed in clean room
- High temperature degassing 800 °C (~ 3hours) in UHV
- Furnace cooldown to (120-200 °C) in UHV
- Nitrogen injection ~ 25 mTorr hold for 24-48 hours
- Furnace cooldown to room temperature in UHV
- High Pressure Rinse (HPR), clean room asselbly and rf test

P. Dhakal "Nitrogen doping and infusion in SRF cavities: A review" Phys Open 5 100034 2020

2-step baking (1.3 GHz)

- HPR and Nb caps installed in clean room
- High temperature degassing 800 °C (~ 3hours) in UHV
- 75C for a few hours in UHV
- 120C for 48 hours in UHV
- Furnace cooldown to room temperature in UHV
- High Pressure Rinse (HPR), clean room asselbly and rf test

Mid-T baking

- HPR and Nb caps installed in clean room
- High temperature degassing 800 °C (~ 3hours) in UHV
- Exposed to air for oxidation on purpose
- 250-400 C for a few hours in UHV
- Furnace cooldown to room temperature in UHV
- High Pressure Rinse (HPR), clean room asselbly and rf test

P. Sha et al. *Appl. Sci.* **12**, 546 (2022)