Low-loss superconducting cavities

Frank Gerigk, CERN, Switzerland
ESSRI 2019, 28/29 November, PSI, Switzerland

with material from:

Marco Arzeo (CERN), Fabio Avino (CERN), Alex Gurevich (OCU), Anton Ivanov (CERN), Mikko Karppinen (CERN), Alick Macpherson (CERN), Akira Myazaki (Uppsala University), Ari Palzcewski (JLAB), Guillaume Rosaz (CERN), Nicolas Shipman (CERN), Lorena Vega Cid (CERN), Walter Venturini (CERN), Vyacheslav Yachovlev (FNAL), Euclid Techlabs, … and many more

Content

Losses in SRF cavities

Classic optimisation

- Beam current
- Pulse length
- Duty cycle
- Beam energy
- AC/RF efficiency

Optimum choice of:

frequency, gradient, temperature, N_{cells}, cavity type, Nb/Cu or Nb

- Collider/fixed target
- Linear/circular acc.
- Static cryo losses
- Cryo efficiency
- Beam velocity

To be analysed for each machine, e.g: V. Yakovlev, 4th Workshop on Energy for Sustainable Science at Research Infrastructures, 2017

Losses in SC RF cavities

Surface Losses

Standard BCS Theory

$$P_s = \frac{V_{acc}^2}{(R/Q) \cdot Q} \longrightarrow \frac{1}{Q} \propto R_S = R_{BCS}(T) + R_{res} = \left(\frac{A\omega^2}{T}\right) e^{-\frac{\Delta}{kT}} + R_{res}$$

Lower temperature and lower frequency reduce the losses, but lower temperature reduces cryogenic efficiency:

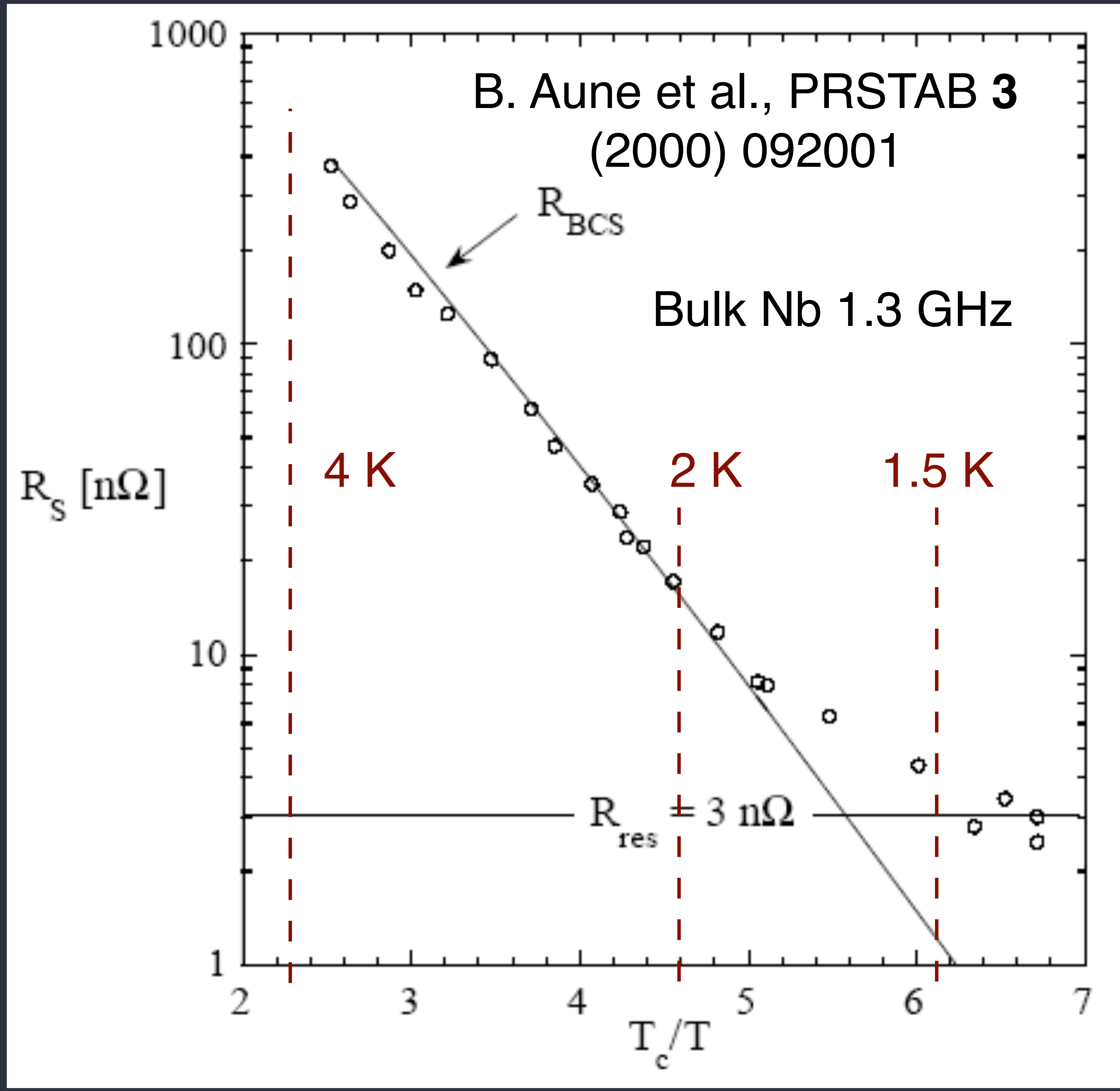
using: $R_{BCS} \approx 2 \times 10^{-4} \frac{1}{T} \left(\frac{f}{1.5}\right)^2 e^{\left(\frac{-17.67}{T}\right)}$

4.5 K		
Frequency	1300 MHz	400 MHz
R_{BCS}	660 nΩ	62 nΩ
$P_{el, cryo}$	~ 300 P_s	

2 K		
Frequency	1300 MHz	400 MHz
R_{BCS}	11 nΩ	1 nΩ
$P_{el, cryo}$	~ 1000 P_s	

Losses in SC RF cavities

$$R_S = R_{BCS}(T) + R_{res} = \underbrace{\left(\frac{A\omega^2}{T}\right) e^{-\frac{\Delta}{kT}}}_{R_{BCS}} + \underbrace{R_{fl} + R_r}_{R_{res}}$$

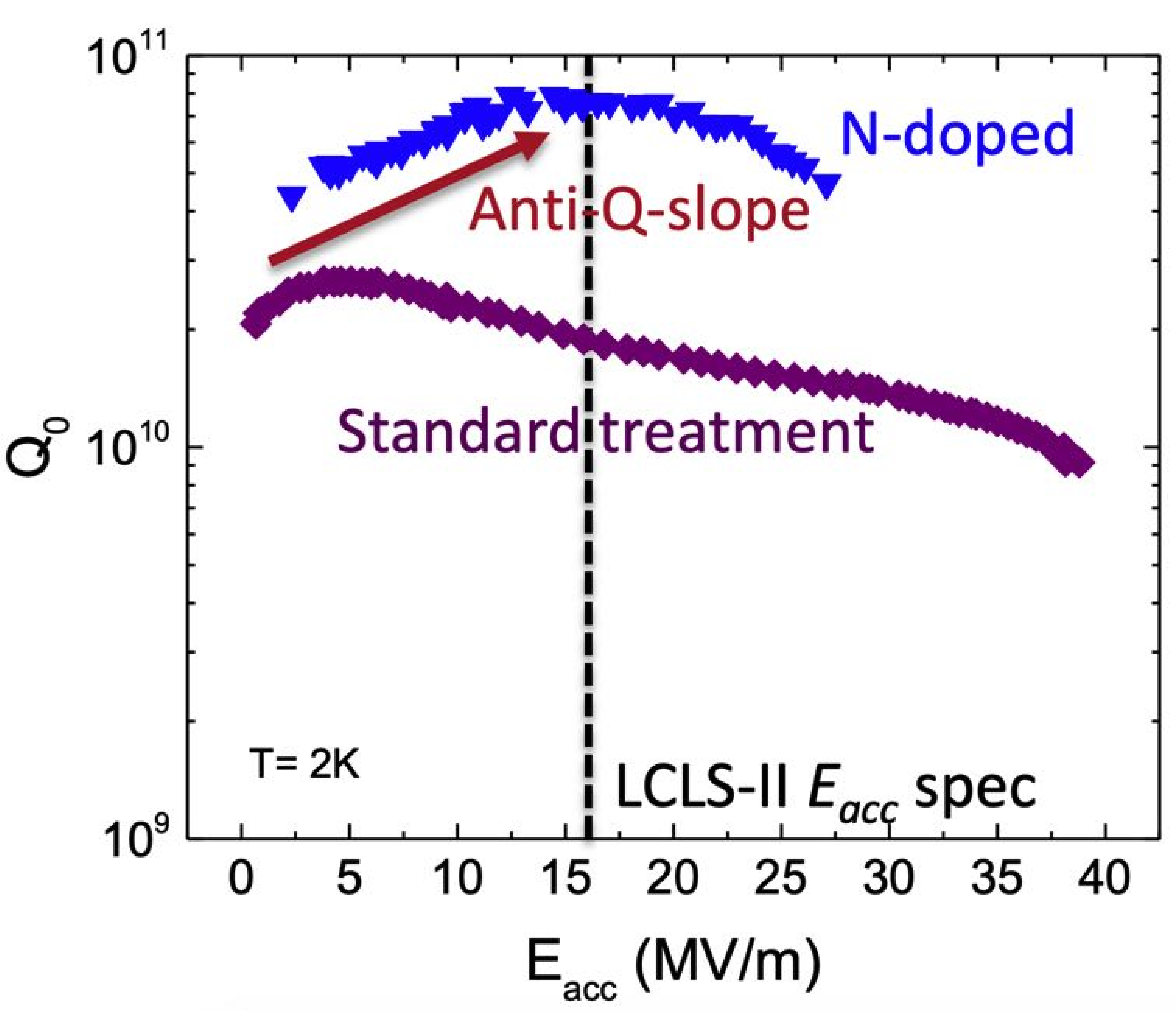


- Material purity

- Temperature treatments
- nitrogen doping
- nitrogen infusion
- …

- Trapped magnetic flux
- Lattice distortions

Reducing R_{BCS} in bulk Nb



V.Yakovlev | 4th Workshop on Energy for Sustainable Science at Research Infrastructures 2017, ELI

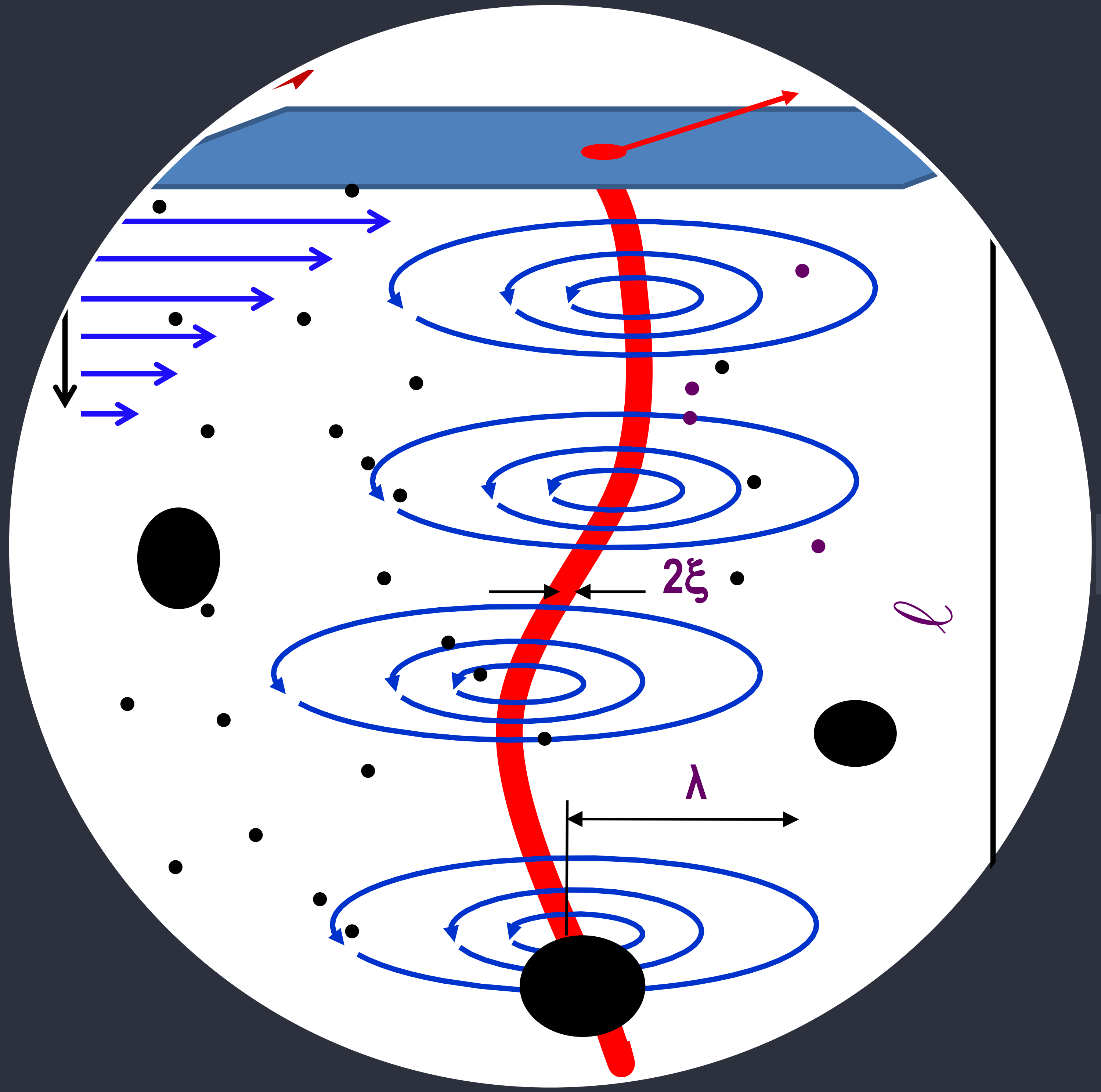
Nitrogen doping/infusion

- reverses the Q-slope,
- successfully used by FNAL for LCLS-II,
- yields unprecedented Q-values,
- can be tailored to lower or higher accelerating gradients.

But:

- **increased sensitivity to magnetic fields,**
- relies on efficient flux expulsion with fast cool-downs.

Flux trapping in SRF cavities



A. Gurevich | TTC/ARIES Flux Trapping Workshop, 2018, CERN

a closer look at flux trapping

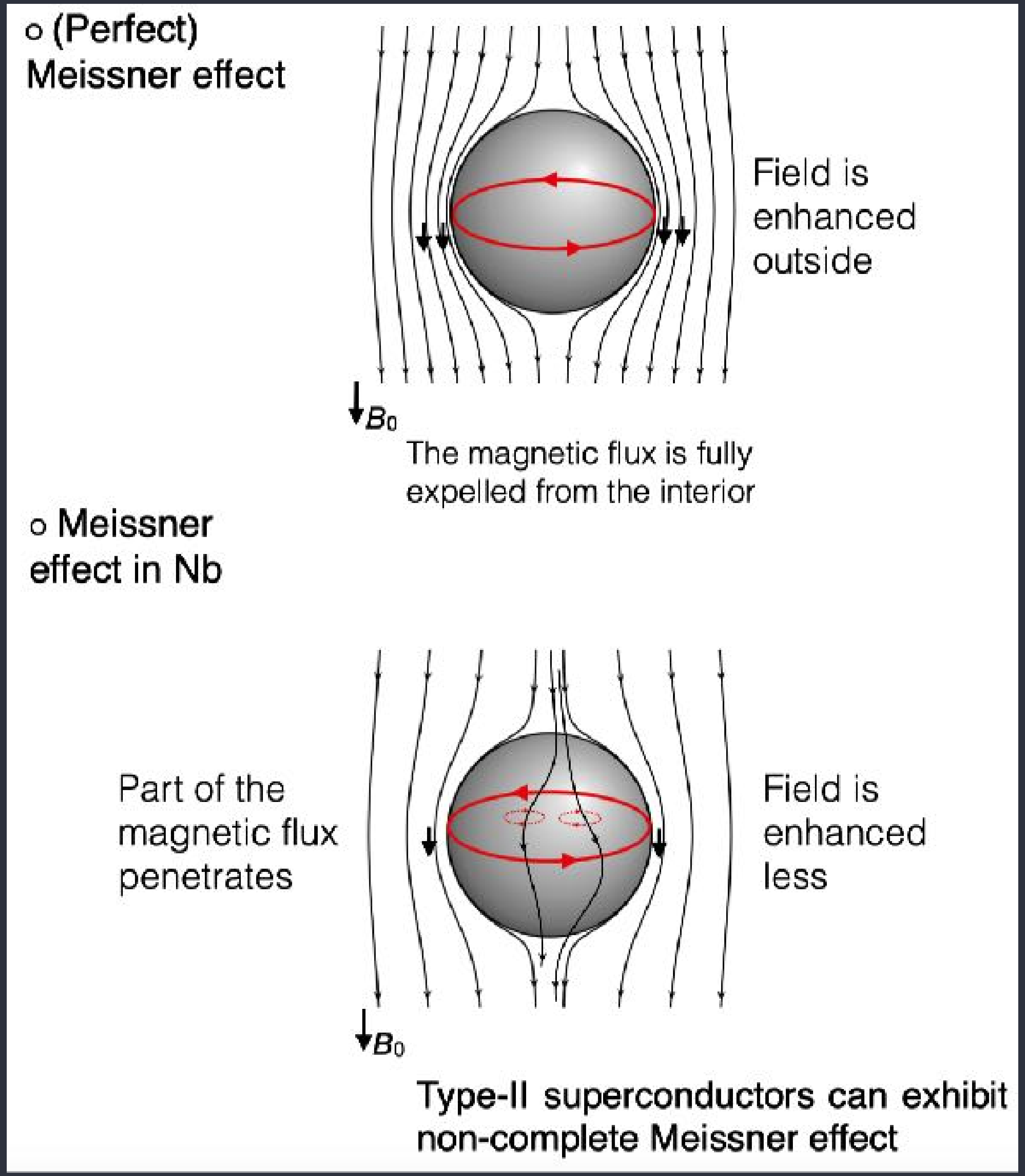
$$R_{fl} = B_0 \cdot \eta\left(l, \nabla T, \ldots\right) \cdot S\left(l, \omega, B_{RF}\right)$$

ambient magnetic field
➜ shielding

flux trapping efficiency
also denoted as:
- expulsion efficiency
- trapping ratio
- expulsion inefficiency
- …

sensitivity to trapped flux
➜ [nΩ/mG]

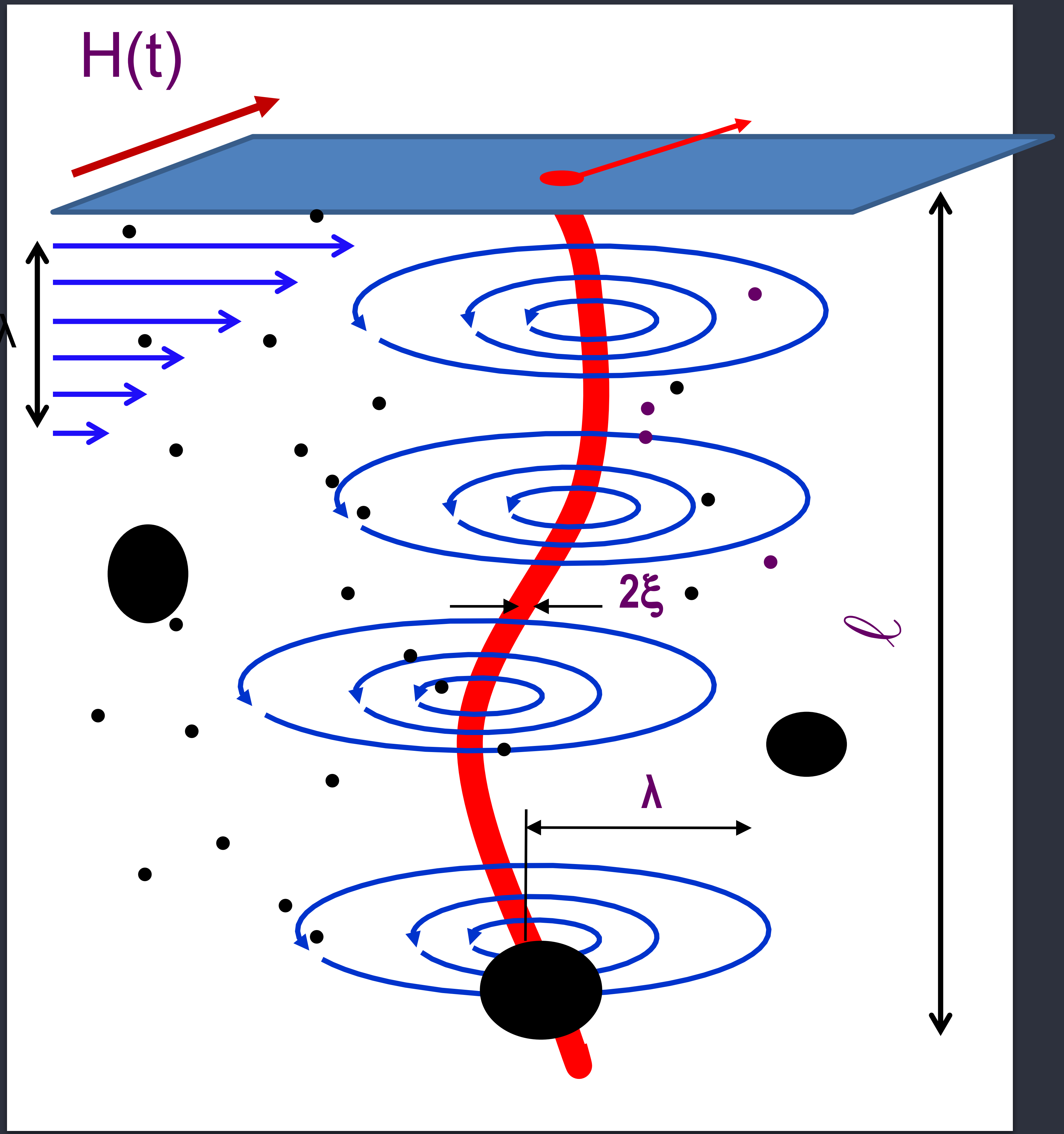
Flux expulsion/trapping



A. Ivanov | ARIES Annual Meeting 2019, Budapest, Hungary

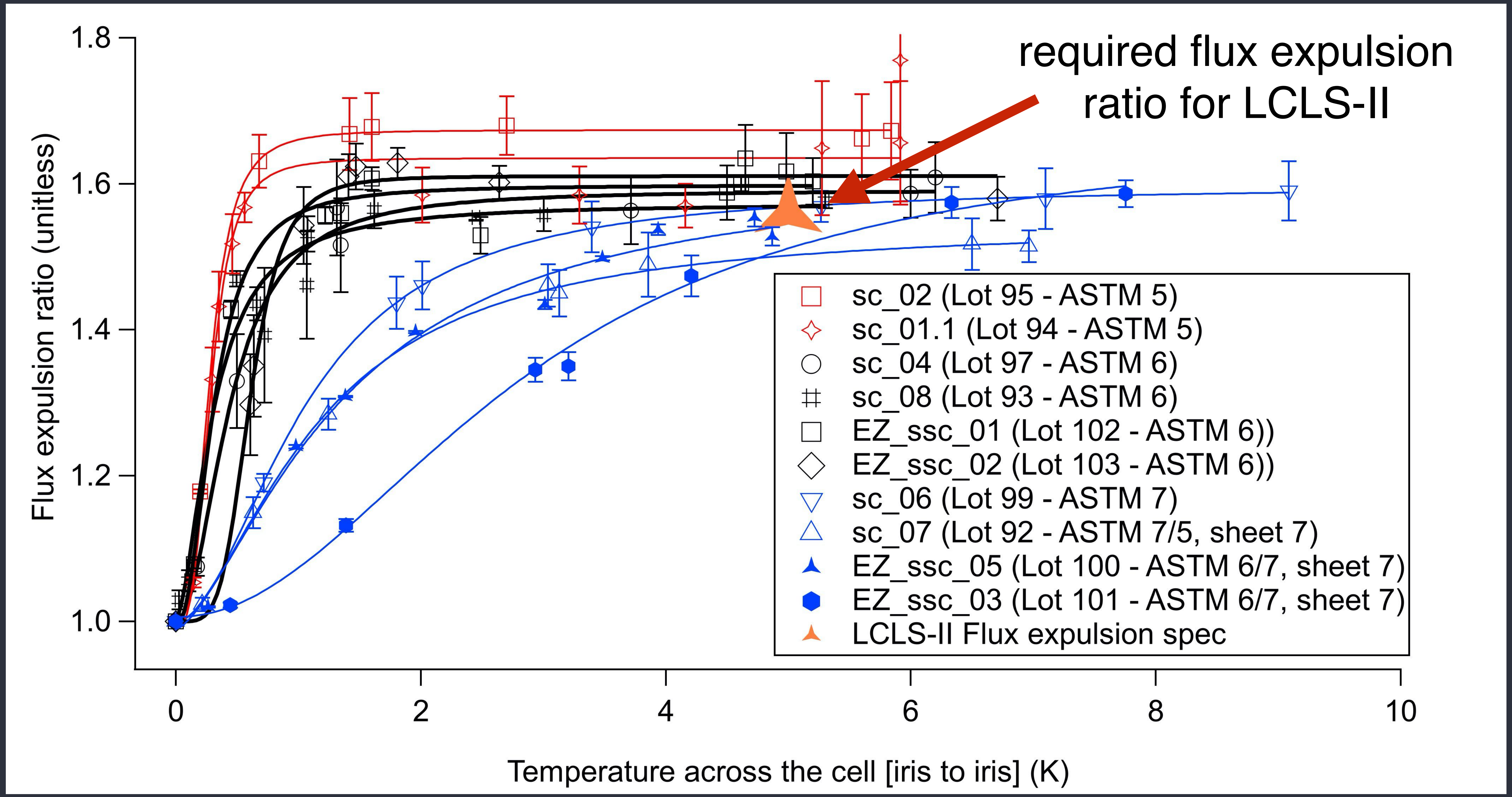
Large temperature gradients help to sweep flux lines out of bulk Nb cavities, but the material properties can make a difference!

Flux may remain "trapped" by pinning centres. The "waggling" of the flux lines with RF causes losses on the surface and in the bulk.



A. Gurevich | TTC/ARIES Flux Trapping Workshop, 2018, CERN

LCLS-II Nb issues



A. Palzcewski | TTC/ARIES Flux Trapping Workshop 2018, CERN

For some LCLS-II cavities the required Q could not be achieved:

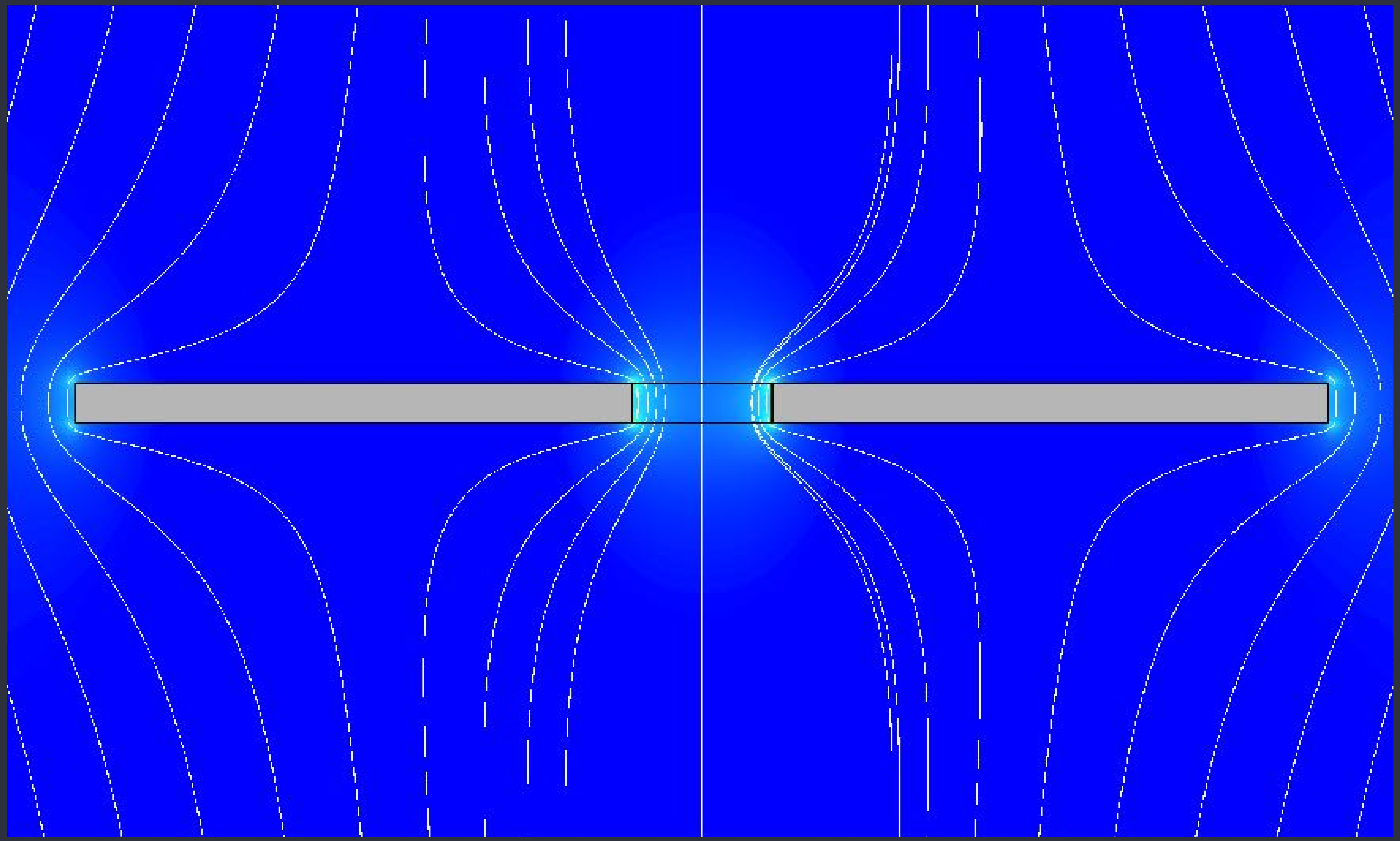
- Triggered an emergency program to produce single cell cavities from different material batches.
- Various temperature treatments were tried.
- Some batches could not reach the required flux expulsion with 900 C heat treatments.

➜ Need for faster high-throughput testing of material

CERN flux lens

A. Ivanov, A. Macpherson

- Flat Nb discs with a hole acting as “flux lens”
- Discs are cooled from the outside to the inside ➜ flux gets expelled towards the hole.
- Magnetic field probe in the hole measures the magnetic field during cool-down.

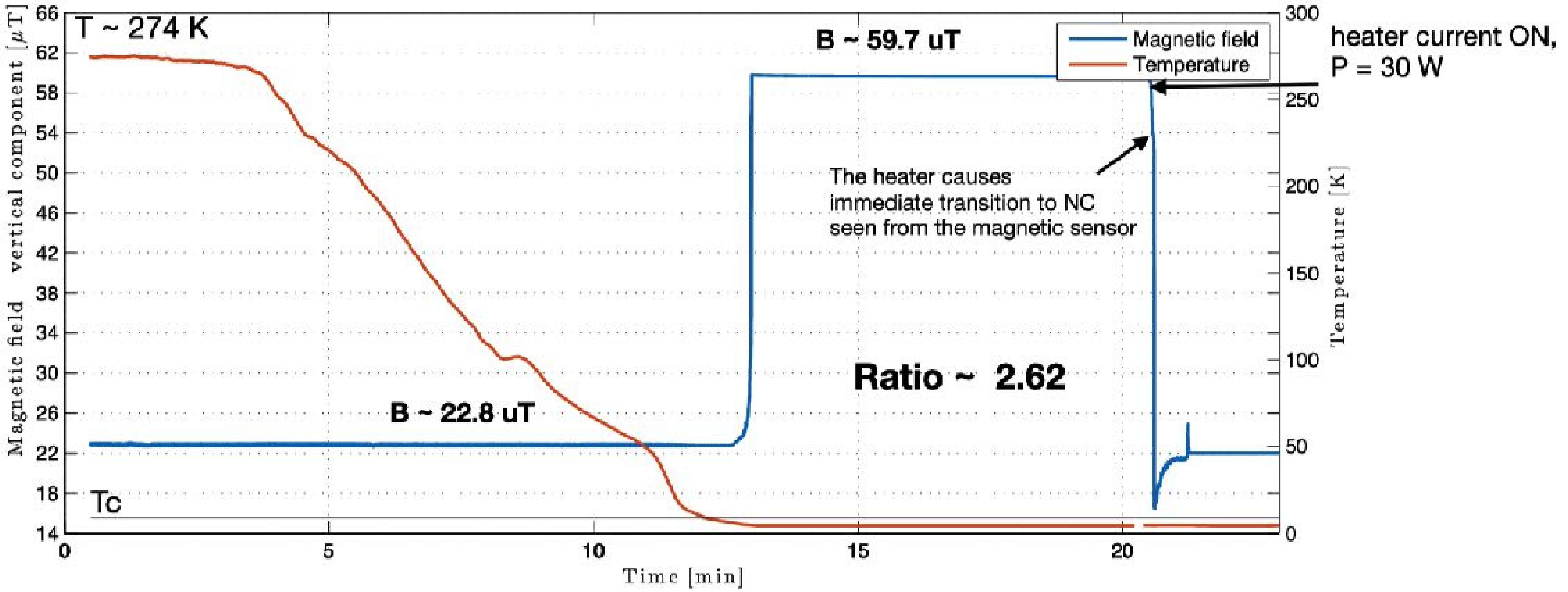


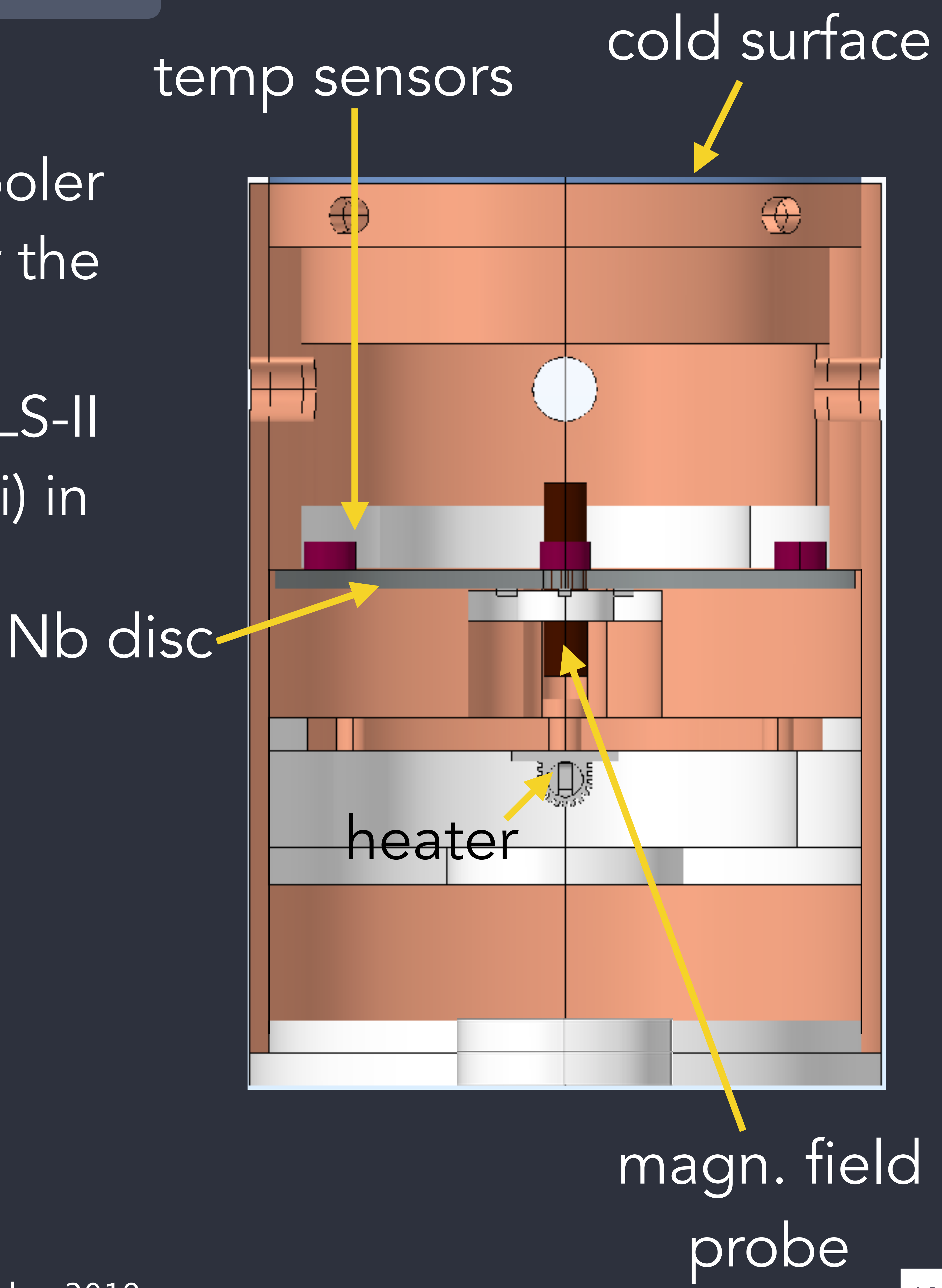
➜ allows systematic tests of Nb sheets before fabrication and comparative studies of materials from different vendors and different treatments w/o building cavities.

CERN flux lens

A. Ivanov, A. Macpherson

- Proof of principle tests done.
- Measurement set-up for round discs will be tested in cryocooler before the end of the year at CERN and then to be used for the Crab Cavity series production.
- The device will be duplicated and evaluated at JLAB for LCLS-II batch testing of Nb sheets (collaboration with Ari Palczewski) in early 2020.

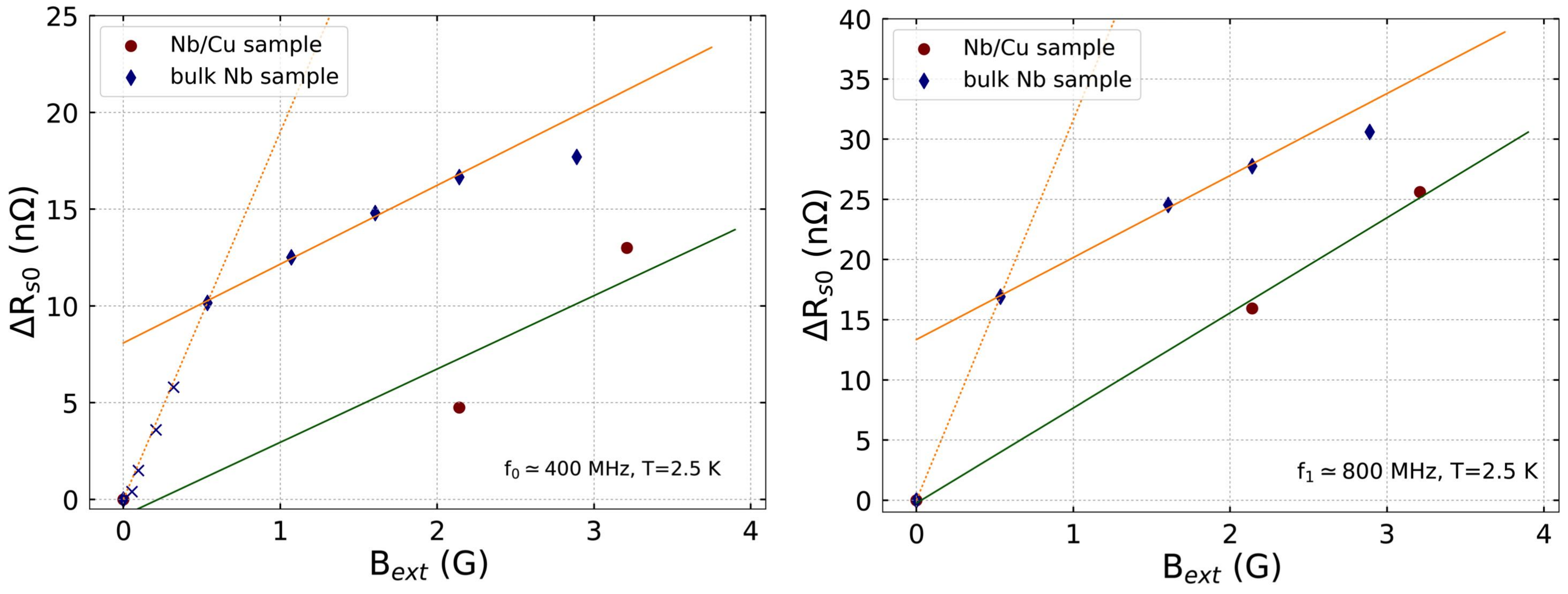




Flux trapping in Nb/Cu cavities?

Flux trapping for Nb/Cu

Nb/Cu samples are less sensitive to trapped flux



More data points are required

Marco Arzeo, CERN, TTC/ARIES flux trapping workshop, CERN 2018

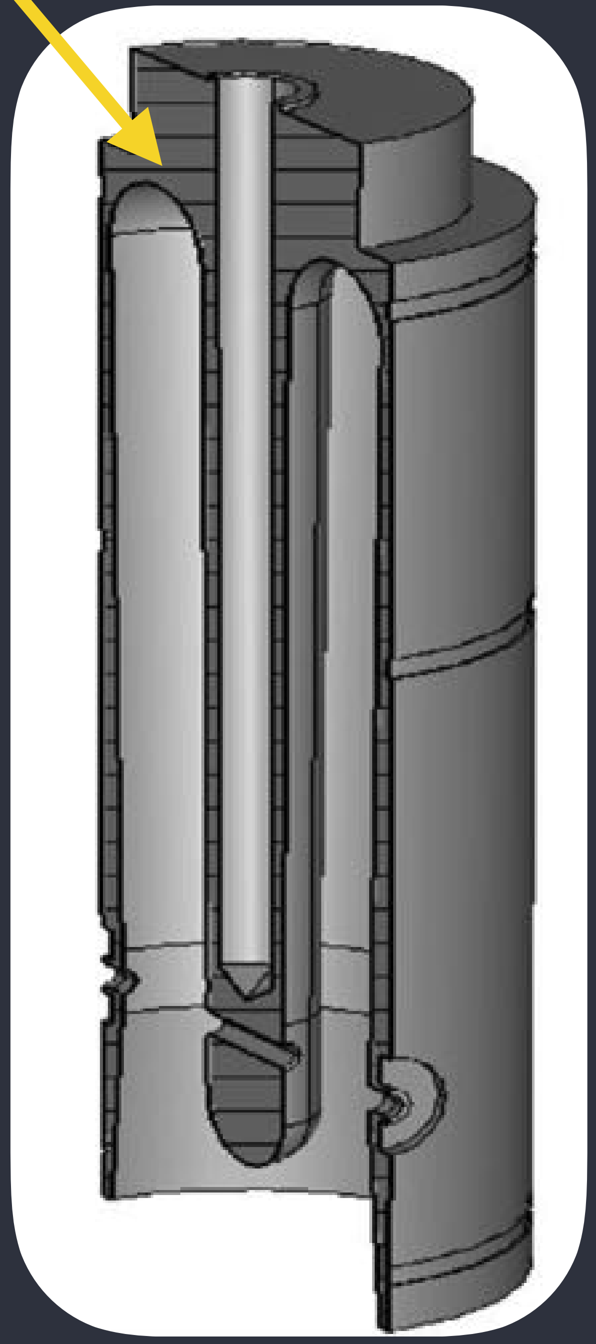
CERN November 9th 2018 TTC Topical Workshop on Flux Trapping, CERN 2018 21

- LEP, LHC, and HIE-Isolde CMs were built without magnetic shields.
- Lower cost, simpler construction, etc.
- But what if we want to push performance?

Seamless HIE-ISOLDE cavity

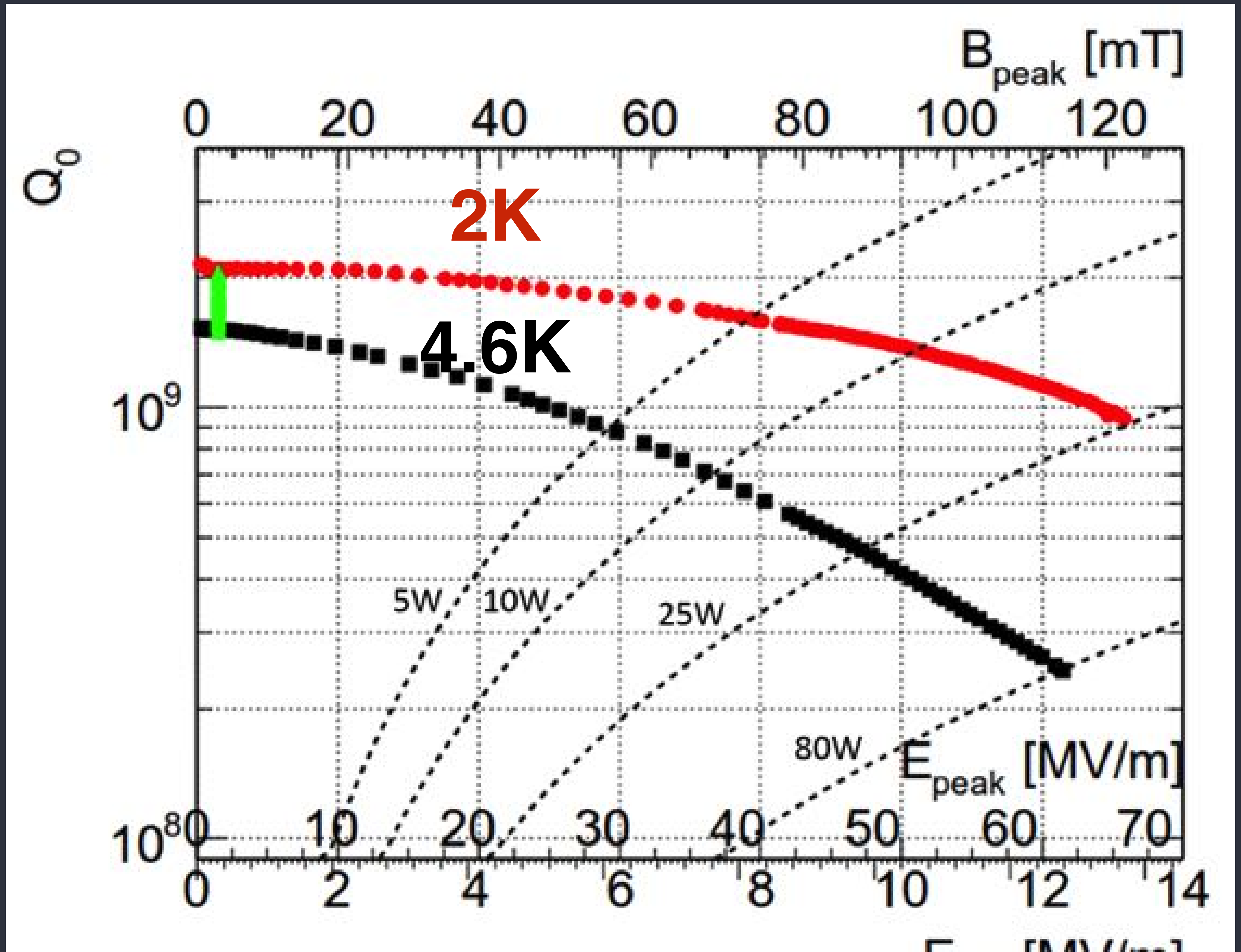
elimination of welding seam

2 pieces welded



machined out of bulk copper

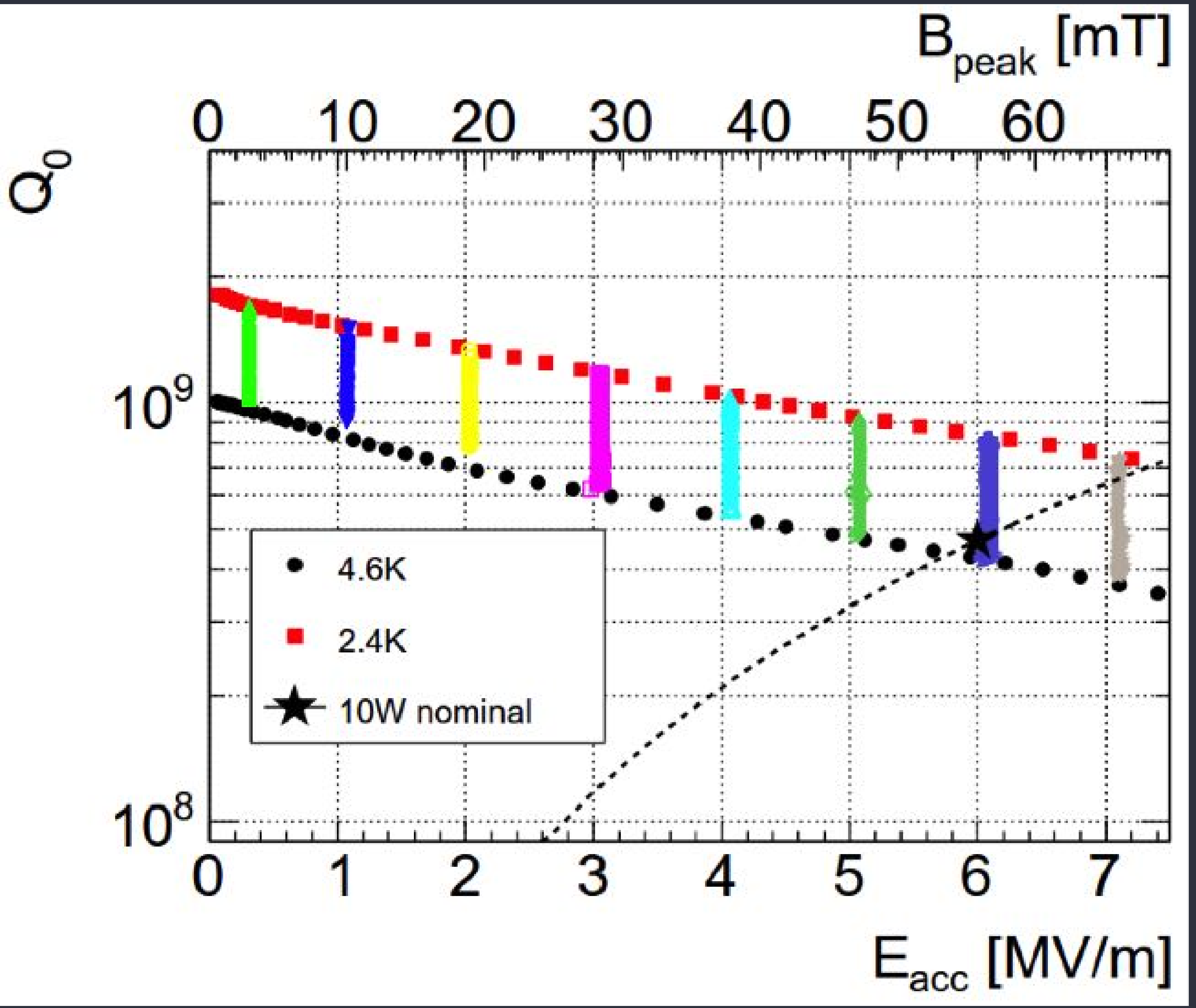
- The seamless HIE-ISOLDE cavity QS22 (Quarter-wave resonator at 100 MHz) achieved a world record field for coated cavities (with magn. field compensation).
- At 2K: 120 mT/13 MV/m
- Q-value comparable to bulk.



W. Venturini I TTC Milano 2018

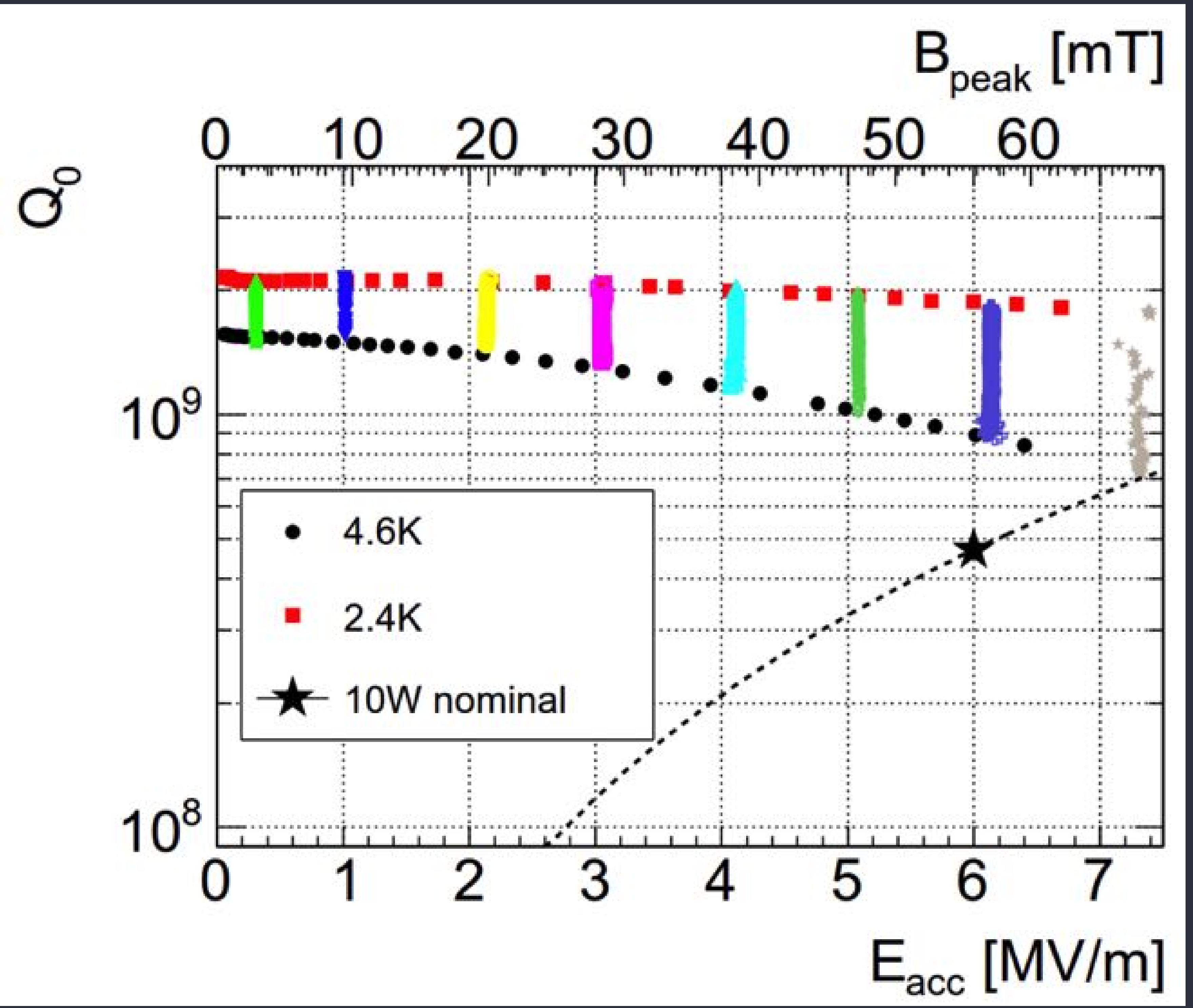
Seamless HIE-ISOLDE cavity

But external magnetic field has a significant influence. Also a higher sensitivity for flux trapping was measured in comparison to the welded HIE cavity (not shown here).



Test with increased B_{ext} (100 µT) during crossing of T_c

A. Miyazaki, W. Venturini, PRAB **22**, 073101



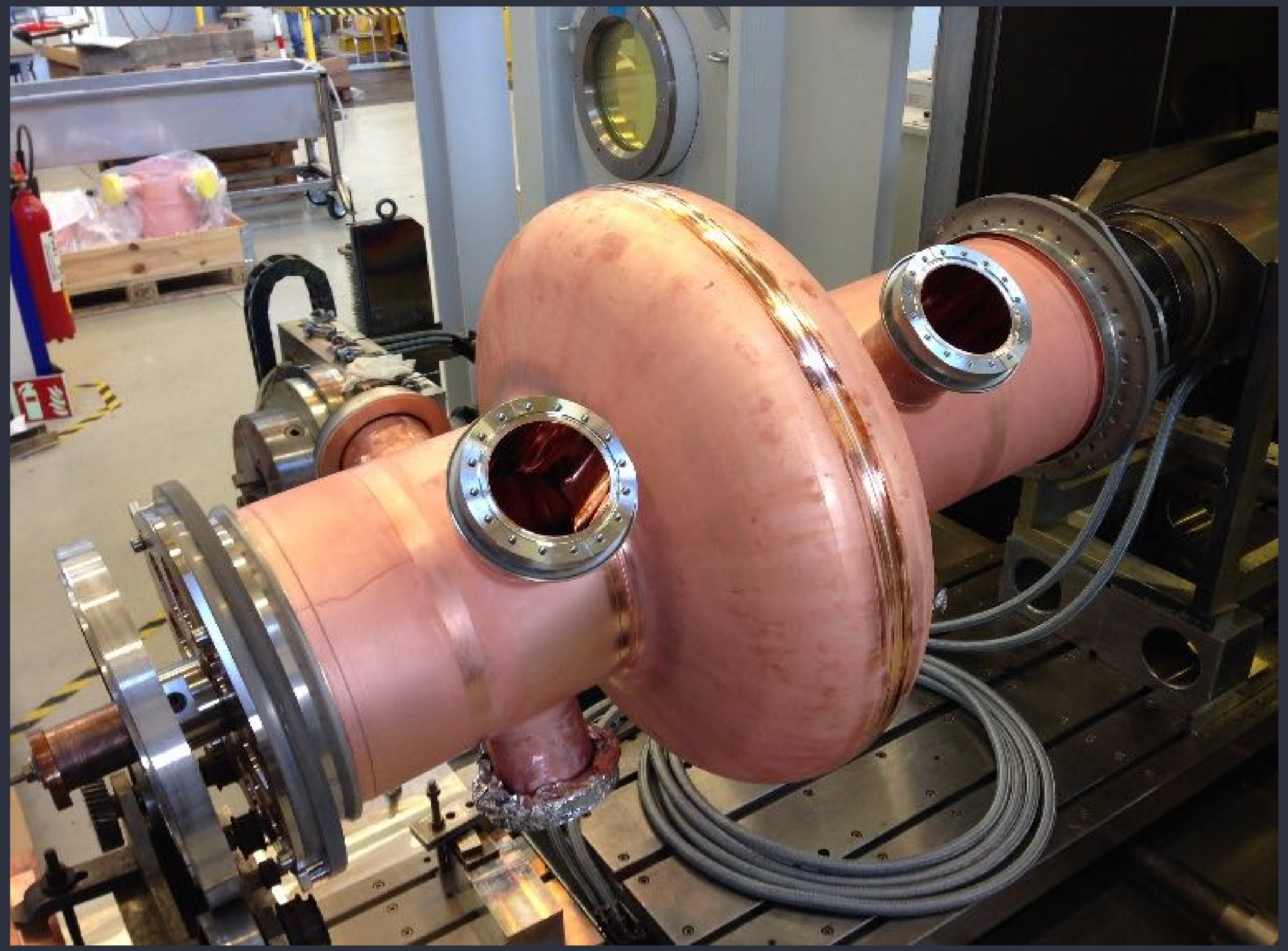
Test with compensated B_{ext} (5 µT) during crossing of T_c

What does this mean for elliptical Nb/Cu cavities?

Even though the HIE-ISOLDE case is particular (e.g. eliminating the weld drastically increased the heat transfer from inner to outer conductor), it seems clear that:

1) Having a weld in region with the highest surface currents is a bad idea (equator in elliptical cavities), ➜ **need to understand the influence of the weld.**
2) Once we get to higher performing coated cavities, the ambient magnetic field becomes more important,➜ **need to understand the influence of ambient magnetic fields.**

1) influence of the weld



The influence of the weld for coated cavities seems more dominant than for bulk Nb cavities. Probably because weld porosities can trap chemicals and spoil the coating.

LEP and LHC cavities were welded from the inside but this technology was lost.

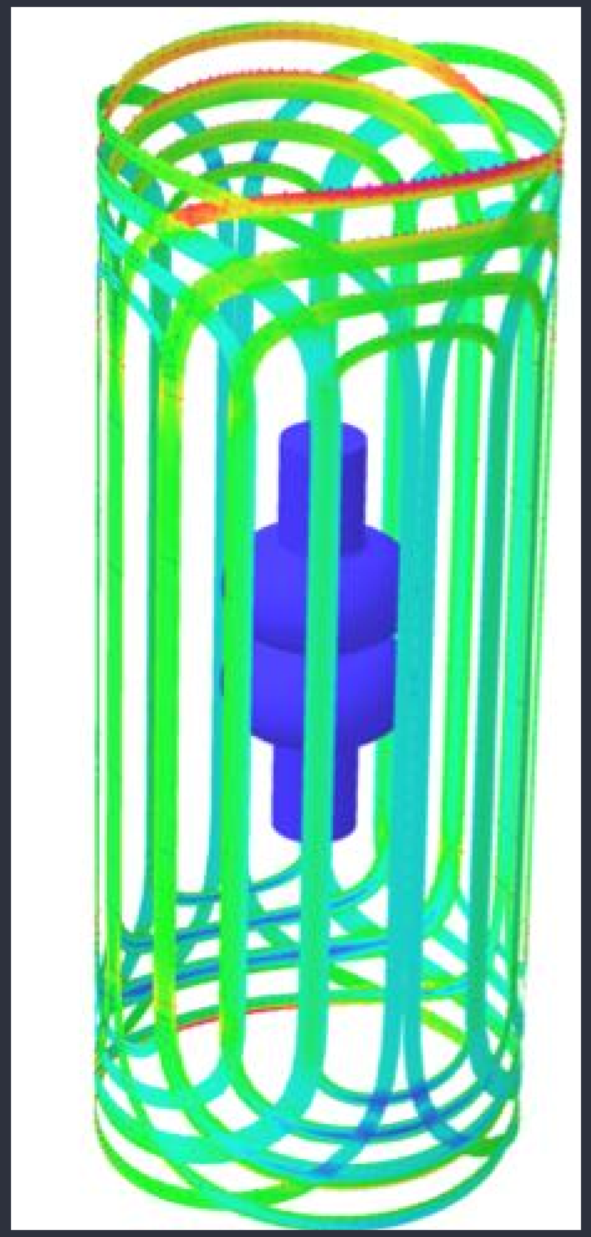
Plan of Action (2020/21)

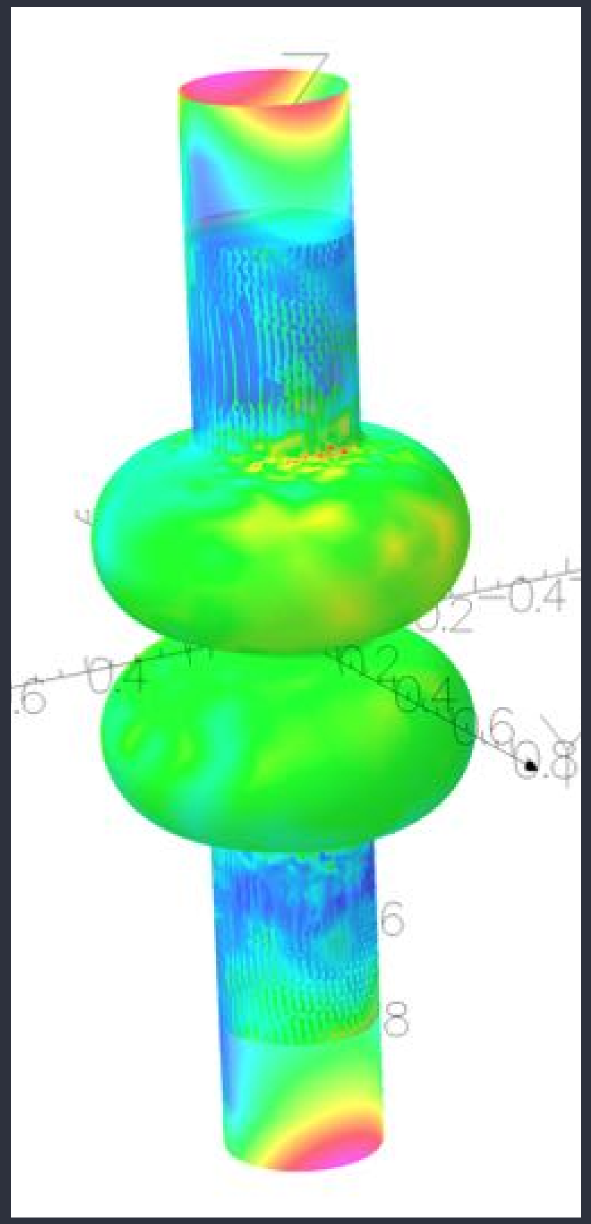
1) Improve understanding of how porosities form (tests with different treatments of the surfaces, which are to be welded).
2) Machining of seamless 1.3 GHz Cu cavity out of bulk Cu and comparison with performance of welded and coated cavities. Test of spun 1.3 GHz seamless coated cavities this week.
3) Trials at CERN with internal welds using a reflector on 400 MHz half cells.
4) Trials in industry using an internal gun on 400 MHz half cells (industry survey started).
5) Continue trials with electrodeposition of cavities on Aluminum mandrels to produce seamless cavities, first on 1.3 GHz, then on larger geometries, pioneered at CERN.
6) Electropolishing of complete LHC cavities will be available at CERN very soon.
7) Coating and cold testing.

2) State of the art shielding

- The quality of magnetic field compensation in many vertical test cryostats is questionable.
- First LHC cavity test to be done in shielded V3 with modified insert this year.
- Study to equip V6 cryostat (used for elliptical 400 MHz LHC type cavities) with a solenoid + 2 dipoles to compensate or enhance the ambient magnetic field (0.4 uT - 100 uT). < 0.5% variation along cell volume.

Courtesy of Mikko Karpinnen

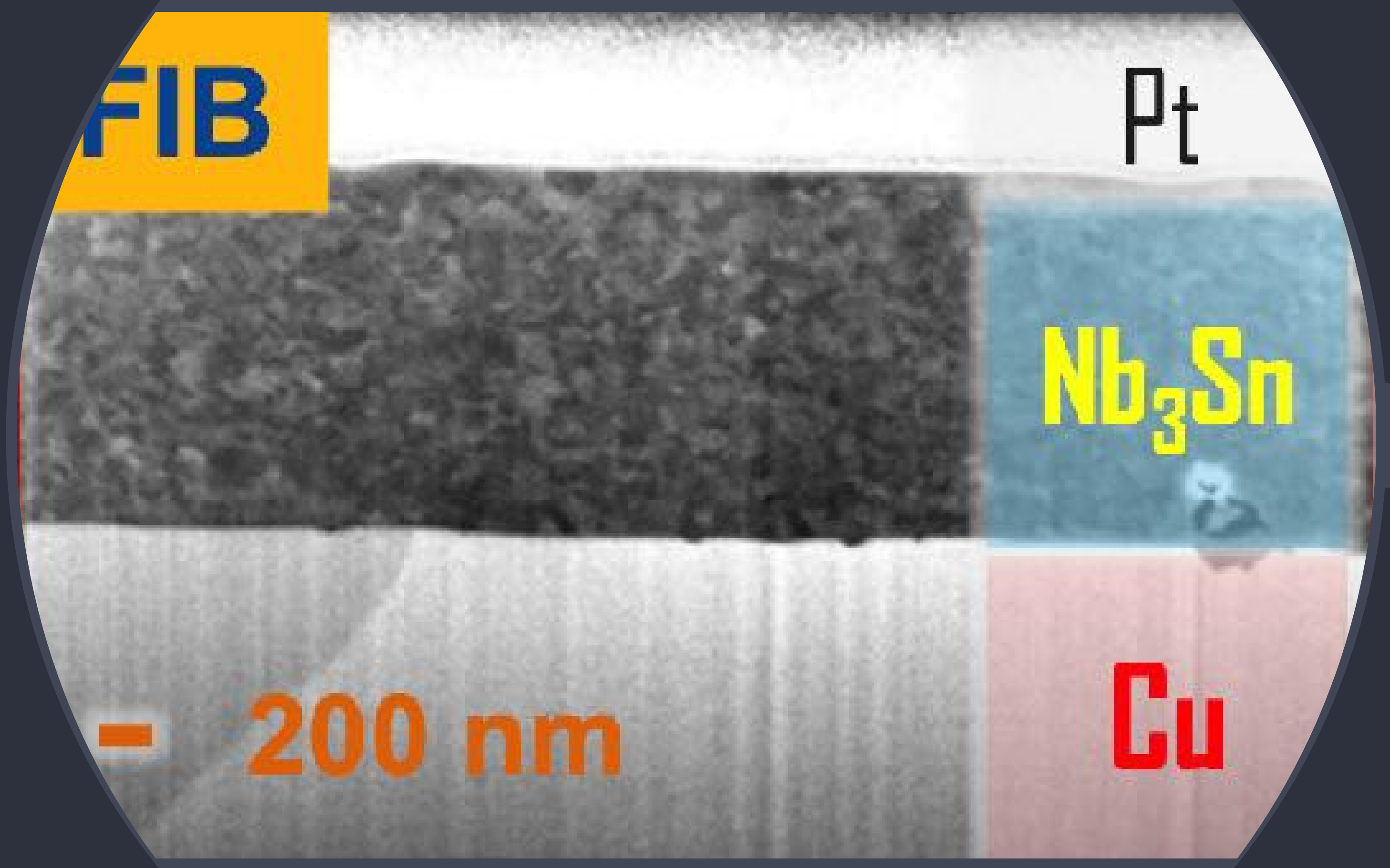




looking for answers

TTC/ARIES sponsored workshop on flux trapping and magnetic shielding, 11/2018, CERN

64 participants



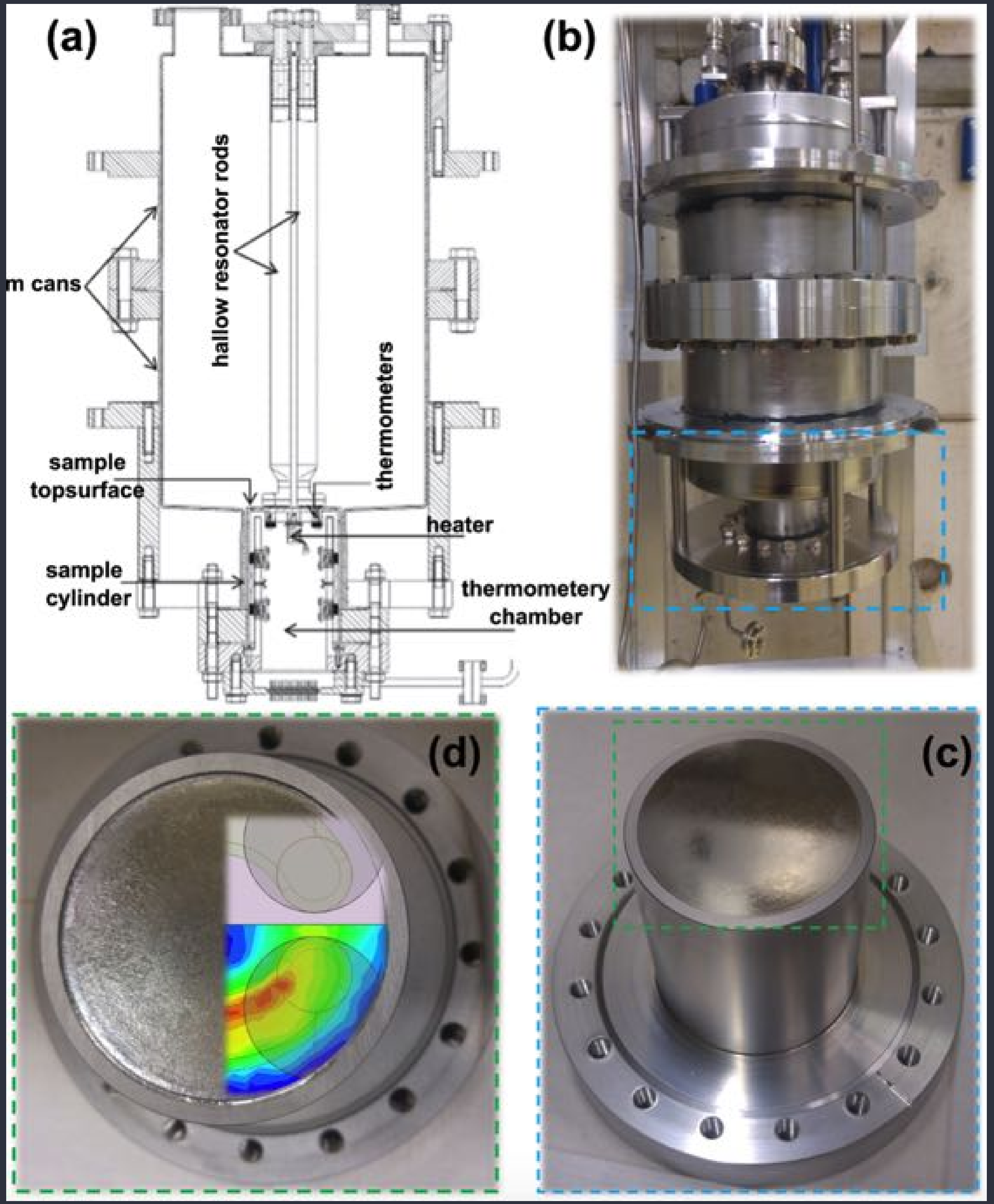
M. Arzeo et al. , SRF 2019

New Materials

A glimpse into the future

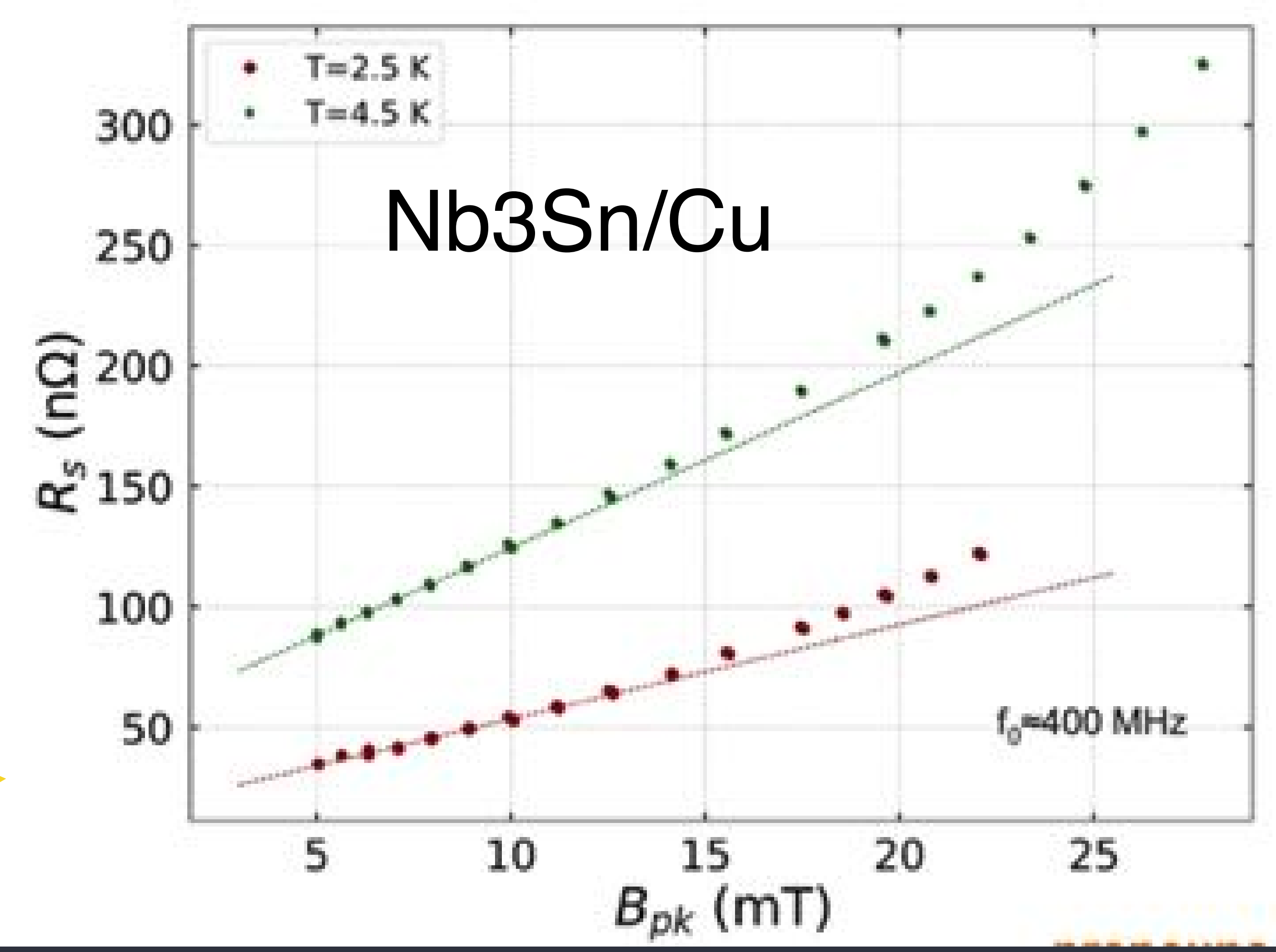
Sample testing with the QPR

Marco Arzeo, SRF 2019



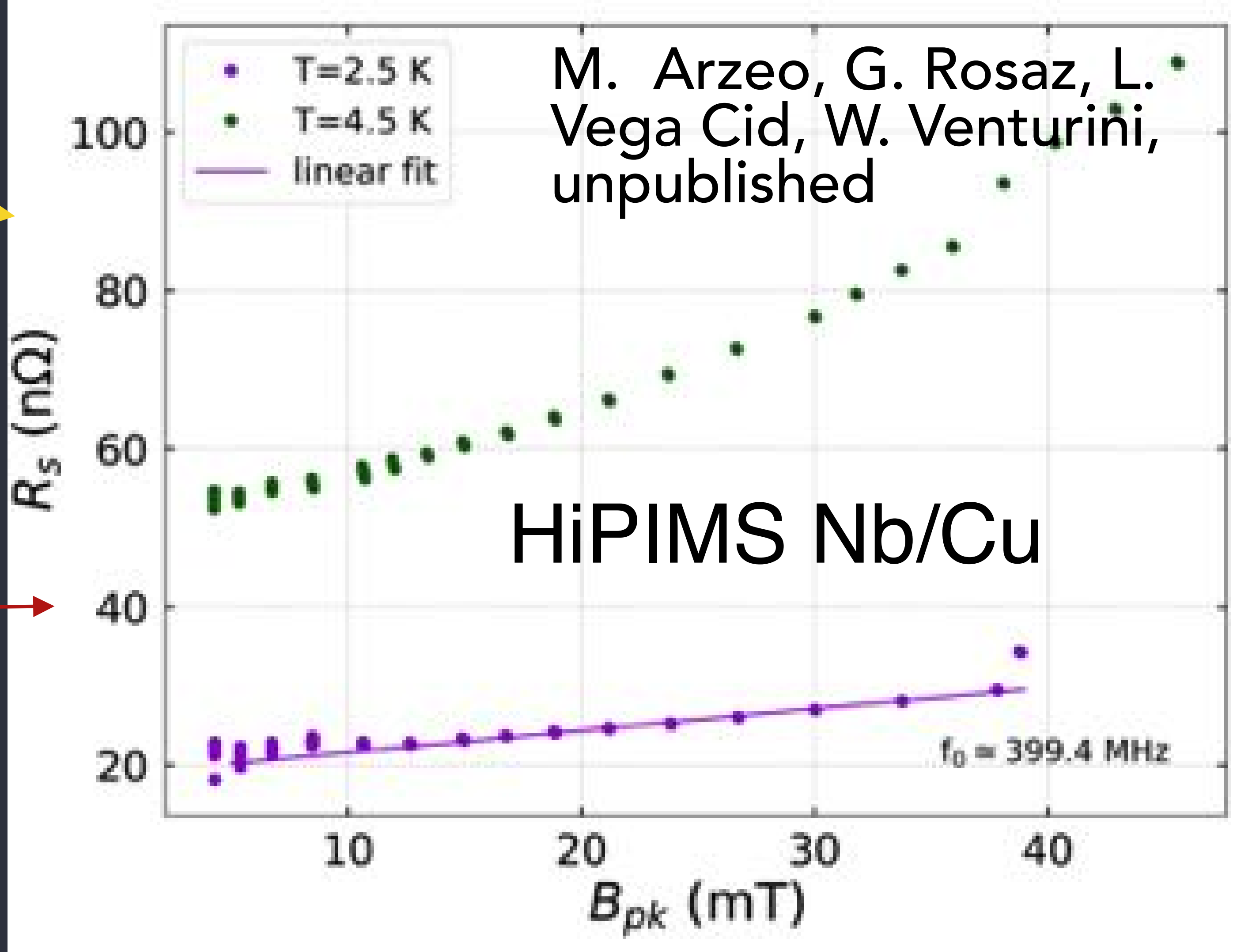
Working at higher temperature:

- Nb_3Sn on Cu: first stable sample with Tc corresponding to bulk Nb_3Sn,
- but still with strong Q-slope

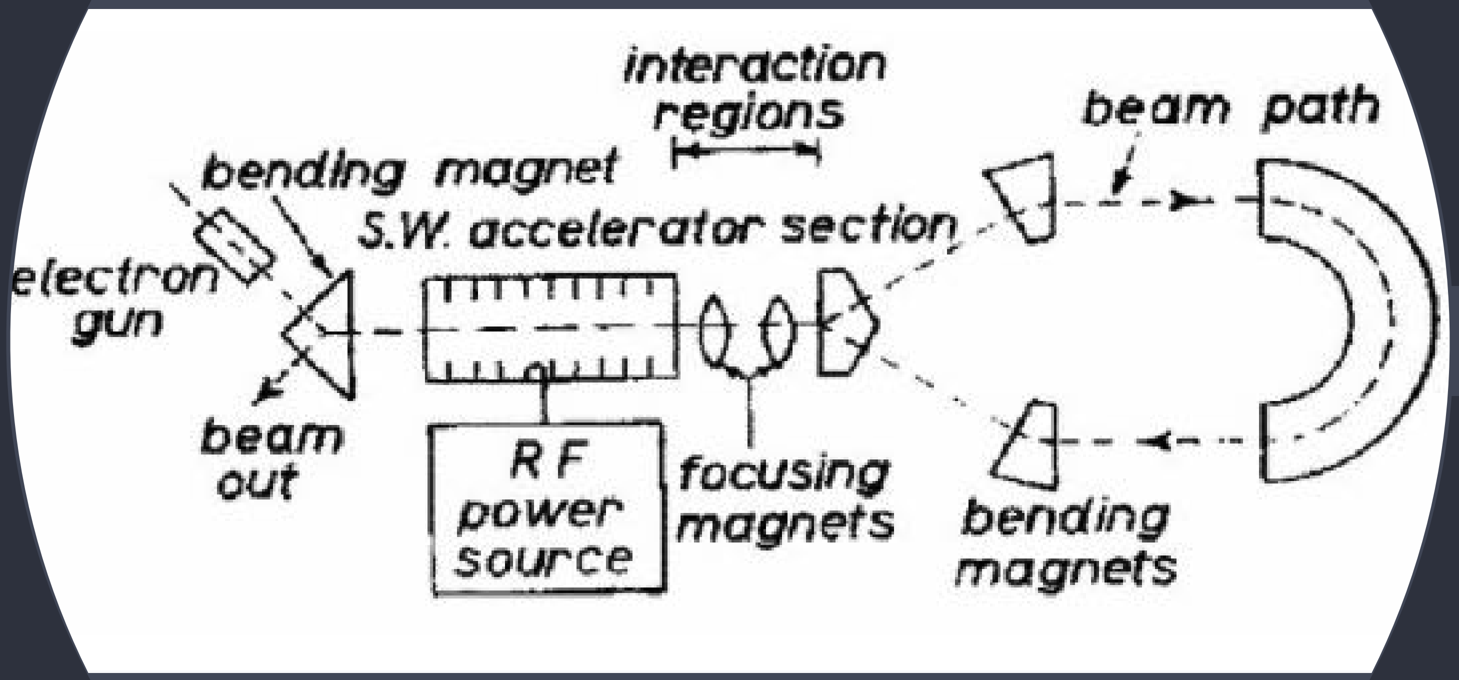


Lowering the Q-slope:

- HiPIMS sample with small Q-slope at 2K.
- Cavity test in preparation.



Pushing new materials or new coatings beyond present performance requires dedicated R&D and a substantial testing effort.

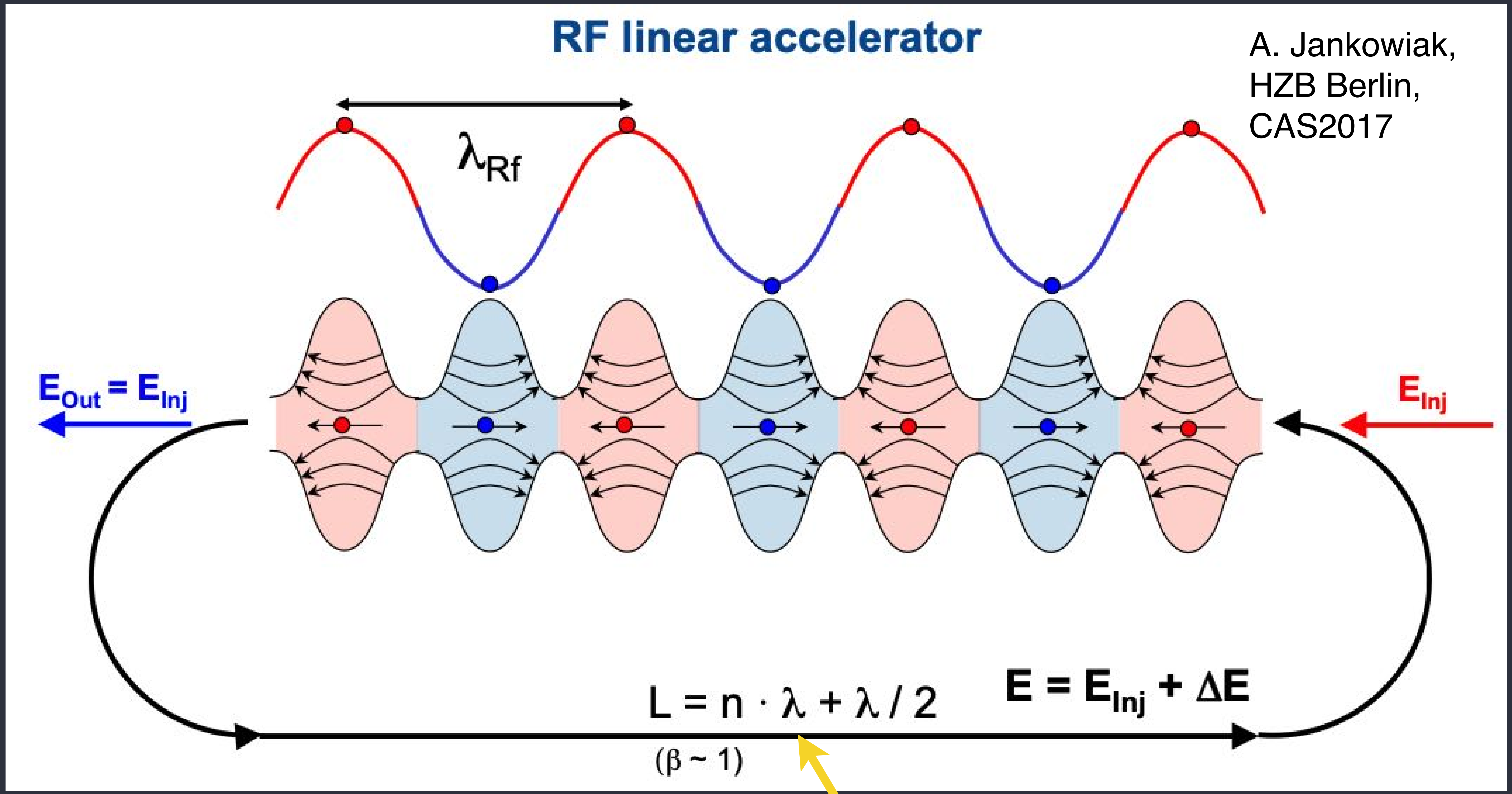


M. Tigner, Nuovo Cimento **37** (1965) 1228

Energy Recovery Linacs

Reducing RF power to “almost” zero

ERL principle

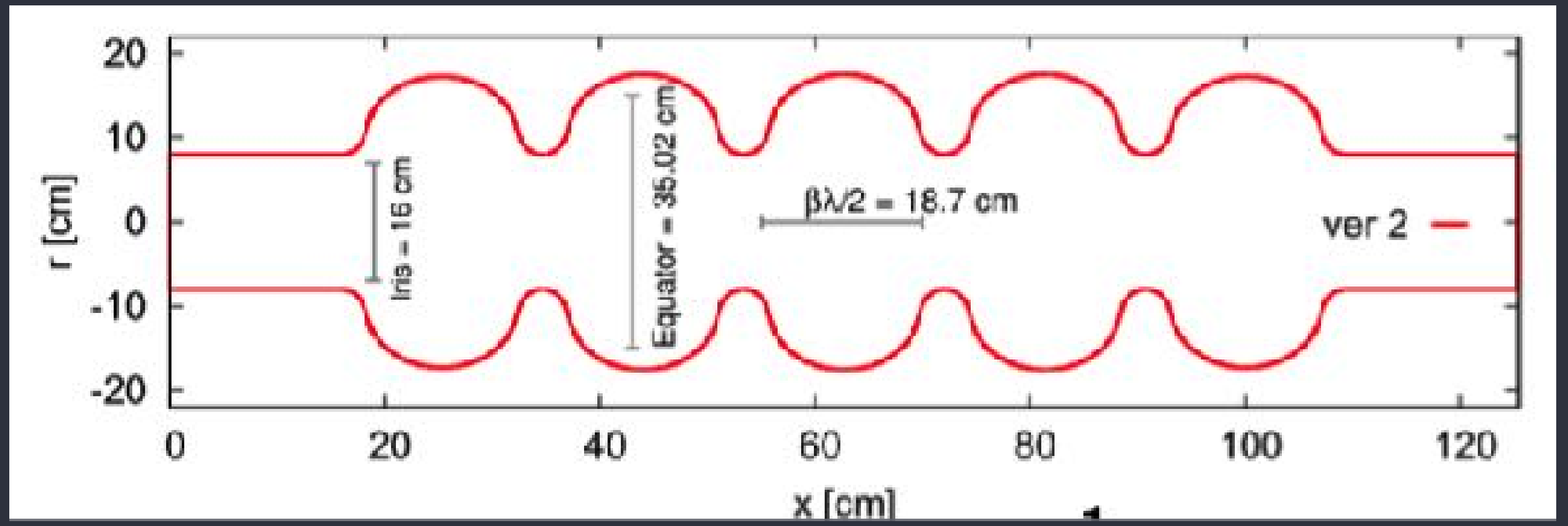


Beautiful idea: i) a beam is accelerated, ii) used for experiments (e.g. synchrotron radiation, collisions, etc), iii) decelerated in the same cavity, and iv) the same energy is used to accelerate a “fresh” batch of bunches.

Superconducting cavities are the natural choice for this “zero-beam loading“ principle.

PERLE/LHeC example

Powerful **ERL** for **E**xperiments[1] is a proposed ERL at Orsay, that could validate ERL operation and hardware for LHeC.



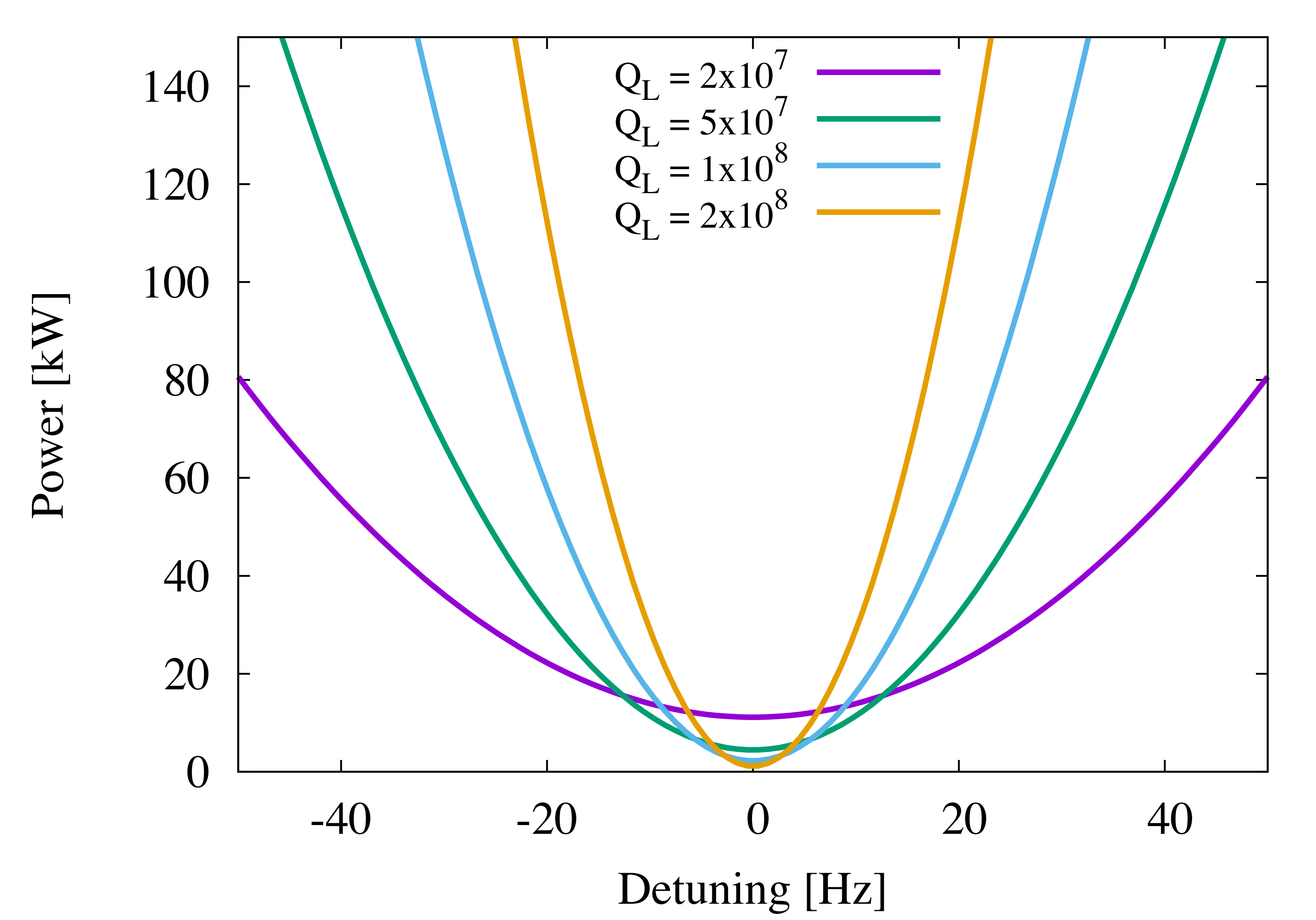
CERN v2 cavity, R. Calaga, CERN-ACC-Note-2015-0015

Beam loading: ≈ 0

Power needed to cover the surface losses: $P_d = \dfrac{V_{acc}^2}{(R/Q)Q_0} = 44\ \text{W}$

However, zero beam loading ➜ high loaded Q ➜ RF power to combat detuning increases.

- Assumption for PERLE: 20 Hz max detuning ➜ P_{RF} = 23 kW
- ~500x of what is needed to cover surface losses.
- **For LHeC with 1069 cavities this is significant!**



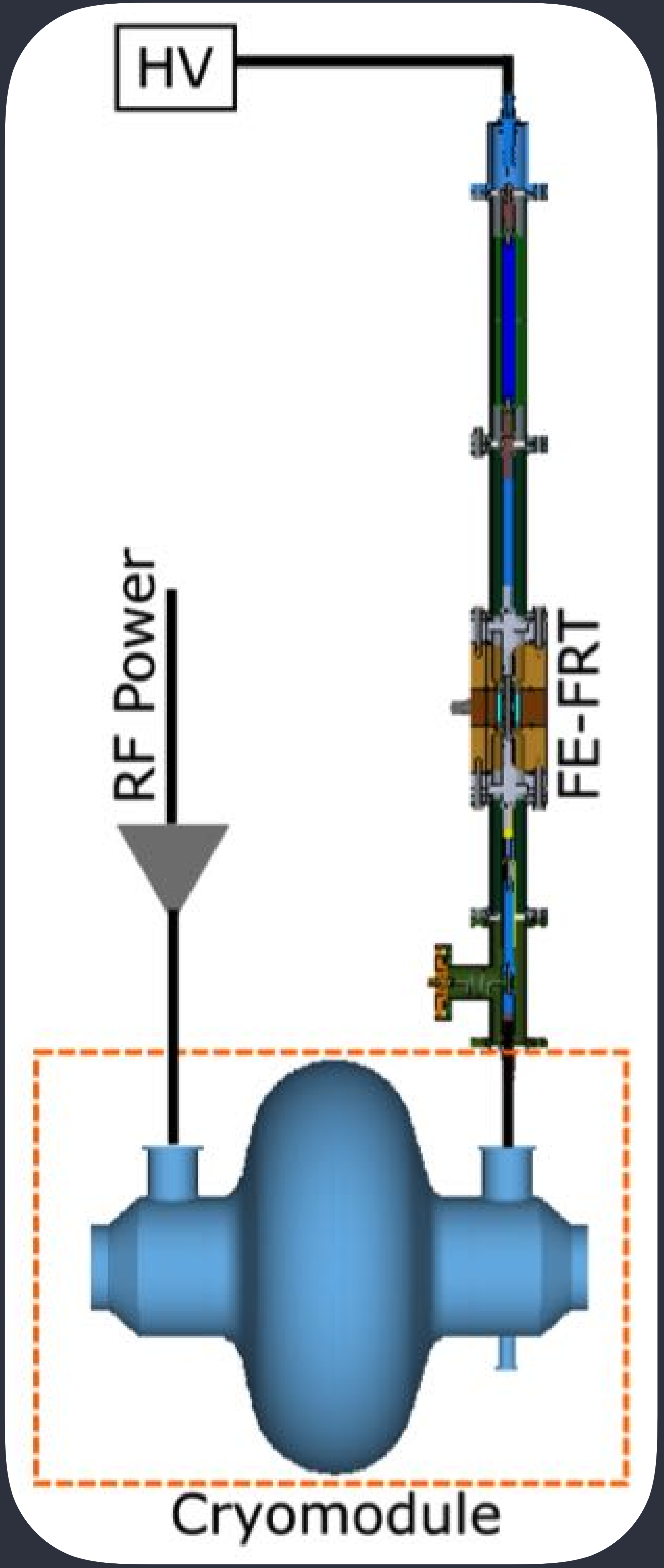
Frequency	**802 MHz**
Q_0	**2×10^{10}**
R/Q	**393 Ω**
V_{acc}	**18.7 MV**

[1] D. Angal-Kalinin et al., J. Physics G, **45,** 6

Possible solution: FE-FRT

Ferro**E**lectric **F**ast **R**eactive **T**uner

- Cavity is coupled to a tunable reactance (FRT),
- Permeability of the ferrite is tuned with a biasing high-voltage ➜ change of "electrical length" of the FRT transmission line ➜ change of cavity frequency.
- No mechanical tuning of the cavity required.
- Made possible by recent development of low-loss ferroelectric material[1] by Euclid Techlabs LLC.
- The principle was developed in the US (V.P. Yakovlev, I. Ben-Zvi, et al.) and prototyped by BNL and Euclid Techlabs LLC.
- CERN bought this prototype and made a **first** proof-of-principle FE-FRT test on a superconducting cavity[2].



[1] E. Nenasheva et al., "Ceramics Materials Based on (Ba, Sr)TiO_3 Solid Solutions for Tunable Microwave Devices", J. of Electroceramics, **13**, pp 235 - 238, Jul. 2004

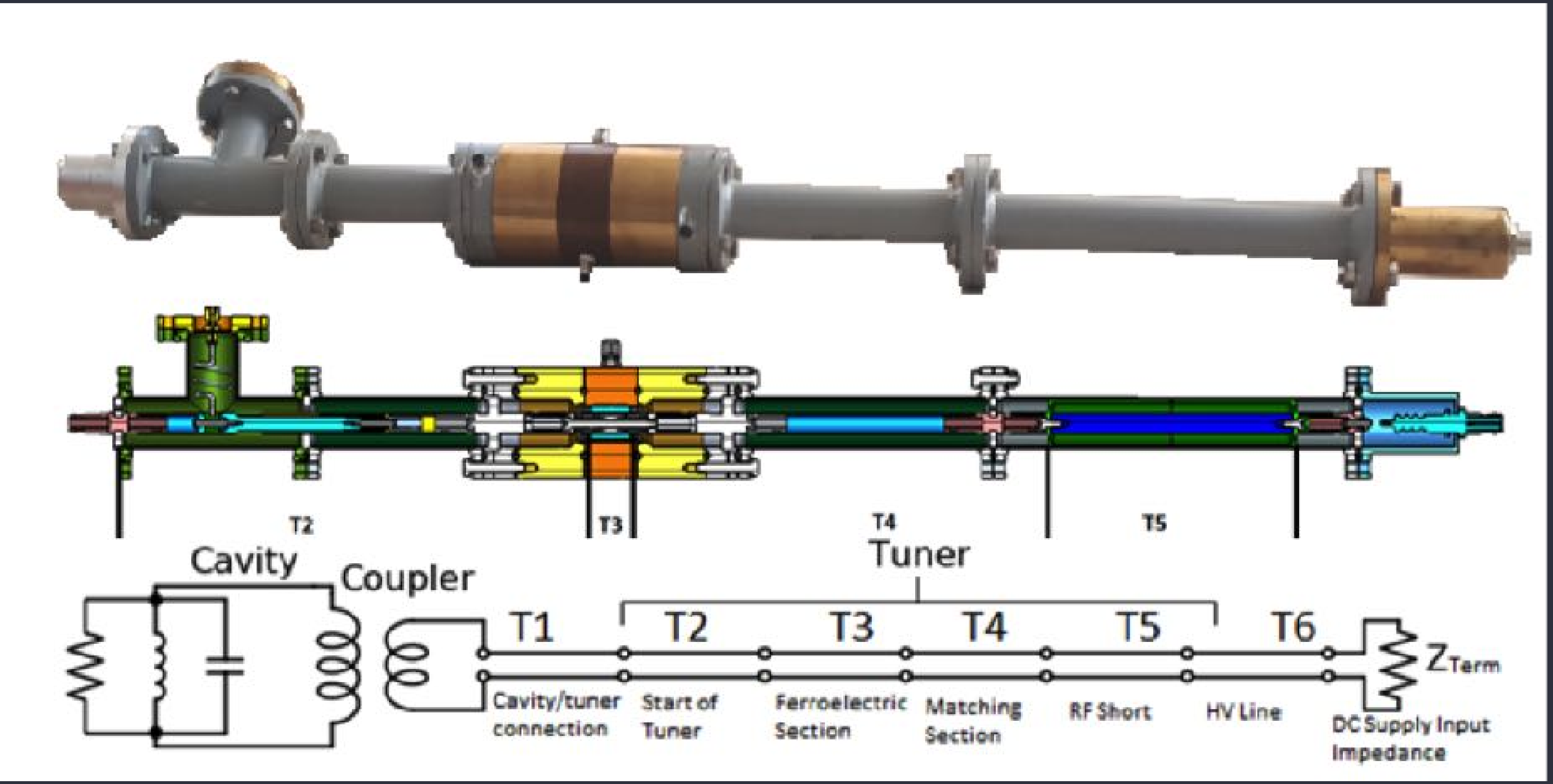
[2] N. Shipman et al., "A Ferroelectric Fast Reactive Tuner for Superconducting Cavities", SRF 2019, Dresden.

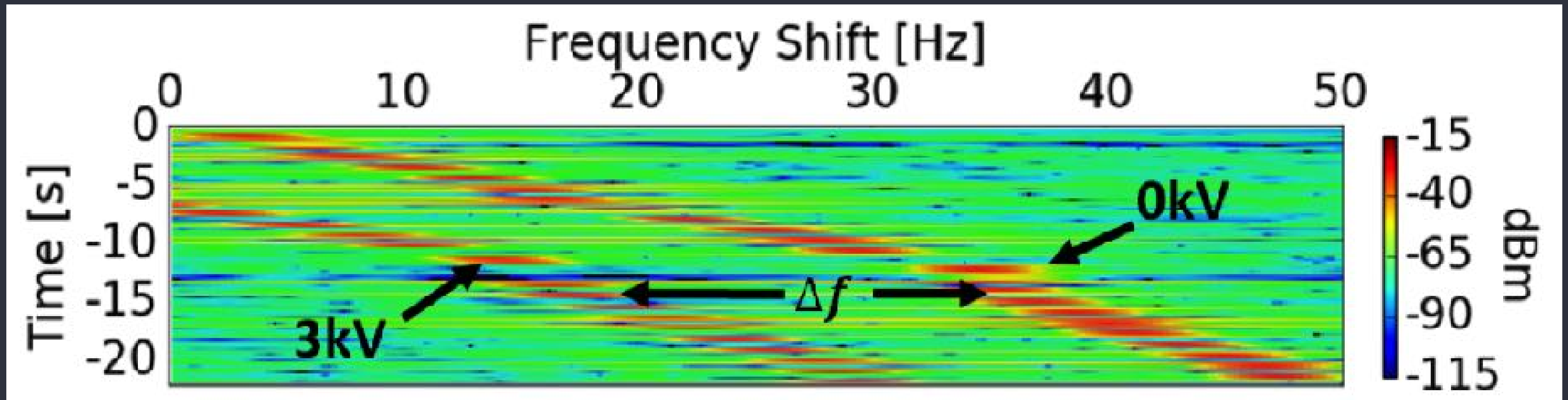
FE-FRT test at CERN

FerroElectric Fast Reactive Tuner

- The FRT was sitting outside of cryostat connected by a coax line to the cavity.
- Frequency shift as a function of biasing voltage was verified.
- Measured cavity response to tuner < 50 μs (probably faster, limited by time resolution of measurement system)
- Cavity time constant ~ 46 ms.

➡ frequency shift much faster than cavity time constant!

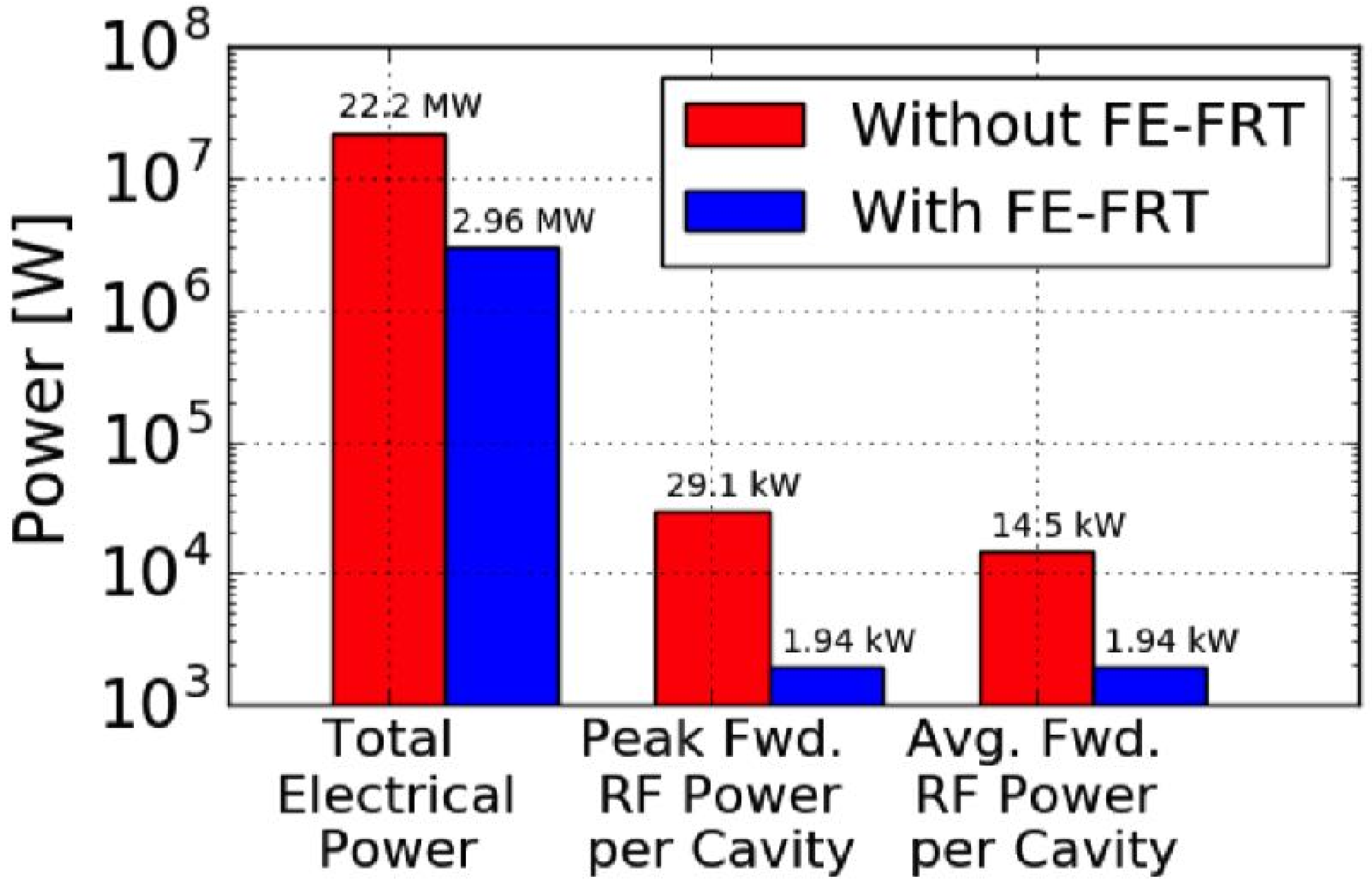




Case study for LHeC

N. Shipman et al., "A Ferroelectric Fast Reactive Tuner (FE-FRT) to Combat Microphonics", ERL 2019, Berlin.

$$P_{RF} = \frac{V_c^2}{4 R/_Q Q_L} \frac{\beta + 1}{\beta} \left[1 + \left(2 Q_L \frac{\Delta\omega_\mu}{\omega_0} \right)^2 \right]$$



- Peak power per cavity $29.1\,\mathrm{kW} \rightarrow 1.94\,\mathrm{kW}$
- Total Electrical Power $\mathbf{22.2\,MW \rightarrow 2.96\,MW}$

Nominal parameters

Project	LHeC
Frequency	801.58 MHz
Cavity Voltage	18.7 MV
External Q of FPC	1.56×10^7
Cavity Q_0	2×10^{10}
R/Q	393 Ω
Peak Detuning	26.2 Hz
RMS Detuning	4.36 Hz
Cavity gradient	20 MV/m
Beam Energy	60 GeV
ERL passes	3
Number of cavities	1069
DC to RF conversion eff.	70%
El. Power for microphonics control	22.2 MW
El. Power for cavity losses at 2K	47 MW

FRT Summary

- ERLs reduce the power consumption for beam loading basically to 0 (demonstrated in various facilities).
- FRTs have the potential to significantly reduce the RF power needs for low-beam loading machines (such as ERLs).
- They can simplify dynamic frequency tuning: no mechanical cavity deformations needed (e.g. via piezos), safe and easy to maintain operation outside of the cryomodule, very fast tuning is ideal to combat microphonics.

Further R&D at CERN:

- Experimental validation of microphonics compensation early 2020.
- Potential for 2nd prototype with improved performance.

Summing up

Summary

- Ambient magnetic fields, flux expulsion and flux trapping became important issues for pushing SRF cavity performance.
- Better understanding of flux trapping and the nature of pinning centres is needed ➜ the flux lens may become a tool for fast and efficient material sample tests.
- Q vs E is not the only parameter influencing efficiency: Microphonics can make a big difference, especially in the case of high-Q, low beam loading (example: ERL). A fast ferroelectric tuner may drastically reduce the effect of microphonics.
- New materials with higher Tc, new coating techniques, and multilayers have the potential to push performance further.
- For large future machines relying on SRF (e.g. FCC), dedicated R&D and substantial testing is required to increase efficiency and push performance.

TESLA Technology Collaboration Meeting

4 - 7th February 2020

TTC Meeting Scientific Program Committee:

Hans Weise (DESY), TTC Chair
Frank Gerigk (CERN), LOC Chair
Sergey Belomestnykh (FNAL), Eiji Kako (KEK),
Robert Laxdal (TRIUMF), Wolf-Dietrich Moeller (DESY),
Paolo Pierini (ESS), Akira Yamamoto (KEK/CERN)

Hosted by CERN

Geneva, Switzerland
https://indico.cern.ch/e/TTC2020

CERN

Working Groups:

(1) High-Q and High-Gradient
(2) Couplers and Auxiliaries
(3) Coating Techniques, Thin Films and New Materials
(4) New Techniques for Fabrication of SRF Components & CM Assembly and Design

THANKS

FOR

Listening