Synergy of PERLE with CERN SRF Developments

Erk Jensen/CERN

PERLE @ Daresbury Meeting, 15/16 January 2018

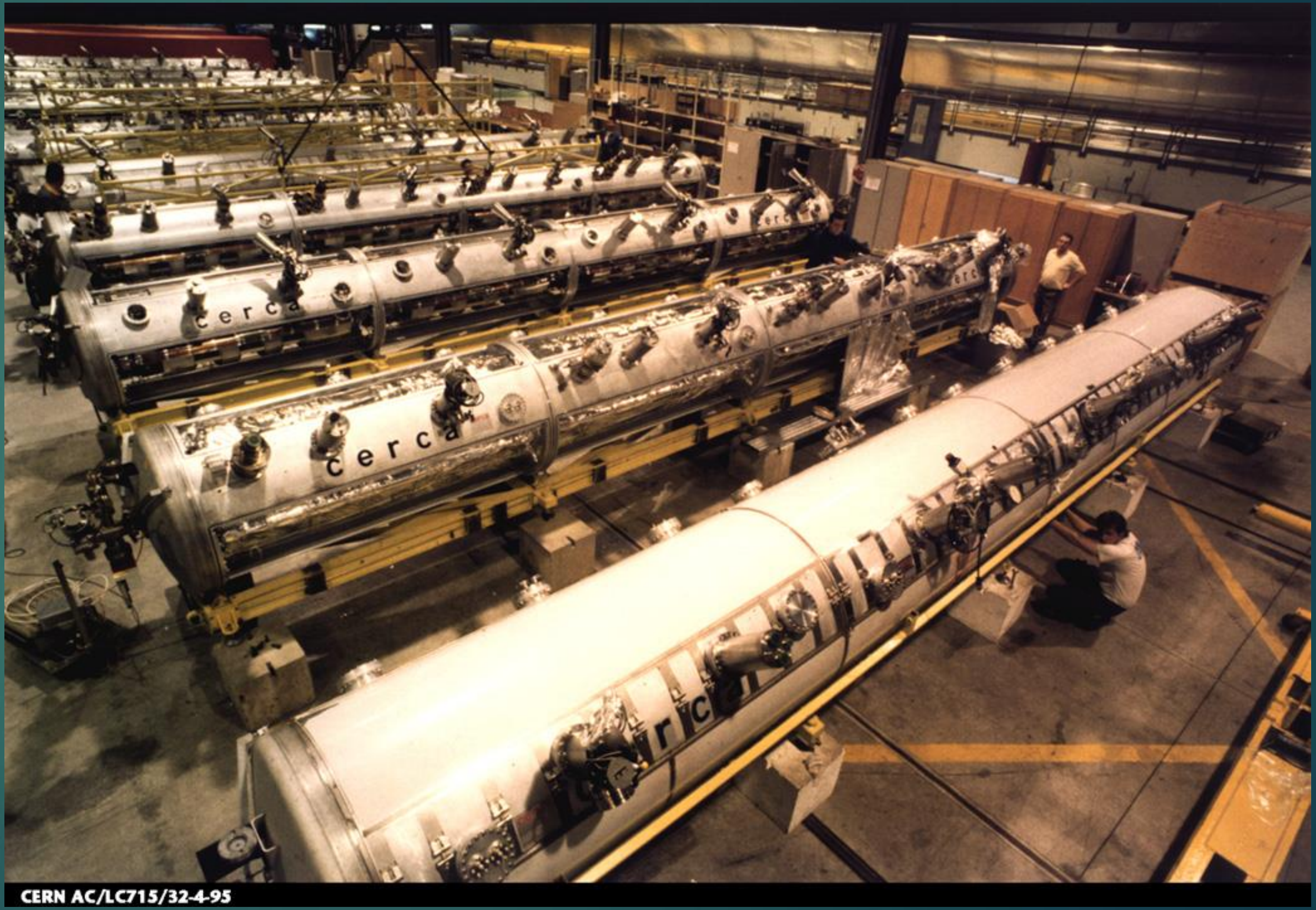
The *raison d'être*

- The original idea PERLE stems from the LHeC study
- PERLE is first and foremost a demonstrator for the LHeC ERL.
- An electron-hadron collider (LHeC or FCC-he) remains a valid complement to a possible future LHC successor.

- But also: a facility like PERLE has many interesting applications
- We have to continue LHC (and HL-LHC) physics for decades to come
- No matter which future HEP machine you prefer – we have to prepare the technologies: High field magnets and superconducting RF

Flashback – LEP times

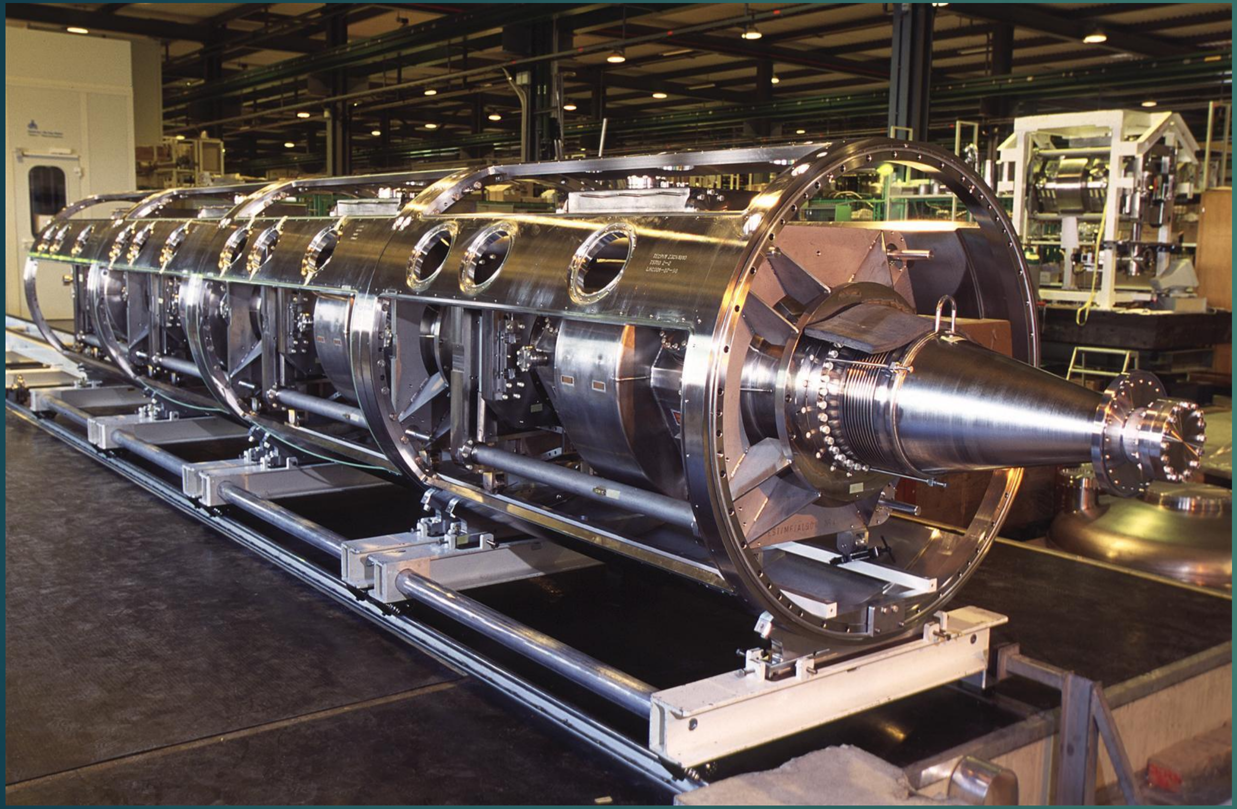
1980 - Tuning of LEP cavities



1999 – Series of LEP cavities in SM18
A total of 288 SRF Cavities were installed in LEP

Thanks to F. Gerigk

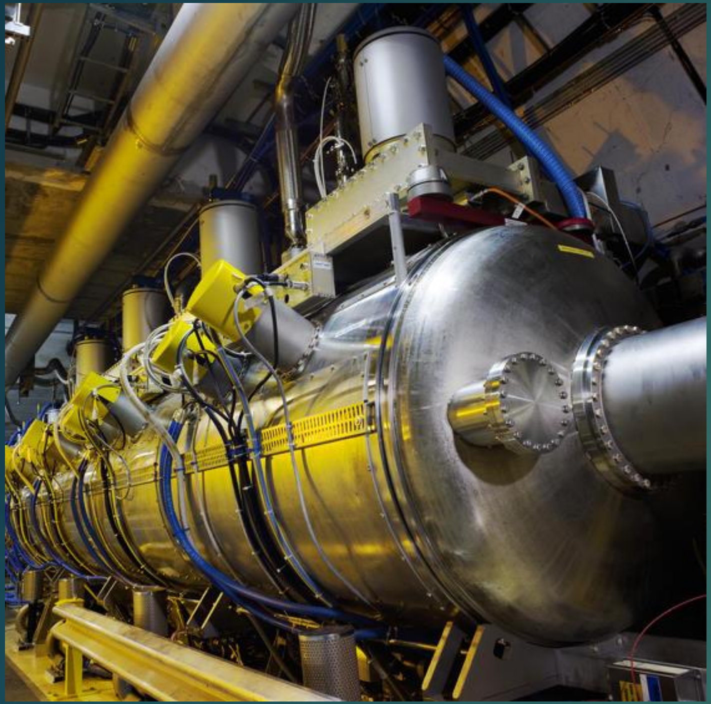
Recent past – LHC cavities/CMs

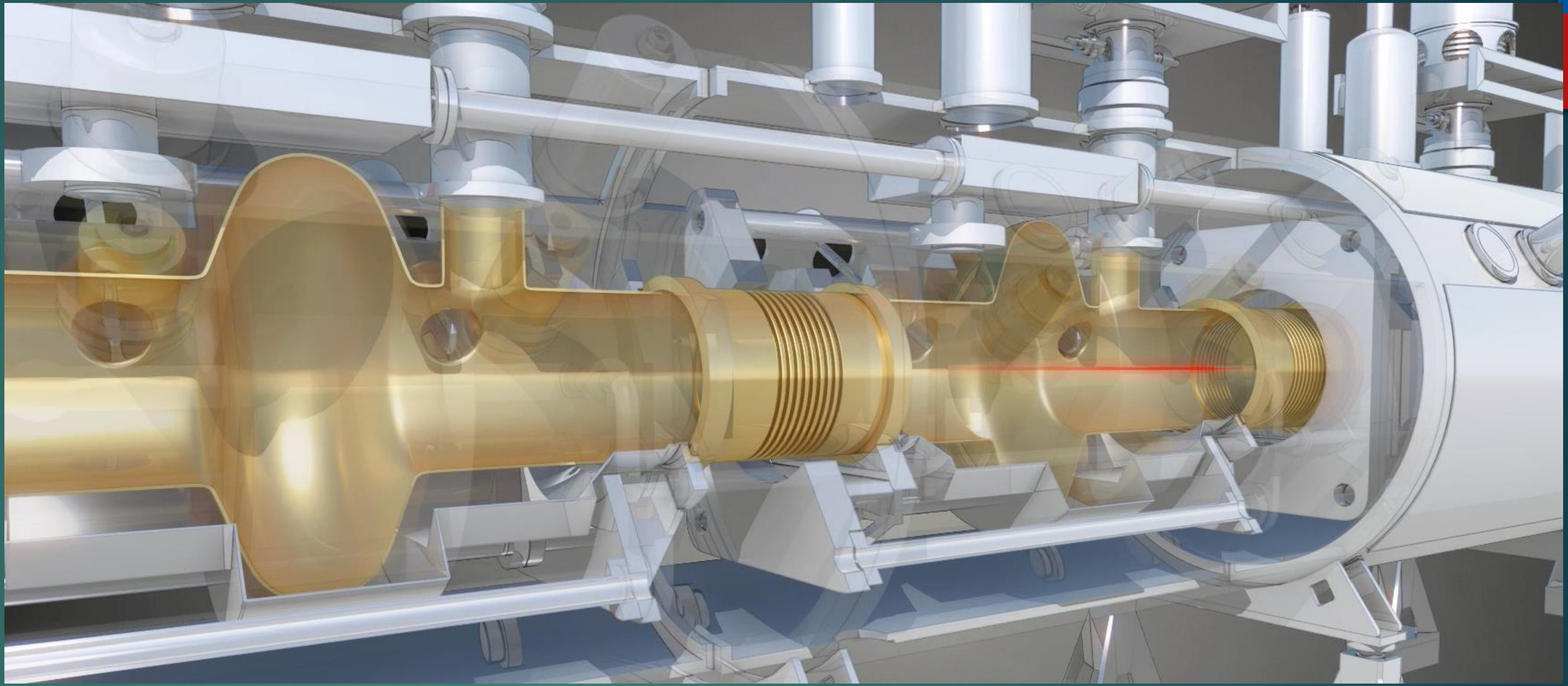


LHC CM (4 single-cell cavities 400 MHz), MLI and outer shell removed

2000: Accomplishment of the 1st LHC CM

Thanks to F. Gerigk

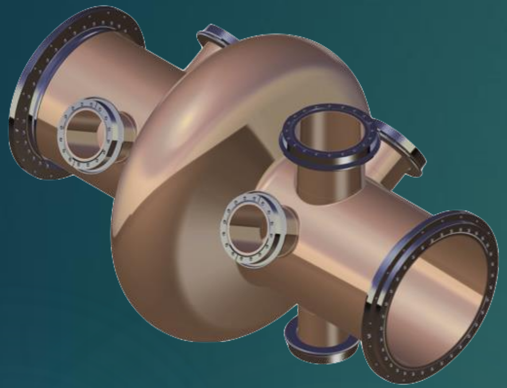




LHC Cavities

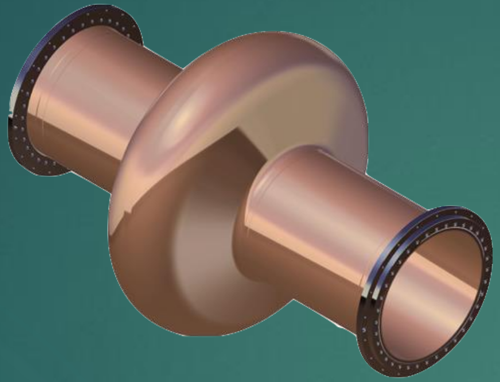
Thanks to F. Gerigk

The LHC (Spare) Cavity program



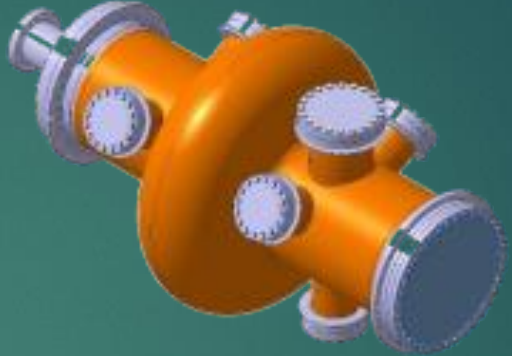
Practice cavity 1, 2

- Full cut-off tubes
- Validation of processes & coating (MS)



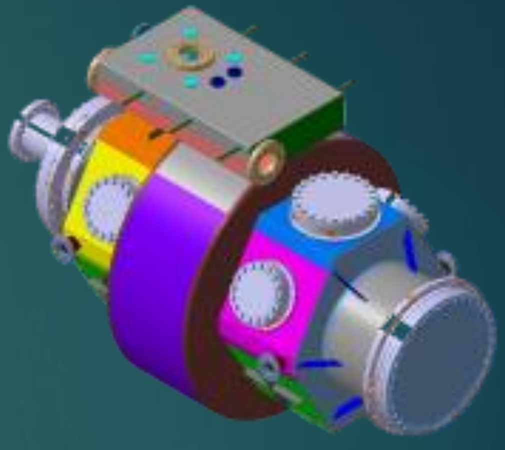
Practice cavity 3, 5

- Simplified cut-offs
- Validation of fabrication method (spinning, EHF)



Model cavity

- Complete validation
- He tank design updated
- If success: valid spare!

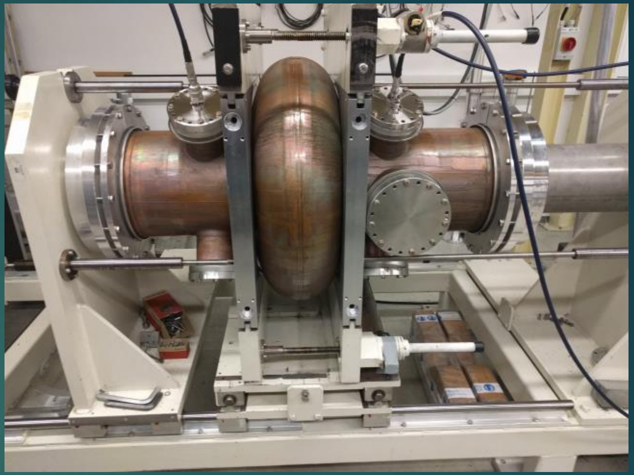


Series

- 8+2 cavities
- Cut-offs fabricated at BINP,
- Production by industry

Thanks to M. Karppinen

The LHC (Spare) Cavity program

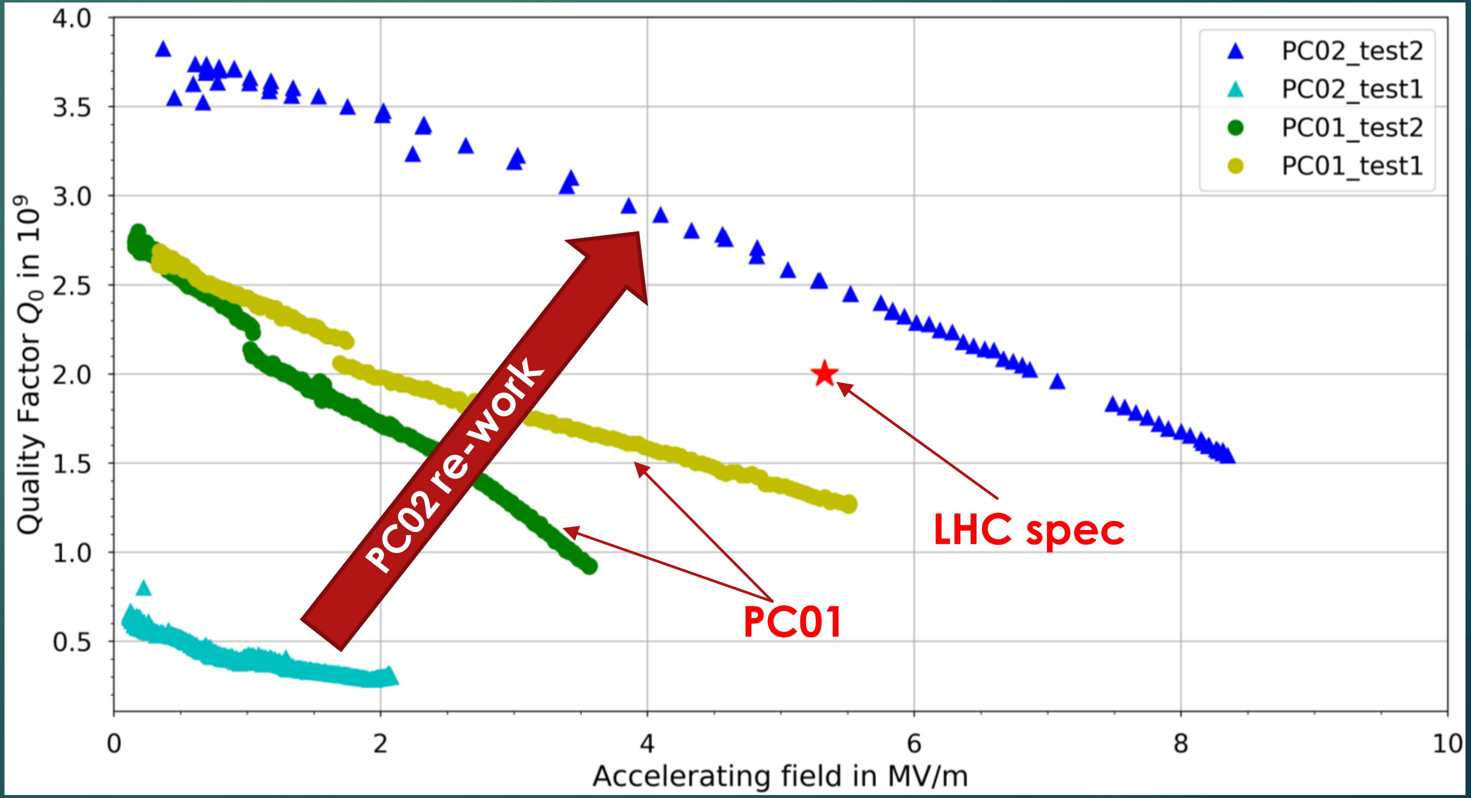


Practice cavity PC05

- Spun and machined half-cells.
- Simplified cut-offs
- Ready for cold test

Practice cavity PC01-PC02

- Spun half-cells
- PC02 successfully stripped, re-worked and re-coated



Thanks to M. Karppinen

Preparing the HL-LHC era

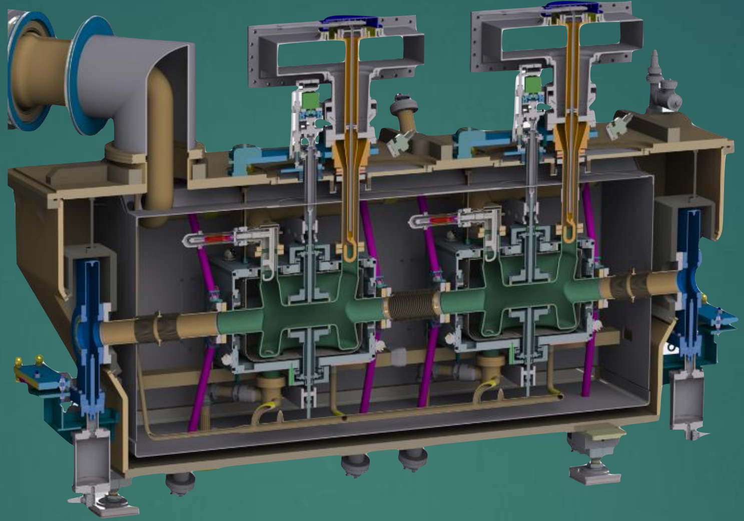
Crab cavities

Harmonic cavities? (200 MHz, 802 MHz(sic!)) – still optional, presently in revision.

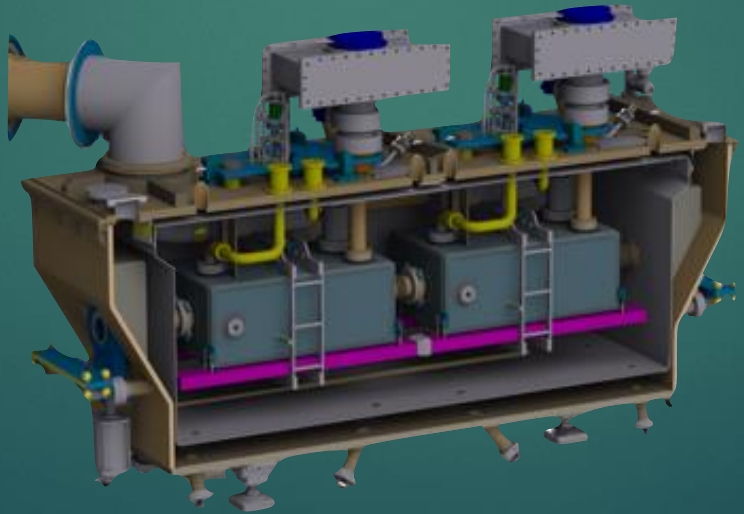
Can the existing system reliably operate with the double beam current?

Two types of crab cavities

Double Quarter Wave
- Vertical crossing for Atlas
- SPS test in 2018



RF Dipole
- Horizontal crossing for CMS
- SPS test in 2021



Voltage	3.4 MV/cavity
E_{peak}	40 MV/m
B_{peak}	70 mT
Frequency	400.79 MHz
Q_0	10^{10}
Q_{ext}	5×10^5
Cavity tuning	±100 kHz
Temperature	2.0 K
RF power (SPS)	40 kW

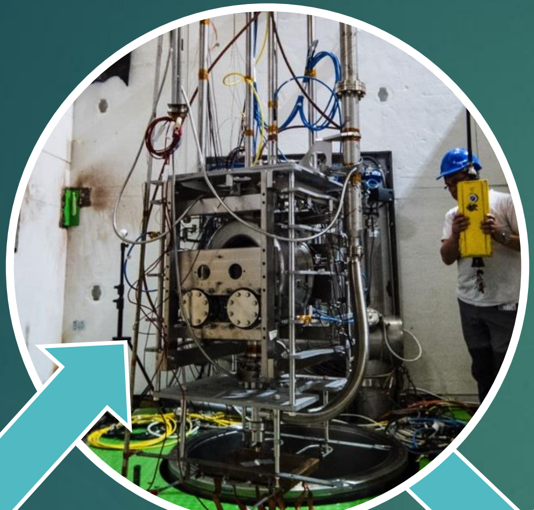
→ 2 cavities/beam/IP side
→ for ATLAS and CMS
→ 16 cavities/8 CMs in total

Thanks to R. Calaga, O. Capatina et al.

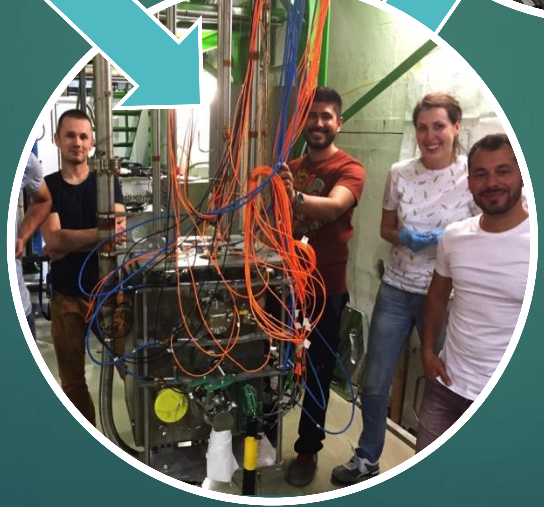
HL-LHC: Crab Cavities for SPS

R. Calaga, A. Macpherson et multi al.

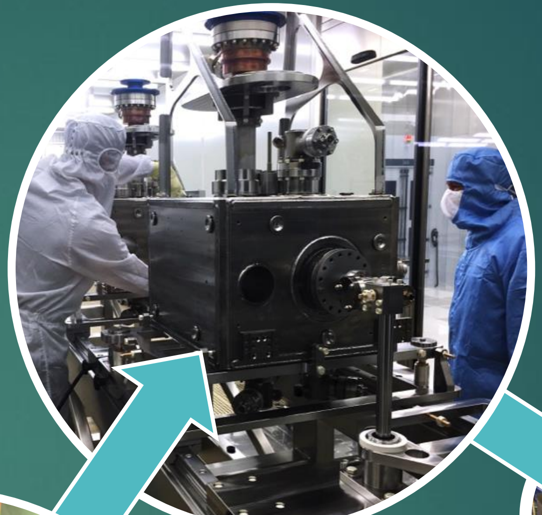
Preparation



Bare Cavity Validation



Dressed Cavity Testing

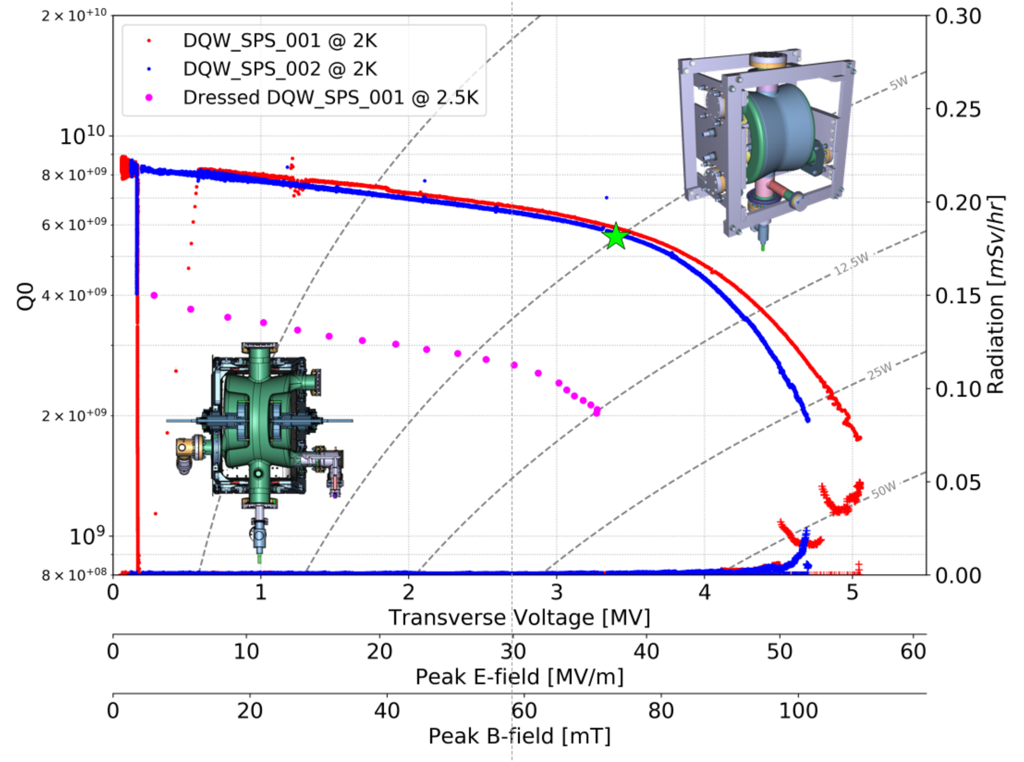


String Assembly

Cryomodule Cold Test

HL-LHC: Crab Cavities for SPS test

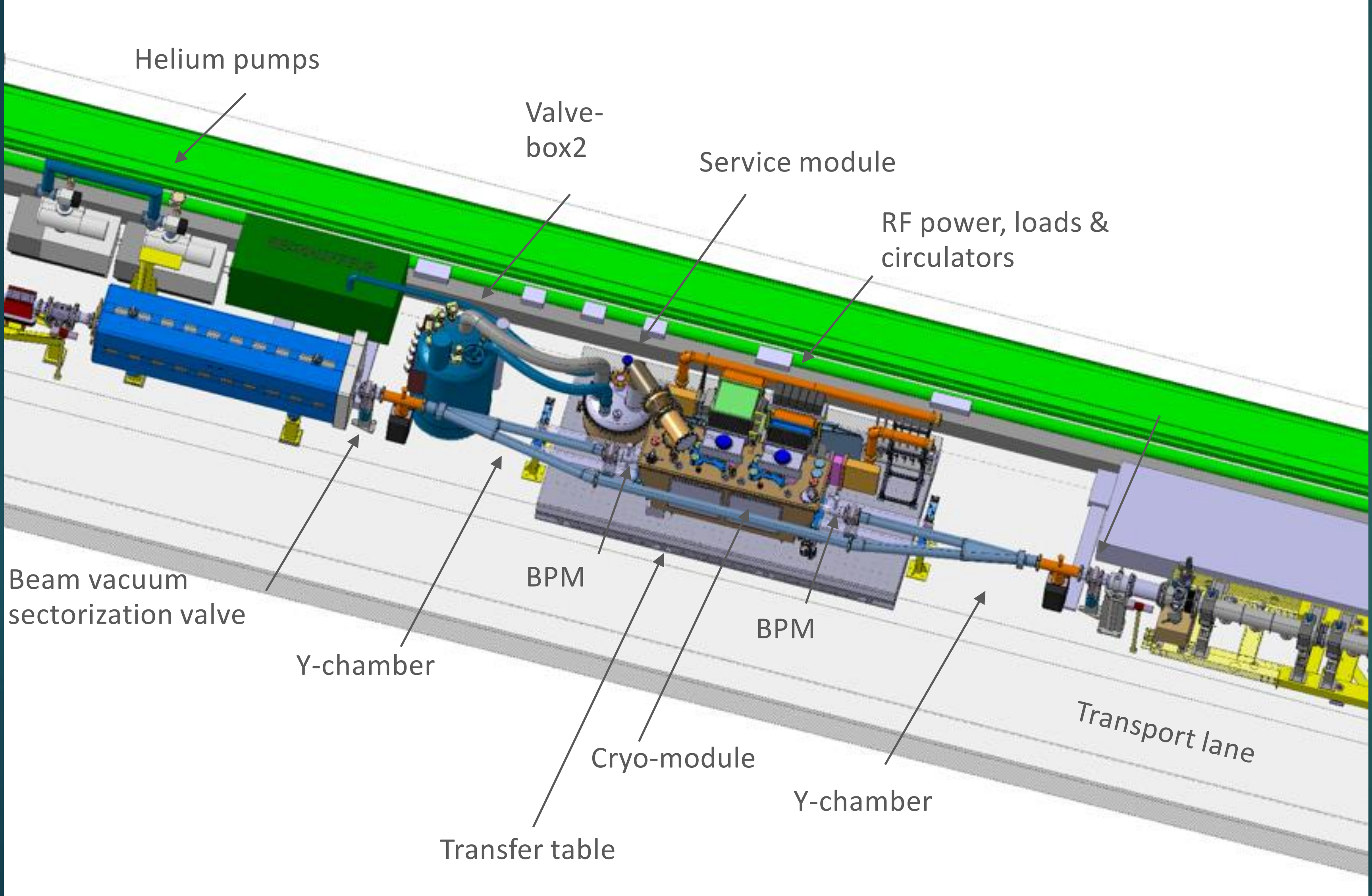
R. Calaga, A. Macpherson et multi al.



Achievements 2017

- 2 bare cavities: Processed & RF validated at 2 K
- 2 dressed cavities: Preparation & cleanroom assembly
- Cold test of dressed cavity at 2K
- Cleanroom string assembly of 2 dressed cavities
- Crab LLRF functionality: Validation at 2K with BE-RF-FB
- Complete refurbishment of SM18_M7 test bunker
- Cold test of SPS cryomodule in M7 (with limited RF)

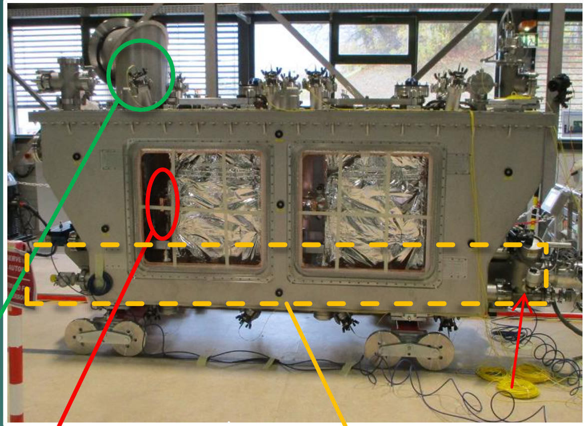
Crab Cavity tests with proton beam in SPS

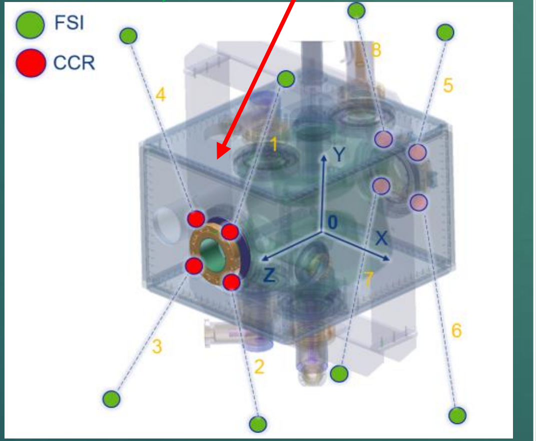


Crab cavity position monitoring systems for SPS test

Frequency Scanning Interferometry (FSI) – main system

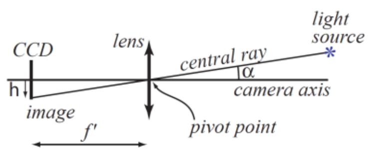
- Cavity position/orientation known thanks to absolute distance measurements between cryostat **FSI heads** and cavity **Corner Cube Reflectors (CCR)**
- System for HL-LHC use (cold, vacuum and radiation compatible)

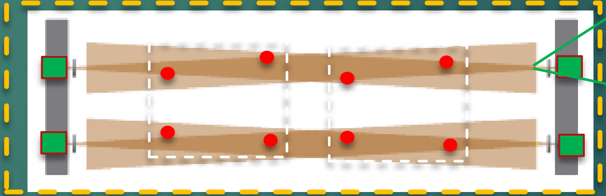




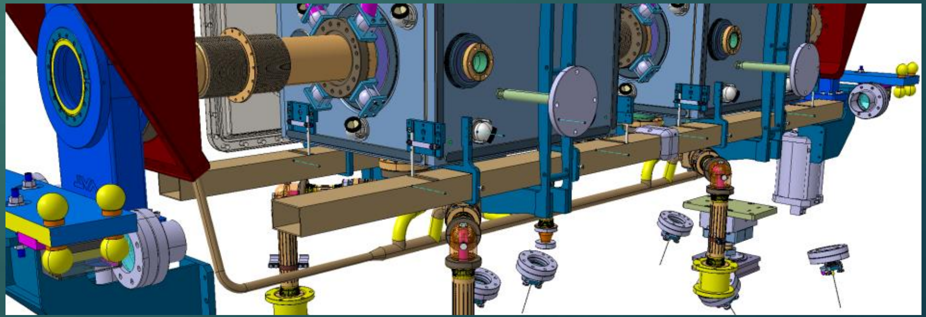
Brandeis Camera Angle Monitoring (BCAM)

- Cavity position/orientation known thanks to **reflective targets** angular position measured by **BCAM cameras** (triangulation method)
- System used for FSI measurements crosscheck - only for SPS prototype alignment validation



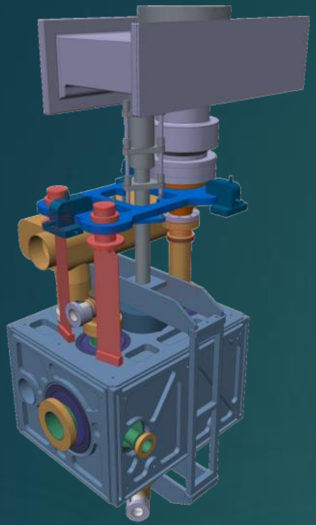


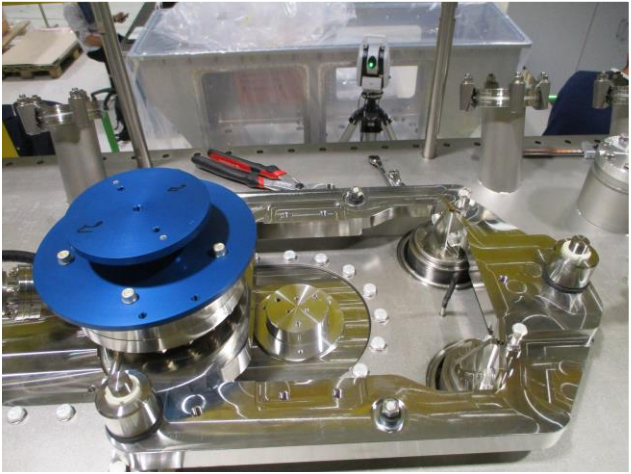
BCAM



Thanks to EN/ACE-SU (T. Dijoud, M. Duquenne, H. Mainaud-Durand, V. Rude, M. Sosin)

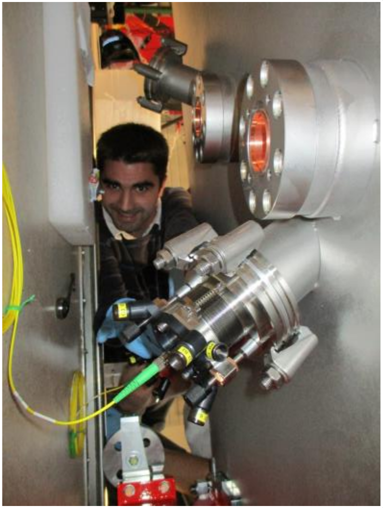
Adjustment and position monitoring systems





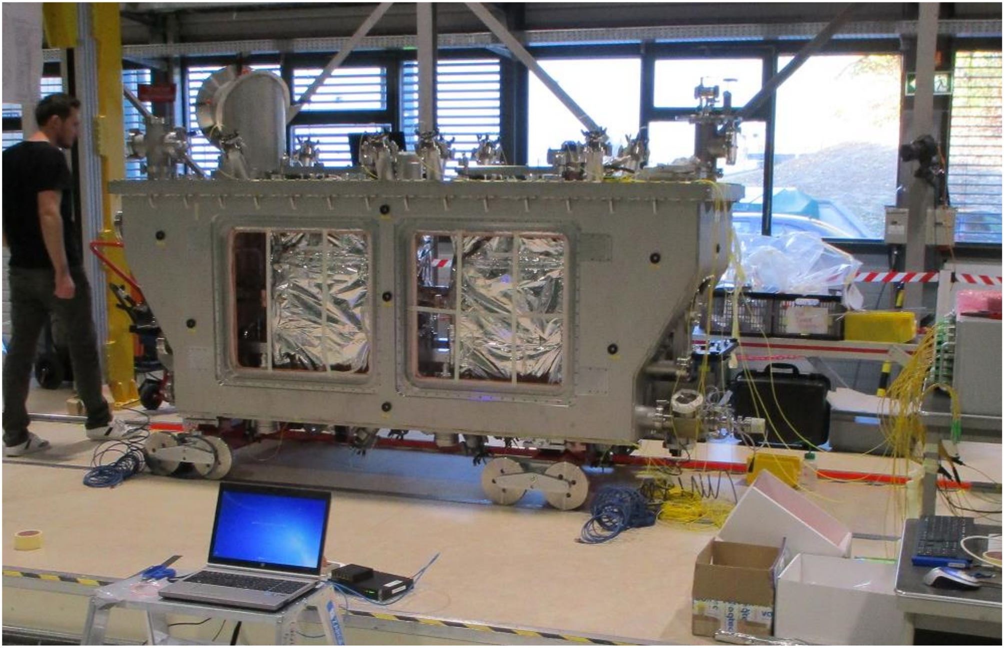
Cavity position adjustment system

- Adjustment/suspension system kinematics intuitive for operator
- Adjustment screws resolution < 20µm
- Intra-cavity position pre-adjustment capability better than 100µm



FSI, BCAM monitoring systems validation

- **FSI, BCAM systems' precision better than 50 µm (1σ), crosschecked with AT401 laser tracker measurements!**
- For now, the tests at room temperature, with open cryostat windows
- Waiting for M7 bunker test:
  - Final validation of the systems under vacuum and cold



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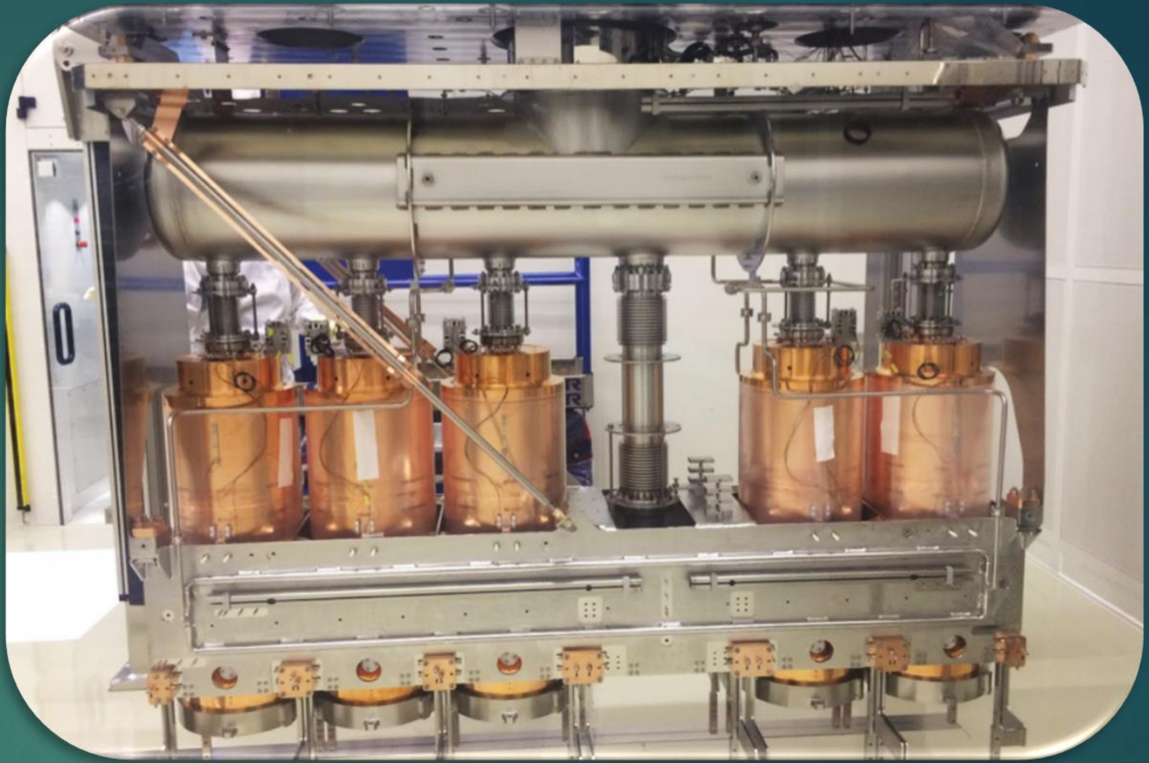
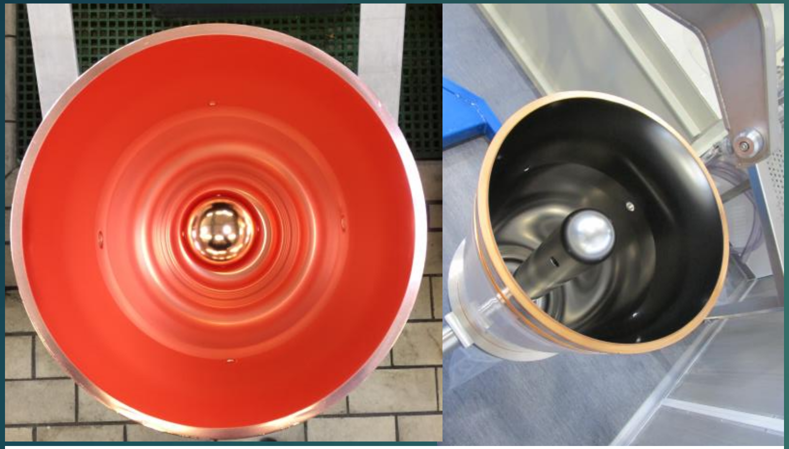


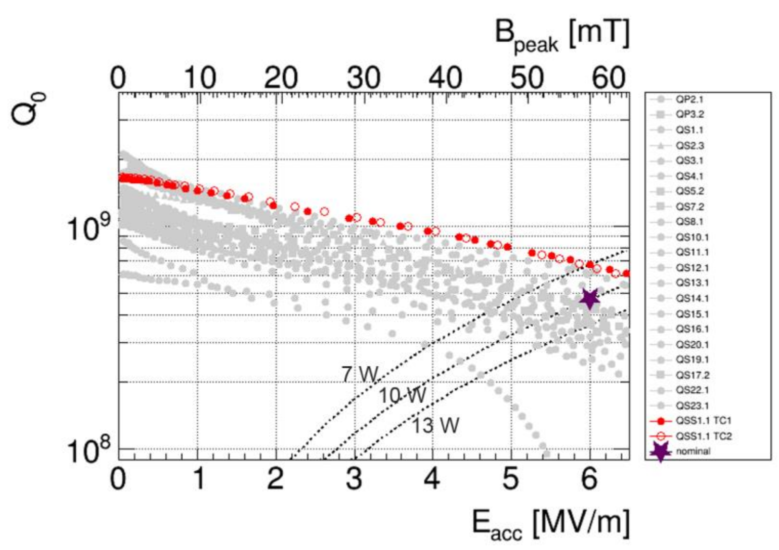
HIE-ISOLDE and its cavity program

HIE ISOLDE cavities, cryomodules and linac commissioning for 2017 physics run

W. Venturini, K. Schirm et al.

Breakthrough! Seamless Cavities

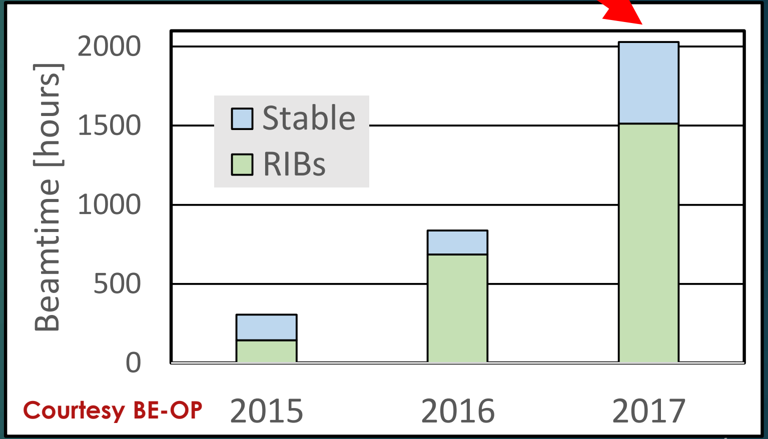




CM4 assembled and ready for installation in HIE ISOLDE

20 QWR produced, qualified and installed in the 4 HIE ISOLDE CMs

HIE ISOLDE 2017 physics run with 3 CM



Courtesy BE-OP

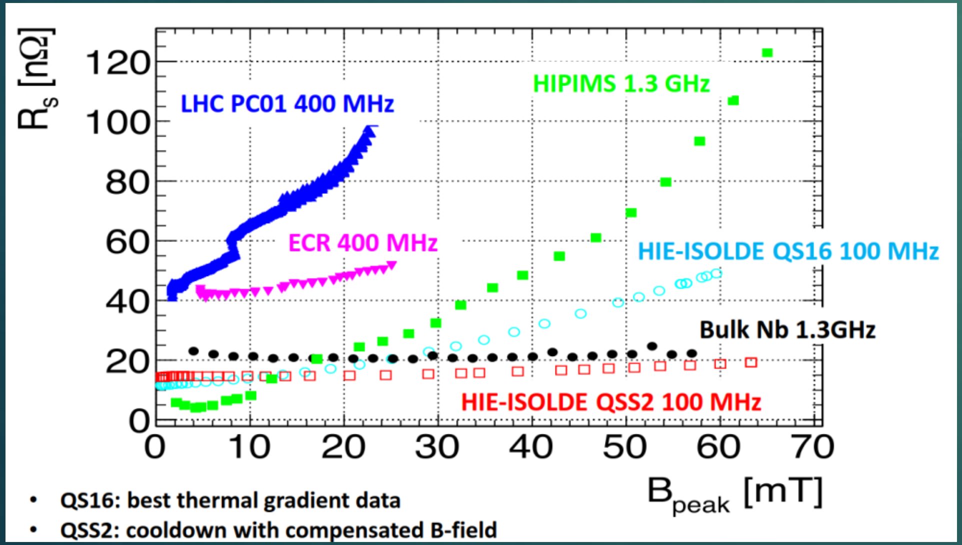
12 RIB experiments done

8 MeV/u achieved

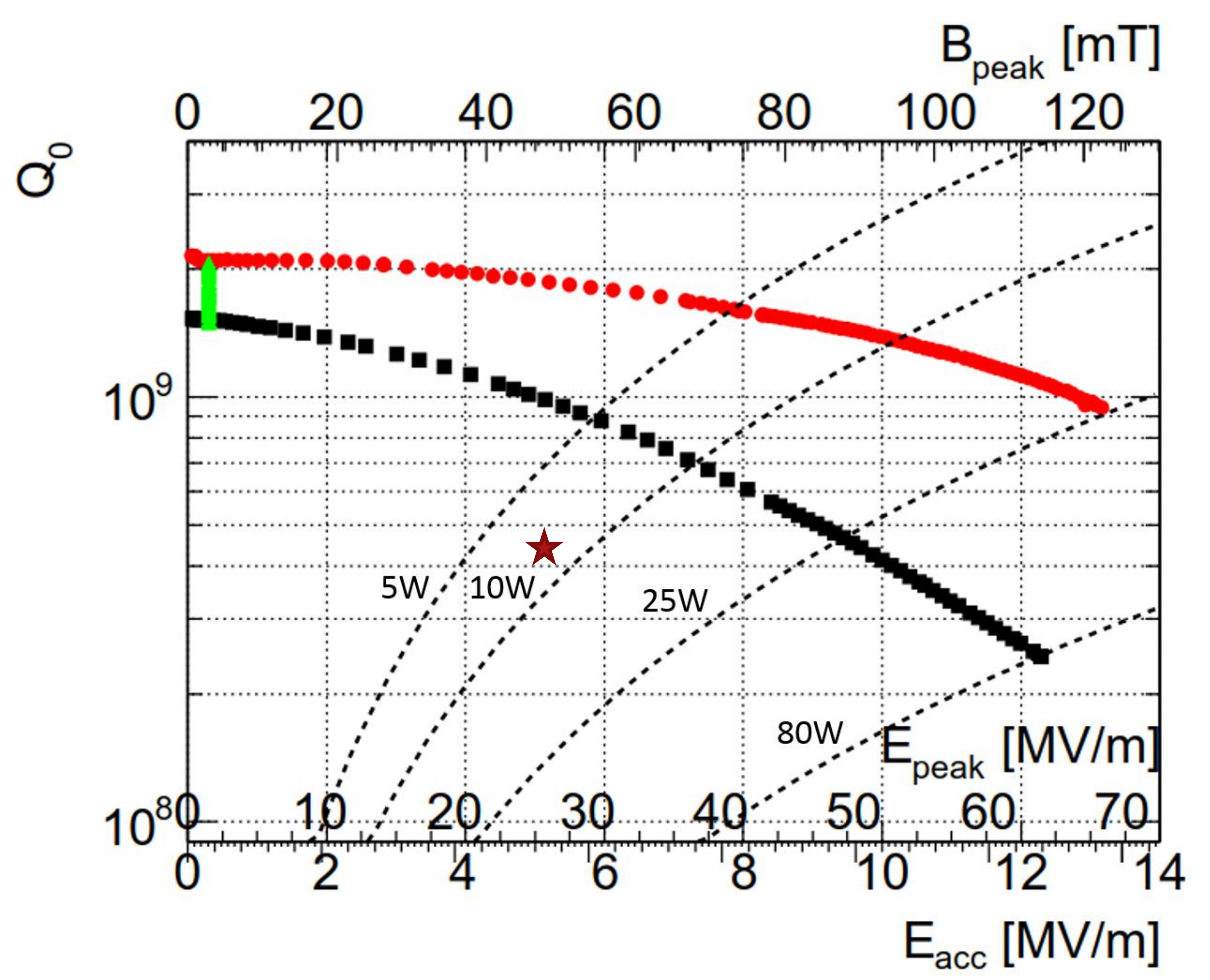
Excellent SRF availability

Recent progress with seamless cavities

QSS2 (seamless QWR)
Measured at 2.3 K (red) and 4.5 K (black)
Acc. Gradient 13 MV/m
Corresponding to surface field of 65 MV/m
Absolute record for CERN!
Absolute record for Nb on Cu!
★ Nominal (at 4.5 K)



- **QS16: best thermal gradient data**
- **QSS2: cooldown with compensated B-field**



W. Venturini, K. Schirm et al.

Preparing the future: FCC and more

FCC-hh

FCC-ee O. Brunner et al.

FCC-he

High gradient bulk Nb studies (→ next talk by L. Dassa!)

New materials & new fabrication methods K. Ilynia, R. Gerard et al.

FCC-ee


RF system re-alignment and modifications

O. Brunner et al.

Working point	$\sqrt{s}$	$\mathcal{L}$ /IP $[\mathrm{cm^{-2}s^{-1}}]$	$\int \mathcal{L}$ /year $[\mathrm{ab^{-1}}]$	Cavity configuration (#, type, f)	Total RF voltage $[\mathrm{GV}]$	Run time $[\mathrm{a}]$
Z	$91.2\ \mathrm{GeV}$	$1 \cdot 10^{36}$	26	112, 1-cell 400 MHz	0.1	2
Z	$91.2\ \mathrm{GeV}$	$2\ \cdot 10^{36}$	52	=	0.1	2
W	$160\ \mathrm{GeV}$	$3.2 \cdot 10^{35}$	7.8	112, 4-cell 400 MHz	0.75	1
ZH	$240\ \mathrm{GeV}$	$7 \cdot 10^{34}$	1.8	272, 4-cell 400 MHz	2	3
Shutdown – RF system reconfiguration						1
$t\bar{t}$	$350\ \mathrm{GeV}$	$0.8 \cdot 10^{34}$	0.2	+ 320, 5-cell 800 MHz*)	8.8	1
$t\bar{t}$	$365\ \mathrm{GeV}$	$1.5 \cdot 10^{34}$	0.34	+ 64, 5-cell 800 MHz	0.3	4

*) Shown here: the hybrid configuration 400/800 MHz. Also a pure 400 MHz configuration is being studied.

Nb_3Sn sputtered films for SRF

Advantages

- **High critical temperature**

T_c	Nb_3Sn ~ 18.3 K
	Nb ~ 9.3 K

- **Low BCS resistance**

R_{BCS} @ 4.2K and 500MHz	Nb_3Sn ~ 0.4 nΩ
	Nb ~ 45 nΩ

Challenges

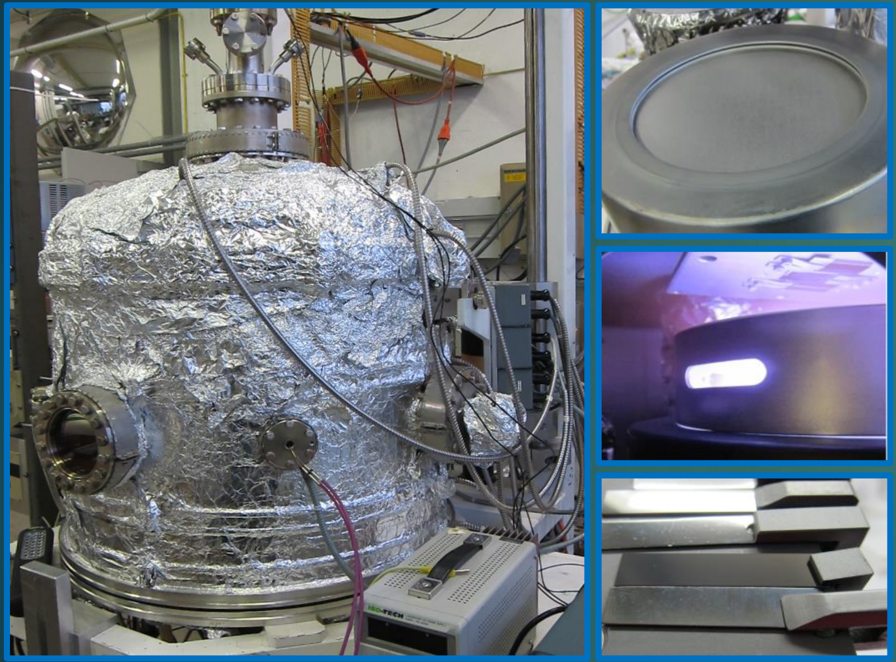
- Stoichiometry control (Sn At% 19-26 %) [1]
- Requires high temperature treatment
- Limited range of annealing temperatures
- Substrate importance

[1] J. Charlesworth, I. MacPhail, and P. Madsen, J. Mater. Sci. 5, 580 (1970).

K. Ilyina et al.

Coating by magnetron sputtering

Reacted **After** Coating



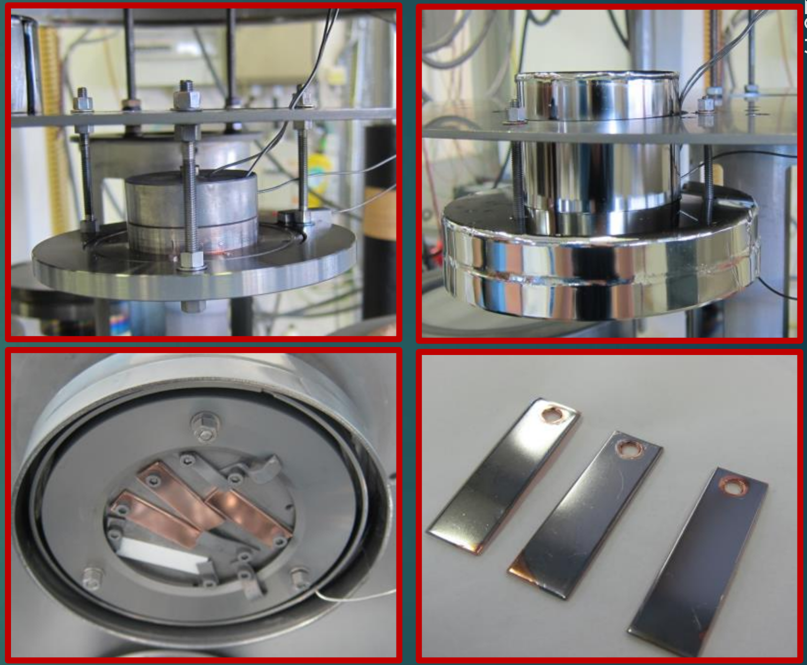
Coating parameters:

Coating gas: Ar or Kr

Coating pressures:
$7 \cdot 10^{-4}$ *mbar … $5 \cdot 10^{-2}$ mbar*

Composition:
Sn 20 At% to 27 At%,

Reacted **During** Coating



Annealing temperatures	**600 - 800°C**
Annealing time	24 h… 72 h

Coating temperatures	**600 - 735°C**
Alternative Additional Annealing	24 h… 72 h

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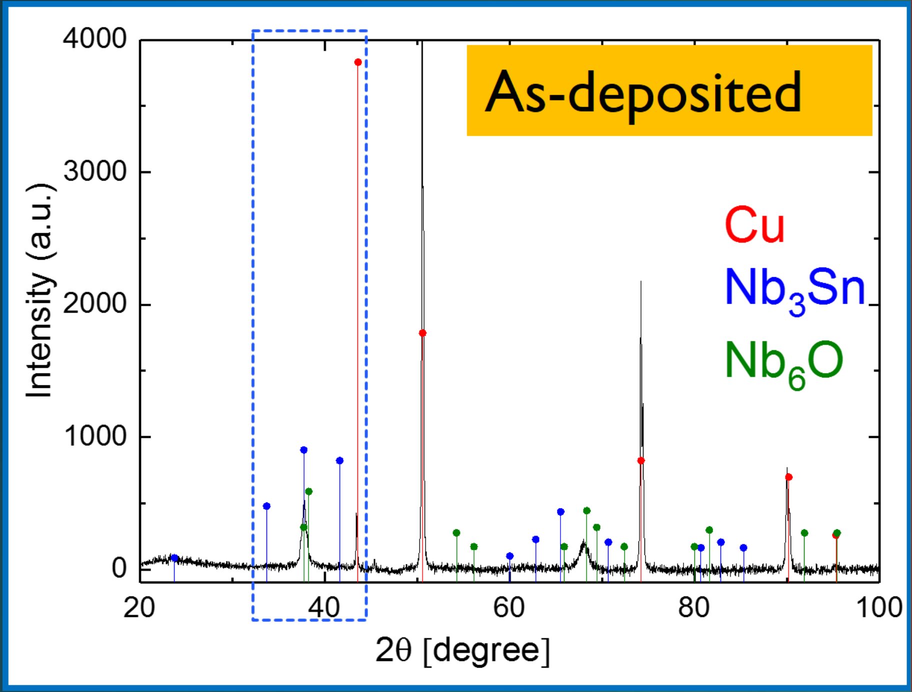
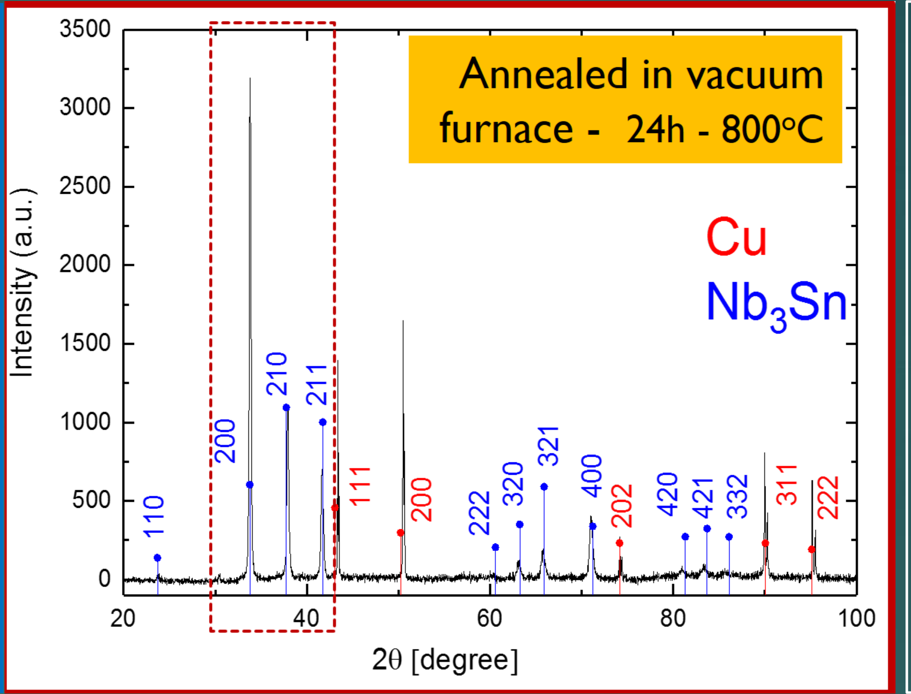
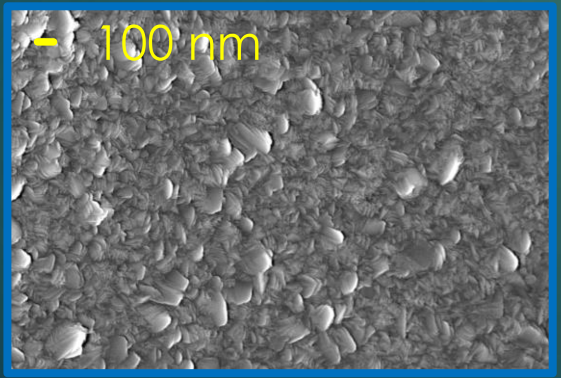
Results: films reacted after coating

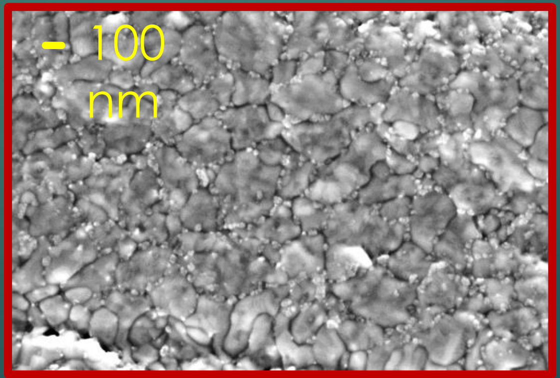
A15 phase formation. XRD analysis & Morphology





- **A15 phase confirmed** by the presence of Nb_3Sn characteristic peaks of (200), (210), (211) … (332)
- **Absence** of non-superconducting phases ***$NbSn_2$, Nb_6Sn_5***





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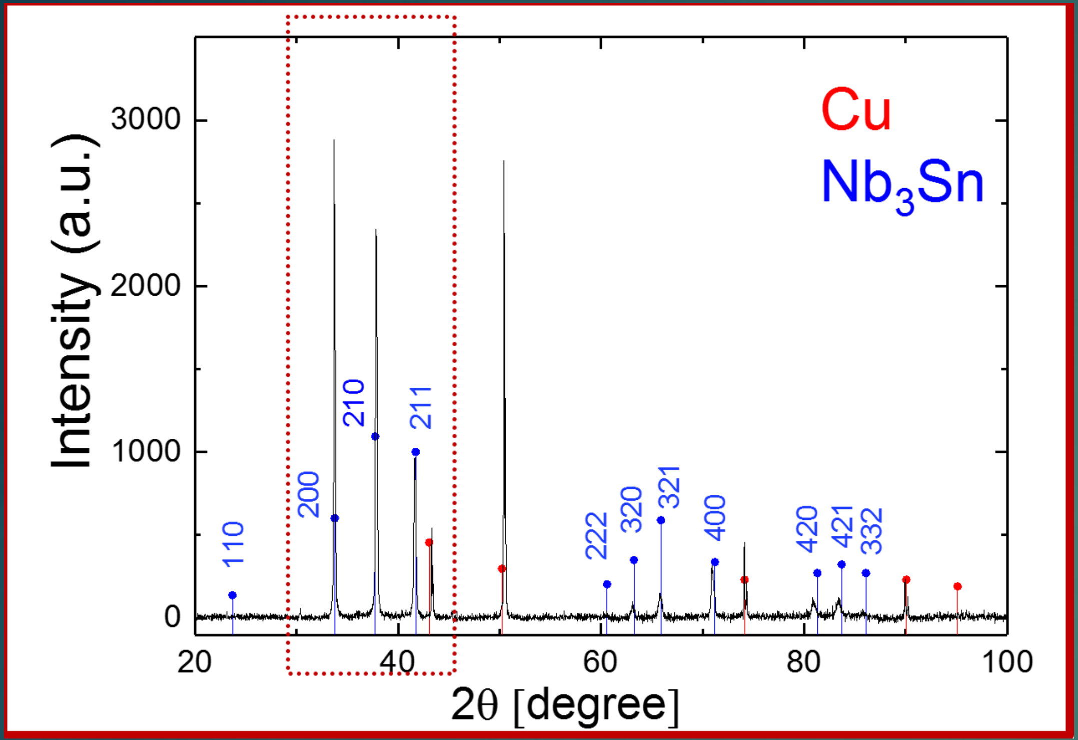
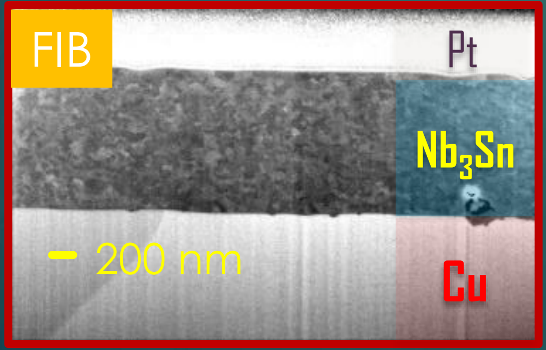
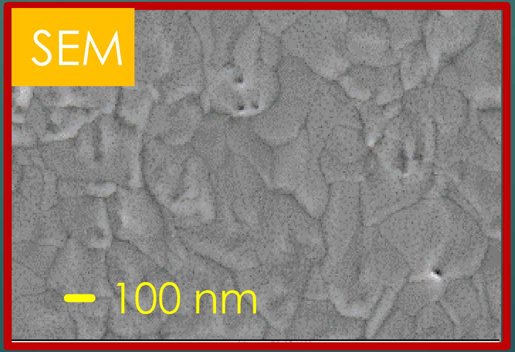
Results: films reacted during coating







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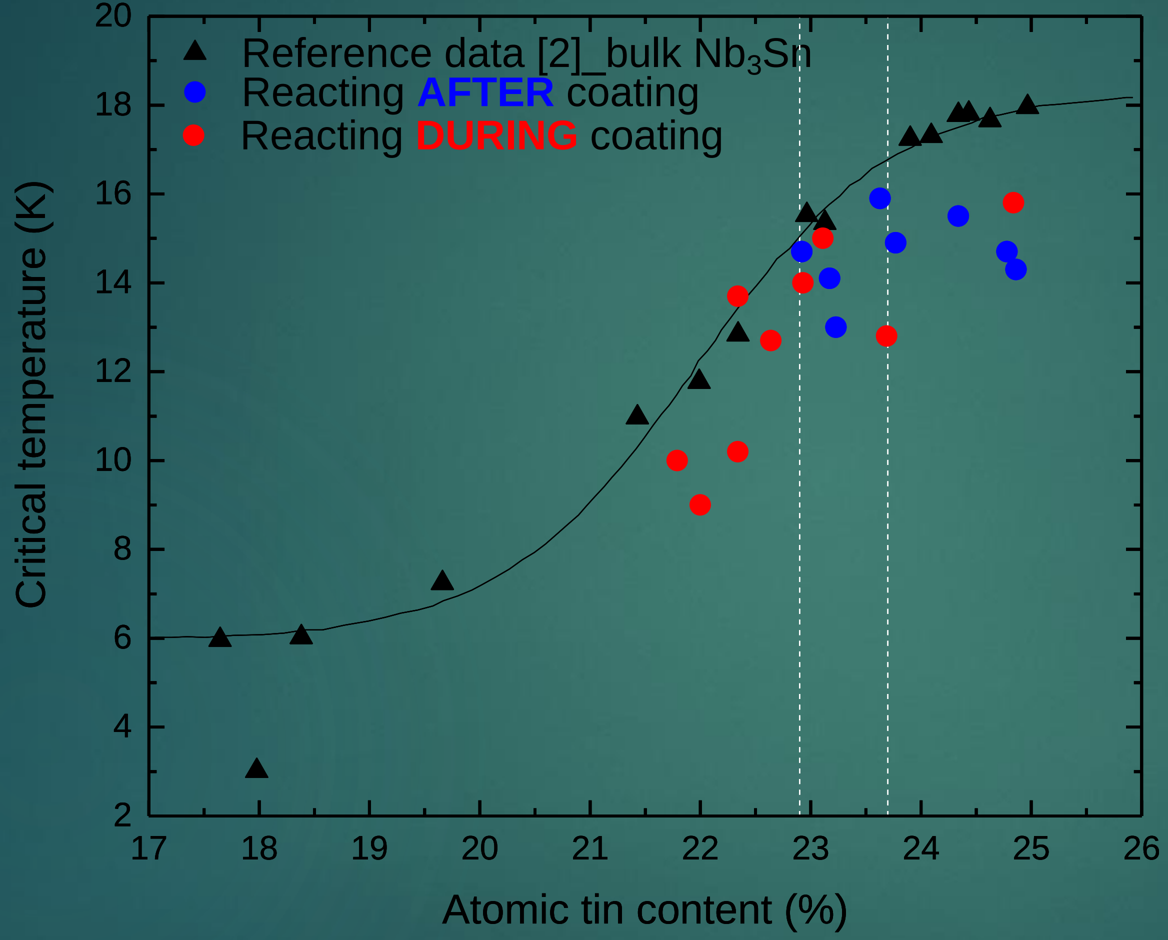
- **Absence** of non-superconducting phases $\boldsymbol{NbSn_2}$, $\boldsymbol{Nb_6Sn_5}$

PERLE meeting @ Daresbury

K. Ilyina et al.

Results: Critical temperature



[2] *A. Godeke. Supercond. Sci. Technol., 19 (2006) R68-R80*

How to increase T_c?

Composition

Films of Nb_3Sn on copper substrate

Reacting AFTER /DURING coating

High temperature treatment duration

Additional Annealing

K. Ilyina et al.

Proposed improvement: intermediate layer

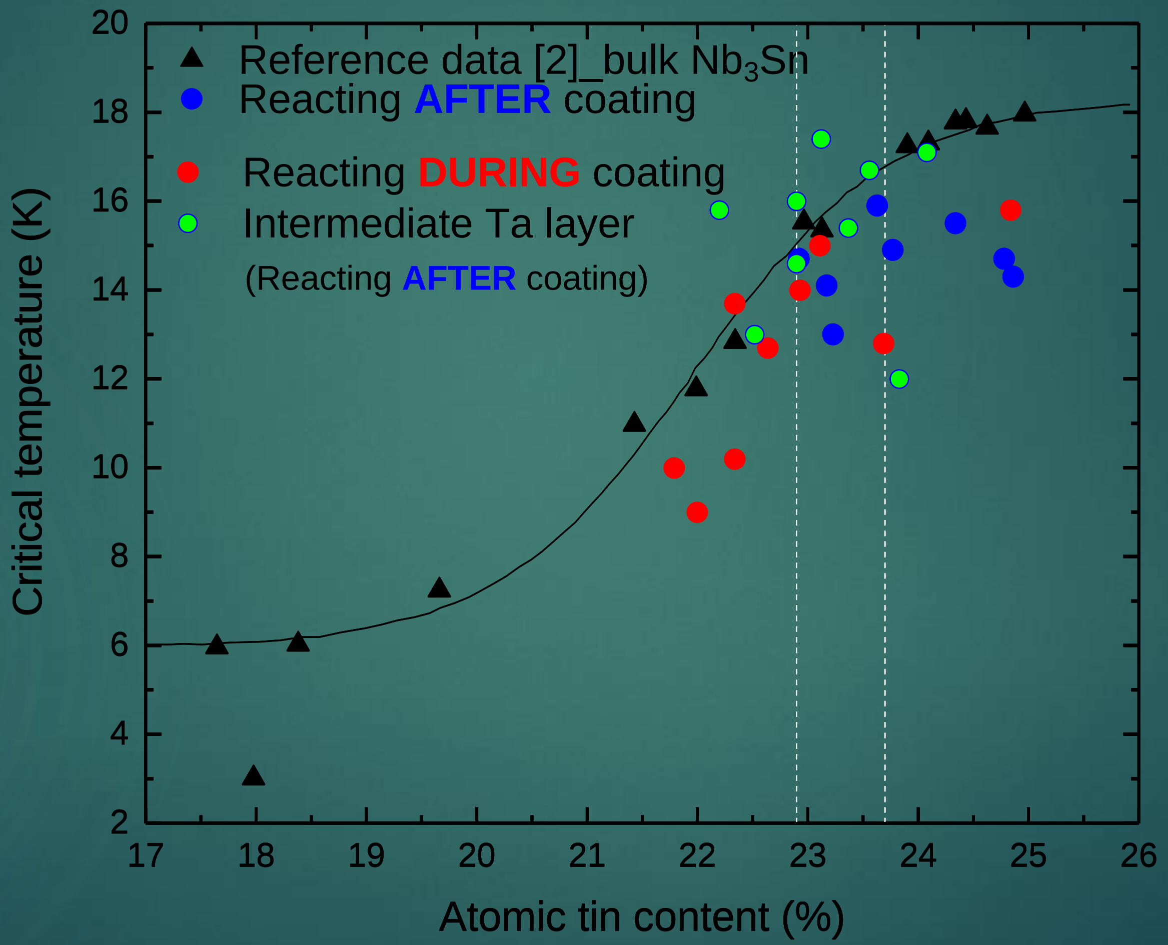
Idea:

- Works as "buffer" layer to reduce residual stresses in the films (to solve cracking problem for the films reacted AFTER the coating)
- Decrease lattice mismatch, i.e. improving crystalline lattice order (to avoid T_c depression) [4]
- Diffusion barrier layer (to prevent copper interdiffusion into Nb_3Sn layer)

Possible candidates – Nb, Ta, Al_2O_3

[4] Hein. The A15 story. The Science and Technology of Superconductivity, pp 333-372

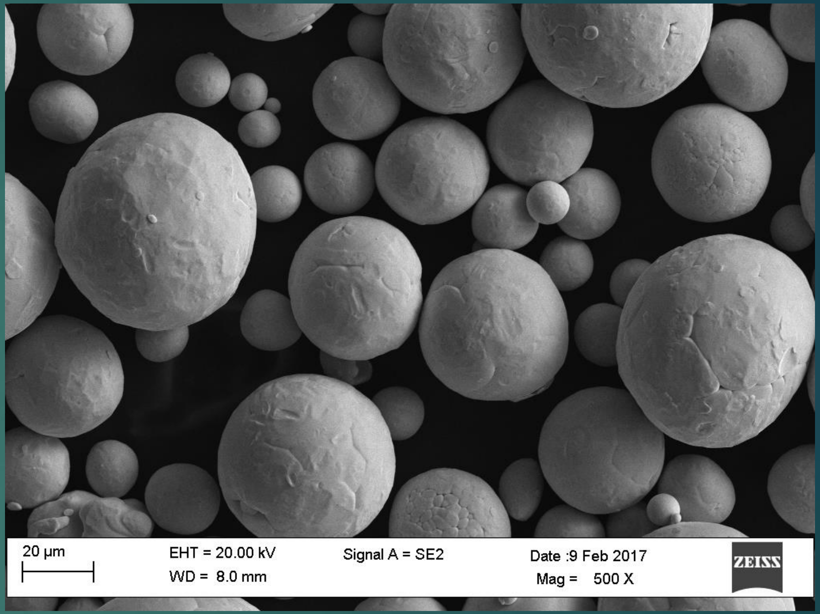
Preliminary results with Ta layer: encouraging



K. Ilyina et al.

Metal additive manufacturing @ CERN

- Started 2nd half of last year
- Supplier of Nb powder found (H. C. Starck), with good characteristics (<500 ppm oxygen, good flow properties …)
- Allows complex geometries …



R. Gerard et al.

Additive manufacturing from powder Nb

- 3-D printed Nb reached 99.91% density! – leak tests ongoing.
- Seamless 6 GHz cavity and other complex shapes successfully printed.
- Physical and electrical characterizations (RRR, T_c …) – first results look encouraging.

3-D printed seamless 6 GHz cavity

R. Gerard et al.

Summary

- The RF R&D at CERN is very diverse.
- It is geared at continued support and improvement of CERN baseline program support (LHC, ISOLDE, …)
- The 802 MHz ERL is baseline for FCC-he (and LHeC).
- Multiples of 40.08 MHz are "CERN standard".
- There are strong synergies with the CERN SRF Development program:
  - Dedicated and motivated team of professionals
  - Successful & promising technologies research & developments ongoing
  - Commonly useable infrastructures, recently updated.
  - Test infrastructures (SM18 and RF power)!
  - Fabrication, CM construction, surface treatments, clean room assembly …

Thank you very much!