SRF

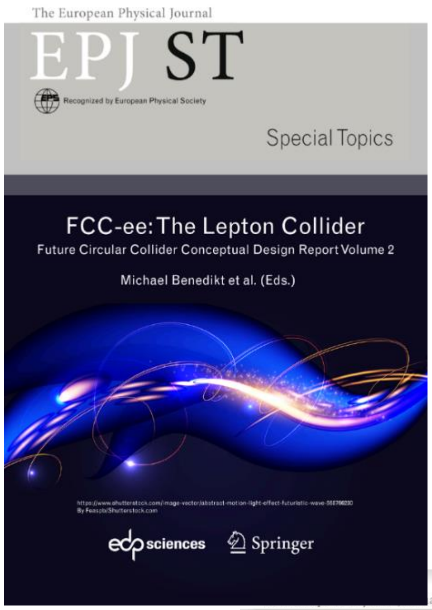
&

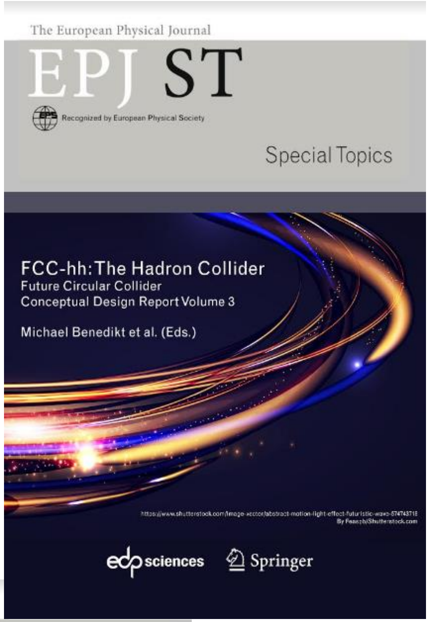
Power sources R&D Overview

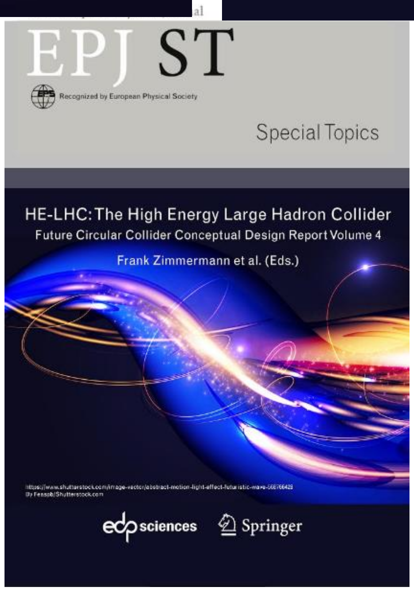
On behalf of the FCC SRF WP Collaboration

A.-M. Valente-Feliciano

SRF & Power Sources for FCC

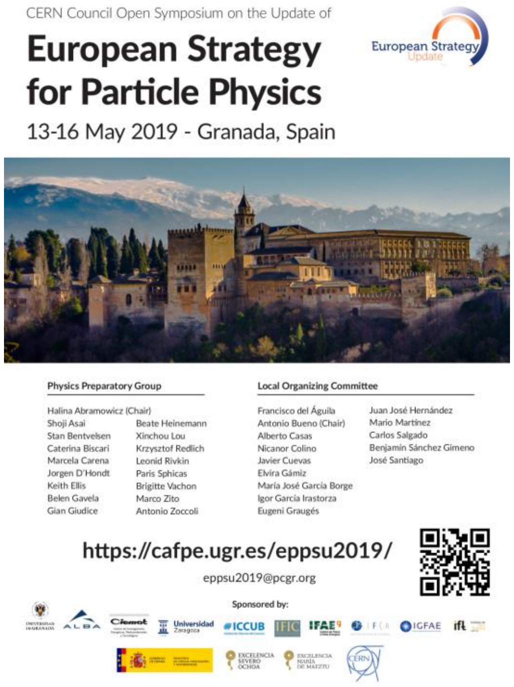






Update of the European Strategy for Particle Physics

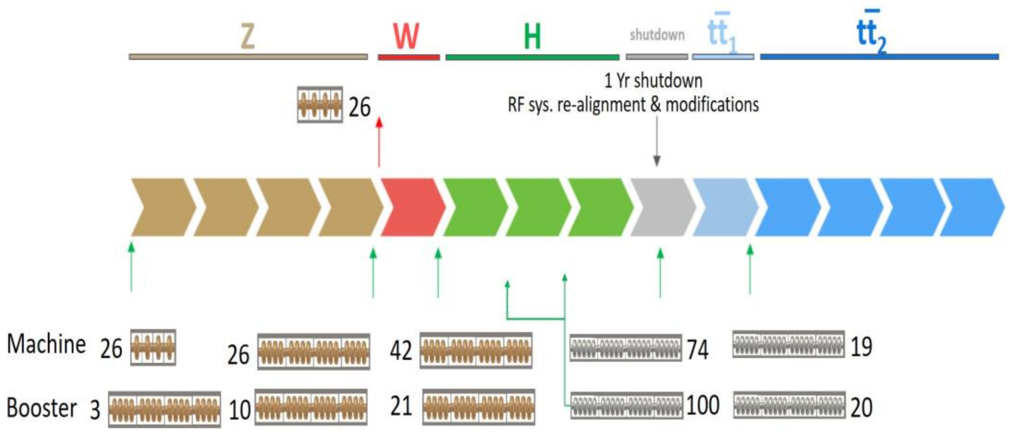
Granada, Spain



Jefferson Lab

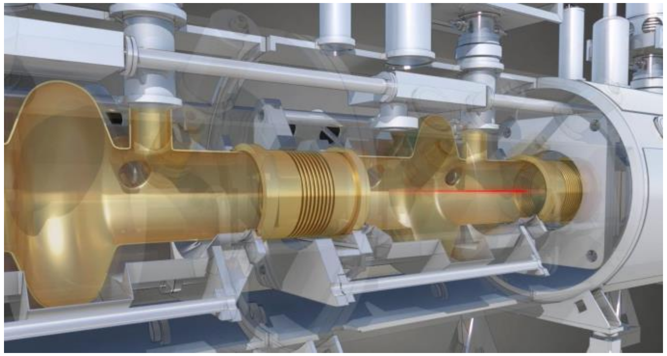
SRF for FCC

3 RF cavities sets for all options for machine & booster, 2 technologies



High current" machine

"High gradient" machine



Z hh

high intensity (Z, FCC-hh): 400 MHz Nb/Cu 1-cell cavities~1 MW source

W H

Higher energy (W, H): 400 MHz 4-cell Nb/Cu cavities (4/CM)

tt_1 tt_2

tt machine complement: 800 MHz 5-cell cavities (4/CM.), based on bulk Nb

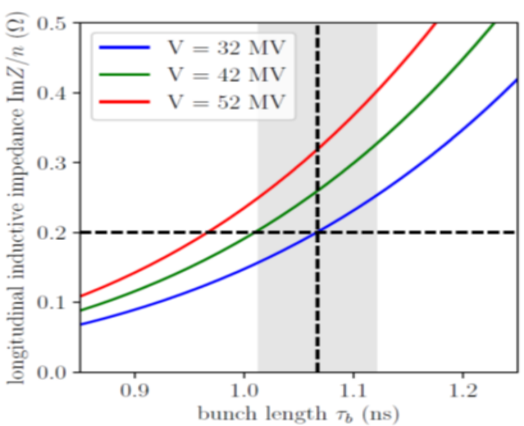
Cheaper in terms of RF power but at 2K so higher cost for cryocooling,

Shorter SRF footprint, reduced radiation

RF similar to LHC 400.8 MHz

Installed voltage of 48 MV (collision)

- 42 MV provides stability for ±5% energy spread bunches
- At injection 12 MV is chosen

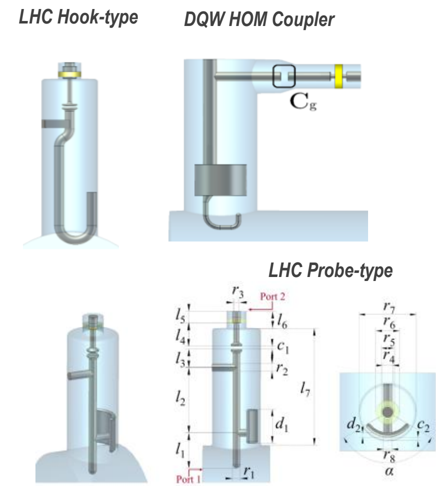


Longitudinal beam stability is provided by controlled emittance blow-up

High Order Modes Damping for FCC-ee

Various damping schemes for the Z Option

Several damping schemes are compared with respect to the power propagated into the couplers and the impedance of the cavities.



LHC (2H2P)

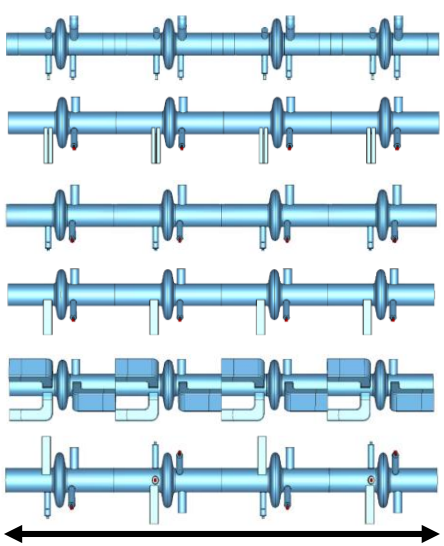
3H1QRWG

4H

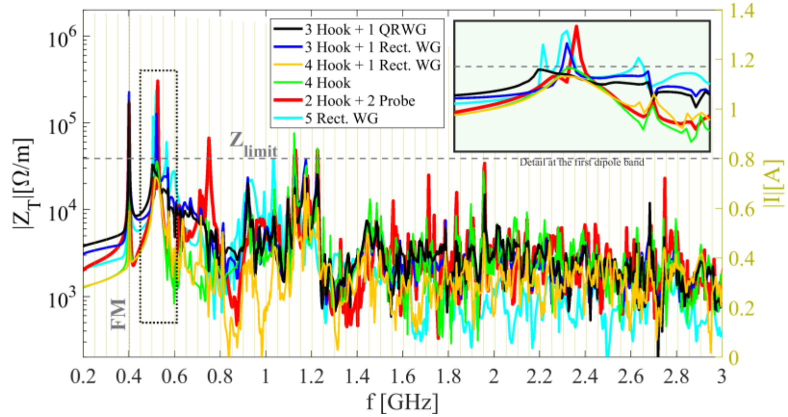
3H1RecWG

5RecWG

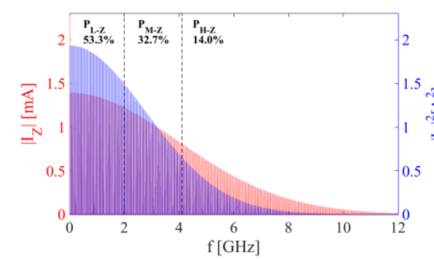
4H1RecWG



7.0 m



	P_{L-z}	P_{M-z}	P_{t-z}	BPs	FPC	Hooks	Probes	RecWGs	QRWGs
	[kW]			[%]					
Four Cavity Module									
4H	5.93	7.93	17.25	61.78	29.65	8.57	-	-	-
2H2P	7.55	10.20	22.13	55.57	30.23	3.05	11.15	-	-
5RecWG	20.31	10.78	35.71	14.98	5.52	-	-	79.50	-
3H1RecWG	10.28	8.89	22.98	33.59	14.62	2.60	-	49.19	-
3H1QRWG	10.76	9.54	24.38	33.18	14.80	2.48	-	-	49.54
4H1RecWG	12.49	9.68	26.32	32.58	16.02	3.89	-	47.51	-



The total power is approximated form

$$P_{tot-z} = P_{L-z} + P_{M-z} + \frac{14.0}{32.7} P_{M-z}$$

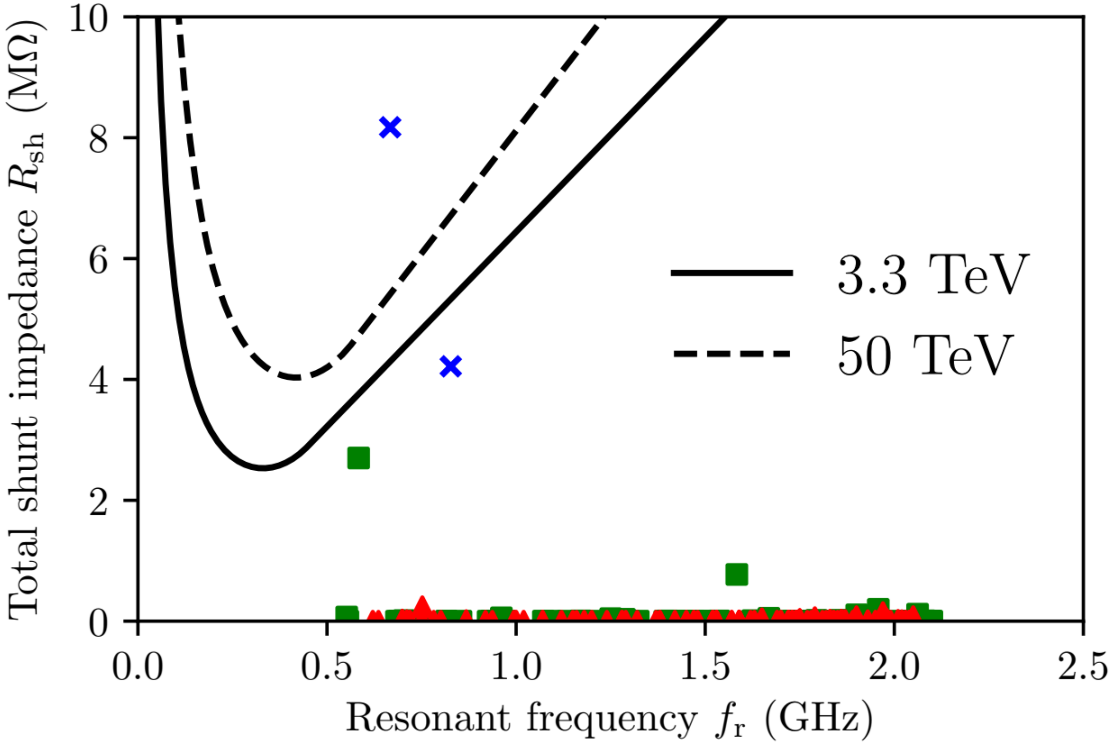
Shanham Gorgi Zadeh, Tues. 06/25, 8:30-8:45

HOM damping design studies for FCC-ee cavities

https://indico.cern.ch/event/656491/contributions/2932265/

High Order Modes Damping for FCC-hh

The threshold of longitudinal coupled-bunch instability was evaluated
→ It defines the maximum shunt impedance of HOM for which the beam is stable



Crab cavity HOMs:
Wide Opened Waveguide × 24
Double Quarter Wave ×12
RF-Dipole ×12

→ Threshold is lower at injection energy than in physics
→ Damping of HOMs may have to be revisited for Wide Opened Waveguide crab cavities

Ivan Karpov, Tues. 06/25, 8:45-9:00
Requirements for longitudinal HOM damping design in FCC-hh
https://indico.cern.ch/event/656491/contributions/2932265/

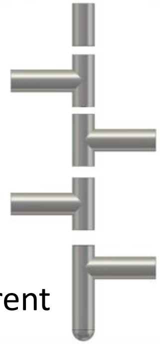
High Order Modes Couplers Optimization for 400 MHz Cavities

- Proton-proton collider center-of-mass collision energy :100 TeV with a beam current of 0.5 A.
- Stable acceleration is critical and therefore higher order modes (HOM) need to be damped.

- Efficient HOM dampers require:
  longitudinal HOM impedance <10 kΩ
  Loaded Q-factor <1000
  corresponding R/Q value ~10 Ω or lower.

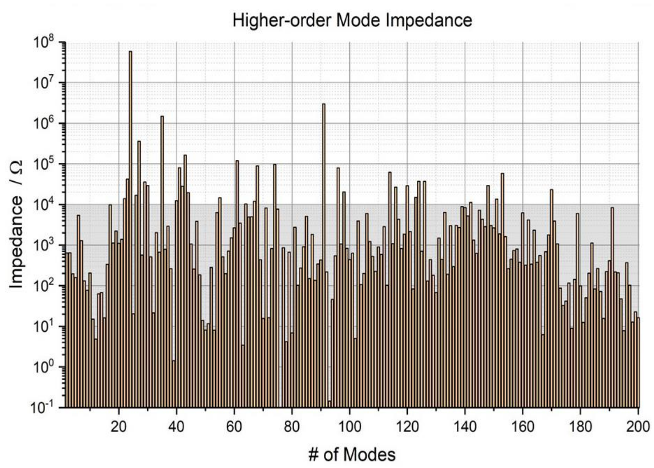
GOETHE UNIVERSITÄT FRANKFURT AM MAIN
IAP Institut für Angewandte Physik

High-pass filter coupler

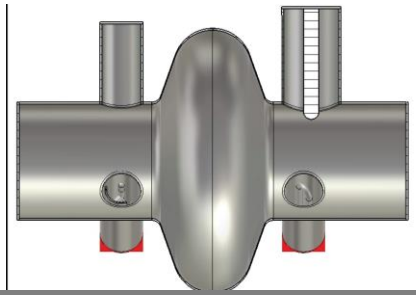


Band-stop filter coupler

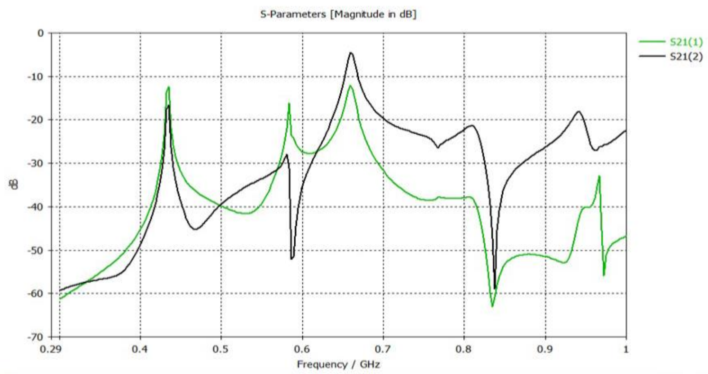
Besides the Hook-type and Probe-type HOM coupler, 2 additional designs were simulated.



Recent results of the different couplers attached to a superconducting 400 MHz RF cavity

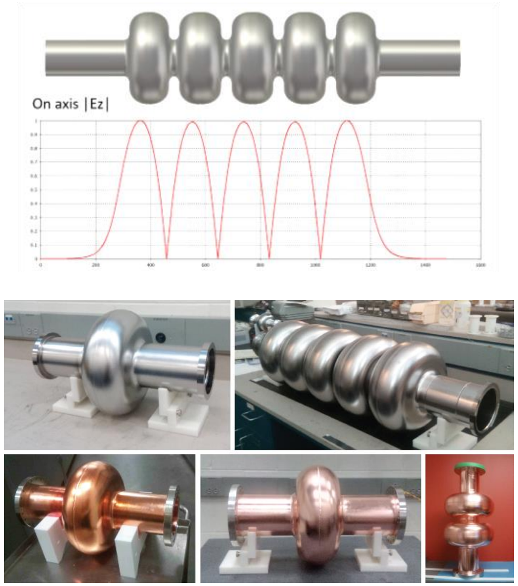


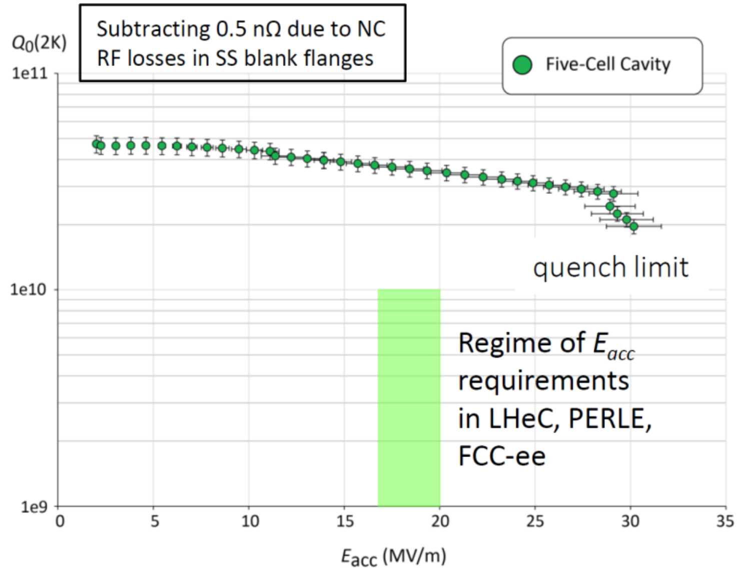
Simulated S-parameters band stop dipole mode



Nils Petry, Tues. 06/25, 09:00-09:15
Optimization of High Order Modes Couplers for 400 MHz Cavities
https://indico.cern.ch/event/656491/contributions/2932265/

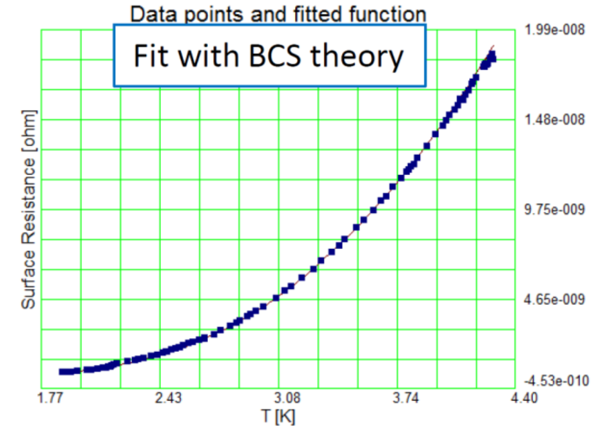
802 MHz Bulk Nb based technology development





Performance limit:
- Quench at $E_{acc,max}$ = 31 MV/m (B_{pk} ~ 130 mT) and Q_0 = 2e10

Beyond specifications for FCC



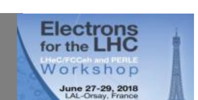
R_{res} = 3.19 ± 0.79 nΩ

Note: This takes into account 2.49 nΩ due to NC RF losses in SS blank flanges for the single-cell cavity

Nb single cell awaiting to be N doped
Recipe 2/0 doping + 7 µm EP
Results to come soon
Fermilab

Bulk Nb 5-cell cavity
Bulk Nb 1-cell cavity
2 OFHC Cu 1-cell cavities –for thin film coating R&D at CERN
OFHC Cu cavity for R&D bench measurements at CERN allowing to add cells

Frank Marhauser, R.A.Rimmer
https://indico.cern.ch/event/698368/contributions/3043484/



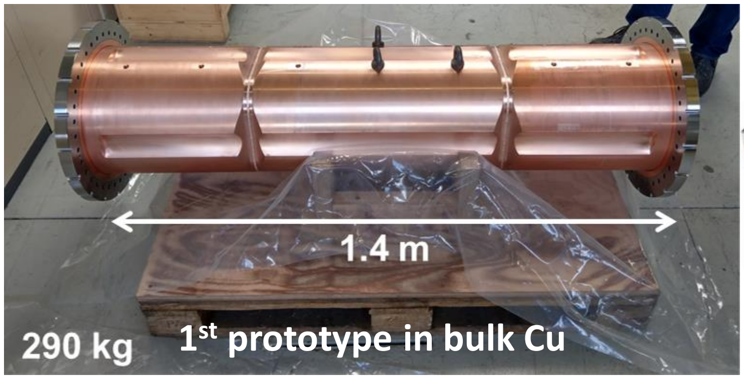
Accelerating cavity - Development for WOW Cavity

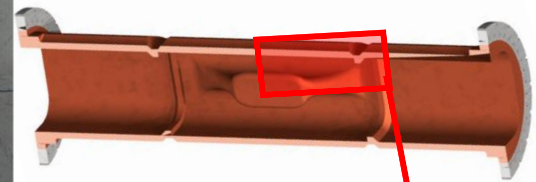
Wide Open Waveguide

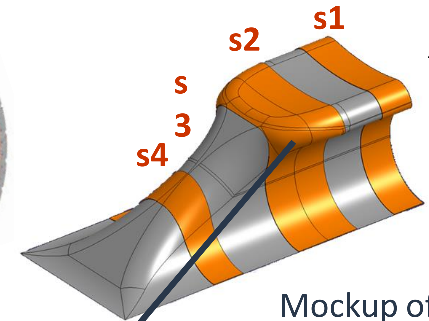
Particle deflected by transverse TE-111 like field between 2 mushroom-shaped ridges

- low longitudinal and transverse impedances
- natural damping for HOMs

A. Grudiev
F. Avino
A. Sublet

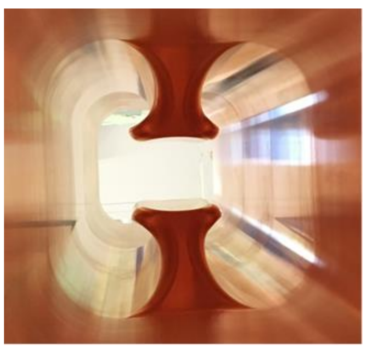






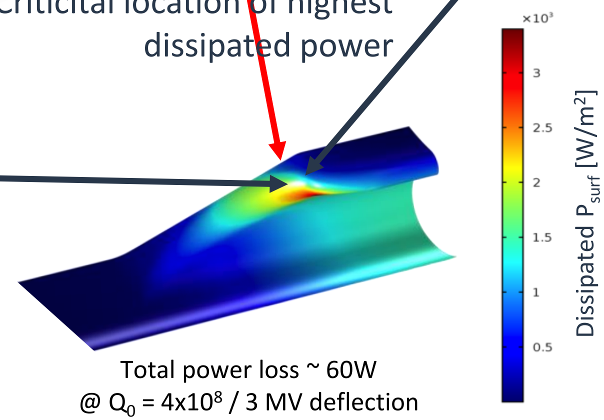
Mockup of 4 sections for coating R&D

Front view



Detail of tapering

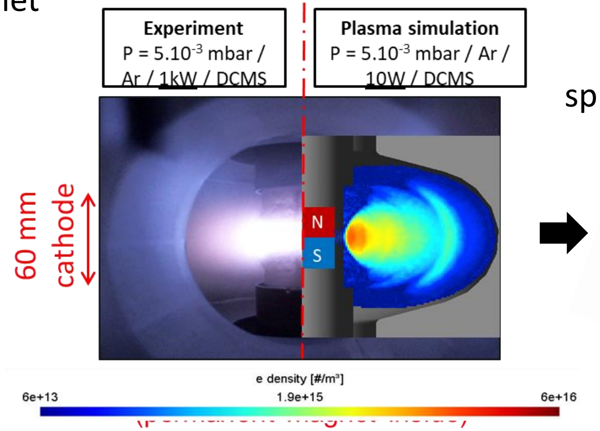
Criticital location of highest dissipated power



Total power loss ~ 60W
@ $Q_0 = 4 \times 10^8$ / 3 MV deflection

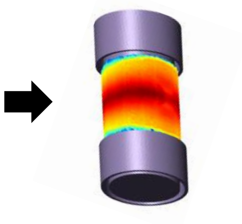
Accelerating cavity - Development for WOW Cavity

A. Grudiev
F. Avino
A. Sublet

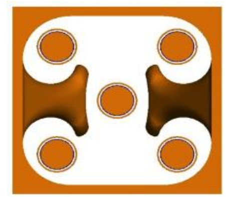


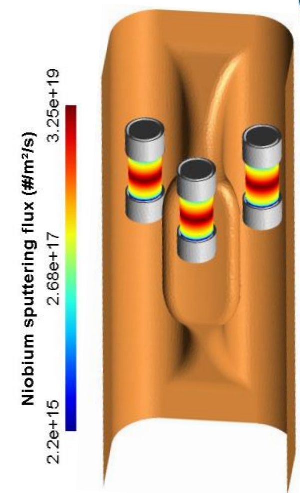
Side view of the cylndrical cathode (permanent magnet inside)

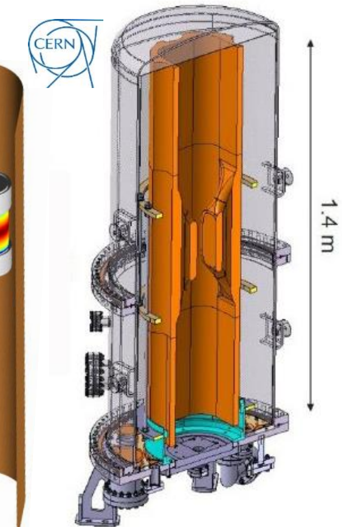
Output: Nb sputtering profile



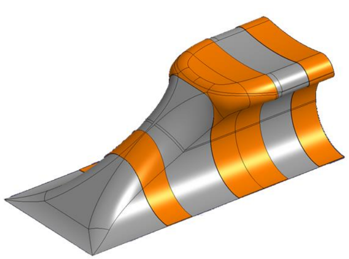
x5 cathodes in WOW





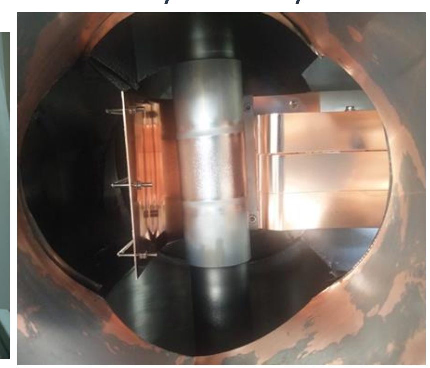


s1

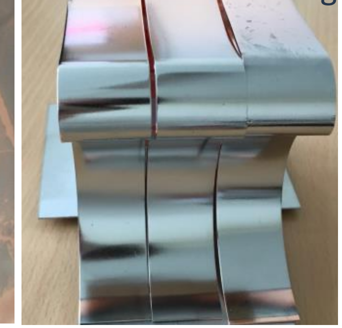


S1 sample mockup

Assembly in 6-way cross

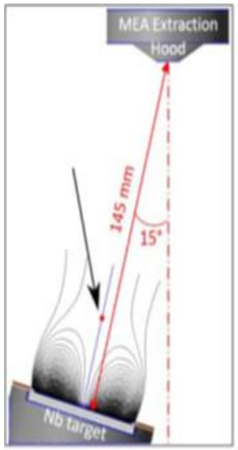


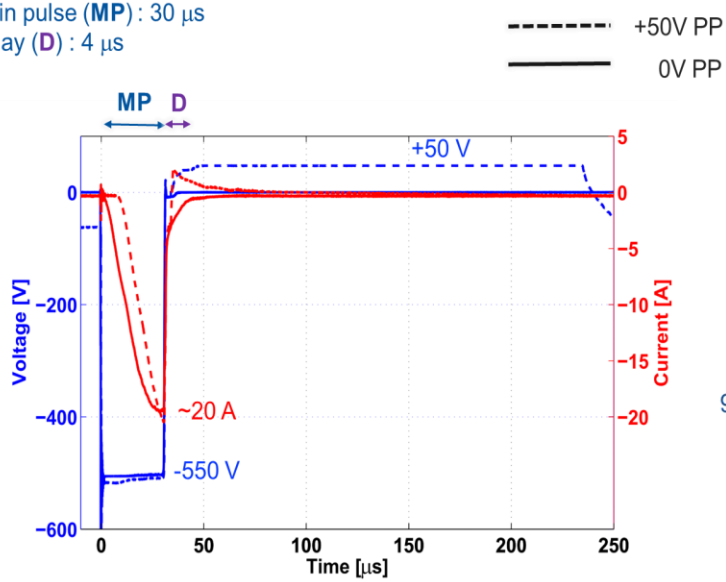
Samples after 1kW,
6 minutes coating



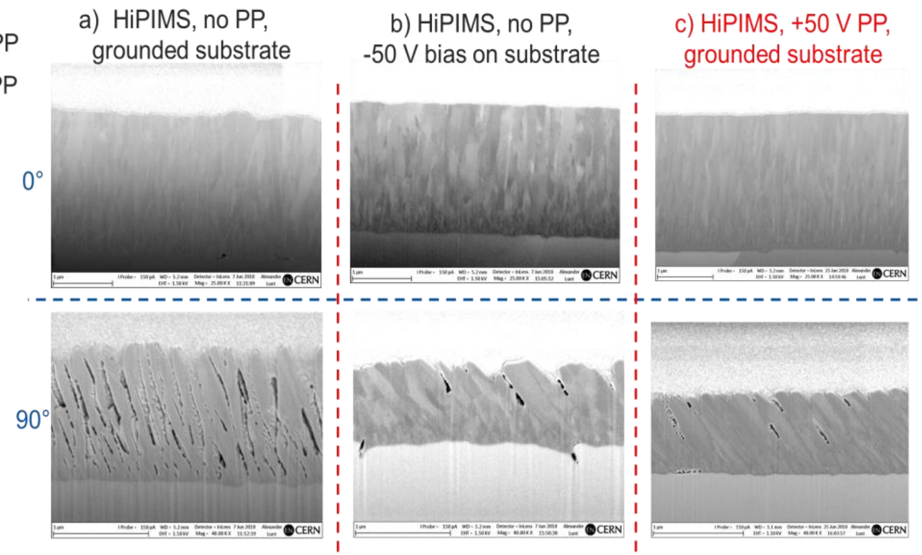
HiPIMS configurations

- Duty cycle : 1 kHz
- Main pulse (**MP**) : 30 µs
- Delay (**D**) : 4 µs





FIB on HiPIMS coatings



Biased-like effect with a positive pulse!

90° sample gets densified with 200 µs positive pulse at +50V

F. Alvino, SRF 2109

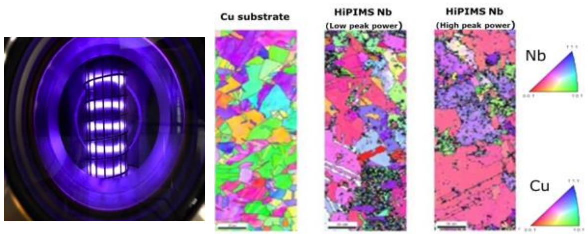
Evidence of ion energy distribution shift in HiPIMS plasmas with positive pulse

Plasma Sources Sci. Technol. 28 (2019) 01LT03

Nb/Cu Technology - Energetic Condensation with HiPIMS

HiPIMS (high power impulse magnetron sputtering)
- ❑ Higher level of stress in HiPIMS vs. DCMS
- ❑ Biased HiPIMS produces denser films

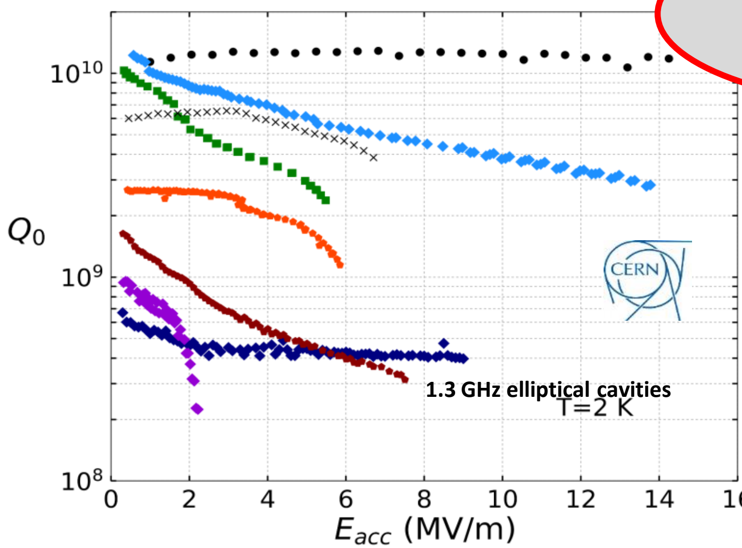
M. Arzeo, Tues. 6/25, 10:48 – 11:06, Crea/Explo
RF Performance of Superconducting coatings on copper for the FCC study
https://indico.cern.ch/event/727555/contributions/3433765/

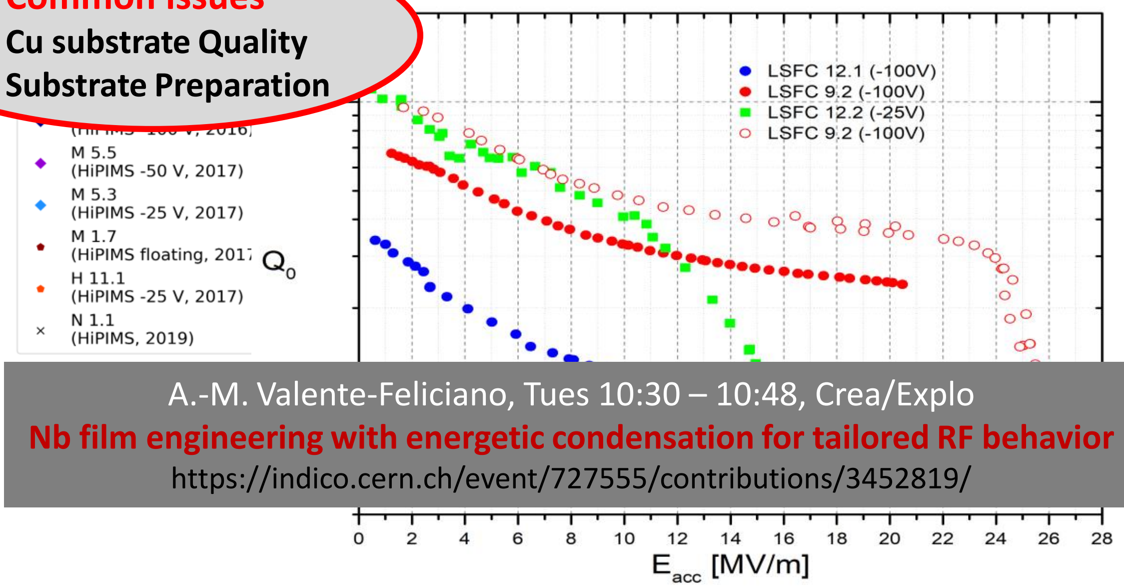


Quality Factor of 1.3 GHz HiPIMS Nb/Cu LSF cavities (B_{peak}/E_{acc}=3.68) at 2 K.
No field emission was detected.

Jefferson Lab

Common issues
Cu substrate Quality
Substrate Preparation

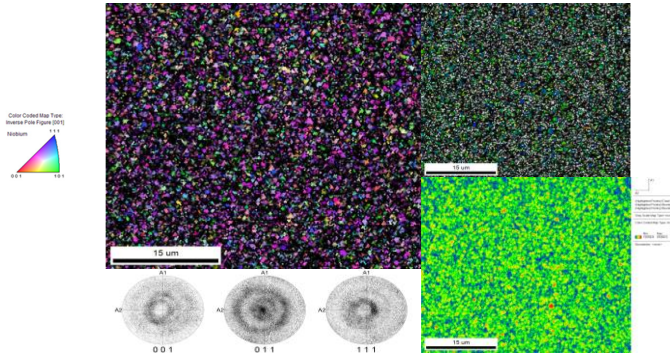


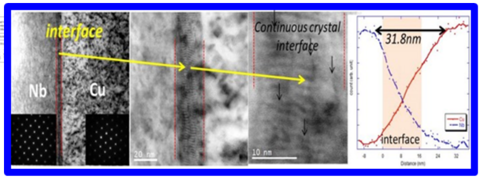


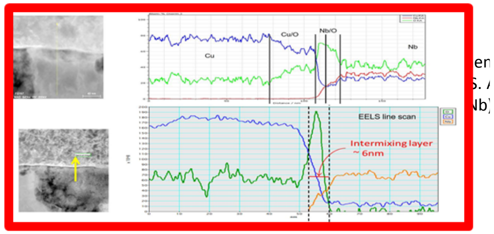
A.-M. Valente-Feliciano, Tues 10:30 – 10:48, Crea/Explo
Nb film engineering with energetic condensation for tailored RF behavior
https://indico.cern.ch/event/727555/contributions/3452819/

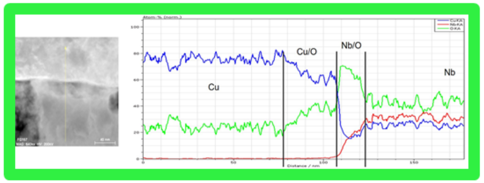
Nb/Cu Technology: Energetic Condensation with ECR

Creation of 64 eV Nb^{+} ions under vacuum (no carrier gas)
Dense films
Excellent adhesion (intermixing)
Film engineering

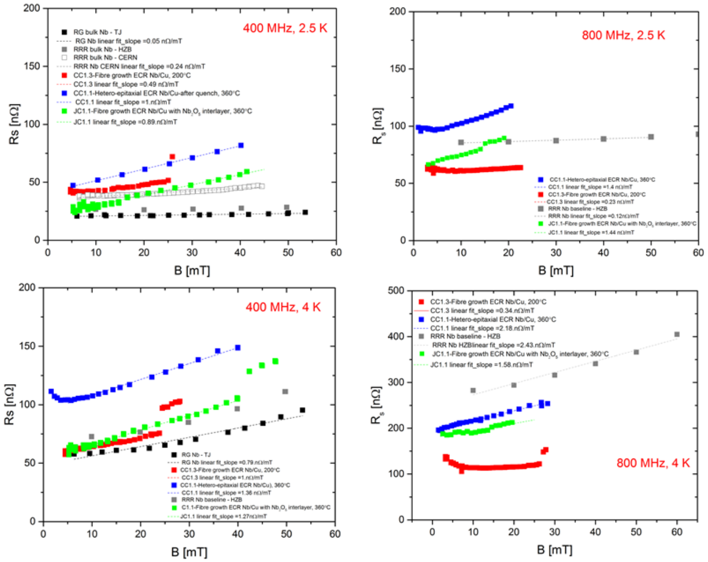


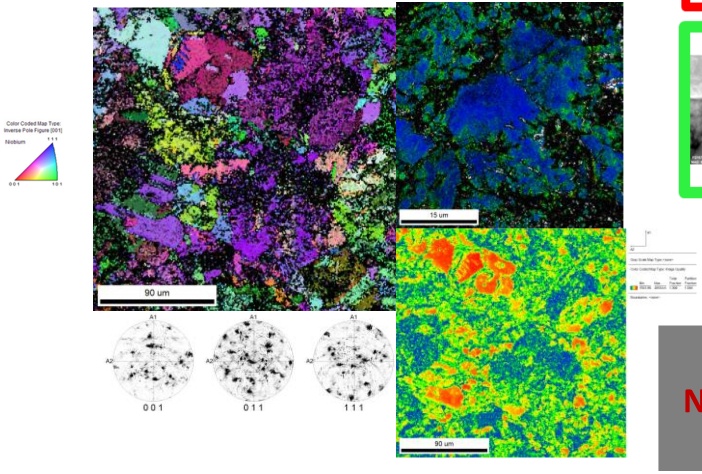






Manipulation of Film Structure
With interlayers, nucleation growth sequencing using ion energy and system thermodynamics

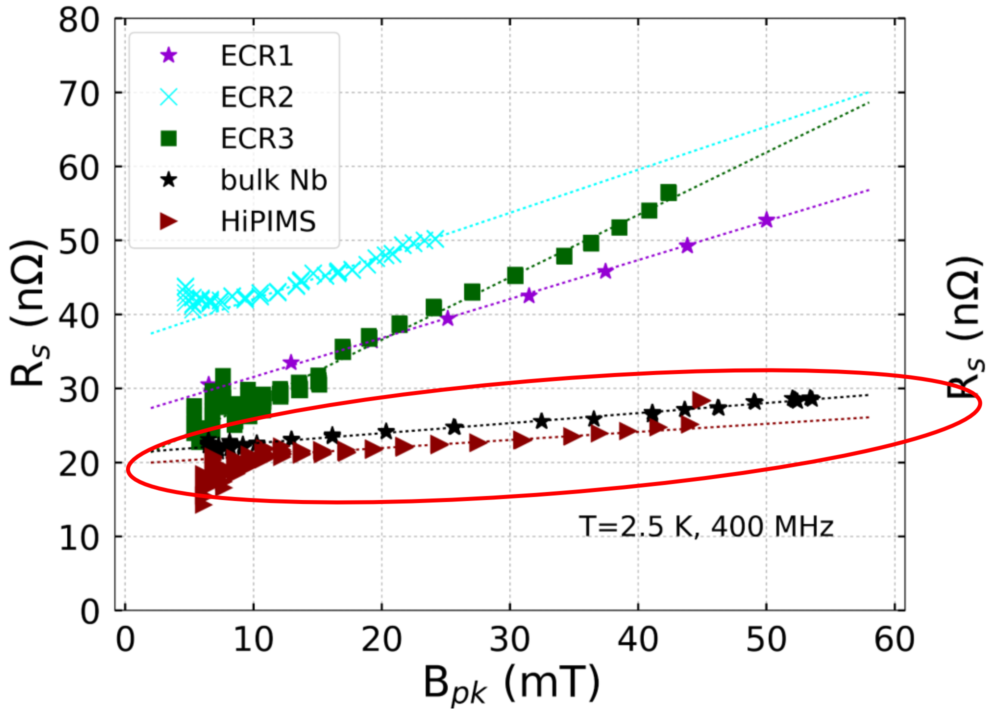


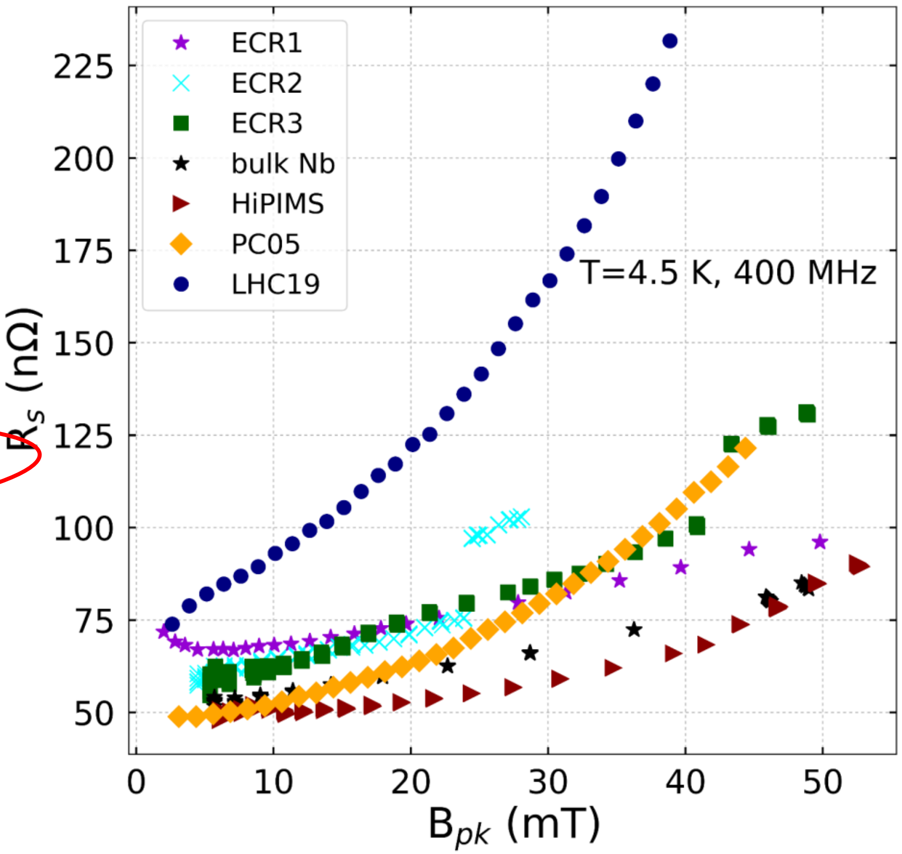


Mitigation of Q-slope

A.-M. Valente-Feliciano, Tues 10:30 – 10:48, Crea/Explo
Nb film engineering with energetic condensation for tailored RF behavior
https://indico.cern.ch/event/727555/contributions/3452819/

Nb/Cu Technology: Energetic Condensation





Towards mitigation of Q-slope

M. Arzeo, Tues. 6/25, 10:48 – 11:06, Crea/Explo

RF Performance of Superconducting coatings on copper for the FCC study

https://indico.cern.ch/event/727555/contributions/3433765/

Nb/Cu: Mitigation of Q-slope with Thick Nb Films

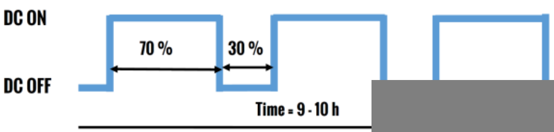
INFN-LNL Group
ARIES Collaboration

Overcome Nb/Cu Q-slope

Thermal boundary resistance at Nb/Cu interface

V. Palmieri and R. Vaglio, *Supercond. Sci. Technol.*, vol. 29, no. 1, p. 015004, Jan. 2016

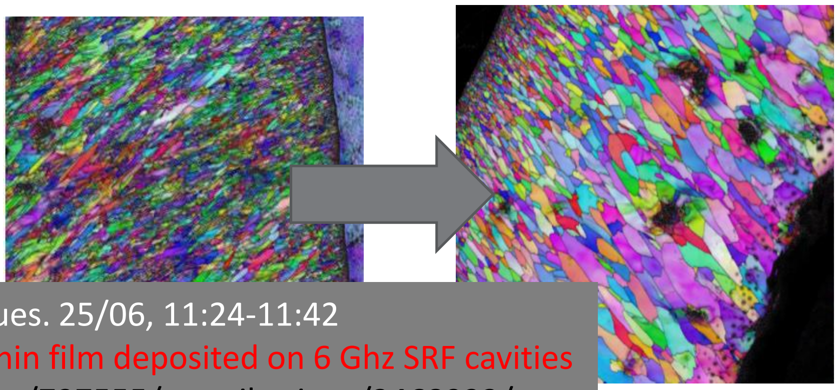
High coating temperature
Thick films



Single Layer Thickness =

Total Thickness (on the cell) = 70 μm

Deposition Rate = 3 nm/s



R.Valizadeh, Tues. 25/06, 11:24-11:42

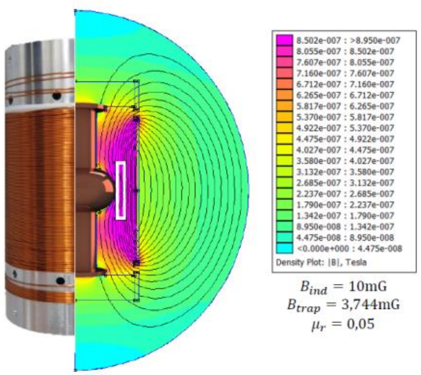
Characterization of a nobium thin film deposited on 6 Ghz SRF cavities

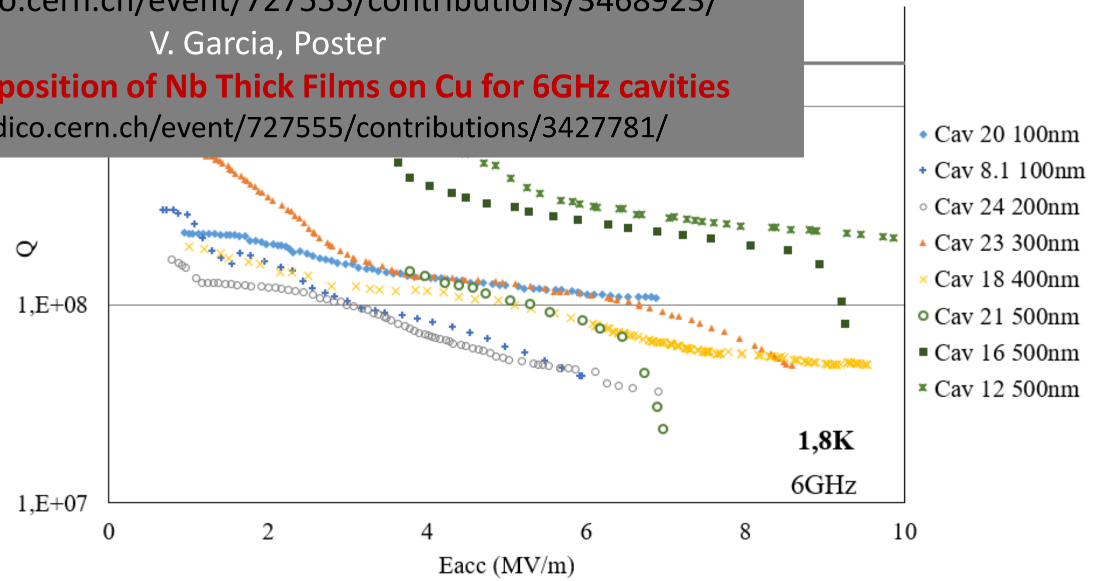
https://indico.cern.ch/event/727555/contributions/3468923/

V. Garcia, Poster

Update in deposition of Nb Thick Films on Cu for 6GHz cavities

https://indico.cern.ch/event/727555/contributions/3427781/

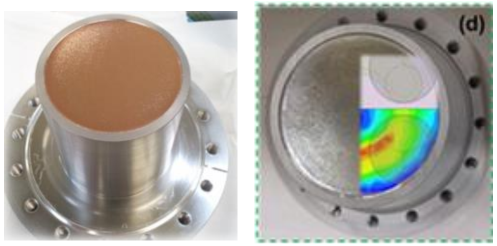




Jefferson Lab

RF & Material analyses

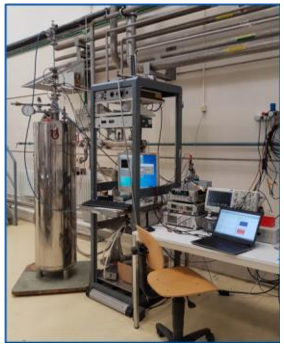
Quadrupole Resonator



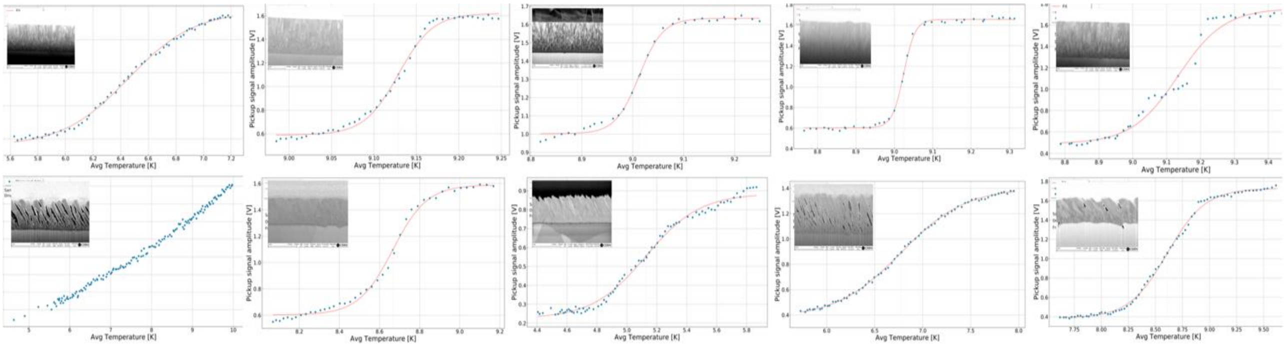
M. Arzeo, Tues. 6/25, 10:48 – 11:06, Crea/Explo
RF Performance of Superconducting coatings on copper for the FCC study
https://indico.cern.ch/event/727555/contributions/3433765/

Dmitry Tikhonov, Tues. 6/25, 10:48 – 11:06, Crea/Explo
Superconducting thin films characterization at HZB with the Quadrupole Resonator
https://indico.cern.ch/event/727555/contributions/3427798/

Operation @ multiple accelerator compatible frequencies [**400, 800**, 1200 MHZ]
New version commissioned



Tc Cryo test stand



Dorothea Fonnesu, Tues. 6/25, 11:06-11:24, Crea/Explo
Development of a Tc test stand to analyze superconducting thin-film coatings
https://indico.cern.ch/event/656491/contributions/2915672/

A15 Materials for SRF cavities

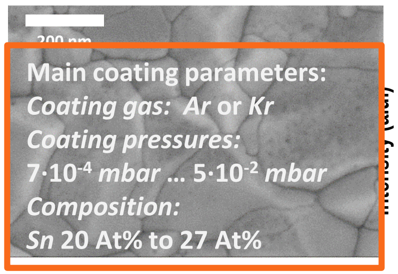
Toward leptonic machine compatible thin film on copper

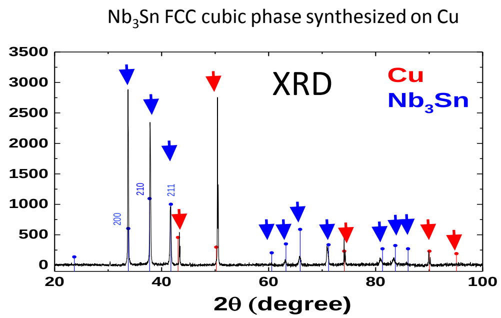
Higher T_c ,Higher efficiency

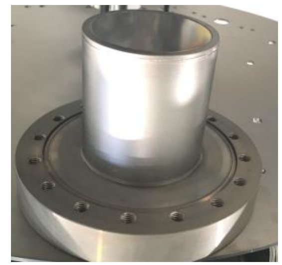
Low surface resistance R_B ~ 0.25 nΩ @ 4.2K / 400MHz (Nb ~ 60 nΩ)

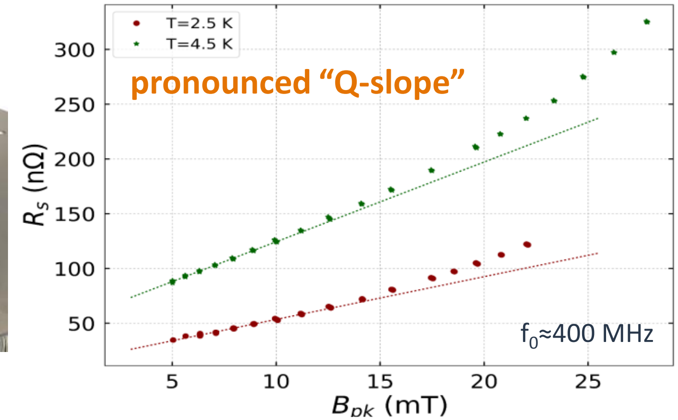
E. A. Ilyina, *et al. Supercond. Sci. Technol.*, **32** *(2019)*

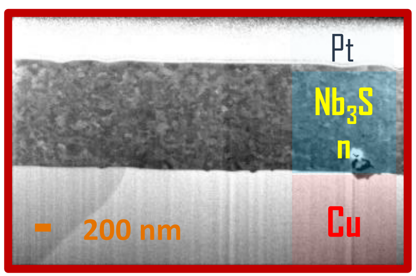
Substrate plays a major role in the layer final properties

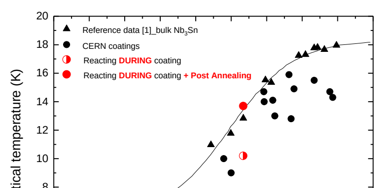




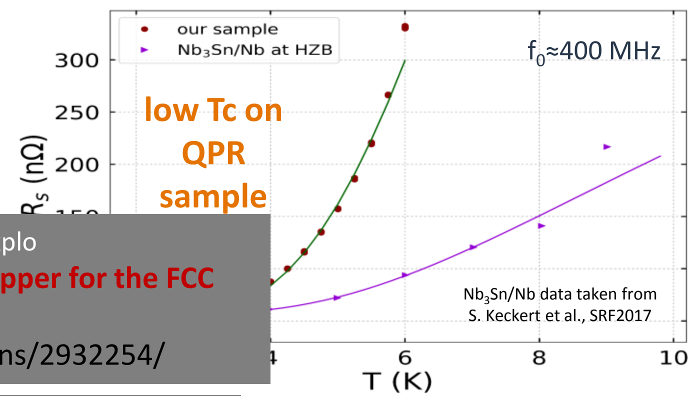








Nb_3Sn on Cu with intermediate Ta layer to prevent cracks



M. Arzeo, Tues. 6/25, 10:48 – 11:06, Crea/Explo

RF performances of superconducting coatings on copper for the FCC study

https://indico.cern.ch/event/656491/contributions/2932254/

Pavlina Trubacova (CERN)

Niobium Polishing for SRF applications

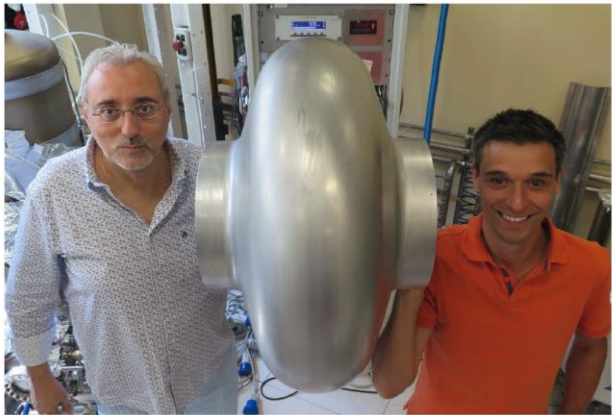
Stewart Bristow Leith

Progress with the Deposition of Niobium Nitride Thin Films on Copper

Poster Session, Tues. 06/25 15:30

Seamless Elliptical Cavities

Laboratori Nazionali di Legnaro



400MHz Seamless Aluminum Cavity prototype

1st Thermal Annealing

2nd Thermal Annealing

Spinning of Cavity #2 completed

1st Thermal Annealing

2nd Thermal Annealing

3rd Thermal Annealing

Feasibility to produce a 400 MHz seamless cavity demonstrated

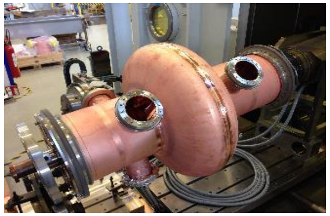
Further developments necessary to avoid cracks, increase geometry accuracy and internal surface quality (for example optimize annealing procedure and insert more intermediate die).

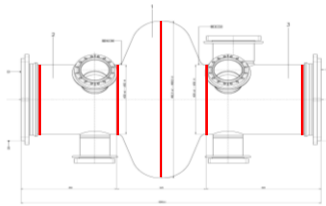
Systematic study on simulacra to correlate spinnability to thermal annealing conditions (temperature and time)
Use of intermediate die to reduce «vacuum spinning» and consequently wrinkling

C. Pira, Tues. 6/25, 9:15-9:30
R&D of Seamless elliptical cavities
https://indico.cern.ch/event/656491/contributions/2915671/

Ideas for industrialization path

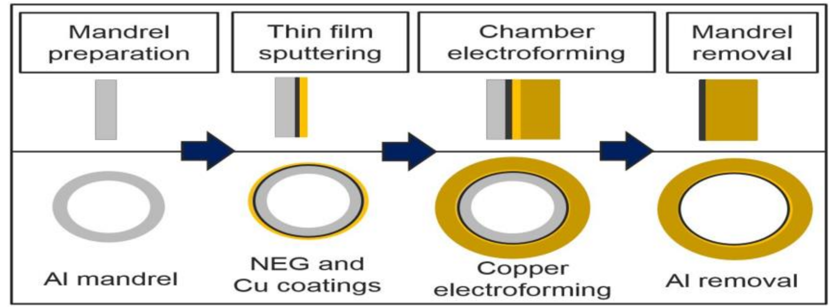
SRF cavity manufacturing by Cu electrodeposition





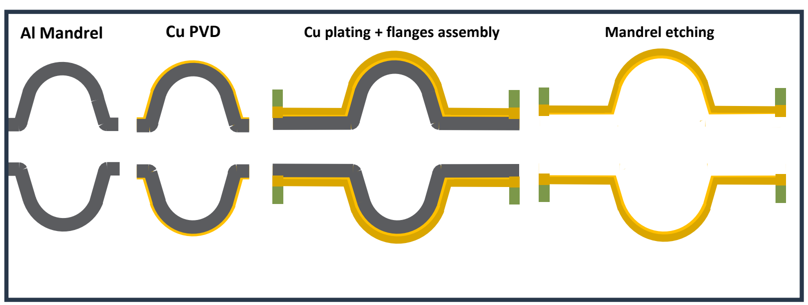
Damaged copper during spinning

Small diameter UHV chambers [1]



Lucia Lain Amador et al.; Journal of Vacuum Science & Technology A 36, 021601 (2018)
DOI: 10.1116/1.4999539

Toward SRF cavities substrates ?



Seamless cavity

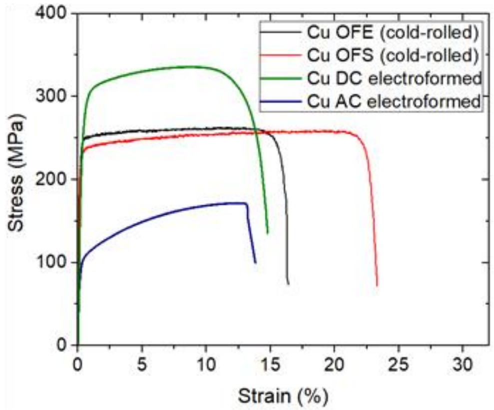
Suppression of ALL welds

No material deformation during forming

Tight mechanical tolerances reachable

SRF cavity manufacturing by Cu electrodeposition

Mechanical



Ultimate Tensile Strengh

DC	PP
352 ± 41 MPa	174 ± 6 MPa

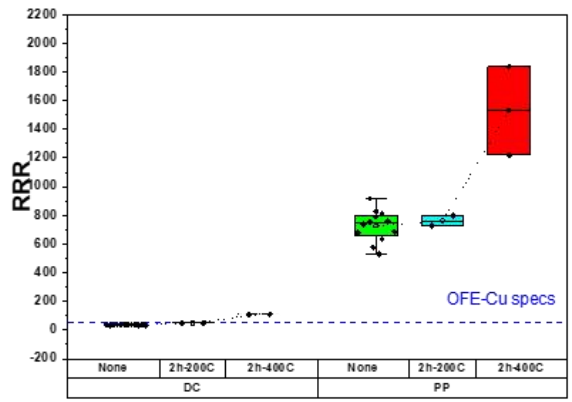
Hardness

DC	PP
1488.4 ± 47.3 MPa	831.4 ± 52 MPa

Young modulus

DC	PP
124 ± 15 GPa	131± 15 GPa

Cryogenics



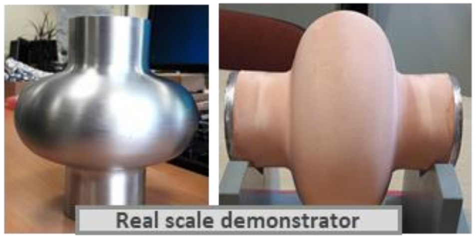
- RRR easily matches Cu OFE specs after thermal treatment
- PP leads to very high RRR
- RRR measured by electrical conductivity confirmed by thermal conductivity measurements

Surface

Cu plating mimics Al mandrel surface quality

Diamond mandrel machining		
µm	DC plating	Pulse Plating
Cu-R_a	0.030	0.030
Al-R_a	0.002	

Scale-up



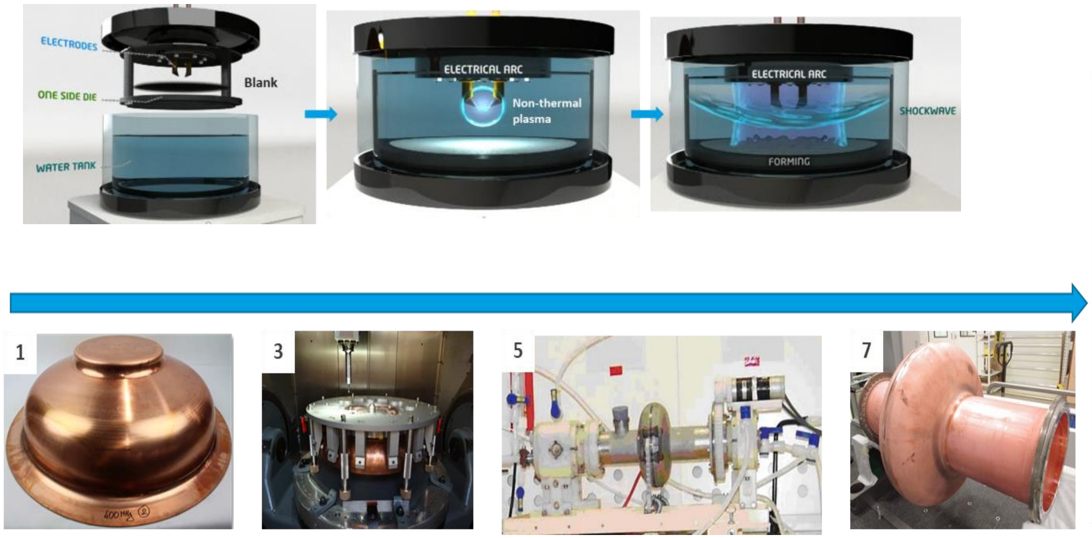
1st prototype for summer 2019

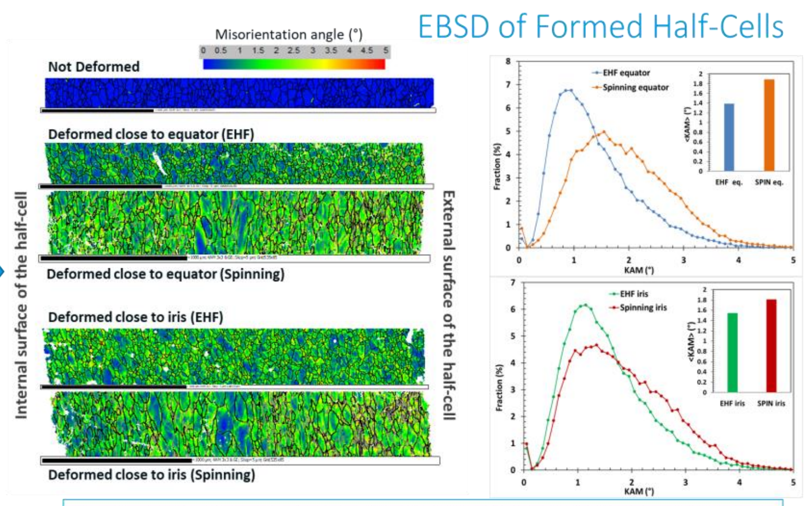
G. Rosaz, Tues. 06/25, 9:30 – 9:45

Electrodeposition of Copper for Seamless Cavities

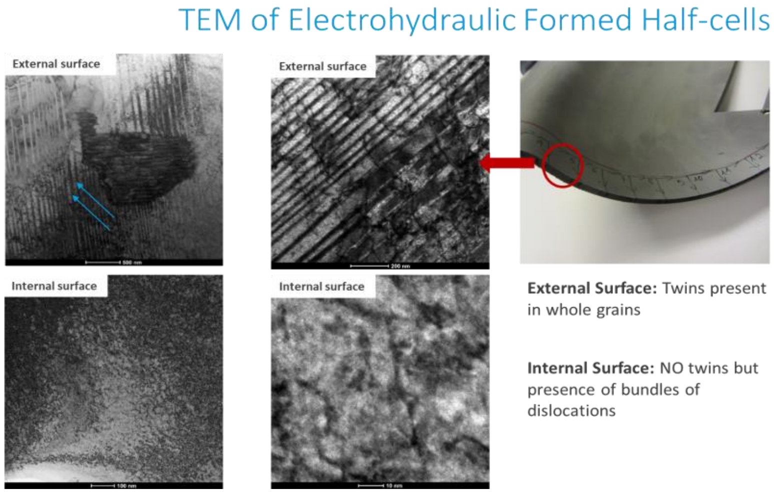
https://indico.cern.ch/event/727555/contributions/3467103/

SRF cavity manufacturing by electrohydraulic forming (EHF)





Low geometrically necessary dislocation density = No plastic strain through thickness



External Surface: Twins present in whole grains

Internal Surface: NO twins but presence of bundles of dislocations

Jean-Francois Croteau, Poster #456

Mechanical characterization of large grain niobium sheets for high-velocity forming of SRF cavities

https://indico.cern.ch/event/656491/contributions/2932264/

A. E. Ivanov et al.

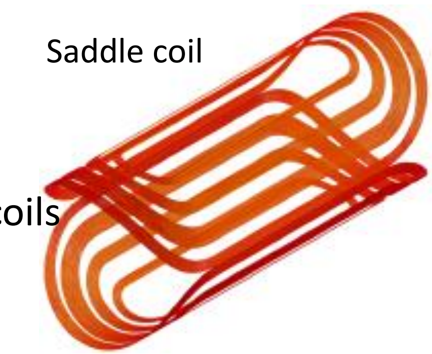
Active shielding study vertical cryostat in SM18

Provisional specs

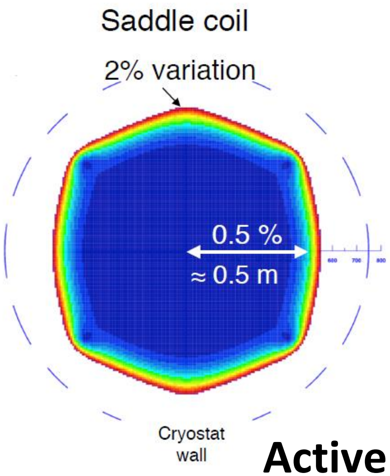
Field uniformity 0.5% —> ~ 0.25 µT in a volume of 400 MHz LHC cavity

Trapping studies —> 100 µT with free orientation

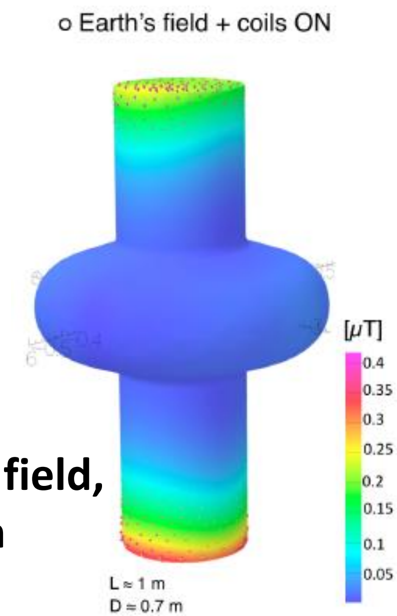
Proposed: solenoid + 2 X cos theta saddle coils



Transverse distribution result



Practically homogenous field can be reached ➡ Earth's field can be minimized to ~ 0.25 µT in the volume of a LHC cavity



Active shielding is very efficient in creating homogeneous field, hence a good candidate for a cryomodule implementation

Anton Evgeniev Ivanov, Tues. 06/25 14:00-14:15
Active Shielding for Cryomodules
https://indico.cern.ch/event/656491/contributions/2932265/

High Efficiency Klystrons

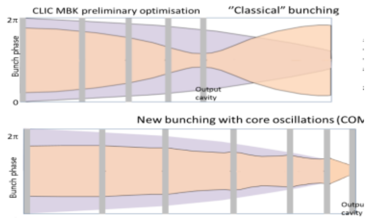
- Increasing energy efficiency & reducing energy demand critical for future accelerators such as FCC
- High Efficiency International Klystron Activity led by CERN
- KlyC1D & KlyC2D codes, cross-checked with other platforms

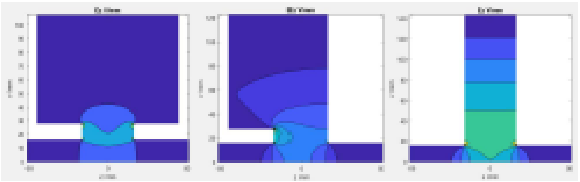
- Development of new klystron bunching technology with increased efficiency (Core Oscillation Method [COM])
- Prototype for high efficiency CSM tube

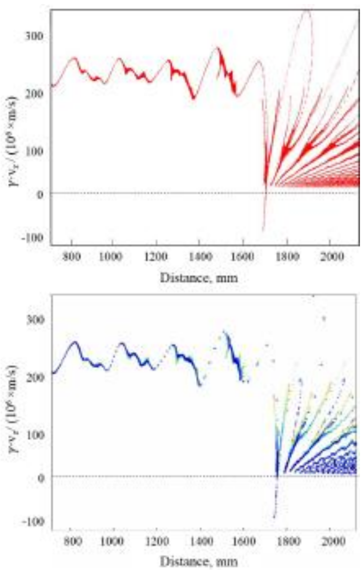
KlyC: 1.5-D Large-Signal Simulation Code for Klystrons

Jinchi Cai and Igor Syratchev,

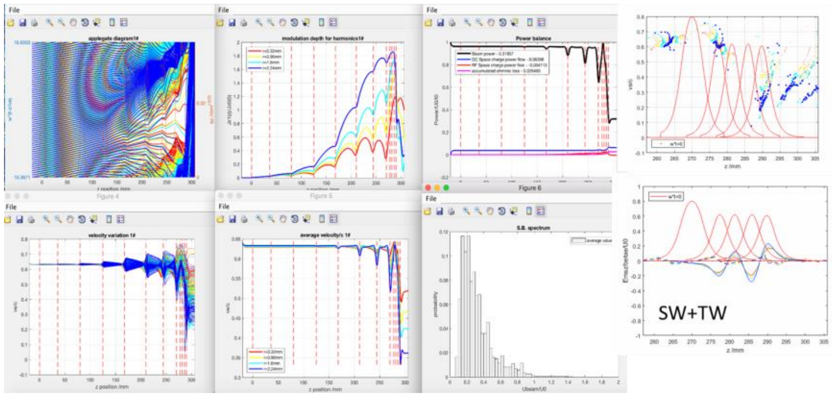
IEEE TRANSACTIONS ON PLASMA SCIENCE, VOL. 47, NO. 4, APRIL 2019



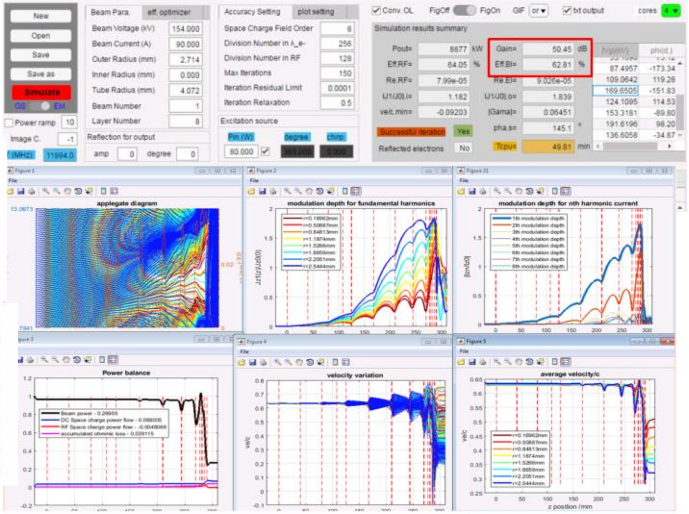




- KlyC optimization is done with the field from real cavity design
- Eff=58.5%
- Min(ve/c)=0.045
- Emax=73kV/mm
- CST model is re-tuned accordingly with every feature included



Optimized design with 4-cell coupler (KlyC)



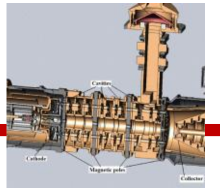
62.8% efficiency (E_{max}=90MV/m)

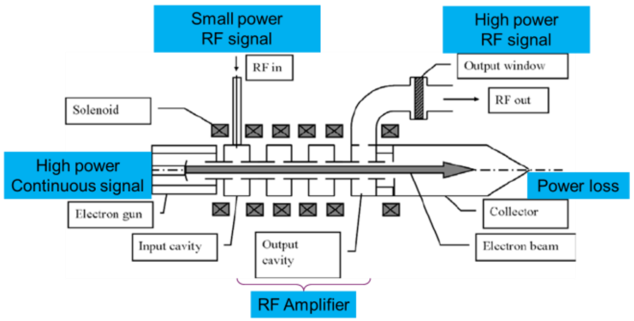
Jinchi Cai, Tues. 06/25, 14:15 -14:30

High efficiency klystrons development at CERN

https://indico.cern.ch/event/656491/contributions/2932265/

High Efficiency Klystron



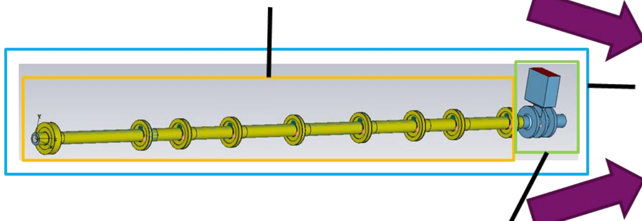


Efficiency : $\eta = \frac{P_{RF\,out}}{P_{electron\,beam}}$ (Neglecting the solenoid power)

Bunching circuit optimization (part 2)

Solver: AJDISK (disk-model code for klystrons simulation)

Optimizer : GOSET (genetic algorithm on Matlab freely available)



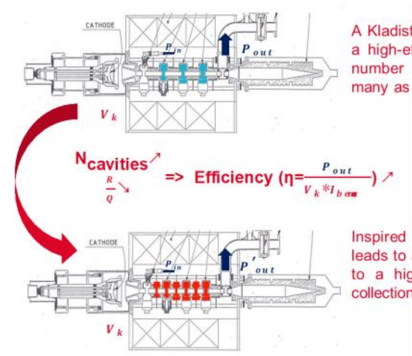
Tube simulation (part 4)

Klyc (code for klystron from CERN)

Multicell output cavity optimization (part 3)

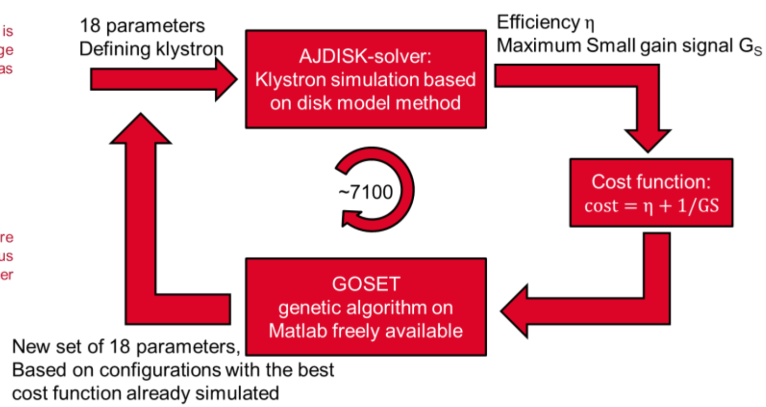
Solver: COMSOL (2D eigen mode)

Optimizer : GOSET (genetic algorithm on Matlab freely available)



A Kladistron (Kl-adi(adiabatic)-stron) is a high-efficiency klystron with a large number of cavities (at least twice as many as in a classical klystron).

Inspired by RFQ, this architecture leads to a smoother bunching and thus to a higher efficiency due to better collection in decelerating cavity.



ARIES Workshop on Energy Efficient RF
18-20 June 2019
Ångström Laboratory

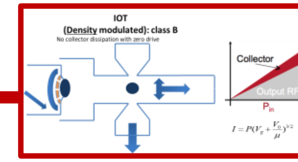
18-20 Jun 2019
Europe/Stockholm
Ångström Laboratory
10132 Häggsalen
Lägerhyddsvägen 1,Uppsala

Armel Beunas, Tues. 06/25 14:00-14:15

Towards a high efficiency klystron for LHC

https://indico.cern.ch/event/656491/contributions/2932265/

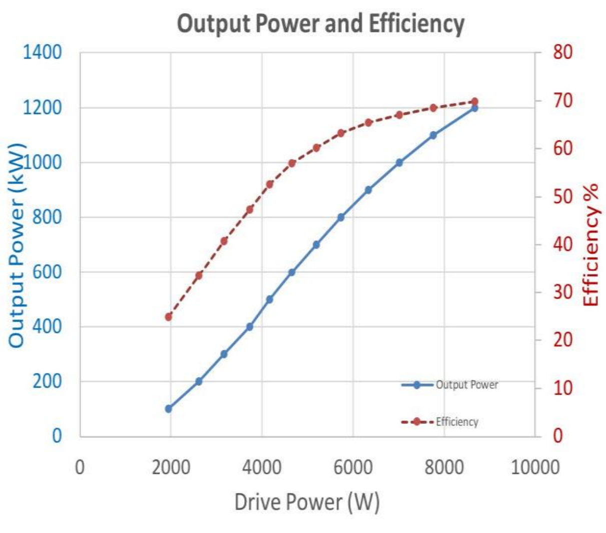
High Power IOT development



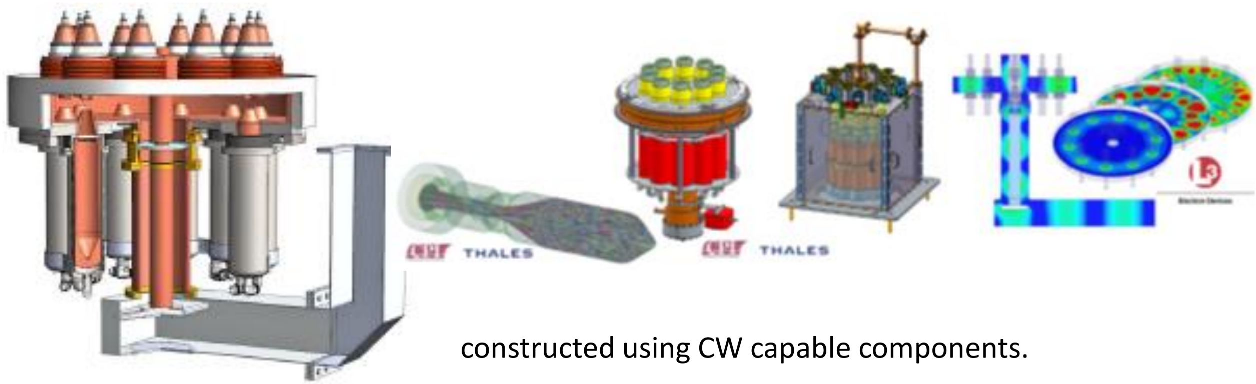
- *L3 Electron Devices*
- Consortium of *Thales Electron Devices (TED)* and *Communications & Power Industries (CPI)*

Key Parameters	Specification
Frequency	704.42 MHz
Maximum Power	1.2 MW
RF Pulse length	Up to 3.5 ms (@ 14 Hz)
Duty factor	Up to 5%
Efficiency	Target > 65%
High Voltage	< 50 kV
Design Lifetime	> 50,000 hrs

- CERN to set up a test stand and carry out site testing



2 successful IOT technology demonstrators



constructed using CW capable components.

- 10 Electron guns placed in a circle
- Cavity with 10 separate interaction gaps and single output
- Magnetic focusing (Permanent magnet or solenoid)
- Output windows based on high power klystron designs
- Suppliers carried out extensive modelling and simulation (beam optics, mode analysis, thermal and structural analysis, innovative manufacturing, …)
- Manufacturing validation : single beam prototyping and sub-assembly test vehicles, …
- Design driven by reliability and efficiency

MBIOTs delivered to CERN for testing
Both MBIOTs have delivered 1.2 MW
Overall Technical Specification achieved

Morten Jensen, Tues. 06/25 14:00-14:15

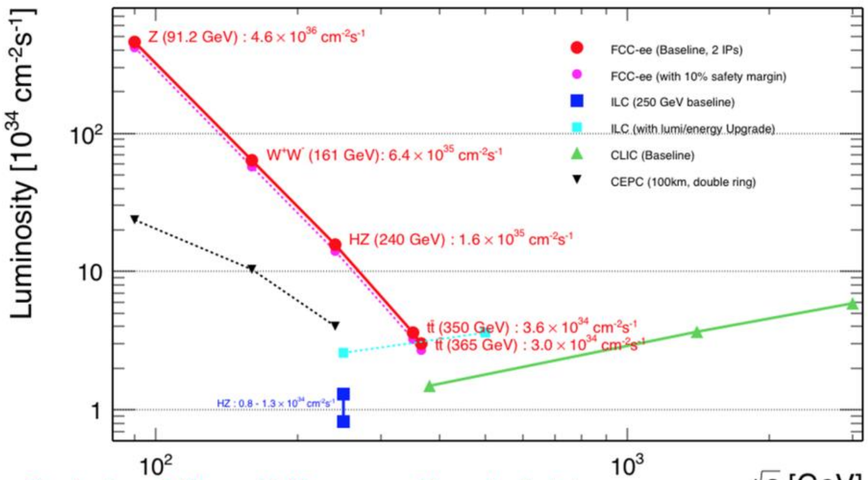
Test results and Operational experience of the High Power IOT development for ESS

https://indico.cern.ch/event/656491/contributions/2932265/

FCC-e$^+$e$^-$ ERL Option

Green FCC ee with 10% of R-R power consumption

Note that 100 MW SR power is not what we are proposing*



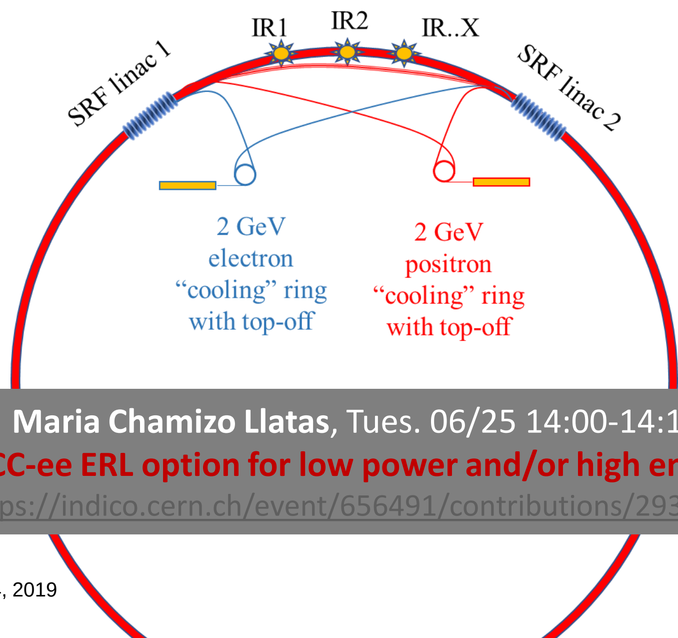
*Luminosity scaled linear with SR power – would see other limitations

ERL option, in combination with 2 GeV cooler rings, would be advantageous for FCC ee high energy operation (>46.5 GeV)

Allows both significant (6-fold to 10-fold) reduction in required RF power while delivering higher luminosities at top energies

No problem with beam stability in ERL – the average current is very low. Modern HOM dumpers will be sufficient to keep beams stable.

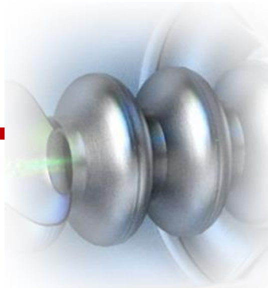
So far no showstoppers for this version of FCC-e$^+$e$^-$



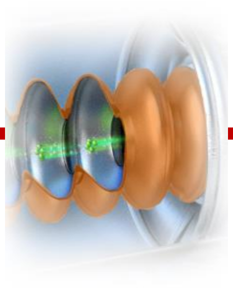
Maria Chamizo Llatas, Tues. 06/25 14:00-14:15

FCC-ee ERL option for low power and/or high energy

https://indico.cern.ch/event/656491/contributions/2932265/



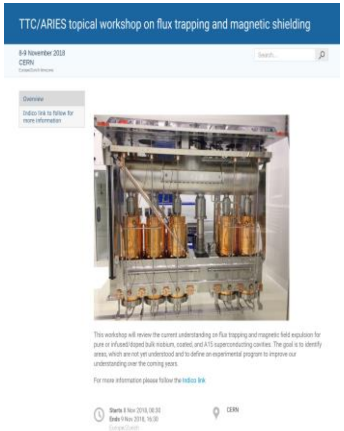
CONCLUSIONS

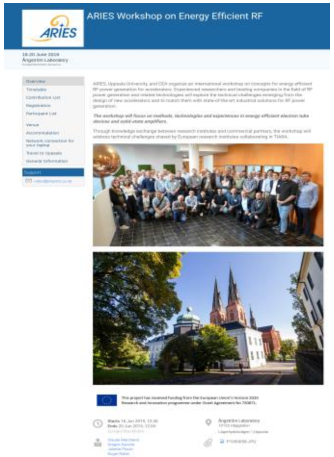


Robust R&D programs and significant progress in the past year for both
SRF surface & manufacturing
Power sources

Developments in this framework will benefit all the FCC schemes and machines beyond

Active collaborations in R&D





MERCI
DANK U

THANK YOU