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Set of RF parameters for the FCC-ee machines

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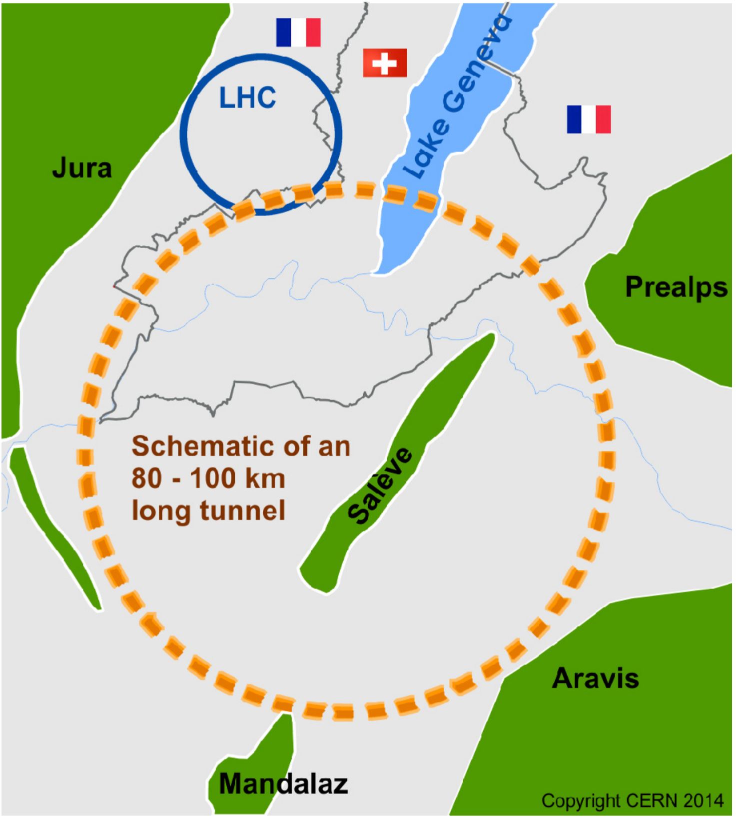
& the FCC RF Working Group

presented by Erk Jensen
CERN
SRF 2017, Lanzhou, China

Outline

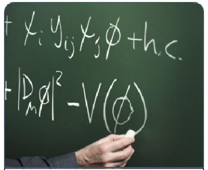
- Introduction: What is the FCC and what are its challenges
- Parameter choices & Layout
- Staging scenarios
- Nb on Cu – potential advantages
- Relevant R&D subjects at a glance
- Summary

The **F**uture **C**ircular **C**ollider Study

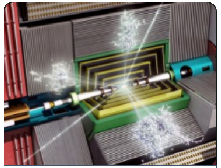


International FCC collaboration (CERN as host lab) to study:

- ***pp*-collider (*FCC-hh*)**
  → main emphasis, defining infrastructure requirements
  ~16 T ⇒ 100 TeV *pp* in 100 km
- **~100 km tunnel infrastructure** in Geneva area, site specific
- **e^+e^- collider (*FCC-ee*),** as potential first step **(SRF challenge!)**
- ***p-e* (*FCC-he*) option,** integration one IP, e from ERL
- **HE-LHC** with *FCC-hh* technology
- **CDR for end 2018**

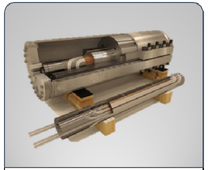


Physics Cases



Experiments

Collider Designs



R&D Programs

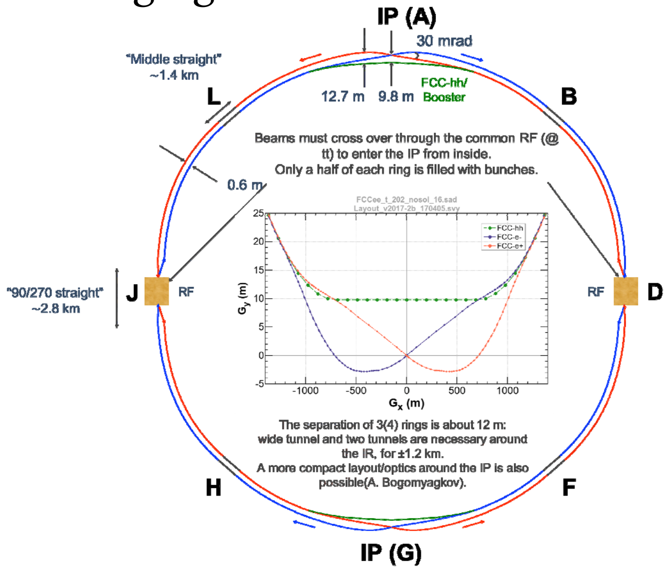
Infrastructures

Cost Estimates

The FCC-ee is similar to the CEPC

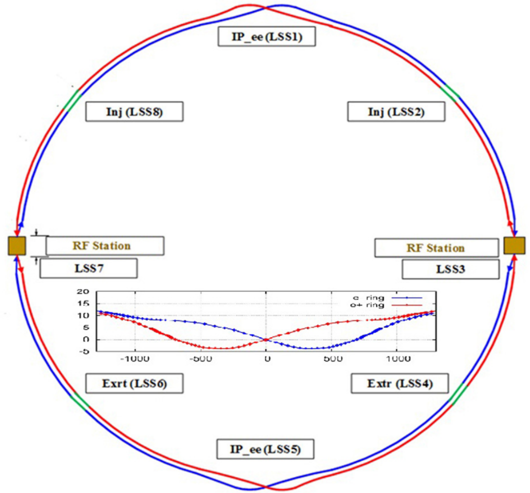
FCC-ee

- 100 km circumference
- Z, W, Higgs & $t\bar{t}$
- Staging



CEPC

- 100 km circumference
- Z, W, Higgs
- Staging not foreseen



Parameters and challenges

	Z	W	H	$t\bar{t}$	unit
Energy (per beam)	45.5	80	120	175	GeV
Luminosity	10^{36}	$1.8 \cdot 10^{35}$	$5 \cdot 10^{34}$	10^{34}	$cm^{-2}s^{-1}$
Current	1450	150	30	6.5	mA
Voltage	0.25	0.8	3	10	GV
RF Power (per beam)	50	50	50	50	MW

- Requires a large scale, highly reliable RF system, to deliver 100 MW in CW!
- … under varying beam current conditions
- Energy efficiency is a major concern
- R&D in these different areas has been launched and is progressing (1 MW CW FPC’s, high efficiency klystrons, Nb on Cu cavity technology, low impedance crab cavities, …

RF System for FCC

Sequence of 5 different machines ranging from high current to high gradient:

- with maximum re-use of components and
- minimum down-time for the installation of upgrades

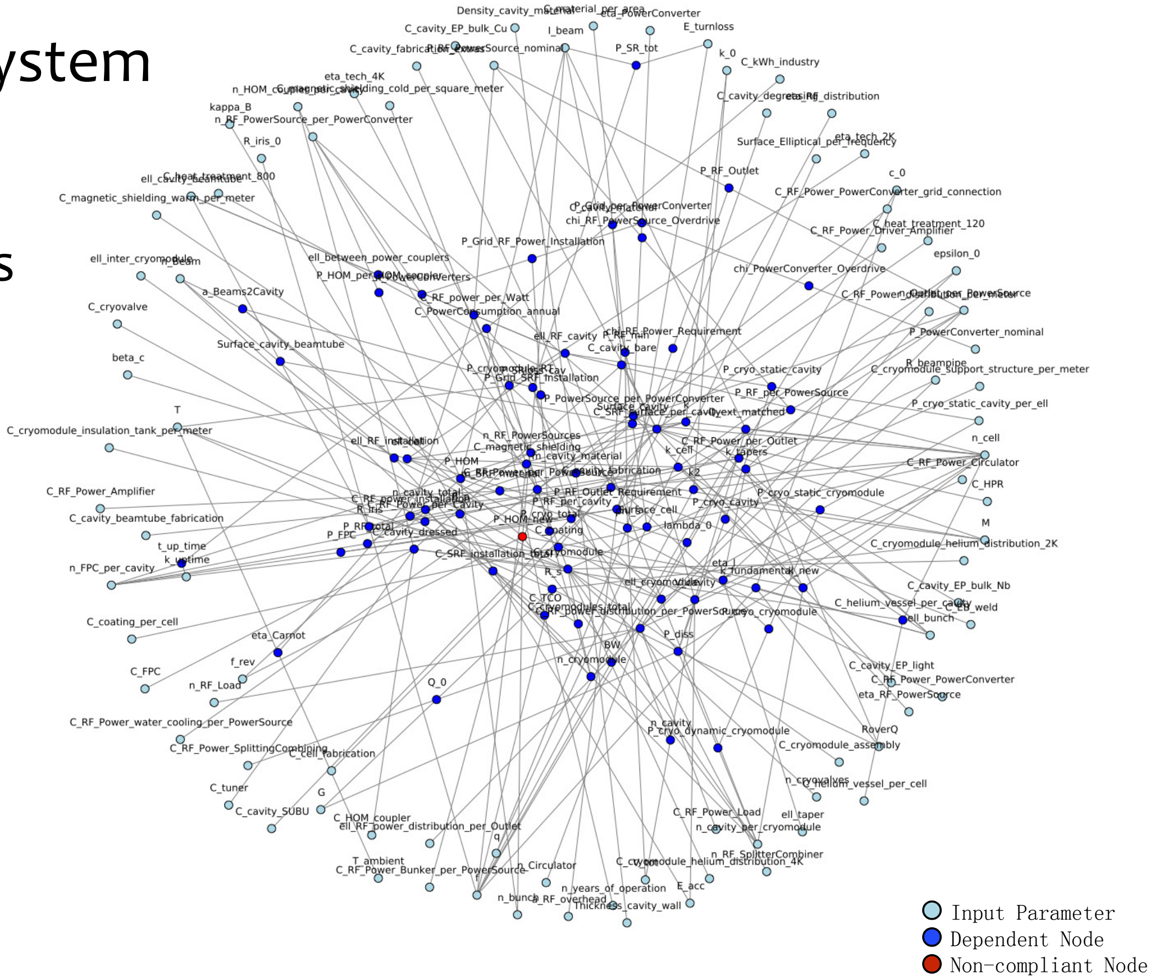
	V_tot (GV)	n_bunch	I_beam (mA)	σ (mm)	E_turnloss (GeV)
FCC-hh	0.032		500		
Z	0.4 / 0.2	30180 / 91500	1450	0.9/1.6	0.03
W	0.8	5260	152	2	0.33
H	3	780	30	2	1.67
t	10	81	6.6	2.1	7.55

Challenges:

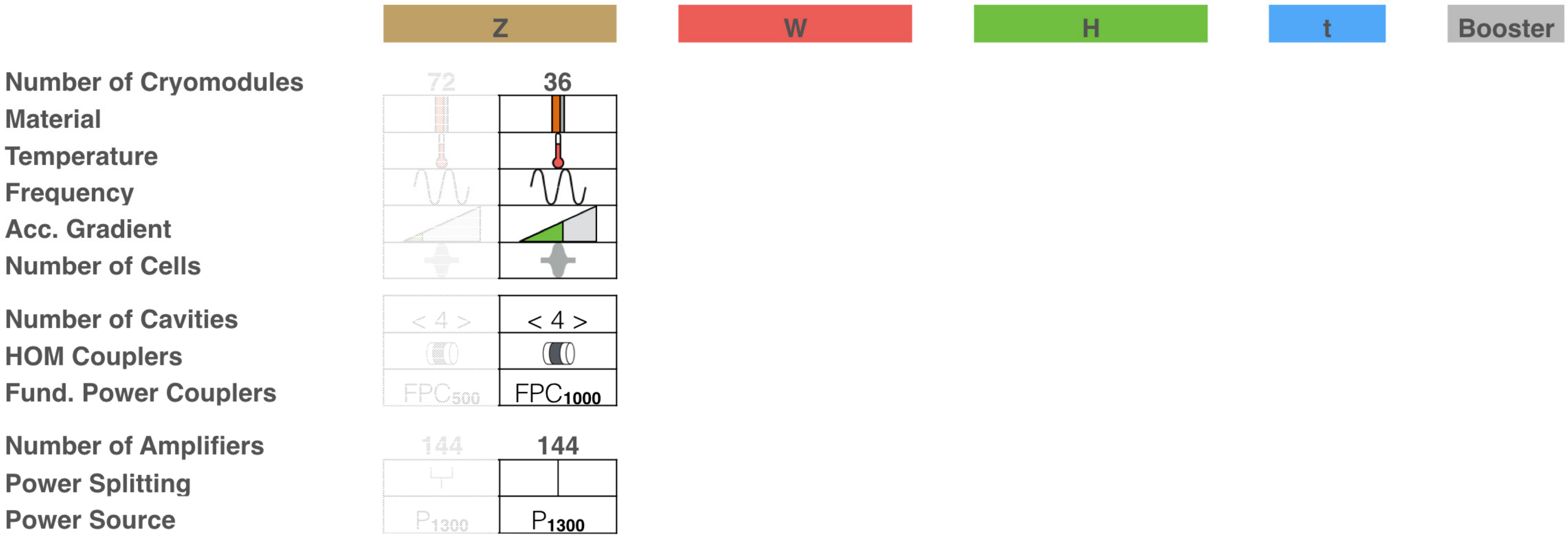
- Dynamic environment with changing parameters
- RF System between the technical feasible and R&D projects

Full Model of the RF System

- Model of all dependencies
- Study of parameter choices
- Direct comparison of scenarios
- Sensitivity analysis
- Constant monitoring of all constraints for non-compliance



Parameter Layout



Z

Constraints

- Wide aperture —> 400 MHz
- low number of cavities —> 10 MV/m

Fall-back for FPC —> lower field

Further developments

- Need for FPC up to 1 MW
- HOM Load Study
- HOM Coupler and Absorber Design

Parameter Layout

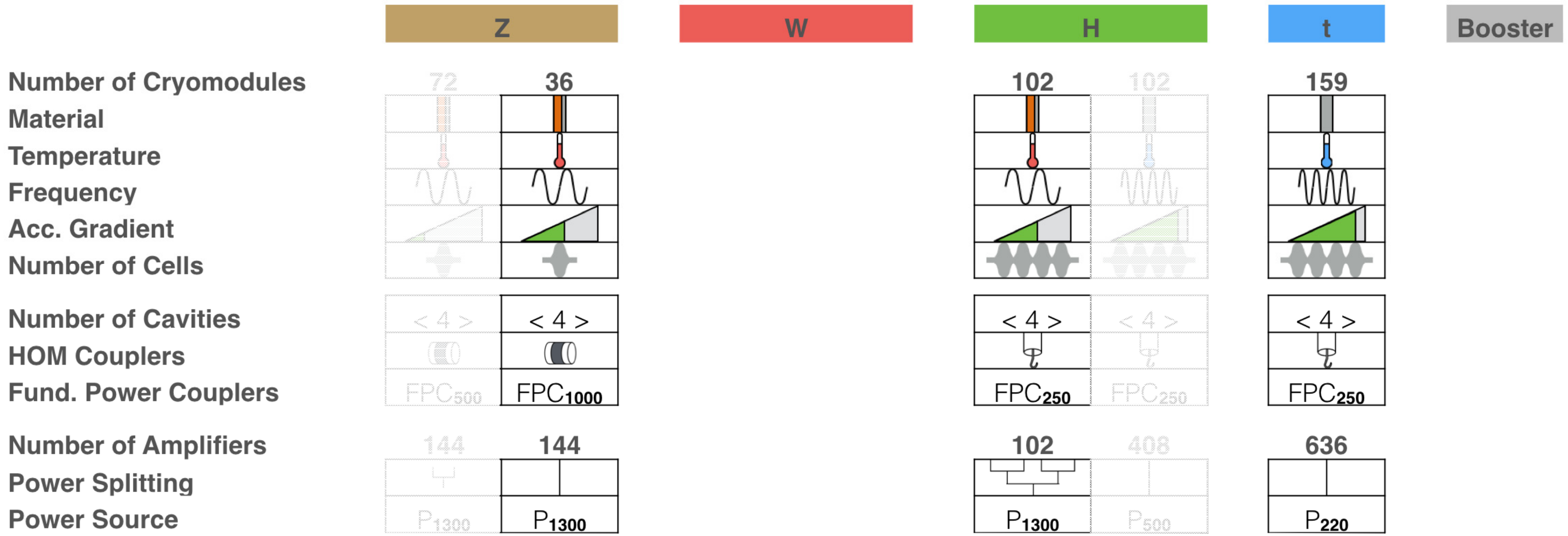
	Z		W	H	t	Booster
Number of Cryomodules	72	36			159	
Material						
Temperature						
Frequency						
Acc. Gradient						
Number of Cells						
Number of Cavities	< 4 >	< 4 >			< 4 >	
HOM Couplers						
Fund. Power Couplers	FPC$_{500}$	FPC$_{1000}$			FPC$_{250}$	
Number of Amplifiers	144	144			636	
Power Splitting						
Power Source	P$_{1300}$	P$_{1300}$			P$_{220}$	

t

Constraints

- Both beams go through the same cavities and beam pipe
- Beam-pipe and installation need to be re-aligned
- For the needed total voltage of 10 GV use of **bulk Nb** at 20 MV/m
- Change of Frequency to **800 MHz**
- RF power requirements are low and may be fulfilled with small sources such as SSPA

Parameter Layout



H

SRF Performance Nb/Cu has the potential to compete with bulk Nb

- maximise use of **400 MHz** equipment
- ease installation effort
- slight cost reduction

Fall-back for Nb/Cu —> bulk Nb @ 800 MHz

Parameter Layout

	Z		W		H		t	Booster
Number of Cryomodules	72	36	56	28	102	102	159	
Material								
Temperature								
Frequency								
Acc. Gradient								
Number of Cells								
Number of Cavities	< 4 >	< 4 >	< 4 >	< 4 >	< 4 >	< 4 >	< 4 >	
HOM Couplers								
Fund. Power Couplers	FPC_{500}	FPC_{1000}	FPC_{500}	FPC_{1000}	FPC_{250}	FPC_{250}	FPC_{250}	
Number of Amplifiers	144	144	108	112	102	408	636	
Power Splitting								
Power Source	P_{1300}	P_{1300}	P_{1300}	P_{1300}	P_{1300}	P_{500}	P_{220}	

W

Machine runs for only 2 years:

- Effort can be reduced by either using equipment similar to the Z- or the H-machine
- Using H-machine cavity with stronger HOM couplers gives advantages for installation

Further developments

- Need for FPC up to 1 MW
- High HOM Load Study
- HOM Coupler and Absorber Design

Fall-back for FPC —> lower field

Parameter Layout

	Z		W		H		t	Booster
Number of Cryomodules	72	36	56	28	102	102	159	159
Material								
Temperature								
Frequency								
Acc. Gradient								
Number of Cells								
Number of Cavities	< 4 >	< 4 >	< 4 >	< 4 >	< 4 >	< 4 >	< 4 >	< 4 >
HOM Couplers								
Fund. Power Couplers	FPC_{500}	FPC_{1000}	FPC_{500}	FPC_{1000}	FPC_{250}	FPC_{250}	FPC_{250}	FPC_{25}
Number of Amplifiers	144	144	108	112	102	408	636	636
Power Splitting								
Power Source	P_{1300}	P_{1300}	P_{1300}	P_{1300}	P_{1300}	P_{500}	P_{220}	P_{25}

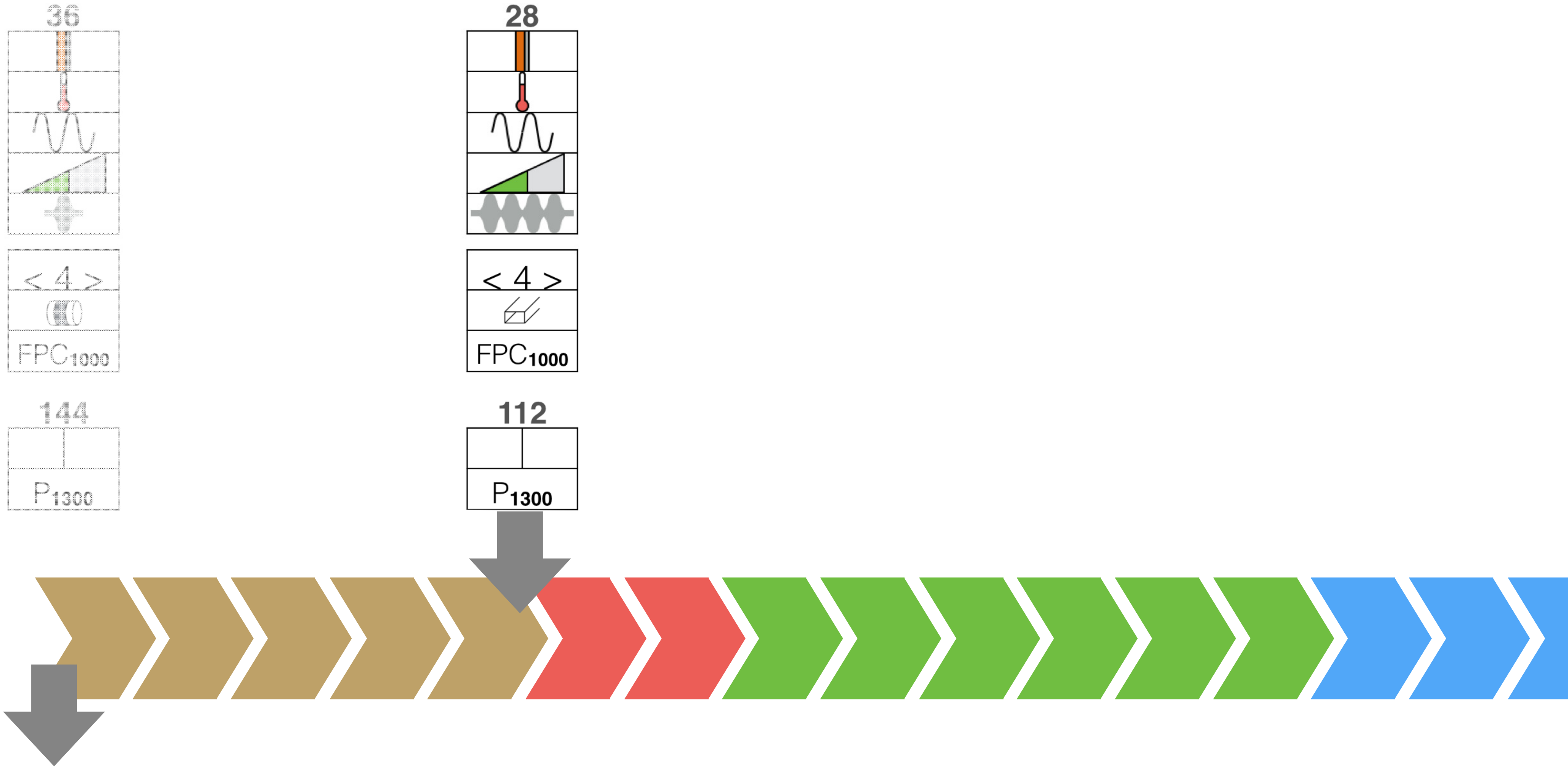
Booster

- Booster needs to accelerate up to 0.255 …9.5 GV
- Installation in stages
- Use same cryomodules as for t-machine
- Low RF power requirement (10%) allow for small individual RF sources per cavity or module

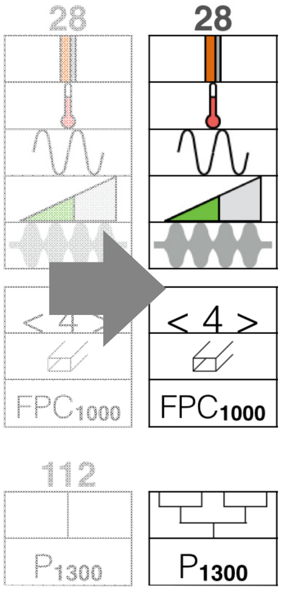
Parameter Layout (Values)

	Z		W		H		t	Booster
	* fall back for FPC		* fall back for FPC			* fall back for SRF Material		
Number Cryomodules	**72**	**36**	**56**	**28**	**102**	**102**	**159**	**159**
Material	Nb/Cu	Nb/Cu	Nb/Cu	Nb/Cu	Nb/Cu	bulk Nb	bulk Nb	bulk Nb
Temperature	4.5 K	4.5 K	4.5 K	4.5 K	4.5 K	2 K	2 K	2 K
Frequency	400 MHz	400 MHz	400 MHz	400 MHz	400 MHz	800 MHz	800 MHz	800 MHz
Acc. Gradient	5 MV/m	10 MV/m	5 MV/m	10 MV/m	10 MV/m	20 MV/m	20 MV/m	20 MV/m
Number of Cells	1	1	4	4	4	4	4	4
Number of Cavities	4 / CM	4 / CM	4 / CM	4 / CM	4 / CM	4 / CM	4 / CM	4 / CM
HOM Couplers	~3 kW	~3 kW	~1 kW	~1 kW	< 1 kW	< 1 kW	< 1 kW	< 1 kW
Fund. Power Couplers	~500 kW	~ 1 MW	~500 kW	~ 1 MW	~250 kW	~250 kW	~250 kW	~25 kW
Number of RF Sources	**144**	**144**	**108**	**112**	**102**	**408**	**636**	**636**
Power Splitting	2	1	2	1	4	1	1	1
Power Source	~1.3 MW	~1.3 MW	~1.3 MW	~1.3 MW	~1.3 MW	~500kW	~220kW	~25kW

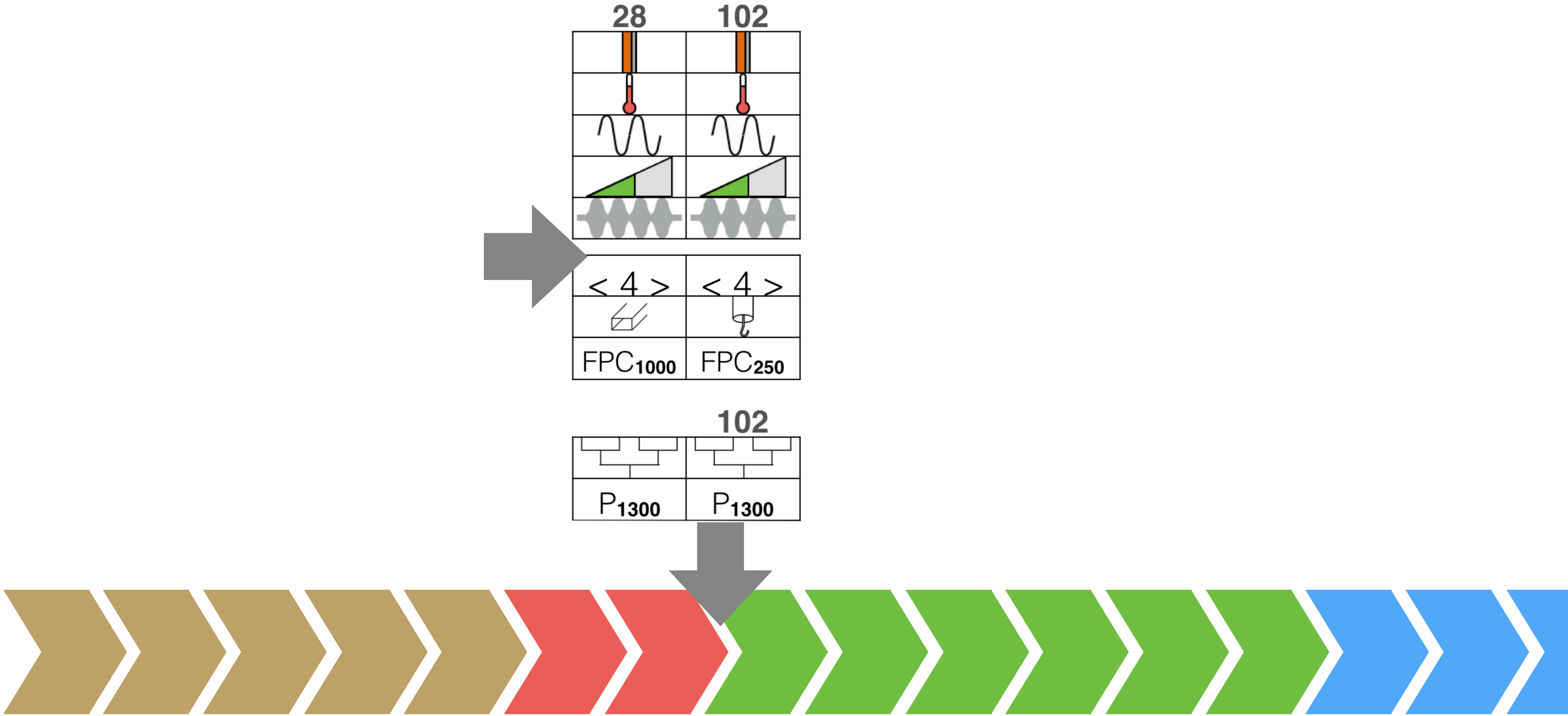
Staging Scenario



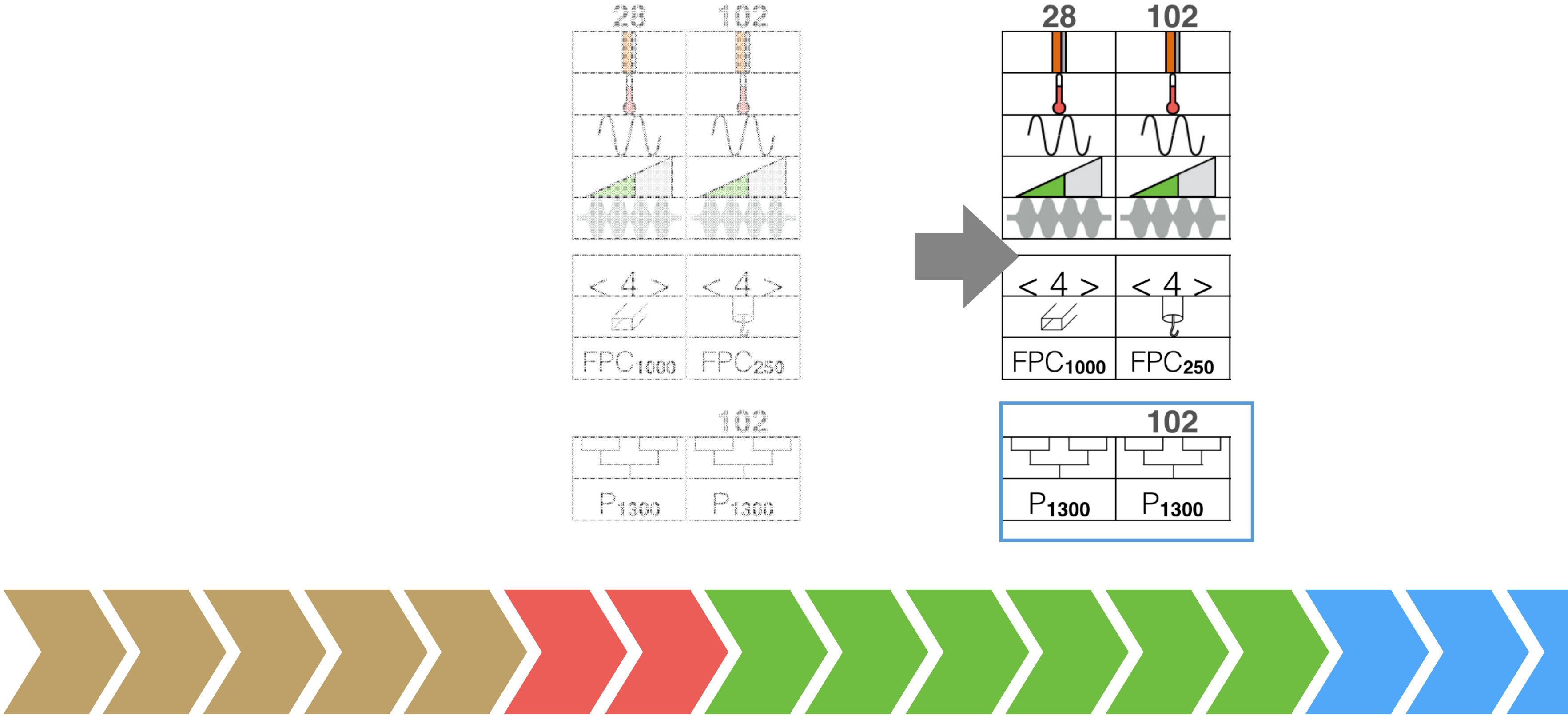
Staging Scenario



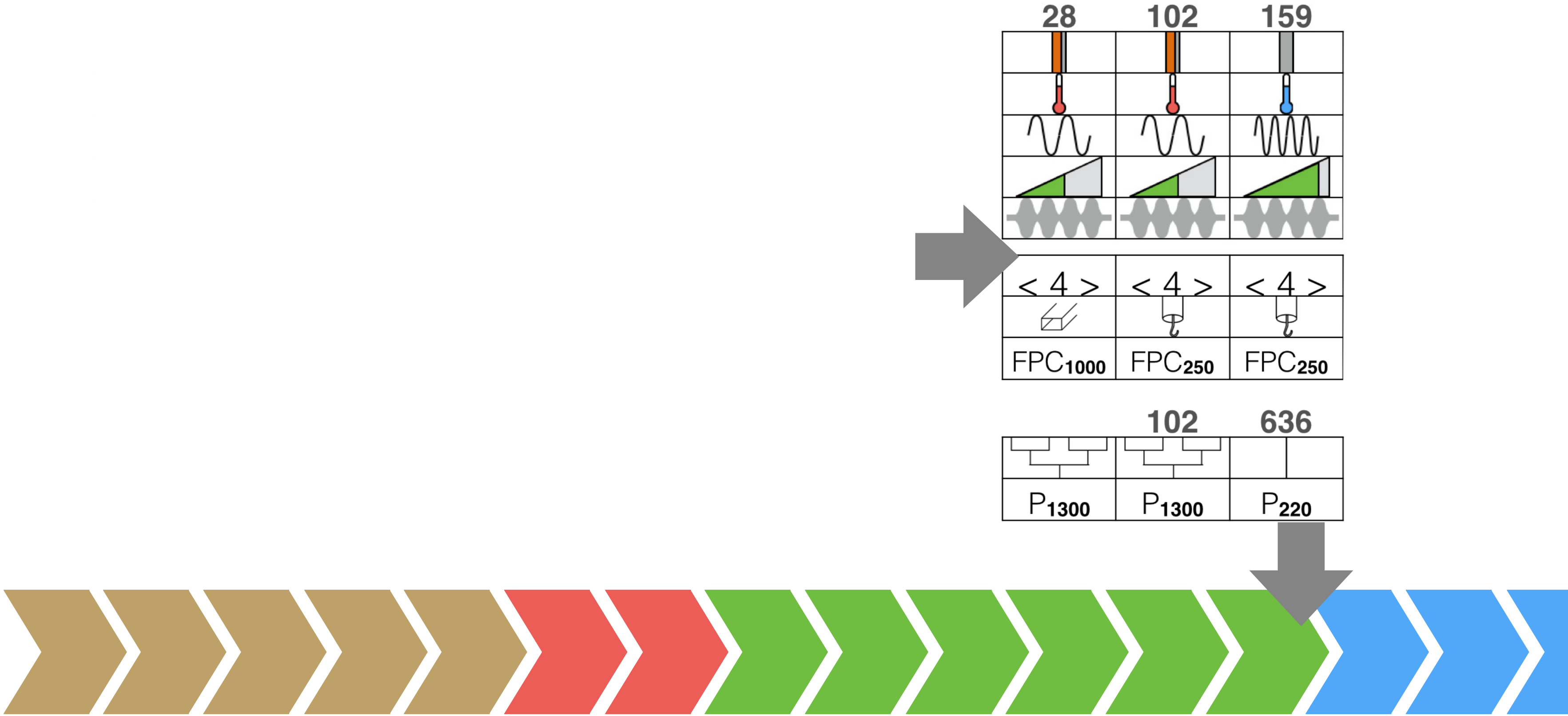
Staging Scenario



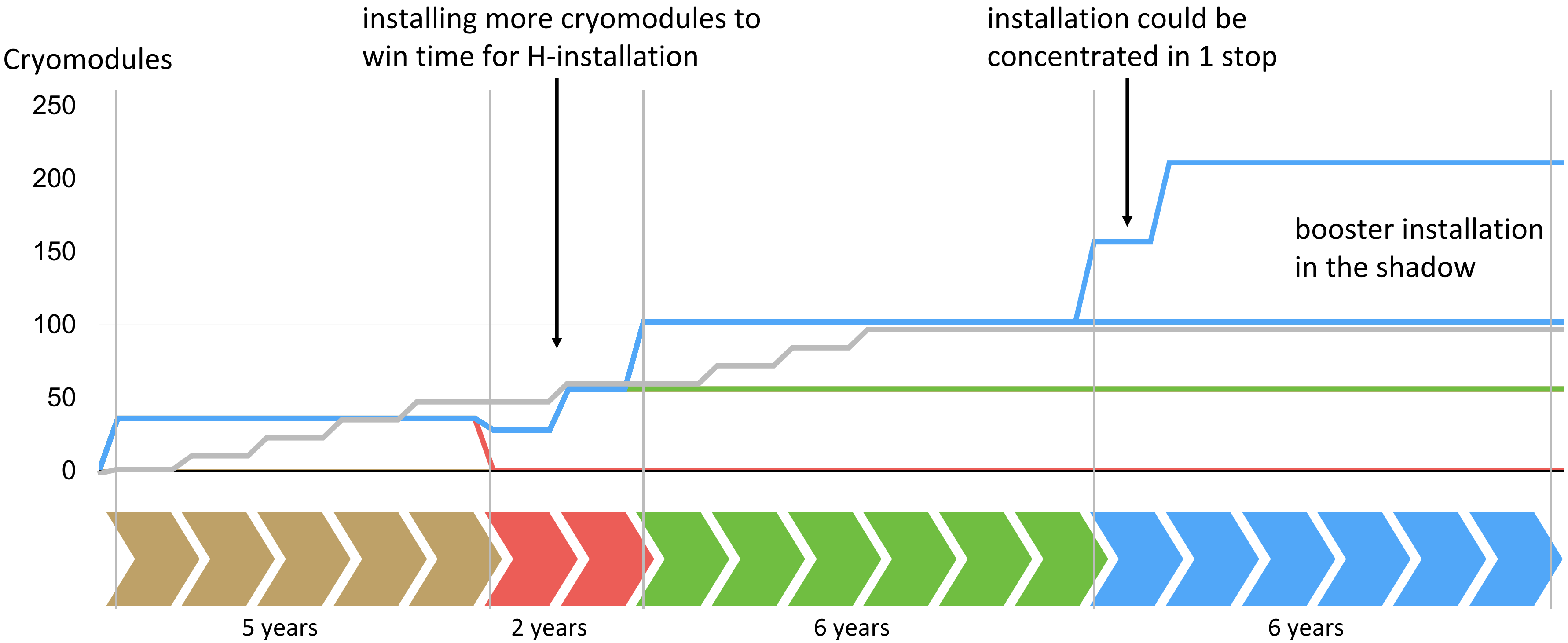
Staging Scenario



Staging Scenario



Installation Sequence



Installation pace during LEP: up to 30 cryomodules per 4 months break

Cryogenic Consumption for FCC-ee H: bulk Nb vs. Nb/Cu

Cryogenic power consumption is one of the cost drivers in a CW machine, in particular for FCC-ee

Machine Impedance

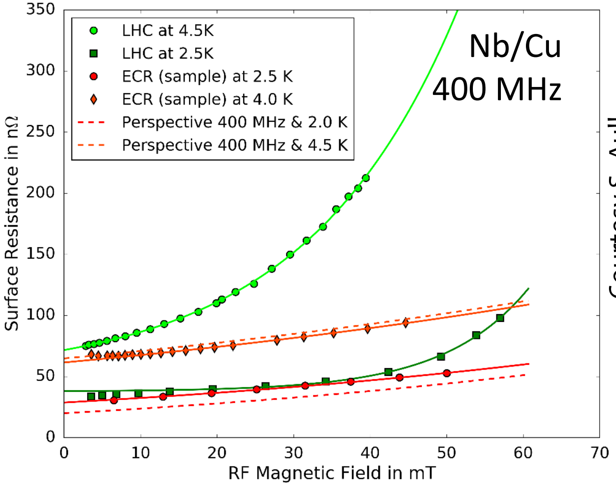
Design Choice

$$P_{cryo,grid} \sim \frac{V^2}{R/Q}\frac{1}{Q_0} \sim R_S\,(f, T, \ell, E_{acc})$$

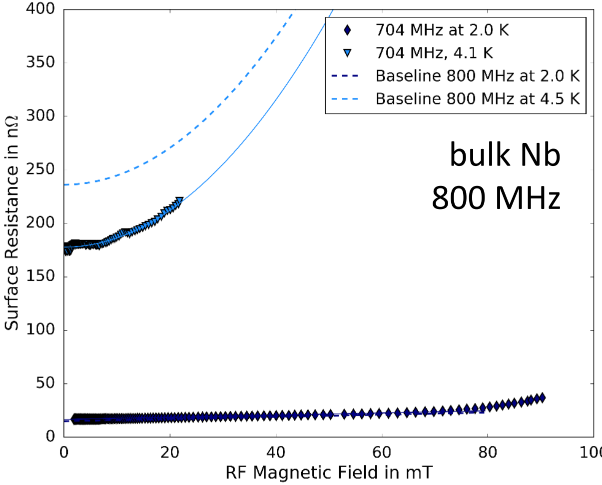
Material

Approach:

- Collect representative Rs(f, T, l, Eacc) data
- Define baseline performance
- Calculate the cryogenic consumption for each (material, frequency, temperature, field)-combination



Courtesy S. Aull



A. Macpherson, MOPB074, SRF2015

Cryogenic Consumption for FCC-ee H: bulk Nb vs. Nb/Cu

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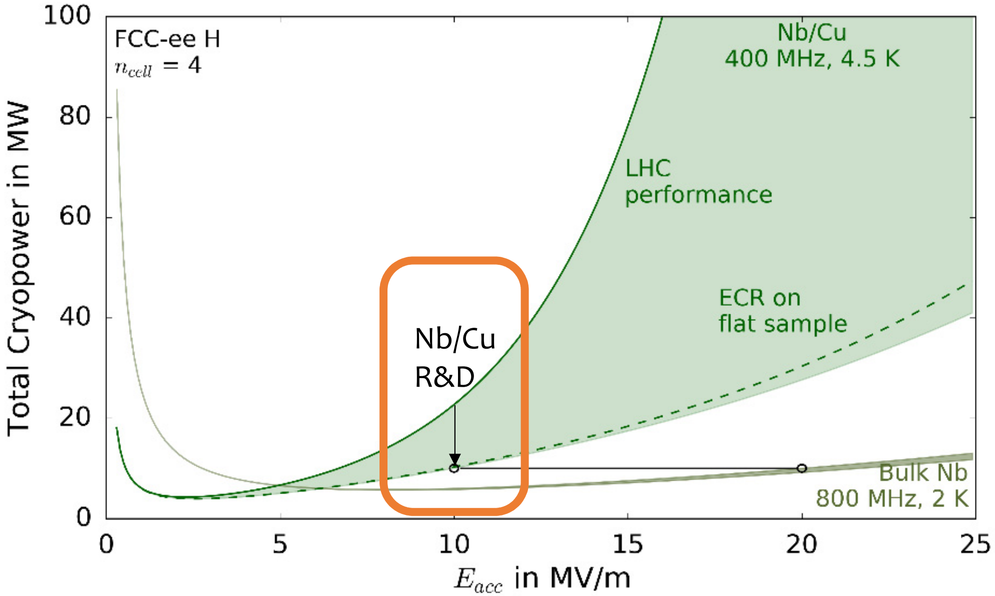
Machine Impedance

Design Choice

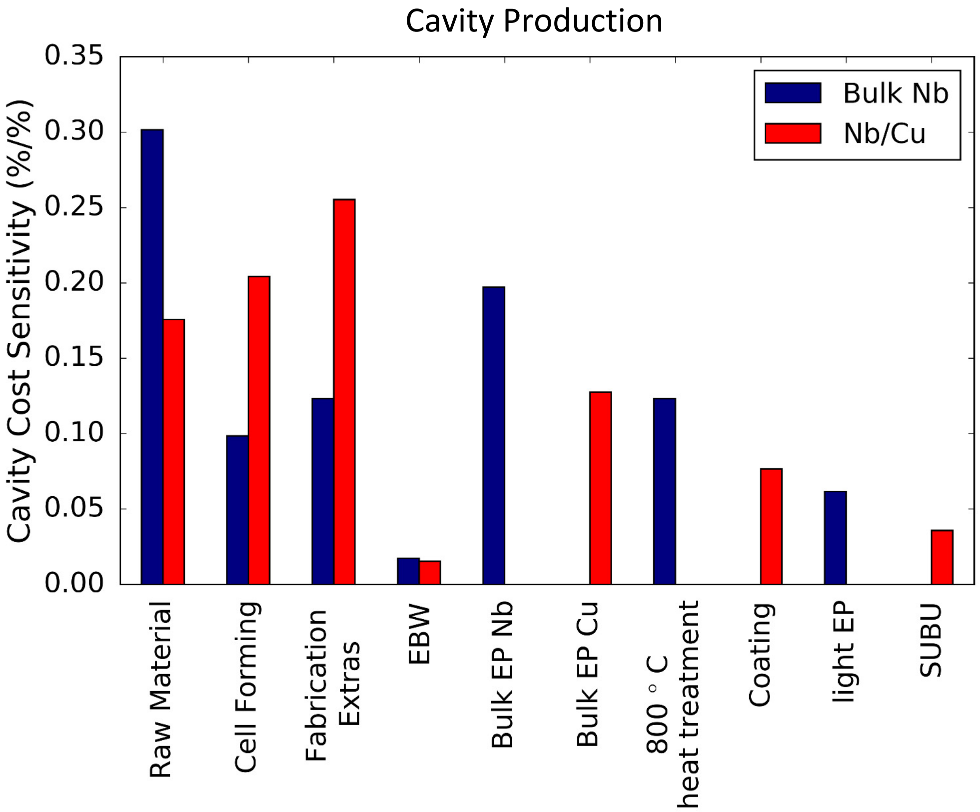
$$P_{cryo,grid} \sim \frac{V^2}{R/Q} \frac{1}{Q_0} \sim R_S\left(f, T, \ell, E_{acc}\right)$$

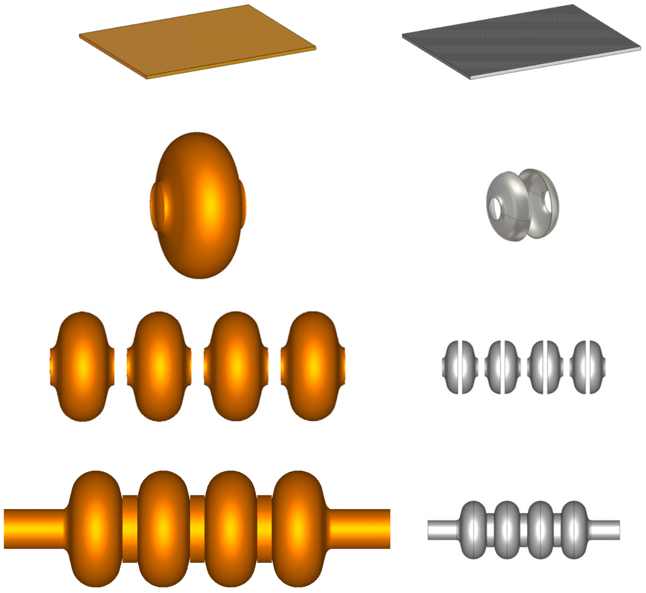
Material

Successful R&D on the energetic condensation techniques will make Nb/Cu at 400 MHz and 4.5 K **competitive** to bulk Nb at 800 MHz and 2.0 K in terms of cryogenic consumption

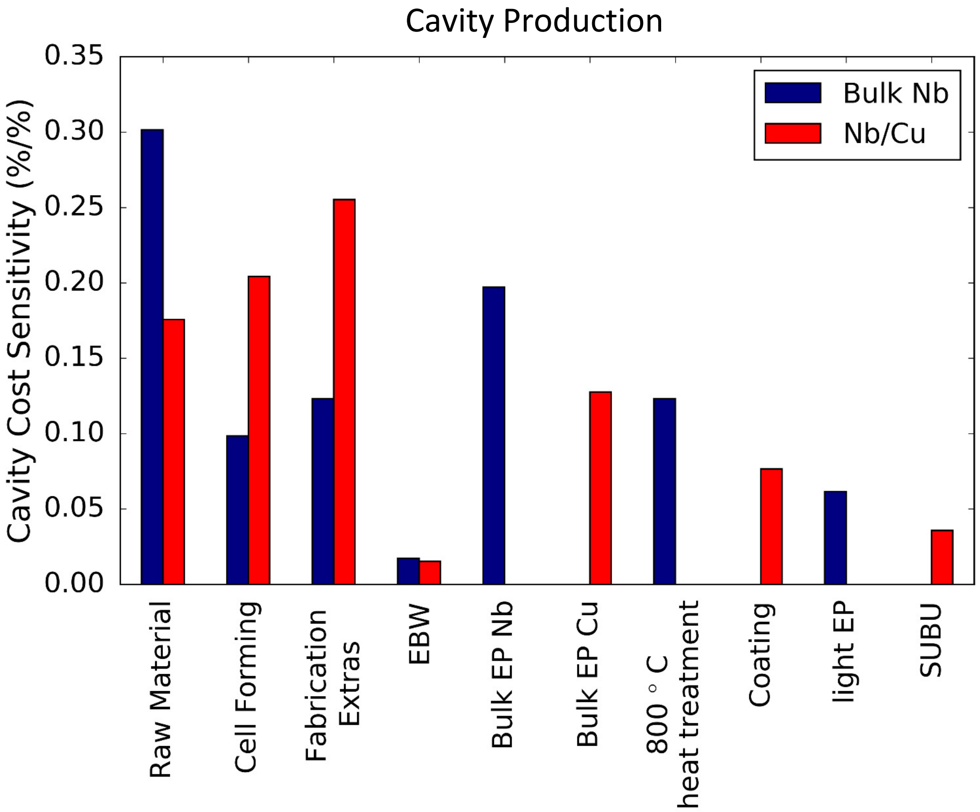


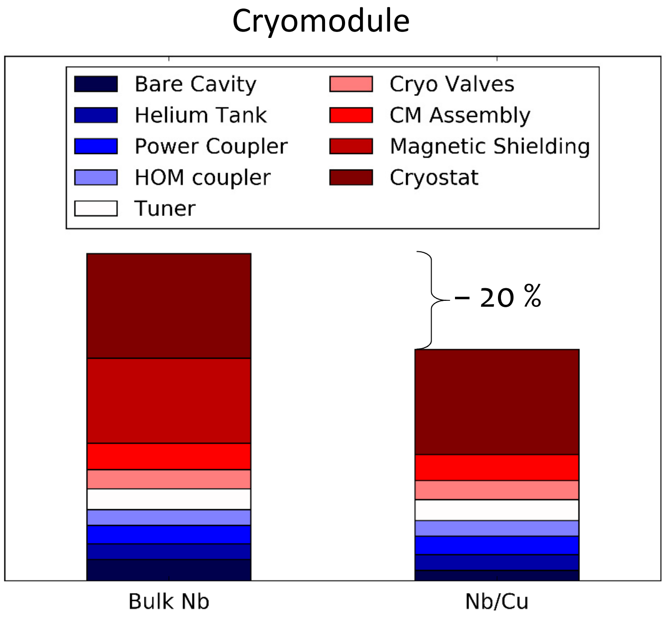
Cost Estimate
Sensitivity to Production Cost





Cost Estimate
Sensitivity to Production Cost





The cost for a CM with 400 MHz Nb/Cu cavities is **about 20 %** less than for a CM with 800 MHz bulk Nb cavities

Cavity design and beam-cavity interaction

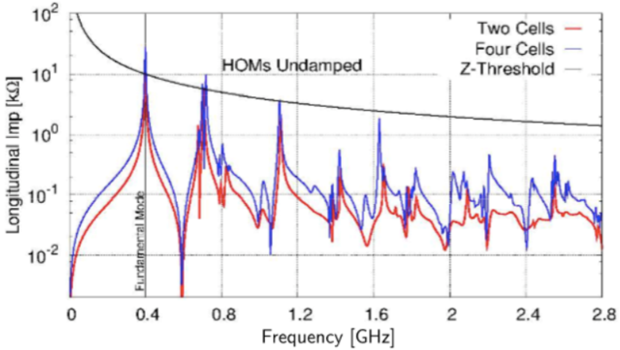
1. Cavity design:
    - High energy
        - Aim at acceleration efficiency
    - High intensity
        - Optimize cell shape with regard to HOMs
        - HOM damping schemes
2. Beam dynamics:
    - Single and coupled bunch stability
    - Impedance studies & HOM power
    - Implications of 5 ns bunch spacing for the FCC-hh injector chain
3. Analysis of the need for a RF harmonic system
4. Low Level RF

Verification of the conformity of the RF structures within the stability limits

Impedance Spectrum, Longitudinal

Coupled bunch threshold from τ_z lowest for Z (80 cavities, 2-Cell)

Cures: Strong damping, avoid main harmonics, single cell



Thresholds for W, H, T are far higher (higher energy)

J. E. Muller, E. Chapochnikova, R. Calaga, S. G. Zadeh

Universität Rostock

GOETHE UNIVERSITÄT FRANKFURT AM MAIN

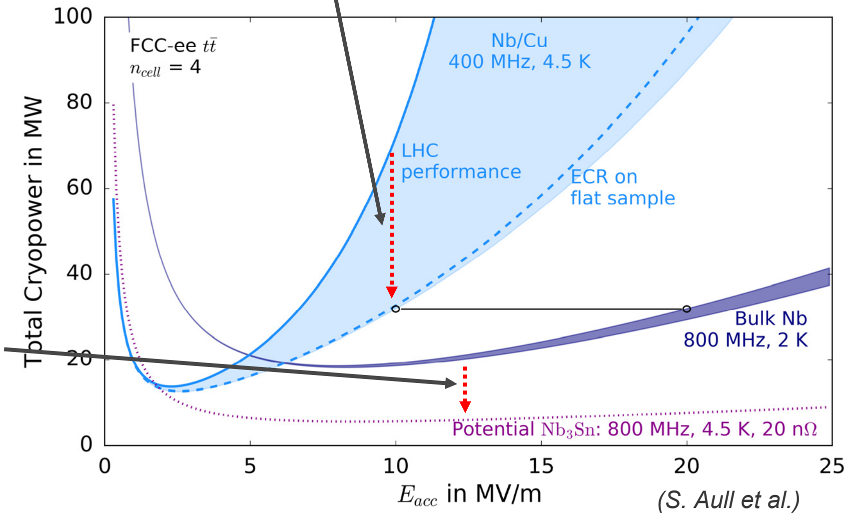
Cavity material & performance

Collaborative effort to evaluate and understand the ultimate performance of the 400 - 800 MHz cavities

1. Review of technology choices and limits
    - *SRF Material Options for FCC (S. Aull et al.)*
2. R&D and perspectives
    - Bulk Nb:
        - N_doping: (FNAL collaboration)
    - Nb/Cu:
        - Development of innovative coating techniques (HIPIMS (CERN), HIPIMS & ECR (JLAB), ECR (FNAL))
        - Improvement surface preparation and Nb coating (CERN-LNL-STFC collaboration)
        - Characterization facility and benchmarking (STFC)
    - Alternative materials A15, strong potential - long term R&D
        - Nb_3Sn on Nb (FNAL collaboration)
        - Nb_3Sn on Cu
        - V_3Si
    - Characterization facility and benchmarking (STFC, UNIGE, CERN)

Nb/Cu R&D program

A15 R&D program



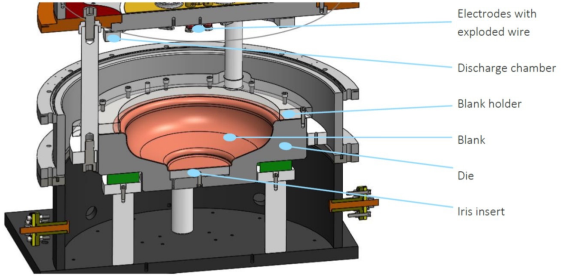
(S. Aull et al.)

Laboratori Nazionali di Legnaro

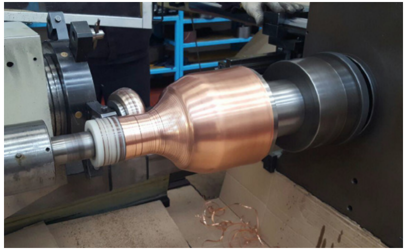
Innovative cavity fabrication techniques

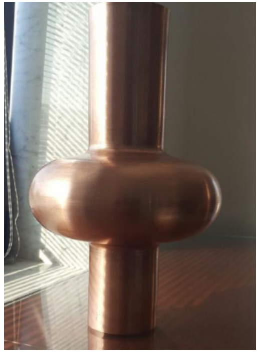
Development of fast & cost effective cavity fabrication techniques

1. High velocity hydroforming:
   - Determine forming limits of high-velocity Electro-Hydraulic Forming (EHF) for Cu structures as substrate for superconducting coating (and for bulk Nb)
2. Spinning:
   - Efforts towards seamless cavity fabrication (LNL)
3. Surface treatment: Electro-polishing:
   - Developments on vertical and/or horizontal EP for 400/800MHz copper cavities



C. Abajo Clemente & Bmax, 2017





E. Palmieri (LNL), FCC week 2016

Laboratori Nazionali di Legnaro

Jefferson Lab Thomas Jefferson National Accelerator Facility

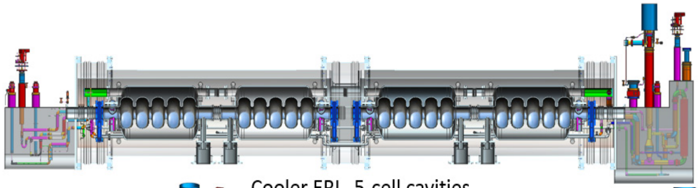
Bmax power to shape

Budker Institute of Nuclear Physics

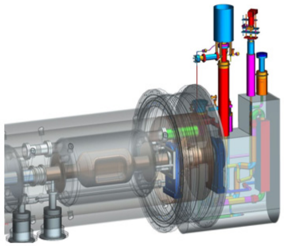
Cryomodule challenges

Specific topics of interest for FCC (and many other machines!)

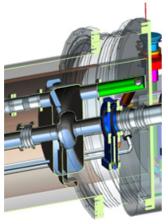
1. Modular CM design approach to hold various different cavities
2. Impact of cooling control on CM design
3. Optimisation of clean room assembly procedures
4. CM cost model



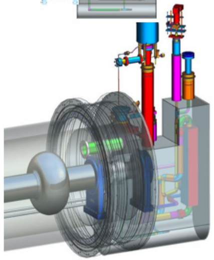
Cooler ERL, 5-cell cavities



476.3 or 952.6 MHz Crab cavity



952.6 MHz Ion ring concept



476.3 MHz 1-cell?

R. Rimmer (JLAB), FCC week 2016

Fundamental power couplers

Impedance reduction is crucial

→ minimize the number of cavities

→ more power per FPC (beyond the S-o-A)

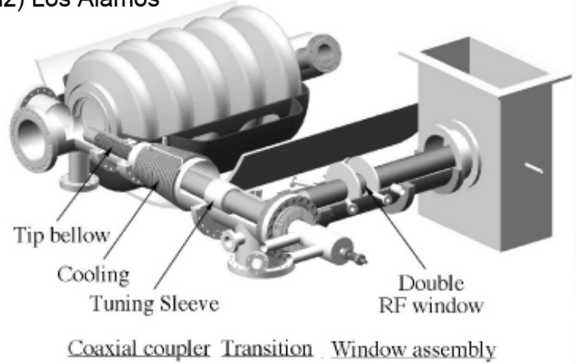
1. Very high CW power FPC (1MW?)
2. Variable and Adjustable FPC
   - Adaptable to different Q_{ext}
3. Large series production

E. Montesinos, CERN

High Power Couplers, examples

Highest CW power reached on a test stand

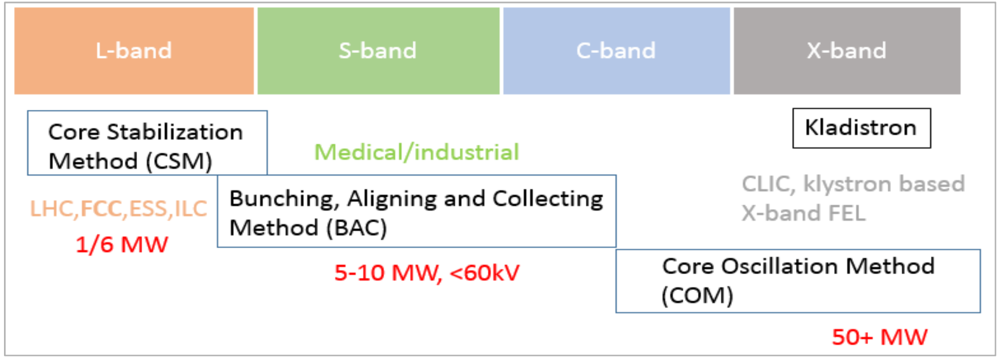
- APT coupler (700 MHz) Los Alamos
- Coaxial coupler
- Two RF windows
- High pumping speed
- 1 MW in TW
- 850 kW in SW



High efficiency klystron technology

FCC: 100 MW beam power ≈ 165 MW grid power
→ every 1% gain in efficiency ≈ 10 GWh/year (saves ≈ 0.4 M€/year)

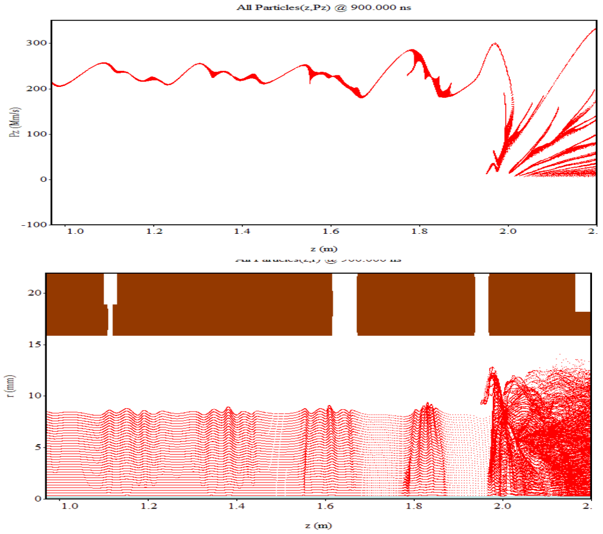
1. Development of new klystron bunching technologies to strongly increase RF power production efficiency was initiated at CERN in 2013 (HEIKA)
2. Fabrication of the first high efficiency CSM tube



HEIKA: High Efficiency International Klystron Activity
CSM: Core Stabilization Method

Single beam, 1.4 MW, 0.8 GHz, 133.9 kV, 12.551 A, m K=0.263

85.7% in PIC simulations



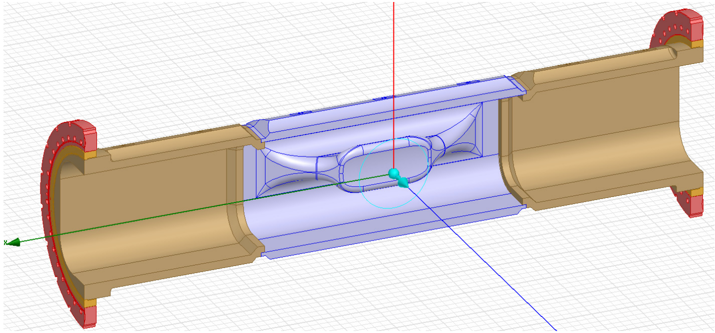
See I. Syratchev's talk on Tuesday

Innovative crab cavity design for FCC_hh

- Very interesting development which provides:
  - low longitudinal and transverse impedances
  - natural damping for HOMs

1. Design and simulation
2. Fabrication is ongoing
3. Nb coating system is under development

	FCC-hh
RF frequency [MHz]	400
Total voltage V [MV]	18 (uncertainty ±20%)
Available length [m]	20
Beam separation [mm]	250 (maybe 204 soon)
Average beta in the ring [m]	(339+67)/2 = 203
Beta* [m]	0.3
Crossing angle [urad]	89
Beta at CC location [m]	10100 ÷ 10900

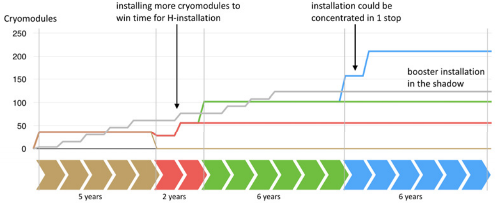


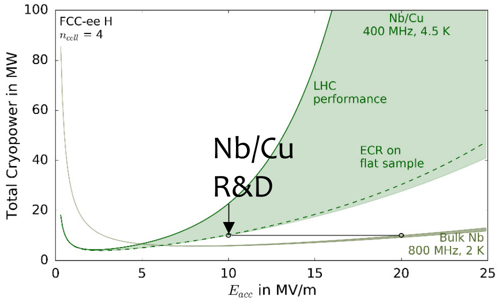
Schematic layout:
E. Cruz-Alaniz,
Nov. 2016, Barcelona

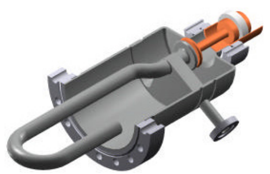
See R. Calaga 's talk on Tuesday

Conclusion

- Relevant R&D subjects:
  - Successful R&D on the energetic condensation techniques will make Nb/Cu at 400 MHz and 4.5 K competitive to bulk Nb at 800 MHz and 2.0 K in terms of cryogenic consumption.
  - Significant reduction of the cryogenic consumption requires the development of alternative SRF materials such as Nb3Sn and V3Si.
  - FPC of 1 MW
  - HOM power mitigation (for the Z-Machine)
  - Fabrication of cavities, helium tanks, power and HOM couplers.
- Staging Scenario allows to re-use components for next accelerator and installation mainly during winter shut down







Thank you very much!