Crab Cavities for FCC

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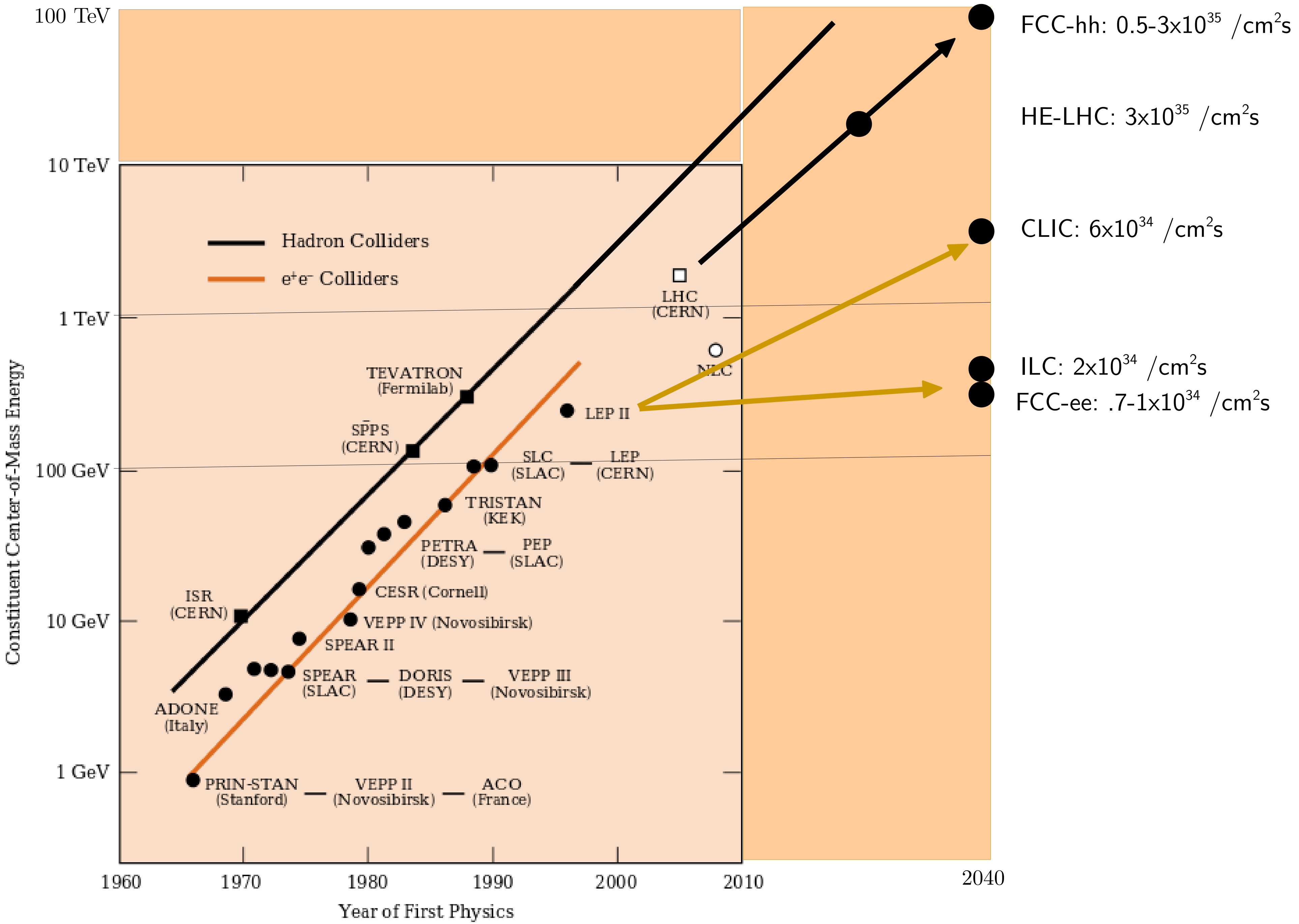
FCC Week 2017, May 30, 2017

Acknowledgements:

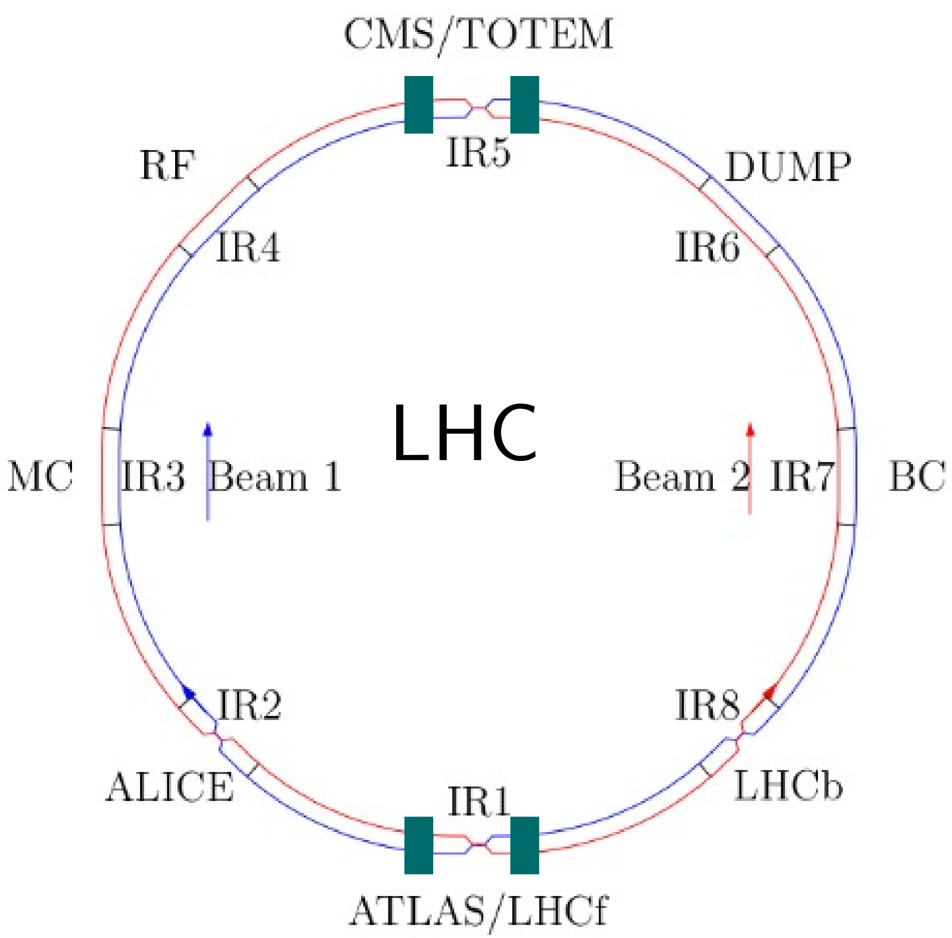
O. Bruning, E. Cruz-Alaniz, K. Ohmi, R. Martin, R. Tomas, F. Zimmermann

Livingston Plot

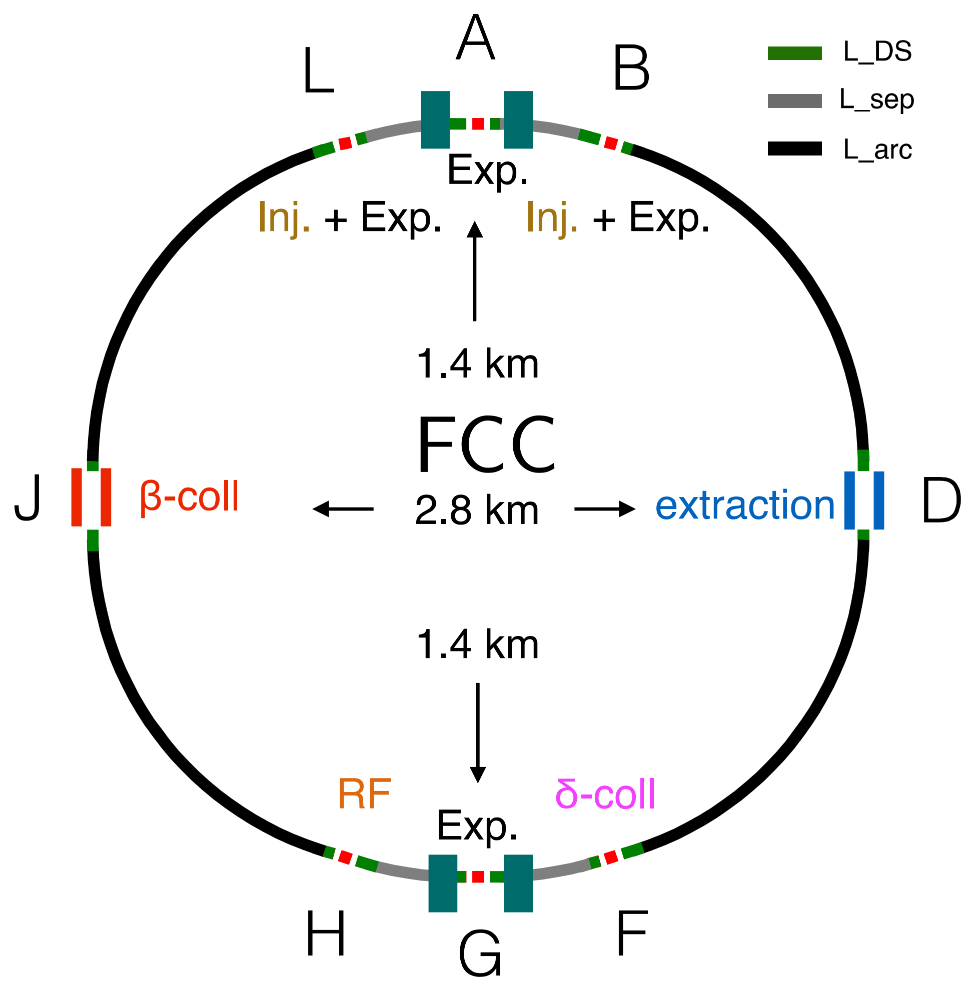


Naive Comparison, FCC -hh

Local crab crossing at two high luminosity experiments with alternating crossing angles



27 km ring, E = 7 TeV



100 km ring, E = 50 TeV

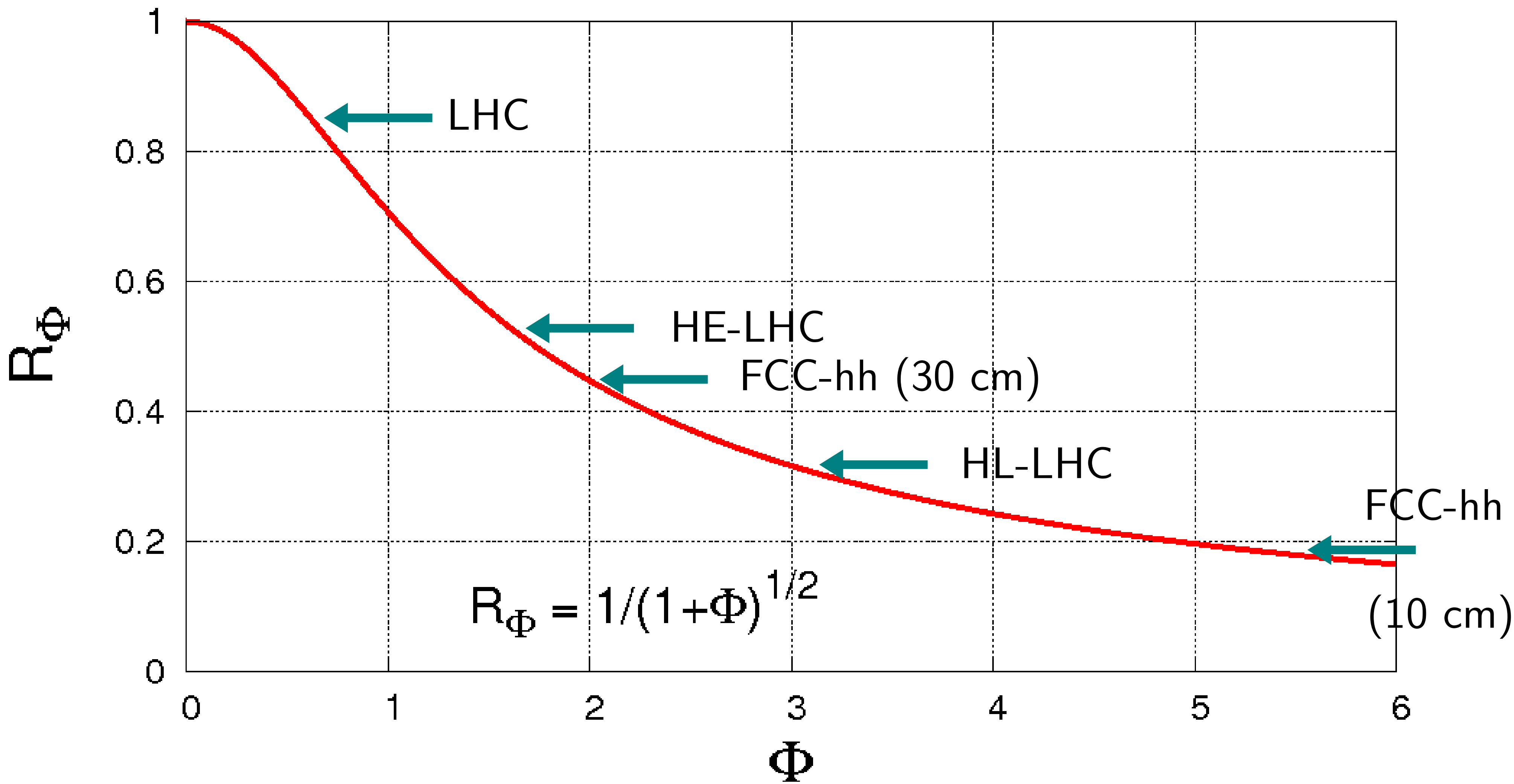
FCC-hh & HE-LHC

Increase the LHC energy by factor 2-7

PW angles close to HL-LHC for small β* option (CCs mandatory)

	LHC	HL-LHC	HE-LHC	FCC-hh
Energy [TeV]	7	7	13.5	50
Current, DC [A]	0.55	1.1	0.51	0.51
B-B Tune shift	0.003	0.01	> 0.03	0.01-0.03
σ_z/σ_x [cm, um]	7.55 / 16	9 / 7	7.55 / 6.6	7.55 / 2-4
X-Angle [rad]	285	590	260	300 - 170
PW-Parameter	**0.65**	**3.1**	**1.5**	**5.5 - 1.8**
Frequency [MHz]	400			
F_rev	11.245	11.245	11.245	**3.0**

Luminosity G. Reduction Factor



Strong reduction of decreasing σ_x during the fill

$\rightarrow$ increasing PW-angle unless x-angle is adjusted

FCC-hh, Some Numbers

Approx 50% increase in required voltage from HL-LHC

The aperture in the cavity region requires careful look, but extra beam-to-beam separation is useful to increase aperture if needed (present is 84mm)

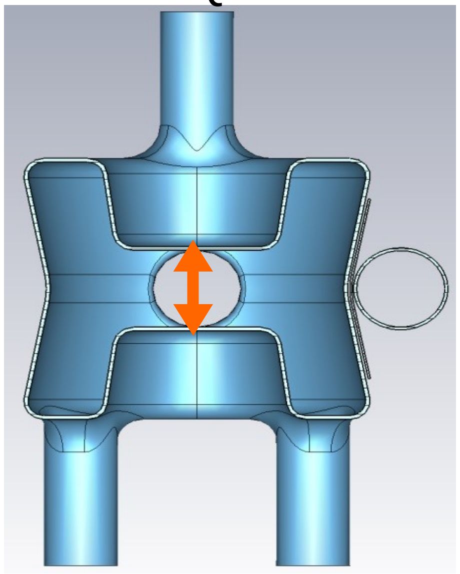
	unit	FCC-hh	HL-LHC
Beam-to-beam separation	[mm]	250	194
Available Length	[m]	20	10
beta*	[m]	0.1-0.3	0.15
beta_CC	[km]	**10-30**	3.5
Crab Voltage	[MV]	**18**	**12**
X-Angle	[urad]	300-170	590
Frequency	[MHz]	400.79	400.79

HL-LHC Crab Cavities

Two designs: horizontal (RF-Dipole) & vertical (Double Quarter Wave)

Bulk Niobium technology with strong HOM damping

Double Quarter Wave



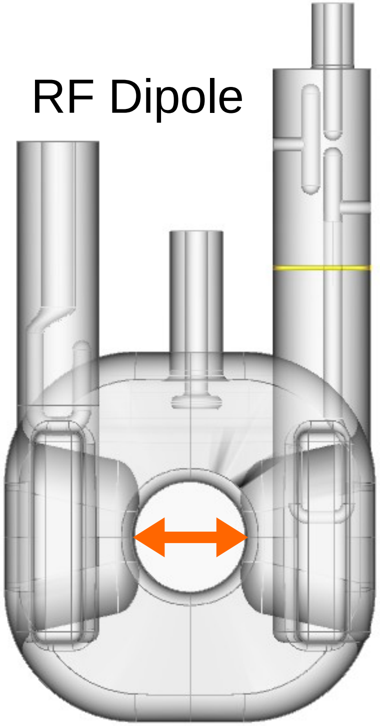
280 mm

400 MHz, HL-LHC

$V_T = 3.4$ MV

(Ep, Bp $<$ 40 MV/m, 70 mT)

RF Dipole



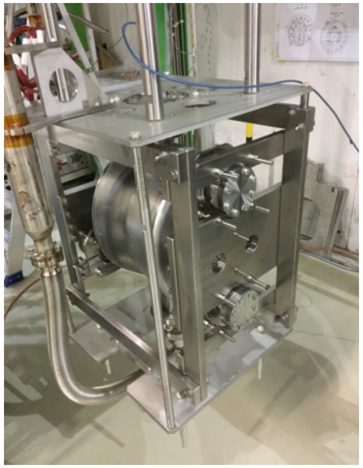
281 mm

Recent Results

The max voltage in the cavities are well beyond the specification

Also low Q0 & field emission with standard SRF process is validated

CERN, DQW



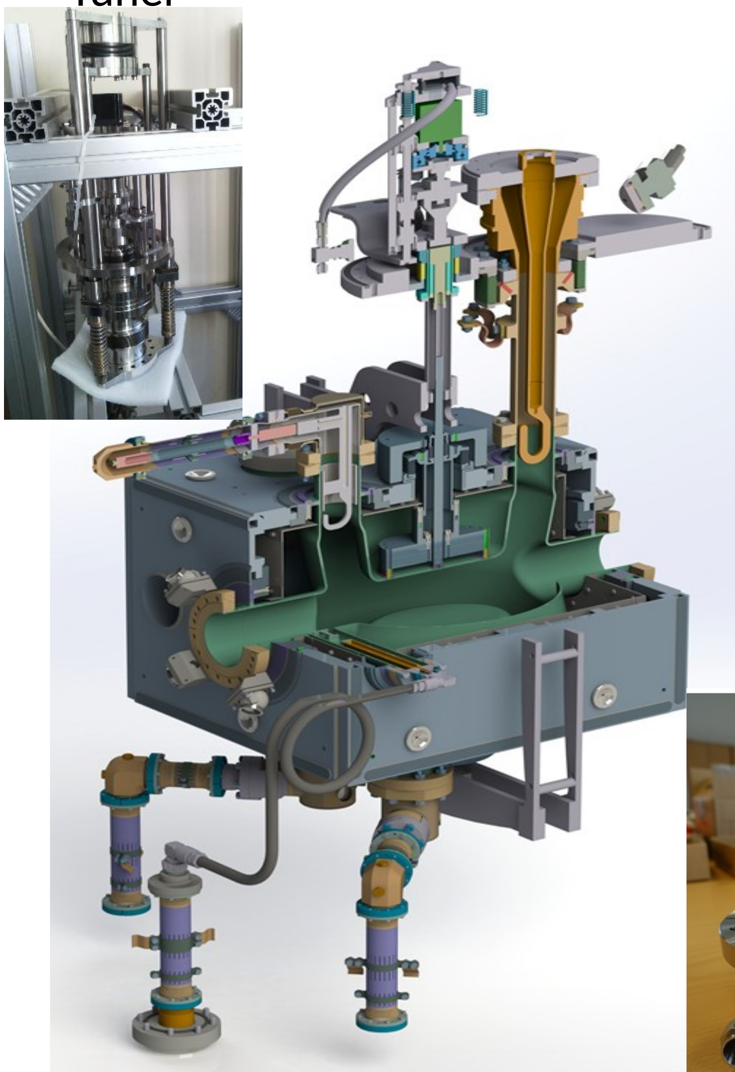
USLARP, DQW

USLARP, RFD

		DQW #1 (CERN)	**DQW #2 (CERN)**	**DQW #1 (USLARP)**	**DQW #2 (USLARP)**	**RFD #1 (USLARP)**	**RFD #2 (USLARP)**
Max Volt	[MV]	**5.04**	**4.8**	**5.8**		**4.4**	
Ep, Bp	[MV/m, mT]	56, 109	54, 103	65, 125		42, 73	
Rs, Min	[nW]	10	10	9		11	
Rs, Nom	[nW]	15	18	15		13	
FE onset	[MV]	4.0	3.5	4.5		No FE	

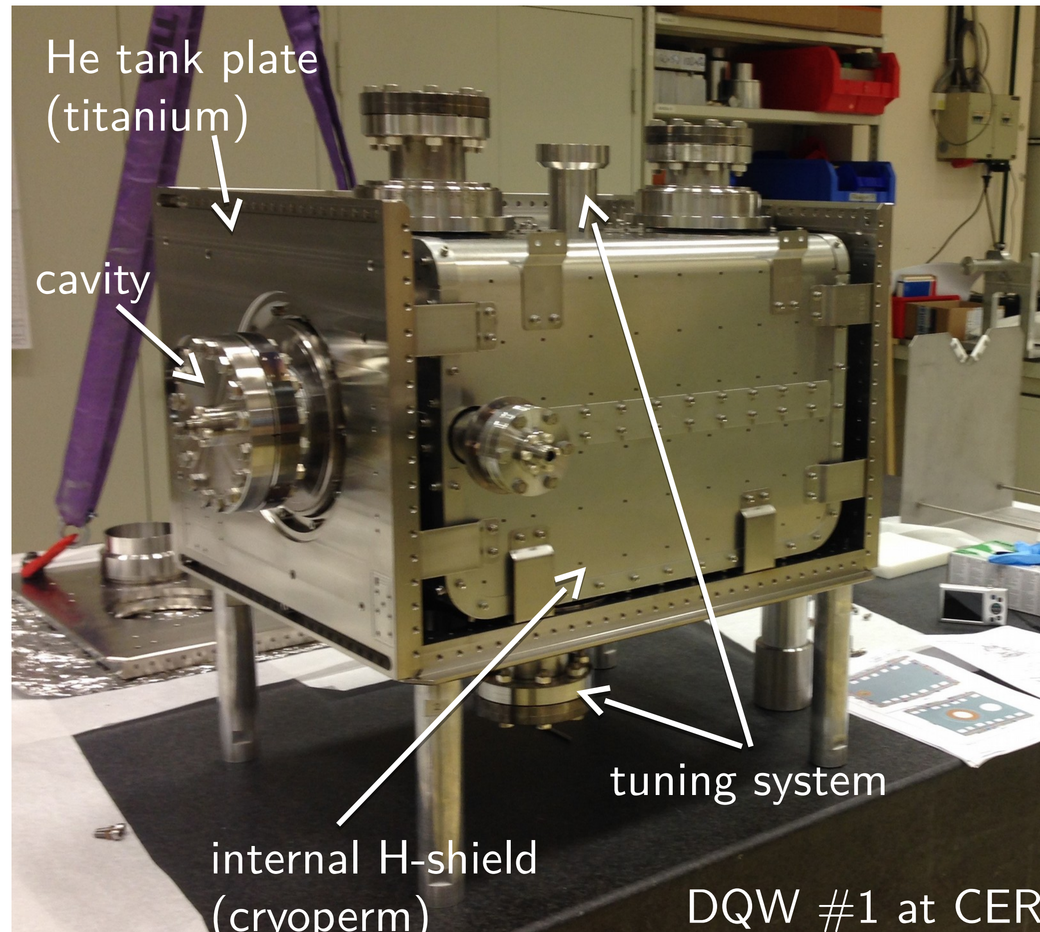
DQW, "Dressed Cavity"

Tuner

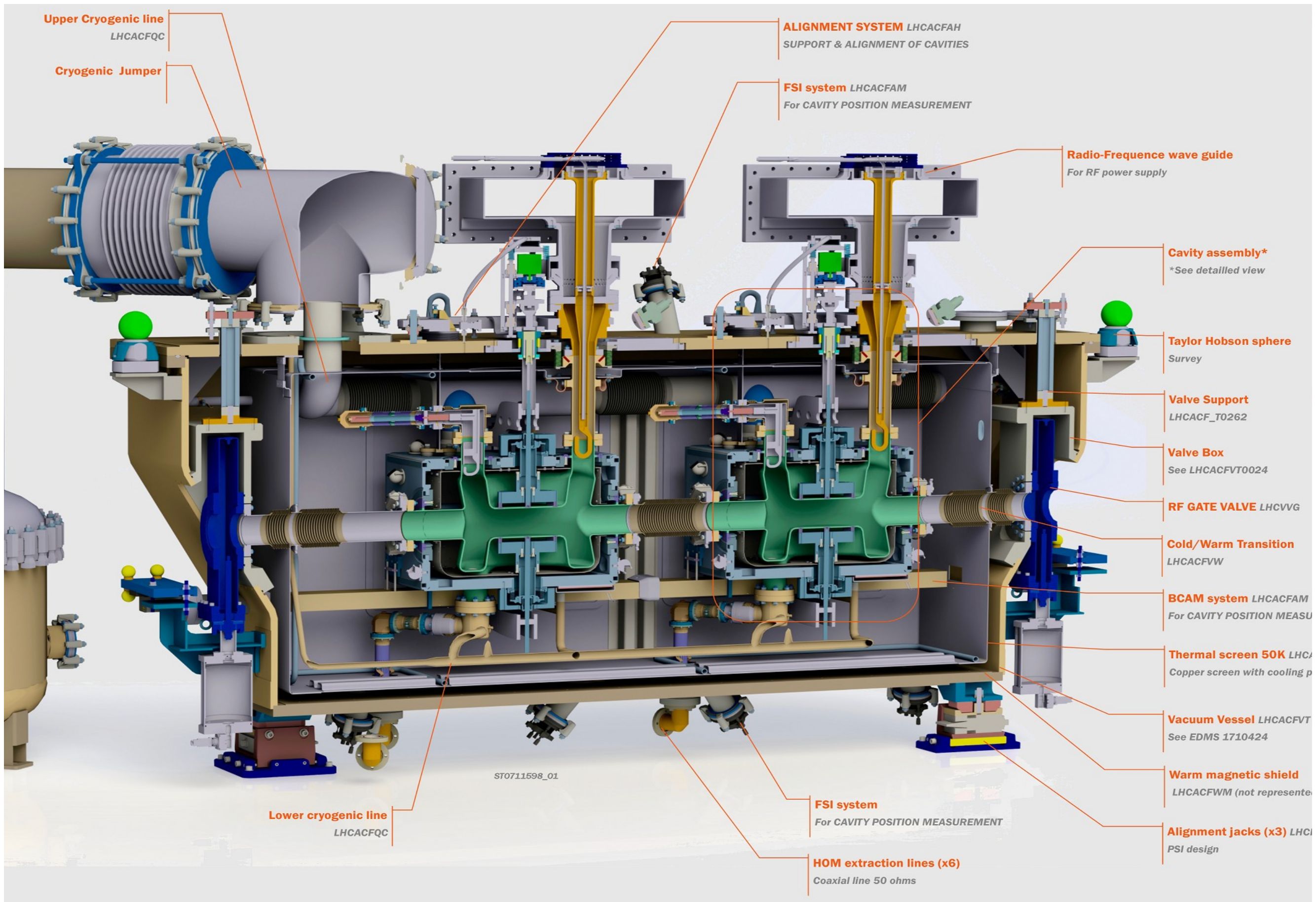


FPC

These cavities require highly complex 2K assembly due to multiple interfaces and strong RF constraints

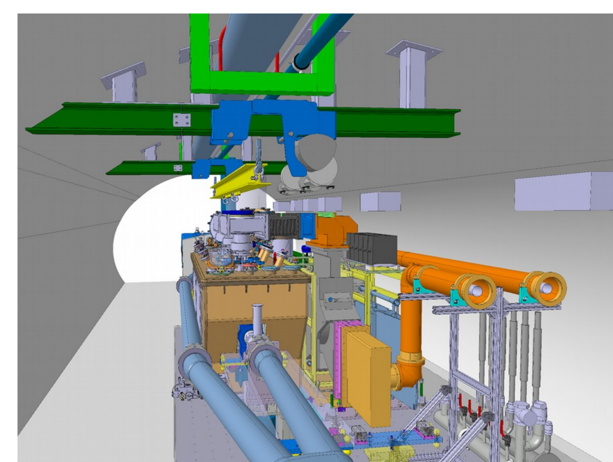


Two Cavity Cryomodule



16 cavities (8 Hor, 8 Ver) to be installed in HL-LHC before 2025

1-module with two cavities into the SPS for beam test validation in 2018

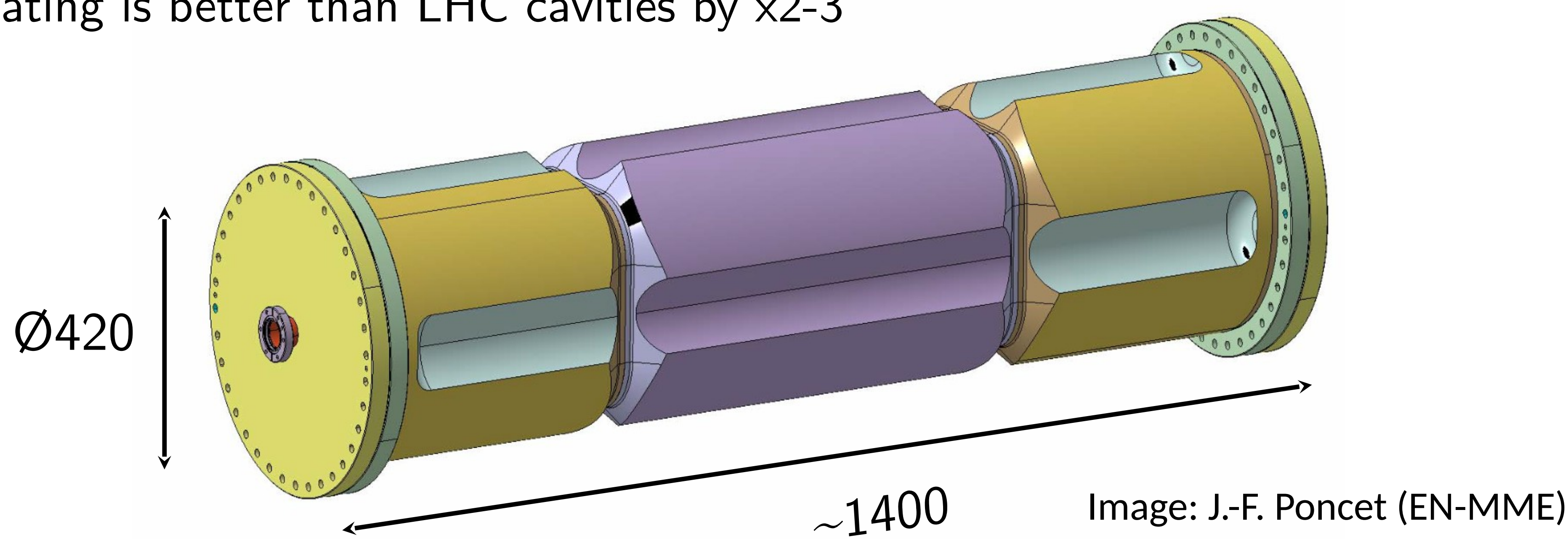


FCC-hh Crab Cavities

Alternative **Niobium coated copper cavity** under R&D (WOW)

Potential advantages:

- Larger Aperture & lower impedance: FCC-hh has up to x8 the beta-function at crab cavities compared to HL-LHC
- Better cavity stability during a hard quench due to the copper substrate
- Simpler cryostat due to less shielding and potential to reach 5 MV if coating is better than LHC cavities by x2-3

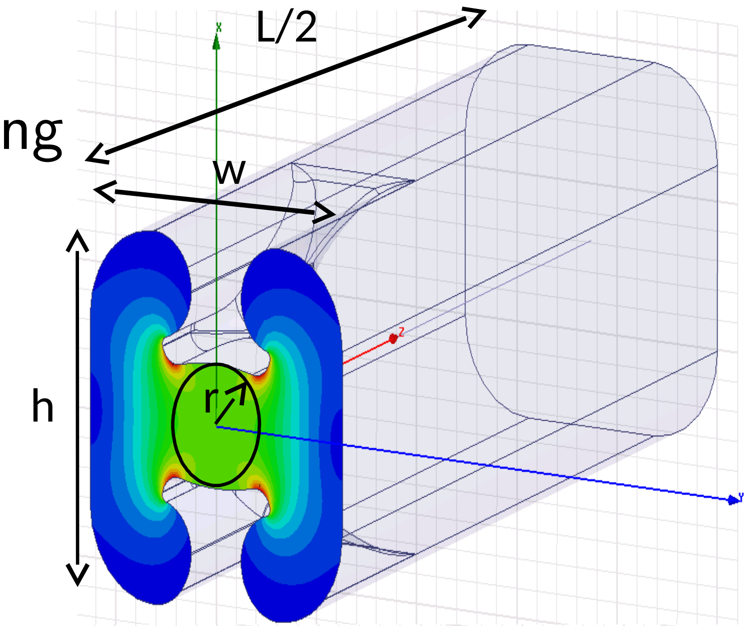


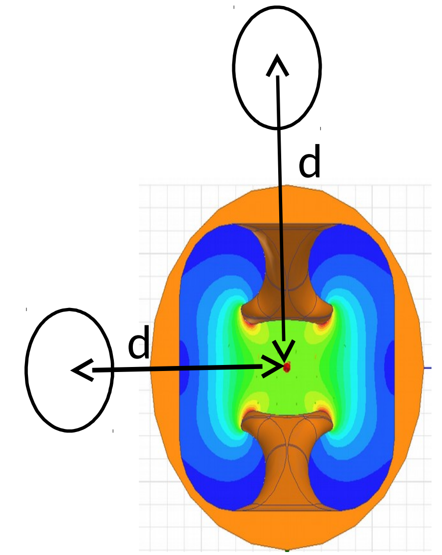
Main Parameters

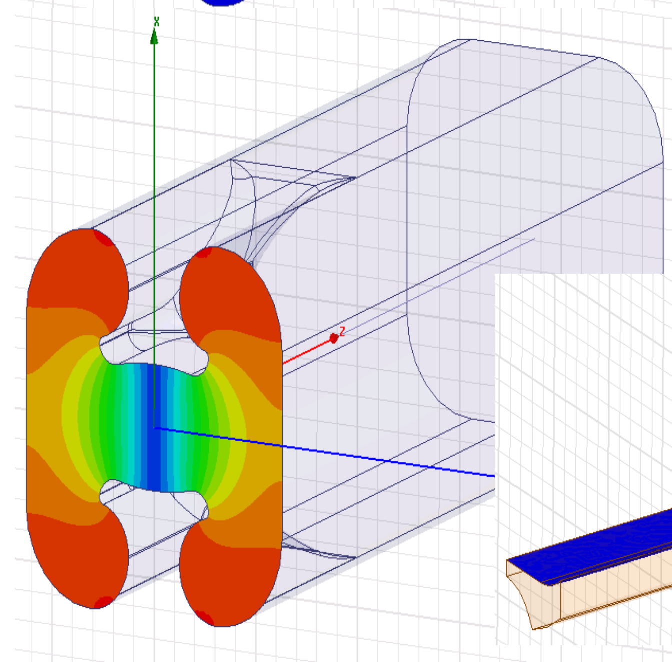
Specially shaped poles for coating

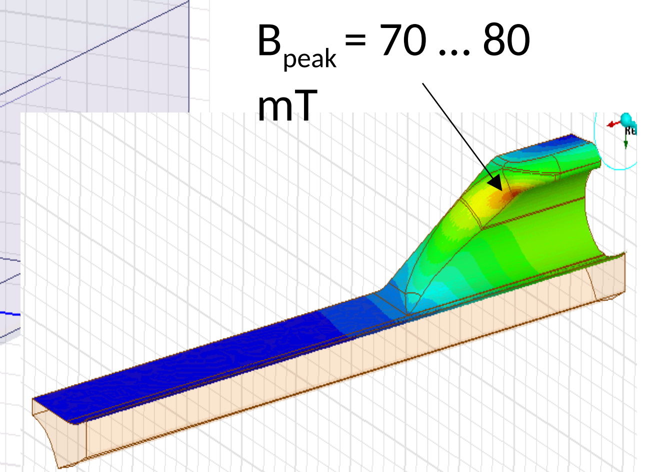
w [mm]	**251.70**
h [mm]	**251.70**
r [mm]	42.00
L [mm]	1400.00
d [mm]	192.00

Freq [MHz]	400.79	400.79
G [Ω]	109	109
Vx [MV]	3.0	3.0
Energy [J]	10.4	10.4
Rx/Q [Ω]	343.5	343.5
E_{peak} [MV]	50	50
B_{peak} [mT]	78	78



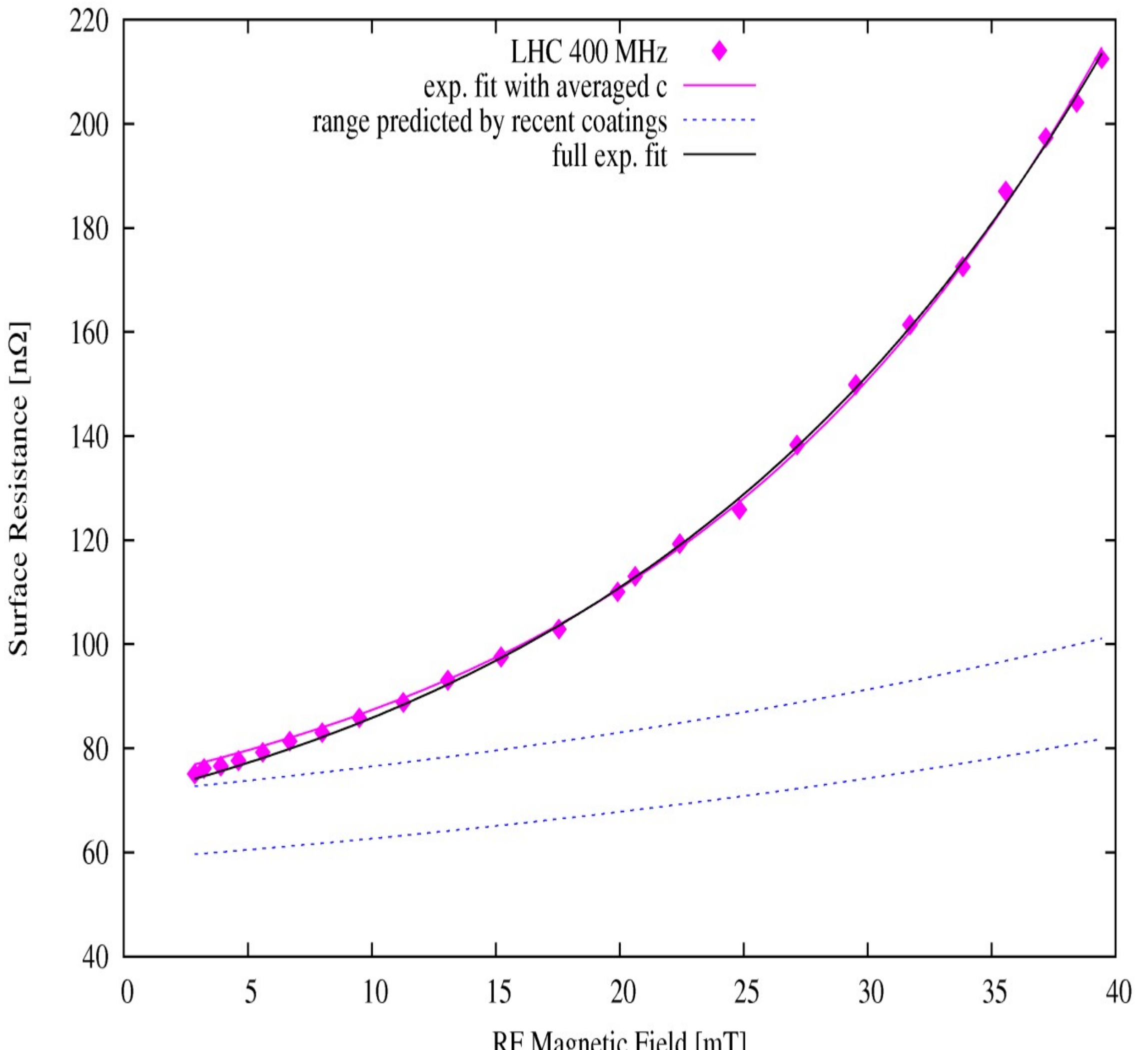






Non-linear behaviour of Rs (Calatroni/Aull)

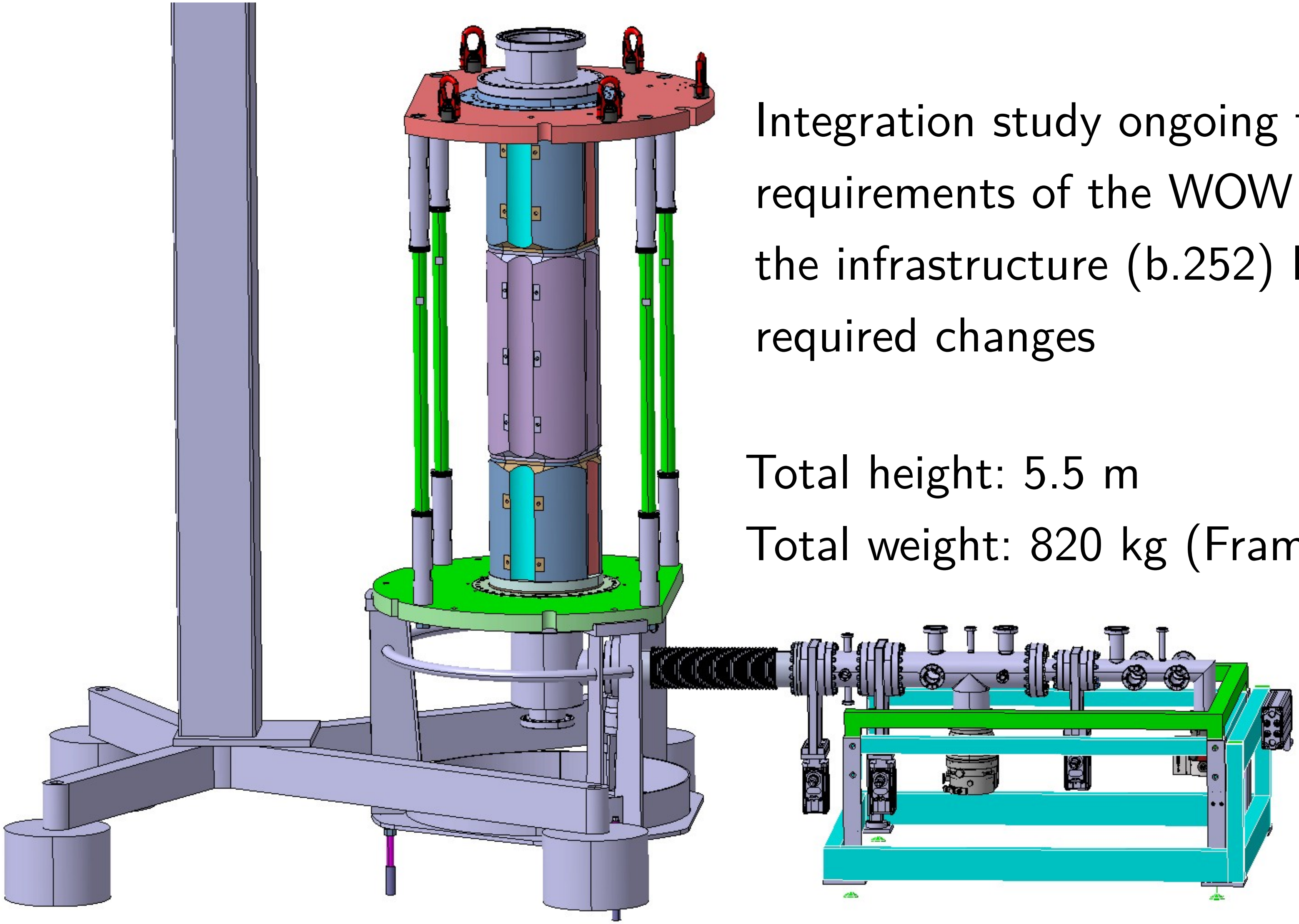
Big potential in the new coatings (both for accelerating & crab RF)



LHC:
Rs(Brf)[nOhm] = 54.7 + 19.0*exp(0.054*Brf[mT])

ECR:
Rs(Brf)[nOhm] = 46.9 + 17.1*exp(0.023* Brf[mT])

Coating the WOW Cavity



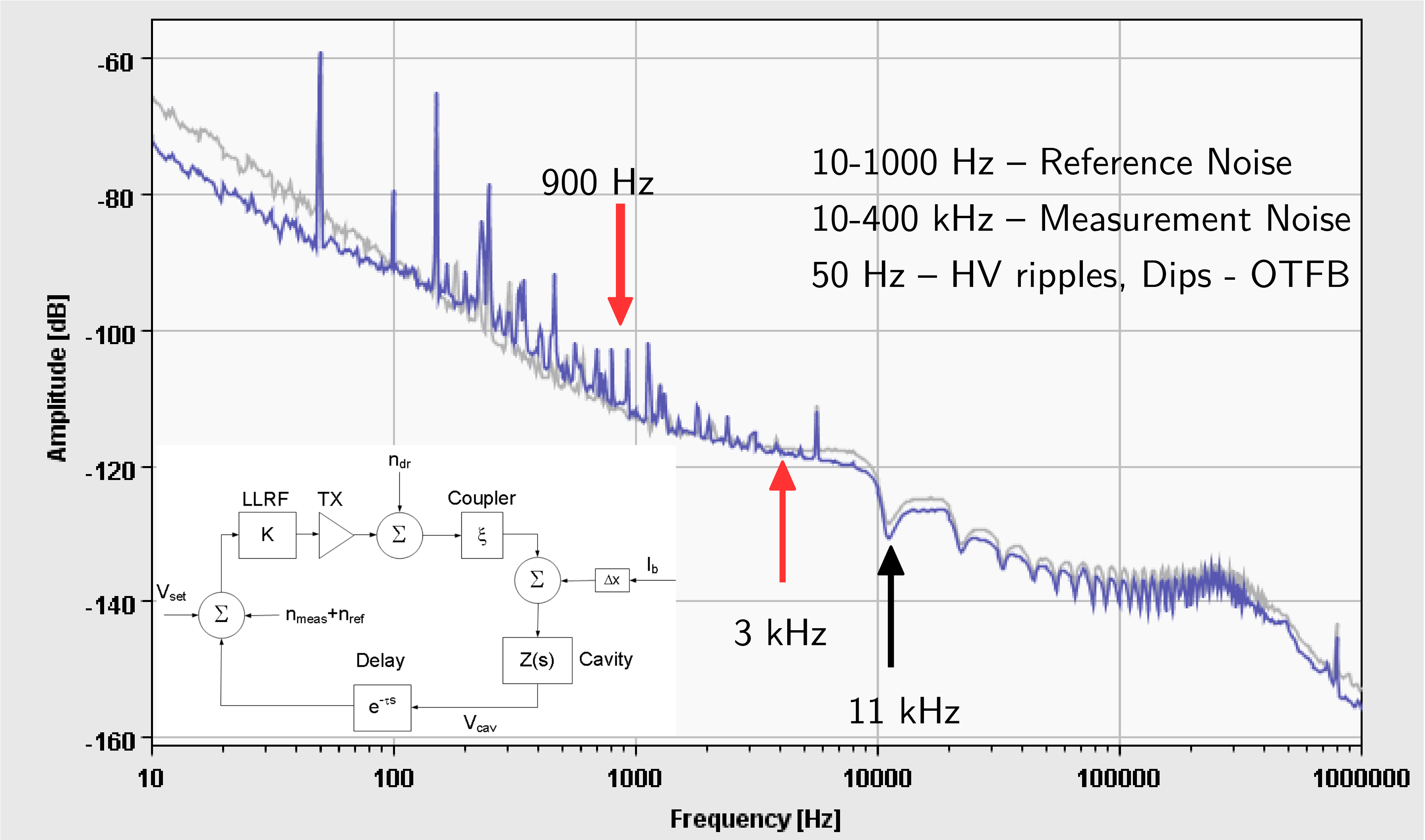
Integration study ongoing to study the requirements of the WOW cavity coating and the infrastructure (b.252) limitations and required changes

Total height: 5.5 m

Total weight: 820 kg (Frame+cavity 517 kg)

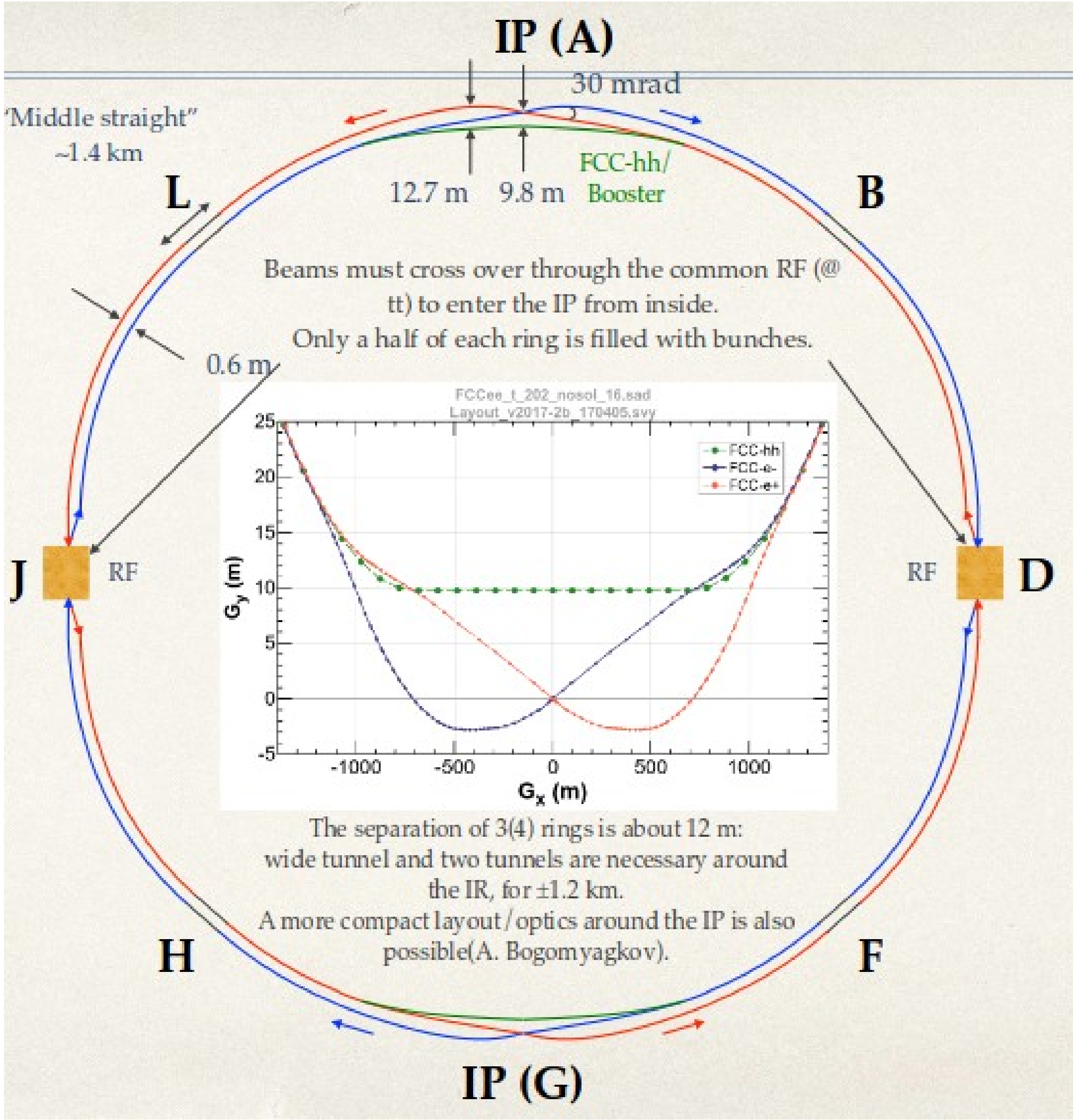
RF Noise !

The low frev (longitudinal noise) and 1st β-sideband ~900 Hz maybe an important aspect for both accelerating & crab cavities



Plot courtesy P. Baudrenghien

FCC ee, Layout



Symmetrically placed straight sections for RF

Available length for RF: ~2.8 km each

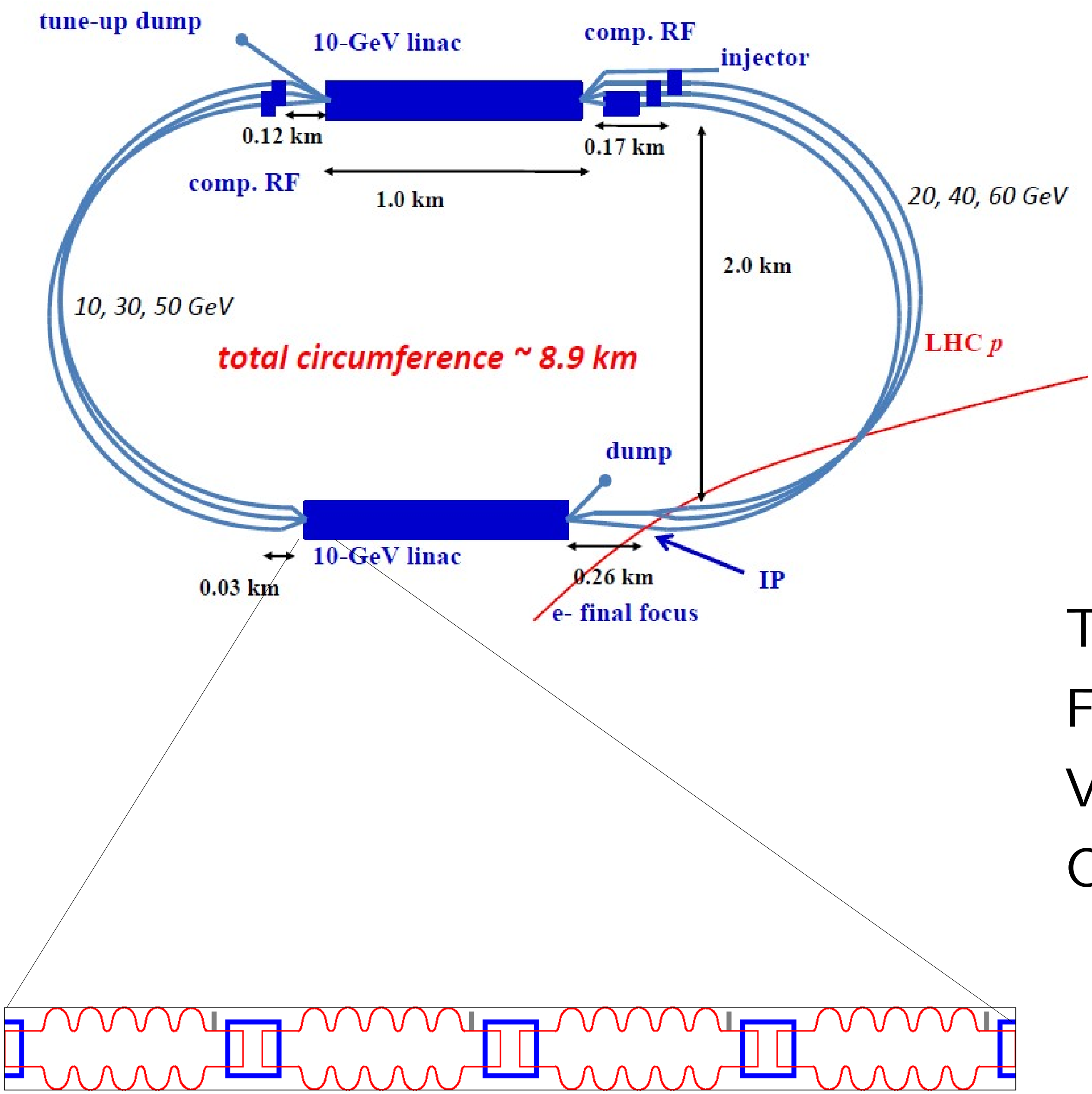
Baseline require **<u>no</u>** crab crossing

FCC-ee

Crab crossing not needed, however x/y – z correlation (AC tune/chroma modulation) can help with HT instability (Ohmi/Oide).

	S-KEKB	FCC-Z	FCC-W	FCC-H	FCC-T
Energy [GeV]	4-7	45.6	80	120	**175**
Current [A]	2.6	**1.45**	0.152	0.03	0.0066
σx,y [um, nm]		10, 48		25 ,49	
σz [mm]		6.7/3.8	3.1	2.4	2.5
θc [mrad]		**30**			
PW Parameter	20	6-10		1.5	
Frequency [MHz]	500	400.79			

FCC -eh, ERL option



Basic unit: 5-cell cavity into 4-cavity module

Energy protons: 50 TeV

Energy electrons: 60 GeV

Number of passes: 6

Beam current: 6.6-25.6 mA

Two 10 GeV linacs

Frequency: 801.58 MHz (h=20)

Voltage: 18.7 MV/cavity

Cryo losses: ($\sim$ 25 MW @3x10^{10})

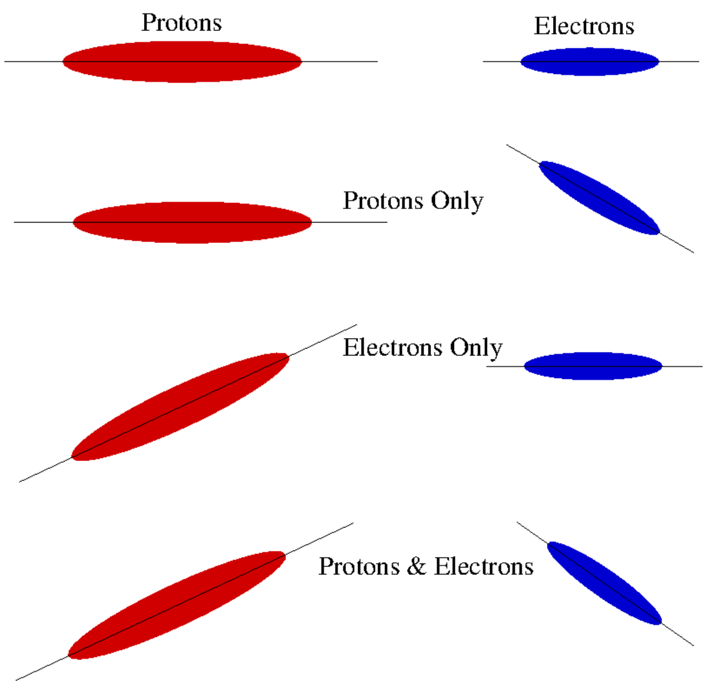
Parameters, FCC -he

Option 1: Use the “LHeC-ERL” to collide 60 GeV on 50 TeV

Option 2: Co-existing ee & hh in the FCC ring up to 200 GeV on 50 TeV

	LINAC-Ring electrons	**Ring-Ring electrons**	**JLEIC**	**eRHIC**
Energy [GeV]	60, 50000	200, 50000	10, 100	18, 275
σx,y [um]	10		18	123
σz [mm]	0.1, 75.5	0.7, 75.5	2, 9	4, 70
θc [mrad]	-	**1**	50	22
PW Parameter	-	-	12.5	6.3
Frequency [MHz]	400.79	400.79	952	338
Crab Volt [MV]	-	-	2.8, 14.5	4, 13

Crab Cavities, FCC -he



$$\Phi_p \sim \frac{\theta_c}{2\sqrt{2}\sigma_x^*}\sqrt{\sigma_{z,1}^2 + \sigma_{z,2}^2}$$

Old Example for the LHeC **Ring-Ring** Scenario (800 MHz)

Scenario	L/L_0
Head-On (with CCs)	1.88 (1.48)
Uncross only e^-	1.007
Uncross only p^+	1.48
X-Angle (**1 mrad**)	1.0

Electron bunch is point like compared to the proton bunch. Therefore, crabbing the proton bunch is important point

Baseline option **doesn't** require crab cavities with head-on collisions, maybe useful for regulating sync. radiation fan

Some Remarks

FCC-hh

Crab cavities are mandatory, scenario for β^* reaching 0.1-0.3 m
Coated cavity alternative with low impedance & larger aperture
promising R&D, technology demonstration by Q1 of 2020

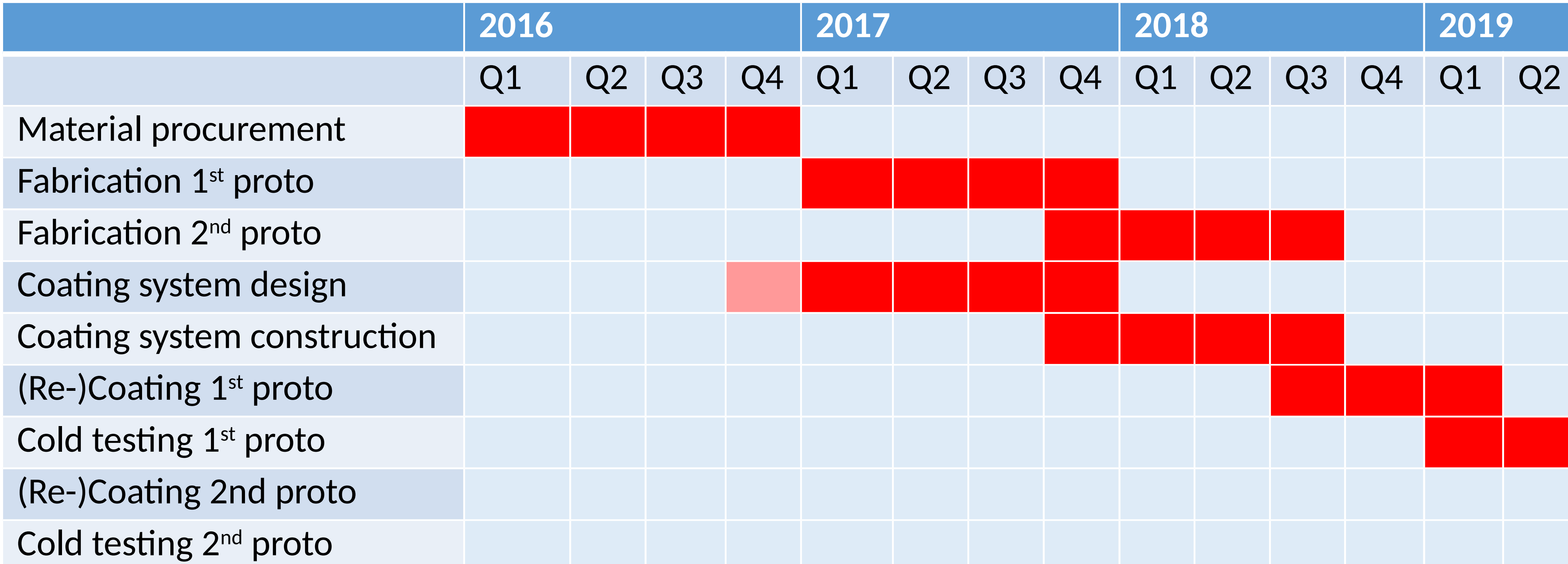
FCC-ee

Most challenging in terms of accelerating RF ! $\sim$3 times LEP RF
No crab cavities required in the present scenarios, possible mitigation of strong head-tail instabilities (tbc)

Electron-Ion

60 GeV-ERL in the Linac-Ring option doesn't nominally require crab crossing (except for a Ring-Ring option).
An x-z correlation at the IP to manipulate the sync radiation fan

Schedule for Coated Cavity Prototype



- Task 1: RF design (BE-RF)
- Task 2: Mech. Design of the prototype and tooling (EN-MME)
- Task 3: Fabrication of the “substrates” (EN-MME)
- Task 4: Surface treatment (TE-VSC)
- Task 5: Coating system and coating (TE-VSC)
- Task 6: Rinsing and clean room assembly testing (BE-RF)
- Task 7: Cold Testing in cryostat (BE-RF)

Q0 Calculation

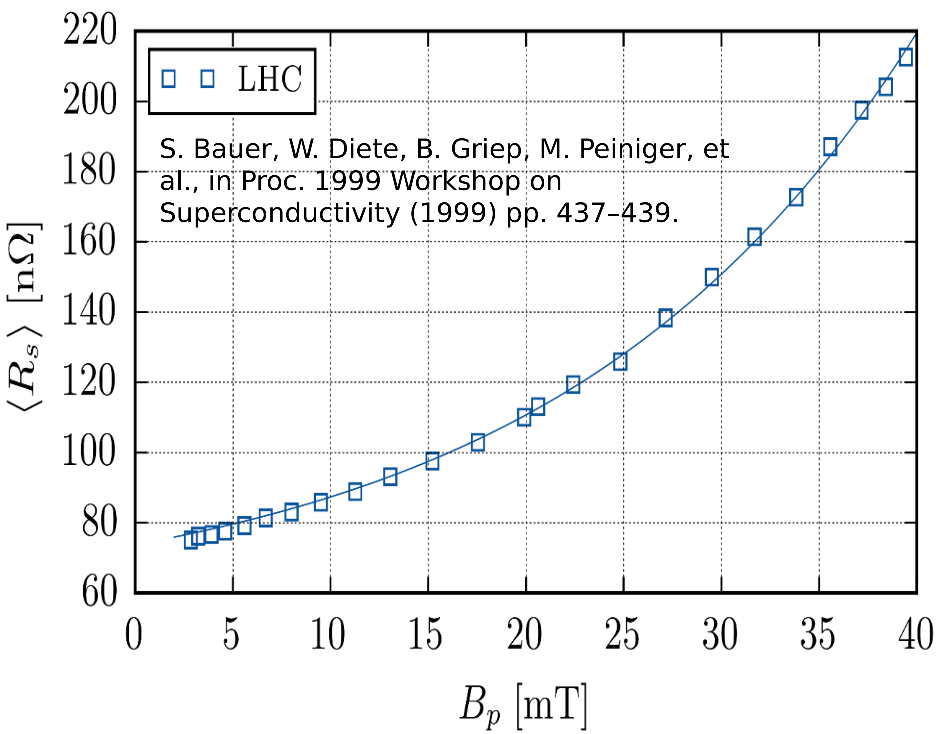
Nominal kick voltage 3 MV B_{peak} up to 80 mT

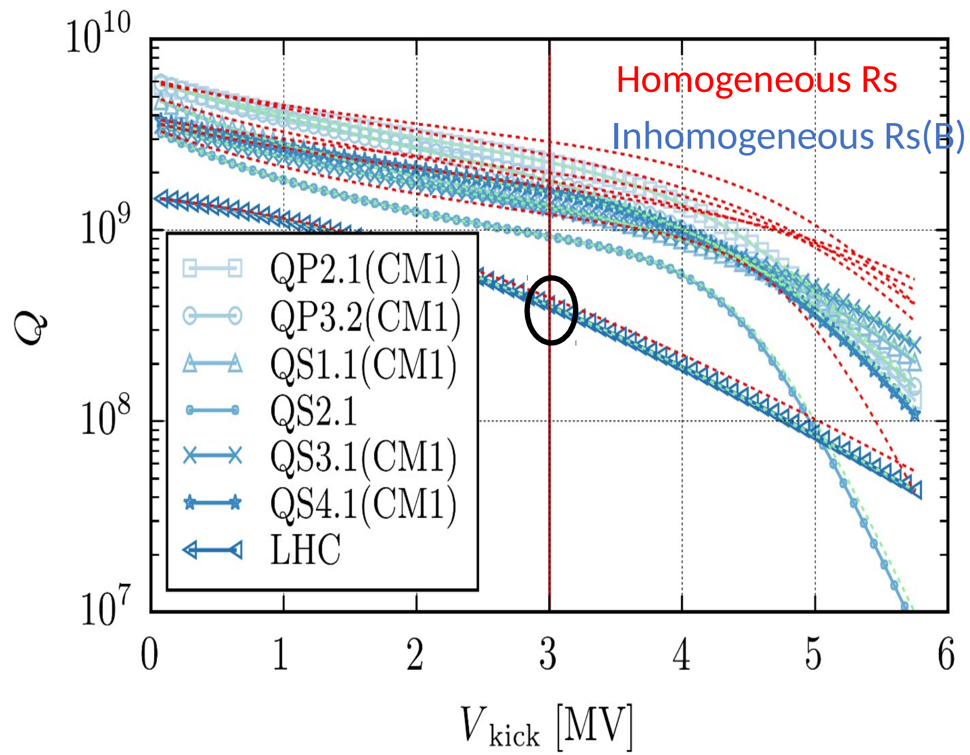
Results above 40mT for LHC uncertain due to lack of measurement data

Q based on extrapolation of Rs from the LHC data

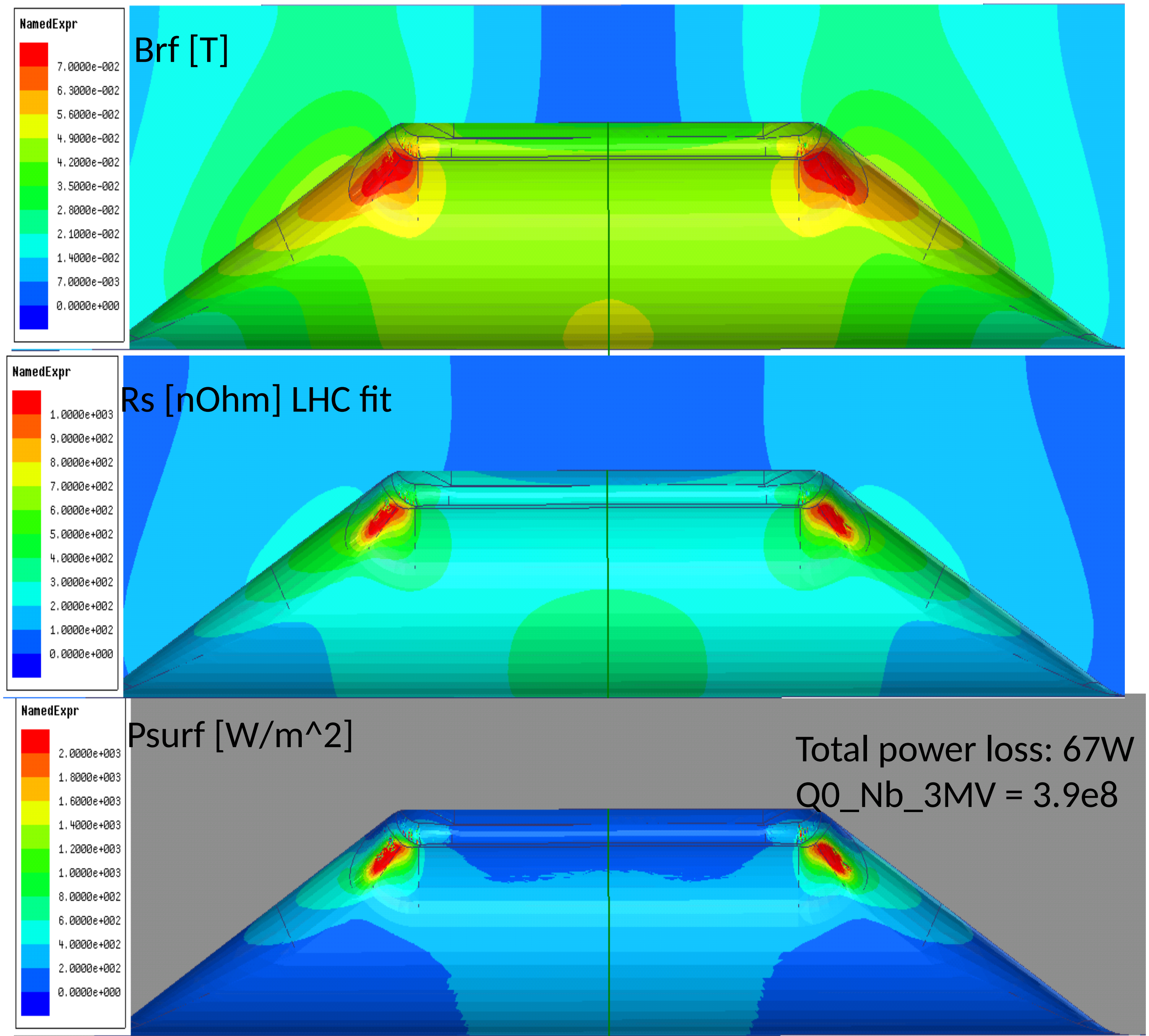
Q_0 (Rs=const.) = 4.45e8

Q_0 (Rs=Rs(B)) = 4.05e8

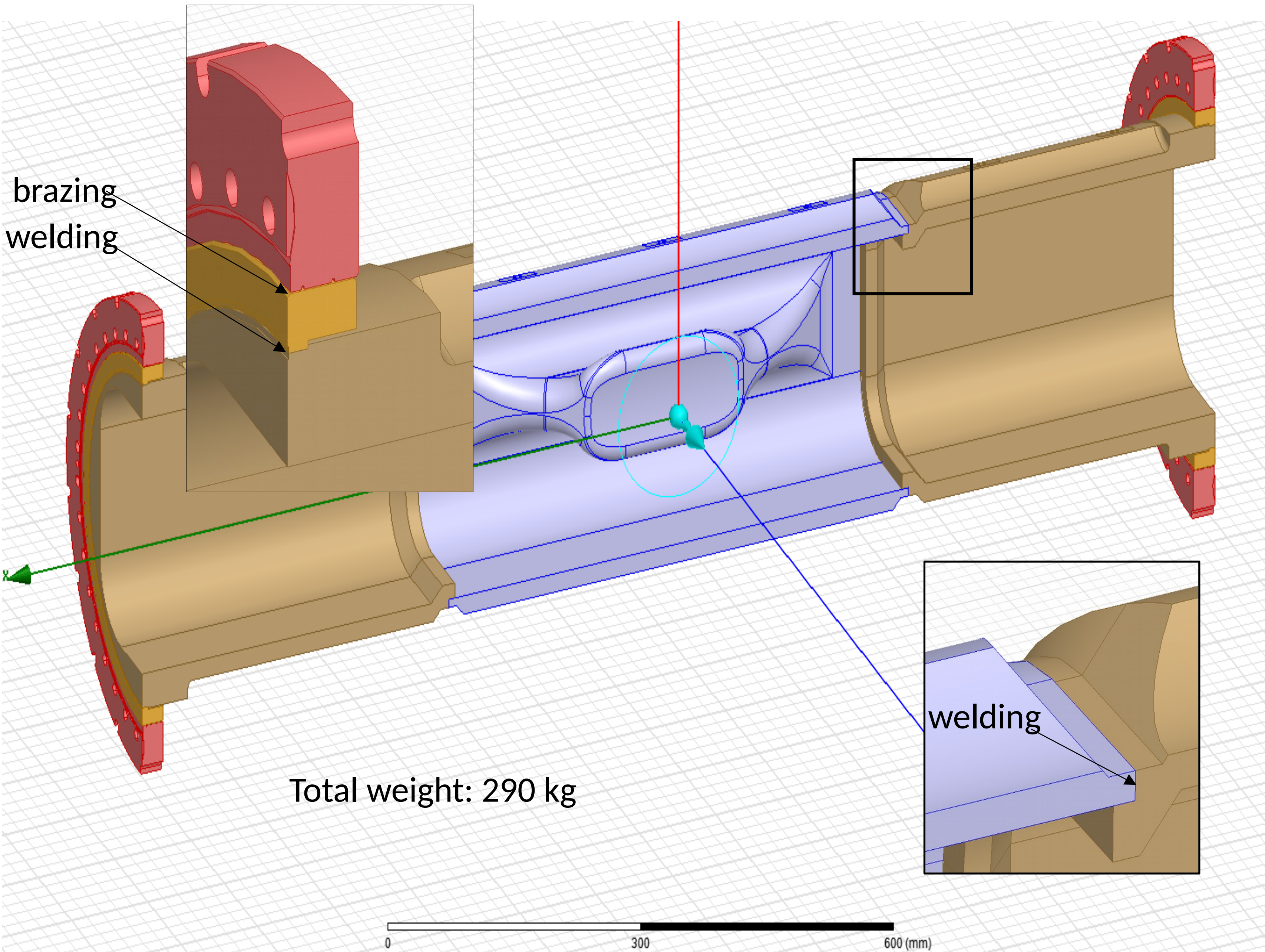




Power loss distribution for 3MV



Assembly of WOW Cu-Substrate



Impedances of WOW Cavity

Monopole

Loss factor [V/pC]	0.012
$(Z_L/N)_{eff}$ [mΩ]	**0.974**

Dipole

Kick factor x [V/pC/m]	1.673
Kick factor y [V/pC/m]	0.460
$(Z_T)_{eff}$ x [Ω/m]	**1562.8**
$(Z_T)_{eff}$ y [Ω/m]	437.6

Quadrupole

Kick factor x [V/pC/m]	0.733
Kick factor y [V/pC/m]	0.769
$(Z_T)_{eff}$ x [Ω/m]	631.9
$(Z_T)_{eff}$ y [Ω/m]	791.9