FCC-ee SRF Cavity Design and RF Powering Scheme

FCC week - San Francisco

11 June 2024

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Outline

- RF parameters
- Elliptical SRF cavities design – with HOM damping
- Cryomodule RF simulations
  - How to manage high HOM power and trapped RF modes
- Generic RF powering scheme (“RF Units”)
  - Including RF waveguide components
- New high efficiency klystron development
- Alternative ideas:
  - SWELL cavity
  - Advanced RF parameters

Outline

- RF parameters
- Elliptical SRF cavities design – with HOM damping
- Cryomodule RF simulations
  - How to manage high HOM power and trapped RF modes
- Generic RF powering scheme ("RF Units")

	Beam Energy (GeV)	Beam Current (mA)	RF voltage (GV)
Z collider *Z booster*	45.6	1280 *128*	0.080 *0.140*
W collider *W booster*	80	135 *13.5*	1.05 *1.05*
H collider *H booster*	120	26.7 *2.67*	2.1 *2.1*
ttb collider *Ttb booster*	182.5	5 *0.5*	11.3 *11.3*

Booster duty cycle: 15 %

Mid-term review - Sept. 2023

	Beam Energy (GeV)	Beam Current (mA)	RF voltage (GV)	Booster duty cycle (%)
Z collider *Z booster*	45.6	1283 *14.3*	0.079 *0.080*	*30-40*
W collider *W booster*	80	135 *11.8*	1 *0.4019*	*15-30*
H collider *H booster*	120	26.8 *2*	2.09 *1.961*	*20-40*
ttb collider *Ttb booster*	182.5	5 *0.3*	11.3 *10.18*	*45-90*

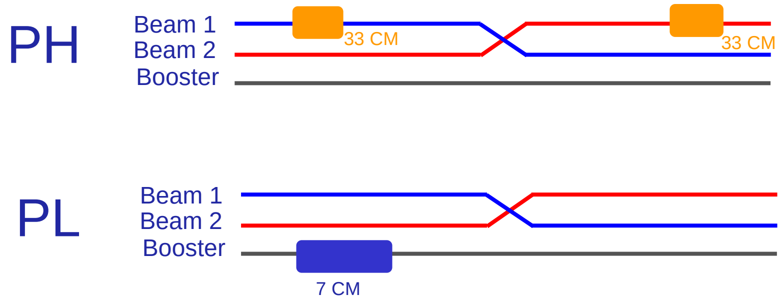
FCC week 2024 - June. 2024

with updated beam optics parameters from K. Oide (29 May 2024) for collider and A. Chance (4 June 2024) for booster

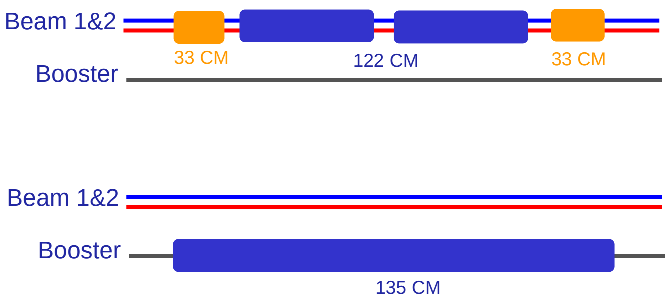
Main RF parameters and layout

	Z		W		H		ttb		
	collider	booster	collider	booster	collider	booster	collider	collider	booster
RF Frequency [MHz]	400.79	801.58	400.79	801.58	400.79	801.58	400.79	400.79	801.58
Cavity type	1-cell	5-cell	2-cell	5-cell	2-cell	5-cell	2-cell	5-cell	5-cell
Eacc [MV/m]	3.77	10.7	10.1	15.35	10.6	19.4	10.6	20.1	20.1
Q0	2.7E+09	3.0E+10	2.7E+09	3.0E+10	2.7E+09	3.0E+10	2.7E+09	3.0E+10	3.0E+10
Epk [MV/m]	8.3	22	20.2	31.5	21.2	39.8	21.3	41.3	41.3
Bpk [mT]	20.2	46.3	54	66.5	56.4	84.1	56.7	87.3	87.3
Beam current [mA]	1283	14.3	135	11.8	53.6	2	10	10	0.3
RF power [kW]	894	110	377	144	378	32	78	163	5
Optimum QL	2.5E+04	1.7E+06	8.4E+05	2.7E+06	9.2E+05	2E+07	4.5E+06	4.2E+06	1.3E+08
Optimum detuning [Hz]	13884	191	601	90	112	11	9	56	1.4
Operating temp. [K]	4.5	2	4.5	2	4.5	2	4.5	2	2
dyn losses/cav [W]	8	2.3	117	4	128	9	129	23	20
# CM (with 4 cav/CM)	14 per beam	2	33 per beam	7	66	27	66	122	135

one RF system per beam



common RF system for both beams



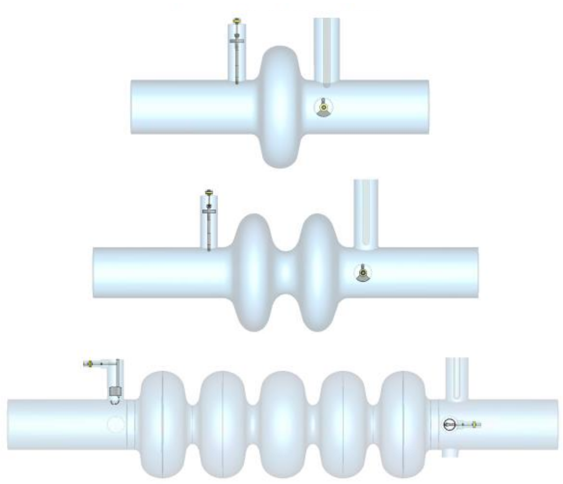
Total of 351 cryomodules and 1404 cavities (38% for booster)

Cavity design – RF performances

Bare cavity perform target in vertical cryostat:

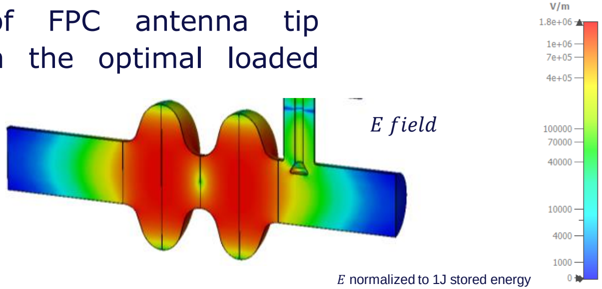
$Q_0 = 3.3 \times 10^9$ at $E_{acc} = 13.2\ \mathrm{MV/m}$ for 2-cell 400 MHz Nb/Cu at 4.5 K

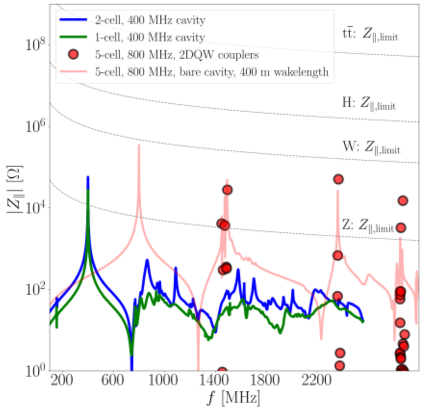
$Q_0 = 3.8 \times 10^{10}$ at $E_{acc} = 24.5\ \mathrm{MV/m}$ for 5-cell 800 MHz Nb at 2 K

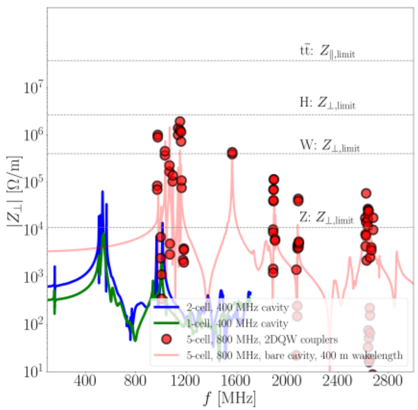


	LHC (reference)	FCC 1 – cell	FCC 2 – cell	FCC 5 – cell
Frequency [MHz]	400.79	400.79	400.79	801.58
R/Q [linac W]	88.1	87.6	181.1	521
G [W]	252	238.5	234.7	272.9
Epk/Eacc	2.3	2.2	2.0	2.05
Bpk/Eacc [mT/(MV/m2)]	5.1	5.36	5.33	4.33
KL [V/pC]	0.146 Sz=12.1 mm	0.132 sZ=12.1mm	0.389 sZ=8mm	2.78 sZ=2.75mm
K coef. [J/(MV/m)2]	0.63	0.63	1.23	0.33

Conical shape of FPC antenna tip required to reach the optimal loaded quality Q_L





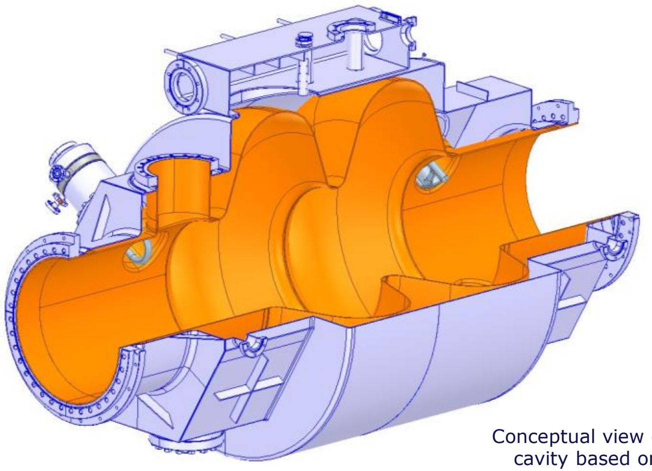


Cavity design – mechanical aspects

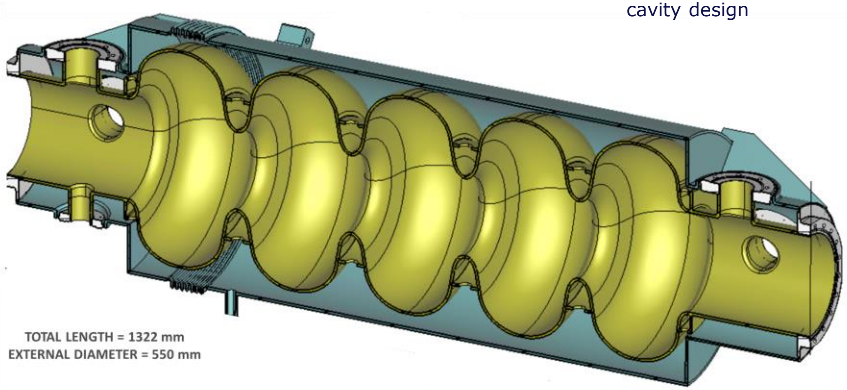
Calculation for bare cavity

	LHC (reference)	FCC 1 – cell	FCC 2 – cell	FCC 5 – cell
Thickness [mm]	2.75	2.75	2.75	3
Stiffening rings diameter [mm]	-	-	-	110
Tuning sensitivity [kHz/mm]	-242.8	-269.5	-139.6	-168.75
Cavity stiffness [kN/mm]	20.4	9.1	8	6
Lorentz force coeff. (fixed ends) [Hz/(MV/m)2]	-1.3	-1.3	-1.3	-0.6
Pressure sensitivity (fixed ends) [Hz/mbar]	9.3	24.4	23.1	8
Max Von-Mises stress (fixed ends, 1 bar)	26.9	36.8	31.6	15.2

Next steps: same calculation with helium vessel and frequency tuner with the goal to keep cavity sensitivity parameters to external perturbation close to these values.



Conceptual view of 2-cell cavity based on LHC cavity design



Courtesy Marco Chiodini

Frequency tuning system

Design of frequency tuner is **critical at low beam current operation**, both at 400 MHz and at 800 MHz with resolution better than 10 Hz.

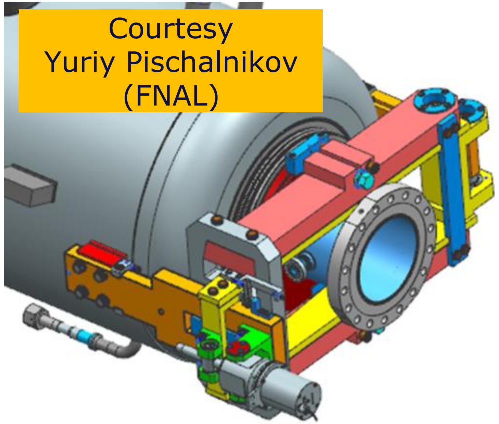
The booster operates in **pulsed mode** with ramp time of 1.5 to 4.2 seconds, including flat top of **100 ms**.

At ttb booster, the 800 MHz cavity shall even be tuned at a frequency **better than 1 Hz**.

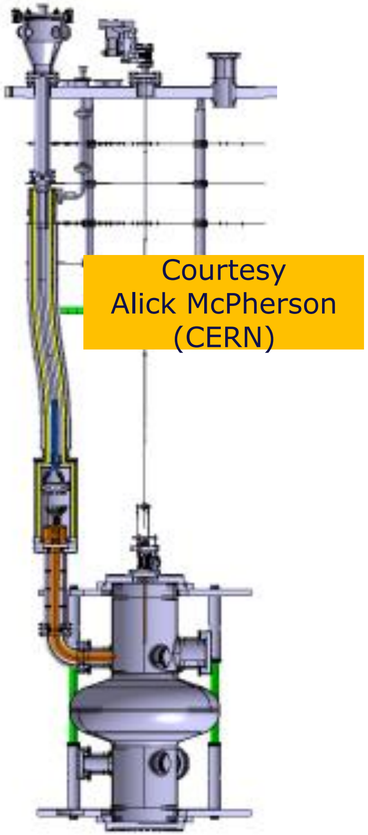
Electromechanical tuner with **stepper motor and piezo actuators** is the obvious choice.

Non mechanical tuners (FRT) currently under development at CERN could be an option.

What about ultra-stiff cavities machined from bulk ?...

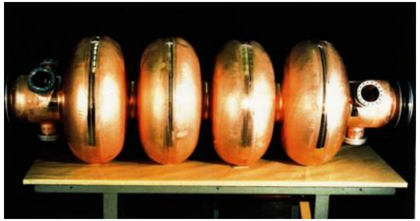


PIP2 650 MHz tuner
(FNAL)



R&D on non-mechanical
Tuner (FRT) (CERN)

Higher order mode damping in circular machines

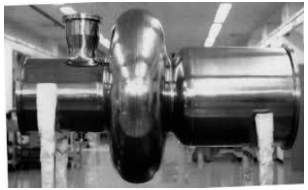


LEP, 352 MHz

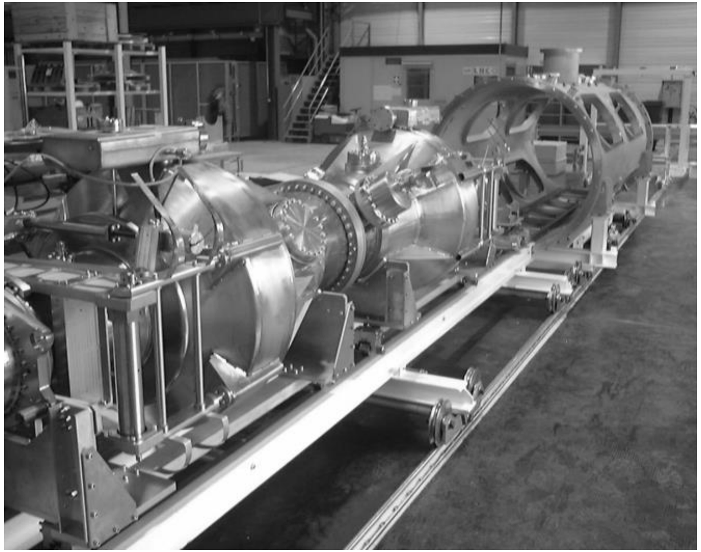
LHC, 400 MHz

HL-LHC, 400 MHz

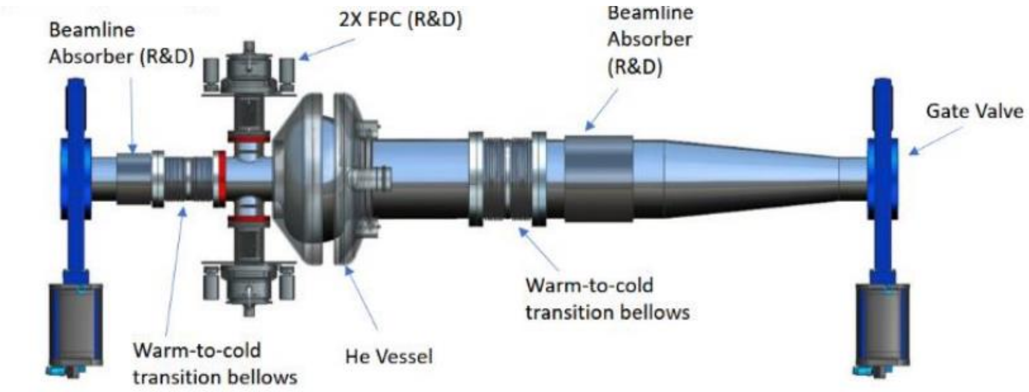
CESR, 500 MHz



KEKB, 500 MHz



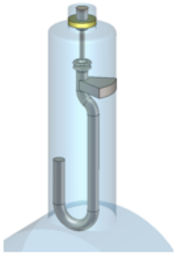
SOLEIL, ESRF
352 MHz



EIC, 591 MHz

HOM management strategy in FCC cavities

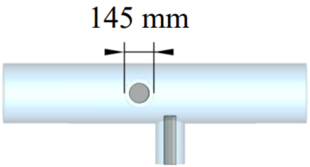
1 Coaxial couplers (with FM rejection) for dipole and monopole mode damping as close as possible to the extremity cell



400 MHz

800 MHz

2 Coaxial couplers for extraction of the high frequency broadband part of the cavity impedance spectrum optimally positioned in between cavities



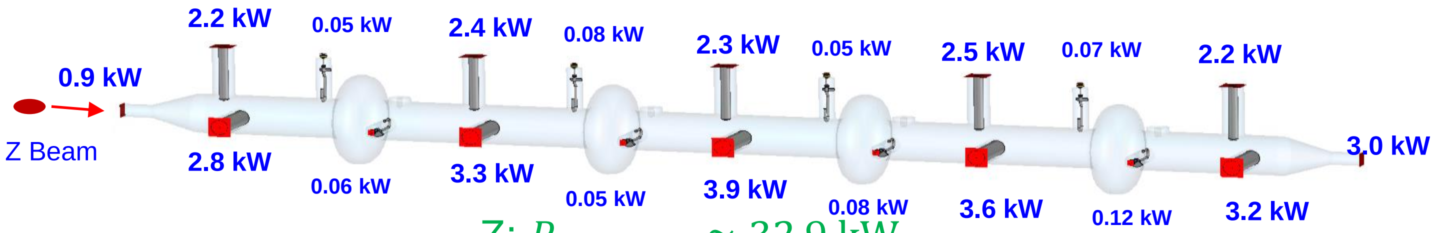
400 MHz

800 MHz

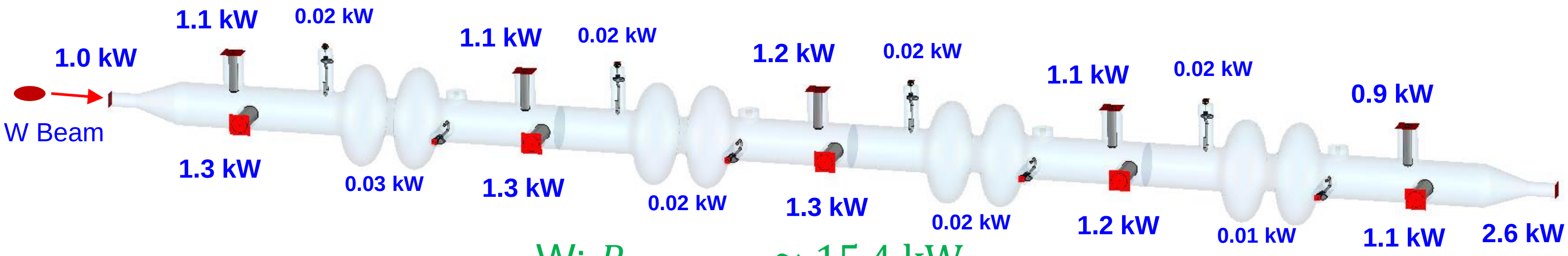
3 Φ300/150 mm tapers at 400 MHz
Φ156/100 mm tapers at 800 MHz
to limit HOM power deposition

4 beam line absorbers and at room temperature

HOM power extracted from cavity string

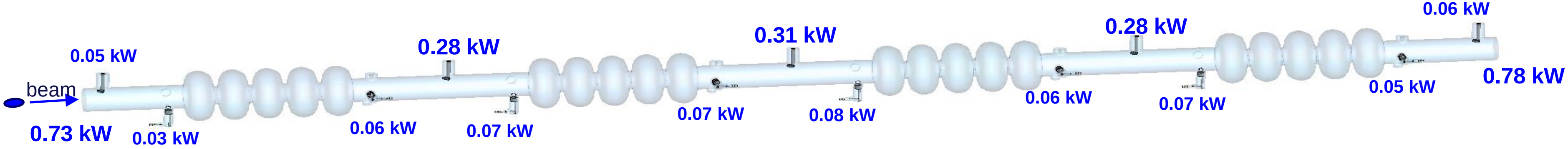


Z: $P_{\mathrm{HOM-tot}} \approx 32.9\ \mathrm{kW}$



W: $P_{\mathrm{HOM-tot}} \approx 15.4\ \mathrm{kW}$

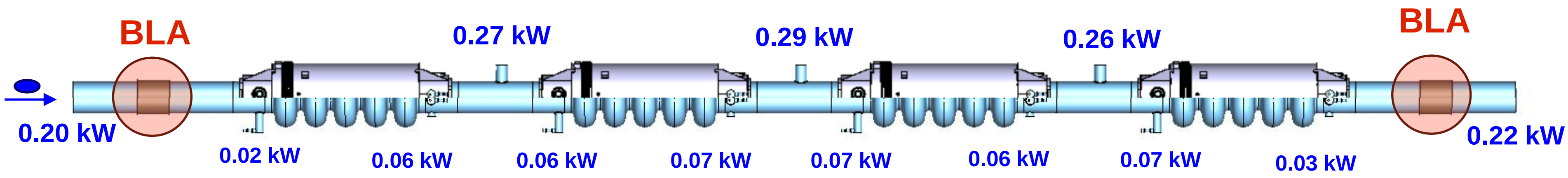
(H: $P_{\mathrm{HOM-tot}} \approx 6.4\ \mathrm{kW}$)



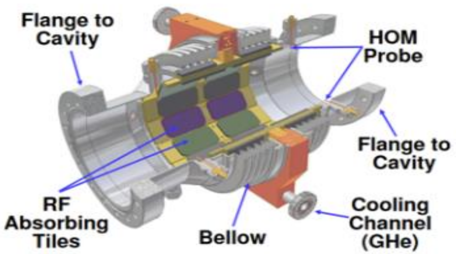
$t\bar{t}$: $P_{\mathrm{HOM-tot}} \approx 2.98\ \mathrm{kW}$

Beam Line Absorbers (BLA)

Two room temperature 1 kW Beam Line Absorbers (BLA) at the end of the module helps to decrease HOM power propagating from one module to the next one



Power lost in each BLA $P_{\mathrm{HOM-BLA}} \approx \mathbf{0.7\ kW}$



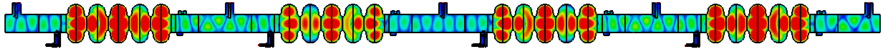
Cornell BLA

Collaborations on BLA developments are welcome

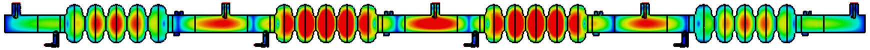
Trapped modes

Careful check of trapped RF modes needs to be performed regularly as the mechanical design of the cryomodule evolves.

Difference between Qtot and Qext shows the amount of radiated power through beam pipe

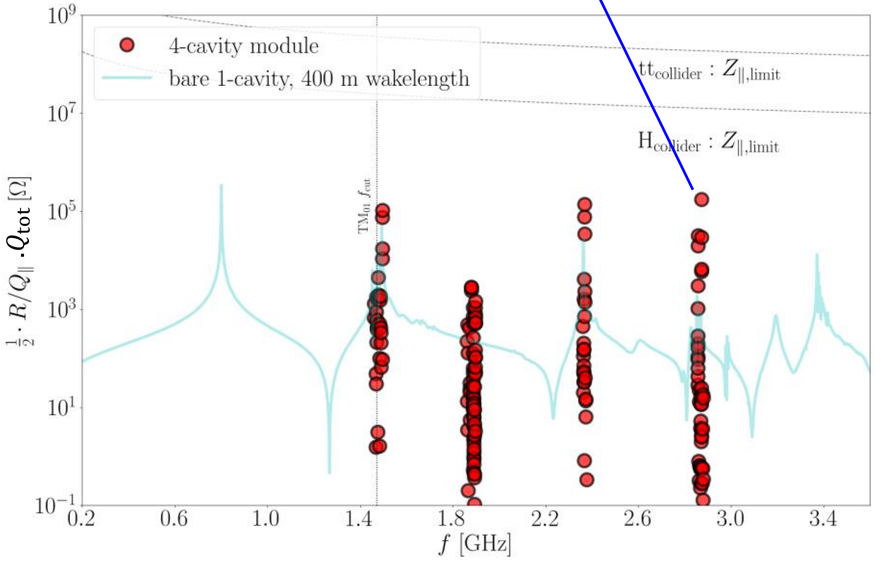


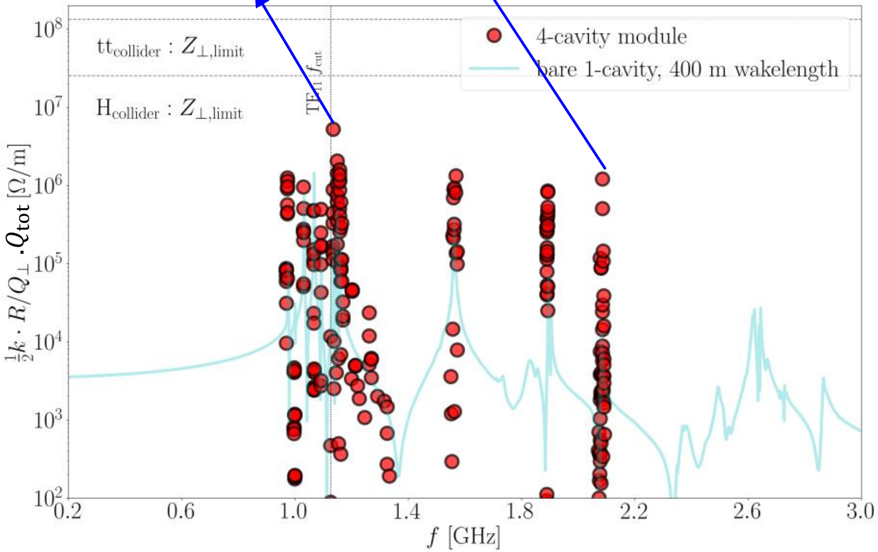
f = 1.892 GHz, $R/Q_{\perp}$ = 1.4 Ω, Q_{tot}=1.5e4, Q_{ext}=3.2e6



f = 1.135 GHz, $R/Q_{\perp}$ = 38.1 Ω, Q_{tot}=1.1e4, Q_{ext}=1.4e4

f = 2.873 GHz, $R/Q_{\parallel}$ = 1.2 Ω, Q_{tot}=2.9e5, Q_{ext}=1.0e6

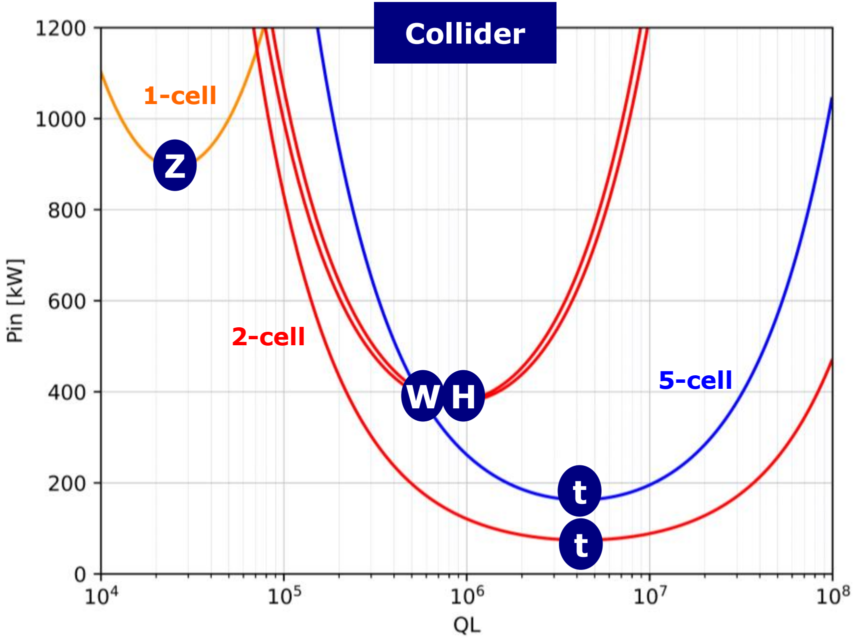




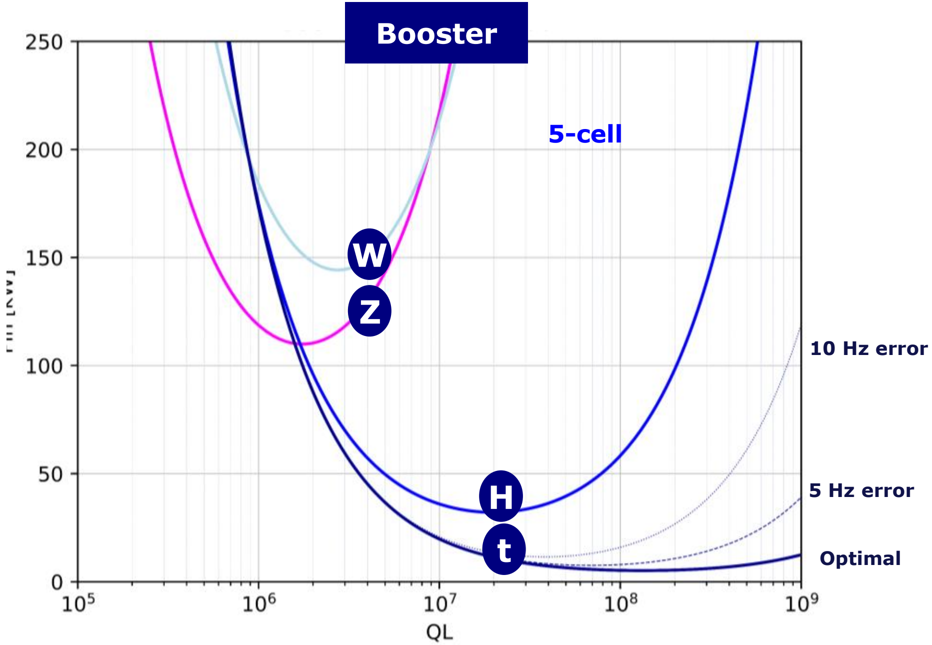
- ❑ RF parameters
- ❑ Elliptical SRF cavities design – with HOM damping
- ❑ Cryomodule RF simulations
  - How to manage high HOM power and trapped RF modes
- ❑ Generic RF powering scheme ("RF Units")
  - Including RF waveguide components
- ❑ New high efficiency klystron development
- ❑ Alternative ideas:
  - SWELL
  - Advanced RF parameters

RF power sources needs

Cavity input power as a function of loaded Q factor with optimal frequency detuning for beam loading compensation.



Operation at optimal QL is mandatory to minimize RF power budget



QL is chosen close to optimal, typically between ~ 4.10^6 to 2.10^7 maximum in order to minimize sensitivity to detuning and minimize variation of QL between different operating modes.

RF power sources table

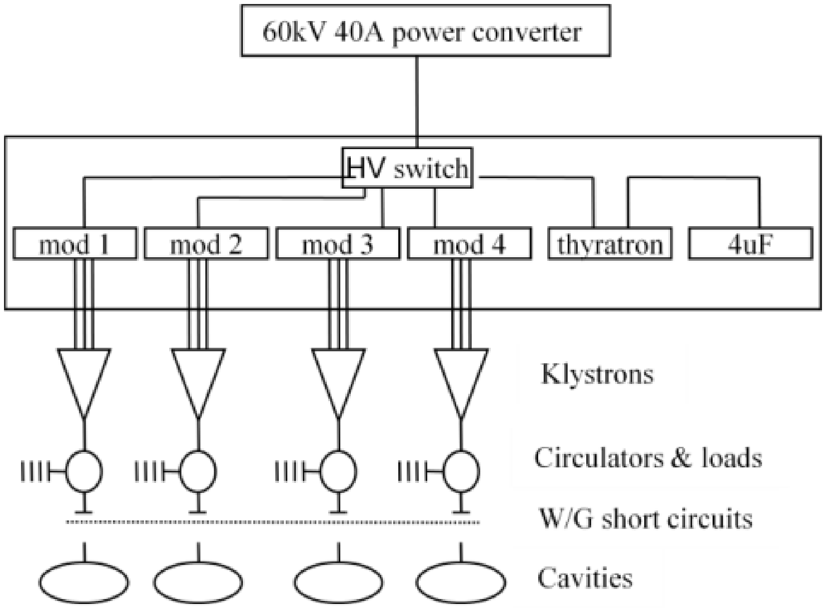
	Z		W		H		ttb		
	collider	booster	collider	booster	collider	booster	collider	collider	booster
RF Frequency [MHz]	400.79	801.58	400.79	801.58	400.79	801.58	400.79	801.58	801.58
RF source type	1 MW klystron	500 kW klystron	1 MW klystron	500 kW klystron	1 MW klystron	500 kW klystron	1 MW klystron	500 kW klystron	10-20 kW SSPA
RF power / cav with beam [kW]	894	110	377	144	378	32	78	163	5
# cavities / RF sources	1	2	2	2	2	8	8	2	1
# RF sources	112	4	132	14	132	14	33	244	540
Installed RF power / RF source [kW]	1000	300	1000	400	1000	400	1000	500	20
RF power overhead [%]	12	36	32	39	32	56	60	54	>200
RF source efficiency [%]	80	80	80	80	80	80	80	80	65
Waveguide network efficiciency [%]	95	95	95	95	95	95	95	95	95
Installed peak/average electrical power [MW]	147.4	1.6 / 0.6	173.7	7.4 / 2	173.7	7.1 / 2.9	43.4	160.5	17.5 / 15.4

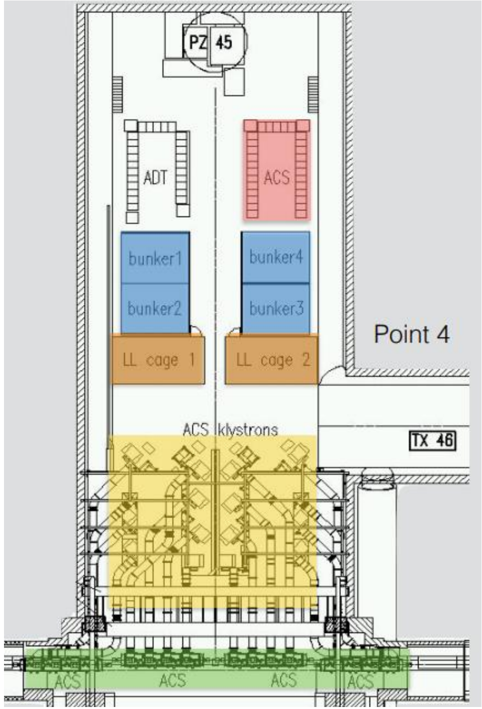
with booster duty cycle of 40-30-40-90 % (worst case)

- **RF power overhead** is evaluated according to cavity bandwidth (and Q_L) and will have to be optimized **when all low-level RF feedback systems** will be defined and their performances evaluated.
- The collider is operated with **new high efficiency klystrons (η>80%) in development at CERN.**
- For the **ttb booster, total RF power has increased, thus** 10 to 20 kW SSPA can be considered provided that the cost and efficiency are competitive (will be developed in industry).

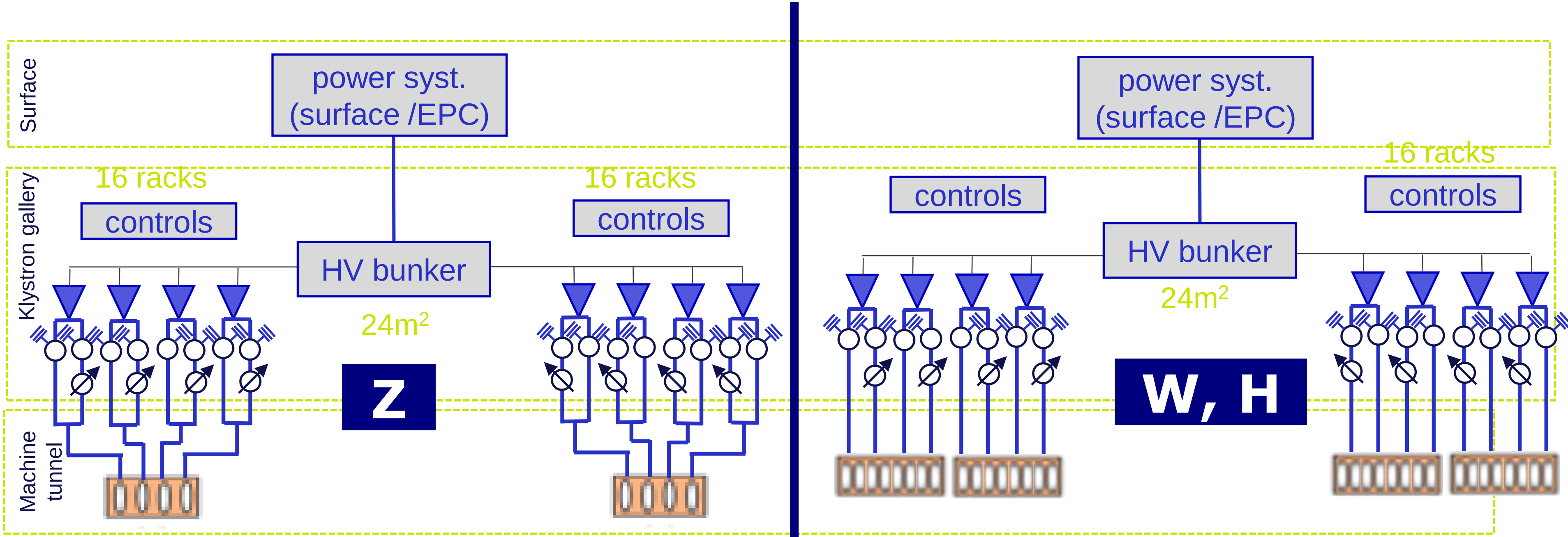
RF power distribution in the LHC

- DC power converters at the surface re-used from LEP - 60 kV (100 kV) / 40 A
- 4 high voltage bunkers for 16 klystrons hosting HV switch, anode modulator and crowbar
- Distance between HV bunker and klystron is limited (by stored energy in HV cable)





400 MHz RF units (Z, W, H)



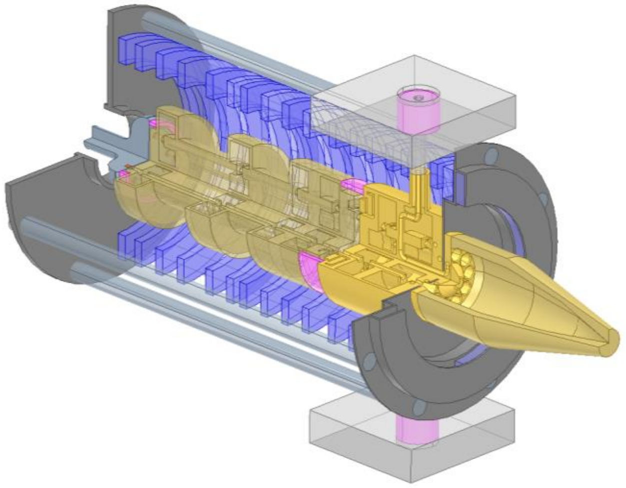
- 1000 kW per cavity with overhead
- 1 MW TS klystron (x8)
- 1 cavity per klystron (split & recombine)
- Total of 8 cavities (2 CM) per RF unit
- Half Height WR2300 Waveguides

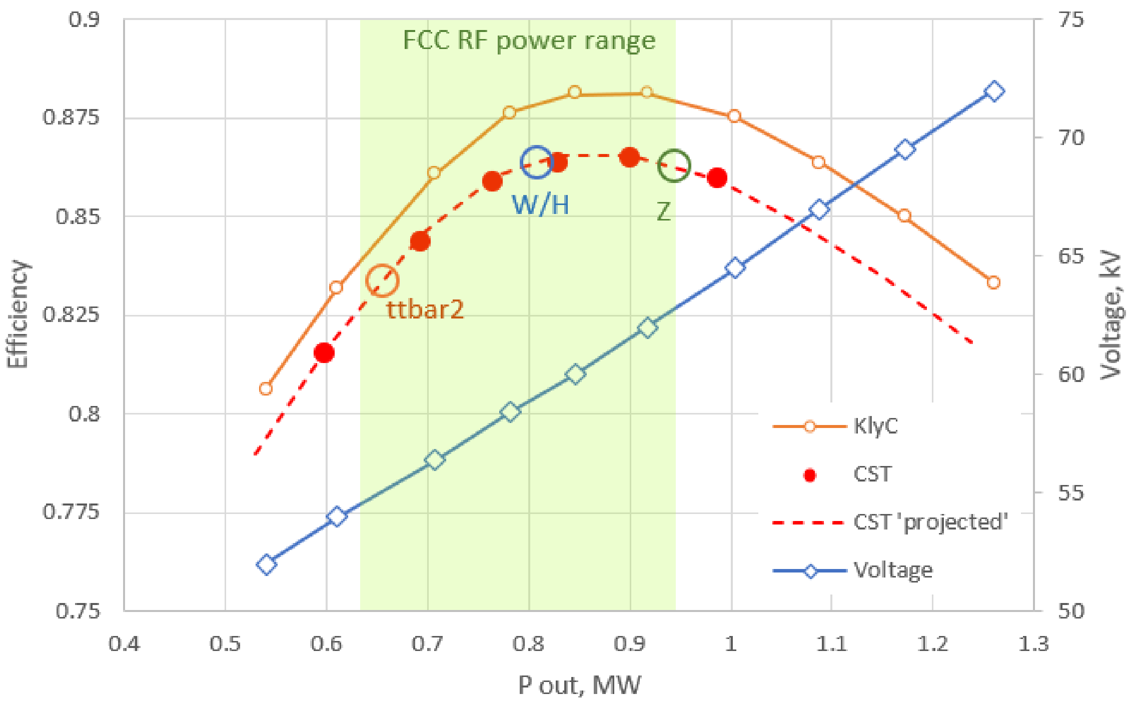
- 500 kW per cavity with overhead
- 1 MW TS klystron (x8)
- 2 cavities per klystron
- Total of 16 cavities (4 CM) per RF unit
- Re-use Z machine RF distribution

1 RF circulator + load per RF line
1 phase shifter per klystron

400 MHz high efficiency klystron project at CERN

- **Multibeam – Two stages**
- **Very efficient.** Above 82.5%
- **Compact.** Total length <3m.
- **Low Voltage.** Up to 64kV @ 1 MW.
- **High RF power gain.** 43dB @ 1MW.
- **Broadband.** 3.5 MHz @ -1dB.
- **Robust.** Can handle -15 dB mismatch

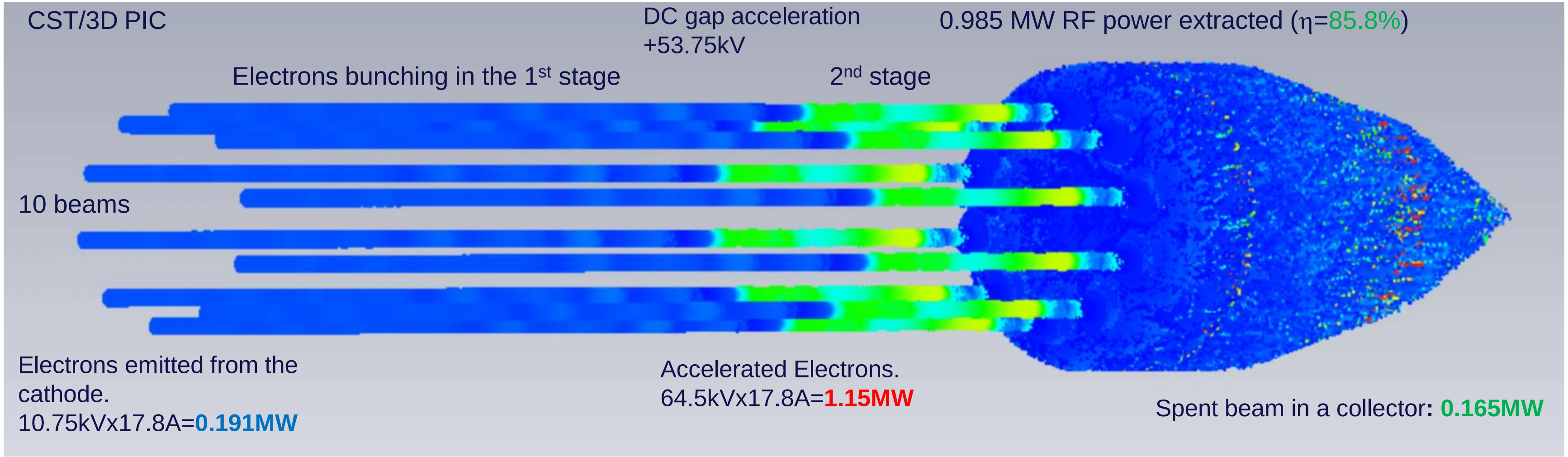


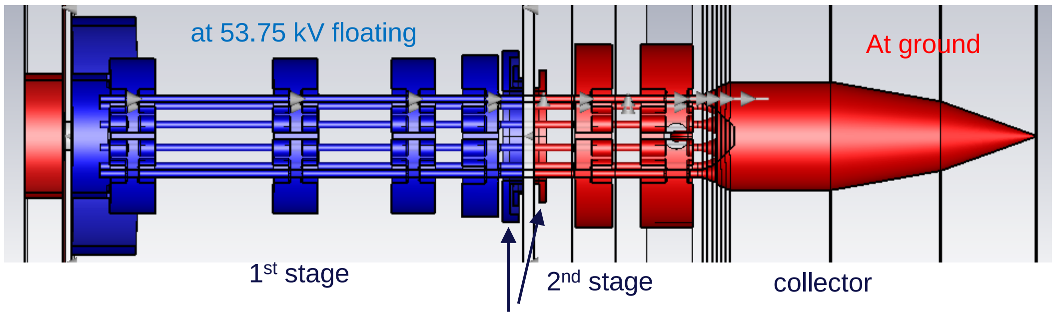


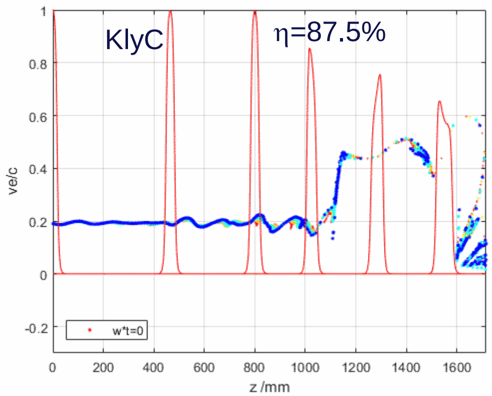
It is planned to complete the project and perform the first test in 2027/28.

Some approach is foreseen at 800 MHz - 500 kW

Particles dynamic in the TS 400 MHz FCCee MBK at 1MW RF output power

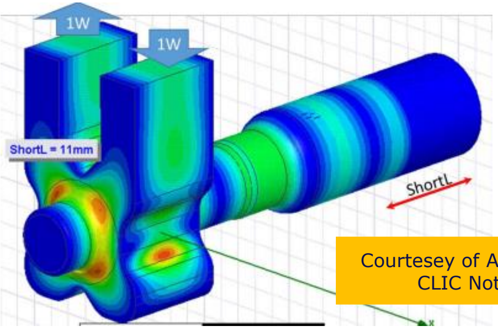






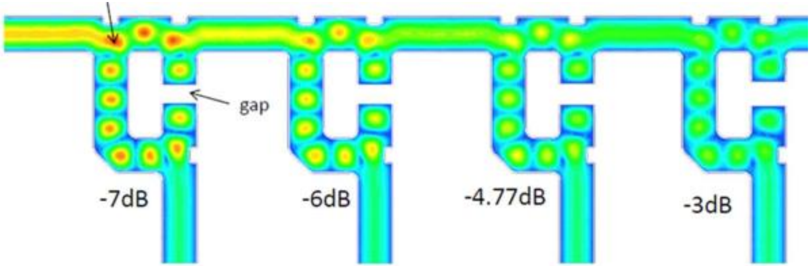
High power RF components

RF design effort will start on special RF components at 400/800 MHz, inspired from previous design (CLIC), including thermal and mechanical analysis.



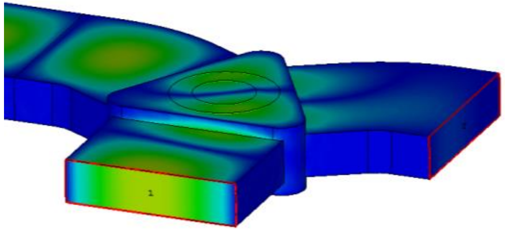
Courtesey of Alexej Grudiev
CLIC Note 1067

Variable phase shifter with 3dB E-hybrid splitter and TE11 mode converter.

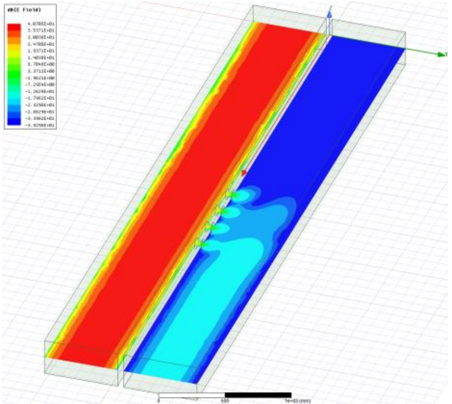


Compact "Adjustable Inline RF distribution system" to split RF power by 2 x 4 :

- 400 MHz for ttb (125 kW).
- 800 MHz for H booster (40 kW).

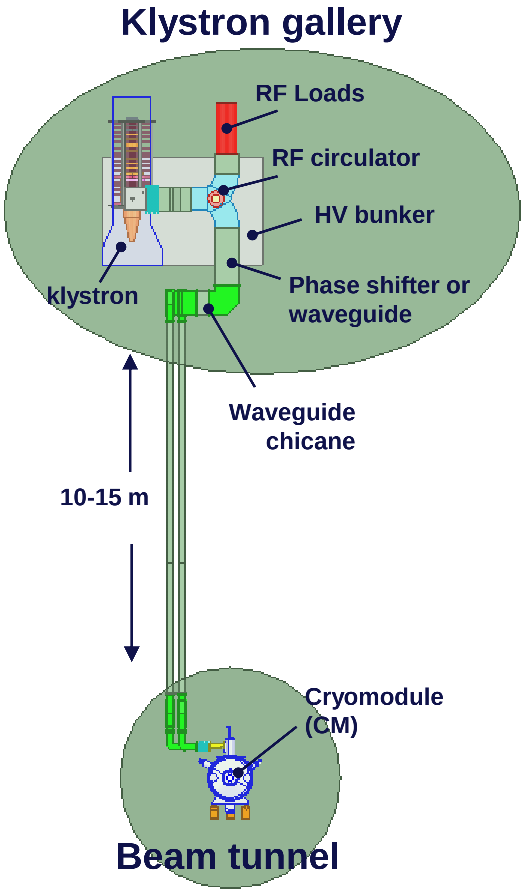


Circulator with ferrite.

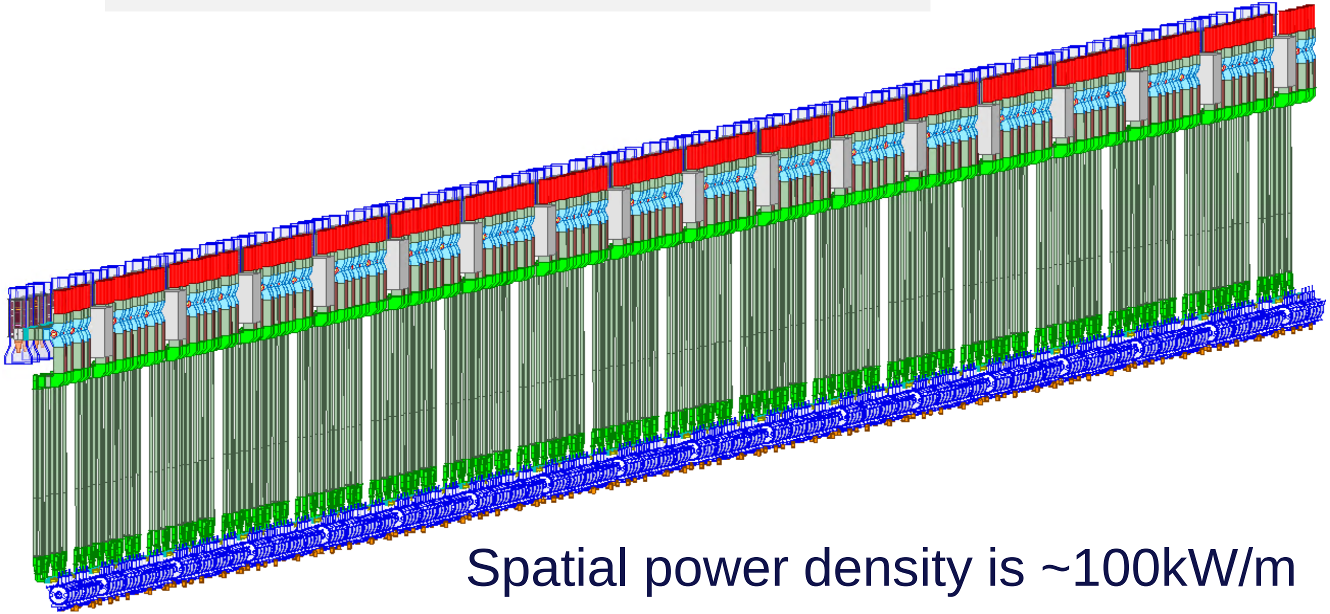


Bidirectional couplers with excellent directivity (better than 80 dB) for accurate measurements.

Integration in the klystron gallery for Higgs factory



- **4 CM per RF Unit**
- **17 x RF Units = 900 m**
- **66 (+2) cryomodules**
- **264 (+8) cavities (4 cav/CM)**

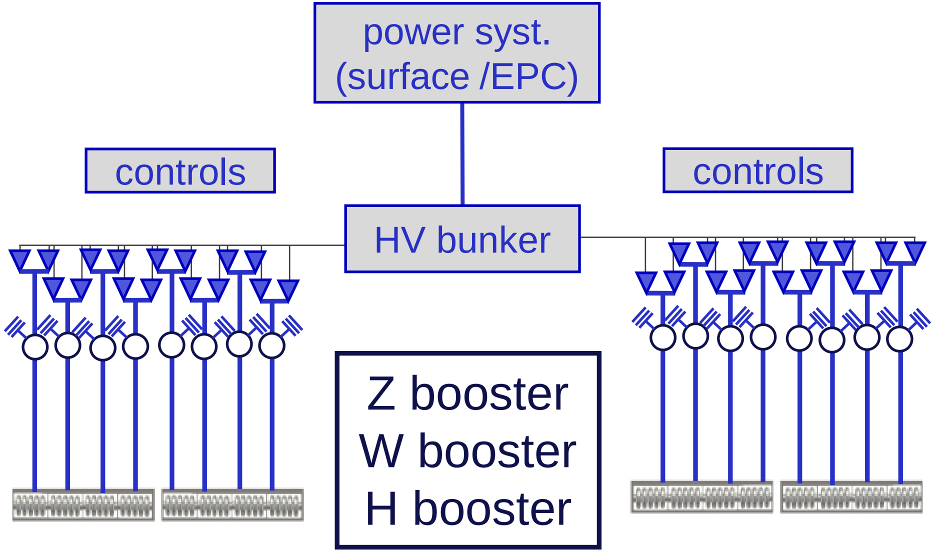


Spatial power density is ~100kW/m

800 MHz IOT option

For Z booster, W booster, H booster where we need **60 to 160 kW per cavity at 800MHz,** the use of **recombined IOTs** is a good alternative to klystrons :

- IOTs provide efficient operation during RF power ramping along acceleration.
- Industrialized IOTs can deliver typically 60 kW with 70 % RF efficiency.

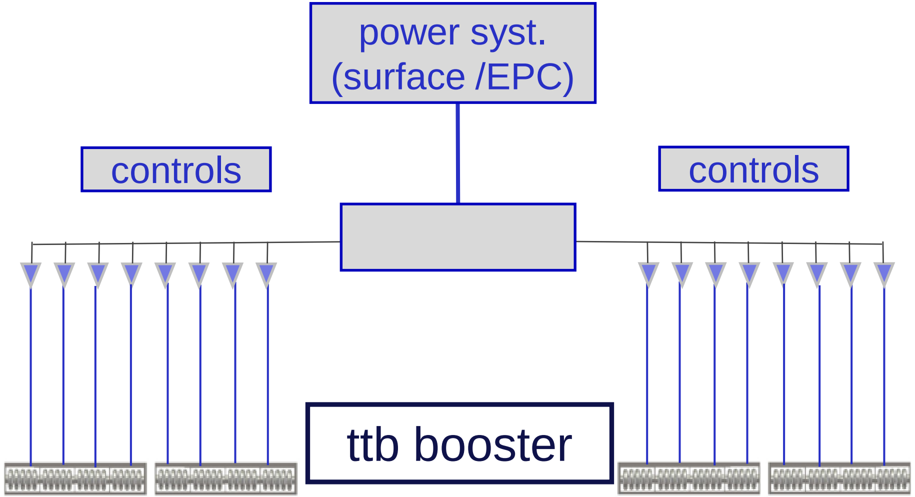


SPS 800 MHz RF system for Landau damping
2 cavities powered by 4 x 60 kW IOT

Courtesey of Eric Montesinos

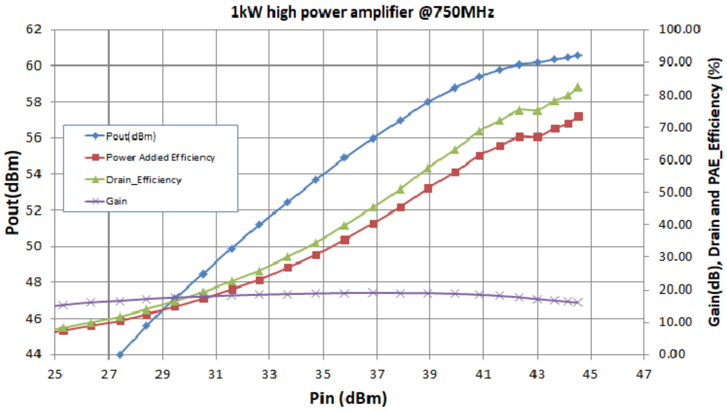
For ttb collider where we need **250 kW per cavity at 800MHz,** the possibility to develop a new type of **high effciency IOTs (>70%)** could be interesting.

800 MHz RF units (ttb booster)



Dragos Dancila and Alireza Mohadeskasaei (Uppsala University - FREIA)

I.FAST 2nd Annual meeting, 19.04.2023



- 5-20 kW per cavity with overhead
- 20 KW Solid State Power Amplifier (SSPA)
- 1 cavity per SSPA
- Total of 16 cavities (4 CM) per RF unit
- Coaxial line or cable

Low voltage distribution in the tunnel is under study (SY/EPC)

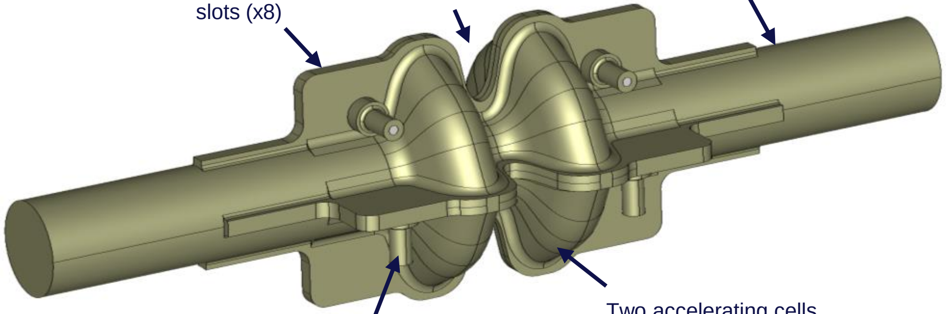
- Efficient (80%) 750MHz, 1.1kW module (6x200W GaN transistor) has been demonstrated last year.
- To generate 6 MW, 30 000 transistors will be needed.
- Currently GaN technology is rather expensive – 7CHF/W; that is 4-5 time more then in electro vacuum devices. One may expect this cost reduction with further development and industrialization.

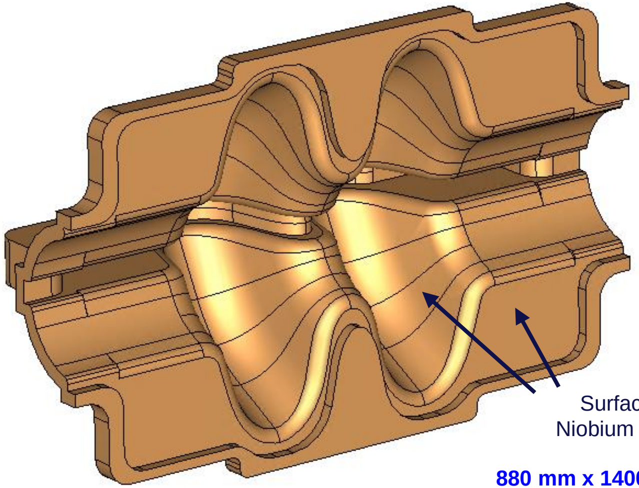
Outline

- RF parameters
- Elliptical SRF cavities design – with HOM damping
- Cryomodule RF simulations
  - How to manage high HOM power and trapped RF modes
- Generic RF powering scheme ("RF Units")
  - Waveguide distributions, circulator, combiner, phase shifter
- New high efficiency klystron development
- Alternative ideas:
  - SWELL cavity
  - Advanced RF parameters

The SWELL cavity option

- An alternative option to replace the 2-cell cavities, being studied since 2022.
- Highly damped RF structure thanks to waveguide slots.
- Precise machining of copper blocks.
- A novel approach for thin film coatings (open structure).
- Very robust against parasitic frequency detuning.
- Compatible with original cooling method (to reduce the volume of liquid helium).

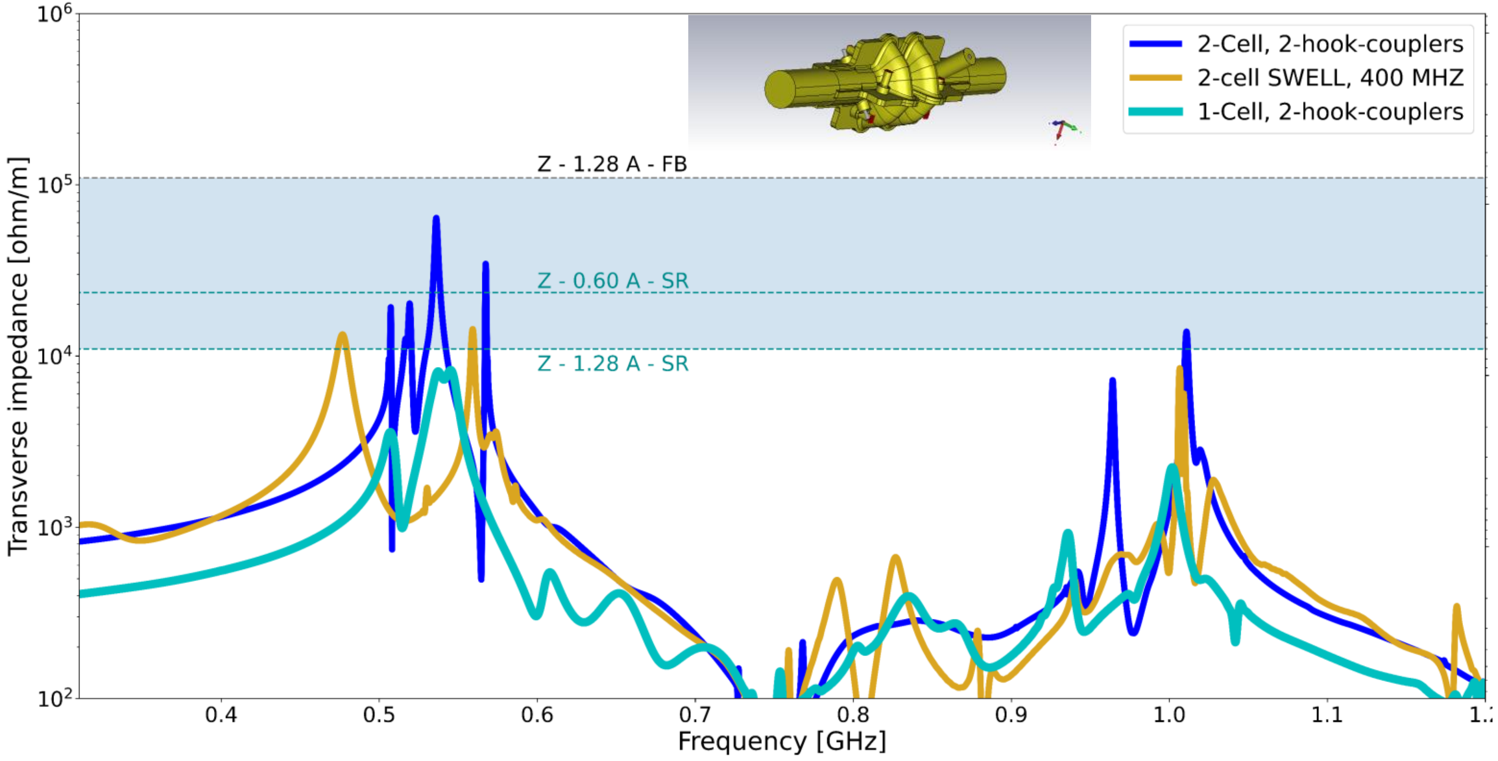




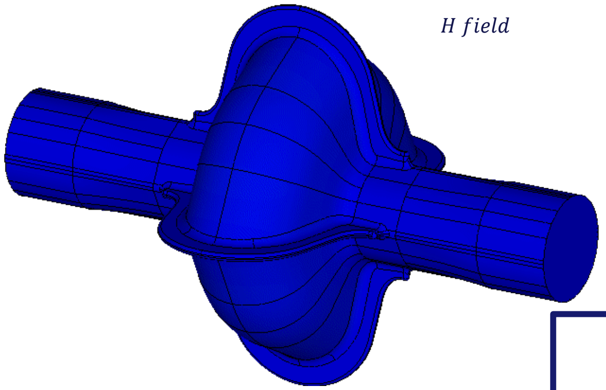
880 mm x 1400 mm
700 kg for 2 quadrants

HOM damping with 400 MHzSWELL cavity option

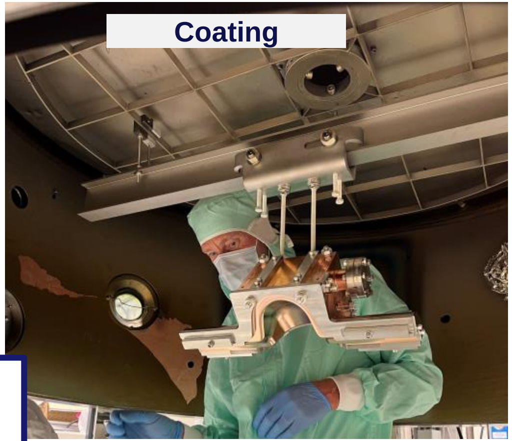
With **new compact design of 2-cell 400 MHz SWELL**, better damping of transverse impedance is demonstrated, allowing to relax the requirement on the transverse feedback system.



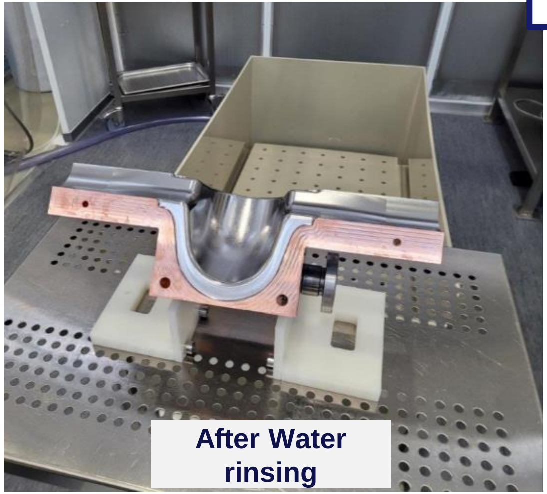
SWELL cavity feasibility demonstration at 1.3 GHz



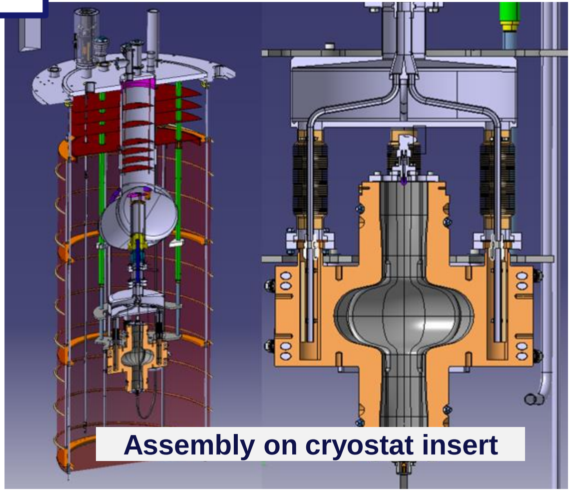

Machining


Coating

First cold test planned in June/July 2024

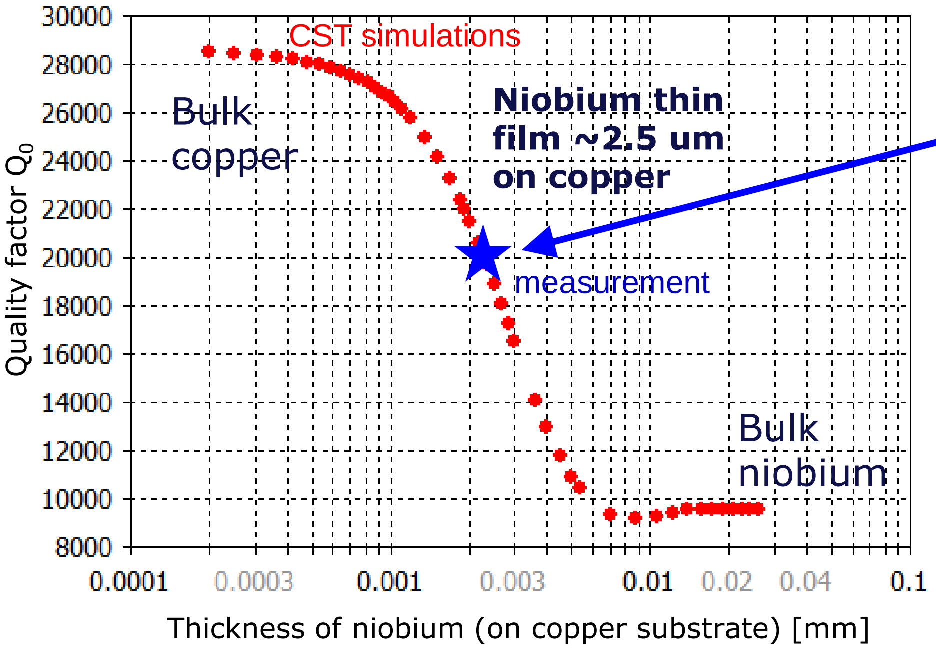

After Water rinsing

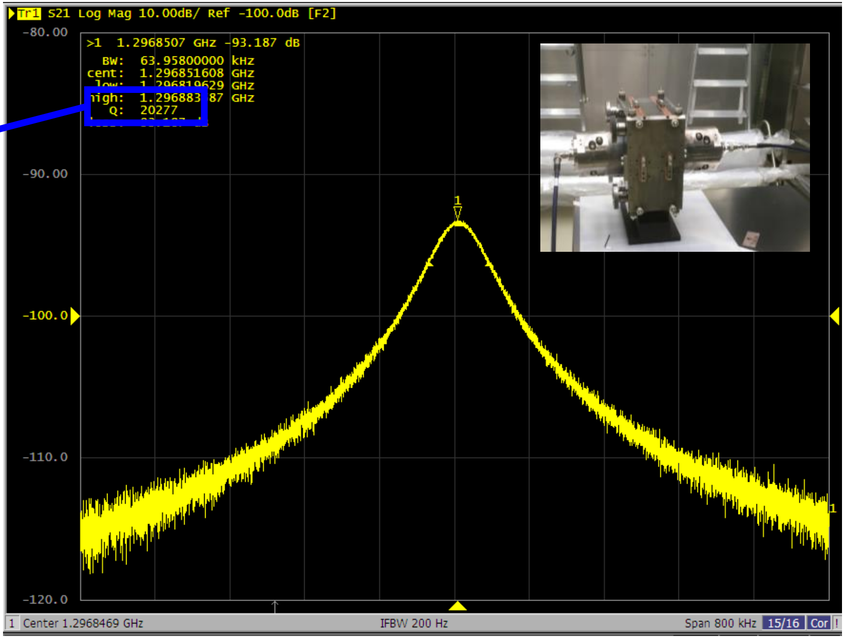

Assembly of quadrants


Assembly on cryostat insert

SWELL frequency change after Nb coating

At room temperature after Nb coating and assembly, the measured Q0 of 20277 corresponds to a Niobium thickness of ~2.5 um, which is in agreement with simulations.





"Advanced" RF parameters

1 → 2-cell for Z at 400 MHz

to save cryomodule removal from Z to W/H operation

5 → 6-cell for ttb and booster at 800 MHz

to reduce the number of cryomodules (and static heat load) with the same accelerating gradient of 20 MV/m.

Total number of cryomodules 351 -> 283 (-20%)

	Z		W		H		ttb		
	collider	booster	collider	booster	collider	booster	collider	collider	booster
RF Frequency [MHz]	400.79	801.58	400.79	801.58	400.79	801.58	400.79	400.79	801.58
Cavity type	**2-cell**	**6-cell**	2-cell	**6-cell**	2-cell	**6-cell**	2-cell	**6-cell**	**6-cell**
Eacc [MV/m]	3.8 **->1.9**	10.7 **->8.9**	10.1	15.3 **->14.9**	10.6	19.4 **->19.9**	10.6	20.2 **->19.9**	20.2 **->19.9**
Q0	2.7E+09	3.0E+10	2.7E+09	3.0E+10	2.7E+09	3.0E+10	2.7E+09	3.0E+10	3.0E+10
Epk [MV/m]	8.3 **->3.77**	22 **->18.3**	20.2	31.5 **->30.6**	21.2	39.8 **->40.7**	21.3	41.3 **->40.8**	41.3 **->40.8**
Bpk [mT]	20.2 **->10**	46.3**->38.6**	54	66.5 **->64.6**	56.4	84.1 **->86**	56.7	87.3 **->86.2**	87.3 **->86.1**
Beam current [mA]	1283	14.3	135	11.8	53.6	2	10	10	0.3
RF power [kW]	894	110	377	144 **->168**	378	32 **->39**	78	163 **->193**	5 **->6**
Optimum QL	2.5E+04 **->1.2e4**	1.7E+06	8.4E+05	2.7E+06 **->3.2e6**	9.2E+05	2E+07 **->2.4e7**	4.5E+06	4.2E+06 **->5e6**	1.3E+08 **->1.6e8**
Optimum detuning [Hz]	13884 **->28704**	191	601	90 **->77**	112	11 **->9**	9	56 **->47**	1.4 **->1.2**
Operating temp. [K]	4.5	2	4.5	2	4.5	2	4.5	2	2
dyn losses/cav [W]	8 **->4**	2.3	117	4 **->5**	128	9 **->13**	129	23 **->32**	20 **->28**
# CM (with 4 cav/CM)	14 per beam	2	33 per beam	7	66	27 **->22**	66	122 **->103**	135 **->114**

Main challenges with “Advanced” RF parameters

400 MHz
2-cell @ Z

- Transient beam loading management with twice higher R/Q
- Transverse feedback system against coupled bunch instabilities becomes mandatory
- Risks of beam instabilities with 0-mode of the cavity
- Higher HOM power losses (32.9 -> ~40 kW per CM)
- QL_{opt} of 1.2e4 @ Z is difficult with present FPC design where antenna tip is fixed and Qx is tuned in the waveguides -> increase of peak surface fields on the FPC side.

See Ivan Karpov’s talk

800 MHz
6-cell

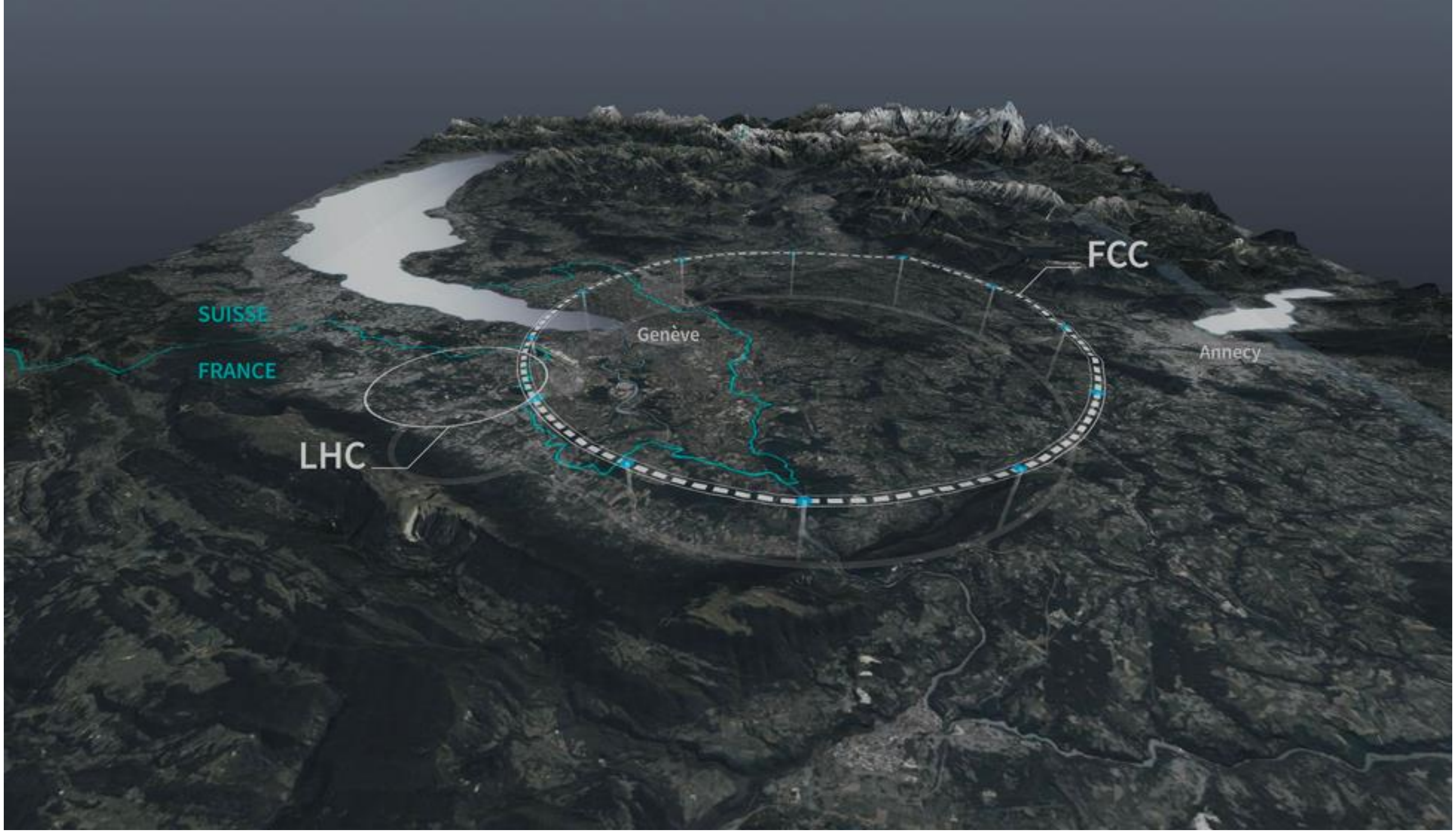
- Max RF power 800 MHz increases close to the limit of 200 kW.
- Trapped modes in the 4-cavity string module to check.
- Higher Q_L which does not help for cavity control (lorentz force detuning, microphonics).
- Chemical electropolishing may be more challenging.
- Compatibility with present infrastructures (chemical benches, furnaces, HPR cabinets, …) with a cavity length of ~**1.5 m from flange to flange**.

The goal is to study these limits by the end of 2024

Summary

- (Minor) changes on the main RF parameters.
- Unchanged RF design of the three cavity types. HOM power extraction scheme proposed for the module. Mechanical design can start.
- Types of RF power sources identified, with novel approach for high efficiency klystron at ~MW level.
- RF waveguides distribution defined for all stages, useful for tunnel/gallery integration.
- R&D on Swell cavity is pursued.
- Continuous effort to reduce the number of cavities without affecting the performances and the margin.

Thank you for your attention



Beam parameters updates for collider

https://indico.cern.ch/event/1416849/

Parameters

FUTURE CIRCULAR COLLIDER

FCC-ee collider parameters for the GHC lattice as of May 29, 2024.

Beam energy	[GeV]	45.6	80	120	182.5
Layout		PA31-3.0			
# of IPs		4			
Circumference	[km]	90.658728			
Bend. radius of arc dipole	[km]	10.021			
Energy loss / turn	[GeV]	0.0390	0.369	1.86	9.94
SR power / beam	[MW]	50			
Beam current	[mA]	1283	135	26.8	5.0
Colliding bunches / beam		11200	1852	300	64
Colliding bunch population	[10^{11}]	2.16	1.38	1.69	1.48
Hor. emittance at collision ε_x	[nm]	0.70	2.16	0.66	1.51
Ver. emittance at collision ε_y	[pm]	1.9	2.0	1.0	1.36
Lattice ver. emittance $\varepsilon_{y,\mathrm{lattice}}$	[pm]	0.87	1.20	0.57	0.94
Arc cell		Long 90/90		90/90	
Momentum compaction α_p	[10^{-6}]	29.2nx		7.52	
Arc sext families		75		146	
$\beta^*_{x/y}$	[mm]	110 / 0.7	220 / 1	240 / 1	900 / 1.4
Transverse tunes $Q_{x/y}$		218.158 / 222.220	218.185 / 222.220	398.150 / 398.220	398.148 / 398.215
Chromaticities $Q'_{x/y}$		0 / +5	0 / +5	0 / 0	0 / 0
Energy spread (SR/BS) σ_δ	[%]	0.039 / 0.110	0.069 / 0.105	0.102 / 0.176	0.152 / 0.184
Bunch length (SR/BS) σ_z	[mm]	5.57 / 15.6	3.46 / 5.28	3.26 / 5.59	1.91 / 2.32
RF voltage 400/800 MHz	[GV]	0.079 / 0	1.00 / 0	2.09 / 0	2.1 / 9.20
Harm. number for 400 MHz		121200			
RF frequency (400 MHz)	MHz	400.787129			
Synchrotron tune Q_s		0.0289	0.0809	0.0334	0.0881
Long. damping time	[turns]	1171	218	65.4	19.4
RF acceptance	[%]	1.06	3.32	2.06	3.06
Energy acceptance (DA)	[%]	±1.0	±1.0	±1.9	-2.8/+2.5
Beam crossing angle at IP θ_x	[mrad]	±15			
Crab waist ratio	[%]	70	55	50	40
Beam-beam ξ_x/ξ_y [a]		0.0022 / 0.0977	0.013 / 0.129	0.0108 / 0.130	0.065 / 0.136
Piwinski angle $(\theta_x \sigma_{z,\mathrm{BS}})/\sigma^*_x$		26.6	3.6	6.6	0.94
Lifetime (q + BS + lattice)	[sec]	11800	4500	6000	7700
Lifetime (lum) [b]	[sec]	1330	960	600	670
Luminosity / IP	[10^{34}/cm^{2}s]	143	20	7.5	1.38

[a] incl. hourglass.
[b] only the energy acceptance is taken into account for the cross section, no beam size effect.

3

- compared to Jul. 2023:
  - higher bunch charge, higher luminosity @Zh.
  - lower bunch charge @$W/t\bar{t}$ for better lifetime.
  - longer lifetime at all energies.
  - ±1.0% momentum acceptance@Z/W.
- At each energy, parameter with slightly higher luminosity is possible by increasing the bunch charge and ξ_y, in sacrifice of the lifetime.

May 29, 2024, K. Oide

FCC

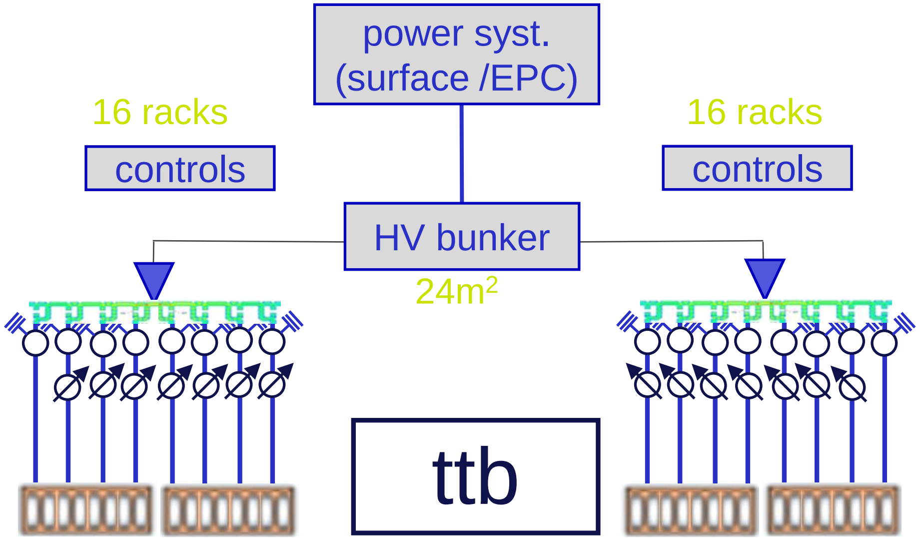
Beam parameters updates for booster

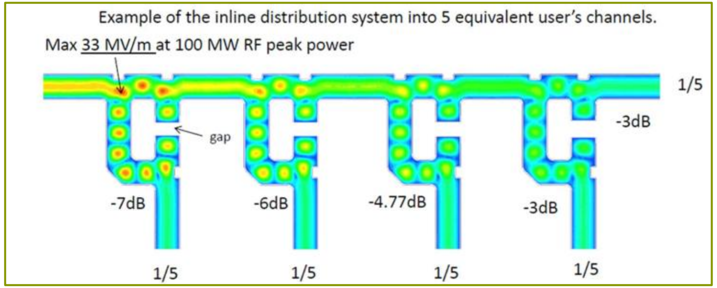
https://gitlab.cern.ch/acc-models/fcc/fcc-ee-heb/-/blob/V24_FODO/Booster_parameter_table.xlsx?ref_type=heads

Parameter	Unit	Z	W	ZH	ttbar	Comments
Layout						
Version		PA31-3.0				
Number of Ips		4				
Circumference	km	90.6587453				
Revolution period	ms	0.30240502				
Offset IP	m	8				
Hor. Arc offset booster-collider	m	-0.16				
General parameters						
Injector		LINAC				
Number of booster cyclings to have a full collider ramp		10	2	1	1	
Number bunches/collider		11200	1780	380	56	
Number bunches/booster		1120	890	380	56	
Collider particles/bunch	1.00E+10	21.4	14.5	13.2	16.4	
Allowable charge balance	%	5	3	3	3	
Particle number / bunch (filling)	1.00E+10	2.5	2.5	1	1	
Bunch charge (filling)	nC	4.00544159	4.00544159	1.60217663	1.60217663	
Mean beam current (filling)	mA	14.83	11.79	2.01	0.30	
Maximum bootstrap particle number / bunch (top-up)	1.00E+10	2.14	0.87	0.792	0.984	
Maximum bootstrap bunch charge (top-up)	nC	3.43E+00	1.39E+00	1.27E+00	1.58E+00	
Mean beam current (top-up)	mA	12.70	4.10	1.59	0.29	
Collider beam life time at collisions	s	868.1	492.4	376.2	348.2	
Collider top-up interval (between e+ and e-)	s	43.405	14.772	11.286	10.446	
Injection Beam parameters						
Injection energy	GeV	20	20	20	20	
Injection magnetic rigidity	Tm	66.712819	66.712819	66.712819	66.712819	
Injection gamma		39139.0237	39139.0237	39139.0237	39139.0237	
Injection beam energy	kJ	89.7218915	71.2968602	12.1765424	1.79443783	
Injection horizontal emittance (norm.)	µm	10	10	10	10	To be validated
Injection vertical emittance (norm.)	µm	10	10	10	10	To be validated
Injection RMS bunch length	mm	4	4	4	4	To be validated
Injection RMS energy spread		1.00E-03	1.00E-03	1.00E-03	1.00E-03	To be validated
Extraction Beam parameters						
Extraction energy	GeV	45.6	80	120	182.5	
Extraction magnetic rigidity	Tm	152.105227	266.851276	400.276914	608.754474	
Extraction gamma		89236.974	156556.095	234834.142	357143.591	
Injection beam energy	kJ	204.565913	285.187441	73.0592545	16.3742452	
Extraction horizontal emittance (RMS)	nm	8.73E-02	2.69E-01	6.05E-01	1.40E+00	To be updated according to ram
Extraction vertical emittance (RMS)	pm	1.75E-01	5.37E-01	1.21E+00	2.80E+00	To be updated according to ram
Extraction bunch length	mm	2.40E+00	2.56E+00	2.26E+00	1.98E+00	To be updated according to ram
Collider bunch length (SR/BS)	mm	5.60 / 15.5	3.46 / 5.09	3.40 / 5.09	1.85 / 2.33	
Extraction RMS energy spread		3.82E-04	6.70E-04	1.01E-03	1.53E-03	
Optics parameters						
Arc optics		V24_FODO	V24_FODO	V24_FODO	V24_FODO	
Momentum compaction		7.12E-06	7.12E-06	7.12E-06	7.12E-06	
Synchrotron integrate I2		5.94E-04	5.94E-04	5.94E-04	5.94E-04	
Synchrotron integrate I3		5.68E-08	5.68E-08	5.68E-08	5.68E-08	
Synchrotron integrate I5		1.70E-11	1.70E-11	1.70E-11	1.70E-11	
Coupling		2.00E-03	2.00E-03	2.00E-03	2.00E-03	
Hor. Damping time at injection energy	s	9.05E+00	9.05E+00	9.05E+00	9.05E+00	
Long. Damping time at injection energy	s	4.52E+00	4.52E+00	4.52E+00	4.52E+00	
Hor. Damping time at extraction energy	s	7.63E-01	1.41E-01	4.19E-02	1.19E-02	
Long. Damping time at extraction energy	s	3.82E-01	7.07E-02	2.09E-02	5.95E-03	
Equilibrium horizontal emittance at extraction energy (RM	nm	8.73E-02	2.69E-01	6.05E-01	1.40E+00	
Equilibrium vertical emittance at extraction energy (RMS)	pm	1.75E-01	5.37E-01	1.21E+00	2.80E+00	
Equilibrium bunch length at extraction energy	mm	2.40E+00	2.56E+00	2.26E+00	1.98E+00	
Equilibrium RMS energy spread at extraction energy		3.82E-04	6.70E-04	1.01E-03	1.53E-03	

RF and voltage parameters						
RF frequency	MHz	800	800	800	800	
RF wavelength	m	0.37474057	0.37474057	0.37474057	0.37474057	
Injection maximum relative energy acceptance	%	3	3	3	3	To be opti
Extraction maximum relative energy acceptance	%	1.00E+00	1.01E+00	1.51E+00	2.29E+00	To be opti
Injection energy loss/turn	MeV/turn	1.34	1.34	1.34	1.34	
Extraction energy loss/turn	MeV/turn	36.14	342.34	1733.11	9271.56	
Injection SR power loss (filling)	MW	0.020	0.016	0.003	0.000	
Extraction SR power loss (filling)	MW	0.536	4.036	3.489	2.751	
Injection SR power loss (top-up)	MW	0.017	0.005	0.002	0.000	
Extraction SR power loss (top-up)	MW	0.459	1.404	2.763	2.707	
Injection synchronous phase	degree	178.47	178.47	178.47	178.47	
Extraction synchronous phase	degree	140.85	121.59	117.90	114.39	
Injection RF voltage	MV	50.08	50.08	50.08	50.08	
Extraction RF voltage	MV	57.24	401.90	1961.05	10180.07	
Injection synchronous tune		2.62E-02	2.62E-02	2.62E-02	2.62E-02	
Extraction synchronous tune		1.63E-02	2.69E-02	4.58E-02	7.95E-02	
Ramp parameters						
Nb linac bunches/pulse		2	2	2	2	
Linac repetition frequency	Hz	200	100	50	50	
Nb linac pulses at injection np		560	445	190	28	
Accumulation time: np/frep	s	2.8	4.45	3.8	0.56	
Average energy gain	GeV/s	80	80	80	80	
Acc time	s	0.32	0.75	1.25	2.03125	
Flat-top	s	0.9	0.1	0.1	0.1	Flat-top to
Ramp time (up + flat + down)	s	1.54	1.6	2.6	4.1625	
Booster cycling time: tacc + tramp	s	4.34	6.05	6.4	4.7225	
Total cycling time: nBR*(tacc + tramp)	s	43.4	12.1	6.4	4.7225	
# of BR ramps (up to 1/2 stored current, with Nmax)		5	3	7	9	
# of BR ramps (up to stored current, with bootstrap)		25	23	15	13	
Collider filling time from scratch	s	2604	629.2	281.6	207.79	
Vacuum chamber parameters						
Shape		Circular				
Vacuum chamber material		Copper	Copper	Copper	Copper	
Inner Diameter	mm	60	60	60	60	
Thickness	mm	2.5	2.5	2.5	2.5	
Outer diameter	mm	65	65	65	65	

400 MHz RF units (ttb)





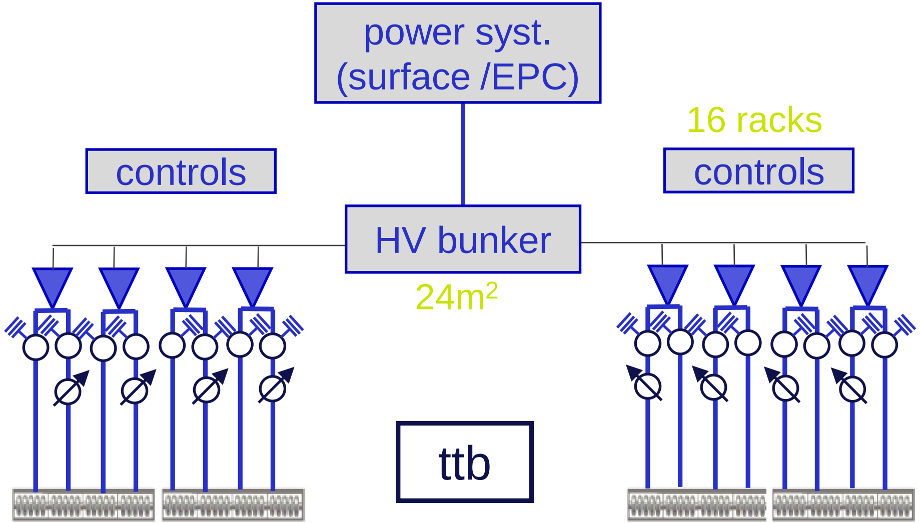
Compact "Adjustable Inline RF distribution system" for cavity fields optimization

- 125 kW per cavity with overhead
- 1 MW TS klystron (x8)
- 8 cavities per klystron
- Total of 16 cavities (4 CM) per RF unit
- 1 RF circulator + load per RF line

Add:
- "Adjustable Inline RF" distribution (x2)
- 1 phase shifter per RF line (to be completed)

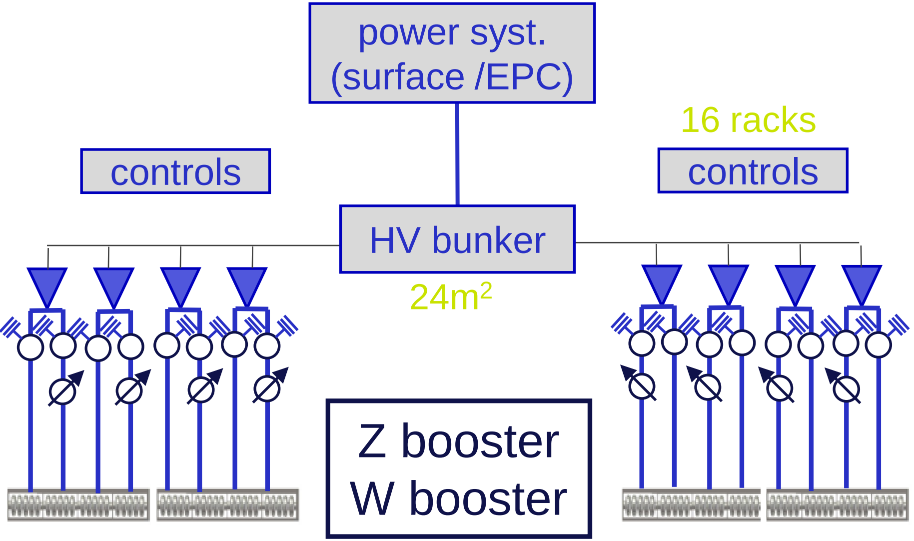
Remove:
- ¼ 1 MW klystrons : 99 spares

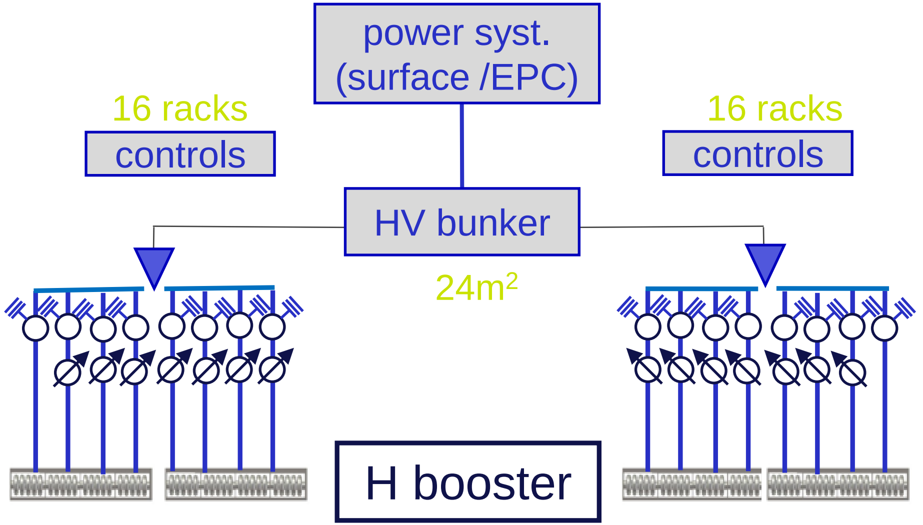
800 MHz RF units using klystrons (ttb)



- 250 kW per cavity with overhead
- 500 kW klystron (x8)
- 2 cavities per klystron
- Total of 16 cavities (4 CM) per RF unit
- Total of 31 RF units

800 MHz RF units (Z booster, W booster, H booster)





- 150-200 kW per cavity with overhead
- 500 kW klystron (x8) operating at 300-400 kW
- 2 cavities per klystron
- Total of 16 cavities (4 CM) per RF unit

- 50 kW per cavity with overhead
- 500 kW klystron (x8)
- “Adjustable Inline RF” distribution: 2 per klystron
- 8 cavity per klystron
- Total of 16 cavities (4 CM) per RF unit

- WR 1150 WG
- 1 RF circulator + load per RF line
- 1 phase shifter per klystron