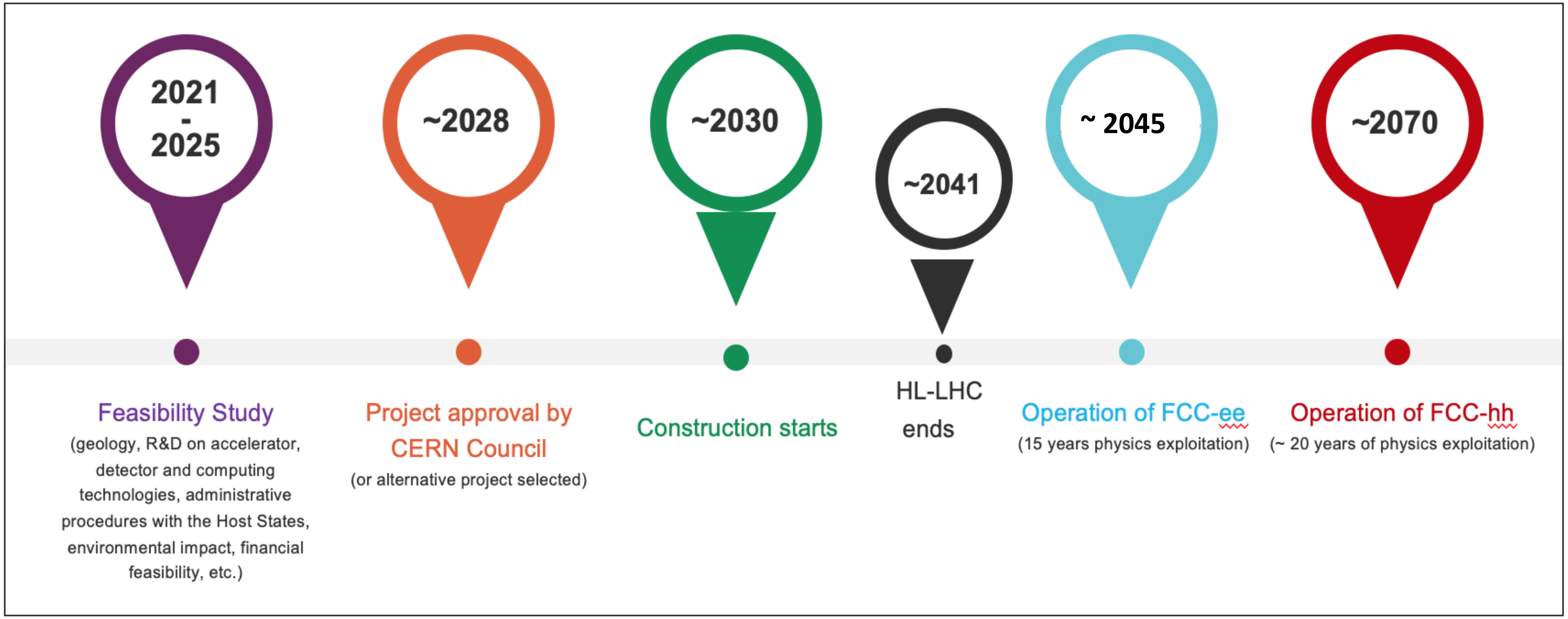
FCC_ee SRF systems

2nd Workshop on efficient RF sources

September 23rd, 2024

O. Brunner, on behalf of the FCC SRF WP

FCC: a century of physics

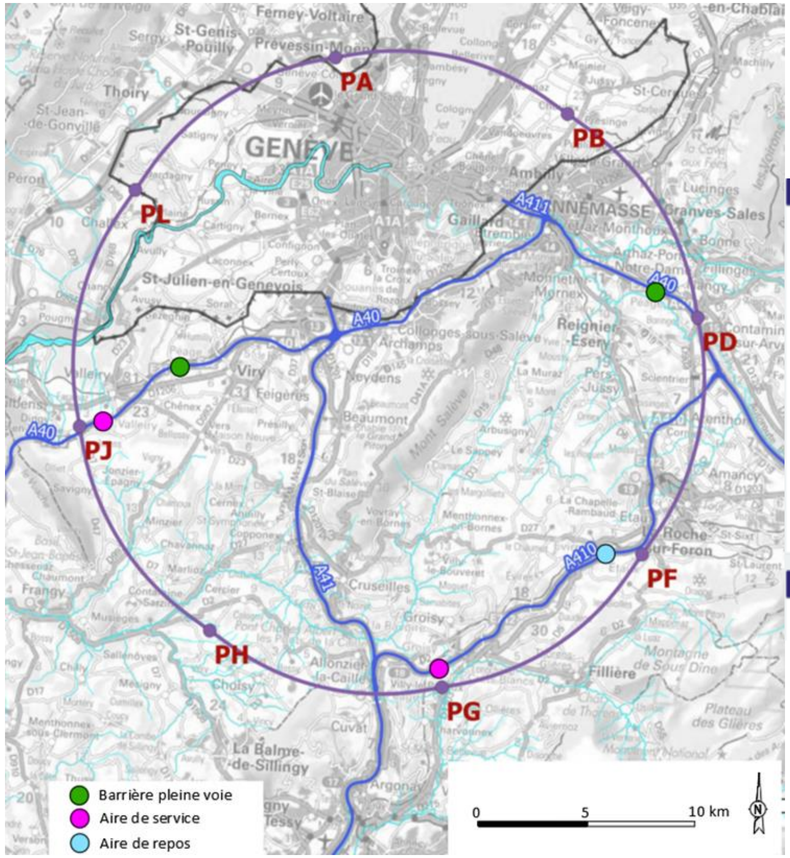


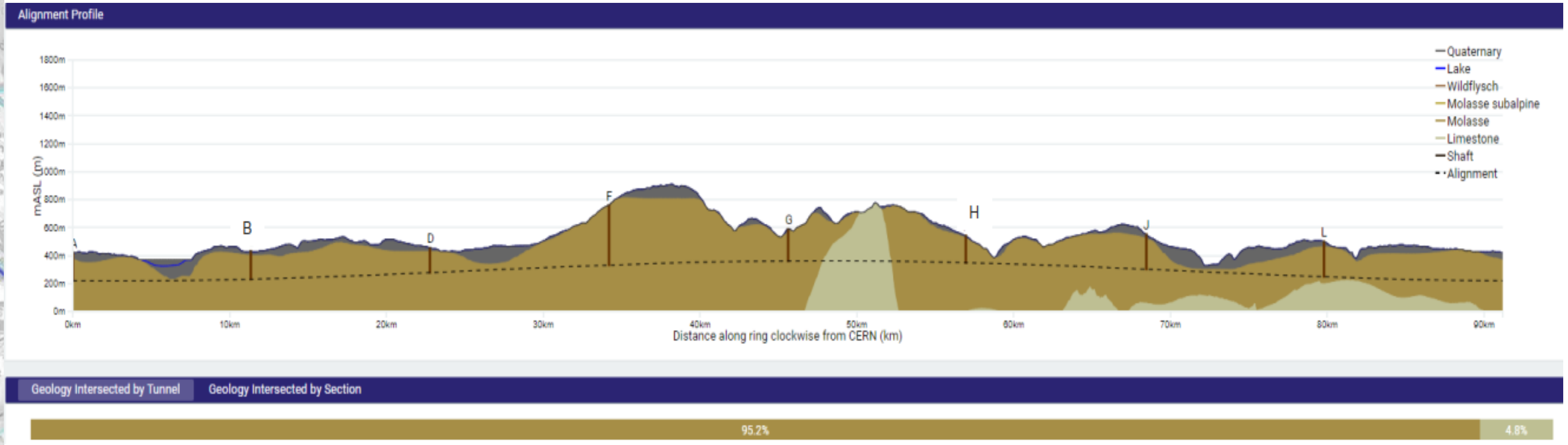
Courtesy, M. Benedikt, CERN

- stage 1: FCC_ee (Z, W, H, $t\bar{t}$) as Higgs factory, electroweak & top factory at highest luminosities
- stage 2: FCC_hh (~ 100 TeV) as natural continuation at energy frontier, pp & AA collisions; e-h option

-- Comprehensive long-term program maximizing physics opportunities --

Optimized implementation





Courtesy, M. Benedikt, CERN

- Layout chosen out of ~ 100 initial variants, based on geology and surface constraints (land availability, access to roads, etc.), environment (protected zones), infrastructure (water, electricity, transport), machine performance etc.
- Tunnel implementation →aim at minimising tunnel construction risks

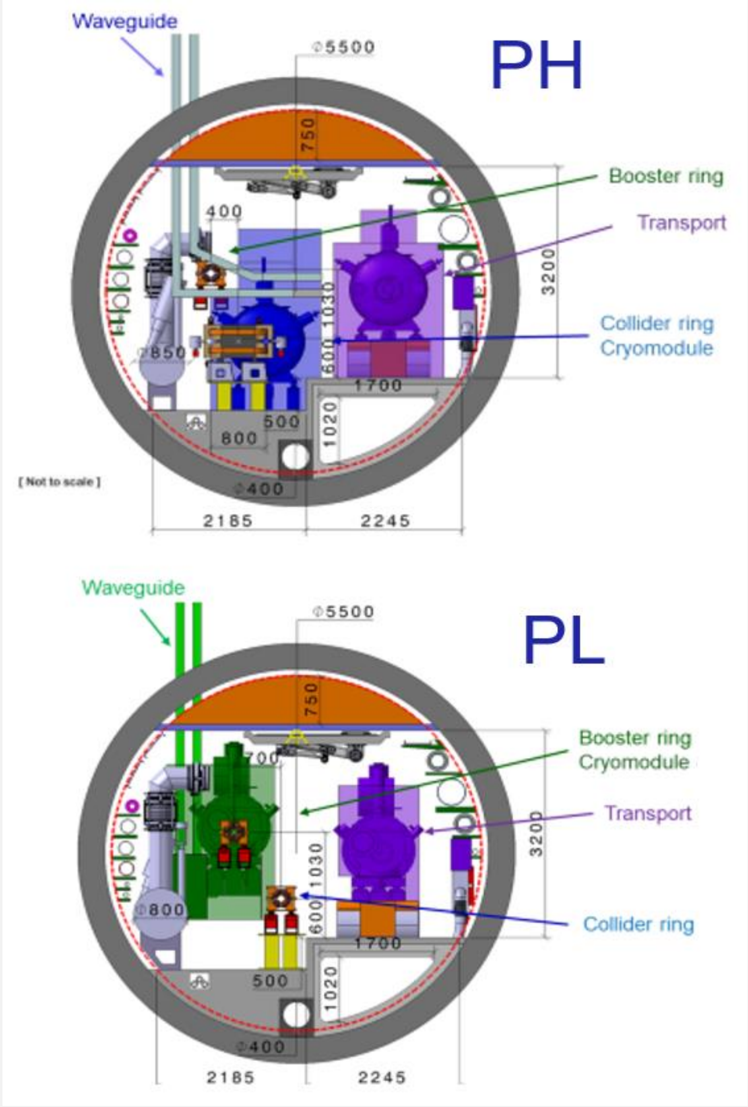
High level RF requirements

	Energy (GeV)	Current (mA)	RF voltage (GV)
Z	45.6	1280	0.080
W	80	135	1.05
H	120	26.7	2.1
ttb	182.5	5	11.3

High current machine

High gradient machine

- Collider (2 rings): 100 MW of RF power in CW (50 MW per ring) to compensate synchrotron radiation losses
- Booster (3rd ring) for top-up injection: to accelerate from 20 GeV to the final energy with 10% beam current and 15% average duty cycle
- *Injector complex (not discussed here)*
- Availability in operation of 80%



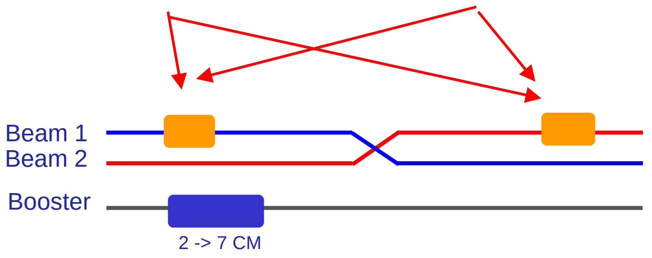
Courtesy, F. Valchkova, CERN

Main RF parameters and layout

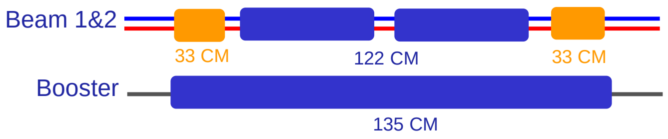
	Z		W		H		ttb		
	collider	booster	collider	booster	collider	booster	collider	collider	booster
RF Frequency [MHz]	400.79	801.58	400.79	801.58	400.79	801.58	400.79	400.79	801.58
Cavity type	1-cell	5-cell	2-cell	5-cell	2-cell	5-cell	2-cell	5-cell	5-cell
Eacc [MV/m]	3.77	10.7	10.1	15.35	10.6	19.4	10.6	20.1	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

~ 1 MW

Courtesy, F. Peauger



one RF system per beam



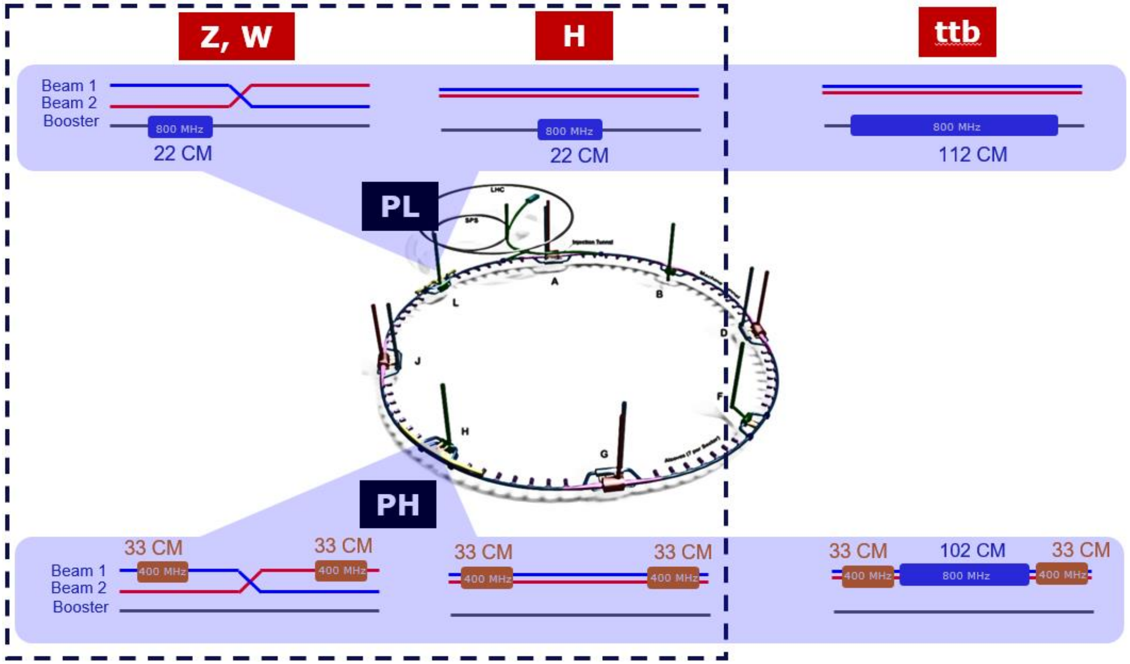
common RF system for both beams

-- Solid but tedious scenario --

-- Dedicated RF system for Z + massive upgrades (CM gymnastics + RF power distribution) --

-- Is there any room for improvement ?? --

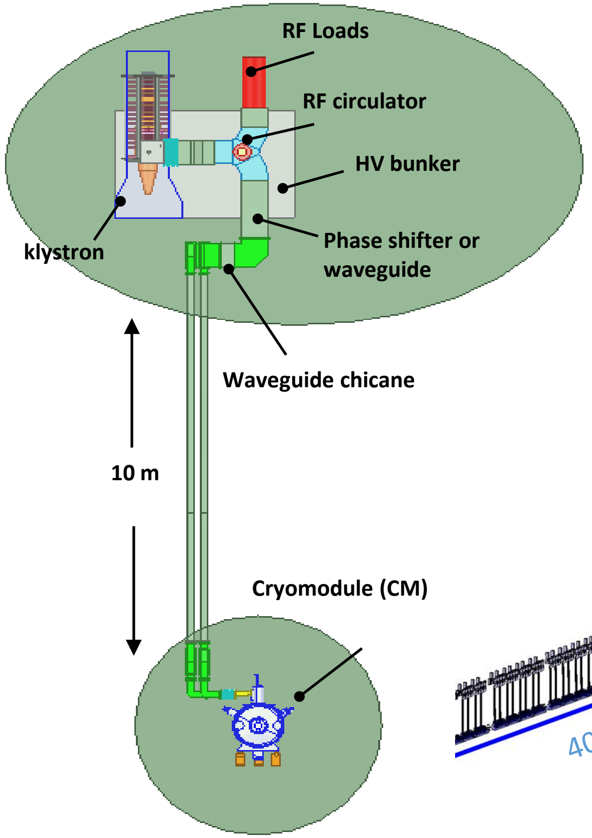
The dream scenario: (Z-W-ZH) - ttbar

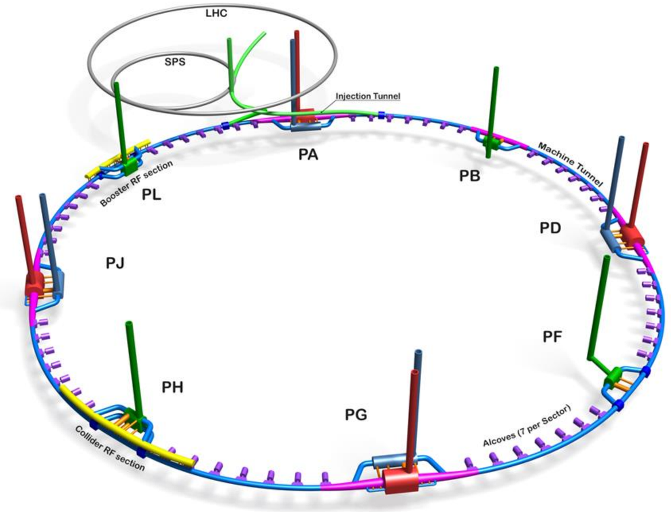


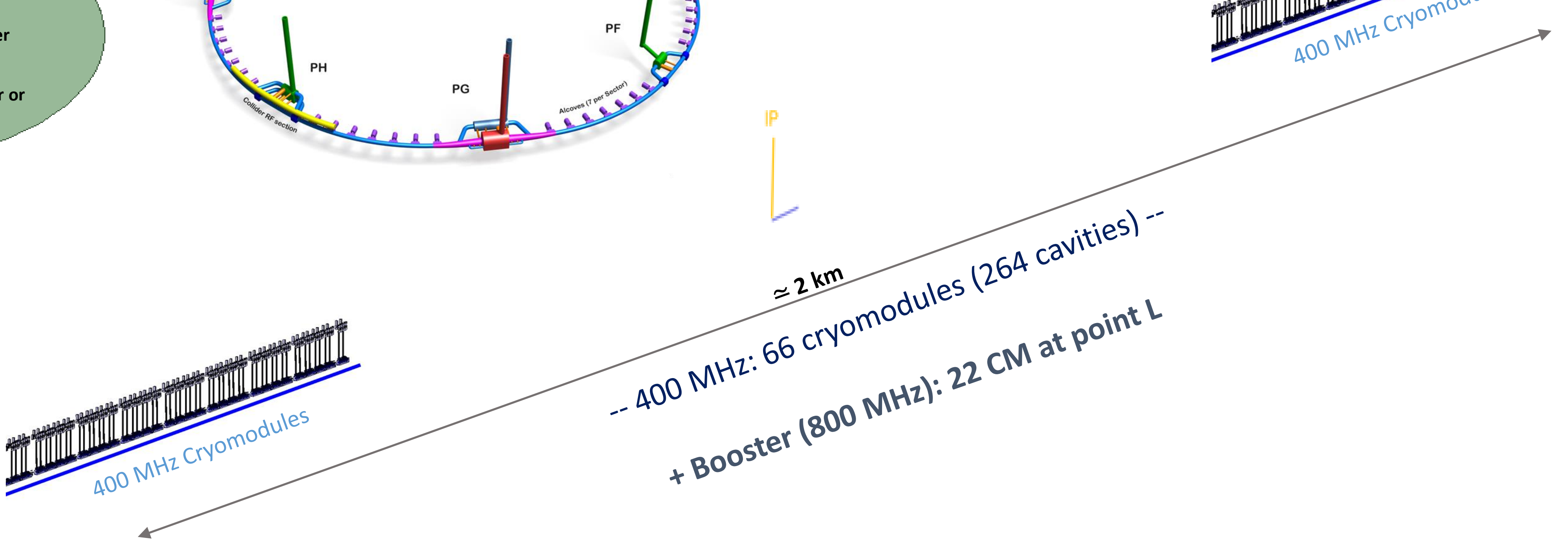
- **Single RF system for Z-W-ZH** → 400 MHz 2_cells cavities compatible with a common operating point ?
- **Increase the "real estate" gradient of the 800 MHz RF system (booster and ttbar)** → 5 to 6 cells per cavity ?
- **Optimize the design and the use of high efficiency (HE) RF power sources** → HE across a wide range of RF power levels ?

-- more operation time + more flexibility – reduced commissioning effort --

RF system integration (point H)





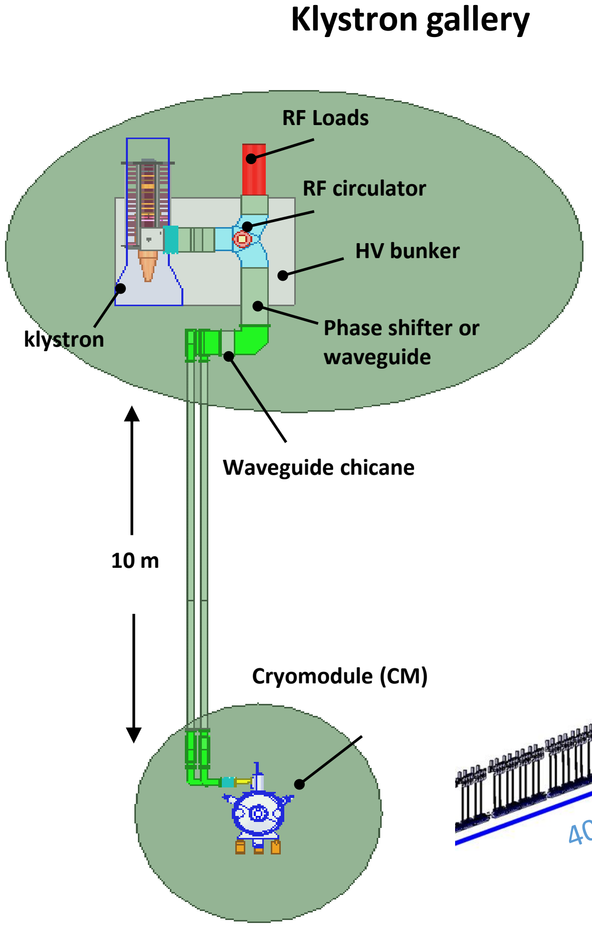


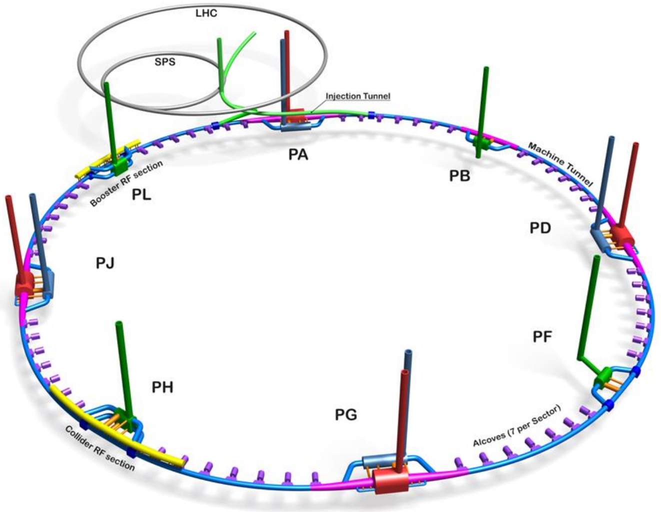
-- 400 MHz: 66 cryomodules (264 cavities) --

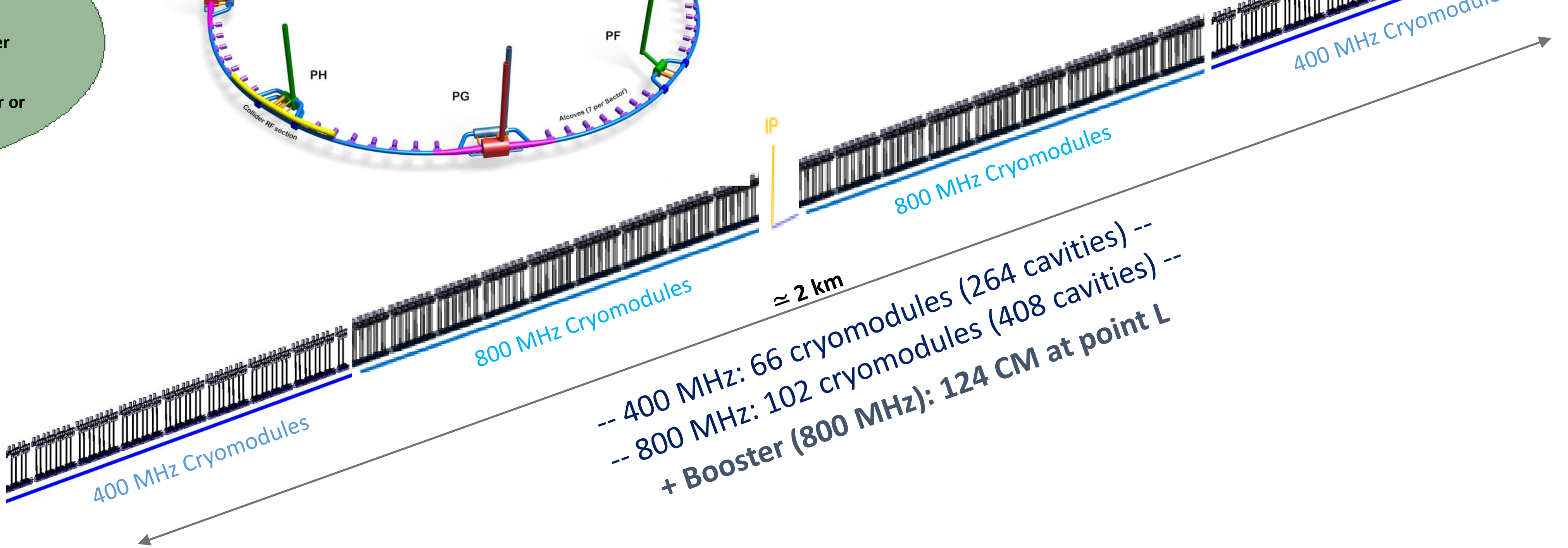
+ Booster (800 MHz): 22 CM at point L

-- RF system length ~ LLS → effort on CM length and E_{acc} --

RF system integration (point H)

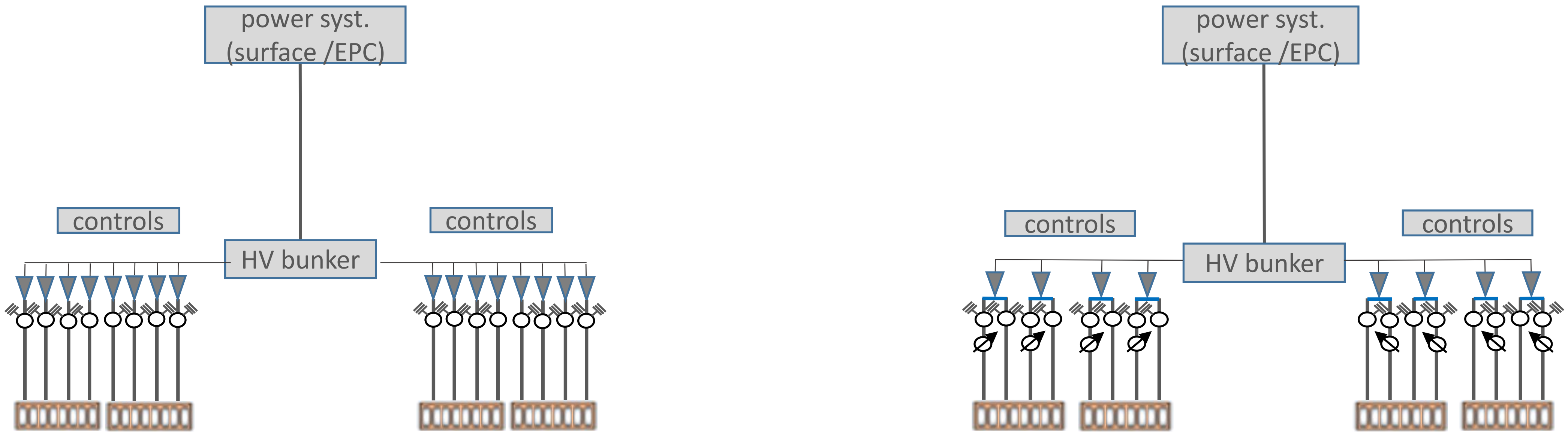






-- RF system length ~ LLS → effort on CM length and E_{acc} --

400 MHz RF units' principle: (Z, W, ZH -- ttbar)



Z, W & ZH

- **~400 kW per cavity**
- 500 KW TS klystrons
- 1 cavities per klystron + strong feedback per cavity

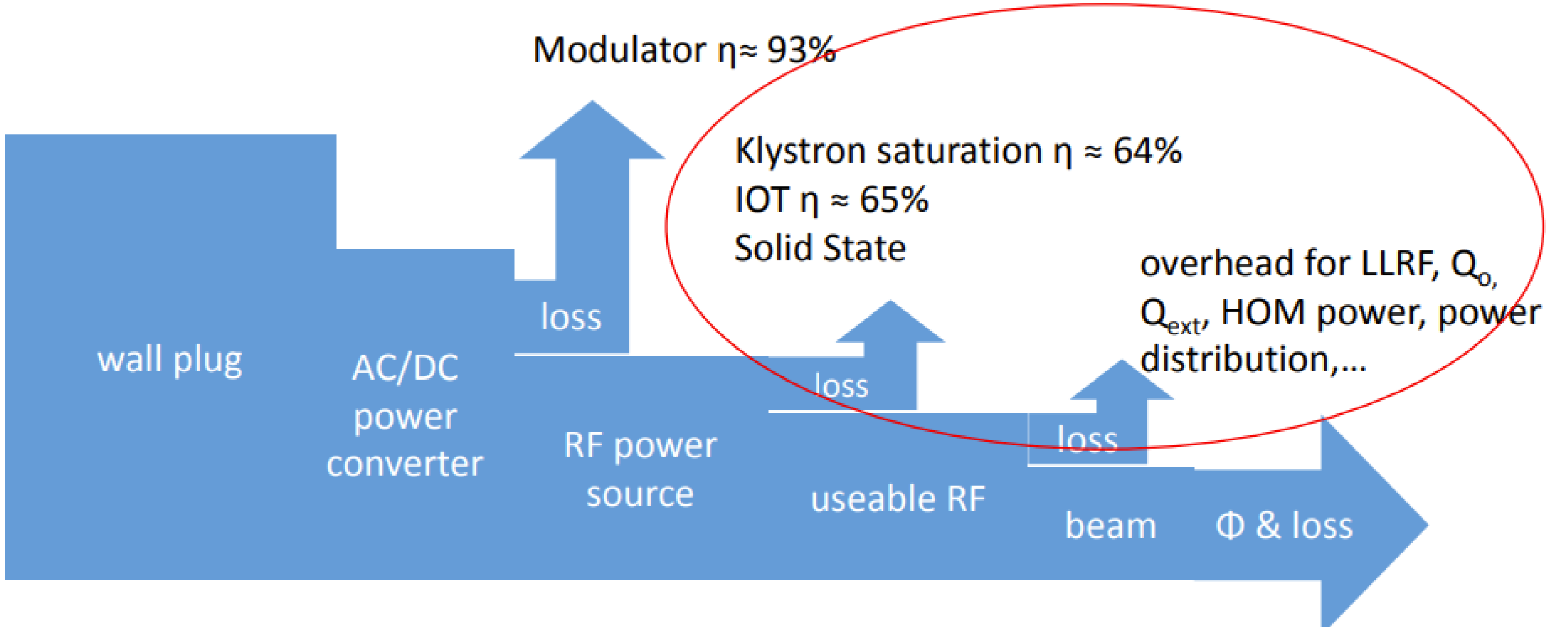
ttbar

- **~ 80 kW per cavity**
- 500 kW TS klystron → 132 spare klystrons
- 2 cavities per klystron
- + magic T + phase shifters

-- high-efficiency RF source across a wide power range would avoid any modification for ttbar --
(also highly desired for the 800 MHz system)

-> See Igor's talk

Power source options



From E. Jensen -EnEfficient RF Sources, The Cockcroft Institute, 3-4 June 2014

Ideally:

- compact
- highly efficient
- reliable
- low power consumption in standby
- large power range
- *'low' cost, several suppliers*

-- The whole system must be optimized – not one efficiency alone --

FUTURE CIRCULAR COLLIDER

CERN

Unique 2-cells cavities RF system for Z, W, ZH ?

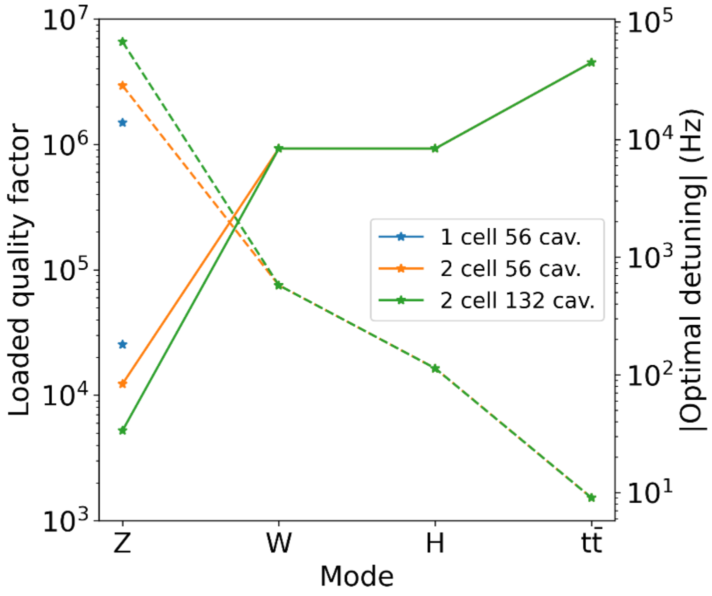
- **Motivation:**
  - **to operate all cavities at the same Q_{ext} and same P_{RF} for all energies**
- **Reverse phase operation (RPO) offers this opportunity:**
  - allows operation at higher cavity voltages : $cos(\phi_s + \phi_{foc}) = cos(\phi_s + \phi_{defoc})$
  - does not required more RF power *(all cavities accelerate the beam)*
  - experimentally verified with high beam loading in KEKB and baseline solution for EIC ESR

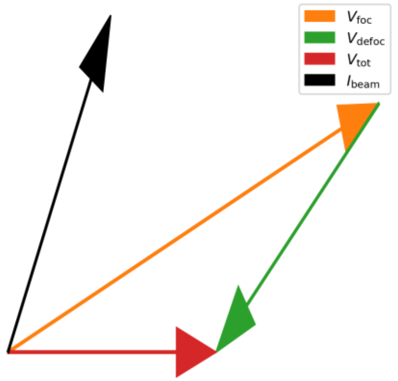
$$Q_{\mathrm{ext,opt}} = \frac{|V_{\mathrm{cav}}|}{|F_b|(R/Q)I_{b,\mathrm{dc}}\cos(\phi_s+\phi_c)}$$

$$P_{g,\mathrm{opt}} = \frac{|V_{\mathrm{cav}}||F_b|I_{b,\mathrm{dc}}\cos(\phi_s+\phi_c)}{2}$$

  - cavity voltage can only be changed in discrete steps of N_foc−N_defoc=2, 4,…
  - Z, W, ZH:

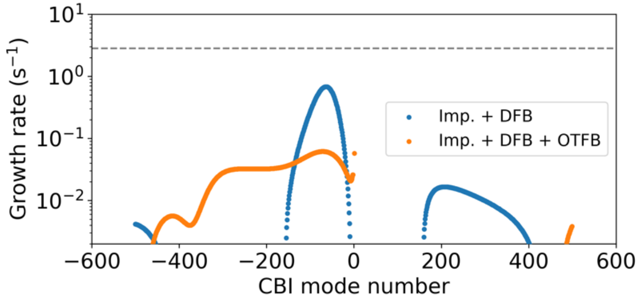
	N_{tot}	N_{foc}	N_{defoc}	V_{tot} Z (MV)	V_{cav} (MV)	Q_L	P_{opt} (kW)
Option 1	132	71	61	88	7.95	9.21e5	378
Option 2	152	81	71	79	6.88	7.93e5	329



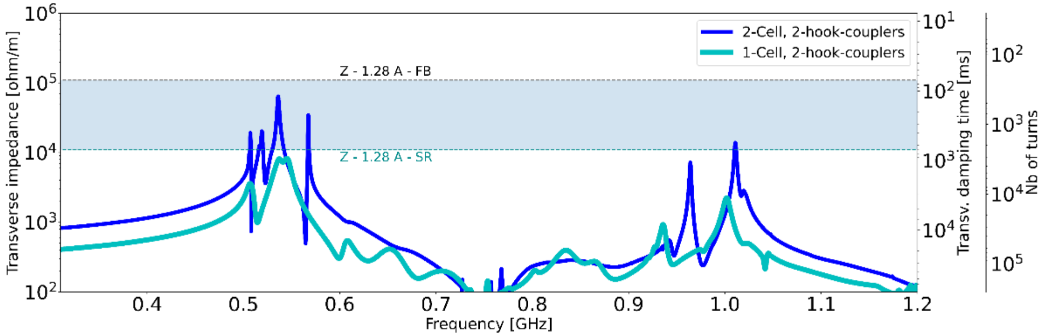


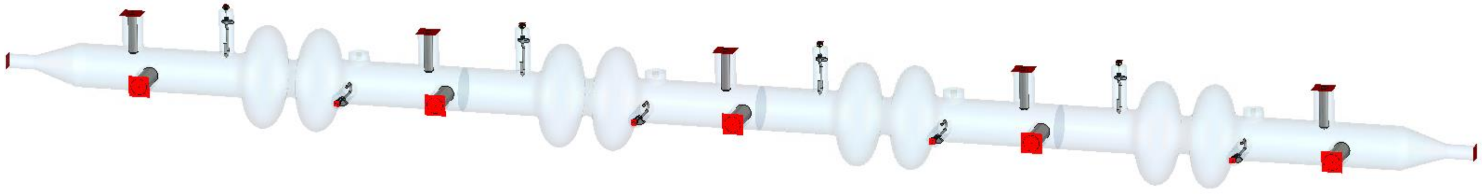
-- RF system: 132 cavities, ~ 400 kW, Q_L ~ 1 e^6 --

Reverse Phase Operation scheme: to do list



- Coupled-bunch instabilities (fundamental & HOM) -> OK with strong FB
- Higher-order-mode power losses -> 31 to 43 kW per CM (OK if 2-coax concept is demonstrated)
- Transient beam loading
- Availability aspects:
  - Reverse phasing with tripped cavities
  - Beam-induced voltage
  - Coupled bunch instabilities due to fundamental mode without feedback
- Sensitivity of RPO on cavity parameters (e.g., spread of Q_L, input power, …)
- Impact on FCC-ee booster with all cavities needed for H being installed from the beginning
- Possibility of powering several cavities with a single RF source



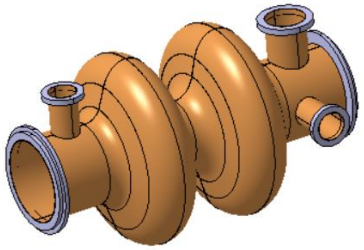


-- Potential showstopper: Synchrotron tune and bunch length spread -- under study

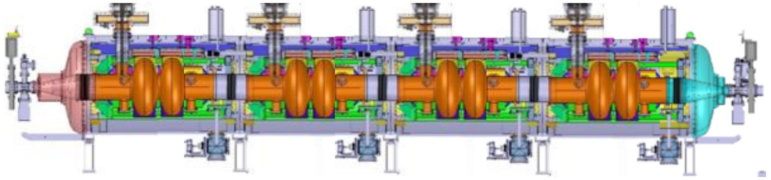
Two design of superconducting RF cavities

Z, W, H

X 264



X 66

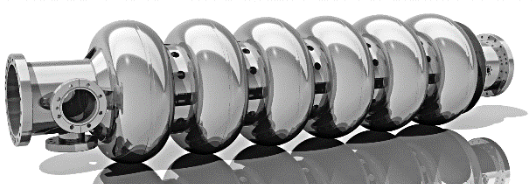


400 MHz cryomodule, ~12 m. long

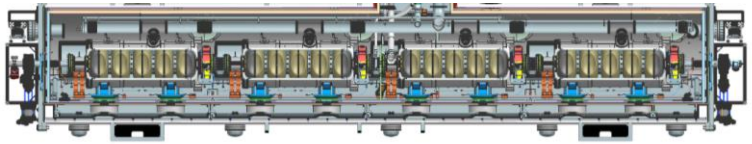
- 400 MHz 2-cell cavity
- Niobium thin film on Copper,
- Operation at 4.5 Kelvin
- Max. Accelerating gradient Eacc = 13 MV/m
- Quality factor $Q_0 = 3.3 \times 10^9$

ttb, booster

X 856 (=88+320+448)



X 214 (=22+80+112)

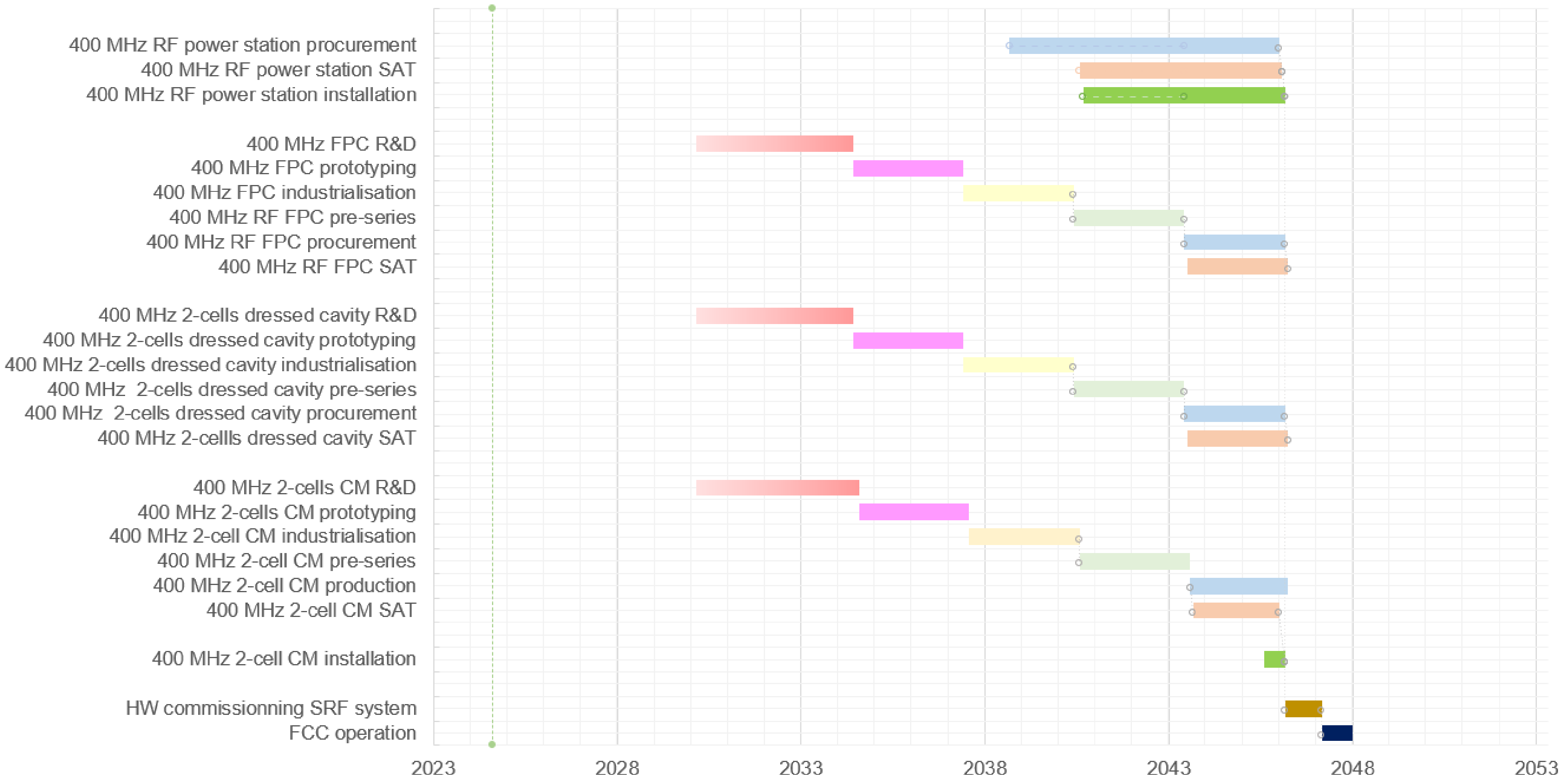


800 MHz cryomodule, ~10 m. long

- 800 MHz 6-cell cavity
- Bulk Niobium
- Operation at 2 Kelvin
- Max. Accelerating gradient Eacc = 24.8 MV/m
- Quality factor $Q_0 = 3.8 \times 10^{10}$

-- streamlined R&D and production effort --

Top-down plan (here 400 MHz only)



-- tight schedule + reduced R&D period --

FUTURE CIRCULAR COLLIDER

Summary

- **The FCC is a long-term program maximizing physics opportunities**
- For FCC-ee, the range of beam energies and beam currents is large between each mode of operation, all scaled to an available 50 MW maximum
- Ideal RF power source:
    - compact
    - highly efficient
    - reliable
    - low power consumption in standby
    - large power range
    - ‘low’ cost, several suppliers

Thank you for your attention!