

# FCC-ee Staging and Rf Configuration

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# Top-Level FCCee Parameters

❖ Max. s.r. power 50 MW/beam

Parameter	<i>Z</i>	<i>WW</i>	<i>H</i>	<i>ttbar</i>	<i>LEP2</i>
E/beam (GeV)	45	80	120	175	105
L ( $10^{34} \text{ cm}^{-2}\text{s}^{-1}$ )/IP	28.0	12.0	5.9	1.8	0.012
Bunches/beam	16700	4490	1330	98	4
I (mA)	1450	152	30	6.6	3
Bunch popul. [ $10^{11}$ ]	1.8	0.7	0.47	1.4	4.2
Cell length [m]	300	100	50	50	79
Tune shift / IP	0.03	0.06	0.09	0.09	0.07
$\Delta E/\text{turn}$ [GeV]	0.035	0.331	1.67	7.60	

# Overall Staging Scheme

- ❖ Get to as much physics as possible, as early as possible
- ❖ There is a meaningful physics program at less than the utmost performance or energy (of FCCee)
  - “Giga-Z”: a few 100/fb integrated luminosity
  - “Mega-W”: 100/fb integrated lumi
  - “Higgs Factory”
  - All can be comfortably exceeded at Stage 1 of FCC-ee.
- ❖ Staging considerations
  - Reach the Higgs in Stage 1
  - Convincing cost profile

## ❖ Lattice staging?

- Missing-dipole lattice (install every 2nd dipole only)
  - initial cost savings  $\approx$  \$50M (?)
  - difficult (expensive) build-out
- 1-ring initially, upgrade to 2-rings
  - luminosity limit of 1 ring.
  - build-out to 2 rings not trivial

## ❖ Rf staging

- easy build-out without changing prior install
- Costs of FCC-ee rf system up to  $10^9$  USD (Rimmer, TLEP5)
  - how much can we shave off initially?
- early commissioning with minimal rf costs
- can include scenarios like shared use between the 2 beams.

# Rf System Considerations & Trade-Offs

- ❖ The FCC-ee rf system is heavily beam-loaded (50 MW)
  - match between cavity/coupler and rf generator is important to get optimum energy transfer to the cavity (beam).
  - implemented in h/w by details of coupler.
    - here assumed fixed, but could be variable (technology challenge)
  - the requirements vary considerably
    - from Z running (nominal 1.5 A, 34 MV/turn) to
    - t-tbar running (nominal 6 mA, 7.5 GV/turn)
- ❖ 400 vs 800 MHz
  - 400 MHz: lower  $Q_s$ ; longer bunches; less wakefield issues
  - 800 MHz: higher gradient; shorter bunches
- ❖ single-cell vs multi-cell cavity
  - single cell better HOM spectrum;
  - multicell: higher voltage/structure

❖ 400 MHz preferred for FCC-hh => adopt that for now.

- right choice for Z running
- but: expensive to generate voltage at the high-energy end

❖ 400/800 MHz hybrid system.

- 400 MHz cavity optimized for high beam current
  - single- or double-cell structure, stringent limits on HOM spectrum
  - $\approx 10 \dots 12$  MV/module
- 800 MHz optimized for high voltage
  - more cells; higher voltage
  - less stringent limits on HOM spectrum
  - $\leq 37.5$  MV/module
- In this talk we will not consider the 800 MHz system.
  - but is not off the table

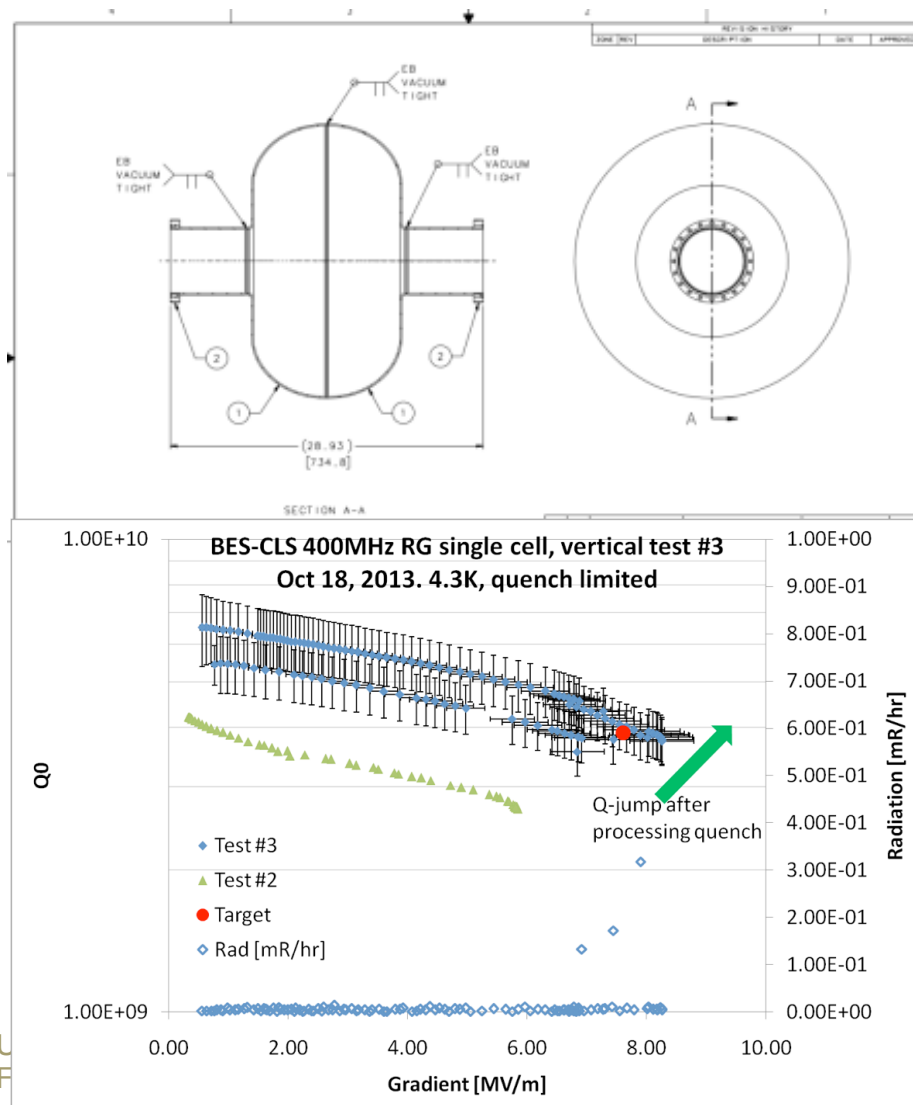
❖ Share 400-MHz rf cavities between rings at least at t-tbar.

# SRF Cavity Performance near 400 MHz

- ❖ Observed performance (high-current accelerator cavities):
  - Cornell CESR: 6...10 MV/m
  - KEKB: 6 MV/m op; 10 MV/c spec.
  - JLab CLS: 6...10 MV/m; 6 MV/m tested
- ❖ All are single-cell cavities, highly damped HOM spectrum
  - needed for Z, W running
- ❖ A 2-cell cavity can have a similarly clean HOM spectrum.
  - $\pi$  mode has  $180^\circ$  phase between gaps => cancellation
- ❖ more cells => satellites unavoidable
  - since these can have high Q at relatively low frequencies, they can cause trouble.

# A 400 MHz Cavity (R.A. Rimmer, JLab CLS Cavity)

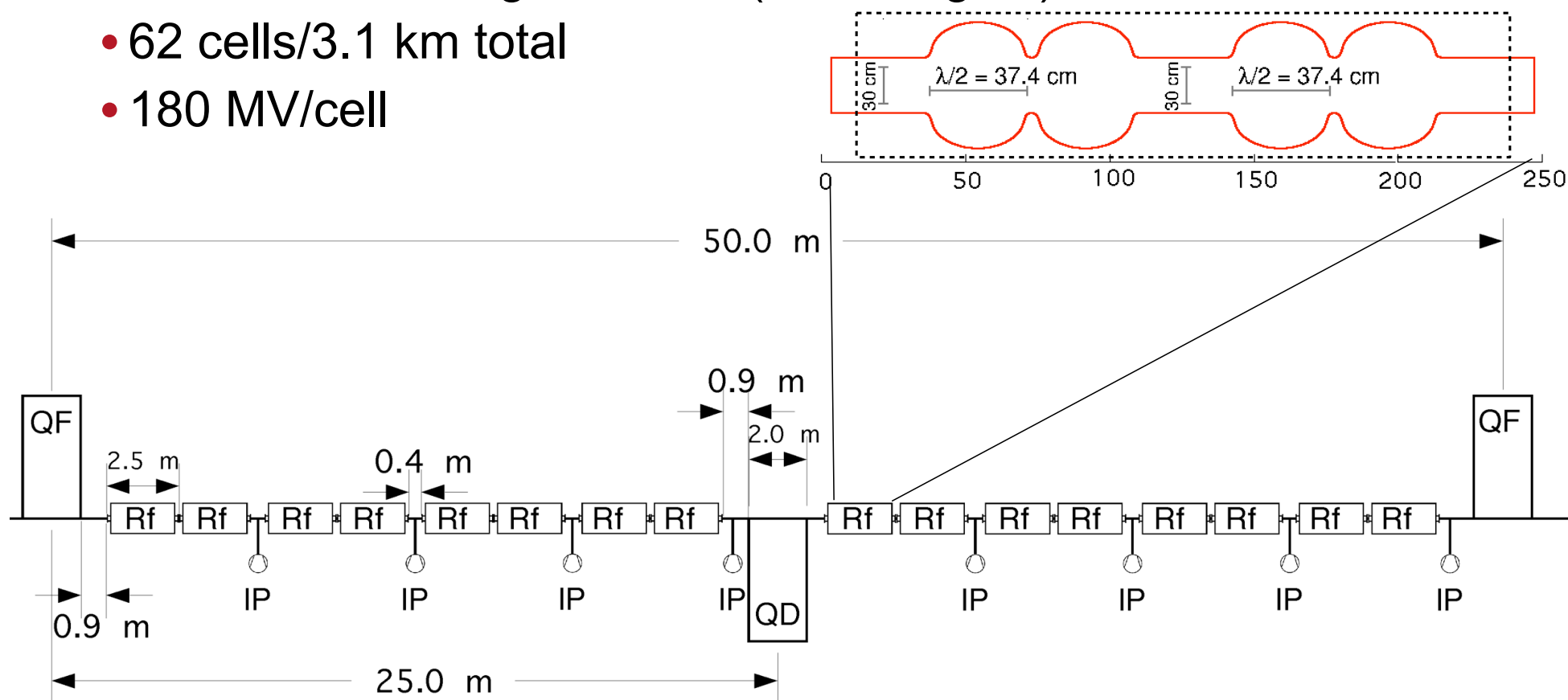
- ❖ single-cell prototype cavity for a 3-cell design



- ❖ Define an “rf station,” i.e. klystron with cavities driven
  - 1 MW klystron driving 8 cavity-modules up to 12 MV (400 MHz)
    - two 2-cell cavities; CLS style, 2.5...3 MV/gap  $\Rightarrow \leq 12$  MV/module
    - 125kW power per module: ok with current coupler technology
- ❖ Keep other parameters at values from FCC-ACC-SPC-0003 EDMS 1346081 Rev. 2.0
  - specifically beam emittance, bunch charge, IP optics,  $\xi$ .
  - hourglass and crossing angle taken into account.
- ❖ Some parameters vary with rf voltage & power
  - bunch length, # of bunches

# Conceptual Layout of Rf Cell

- ❖ Based on 50-m arc cell by Härer et al.
- ❖ 62 such cells needed for 11 GV installed rf
  - 31 half cells/straight; 775 m (4 rf straights)
  - 62 cells/3.1 km total
  - 180 MV/cell



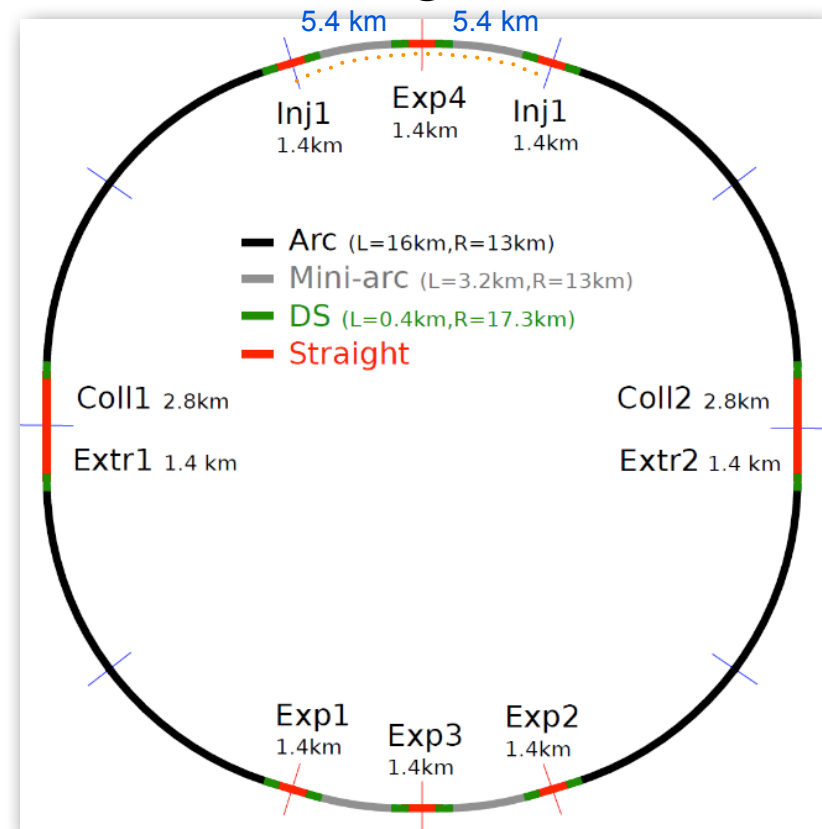
# To Share or not to Share?

## ❖ Can we share cavity modules between the rings?

- Yes, but cannot have both bunches in cavity at the same time
  - Limits the bunch pattern!
  - Power doubles: 250 kW/module: ok.

## ❖ If rf x km away from detectors, max. train length is $< 2x$ .

- Z: 16700 bunches  
min. separation 0.76 m  
**12.7 km long;**  
W: 3.4 km;  
H: 1 km;  
t-tbar: 75 m.
- The rf system may force us to run Z more evenly distributed
  - not good for sharing @ Z



## ❖ Stage 1:

- 48 Klystrons, 8 cryo modules ea., 2.2 GV voltage/ring
  - Z:  $1.0 \times 10^{35}/\text{cm}^2/\text{s}$ ; W:  $3.6 \times 10^{34}/\text{cm}^2/\text{s}$ ; H:  $1.1 \times 10^{34}/\text{cm}^2/\text{s}$

## ❖ Stage 2:

- 100 Klystrons, 8 cryo modules ea., 4.5 GV voltage/ring
  - Z:  $2.6 \times 10^{35}/\text{cm}^2/\text{s}$ ; W:  $9.7 \times 10^{34}/\text{cm}^2/\text{s}$ ; H:  $3.7 \times 10^{34}/\text{cm}^2/\text{s}$

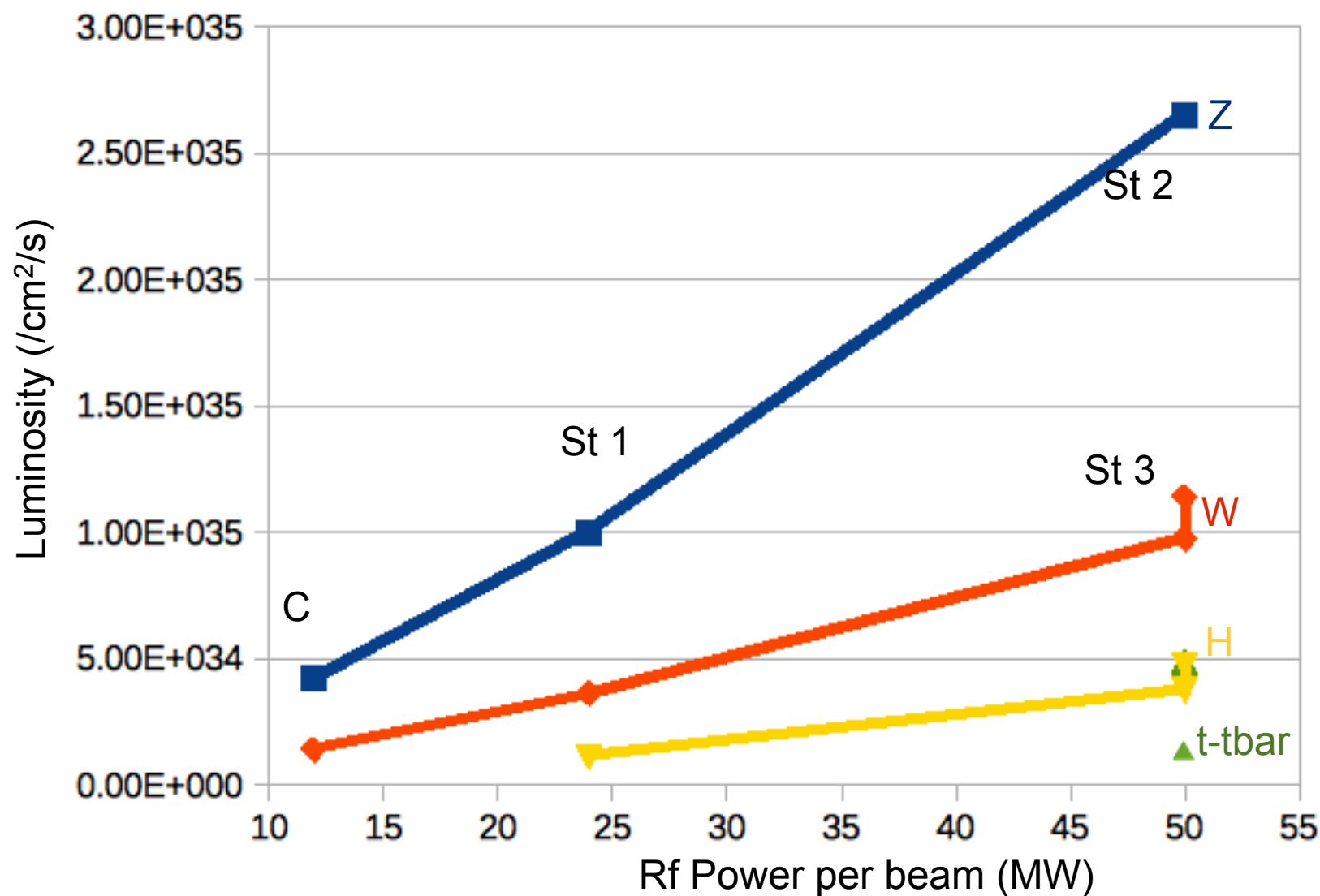
## ❖ Stage 3:

- reconfiguration to share cavities => double the voltage (9.6 GV)
  - Z: n/a: bunch pattern
  - W:  $1.1 \times 10^{35}/\text{cm}^2/\text{s}$ ; H:  $4.7 \times 10^{34}/\text{cm}^2/\text{s}$ ; tt:  $1.2 \times 10^{34}/\text{cm}^2/\text{s}$

## ❖ Commissioning stage (if applicable)

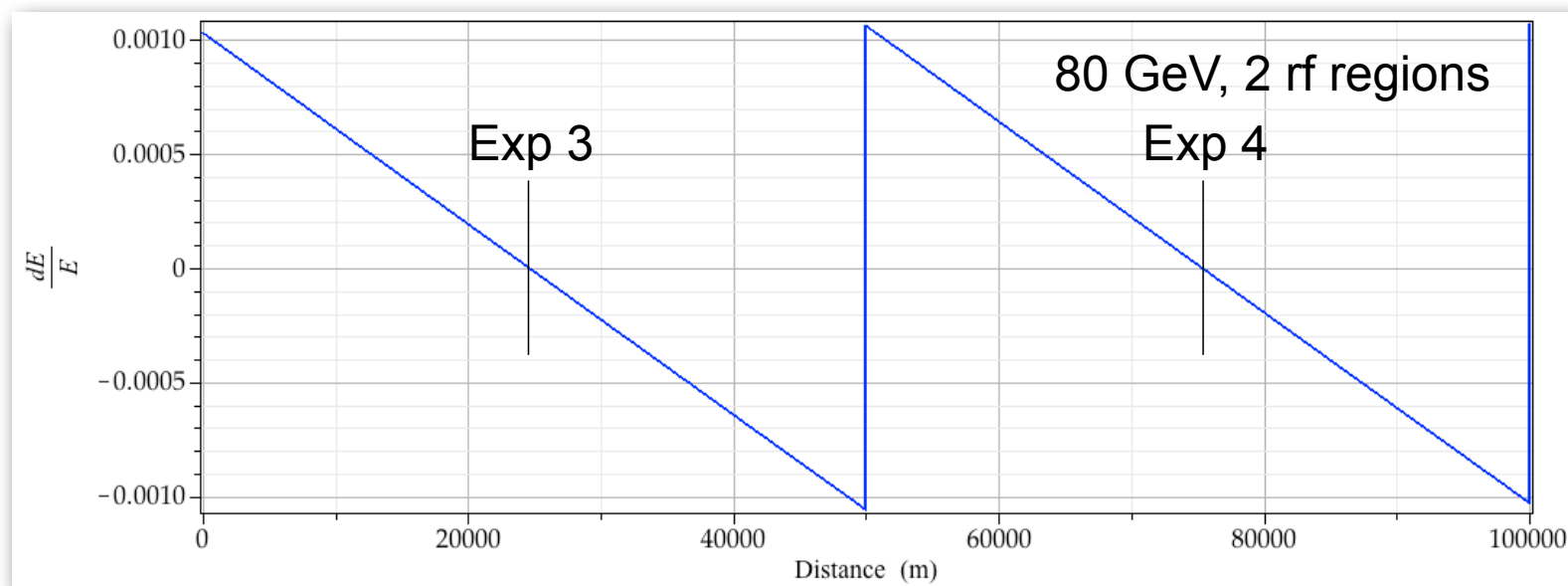
- 24 Klystrons, 8 cryomodules ea., 1.1 GV voltage/ring
  - Z:  $4.7 \times 10^{34}/\text{cm}^2/\text{s}$ ; W:  $1.6 \times 10^{34}/\text{cm}^2/\text{s}$ ; H: n/a: voltage limit

# 400 MHz Cavities only, shared last Stage

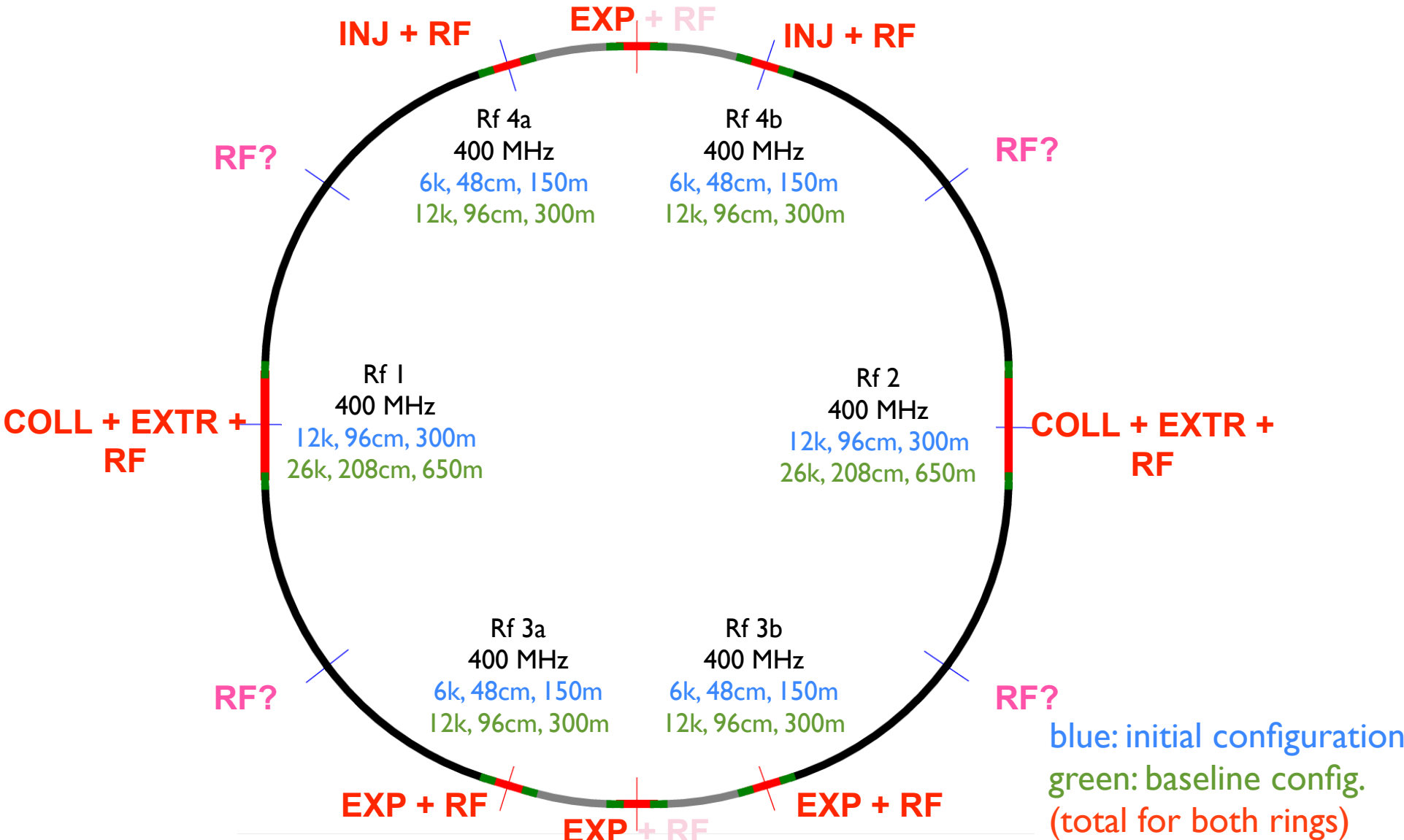


# Energy Sawtooth

- ❖  $-0.08\%$  @ 45 GeV,  $-0.41\%$  @ 80 GeV,  $-1.39\%$  @ 120 GeV,  $-4.34\%$  @ 175 GeV
- ❖ compared to an aimed-for acceptance of 2%.
- ❖ Need to fix this:
  - 2, 2, 4, 8 rf regions
  - modulating the bending strength (& possibly focusing)

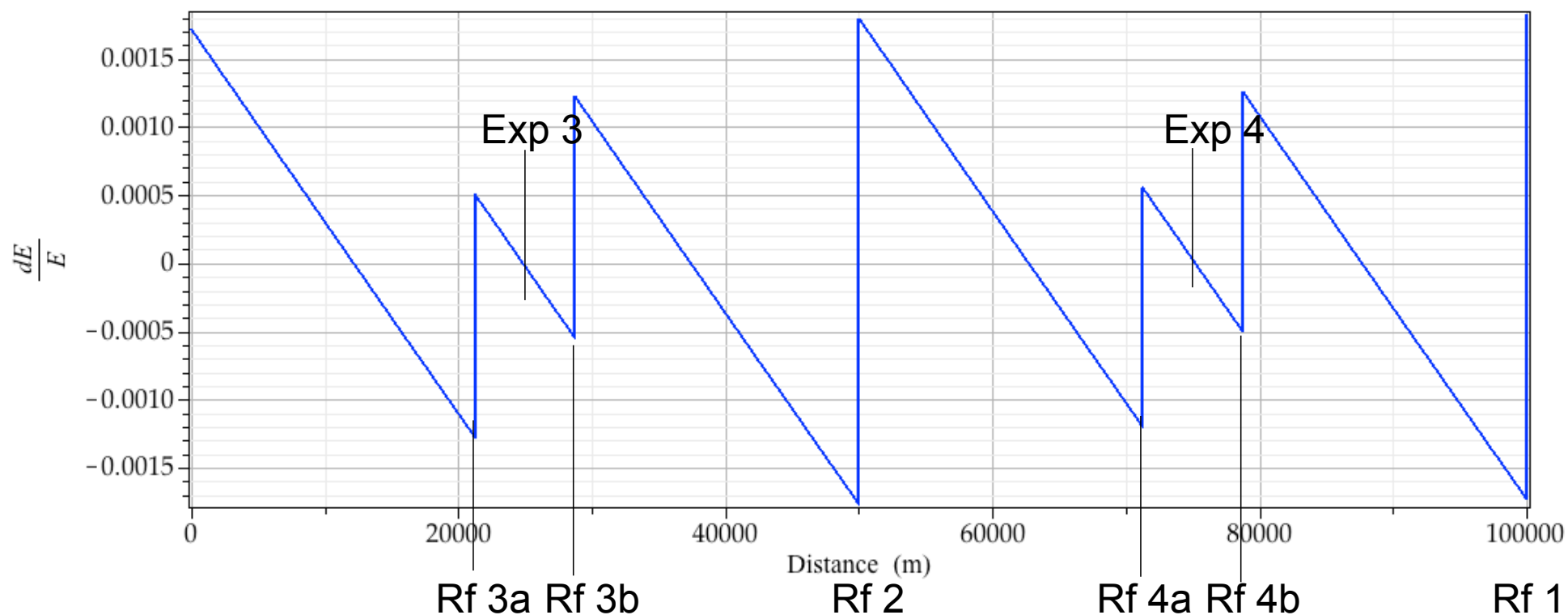


# FCC-ee preliminary layout



# Energy Sawtooth @ 120 GeV

(Schematic plot; exact locations & voltages of rf stations tbd)



The sawtooth causes some uncertainty of beam energy at the experiments  
Order of magnitude guess: 0.5 MeV @ 120 GeV; 5 MeV @ 175 GeV

# Summary of Installed Rf (full build-out)

Rf Region	Frequency (MHz)	Per ring			
		Tubes 1 MW ea	Modules per tube	Modules 2 couplers ea	Voltage (MV)
1	400	13	8	104	1248
2	400	13	8	104	1248
3a	400	6	8	48	576
3b	400	6	8	48	576
4a	400	6	8	48	576
4b	400	6	8	48	576
<b>Total</b>		<b>50</b>		<b>400</b>	<b>4800</b>
<b>Total for shared rf</b>		<b>100</b>		<b>800</b>	<b>9600</b>

- ❖ 2-cell 400 MHz cavity (2 per cryo module) seems appropriate
  - HOM spectrum of such an assy can be acceptable
  - 2.5 m length of cm  $\Rightarrow \approx 5$  MeV/m “real estate” gradient.
- ❖ Initial rf of about 1/2 of full complement appears to be a credible scenario.
  - Useable Z, W and Higgs luminosities
  - Possibility of early commissioning with 1/2 of this initial set
    - Z, W reach
- ❖ Energy sawtooth partially corrected
  - at 175 GeV will need modulated arc bending.
  - or additional 800 MHz rf in mid-arc (also shorter bunches)
- ❖ Full power running for Z, W, H
- ❖ Highest voltage for t-tbar running reached by sharing cavities.
  - assume Z lumi-run completed at that time.