SRF for Future Circular Colliders

Rama Calaga, CERN

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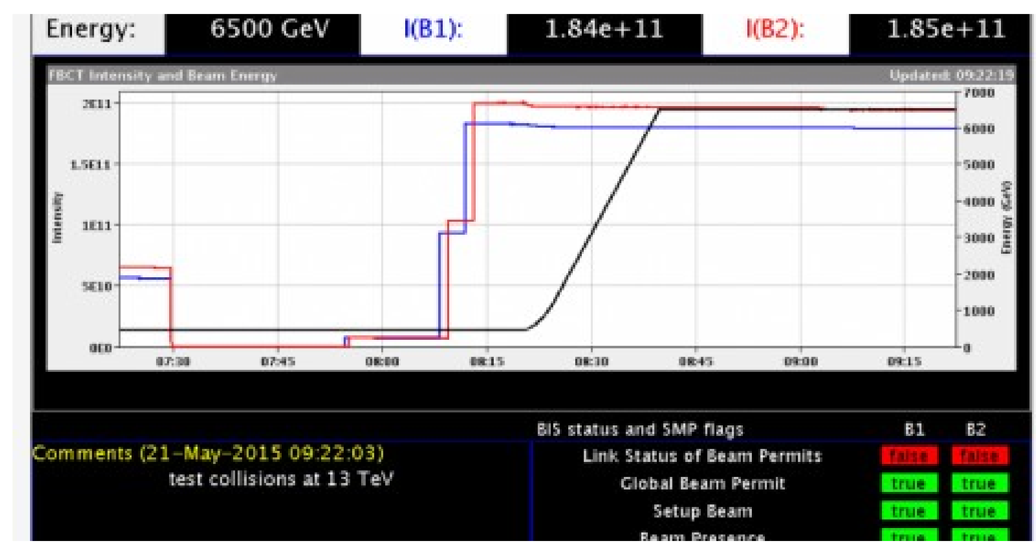
Acknowledgements:

O. Brunner, A. Butterworth, E. Jensen, E. Montesinos, E. Shaposhnikova

May 2015: Record collisions at 13 TeV CM!



FCC Study Scope

Courtesy: M. Benedickt

FCC-hh: 50 TeV proton collider as a long term goal

FCC-ee: 45.5-175 GeV e^+e^- collider as an intermediate step

FCC-he: Study integration aspects for electron-ion collisions

<u>Main Goal</u>

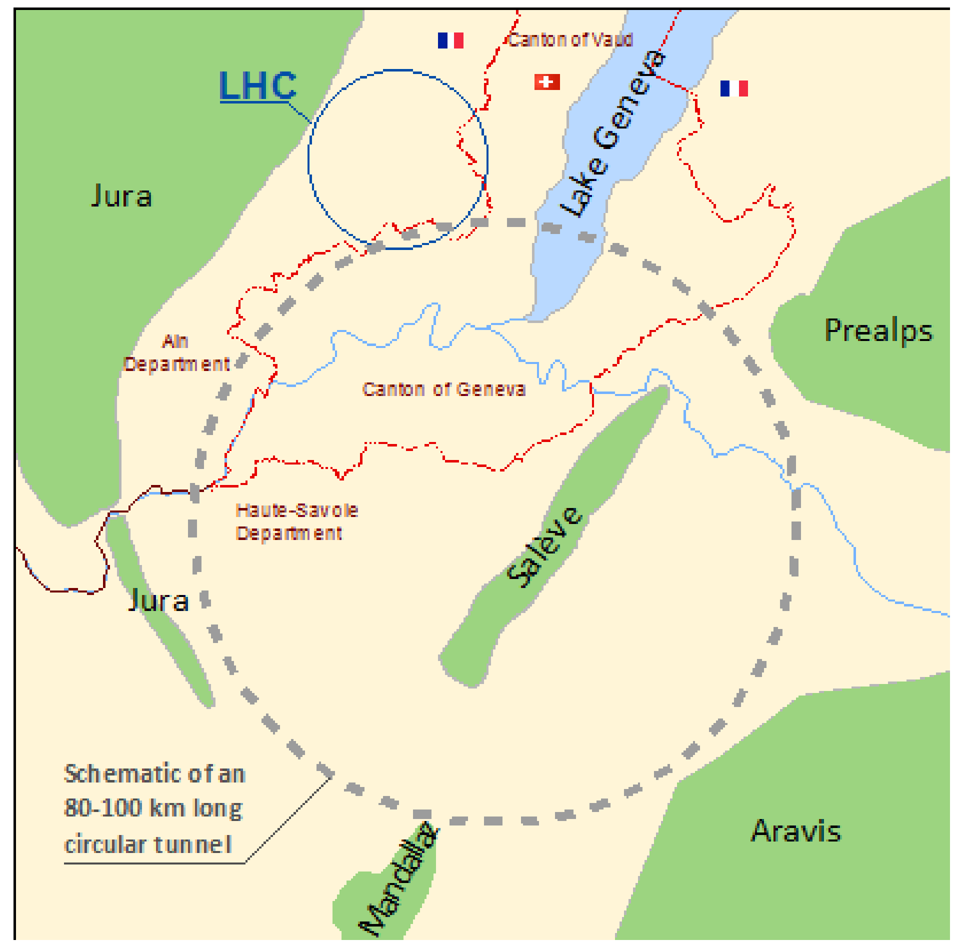
-Complete exploration of Higgs

-Direct/indirect probes beyond SM

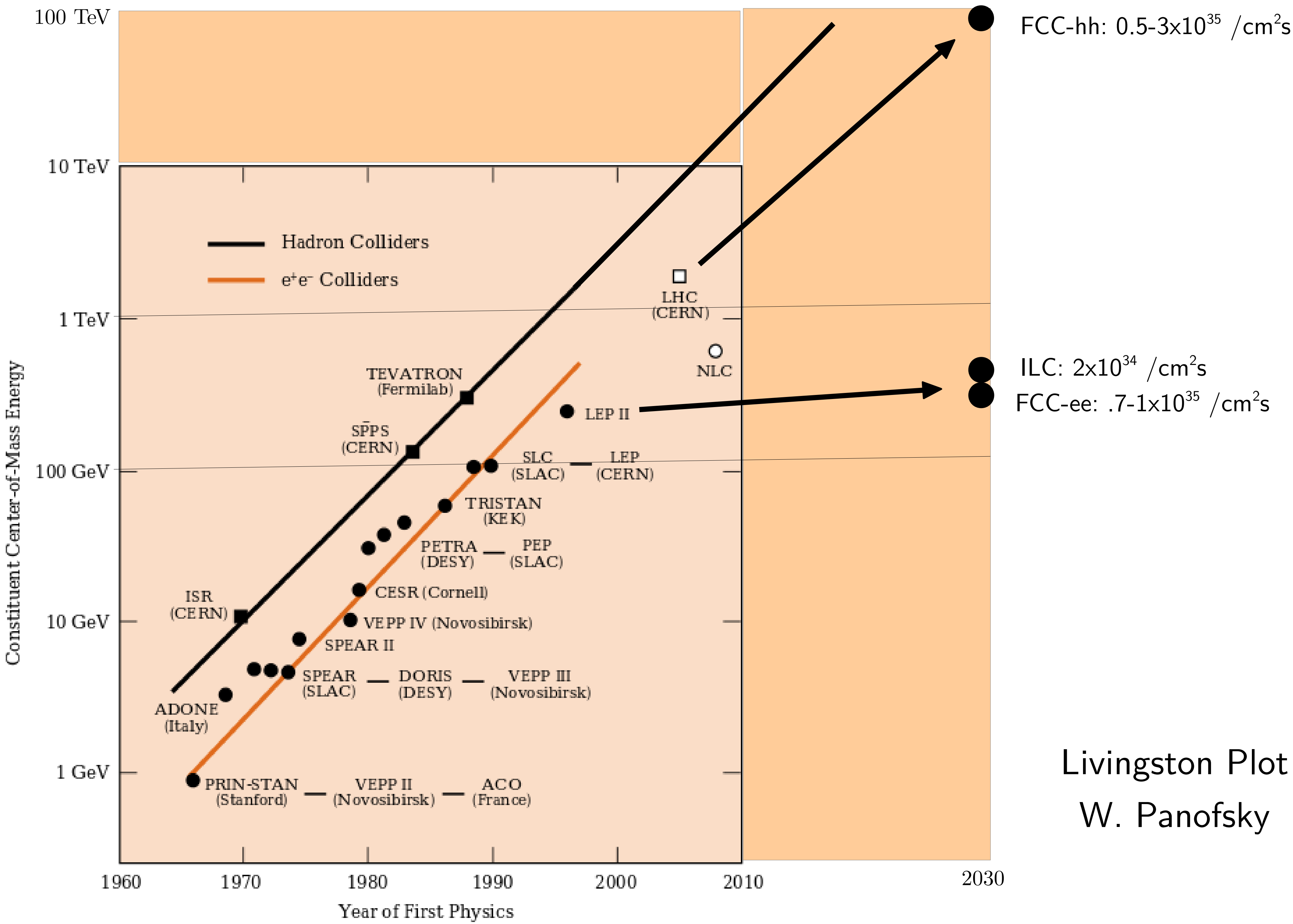
<u>Dedicated SC R&D programs</u>

-16 T dipole magnets for 100 TeV in 100 km

-SRF technologies & RF power sources



Livingston Plot



Livingston Plot
W. Panofsky

Parameters, FCC-hh

Main goal increase the LHC energy by factor ~7

Increase ramp rate (~30 min) by factor ~18 from LHC

	LHC	HL-LHC	FCC-hh
Energy [TeV]	7	7	50
Current, DC [A]	0.55	1.1	**0.51**
Rad Loss [MeV]	0.007	0.007	3.9
Total Voltage [MV]	16	16	>32
# of Cavities	8	8	16
RF Power [kW]*	300	450	**300-500**
Frequency [MHz]	400		

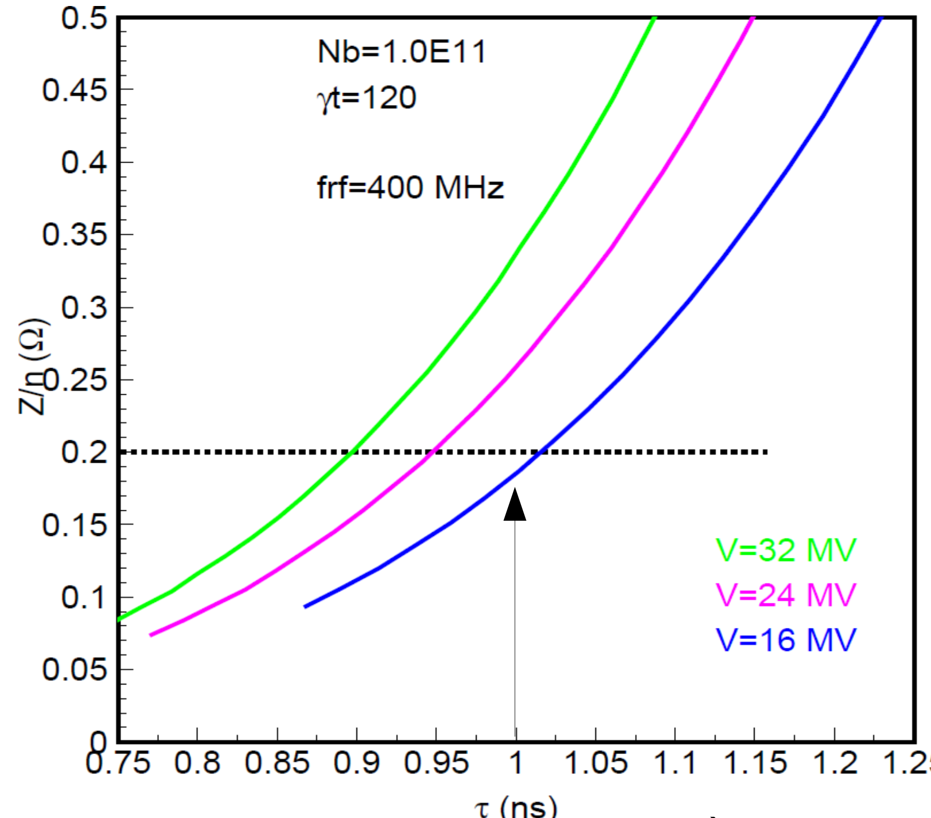
← High current (Current, DC row)

← High Power (RF Power row)

*Using ½-detuning: $R/Q=45\Omega$ & $QL=60k$, $V=2$ MV/cavity

FCC -hh, Stability

Courtesy E. Shaposhnikova



Bunch length = 1ns

Bunch spacing = 5ns, 25 ns

Frequency = 400 MHz

Optimum filling factor (bucket losses vs. instability threshold)

Single bunch instability, loss of landau damping

For example: 16 MV (ε_L=7.0 eVs) $\rightarrow$ 0.2 Ω (LHC ~0.1 Ω)

Continuous longitudinal blow necessary due to sync radiation

2nd harmonic system may be necessary, not considered here

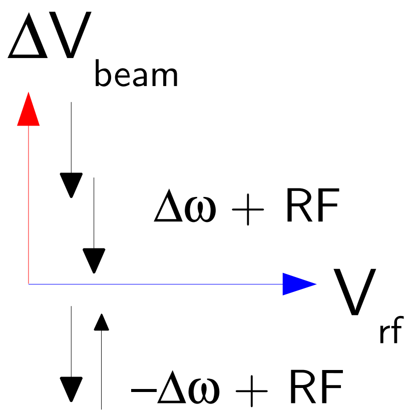
FCC -hh, RF

Inject, capture & ramp 10600 bunches 3.3 – 50 TeV

Store 50 TeV beams

Keep peak power & voltage <u>constant</u>

$$\Delta f = \frac{1}{4} I_b \frac{R/Q}{V_{RF}} f_{RF}$$



½- detuning is -3.1 kHz @0.51A, at 2 MV

Remember that revolution freq (100 km) = 3 kHz

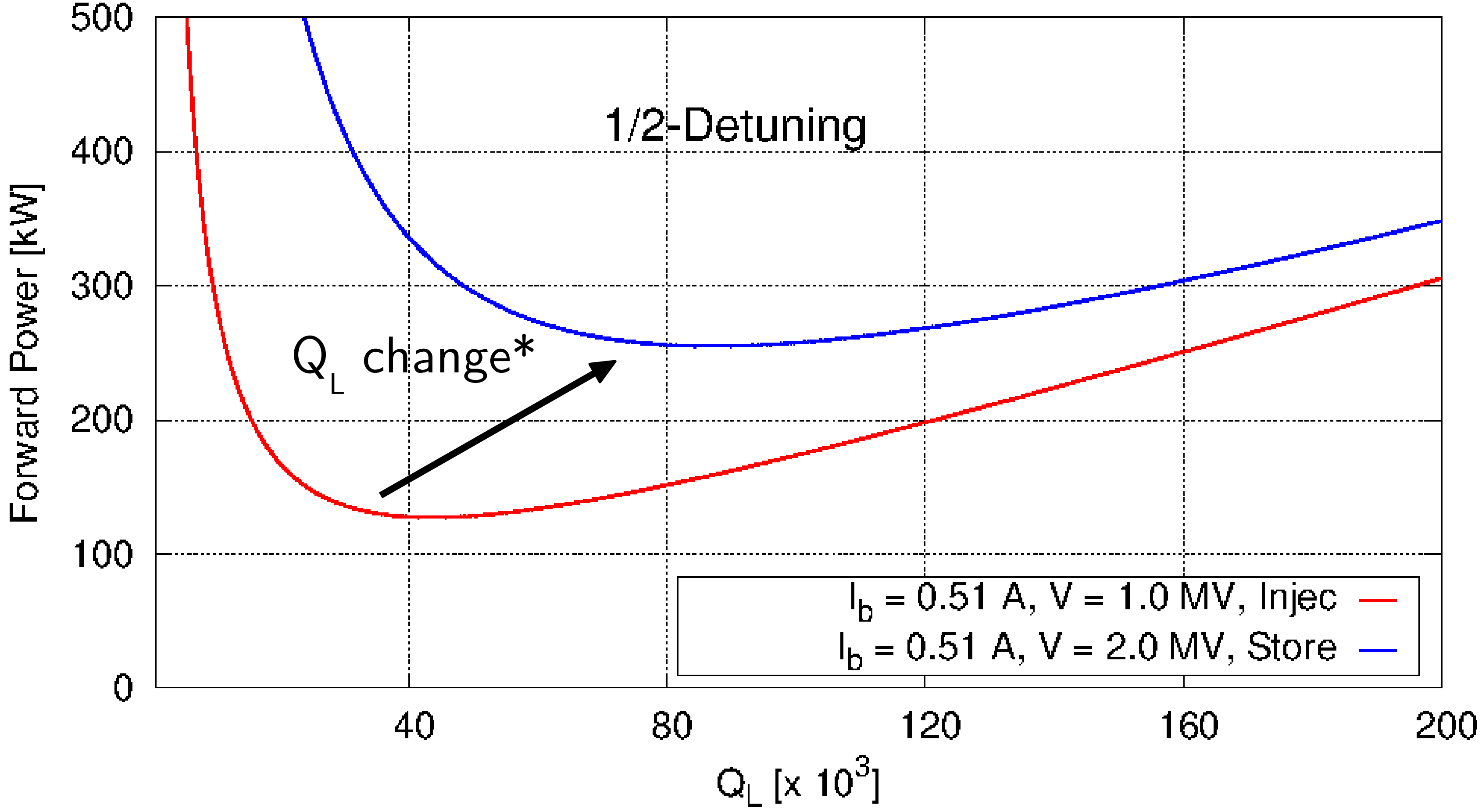
Will excite strong coupled bunch instabilities (feedback!)

Synchrotron freq. is 2.9 Hz! RF Noise may become an issue

FCC -hh, RF Power

Additional 4.5 MW total power to ramp the beam

(+ synchrotron radiation power)



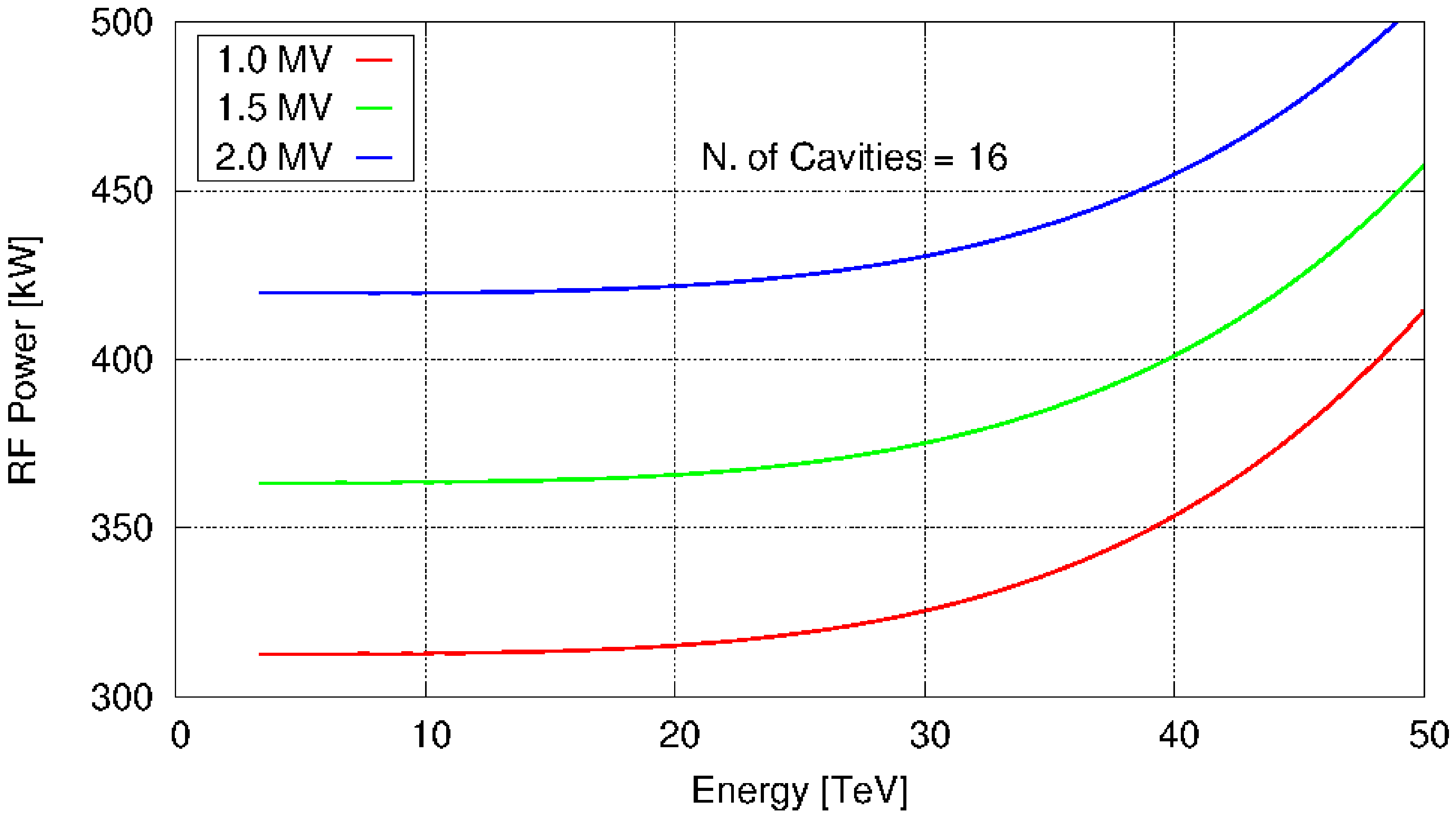
* Possibly requires variable coupler

If beam current increases, the ramp rate must proportionally increase

FCC -hh, Energy Ramp

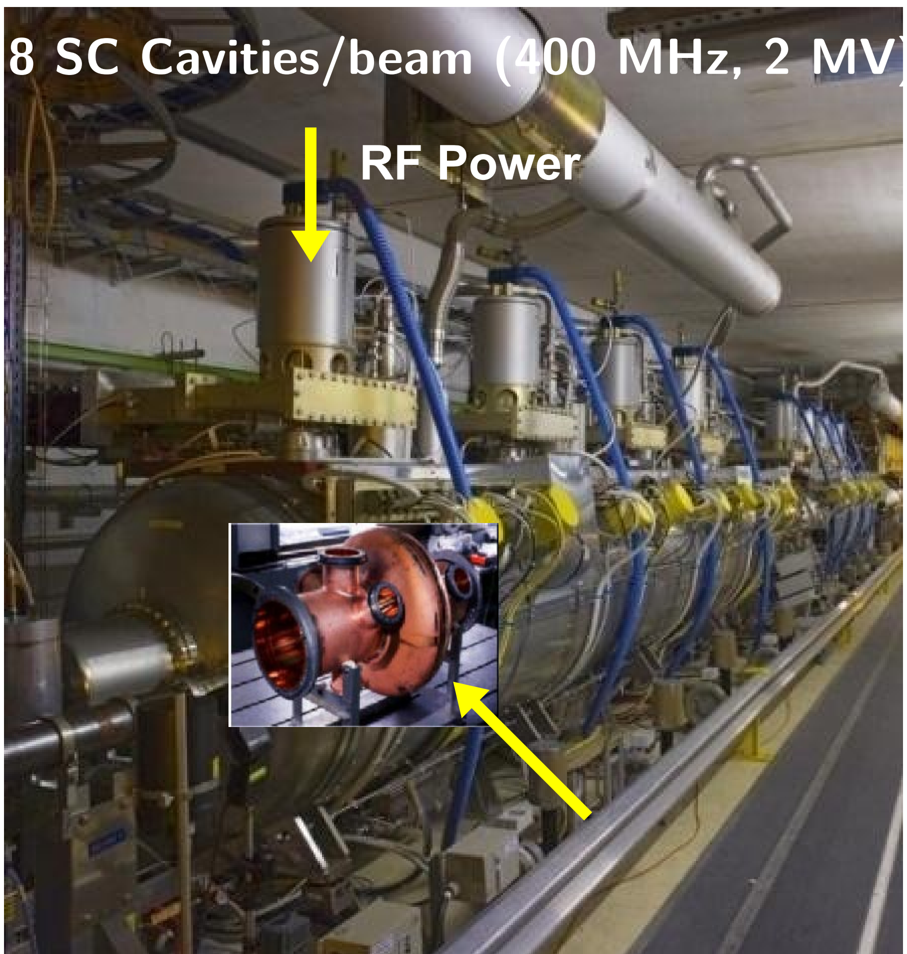
A simple RF program during the energy ramp (30 min)

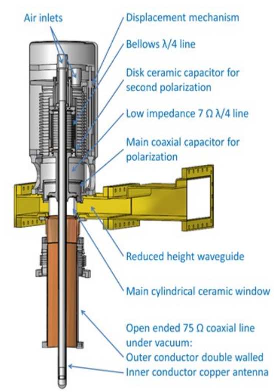
Energy ramp is the dominant factor, optimization feasible



Present LHC RF System

FCC -hh: Atleast 2-3 times the LHC system & increased power handling capacity to ~500 kW – CW is necessary





300 kW LHC
Variable Coupler
4-HOM Couplers

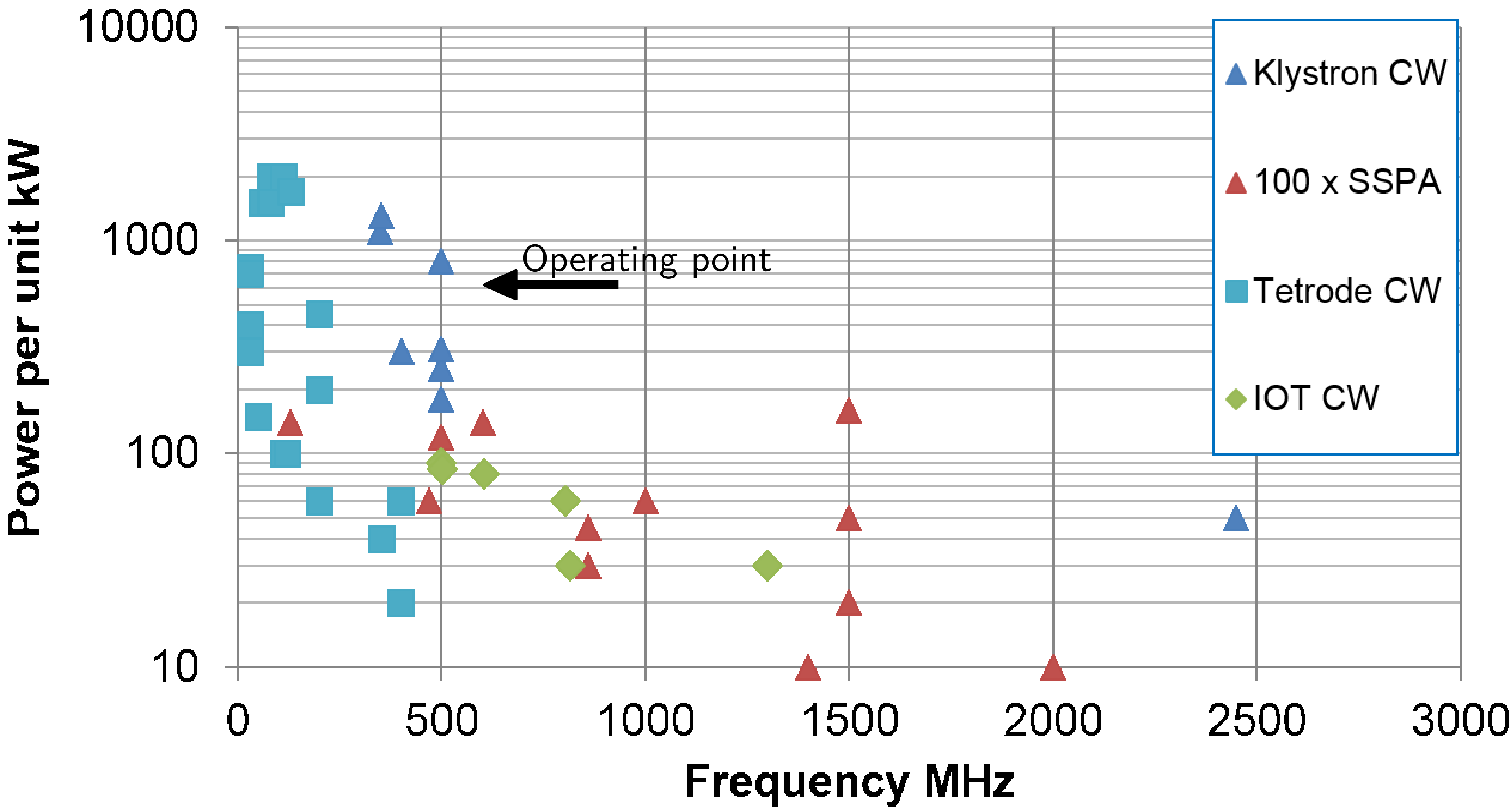
300 kW Klystron
LHC 400 MHz

Available Power Sources

Courtesy E. Montesinos

Handful of sources available at low freq with high power CW

SSA in this power range (& low noise) could be expected in 2 decades (?)

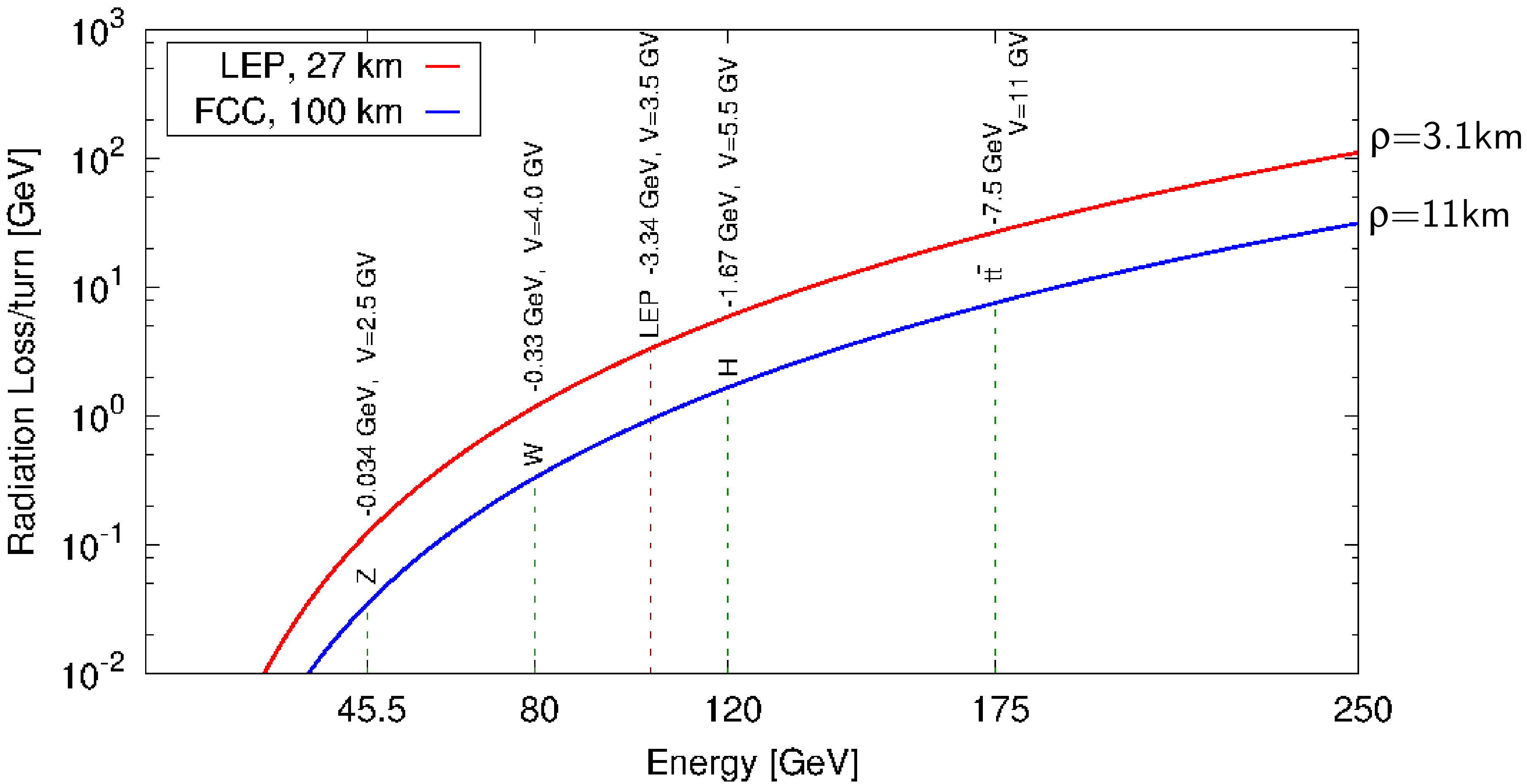


FCC -ee, RF

The maximum energy (physics) → appropriate circumference (sync radiation)

Radiation loss + energy acceptance → required voltage

Available power (~50 MW) → maximum current at each energy



Parameters, FCC-ee

Main goal to provide Higgs~5-30 x 10^{34} $cm^{-2}s^{-1}$ (in 2-phases)

From LEP2 → Extend energy ~factor 2 & current by several orders

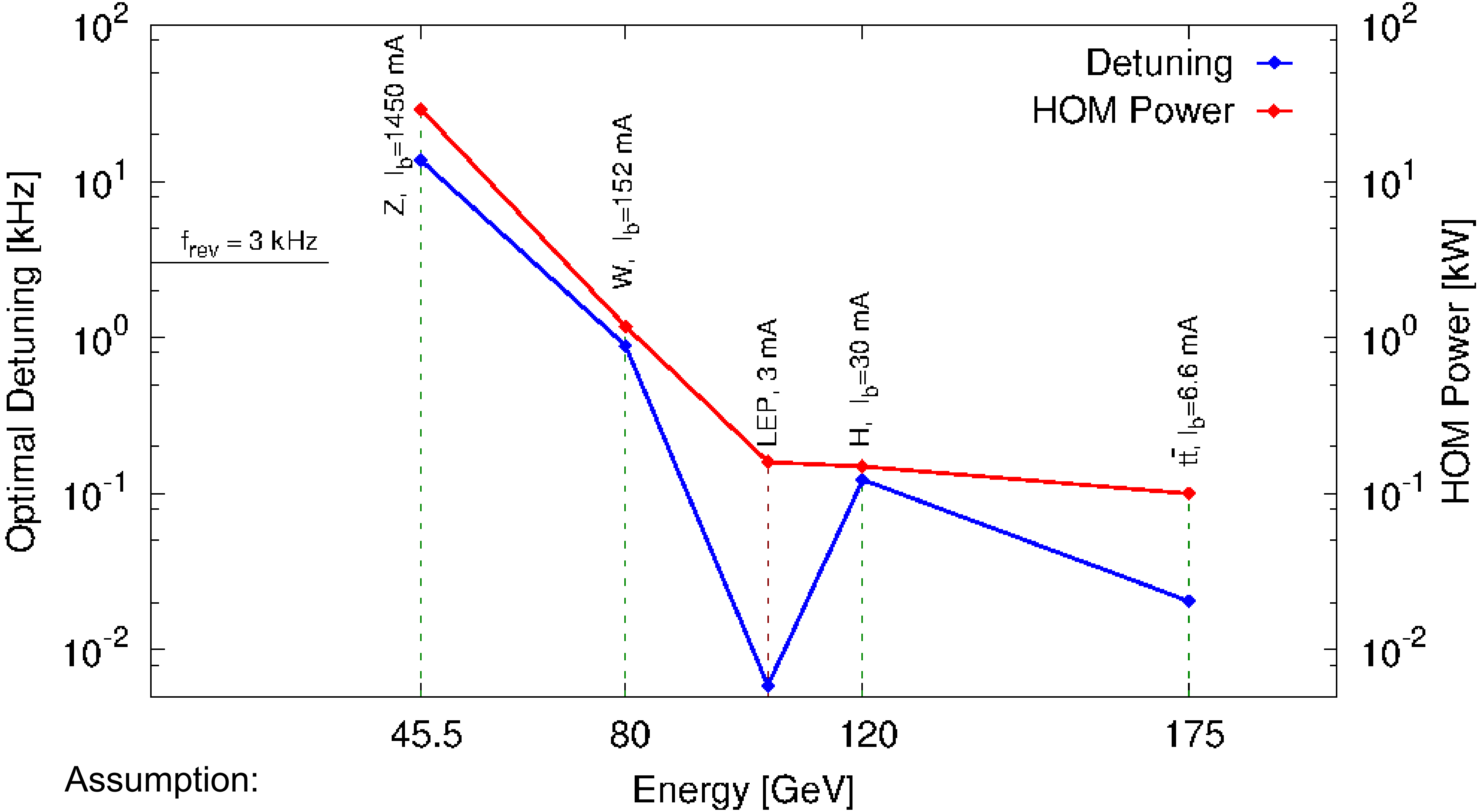
	LEP2	FCC-Z	FCC-W	FCC-H	FCC-T
Energy [GeV]	104	45.5	80	120	175
Current [A]	0.003	**1.45**	0.152	0.03	0.0066
Rad Loss [GV]	3.34	0.03	0.33	1.67	7.55
Total Voltage [GV]	3.5	2.5	4.0	5.5	**11.0**
Frequency [MHz]	352.2	400.79			
Harmonic #	31320	133689			

2^{nd} harmonic is not considered but maybe needed

FCC-ee, RF & Staging

Large variation in detuning angle (Z-energy > factor 4.f_{rev})

Extremely large HOM power for high current → limit on number of cells

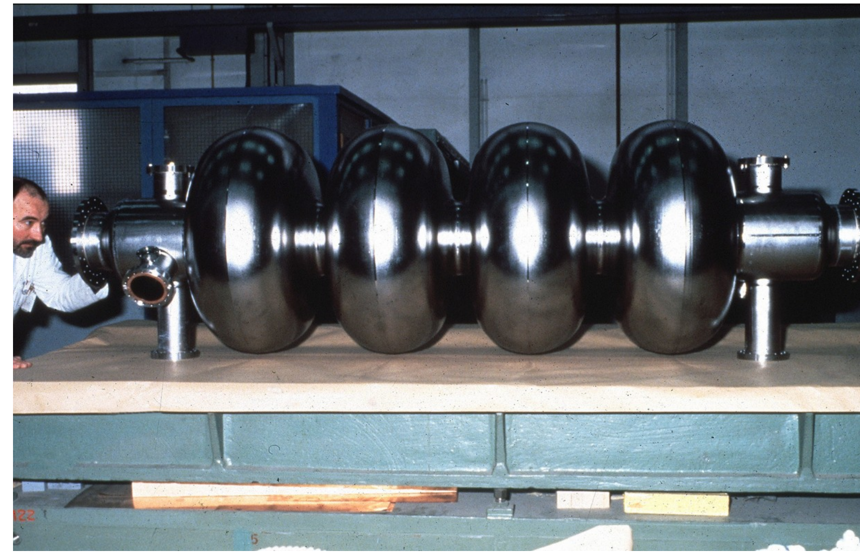


Assumption:

Existing Cavity Options

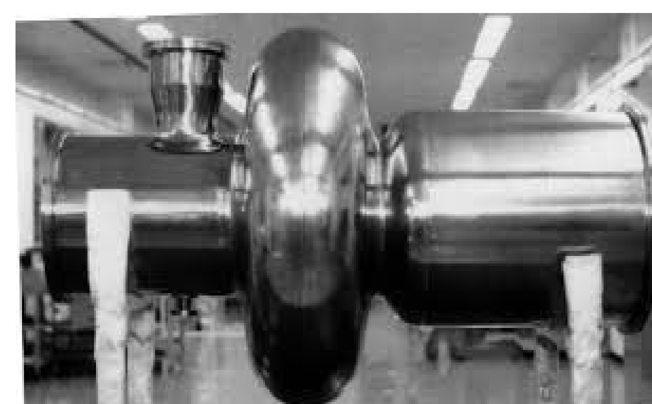
Frequency: 350-500 MHz

352 MHz: LEP, Nb-Cu



352 MHz: Bulk Nb Variant

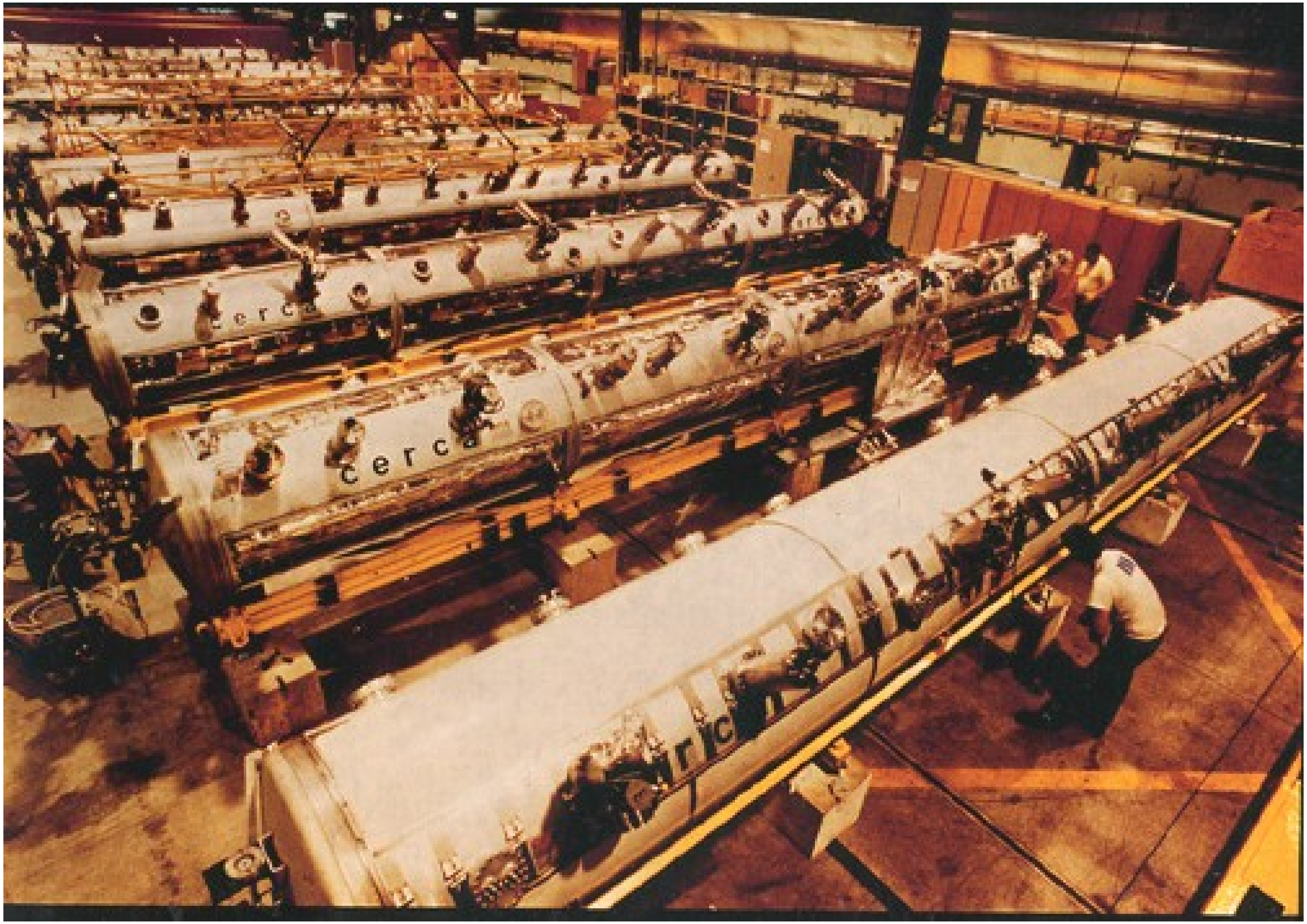
400 MHz: LHC, Nb-Cu



500 MHz: CESR-B, KEK-B

LEP Experience, Nb/Cu

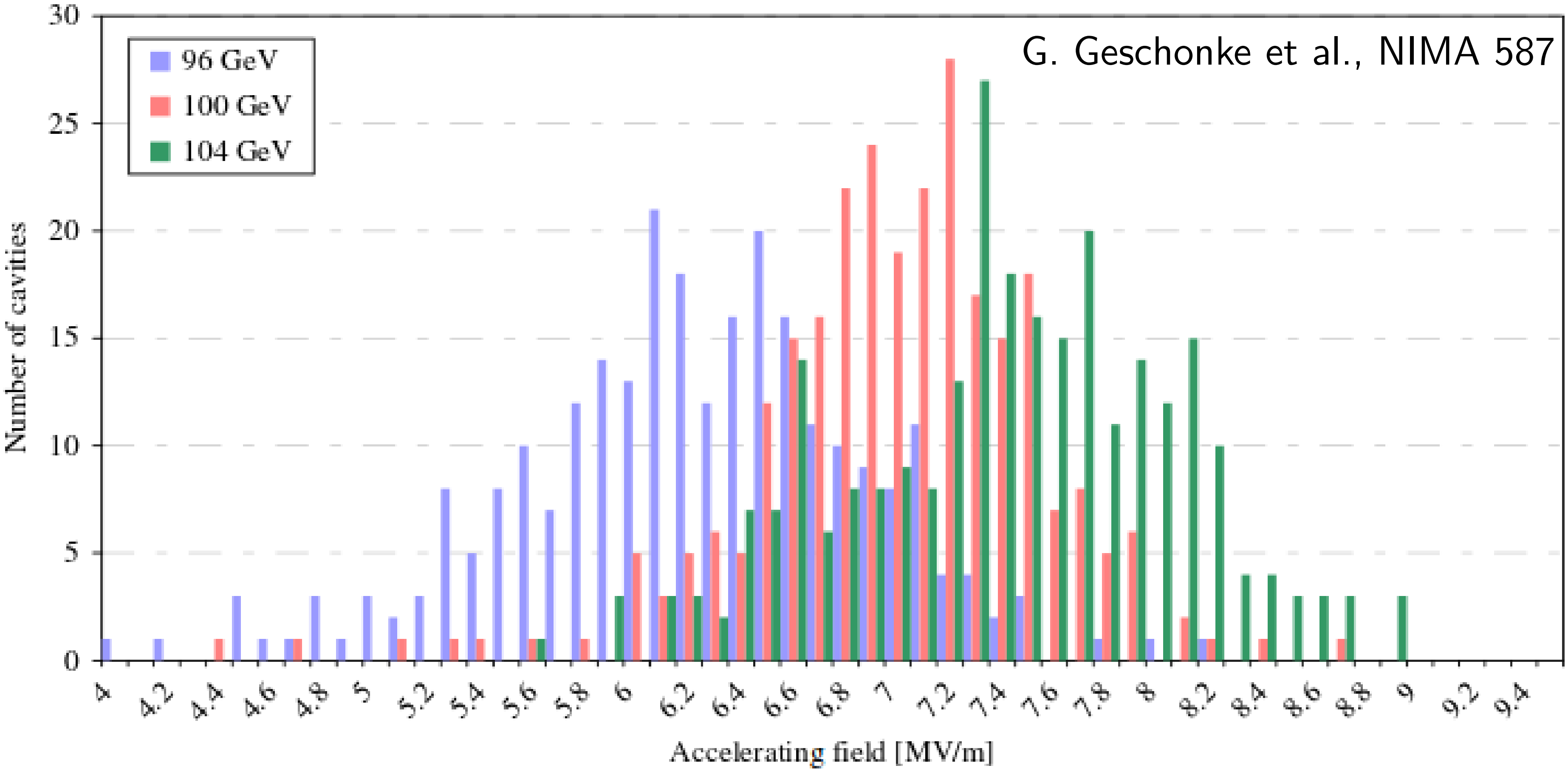
One of the largest SRF installation to date, the only to successfully exploit thin-film technology to record energies



LEP 2 SC-Cavity Performance

Mean value of approximately 7.2 MV/cavity $\rightarrow$ 12 MV/cavity (4-cells)

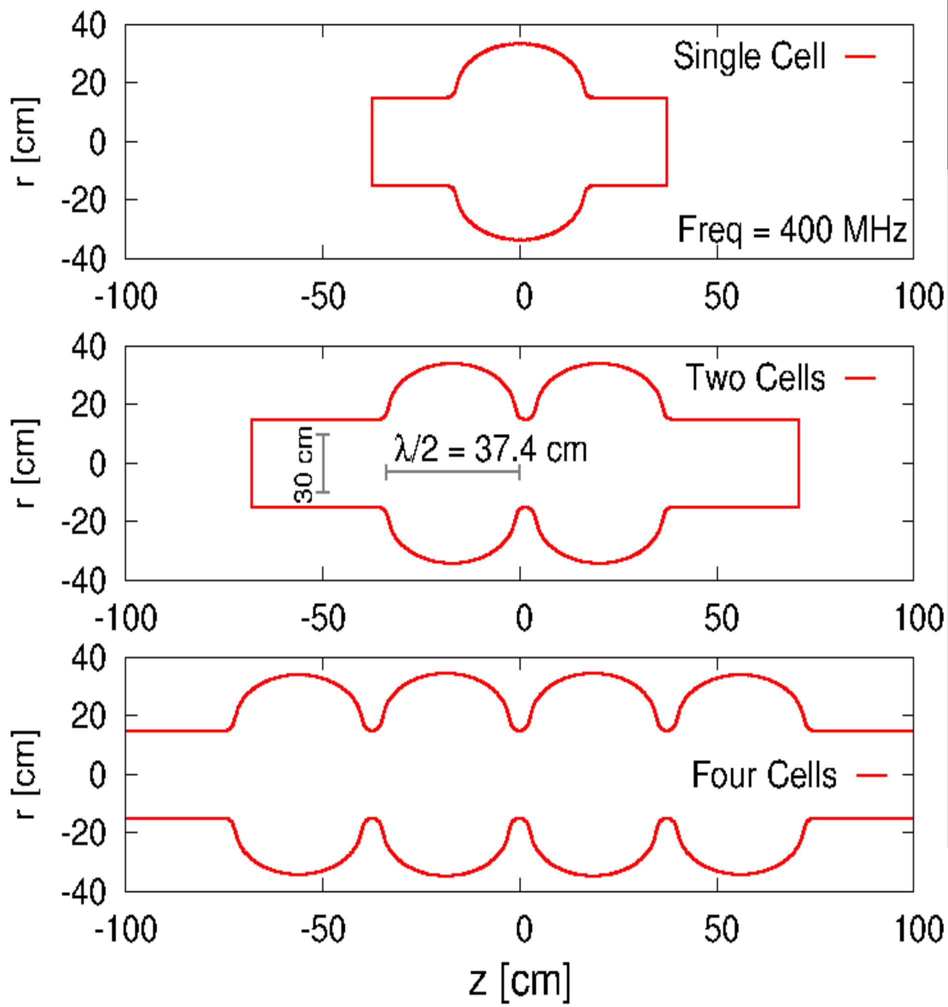
We assume same performance for a 4-cell equivalent



Cavity Options, 400 MHz

2+2 cells is assumed as a reference – study ongoing

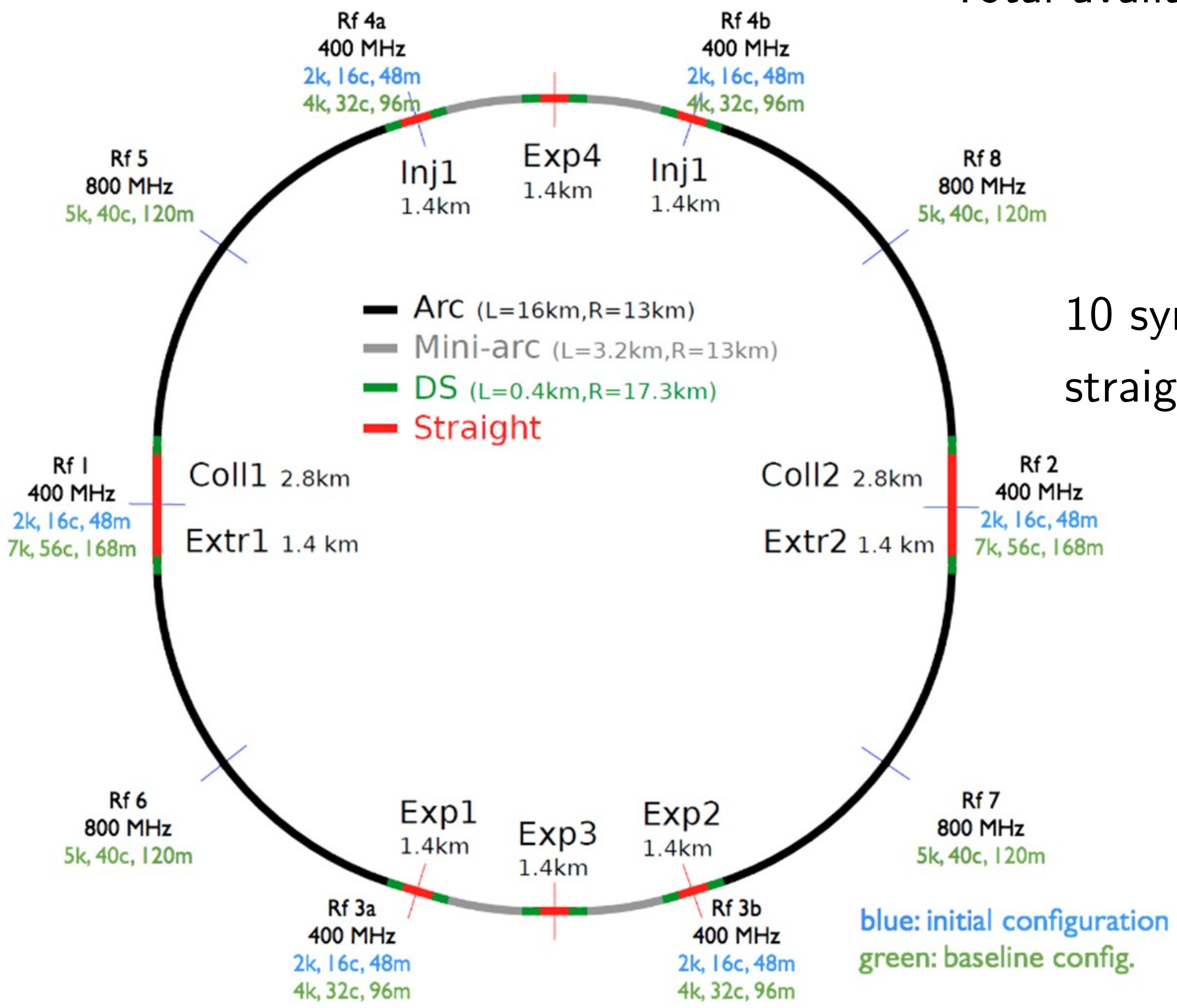
Minimize beam loading & HOM power



	1-Cell	2-Cells	4-Cells
L[m], Active	.374	.748	1.5
V [MV] /cav	3.75	7.5	15
Ep /Ea	3.1	3.3	3.3
Bp [mT]/Ea	4.2	4.7	4.7
R/Q [Ω]	87	169	310
U [J]	0.54	1.3	2.7

FCC ee, RF Layout

Total available length: 1.2 km

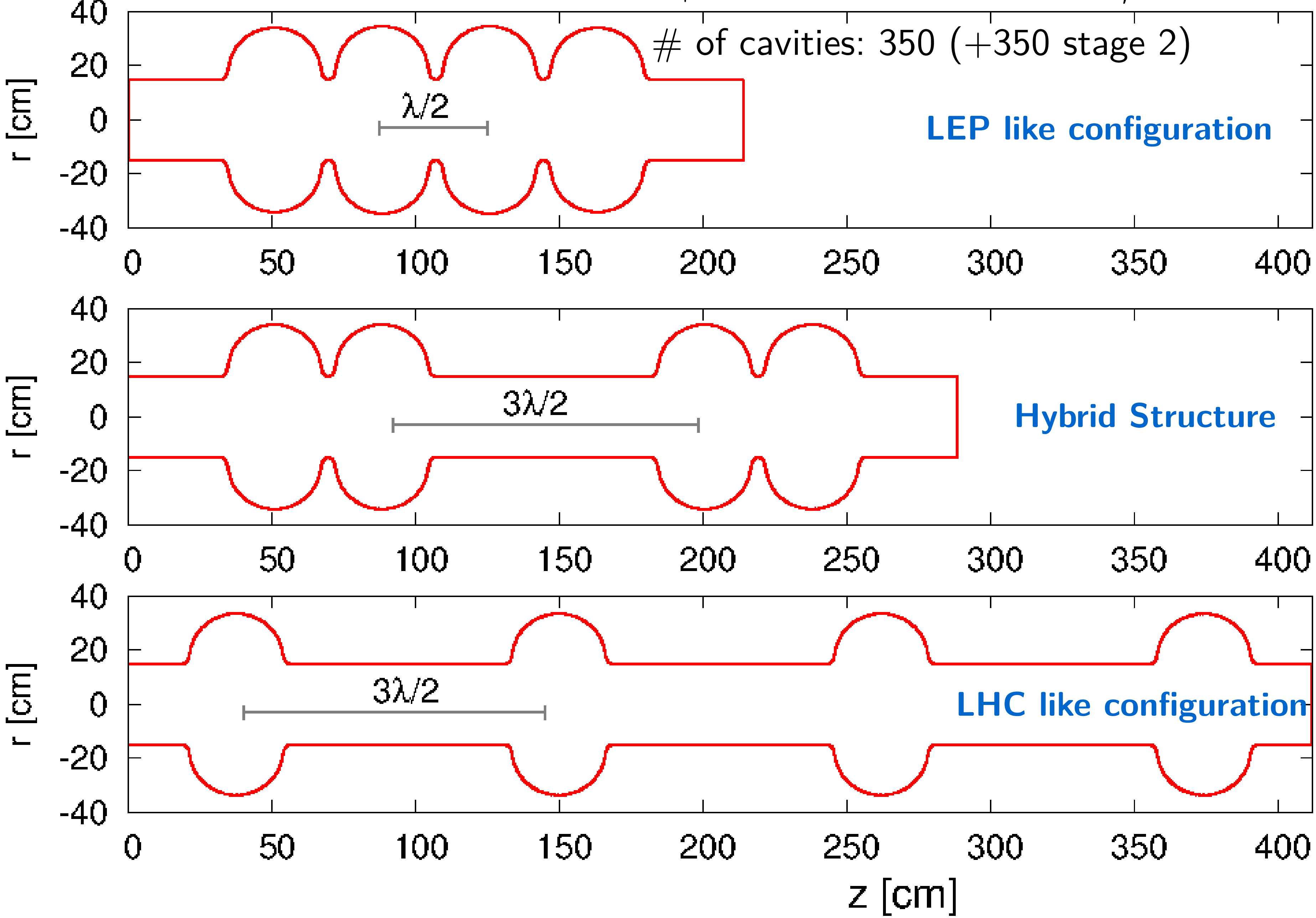


10 symmetrically placed straight sections for RF

Layout Options, 4-Cell Equivalent

2+2 cell structure as baseline, 1.2-1.4 km (tt)

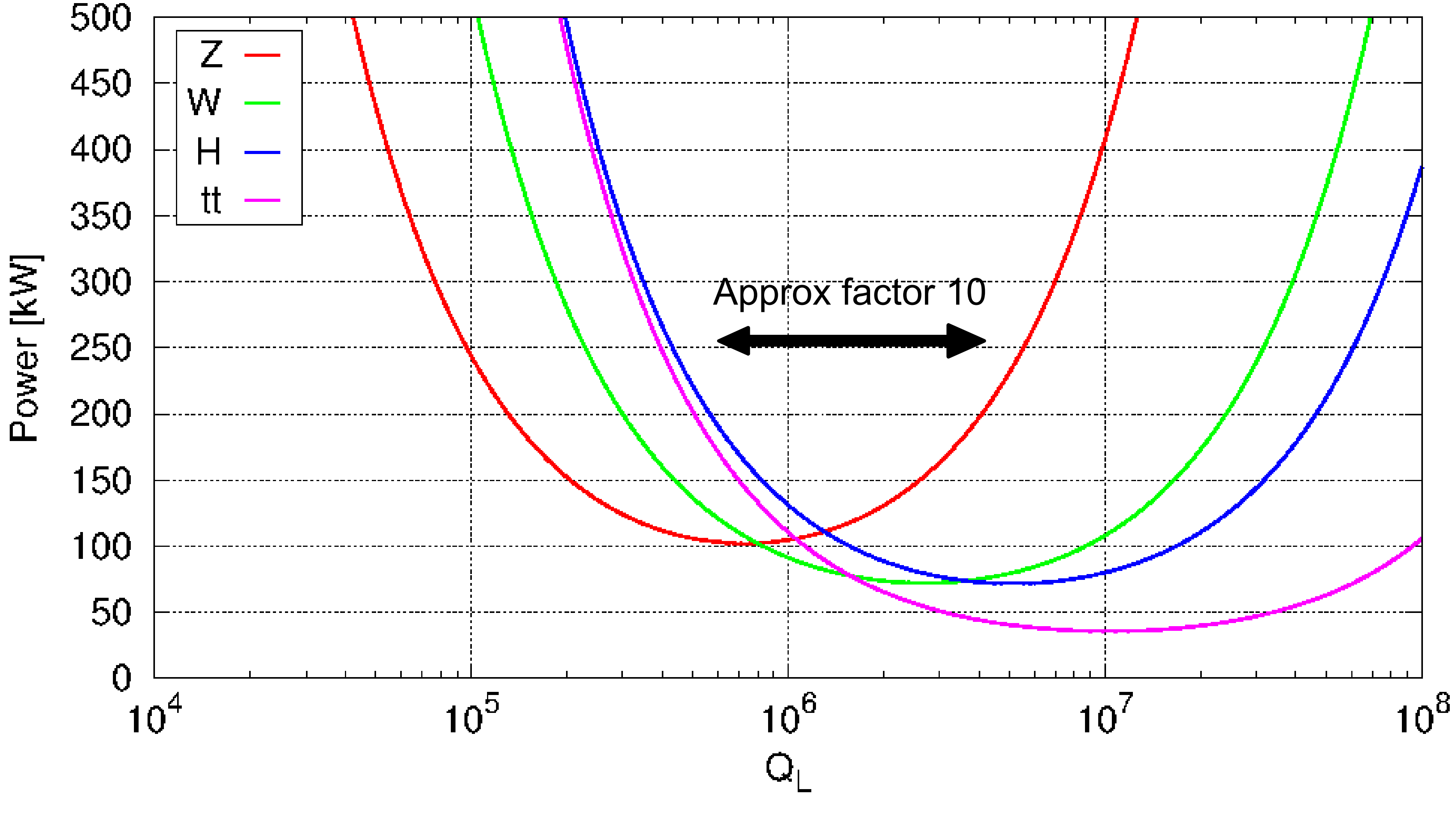
# of cavities: 350 (+350 stage 2)



FCC-ee, RF Power

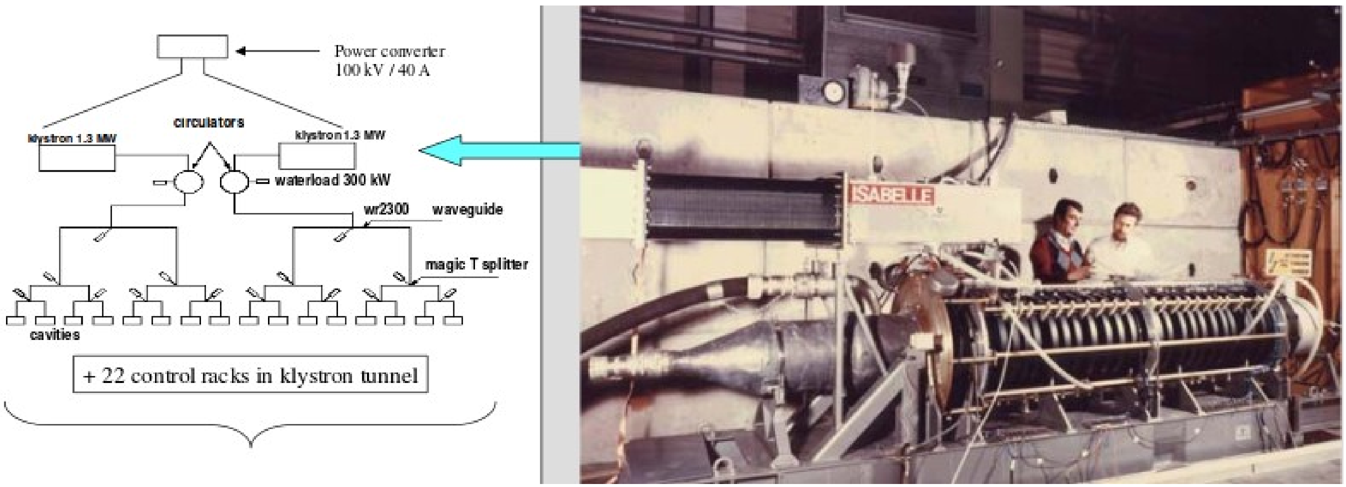
At optimum coupling at QL $\sim 10^6 - 10^7$, Power of ~100 kW

Z-nominal is most demanding case – RF staging



FCC-ee, RF Power Options

LEP 1.3 MW Klystrons driving 8 Cavities



But, single source failure leads to large voltage drop (LEP ~100 MV)

For FCC -ee

High efficiency klystrons using core oscillation method (Lingwood et al.)

Multibeam IOT development (Morten et al., ESS)

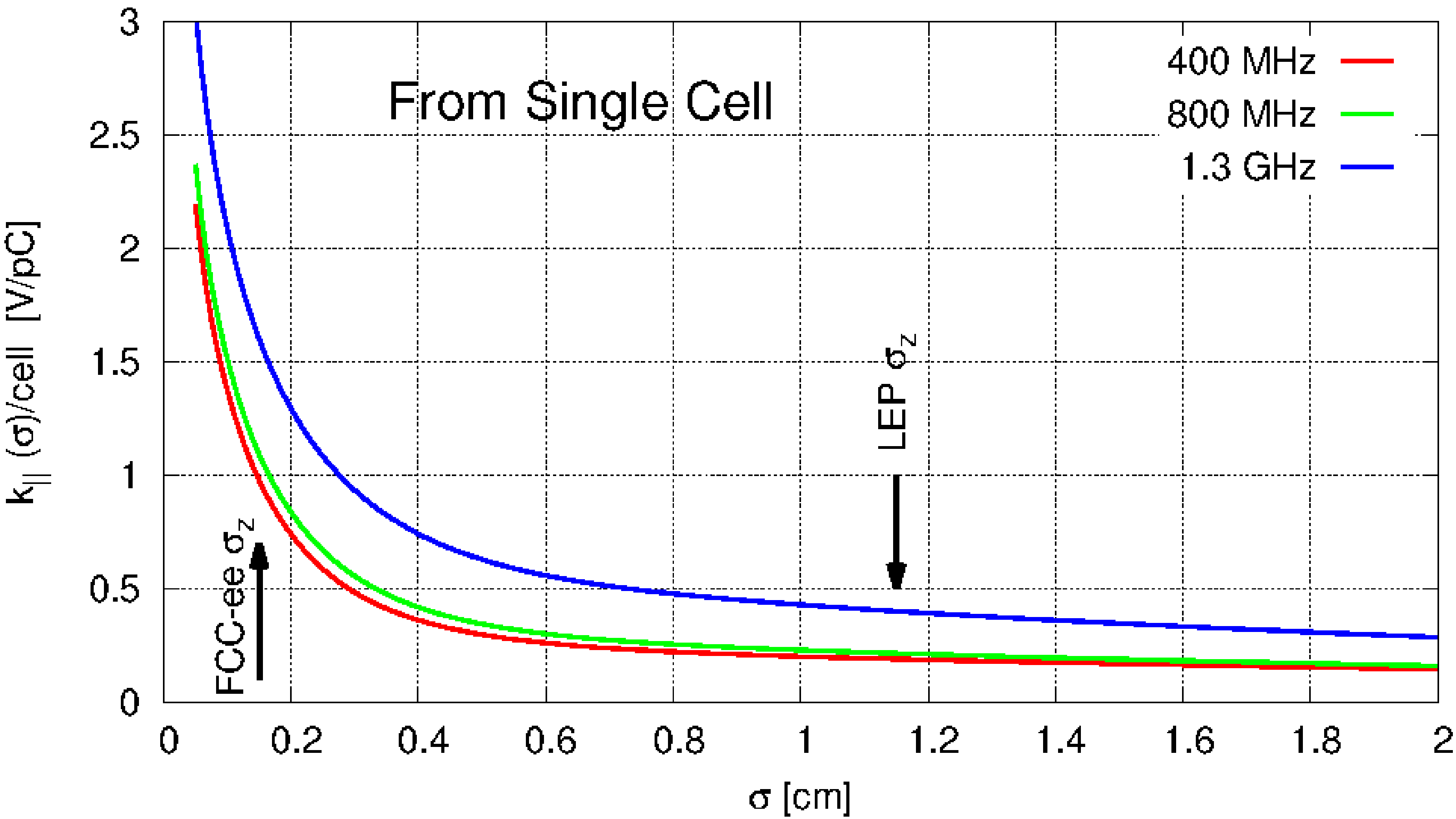
Single source (~100 kW range), single cavity (IOT & SSA) more appropriate

Low RF noise & RF distribution system needs careful study

Loss Factor vs Bunch Length

$$k_{(loss)} \propto \frac{1}{R_{(iris)}} \sqrt{\frac{gap}{\sigma_z}} \sqrt{(N_{cell})}$$

Longer bunch lengths to be considered also for transverse impedance



*Remember: 400 → 800 MHz: approx x1.5 increase in # of cells

Parameters, FCC-ee

Z-nominal is most demanding case – input power & HOM power

Higher freqs. become incompatible with high current case

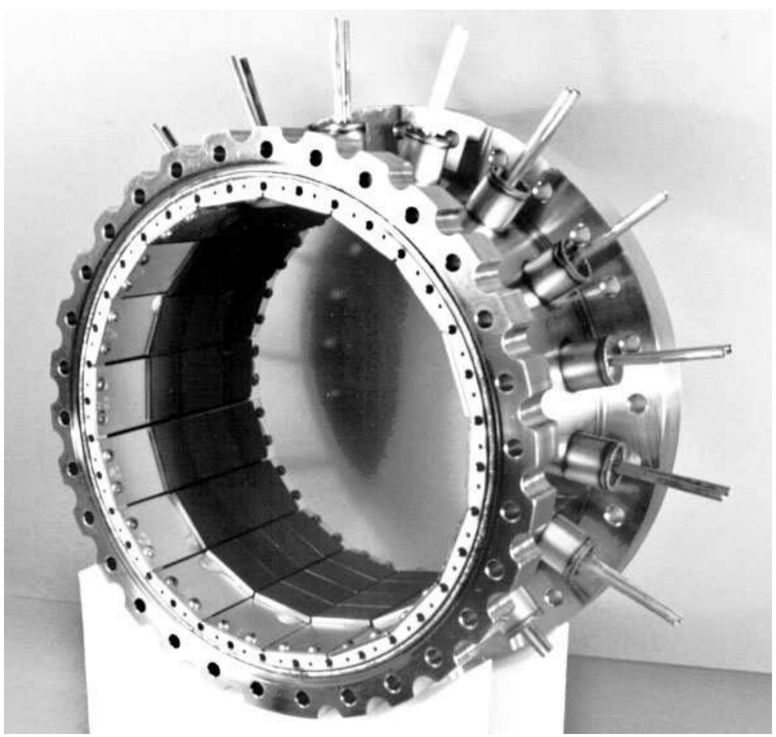
	FCC-Z	FCC-W	FCC-H	FCC-T
Energy [GeV]	45.5	80	120	175
Beam Current [mA]	1450	152	30	6.6
Voltage [MV, 2+2 Cells]	3.57	5.71	7.85	7.85
Opt Detuning [kHz]	**-13.6**	-0.89	-0.12	-0.02
QL, opt	0.7×10^6	2.7×10^6	5.3×10^6	1.0×10^7
Input Power [kW]	100	72	72	36
HOM Power [kW]	**29**	1.2	0.15	0.1

HOM Power Extraction

Two known solutions for HOM extraction

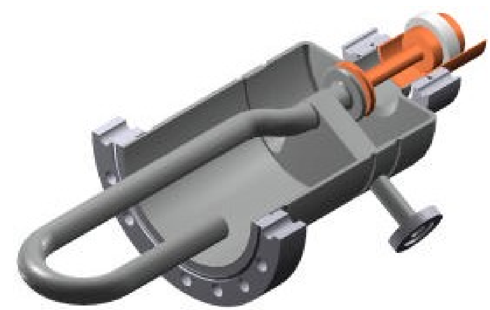
Cornell/KEKB like ferrites, 300K

~10 kW (approx 8^0C/kW temp rise)

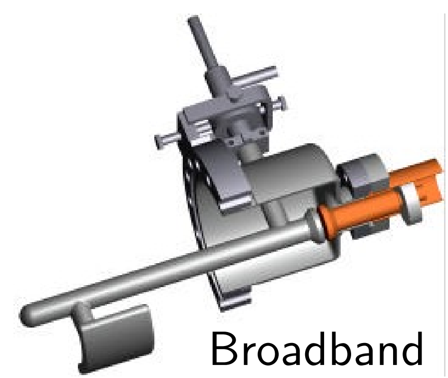


LEP/LHC like loops, 4.5K

~1 kW maximum



Narrow-band



Broadband

Parameters, FCC -he

Goal: Luminosity > $1\text{x}10^{34}$ cm^{-2} s^{-1}

LHeC design study is the reference baseline for FCC -he

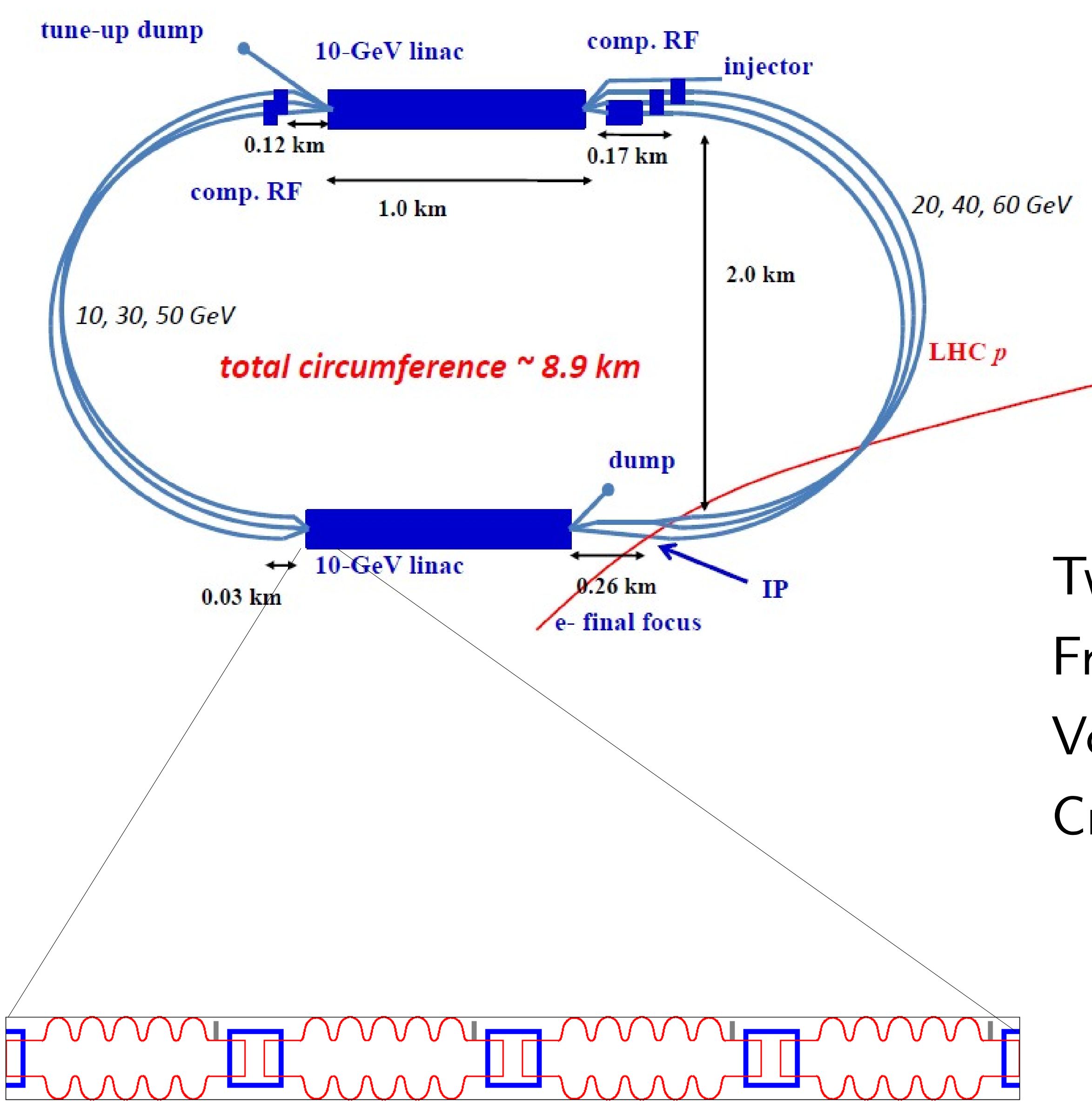
Option 1: Use the LHeC-ERL to collide 60 GeV on 50 TeV

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

	LHeC-ERL (Electrons)	LHC (Protons)	FCC (Protons)
Energy [TeV]	0.06	7.0	50
Current, DC [A]	0.15 (6-passes)	1.1	0.51
Total Voltage/turn [MV]	2000	16	32
# of Cavities	1069	8	16
RF Power [kW]*	~25	300	340

* RF power for ERL linac (~20 Hz detuning, QL=$3\text{x}10^{7}$)

ERL Option, FCC -he



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

Energy: 60 GeV

Number of passes: 6

Beam current: 6.6-25.6 mA

Two 10 GeV linacs

Frequency: 801.58 MHz (h=20)

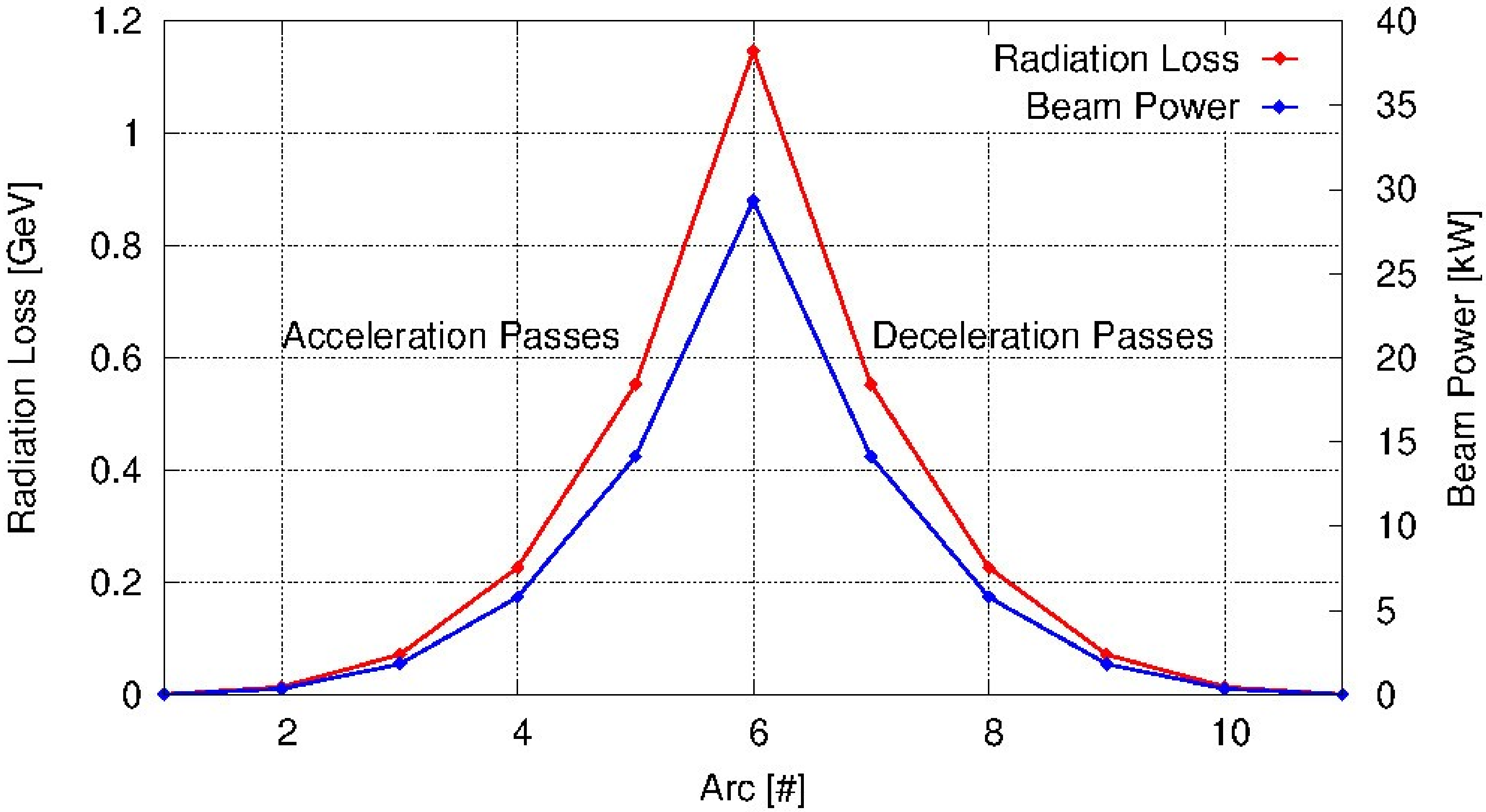
Voltage: 18.7 MV/cavity

Cryo losses: (~ 25 MW @3x10^{10})

ERL Option, FCC -he

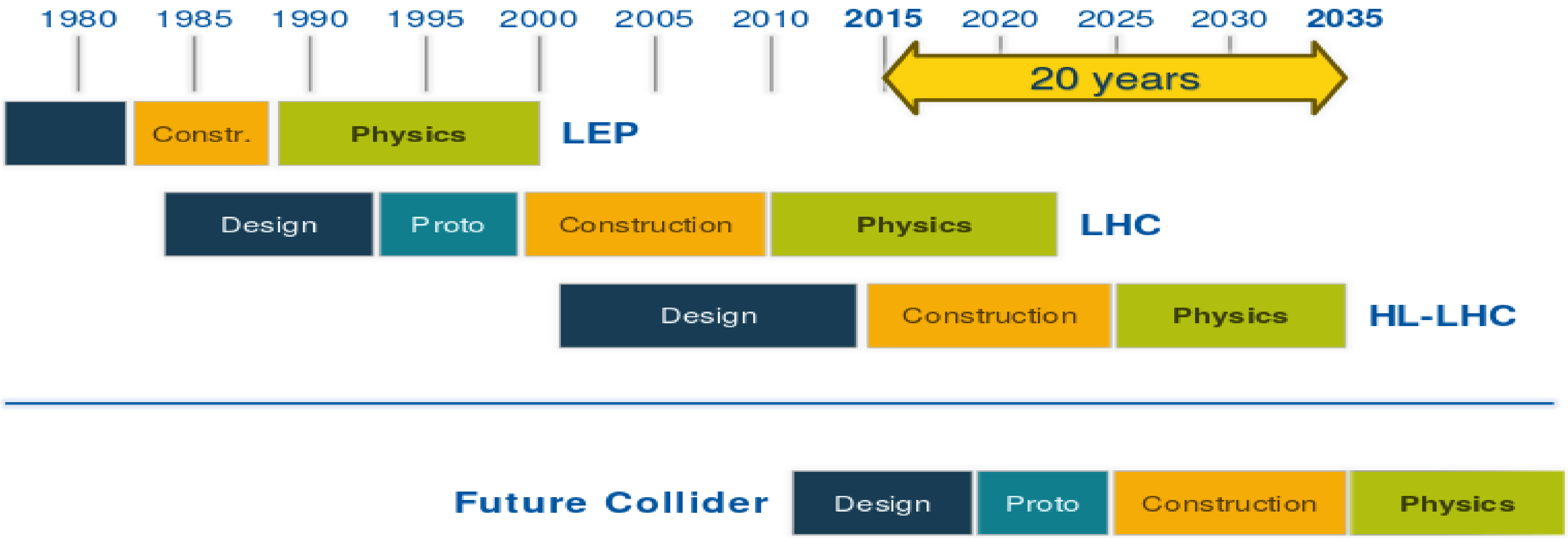
Energy recovery after total 6 passes: 95.2 %

- Sync radiation loss: 2.88 GeV (73.6 MW accumulated beam power)
- Extra power for finite bandwidth of ERL cavities (~15 MW)



Note: ERL in the LHC tunnel or FCC tunnel would reduce the beam power by <u>x3-10</u>

Why Now ?



(Estimates)	FCC-hh	FCC-ee	FCC-he
Energy [TeV]	50 TeV	45.5-175 GeV	50 / 0.06
RF Voltage/turn [GV]	0.03-0.05	2.5-11.0	20
RF Power [MW]	8.0	50	70
Cryo Losses [MW]	0.002	23	25

Next Steps

Proton-proton

Approximately 2-3 times the LHC RF (400 MHz, 32-50 MV, 500 kW)

Heavy R&D on RF power chain, FPC, low noise amplifiers, feedback

Electron-Positron

Most challenging! $\sim$3 times LEP RF (2.5-11 GV, 400 MHz)

High Q_0 (thin films), low impedance, high power HOM coupler

Electron-Ion

60 GeV-ERL feasible, power 100+ MW (High Q_0 $\sim 10^{11}$ is essential)

"ERL" in FCC-ring will be optimum (+ top up injector)

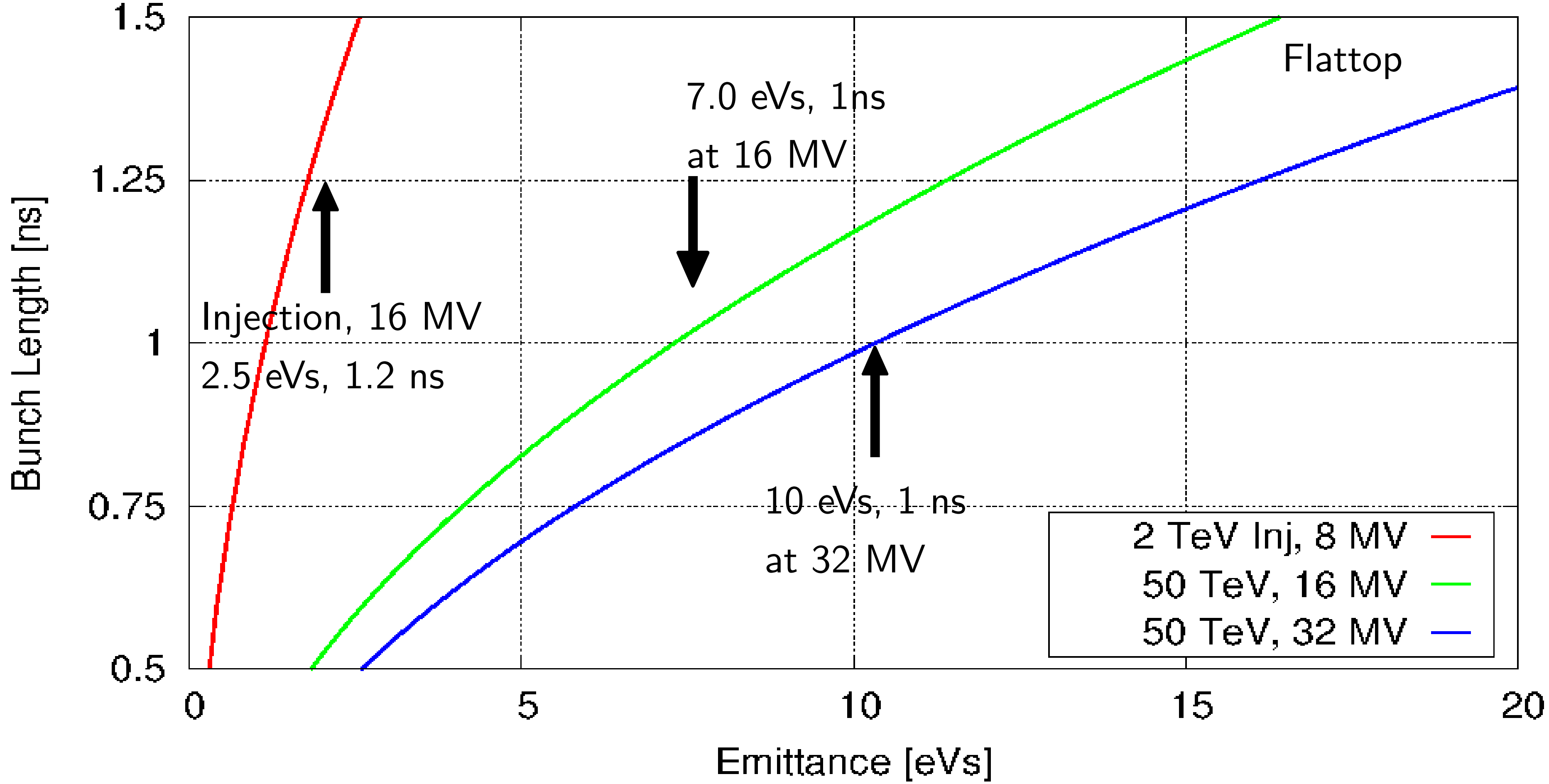
Additional Slides: FCC -hh, RF

Assume: 16 Cavities/beam with 500 kW/cavity

Injection, 3.3 TeV (16 MV capture voltage)

Ramp rate ~30 min, ~ 9MeV/turn, Power = 4.5 MW/beam

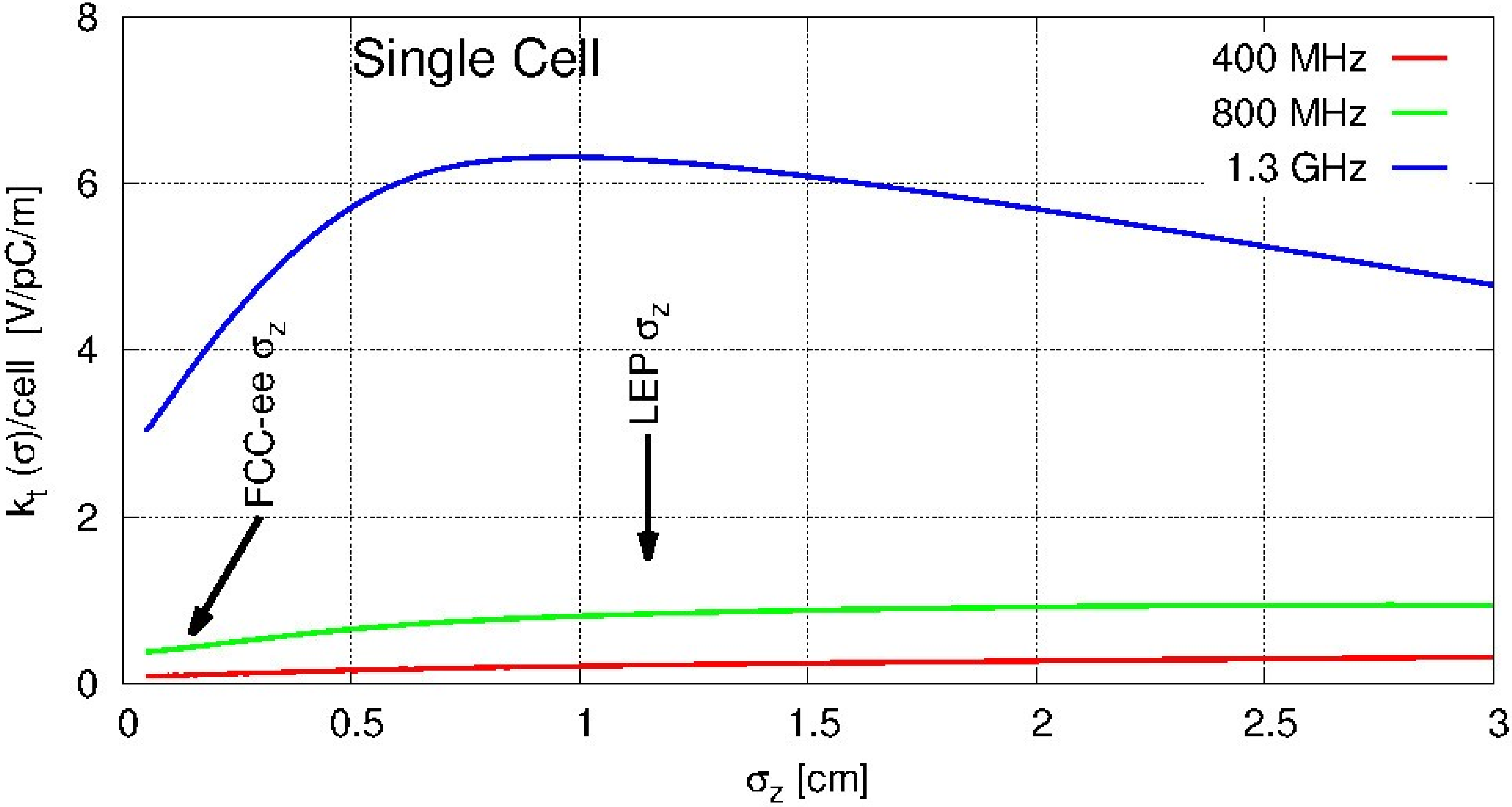
Top energy, rad loss 3.9 MeV (32 MV total)



Transverse Loss Factor vs Bunch Length

$$k_{(trans)} \propto \frac{1}{R_{iris}^3} \sqrt{gap \,.\, \sigma_z \, N_{cells}}$$

Limiting factor for transverse instabilites. 400 MHz with large aperture is clearly beneficial

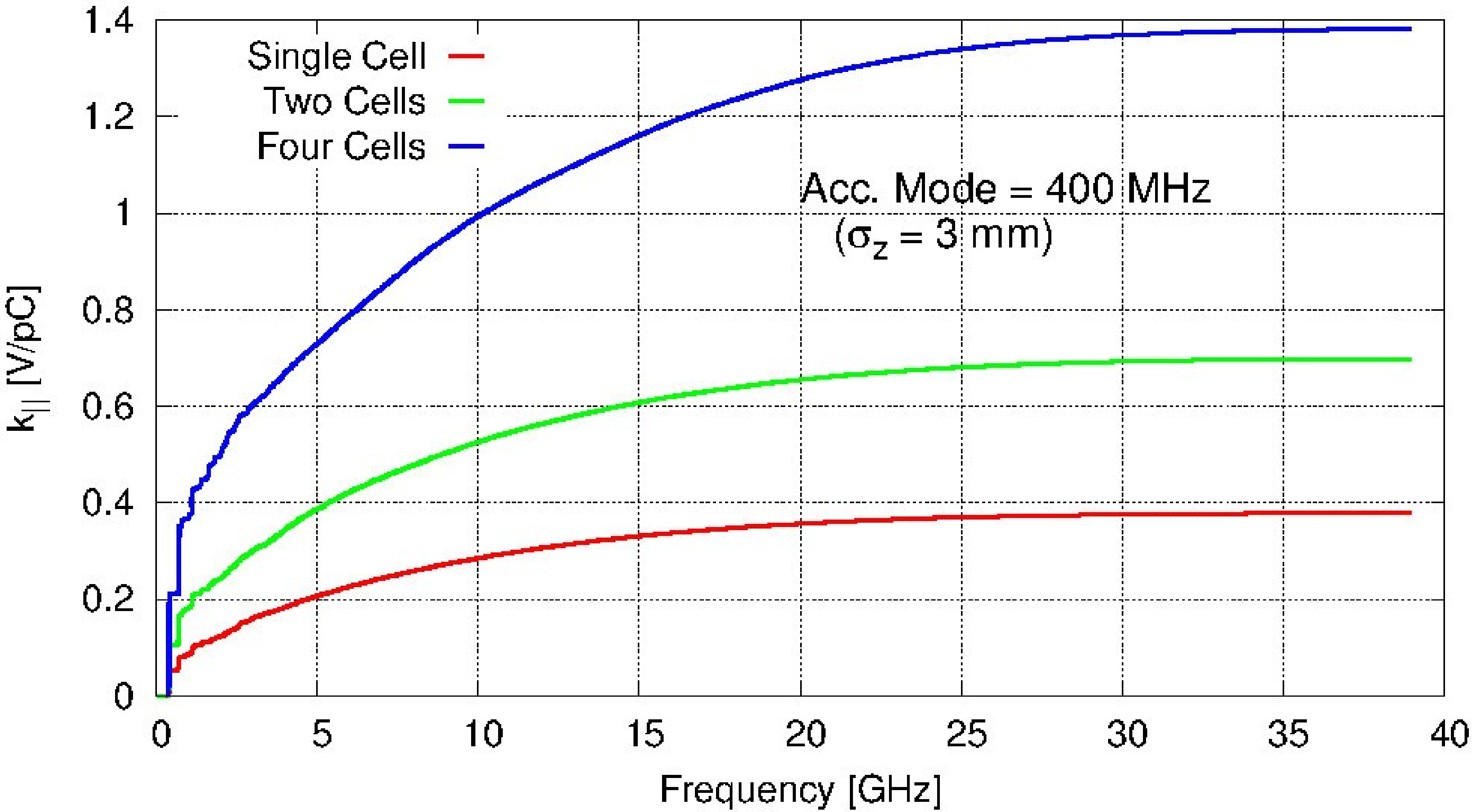


Longitudinal Loss Factors

$$P_{ave} = (k_{loss} Q)\, I_{beam}$$

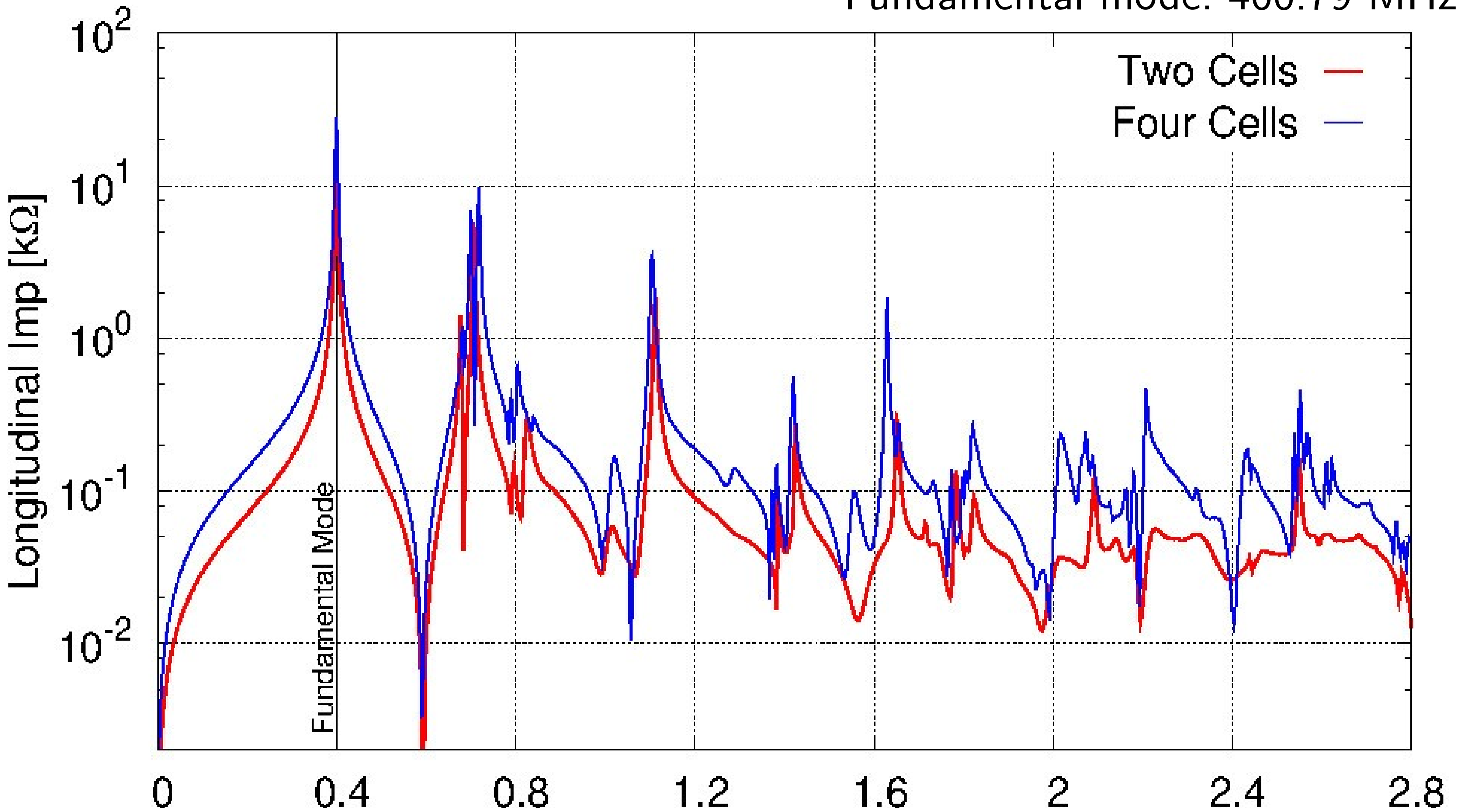
1 V/pC ~42 kW of HOM power /cavity

4-cell cavities starts to become unfeasible



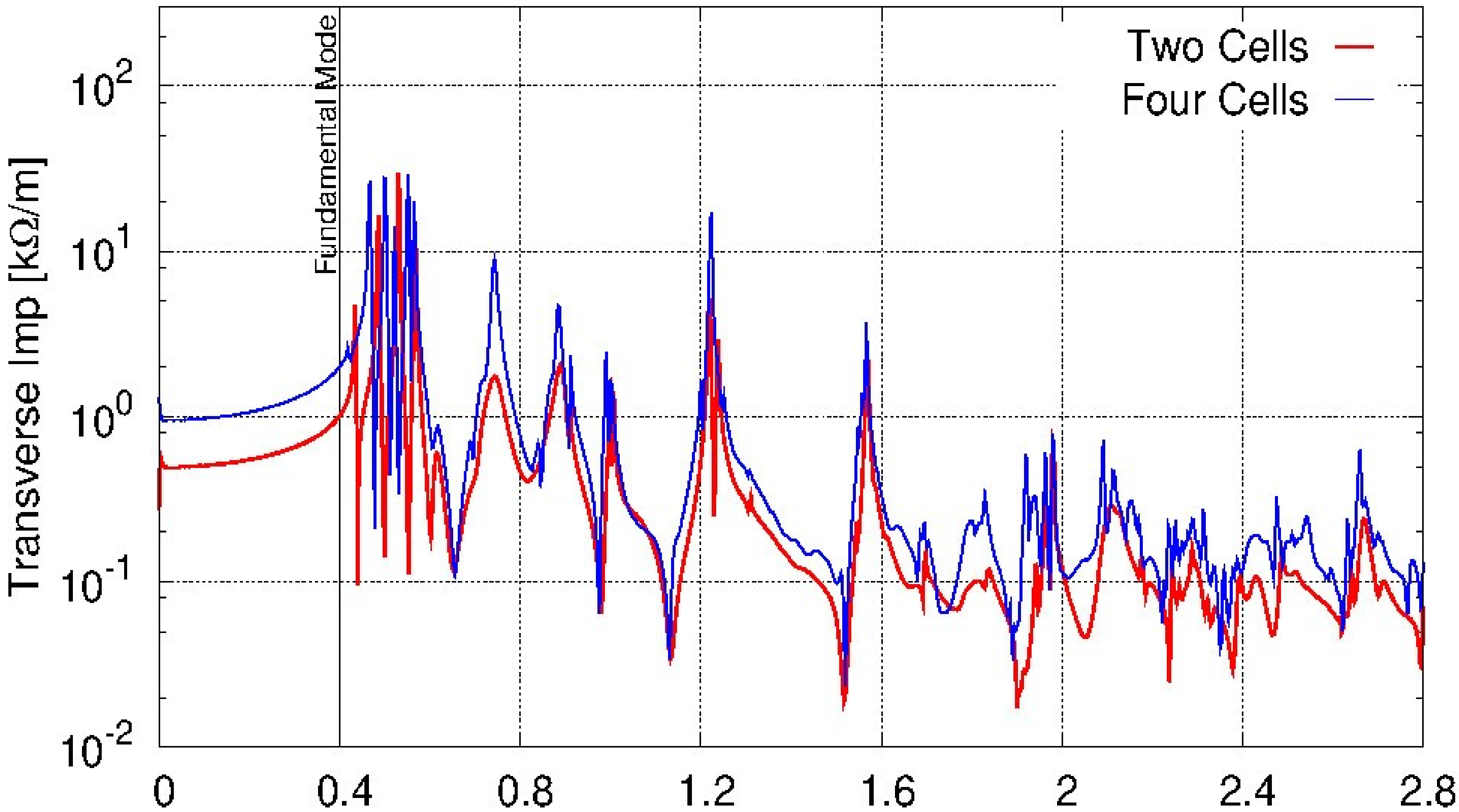
Impedance Spectrum, Longitudinal

Fundamental mode: 400.79 MHz

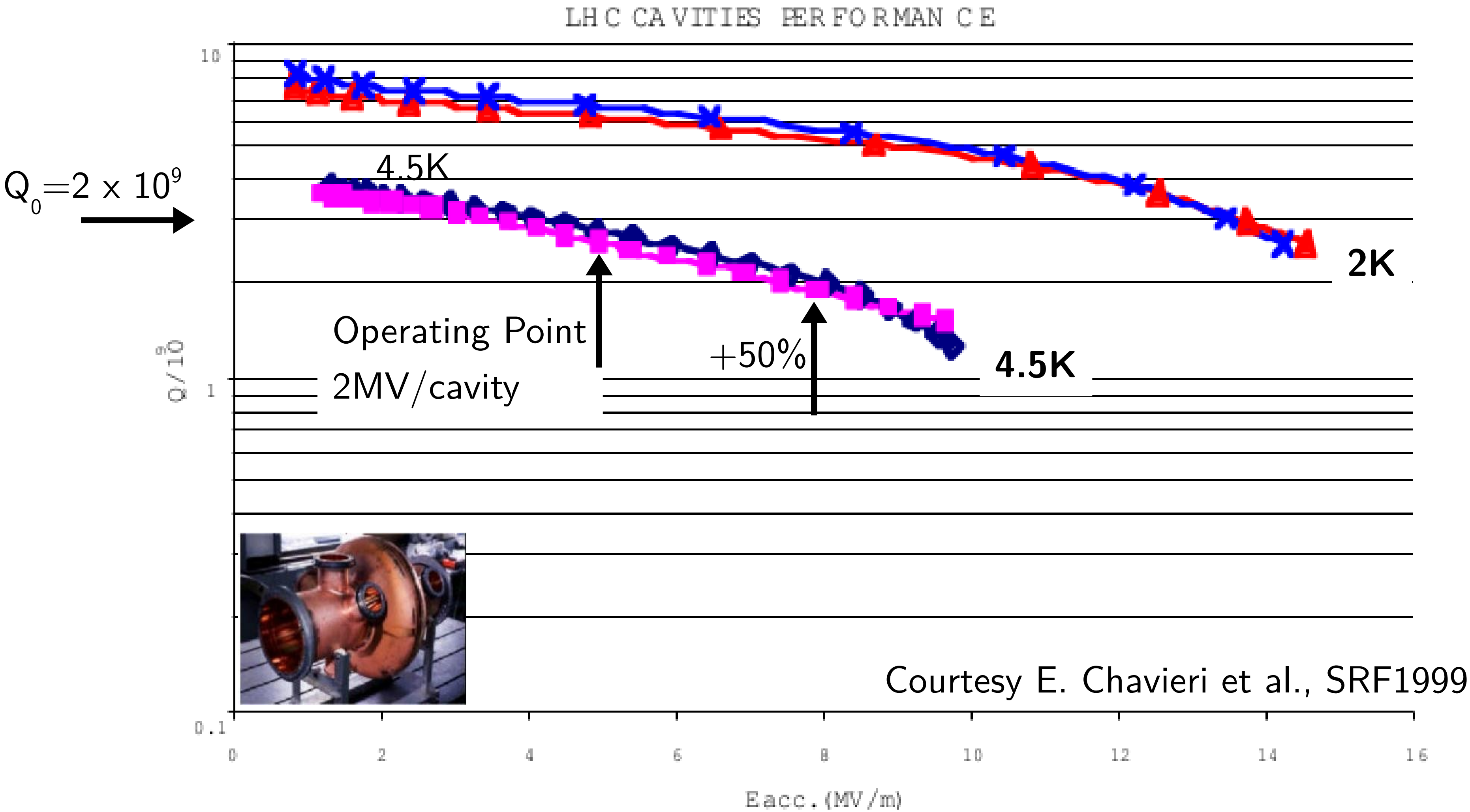


Impedance Spectrum, Transverse

Fundamental mode: 400.79 MHz



Cryogenic Estimate, FCC-hh

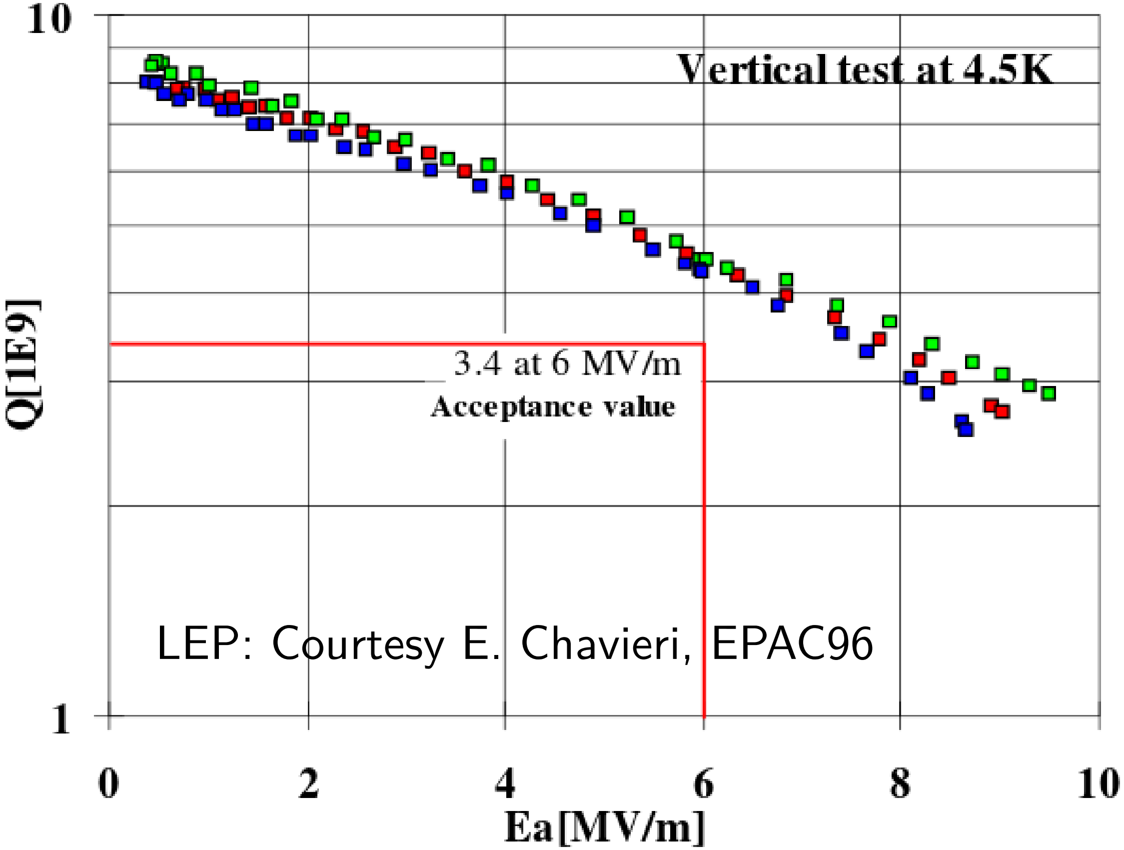


Assume for FCC ~25W @4.5K, 2MV (dynamic)/cavity

~45W @4.5K (static+dynamic)/cavity

Total ~1.5 kW @4.5K (32 cavities – 2 beams) – not very big

Cryogenic Losses, FCC-ee



Freq [MHz]	400	800
Eacc [MV/m]	10	17
V/cav [MV]	15	11
# of cells	4	5
R/Q	297	443
G	297	282
Q0	$3\text{x}10^9$	$1\text{x}10^9$
Rs	99	280
Cavity losses [W]	253	508

At 800 MHz, R_{BCS}=250 nΩ

Q_0 increase beyond 10^9 difficult while at 400 MHz easier

(2+2) cells @400 MHz ~126W (for 15MV total, for approx 30% more length),

ERL, Power Options

Good experience with 800 MHz IOTs (~60 kW) for the SPS 3rd harmonic system

Chain of 8 IOTs installed powering two cavities in the SPS