RF scenarios and challenges for FCC-ee

A. Butterworth, O. Brunner, CERN

with input from R. Calaga, E. Jensen, S. Aull, E. Montesinos, U. Wienands

Outline

- Operation at different energies
  - Cavity options, layout and staging
- RF in different FCC-ee operation modes: H, tt, Z
  - Fundamental power & beam loading
  - Higher order mode power
- Power sources
- Conclusions and topics for R&D

Dynamic range: energy vs. intensity

parameter	FCC-ee baseline			
	Z	W	H	t
E_{beam} [GeV]	**45**	**80**	**120**	**175**
SR energy loss/turn U_0 [GeV]	0.03	0.33	1.67	7.55
current [mA]	1450	152	30	6.6
$P_{SR,tot}$ [MW]	**50**	**50**	**50**	**50**

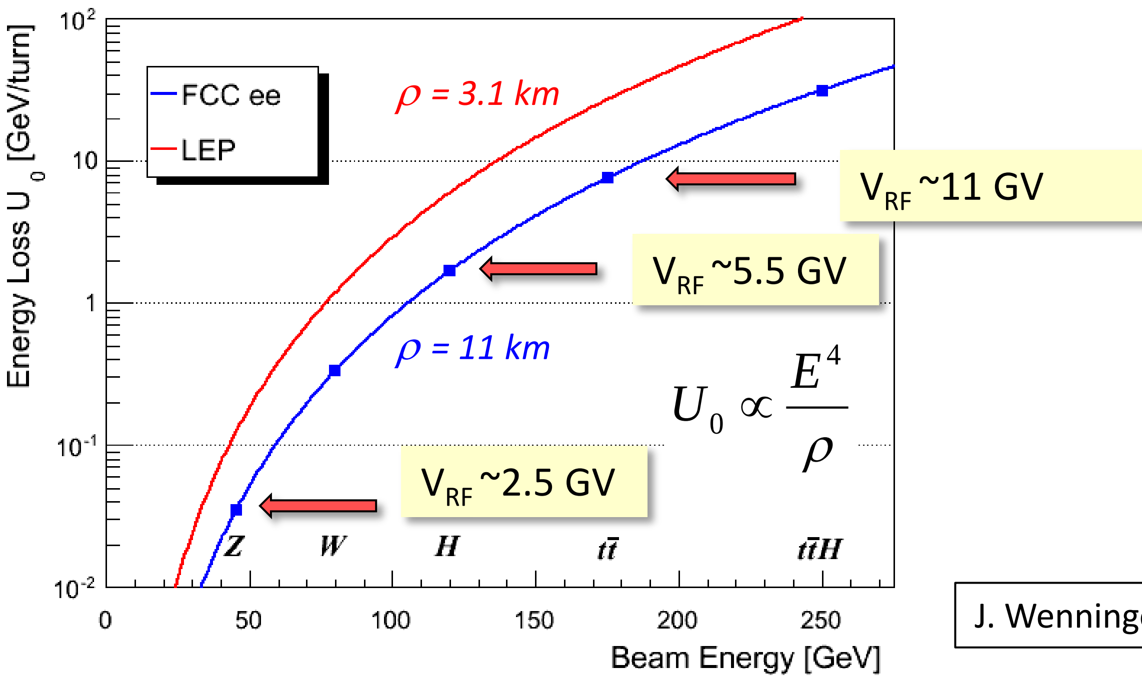
Total beam power limited to 50 MW (design choice)

↓

SR loss/turn (+ beamstrahlung + ...)

↓

Defines maximum beam current at each energy

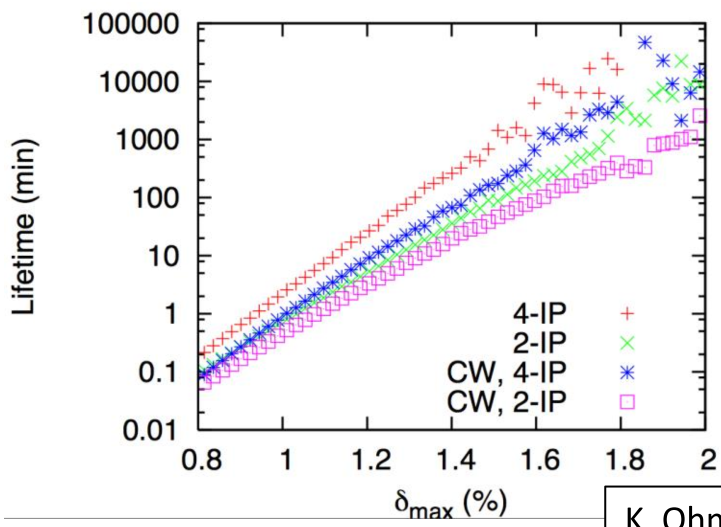


J. Wenninger

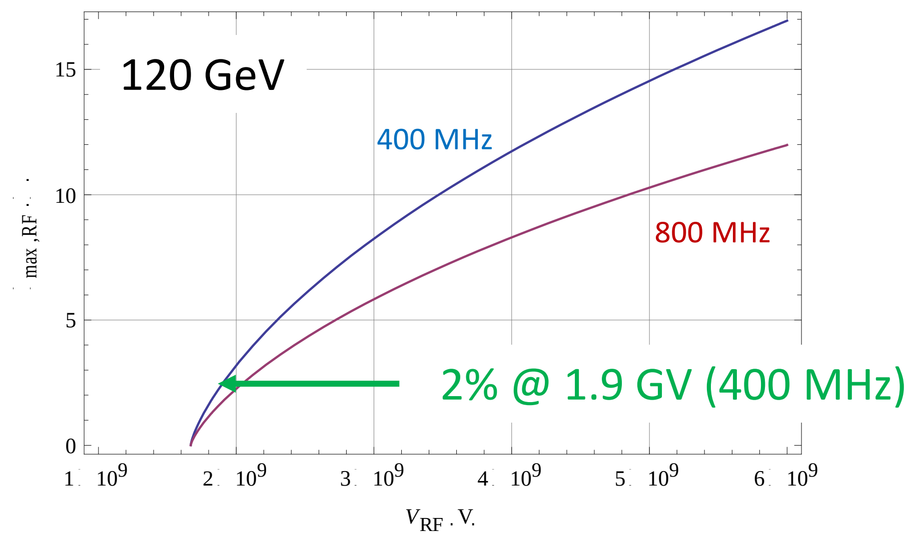
Beamstrahlung

- Beamstrahlung increases the energy spread
- Need slightly more RF voltage to provide additional momentum acceptance

parameter	Z	W	H	t
E_{beam} [GeV]	45	80	120	175
SR energy loss/turn U_0 [GeV]	0.03	0.33	1.67	7.55
$\sigma_{\delta,SR}$ [%]	0.052	0.092	0.139	0.202
$\sigma_{\delta,tot}$ [%] (w beamstr.)	0.061	0.104	0.154	0.215



K. Ohmi



Staging for operation

- Phase 1: Install enough V_{RF} to reach the Higgs in first stage
  - 1.9 to 2.2 GV, ~20 MW/beam, 12 mA Higgs
  - "Low" Luminosity Higgs (12 mA) and Z (60 mA)

↓

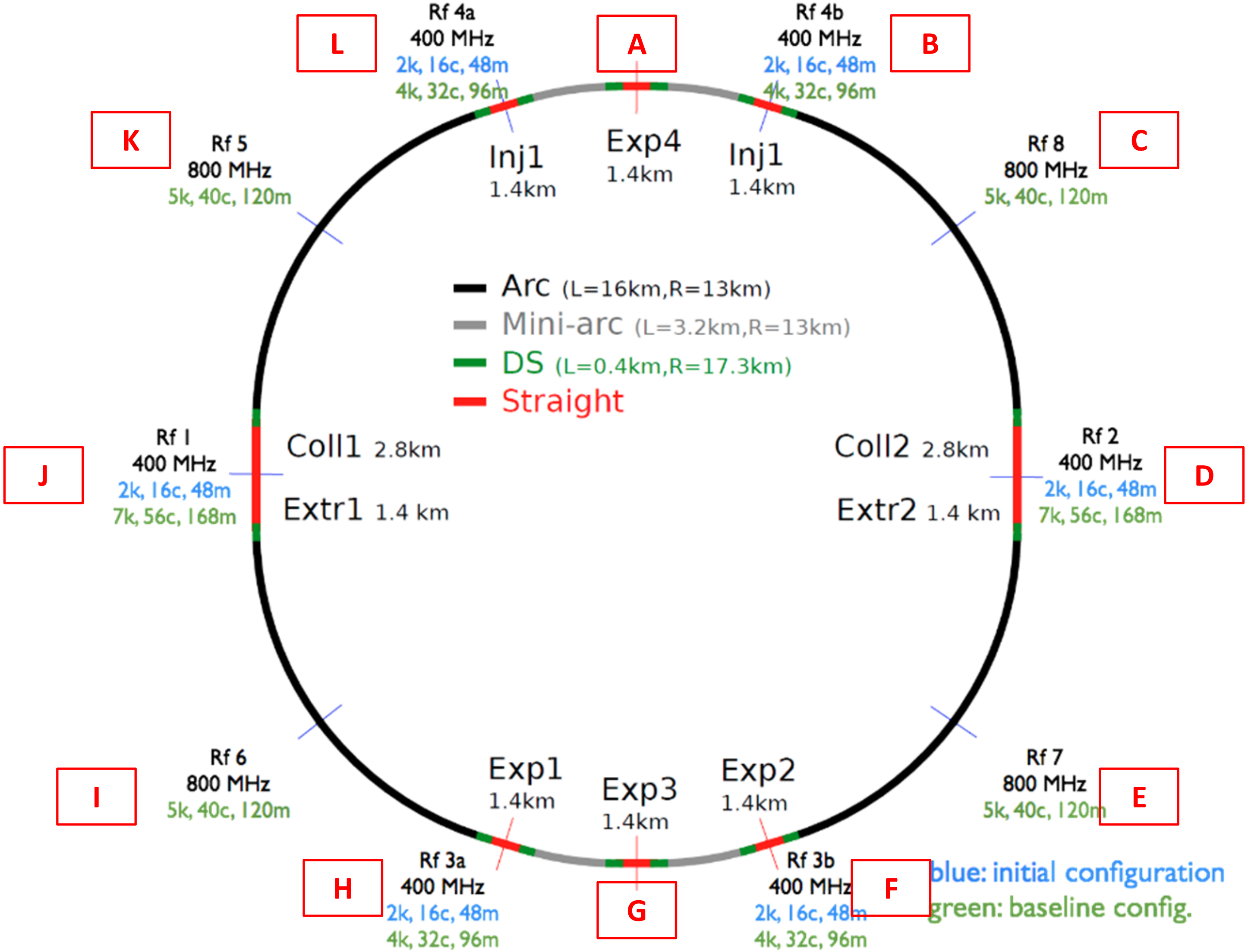
- Phase 2: Full installation of 400 MHz RF, Higgs & Z at nominal intensity
  - Higgs, high Luminosity: 5.5 GV, 30-50 MW/beam, 18-30 mA
  - Z, high currents: 2.5 GV, 30-50 MW/beam, 870-1450 mA

↓

- Phase3: Physics @ 175GeV : Additional 800 MHz RF
  - total 50 MW/beam
  - ttbar 6.6 mA/beam

FCC-ee

RF layout (per ring)

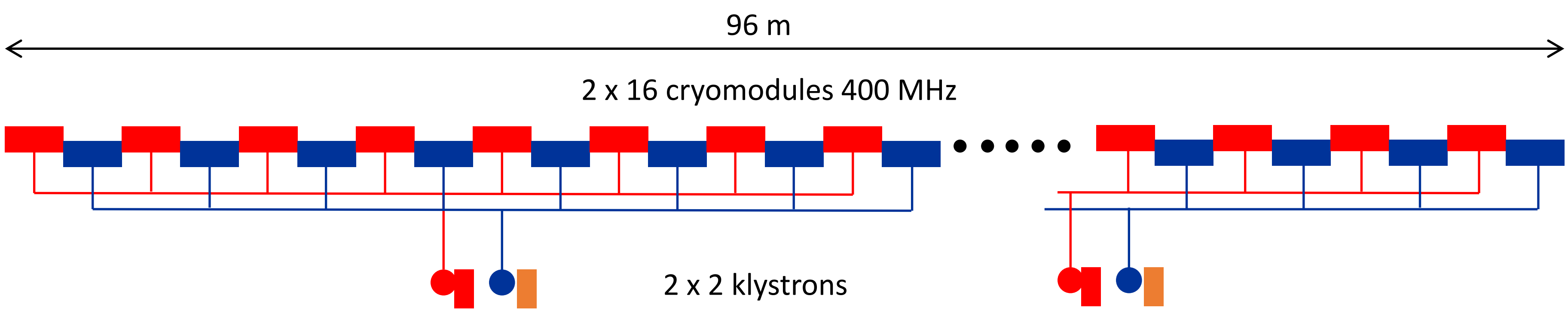


FCC-ee RF staging

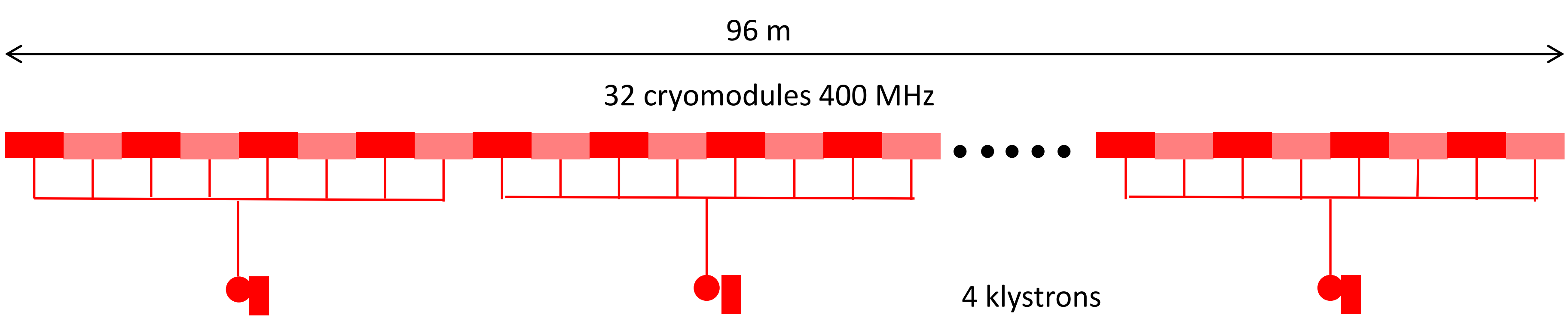
4 values of beam energy, 3 RF configurations

Beam Energy	Parameter	Unit	Initial 400 MHz	Full 400 MHz	Baseline 400/800 MHz
Power (=# tubes)		MW	12	30	50
Max. Rf voltage		MV	1900.00	4700.00	10700.00
45 GeV (Z running)					
	beam current	mA	350.000	850.000	
	# bunches		4000	10000	
	Luminosity	**/cm²/s**	**5.06E+034**	**1.53E+035**	
80 GeV (W running)					
	beam current	mA	36	90	150
	# bunches		1100	2700	4490
	Luminosity	**/cm²/s**	**1.75E+034**	**5.89E+034**	**1.19E+035**
120 GeV (H running)					
	beam current	mA	7.2	18	30
	# bunches		320	800	1360
	Luminosity	**/cm²/s**	**4.89E+033**	**2.34E+034**	**5.09E+034**
175 GeV (t-tbar running)					
	beam current	mA			0.0065
	# bunches				98
	Luminosity	**/cm²/s**			**1.43E+034**

Alternative (400 MHz only) scenario



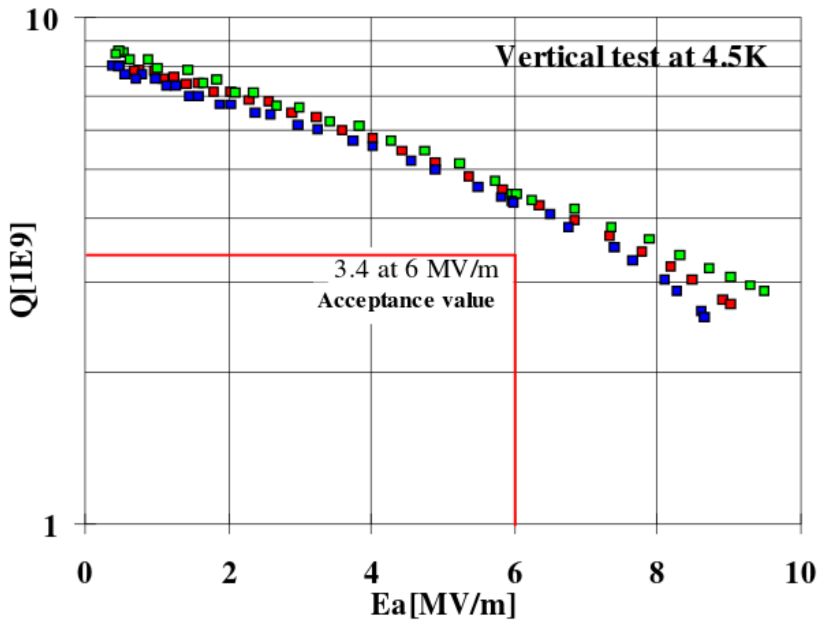
Displace modules to share between the 2 beams



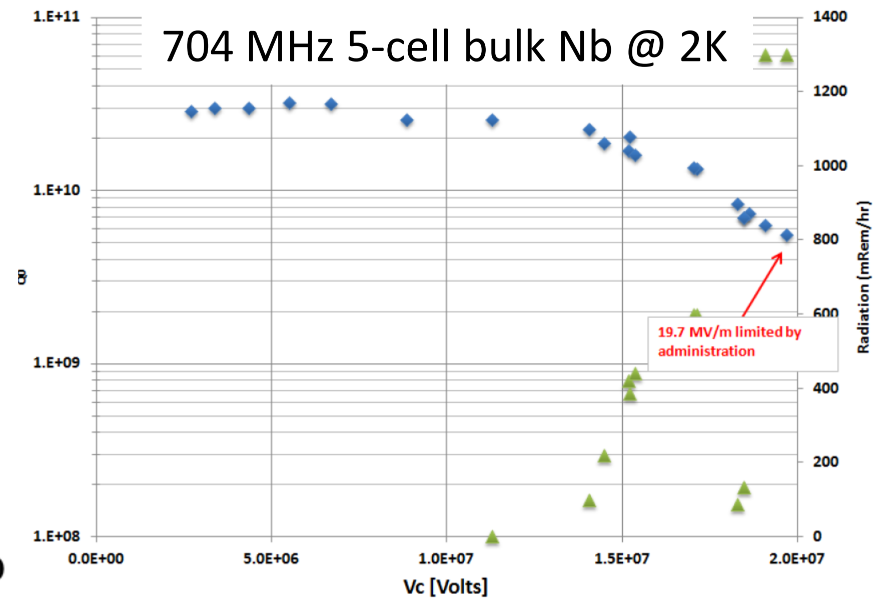
Talk by Uli Wienands tomorrow

400 vs 800 MHz, 4.5 vs 2K

LEP2 352 MHz 4-cell Nb film @ 4.2K



E. Chiaveri, EPAC96



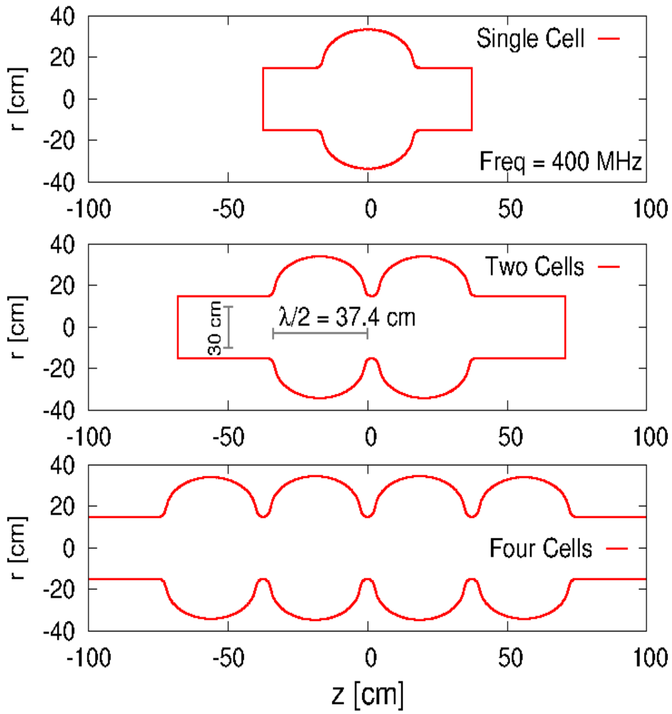
Xu et al. LINAC2014

- 800 MHz
  - higher Q_0 and MV/m, lower heat load and shorter RF sections
- 400 MHz
  - better for HOM loss factor
  - lower Q_0, higher heat load but 4.5 K instead of 2K ?
  - lower MV/m, longer RF sections

Talk by Sarah Aull this afternoon

Also Nb_3Sn, M. Liepe this morning

400 MHz cavity options

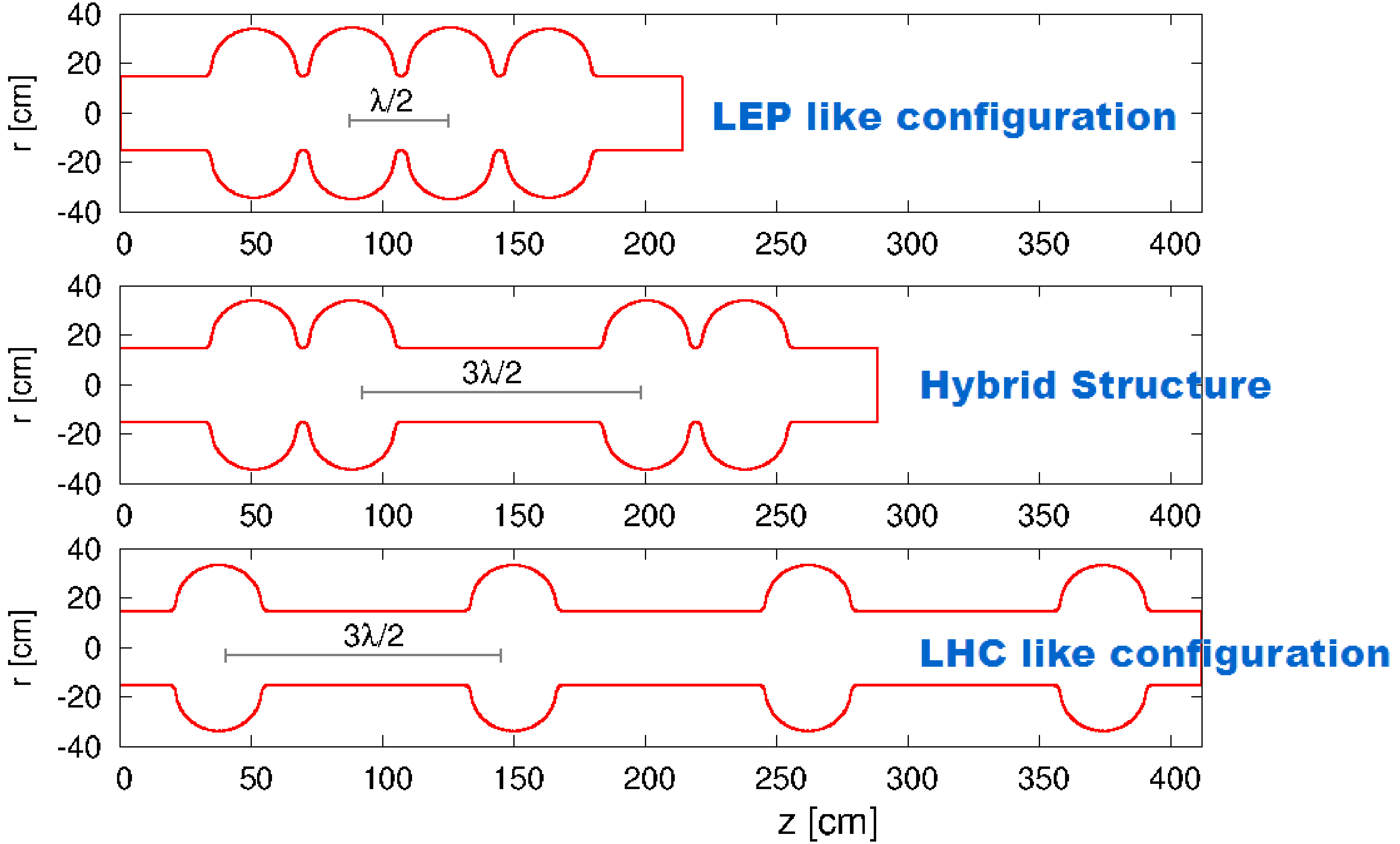


	1-Cell	2-Cells	4-Cells
L[m], Active	.374	.748	1.5
V [MV] /cav	3.75	7.5	15
Ep /Ea	3.1	3.3	3.3
Bp [mT]/Ea	4.2	4.7	4.7
R/Q [Ω]	87	169	310
U [J]	0.54	1.3	2.7
G [Ω]	297	297	297

R. Calaga

- 400 MHz cavities with 1, 2 or 4 cells considered
  - 4 cells better for "real estate" gradient
  - Single cell has lowest HOM loss factor, but 2-cell can be almost as good (mode cancellation)

Add ~50 cm on each side for end-group tapers



RF power: 120 GeV, 12 mA

	1-cell	2-cell	4-cell
RF voltage [MV]	5500		
SR power per beam [MW]	50		
Synchronous phase [deg]	162.3		
Gradient [MV/m]	10		
Active length [m]	0.375	0.75	1.5
Voltage/cavity [MV]	3.8	7.5	15.0
Number of cavities	1467	734	367
Total cryomodule length [m]	2569	1468	1012

Optimistic but realistically achievable

1467 cells @10 MV/m

RF sections 1 – 2.5 km per beam

R/Q [linac ohms]	87	169	310
RF power per cavity [kW]	34.1	68.1	136.2
Matched Qext	4.7E+06	4.9E+06	5.3E+06
Bandwidth @ matched Qext	84.3	81.9	75.1
Optimal detuning [Hz]	-132.6	-128.8	-118.1

cf. LHC couplers 500kW CW

Quite small →careful tuning design

Moderate detune

Q_0 [10e9]	3.0		
Heat load per cavity [W]	53.9	110.9	241.9
Total heat load per beam [kW]	79.0	81.4	88.8

Optimistic but realistically achievable

Total heat load around 80 kW (x2)

RF power: 45.5 GeV, 1.45 A

	1-cell	2-cell	4-cell
RF voltage [MV]	2500		
SR power per beam [MW]	50		
Synchronous phase [deg]	179.2		
Gradient [MV/m]	10		
Active length [m]	0.375	0.75	1.5
Voltage/cavity [MV]	1.7	3.4	6.8
Number of cavities	1467	734	367
Total cryomodule length [m]	2569	1468	1012

R/Q [linac ohms]	87	169	310
RF power per cavity [kW]	34.1	68.1	136.2
Matched Qext	9.8E+05	1.0E+06	1.1E+06
Bandwidth @ matched Qext	408	397	364
Optimal detuning [Hz]	-14804	-14388	-13196

Q_0 [10e9]	3.0		
Heat load per cavity [W]	11.1	22.9	49.9
Total heat load per beam [kW]	16.3	16.8	18.3

Large detuning to compensate reactive beam loading

$$\Delta\omega/\omega = \frac{I_b \cos\phi_s R/Q}{V}$$

cf. revolution frequency 3 kHz → will need strong RF feedback to control coupled bunch modes

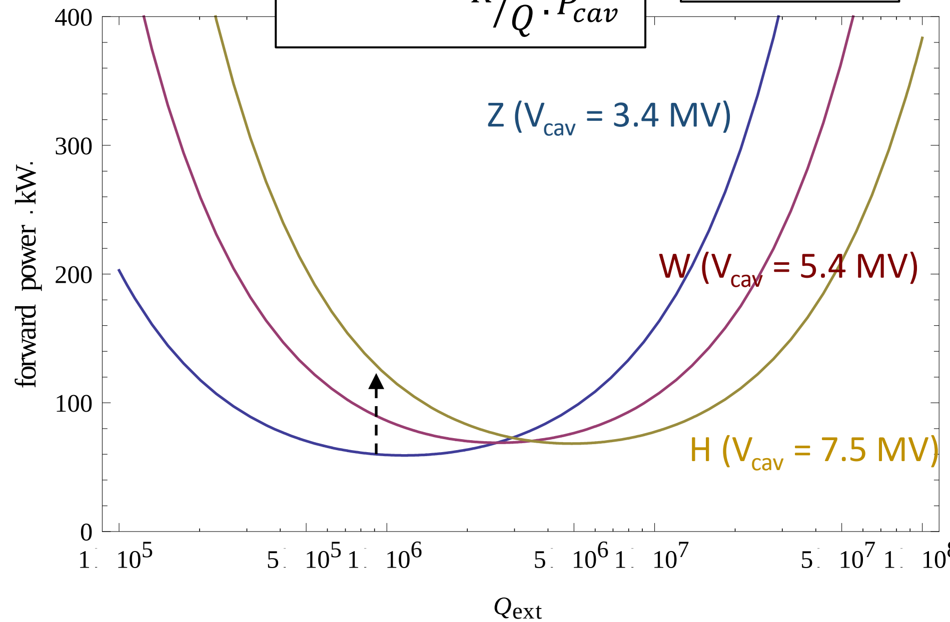
Power couplers: Fixed or variable?

parameter	Z	W	H	t
E_{beam} [GeV]	**45**	**80**	**120**	**175**
RF voltage [GV]	**2.5**	**4**	**5.5**	**11**
current [mA]	1450	152	30	6.6
Matched Qext	**1×10^6**	**2.6×10^6**	**5×10^6**	**5×10^6**

- Choose Q_{ext} for optimum power transfer to beam
- Matching a fixed coupler for the Z costs power at the H
- But: variable coupler costs around 2-5 x fixed
- Couplers are a major cost driver of cryomodule
- Trade-off to be considered

$$Q_{ext,opt} = \frac{V_{cav}{}^2}{R/Q \cdot P_{cav}}$$

R/Q : 84 Ω
P_{beam}: 50 MW



Cavity higher order mode power

parameter	Z	W	H	t
current [mA]	1450	152	30	6.6
no. bunches	16700	4490	1360	98
N_b [10^{11}]	1.8	0.7	0.46	1.4
$\sigma_{z,SR}$ [mm]	**3.29**	**2.02**	**1.62**	**2.31**
$\sigma_{z,tot}$ [mm] (w beamstr.)	**3.80**	**2.27**	**1.80**	**2.45**

HOM power $P_{avg} = (\, k_{loss}\, Q \,)\, I_{beam}$

HOM an issue especially for Z running:

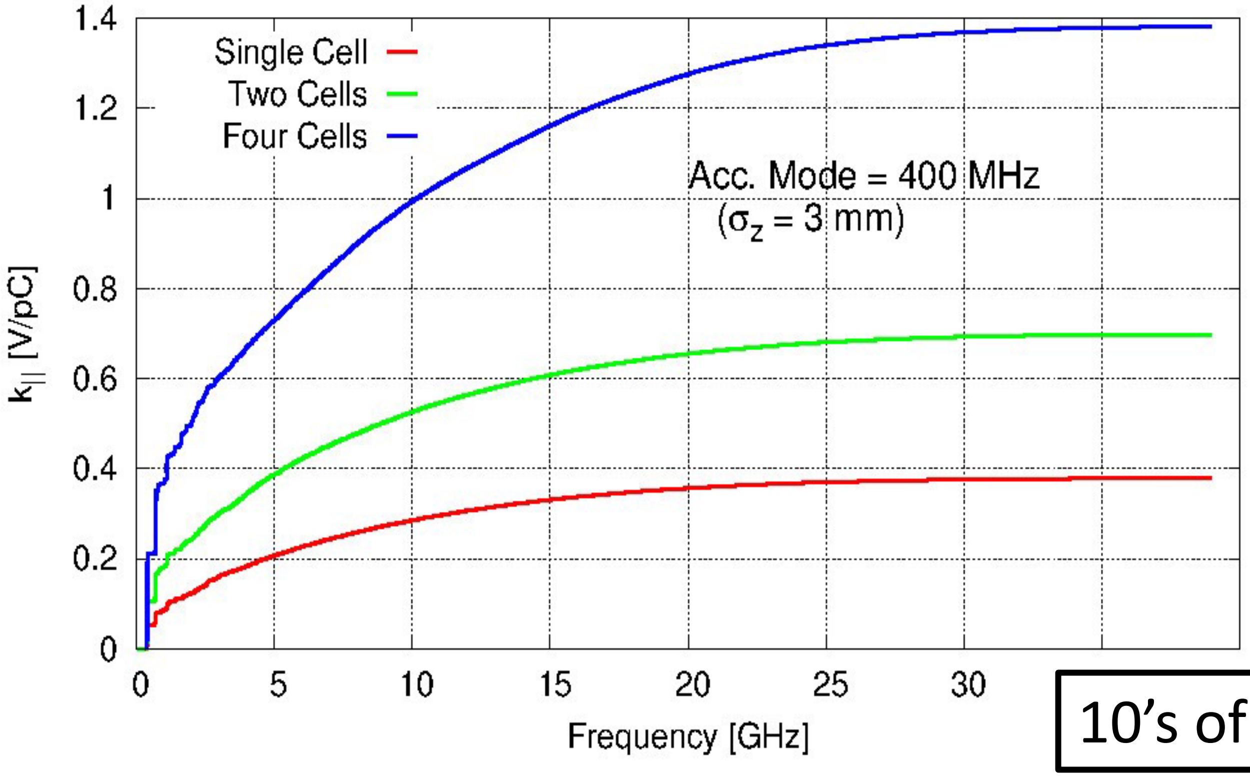
- Short bunches
- high bunch population
- high beam current

Longitudinal loss factors

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

1 V/pC ~42 kW of HOM power/cavity @ Z nominal

4-cell cavities starts to become unfeasible



1.38 V/pC → **58 kW/cavity**

0.65 V/pC → **27 kW/cavity**

0.38 V/pC → **16 kW/cavity**

10's of MW of HOM power

R. Calaga

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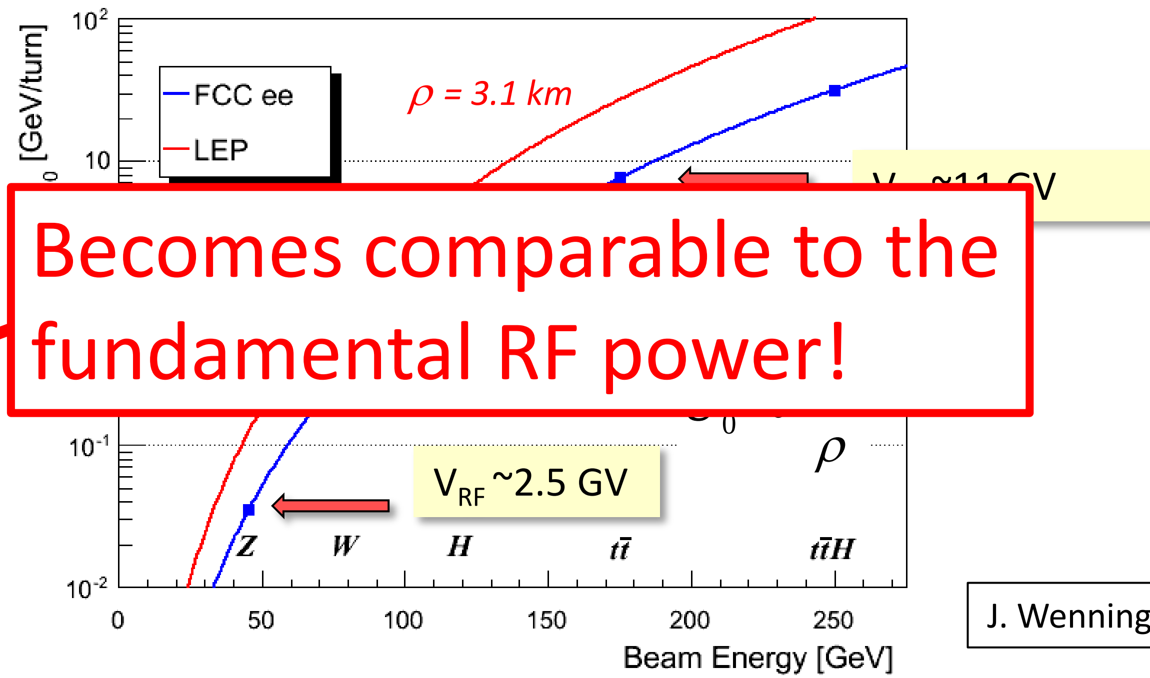


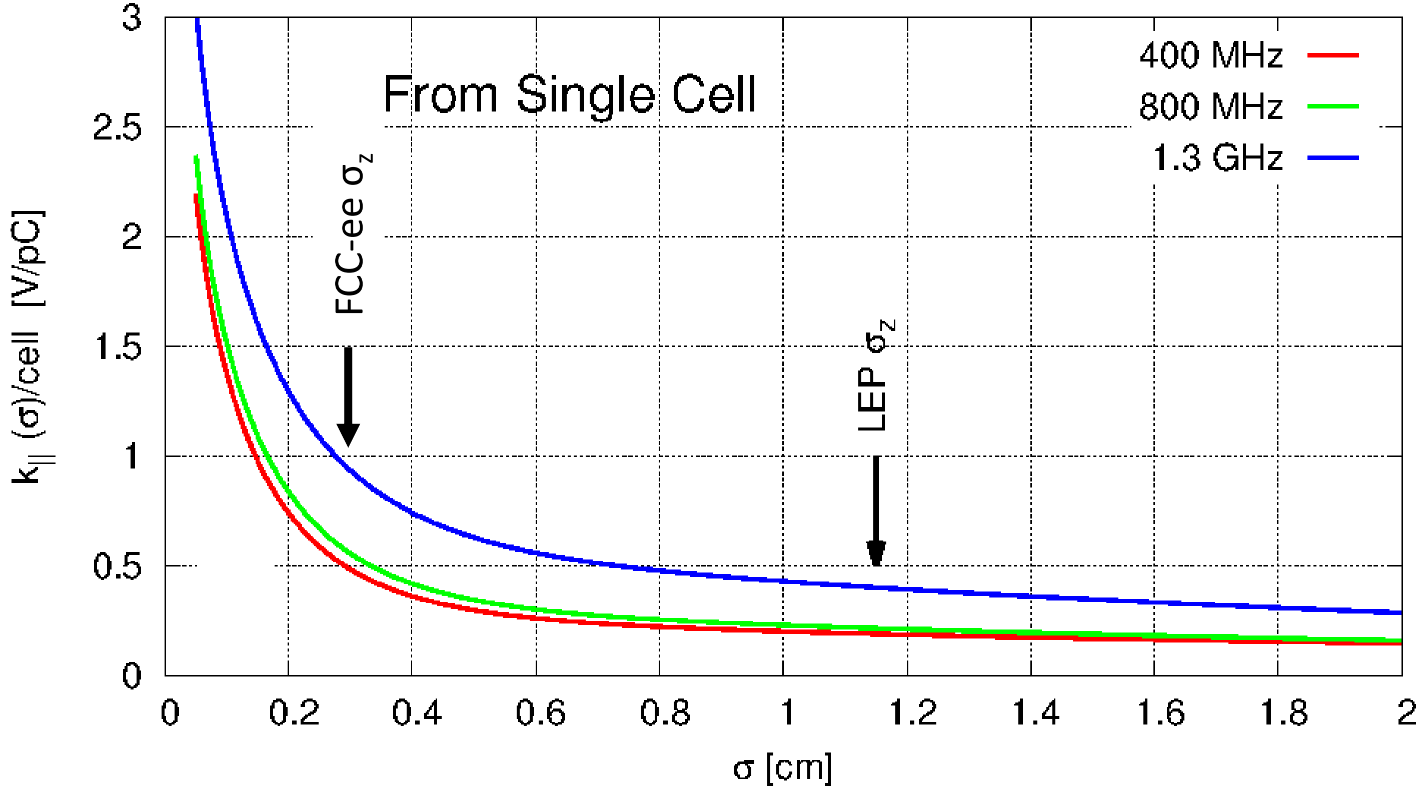
Becomes comparable to the fundamental RF power!

J. Wenninger

Loss factor vs. bunch length

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

Note: 1-cell ≥ 1 V/pC for < 2mm

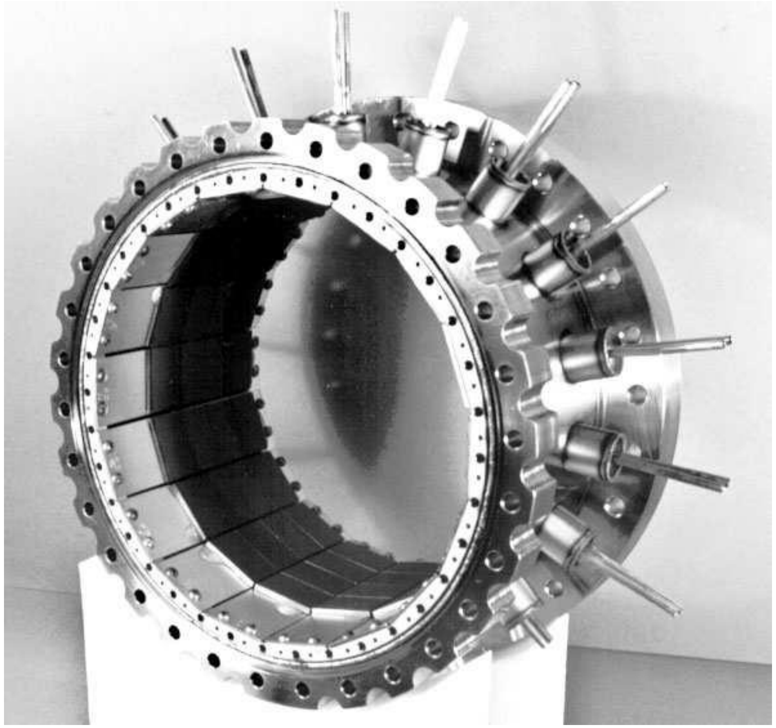


R. Calaga

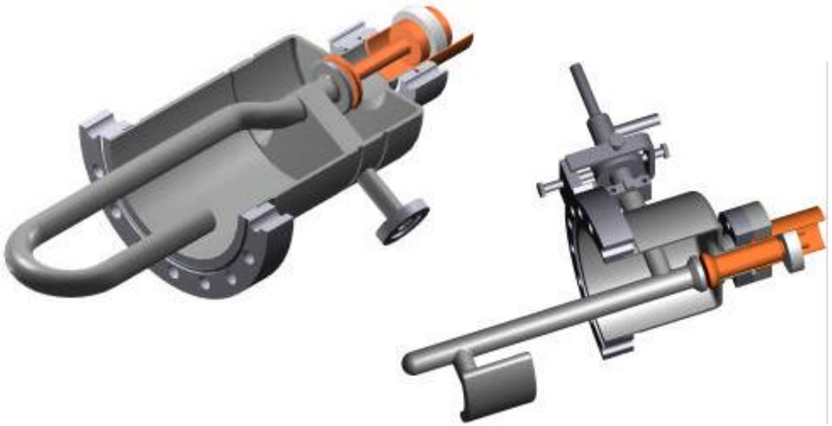
*Remember: 400 → 800 MHz: approx x1.5 increase in # of cells

HOM power extraction

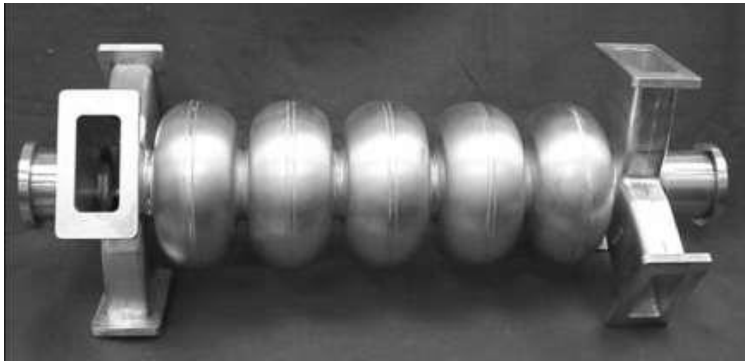
Cornell/KEKB like ferrites, 300K
~20 kW (approx 8°C/kW temp rise)



LEP/LHC like loops, 4.5K
~1 kW maximum

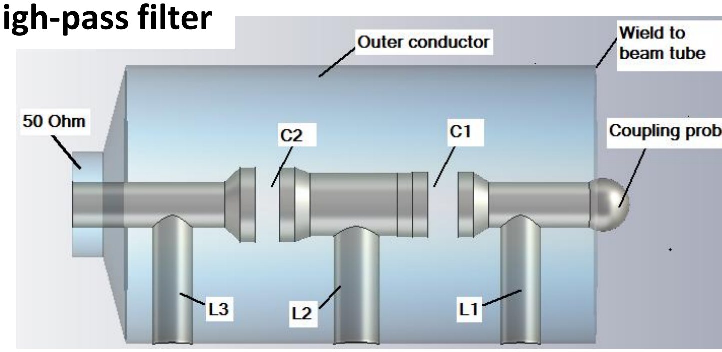


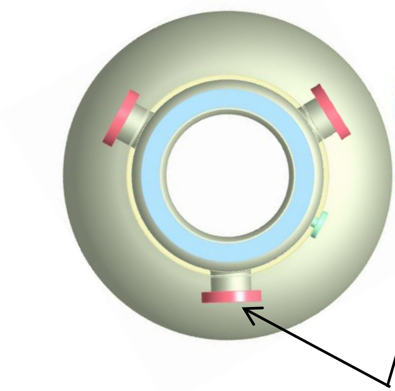
Waveguides

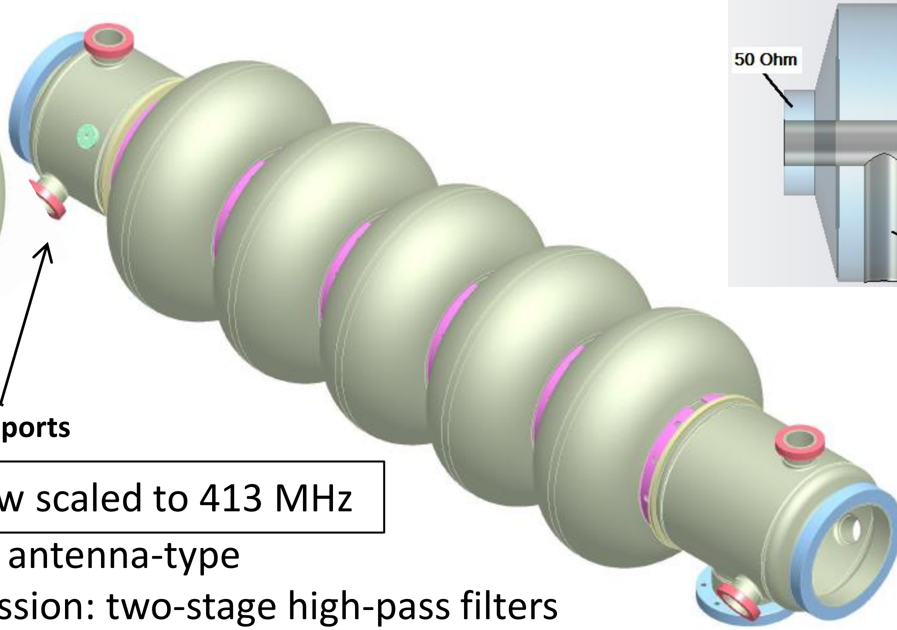


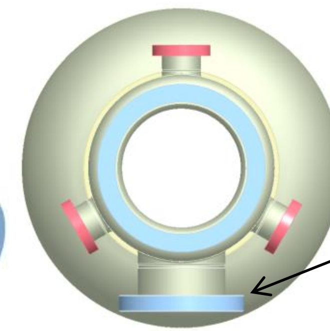
5-cell SRF cavity with strong HOM damping for eRHIC at BNL

HOM high-pass filter









HOM ports

FPC port

F = 703.5MHz

Now scaled to 413 MHz

HOM couplers: 6 of antenna-type

Fundamental supression: two-stage high-pass filters

E_{acc} = 20 MV/m

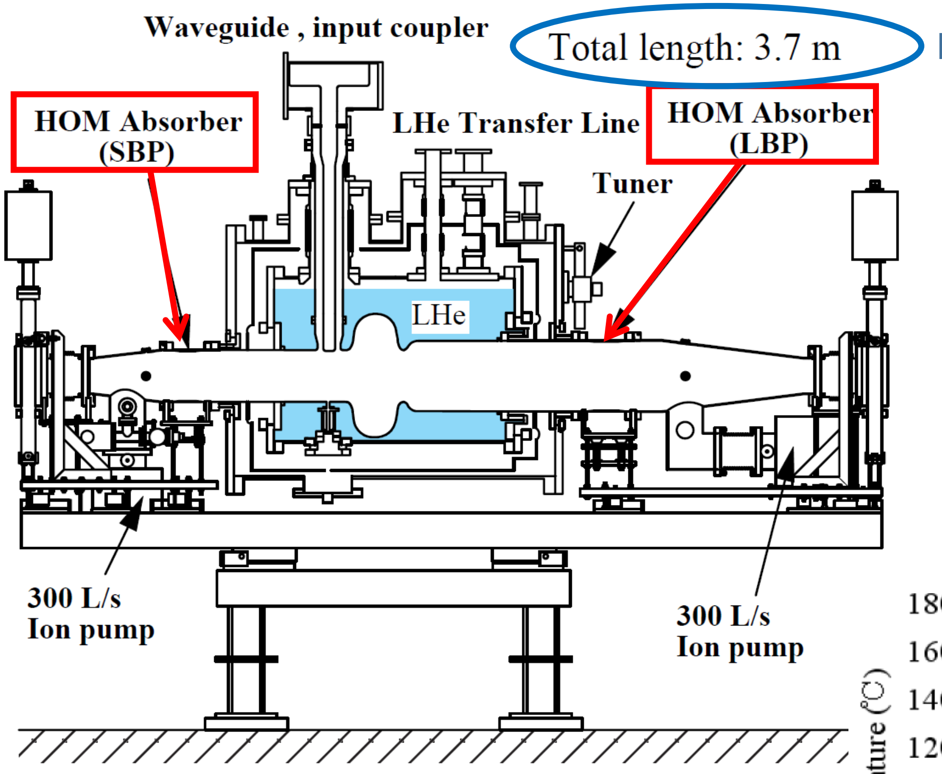
Design HOM power: 7.5 kW

- BNL3 cavity optimized for high-current applications such as eRHIC and SPL.
- Three antenna-type HOM couplers attached to large diameter beam pipes at each end of the cavity provide strong damping
- A two-stage high-pass filter rejects fundamental frequency, allows propagation of HOMs toward an RF load.

S. Belomestnykh later this morning

M. Tigner, G. Hoffstaetter, SRF2011, W. Xu et al, SRF2011

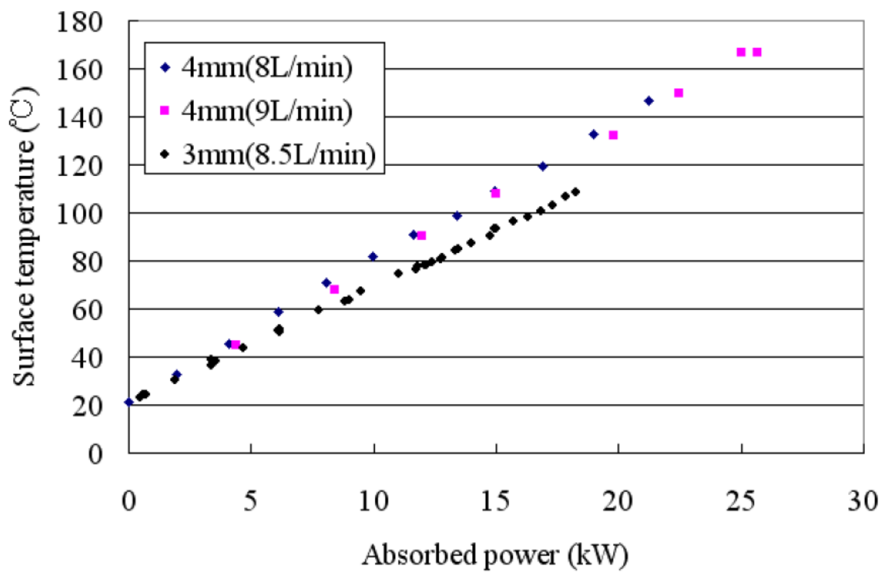
Warm beamline absorbers



x 1400 x 2 ≈ **10 km**

- 509 MHz single cell cavity
- Iris diameter 220 mm
- Ferrite HOM absorbers on both sides (outside cryostat)
- HOM power: 16 kW/cavity

KEKB SC cavity



Y. Morita et al., IPAC10, Kyoto

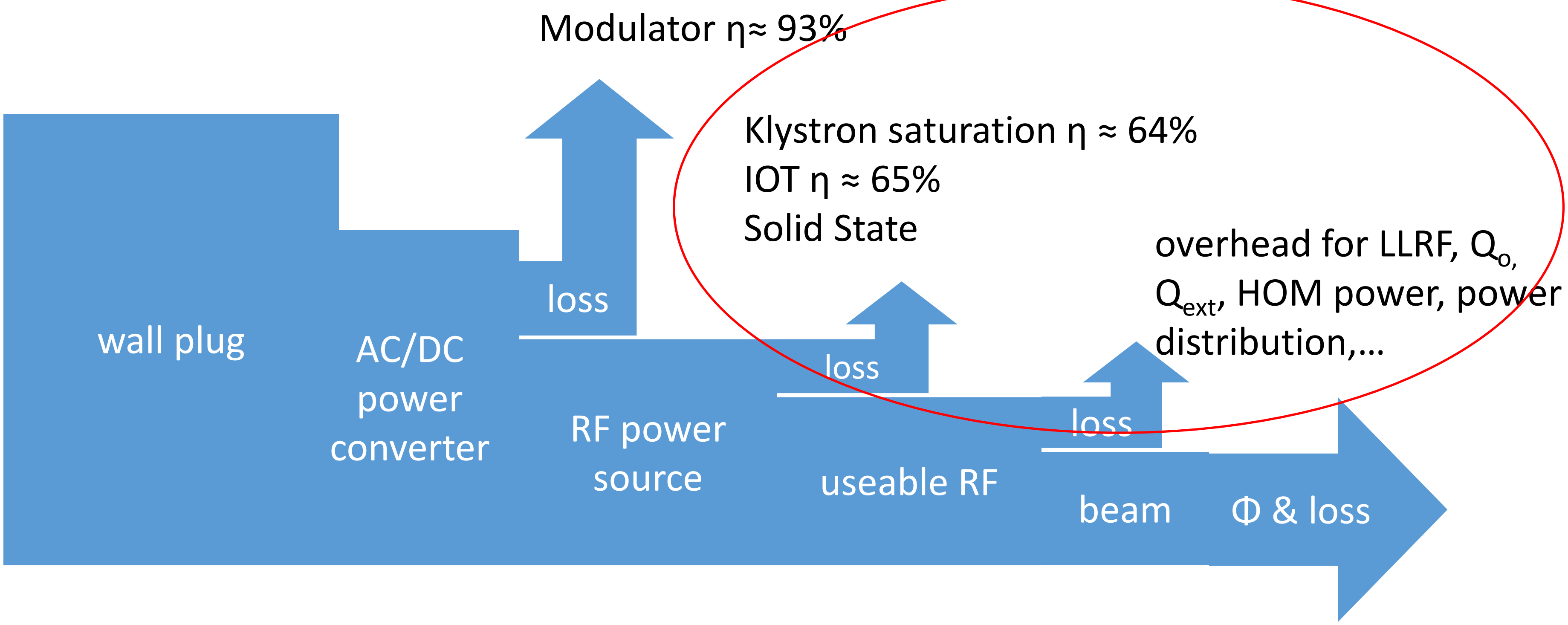
HOM power: summary

- HOM power may well be a severe limitation for the Z running (with the currently proposed beam intensity)
- R&D on cavities with low loss factors and strong HOM damping ?
- Design of compact warm absorber solution to avoid very long RF sections & minimize heat load due to cold/warm transitions ?
- In the last resort, what compromises are possible on the beam parameters ?

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

k_{loss}	Q	I_{beam}
increase bunch length	reduce bunch intensity	reduce number of bunches

Power source options - 1



The whole system must be optimized – not one efficiency alone

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

Power source options - 2

- ≈ 40 kW / cell (2cells cavities < 100kW) opens the way to different powering schemes
  - 1 klystron powering several cavities (long WG, power splitting, etc)
  - 1 solid state amplifiers
  - 1 IOT's
  - 1 tetrodes (or diacrodes)

  } per cavity

Need to consider the whole system and the actual point of operation

- Ideally:
  - Small
  - Highly Efficient
  - Reliable
  - With a low power consumption in standby or for reduced output power

3 talks this afernoon: G. Sharkov, C. Lingwood, M. Jensen

Conclusions

- Iterations are ongoing on RF scenarios and staging, choice of cavities and cryomodule layout, RF frequency and cryogenic temperature.
- The major challenges come from the requirements for both the highest possible accelerating voltage and very high beam currents with the same machine.
- HOMs will be a major issue for running at the Z pole, and will dictate to a large extent the RF system design.
- Variable Q_{ext} fundamental power couplers would seem to be desirable for energy efficiency
- Strong RF feedback will be necessary for Z pole running to suppress coupled bunch modes driven by the fundamental cavity impedance

R&D areas

- SRF cavity development: cavity design, coatings, Q_0 and max. gradient, Q-slope of Nb film cavities
- HOM damping systems: highly damped cavities, compact warm absorbers
- Production optimization
- Cryomodule design and assembly (including auxiliaries, tuner etc, mechanical stability, industrialization & production costs)
- Power generation and distribution, circulators, distribution schemas, klystrons vs IOTs and SS
- Power couplers, Q_{ext} range
- LLRF: Fast cavity feedbacks for coupled bunch modes. Cavity trip handling

Thank you for your attention!