The RF system for FCC-ee

A. Butterworth, CERN

Thanks to: O. Brunner, R. Calaga, E. Jensen, E. Montesinos, F. Zimmermann (CERN), U. Wienands (SLAC)

Outline

- FCC and the e^+e^- option
- FCC-ee requirements for operation at different beam energies (ZH, $t\bar{t}$, Z-pole …)
- RF in different FCC-ee operation modes:
  - Cavity options, layout and staging
  - Fundamental power & beam loading
  - Higher order mode power
- Top-up injection booster ring
- Conclusions

Future Circular Collider Study - SCOPE

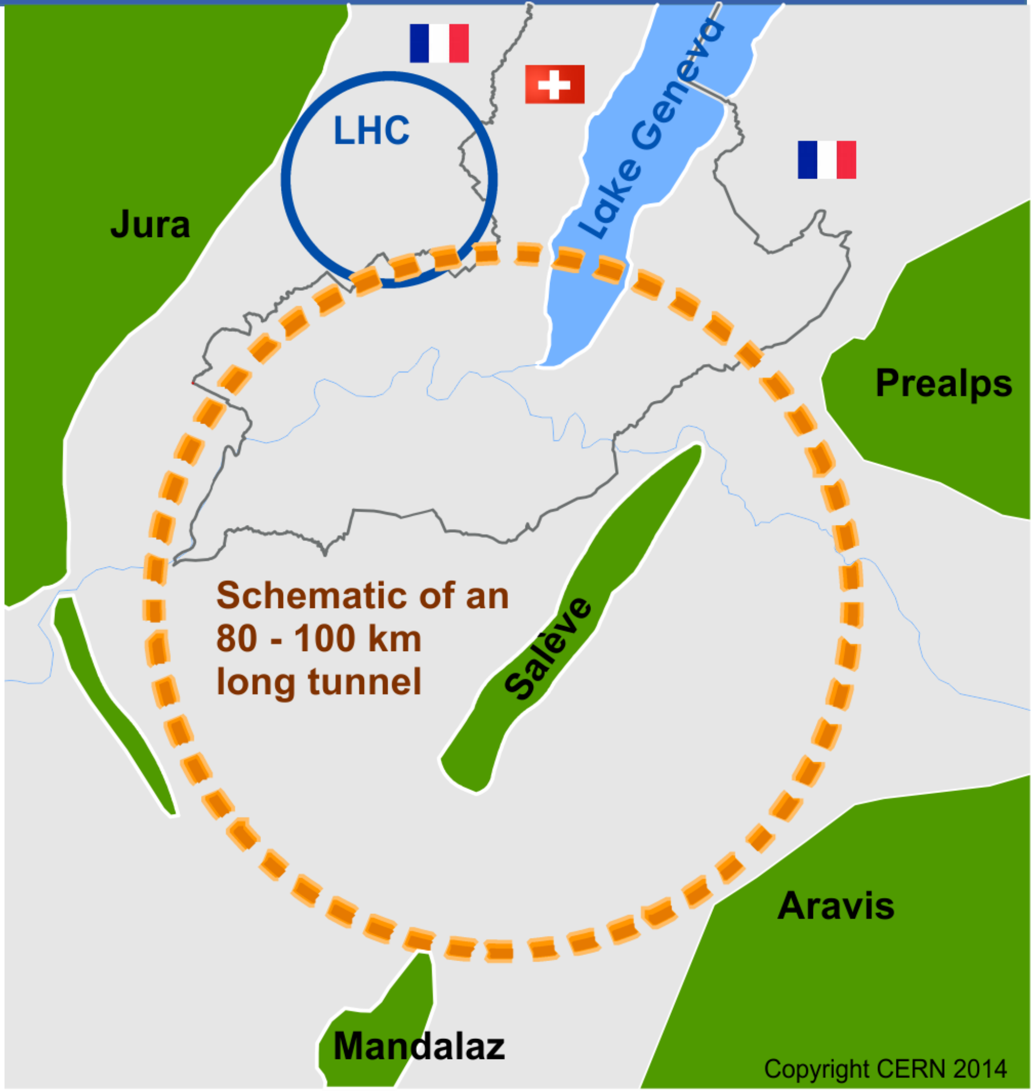
CDR and cost review for the next ESU (2018)

Forming an international collaboration to study:

- *pp*-collider (*FCC-hh*) → main emphasis, defining infrastructure requirements

~16 T ⇒ 100 TeV *pp* in 100 km

- 80-100 km infrastructure in Geneva area
- **e^+e^- collider (*FCC-ee*) as potential intermediate step**
- *p-e* (*FCC-he*) option



F. Zimmermann

Physics requirements for FCC-ee

- highest possible luminosity
- *beam energy range from 45 GeV to 175 GeV*

- main physics programs / energies:
  - *Z (45.5 GeV): Z pole, 'TeraZ' and high precision M_Z & Γ_Z,*
  - *W (80 GeV): W pair production threshold, high precision M_W*
  - *H (120 GeV): ZH production (maximum rate of H's),*
  - *t (175 GeV): $t\bar{t}$ threshold*

- optimized for operation at 120 GeV?! (2nd priority "*Tera-Z*")

F. Zimmermann

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

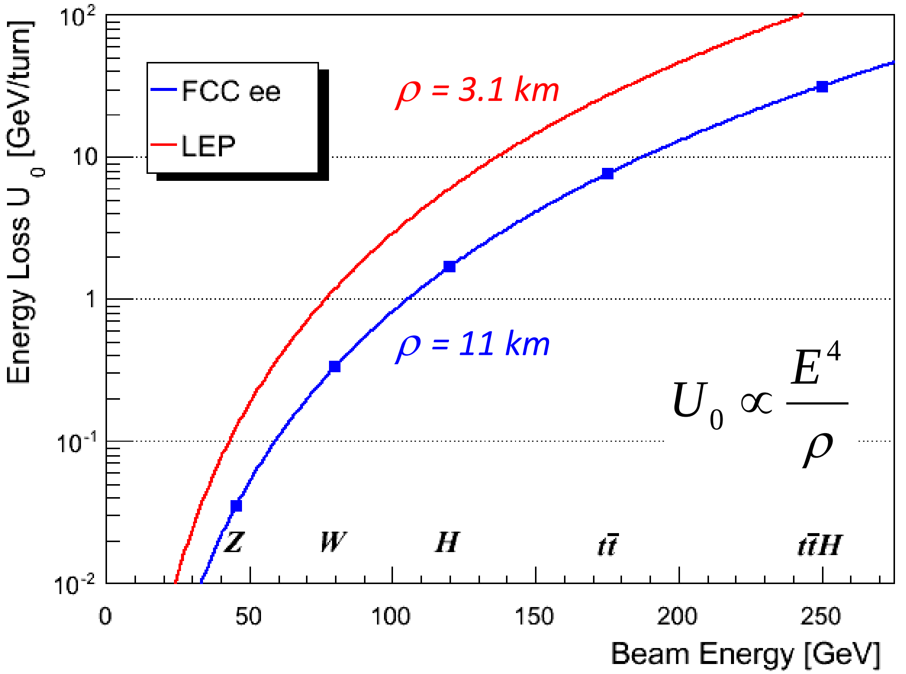
Total beam power limited to 50 MW (design choice)

↓

SR loss/turn (+ other losses)

↓

Defines maximum beam current at each energy



J. Wenninger

Cavity choice

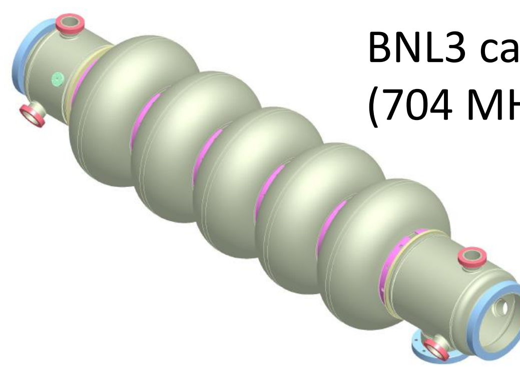
Baseline: SC cavities @ 400 and 800 MHz

- Main RF system at 400 MHz for lower energy/higher beam currents
- lower loss factors → HOM power (see later), transverse stability
- possibly Nb/Cu technology @ 4.5 K cf. LEP, LHC

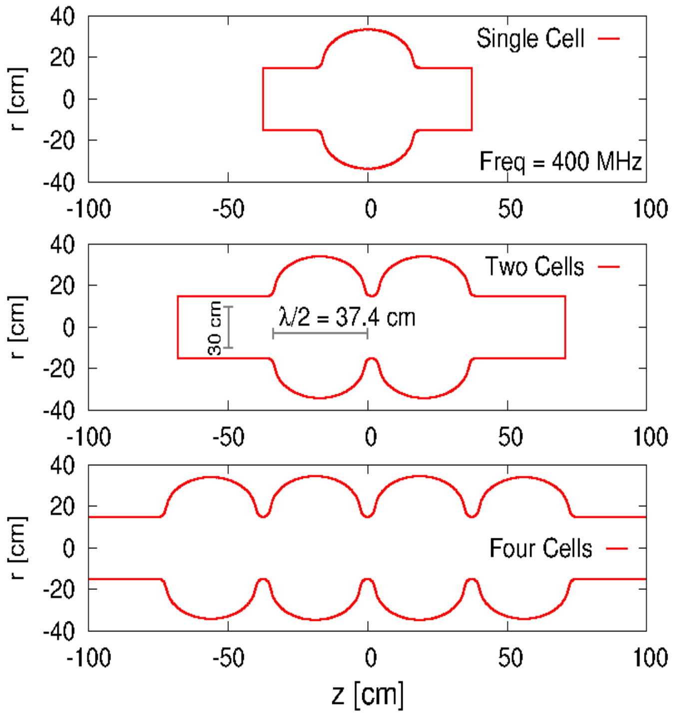
LHC cavities (400 MHz)

- Additional 800 MHz cavities to reach highest energy/lowest beam currents
- higher gradients (with bulk Nb @ 2K)
- higher loss factors → less interesting for high beam current operation

BNL3 cavity (704 MHz)



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

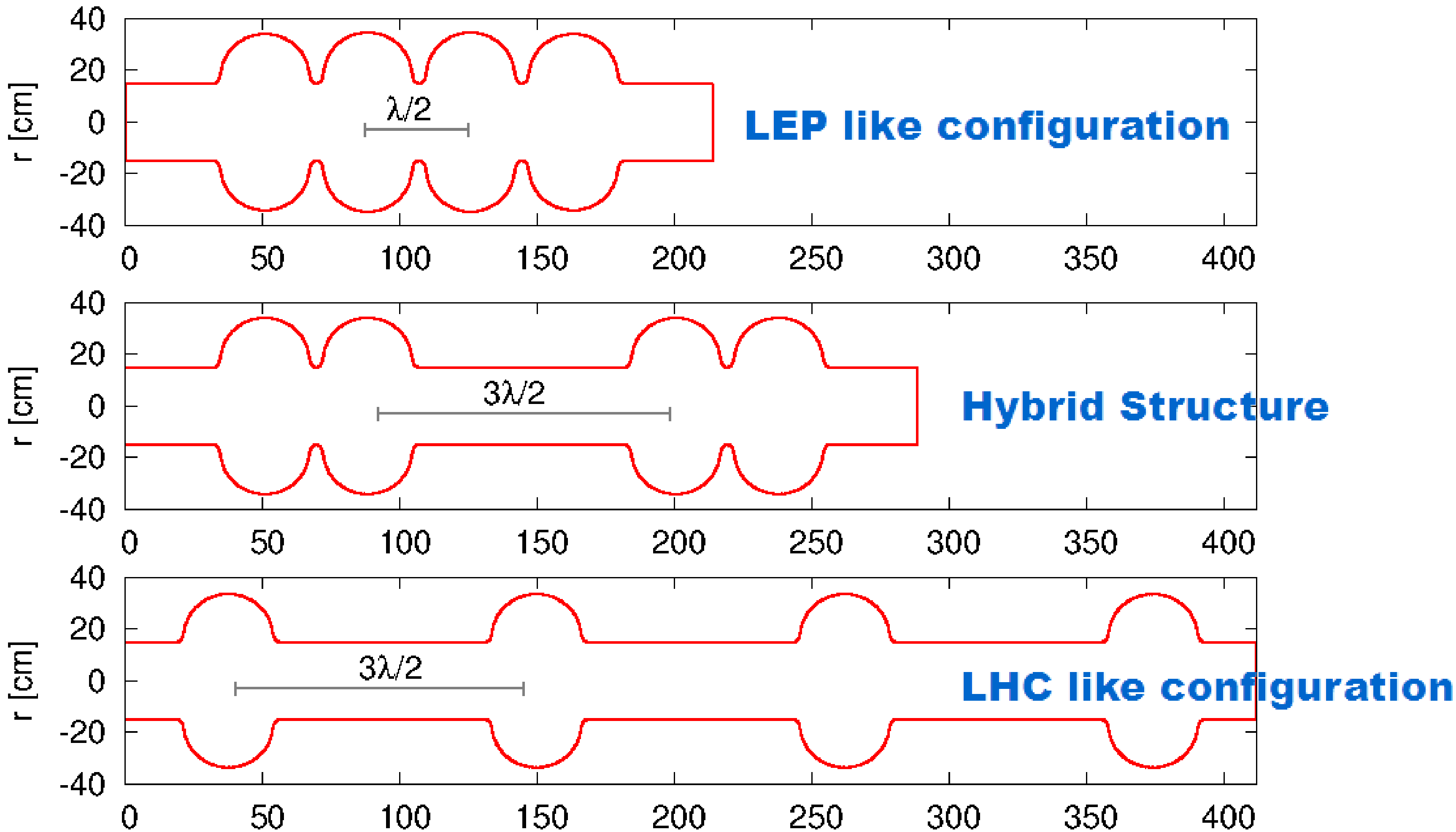
R. Calaga

- 400 MHz SC cavities with 1, 2 or 4 cells considered
  - 4 cells better for “real estate” gradient
  - Single cell has lowest HOM loss factor

  → 2 cells a compromise

Cryomodule layout options

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



Collaboration with Uni. Rostock: e.m. & thermal simulations

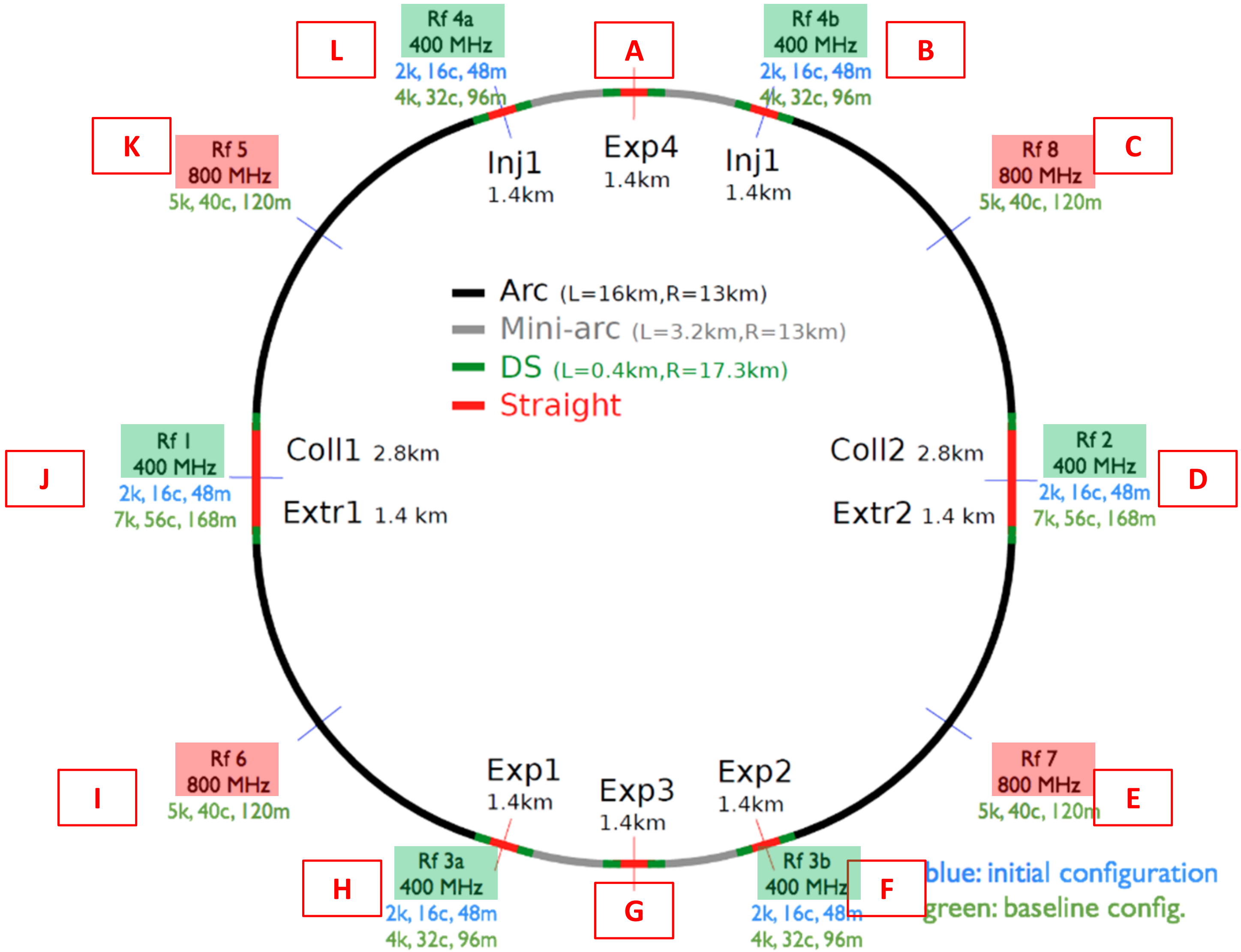
FCC-ee RF staging

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	**/cm^2/s**	**5.06E+034**	**1.53E+035**	
80 GeV (W running)					
	beam current	mA	36	90	150
	# bunches		1100	2700	4490
	Luminosity	**/cm^2/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	**/cm^2/s**	**4.89E+033**	**2.34E+034**	**5.09E+034**
175 GeV (t-tbar running)					
	beam current	mA			0.0065
	# bunches				98
	Luminosity	**/cm^2/s**			**1.43E+034**

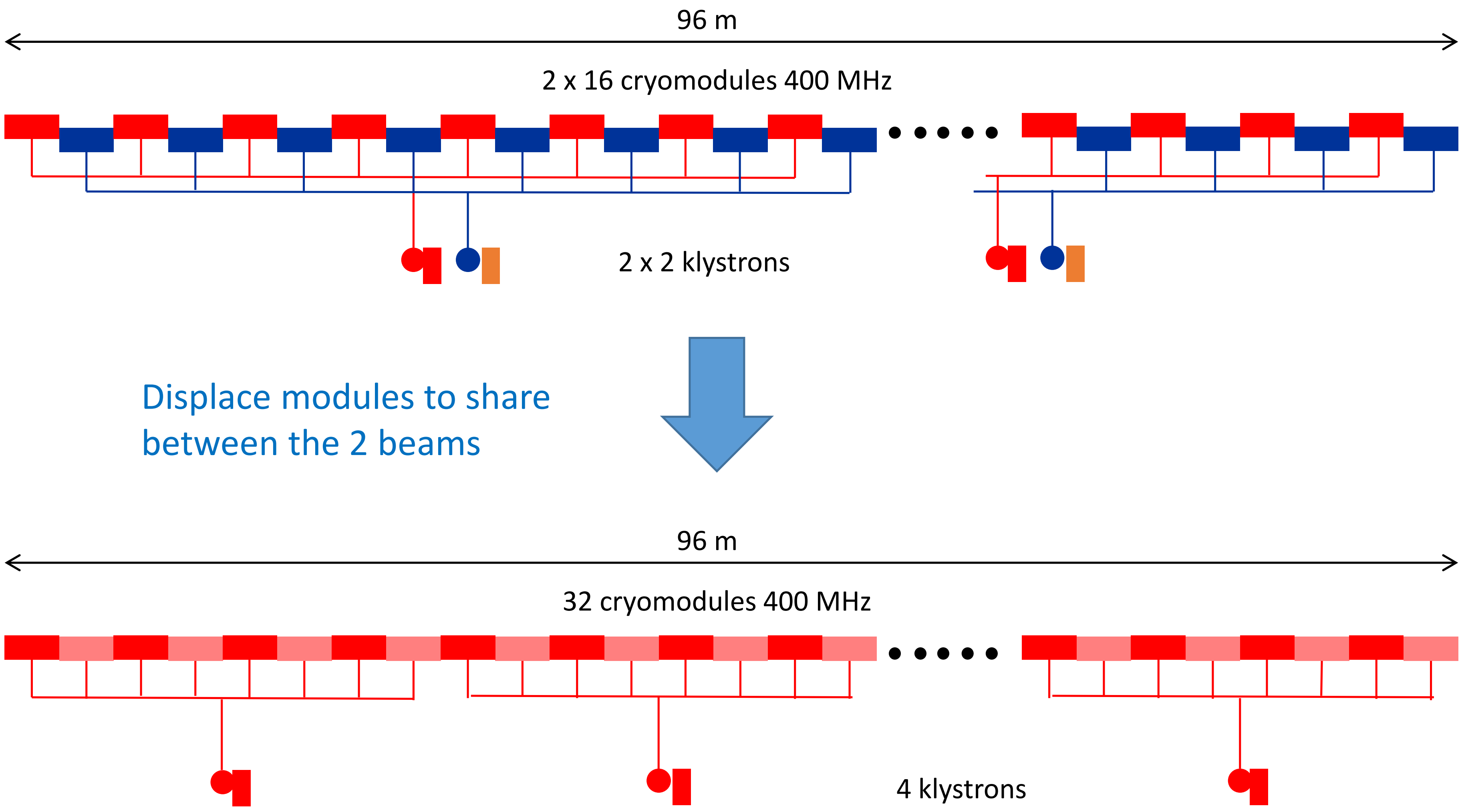
FCC-ee

RF layout (per ring)



blue: initial configuration
green: baseline config.

Alternative (400 MHz only) scenario



Fundamental 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)

Fundamental 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

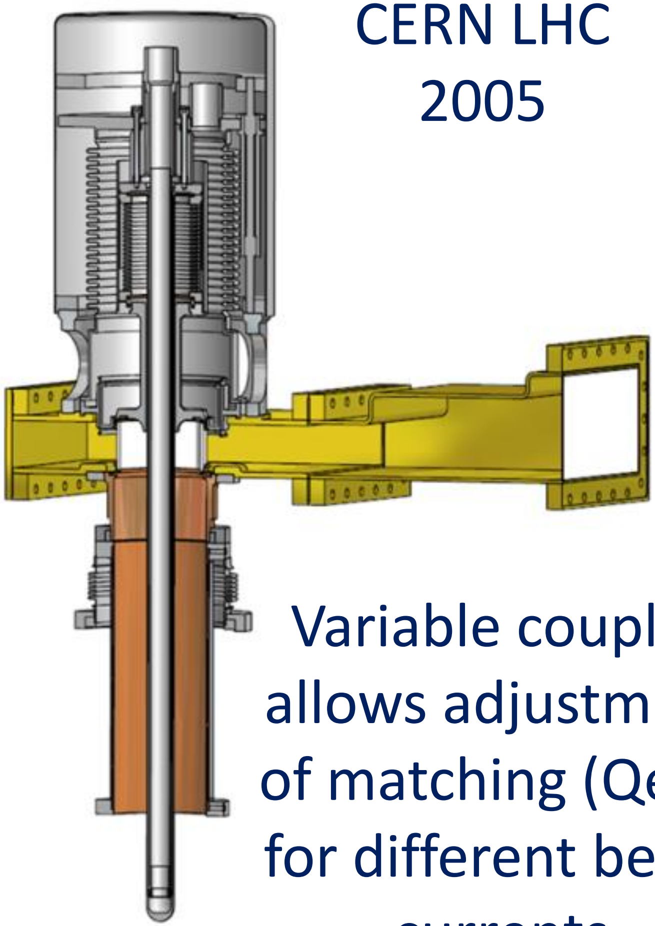
Q_0 [10e9]	3.0		
Heat load per cavity [W]	11.1	22.9	49.9
Total heat load per beam [kW]	16.3	16.8	18.3

Large detuning to compensate reactive beam loading

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

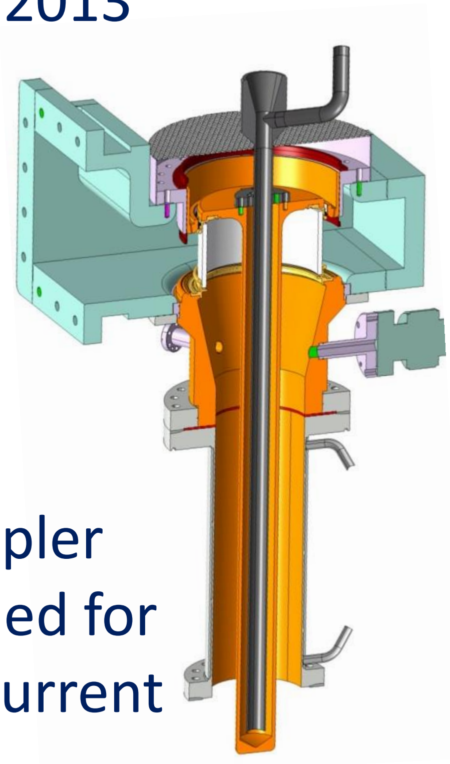
cf. revolution frequency 3 kHz
→ will need strong RF feedback to control coupled bunch modes

Power couplers: Fixed or variable?



CERN LHC
2005

Variable coupler allows adjustment of matching (Qext) for different beam currents



CERN SPL
2013

Fixed coupler Qext matched for one beam current only

E. Montesinos

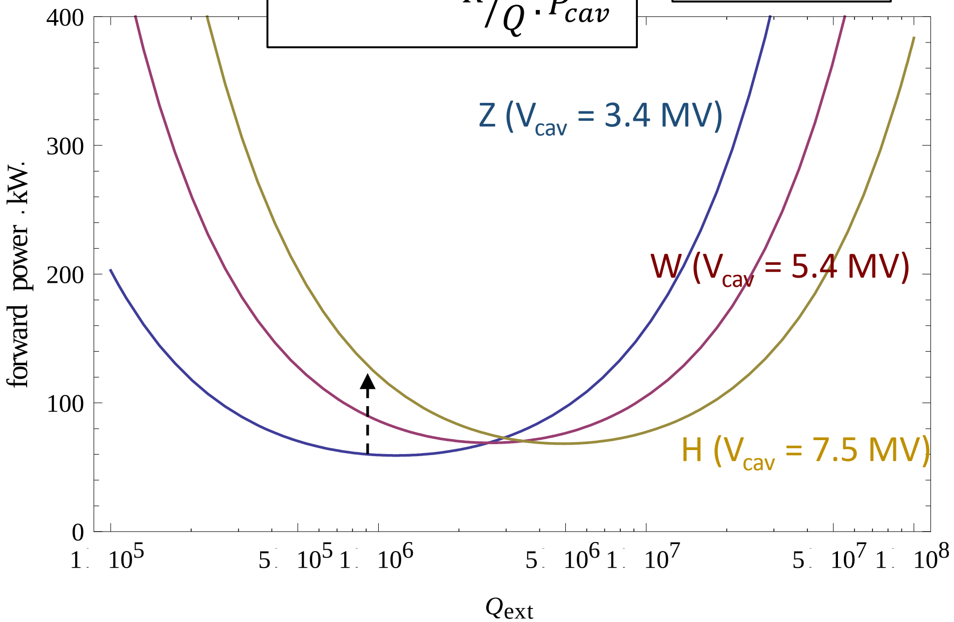
Power couplers: Fixed or variable?

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 x 10^6	2.6 x 10^6	5 x 10^6	5 x 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:

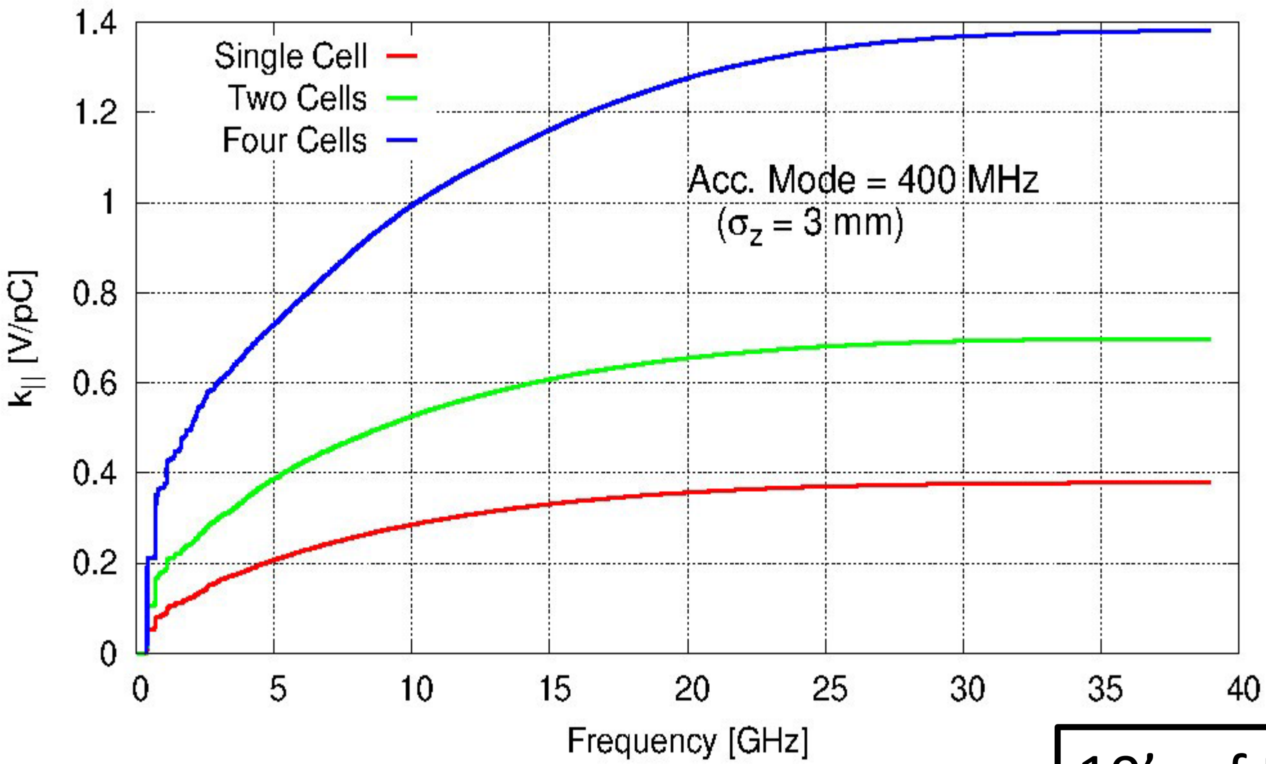
- Short bunches
- high bunch population
- high beam current

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

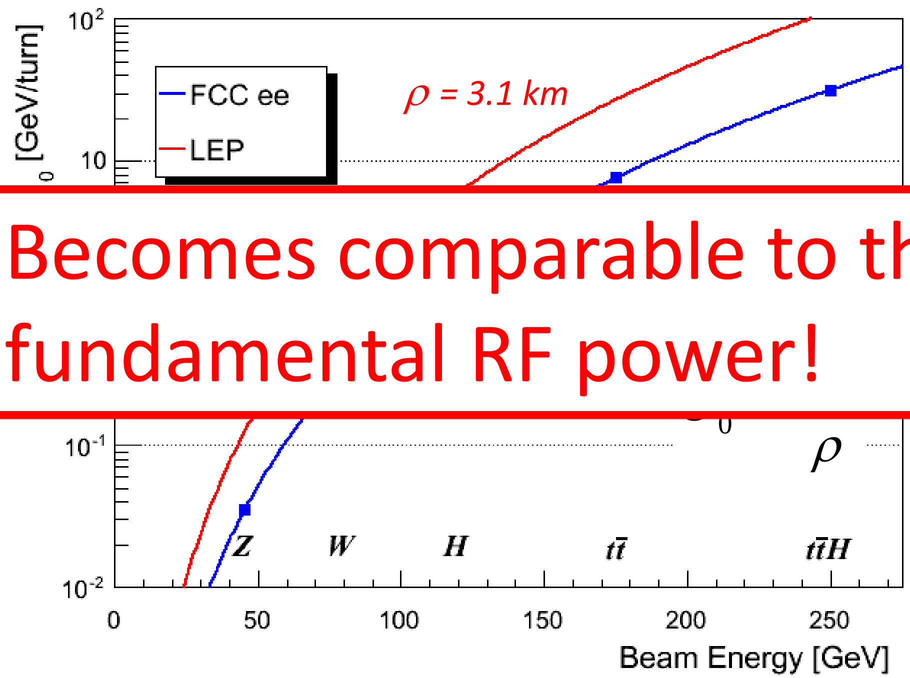
Dynamic range: energy vs. intensity

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 (+ other losses)

Defines maximum beam current at each energy



Becomes comparable to the fundamental RF power!

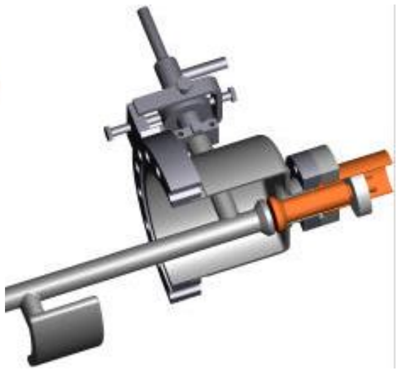
J. Wenninger

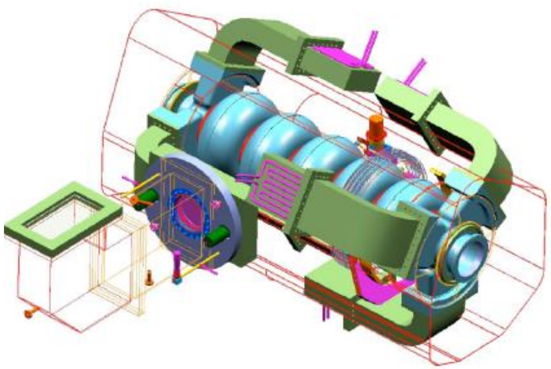
HOM power extraction

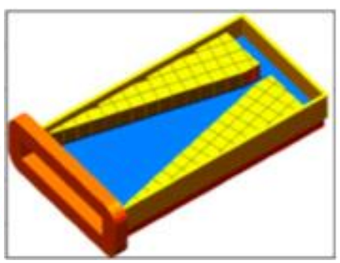
S. Belomestnykh

COLD

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



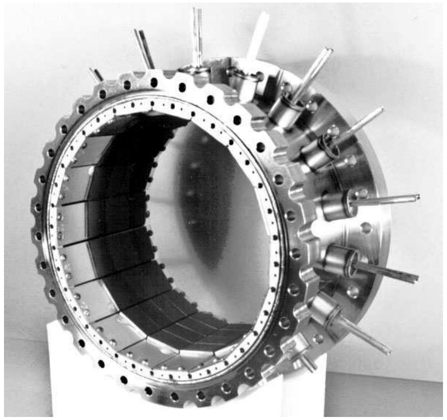


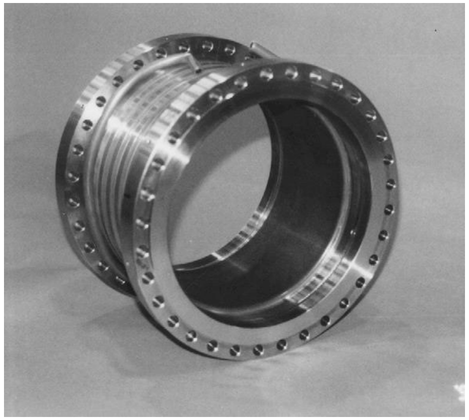


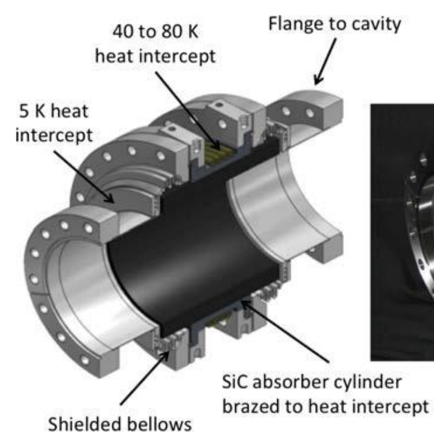
Jlab
Waveguide
HOMs
~30 kW

WARM

Cornell/KEKB like ferrites, 300K
~20 kW (approx 8^{0}C/kW temp rise)

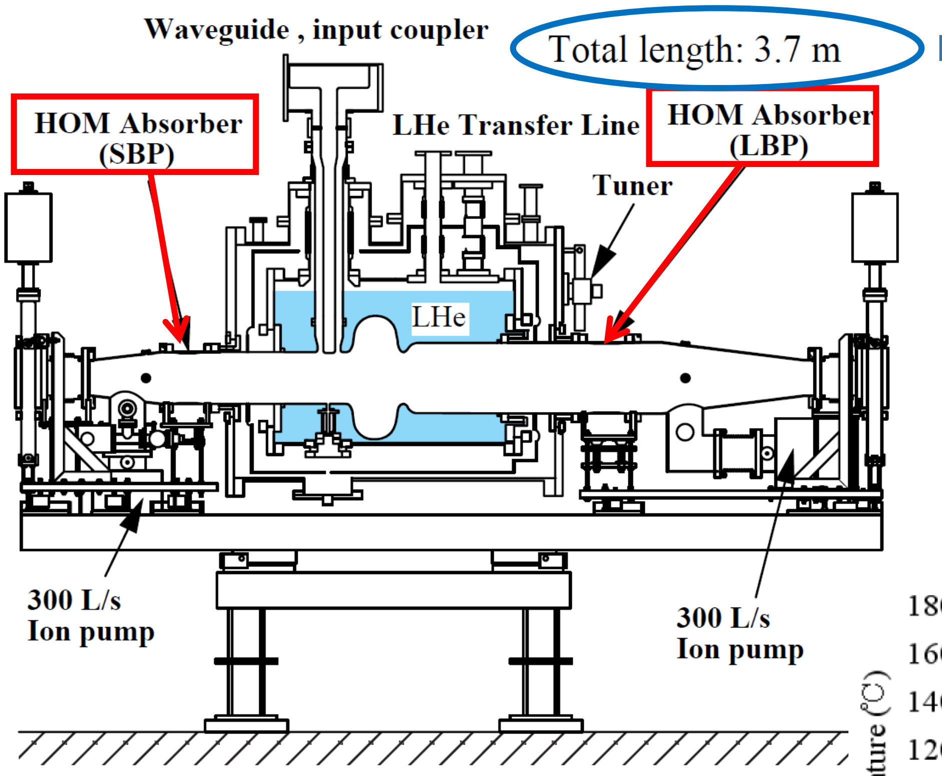






Cornell ERL

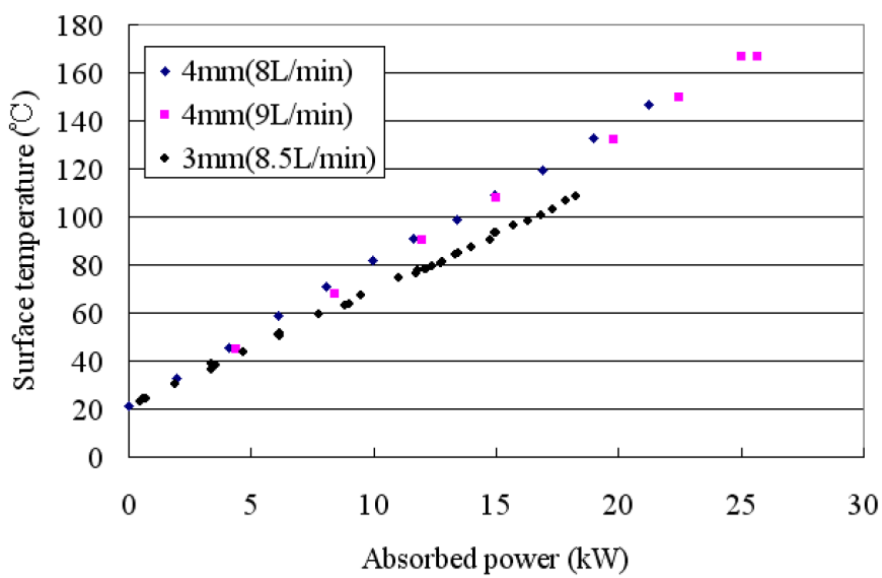
Warm beamline absorbers



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

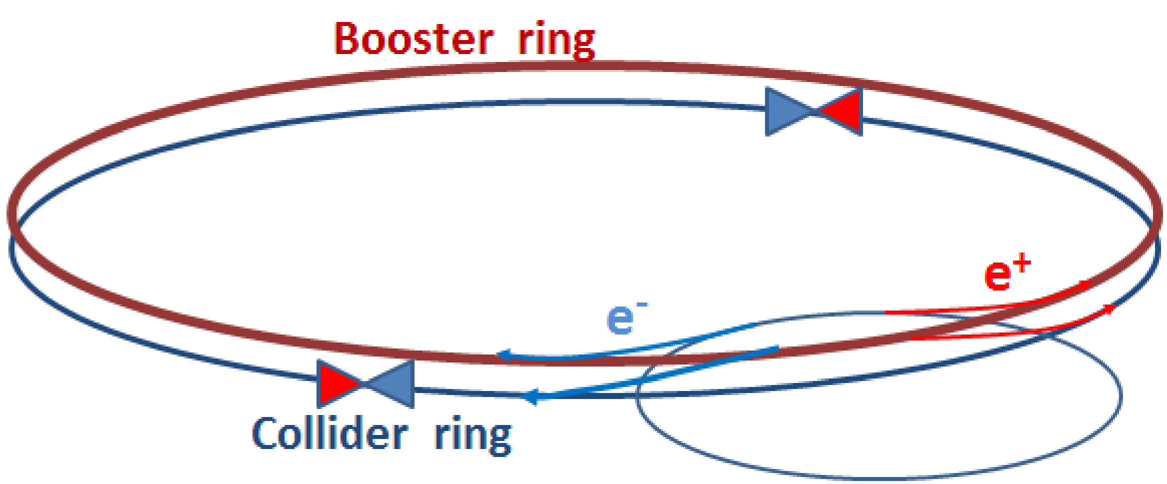
KEKB SC cavity



Y. Morita et al., IPAC10, Kyoto

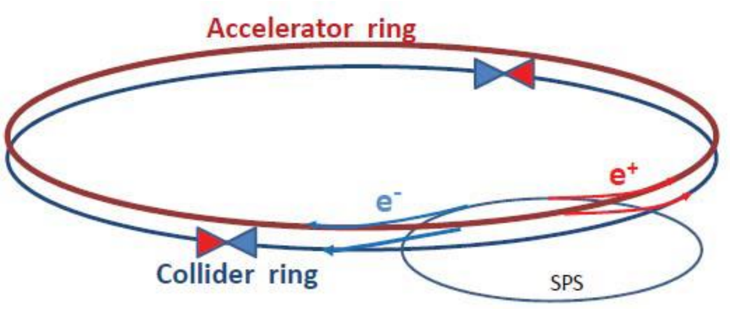
Top-up injection booster ring

- Top-up injection is essential because of very short luminosity lifetime (τ ≈ 21 min @ 120 GeV)
- Beside the collider ring(s), a booster of the same size (same tunnel) must provide beams for top-up injection
  - Repetition < 0.1 Hz
  - Top-up injection frequency < 0.05 Hz (one booster filling two rings)
  - booster injection energy ~20 GeV
  - bypass around the experiments



Top-up injection booster ring

- Beam current ~ 1% of collider ring
  - SR power very small, ~ 0.5 MW
  - HOM power very small
- Peak power is dominated by ramp acceleration:
  - for a 1.6 second ramp length:



	Z	H	tt
Beam current [mA]	14.5	0.3	0.054
Energy swing [GeV]	25.5	100	155
Acceleration power [MW]	231	18.8	6.4
Max. power per cavity [kW]	814	66	22,5

Well within our 200 kW budget for H and tt
Large for Z → intensity/ramp rate limit

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.
  - 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
- 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

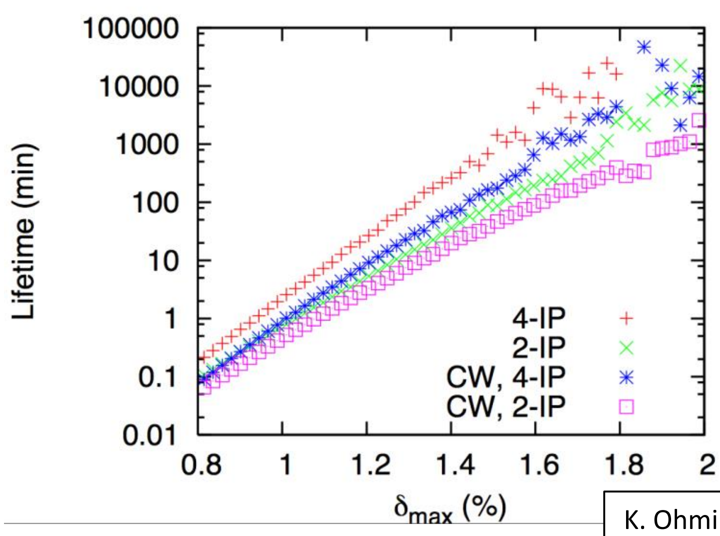
Thank you for your attention!

Spare slides

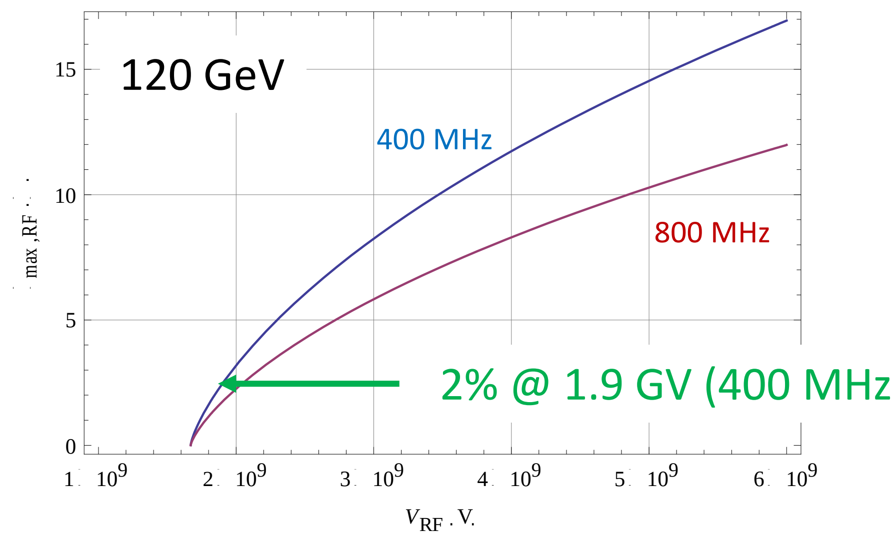
Beamstrahlung

- 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

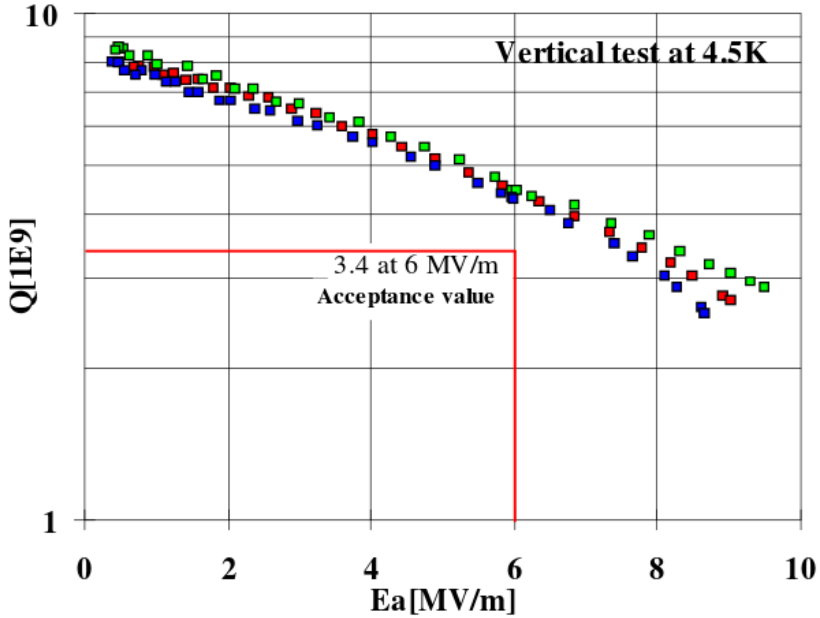


K. Ohmi

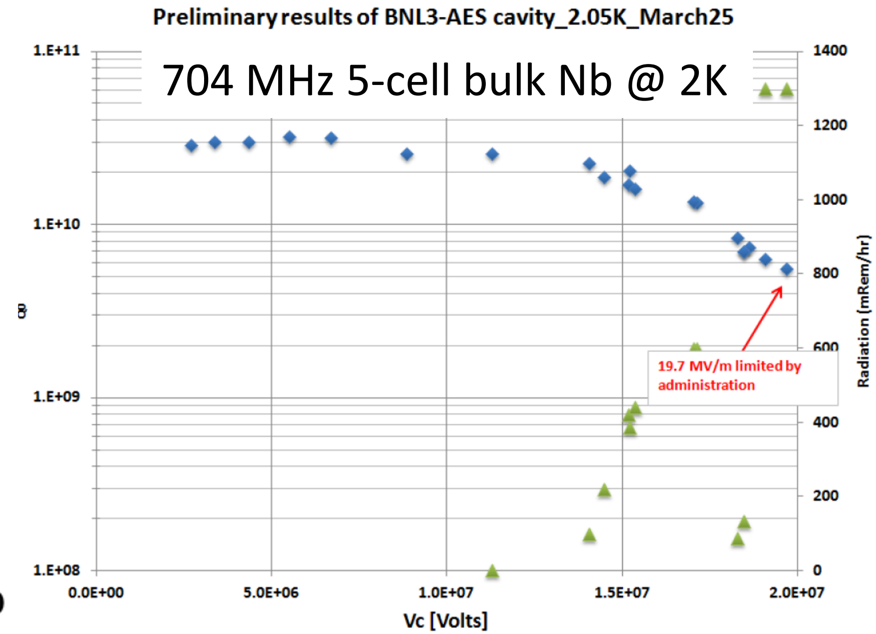


400 vs 800 MHz, 4.5 vs 2K

LEP2 352 MHz 4-cell Nb film @ 4.2K



E. Chiaveri, EPAC96



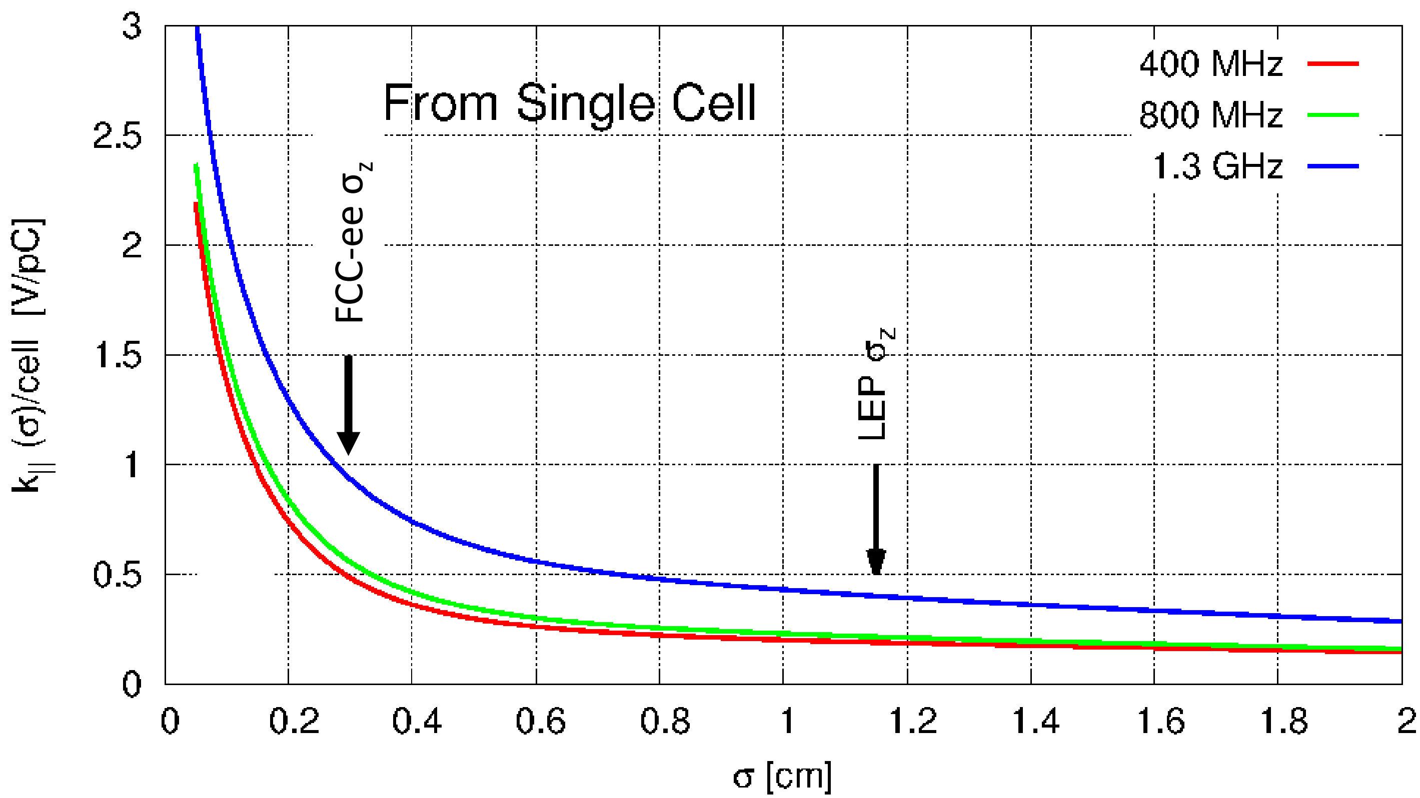
Xu et al. LINAC2014

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

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



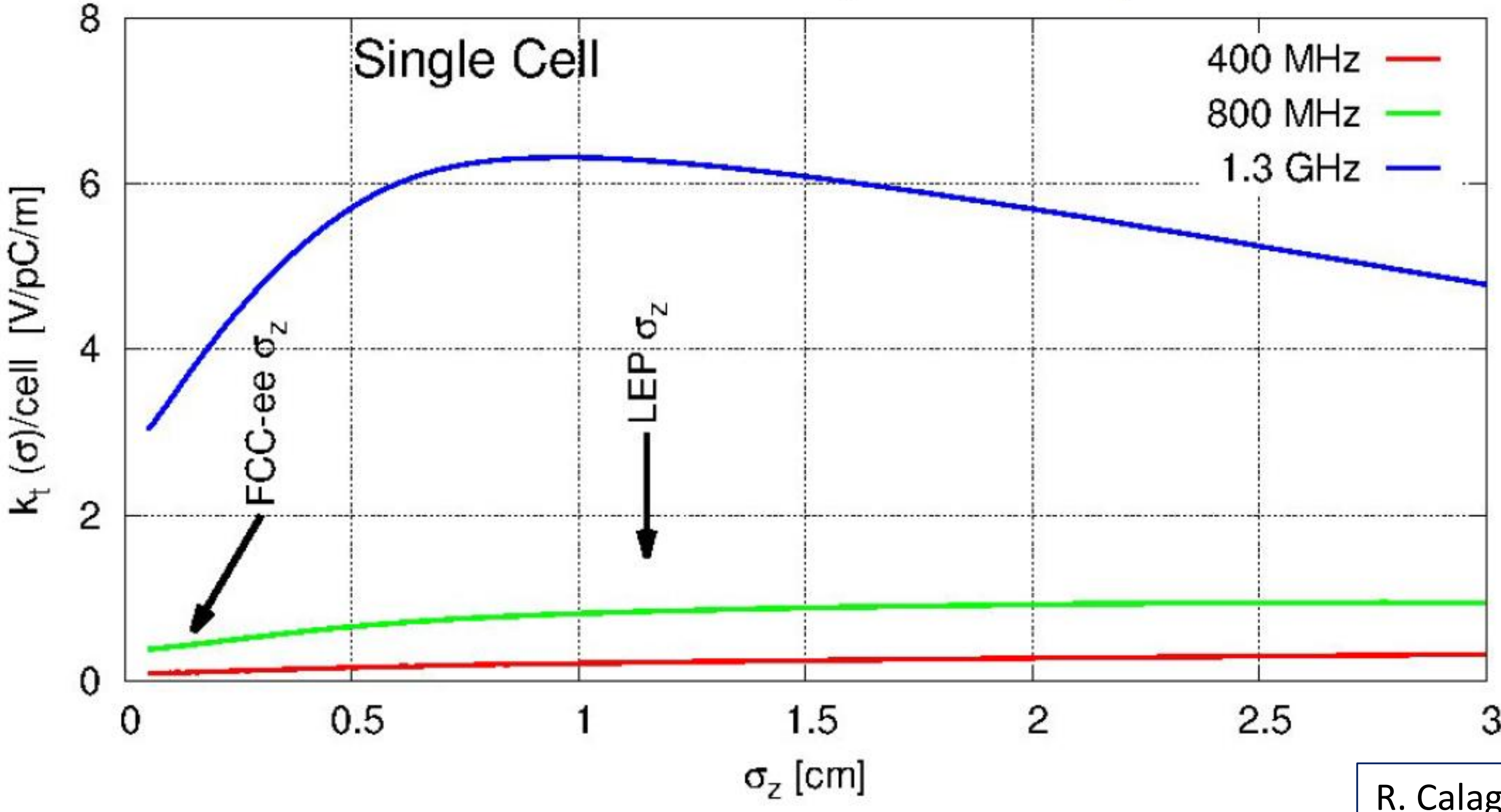
R. Calaga

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

Transverse loss factor vs. bunch length

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

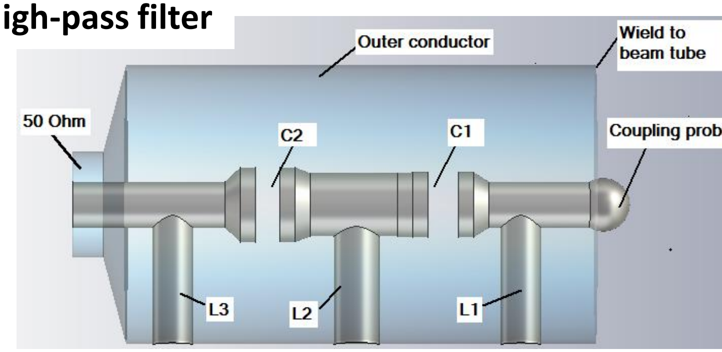
Limiting factor for transverse instabilites. 400 MHz with large aperture is clearly beneficial

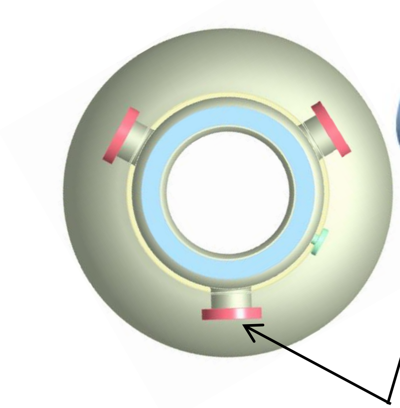


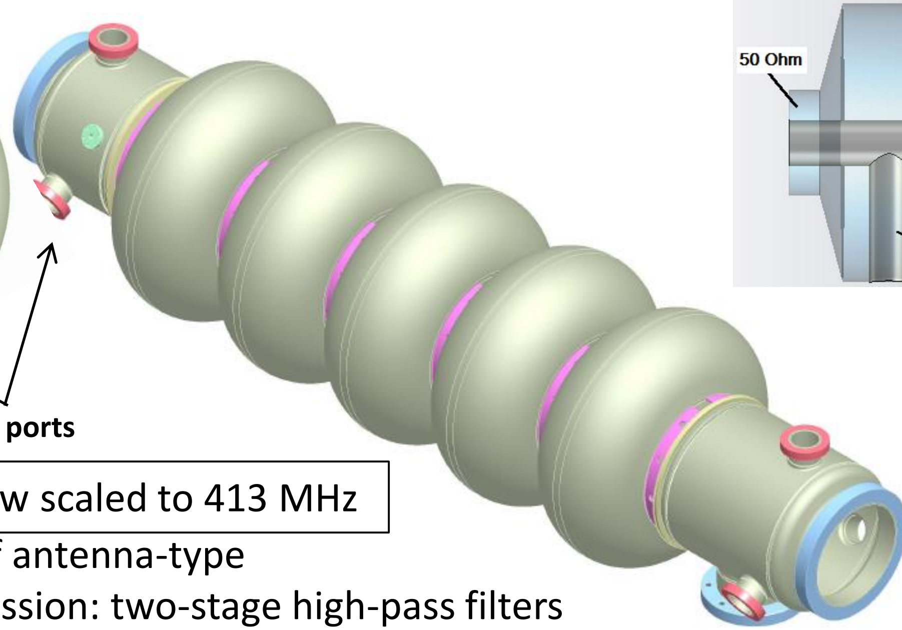
R. Calaga

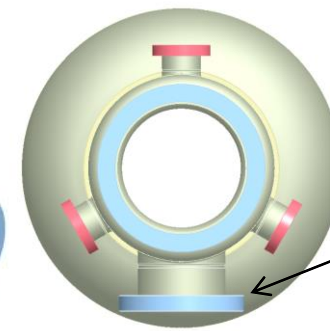
5-cell SRF cavity with strong HOM damping for eRHIC at BNL

HOM high-pass filter









F = 703.5MHz

Now scaled to 413 MHz

HOM couplers: 6 of antenna-type

Fundamental supression: two-stage high-pass filters

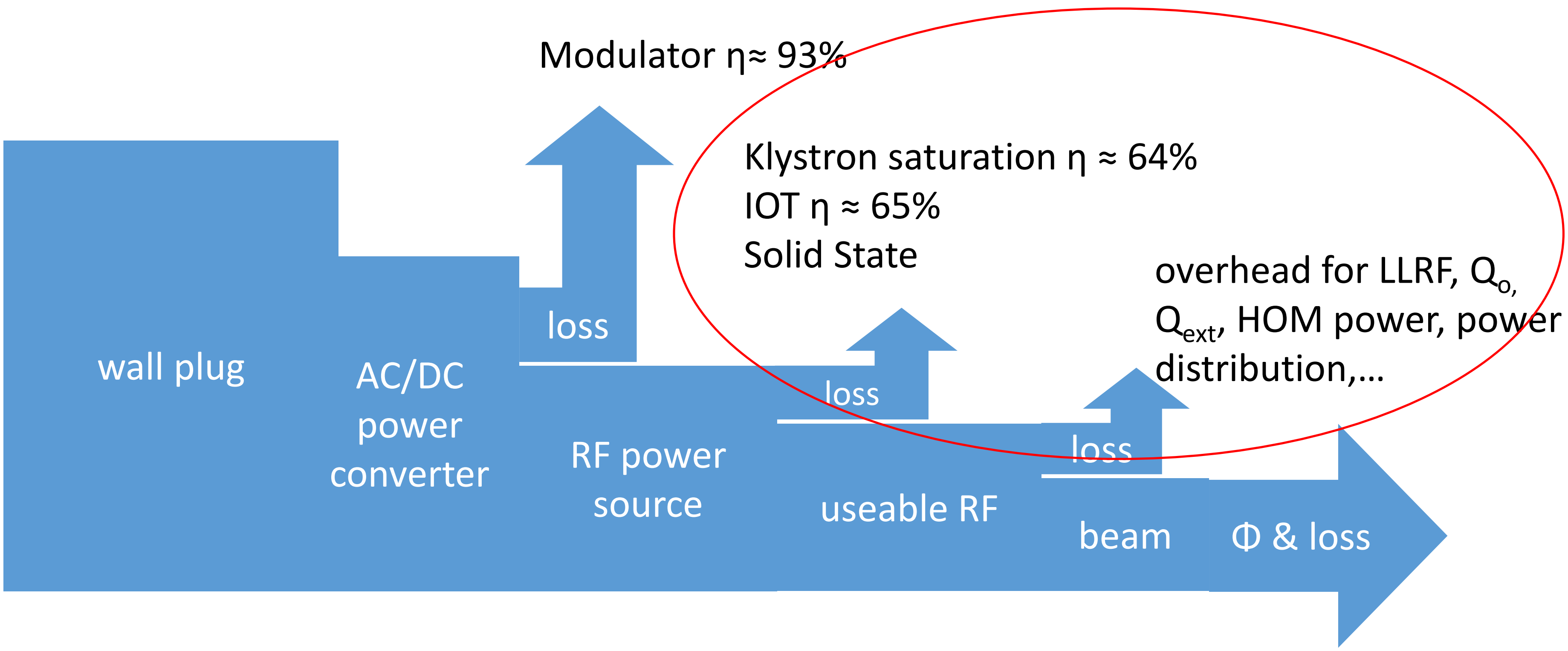
E_{acc} = 20 MV/m

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.

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

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