RF system for TLEP

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Thanks to E. Ciapala, R. Calaga, E. Montesinos, O. Brunner,
P. Baudrenghien, S. Claudet, D. Nisbet

4th TLEP3 Workshop 05.04.2013

Overview

- RF requirements
  - total accelerating voltage
  - beam power
- Technology
  - Cavities
  - Power couplers
  - Higher order mode damping
  - Power sources and efficiency
  - Low level RF & feedbacks
- Conclusions

RF requirements: voltage

- replace the energy lost U_0 at each turn by synchrotron radiation
  - total power needed by the beam = $U_0 \times I_{\text{beam}}$

$$P_{SR} = \frac{ec}{6\pi\varepsilon_0} \cdot \frac{\gamma^4}{\rho^2} \cdot \frac{I_b}{f_{rev}}$$

Strongly dependent on beam energy

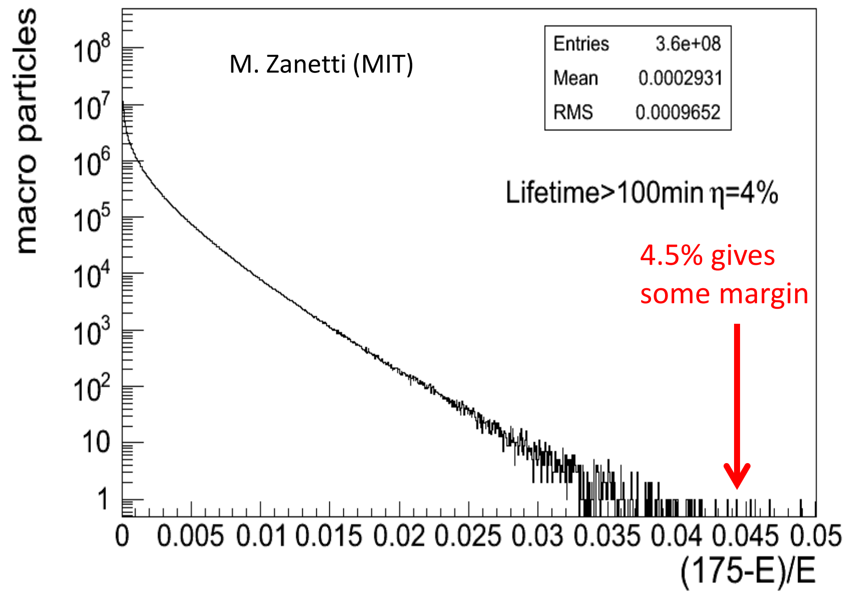
- maintain longitudinal focusing with sufficient momentum acceptance $|\delta|_{\text{max,RF}}$ to keep a good beam lifetime, given
  - the equilibrium energy spread due to quantum excitation/radiation damping (quantum lifetime)
  - the energy spread (tail) due to beamstrahlung

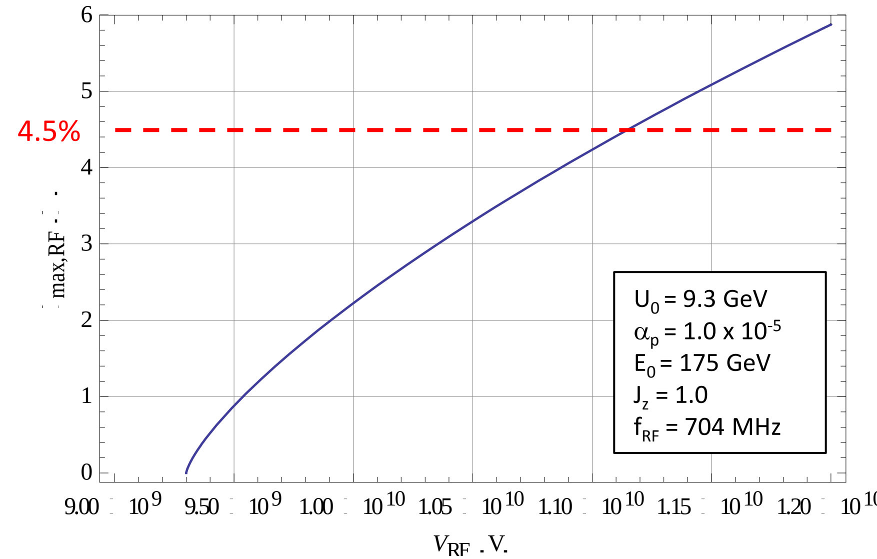
RF voltage TLEP (704 MHz)

RF voltage requirement is defined by:

- Accelerator ring: acceptable quantum lifetime (very steep function of V_{RF})
- Collider ring: momentum acceptance needed to cope with beamstrahlung
  - 3.0% for TLEP @ 120 GeV
  - 4.5% for TLEP @ 175 GeV

Energy [GeV]	V_{RF} [GV] for τ_q = 100h	V_{RF} [GV] for $\delta_{max,RF}$
120	**2.2**	**2.7**
175	**9.7**	**11.2**





$|\delta|_{max,RF}$ vs V_{RF}

General considerations

- RF frequency:
  - higher is better, for short bunch length (hourglass effect)
  - but higher frequency components limited in power handling

Good choice: 720 MHz or 802 MHz!

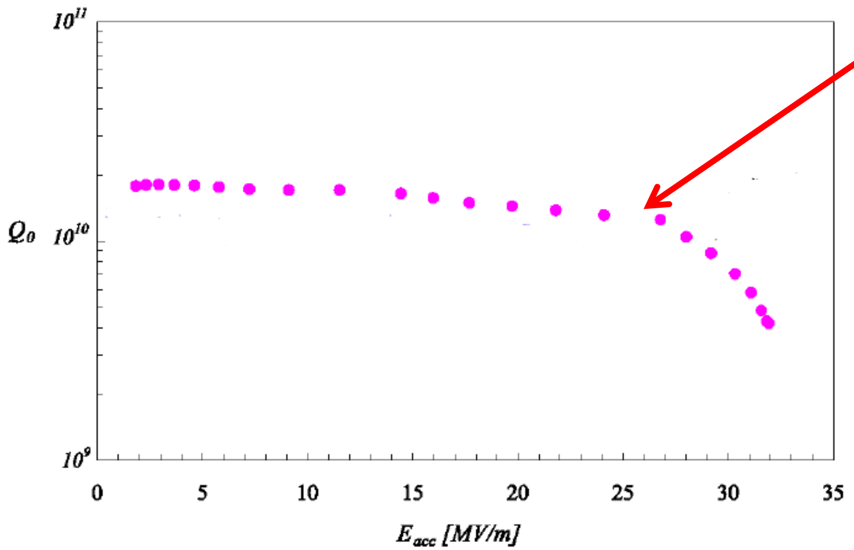
- Gradient:
  - higher is better: space, cost
  - but tradeoff with cryogenic power

Gain linearly on number of cavities

Power dissipation = $\frac{V_{cav}^2}{Q_0(R/Q)}$

But lose quadratically on power dissipation per cavity

Also lose because of decrease in Q_0

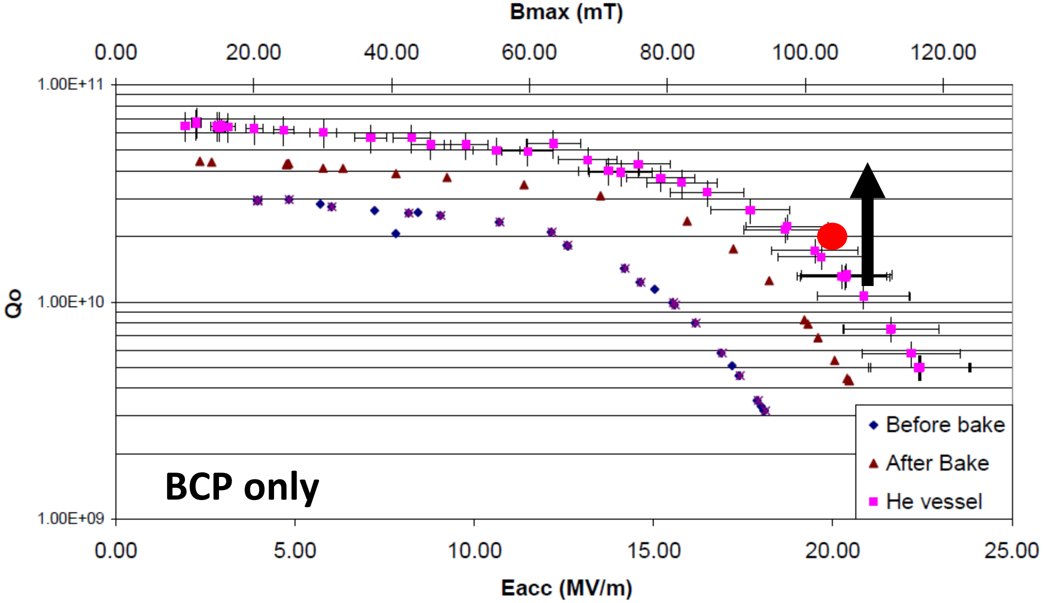


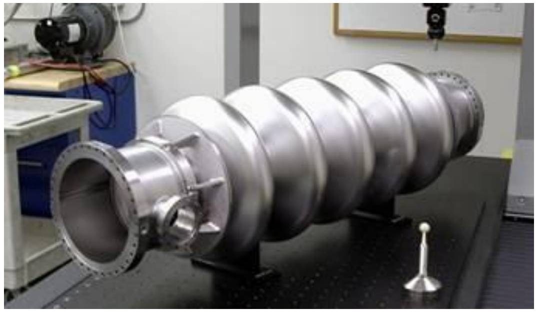
General considerations (2)

- Higher order mode power:
  - cavity loss factors, bunch length, bunch charge, beam current
  - power limits of HOM damping
  - beam break-up from transverse modes…
- RF power sources:
  - klystrons, IOTs, solid state amplifiers?
  - available power, efficiency, cost

Cavities: 704 MHz eRHIC/SPL

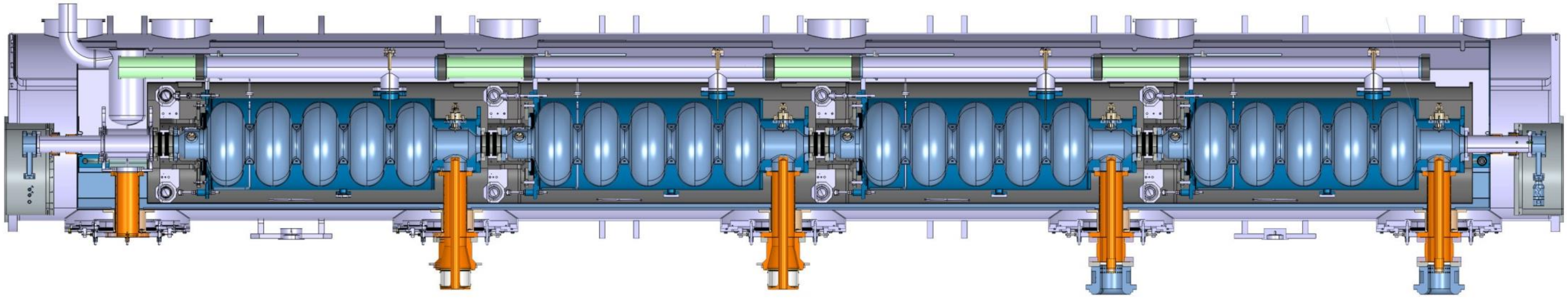
- BNL 5-cell 704 MHz test cavity
  (A. Burill, AP Note 376, 2010)





● SPL/ESS design value
2.0×10^{10} @ 20MV/m

- 700 MHz seems good compromise between high f_{RF}, power handling, gradient and Q_0
- First cavities, lots of room for improvement
- Assume SPL/ESS design values



SPL type cryomodule (4-cavity prototype)

RF in numbers: TLEP 175 GeV

	704 MHz 5-cell
Gradient [MV/m]	**20**
Active length [m]	1.06
Voltage/cavity [MV]	21.2
Number of cavities	**567**
Number of cryomodules	71
Total cryomodule length [m]	**902**

V_{RF} = 12 GV
P_{beam} = 100 MW

cf. LEP2: 812 m

R/Q [linac ohms]	506
Q_0 [10^{10}]	2.0
Dynamic heat load per cavity [W]	44.4
Total dynamic heat load [kW]	**25.2**

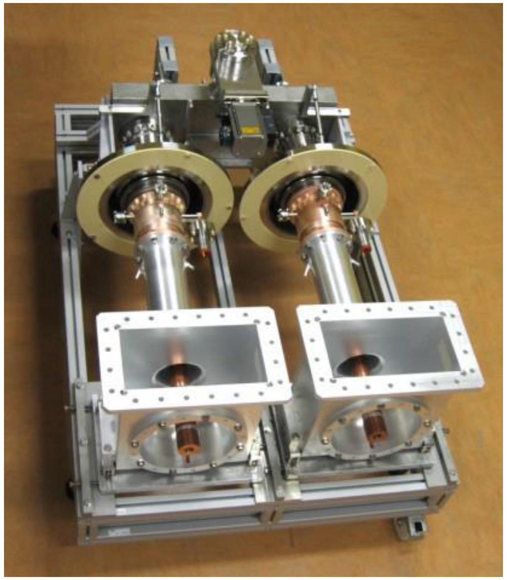
cf. LHC cryoplant capacity @ 1.9K of **18** kW

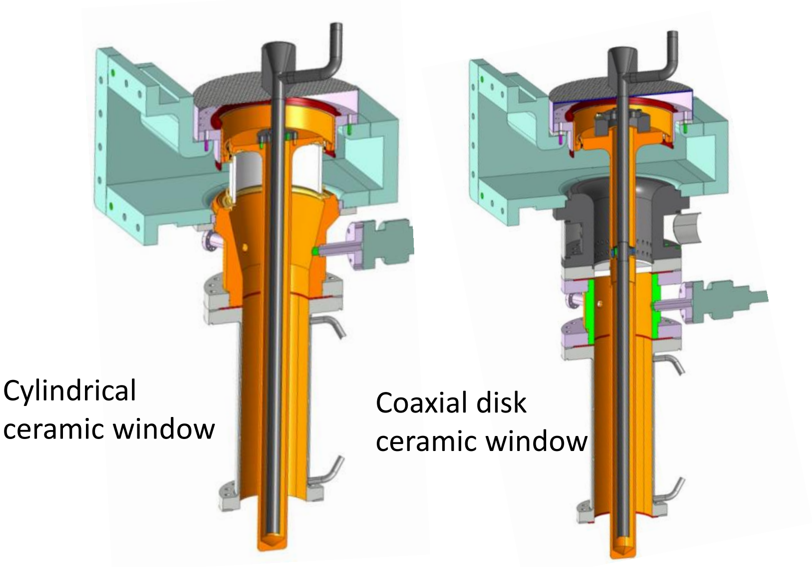
RF power per cavity [kW]	**176**
Matched Q_{ext}	5.0E+06

Input power couplers at 700 MHz for these power levels?

700 MHz power couplers

- CEA Saclay HIPPI water cooled coupler (SPL/ESS)
  - tested up to 1.2 MW 10% duty cycle in travelling wave, and 1 MW in standing wave
- CERN SPL air-cooled single window coupler
  - 2 designs currently under test: cylindrical and planar disk windows
  - design goal: 1 MW 10% duty cycle for SPL
  - cylindrical window design uses LHC coupler ceramic window with tapered outer conductor
  - LHC windows are routinely tested to > 500 kW CW





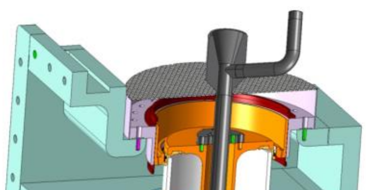
E. Montesinos

700 MHz power couplers

Latest R&D results

High average power air cooled couplers (CERN BE-RF-PM)

- Cylindrical window :
  - TW: 1000 kW 2 ms 20 Hz
  - SW: 550 kW 500 µs 8 Hz

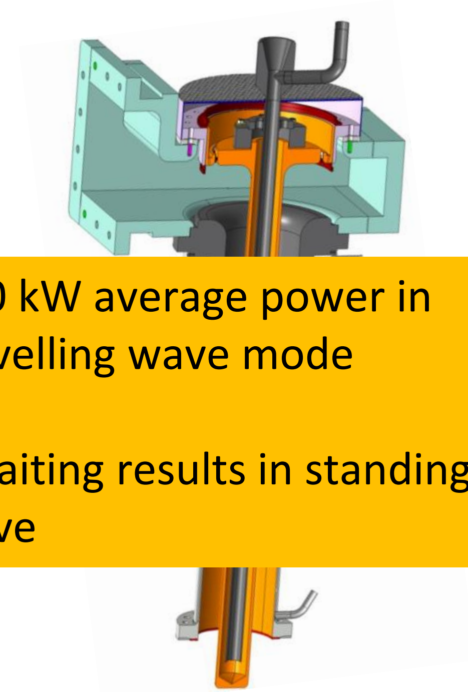


40 kW average power

Limited by arcing on air side of window

→ Improvements underway in window air flow and screen at braze

- Coaxial disk window :
  - TW: 1000 kW 2 ms 50Hz
  - SW: 1000 kW 1.5 ms 20 Hz



100 kW average power in travelling wave mode

Awaiting results in standing wave

TLEP 120 GeV option?

	704 MHz 5-cell
Gradient [MV/m]	**20**
Active length [m]	1.06
Voltage/cavity [MV]	21.2
Number of cavities	**284**
Number of cryomodules	36
Total cryomodule length [m]	**457**

R/Q [linac ohms]	506
Q_0 [10^{10}]	2.0
Dynamic heat load per cavity [W]	44.4
Total dynamic heat load [kW]	**12.6**

RF power per cavity [kW]	~~**350**~~ **200**
Matched Q_{ext}	1.7E+06

V_{RF} = 3 GV

P_{beam} = ~~100 MW~~ **57 MW**

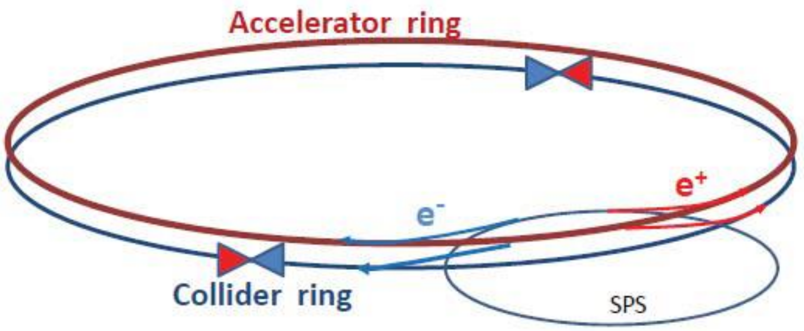
cf. LEP2: 812 m

cf. LHC cryoplant capacity @ 1.9K of **18** kW

Very high power per cavity: will be limitation on beam current and luminosity!

Top-up injector ring

- $V_{RF} \geq 9.7$ GV
  - (only for quantum lifetime)
- SR power very small
  - (beam current ~ 1% of collider ring)
- Average cryogenic heat load very small
  - (duty cycle < 10%)
- Power is dominated by ramp acceleration:
  - for a 1.6 second ramp length:

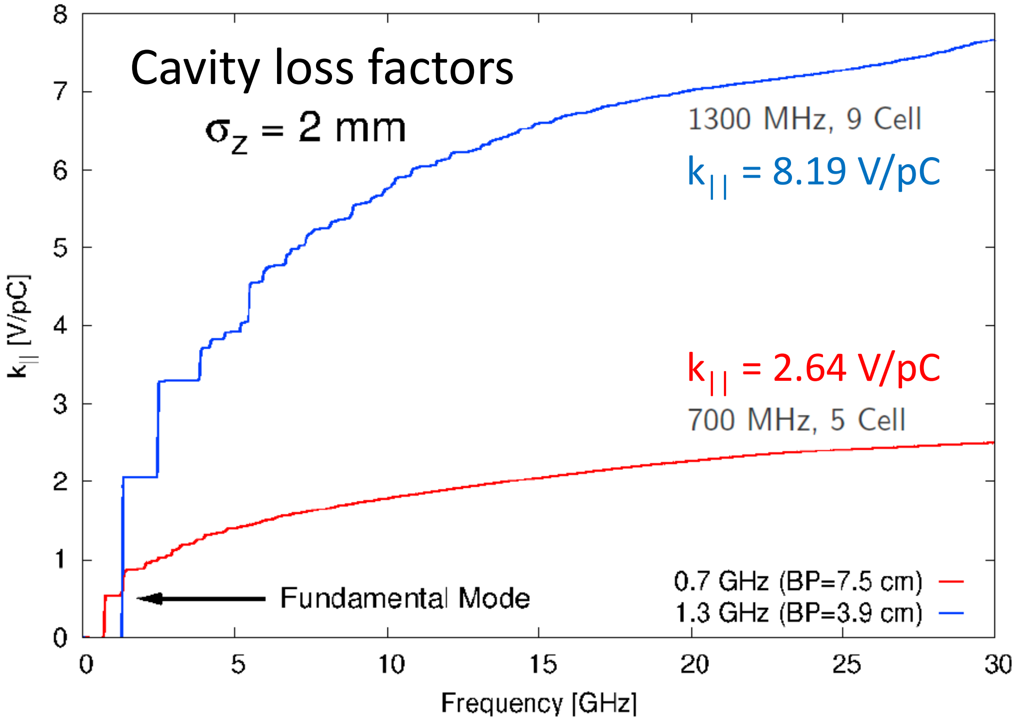


	TLEP-t
Beam current [mA]	0.054
Energy swing [GeV]	155
Max. SR power/cavity [kW]	6.2
Acceleration power [kW]	18
Max. power per cavity [kW]	**24**

Well within our 200 kW budget

Higher order mode power

R. Calaga



Average $P_{HOM} = k_{||}.Q_{bunch}.I_{beam}$

	TLEP-H	TLEP-t
Beam current [mA]	48.6	10.8
Num. bunches	160	24
Bunch charge [nC]	41	60
HOM power (704 MHz cavities) [kW]	**5.2**	**0.85**
HOM power (1.3 GHz cavities) [kW]	16.1	5.3

- Challenge: HOM powers in the kW range to remove from the cavity at 2 K

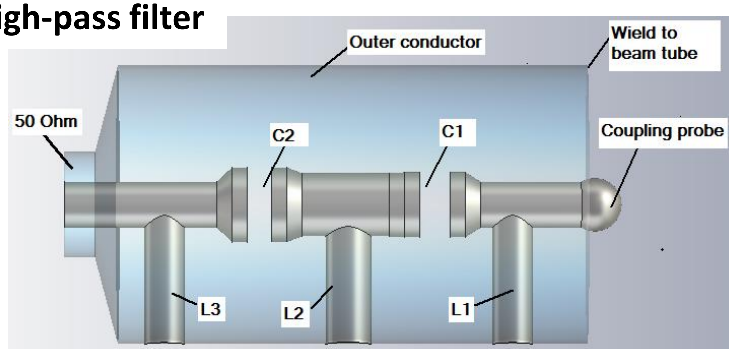
HOM power “league table”

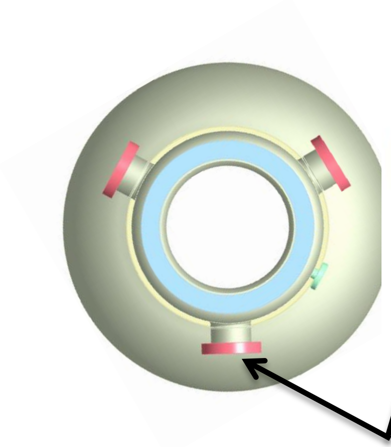
Project	Beam current [mA]	Average HOM power per cavity [W]
CEBAF 12GeV	0.10	0.05
Project X	1	0.06
XFEL	5	1
SPL	40	22
APS SPX	100	2,000
BERLinPro	100	150
KEK-CERL	100	185
Cornell ERL	100	200
eRHIC	300	7,500
KEKB	1,400	15,000
TLEP-H 704 MHz	49	5,200
TLEP-t 704 MHz	11	850

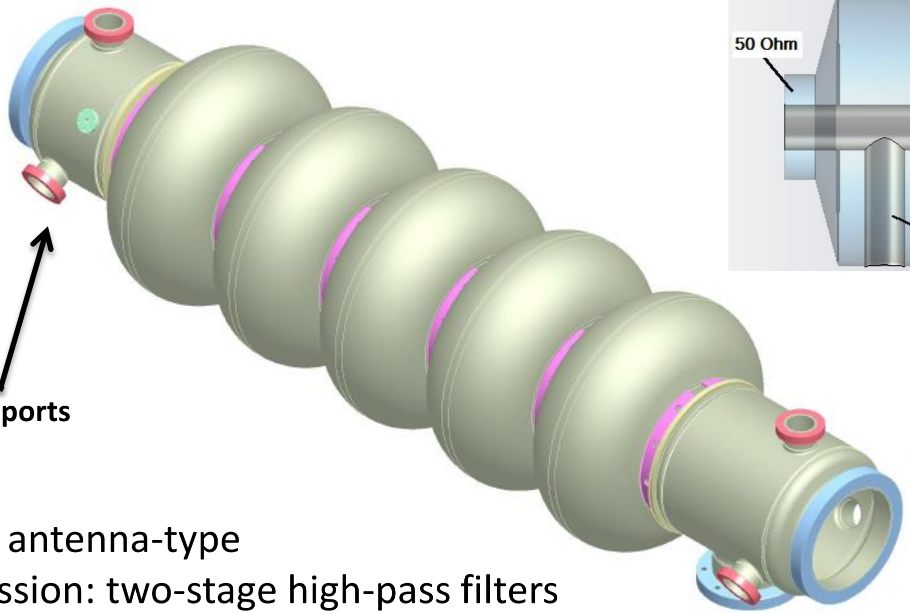
After M. Liepe, SRF2011

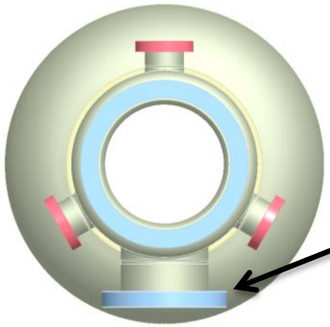
5-cell SRF cavity with strong HOM damping for eRHIC at BNL

HOM high-pass filter









f = 703.5MHz
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

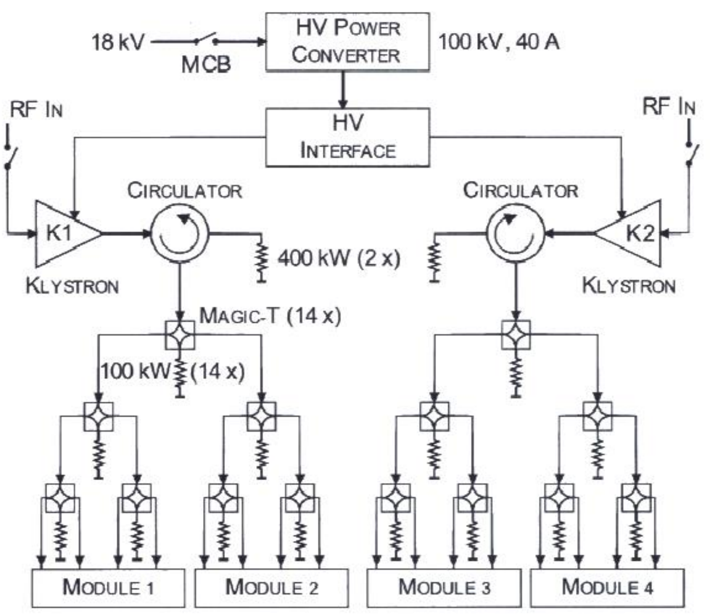
RF power sources

- "Super-power" klystrons at 700 MHz
- Multiple cavities per klystron
  - 4 for collider ring?
  - 16 or more for accelerator ring?
  - cf. 8 in LEP2

Type	Frequency (MHz)	Output Power (kW)	Efficiency (%)
VKP-7952B	704	1000	65

Type	Frequency (MHz)	Output Power (kW)	Efficiency (%)
E3732	508.6	1200	63
E37701*	1071.8	1200	63

Type	Frequency (MHz)	Output Power (kW)	Efficiency (%)
TH2178	508.6	1200	62



LEP2 SC RF unit:
4 cavities per cryomodule, 8 cavities per klystron

Energy efficiency

- High voltage power converter
  - thyristor 6 pulse: 95%
    - AC power quality, DC ripple @ multiples of 50 and 300 Hz
  - switched mode: 90%
    - lower ripple on the output, and/or smaller size
- Klystron: 65%
  - if run at saturation as in LEP2
  - i.e. no headroom for RF feedback
- RF distribution losses: 5 to 7%
  - waveguides, circulators

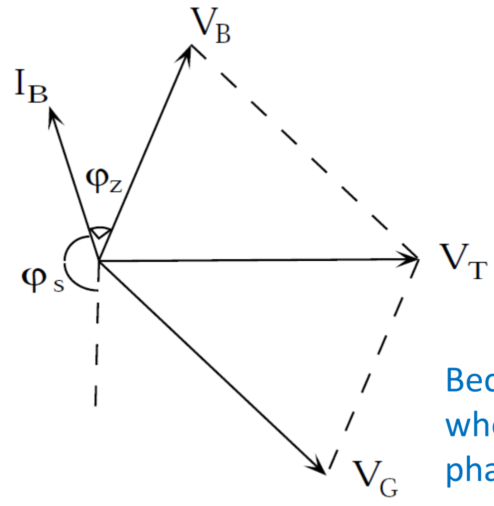
For comparison: CLIC wall to drive beam: 55%

Overall RF efficiency (wall to beam) between 54% and 58%
without margin for RF feedback

LLRF: instabilities and feedbacks

- Is fast RF feedback necessary?
  - LEP2: slow scalar sum feedback acting on the klystron modulation anode, with the klystrons operated at saturation for maximum efficiency
  - if the detuning due to beam loading is sufficiently large it can drive coupled bunch modes
  - however: f_{rev} = 3750 Hz, f_s = 430 Hz, cavity BW = 100 Hz

    → cavity BW << $f_{rev} - f_s$
  - Fast RF feedback incompatible with klystron operation in saturation!



Becomes unstable when V_G is in anti-phase with I_B

- Microphonics/ponderomotive oscillations
  - due to Lorentz detuning driving mechanical resonances
  - problem at LEP2: "cured" by cavity detuning
  - better handled by feedback on Piezo tuners
- Beamloading: "second Robinson" instability
  - loss of longitudinal focusing due to large detune angle under strong beamloading
  - occurs at low RF voltage with high beam current
  - seen in LEP2 at injection energy
  - cured by using fast RF feedback on a few RF stations
  - an issue if we don't have top-up injection

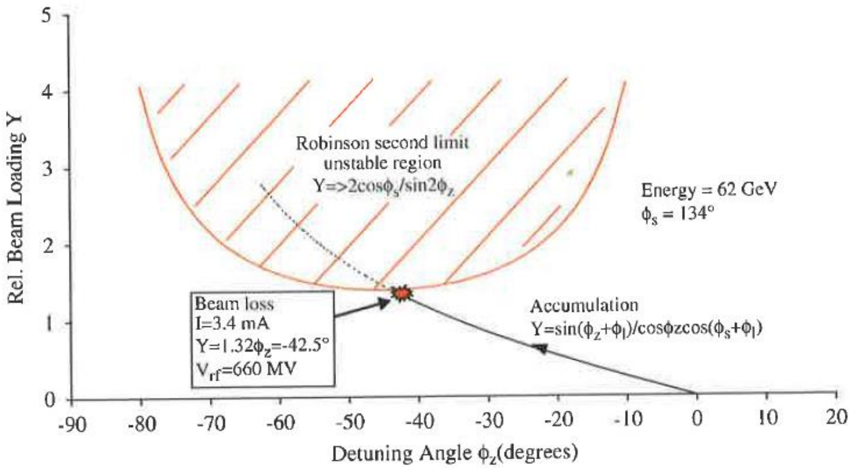


Fig. 21. Beam loading plot Y vs. Φ_z at 62 GeV in low RF voltage ramp.

Cryogenics

- Estimate based on LHC figures for cryogenic power consumption (900 W/W @ 1.9 K) to compensate fundamental frequency dynamic load only:

Beam energy [GeV]	**175**	**120**
Number of cavities @ 20 MV/m	567	284
Total dynamic heat load [kW]	25.2	12.6
Power consumption [MW]	**22.7**	**11.3**

- But we also have to take into account
  - static heat loads (~1 W/cavity cf. SPL estimate?)
  - HOM dissipation in cavity
  - overhead for cryogenics distribution etc.

- Quick estimate: dynamic load x 1.5 (as suggested by S. Claudet) gives:

Beam energy [GeV]	**175**	**120**
Power consumption [MW]	**34**	**17**

Total power consumption

- For TLEP @ 175 GeV with 100 MW of beam power:

Wall-plug power [MW]	η = 54%	η = 58%
RF (collider ring)	185	172
RF (accelerator ring)	1	1
Cryogenics (collider ring)	34	34
Cryogenics (accelerator ring)	4	4
Total RF + cryo	**224**	**211**
wall-plug → beam η	**44.6%**	**47.4%**

Compare LEP2 experience: 42%
(F. Zimmermann this morning)

- For TLEP @ 120 GeV, the figure would be at least:
  - (minimal system limited to 57 MW beam power)

Wall-plug power [MW]	η = 54%	η = 58%
RF	106	99
Cryogenics	12	12
Total RF + cryo	**118**	**111**
wall-plug → beam η	**48.3%**	**51.3%**

Conclusions

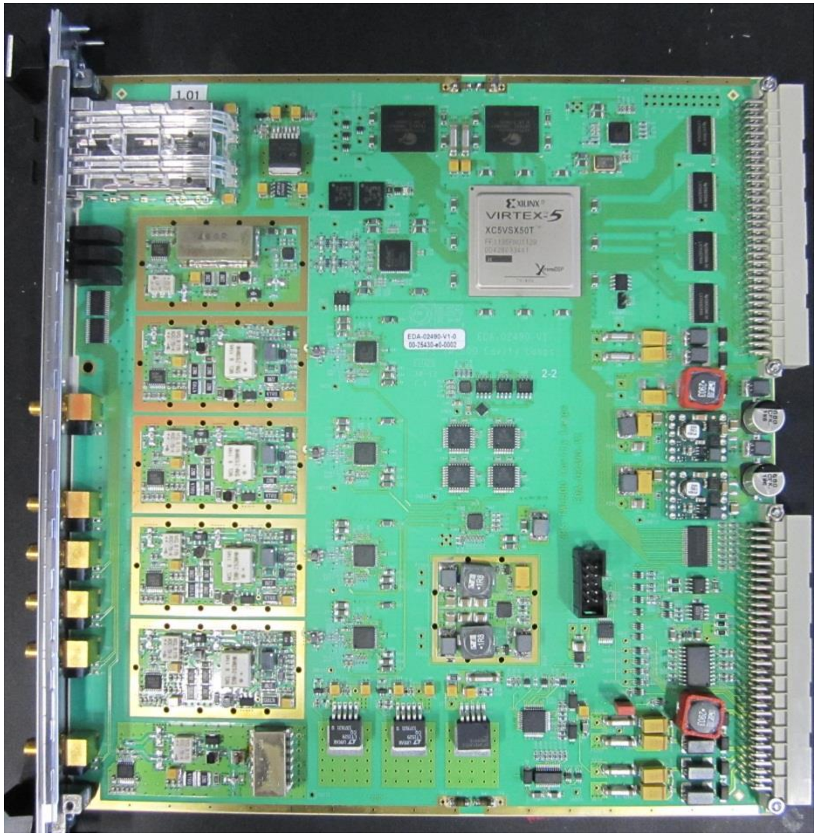
- An RF system based on 700 MHz SC cavity technology such as being developed for eRHIC, SPS, ESS seems to be a good choice.
  - ongoing R&D at BNL, CERN, ESS for 704 MHz cavities and components
  - 802 MHz synergetic with SPS and LHC harmonic systems and LHeC
  - fundamental power couplers look possible at 200 kW CW
  - eRHIC HOM damping scheme promises sufficient performance
  - high-power klystrons available
  - RF wall-plug to beam efficiency around 54 – 58% (w/o cryo)
  - total power consumption for 175 GeV around 220 MW including cryogenics, resulting in efficiency around 48 – 51%.

- Open questions and R&D necessary
  - fundamental power couplers: R&D ongoing
  - HOM damping scheme: study needed
  - low level RF & feedback requirements: study needed
  - construction cost?

Thank you for your attention!

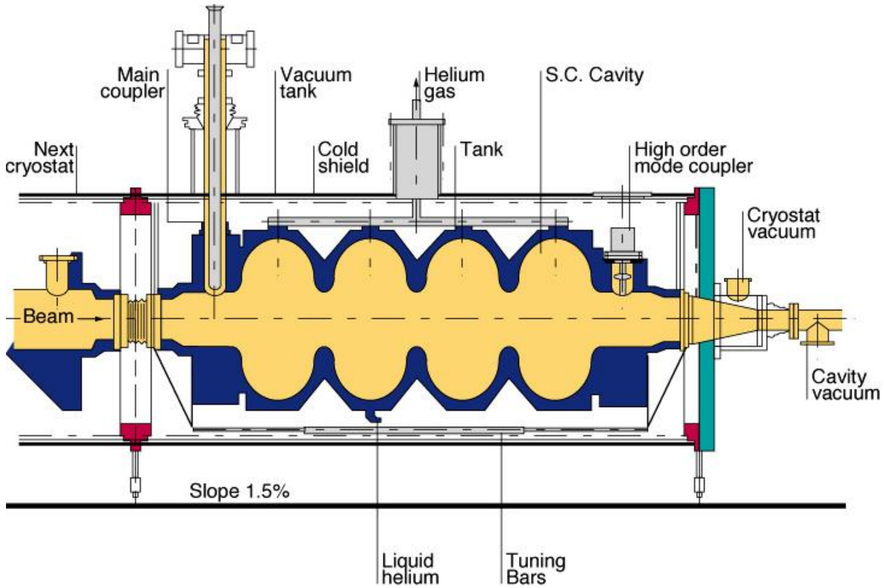
Backup slides

- SPS 800 MHz TWC prototype feedback board

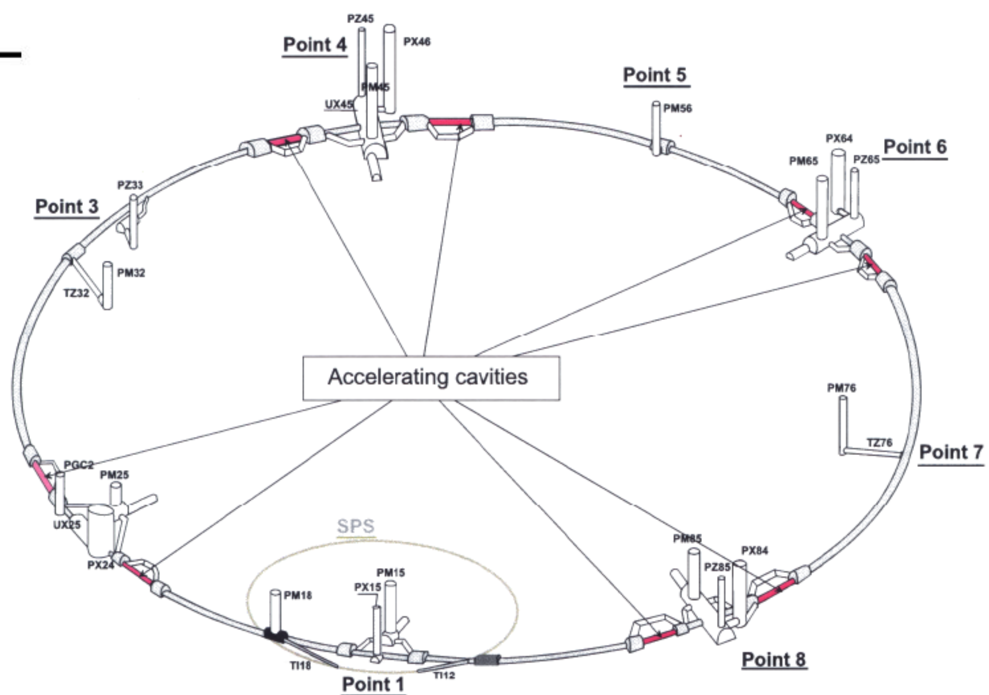


G. Hagmann BE-RF-FB
designer

LEP2 SC RF system



Circumference	26.7 km
Beam energy	104.5 GeV
Energy loss per turn	3.4 GeV
Beam current	5 mA
Synchrotron radiation power	17 MW
Available cooling power	53 kW @ 4.5K



RF frequency	352 MHz
Number of cavities *	288
Total accelerating voltage *	3500 MV
Number of klystrons *	36
Total cryomodule length	812 m
Cavities per klystron	8
Average (nom.) power per klystron	0.6 (1.3) MW
Average power per cavity	90 kW

* Plus 56 copper cavities (130 MV) driven by 8 klystrons

LEP2 SC RF system

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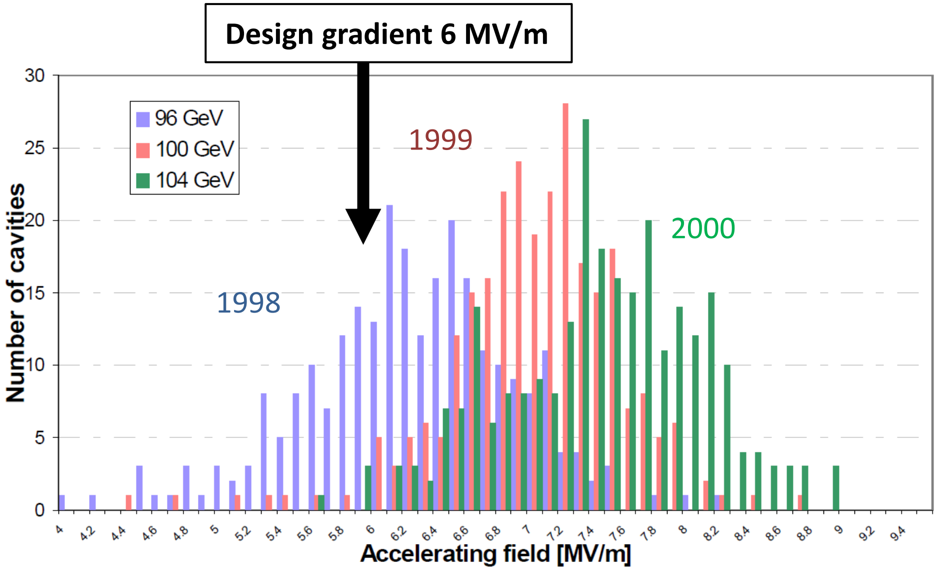

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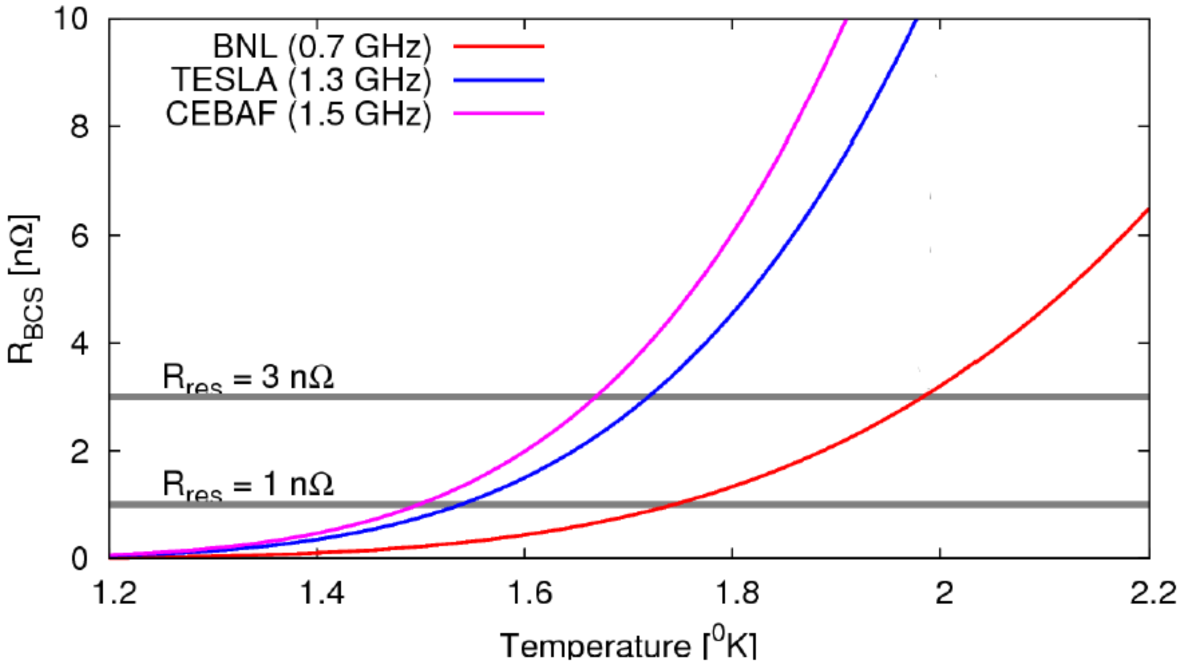
Temperature: Why 2K not 4.5?

RF surface resistance $R_{surf} = R_{res} + R_{BCS}$

BCS surface resistance

Residual resistance (impurities, trapped flux, etc.)



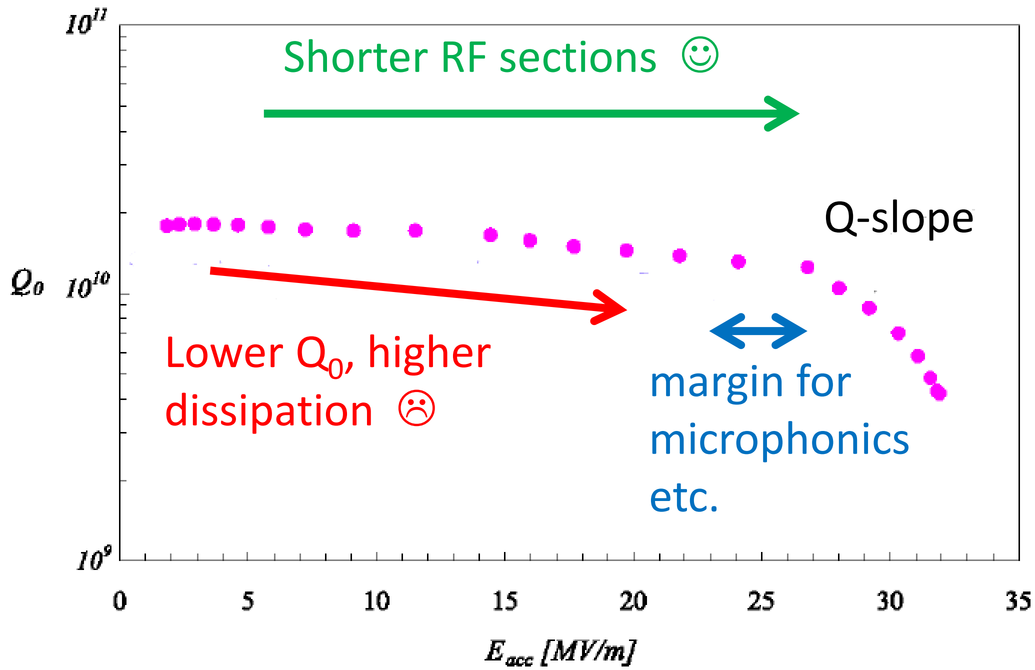
Increases with frequency

$$R_{BCS} \propto \frac{\omega^2}{T} e^{-\frac{\Delta}{k_B T}}$$

$$\Delta = 1.76 k_B T_c$$

Increases with temperature

Gradient and dynamic heat load



Power dissipation = $$\frac{V_{cav}^2}{Q_0(R/Q)}$$

Q_0 depends on losses in cavity walls

R/Q depends only on cavity geometry

LEP2 vs. TLEP SC RF systems

	LEP2	TLEP
Circumference	26.7 km	80 km
Beam energy	104.5 GeV	175 GeV
Energy loss per turn	3.4 GeV	9.3 GeV
Beam current	5 mA	5.4 mA
Synchrotron radiation power	22 MW	100 MW
RF frequency	352 MHz	700 MHz
Total accelerating voltage	3500 MV *	12 GV
Nominal gradient	6 MV/m	20 MV/m
Number of cavities *	288 *	567
Number of cryomodules	72	71
Number of klystrons	36 *	142
Total cryomodule length	812 m	902 m
Cavities per klystron	8	4
Average (nom.) power per klystron	0.6 (1.3) MW	0.7 (1.0)
Average power per cavity	90 kW	176 kW

* Plus 56 copper cavities (130 MV) driven by 8 klystrons

Parameters: LEP3 (27 km ring) and TLEP (80 km ring)

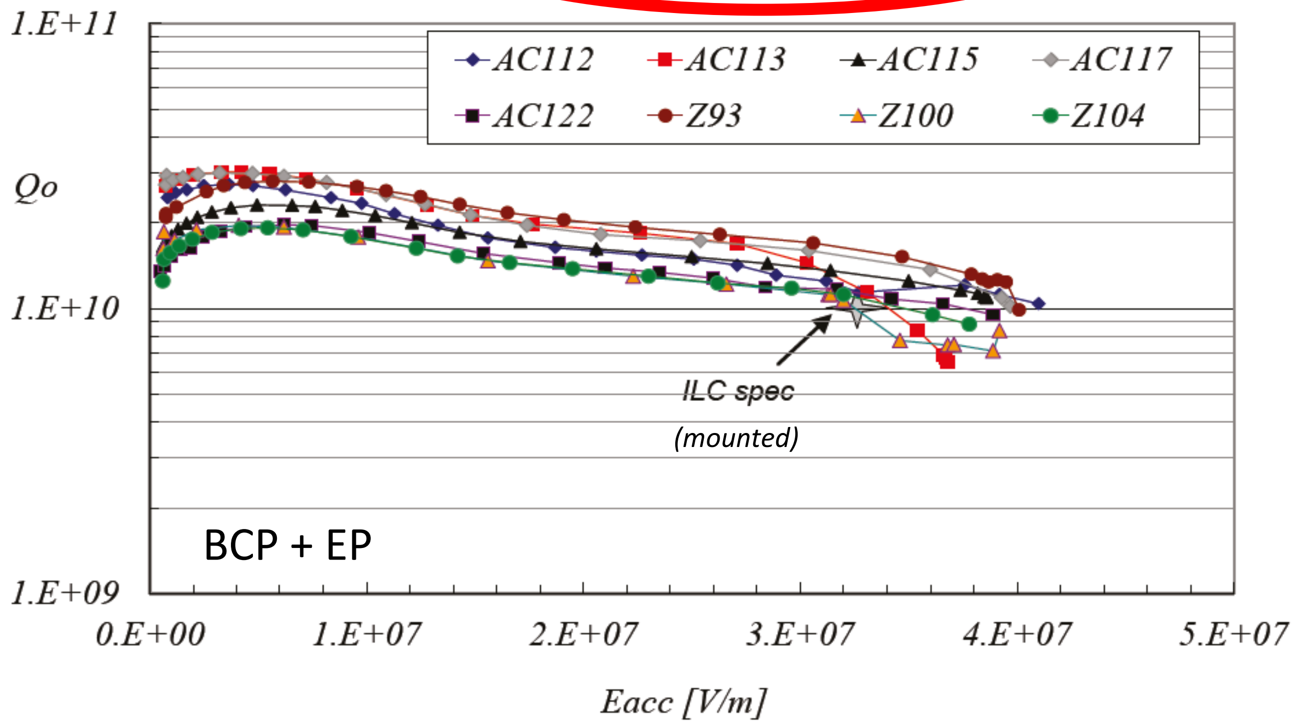
	LEP2	LEP3	TLEP-Z	TLEP-H	TLEP-t
beam energy E_b [GeV]	104.5	120	45.5	120	175
circumference [km]	26.7	26.7	80	80	80
beam current [mA]	4	7.2	1180	24.3	5.4
#bunches/beam	4	4	2625	80	12
$\#e^-$/beam [10^{12}]	2.3	4	2000	40.5	9
bending radius [km]	3.1	2.6	9	9	9
partition number J_ε	1.1	1.5	1	1	1
momentum comp. α_c [10^{-5}]	18.5	8.1	9	1	1
SR power/beam [MW]	11	50	50	50	50
ΔE^{SR}_{loss}/turn [GeV]	3.41	6.99	0.04	2.1	9.3
$V_{RF,tot}$ [GV]	3.64	12	2	6	12
$\delta_{max,RF}$ [%]	0.77	4.2	4	9.4	4.9
f_s [kHz]	1.6	3.91	1.29	0.44	0.43
E_{acc} [MV/m]	7.5	20	20	20	20
eff. RF length [m]	485	600	100	300	600
f_{RF} [MHz]	352	1300	700	700	700
δ^{SR}_{rms} [%]	0.22	0.23	0.06	0.15	0.22
$\sigma^{SR}_{z,rms}$ [cm]	1.61	0.23	0.19	0.17	0.25

Why not 1.3 GHz?

- ILC cavity specifications:

	Gradient	Q_0
Vertical test (bare cavity)	35 MV/m	> 0.8 x 10^{10}
Mounted in cryomodule	**31.5 MV/m**	**> 1.0 x 10^{10}**

Test results for eight 1.3 GHz 9-cell TESLA cavities achieving the ILC specification (DESY)



1.3 GHz (TLEP 175 GeV)

LEP3	1300 MHz 9-cell	
Gradient [MV/m]	**20**	**25**
Active length [m]	1.038	1.038
Voltage/cavity [MV]	20.76	25.95
Number of cavities	**579**	**463**
Number of cryomodules	72	58
Total cryomodule length [m]	**927**	**737**

V_{RF} = 12 GV
P_{beam} = 100 MW

cf. 1.06 m for 704 MHz 5-cell

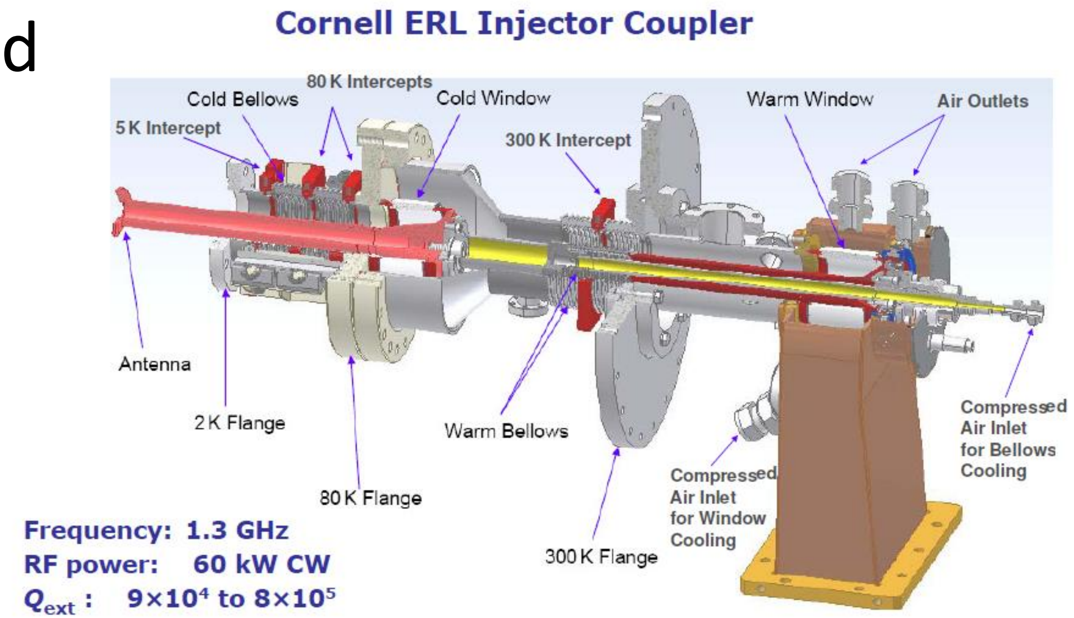
R/Q [linac ohms]	1036	1036
Q_0 [10^{10}]	1.5	1.3
Dynamic heat load per cavity [W]	27.7	50.0
Total dynamic heat load [kW]	**16.1**	**23.2**

RF power per cavity [kW]	**173**	**216**
Matched Q_{ext}	2.4E+06	3.0E+06

Input power couplers @ 1.3 GHz ??

1.3 GHz power couplers

- TTF-III couplers tested to 5 kW in CW
  - 8kW with improved cooling (BESSY)
- Some higher power adaptations for ERL injectors
  - e.g. Cornell 60 kW CW



2 couplers per 2-cell cavity in ERL injector cryomodule
Gradient: 5-15MV/m
Beam current: 100 mA

V. Vescherevitch, ERL'09

power coupler for 1.3 GHz 200 kW CW looks challenging…

2 K Heat Loads (per β=1 cavity)

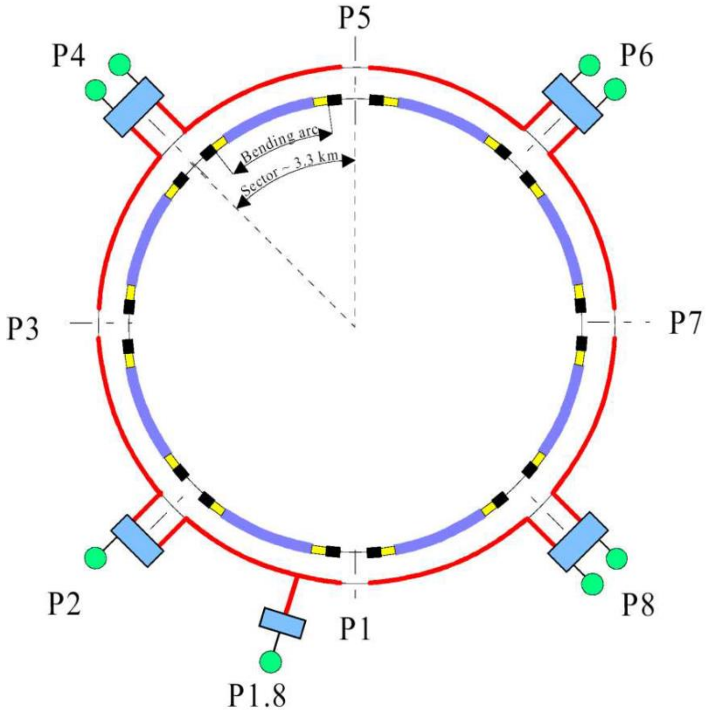
Operating condition	**Value**	
Beam current/pulse lenght	**40 mA/0.4 ms beam pulse**	**20 mA/0.8 ms beam pulse**
cryo duty cycle	4.11%	8.22%
quality factor	10×10^9	5×10^9
accelerating field	25 MV/m	25 MV/m

Source of Heat Load	**Heat Load @ 2K (per cavity)**	
Beam current/pulse lenght	**40 mA/0.4 ms beam pulse**	**20 mA/0.8 ms beam pulse**
dynamic heat load per cavity	5.1 W	20.4 W
static losses	<1 W (tbc)	~ 1 W (tbc)
power coupler loss at 2 K	<0.2 W	<0.2 W
HOM loss in cavity at 2 K	<1	<3 W
HOM coupler loss at 2 K (per coupl.)	<0.2 W	<0.2 W
beam loss	1 W	1 W
Total @ 2 K	**8.5 W**	**25.8 W**

LHC cryogenic plant capacity

- For LEP3 it would be very advantageous if the cryogenic power required for the RF could be supplied by the existing LHC cryogenics plants

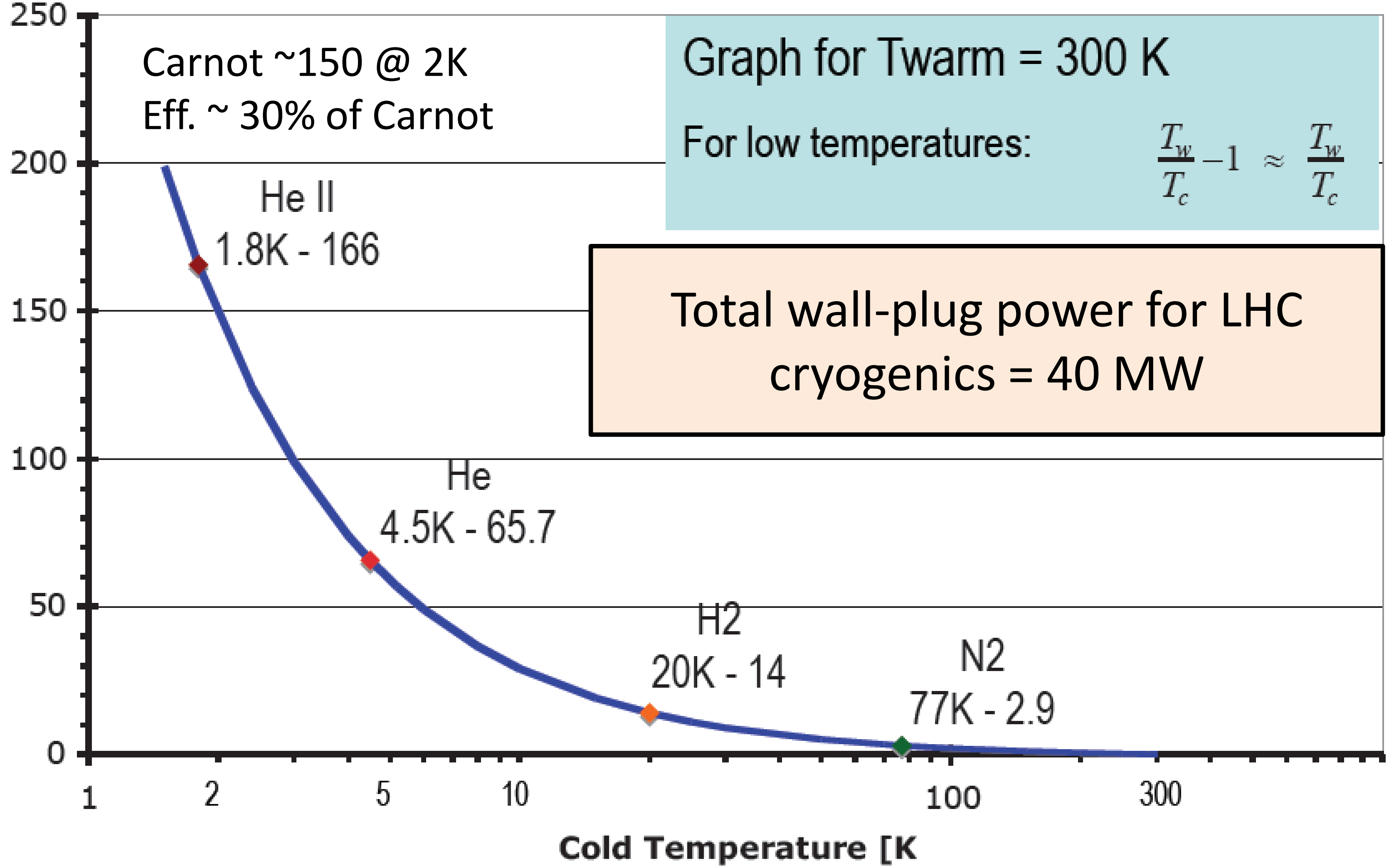
Installed refrigeration capacity in the LHC sectors			
Temperature level		High-load sector (1-2, 4-5, 5-6, 8-1)	Low-load sector (2-3, 3-4, 6-7, 7-8)
50-75 K	[W]	33000	31000
4.6-20 K	[W]	7700	7600
4.5 K	[W]	300	150
1.9 K LHe	**[W]**	**2400**	**2100**
4 K VLP	[W]	430	380
20-280 K	[g.s-1]	41	27



- LHC cold compressors (125 g/s@15mbar
(250g/s@30mbar=2.0K)
- However, piping, motors and so on woul
- A more detailed study would be necessa
some parts would be changed (motors, b

Total wall-plug power for LHC cryogenics = 40 MW

The Carnot Factor (2/3)



Graph for Twarm = 300 K

For low temperatures: $\frac{T_w}{T_c} - 1 \approx \frac{T_w}{T_c}$

Total wall-plug power for LHC cryogenics = 40 MW