RF system for LEP3 and TLEP

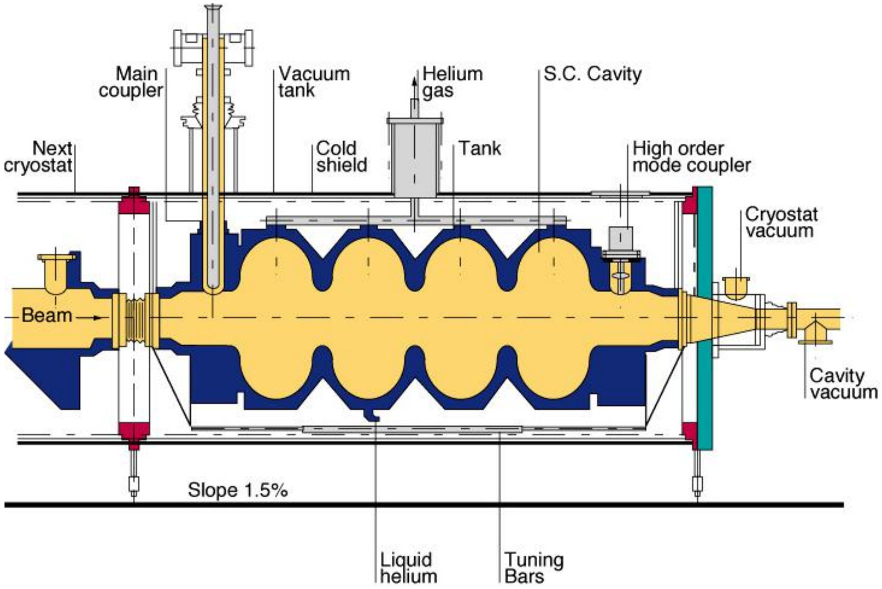
Andy Butterworth (CERN BE/RF)

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

Overview

- Introduction and general considerations
  - A bit of history: the LEP2 RF system
  - Cryogenic cooling capacity
- Technology choices: which is the best fit for a 120 GeV e^+e^- storage ring?
  - Producing the voltage
  - Handling the RF power
  - Damping higher order modes
  - Controlling the impedance: Low Level RF
- Tentative conclusions

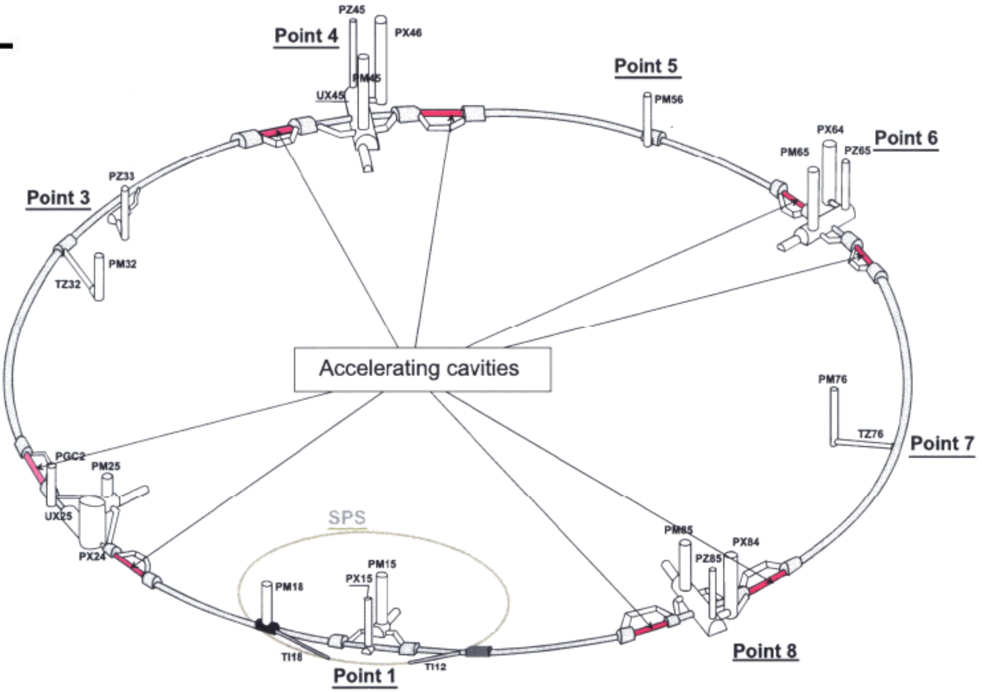
LEP2 SC RF system



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



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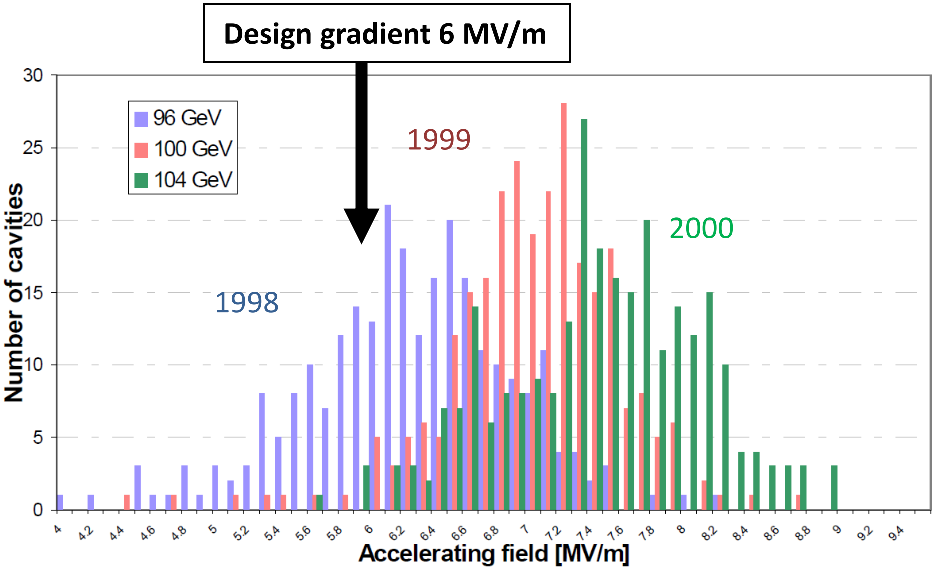


Design gradient 6 MV/m

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

Introduction

The RF system of an e^+e^- collider has to:

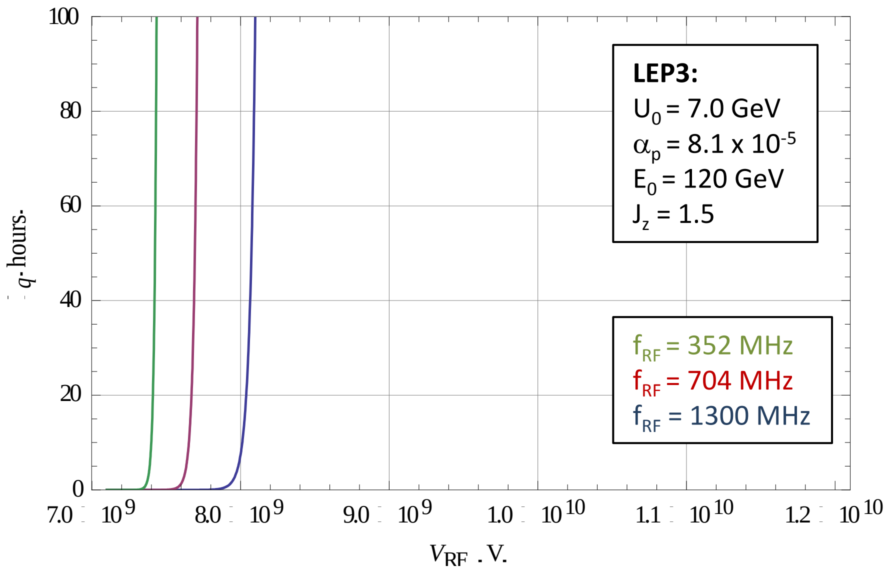
- replace the energy lost U_0 at each turn by synchrotron radiation
  - total power needed by the beam = $U_0 \times I_{beam}$

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

- maintain longitudinal focusing with sufficient momentum acceptance $|\delta|_{max,RF}$ 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

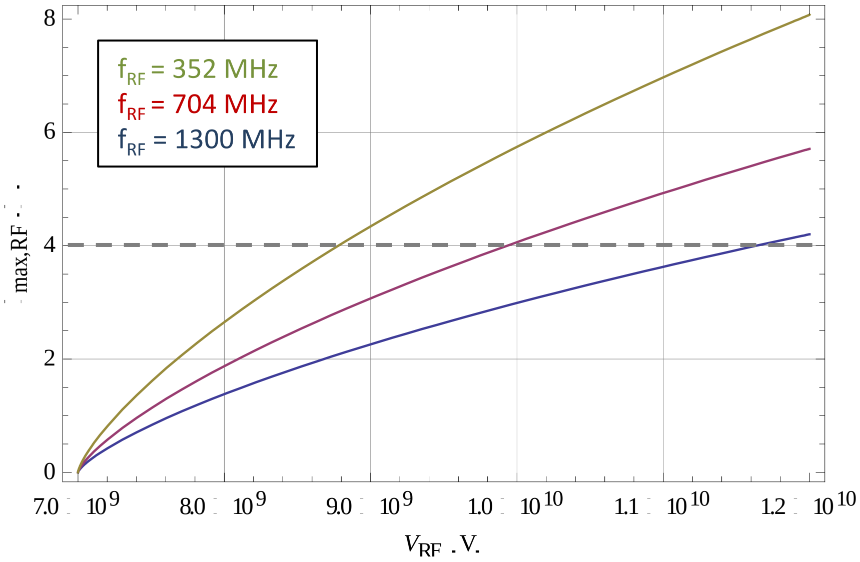
RF voltage

- Quantum lifetime is a very steep function of V_{RF}
- RF voltage is defined by the momentum acceptance needed to cope with beamstrahlung
  - 4% for LEP3
  - 3% for TLEP-H



Machine	RF frequency [MHz]	V_{RF} [GV] for τ_q = 100h	V_{RF} [GV] for $\delta_{max,RF}$ = 4%
LEP3	352	7.4	8.8
	704	7.7	10.0
	1300	8.1	11.7

$\delta_{max,RF} \sim f_{RF}^{-1/2}$ for a given RF voltage



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

RF: General considerations for LEP3 and TLEP-H

	LEP3	TLEP-H	Top-up injector rings
RF voltage	12 GV ($\delta_{max,RF}$ = 4.2%) needed for beamstrahlung	6 GV ($\delta_{max,RF}$ = 5.7%) needed for beamstrahlung	**LEP3:** 9 GV **TLEP-H:** 2.5 GV for quantum lifetime
Gradient	High (≥ 20 MV/m?) Overall length of the RF sections, available space in the LHC tunnel. Tradeoff with cryogenic power.	Moderate, as the space constraints are less important, required RF voltage is lower. Defined by beam power considerations.	High, to keep the RF sections short (cost, space). Cryogenic power less critical (low duty cycle)
RF power	High power throughput per cavity to supply the required 100 MW of SR power.	The same 100 MW total power throughput. Maximum power rating of the input couplers dictates the number of cavities and gradient.	SR power low (kW per cavity) due to low beam currents. Power dominated by acceleration during energy ramp.

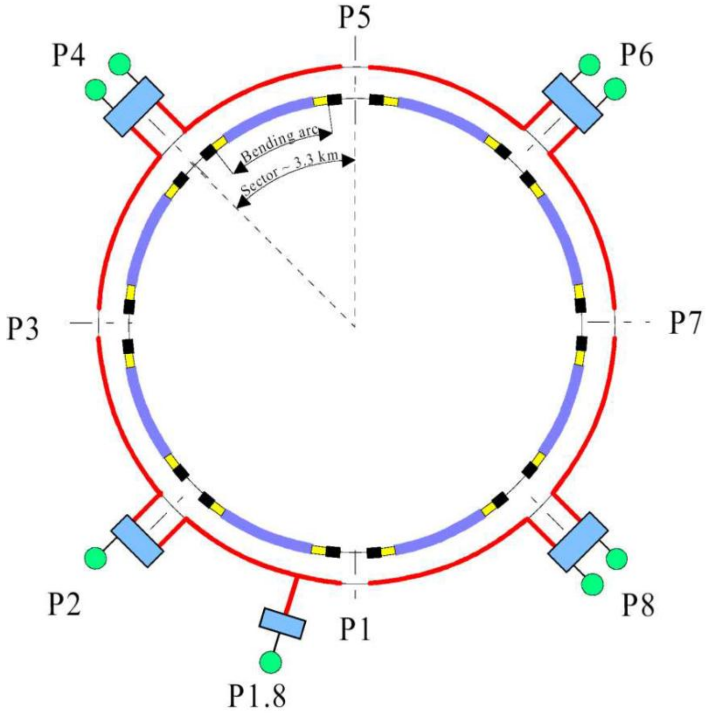
General considerations (2)

- RF frequency:
  - higher is better, for short bunch length (hourglass effect)
- Higher order mode power:
  - cavity loss factors, bunch length, bunch charge, beam current
  - power limits of HOM damping
  - bunch break-up from transverse modes
- RF power sources:
  - klystrons, IOTs, solid state amplifiers?
  - available power, efficiency, cost
- Feedbacks and Low-Level RF:
  - beamloading (especially if no top-off injection)
  - longitudinal impedance control (coupled bunch modes)

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

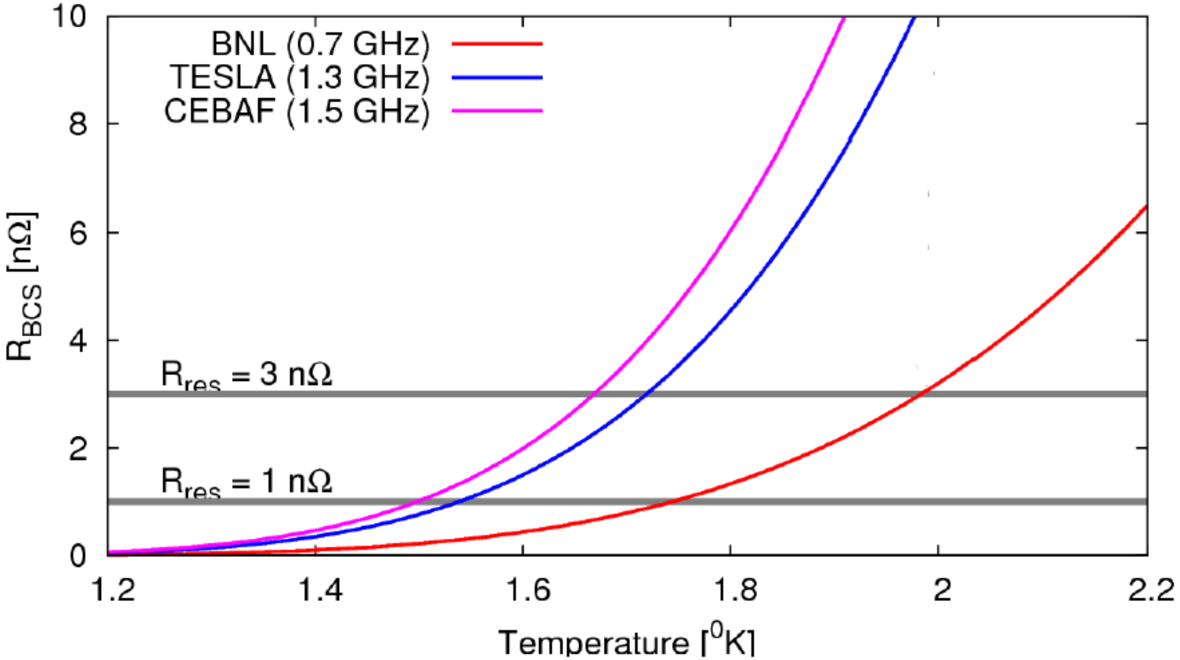
Temperature: Why 2K not 4.5?

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

BCS surface resistance

Residual resistance (impurities, trapped flux, etc.)

Increases with frequency

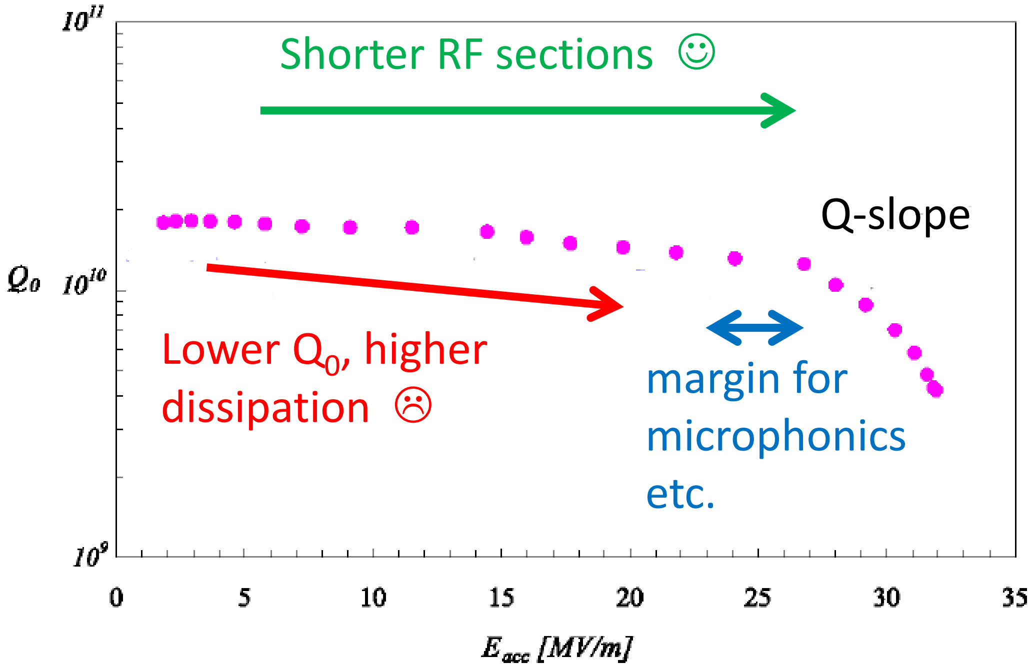


$$R_{BCS} \propto \frac{\omega^2}{T} e^{-\frac{\Delta}{k_B T}}$$

$$\Delta = 1.76 k_B T_c$$

Increases with temperature

Gradient and dynamic heat load



Shorter RF sections ☺

Q-slope

Lower Q_0, higher dissipation ☹

margin for microphonics etc.

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

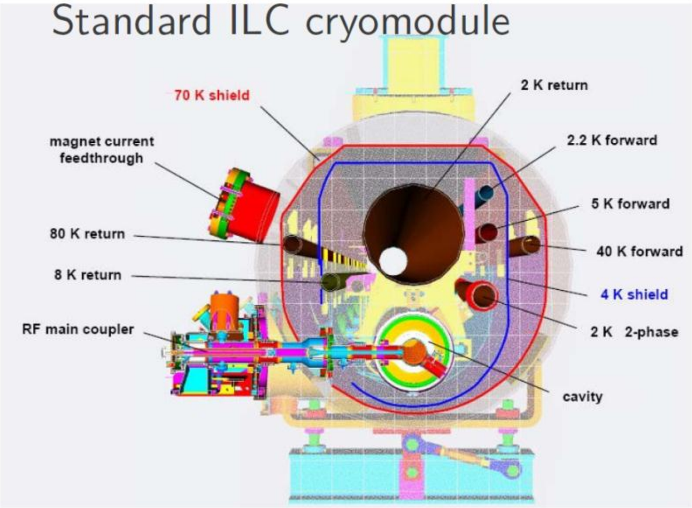
Q_0 depends on losses in cavity walls

R/Q depends only on cavity geometry

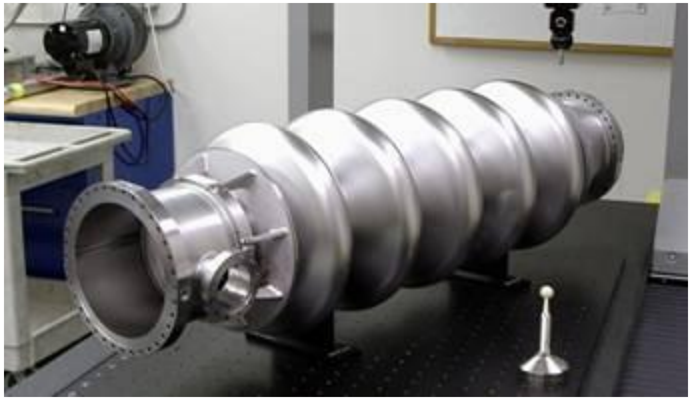
LEP3/TLEP RF: Potential options

ILC collaboration

1300 MHz 9-cell cavity

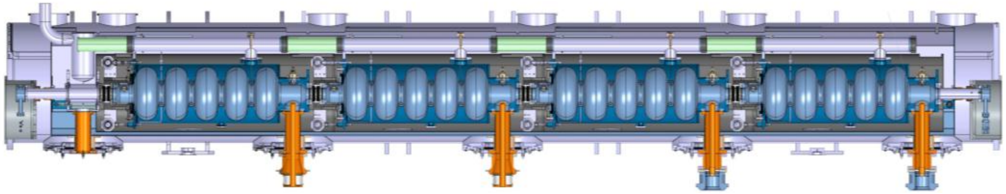


ESS, eRHIC, SPL



704 MHz 5-cell cavity

SPL type cryomodule

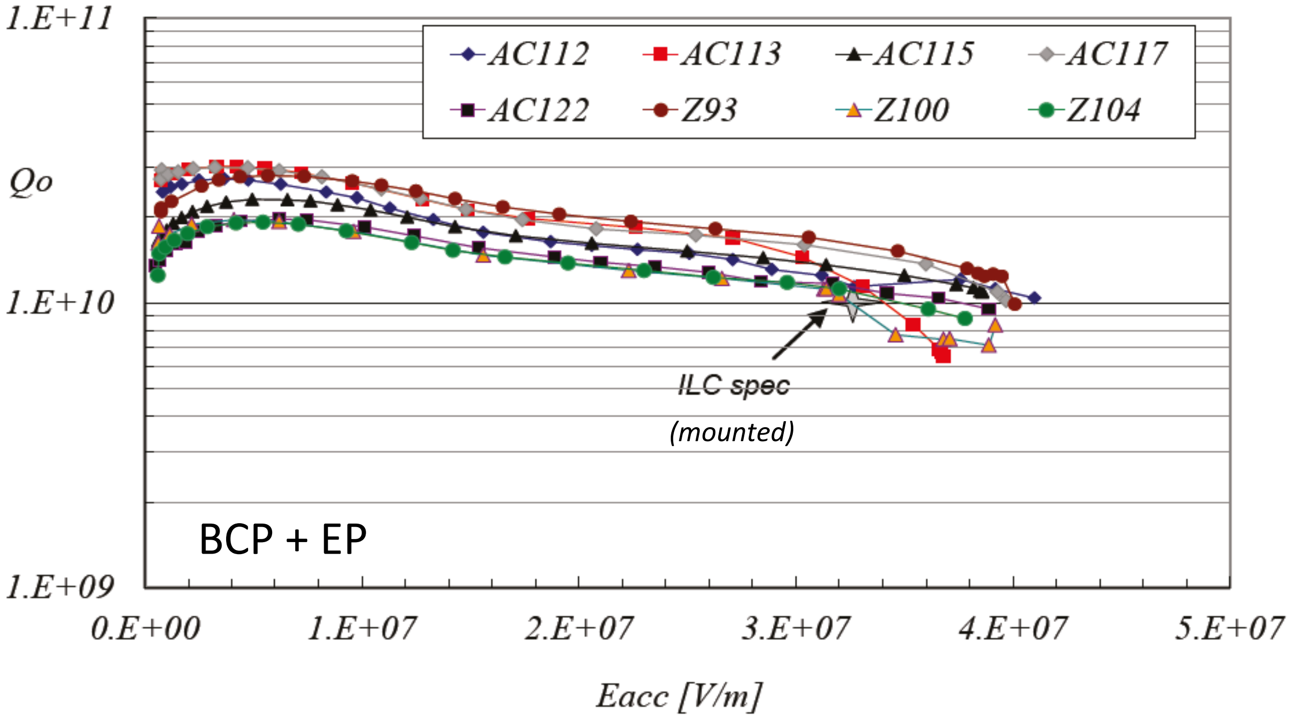


Option 1: 1.3 GHz TESLA/ILC

- ILC cavity performance requirements:

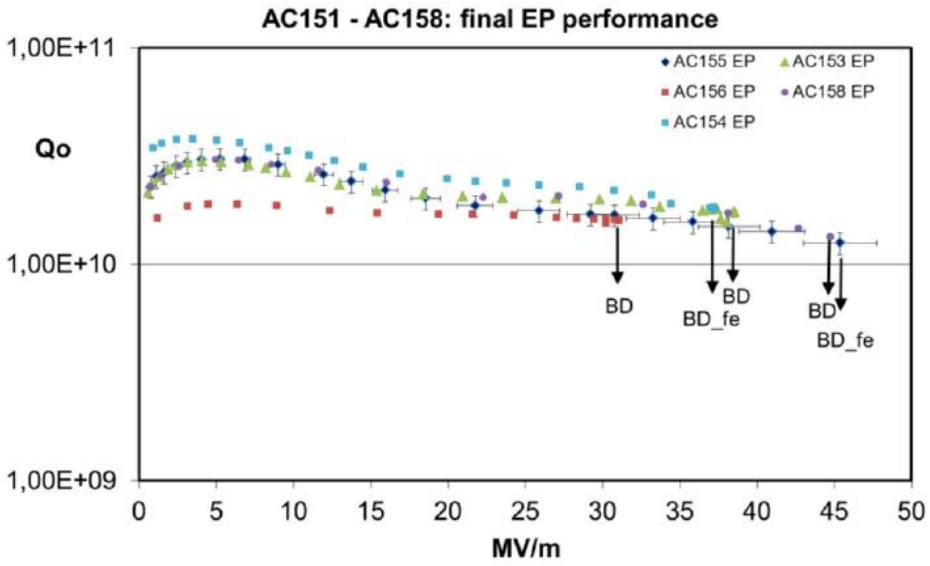
	Gradient	Q_0
Vertical test (bare cavity)	35 MV/m	$> 0.8 \times 10^{10}$
Mounted in cryomodule	31.5 MV/m	$> 1.0 \times 10^{10}$

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



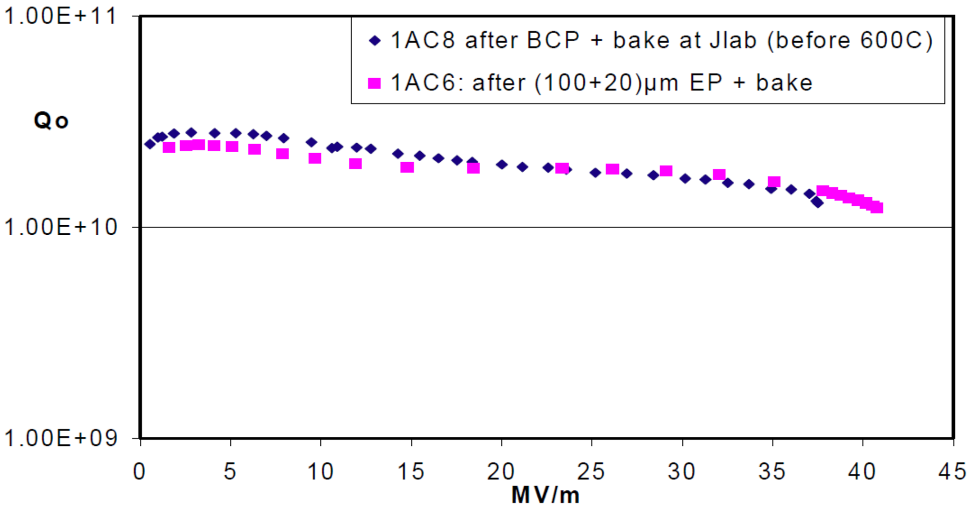
Option 1: 1.3 GHz TESLA/ILC

- Promise of even higher cavity performance in future
  - ongoing R&D in new techniques
  - e.g. large grain and single crystal niobium cavities



Large-grain 9-cell cavities at DESY

D. Reschke et al. SRF2011



Single-crystal 9-cell cavities at DESY

A Brinkman et al. SRF07

Option 1: 1.3 GHz (LEP3)

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**
Total cryomodule length [m]	**927**	**737**
R/Q [linac ohms]	1036	1036
Q_0 [10^{10}]	1.5	1.3
Heat load per cavity [W]	27.7	50.0
Total heat load [kW]	16.1	23.2
Heat load per sector [kW]	**2.0**	**2.9**
Accel. ring @ 10% DF [kW]	**0.15**	**0.22**
RF power per cavity [kW]	**173**	**216**
Matched Q_{ext}	2.4E+06	3.0E+06

	Collider ring	**Accel. ring**
V_{RF} [GV]	12	9
P_{SR} [MW]	100	1

cf. LEP2: 812 m

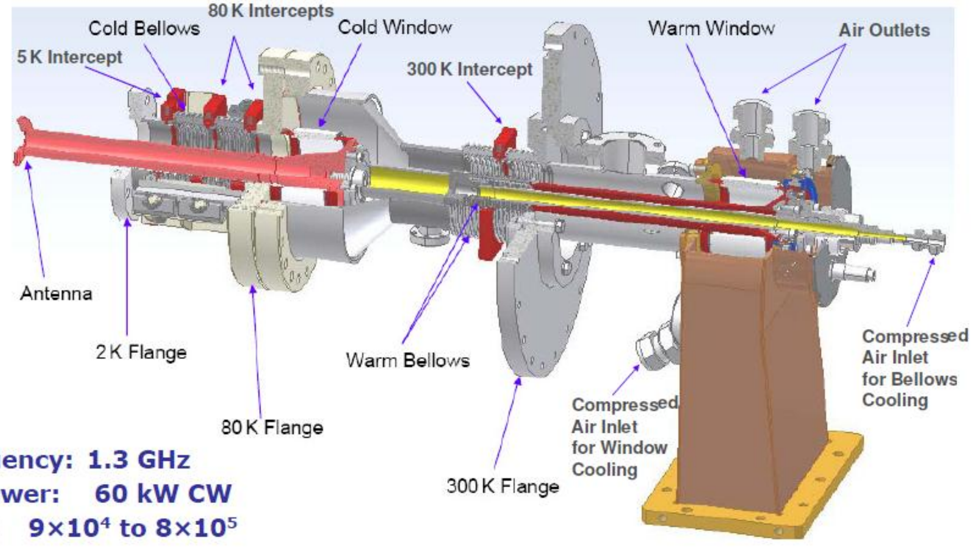
cf. LHC cryoplant capacity @ 1.9K of **2.4** or **2.1** kW per sector

Input power couplers which can handle these CW power levels?

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

Cornell ERL Injector Coupler



Frequency: 1.3 GHz
RF power: 60 kW CW
Q_{ext} : 9×10^4 to 8×10^5

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

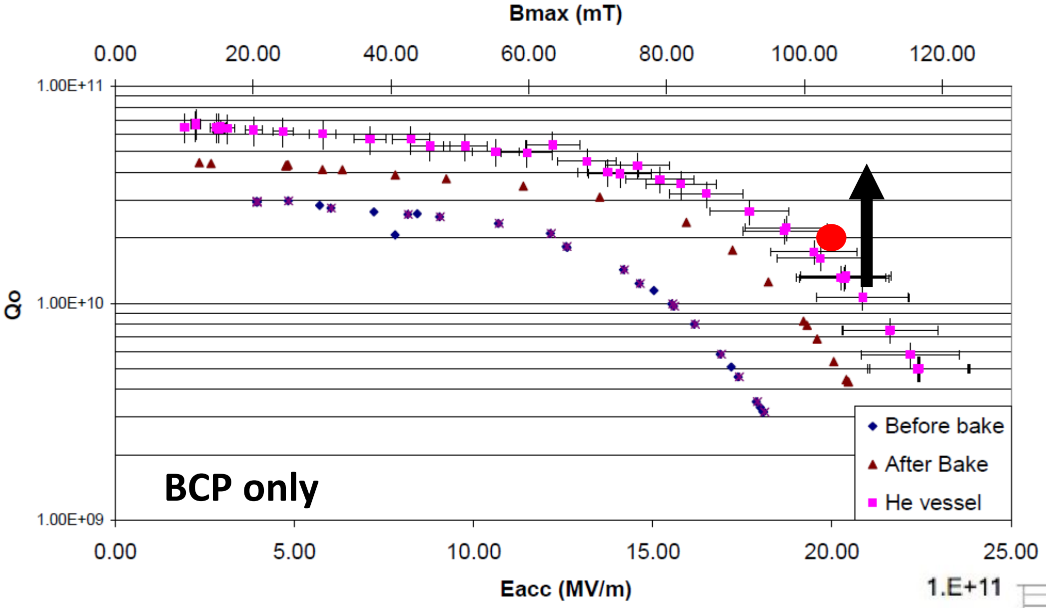
V. Vescherevitch, ERL’09

Developing a power coupler for 1.3 GHz high gradient and 200 kW CW looks challenging…

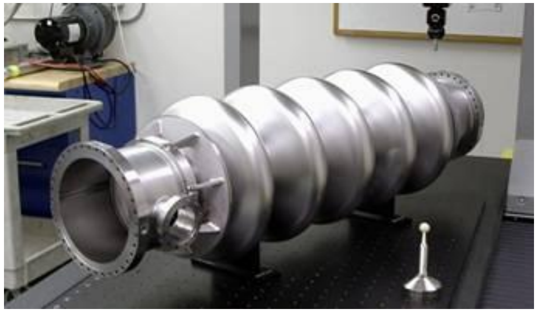
Option 2: 704 MHz eRHIC/SPL

- BNL 5-cell 704 MHz test cavity

  (A. Burill, AP Note 376, 2010)

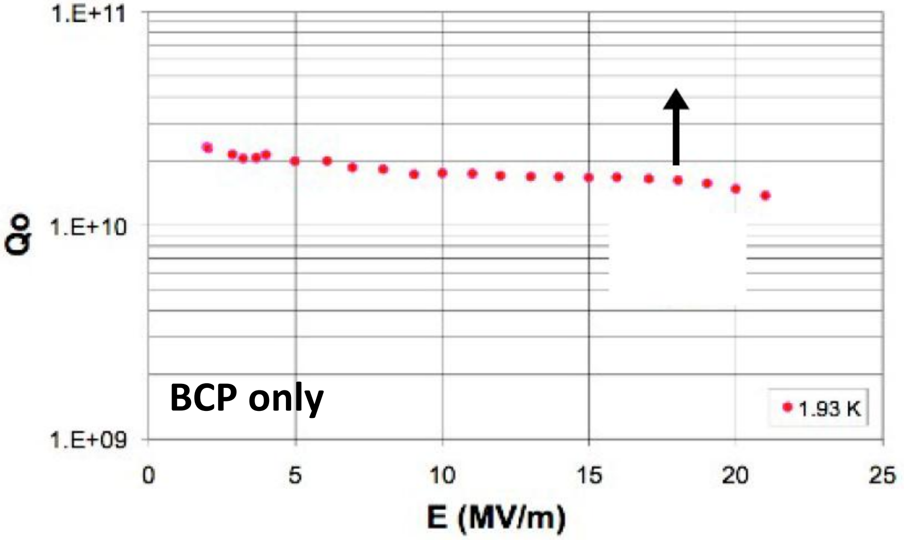


- First cavities, lots of room for improvement
- Measurement after only BCP surface treatment (no EP cf. TESLA cavities)



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

- JLab 748 MHz Cavity Test for high-current cryomodule



Option 2: 704 MHz (LEP3)

LEP3	**704 MHz 5-cell**
Gradient [MV/m]	**20**
Active length [m]	1.06
Voltage/cavity [MV]	21.2
Number of cavities	**567**
Total cryomodule length [m]	**902**
R/Q [linac ohms]	506
Q_0 [10^{10}]	2.0
Heat load per cavity [W]	44.4
Total heat load [kW]	25.2
Heat load per sector [kW]	**3.1**
Accel. ring @ 10% DF [kW]	**0.24**
RF power per cavity [kW]	**176**
Matched Q_{ext}	5.0E+06

	Collider ring	**Accel. ring**
V_{RF} [GV]	12	9
P_{SR} [MW]	100	1

cf. LEP2: 812 m

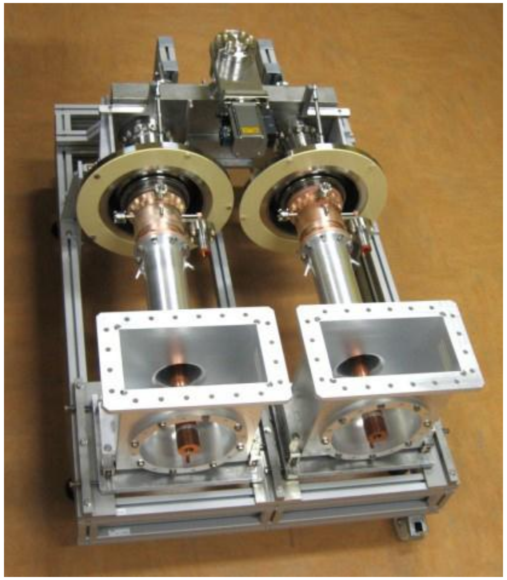
higher heat load despite higher Q_0 because of lower R/Q

cf. LHC cryoplant capacity @ 1.9K of **2.4** or **2.1** kW per sector

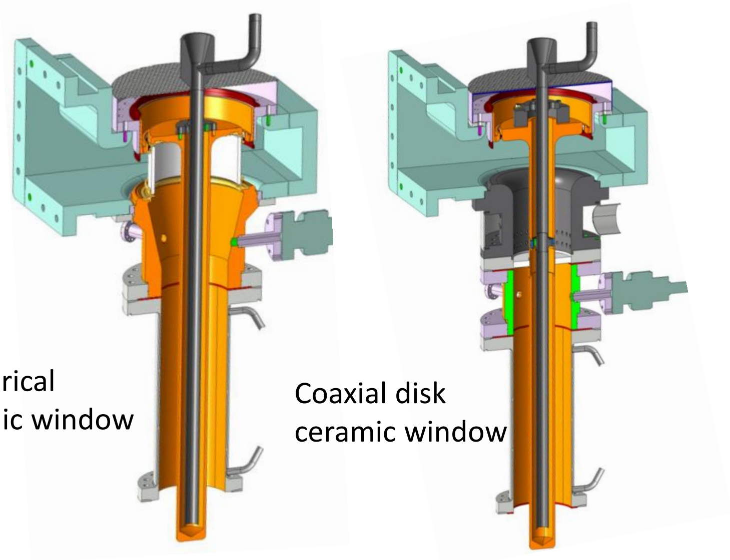
Input power couplers at 704 MHz for these power levels?

704 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



Cylindrical ceramic window

Coaxial disk ceramic window

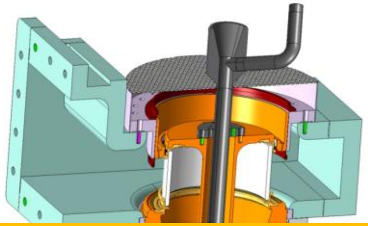
E. Montesinos

704 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 us 8 Hz

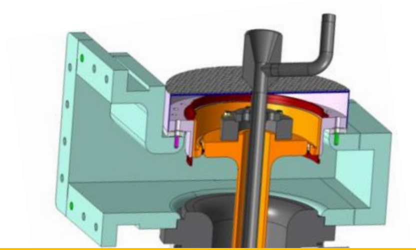


40 kW average power

Limited by arcing on air side of window

→ Improvements in window air flow and screen at braze

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



40 kW average power

Limited by losses in uncoated outer double walled tube

→ Improvements in coating

TLEP-H

TLEP-H	1300 MHz 9-cell		704 MHz 5-cell
Gradient [MV/m]	**20**	**25**	**20**
Active length [m]	1.038	1.038	1.06
Voltage/cavity [MV]	20.76	25.95	21.2
Number of cavities	**290**	**232**	**284**
Total cryomodule length [m]	**470**	**368**	**457**
R/Q [linac ohms]	1036	1036	506
Q_0 [10^{10}]	1.5	1.3	2.0
Heat load per cavity [W]	27.7	50.0	44.4
Total heat load [kW]	8.0	11.6	12.6
Heat load per sector [kW]	**1.01**	**1.45**	**1.58**
Accel. ring @ 10% DF [kW]	**0.04**	**0.06**	**0.07**
RF power per cavity [kW]	**344.8**	**431.0**	**352.1**
Matched Q_{ext}	1.2E+06	1.5E+06	2.5E+06

	Collider ring	**Accel. ring**
V_{RF} [GV]	6	2.5
P_{SR} [MW]	100	1

cf. LEP2: 812 m

- **Limited by power per cavity**
- **Install twice the # cavities with half the gradient?**

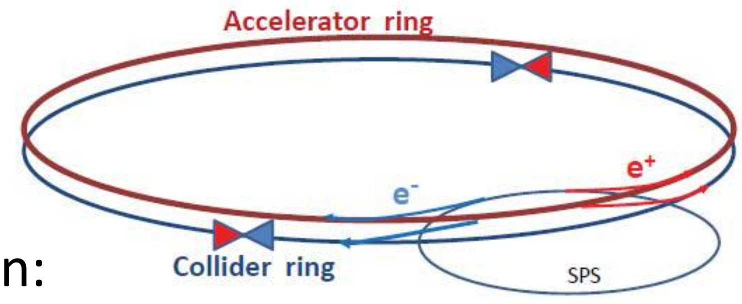
Very high power levels!
(2 x LEP3)

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

Top-up injector rings

- 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:

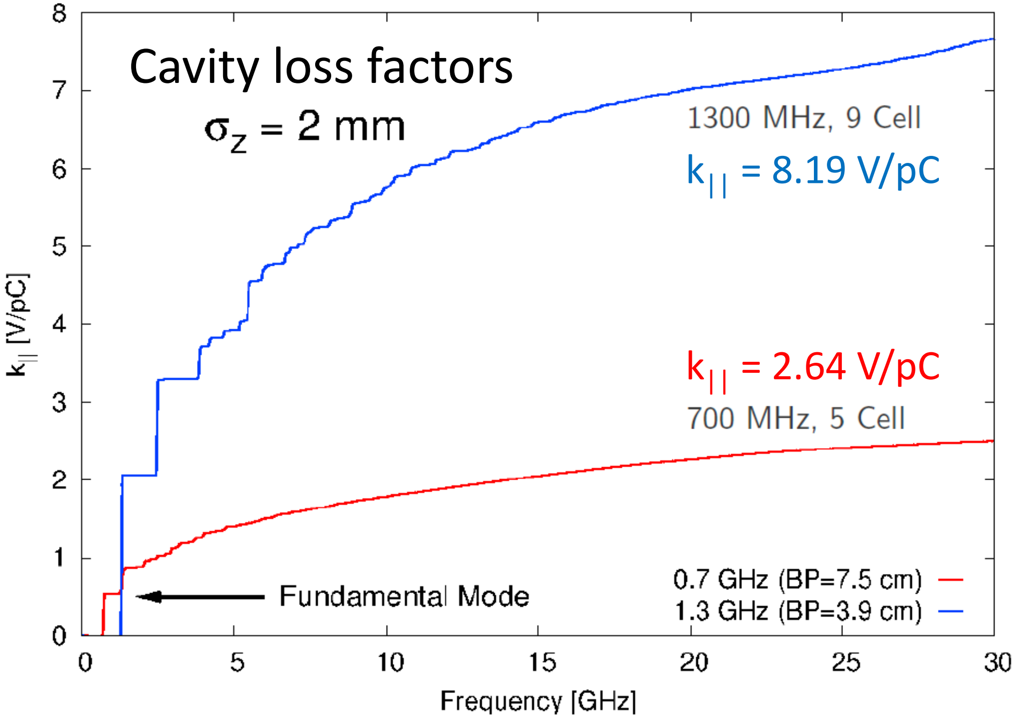


	LEP3	TLEP-H	TLEP-t
Beam current [mA]	0.14	0.48	0.054
Energy swing [GeV]	100	100	155
Max. SR power/cavity [kW]	6.2	8.5	6.2
Acceleration power [kW]	32	100	18
Max. power per cavity [kW]	**38**	**109**	**24**

Well within our 200 kW budget

Higher order mode power

R. Calaga



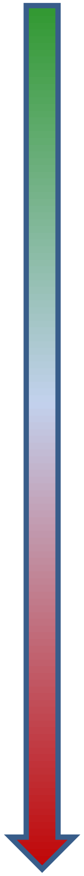
Average $P_{HOM} = k_{||} . Q_{bunch} . I_{beam}$

	LEP3	TLEP-H
Beam current [mA]	14.4	24.3
Bunch charge [nC]	160	41
HOM power (704 MHz cavities) [kW]	**6.1**	**10.4**
HOM power (1.3 GHz cavities) [kW]	18.8	32.3

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

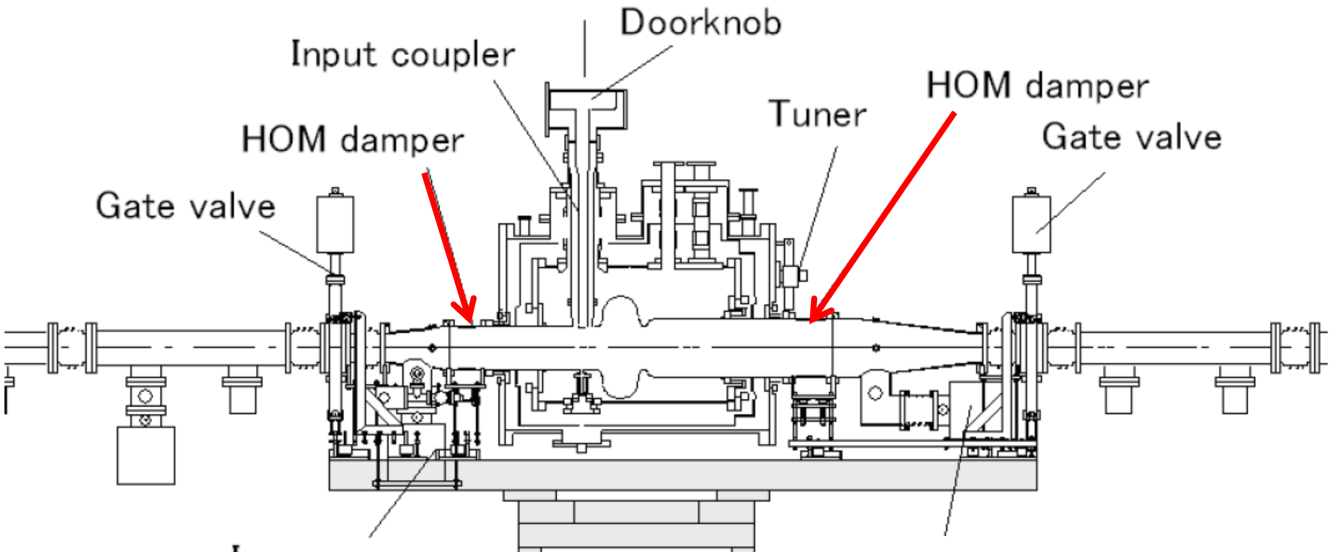
HOM power "league table"

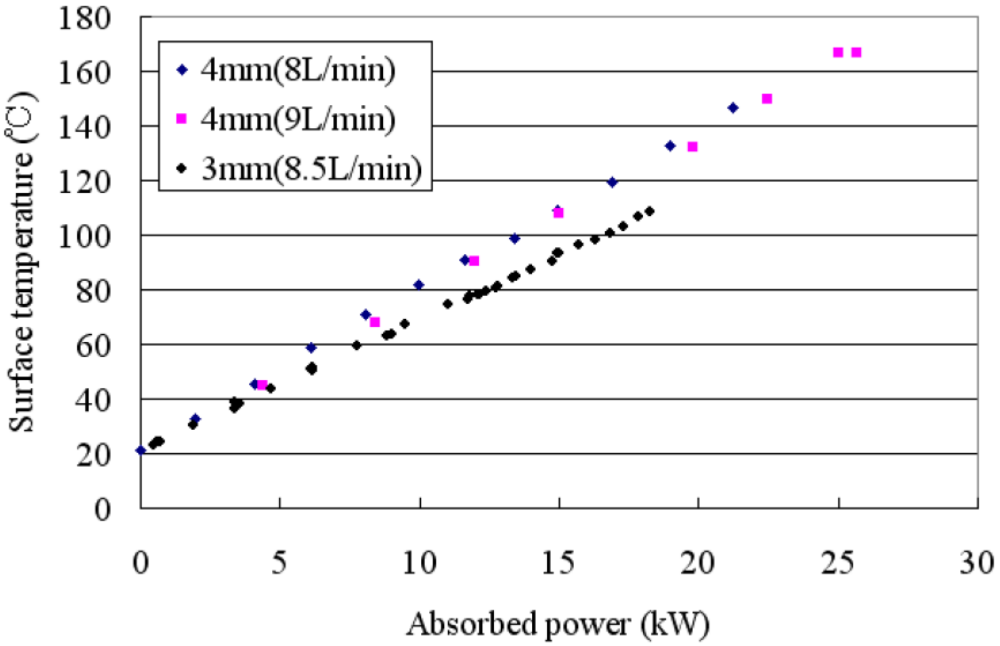
Project	**Beam current [mA]**	**Average HOM power per cavity [W]**
CEBAF 12GeV	0.10	0.05
Project X	1	0.06
XFEL	5	1
SPL	40	22
APS SPX	100	2,000
BERLinPro	100	150
KEK-CERL	100	185
Cornell ERL	100	200
eRHIC	300	7,500
KEKB	1,400	15,000
LEP3 704 MHz	**14**	**6,100**
TLEP-H 704 MHz	**49**	**10,400**
LEP3 1.3 GHz	**14**	**18,800**
TLEP-H 1.3 GHz	**49**	**32,100**



After M. Liepe, SRF2011

KEKB SC cavity HOM dampers





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

Y. Morita et al., IPAC10, Kyoto

HOM power “league table”

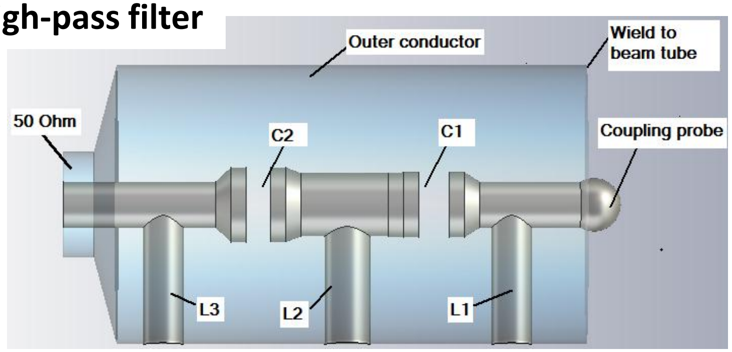
Project	Beam current [mA]	Average HOM power per cavity [W]
CEBAF 12GeV	0.10	0.05
Project X	1	0.06
XFEL	5	1
SPL	40	22
APS SPX	100	2,000
BERLinPro	100	150
KEK-CERL	100	185
Cornell ERL	100	200
eRHIC	300	7,500
KEKB	1,400	15,000
LEP3 704 MHz	**14**	**6,100**
TLEP-H 704 MHz	**49**	**10,400**
LEP3 1.3 GHz	**14**	**18,800**
TLEP-H 1.3 GHz	**49**	**32,100**

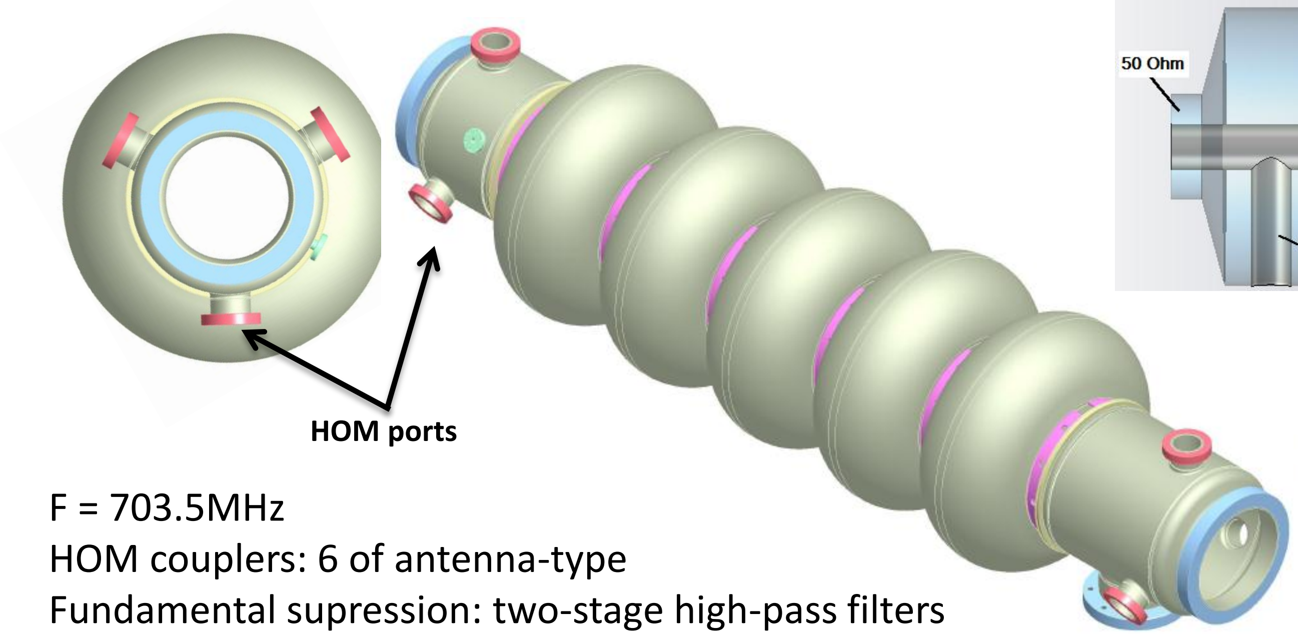
eRHIC /SPL/ESS
704 MHz cavities

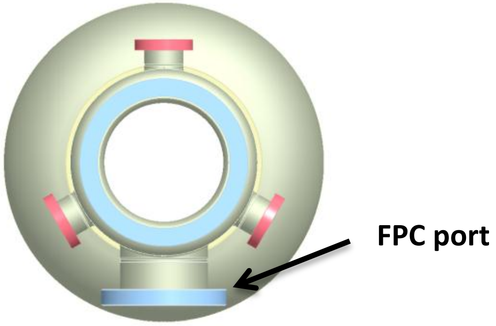
After M. Liepe, SRF2011

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

HOM power "league table"

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due to higher beam intensity.

→ needs study

After M. Liepe, SRF2011

RF power sources

- "Super-power" klystrons at 700 MHz
- Multiple cavities per klystron as in LEP2
- Could perhaps use IOTs (inductive output tubes) or solid state amplifiers for the injector ring (lower power required)

CPI
Communications & Power Industries

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

TOSHIBA

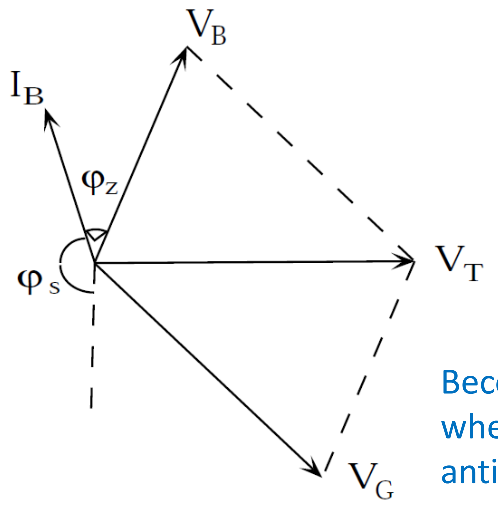
Type	Frequency (MHz)	Output Power (kW)	Efficiency (%)
E3732	508.6	1200	63
E37701*	1071.8	1200	63

THALES

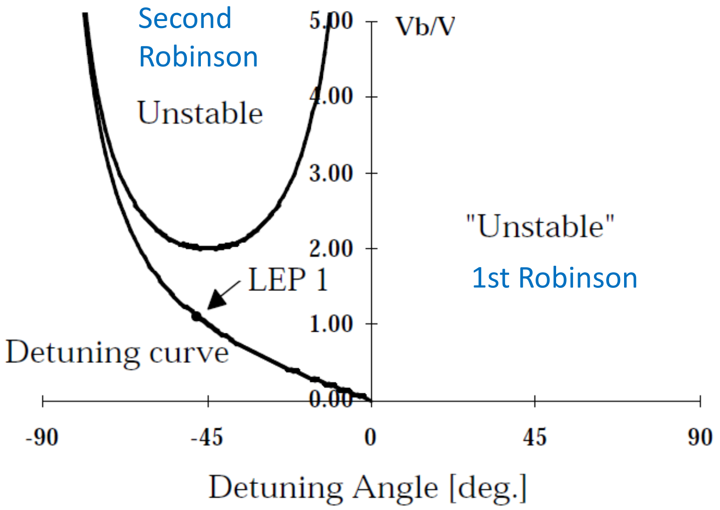
Type	Frequency (MHz)	Output Power (kW)	Efficiency (%)
TH2178	508.6	1200	62

LLRF: instabilities and feedbacks

- LEP2:
  - slow scalar sum feedback acting on the klystron modulation anode, with the klystrons operated at saturation for maximum efficiency
- Fast RF feedback may be desirable
  - especially for TLEP where f_{rev} is lower, detuning may drive coupled bunch modes
- 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



Becomes unstable when V_G is in antiphase with I_B



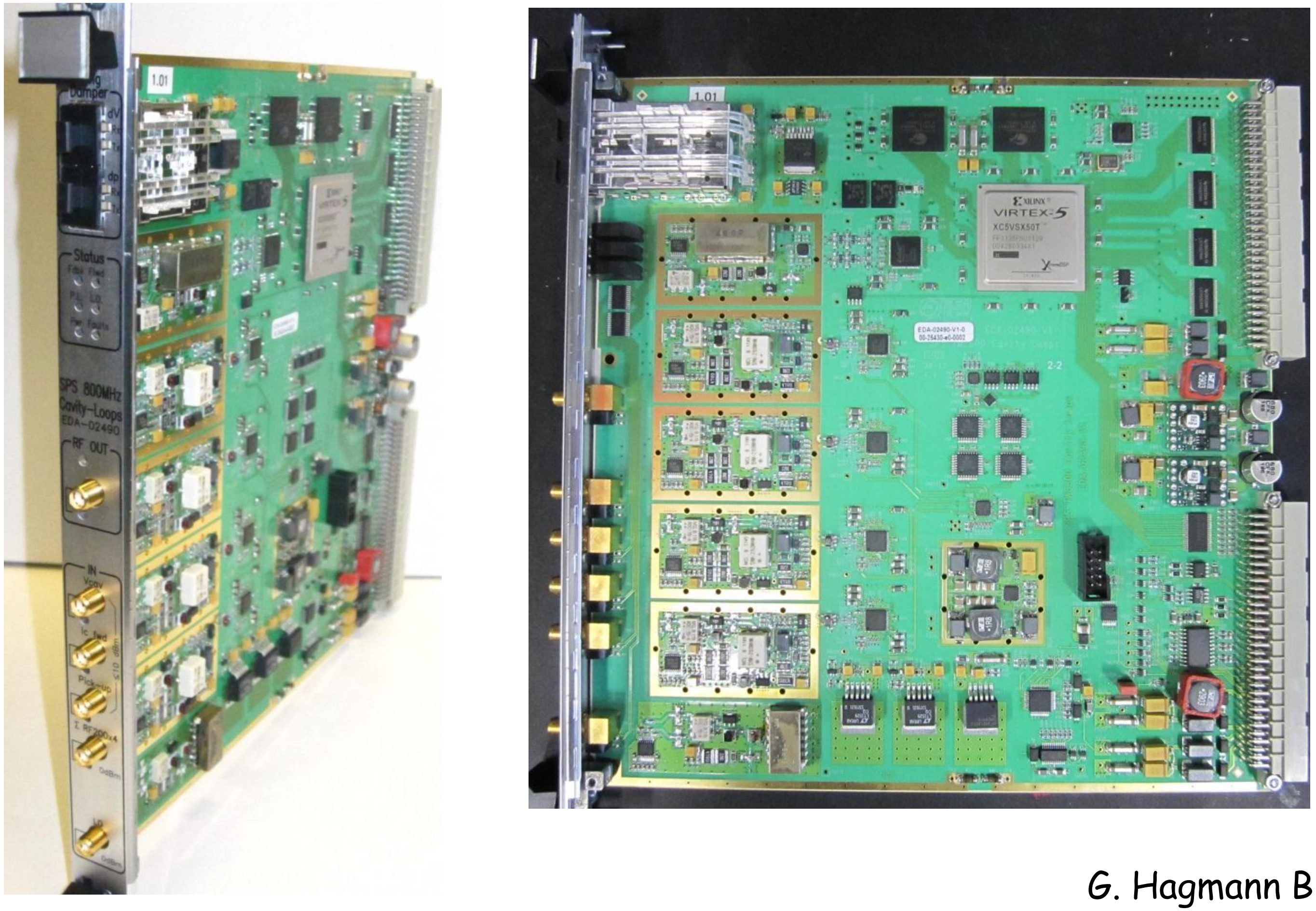
Tentative conclusions

- We cannot use ILC technology “off the shelf”
  - power coupler limitations
  - loss factors and HOM damping
- Backing off in frequency to 700 MHz seems preferable
  - ongoing R&D at BNL, CERN, ESS for 704 MHz cavities and components
  - fundamental power couplers look feasible at > 200 kW CW
  - compatible with HOM damping scheme for eRHIC
  - high-power klystrons available
- Cryogenic power will probably fit into the envelope of the existing LHC cryoplants (for LEP3)
- Open questions
  - power coupler design
  - HOM damping (especially for TLEP)
  - low level RF & feedback requirements

An RF system for a circular Higgs factory such as LEP3 or TLEP is not without its challenges but appears to be very feasible, especially as there are strong synergies with other ongoing development projects.

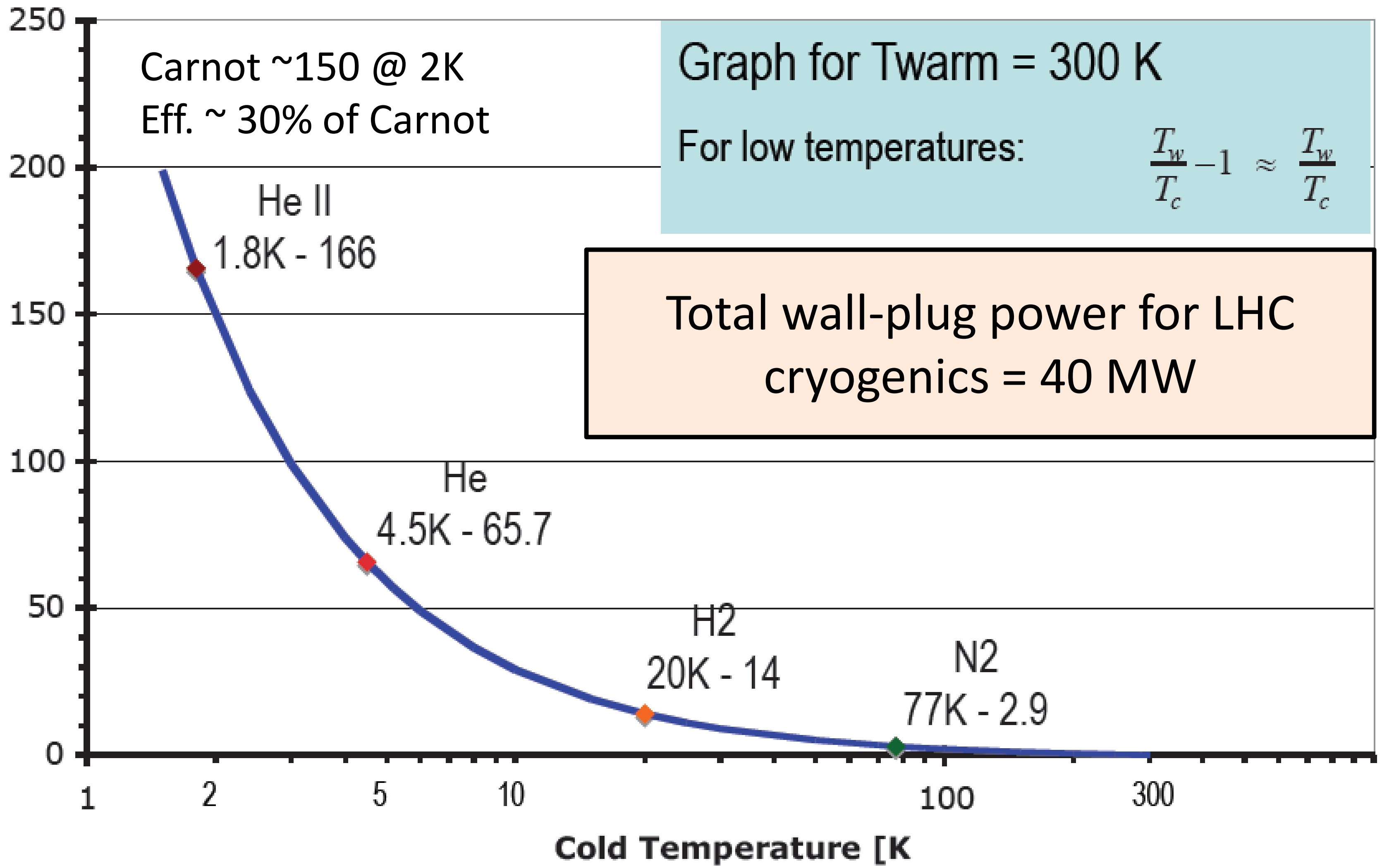
Thank you for your attention!

- SPS 800 MHz TWC prototype feedback board



G. Hagmann BE-RF-FB
designer

The Carnot Factor (2/3)



Carnot ~150 @ 2K
Eff. ~ 30% of Carnot

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