RF System Specifications for Nominal and 10Hz Operation

A. Gallo and R. Boni, INFN – LNF

(+ contributions of S. Belomestnykh, BNL)

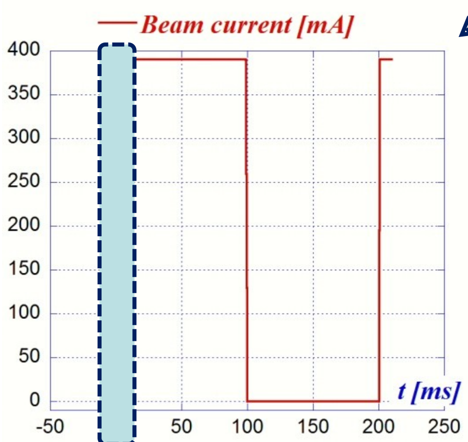
Damping Ring Technical Baseline Review

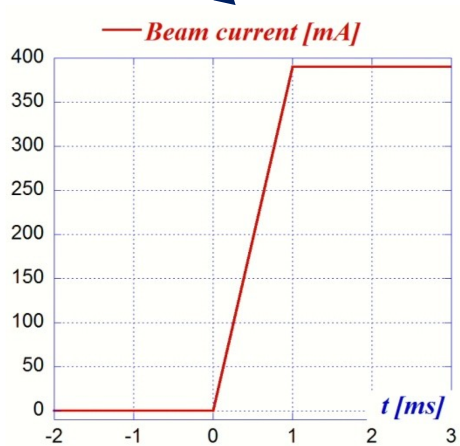
Frascati (Italy), July 7-8 2011

Presentation Outline

- *ILC Damping Ring parameters and operating options;*
- *e^+ DR RF system operation for the e^- linac 10 Hz configuration. Cavity tuning and coupling criteria;*
- *Characteristics of SC cavity scaled from 500 to 650 MHz;*
- *DR RF system parameter list compatible with all proposed operational configurations;*
- *DR RF system schematic layout;*
- *Harmonic cavities option;*
- *Costs and conclusions*

ILC Damping Ring: main parameter Table



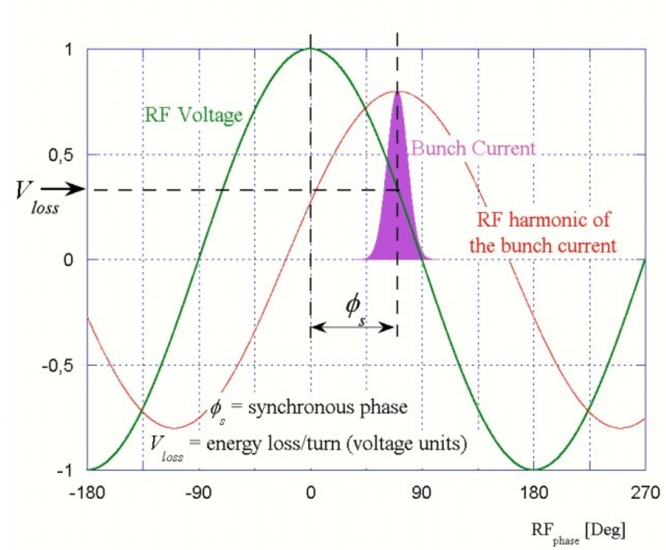


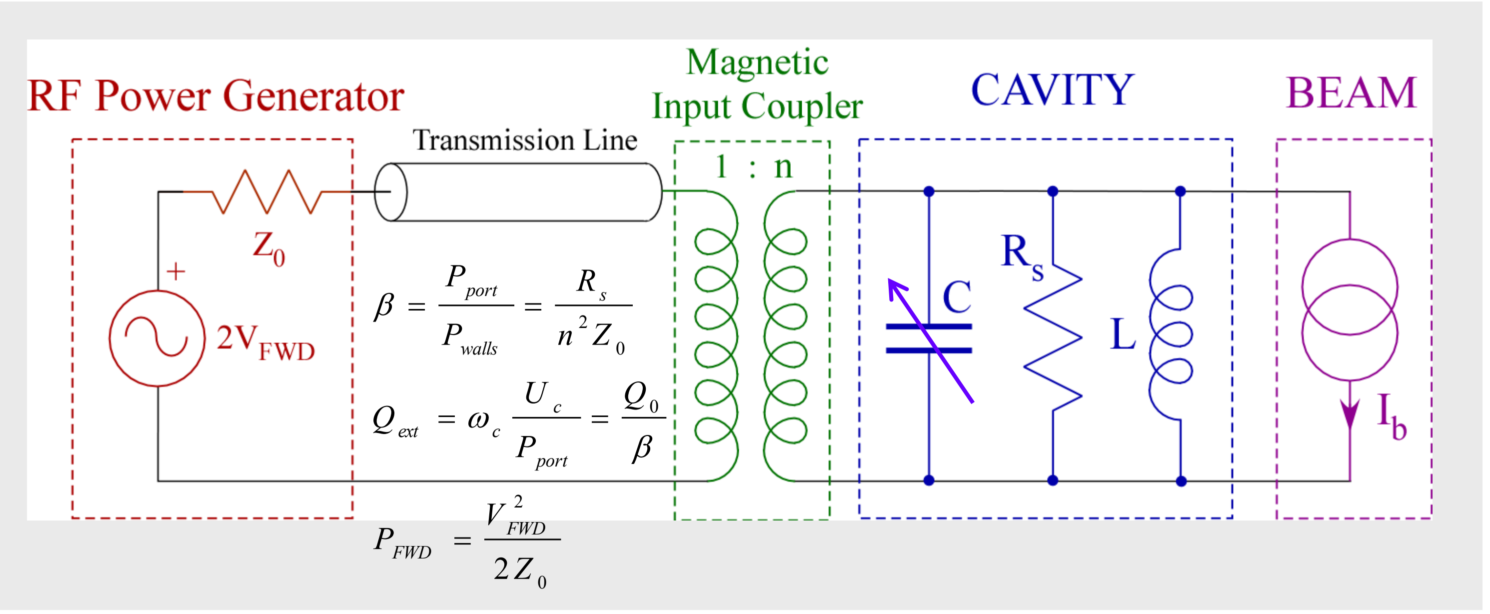
Parameter	5 Hz e^+/e^- (Low power)	5 Hz e^+/e^- (High power)
Energy [GeV]	5	
Circumference [m]	3200	
Emittance $\gamma\varepsilon_x$ [µm]	4.4	4.4
Damping time τ_x/τ_y [ms]	24.1	24.1
Beam current [mA]	390	780
Energy loss/turn [MeV]	4.5	4.5
Total beam power [MW]	1.76	3.51
Number of bunches	1305	2610
Bunch length σ_s [mm]	6	6
Energy spread σ_δ	0.11 %	0.11 %
Momentum compaction α_p	3.3×10^{-4}	3.3×10^{-4}
Overvoltage factor	3.11	3.11
RF frequency	650 MHz	

Generator - Cavity - Beam model: Beam loading

Beam loading problem is approached on the base of a circuital model allowing to compute:

- the overall **contribution** of the **beam** to the **accelerating voltage**;
- the **RF generator power** needed to sustain both cavity fields and beam;
- the **optimal values** of **cavity detuning** and **cavity-to-generator coupling** to minimize the power request to the generator.





$$\beta = \frac{P_{port}}{P_{walls}} = \frac{R_s}{n^2 Z_0}$$

$$Q_{ext} = \omega_c \frac{U_c}{P_{port}} = \frac{Q_0}{\beta}$$

$$P_{FWD} = \frac{V_{FWD}^2}{2Z_0}$$

Generator - Cavity - Beam model: Beam loading

The reflection coefficient ρ on the RF power transmission line according to the system model is given by:

$$\rho = \frac{\beta - 1 - \frac{R_s I_b}{V_c}\cos\phi_s - jR_s\left(\frac{\delta}{R/Q} + \frac{I_b}{V_c}\sin\phi_s\right)}{\beta + 1 + \frac{R_s I_b}{V_c}\cos\phi_s + jR_s\left(\frac{\delta}{R/Q} + \frac{I_b}{V_c}\sin\phi_s\right)}$$

Zero for optimal coupling factor

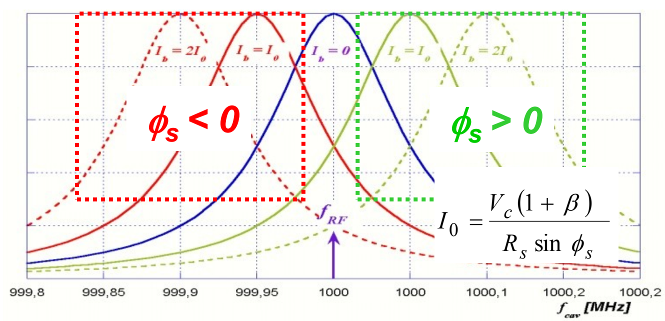
Zero for optimal cavity detuning

Being the detuning parameter δ defined as:

$$\delta = \frac{\omega_{RF}}{\omega_{cav}} - \frac{\omega_{cav}}{\omega_{RF}} \approx 2\frac{\Delta\omega_{RF-cav}}{\omega_{RF}}$$

minimizing the power reflection requires an optimal cavity detuning given by:

$$\delta = -\frac{I_b R/Q}{V_c}\sin(\phi_s) \quad \Rightarrow \quad \Delta\omega_{RF-cav} = -\omega_{RF}\frac{I_b R/Q}{2V_c}\sin(\phi_s)$$



Complete minimization of the power reflection requires also an optimal value of the input coupling coefficient β:

$$\beta_{opt} = 1 + \frac{I_b R_s}{V_c}\cos(\phi_s) = 1 + \frac{P_{beam}}{P_{cav}}$$

$$P_{FWD} = \frac{1}{2}\frac{V_c^2}{R_s} + \frac{1}{2}I_b V_c \cos(\phi_s) = P_{cav} + P_{beam}$$

acceleration off-crest of a large beam current may require large cavity detuning !

Operation of the e^+ Damping Ring RF system in the e^- linac 10 Hz modality

The standard storage ring approach consisting in RF cavity real time tuning to perfectly compensate the reactive beam loading is unrealistic in the e^+ DR in ILC 10 Hz modality because:

- Injection/extraction times are **orders of magnitude smaller** compared to ordinary storage rings;
- SC Cavity tuners are **slower** and **excursion limited** respect to NC cavity ones.

The simplest solution is to find conditions to operate the cavities at some optimal fixed tuning position, provided that the resulting mismatch could be limited and the RF power sources need to be oversized only by a small amount.

Operation of the e^+ Damping Ring RF system in the e^- linac 10 Hz modality

According to the generator-cavity-beam circuital model, the RF power needed to sustain the beam and the cavity field is given by:

$$P_{FWD} = \frac{V_c^{\,2}}{4\,R/Q \cdot Q_{ext}} \cdot \frac{(\beta+1)^2}{\beta^2} \cdot \left\{ \left[1 + \frac{I_b\, R/Q \cdot Q_L}{V_c} \cos\varphi_0 \right]^2 + \left[\tan\psi + \frac{I_b\, R/Q \cdot Q_L}{V_c} \sin\varphi_0 \right]^2 \right\} \approx$$

$$\approx \frac{V_c^{\,2}}{4\,R/Q \cdot Q_L} \cdot \left\{ \left[1 + \frac{I_b\, R/Q \cdot Q_L}{\eta\, V_c} \right]^2 + \left[\tan\psi - \frac{I_b\, R/Q \cdot Q_L}{V_c} \frac{\sqrt{\eta^2 - 1}}{\eta} \right]^2 \right\}$$

where $\beta >> 1$ is the coupling factor, $Q_L \approx Q_{ext}$ is the cavity loaded quality factor, φ_0 is the synchronous phase, ψ is the cavity tuning angle ($\tan\psi = Q_L\delta$), $\eta = V_c/V_{loss}$ is the overvoltage factor.

The first term includes active part of beam loading (due to particle energy loss), the second term includes reactive beam loading. The latter is usually compensated in real time by appropriate cavity detuning with a mechanical tuner so that the second term in square brackets is always zero. And then for maximum beam current and optimal cavity coupling the power demand is simply equal to the beam power per cavity.

Cavity operation at fixed detuning. Case $\eta \leq 2$

The optimization of the parameter set for the operation of a cavity at fixed tuning has been studied analytically.

As a first step, we assumed to set the input coupling and the cavity detuning at the values matching the maximum current value expected in operation:

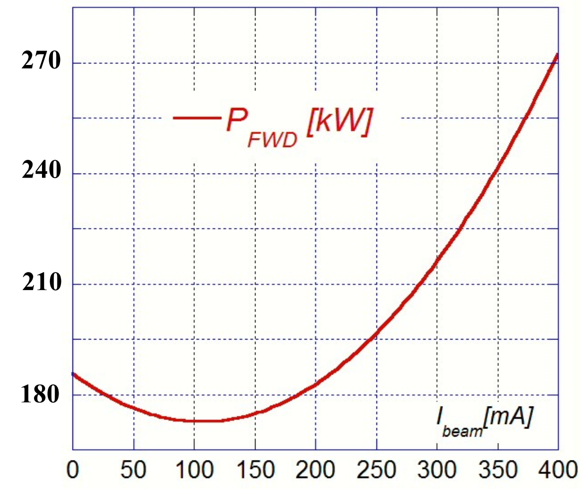
$$Q_{ext}^{match} \approx \frac{V_c}{(R/Q)\, I_{b_{\max}} \cos \varphi_0} = \frac{\eta V_c}{(R/Q)\, I_{b_{\max}}}$$

$$\tan \psi_{\max} \approx -\frac{(R/Q)\, Q_{ext}\, I_{b_{\max}}}{V_c} \sin \varphi_0 = \frac{(R/Q)\, Q_{ext}\, I_{b_{\max}}}{V_c} \sqrt{1 - \frac{1}{\eta^2}} = \sqrt{\eta^2 - 1}$$

Under this conditions the system is maximally mismatched at $I_b=0$. The RF power necessary to sustain the cavity fields at the required level is given by:

$$P_{FWD}(I_b = 0) = P_{beam_{\max}} \left[\frac{1}{4} + \frac{\tan^2 \psi_{\max}}{4} \right] = \left(\frac{\eta}{2} \right)^2 P_{beam_{\max}}$$

where η is the overvoltage factor. One can see that for $\eta \leq 2$ the cavities can be operated constantly tuned for the maximum current, and the power demand for zero beam current does not exceed the maximum beam power.



Cavity operation at fixed detuning. Case $\eta \geq 2$

In the case $\eta \geq 2$ the previous approach is no longer optimal since the RF power demand at 0 current overcomes the full current beam one. The cavity tuning and coupling optimization starts again from the forward RF power expression for generic values of input coupling Q_{ext} and cavity tuning angle ψ :

$$P_{FWD}(I_b) \approx \frac{V_c^2}{4(R/Q)Q_{ext}}\left[\left(1+\frac{I_b(R/Q)Q_{ext}}{\eta V_c}\right)^2+\left(\tan\psi-\frac{I_b(R/Q)Q_{ext}}{\eta V_c}\sqrt{\eta^2-1}\right)^2\right]$$

Since for $\eta \geq 2$ a generator power P_{gen} larger than the maximum beam power is required at $I_b=0$, it is worth to optimize the 2 free parameters Q_{ext} and ψ to fulfill the 2 conditions:

Power equalization at the range edges

$$\begin{cases} P_{FWD}(I_b=0)=P_{FWD}(I_{b_{max}})=P_{Gen} \\ \dfrac{dP_{Gen}}{dQ_{ext}}=0 \end{cases}$$

$$\Rightarrow \quad \tan\psi = \frac{1}{\sqrt{\eta^2-1}}\left(1+\frac{\eta}{2}\frac{I_{b_{max}}(R/Q)Q_{ext}}{V_c}\right)$$

Power minimization

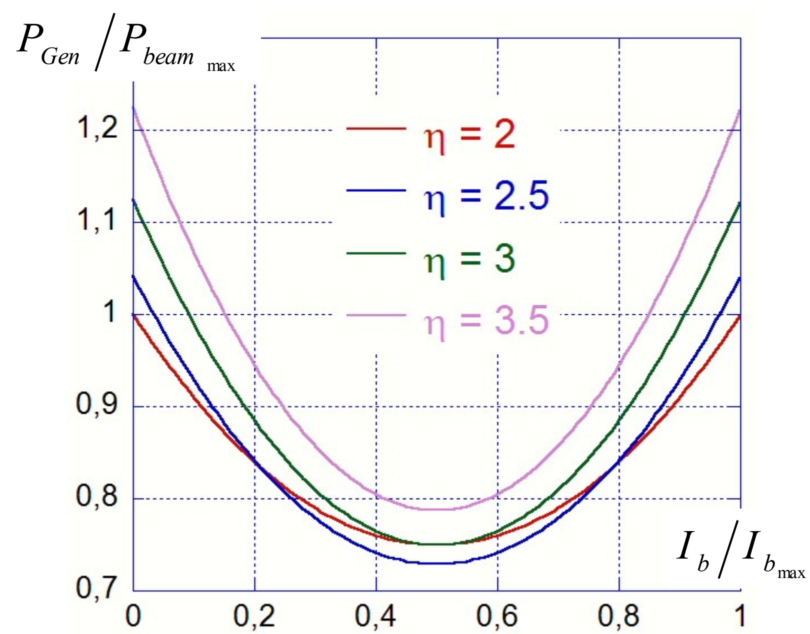
Cavity operation at fixed detuning. Case $\eta \geq 2$ (cnt'd)

Through some algebra, optimal values of Q_{ext} and ψ are obtained:

$$Q_{ext}^{opt} = \frac{2V_c}{I_{b_{\max}}(R/Q)} = \frac{2}{\eta} Q_{ext}^{match}$$

$$\tan \psi'_{opt} = \frac{1+\eta}{\sqrt{\eta^2 - 1}} = \sqrt{\frac{\eta + 1}{\eta - 1}}$$

$$P_{Gen} / P_{beam_{\max}} = \frac{\eta^2}{4(\eta - 1)}$$



Optimal choice of Q_{ext} and ψ parameters allows limiting the required generator power overhead.

For instance, it is possible to run the system with an overvoltage factor $\eta = 3$ at the cost of only 12.5 % of increased RF power.

First Robinson limit and direct RF feedback cure

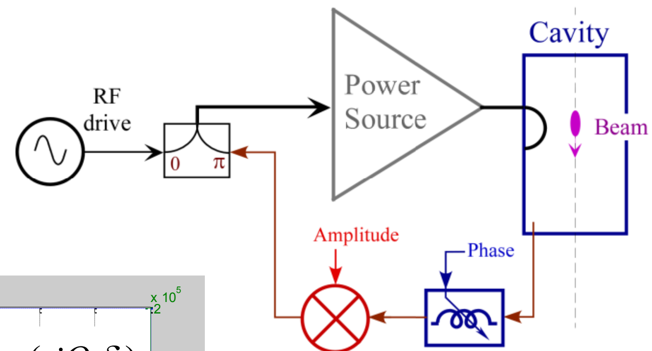
A fixed tuning working point is potentially unstable with respect to the Robinson first limit (decrease of the coherent frequency for barycentric synchrotron oscillations). The ratio between coherent and incoherent synchrotron frequencies is given by:

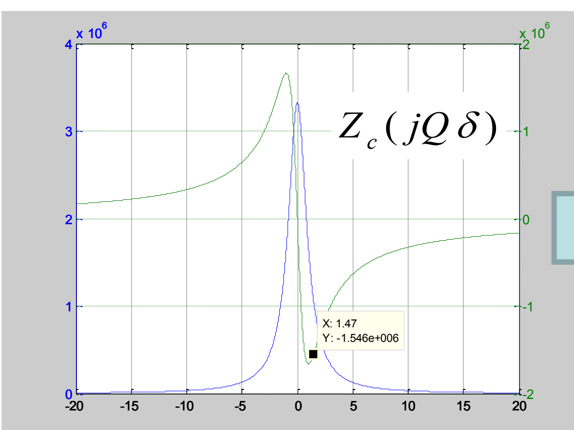
$$\left(\frac{\omega_{sc}}{\omega_{si}}\right)^2 = 1 - \frac{I_b\left(Z_i^+ + Z_i^-\right)}{V_c \sin\phi_0}$$

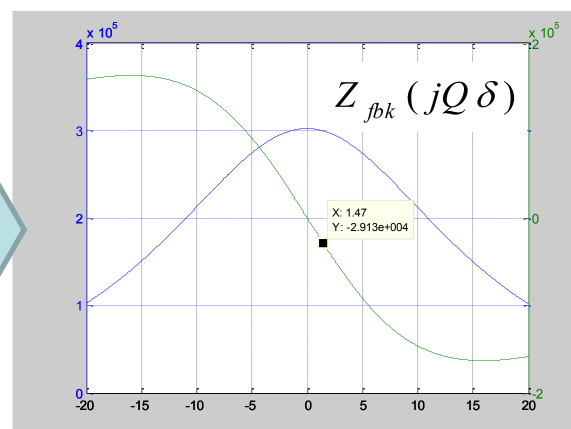
$Z_i^{\pm}$ = cavity impedance imaginary part sampled at the synchrotron sidebands around the RF harmonics

Direct RF feedback connection can be used to reduce the effective impedance imaginary parts, limiting the frequency shift.

$$Z_{fbk}(j\omega) = \frac{Z_c(j\omega)}{1 + H(j\omega)}$$







Impedance reduction of two orders of magnitude can be obtained (negligible frequency shift)

SUMMARY: 10 Hz operation of the e^+ DR

- 10 Hz operation of the ILC Damping Ring RF system seems to be feasible.
- Cavity operation at fixed tuning is the most easily implementable configuration. No extra RF power is required for overvoltage factors η lower than 2, while optimal choice of the coupling and tuning parameters allow working up to $\eta = 3$ with modest RF power increase.

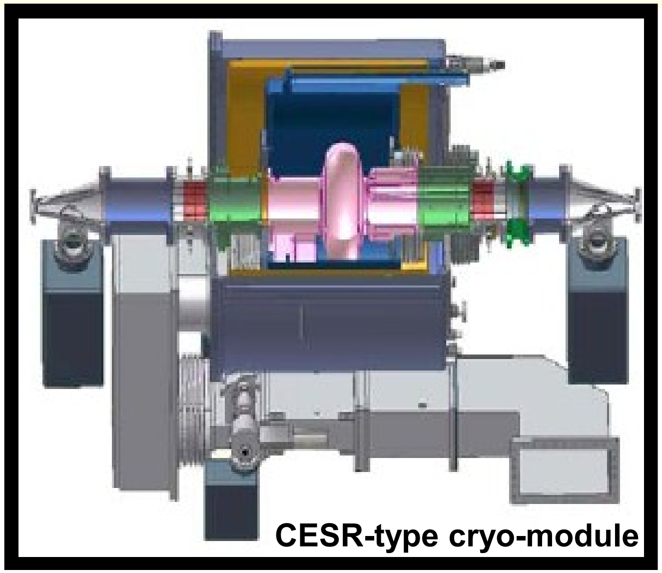
Concerns & studies needed (in addition to those listed for individual options):

- RF window/coupler power handling with full reflection
- Feedforward to mitigate transients during beam injection/extraction
- Pulsed operation of the RF system is worth considering as it will save power and reduce thermal load on RF window/coupler. Pulsed RF operation can be obtained through different techniques, depending on the RF power transmitter technology (most likely klystrons).

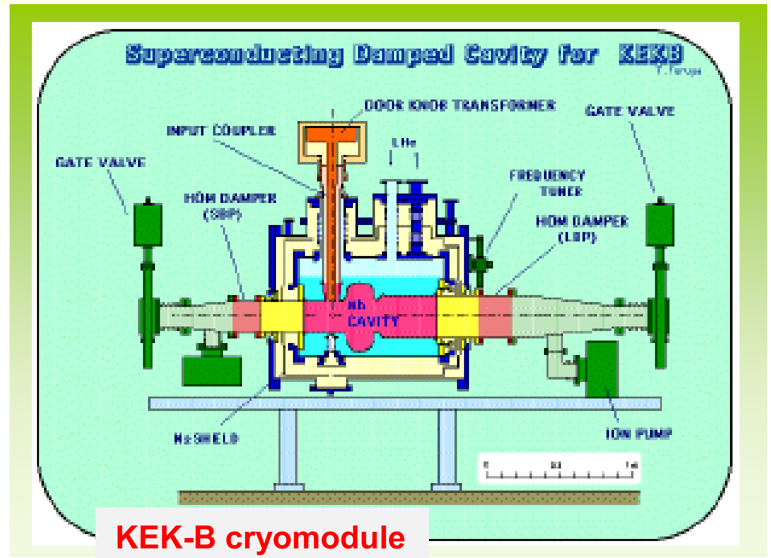
CAVITY CHOICE

- **SRF Cavities operating @ 500 MHz**

  are widely and successfully utilized in various storage rings (CESR, Diamond, KEKB, SRRC, CLI, Soleil, SLS, ...)



CESR-type cryo-module



KEK-B cryomodule

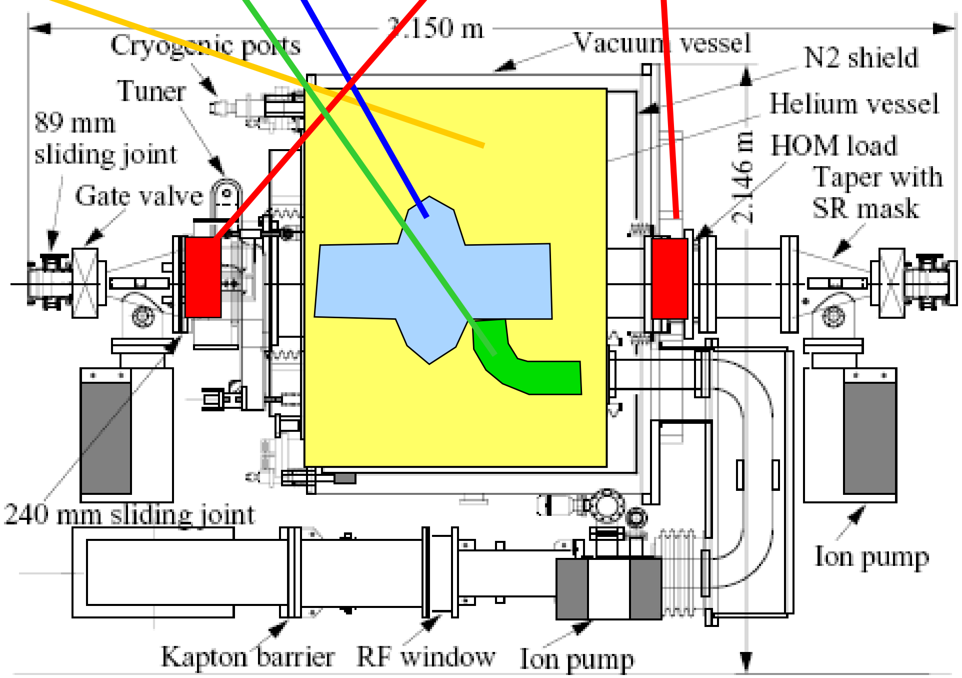
- *They are " single Nb-cell " housed in cylindrical cryo-modules and immersed in 4.5K liquid He.*
- *The cavities are in practice "single-mode" resonators thanks to highly effective HOM dampers wrapped-around the cavity ends beam pipe.*
- *Those SRF cavities are being routinely operated at 5 ÷ 7 MV/m.*

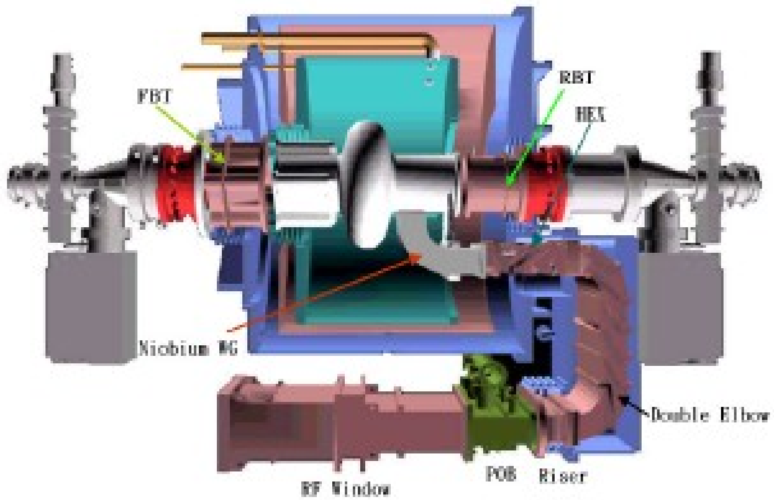
- *The development of 650 MHz SRF cavities, derived from existing 500 MHz units, requires to be in part re-designed .*

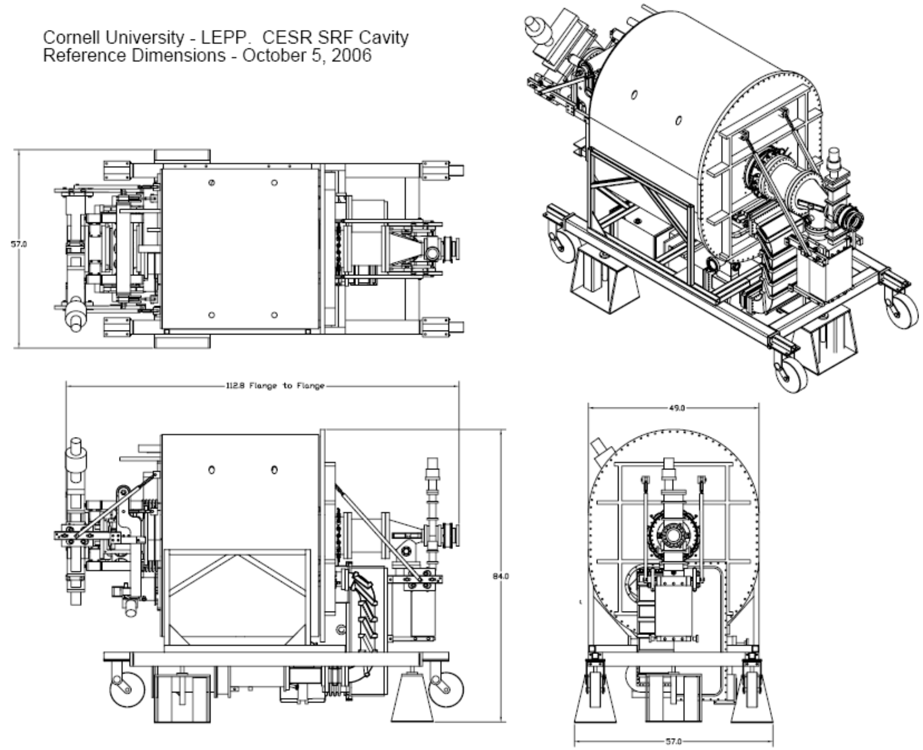
The main modifications are :

- *Cavity profile scaling to 650 MHz*
- *New HOM characterization and new re-sized HOM dampers*
- *New design of the power coupler*
- *Cryostat revision (… possible operation @ 2 K ?)*

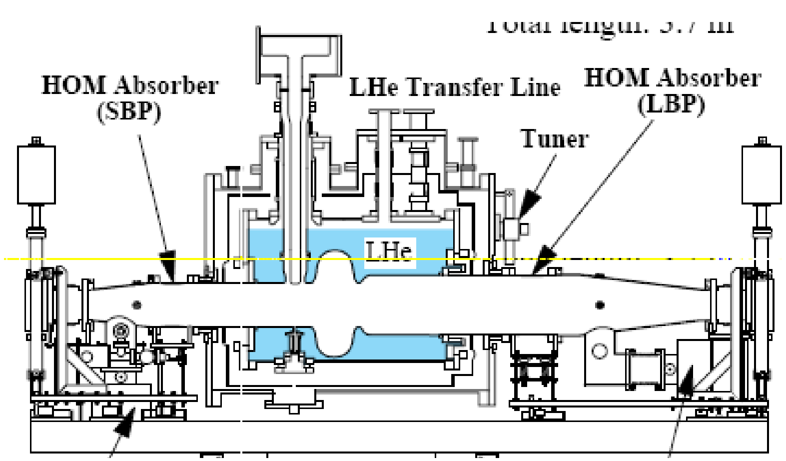
SRRC 500 MHz cryo-module





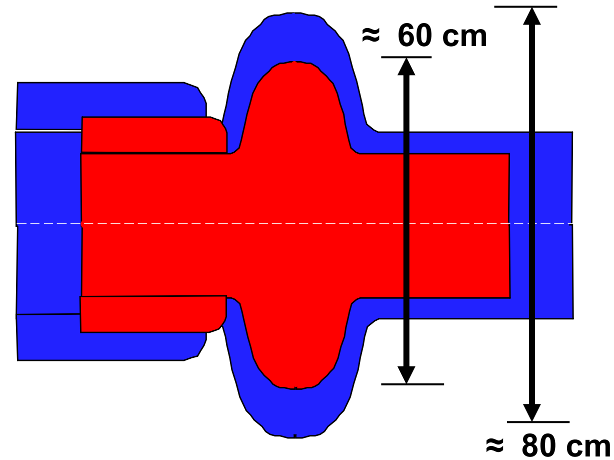


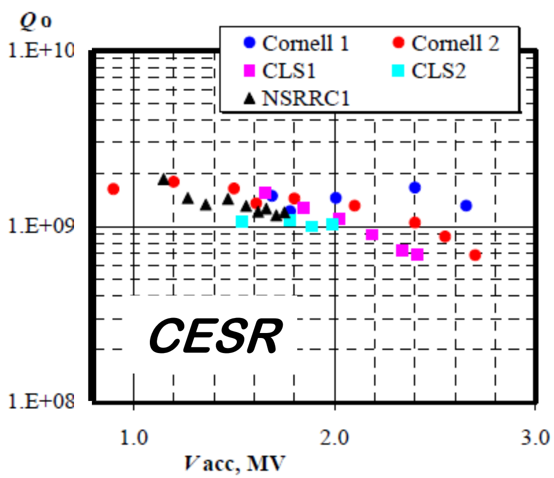
CESR 500 MHz CRYO-MODULE

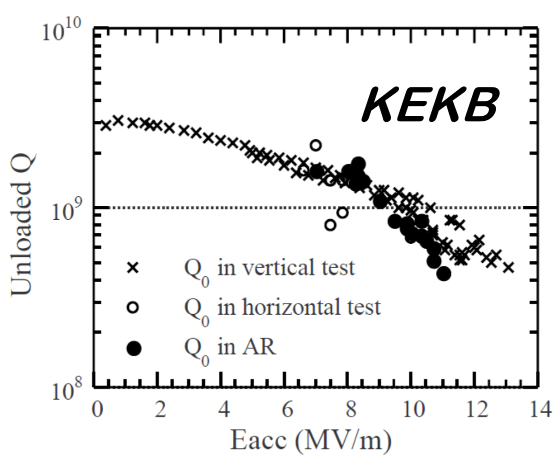


KEK-B 500 MHz CRYO-MODULE

- The specifications of a new 650 MHz sc cavity may be estimated by scaling dimensions and parameters of the 500 MHz sc cell.







Frequency	500 MHz	650 MHz
Active cavity lenght	0.30 m	0.23 m
R/Q (CESR cell)	89 Ω	89 Ω
Operating tempature	4.5 K	4.5 K
Static losses	≤ 30 W	≈ 30 W
Accelerating gradient	> 8 MV/m	≈ 7.5 MV/m
Q_0 [x10^9]	≈ 1.0 @ 7 MV/m ≈ 1.5 @ 5 MV/m	≈ 0.6 @ 7 MV/m ≈ 1.0 @ 5 MV/m

DR RF System specifications *(scaling from 500 MHz cryo-modules)*

Parameter	10 Hz e^+	5 Hz e^+/e^- (Low power)	5 Hz e^+/e^- (High power)
RF frequency	650 MHz		
Total RF voltage [MV]	19.7	14	14
Overvoltage factor	2.46	3.11	3.11
Cavity R/Q [Ω]	89		
Cavity active length [m]	0.23		
Number of cavities	12	12	12
Cavity RF voltage [MV]	1.64	1.17	1.17
Cavity average gradient [MV/m]	7.1	5.1	5.1
Cavity input power [kW]	260	146	293
Ideal input coupling Q_{ext} [$\cdot 10^3$]	116.5	104.6	52.3
Input coupler Q_{ext} [$\cdot 10^3$]	65		
Cavity tuning	fixed, $\tan\psi \approx 1.2$ (#)	stationary	stationary
RF Reflected power @ nominal beam current	8.91 %	5.76 %	1.19 %
Total RF power [MW] (*)	3.40	1.86	3.55
Number of klystrons/ring	6	6	6
Klystron power [kW]	650 kW (including ≈10 % overhead)		
Operating temperature [K]	4.5		
Q_0 ($\times 10^9$) @ operating gradient	0.6	1	1
Cryo-RF losses per cavity [W]	50	15	15
N. of cryomodules per ring	12	12	12
Static cryo-losses [W]	30		
Total cryo-losses per ring [W]	960	540	540

- Efficiency of standard refrigerators:

  @ 4.5 K ≈ 0.3 %

- Wall-plug power per refrigerator per ring

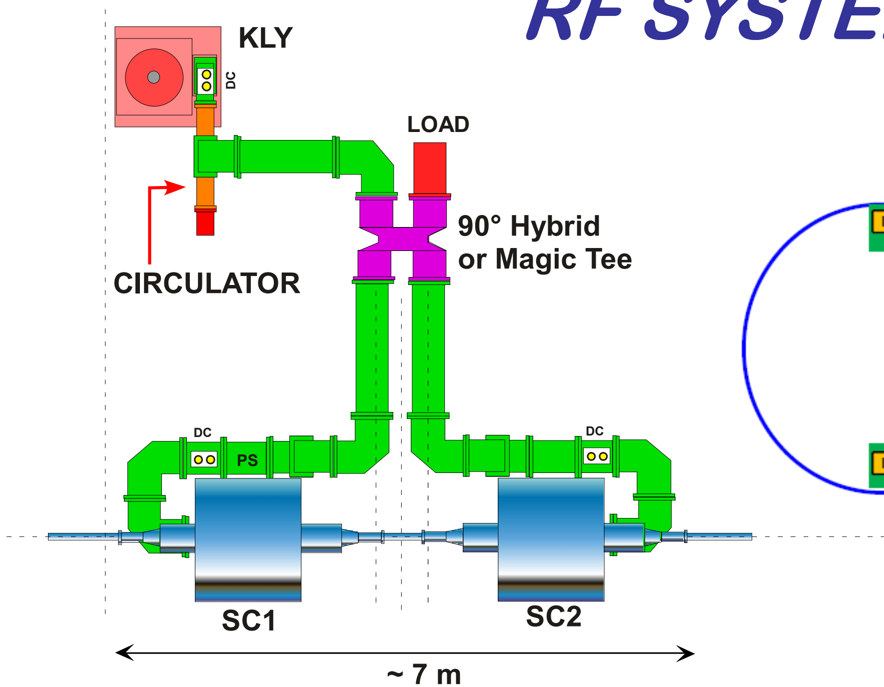
  ≈ 320 kW

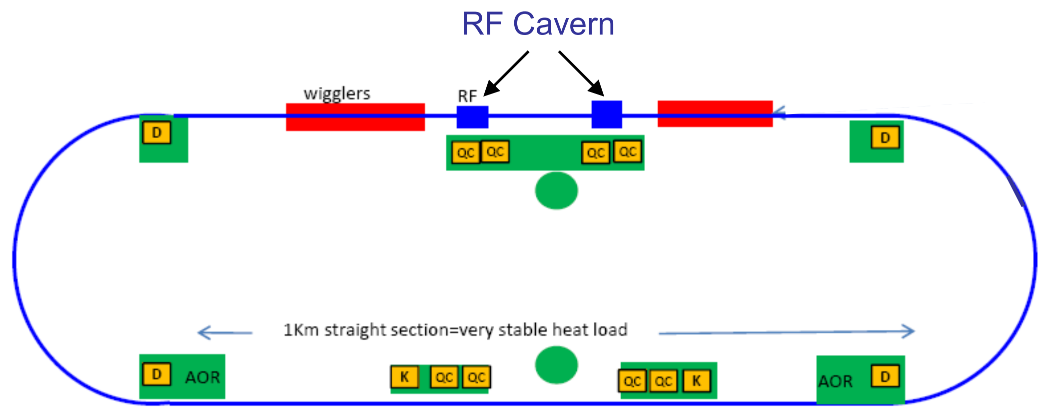
(*) HOM Power not included

(#)

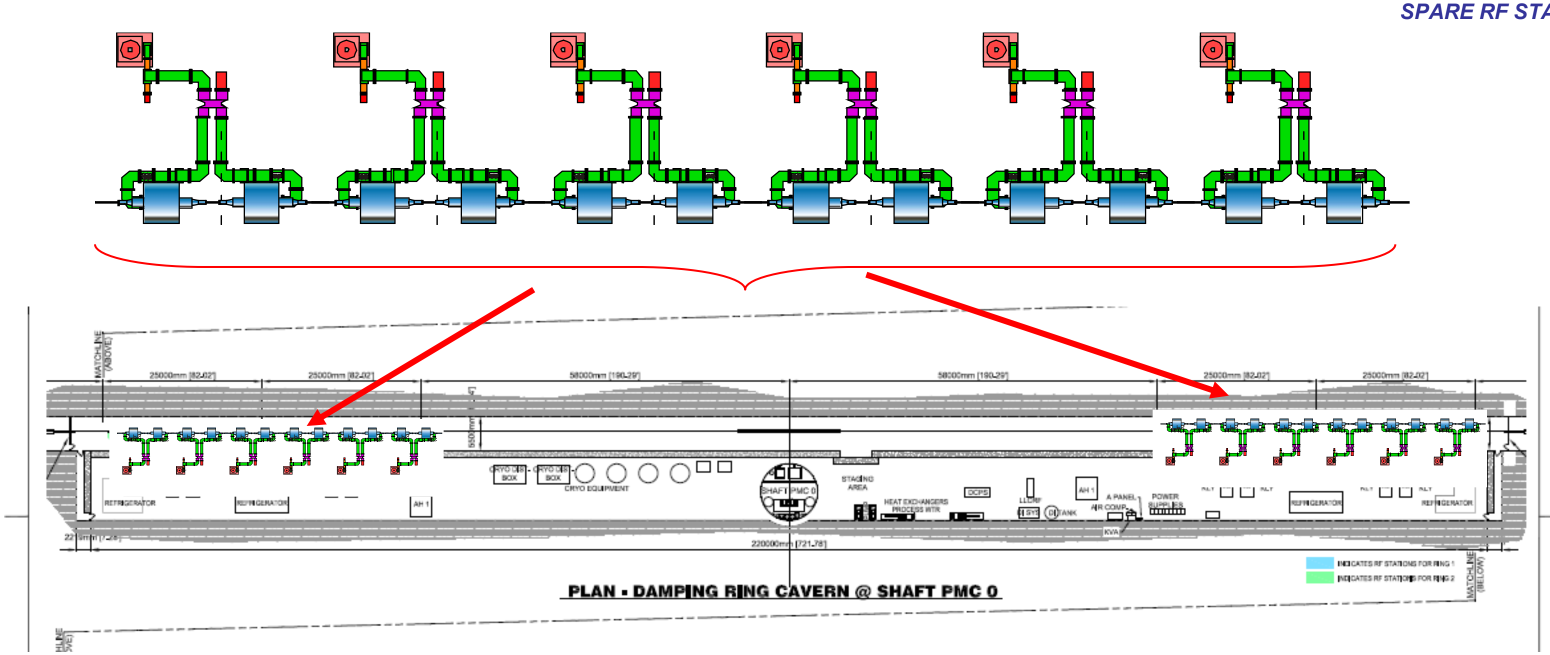
$$\tan\psi = \frac{1}{\sqrt{\eta^2 - 1}}\left(1 + \frac{\eta}{2}\frac{I_{b_{max}}(R/Q)Q_{ext}}{V_c}\right)$$

RF SYSTEM LAYOUT

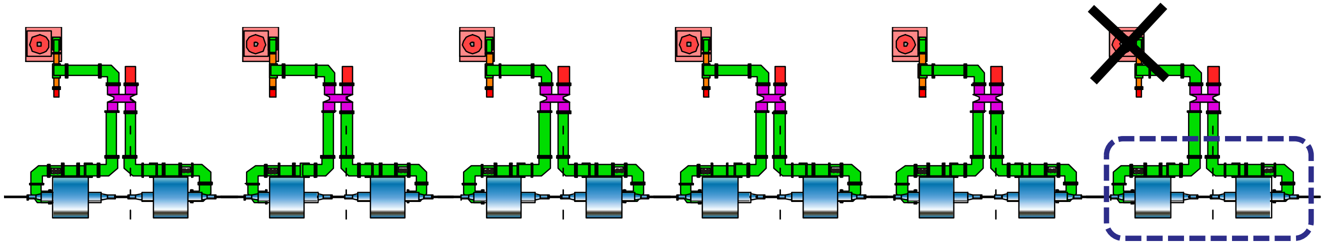




SPARE RF STATION **?**



DR RF System operation against failure of 1 klystron



→ *Passive cavities*

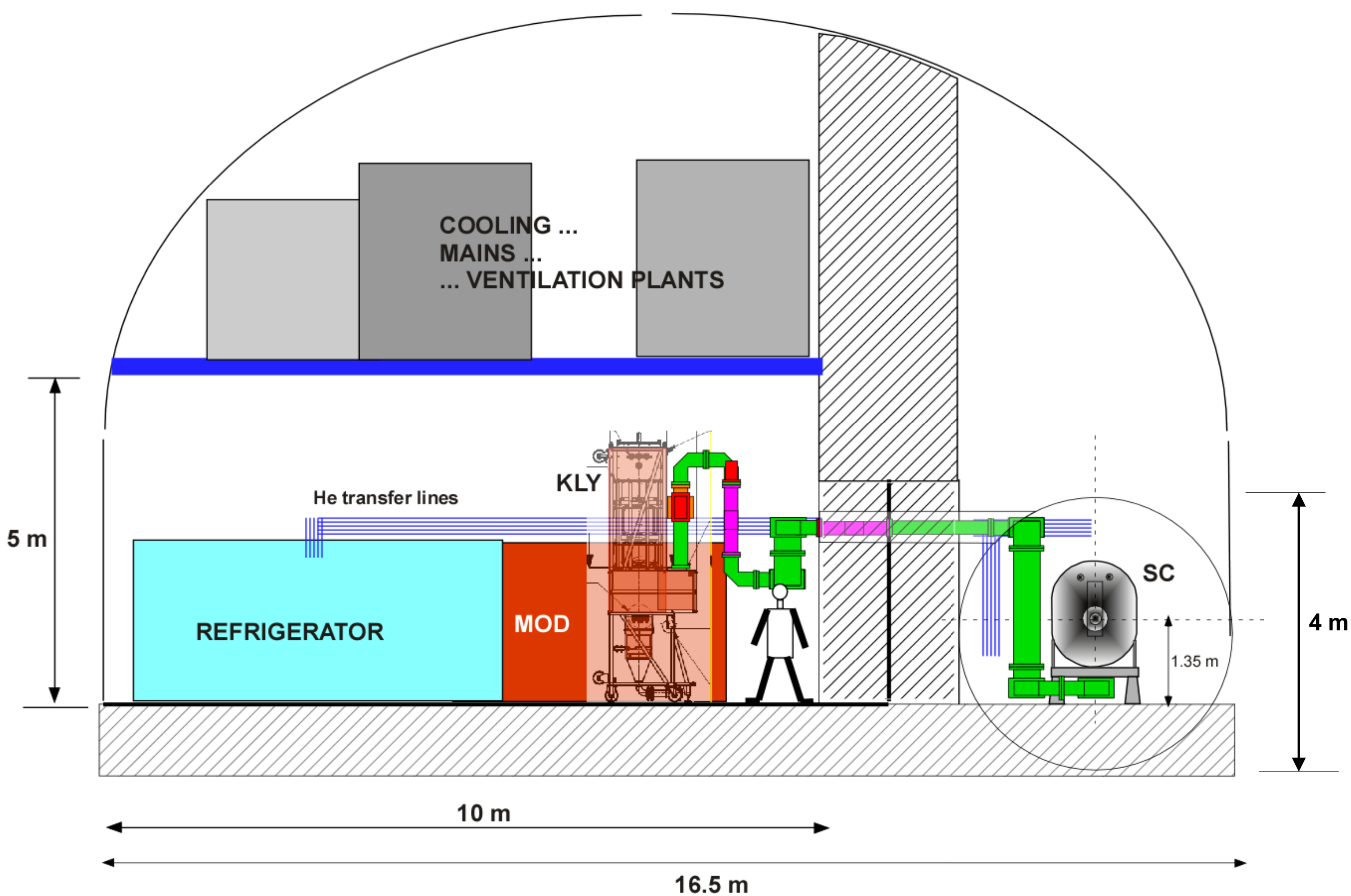
Parameter	10 Hz e^+	5 Hz e^+/e^- (Low power)	5 Hz e^+/e^- (High power)
Total RF voltage [MV]	19.7	14	14
Number of active cavities	10	10	10
Number of passive cavities	2	2	2
Cavity RF voltage [MV] (both active and passive)	1.64	1.17	1.17
Overvoltage factor (active cavities)	2.05	2.59	2.59
Cavity input power [kW]	312	176	351
Ideal input coupling Q_{ext} [$\cdot 10^3$]	97.1	87.1	43.6
Input coupler Q_{ext} [$\cdot 10^3$]	65		
Cavity tuning (active cavities)	fixed, $\tan\psi \approx 1.34$	stationary	stationary
Cavity tuning (passive cavities)	fixed, $\tan\psi \approx 1.37$	fixed, $\tan\psi \approx 1.93$	fixed, $\tan\psi \approx 3.87$
RF Reflected power @ nominal beam current	4.9 %	2.2 %	4.1 %
Total RF power [MW]	3.27	1.69	3.65
# of operating klystrons/ring	5	5	5
Klystron power [kW]	800 kW (including ≈10 % overhead)		

In case of failure of 1 klystron the system can be retuned to exploit the 2 unpowered cavities as passive, beam excited devices providing the same RF gradient across the bunch for longitudinal focalization.

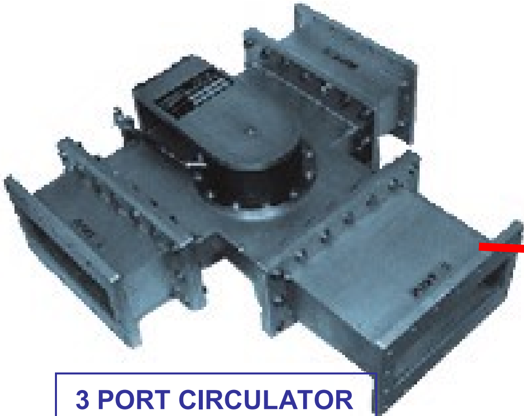
The power to restore the beam losses will be transferred through the 10 residual active cavities and will be 20 % larger than the normal operation case. The klystron power should be oversized by approx. the same amount.

ILC DAMPING RING

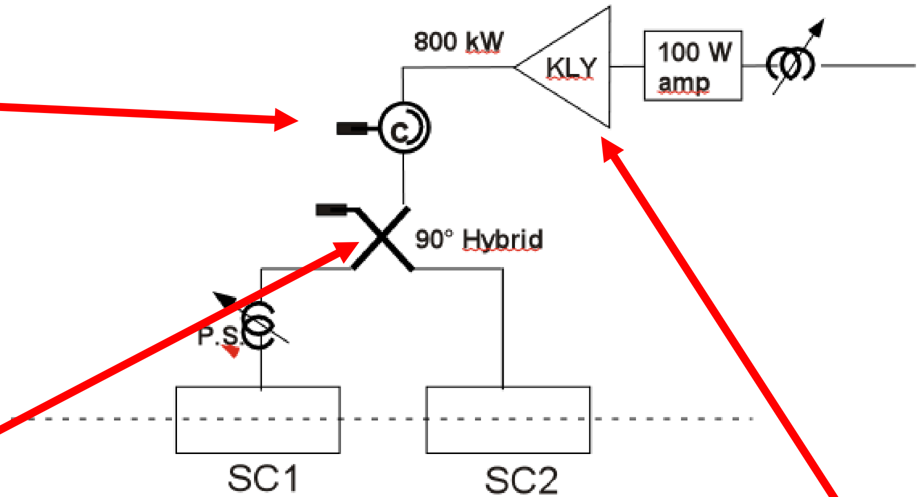
ALCOVE ARRANGEMENT LAYOUT SIDE VIEW



RF STATION LAYOUT



3 PORT CIRCULATOR



90° HYBRID or MAGIC TEE

TH 2178

800 kW CW at 500 MHz

4 mt

RF performance

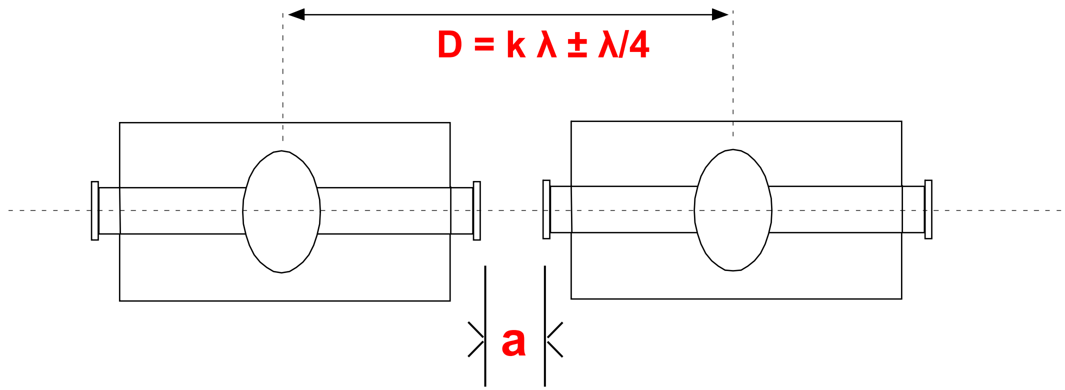
Frequency	499.67	MHz	
RF output power	800	kW	
RF drive power	80	W	max.
-1 dB bandwidth	+/- 1	MHz	min.
Efficiency	62	%	typ.
Saturated gain	40	dB	typ.

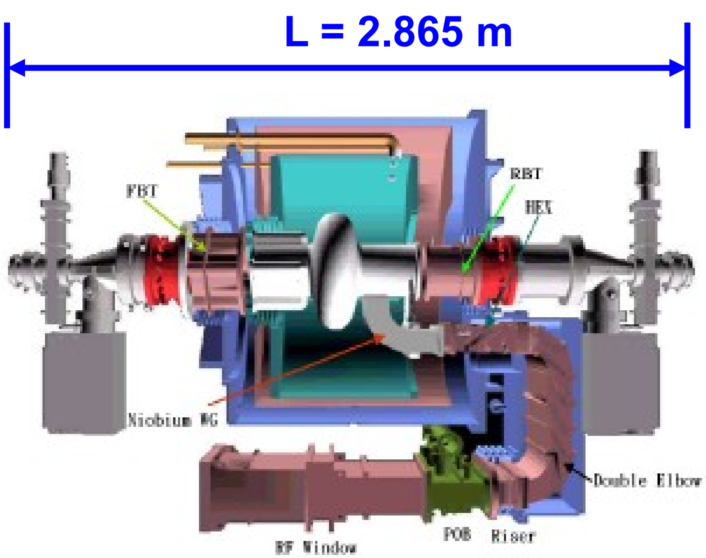
Electrical characteristics

Cathode voltage	75	kV	max.
Beam current	18	A	max.
Anode voltage	55	kV	max.
Heater voltage	25	V	max.
Heater current	25	A	max.

CAVITY SPACING and PHASING

Cavity pairs feeding, with *3dB quadrature hybrids,* requires “k λ ± λ/4“ spacing, with k = any integer.





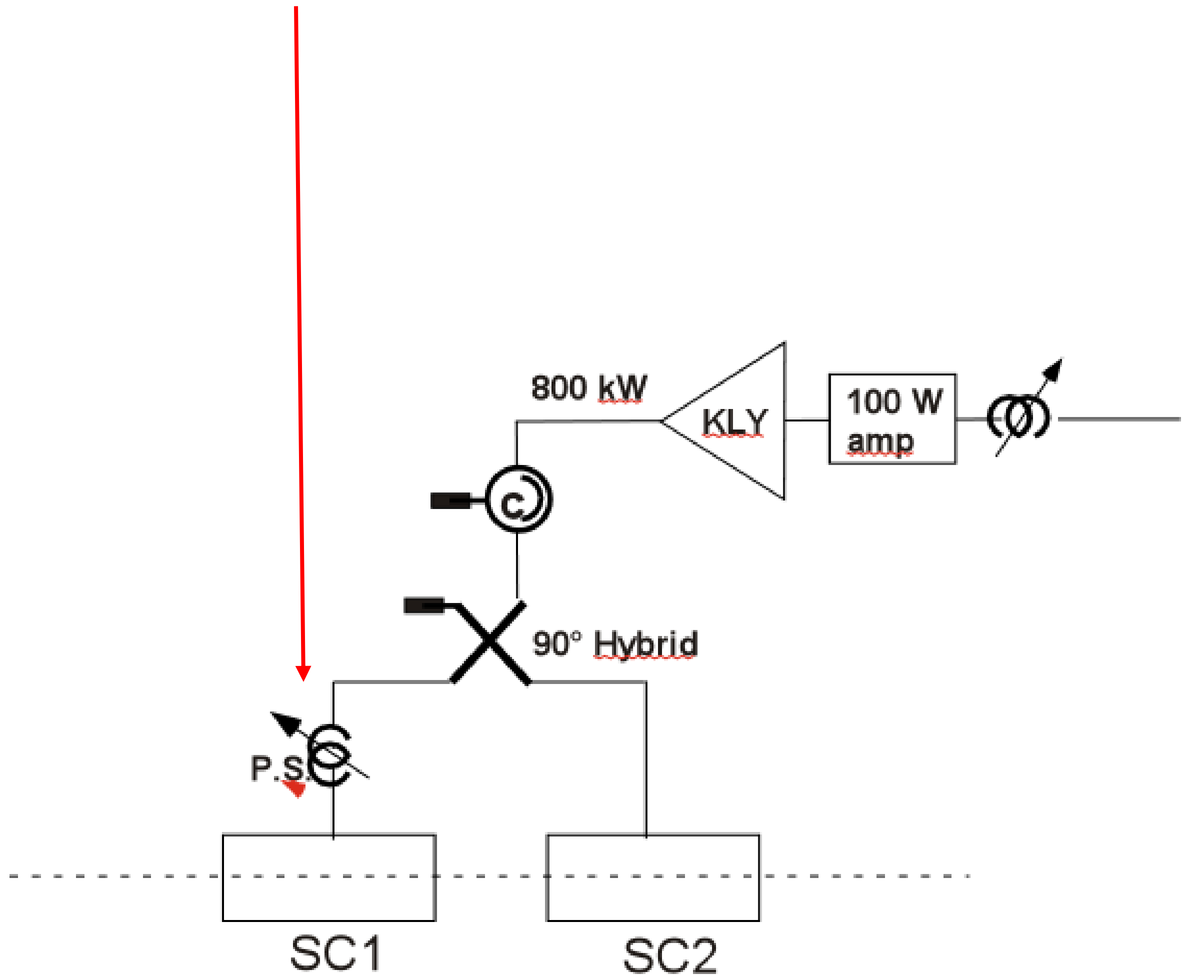
Phasing is essential to preserve uniform RF power transfer to the beam among the various cavities. A cavity phase error Δφ will produce an extra RF power transfer ΔP to the beam equals to:

$$\frac{\Delta P}{P} \approx \sqrt{\eta^2 - 1} \cdot \Delta\varphi$$

accelerating fields need to be phased with < 1° accuracy to limit to < 5 % the deviation of the RF power flow respect to the nominal value.

CAVITY PHASING

To compensate for small differences of the waveguide branches length, fine adjustment of the cavity RF field phase, can be achieved with “ phase-shifters “.



Waveguides

Standard WR1150 or WR1500 rectangular Aluminium waveguides

Typical Specifications									
							Dimensions		
Size EIA WR	Size IEC R( )	Recom-mended Frequency Range (GHz)	Cut-off for TE_{10} Mode (GHz)	Attenuation* Max/Min***	Peak Power In Megawatts* Max/Min***	Material Alloy	Inside Width Height Inches (mm)	Outside Width Height Inches (mm)	Wall Thickness Inches (mm)
1150	8	.64-.96	0.513	.113	87.1	Al	11.500 (292.10)	11.750 (298.45)	0.125 (3.18)
				.076	61.5		5.750 (146.05)	6.000 (152.40)	
1500	6	.49-.75	0.393	.076	148	Al	15.000 (381.00)	15.250 (387.35)	0.125 (3.18)
				.051	104		7.500 (190.50)	7.750 (196.85)	

WR1150 → 292 mm × 146 mm

Att. ≈ 0.05 dB per 20 meters (negligible)

more compact, lighter and cheaper.

WR1500 → 381 mm × 190 mm

Att. ≈ 0.034 dB per 20 meters (negligible)

Exercise: adding 2nd harmonic cavities

Parameter	10 Hz e^+	5 Hz e^+/e^- (Low power)	5 Hz e^+/e^- (High power)
RF frequency	650 MHz		
RF gradient across the bunch [MV/ns] (@ σ_z=6 mm)	73.5	54.1	54.1
Total RF voltage [MV] ***(fund.)***	**14**	**10**	**10**
Total RF voltage [MV] ***(2nd harm.)***	**3.26**	**2.16**	**2.16**
Overvoltage factor	1.75	2.22	2.22
Cavity R/Q [Ω]	89 *(both fund. and harm.)*		
Cavity active length [m]	0.230 *(fund.)* ; 0.115 *(harm.)*		
Number of cavities (fund.)	12	12	12
Number of cells (harm.)	3	3	3
Fund. cavity RF voltage [MV]	1.17	0.83	0.83
Fund. cavity gradient [MV/m]	**5.1**	**3.6**	**3.6**
Harm. cavity gradient [MV/m]	**9.44**	**6.27**	**6.27**
Cavity input power [kW]	260	146	293
Ideal input coupling Q_{ext} [$\cdot 10^3$]	58.8	53.4	26.7
Input coupler Q_{ext} [$\cdot 10^3$]	35		
Cavity tuning *(fund.)*	fixed, tan ψ ≈0.85	stationary	stationary
RF Reflected power @ nominal beam current	6.9 %	4.9 %	1.9 %
Q_0 (x10^9) @ oper. gradient ***(fund.)***	**1** ***(@ 4.5 K)***	**1.5** ***(@ 4.5 K)***	**1.5** ***(@ 4.5 K)***
RF-Cryo losses per cavity [W] ***(fund.)***	**15**	**5.2**	**5.2**
Total cryo-losses per ring [W] *(fund.)*	540	420	420
Q_0 (x10^9) @ oper. gradient ***(harm.)***	**10** ***(@ 1.8 K)***	**15** ***(@ 1.8 K)***	**15** ***(@ 1.8 K)***
RF-Cryo losses per cell [W] ***(harm.)***	**1.4**	**0.4**	**0.4**

- *Same bunch length with less fund. voltage;*
- *Larger Q_0, lower RF-cryo losses;*
- *Possibility to shorten further the bunch by increasing the harmonic voltage;*
- *Beam powered only through fund. cavities*

Estimate of DR RF Cost & Power Consumption

Cost in M€	12 cryo-mod's per ring
Cryogenic plants	3.5
Cryo-modules	25
Klystrons + RF drivers	7
HV Power supplies	16
Waveguide & accessories	3
Low level electronics	3
Total cost [M€]	**57.5**

Wall-plug Power in MW	
Cryogenic plants	0.7
Klystrons + LLRF	15
Total [MW]	**15.7**

CONCLUSIONS

- RF operation of the e^+ Damping Ring in the e^- linac 10 Hz modality is feasible by keeping the cavities at a proper fixed tune. A very modest efficiency degradation results. Issues related to RF window/coupler power handling with full reflection and transient beam loading seem manageable but need attention.

- Cavity and cryostat design could be scaled from existing and very long time tested hardware (CESR and KEKB 500 MHz SC RF).

- A layout based on 12 SC cavities per ring is compatible with all the 3 proposed operation modalities, all accessible with a single trade off value of the cavity coupling parameter Q_{ext}.

- The proposed layout is “robust”, in the sense that it can tolerate failures of 1 power station if the cavities connected to the faulty station are retuned to be passively excited by the beam at the same field amplitude. The klystrons need to be properly oversized to sustain this kind of operation.

- Costs seems hardly compressible, since they are dominated by the required beam power, which sets the number of power stations and the minimum number of cryo-modules (≈ 10) needed to prevent overload of cavity input couplers.