Super-B:
RF System parameters and Impedance Budget

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Super -B Workshop

February 17, 2009

LAL, Orsay, France

Super-B parameters
June 2008-January 2009

ability/Impedance/RF"

PARAMETER	LER (e+)	HER (e-)
Energy (GeV)	4	7
Luminosity x 10^{36}	1.0	
Circumference (m)	1800	1800
Revolution frequency (MHz)	0.167	
Eff. long. polarization (%)	0	80
RF frequency (MHz)	476	
Momentum spread ($x10^{-4}$)	8.0	5.8
Momentum compaction (x10⁻	3.2	3.8
Rf Voltage (MV)	5	8.3
Energy loss/turn (MeV)	1.13	1.95
Number of bunches	1251	
Particles per bunch ($x10^{10}$)	5.52	
Beam current (A)	1.85	
Beta y* (mm)	0.22	0.39

LER/HER	Unit	June 2008	Jan. 2009	$2N_b$, $I_b/\sqrt{2}$	$4\varepsilon_y$, $2N_b$
E+/E-	GeV	4/7	4/7	4/7	4/7
L	$cm^{-2}\ s^{-1}$	10^{36}	10^{36}	10^{36}	10^{36}
I^+/I^-	Amp	1.85 /1.85	2.03/2.03	2.87/2.87	4.06/4.06
N_{part}	$x10^{10}$	5.52 /5.52	6.05/6.05	4.28/4.28	6.05/6.05
N_{bun}		1250	1250	2500	2500
σ_z	mm	5/5	5/5	5/5	5/5

RF power is needed to compensate:

1) Beam synchrotron radiation losses

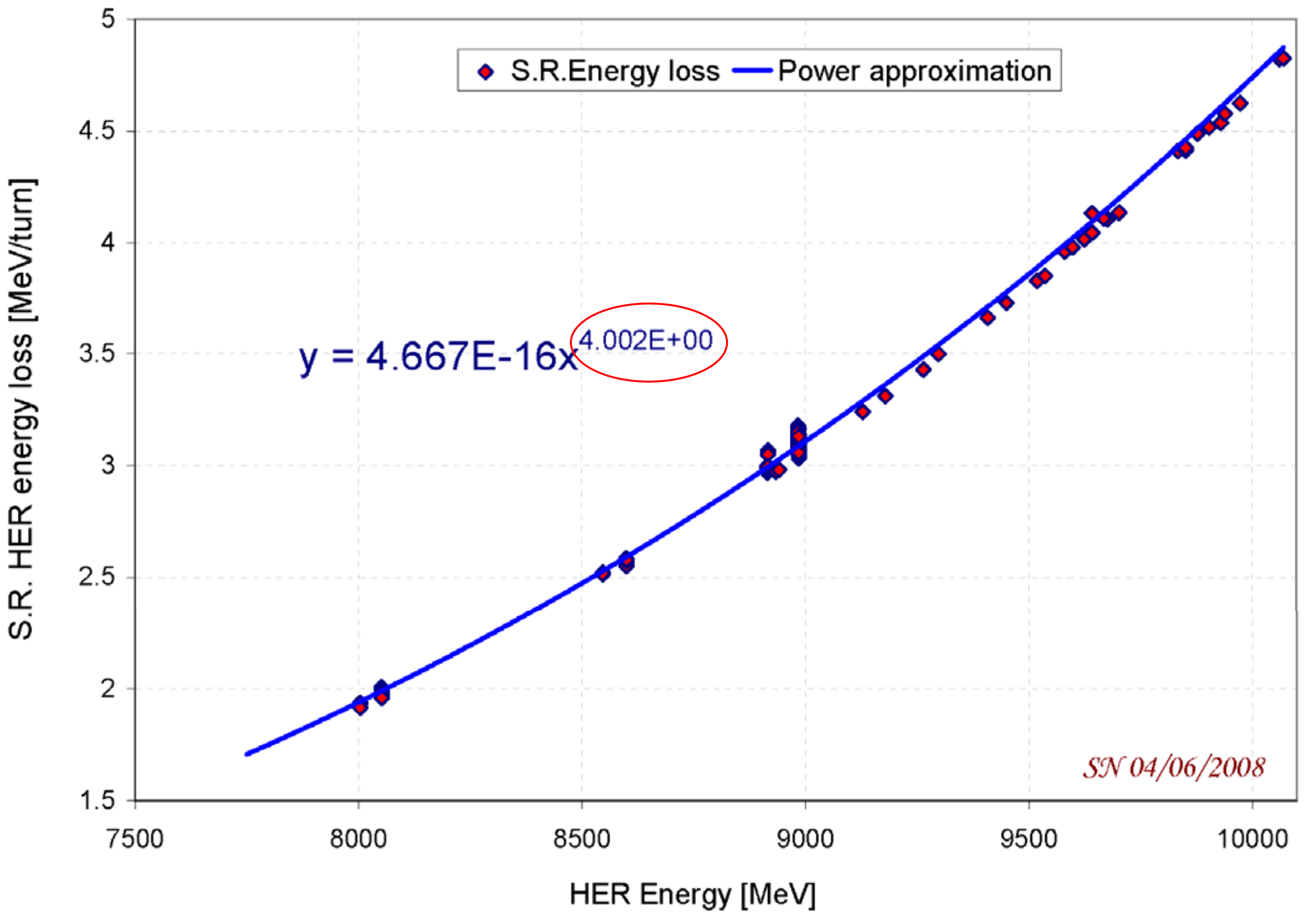
Beam energy *E*, bending radius *ρ* and beam current *I* define the power of the synchrotron energy loss

$$P_{s.r.} = \frac{4\pi}{3} m_0 c^2 \left(\frac{E}{m_0 c^2} \right)^4 \frac{r_0}{\rho} \times I$$

Forth power of beam energy

Everybody knows, but just to be sure…

Measurement at PEP-II during energy scan



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Bending radius and beam current

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Bending radius is much smaller than the average radius of the machine

Super-B HER: bending radius is 109 m
Super-B LER , bending radius is 20 m

Currents we know we can achieve
2-4 A

RF power is needed to compensate:

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2) Energy loss in the room-temperature cavities

$$P_{cav} = \frac{V_{total}^{2}}{2N_{cav}Z_{shunt}}$$

More cavities – less power

RF power is needed to compensate:

3) Reflected power from cavities back to klystrons if coupler is not matched

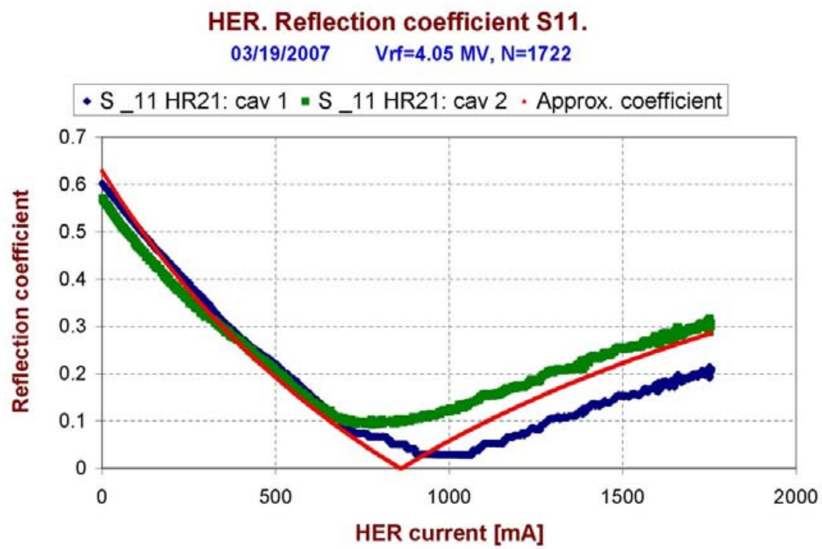
Reflected power $$P_{ref} = P_{in} \left|\Gamma\right|^2$$

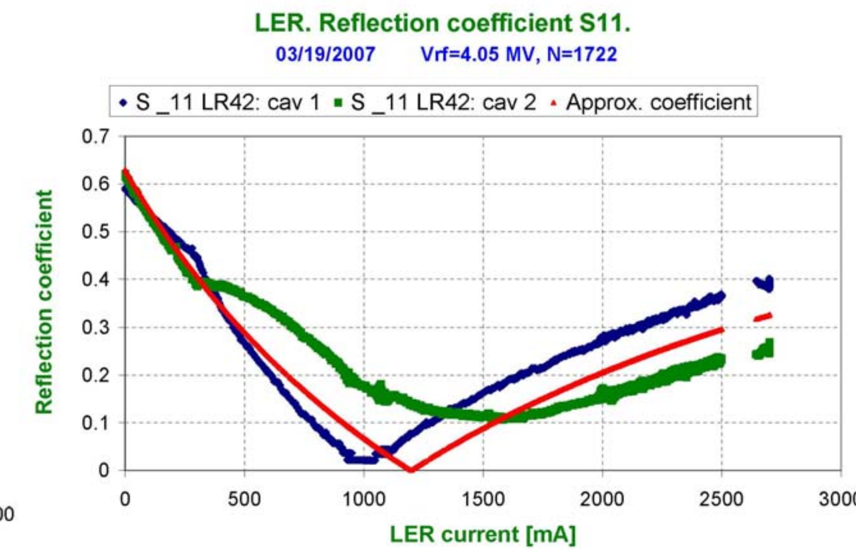
$$\Gamma = 1 - \frac{\text{geometrical parameter}}{1 + \frac{\text{beam losses}}{\text{all loaded cavity losses}}} = 1 - \frac{\alpha_{cav}}{1 + \frac{P_{S.R.} + P_{HOM}}{(\beta + 1) P_c}}$$

PEP-II cavity: $\alpha_{cav} = 1.57$ $\beta = 3.6$

Reflected power may not take minimum value when forward power gets minimum.

PEP-II cavities have minimum reflected power at the beam current of 1 A.





At zero currents the reflected coefficient is 0.6
that means that 36% of forward power comes back

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RF power is needed to compensate:

- HOM losses
  - Wake fields excited in the cavities and vacuum chamber elements (collimators, transitions…)

$$K = K(\sigma) \quad \sigma = \sigma(I)$$

$$P = \tau_b \times K \times I^2$$

HOM Power   Bunch Spacing   Loss Factor   Current

RF limits

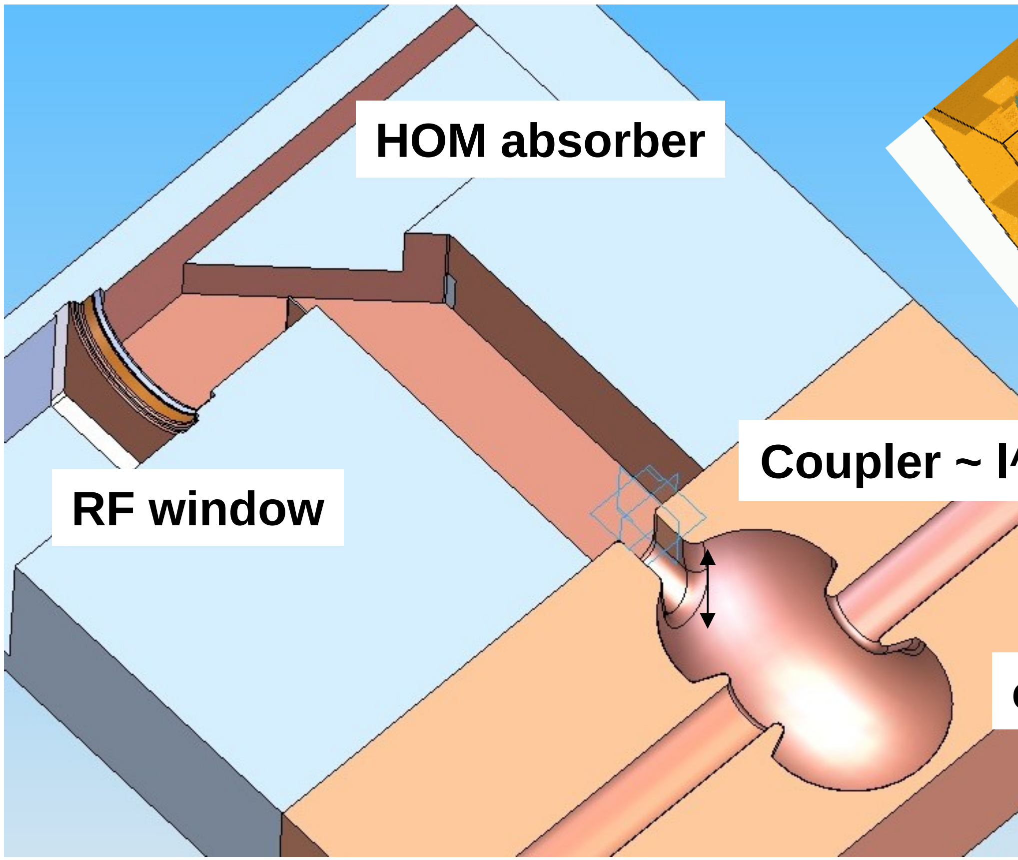
- Cavity voltage and forward power
  - Voltage in a cavity is limited by sparks and breakdowns
    - SLAC RF people consider voltage less than 0.6-0.7 MV per cavity
  - Forward power into a cavity and reflected power are limited by sparks in RF windows
    - SLAC people consider power less than 500 KW per cavity and less than 10% reflected

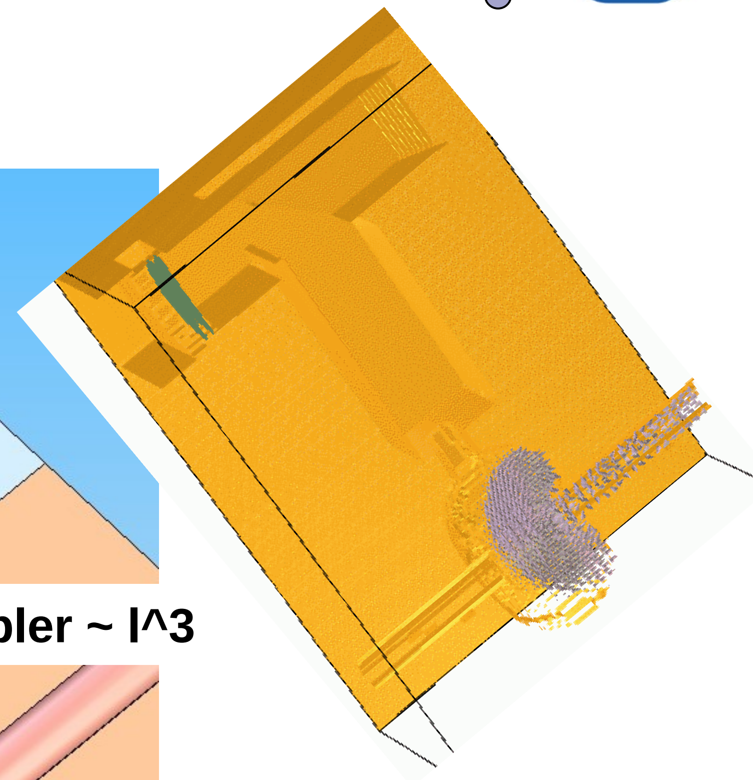
Super-B RF: Supply power 2009

HER Lumi	HER Beam energy GeV	HER Beam current A	HER S.R. energy loss per turn MeV	HER Momen- tum com- paction	HER Momen- tum spread	HER Total RF voltag MV	HER Zero I Bunch length mm	HER Bunch spacing nsec	HER Max voltage er cavit MV	HER Number of cavities klystro	HER S.R. power MW	HER HOM power MW	HER Total cavity loss MW	HER Total reflected power MW	HER Total forward power MW	HER Power for one cavity MW	HER+ LER Total forward MW
1E+36	7	2	1.95	3.8E-04	5.8E-04	8	5.1	4.2	0.65	12	3.9	0.386	0.702	0.5912	5.58	0.46	8.98
										6							
1E+36	7	2.82	1.95	3.8E-04	5.8E-04	10	4.5	2.1	0.65	16	5.499	0.4901	0.822	1.2384	8.05	0.50	12.73
										8							
1E+36	7	4	1.95	3.8E-04	5.8E-04	16	3.6	2.1	0.7	22	7.8	1.517	1.531	1.2733	12.12	0.55	19.63
										11							

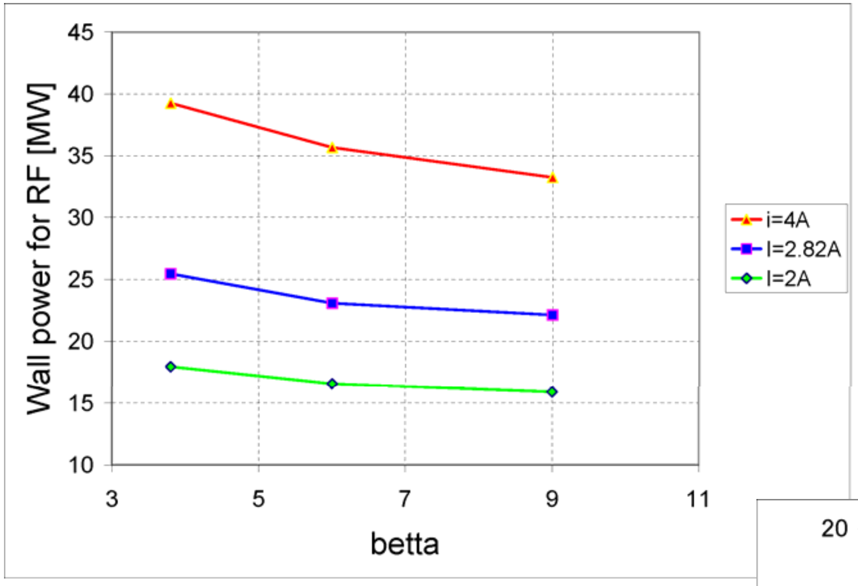
LER Lumi	LER Beam energy GeV	LER Beam current A	LER S.R. energy loss per turn MeV	LER Momen- tum com- paction	LER Momen- tum spread	LER Total RF voltag MV	LER Zero I Bunch length mm	LER Bunch spacing nsec	LER Max voltage er cavit MV	LER Number of cavities klystro	LER S.R. power MW	LER HOM power MW	LER Total cavity loss MW	LER Total reflected power MW	LER Total forward power MW	LER Power for one cavity MW	HER+ LER Supply Power eff.~50% MW
1E+36	4	2	1.16	3.2E-04	8.0E-04	6	5.6	4.2	0.65	10	2.32	0.3205	0.474	0.2863	3.40	0.34	17.96
										5							
1E+36	4	2.82	1.16	3.2E-04	8.0E-04	7	5.2	2.1	0.65	10	3.2712	0.3569	0.645	0.4038	4.68	0.47	25.45
										5							
1E+36	4	4	1.16	3.2E-04	8.0E-04	9	4.5	2.1	0.65	14	4.64	0.9391	0.761	1.1691	7.51	0.54	39.26
										7							

Cavity structure





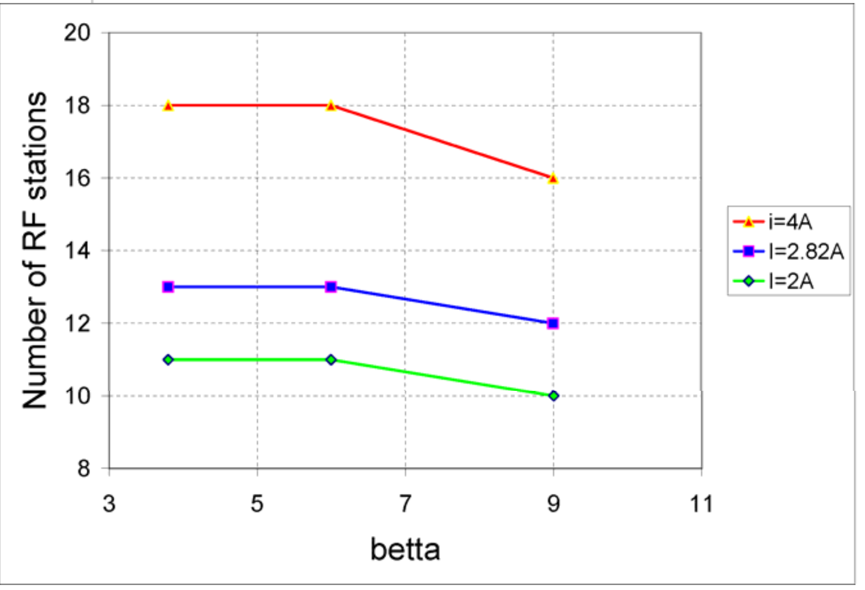
Some improvement gives less power and less number of RF stations



Coupling coefficient 3.8 → 9

18 RFs → 16 RFs

PEP-II has 15 RF stations and 36 cavities

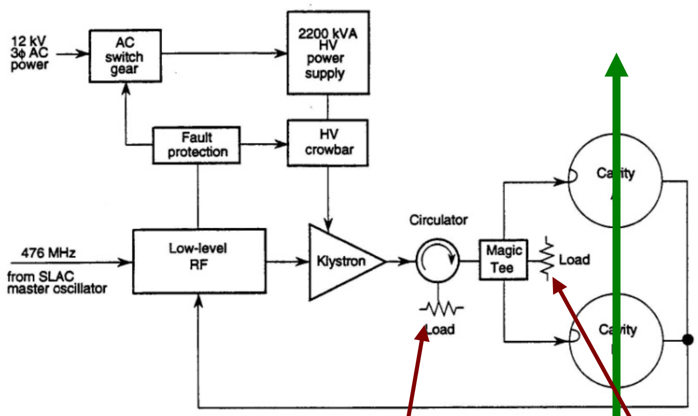


Coupling coefficient 3.8 → 9

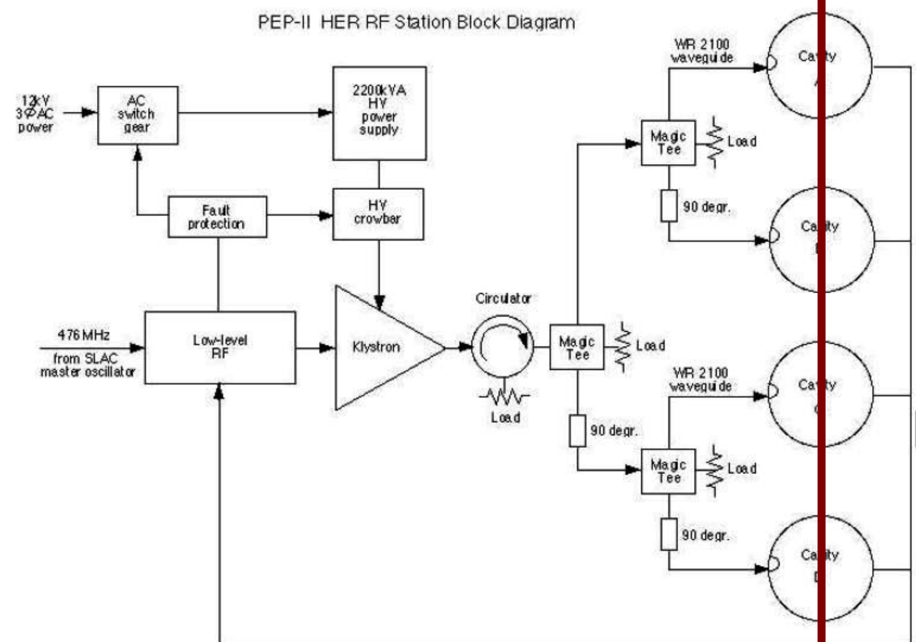
39 MW → 33 MW

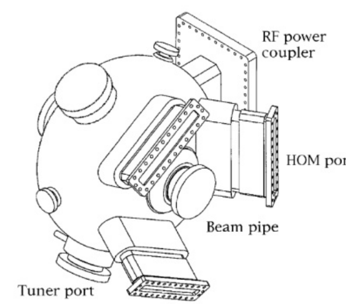
ΔI=+36% and bring resonance frequency back

RR power : from klystron to cavities



Block diagram of a single PEP-II RF station.





Power reflected form a cavity dissipates in Circulator loads and Magic Tee loads

Maximum RF in PEP-II HER during energy scan

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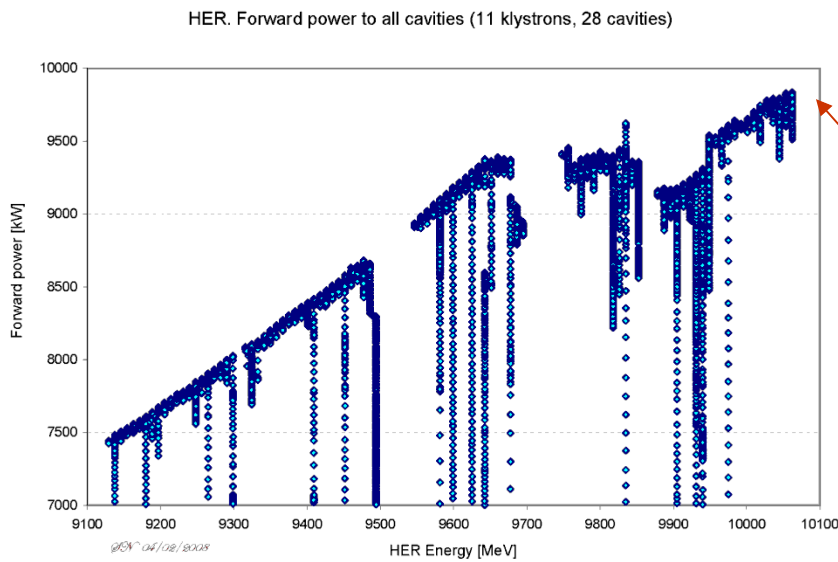
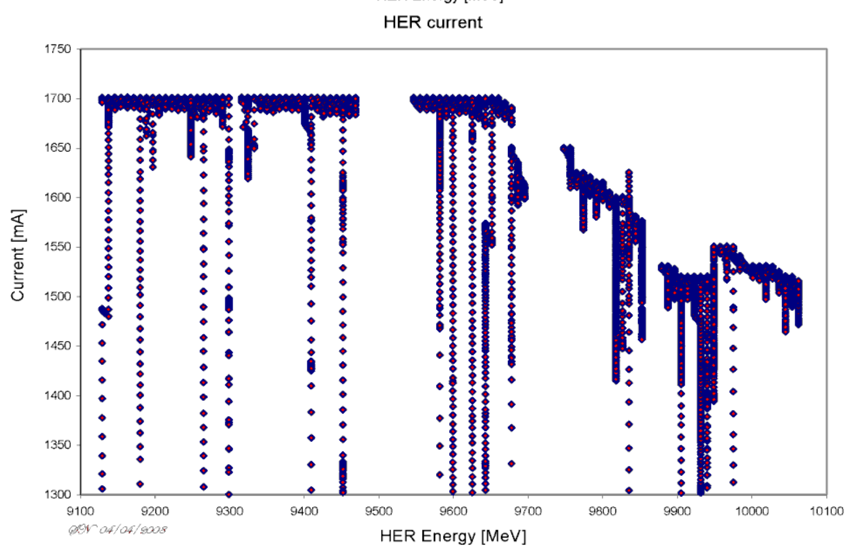


Forward power: almost 10 MW

In average 350 KW per cavity

11 klystrons
28 cavities



HER current

Maximum RF: Reflected power and cavity losses

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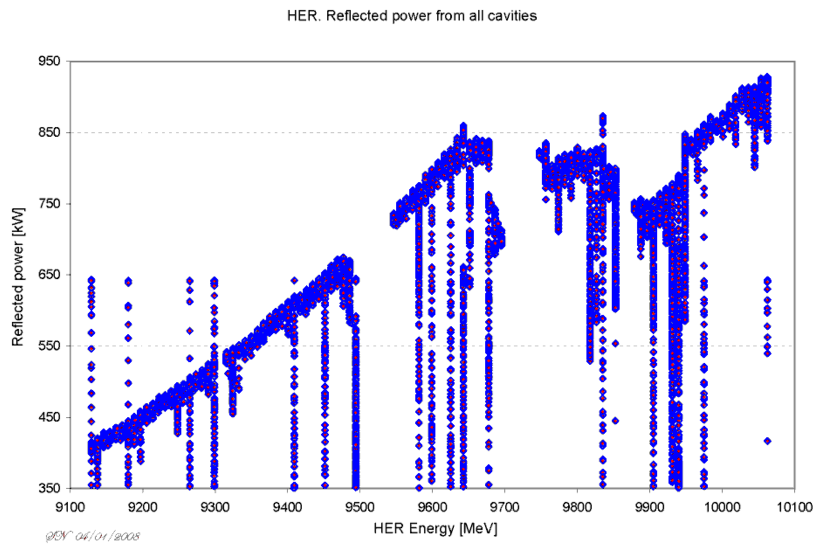
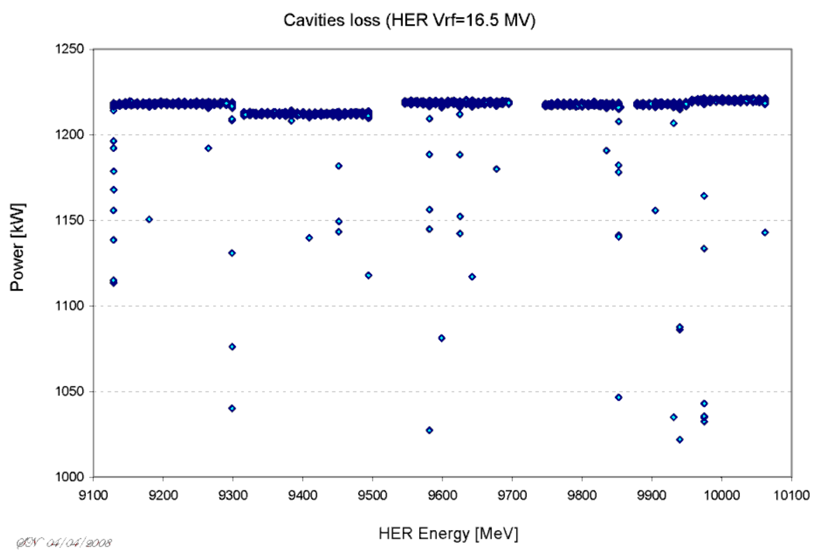


Reflected waves
carry equivalent
power of a klystron



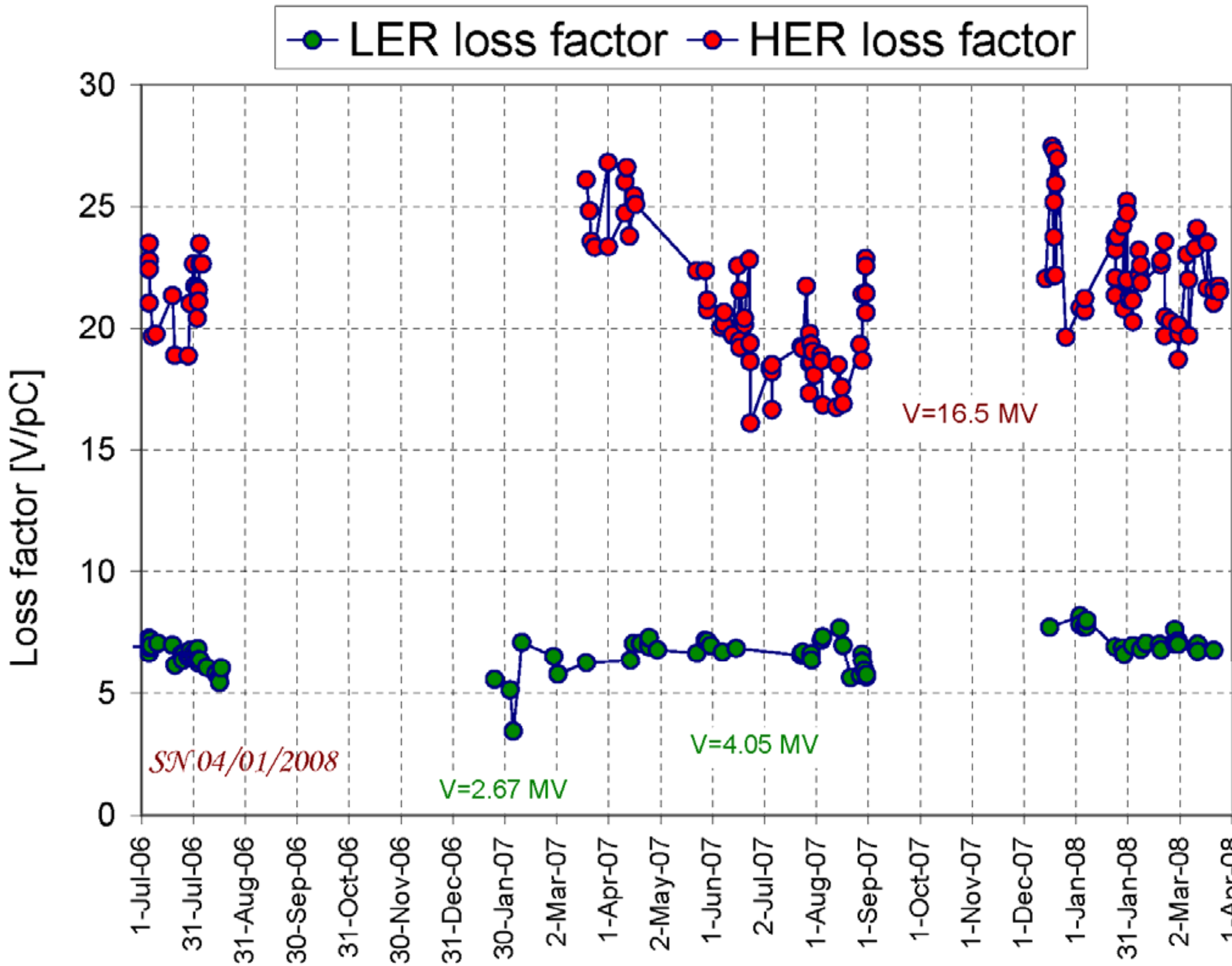
Cavities dissipate
the power of a klystron

Finally
Power of 9 klystrons
goes to the beam.
80% efficiency, almost
optimum number

Loss factor and bunch lengthening

- Characterize wake fields by two parameters:
  - Loss factor $$k = \int W(s)\rho(s)ds$$
  - Energy spread (or inductance) $$L = \sigma_0 \frac{\partial W}{\partial s}$$

Loss factor of PEP-II vacuum chamber



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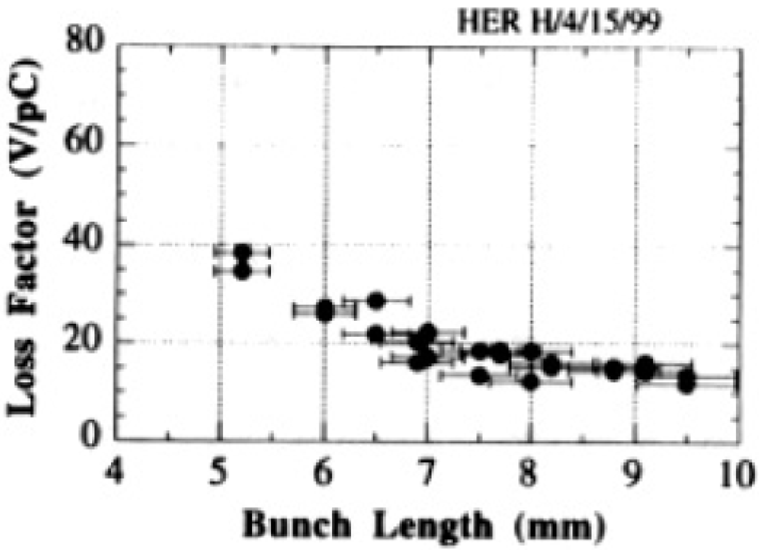
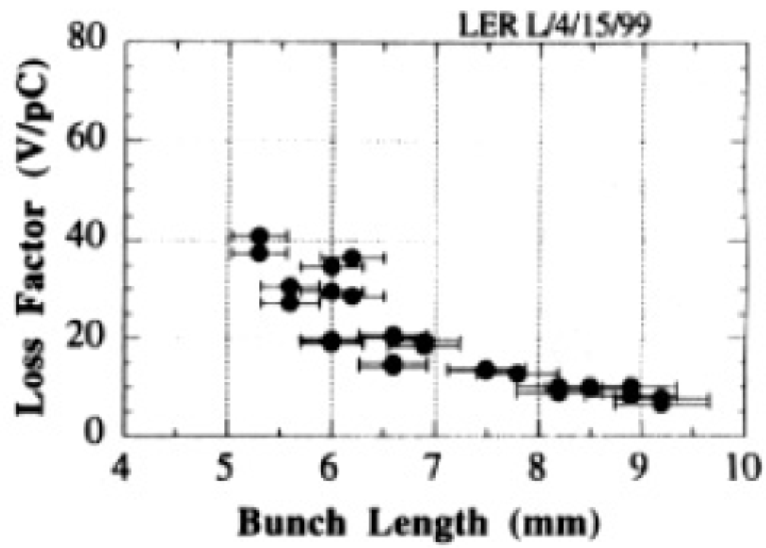
Measured loss factor of KEK-B
Takao Ieiri (1999)

HER



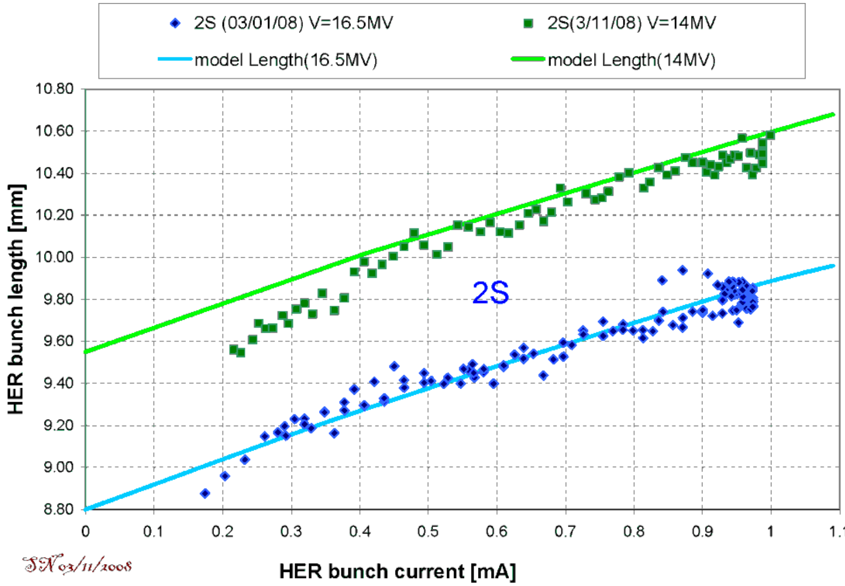
LER



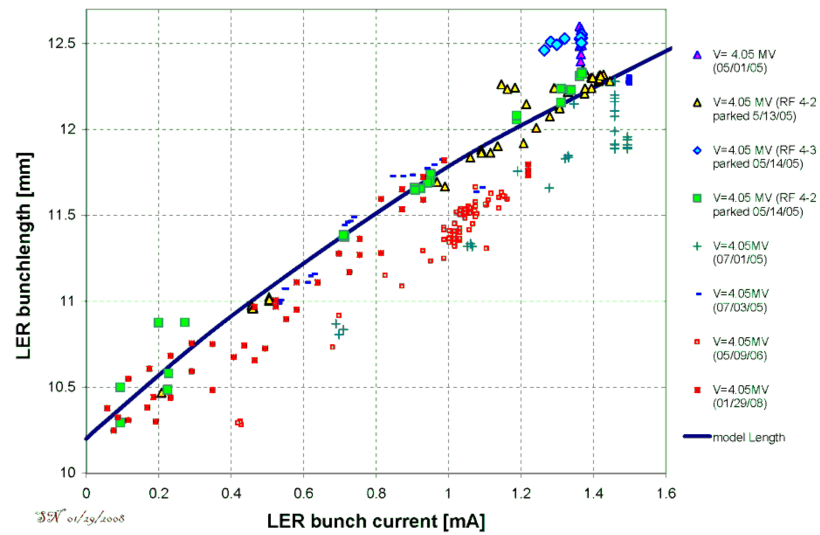
-> The loss factor is k=20 - 30 V/pC @ σ = 6 - 7 mm in both rings
Beam loss power is P_{beam} = 170 - 260 kW @ 1A

Bunch lengthening in PEP-II

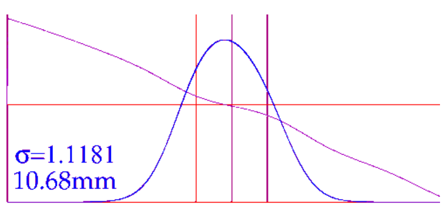
HER

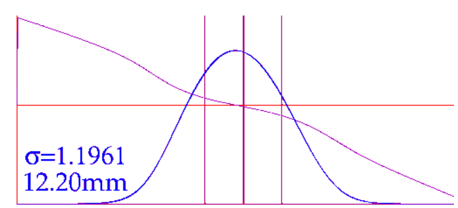


LER



Solid lines show simulation results.
Bunch length was calculated using the HER impedance model





Bunch lengthening in KEK-B
Takao Ieiri (1999)

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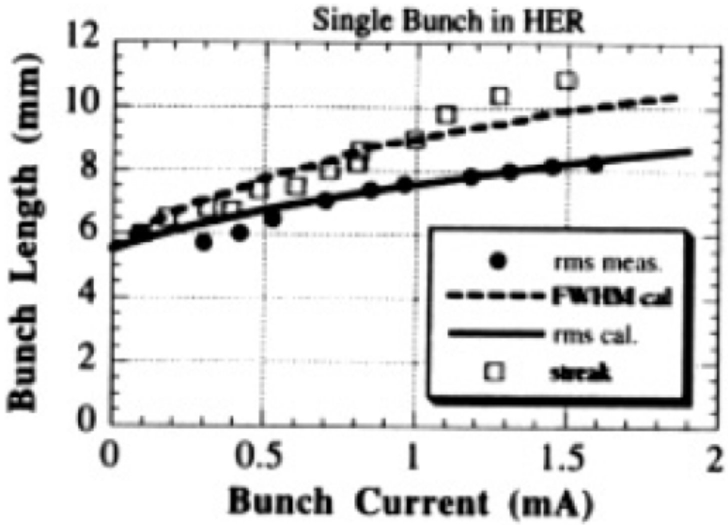
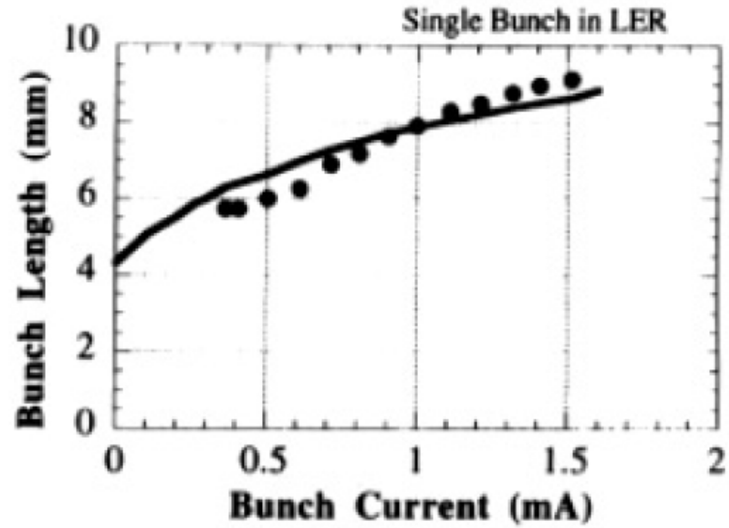
HER



LER



Lines are calculated bunch length, assuming $|Z_i/n| = 0.076\ \Omega$ for HER and $|Z_i/n| = 0.072\ \Omega$ for LER. -> good agreement in HER -> rough agreement in LER

Measured impedance of both rings is 5 times larger than the design of 0.015 Ω.

Haissinski equation

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$$\rho(\xi) = \rho_0 \ell^{-\frac{\xi^2}{2} + \Lambda_W \int_{-\infty}^{\xi} W(s)ds} \qquad W(s) = \int_{-\infty}^{s} w(s-s')\rho(s')ds'$$

$$\int_{-\infty}^{\xi} W(s)ds \approx const + W(o) * \xi + \frac{1}{2}\frac{\partial W}{\partial s} * \xi^2$$

$$\rho(\xi) = \tilde{\rho}_0 \ell^{-\frac{(\xi-\xi_0)^2}{2}\left(1-\Lambda_W * \sigma_0 \frac{\partial W}{\partial s}\right)} = \tilde{\rho}_0 \ell^{-\frac{(\xi-\xi_0)^2}{2\left(\frac{\tilde{\sigma}}{\sigma_0}\right)^2}} \qquad \xi_0 = \frac{1}{2}\frac{\Lambda_W * W(o)}{1-\Lambda_W * \sigma_0 \frac{\partial W}{\partial s}}$$

Bunch lengthening or shortening

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$$\tilde{\sigma} = \sigma_0 * \left(1 + \frac{1}{2}\Lambda_W * L\right)$$

$$L = \sigma_0 \frac{\partial W}{\partial s} \qquad \sigma_0 = \lambda_{RF} \frac{\Delta E}{E} \sqrt{\frac{\alpha h E}{2\pi V_{RF} \cos\varphi}}$$

$$\Lambda_W = \frac{\sigma_0}{\Pi} \frac{Q_{bunch}}{\alpha E \left(\frac{\Delta E}{E}\right)^2} = \frac{Q_{bunch}}{\frac{\Delta E}{E}} \sqrt{\frac{1}{2\pi\alpha h E V_{RF} \cos\varphi}}$$

Estimations for bunch lengthening in Super-B

Parameters	PEP-II (12 mm)	PEP-II (6 mm)	Super-B LER
Energy [GeV]	3.11860	3.11860	4
Relative energy spread	7.70E-04	7.70E-04	8.00E-04
Momentum compaction	1.23E-03	1.23E-03	3.20E-04
Circumference [m]	2200	2200	1800
Natural bunch length [mm]	12	6	6
Bunch charge [nC]	8.832	8.832	8.832
Lambda	0.02118	0.01059	0.03594

Because of smaller momentum compaction Super-B should have twice less impedance than PEP-II

PEP-II HER and LER wake potentials,

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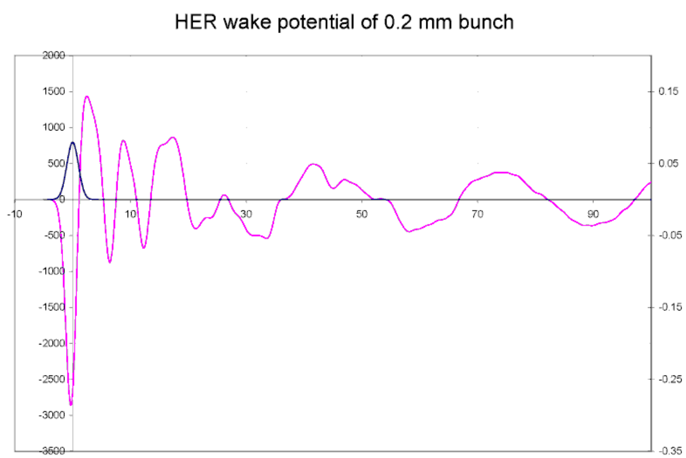
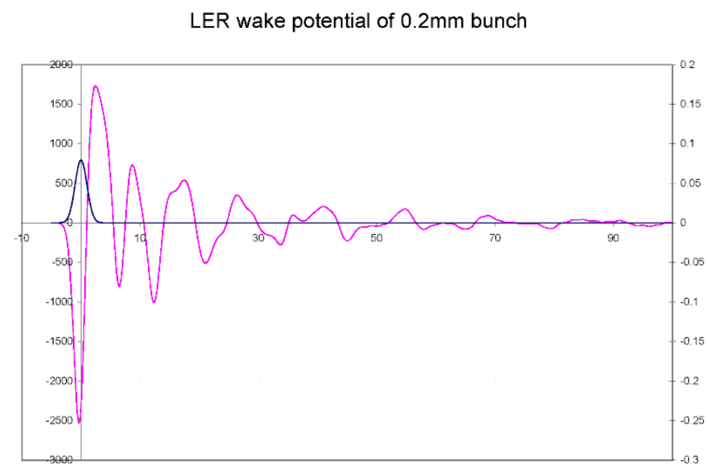
which are used to calculate the bunch lengthening in Super-B



HER



LER

Bunch lengthening in Super-B

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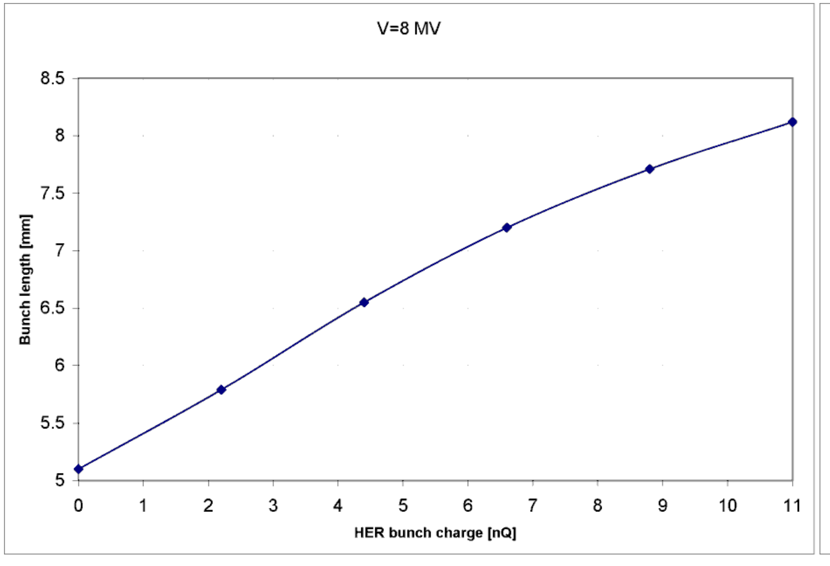
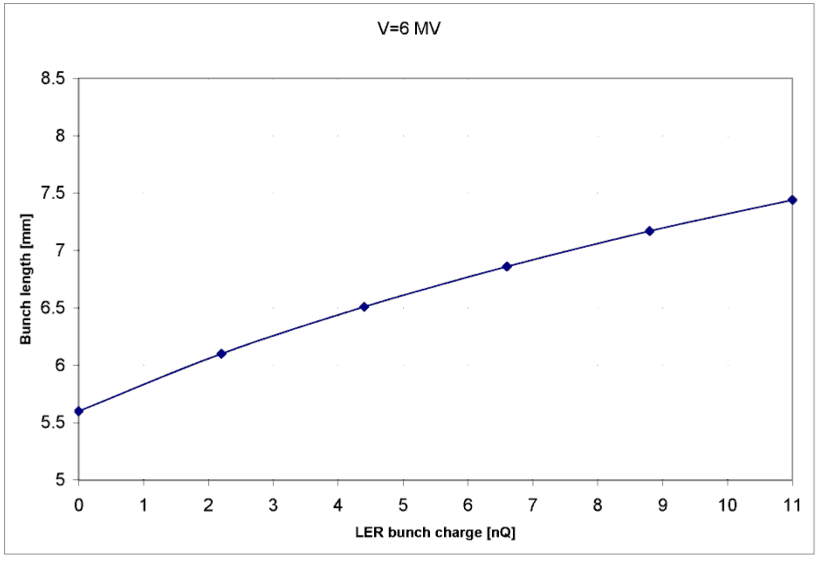
HER



LER



If the impedance of the Super-B vacuum chamber is two times smaller than the impedance is the PEP-II chamber.

Bunch lengthening and threshold current

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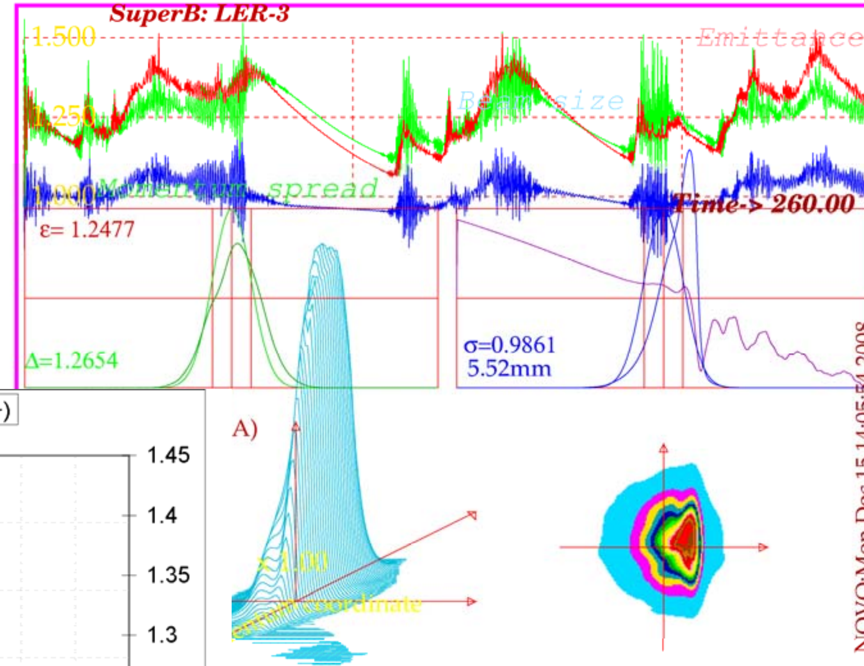
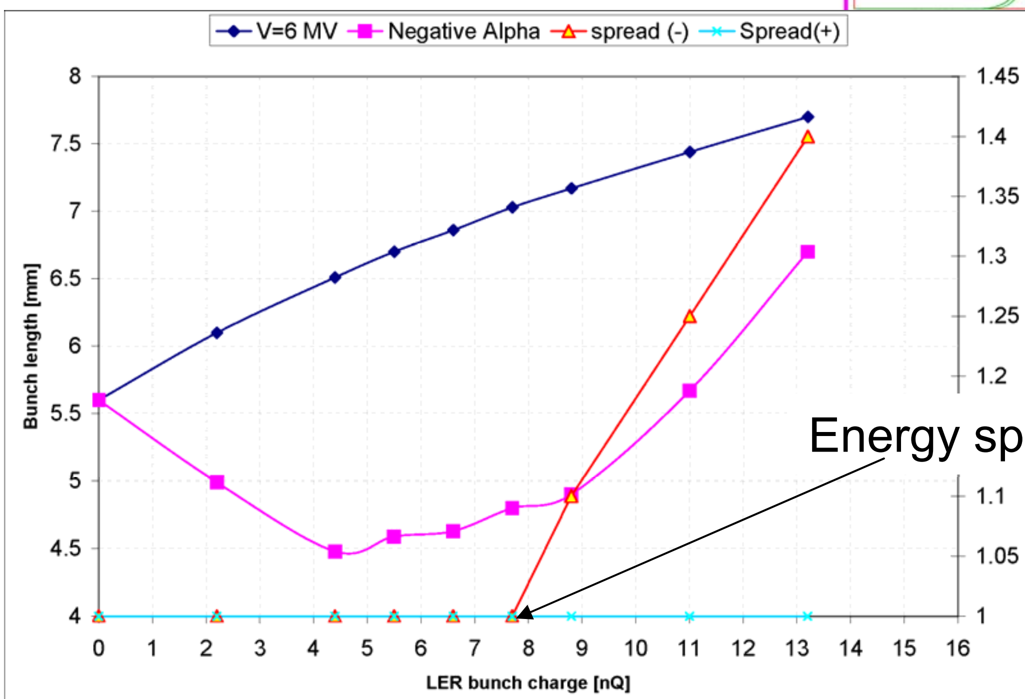
HER Lumi	HER S.R. energy loss per turn MeV	HER Momen-tum com-paction	HER Momen-tum spread	HER Total RF voltage MV	HER Bunch length at zero curren mm	HER Beam current A	HER Number of bunches	HER Bunch charge nC	HER Bunch length mm	Current Threshold A	HER Bunch spacing nsec	HER voltage er cavit MV	HER Numbe of cavities	HER S.R. power MW	HER HOM power MW
1E+36	1.95	3.8E-04	5.8E-04	8	5.1	1.85	1251	10.87	8.12	2.43	4.2	0.7	12	3.61	0.33

LER Lumi	LER S.R. energy loss per turn MeV	LER Momen-tum com-paction	LER Momen-tum spread	LER Total RF voltage MV	LER Bunch length mm	LER Beam current A	LER Number of bunches	LER Bunch charge nC	LER Bunch length mm	Current Threshold A	LER Bunch spacing nsec	LER voltage er cavit MV	LER Numbe of cavities	LER S.R. power MW	LER HOM power MW
1E+36	1.13	3.2E-04	8.0E-04	6	5.6	1.85	1251	10.87	7.44	2.25	4.2	0.6	10	2.09	0.27

Negative momentum compaction



A.Novokhatski SLAC Stanford



Energy spread starts to grow

Beam pipe detailed analysis

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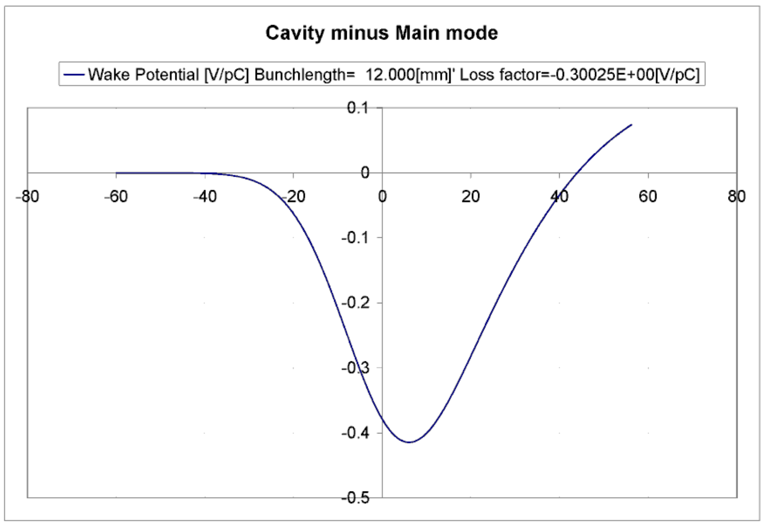
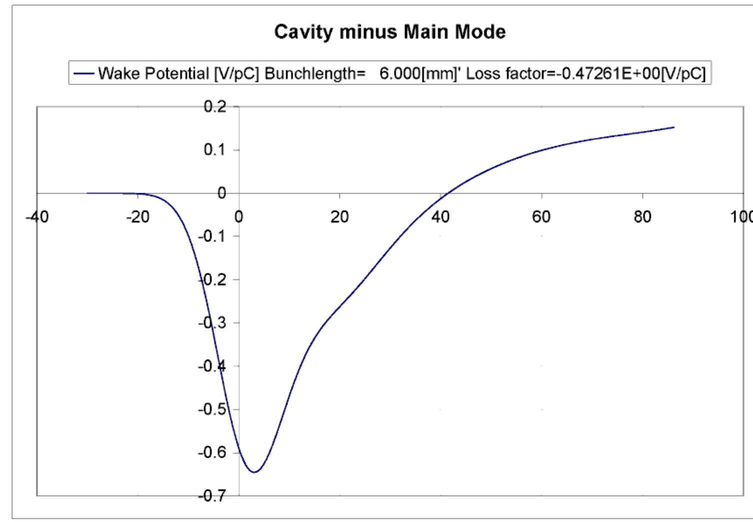
- PEP-II wake function for Super-B wake calculation
- Bunch length changes from 12 mm to 6 mm.
- Check every element to decrease total impedance

Cavity minus Main Mode





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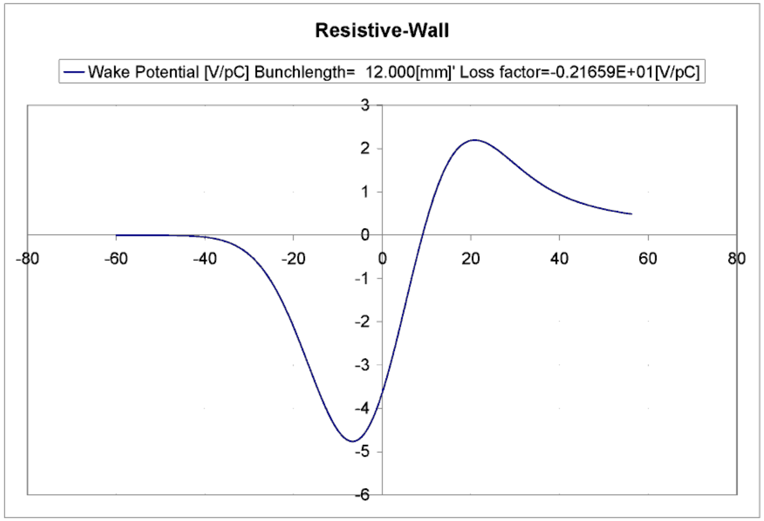
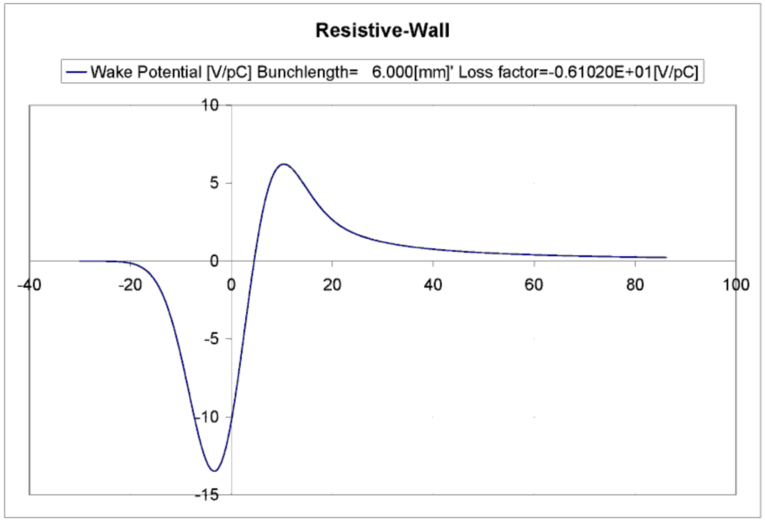
Resistive-Wall





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Interaction Region

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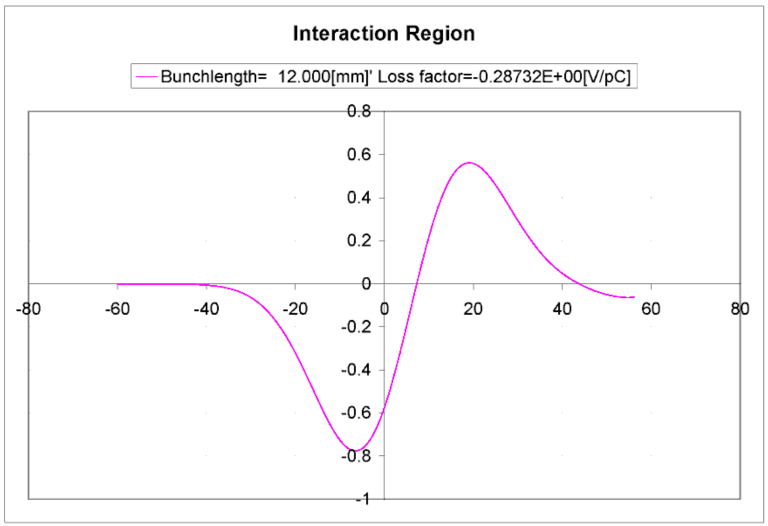

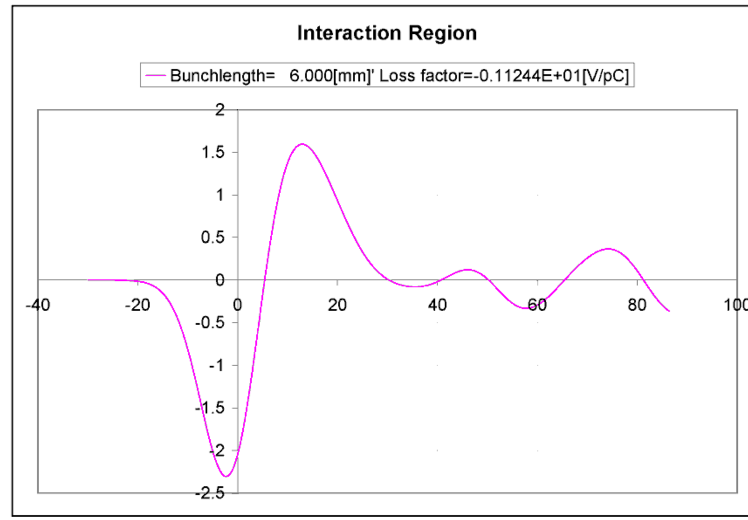

Longitudinal Kicker

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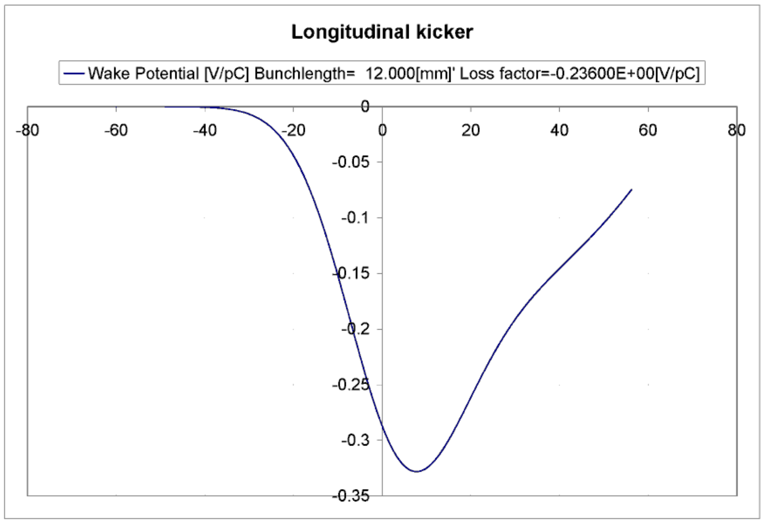
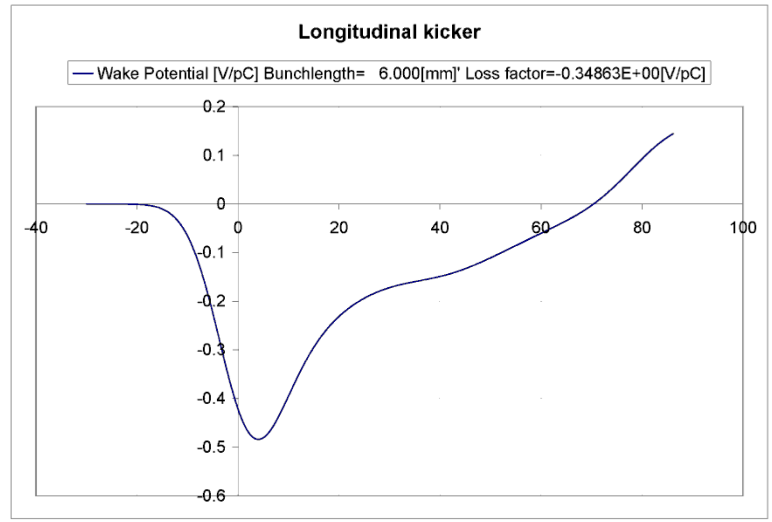
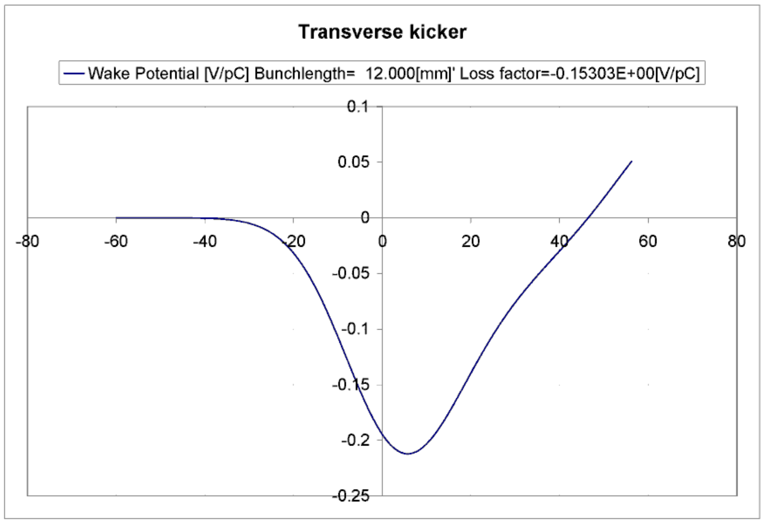
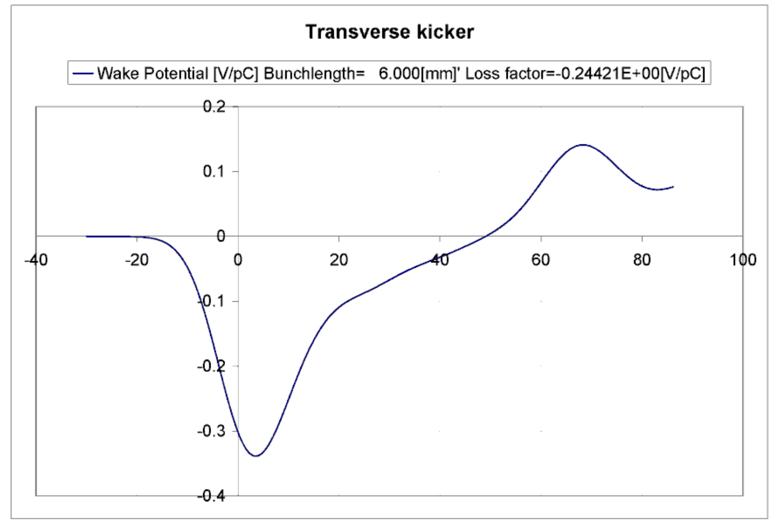




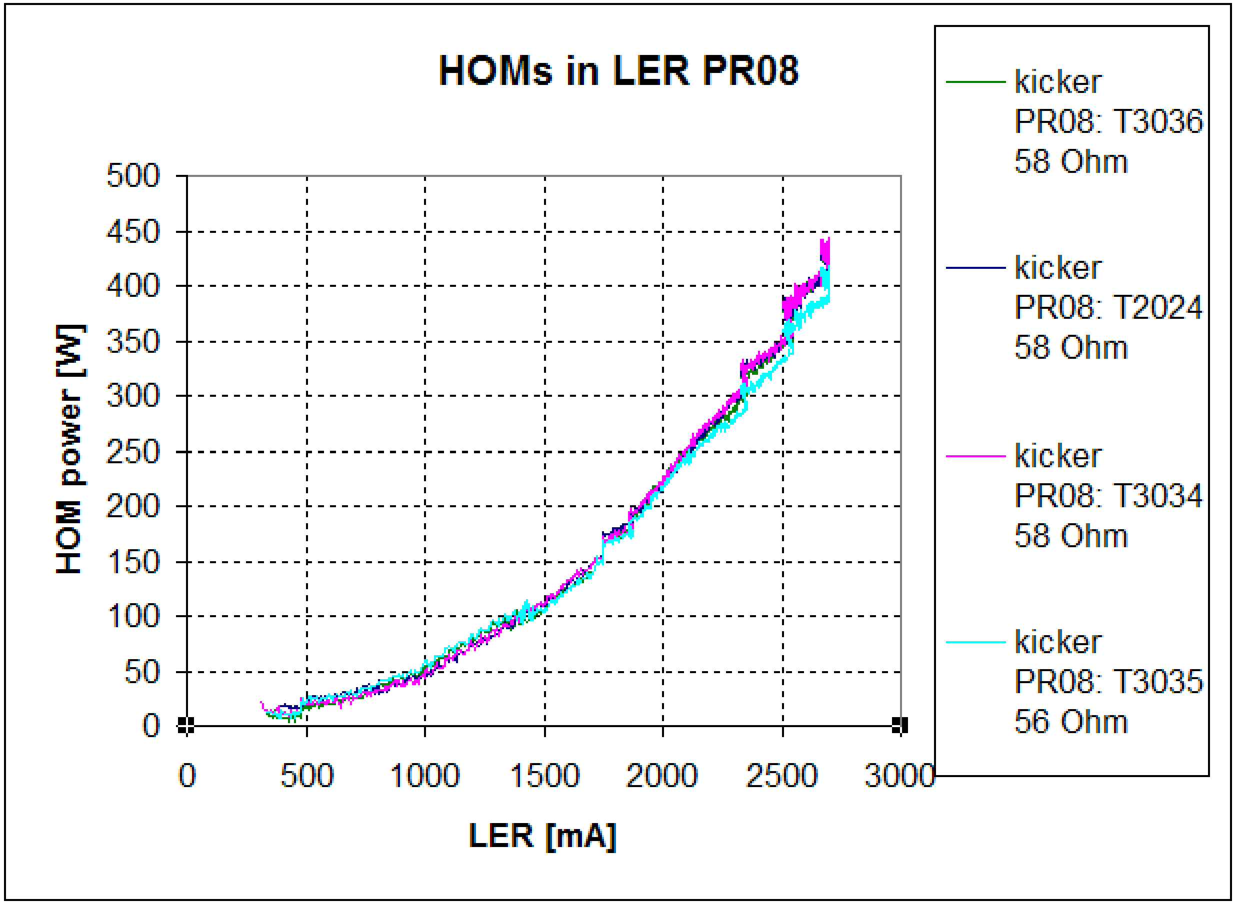
Transverse Kicker





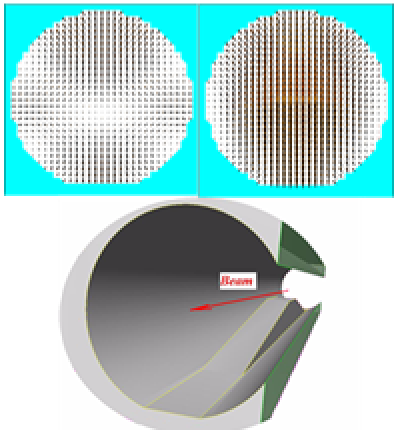
Sasha Novokhatski "Stability/Impedance/RF"

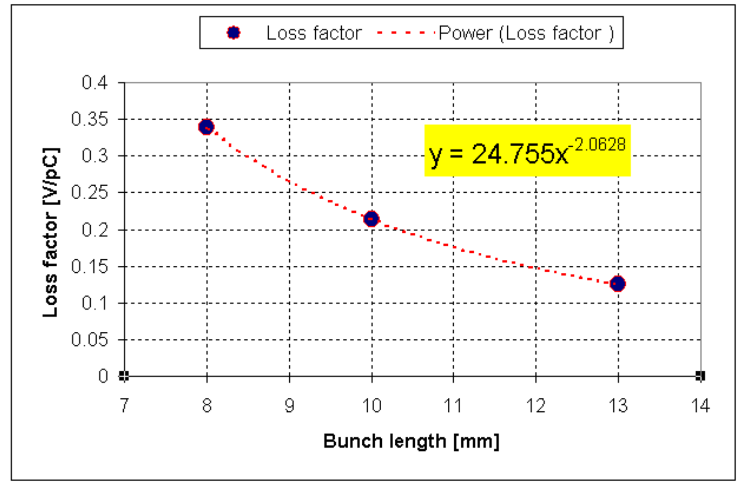
Injection and Abort Kicker

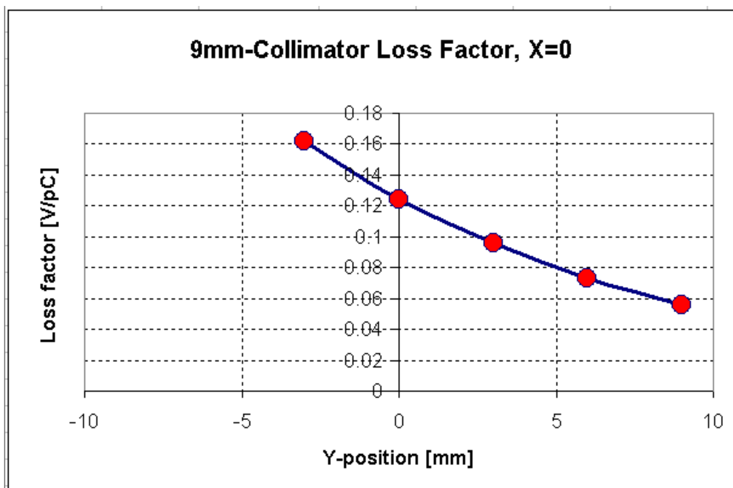


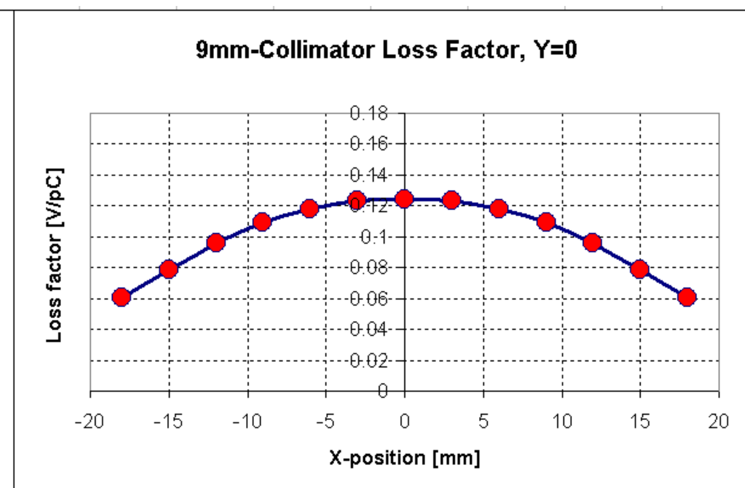
Collimator

Sasha Novokhatski "Stability/Impedance/RF"





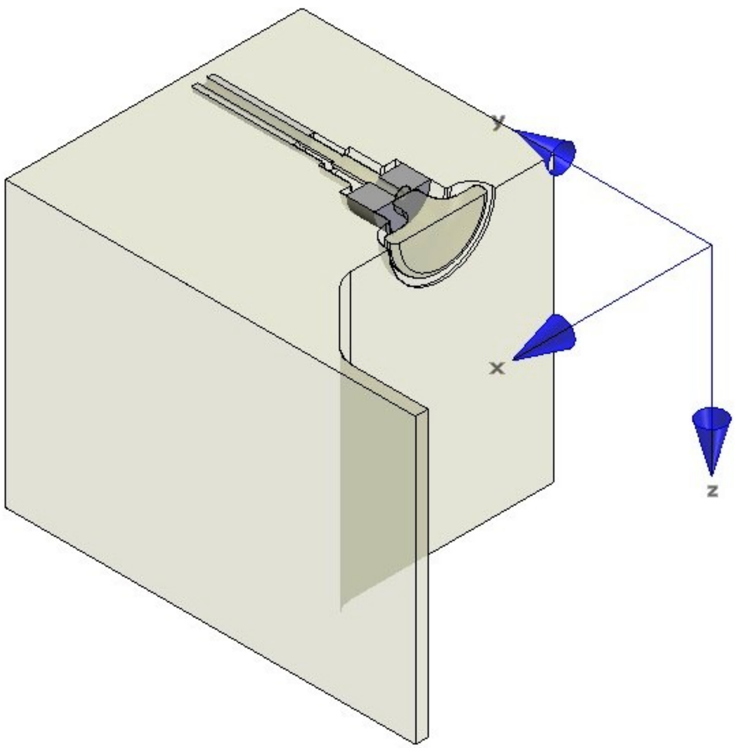


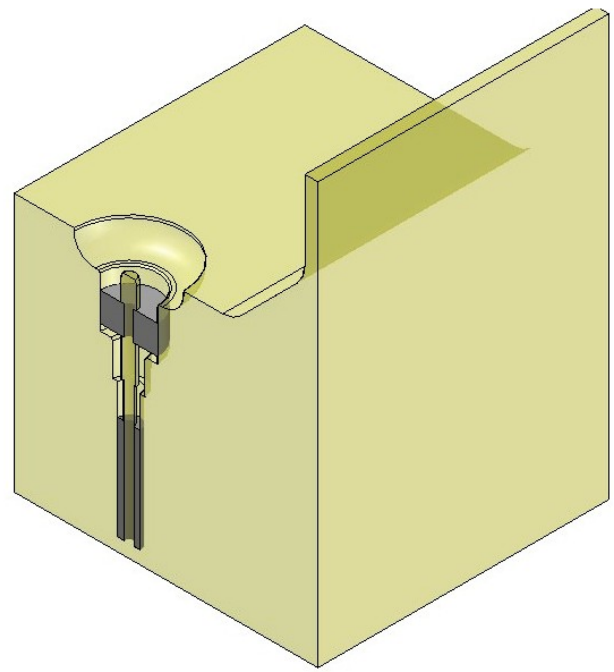


BPMs

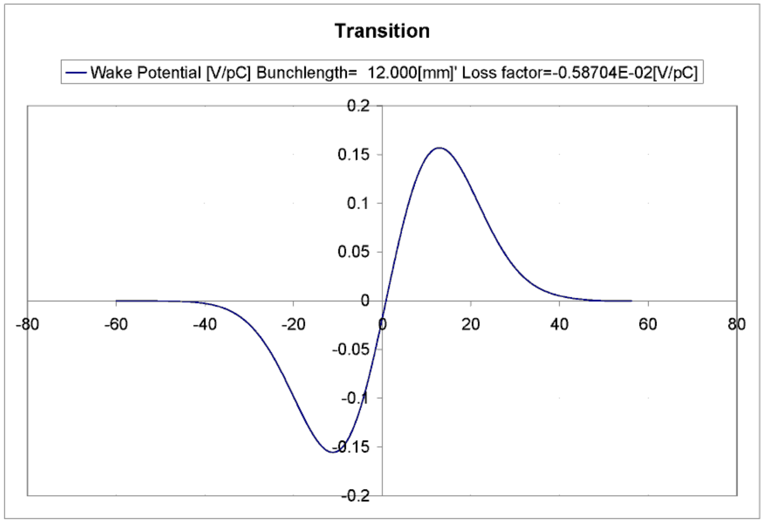
Loss factor = 0.00177 V/pC

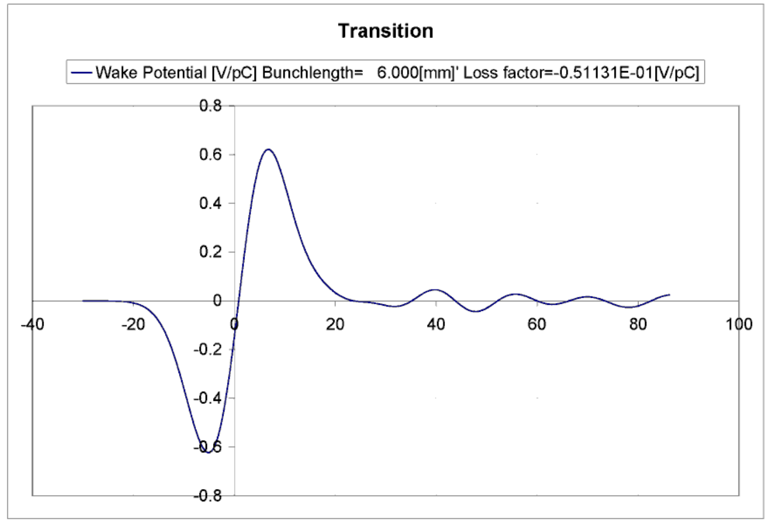
Loss factor = 0.00085 V/pC





Transitions





A sum

LER	PEP-II					Super-B		
		loss Factor	lengthening	loss Factor	lengthening		loss Factor	lengthening
bunch [mm]		12	12	6			6	6
Element	Quantity					Quantity		
RF cavity minus main mode	8	2.402	-0.569472	3.78088	-0.979572	10	4.7261	
Resistive-wall	1	2.1659	3.88056	6.102	11.04654	1	3	1.7" Cu
Interaction region	1	0.2873	0.729165	1.1244	1.342027	1	1.1244	
Longitudinal Kicker	2	0.472	1.45833	0.69726	-0.364518	2	0.69726	
Transverse Kicker	4	0.61212	-0.284739	0.97684	-0.489786	4	0.97684	
Injection kicker	2	0.02644		0.07482		2	0.07482	
Abort kicker	2	0.02644		0.07482		2	0.07482	
Collimators	6	0.875		3.5		6	3.5	
Transition round to octagona	12	0.07044		0.613572		12	0.61357	
Other Inductive elements	60	0.3522		3.06786		60	3.06786	
Round BPM	150	0.075						
Octagonal BPM	200	0.354						
Total loss factor		7.71884		20.01245			17.8557	

Summary for Super KEKB Y. Suetsugu

- Loss factors of components (expected):
  - Calculation for σ_z = 3 mm, antechamber
  - Except for RF cavities (16~24 V/pC)

Components	Number	Loss factor [V/pC] (ϕ90)
Resistive wall (Copper)	3016 [m]	6.9
Pumping port (screen)	2200 [m]	9.7 → 1.9E-03
SR mask (5 mm)	1000	10.2 → 1.0E-05
Movable mask (Ver. 6)	16	19.2 → 2.0 (?)
Bellows (Comb)	1000	11.0 → 4.0
Gate valve (Comb)	30	0.3 → 0.1
Connection flange (MO)	2000	1.6 → 1.0E-2
Taper	40	1.6
BPM (Button)	400	1.1
Total		60.0 → 15.7

Sasha Novokhatski "Stability/Impedance/RF"

- The impedance of the Super-B vacuum chamber should be two times smaller than impedance of the PEP-II chamber.
- Careful wake field analyzes should be included in engineering design of every beam chamber element.