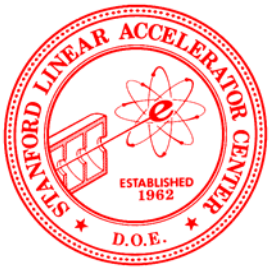

Super-B: RF Power and Bunch lengthening

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May, 2008

RF power is needed to compensate:

- Synchrotron radiation losses
  - S.R. energy loss per turn and beam current
- Cavity Joule losses
  - Shunt impedance, cavity voltage and number of cavities.
- Reflected power
  - Cavity coupling coefficient, beam current, cavity voltage and number of cavities
- HOM power

Power balance

$$\sum_{cav} P_{cav}^{forward} = \sum_{cav} P_{cav}^{reflected} + \sum_{cav} P_{cav}^{loss} + P_{beam}$$

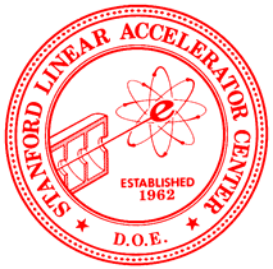
$$P_{beam} = U_{S.R.} \times I + Z_{HOMs} \times I^2$$

incoherent radiation

coherent radiation

HOM power

- Beam current
- Vacuum chamber loss factor
  - Bunch length
    - Zero current bunch length
      - Momentum compaction, momentum spread, RF voltage
    - Bunch lengthening
      - Vacuum chamber impedance
- Bunch spacing



Super-B parameters (2007)

PARAMETER	LER	HER	LER	HER	LER	HER
Particle type	e+	e-	e+	e-	e+	e-
Energy (GeV)	4	7	4	7	4	7
Luminosity x 10^{36}	1,0		2,4		3,4	
Circumference (m)	2250	2250	2250	2250	2250	2250
Revolution frequency (MHz)	0,13	0,13	0,13	0,13	0,13	0,13
Eff. long. polarization (%)	0	80	0	80	0	80
RF frequency (MHz)	476	476	476	476	476	476
Harmonic number	3570	3570	3570	3570	3570	3570
Momentum spread	8,4E-04	9,0E-04	1,0E-03	1,0E-03	1,0E-03	1,0E-03
Momentum compaction	1,8E-04	3,0E-04	1,8E-04	3,0E-04	1,8E-04	3,0E-04
Rf Voltage (MV)	6	18	6	18	7,5	18
Energy loss/turn (MeV)	1,9	3,3	2,3	4,1	2,3	4,1
Number of bunches	1733	1733	3466	3466	3466	3466
Particles per bunch x10^{10}	6,16	3,52	5,34	2,94	6,16	3,52
Beam current (A)	2,28	1,30	3,95	2,17	4,55	2,60
Beta y* (mm)	0,30	0,30	0,20	0,20	0,20	0,20
Beta x* (mm)	20	20	20	20	20	20
Emit y (pmr)	4	4	2	2	2	2
Emit x (nmr)	1,6	1,6	0,8	0,8	0,8	0,8
Sigma y* (microns)	0,035	0,035	0,020	0,020	0,020	0,020
Sigma x* (microns)	5,657	5,657	4,000	4,000	4,000	4,000
Bunch length (mm)	6	6	6	6	6	6
Full Crossing angle (mrad)	34	34	34	34	34	34
Wigglers (#)	4	2	4	4	4	4
Damping time trans/long(ms	32/16	32/16	25/12.5	25/12.5	25/12.5	25/12.5
Luminosity lifetime (min)	10,4	5,9	7,4	4,1	6,1	3,5
Touschek lifetime (min)	5,5	38	2,9	19	2,3	15
Effective beam lifetime (min)	3,6	5,1	2,1	3,4	1,7	2,8
Injection rate pps (100%)	4,9E+11	2,0E+11	1,5E+12	5,0E+11	2,1E+12	7,2E+11
Tune shift y (from formula)	.17	.17	0.16	0.16	0.02	0.02
Tune shift x (from formula)	0.004	0.004	0.007	0.007	0.009	0.009
RF Power (MW)	17		35		44	

Synchrotron radiation losses

HER	HER	HER	HER	HER	HER+LER
			S.R. energy		Total
Lumi	Beam energy	Beam current	per turn	S.R. power	power
	GeV	A	MeV	MW	MW
1E+36	7	1.3	3.3	4.29	8.622
2.4E+36	7	2.17	4.1	8.897	17.982
3.4E+36	7	2.6	4.1	10.66	21.125
LER	LER	LER	LER	LER	
			S.R. energy		
Lumi	Beam energy	Beam current	per turn	S.R. power	
	GeV	A	MeV	MW	
1E+36	4	2.28	1.9	4.332	
2.4E+36	4	3.95	2.3	9.085	
3.4E+36	4	4.55	2.3	10.465	

Minimum number of cavities

- Due to 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 is limited by sparks in RF windows
    - SLAC people consider power less than 500 KW per cavity

Cavity losses

Dissipated power in all cavities $P_c = \frac{V_c^2}{2Z_{sh}} N_c = \frac{V_{tot}^2}{2N_c Z_{sh}}$ $Z_{sh}^{PEP-II} = 3.8\,MOhm$

HER Lumi	HER Total RF voltage MV	HER Max voltage per cavity MV	HER Number of cavities	HER All cavity loss MW	HER and LER total cavity loss MW
1E+36	18	0.7	26	1.64	2.24
2.4E+36	18	0.7	26	1.64	2.94
3.4E+36	20	0.7	28	1.88	3.76

LER Lumi	LER Total RF voltage MV	LER Max voltage per cavity MV	LER Number of cavities	LER All cavity loss MW	r
1E+36	8	0.6	14	0.60	
2.4E+36	16	0.6	26	1.30	
3.4E+36	20	0.7	28	1.88	

Reflected power

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

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

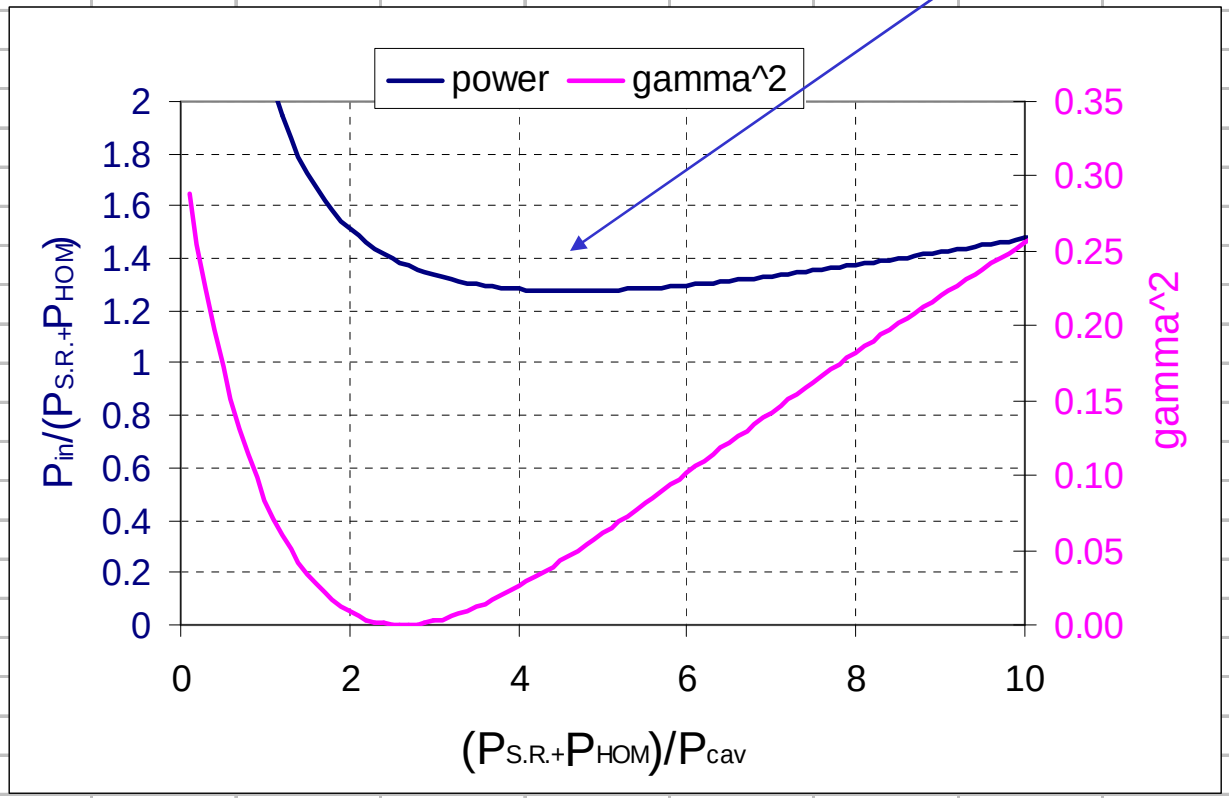
PEP-IIcavity: $\alpha_{cav} = 1.57$ $\beta = 3.6$

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

Minimum forward power

alpha	1.57	ratio	gamma	gamma^2	power
betta	3.6	0.1	-0.5366	0.287935	15.44803
			2.2	-0.06206	0.003851	1.460169

Wide minimum



Minimum $P_{in}/(P_{S.R.}+P_{HOM})=1.28$ at $/(P_{S.R.}+P_{HOM})/ P_{cav} =4.6$

Pin – forward power

Reflected power

HER Lumi	HER Beam current A	HER Total RF voltage MV	HER Max voltage per cavity MV	HER Number of cavities	HER All reflected power MW	HER and LER Total reflected MW
1E+36	1.3	18	0.7	26	0.00	1.44
2.4E+36	2.17	18	0.7	26	1.01	4.01
3.4E+36	2.6	20	0.7	28	1.41	4.01
LER Lumi	LER Beam current A	LER Total RF voltage MV	LER Max voltage per cavity MV	LER Number of cavities	LER All reflected power MW	
1E+36	2.28	8	0.6	14	1.44	
2.4E+36	3.95	16	0.6	26	3.00	
3.4E+36	4.55	20	0.7	28	2.60	

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HOM power

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

HOM Power Bunch Spacing Loss Factor Current

$$K = K(\sigma)$$

$$\sigma = \sigma(I)$$

Zero current bunch length

HER	HER	HER	HER	HER	HER
Lumi	S.R. energy loss per turn MeV	Momen-tum com-paction	Momen-tum spread	Total RF voltage MV	Bunch length at zero current mm
1E+36	3.3	3.0E-04	9.0E-04	18	4.7
2.4E+36	4.1	3.0E-04	1.0E-03	18	5.2
3.4E+36	4.1	3.0E-04	1.0E-03	20	4.9

LER	LER	LER	LER	LER	LER
Lumi	S.R. energy loss per turn MeV	Momen-tum com-paction	Momen-tum spread	Total RF voltage MV	Bunch length mm
1E+36	1.9	1.8E-04	8.4E-04	8	3.8
2.4E+36	2.3	1.8E-04	1.0E-03	16	3.2
3.4E+36	2.3	1.8E-04	1.0E-03	20	2.9

In dark red are Corrected numbers

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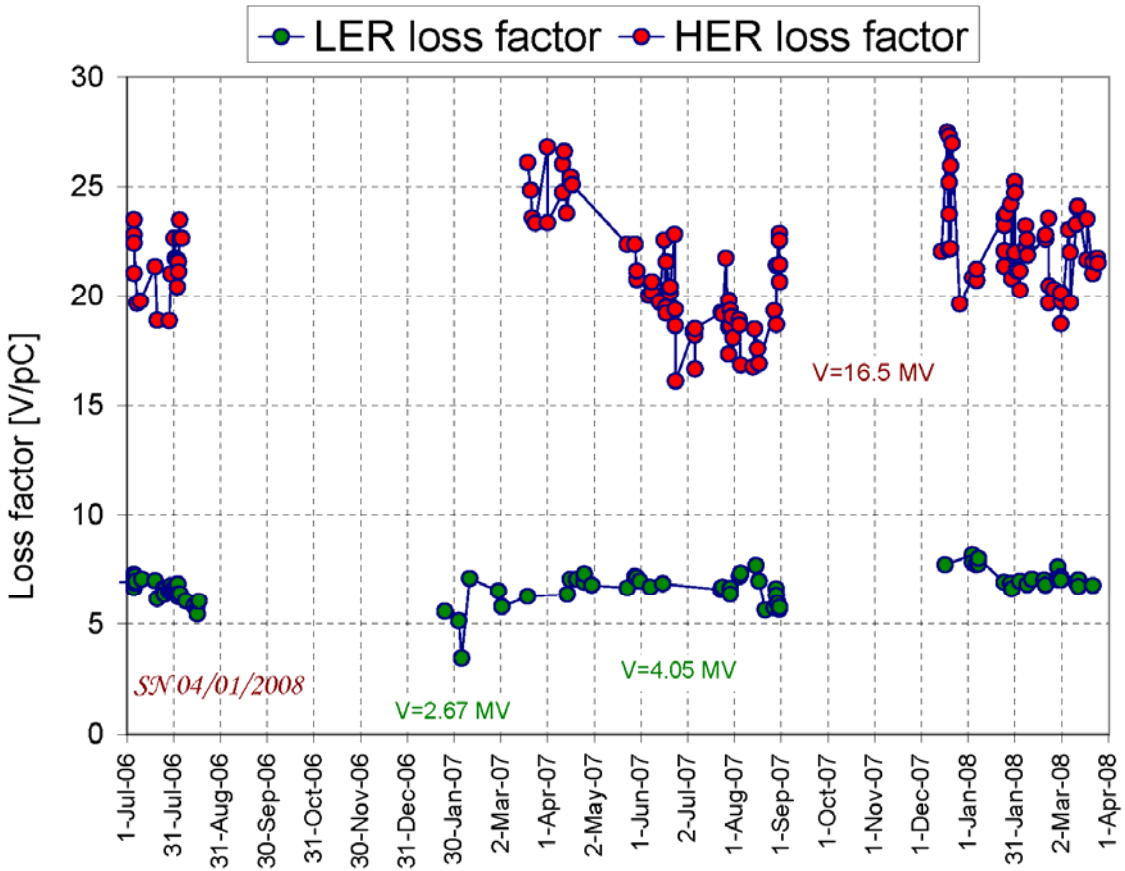
Loss factor of PEP-II vacuum chamber

Power balance measurement



HOM power

HER Lumi	HER Beam current A	HER Total RF voltage MV	HER Bunch length mm	HER Bunch spacing nsec	HER Number of cavities	HER HOM power MW	HER and LER HOM Power MW
1E+36	1.3	18	4.7	4.2	26	0.24	1.02
2.4E+36	2.17	18	5.2	2.1	26	0.29	2.09
3.4E+36	2.6	20	4.9	2.1	28	0.46	3.32

LER Lumi	LER Beam current A	LER Total RF voltage MV	LER Bunch length mm	LER Bunch spacing nsec	LER Number of cavities	LER HOM power MW
1E+36	2.28	8	3.8	4.2	14	0.78
2.4E+36	3.95	16	3.2	2.1	26	1.80
3.4E+36	4.55	20	2.9	2.1	28	2.86

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Super-B RF: Supply power

HER	HER	HER	HER	HER	HER	HER	HER	HER	HER	HER	HER	HER	HER	HER	HER	HER	HER+
		S.R. energy				Total			Max				Total	Total	Total	Power for	LER
Lumi	Beam	Beam	loss	Momen-	Momen-	RF	Bunch	Bunch	voltage	Numbe	S.R.	HOM	cavity	reflected	forward	one	Total
	energy	current	per turn	tum com	tum	voltag	length	pacing	er cavit	of	power	power	loss	power	power	cavity	forward
	GeV	A	MeV	paction	spread	MV	mm	nsec	MV	cavities	MW	MW	MW	MW	MW	MW	MW
1E+36	7	1.3	3.3	3.0E-04	9.0E-04	18	4.7	4.2	0.7	26	4.29	0.2393	1.64	0.0022	6.17	0.24	13.32
2E+36	7	2.17	4.1	3.0E-04	1.0E-03	18	5.2	2.1	0.7	26	8.897	0.2902	1.64	1.0105	11.84	0.46	27.02
3E+36	7	2.6	4.1	3.0E-04	1.0E-03	20	4.9	2.1	0.7	28	10.66	0.4613	1.88	1.4148	14.42	0.51	32.22

LER	LER	LER	LER	LER	LER	LER	LER	LER	LER	LER	LER	LER	LER	LER	LER	LER	HER+ LER
		S.R. energy				Total			Max				Total	Total	Total	Power for	Supply
Lumi	Beam	Beam	loss	Momen-	Momen-	RF	Bunch	Bunch	voltage	Numbe	S.R.	HOM	cavity	reflected	forward	one	Power
	energy	current	per turn	tum com	tum	voltag	length	pacing	er cavit	of	power	power	loss	power	power	cavity	eff.~50%
	GeV	A	MeV	paction	spread	MV	mm	nsec	MV	cavities	MW	MW	MW	MW	MW	MW	MW
1E+36	4	2.28	1.9	1.8E-04	8.4E-04	8	3.8	4.2	0.6	14	4.332	0.7773	0.602	1.4376	7.15	0.51	26.64
2E+36	4	3.95	2.3	1.8E-04	1.0E-03	16	3.2	2.1	0.6	26	9.085	1.799	1.296	2.9991	15.18	0.58	54.03
3E+36	4	4.55	2.3	1.8E-04	1.0E-03	20	2.9	2.1	0.7	28	10.465	2.8578	1.88	2.5988	17.80	0.64	64.43

In dark red are Corrected numbers

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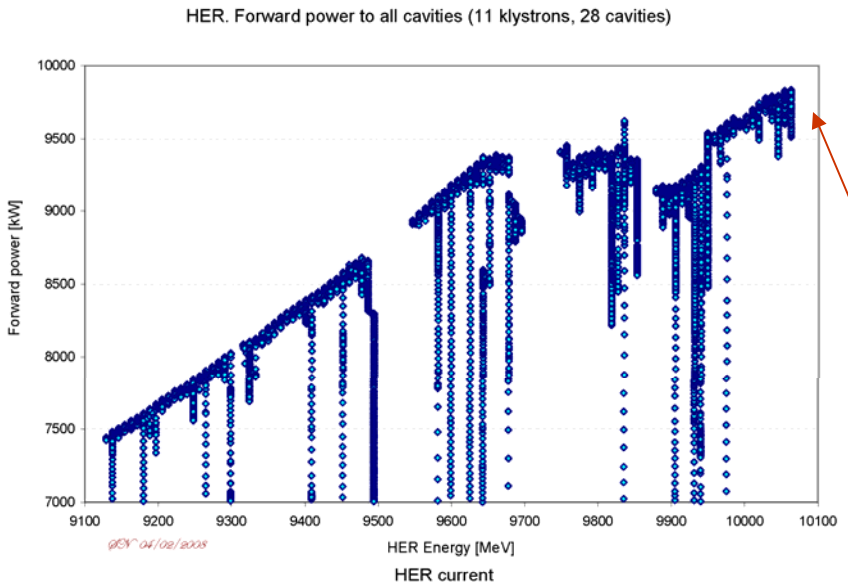
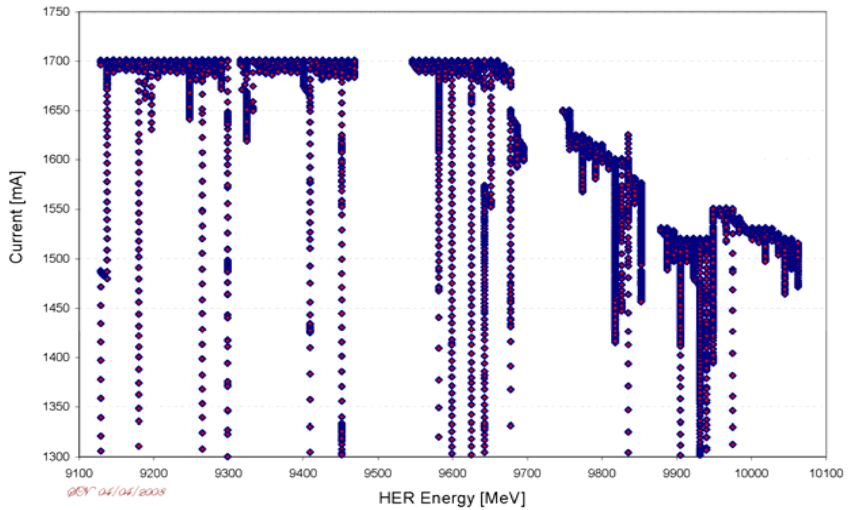
Maximum RF in PEP-II: Forward power





During energy scan

11 klystrons

In average
350 KW per cavity

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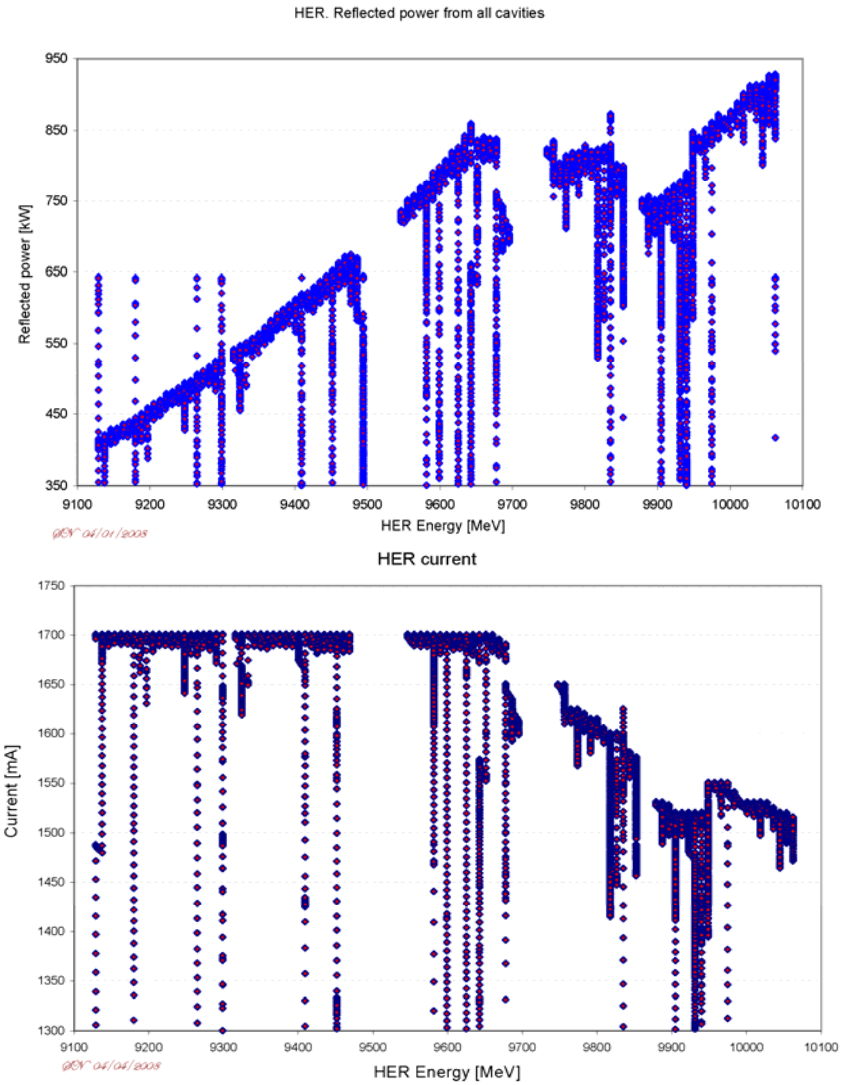
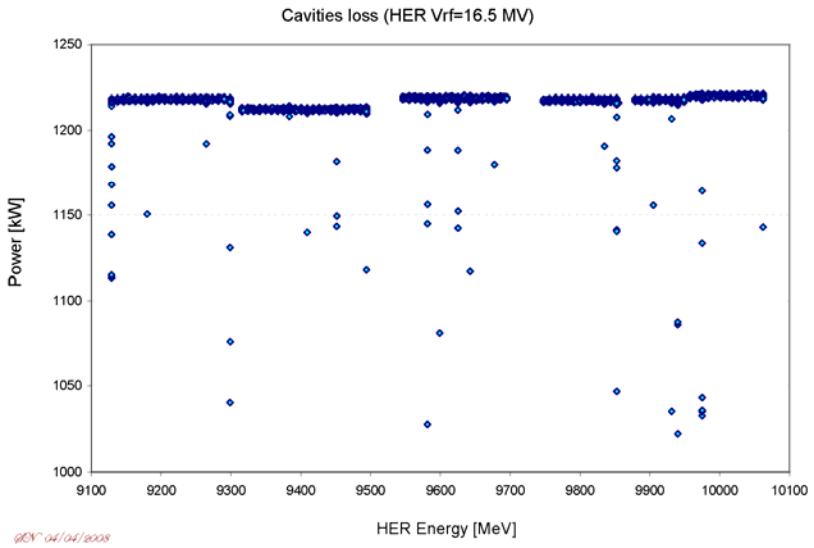
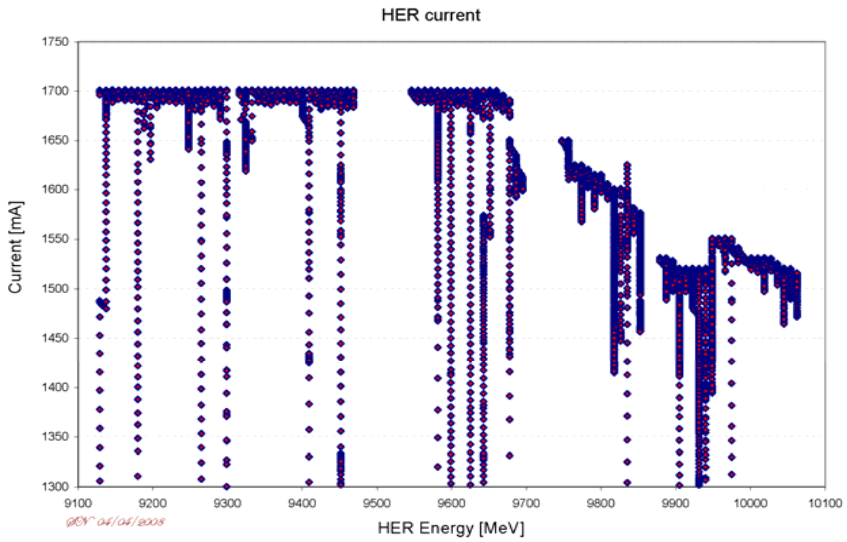
Maximum RF in Pep-II: Reflected power



Reflected waves carry equivalent power of a klystron

PEP-II cavity losses





Cavities dissipate
the power of a klystron

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

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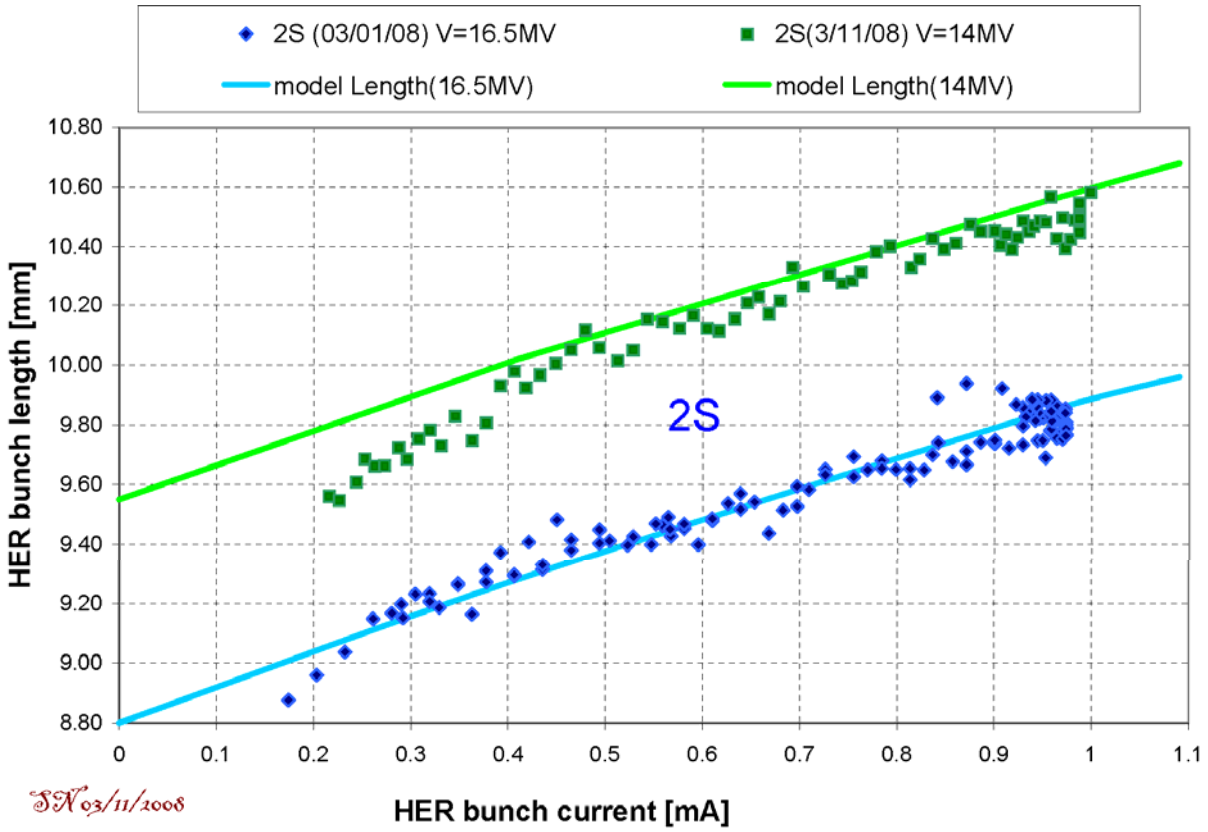
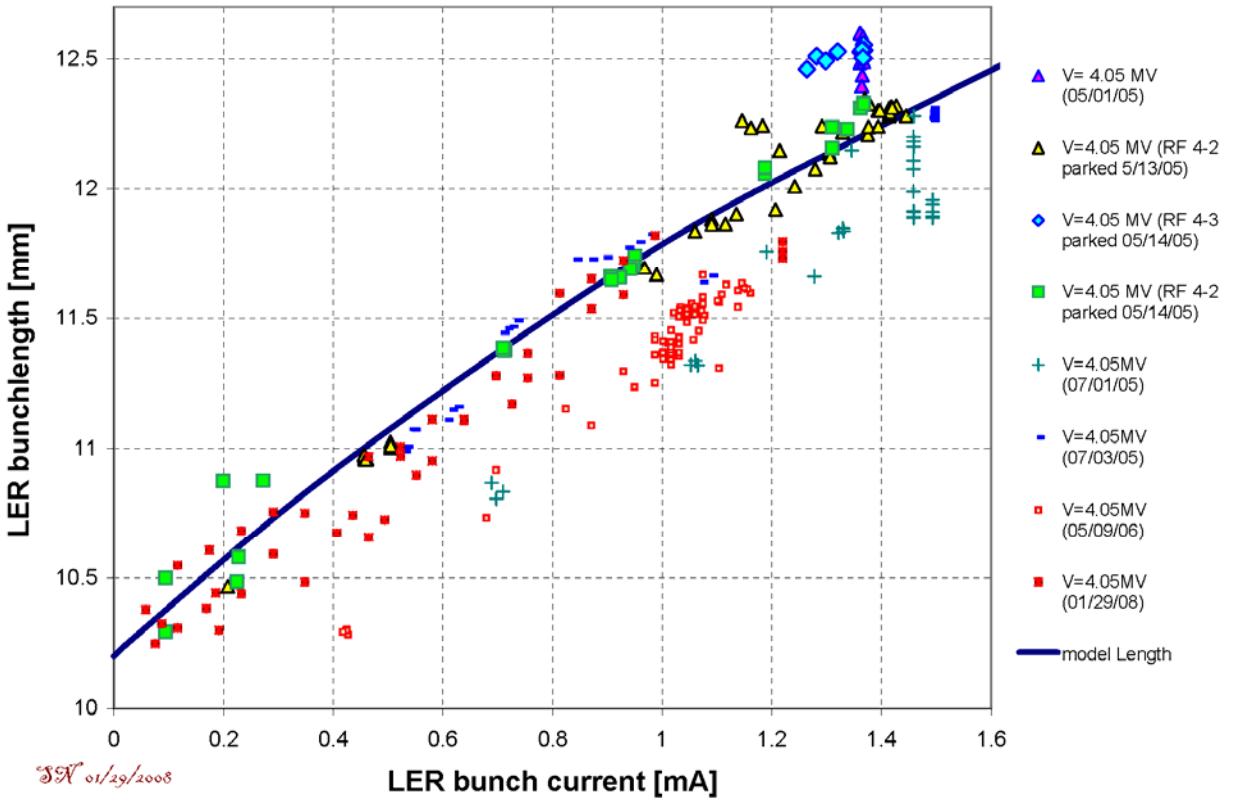
Bunch lengthening in PEP-II: HER



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

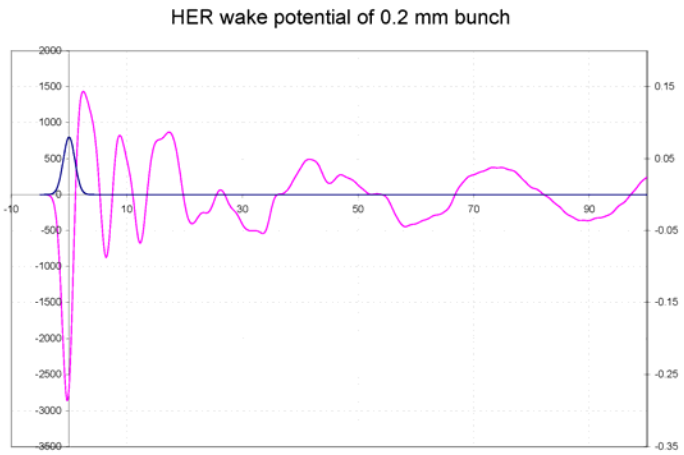
Bunch lengthening in PEP-II: LER

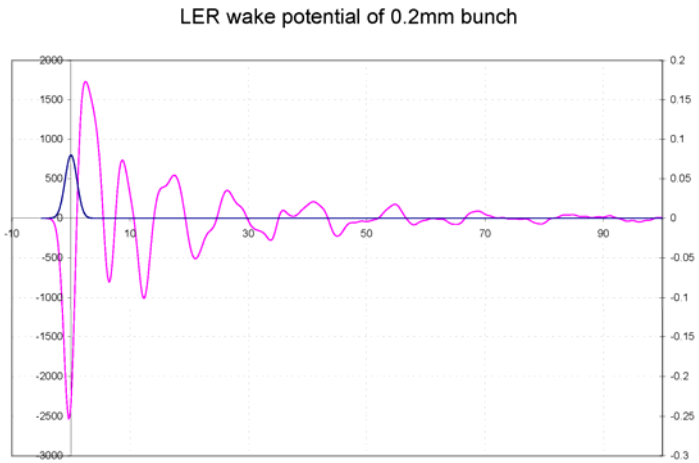


Solid line shows the bunch length, which was calculated using the LER impedance model

PEP-II HER and LER wake potentials,

which were used to calculate bunch lengthening in SuperB





Bunch lengthening in Super-B

HER Lumi	HER E. energy loss per turn MeV	HER Momentum compaction	HER Momentum spread	HER Total RF voltage MV	HER Bunch length at zero current mm	HER Beam current A	HER Number of bunches	HER Bunch charge nC	HER Bunch length mm	
1E+36	3.3	3.0E-04	9.0E-04	18	4.7	1.3	1733	5.52	6.61	
2.4E+36	4.1	3.0E-04	1.0E-03	18	5.2	2.17	3466	4.60	6.51	
3.4E+36	4.1	3.0E-04	1.0E-03	20	4.9	2.6	3466	5.52	6.57	

LER Lumi	LER E. energy loss per turn MeV	LER Momentum compaction	LER Momentum 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
1E+36	1.9	1.8E-04	8.4E-04	8	3.8	2.28	1733	9.67	Unstable	0.94
2.4E+36	2.3	1.8E-04	1.0E-03	16	3.2	3.95	3466	8.38	Unstable	1.79
3.4E+36	2.3	1.8E-04	1.0E-03	20	2.9	4.55	3466	9.65	Unstable	1.65

In dark red are Corrected numbers

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"RF Power and Bunch Lengthening"

Summary

- Adjustment of the PEP-II RF cavities to transfer high power to the beam in SuperB requires high RF voltage.
- Bunch length is shortening with higher RF voltage, if it cannot be compensated by increasing the momentum compaction.
- Short bunches are unstable in SuperB LER, if the vacuum chamber impedance is the same as in PEP-II LER.
- Situation will change if impedance of the SuperB chamber is 3 times less than impedance of PEP-II.