Beam-beam Performance of the SLAC *B*-Factory

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- **Introduction: PEP-II collision parameters**
- **Interplay between e^- - cloud & beam-beam issues**
- **Observation of beam-beam flip-flop**
- **Experimental determination of beam-beam limits**
- **Simulation vs. experiment**
- **Summary**

J. Seeman, et. al.,
EPAC'02, PAC'03

PEP-II Collision Parameters

IP Parameter	Design	Recent peak performance
C-M energy (GeV) (e^+: 3.1 ; e^-: 9.0)	10.28	10.28
Crossing angle (mrad)	0.0	< 1.0
Luminosity (x $10^{33}/cm^2/s$)	3.00	6.11
Number of bunches	1658	939
LER current (mA, e^+)	2146	1750
HER current (mA, e^-)	750	1070
β_y^*/β_x^* (cm/cm)	1.5 / 50	1.2 / 35+, 1.2 / 41-
Emittance (nm-rad) (y/x)	1.5 / 49	1.4 / 33+, 3.1 / 49-
IP rms beam size σ_y/σ_x (μm)	4.7 / 157	5.0 / 140
LER tunes (x/y)	38.64 / 36.57	38.52 / 36.57
HER tunes (x/y)	24.62 / 23.64	24.52 / 23.62
Beam-beam parameter (vertical +/-)	0.03	0.048 / 0.060
Beam-beam parameter (horizontal +/-)	0.03	0.065 / 0.075

- **Energy-transparency conditions**

  $\xi^{+}_{x,y} = \xi^{-}_{x,y}$ <====> $I^{+}_{b}\ E^{+} = I^{-}_{b}\ E^{-}$

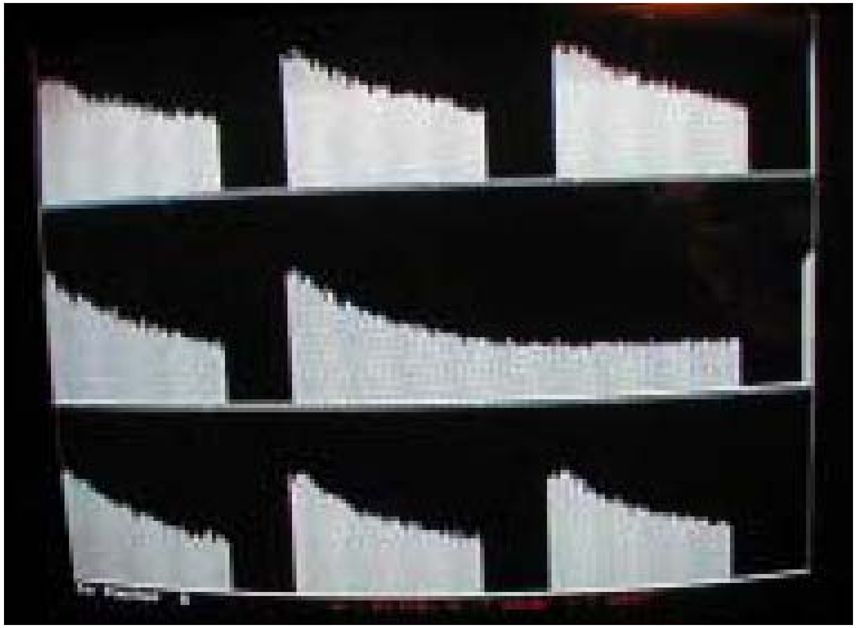
  (provided $\beta^{+}_{x,y} = \beta^{-}_{x,y}$, $\varepsilon^{+}_{x,y} = \varepsilon^{-}_{x,y}$, $\nu^{+}_{x,y} = \nu^{-}_{x,y}$...)

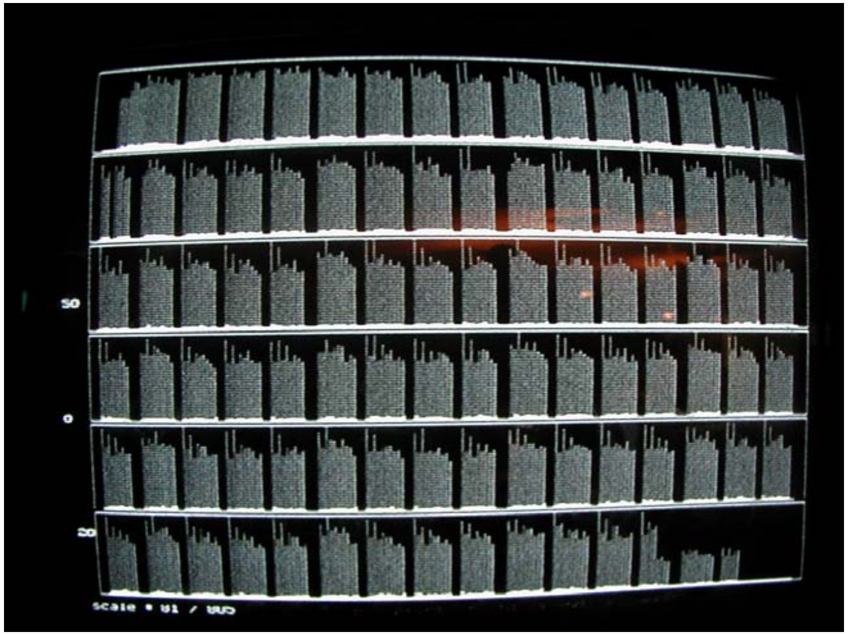
  - **largely violated in PEP-II**
  - **best performance repeatedly achieved with $I^{+} / I^{-} \sim 1.7 – 2$ (not 2.9!)**

- **In contrast to 'classical' single-ring collider,**
  - $\varepsilon^{+}_{x,y} \neq \varepsilon^{-}_{x,y}$ **(and** $\beta^{+}_{x,y} \approx \beta^{-}_{x,y}$ **only) =>** $\sigma^{+}_{x,y} \neq \sigma^{-}_{x,y}$
  - **interpreting luminosity in terms of ξ requires additional knowledge and/or assumptions on individual IP spot sizes**

F.-J. Decker,
et. al.,
PAC'01, '03

Interplay between e^- - cloud & beam-beam issues





Bunch-by-bunch luminosity versus position along the whole train. Pattern: 'by-4' (8.4 ns spacing) with 7 additional big gaps, July 2000.

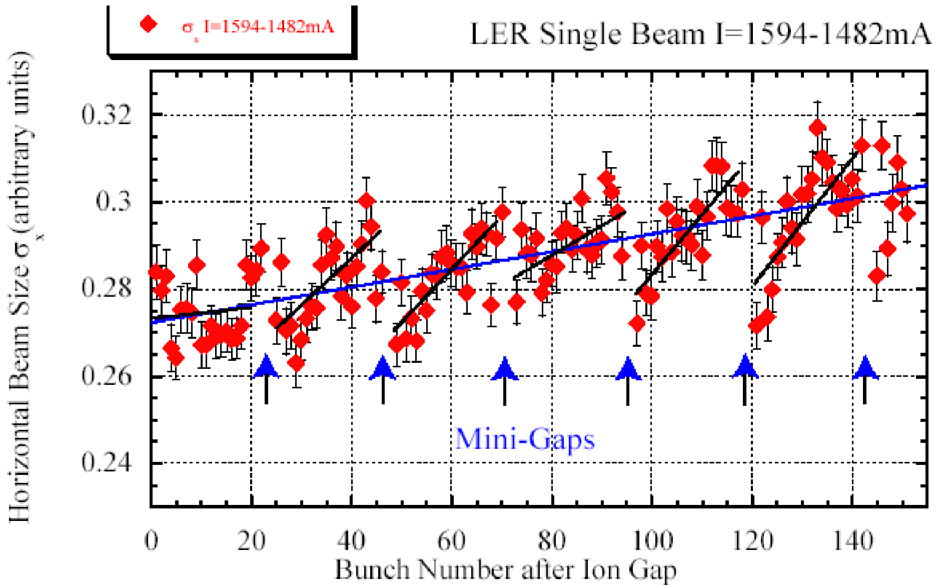
The first bunches of each mini-train have a high luminosity, which drops to 40 % of its initial value at the end of the longest train. The long gaps clear the electron cloud, which slowly builds up again over along the mini-train. Solenoids had been installed in part of the straights only.

Standard luminosity pattern in 2003
Pattern: 'by-3' (6.3 ns spacing)

Mini-trains of 10 and 11 bunches are alternating. There is an ion gap of about 3%. In this pattern each mini-train has constant luminosity (except for bunches 1+3). Solenoids now cover most of the beam pipe in all straights and arcs.

Interplay between e$^-$ - cloud & beam-beam issues (2)

- At high I$^+$, e$^-$ cloud strength varies along minitrain =>
  - e$^+$ beam size varies (long range + within train) => Luminosity varies



Gated-camera measurements

(2001 data, 4-by-22 pattern)

R. Holtzapple, PEP-II Performance Workshop, Jan 2002

  - e$^-$ beam-beam tune-shift varies (=> e$^-$ beam size may vary ??)
  - tunes optimized on the average only =>
    - slight L loss
    - 'raining' buckets (rapid loss of charge, background spikes, flip-flop)
    - electron-cloud enhanced beam-beam blowup of the e$^+$ beam

Interplay between e$^-$ - cloud & beam-beam issues (3)

- **Bunch pattern optimization: maximize I_{bunch}, taking into account**
  - total-current budget (RF power, beam-heating problems)
  - minitrain spacing (larger minigaps => better e$^-$ cloud suppression)
  - minitrain length (shorter minitrains => less e$^-$ cloud buildup)
  - # of minitrains (fewer minitrains => fewer 'fragile' bunches)
  - need for current ramps at start of train (and/or minitrains)

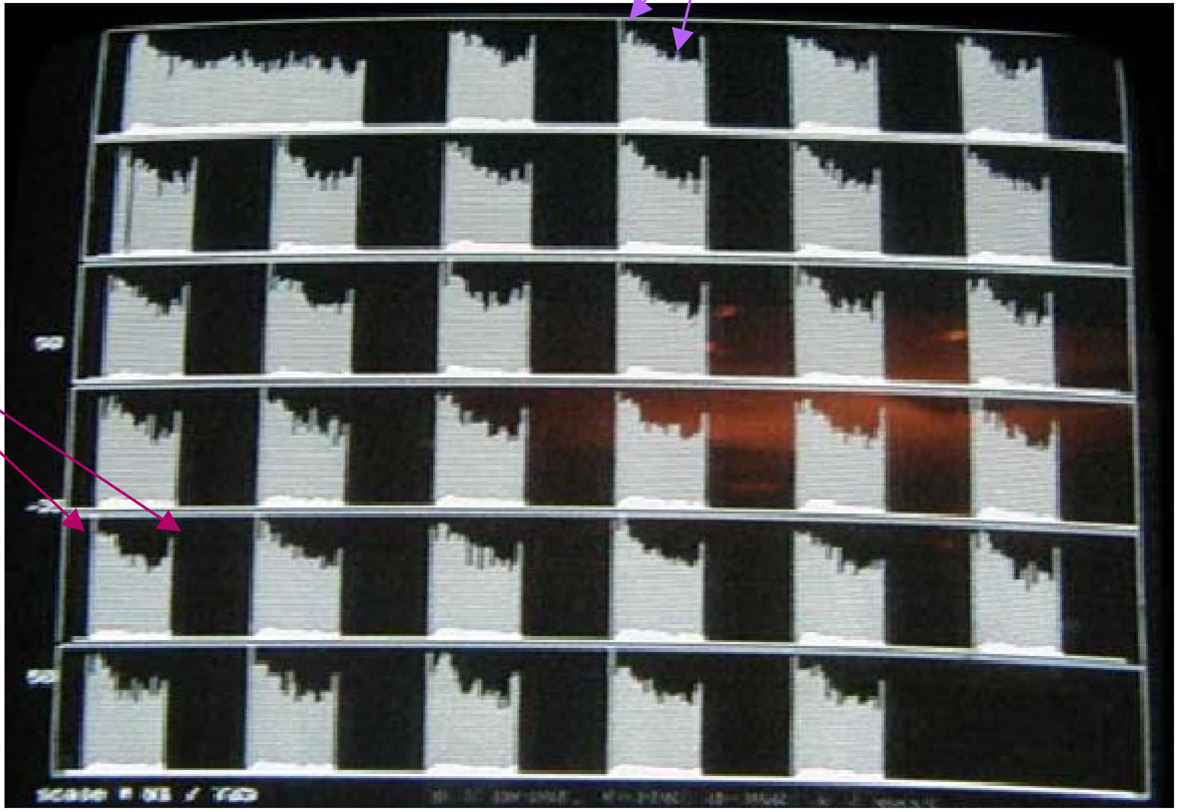
- **The severity of electron-cloud effects (for a fixed bunch pattern) has been steadily decreasing over the years**
  - Low-field (25-35 G) solenoids now cover most of the accessible beam-pipe sections. This system will be upgraded this summer (higher field)
  - Vacuum-pipe scrubbing has clearly played a significant role
  - Some e$^-$ cloud effects are no longer apparent
    - single-beam e$^+$ blowup at high I^+ no longer observed (but what once $I^+ \uparrow$?)
  - In typical recent running, only 1st (few) bucket(s) in each minitrain affected by electron cloud

Interplay between e$^-$ - cloud & beam-beam issues (4)

- **Towards higher luminosities...**
  - **impact of e$^-$ cloud may be more severe once higher currents force the use of a denser pattern ('by-2', 4.2 ns spacing), and *may* become a major limitation**
  - **parasitic crossings do matter!**

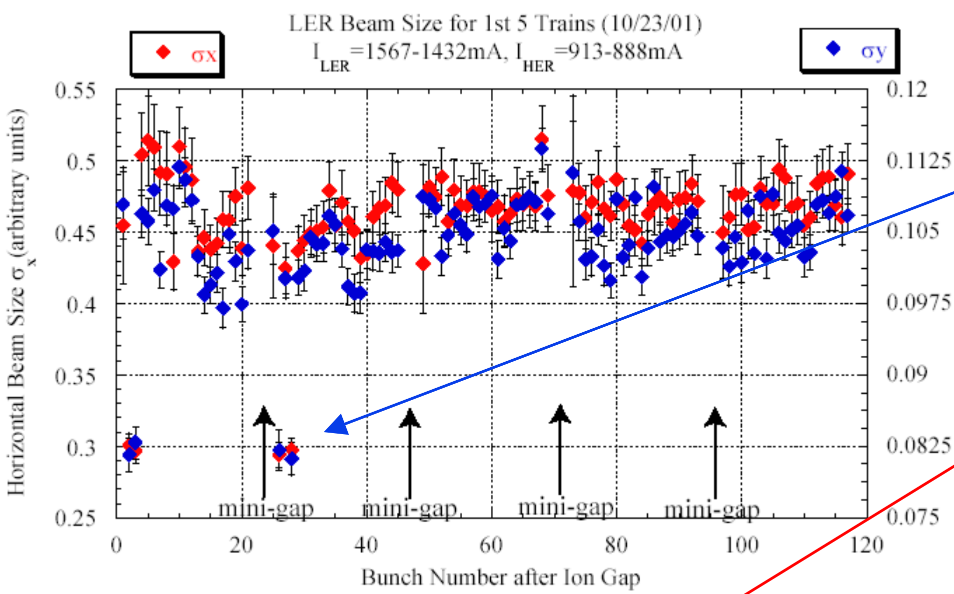
e$^-$ cloud

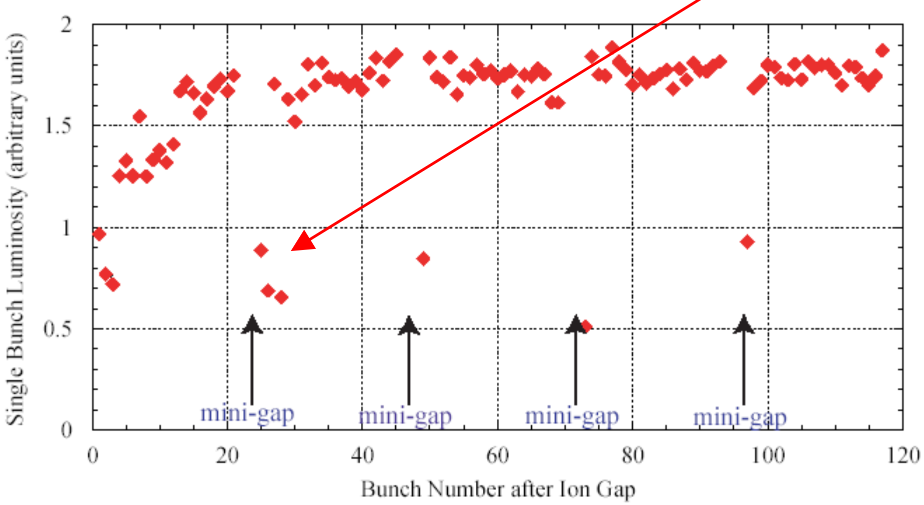
1 parasitic crossing @ minitrain edges (instead of 2)



R. Holtzapple, et. al.,
SLAC-PUB-9238

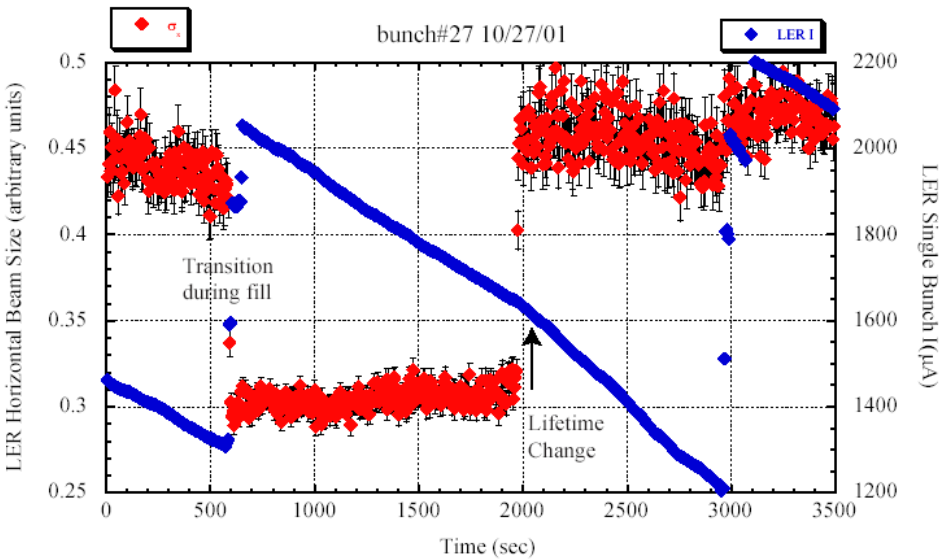
Beam-beam flip-flop

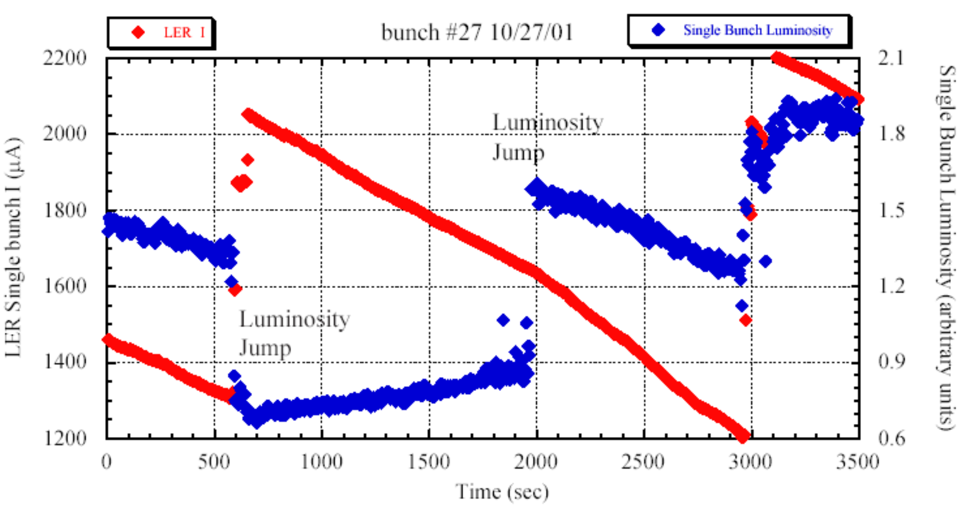




- Near the top of a fill:
  - Several LER bunches have reduced beam size (~30% reduction in beam size)
  - Several bunches - typically near the head of the train - have ~ ½ luminosity.
  - **2 states** of low-luminosity bunches: they have either reduced LER current or reduced LER beam size
    - I_b^+ **= low**; I_b^- = average
    - I_b^+, I_b^- = average; $\sigma_{x,y}^+$ **= small**. Small LER bunches + low Luminosity implies transverse blow-up of the elctron beam (HER), since bunch currents are not particularly low for these.

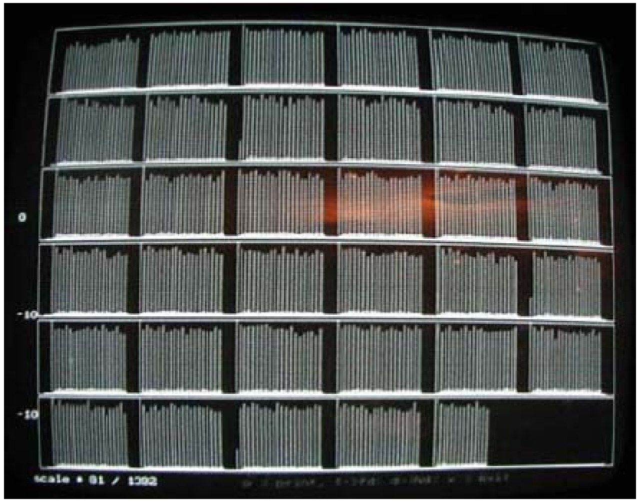
Beam-beam flip-flop (2)



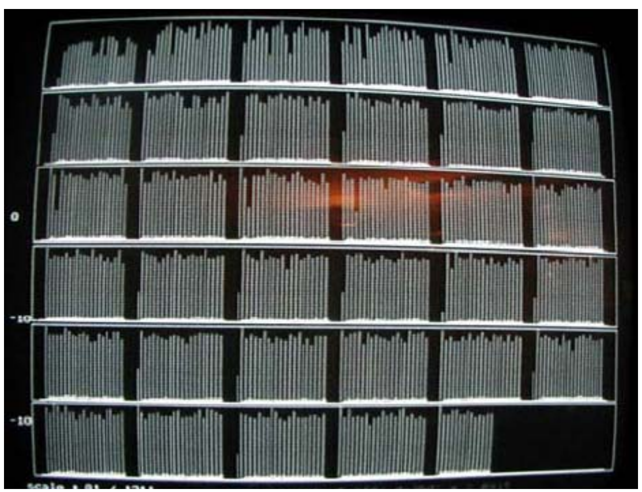


- Single Bunch Transition to low-luminosity state
  - Initially at average beam size
  - Luminosity dropped when rings were filled
  - The bunch experiences a sudden change in luminosity/beam size
  - This bunch went from one unstable state (low luminosity / small x, y) to the other unstable state (short lifetime)
    - Transition between states is fast (~0.5 sec.)
    - Horizontal beam size oscillation accompanies the transition

Beam-beam flip-flop (3)



Start of the store (high I): L/bunch (almost) uniform throughout each train.



End of the store (low I): single-bunch L dropouts are prevalent in the 1st few trains

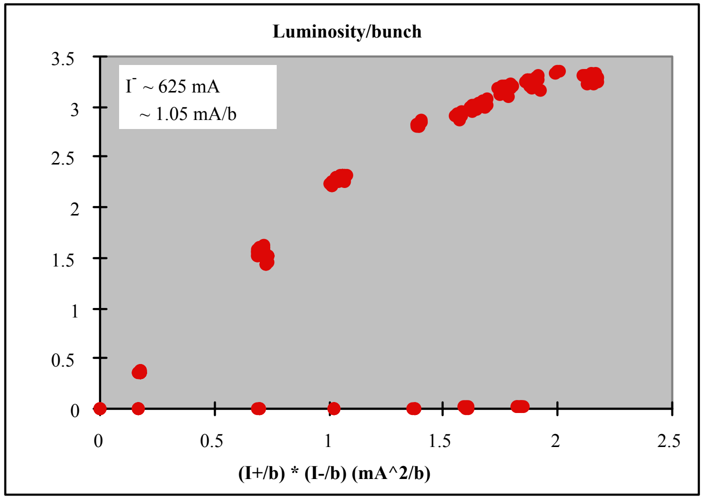
- At some time it was possible to force transitions between these states by tune manipulations
- Possible Explanation of Beam Size Flip-Flop Dynamics
  - The LER bunches at the front of the train have a smaller transverse beam size (lower electron cloud density). These small (strong) LER bunches blow-up the HER bunches.
  - The resulting tune shift (horizontal) for the these LER bunches is smaller than "normal", and as a result, they have a horizontal tune located near a resonance which gives them a shorter lifetime.
  - The LER bunches lose charge. Eventually the HER becomes strong enough to flop itself, and the LER bunch, back to "normal" size.
  - To confirm this theory, a gated camera will be installed in the HER.

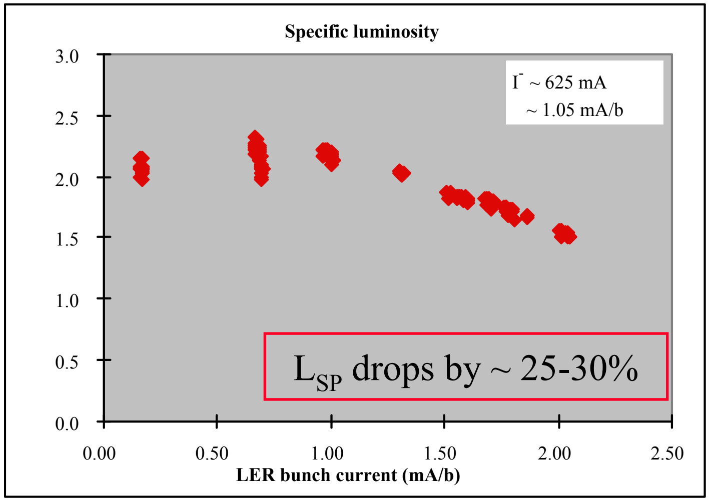
Beam-beam limit studies

- **Experimental procedure**
  - Fix one beam current (typically similar to physics conditions)
  - Vary the current of the other beam from 0 to maximum possible; at each setting, optimize luminosity on tunes
  - Measure L/bunch, specific luminosity L_{sp}, individual beam sizes $\sigma^{-}_{x,y}$ in- & out-of-collision

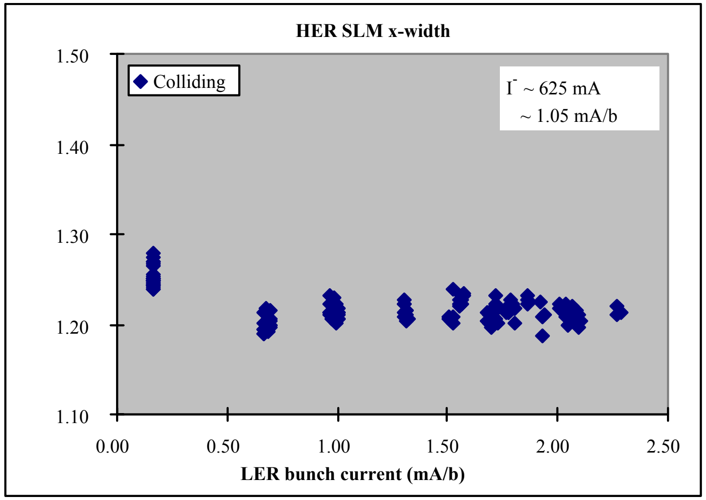
- **Diagnostics**
  - Fast luminosity monitor ($e^+e^- \rightarrow e^+e^- \gamma$)
  - Horizontal beam sizes: synchrotron-light monitor (SLM)
  - Vertical beam sizes: SR-light interferometer

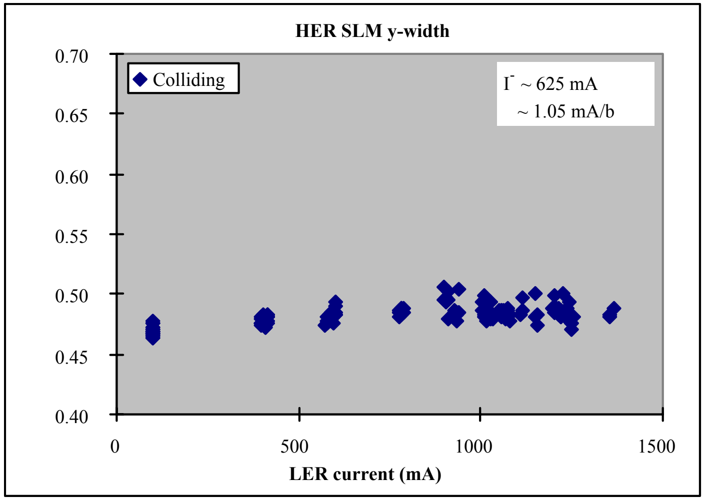
HER b-b limit @ high e^- current: I^- =625 mA, I^+ = 100-1400 mA, 597 bunches





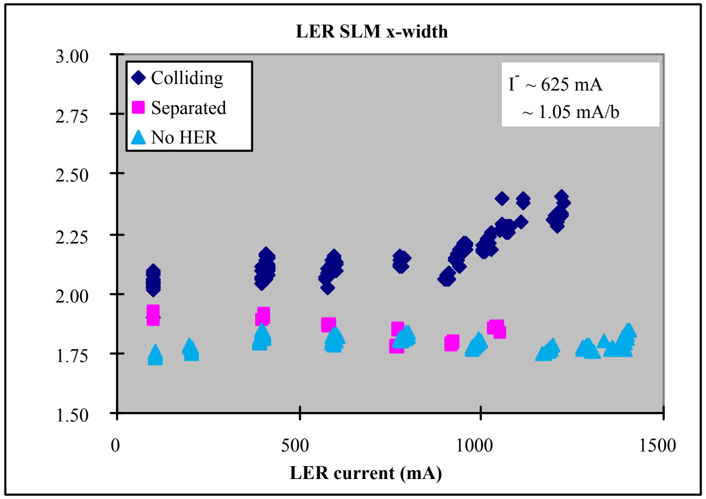
- HER:SLM x & y size in collision <u>flat with I^+</u> => where does L_{SP} drop come from?
- LER: dependence of x, y SLM size on LER current ?





HER b-b limit (continued)

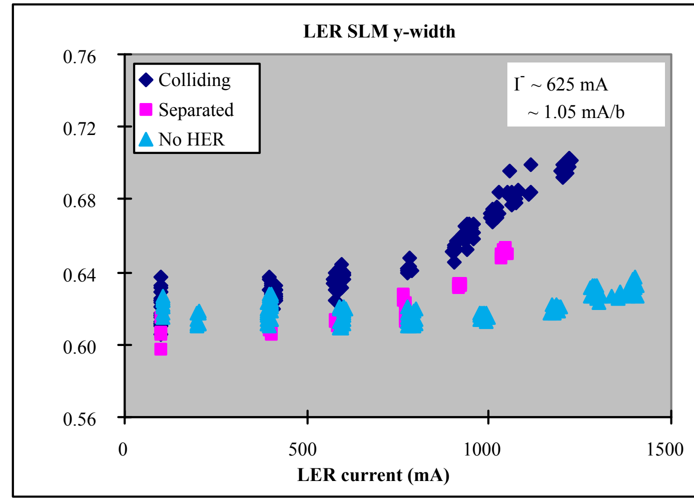
By-5 - 1/50th, 597 bunches , $\beta^*_y = 1.25$, July 00



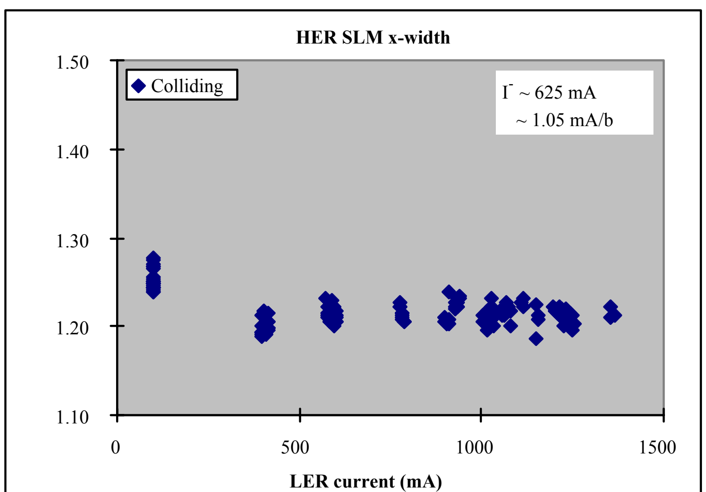
Collisions: LEB blowup in both x & y

(N.B.: y blowup instrumental??)

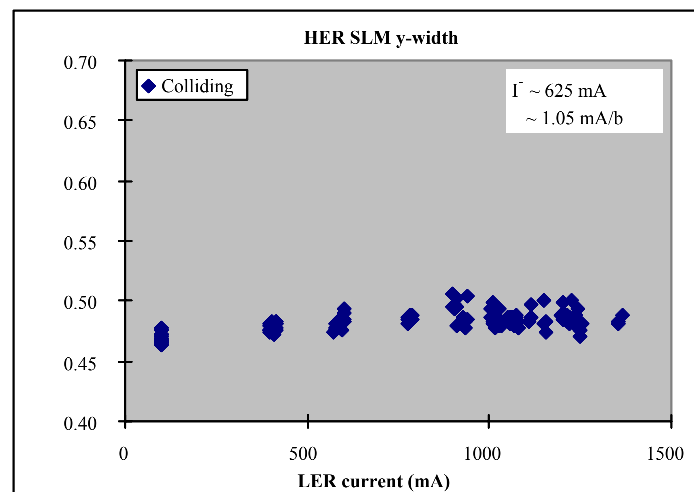
Single-beam or separated: LEB blowup mostly in y



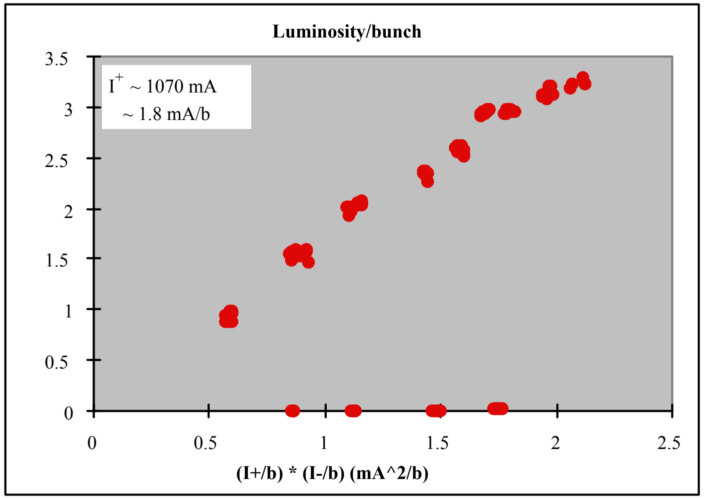
- LEB blowup in collision >> single-beam blowup, by an amount that depends on its own current => L_{SP} drops!
- LEB blowup with both beams present but out of collision, is similar to single-beam blowup

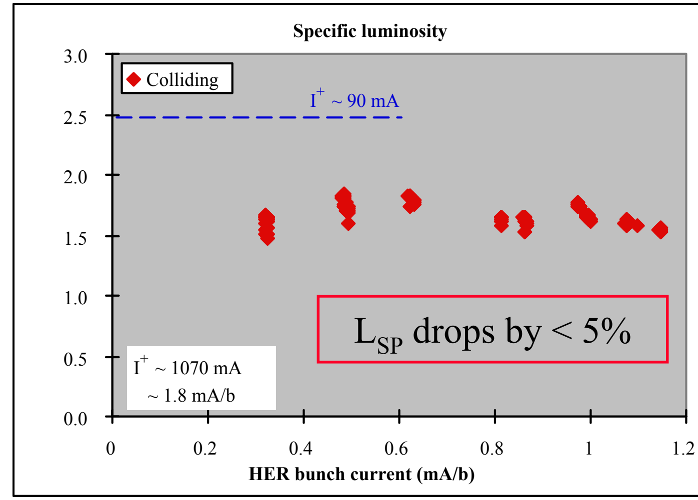


No indication of b-b induced HER blowup (in this data set)

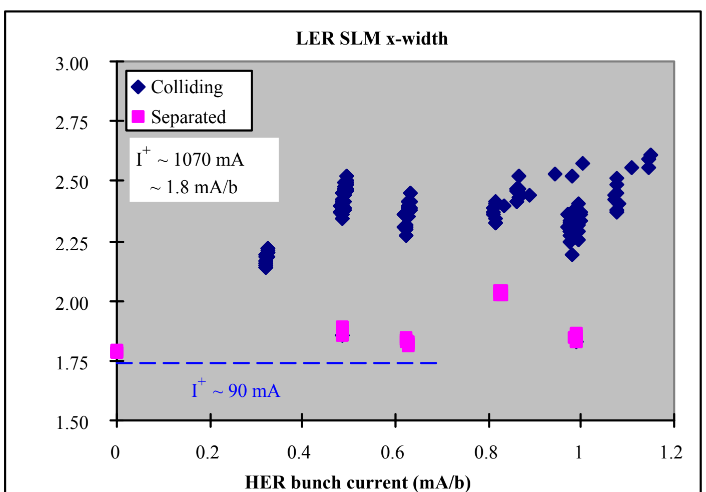


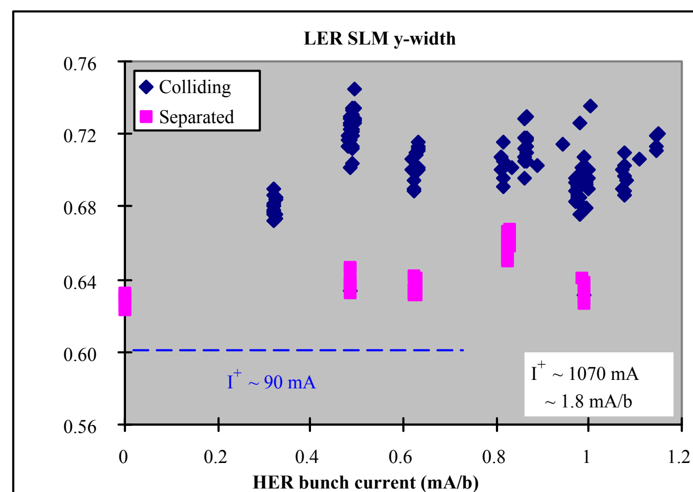
LER b-b limit @high e^+ current: I^+ =1070 mA, I^- =200-630 mA, 597 bunches



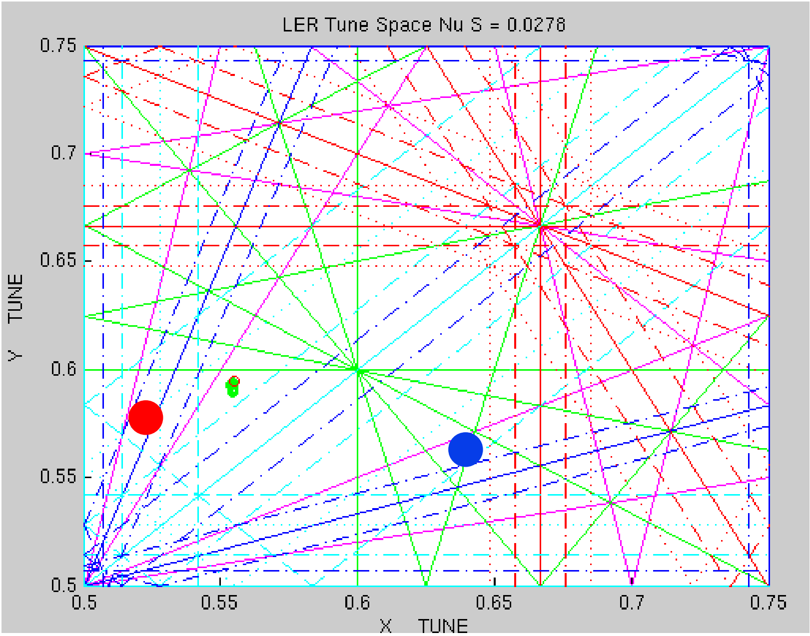


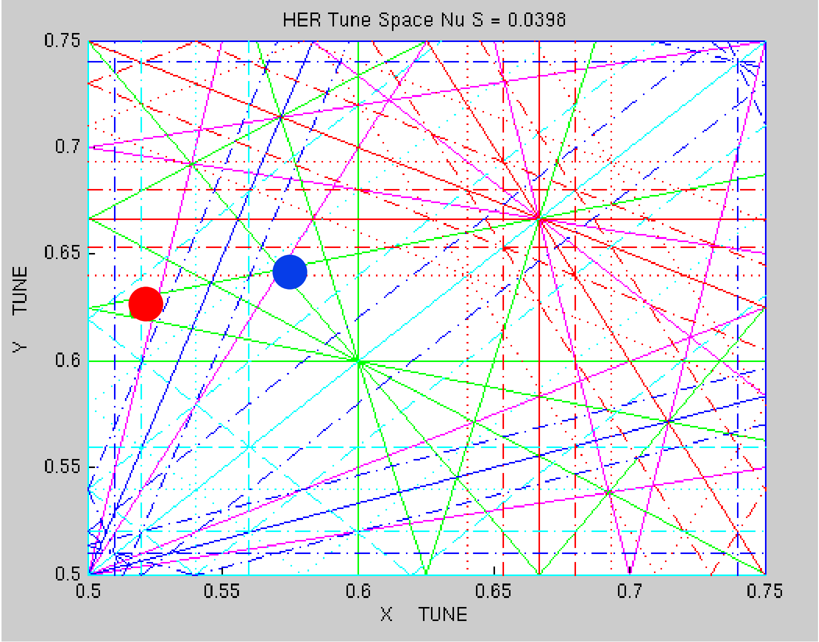
- LER:SLM x & y size in collision >> separated, <u>but</u> both are <u>flat with electron</u> current (not "naive" b-b!)
- HER: I^- dep. of x, y SLM size in collision, consistent with single-beam behavior (flat)





Wandering in tune space...



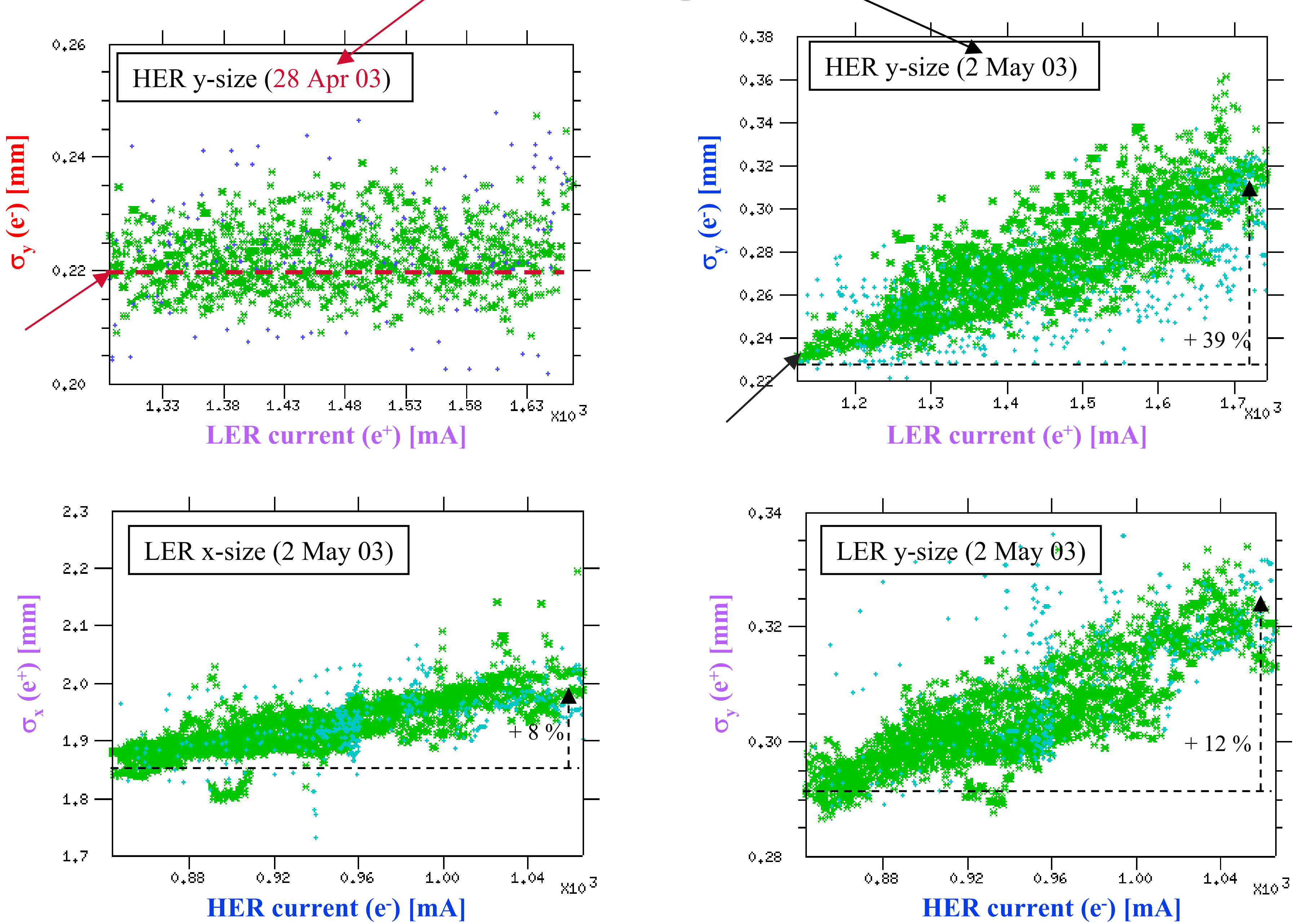


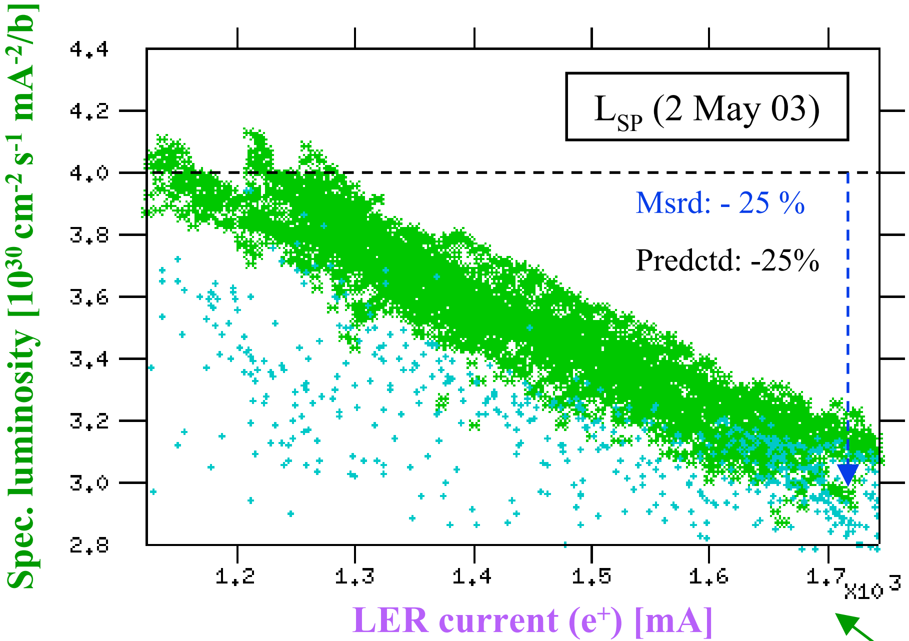
- **LER**
  - **→ Apr 03:**
    - ν_x **= .64**
    - ν_y **= .56**
  - **since May 1, 2003:**
    - ν_x **= .52**
    - ν_y **= .57**

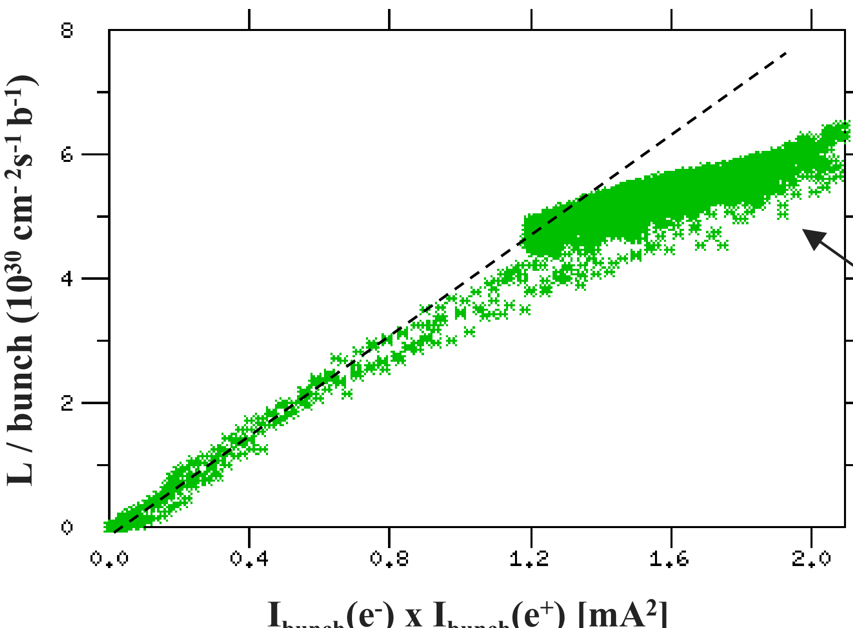
The values quoted here are nominal, unshifted tunes

- **HER**
  - **→ Apr 03:**
    - ν_x **= .57**
    - ν_y **= .64**
  - **since May 1, 2003:**
    - ν_x **= .52**
    - ν_y **= .62**

"Before" ½ integer vs. "after"







- **Original tunes ($\nu^{+}_{x/y}$ ~ 0.64/0.56)**
  - e^- size ~ independent of e^+ current
  - e^+ size ~ ↑ with ↑ e^+ current (mostly x: proximity to 2/3?)

- **Near ½ integer ($\nu^{+}_{x/y}$ ~0.52/0.57)**
  - e^- size ↑ with ↑ e^+ current
  - e^+ size ↑ with ↑ e^- current
  - Specific luminosity
    - scales (primarily) with e^+ current
    - => HEB the 'weaker' beam
  - Total luminosity
    - some tune-shift saturation (prob. HEB), but potential for more luminosity!

Beam-beam simulations

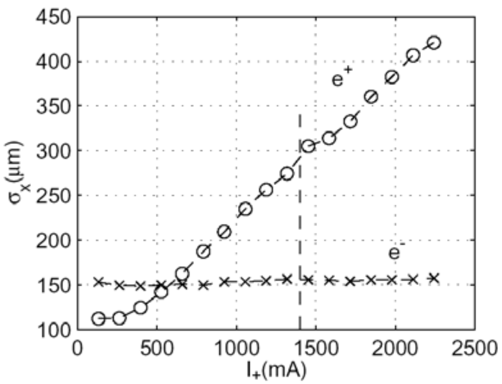
- **Strong-strong**

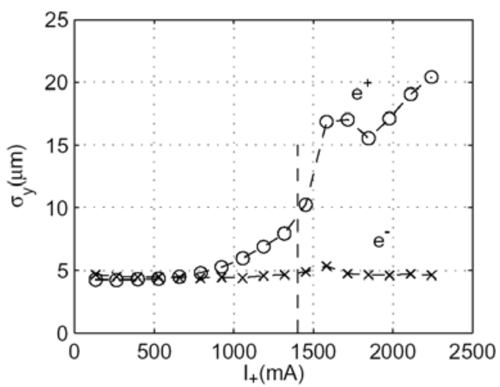
Y. Cai, et. al., Phys.Rev.ST Accel.Beams 4:011001,2001
Y. Cai, SLAC-PUB-8811 (2001)

  - particle-in-cell
  - 3-D: dynamically-tracked macroparticles in x+y; slices[1)] in z
  - solves Poisson's equation in a reduced region (=> better accuracy in beam core), with an 'inhomogeneous' boundary condition
  - each ring
    - 1-turn map
    - radiation damping & quantum excitation in normalized coordinates
  - loops over a few damping times to reach equilibrium distributions
  - not included:
    - rings: x-y coupling, machine imperfections & non-linearities
    - IP: bunch length, hourglass effect
    - physics: e^- cloud
- **Parallel computing: macroparticles distributed on many processors**
  - 2 groups of processors: e^+/e^-. Beam distributions are summed within each group, then exchanged between the 2 processor groups

[1)] PEP-II example shown in this talk is effectively 2-d (single z-slice)

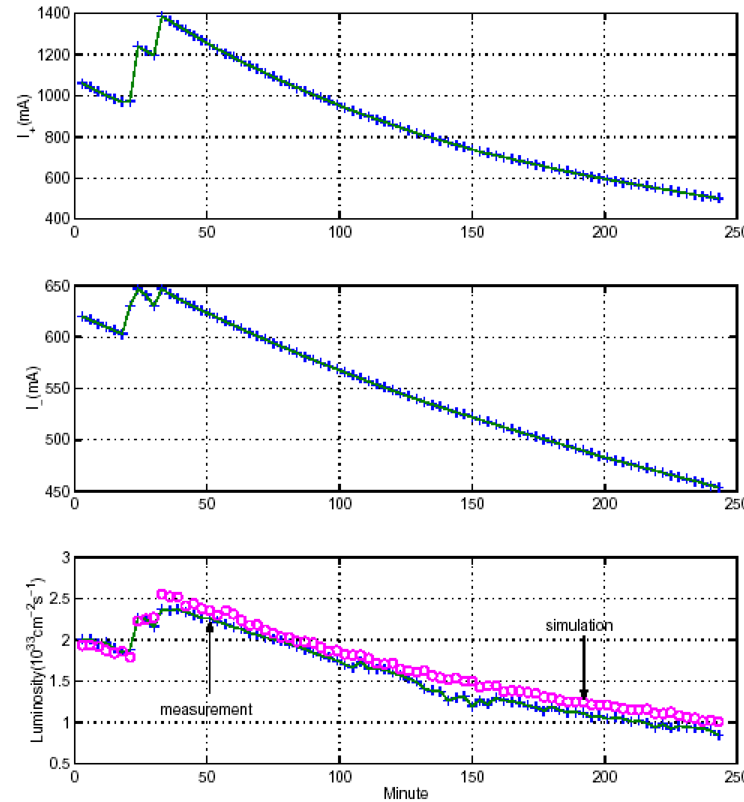
Beam-beam simulations (2)





Simulated e^+/e^+ beam sizes (x: top, y: bottom. I^+/I^- kept in 2/1 ratio)

In qualitative agreement with data.



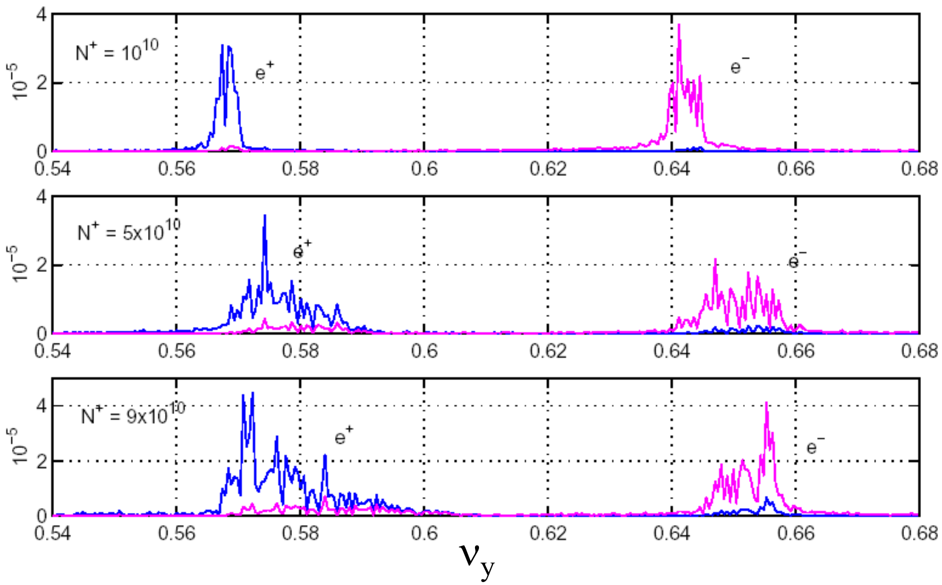
Measured (crosses) & simulated (circles) luminosity during routine PEP-II operation (605 bunches).

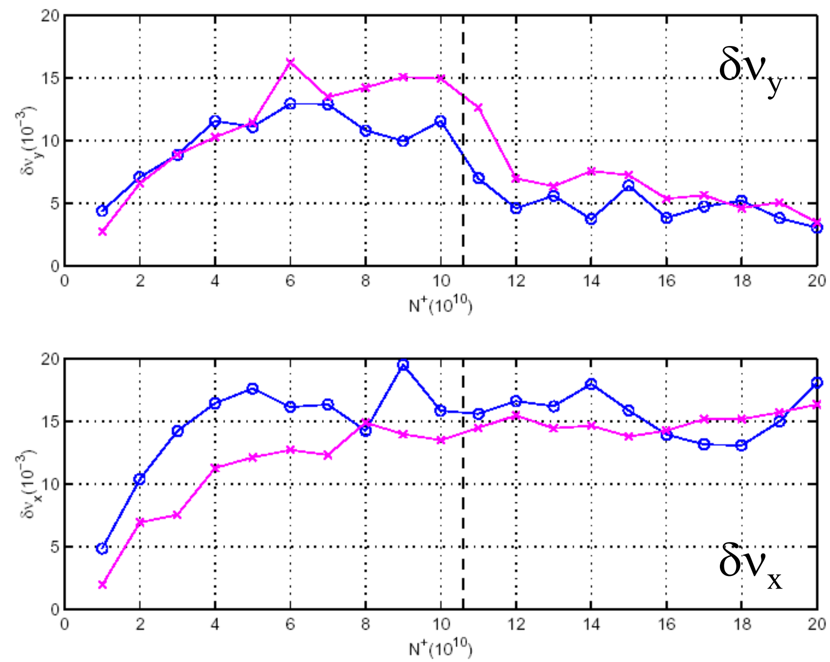
Simulated PEP-II parameters

Parameter	Description	LER(e+)	HER(e-)
E (Gev)	Beam energy	3.1	9.0
β_x^* (cm)	Beta X at the IP	50.0	50.0
β_y^* (cm)	Beta Y at the IP	1.25	1.25
τ_t (turn)	Transverse damping time	9740	5014
ϵ_x (nm-rad)	Emittance X	24.0	48.0
ϵ_y (nm-rad)	Emittance Y	1.50	1.50
ν_x	X tune	0.649	0.569
ν_y	Y tune	0.564	0.639

However:
- ***no e^- cloud effects have been included***
- ***code needs to be confronted with a wider parameter set***

Beam-beam simulations (3)

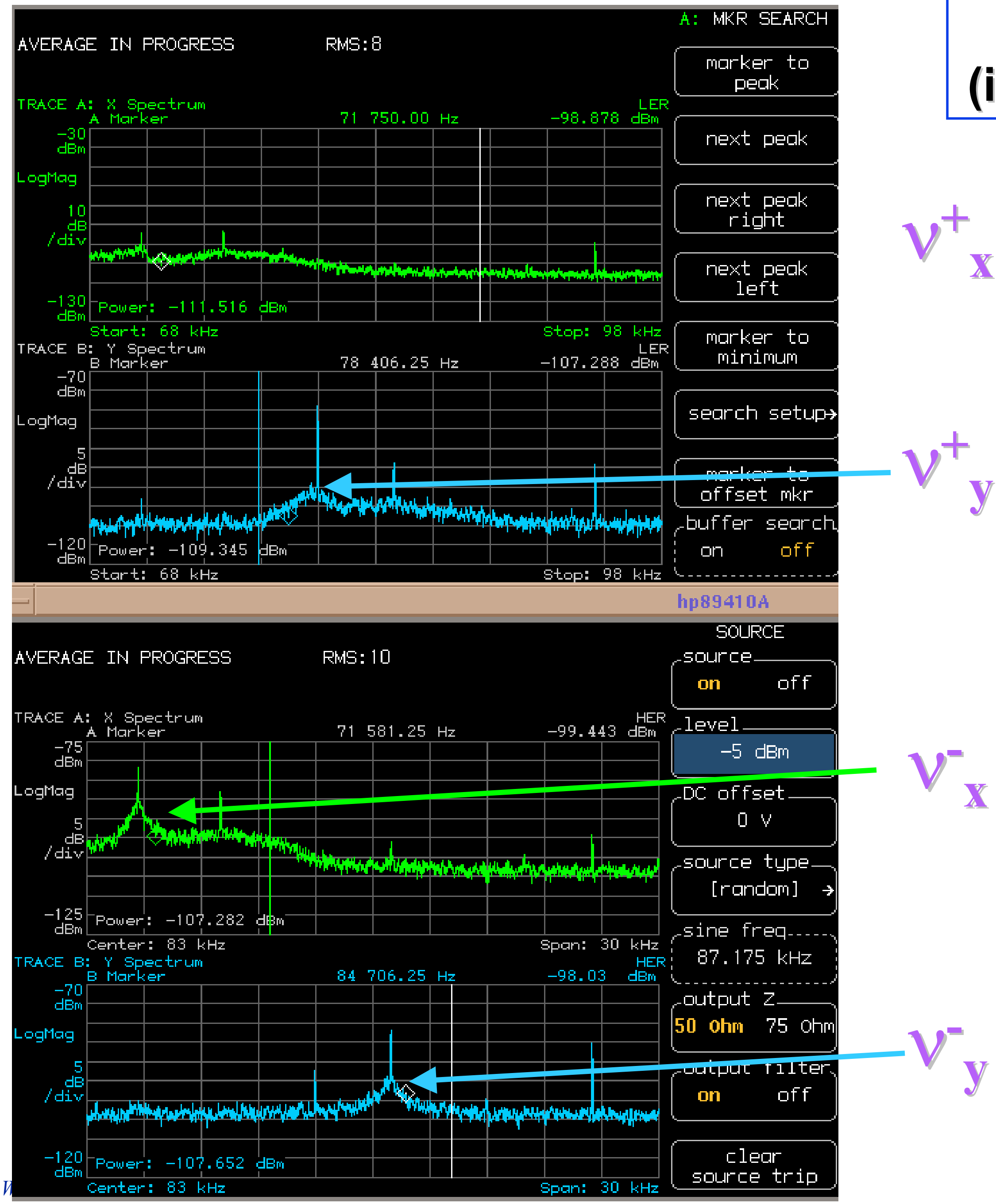




<u>Simulated vertical power spectra</u>
@ various beam intensities

Vertical (top) & horizontal (bottom) average <u>tune shift</u> as a function of bunch intensity, for **e^+ (circles)** and **e^- (crosses)**.

Tune spectra
(in collision, near ½ integer)



J. Seeman,3 May 03

Beam-beam performance summary

Parameter	Units	16-Apr-03	**3-May-03**	Parameter	Units	16-Apr-03	**3-May-03**
		High lumi	Top of fill			High lumi	Top of fill
E+	GeV	3.1	3.1	$\nu_{x/y}$ (LER)		0.64 / 0.56	**0.52 / 0.57**
E-	GeV	9	9	$\nu_{x/y}$ (HER)		0.57 / 0.64	**0.52 / 0.63**
Estimated from model or inferred from meas'mts				**Computed**			
Beta x +	cm	35	35	N+		9.30E+10	8.56E+10
Beta y +	cm	1.2	1.1	N-		5.04E+10	5.24E+10
Emit x +	nm	40	33				
Emit y +	nm	4.4	1.4	Sig x +	microns	118.3	107.5
Bunch length	cm	1.3	1.05	Sig y +	microns	7.3	3.9
				Sig x -	microns	131.0	141.7
Beta x -	cm	35	41	Sig y -	microns	4.9	6.0
Beta y -	cm	1.2	1.2				
Emit x -	nm	49	49	R (hourglass factor)		0.845	0.86
Emit y -	nm	2	3.05				
Bunch length	cm	1.3	1.25				
				Lum (calc)	**/cm2/s**	5.21E+33	**6.11E+33**
Directly measured				**Tune shift x+**		0.074	**0.065**
Num Bunch		939	939	**Tune shift y +**		0.068	**0.048**
I+	mA	1900	1750	**Tune shift x-**		0.056	**0.075**
I-	mA	1030	1070	**Tune shift y -**		0.031	**0.060**

Summary

- **Electron-cloud effects**
  - have been minimized by a combination of scrubbing, solenoid-suppression, and bunch-pattern optimization;
  - still play an ubiquitous role in the beam-beam performance of the PEP-II *B*-factory;
  - may constitute one of the fundamental limitations at higher luminosity.
- **Luminosity (& background!) optimization relies on a delicate balance between the currents, tunes, beam-beam parameters and e-cloud effects as these parameters vary along each bunch train.**
- **Spot-size, beam-current & luminosity diagnostics (both bunch-by-bunch & averaging over an entire train) have proven essential to unravel competing phenomena.**
- **Beam-beam simulations show encouraging agreement with experiment, but more extensive comparisons are needed**
- **PEP-II has recently achieved, near the ½ integer, beam-beam parameters ξ_x / ξ_y of about .065 / .048 (.075 / .060) in the LER (HER). This is a significant increase in HER tune shift compared to the previous working point.**