A Few Issues on the Upgrade of KEKB B-Factory

4 MAY 2009 @ PAC

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We thank K. Yokoya, K. Satoh, Y. Cai, M. Zobov, KEKB Accelerator Group

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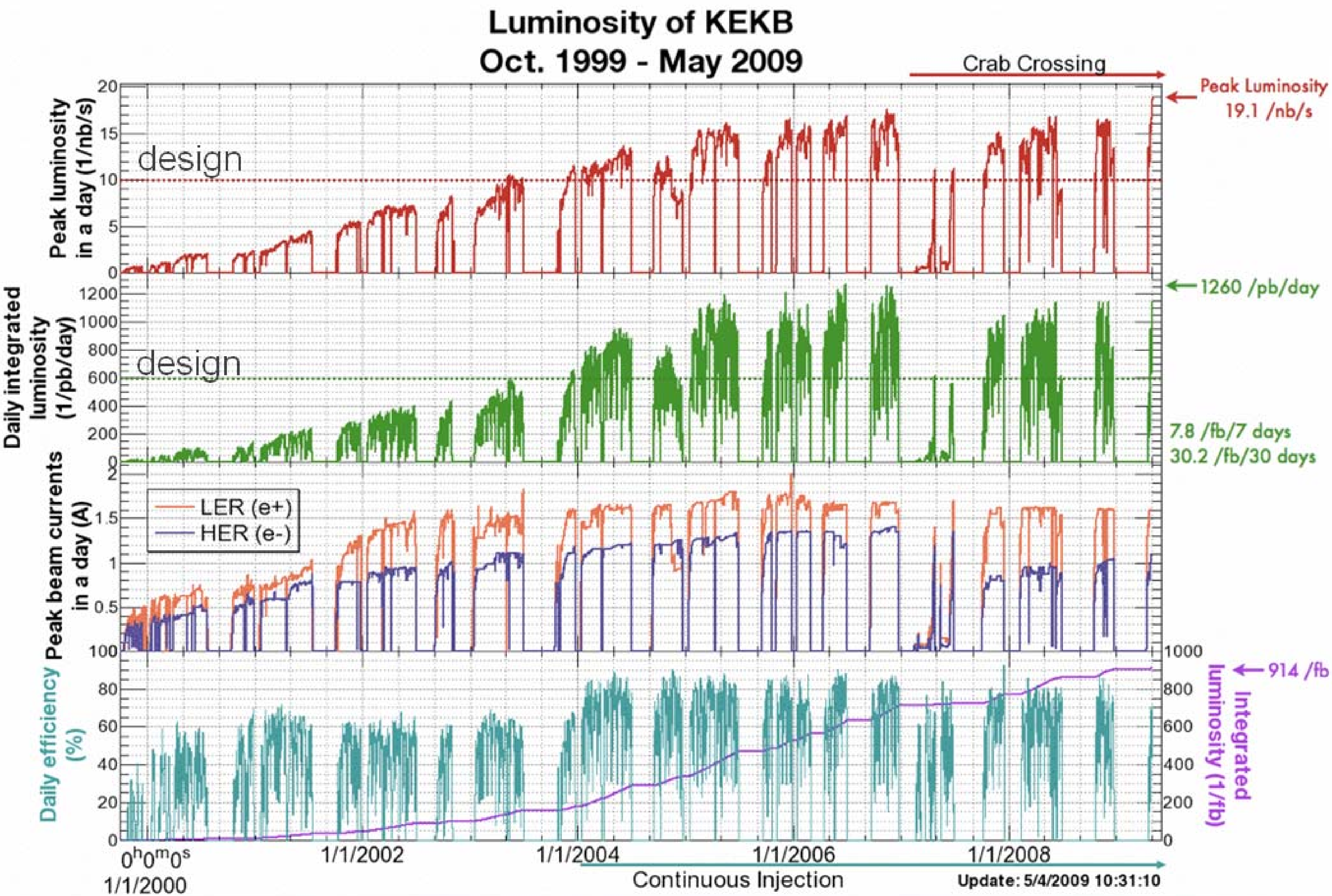
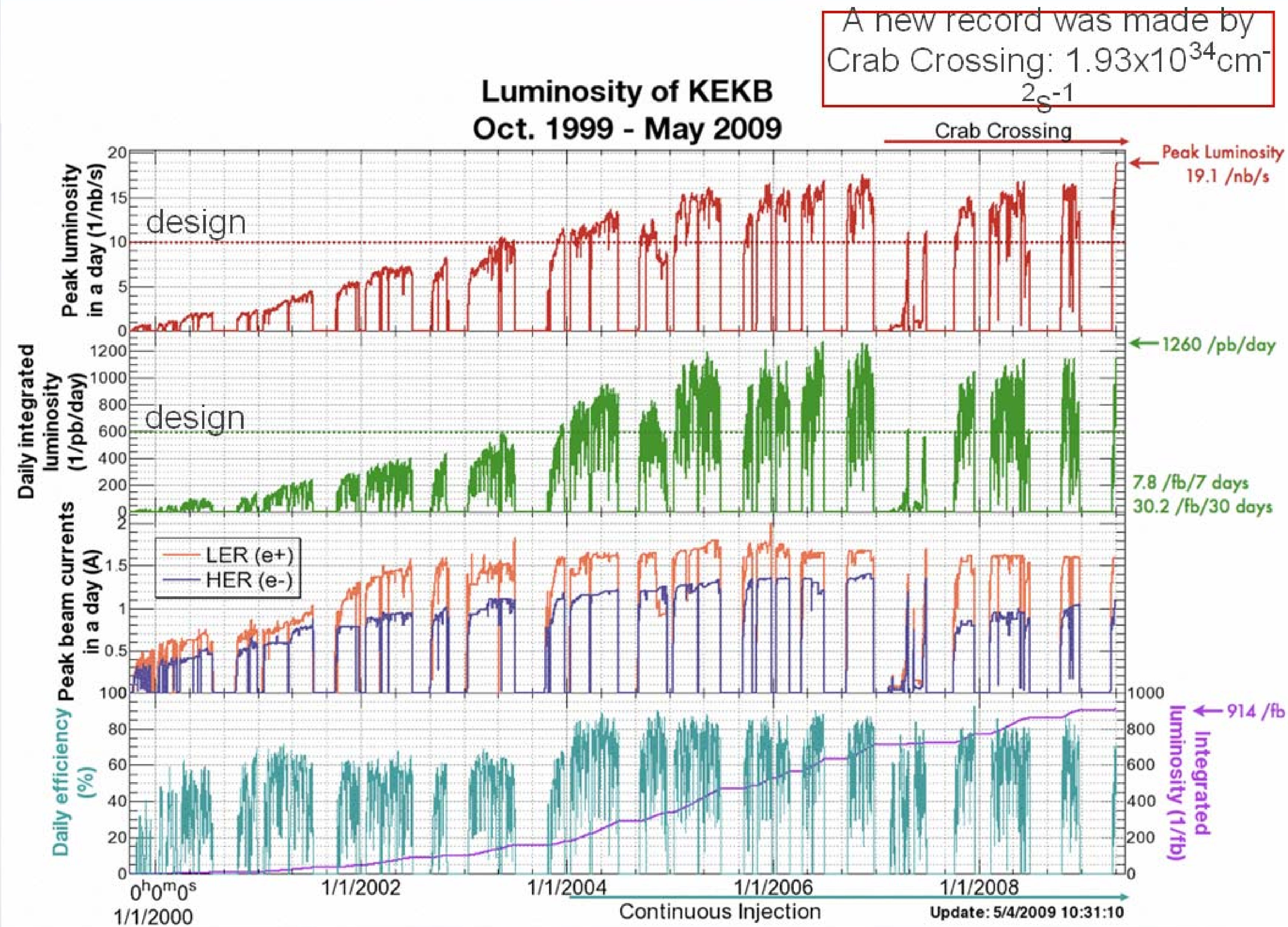


Luminosity of KEKB
Oct. 1999 - May 2009
Crab Crossing
Peak Luminosity
19.1 /nb/s
Peak luminosity in a day (1/nb/s)
design
1260 /pb/day
Daily integrated luminosity (1/pb/day)
design
7.8 /fb/7 days
30.2 /fb/30 days
Peak beam currents in a day (A)
LER (e+)
HER (e-)
914 /fb
Daily efficiency (%)
Integrated luminosity (1/fb)
0h0m0s 1/1/2000
1/1/2002
1/1/2004
1/1/2006
1/1/2008
Continuous Injection
Update: 5/4/2009 10:31:10



A new record was made by Crab Crossing: 1.93x10^34cm^-2s^-1
Luminosity of KEKB
Oct. 1999 - May 2009
Crab Crossing
Peak Luminosity 19.1 /nb/s
Peak luminosity in a day (1/nb/s)
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Continuous Injection
Update: 5/4/2009 10:31:10

“High CURRENT SCHEME” of KEKB UPGRADE

$$\mathcal{L} \propto \gamma \left(\frac{I\xi_y}{\beta_y^*} \right)$$

	Present KEKB (LER / HER)	High-Current Scheme (LER / HER)	
Beam energy E	3.5 / 8	3.5 / 8	GeV
Beam current I	1.6 / 1.1	9.4 / 4.1	A
β_y^*	6	3	mm
Vert. beam-beam ξ_y	0.14 / 0.09	~ 0.3	
$\mathcal{L}$	0.19	8	$10^{35}\mathrm{cm}^{-2}\mathrm{s}^{-1}$

Also assumes $\sigma_z \lesssim \beta_y^*$.

CSR revisited

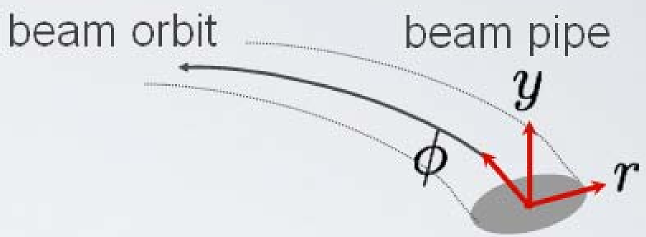
- Coherent Synchrotron Radiation (CSR) in SuperKEKB has been studied by T. Agoh since 2004 as reported at KEKB Accelerator Review Committee.
  http://www-kekb.kek.jp/MAC/2005/ (2005)
- An independent estimation was done in 2008, which takes realistic shape of the beam pipe and other impedances into account.

- Confirmed the results by T. Agoh.

- This is a heavy impact on the design parameters of SuperKEKB.

Maxwell's Equations

$$
\begin{aligned}
\frac{1}{r}\frac{\partial r E_\phi}{\partial r} - \frac{1}{r}\frac{\partial E_r}{\partial \phi} &= -\frac{\partial B_y}{\partial t} \\
\frac{1}{r}\frac{\partial E_y}{\partial \phi} - \frac{\partial E_\phi}{\partial y} &= -\frac{\partial B_r}{\partial t} \\
\frac{\partial E_r}{\partial y} - \frac{\partial E_y}{\partial r} &= -\frac{\partial B_\phi}{\partial t} \\
\frac{1}{r}\frac{\partial r B_\phi}{\partial r} - \frac{1}{r}\frac{\partial B_r}{\partial \phi} &= \mu_0 j_y + \frac{1}{c^2}\frac{\partial E_y}{\partial t} \\
\frac{1}{r}\frac{\partial B_y}{\partial \phi} - \frac{\partial B_\phi}{\partial y} &= \mu_0 j_r + \frac{1}{c^2}\frac{\partial E_r}{\partial t} \\
\frac{\partial B_r}{\partial y} - \frac{\partial B_y}{\partial r} &= \mu_0 j_\phi + \frac{1}{c^2}\frac{\partial E_\phi}{\partial t} \\
\frac{1}{r}\frac{\partial r E_r}{\partial r} + \frac{1}{r}\frac{\partial E_\phi}{\partial \phi} + \frac{\partial E_y}{\partial y} &= \frac{\rho}{\varepsilon_0}
\end{aligned}
$$



$$j_r = j_y = 0, \qquad j_\phi = \rho c$$

$$
\begin{aligned}
\frac{\partial}{\partial r}\frac{1}{r}\frac{\partial r E_r}{\partial r} + \frac{1}{r^2}\frac{\partial^2 E_r}{\partial \phi^2} + \frac{\partial^2 E_r}{\partial y^2} - \frac{1}{c^2}\frac{\partial^2 E_r}{\partial t^2} - \frac{2}{r^2}\frac{\partial E_\phi}{\partial \phi} &= \frac{1}{\varepsilon_0}\frac{\partial \rho}{\partial r} \\
\frac{\partial}{\partial r}\frac{1}{r}\frac{\partial r E_\phi}{\partial r} + \frac{1}{r^2}\frac{\partial^2 E_\phi}{\partial \phi^2} + \frac{\partial^2 E_\phi}{\partial y^2} - \frac{1}{c^2}\frac{\partial^2 E_\phi}{\partial t^2} + \frac{2}{r^2}\frac{\partial E_r}{\partial \phi} &= \frac{1}{\varepsilon_0}\left(\frac{1}{r}\frac{\partial \rho}{\partial \phi} + \frac{1}{c}\frac{\partial \rho}{\partial t}\right)
\end{aligned}
$$

Maxwell's Equations

$$\frac{\partial}{\partial r}\frac{1}{r}\frac{\partial r E_r}{\partial r}+\frac{1}{r^2}\frac{\partial^2 E_r}{\partial \phi^2}+\frac{\partial^2 E_r}{\partial y^2}-\frac{1}{c^2}\frac{\partial^2 E_r}{\partial t^2}-\frac{2}{r^2}\frac{\partial E_\phi}{\partial \phi} = \frac{1}{\varepsilon_0}\frac{\partial \rho}{\partial r}$$

$$\frac{\partial}{\partial r}\frac{1}{r}\frac{\partial r E_\phi}{\partial r}+\frac{1}{r^2}\frac{\partial^2 E_\phi}{\partial \phi^2}+\frac{\partial^2 E_\phi}{\partial y^2}-\frac{1}{c^2}\frac{\partial^2 E_\phi}{\partial t^2}+\frac{2}{r^2}\frac{\partial E_r}{\partial \phi} = \frac{1}{\varepsilon_0}\left(\frac{1}{r}\frac{\partial \rho}{\partial \phi}+\frac{1}{c}\frac{\partial \rho}{\partial t}\right)$$

Beam: traveling on a circle, r = R with the velocity of light.

$$\rho \propto \delta(r-R)\delta(y)\exp\left(ik(R\phi - ct)\right)$$

$$E_{r,\phi} = \overline{E}_{r,\phi}(\phi)\exp\left(ik(R\phi - ct)\right)$$

$$\overline{E}_r = \overline{E}_r + \overline{E}_{r0}\ ,$$

source term:

$$\frac{\partial}{\partial r}\frac{1}{r}\frac{\partial r \overline{E}_{r0}}{\partial r}+\frac{\partial^2 \overline{E}_{r0}}{\partial y^2} = \frac{1}{\varepsilon_0}\frac{\partial \rho}{\partial r}$$

- Ignore $\dfrac{\partial^2 \overline{E}}{\partial \phi^2}$ terms (Agoh-Yokoya)

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VOLUME **7**, 054403 (2004)

Calculation of coherent synchrotron radiation using mesh

T. Agoh and K. Yokoya

Maxwell's Equations

THEN WE OBTAIN FIRST ORDER DIFFERENTIAL EQUATIONS FOR $\overline{E}_{r,\phi}$.

$$
\begin{aligned}
\frac{\partial \overline{E}_r}{\partial \phi} &= \frac{i}{2(k^2R^2-1)}\Bigg[kR\left(\left(k^2(r^2-R^2)+1\right)(\overline{E}_r+\overline{E}_{r0})+r\frac{\partial}{\partial r}(\overline{E}_r+\overline{E}_{r0})+r^2\left(\frac{\partial^2\overline{E}_r}{\partial r^2}+\frac{\partial^2\overline{E}_r}{\partial y^2}\right)\right) \\
&\quad +\left(k^2(r^2+R^2)-1\right)\overline{E}_\phi+r\frac{\partial\overline{E}_\phi}{\partial r}+r^2\left(\frac{\partial^2\overline{E}_\phi}{\partial r^2}+\frac{\partial^2\overline{E}_\phi}{\partial y^2}\right)\Bigg] \\
\frac{\partial \overline{E}_\phi}{\partial \phi} &= \frac{i}{2(k^2R^2-1)}\Bigg[kR\left(\left(k^2(r^2-R^2)+1\right)\overline{E}_\phi+r\frac{\partial\overline{E}_\phi}{\partial r}+r^2\left(\frac{\partial^2\overline{E}_\phi}{\partial r^2}+\frac{\partial^2\overline{E}_\phi}{\partial y^2}\right)\right) \\
&\quad +\left(k^2(r^2+R^2)-1\right)(\overline{E}_r+\overline{E}_{r0})+r\frac{\partial}{\partial r}(\overline{E}_r+\overline{E}_{r0})+r^2\left(\frac{\partial^2\overline{E}_r}{\partial r^2}+\frac{\partial^2\overline{E}_r}{\partial y^2}\right)\Bigg]
\end{aligned}
$$

- Further approximation is possible as Agoh-Yokoya did, but not done here.

SOLVER

$$\frac{d\boldsymbol{f}}{d\phi} = A\boldsymbol{f} + \boldsymbol{b}\ , \qquad \boldsymbol{f} = (\overline{E}_r, \overline{E}_\phi)\ ,$$

$$\boldsymbol{f}(\phi) = \exp(A\phi)\boldsymbol{f}_0 + \int_0^\phi \exp\left(A(\phi - \phi')\right) d\phi' \boldsymbol{b}$$

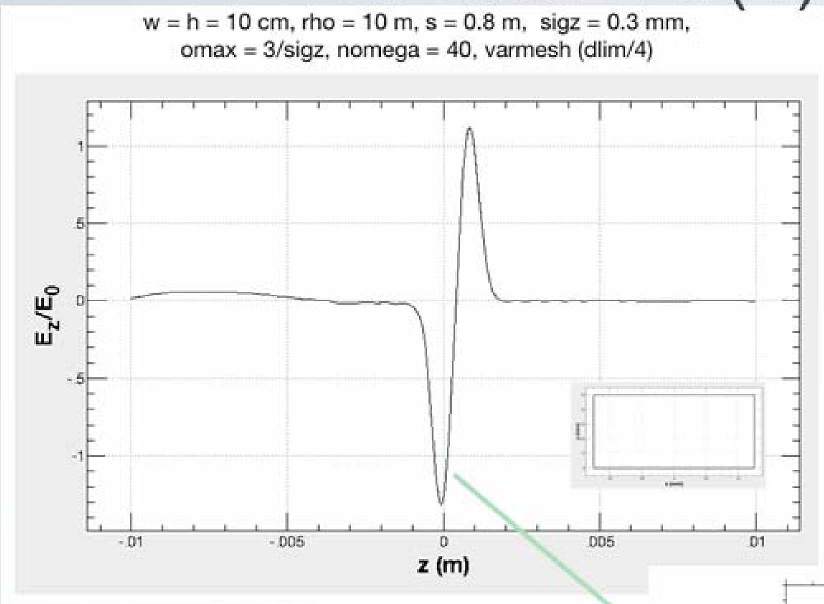
- An uniform shape of the beam pipe has been assumed,

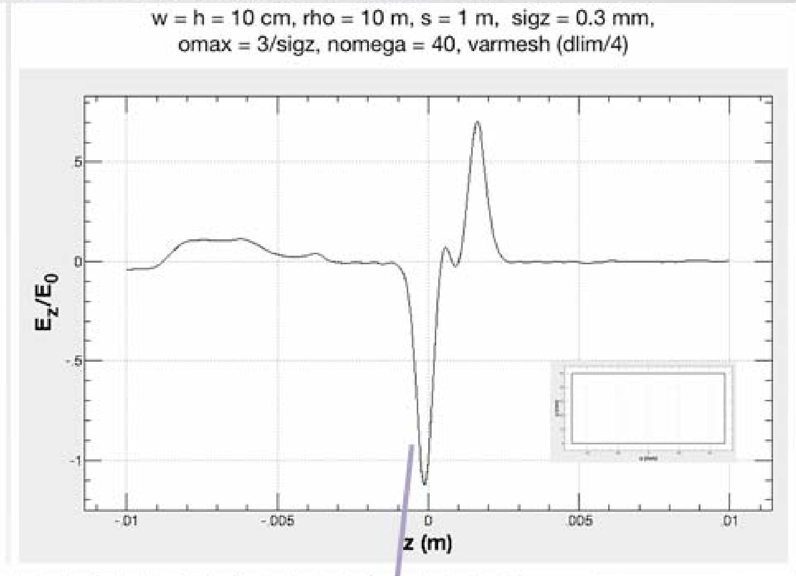
$\boldsymbol{A}$: Spatial differentiation matrix with boundary condition

$\boldsymbol{b}$: driving term by $\overline{\boldsymbol{E}}_{\boldsymbol{r}0}$.

- The exponent is evaluated by the eigen system of A .
- The mesh size for A varies with $\boldsymbol{k}$. $\quad \Delta x = \Delta y = \frac{(R/k^2)^{1/3}}{M}\ , \qquad M \gtrsim 4$

RESULTS(1) Electric Field





THE TRANSIENT ELECTRIC FIELD FOR A SQUARE PIPE AGREES WITH AGOH-YOKOYA'S VERY WELL.

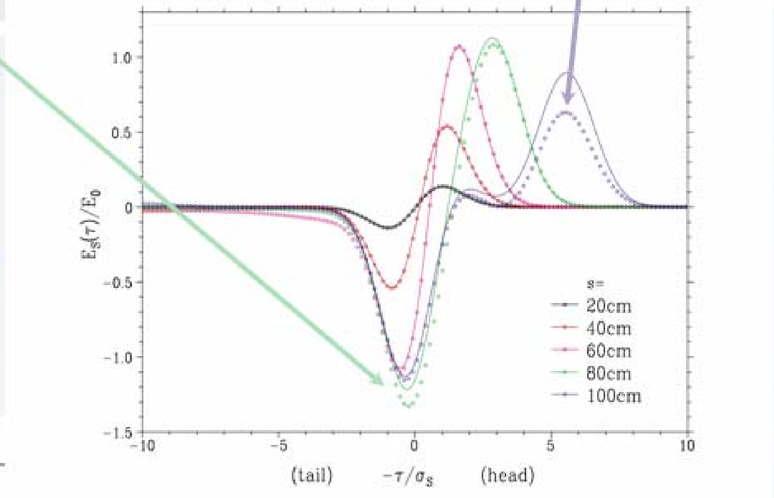


FIG. 4. (Color) The longitudinal electric field E_s in transient state with shielding. The chamber size is $w \times h = 10$ cm $\times$ 10 cm. The other parameters are the same as in Fig. 3.

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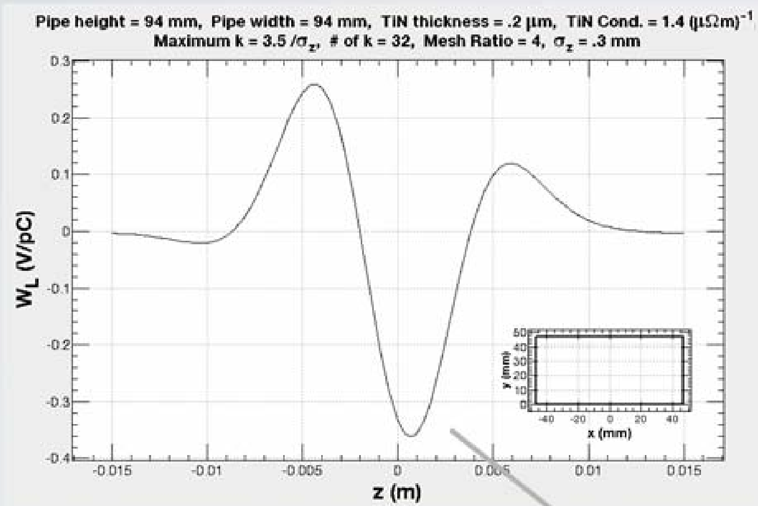
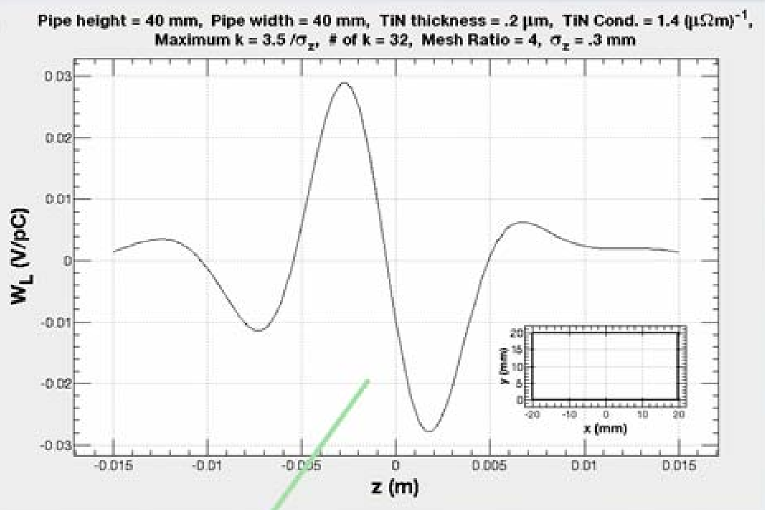
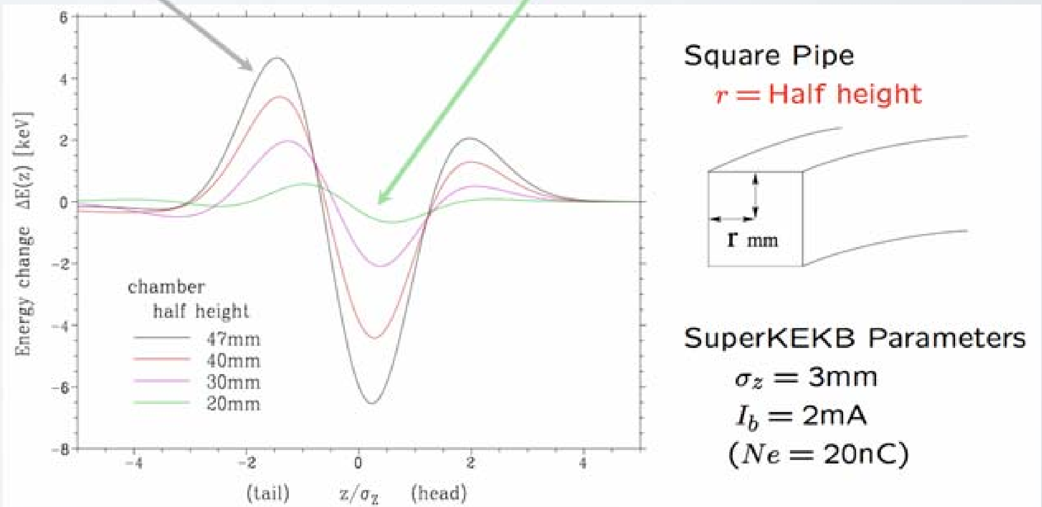
RESULTS(2) WAKE FIELD





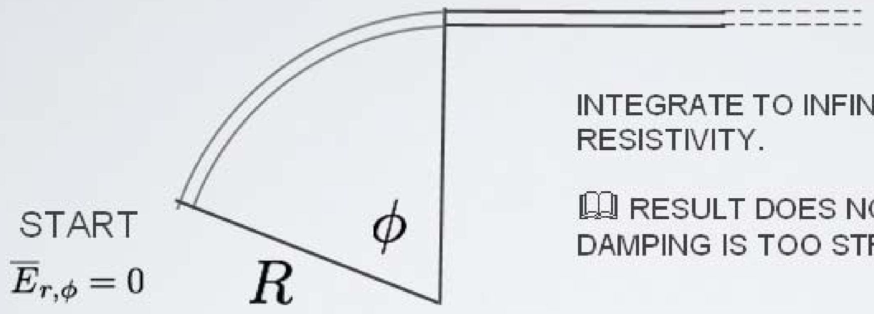
wake field for 3 mm bunch

THE WAKE FIELD FOR A SQUARE PIPE ALSO AGREES WITH T. AGOH'S VERY WELL.



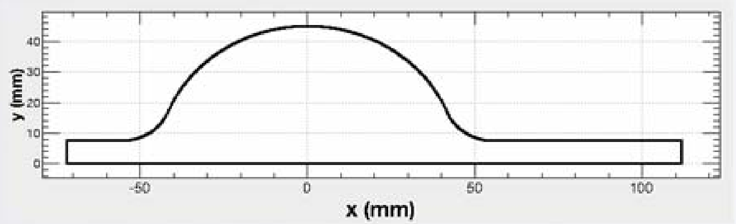
T. AGOH, MAC05

RESULTS(2): WAKES of SuperKEKB ANTECHAMBERS

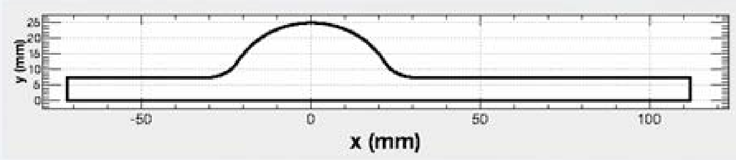


INTEGRATE TO INFINITY, ASSUMING DAMPING BY SURFACE RESISTIVITY.

📖 RESULT DOES NOT DEPEND ON THE RESISTIVITY UNLESS DAMPING IS TOO STRONG.

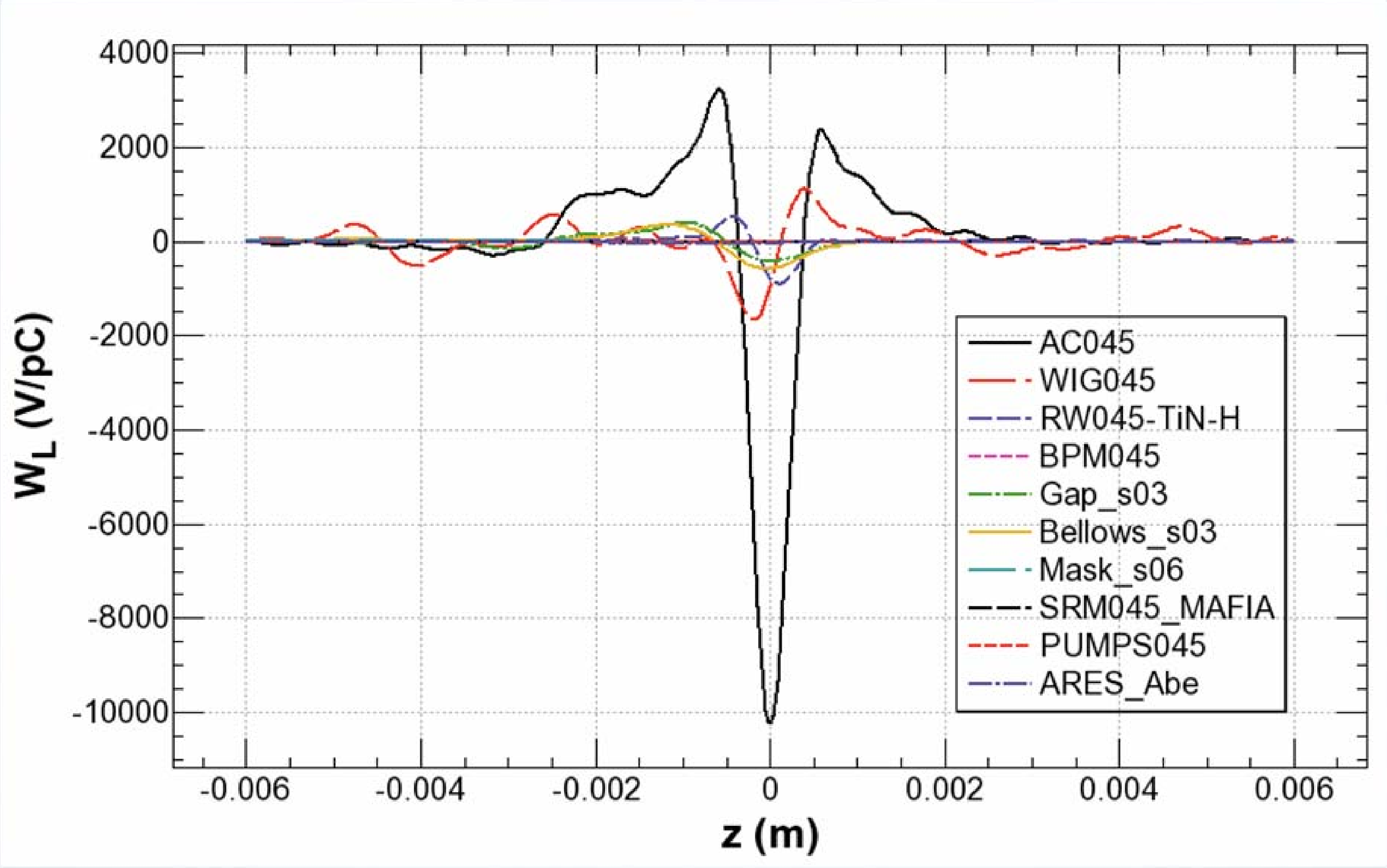


$a = 45$ mm



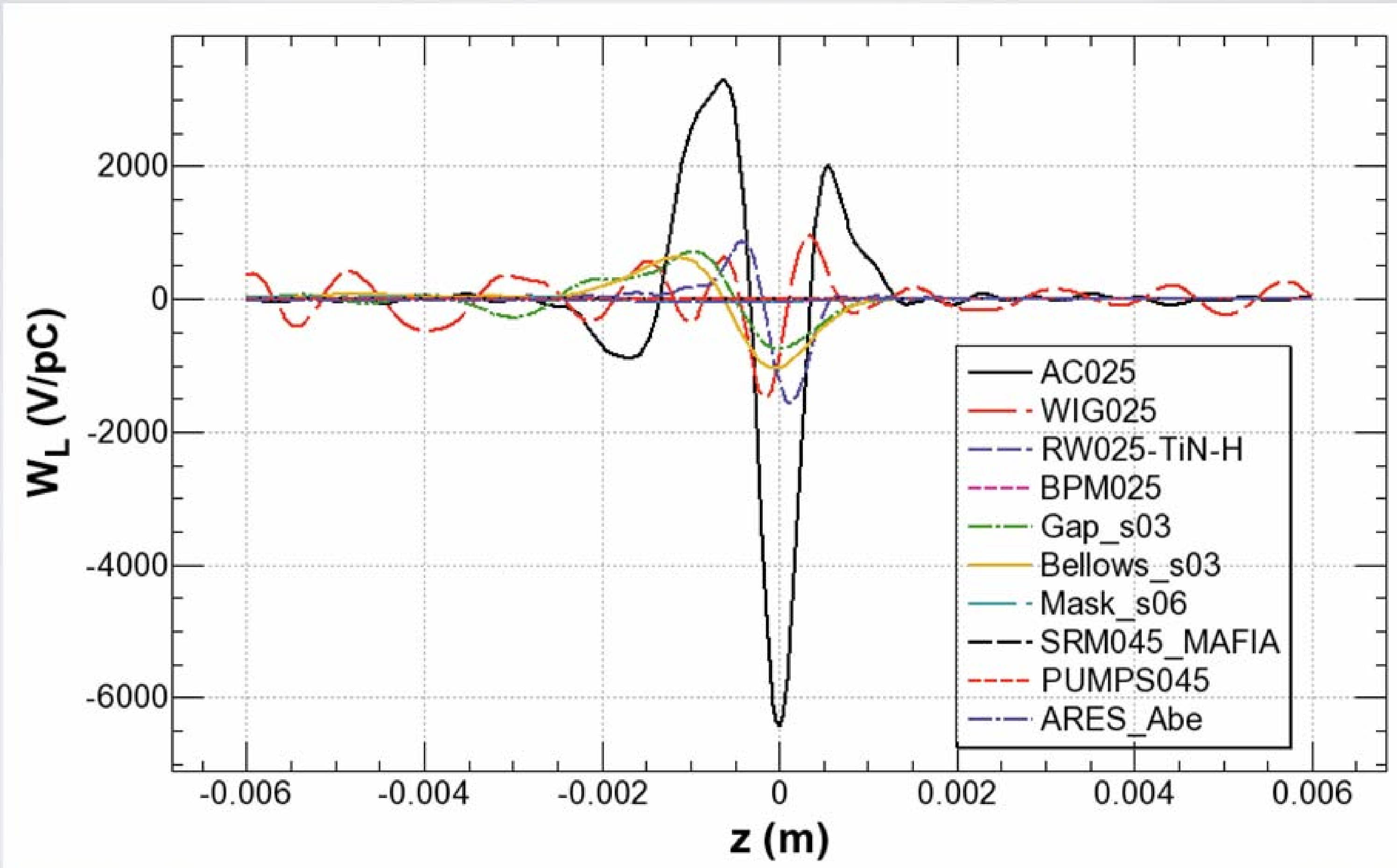
$a = 25$ mm

a = 45 mm wake functions



23 Sep 2008

a = 25 mm wake functions



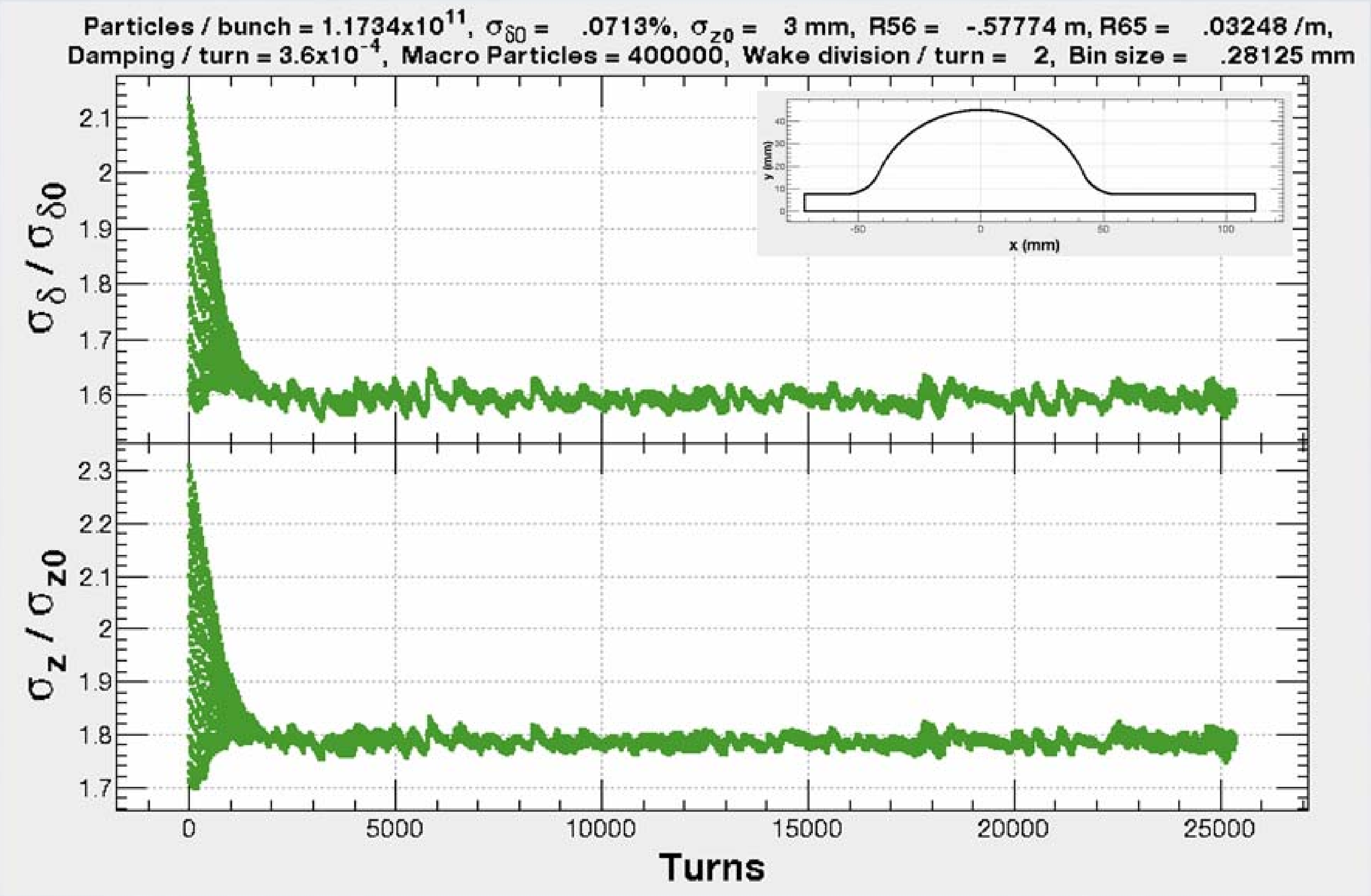
23 Sep 2008

TRACKING SIMULATION OF BUNCH STABILITY

- Sum up all wakes.
- TiN coated resistive wall: $\sigma = 1.4\ (\mu\Omega m)^{-1}$ thickness = 0.2 μm.
- SuperLER parameters.
- 400,000 macro particles, checked convergence by doubling the number of particles.

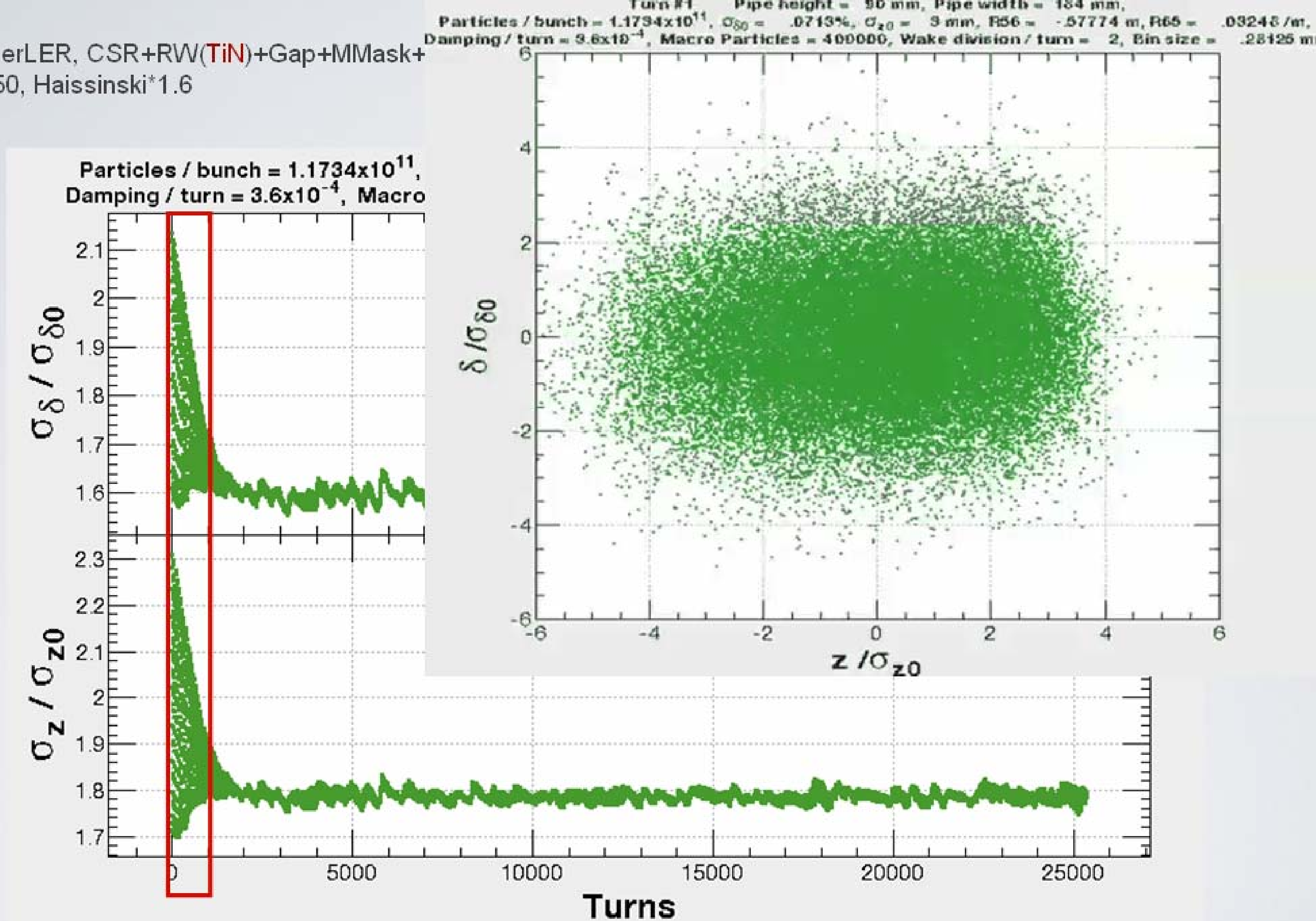
Part. / bunch (design), N	11.7	10^{10}
Bunch length @ $N = 0$, σ_{z0}	3	mm
Mom. spread @ $N = 0$, $\sigma_{\varepsilon 0}$	7.1	10^{-4}
Synch. tune, ν_z	-0.022	

SuperLER, CSR+RW(TiN)+Gap+MMask+Bellows+ARES(Satoh)+BPM+SRM+PUMPS, rac = 45 mm, # of bends = 150, Haissinski*1.6



Microwave instabilities: no stable state is reached.

SuperLER, CSR+RW(TiN)+Gap+MMask+
= 150, Haissinski*1.6



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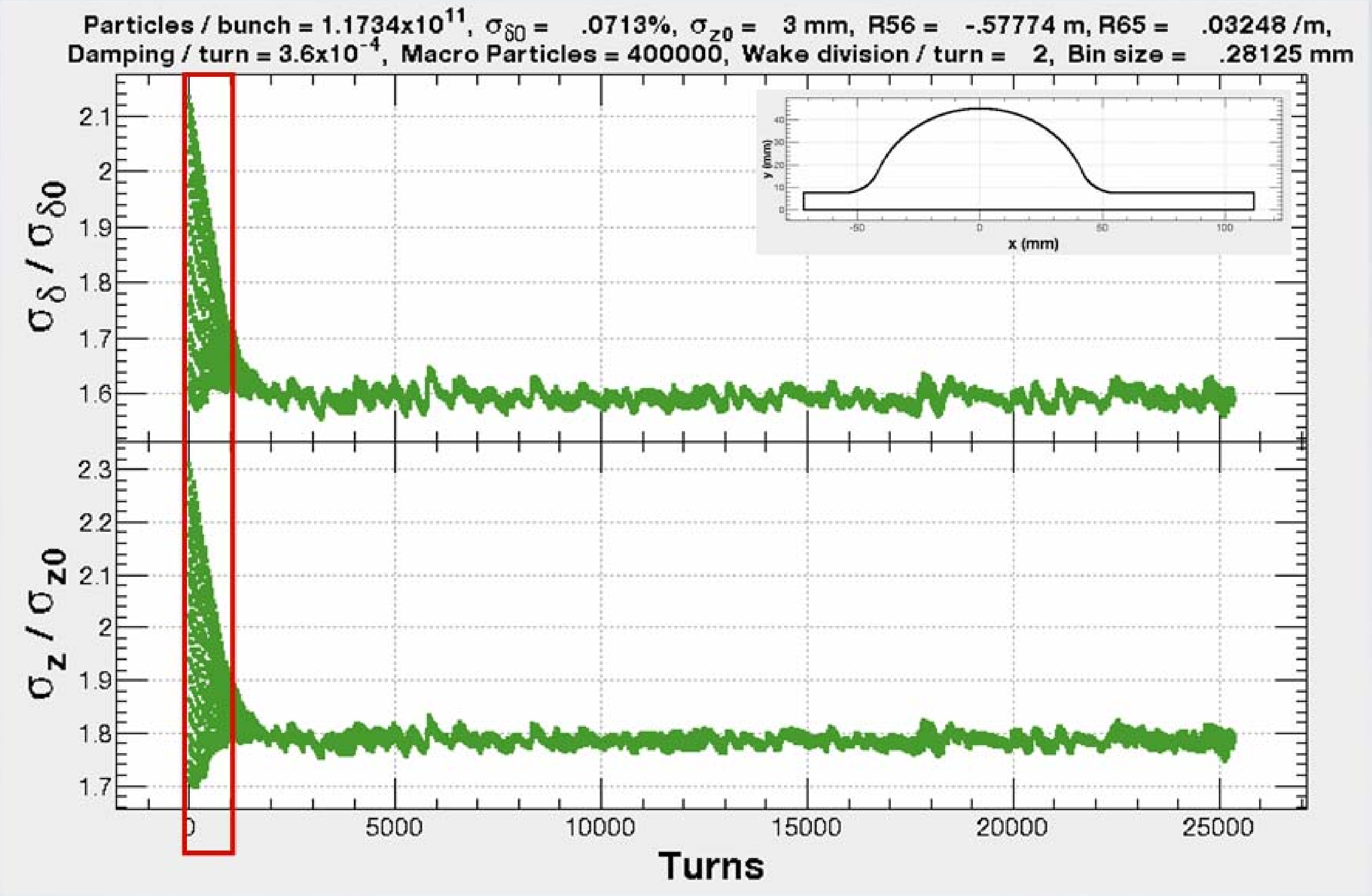

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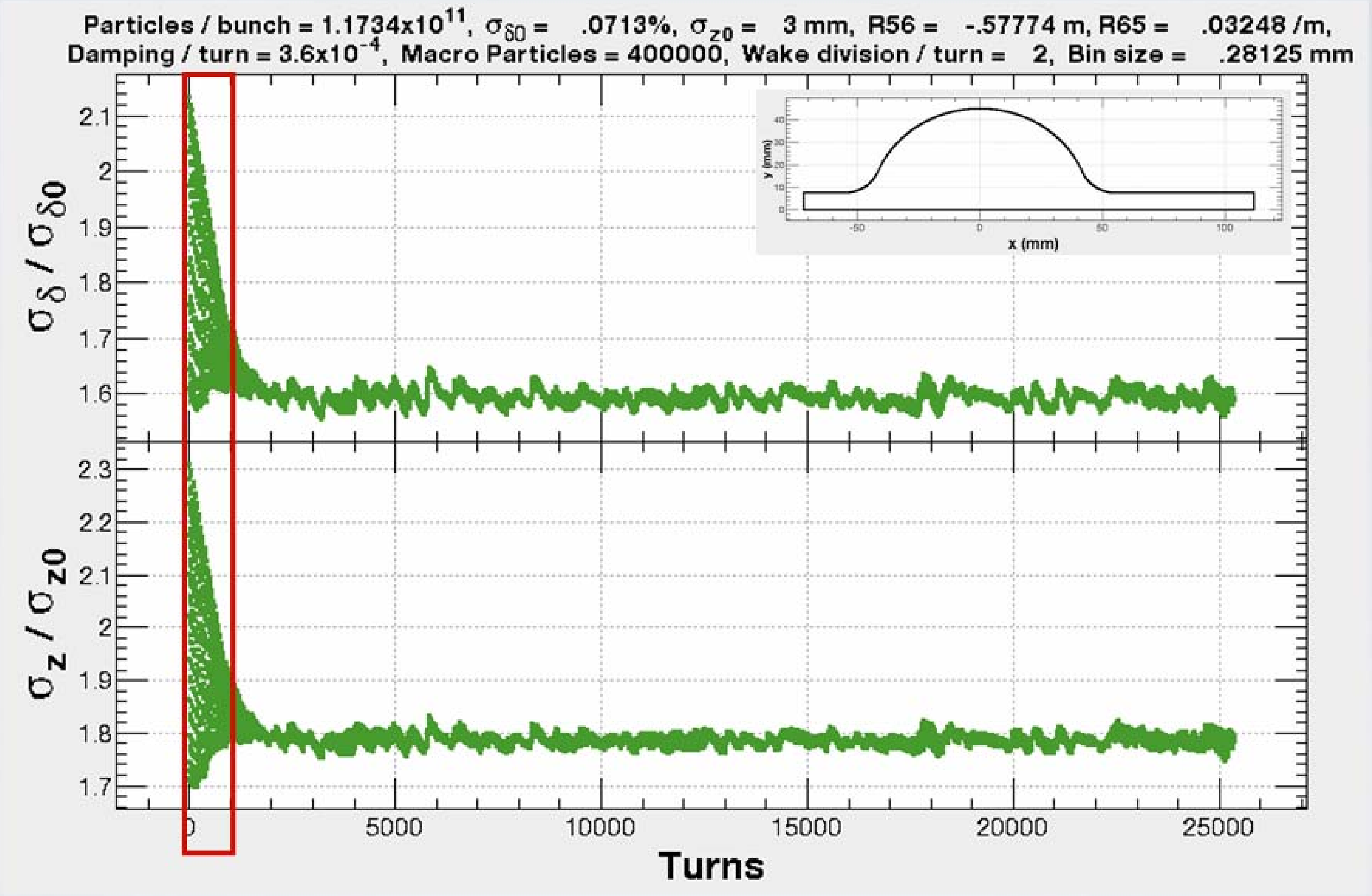

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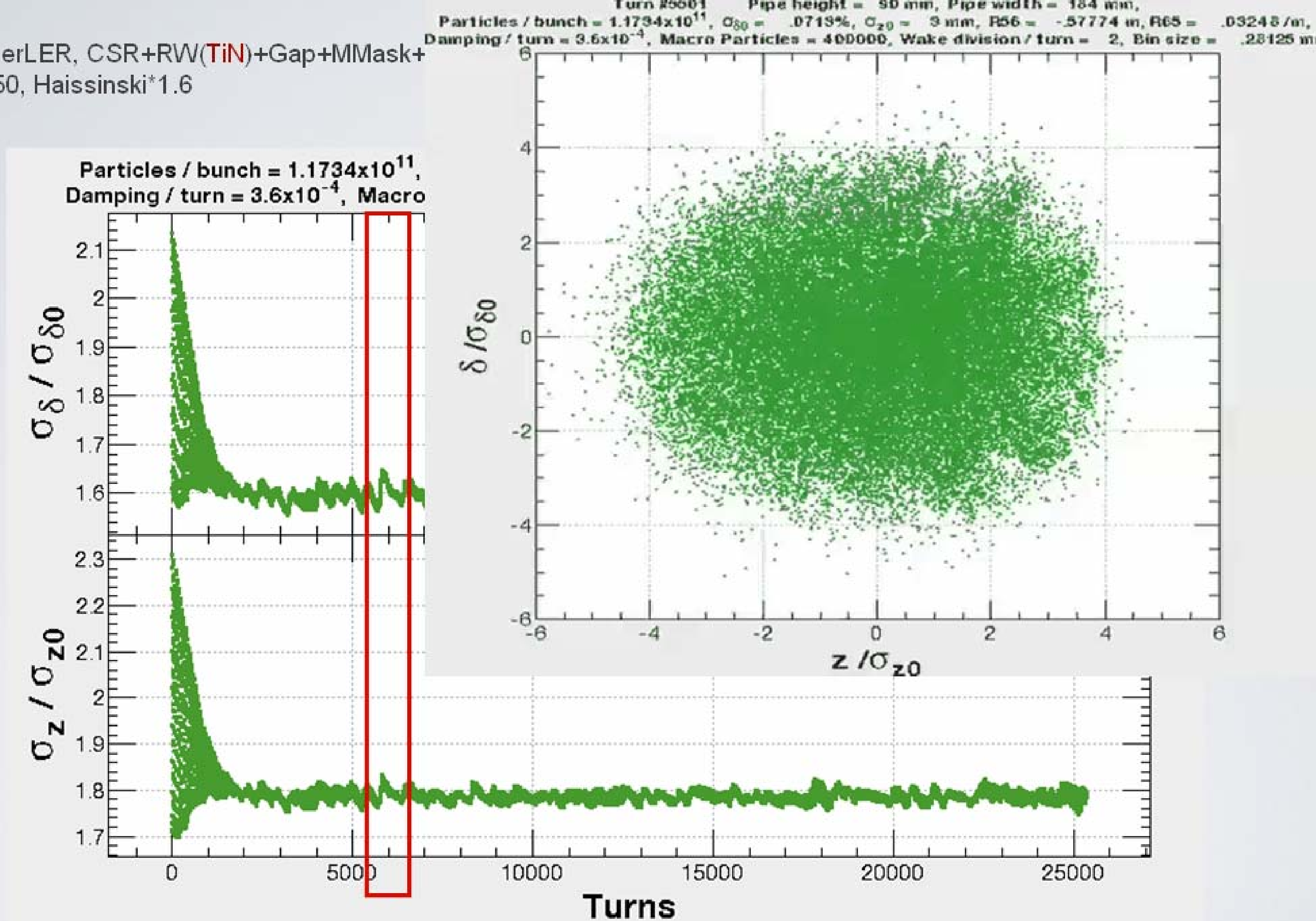
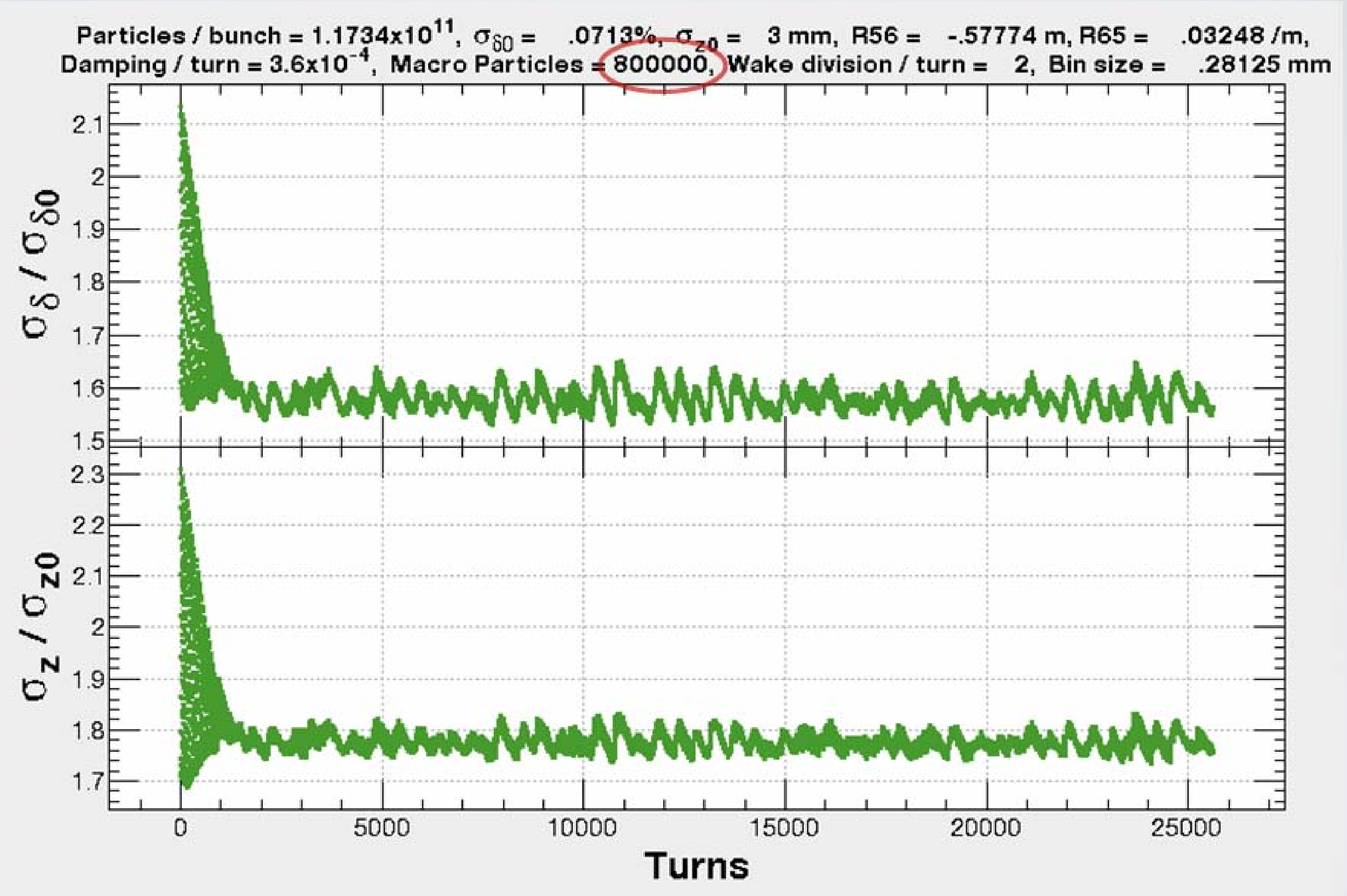


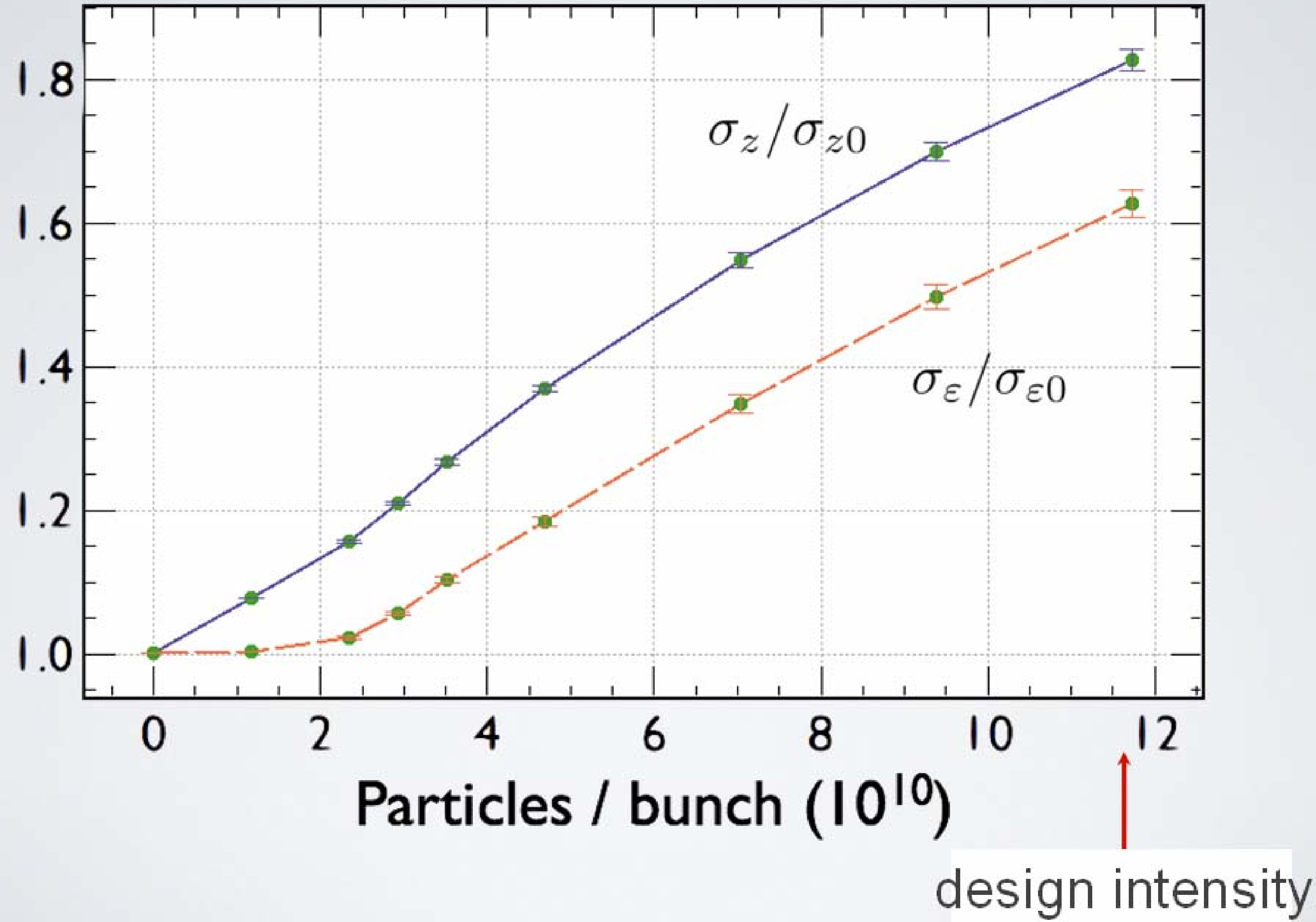
Microwave instabilities: no stable state is reached.

SuperLER, CSR+RW(TiN)+Gap+MMask+Bellows+ARES(Satoh)+BPM+SRM+PUMPS, rac = 45 mm, # of bends = 150, Haissinski*1.6

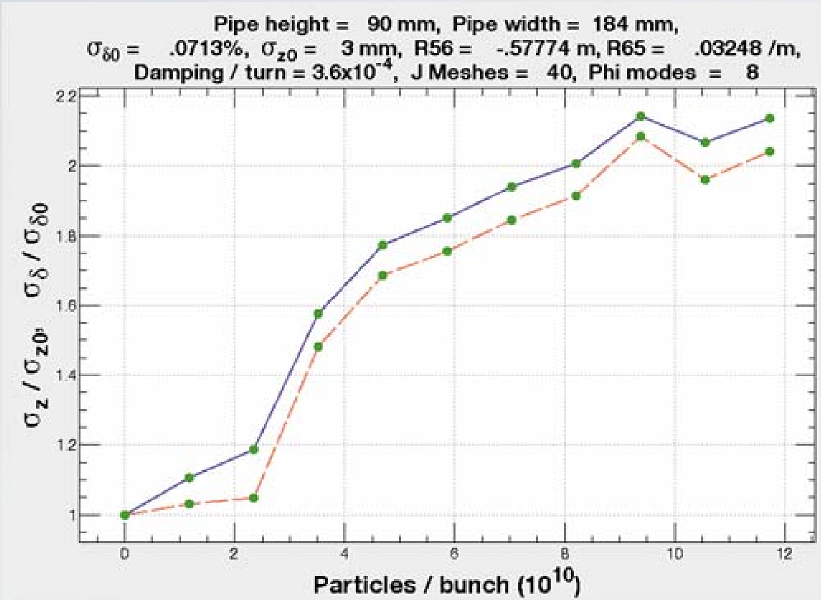


Convergence was checked by doubling the number of particles.

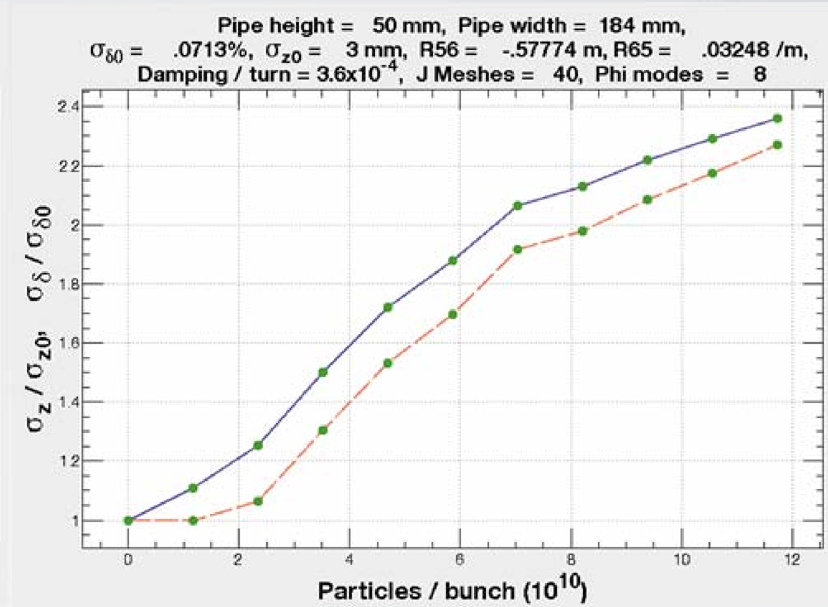
All wakes, incl. wigglers



Results with "Oide-YOKOYA" method No wigglers



a = 45 mm

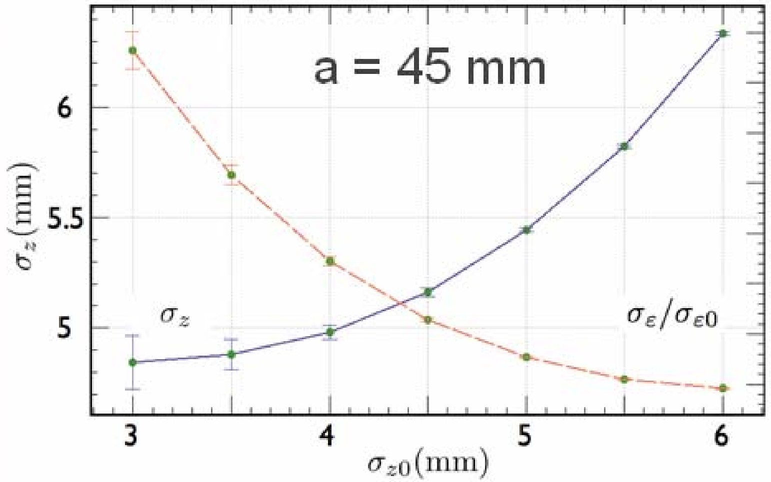


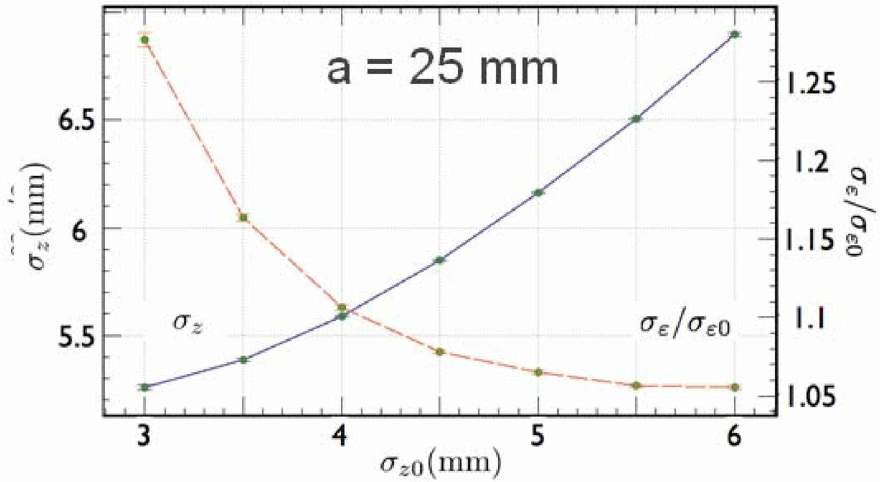
a = 25 mm

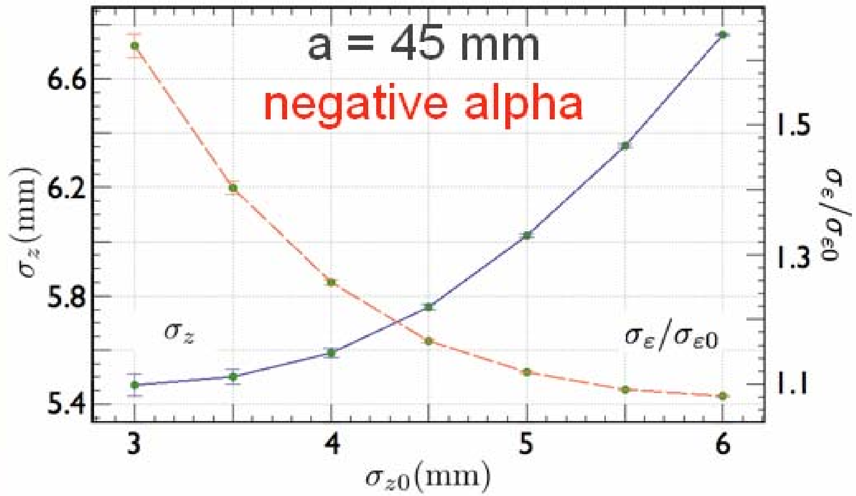
$$\begin{aligned} M_{jmj'm'} &= m^2\omega_j^2\delta_{jj'}\delta_{mm'} + \frac{k}{\pi} mm'\omega_j\omega_{j'}\left(-g'_j\Delta J_j\right)^{1/2}\left(-g'_{j'}\Delta J_{j'}\right)^{1/2} \\ &\times \int_0^{2\pi}\int_0^{2\pi} \cos m\phi \cos m'\phi' F\left(q(J_{j'},\phi') - q(J_j,\phi)\right) d\phi d\phi' . \end{aligned}$$

- This method is more powerful in predicting the threshold than estimating the magnitude of blowup beyond that.

- A longer bunch length relaxes the instability.







- a = 25 mm beam pipe is better but does not solve the problem.
- a = 45 mm with negative alpha may be the best choice
- No problem in the HER.

THE MINIMUM ACHIEVABLE BUNCH LENTH for a = 45 mm beam pipe

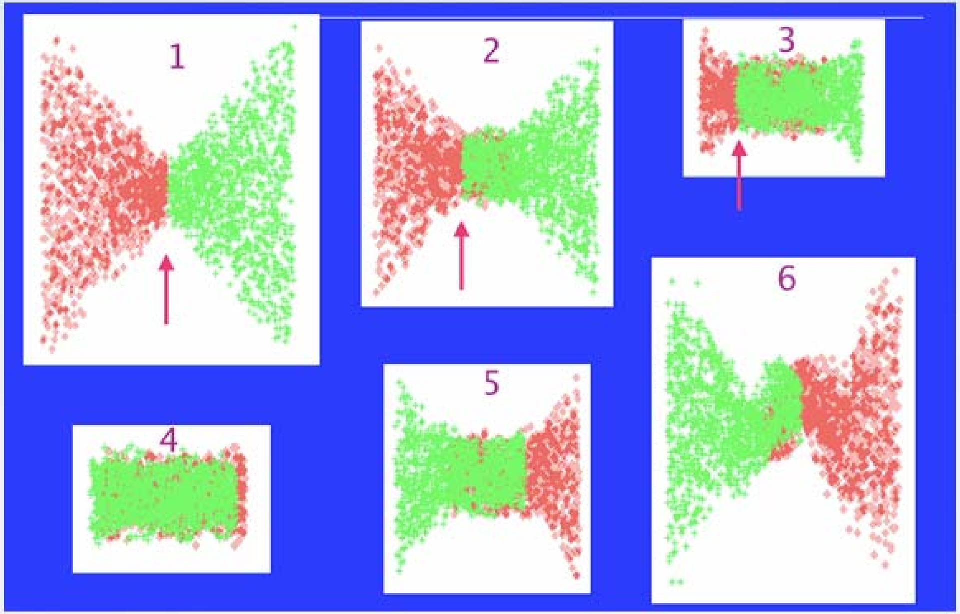
		zero bunch current	design bunch current	
LER	σ_z	5	6	mm
	σ_ε	7.1	8.0	10^{-4}
LER neg. alpha	σ_z	4.5	5.3	mm
	σ_ε	7.1	8.5	10^{-4}
HER	σ_z	3	3.6	mm
	σ_ε	6.8	7.0	10^{-4}
HER neg. alpha	σ_z	3	3.1	mm
	σ_ε	6.8	7.7	10^{-4}

Design of the Interaction Region

- Crab crossing needs a horizontal tune very close to a half integer ($\nu_x = 0.503$) to achieve the very high beam-beam parameter $\xi_y = 0.3$.
- Such a horizontal tune enhances the dynamic β and dynamic emittance effects to enlarge the bam size at the final quads by more than factor 10.
- No design of the IR has been technically found which is compatible with $\nu_x = 0.503$ and $\beta_x^* = 20$ cm.
- Thus the parameters were relaxed to $\nu_x = 0.505$ and $\beta_x^* = 40$ cm.

Travel Waist Scheme

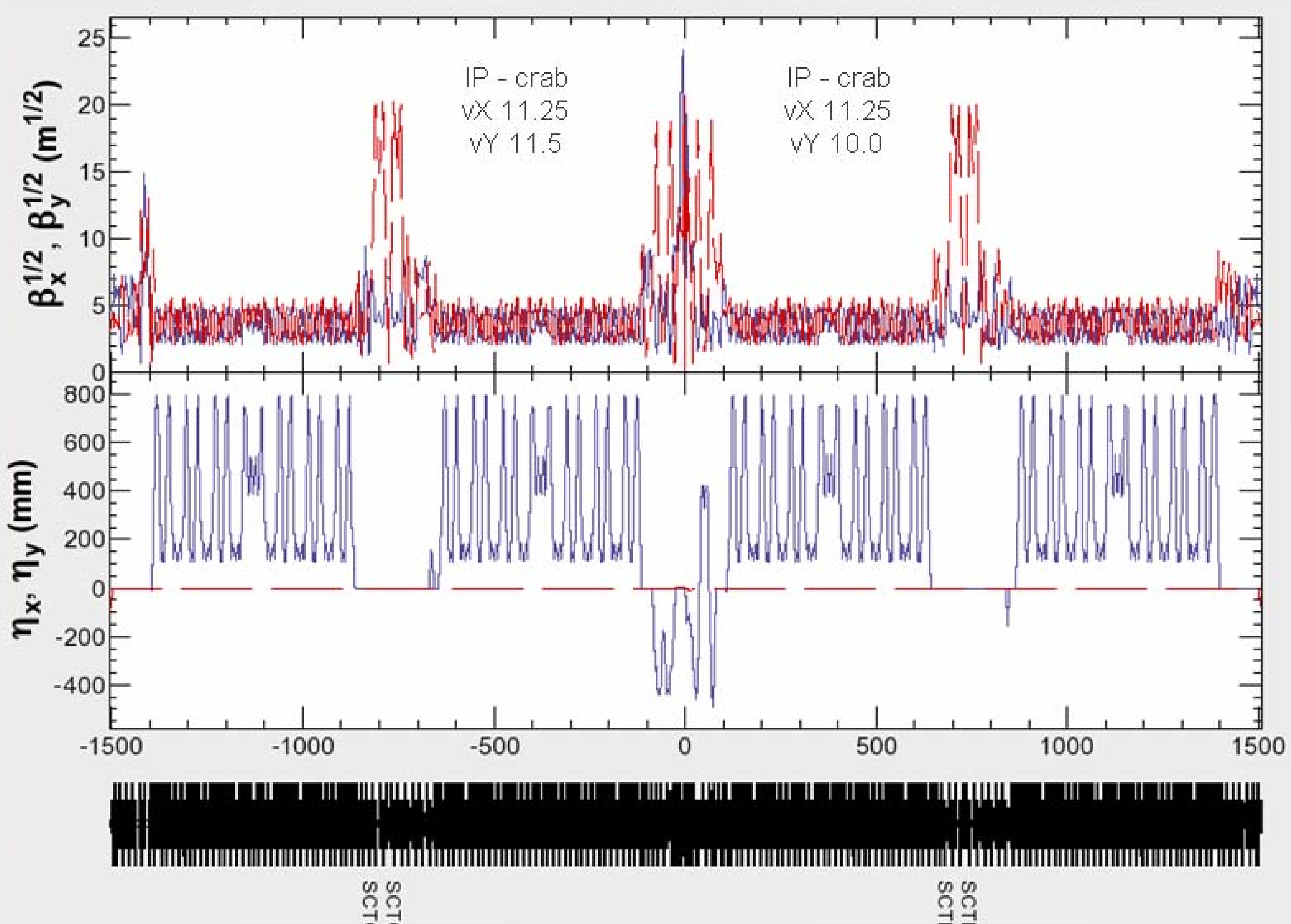
- Known technique for a linear collider (Balakin, et al).
- Move vertical waist backward along z.



N. Walker

- Two crab cavities, each sits in the middle of -I pair of sextupoles, are necessary for a ring.
- Very hard to accommodate them in the HER.

LER TRAVEL WAIST LATTICE



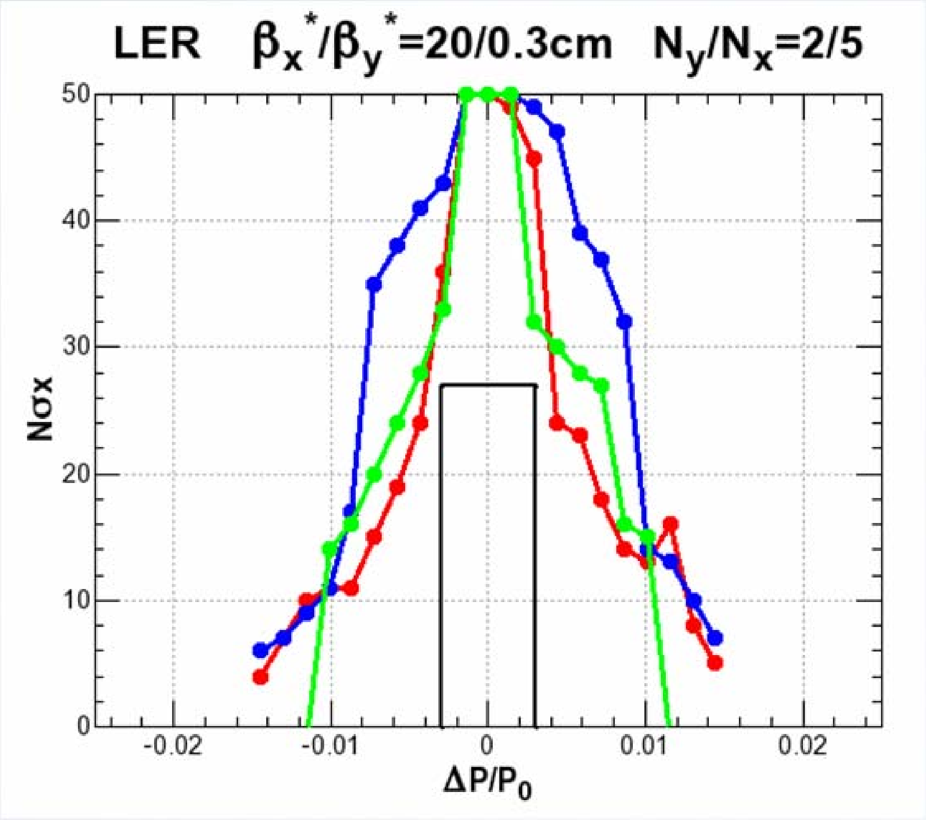
Sext - crab - Sext
Sext - Sext = -I'
$K2 = -1.846\ m^{-2}$

Sext - crab - Sext
Sext - Sext = -I'
$K2 = -1.846\ m^{-2}$

βx/y @ SX = 15/350 m
βx @ crab = 50 m
Vcrab = 1.56 MV

Sextupoles are not strong.

LER Dynamic Aperture with TRAVEL WAIST



RF ON
Crab OFF, OFF, ON
sext thickness: 0.334 m
K2= 0, +-1.846

Acceptance
Ax = 7.5e-6 m
Ay = 1.2e-6 m
$\Delta p/p$ = 0.003

The aperture shrinks, but still acceptable.

HOW MUCH IS THE IMPACT ON THE LUMINOSITY?

ν_x	β_x^* (cm)	$\sigma_{z,\mathrm{LER}}$ (mm)	$\mathcal{L}$ (10^{35})	
0.503	20	3	8	Original
0.505	40	3	5	+ Possible IR design
0.505	40	5	3	+ CSR
0.505	40	5	4	+ Travel Focus
0.503	20	5	5.5	+ Recovery of the IR design

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0.505	40	5	3	+ CSR
0.505	40	5	4	+ Travel Focus
0.503	20	5	5.5	+ Recovery of the IR design

* All luminosities assume that Crab Crossing works perfectly.

No technical solution has been found yet.

HOW MUCH IS THE IMPACT ON THE LUMINOSITY?

ν_x	β_x^* (cm)	$\sigma_{z,\mathrm{LER}}$ (mm)	$\mathcal{L}$ (10^{35})	
0.503	20	3	8	Original
0.505	40	3	5	+ Possible IR design
0.505	40	5	3	+ CSR
0.505	40	5	4	+ Travel Focus
0.503	20	5	5.5	+ Recovery of the IR design

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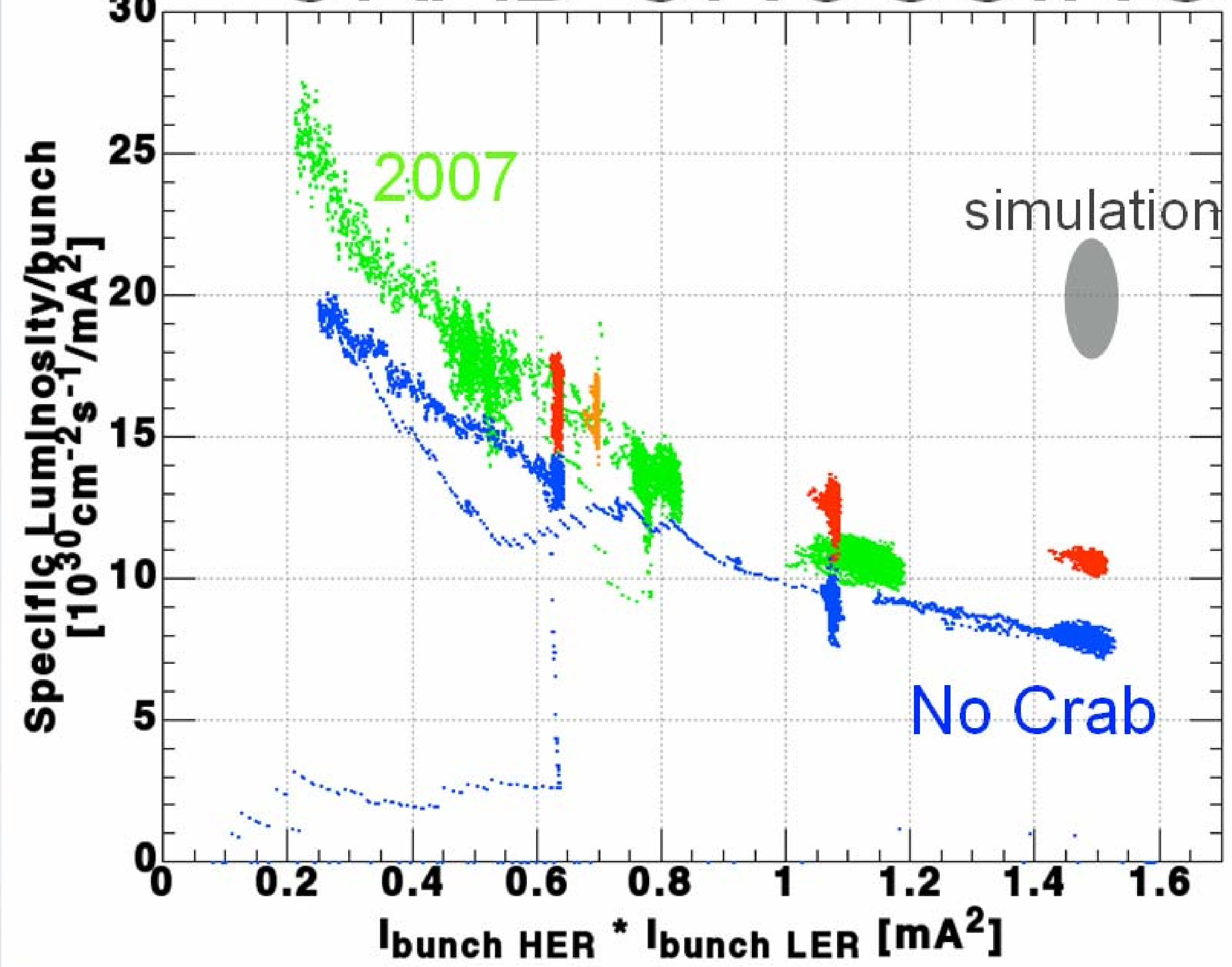
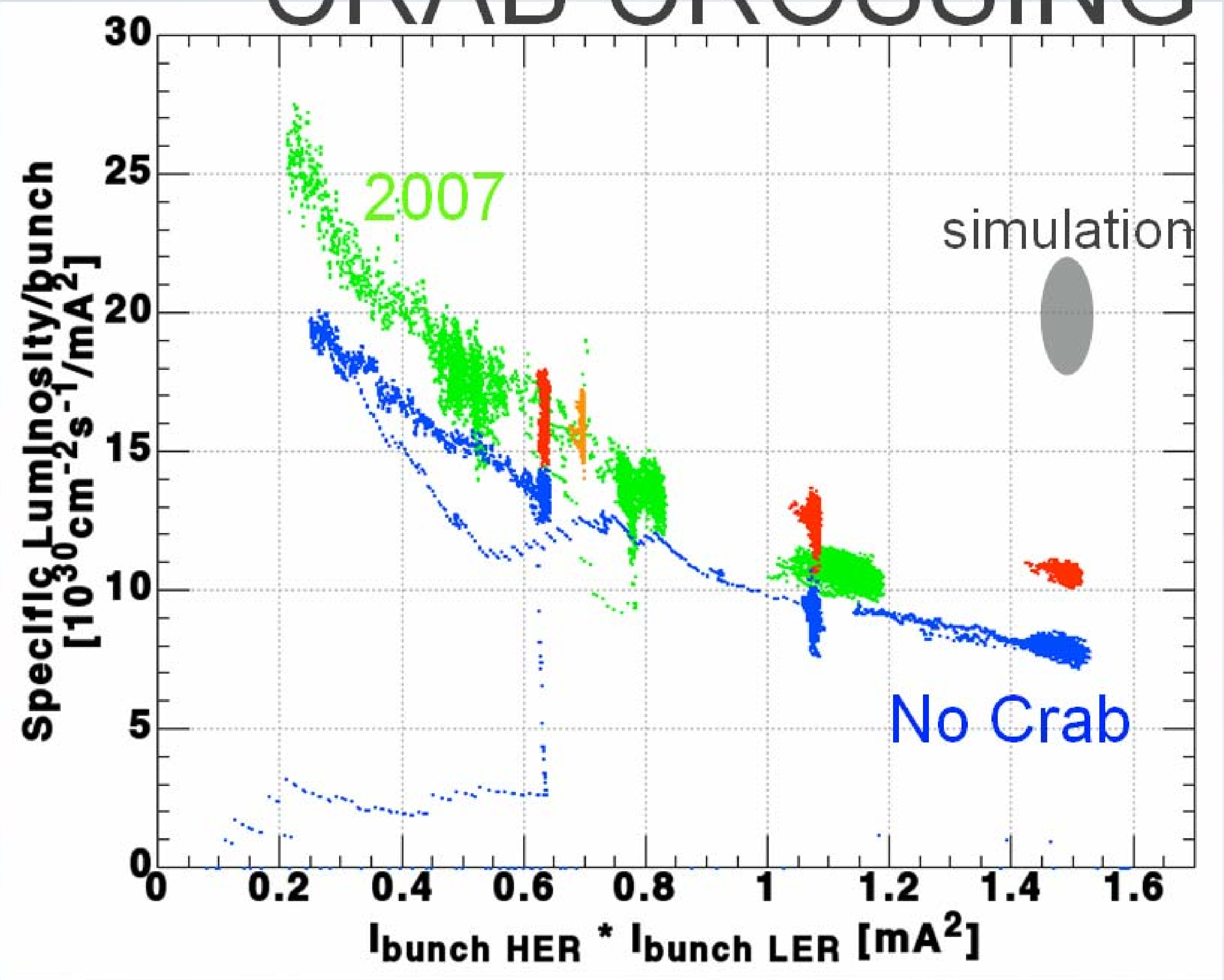
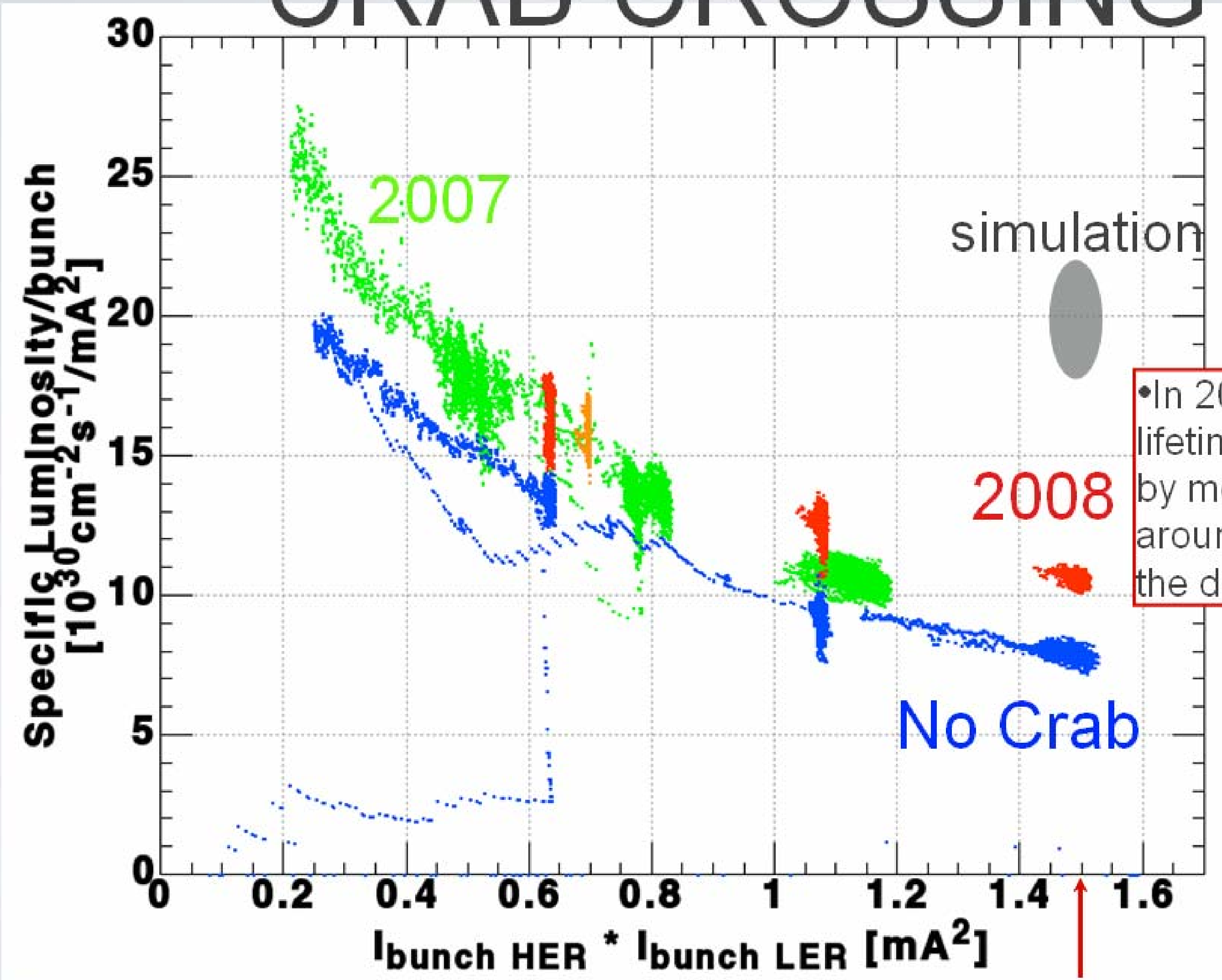
CRAB CROSSING



CRAB CROSSING



CRAB CROSSING



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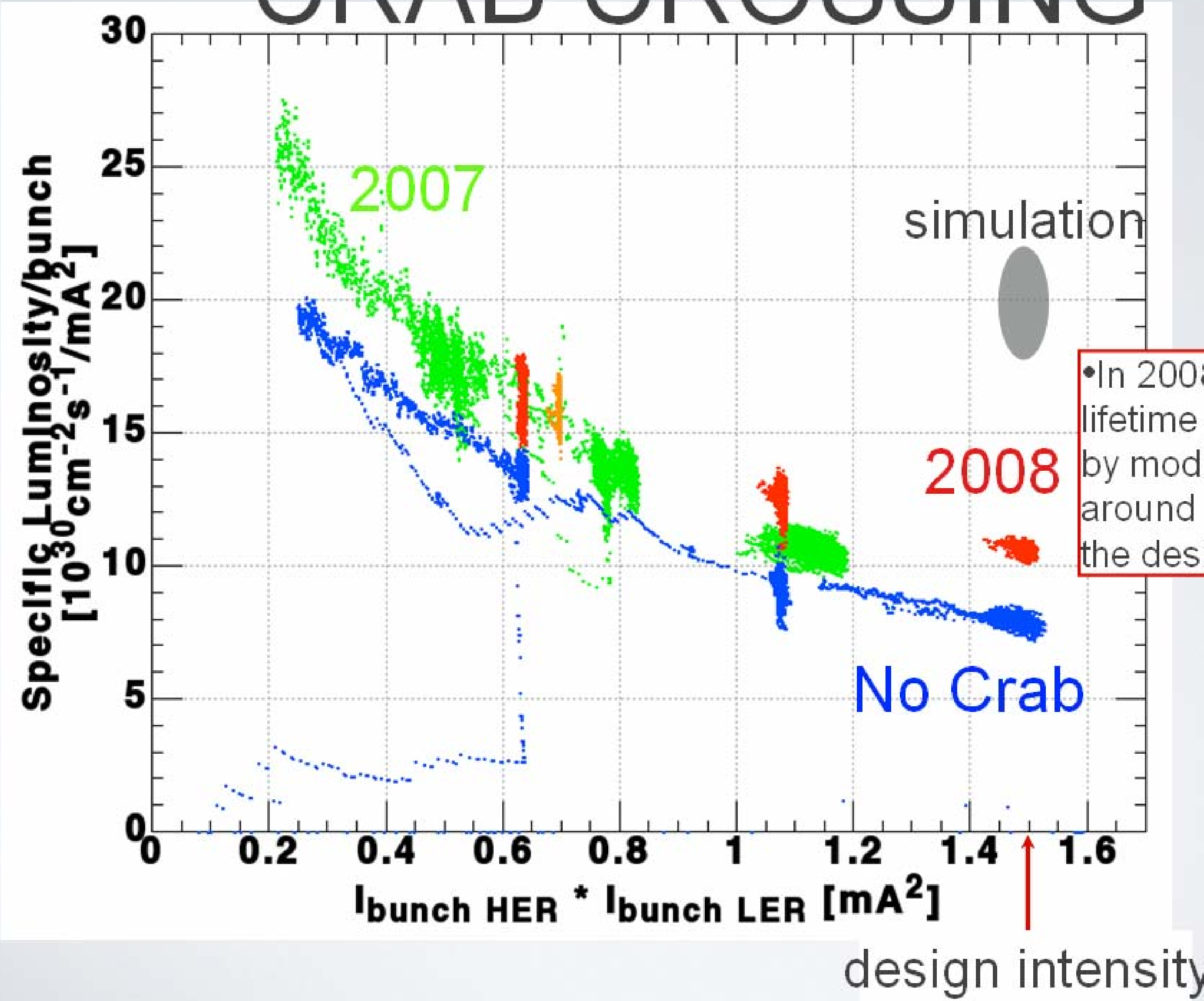

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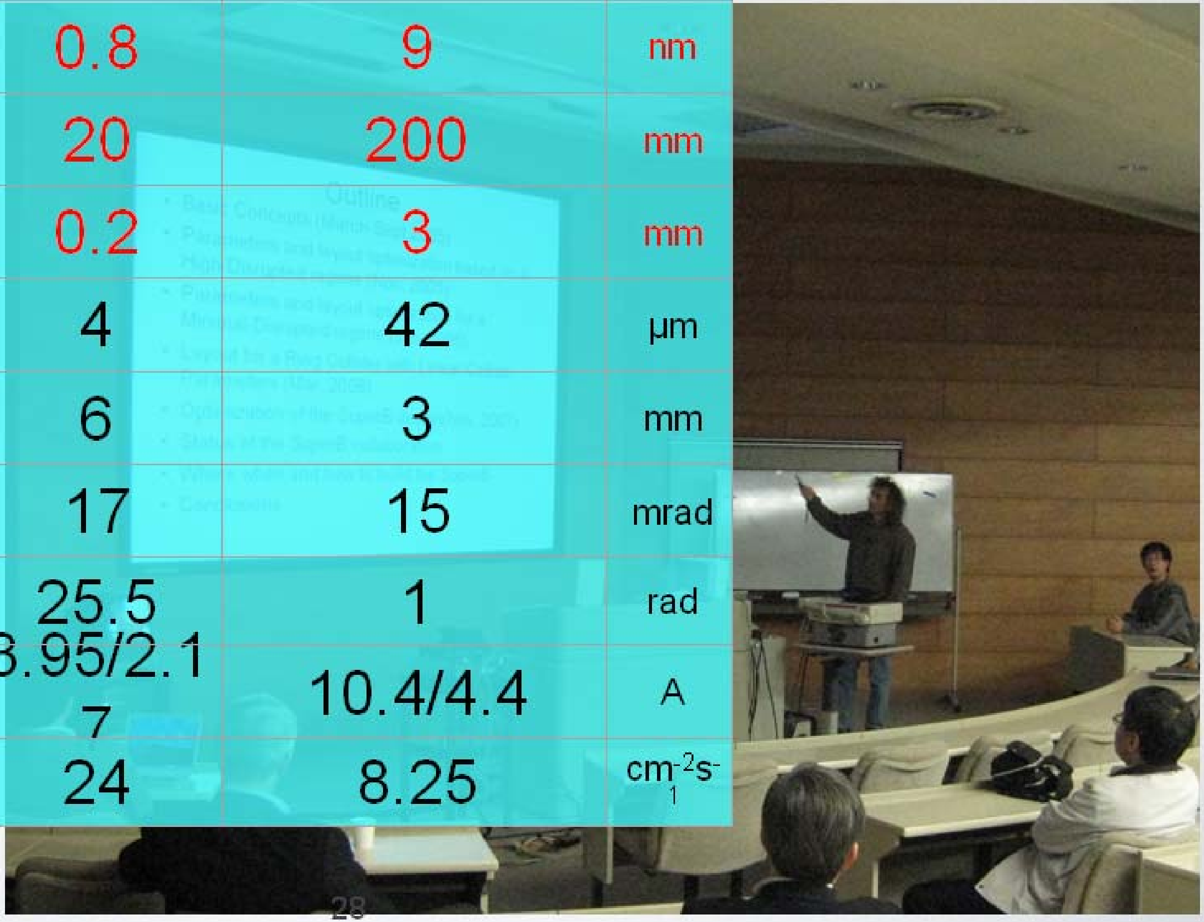
IS HIGH-CURRENT MORE DIFFICULT THAN "NANO-BEAM"?

P. Raimondi @ KEK, 2007

		SuperB (Upgrade)	High-Current (2006)	
Emittance	ε_x	0.8	9	nm
Horizontal beta	β_x^*	20	200	mm
Vertical beta	β_y^*	0.2	3	mm
Horizontal beam size	σ_x^*	4	42	µm
Bunch length	σ_z	6	3	mm
Half crossing angle	φ_x	17	15	mrad
Piwinski angle	φ	25.5	1	rad
Current(LER/HER)	I_b	3.95/2.17	10.4/4.4	A
Luminosity (x10[35])	L	24	8.25	$cm^{-2}s^{-1}$



AN ALTERNATIVE: NANO-BEAM SCHEME

	High-Current (LER / HER)	Nano-Beam (LER / HER)	
I	9.4 / 4.1	3.3 / 1.9	A
ε_x	24 / 18	2.8 / 1.6	nm
$\varepsilon_y/\varepsilon_x$	1 / 0.5	0.84 / 0.46	%
ν_x	0.505	0.530	
β_x^*	400	44 / 25	mm
β_y^*	3 / 6	0.21 / 0.37	mm
ϕ_x	15	30	mrad (half crossing angle)
σ_z	5 / 3	6	mm
ξ_y	0.2 / 0.3	0.07	
$\mathcal{L}$	~ 4	~ 6	10^{35}

$$\mathcal{L} \propto \gamma \left(\frac{I \xi_y}{\beta_y^*} \right)$$

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Possible with existing rf system at KEKB

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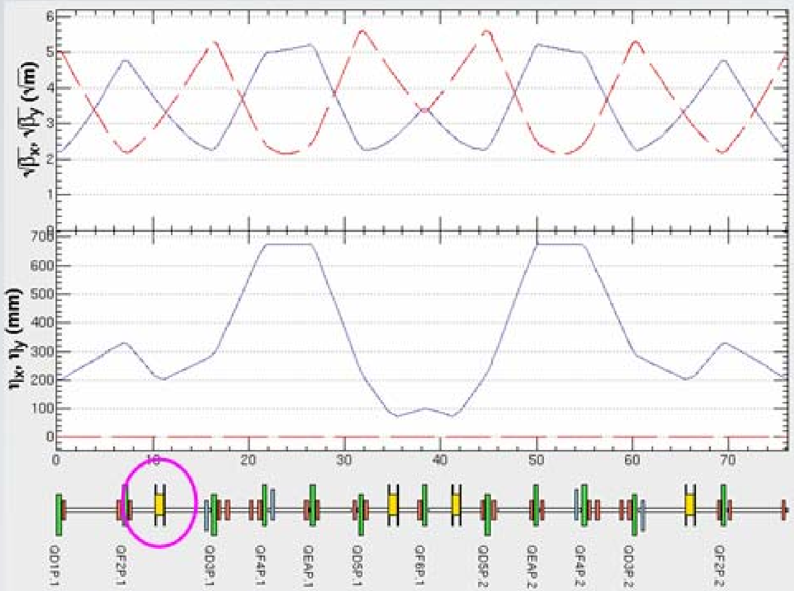
A conservative choice: does NOT assume Crab Waist

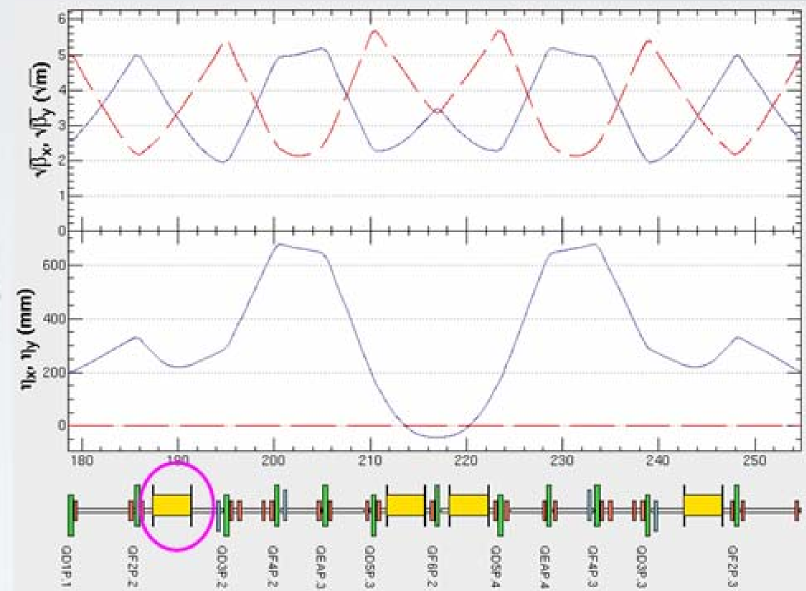
LER Nano-Beam Lattice

LER arc cell **Preliminary**



L bend = 0.9 m

ε_X = 6.8 nm



L bend = 4.0 m

ε_X = 2.2 nm

- The arc cell lattice of the KEKB LER (left) can be modified to the low-emittance version (right), by weakening the magnetic field of the dipoles.
- No need for changing other components, beam pipes, geometry.
- The HER's emittance is reduced by replacing the arc cells.

Summary

- The High-Current Scheme for upgrading KEKB has a few issues which are not easy to be conquered: CSR, IR design, high ξ_y with crab crossing, and construction/operation costs for high current.
- Mitigation such as Travel Waist may work, but also introduces more complexity.
- More attention should be paid for the Nano-Beam Scheme, and the design work is on going in that direction.