

beam dynamics challenges at future circular colliders

*Frank Zimmermann, CERN AB/ABP
EPAC'04 Lucerne, 06/07/2004*

perspective

beam-beam interaction

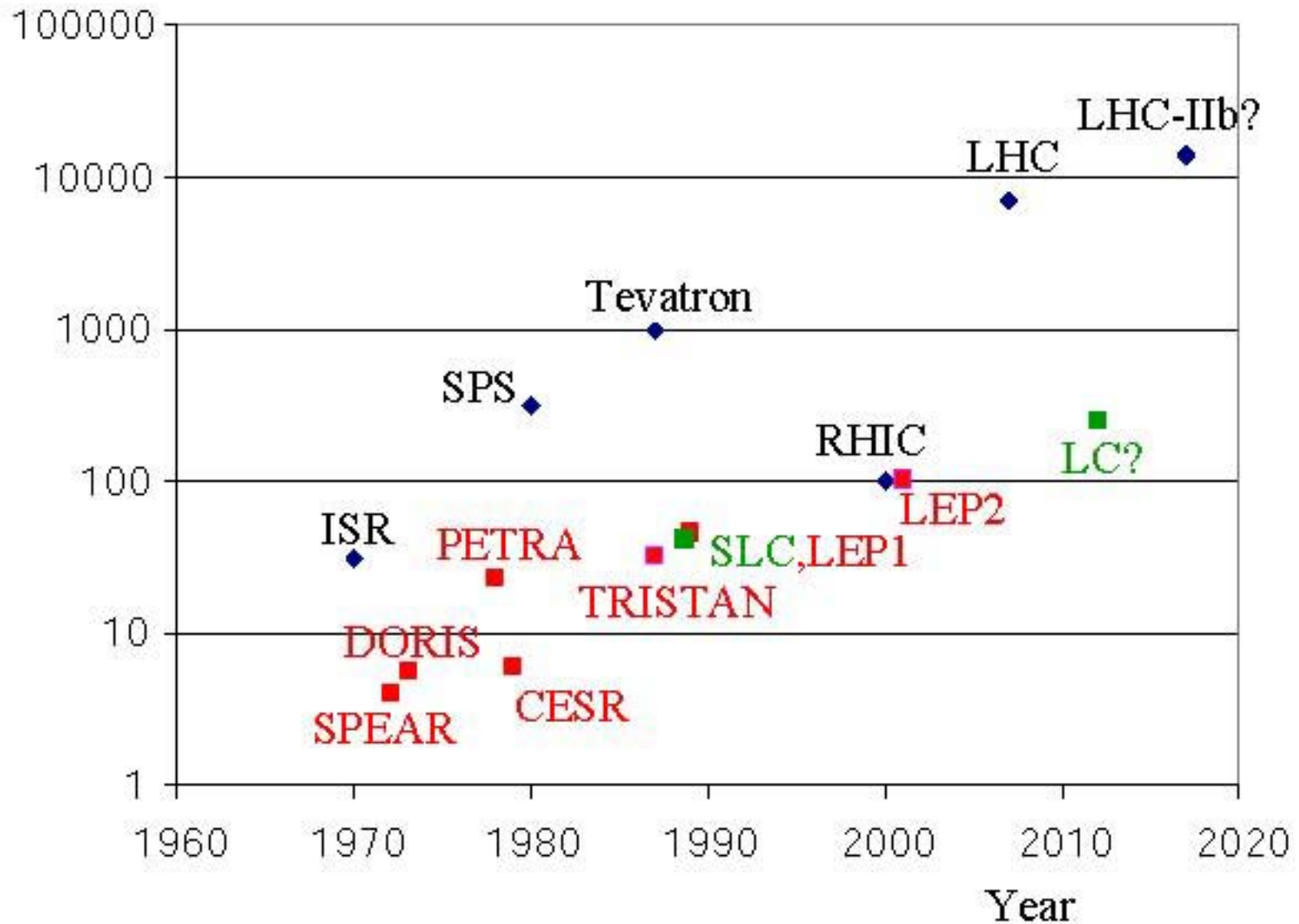
collective effects

electron cloud

outlook

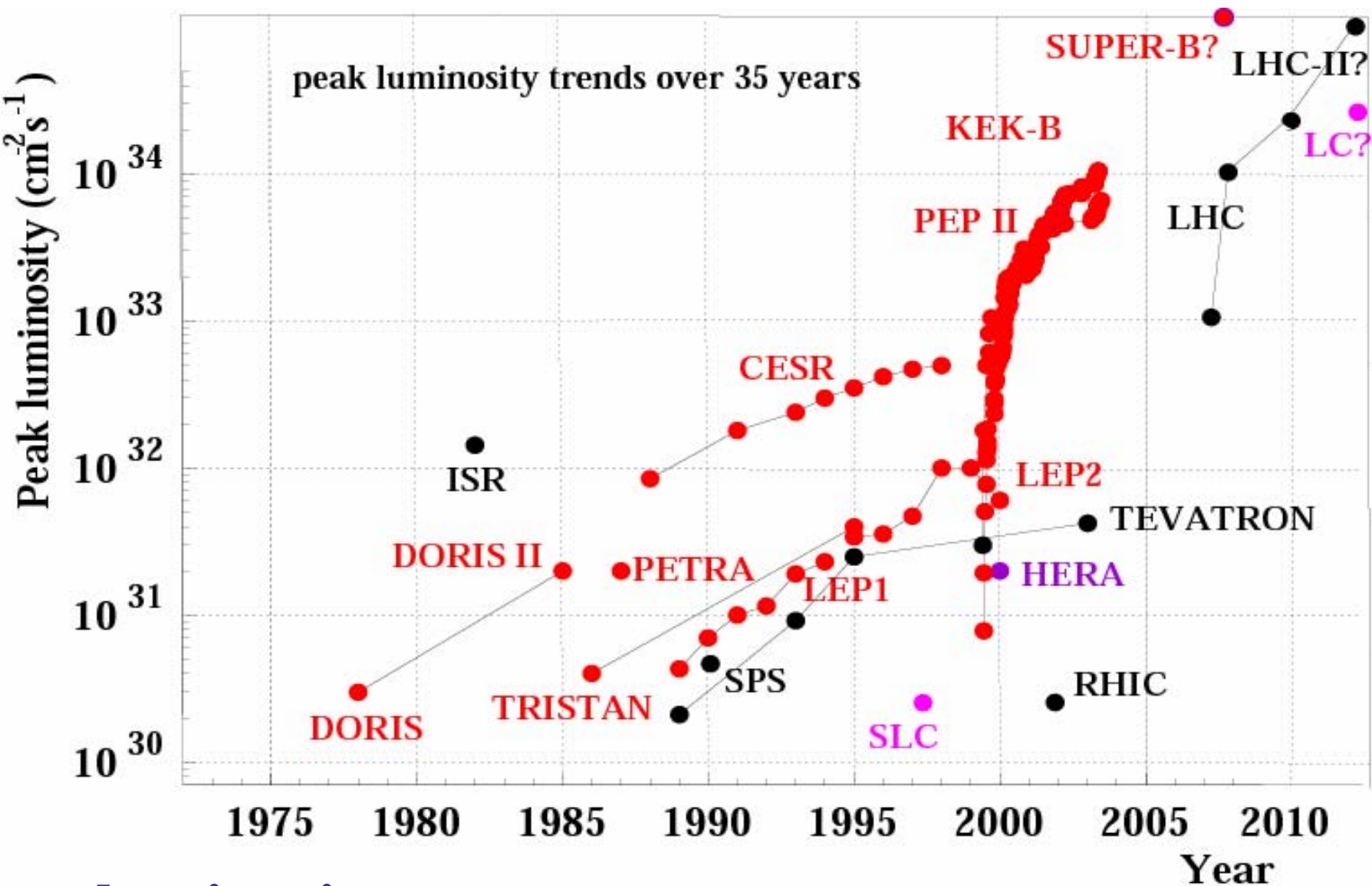
beam energy [GeV]

average increase factor 1.2 / year



energy

average increase factor 1.4 / year



luminosity

past & present limits

beam-beam
head-on ξ_{HO} & ξ_{LR} long-range
e+/e- colliders, Tevatron
SPS, ...

e⁻ cloud
PEP-II, KEKB, RHIC

unbunched beam
HERA, Tevatron

$\Delta\varepsilon/\Delta t$ due to IBS
RHIC, SPS

impedance
Tevatron, LHC collimators

dynamic aperture
Tevatron?

future limits?

machine protection
LHC or SuperLHC

debris @ collision
LHC ion operation

pressure rise in cold machines

stability of collision offsets

new concepts

beam-beam compensation
electron lenses & electro-magnetic lenses

superbunch collision
SBHC, SuperLHC?

strong rf focusing
DAFNE-2

induction rf
KEK PS

nonlinear collimation
CLIC?, SuperLHC?

high-energy
electron cooling
RHIC-II, FNAL

high-energy bunched beam
stochastic cooling
BNL, FNAL

optical stochastic cooling LBNL?

linac-ring collisions
ERHIC, ELIC, TERA, QCDE

LHC: nominal, ultimate, and possible upgrades

	nominal	ultimate	upgrade	upgrade
#bunches	2808	2808	2808	1
rms bunch length [cm]	7.6	7.6	7.6, 4.2	7500
rms energy spread [10^{-4}]	1.1	1.1	1.1, 3.7	5.8
beta at IP [m]	0.5	0.5	0.25	0.25
crossing angle [μ rad]	300	315	485	1000
beam current [A]	0.56	0.86	1.3, 1.3	1.0
luminosity [10^{34} $\text{cm}^{-2} \text{s}^{-1}$]	1	2.3	7.3, 9.7	9.0

LHC Upgrade Feasibility Study (F. Ruggiero et al.)

→ “LHC-II”, “SuperLHC”

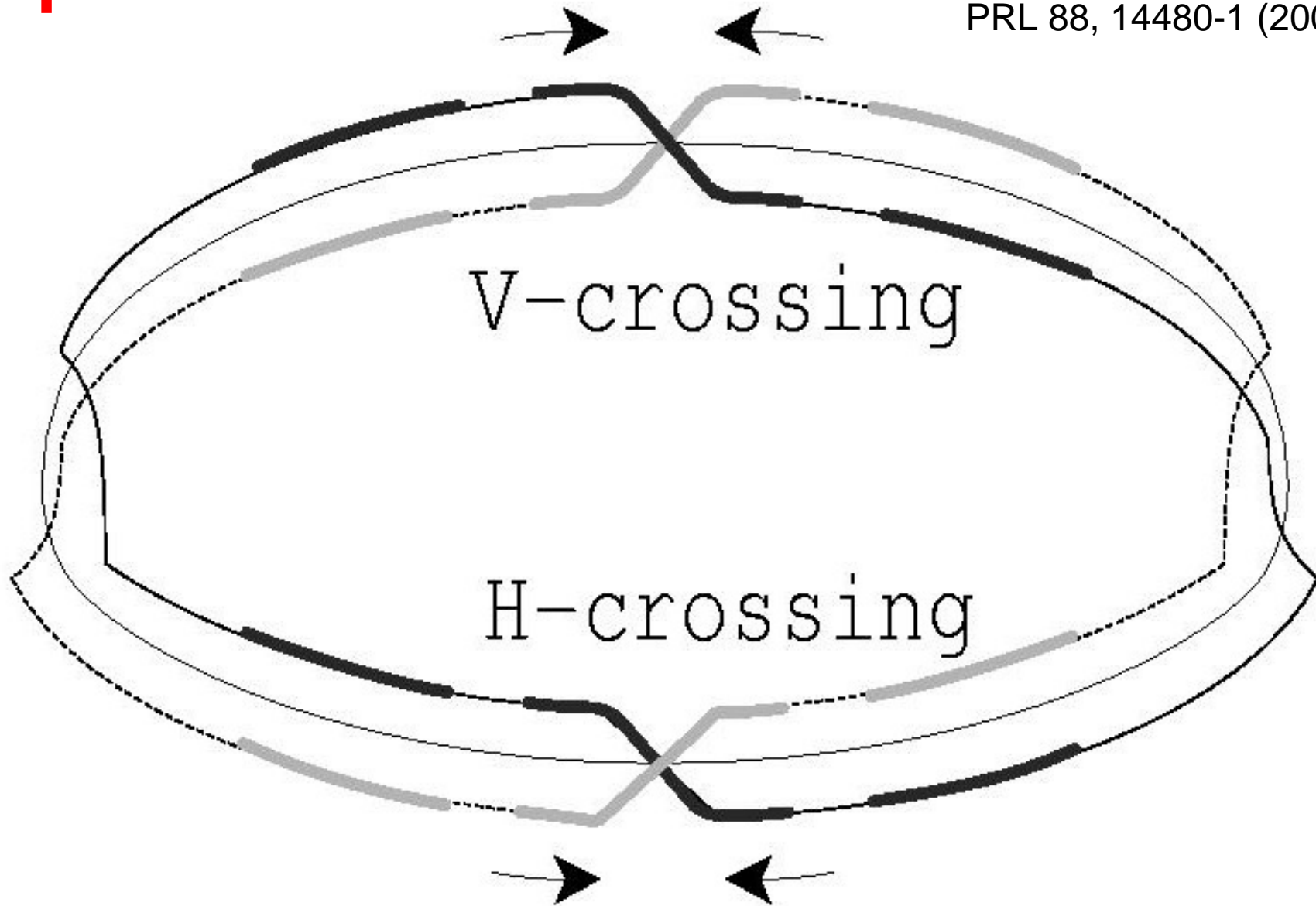
CERN-LHC-PROJECT-REPORT-626

one possibility: **Superbunches**

[F. Ruggiero, F.Z., PRST-AB 5:061001 (2002);
see also K. Takayama/KEK & RPIA2002 Proc.]

superbunch hadron collider

K. Takayama et al.,
PRL 88, 14480-1 (2002)



x-y crossing or 45/135 degree crossing

for large Piwinski parameter $\theta\sigma_z / (2\sigma^*) \gg 1$,
 with alternating crossing at two collision points

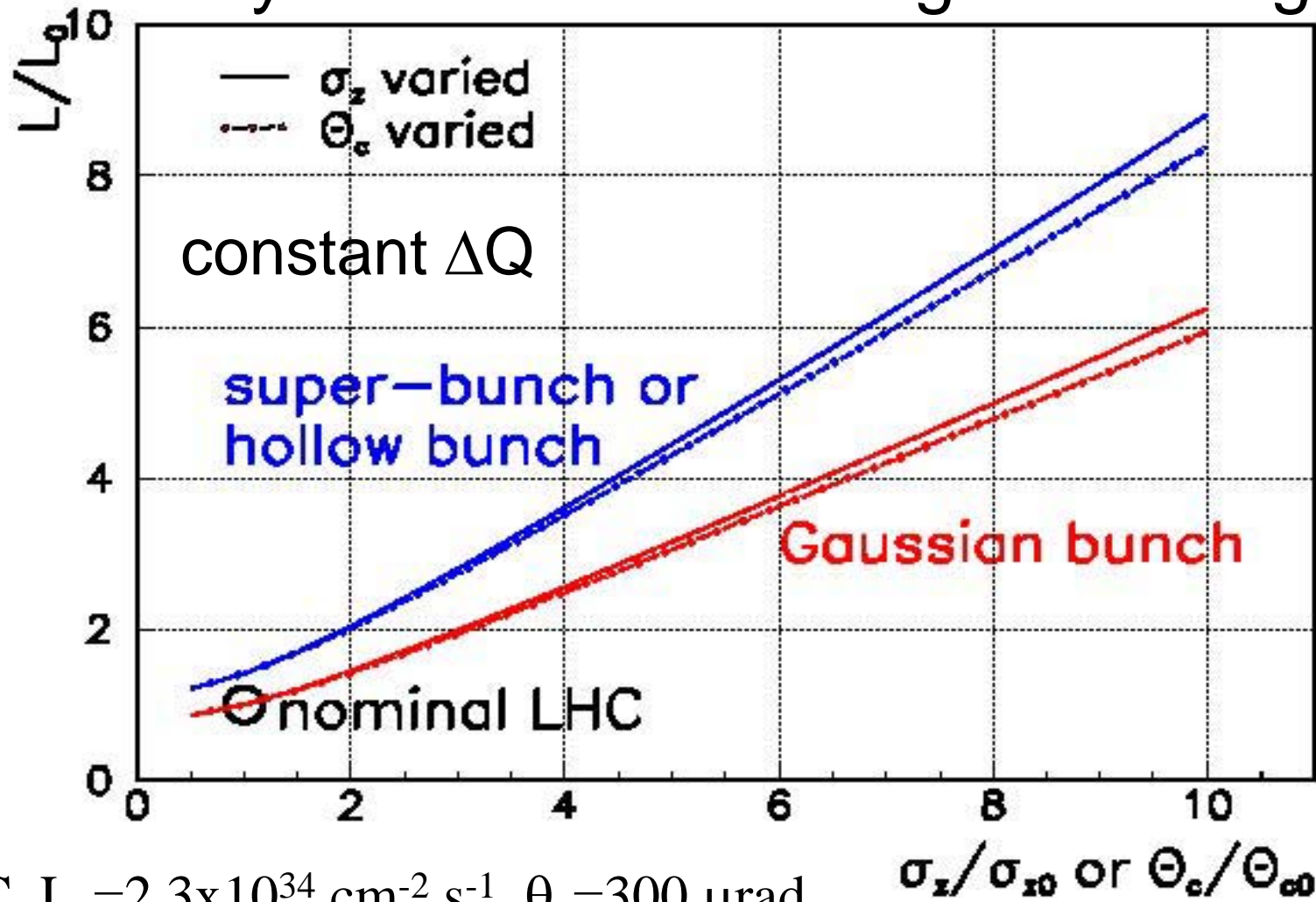
SuperLHC

$$L^{flat} \approx \frac{1}{\sqrt{2}} \frac{f_{coll} \gamma}{r_p \beta^*} \Delta Q_{tot} N_b$$

$$L^{Gauss} \approx \frac{1}{2} \frac{f_{coll} \gamma}{r_p \beta^*} \Delta Q_{tot} N_b$$

F. Ruggiero, F. Zimmermann, G. Rumolo, Y. Papaphilippou,
 “**Beam Dynamics Studies for Uniform (Hollow) Bunches or Super-**
bunches in the LHC : Beam-beam effects, Electron Cloud,
Longitudinal Dynamics, and Intrabeam Scattering”, RPIA2002
 “**Beam-Beam Interaction, Electron Cloud and Intrabeam Scattering**
for Proton Super-bunches”, PAC2003

luminosity increase in the long-bunch regime

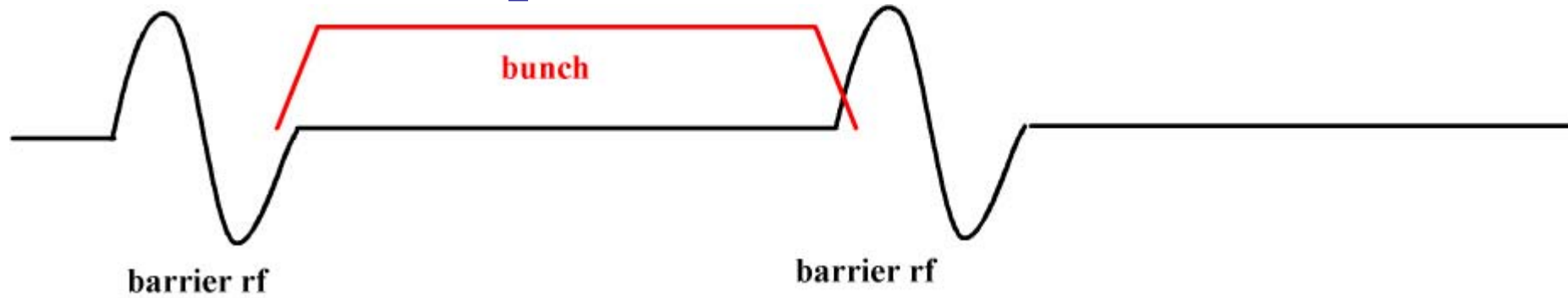


factor
10 gain
possible
for LHC
upgrade

LHC, $L_0 = 2.3 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$, $\theta_0 = 300 \text{ } \mu\text{rad}$

relative increase in LHC luminosity vs σ_z (θ_c) for Gaussian or hollow bunches, maintaining $\Delta Q_{\text{tot}} = 0.01$ with alternating x-y crossing at 2 IPs [F. Ruggiero & F.Z., PRST-AB 5, 061001 (2002)]

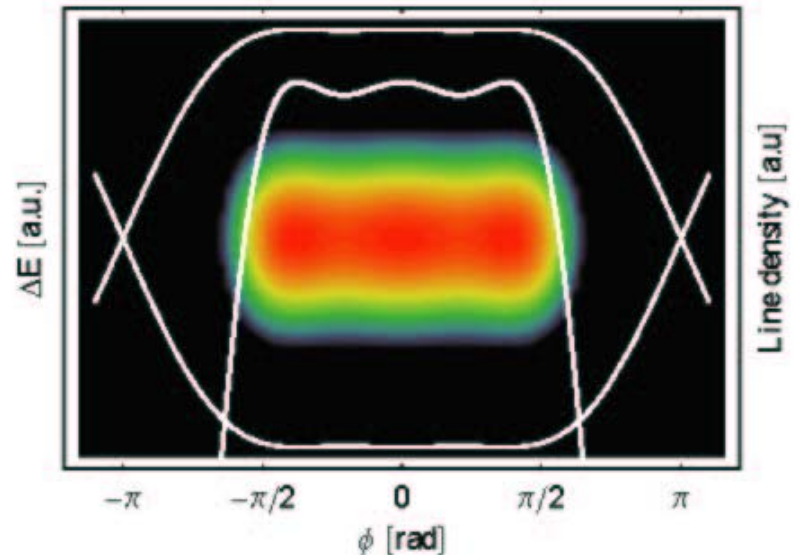
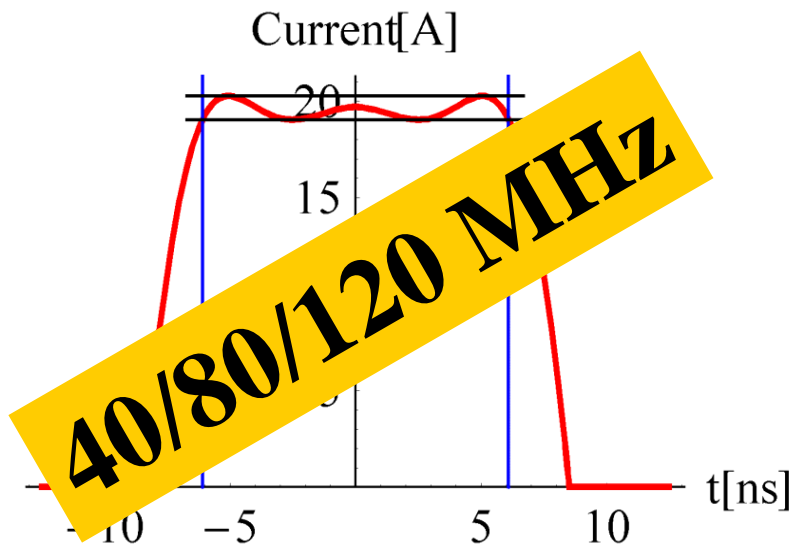
schematic of super bunch in rf barrier bucket

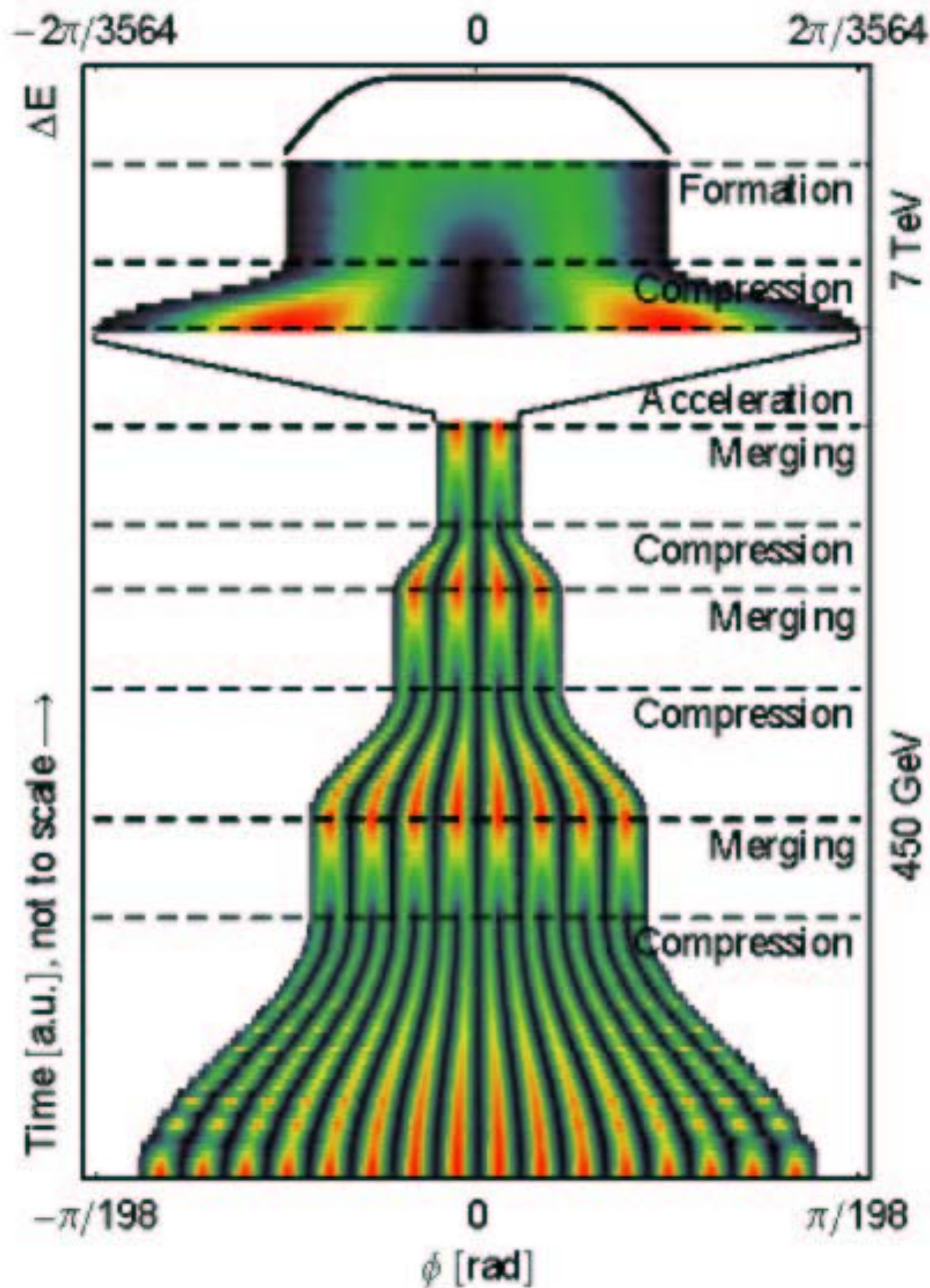


alternative CERN scheme: 3 rf systems

(H. Damerau, R. Garoby, WEPLT015)

of RF systems, n	1	2	3	4	5
$\int \lambda^2(\phi) d\phi$	0.51	0.70	0.81	0.84	0.88
Luminosity gain	1.00	1.44	1.58	1.66	1.72
Tot. voltage [MV]	16	2.6	1.5	1.1	1.2





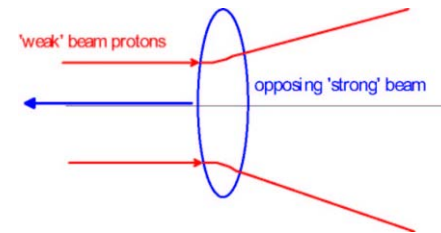
mountain-range plot illustrating the formation of long flat "superbunches" in the LHC, by a sequence of compressions and bunch mergings

H. Damerau, R. Garoby, WEPLT015

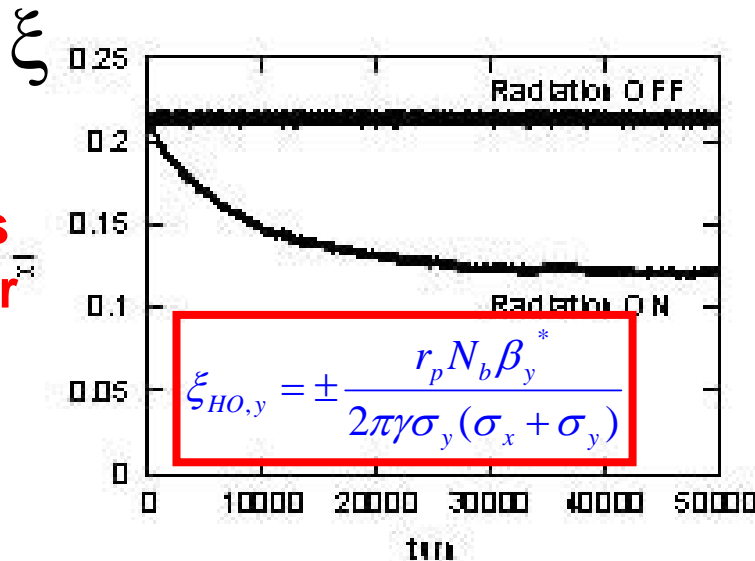
beam-beam interaction

- *beam-beam limit*
- *random & ground motion*
- *long-range collisions*
- *alternating crossing?*
- *crab crossing*
- *beam-beam compensation*

head-on beam-beam interaction



performance of lepton colliders is reliably predicted – but same **simulations suggest much higher tune shifts possible without synchrotron radiation** - contrary to experience!

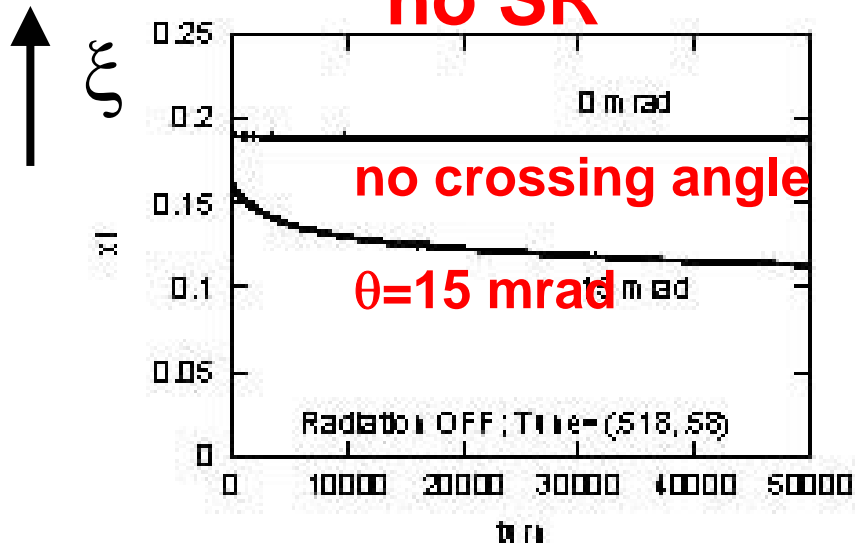


no SR

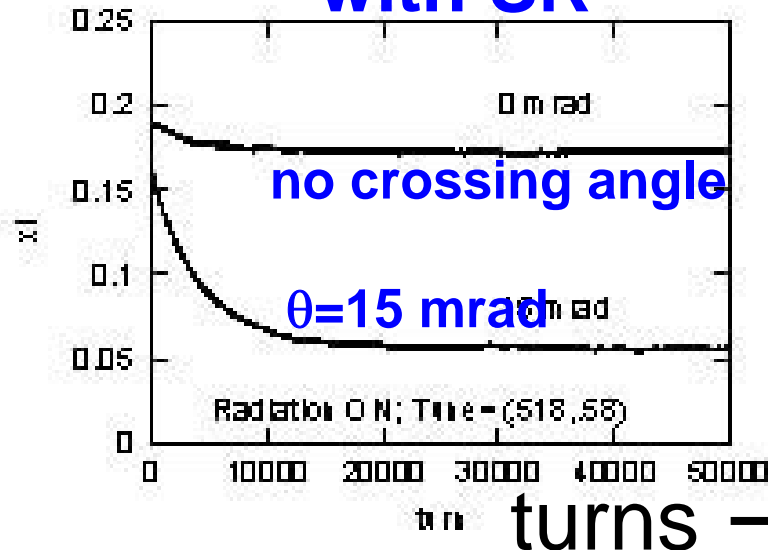
with SR

K. Ohmi et al.,
APAC 2004

no SR



with SR



for hadrons: mismatch, noise, errors, small imperfections important

p emittance growth due to random offsets

$$\frac{\Delta\varepsilon}{\Delta t} \approx \frac{n_{IP} 4\pi^2 (\Delta x)_{rms}^2 \xi_{HO}^2 f_{rev}}{\beta^*}$$

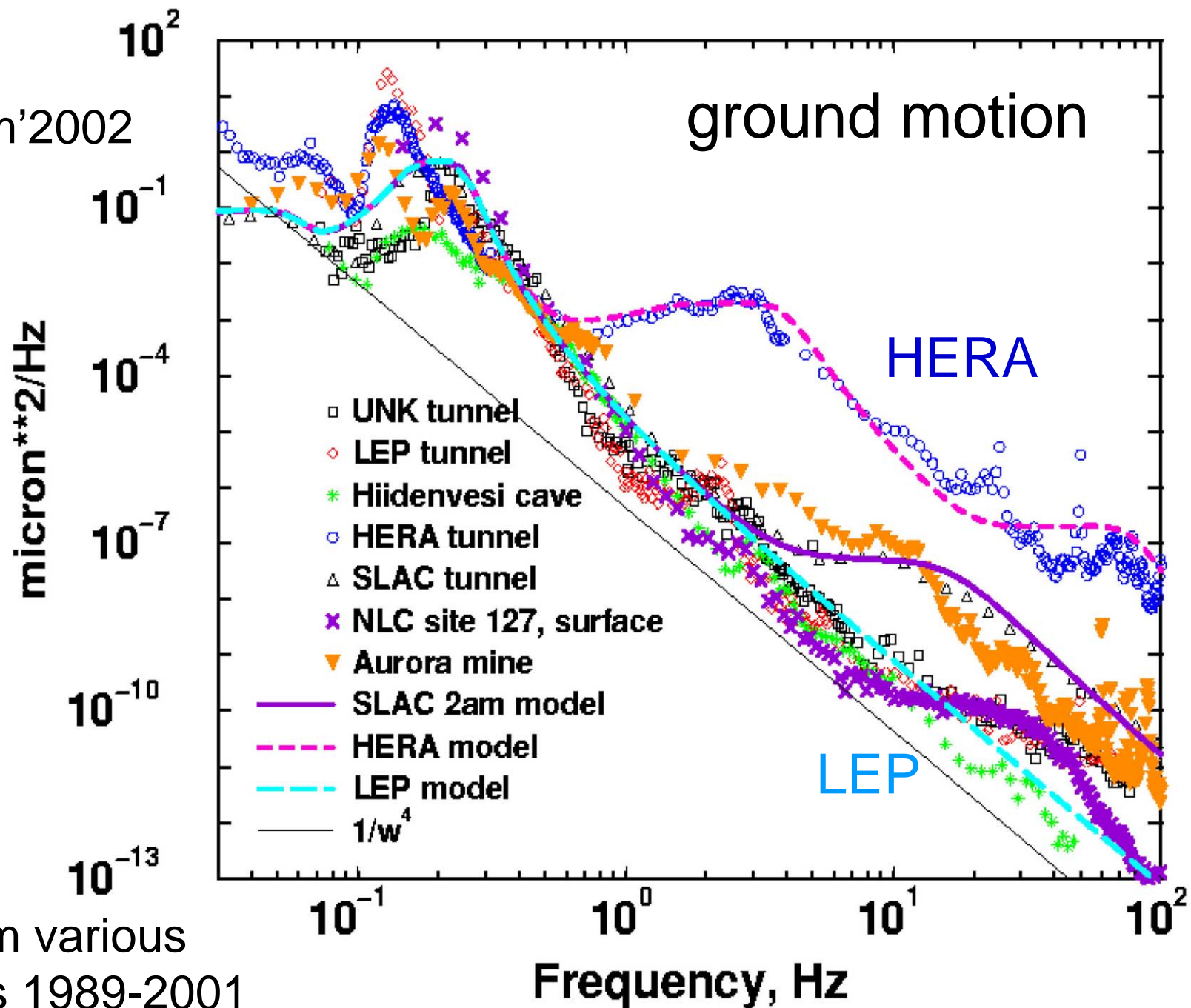
emittance growth
from turn-by-turn
random offsets Δx

SuperLHC: $\beta_{x,y}^* = 0.25$ m, $n_{IP} = 2$, $\xi_{HO} = 0.005$,
 $\gamma = 7500$, $\gamma\varepsilon = 3.75$ μm

requiring less than 10%/hr emittance growth

→ $\Delta x_{rms} < 12$ nm $\sim 10^{-3}\sigma^*$

A. Seryi
Nanobeam'2002
Lausanne



data from various
locations 1989-2001

emittance growth from beam-beam offsets caused by natural ground motion

lattice
response
function



$$\frac{\Delta \varepsilon}{\Delta t} \approx \frac{n_{IP} 8\pi^2 (\Delta x)_{rms}^2 \xi_{HO}^2 R^2 P(f_0) f_0^2}{\beta^*}$$

ground
motion
power
spectrum

$$P(f) \propto \frac{1}{f^3} \dots \frac{1}{f^4}$$


lower
cutoff
frequency $f_0 \approx \frac{vQ}{C}$

LHC: $R^2 \sim 20$

quiet LEP tunnel

$$P(f) \approx \frac{10^{-16}}{f[\text{Hz}]^3} \frac{\text{m}^2}{\text{Hz}}$$

**$\Delta\varepsilon/\Delta t$ only several 10^{-6}
per hour in SuperLHC
however at HERA site:
several % hour**



E. Keil, CERN SL/97-61 (AP); J.M. Juravlev e tal., CERN SL/95-53.

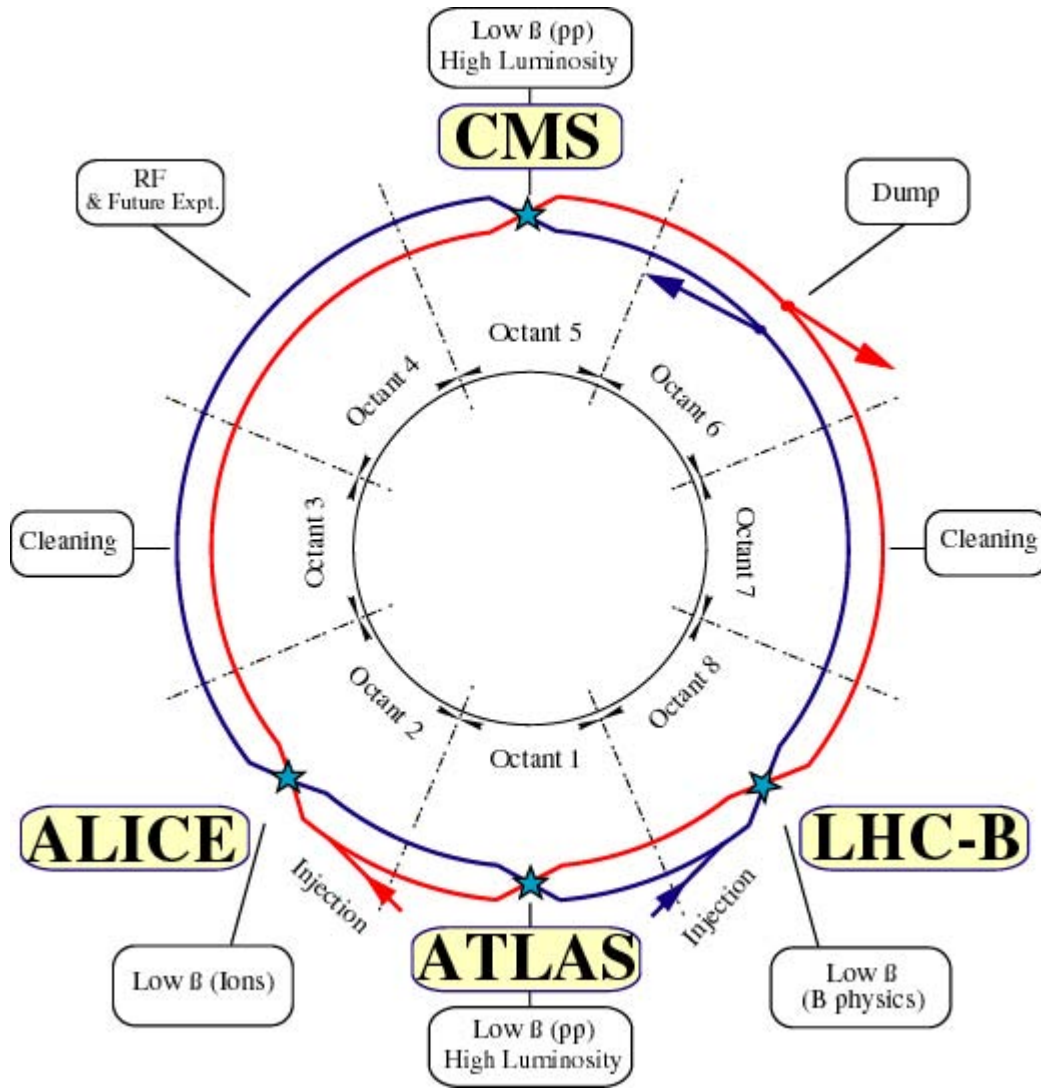
lower frequencies may contribute for asymmetric optics as in LHC

long-range beam-beam collisions

- **perturb motion at large betatron amplitudes**, where particles come close to opposing beam
- cause **'diffusive aperture'** (Irwin), high background, poor beam lifetime
- **increasing problem** for SPS, Tevatron, LHC,...
that is for operation with larger # of bunches

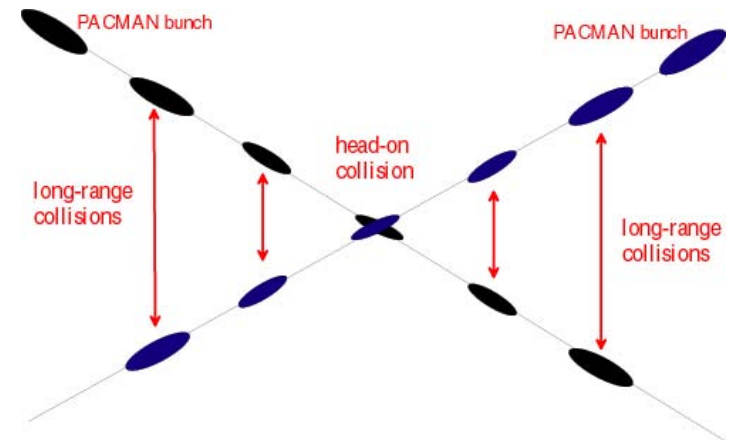
	#LR encounters
SPS	9
Tevatron Run-II	70
LHC	120

LHC: 4 primary IPs



and

30 long-range collisions per IP



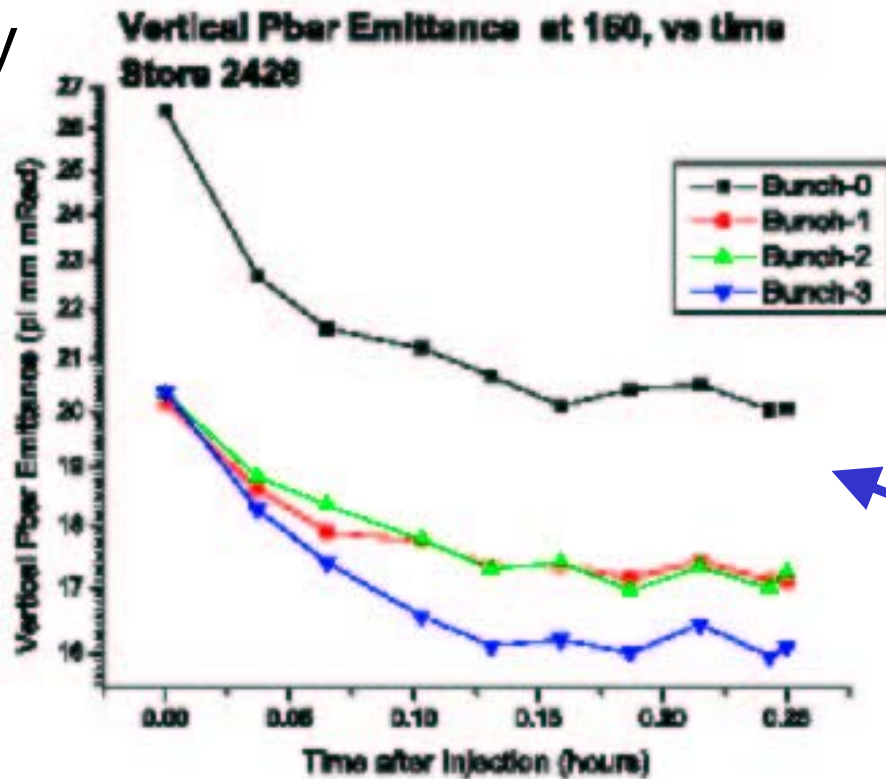
120 in total

partial mitigation by alternating planes of crossing at IP1 & 5 etc.

experience from Tevatron Run-II

“long-range beam-beam interactions in Run II at the Tevatron are the dominant sources of beam loss and lifetime limitations of anti-protons ...” (T. Sen, PAC2003)

ϵ_y



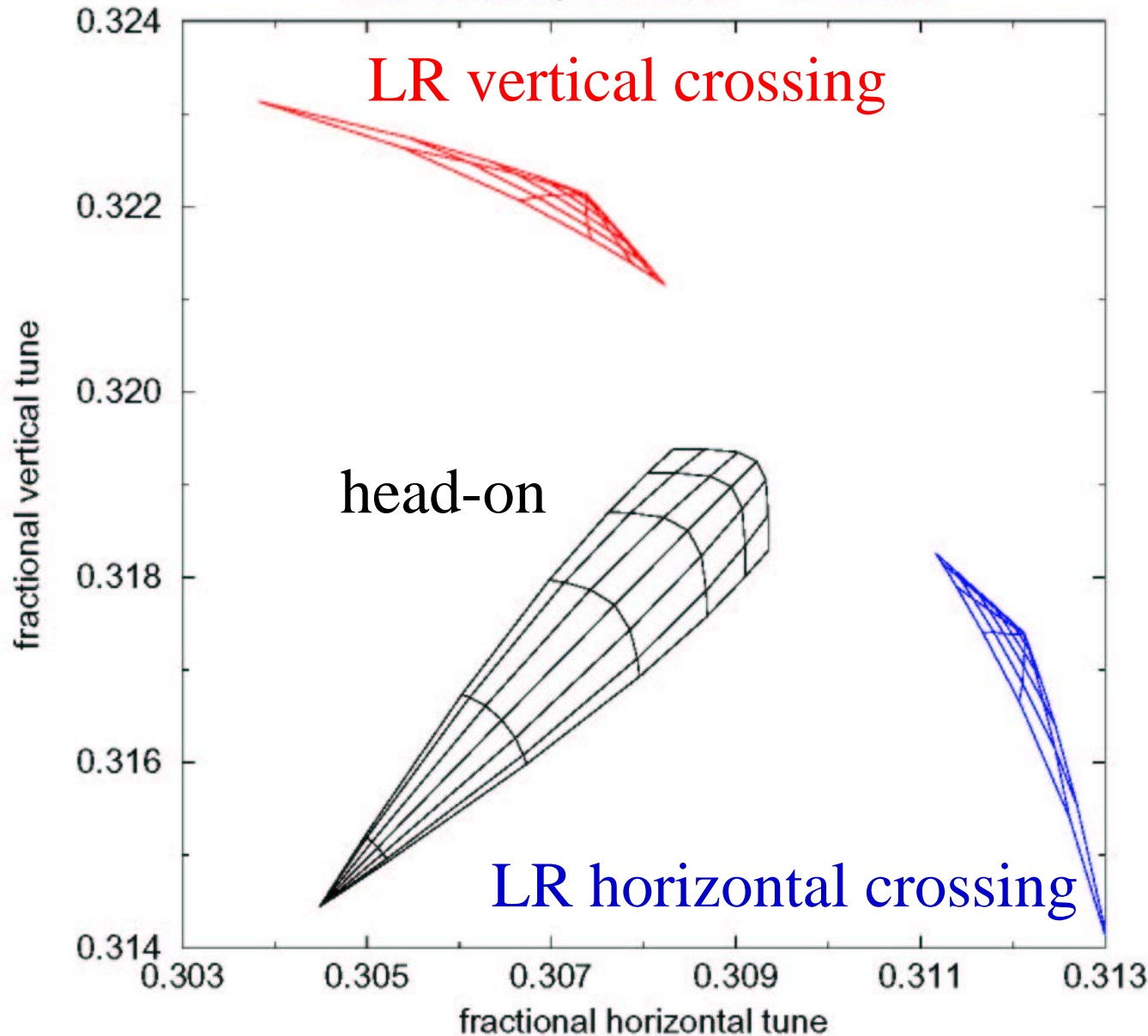
time

LR collisions reduce the dynamic aperture by about 3σ to a value of $3-4\sigma$; little correlation between tune footprint and dynamic aperture

drop in ϵ_y for first 4 pbar bunches after injection; asymptotic emittance is measure of their dynamic aperture

LHC collision, IP1 and IP5 only

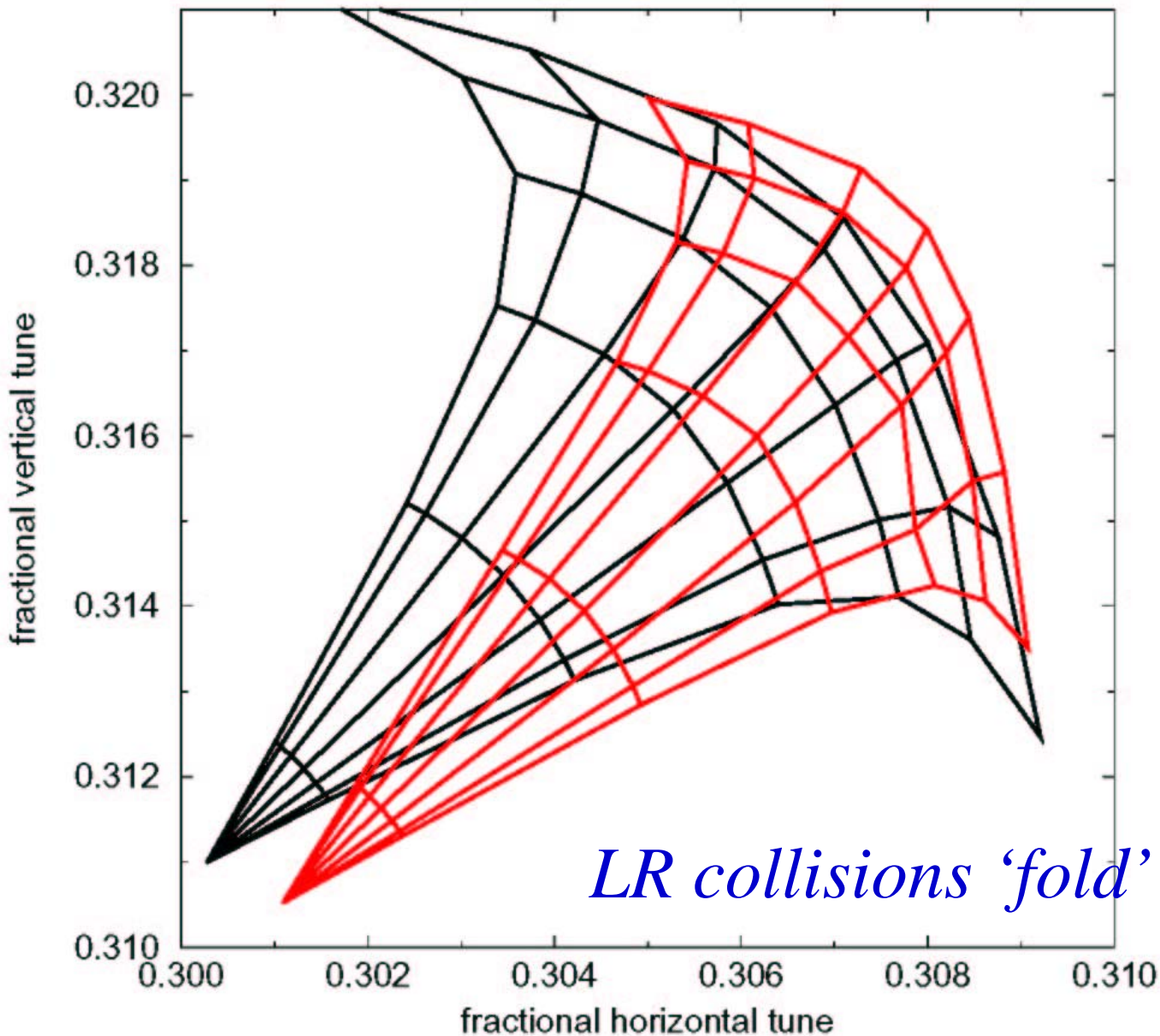
head-on and parasitic at ± 150 μ rad



LHC tune
“footprint”
due to
head-on &
long-range
collisions
in IP1 & IP5
(Courtesy
H. Grote)

LHC nominal collision

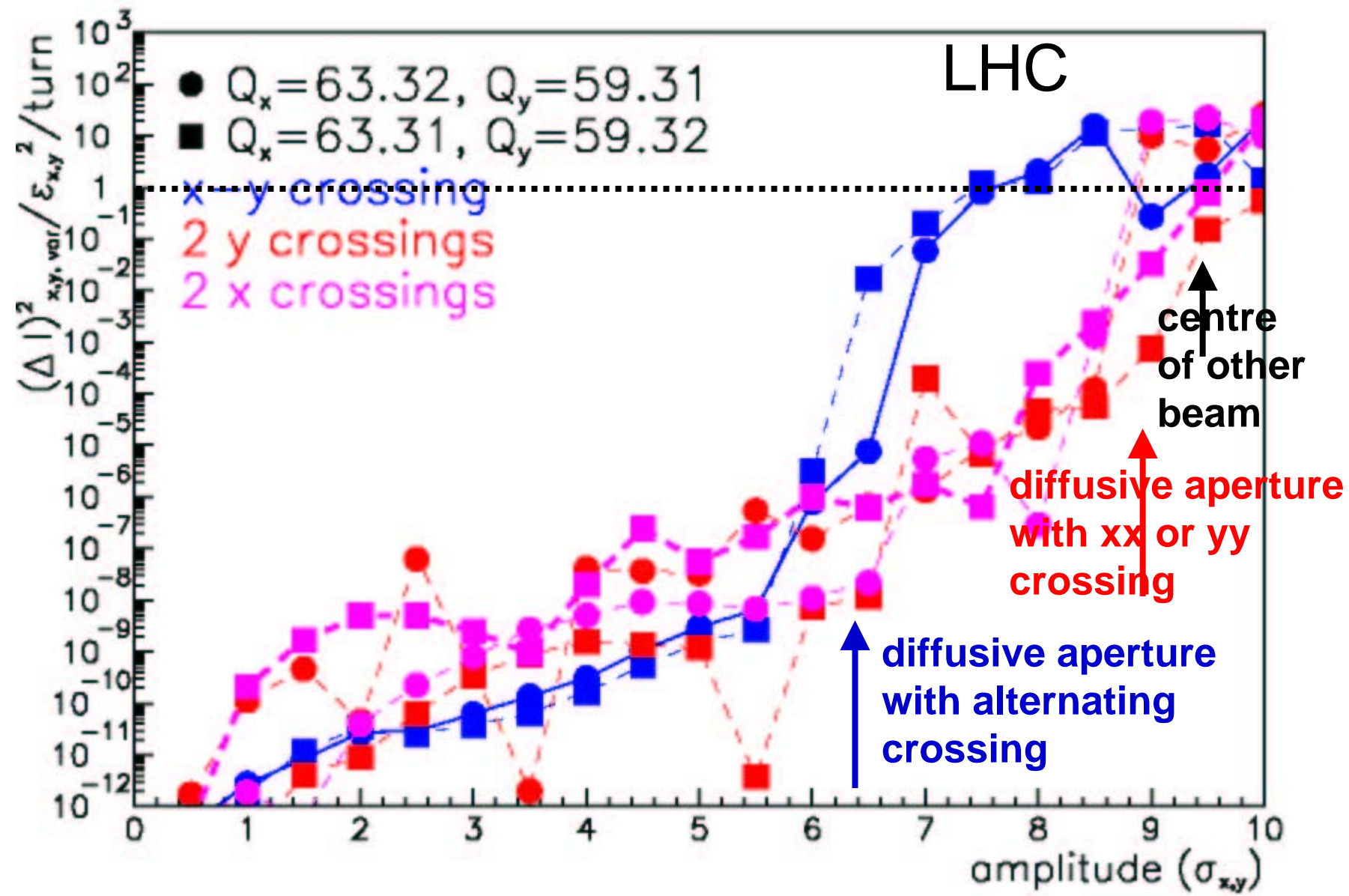
± 150 μ rad, with and without pacman



total LHC
tune
“footprint”
for regular
and
“PACMAN”
bunch
(Courtesy
H. Grote)

LR collisions ‘fold’ the footprint!

diffusion rate (log scale) as a function of amplitude



comparing xy, xx and yy crossing for two working points

long-range collisions

long-range tune shift

head-on beam-beam tune shift

$$\xi_{HO} = \pm \frac{r_p N_b \beta^*}{4\pi\gamma\sigma^2}$$

$$\xi_{LR} = \pm 2n_{LR}\xi_{HO} \frac{1}{d^2}$$

$$d = \frac{\theta}{\sqrt{\beta_x^*/(\gamma\varepsilon)}} \quad \tilde{x} = x/\sqrt{\beta_x}$$
$$x' = (\alpha_x x + \beta_x x')/\sqrt{\beta_x}$$

$$\text{LHC: } \xi_{LR} \approx 0.33\xi_{HO}$$

Hamiltonian for horizontal crossing

$$H_{LR} = 2\pi\xi_{LR}d^2 \ln \left[\left(1 + \frac{\tilde{x}}{d} \right)^2 + \left(\frac{\tilde{y}}{d} \right)^2 \right]$$

$$\Delta\tilde{x}' \approx -4\pi\xi_{LR} \left(d - \tilde{x} + \frac{\tilde{x}^2}{d} - \frac{\tilde{y}^2}{d} + \dots \right), \quad \Delta\tilde{y}' \approx -4\pi\xi_{LR} \left(\tilde{y} - 2\frac{\tilde{x}\tilde{y}}{d} + \dots \right)$$

horizontal crossing: horizontal dipole, quadrupole, sextupole,...

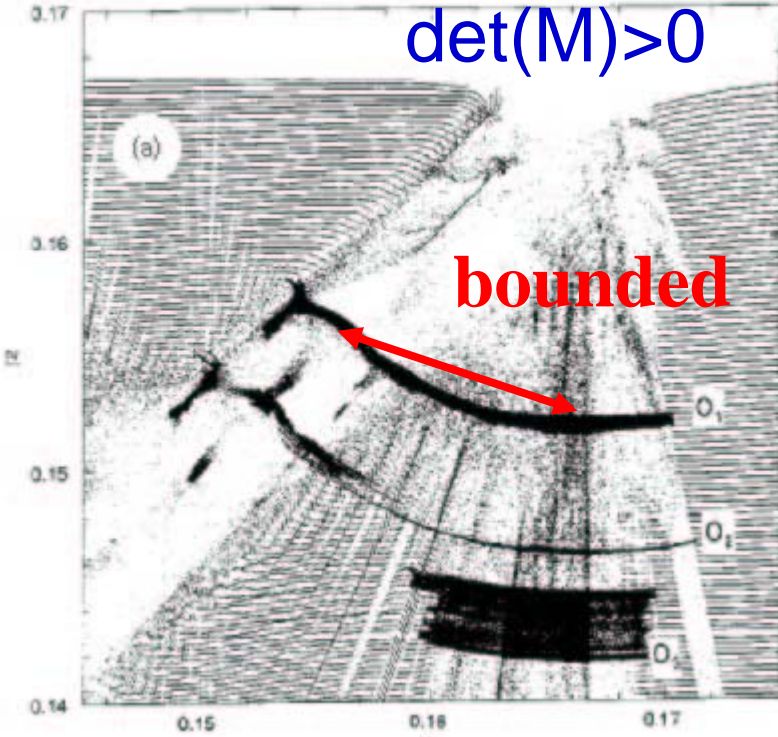
vertical crossing: vertical dipole, quadrupole, skew sextupole,...

alternating crossing: less tune spread, but more resonances

a1 = -1.21; a2 = -1.01; b = 0.01

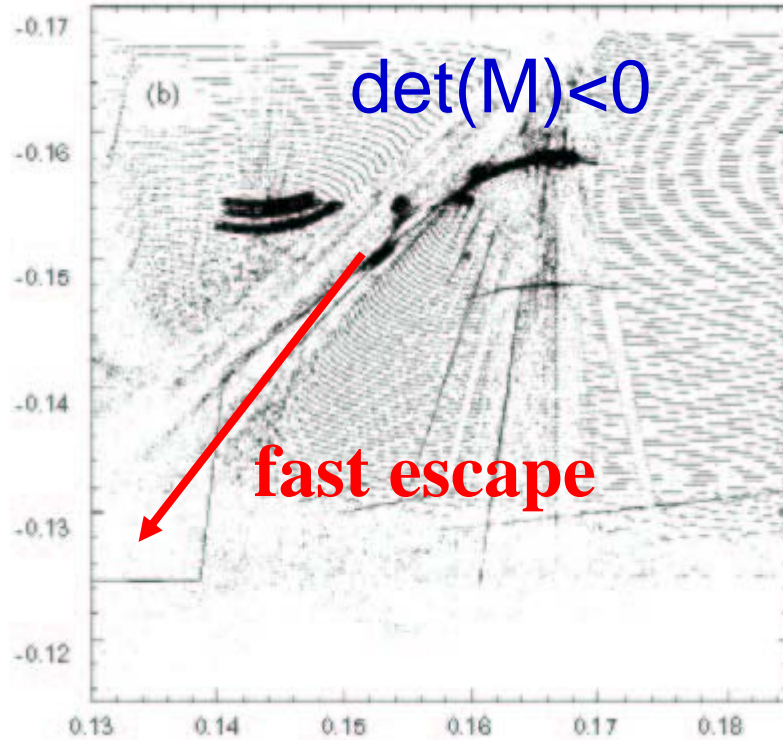
$\det(M) > 0$

bounded



$\det(M) < 0$

fast escape



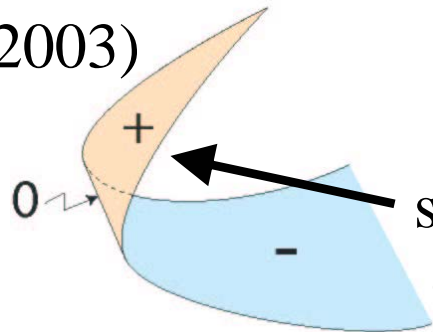
model
system

$$M = \begin{pmatrix} \frac{\partial Q_{x,y}}{\partial I_{x,y}} \\ \frac{\partial^2 H}{\partial I_{x,y}^2} \end{pmatrix}$$

tune evolution for three trajectories **without folding**; the motion remains bounded

tune evolution for three trajectories **with folding**; the resonance 1:1 is a direction of fast escape

(J. Laskar, PAC2003)

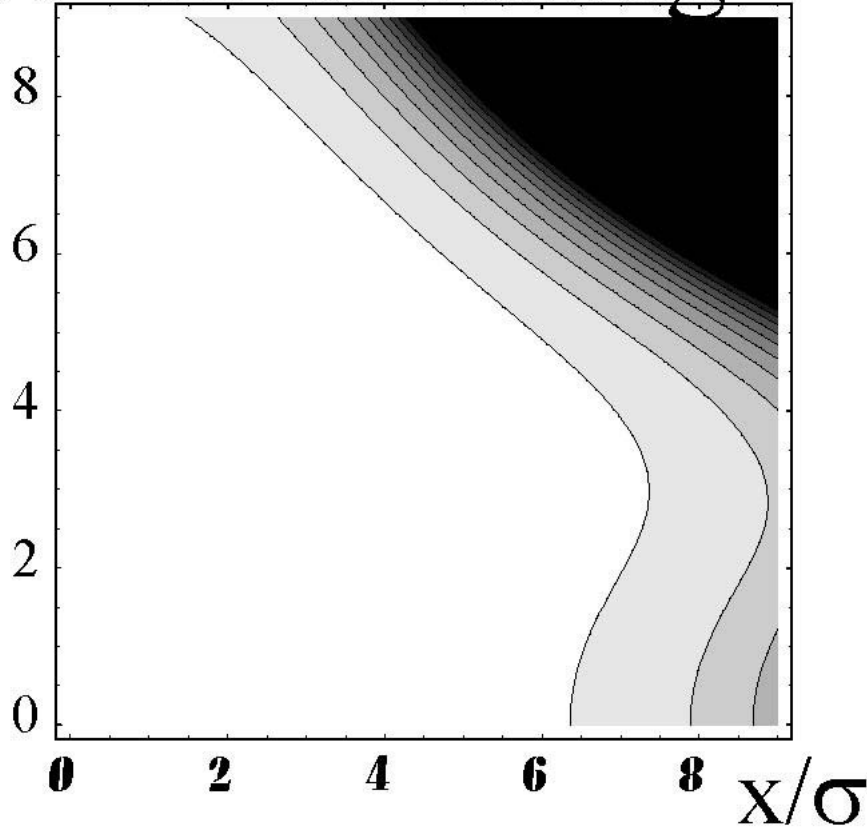


schematic of folded frequency map
(J. Laskar)

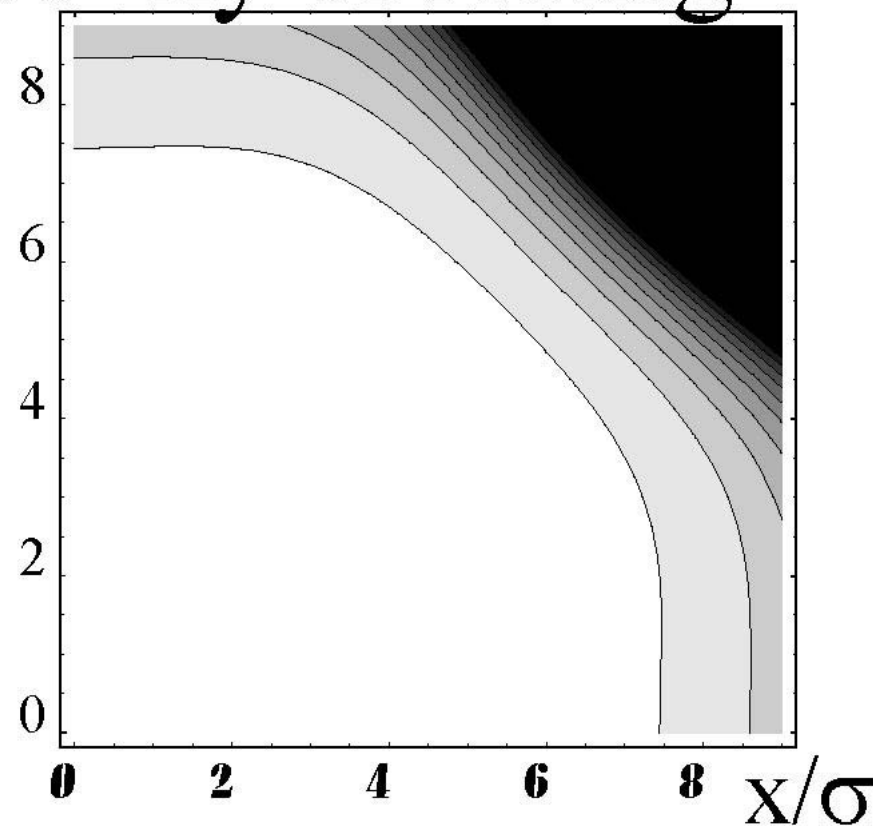
$$M = \begin{pmatrix} \frac{\partial Q_{x,y}}{\partial I_{x,y}} \\ \frac{\partial Q_{y,x}}{\partial I_{y,x}} \end{pmatrix} = \begin{pmatrix} \frac{\partial^2 H_{LR}}{\partial I_{x,y}^2} \\ \frac{\partial^2 H_{LR}}{\partial I_{y,x}^2} \end{pmatrix}$$

for $\det(M) < 0$: system inherently unstable

y/σ **XX crossing**



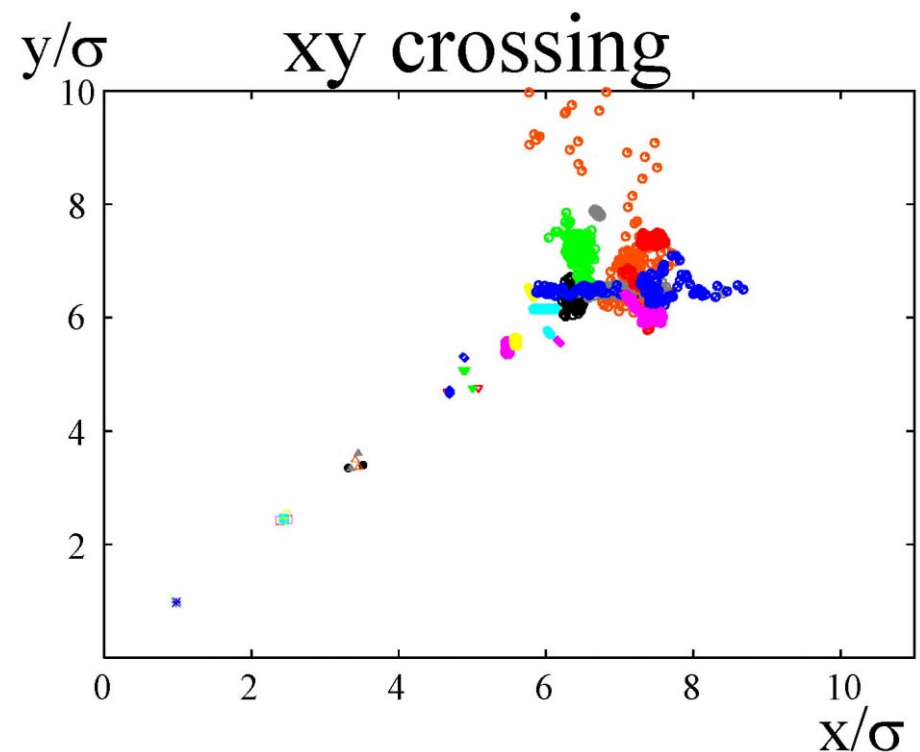
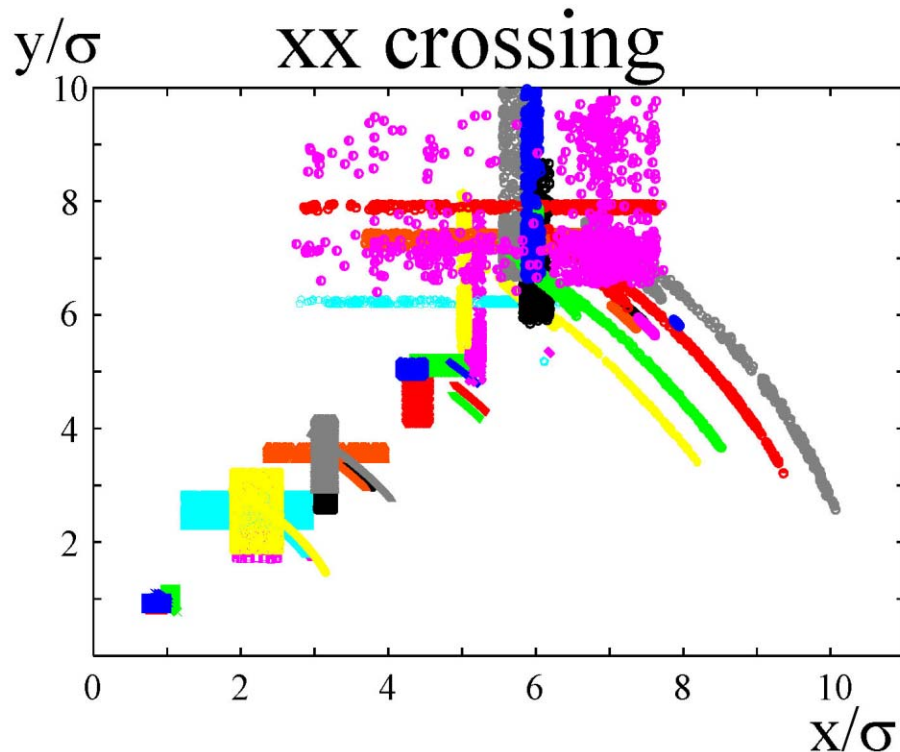
y/σ **XY crossing**



contour plot of $\det(M)$; **determinant is negative for all amplitudes**; darker areas signify larger negative values

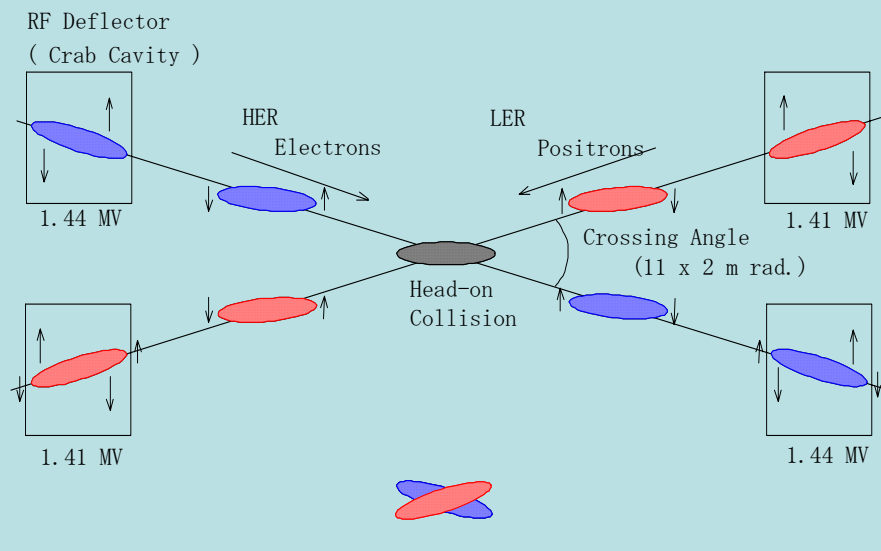
*nonlinear ‘coupling’ between the planes? but **stable***

*little motion at small amplitudes but **particle loss at 6 σ***



sample trajectories projected on amplitude plane

tune spread gives incomplete characterization of the dynamics;
experimental simulations of the two crossing schemes will be compared at the SPS



Crab Cavity

R. Palmer, 1988
K. Oide, K. Yokoya

combines all advantages of head-on collision and crossing angle

KEK



Crab Cavity Group

$$V_{crab} = \frac{cE_b \tan(\theta_c / 2)}{e\omega_{rf} \sqrt{\beta^* \beta_{crab}}}$$

$$\Delta\phi_{crab} \leq \frac{\Delta x_{max} 2\pi}{\lambda_{rf} \theta_c}$$

variable	symbol	KEKB	SuperLHC
beam energy	E_b	8 GeV	7 TeV
rf frequency	f_{crab}	508 MHz	1.3 GHz
crossing angle	Θ_c	11 mrad	8 mrad
IP β	β^*	0.33 m	0.25 m
cavity β	β_{cav}	100 m	2 km
kick voltage	V_{crab}	1.44 MV	46 MV
phase tolerance	$\Delta\phi$		0.06 mrad

historical attempts of beam-beam 'simulation' & compensation

- 4-beam collisions at DCI ~1970 charge neutralization; limited by collective instabilities (J. Augustin et al., Y. Derbenev)
- nonlinear lens at ISR, 1975 'simulation' of head-on collision, copper bars with 1000 A current (E. Keil, G. Leroy)
- octupoles compensating BB tune spread for LEP, 1982 (S. Myers)
- octupoles at VEPP-4/-2M & DAΦNE, 1986, 2001 (A. Temnykh, M. Zobov)
- plasma compensation for linear & muon colliders, 1988 (D. Whittum, A. Sessler et al.)
- Tevatron Electron Lens, FNAL, operational since 2001 compensating intra-&inter-bunch tune spread (E. Tsyganov, 1993
V. Shiltsev, 1998)

INCREASE OF THE BEAM-BEAM LIMIT BY COMPENSATION
OF THE BEAM-BEAM TUNE DEPENDENCE ON AMPLITUDE

S. Myers

Conclusions

Compensation of the vertical tune dependence on amplitude brings about a significant increase in the beam-beam limit for LEP. Unfortunately the use of magnetic octupoles to provide such compensation seems excluded due to the large required integrated field strength.

(Courtesy A. Verdier)

Fermilab Tevatron Electron Lens

V. Shiltsev



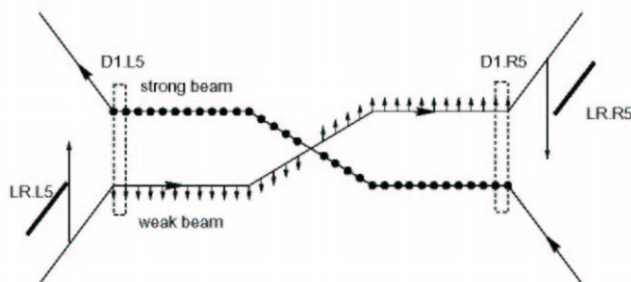
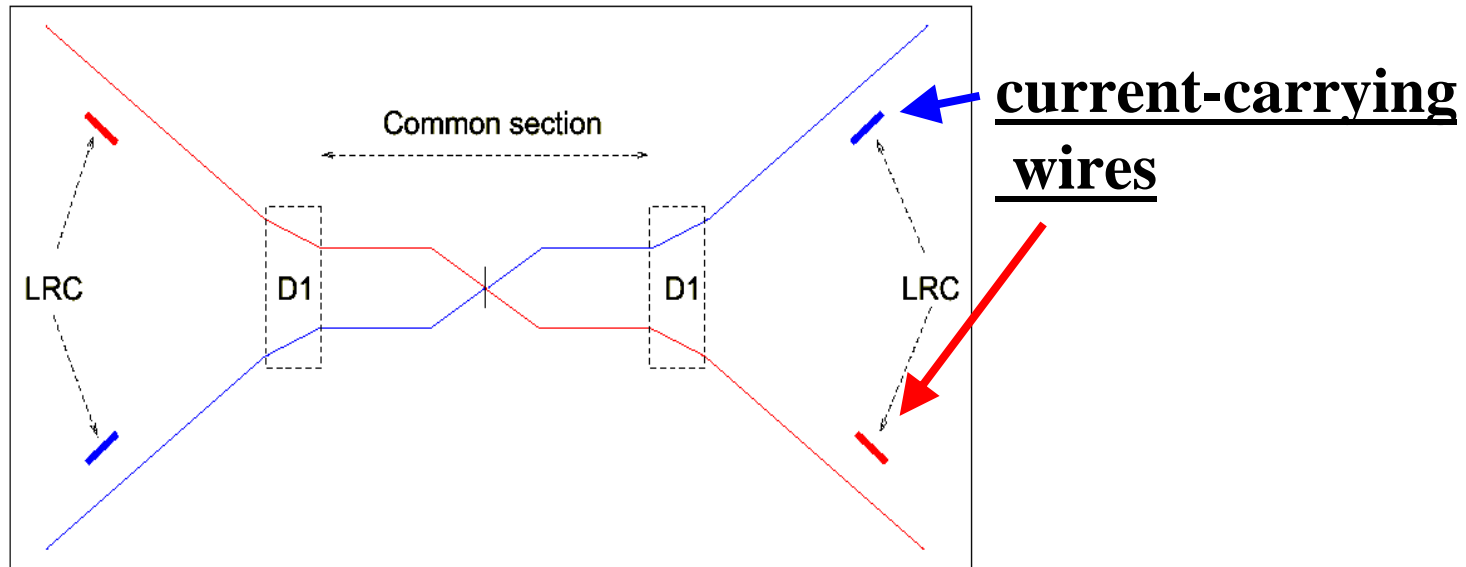
designed
to compensate
beam-beam
tune shift
of pbars

current: ~ 1 A
solenoid field:
3.5 T
rms radius:
0.66 mm
length: 2 m

in operation
since 2001

Long-Range Beam-Beam Compensation for the LHC

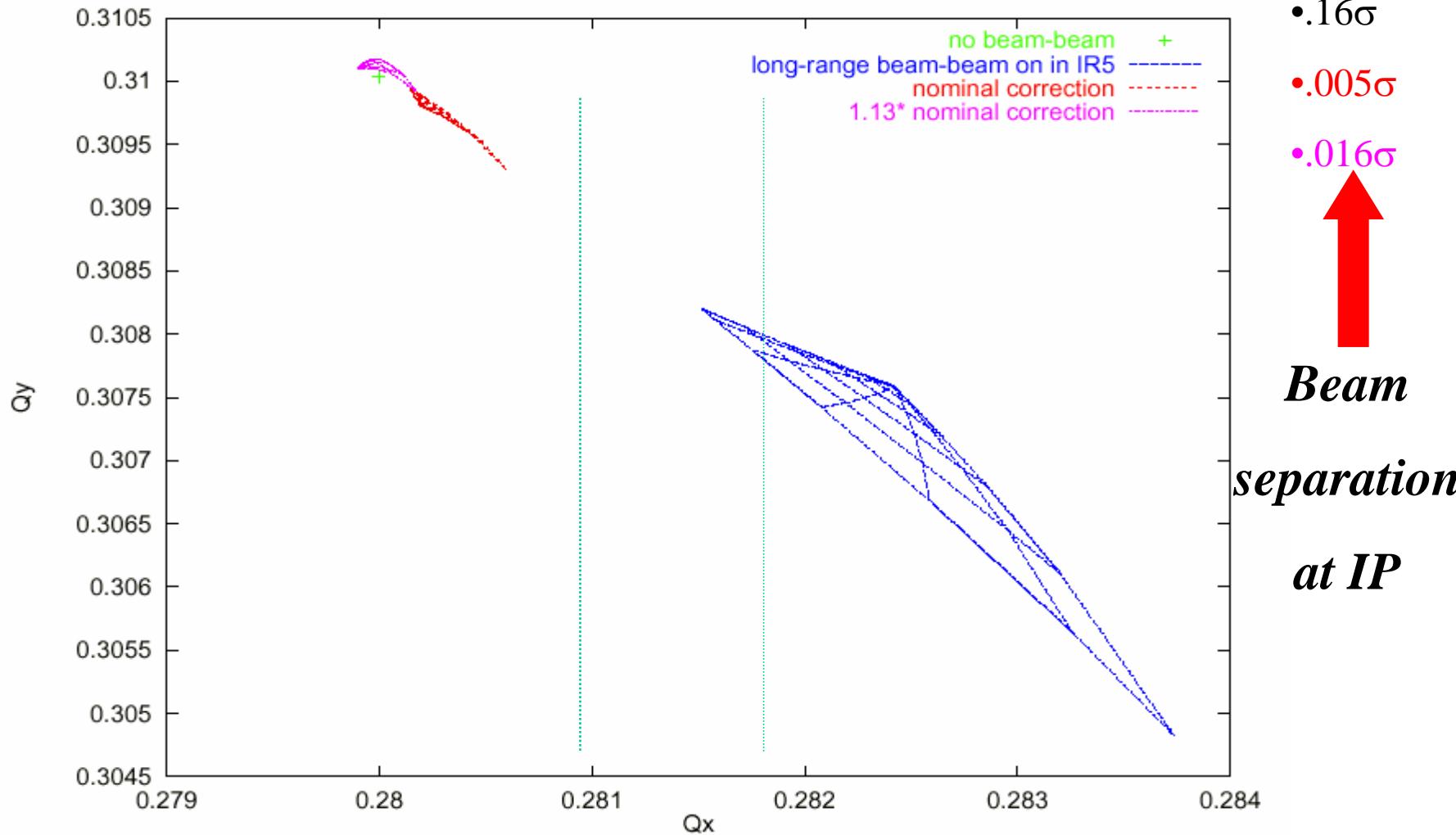
- To correct **all** non-linear effects correction must be local.
- Layout: 41 m upstream of D2, both sides of IP1/IP5



Phase difference between BBLRC & average LR collision is 2.6°

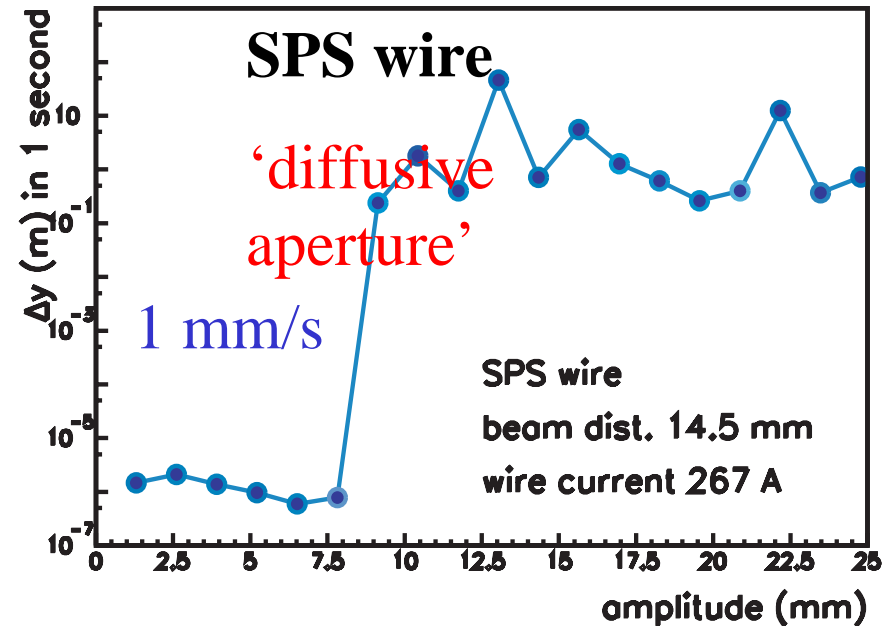
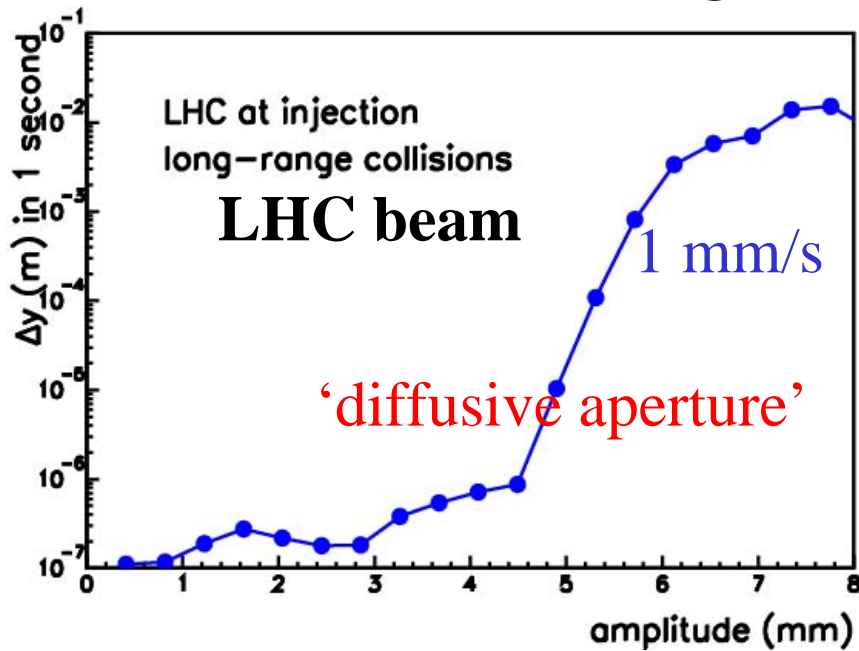
(Jean-Pierre Koutchouk)

simulated LHC tune footprint with & w/o wire correction



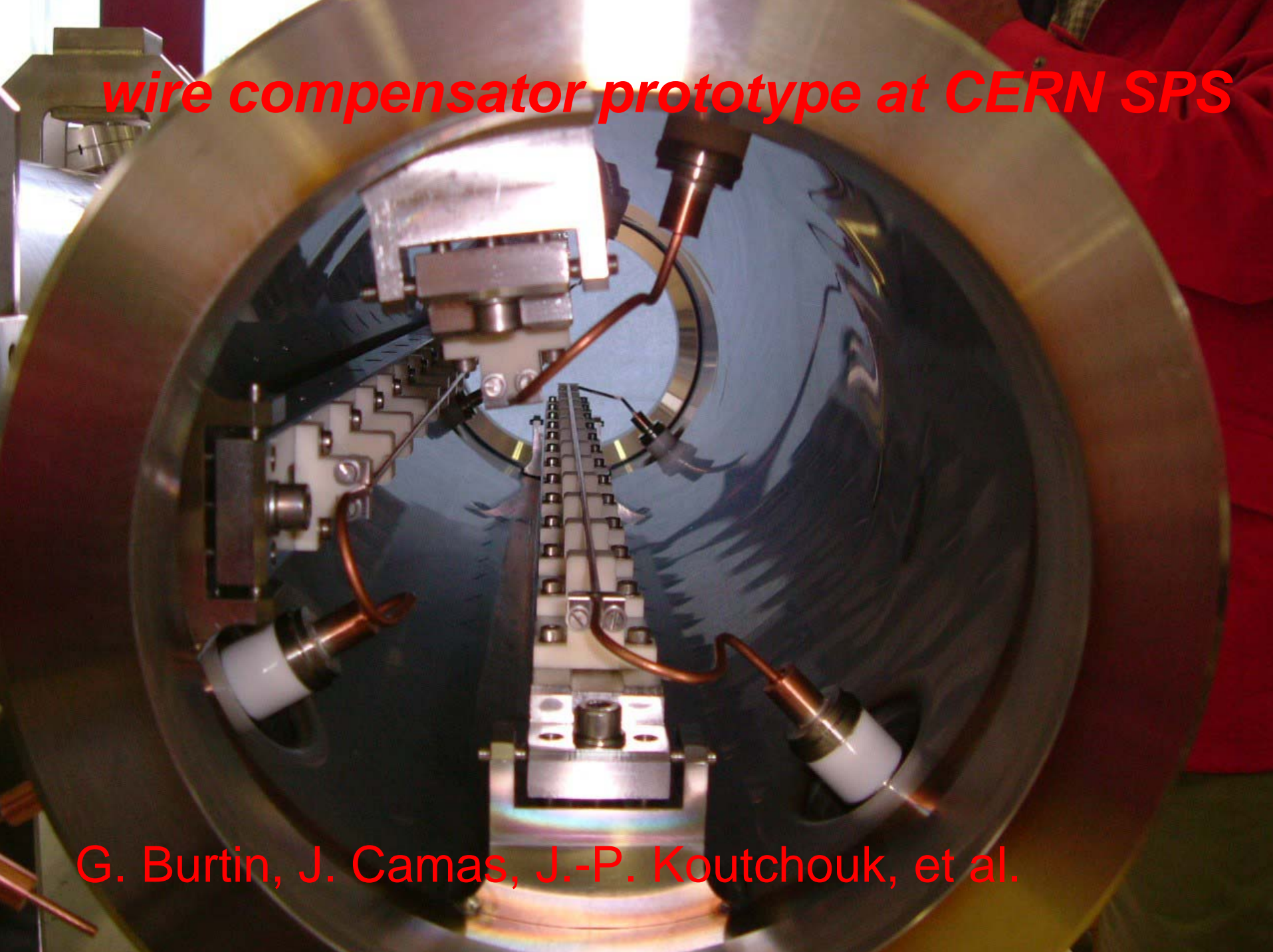
(Jean-Pierre Koutchouk, LHC Project Note 223, 2000)

in simulations LHC long-range collisions & SPS wire cause similar fast losses at large amplitudes



effect of the 1-m long wire at 9.5σ from the beam center, carrying 267 A current, in the SPS resembles 60 long-range collisions in the LHC

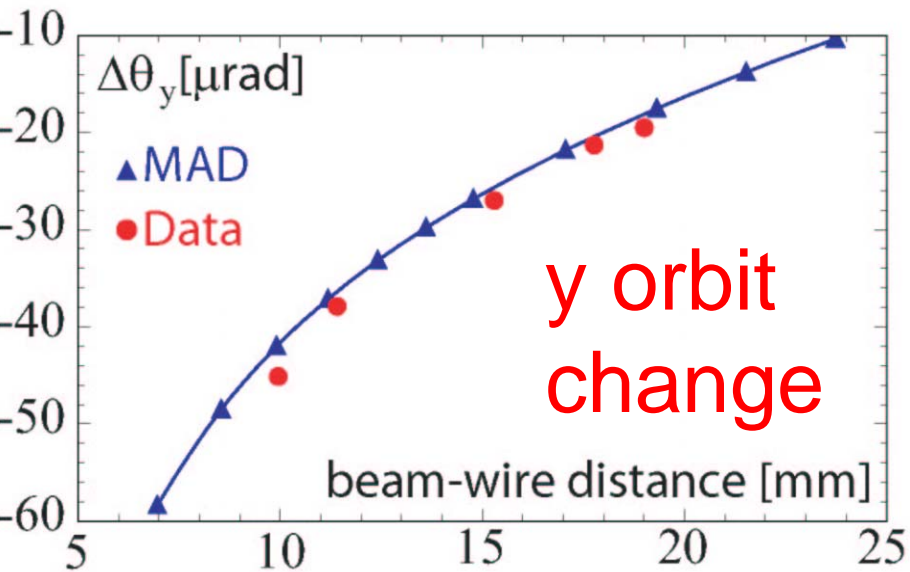
wire compensator prototype at CERN SPS



G. Burtin, J. Camas, J.-P. Koutchouk, et al.

measured vs. predicted changes in orbit & tunes induced by SPS beam-beam compensator

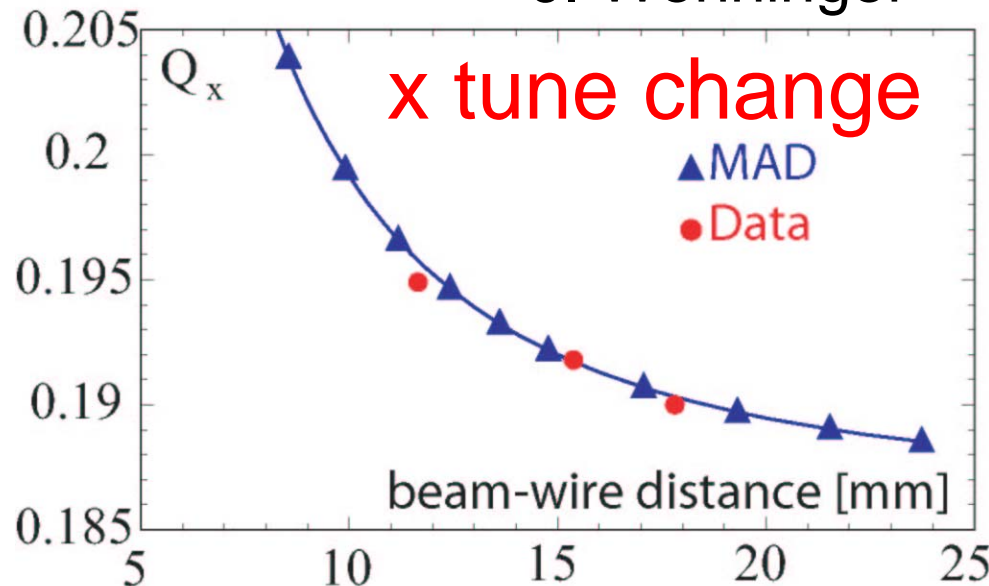
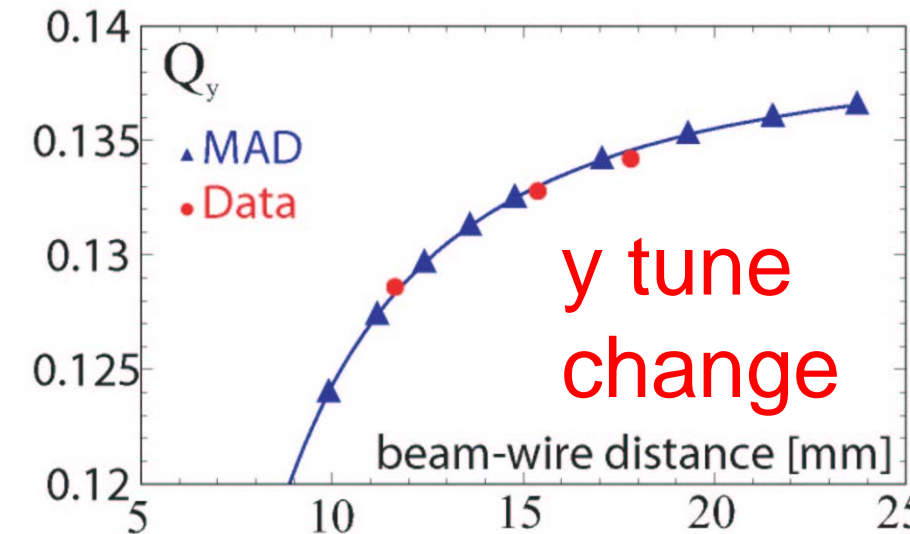
WEPLT045



$$\Delta d = \frac{\beta_y I_w l_w r_p}{\gamma e c (d + \Delta d) \tan(\pi(Q_y + \Delta Q_y))}$$

$$\Delta Q_{x,y} = \mp \frac{r_p \beta_{x,y} I_w l_w}{2\pi \gamma e c} \frac{1}{(d + \Delta d)^2}$$

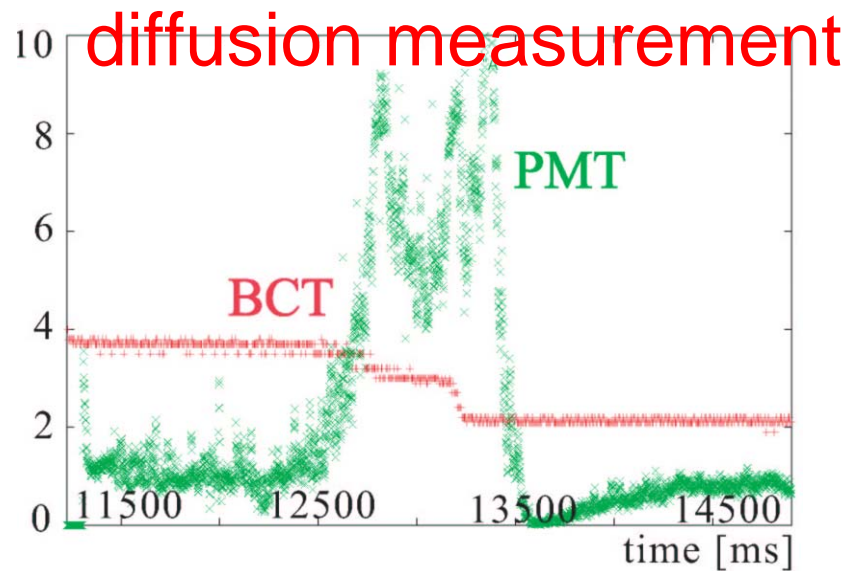
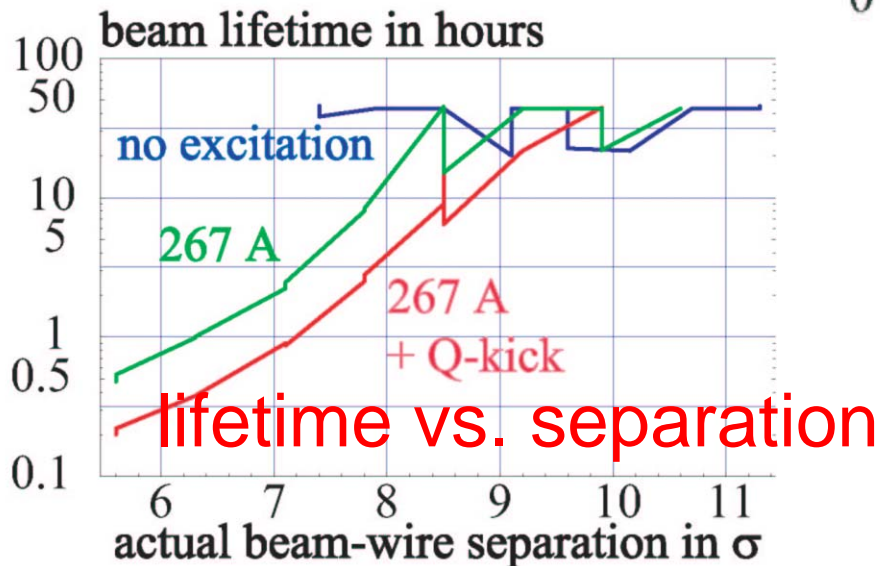
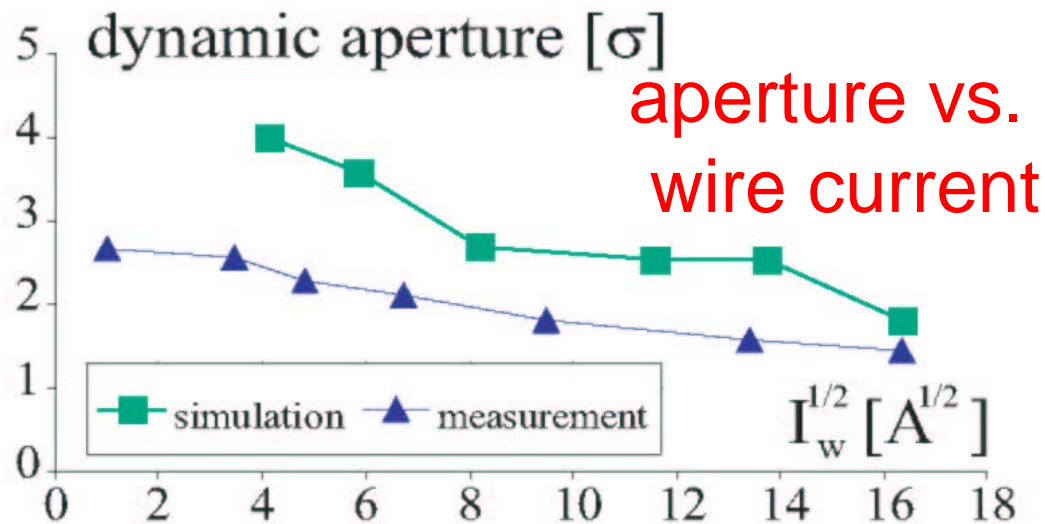
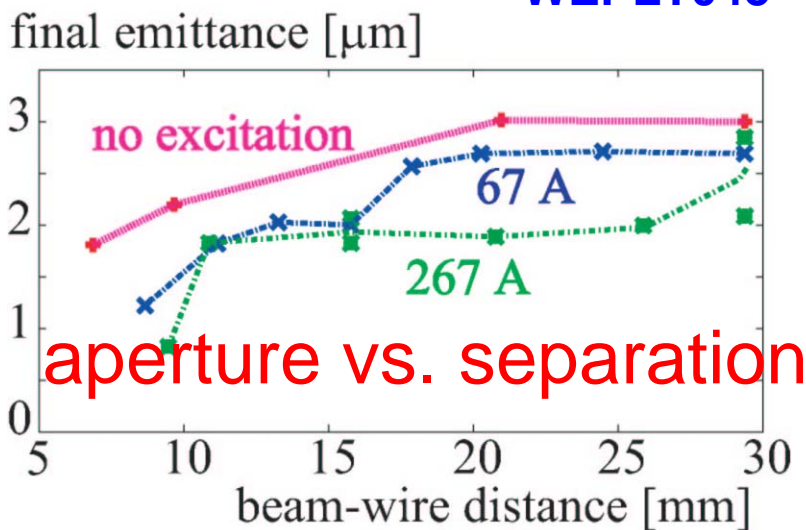
J. Wenninger



emittance shrinkage , dynamic aperture, lifetime drop & diffusion induced by SPS beam-beam compensator

WEPLT045

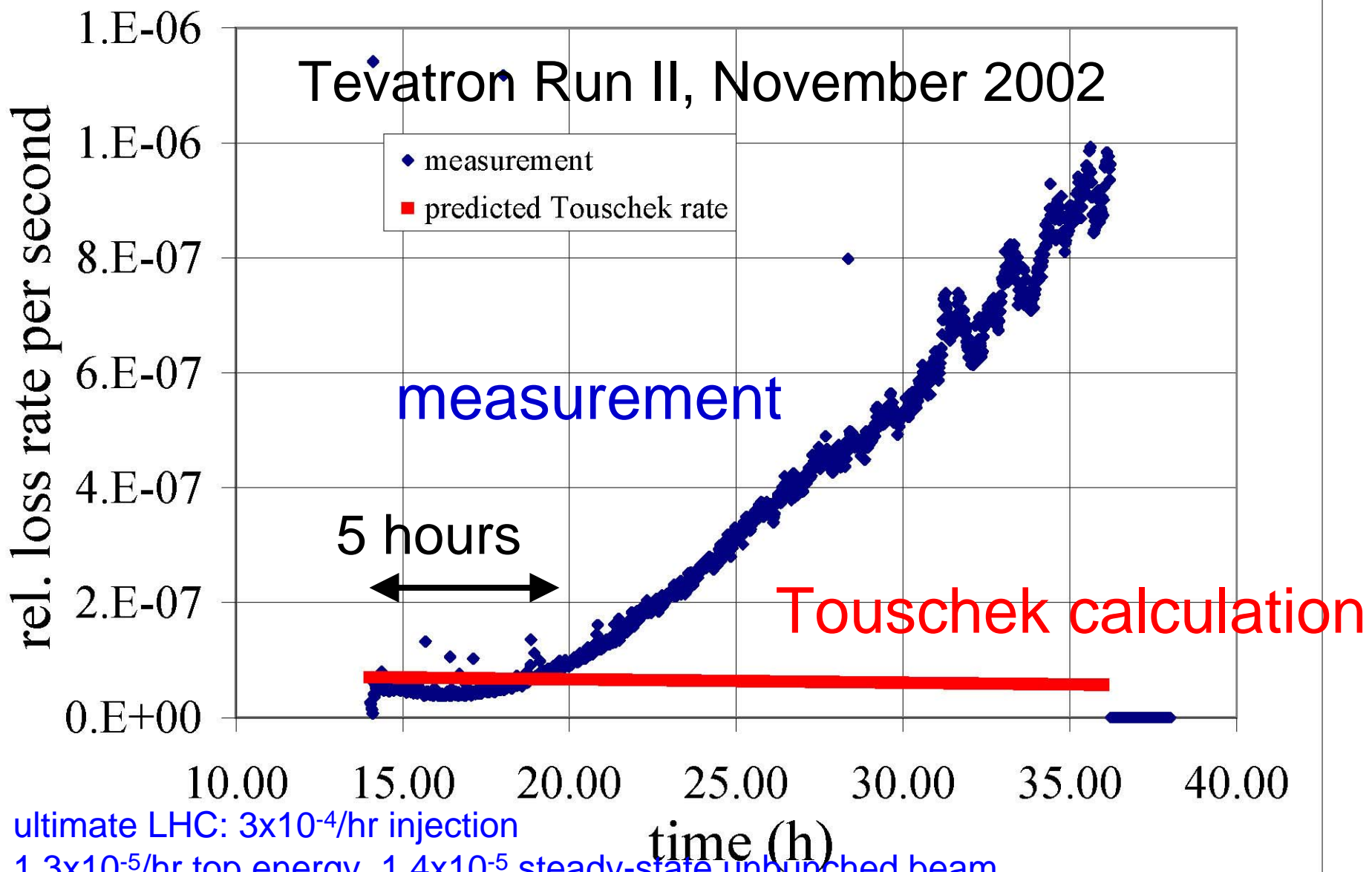
J. Wenninger, J.-P. Koutchouk, et al.



Touschek
&
intrabeam scattering

$$N_{unb} = \frac{\alpha N_0^2 t}{1 + \alpha N_0 t} \quad \alpha_{rd} = \frac{\pi r_0^2 c \beta^2}{\gamma^4 \sigma^2 V \eta} D\left(\frac{\eta}{\delta q}\right) \quad V = 8\pi^{3/2} \sigma^2 \sigma_z \quad \eta \equiv \left(\frac{\Delta E}{E}\right)_{\max} \quad \delta q \equiv \frac{\gamma \sigma_x}{\beta_x}$$

for $\varepsilon > 20 : D(\varepsilon) \approx e^{-6-\varepsilon}$



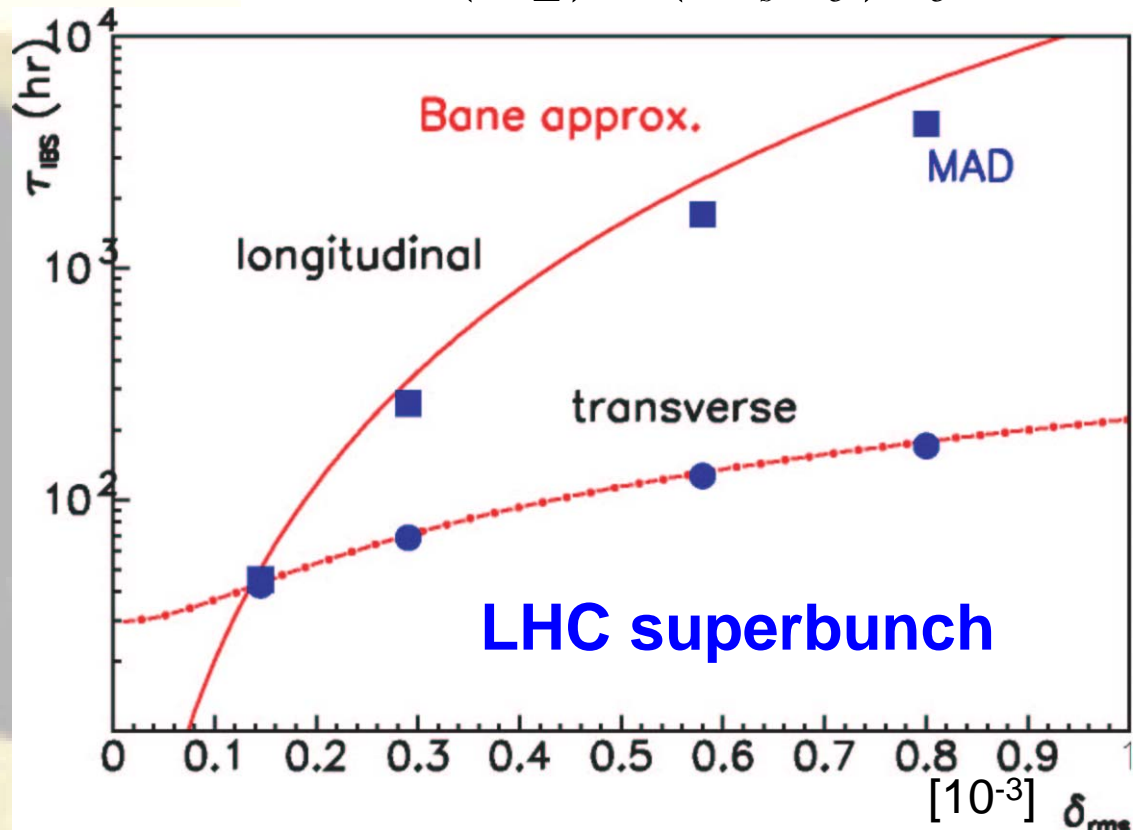
intrabeam scattering (IBS)

approximate IBS formulae developed by K. Bane (further simplified) [SLAC-PUB-9226 (2002)]

$$D_x \sigma_\delta < \sqrt{\beta_x \varepsilon_x} :$$

$$\frac{1}{T_\delta} = \frac{d\sigma_\delta}{dt} \approx \frac{r_p^2 c N_b \log}{16 \gamma (\gamma \varepsilon_\perp)^{3/2} (\gamma \sigma_s \sigma_\delta) \sigma_\delta \beta^{1/2}}$$

$$\frac{1}{T_x} \approx \frac{\sigma_\delta^2 D_x^2}{\beta_x \varepsilon_\perp} \frac{1}{T_\delta}$$



if increased momentum spread requires **larger energy bandwidth** of low-beta optics
adapt **Raimondi-Seryi final focus** to hadron collider
[Phys.Rev.Lett.86:3779-3782,2001]

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Novel Final Focus Design for Future Linear Colliders

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(Received 25 May 2000)

The length, complexity, and cost of the present final focus designs for linear colliders grow very quickly with the beam energy. In this Letter, a novel final focus system is presented and compared with the one proposed for the Next Linear Collider (NLC Zeroth-Order Design Report, edited by T. O. Raubenheimer, SLAC Report No. 474, 1996). This new design has fewer optical elements and is much shorter, nonetheless achieving better chromatic properties. Moreover, the new system is more suitable for operation over a larger energy range.

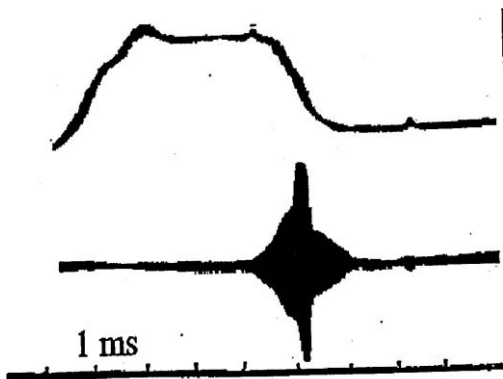
local chromatic correction

dispersion across the low-beta quadrupoles

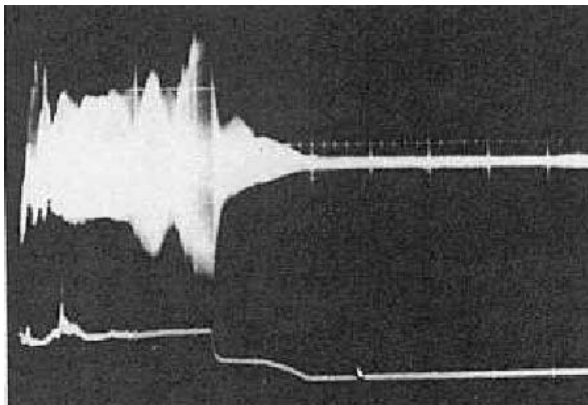
tested for ring μ -collider (CERN SL Note 2001-20)

electron cloud

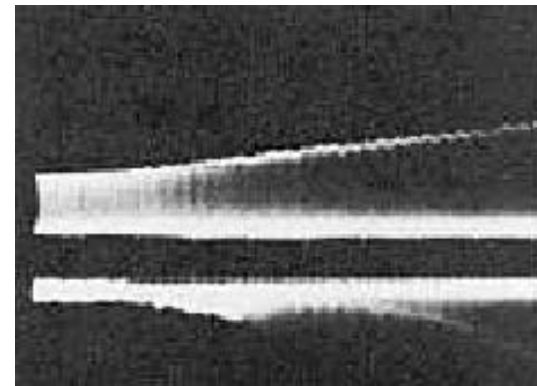
INP Novosibirsk, 1965



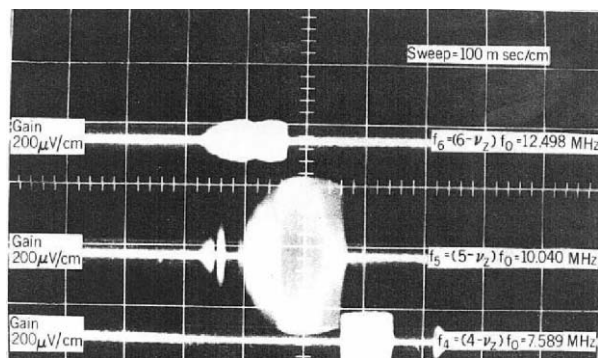
Argonne ZGS, 1965



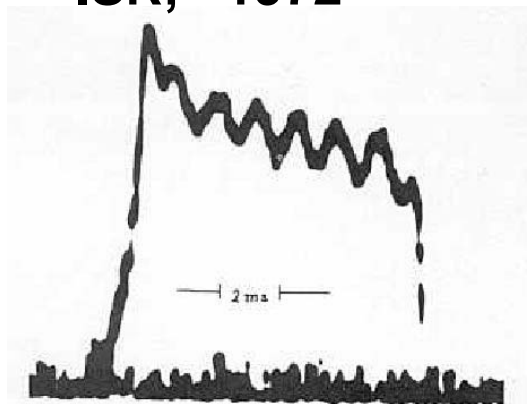
BNL AGS, 1965



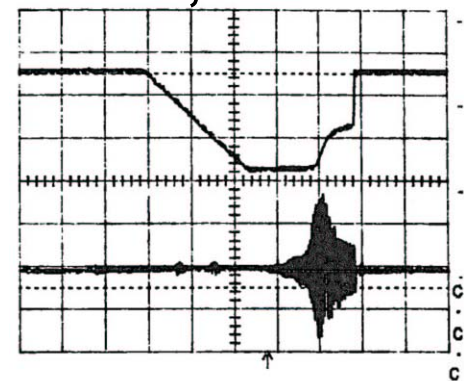
Bevatron, 1971



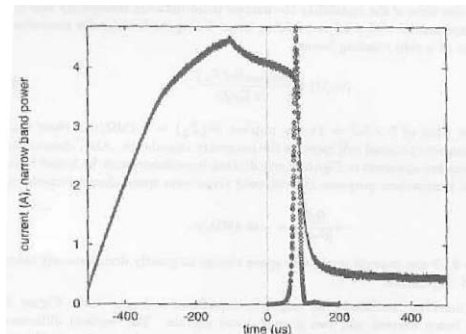
ISR, ~1972



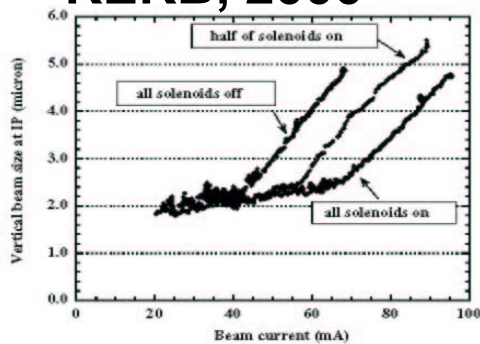
PSR, 1988



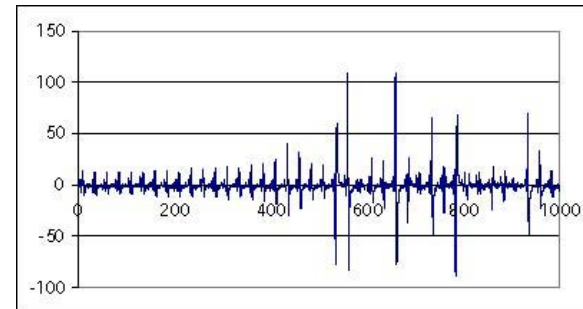
AGS Booster, 1998/99



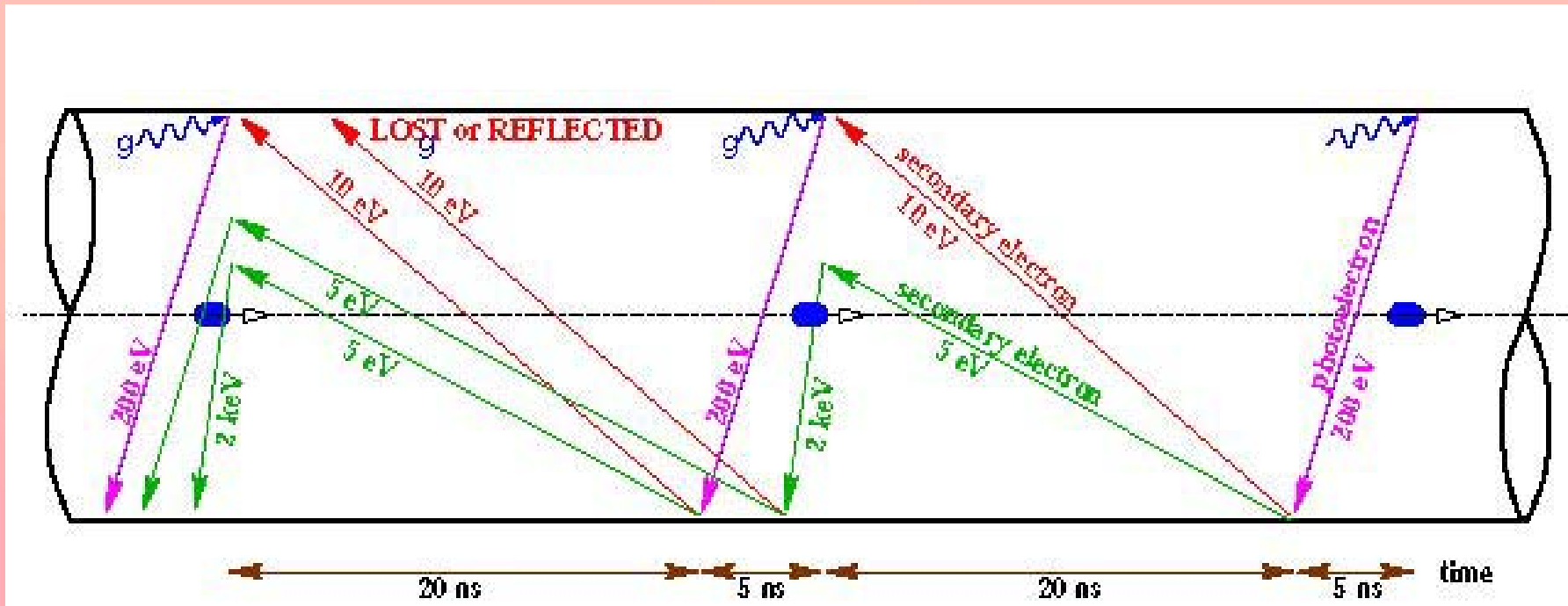
KEKB, 2000



CERN SPS, 2000



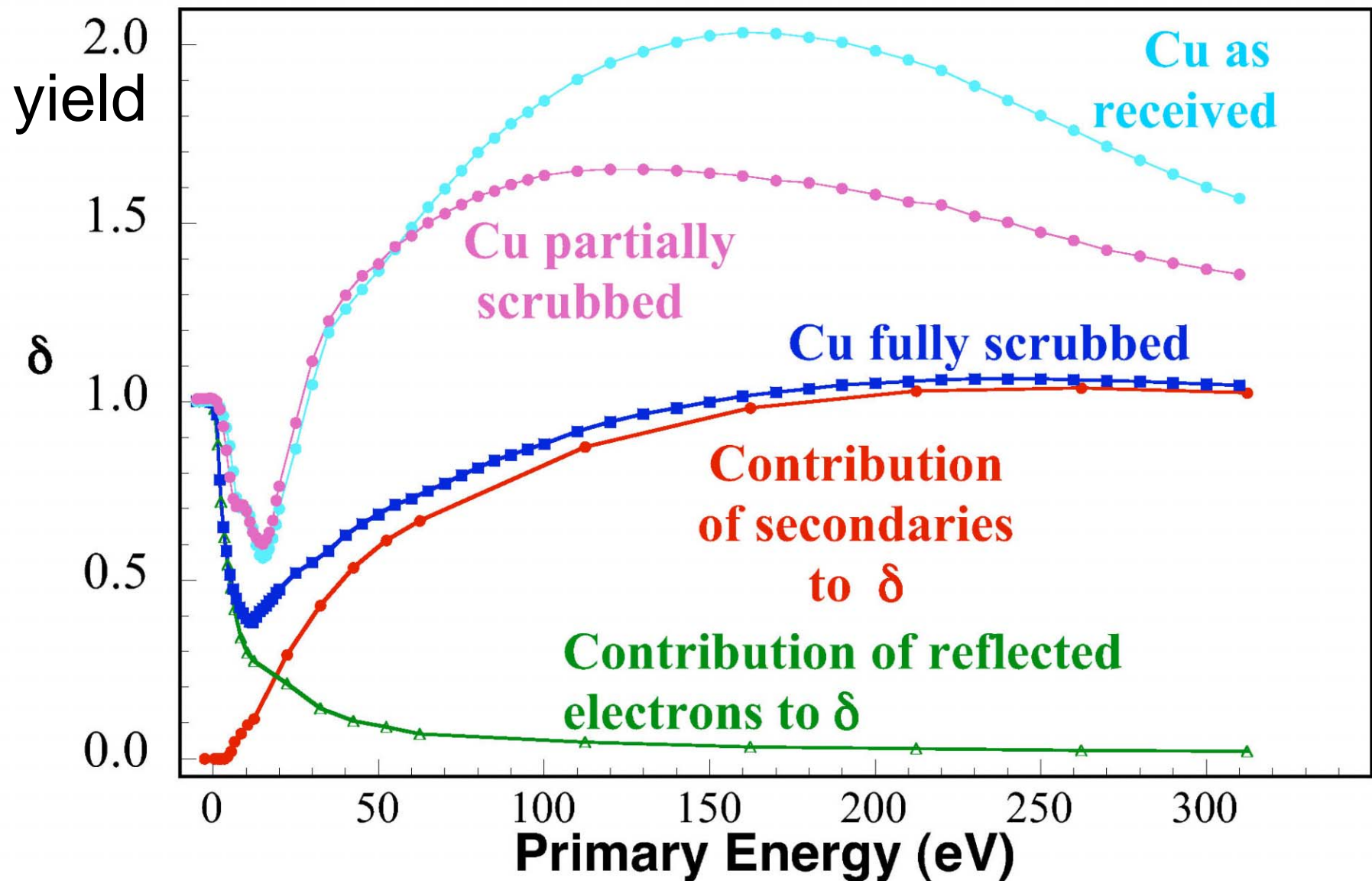
electron cloud in the LHC



schematic of e- cloud build up in the arc beam pipe,
due to **photoemission** and **secondary emission**

[F. Ruggiero]

in the background: simulation of bunch passing through e- plasma using the

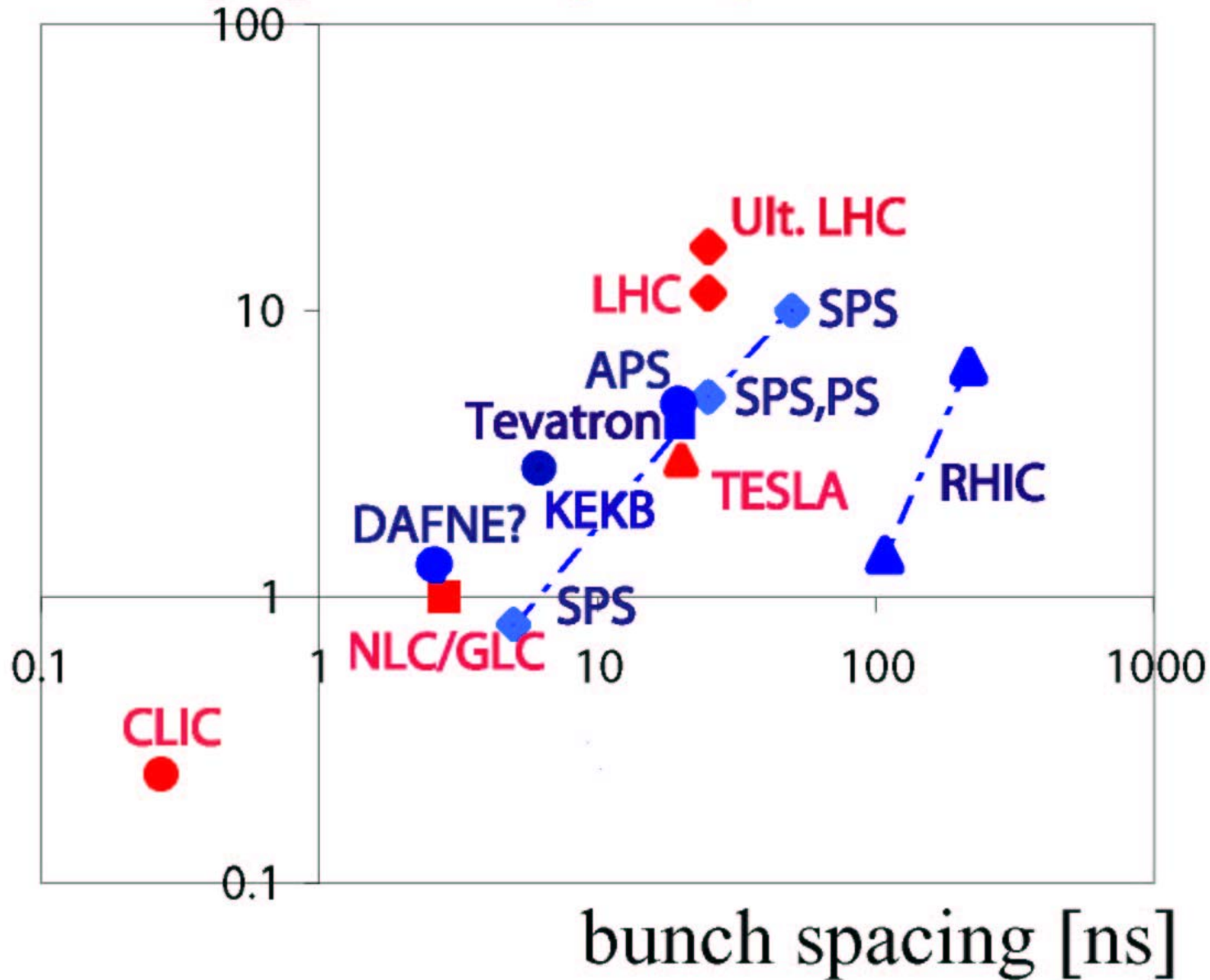


probability of elastic electron reflection approaches 1 for zero incident energy and is independent of δ_{max}^*

blue: e-cloud effect observed

red: planned accelerators

bunch population [10^{10}]



multitude of countermeasures:

- multi-bunch & intrabunch feedback
(INP PSR, Bevatron, SPS, KEKB)
- clearing electrodes
(ISR, BEPC, SNS)
- antechamber (PEP-II)
- TiN coating (PEP-II, PSR, SNS)
- high Q' (SPS)
- octupoles (BEPC)
- solenoids (KEKB, PEP-II, SNS)
- grooved surfaces (NLC)

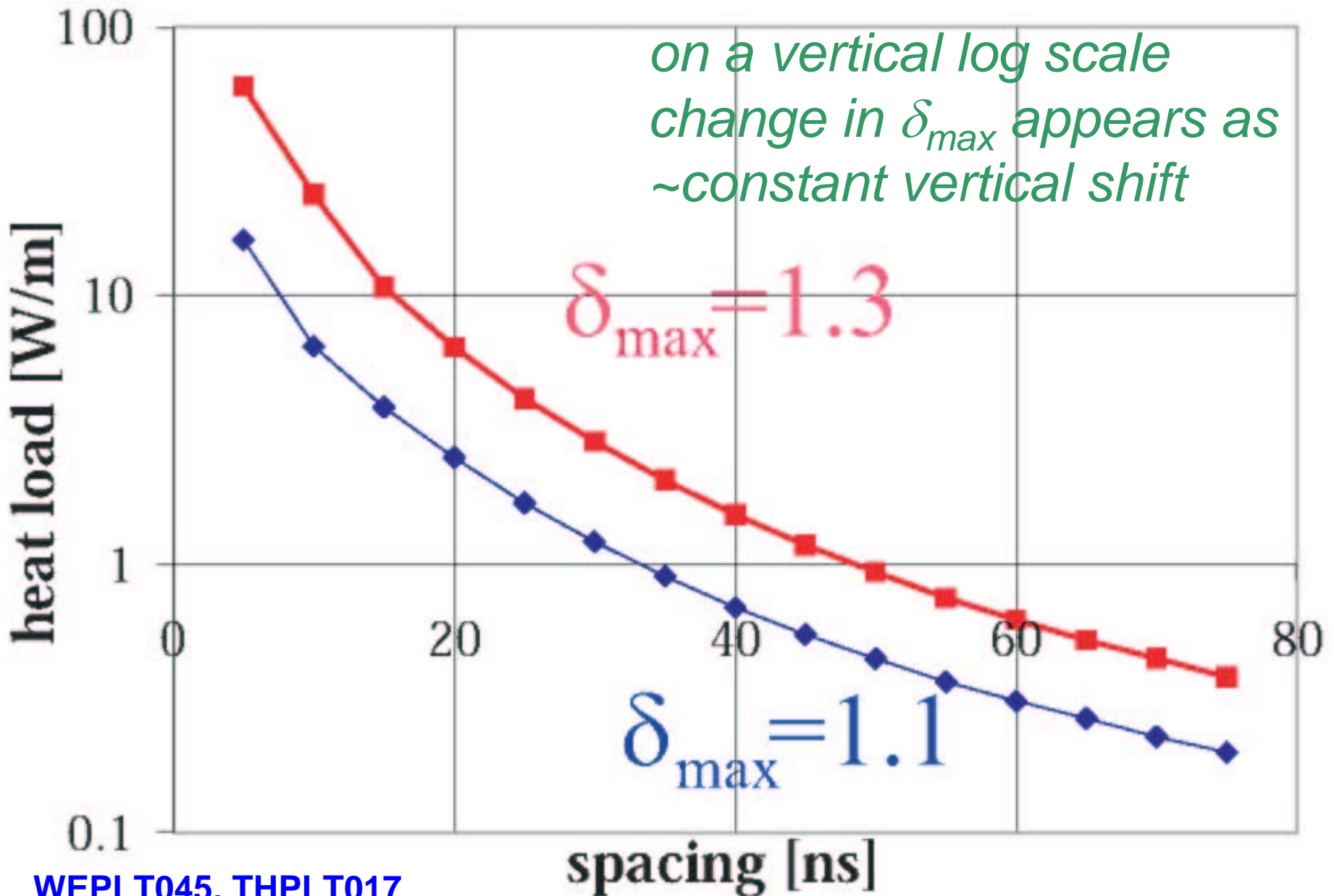
LHC strategy against electron cloud

- 1) warm sections (20% of circumference) coated by TiZrV getter developed at CERN; low secondary emission; if cloud occurs, ionization by electrons (high cross section ~ 400 Mbarn) aids in pumping & pressure will even improve
- 2) outer wall of beam screen (at 4-20 K, inside 1.9-K cold bore) will have a sawtooth surface ($30 \mu\text{m}$ over $500 \mu\text{m}$) to reduce photon reflectivity to $\sim 2\%$ so that photoelectrons are only emitted from outer wall & confined by dipole field
- 3) pumping slots in beam screen are shielded to prevent electron impact on cold magnet bore
- 4) rely on surface conditioning ('scrubbing'); commissioning strategy; as a last resort doubling or tripling bunch spacing suppresses e-cloud heat load

e- cloud effect may also be reduced by:

- *larger bunch spacing*
- *high bunch intensity*
- *superbunches*

predicted heat load in LHC vs. bunch spacing

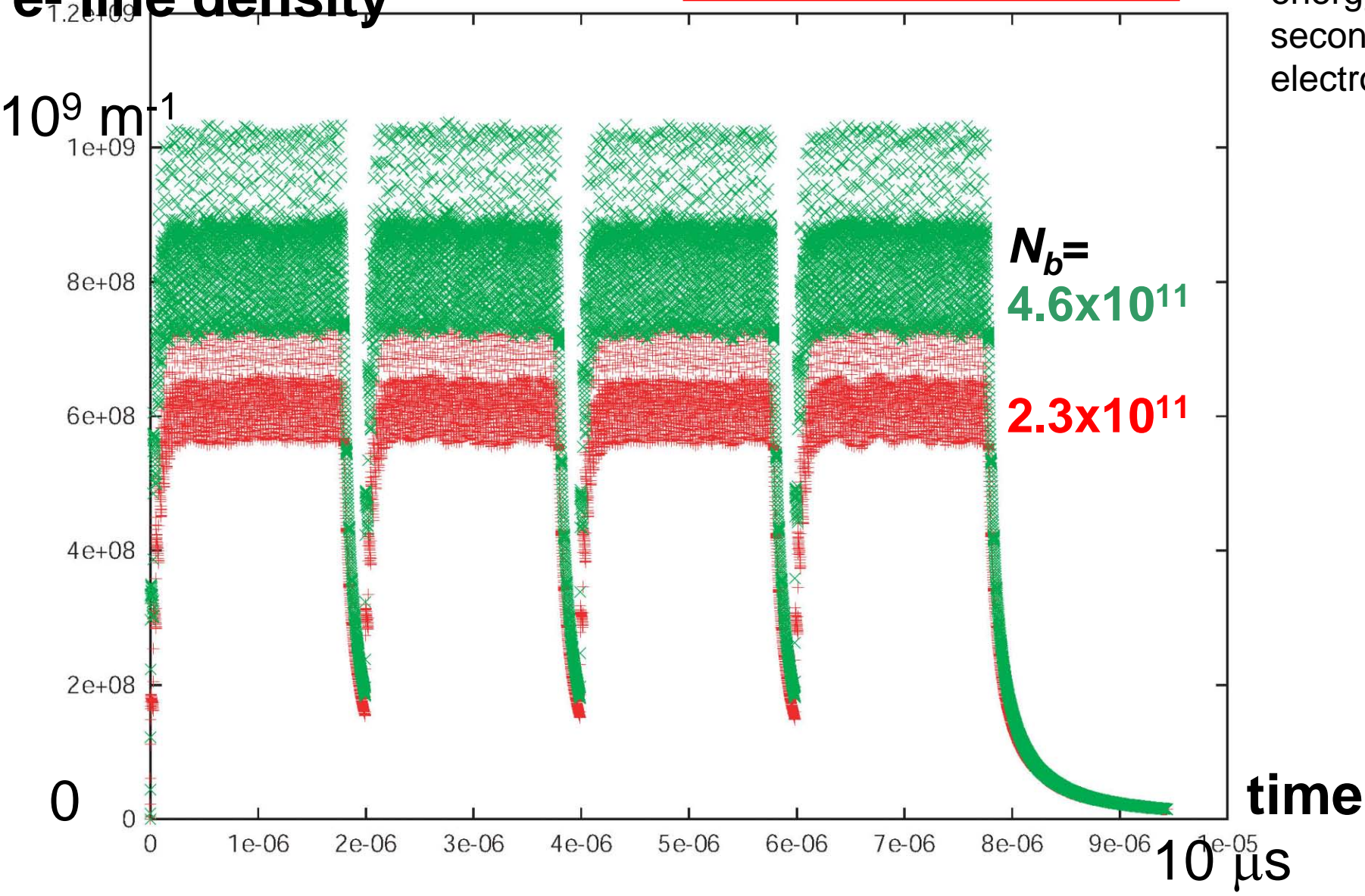


*saturation of e- build up
for high bunch intensities*

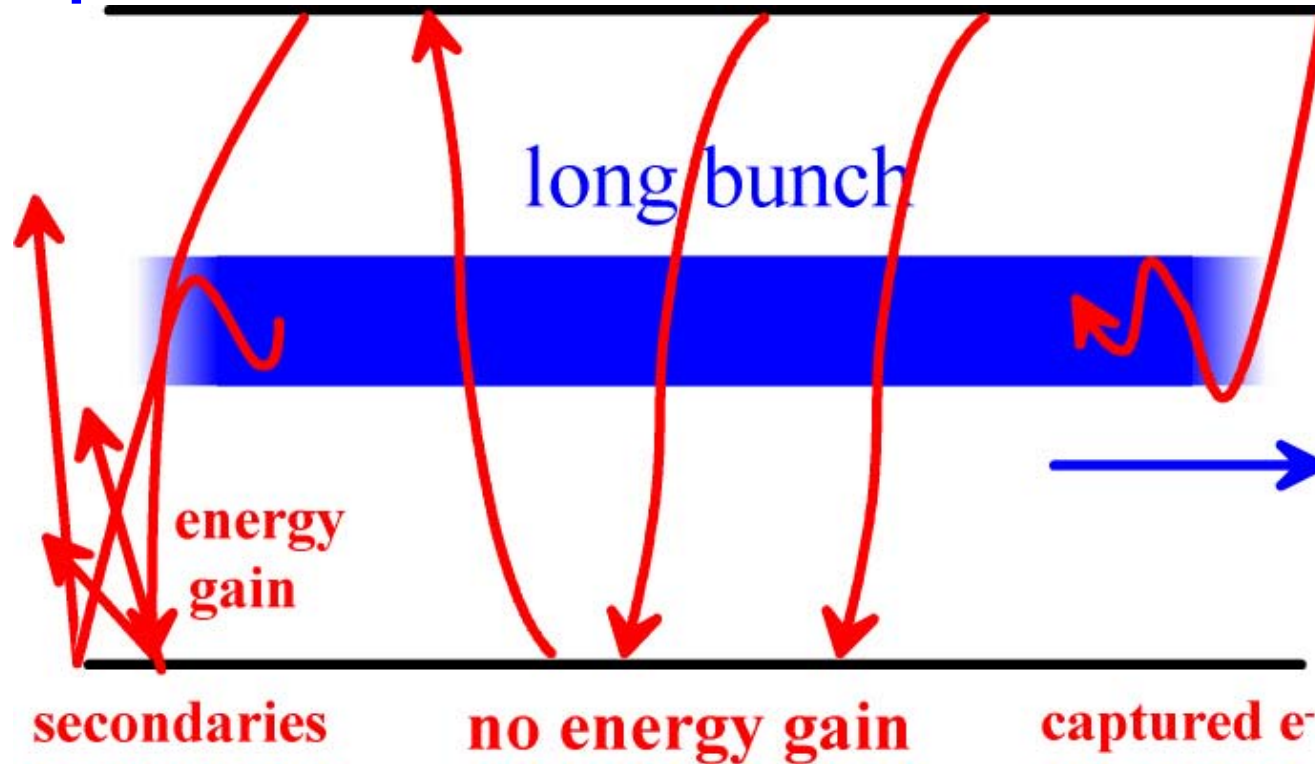
$$\lambda_e < \frac{E_0}{r_e m_e c^2} \approx 1.3 \times 10^9 \text{ m}^{-1}$$

$E_0 \approx 1.9 \text{ eV}$
~average
energy of
secondary
electrons

e-line density



superbunch



schematic of e- motion during passage of long proton bunch; most e- do not gain any energy when traversing the chamber in the quasi-static beam potential

negligible heat load

[after V. Danilov]

outlook

another prime challenge for the future:

collimation & machine protection

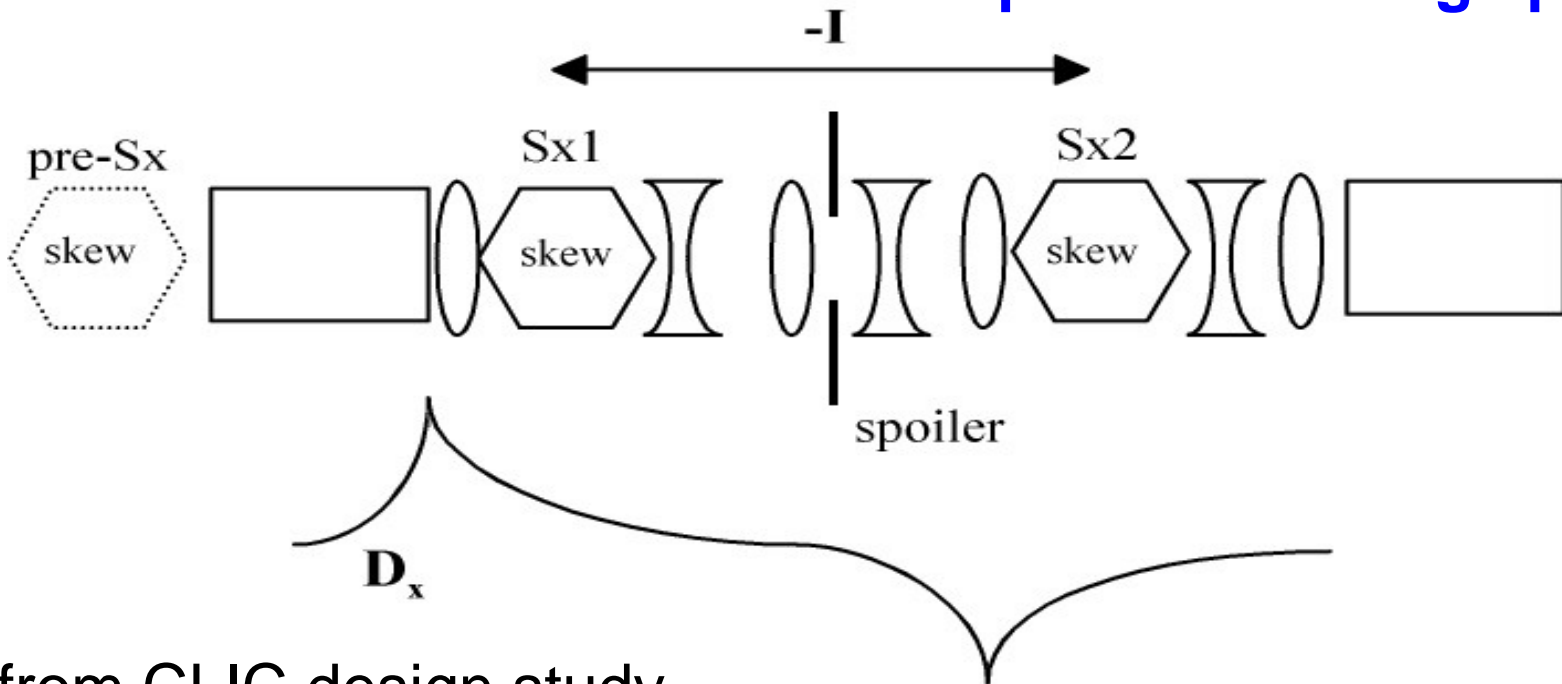
conflicting requirements: high cleaning efficiency, acceptable impedance, collimator survival in case of poor lifetime or kicker failure

possible solution: nonlinear collimation

- (1) single-turn collimation with pair of nonlinear elements
- (2) multi-turn collimation with single element

schematic of single-turn two-element nonlinear collimation

effect of 1st skew sextupole is cancelled by 2nd except for particles hitting spoiler



[from CLIC design study
see A. Faus-Golfe, F.Z.,
EPAC 2002]

similar layout should be
suitable for storage ring

many other challenges ...

cooling of high-energy hadron beams –
counteract emittance growth due to
IBS & beam-beam, reduce emittances

e.g.,

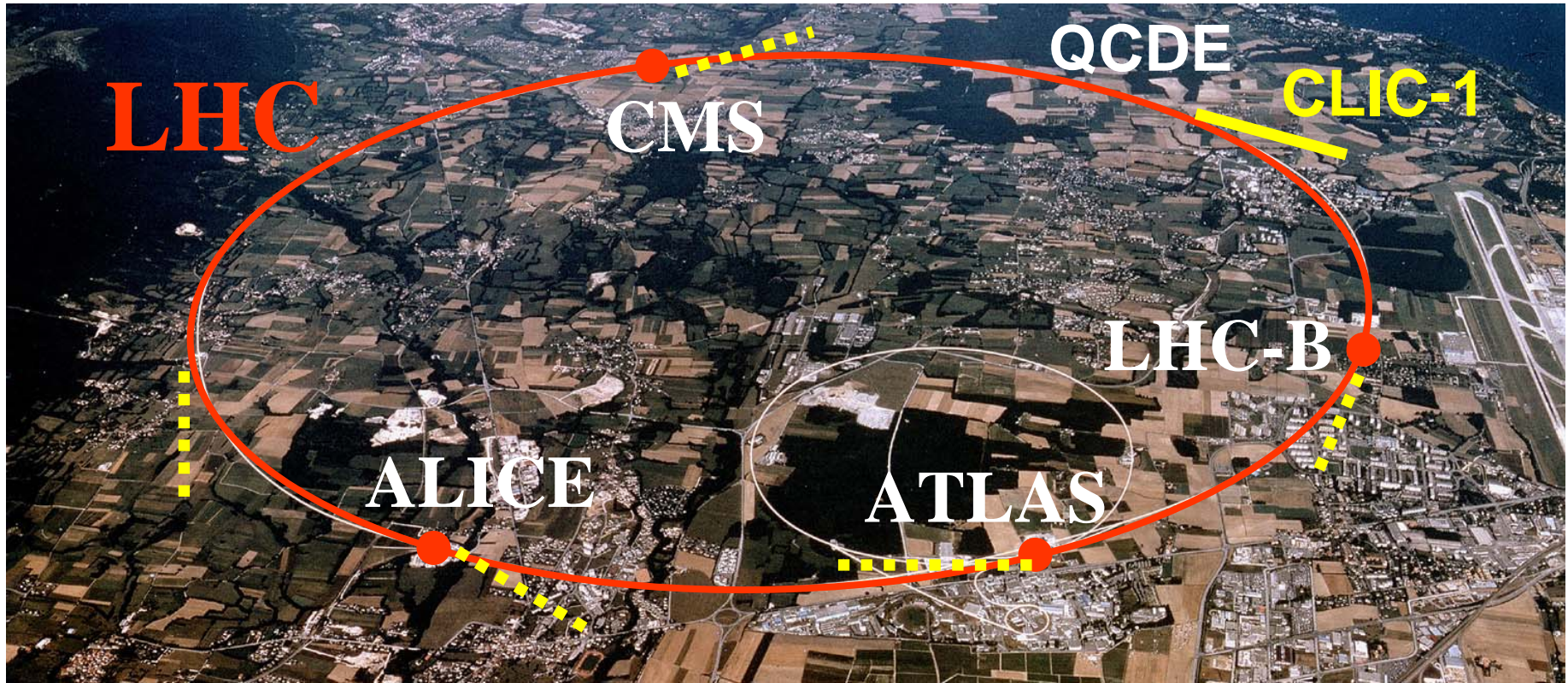
- **e-cooling** using 100-mA, 54-MeV, 5-MW bunched e- beam accelerated by ERL will increase RHIC luminosity by factor 10
- **bunched-beam stochastic cooling**
- **optical stochastic cooling** → **control of beam tails**
- **SR damping rate > IBS rate in LHC**

... and second approach to high energy scale:

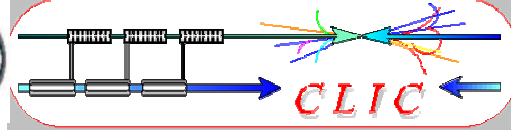
linac-ring (e- ion) colliders

- first proposed by P. Csonka & J. Rees, 1971 (e+e-)
- recently ERHIC, ELIC, T(H)ERA
- at very high energy ...

QCD Explorer based on LHC and CLIC-1

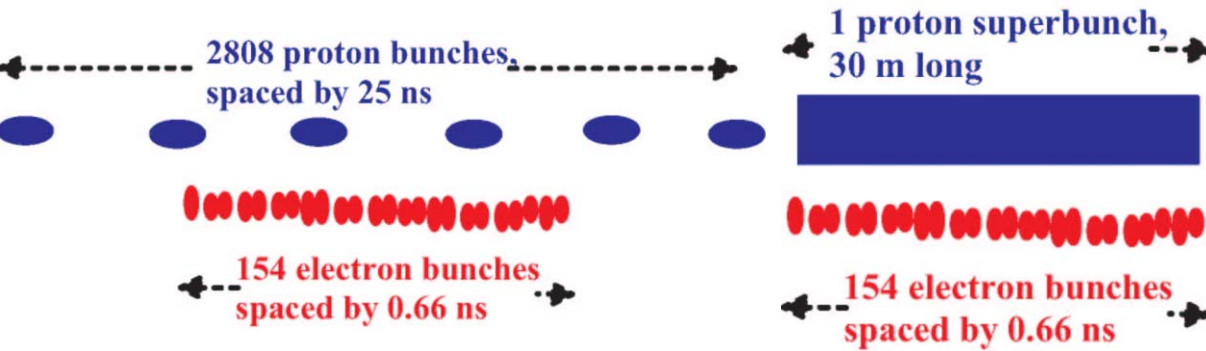


QCD Explorer Colliding LHC with CLIC-1

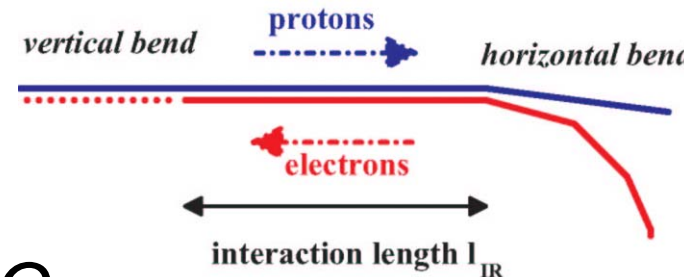


D. Schulte et al.,
MOPLT039

bunch filling patterns



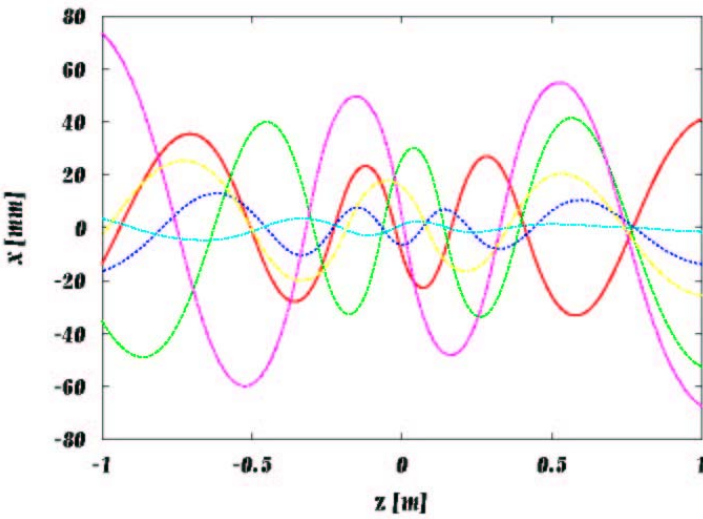
QCDE IR layout



$$D_{x,y} \equiv \frac{2\lambda_p r_e l_{IR}}{\gamma \epsilon_{x,y}} \arctan\left(\frac{l_{IR}}{2\beta^*}\right) \approx 430$$

$$\sqrt{D_{x,y}} / (2\pi) \approx 3$$

e- beam disruption



$$L = f_{coll} \frac{l_b \lambda_e \lambda_p}{\pi \epsilon_{x,y}} \arctan\left(\frac{l_{IR}}{2\beta^*}\right)$$

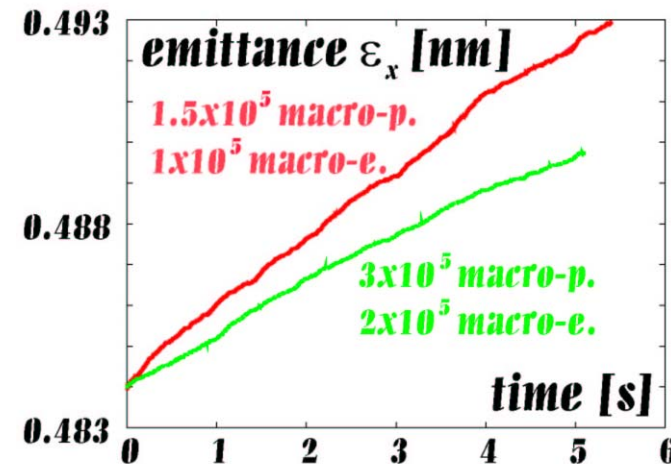
$L > 10^{31} \text{ cm}^{-2} \text{ s}^{-1}$

relaxed CLIC parameters

$\xi_p \sim 0.004$ every 111th turn

100 Hz repetition rate

p beam blow up



QCDE parameters

parameter		e-	P
beam energy	E_b	75 GeV (or higher)	7 TeV
bunch population	N_b	4×10^9	6.5×10^{13}
rms bunch length	σ_z	35 μm (Gaussian)	12.4 m (uniform)
Spacing	L_{sep}	0.66 ns	N/A
# bunches	n_b	154	1
effective line density	λ_b	$2.0 \times 10^{10} \text{ m}^{-1}$	$2.1 \times 10^{12} \text{ m}^{-1}$
IP beta	β^*	0.25 m	0.25 m
interaction length	l_{IR}	2 m	
collision frequency	F_{coll}	100 Hz	
luminosity	L	$1.1 \times 10^{31} \text{ cm}^{-2} \text{ s}^{-1}$	
beam-beam tune shift	$\xi_{x,y}$	N/A	0.004
rms norm. emittance	$\gamma \varepsilon_{x,y}$	73 μm	3.75 μm
IP spot size	$\sigma_{x,y}$	11 μm	11 μm

Summary of Beam-Beam

- (1) prediction of beam-beam limit for hadrons based on experience, not on simulation
- (2) small spot sizes & high collision rate introduce IP-offset sensitivity at 10^{-3} of the spot size; natural ground motion safe
- (3) still open questions concerning effect of long-range collision schemes
- (4) compensation experiments at FNAL and SPS; proposal for (Super-)LHC

Summary of Touschek & IBS

- (1) solid prediction by simplified theory
- (2) larger momentum spread helps

Summary of e- cloud

- (1) soon 40th anniversary
- (2) causes heat load & instabilities
- (3) suite of countermeasures
- (4) may exclude certain LHC upgrade paths & favors some others

Summary of Superbunches

- (1) negligible electron-cloud heat load +
- (2) no PACMAN bunches +
- (3) reduced IBS +
- (4) higher luminosity for the same tune shift
& smaller beam current +
- (5) tailored to CLIC bunch structure
 → maximum QCDE luminosity +
- (6) not compatible with present detector
 electronics & architecture?, disliked
 by some LHC experimenters -

thank you for your attention!

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