LHC beam-beam compensation studies at RHIC

Wolfram Fischer

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BROOKHAVEN NATIONAL LABORATORY

U.S. LARP

6 May 2009

Particle Accelerator Conference 2009, Vancouver

Outline

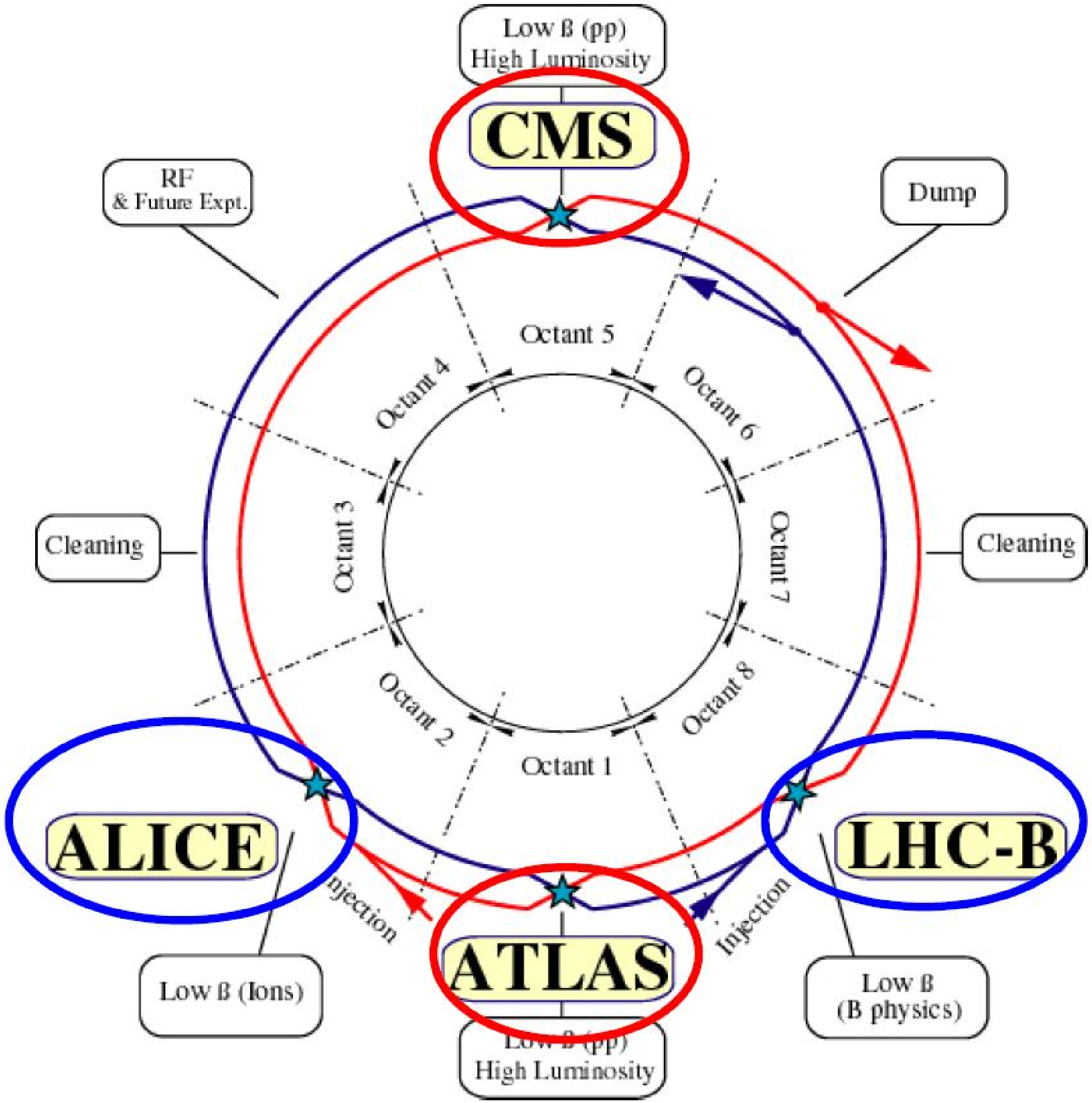
1. Beam-beam effects in LHC and RHIC

2. Beam-beam compensation techniques
    - For long-range effects (wires)
    - For head-on effects (electron lenses)

3. RHIC studies for beam-beam compensation
    - For long-range effects (wire experiments)
    - For head-on effects (simulations)

4. Summary

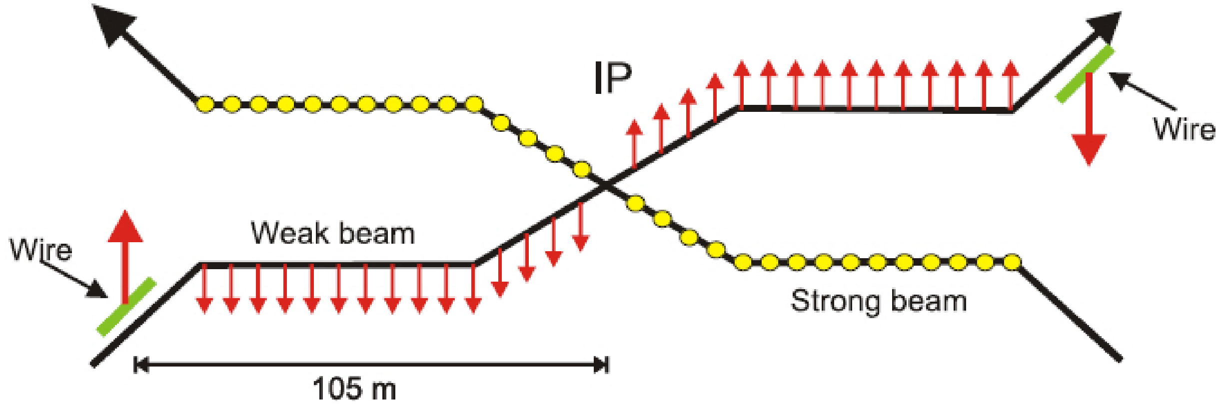
Beam-beam effects in LHC

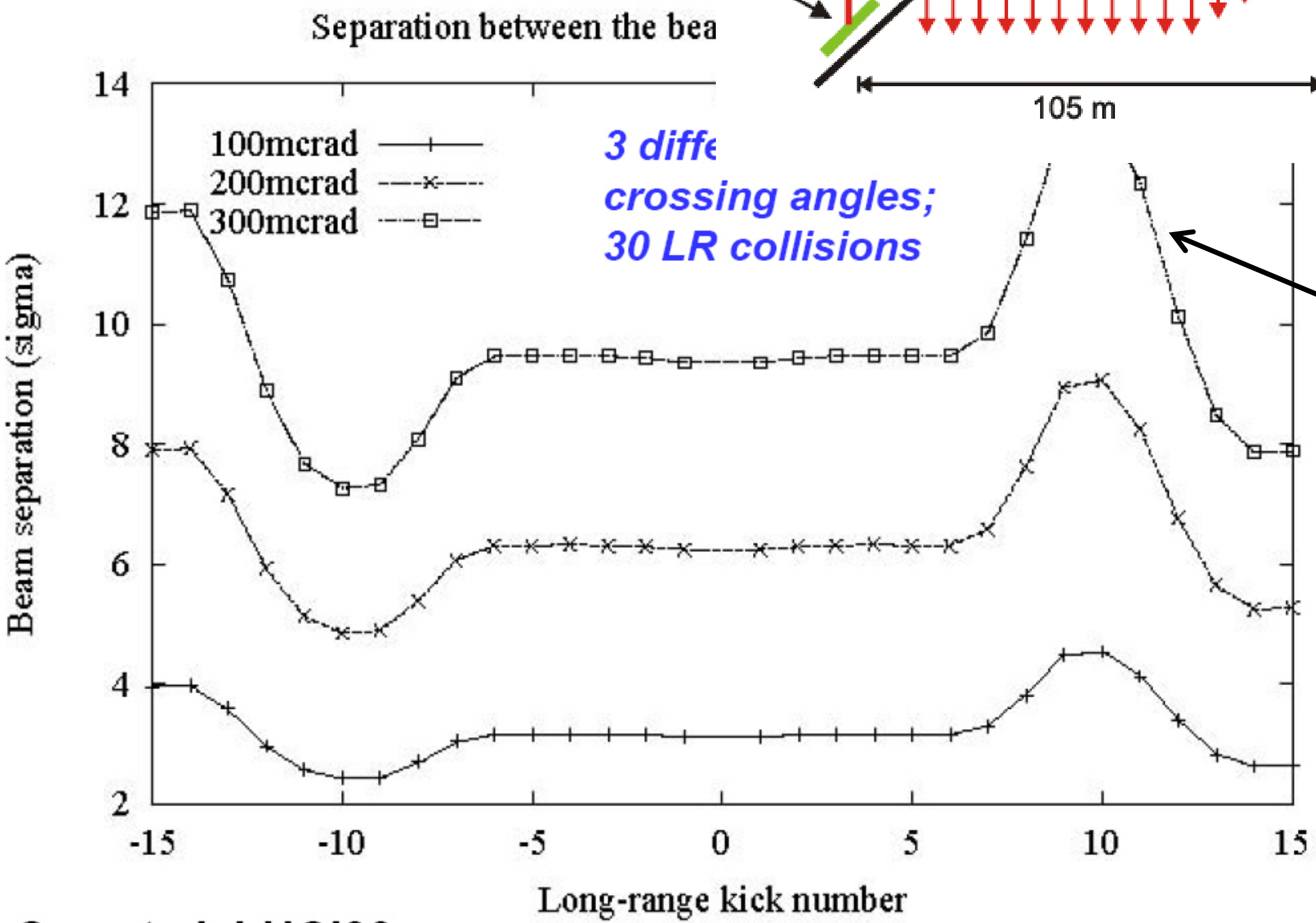


2 high-luminosity IPs (CMS & ATLAS)

2 lower luminosity IPs (ALICS & LHC-B)

Beam-beam effects in LHC





design θ = 285 μrad

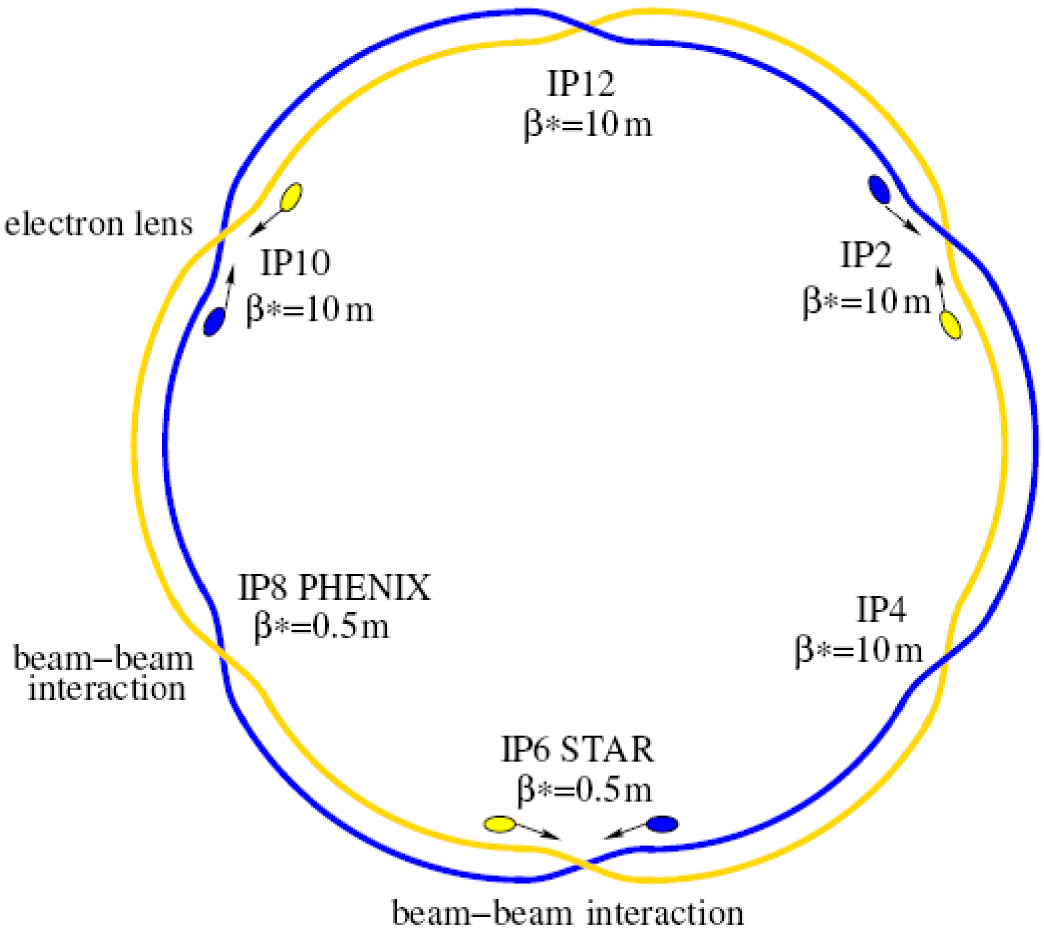
Per IR

- ξ = 0.0033
- 30 long-range
- 14 at about 9 σ

T. Sen et al, LHC'99

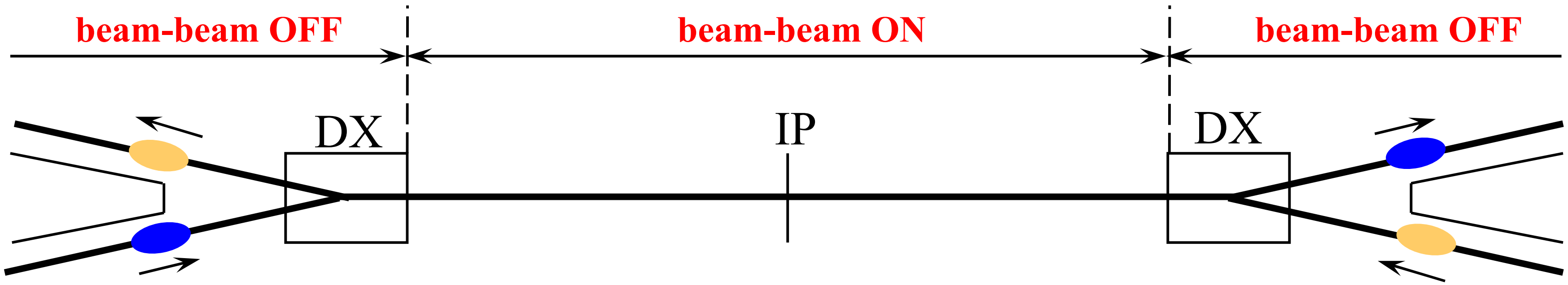
[U. Dorda, PhD thesis, Vienna University of Technology (2008).
LHC Design Report, CERN-2004-003 (2004).]

Beam-beam effects in RHIC



- Two independent rings
- Dipole first IR
- Nominally no crossing angle
- 2 head-on collisions
- 4 long-range collisions (15σ vertical separation)
- Beam-beam couples 6 bunches (3 Blue and 3 Yellow)

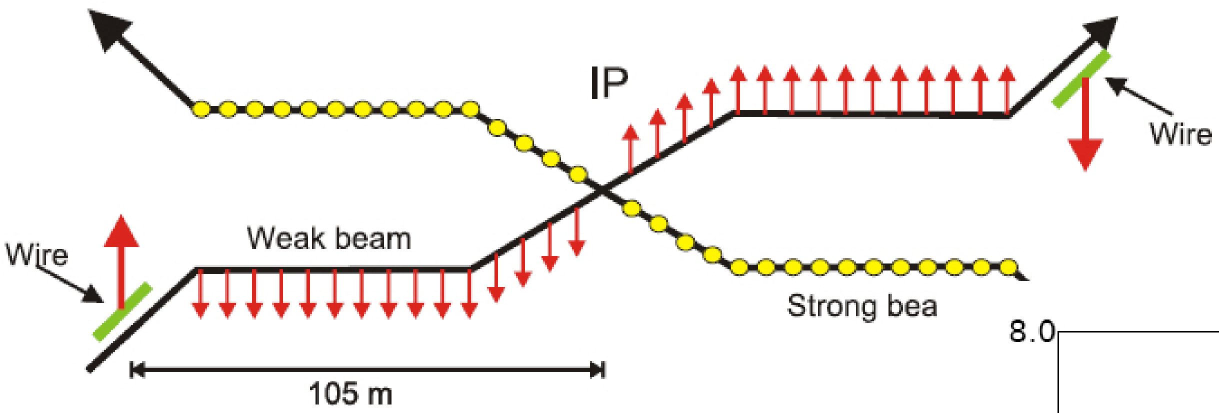
Need special setup of long-range experiments



LHC long-range beam-beam compensation with wires

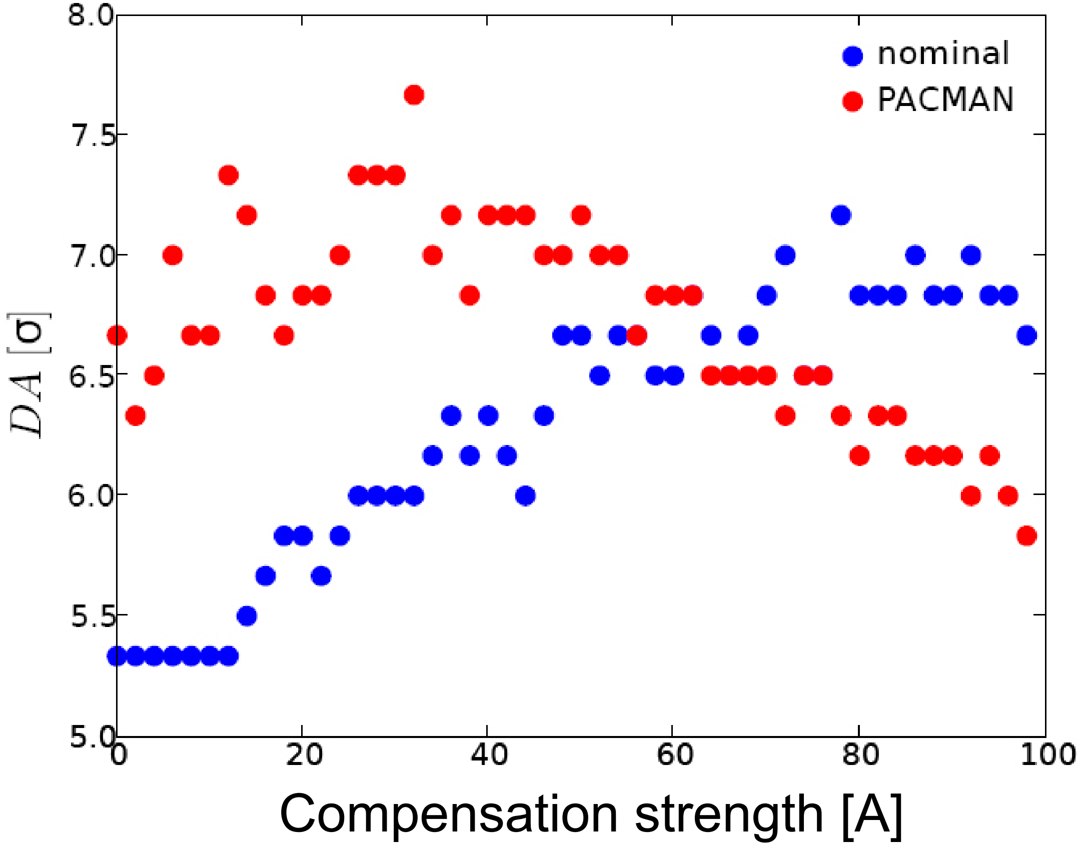
Nominal LHC

J.-P. Koutchouk, F. Zimmermann,
U. Dorda, G. Sterbini, CERN



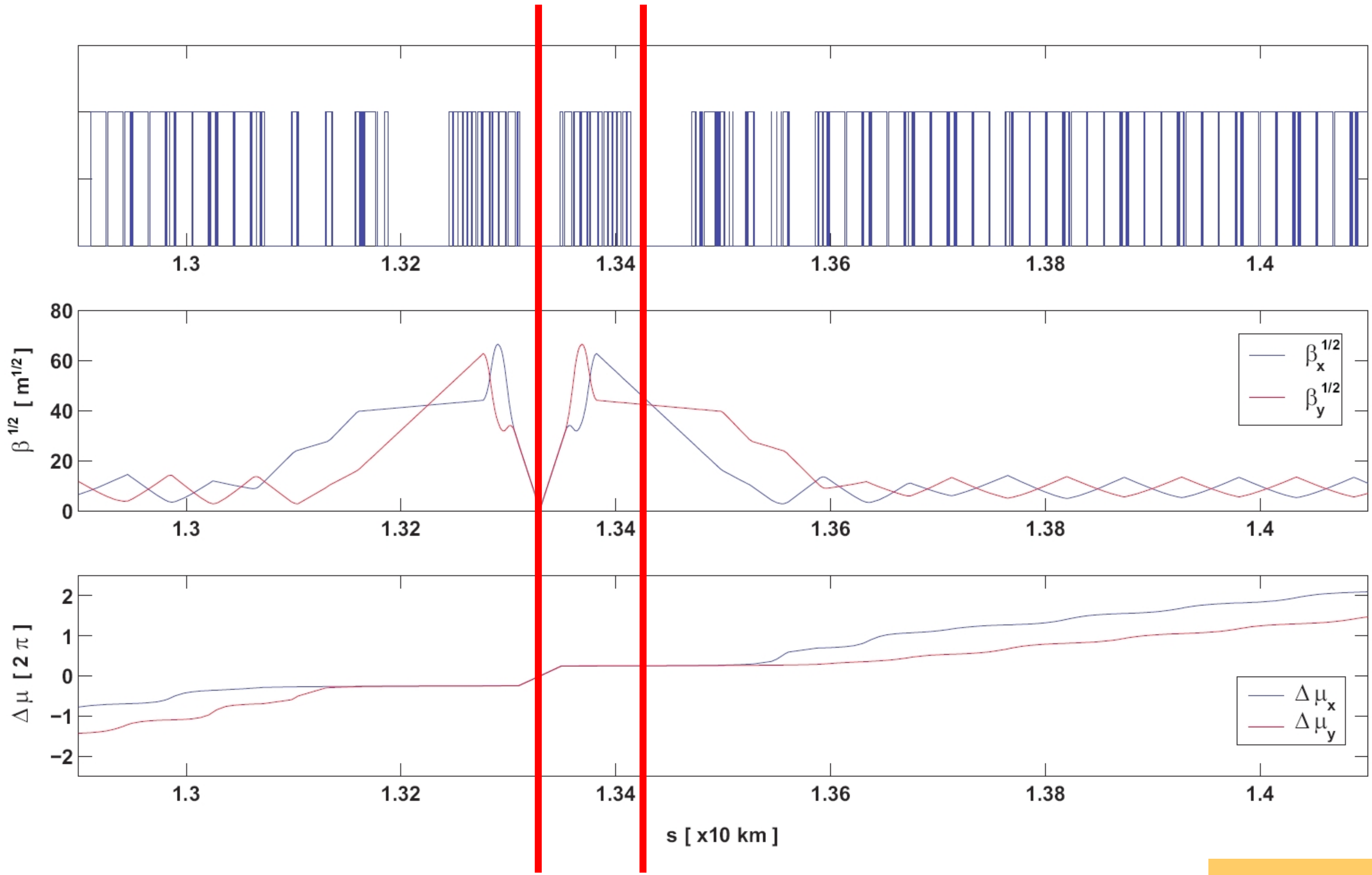
Expect 1-2 σ larger DA with long-range beam–beam compensation from simulation.

Experimental data and simulation verification desirable.



[U. Dorda, PhD thesis, Vienna University of Technology (2008).]

Location for beam-beam compensators in LHC



IP

s = 13329 m

β_x = 0.55 m μ_x = 32.049 [2π]

β_y = 0.55 m μ_y = 29.604 [2π]

BBLR or e-lens

s = 13433 m

β_x = 1925 m μ_x = 32.303 [2π]

β_y = 1784 m μ_y = 29.857 [2π]

$\Delta\mu_x$ = 91°

$\Delta\mu_y$ = 91°

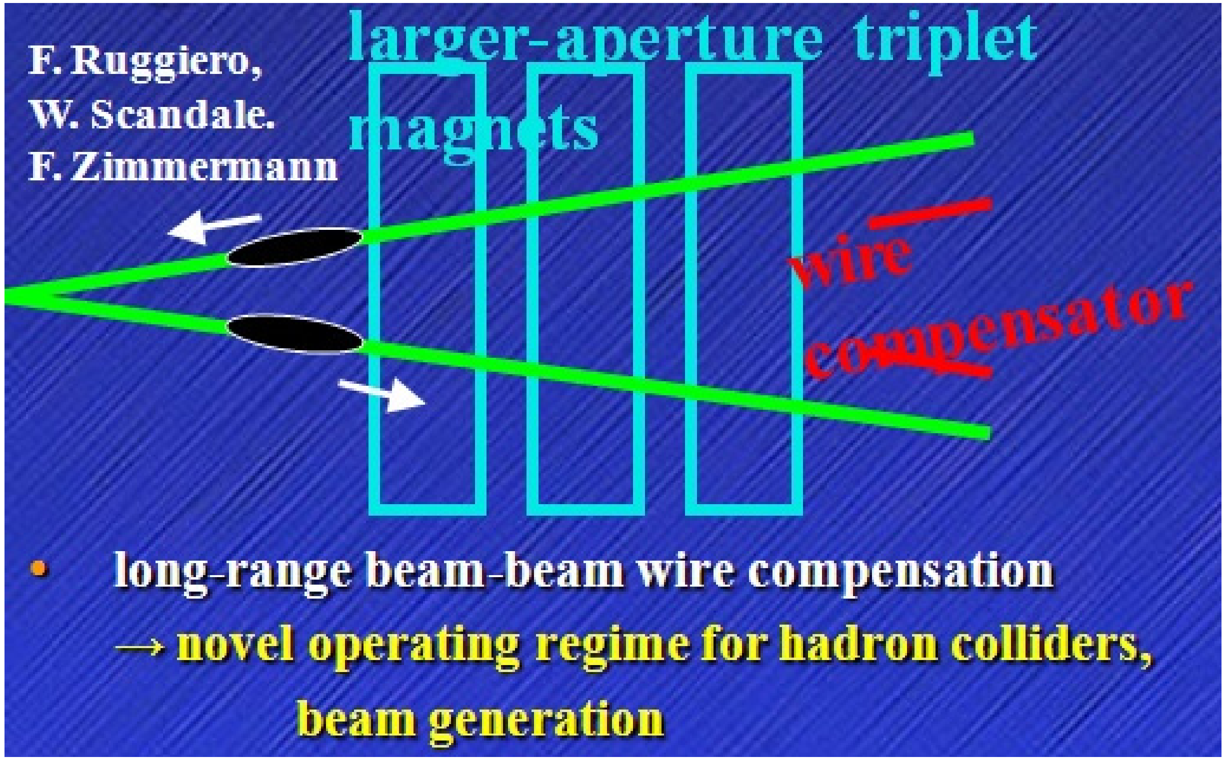
LHC long-range beam-beam compensation with wires

LHC Upgrade – option with Large Piwinski Angle (LPA)

(1 of 4 options currently under considerations)

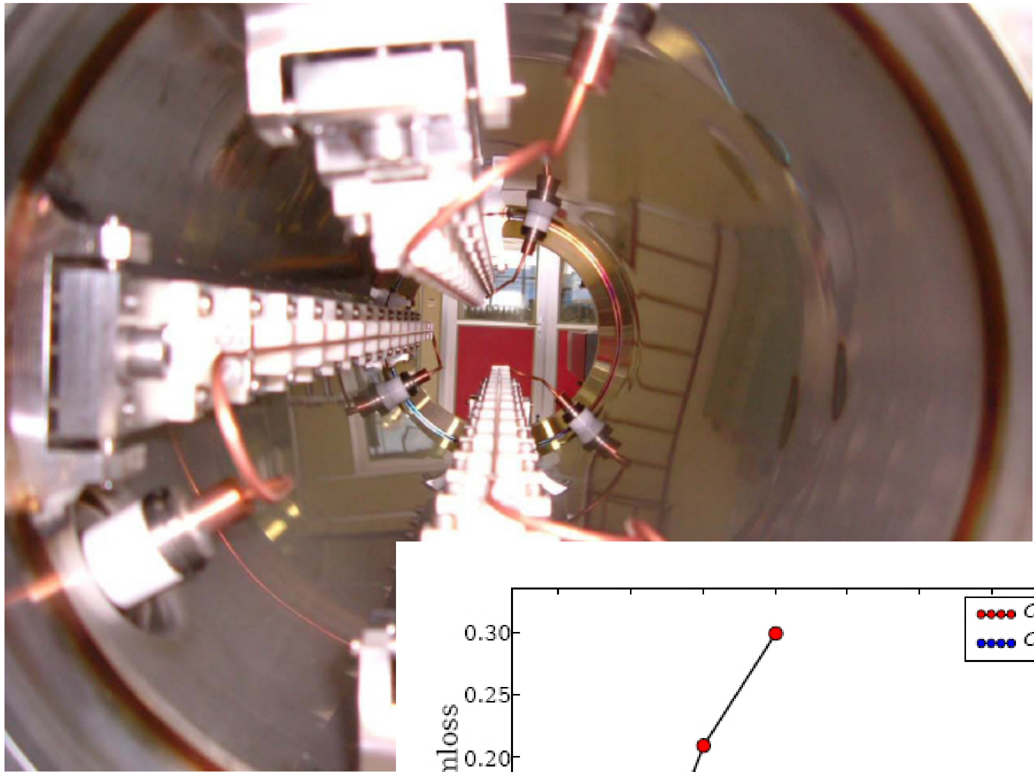
Long "flat" bunches with crossing angle
[β^* = 0.25 m, 50 ns bunch spacing, N_b=4.9x10^{11}]

- Maintains beam-beam parameter ξ/IP
- Increases long-range interaction strength for same θ



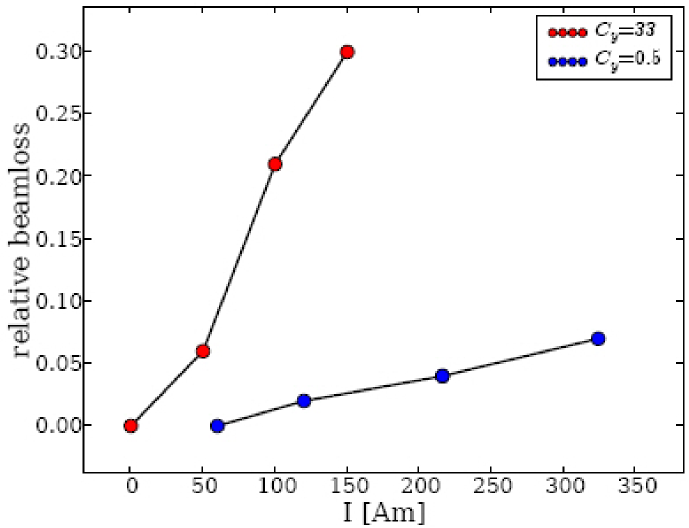
Long-range wire experiments in CERN SPS

Test wires installed in CERN SPS

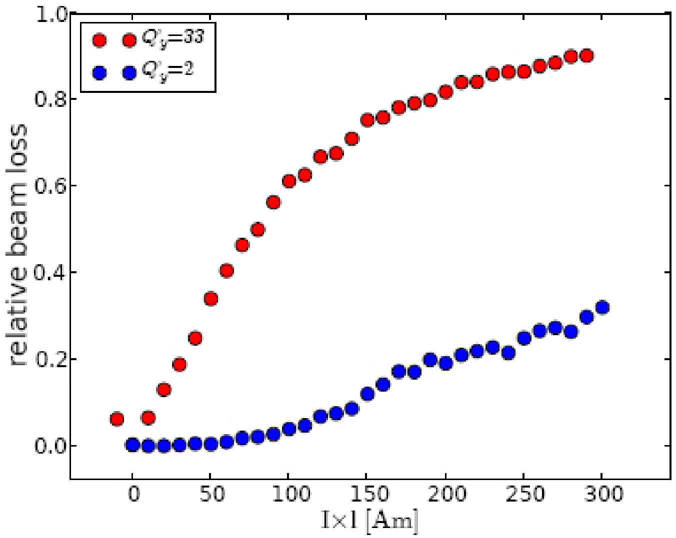


J.-P. Koutchouk, F. Zimmermann,
U. Dorda, G. Sterbini, CERN

55 GeV, d = 6.6 σ
Q_y' = 2, 33



(a) Experimental data



(b) Simulations

[U. Dorda, PhD thesis, Vienna University of Technology (2008).]

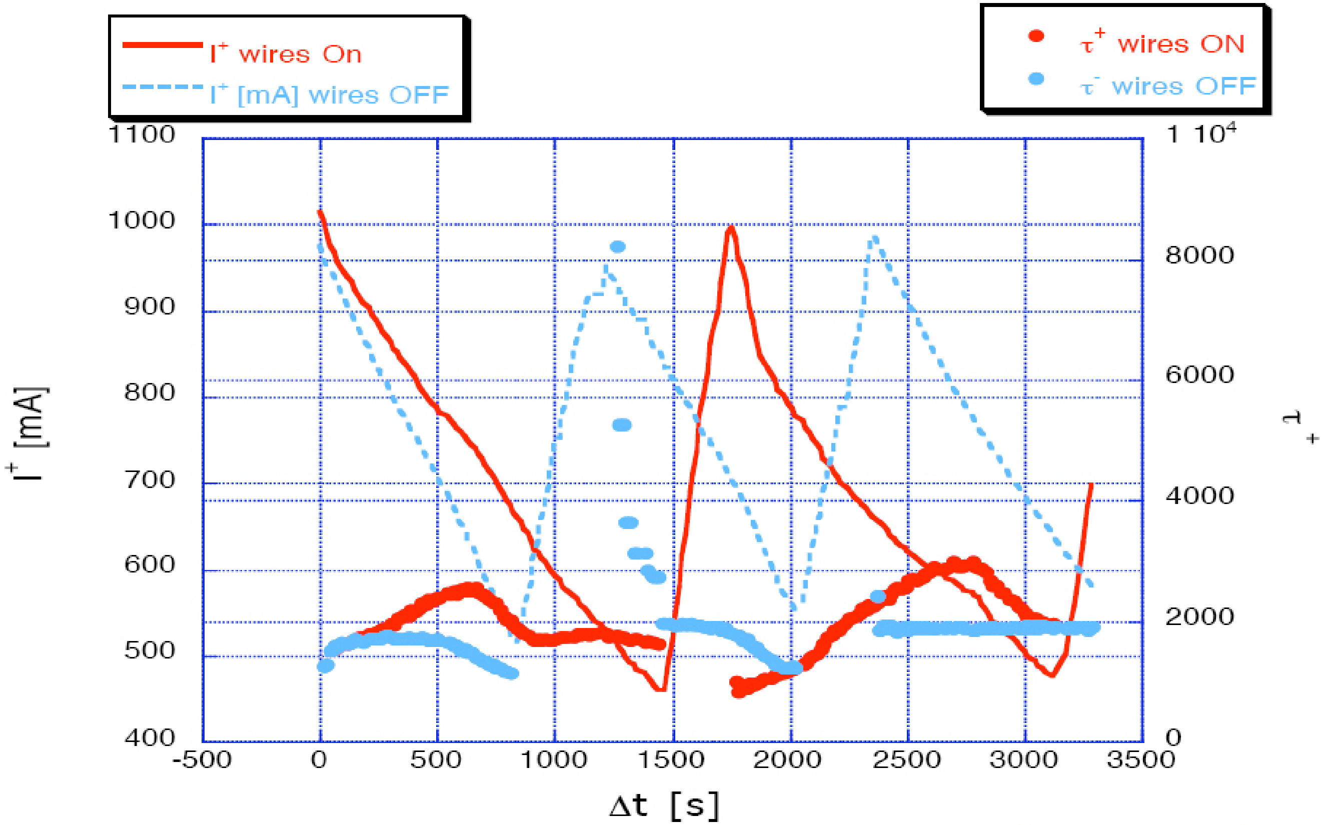
Partial long-rang beam-beam compensation in DAΦNE

C. Milardi et al., INFN

Wires installed near IP between separated beams

[C. Milardi et al., EPAC'06]

Wires improved beam lifetime of weak positron beam in collision, in agreement with simulations (LIFETRACK)



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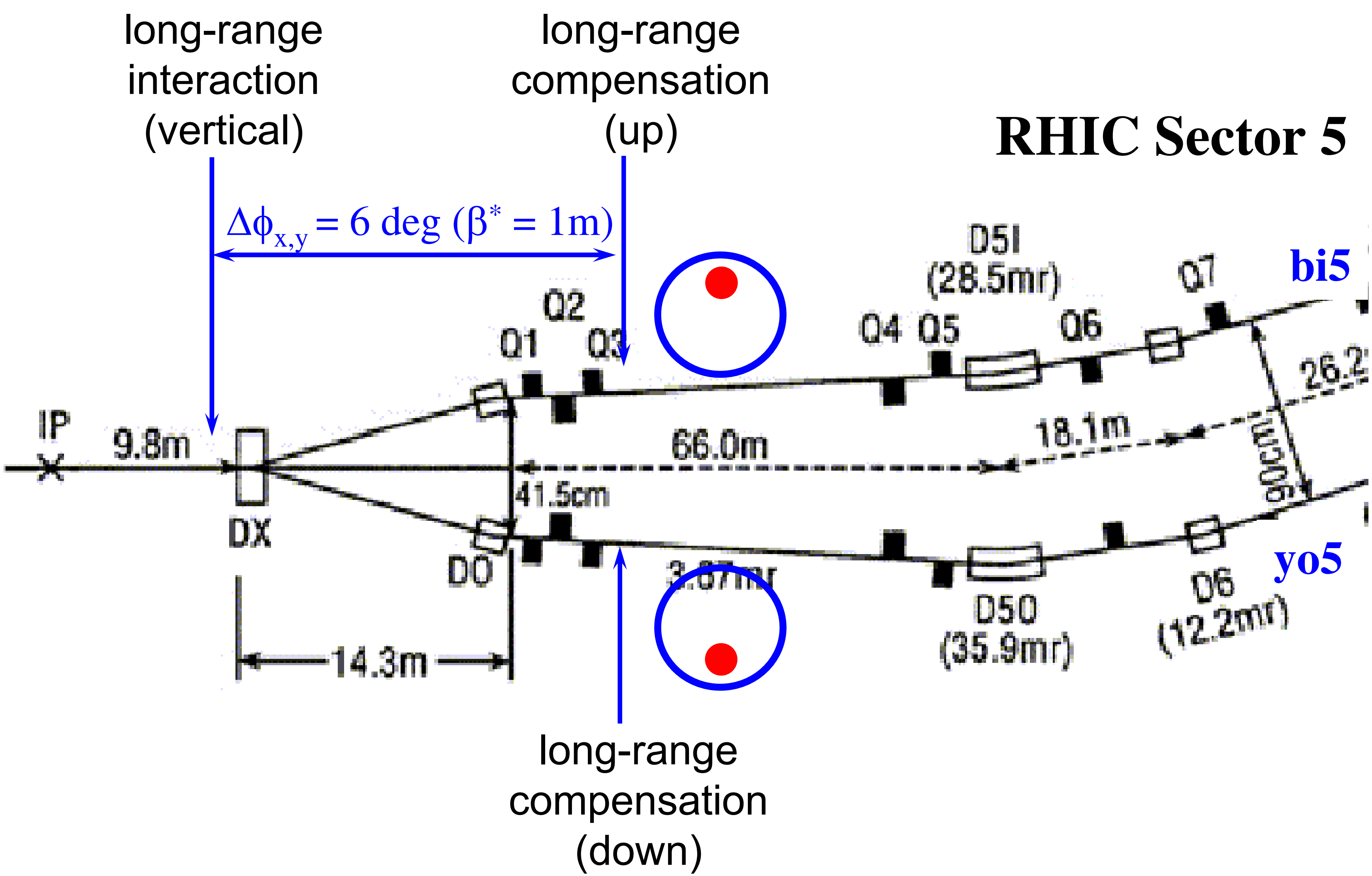
RHIC long-range beam-beam studies for LHC

Motivation:

- RHIC with wires allows to study strong localized long-range beam-beam effect – like in LHC
  (long-range not localized in Tevatron)
- Beam lifetime in RHIC is typical for hadron collider
  (unlike SPS during wire experiments due to low beam energy)
- Head-on beam-beam effect can be added
  (not possible in SPS)
- Experimental data used to benchmark simulations, compensation of single long-range interaction possible

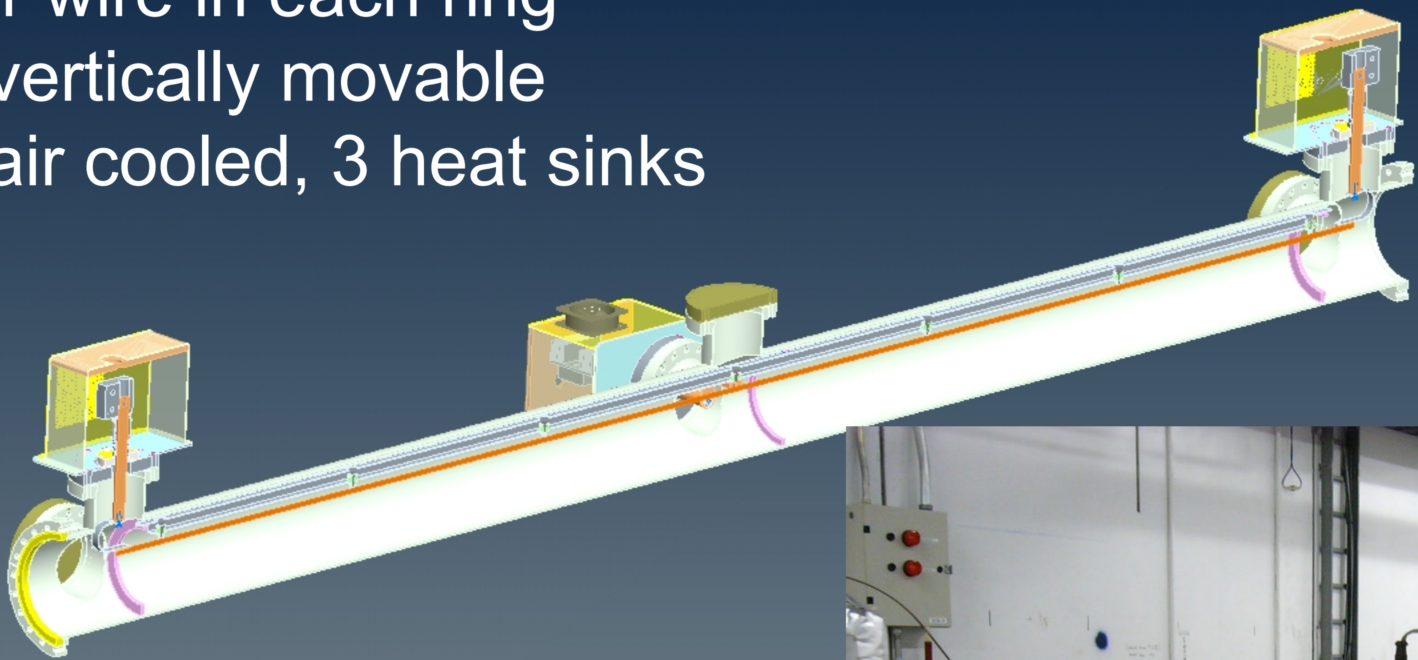
RHIC long-range wire layout

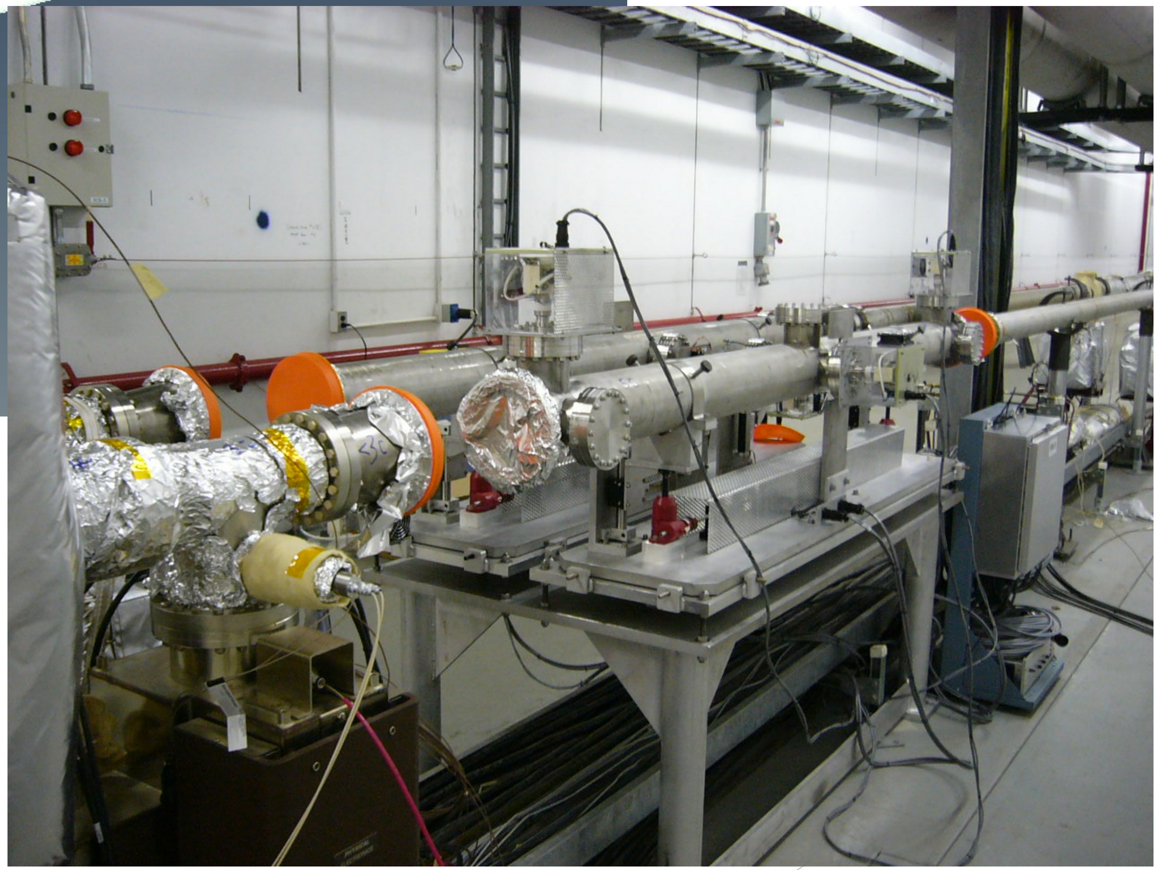


Small phase advance between long-range beam-beam interaction and possible compensator can only be realized at store.

RHIC long-range wires

1 wire in each ring
vertically movable
air cooled, 3 heat sinks





2 parameters to vary:

- Distance to beam (0 – 65 mm)
- Strength (0 – 125 Am)

RHIC long-range wire experiments

Measurements are beam lifetime observations with variations in

- Separation
- Strength (wire current)
- Other parameters (tune, chromaticity)

2005: p-beam at injection

2006: p-beam at store

2007: Au-beam & wire at store

2008: d-beam & wire at store

2009: p-beam & wire at store

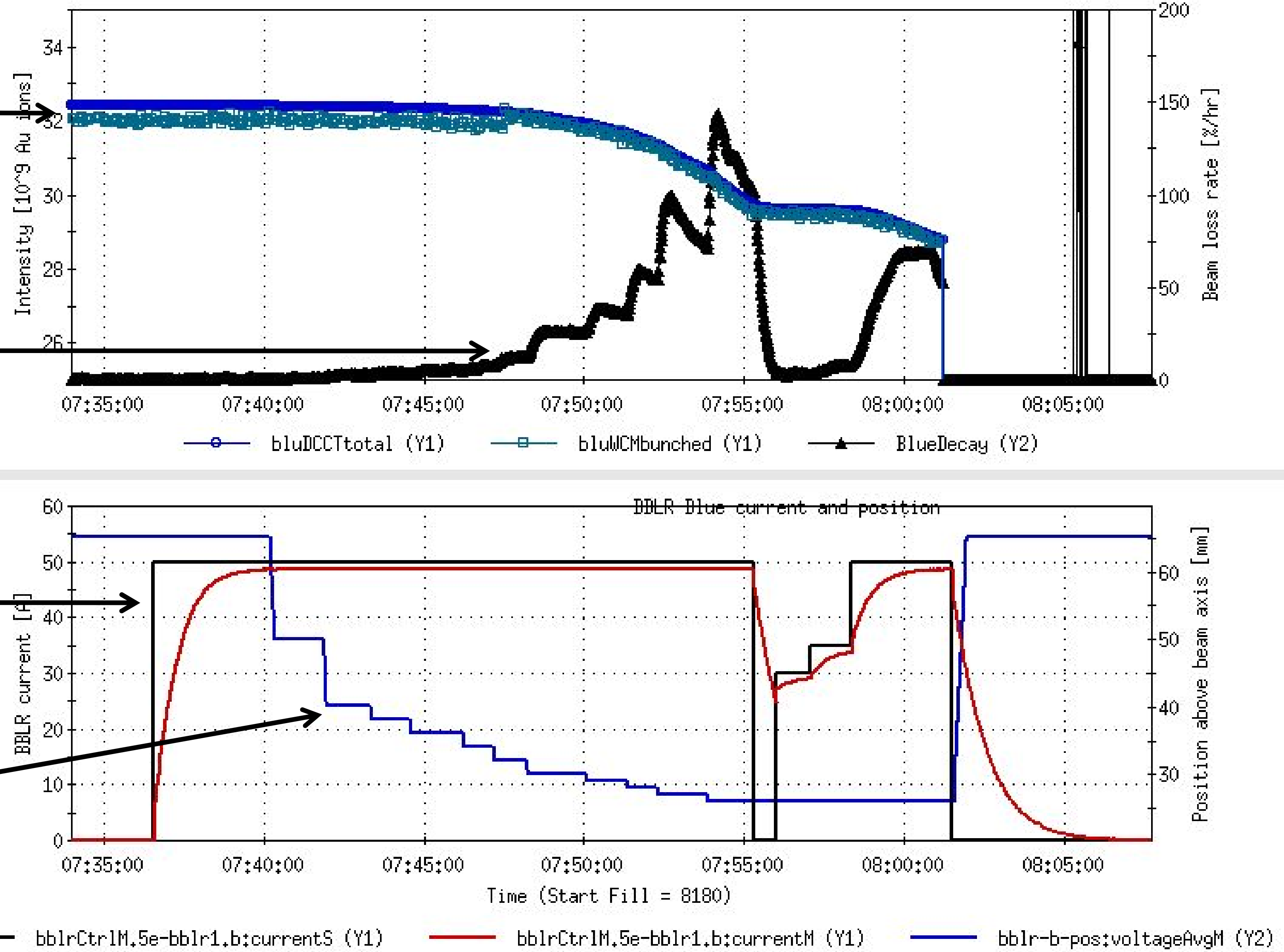
Typical RHIC long-range wire experiments

Beam intensity

Beam lifetime

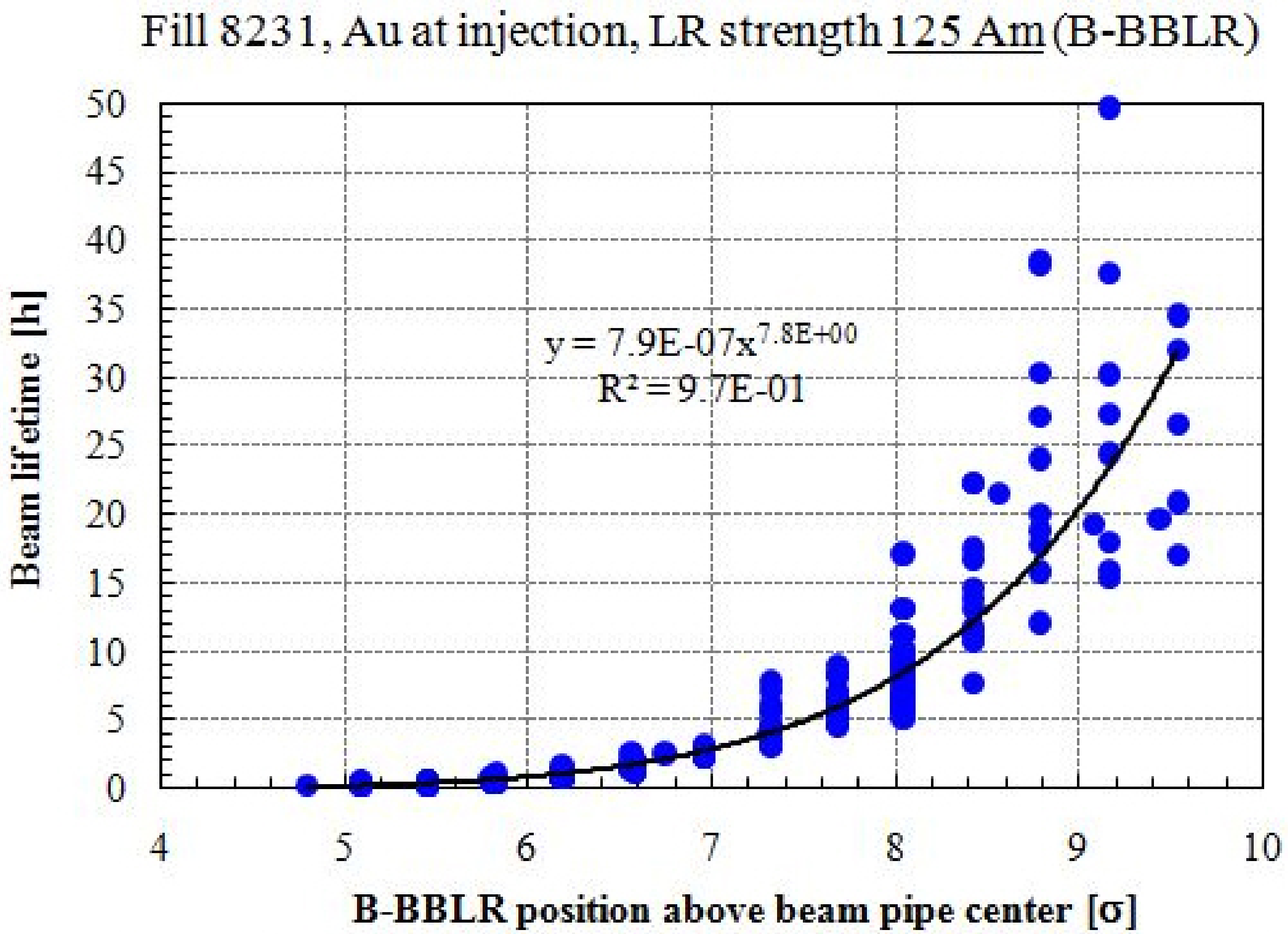
Wire current (set point and measured)

Wire position



RHIC wire experiments – fitted beam lifetimes

Beam lifetimes τ fitted to $\tau = A\, d^{p}$. Fitted exponents p varies from 1.7 to 16.

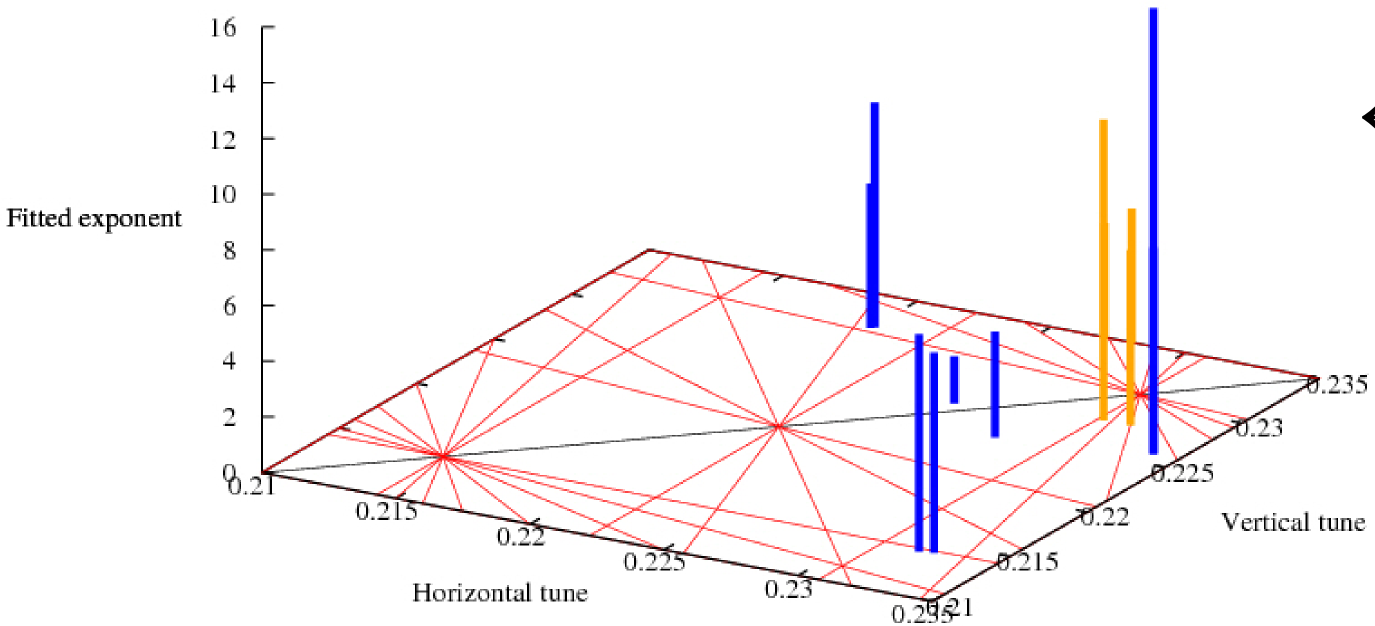


SPS found $\tau \propto d^5$ [measurement 11/09/04]

Tevatron found $\tau \propto d^3$ [reported in F. Zimmermann, LTC 11/24/04]

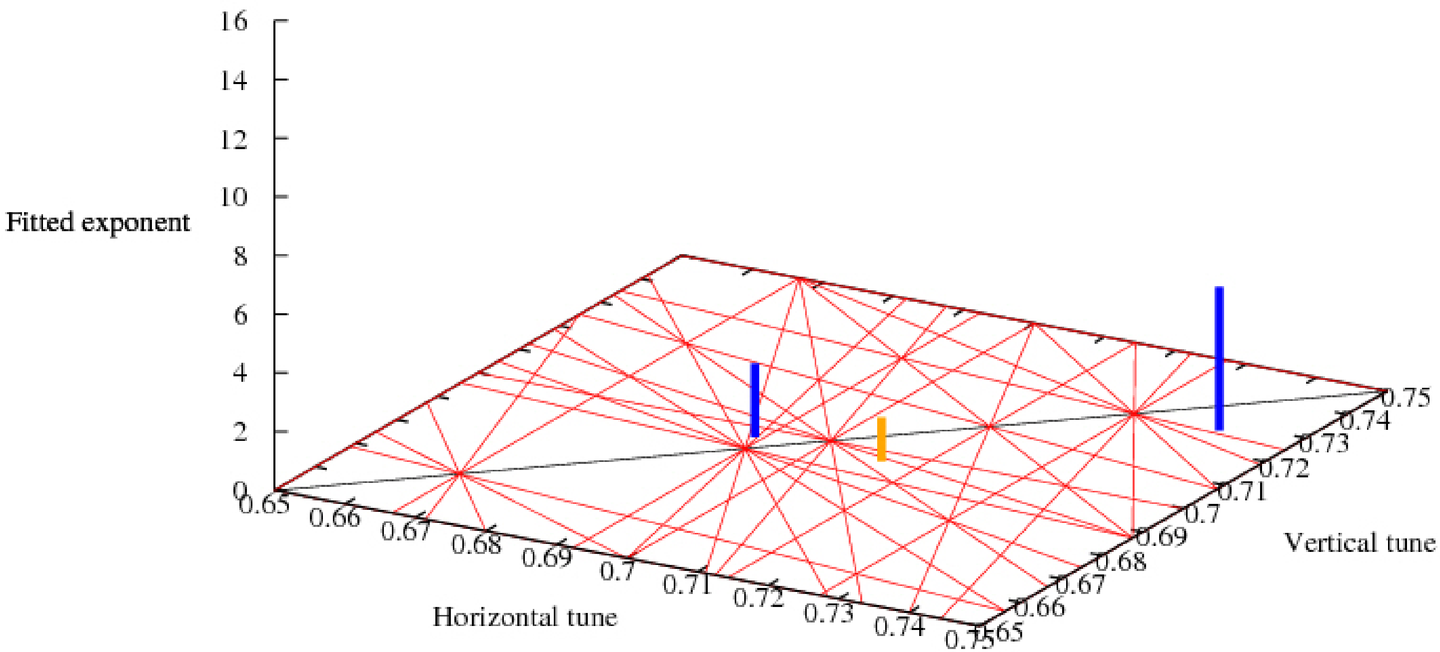
RHIC wire experiments – fitted beam lifetimes

Beam lifetimes τ fitted to $\tau = A\, d^{\,p}$. Fitted exponents *p* varies from 1.7 to 16.



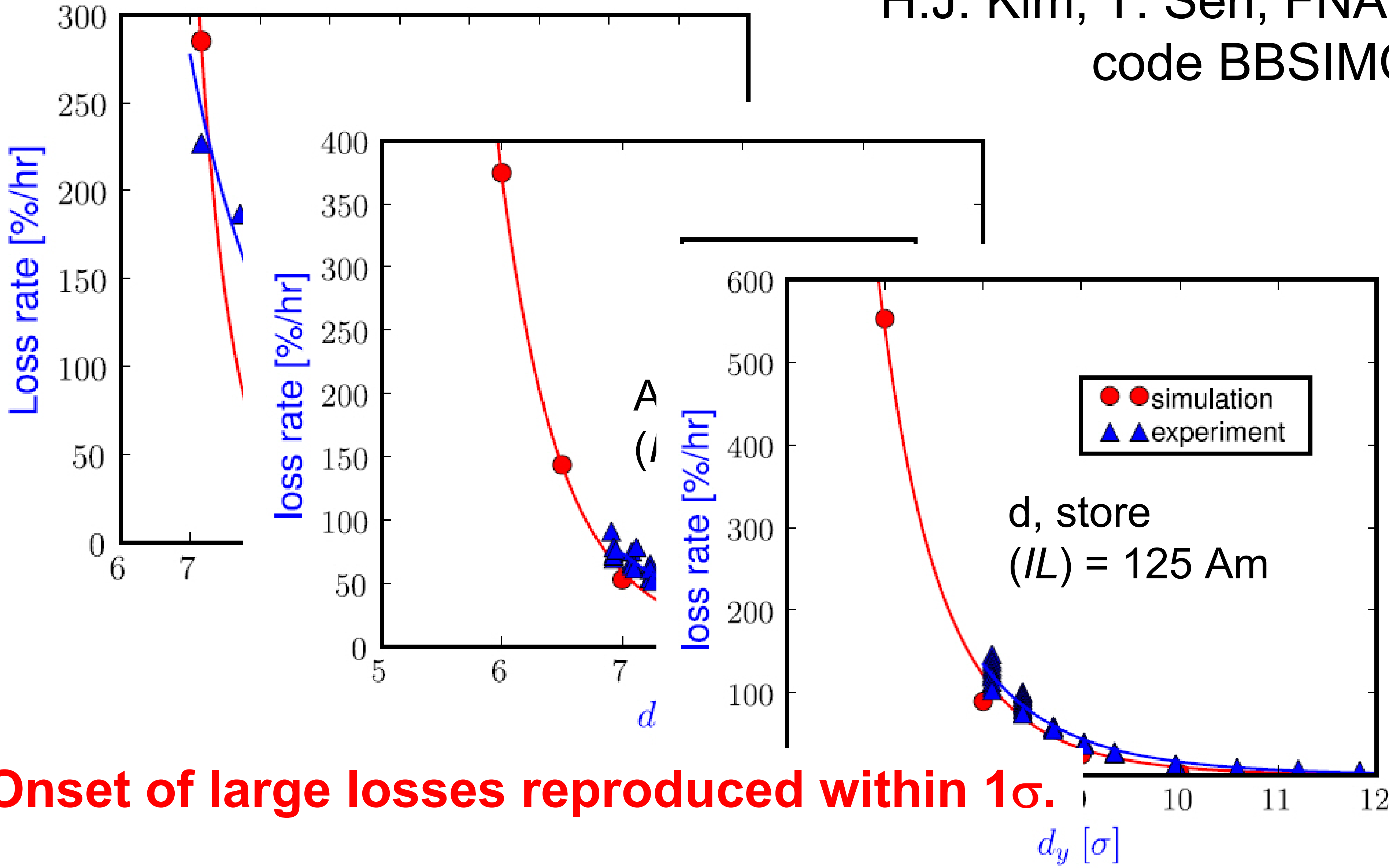
← Tune range [0.21,0.235] (heavy ions)

Tune range [0.65,0.75] → (protons)



RHIC wire experiments – comparison with simulations (1)

H.J. Kim, T. Sen, FNAL
code BBSIMC



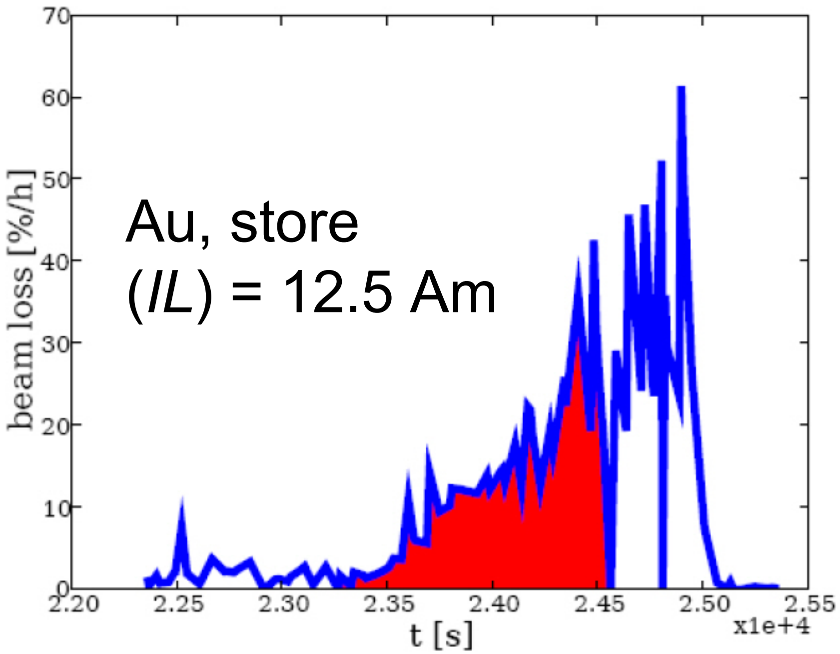
Onset of large losses reproduced within 1σ.

[H.-J. Kim et al., Phys. Rev. ST Accel. Beams 12, 031001 (2009).]

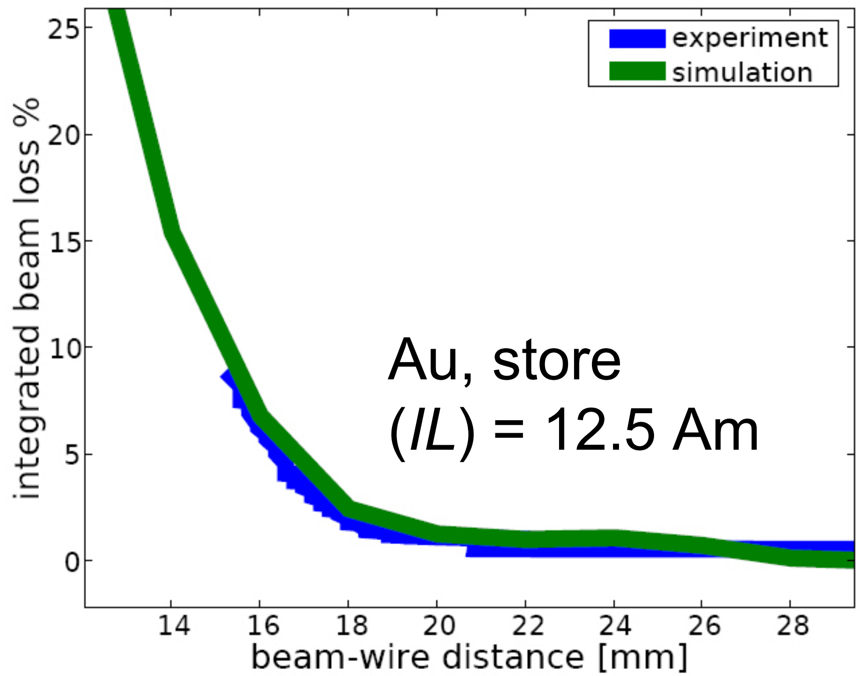
RHIC wire experiments – comparison with simulations (2)

U. Dorda, CERN
code BBTrack

Integrated loss rate used as observable in RHIC experiments



Comparison to simulation in a distance scan

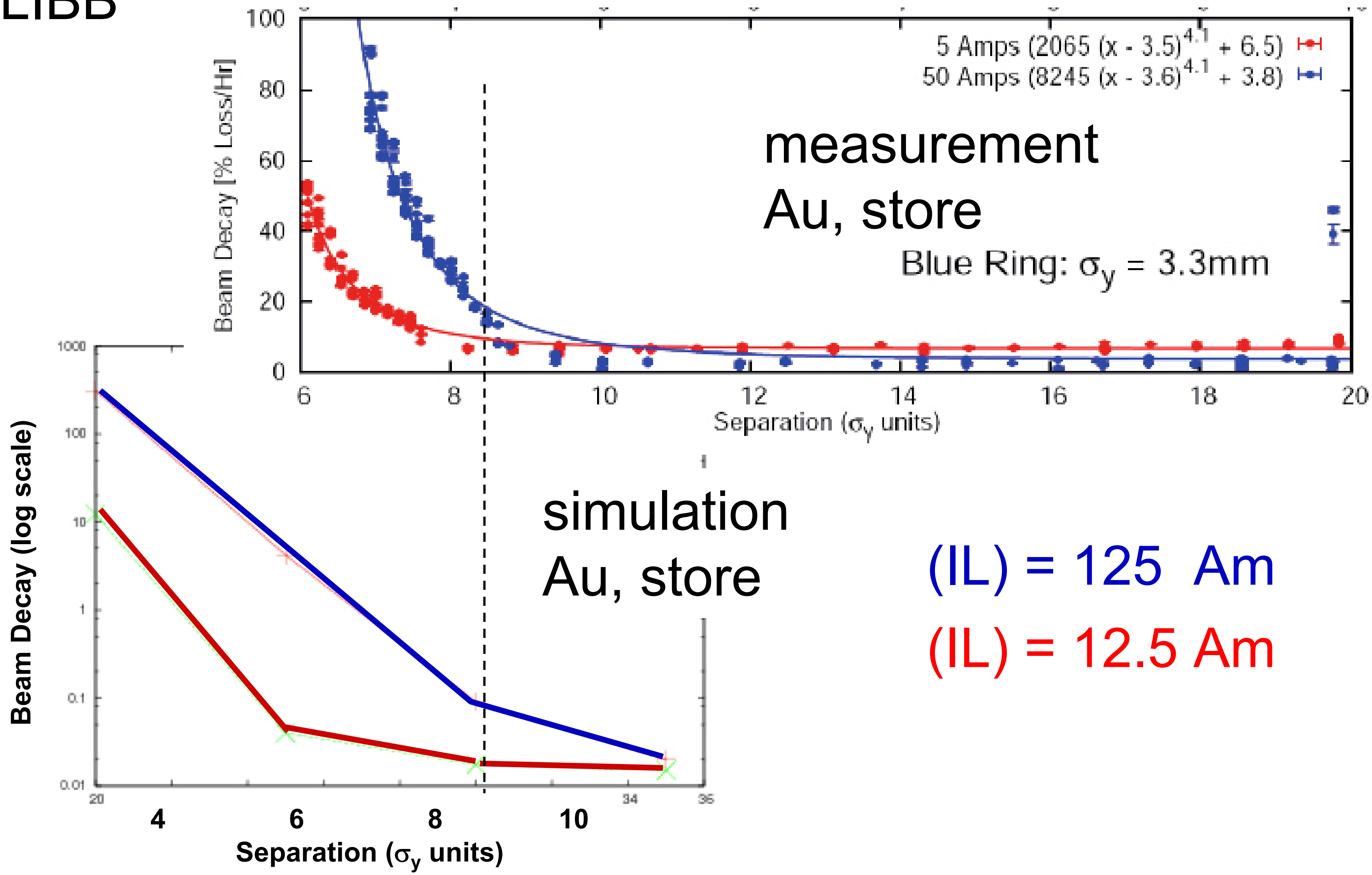


Onset of large losses reproduced within 1σ.

[U. Dorda, PhD thesis, Vienna University of Technology (2008).]

RHIC wire experiments – comparison with simulations (3)

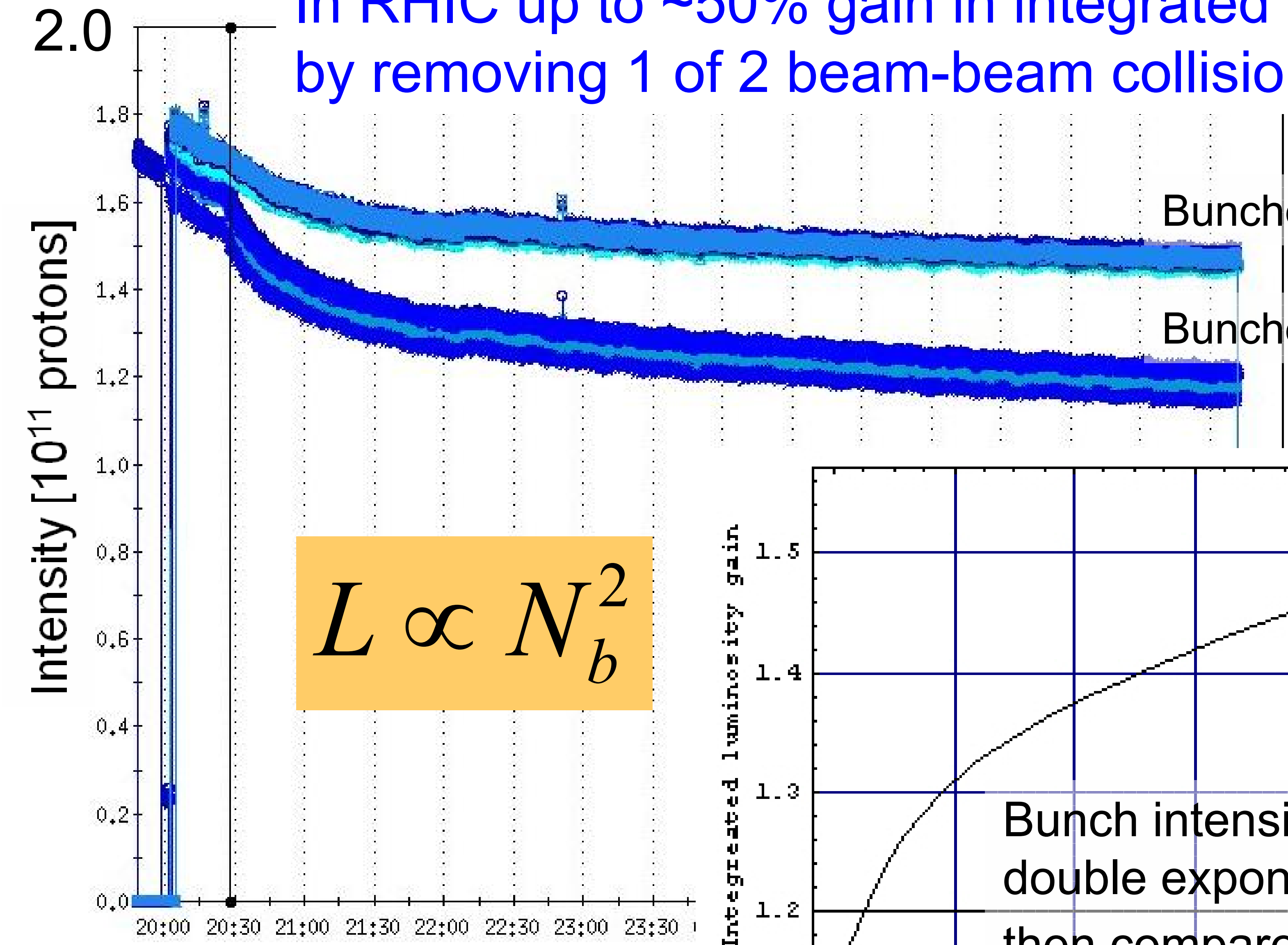
A. Kabel, SLAC
code PLIBB



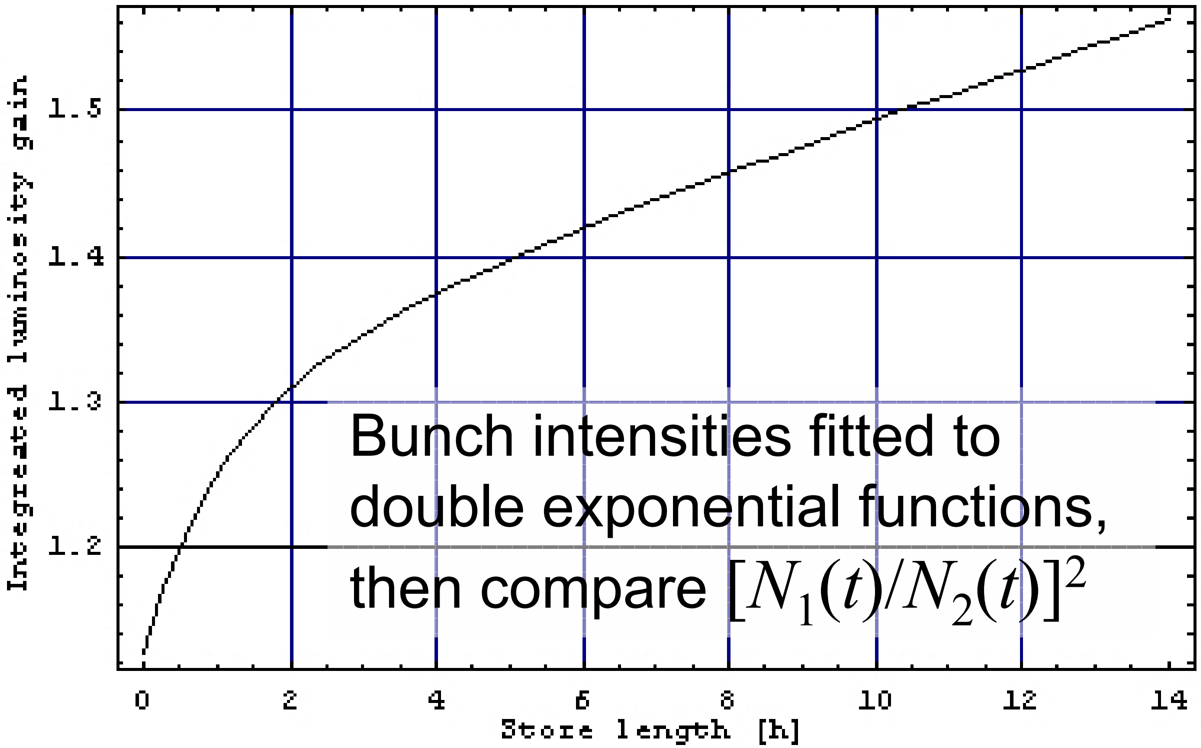
Onset of large losses reproduced within 1σ.

Head-on beam-beam compensation – Motivation

In RHIC up to ~50% gain in integrated luminosity by removing 1 of 2 beam-beam collisions,



$$L \propto N_b^2$$



Bunch intensities fitted to double exponential functions, then compare $[N_1(t)/N_2(t)]^2$

Wolfram Fischer

LHC head-on beam-beam compensation with e-lens

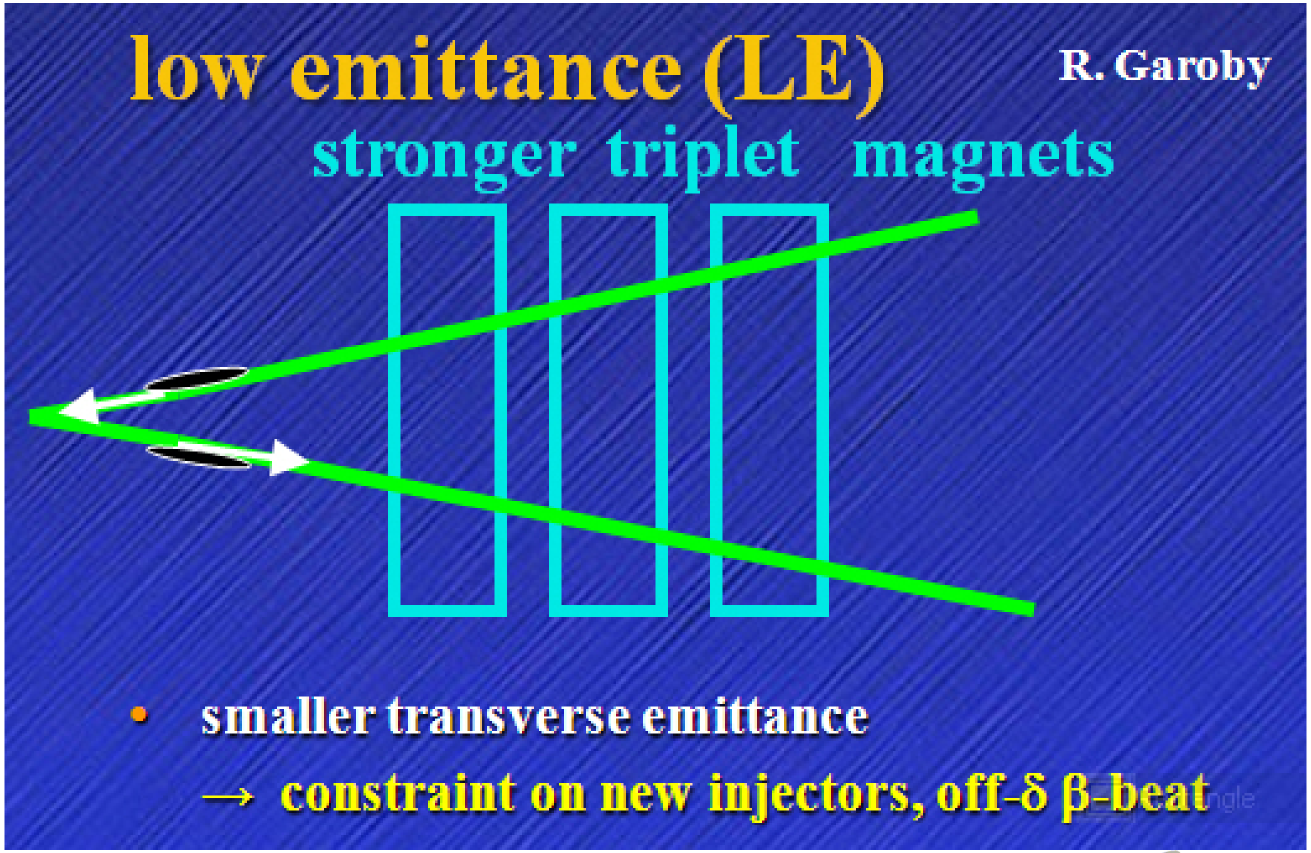
LHC Upgrade – option with Low Emittance (LE)

(1 of 4 options currently under considerations)

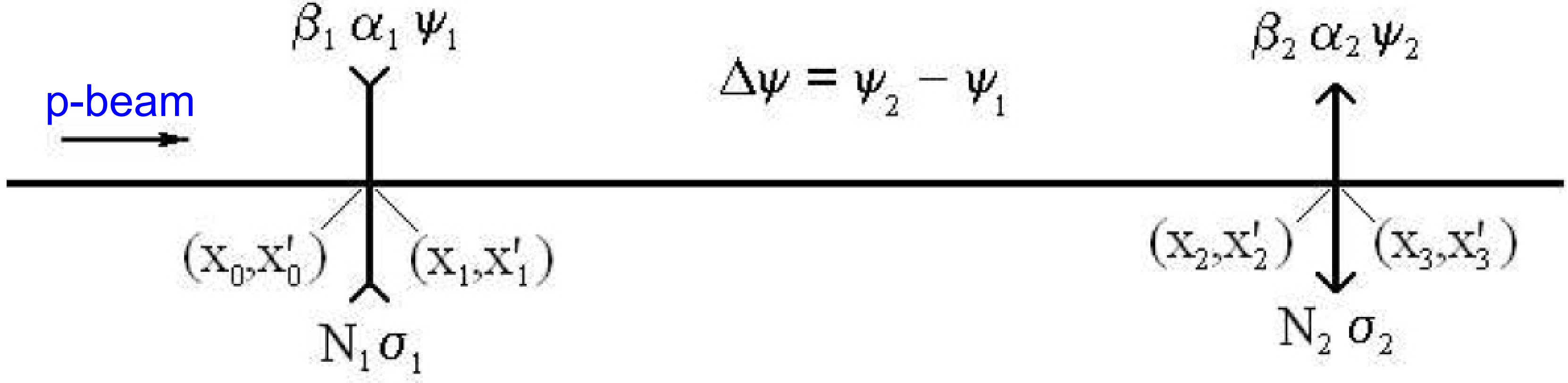
Reduced emittance and stronger focusing

[25 ns bunch spacing, N_b=1.7x10^{11}, ε_n = 1 μm (3.75 μm nominal)]

Increases beam-beam parameter ξ/IP for head-on collisions



Beam-beam compensation concept with electron lens



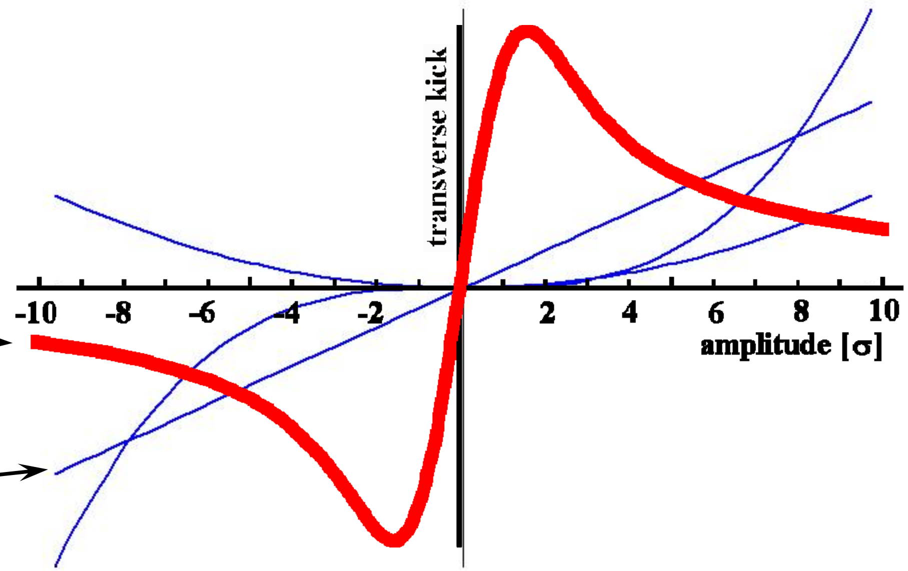
Exact compensation if $x_3(N_1,N_2) = x_3(0,0)$ and $x'_3(N_1,N_2) = x'_3(0,0)$:

1. Same amplitude dependent force in p-beam and e-beam lens, and
2. Phase advance between p-beam and e-beam lens is $\Delta\Psi = k\pi$, and
3. No nonlinearities between p-beam and e-beam lens

Condition 1 cannot be realized with magnets, requires an electron beam

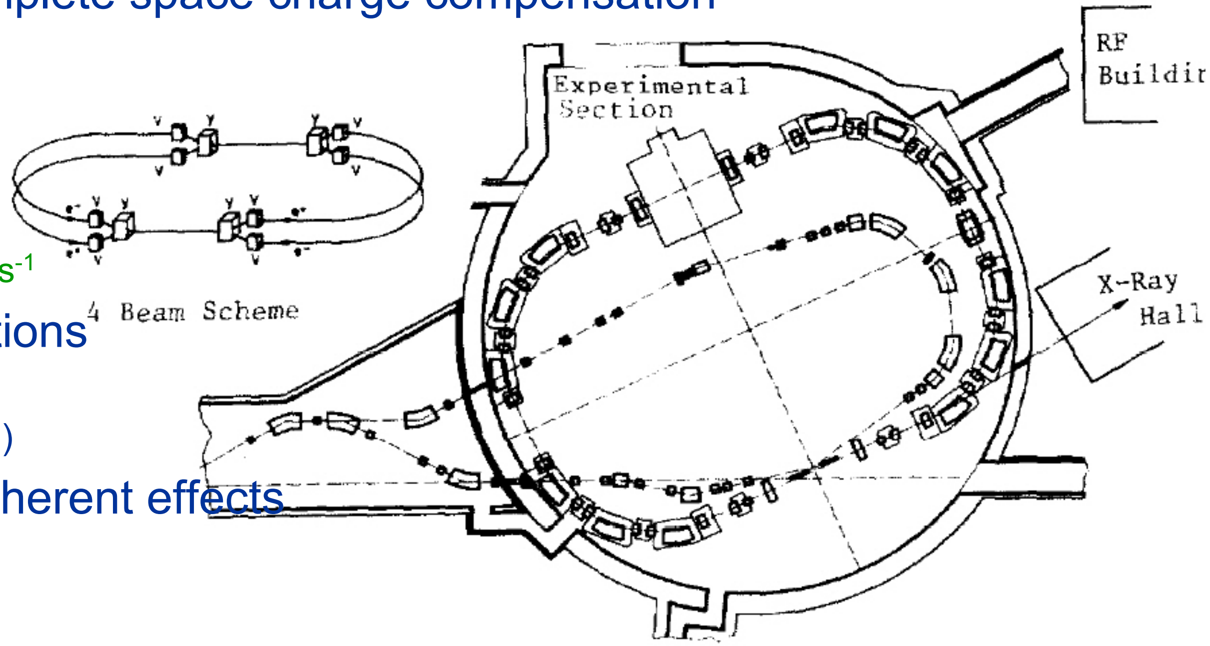
beam-beam kick

magnet kicks



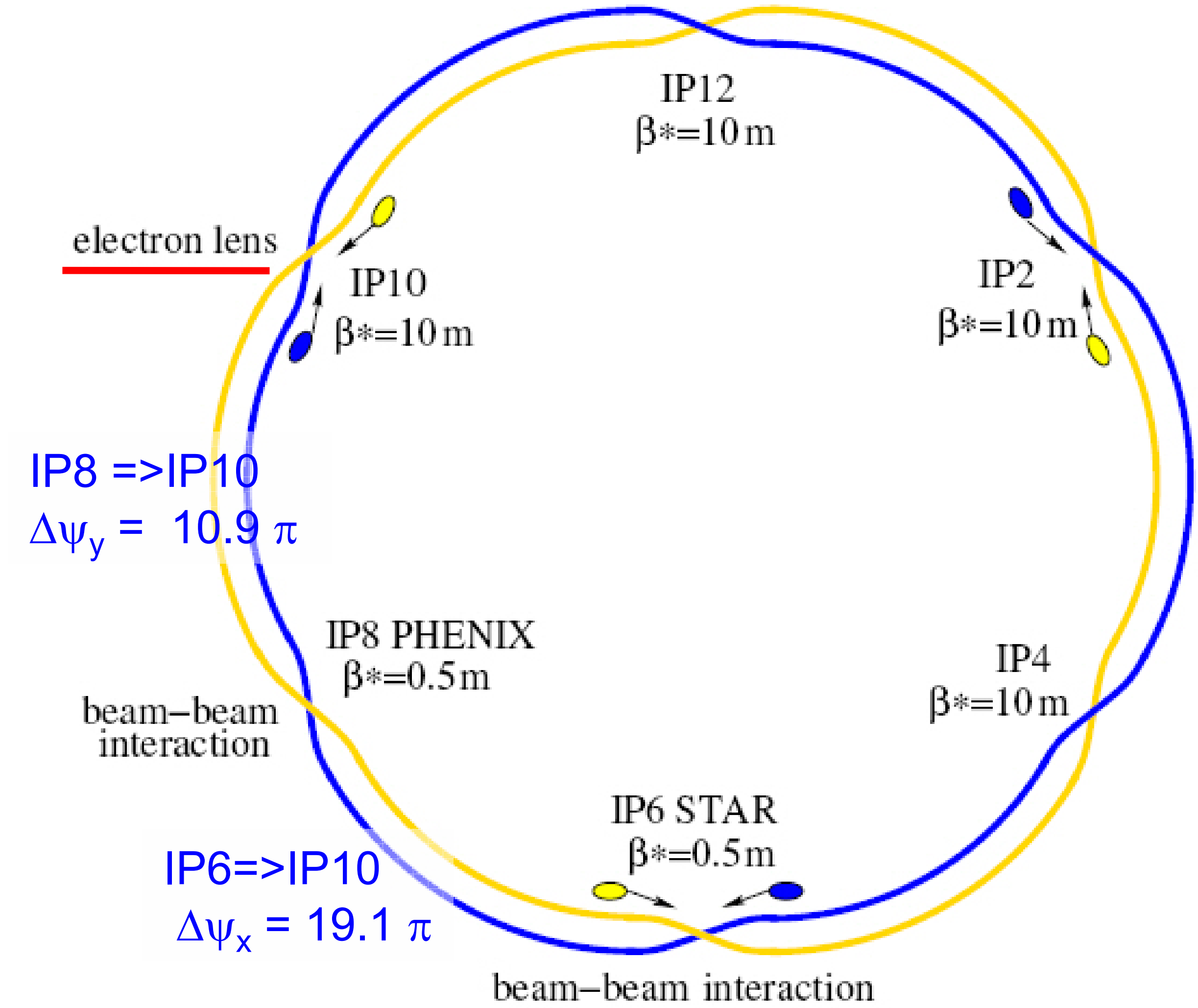
Head-on beam-beam compensation

- Head-on beam-beam compensation was only tested in DCI (~1975)
  - 4-beam collider ($e^+e^-e^+e^-$) for complete space charge compensation
  - Main parameters:
    - Circumference 94.6 m
    - Energy 1.8 GeV
    - Beam-beam ξ ~0.05-0.1
    - Luminosity (design) ~10^{32} $cm^{-2}s^{-1}$
  - Luminosity fell short of expectations by 2 orders of magnitude
    (2- and 4-beam luminosity about the same)
  - Short-fall attributed to strong coherent effects



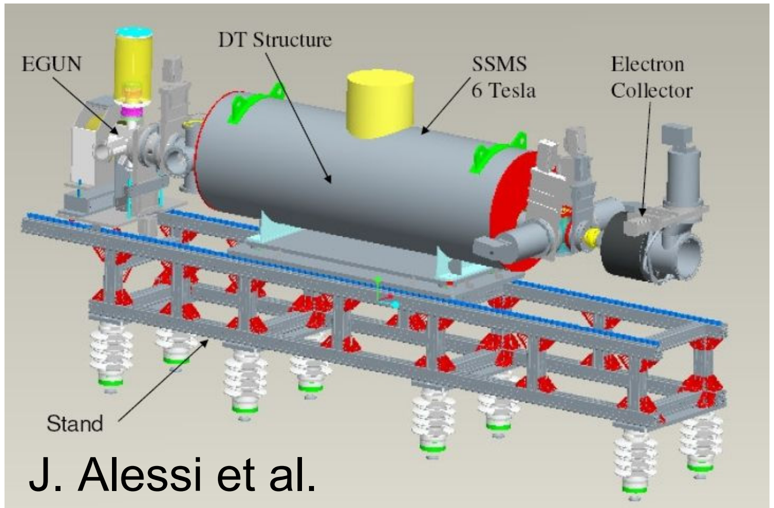
- 2 Electron lenses in Tevatron
  - Operationally used as gap cleaner (very reliable)
  - Shown to have increased beam lifetime of pbar bunches affected by PACMAN effect
    (by factor 2 at beginning of store, mostly tune shift)
  - Not used as head-on compensators
  - Have learned sensitivity to some parameters
    (relative beam position, e-beam shape, current)

RHIC head-on beam-beam compensation



2 electron lenses
to be build in RHIC
(funding for stimulus package)

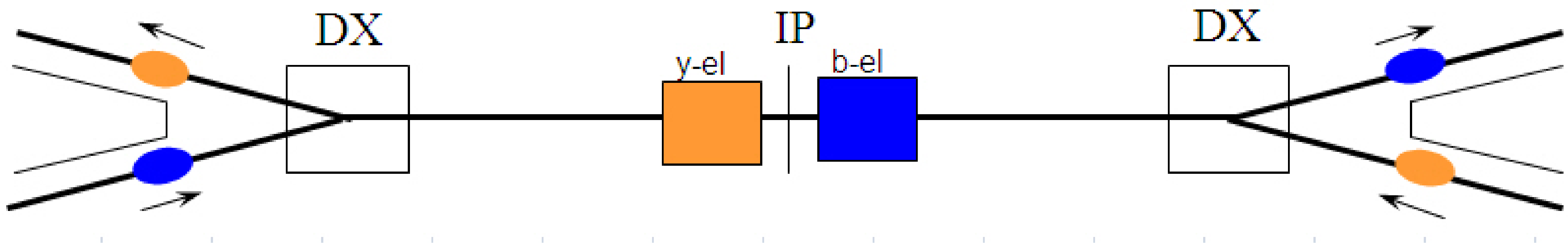
Device similar to
Electron Beam Ion Source
under construction at BNL:
e-beam guided in solenoid



[Y. Luo and W. Fischer, “Outline of using an electron lens for the RHIC …”, BNL C-AD/AP/284 (2007)]

RHIC head-on beam-beam compensation

IP10 top view of 2 electron lenses



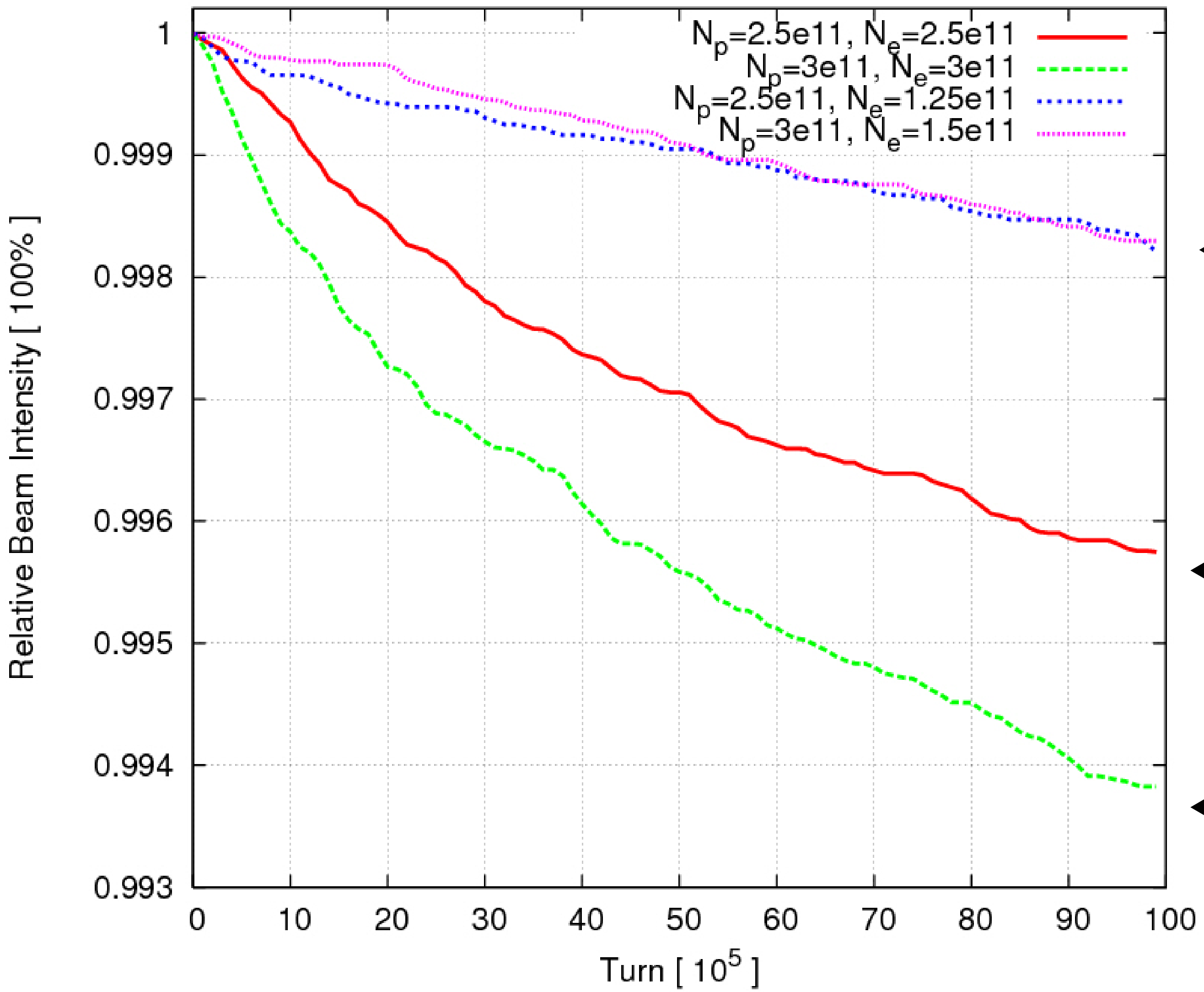
Features:

- Blue and Yellow beam vertically separated (like in other IRs)
- 2 solenoids with opposite polarity to guarantee
  - No effect on spin
  - No effect on coupling
- Aim for partial compensation only (1 of 2 beam-beam interactions)
  - Avoids footprint folding
  - $\Delta\phi_y$ close to π between IP8 and IP10 by default
  - $\Delta\phi_x$ close to π between IP6 and IP10 by default

Beam lifetime simulations for electron lenses – RHIC

Y. Luo et al. MO4RAC05

Scan of electron lens strength



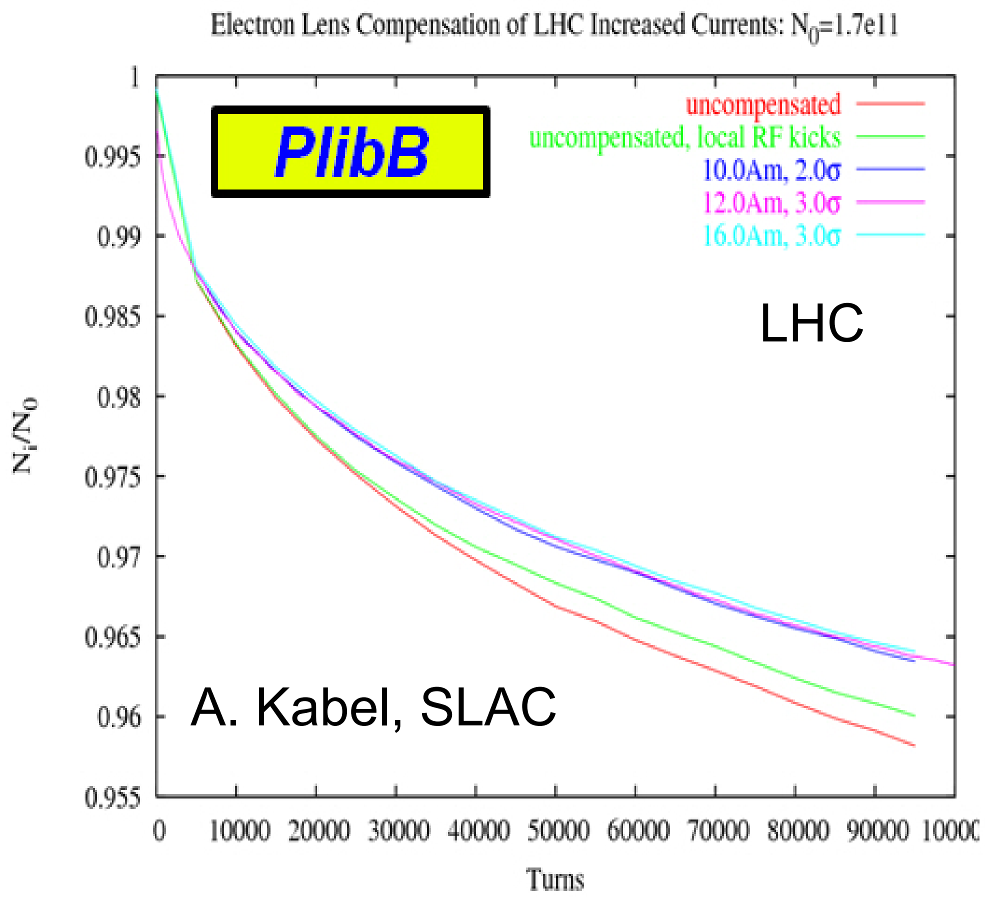
Half HOBBC
N_b = 2.5, 3x10^{11}
τ = 19.7 h

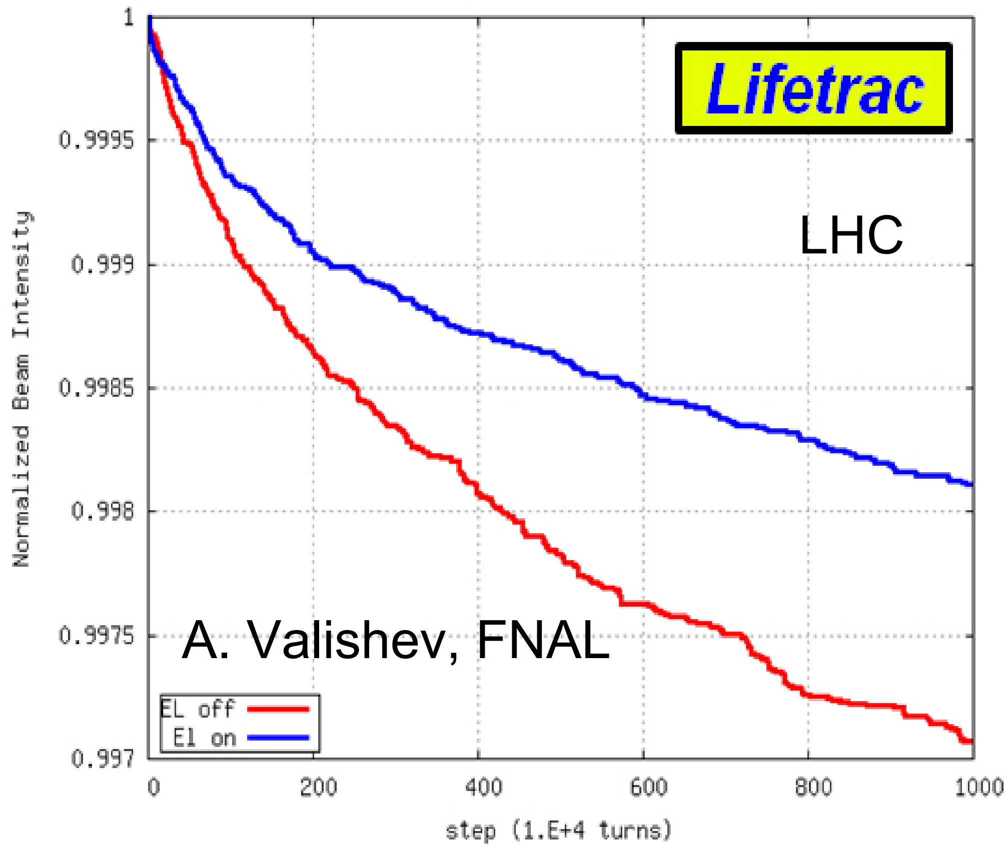
Full HOBBC
N_b = 2.5x10^{11}
τ = 8.5 h

Full HOBBC
N_b = 3x10^{11}
τ = 5.7 h

Best results with half compensation (avoids footprint folding).

Beam lifetime simulations for electron lenses – LHC





Head-on beam-beam compensation with electron lenses

Important considerations driven by p-beam

- RHIC beam size: σ = 0.25 mm rms (β_{xy} ~ 10-20 m)
- LHC beam size: σ = 1 mm rms (β_{xy} ~ 2000 m)

- Solenoid strength
  - Magnetic compression of electron beam to p-beam ✹ 6 T
- Alignment of proton and electron beam
  (found to be of critical importance in Tevatron)
  - Straightness of solenoid field (⌖25μm)
  - Instrumentation (BPMs, luminosity monitors)
- Electron gun parameters
  - Small RHIC beam sizes with possible magnetic compression from 0.2 T on gun to 6 T in electron lens requires current densities of 14 A/cm^2, need IrCe cathodes for good lifetime (A. Pikin)

Summary – LHC beam-beam compensation studies in RHIC

Long-range:

- Long-range compensation useful for nominal LHC, and particularly Large Piwinski Angle (LPA) upgrade option
- RHIC wire studies complement SPS studies and operational experience from other machines
- For RHIC experiments, onset of loss as a function of wire distance reproduced within 1 σ by 3 simulation programs

Head-on:

- Head-on compensation particularly useful for Low Emittance (LE) LHC upgrade, perhaps other scenarios
- 2 electron lenses to be constructed for RHIC
- Simulations challenging since all particles are chaotic, need to rely on beam lifetime calculations

Acknowledgments

J. Alessi, R. Alforge, E. Beebe, J. Beebe-Wang, A. Fedotov, D. Gassner, A. Jain, R. Lambiase, M. Okamura, A. Pikin, D. Raparia, S. Tepikian, J. Tuozzolo, BNL

O. Brüning, U, Dorda, W. Herr, J.-P. Koutchouk, E. McIntosh, T. Pieloni, G. Sterbini, F. Schmidt, F. Zimmermann, CERN

Y. Alexahin, V. Kamerdzhiev, A. Valishev, V. Shiltsev, FNAL

C. Milardi, INFN

K. Ohmi, KEK

J. Qiang, LBNL

A. Kabel, SLAC