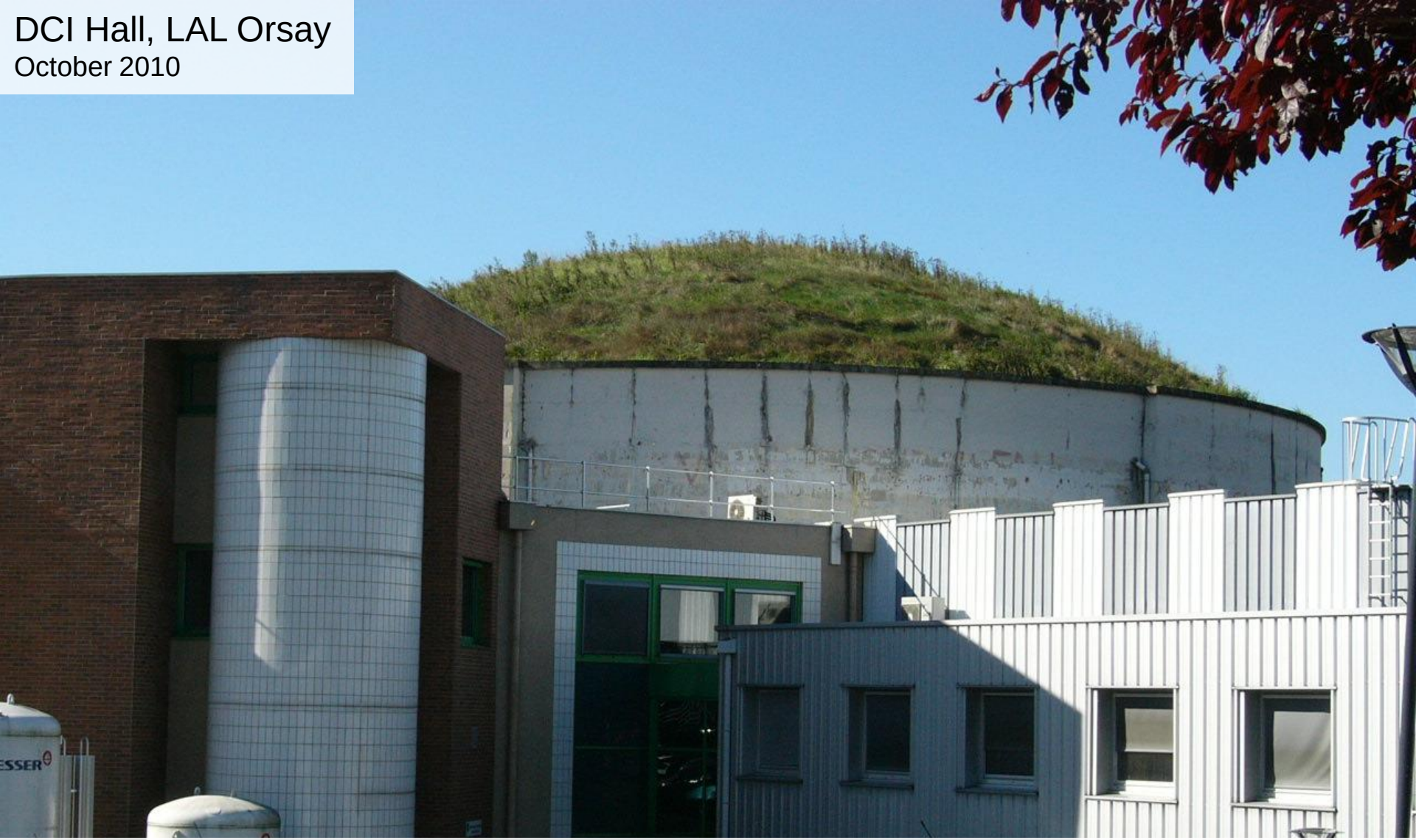


Summary beam-beam compensation

Wolfram Fischer, BNL

ICFA Mini-Workshop on Beam-Beam Effects in Hadron Colliders 18-22 March 2013, CERN

Beam-beam compensation – program

- Long-range beam-beam compensation

  long-range effects in SP(pbar)S, Tevatron, SPS, LHC, DAΦNE, and other e^+e^- colliders

  wire experiments in SPS F. Zimmermann, RHIC R. Calaga

  compensation of PACMAN effect in Tevatron (with lens) G. Stancari

  partial compensation in DAΦNE (with wire) C. Milardi

  possible compensation in LHC T. Rijoff

- Head-on beam-beam compensation

  head-on effects in Tevatron, HERA, RHIC, LHC, and e^+e^- colliders

  RHIC HOBBC with electron lenses W. Fischer

  TEL technology compensation studies G. Stancari

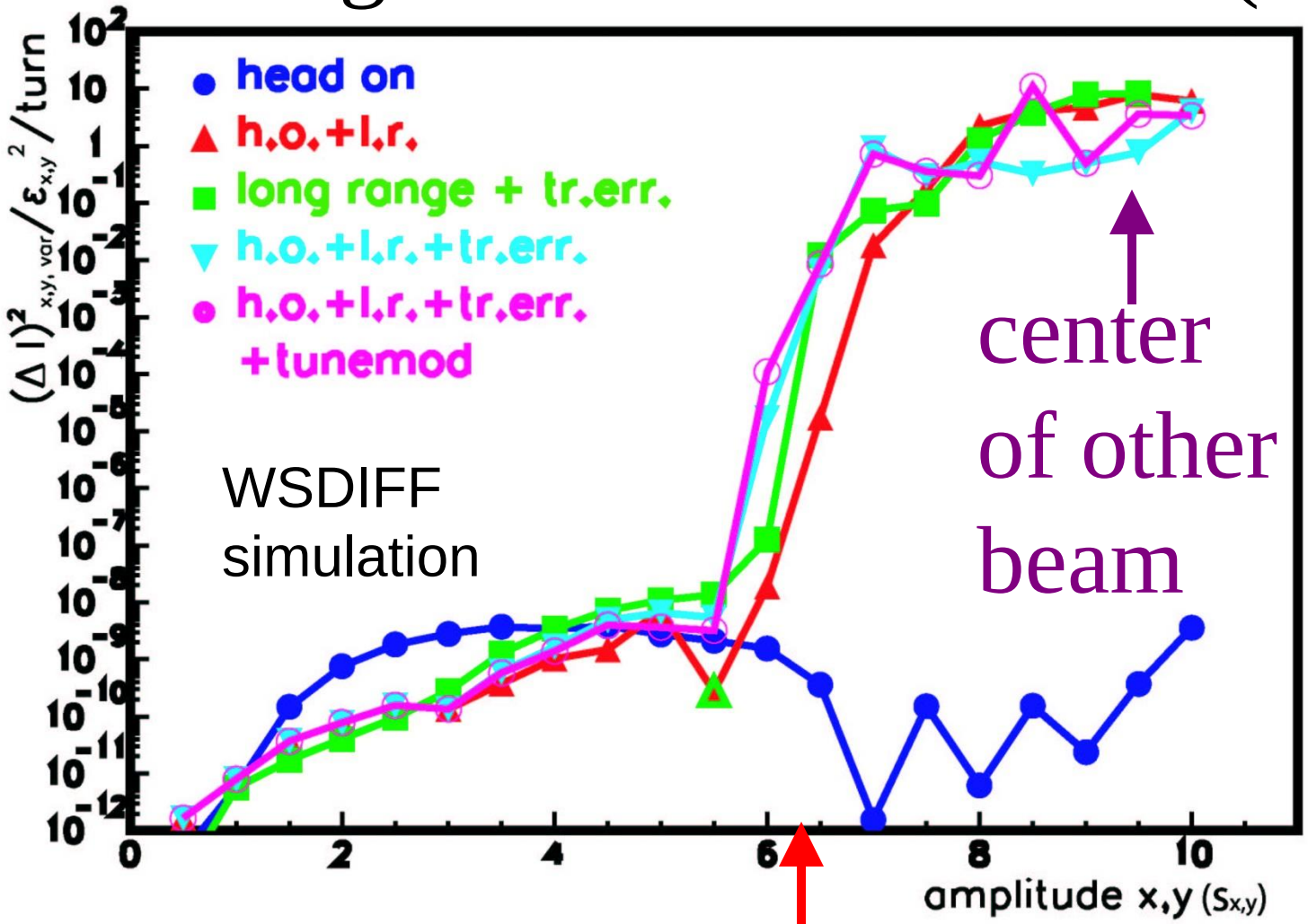
  Weak-strong simulation of RHIC HOBBC Y.Luo

  SS simulations RHIC HOBBC, instabilities S. White, comment by K. Ohmi

LONG-RANGE BEAM-BEAM COMPENSATION

weak-strong simulations for LHC (1999)

F. Zimmermann, CERN



Y. Papaphilippou
& F.Zimmermann, LHC 99

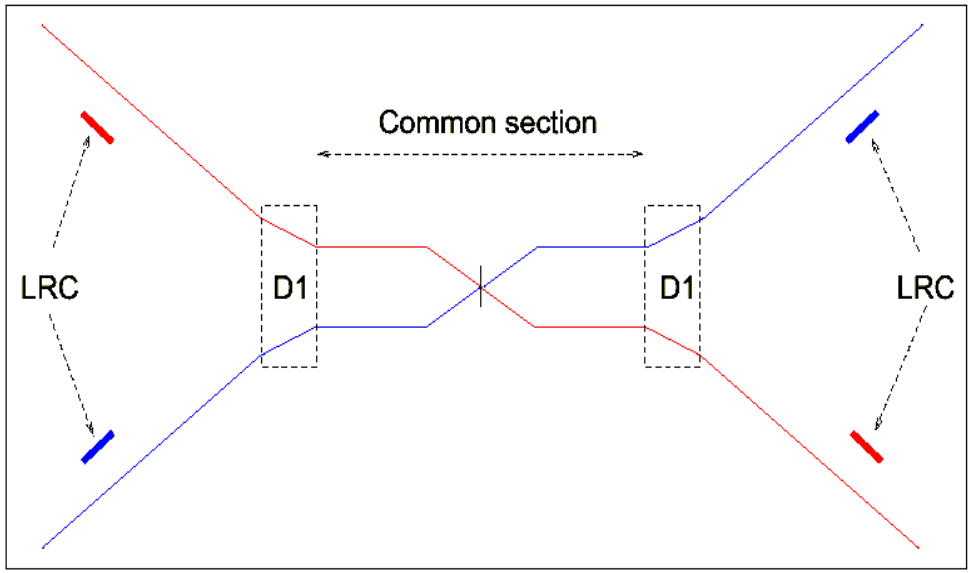
'diffusive aperture'

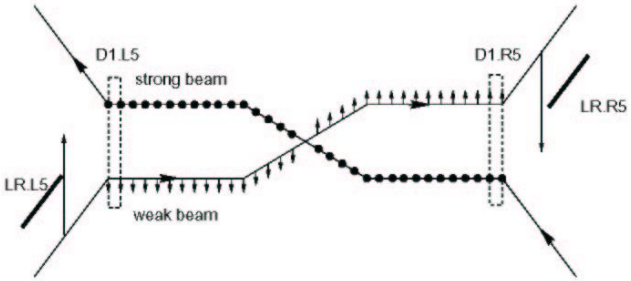
BROOKHAVEN
NATIONAL LABORATORY

proposed long-range beam-beam compensation for the LHC (2000)

F. Zimmermann, CERN

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





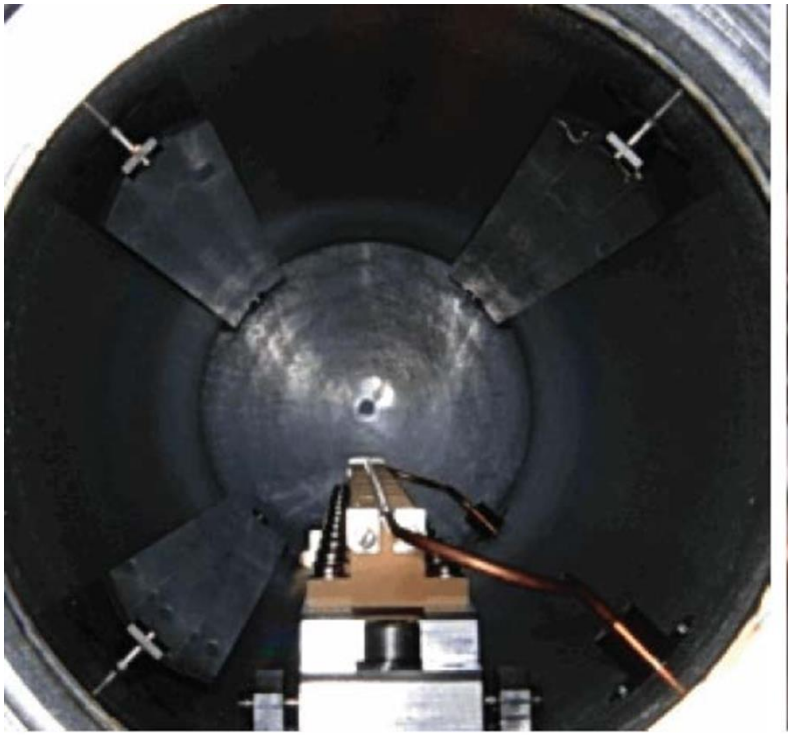
Phase difference between BBLRC & average LR collision is 2.6°

(Jean-Pierre Koutchouk)

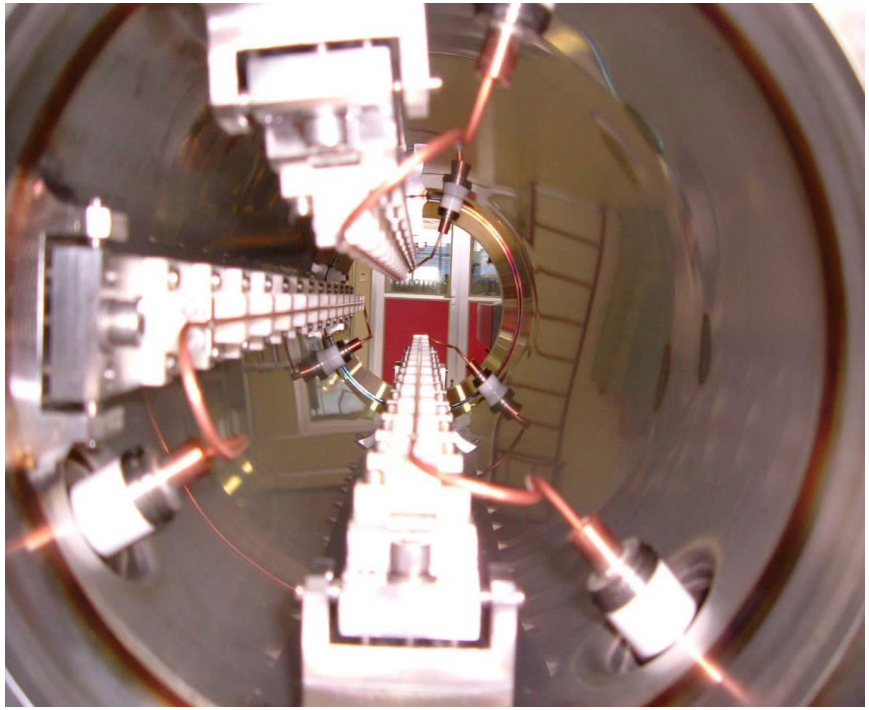
SPS wire "BBLRs"

F. Zimmermann, CERN

1st (2002)



2nd (2004)



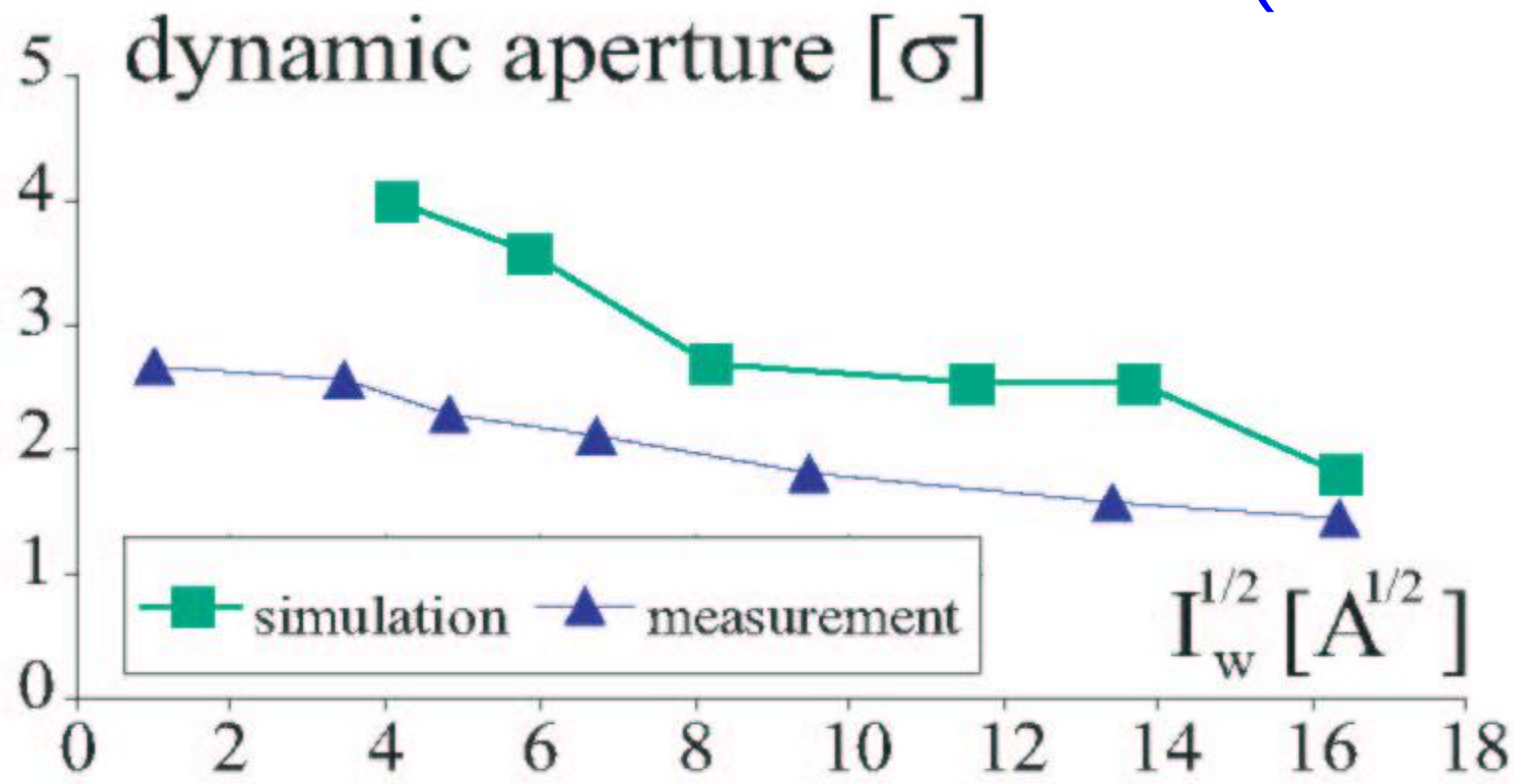
J.-P. Koutchouk, G. Burtin, J. Camas, J. Wenninger, U. Dorda, G. Sterbini, F. Zimmermann, et al

BROOKHAVEN NATIONAL LABORATORY

F. Zimmermann, CERN

effect of wire current on SPS dyn.ap.

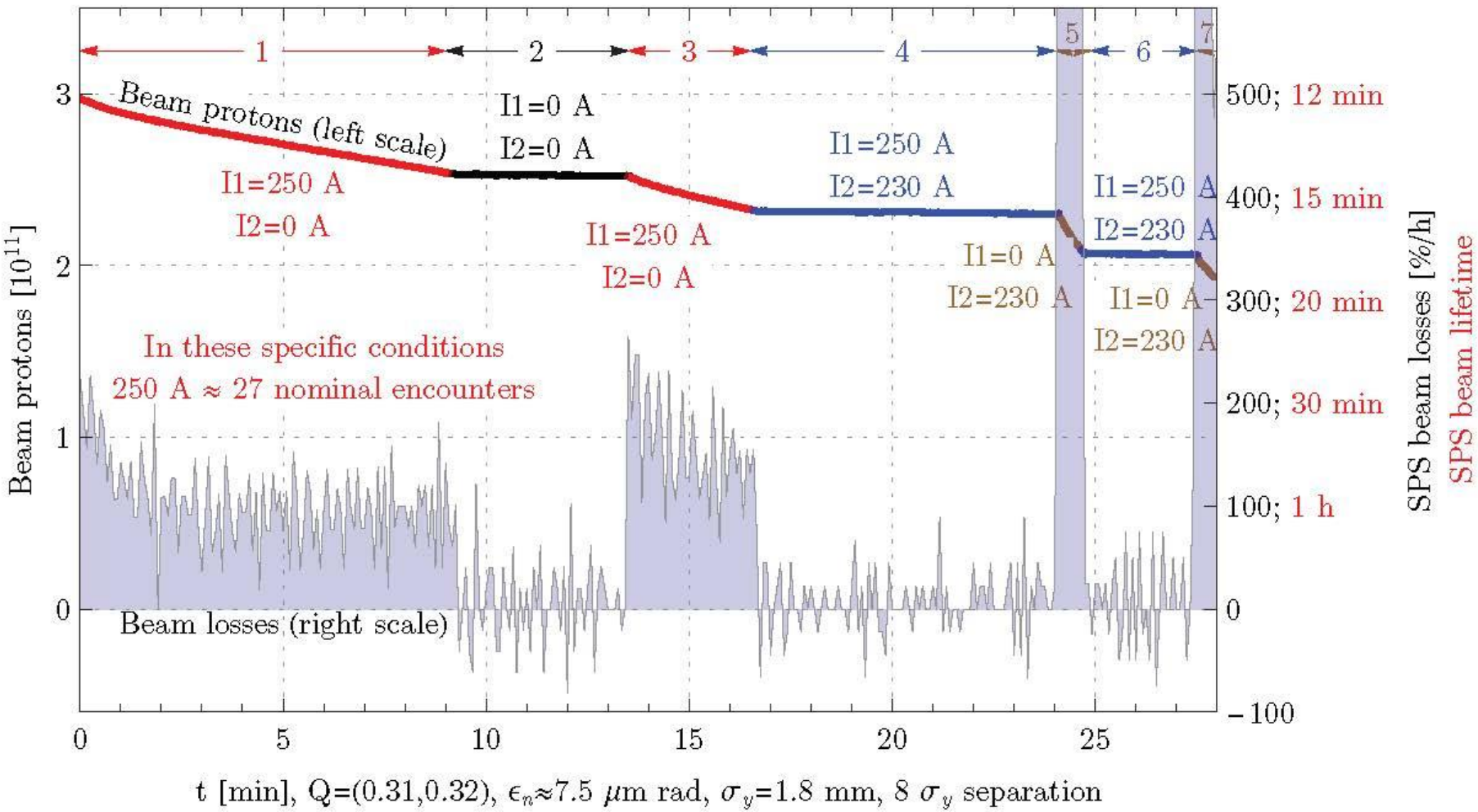
(26 GeV/c)



linear dependence DA($I_w^{1/2}$) consistent with Irwin scaling law; measured dynamic aperture is smaller than simulated

two-wire compensation: CR7, CR at 30 distance, coast at 120 GeV/c (2009)

G. Sterbini, F. Zimmermann, CERN

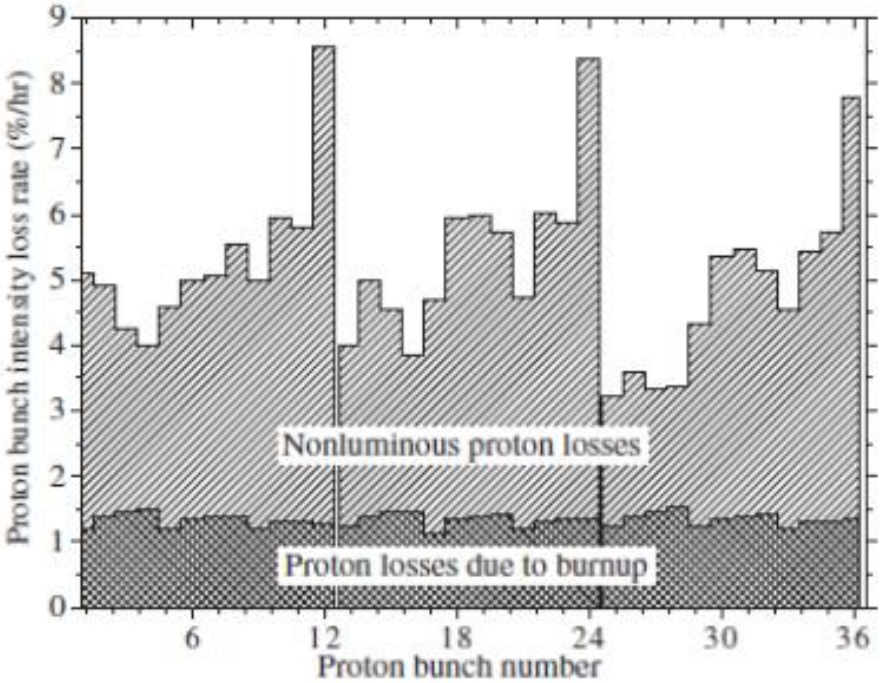


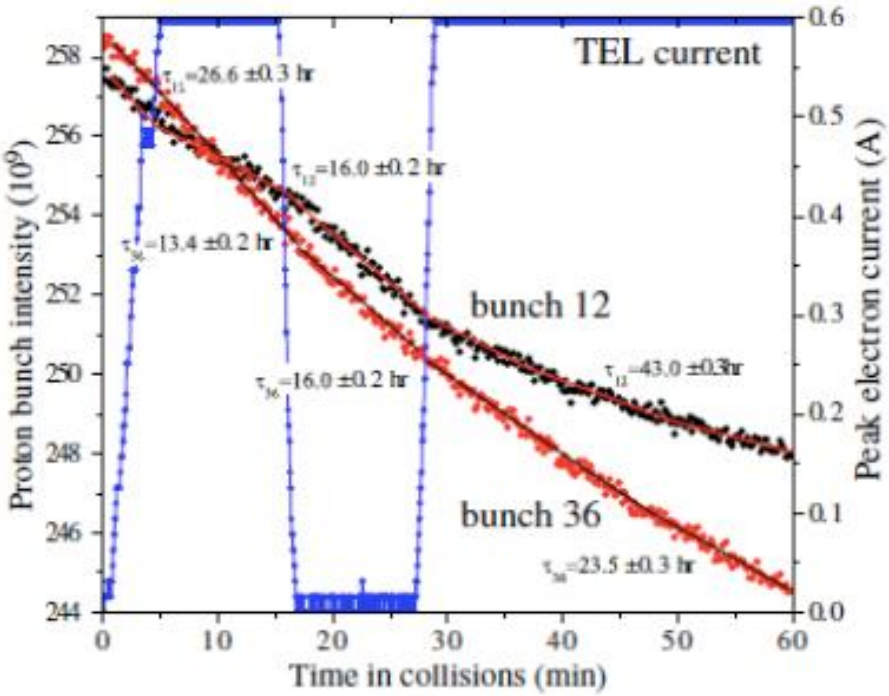
G. Sterbini

Tevatron electron lenses for long-range beam-b

G. Stancari, CERN

- 36 (3x12) proton bunches collide with 36 (3x12) antiproton bunches
- Because of collision pattern, beam-beam tune shift and losses depend on position in bunch train





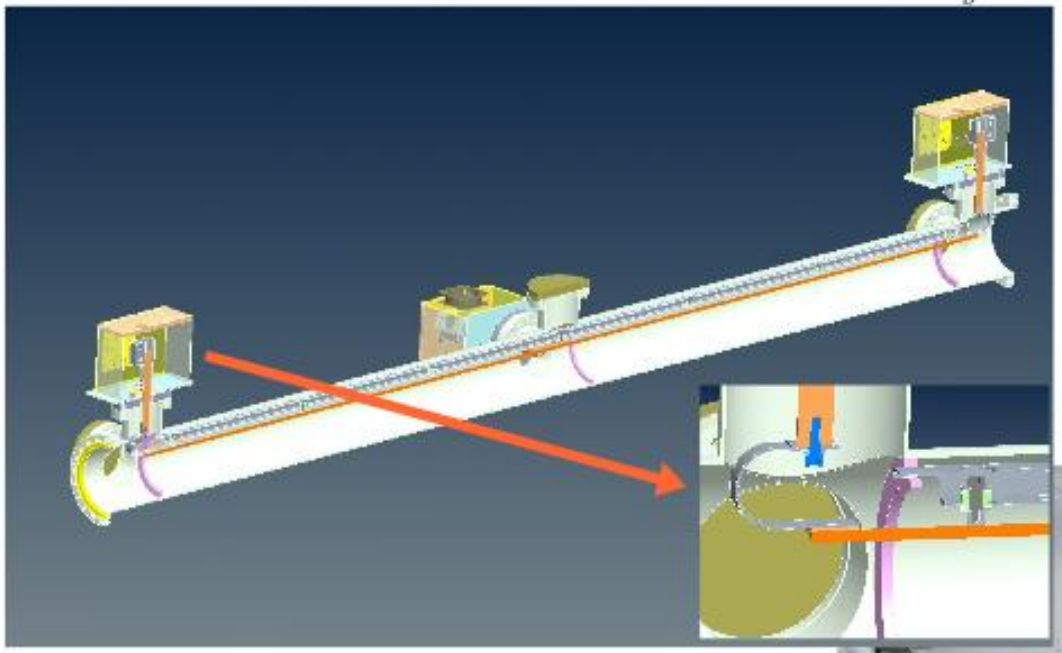
Electron lens with flat profile improves lifetime of chosen bunch

Shiltsev et al., Phys. Rev. Lett. **99**, 244801 (2007)

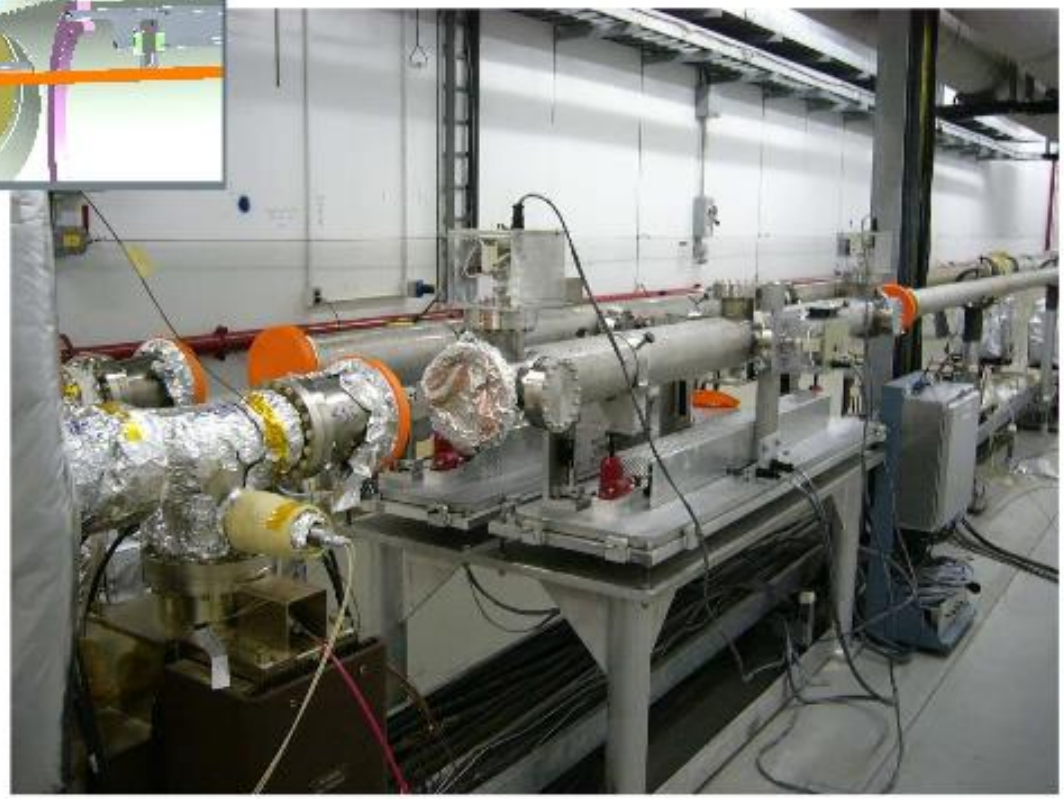
RHIC DC Wires

R. Calaga, CERN

$$IL = N_b e c$$



- Based on experience from SPS
- Vertically movable wire in each ring
- Air cooled, ΔT_{max} = 15K



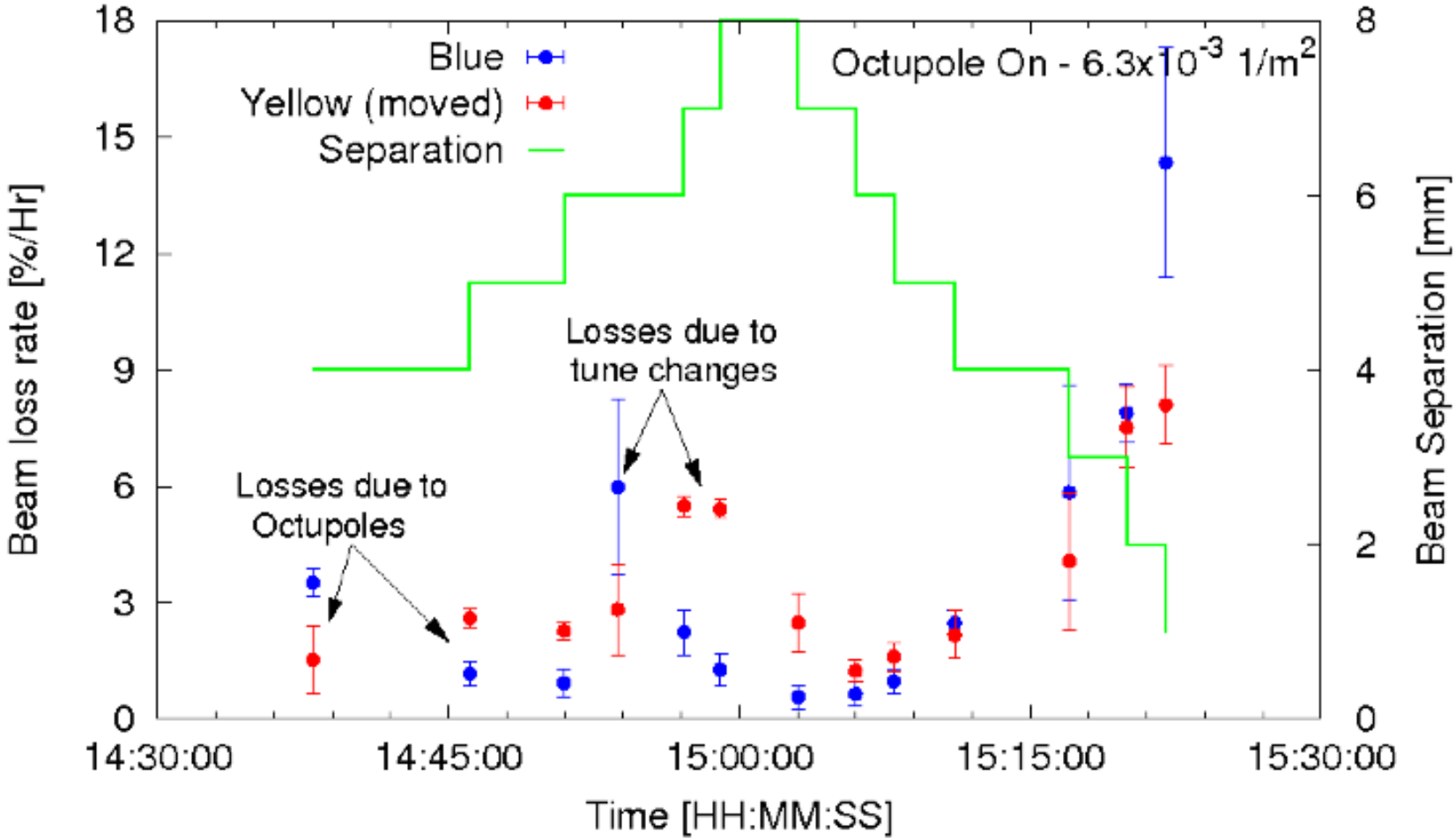
Length	=	2.5 m
Radius	=	3.5 mm
IL	=	10-125 A.m
Ripple	<	1.7×10^{-4}

I: Beam Losses, Position Scan

R. Calaga, CERN

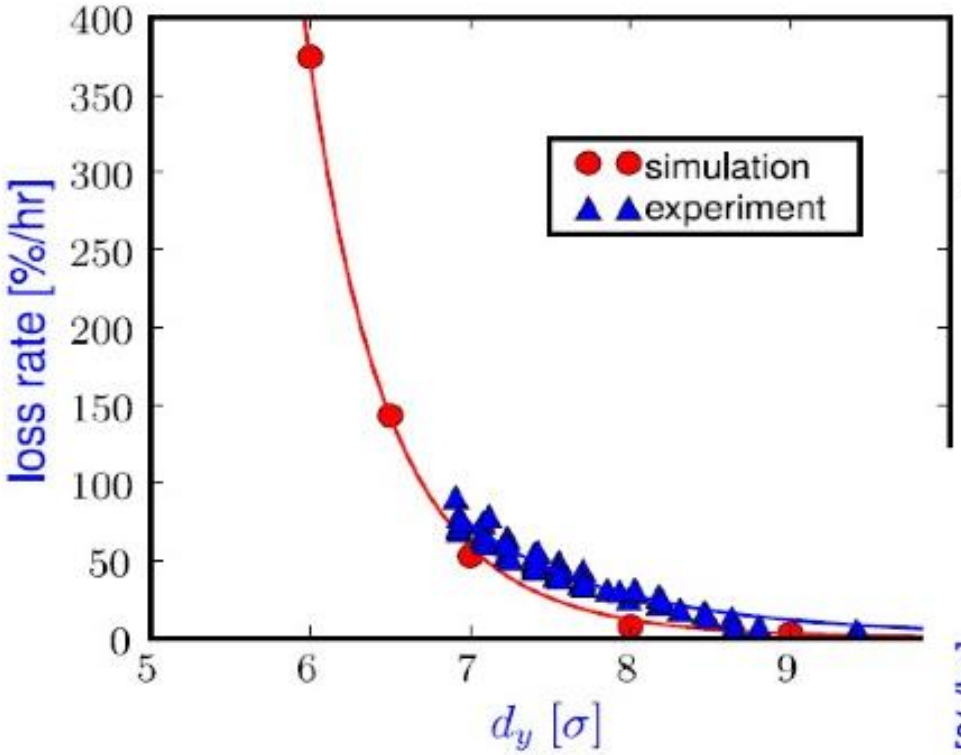
Observe Blue lifetime from movement of Yellow beam

Separation 8 → 2 σ

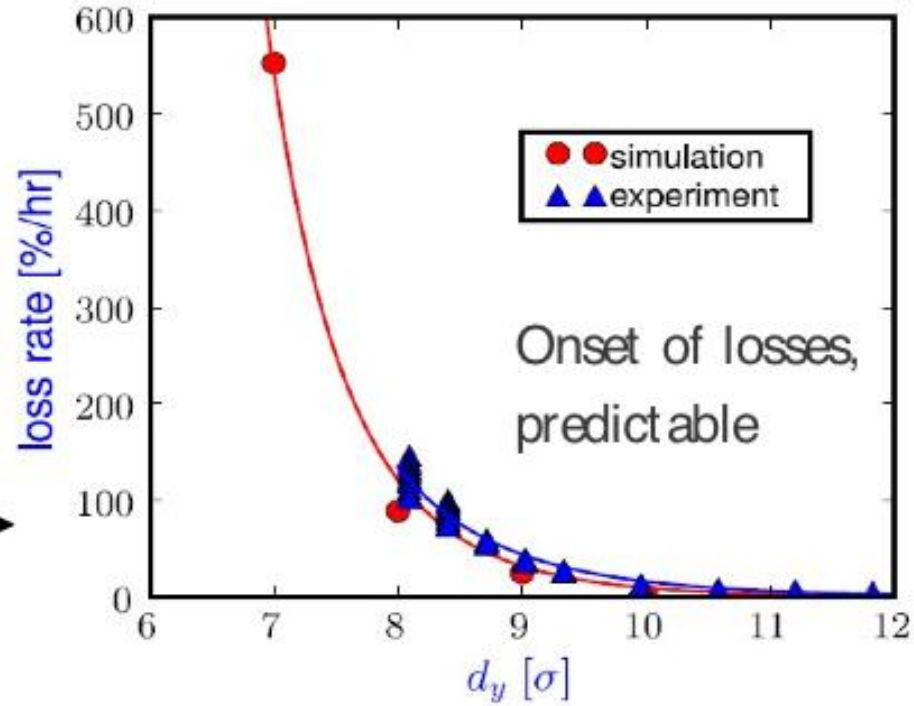


II: Loss Rates & Simulations

R. Calaga, CERN



Au @100 GeV
Wire Current, 50 A



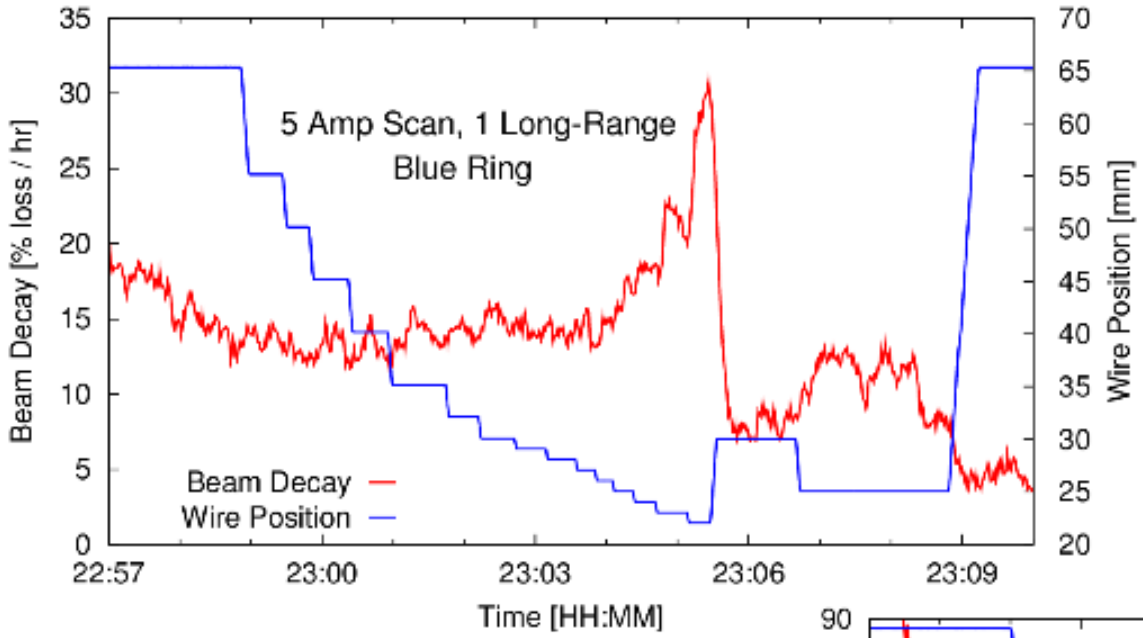
Deuterons @100 GeV
Wire Current, 50 A

BBSIMC Code, T. Sen, H.-J. Kim

H.-J. Kim et al., PRST-AB 12, 031001 (2009)

III: LRC Compensation Exp, 5A

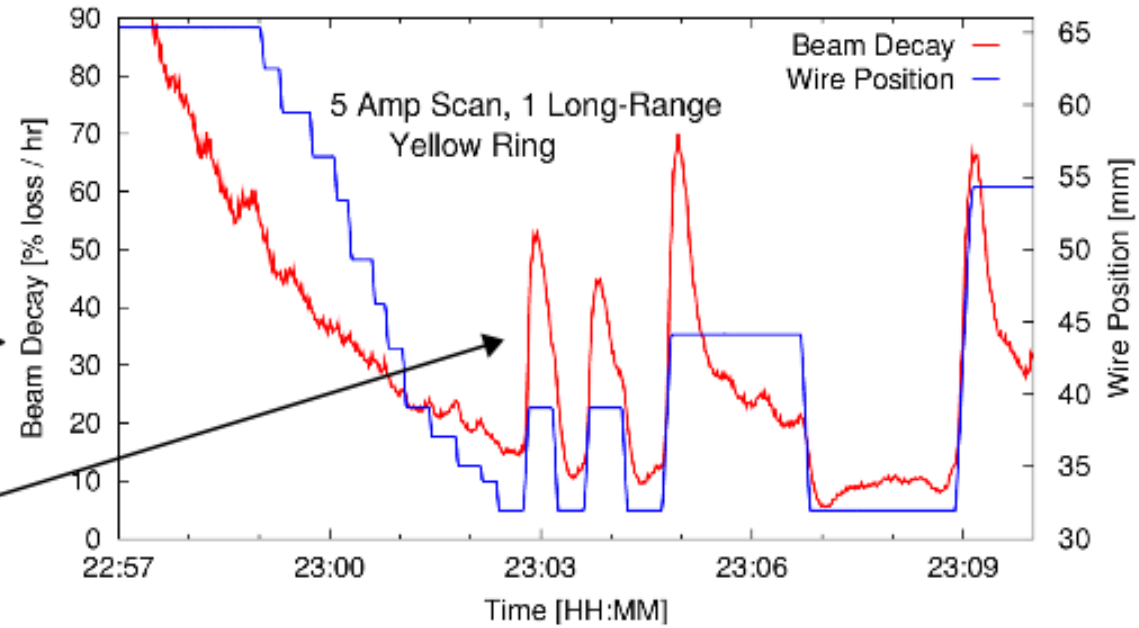
R. Calaga, CERN



Blue Ring

No visible effect

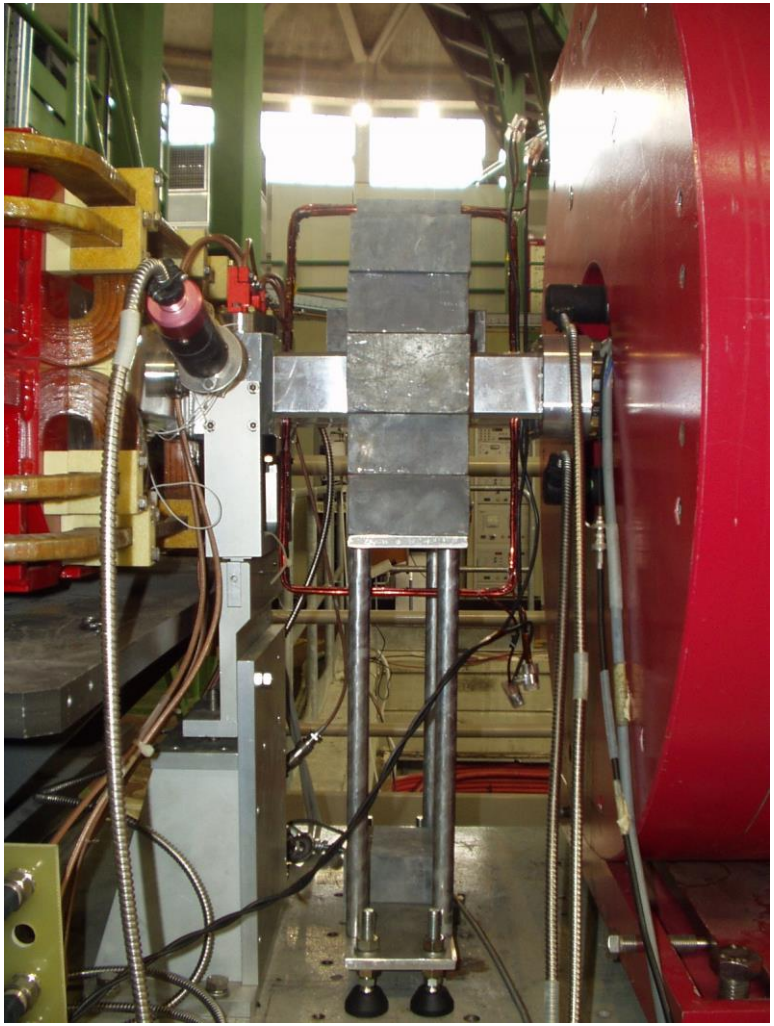
Yellow Ring



Losses increase when compensation is removed !!!

C. Milardi, INFN

The wires installed on one side of the IR1 between the splitter magnet (left) and the compensator solenoid (right)

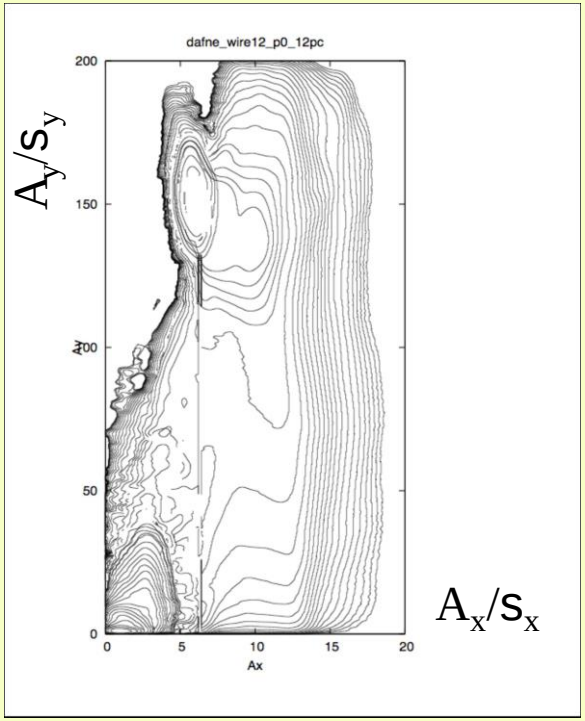


Wires in DAΦNE
(outside vacuum)

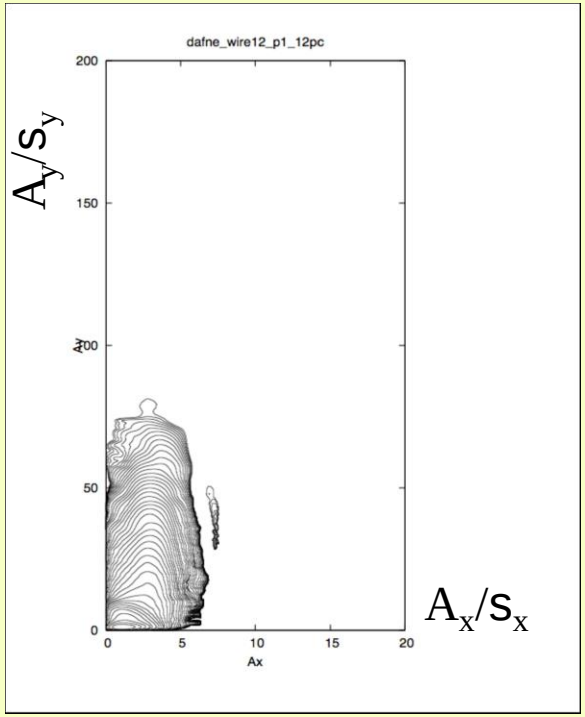
RESULTS from LIFETRACK

C. Milardi, INFN

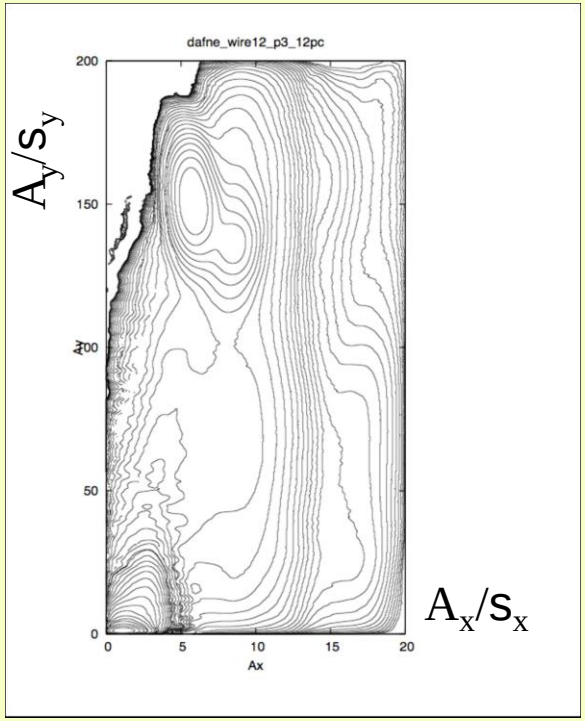
$A_{x,y}$ are the particle equilibrium density in the transverse space of normalized betatron amplitude



Wires OFF



Wires ON

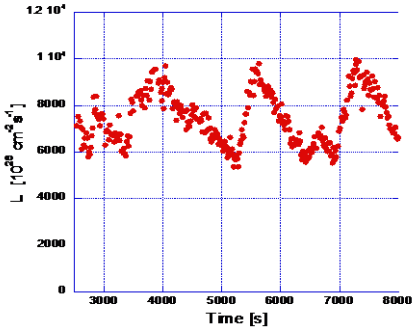


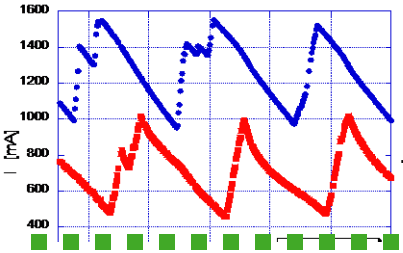
Wires ON (wrong polarity)

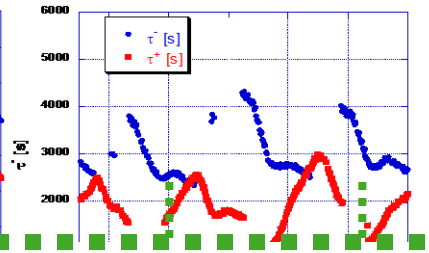
Systematic study (March 2006)

C. Milardi, INFN

WIRES ON

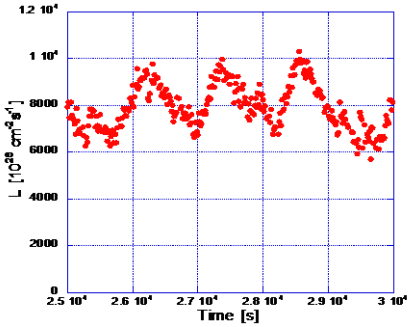


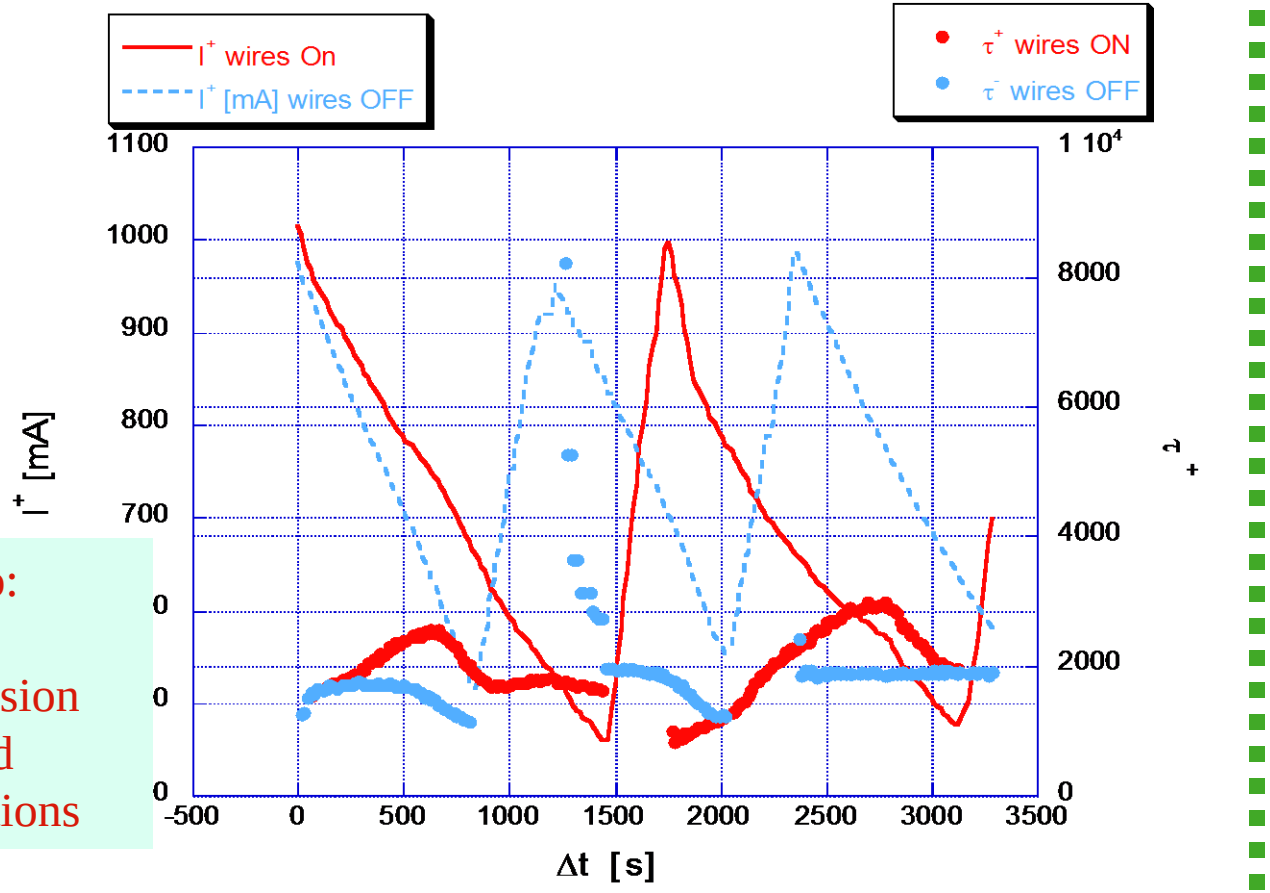




L

WIRES OFF

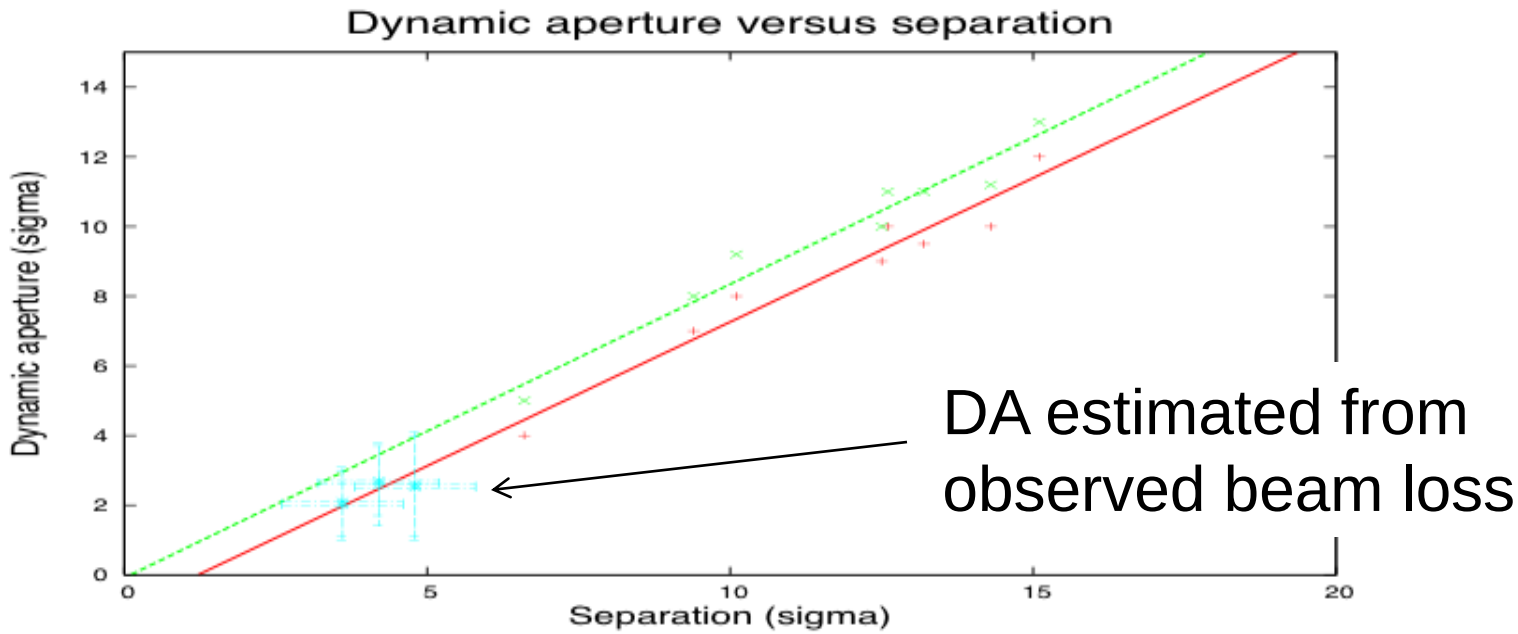




Have shown that is possible to:

- improve the lifetime t^+ of 'weak' e+ beam in collision
- deliver the same integrated luminosity with less injections

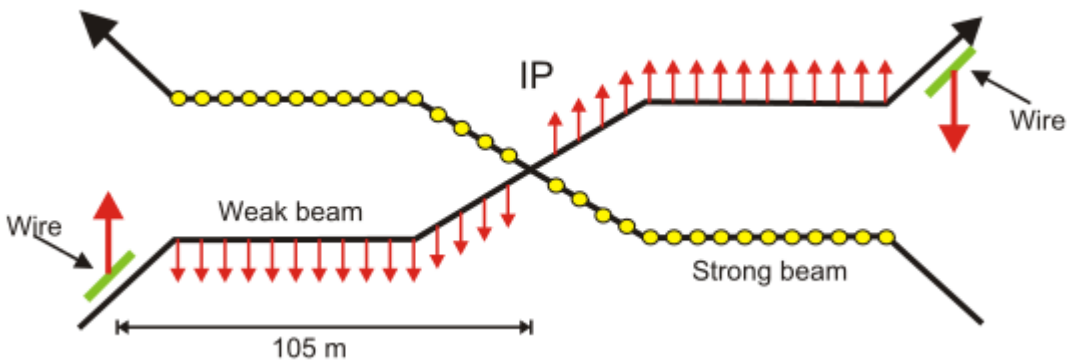
Comparison with our expectations



- Data estimated from separation scan (50 ns, 3.5 TeV, 1.25 10^{11}p)
- Dynamic aperture as function of normalized separation (W.Herr, D.Kaltchev, LPN 416, (2008))

The Wire Compensator

Compensate long range beam beam with a wire



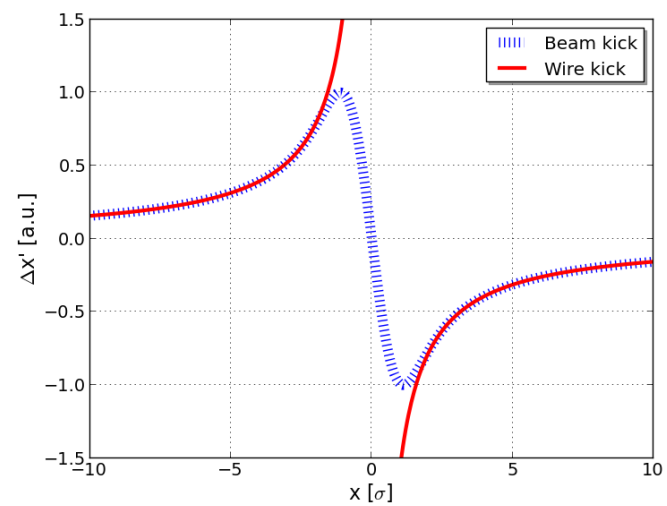
Motivation:

Head On: at IP beams collision

Long Range: electromagnetic beam be

In our analysis

HOLR -> Head On at IP1 and IP5
16 Long Range before IP
16 Long Range after IP



Prototype solutions

BBC location not available for

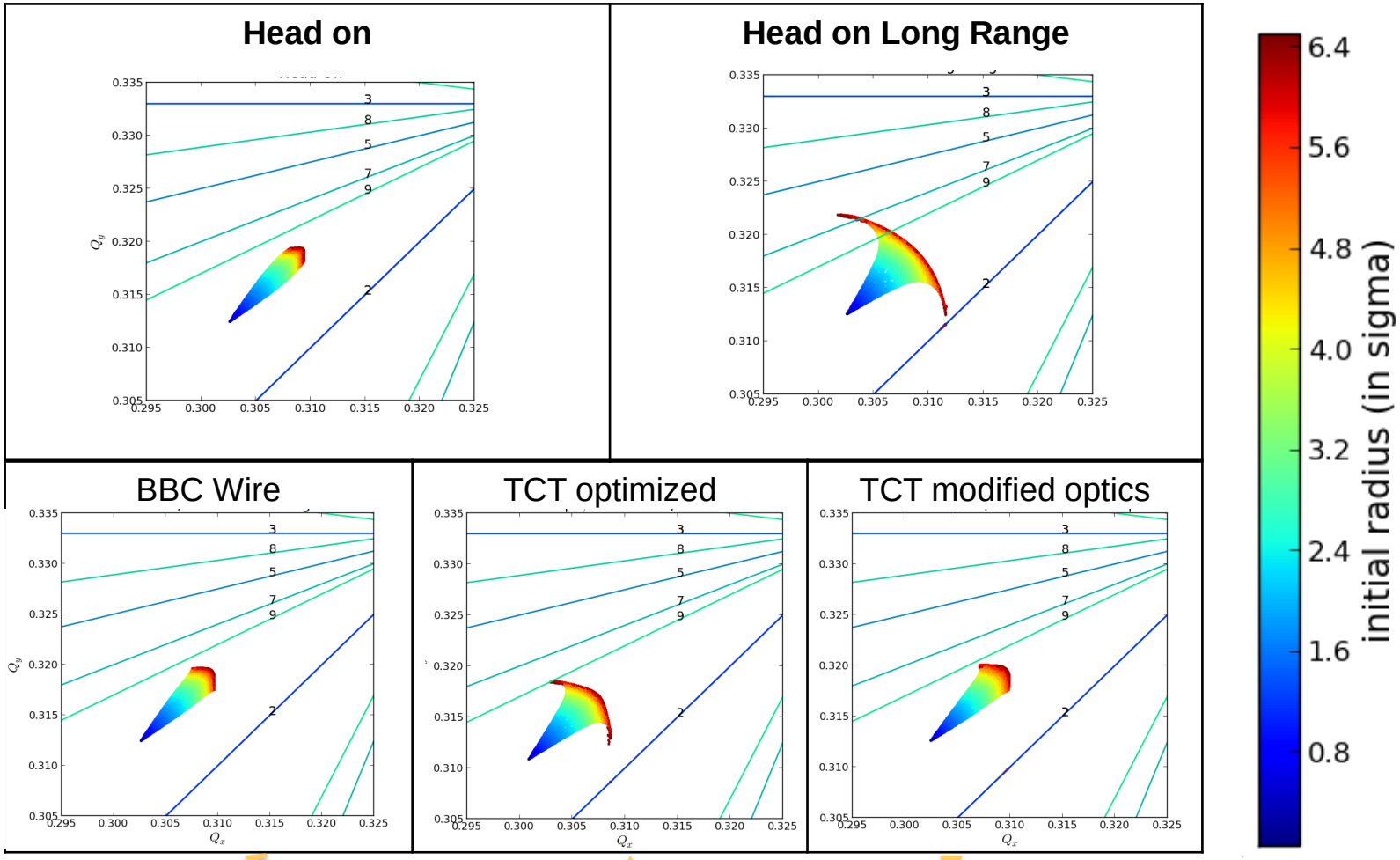
Different solutions analized, best for:

Wire in the shadow of TCT

- Using nominal optics (with β= 0.55m at IP):
  - 147 m after IP1
  - 147 m before IP5
- Using a modified optics [1] (with β= 0.60m at IP):
  - 147 m before IP1 and IP5

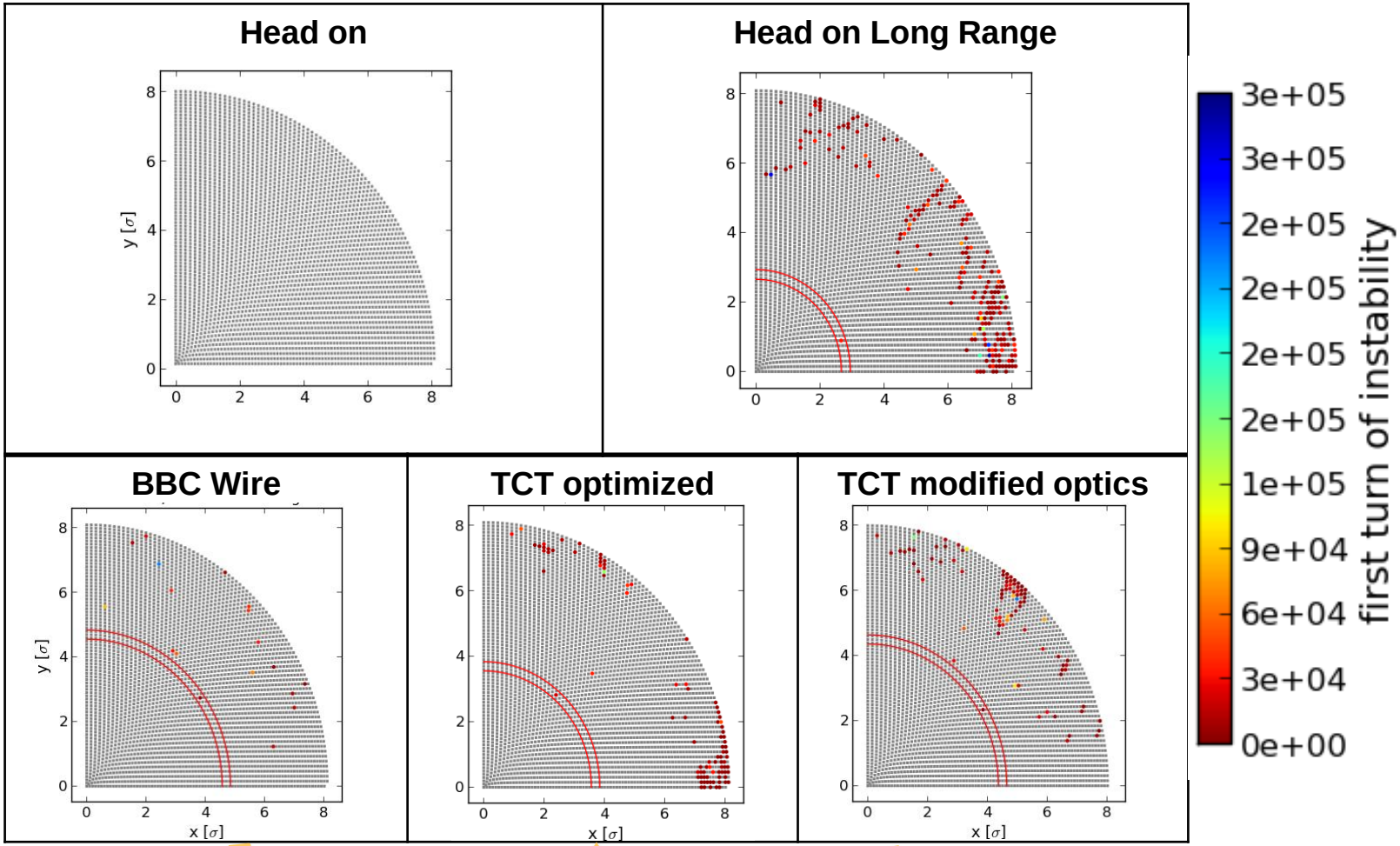
1) Courtesy of S. Fartoukh

Best Tune results



Wire at 9.5 σ – 177 A

Best Stability results



Wire at 11 σ – 237 A

Conclusions

- ✓ We studied a possible compensation of long range beam beam effects in LHC with a DC wire compensator
- ✓ We analyzed the tune and stability for different configurations
  - ✓ Wire Longitudinal positions
  - ✓ Wire Transverse position
  - ✓ Wire Current
  - ✓ LHC optics
- ✓ From tune analysis
  - ✓ best transverse location 9.5 σ with current 177 A
- ✓ From stability analysis
  - ✓ best transverse location 11 σ with current 237 A
- ✓ Longitudinally, best compensation at BBC location
- ✓ Promising results also at TCT opt β or TCT with modified optics

- ✓ Varying the crossing angle we see that wire compensator allows to reduce crossing angle of 1-2 σ maintaining the same stable region
- ✓ Wire shape (sqare vs pencil like) doesn't affect our results

Long-range beam-beam compensation

- Large body of experimental long-range data

  SP(pbar)S, Tevatron, SPS RHIC, DAΦNE, other e^+e^- colliders…

- Still no reliable calculation/simulation of $N(t)$ and $\sigma(t)$ over time scale of interest (~h) with strong beam-beam effects

  models ok if BB moderate (e.g. Tevatron), or adjusted with free parameters

- Dynamic/diffusive aperture/distance with onset of losses reproduced with ~1σ in SPS/RHIC/(LHC)

  (DA is a better measure for LR than for HO)

- Partial long-range compensation demonstrated in DAΦNE

  improvement of e^+ beam lifetime, consistent with LIFETRACK simulations of transvers density

- Can expect that simulations provide good guidance for LHC

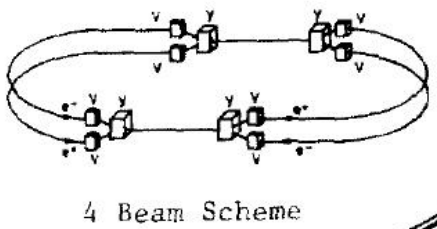
- Challenge in LHC: wire needs be within constraints of machine protection system (part of a collimator)

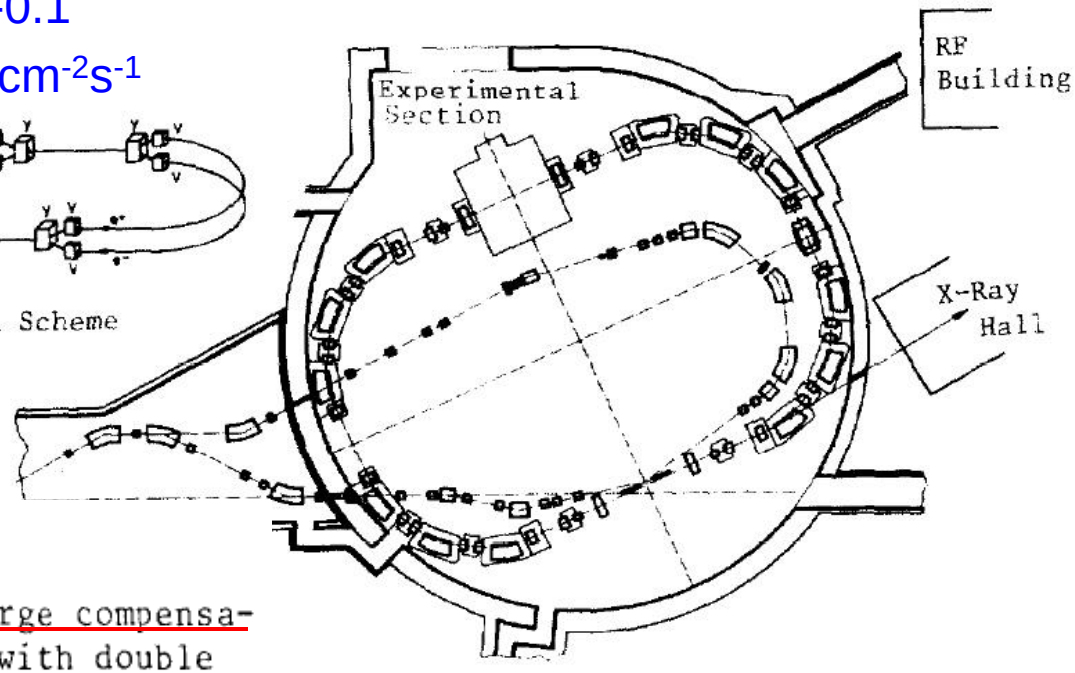
HEAD-ON BEAM-BEAM COMPENSATION

Head-on beam-beam compensation in DCI

- Head-on beam-beam compensation was only tested in DCI (starting in 1976)
- 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 by ~100x compared to expectations
  (2-, 3-, and 4-beam *L* about the same)

The Orsay Storage Ring Group, "Status report on D.C.I.", PAC77



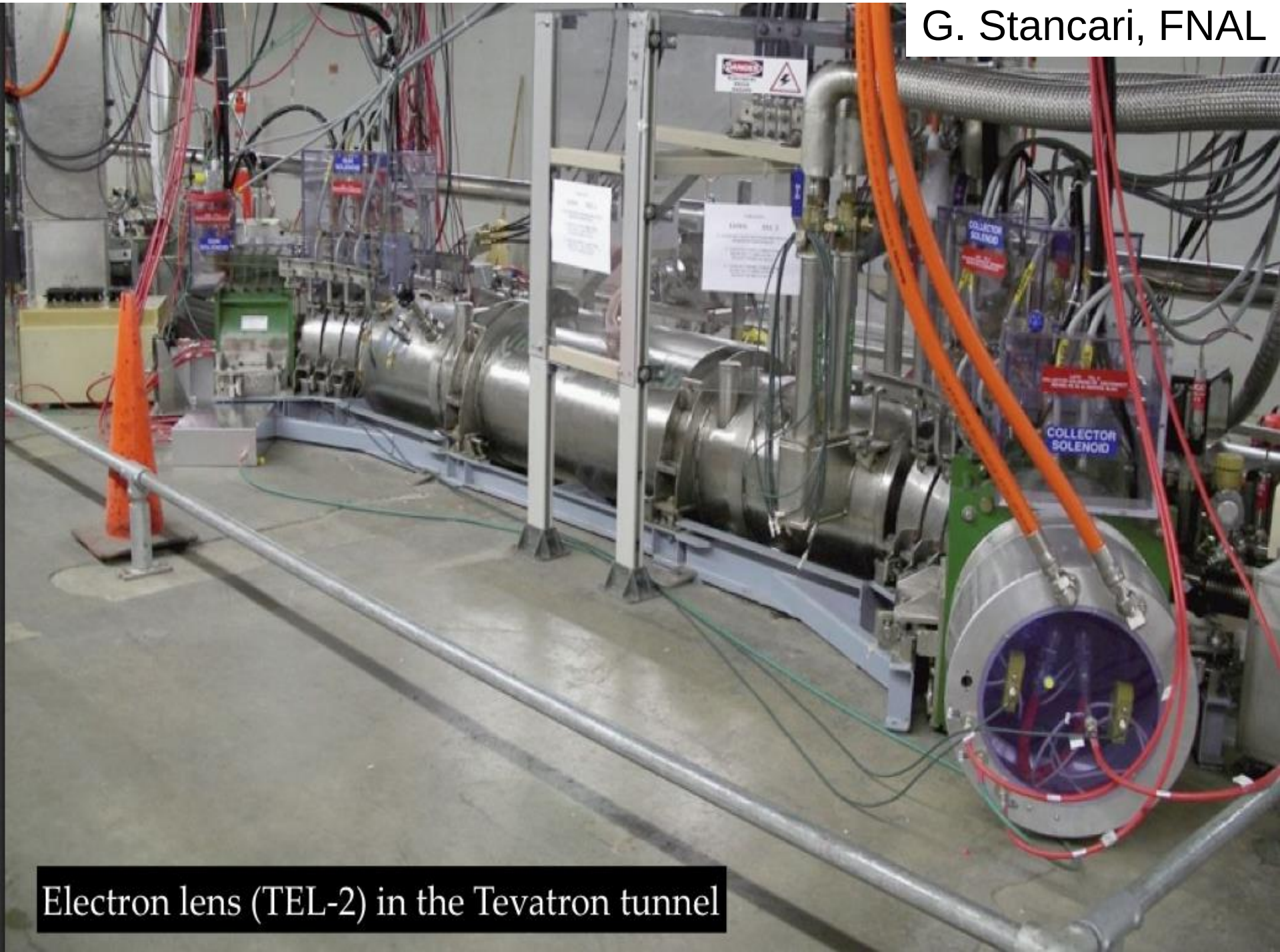


The Orsay Storage Ring Group, "Status report on D.C.I.", PAC79

Conclusion

The present status of the space charge compensation does not permit a gain in luminosity with double ring operation, apart from a factor 2 that could be achieved with two independent rings, as soon as the upper ring will be better conditioned from the vacuum point of view.

G. Stancari, FNAL

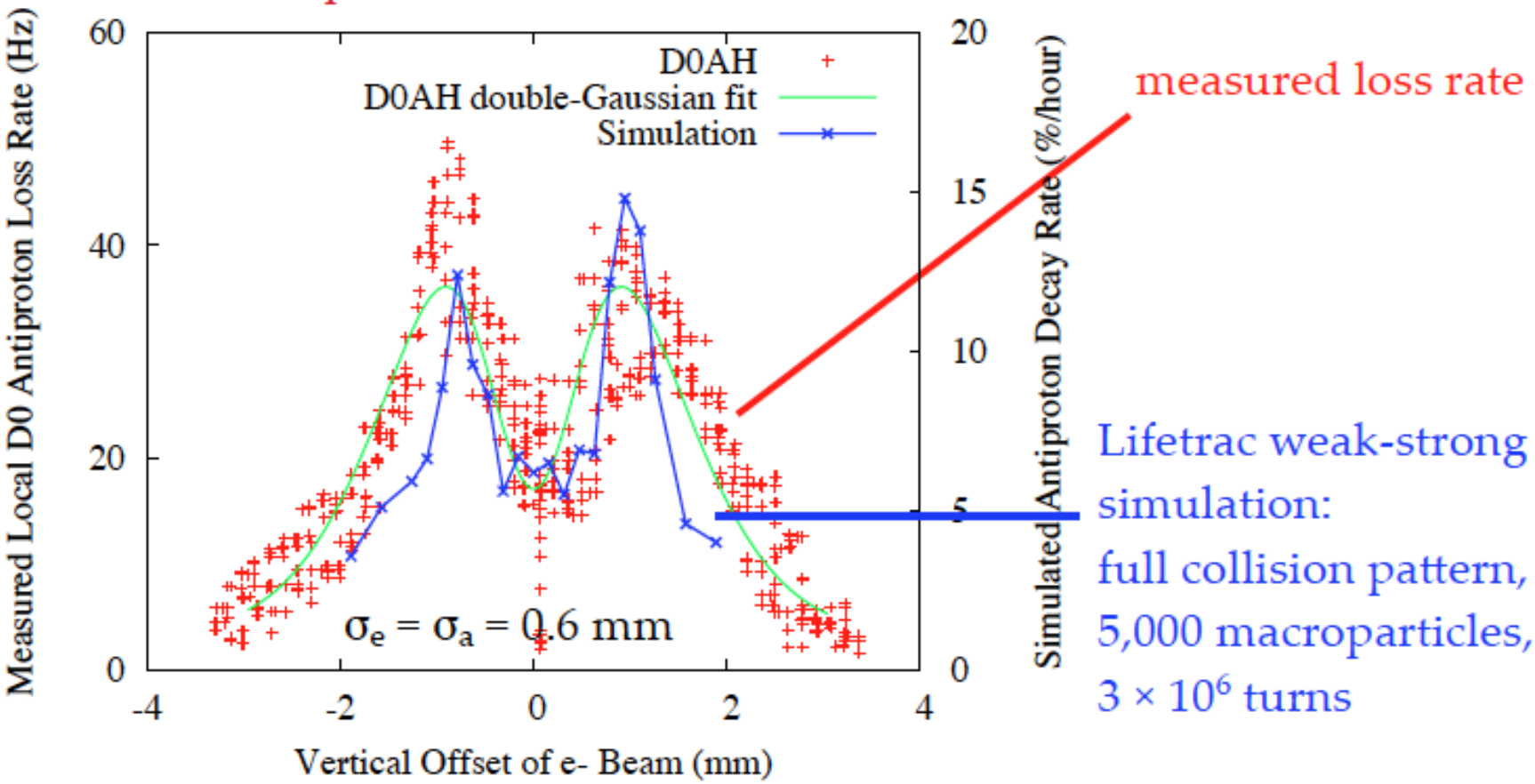


Electron lens (TEL-2) in the Tevatron tunnel

Observations in electron beam positi

G. Stancari, FNAL

1. No increase in losses with nominal tunes (Q_x=0.575, Q_y=0.581)
2. With tunes lowered by 0.003 (towards 7th order resonance):
   - good BPM alignment and no e^-/p^- systematic difference
   - double hump structure



3. Lifetrac simulation reproduces both (1) and the double hump

Conclusions

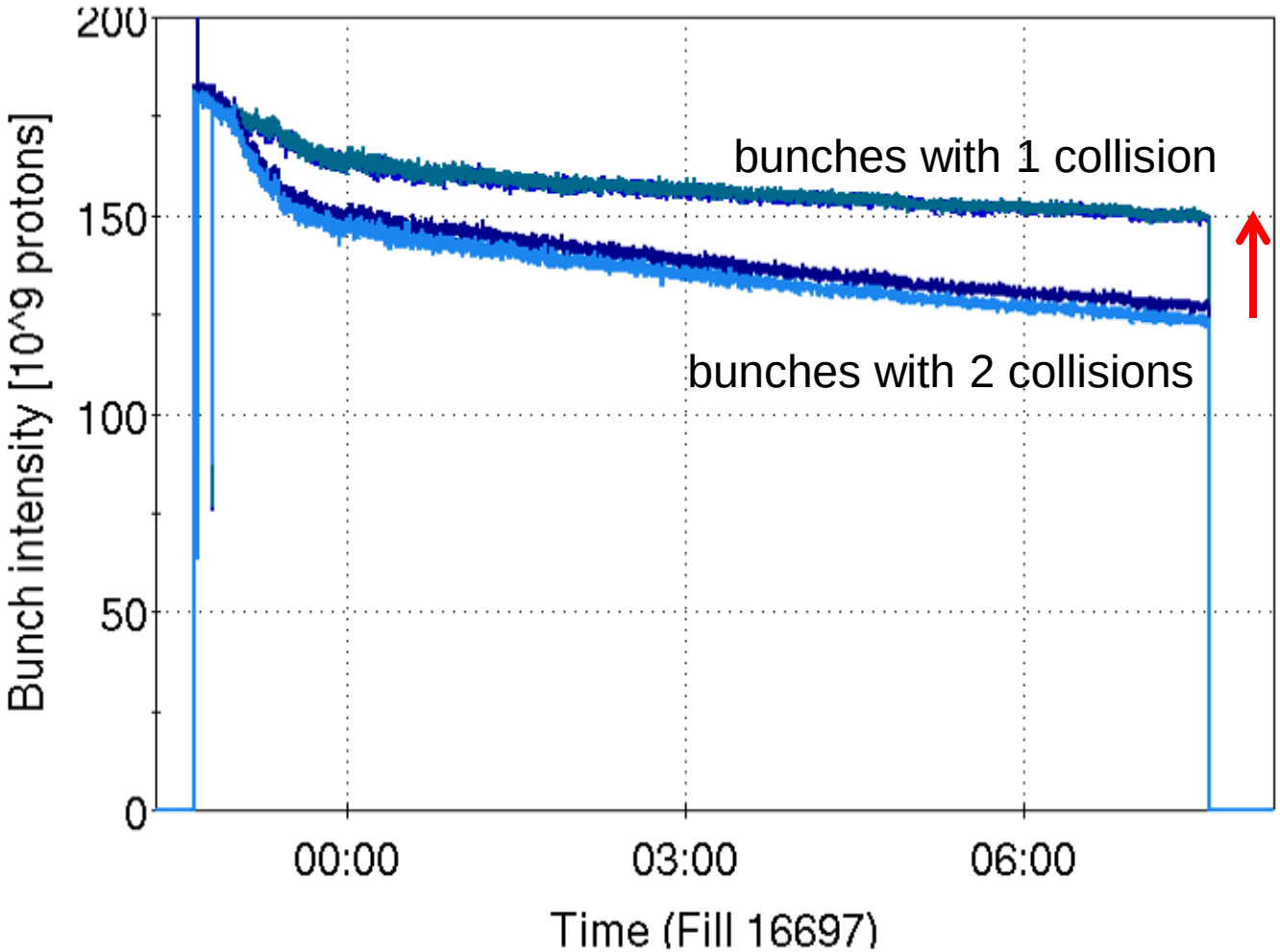
G. Stancari, FNAL

- **Electron lenses** as a tool for beam manipulation in circular machines:
  - demonstrated **bunch-by-bunch betatron tune shifts** with flat electron profiles
  - studied **nonlinear beam-beam compensation** with Gaussian profiles
  - operated reliably for **abort gap clearing** over many years
  - developed **smooth scraping with hollow electron beams**; promising technique for the LHC
- Key observations on **head-on beam-beam compensation** using **Gaussian electron lenses** in Tevatron
  - alignment is reliable and reproducible
  - with aligned beams, no instabilities or emittance growth, even at high intensity and luminosity
  - observed tune shift and tune spread generated by electron beam
  - Tevatron not suitable for direct demonstration of concept: cold antiprotons in normal operations, limited dedicated study time

Thank you

Motivation

Bunch intensity in 2012 polarized proton physics store



Goal:

Compensate for 1 of 2 beam-beam interactions with electron lenses

Then increase bunch intensity
⇒ up to 2× luminosity

Need new polarized proton source – under commissioning in 2013, A. Zelenski

$$L \mu N_b^2$$

Deviations from ideal head-on compensation

1. Deviations from: Same amplitude dependent force in p-beam and e-beam lens

   - e-beam current does not match p-beam intensity
   - e-beam profile not Gaussian
   - e-beam size ≠ p-beam size
   - time-dependence (noise) of e-beam and p-beam parameters

   => technology and instrumentation

1. Deviations from: Phase advance between p-beam and e-beam lens is $\Delta\Psi = k\pi$

   - linear phase error in lattice
   - long bunches ($\sigma_s > \beta^*$)

   => lattice design
   => choice of β^* (not too small)

2. Deviations from: No nonlinearities between p-beam and e-beam lens

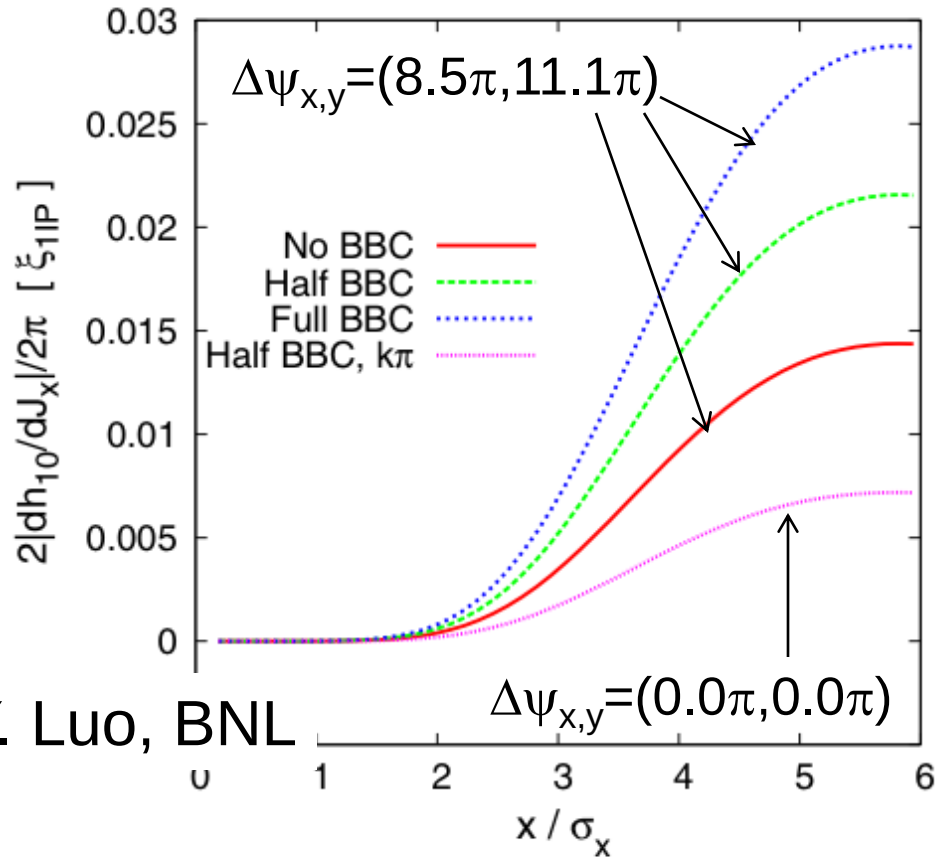
   - sextupoles, octupoles, magnetic triplet errors between p-p and e-p

   => need to be able to tolerate

Studied all tolerances with simulations [Y. Luo et al, PRSTAB 15, 041001 (2012)]

Phase advance and resonance driving terms

- E-lens profile and current => reduces tune spread
- $\Delta\psi = k\pi$ phase advance => minimizes resonance driving terms



Y. Luo, BNL

FIG. 3. 10th order horizontal beam-beam resonance widths under different beam-beam conditions. The vertical axis is in units of the incoherent beam-beam tune shift ξ_{1IP} with one IP.

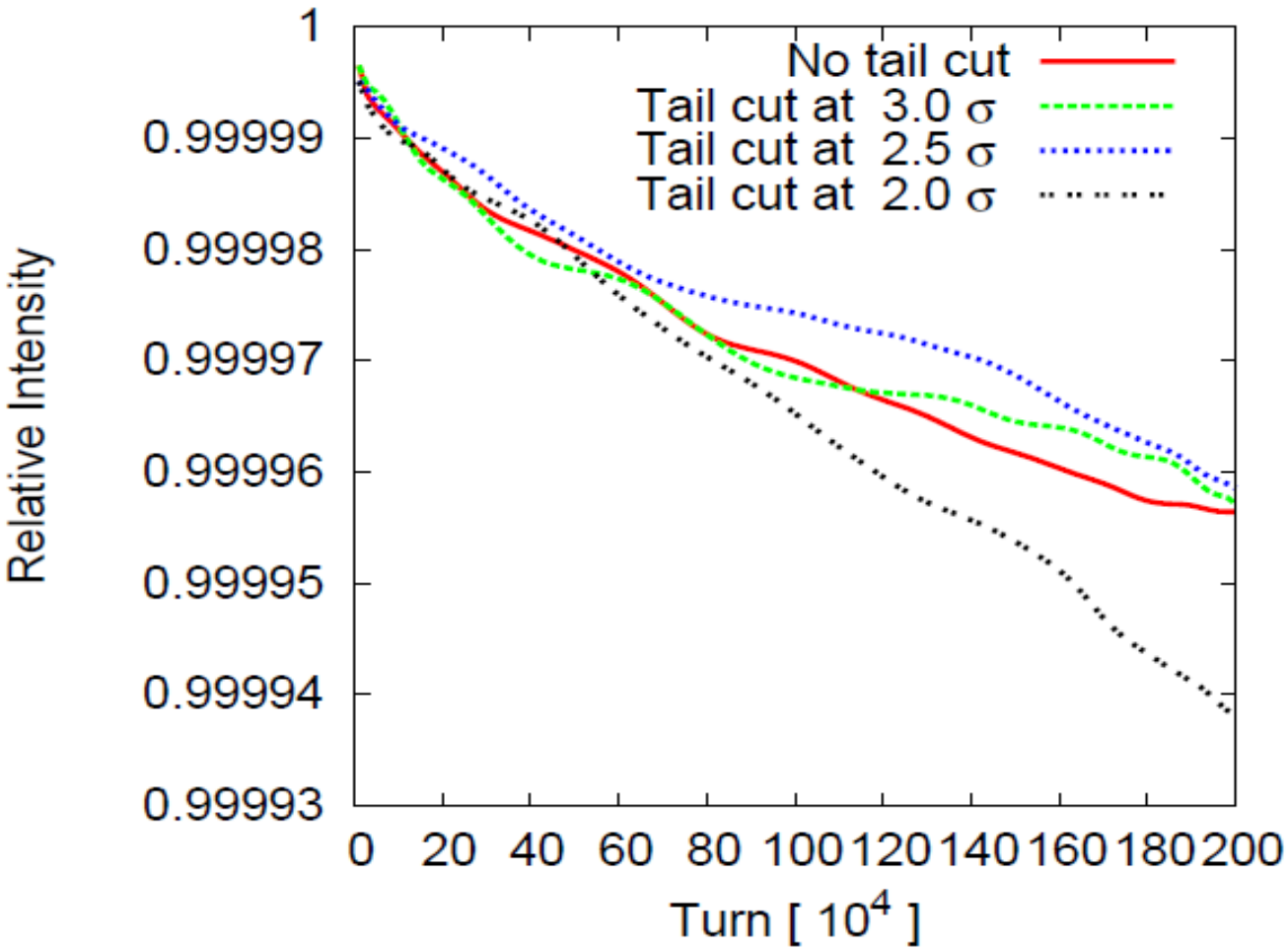
- Installed additional power supplies in all planes (B+Y; hor+ver) that allow for shifting phase between IP8 (p-p) and IP10 (p-e)
- Also required change of integer tunes
  B: (28,29) => (27,29)
  Y: (28,29) => (29,30)

C. Montag

Y. Luo et al, Phys. Rev. ST – Accel. Beams 15, 051004 (2012).

Y. Luo, BNL

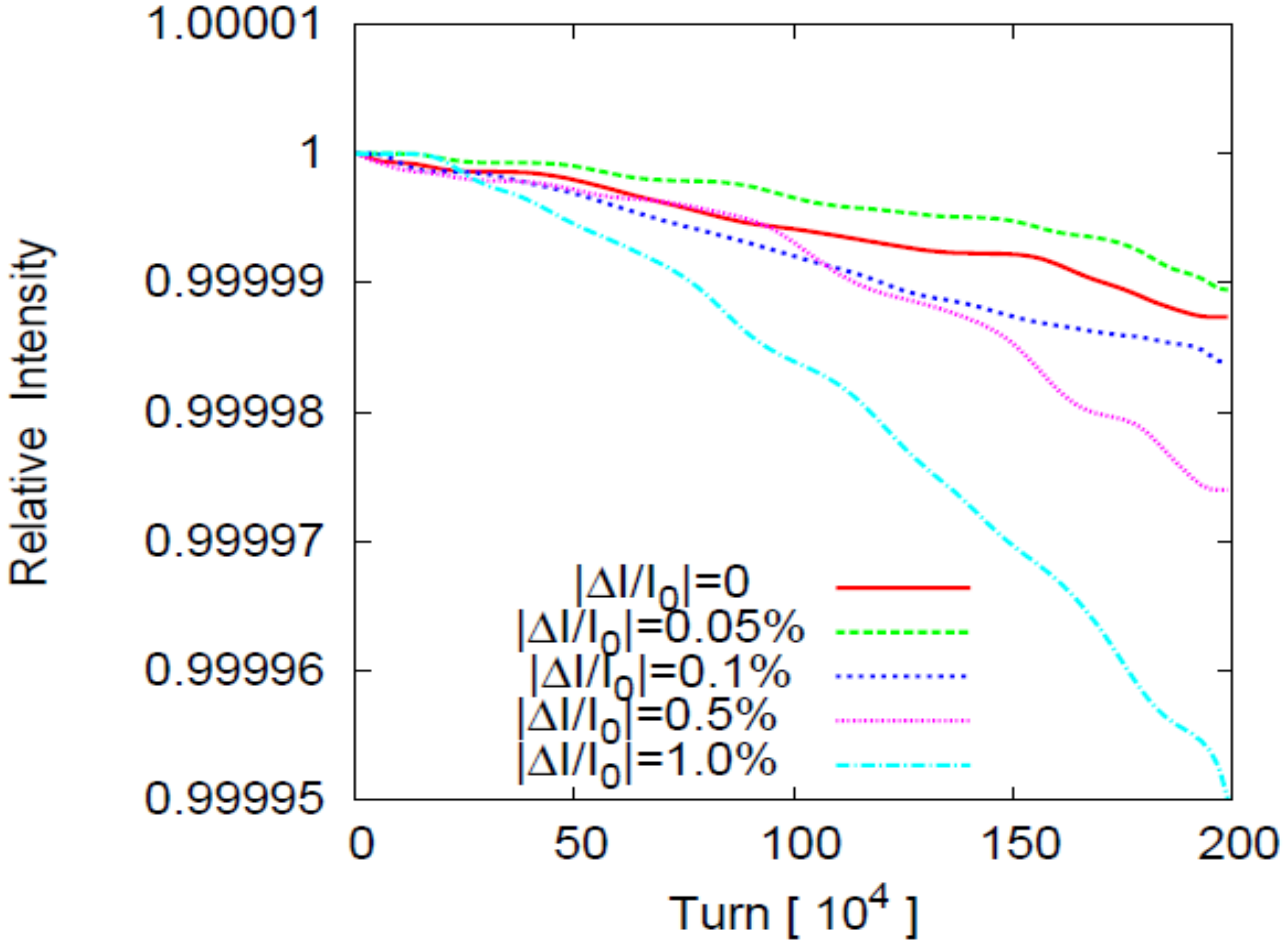
Truncated Gaussian Tail



- RHIC e-lens gun design and real measurement show that the electron beam has a Gaussian tail cut off at 2.8 . This is determined by electric field distribution on cathode.
- Simulation shows that Gaussian tail cut at 2.8 from the current electron gun design is acceptable.

Y. Luo, BNL

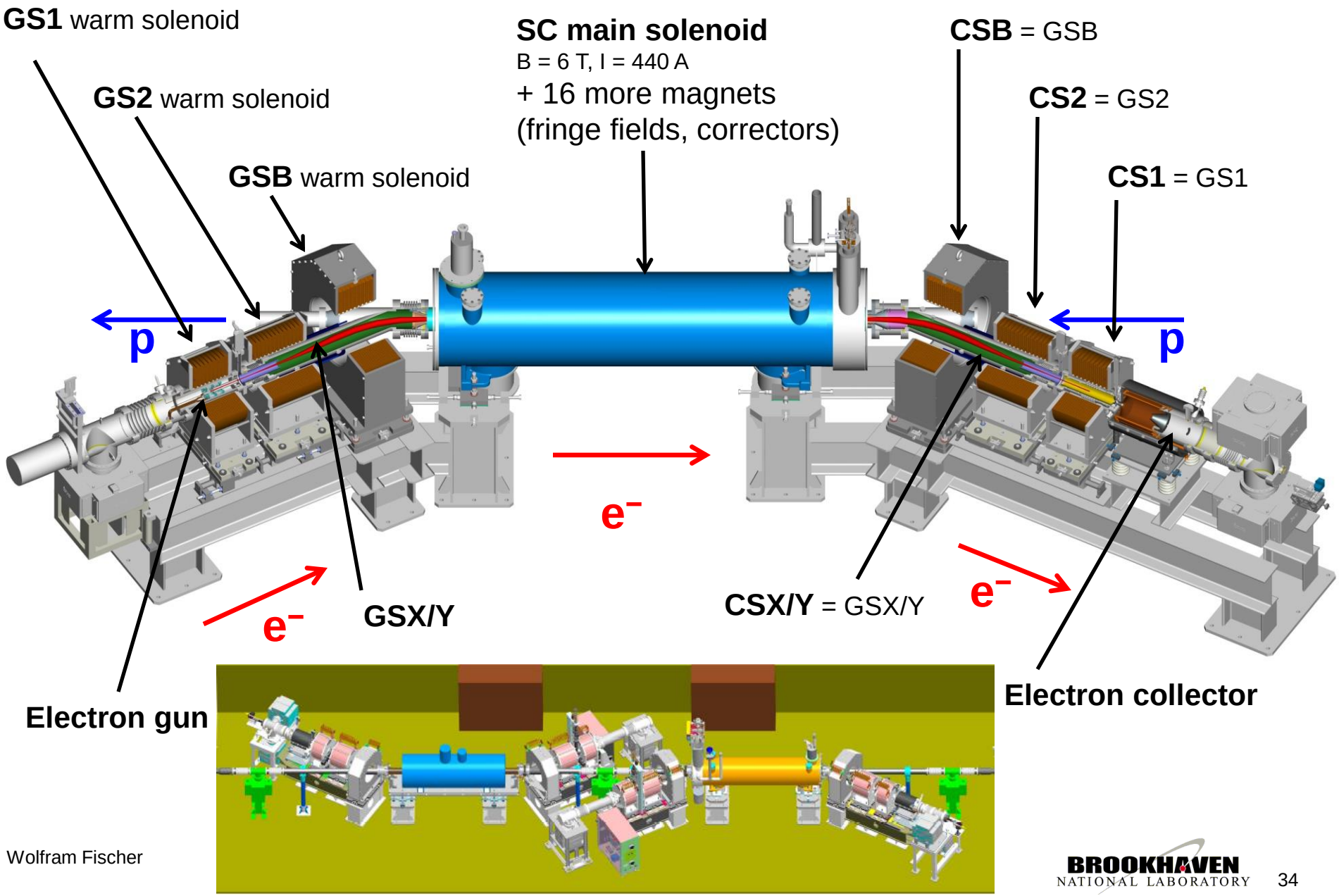
Noise in electron current



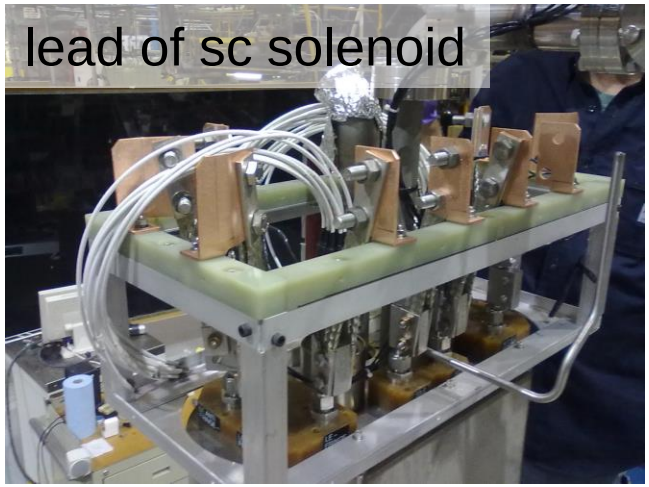
- Due to the instability of the power supplies of the electron gun, there is noise in the electron beam current.
- Based on particle loss rate calculation, we require that the stability of the power supplies of the electron gun should be better than 0.1% .

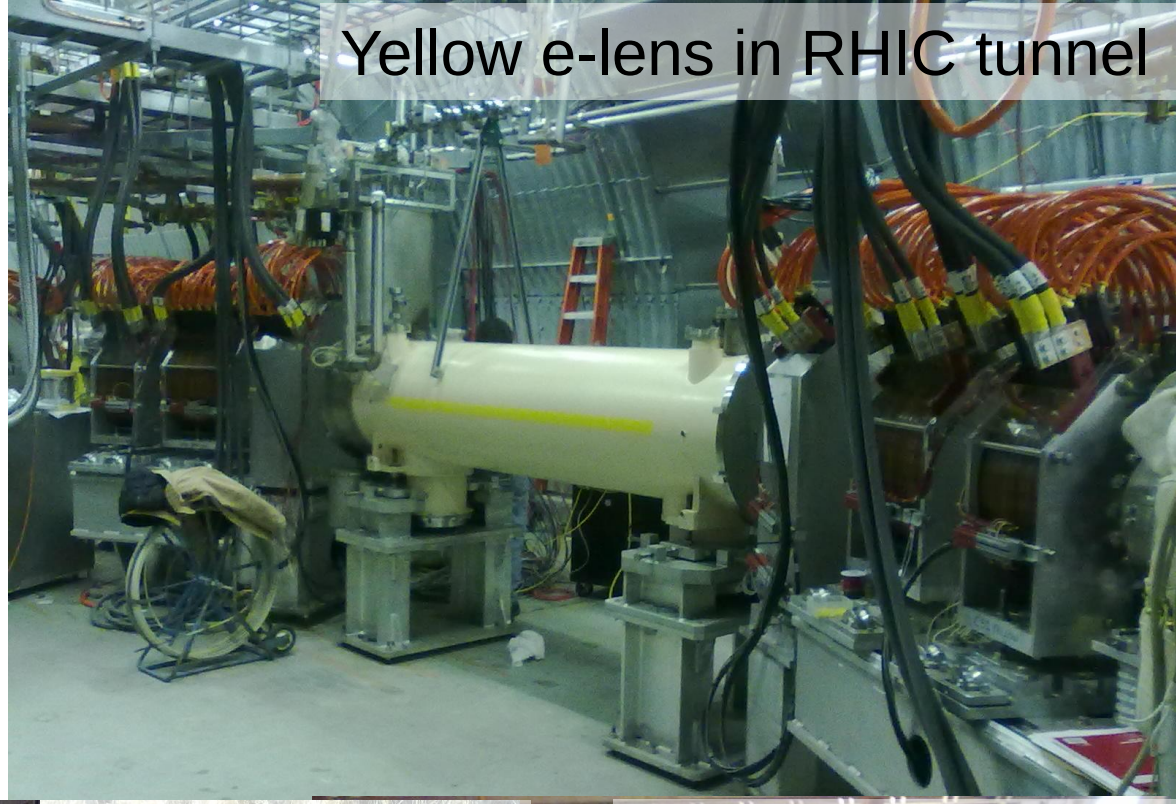
RHIC electron lenses

Compensation overview



RHIC Electron lenses





Electron Lens Driver: TMCI

S. White, BNL/CERN

- Low energy electrons acquire a transverse momentum when interacting with the protons and as a result will start spiraling around the solenoid field lines. The kick received by the protons will therefore depend on their longitudinal position. This electron lens transverse impedance was introduced in: *A. Burov et al. "Transverse beam stability with an electron lens", Phys/Rev. E, 59.*

- The s-dependent momentum change of the protons can then be modeled using a wake function:

$$\Delta p_{x,y} = W[\Delta_{x,y}\sin(ks) + \Delta_{y,x}(1-\cos(ks))], k = \frac{\omega_L}{(1+\beta_e)c}$$

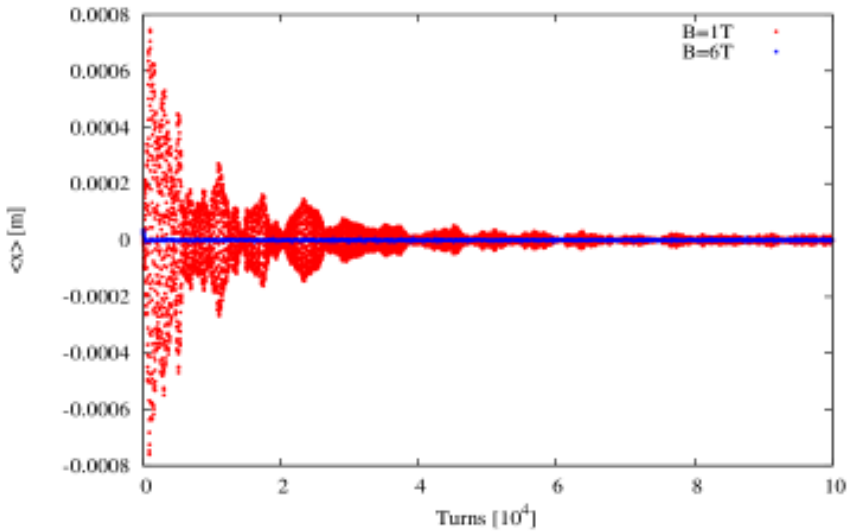
W is a constant and ω_L is the Larmor angular frequency which depends on the field. The kick depend on both the horizontal and vertical displacement of preceding slices.

- Using a linearized model (no Landau damping or chromaticity) one can derive a threshold field required to provide stability:

$$B_{th} = \frac{1.3\, e N_p \xi_{el}}{r^2 \sqrt{\Delta Q Q_s}}$$

- For RHIC parameters (N_p = 3.0e11, ξ_{el} = 0.011, ΔQ = 0.011, Q_s = 5.0e-4, $r = 2\sigma$) we find a threshold of about 14T. Well above the design field of 6T.

Including Landau damping



→ Electron lens only: tune spread is provided by the electron beam (opposite sign as p-p)

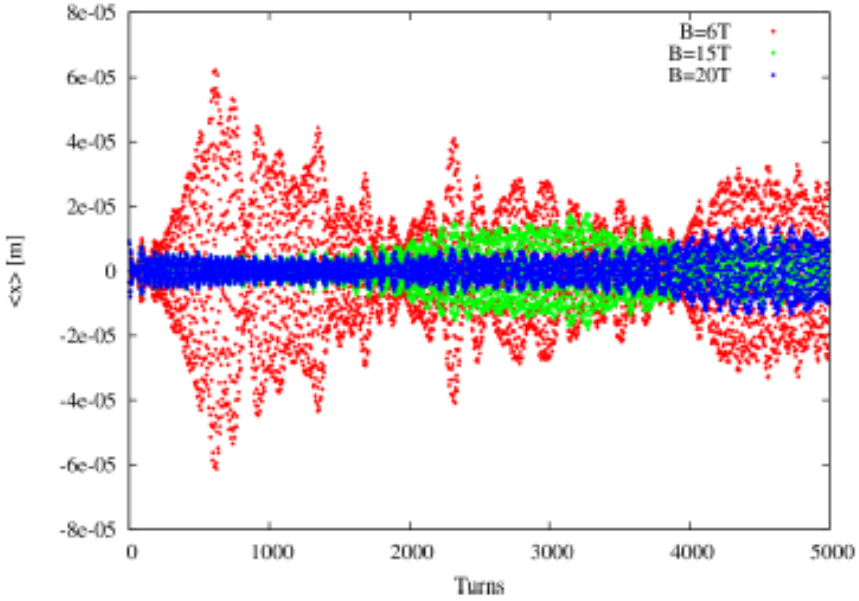
→ Same beam parameters as the ones used in the previous slides

→ Appears stable for 6T solenoid field unstable for 1T

→ Electron lens and a single proton-proton interaction with twice the intensity to reproduce RHIC tune spread

→ Even with Landau damping the situation is much worse as soon as coherent beam-beam modes are included

→ Although a clear improvement is observed the beam is still unstable at 20T



Summary

S. White, BNL/CERN

- Beam stability with electron lens was studied in multi-particle tracking. Although they seem to match the theory these results came up very recently and need to be confirmed. Open questions:
  - Poisson solver for electron lens (already the case for pp) – most likely the beams do not remain Gaussian
  - Sampling rate of the electron beam – in this talk ~$10\lambda_L$ (50 proton slices)

- Machine impedance:
  - RHIC operates far below TMCI
  - Although this year some instabilities were observed this is generally not the case. New impedance measurements are planned this year to asses the situation
  - Simulations with electron lenses show no issues related to machine impedance

- Electron lens driven TMCI:
  - The RHIC design solenoid field is about a factor 2 below theoretical expectation with nominal beam parameters
  - This threshold was verified in tracking with linearized model and seem to be confirmed
  - Coherent beam-beam effects moves the modes around and significantly degrades the situation
  - Landau damping stabilizes the beams with electron lens only (no beam-beam modes) but not when beam-beam is included
  - The only cure that was found to be working so far is to use a transverse damper with chromaticity
  - Some beam parameters can change the threshold without affecting the luminosity reach – they are currently under investigation

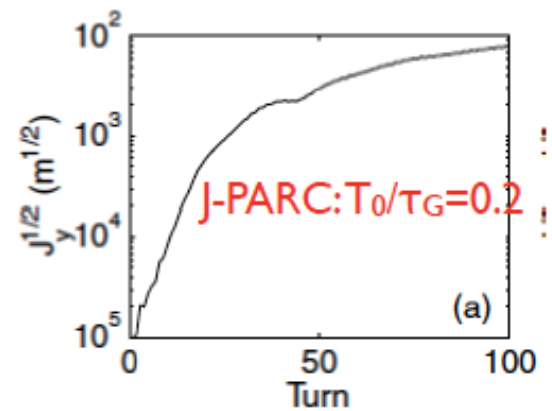
Situation with BB + e-lens still under study, may need damper in RHIC

Frequency range of the wake

$$\omega_e = \frac{eB}{m_e} = 2\pi \times 6.6 \times 10^{12}\ \mathrm{Hz} \qquad B = 6\ \mathrm{T}$$

$$\omega_e \sigma_z / c = 1550 \quad \sigma_z = 0.44\ \mathrm{m}$$

- Stability



$$U = \frac{\sqrt{3}}{\Delta\omega\tau_G} = 1$$

$$\Delta\omega = \omega_e \eta \sigma_{\Delta p/p} = \frac{2\pi\nu_s\omega_e\sigma_z/c}{T_0} = \frac{3.5}{T_0} \qquad \nu_s = 0.00036$$

- Unstable T_0/τ_G>2

Higher field -> stronger damping

Head-on beam-beam compensation

- First attempt in DCI in 1970 with 4-beam scheme, no luminosity increase due to coherent effects
  - proposals for other machines but no further realization since
- Simple principle, need to control deviations from ideal
- Still no reliable calculation/simulation of $N(t)$ and $\sigma(t)$ over time scale of interest (~h) with strong beam-beam effects
  - models ok if BB moderate (e.g. Tevatron), or adjusted with free parameters
- Simulations of changes in DA and $N(t)$ for study of parameter space well developed
- Technology (TEL, EBIS, …) well developed
  - TEL: operational experience, study of parameter tolerance and beam compensation experiments
- RHIC 2 electron lenses partially installed
  - hardware commissioning in 2013
  - complete installation in summer of 2013
  - instabilities with BB and e-lens still needs study