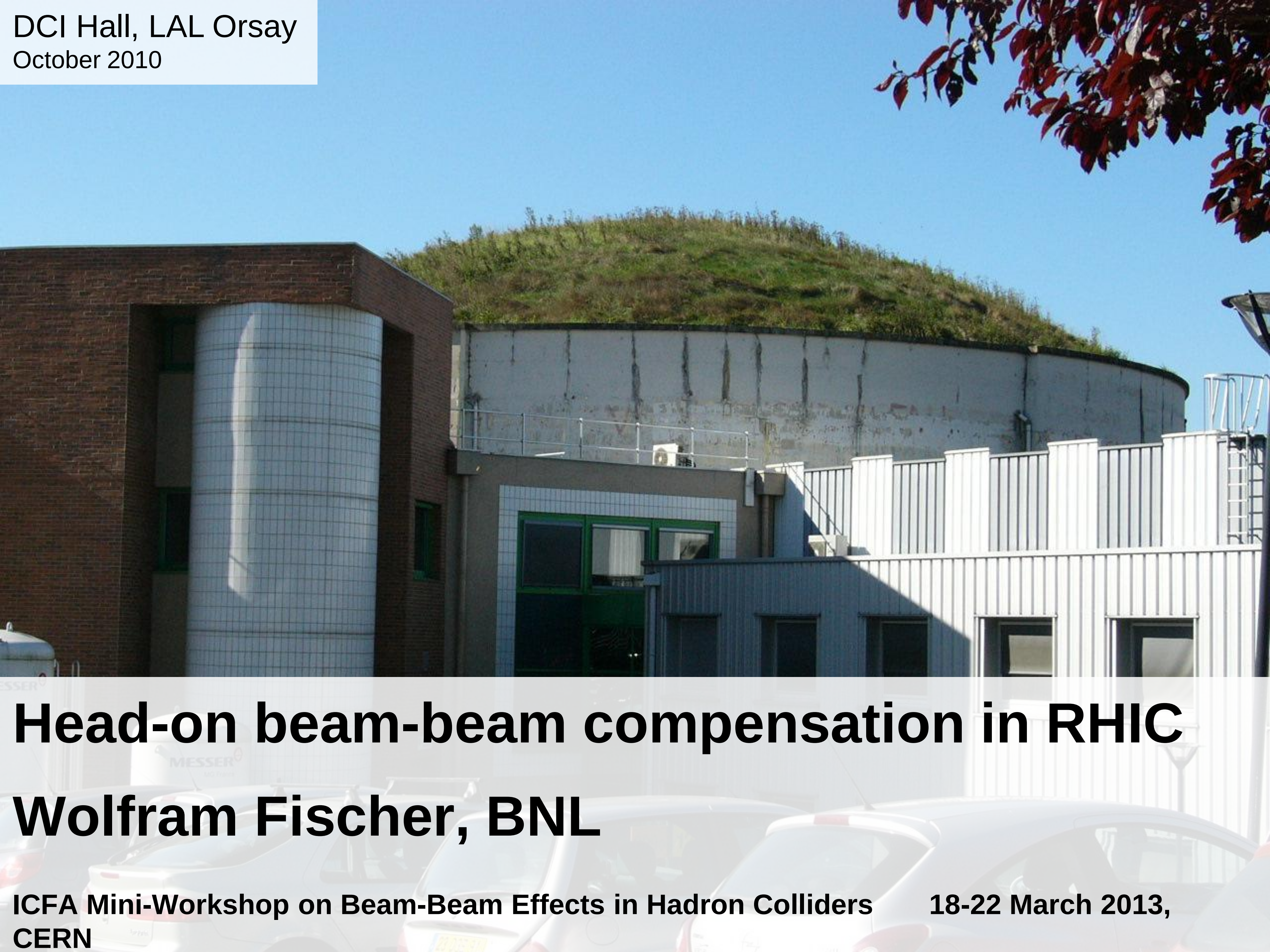

DCI Hall, LAL Orsay
October 2010

Head-on beam-beam compensation in RHIC

Wolfram Fischer, BNL

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

Co-authors and Acknowledgements

Co-authors

Z. Altinbas, M. Anerella, D. Bruno, C.D. Dawson, A.K. Drees, D.M. Gassner, X. Gu, R.C. Gupta, P. Joshi, J. Hock, L. Hoff, A.K. Jain, P. Kovach, R. Lambiase, Y. Luo, M. Mapes, A. Marone, A. Marusic, R. Michnoff, T. Miller, R. Michnoff, M. Minty, C. Montag, S. Nemesure, S. Plate, A.I. Pikin, L. Snydstrup, Y. Tan, S. Tepikian, R. Than, C.W. Theisen, P. Thieberger, J. Tuozzolo, P. Wanderer, S. White, W. Zhang

Acknowledgments – Institutions

FNAL: TEL experience, beam-beam experiments and simulations
US LARP: beam-beam simulation
CERN: beam-beam experiments and simulations

Acknowledgments – Individuals

FNAL: H.-J. Kim, V. Shiltsev, T. Sen, G. Stancari, A. Valishev, G. Kuznezov
BINP: G. Kuznezov
CERN: X. Buffat, R. DeMaria, J.-P. Koutchouk, T. Pieloni, F. Schmidt, F. Zimmermann
FZJ: V. Kamerdziev
SLAC: A. Kabel

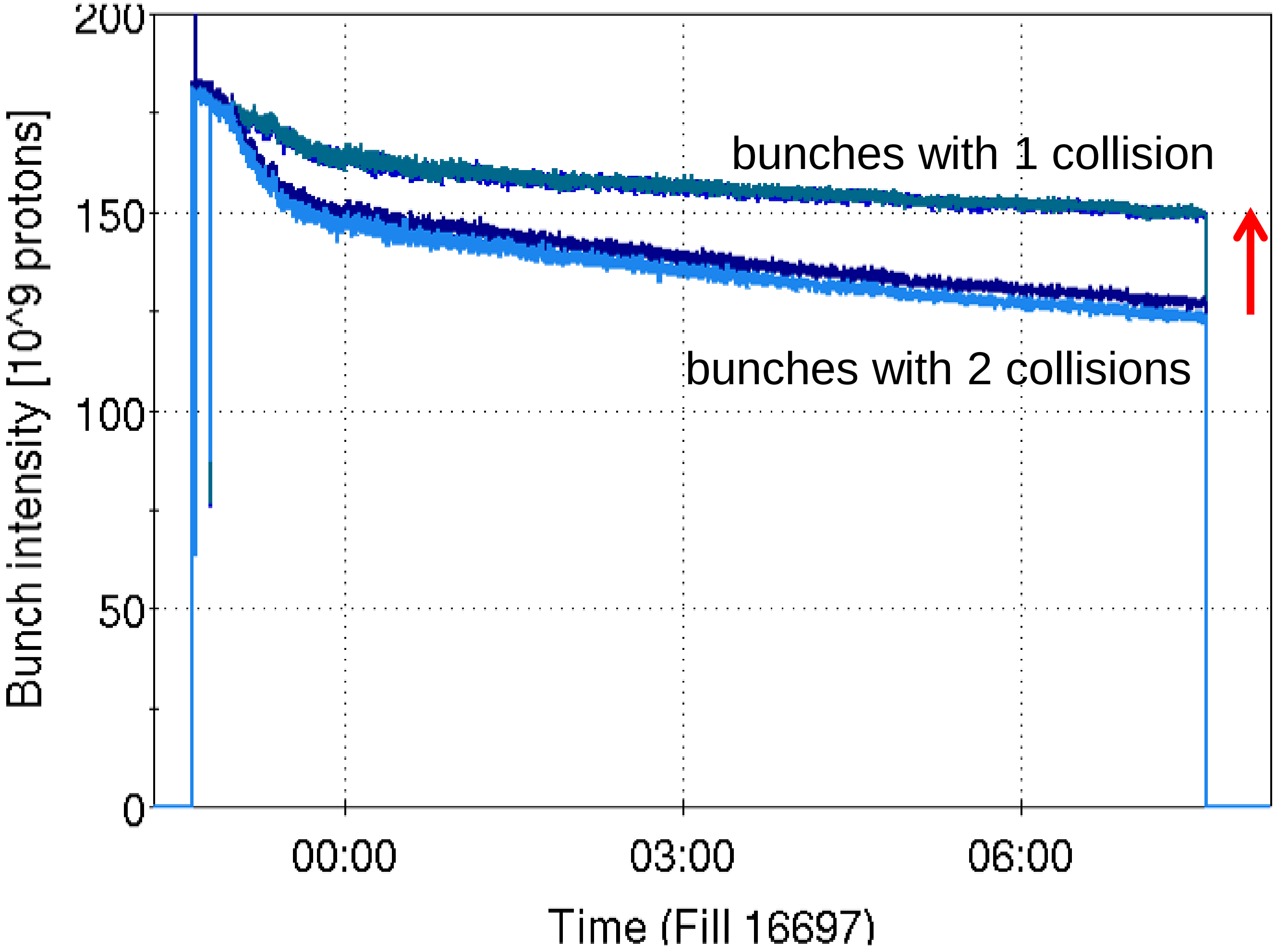
Outline – head-on beam-beam compensation

- RHIC goals, Historical survey
  DCI experience, proposals for other machines
- Head-on beam-beam compensation
  ideal, deviations from ideal
- Technology developments for hadron beams
  Tevatron electron lenses, Electron Beam Ion Sources
- RHIC electron lenses
  design, simulations, lattice, hardware, test bench, commissioning

RHIC electron lenses

Motivation

Bunch intensity in 2012 polarized proton physics store



Goal:

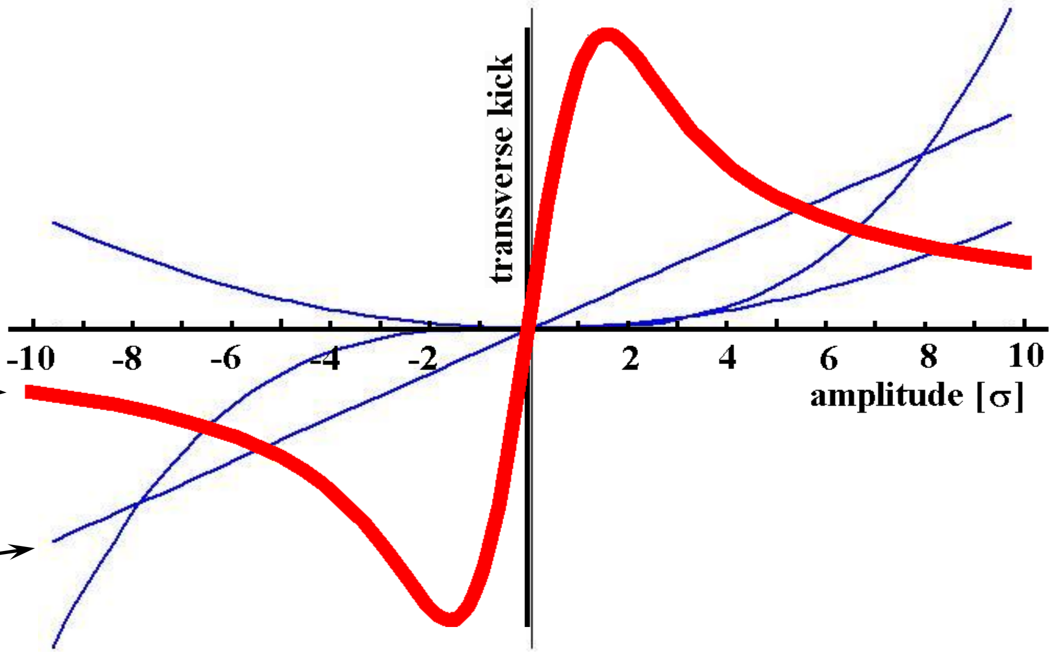
Compensate for 1 of 2 beam-beam interactions with electron lenses

Then increase bunch intensity
⇒ up to 2× luminosity

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

$$L \mu N_b^2$$

Head-on beam-beam compensation



beam-beam kick

magnet kicks

- Amplitude dependence of beam-beam kick fundamentally different from magnets (strength not monotonically increasing in BB)
- Another beam can produce same kick of opposite sign

History of head-on beam-beam compensation (HOBBC)

- Compensation schemes (S. Peggs, Handbook):
  1. Direct space charge compensation (4 beams)
  2. Indirect space charge compensation (electron lenses) ← **considered for RHIC**
  3. Betatron phase cancellation between neighboring IPs (for certain order resonances only)

- Proposals/studies of head-on beam-beam compensation to date:
  - COPPELIA → 4-beam (J.E. Augustine, HEACC, 1969)
  - DCI → 4-beam (G. Arzelia et al., HEACC, 1971) → **only real attempt so far**
  - CESR → e-lens (R. Talman, unpublished, 1976)
  - SSC → e-lens (E. Tsyganov et al., SSCL-PREPRINT-519 ,1993)
  - LHC → e-lens (E. Tsyganov et al., CERN SL-Note-95-116-AP, 1995)
  - Tevatron → e-lens (Shiltsev et al., PRST-AB, 1999)
  - e^+e^- collider → 4-beam (Y. Ohnishi and K. Ohmi, Beam-Beam’03, 2003)

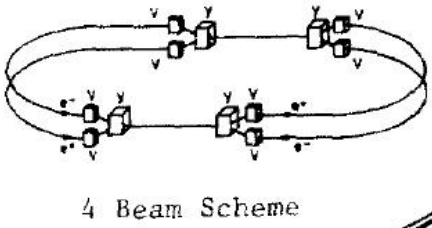
Head-on beam-beam compensation in DCI

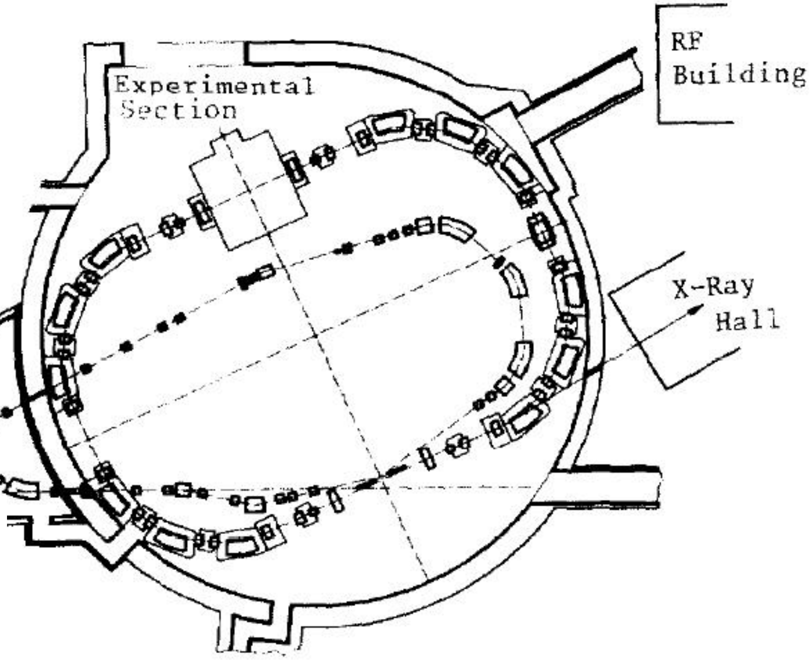
- Head-on beam-beam compensation was only tested in DCI (starting in 1976)
- 4-beam collider ($e^+e^-e^+e^-$) for complete space charge compensation
- Main parameters:

Circumference	94.6 m
Energy	1.8 GeV
Beam-beam ξ	~0.05-0.1
Luminosity (design)	~10^{32} cm^{-2}s^{-1}

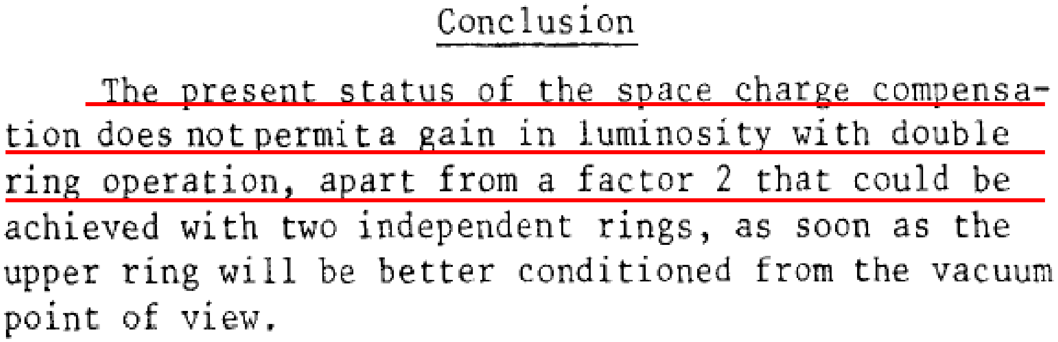
- Luminosity fell short by ~100x compared to expectations (2-, 3-, and 4-beam *L* about the same)

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


4 Beam Scheme



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.

Coherent beam motion in DCI

- Luminosity shortfall in DCI attributed to coherent instabilities
  (Derbenev, Chau, Potau – later Podobedov and Siemann)
- Considered tune-split and feedback

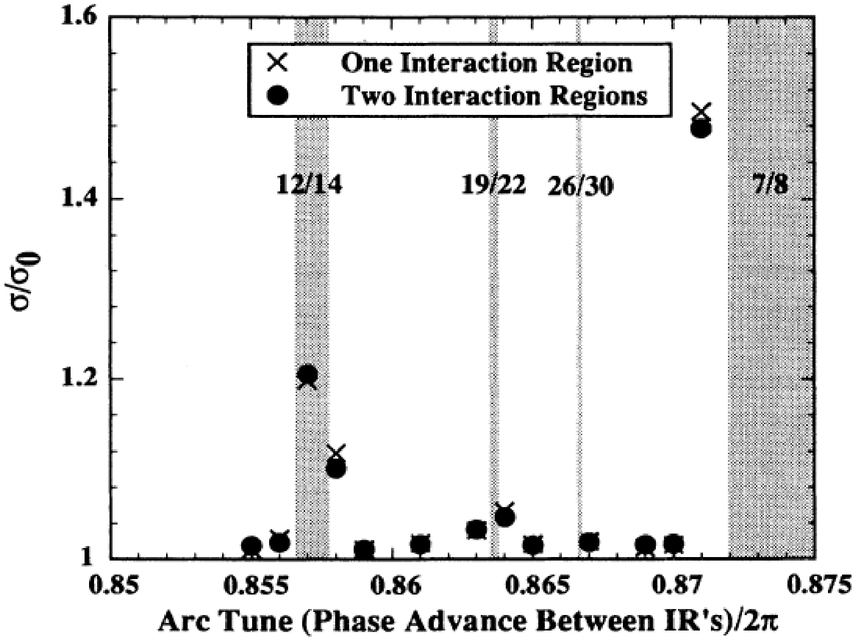


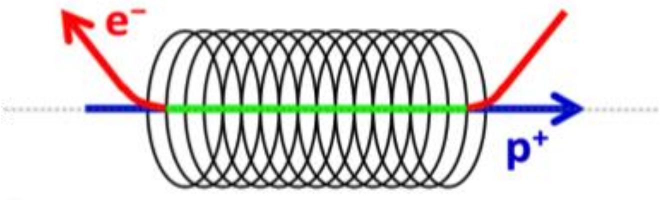
FIG. 10. rms beam size in DCI normalized to the nominal size for region I: $Q \sim 0.865$, $\xi = 0.0218$. Even order resonances up to 30th order are plotted with widths calculated using the m dependence in Eq. (20) and a coefficient three times larger.

from Podobedov & Siemann:

- beam-size increase at even-order resonances of high order
- regions of stability in simulations 3-5 times wider than observed

- Ya. S. Derbenev, “Collective instability of compensated colliding beams”, Nuclear Physics Institute, Siberian Division, Academy of Sciences USSR, Novosibirsk, Report No IYAF 70-72, in Russian (1972), SLAC-TRANS 151 in English.
- N.N. Chau and D. Potau, “Stabilité des oscillations transverse dans un anneau à charge d’espace compensée”, LAL Orsay (1974 and 1975).
- B. Podobedov and R.H. Siemann, “Coherent beam-beam interaction with four colliding beams”, Phys. Rev. E 52, No 3, pp. 3066-3073 (1995).

Beam-beam compensation with electron lens

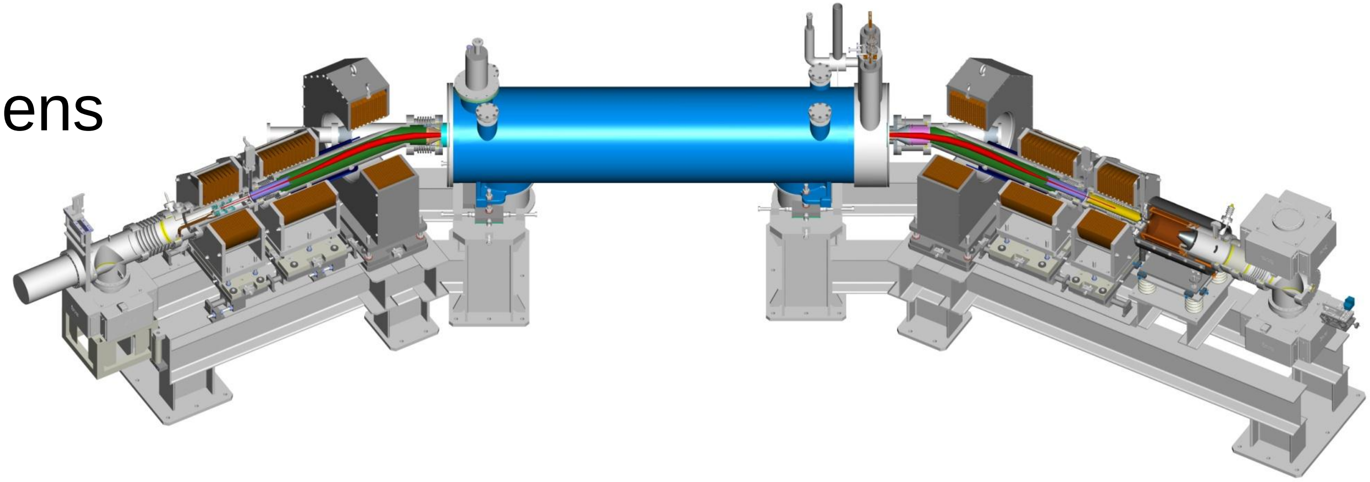


2-beam coherent instabilities not an issue with electron lenses:

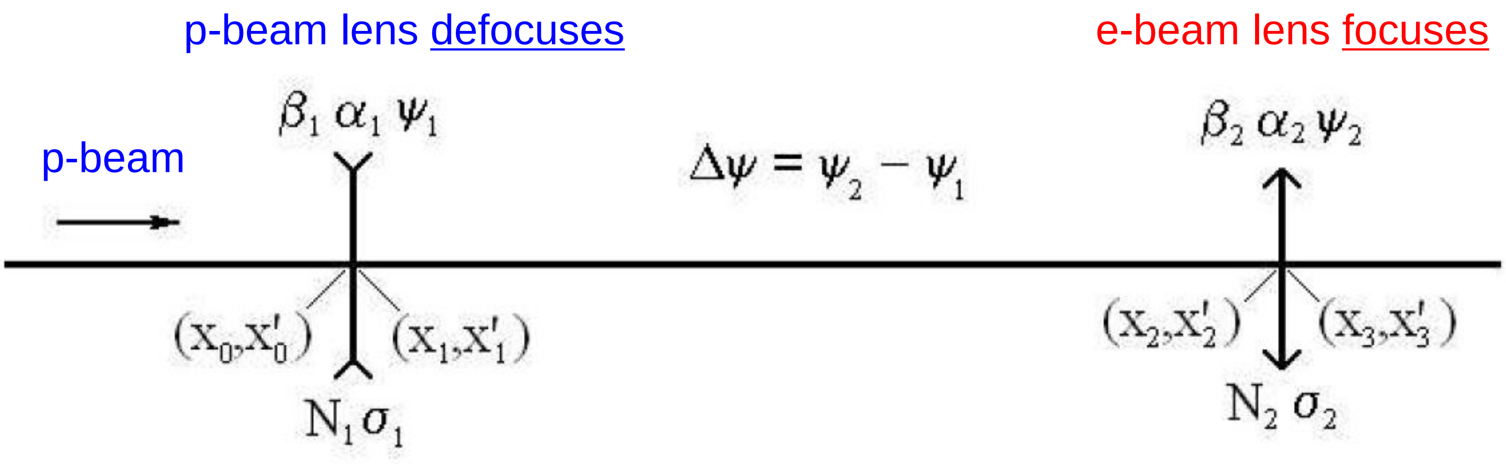
No feedback loop with compensating electron beam
(single pass effects – require sufficient rigidity of electron beam required, see S. White)

Also: beam-beam parameter ξ in hadron colliders order of magnitude smaller than in lepton colliders

RHIC electron lens



HOBBC with electron lens – beam line view



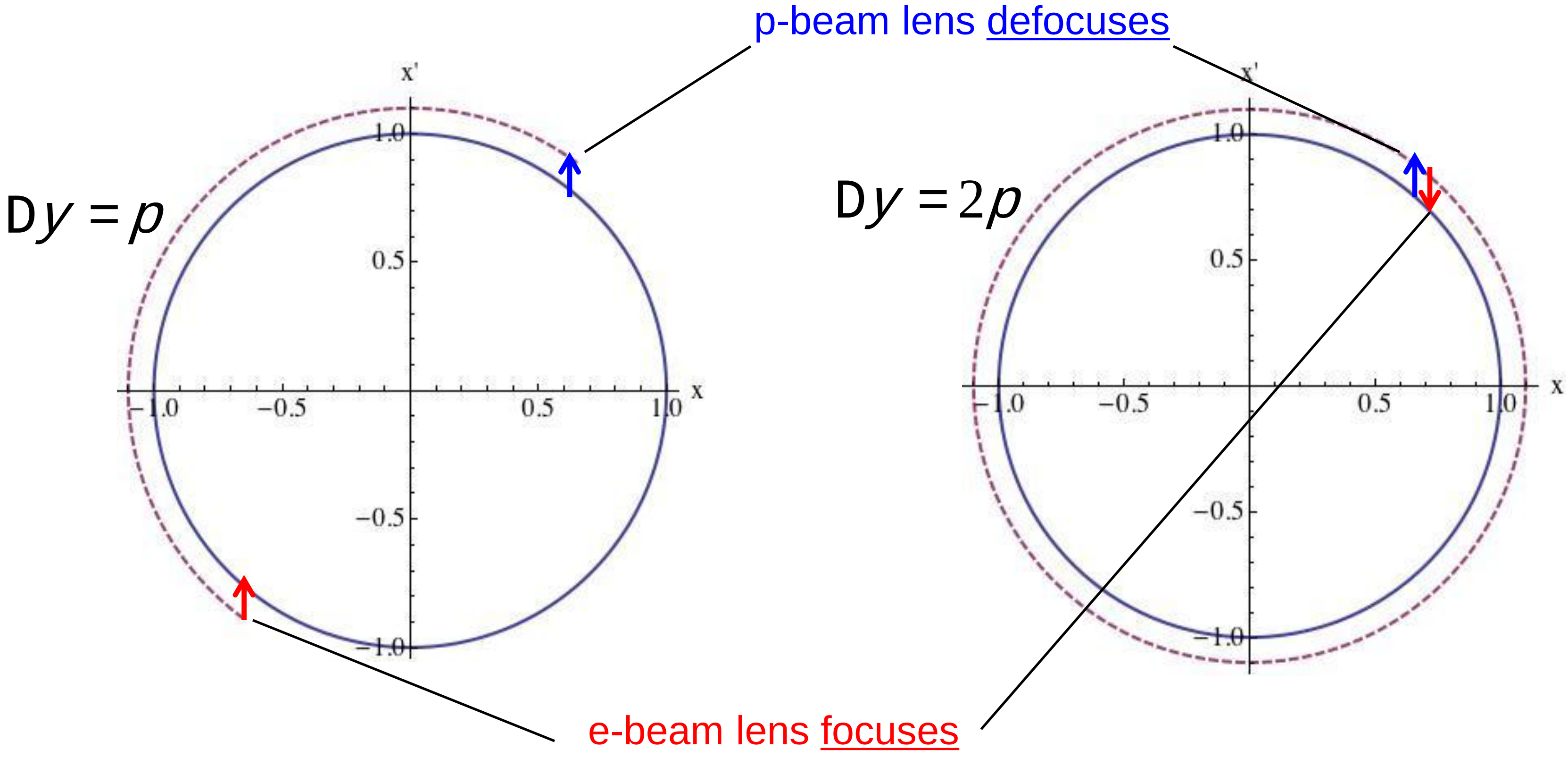
lenses characterized by intensity and size

Single-pass compensation:

exact 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

HOBBC with electron lens – <u>phase space view</u>



p-beam lens <u>defocuses</u>

$Dy = p$

$Dy = 2p$

e-beam lens <u>focuses</u>

Exact compensation if:

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

HOBBC with electron lens – Hamiltonian view

$$H(J_x, F_x) = 2pQ_x J_x + V_{p-p}(x_n) + V_{p-e}(x_n)$$ (1-D only)

$$V(J_x, \Phi_x)|_{p-p} = -\frac{N_p r_0}{\gamma} \int_0^{J_x \beta^*_{\mathrm{IP}}/2\sigma^2_{p,\mathrm{IP}}} \times \frac{d\alpha}{\alpha}(1 - e^{-2\alpha\cos^2(\Phi}$$

$$V(J_x, \Phi_x)|_{p-e} = \frac{N^*_e r_0}{\gamma} \int_0^{J_x \beta_{\mathrm{e-lens}}/2\sigma^2_e} \times \frac{d\alpha}{\alpha}(1 - e^{-2\alpha\cos^2(\Phi_x + \phi_{x,p-e})}).$$

$V_{p-p}(x_n) + V_{p-e}(x_n) = 0$ if:

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

$$N_p = N^*_e \quad \text{and} \quad b^*_{IP} / 2s^2_{p,IP} = b^*_{e-lens} / 2s^2_e$$

2. Phase advance between p-beam and e-beam lens is $\Delta\Psi = k\pi$, and

$$f_{x,p-e} - f_{x,p-e} = kp$$

3. No nonlinearities between p-beam and e-beam lens

Y. Luo et al, “Six-dimensional weak-strong simulations of head-on beam-beam compensation in the Relativistic Heavy Ion Collider”, Phys. Rev. ST – Accel. Beams 15, 051004 (2012).

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

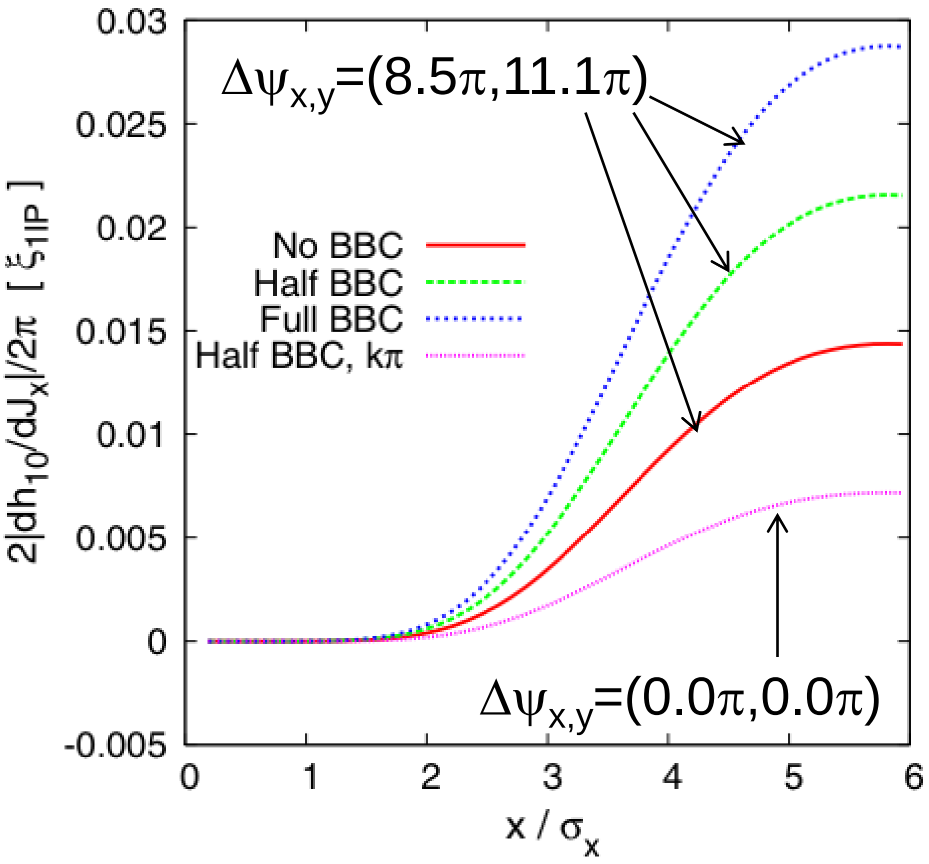


FIG. 3. 10th order horizontal beam-beam resonance widths under different beam-beam conditions. The vertical axis is in units of the incoherent beam-beam tune shift ξ_{1IP} with one IP.

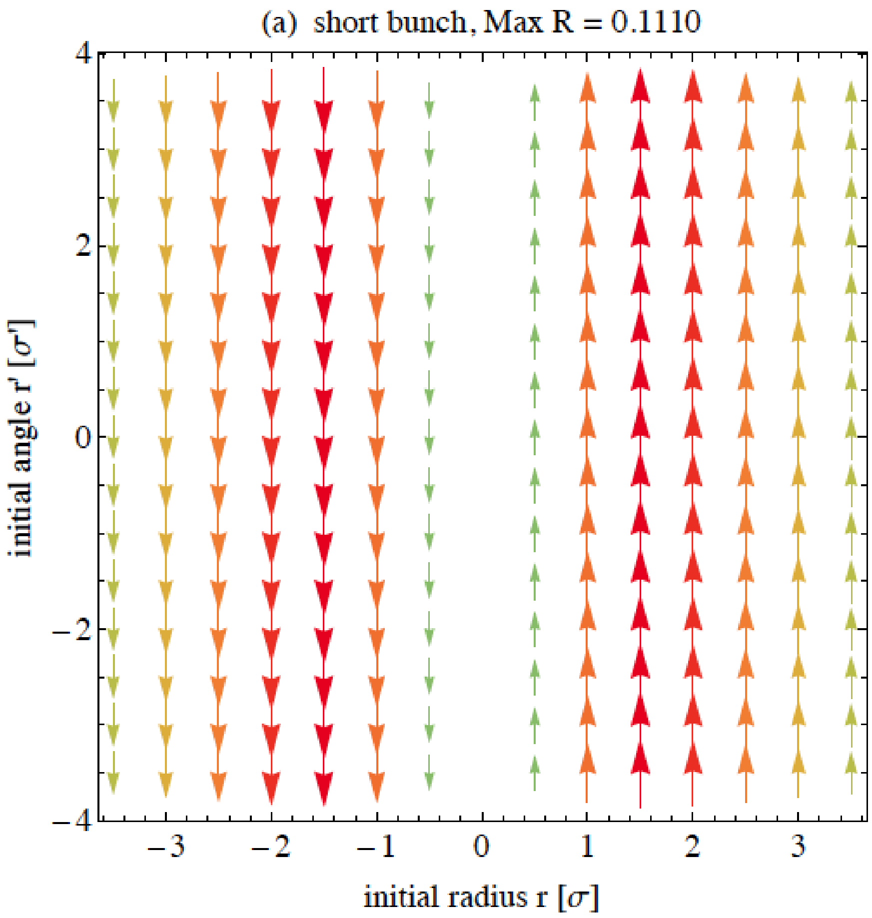
- Installed additional power supplies in all planes (B+Y; hor+ver) that allow for shifting phase between IP8 (p-p) and IP10 (p-e)
- Also required change of integer tunes
  B: (28,29) => (27,29)
  Y: (28,29) => (29,30)

C. Montag

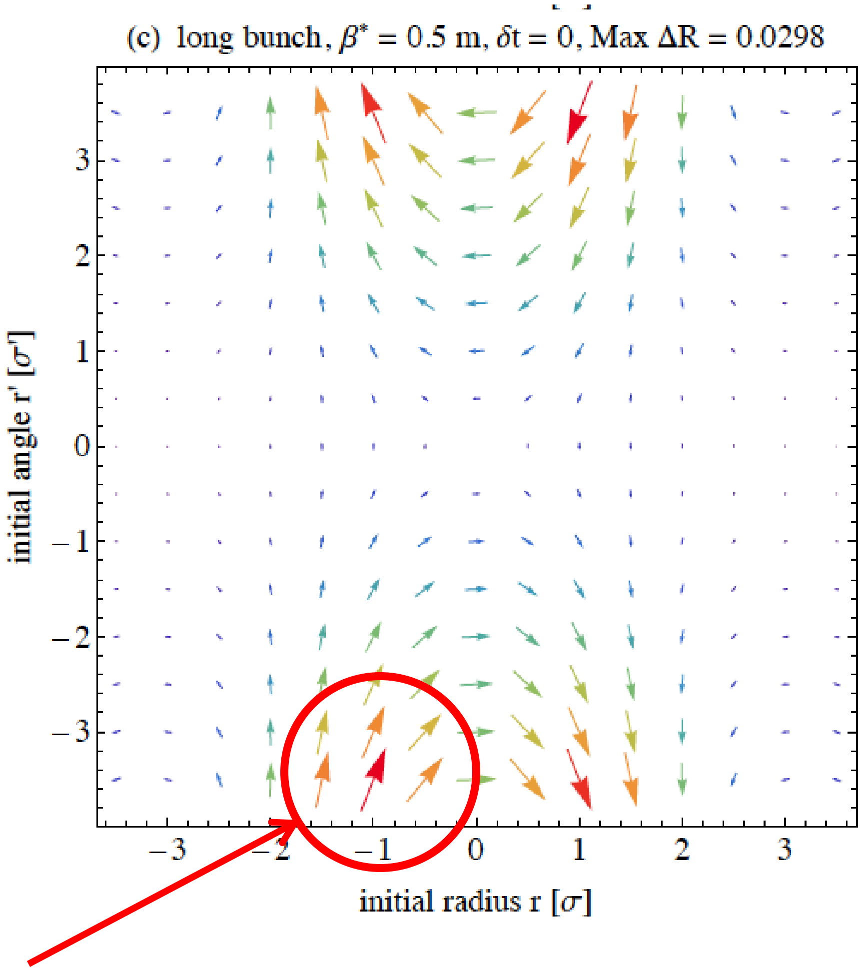
Y. Luo et al, Phys. Rev. ST – Accel. Beams 15, 051004 (2012).

Effect of long bunches on HOBB

short bunch, σ_s=0


(a) short bunch, Max R = 0.1110

long bunch, σ_s=0.2 m, β^*=0.5 m

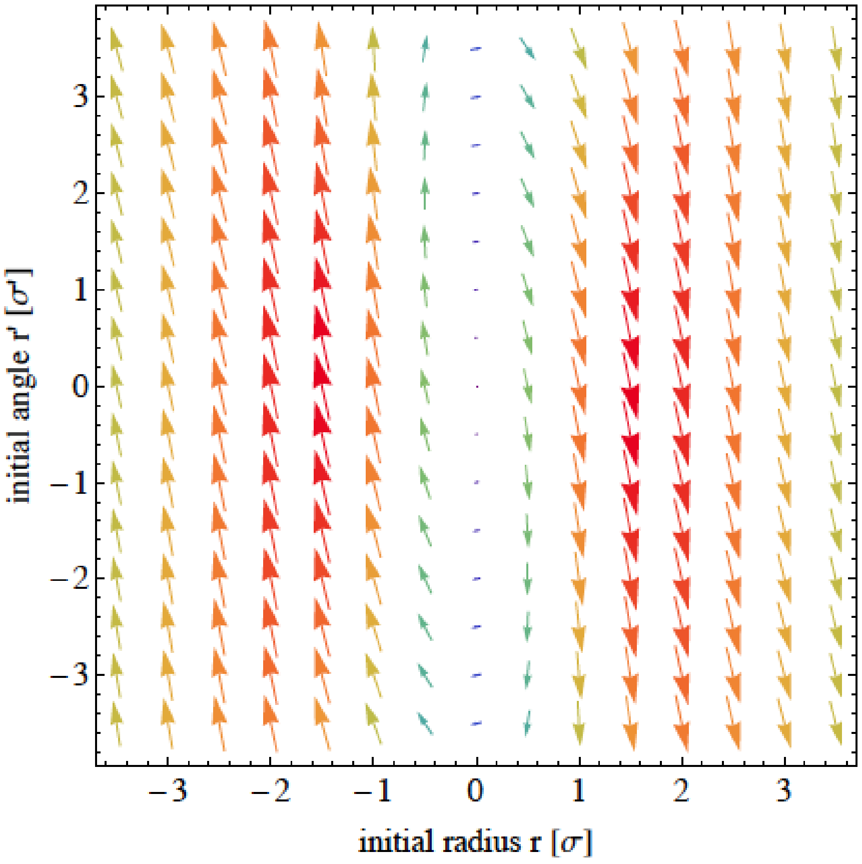

(c) long bunch, β^* = 0.5 m, δt = 0, Max ΔR = 0.0298

significant deviations from short-bunch case (~30%) for r ≈ σ and large r'

Effect of long – bunches on HOBBC

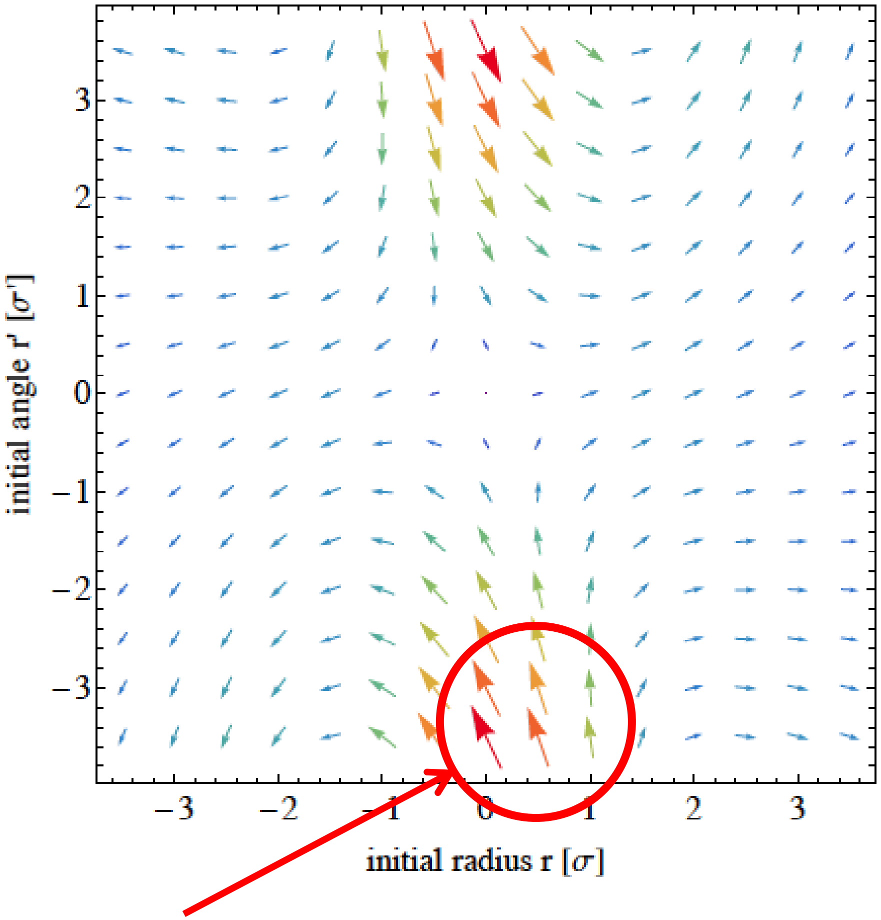
no HOBBC, RHIC case

(a) no HOBBC, Max R = 0.1080



HOBBC, -10 deg phase error

(d) HOBBC, $\Delta\psi = -10$ deg, Max R = 0.0656

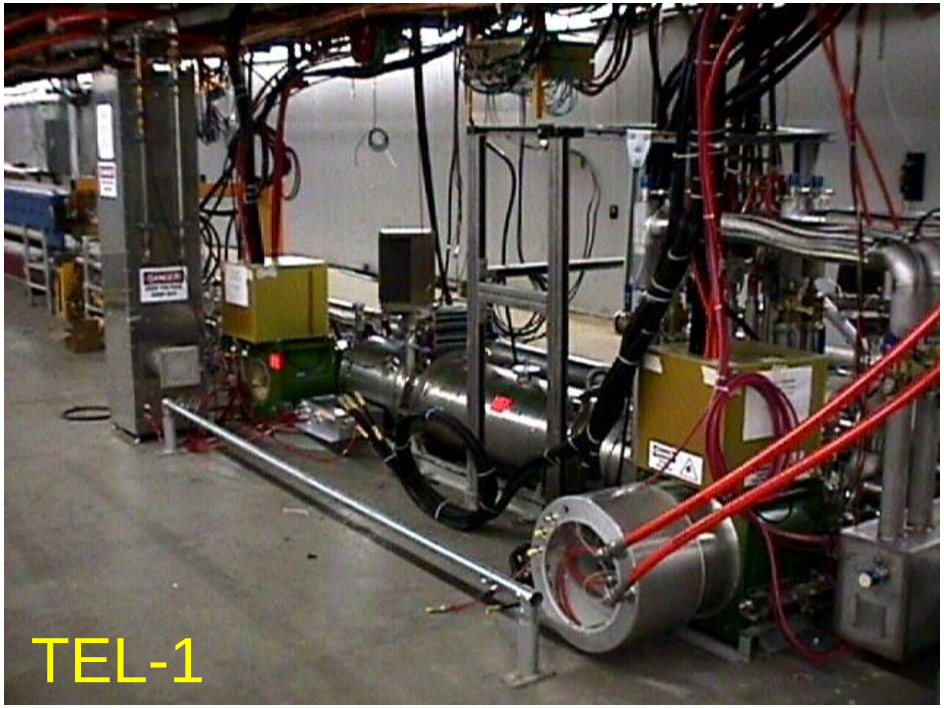


significant part uncompensated (~60%) for r ≈ 0 and large r’

Wolfram Fischer

BROOKHAVEN
NATIONAL LABORATORY

E-lenses technology – Tevatron electron lenses



V. Shiltsev, A. Burov, A. Valishev, G. Stancari, X.-L. Zhang, et al.

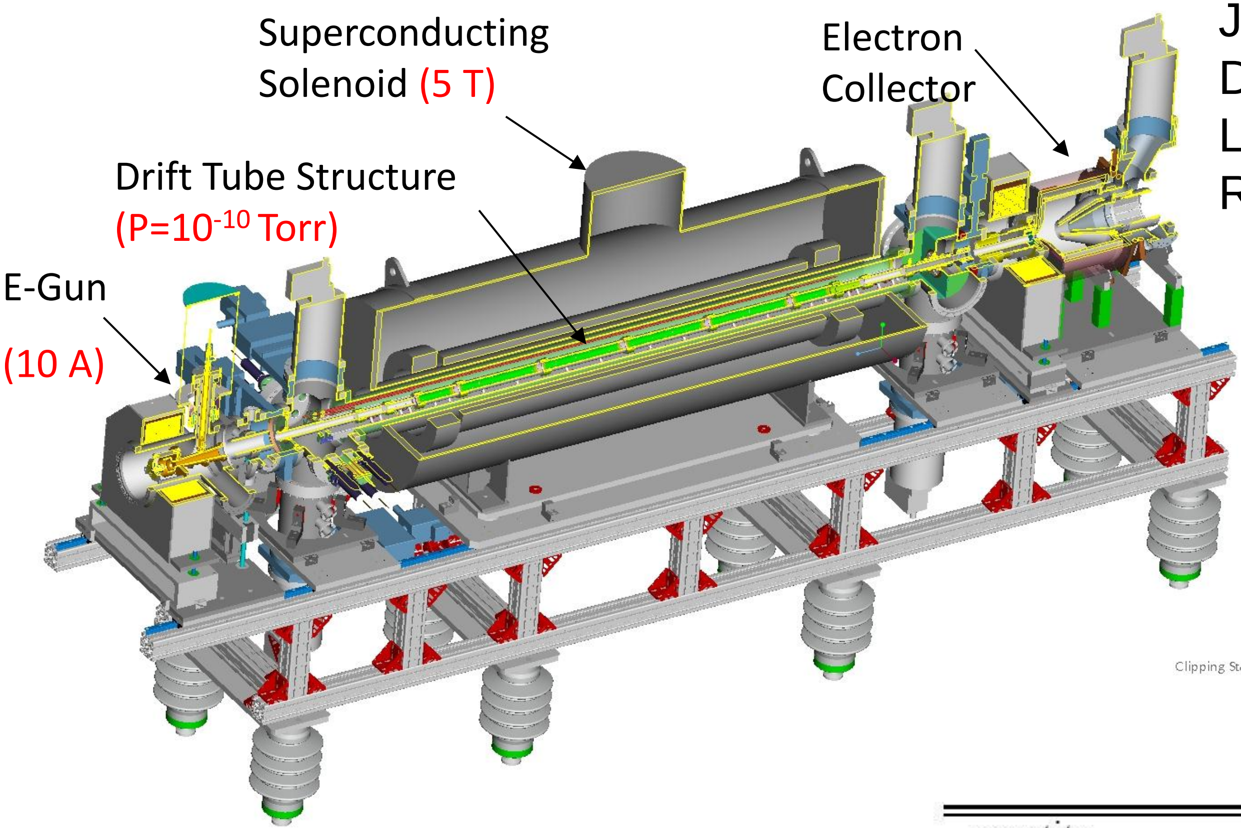
2 lenses in Tevatron:

- Energy: 5/10 kV
- Current: 0.6/3 A
- pulsed, 200 ns rise time [RHIC: also DC]
- Length: 2 m
- e-beam radius: 2.3 mm [RHIC: 0.3 mm]

- 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)
- Have learned sensitivity to parameters (relative beam position – important, e-beam shape – important, current – 10^{-3} variations ok)
- Experiments with Gaussian gun (Sep. 2009, Jul 2010) (alignment and losses, tune shifts, coherent modes, tune space scan with e-lens)

[V. Shiltsev et al., PRST-AB 2, 071001 (1999); PRL 99, 244801 (2007); PRSTAB 11, 103501 (2008); New J. Phys. 10, 043042 (2008)]

E-lens technology – BNL Electron Beam Ion Source



Superconducting Solenoid (5 T)

Electron Collector

Drift Tube Structure (P=10^{-10} Torr)

E-Gun (10 A)

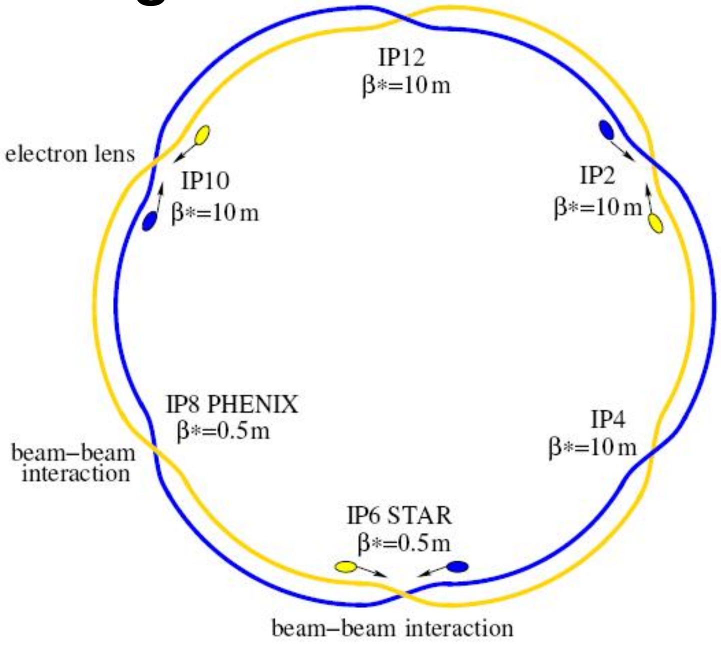
J. Alessi, E. Beebe, S. Pikin,
D. Raparia, M. Okamura,
L. Snydstrup, J. Ritter,
R. Lambiase et al.

Operated for NASA Space Radiation Laboratory in 2011-12 with He^{+}, He^{2+}, Ne^{5+}, Ne^{8+}, Ar^{10+}, Kr^{18+}, Ti^{18+}, Fe^{20+}, Xe^{27+}, Ta^{33+}, Ta^{38+}

Operated for RHIC in 2012 with U^{39+} (not possible previously), Cu^{11+}, Au^{31+}

quantity	unit	RHIC EBIS	Test EBIS achieved
e-beam current	A	10	10
e-beam energy	keV	20	20
ion trap length	m	1.5	0.7
trap charge capacity	10^{11}	11	5.1
charge yield (Au)	10^{11}	5.5 (10 A)	3.4 (8 A)
pulse length	μs	$\leq$40	20
yield Au^{32+}	10	3.4	$>$ 1.5

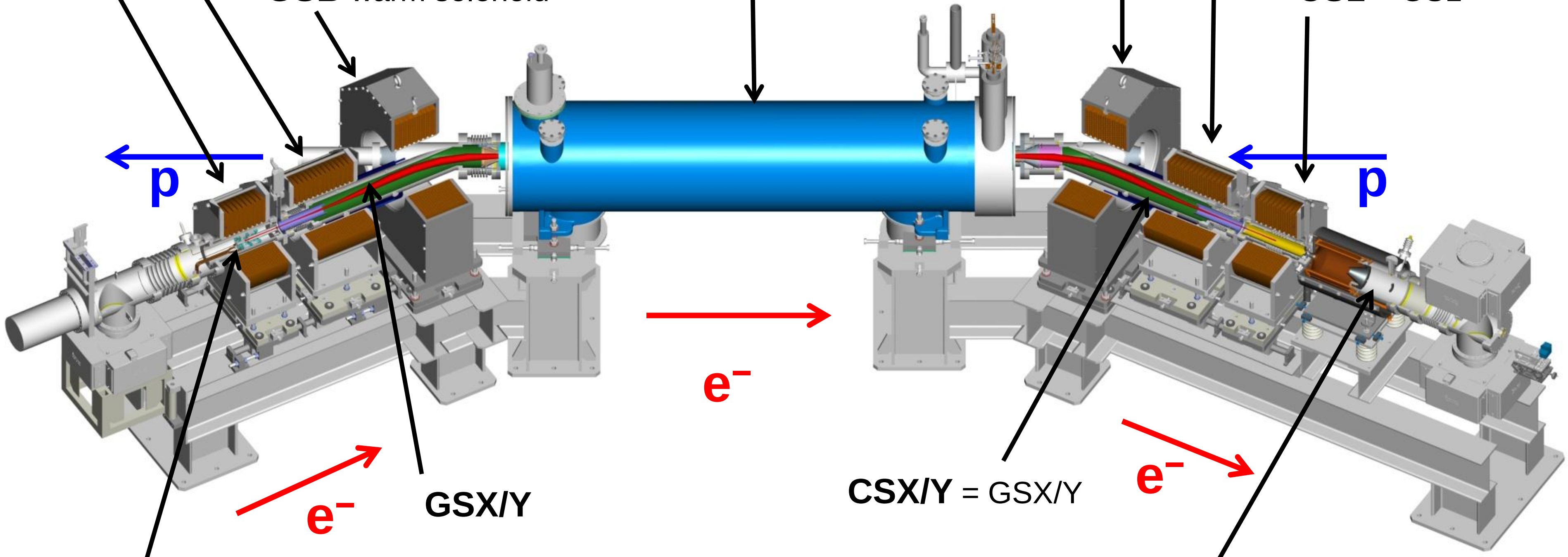
RHIC electron lenses – Basic design decisions



1. Electron lenses in IR10
   smallest distance to IP8 head-on beam-beam interaction (nonlinearities), available space
2. Both lenses in common area
   main solenoids compensate each other for coupling and spin, $\beta_x = \beta_y$ at e-lens locations
   drawback: β-functions relatively small (<= 10 m)
3. DC beam for compensation
   avoids noise introduced with HV switching (have pulsed operation for set-up and diagnostics)
4. Superconducting main solenoid
   need high field to match electron and proton beam size
5. Field straightness correctors incorporated in sc main solenoid
   compact solenoid
6. Transport solenoids and orbit correctors warm
   capital cost lower than for sc (sc transport solenoids with break-even time 5-10 years)
7. Diagnostics
   basic diagnostic consists of BPMs and RHIC instrumentation (BTF, lifetime),
   e-bam profile monitors, backscattered electron monitor, halo detection

RHIC electron lenses

Compensation overview



GS1 warm solenoid

GS2 warm solenoid

GSB warm solenoid

SC main solenoid
B = 6 T, I = 440 A
+ 16 more magnets
(fringe fields, correctors)

CSB = GSB

CS2 = GS2

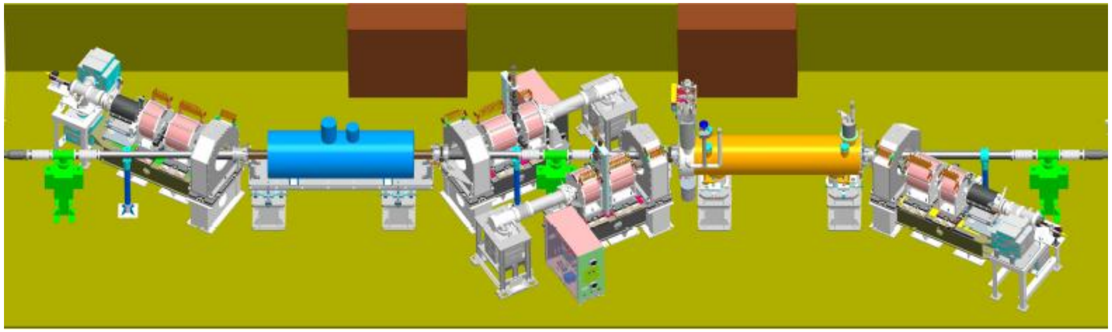
CS1 = GS1

GSX/Y

CSX/Y = GSX/Y

Electron gun

Electron collector



Requirement for electron lens

1. Electron beam size in the main solenoid
   RMS beam size: 0.3 mm - 0.8 mm (issue: relatively small)
2. Gaussian shape of electron beam
   good fit to 3 σ (issue: cathodes have limited size)
3. Straightness of magnetic field in main solenoid
   target of ± 50 μm after correction (issue: good overlap of e and p beam)
4. Steering electron beam in e-lens
   maximum shifting : ± 5 mm in X and Y planes
   maximum angle   : 0.1 mrad
5. Stability in electron current
   power supplies stability better than 10^{-3}
6. Overlap of electron and proton beams
   robust real-time measurement with resolution better than 100 μm

Gun and collector (A. Pikin)

Gun

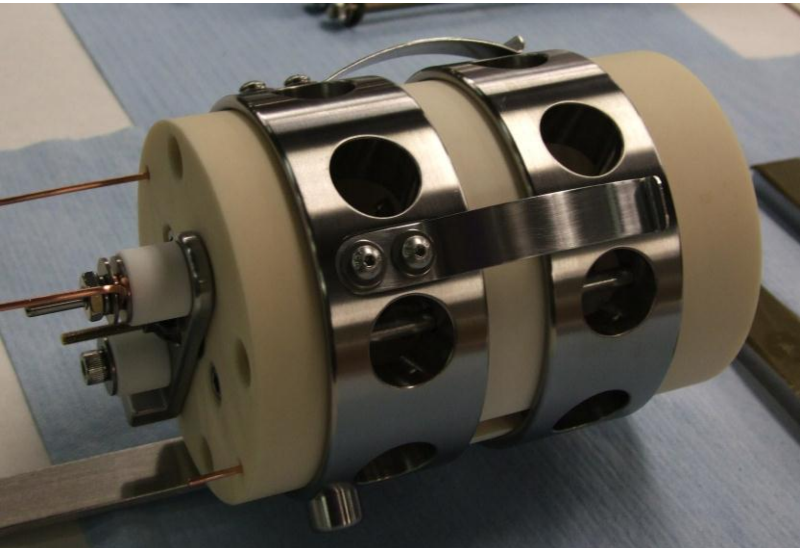
Designed for: current density, profile

3 modes:

- DC (full compensation)
- 100 Hz (positioning)
- 78 kHz (single bunch compensation)

V_{max} = 10 kV, I_{max} = 1 A, P = 1×10^{-6} $AV^{-3/2}$

Cathodes: LaB_6 and IrCe (from Budker),
4.1 mm radius, Gaussian profile (2.8 σ)



Collector

Designed for: Reliability

Water cooled,
can take 4x nominal load of 15 kW

$\rho_P < 50$ W/cm^2, $T < 125$°C

Warm magnets (A. Pikin, X. Gu)

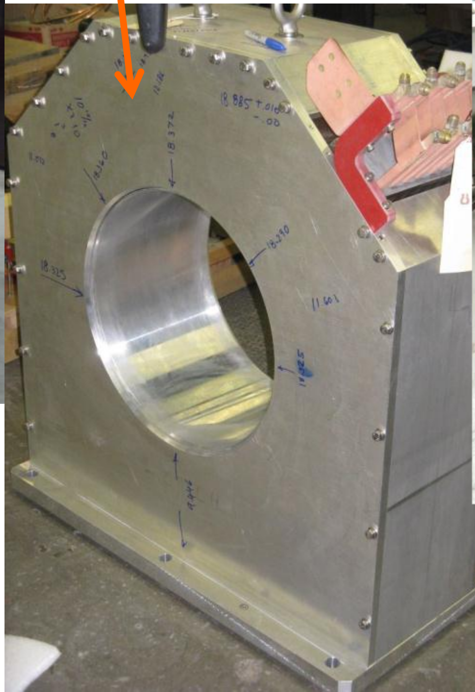
4 types: GS1, GS2, GSB, GSX/Y

Designed for: 0.3 T min transport field, power consumption (total < 0.5 MW)

GS1 (gun, collector)
B = 0.8 T, I = 1200 A, P = 58 kW

GSB (bend)
B = 0.3 T, I = 770 A, P = 45 kW

GS2
B = 0.5 T, I = 730 A, P = 25 kW



PS in assembly
(1 each for GS1-CS1, GS2-CS2, GSB-CSB)

RHIC electron lenses **Superconducting magnets (R. Gupta)**

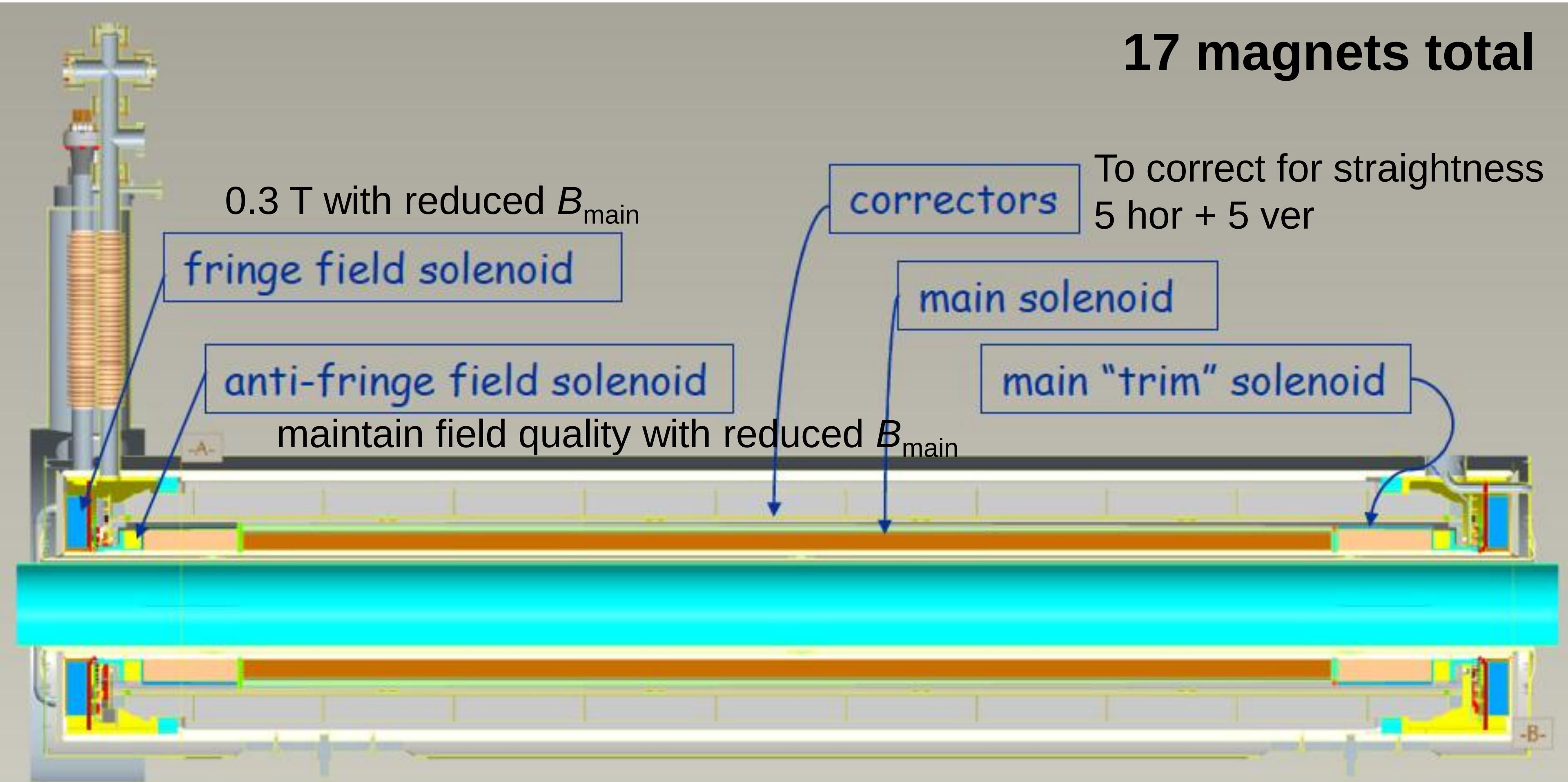
Designed for: solenoid field strength (6T), field straightness (±50 μm)

$$s_{main} = s_{gun}\sqrt{\frac{B_{gun}}{B_{main}}}$$

Stabilizes e-beam

Magnetic compression (need 310 μm rms beam size)

Maximize overlap of p- and e-beams



17 magnets total

0.3 T with reduced B_{main}

fringe field solenoid

anti-fringe field solenoid

maintain field quality with reduced B_{main}

correctors

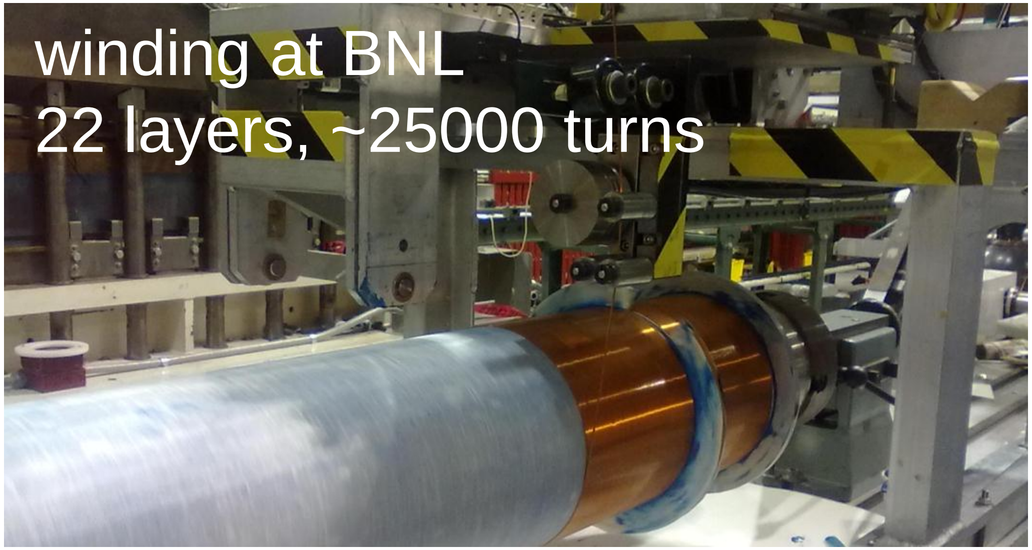
To correct for straightness
5 hor + 5 ver

main solenoid

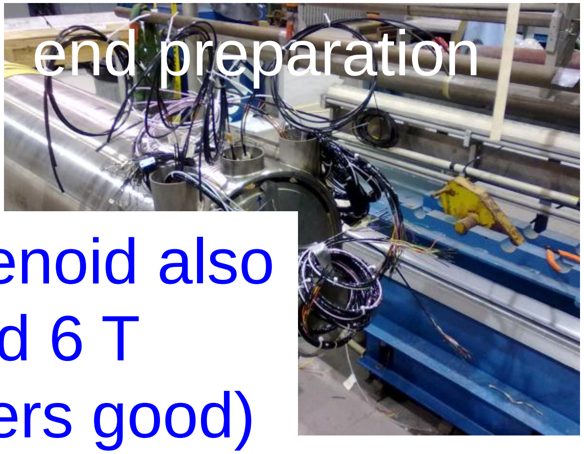
main “trim” solenoid

RHIC electron lenses

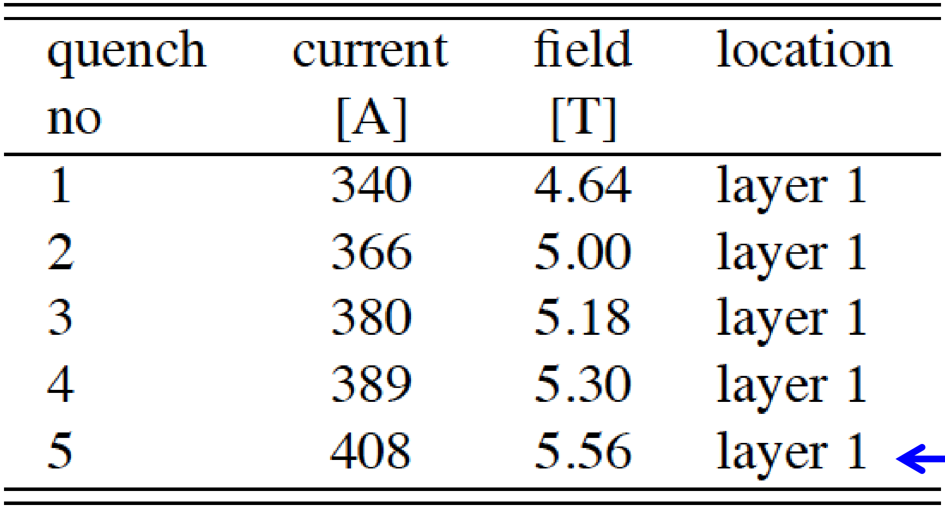
Superconducting magnets


winding at BNL
22 layers, ~25000 turns


shell with correctors


end preparation

1st solenoid tested cold:



quench no	current [A]	field [T]	location
1	340	4.64	layer 1
2	366	5.00	layer 1
3	380	5.18	layer 1
4	389	5.30	layer 1
5	408	5.56	layer 1

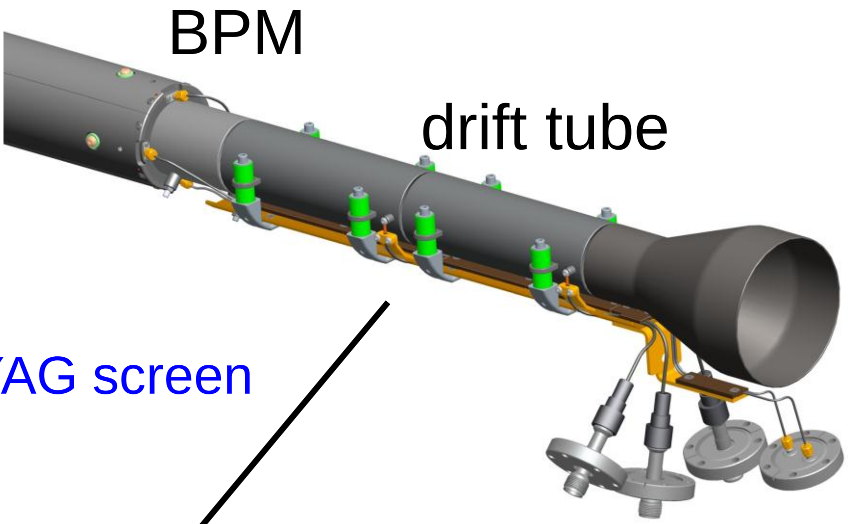
← Ground fault developed in layer 1, decided to disable layers 1&2

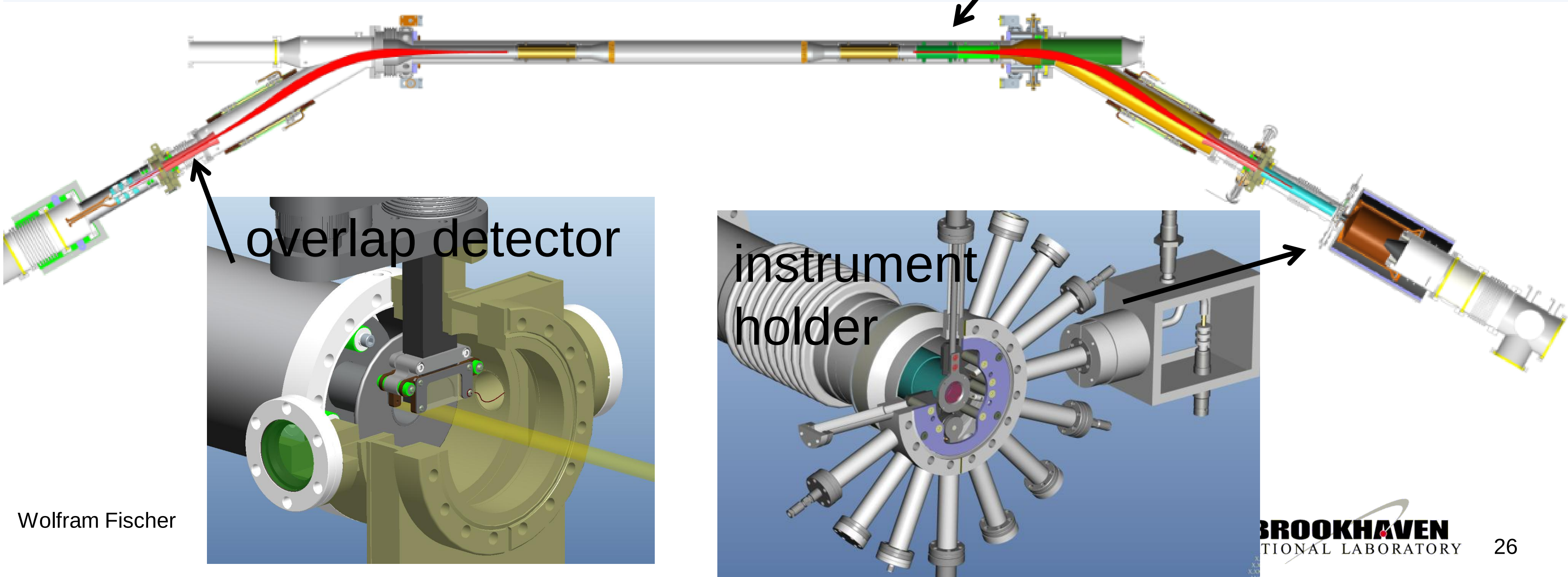
2nd solenoid also reached 6 T (all layers good)

Instrumentation

Designed for:

- e-beam position
- e-current and losses halo monitor
- Drift tubes
  ion extraction with DC e-beam
- e-beam profiles pin-hole detector, YAG screen
- Overlap of p- and e-beam

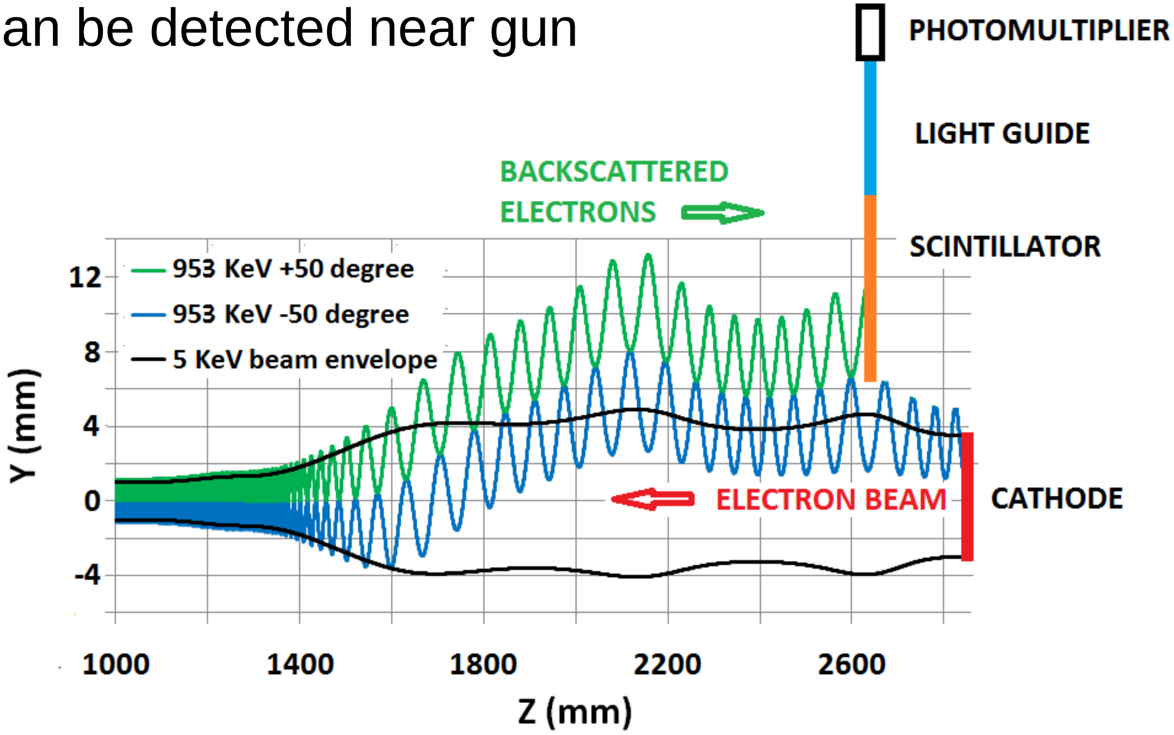


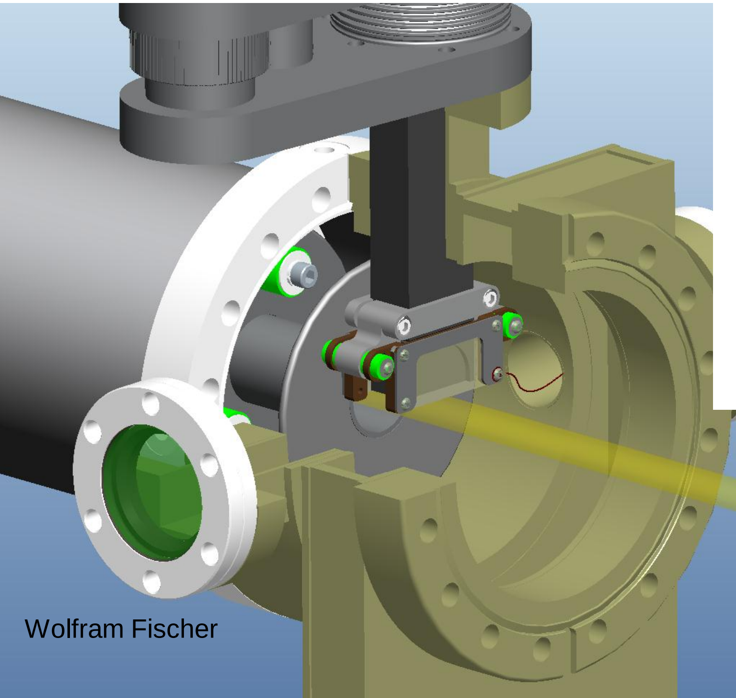


Instrumentation

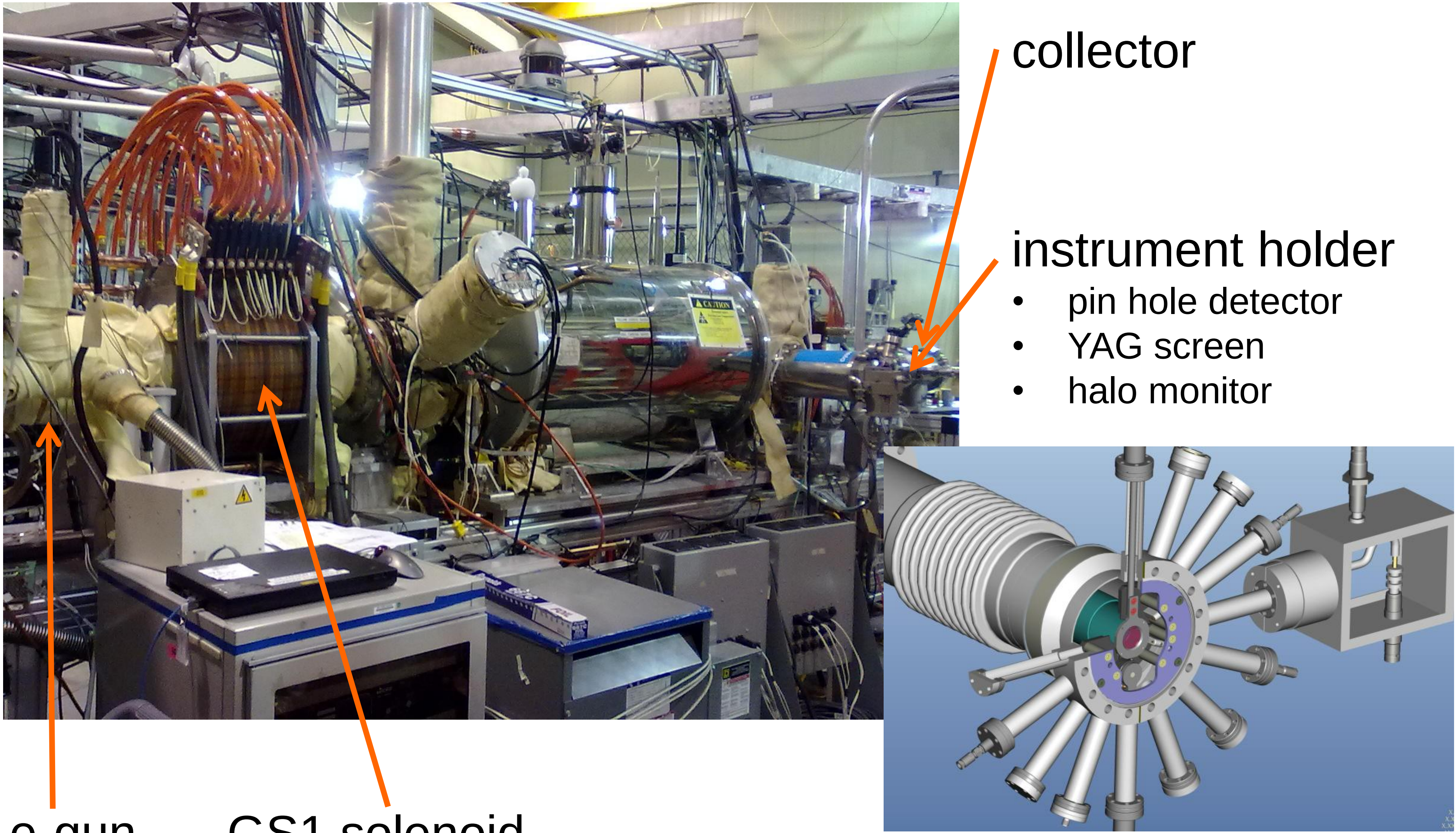
Beam overlap monitor (P. Thieberger):

- p-e beam interaction creates bremsstrahlung (photons) and backscattered electrons
- Backscattered electrons can be detected near gun (above e-beam)





Test bench 2012



collector

instrument holder

- pin hole detector
- YAG screen
- halo monitor

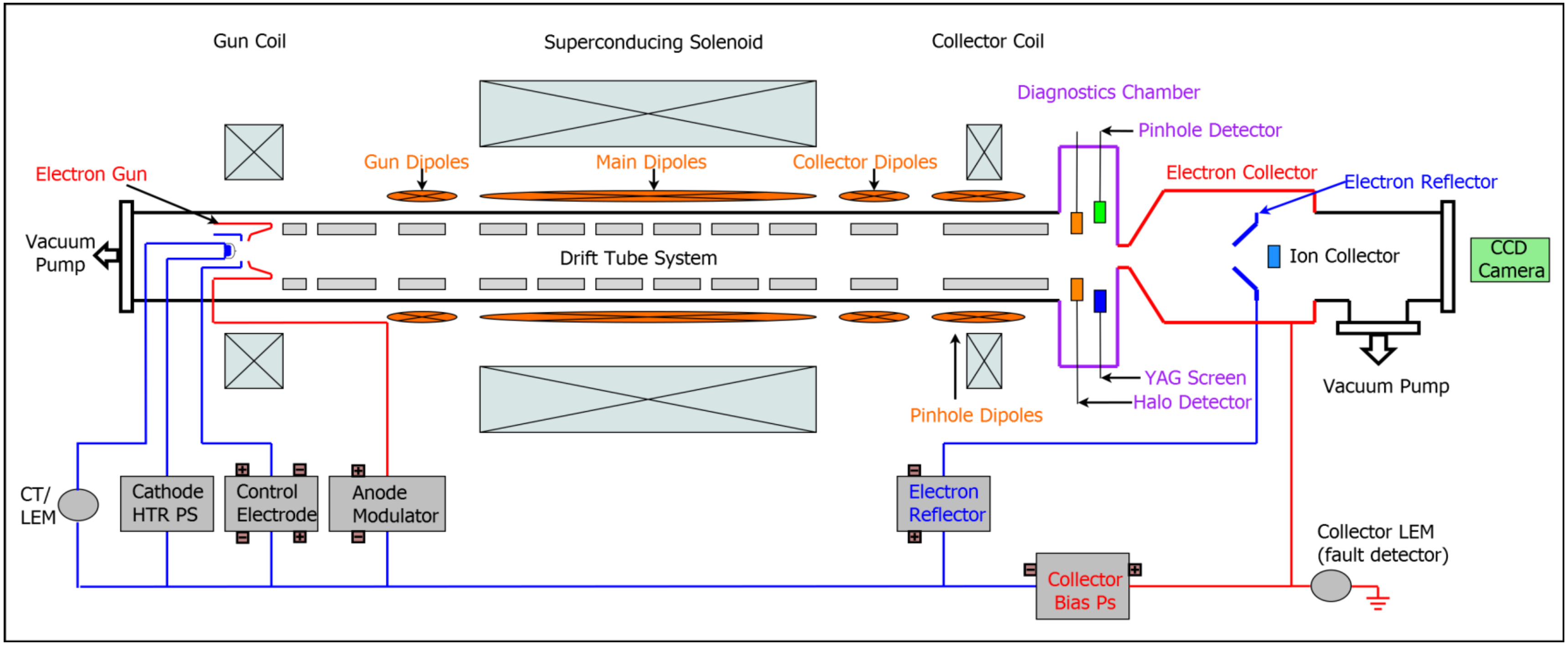
e-gun

GS1 solenoid

More details: X. Gu et al., IPAC12, paper in preparation

RHIC electron lenses **Test bench results 2012**

1. Gun operation in all modes (100 Hz, 78 kHz, DC) – 1 A, $\Delta I/I_{rnd}$ = 0.075% OK
2. Measured gun perveance (I vs. U): 0.93 $\mu AV^{-3/2}$ OK
3. Measured collector temperature and pressure with high load OK
4. Commissioning of pin hole detector and YAG screen done
5. Verified transverse Gaussian profile OK
6. Prototype of machine protection system done
7. Test of software controls done

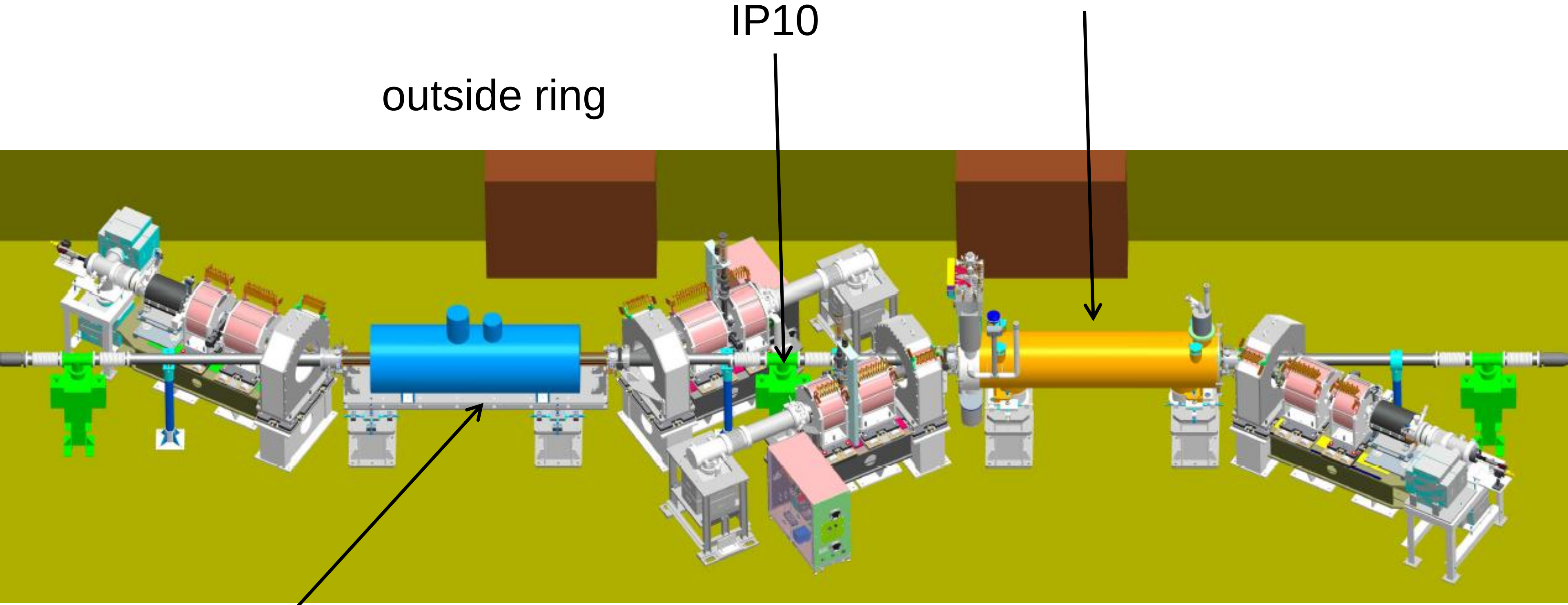


More details: X. Gu et al., IPAC12, paper in preparation

Installation for 2013

Electron lens main solenoid #1

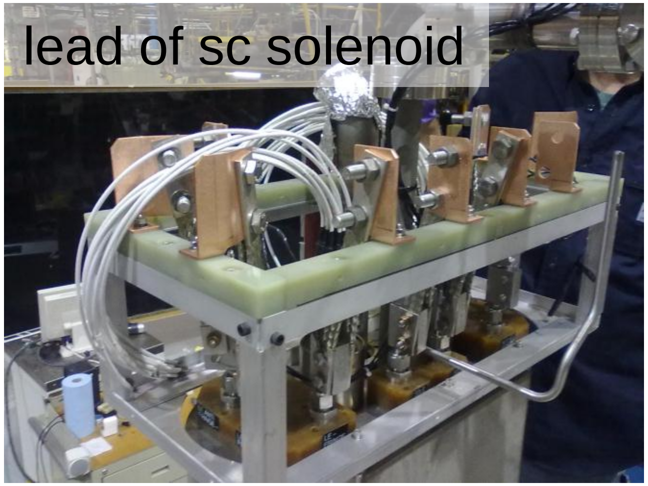
- straight beam pipe (Y-pipes not ready)
- allows for commissioning of all solenoid magnets
- does not allow for electron beam commissioning



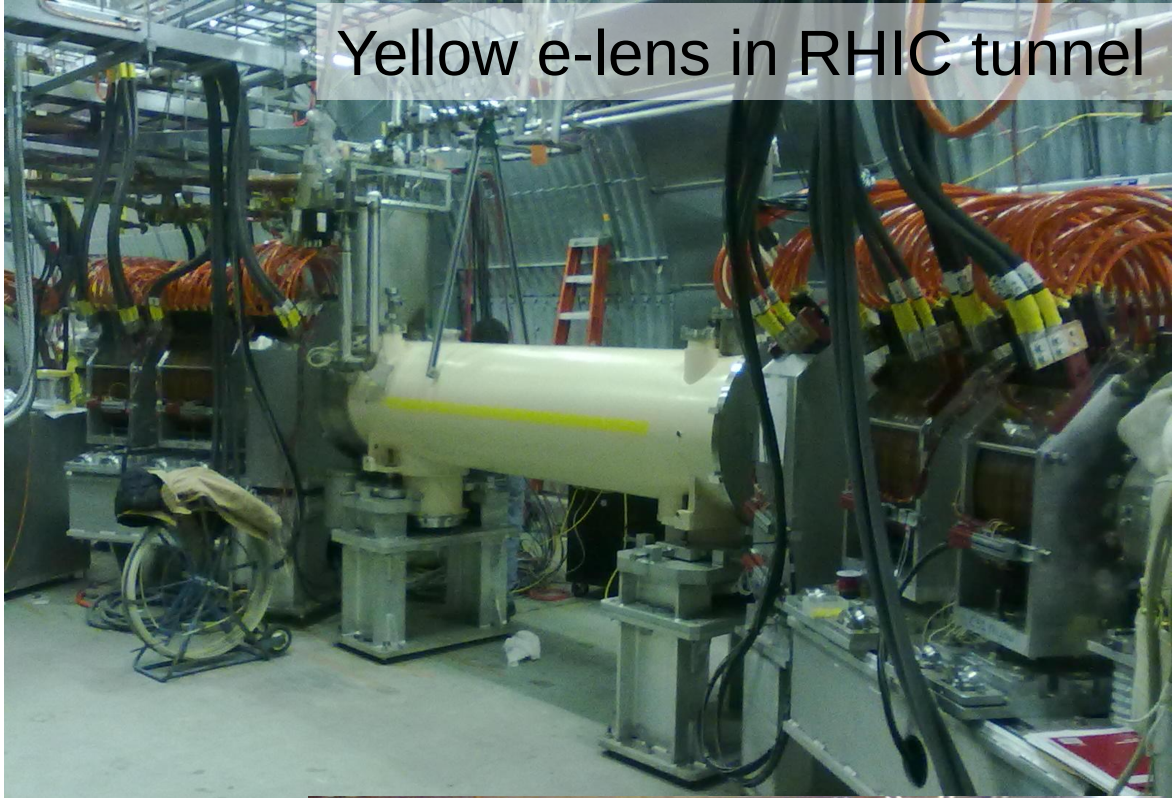
EBIS spare solenoid

- allows for electron transport from gun to collector with 2 Tm integrated strength
- does not allow for beam-beam compensation
  (field lines not straight enough)

RHIC Electron lenses



lead of sc solenoid



Yellow e-lens in RHIC tunnel

drift tube

Y-pipe

water-cooled bus for warm solenoids

ps for warm solenoids

RHIC electron lenses - commissioning

2013 polarized proton run

- Commission new lattice ($\Delta\psi_{x,y} = k\pi$)
- Commission new p-beam diagnostics
  (single bunch BTF, single bunch beam loss rates)
- Commission Yellow lens superconducing solenoid
- Commission Blue and Yellow lens warm magnets
- Commission Blue lens electron beam and instrumentation

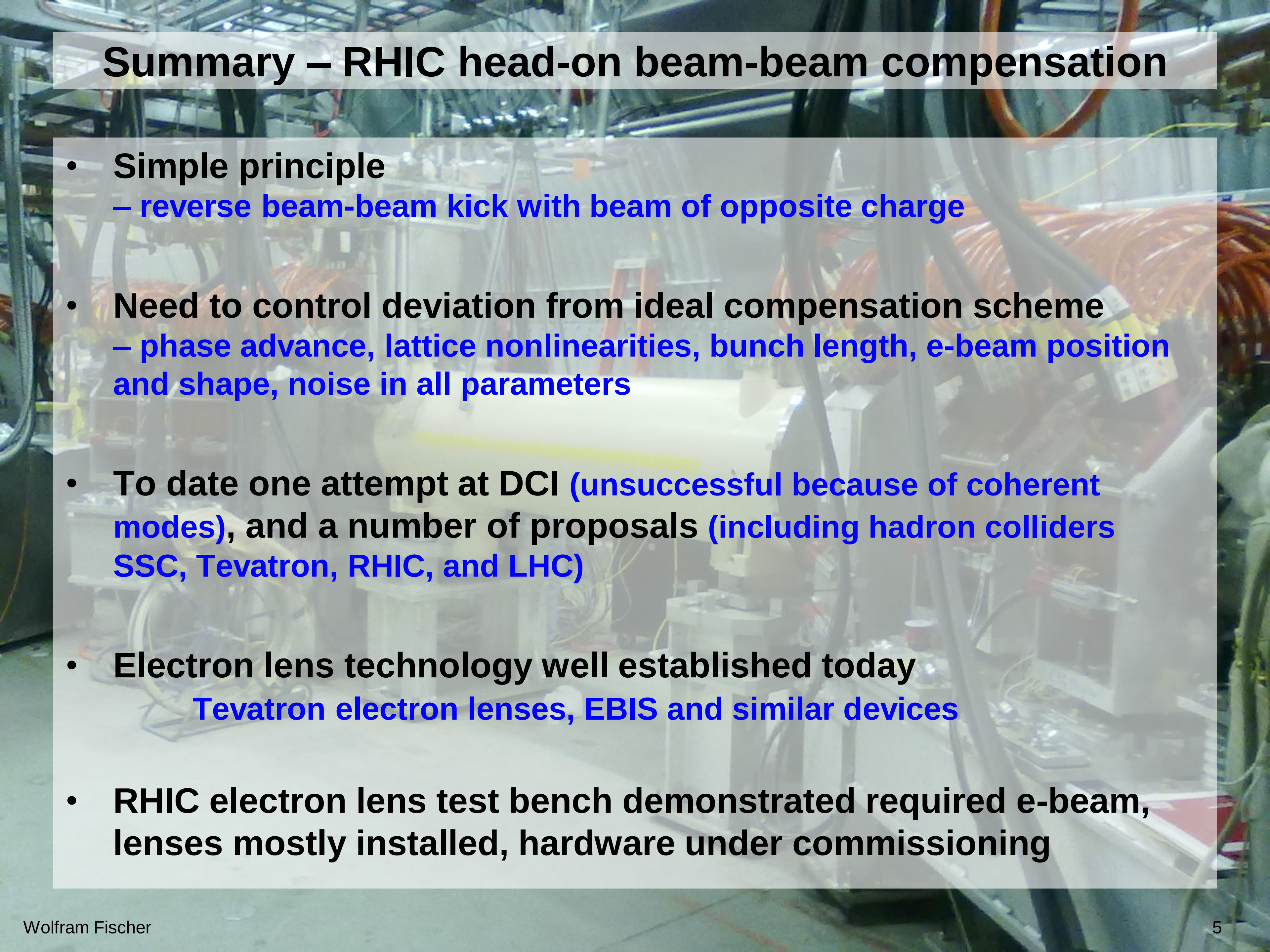
Summer 2013 shut-down

- Install Blue superconducting solenoid
- Measure/correct Blue and Yellow field straightness in tunnel
- Complete installation
  (Yellow vacuum system, backscattered electron detectors)

2014 run

- Commission both lenses with ion/proton beams

Summary – RHIC head-on beam-beam compensation



- **Simple principle**
  – reverse beam-beam kick with beam of opposite charge

- **Need to control deviation from ideal compensation scheme**
  – phase advance, lattice nonlinearities, bunch length, e-beam position and shape, noise in all parameters

- **To date one attempt at DCI (unsuccessful because of coherent modes), and a number of proposals (including hadron colliders SSC, Tevatron, RHIC, and LHC)**

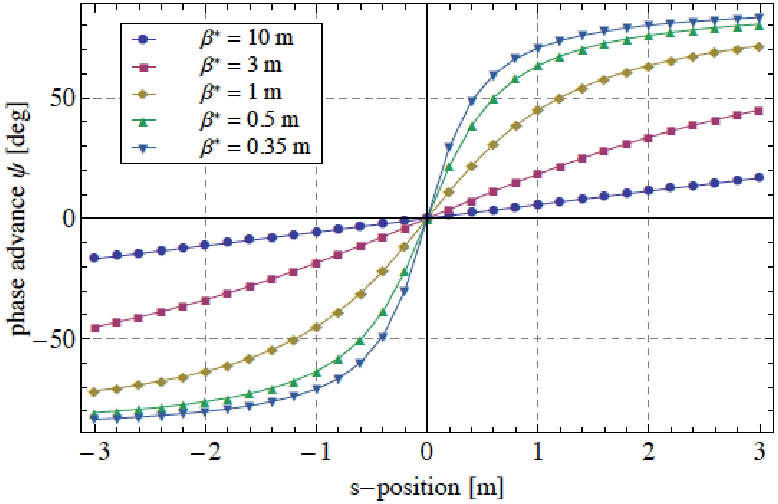
- **Electron lens technology well established today**
  Tevatron electron lenses, EBIS and similar devices

- **RHIC electron lens test bench demonstrated required e-beam, lenses mostly installed, hardware under commissioning**

Additional slides

Effect of long bunches on beam-beam

phase advance near IP w/o BB
(phase averaging usual beneficial)



differential eqs. for (r,r’) for BB with long bunches

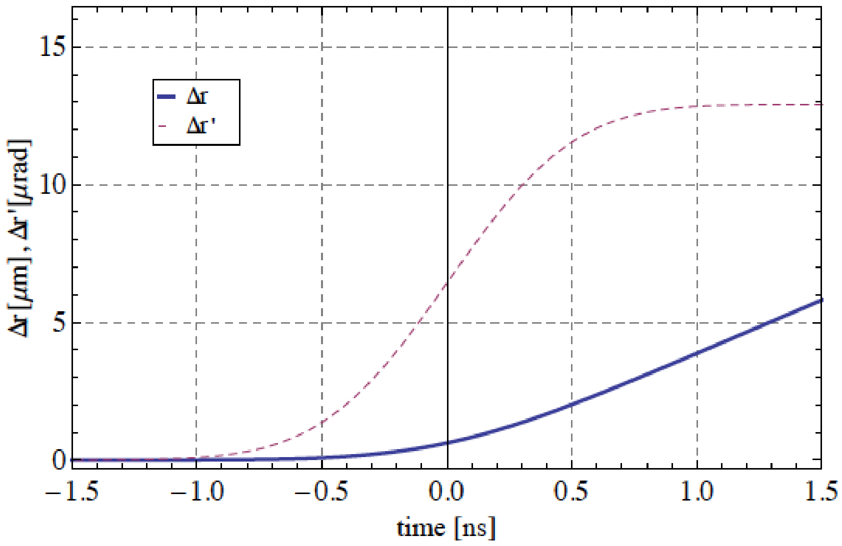
$$\frac{dr}{dt} = cr'$$

$$\frac{dr'}{dt} = \frac{2N_p r_p c(1+\beta_{p1}\beta_{p2})}{\sqrt{2\pi}\beta_{p1}\gamma_{p1}\sigma_s} \times$$

$$\times \exp\left[-\frac{c^2((\beta_{p1}+\beta_{p2})t-\beta_{p1}\delta t)^2}{2\sigma_s^2}\right] \times$$

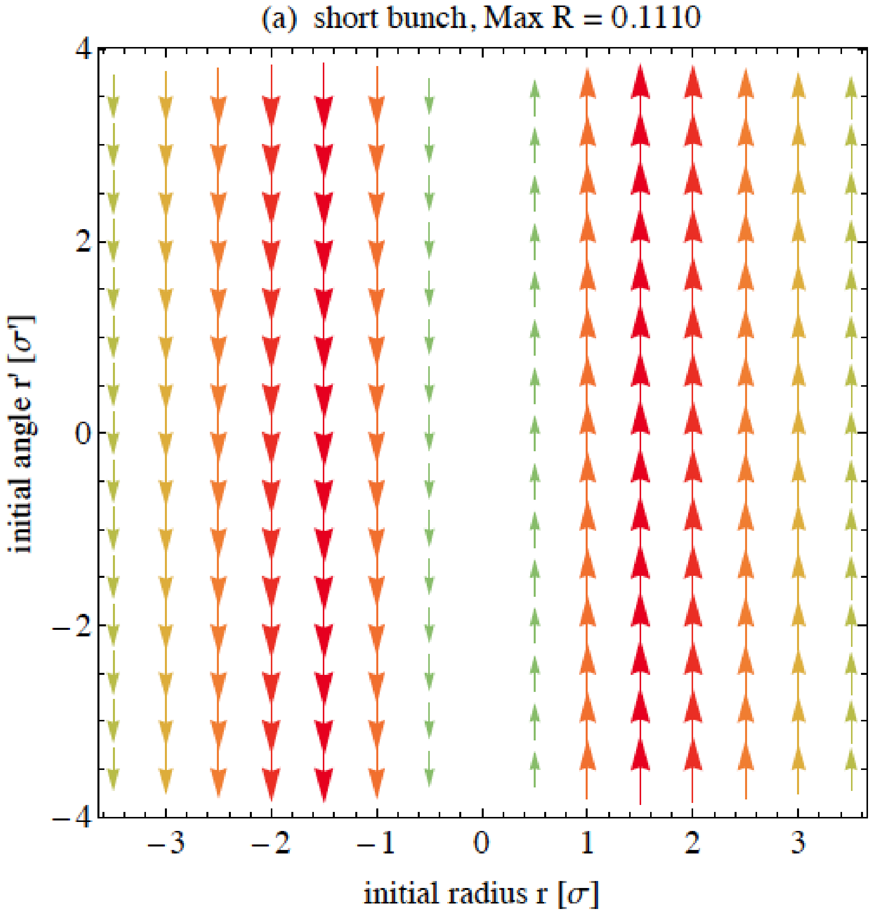
$$\times \frac{1}{r}\left[1-\exp\left(-\frac{r^2}{2\sigma_p^2(\beta_{p1}c(t-\delta t))}\right)\right]$$

change of (r,r’) for r=1σ_p, r’=0

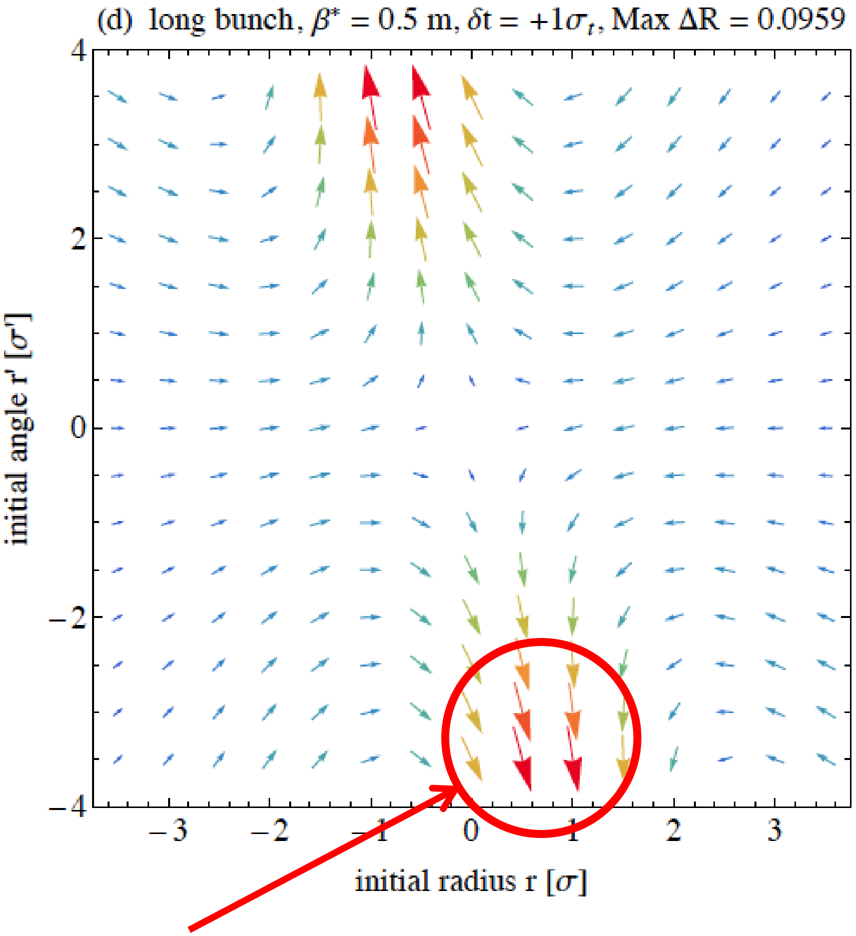


Effect of long bunches on HOBB (II)

short bunch, $\sigma_s=0$



long bunch, σ_s=0.2m, β^*=0.5 m and σ_t late arrival

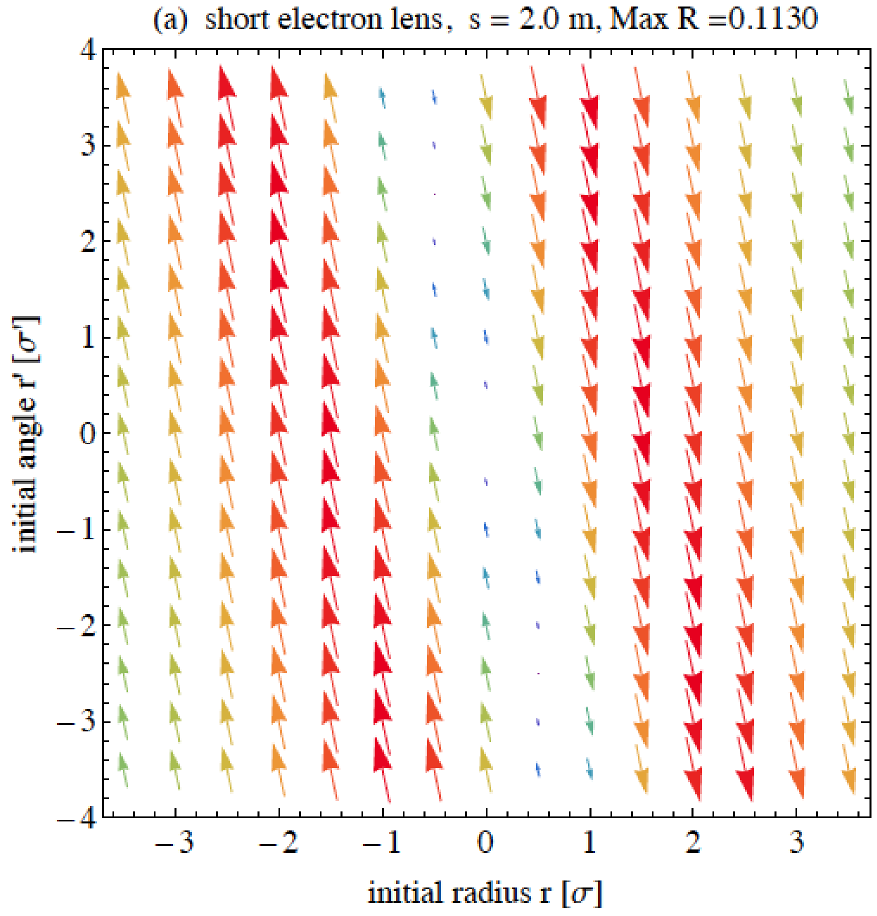


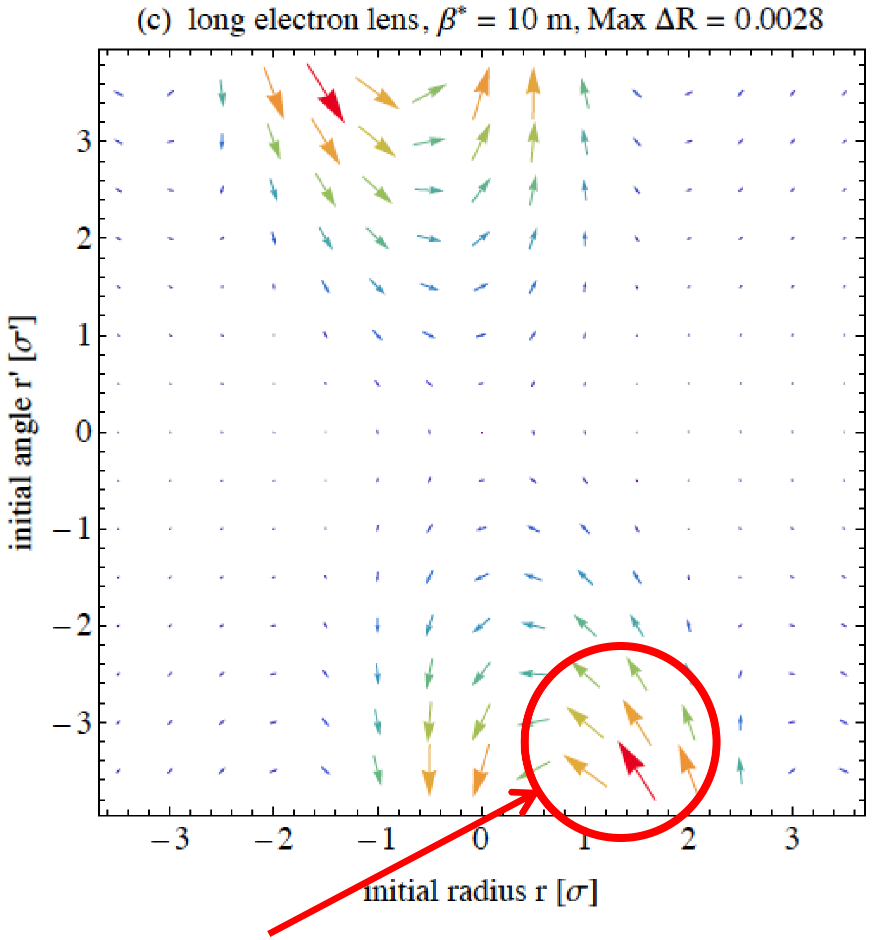
significant deviations from short-bunch case (~100%) for r ≈ σ and large r'

Effect of long bunches on HOBB with e-lens

short e-lens (1.55m off IP)

long bunch, $\sigma_s = 0.2\text{m}$, $\beta^* = 0.5$ m


(a) short electron lens, s = 2.0 m, Max R =0.1130


(c) long electron lens, β^* = 10 m, Max ΔR = 0.0028

small deviations from short-lens case (~3%) for r ≈ σ and large r’