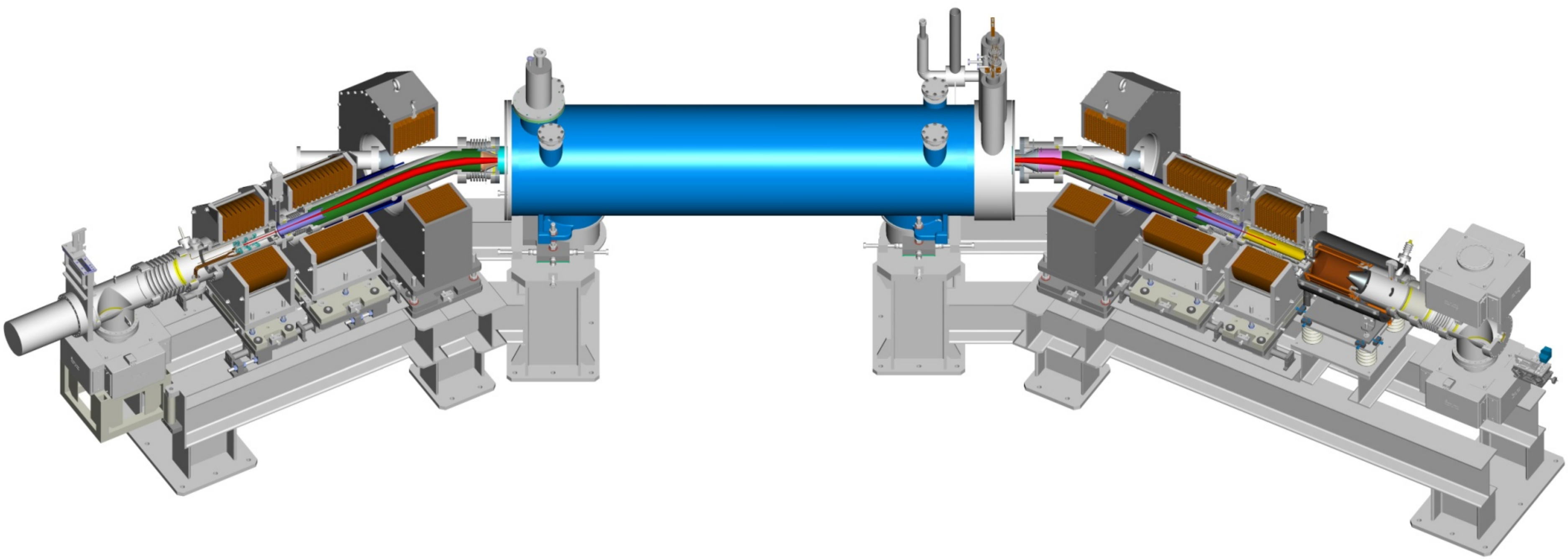
First experience with electron lenses for beam-beam compensation in RHIC

W. Fischer, X. Gu, S.M. White, Z. Altinbas, D. Bruno, M. Costanzo, J. Hock, A. Jain, Y. Luo, C. Mi, R. Michnoff, T.A. Miller, A.I. Pikin, T. Samms, Y. Tan, R. Than, P. Thieberger

Brookhaven National Laboratory



IPAC 2014, Dresden

Contents

Head-on beam-beam compensation

motivation, principle, history

RHIC electron lens design overview

magnetic structure

electron beam

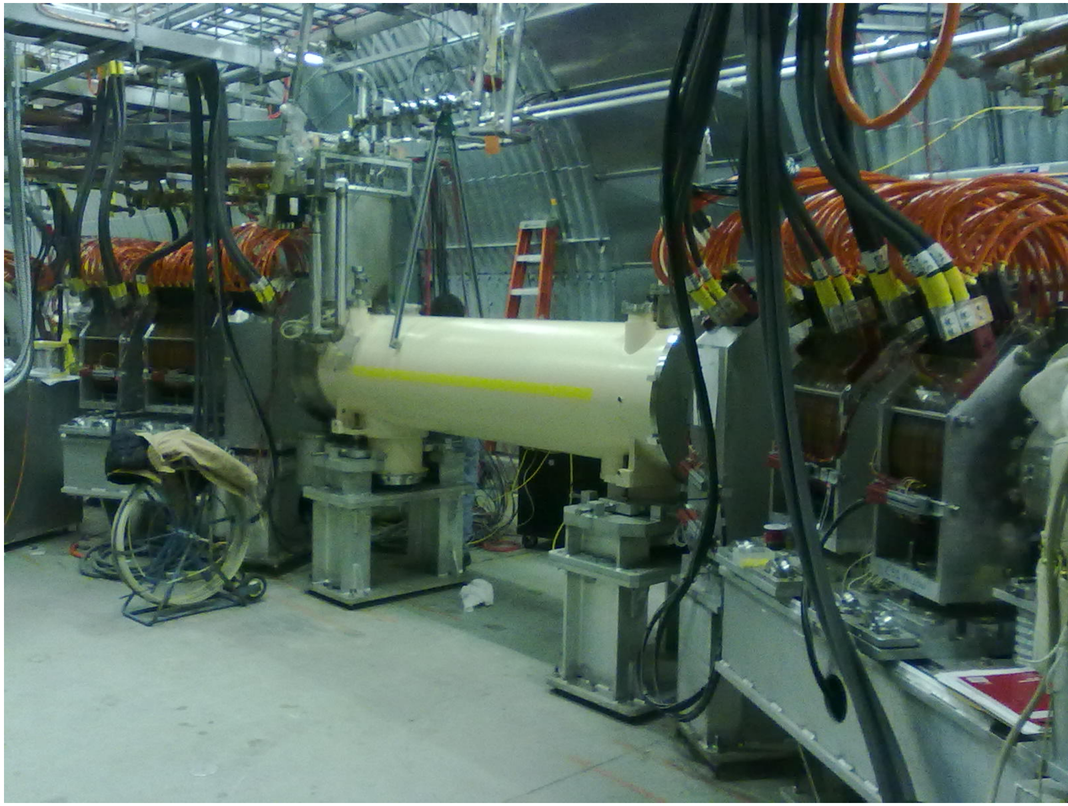
Commissioning to date

hardware

electron beam

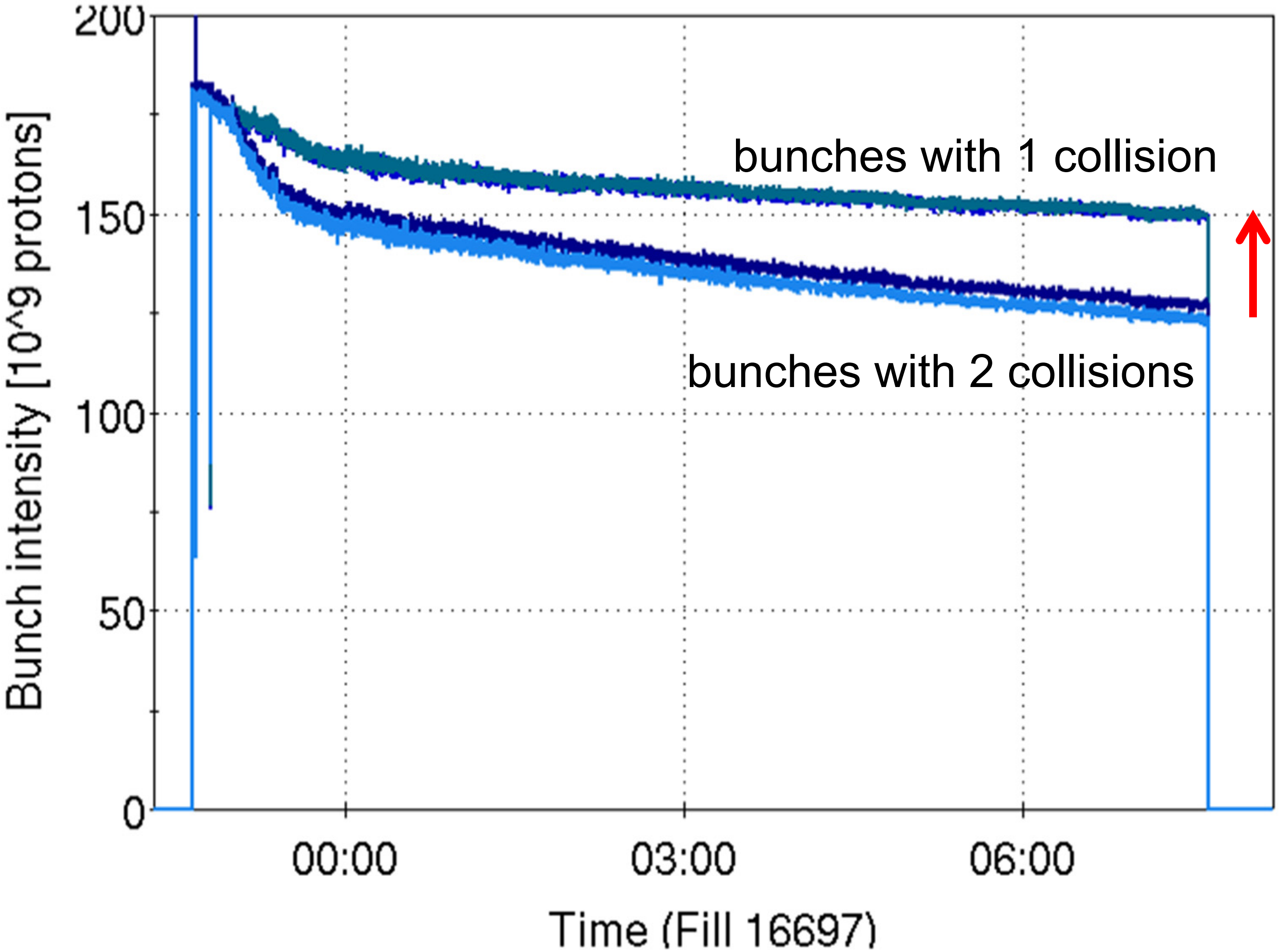
gold beam

Outlook



Motivation

Bunch intensity in 2012 polarized proton physics store



Goal:

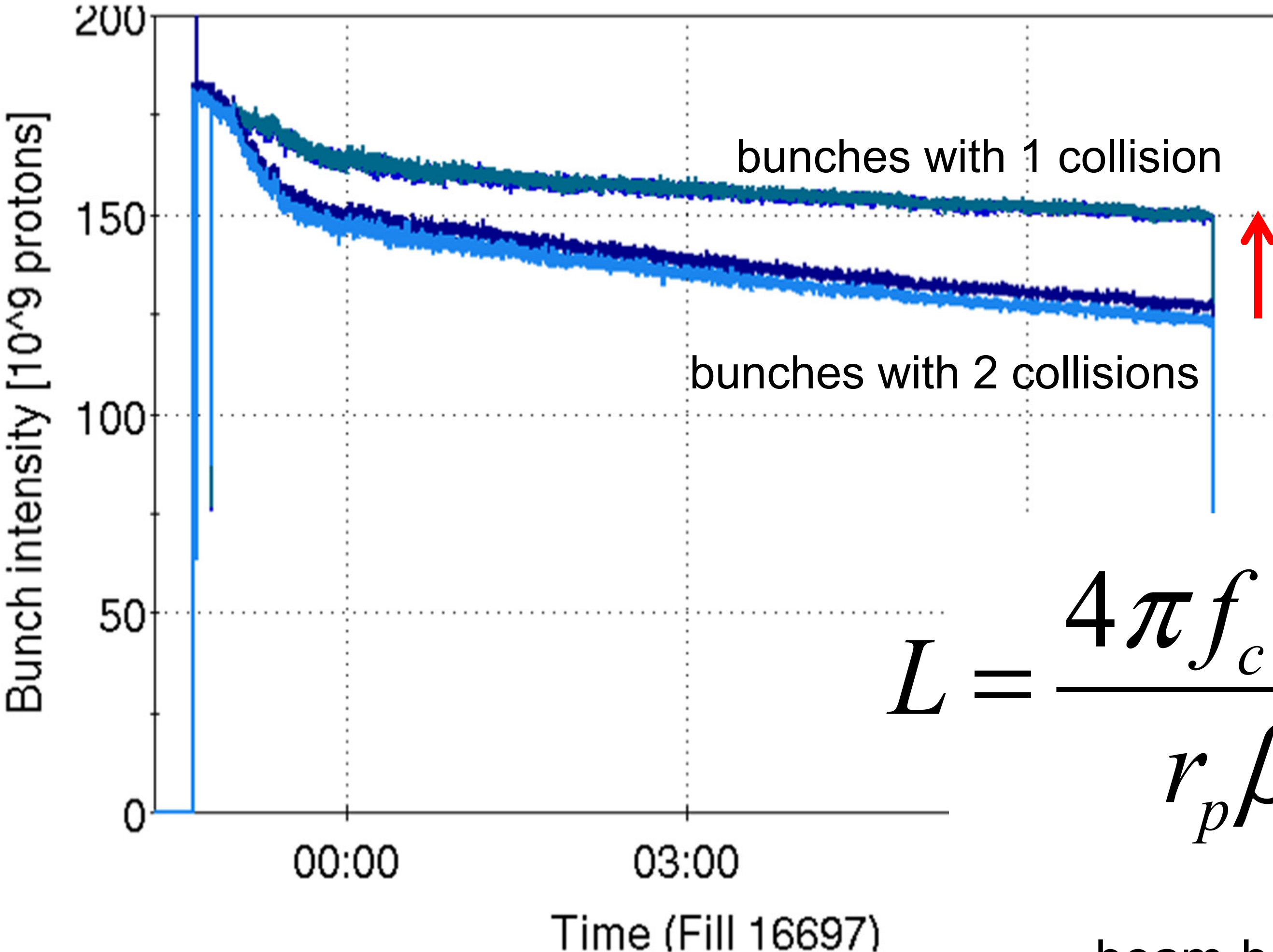
Compensate for 1 of 2 beam-beam interactions with electron lenses

Then increase bunch intensity
$\Rightarrow$up to 2 $\times$ luminosity

RHIC electron lenses

Motivation

Bunch intensity in 2012 polarized proton physics store



Goal:

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

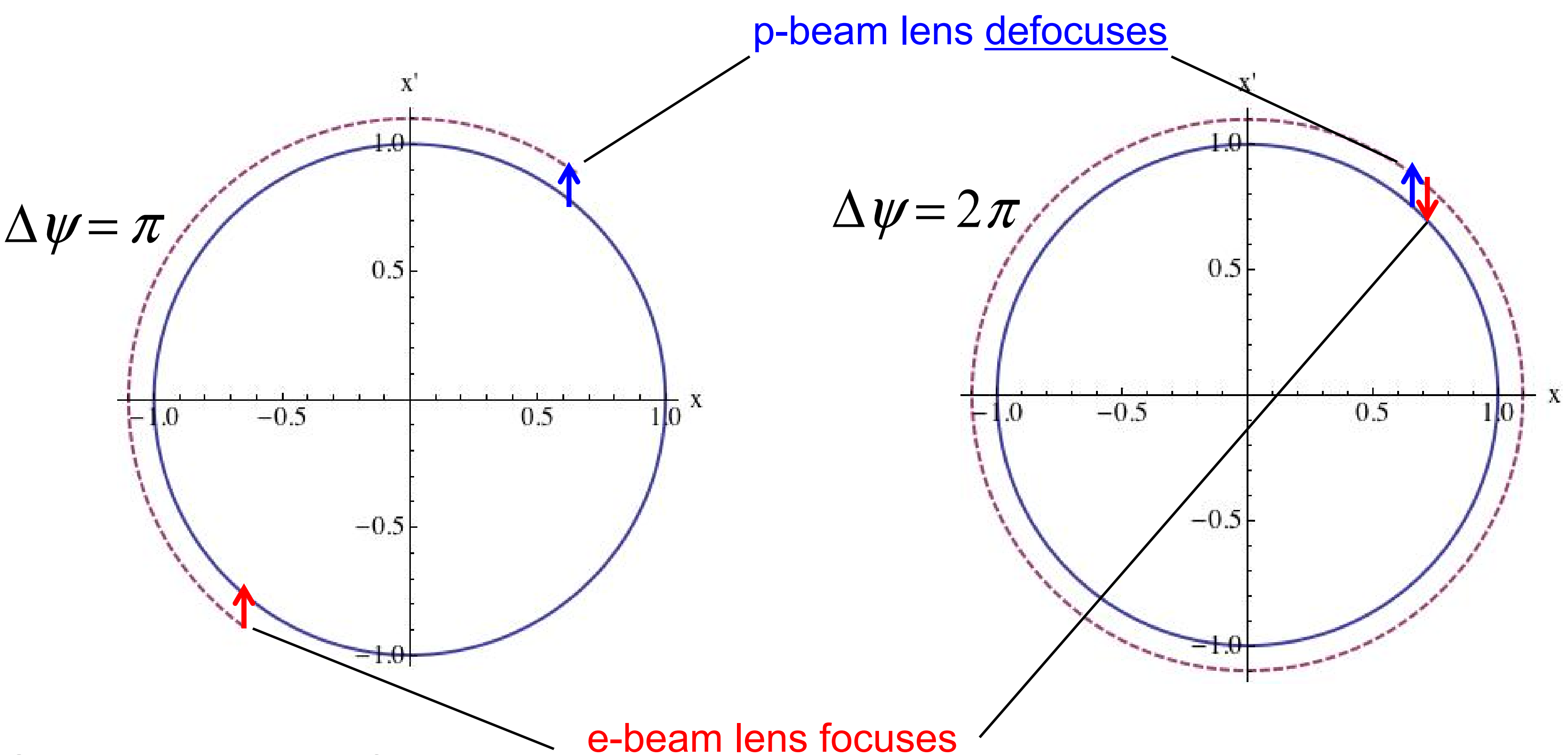
Then increase bunch intensity
⇒up to 2 × luminosity

$$L = \frac{4\pi f_c \gamma^2 \varepsilon_n}{r_p \beta^*} F \xi^2$$

beam-beam parameter

Head-on beam-beam compensation

Phase space



Compensation of:

1. Tune spread

=> e-p has same amplitude dependent force as p-p

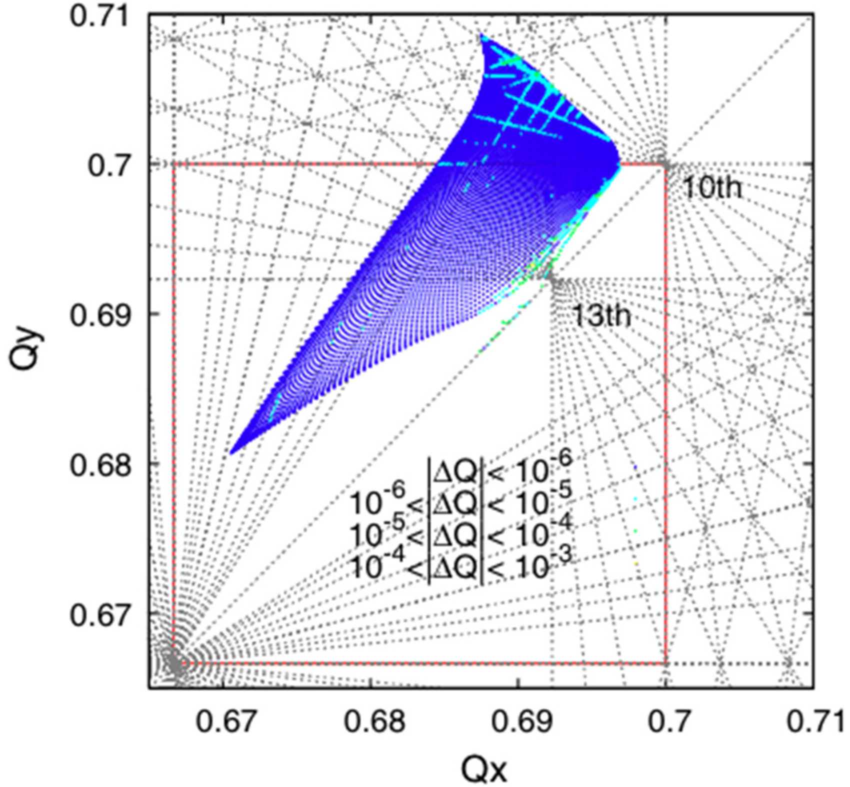
2. Resonance driving terms

=> phase advance between p-p and e-p is $\Delta\psi = k\pi$

Head-on beam-beam compensation

Tune distrib. and RDT

Lens compresses footprint

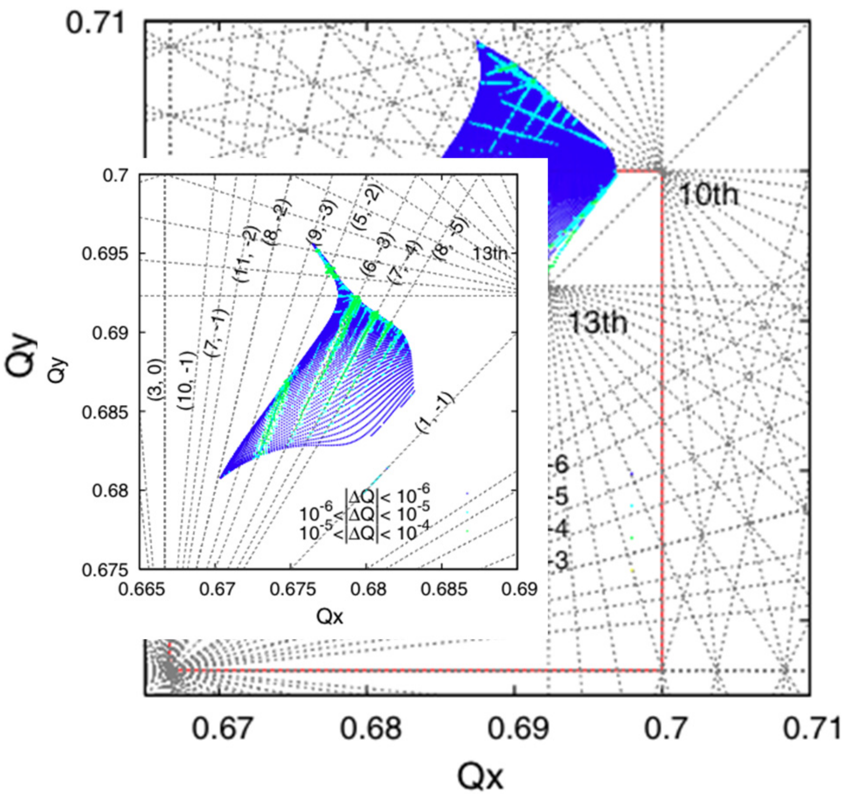


$N_b = 3x10^{11}$ p, w/o and w/ 50% HOBBC

[Y. Luo et al., PRSTAB 15, 051004 (2012).]

Tune distrib. and RDT

Lens compresses footprint



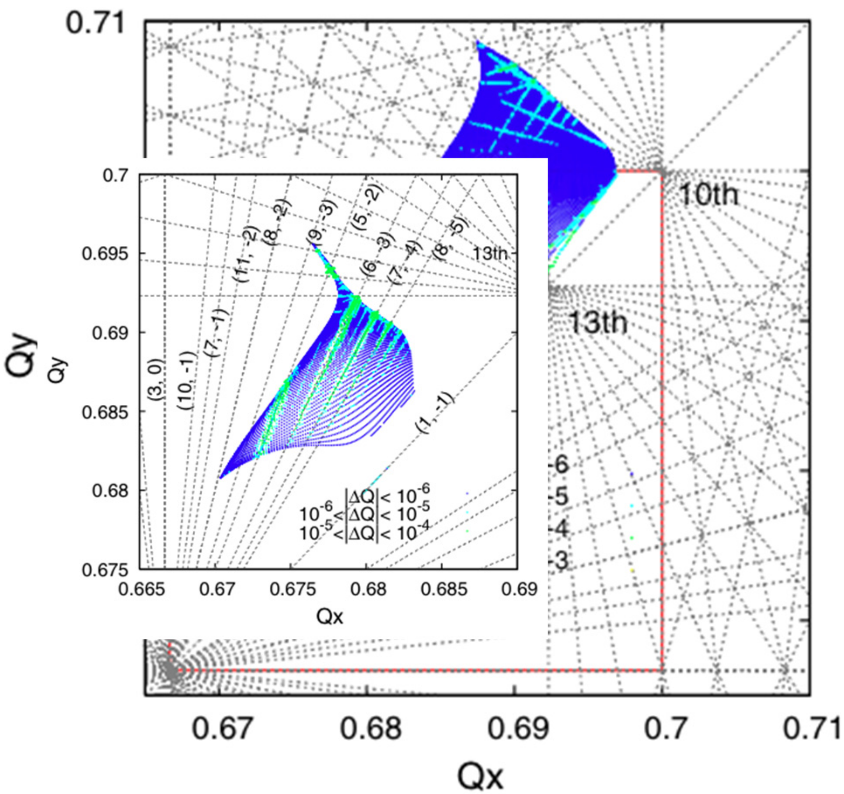
N_b = 3x10^{11} p, w/o and w/ 50% HOBBC

[Y. Luo et al., PRSTAB 15, 051004 (2012).]

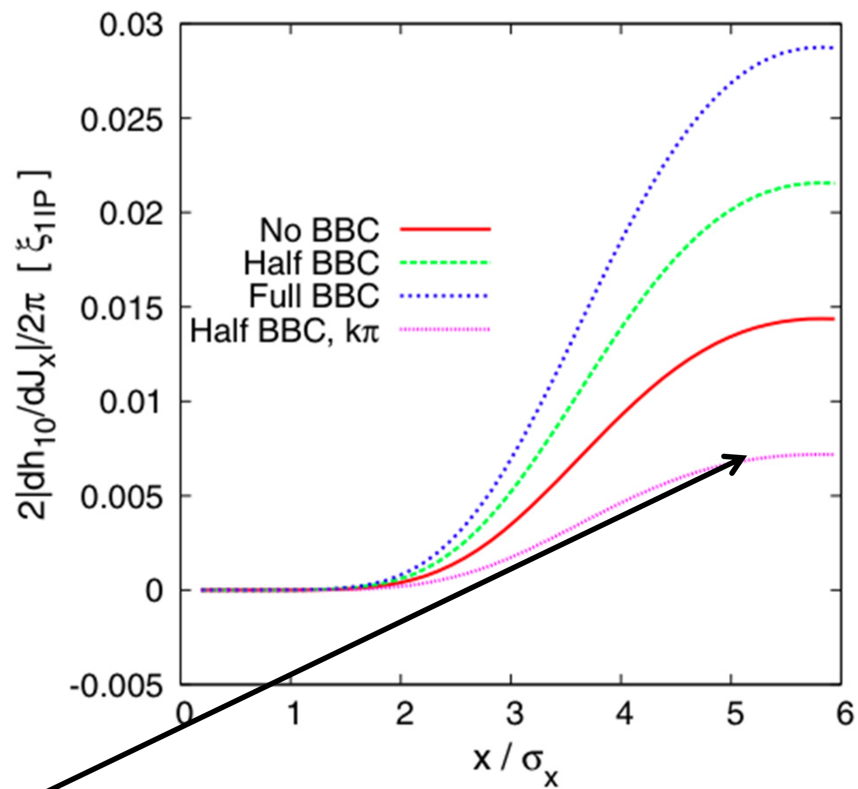
Head-on beam-beam compensation

Tune distrib. and RDT

Lens compresses footprint



Lattice minimizes RDTs



$N_b = 3 \times 10^{11}$ p, w/o and w/ 50% HOBBC

Horizontal 10^{th} order RDT

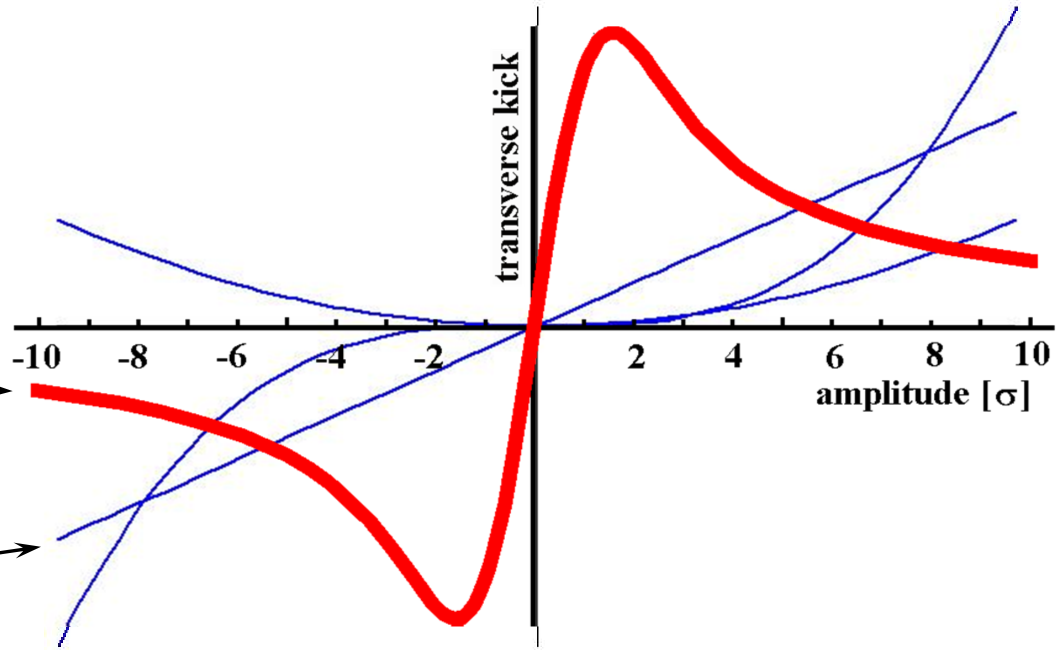
[Y. Luo et al., PRSTAB 15, 051004 (2012).]

Head-on BB compensation

Amplitude dependent kick

beam-beam kick

magnet kicks



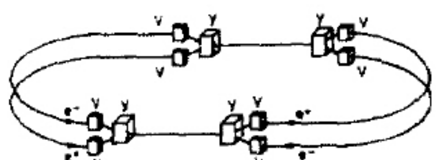
- Amplitude dependence of beam-beam kick fundamentally different from magnets (strength not monotonically increasing in BB)
- Another beam can produce same kick of opposite sign

Head-on beam-beam compensation in DCI

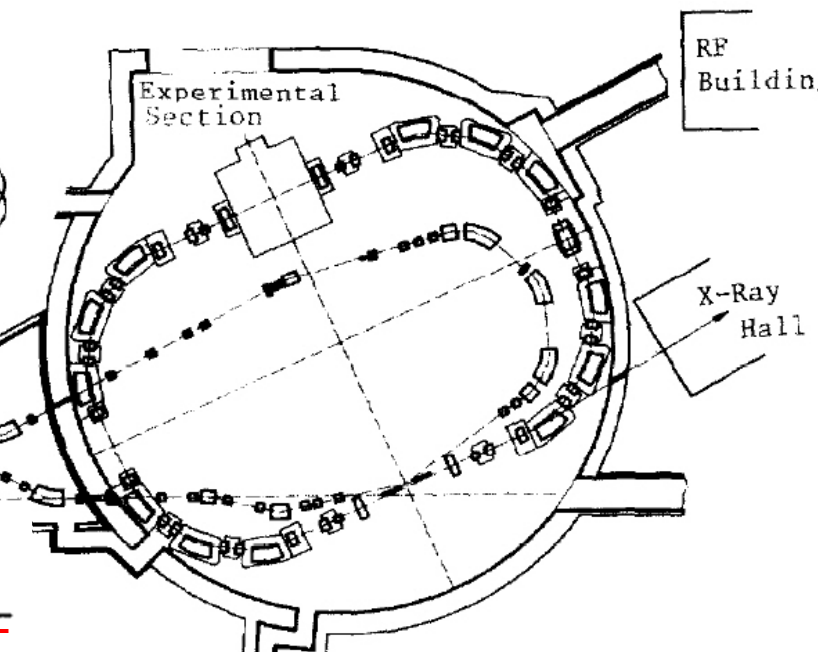
- Head-on beam-beam compensation was only tested in DCI (starting in 1976)
- 4-beam collider ($e^+e^-e^+e^-$) for complete space charge compensation
- Main parameters:
  - Circumference 94.6 m
  - Energy 1.8 GeV
  - Beam-beam ξ ~0.05-0.1
  - Luminosity (design) ~10^{32} $cm^{-2}s^{-1}$
- Luminosity fell 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.

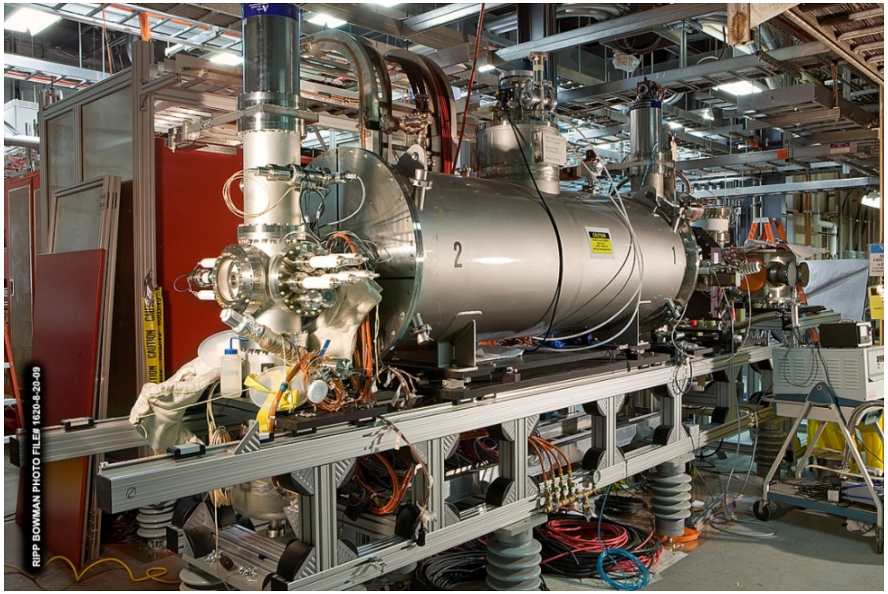
Technology

Tevatron lenses and EBIS

Fermilab Tevatron E-lens

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

BNL Electron Beam Ion Source



J. Alessi, E. Beebe, D. Raparia, M. Okamura, A. Pikin et al.

2 lenses in Tevatron:		**RHIC e-lens**
• Solenoid field	6 T	**6 T** (±50 μm straight)
• Solenoid length	2.7 m	**2 m**
• e-beam energy	5/10 kV	**10 kV**
• e-beam current	0.6/3 A (pulsed)	**1 A (DC)**

Ion source for RHIC:

• Solenoid field	5 T
• Solenoid length	2 m
• e-beam energy	20 kV
• e-beam current	10 A (pulsed)

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 $\Delta\Psi = k\pi$

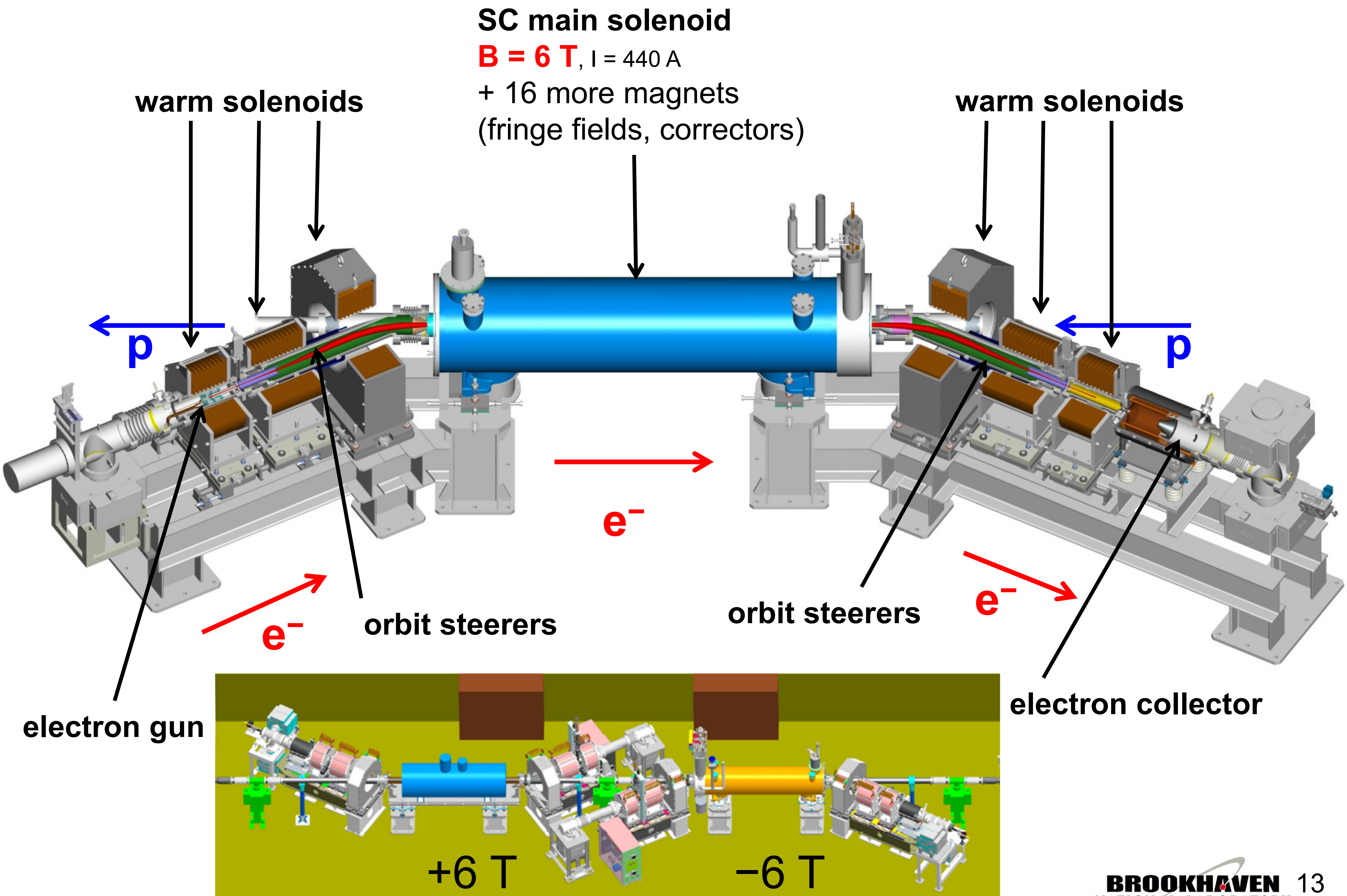
- linear phase error in lattice
- long bunches ($\sigma_s > \beta^*$)
- sextupoles, octupoles, magnetic triplet errors between p-p and e-p

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

=> need to be able to tolerate

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

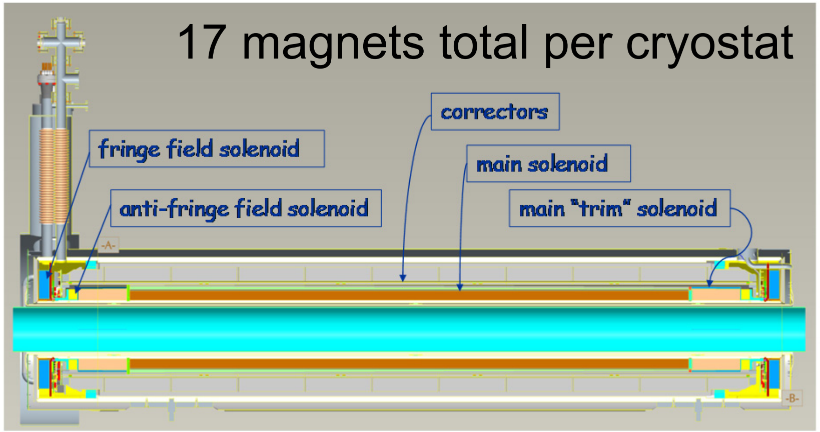
RHIC electron lenses

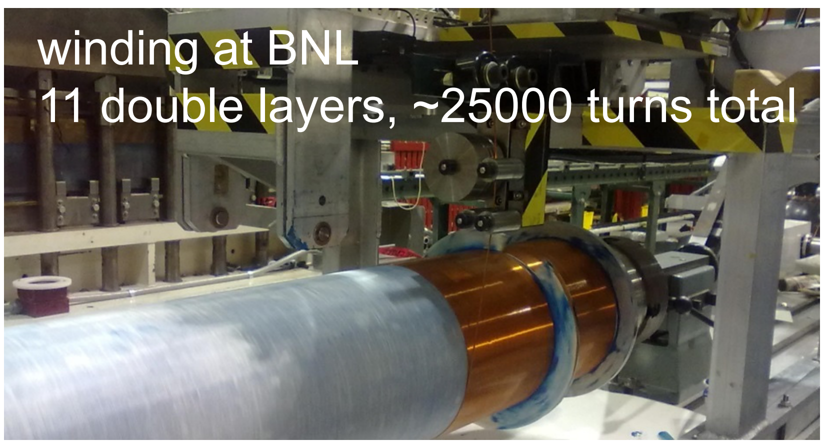


Hardware

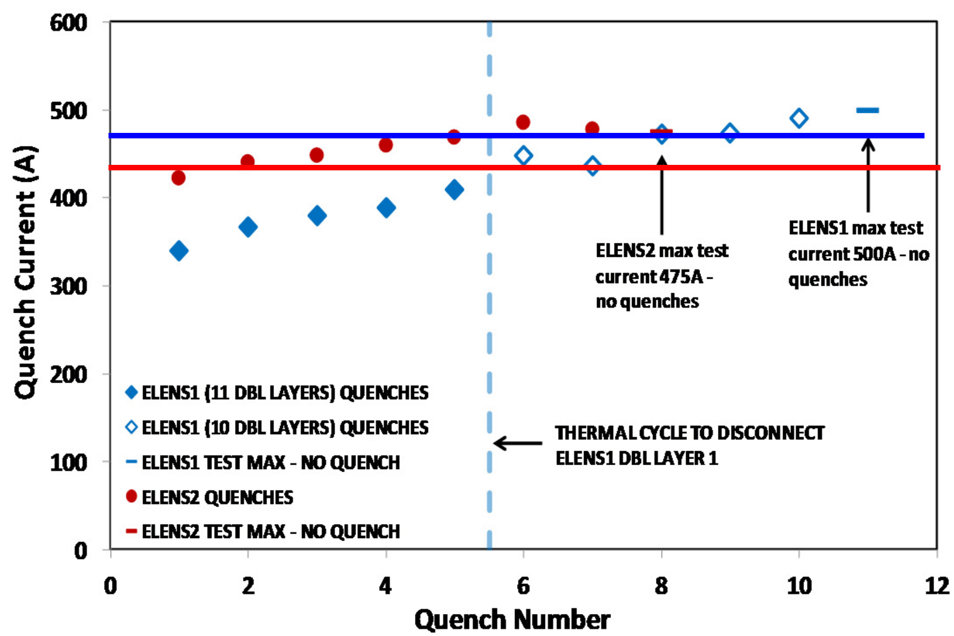
Superconducting solenoid main field

Main solenoid field provides transverse electron beam profile with p-beam





Vertical test



Horizontal test

- Solenoid 1: 5/4.4 T (10 double-layers)
- Solenoid 2: 6 T (11 double-layers)

J. Muratore et. al, MT-23 (2013).

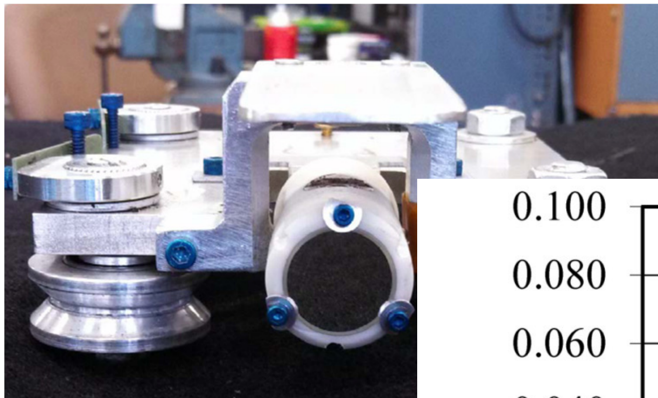
BROOKHAVEN NATIONAL LABORATORY

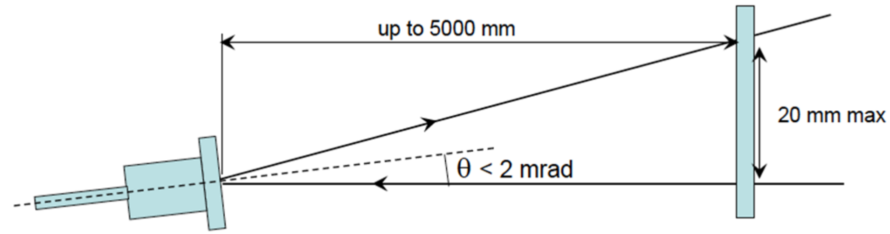
Hardware

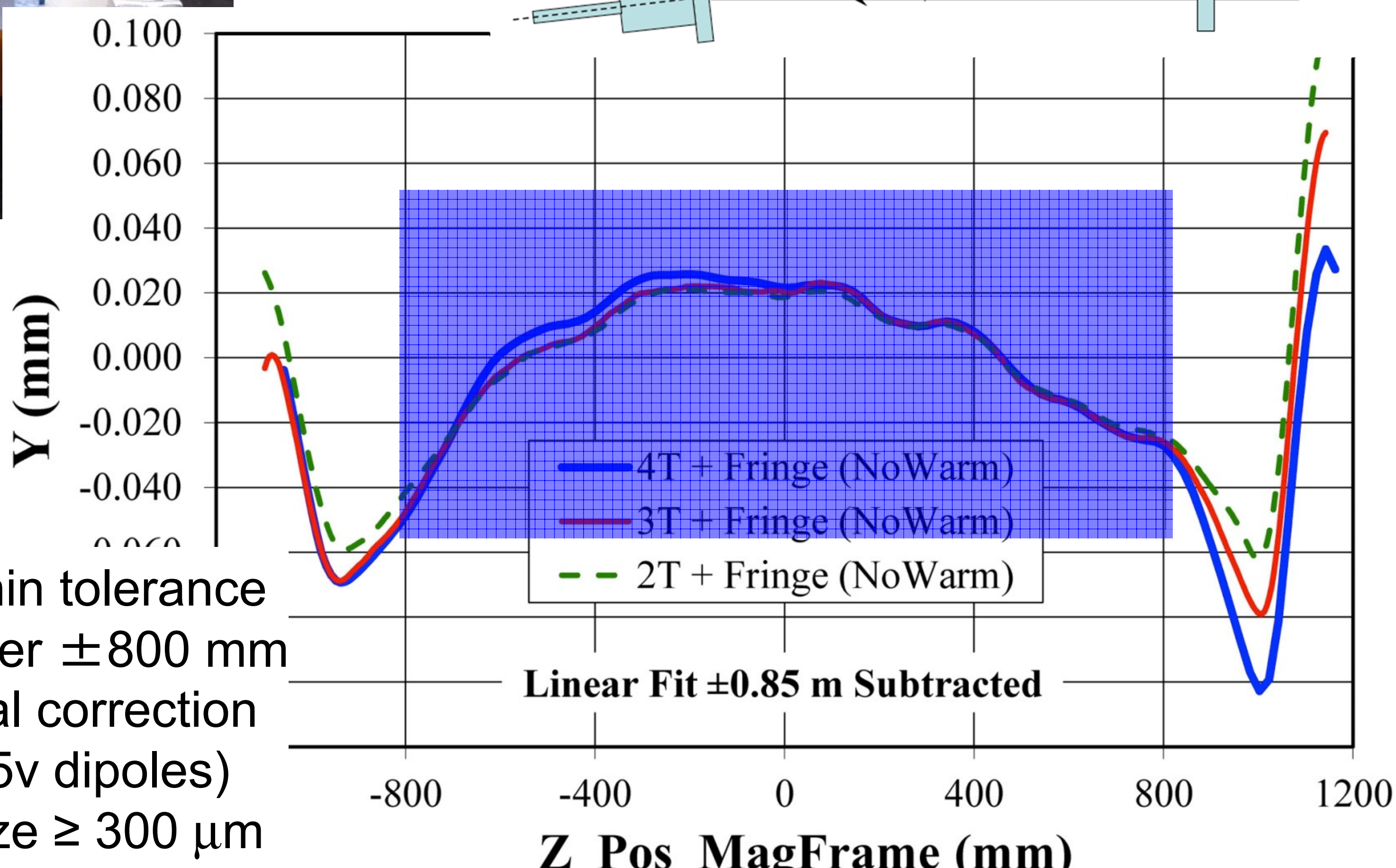
Solenoid field straightness (A. Jain)

Straightness tolerances (±15% rms beam size) **for sufficient overlap**

Measured with magnetic needle and mirror, pulled on track





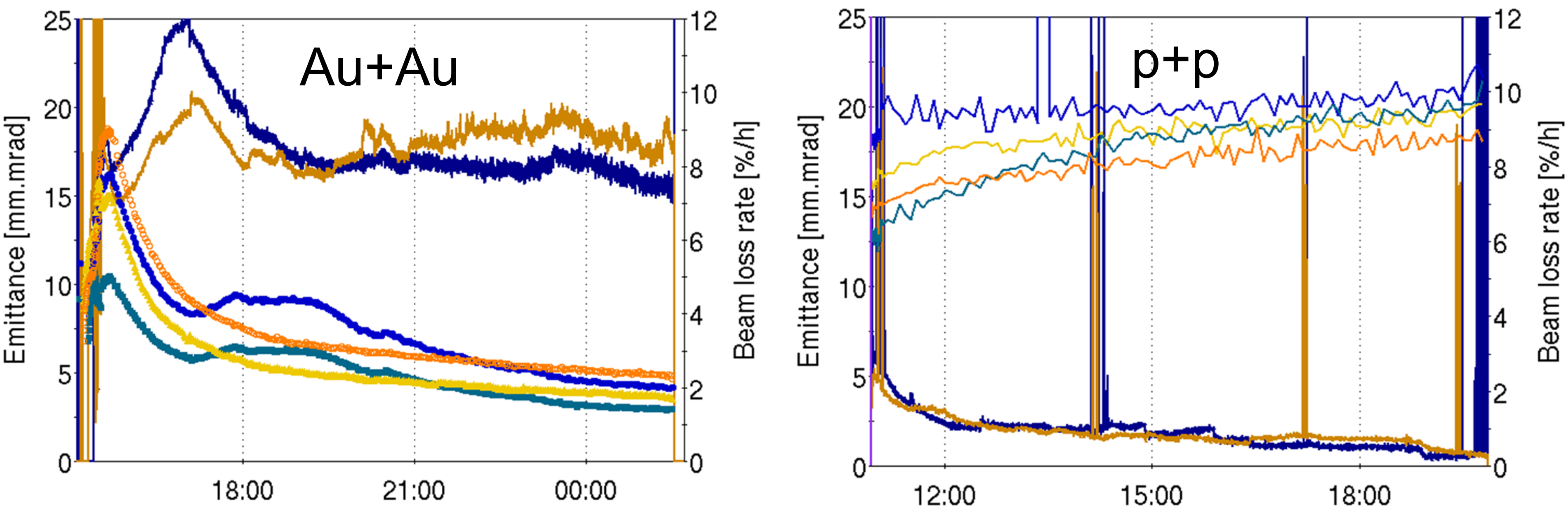


- All planes within tolerance of ±50 μm over ±800 mm without internal correction system (5h + 5v dipoles)
- RMS beam size ≥ 300 μm

Electron lens commissioning

Au vs p beams

	Au+Au 2014	p+p 2015 (100 GeV)
Beam loss	~8 %/hour burn-off dominated	~3 %/hour beam-beam dominated
Emittance growth	negative IBS + stoch. cooling	positive beam-beam
Max beam-beam param. ξ	0.006 / IP	0.012 / IP
$\sigma_{e\text{-beam}} / \sigma_{p\text{-beam}}$	≈ 2	≈ 1

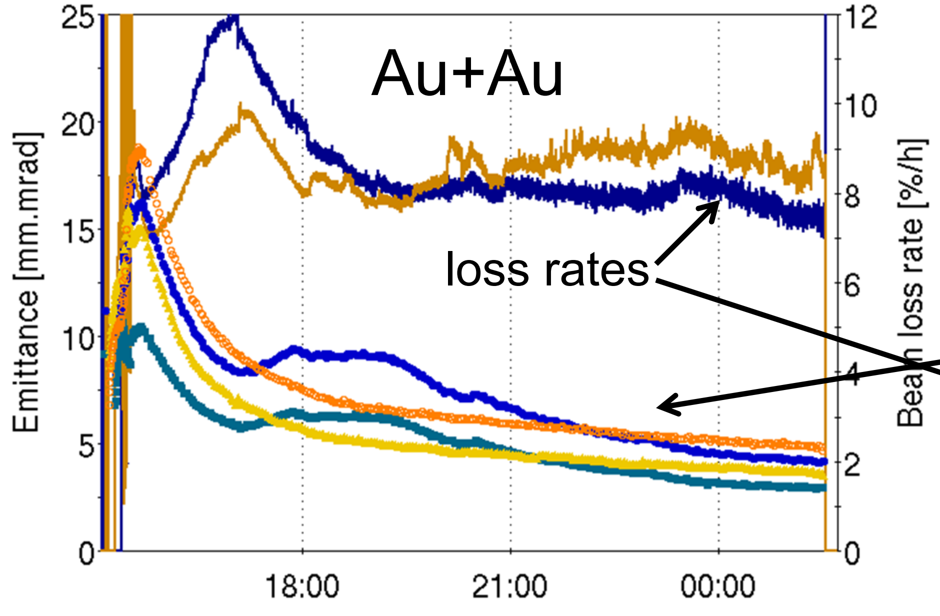


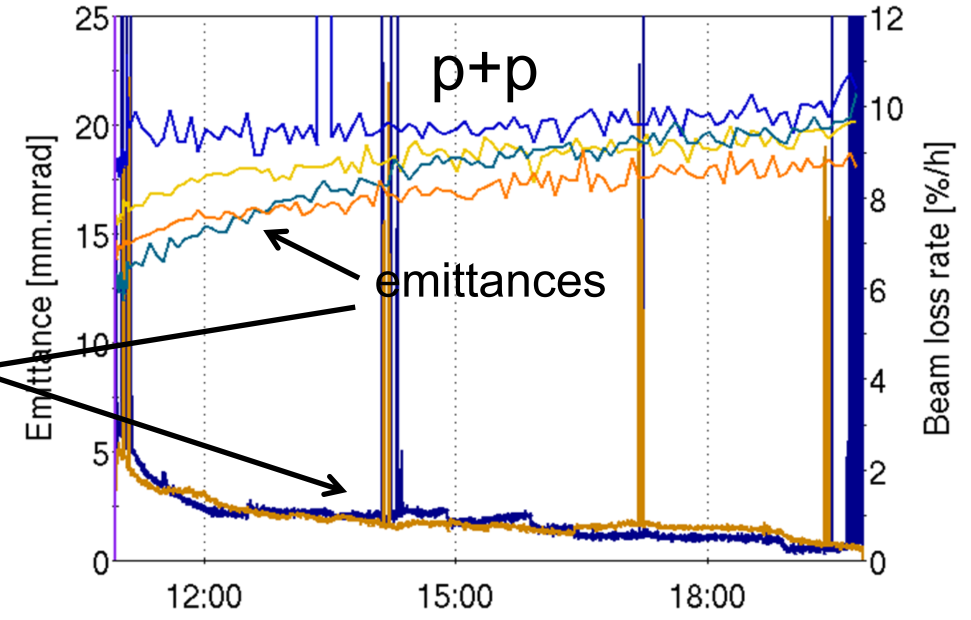
Electron lens commissioning

Au vs p beams

	Au+Au 2014	p+p 2015 (100 GeV)
Beam loss	~8 %/hour burn-off dominated	~3 %/hour beam-beam dominated
Emittance growth	negative IBS + stoch. cooling	positive beam-beam
Max beam-beam param. ξ	0.006 / IP	0.012 / IP
$\sigma_{e\text{-beam}} / \sigma_{p\text{-beam}}$	≈ 2	≈ 1

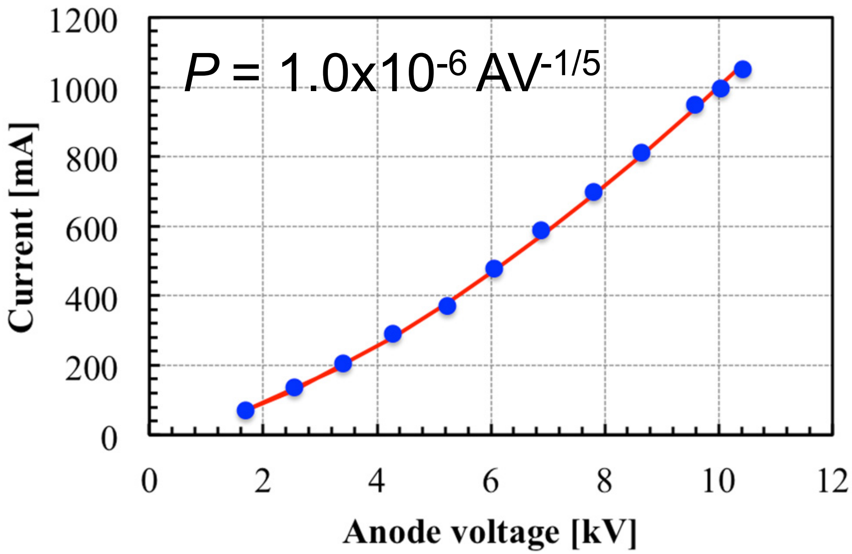
Cooled Au beam allows for reversal of emittance growth in tests during physics stores, even training quenches of solenoids.





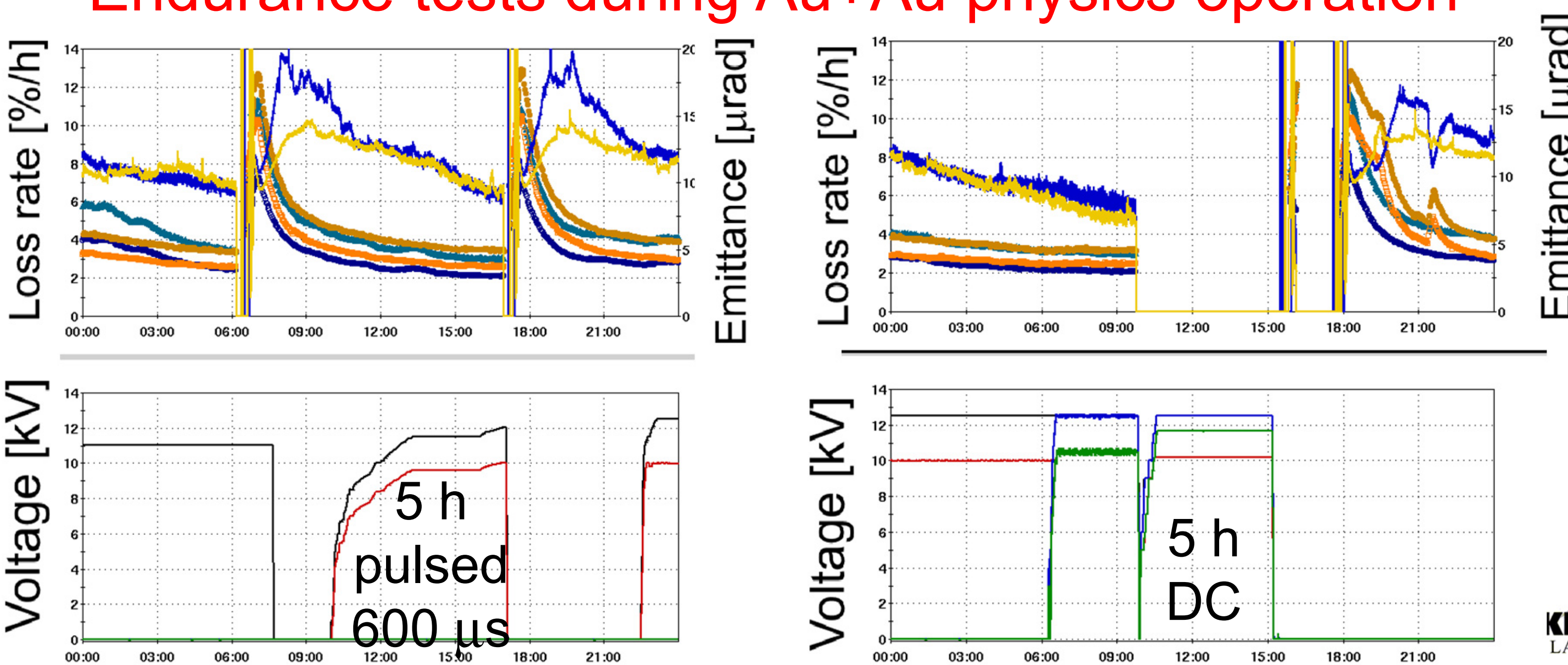
Electron beam

Current



- thermionic gun (IrCe - BINP, LaB_6)
- pulsed (<1 turn) or DC
- R = 4.1 mm, ρ = 7.5 A cm^{-2}
- fitted perveance: 1.0x10^{-6} AV$^{-1/5}$

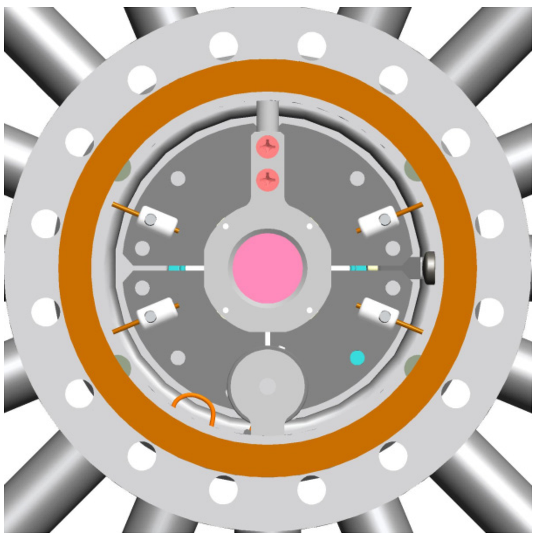
Endurance tests during Au+Au physics operation

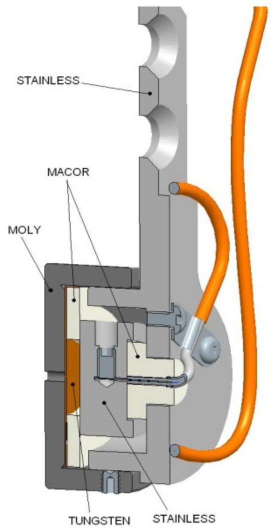


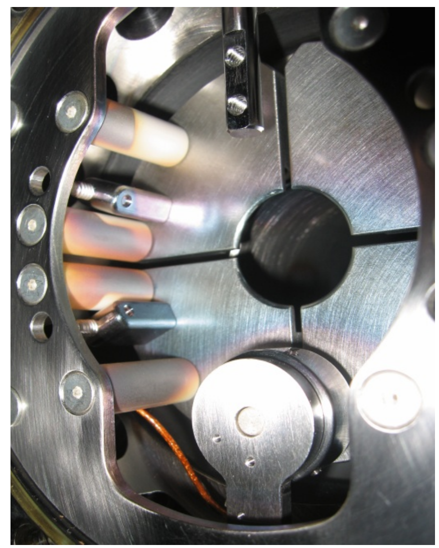
Gaussian profile critical for correction of nonlinear effects

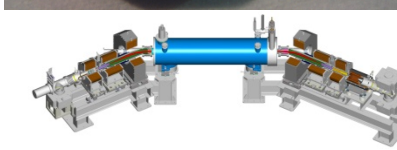
2 devices for transverse profile measurement:

- YAG screen
- pinhole detector









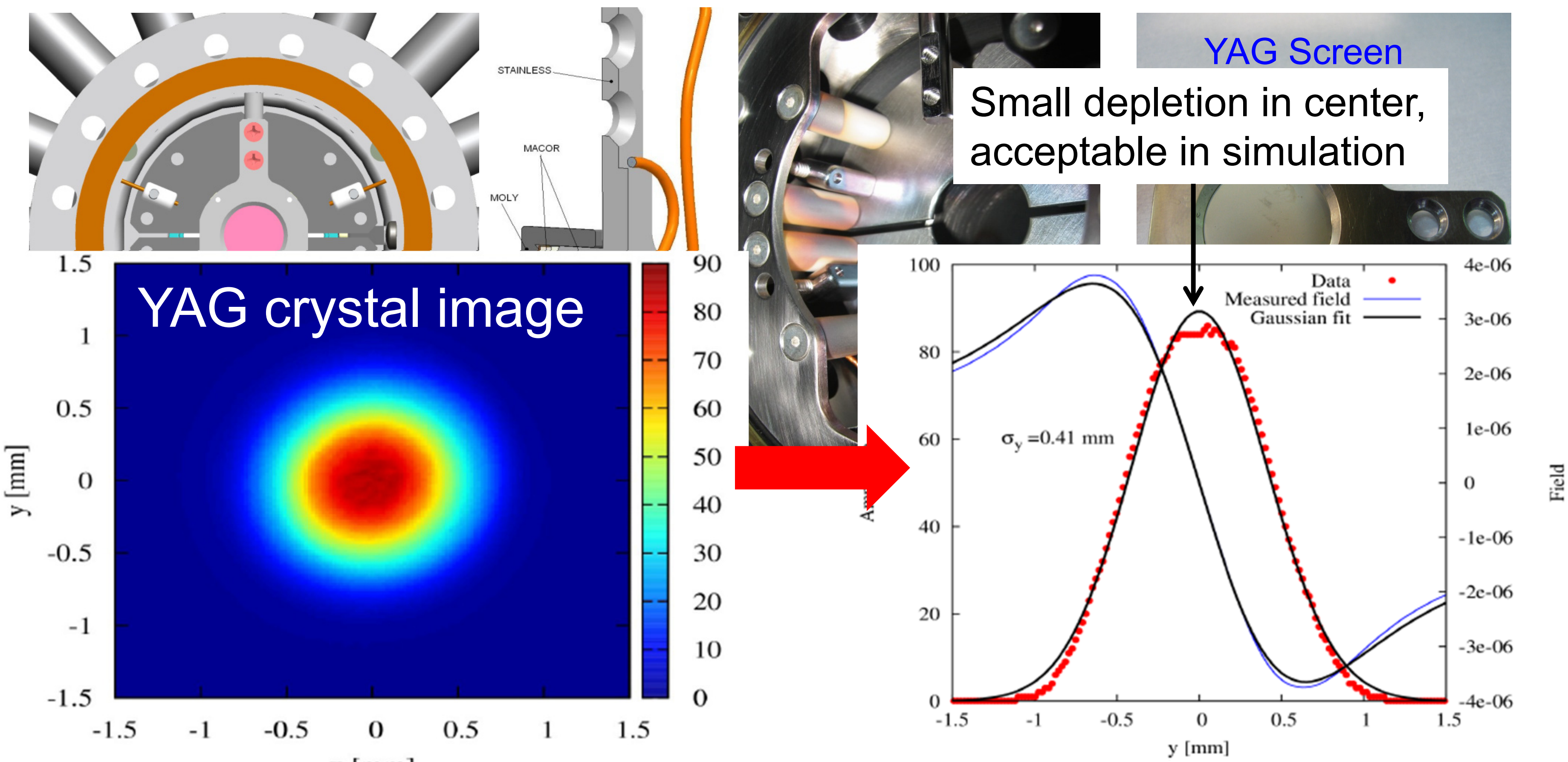
Electron beam

Transverse profile

Gaussian profile critical for correction of nonlinear effects

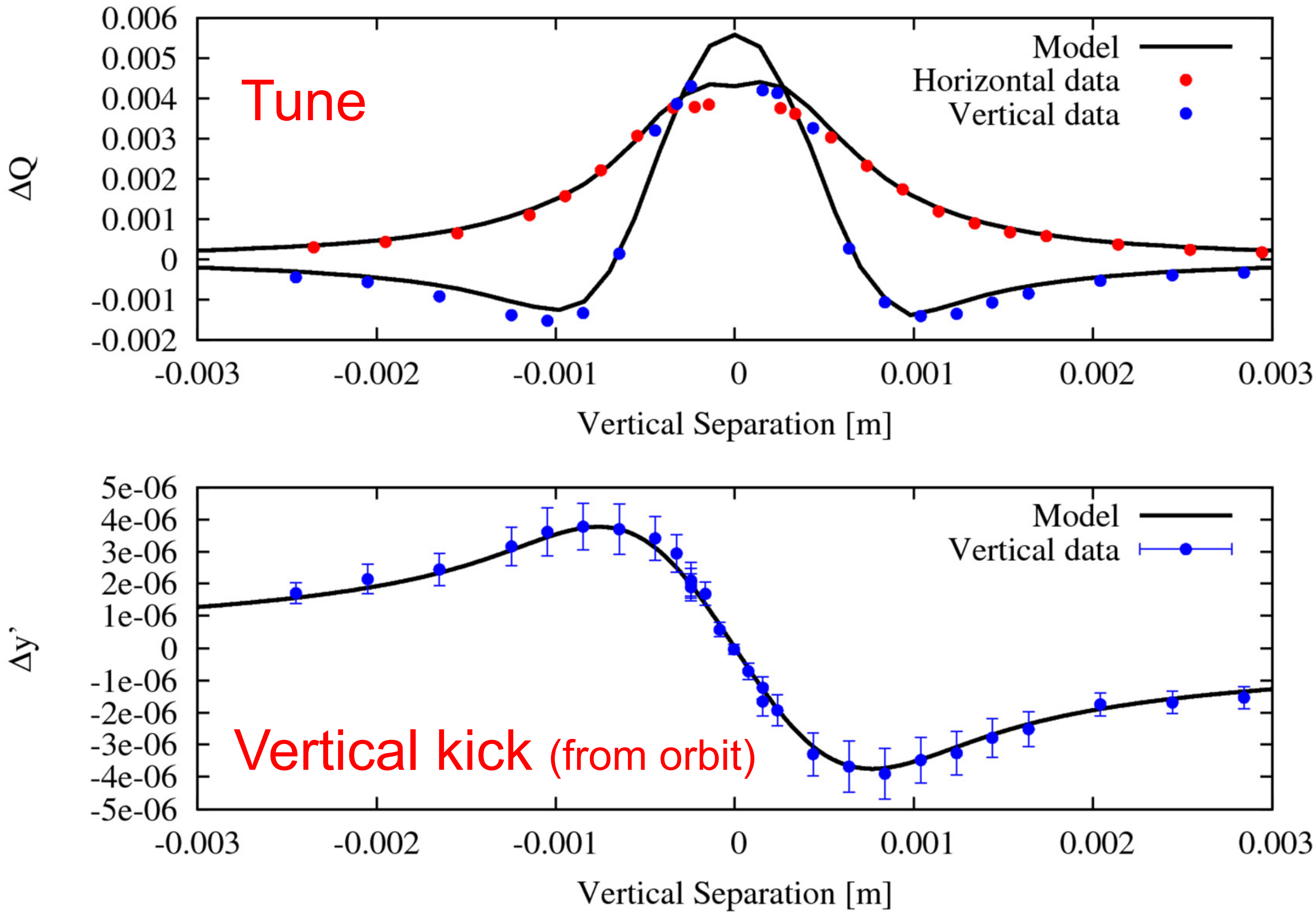
2 devices for transverse profile measurement:

- YAG screen
- pinhole detector



Effect on orbit and tune

Response to vertical displacement of Yellow beam at store

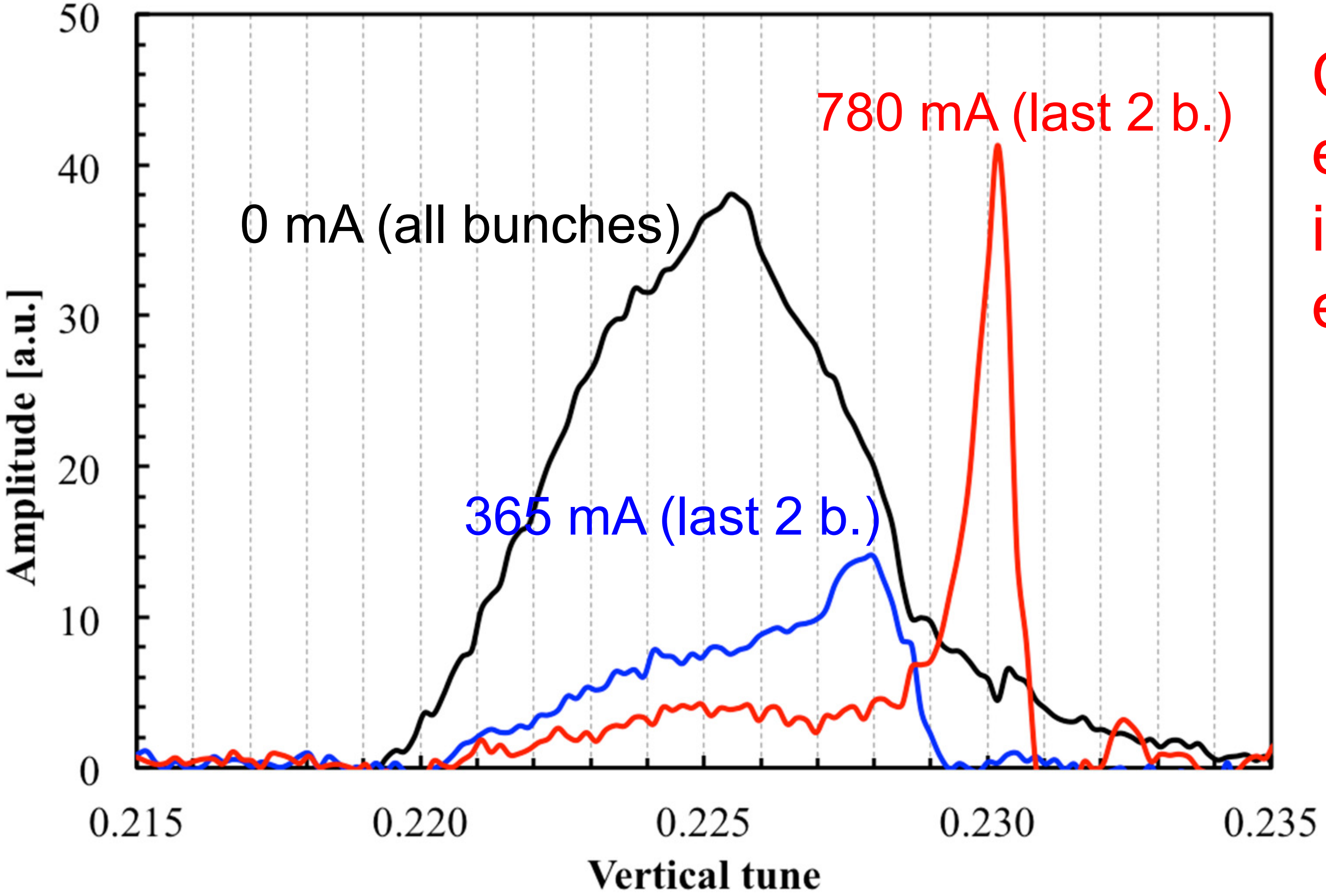


Also used as first alignment tool (slow)

Beam Transfer Function

BB + e-lenses

Vertical BTF measurement during physics store (most bunches with 2 collisions)

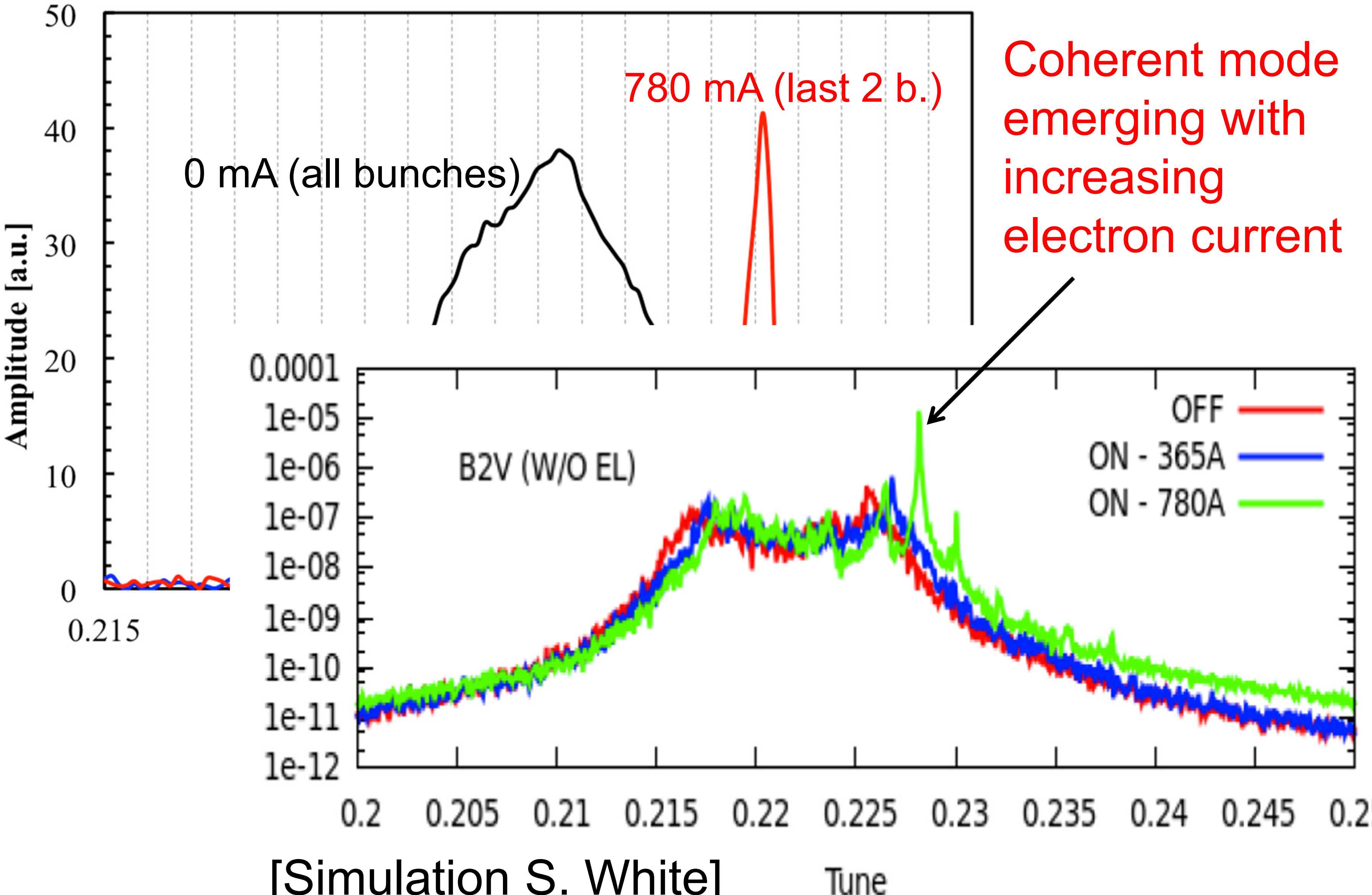


Coherent mode emerging with increasing electron current

Beam Transfer Function

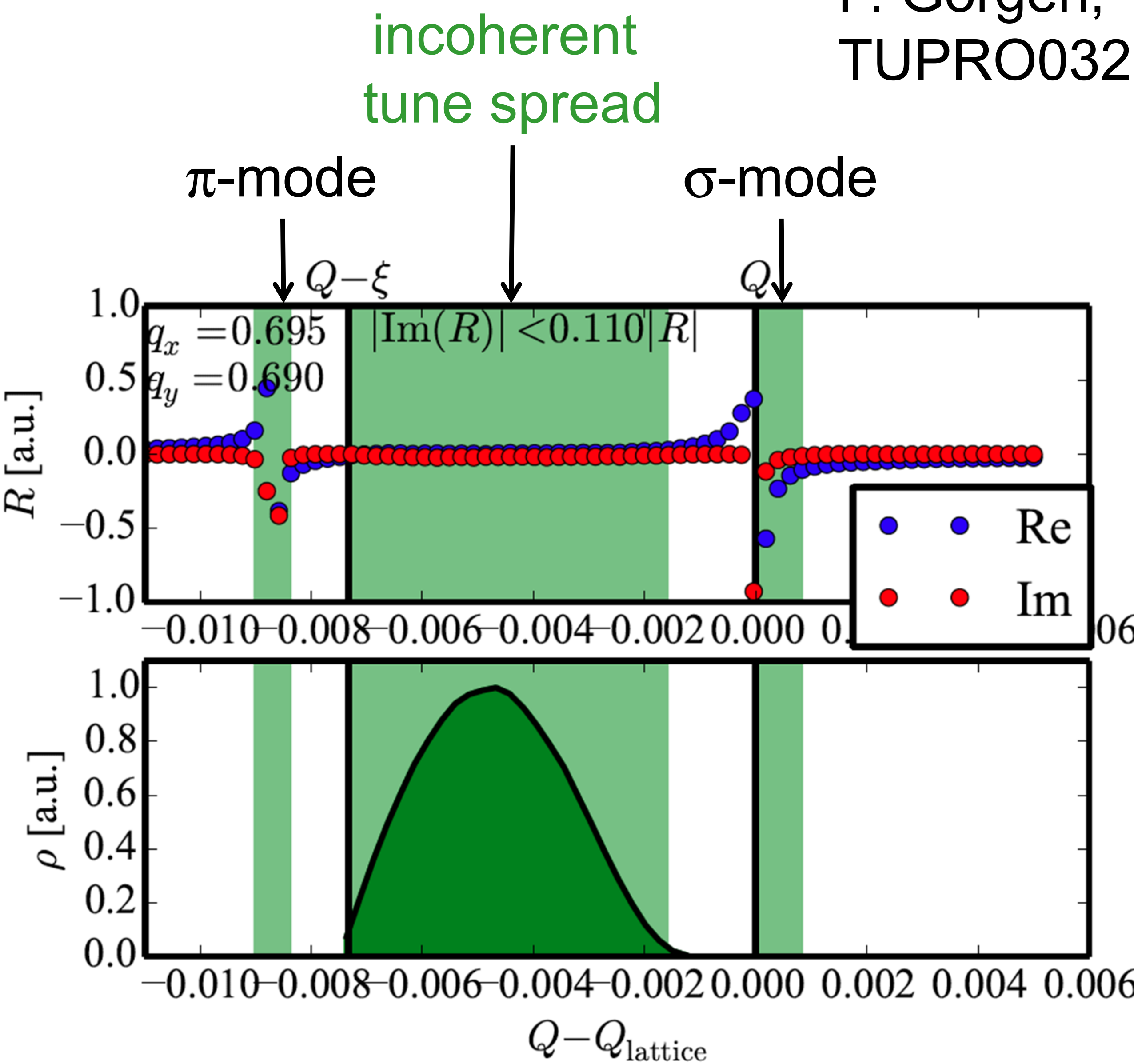
BB + e-lenses

Vertical BTF measurement during physics store (most bunches with 2 collisions)



Tune spread from BTF in presence of coherent modes

P. Görgen, TU Darmstadt, TUPRO032, Ph.D. thesis soon

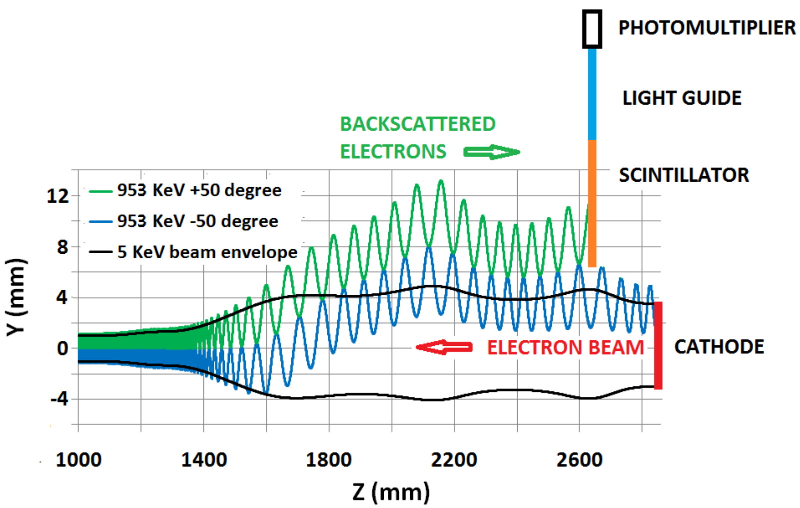


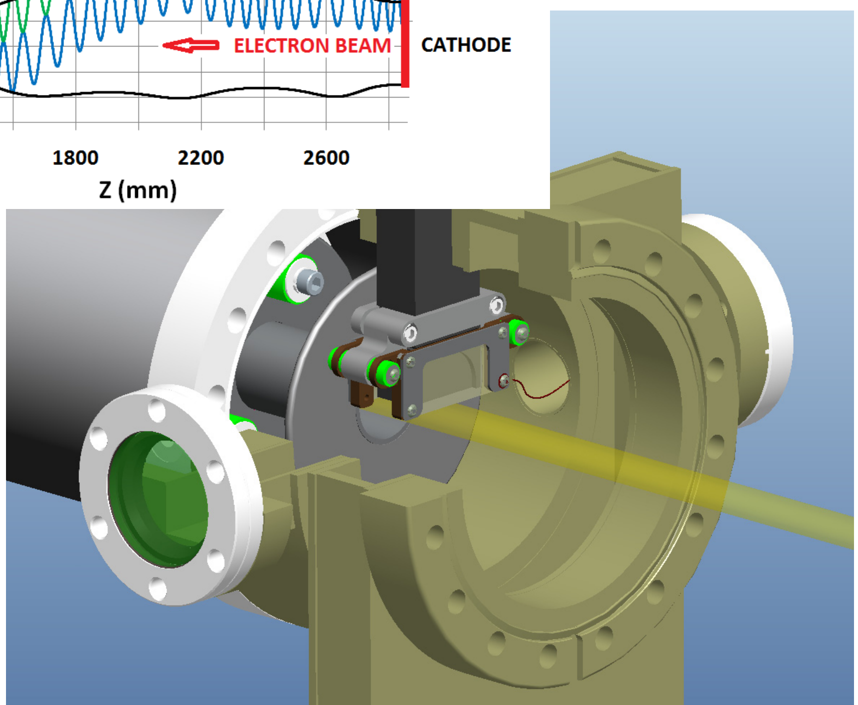
- Determine *Im*(BTF)
- Suppress coherent modes in analysis (location known)

Transverse alignment

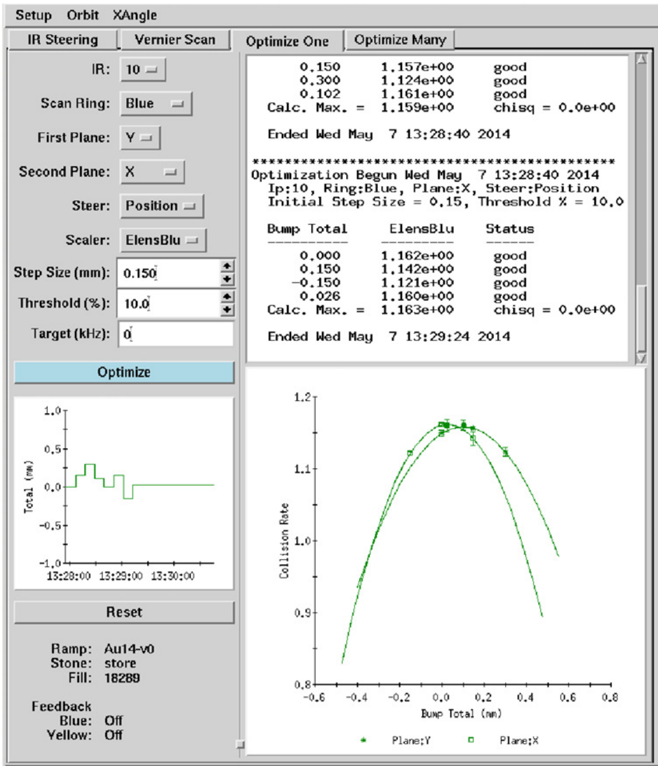
Backscattered electrons

- 2 BPMs in both lenses to bring e- and A- beam in proximity
  BPMs see 3 beams: 2 hadron and 1 electron beam (rise/fall time 10x longer)
- Use detection of backscattered electrons to maximize overlap
  P. Thieberger, BIW12, IBIC2014

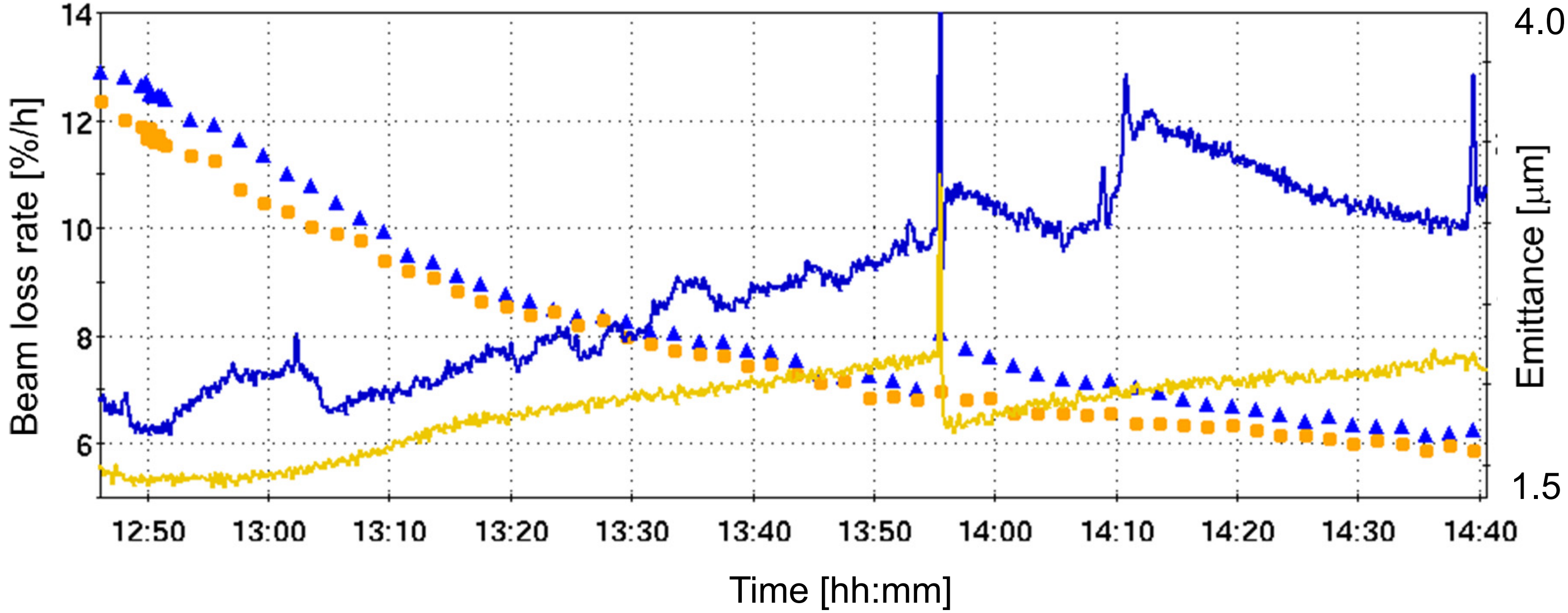


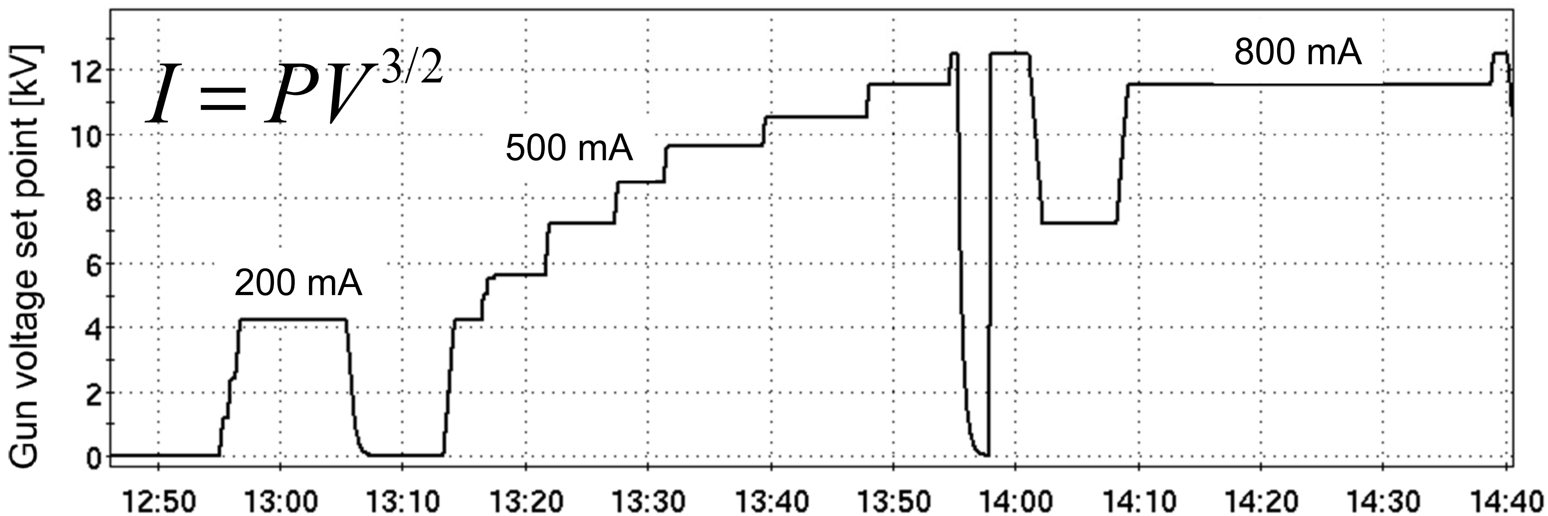


- Signal with large dynamic range (~10^6)
- Used for automatic position and angle alignment, same as luminosity maximization

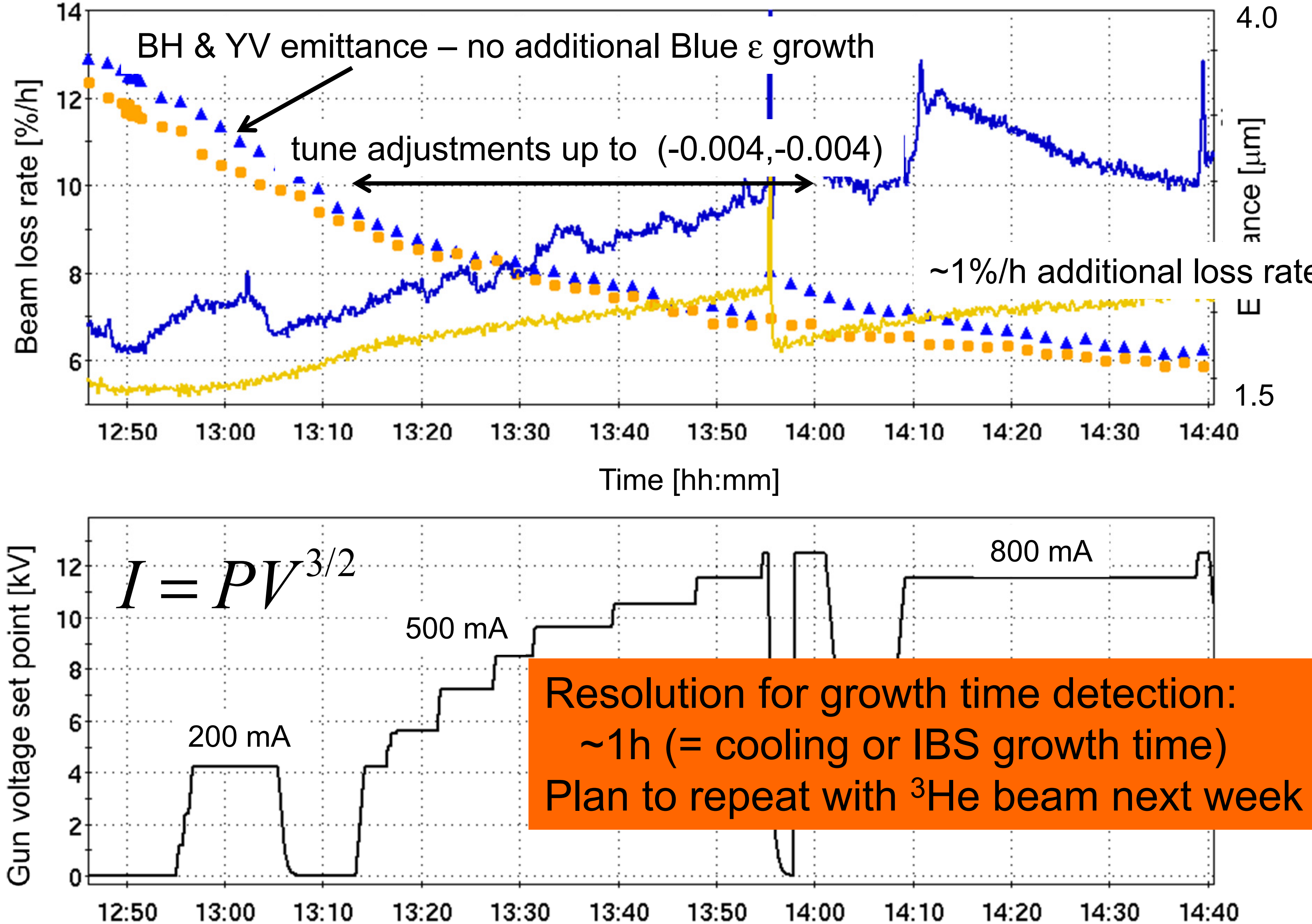


Loss rate and emittance growth with Blue DC e-beam



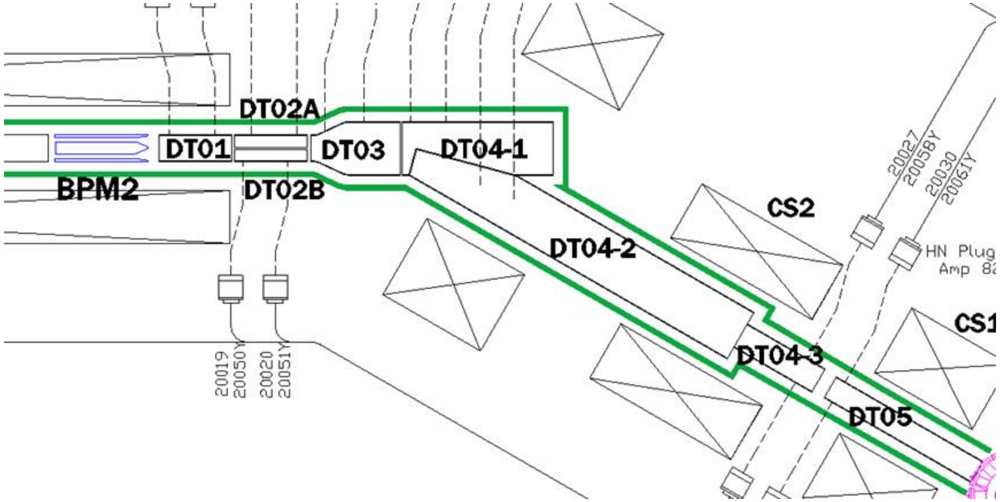


Loss rate and emittance growth with Blue DC e-beam



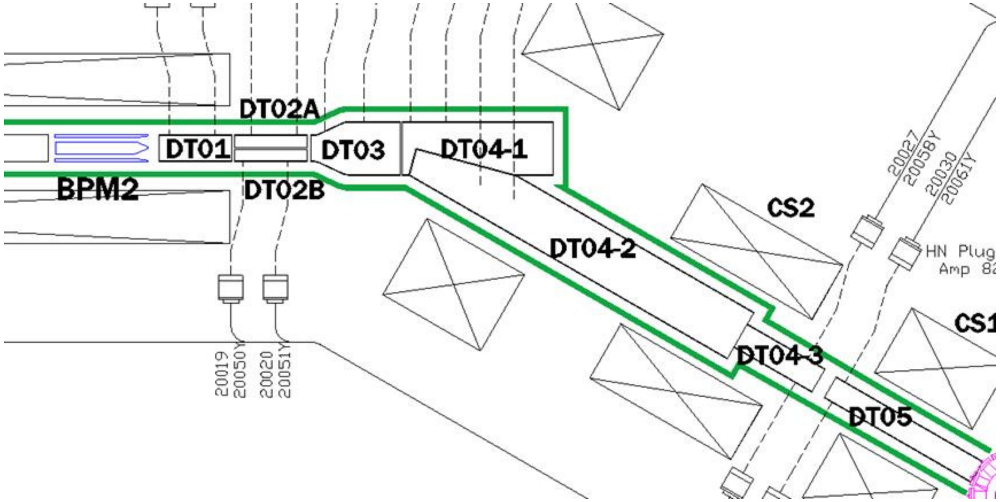
Resolution for growth time detection:
~1h (= cooling or IBS growth time)
Plan to repeat with ^3He beam next week

Ion accumulation and relative emittance with Blue DC e-beam

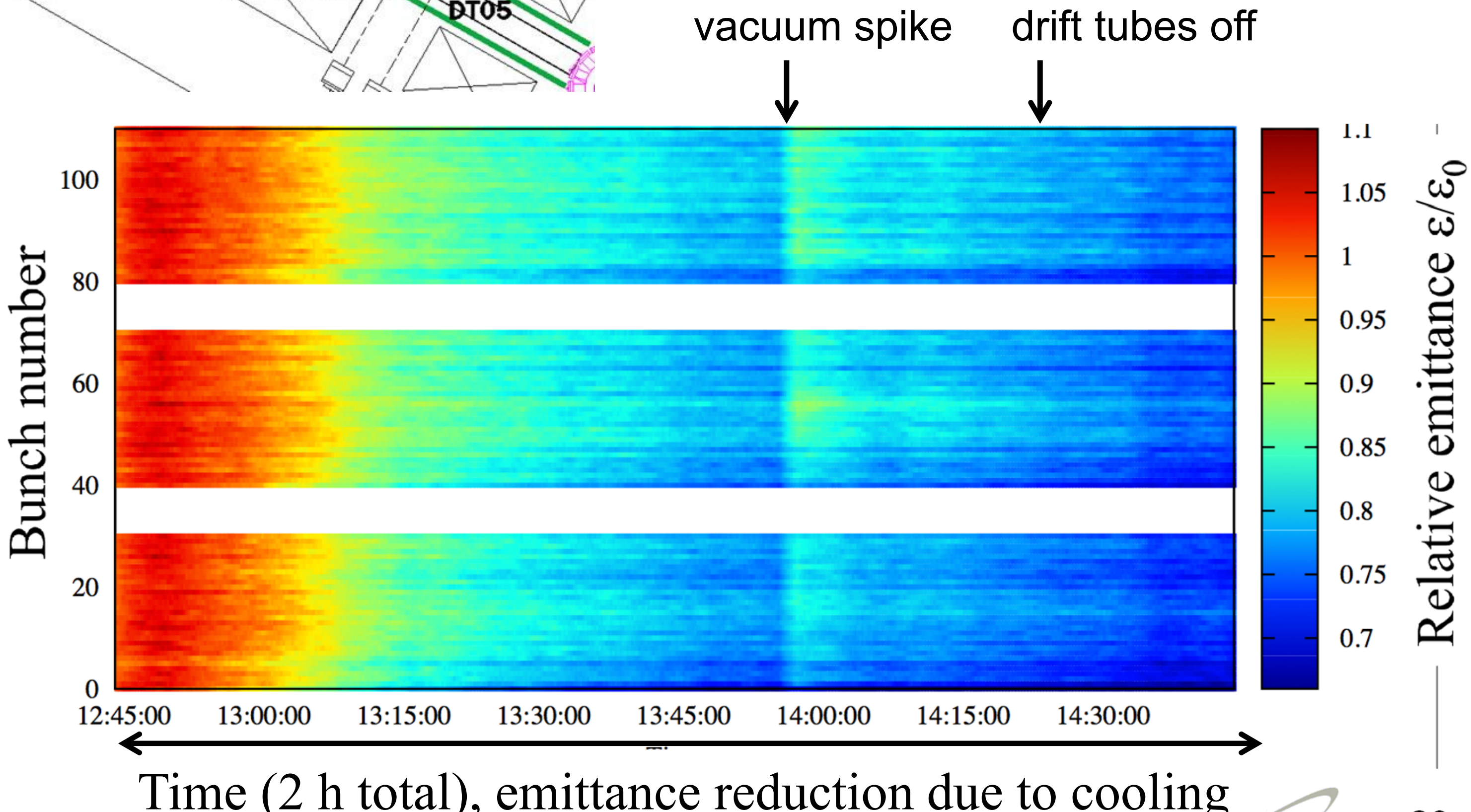


- Residual gas ionization by hadron and electron beam
- DC electron beam forms transverse potential
- Drift tubes create longitudinal voltage for ion extraction (damaged some feedthroughs during bake-out)

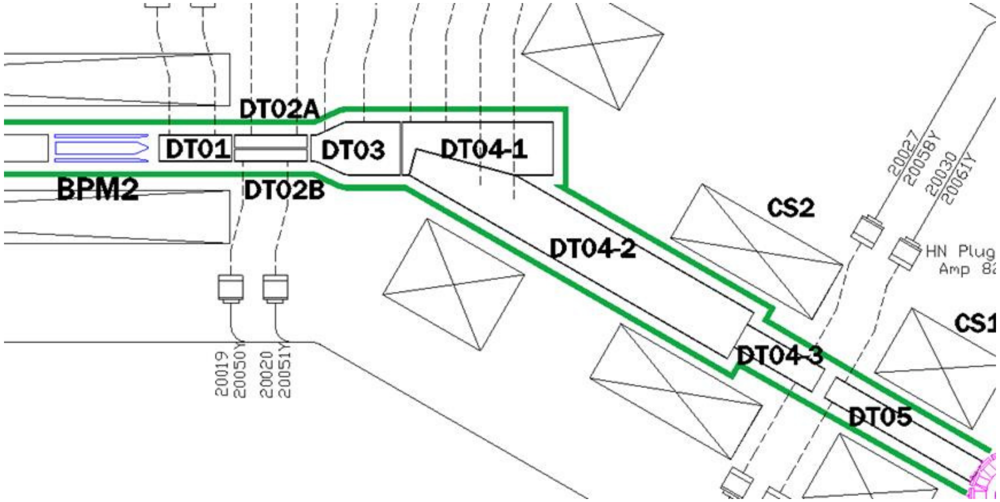
Ion accumulation and relative emittance with Blue DC e-beam



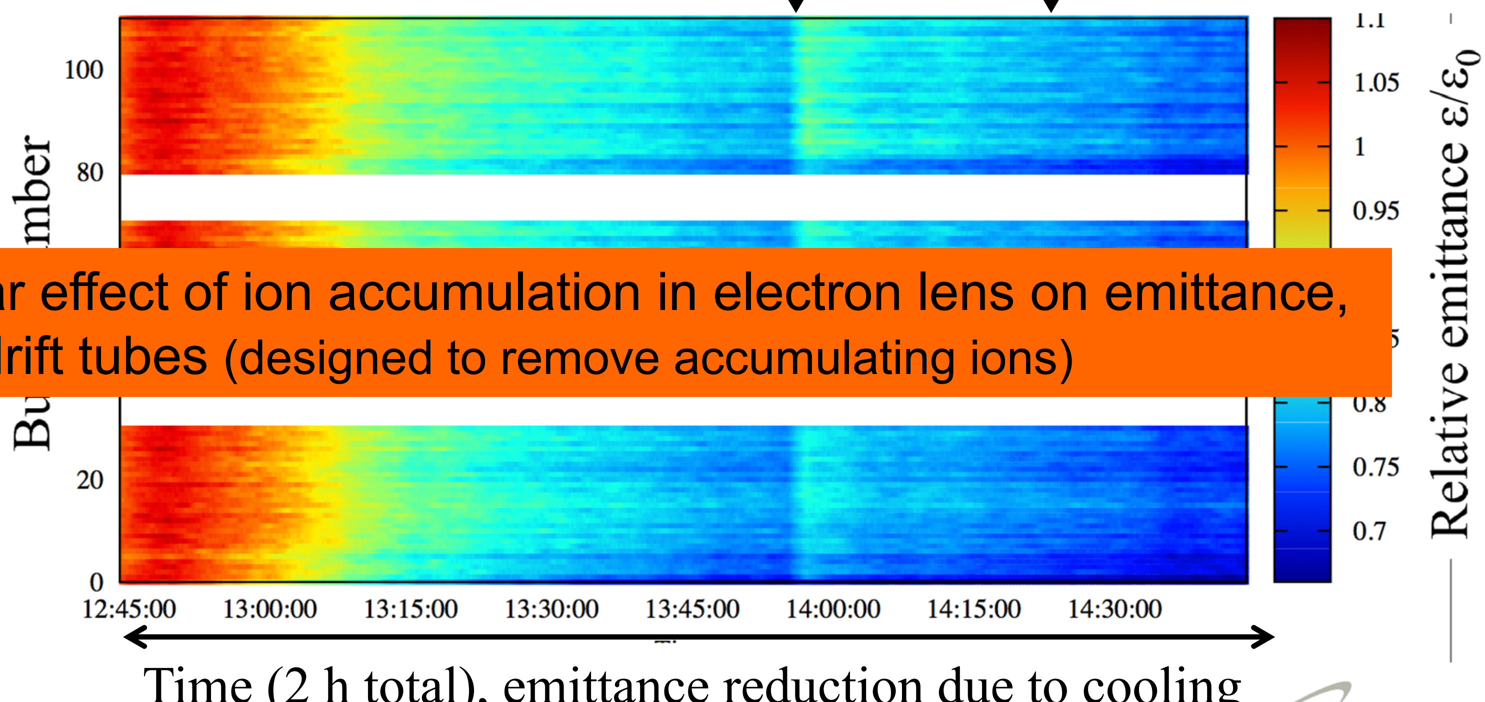
- Residual gas ionization by hadron and electron beam
- DC electron beam forms transverse potential
- Drift tubes create longitudinal voltage for ion extraction (damaged some feedthroughs during bake-out)



Ion accumulation and relative emittance with Blue DC e-beam



- Residual gas ionization by hadron and electron beam
- DC electron beam forms transverse potential
- Drift tubes create longitudinal voltage for ion extraction (damaged some feedthroughs during bake-out)



Observe no clear effect of ion accumulation in electron lens on emittance, with or without drift tubes (designed to remove accumulating ions)

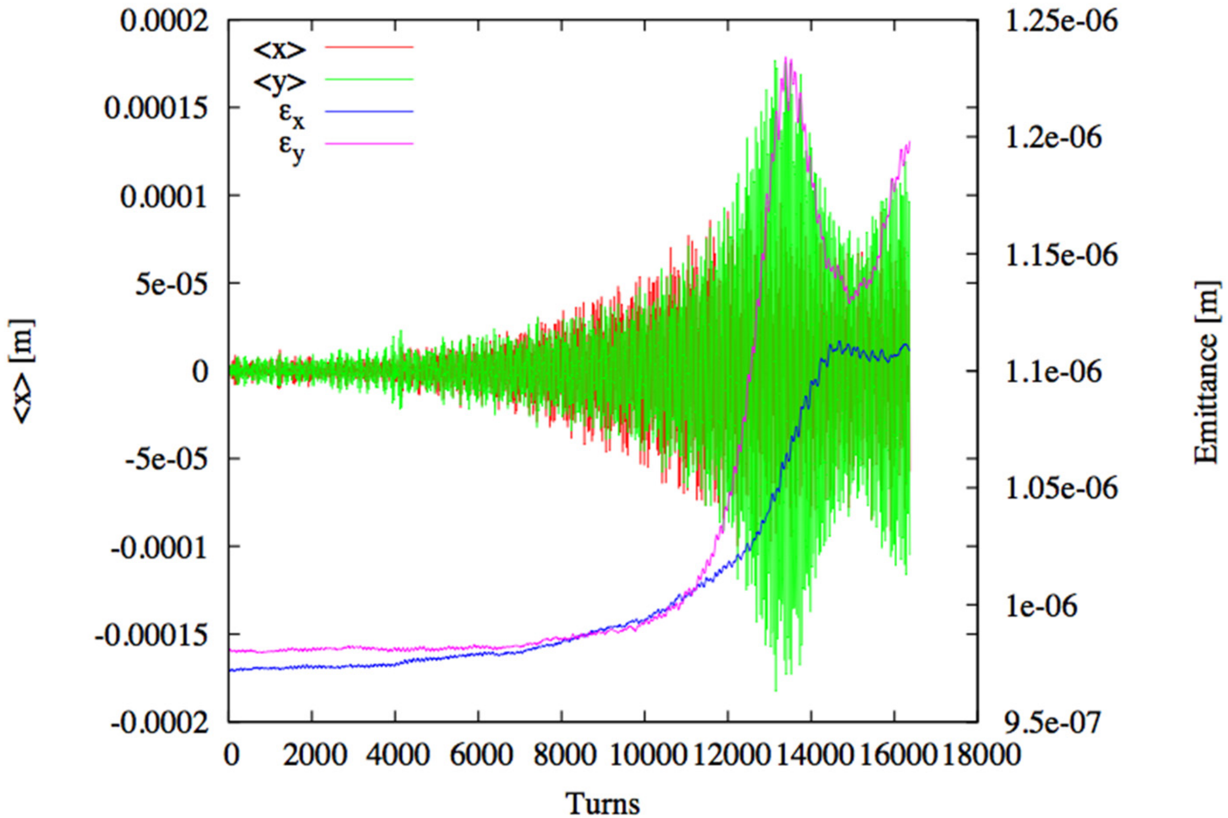
Beam-beam driven instabilities

S. White

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

Instability threshold for solenoid field (approximate)
[A. Burov et al. PRE 59, 3605 (1999), also see S. White, BB2014 for simulations]

Simulation shows instability with
$N_b = 1.2 \times 10^9$ Au/bunch and 1.5 T



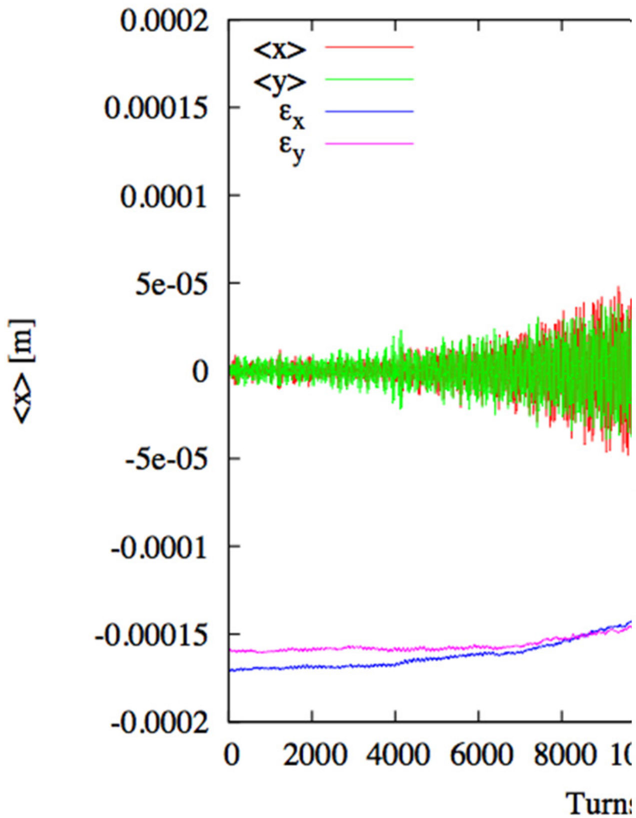
Beam-beam driven instabilities

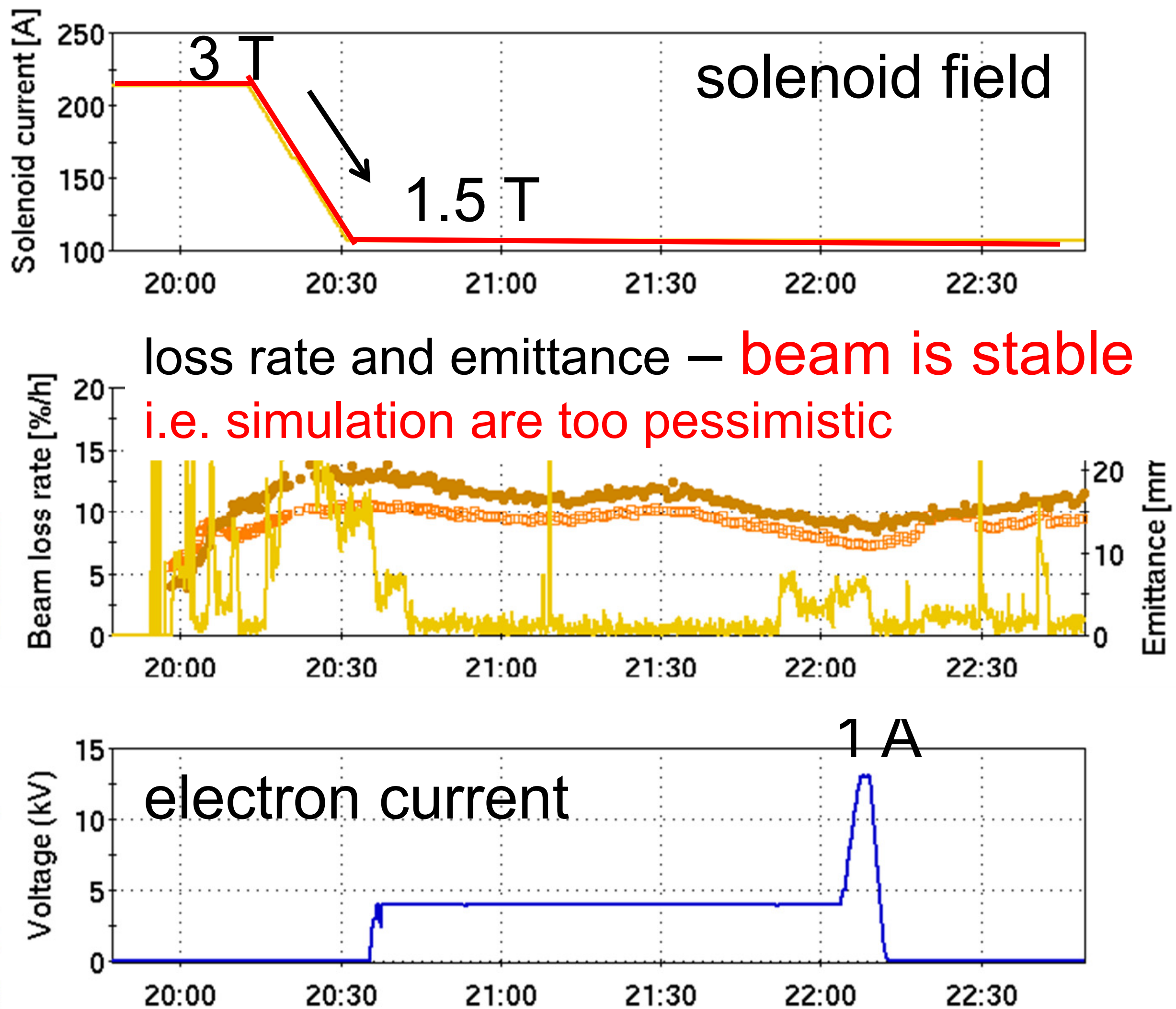
S. White

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

Instability threshold for solenoid field (approximate)
[A. Burov et al. PRE 59, 3605 (1999), also see S. White, BB2014 for simulations]

Simulation shows inst
N_b = 1.2x10^9 Au/bunc





Preparation for 2015

2015 – First proton run with electron lenses => compensation

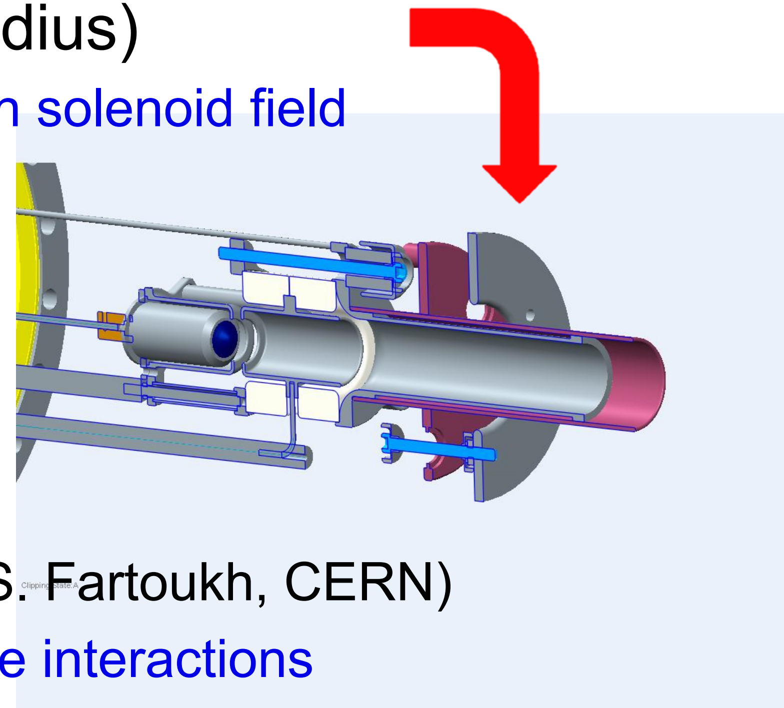
Upgrades for 2015

•Larger cathodes (7.5 vs. 4.1 mm radius)

=> allows for matched beam size with high solenoid field

=> raises instability threshold

=> easier alignment



•Transverse damper

=> raises instability threshold

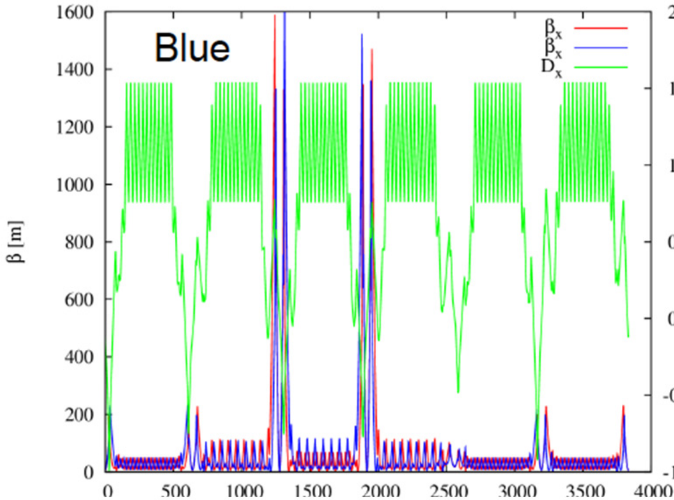
•New lattice, based on ATS optics (S. Fartoukh, CERN)

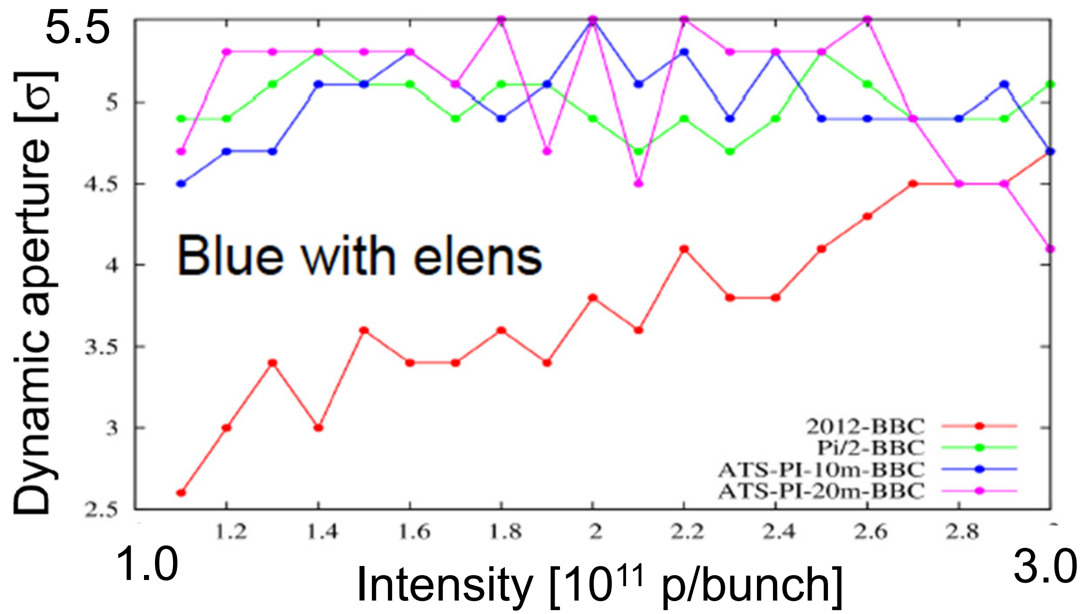
=> phase advance kp between p-p and p-e interactions

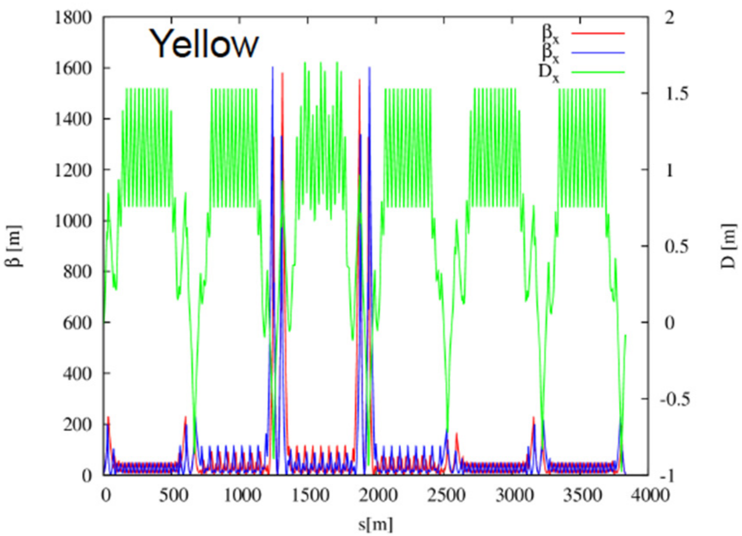
=> small nonlinear chromaticity

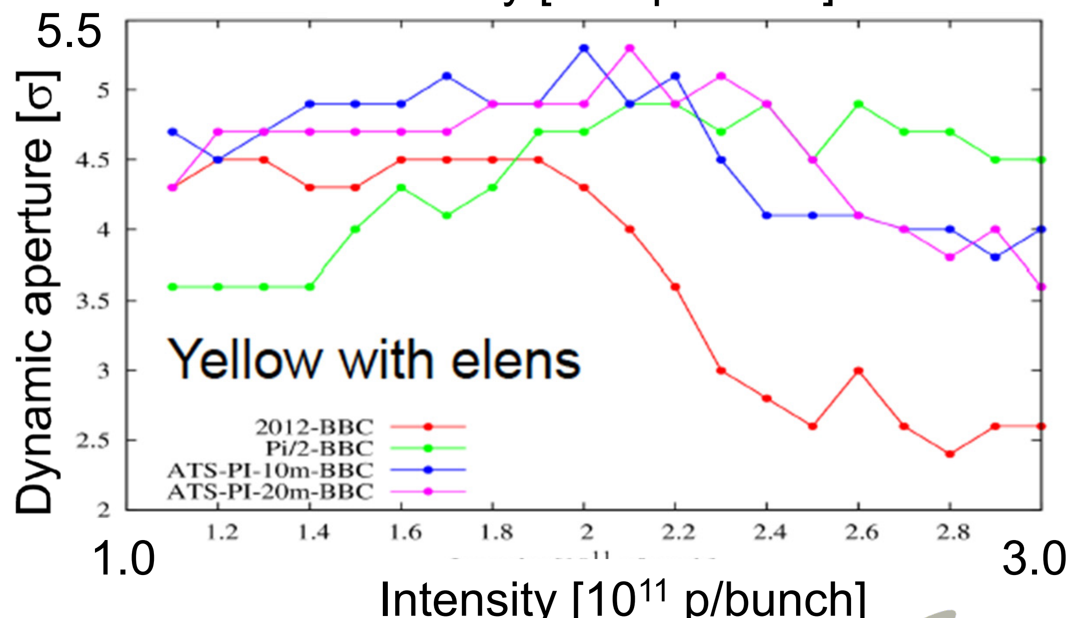
=> no depolarization

Lattice for 2015 (S. White) – Simulations (Y. Luo)

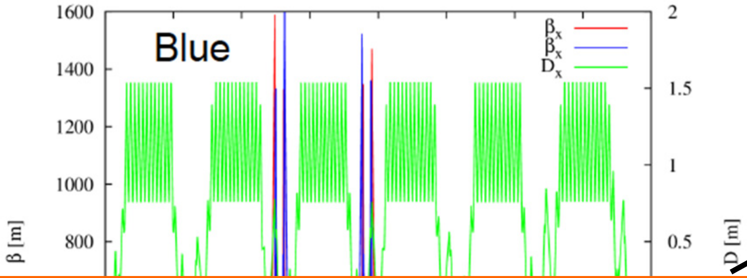


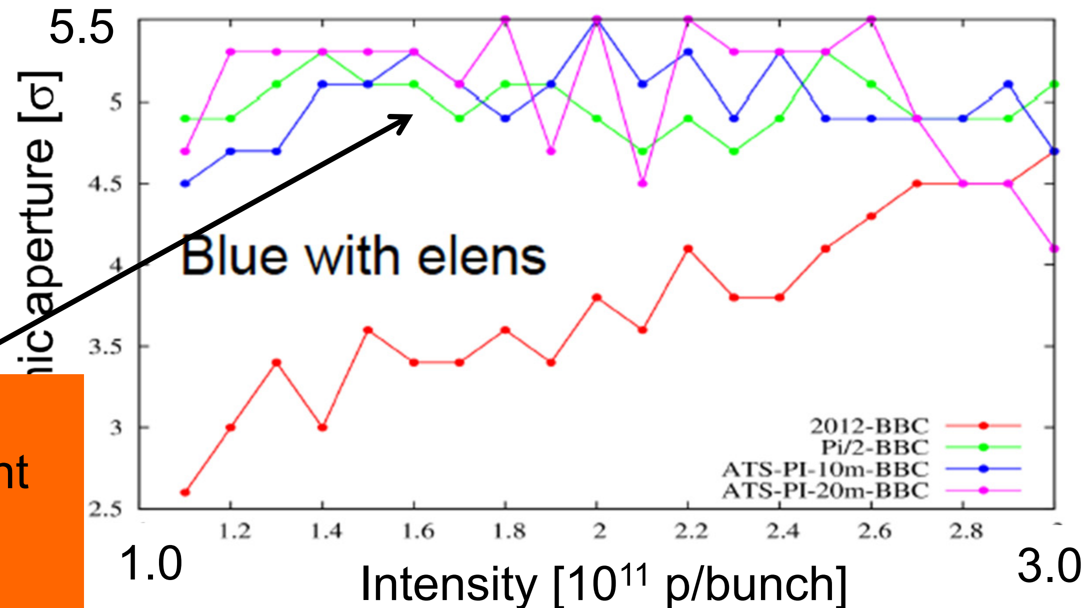




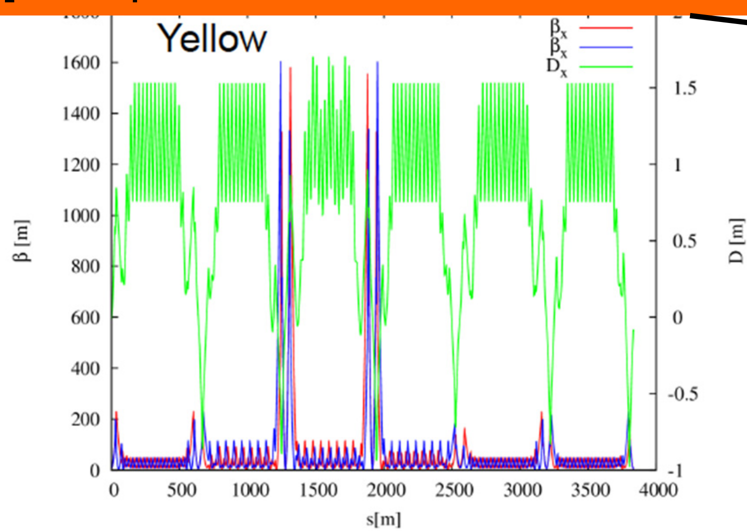


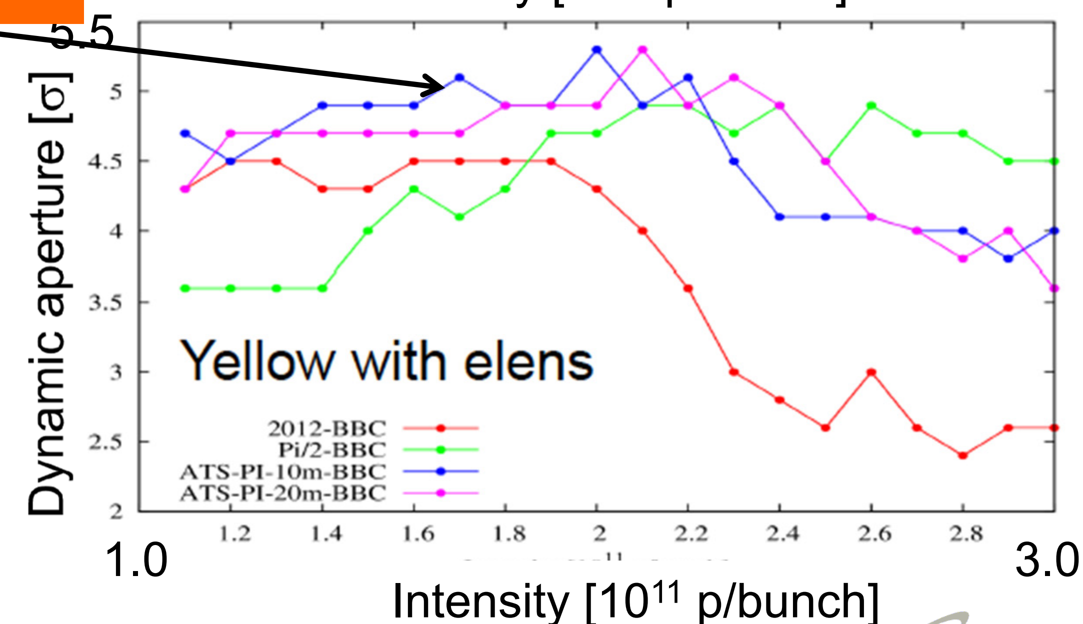
Lattice for 2015 (S. White) – Simulations (Y. Luo)





DA with half head-on beam-beam compensation only weakly dependent on bunch intensity up to 3×10^{11}
[last operation at 100 GeV: 1.6×10^{11}]





Acknowledgements

Brookhaven National Laboratory

M. Anerella, M. Bai, C.D. Dawson, A.K. Drees, B. Frak, G. Ganetis, D.M. Gassner, R.C. Gupta, P. Joshi, K. Hock, L. Hoff, P. Kovach, R. Lambiase, K. Mirabella, M. Mapes, A. Marone, A. Marusic, K. Mernick, M. Minty, C. Montag, J. Muratore, S. Nemesure, S. Plate, G. Robert-Demolaize, L. Snydstrup, S. Tepikian, C.W. Theisen, J. Tuozzolo, P. Wanderer, W. Zhang

STAR and **PHENIX** experiments – supported parasitic commissioning

Institutions

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

Individuals

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

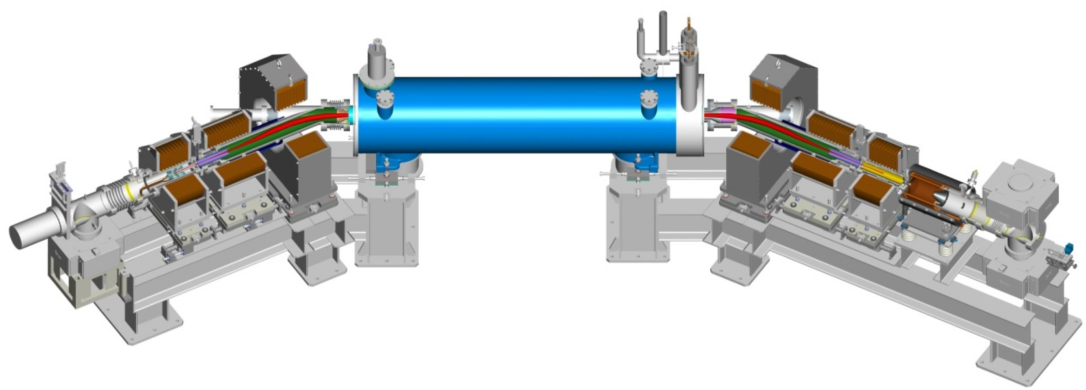
RHIC electron lenses commissioning Summary/Outlook

Status

- Electron lenses installed in both rings
- Magnetic structure commissioned – one solenoid still to reach design field, straightness requirements met (<15% deviation from rms beam size)
- Electron beam current (pulsed and DC) and Gaussian profile demonstrated
- Instrumentation commissioned – novel detector of backscattered electrons used for automatic alignment
- Measured effect of e-beam on orbit, tune, BTF – as expected
- Demonstrated no additional emittance growth (resolution ~1h)

Upgrades for 2015

- Larger cathode
- Transverse damper
- New lattice



2015 polarized proton run will be first opportunity for head-on beam-beam compensation