The Physics and Use of Electron Lenses at BNL

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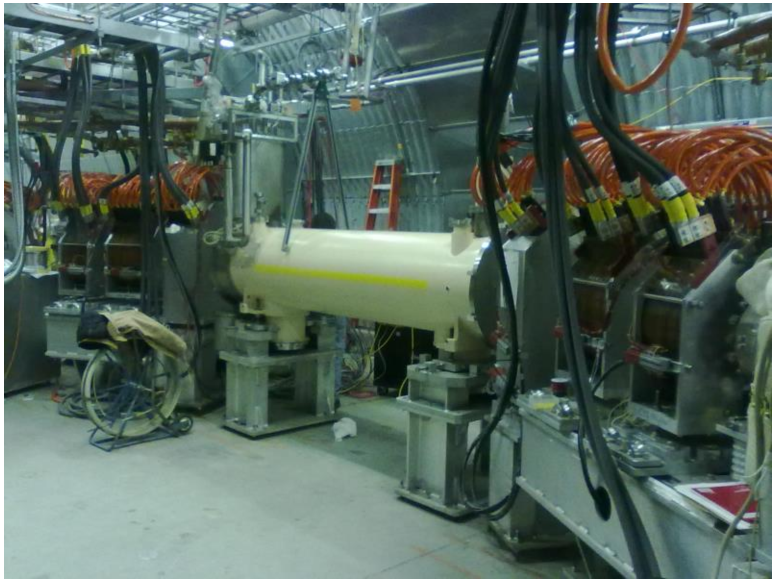
Outline

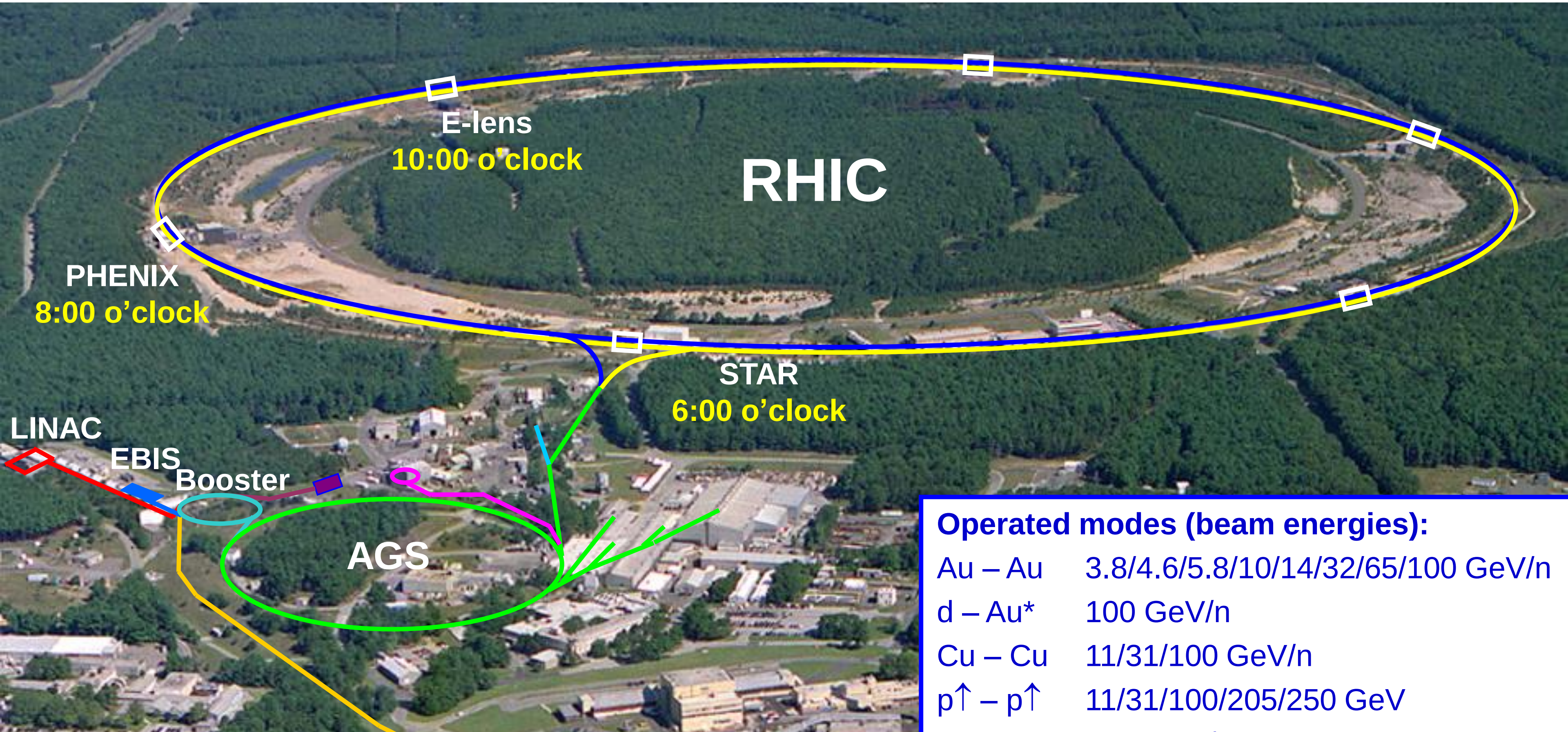
- **Introduction**

- **Hardware commissioning**
  - Super conducting magnets
  - Normal conducting magnets
  - Instrumentation

- **Electron beam commissioning**
  - Current
  - Transverse profile
  - Effect on orbit and tune
  - Others



RHIC – a High Luminosity (Polarized) Hadron Collider



Achieved peak luminosities:

Au–Au (100 GeV/n)	195×10^{30} cm^{-2} s^{-1}
p↑–p↑ (250 GeV)	150×10^{30} cm^{-2} s^{-1}

Performance defined by

1. Luminosity L
2. Proton polarization P
3. Versatility (species, E)

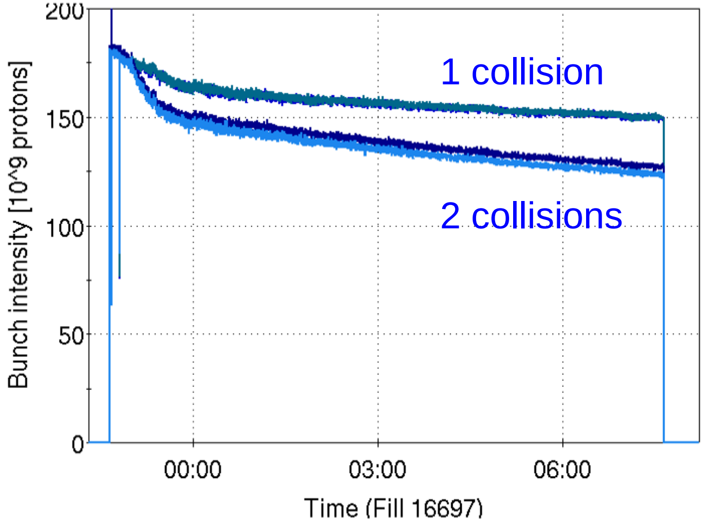
Operated modes (beam energies):

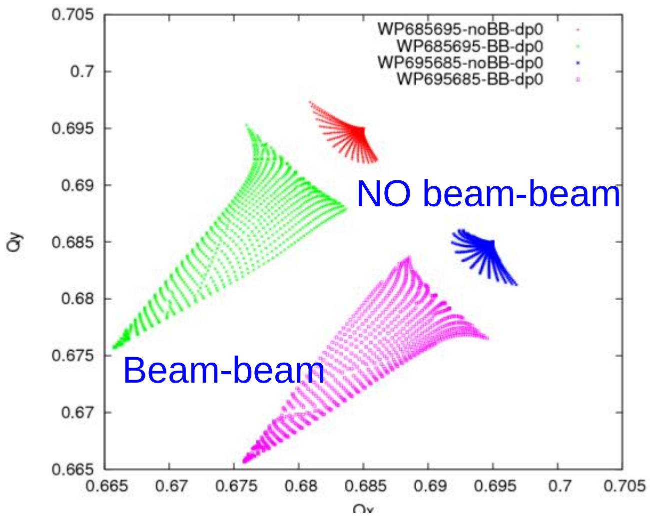
Au – Au	3.8/4.6/5.8/10/14/32/65/100 GeV/n
d – Au*	100 GeV/n
Cu – Cu	11/31/100 GeV/n
p↑ – p↑	11/31/100/205/250 GeV
H3 – Au	100 GeV/n

Planned or possible future modes:

Au – Au	2.5 GeV/n (~ SPS cm energy)
U – U	100 GeV/n
p↑ – Au*	100 GeV/n
Cu – Au*	100 GeV/n (*asymmetric rigidity)
e – p	

Introduction -- E-lens Motivation





RHIC proton intensity threshold:

1 2013 RHIC polarized proton run:

- 2.2E11 for Blue (beam-beam)
- 2.0E11 for Yellow (longitudinal stability)

2 Beam-Beam Tracking:

If intensity >2.0 × 1011, no enough tune space for large beam-beam tune spread

Electron lenses (e-p):

compensate for 1 of 2 beam-beam interactions (p-p), then have the capability to increase bunch intensity (Luminosity)

Coherent Instability:

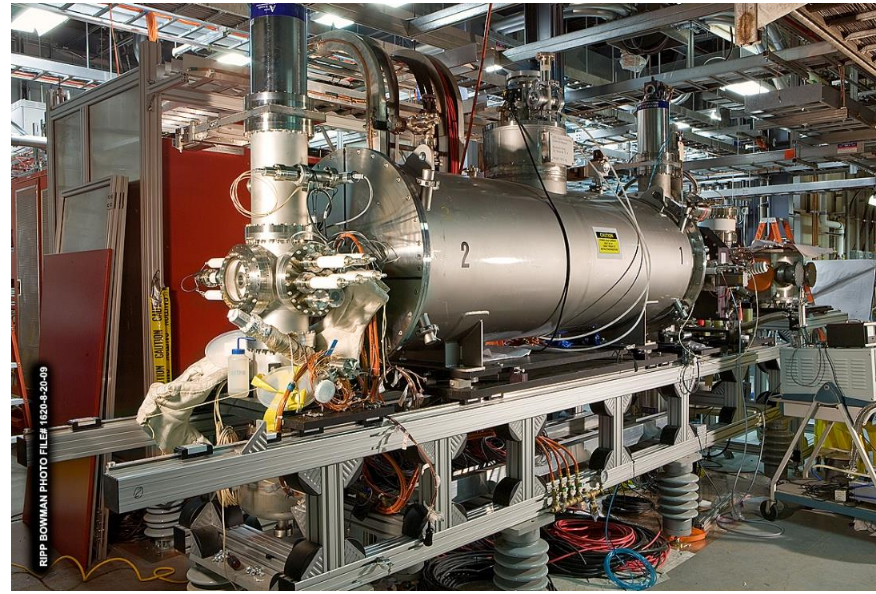
Transverse bunch by bunch damper
Larger beam size and beta*

Introduction -- Technology

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:

- Solenoid field 6 T
- Solenoid length 2.7 m
- e-beam energy 5/10 kV
- e-beam current 0.6/3 A (pulsed)

→

RHIC e-lens

6 T ($\pm$50 μm straight)
2 m
10 kV
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)

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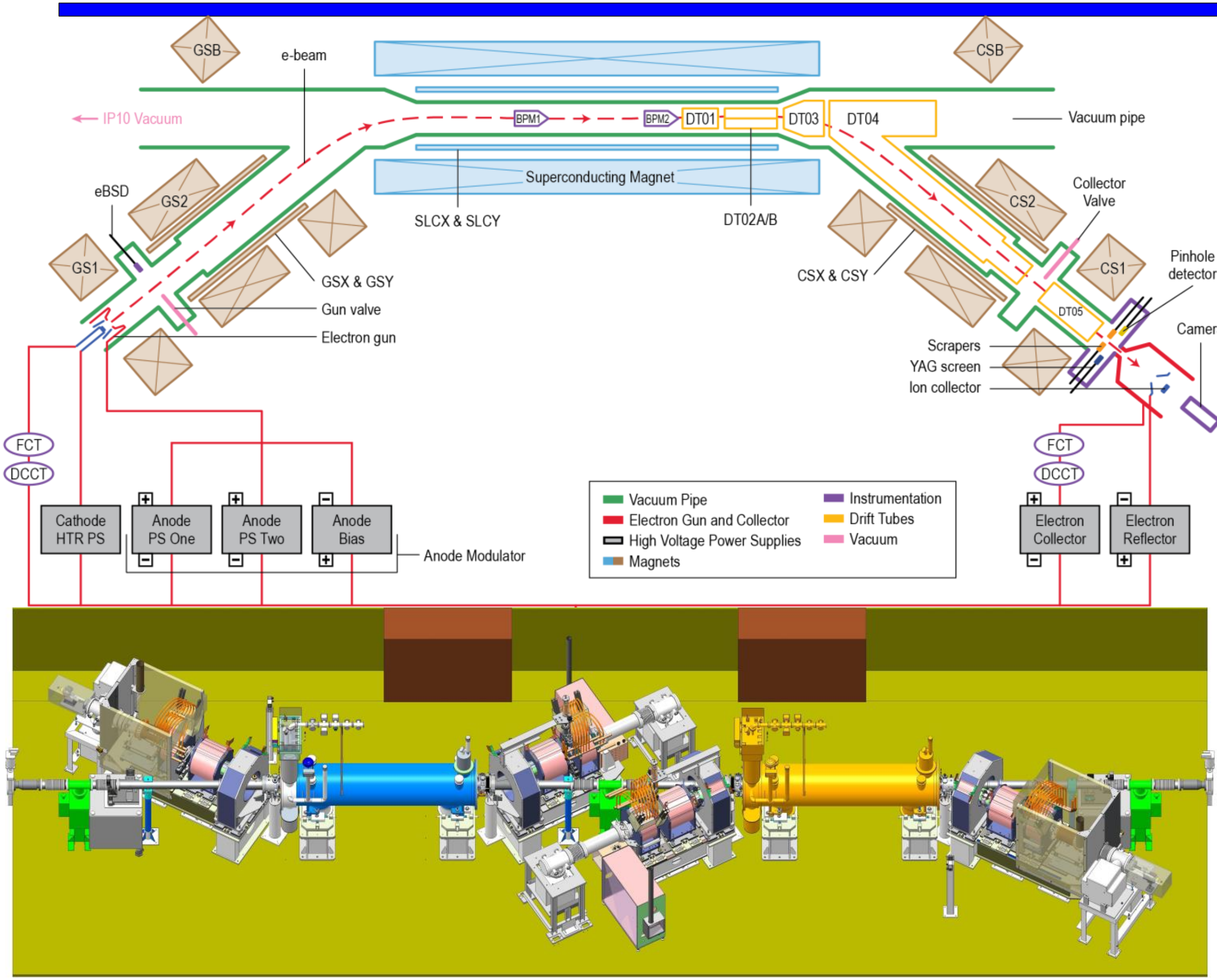
Introduction -- E-lens Layout



1. Warm Magnets
2. Cold Magnets
3. E-gun & Collector
4. Instrumentations
5. Vacuum
6. HV power supplies
7. Drift tube

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  - Transverse profile
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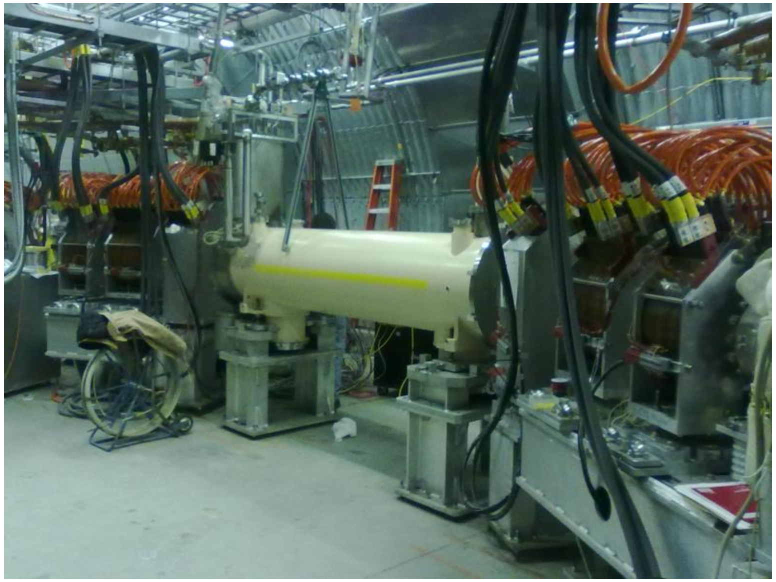
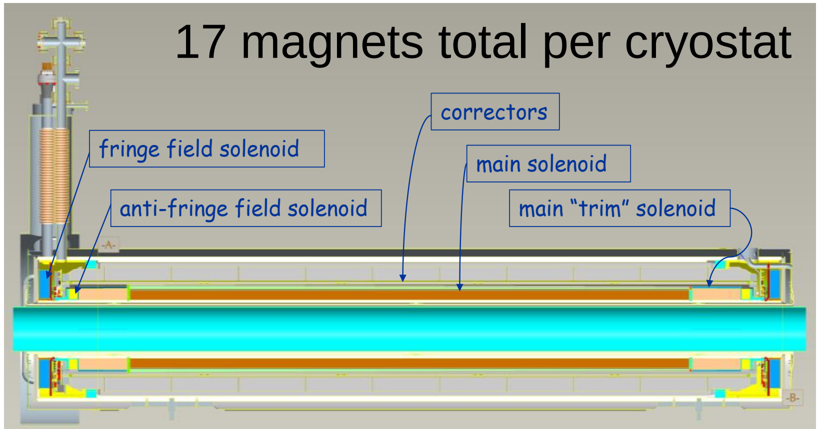
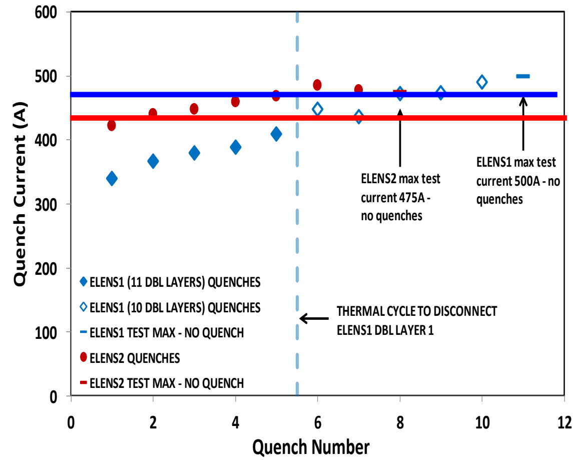
  - Others



Hardware - Superconducting Magnets Field

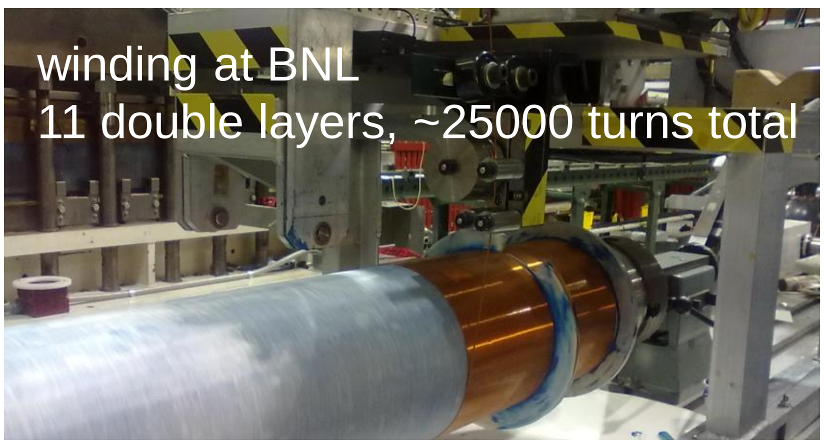
Main solenoid field provides transverse electron beam profile to match p-beam

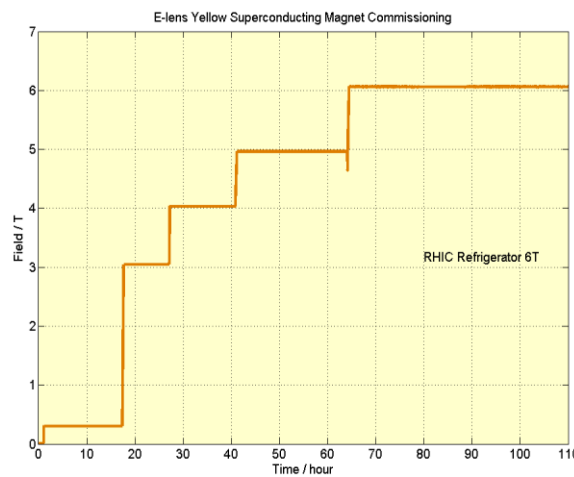




Vertical test (10% more):

1. Blue : 500A
2. Yellow: 475 A





Horizontal test:

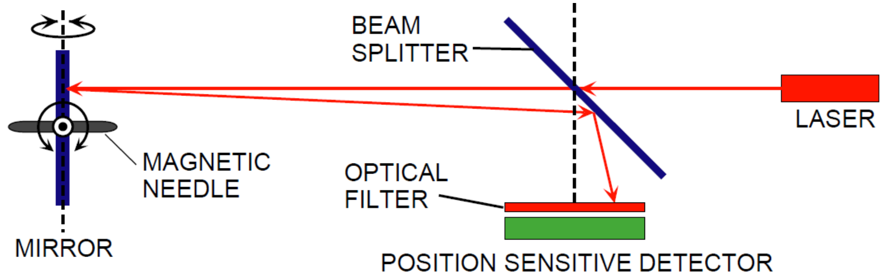
1. Blue: 5 T/4.5 T
1. Yellow: 6 T

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

IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, VOL. 24, NO. 3, JUNE 2014

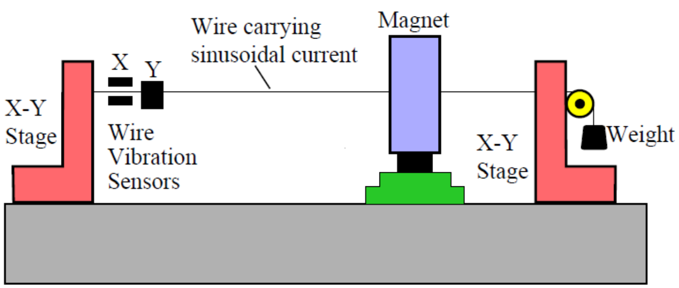
Hardware - Field Straightness Measurement

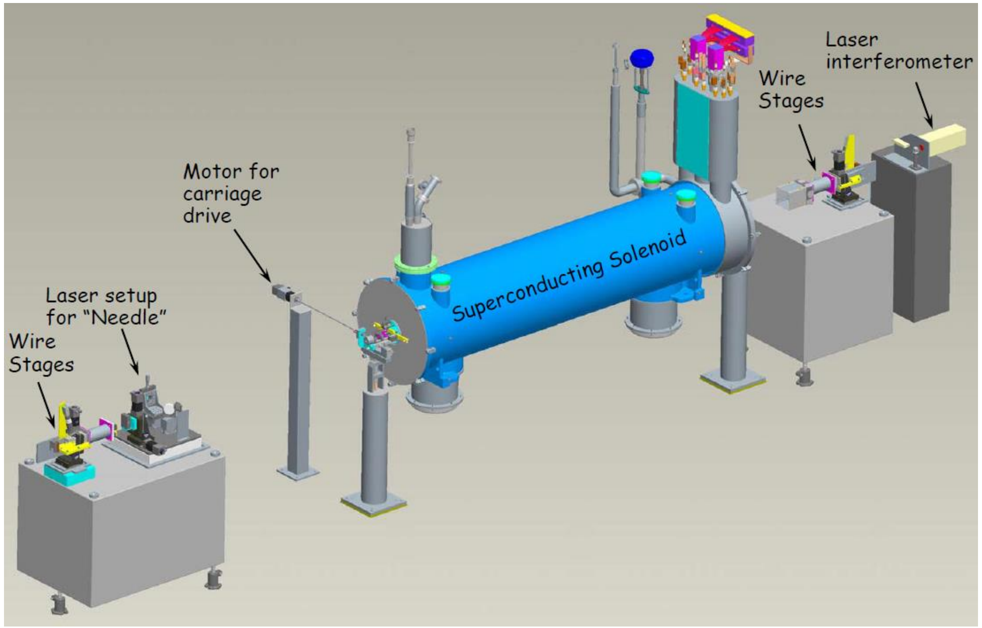
Needle & mirror



(Based on *C. Crawford et al., FNAL and BINP, Proc. PAC'99, p. 3321-3*)

Vibrating Wire

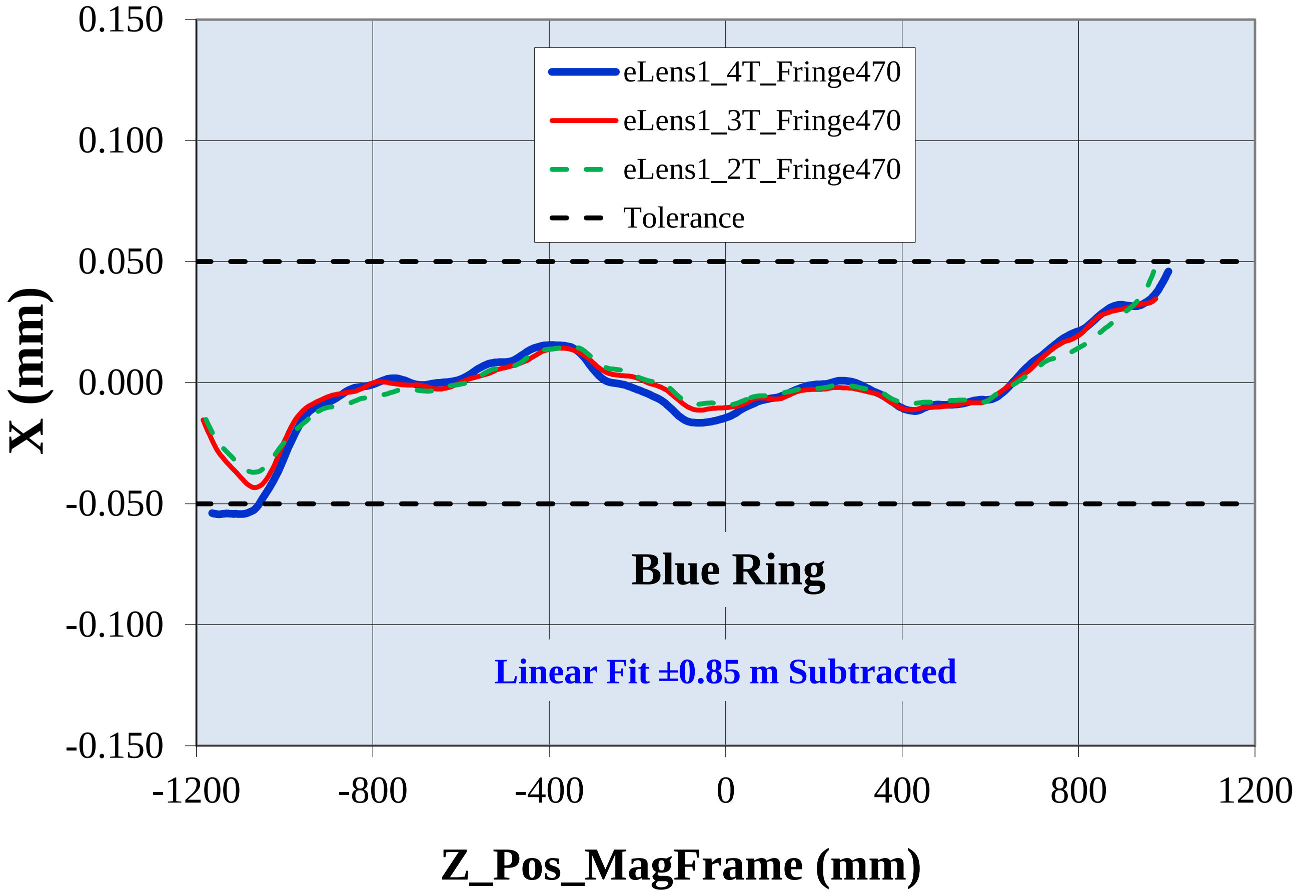




1. Needle & mirror: straightness
2. Vibrating wire: straightness, multi-poles
3. Use needle & mirror because of NSLS-II, space and risks from vibrating wire:

- Effect of large sag (~300 microns) of ~5 m long wire;
– Separate offset/tilt/sag from a local bending of field lines;
– Large fringe field outside the solenoid.

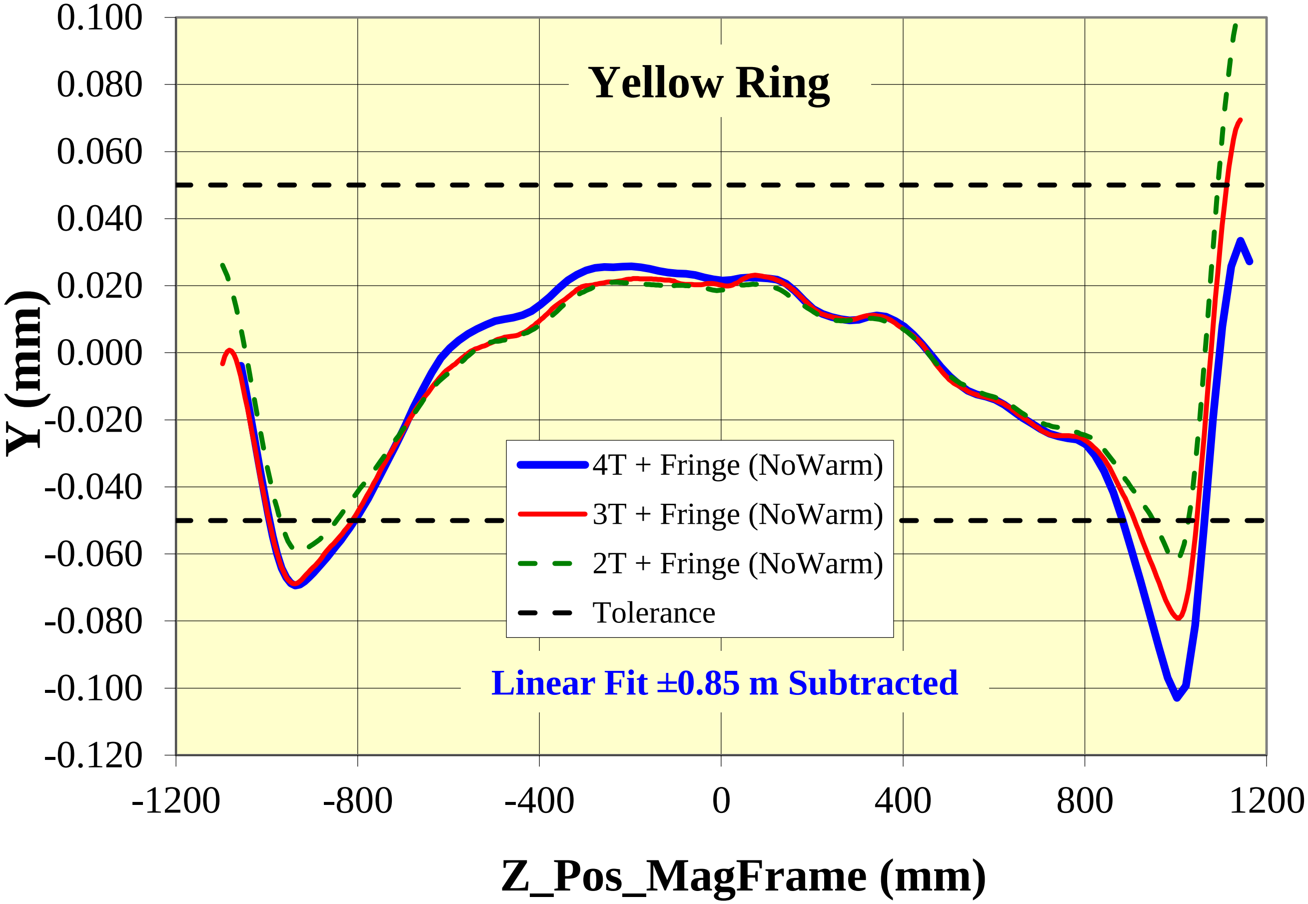
Hardware – Magnetic Field Straightness Measurement



Straightness within tolerance

1. Tolerance = ± 50um
2. Three different fields
3. ±800 mm good field
4. Without correction
5. With warm magnets
6. Blue and Yellow (H & V)
7. Needle & mirror

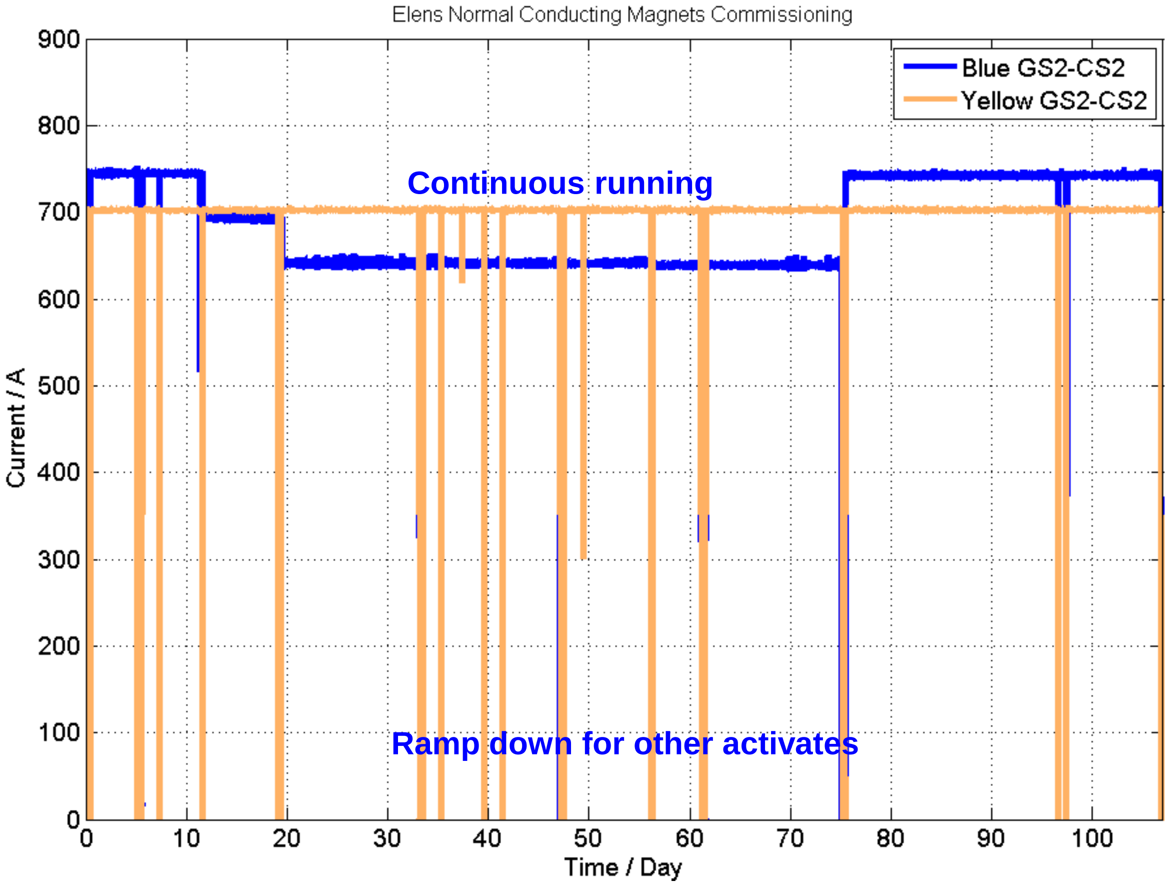
Hardware - Yellow vertical



Straightness within tolerance

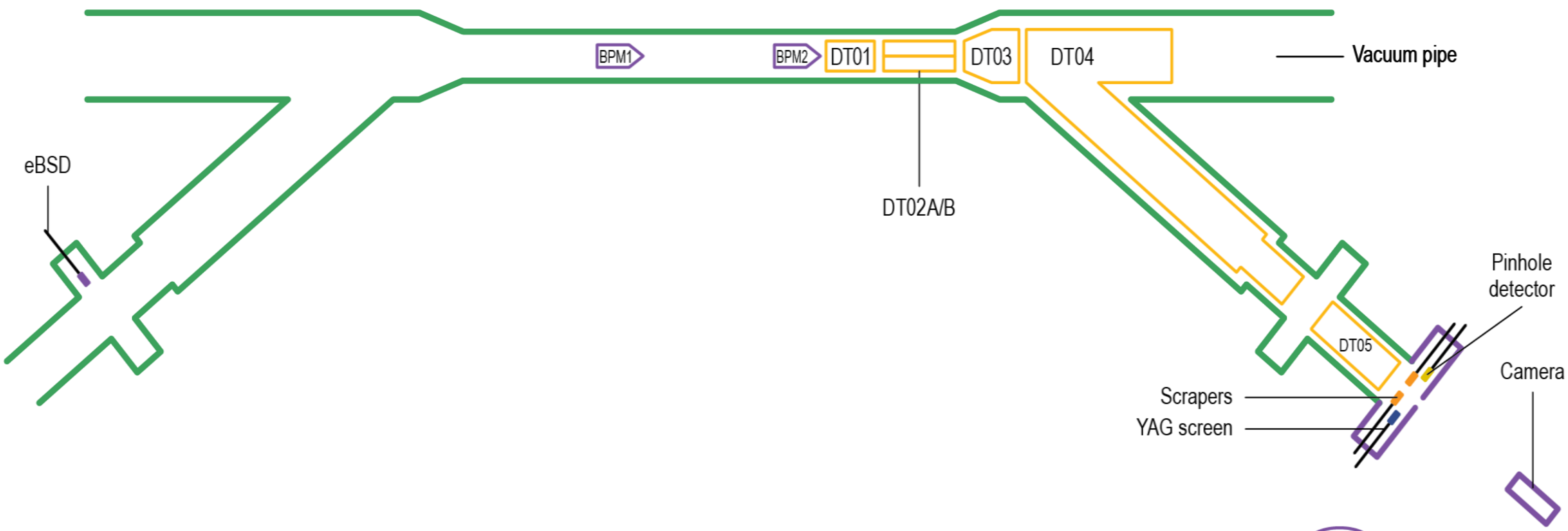
1. Tolerance = ± 50um
2. Three different fields
3. **±800** mm good field
4. Without correction
5. NO warm magnets

Hardware - Normal Conducting Magnets



1. Totally 12 solenoids and 6 power supplies.
2. All magnets run very reliable from 2013;
3. Most of magnets PS run very well;
4. Only the yellow GS2-CS2 PS has a fault during 2014 RHIC run and took 4 hours to fix it.

Hardware - Instrumentation



FCT
DCCT

E-Beam Instrumentation System

FCT
DCCT

Beam Alignment : BPM (2) (also for p-beam), Backscattered electron monitor(1)

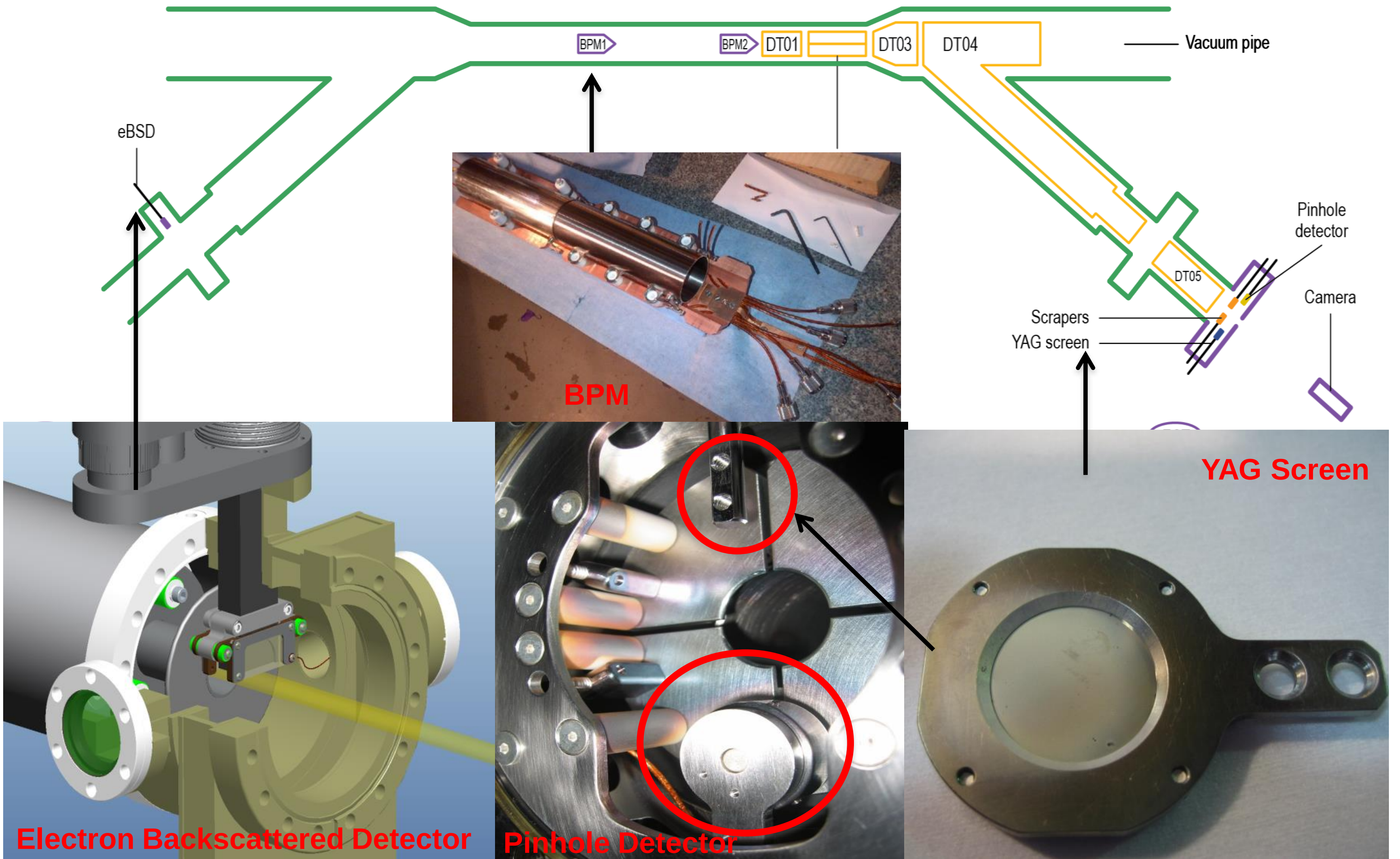
E-beam Current : BCT (4), e-beam Loss (drift tubes)

E-beam Profile : YAG Screen (1), Pin-hole detector (1)

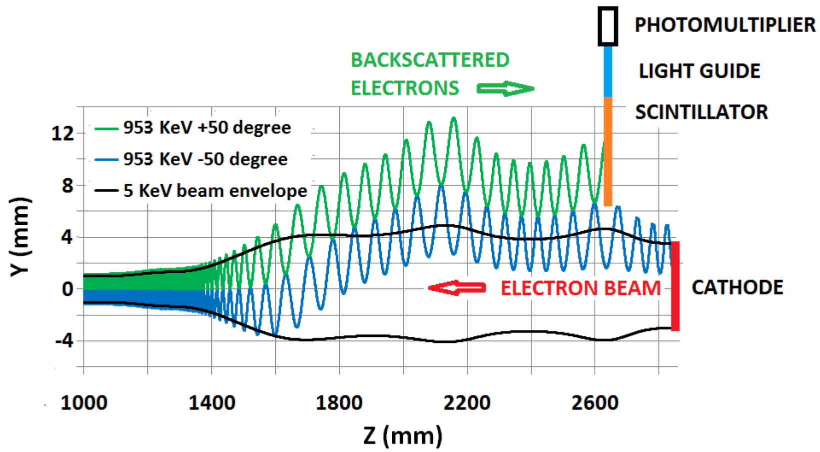
Ion Current : Ion collector (1)

Collector Temperature: RTD (8)

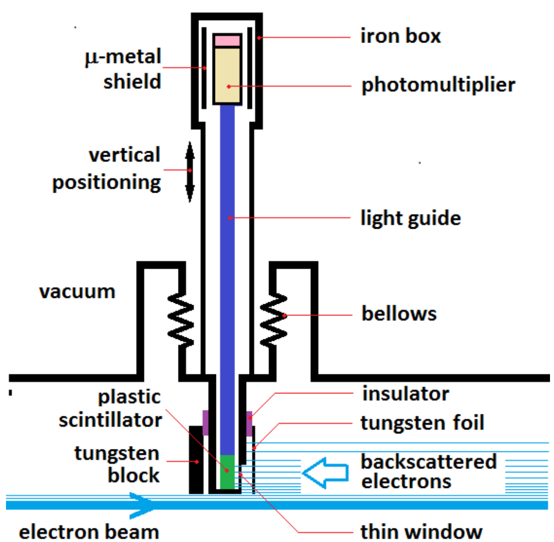
Hardware - Instrumentation

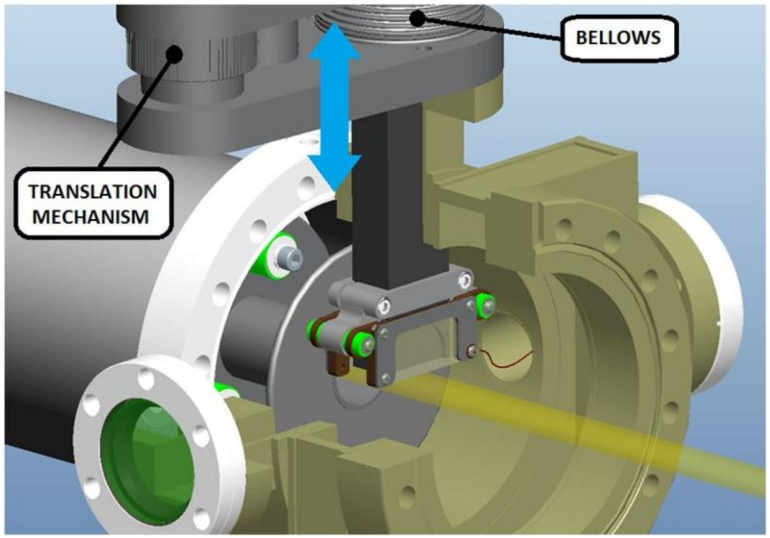


Hardware - The Electron Backscattering Detector



1. The backscattered electrons: scattered by collisions with the ions or proton, reach the detector located close to the gun;
2. The detector position: the centroid of the backscattered electrons moves up or down because of the bending B field.
3. Used for ion and ^{3}He during 2014 RHIC run





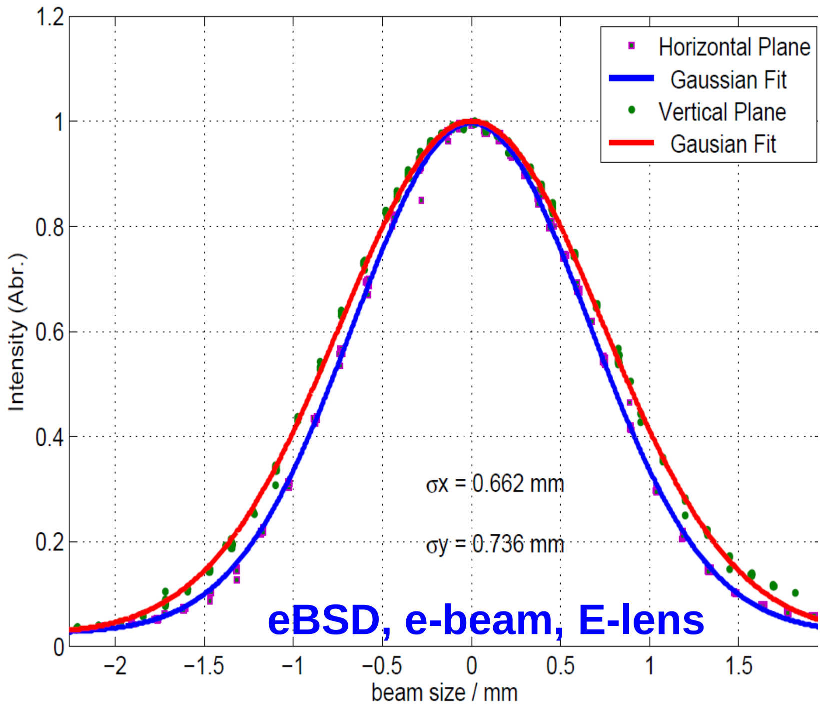
courtesy of Peter Thieberger

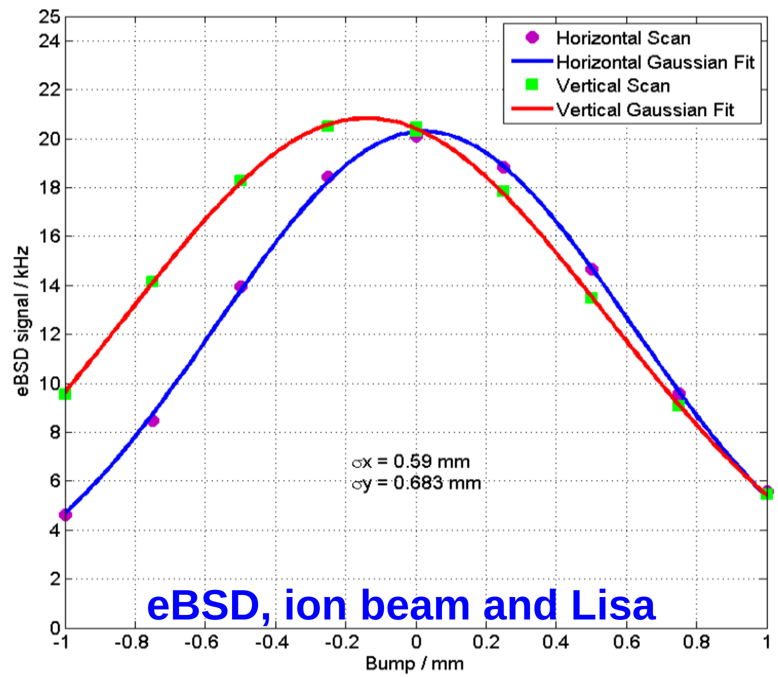
Hardware - Proof-of-principle eBSD scans

1. BPMs in both lenses to bring electron and ion beam in proximity. Backscattered electron detector to maximize overlap (P. Thieberger, BIW12, IBIC2014)

2. The program LISA (Luminosity and IR Steering Application) routinely used for optimizing luminosity, which is the signal from eBSD instead of the ZDC (Zero Degree Calorimeter) coincidence signals.

3. The eBSD is a excellent tool for e-lens alignment.





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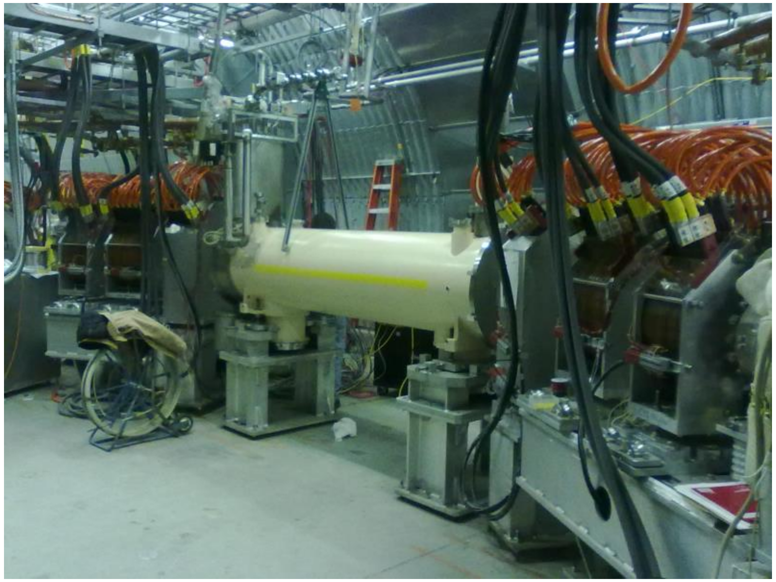

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  - Current
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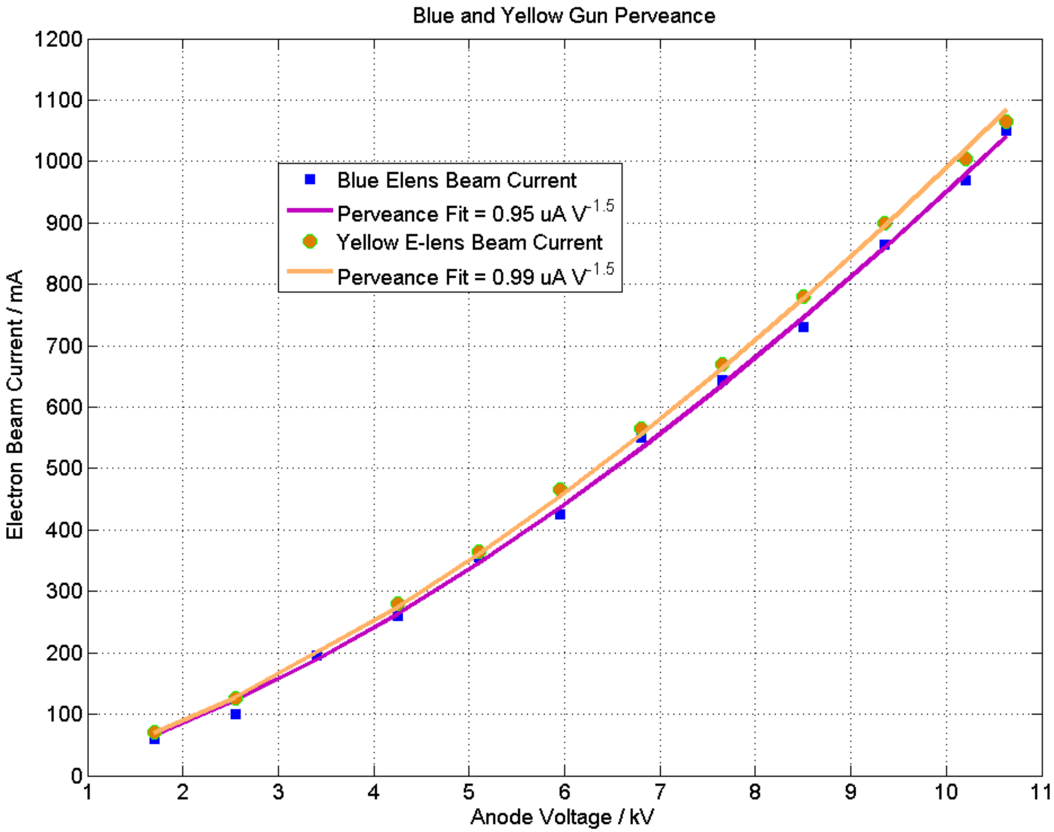
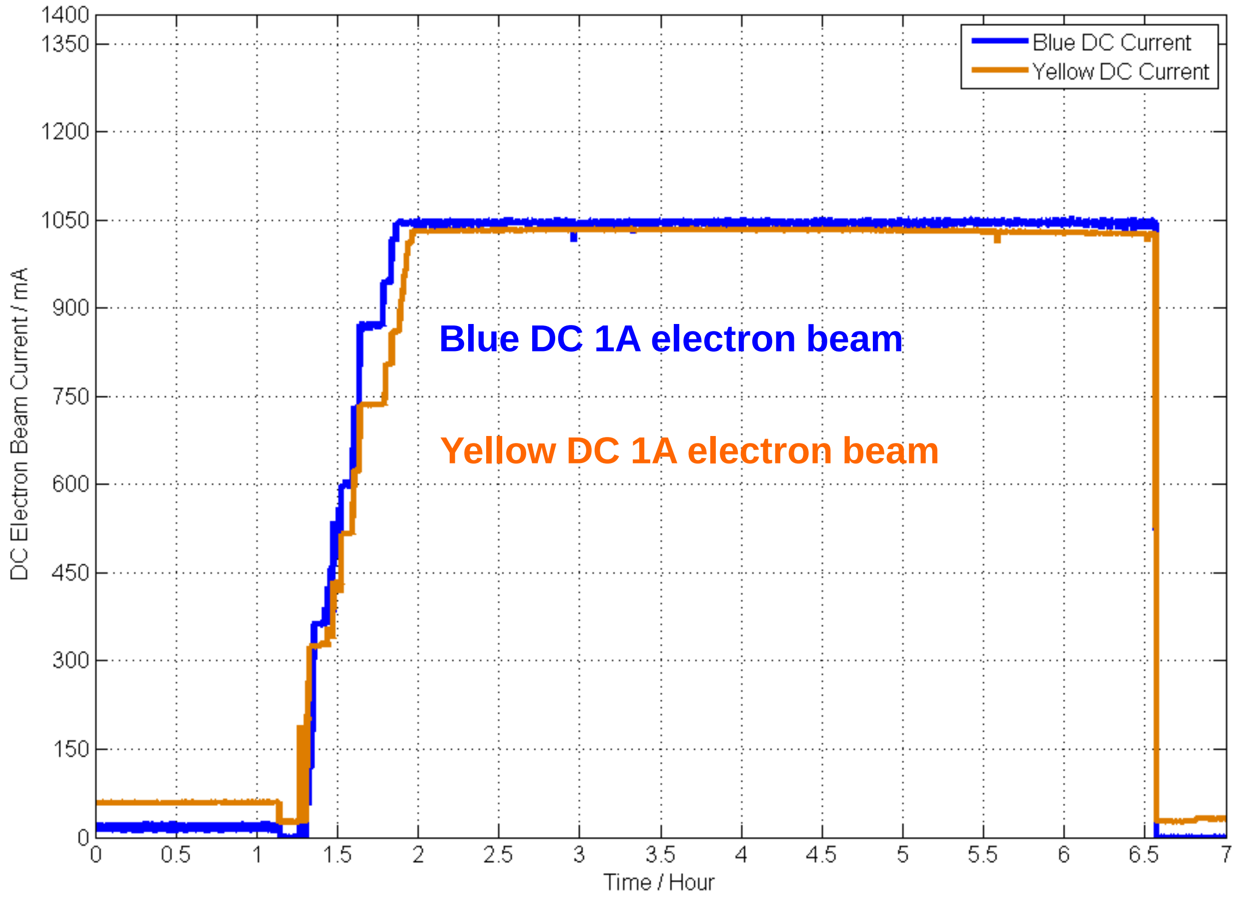
Electron beam – Current



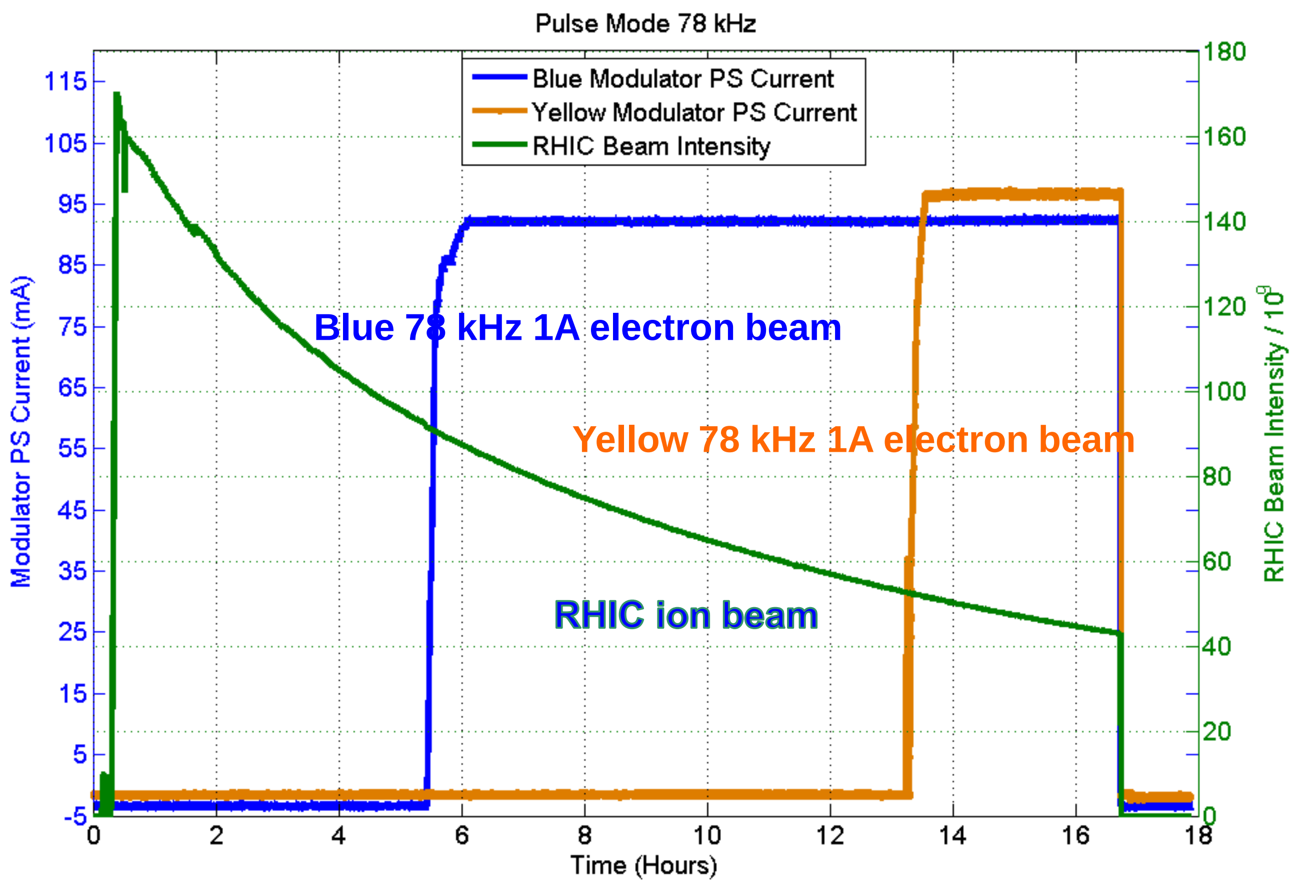
1. Electron gun perveance is measured in pulse mode, which agrees with simulation.
2. Blue electron gun perveance **0.95 μA $V^{-1.5}$**
3. Yellow electron gun perveance **0.99 μA $V^{-1.5}$**
4. DC beam dark current issue is understood and resolved.

Electron beam – DC mode



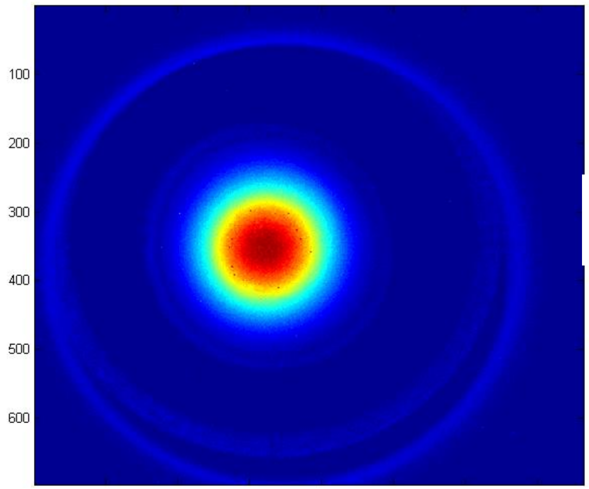
1. NO RHIC ion beam
2. Blue and Yellow were running simultaneously
3. Beam current is **1 A**
4. Blue was running for 9.5 hours during 2013 commissioning.

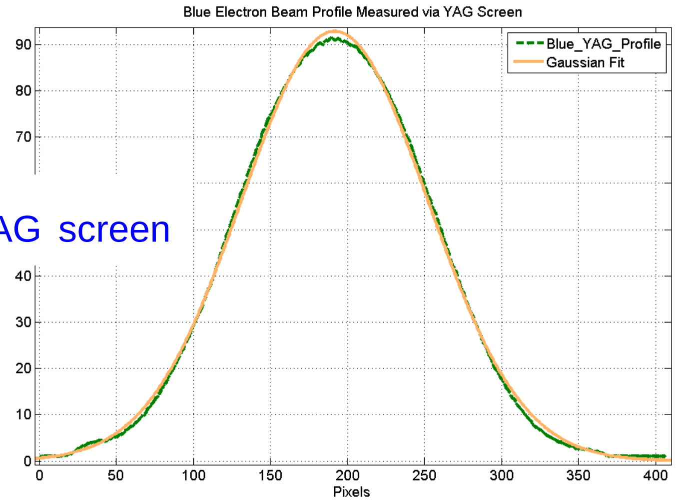
Electron beam – Pulsed Mode



1. Modulator current indicates 78 kHz is running.
2. Blue and Yellow were running **78 kHz pulse** mode with 1A **simultaneously** within RHIC beam abort gap;
3. Parasitic to RHIC beam provides more commissioning time;
4. Blue e-lens 78 kHz was running for 14 hours during 2013;

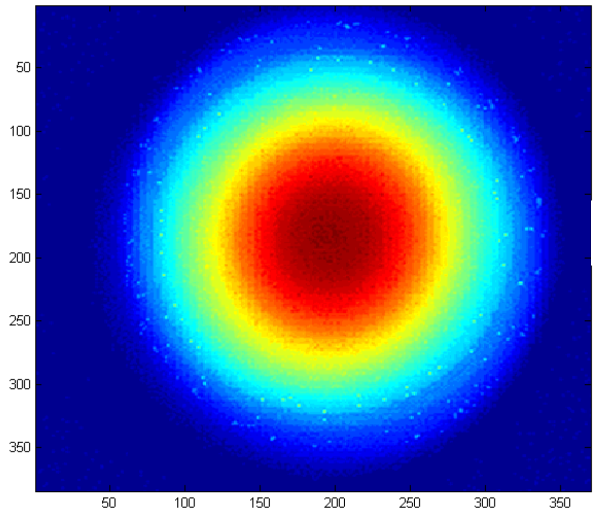
Electron beam Blue Transverse Profile

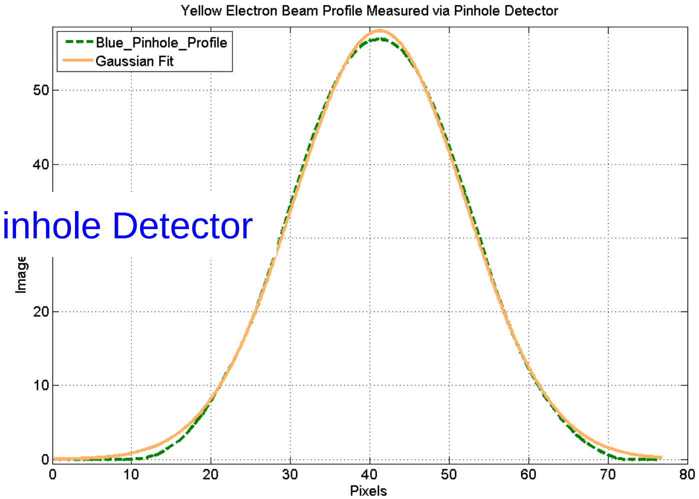




YAG screen

- Current 70 mA
- Beam profile from YAG is a Gaussian
- Profile does not change with current

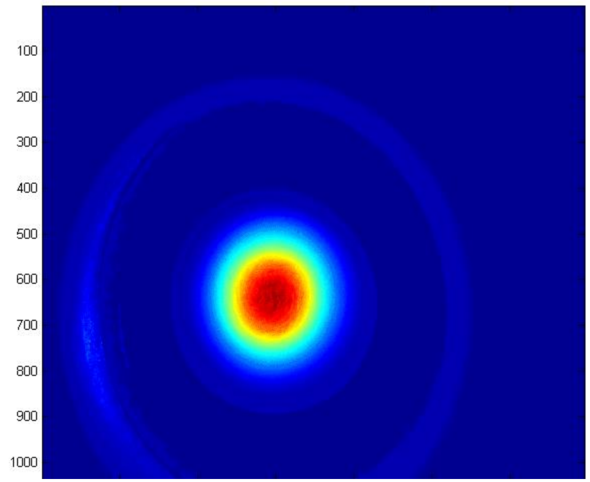


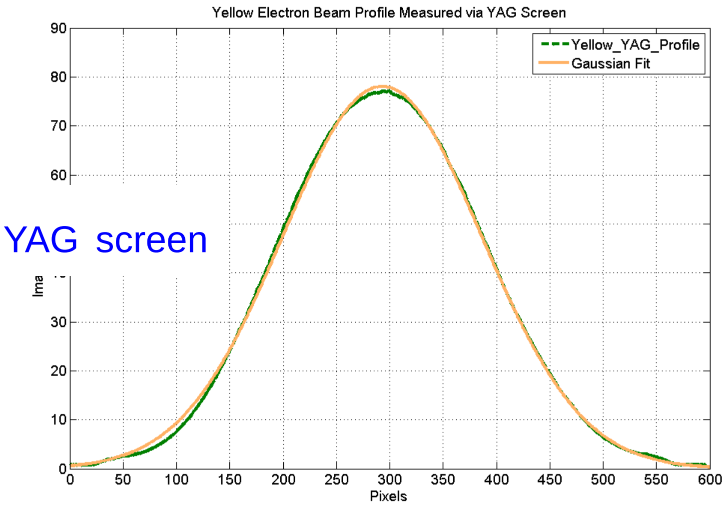


Pinhole Detector

- Current 1150 mA.
- Pinhole profile is Gaussian

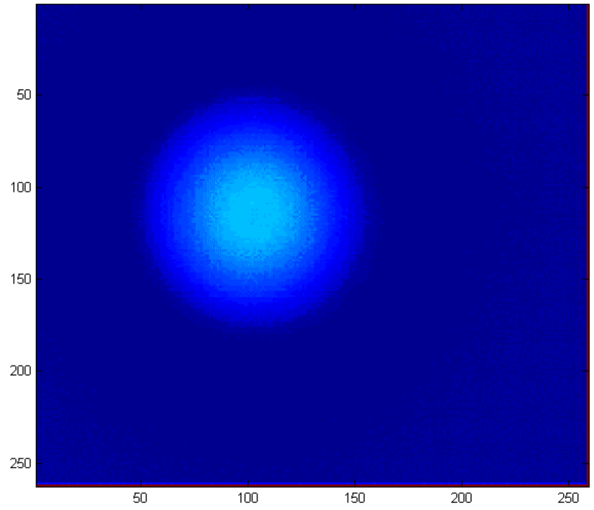
Electron beam Yellow Transverse Profile

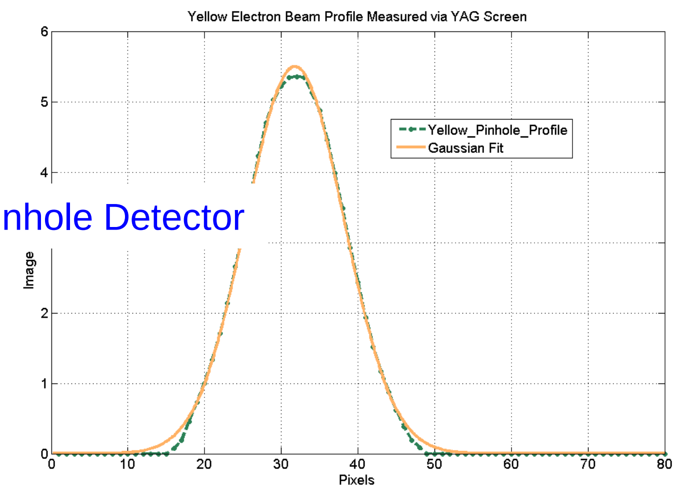




YAG screen

1. Current 100 mA
2. Beam profile from YAG is a Gaussian

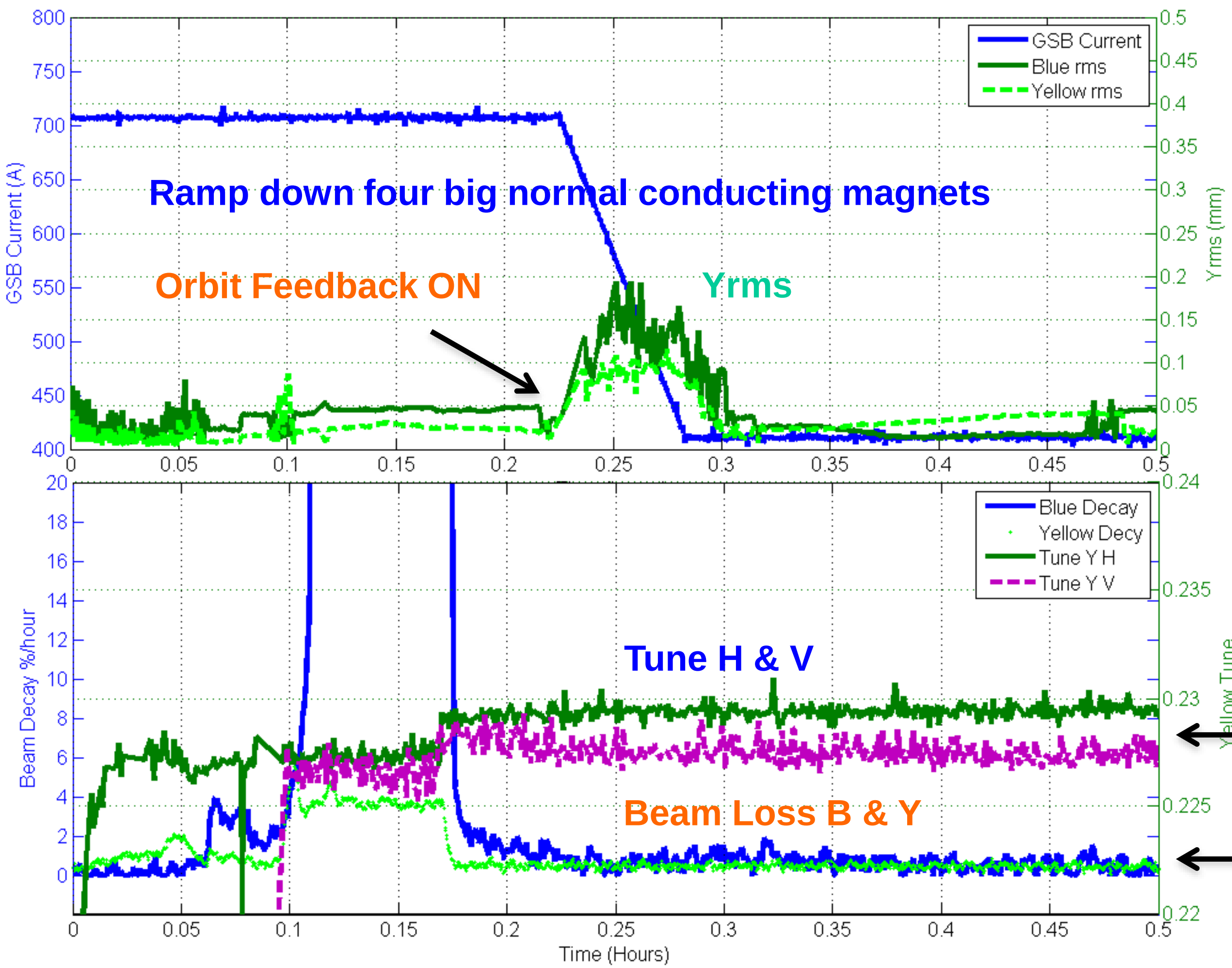




Pinhole Detector

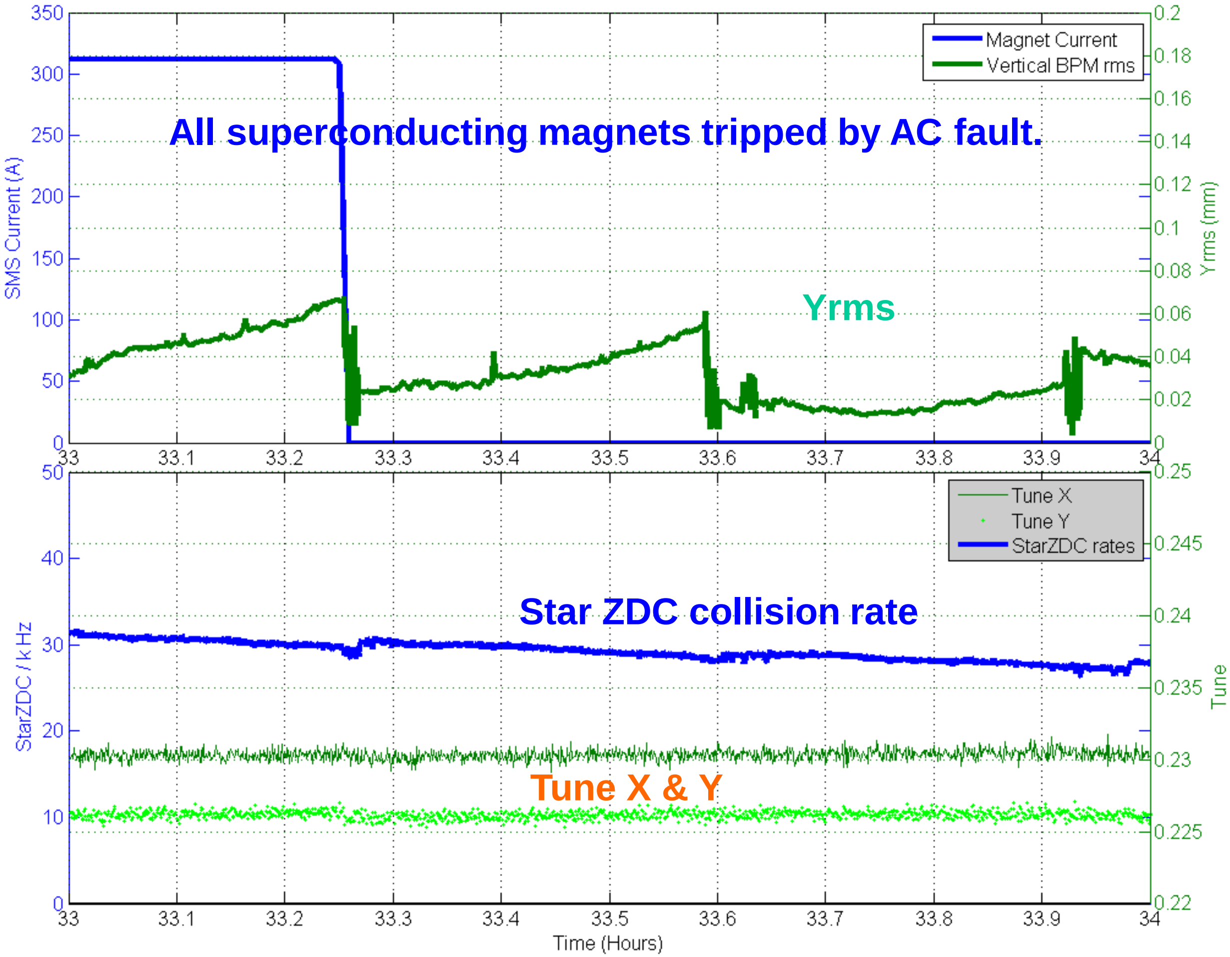
3. Current 100 mA.
4. Pinhole profile is Gaussian with a flat top
5. Maybe caused by fewer data points
6. Center depression ok in simulations

Normal Conducting Magnets and Orbit



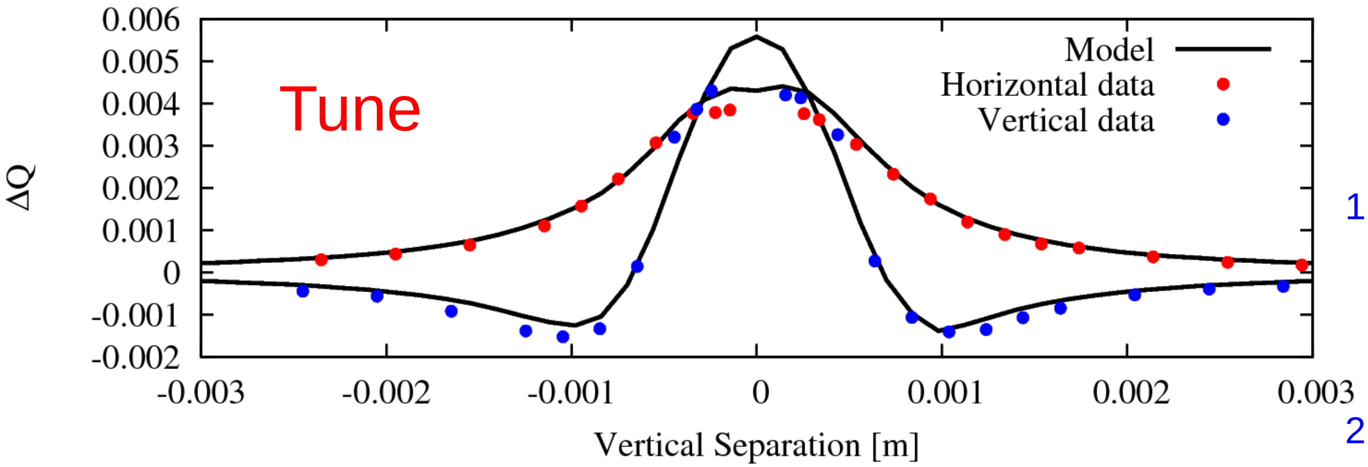
1. Ramp down four big normal conducting magnets during store
2. Affected the vertical orbit rms
3. RHIC orbit feedback can handle it
4. Orbit feedback runs routinely every 20 min. for orbit drift correction.
5. No effect on tune
6. No effect on beam loss

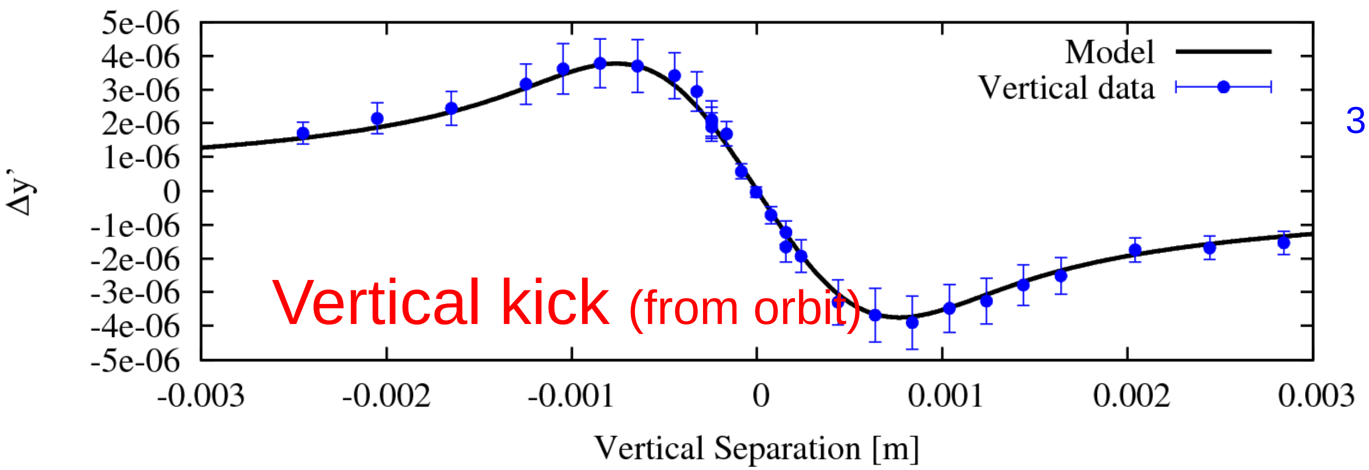
Superconducting magnets and orbit



1. Superconducting magnets tripped by AC fault from 4T to 0
2. Also effected orbit rms, 3~4 times less than ramp down of normal conducting magnets
3. RHIC orbit feedback can handle it
4. No effect on tune
5. No effect on beam loss

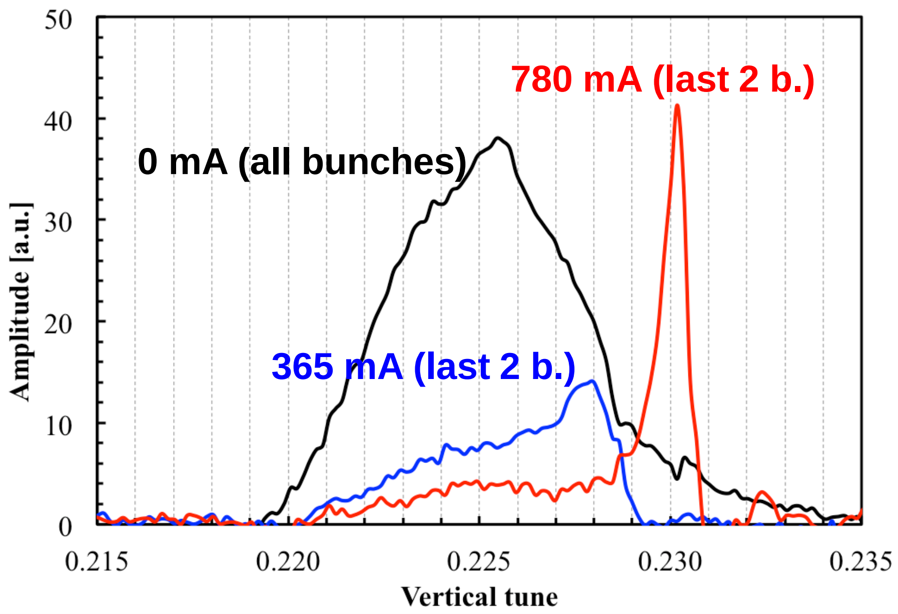
Electron beam – Orbit and Tune



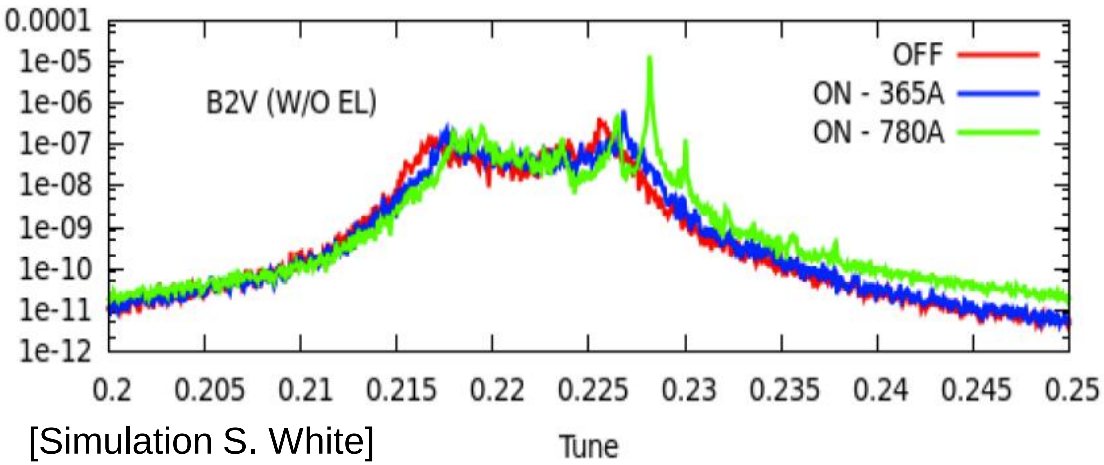


1. The first electron and ion beam alignment by moving electron beam;
2. Yellow ion beam at store
3. Vertical kick strength agree with model

Beam Transfer Function BB + e-lenses



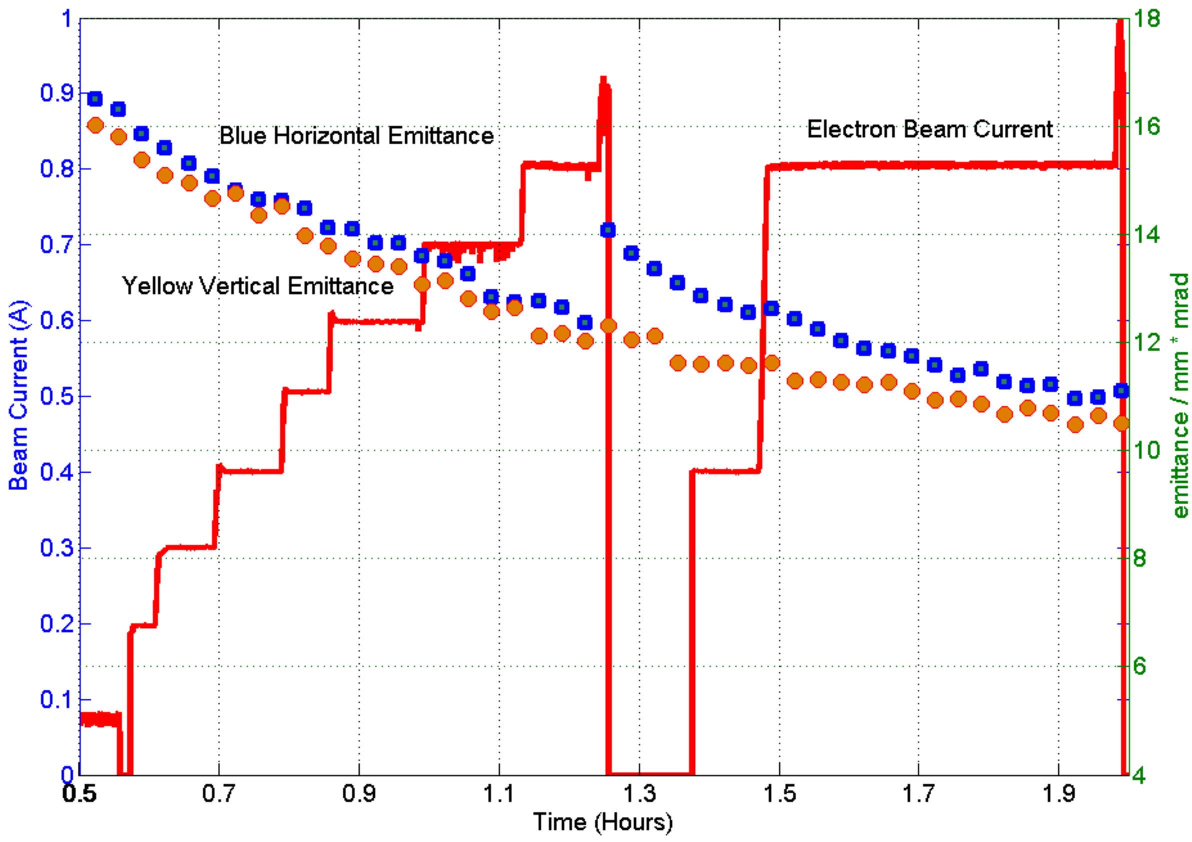
Vertical BTF measurement during physics store (most bunches with 2 collisions)



[Simulation S. White]

Coherent mode emerging with increasing electron current.

Electron beam – Emittance Growth



1. Blue DC mode with **ion** beam;
2. Emittance decreasing because of cooling;
3. Increasing electron beam current (red);
4. **No additional emittance growth;**
5. Vacuum spike caused emittance growth;
6. With stochastic cooling ;
7. With rebucketing;
8. 1 hour = cooling or IBS growth time.

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Electron Beam – Beam-beam driven instabilities

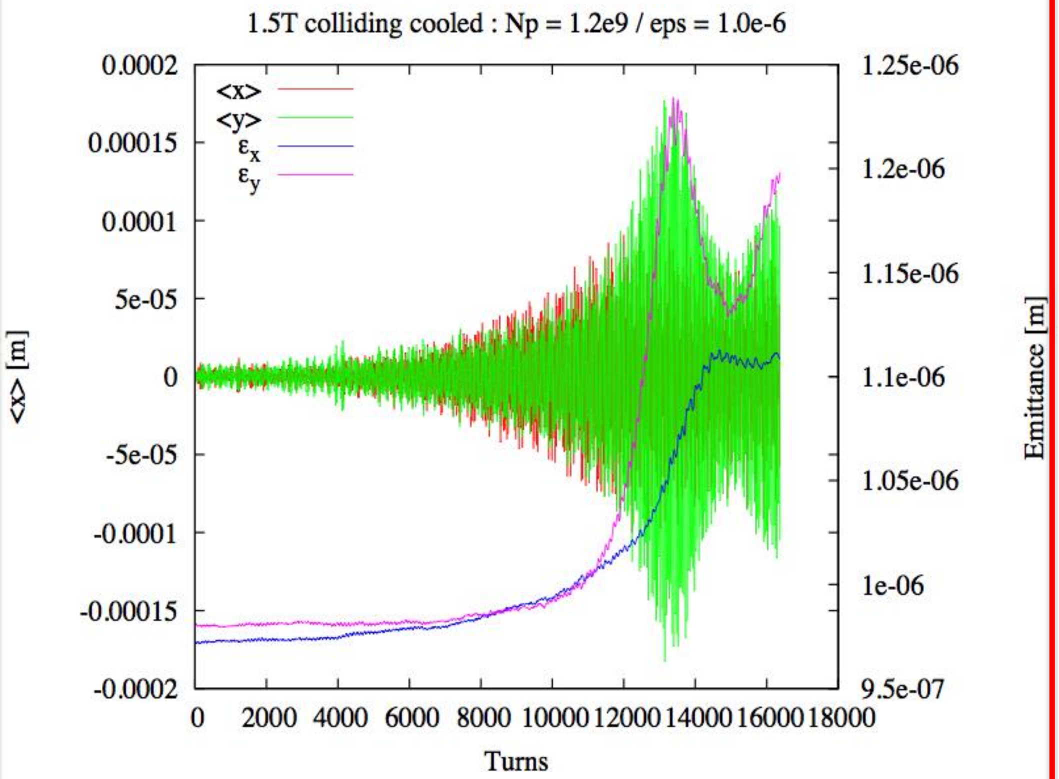
Transverse beam stability with an "electron lens"

Instability threshold for solenoid field (approximate)

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

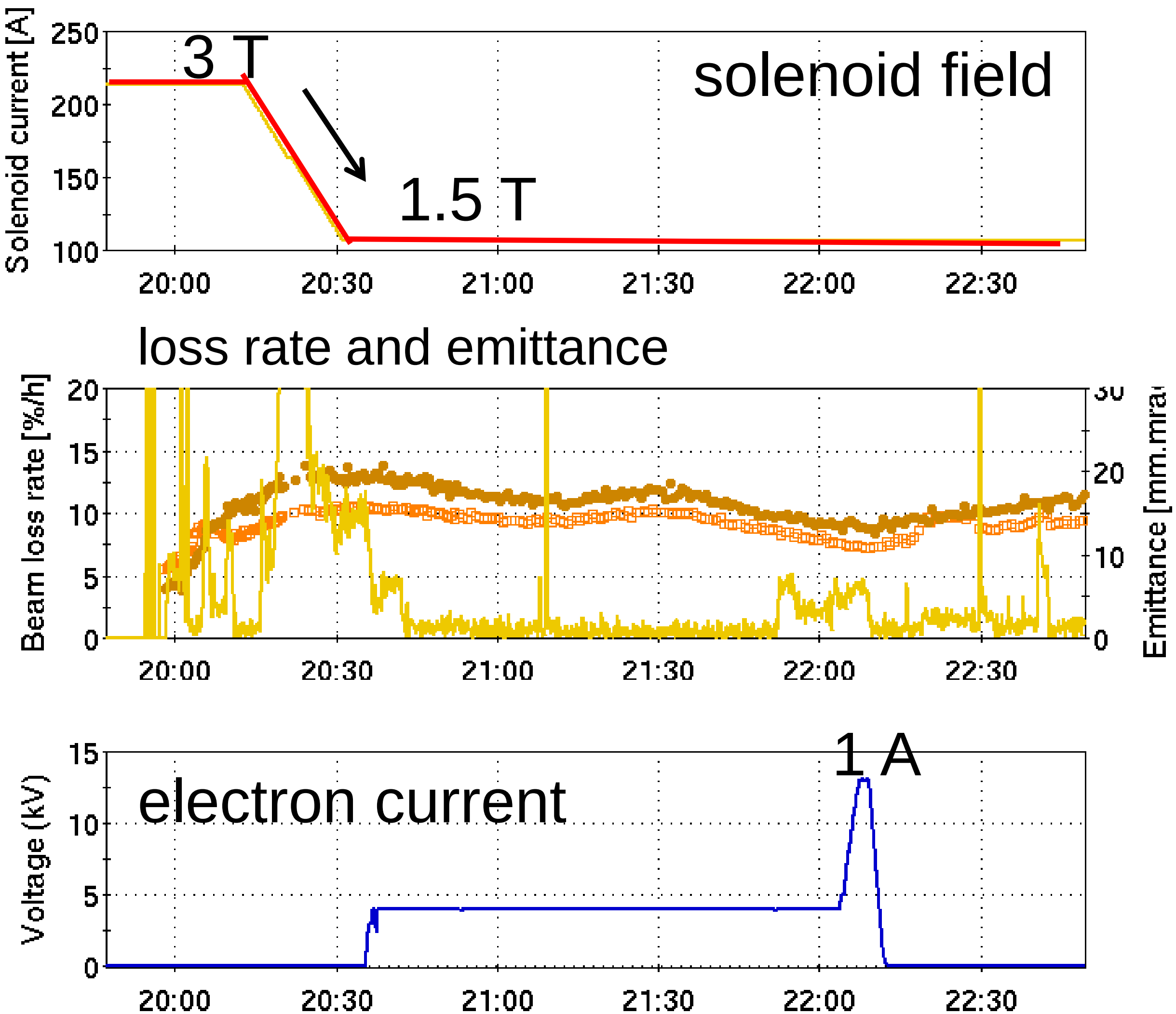
A. Burov et al. Physics Review E 59, 3605 (1999)

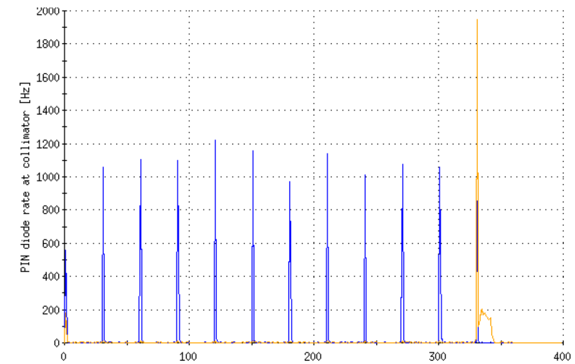
Simulation shows instability with Nb = 1.2x109 Au/bunch and 1.5 T



S. White, BB2014 for simulations

Electron Beam – Beam-beam driven instabilities





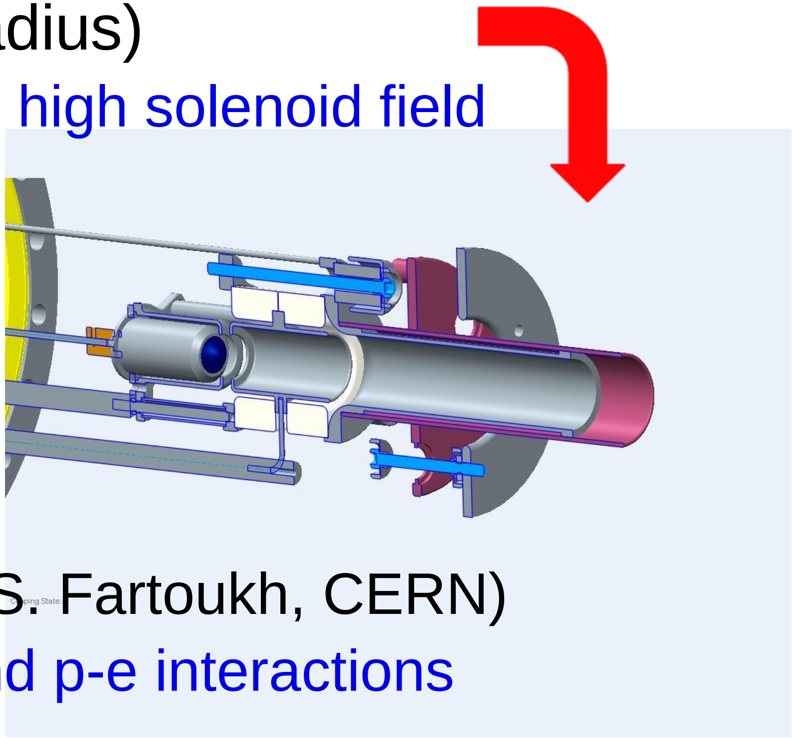
1. Last bunch only
2. Field from 3T to 1.5T;
3. The last bunch is stable, and its luminosity doesn't change;
4. Unstable in simulation, emittance blow up, and luminosity drop

courtesy of S. White

RHIC electron lenses - Preparation for 2015

2015 – First proton run with electron lenses => compensation

•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

Summary

1) A minimum main solenoid field of 5 T with the completed magnet.

2) A maximum deviation of the main solenoid field lines from a straight line of ±50 um without correction at a main field of 4 T, and over a range of at least ±800 mm)

3) All instrumentation are commissioned. eBSD was used for beam-beam alignment;

4) A Gaussian transverse beam profile as verified by the two installed profile monitors (YAG screen and pin hole detector)

5) Both blue and yellow e-lens provided the electron beam for beam-beam studies for several times.

THANK YOU!

ACKNOWLEDGMENTS:
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