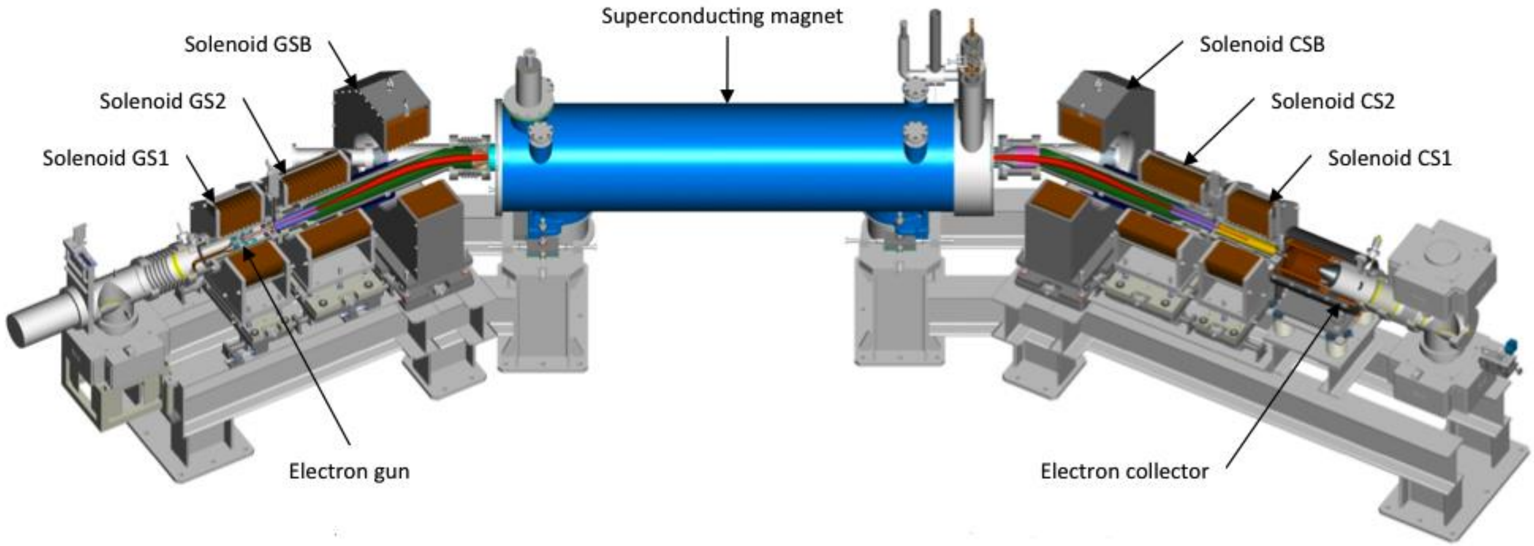

Operational experience of RHIC electron lenses and their effect on collimation and halo populations

W. Fischer, A. Drees and X. Gu

Brookhaven National Laboratory

Review of the need for a hollow e-lens for the HL-LHC

6-7 October 2016, CERN

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Contents

1. RHIC electron lenses
   - Overview
   - Main design parameters and tolerances

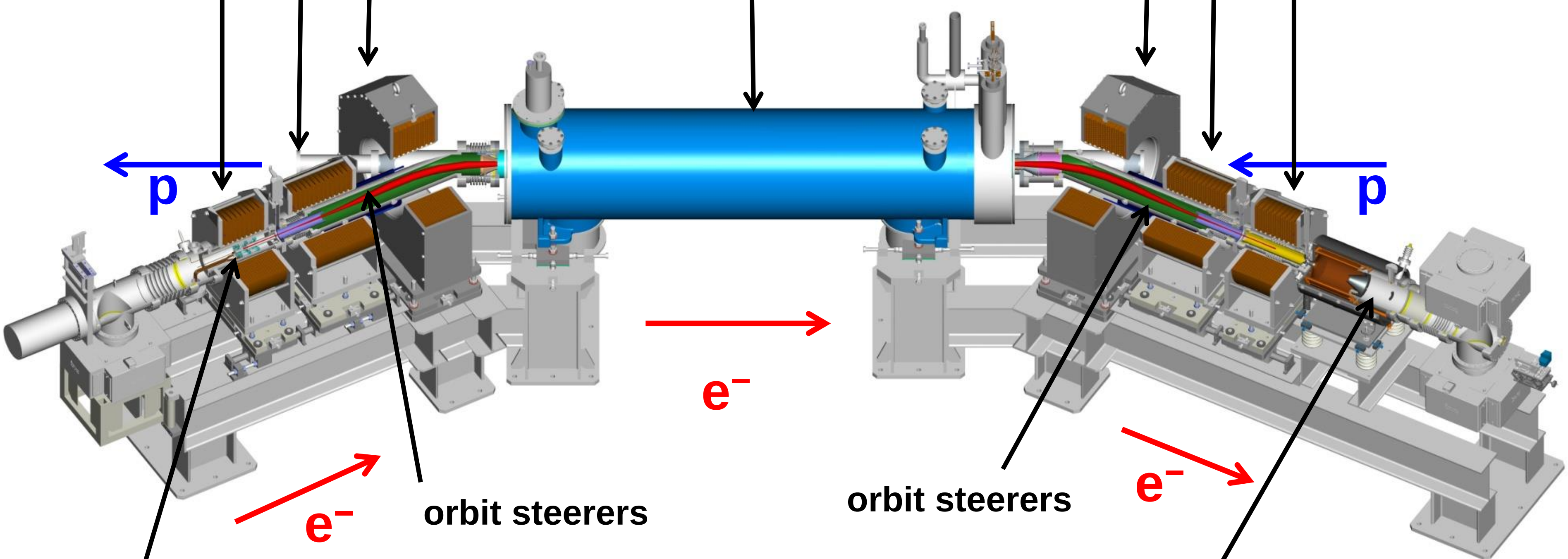
2. Use in operation

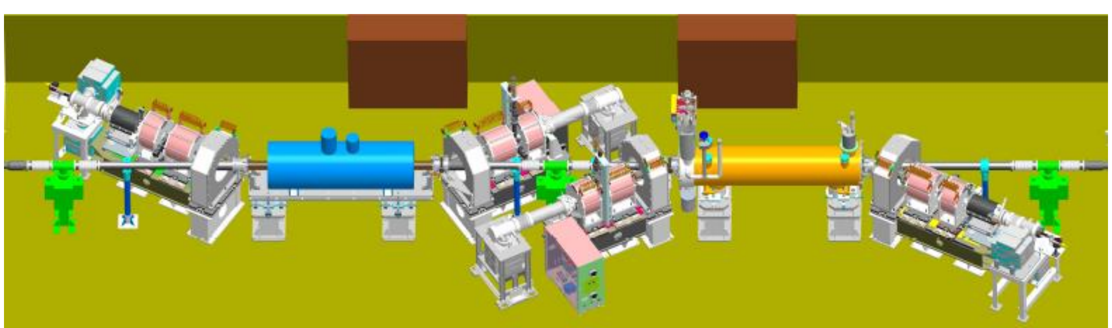
3. Effect of the electron lenses on
   - Beam loss rate
   - Emittance
   - Experimental background rates

RHIC electron lenses

Overview

Xiaofeng Gu, liaison physicist





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RHIC e-lens Parameters

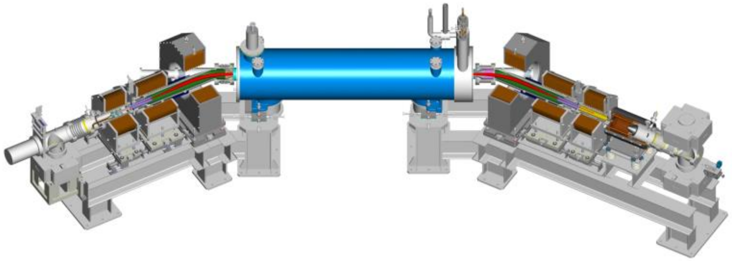


TABLE I. Typical electron lens parameters for 2015 and design values (for up to 250 GeV proton energy).

Quantity	Unit	2015 value	Design value
Distance of center from IP10	m	3.3	
Magnetic length L_e	m	2.4	
Gun solenoid field B_g	T	0.31	≤ 0.69
Main solenoid field B_m	T	5.0	2–6
Cathode radius (2.7σ)	mm	7.5	4.1, 7.5
rms beam size in main solenoid σ_e	μm	650	≥ 300
Kinetic energy E_e	keV	5.0	≤ 10
Relativistic factor β_e	...	0.14	≤ 0.2
Electron beam current I_e	mA	600	≤ 1000
Beam-beam parameter from lens ξ_e	0.001	$+10$	$\leq +15$

±50 μm straightness

Gaussian profile alignment to ±15% of rms size (45 μm at 255 GeV)

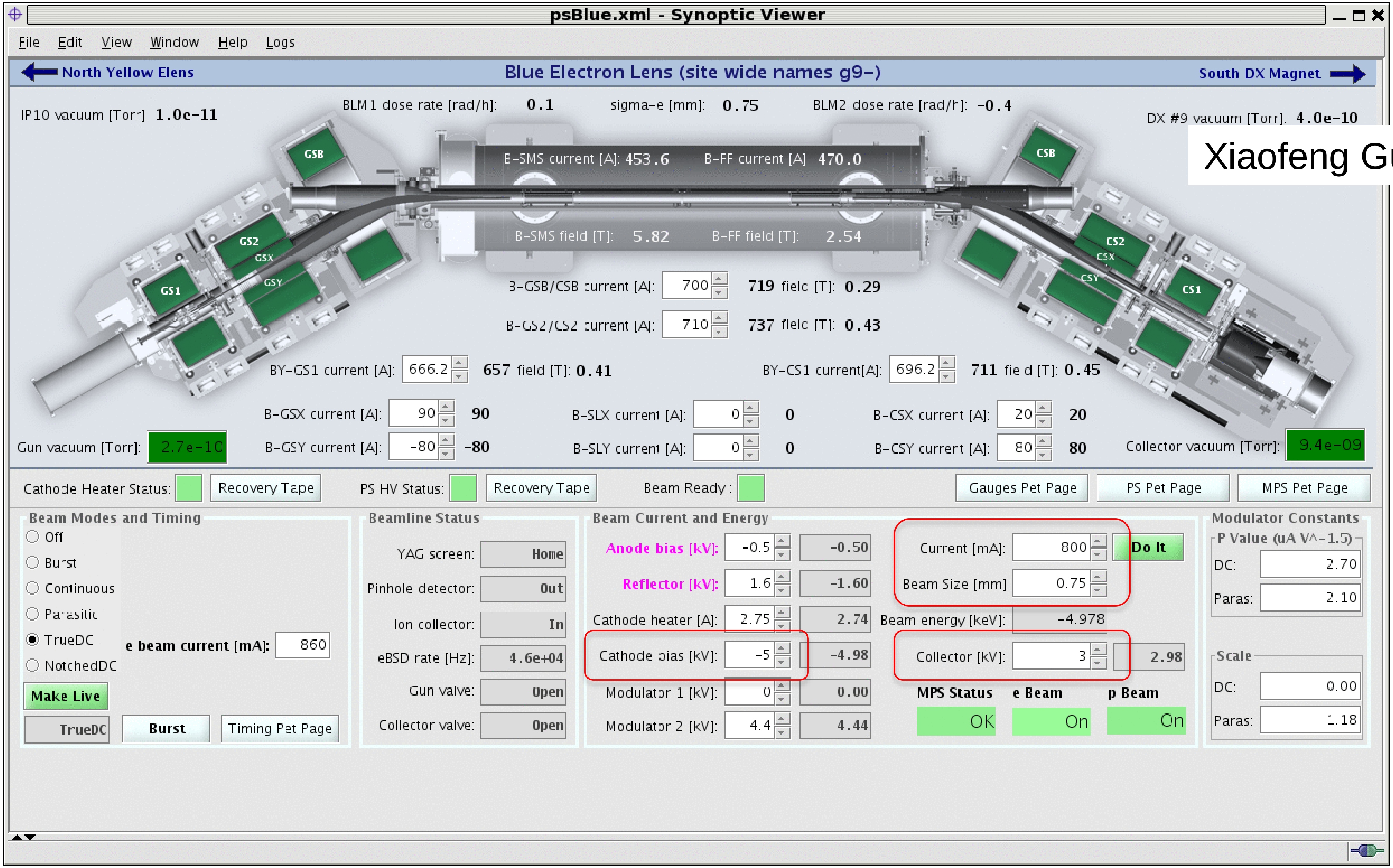
$\Delta I_e/I_e \leq 0.1\%$

Technology sources: Tevatron e-lenses, RHIC EBIS

RHIC electron lens

Operational control

Xiaofeng Gu



Operational turn-on by sequencer. Synoptic display for control,.

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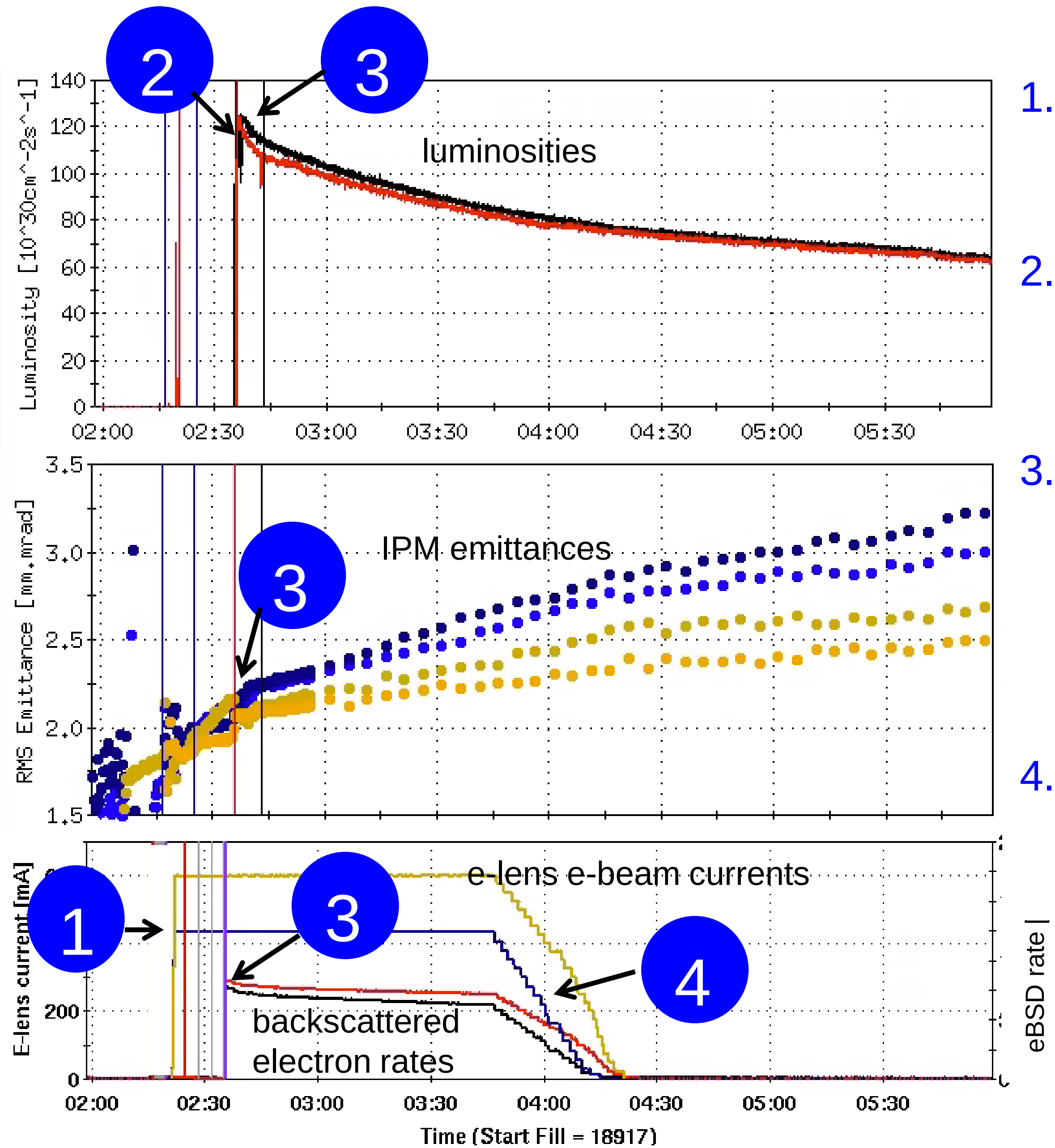
e-lenses in operation with collisions at 2 experiments



1. e-lenses turn on before collision
   (112 stores with both lenses without a single turn-on failure)
2. Beams into collision at PHENIX, collimators to store positions
   (requires PHENIX collisions)
3. Beams into collision at STAR and e-lenses
   e-lenses prevent emittance growth and/or beam loss for large beam-beam param. ξ
4. Lenses are gradually turned off when lattice alone can sustain bb parameter ξ

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Operational reliability

Commissioning with Au beam in 2014

- commissioning in parallel to Au+Au operation,
  using last bunch(es) in train
- a few instances with large vacuum excursions, ~2 stores terminated
- a few instances with emittance growth, including solenoid quenches, recoverable with stochastic cooling

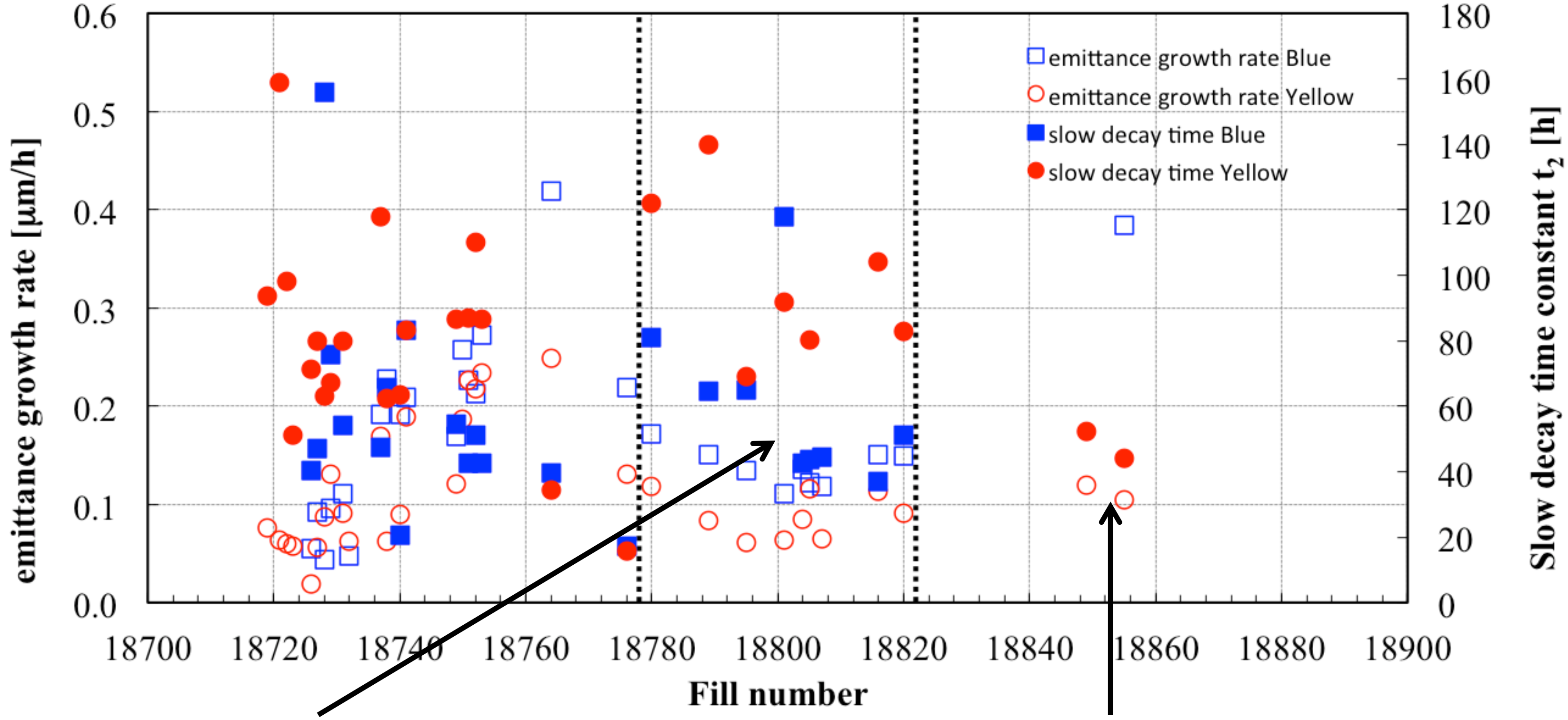
Operation with polarized p beam in 2015

- after commissioning 112 of 156 p+p stores used both lenses
- no turn on failure, no store aborted due to equipment failure
- some stores aborted shortly after going into collision,
  after reducing e-beam size
- typical e-lens on-time ~1-1.5 h
- a few stores negatively affected by Blue e-lens e-beam instability (observed for I_e > 500 mA), terminated early

Additional emittance growth and loss rates from e-lens

E-lens in operation typically on for ~1h.

Tested additional emittance growth and loss in Yellow with 2 stores (6.75 h, 5.25 h long).



- 8 good stores, e-lenses on for ~1 h
- Yellow emittance growth ~0.1 μm/h
- Yellow intensity decay time ~90 h
  [loss rate ≤1%/h]

- e-lenses on for 6.75, 5.25 h
- Yellow emittance growth ~0.1 μm/h
- Yellow intensity decay time ~50 h
  [loss rate 2.5%/h]

When not limited by beam-beam there is no additional emittance growth from the Yellow lens (400 mA), additional losses of 1−2%/h.

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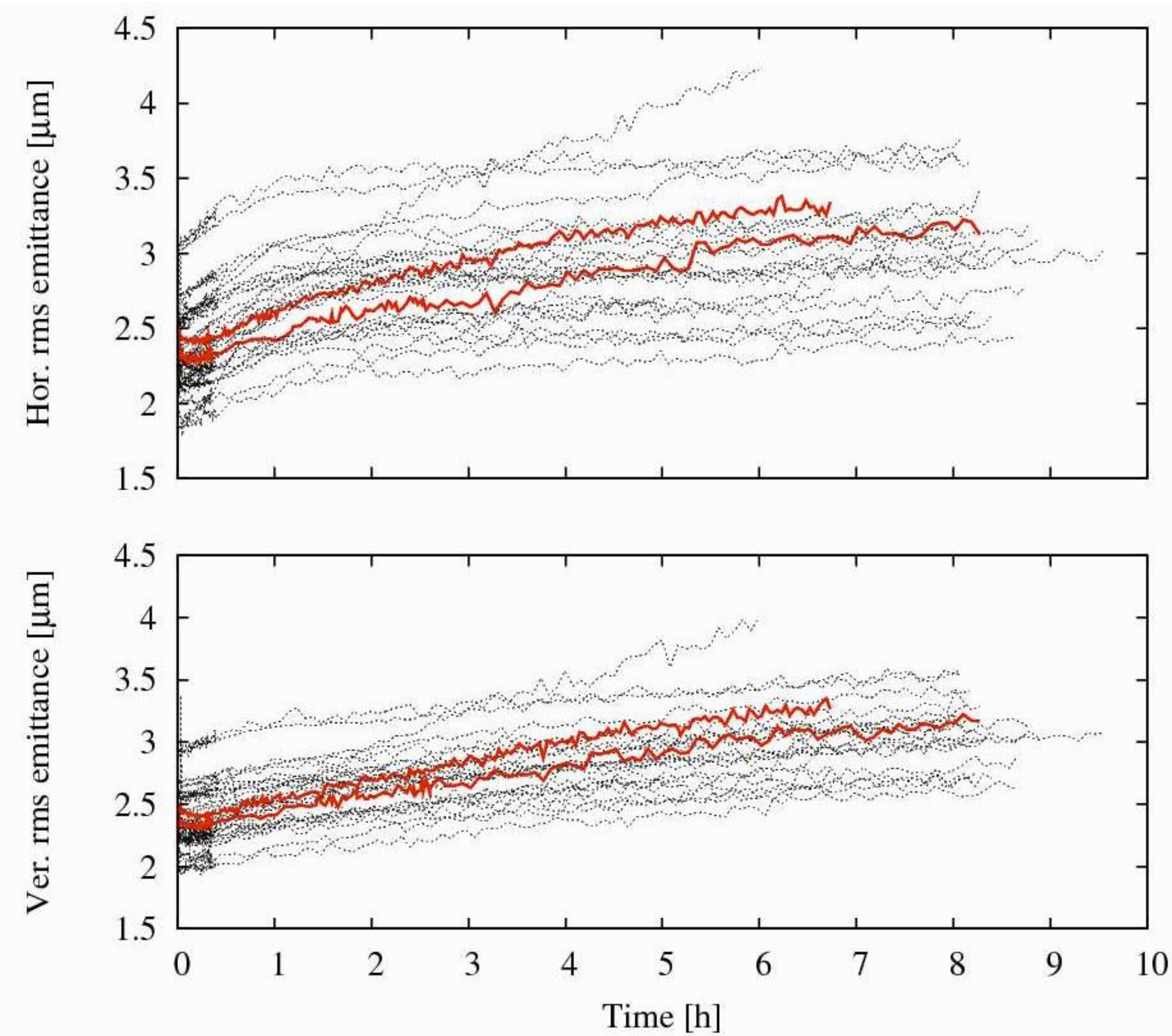
Effect on emittance growth



The plot shows the Yellow horizontal and vertical emittances, as measured by the Ionization Profile Monitor (IPM) for stores 18794 to 18857 in red.

Of the 35 stores shown, stores 18849 and 18855 had the Yellow electron lens on for 6.75 and 5.28 h respectively. For all other stores, the Yellow electron lens was on between 0.45 h and 1.83 h.

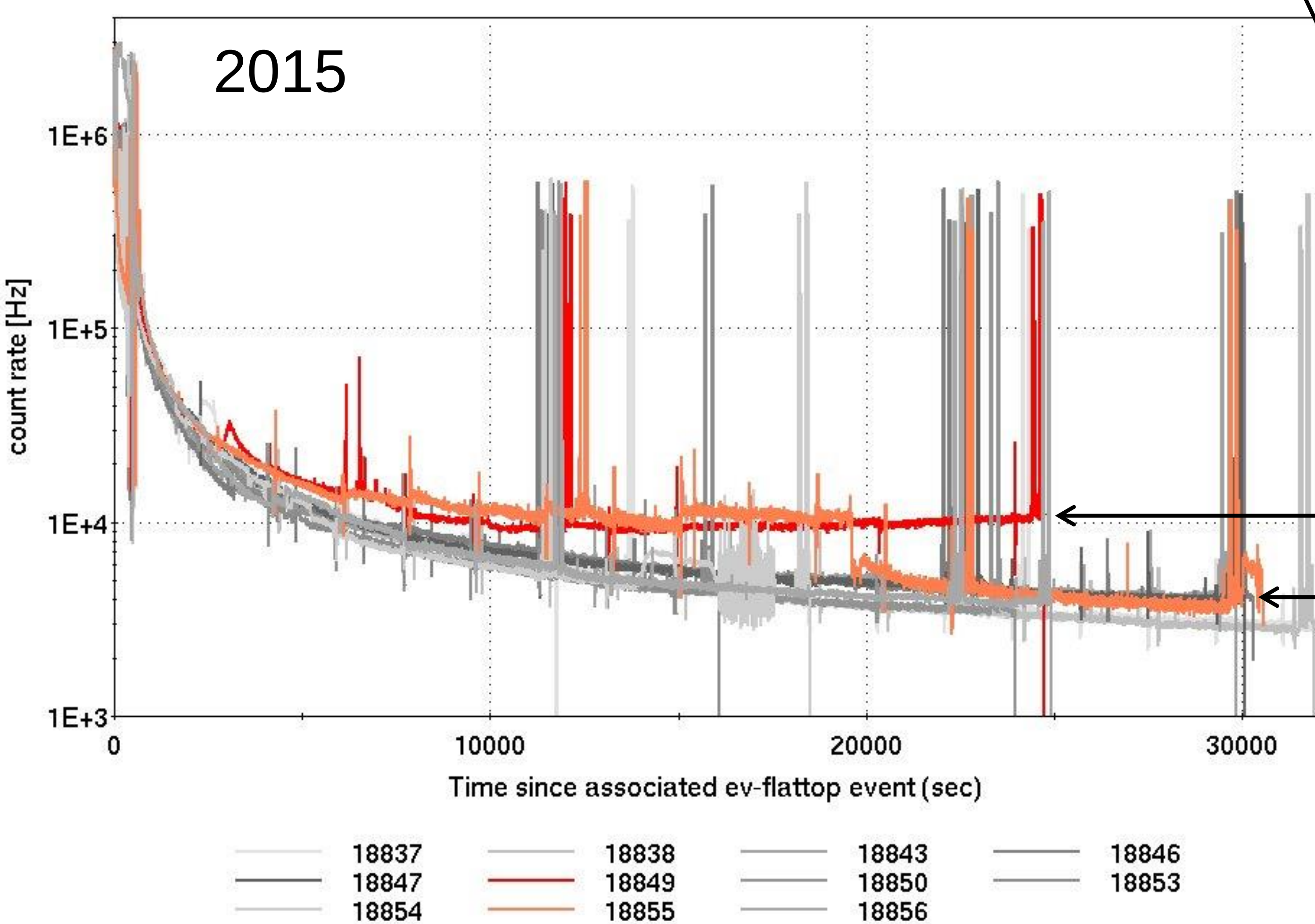
The time period for the selection of stores ends when the spin direction in the STAR experiment was changed from vertical to longitudinal. After a configuration change there may be transition effects, which we would like to exclude.

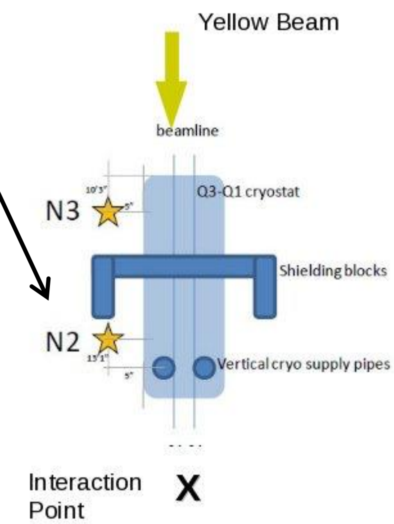
The time-dependent emittances for the two stores with significantly longer e-lens on-times are within the distribution of all stores.

RHIC e-lenses Effect on experimental background (I)

A. Drees

- Background signal: PHENIX North scintillator N2



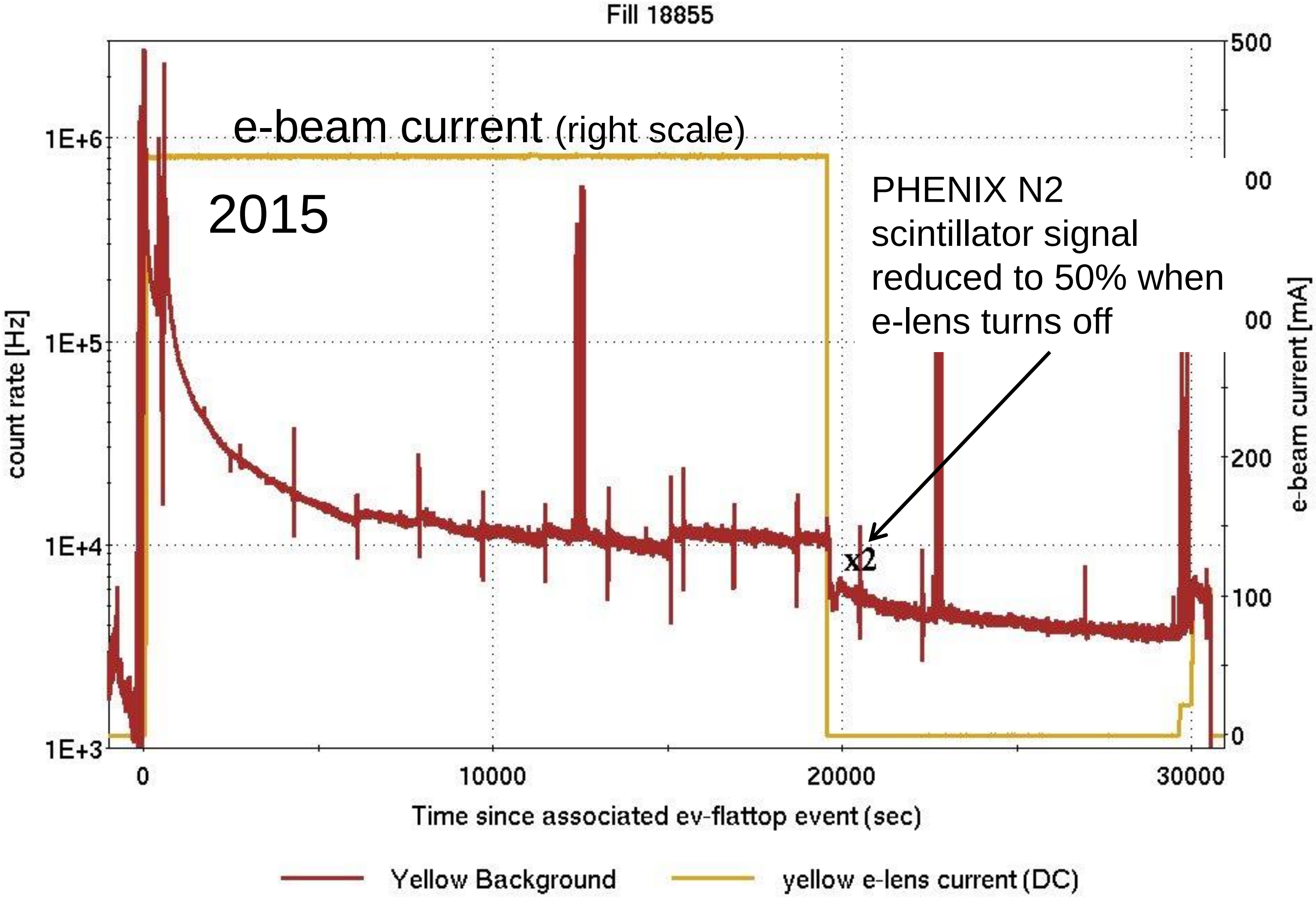


e-lens on ~6h
(N2 acceptable)

e-lens on ~1.5h
(N2 ~3x lower after 7h)

RHIC e-lenses Effect on experimental background (II)

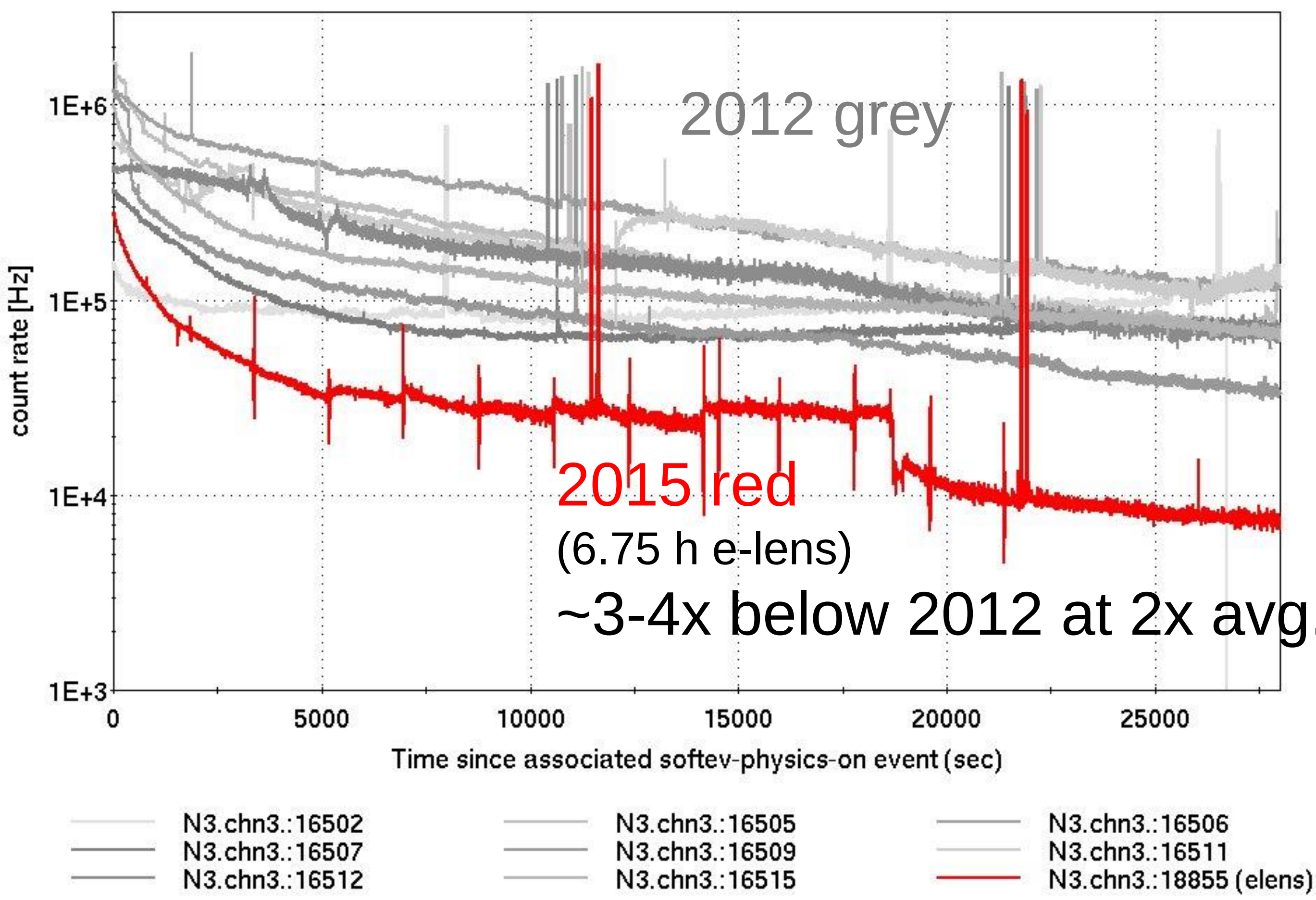
A. Drees

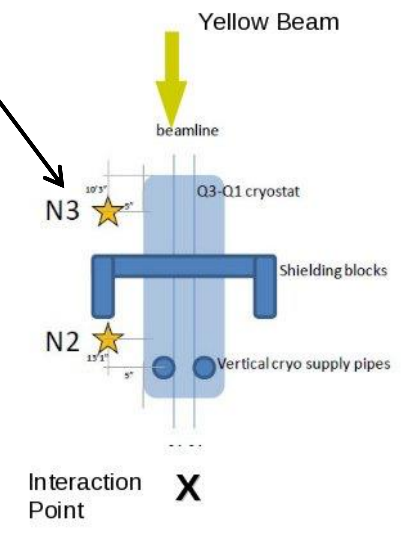


Effect on experimental background (III)

A. Drees

- Background signal: PHENIX North scintillator N3

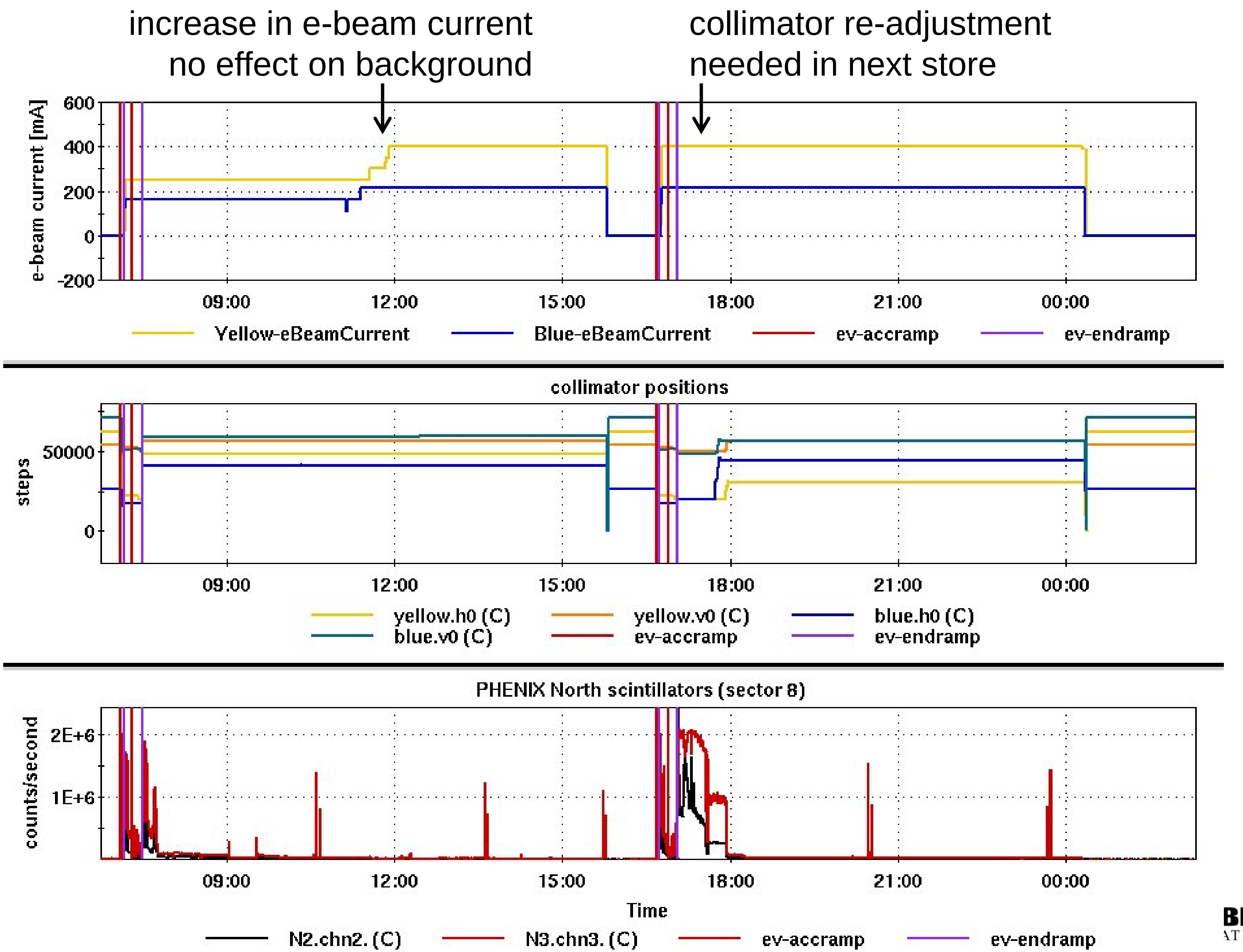




Effect on collimation

Operational collimator setup with e-lenses, not a lot of comparison data.

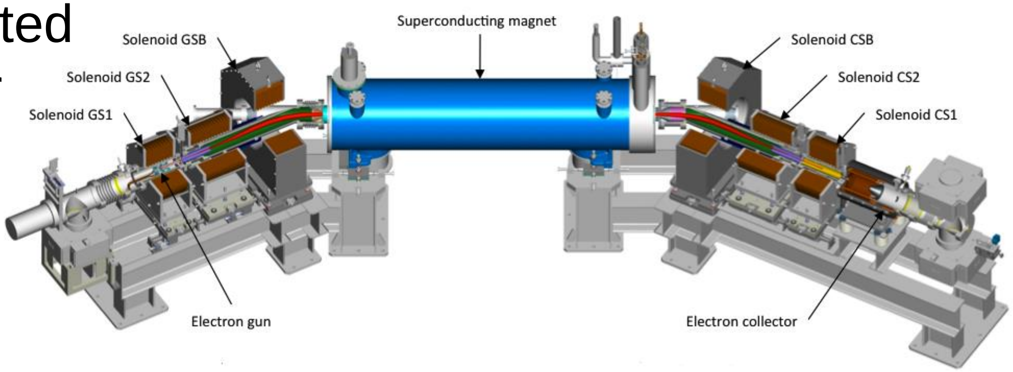
A. Drees



Summary

- 2014: e-beam commissioning with Au+Au beam (stochastically cooled)
- 2015: operational head-on beam-beam compensation with p+p

- No turn-on failure, no abort due to equipment failure (112 stores)
- Effect on proton beam
  - beam loss rate increase: 1−2%/h
  - emittance growth: long e-lens on-time within distribution of typical stores
    typical stores 1−1.5 h long, only 2 stores with 5.28 and 6.75 h e-lens on-time
  - experimental background: ~2−3x increase
    acceptable, still lower than 2012 with 2x higher average luminosity
- Collimator settings can be affected by e-lens parameters, like other beam parameters



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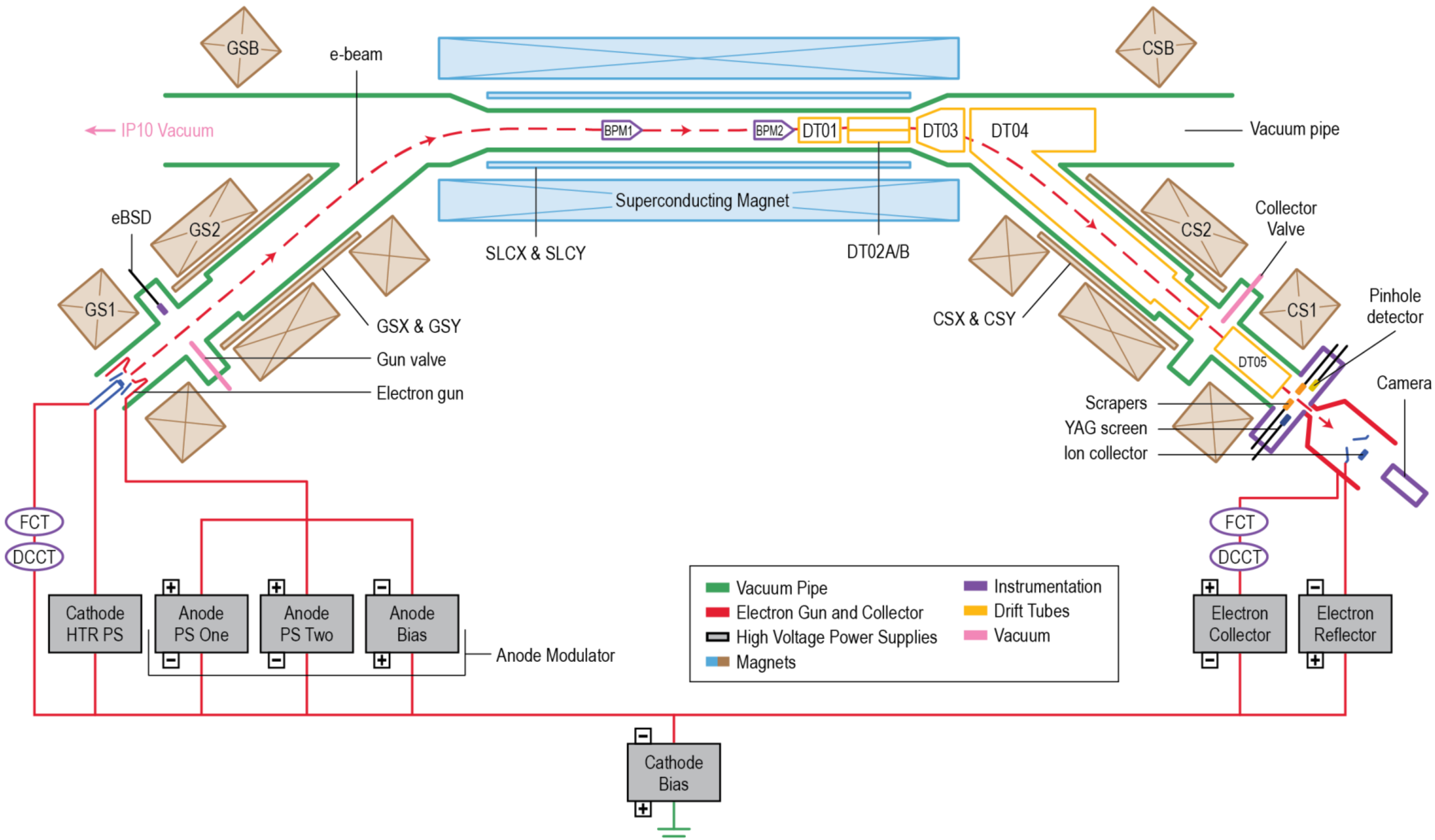
Additional material

RHIC electron lens

Layout



1 Anode-Beam Current
2 Bias-Beam Energy

3 Collector-Beam Power
4 GS1-Beam Size

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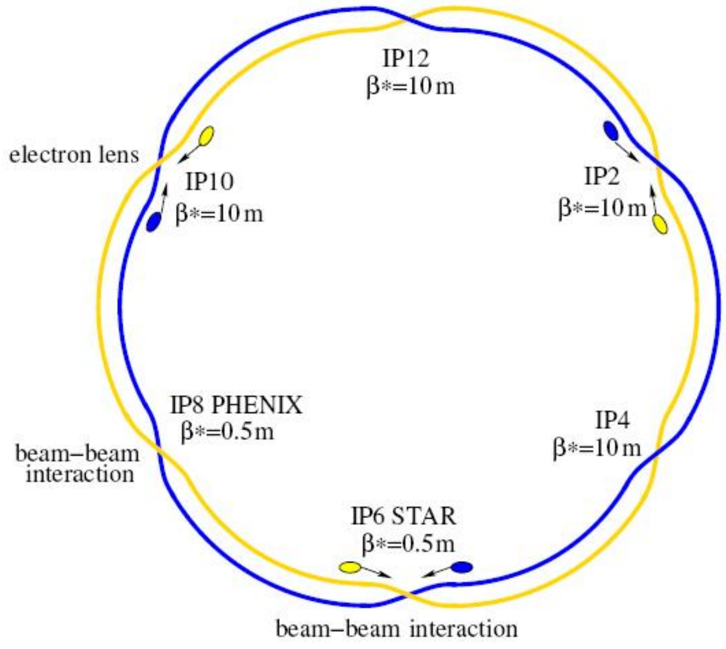
RHIC electron lenses

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
8. Allow for commissioning in parallel to physic operation

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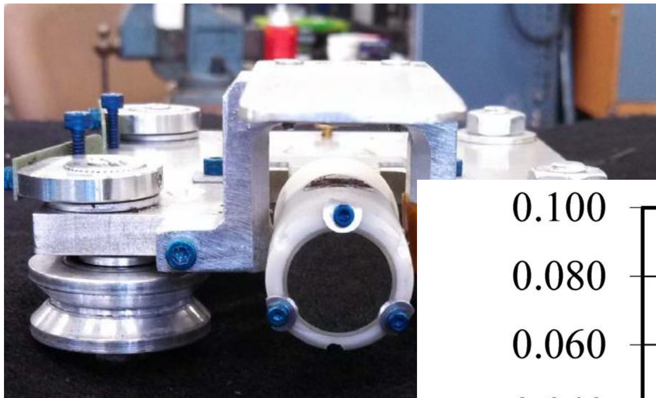
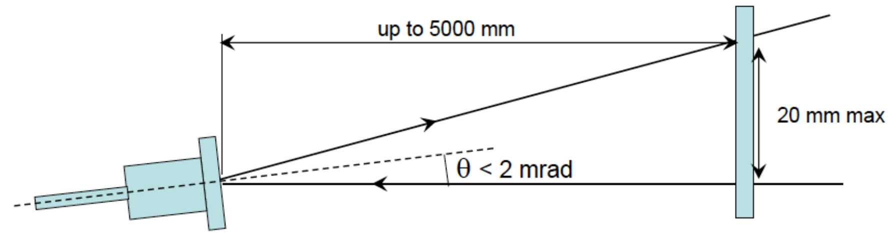
Hardware

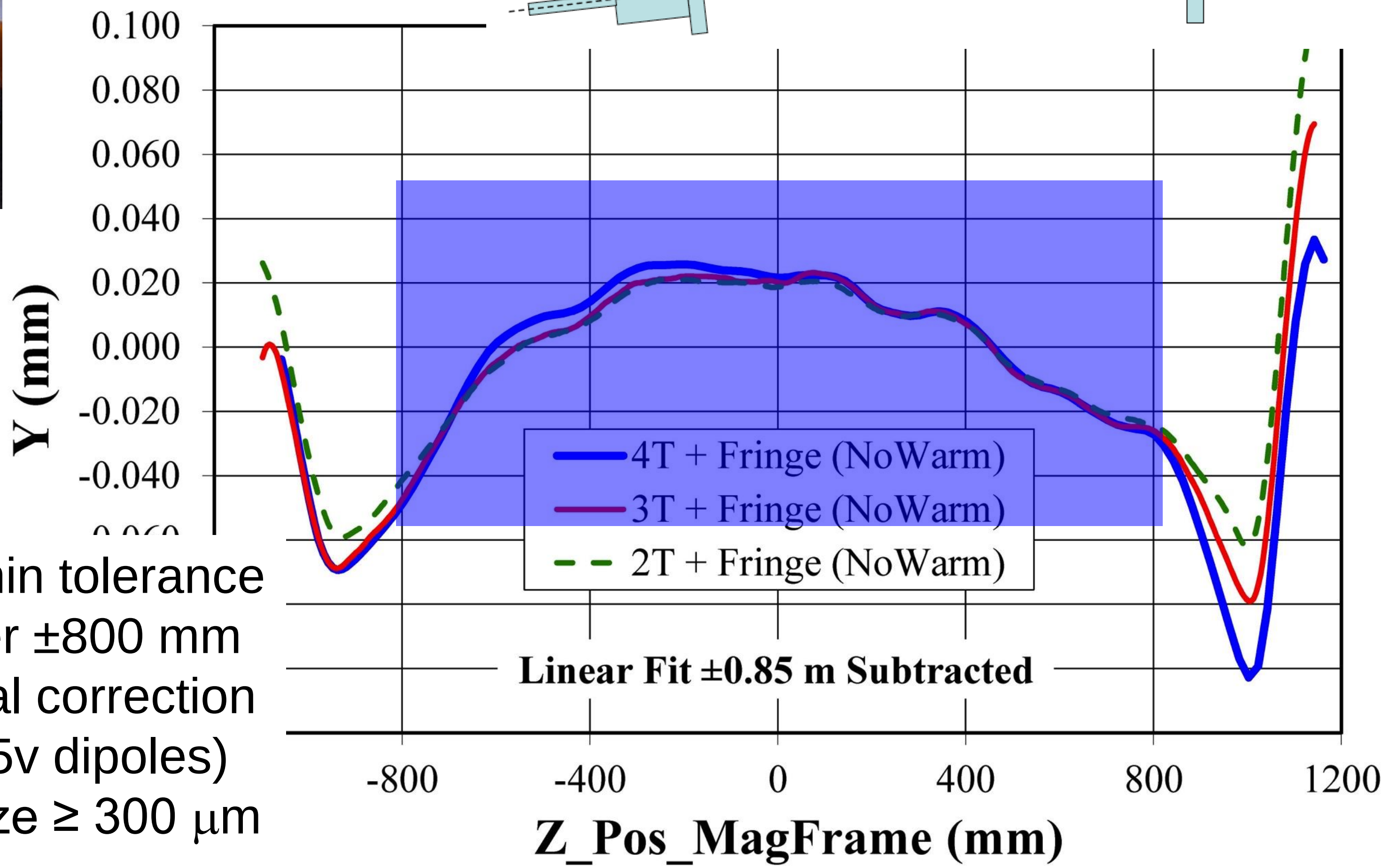
Solenoid field straightness (A. Jain)

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 beam

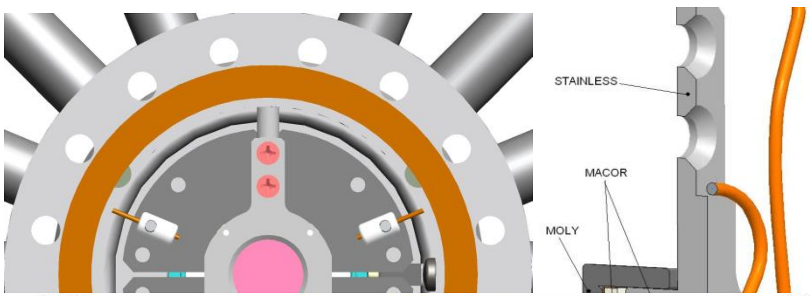
Transverse profile (I)

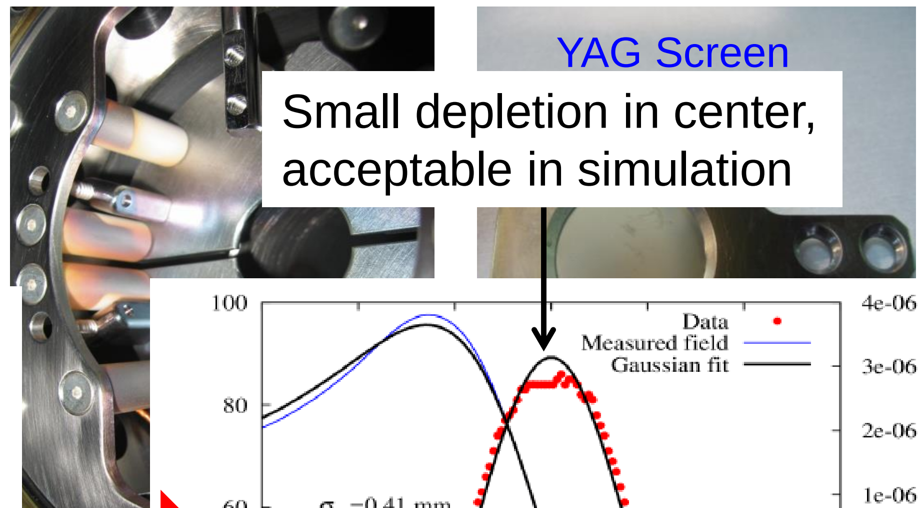
Gaussian profile critical for correction of nonlinear effects

2 devices for transverse profile measurement:

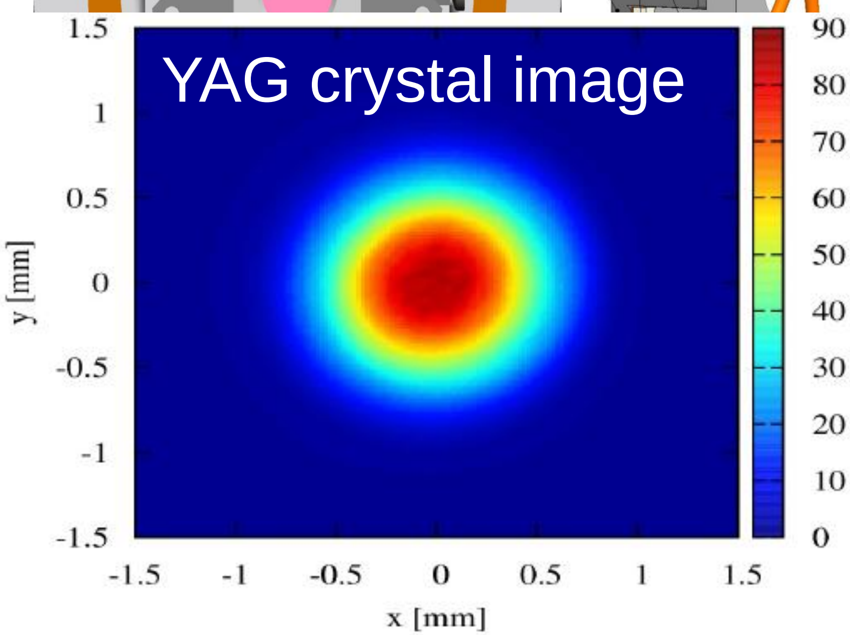
Xiaofeng Gu

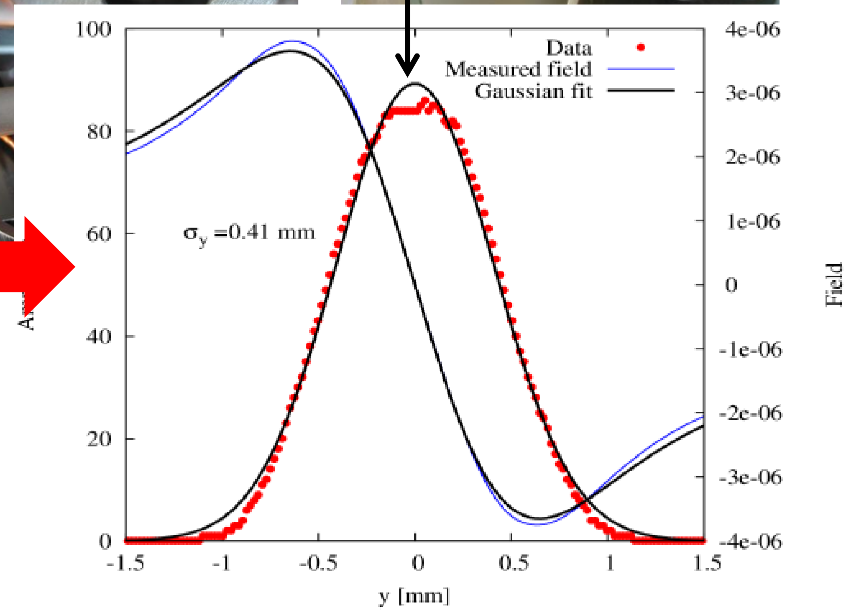
- YAG screen
- pinhole detector





Small depletion in center, acceptable in simulation

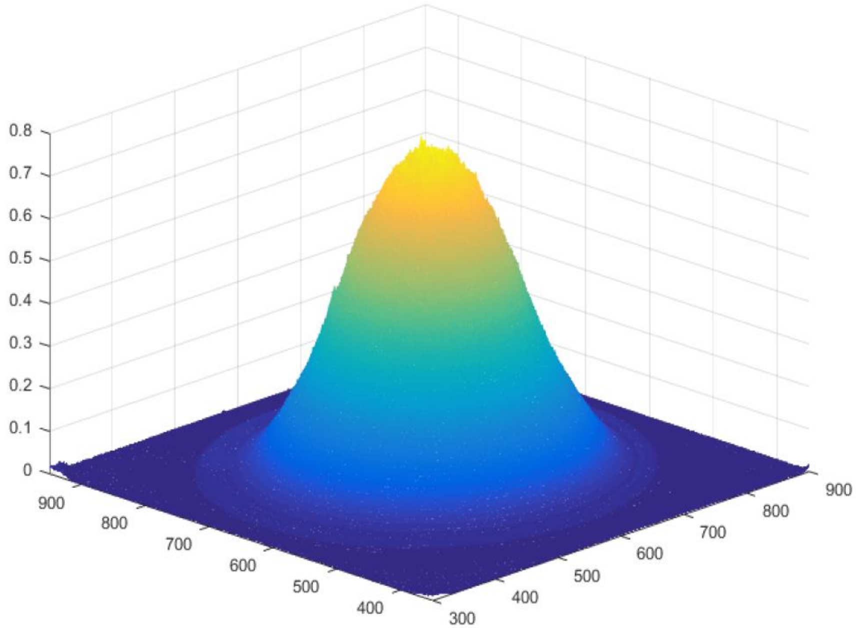




Electron beam

Transverse profile (II)

Xiaofeng Gu



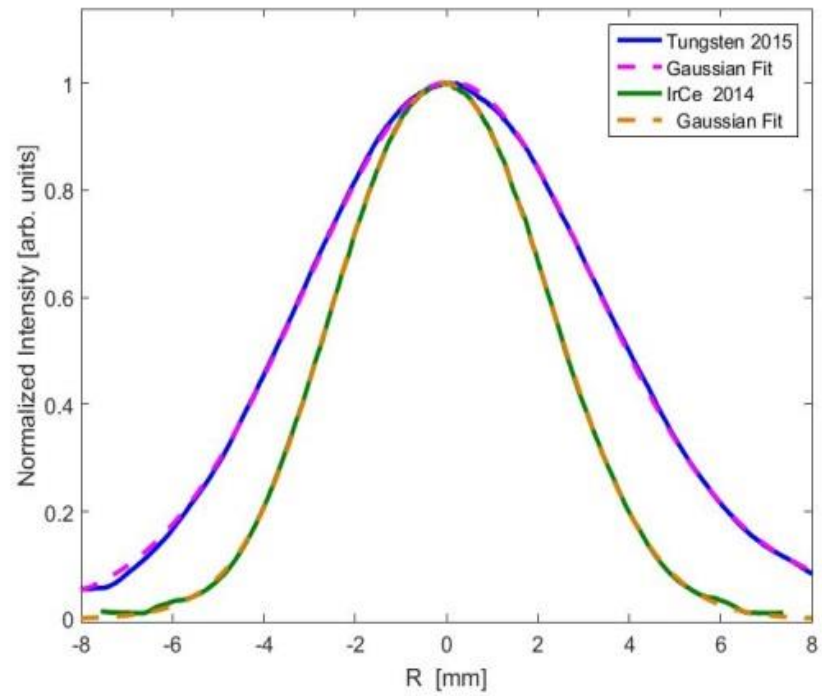


Fig. 5 shows electron beam profiles and their Gaussian fits for the IrCe cathode and the tungsten dispenser cathode, measured using a YAG screen near the collector. The measured profiles were fitted to Gaussian distributions with the coefficient of determination R^2 of 0.9995 and 0.9999 respectively. The measured cathode radius to rms beam size ratio r/σ was 2.8 for the IrCe and 2.7 for the tungsten cathode, while the designed value was 2.8.

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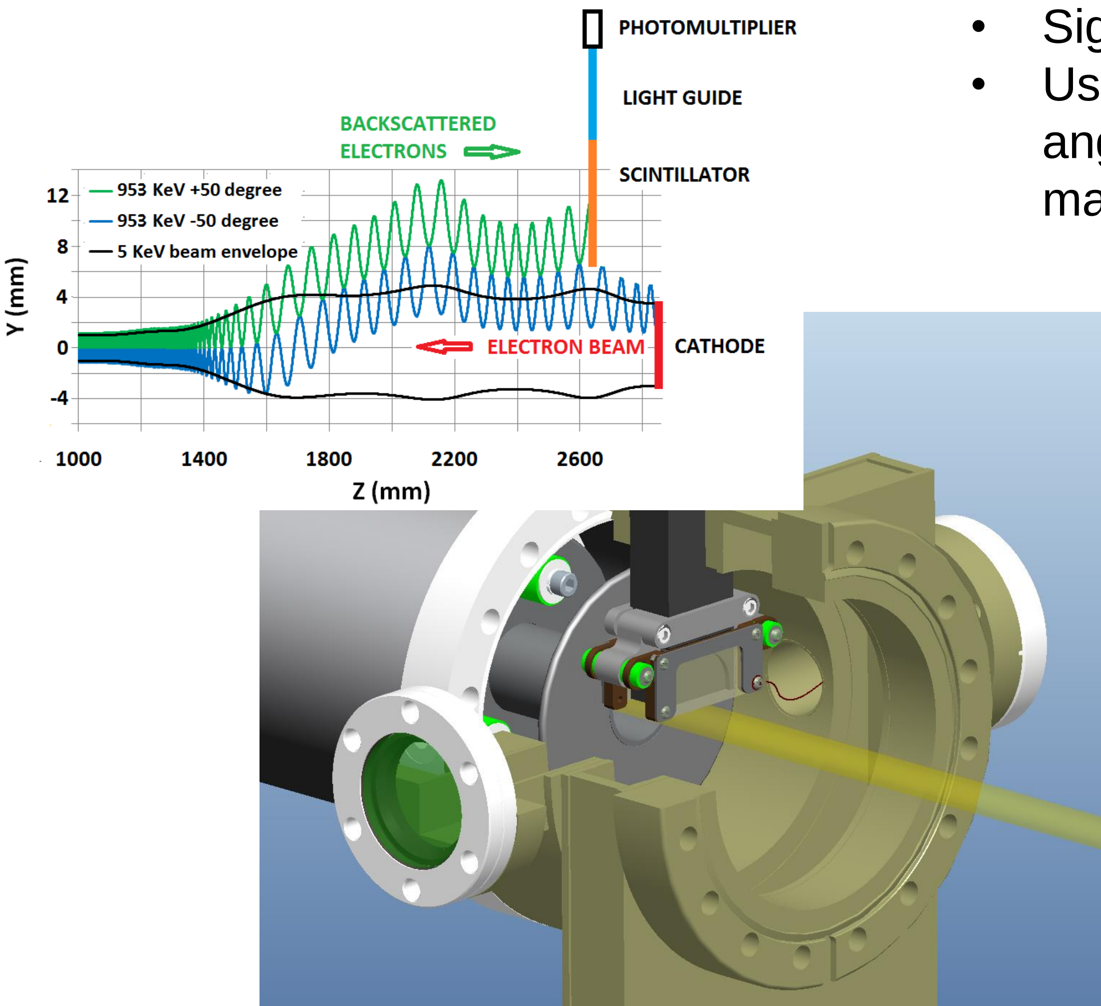
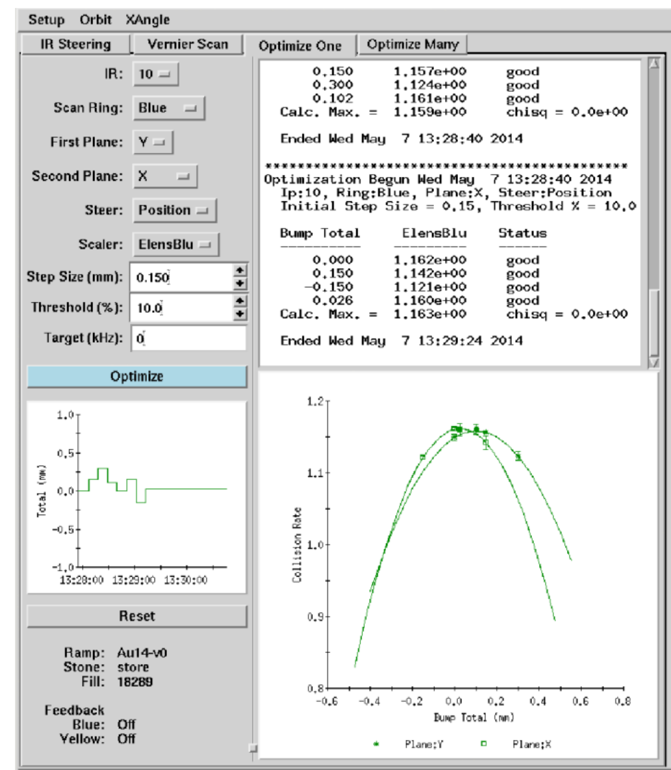
Transverse alignment

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 [PRAB 19, 041002 (2016)]



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

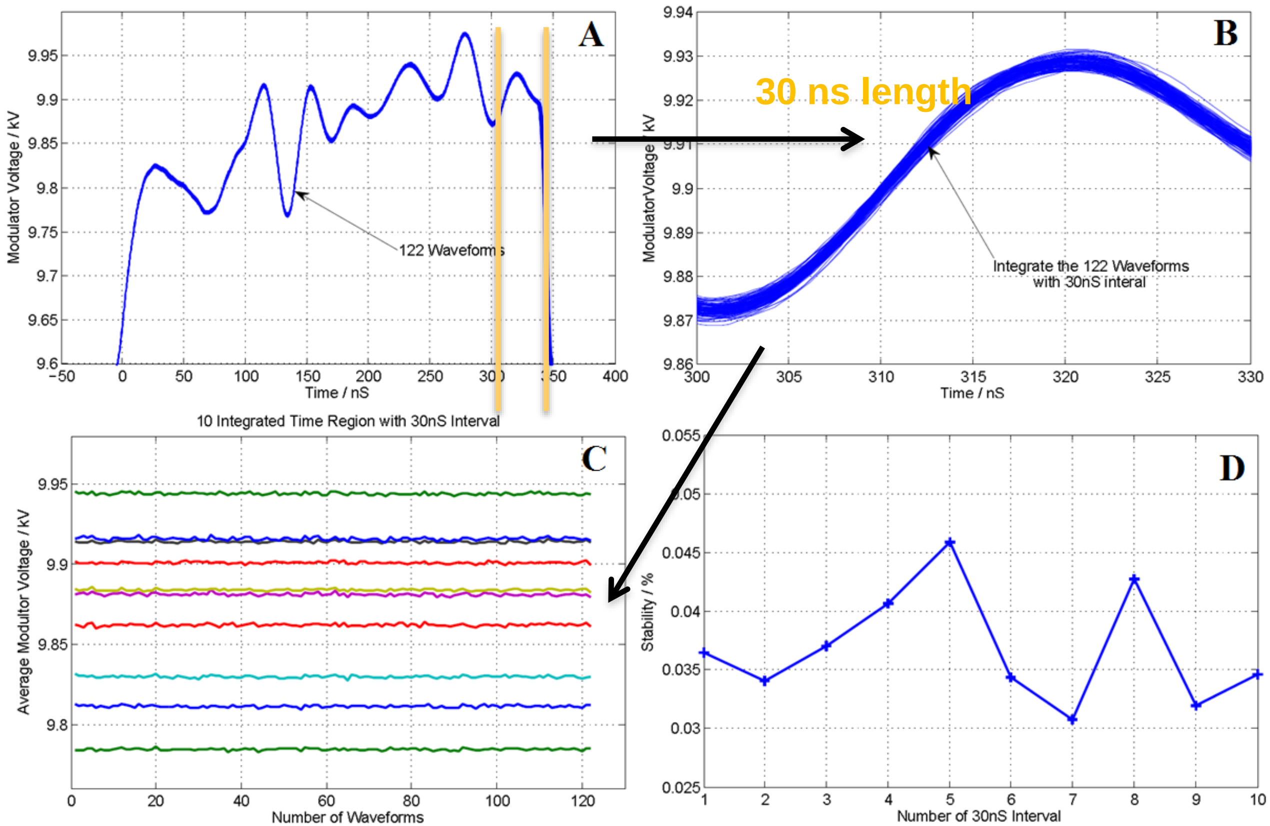


Electron beam

Current ripple

A stable DC electron beam current of 0.9 A with a turn-to-turn ripple of ≤0.1%

Xiaofeng Gu



1. **Ripple is less than 0.075%;**
2. Measured anode voltage via 78 kHz pulse mode, which the pulse itself has more noise than DC;
3. Took 122 waveforms. Each waveform is divided to 10 intervals with 30 ns length;
4. Average each 122 waveforms for these ten intervals; The total force seen from e-beam;
5. Change voltage ripple to current ripples with 1.5 times;
6. Current is **950 mA**

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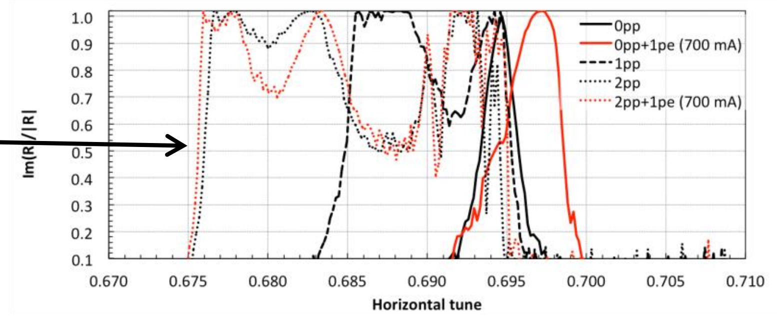
Head-on bb compensation

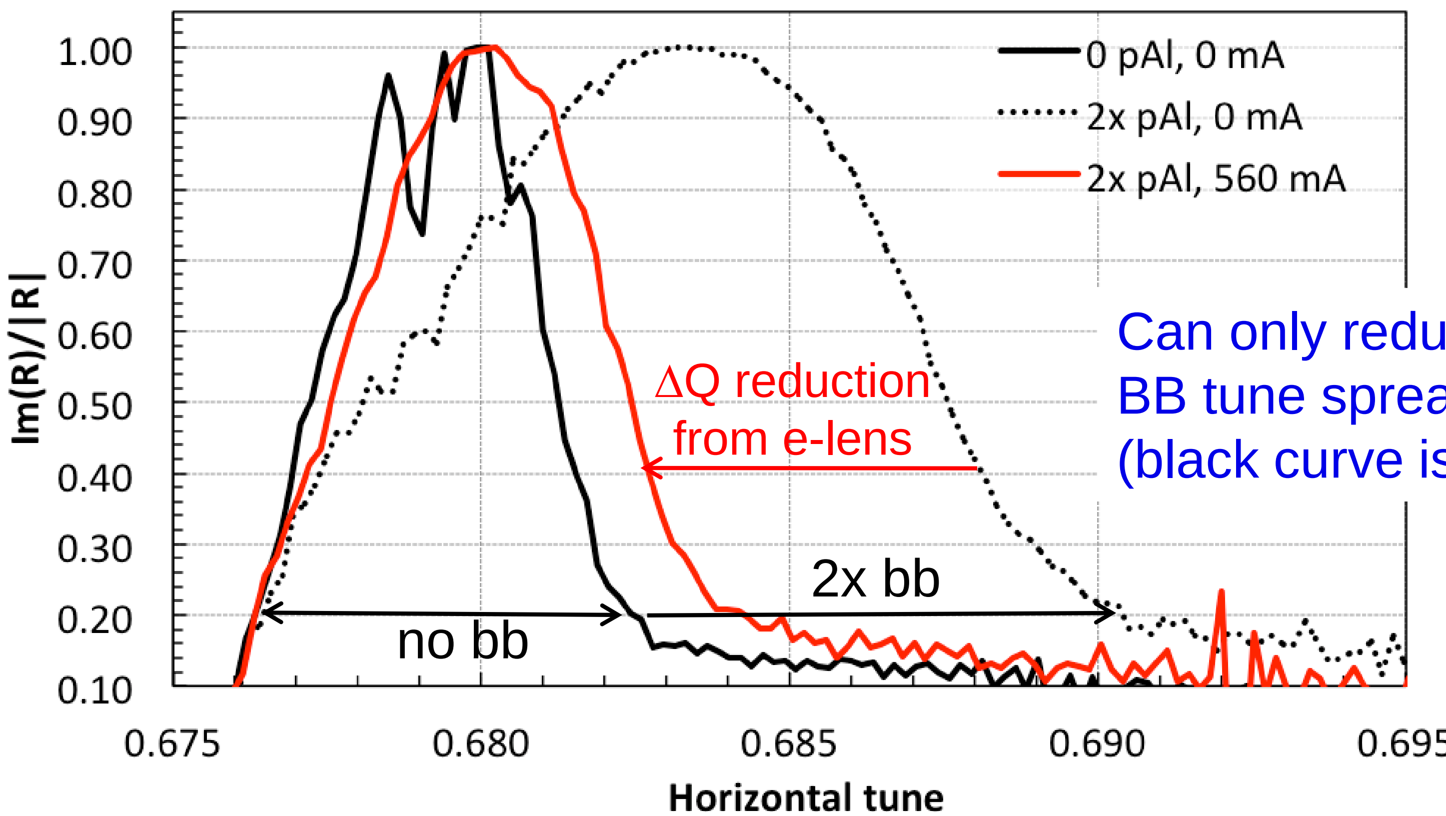
Footprint compression

tune distribution could not be measured with BTF and p+p collisions due to coherent modes
(works in simulations – P. Görgen et al. NIM A 777, pp. 43-53 (2015))



tune distribution can be measured with BTF and p+Al collisions

proton beam: (Q_x,Q_y) = (.685,.695); Al beam: (Q_x,Q_y) = (.685,.695); ΔQ_x, ΔQ_y >> ξ => no coherent modes

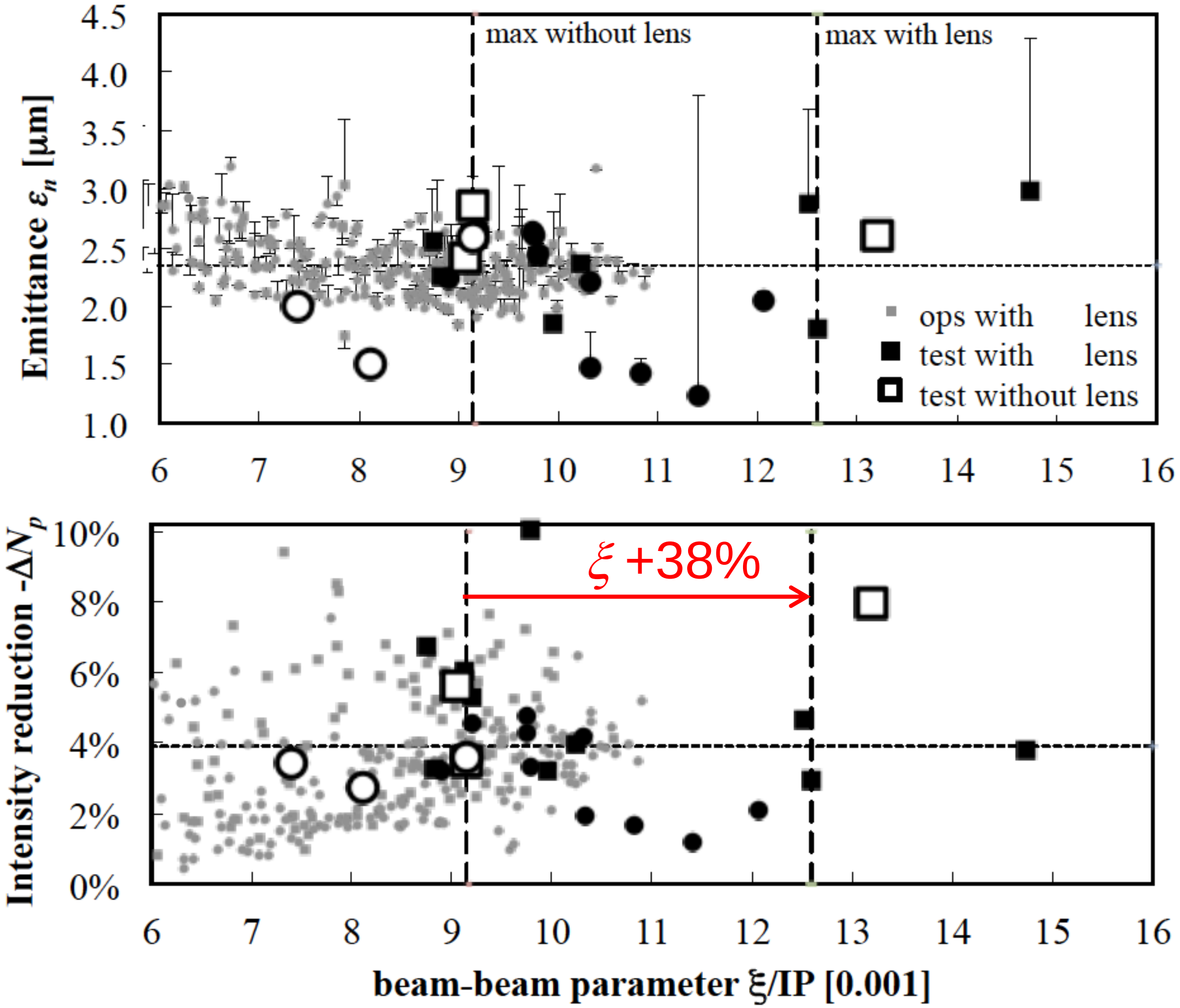


Can only reduced BB tune spread (black curve is limit)

Head-on bb compensation

increase in bb parameter ξ with lens

Initial emittance and 5 min later, beam loss over 5 min



ops: 111 bunches

tests: 30/48 bunches

=> higher intensity and brightness

Note: It is possible that higher beam-beam parameters ξ can demonstrated in the future, without and with lens (ξ sensitive to orbit, tune, chromaticity etc.)

Head-on bb compensation

increases in L and ξ

quantity	unit	operations (avg. over 10 best stores) 2012	2015	tests for max ξ_p without e-lens	with e-lens	with e-lens
		2012	2015	— 2015 —		
bunch intensity N_p	10^{11}	1.6	2.25	2.6	2.15	2.0
no of bunche k_b	...	109	111	48	111	30
$\beta^*_{x,y}$ at IP6, IP8 (p+p)	m	0.85	0.85	— 0.85 —		
$\beta^*_{x,y}$ at e-lens (p+e)	m	10.5	15.0	— 15.0 —		
lattice tunes (Q_x, Q_y)	...	(0.695,0.685)		— (0.695,0.685) —		
rms emittance ϵ_n	μm	3.3	2.8	3.5	2.4	1.9
rms beam size IP6/8 σ^*_p	μm	165	150	170	150	125
rms beam size e-lens σ_p	μm	—	630	700	645	520
rms bunch length σ_s	m	0.63	0.70	0.77	0.70	0.56
hourglass factor H	...	0.74	0.75	0.78	0.81	0.86
beam-beam param. ξ_p/IP	0.001	−5.8	−9.7	−9.1	−10.9	−12.6
# of beam-beam IPs	...	2	2+1*	2	2+1*	2+1*
luminosity $\mathcal{L}_{peak}$	10^{30}cm^{-2}s^{-1}	46	115	72	115	40
luminosity $\mathcal{L}_{avg}$	10^{30}cm^{-2}s^{-1}	33	63	—	—	—

ξ +38% w/o and w/ electron lens

L_{peak} 2.5× increase

L_{avg} 1.9× increase (+66% w/o e-lens, +91% w/ e-lens)

Note: It is possible that higher beam-beam parameters ξ can demonstrated in the future, without and with lens (ξ sensitive to orbit, tune, chromaticity etc.)

[W. Fischer et al., PRL 115, 264801 (2015).]