RHIC Operation and Electron Lens Commissioning

Xiaofeng Gu

for E-lens team and CAD

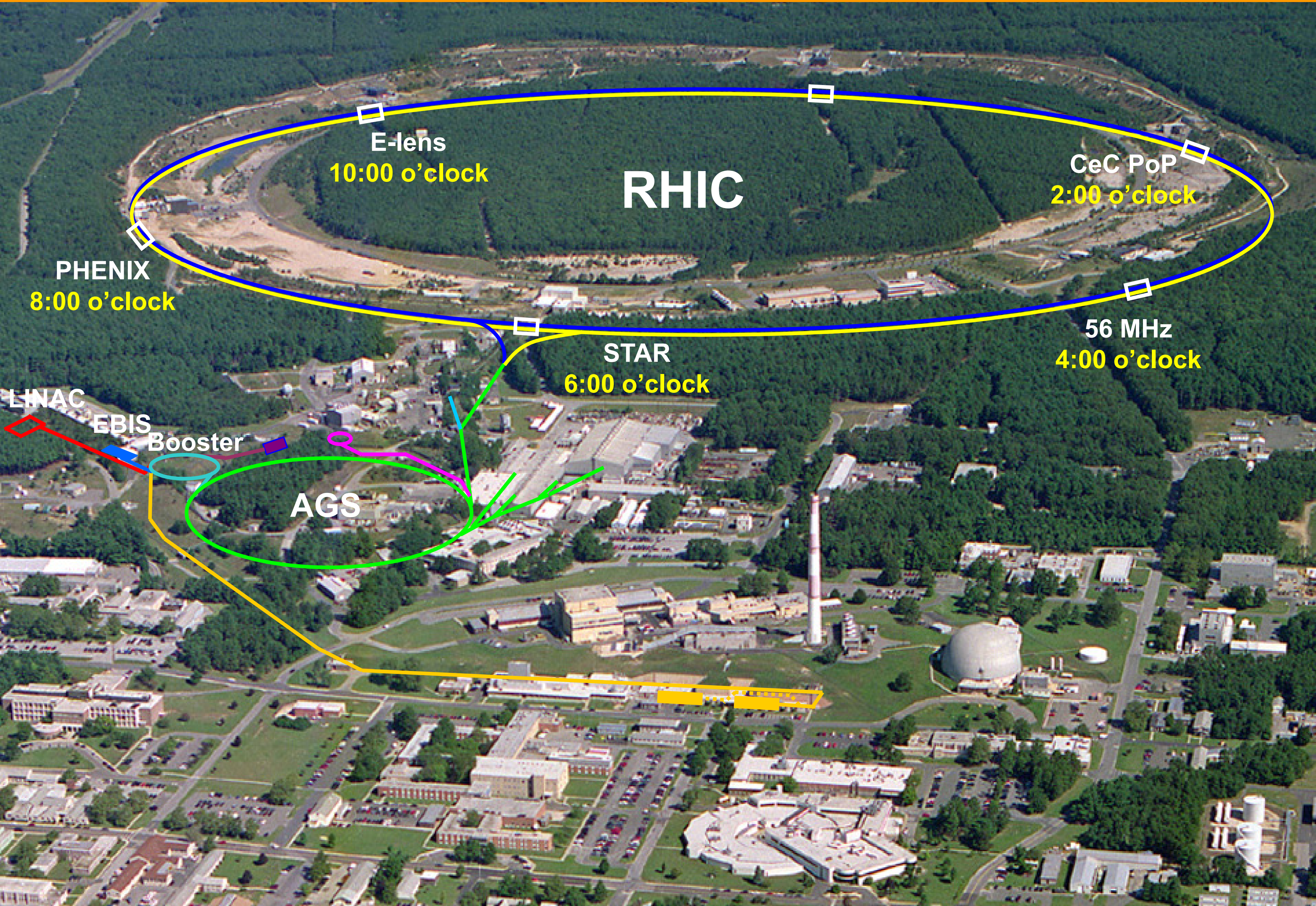
Thank the HB 2016 Committee for invitation!

July 03 ~ July 08, 2016
The 57th ICFA Advanced Beam Dynamics Workshop on High-Intensity and
High-Brightness Hadron Beams

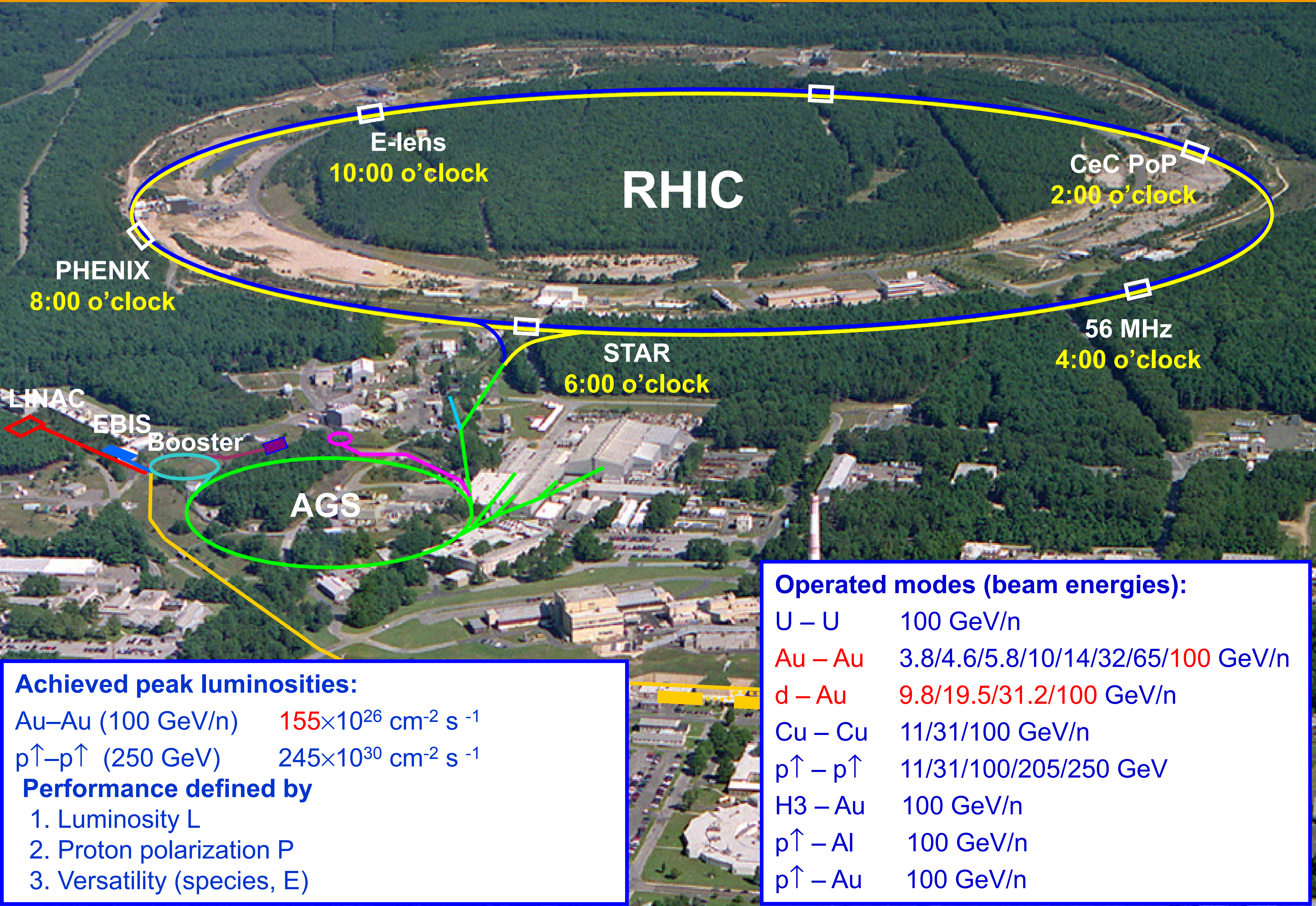
Outline

- ☐ Proton Beam Intensity
- ☐ Electron Lens introduction
- ☐ E-lens Commissioning and Operation
- ☐ Run16 Operation with Au-Au
- ☐ Summary

RHIC – a High Luminosity (Polarized) Hadron Collider



RHIC – a High Luminosity (Polarized) Hadron Collider



Achieved peak luminosities:

Au–Au (100 GeV/n)	155×10^{26} cm^{-2} s^{-1}
p↑–p↑ (250 GeV)	245×10^{30} cm^{-2} s^{-1}

Performance defined by

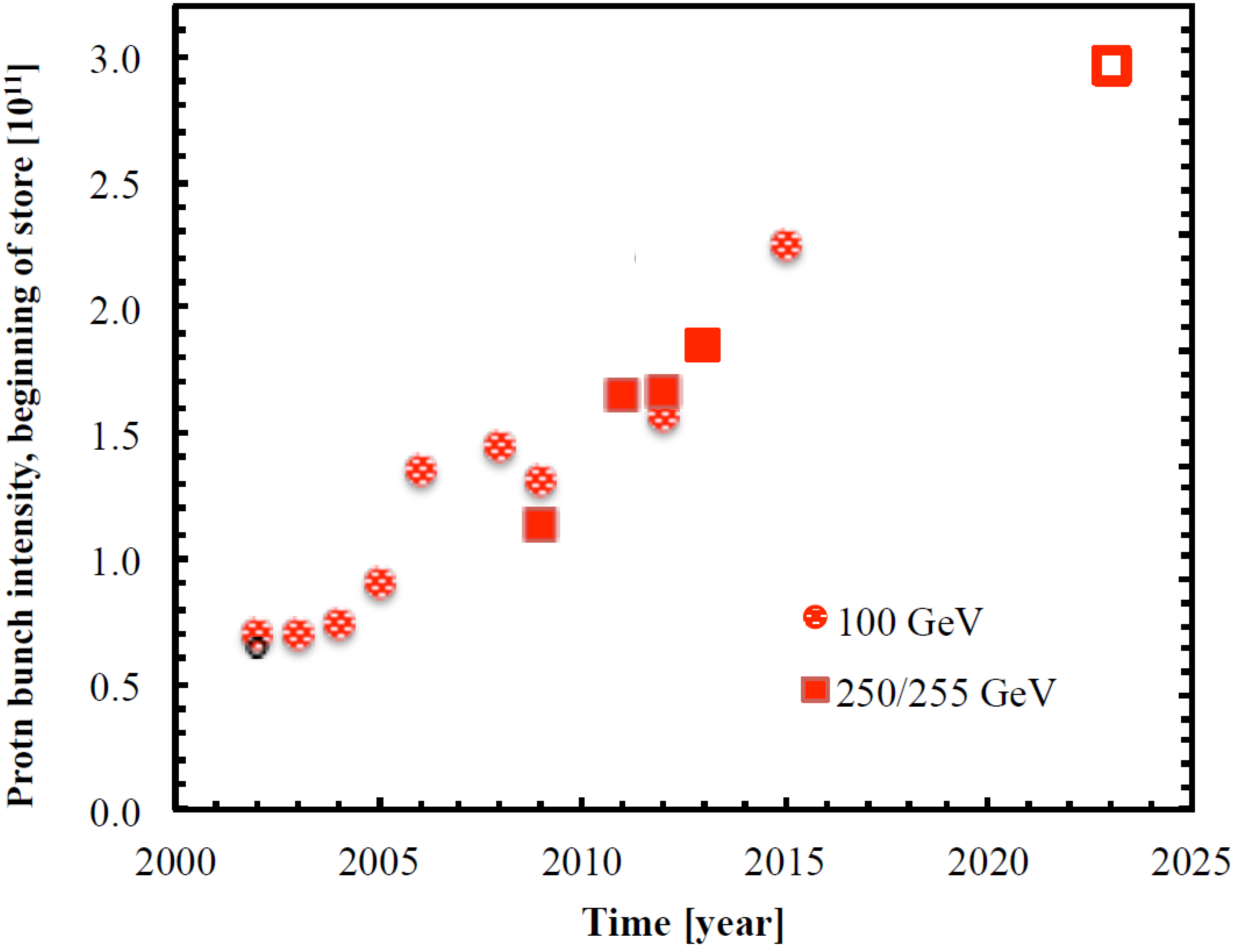
1. Luminosity L
2. Proton polarization P
3. Versatility (species, E)

Operated modes (beam energies):

U – U	100 GeV/n
Au – Au	3.8/4.6/5.8/10/14/32/65/100 GeV/n
d – Au	9.8/19.5/31.2/100 GeV/n
Cu – Cu	11/31/100 GeV/n
p↑ – p↑	11/31/100/205/250 GeV
H3 – Au	100 GeV/n
p↑ – Al	100 GeV/n
p↑ – Au	100 GeV/n

Intensity Limit during Run13 and Run15 (Polarized Proton)

$$L(t)=\frac{1}{4\pi}f_0 N\frac{N_b^2(t)}{\varepsilon(t)\beta^*(t)}h(\beta^*,\sigma_s,\theta)$$



20% more proton Intensity 2015

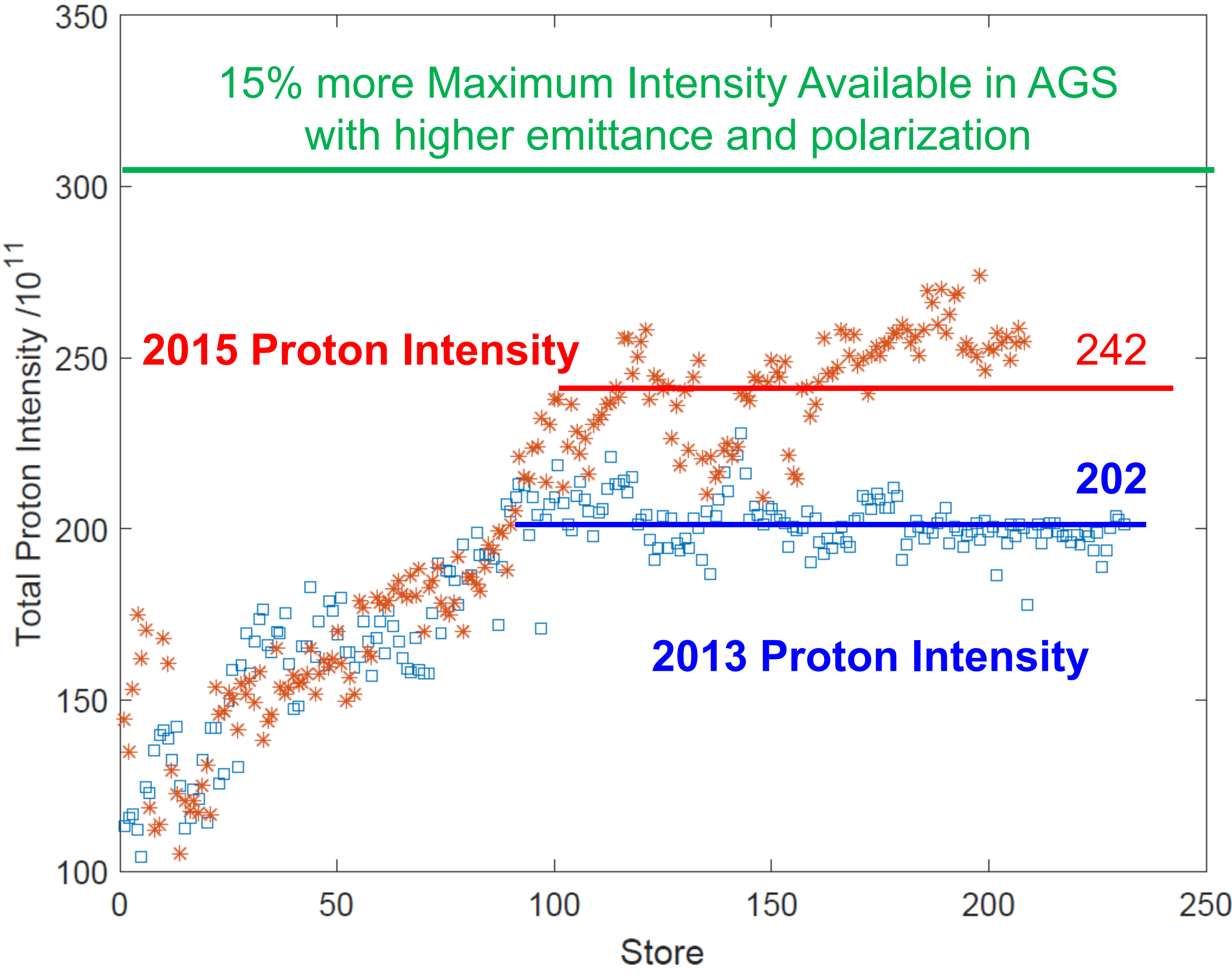
Improved by AGS + Source

15% more intensity available

Limited by AGS brightness

A. Zelenski, H. Huang,
K. Gardner, K. Zeno, RF, et al.

Intensity during Run13 and Run15 (Polarized Proton)



Was limited by RHIC during 2013

20% more proton Intensity 2015

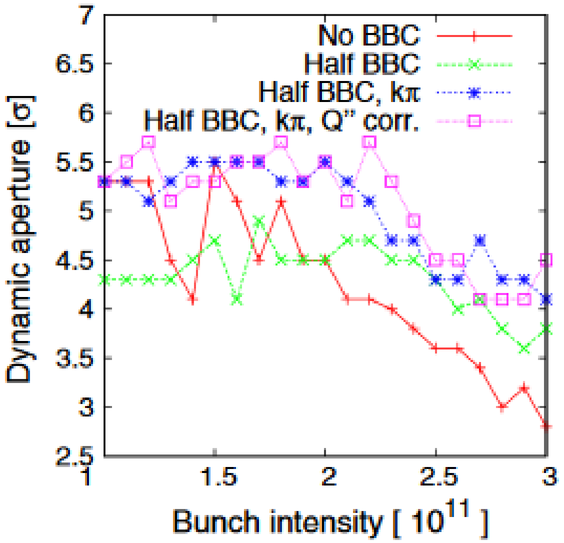
Improved by AGS + Source

This talk focuses on how to overcome this limit during 2015.

15% more intensity available

Limited by AGS brightness

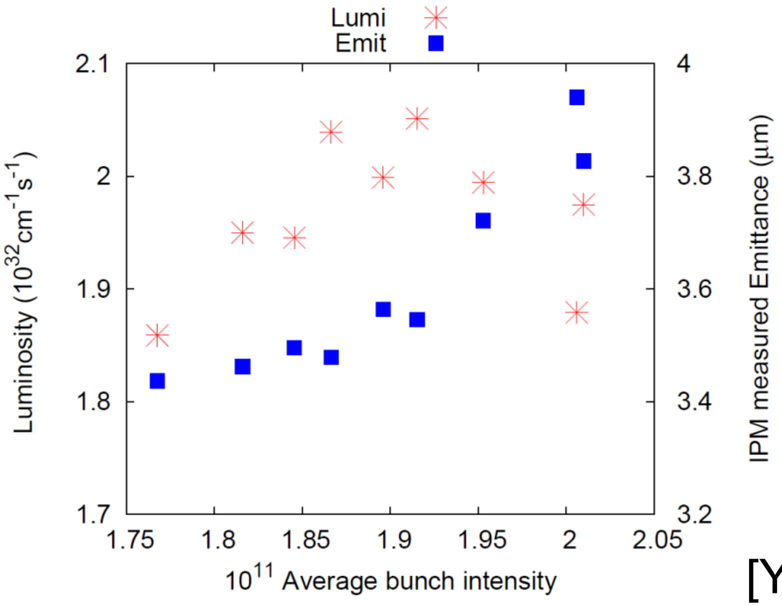
Proton Beam Intensity Limit in RHIC before Run 15



1 Beam-Beam DA Tracking:
If intensity >2.0E11, then DA is less than 4 sigma which is not good for the proton beam life time in RHIC

There was an intensity limit in RHIC before Run15.

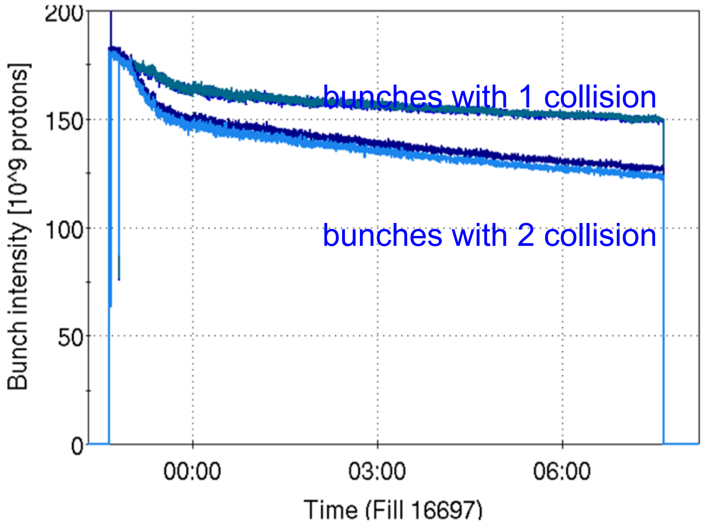
Reason?

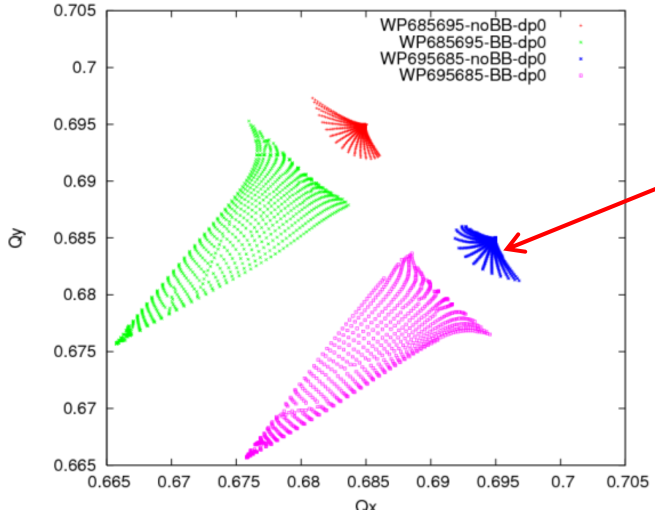


2 2013 polarized proton run:
if average intensity is greater than 2.0E11 the emittance would blow up and luminosity decreased.

[Yun Luo et al., PRAB19, 041002 (2016)]

Beam-Beam Caused Proton Intensity Limit





Reason->Beam-Beam:

1. Proton-Proton lumi is limited by beam-beam. Oncoming proton beam acts as a **nonlinear defocusing force**, leads to beam decay, emittance increase;

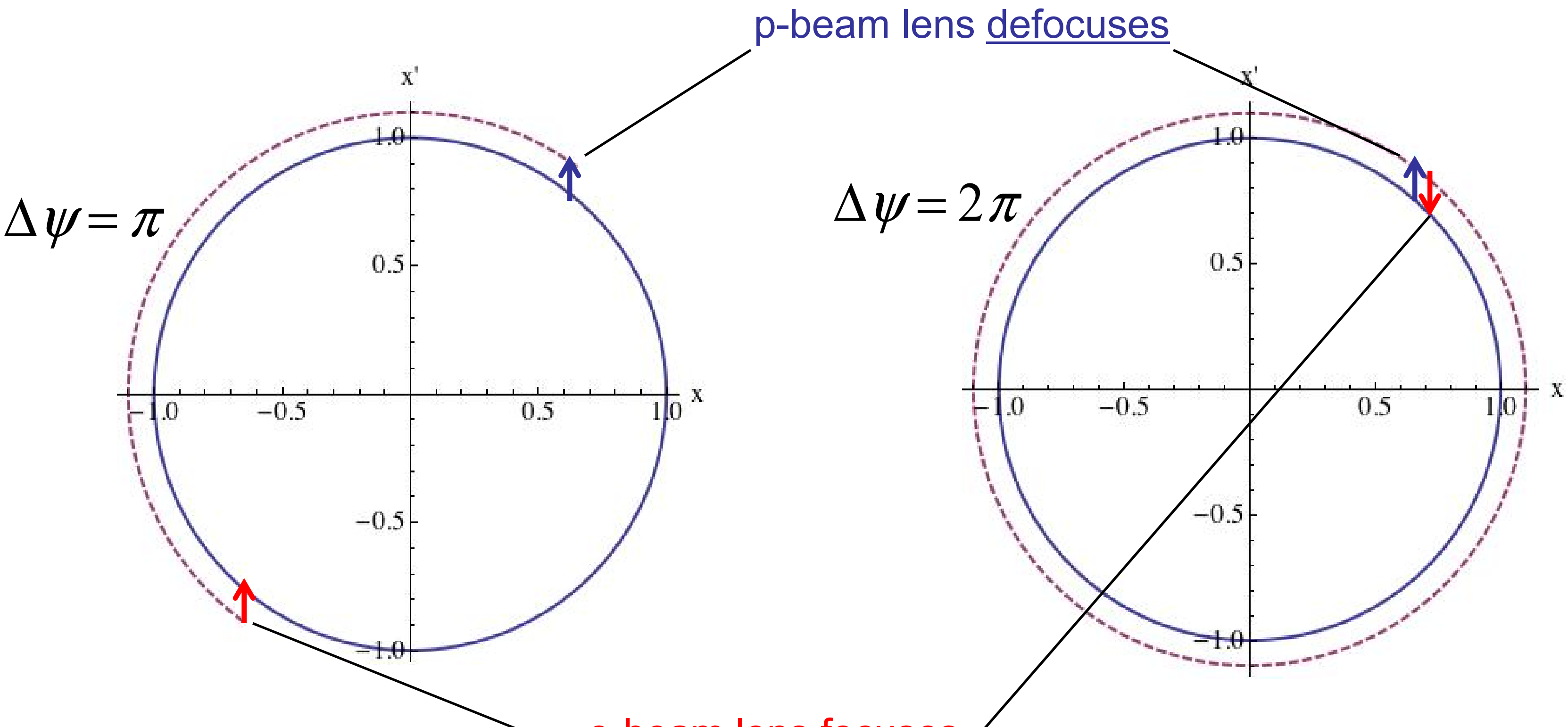
2. Bunches with 2 collision point has more beam decay comparing with 1 collision points (less beam-beam).

3. **Tune spread** with beam-beam is larger than without beam-beam effect.

Solution->Electron lenses (e-p):

Electron beams provide equal **but focusing force** to compensate for 1 of 2 beam-beam interactions (p-p), then increase bunch intensity (Luminosity)

Head-on beam-beam compensation

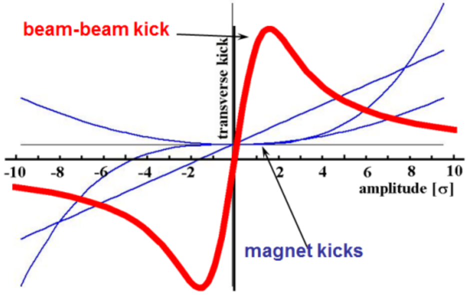


$\Delta\psi = \pi$

$\Delta\psi = 2\pi$

p-beam lens defocuses

e-beam lens focuses



1. Tune spread compensation

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

=> provided by electron lens

2. Resonance driving terms compensation

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

=> provided by lattice (new lattice in 2015, based on ATS – S. White)

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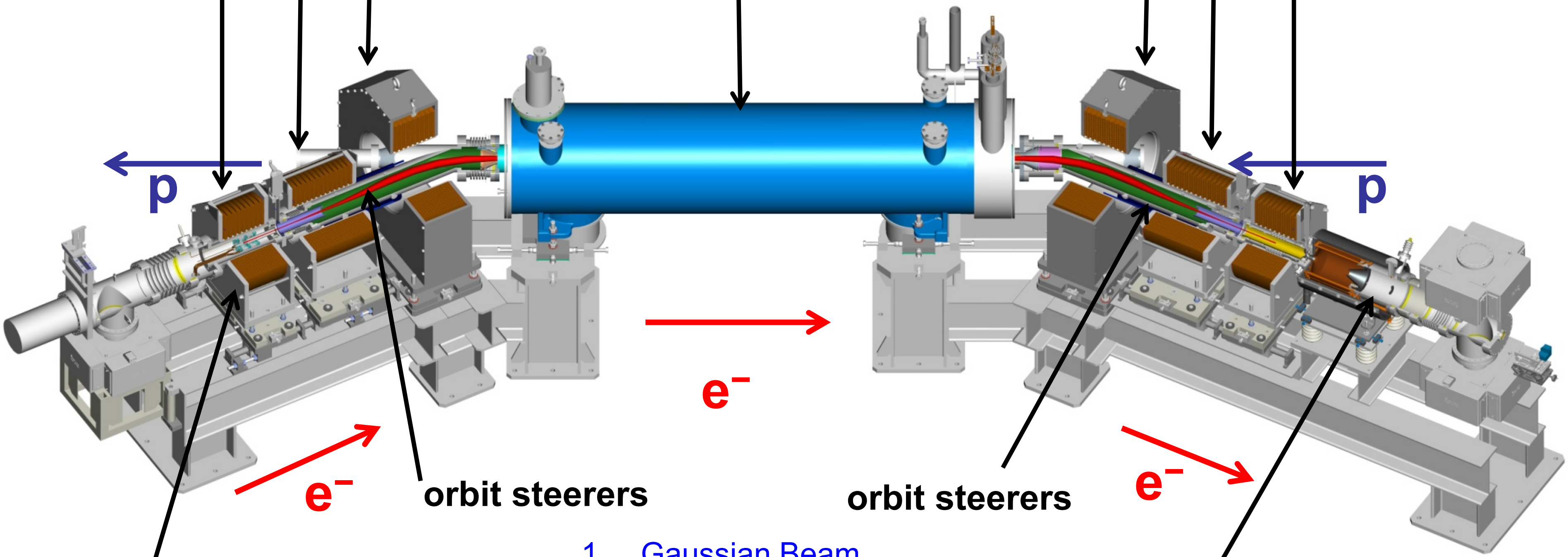
Electron Lens for Beam-Beam Compensation



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

warm solenoids

warm solenoids

orbit steerers

orbit steerers

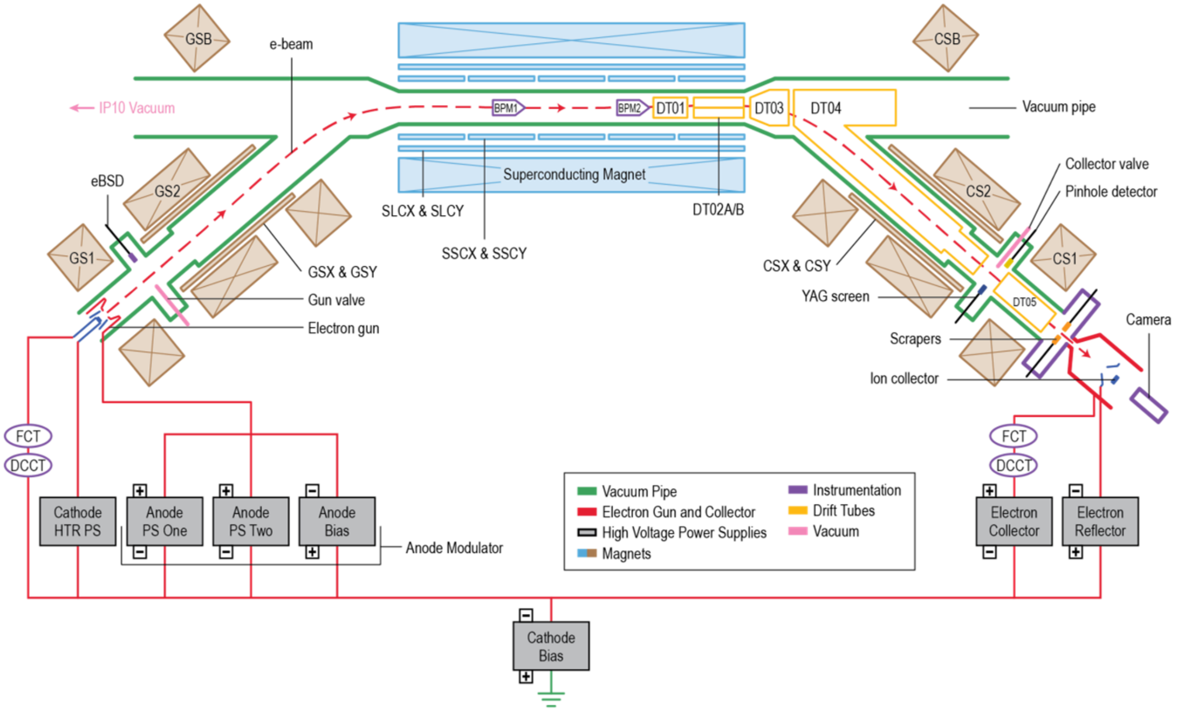
electron gun

electron collector

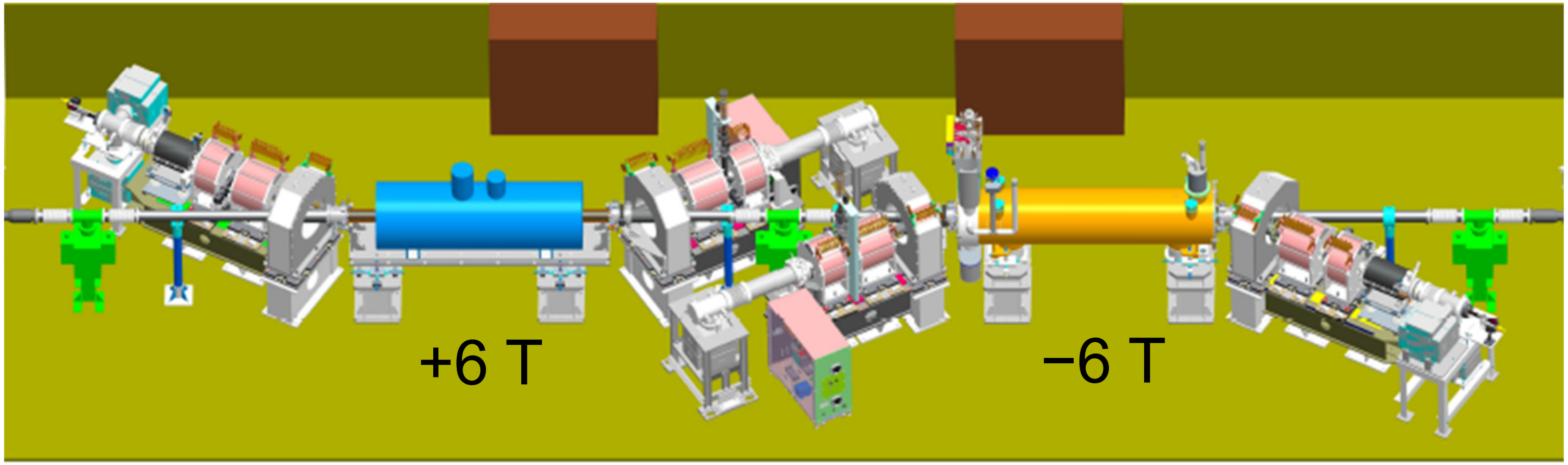
1. Gaussian Beam
2. 1A DC current
3. 78 kHz pulsed beam
4. 5~10 keV

E-lens Layout

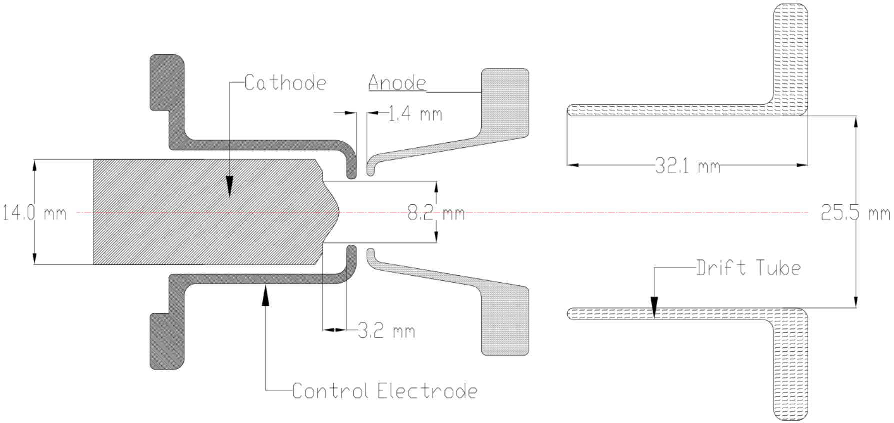
1. Detector
2. BPM
3. Electron gun

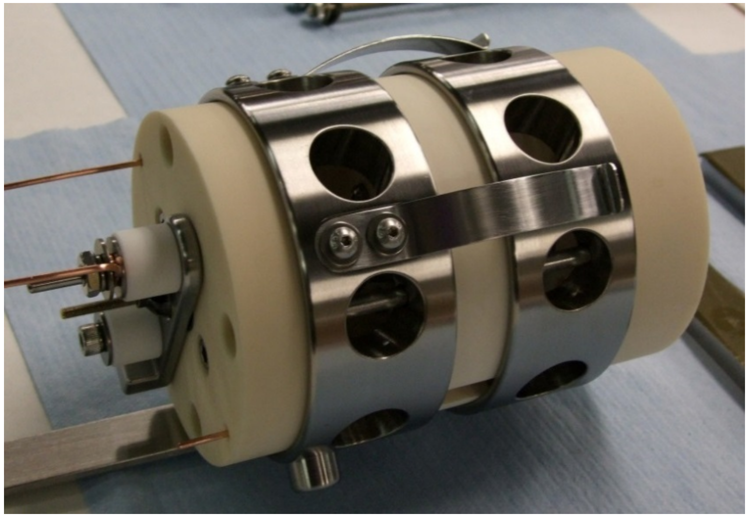


1. YAG screen
2. Collector
3. CTs

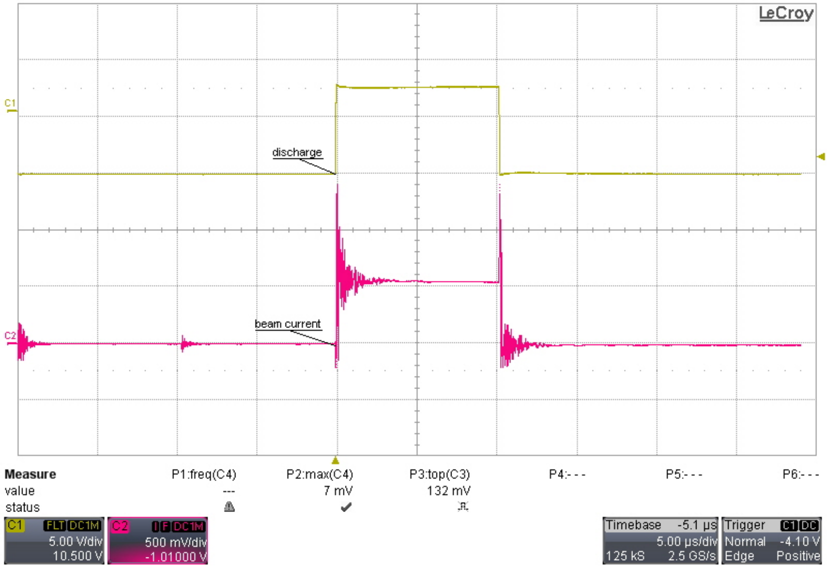


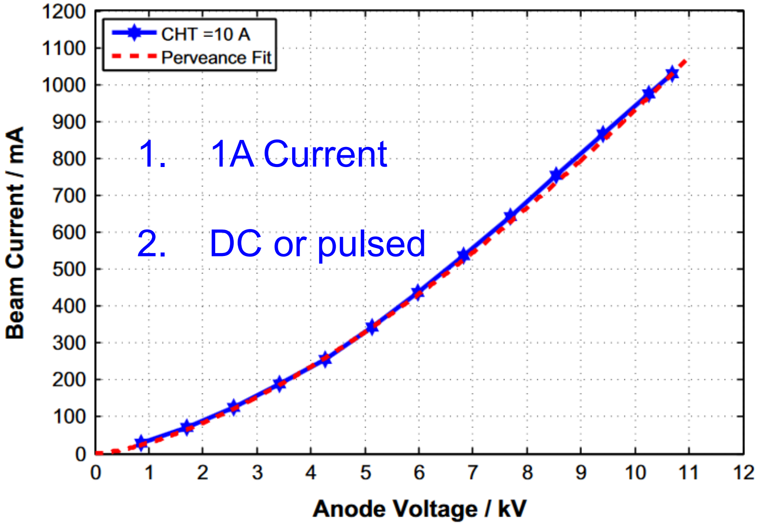
E-gun





1. Thermal cathode
2. IrCe and Tungsten

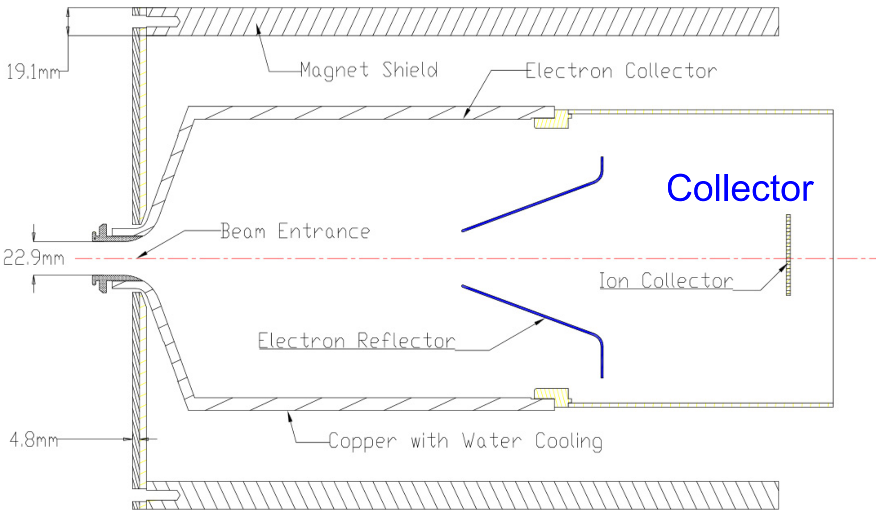


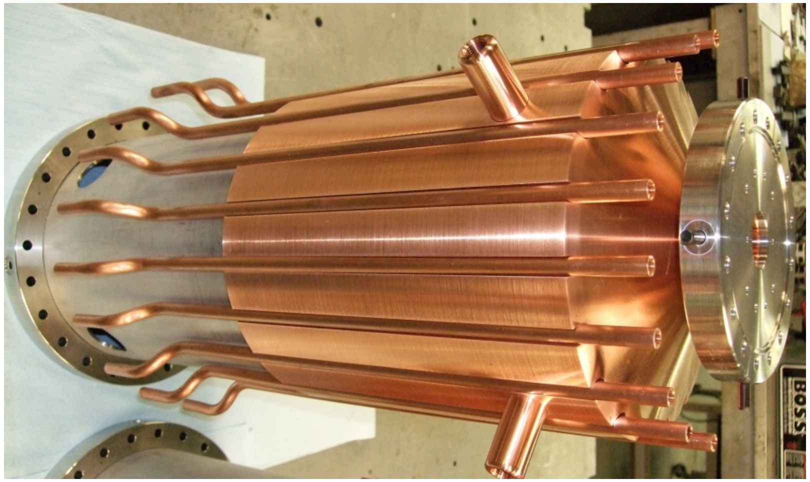


1. 1A Current
2. DC or pulsed

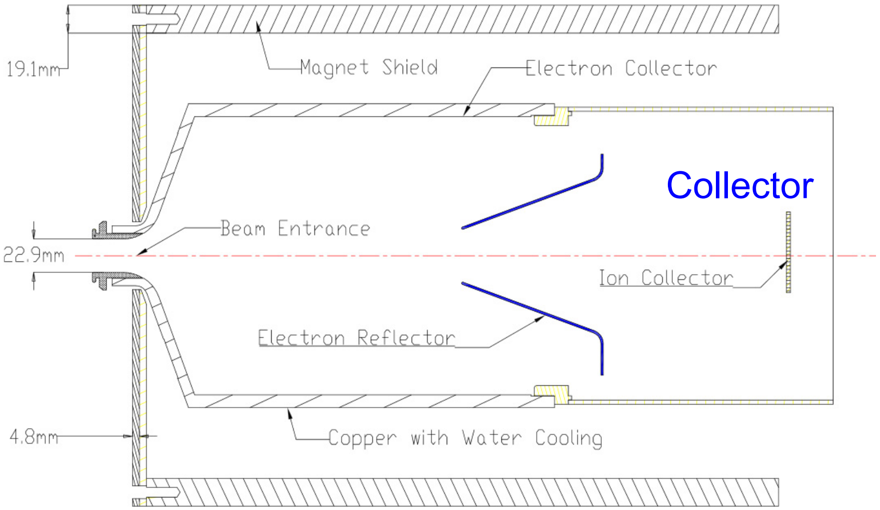
[Xiaofeng Gu et al., NIM*A*, Volume 743 (2014)]

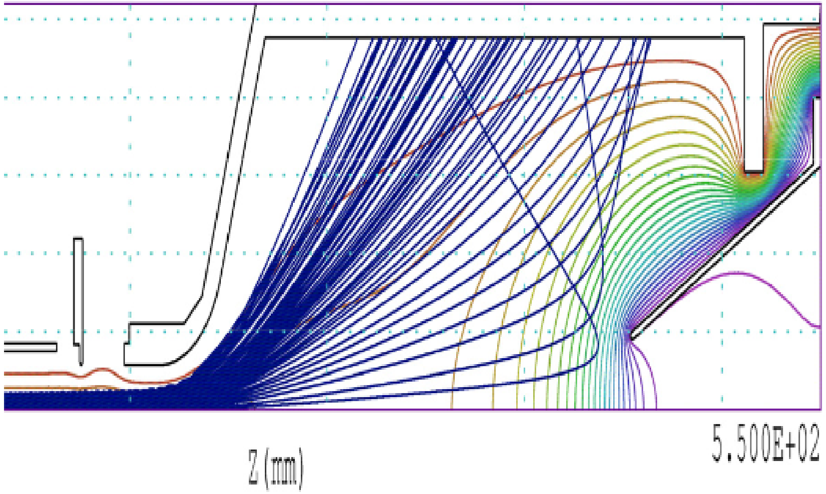
Collector, YAG, Pinhole and BPM



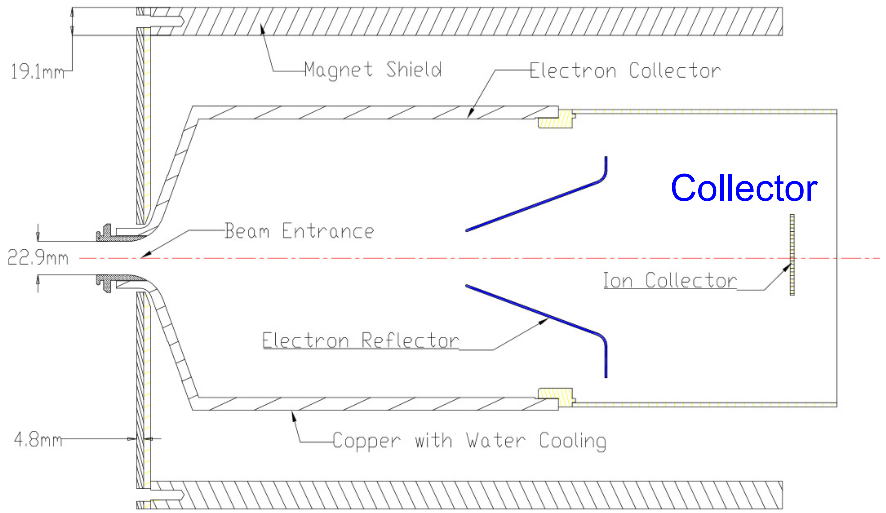


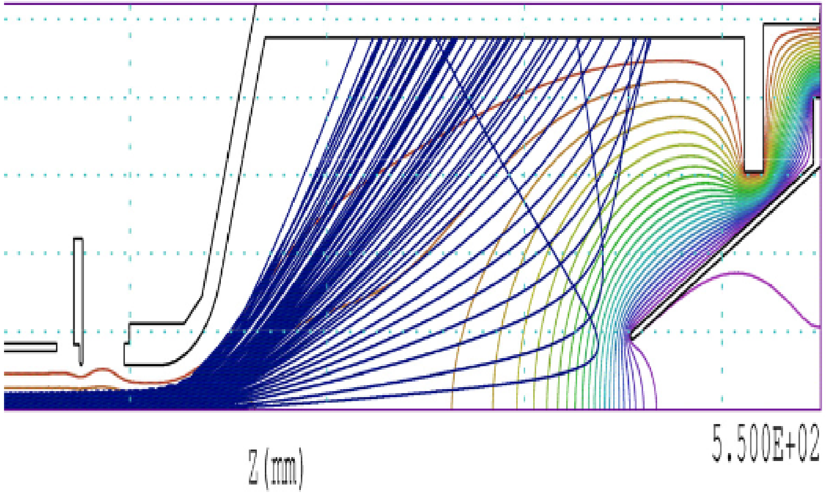
Collector, YAG, Pinhole and BPM

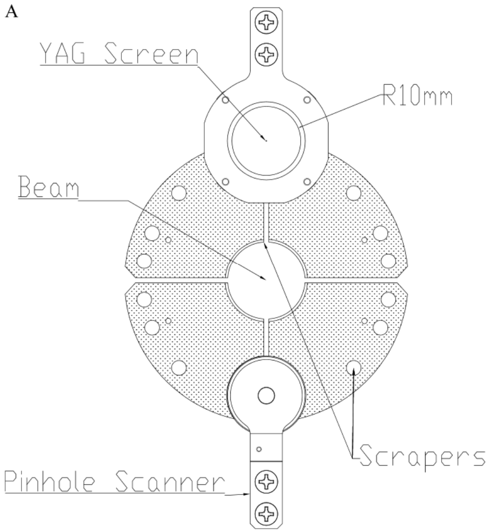


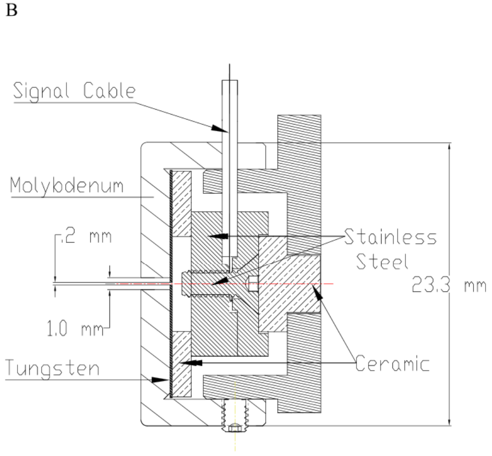


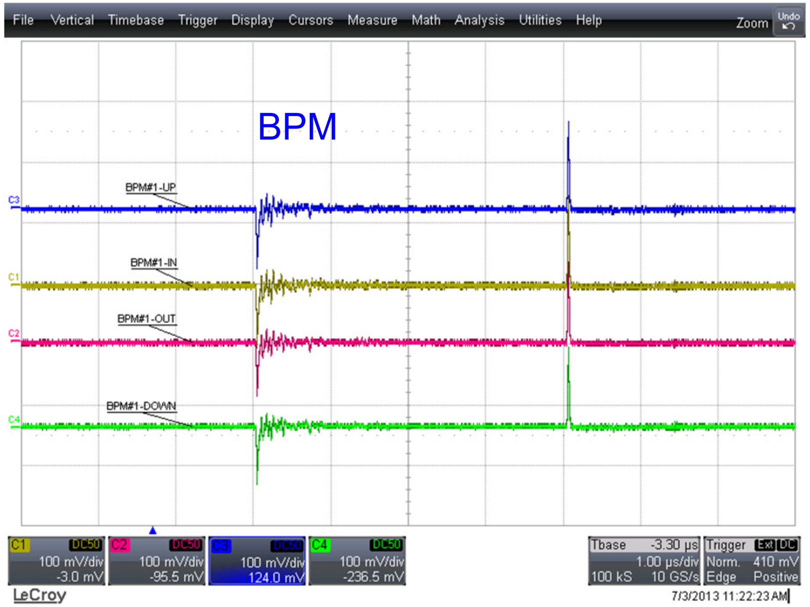
Collector, YAG, Pinhole and BPM





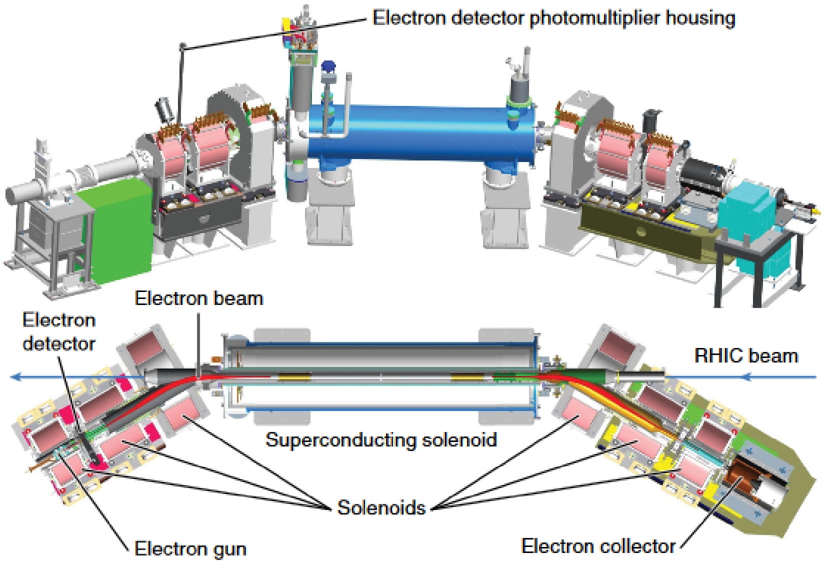


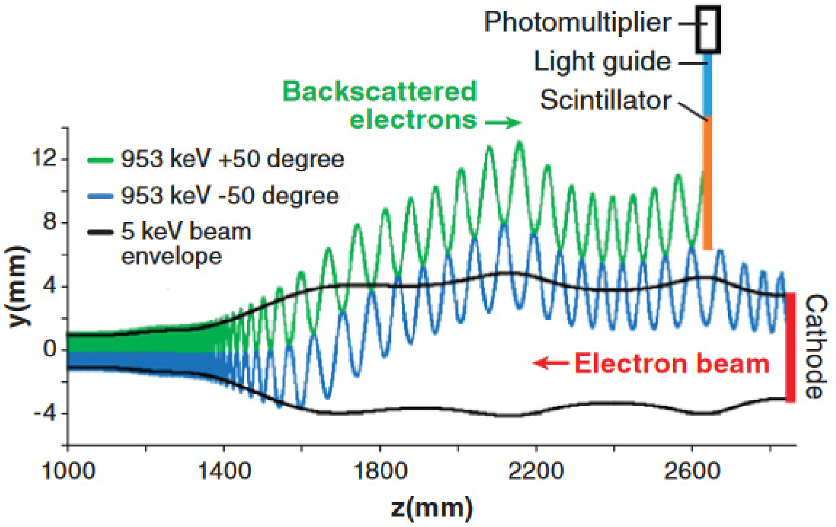


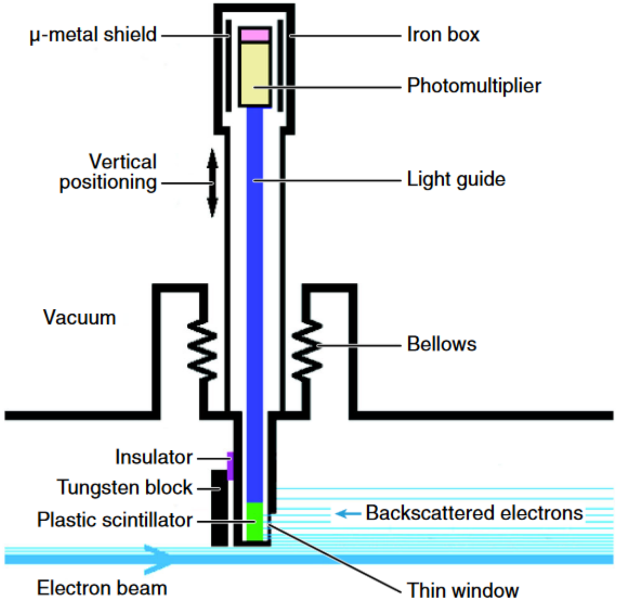


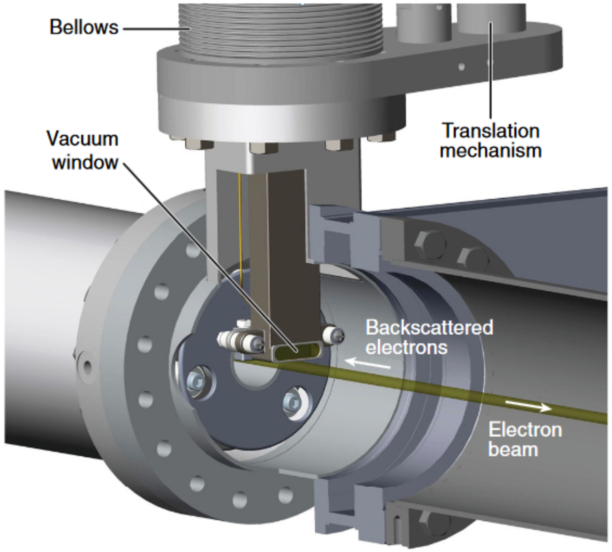
C1 DC50 100 mV/div -3.0 mV
C2 DC50 100 mV/div -95.5 mV
C3 DC50 100 mV/div 124.0 mV
C4 DC50 100 mV/div -236.5 mV
Tbase -3.30 µs 1.00 µs/div 100 kS 10 GS/s
Trigger Ext DC Norm. 410 mV Edge Positive
7/3/2013 11:22:23 AM

Electron beam backscattering detector (eBSD)

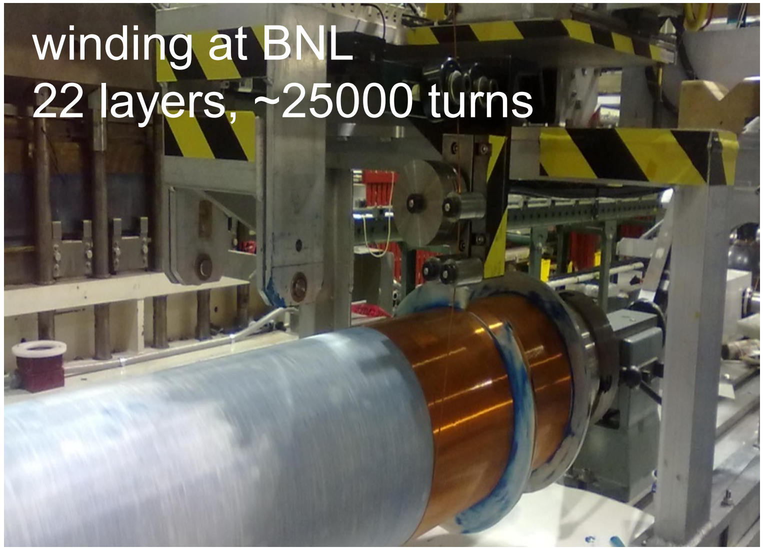








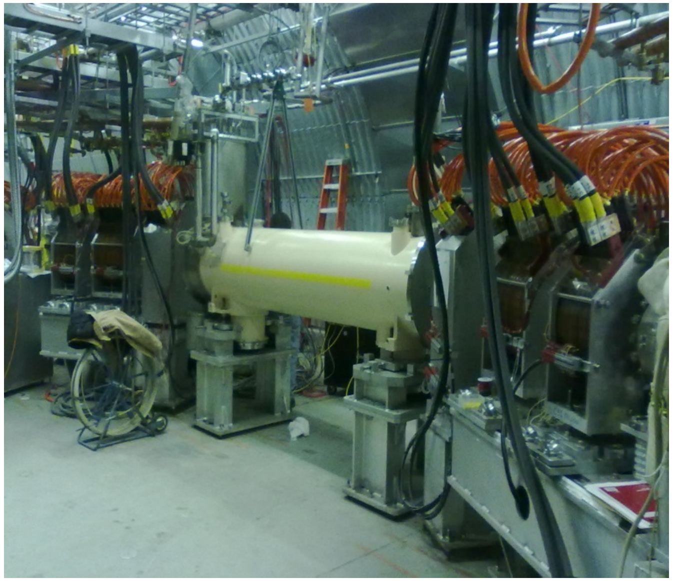
Superconducting Solenoid


winding at BNL
22 layers, ~25000 turns

1. 6T field
2. Field straightness
3. Angle correctors
4. 2.8 m long total

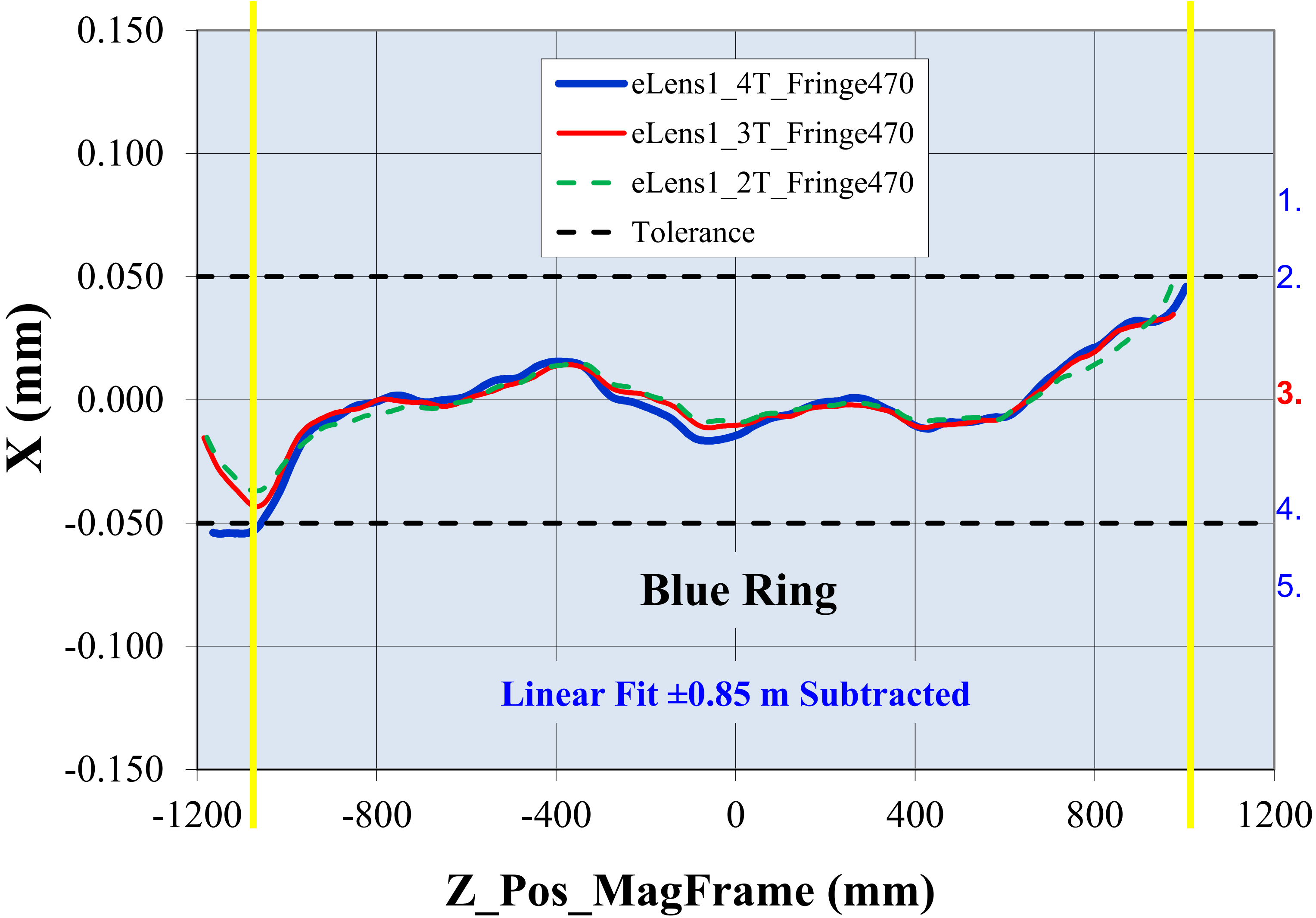

shell with correctors

Solenoid



Superconducting Magnet

A maximum ±50 μm deviation of the main solenoid field lines within ±800 mm



1. Tolerance ± 50 μm
2. Three different fields
3. **±1000** mm good field
4. Without correction
5. With warm magnets

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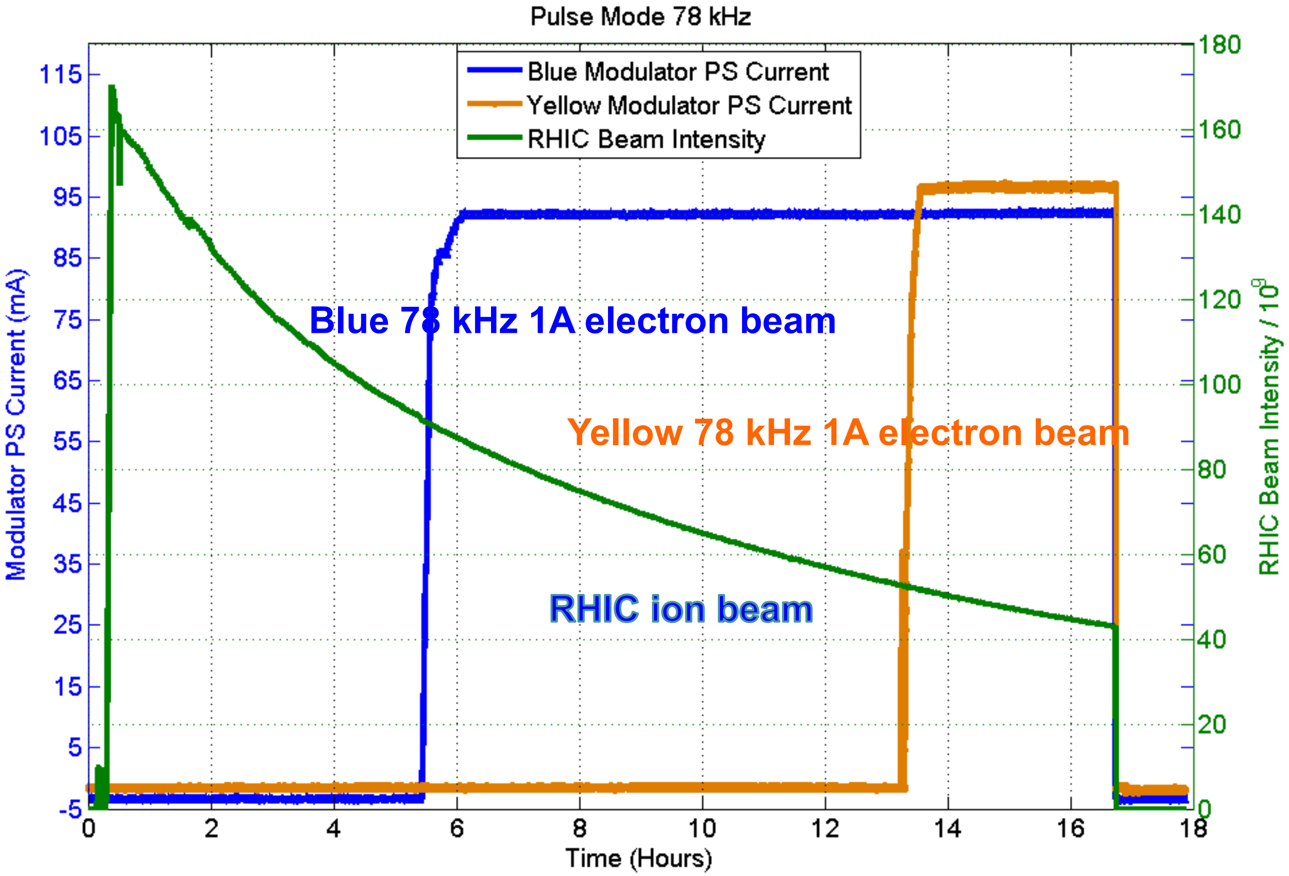
Parasitic Mode Electron Beam (2014)



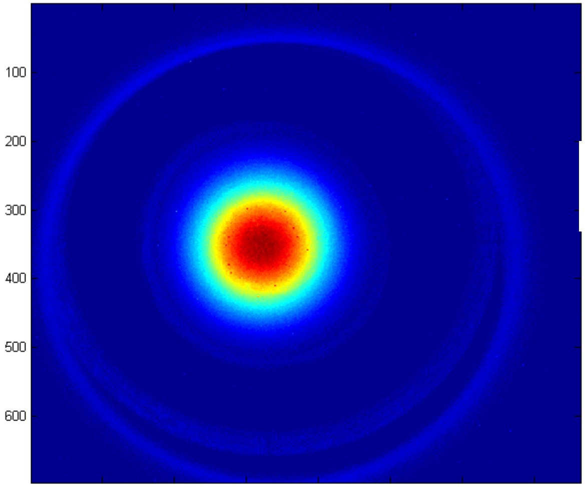
1. Modulator current indicates 78 kHz is running.

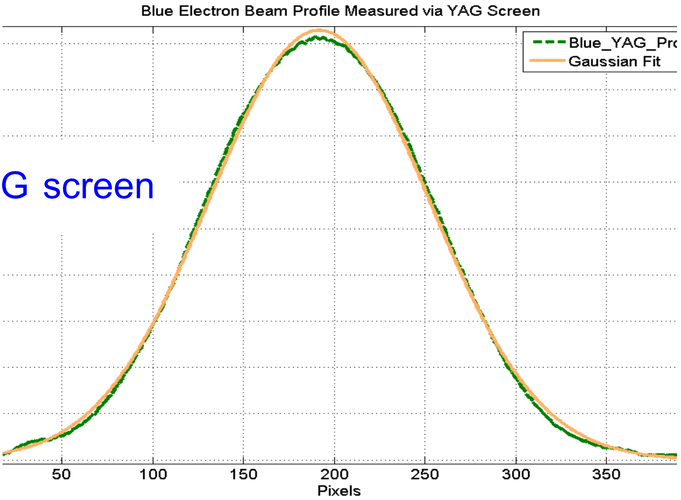
2. Blue and Yellow were running **78 kHz pulse** mode with 1A **simultaneously** within RHIC beam abort gap;

3. Parasitic to RHIC beam provides more commissioning time;

4. Blue e-lens 78 kHz was running for 14 hours during 2013;

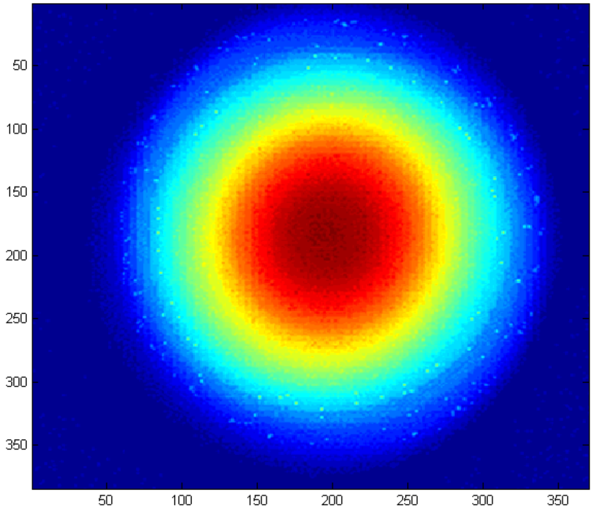
Electron beam profile measurement (2014)

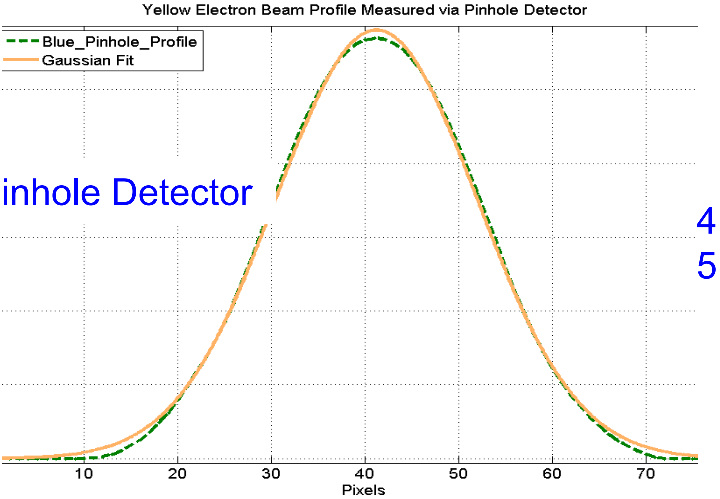




YAG screen

1. Current 70 mA
2. Beam profile from YAG is a Gaussian
3. Profile does not change with current





Pinhole Detector

4. Current 1150 mA.
5. Pinhole profile is Gaussian

Transverse e-Beam Alignment With Au Beam (2014)

- Two methods to do transverse position and angle alignment: BPM or eBSD (detector) [P. Thieberger, PRSTAB 19, 041002 2016]
- BPMs in both lenses to bring e- and A- beam in proximity (transverse electron beam position for blue and yellow, electron beam angle steering for yellow)
- Backscattered electron detector to maximize overlap

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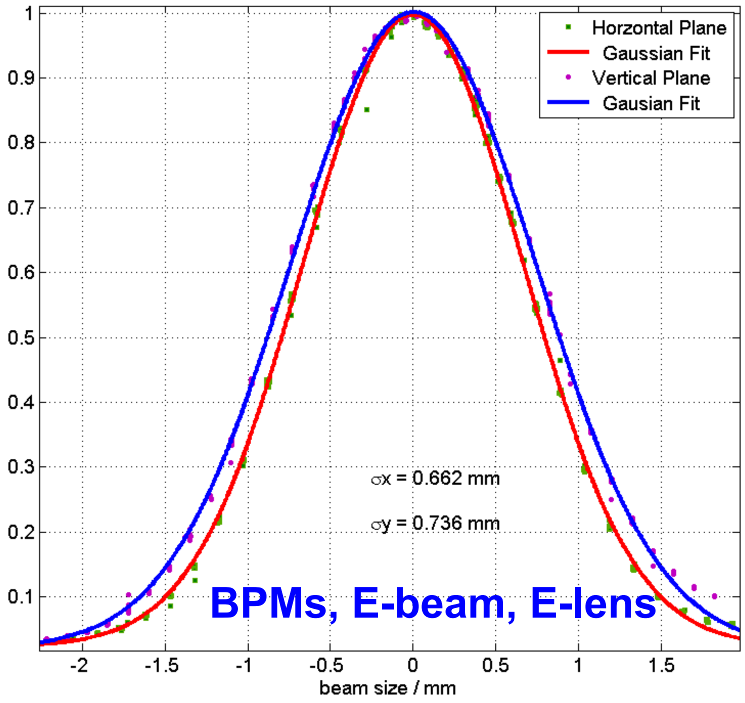
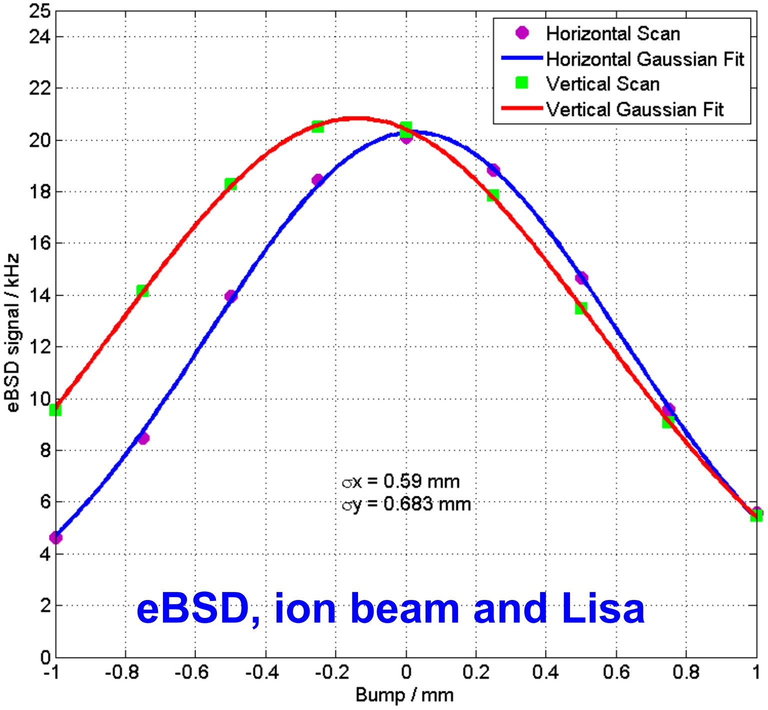
- BPMs in both lenses to bring e- and A- beam in proximity (transverse electron beam position for blue and yellow, electron beam angle steering for yellow)





[Peter Thieberger et al., PRAB19, 041002 (2016)]

Electron Lattice for Operation

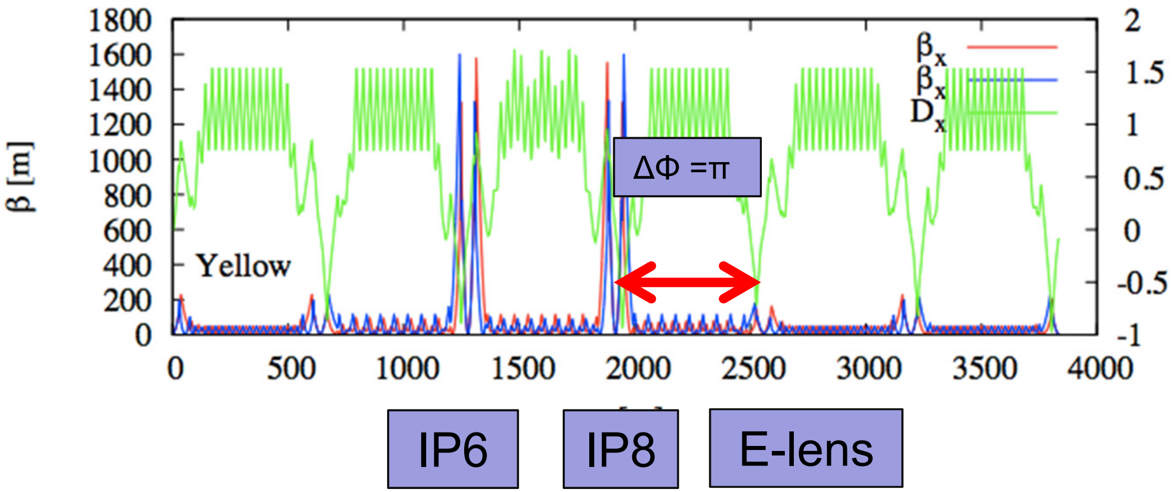
Lattice improvements

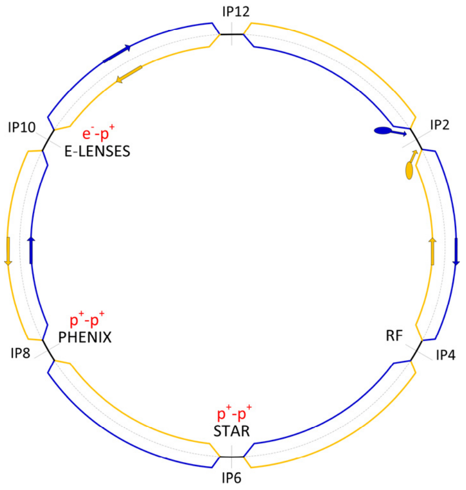
E-lens requires π phase advance from lens to one colliding IP.

π/2 phase advance per cell and ‘ATS’ style beta squeeze allow passive compensation of sextupole driving terms

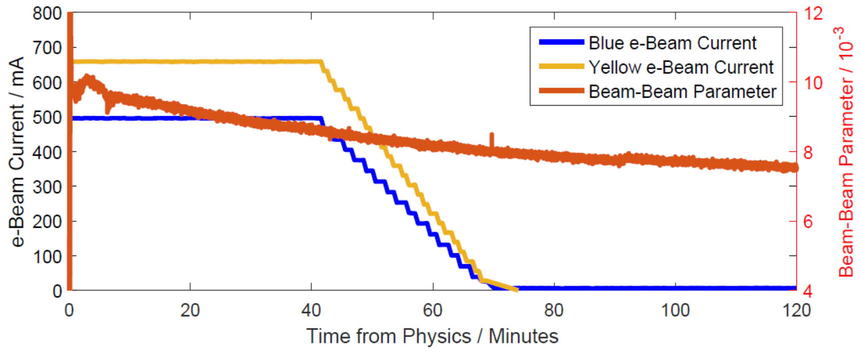
Optics measured-to-model agreement quite good (10-15% beat beat) without additional correction.

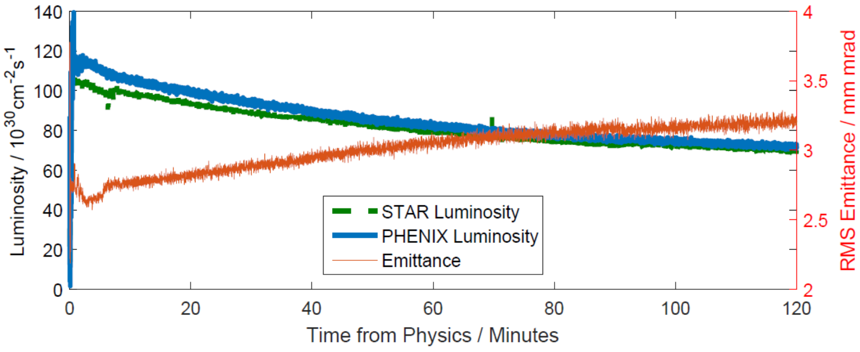
Momentum aperture improved, shown by increase in tolerable radial shift:
Run 12: +/- 0.7 mm radial shift;
Run 15: +/- 1.25 mm radial shift





Electron Operation





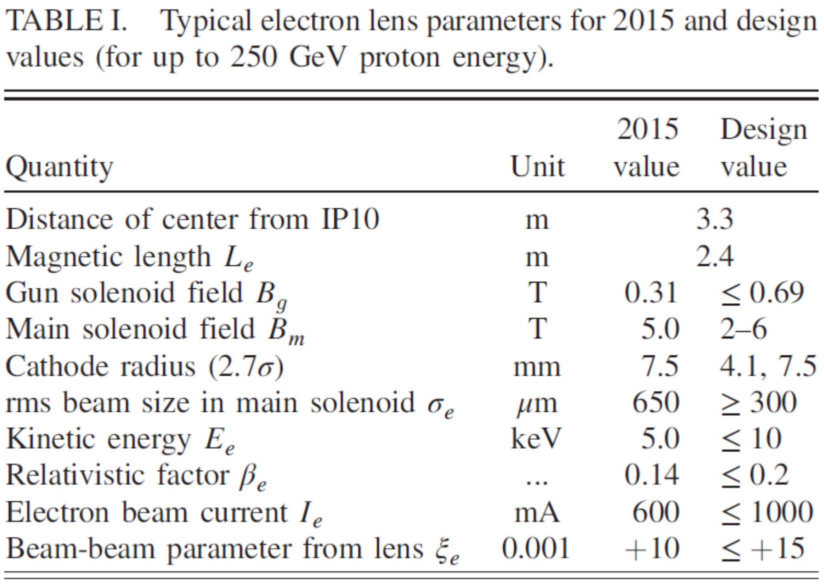


TABLE I. Typical electron lens parameters for 2015 and design values (for up to 250 GeV proton energy).

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	$+10$	$\leq +15$

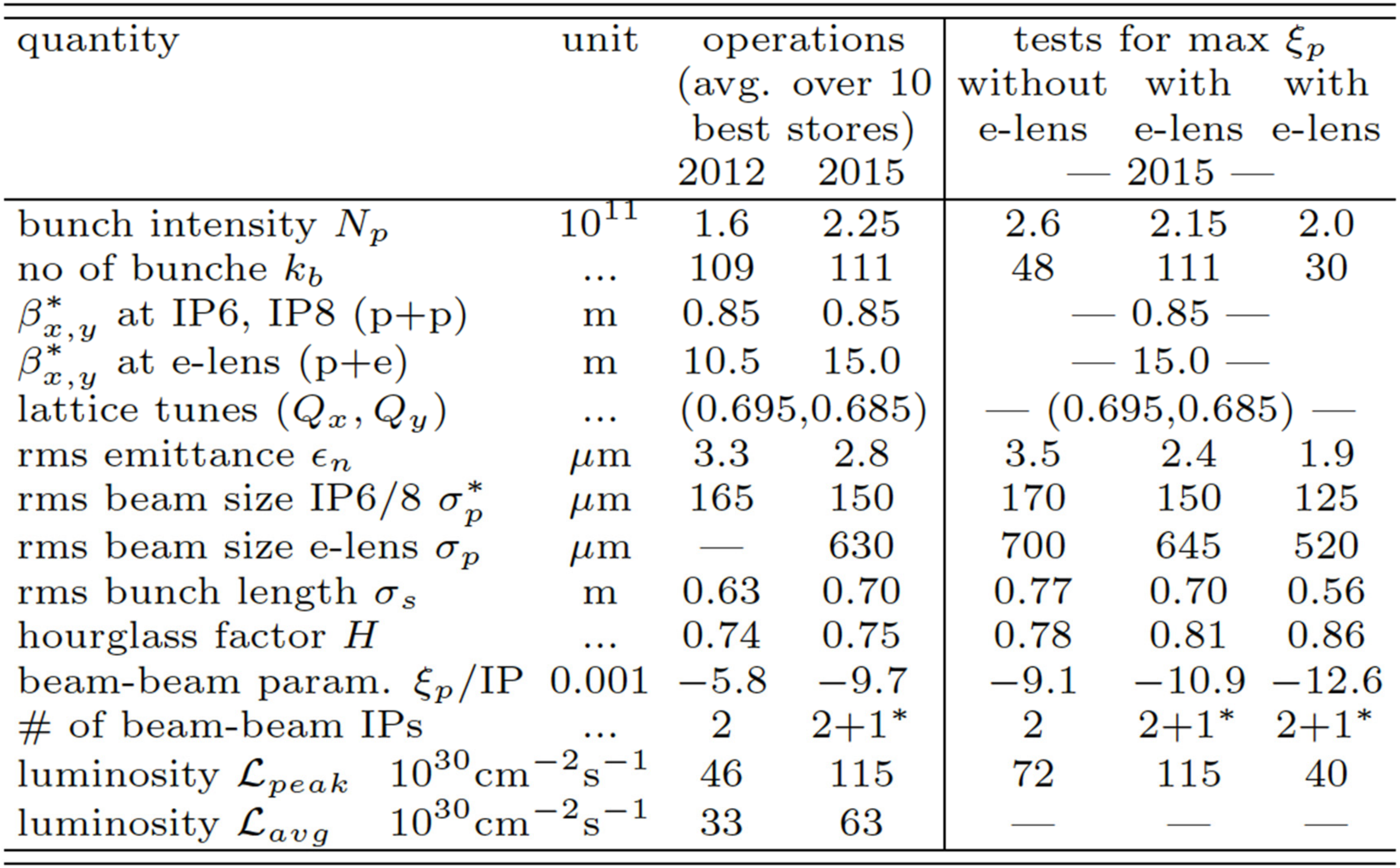
1. Turned on for every store (45~60 min.)

2. High reliability: available for all stores after running

3. Blue e-lens limited to ~ 500 mA by onset of e-current instability
Yellow e-lens operating at > 1 A

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

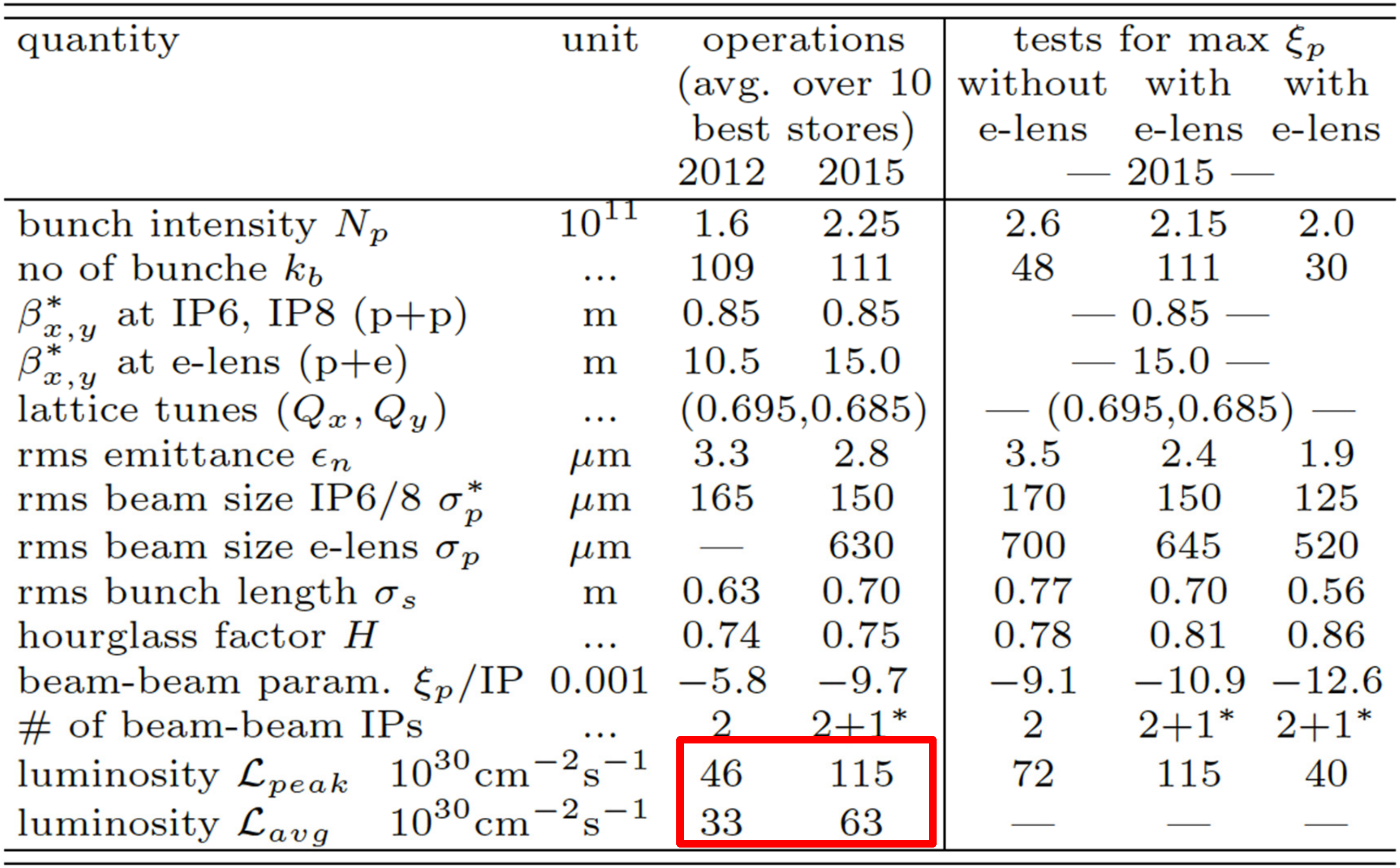
Electron Lens Operation increases in *L* and ξ



quantity	unit	operations (avg. over 10 best stores)		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 $\mathcal{L}_{peak}$	$10^{30}\text{cm}^{-2}\text{s}^{-1}$	46	115	72	115	40
luminosity $\mathcal{L}_{avg}$	$10^{30}\text{cm}^{-2}\text{s}^{-1}$	33	63	—	—	—

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.)

Electron Lens Operation increases in L and ξ

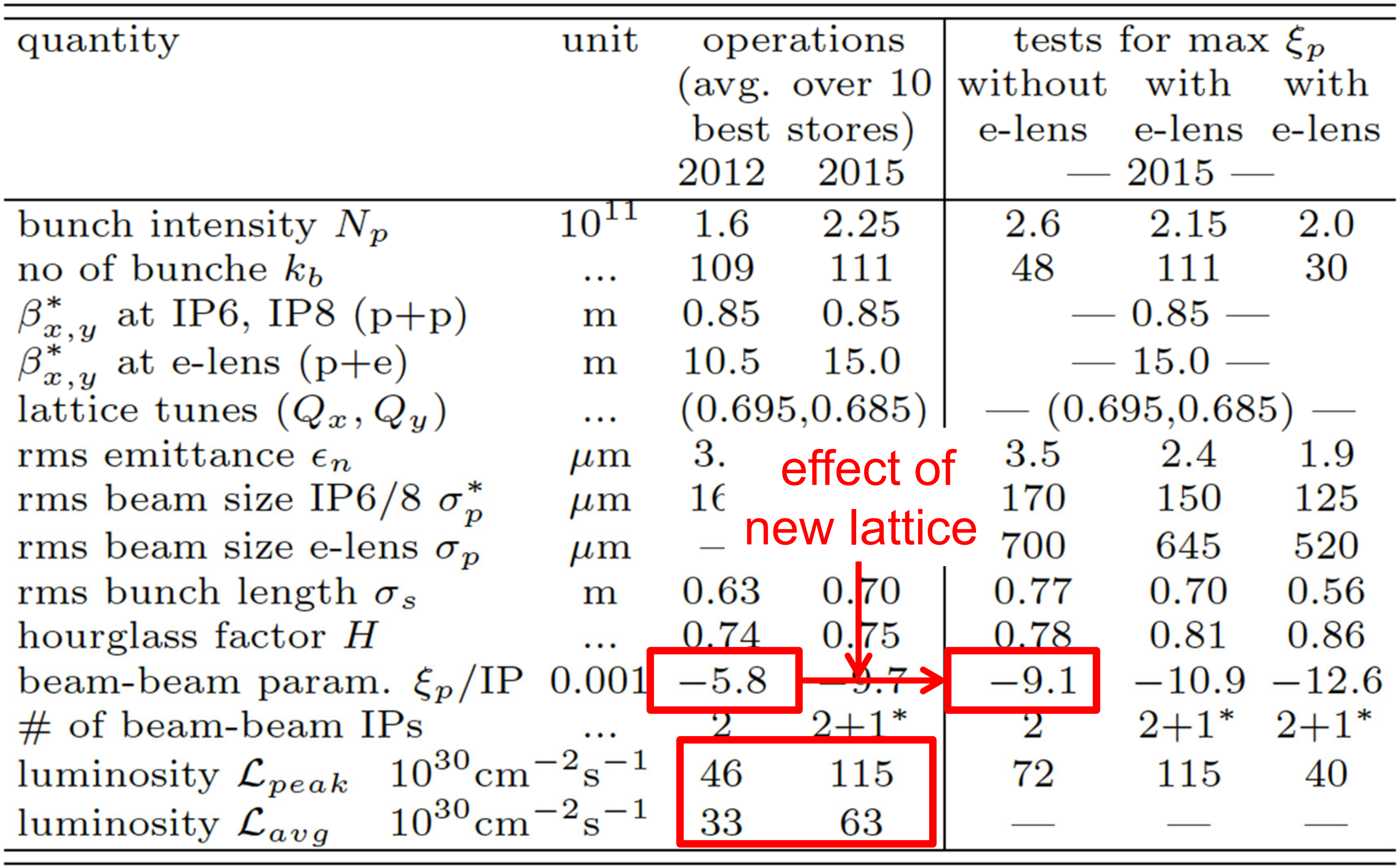


quantity	unit	operations (avg. over 10 best stores)		tests for max ξ_p		
		2012	2015	without e-lens	with e-lens	with e-lens
				— 2015 —		
bunch intensity N_p	10^{11}	1.6	2.25	2.6	2.15	2.0
no of bunche k_b	...	109	111	48	111	30
$\beta^*_{x,y}$ at IP6, IP8 (p+p)	m	0.85	0.85	— 0.85 —		
$\beta^*_{x,y}$ 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 $\mathcal{L}_{peak}$	$10^{30}\text{cm}^{-2}\text{s}^{-1}$	46	115	72	115	40
luminosity $\mathcal{L}_{avg}$	$10^{30}\text{cm}^{-2}\text{s}^{-1}$	33	63	—	—	—

L_{peak} 2.5× increase L_{avg} 1.9× increase

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.)

Electron Lens Operation increases in *L* and ξ



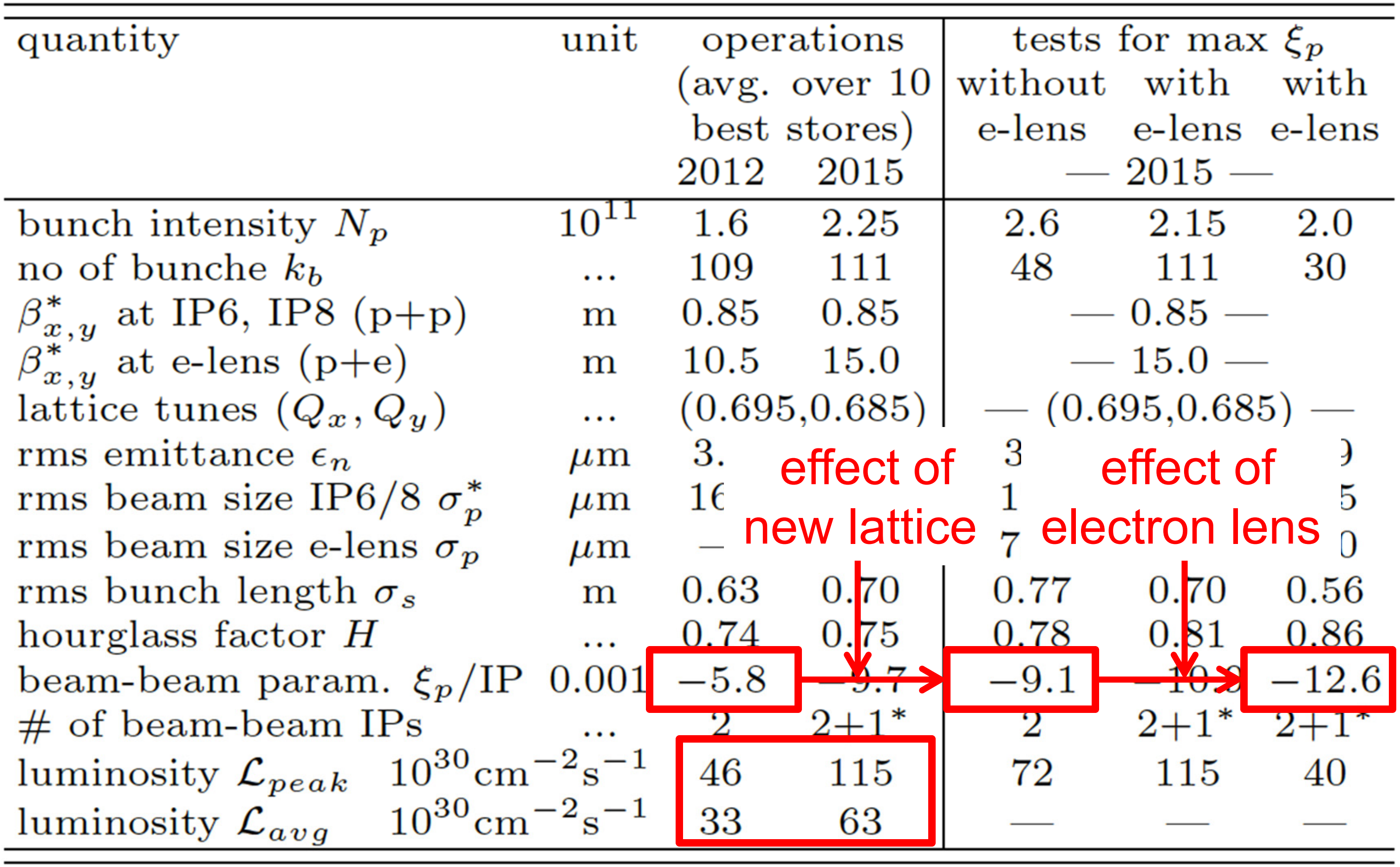
quantity	unit	operations (avg. over 10 best stores)		tests for max ξ_p		
				without e-lens	with e-lens	with e-lens
		2012	2015	— 2015 —		
bunch intensity N_p	10^{11}	1.6	2.25	2.6	2.15	2.0
no of bunche k_b	…	109	111	48	111	30
$\beta^*_{x,y}$ at IP6, IP8 (p+p)	m	0.85	0.85	— 0.85 —		
$\beta^*_{x,y}$ at 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.	[illegible]	3.5	2.4	1.9
rms beam size IP6/8 σ^*_p	μm	16	[illegible]	170	150	125
rms beam size e-lens σ_p	μm	—	[illegible]	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 $\mathcal{L}_{peak}$	$10^{30}\mathrm{cm}^{-2}\mathrm{s}^{-1}$	46	115	72	115	40
luminosity $\mathcal{L}_{avg}$	$10^{30}\mathrm{cm}^{-2}\mathrm{s}^{-1}$	33	63	—	—	—

effect of new lattice

L_{peak} 2.5× increase L_{avg} 1.9× increase

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.)

Electron Lens Operation increases in *L* and ξ



quantity	unit	operations (avg. over 10 best stores) 2012	2015	tests for max ξ_p without e-lens — 2015 —	with e-lens	with e-lens
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.	[illegible]	3	[illegible]	9
rms beam size IP6/8 σ^*_p	μm	16	[illegible]	1	[illegible]	5
rms beam size e-lens σ_p	μm	—	[illegible]	7	[illegible]	0
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 $\mathcal{L}_{peak}$	$10^{30}\text{cm}^{-2}\text{s}^{-1}$	46	115	72	115	40
luminosity $\mathcal{L}_{avg}$	$10^{30}\text{cm}^{-2}\text{s}^{-1}$	33	63	—	—	—

effect of new lattice

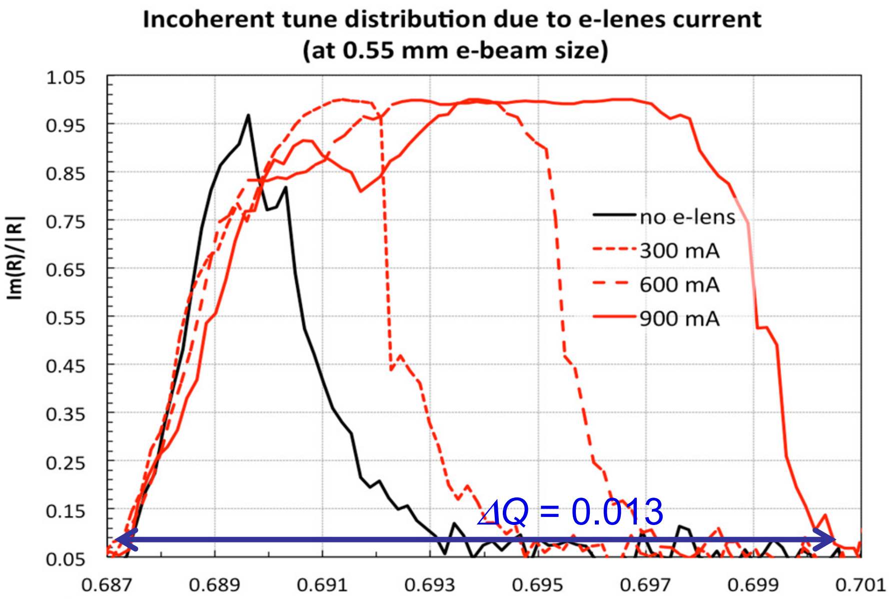
effect of electron lens

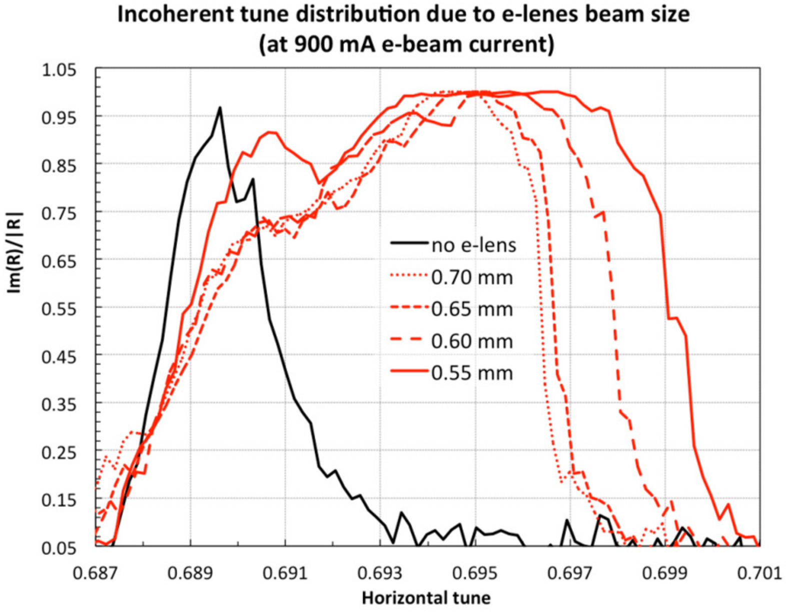
ξ +38%
w/o and w/
electron lens

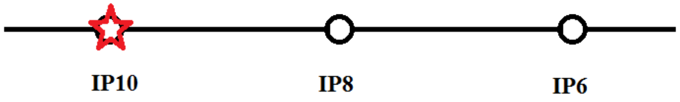
L_{peak} 2.5× increase L_{avg} 1.9× increase

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.)

Tune spread Compensation with 0BB from e-lens (PP run)


Incoherent tune distribution due to e-lenes current (at 0.55 mm e-beam size)

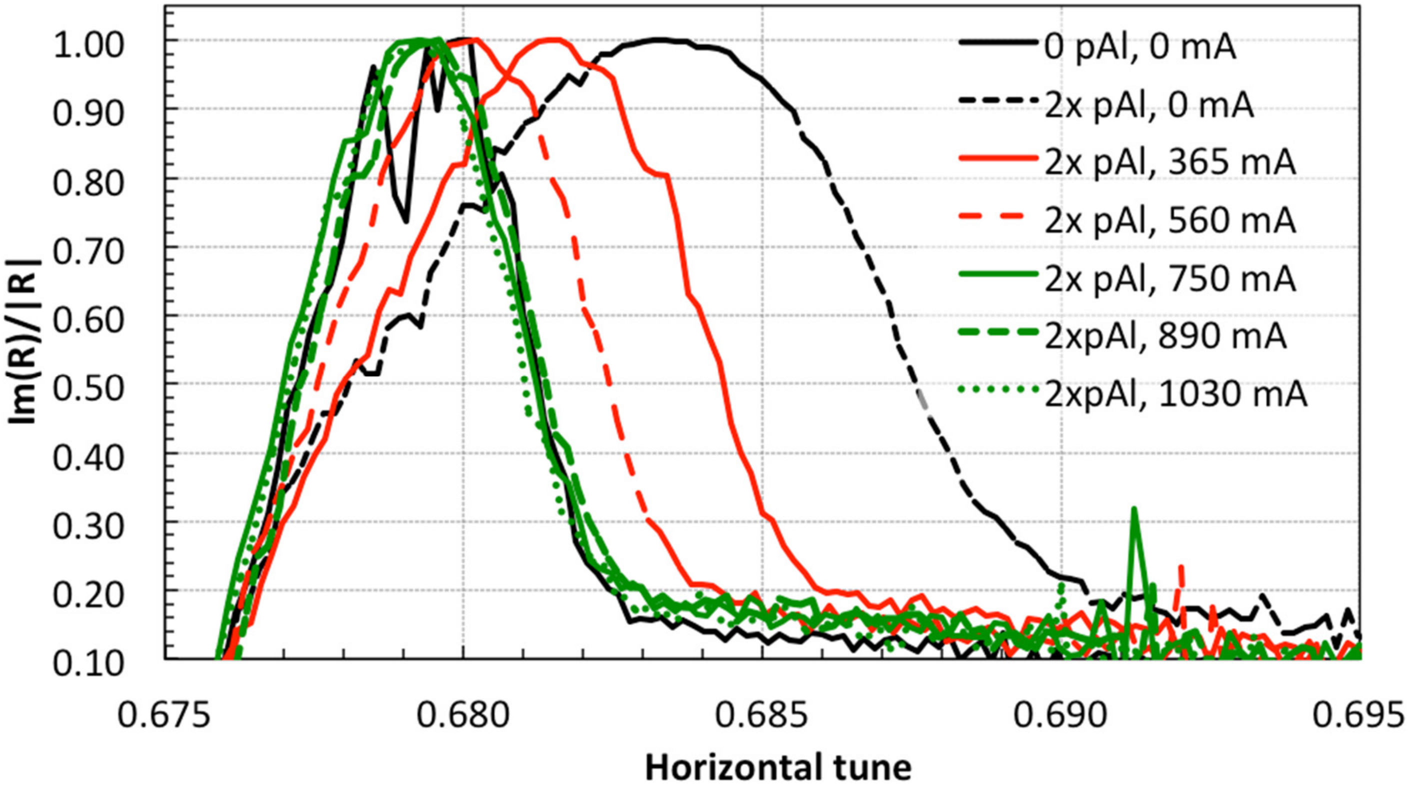

Incoherent tune distribution due to e-lenes beam size (at 900 mA e-beam current)



1. e-p collision (only negative beam force), no p-p
2. Incoherent tune vs e-beam current
3. Incoherent tune vs e-beam size
4. e-lens creates as much ΔQ = 0.013 as one beam-beam collision

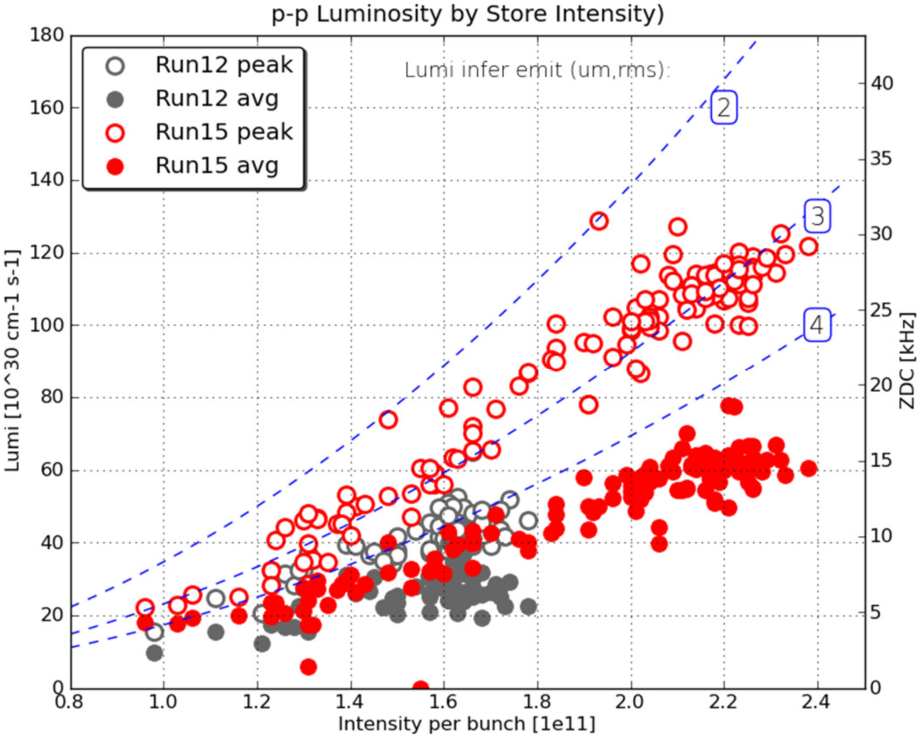
Demonstration Tune Spread Compensation

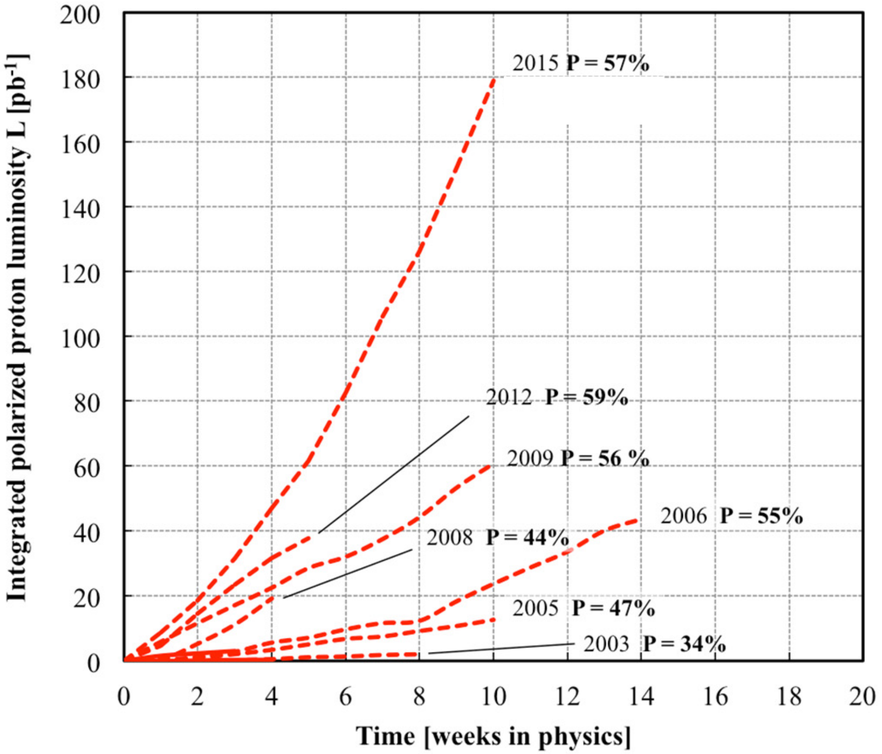
1. tune spread without bb and without e-lens
2. tune spread expands with bb
3. tune spread contracts again with bb and e-lens, but only up to ~750 mA (first such direct observation)
4. tune spread is only compressed to the value without bb, even with e-currents up to 1030 mA



Intensity Limit during Run13 and Run15 (Polarized Proton)

L_{peak} +150% L_{avg} +90%

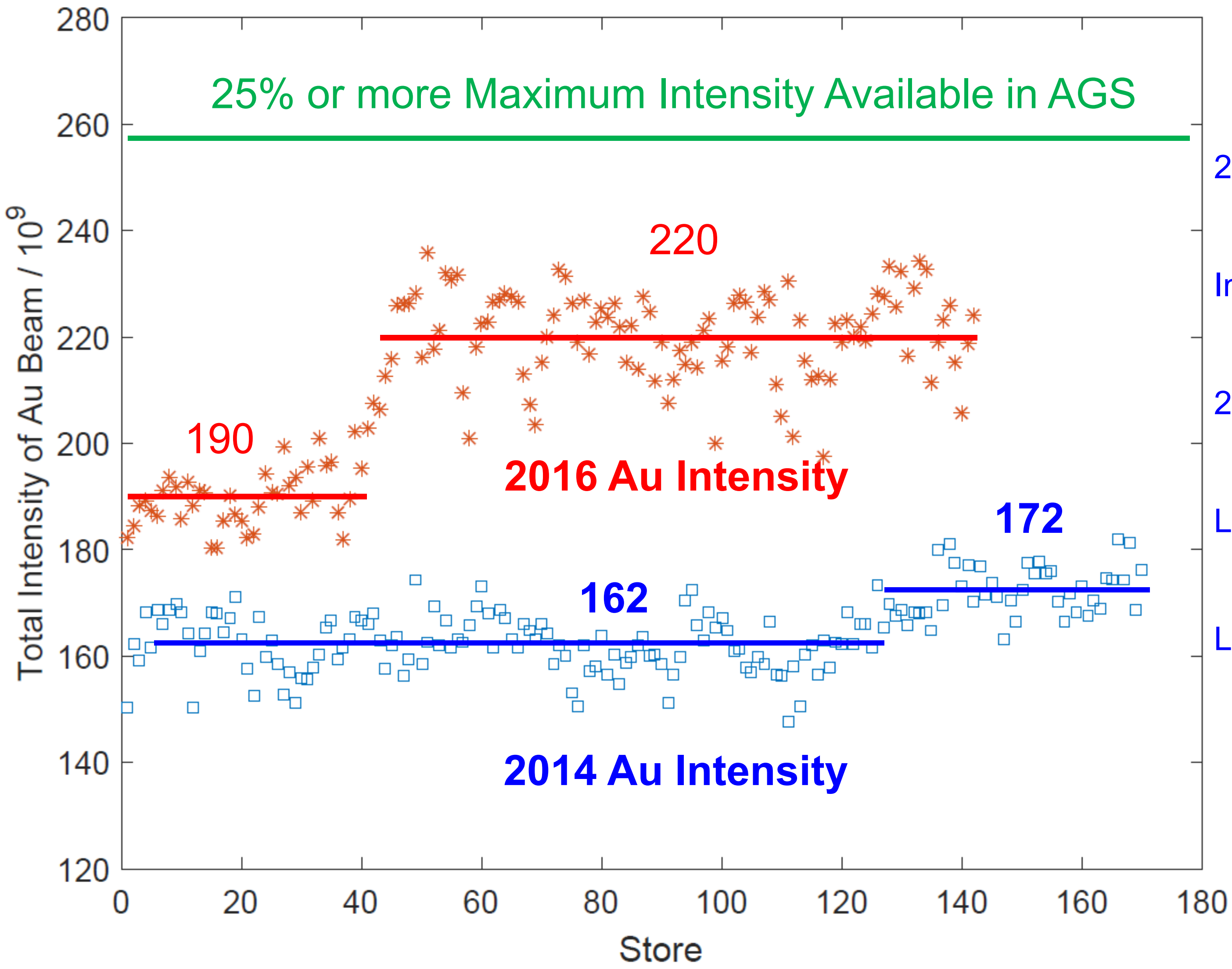




Outline

- ☐ Proton Beam Intensity
- ☐ Electron Lens introduction
- ☐ E-lens Commissioning and Operation
- ☐ Run16 Operation with Au-Au
- ☐ Summary

Intensity RHIC during 2016 Au-Au



28% more Au Intensity.

Improved by AGS

25% more intensity available

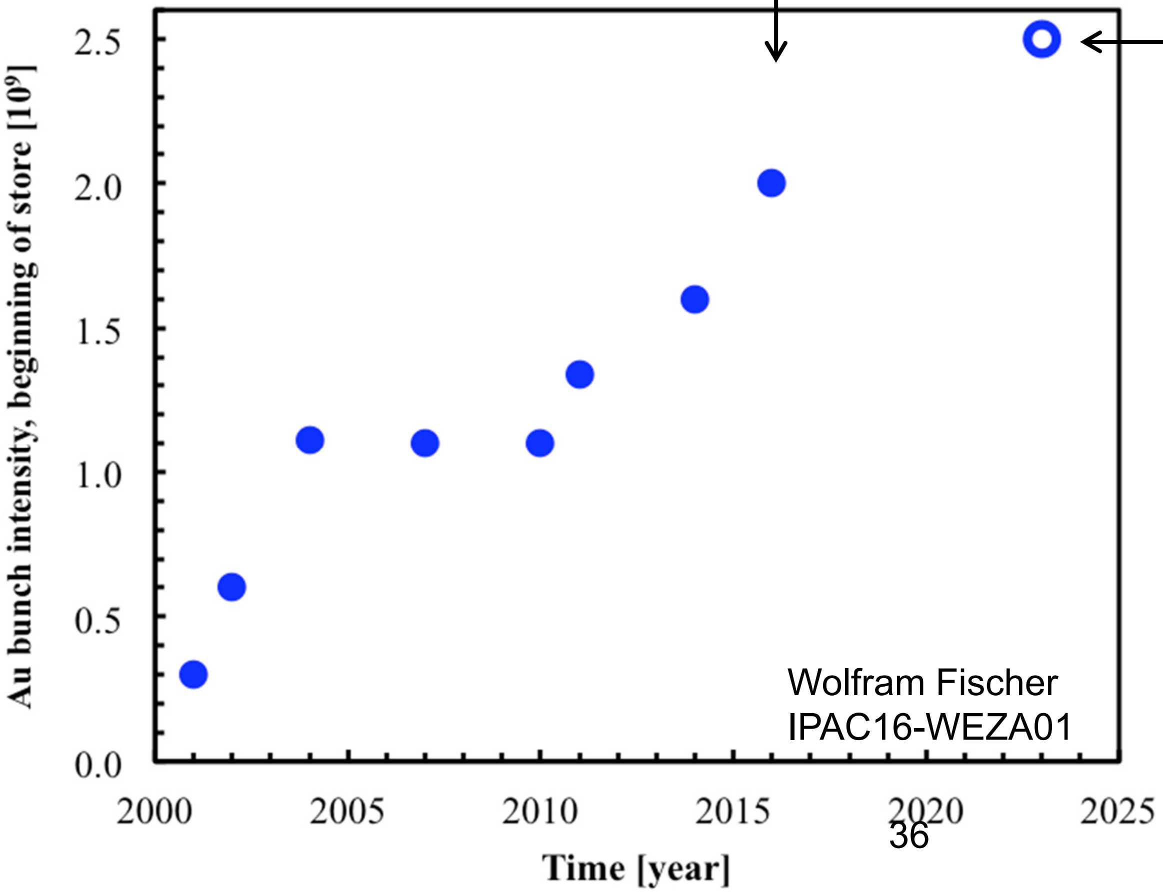
Limited by RHIC RF

Lumi. Limited by detector

Au Bunch Intensity Evolution

$$L(t) = \frac{1}{4\pi} f_0 N \frac{\boxed{N_b^2(t)}}{\varepsilon(t)\beta^*(t)} h(\beta^*, \sigma_s, \theta)$$

AGS 12→6→2 merge



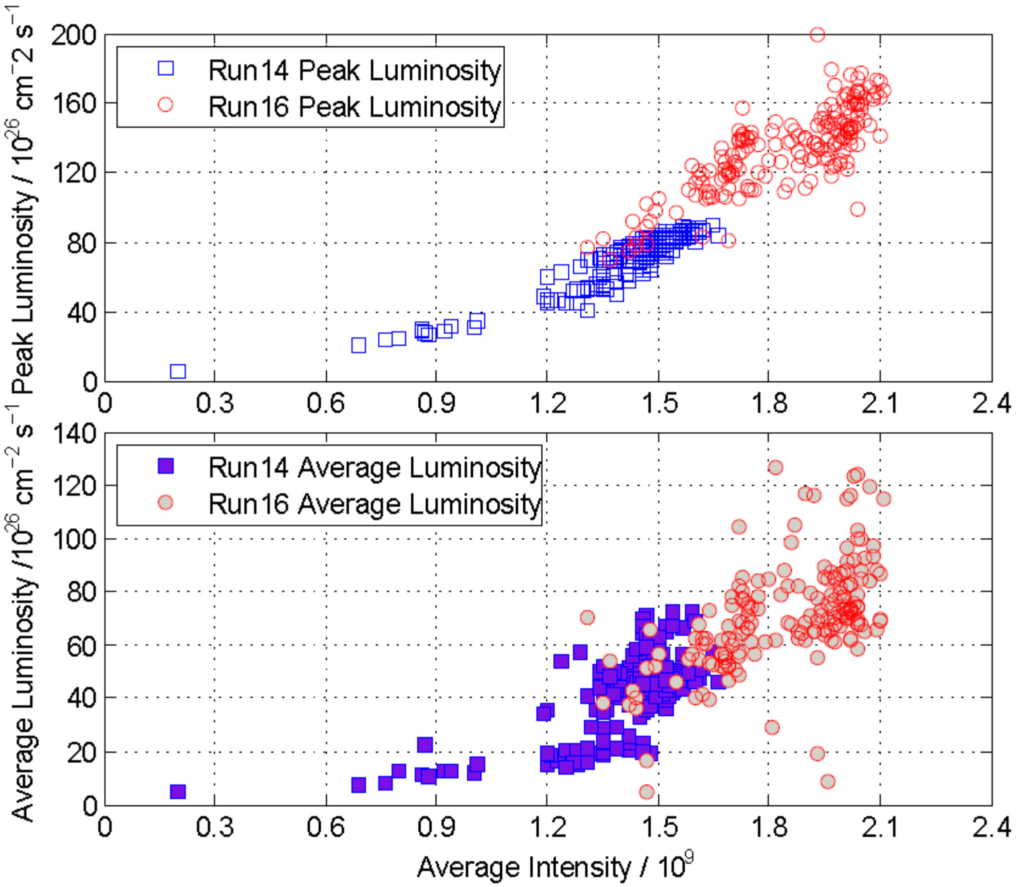
Wolfram Fischer
IPAC16-WEZA01

ultimate goal (25% more)

main limits:
- injectors output
- transition instability in RHIC (e-clouds)
- **presently Landau cavity RF amplifiers**

H. Huang, K. Gardner,
K. Zeno, RF, et al.

Peak and Average Luminosity



1. ***L_{peak}* +80%**
2. ***L_{avg}* +60%**

1. Average all peak luminosity: 80% more
2. Average all average luminosity: 60% more
3. Excluded 12 extremely low intensity store for Run14 for luminosity.

Outline

- ☐ **Proton Beam Intensity**
- ☐ **Electron Lens introduction**
- ☐ **E-lens Commissioning and Operation**
- ☐ **Run16 Operation**
- ☐ **Summary**

Summary – progress towards demonstrating HBBC

1. Head-on beam-beam compensation scheme in operation in 2015, consisting of new lattice (RDT compensation) + e-lenses (DQ compensation)
   L_{peak} +150% **L_{avg} +90%**

2. Higher ξ/IP possible, presently constrained by injectors (potential for 3~4× L in future runs)

3. The gold (Au) intensity in the RHIC during the 2016 run exceeded the previously achieved intensity by **28%**. **L_{peak} +80%** **L_{avg} +60%**

4. There is **20%** (compared with the max. intensity in 2016) more Au intensity available from AGS.

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Institutions

FNAL: TEL experience, beam-beam experiments and simulations

US LARP: beam-beam simulation

CERN: beam-beam experiments and simulations

Individuals

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