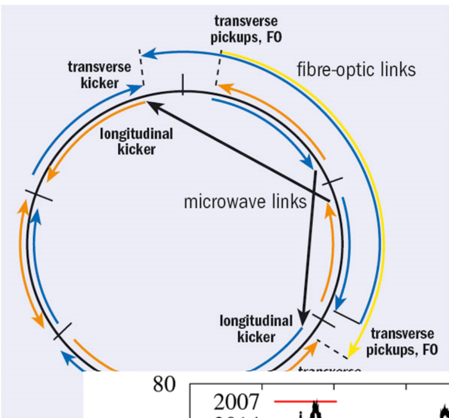
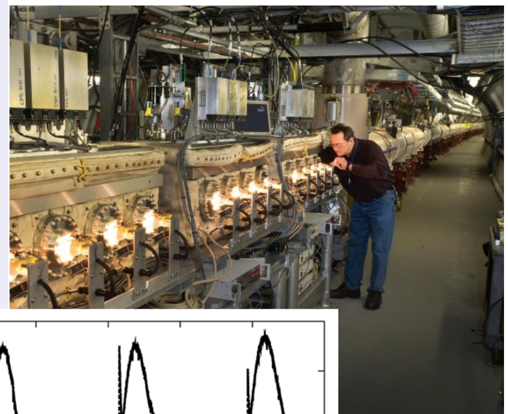
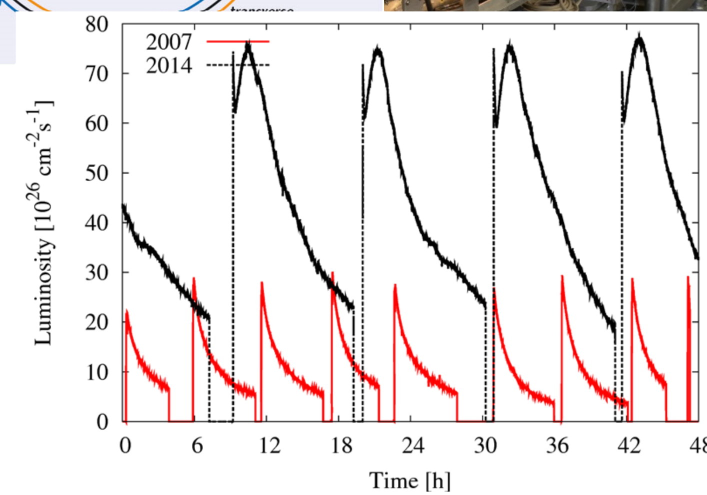
RHIC Performance

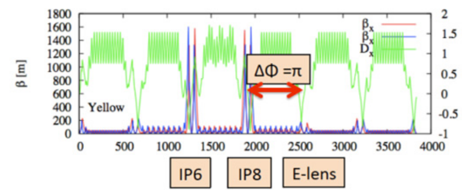
with Stochastic Cooling for Ions

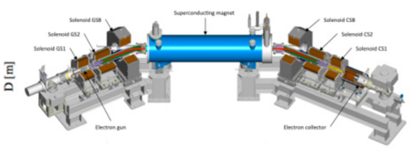
and Head-on Beam-Beam Compensation for Protons

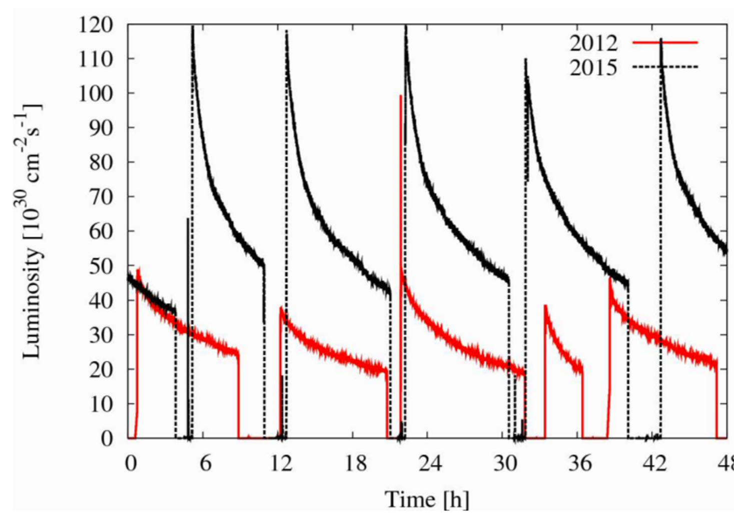












IPAC16

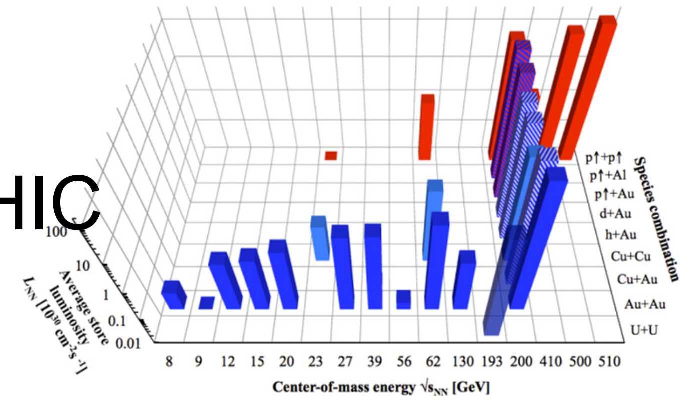
Wolfram Fischer, Brookhaven National Laboratory

for all of the RHIC team

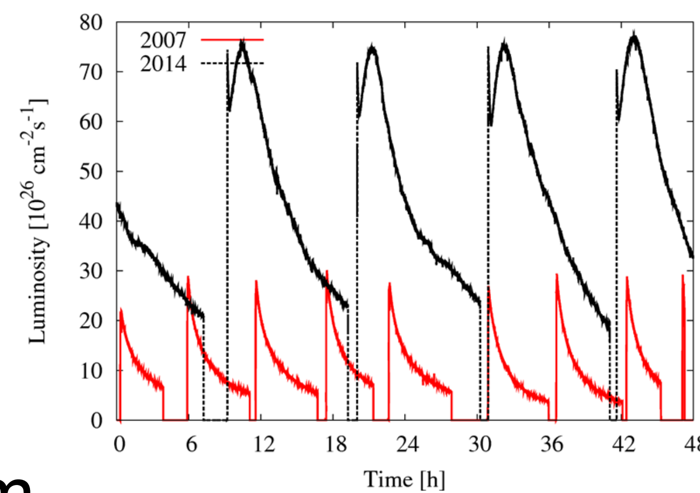
11 May 2016, Busan

Contents

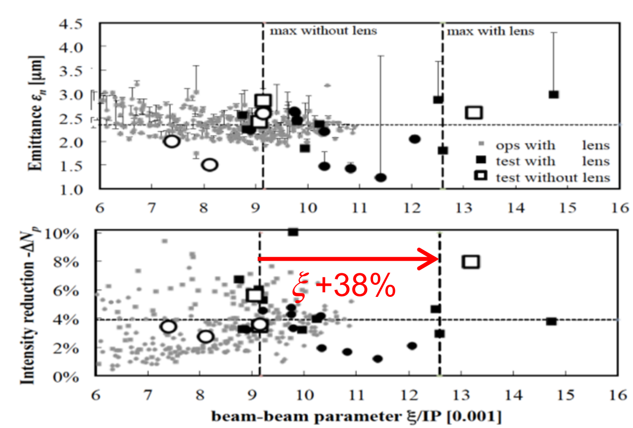
1. A short history and outlook of RHIC
   species, energies, polarization,
   luminosity, low-energy operation



2. Au+Au with stochastic cooling
   bunch intensity
   stochastic cooling

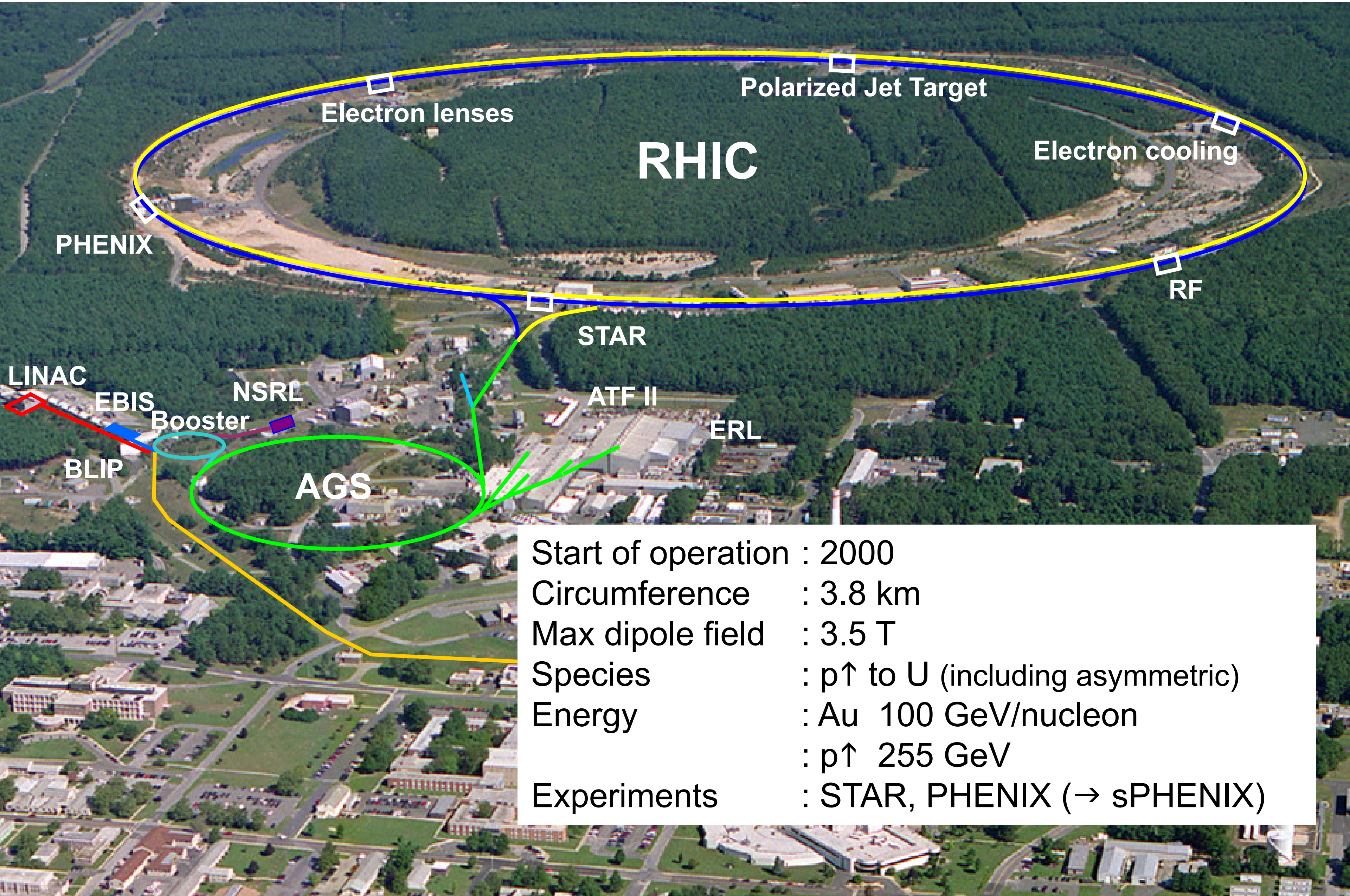


3. p↑+p↑ with head-on beam-beam compensation
   bunch intensity, polarization
   lattice + electron lenses



Wolfram Fischer

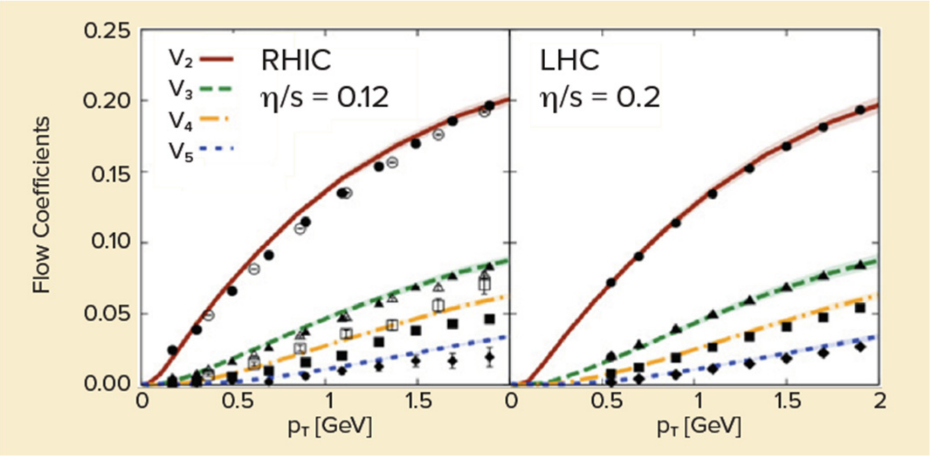
Relativistic Heavy Ion Collider – main parameters



Start of operation	: 2000
Circumference	: 3.8 km
Max dipole field	: 3.5 T
Species	: p↑ to U (including asymmetric)
Energy	: Au 100 GeV/nucleon
	: p↑ 255 GeV
Experiments	: STAR, PHENIX (→ sPHENIX)

RHIC science programs

1. Creation and study of the Quark Gluon Plasma (A+A)



[2015 NSAC Long Range Plan for Nuclear Science]

QGP close to perfect liquid

The QGP is a strongly coupled nearly "**perfect**" liquid (η/s near the quantum limit 1/4π). RHIC's cooler QGP is (on average) closer to perfection than the 40% hotter QGP produced at LHC.

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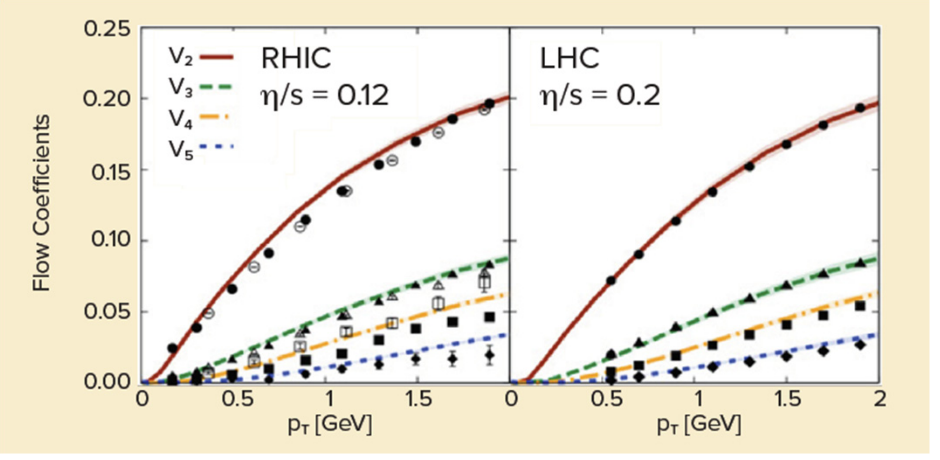

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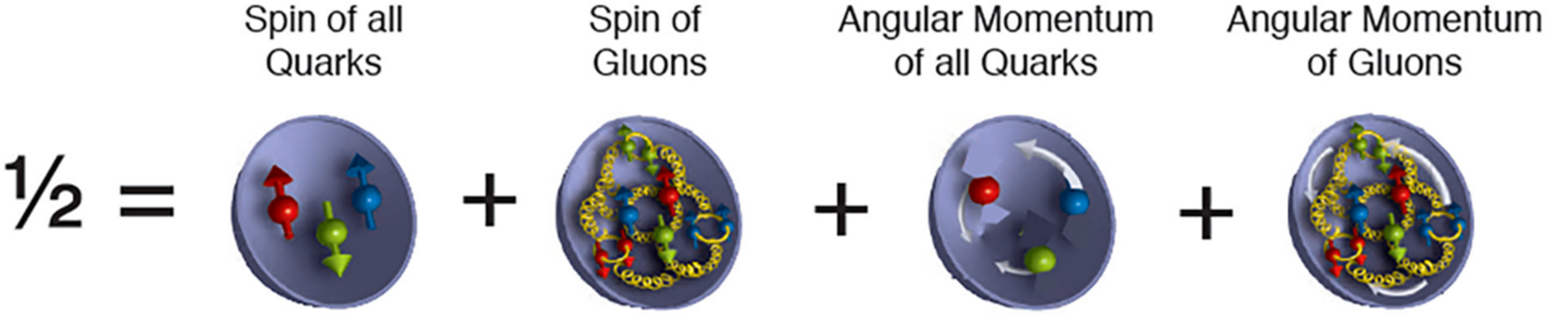

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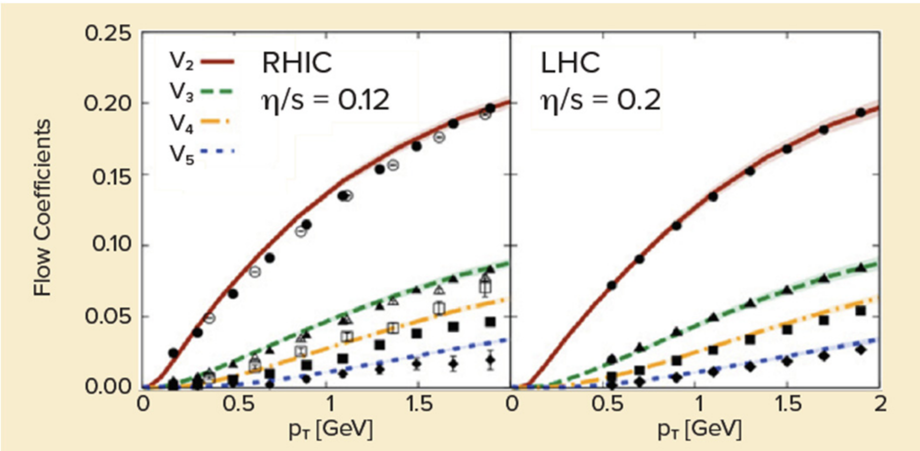

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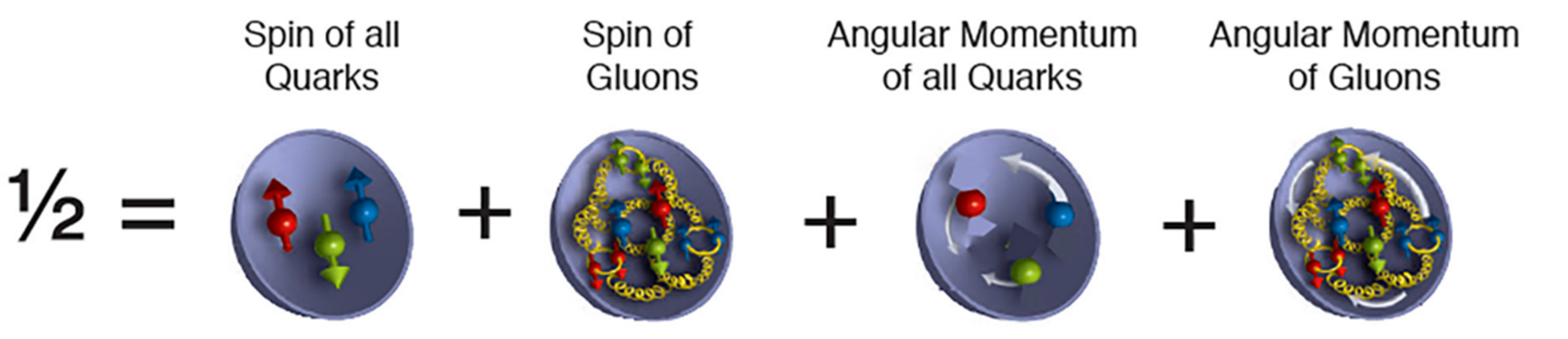


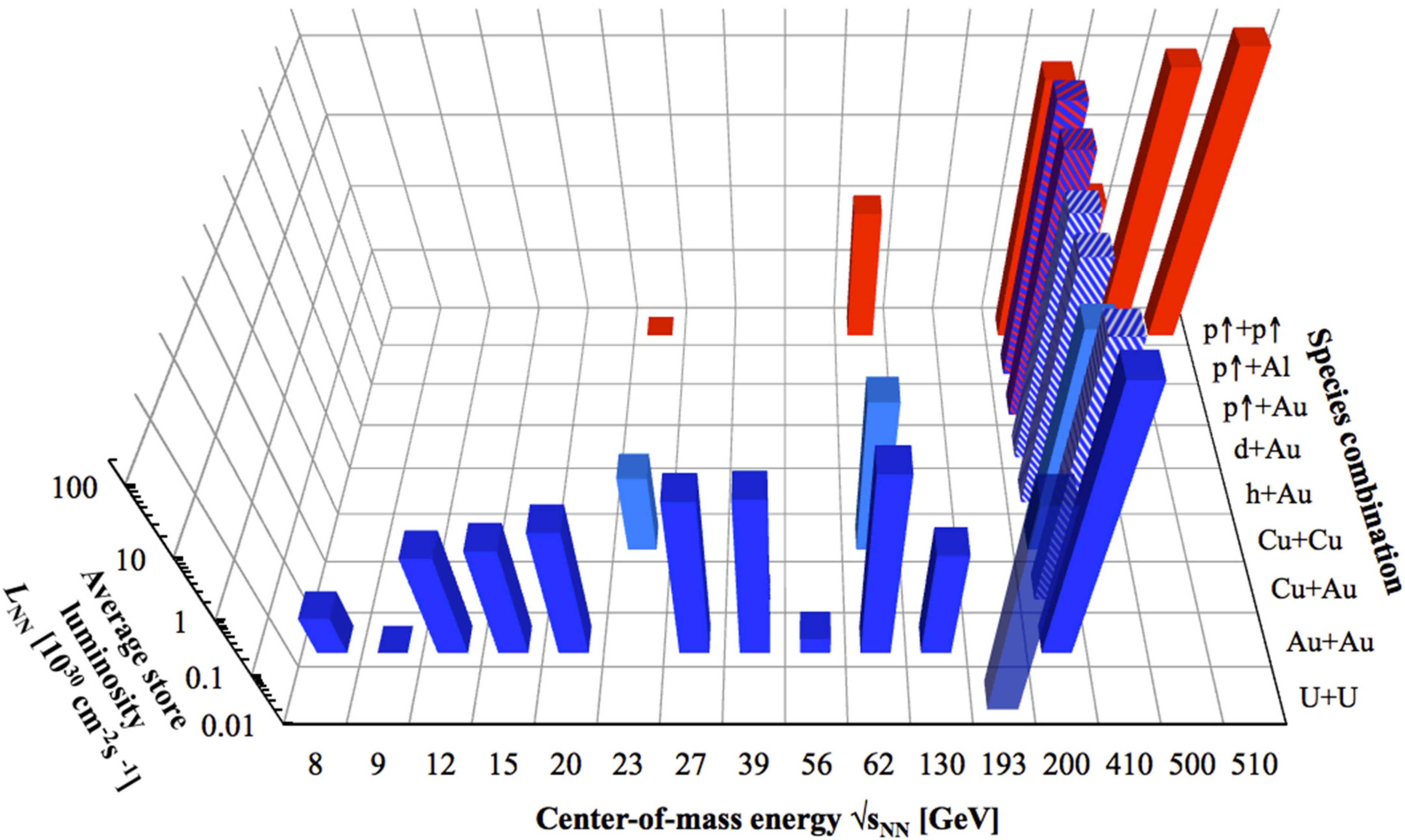
[2015 NSAC Long Range Plan for Nucl. Science]

↑ **RHIC result: not zero** (2009 data only)

major emphasis. Data from the RHIC run in 2009 have **for the first time shown that gluons inside a proton are polarized.** The integral of $\Delta g(x,Q^2=10\,\mathrm{GeV}^2)$ in the region $x > 0.05$ is $\mathbf{0.20}^{+0.06}_{-0.07}$ at 90% C.L.

RHIC – all running modes to date

2001 to 2016



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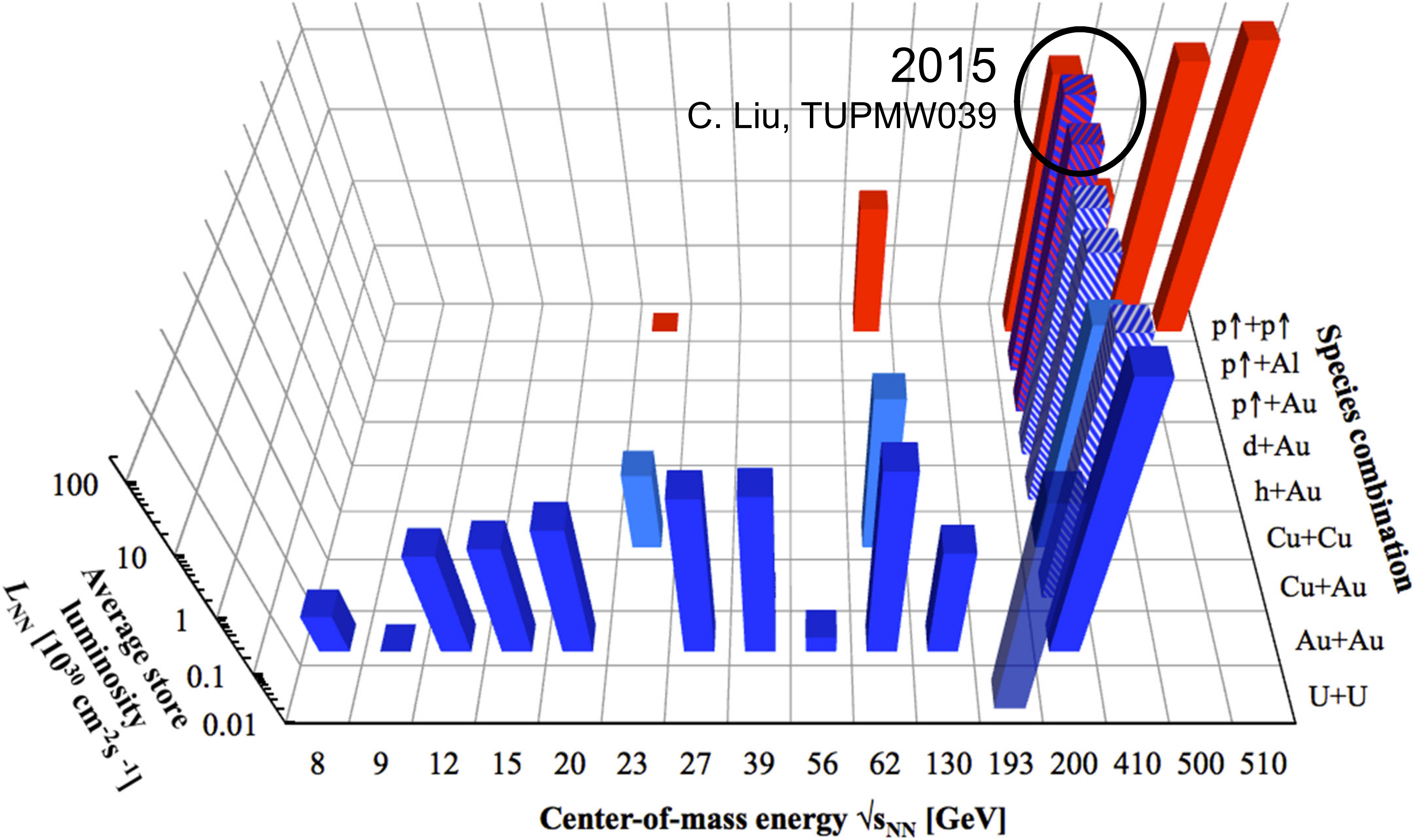
RHIC – all running modes to date

2001 to 2016



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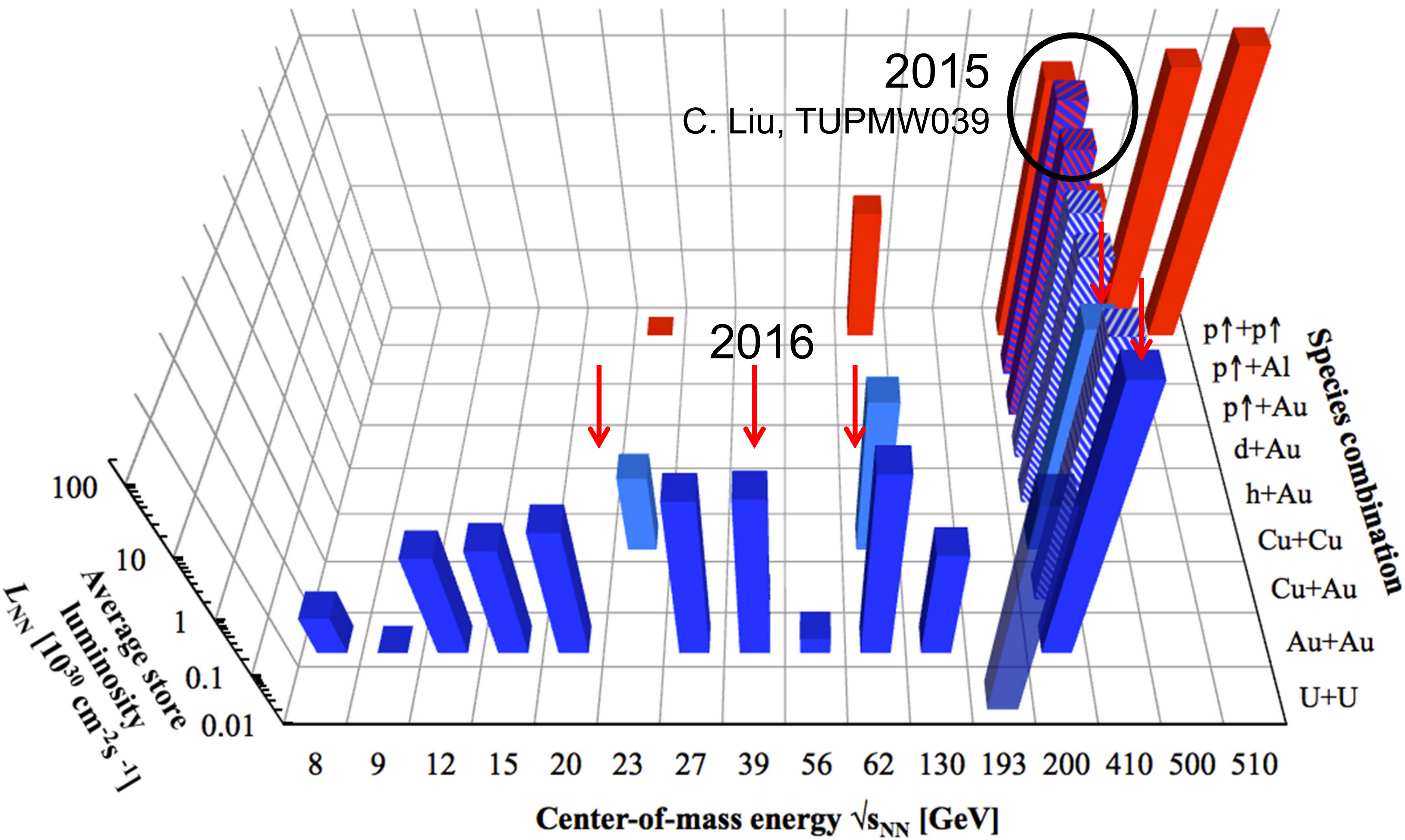

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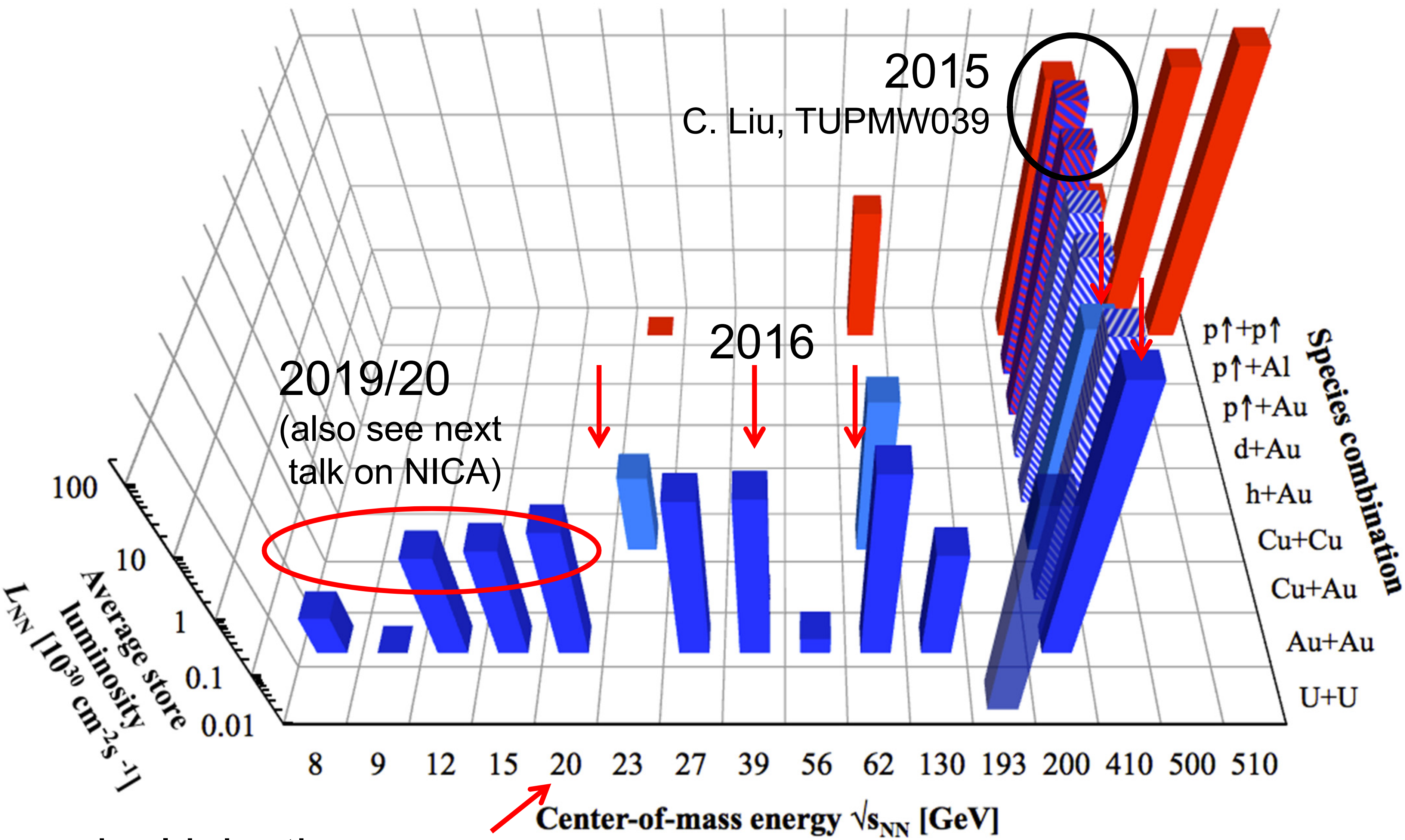

nominal injection energy

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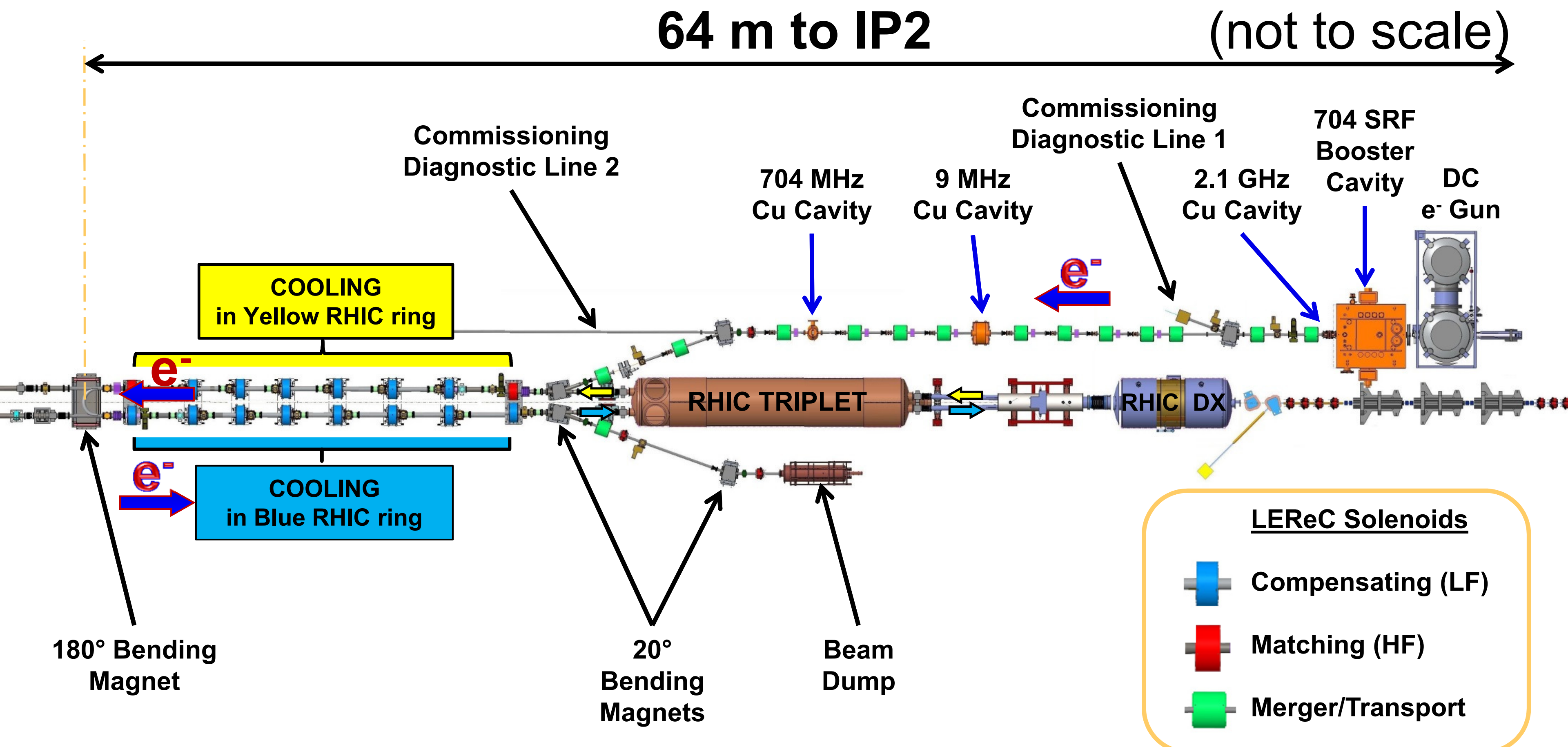
Low Energy RHIC electron Cooling (LEReC)

A. Fedotov



Energies E : 1.6, 2.0 (2.65) MeV

Avg. current I_{avg} : 27 mA

Momentum $\delta p/p$: 5×10^{-4}

Luminosity gain : 4×

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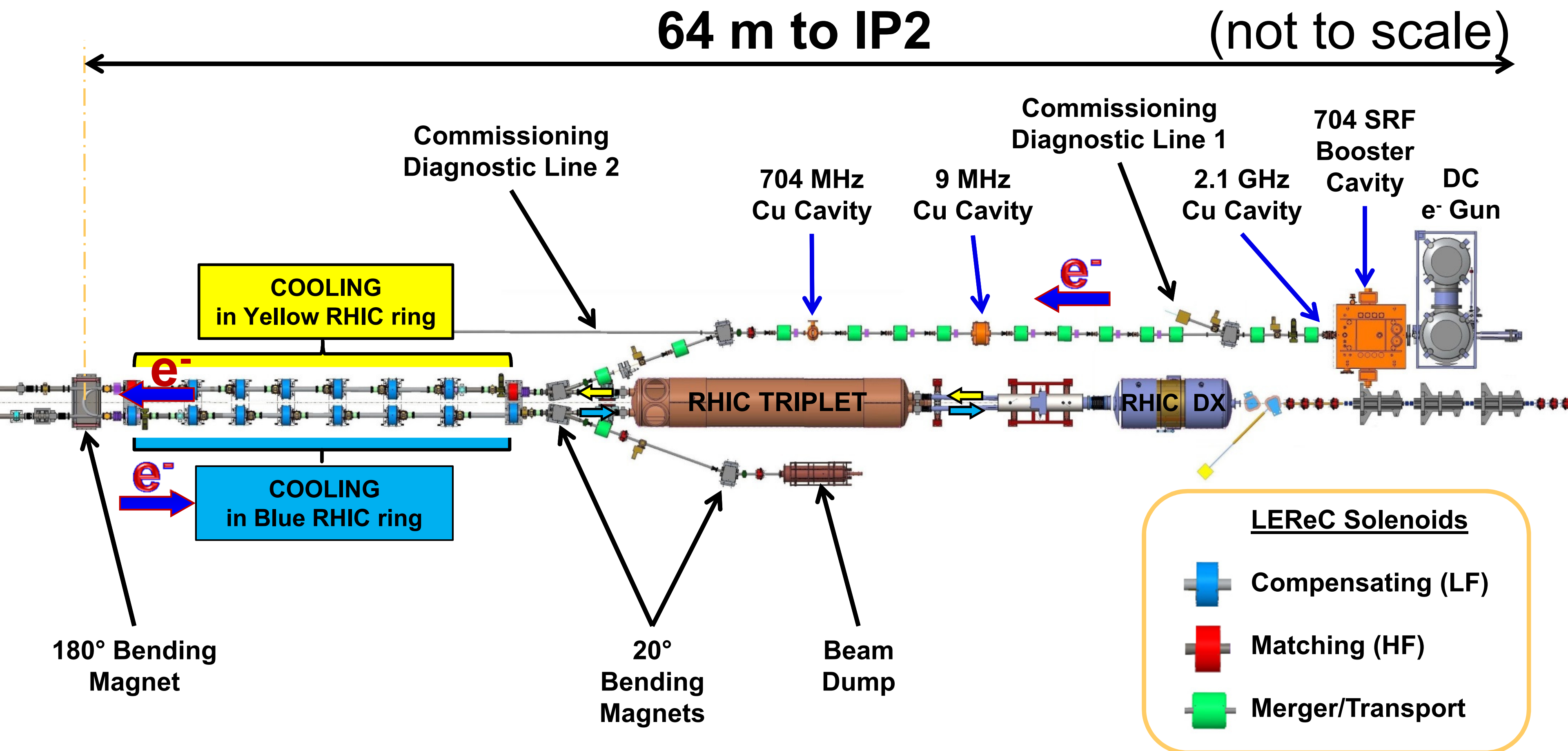

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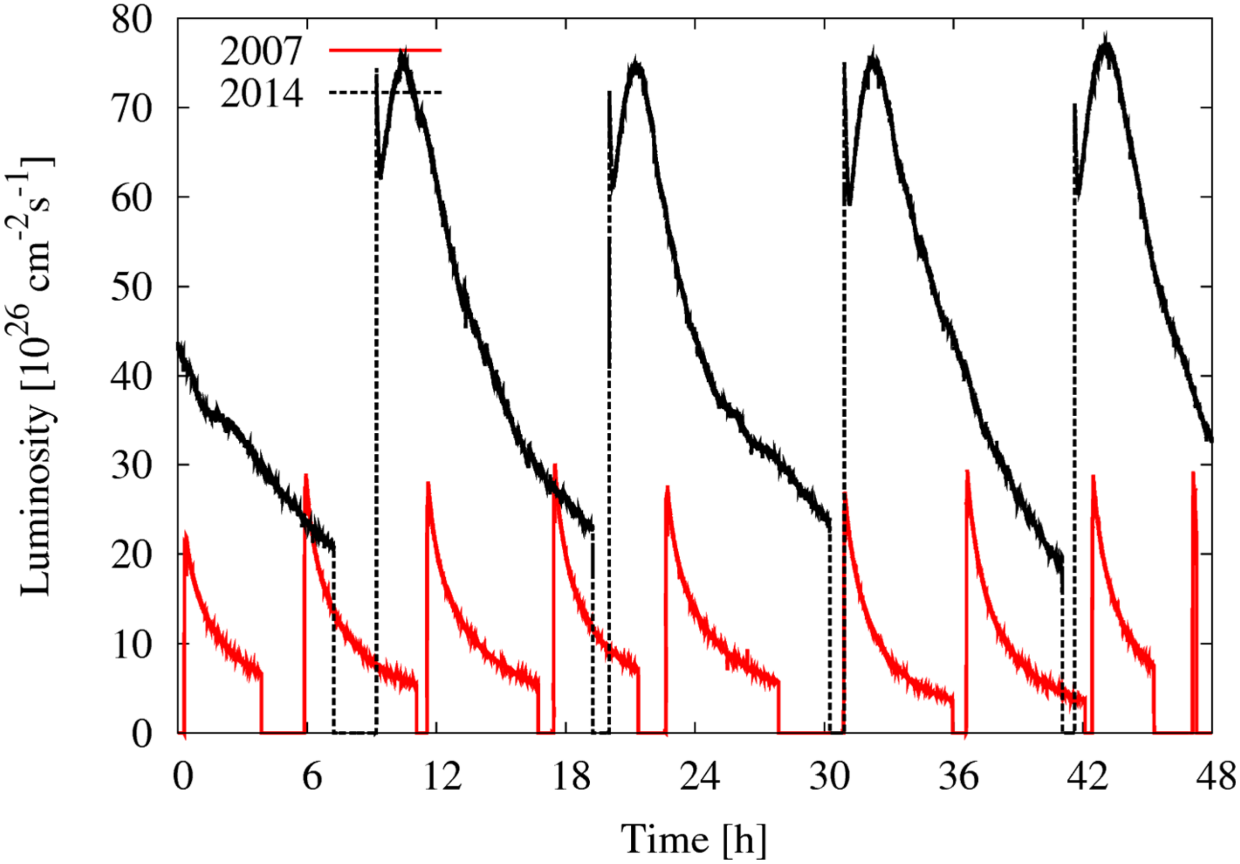
1st bunched beam electron cooler

planned operation in 2019/2020

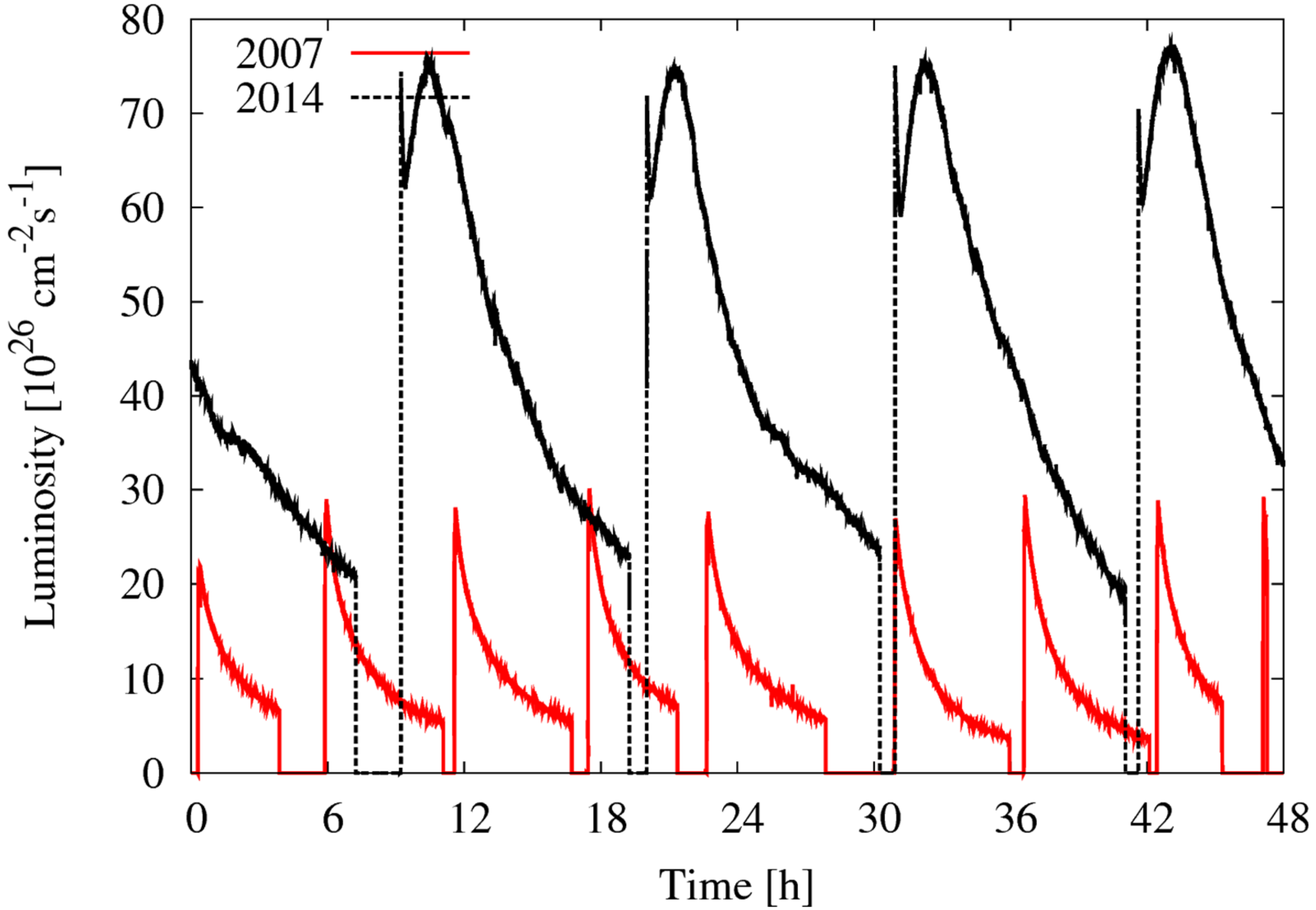


RHIC Au+Au operation with stochastic cooling

Main luminosity limit: intrabeam scattering

RHIC Run-14

Delivering RHIC-II Au+Au luminosity



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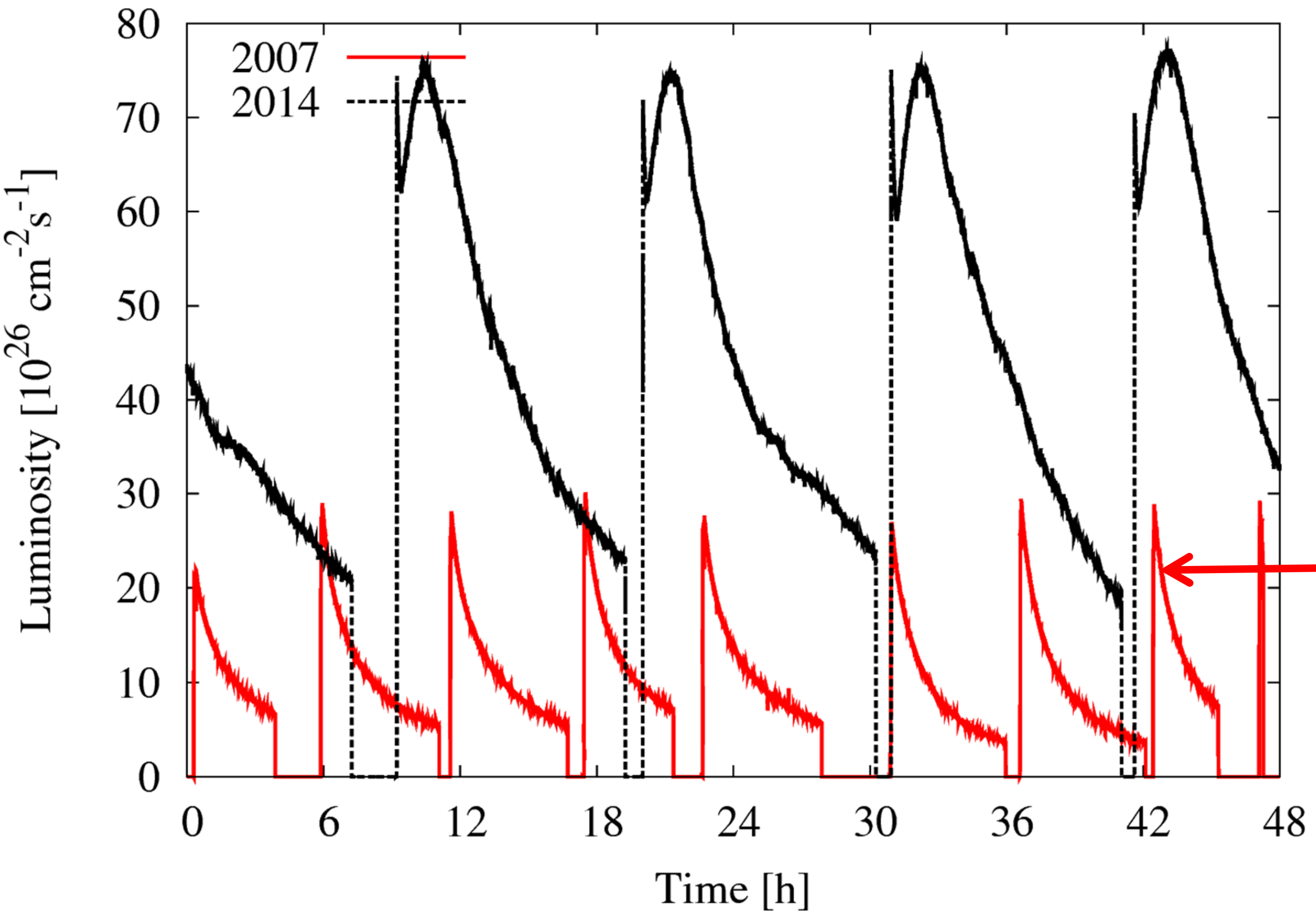

2007, Beginning of RHIC-II upgrade

RHIC Run-14

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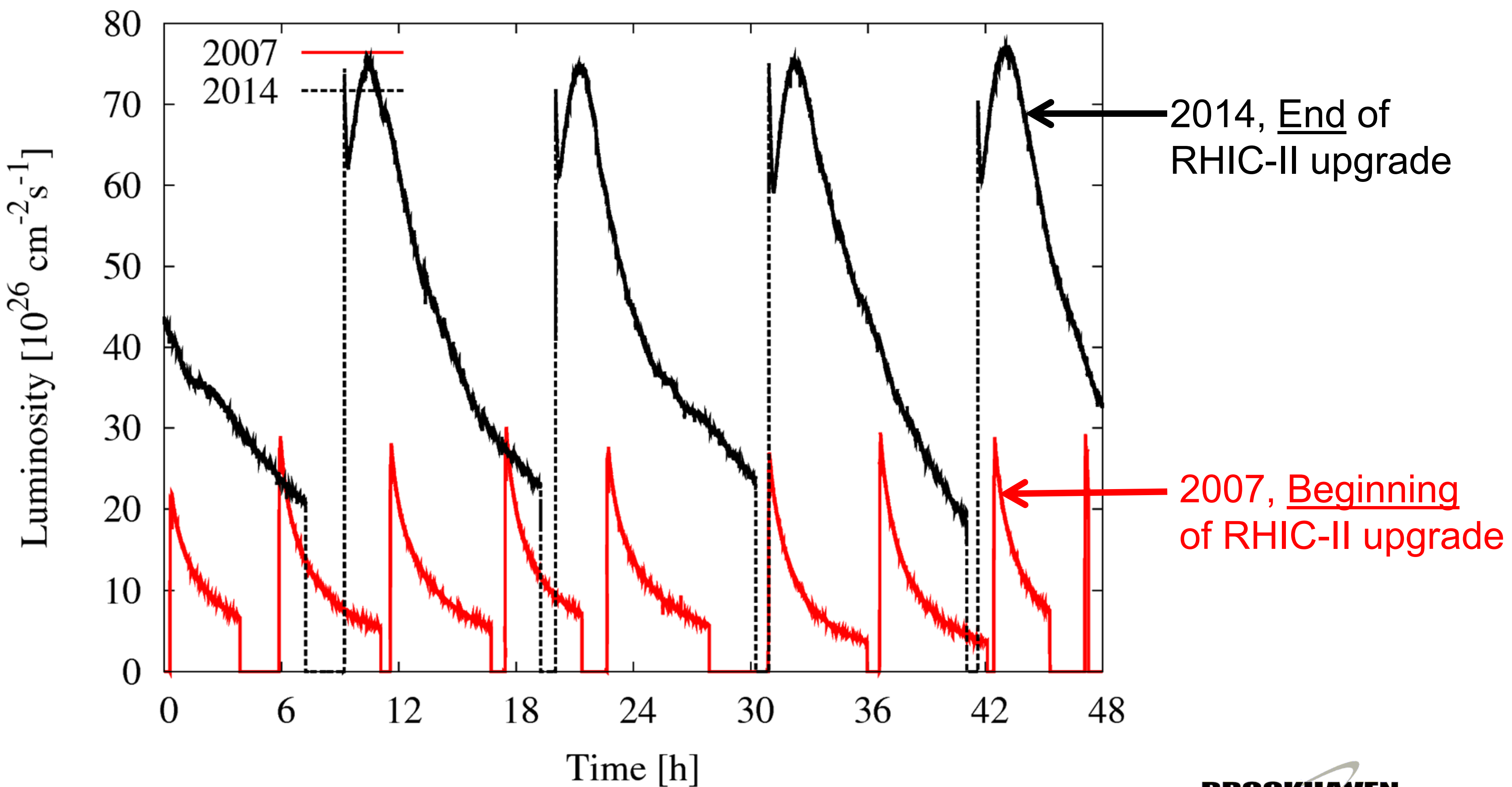

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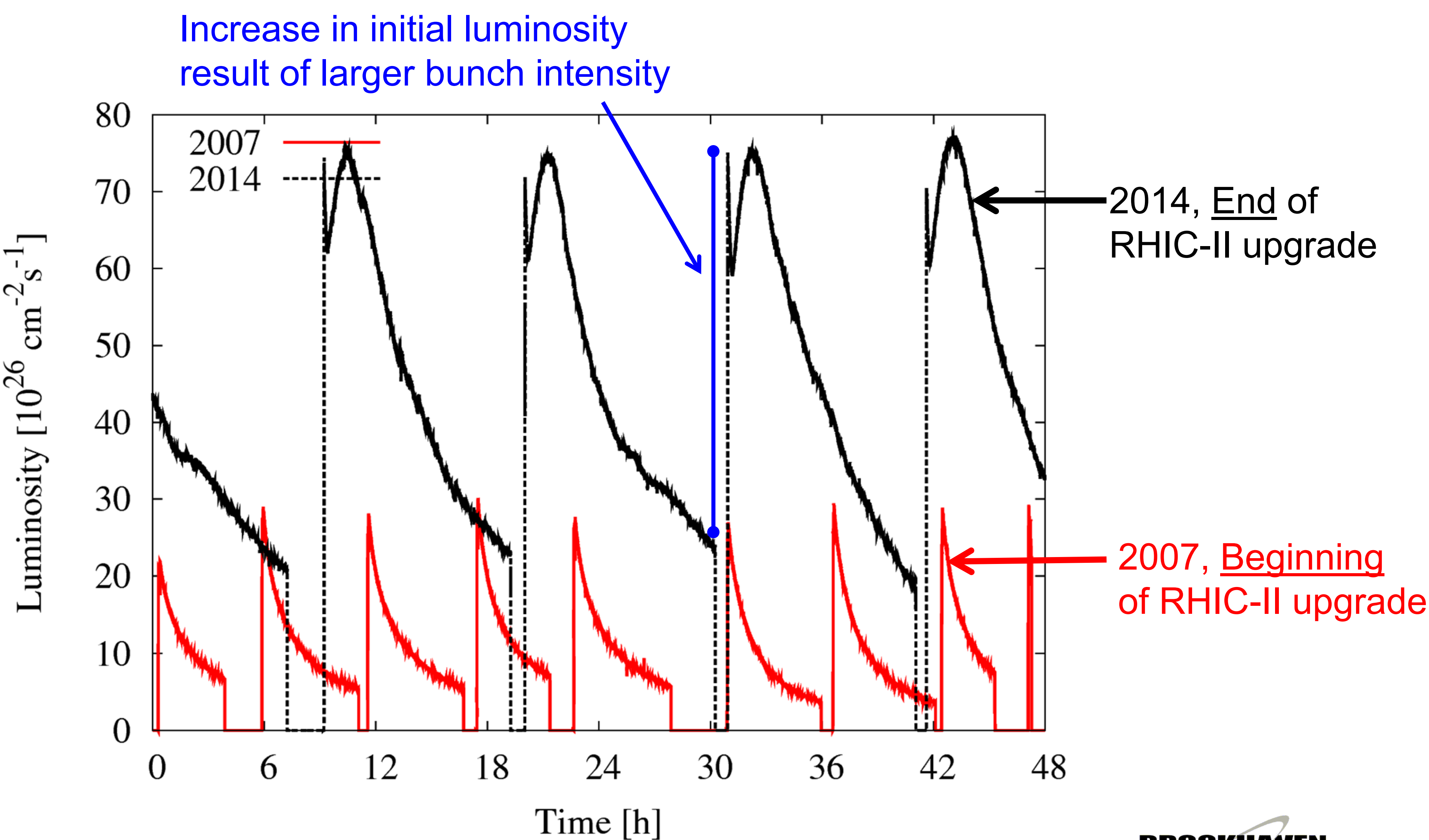

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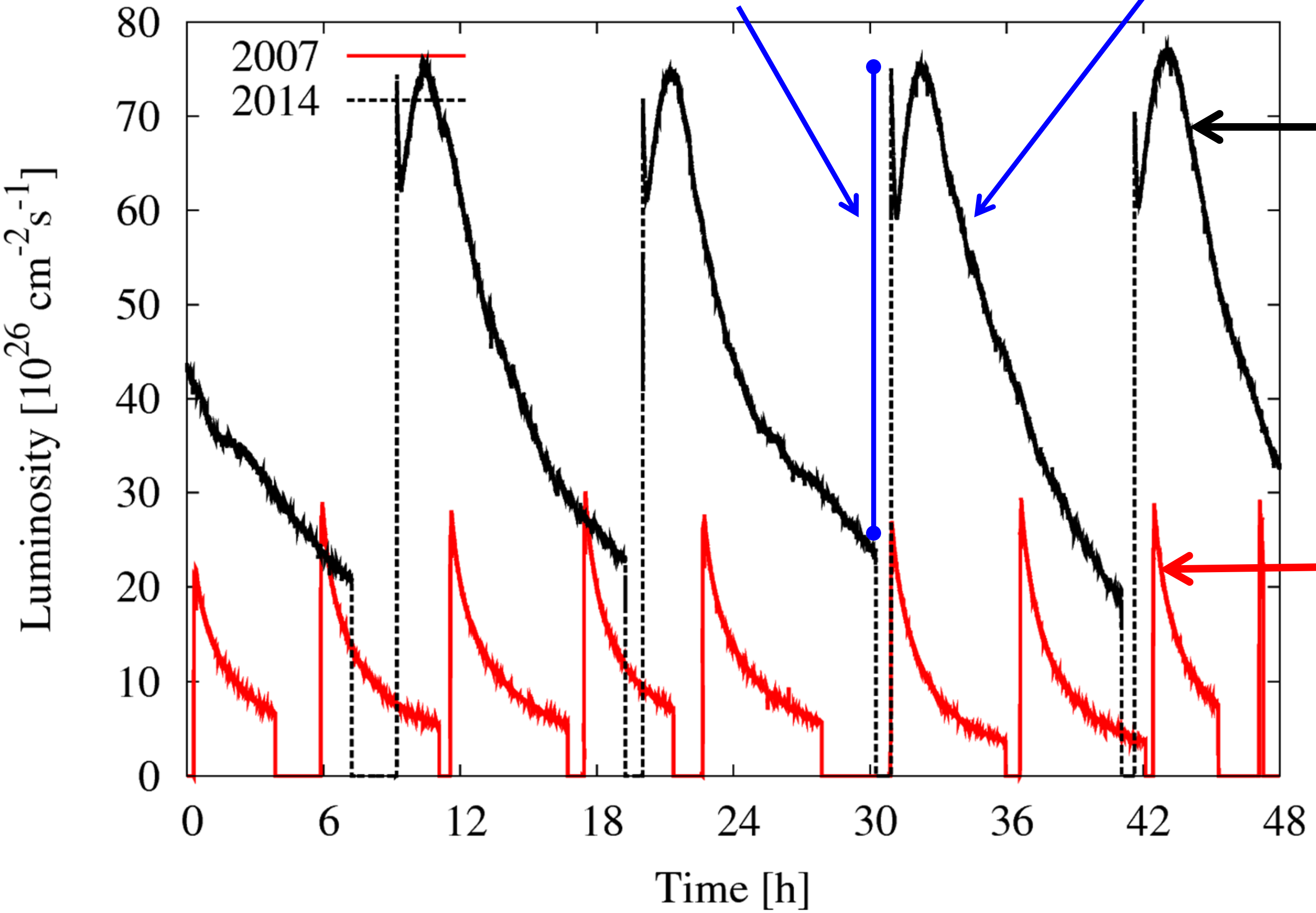
RHIC Run-14

Delivering RHIC-II Au+Au luminosity

Increase in luminosity lifetime result of 3D stochastic cooling, high peak luminosity not useful without cooling (IBS), losses burn-off dominated

Increase in initial luminosity result of larger bunch intensity

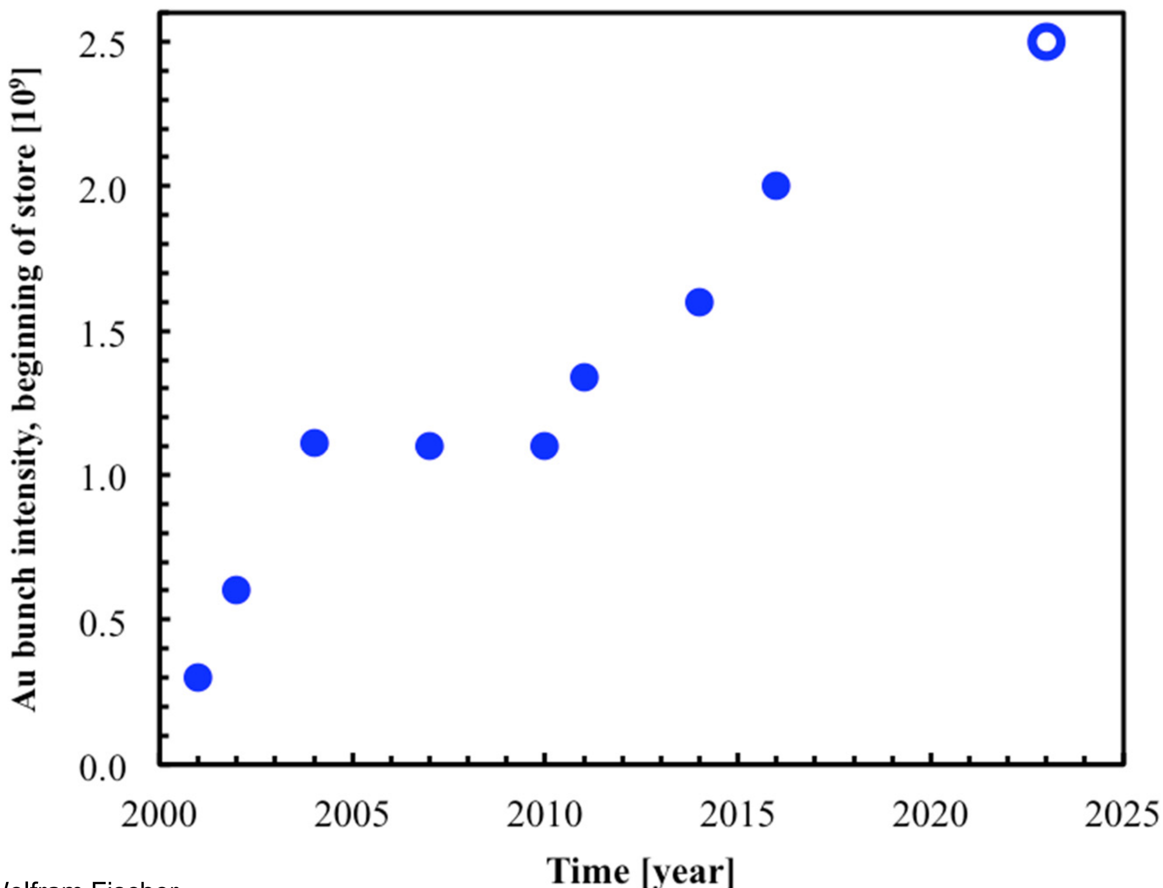


2014, End of RHIC-II upgrade

2007, Beginning of RHIC-II upgrade

Au bunch intensity evolution

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



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

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

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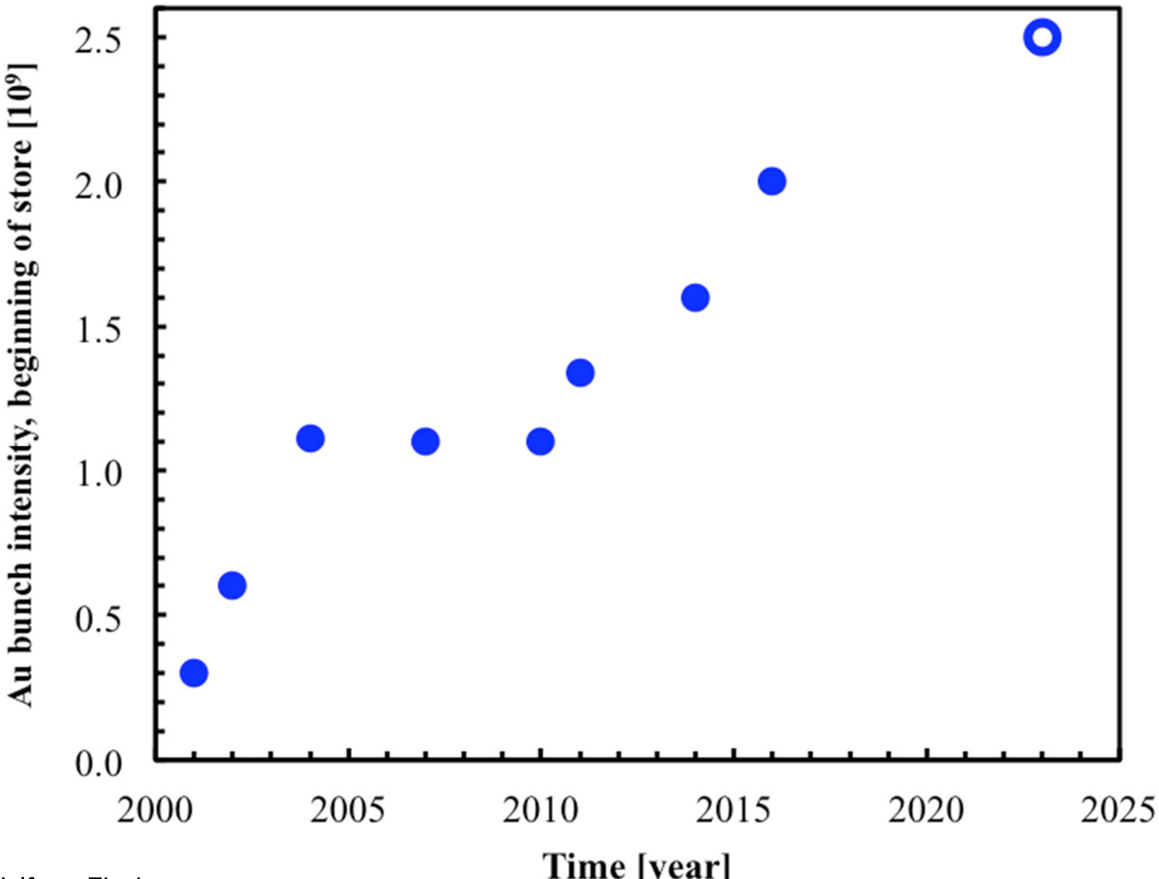

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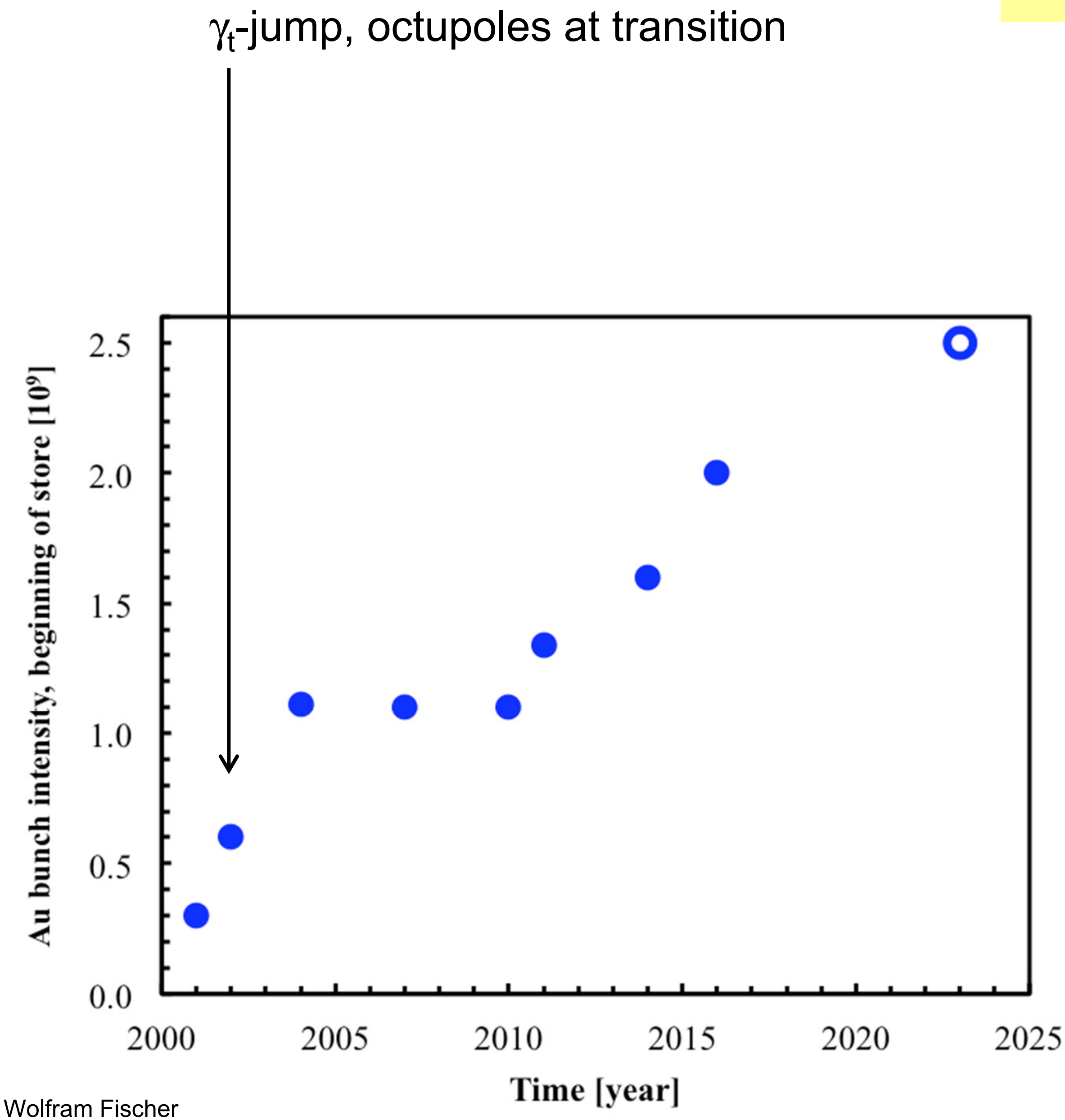

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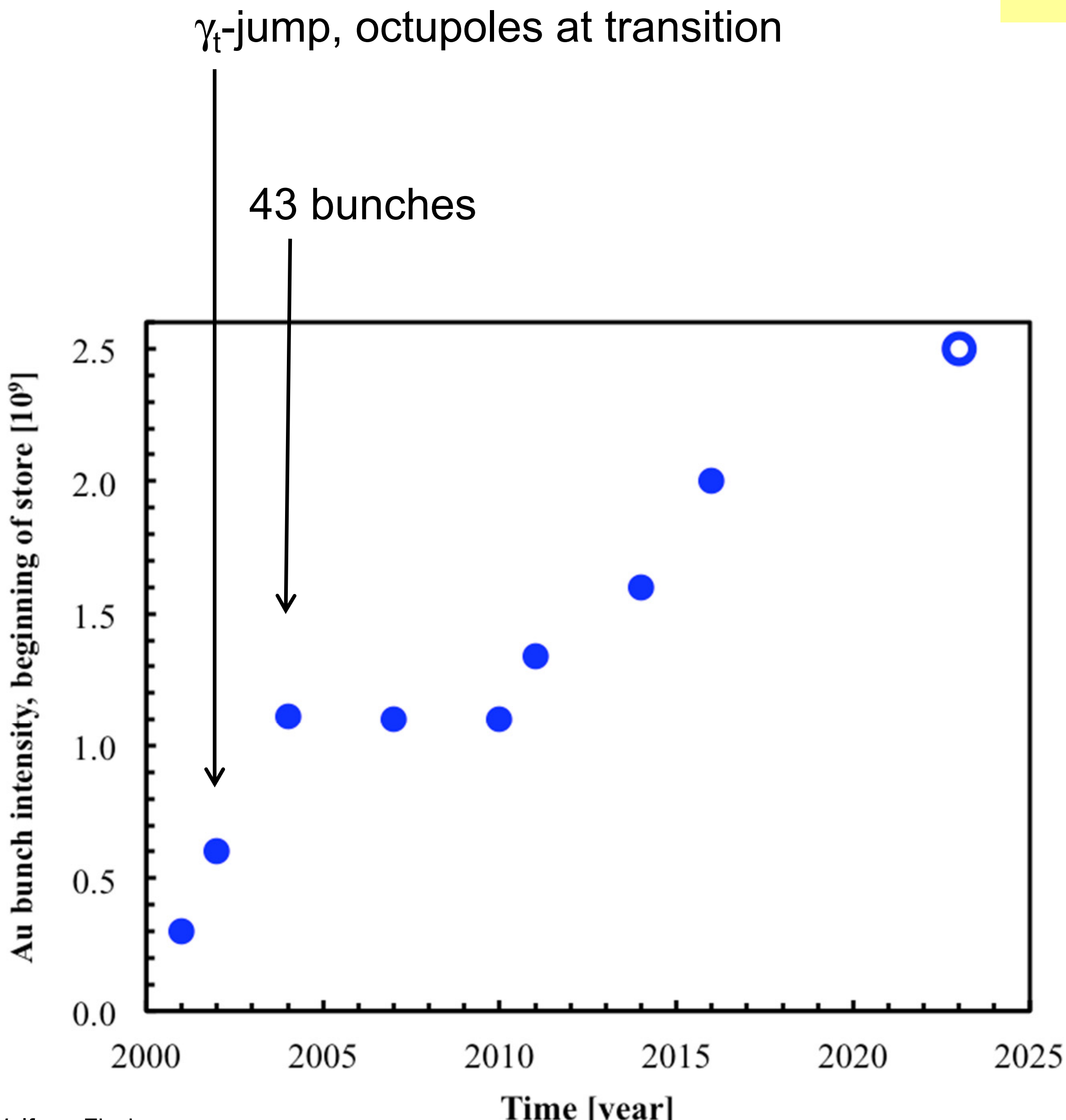

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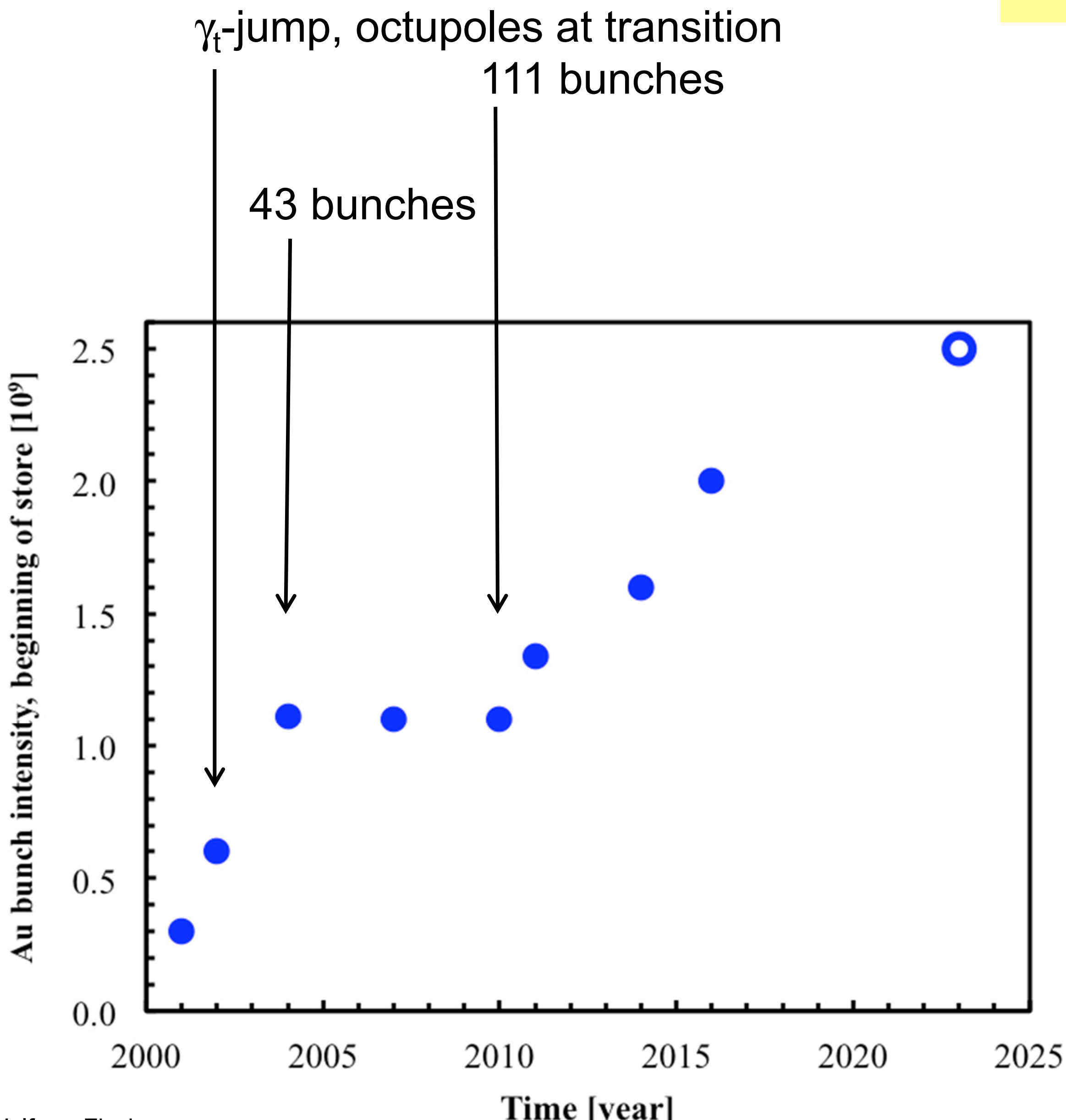

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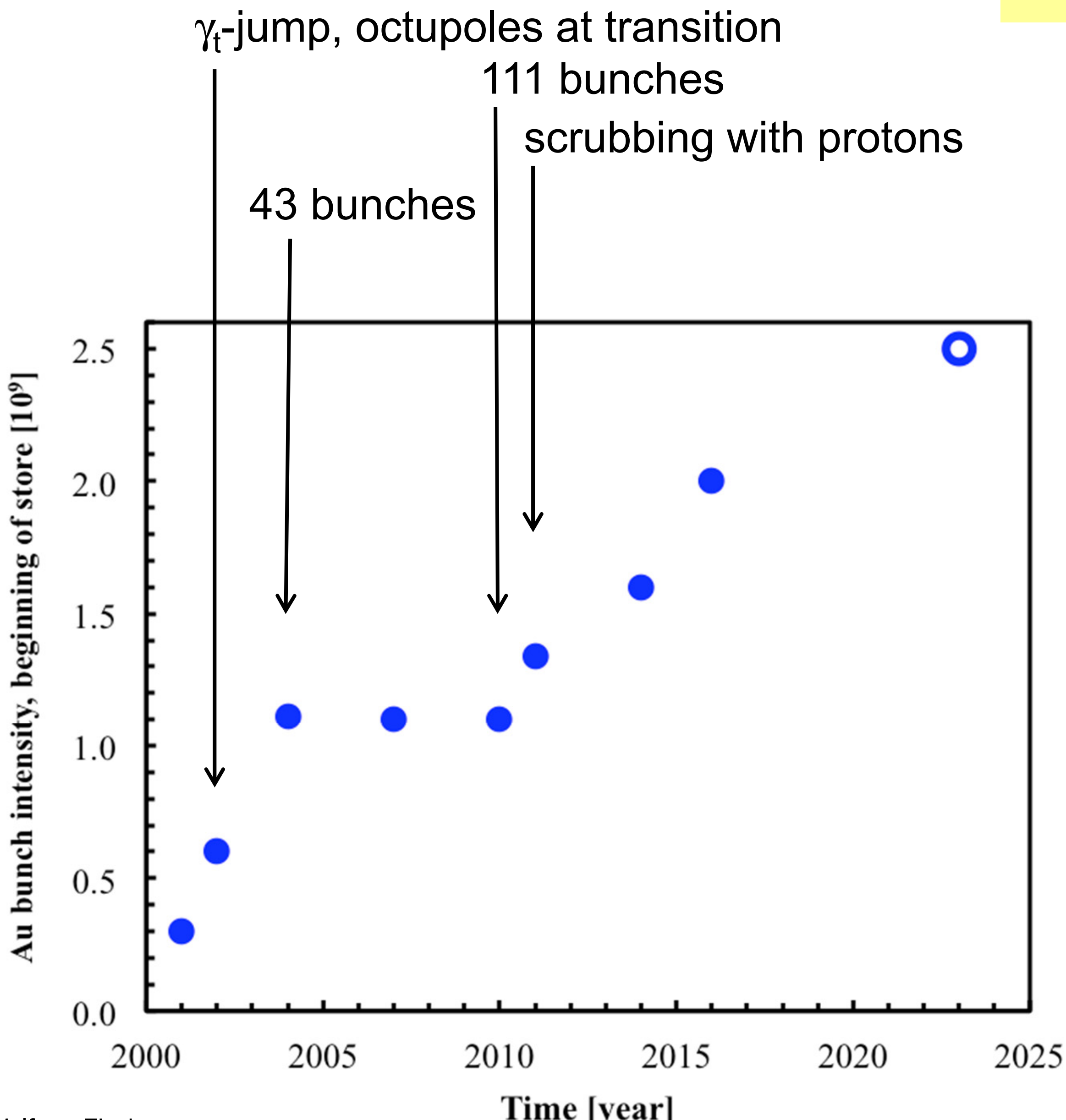

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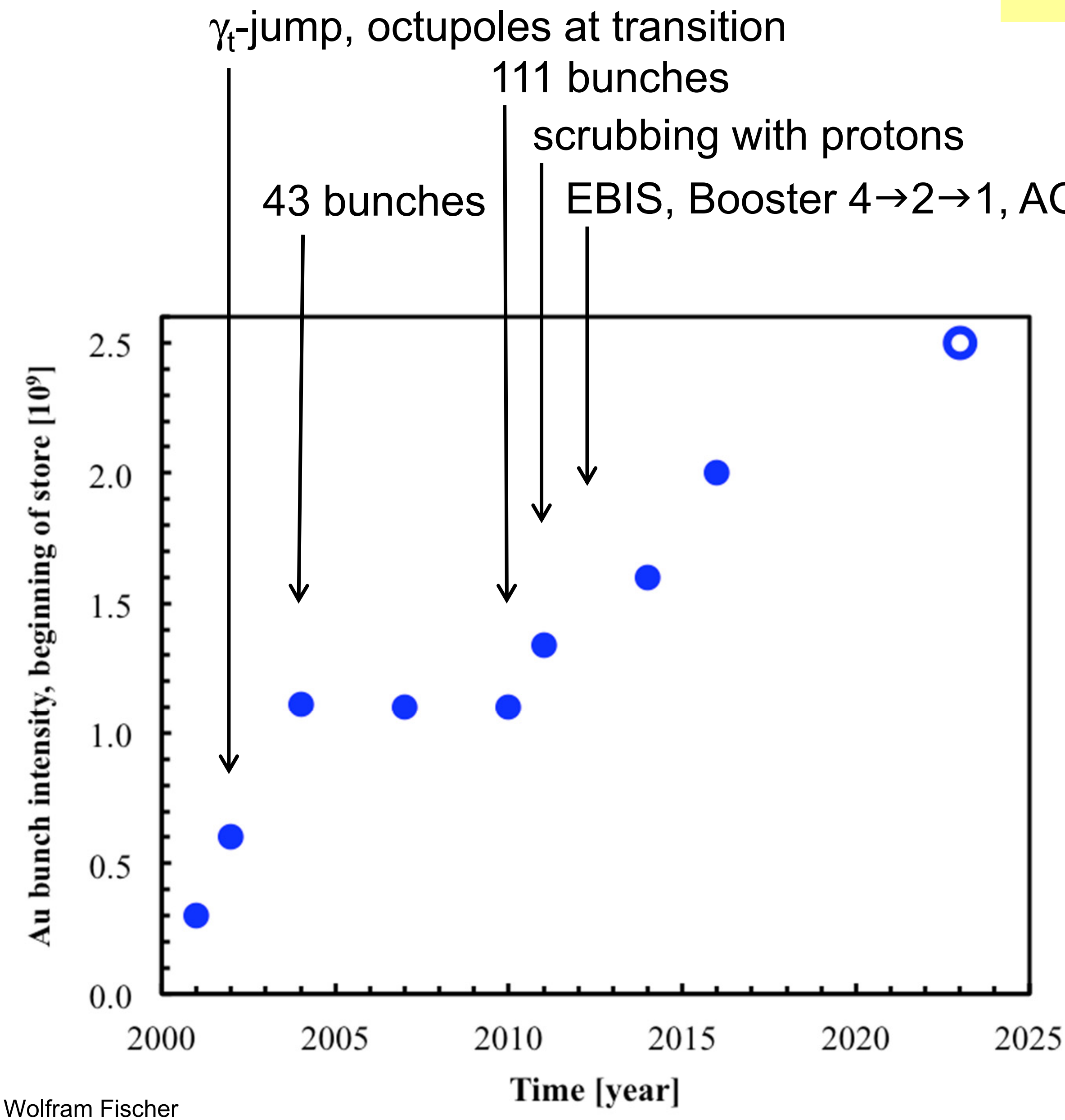

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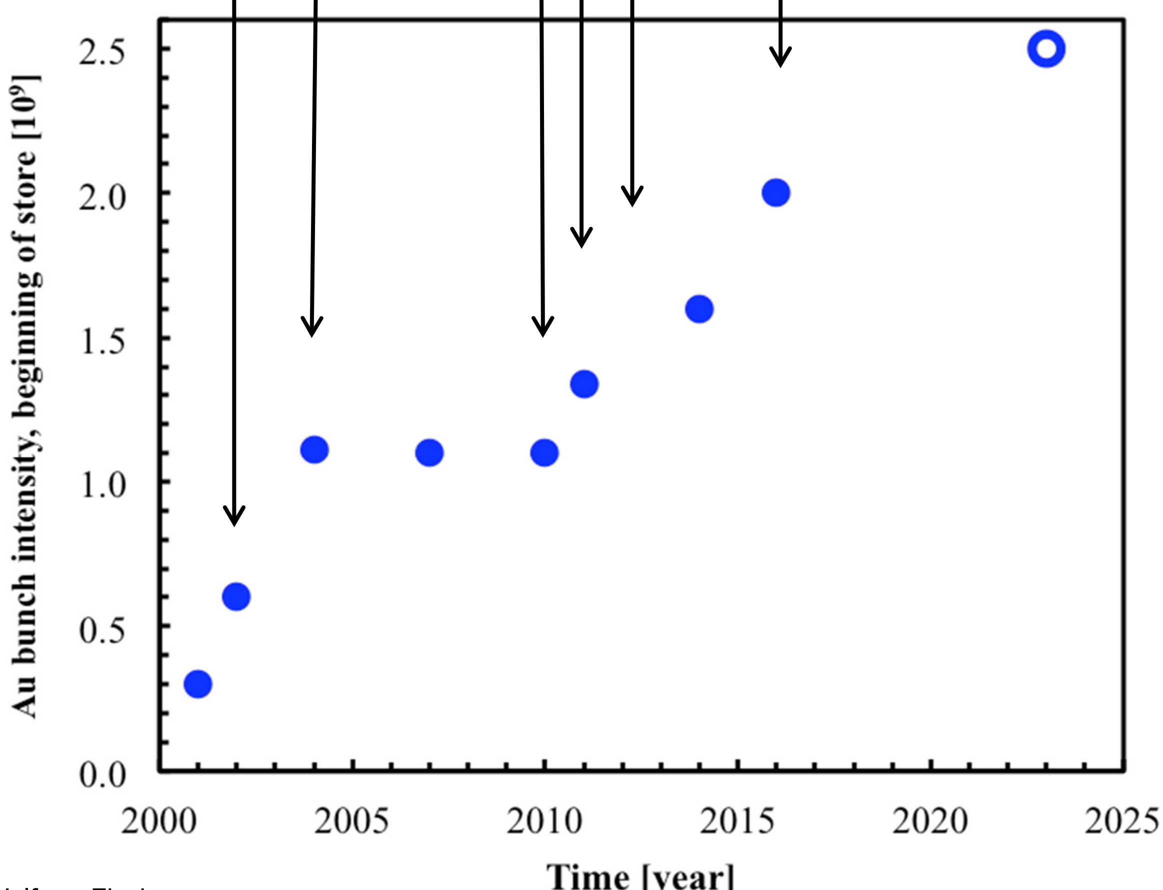

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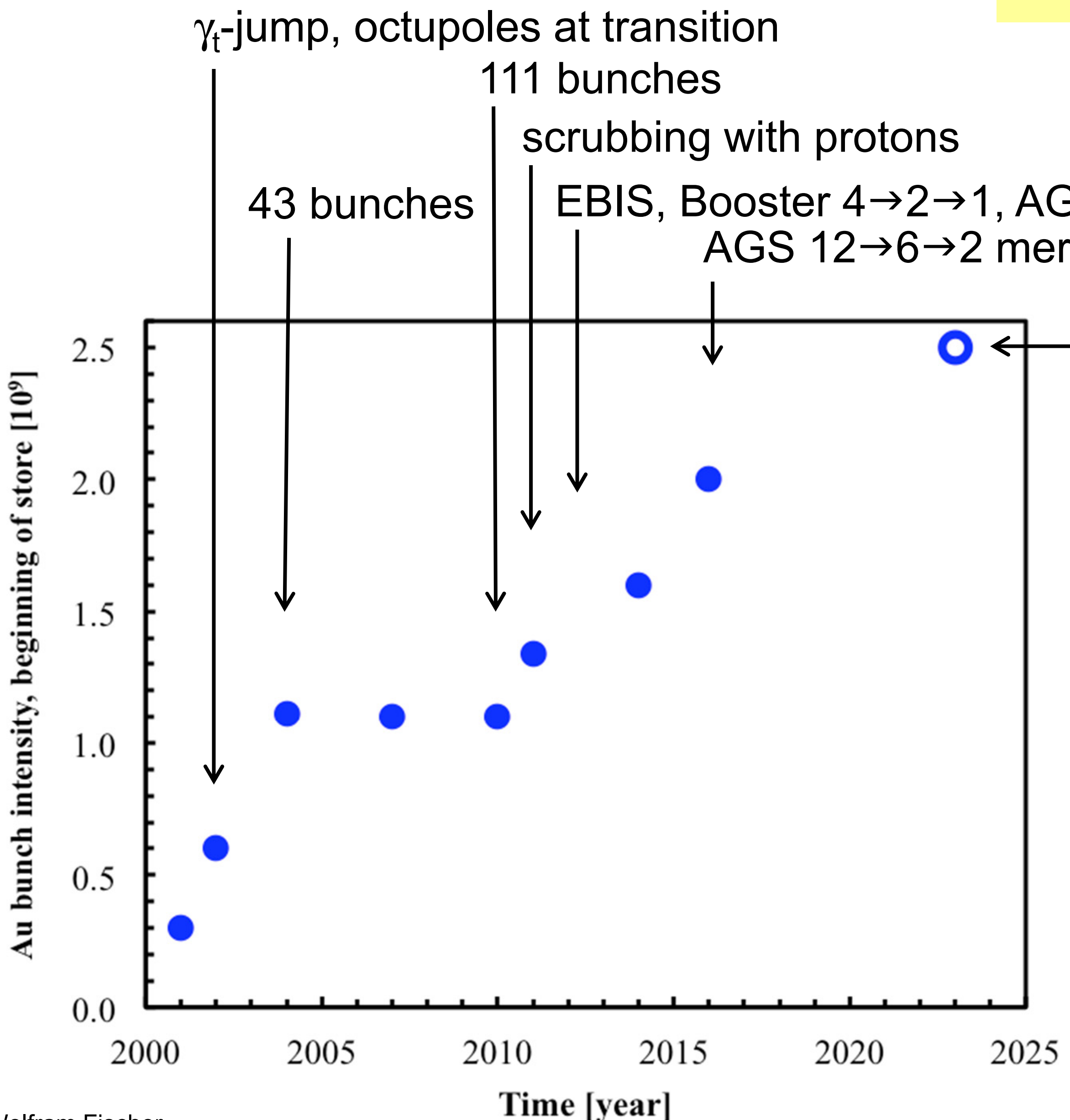

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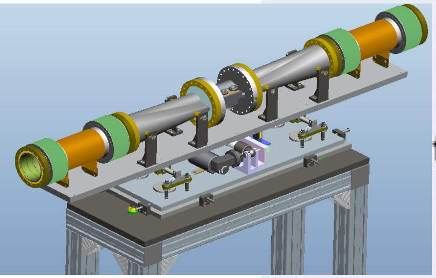
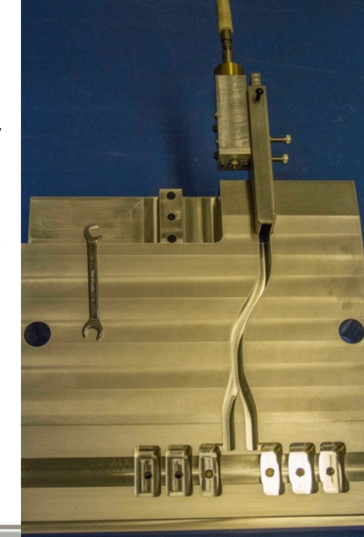
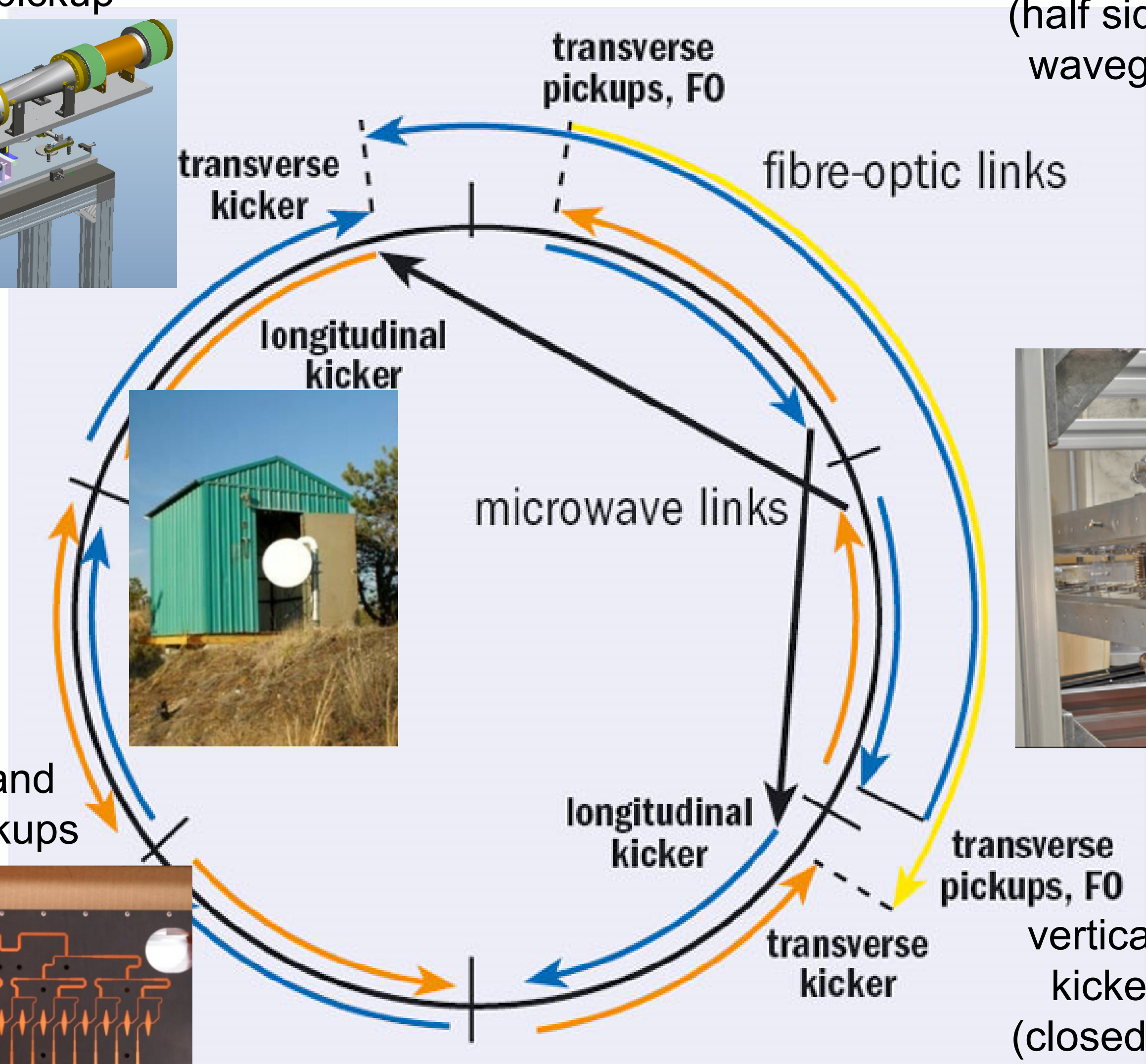
3D stochastic cooling for heavy ions

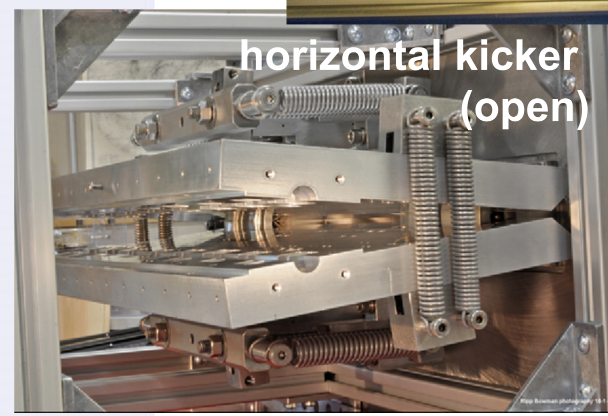
longitudinal pickup



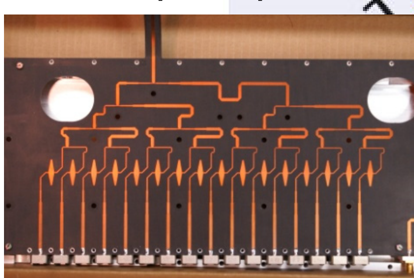
longitudinal kicker cavity (half side with waveguides)



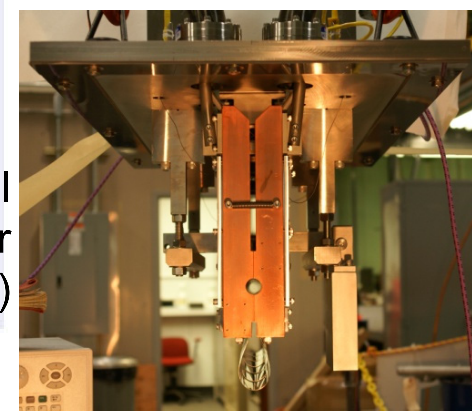




horizontal and vertical pickups



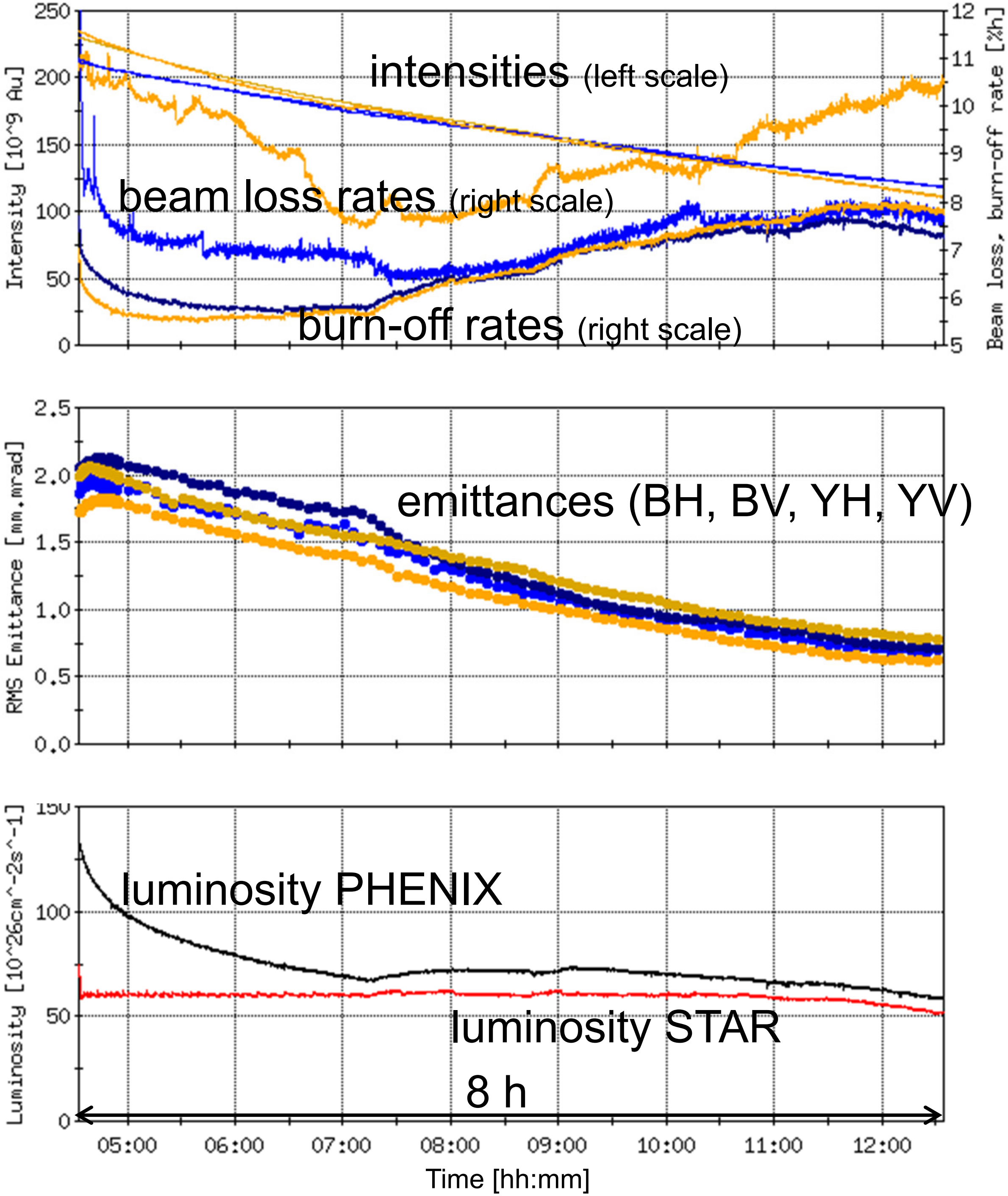
vertical kicker (closed)



5-9 GHz, cooling times ~1 h

M. Brennan, M. Blaskiewicz, F. Severino, PRL **100** 174803 (2008); K. Mernick PRSTAB, PAC, EPAC

Au+Au operation in 2016



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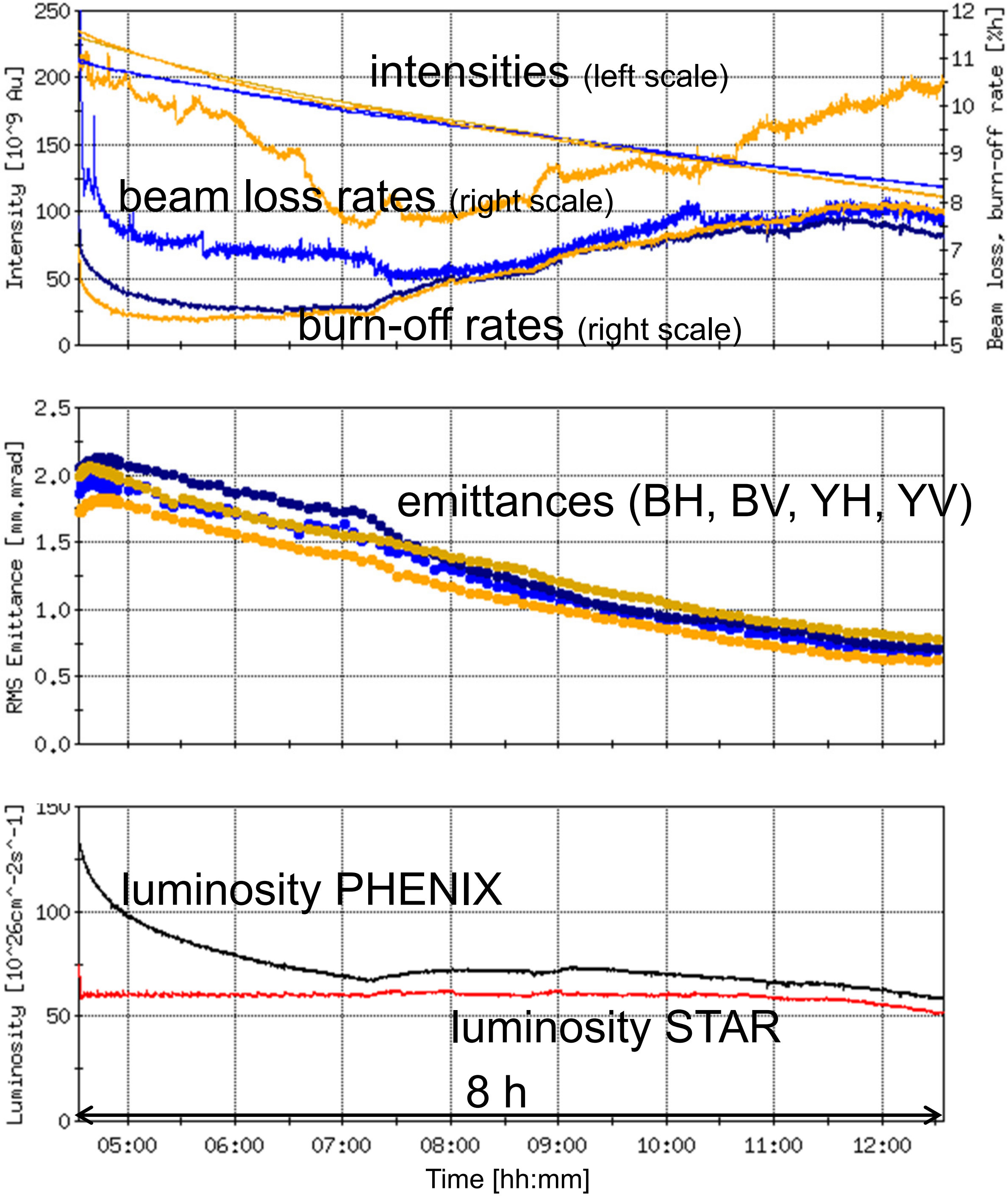
Au+Au operation in 2016



1. One experiment (STAR) with max leveled *L* (use transverse offset for leveling)
   other experiment (PHENIX) without max *L*

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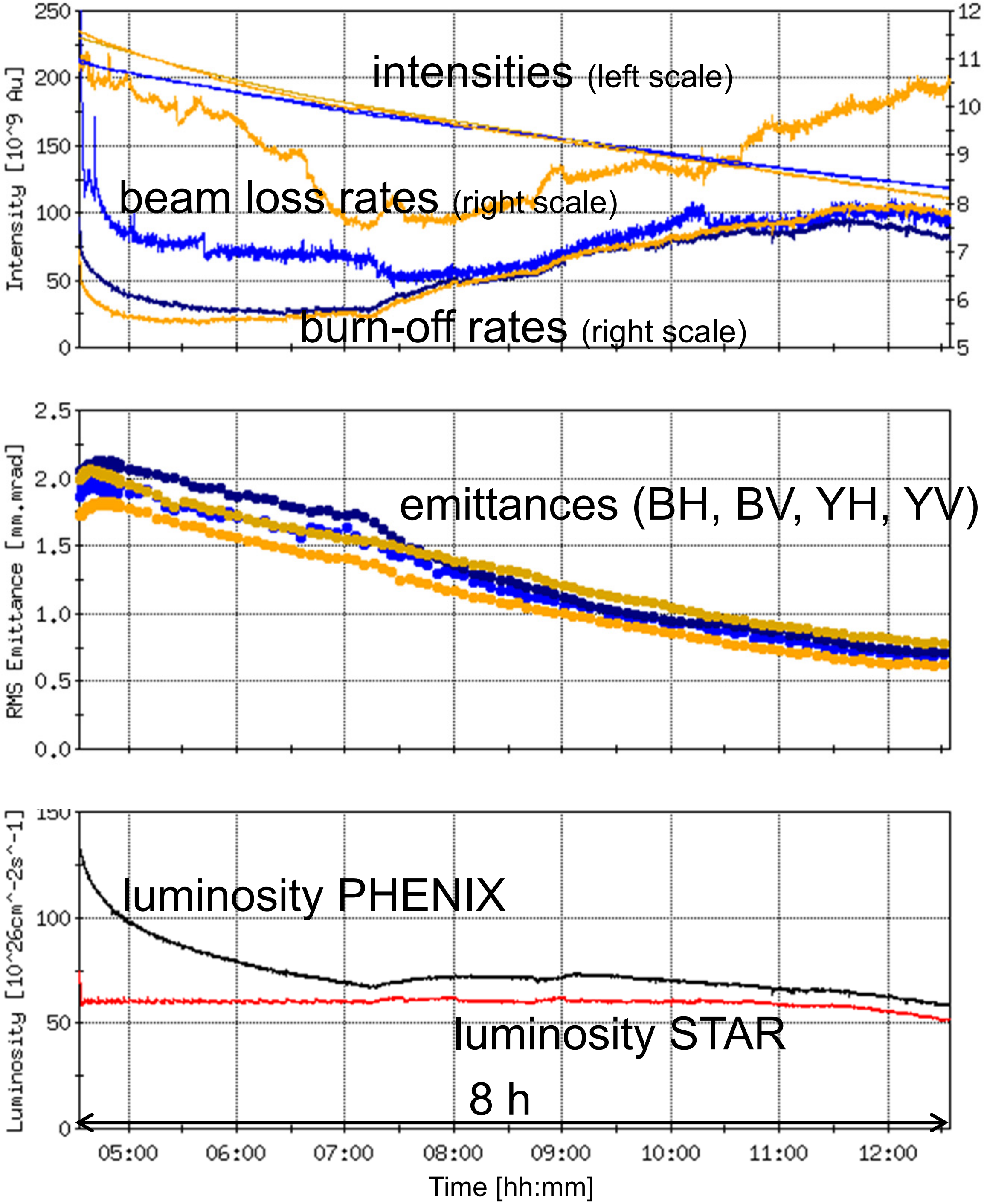
Au+Au operation in 2016



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2. Operate close to burn-off limit (all beam losses due to collision)

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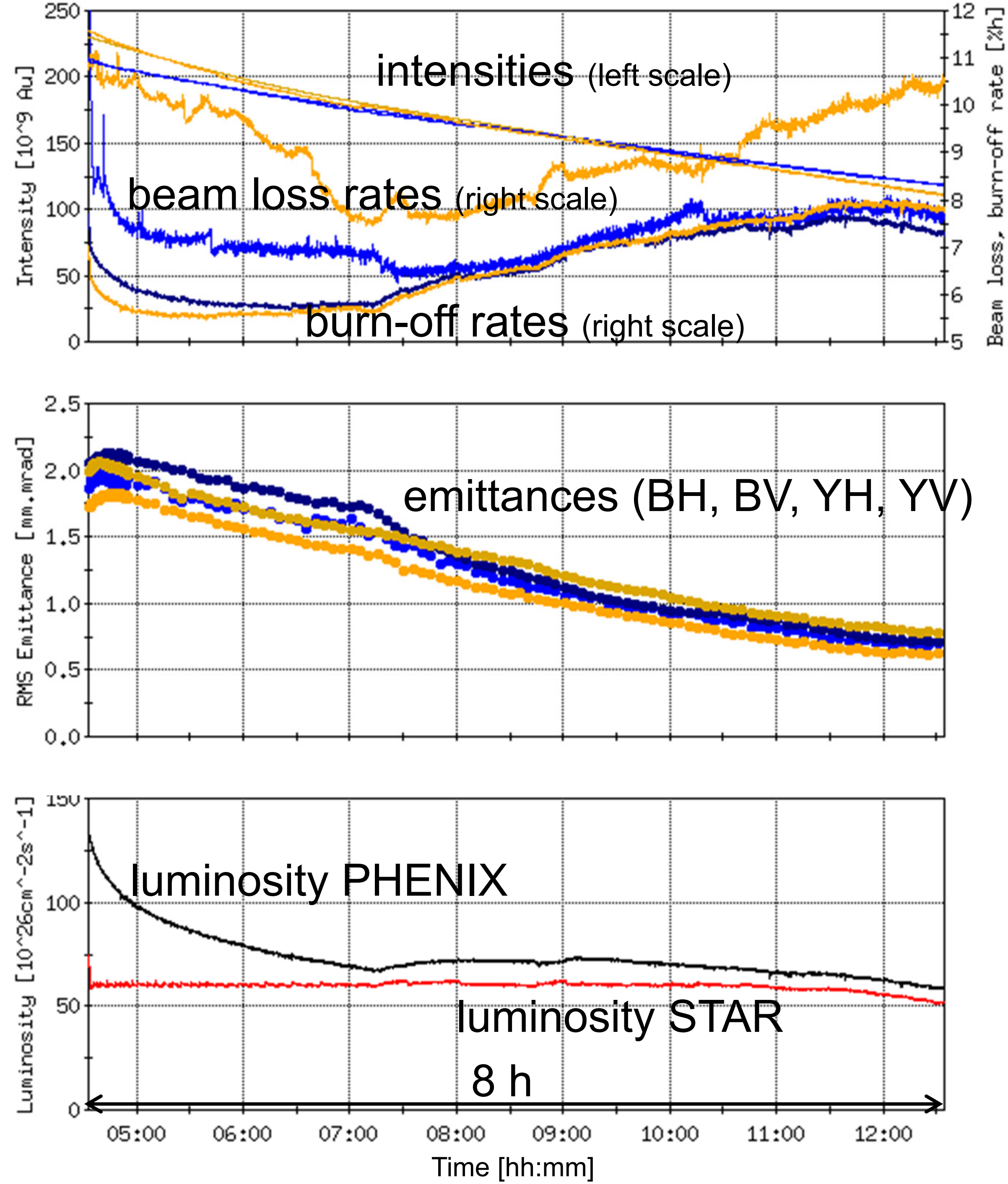

1. One experiment (STAR) with max leveled *L* (use transverse offset for leveling) other experiment (PHENIX) without max *L*

2. Operate close to burn-off limit (all beam losses due to collision)

3. Reduced initial cooling reduces *L* in PHENIX, preserves intensity, and allows for longer leveled stores for STAR

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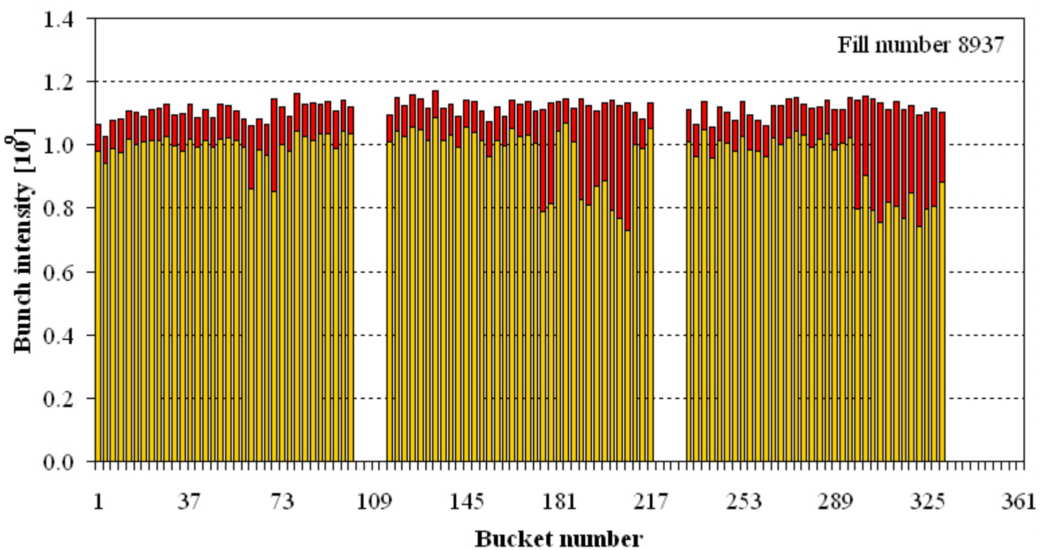
Ion beams with cooling – tolerance for emittance growth

$$L(t)=\frac{1}{4\pi}f_0N\frac{N_b^2(t)}{\varepsilon(t)\beta^*(t)}h(\beta^*,\sigma_s,\theta)$$

- Bunch intensity N_b, was limited by
  transition instability in RHIC

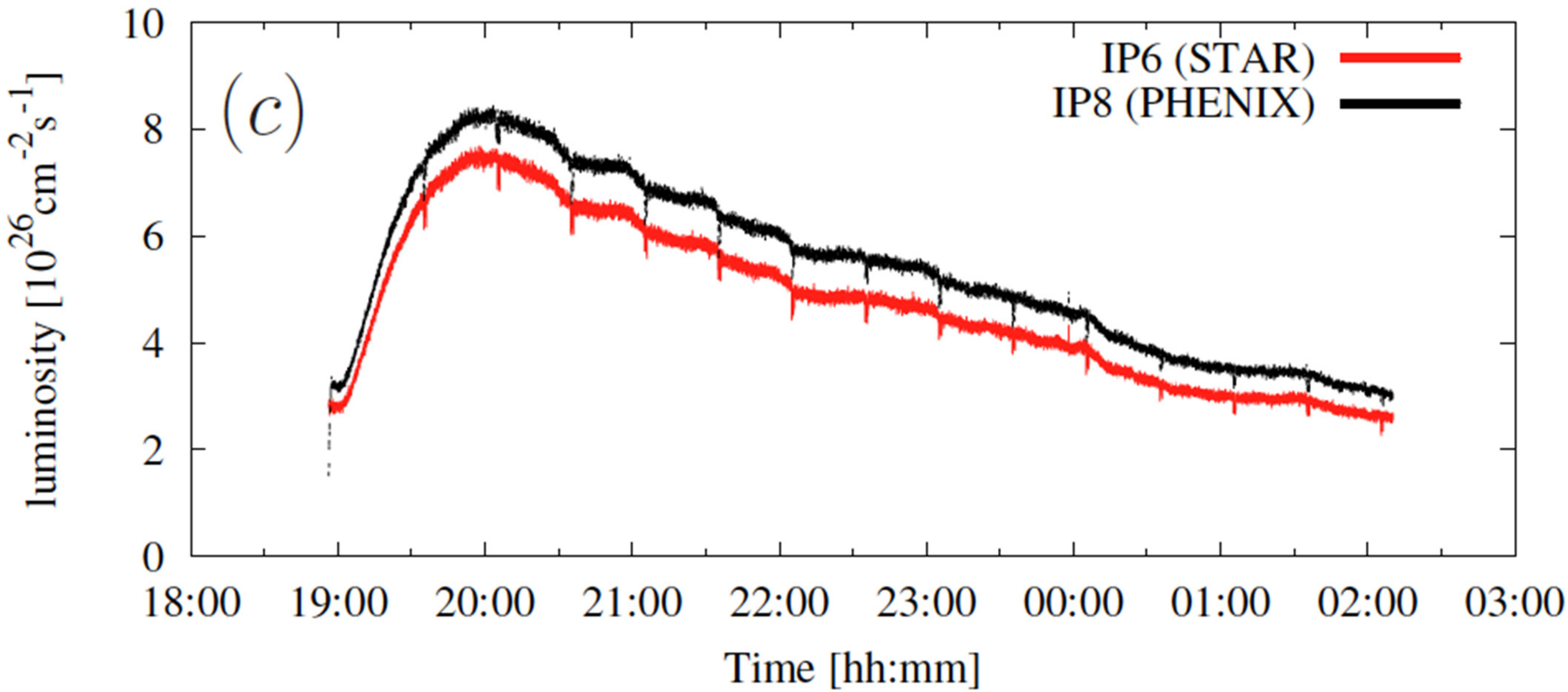
  (1) high peak current – (2) also triggers e-clouds, (3) no synchrotron motion, (4) chromaticity does not change fast enough through transition



- Can tolerate emittance growth at transition
  as long as it does not lead to intensity loss (need all ions for burn-off)

- Useful feature during electron lens commissioning with Au beams
  experiments tolerated intermittent emittance growth from electron beam commissioning or quenched solenoids

U+U operation at burn-off limit – allows measurement of σ_{tot}



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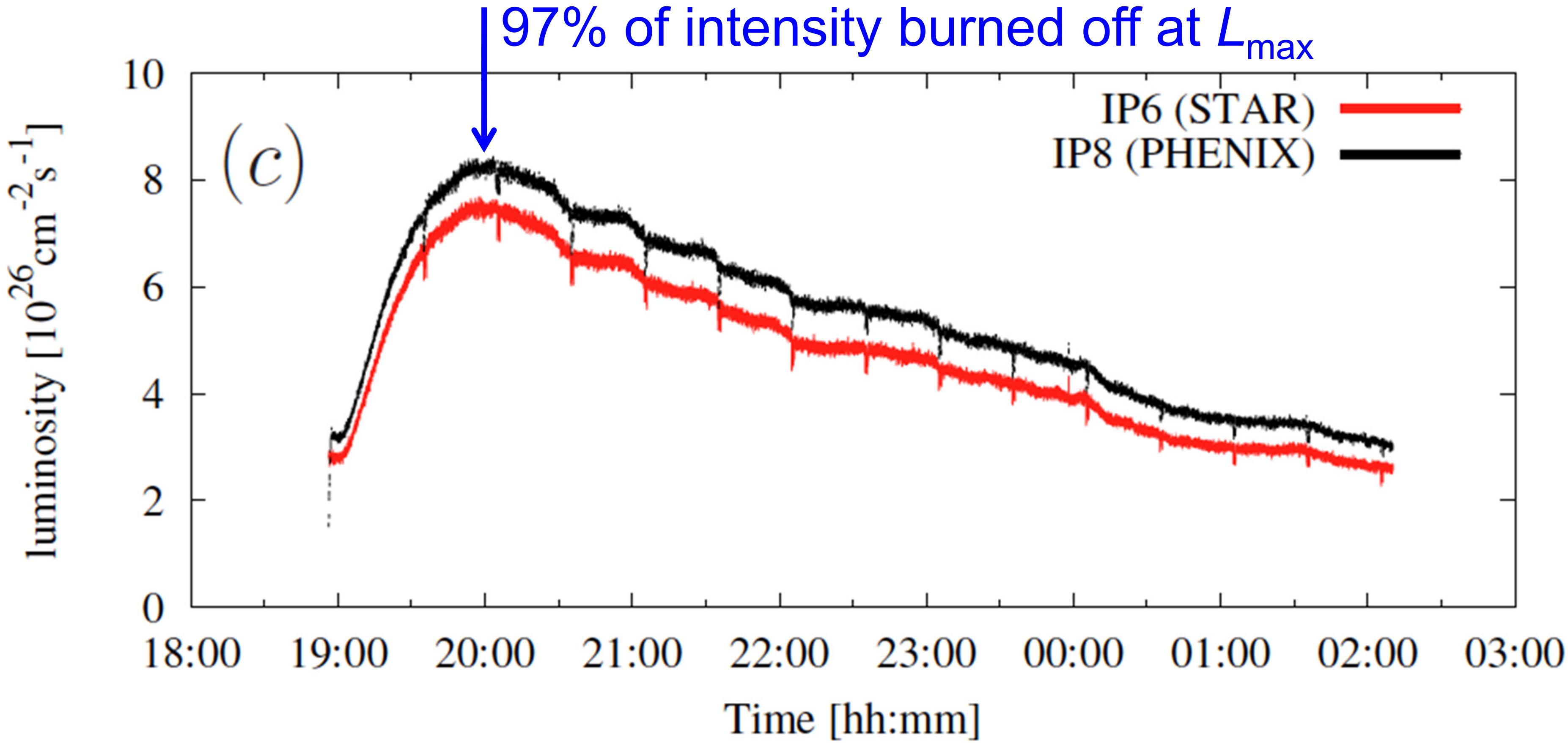

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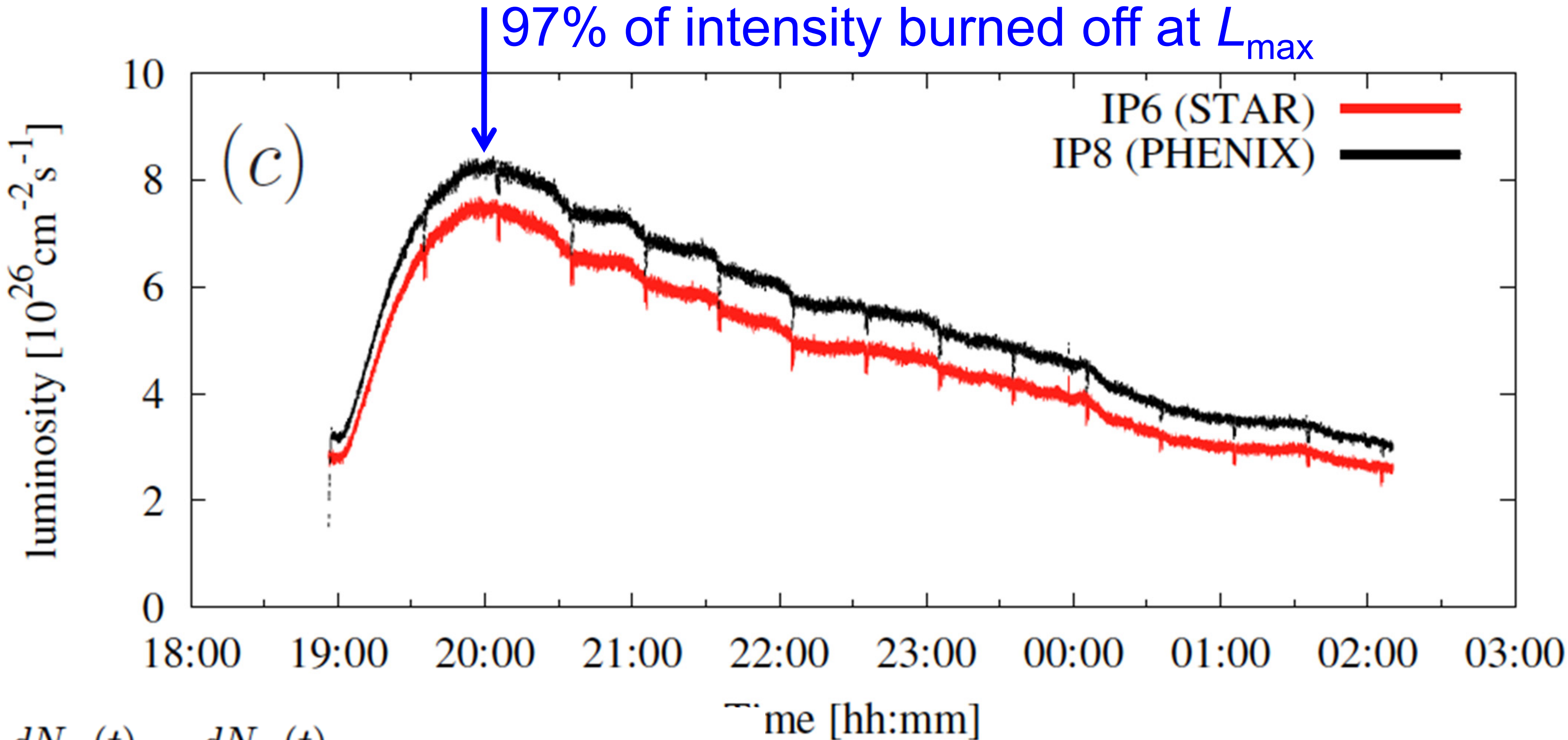
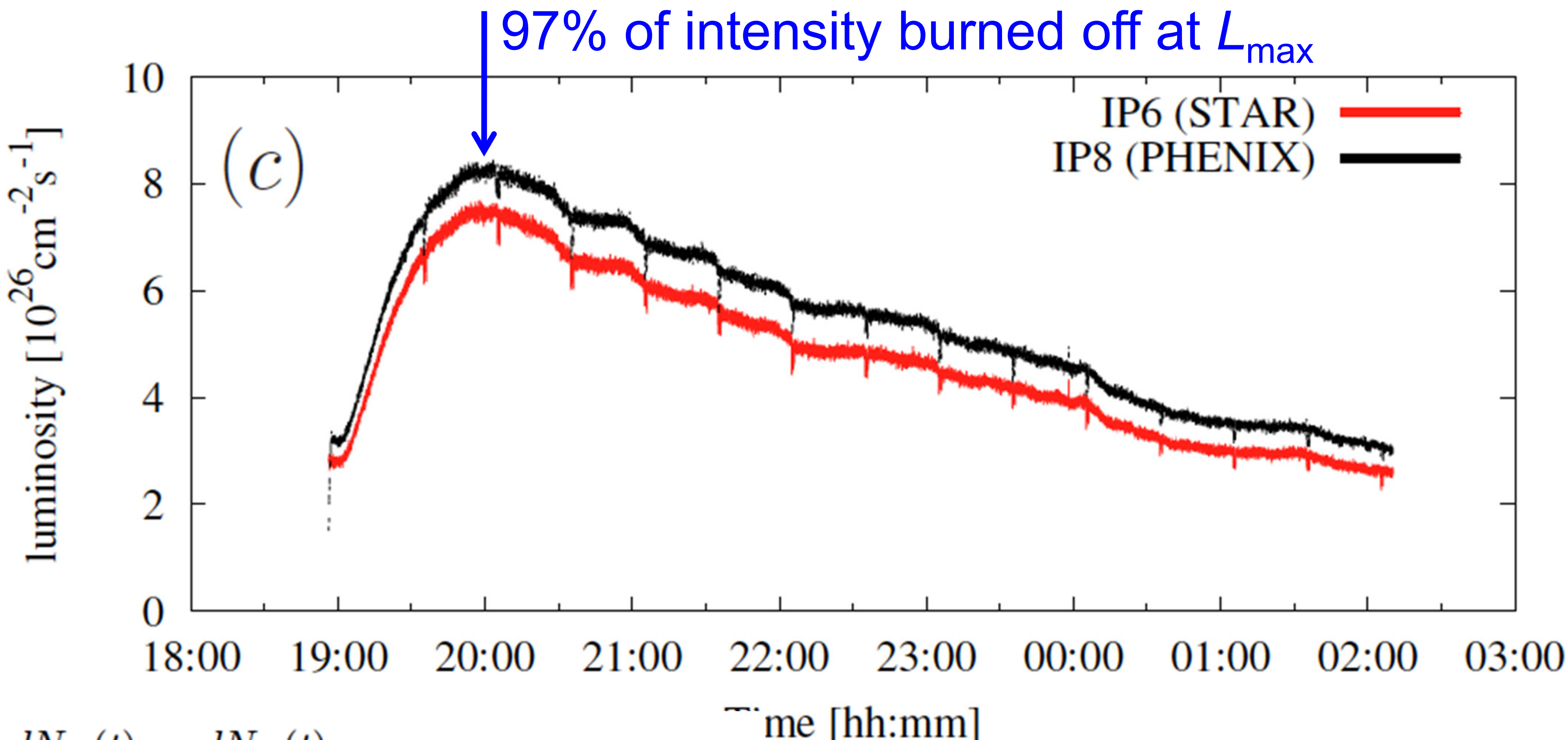


$$\frac{dN_B(t)}{dt} = \frac{dN_Y(t)}{dt} = -\left[\mathcal{L}_6(t) + \mathcal{L}_8(t)\right]\sigma_{tot}$$

U+U operation at burn-off limit – allows measurement of σ_{tot}



$$\frac{dN_B(t)}{dt} = \frac{dN_Y(t)}{dt} = -\left[\mathcal{L}_6(t) + \mathcal{L}_8(t)\right]\sigma_{tot}$$

Burn-off dominated operation allows for determination of total U+U cross section σ_{tot} – and comparison with calculation (mostly QED)

published in Phys. Rev. C =>

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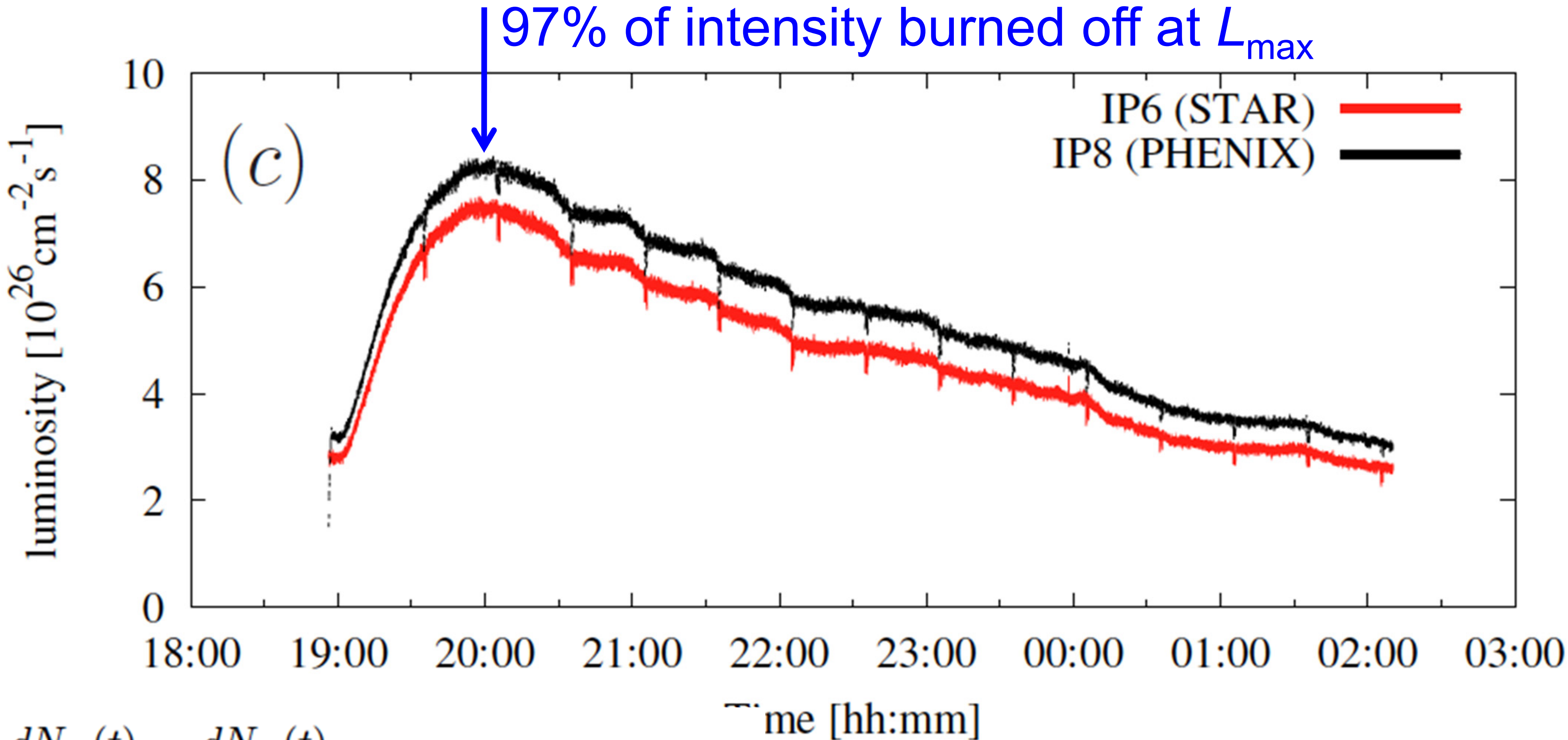

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published in Phys. Rev. C =>

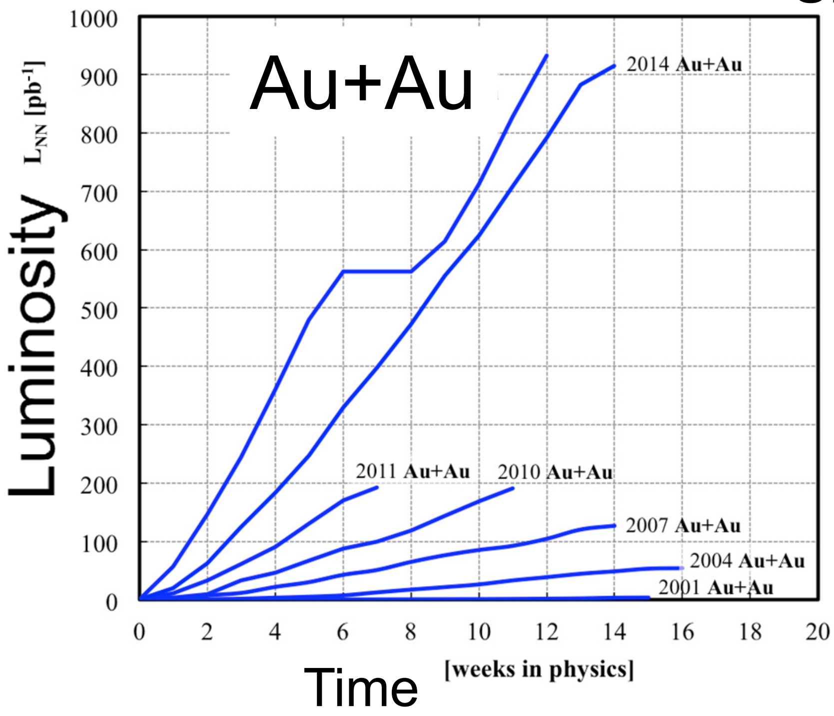
Measurement of the total cross section of uranium-uranium collisions at $\sqrt{s_{NN}} = 192.8$ GeV

Baltz, M. Blaskiewicz, D. Gassner, K.A. Drees, Y. Luo, M. Minty, P. Thieberger, and M. Wilinski
Brookhaven National Laboratory, Upton, NY 11973, USA

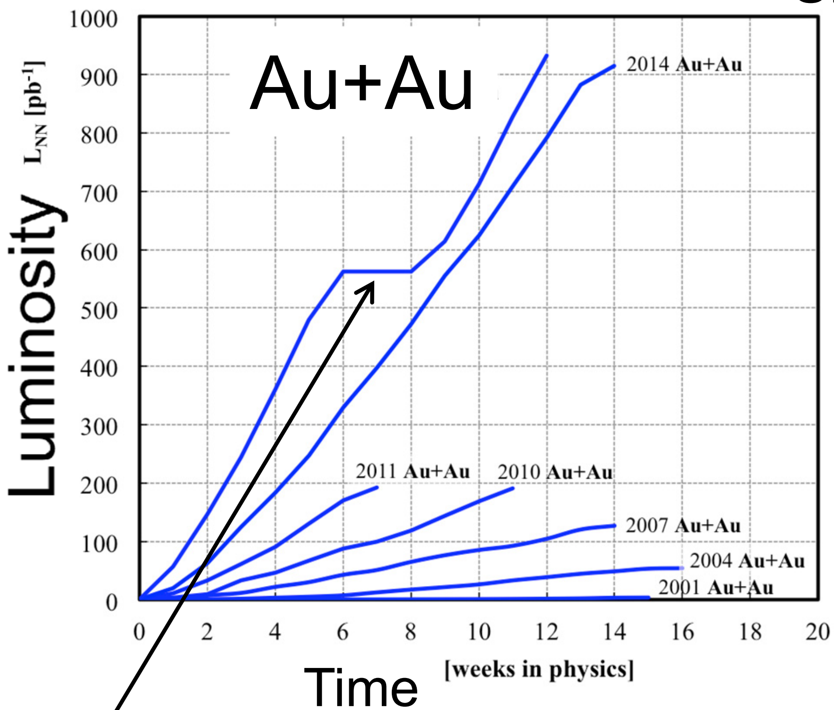
I.A. Pshenichnov
Institute for Nuclear Research, Russian Academy of Sciences, Moscow, Russia

vy ion cross sections totaling several hundred barns have been calculated previously for the
vistic Heavy Ion Collider (RHIC) and the Large Hadron Collider (LHC). These total cross

2016 event with increased luminosity (L_{avg} now 40x design) – shorted quench protection diode



2016 event with increased luminosity (L_{avg} now 40x design) **– shorted quench protection diode**



19 d for exchange
of shorted quench
protection diode

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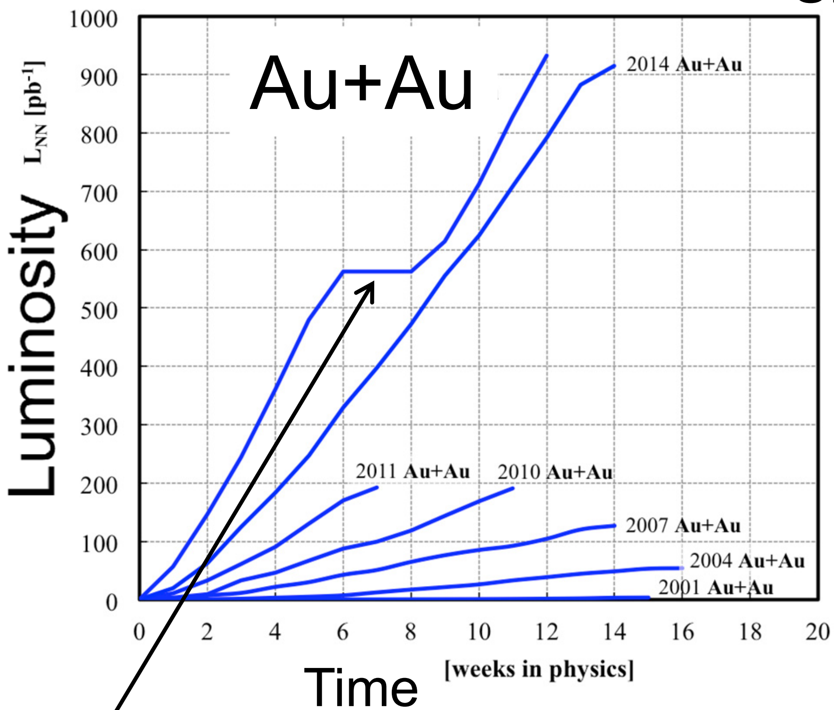

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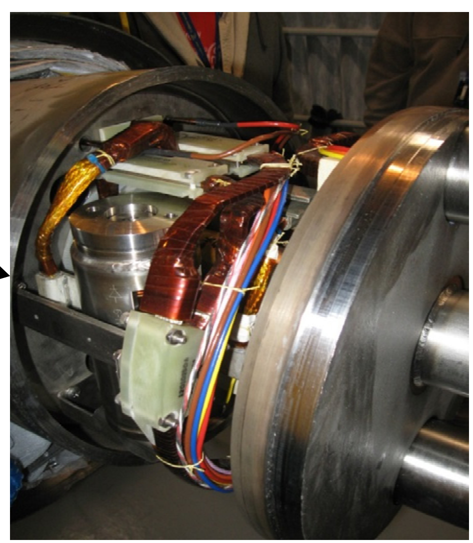

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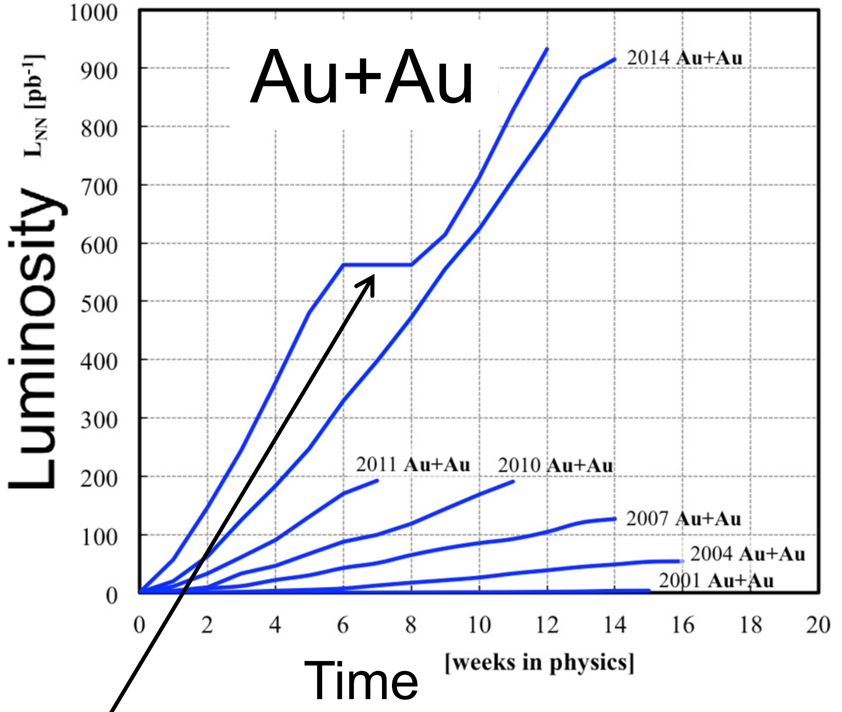

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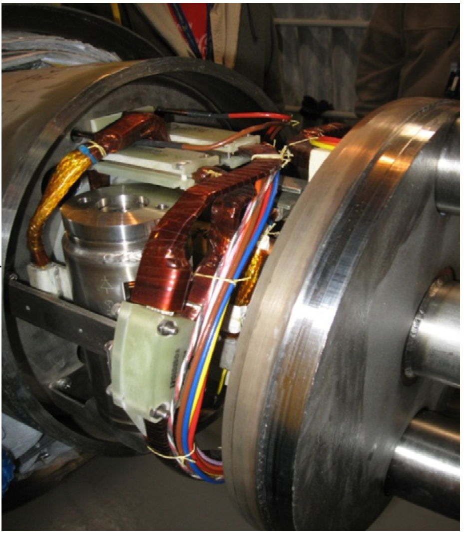
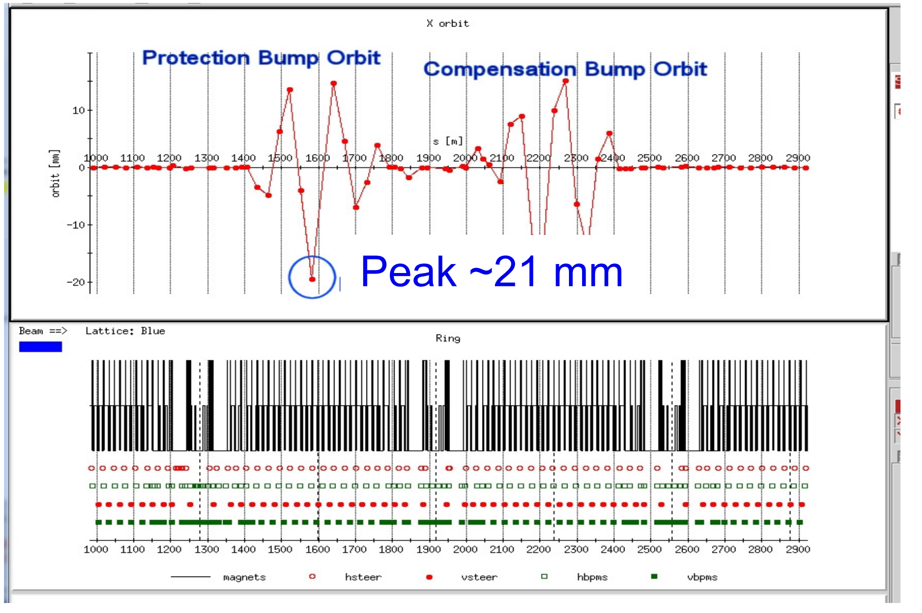


Large orbit bumps protect experiments in abort kicker pre-fire



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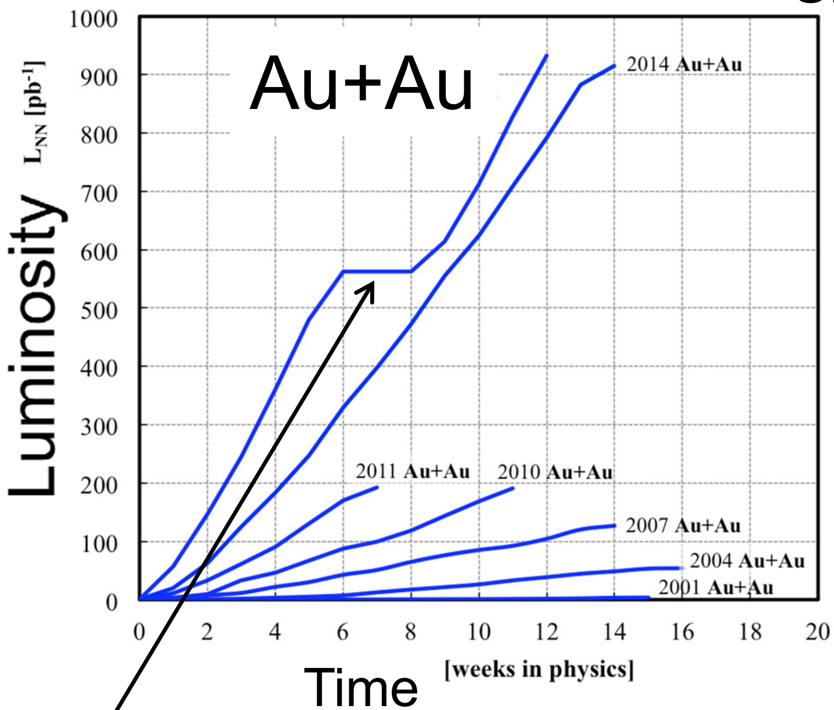

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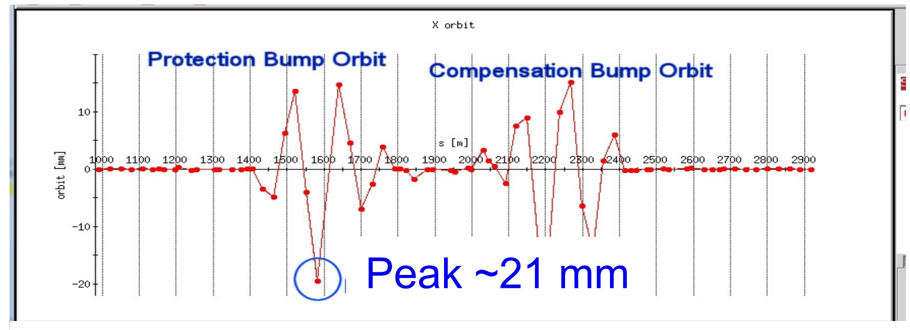
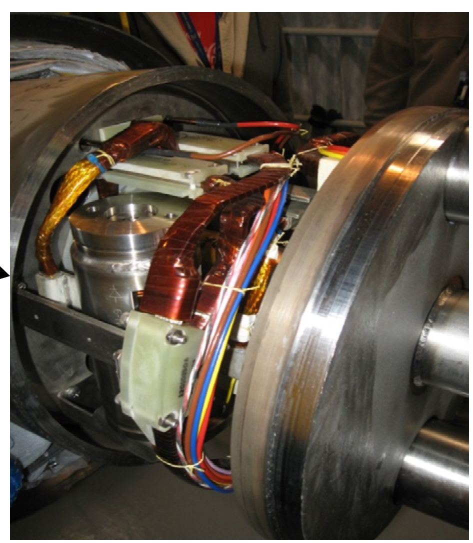
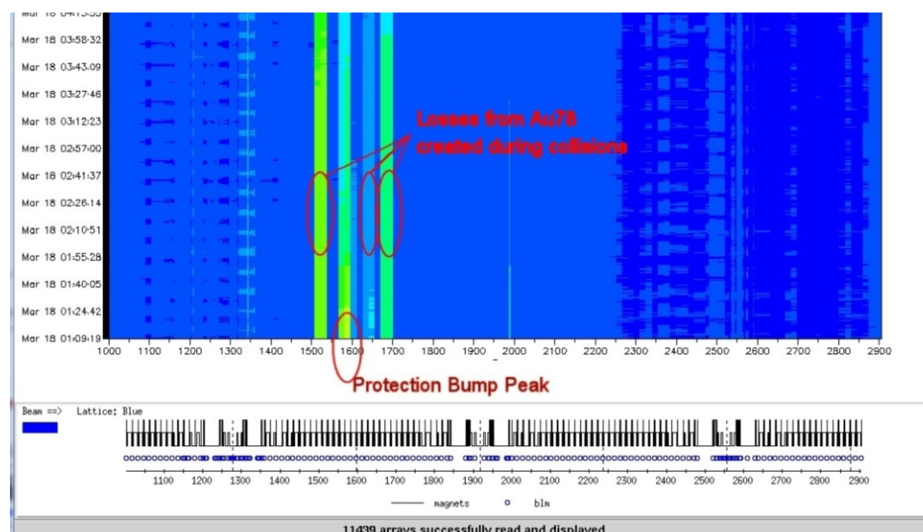


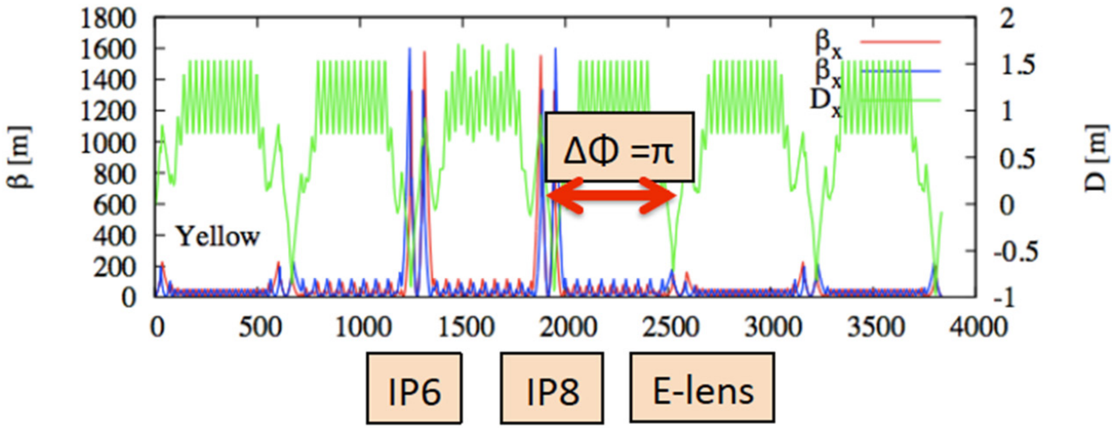
Locations of max orbit deviation are momentum collimators for secondary beams generated in collision
(Au ions with captured *e*, or expelled *n*)
=> radiation damage to diode (~15 kGy)

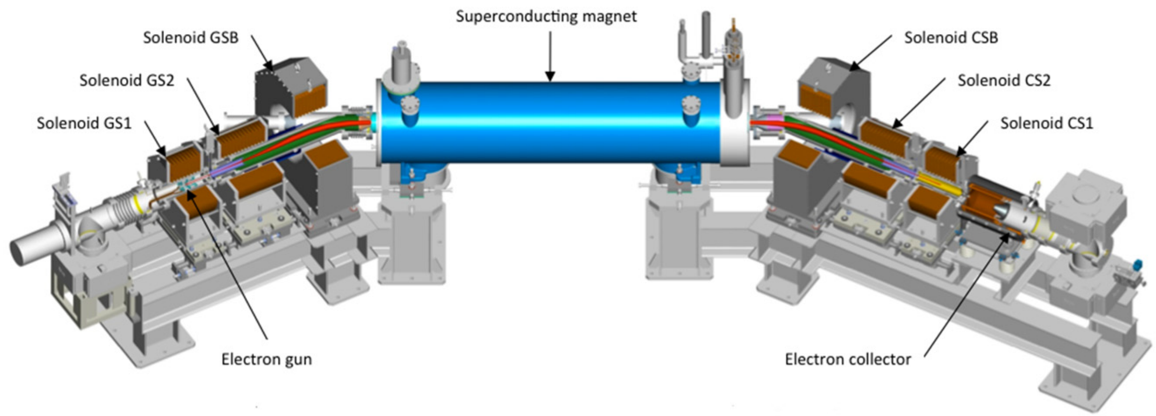
19 d for exchange of shorted quench protection diode





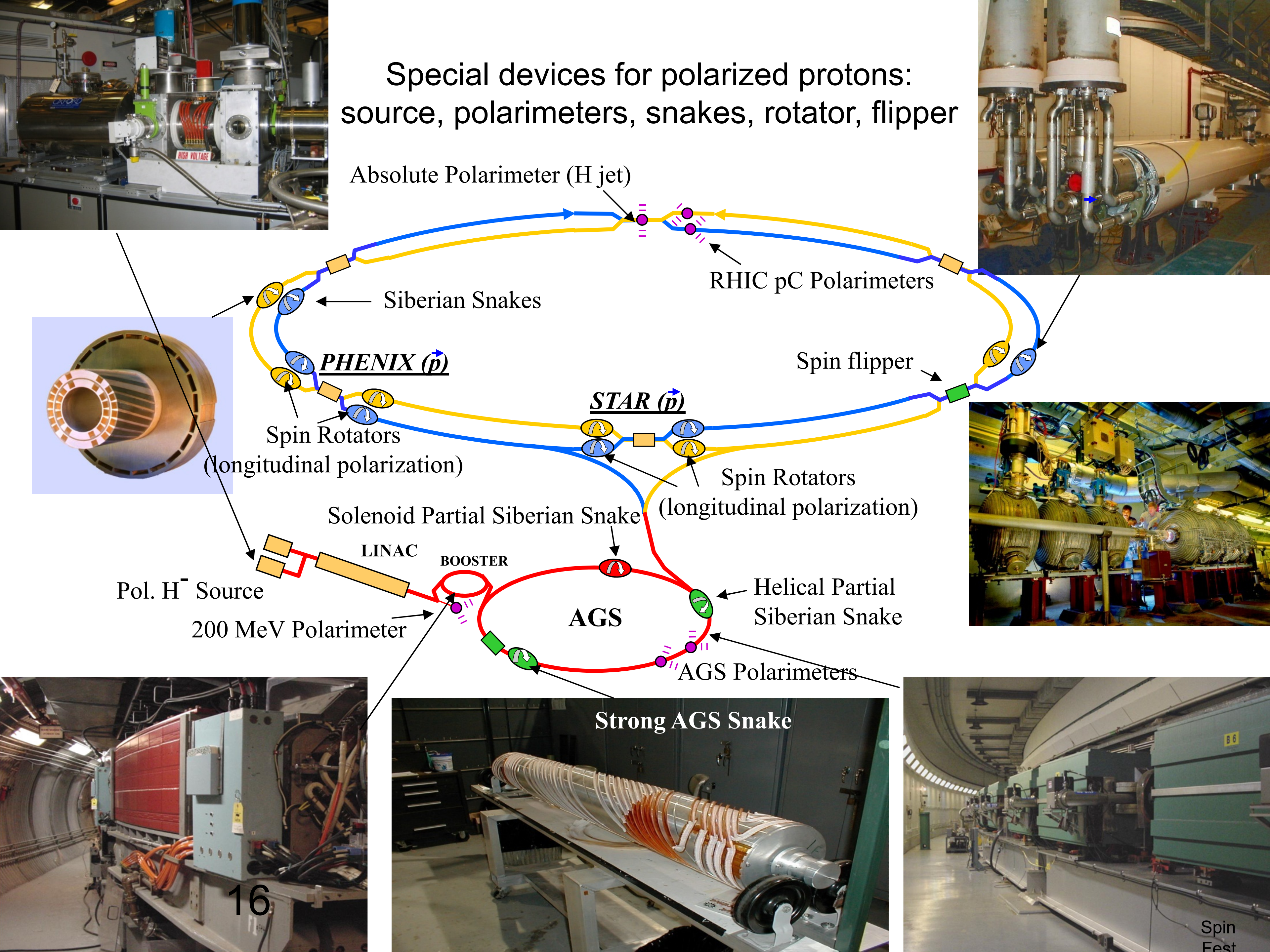
Wolfram Fischer





RHIC p↑+p↑ operation with head-on beam-beam compensation

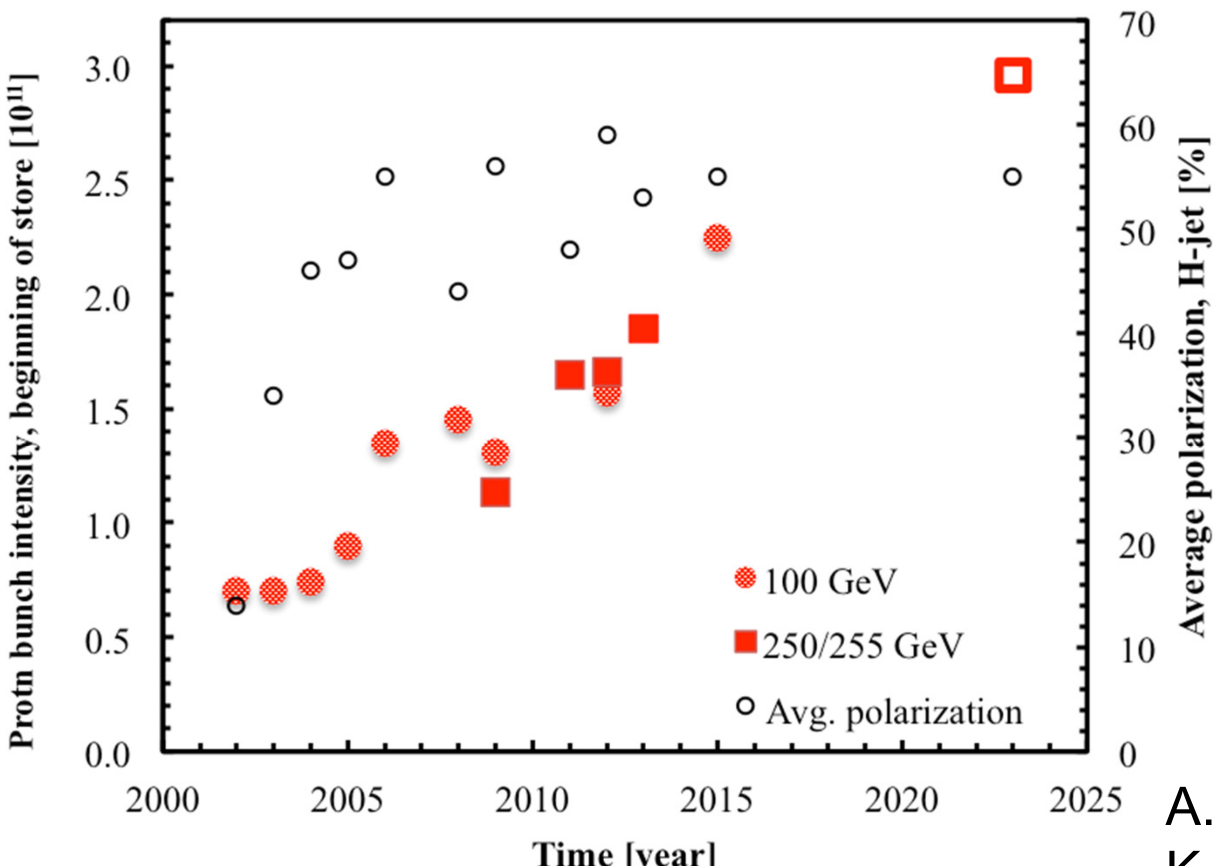
Main luminosity limit: beam-beam


Special devices for polarized protons:
source, polarimeters, snakes, rotator, flipper
Absolute Polarimeter (H jet)
RHIC pC Polarimeters
Siberian Snakes
PHENIX (p⃗)
Spin flipper
STAR (p⃗)
Spin Rotators
(longitudinal polarization)
Spin Rotators
(longitudinal polarization)
Solenoid Partial Siberian Snake
LINAC
BOOSTER
Pol. H⁻ Source
Helical Partial
Siberian Snake
AGS
200 MeV Polarimeter
AGS Polarimeters
Strong AGS Snake

p bunch intensity and polarization

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

$$FOM = LP^4 \sim N_b^2 P^4$$



main limits:
- injectors output
- polarization
- beam-beam in RHIC

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

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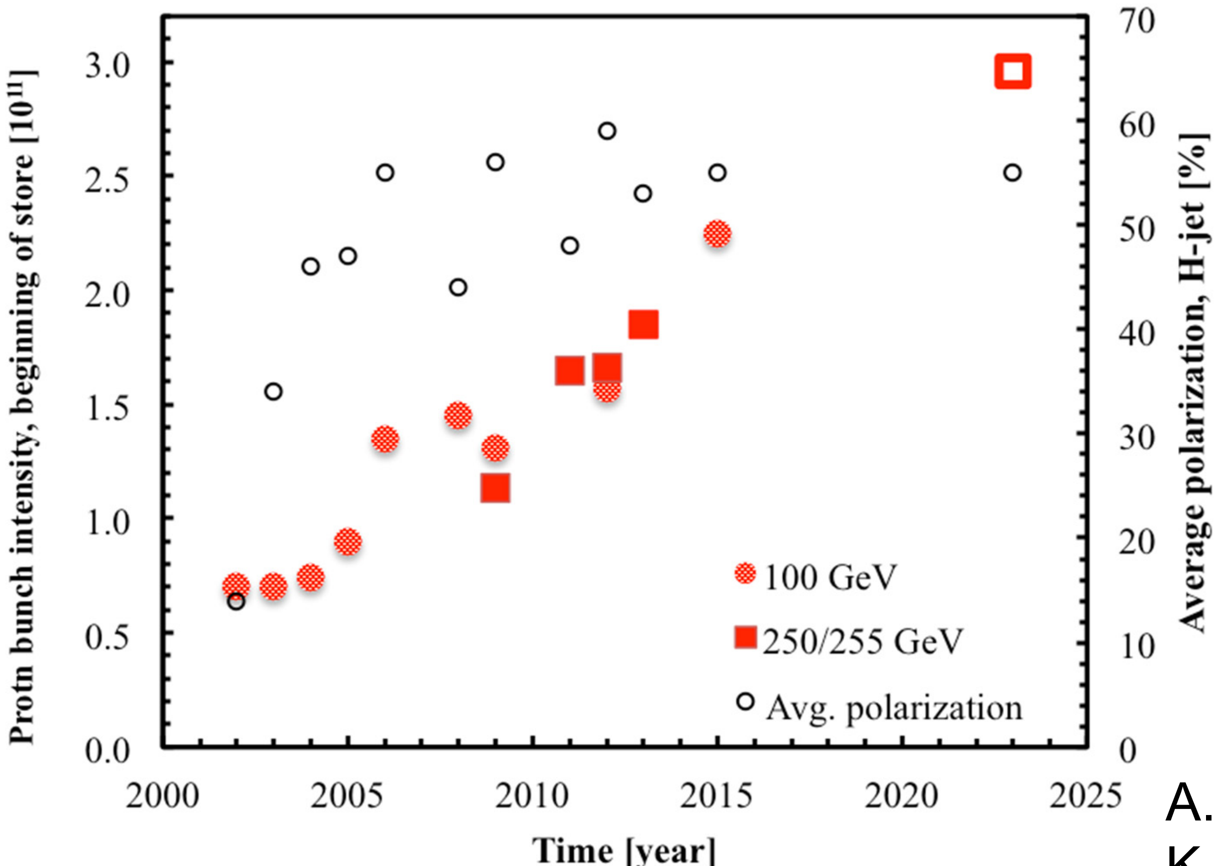

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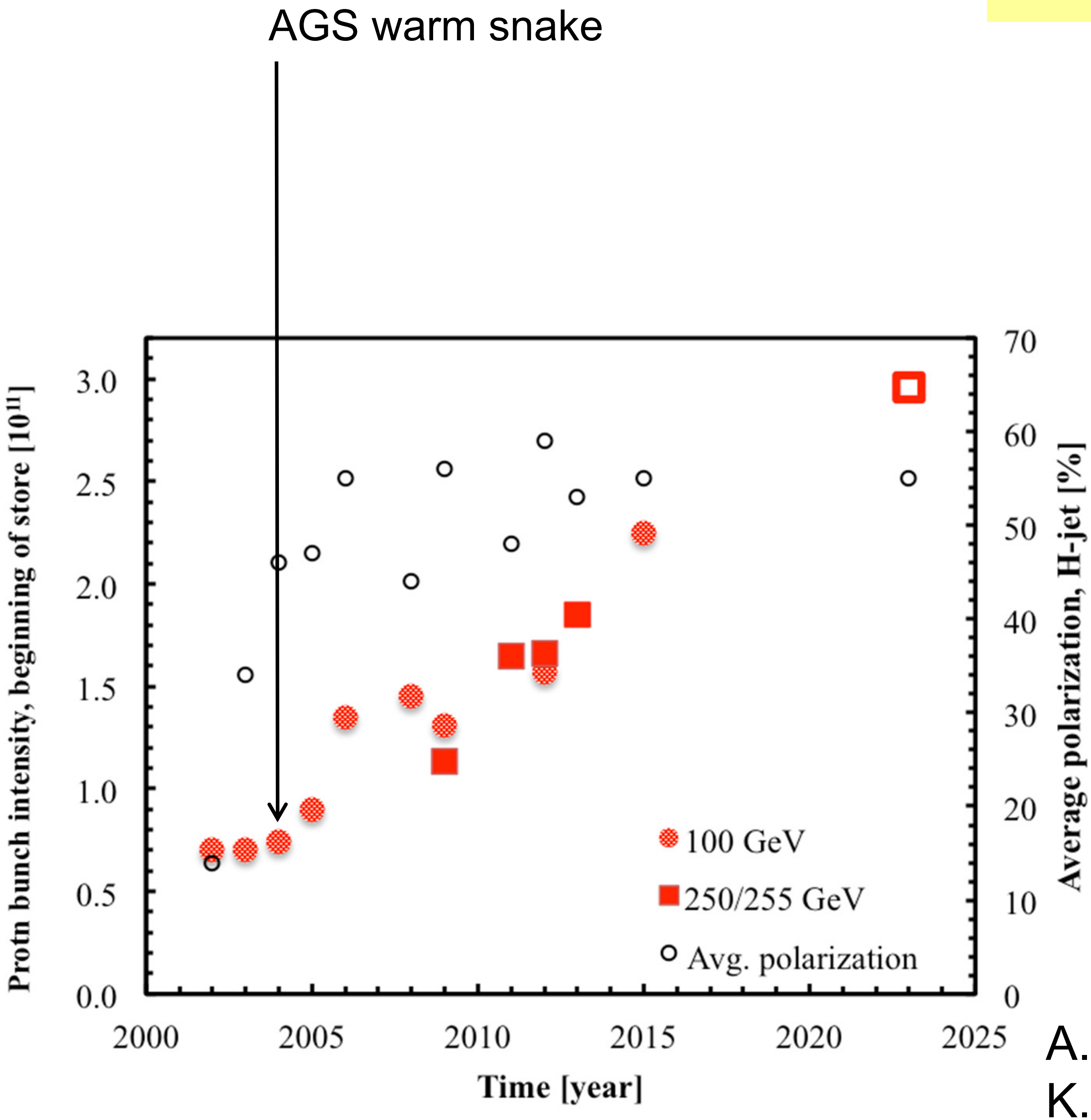

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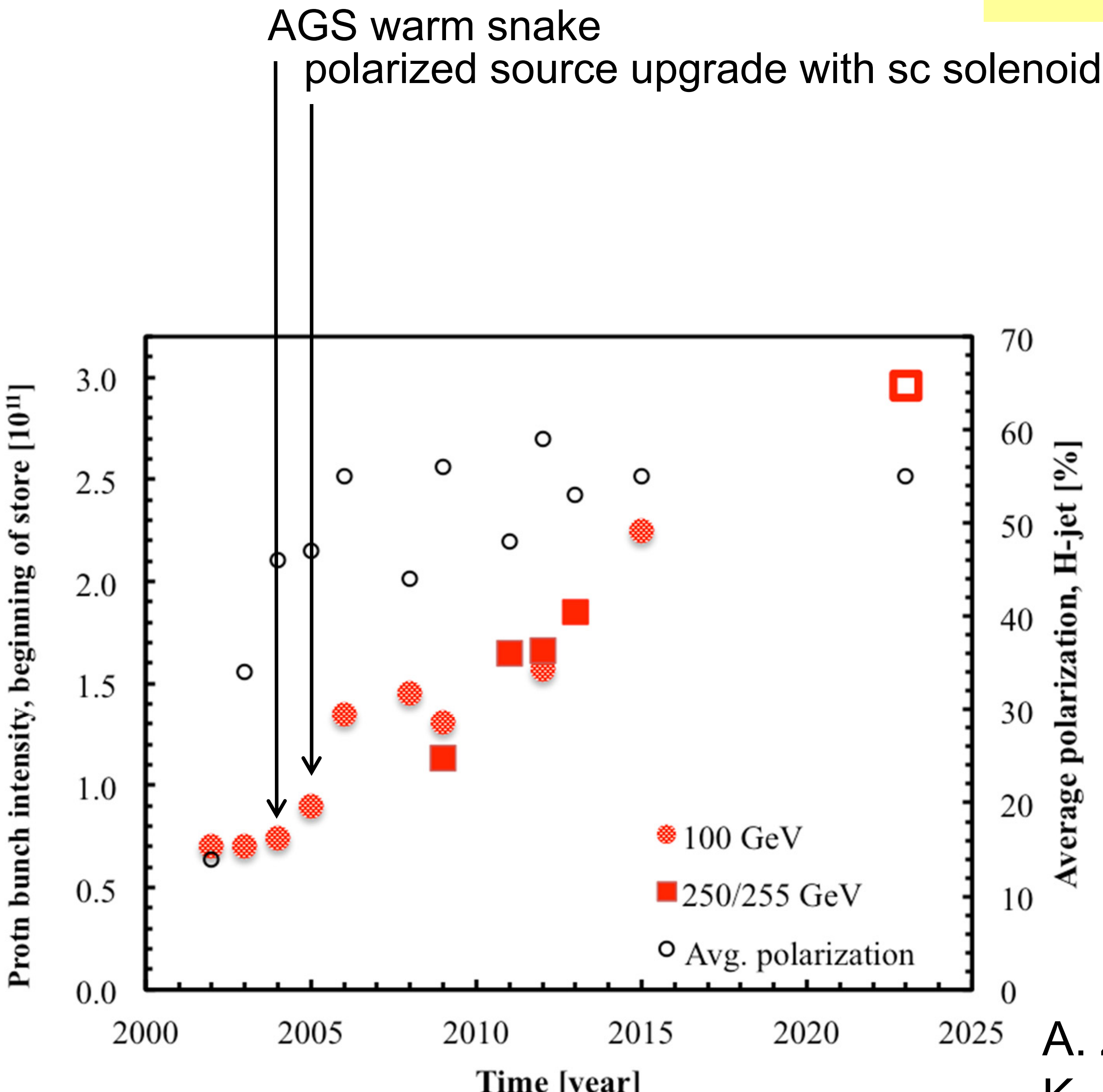

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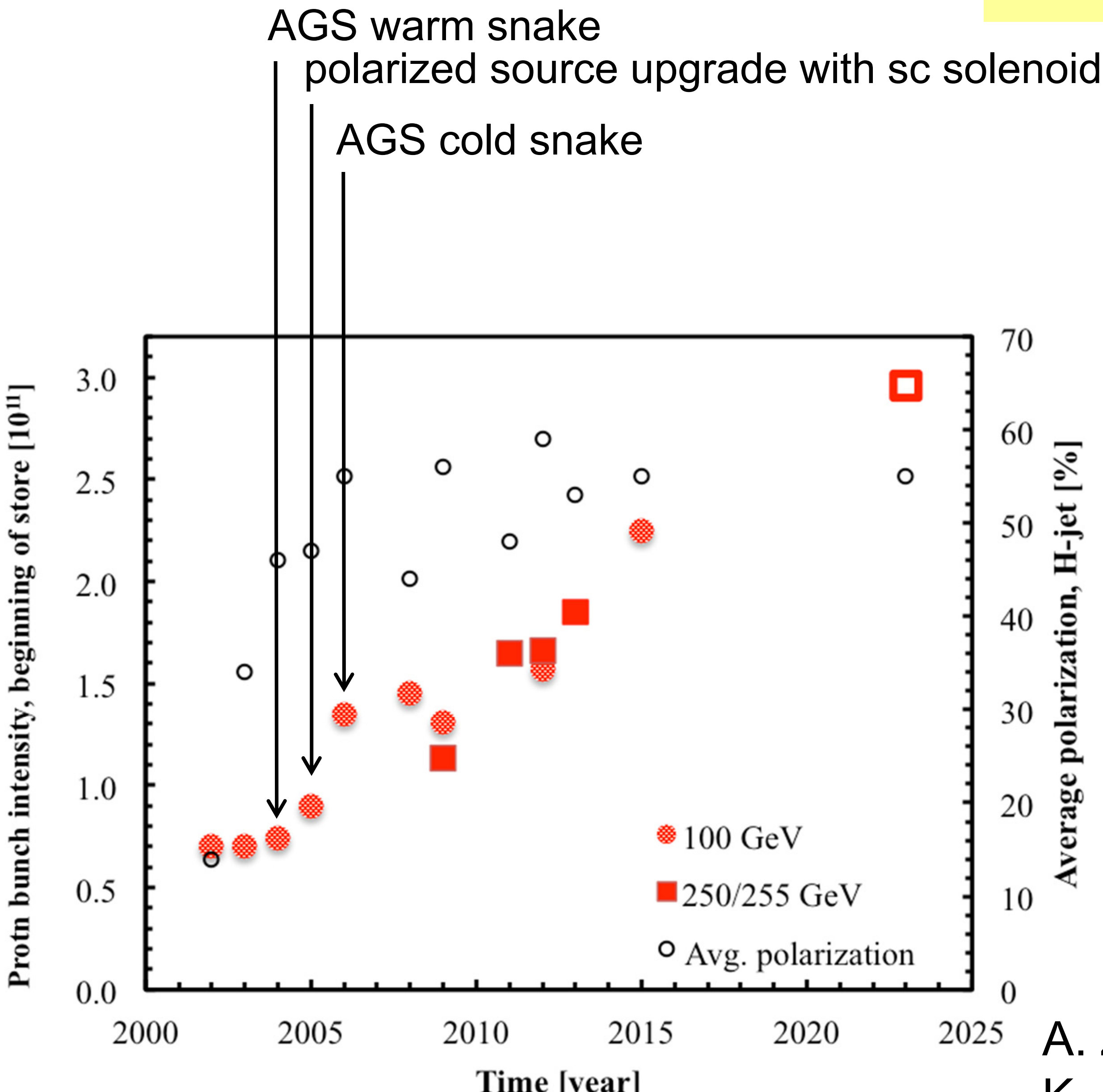

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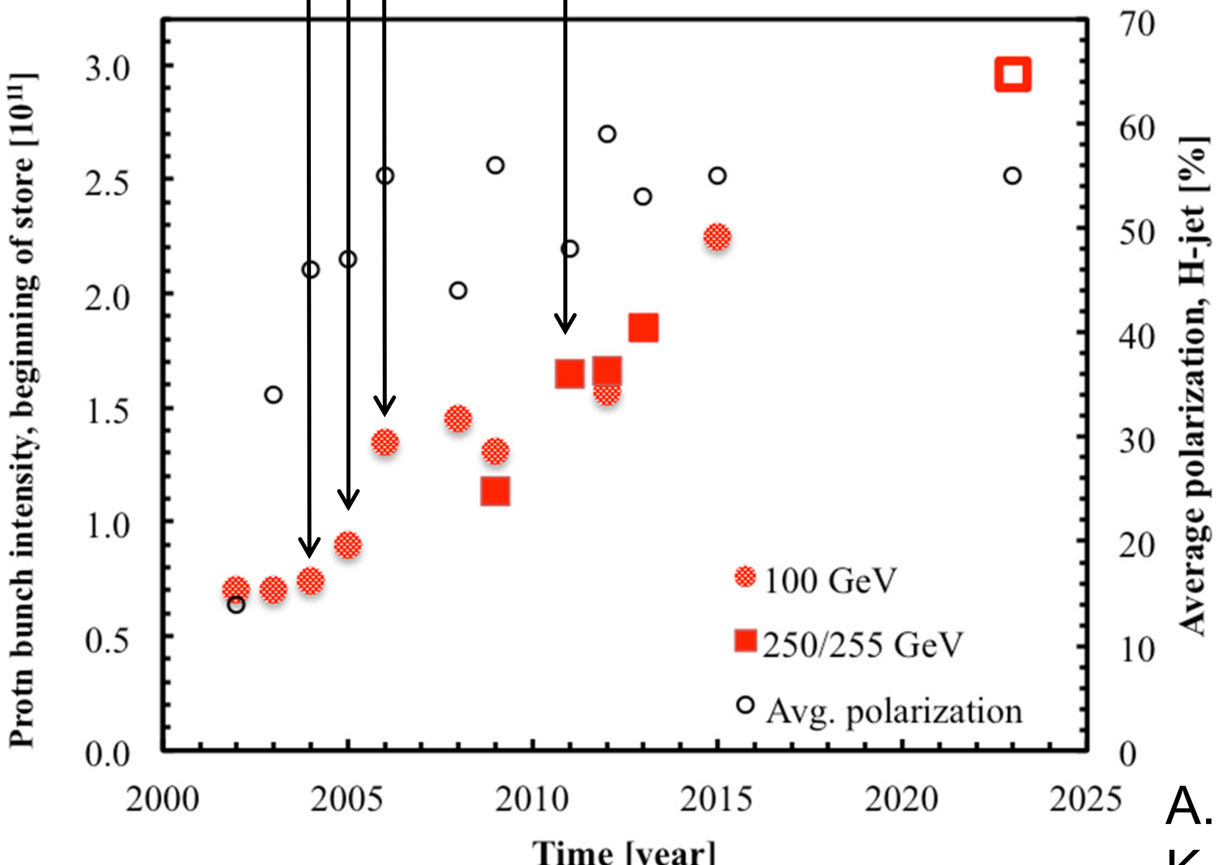
AGS warm snake

polarized source upgrade with sc solenoid

AGS cold snake

AGS tune jumps, RHIC 9 MHz RF



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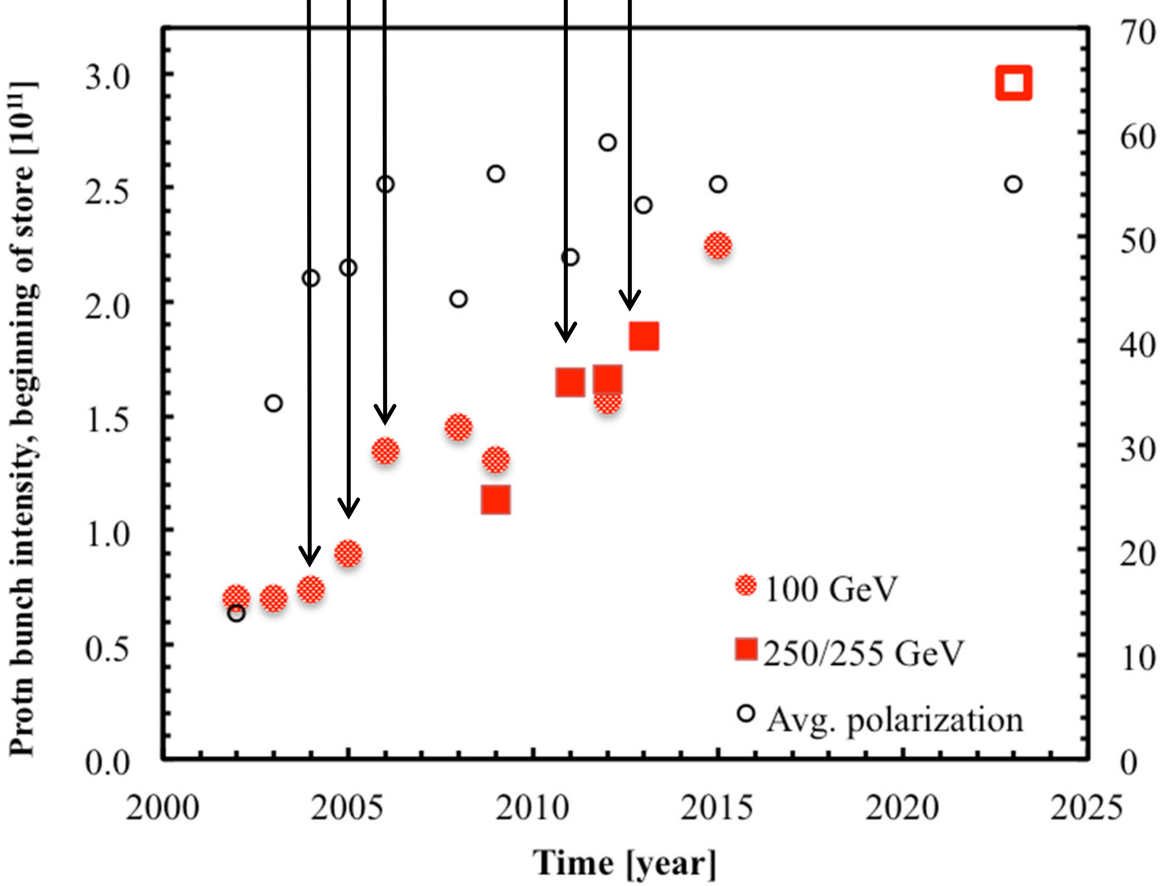
polarized source upgrade with sc solenoid
AGS cold snake
AGS tune jumps, RHIC 9 MHz RF
polarized source upgrade with Atomic Beam Source



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AGS warm snake
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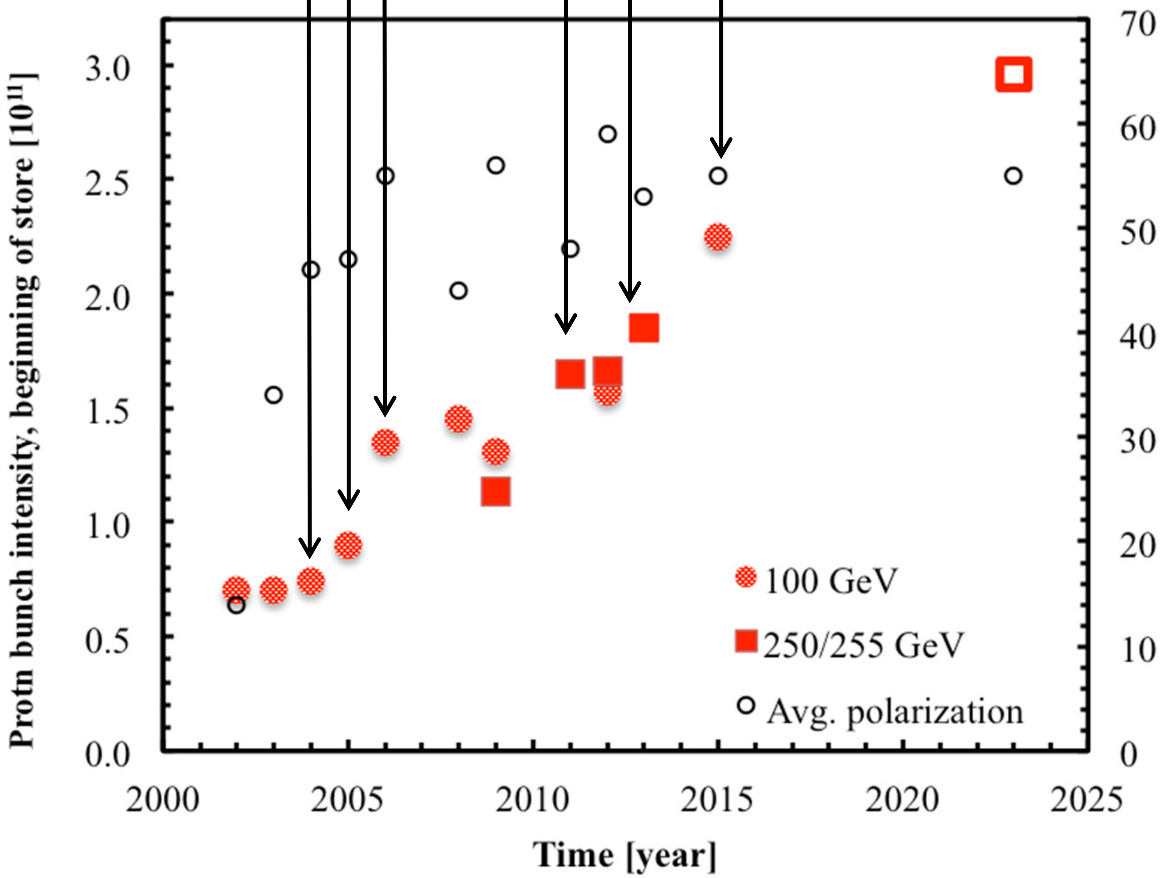
polarized source upgrade with Atomic Beam Source
beam-beam compensation



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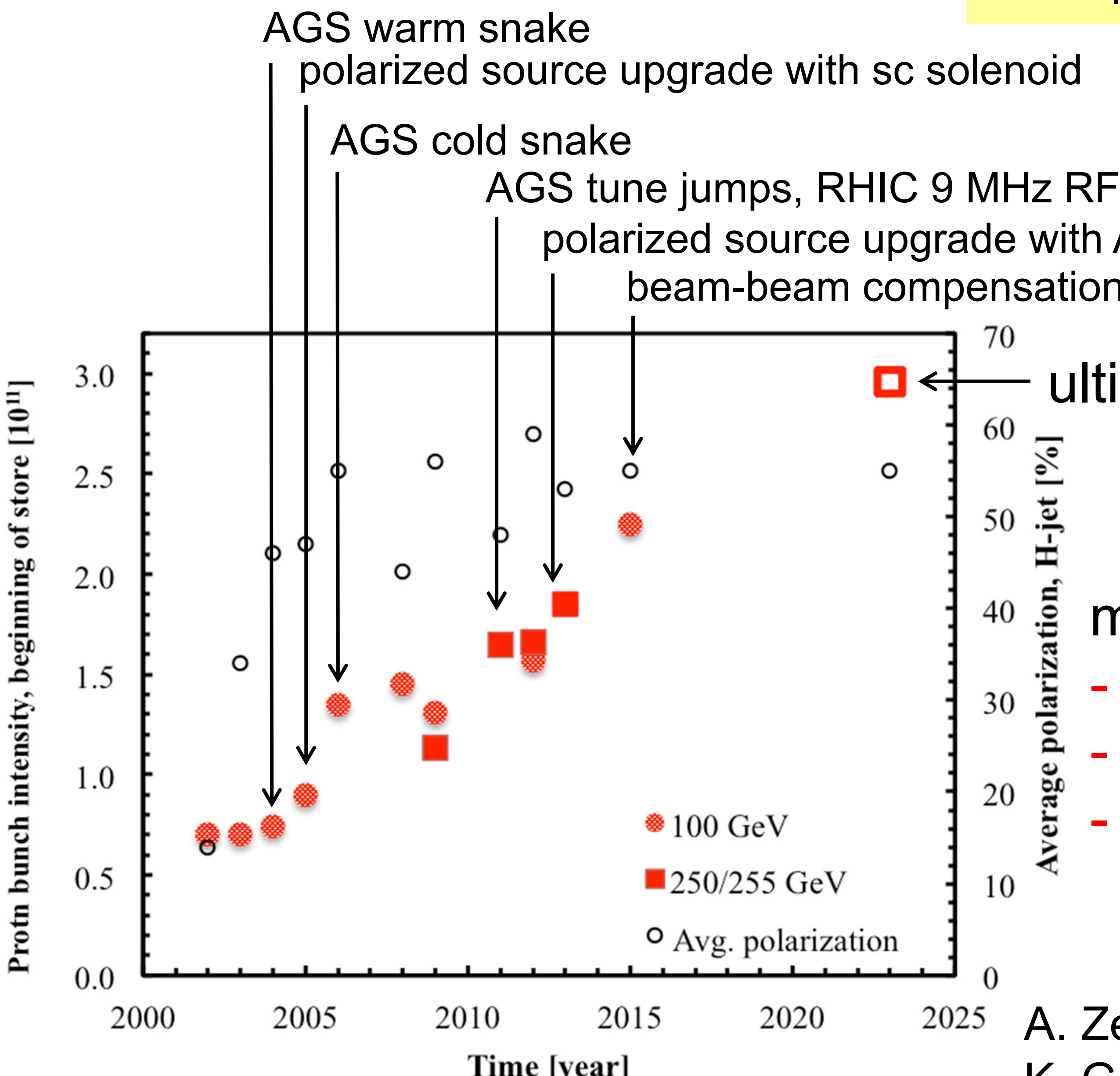


ultimate goal

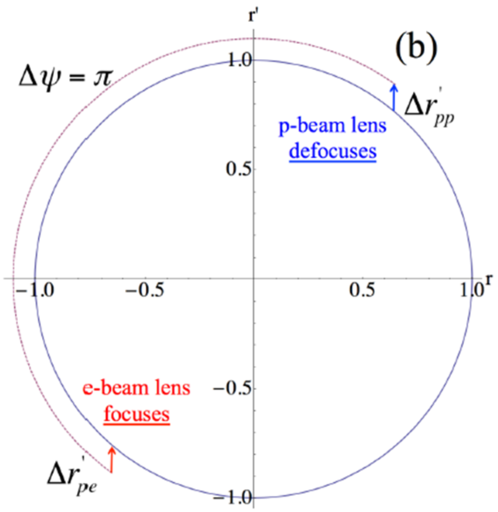
main limits:
- injectors output
- polarization
- beam-beam in RHIC

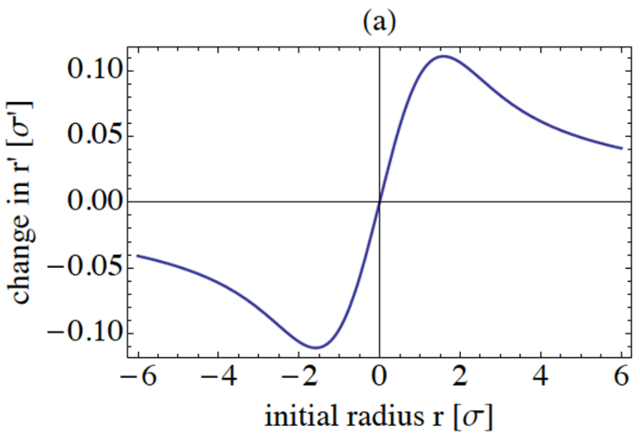
A. Zelenski, H. Huang,
K. Gardner, K. Zeno, RF, et al.

Head-on beam-beam compensation

Principle

Correction in same turn, need to fulfill 2 conditions:





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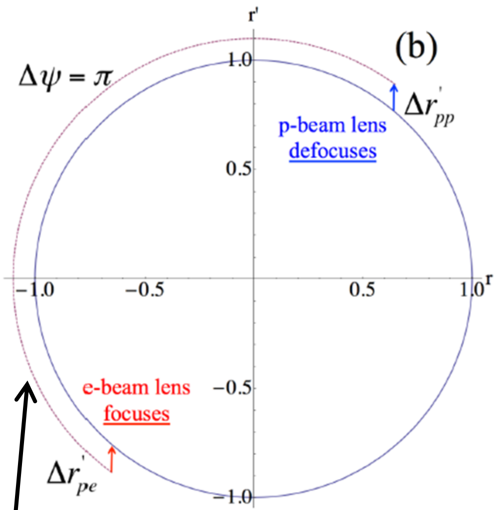
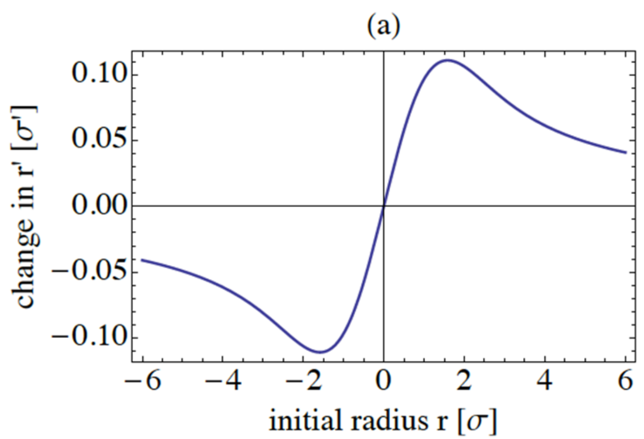
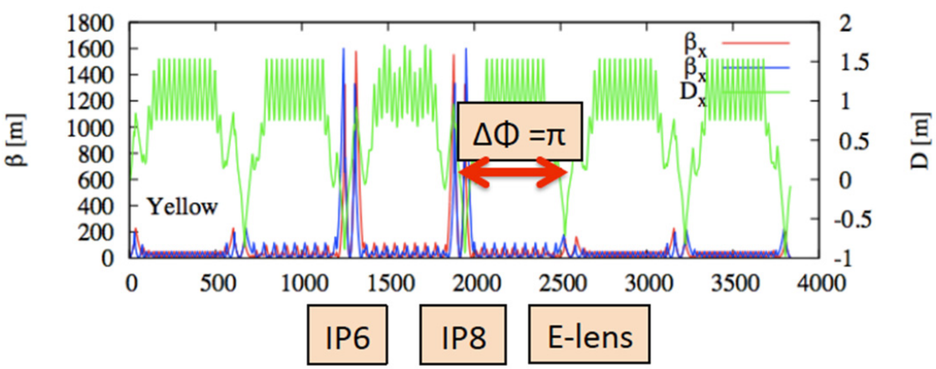




(1) $k\pi$ phase advance minimizes beam-beam resonance driving terms – implemented with ATS type lattice (Simon White, now ESRF)

new lattice with better DA and larger bb param. ξ



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Head-on beam-beam compensation

Principle

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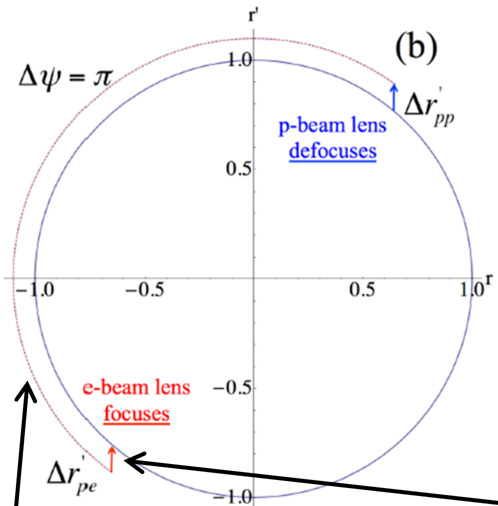

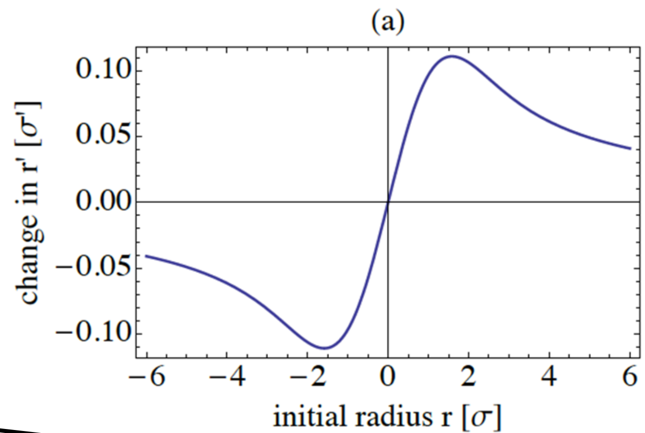

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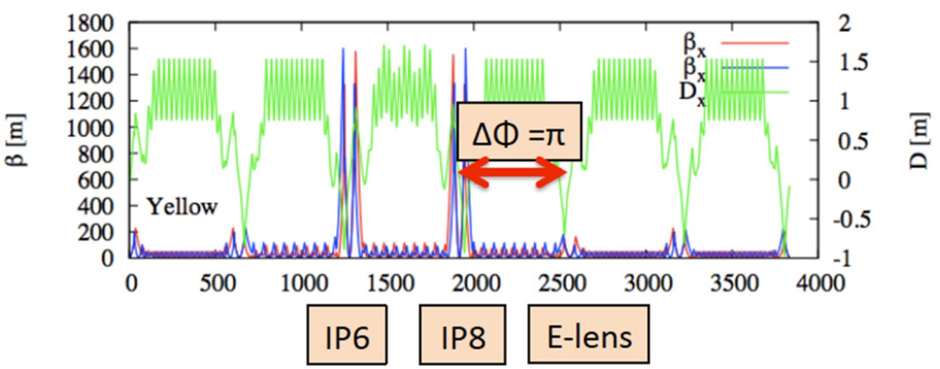
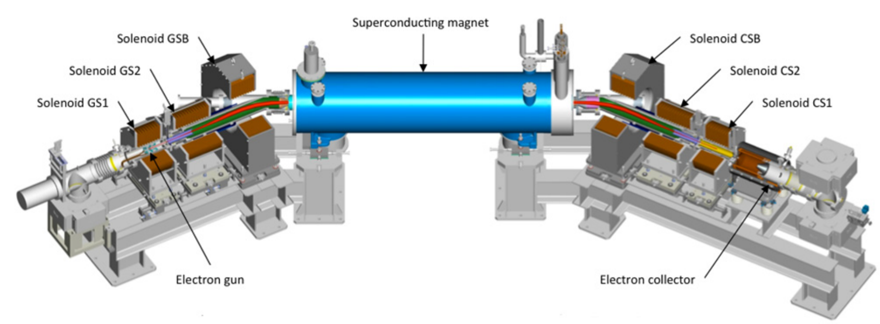


(2) Same amplitude correction kick as bb kick reduces beam-beam tune spread – implemented with electron lenses (not possible with magnets)



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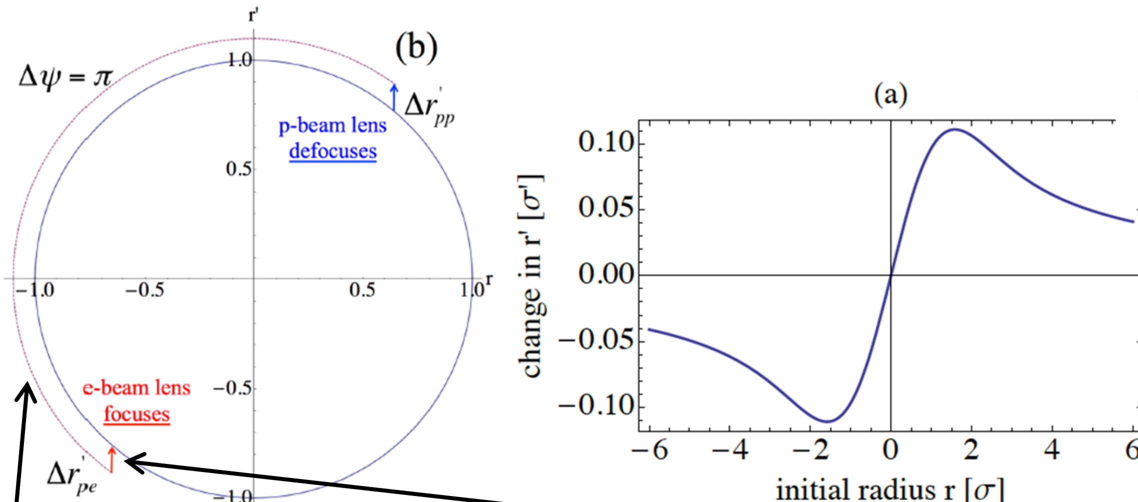

$$\mathcal{L} = \frac{f_c}{4\pi}\frac{N_p^2}{\sigma_p^{*2}}H = \frac{4\pi f_c}{r_p^2}\frac{(\beta_p\gamma_p)\epsilon_n}{\beta^*}H\xi_p^2,$$

beam-beam parameter

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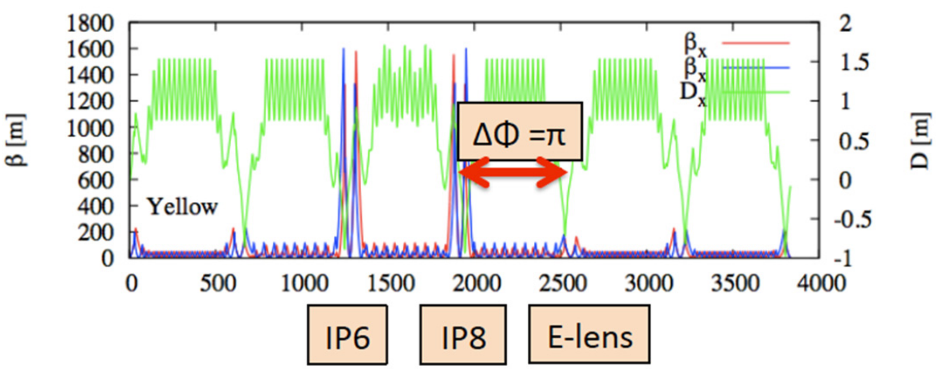

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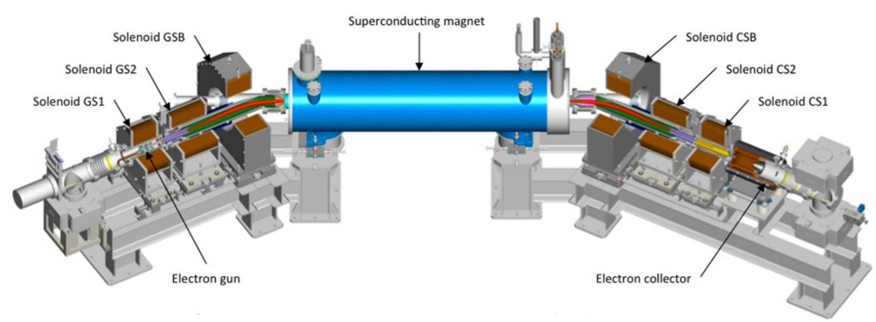
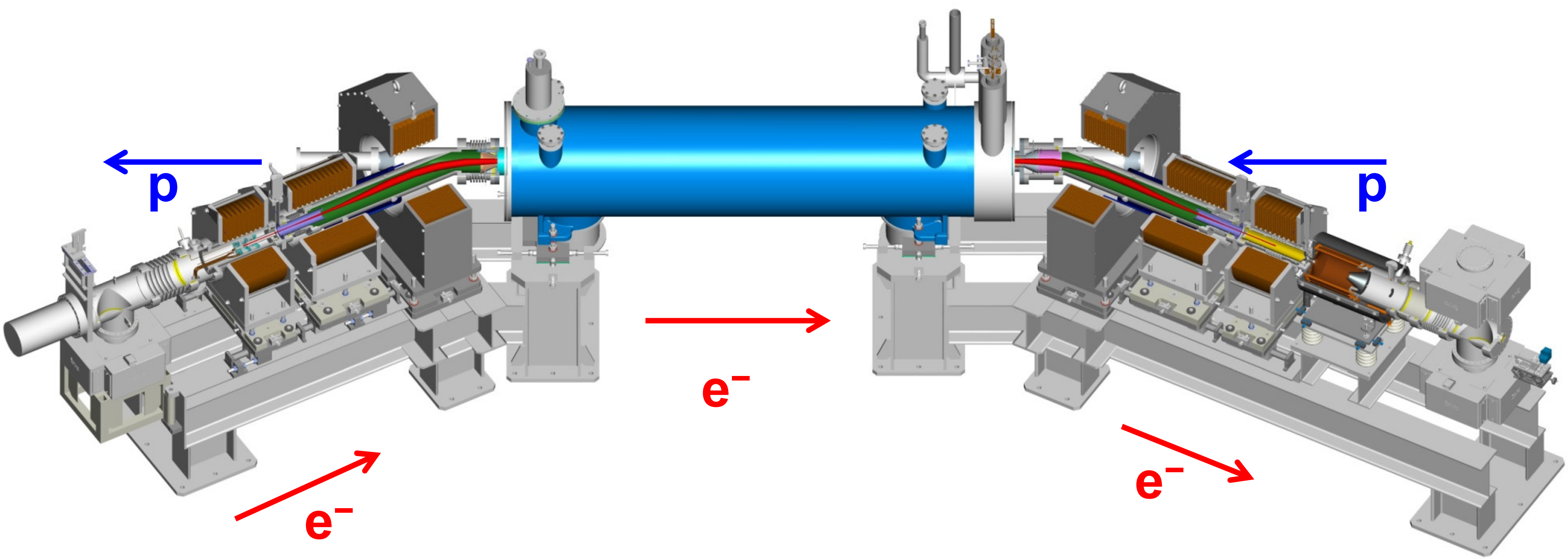
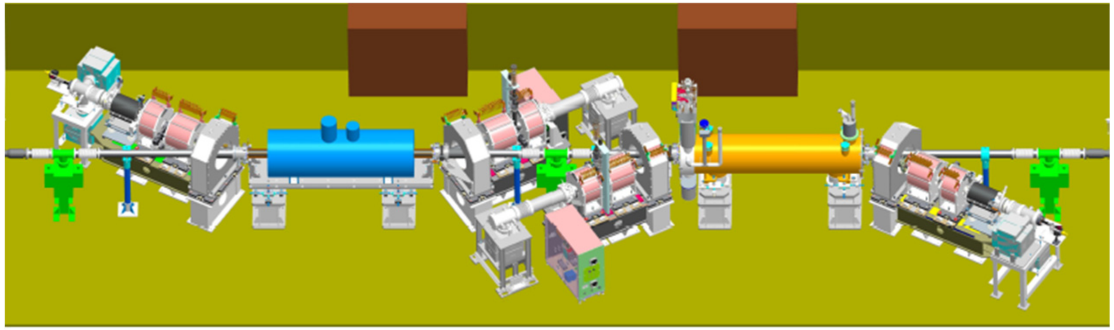


RHIC electron lenses

Overview

Xiaofeng Gu, liaison physicist





RHIC electron lenses

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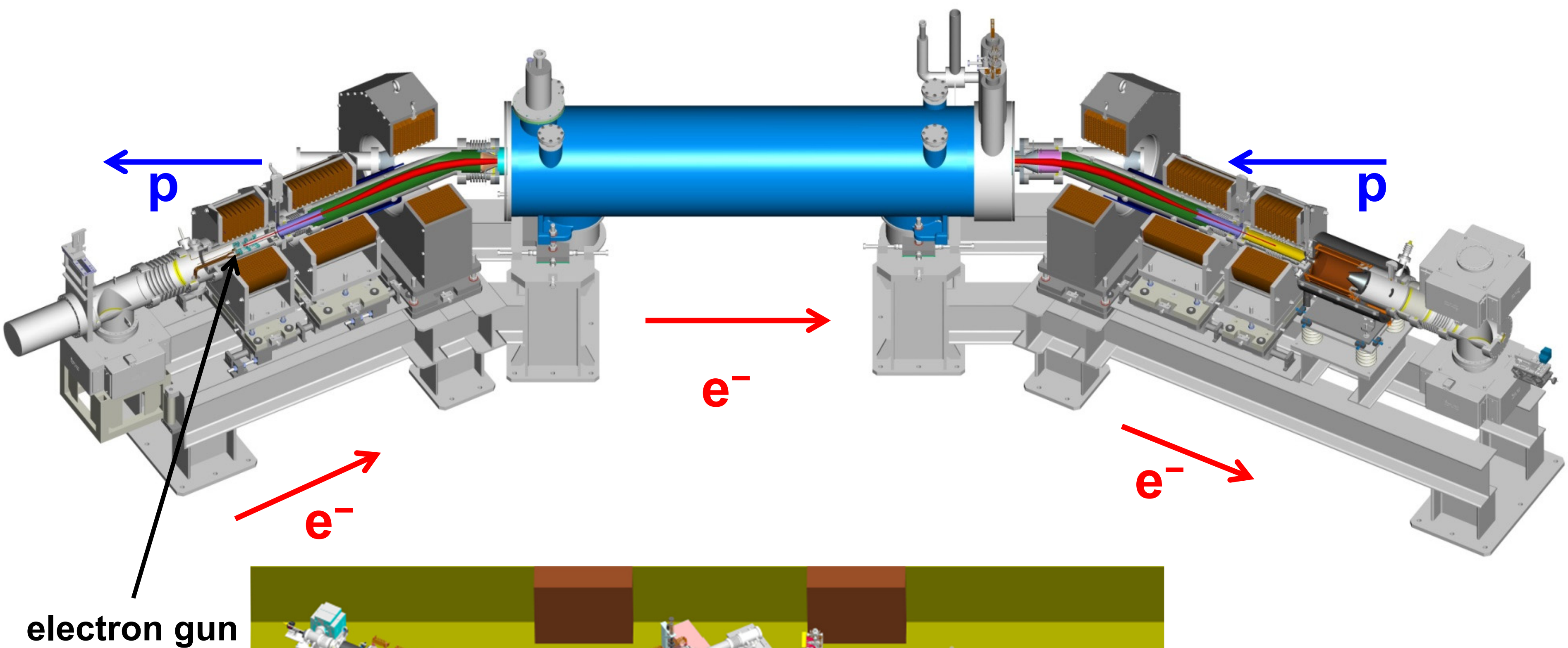

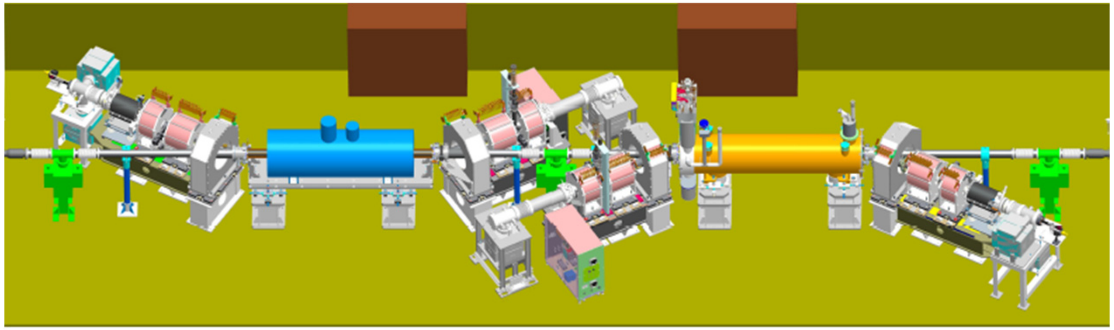

RHIC electron lenses

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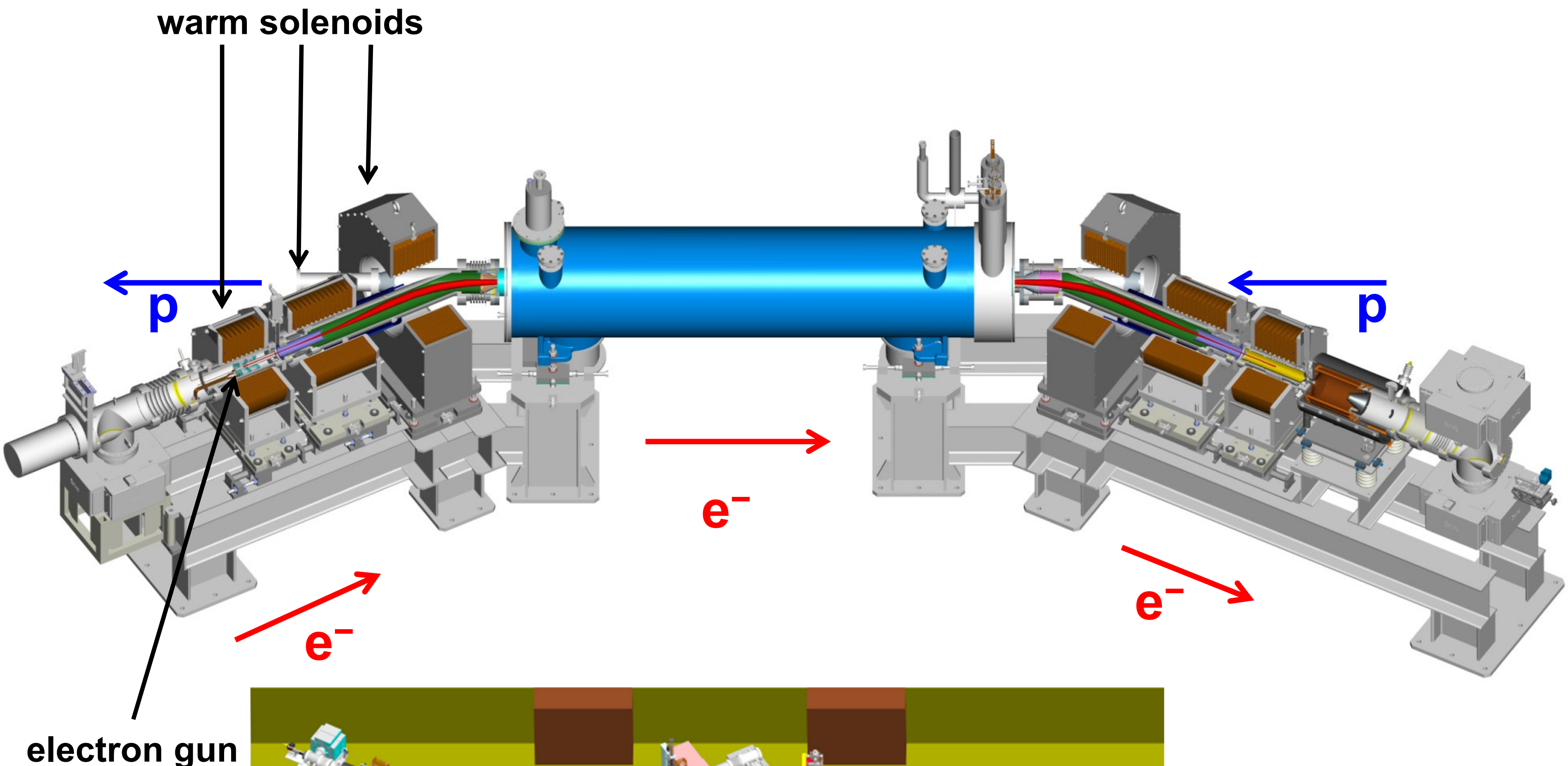

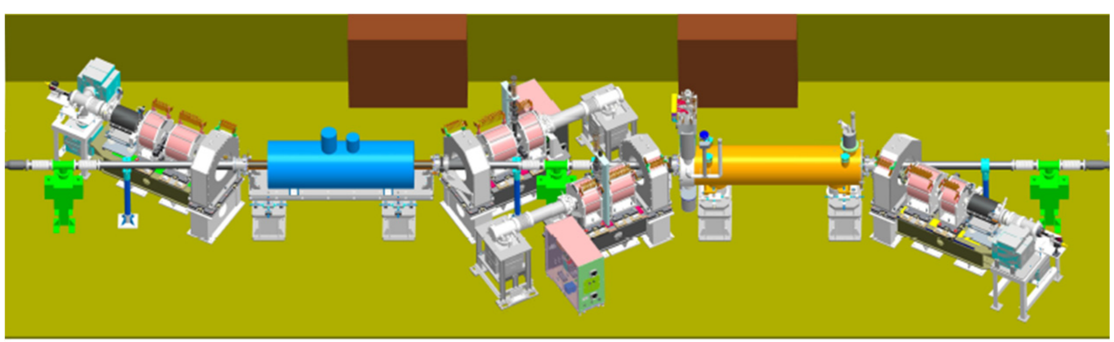

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RHIC electron lenses

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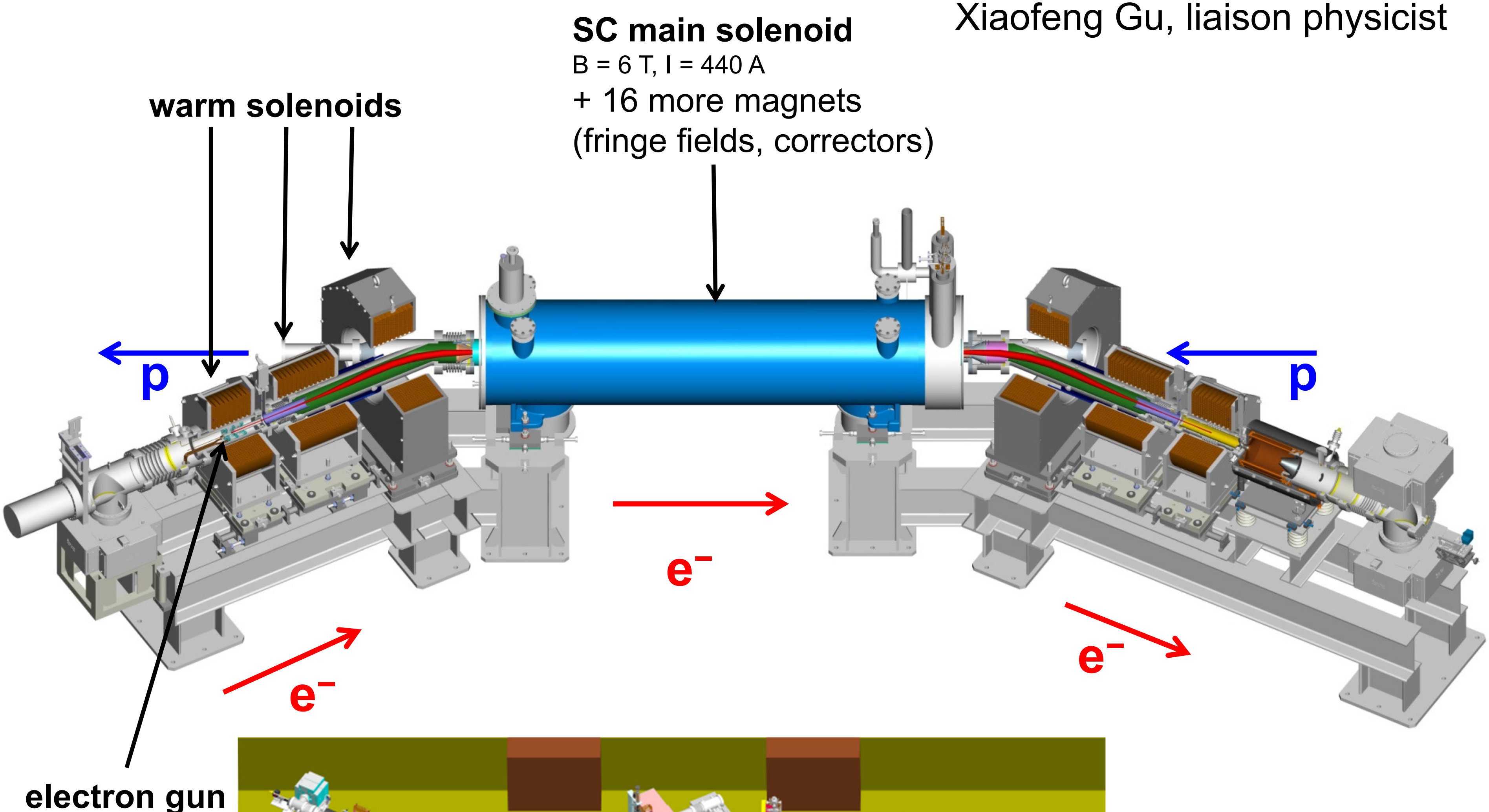

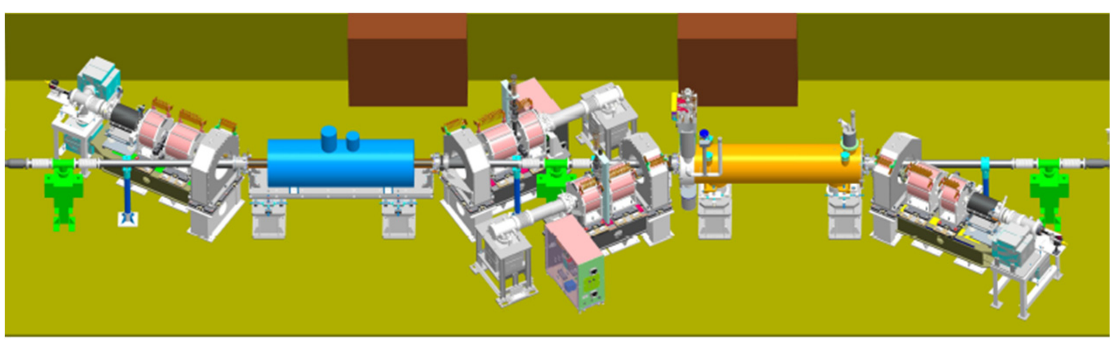

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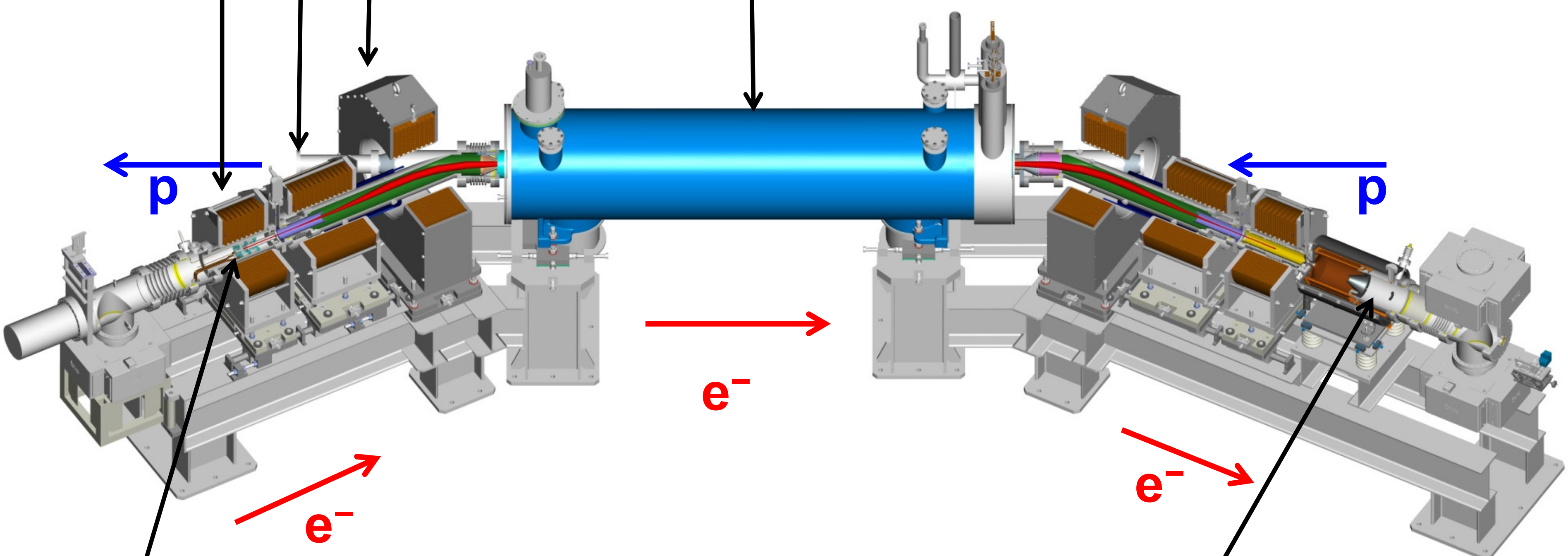

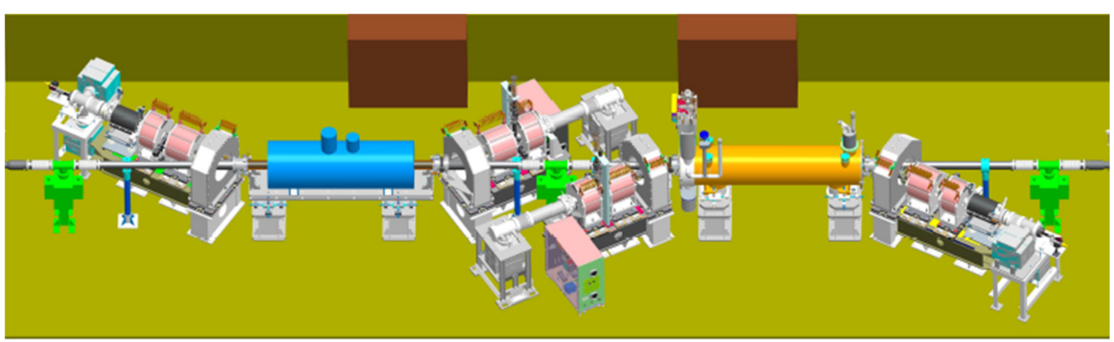

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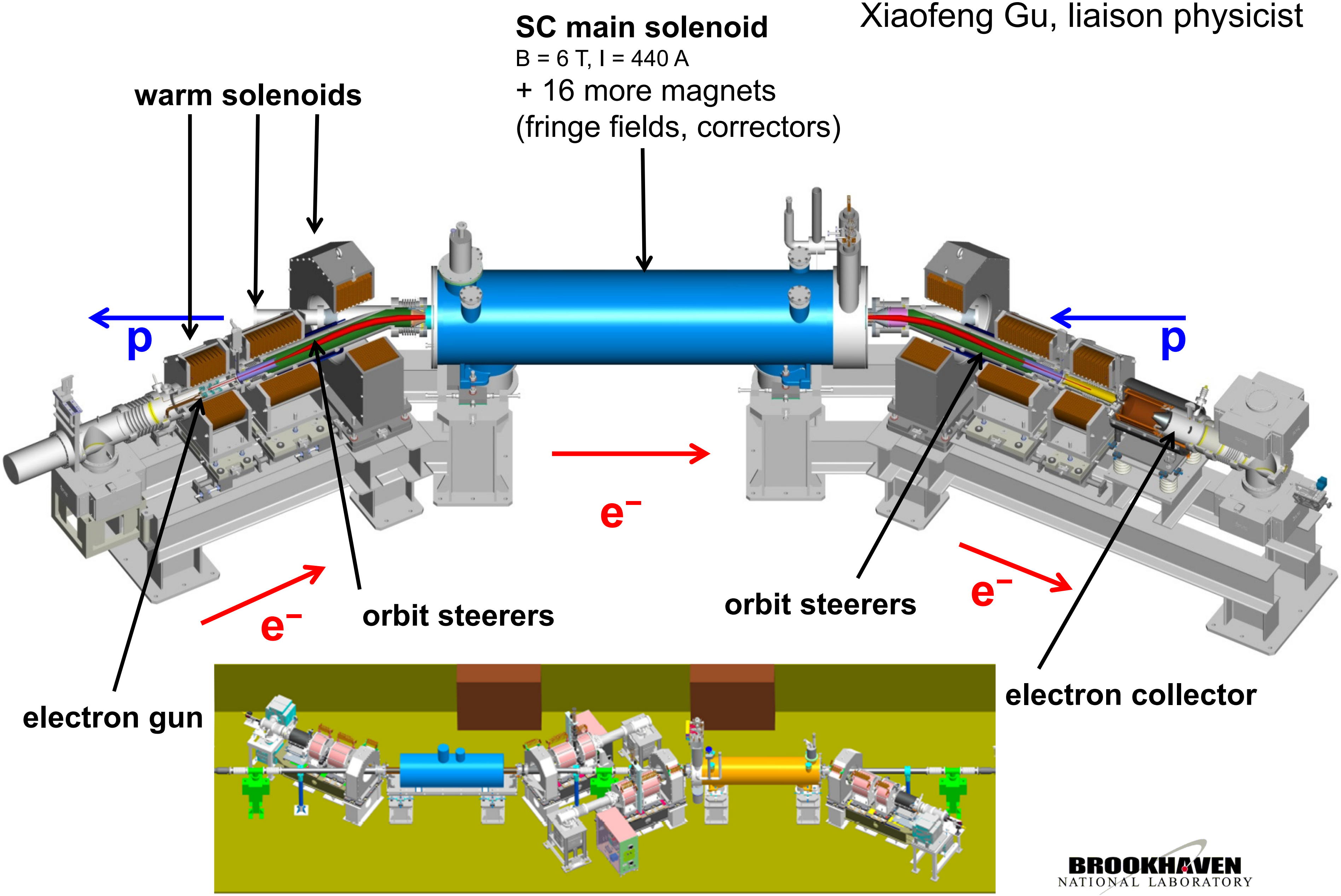

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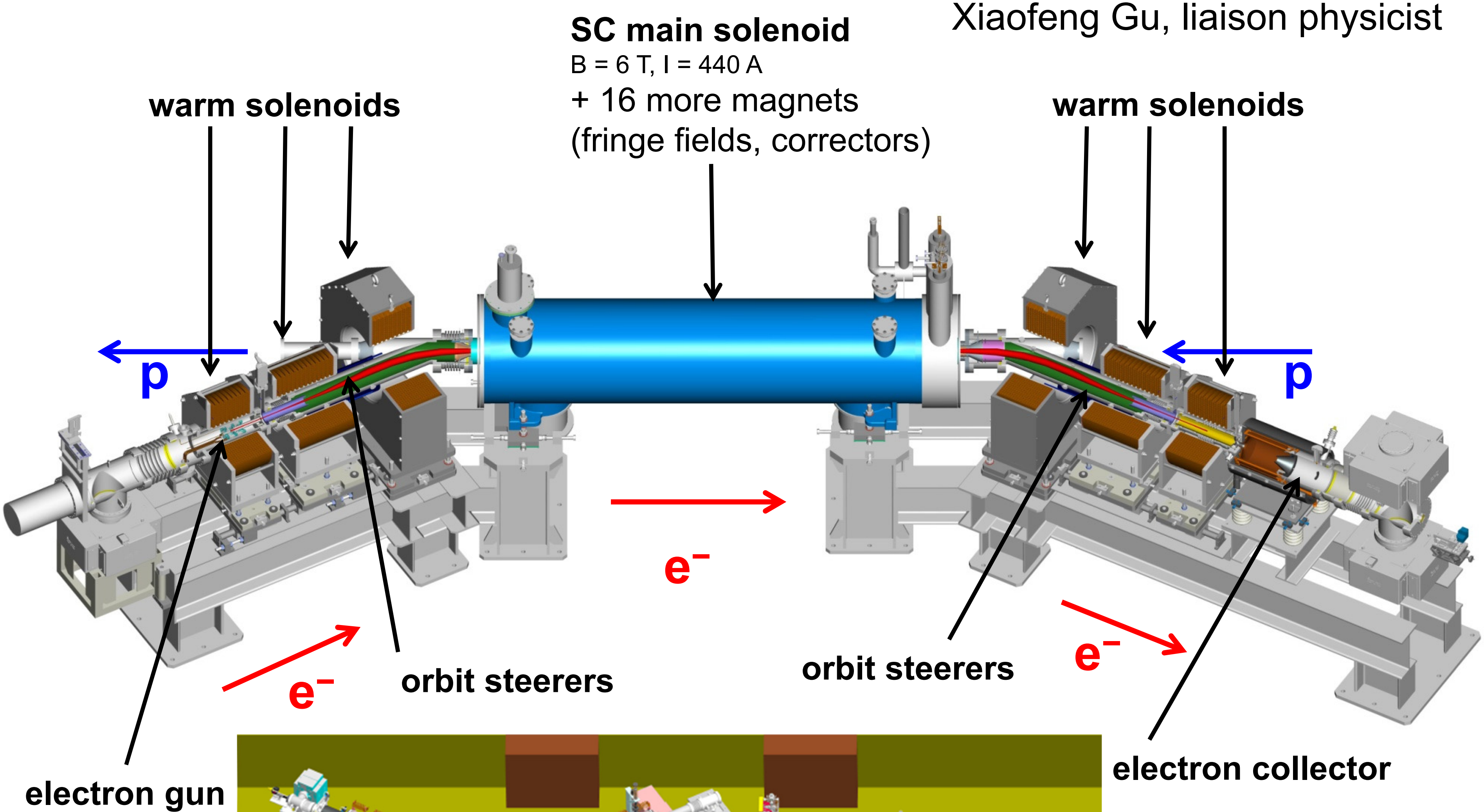

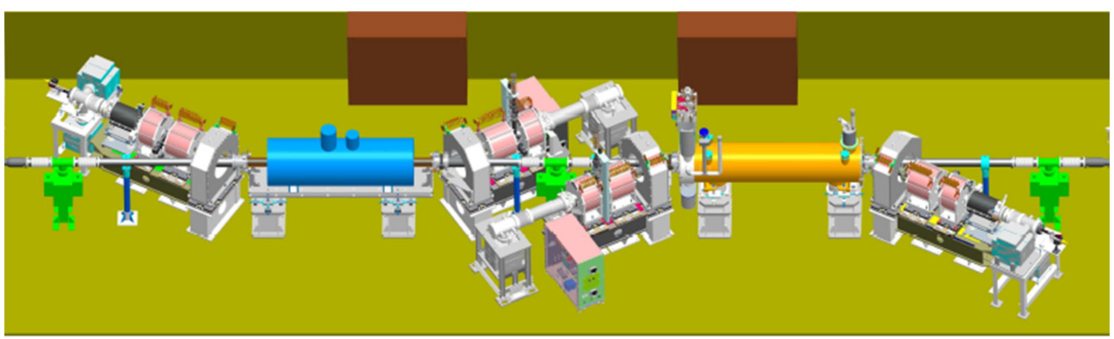

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RHIC e-lens Parameters

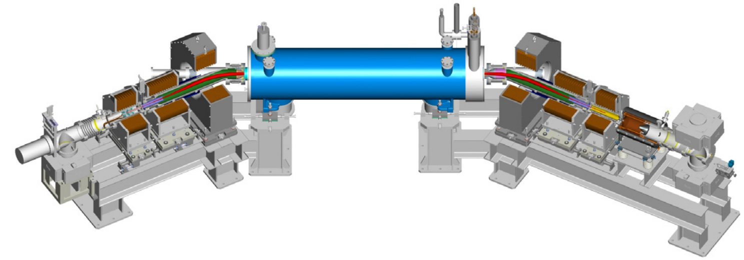
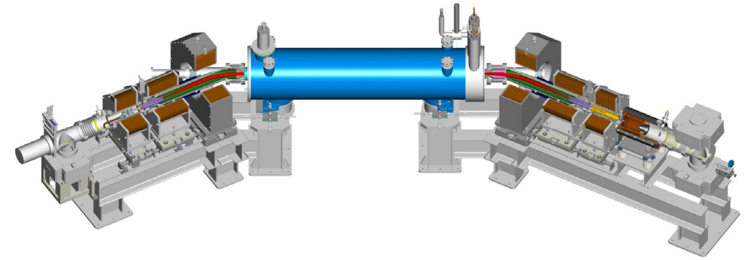


TABLE I. Typical electron lens parameters for 2015 and design values (for up to 250 GeV proton energy).

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	$+10$	$\leq +15$

Technology sources: Tevatron e-lenses (V. Shiltsev et al.),
RHIC Electron Beam Ion Source (EBIS) (J. Alessi et al.O

RHIC e-lens Parameters



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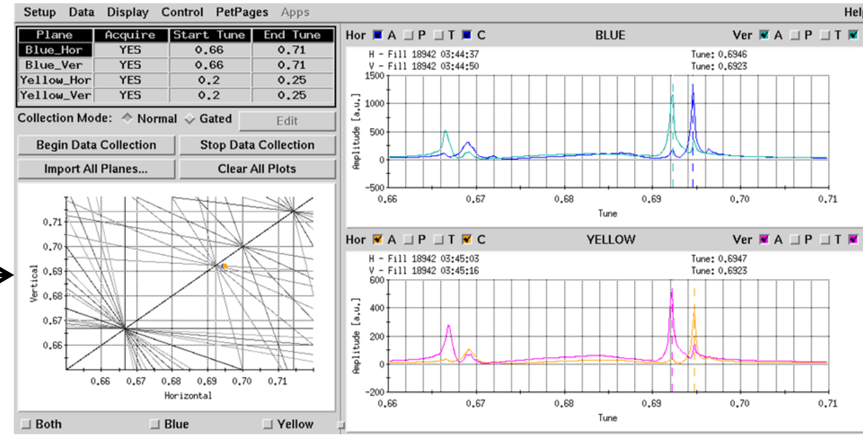
Head-on bb compensation Tune distributions from e-lens

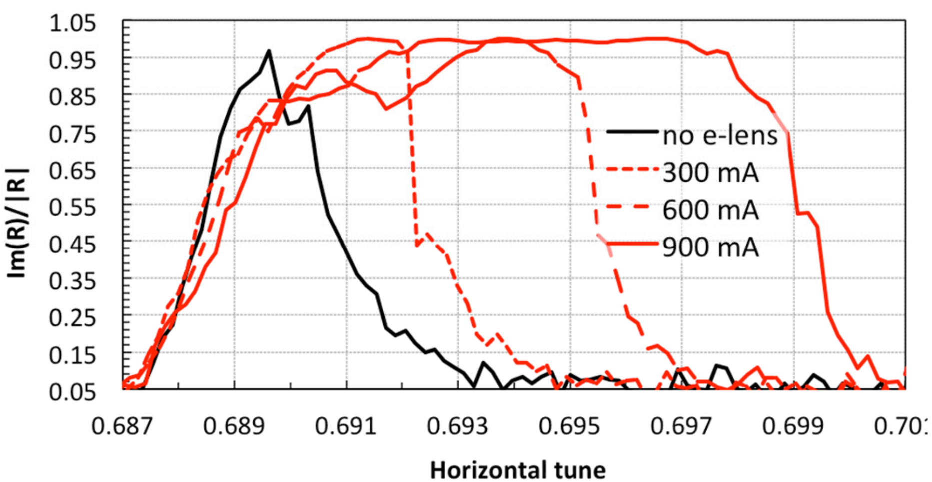
tune distribution measured with transverse BTF →



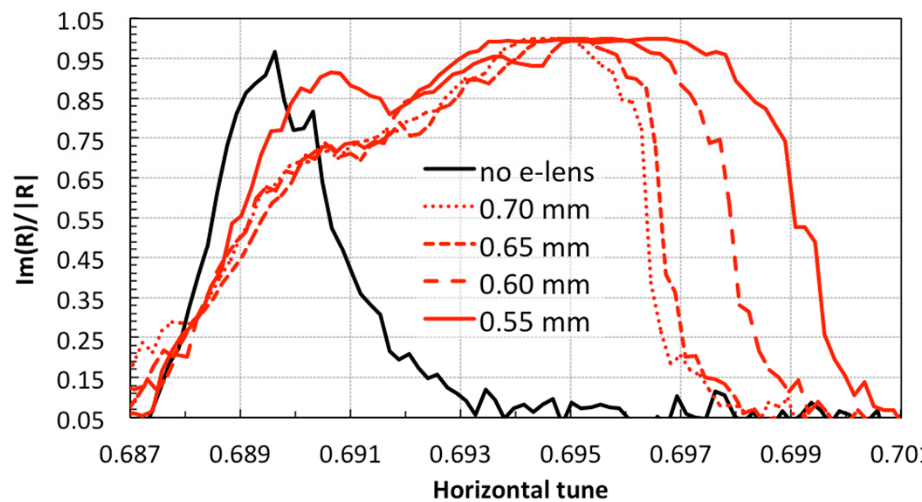
complex coherent response $R(Q)$ to small sinusoidal excitation at tune Q

non-zero Im(R) = non-zero particle distribution

current scan (σ_e = 0.55 mm)



size scan (I_e = 900 mA)



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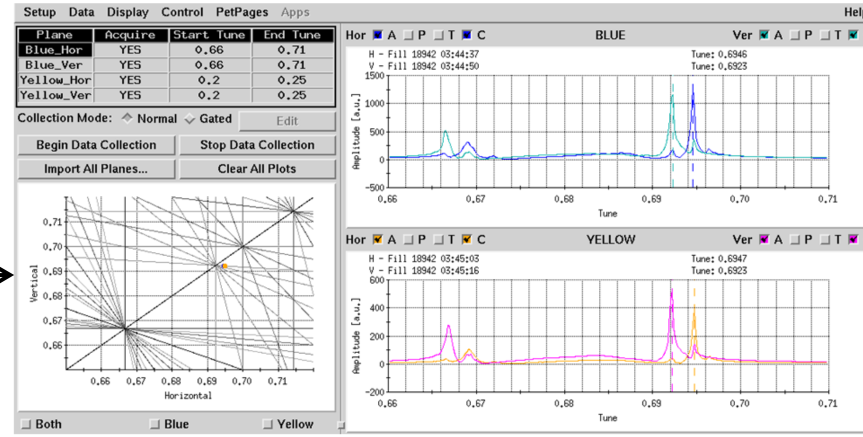

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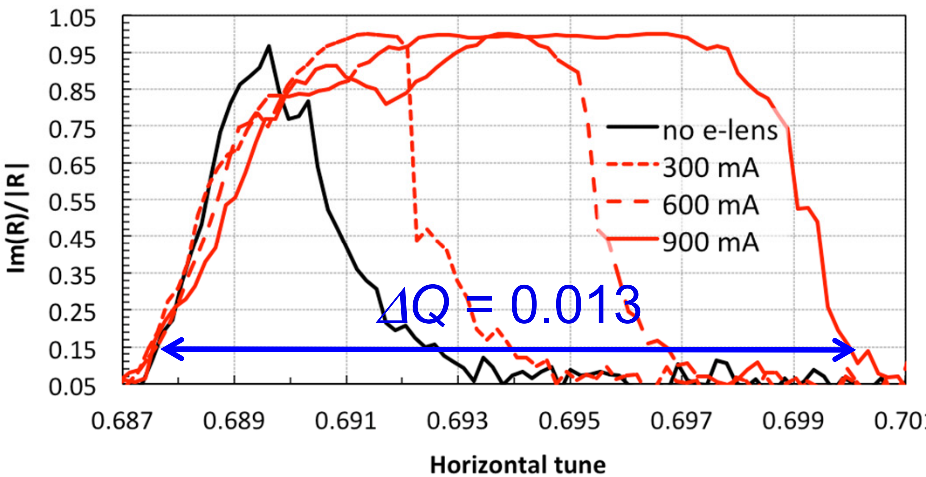

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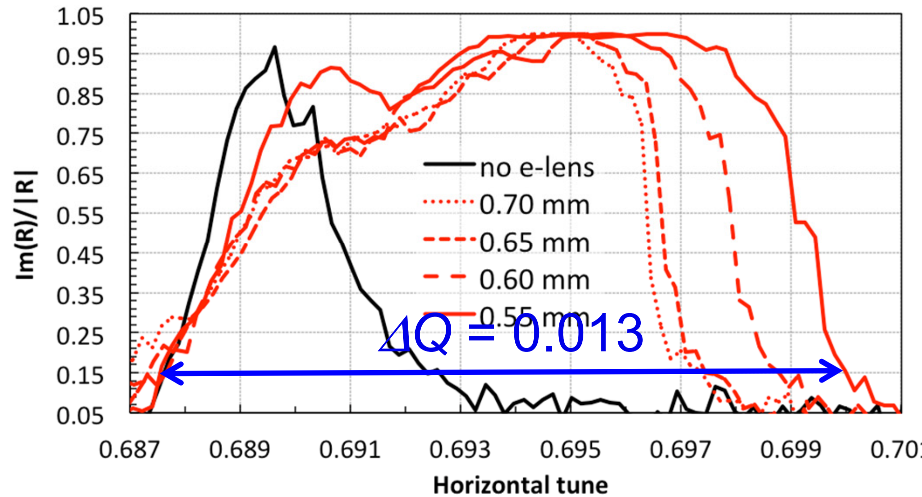


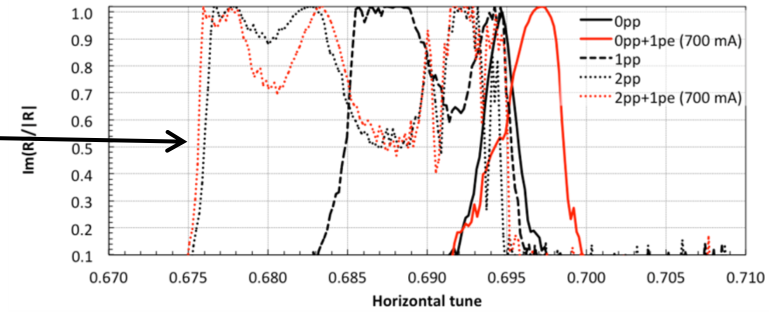
ξ_{max} = −0.011 (max in 2015 RHIC operations)

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))



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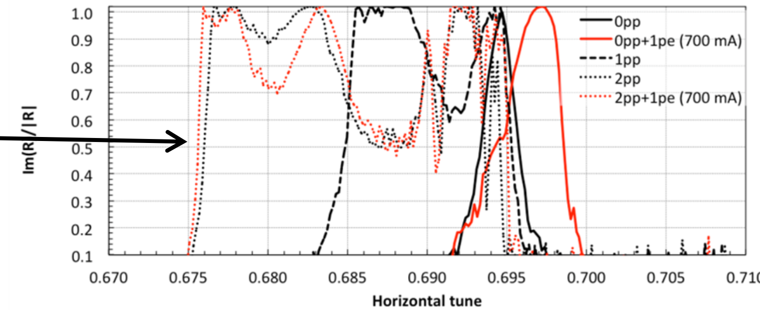

tune distribution can be measured with BTF and p+Al collisions

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

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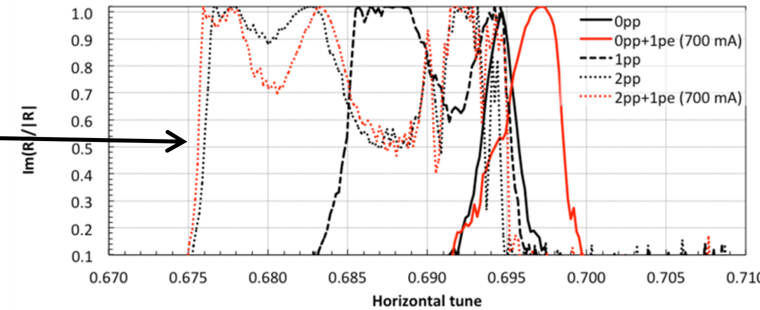

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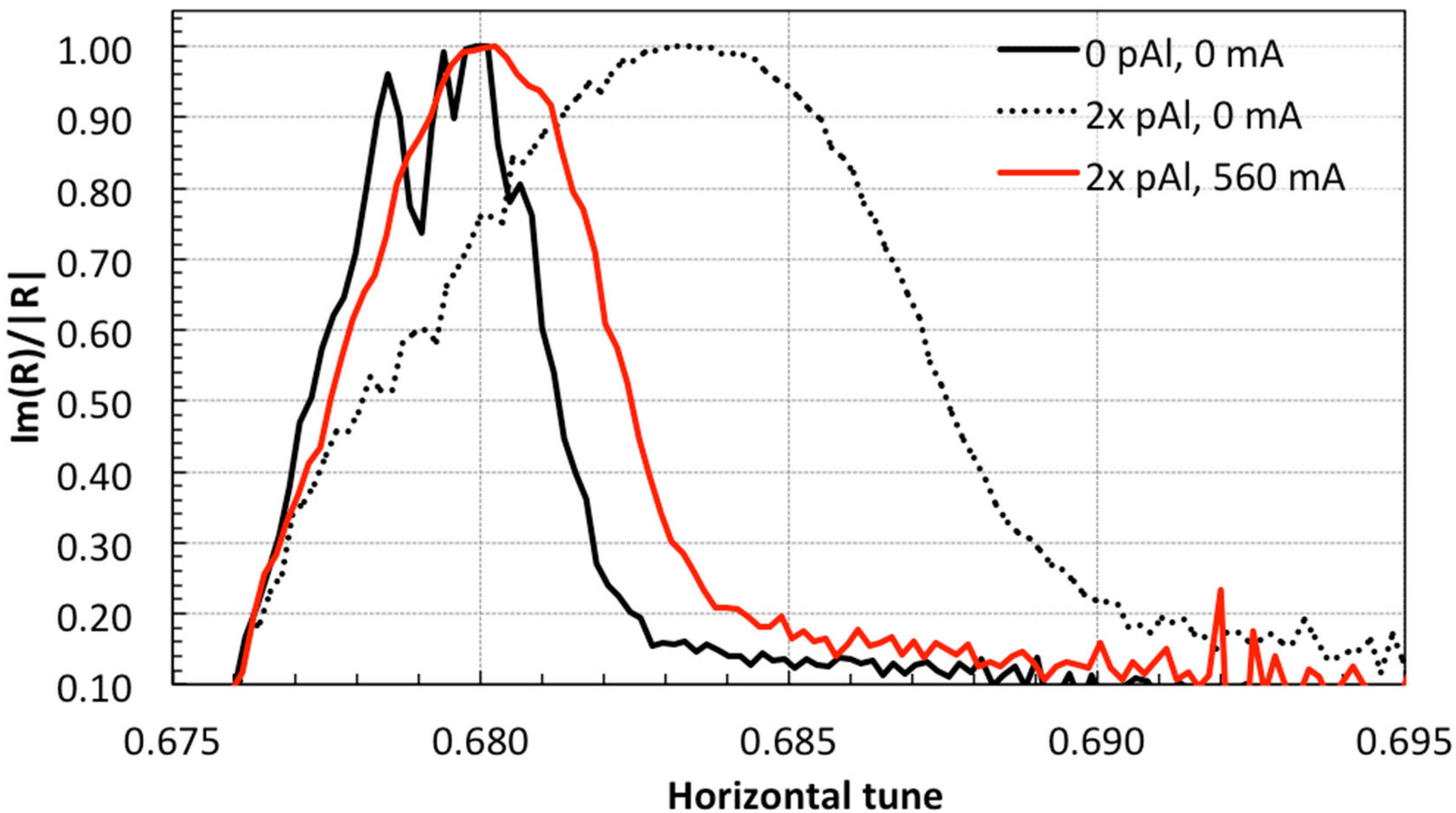

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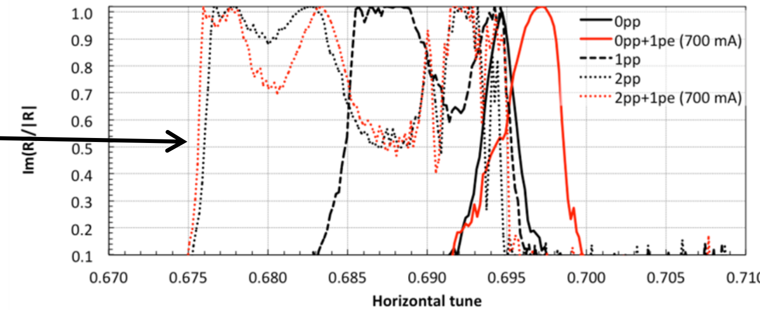

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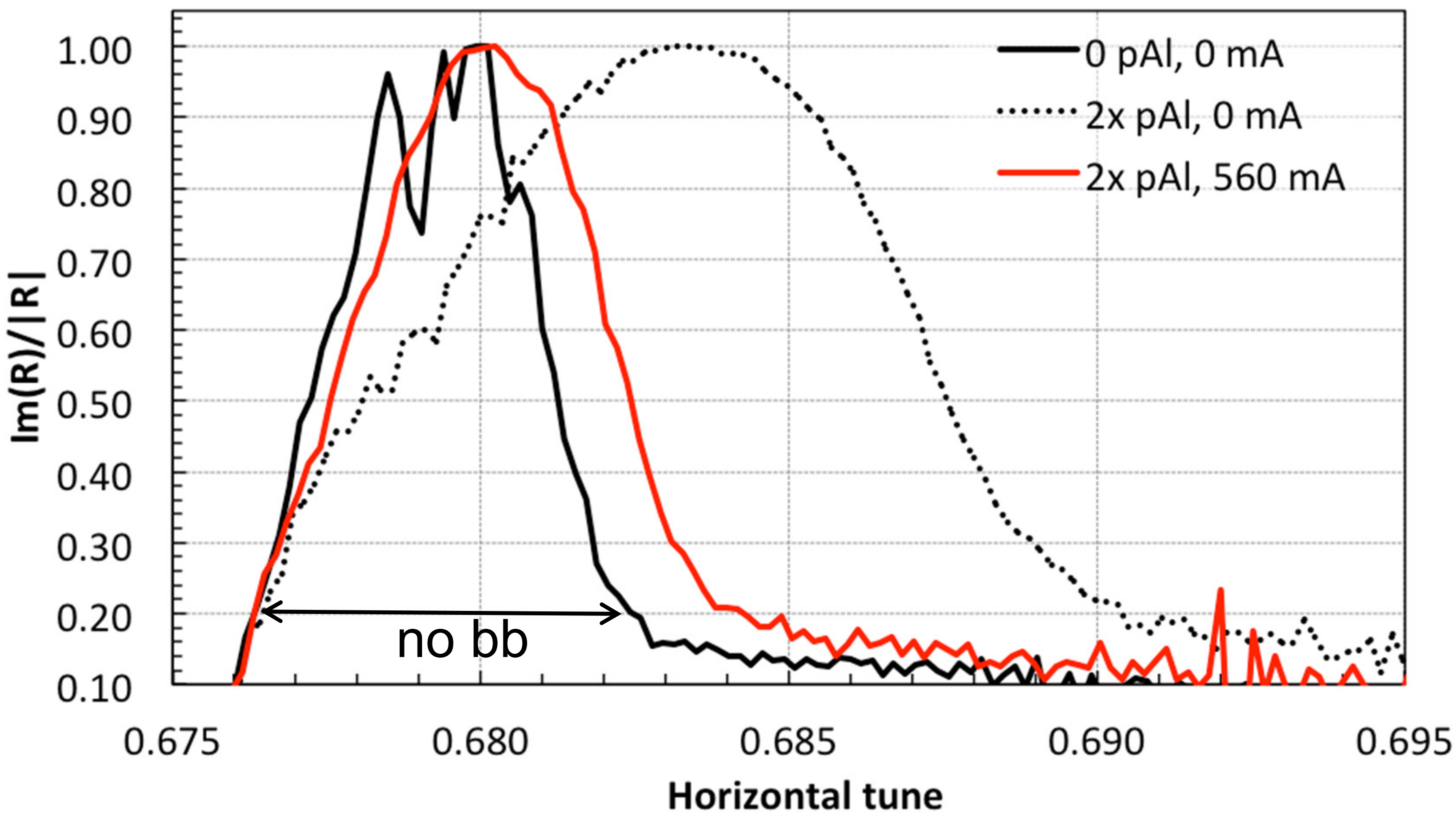

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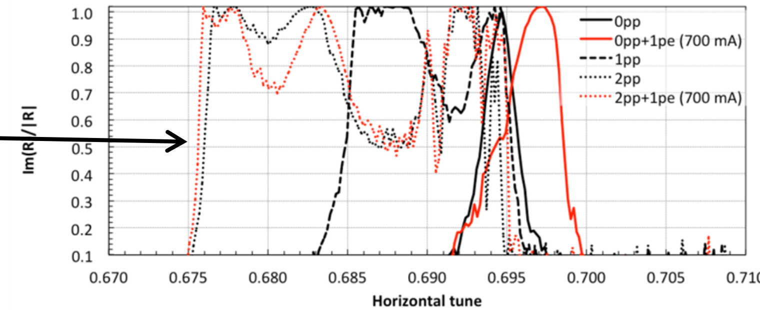

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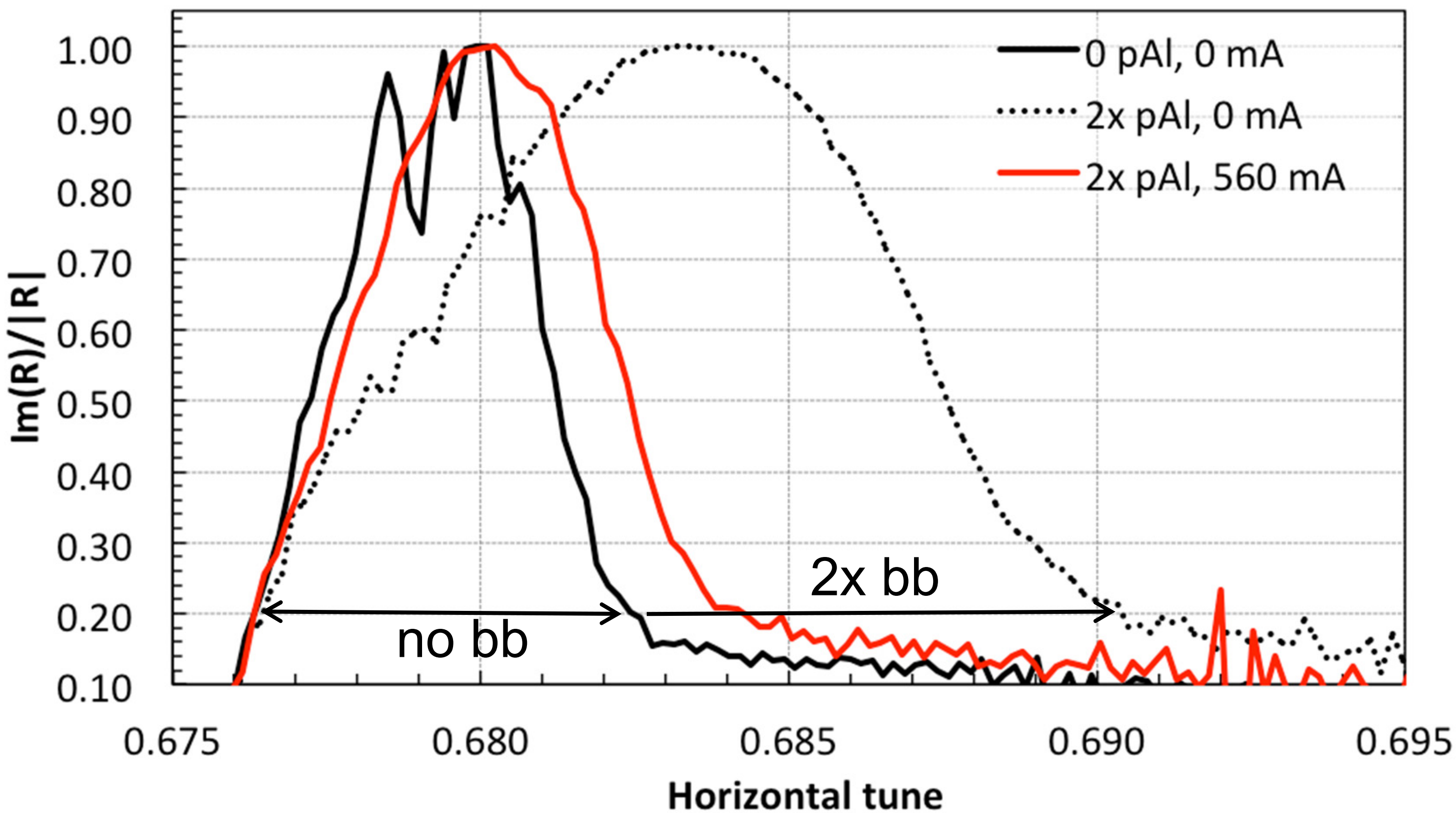

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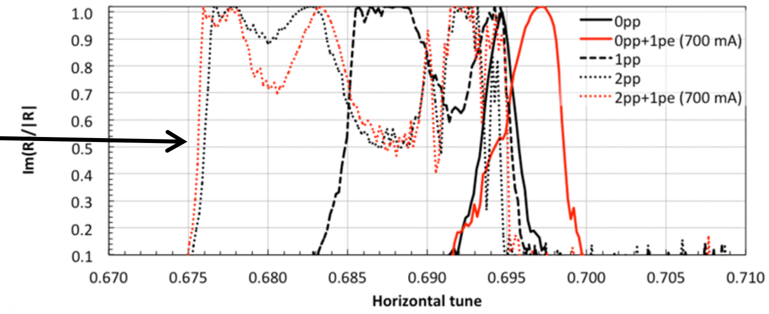

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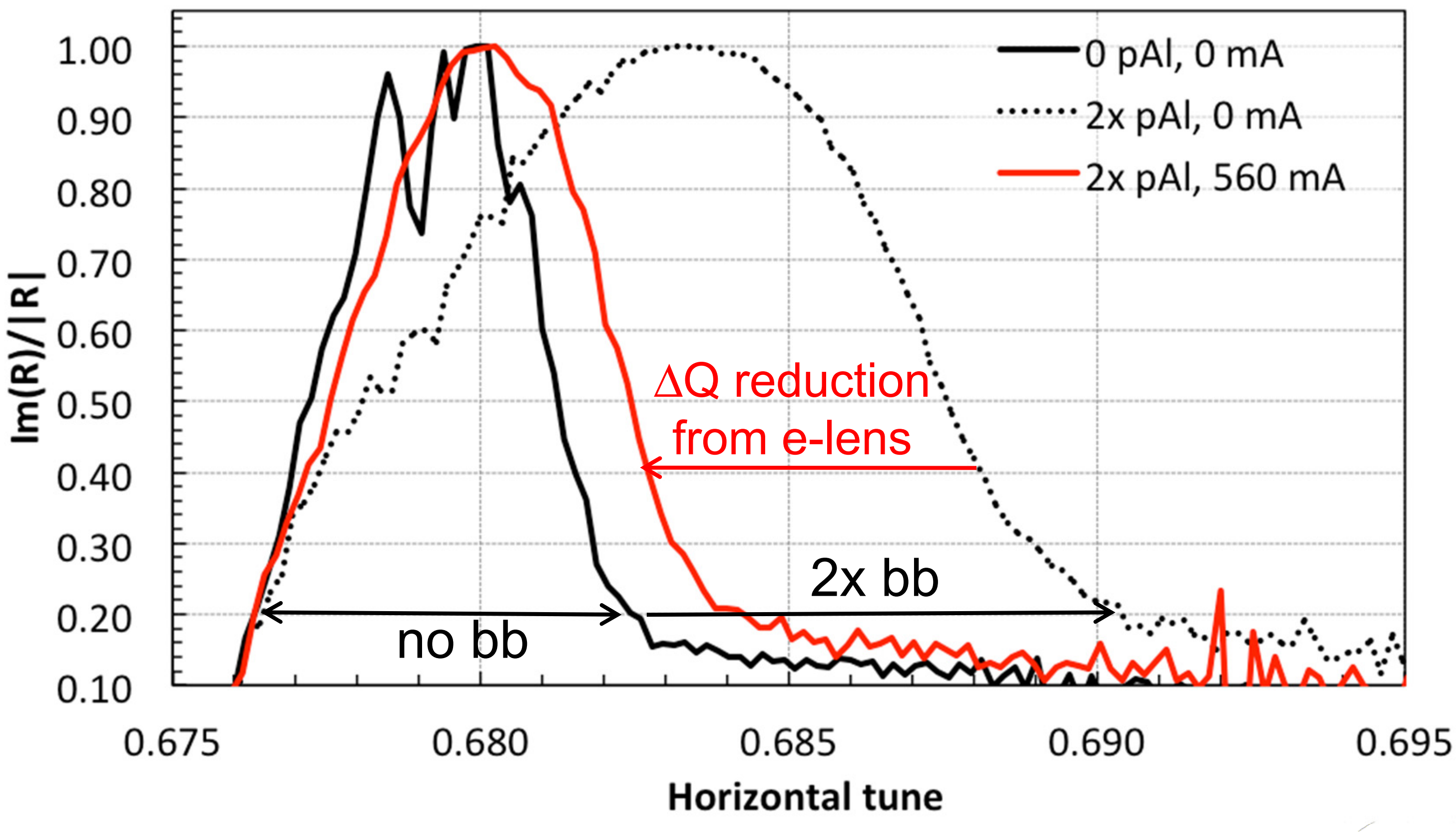

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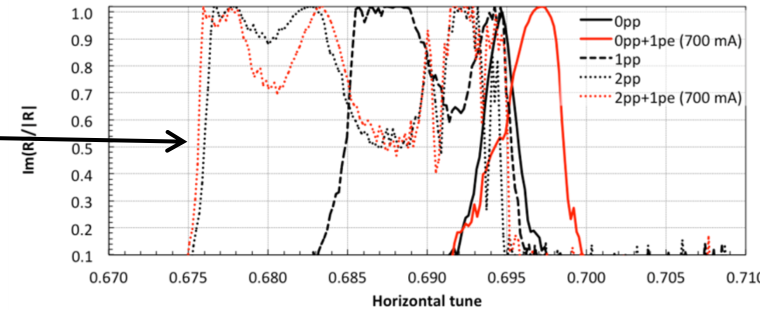

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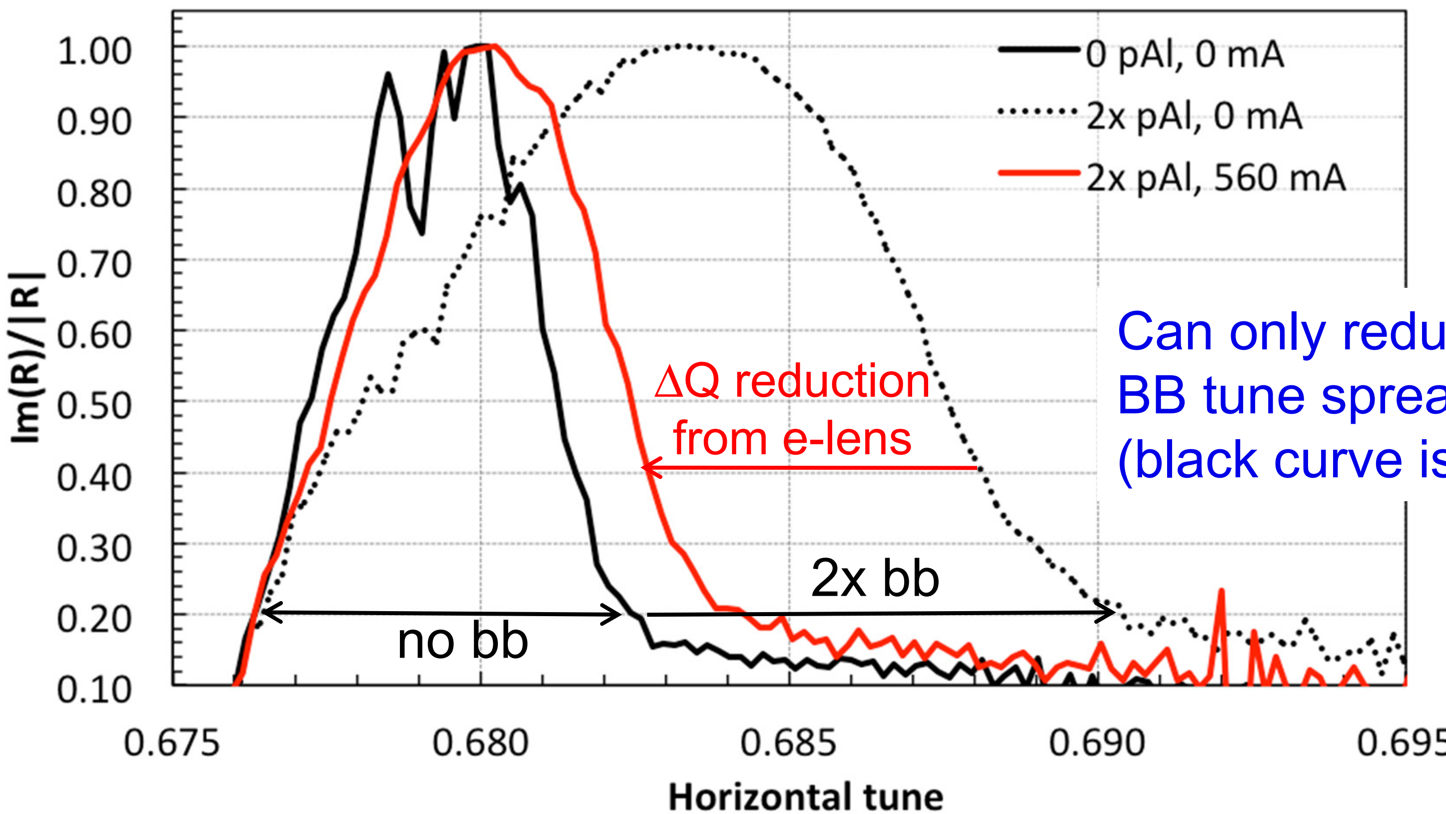
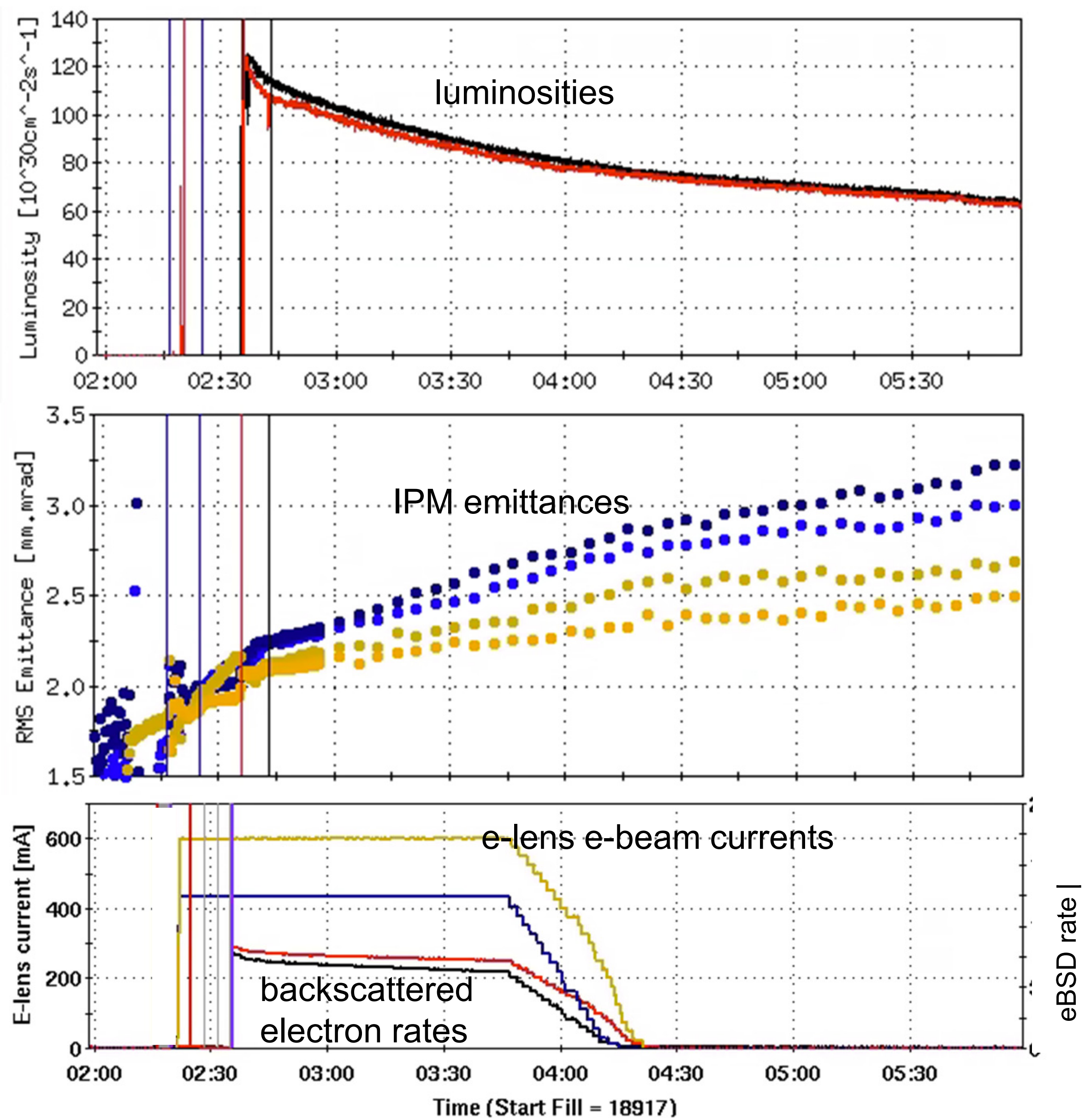


Can only reduced BB tune spread (black curve is limit)

e-lenses in operation with collisions at 2 experiments



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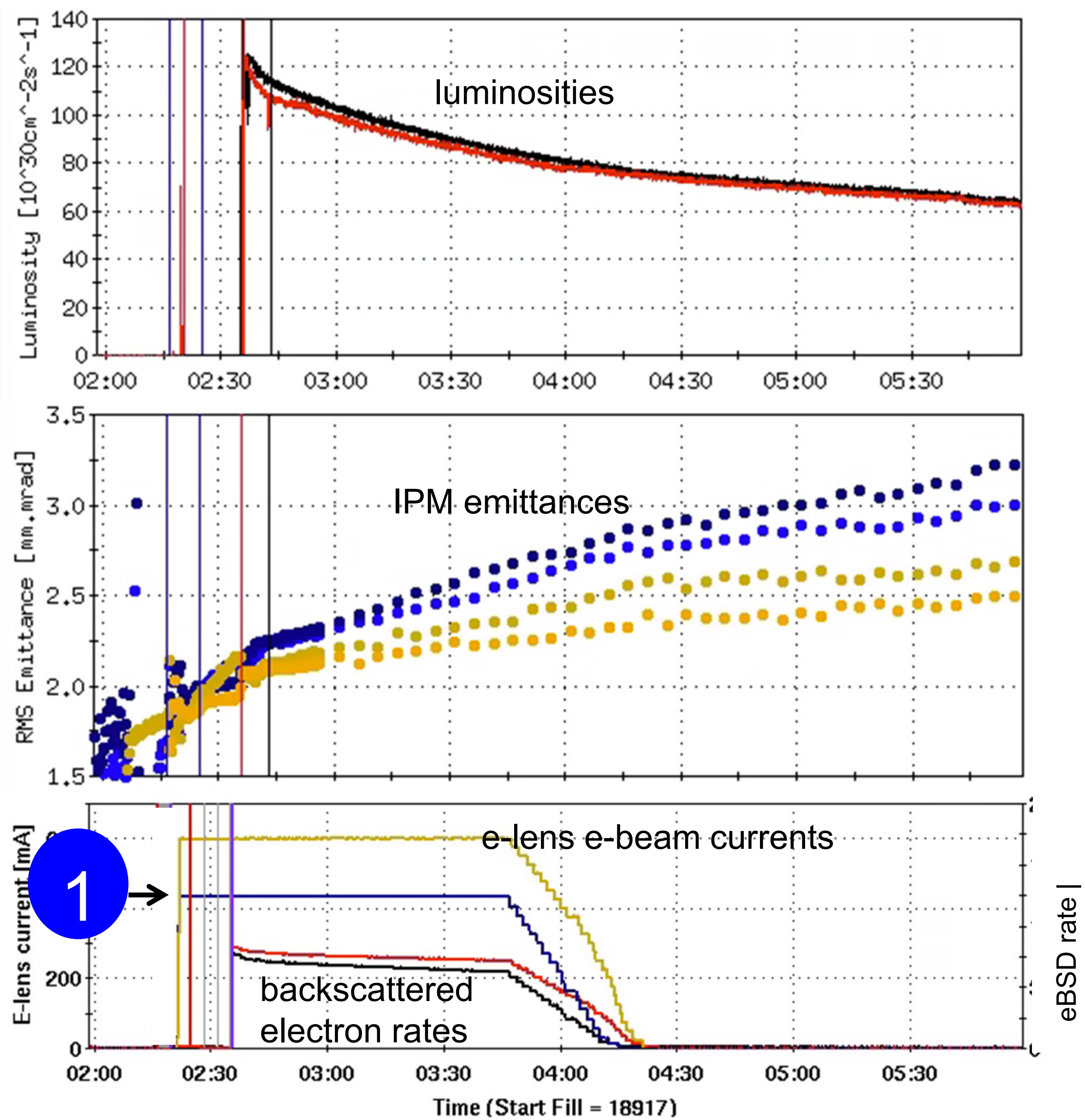

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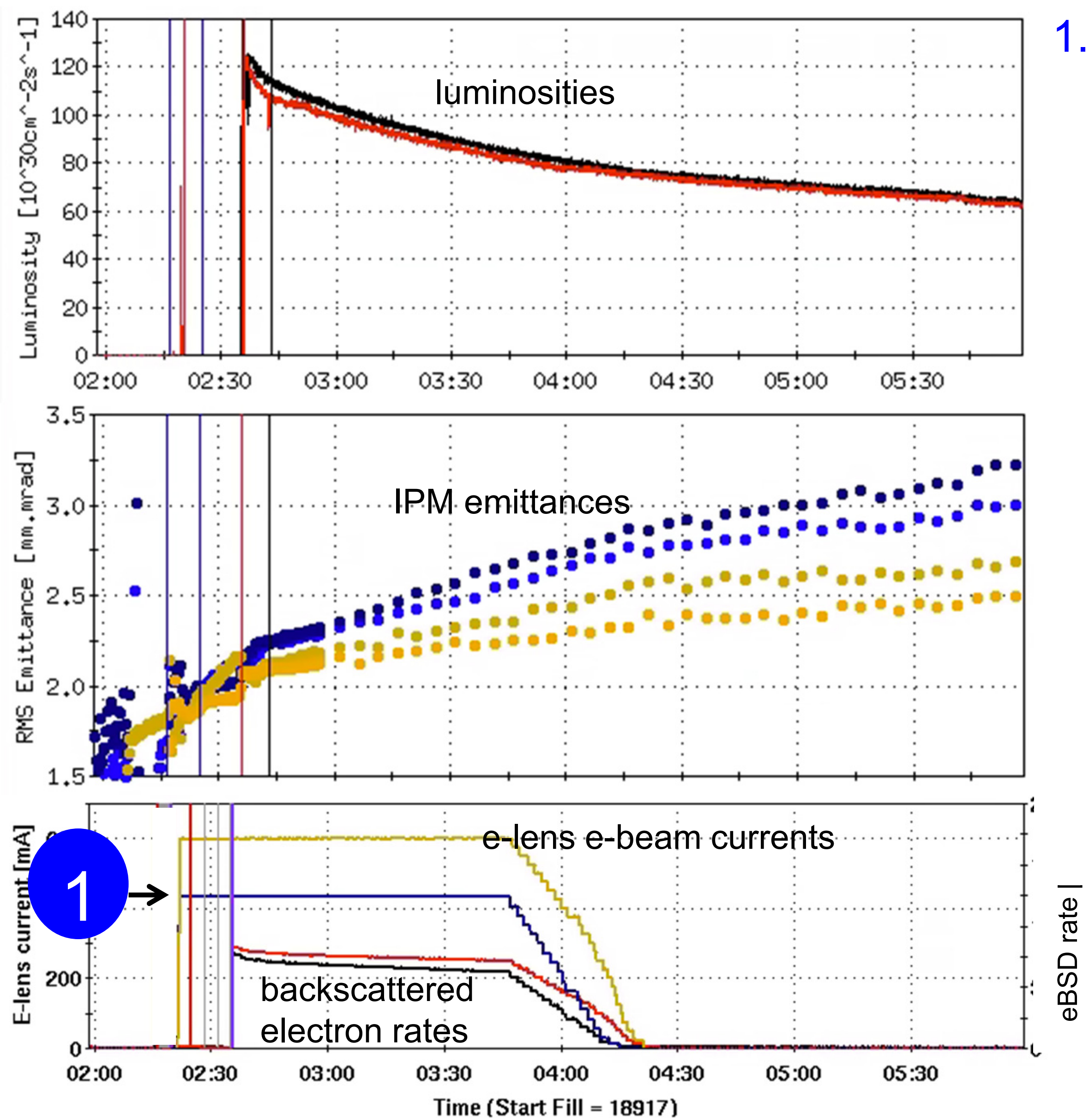

1. e-lenses turn on before collision
   (112 stores with both lenses without
   a single turn-on failure)

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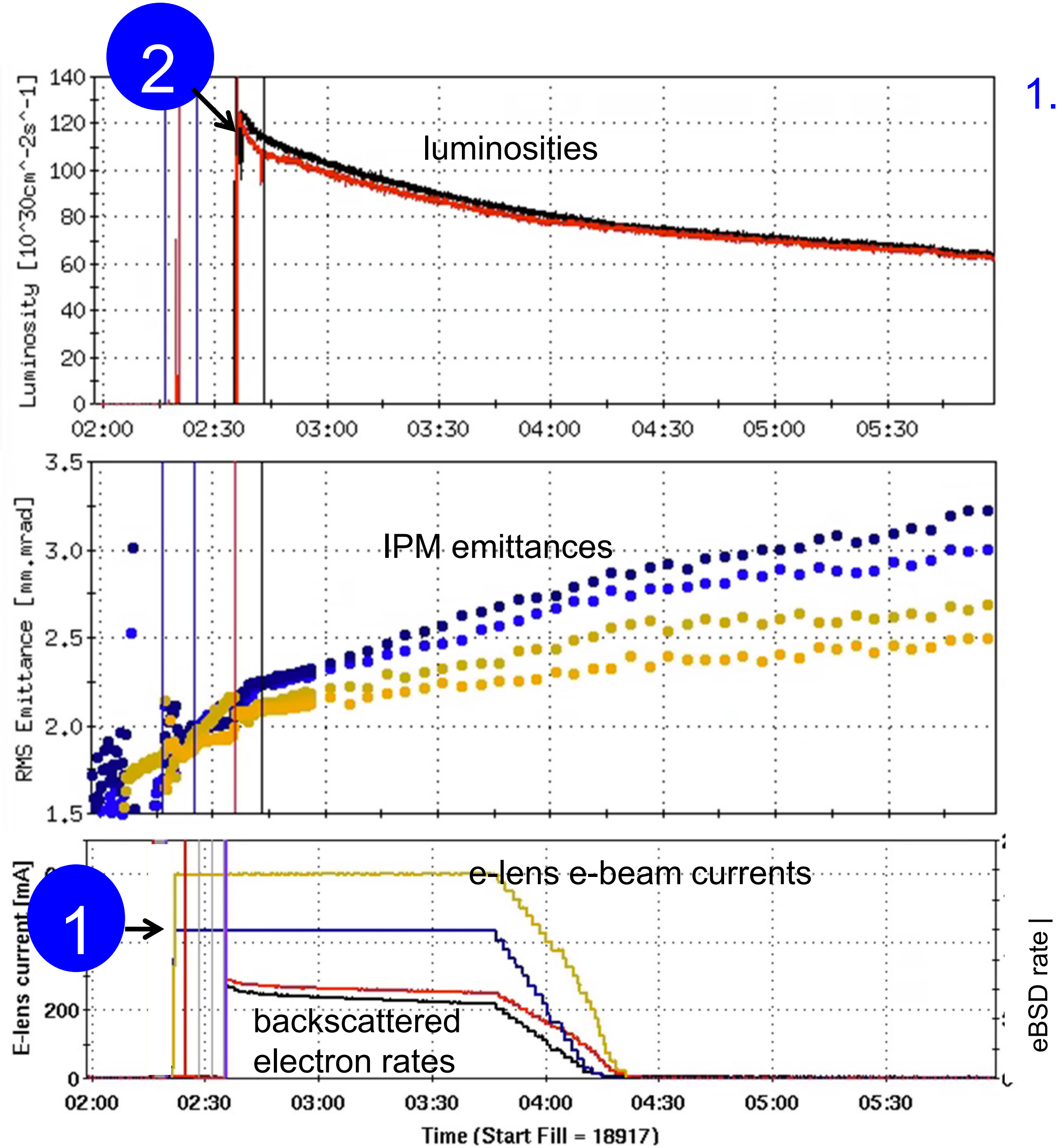

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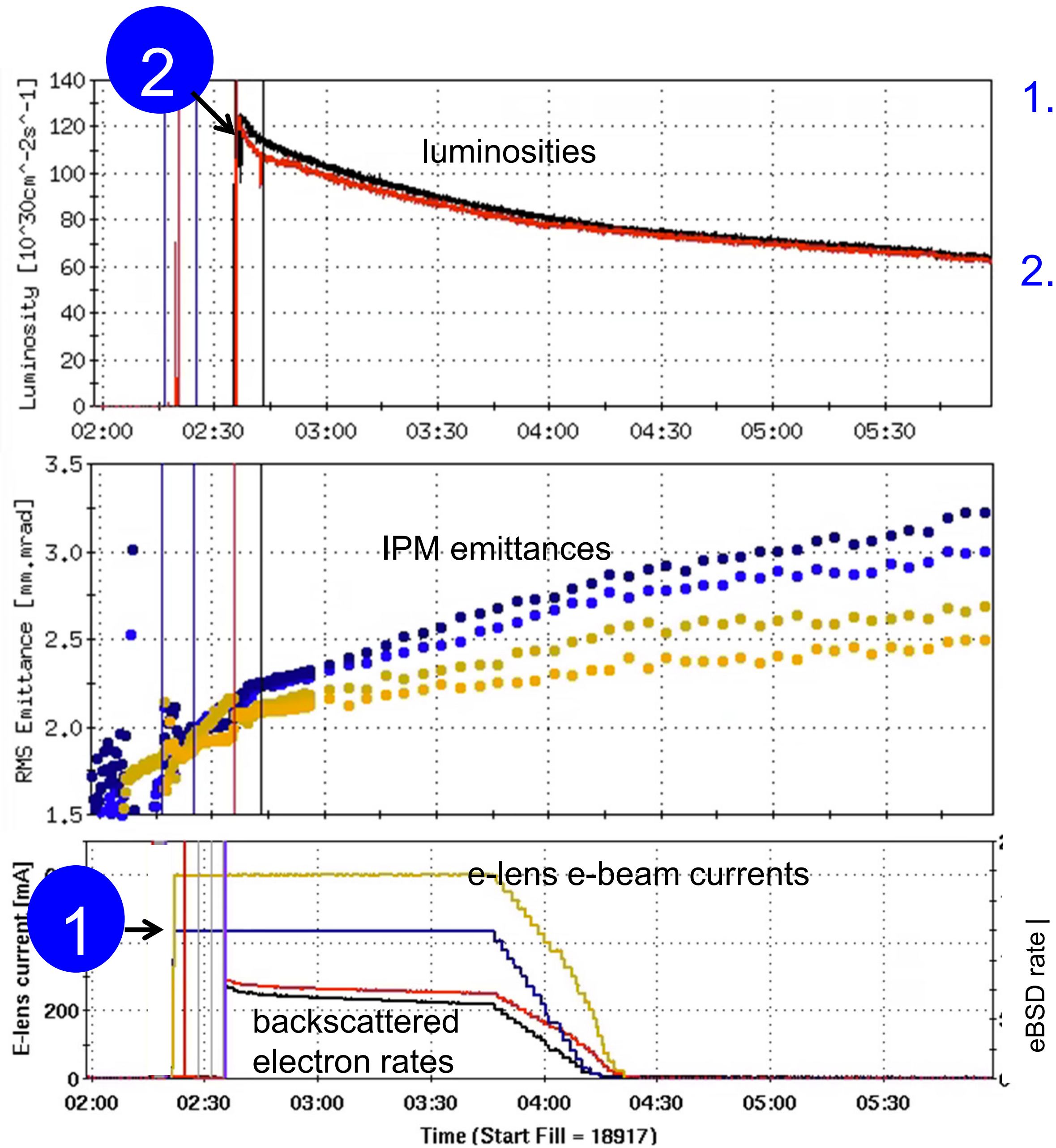

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2. Beams into collision at PHENIX, collimators to store positions
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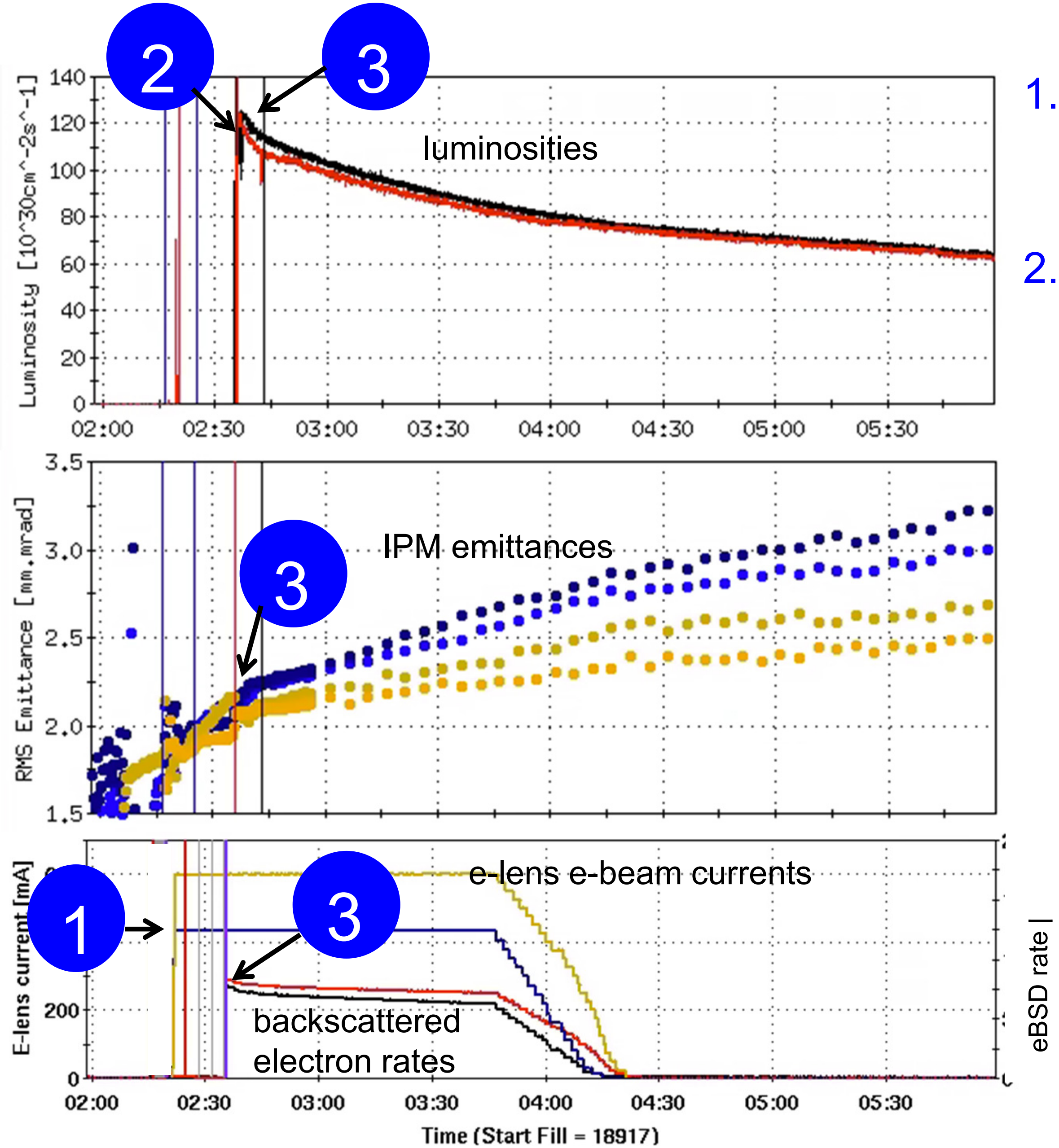
e-lenses in operation with collisions at 2 experiments



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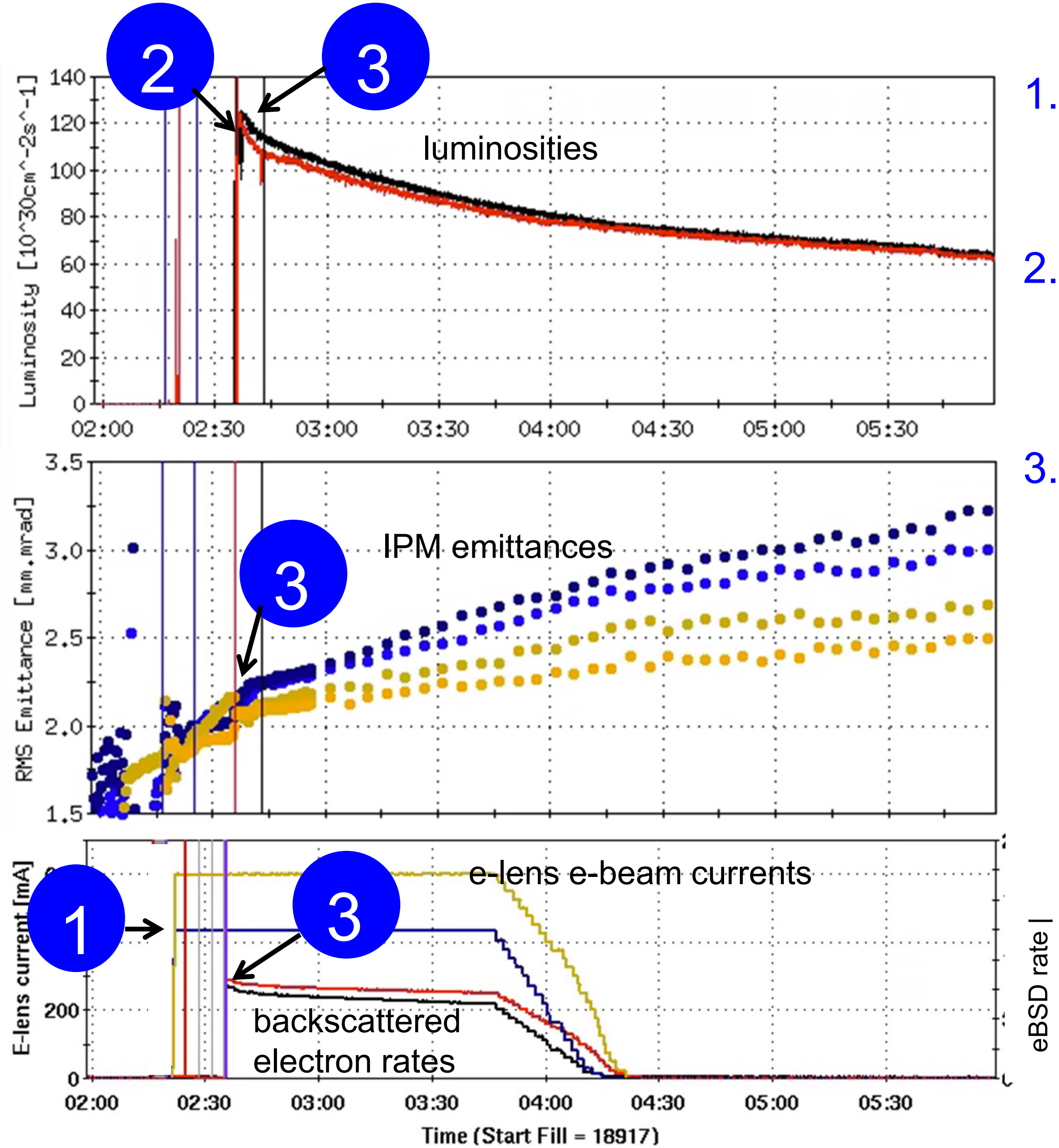

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3. Beams into collision at STAR and e-lenses
   e-lenses prevent emittance growth and/or beam loss for large beam-beam param. ξ

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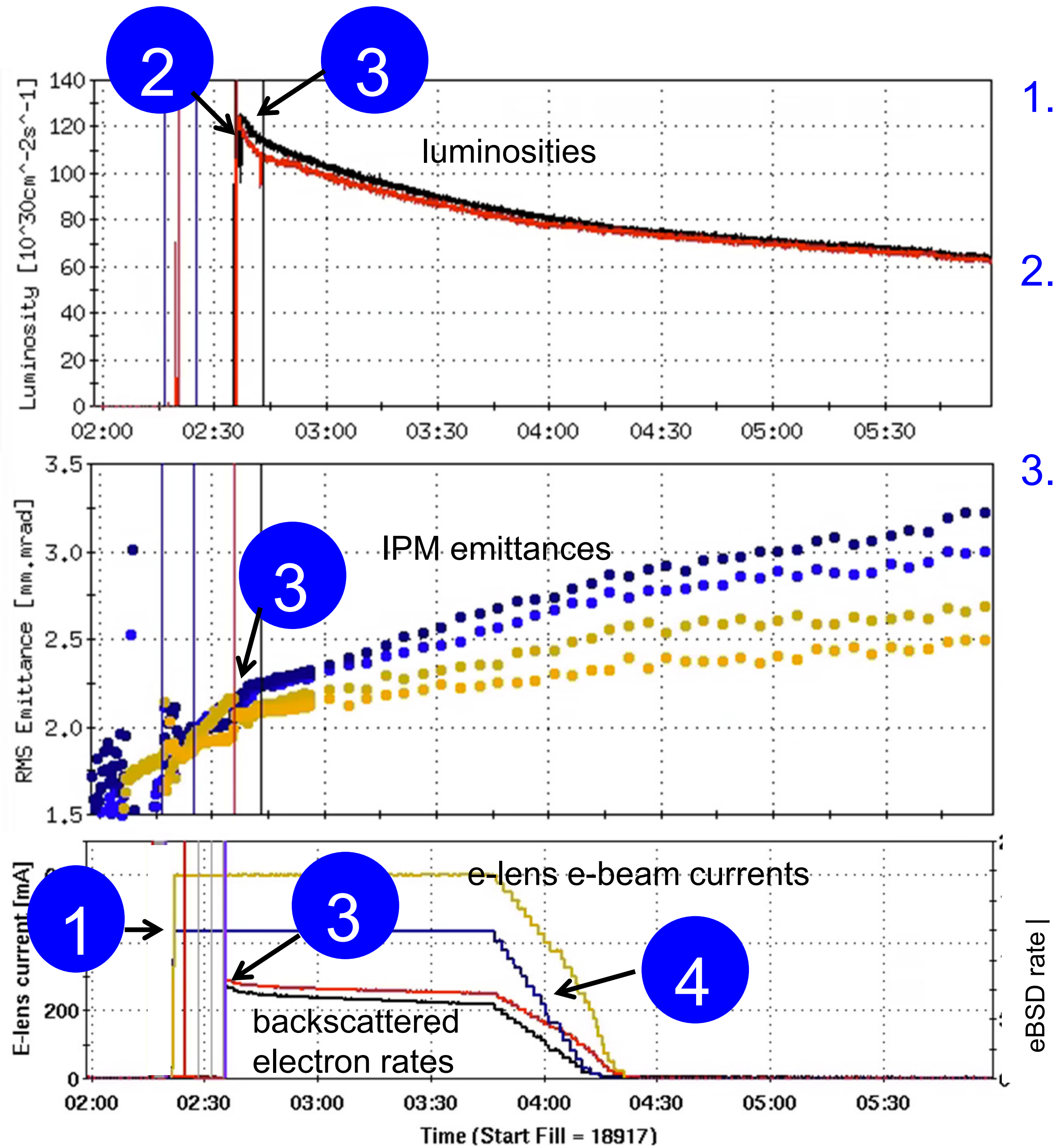
e-lenses in operation with collisions at 2 experiments



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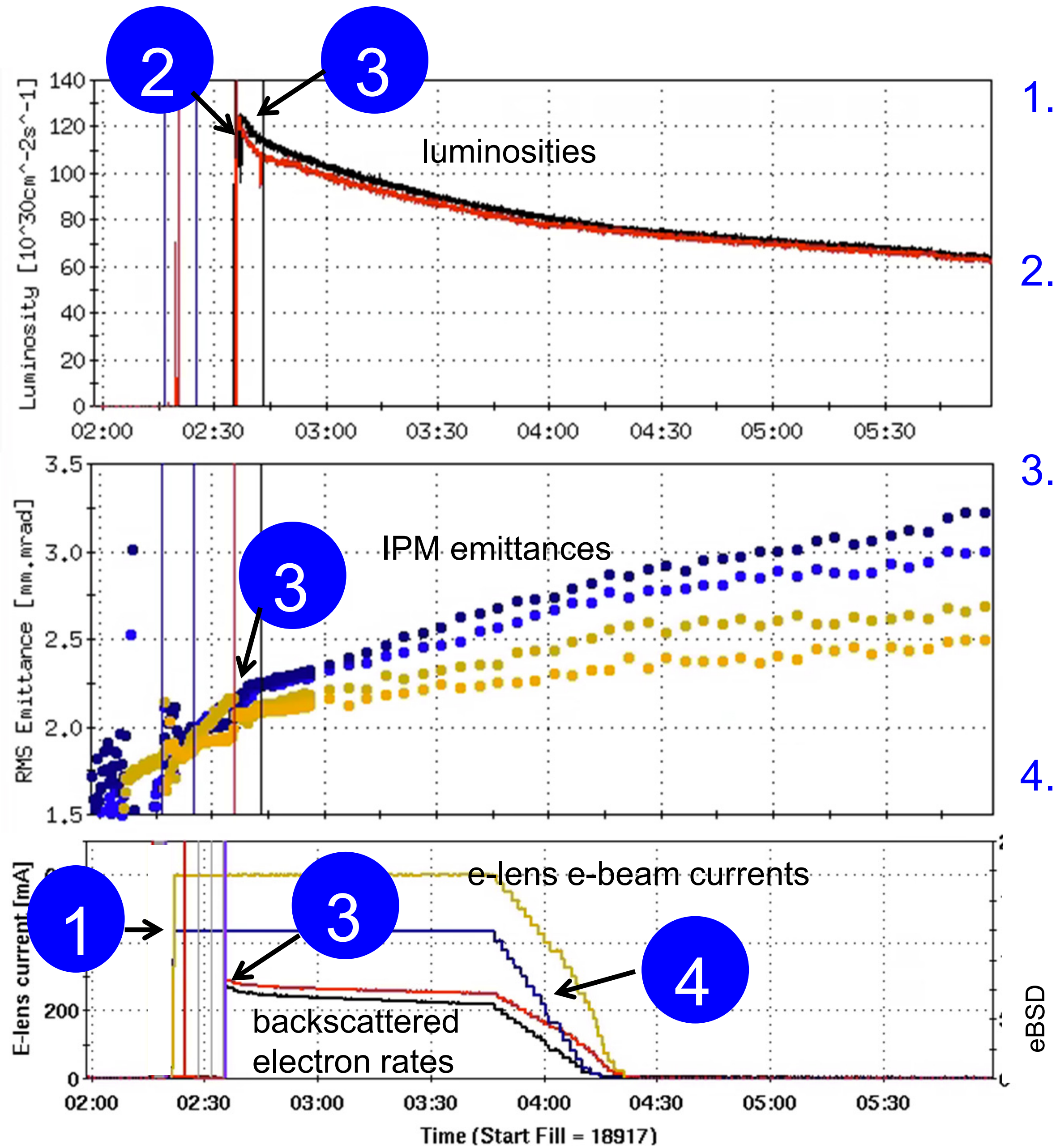

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3. Beams into collision at STAR and e-lenses
   e-lenses prevent emittance growth and/or beam loss for large beam-beam param. ξ
4. Lenses are gradually turned off when lattice alone can sustain bb parameter ξ

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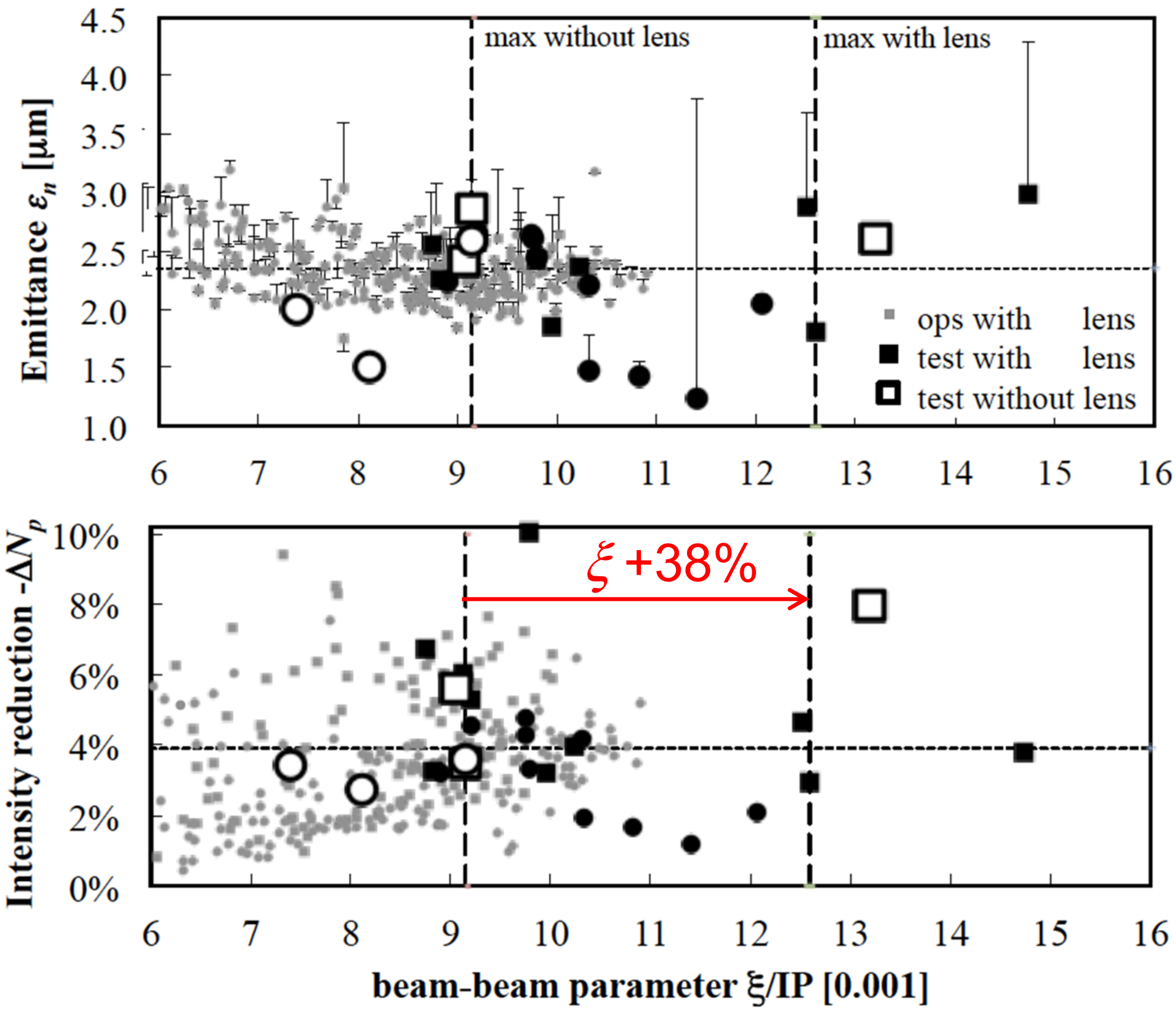
Head-on bb compensation

increase in bb parameter ξ with lens

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



2 data sets:

(1) 2015 ops

(2) tests for max |ξ|

— avg. over good stores

ops: 111 bunches

tests: 30/48 bunches

=> higher intensity and brightness

— avg. over good stores

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)		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	—	—	—

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

2 data sets:
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(2) tests for max |ξ|

quantity	unit	operations (avg. over 10 best stores) 2012	2015	tests for m[…] without e-lens —	witl[…] e-ler[…] 2015	
bunch intensity N_p	10^{11}	1.6	2.25	2.6	2.15	[illegible]
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	—
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increases in L and ξ

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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.)

Head-on bb compensation

increases in L and ξ

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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.)

Head-on bb compensation

increases in *L* and ξ

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$\beta^*_{x,y}$ 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]	[illegible]	3[illegible]	[illegible]	[illegible]
rms beam size IP6/8 σ^*_p	μm	16[illegible]	[illegible]	1[illegible]	[illegible]	[illegible]
rms beam size e-lens σ_p	μm	—	[illegible]	7[illegible]	[illegible]	[illegible]
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	[illegible]	−9.1	[illegible]	−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.)

Head-on bb compensation

increases in L and ξ

quantity	unit	operations (avg. over 10 best stores) 2012	2015	tests for m without e-lens —	with e-ler 2015	
bunch intensity N_p	10^{11}	1.6	2.25	2.6	2.1	
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		
rms beam size IP6/8 σ^*_p	μm	16		1		5
rms beam size e-lens						
rms b						
hourg						
beam-						
# of l						
lumin						
lumin						

2 data sets:
(1) 2015 ops
(2) tests for max |ξ|

effect of new lattice

effect of electron lens

ξ +38% w/o and w/ [elect]ron lens

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Operational Head-on Beam-Beam Compensation with Electron Lenses in the Relativistic Heavy Ion Collider

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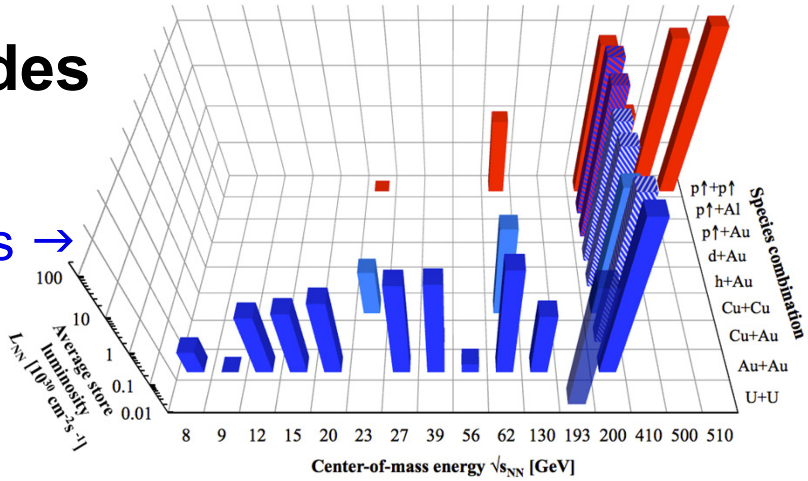
Head-on beam-beam compensation has been implemented in the Relativistic Heavy Ion Collider in order to increase the luminosity delivered to the experiments. We discuss the principle of combining a lattice for

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.)

IPAC16

Summary – RHIC upgrades

Continue to run new species combinations at various energies →



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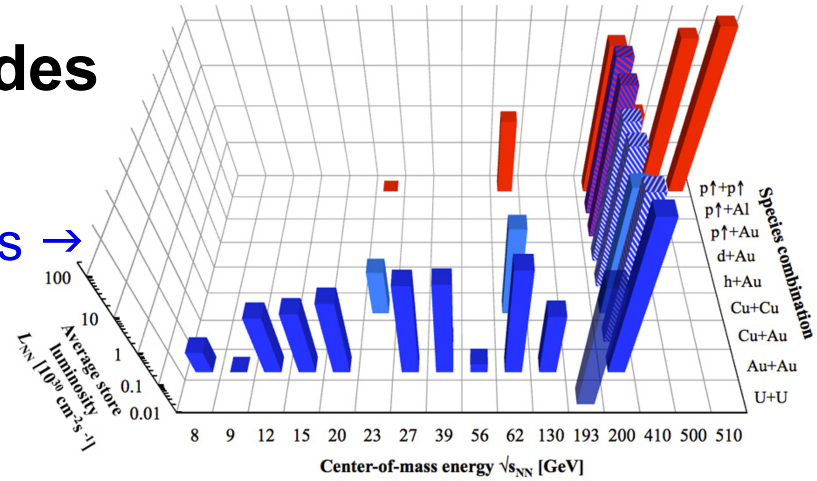
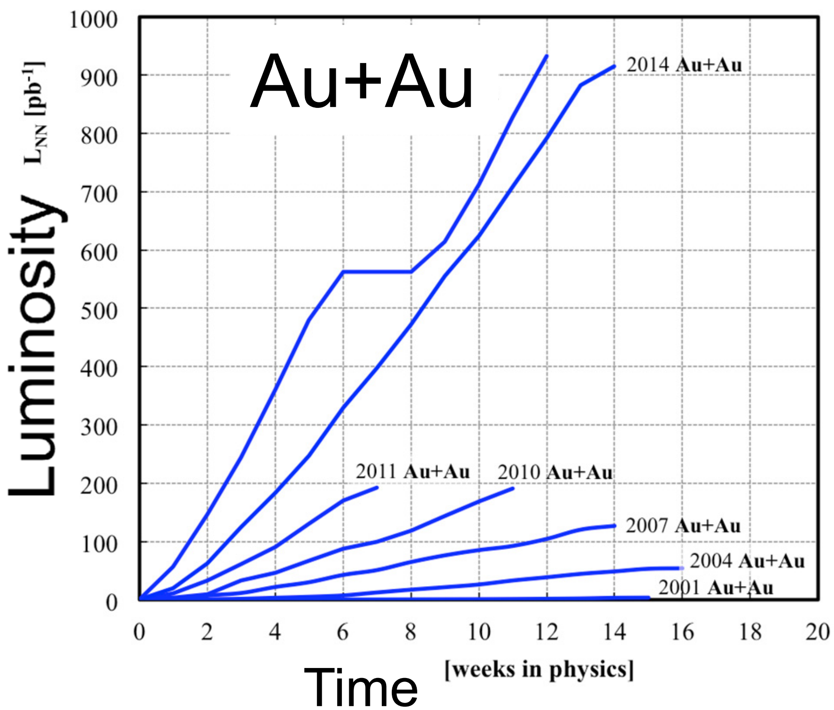
Summary – RHIC upgrades

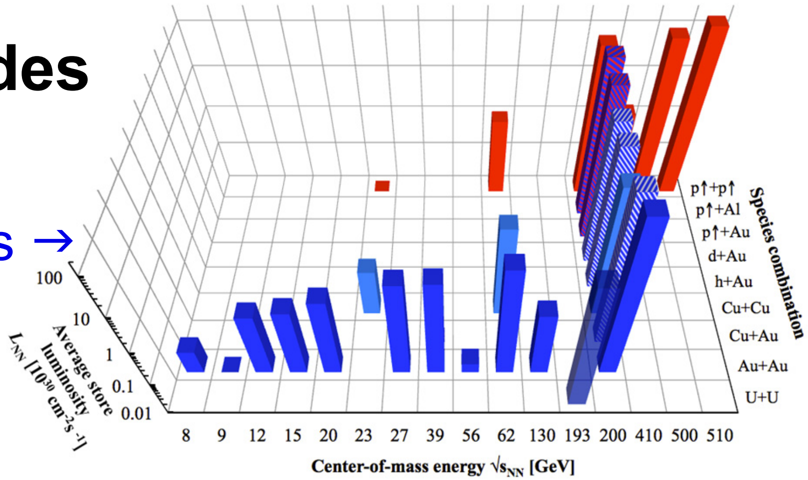
Continue to run new species combinations at various energies →

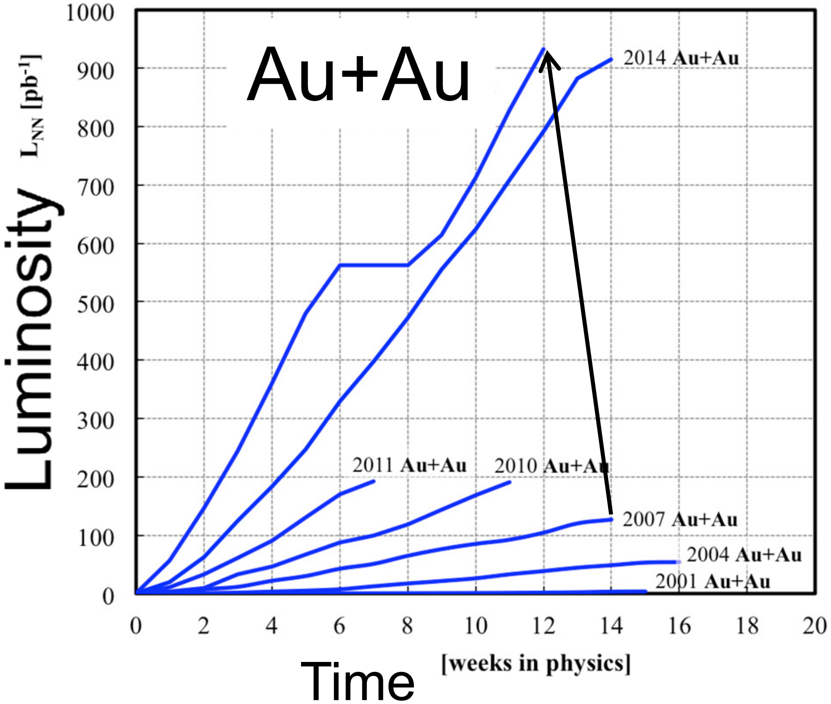




Summary – RHIC upgrades

Continue to run new species combinations at various energies →

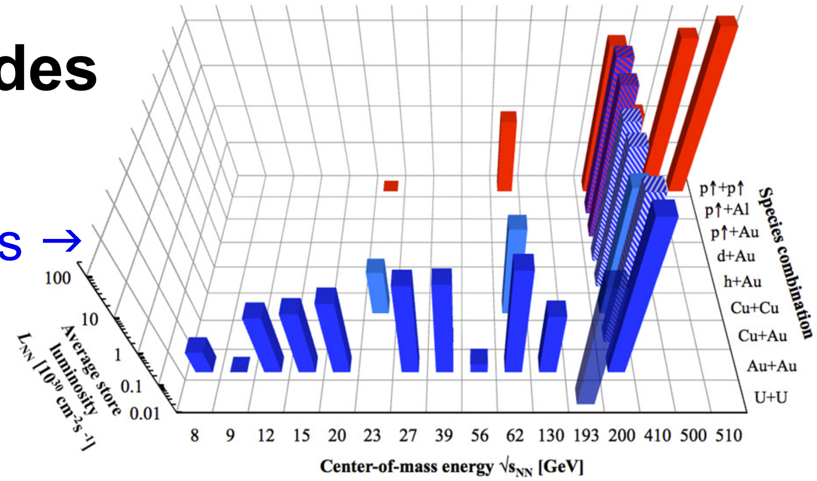


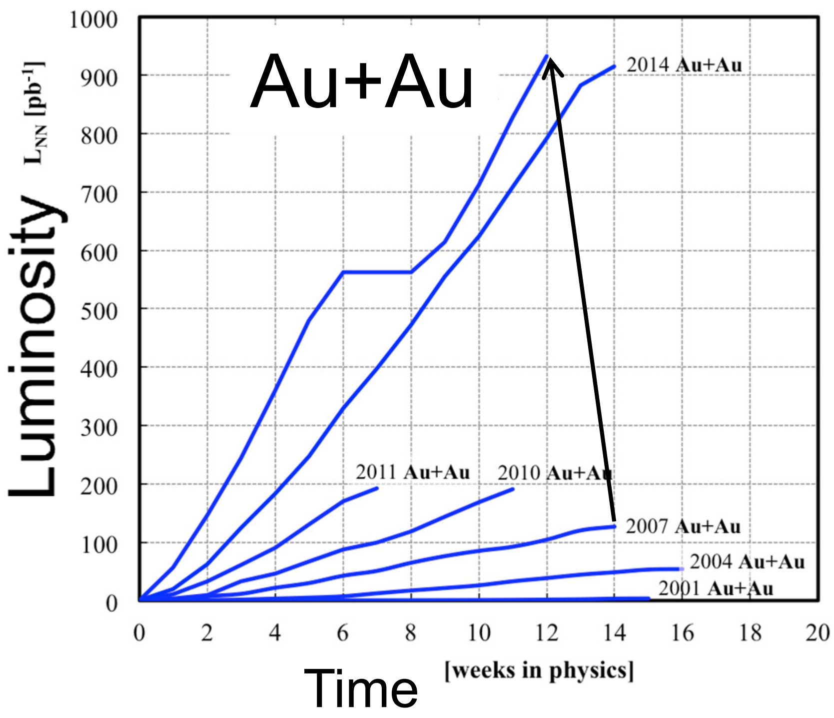


Completed stochastic cooling upgrade for A+A, increase in N_b
← 7x increase in avg. luminosity
(further 2x luminosity increase planned)

Summary – RHIC upgrades

Continue to run new species combinations at various energies →





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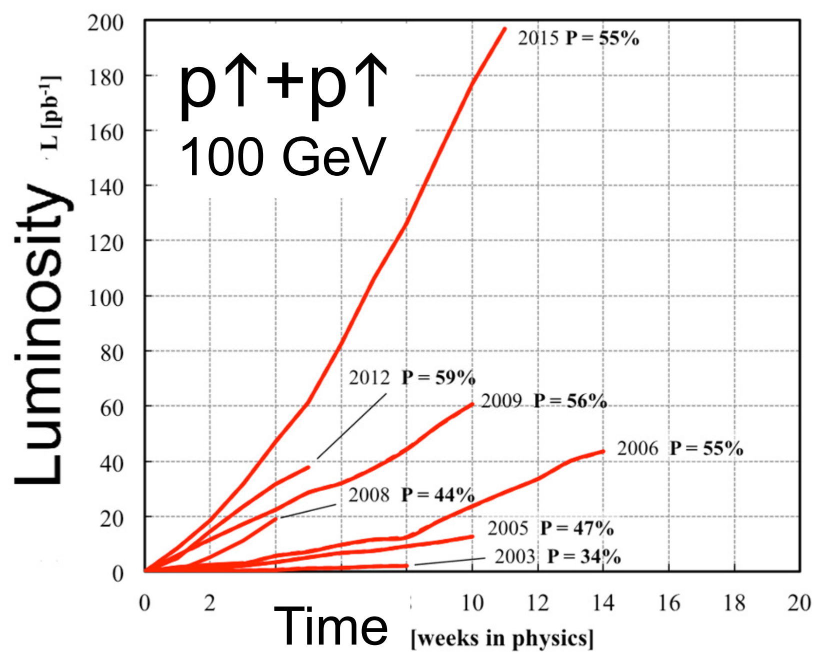
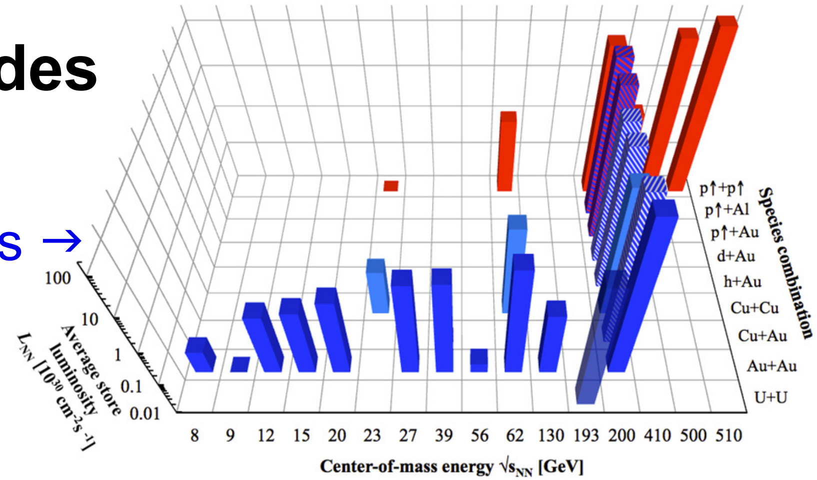
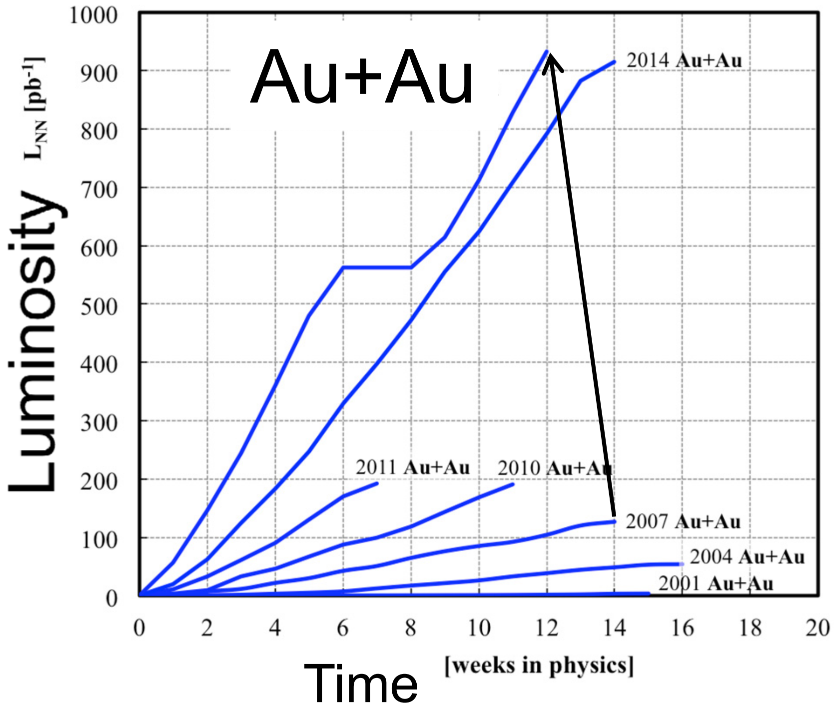


Summary – RHIC upgrades

Continue to run new species combinations at various energies →





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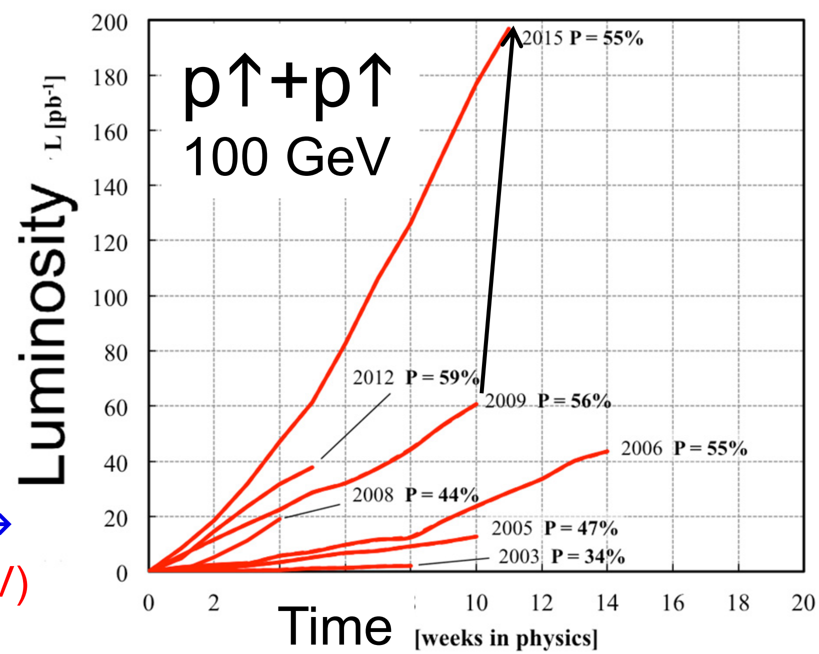

First operational use of head-on beam-beam compensation for p↑+p↑ (lattice + e-lenses), increase in N_b, 2x increase in avg. L at 100 GeV →

(further 3/4x luminosity increase planned at 100/250 GeV)