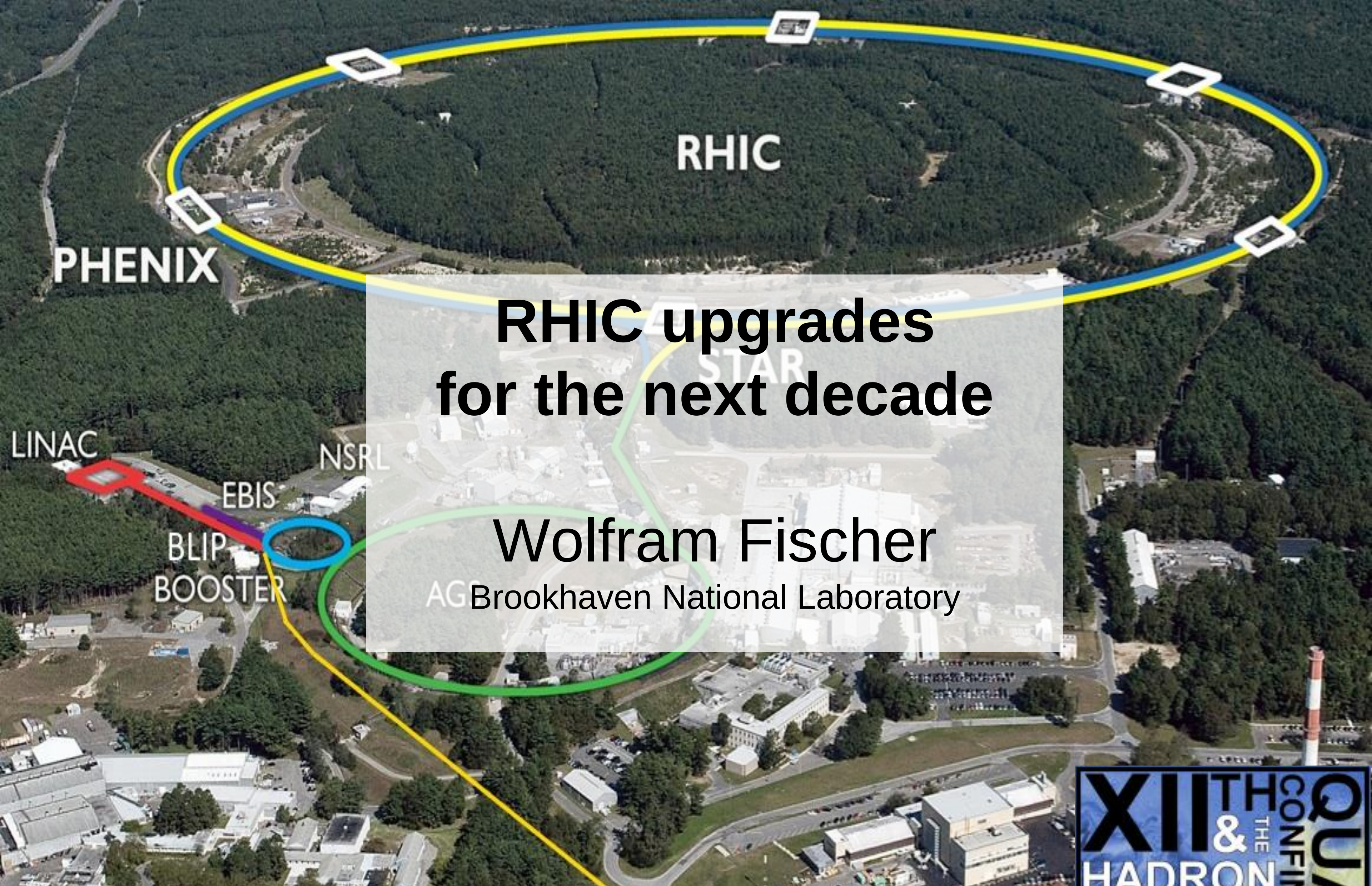


RHIC upgrades for the next decade

Wolfram Fischer
Brookhaven National Laboratory

Accelerators Revealing the QCD Secrets

Satellite Workshop, XIIth Quark Confinement and Hadron Spectrum – CONF 12

Thessaloniki, 4 September 2016

Abstract

The average Au+Au luminosity at full energy is now 44x the design value after a number of upgrades including stochastic cooling. Ion operation is also highly flexible with numerous ion combinations and energies. To support the physics program into the mid 2020s an upgrade of the luminosity at the lowest energies by a factor 3-4 is being implemented, and another factor of 2 at the highest energy.

For the lowest collision energies, in support of a critical point search in the QCD phase diagram, the first bunched beam electron cooler is under construction.

For polarized proton operation, further increases in the luminosity by a factor 3-4x are planned while maintaining the beam polarization.

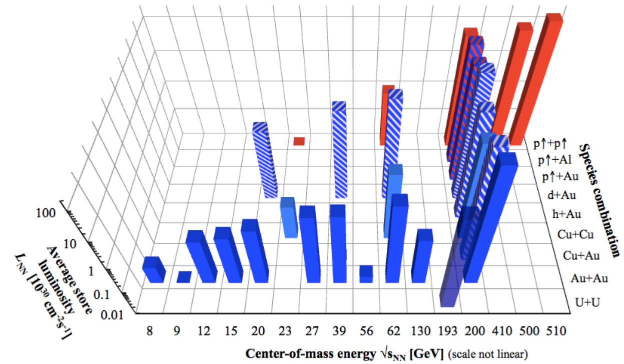
Contents

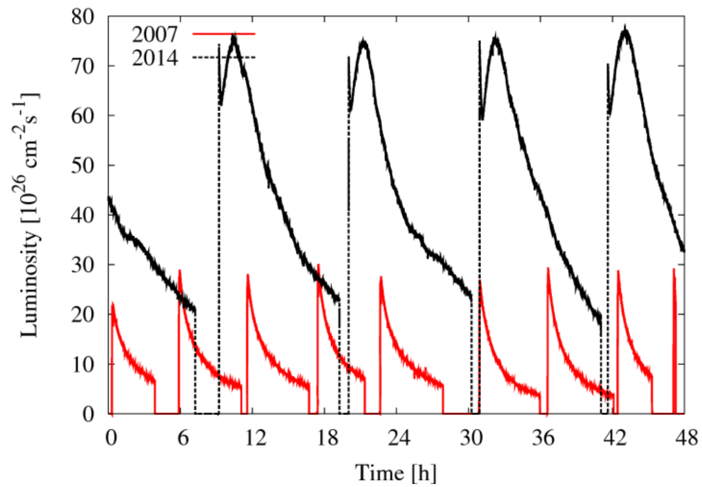
1. A short history and outlook of RHIC
   species, energies, luminosity, polarization

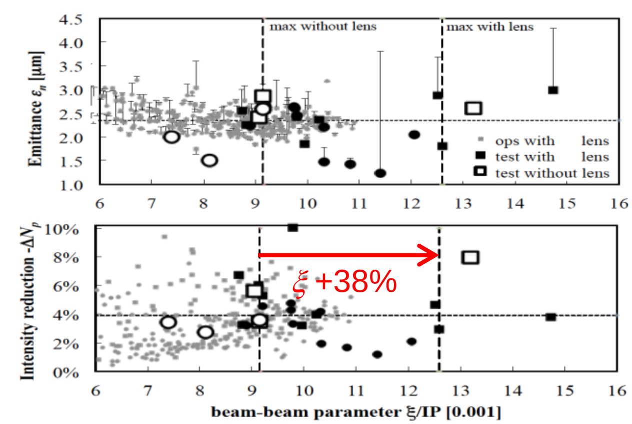
2. High energy A+A
   bunch intensity + stochastic cooling

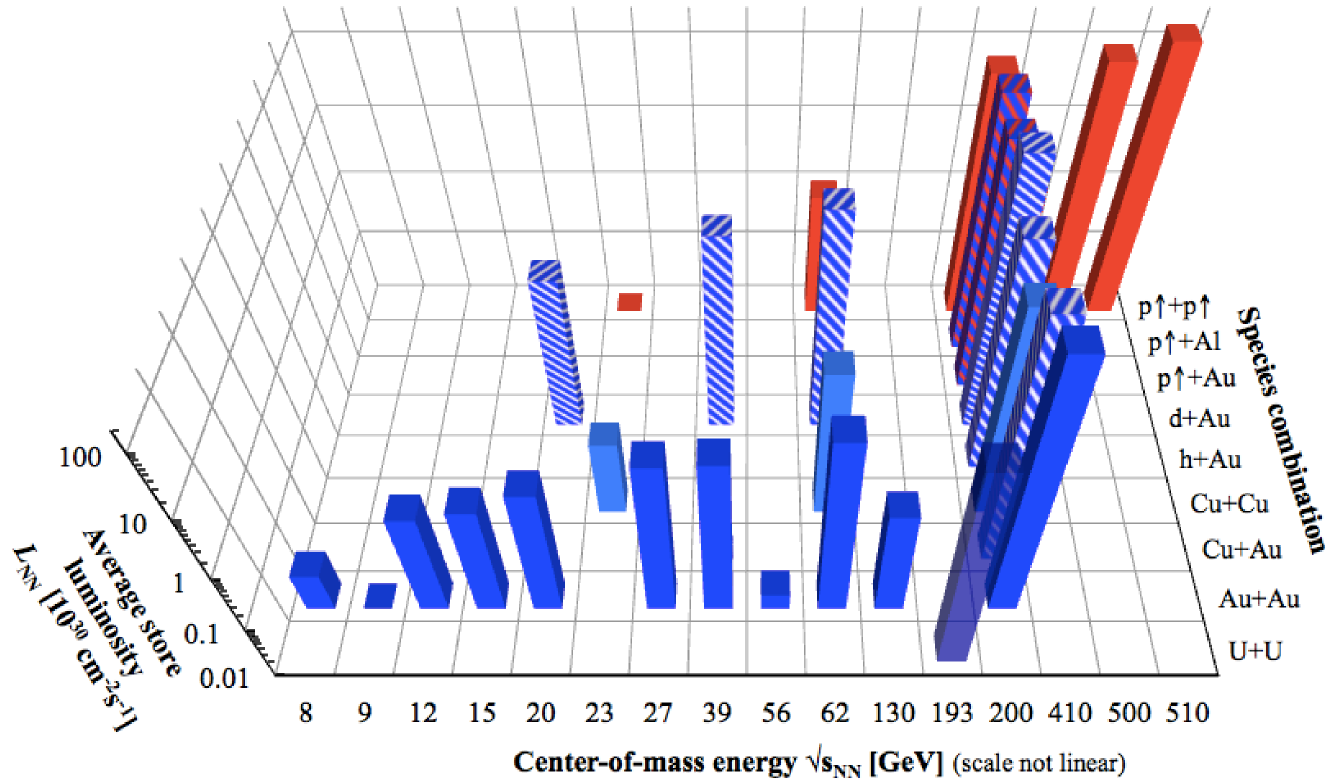
3. Low energy A+A
   bunch intensity + electron cooling

4. p↑+p↑
   bunch intensity + head-on beam-beam compensation, polarization



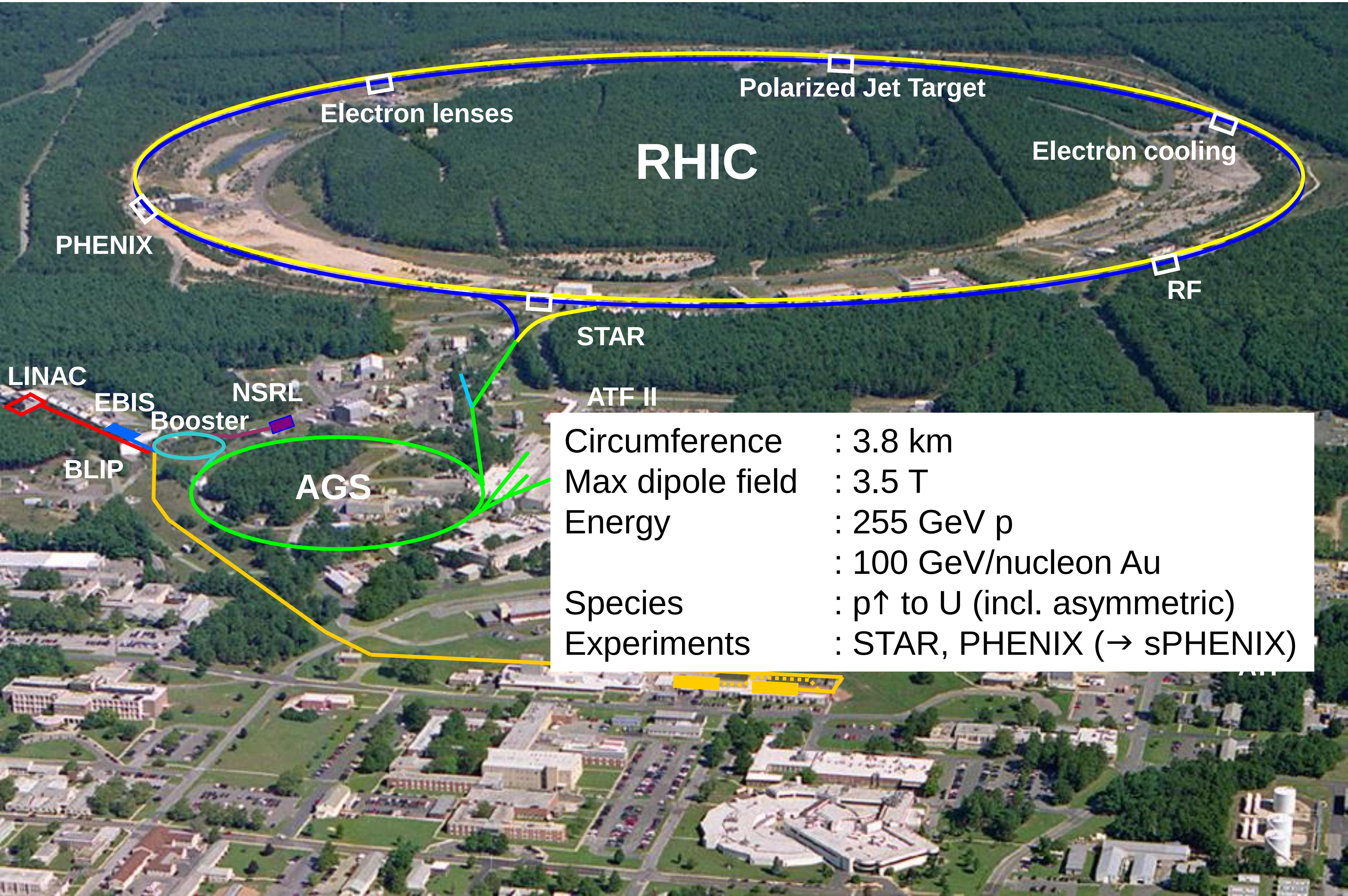






A short history and outlook of RHIC

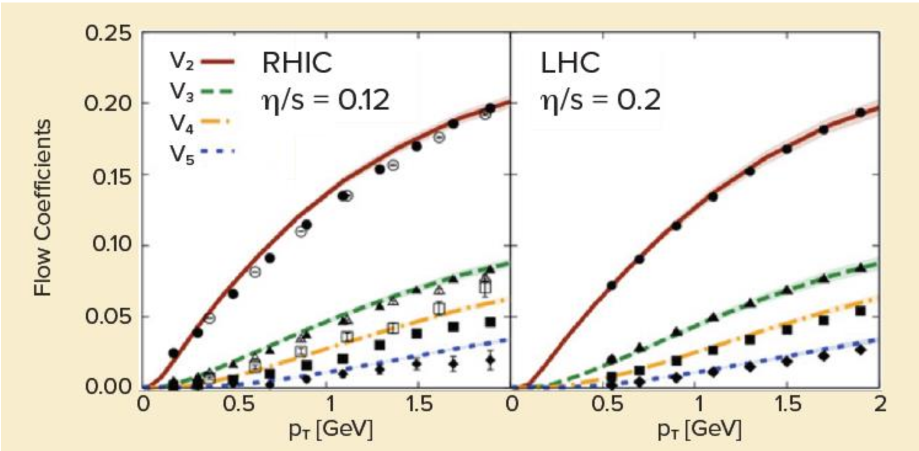
Relativistic Heavy Ion Collider – main parameters



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

RHIC science programs

1. Creation and study of the Quark Gluon Plasma

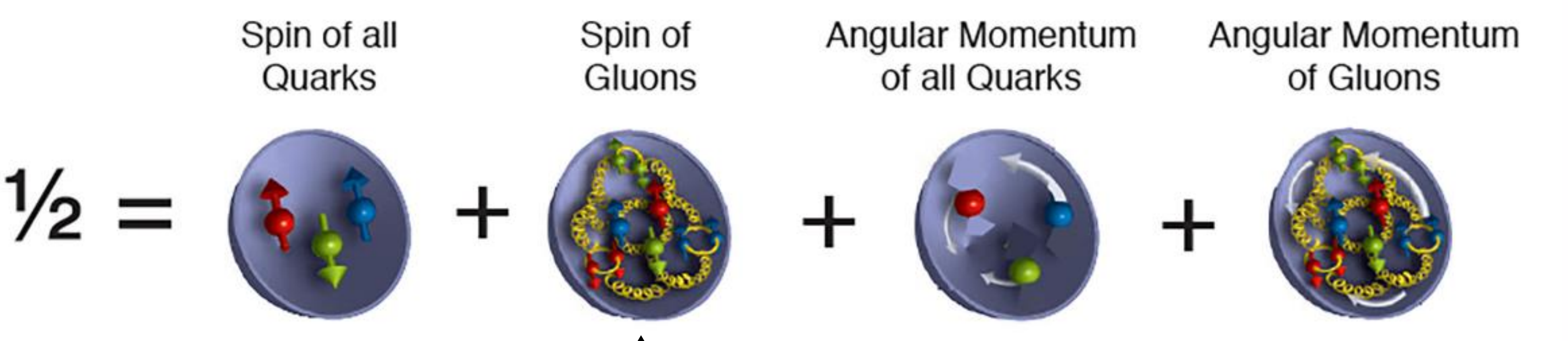


[2015 NSAC Long Range Plan for Nuclear Science]

QGP close to perfect liquid

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

2. Origin of the proton spin



[2015 NSAC Long Range Plan for Nucl. Science]

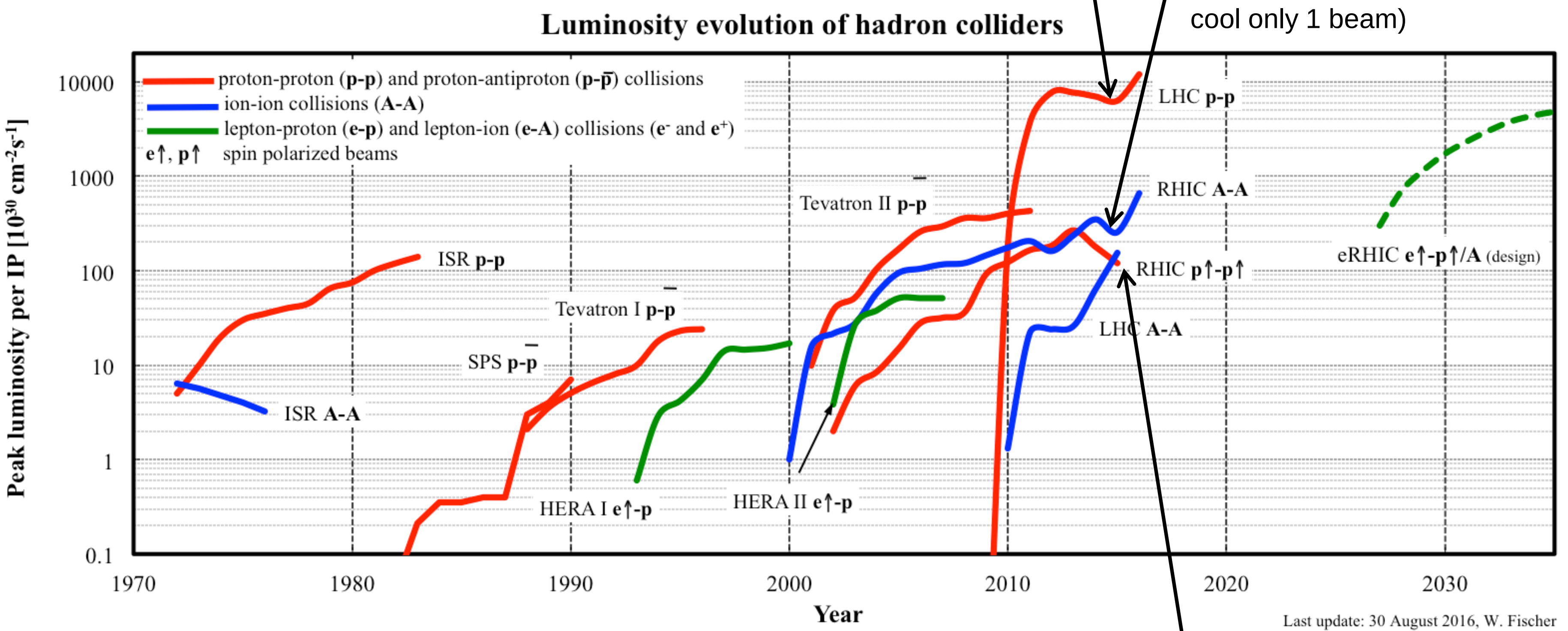
↑ **RHIC result: not zero**

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 $\Delta g(x,Q^2=10\,\text{GeV}^2)$ in the region $x > 0.05$ is $\mathbf{0.20^{+0.06}_{-0.07}}$ at 90% C.L.

Hadron collider luminosities

LHC 25 ns bunch spacing at 6.5 TeV
(previously 50 ns at 4 TeV, e-cloud)

RHIC p↑+A
(previously A+A,
cool only 1 beam)



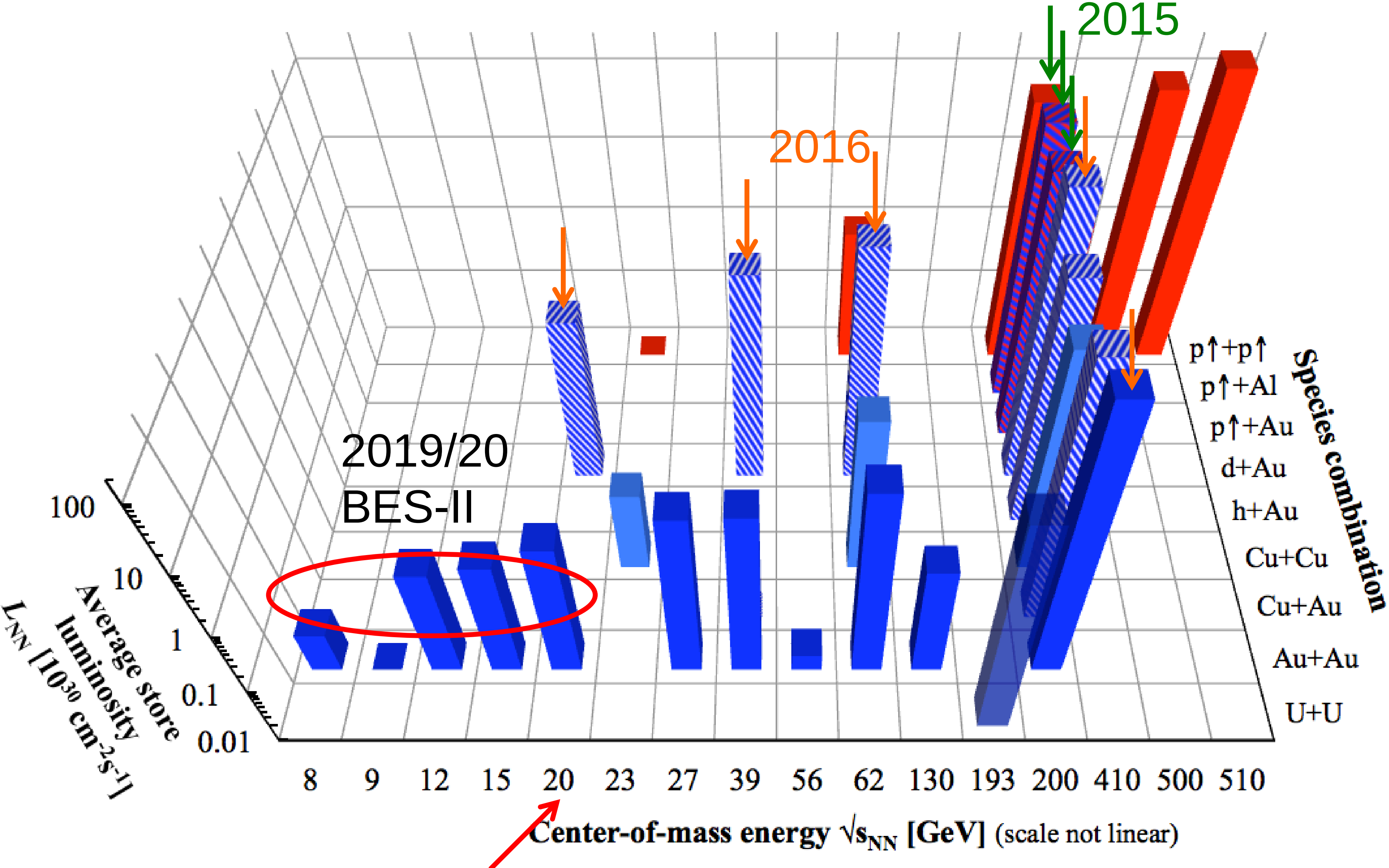
RHIC 100 GeV p↑+p↑
(previously 255 GeV)

average or leveled luminosity L_{avg} now more important than peak luminosity L_{peak}
(burn-off in RHIC, pile-up limit in LHC)

some recent dips explained above

RHIC – all running modes to date

2001 to 2016



nominal injection energy

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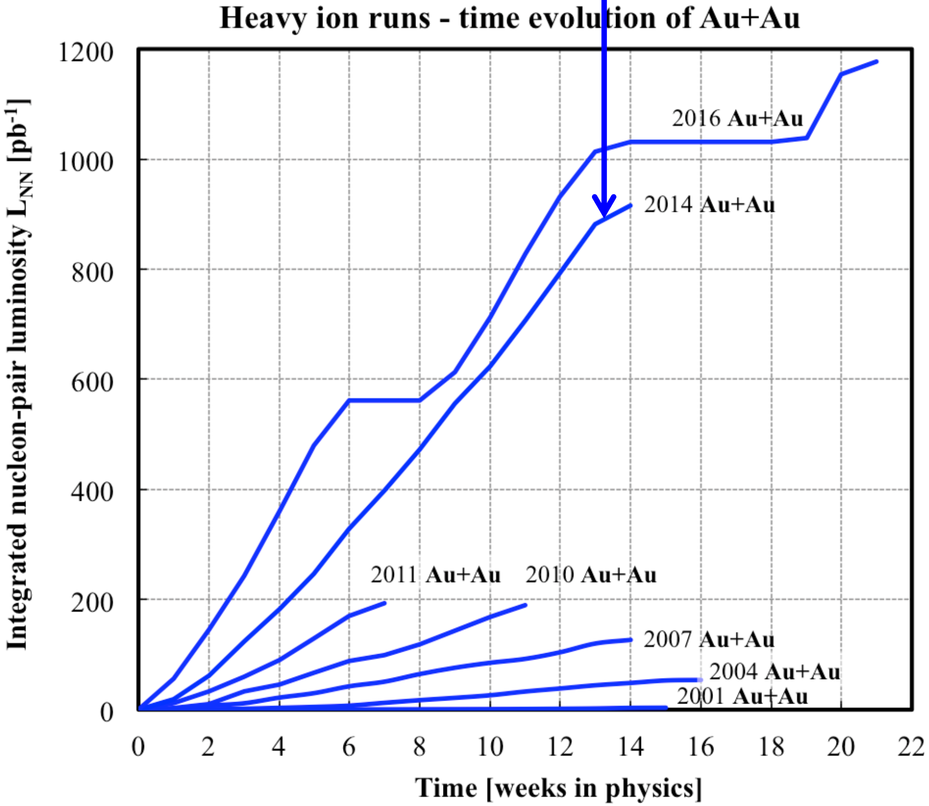
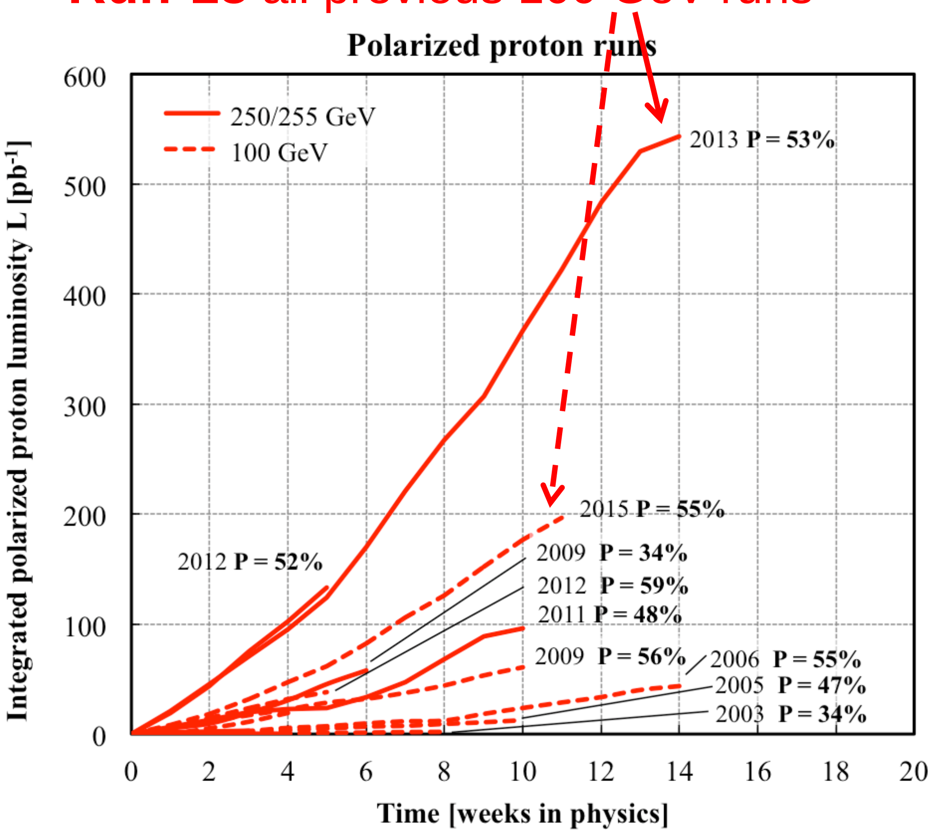
Delivered Integrated Luminosity – symmetric species

Run-14 Au+Au luminosity exceeds all previous Au+Au runs combined



Run-13 p+p luminosity exceeds all previous p+p runs combined,
Run-15 all previous 100 GeV runs



Nucleon-pair luminosity: luminosity calculated with nucleons of nuclei treated independently; allows comparison of luminosities of different species; appropriate quantity for comparison runs.

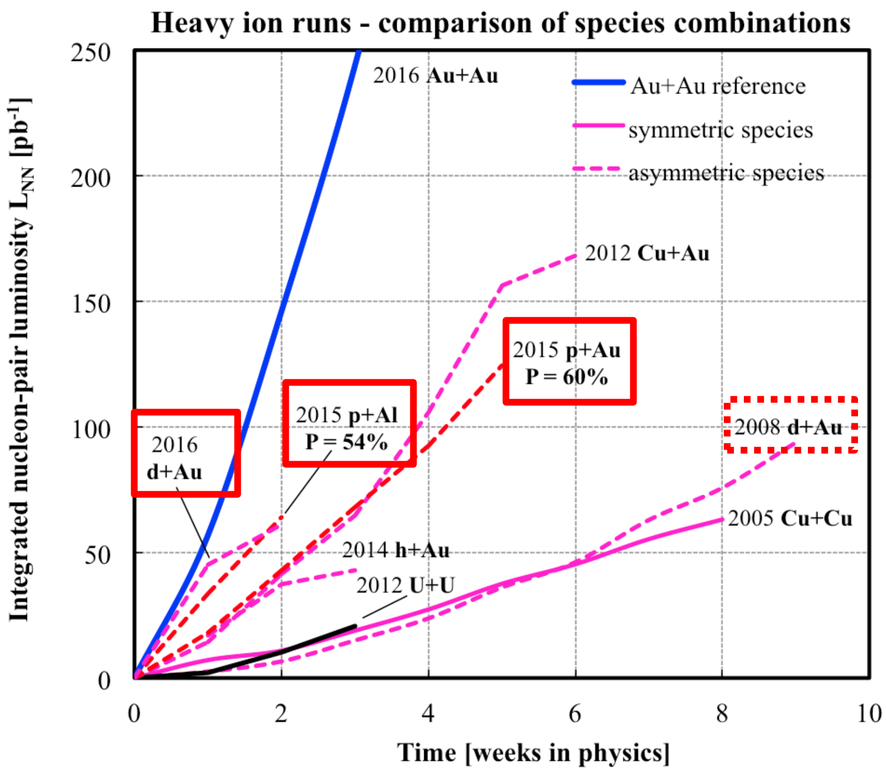
Dramatic increase in performance as a result of R&D, capital projects, Accelerator Improvement Projects, and replacement of obsolete technology

Delivered Integrated Luminosity – asymmetric species

5 asymmetric combination to date:

- p↑+Au,
- p↑+Al (never done before)
- h+Au
- d+Au (at 4 different energies)
- Cu+Au

can collide any species with any other species



Best week d+Au Run-16 10x better than Run-8

Asymmetric operation requires:

- sources for two different beams (laser ion source + EBIS; Tandems)
- reliable injector switch-over during RHIC injection (AGS cold snake turn on/off for p↑)
- accommodation of tighter apertures in IRs (DX magnet move for p↑+A, limitations from CeC PoP chamber in Run-16)
- in p↑+A: acceleration of A to plateau near transition for proton injection
- increased experimental protection (PHENIX MPC-EX damage in Run-15)

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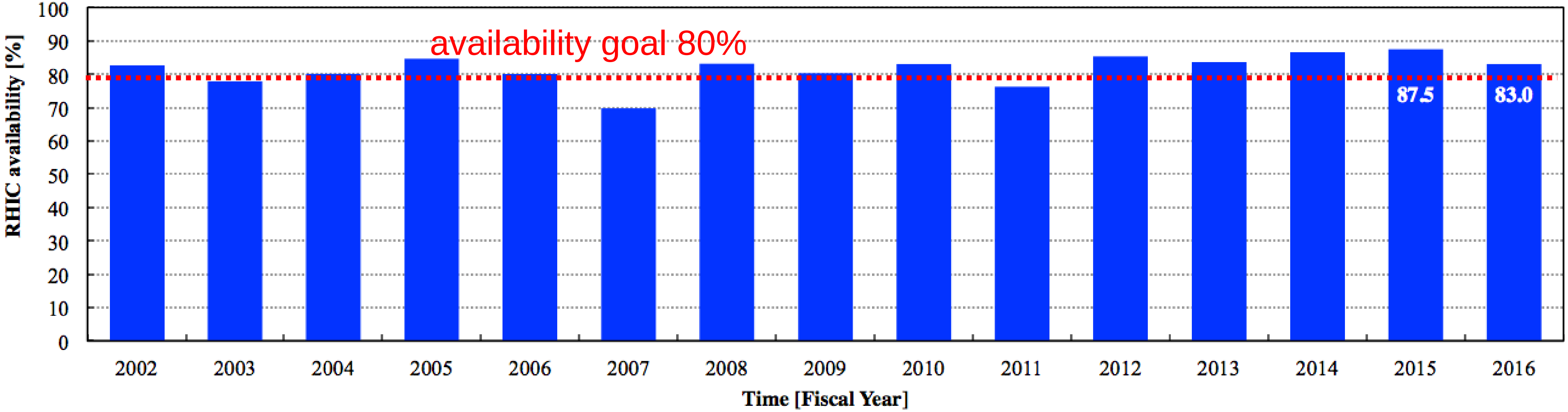
Operational efficiency availability reported to DOE

Availability = beam time / scheduled beam time (excl. scheduled maintenance)



- Exceeded availability goal in FY2015 and 2016
  Record availability in FY2015 (87.5%)

More efficiency measures:

- setup time to physics
- store-to-store time
- calendar time in store
- cost per collision

Typical times:

50K to 4K cool-down	: 0.5 weeks
Initial set-up	: 2 weeks
Changing species	: 0.5 weeks
Beam studies (APEX)	: 16h / 2 weeks
Maintenance	: 14h / 2 weeks
Warm-up	: 0.5 weeks

RHIC proposed run plan – extents to mid 2020s

Years	Beam Species and Energies	Science Goals	New Systems Commissioned
2016	High statistics Au+Au d+Au beam energy scan	Complete heavy flavor program First measurement of Λ_c Collectivity in small systems	Coherent e-cooling test I
2017	High statistics Pol. p+p at 510 GeV	Transvers	ing test II
2018	$^{96}Zr+^{96}Ru$ at 200 GeV Au+Au at 27 GeV ?	Establish	ooling
2019-20	7.7-20 GeV Au+Au (BES-2)	Search for of deconfi	
2021	TBD	Contingency for BES-2 extension ?	sPHENIX installation
2022-??	200 GeV Au+Au with upgraded detectors Pol. p+p, p+Au at 200 GeV	Jet, di-jet, γ-jet probes of parton transport Color scre	s ?
mid-2020s	Transition to eRHIC ?	Gluon stru	ENIX" ?

today

High-energy p+p and A+A
STAR (need leveled *L*)

Low-energy A+A
STAR (*L* requests require new e-cooler)

High-energy p+p and A+A
STAR and sPHENIX
(sPHENIX *L* requests require upgrades)

RHIC ultimate luminosity and polarization goals at high energy

parameter	unit	achieved		goals	
Au-Au operation		**2016**		**≥ 2021** 56 MHz SRF + AGS + 9 MHz RF	
energy	GeV/nucleon	100		100	
no colliding bunches	…	111		111	
bunch intensity	10^9	2.0		2.5 (2.0)	
avg. luminosity	10^{26} cm^{-2}s^{-1}	**87**		**175** (100) 2× achieved	
p↑-p↑ operation		**2015**		**≥ 2021** OPPIS + 9 MHz RF + e-lenses	
energy	GeV	100	255	100	255
no colliding bunches	…	– 111 –		– 111 –	
bunch intensity	10^{11}	2.25	1.85	3.0	3.0
avg. luminosity	10^{30} cm^{-2}s^{-1}	**63**	**160**	**175** 2.8× achieved	**600** 3.8× achieved
avg. polarization*	%	**55**	**52**	**60**	**55**

Last year's numbers: (2.0), (100)

*Intensity and time-averaged polarization as measured by the H-jet. Luminosity-averaged polarizations are higher.

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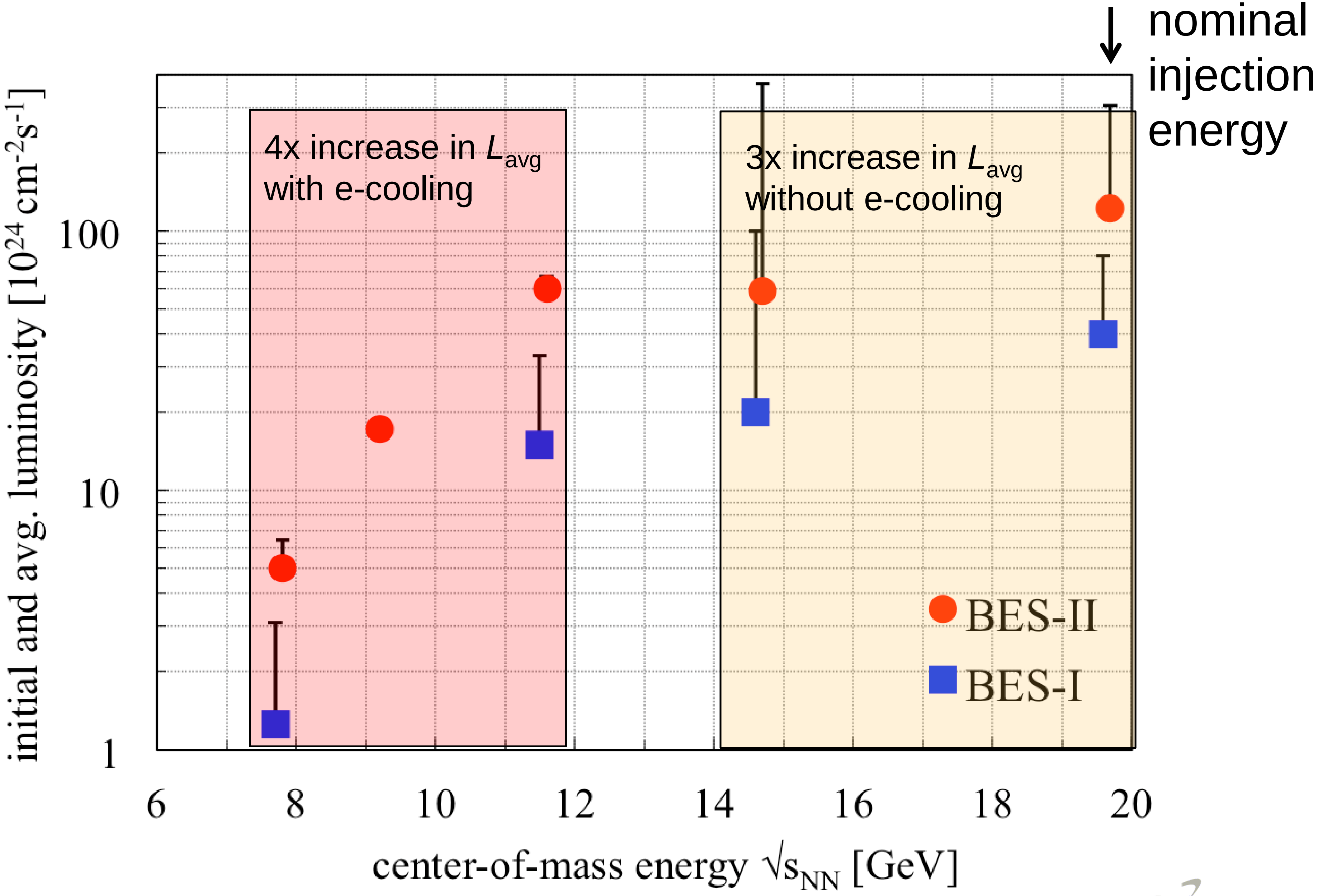
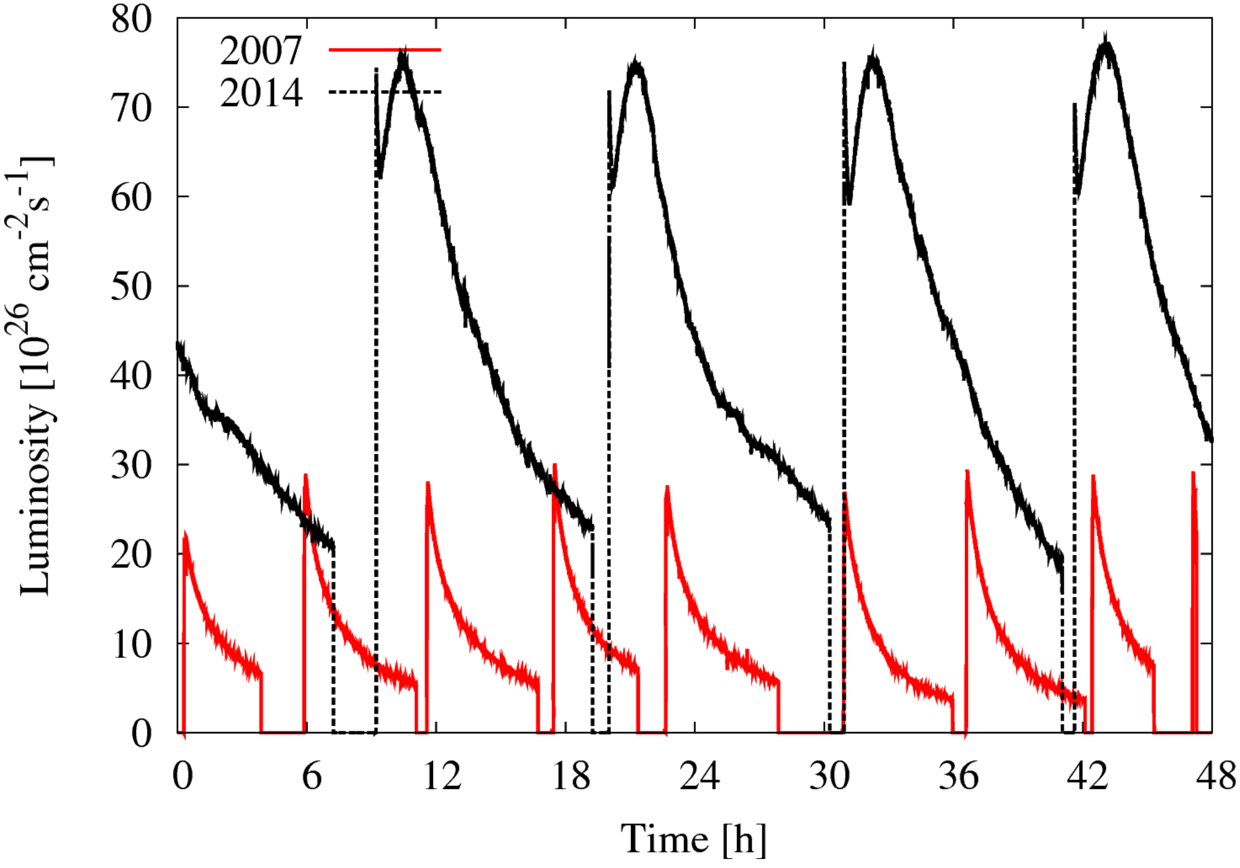
Physics integration

BES-I and BES-II luminosities

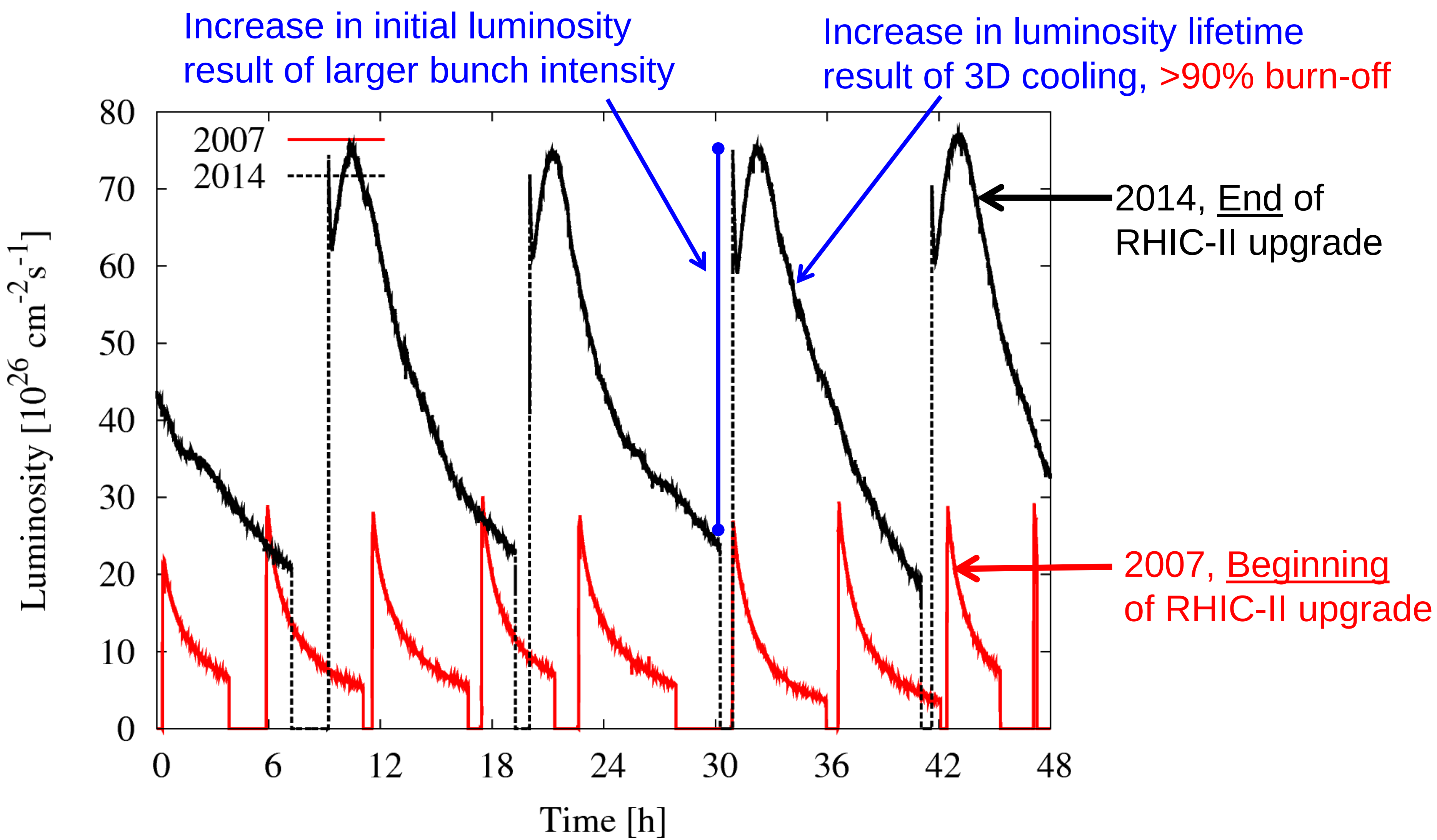




RHIC high-energy A+A operation with stochastic cooling

RHIC Run-14

Delivering RHIC-II luminosity



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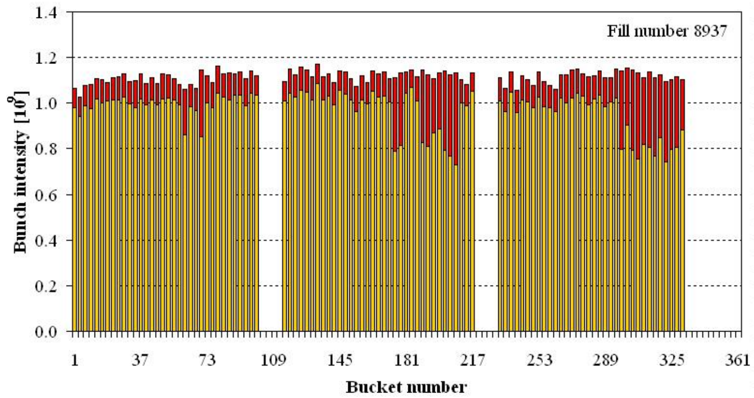
Performance limits – RHIC ions, high energy

$$L(t) = \frac{1}{4p} f_0 N \frac{N_b^2(t)}{e(t)b^*(t)} h(b^*, s_s, q)$$



- Bunch intensity N_b, limited by
  injectors => EBIS, bunch merges in
  Booster and AGS
  transition instability
  Landau cavity RF amplifiers (upgraded)
  aim for 2.5x10^9 in store ultimately

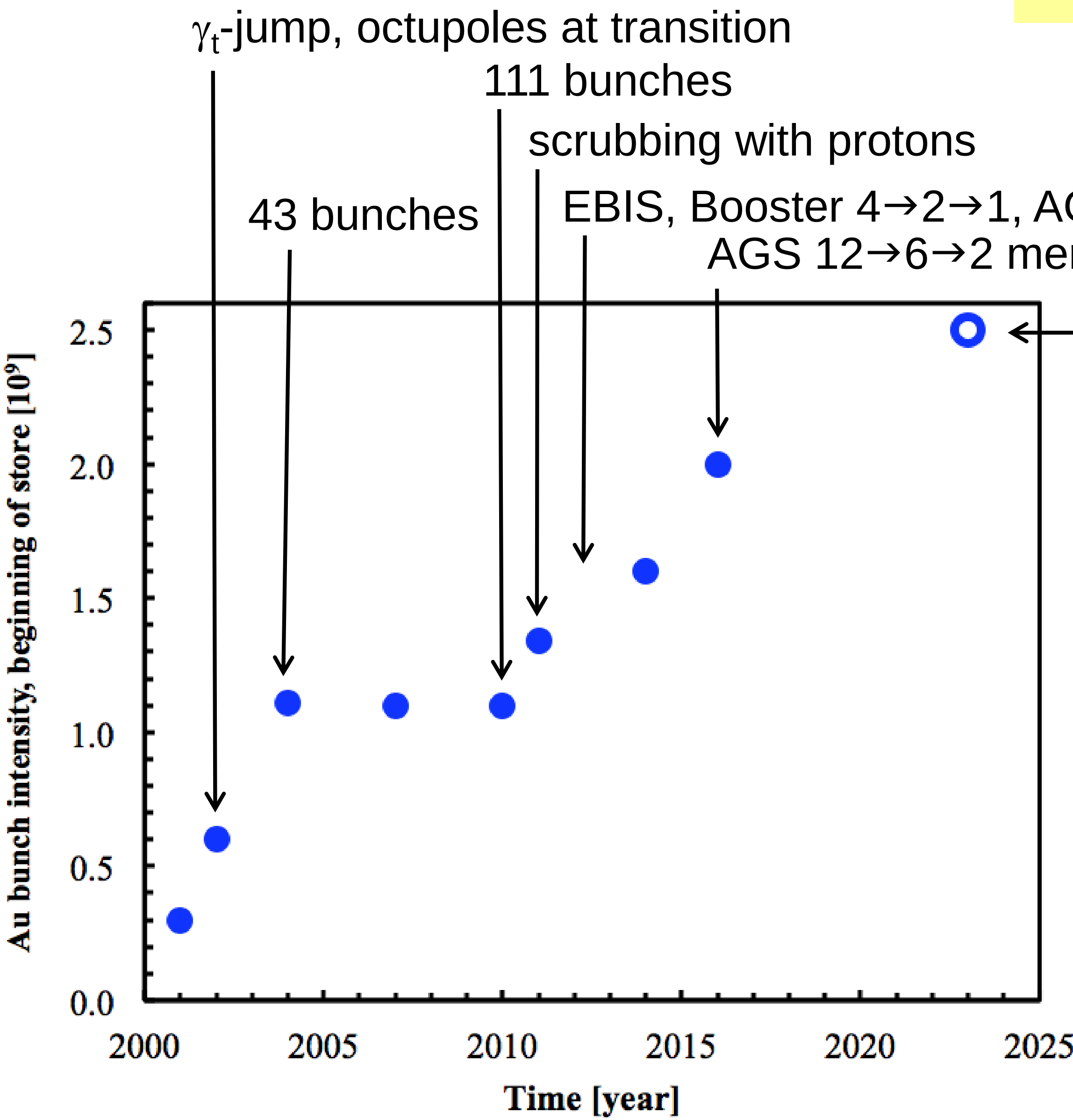
- Intrabeam scattering
  => stochastic cooling
  => 56 MHz SRF (stronger longitudinal focusing)

- Lattice with small β* and large off-momentum dynamic aperture
  with hourglass factor ≈0.5 at end of store, need large β* reduction
  any lattice change must not result in additional beam losses
  (momentum spread with 56 MHz SRF will be increased)
  dynamic β* reduction after emittance decreased by cooling

Goal is to have burn-off as the dominant beam loss mechanism.

Au bunch intensity evolution

$$L(t) = \frac{1}{4p} f_0 N \frac{N_b^2(t)}{e(t) b^*(t)} h(b^*, s_s, q)$$



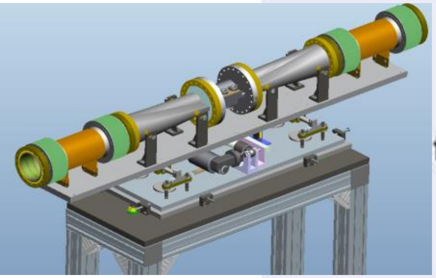
ultimate goal
(raised from 2.0×10^9 this year)

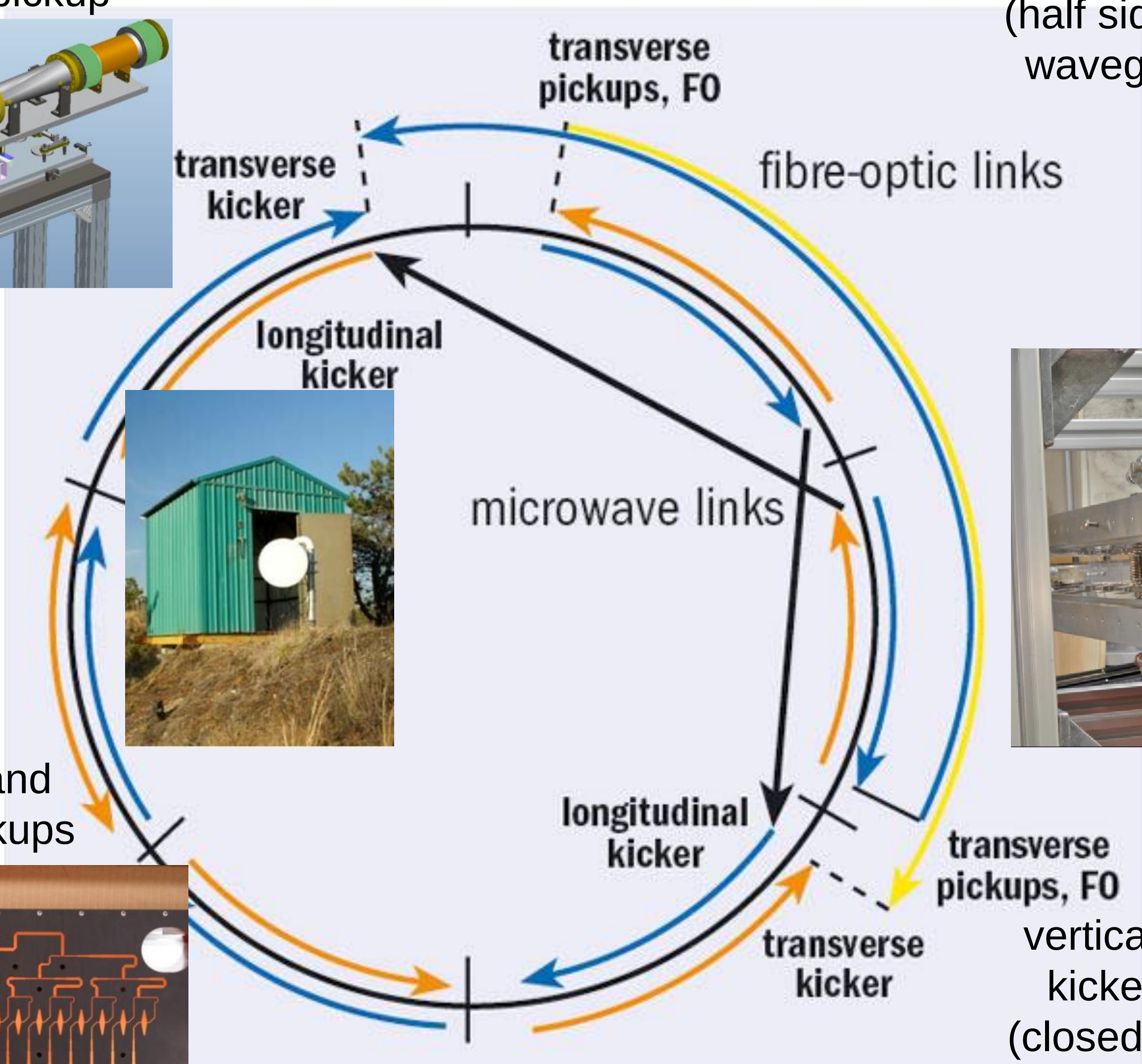
main limits:
- injectors output
- e-cloud in RHIC
- transition instability in RHIC

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

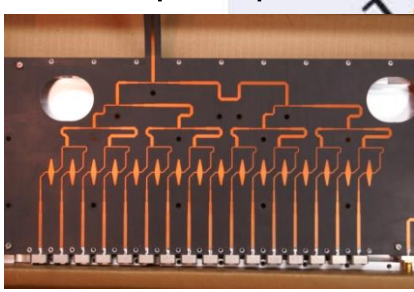
3D stochastic cooling for heavy ions

longitudinal pickup

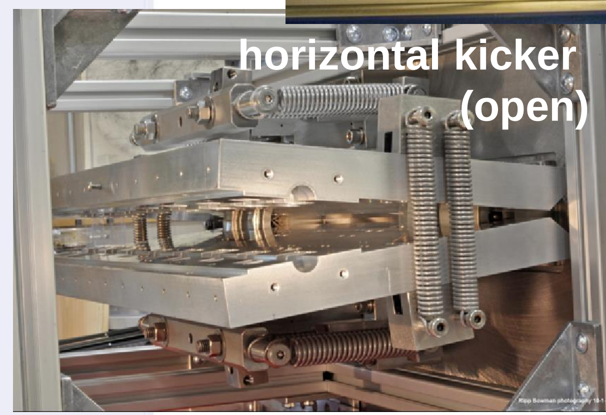




horizontal and vertical pickups



longitudinal kicker cavity (half side with waveguides)



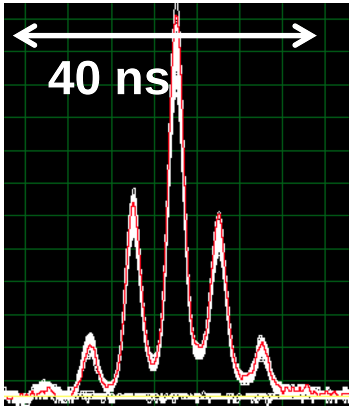
vertical kicker (closed)

5-9 GHz, cooling times ~1 h

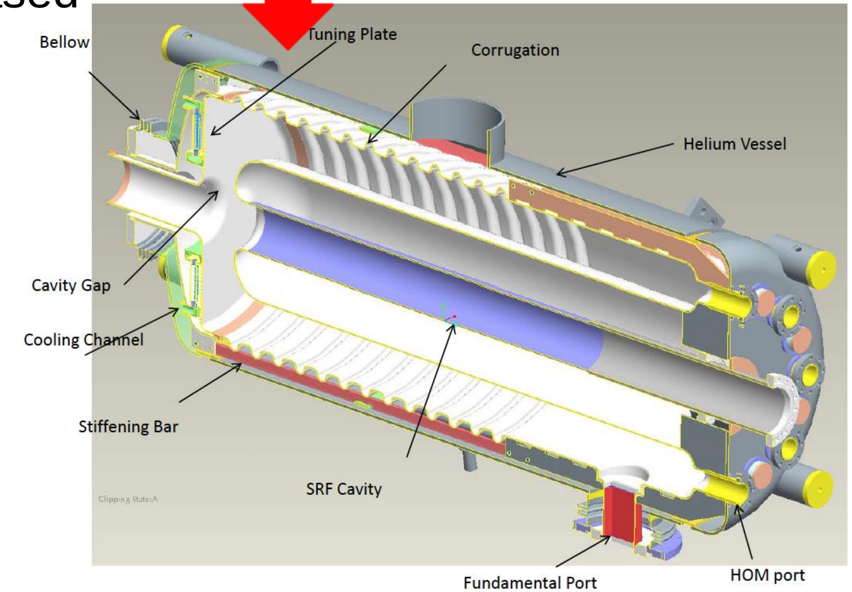
M. Brennan, M. Blaskiewicz, F. Severino, PRL **100** 174803 (2008); K. Mernick PRSTAB, PAC, EPAC

56 MHz SRF

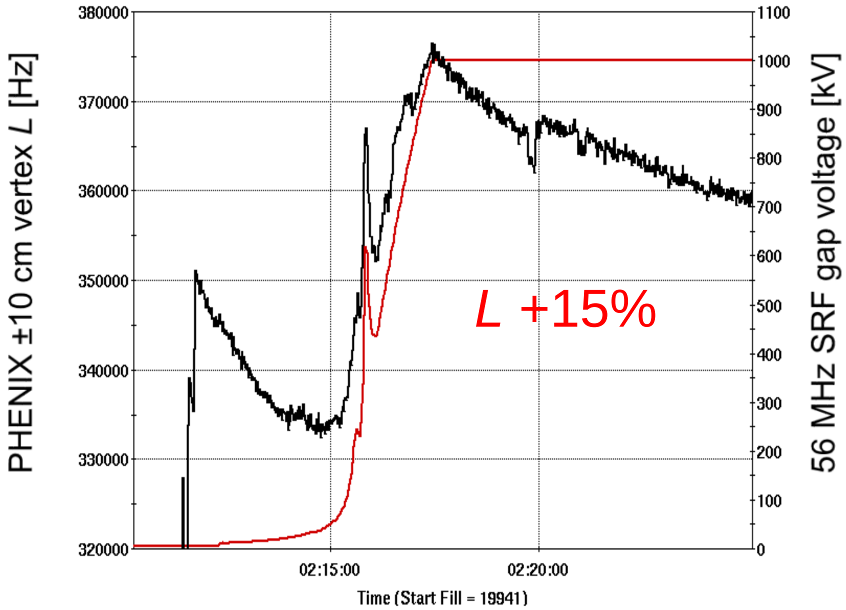
more longitudinal focusing



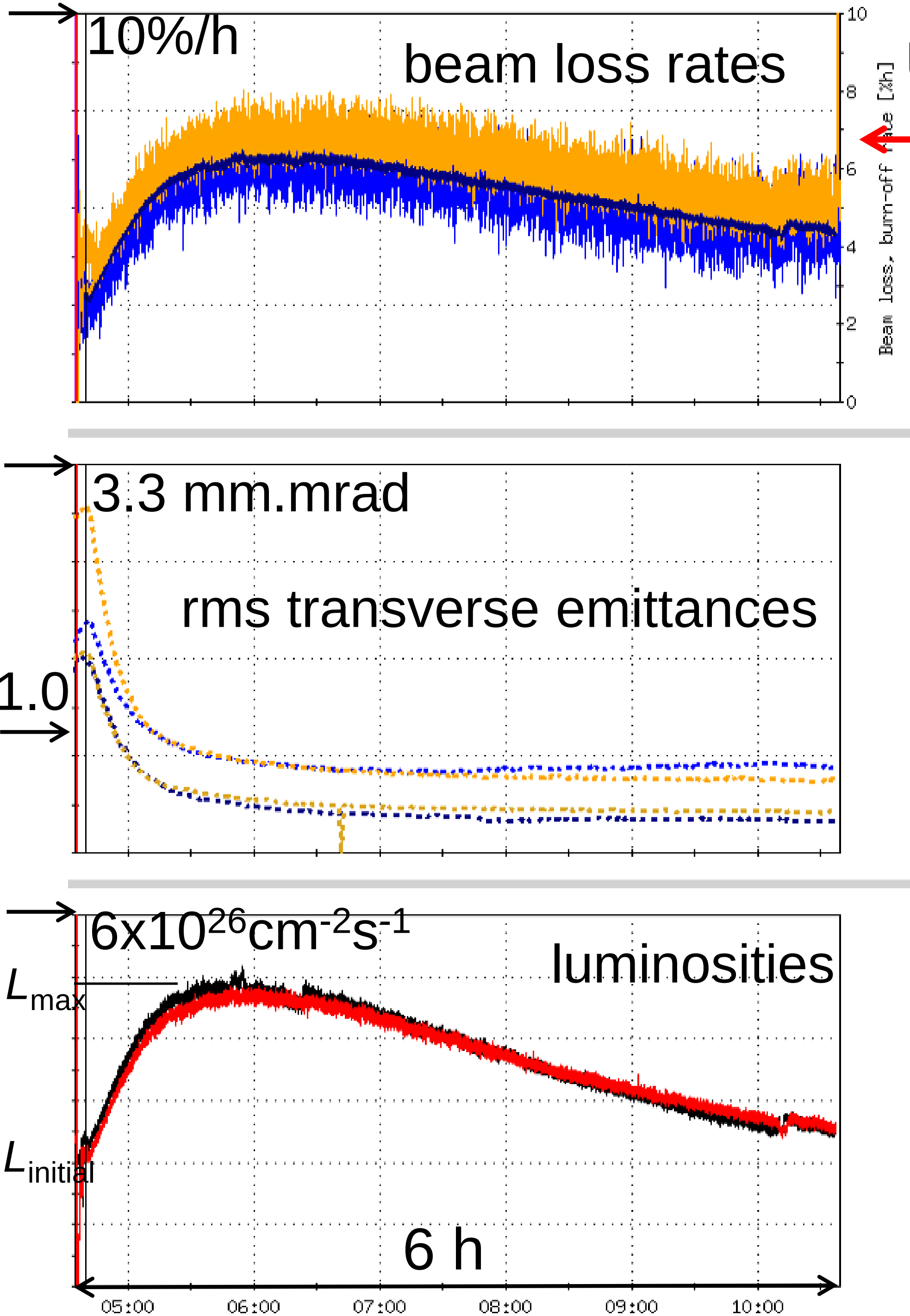
Longitudinal profile at end of store
- even with cooling ions migrate into neighboring buckets
- can be reduced with increased longitudinal focusing



56 MHz SRF at 1 MV (2 MV design) without HOM damper, used operationally for first time 2016 d+Au (first operational SRF cavity in RHIC)



- λ/4 Ni resonator
- common to both beams
- beam driven
- 56 MHz, 2 MV



U-U store – new mode in 2012

(1) Lattice optimized for large off-momentum dynamic aperture, <u>not</u> for smallest β* (Y. Luo)

$$L \propto \frac{N_b^2}{\beta^*} H\left(\frac{\beta^*}{\sigma_s}\right)$$

(2) Minimum loss rates given by total U-U cross sections, 2 largest contributions from BFPP and EMD:

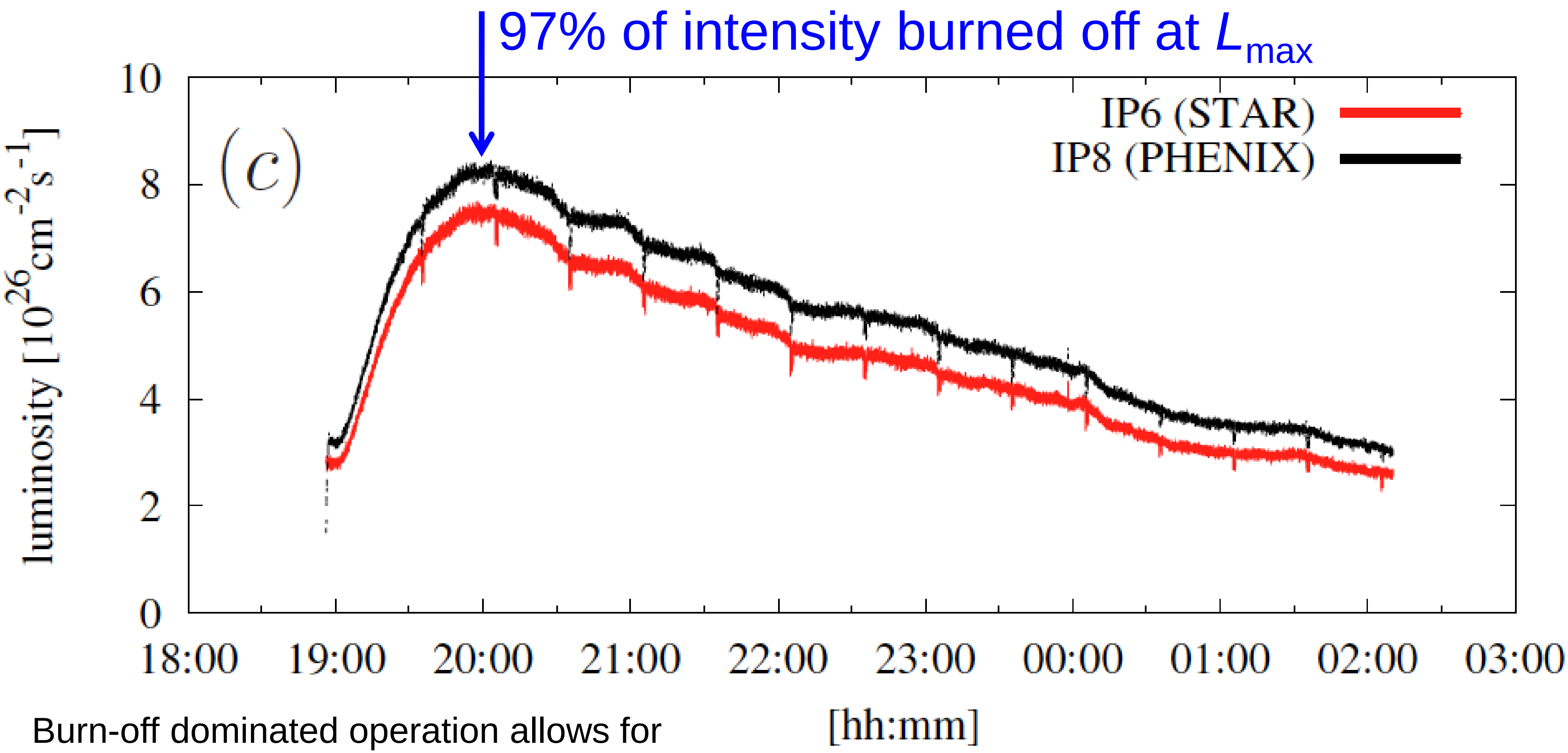
	Au-Au	U-U
BFPP	117 b	329 b
EMD	99 b	160 b

$\sigma_{BFPP} \propto Z^7$

Nearly all beam loss though luminosity (burn-off)!

3D stochastic cooling leads to
new feature in hadron collider:
$L_{max} > L_{initial}$

Operation at burn-off limit in U+U



Burn-off dominated operation allows for determination of total U+U cross section – and comparison with calculation (mostly QED) (published in Phys. Rev. C) =>

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

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

tz, 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

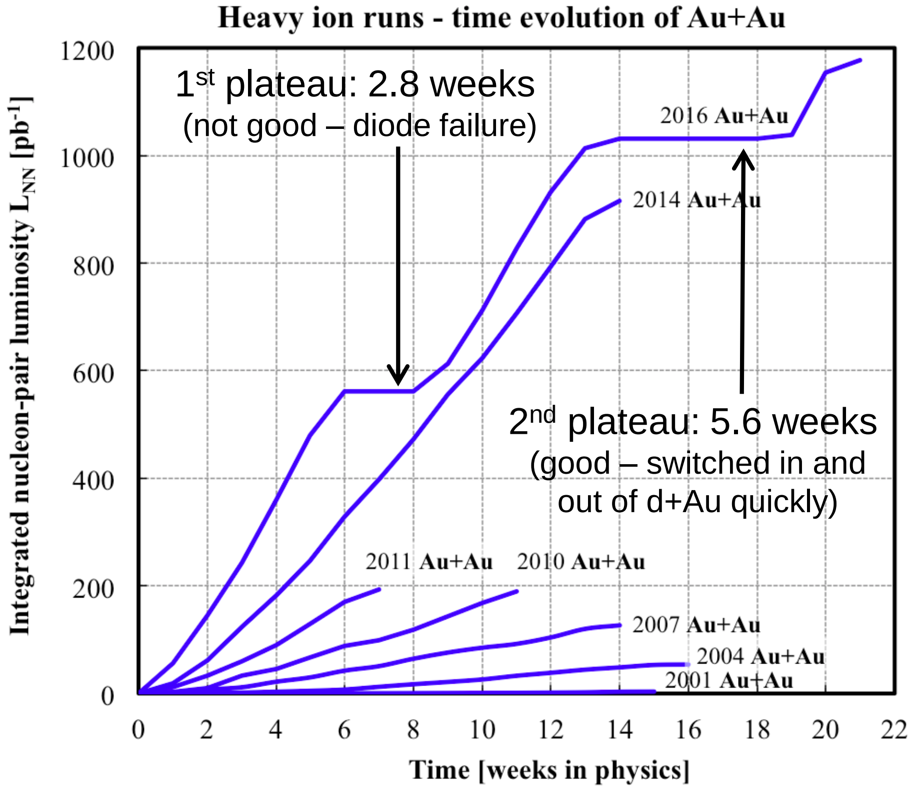
Heavy ion cross sections totaling several hundred barns have been calculated previously for the Relativistic Heavy Ion Collider (RHIC) and the Large Hadron Collider (LHC). These total cross

Run-16 Au+Au at 100 GeV/nucleon

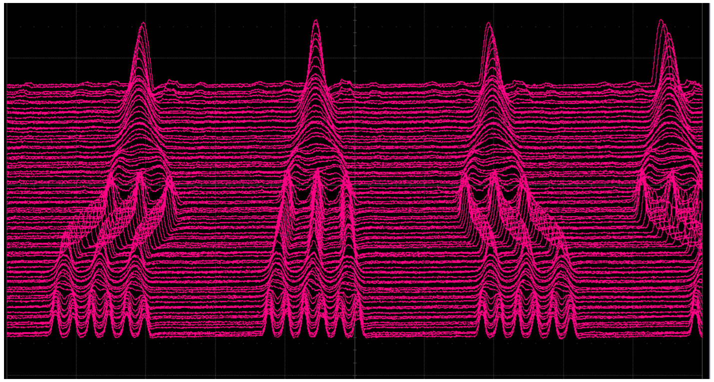
Luminosity

Run Coordinator: Xiaofeng Gu

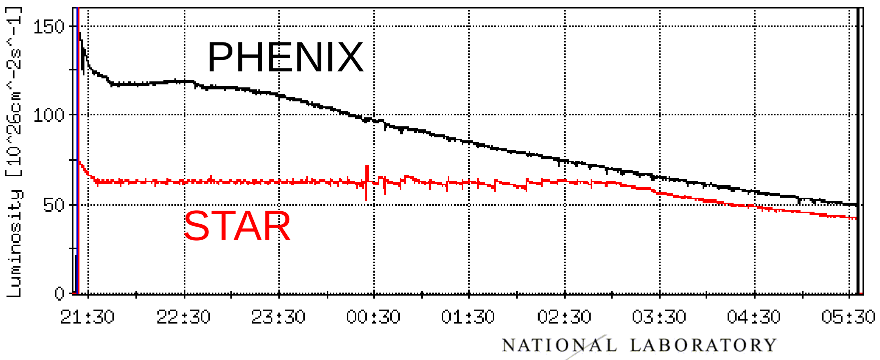
- More collisions in 10 min than in entire 5-week commissioning run in 2001
- L_{week} = 1.4× 2014
- L_{avg} now 44x design



25% increase in bunch intensity due to AGS bunch merging scheme at injection change from 8→4→2 to 12→6→2
(with minimal increase in longitudinal emittance!)



Maximized *L* to PHENIX and delivered leveled *L* to STAR using stochastic cooling and transverse offset at IP

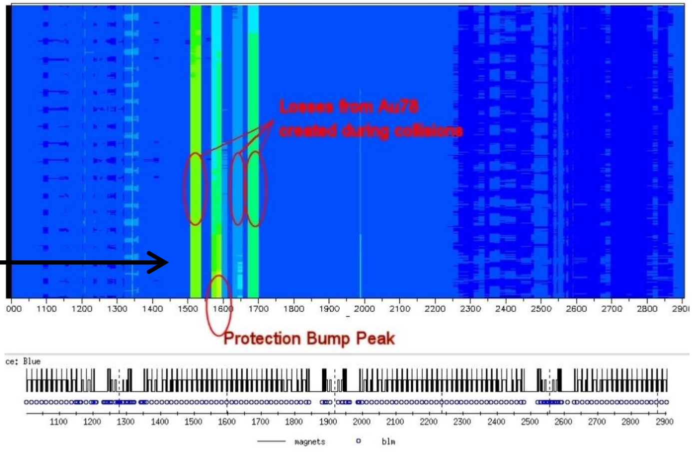


Machine protection

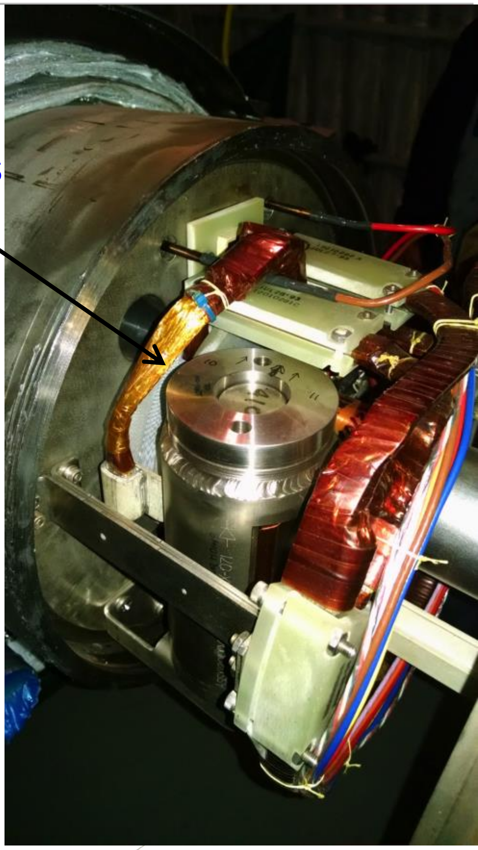
Quench protection diode failure

What happened:

- orbit bumps installed to protect experiments in pre-fire events (e.g. PHENIX MPC damage)
- at bump locations localized losses of secondary beams created in Au+Au collisions:
  BFPP creates $^{197}Au^{78+}$, EMD creates $^{196}Au^{79+}$
  with stochastic cooling ~90% of beam loss is in BFPP and EMD created secondary beam

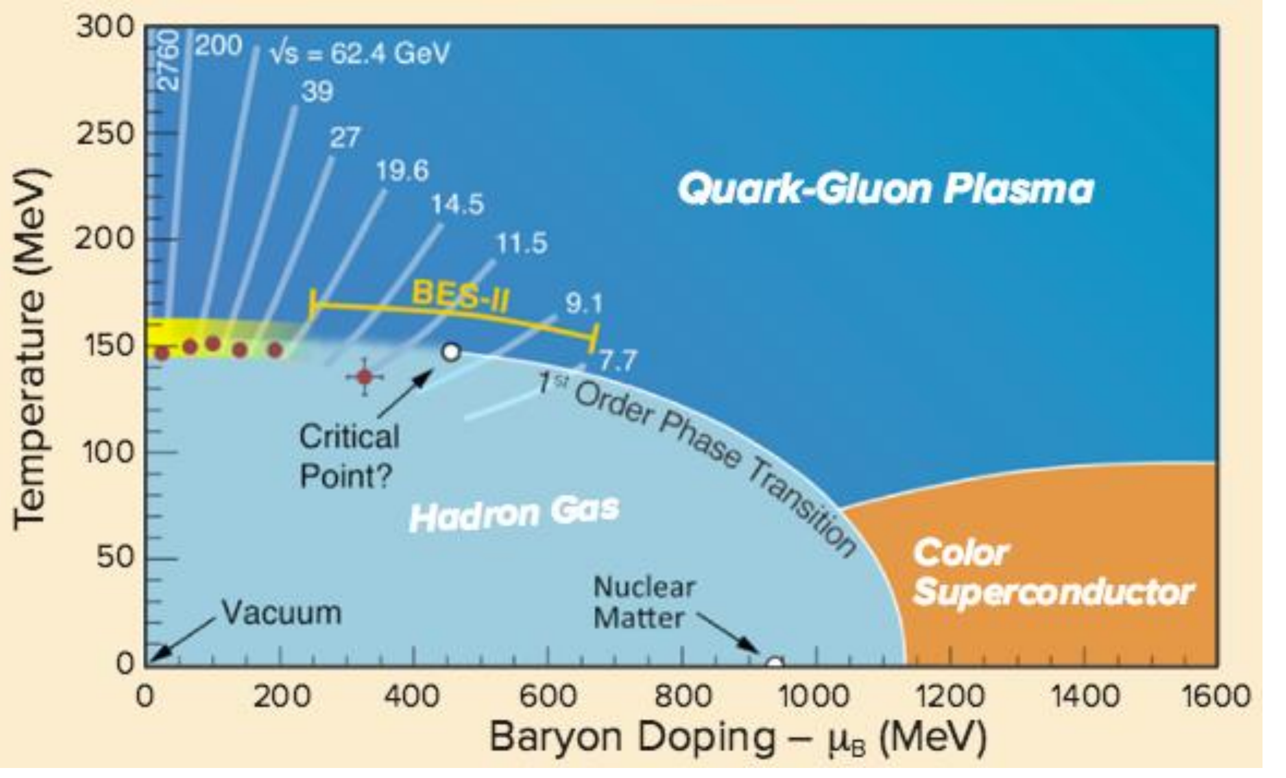


- secondary beam loss proportional to *L* (now 44x design value)
- quench protection diode near 1 local loss point shorted
- warm-up, replacement, cool-down: 19.5 days physics-to-physics
- outstanding support form all lab organizations (Central Shop welders, Radiological Control, SC Magnet Division, all C-AD groups)
- first time partial RHIC warm up during run



Path forward:

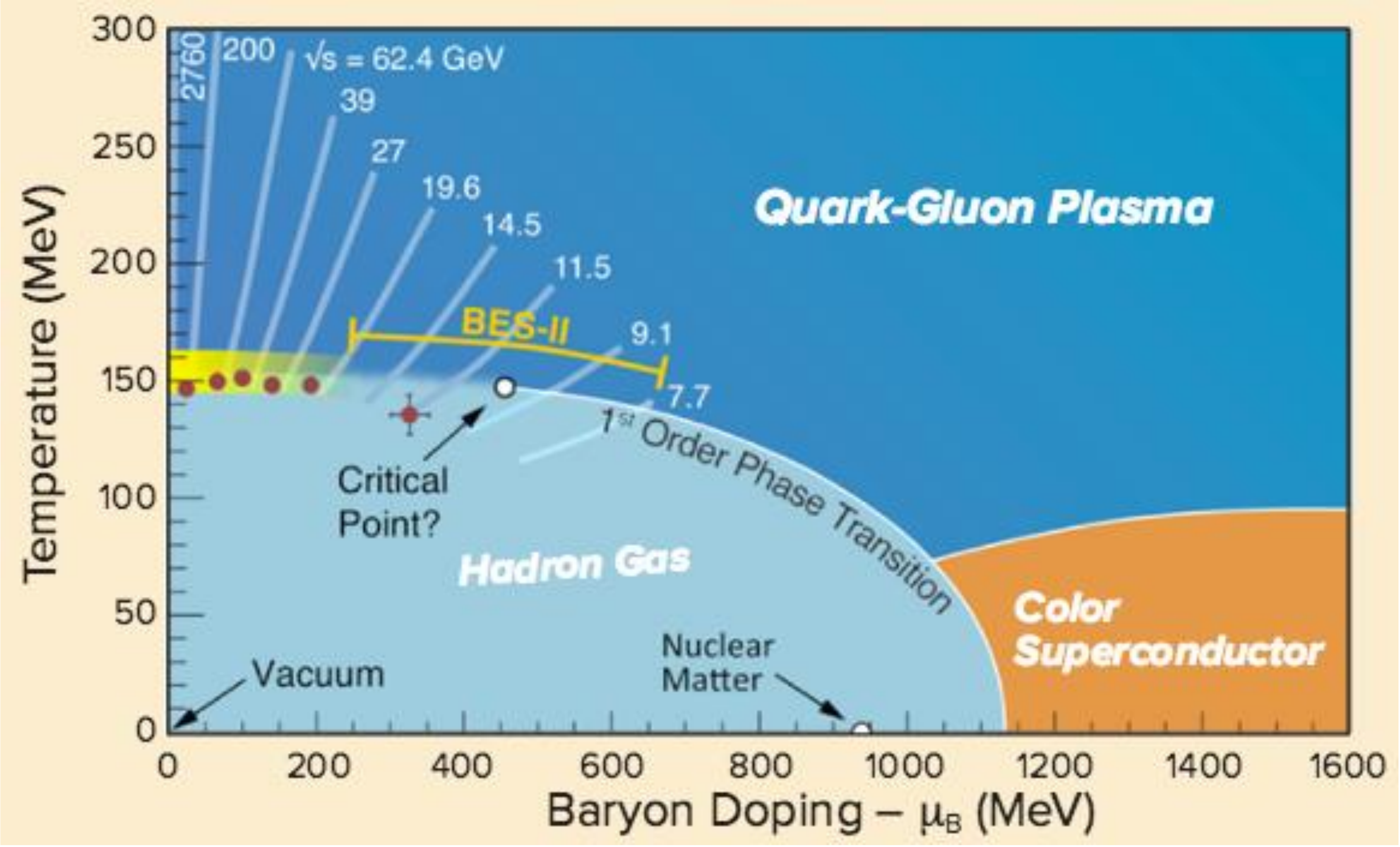
1. Need solution for sPHENIX era (≥2022)
2. Continue annual warm-up (reverses radiation effects)
3. Primary strategy: prevent strongly localized losses in arcs
   => requires avoidance of orbit bumps in arcs
   => requires suppression of abort pre-fires (with serial switches)



RHIC low-energy A+A operation with electron cooling

RHIC

Beam Energy Scan II



[2015 NSAC Long Range Plan for Nuclear Science]

BES-II required events

RHIC Beam Energy Scan II (BES-II) for search of critical point in QCD phase diagram

center-of-mass energy $\sqrt{s_{NN}}$	GeV	7.7	9.1	11.5	14.6	19.6
events BES-I, actual	M	4.3		11.7	24	36
events BES-II, **min goal**	M	80	100	150	200	300
events BES-II, **full goal**	M	100	160	230	300	400

General strategy to maximize integrated luminosity:

Cooling at the 3 lowest energies (4x gain in L_{avg}),
no cooling at the 2 highest energies (3x gain in L_{avg})
=> demonstrated at $\sqrt{s_{NN}}$ = 19.6 GeV in Run-16

Increase cryo-time from 22 to 24 weeks/year

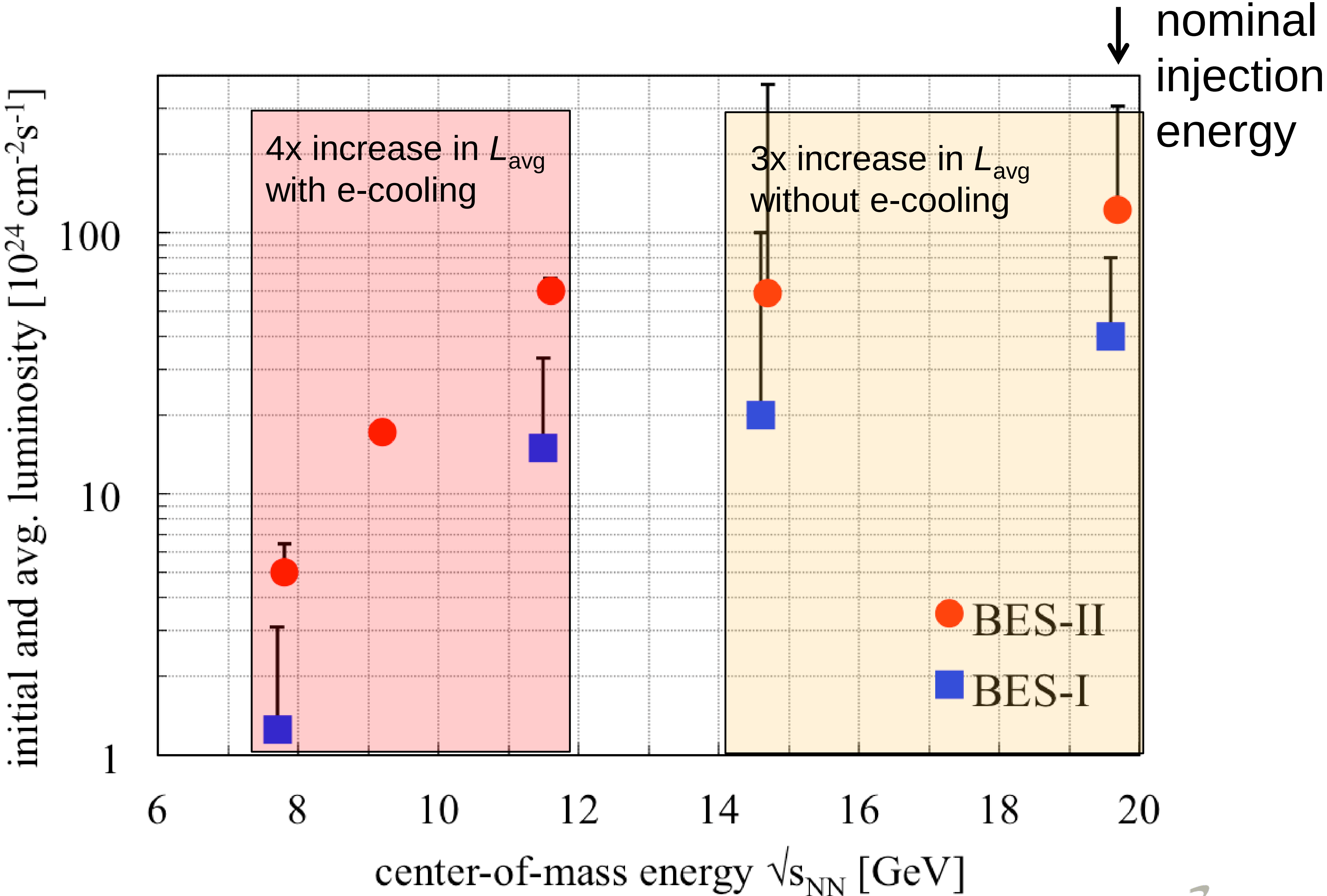
Start BES-II at highest energies (machine ready w/o cooling)

Interleave cooling commissioning with physics operation

Finish BES-II at lowest energies (largest gain in L_{avg} and time)

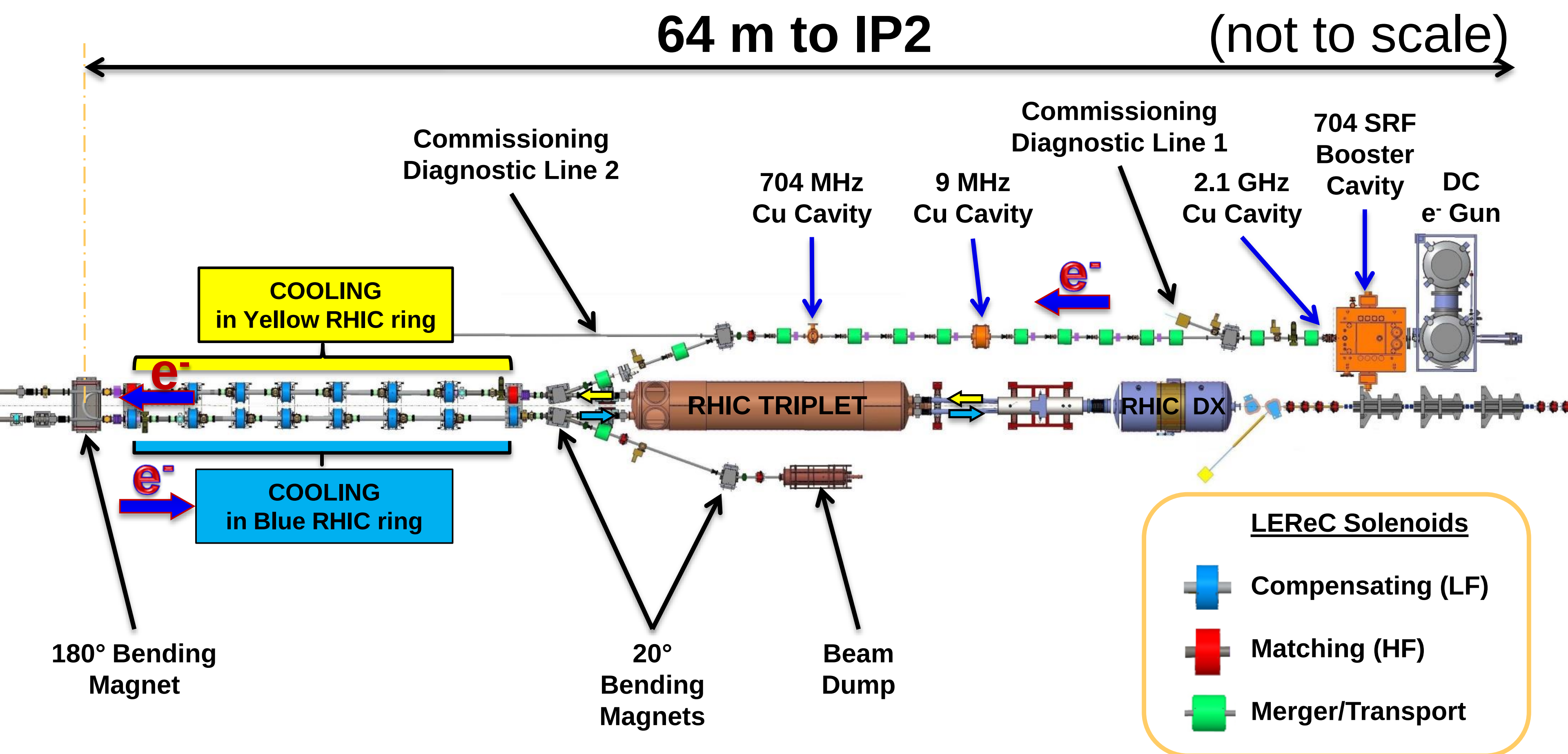
Physics integration

BES-I and BES-II luminosities



Low Energy RHIC electron Cooling (LEReC)

A. Fedotov et al.



Energies E : 1.6, 2.0 (2.65) MeV

Avg. current I_{avg} : 27 mA

Momentum $\delta p/p$: 5×10^{-4}

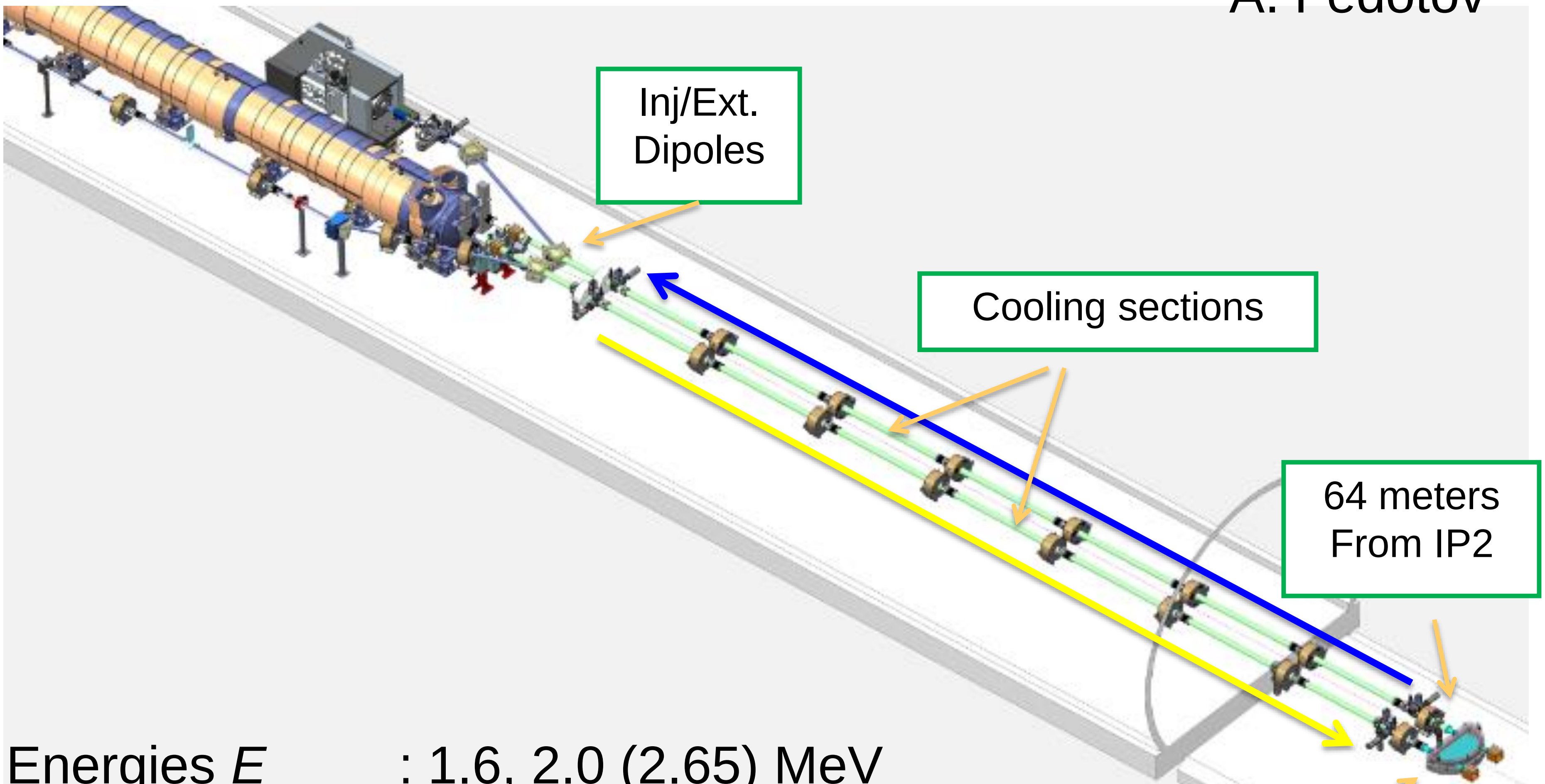
Luminosity gain : 4×

1st bunched beam electron cooler

planned operation in 2019/2020

Low Energy RHIC electron Cooling (LEReC)

A. Fedotov



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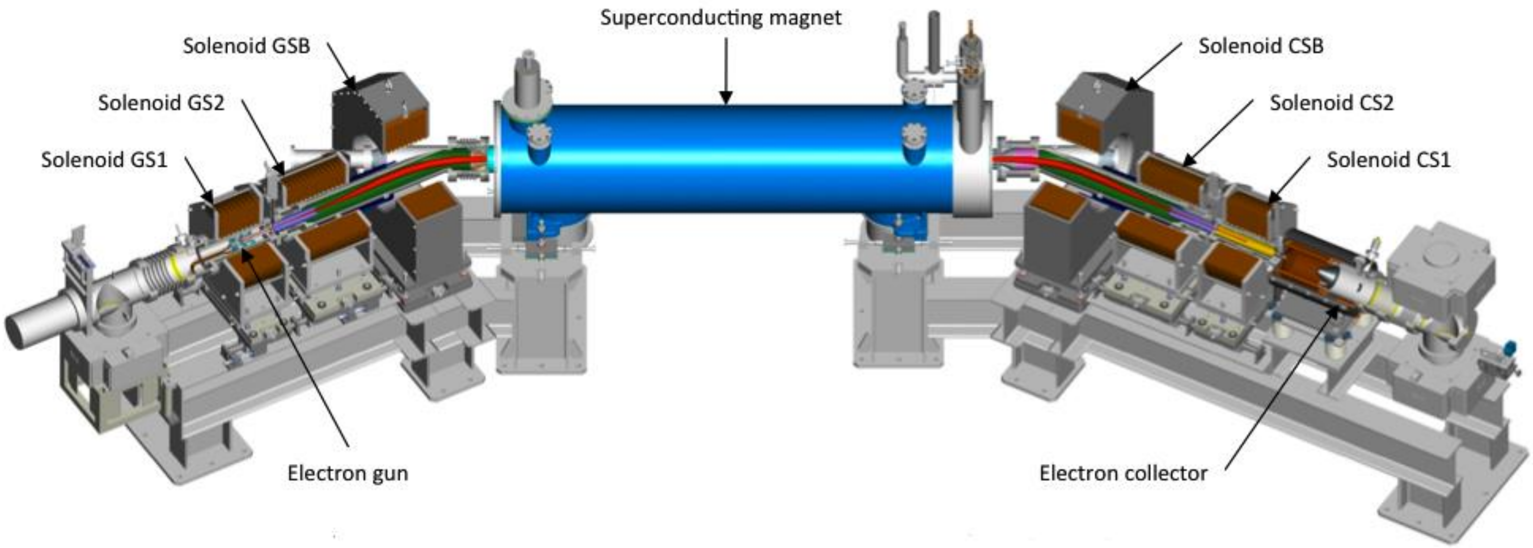
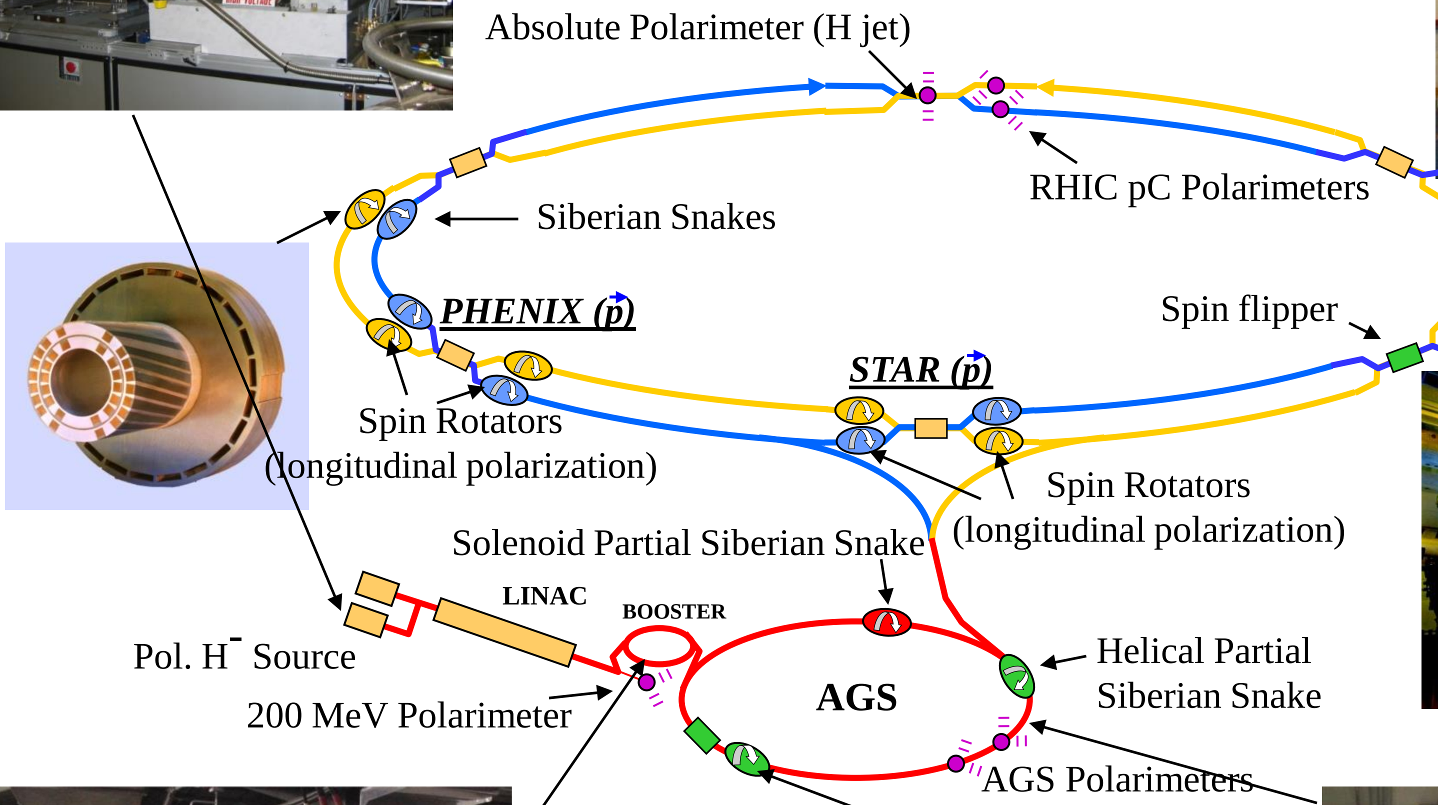
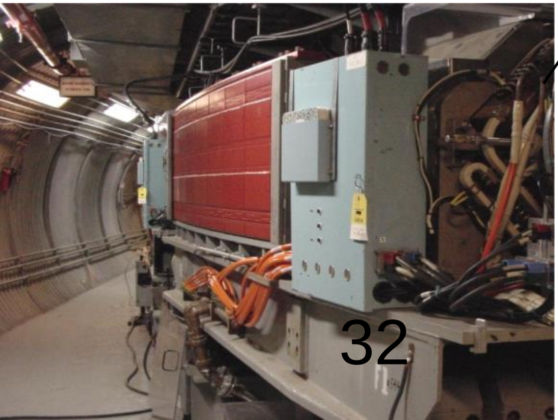
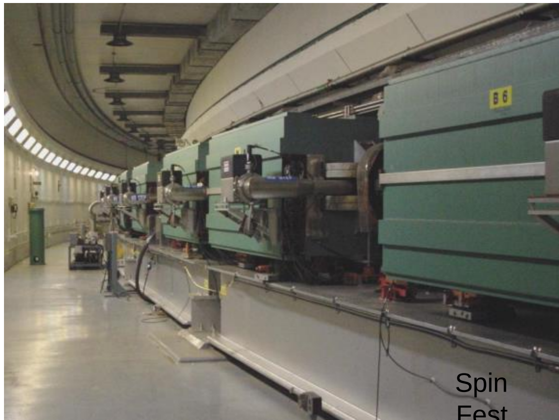


RHIC p↑+p↑ operation with head-on beam-beam compensation

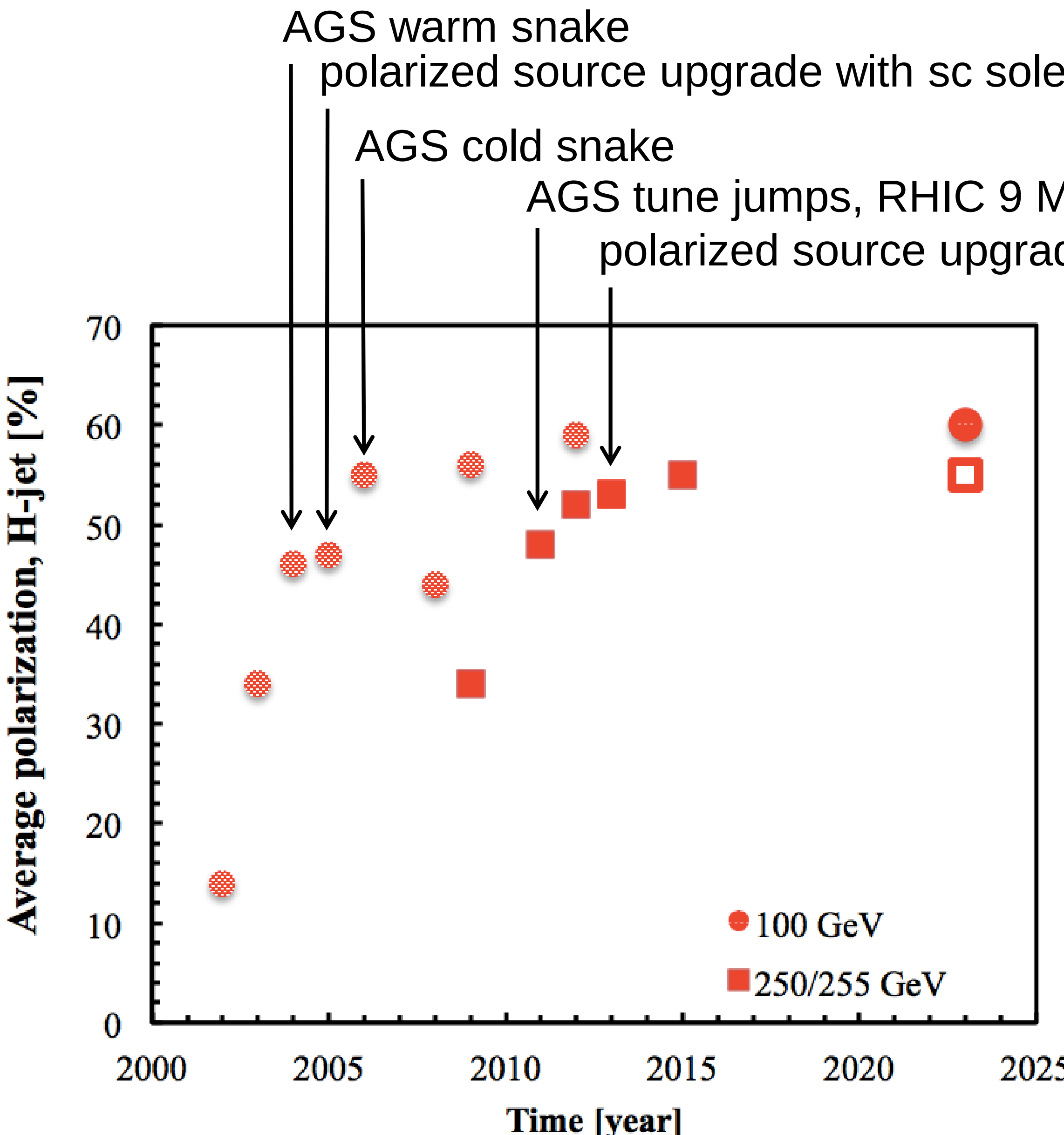
Special devices for polarized protons: source, polarimeters, snakes, rotator, flipper







RHIC p↑+p↑
Polarization



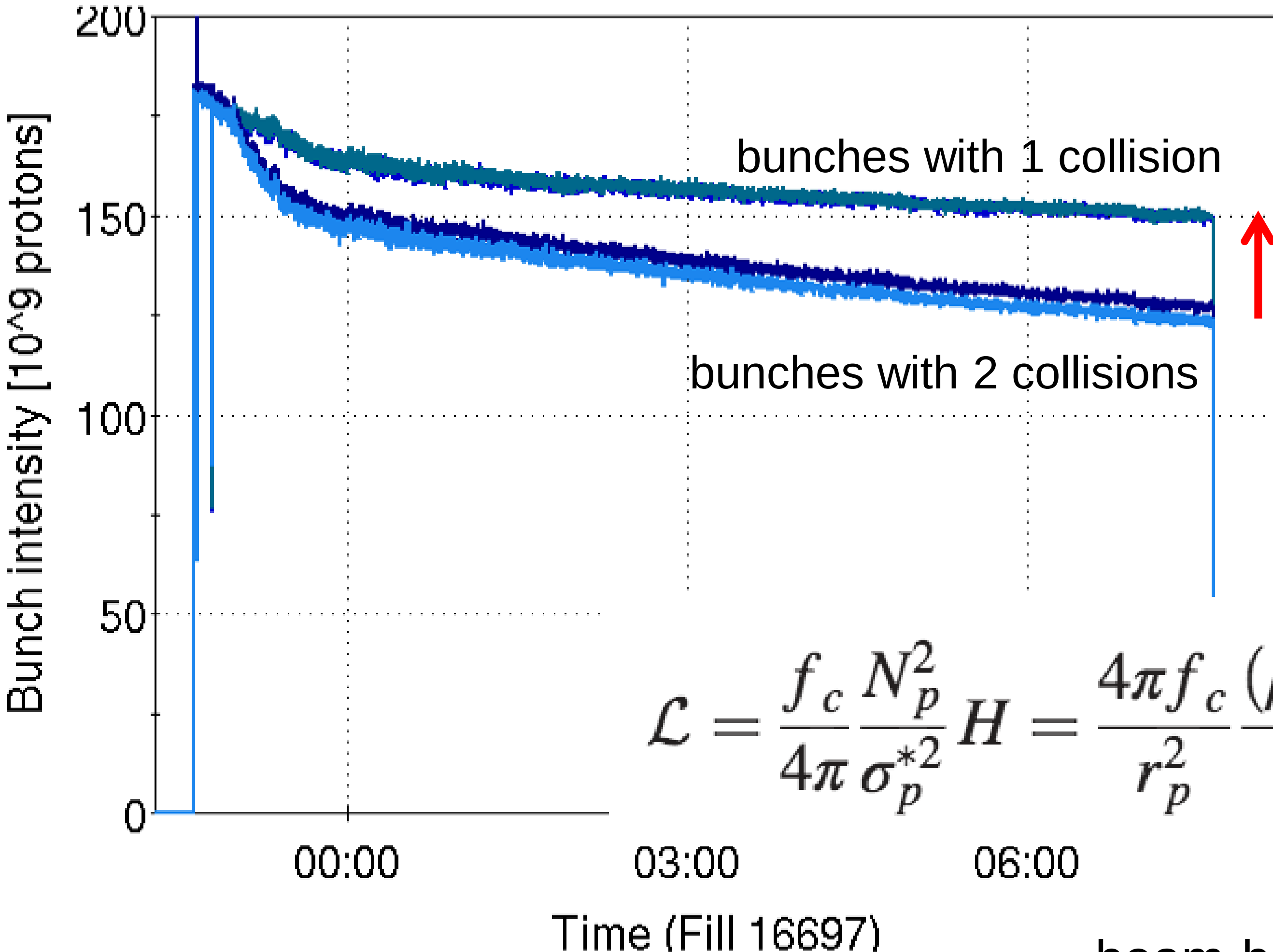
Made extensive parameter scans in AGS and RHIC, and expect only small improvements in *P* in the future

Goal: maintain *P* while increasing bunch intensity further

RHIC head-on beam-beam compensation

Motivation

Bunch intensity in 2012 polarized proton physics store



Goal:

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

Then increase bunch intensity
⇒ up to 2× luminosity

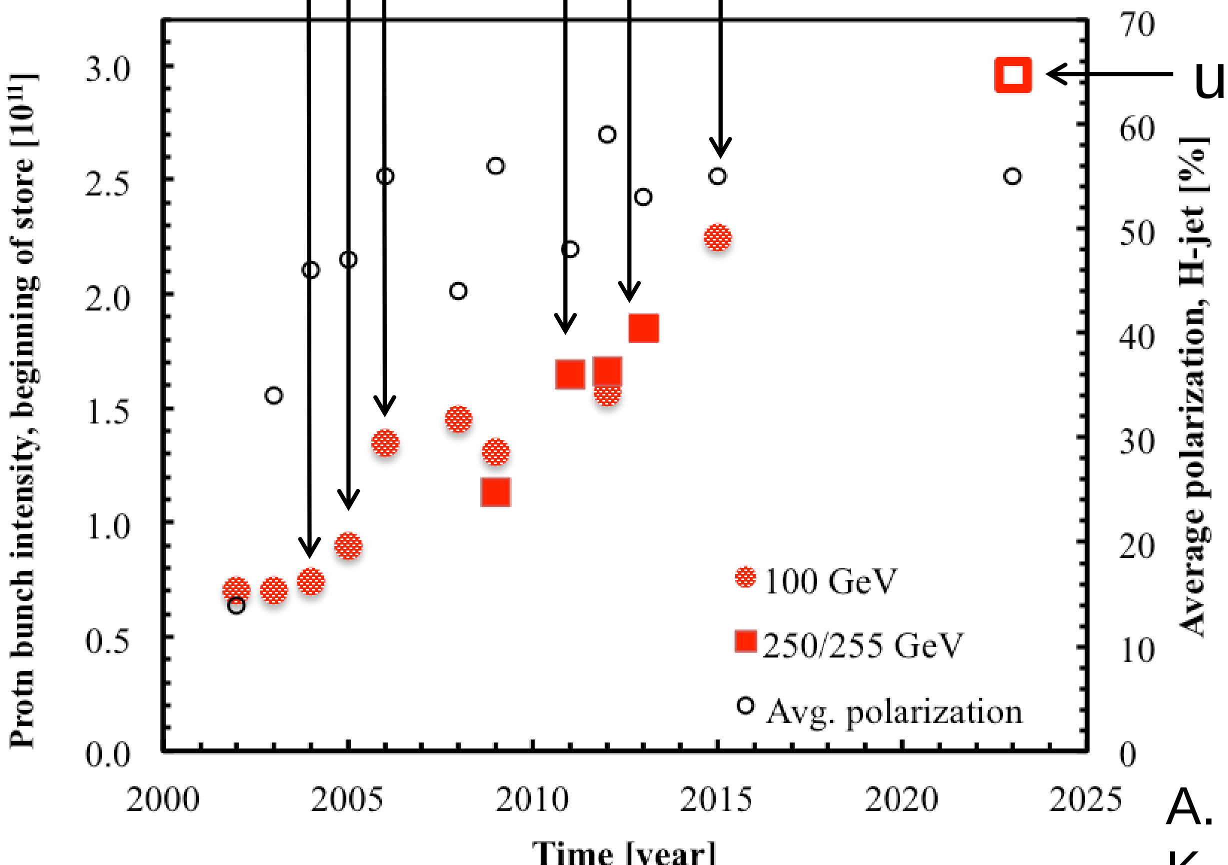
$$\mathcal{L} = \frac{f_c}{4\pi}\frac{N_p^2}{\sigma_p^{*2}}H = \frac{4\pi f_c}{r_p^2}\frac{(\beta_p\gamma_p)\epsilon_n}{\beta^*}H\xi_p^2,$$

beam-beam parameter

p bunch intensity and polarization

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

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



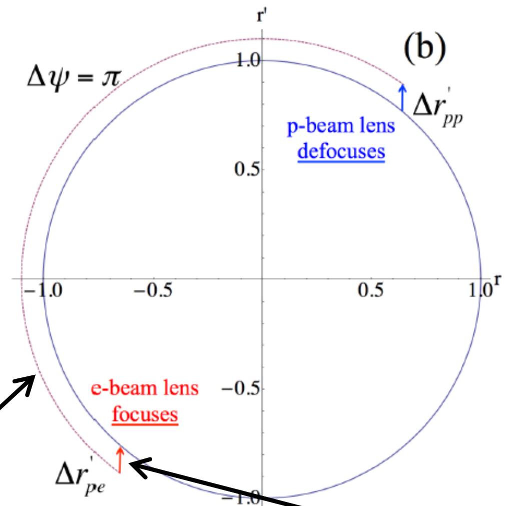
main limits:
- injectors output
- polarization
- e-cloud in RHIC
- beam-beam in RHIC

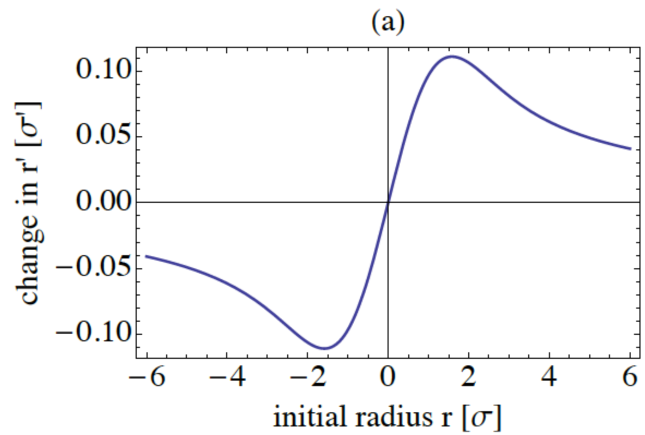
A. Zelenski, H. Huang,
K. Gardner, K. Zeno, RF, et al.

Head-on beam-beam compensation

Principle

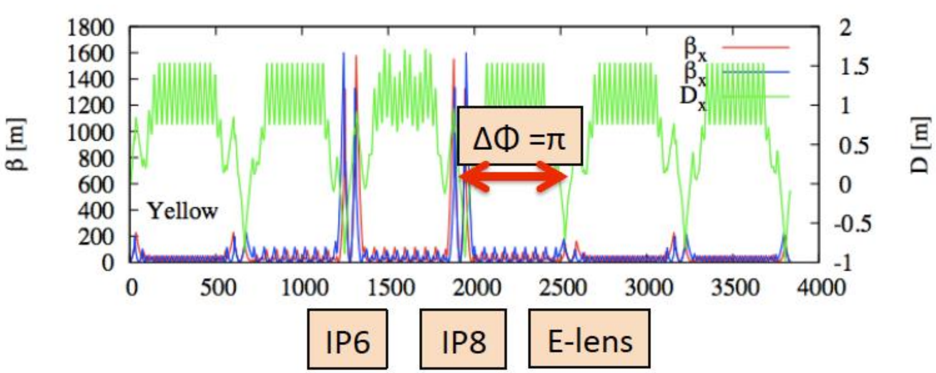
Correction in same turn, need to fulfill 2 conditions:

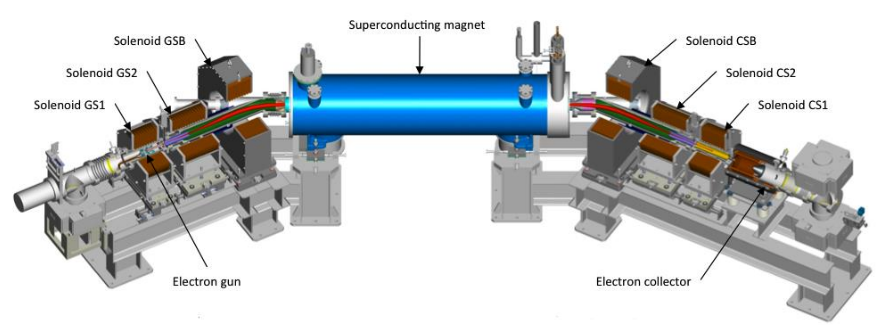




(1) $k\pi$ phase advance minimizes beam-beam resonance driving terms – implemented with ATS type lattice (Simon White)

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

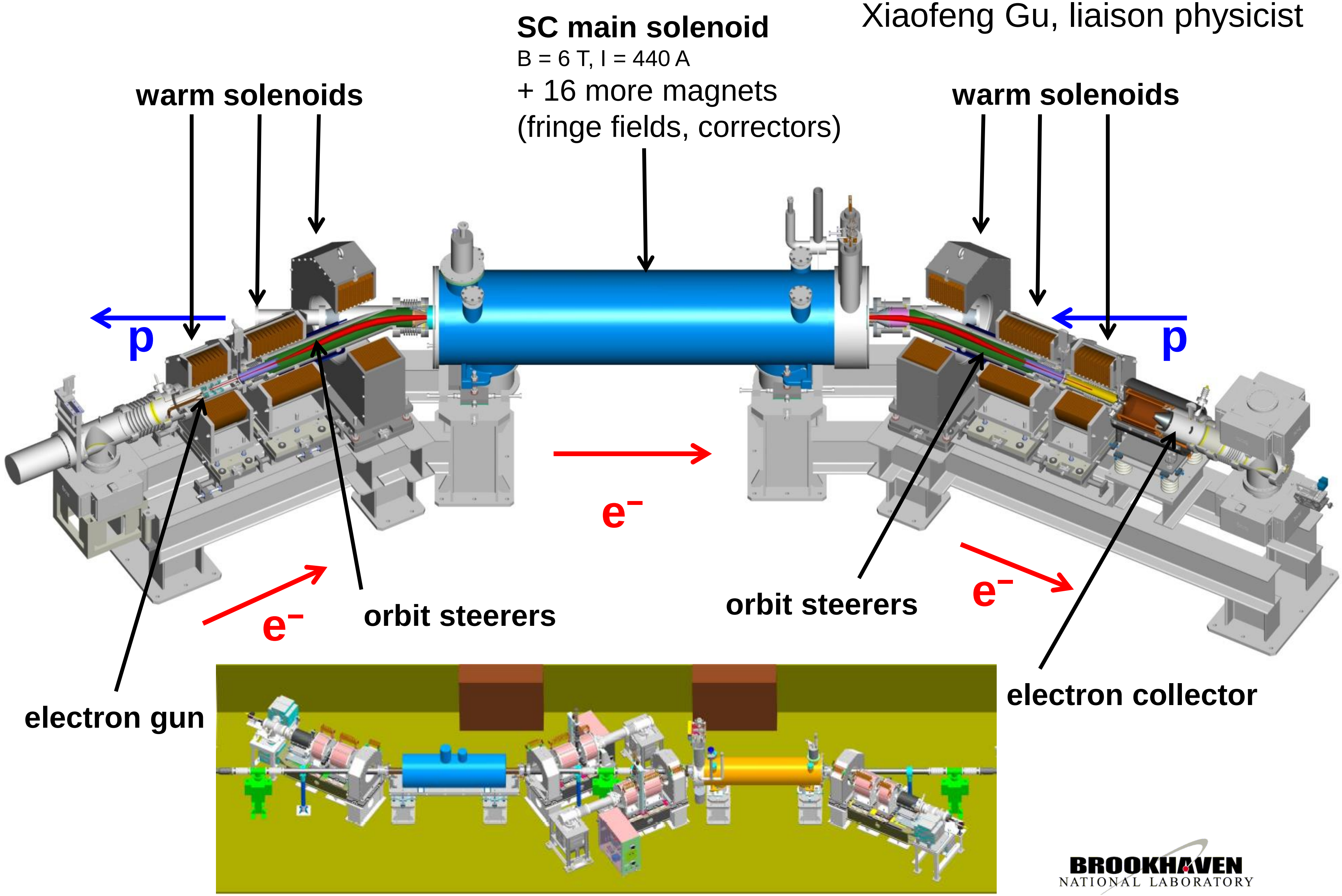




RHIC electron lenses

Overview

Xiaofeng Gu, liaison physicist



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RHIC e-lens Parameters

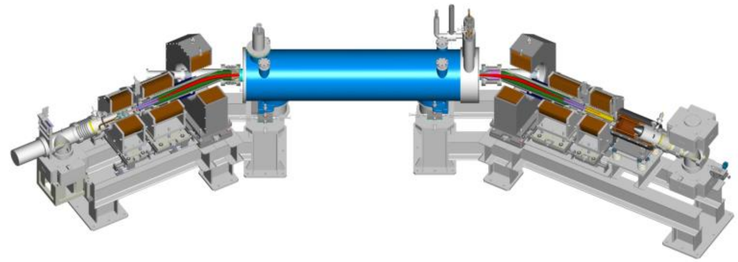


TABLE I. Typical electron lens parameters for 2015 and design values (for up to 250 GeV proton energy).

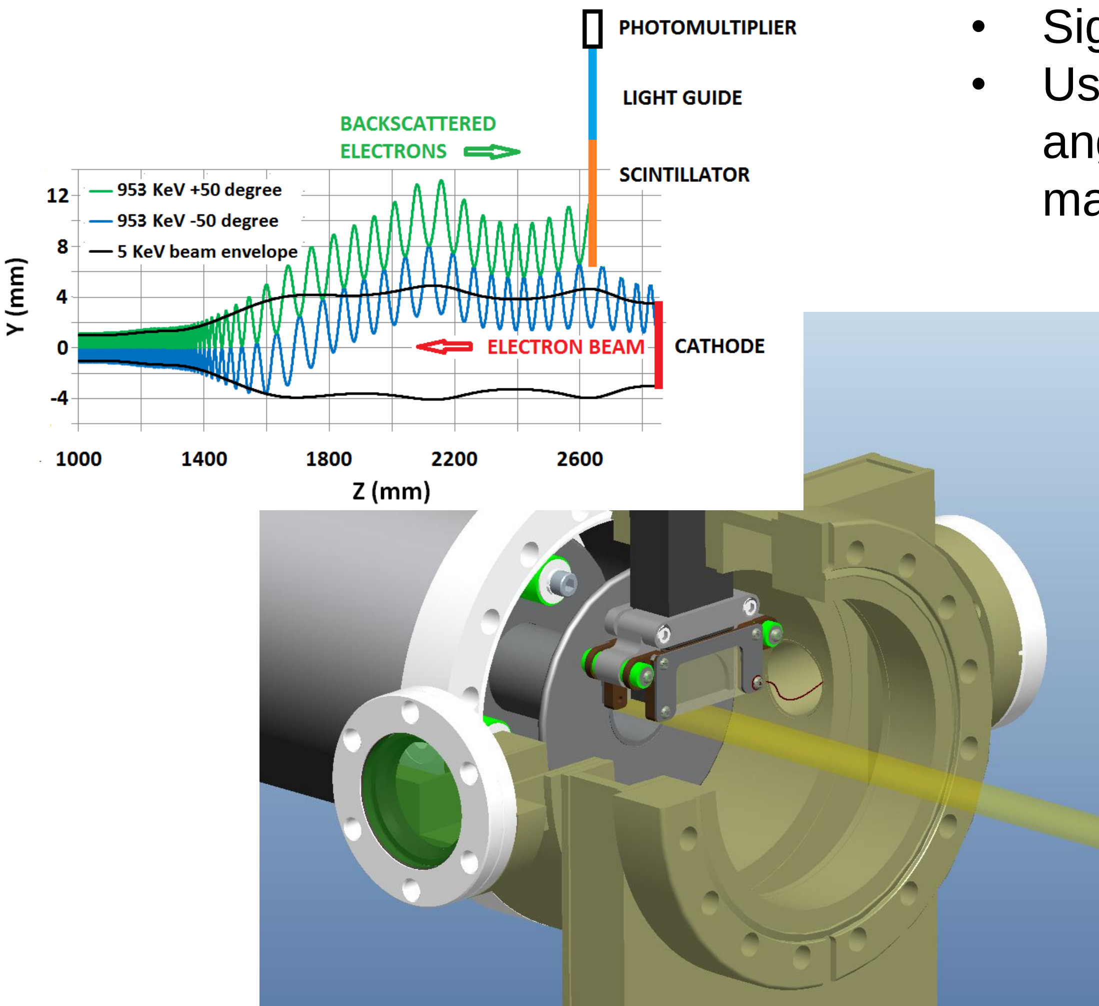
Quantity	Unit	2015 value	Design value
Distance of center from IP10	m	3.3	
Magnetic length L_e	m	2.4	
Gun solenoid field B_g	T	0.31	≤ 0.69
Main solenoid field B_m	T	5.0	2–6
Cathode radius (2.7σ)	mm	7.5	4.1, 7.5
rms beam size in main solenoid σ_e	μm	650	≥ 300
Kinetic energy E_e	keV	5.0	≤ 10
Relativistic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

Technology sources: Tevatron e-lenses, RHIC EBIS

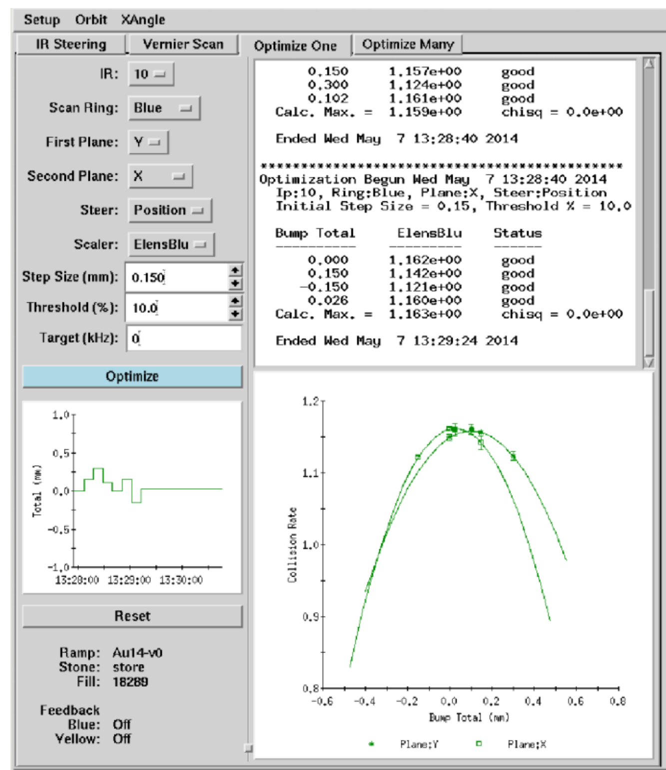
Transverse alignment

Backscattered electrons

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



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

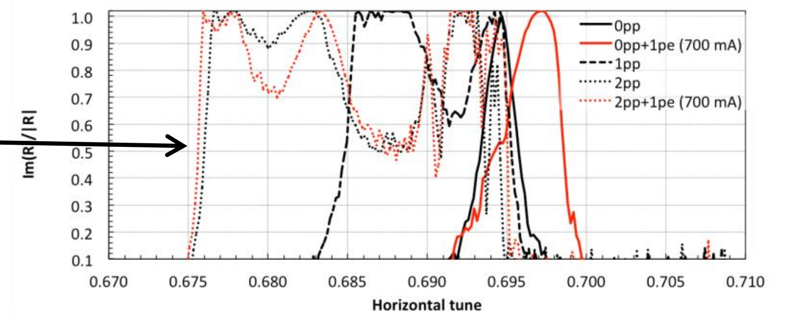


Head-on bb compensation

Footprint compression

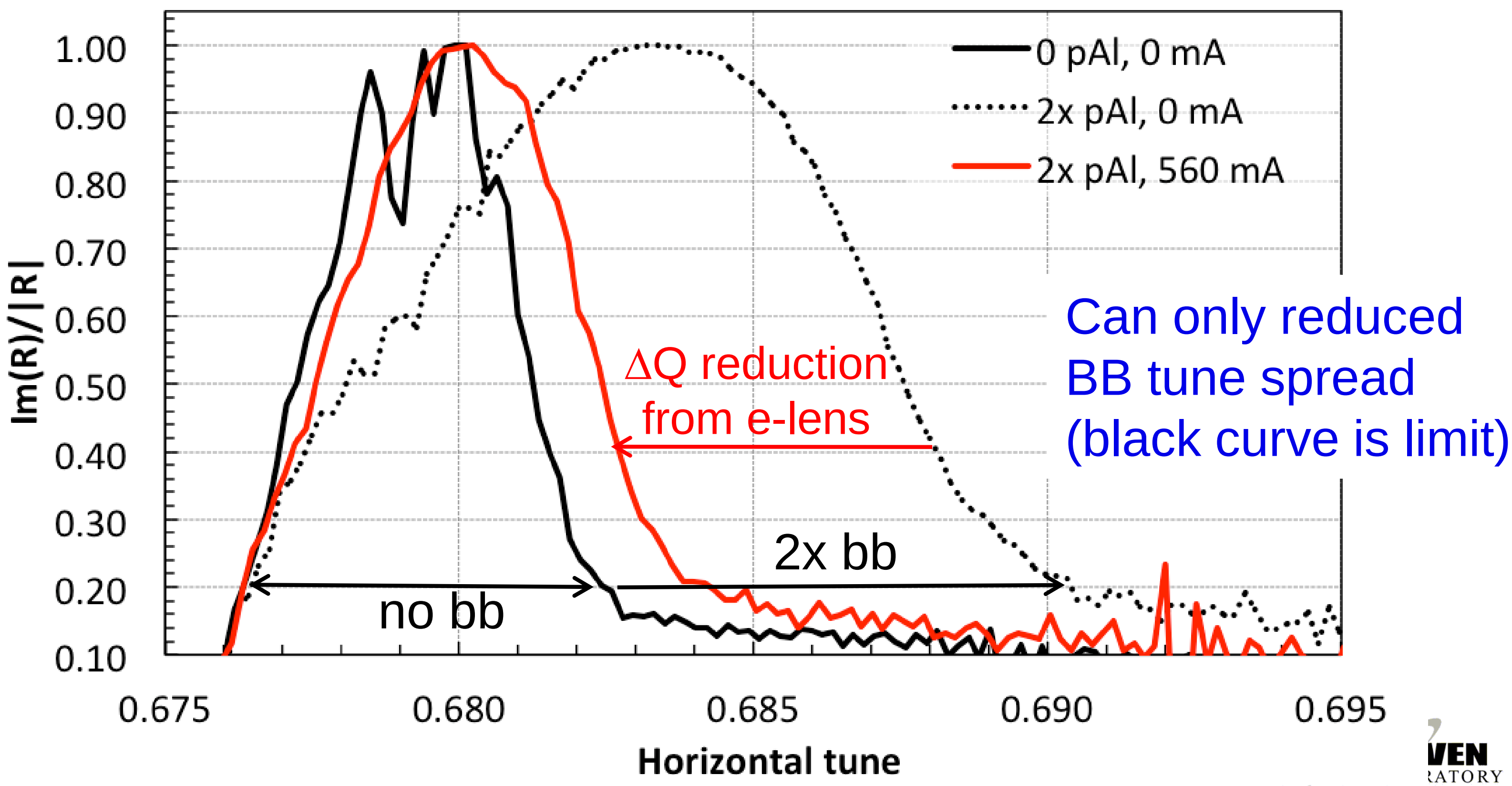
tune distribution could not be measured with BTF and p+p collisions due to coherent modes

(works in simulations – P. Görgen et al. NIM A 777, pp. 43-53 (2015))

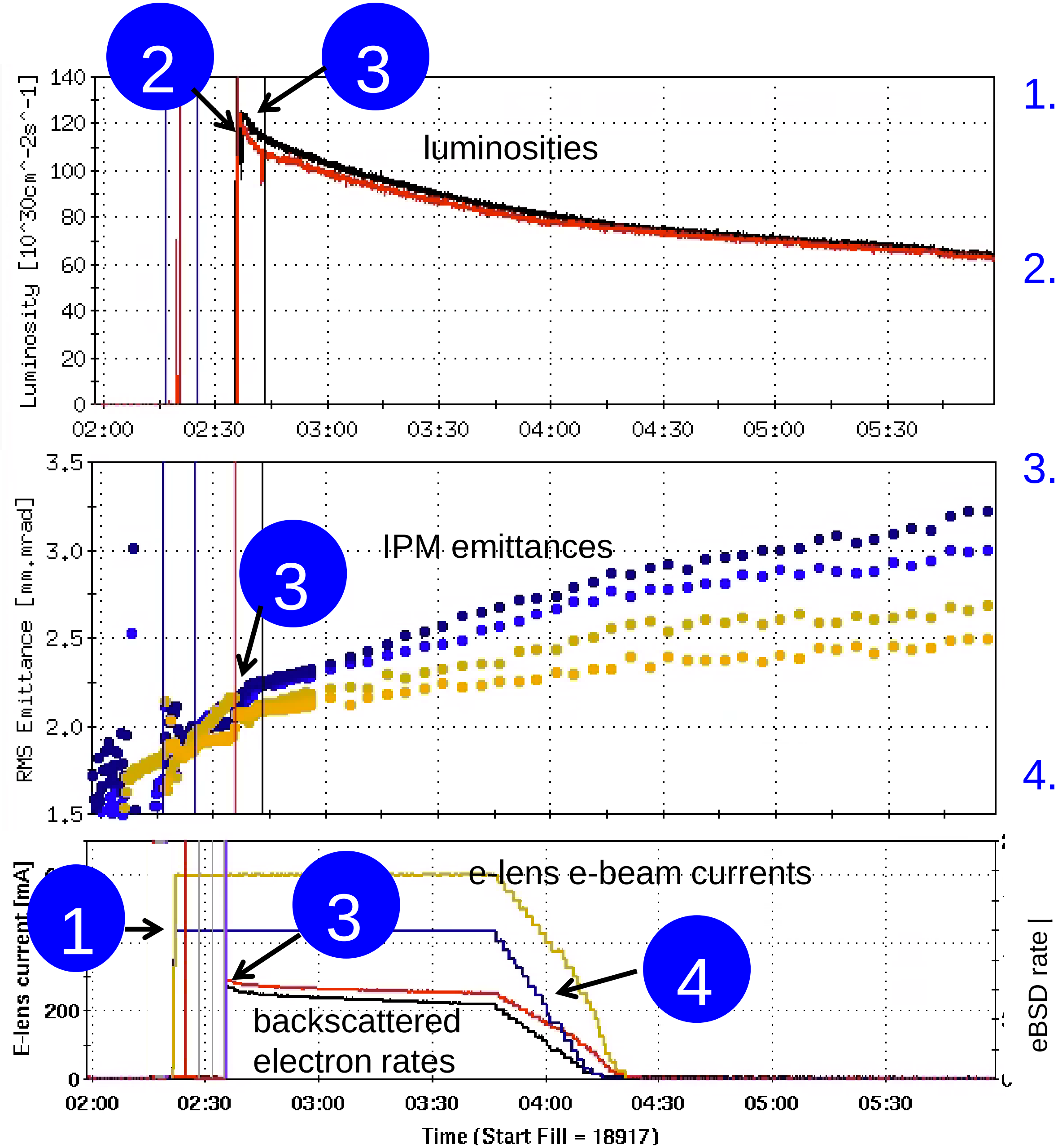


tune distribution can be measured with BTF and p+Al collisions

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



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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Head-on bb compensation

increases in L and ξ

quantity	unit	operations (avg. over 10 best stores) 2012	operations (avg. over 10 best stores) 2015	tests for max ξ_p — 2015 — without e-lens	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	3.3	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						
hour						
bear						
# of						
lumi						
lumi						

PRL 115, 264801 (2015) PHYSICAL REVIEW LETTERS week ending 31 DECEMBER 2015

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

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(Received 28 September 2015; published 23 December 2015)

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

38%
) and w/
ctron lens

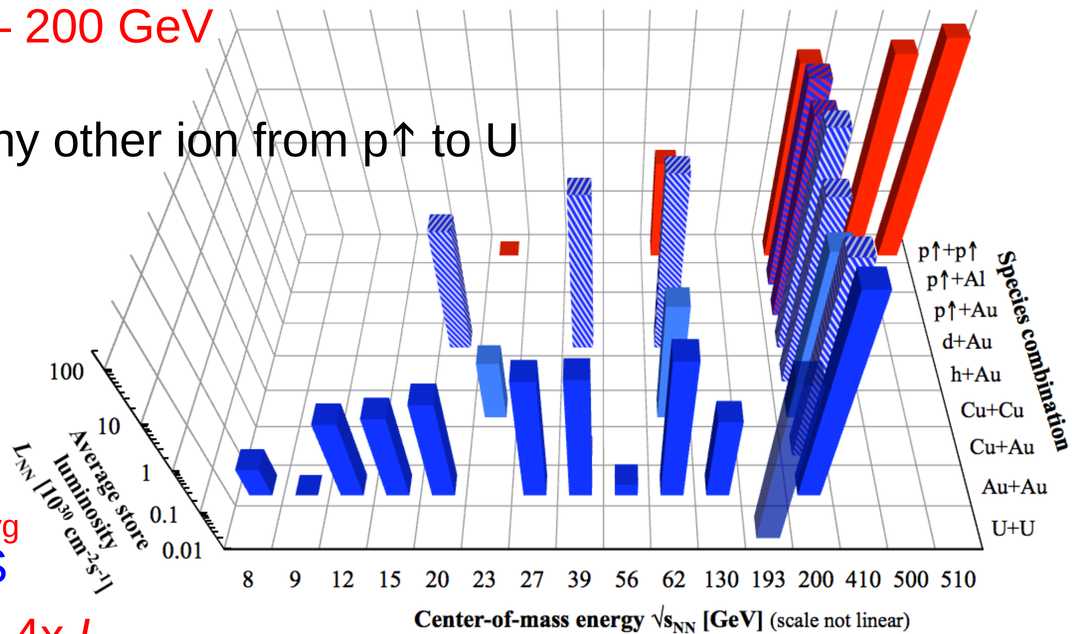
future, without and with lens (ξ sensitive to orbit, tune, chromaticity etc.)

RHIC for the next decade

Summary

Status

- Au+Au L_{avg} = 8.7x10^{27} cm^{-2}s^{-1} (44x design)
- p↑+p↑ L_{avg} = 1.6x10^{32} cm^{-2}s^{-1} (1.3x design), P_{avg} = 53%
- Au+Au energy range $\sqrt{s_{NN}}$ = 7.7 – 200 GeV
  (lowest E ~1/3 of nominal injection)
- flexibility to collide any ion with any other ion from p↑ to U
- leveled luminosity for STAR



Upgrades

- Au+Au at $\sqrt{s_{NN}}$ = 200 GeV: 2x L_{avg}
  increase in bunch intensity, MPS
- Au+Au at $\sqrt{s_{NN}}$ = 7.7 – 20 GeV: 3-4x L_{avg}
  increase in bunch intensity, construction of 1st bunched beam electron cooler
- p↑+p↑ : 3-4x L_{avg}
  increase in bunch intensity while maintaining polarization
  full use of head-on beam-beam compensation
- maintain flexibility