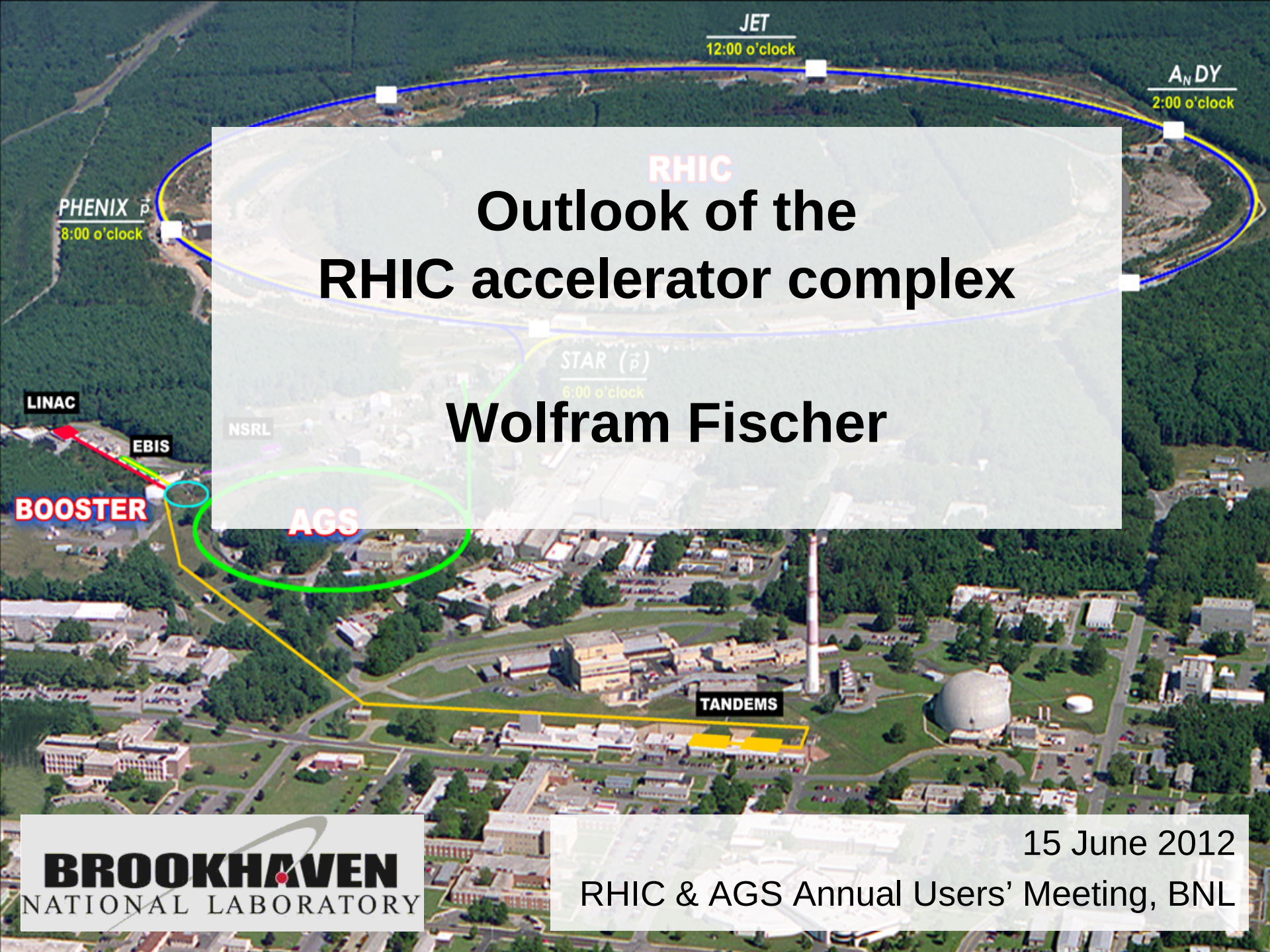


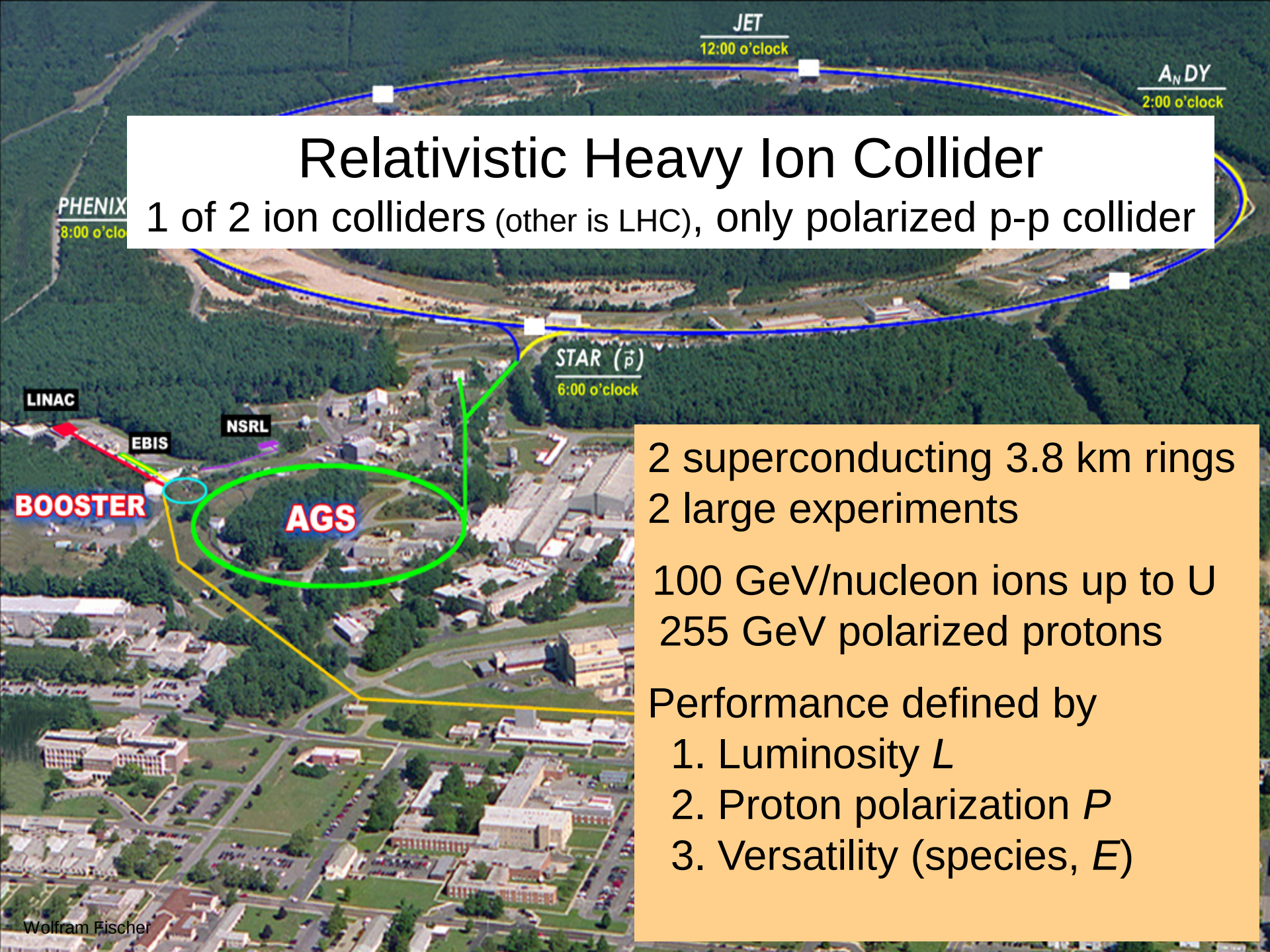

# Outlook of the RHIC accelerator complex

Wolfram Fischer

BROOKHAVEN NATIONAL LABORATORY

15 June 2012

RHIC & AGS Annual Users' Meeting, BNL




# Relativistic Heavy Ion Collider

1 of 2 ion colliders (other is LHC), only polarized p-p collider

2 superconducting 3.8 km rings
2 large experiments

100 GeV/nucleon ions up to U
255 GeV polarized protons

Performance defined by
1. Luminosity *L*
2. Proton polarization *P*
3. Versatility (species, *E*)

# Content

## Run-12 overview (= status, operation in all modes possible)

- Polarized protons, $\sqrt{s}$ = 200, 510 GeV
- Uranium-uranium $\sqrt{s_{NN}}$ = 193 GeV, copper-gold $\sqrt{s_{NN}}$ = 200 GeV

## Heavy upgrades

- Luminosity with stochastic cooling & 56 MHz SRF
- Low energy cooling

## Polarized proton upgrades

- Polarization and luminosity with source upgrade
- Luminosity with RHIC electron lenses
- R&D for polarized $^3$He

## More upgrades

# 2012 RHIC Run (23 weeks of cryo ops) – most varied to date

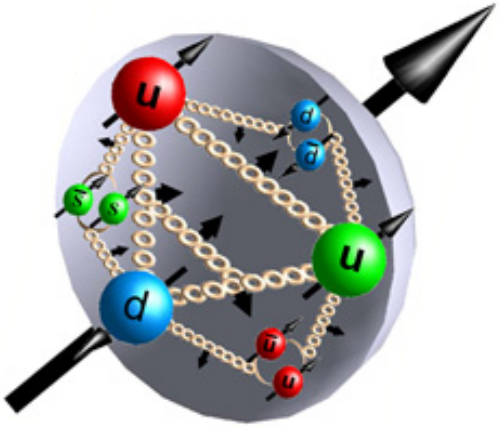
**100 GeV polarized protons**

new records for $L_{peak}$ (1), $L_{avg}$ (2), $P$ (3)

**255 GeV polarized protons**

highest energy polarized proton beam (4)

new records for $L_{peak}$ (5), $L_{avg}$ (6), $P$ (7)

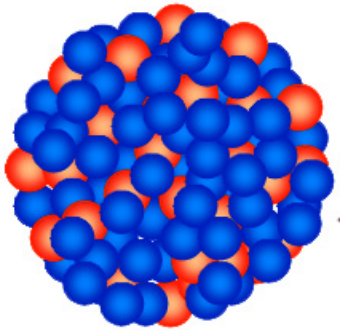



**96.4 GeV/nucleon uranium-uranium**

heaviest element in collider (8), shape

stochastic cooling: $L_{max} > L_0$ 1st time in hadron collider! (9)

all ions lost through burn-off 1st time in hadron collider! (10)



Uranium Nucleus

**100 GeV/nucleon copper-gold** – under way

new species combination in collider (11)

Still to come:

**2.5 GeV/nucleon gold-gold collision test** (2 days)

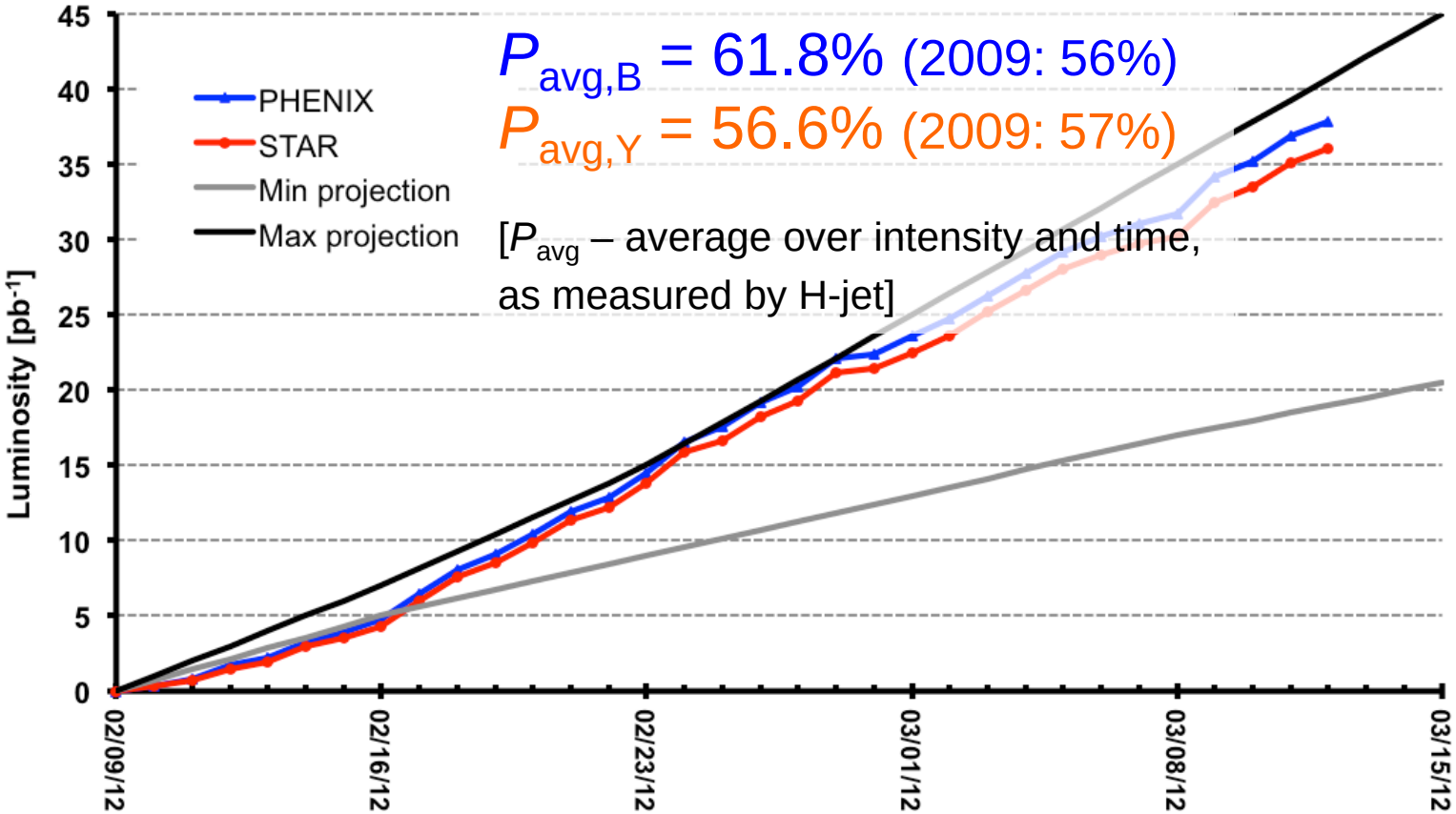
lowest energy to date, 20% of nominal injection ($B\rho$) (12)

**He-3 acceleration (unpolarized) in Booster and AGS**

highest energy He-3 beam (13)

# Run-12 – Polarized protons 100 GeV

Run Coordinator: V. Schoeffer



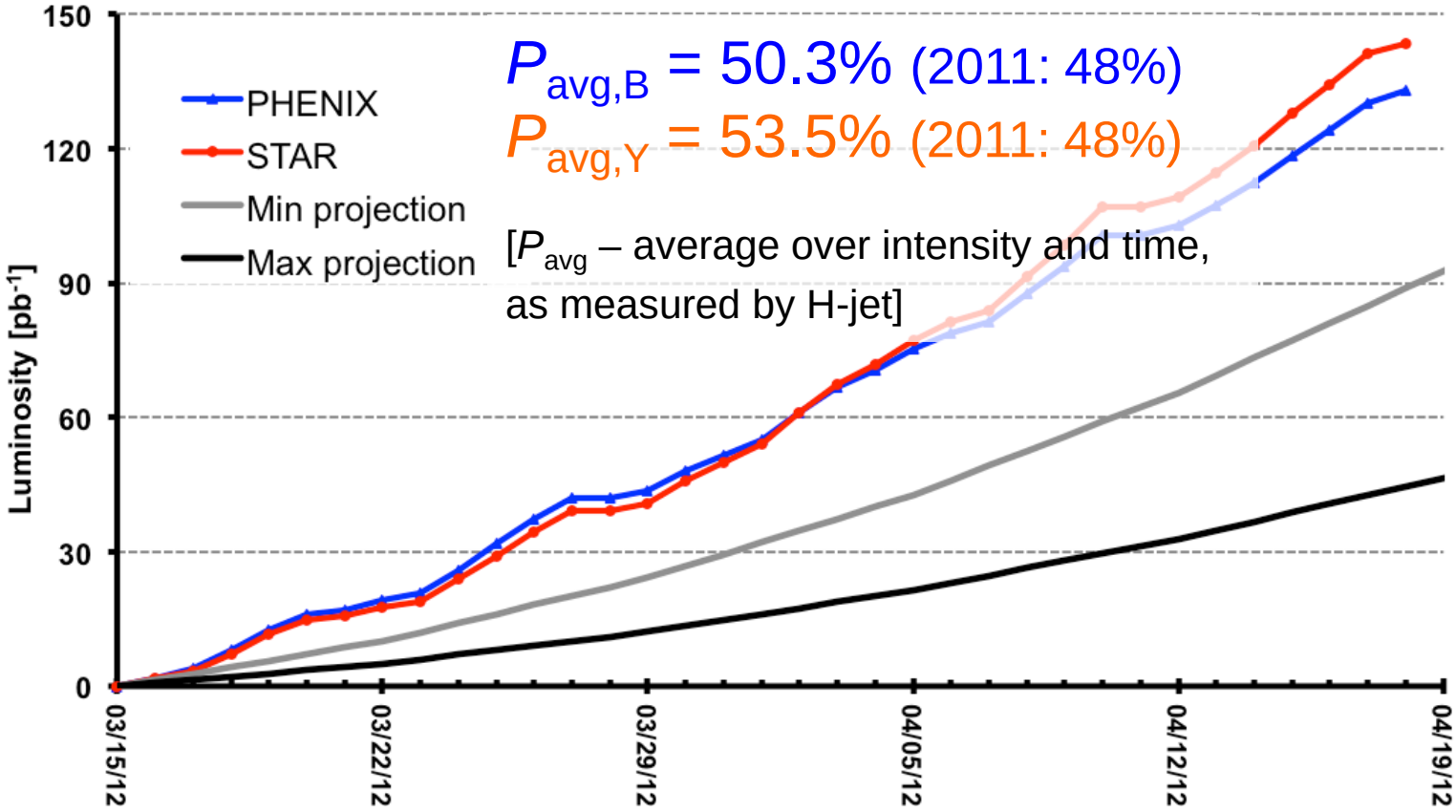

5 weeks

New: 2 new Landau cavities installed in RHIC; AGS horizontal alignment; 9 MHz system upgraded; AGS horizontal tune jump timing improved; operation from new Main Control Room; down ramp does not stop at injection any more, ramp from park to injection with 2x ramp speed compared to previous runs (saves 2.9 min per ramp)

Polarization details at www.phy.bnl.gov/cnipol (D. Smirnov)

# Run-12 – Polarized protons 255 GeV

Run Coordinator: V. Schoeffer




5 weeks

New: same as for 100 GeV; increased store energy to increase polarization lifetime; snakes ramp between 100 GeV and 255 GeV; scan of snake spin rotation axis angle and spin rotation angle; test of longitudinal injection damper; test of Landau phase error compensation (phase error from Booster) compensation

Polarization details at www.phy.bnl.gov/cnipol (D. Smirnov)

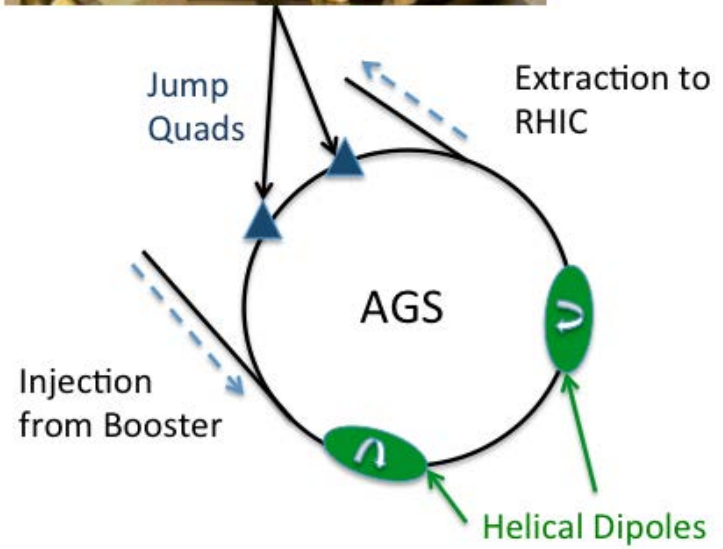
# RHIC Polarization status

## 2 types of depolarizing resonances

- Imperfection resonances (from vertical closed orbit errors): $G\gamma = k$
- Intrinsic resonances (from vertical betatron motion): $G\gamma = kP \pm Q_v$
- $G$ – anomalous magnetic moment (+1.79 for p, −4.18 for $^3$He)

## Recent improvements (2011-2012)

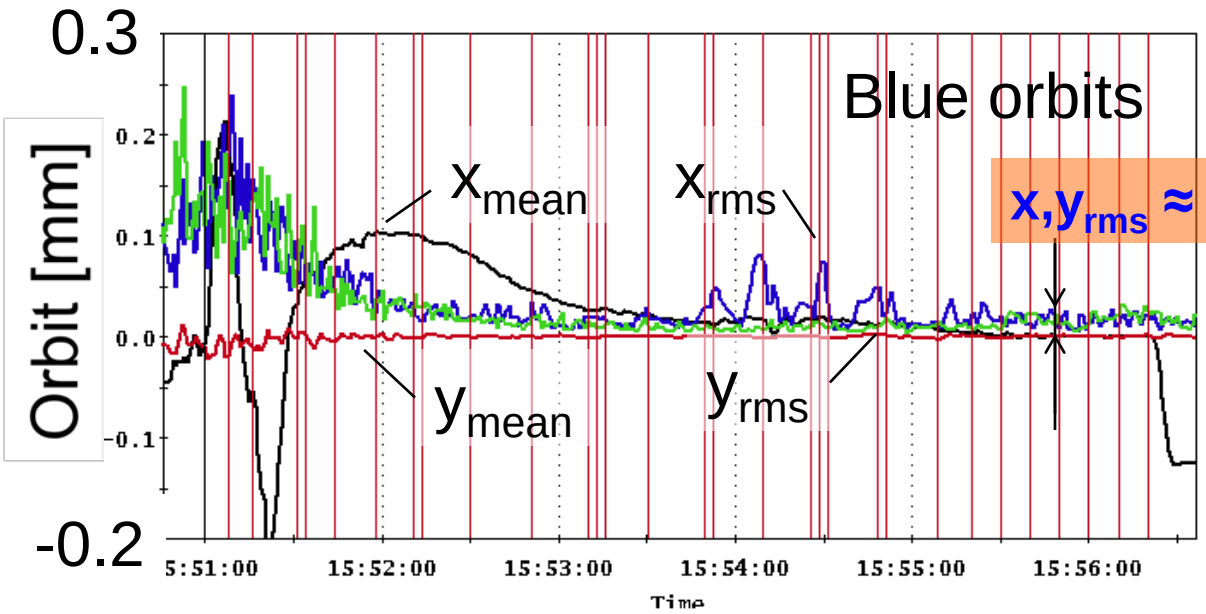
- 80 horizontal tune jumps in AGS (weak horizontal resonances)
- AGS and RHIC re-alignment
- Operation with 9 MHz rf system (low $\delta p/p$)
- Acceleration near 2/3 (only 0.006 off; need orbit, tune, coupling feedback on every ramp)
- pC-polarimeter upgrade (rate dependence)

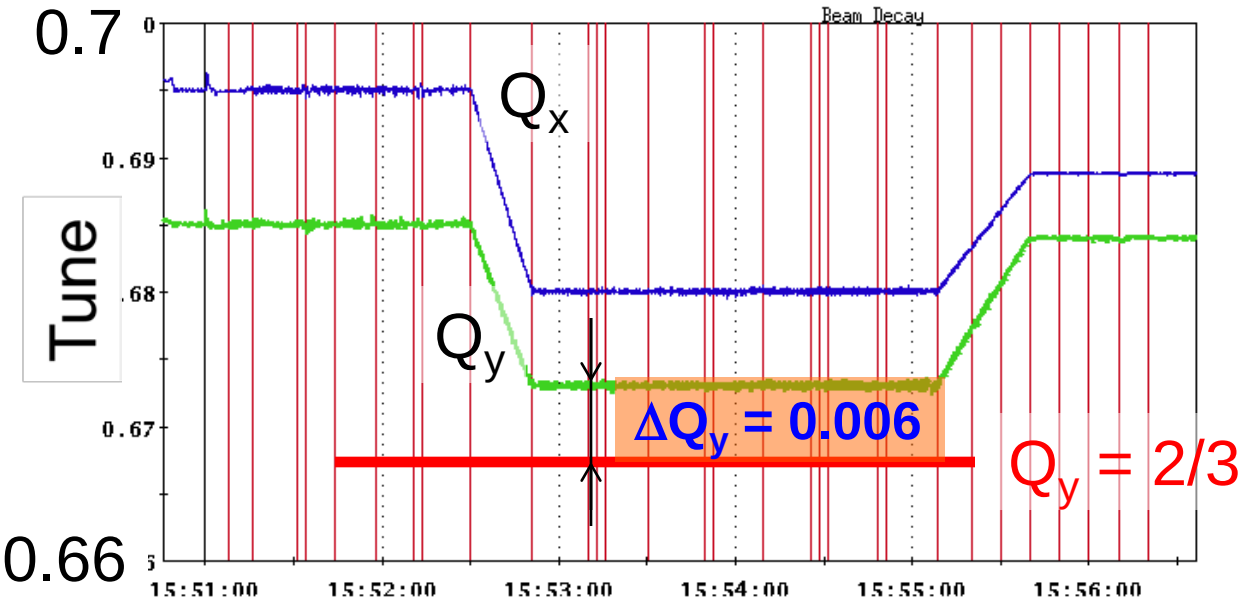



## Future improvements

- Polarized source upgrade
- Possibly more RHIC snakes (also for $^3$He)

# Beam control improvement – feedbacks on ramp




M. Minty,
A. Marusic et al.

**$x,y_{rms} \approx 20$ μm (!) ≈ 3% of rms size**

Orbit feedback on every ramp allows for

- Smaller $y_{rms}$ (smaller imperfection resonance strength)
- Ramp reproducibility (have 24 h orbit variation)

Tune/coupling feedback on every ramp allows for

- Acceleration near $Q_y = 2/3$ (better P transmission compared to higher tune)

# Polarization tests during Run-13 (M. Bai et al.)

**Polarization lifetime at store** (0.5-1.0%/h loss at 100 and 250 GeV)

- Energy change from 250 to 255 GeV => no difference
- Depolarization of non-colliding beam on/off the strongest snake resonance (=11/16) => no difference
- Spin tune change ±0.01=> no difference
- Snake spin rotation angle scan ±10 deg => small effect for –10 deg

**Depolarization during energy and rotator ramps**

- Orbit effect of last 2 strong intrinsic resonances
  => small effect for large orbit error
- Contribution of final $\beta^*$-squeeze => no difference
- Snake spin rotation angle => 5% (absolute) gain in Yellow
- Spin tune change ±0.01 => no difference

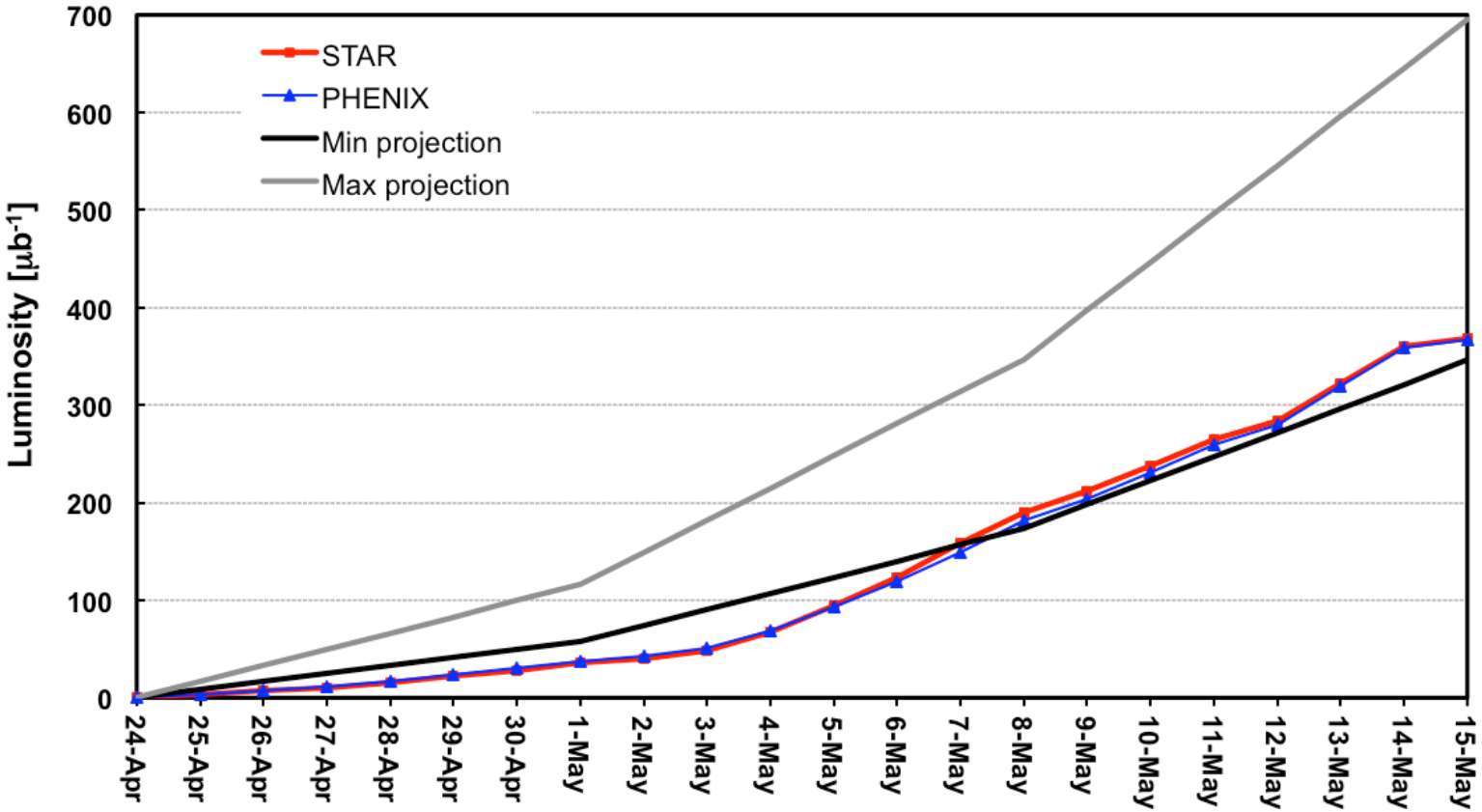
**Absolute polarization at injection with H-jet**

- 10 h for measurement in Yellow only (background minimization)
- $P_{avg}$ = (63±4.4)%

=> Unlikely that large polarization gains can be made by further parameter changes, i.e. depolarization due to many small effects

# Run-12 – Uranium-uranium 96.4 GeV/nucleon

Run Coordinator: Y. Luo

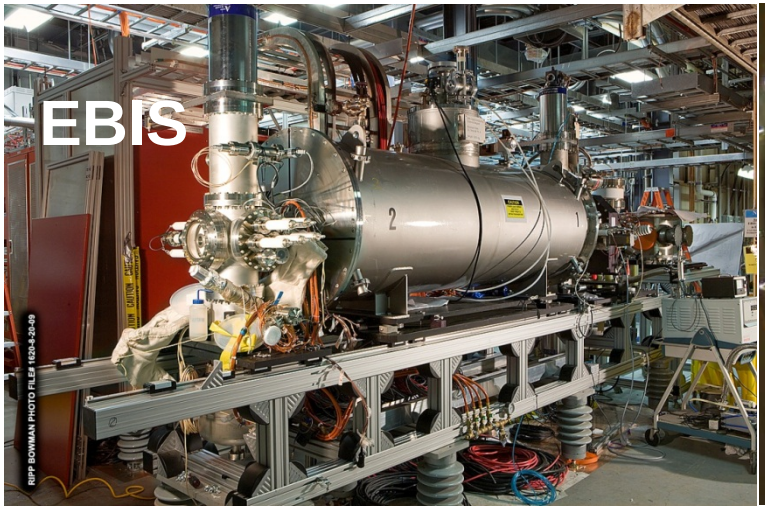



3 weeks

New: first use of EBIS for RHIC operation; first U-U operation in a collider; used standard lattice to increase off-momentum dynamic aperture; first use of Blue and Yellow horizontal stochastic cooling (resulting in 3D cooling in both rings); due to small beam size need micro-vernier scan every 1/2 h

# Electron Beam Ion Source (EBIS)

- Inject single charge ion from primary source (e.g. hollow cathode source)
- 10 A electron beam creates desired charge state in trap (5 T sc solenoid)
- Source for high-charge state, high brightness ion beams
- Accelerated through RFQ and linac, injected into AGS Booster
- All ion species including noble gas, uranium and polarized $^{3}He$






Operated for NASA Space Radiation Laboratory in 2011-12 with

- $He^{+}$, $He^{2+}$, $Ne^{5+}$, $Ne^{8+}$, $Ar^{10+}$, $Kr^{18+}$, $Ti^{18+}$, $Fe^{20+}$, $Ta^{33+}$, $Ta^{38+}$

Operated for RHIC in 2012 with

- $U^{39+}$ (not possible previously), $Cu^{11+}$, $Au^{31+}$

# Preparation of U beams for RHIC

**EBIS out: $U^{39+}$**


**AGS-to-RHIC transfer line**

Stripping foil:

$Al_2O_3$ (5.2 mg/cm$^{2)}$

$E_{kin}$ = 8.51 GeV/nucleon

**$U^{90+}$ ♍ $U^{92+}$** (99.9% of intensity)

P. Thieberger, K. Zeno

**Booster-to-AGS transfer line**

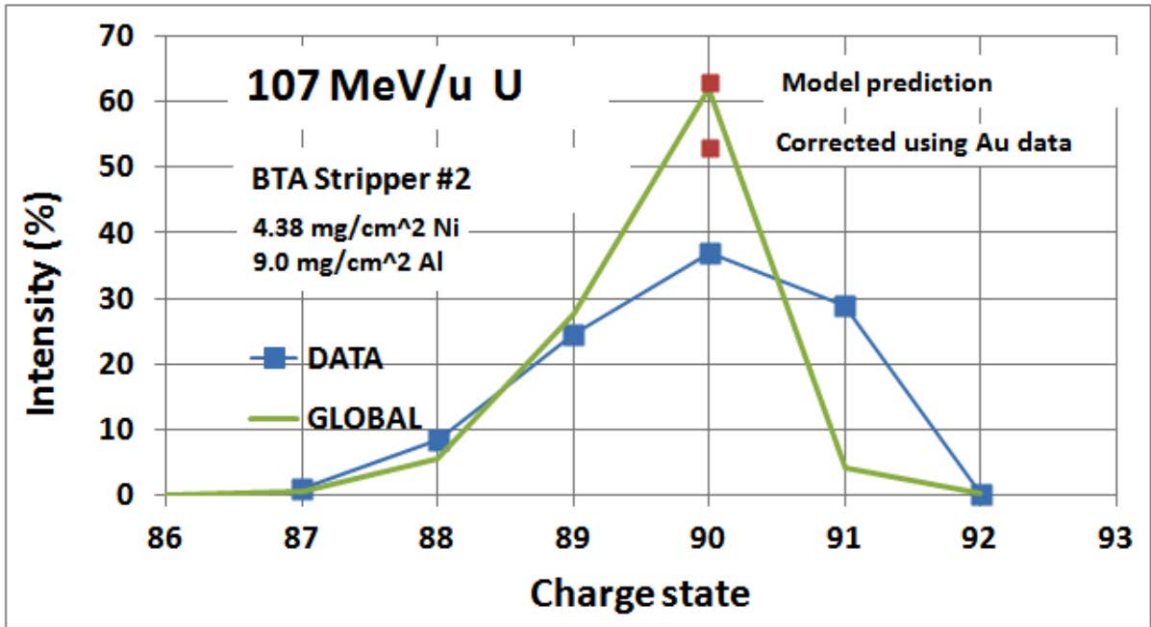
Stripping foil:

Ni (4.4 mg/cm$^{2)}$ + Al (9.0 mg/cm$^2$)

$E_{kin}$ = 107 MeV/nucleon

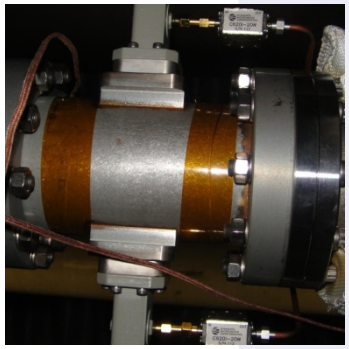
**$U^{39+}$ ♍ $U^{90+}$** (35% of intensity)

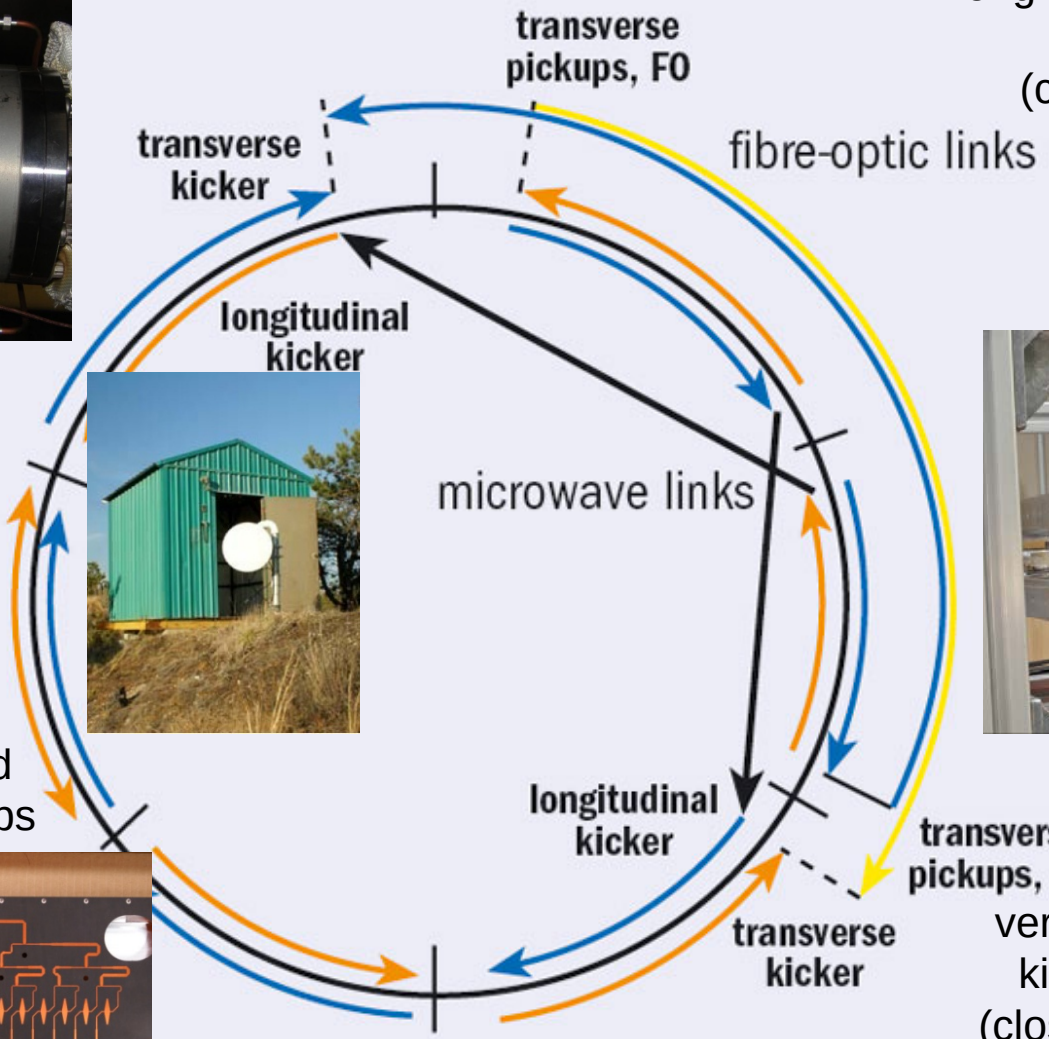
**(had expected >50% based on GLOBAL)**



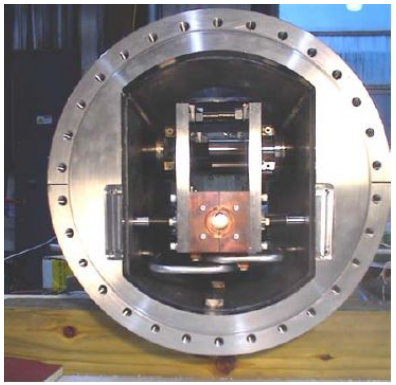
# Now have full 3D stochastic cooling for heavy ions

longitudinal pickup

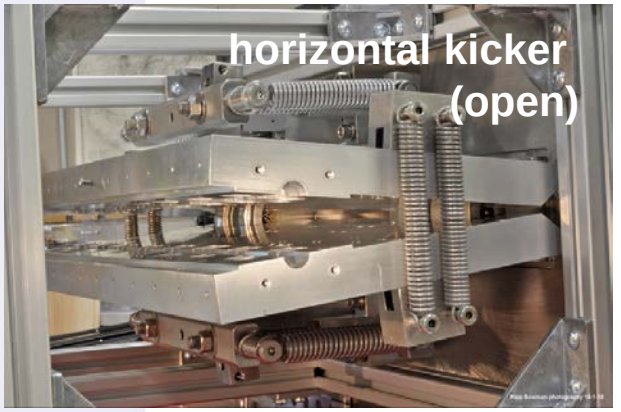




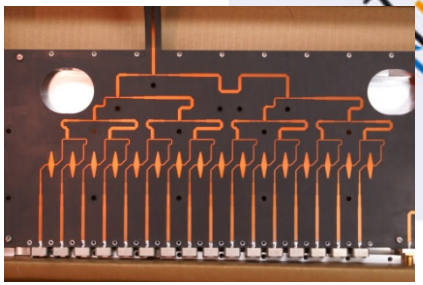

longitudinal kicker (closed)



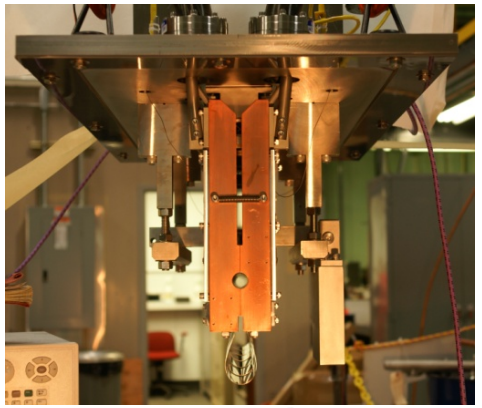





horizontal and vertical pickups

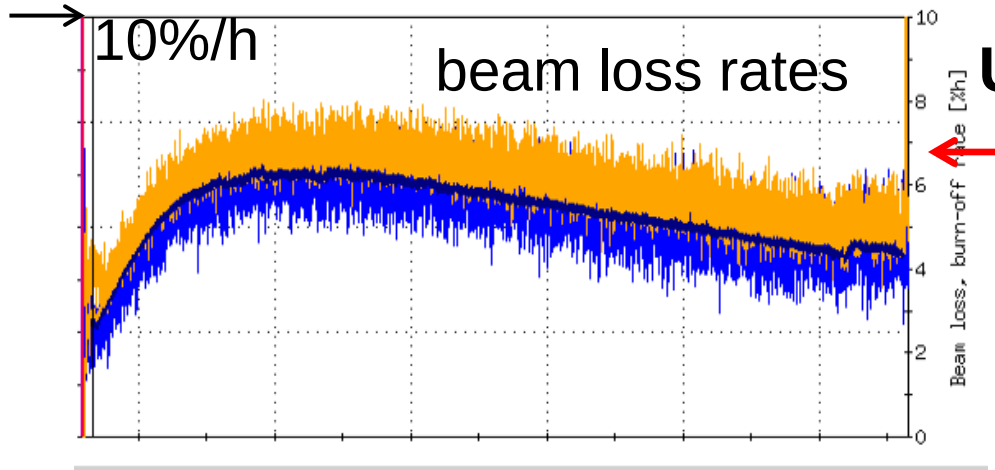


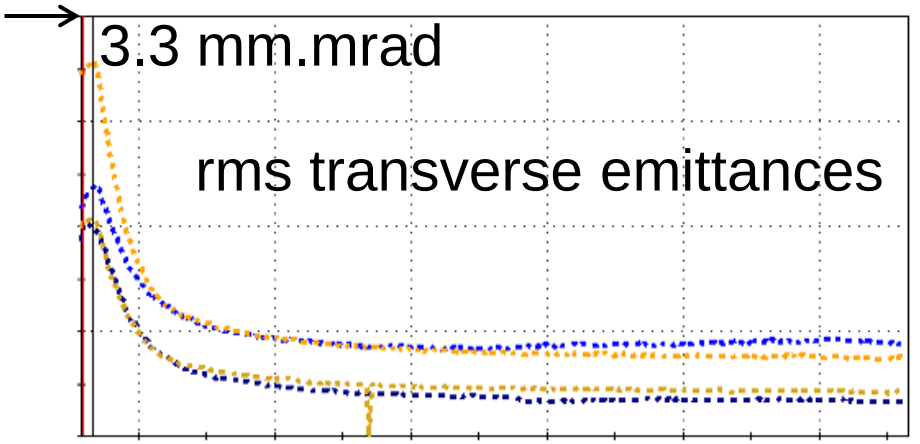
vertical kicker (closed)

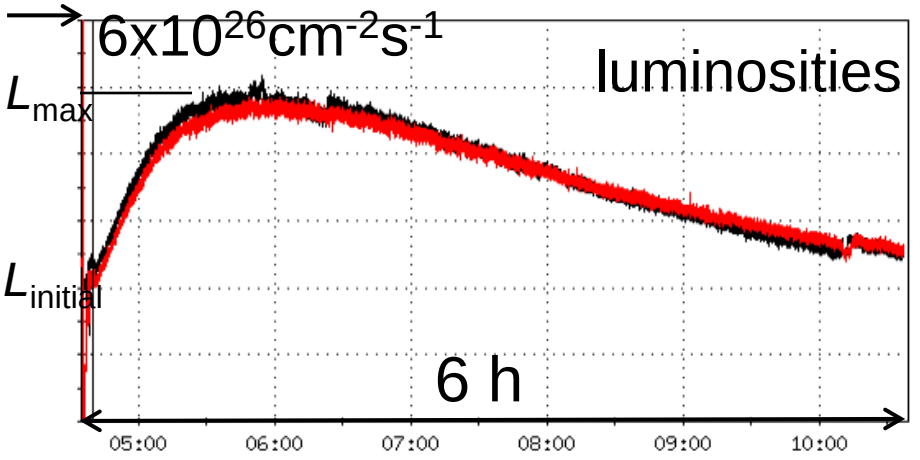


5-9 GHz, cooling times ~1 h

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




# U-U store – new mode in 2012

(1) Lattice optimized for large off-momentum dynamic aperture, not 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 |

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

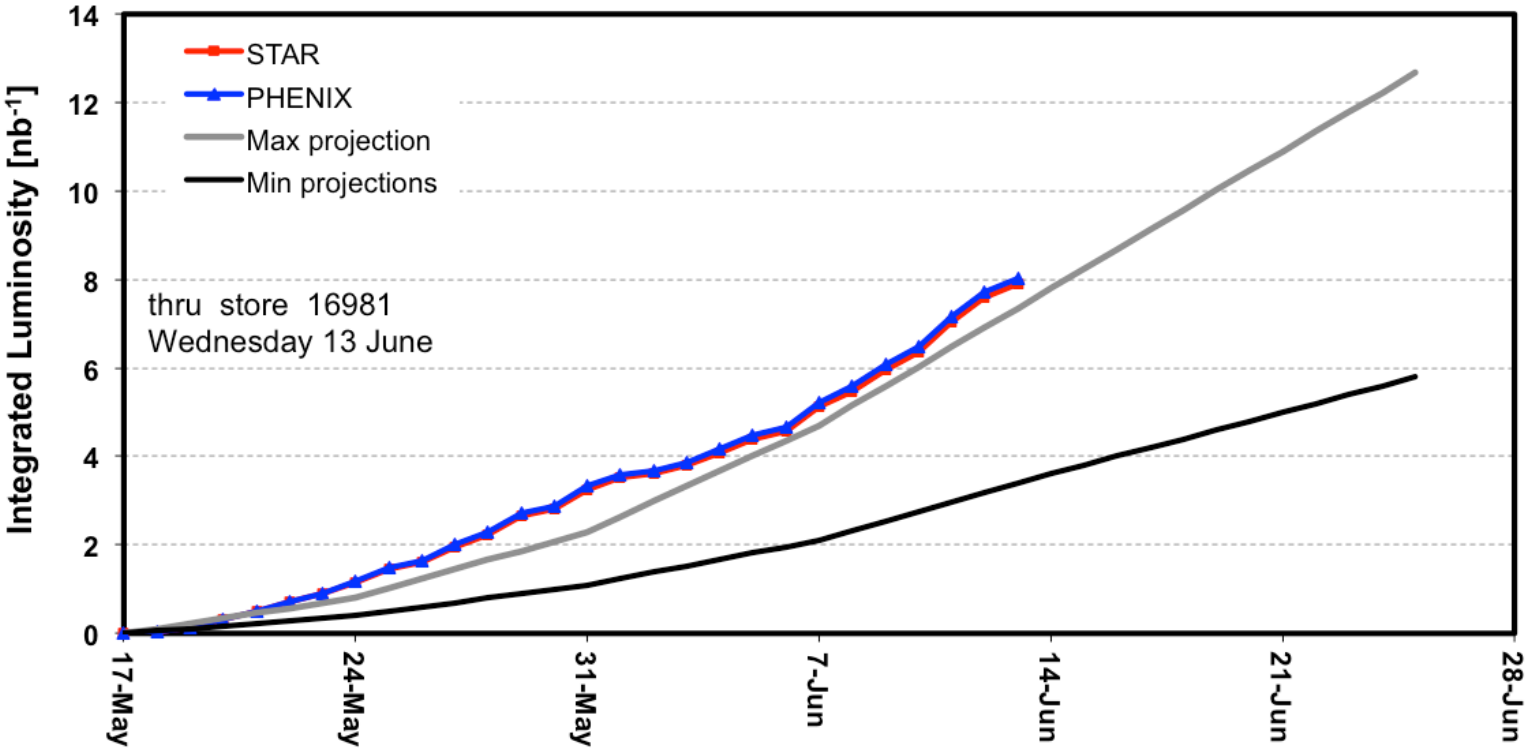
**All beam loss though luminosity (burn-off)!**

**3D stochastic cooling leads to new feature in hadron collider:**

$L_{max} > L_{initial}$

# Run-12 – Copper-gold 100 GeV/nucleon (still running)

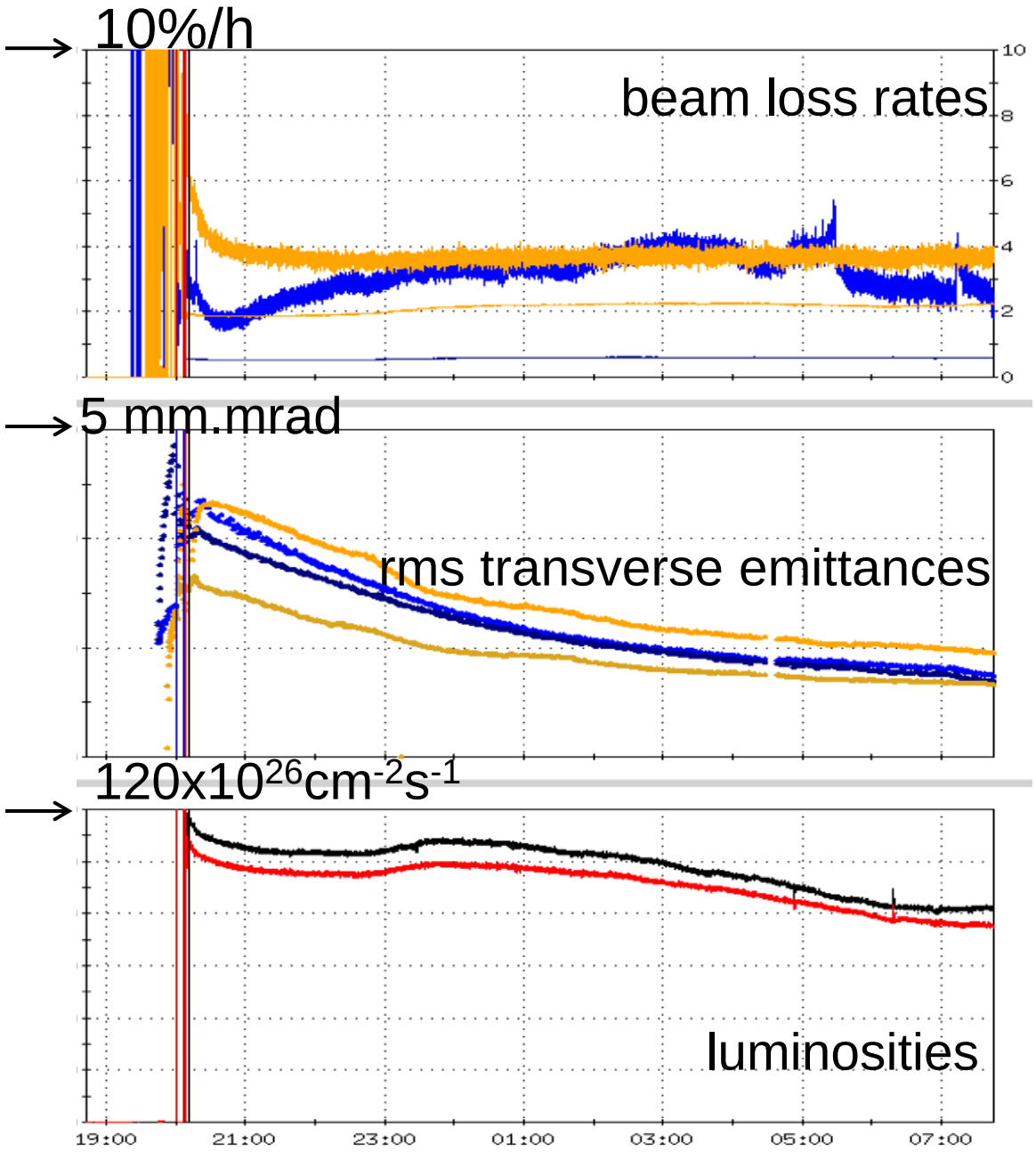
Run Coordinator: Y. Luo




~6 weeks

New: first Cu-Au operation in a collider; used standard lattice to increase off-momentum dynamic aperture; first use of Blue and Yellow horizontal stochastic cooling (resulting in 3D cooling in both rings)

# Cu-Au store – new mode in 2012



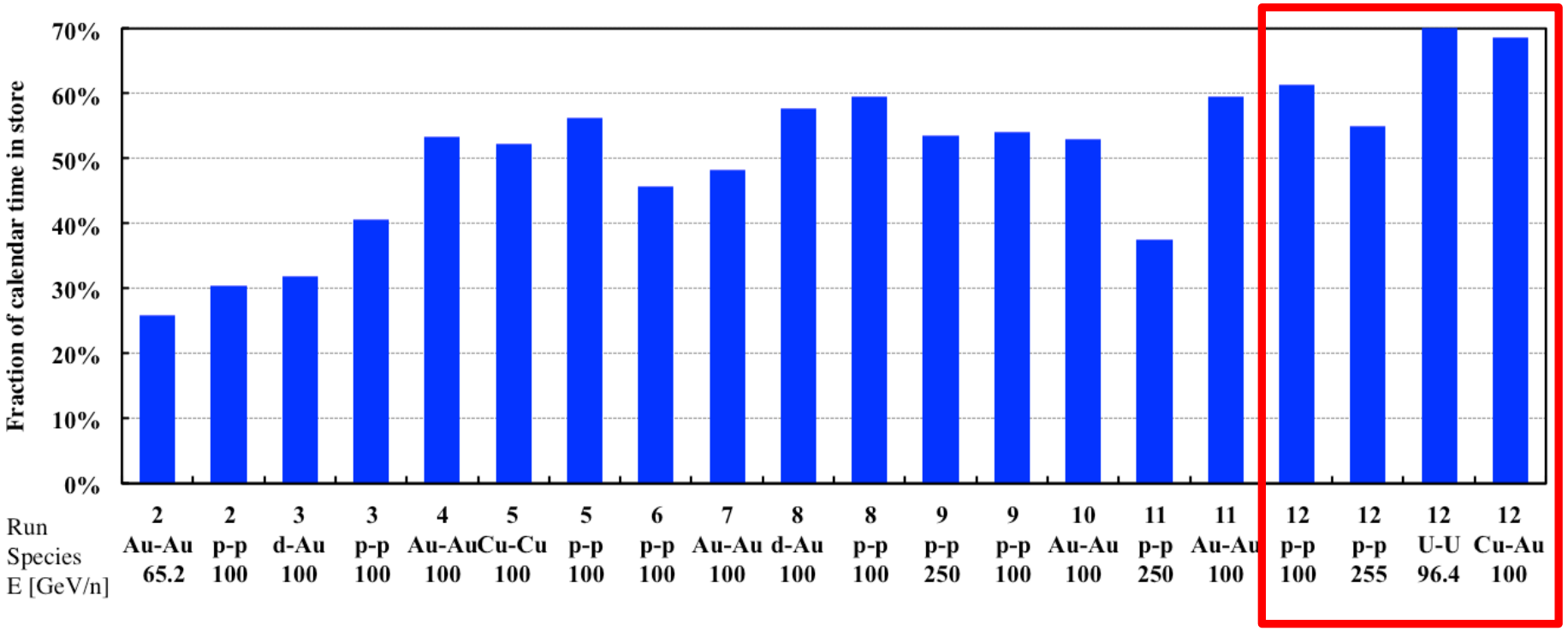

Cu and Au have different

- intrabeam scattering growth rates (~$Z^4N_b/A^2$)
  $r_{IBS,Au} \approx 2x\ r_{IBS,Cu}$
- cooling rates (~$1/N_b$)
  $r_{SC,Au} \approx 3x\ r_{SC,Cu}$

**Optimization of Cu/Au cooling rates:**
Overcooling of one beam creates large loss rate in other beam

14 h store length

# Time-in-store as fraction of calendar time




As of 06/14/12

- Run-12 with low failure rates in all systems
- Highest time-in-store ratios to date
  (even with increased APEX time during 255 GeV protons compared to Run-11)

# RHIC ions – 6 species and 15 energies to date

$^{238}U^{92+}$–$^{238}U^{92+}$ ♑ first time in 2012, 3 weeks physics, complete

96.4 GeV/nucleon

$^{197}Au^{79+}$–$^{197}Au^{79+}$

3.85, 4.6, 5.75, 9.8, 13.5, 19.5, 27.9, 31.2, 65.2, 100.0 GeV/nucleon

$^{63}Cu^{29+}$–$^{197}Au^{79+}$ ♑ first time in 2012, 5 weeks, under way

99.9/100.0 GeV/nucleon

$^{63}Cu^{29+}$–$^{63}Cu^{29+}$

11.2, 31.2, 100.0 GeV/nucleon

d–$^{197}Au^{79+}$

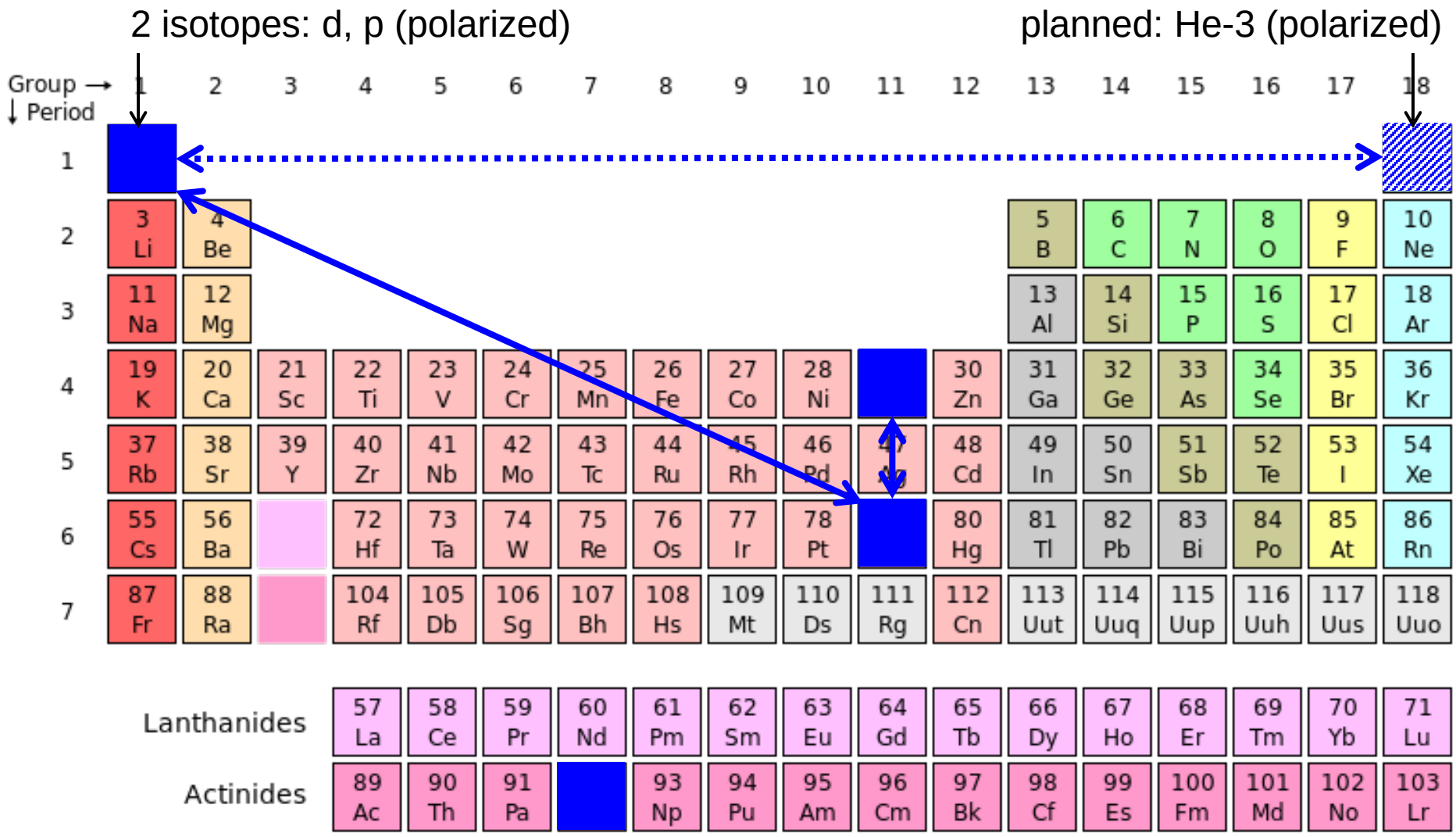
100.7/100.0 GeV/nucleon

p♒–p♒

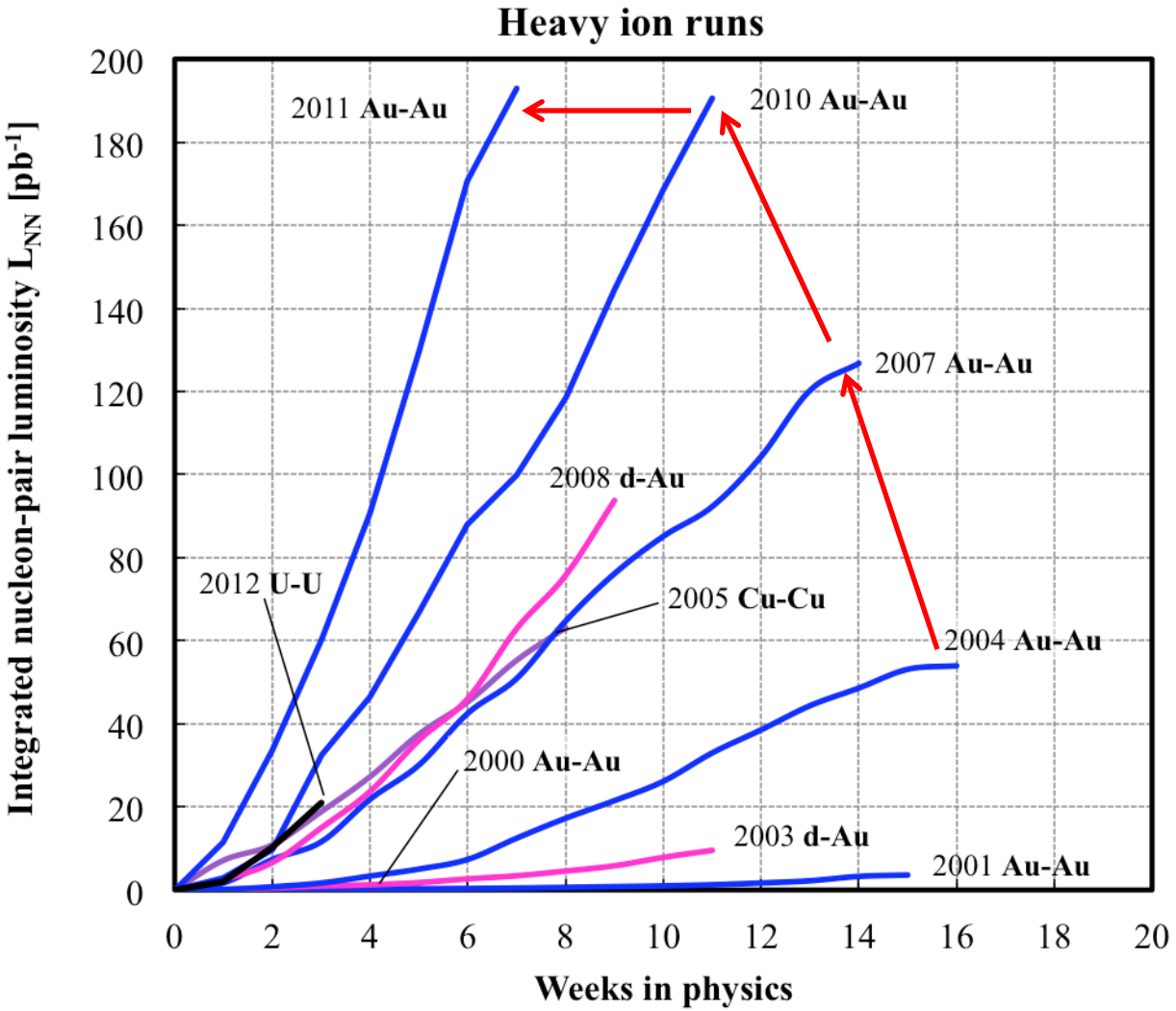
31.2, 100.2, 204.9, 249.9, 254.9 GeV

Can collide any species from protons (polarized) to uranium – with each other or with another species

# RHIC ions – 6 species and 15 energies to date



# RHIC heavy ions – luminosity evolution to date




**<L> = 15x design in 2011**

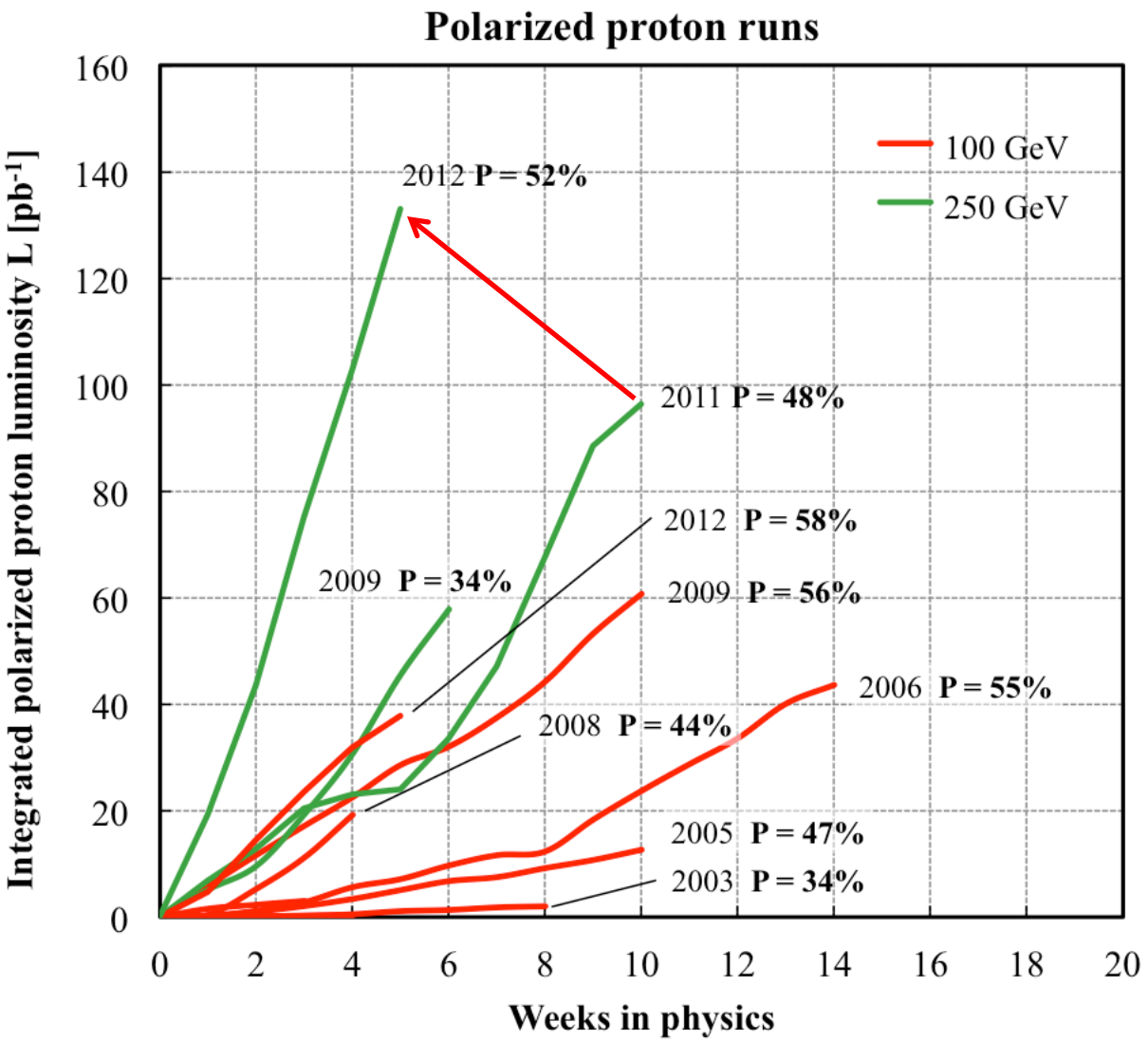
About 2x increase in $L_{int}$/week each

- Run-4 to Run-7
- Run-7 to Run10
- Run-10 to Run-11

About 50% of Au beam is burned-off in collisions already

$L_{NN} = L\, N_1 N_2$ (= luminosity for beam of nucleons, not ions)

# RHIC polarized protons – luminosity and polarization




At 255 GeV in 2012

$L_{avg}$ = 105x10$^{30}$cm$^{-2}$s$^{-1}$

$P_{avg}$ = 52%

$L_{avg}$ +15% relative to 2011

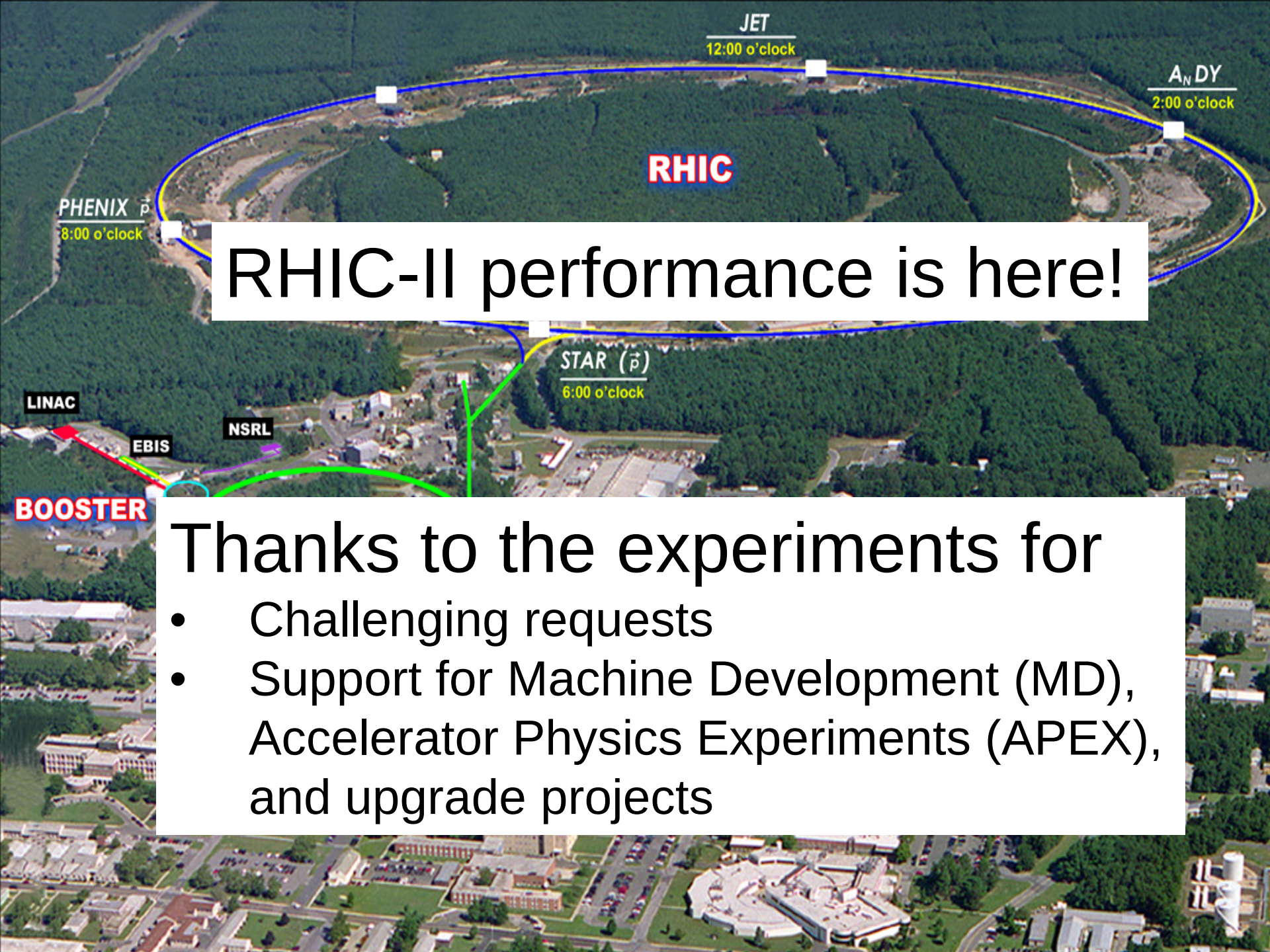
$P_{avg}$ +8% relative to 2011

$FOM = LP^2$

(single spin experiments)

$FOM = LP^4$

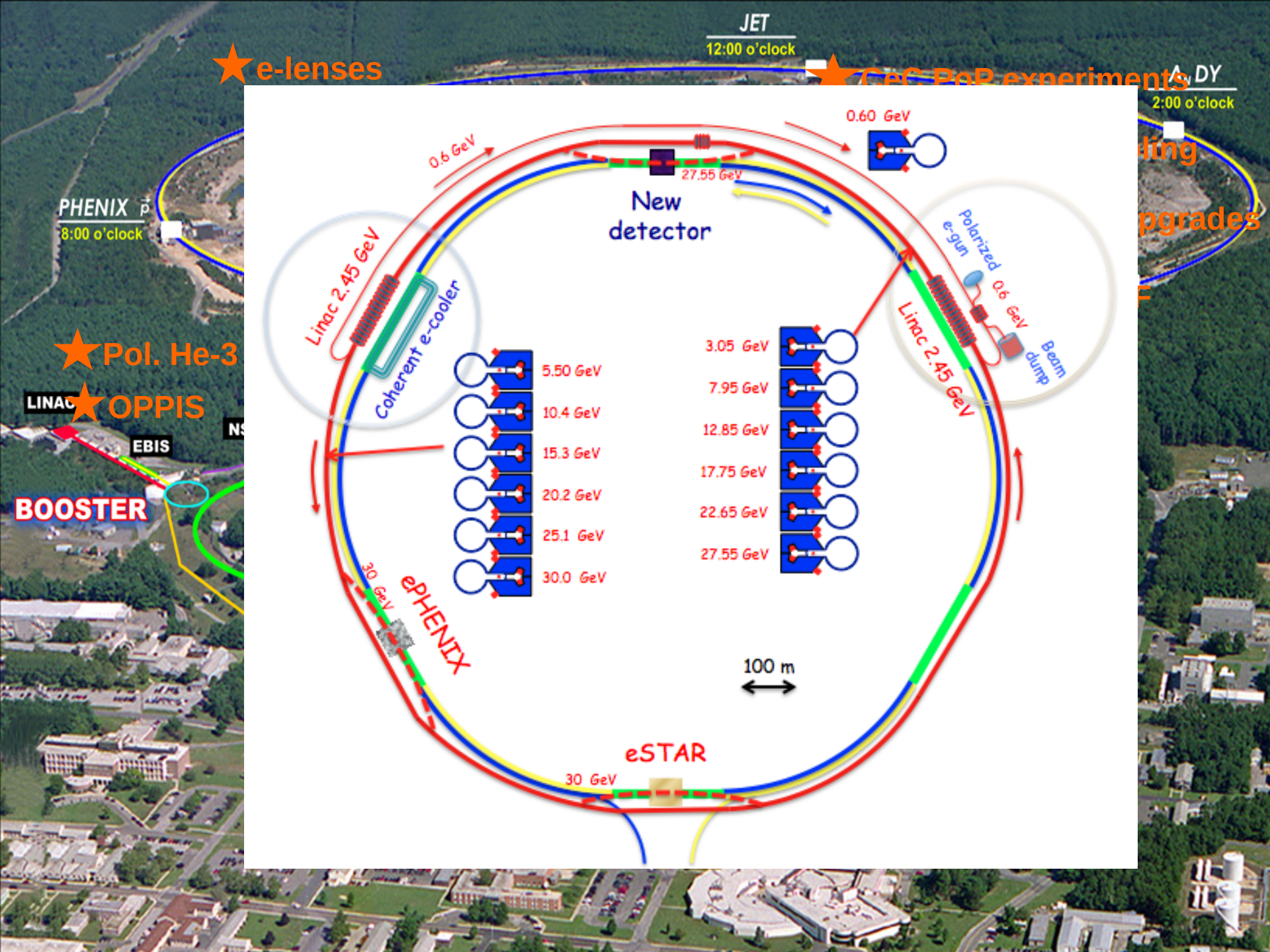
(double spin experiments)

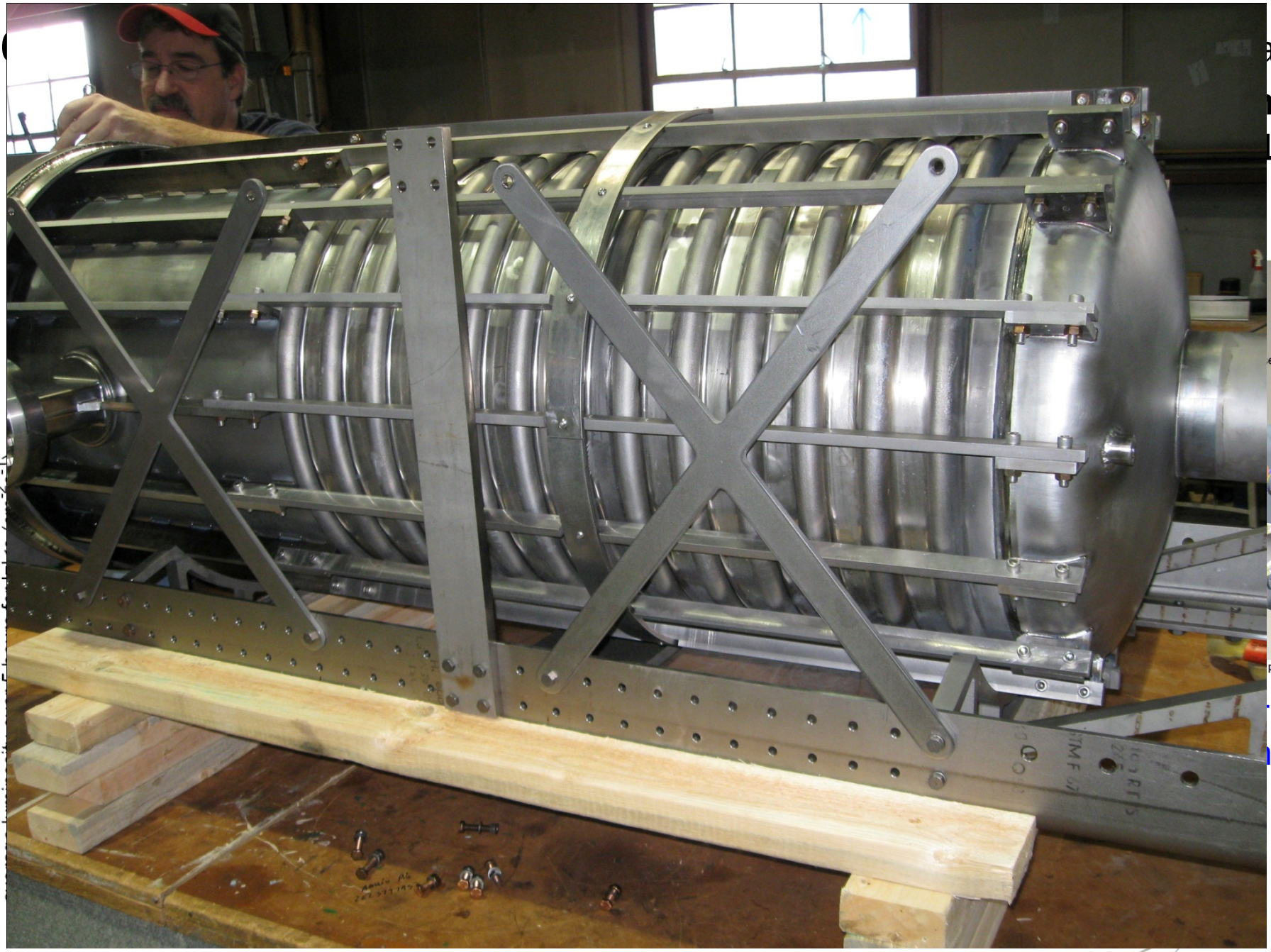



# RHIC-II performance is here!

## Thanks to the experiments for

- Challenging requests
- Support for Machine Development (MD), Accelerator Physics Experiments (APEX), and upgrade projects


JET
12:00 o'clock
DY
2:00 o'clock
PHENIX
8:00 o'clock
LINAC
EBIS
BOOSTER
e-lenses
Pol. He-3
OPPIS
0.60 GeV
0.6 GeV
27.55 GeV
New detector
Linac 2.45 GeV
Coherent e-cooler
Polarized e-gun
0.6 GeV
Beam dump
Linac 2.45 GeV
3.05 GeV
7.95 GeV
12.85 GeV
17.75 GeV
22.65 GeV
27.55 GeV
5.50 GeV
10.4 GeV
15.3 GeV
20.2 GeV
25.1 GeV
30.0 GeV
30 GeV
ePHENIX
100 m
eSTAR
30 GeV

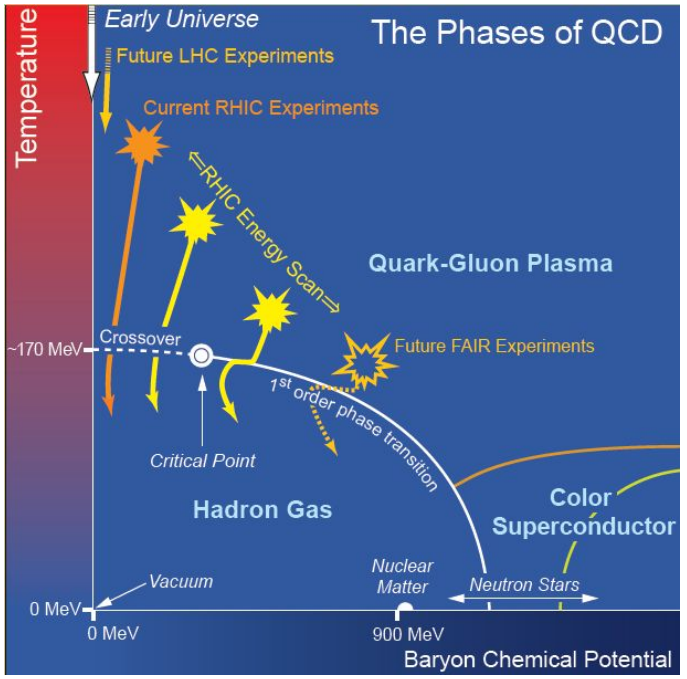


Calculation by M. Blaskiewicz

# RHIC – Au-Au energy scan

US NSAC report 2007

Energy scan – extends <u>below nominal injection energy</u> in search of critical point in QCD phase diagram

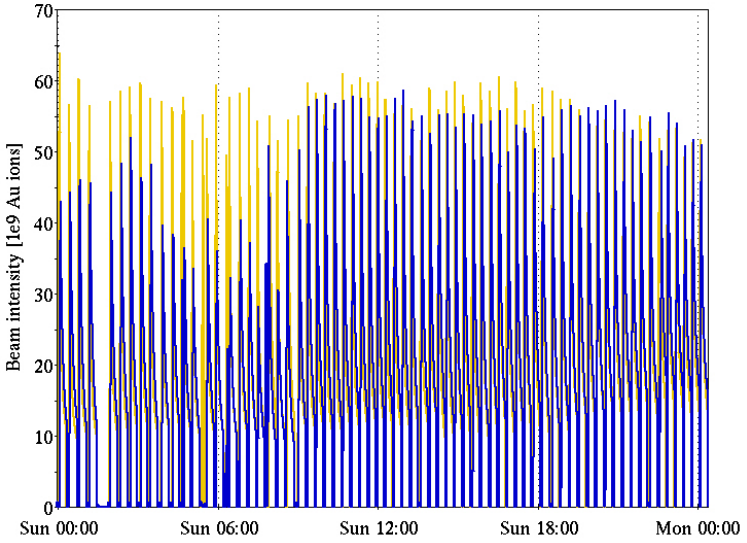



Effects to contend with (#s for 20% nominal ($B\rho$):

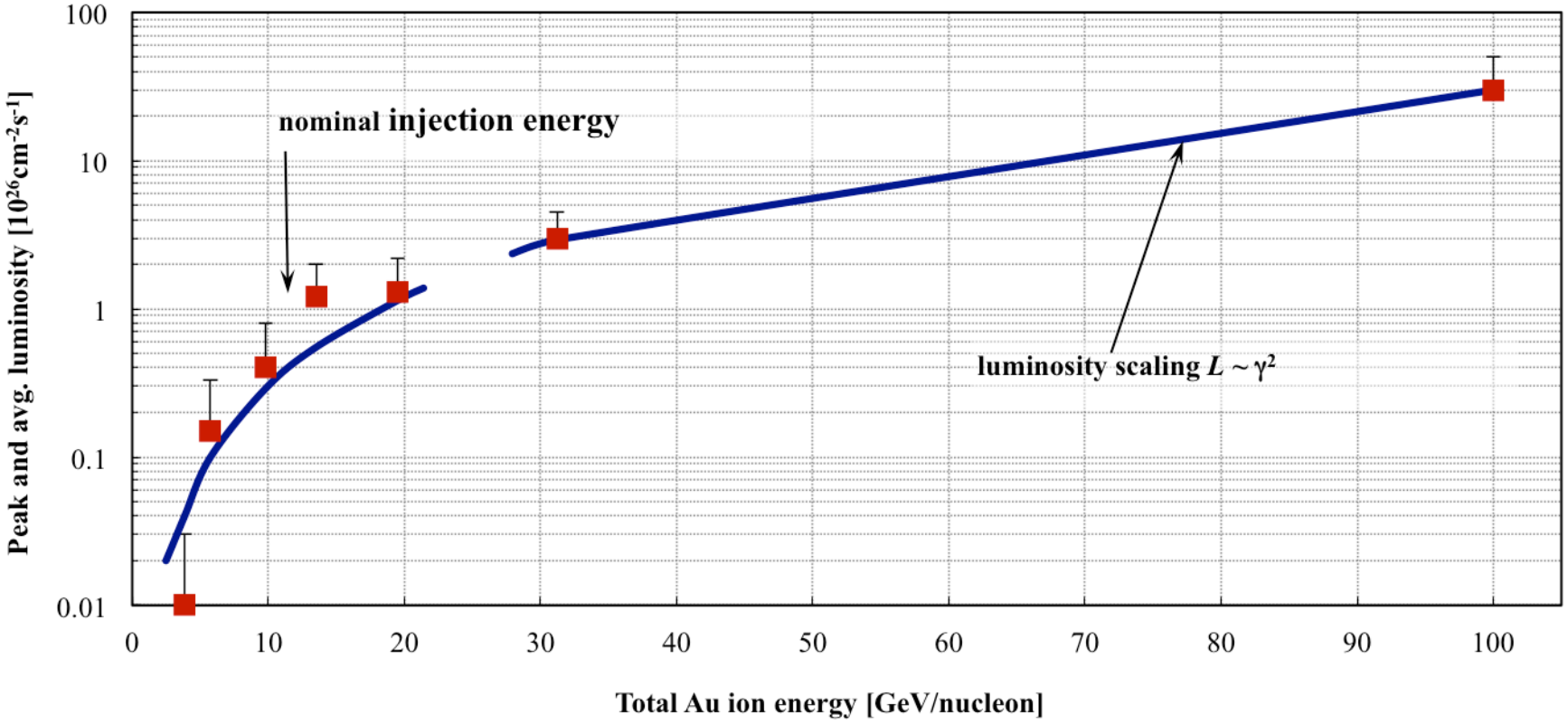
- Large beam sizes **(longitudinal and transverse) controlling losses becomes critical**
- Large magnetic field errors **($b_3$ ~ 10, $b_5$ ~ 6 units from persistent currents in superconducting magnets)**
- Intrabeam scattering **(debunching ~min)**
- Space charge **($\Delta Q_{Laslett}$ ~ 0.1 – new regime for collider)**
- Beam-beam **($\xi$/IP ~ 0.003)**
- Low event rates **(~ 1 Hz)**

Full energy injection allows for short stores

- At 38% of nominal injection ($B\rho$)
- **May operate at 20% of nominal injection ($B\rho$)**



# Au-Au energy scan to date




Peak and average luminosities fall faster than $1/\gamma^2$ at lowest energies
Need cooling at low energies to significantly increase luminosities

## **e-cooling for low energy collider operation** (A. Fedotov et al.)

Fermilab Pelletron (cooled 8 GeV pbar for Tevatron use) usable –

**Alternative option with e- beam from 112 MHz SRF gun**


Cooling into space charge limit

$\Delta Q_{sc} \sim 0.05$ (new collider regime)

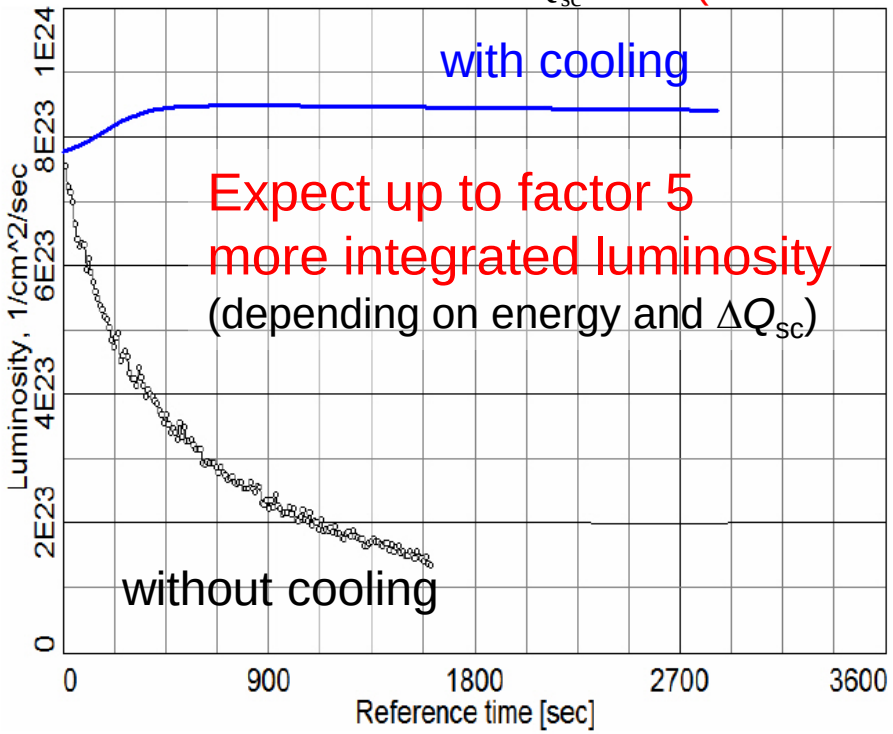


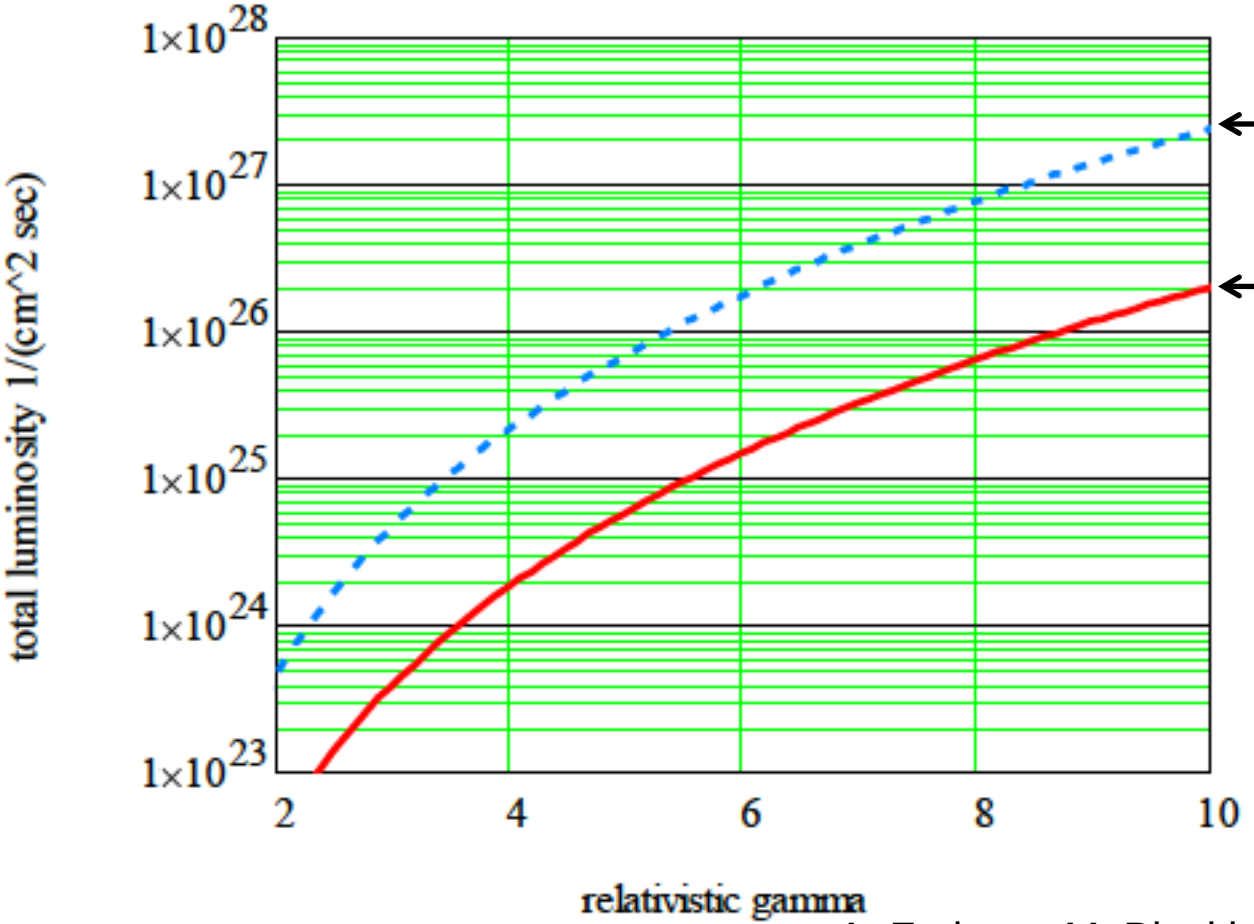

Figure 4. Simulation of luminosity with (blue line) and without (black dots) electron cooling at $\gamma$=2.7.

A. Fedotov, M. Blaskiewicz, BNL C-A/AP/449 (2012)

BROOKHAVEN NATIONAL LABORATORY

# Low energy operation with cooling AND long bunches

**Additional gain by operating with long bunches** (at space charge limit)



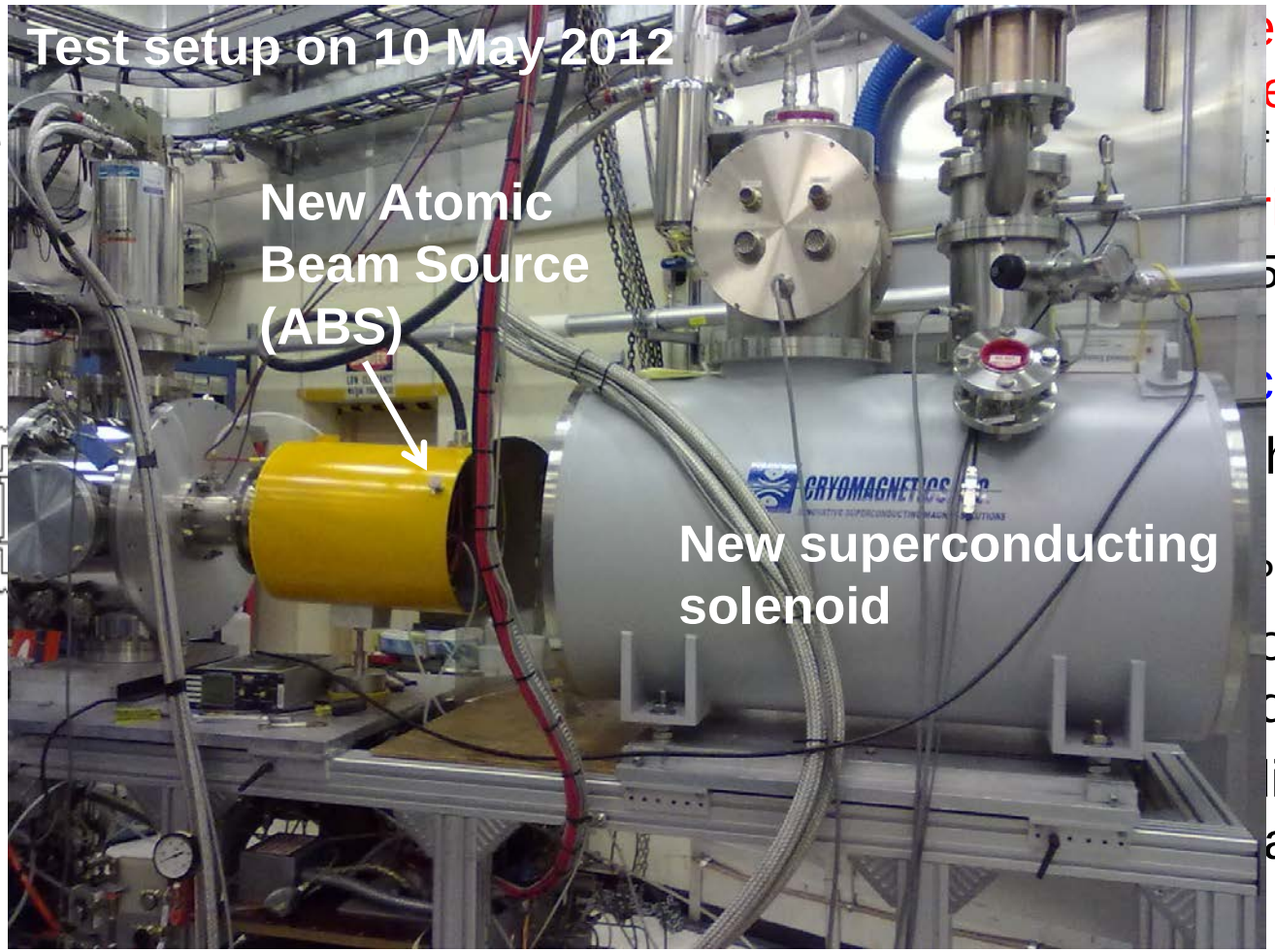

RHIC with cooling and long bunches ($\Delta Q_{sc}$ = 0.05, $\sigma_s$ = 3m)

RHIC w/o cooling

A. Fedotov, M. Blaskiewicz, BNL C-A/AP/449 (2012)

# Optically Pumped Polarized H⁻ source (OPPIS) – A. Zelenski

## Upgraded OPPIS (2013)




Goals:

eam current
e to 10mA
magnitude)
rization to 85-
5% increase)

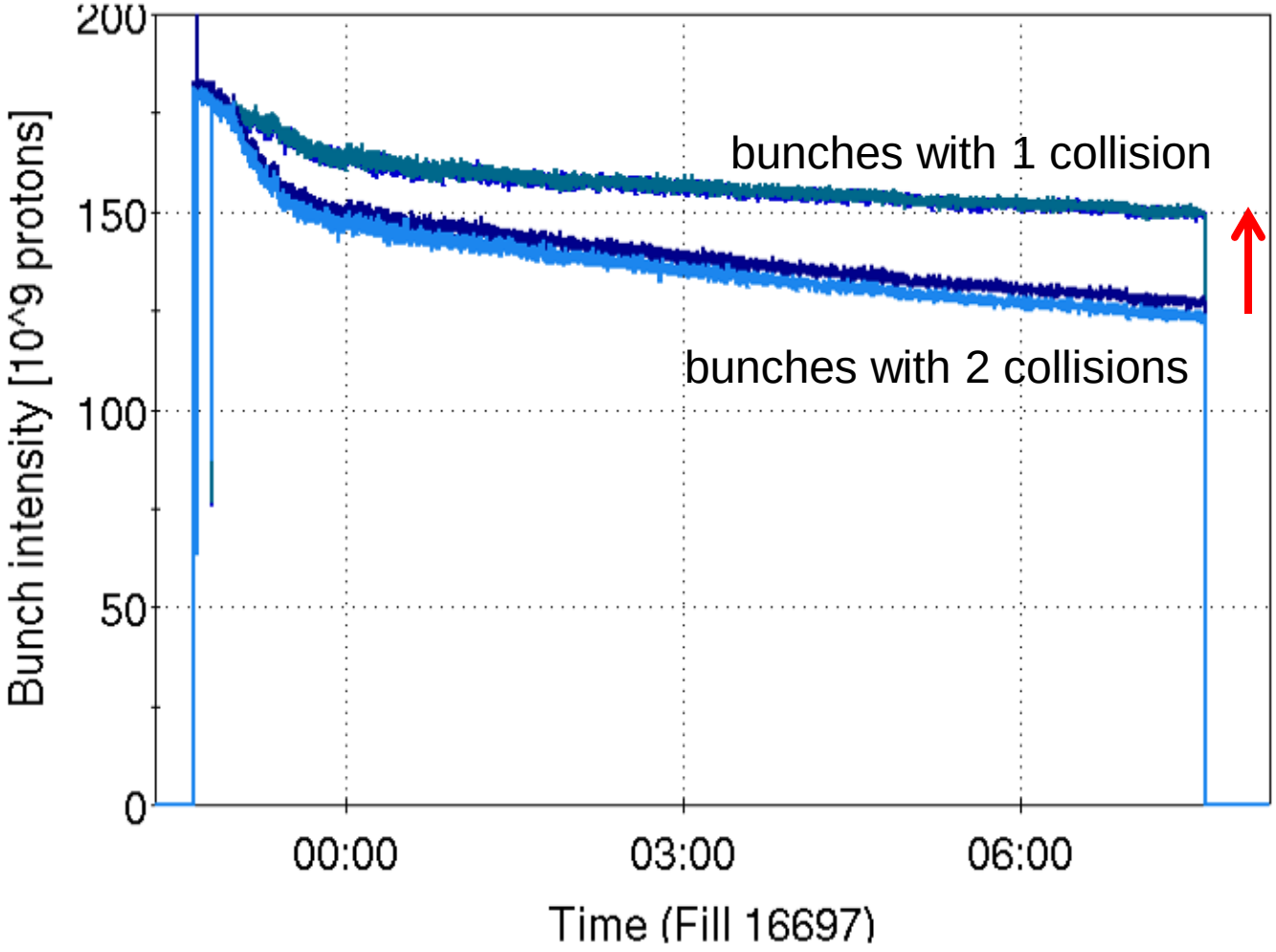
components:

hydrogen
(collaboration
Novosibirsk)
onducting
d (3 T)
liagnostics
arimetry

=> 10x intensity from ABS was accelerated through Linac

# Motivation

Bunch intensity in 2012 polarized proton physics store




## Goal:

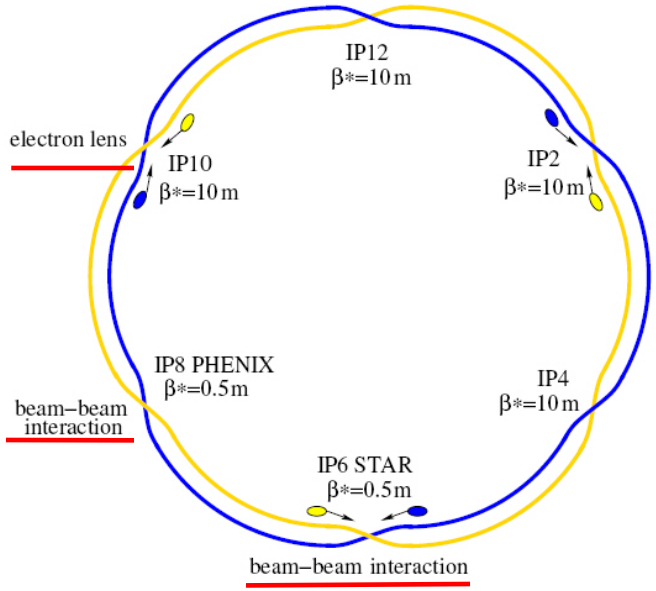
Compensate for 1 of 2 beam-beam interactions with electron lenses

Then increase bunch intensity
$\Rightarrow$ up to 2× luminosity

Need new polarized proton source − under construction, A. Zelenski

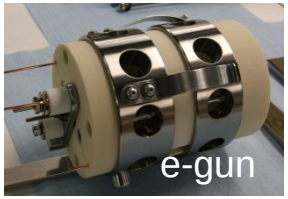
$$L \propto N_b^2$$

# Electron lenses – partial head-on beam-beam compensation




## Basic idea:

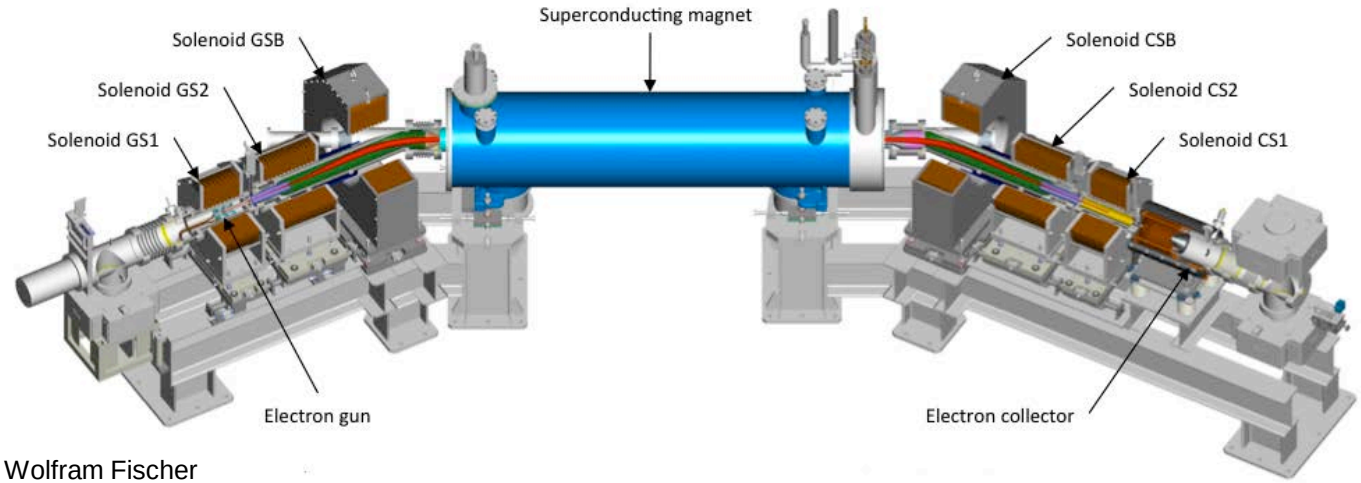
- 2 beam-beam collisions with **positively** charged beam
- Add collision with a **negatively** charged beam – with matched intensity and same amplitude dependence



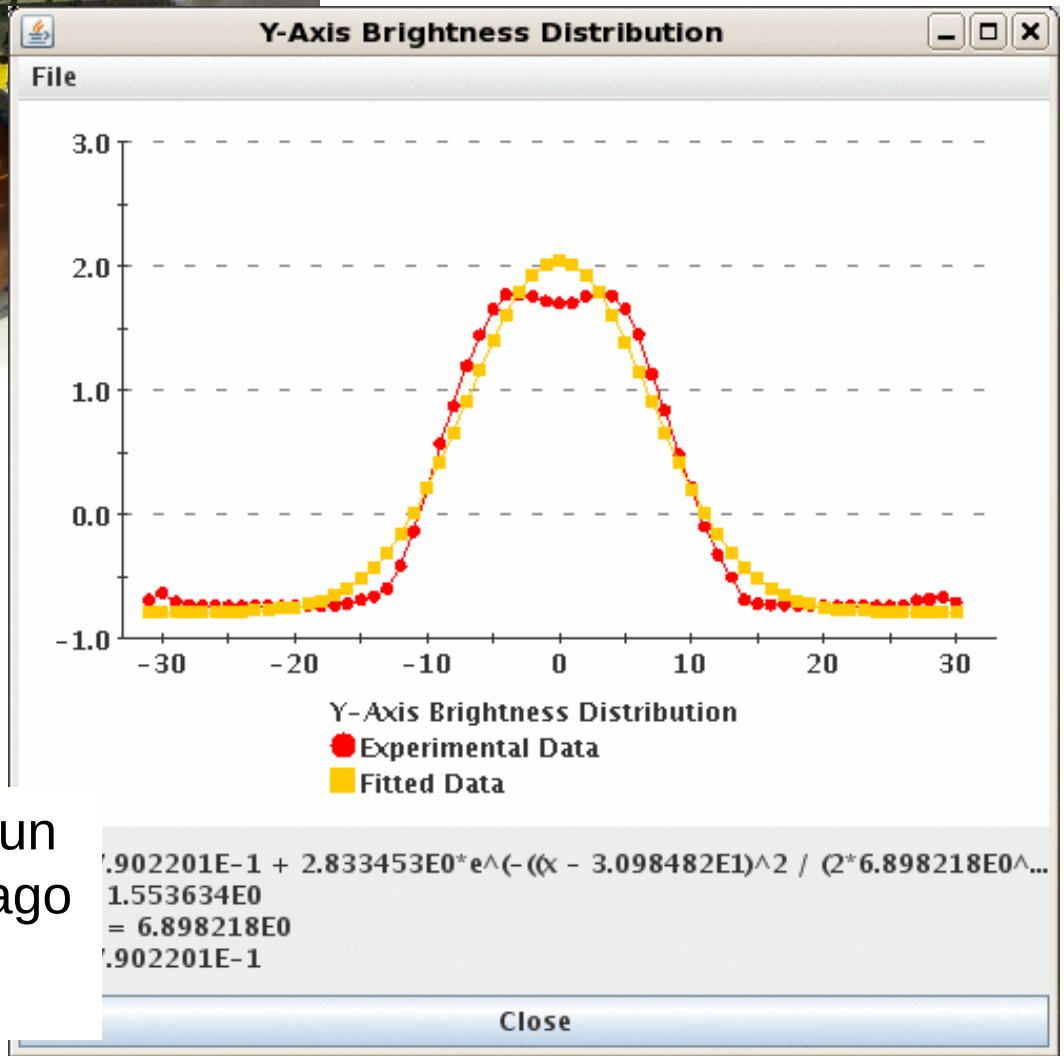

## Compensation of nonlinear effects:

- e-beam current and shape
  => reduces tune spread
- $\Delta\psi_{x,y} = k\pi$ between p-p and p-e collision
  => reduces resonance driving terms


## Installation in 2012
## Expect up to 2x more luminosity

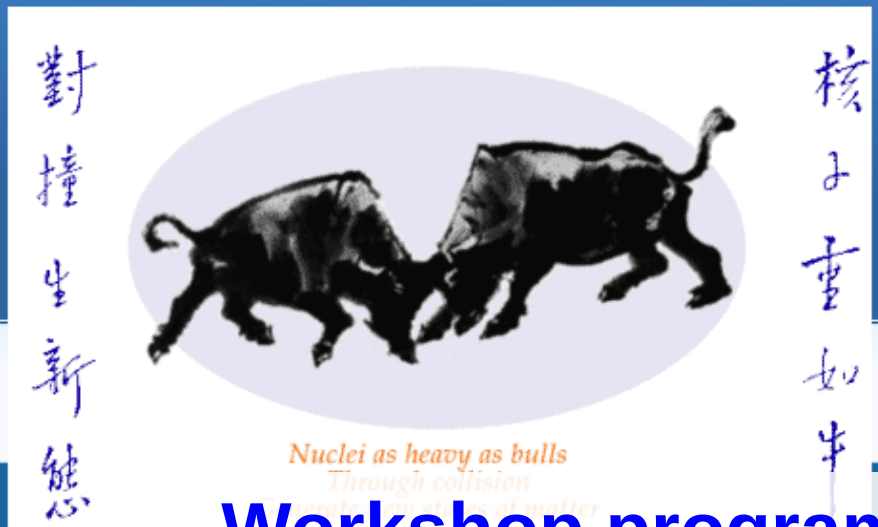

# Electron lenses – recent progress


Electron beam transported from gun to collector on test bench 2 days ago

X. Gu, Z. Altinbas, T. Miller, J. Aronson, A. Pikin, Y. Than

# Polarized $^3$He – Workshop 28-30 September 2011




Workshop on Opportunities for polarized He-3 in RHIC and EIC -- sponsored by the RIKEN BNL Research Center

28-30 September 2011
*Universe*
US/Eastern timezone

## Workshop program

- $^3$He$^{\uparrow\uparrow}$ source, $^3$He$^{\uparrow\uparrow}$ beams from EBIS
- $^3$He$^{\uparrow\uparrow}$ in Booster/AGS
- $^3$He$^{\uparrow\uparrow}$ in RHIC and EIC
- Polarimetry (low and high energy)
- Physics with $^3$He$^{\uparrow\uparrow}$ beams (theory and experiments)

Overview
Agenda
Call for Abstracts
View my abstracts
Submit a new abstract
Timetable
Contribution List
Book of abstracts
Registration

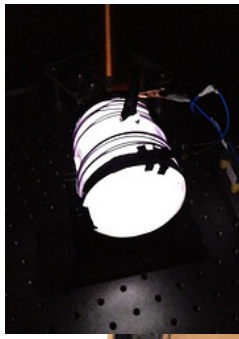
Timezone: US/Eastern
Room: Brookhaven Center, Bldg. 30
Dr. Aschenauer, Elke
Additional info: Guest Information System (GIS)

If you have a current BNL Appointment and a valid BNL Guest Number or you have a pending Guest Registration (GR) Number, it is not necessary to complete

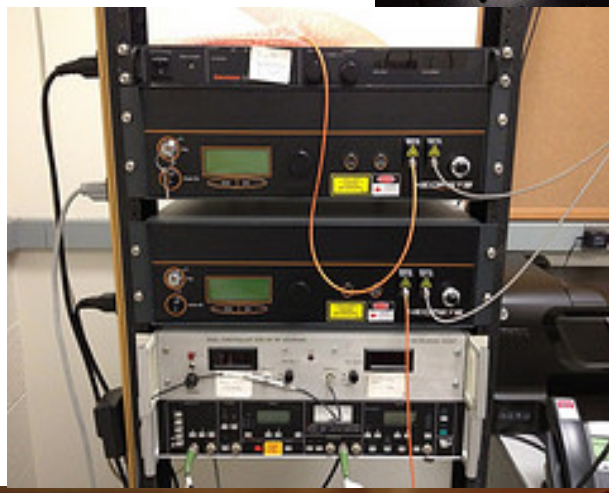
# Development of Polarized $^3$He Ion Source for RHIC

## BNL-MIT Collaboration http://he3.xvm.mit.edu/

R. Milner, C. Epstein, MIT



- Spec.: deliver $^3He^{++}$ at ≈ 3 x $10^{12}$ atoms/sec with 70% polarization
- Concept: polarize $^3$He gas in glass cell using MEOP in fringe field of ≈ 5 Tesla EBIS solenoid and feed into EBIS
- MEOP technology under development at MIT
  - two Keopsys 10 Watt lasers operational
  - data acquisition system operational
  - 20 liters of $^3$He gas ordered
  - glass systems under construction
- Goal: to test principle of source using spare EBIS solenoid within the next year



*Funded by DOE Office of Nuclear Physics R&D Program for Next Generation Nuclear Physics Accelerator Facilities*

# Polarized $^3$He in RHIC – plan under development

- Polarized $^3$He source developed at MIT (R. Milner)
- Polarized $^3$He beams from EBIS
- Polarimeter after EBIS linac at 2 MeV/nucleon
- Un-polarized $^3$He from EBIS:
  - Injection into Booster at low rigidity
  - Acceleration in Booster, AGS, RHIC?
  - Test carbon polarimeters

Plan acceleration of unpolarized $^3$He in Booster and AGS after RHIC Run ends

- Acceleration of polarized $^3$He in Booster and transfer to AGS
  - Vertical tune in Booster < 4.19 !!
- Measure polarization at AGS injection energy, no depolarization?
- Accelerate $^3$He in AGS and measure polarization on ramp and extraction
- Calibrate $A_N$ of carbon polarimeter at extraction energy with up/down ramp?
- Transfer to RHIC and calibrate carbon polarimeter in RHIC (which ring?)
- Absolute polarization measurement at RHIC injection with pol. $^3$He jet/cell
- Accelerate in RHIC and measure polarization on ramp and at store energy
  - May need 4 more snakes in Blue ring
- Calibrate $A_N$ of carbon polarimeter at store energy with up/down ramp
- Absolute polarization measurement at RHIC store with pol. $^3$He jet/cell

# RHIC luminosity and polarization goals

| parameter | unit | achieved | goals | |
|---|---|---|---|---|
| **Au-Au operation** | | **2011** | **≥ 2014**<br>3D stochastic cooling + 56 MHz SRF | |
| energy | GeV/nucleon | 100 | 100 | |
| no colliding bunches | … | 111 | 111 | |
| bunch intensity | $10^9$ | 1.3 | ≥ 1.1 | |
| **avg. luminosity** | $10^{26}\,cm^{-2}s^{-1}$ | **30** | **40** | |
| **p↑-p↑ operation** | | **2012** | **≥ 2013**<br>source | **≥ 2014**<br>source + e-lenses |
| energy | GeV | 100 255 | 100 250 | 100 250 |
| no colliding bunches | … | – 107 – | – 107 – | – 107 – |
| bunch intensity | $10^{11}$ | 1.6 1.7 | 1.6 2.0 | 1.8 2.5 |
| **avg. luminosity** | $10^{30}\,cm^{-2}s^{-1}$ | **33 105** | **30 150** | **60 300** |
| **avg. polarization*** | % | **58 52** | **– 60 –** | **– 70 –** |

*Intensity and time-averaged polarization as measured by the H-jet. Luminosity-averaged polarizations, relevant in single-spin colliding beam experiments, are higher. For example, for intensity-averaged $P$ = 48% and $R_x = R_y$ = 0.2 (250 GeV, 2011), the luminosity-averaged polarization is $P$ = 52%.

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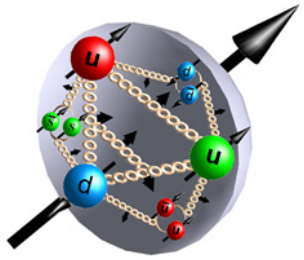
# RHIC status and upgrades

**Coming to the end of a major upgrade phase**

- More than 10 firsts and records in Run-12

"RHIC-II performance without the RHIC-II upgrade project"



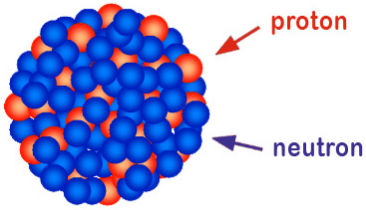

**More upgrades coming:**

Run-13 – mainly for polarized protons

- Polarized source upgrade (partial or full) 10x source intensity, +5% P
- Electron lenses requires new lattice, commissioning in Run-13

Run-14 – mainly for heavy ions

- 56 MHz SRF, +30-50% *L*




Uranium Nucleus

**Further upgrades possible in out-years**

Stochastic cooling upgrades

Low-energy cooling for Au-Au up to ~10x *L*; ≥ 2017

Polarized He-3 source, more snakes in Blue ring

Beam pipe coating for intensity increases / shorter bunches

Very high pp luminosity with CeC

…

**eRHIC**