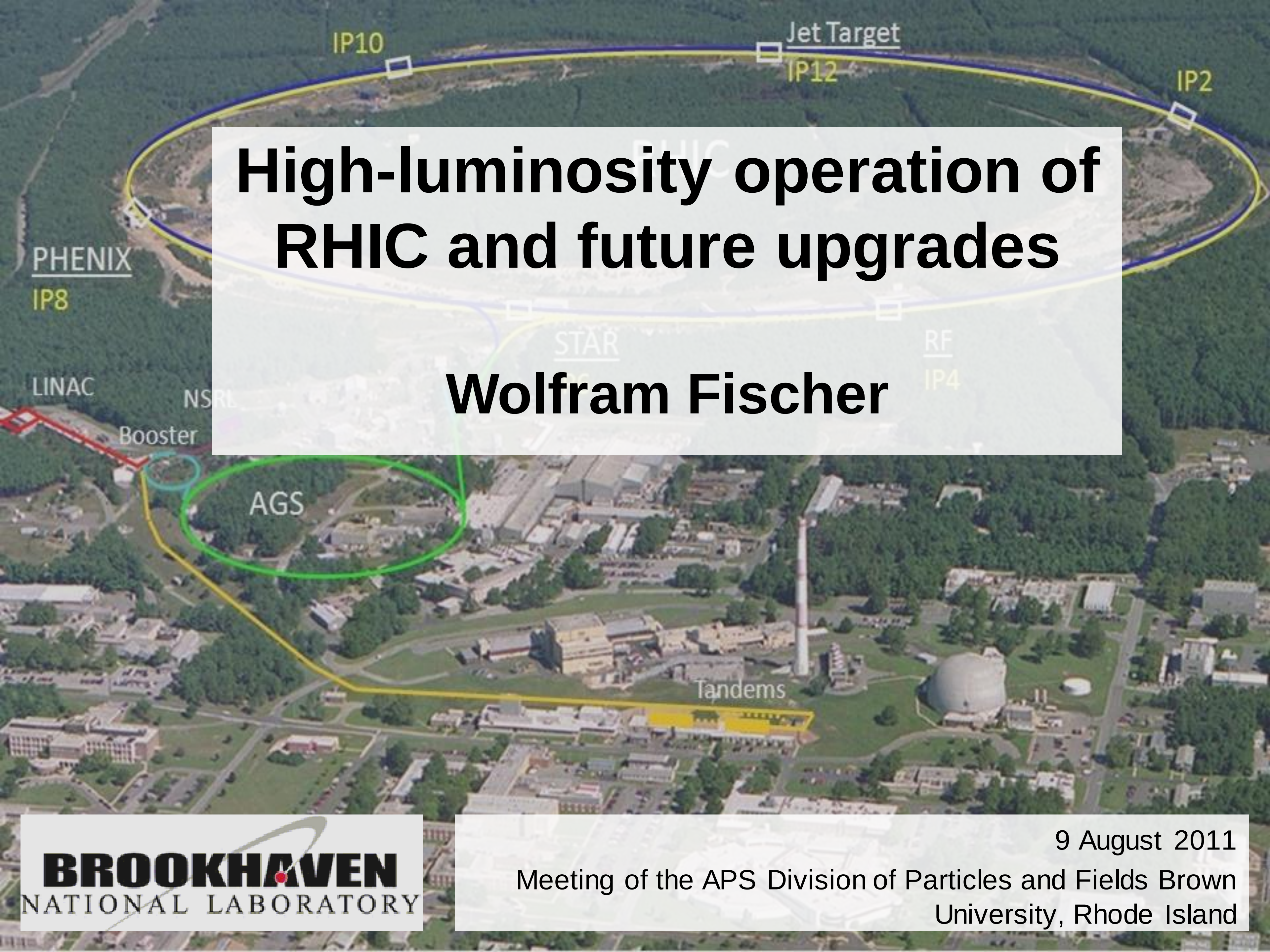
High-luminosity operation of RHIC and future upgrades

Wolfram Fischer



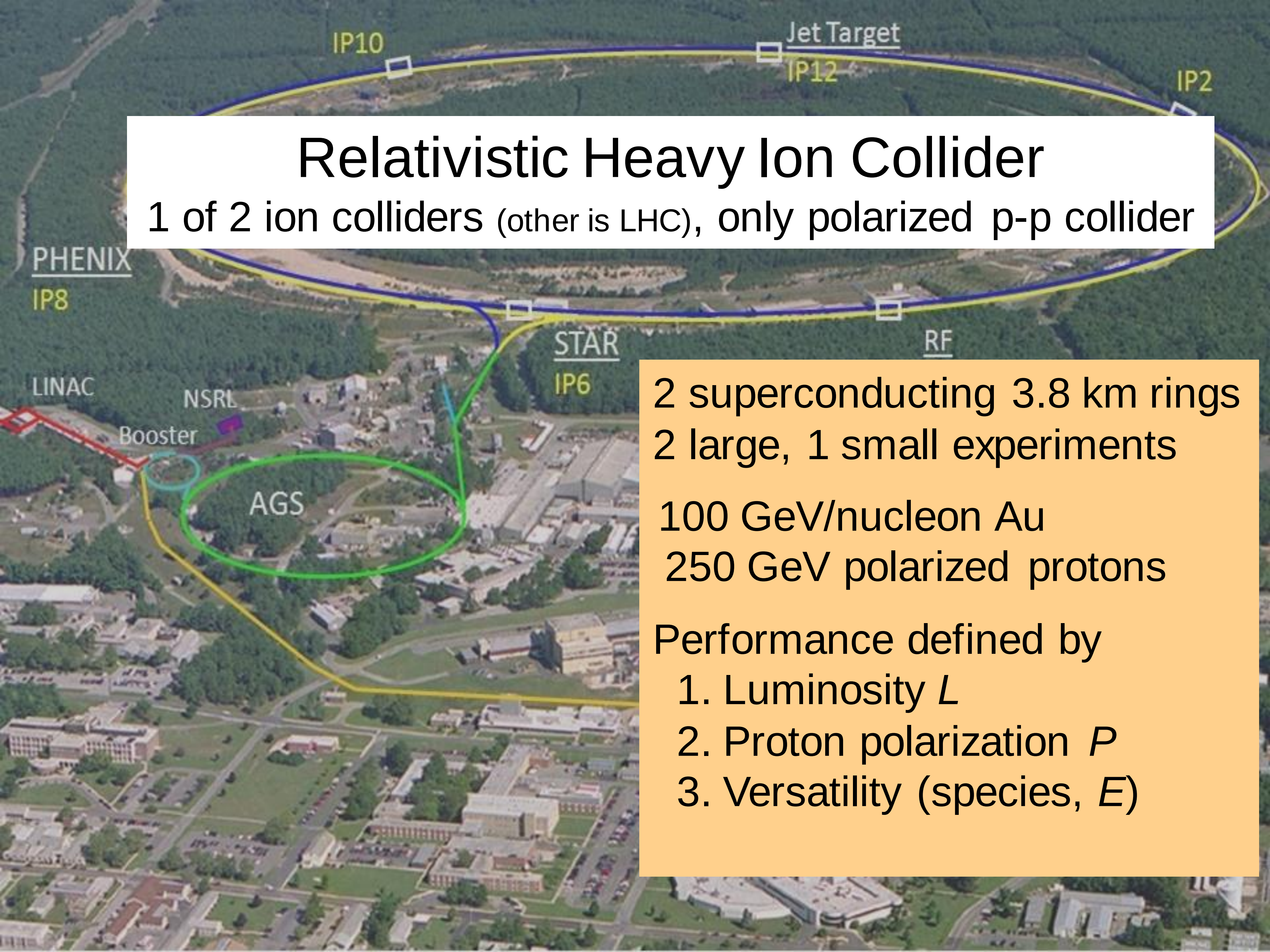
BROOKHAVEN NATIONAL LABORATORY

9 August 2011

Meeting of the APS Division of Particles and Fields Brown University, Rhode Island

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, 1 small experiments

100 GeV/nucleon Au
250 GeV polarized protons

Performance defined by

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

Content

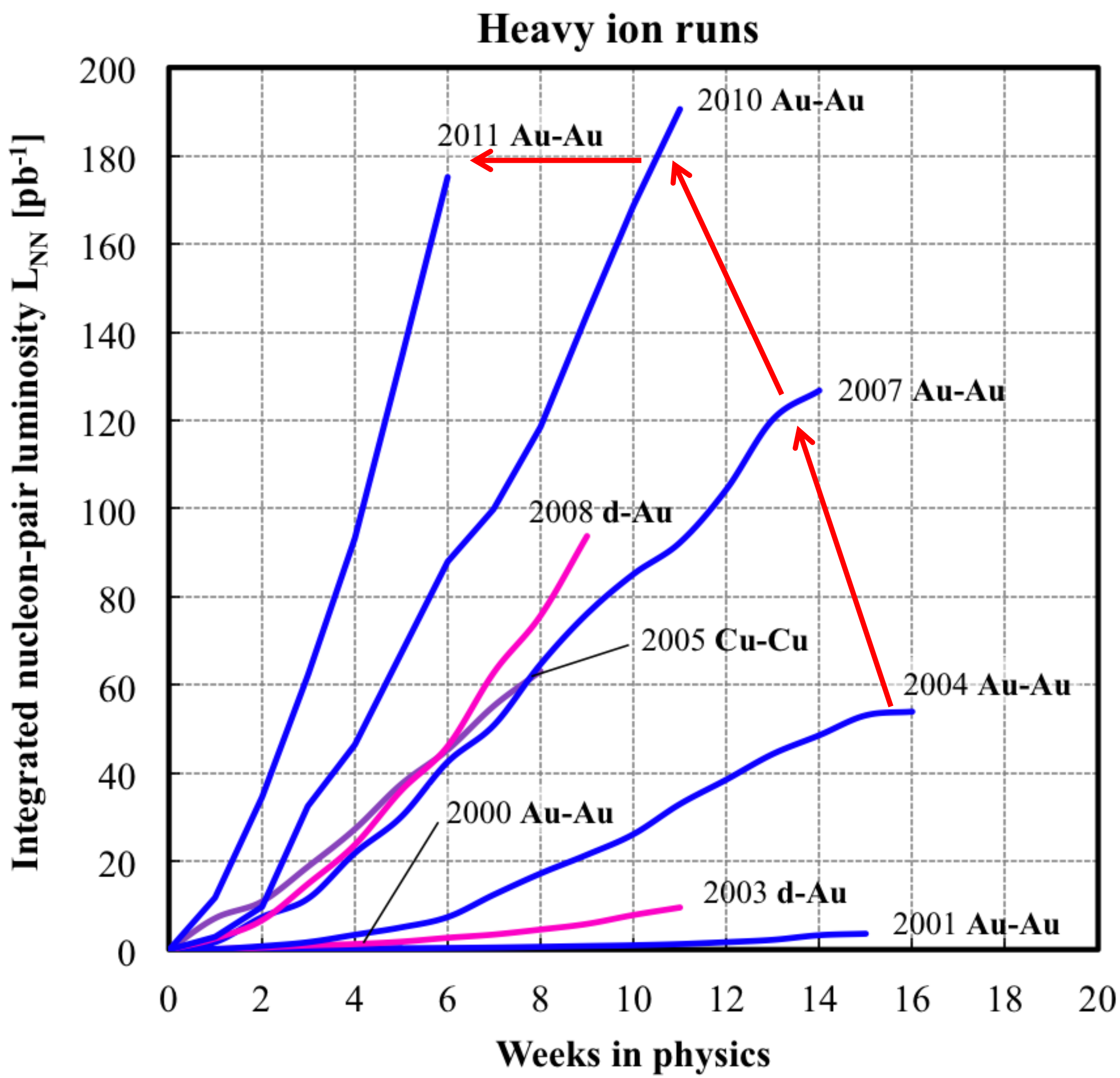
Heavy ion status and upgrades

- Stochastic cooling & 56 MHz SRF
- Electron Beam Ion Source (EBIS)
- Energy scan and low energy cooling

Polarized proton status and upgrades

- Polarized source
- RHIC electron lenses
- Polarization in RHIC
- New 3rd experiment A_NDY
- Polarized ^{3}He

RHIC heavy ions – luminosity evolution to date



<L> = 15x design in 2011

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

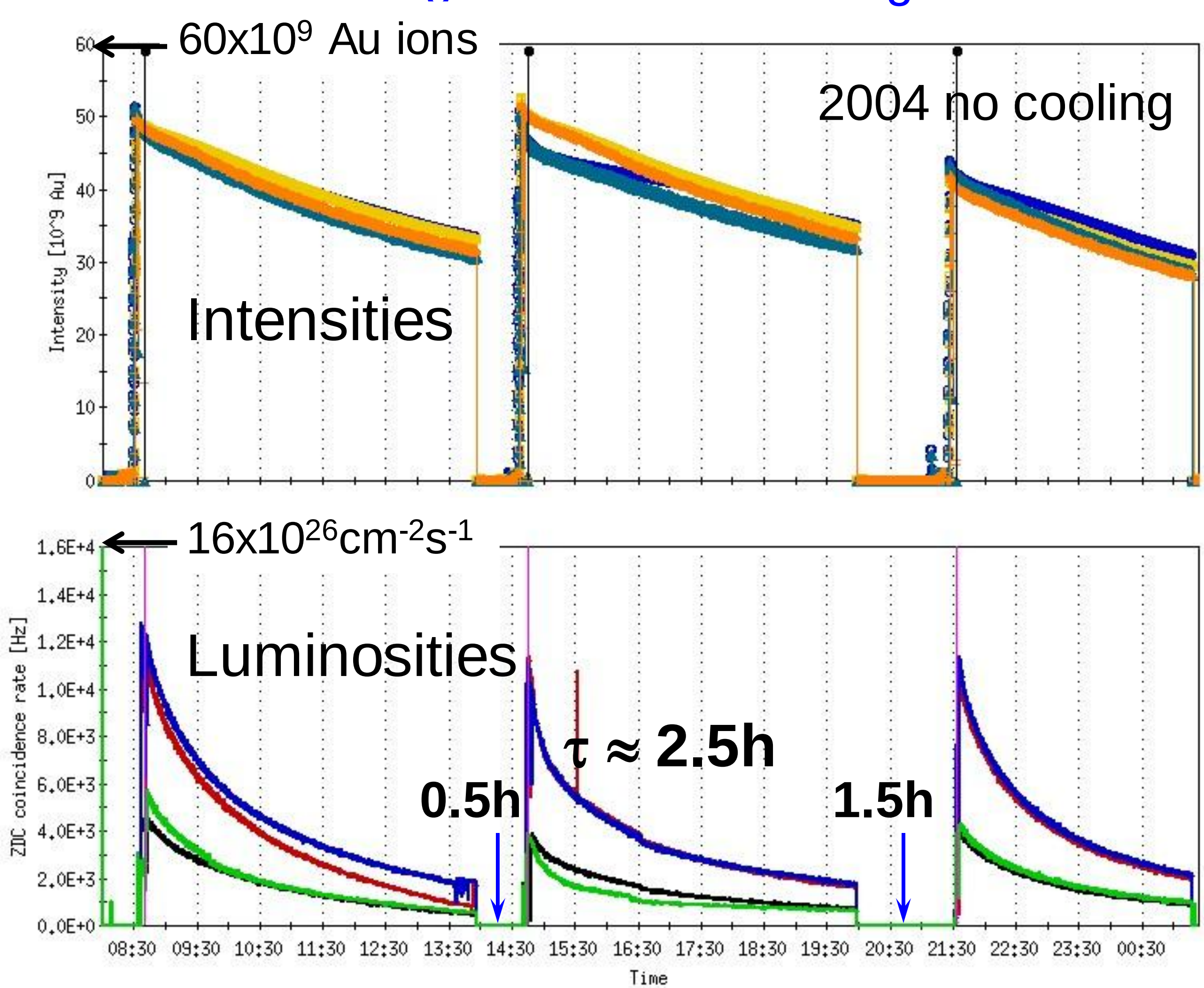
- Run-4 to Run-7
- Run-7 to Run10
- Run-10 to Run-11

Rate of progress will slow down – burn off 50% of beam in collisions already

$L_{NN} = L\,N_1N_2$ (= luminosity for beam of nucleons, not ions)

RHIC heavy ions – luminosity limit IBS

Intrabeam scattering leads to debunching and transverse emittance growth



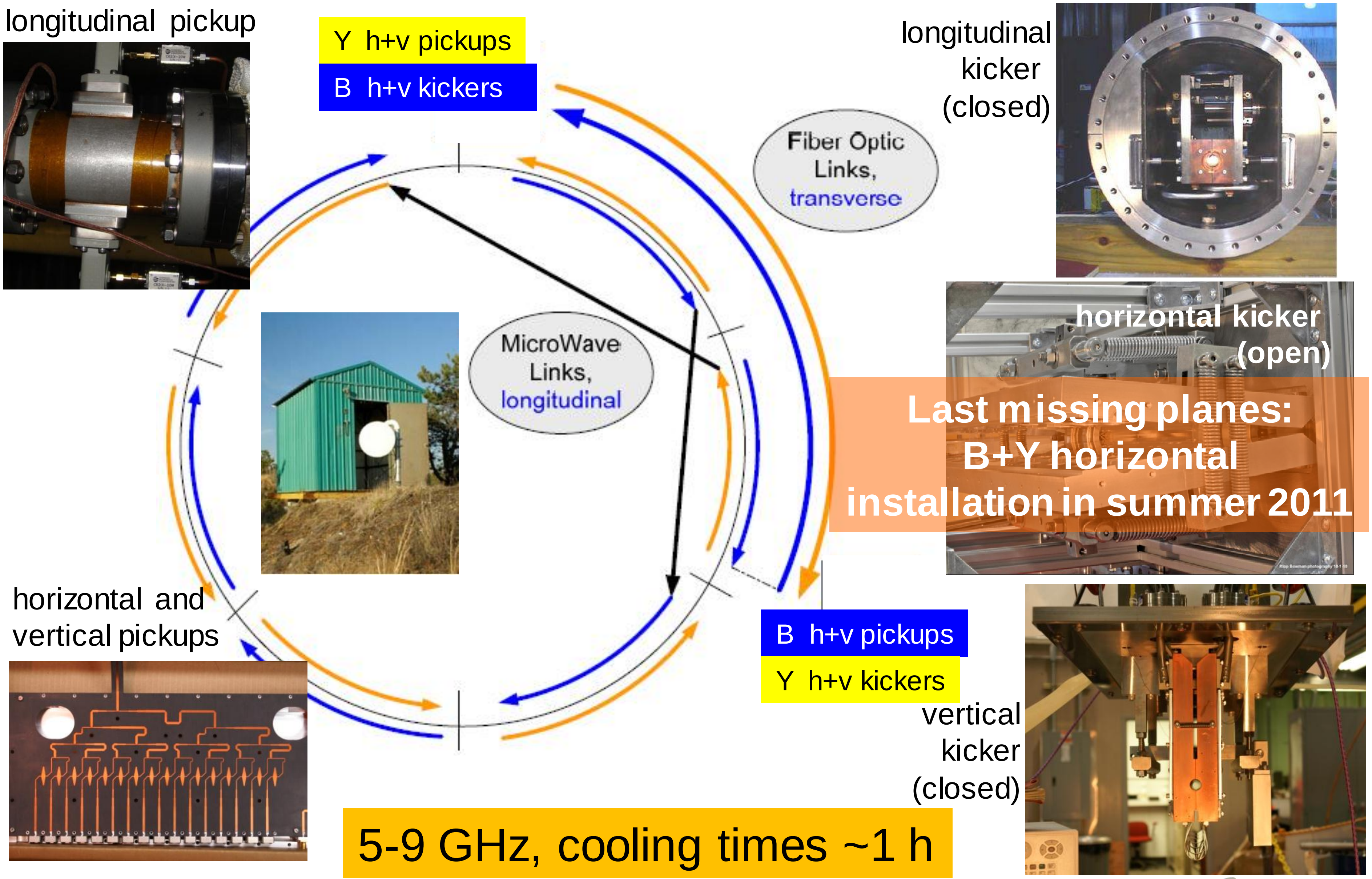
growth rates

$$t^{-1}\ \mu\ \frac{Z^4}{A^2}\frac{N_b}{g}$$

[Factor 15 between Au an p]

- Maximize focusing in all dimensions
- Frequent refills
- Cooling at full energy

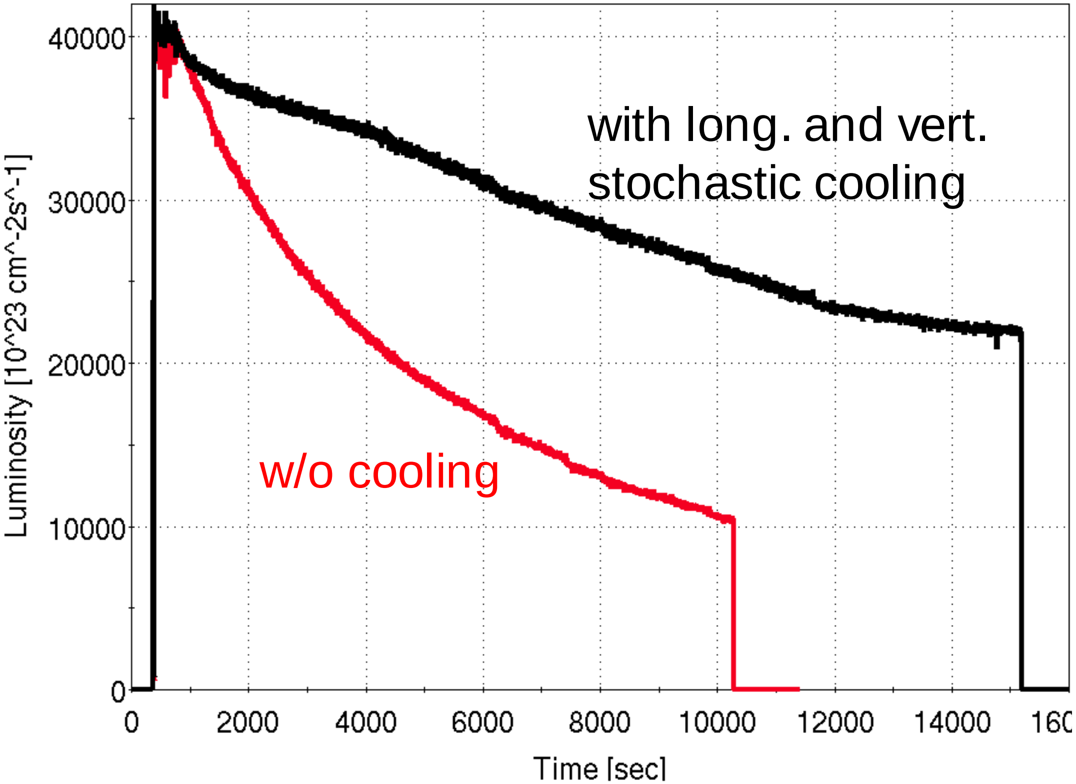
RHIC – 3D stochastic cooling for heavy ions



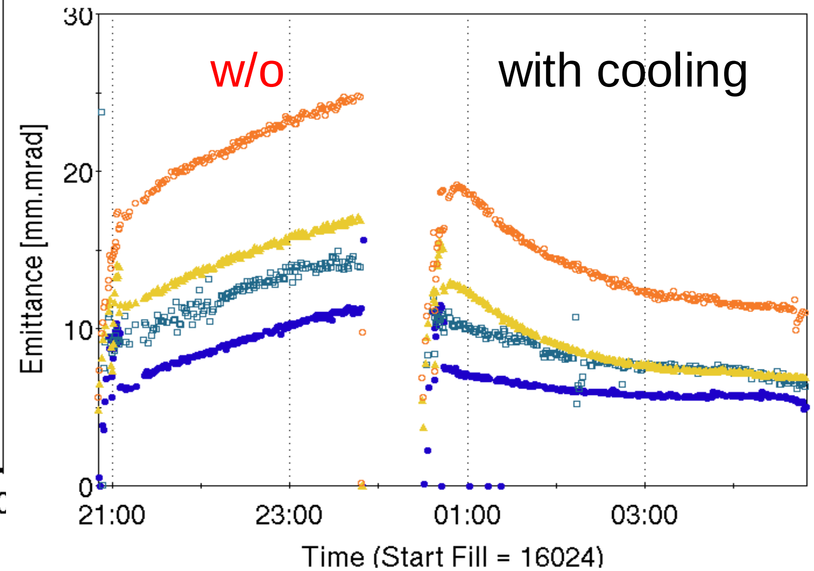
M. Brennan, M. Blaskiewicz, F. Severino, PRL **100** 174803 (2008); PRSTAB, PAC, EPAC

RHIC – effect of stochastic cooling in 2011

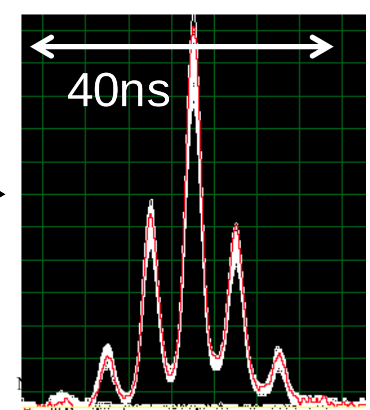
luminosity in 2 consecutive stores



Factor 2 gain in average luminosity from stochastic cooling so far

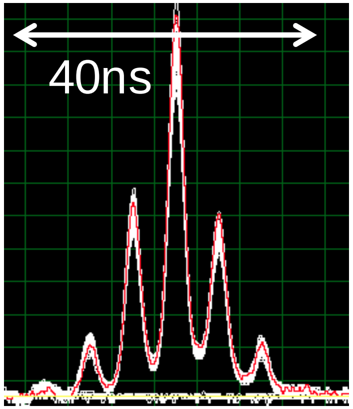


strong transverse cooling makes longitudinal cooling less efficient, i.e. these longitudinal profiles at the end of a store with be more pronounced with horizontal cooling next year →



[hourglass factor 0.75 at beginning, 0.55 at end of store]

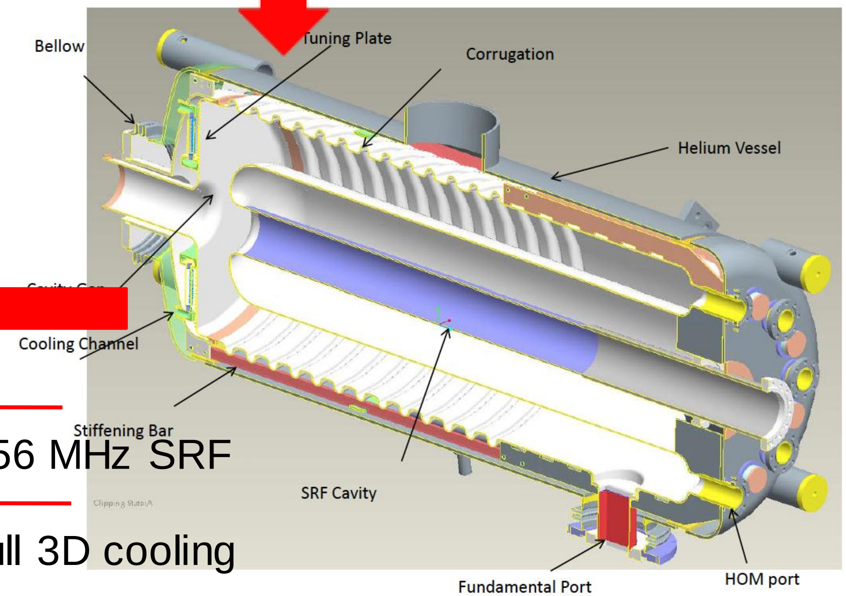
56 MHz SRF for heavy ions – under construction (I. Ben-Zvi et al.)



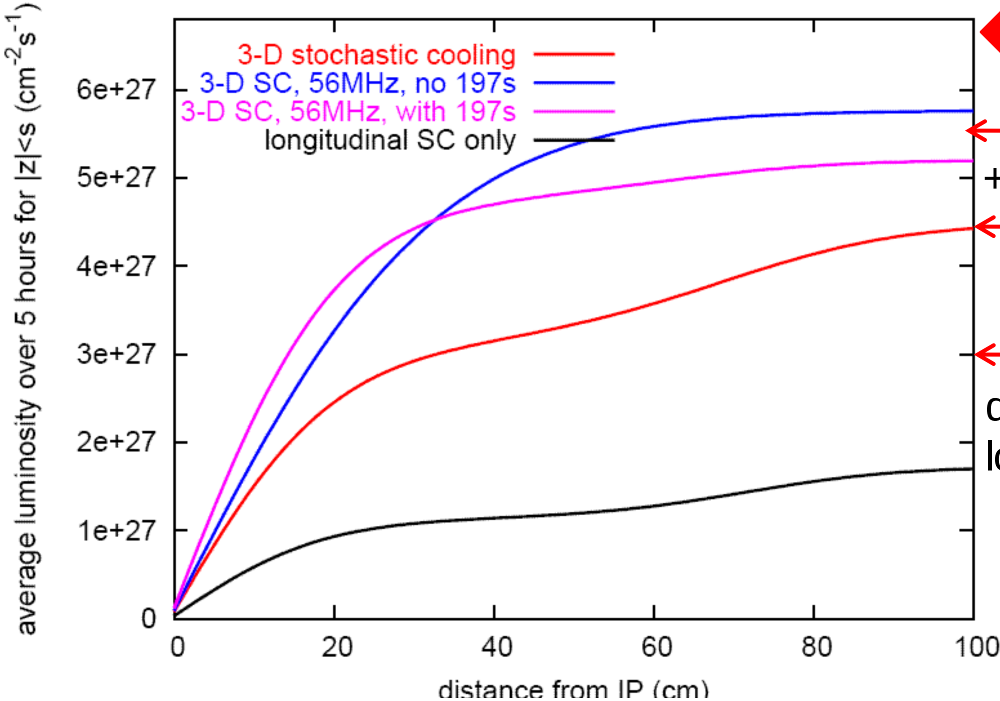
Longitudinal profile at end of store

- even with cooling ions migrate into neighboring buckets
- can be reduced with increased longitudinal focusing

Commissioning planned for 2014



Average luminosity vs. vertex size



\+ 56 MHz SRF

full 3D cooling

demonstrated 2011
long. + ver. cooling

Calculation by M. Blaskiewicz

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

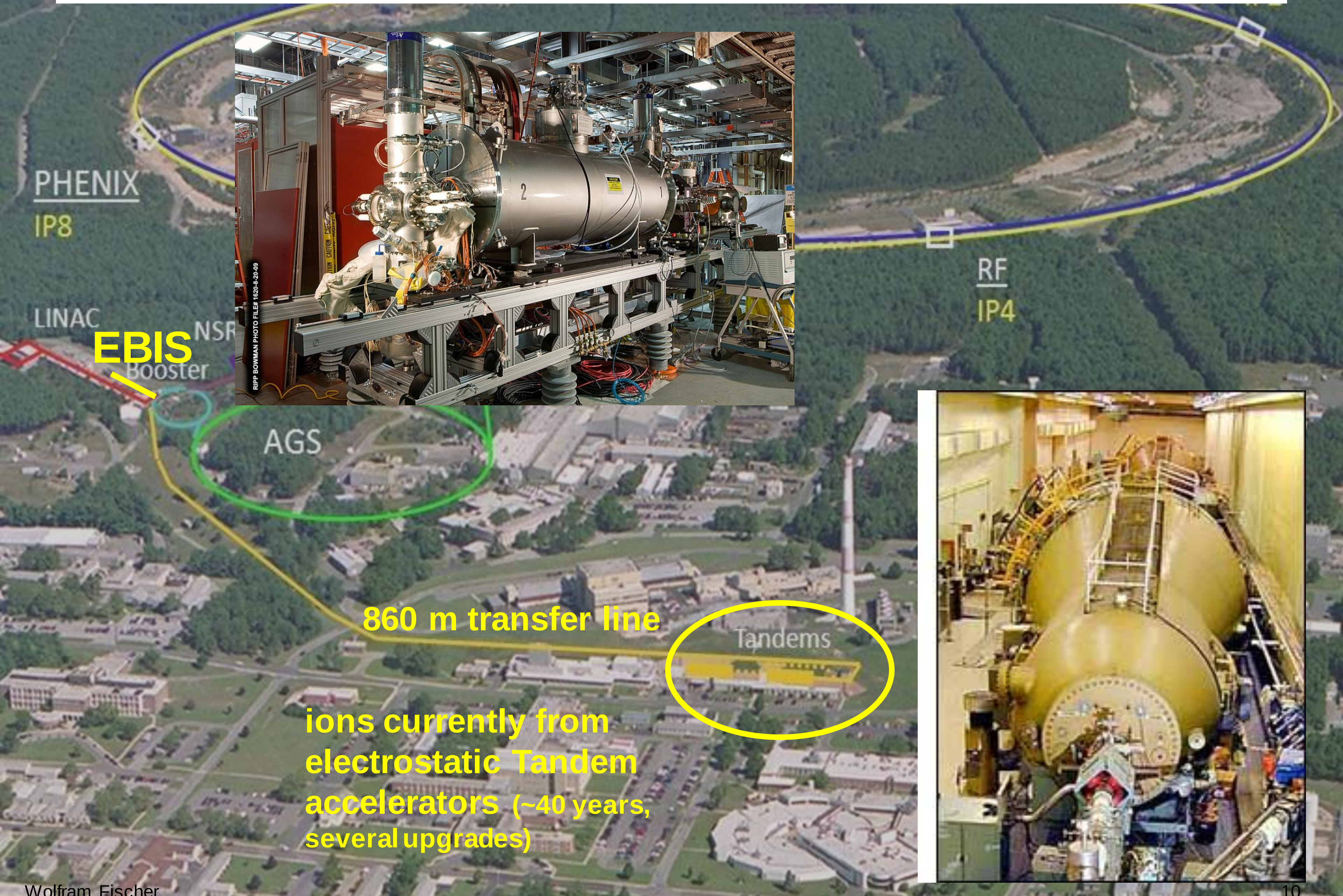
RHIC heavy ions – other luminosity limits

Operate close to a number of other limits:

- Instabilities on ramp at transition (γ_{tr} = 26) ← at limit in 2007
  driven by machine impedance and electron cloud
- Beam loading during rf rebucketing ← at limit in 2010
  limit removed last summer by separating common storage cavities
- Intensity limit of beam dump (quench Q4) ← at limit in 2010
  limit removed last summer by inserting sleeves in beam dump pipe
- Bunch intensity limit from injector chain ← at limit in 2011
  injected $N_b = 1.5\text{x}10^9$ in Run-11
- Chromatic aberrations with small β^*
  about 50% of particle loss due to burn-off,
  other 50% largely due to off-momentum dynamic aperture
  tested β^* squeeze in store after cooling to equilibrium

Above list changes from year to year as most limiting effects are mitigated.

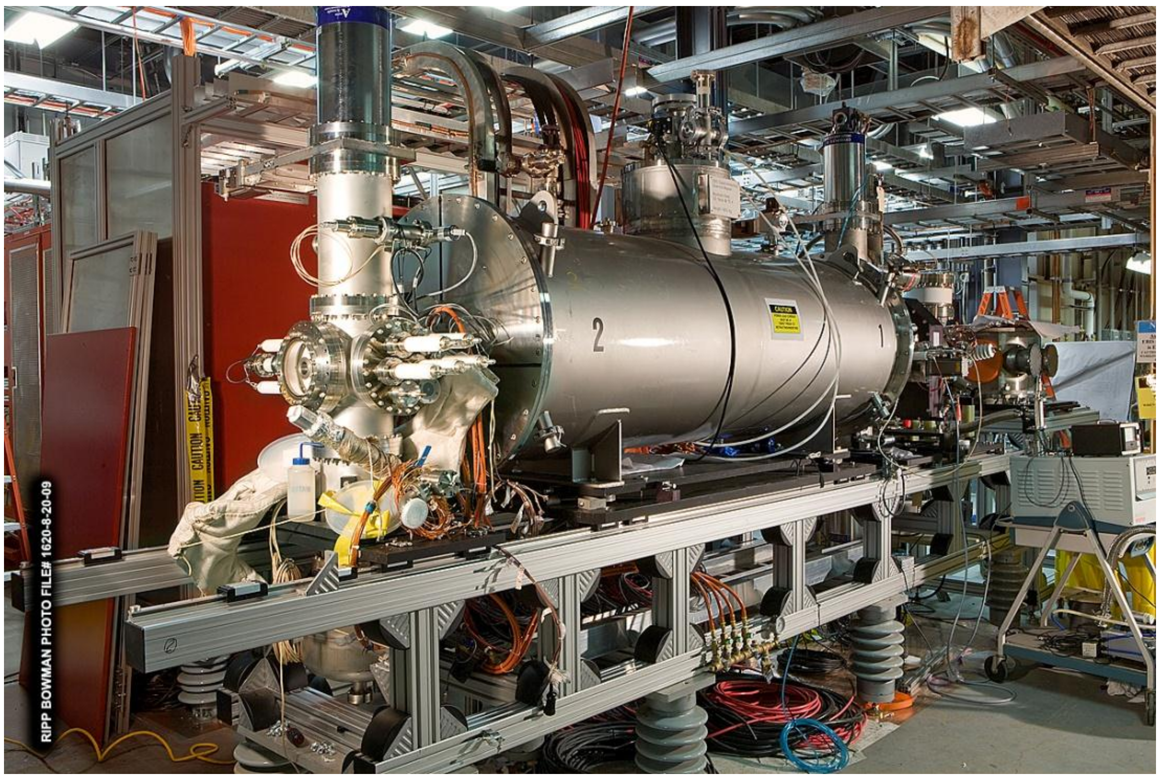
Electron Beam Ion Source (EBIS) (J. Alessi et al.)



ions currently from electrostatic Tandem accelerators (~40 years, several upgrades)

Electron Beam Ion Source (EBIS) (J. Alessi et al.)

- 10 A electron beam creates desired charge state(s) in trap within 5 T superconducting solenoid
- Accelerated through RFQ and linac, injected into AGS Booster
- All ion species incl. noble gas, uranium and polarized ^3He



Operated for NSRL with

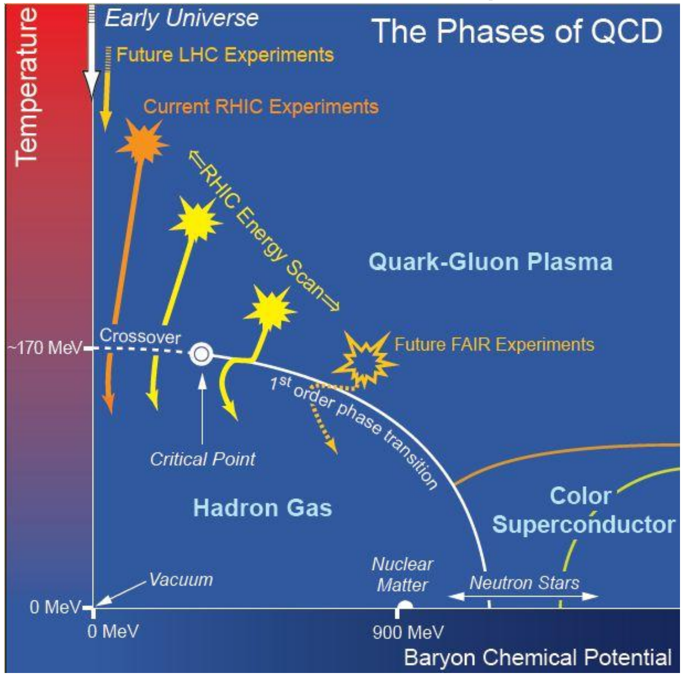
- He^{+}, He^{2+}, Ne^{5+}, Ne^{8+}, Ar^{11+}, Ti^{18+}, Fe^{20+}

Commissioning for RHIC under way

- Work on 4x Au^{32+} increase to design intensity
  2x from electron current,
  2x from transmission
- Received U cathode

RHIC – Au-Au energy scan

US NSAC report 2007



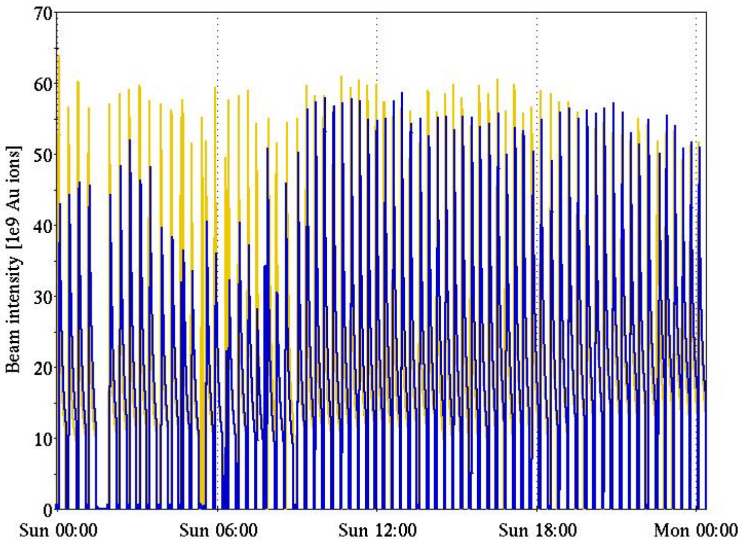
Energy scan – now extends below nominal injection energy in search of critical point in QCD phase diagram

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

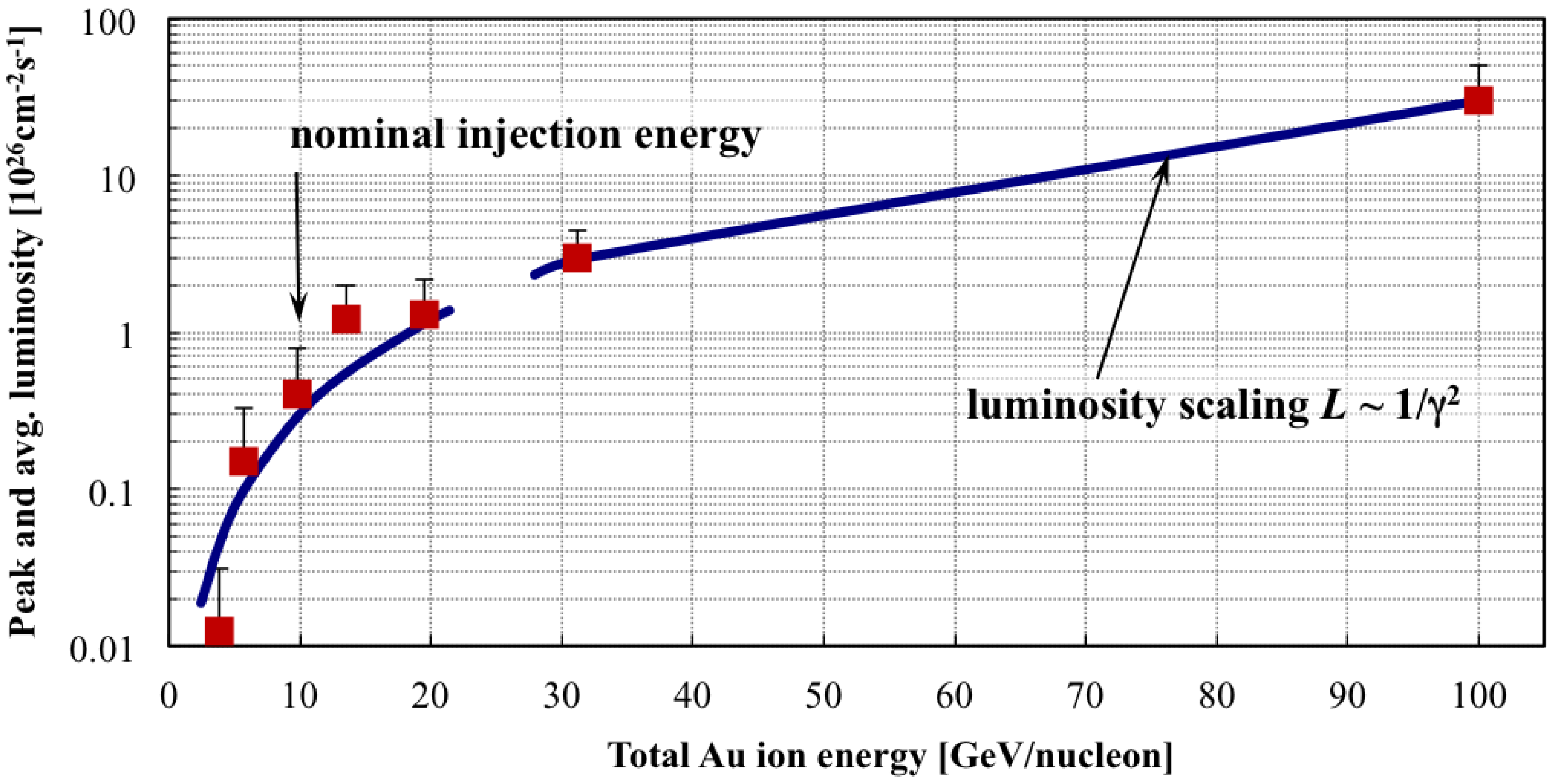
- Large beam sizes **(longitudinal and transverse)**
  controlling losses becomes critical
- Large magnetic field errors **(b_3 ~ 10, b_5 ~ 6 units from persistent currents in superconducting magnets)**
- Intrabeam scattering **(debunching ~min)**
- Space charge **($\Delta Q_{Laslett}$ ~ 0.1 – new regime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

Considering use of Fermilab Pelletron (used for pbar cooling at 8 GeV) **after Tevatron operation ends**

Cooling into space charge limit

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

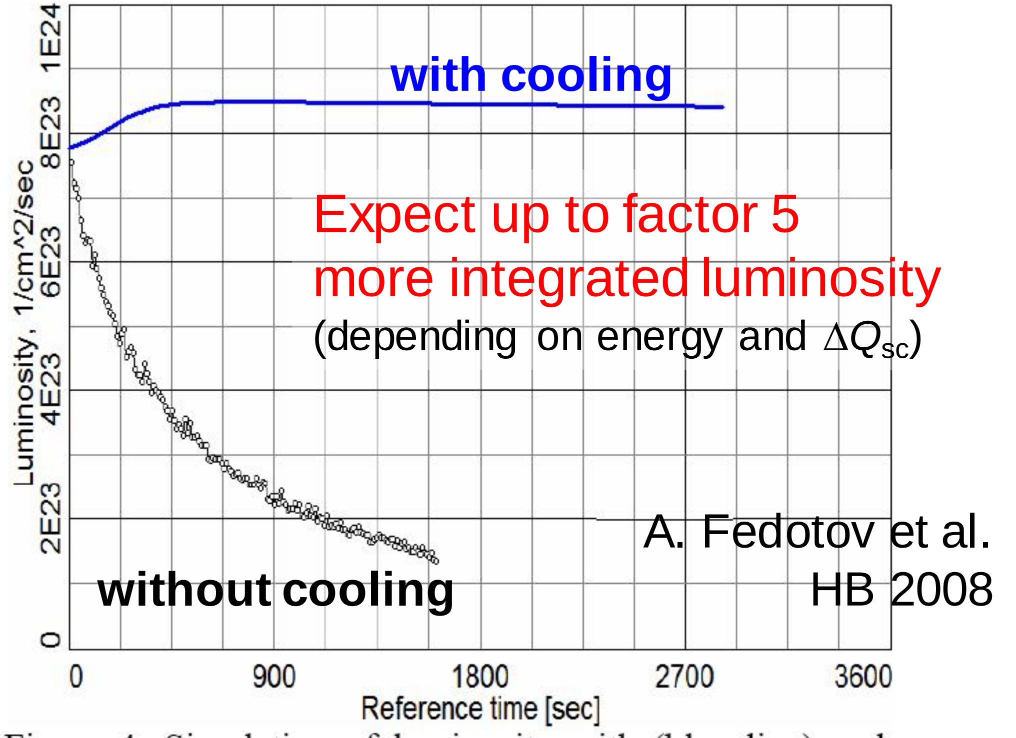
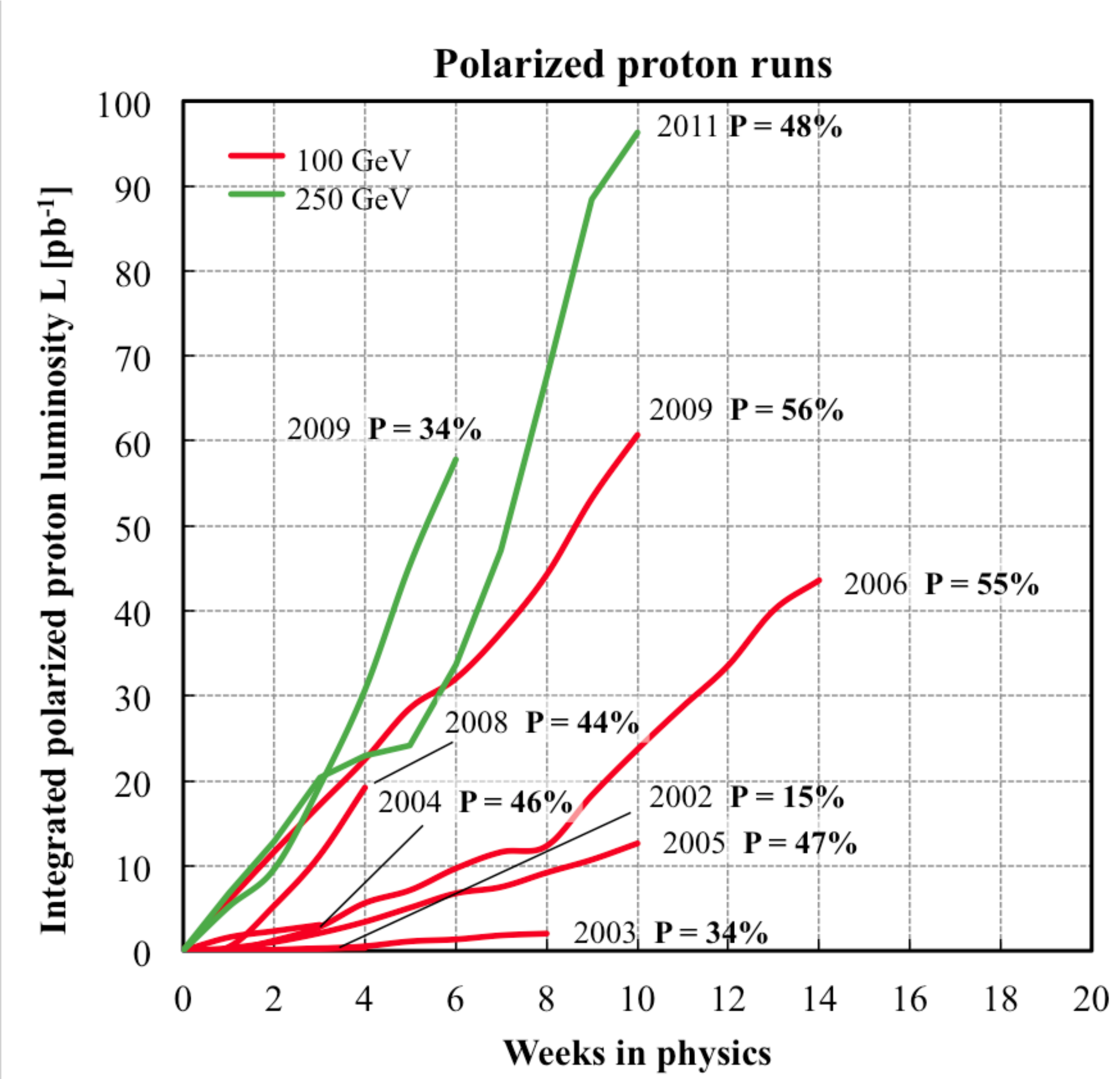


Figure 4. Simulation of luminosity with (blue line) and without (black dots) electron cooling at γ=2.7.

New heavy ion modes under consideration

- Cu-Au
  requested for 2012 (so far: Au-Au, Cu-Cu, d-Au)
- U-U
  possible with EBIS, football shaped nuclei
- p-Au
  considered in design, not yet operated
  requires ~4cm horizontal shift of DX magnets (not needed for d-Au)
- Au-Au at $\sqrt{s_{NN}}$ = 5 GeV
  24% of nominal injection rigidity
  issues: space charge, IBS, longitudinal and transverse acceptance, field quality of superconducting magnets
- Higher luminosity at low energies
  requires cooling

RHIC polarized protons – luminosity and polarization

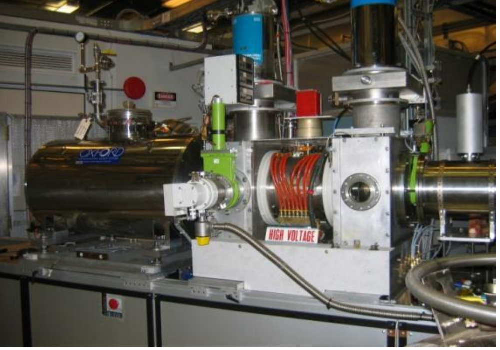


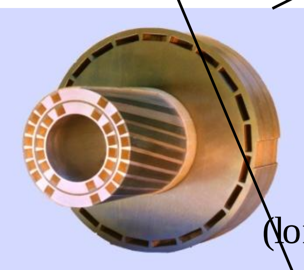
At 250 GeV in 2011
L_{avg} = 90x10^{30}cm^{-2}s^{-1}
P_{avg} = 48%

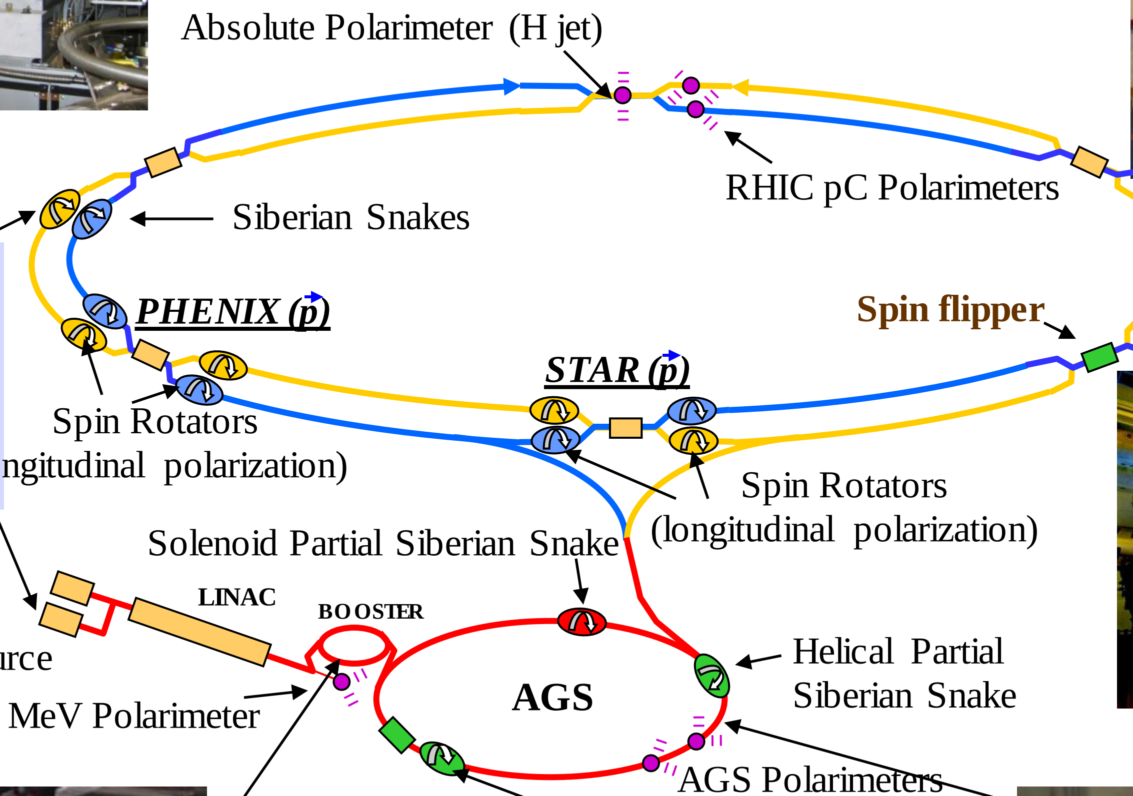
L_{avg} +60% rel. to 2009
P_{avg} +40% rel. to 2011

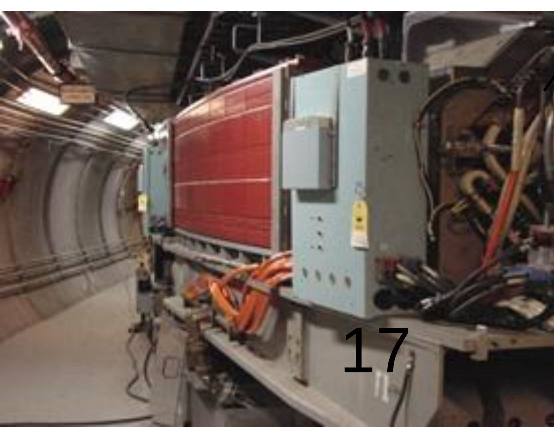
$FOM = LP^4$
(longitudinally polarized beams)

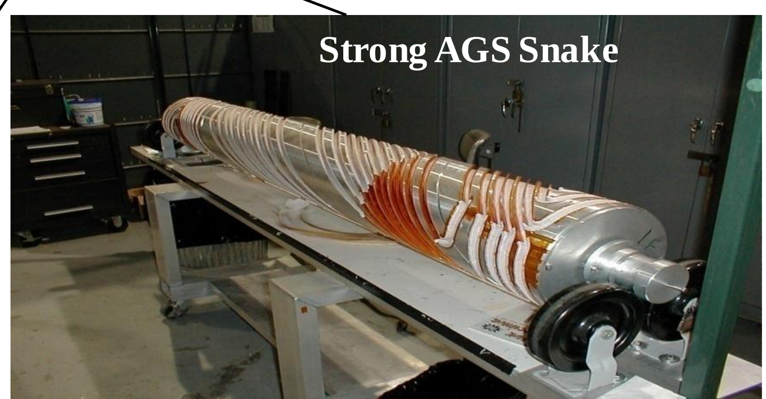
Special devices for polarized protons: source, polarimeters, snakes, rotator, flipper











RHIC protons – polarization and luminosity limits

1. **AGS bunches with high N_b, high P, low ε_N**
   - AGS horizontal tune jump system fully operational in 2011 (82 resonances)
   - polarized source upgrade for 2013 (see later)

2. **RHIC polarization transmission to 250 GeV**
   - measured vertical orbit rms ~ 20 μm
   - acceleration near Q_v = 2/3 resonance
   - possible acceleration near Q_v = 1 resonance

3. **RHIC intensity transmission to 250 GeV**
   - beam dump system modified in 2010 (thicker beam pipe in dump)
   - new 9 MHz rf system
   - feedbacks for x,y_{rms}, Q, Δq_{min}, on every ramp (Q' available on demand)

4. **RHIC peak luminosity and luminosity lifetime**
   - new source allows for N_b increase
   - electron lenses allow for larger beam-beam parameter

Main improvements for polarized protons in 2011

RHIC

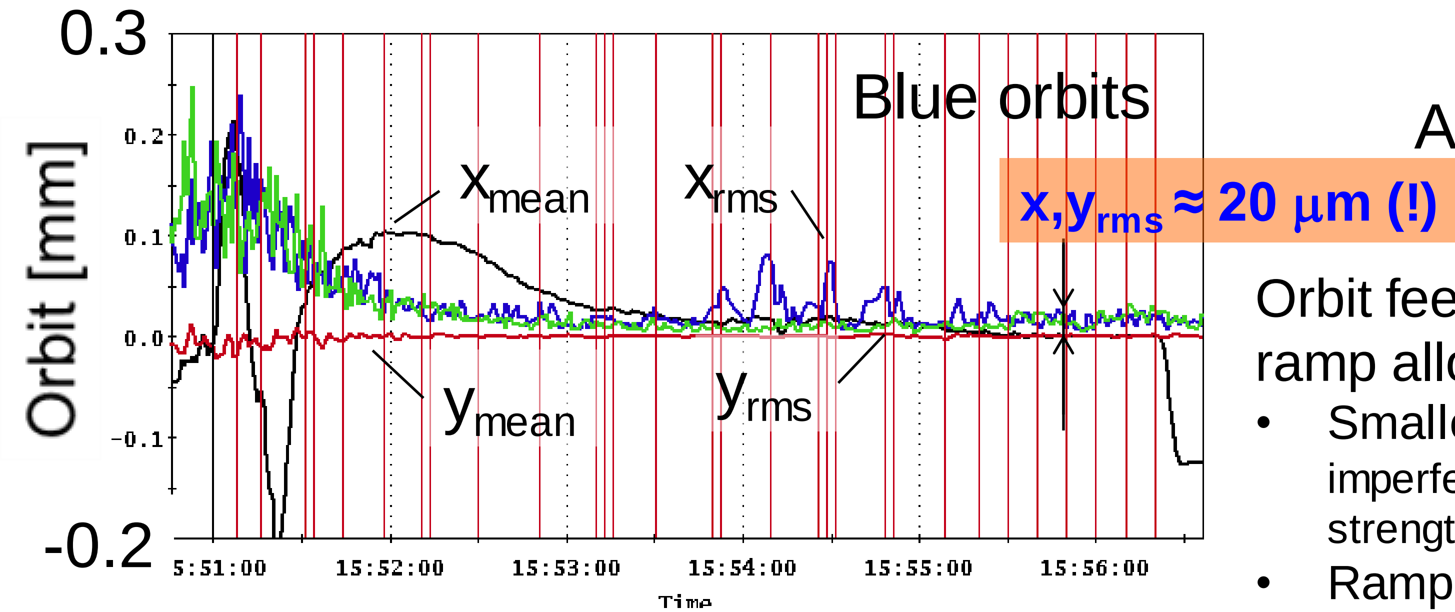
- 2 storage cavities permanently converted to 9 MHz, 1 bouncer cavity install in each ring (9 MHz) (*P*+, *L*+)
- Current limit for tq increased from 100 A to 140A IR6 to IR8 (*L*+)
- Collimation on ramp with continuous set point changes (*L*+)
- RHIC CNI polarimeters with new electronics (mitigates rate dependence)
- First H-jet polarization measurement at injection

RHIC beam and optics control

- All ramps with orbit, tune, and coupling feedback (*P*+, *L*+)
- Ramps $Q_v = 0.673$ (near low order resonance) (*P*+)
- Radial loop control via all BPMs (previously only 2) (*P*+, *L*+)
- Octupoles on ramp to suppress instabilities (*L*+)
- Operational use of 10 Hz orbit feedback in store (*L*+)
- First use of beta-beat correction in operation (*L*+)

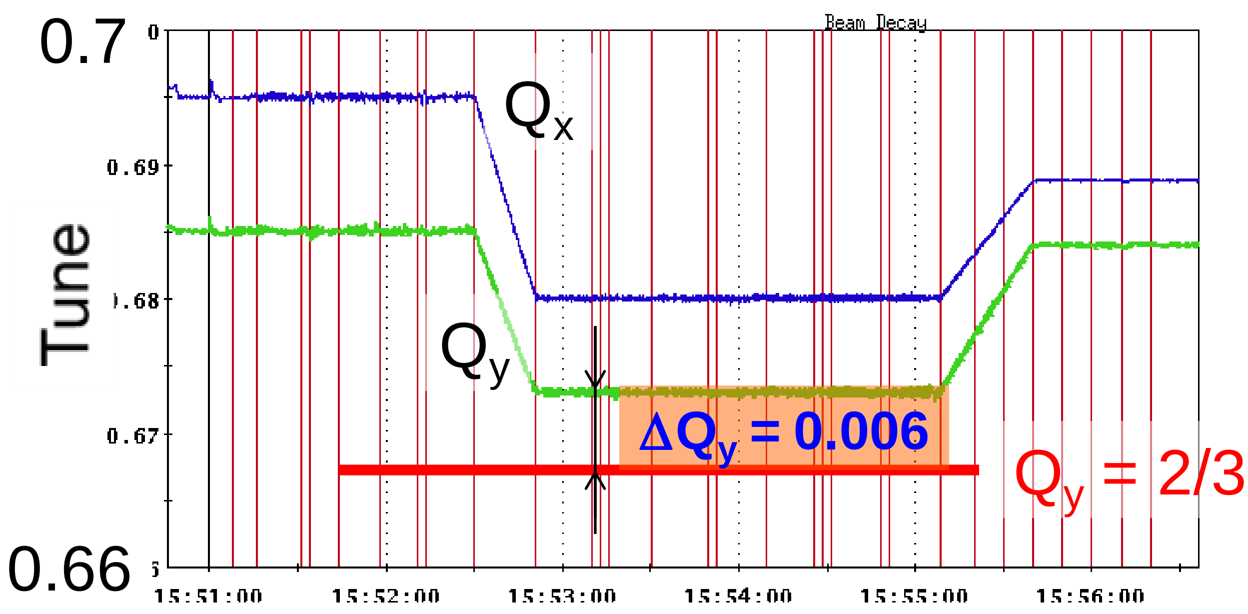
Beam control improvement – feedbacks on ramp

M. Minty,
A. Marusic et al.



Orbit feedback on every ramp allows for

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

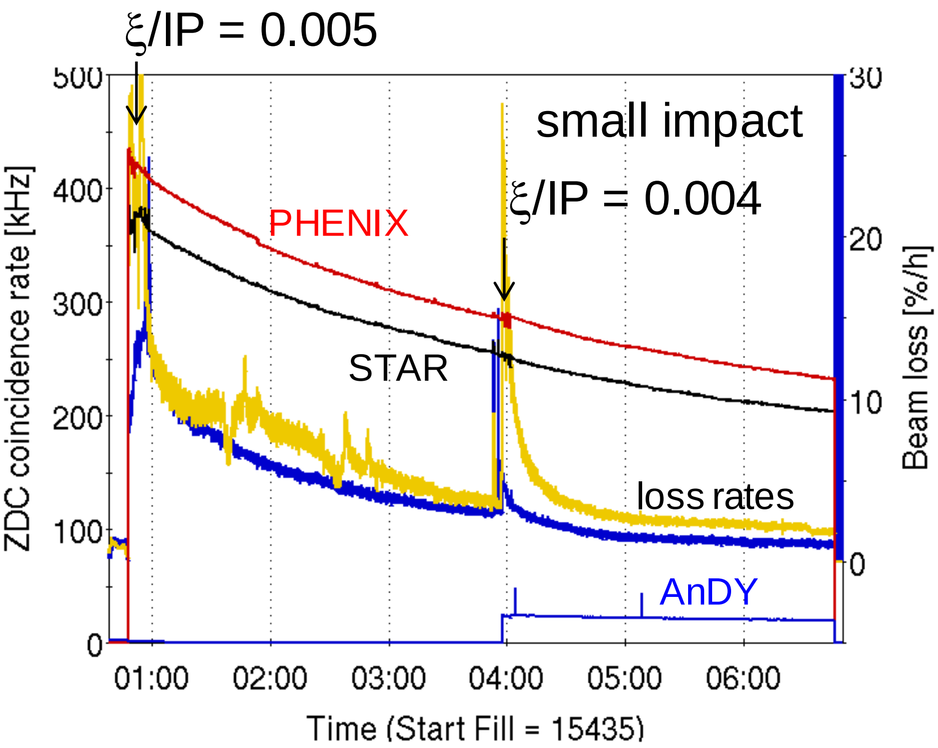


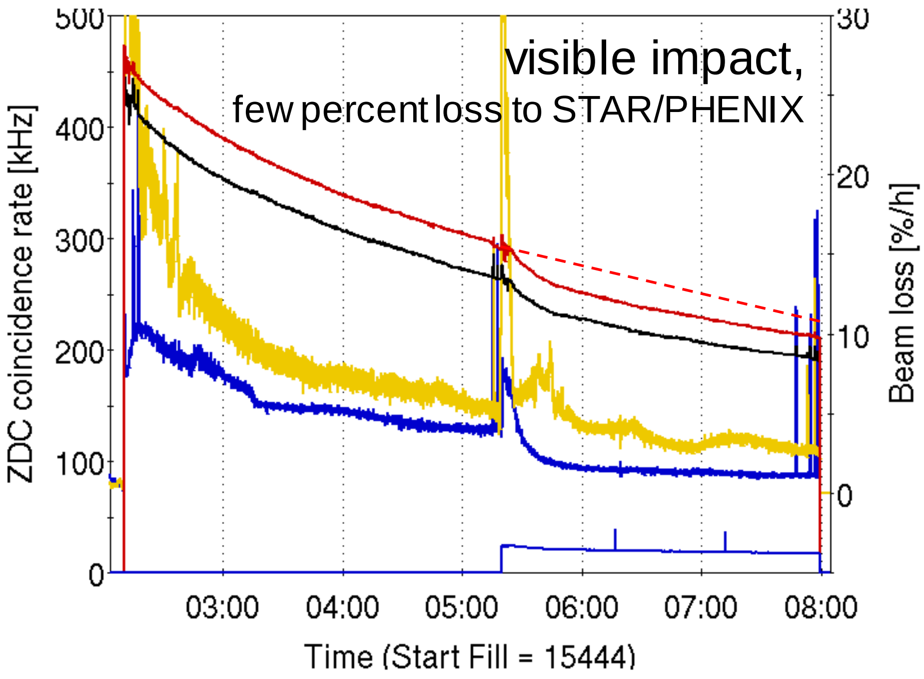
Tune/coupling feedback on every ramp allows for

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

A_nDY in 2011 (250 GeV pp)

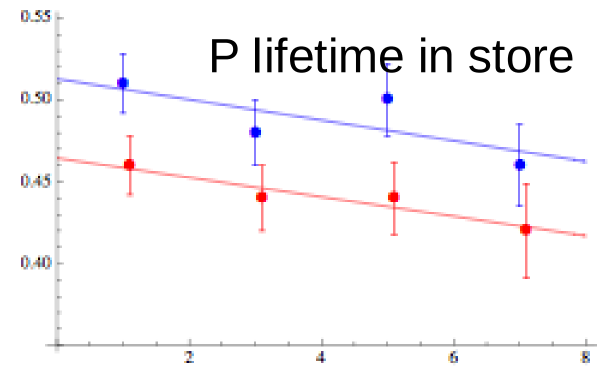
- Beam envelope function $\beta^* = 3.0$ m at IP2
- Reduced IP2 crossing angle from initially 2.0 mrad to zero
- Added 3rd collision with following criteria:
    1. $N_b \leq 1.5\text{x}10^{11}$
    2. Beam loss rate <15%/h in both beams
    3. Not before first polarization measurement 3h into store

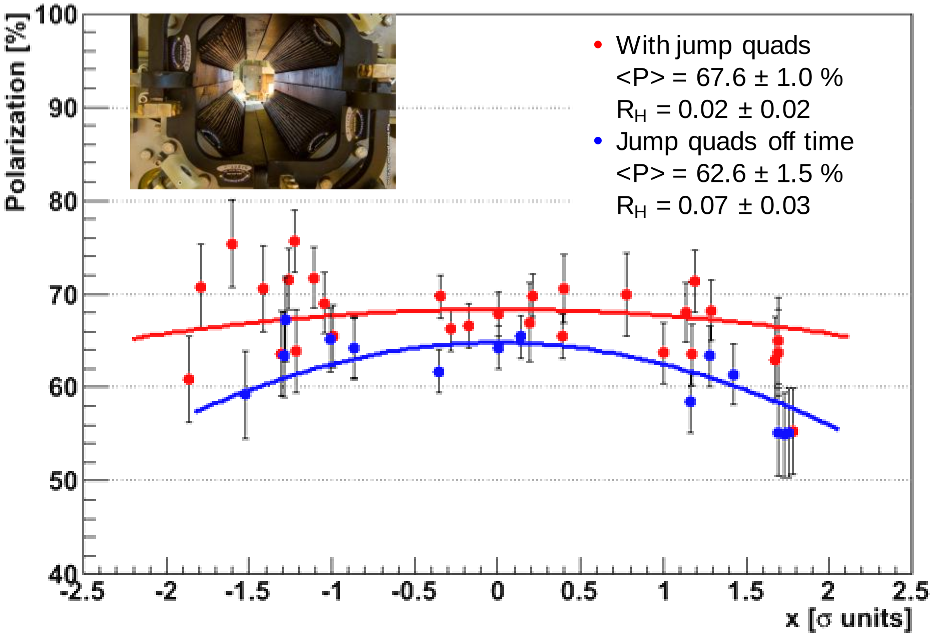


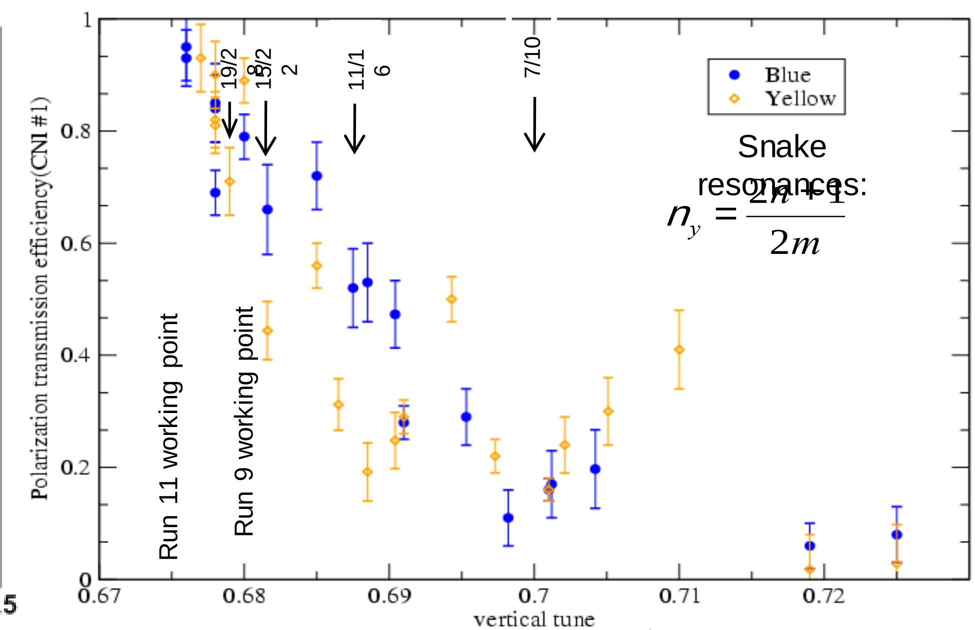


2011 Polarization Performance, 2012 plans

- AGS horizontal tune jump system operational: *P* +8% with high intensity
- Acceleration near Q_v = ⅔ in RHIC, measured orbit rms ~20 μm: *P* +25%
- Polarization at end of 250 GeV ramp: 53%
- With incremental improvements <P> = 55 – 60% possible for next run:
  - Changes in source/LEBT/MEBT: +6% in <P>
  - Smaller emittance growth (24 → 18 μm): +8% in <P>
  - Small change in store energy: no P decay during store: +5% in <P>
- Remaining pol. Loss during AGS (~15%) and RHIC (~15%) accel., to be studied with tracking simulations





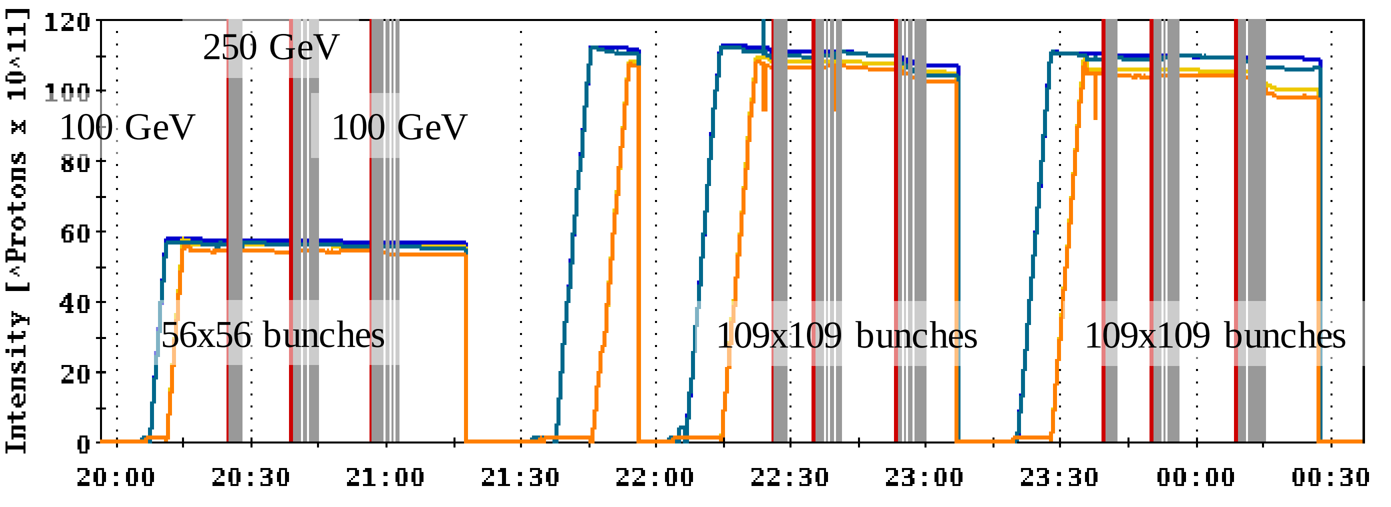


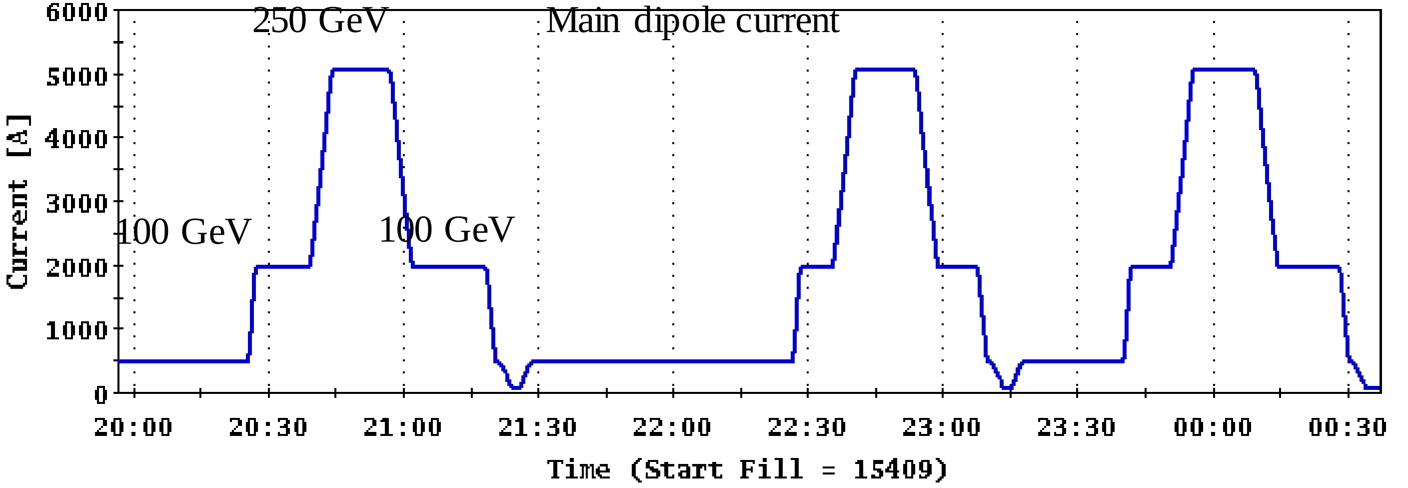
Up/down ramp with polarized protons in Run-11

Another measurement of the store polarization

Setup and 3 up and down ramps with up to 109x109 bunches in only 2 shifts

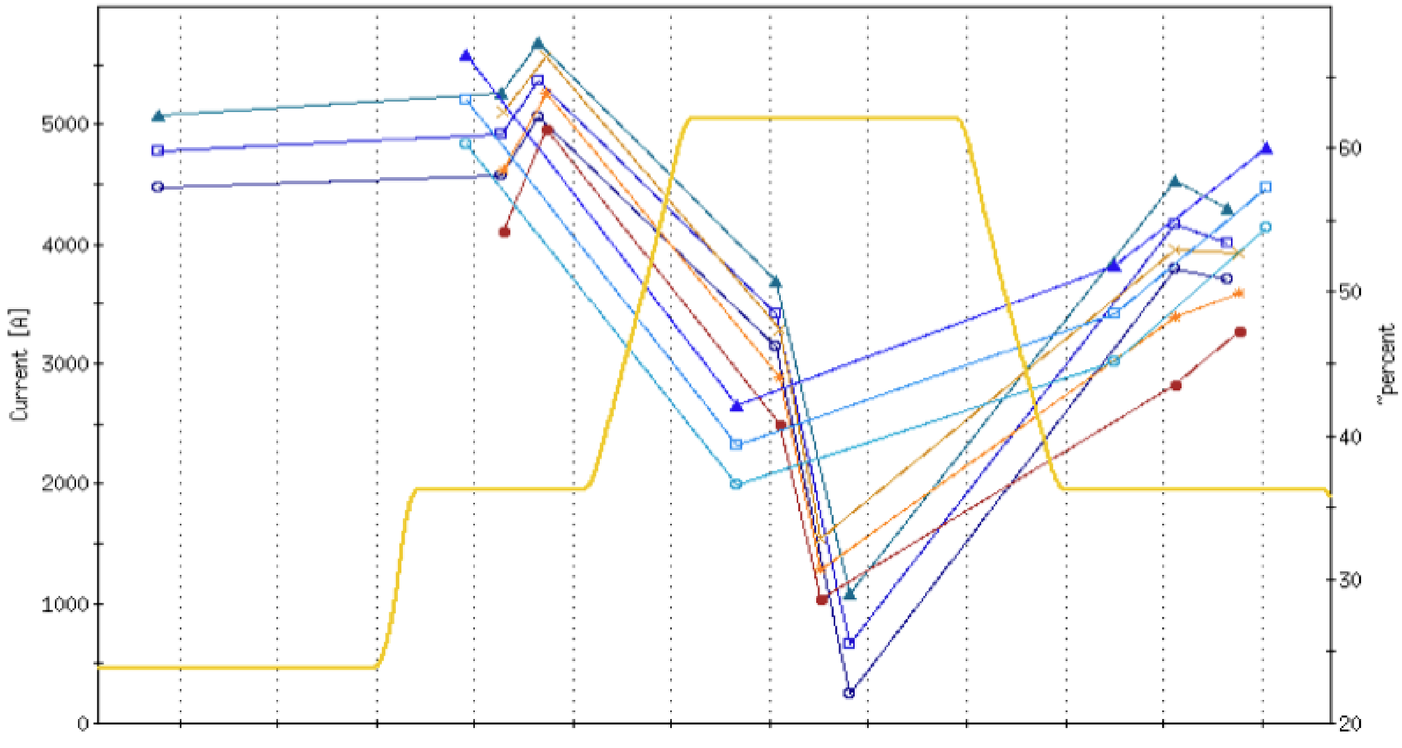
(simultaneous orbit/tune/coupling/chromaticity feedback essential)





Up/down ramp with polarized protons in Run-11

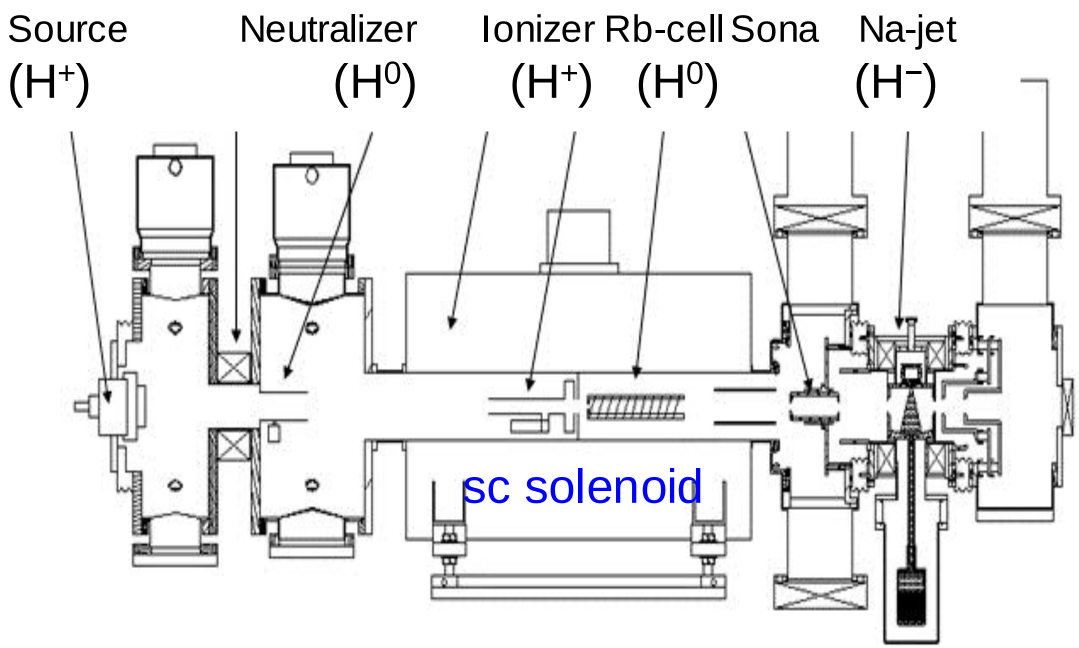
Compare CNI measurement at 100 GeV before and after up/down ramp



- Polarization ratio 100 GeV before / 100 GeV after: **0.79±0.02%**
- If up and down ramps are identical, loss from 100 to 250 GeV is **11%**
- With 63% polarization at 100 GeV (Run-9 H-jet) expect **56%** at 250 GeV
- H-jet measurement in Run-11 was **46%**

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

Upgraded OPPIS (2013)



10x intensity increase was demonstrated in a pulsed operation by using a very high-brightness Fast Atomic Beam Source instead of the ECR source

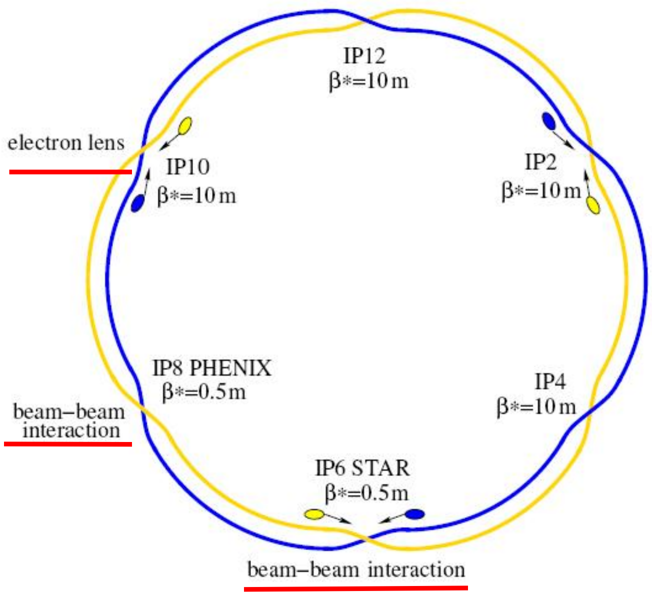
Goals:

1. H^- beam current increase to 10mA (order of magnitude)
2. Polarization to 85-90% (~5% increase)

Upgrade components:

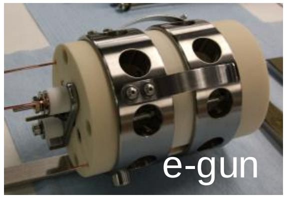
1. Atomic hydrogen injector (collaboration with BINP Novosibirsk)
2. Superconducting solenoid (3 T)
3. Beam diagnostics and polarimetry

Electron lenses – partial head-on beam-beam compensation



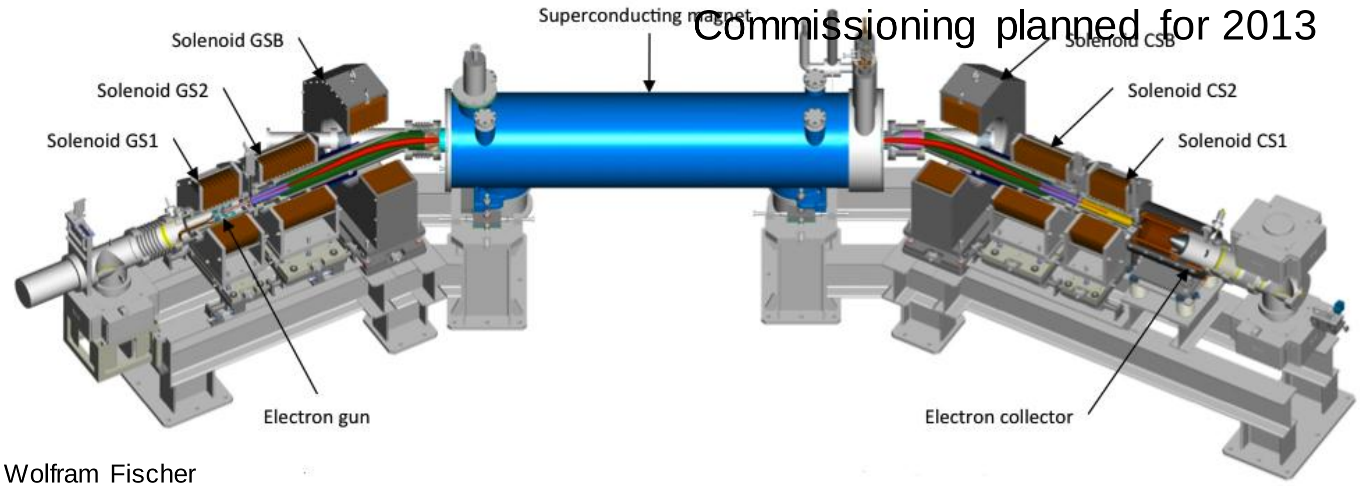
Polarized proton luminosity limited by head-on beam-beam effect ($\Delta Q_{bb,max}$ ~ 0.02)

Basic idea:
In addition to 2(3) beam-beam collisions with **positively** charged beam have another collision with a **negatively** charged beam with the same amplitude dependence.
-- Electron lenses are used in the Tevatron --



Exact compensation for:
- short bunches
- $\Delta\psi_{x,y} = k\pi$ between p-p and p-e collision
- no nonlinearities between p-p and p-e
- same amplitude dependent kick from p-p, p-e
- only approximate realization possible

Expect up to 2x more luminosity
with OPPIS upgrade
Commissioning planned for 2013



Polarized ^{3}He – Workshop 28-30 September 2011

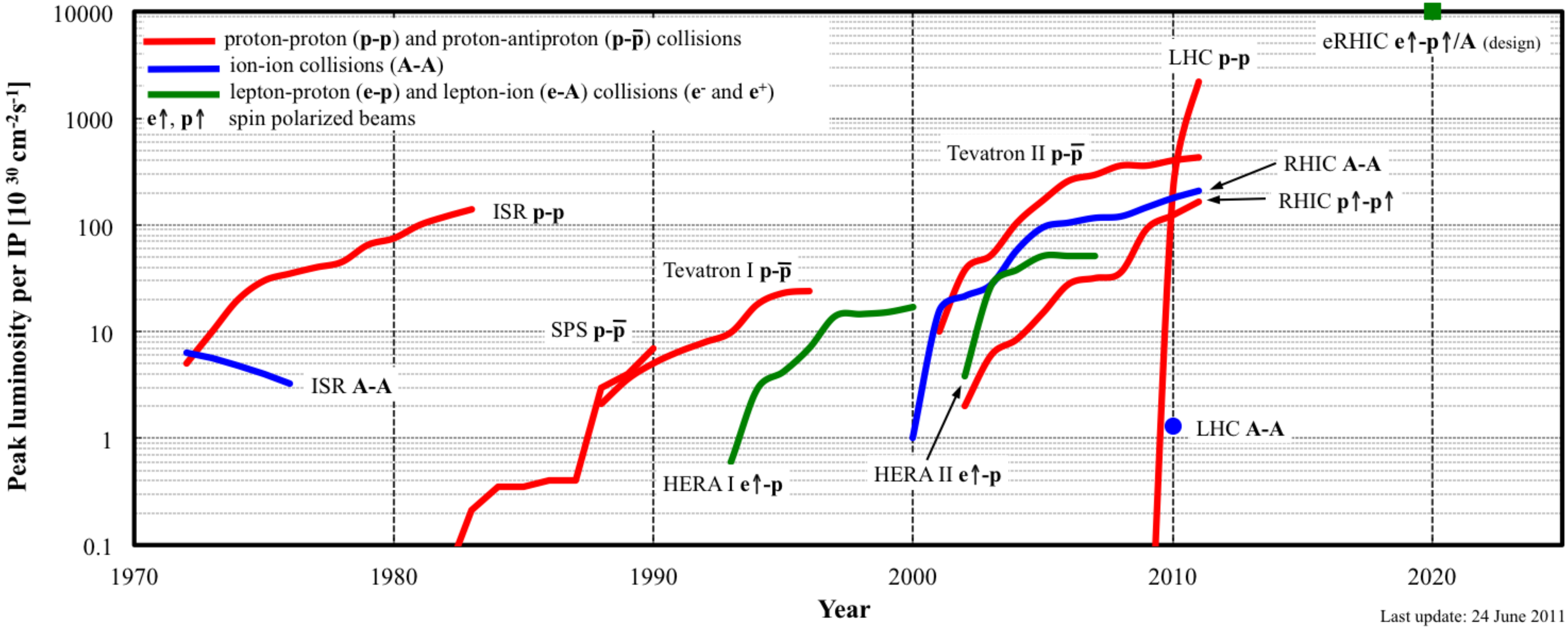
Workshop program

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

Luminosity and Polarization Goals

Parameter	unit	Achieved	With 3D stoch. cooling and 56 MHz SRF	
Au-Au operation		**2011**	**≥ 2014**	
Energy	GeV/nucleon	100	100	
No of bunches	…	111	111	
Bunch intensity	10^9	1.3	1.1	
Average Luminosity	**10^{26} cm^{-2} s^{-1}**	**30**	**40**	
p↑- p↑ operation		**2011**	**≥ 2012**	**≥ 2014**
Energy	GeV	100 / 250	100 / 250	250
No of bunches	…	109	109	109
Bunch intensity	10^{11}	1.3 / 1.65	1.3 / 1.7	2.0
Average Luminosity	**10^{30} cm^{-2} s^{-1}**	**24 / 90**	**30 / 150**	**300**
Polarization	**%**	**56 / 46**	**65**	**70**

Hadron collider peak luminosities



- For ion beams $L_{NN} = L\, N_1 N_2$ plotted (= luminosity for beam of nucleons, not ions)
- Luminosity not normalized for energy

RHIC – summary

Heavy ions

Reached: 100 GeV/nucleon (design) L_{avg} = 30x10^{26}cm^{-2}s^{-1} (15x design)

- 2-3x more luminosity more stochastic cooling, 56 MHz SRF
- Finished 1st Au-Au energy scan consider e-cooling for low energies
- Electron Beam Ion Source under commissioning U, ^{3}He♒ beams

Polarized protons

Reached: 250 GeV (design) L_{avg} = 90x10^{30}cm^{-2}s^{-1} (0.6x design) P_{avg} = 48% (0.7x design)

- 9 MHz rf system longitudinal emittance reduction
- New 3rd experiment likely A_NDY in IP2
- New polarized source under construction 10x intensity, 5% polarization
- Electron lenses reduction of head-on beam-beam effect

Abstract

The Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory has now operated for a decade. Over this time the 2 physics programs at RHIC, based on heavy ion and polarized proton collisions respectively, have seen a substantial increase in performance and a variety of species and energies. The performance increases are presented with the dominant limiting effects, and upgrade plans for the next decade. The heavy ion luminosity upgrade is primarily based on stochastic cooling in store, and an increase in the longitudinal focusing. A new polarized source is expected to increase both the polarization and luminosity. For the latter electron lenses are also implemented to partially compensate the head-on beam-beam effect. In addition, a number of new operating modes are considered.