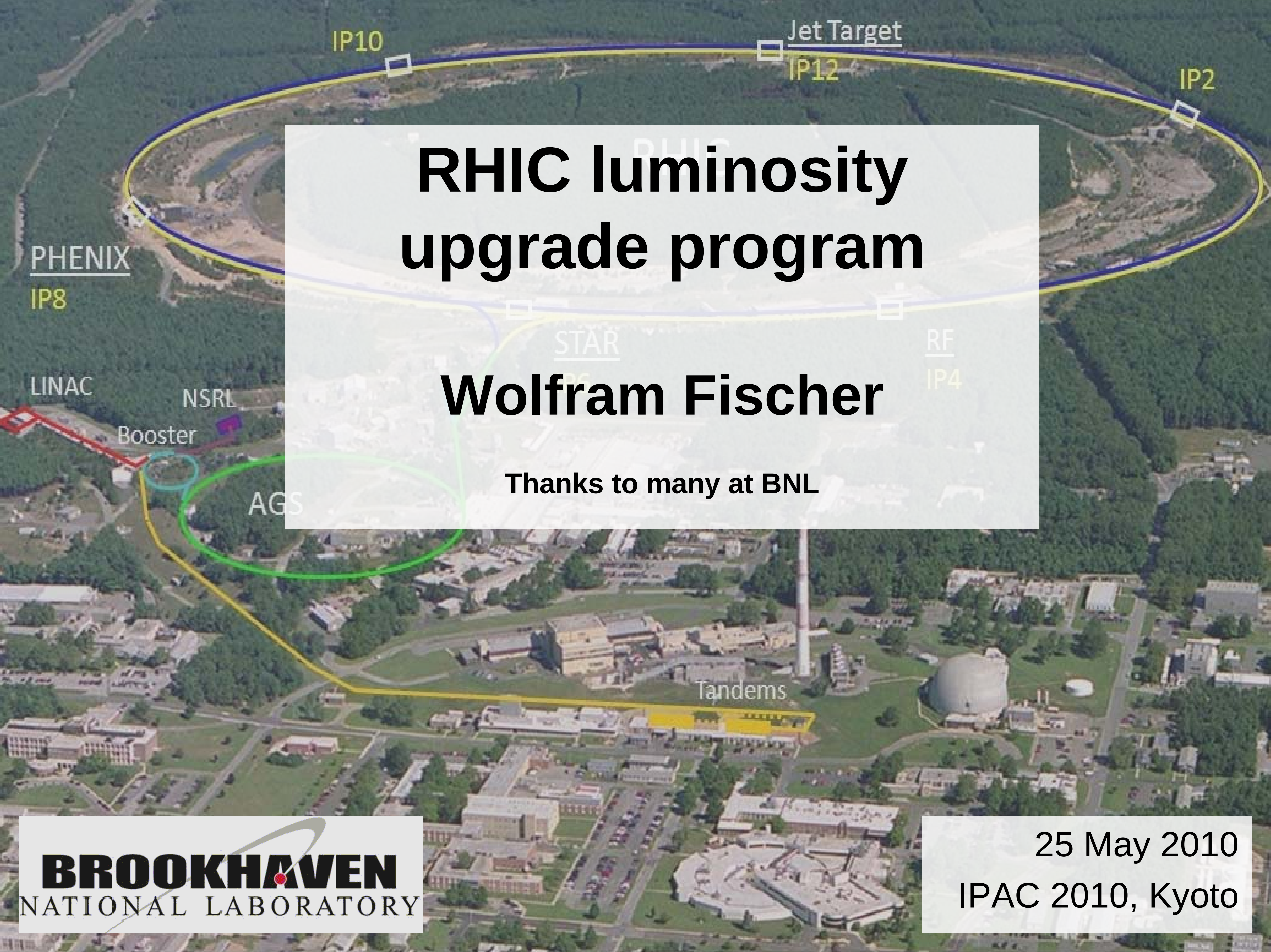


RHIC luminosity upgrade program

Wolfram Fischer

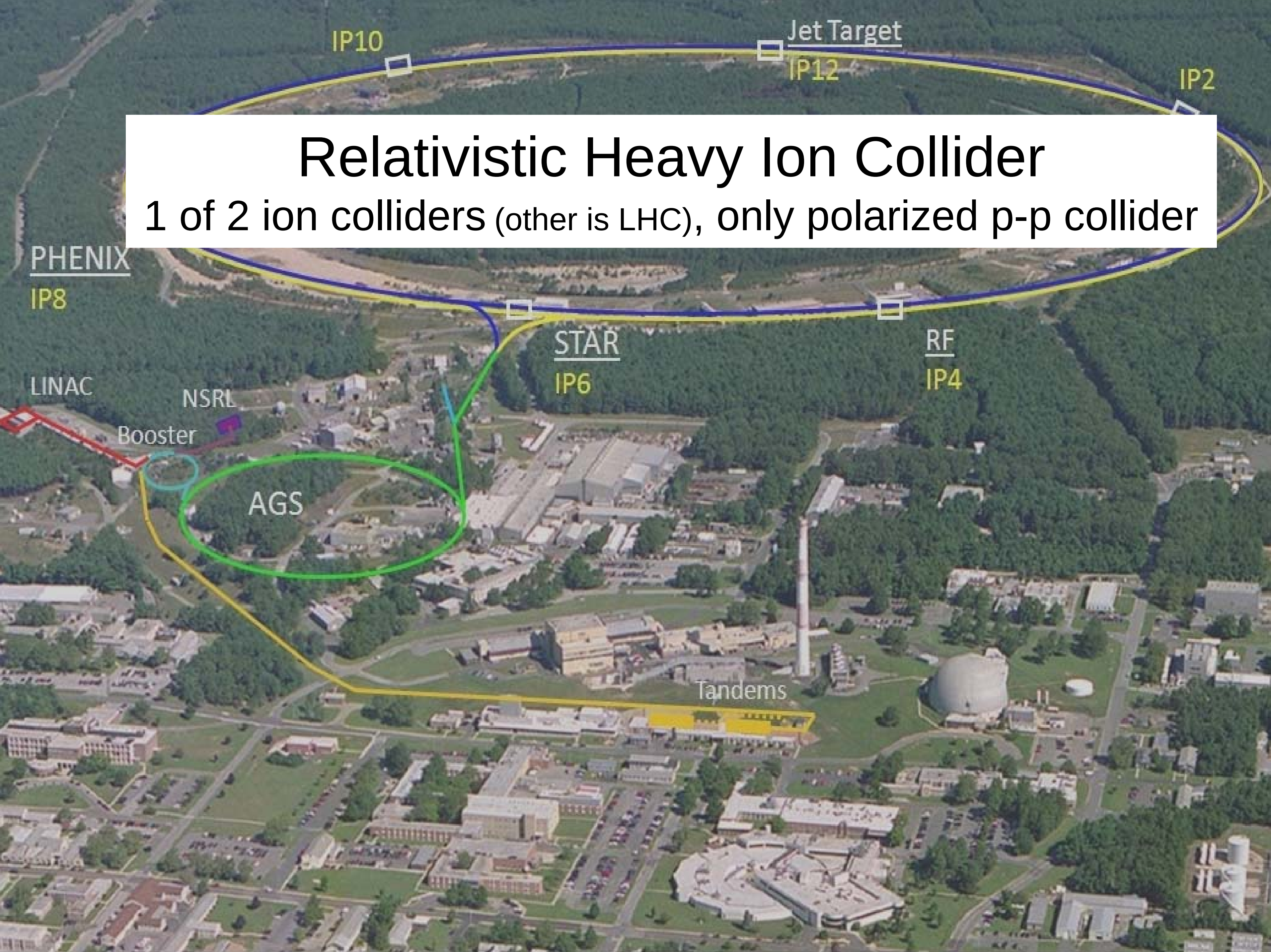
Thanks to many at BNL

BROOKHAVEN
NATIONAL LABORATORY

25 May 2010
IPAC 2010, Kyoto

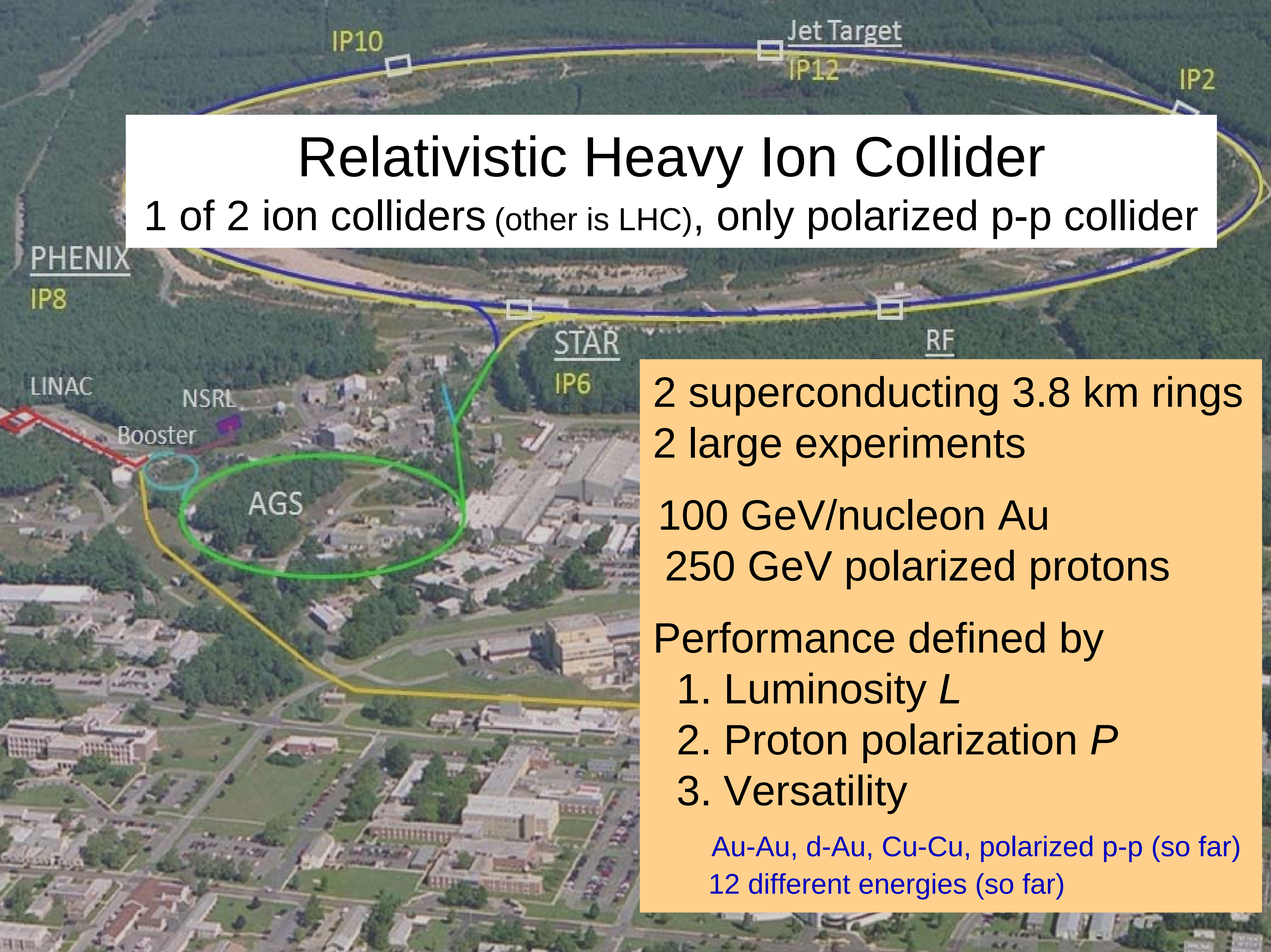
Relativistic Heavy Ion Collider

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



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 Au

250 GeV polarized protons

Performance defined by

1. Luminosity *L*
2. Proton polarization *P*
3. Versatility

Au-Au, d-Au, Cu-Cu, polarized p-p (so far)

12 different energies (so far)

Content

Heavy ion status and upgrades

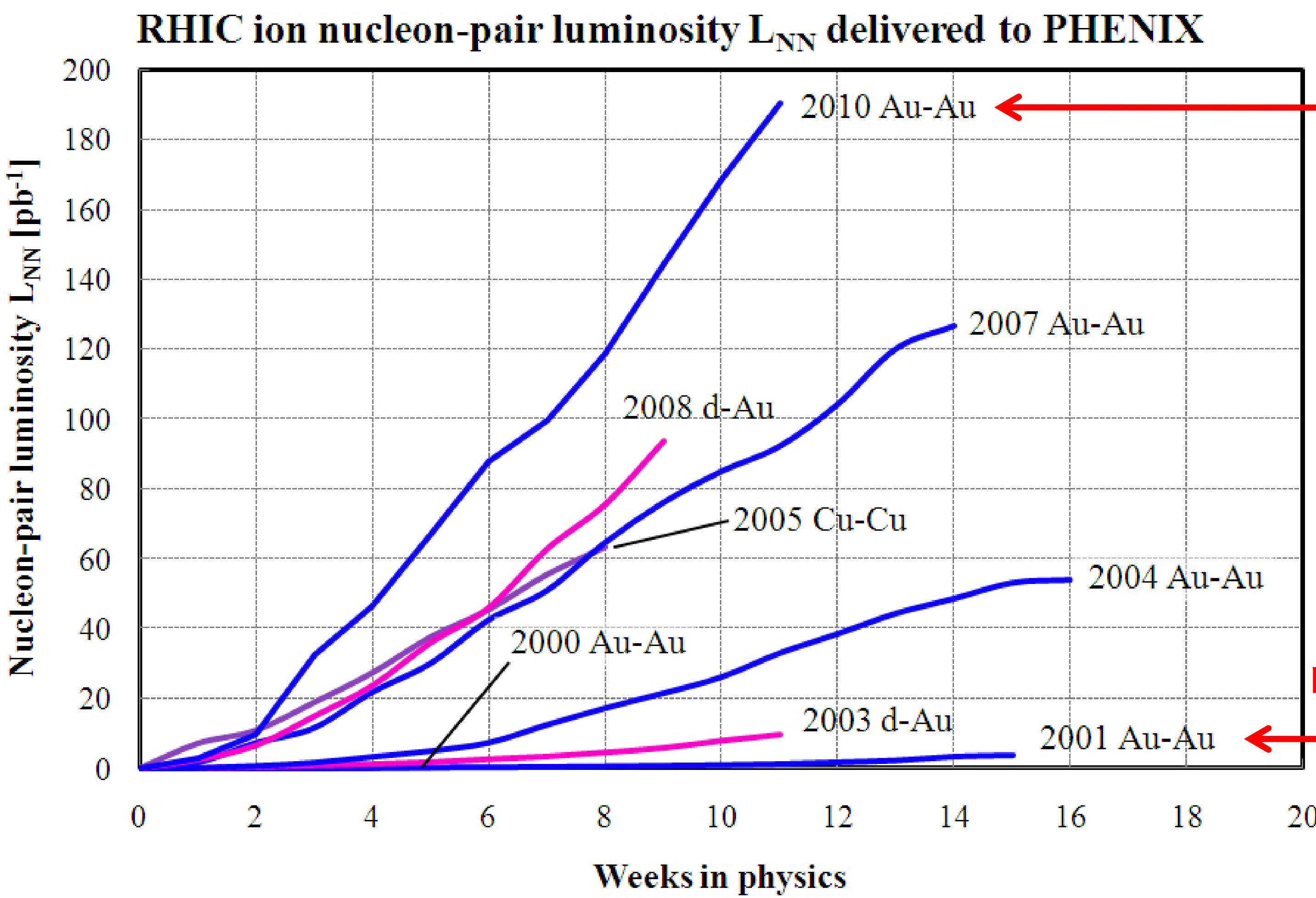
- Stochastic cooling & 56 MHz SRF
- Electron Beam Ion Source (EBIS)
- RHIC low energy operation and cooling

Polarized proton status and upgrades

- Polarized source
- AGS injector
- RHIC

RHIC heavy ions – luminosity evolution

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



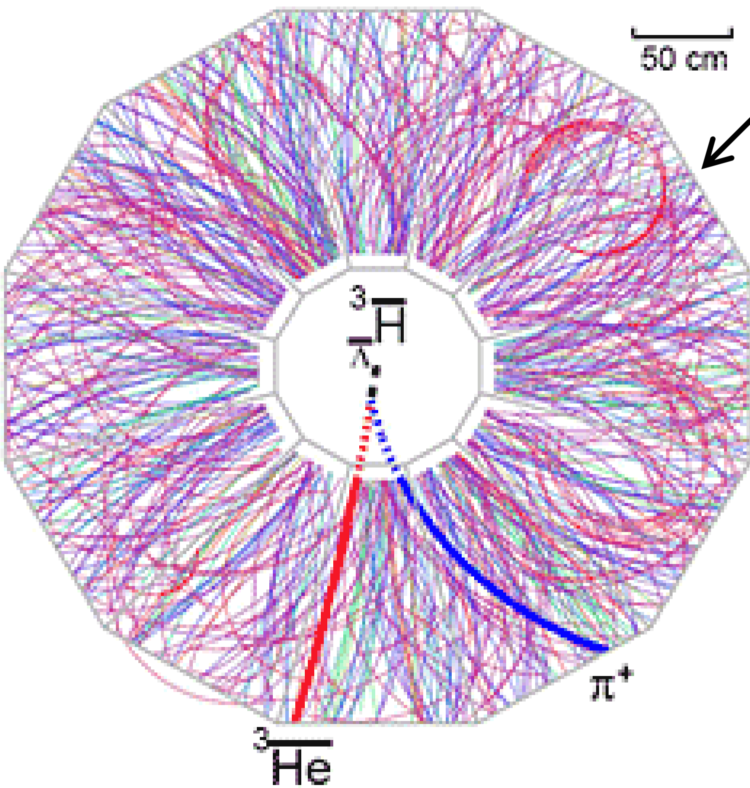
10x design in 2010

K. Brown et al.

MOPEC023

reached design in 2001

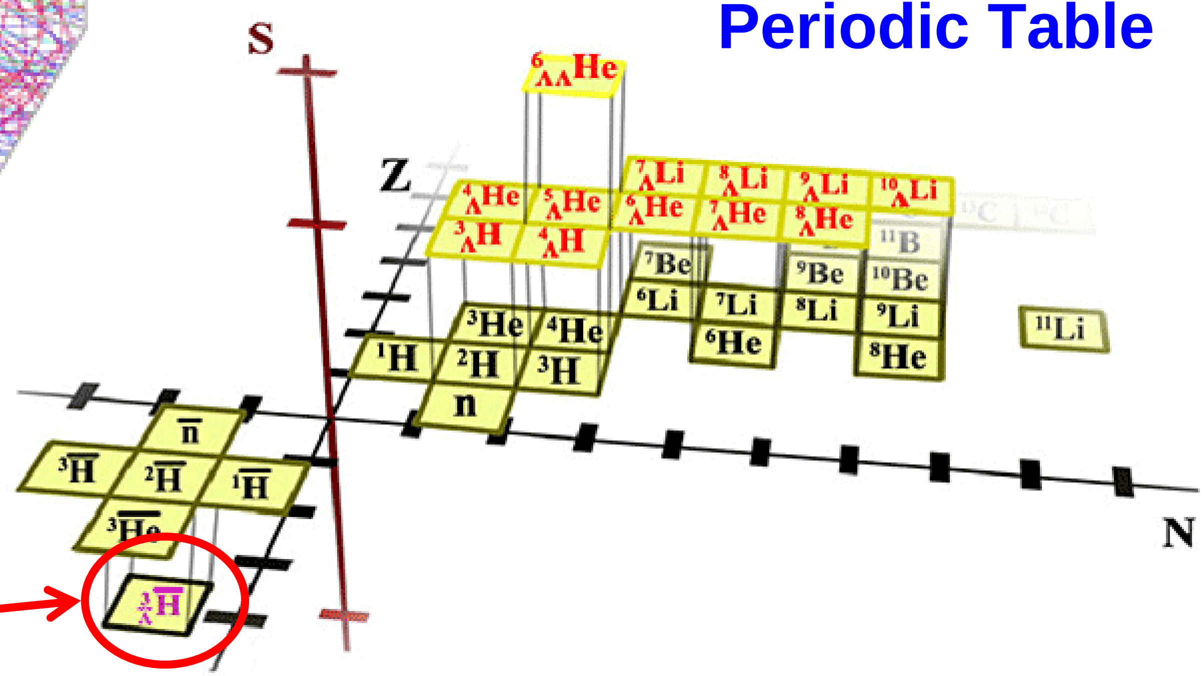
Recent RHIC result: heaviest anti-nucleus to date



STAR detector, Au-Au collision:

anti-nuclei form in quark-gluon plasma

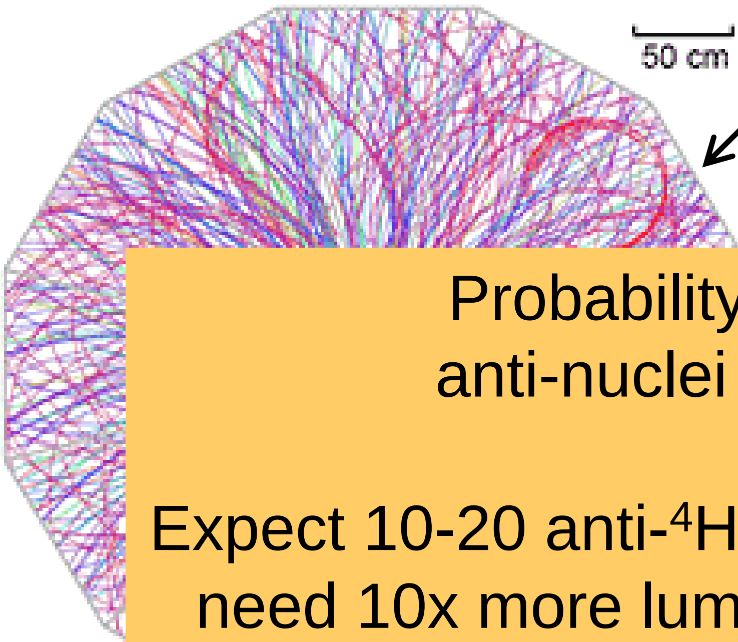
Periodic Table



New anti-nucleus

B.I. Abelev et al. (STAR Collaboration) *Science* 328 (2010).

Recent RHIC result: heaviest anti-nucleus to date

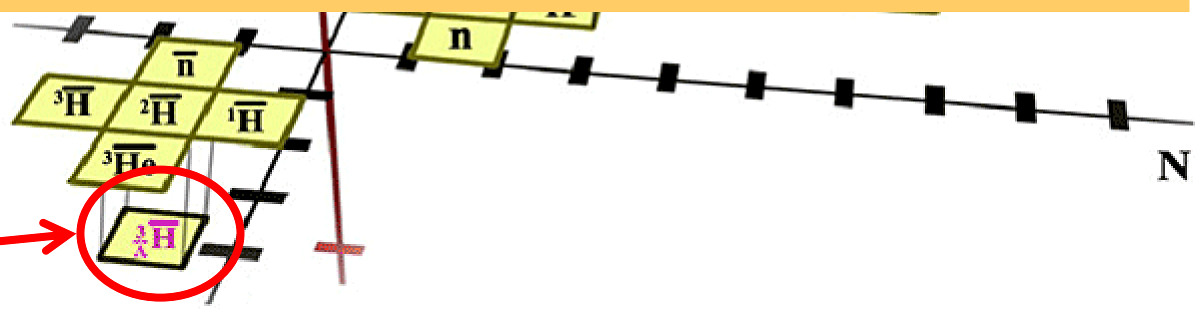


STAR detector, Au-Au collision:
anti-nuclei form in quark-gluon plasma

Probability for observing even heavier
anti-nuclei decreases rapidly with mass

Expect 10-20 anti-^{4}He nuclei from 11 weeks Au-Au in 2010,
need 10x more luminosity for anti-^{4}He(Λ) (Z. Xu, STAR)

Only large luminosity makes detection possible

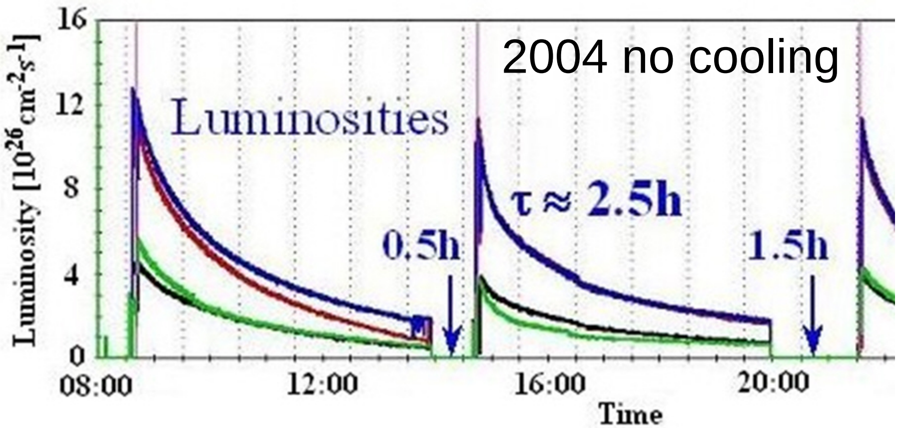


New anti-nucleus

B.I. Abelev et al. (STAR Collaboration) *Science* 328 (2010).

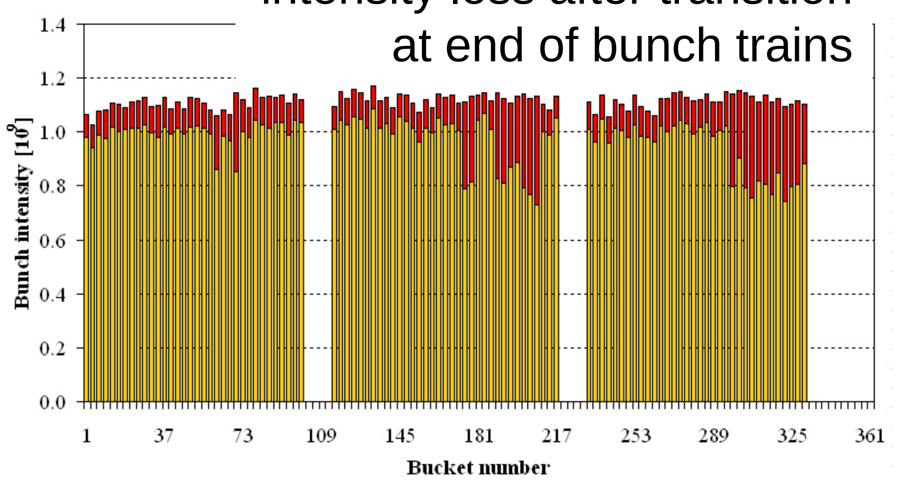
RHIC heavy ions – luminosity limits

1. Intrabeam scattering
   Leads to debunching and transverse emittance growth
   Bunched beam stochastic cooling during stores

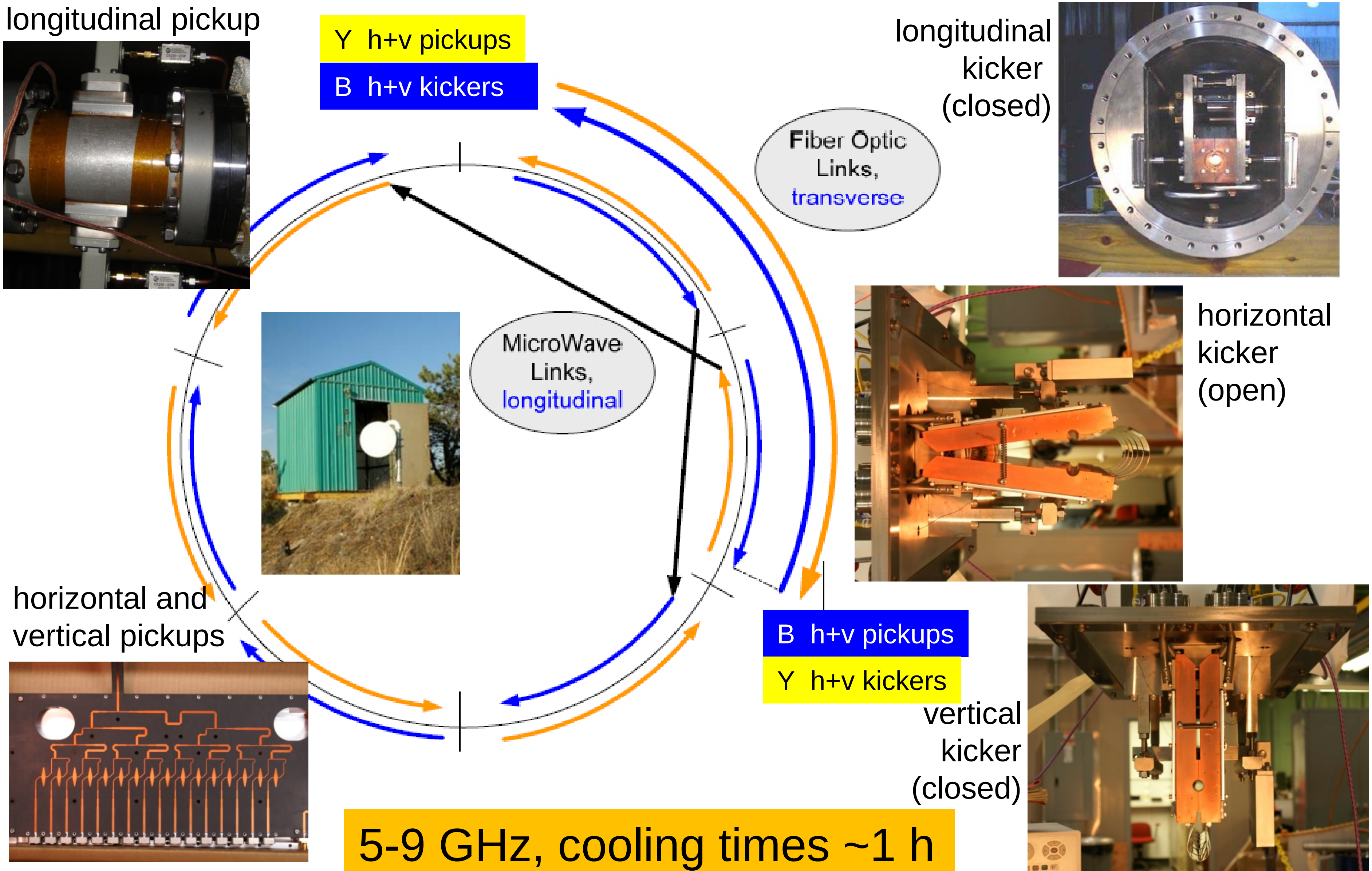


2. Chromatic abberations with small β^*
   With β^* = 60 cm could not correct nonlinear chromaticity with beam-based method (momentum aperture too small), retreated to β^* = 70 cm
   Include chromatic corrections in lattice design

3. Instabilities at transition
   Limit bunch intensity, driven by impedance and electron clouds
   Reduce SEY in arcs (straights are NEG coated)**, feedback**



RHIC – 3D stochastic cooling for heavy ions

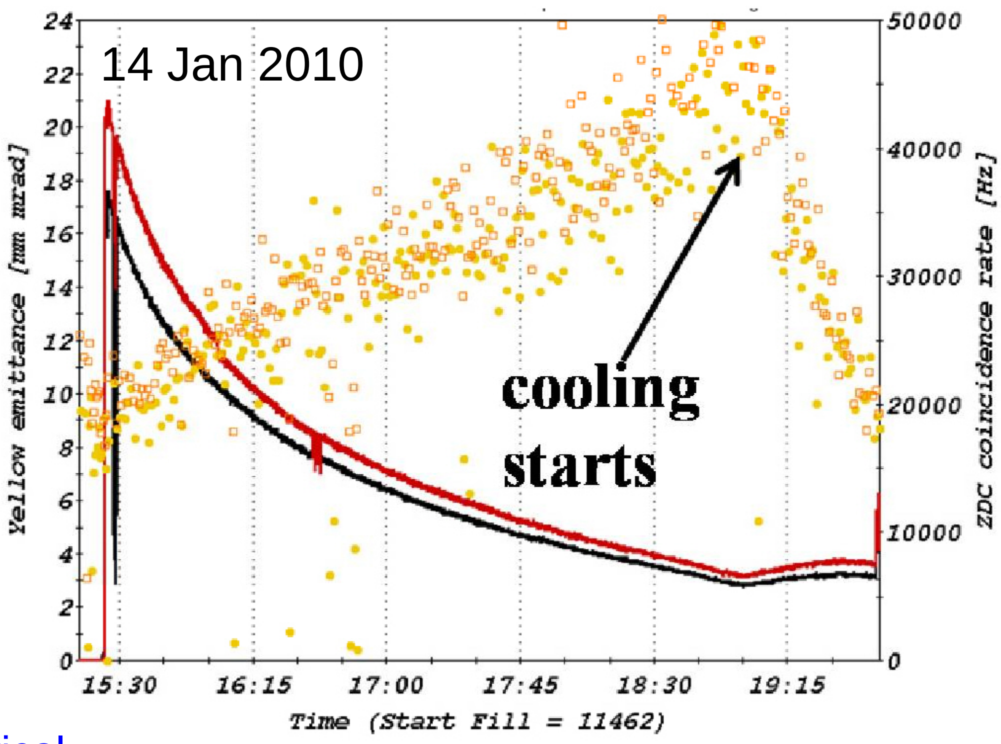


M. Brennan, M. Blaskiewicz, F. Severino, Phys. Rev. Lett. **100** 174803 (2008); PRST-AB, PAC, EPAC

RHIC – bunched beam stochastic cooling for heavy ions

M. Brennan
M. Blaskiewicz et al.

- **Longitudinal cooling since 2007**
- **First transverse (vertical) cooling in 2010**

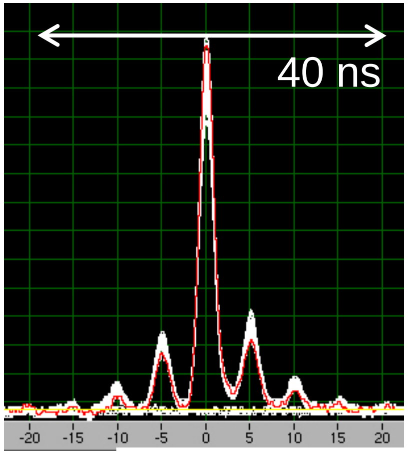


- **So far stochastic cooling increased average store luminosity by factor 2**
- **Expect another factor 2 with full 3D cooling**

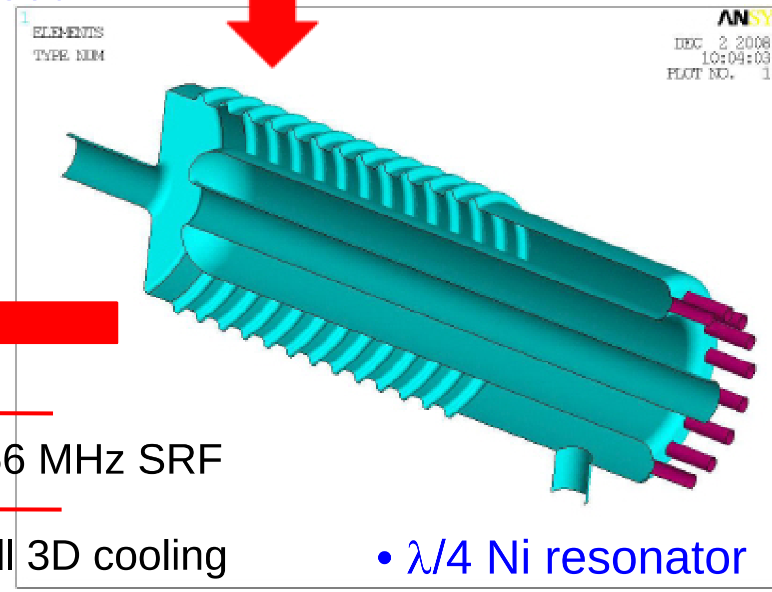
Issues:

- Vacuum leaks at feedthroughs
- Mechanical motion of long. kickers
- Cross-talk between Blue and Yellow vertical system (addressed by 100 MHz shift in Blue)
- Construction, installation, and commissioning of horizontal systems

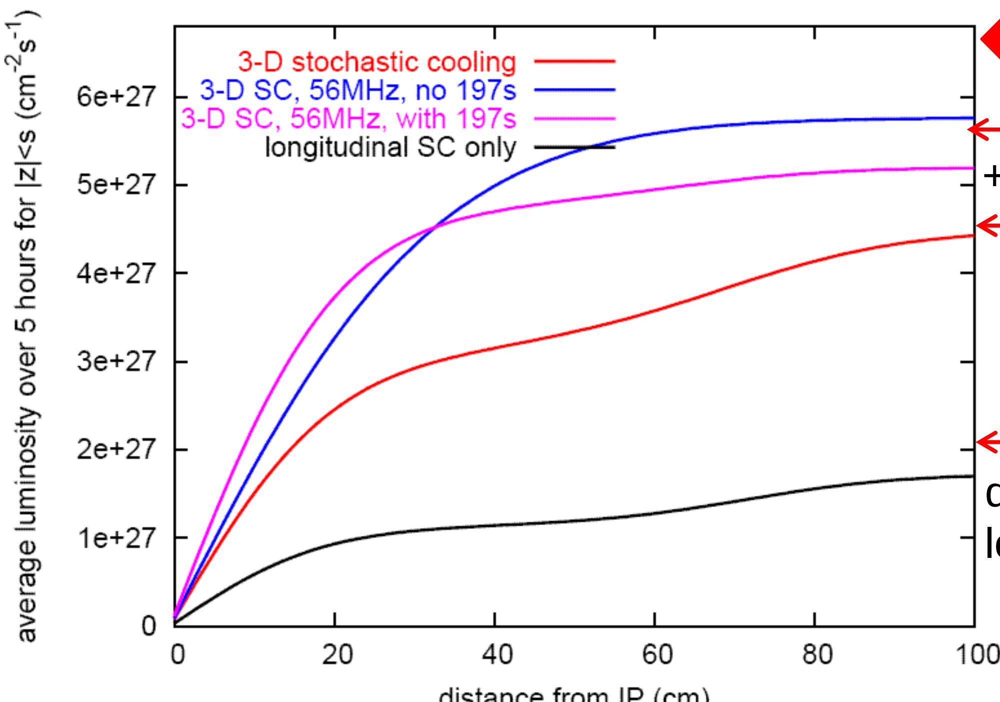
56 MHz SRF for heavy ions – under construction (I. Ben-Zvi et al.)



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



Average luminosity vs. vertex size



+ 56 MHz SRF

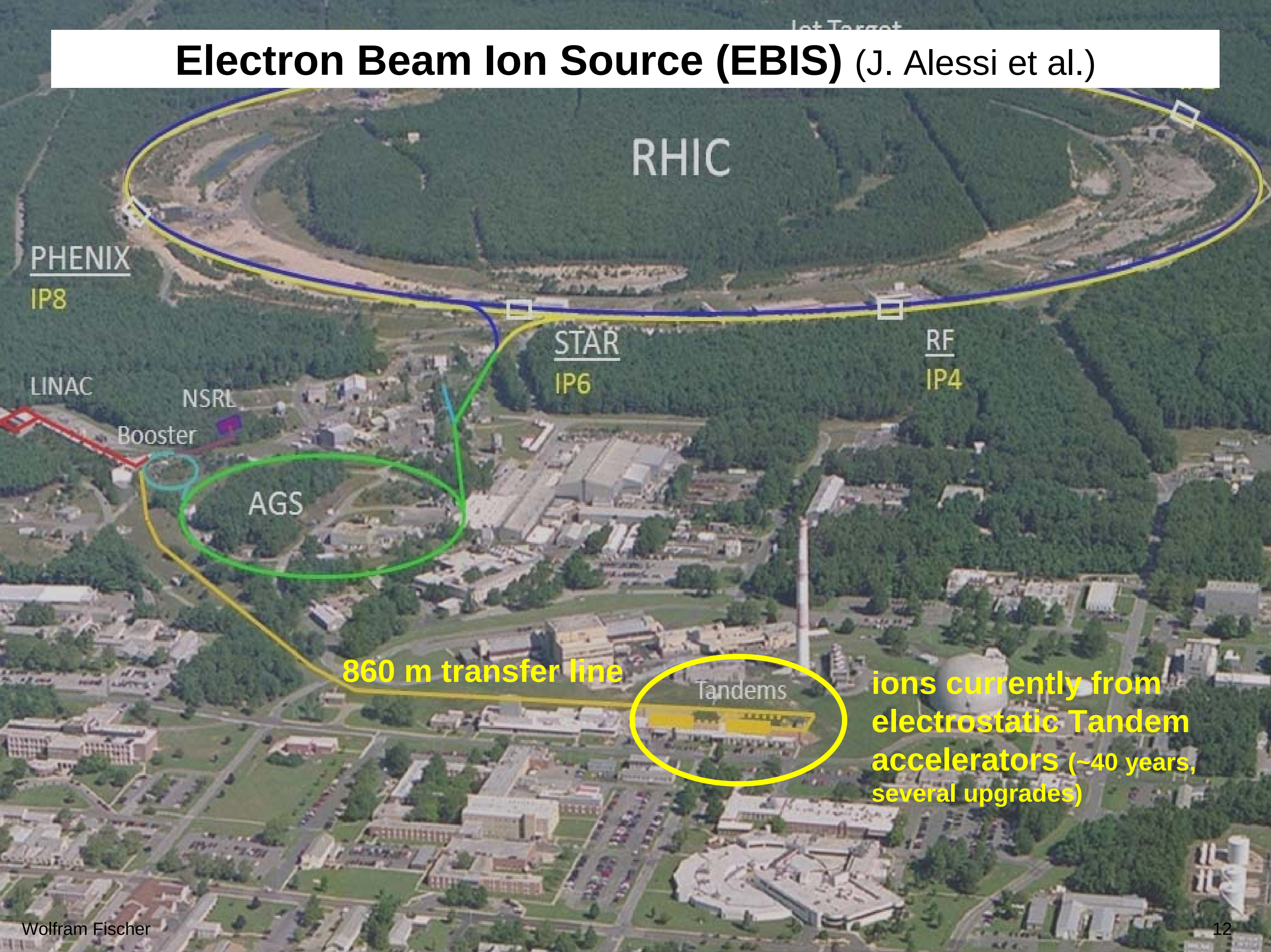
full 3D cooling

demonstrated 2010
long. + ver. cooling

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

Calculations by M. Blaskiewicz

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



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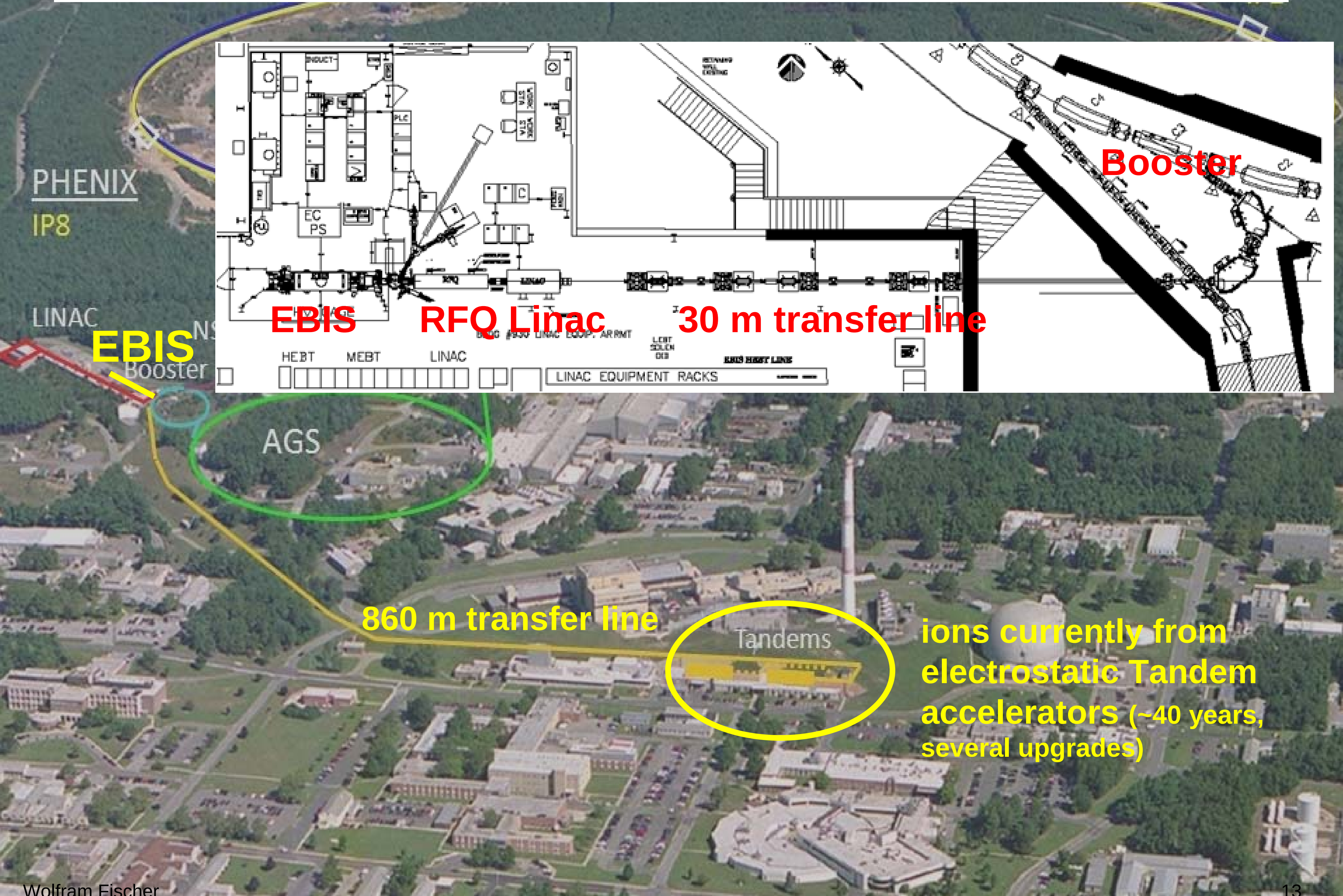
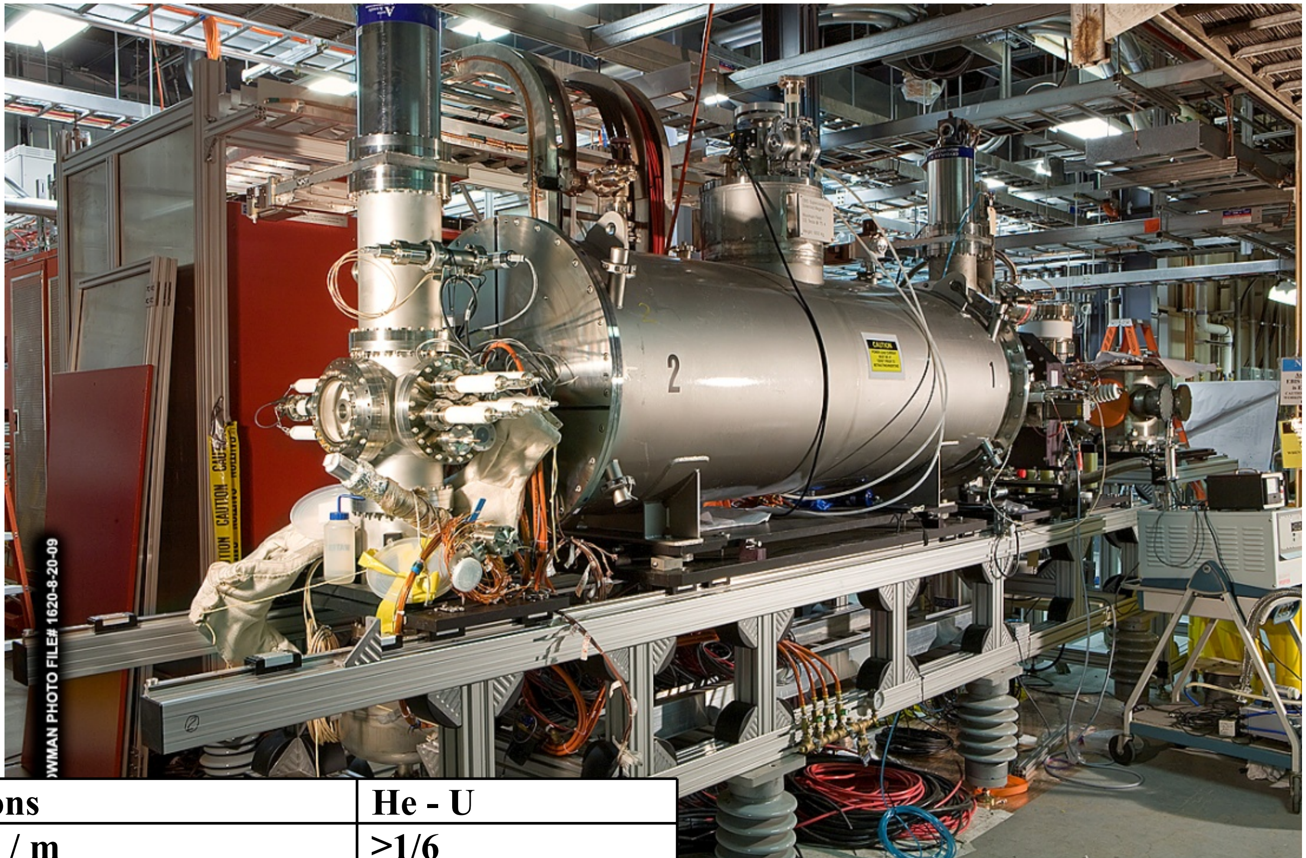


Electron Beam Ion Source (EBIS) (J. Alessi et al.)

10 A electron beam creates desired charge state in trap within 5 T superconducting solenoid



Ions	**He - U**
Q / m	**≥1/6**
Current	**> 1.5 emA**
Pulse length	**10 μs (1-turn injection)**
Repetition rate	**5 Hz**
Output energy	**2 MeV/nucleon**
Time to switch species	**1 second**

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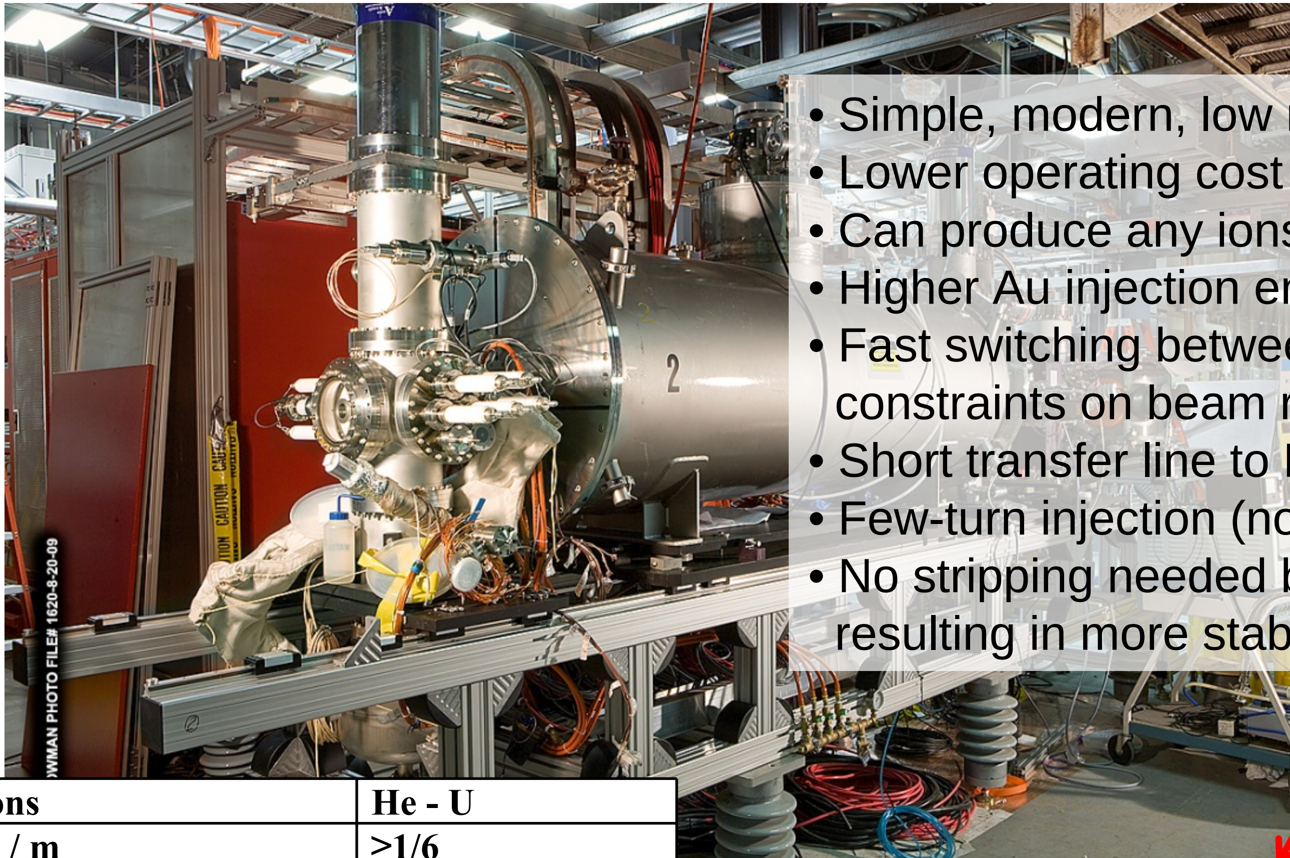

- Simple, modern, low maintenance
- Lower operating cost
- Can produce any ions (noble gases, U, He^3↑)
- Higher Au injection energy into Booster
- Fast switching between species, without constraints on beam rigidity
- Short transfer line to Booster (30 m)
- Few-turn injection (now about 50)
- No stripping needed before the Booster, resulting in more stable beams

Ions	**He - U**
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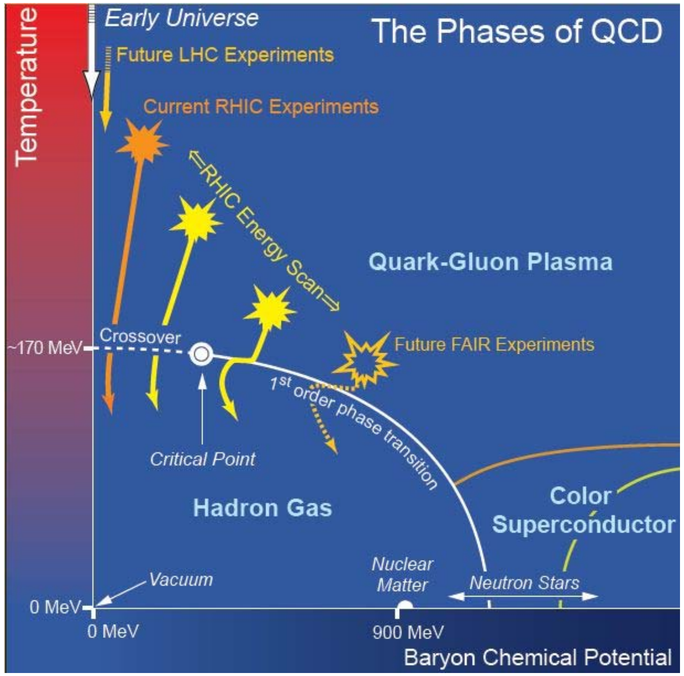
RHIC experiments eager to have collision of U nuclei in 2011
(heavier than Au, non-spherical)

RHIC – low energy heavy ion operation (T. Satogata et al.)

US NSAC report 2007

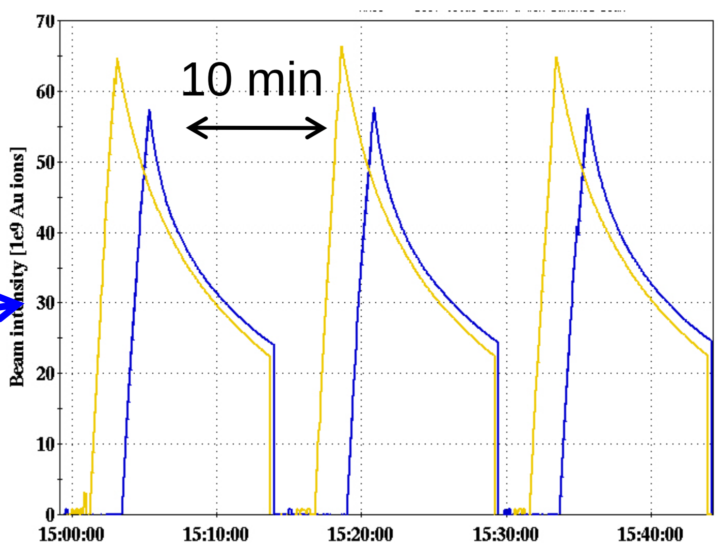


Energy scan now extends <u>below nominal injection energy</u> in search of critical point in QCD phase diagram

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 **($\Delta Q_{\mathrm{Laslett}}$ ~ 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 ($B\rho$)**



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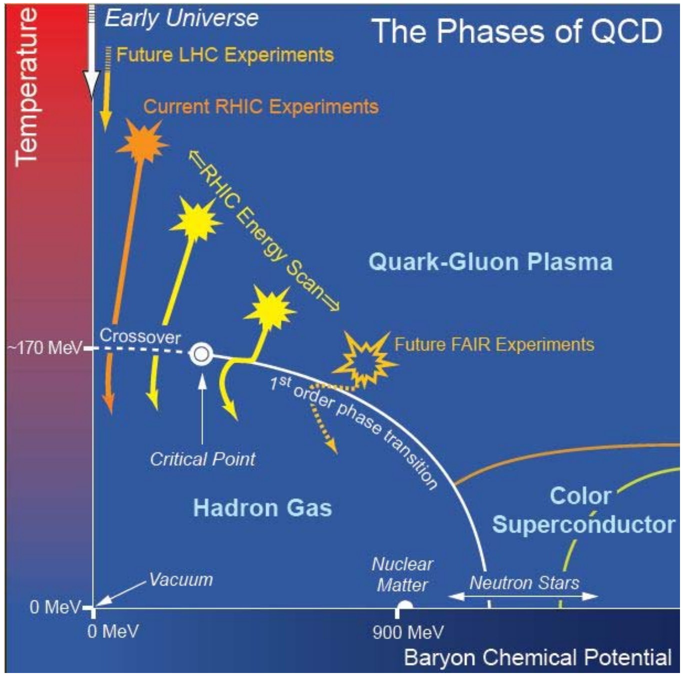

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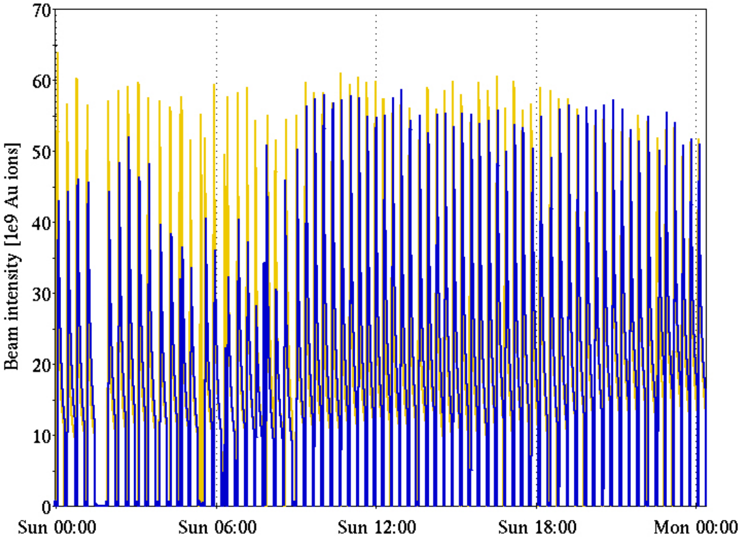


e-cooling for low energy collider operation (A. Fedotov et al.)

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)**

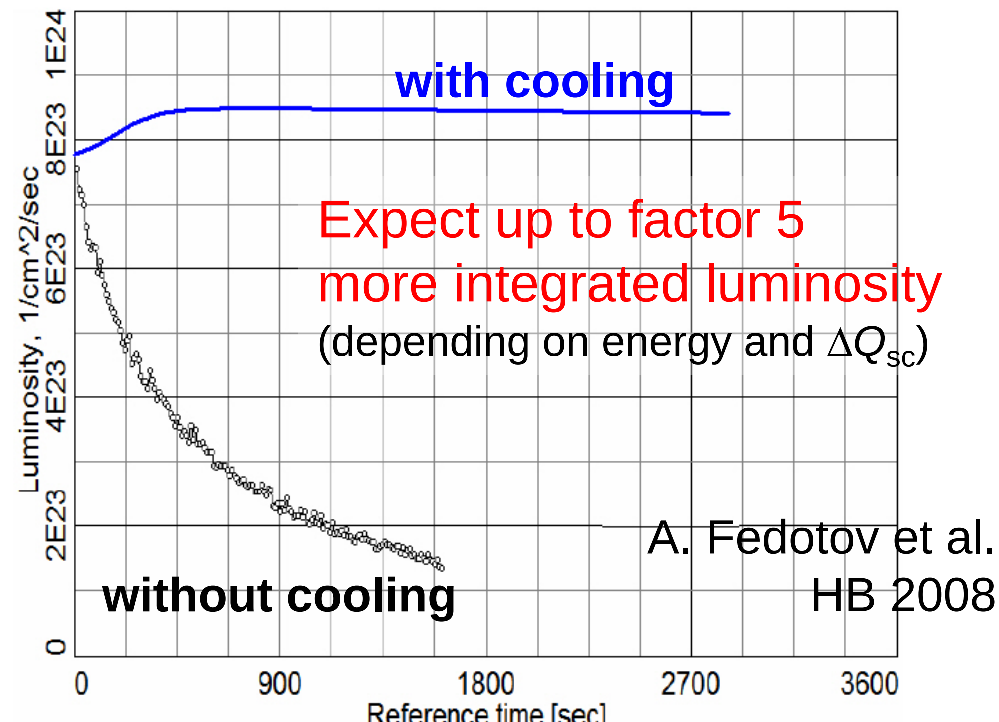


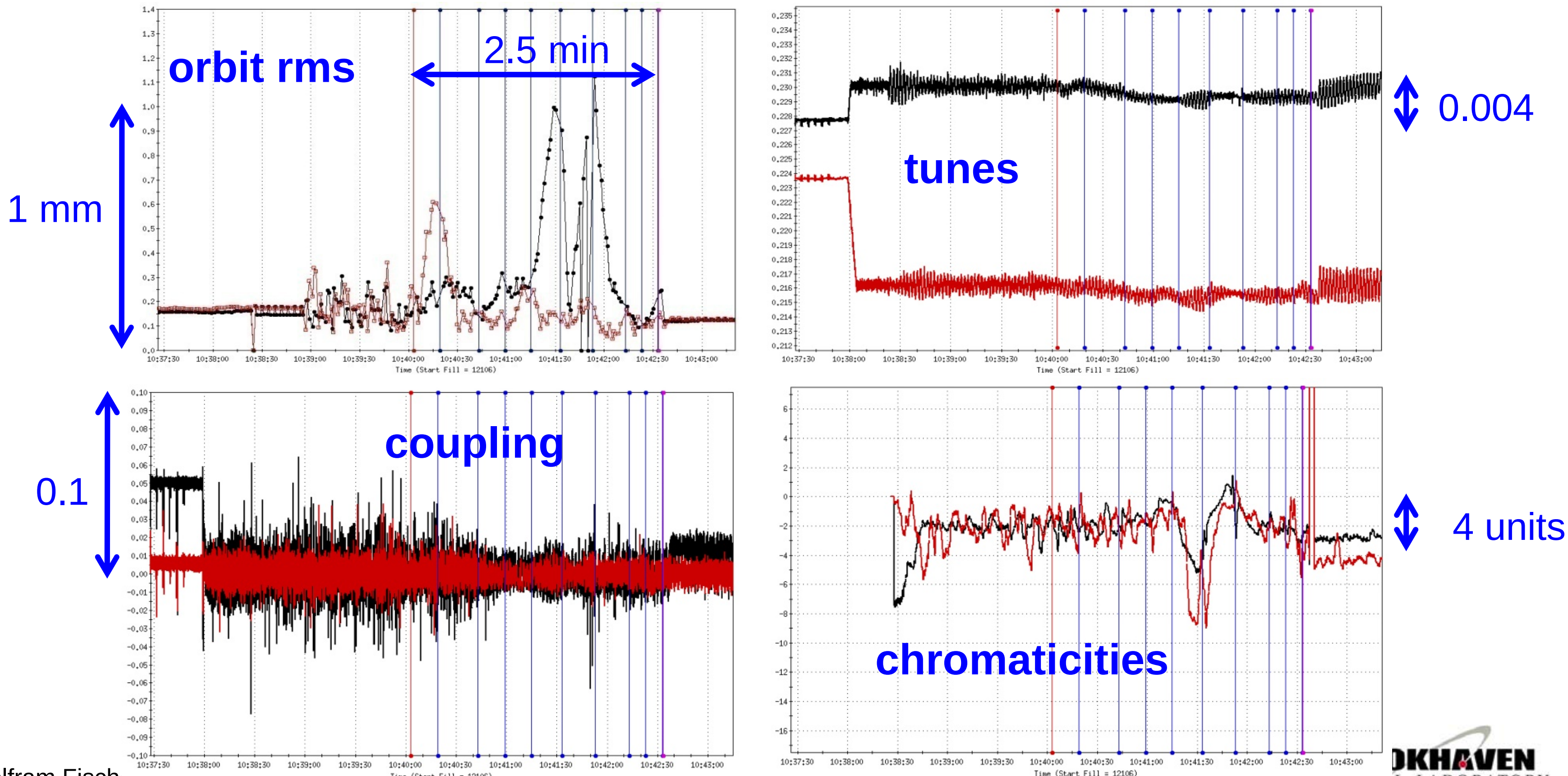
Figure 4. Simulation of luminosity with (blue line) and without (black dots) electron cooling at γ=2.7.

Upgrades for heavy ions and polarized protons – feedbacks

- 1 Hz global orbit feedback (ramp and store)
- 1 Hz orbit, tune, coupling, chromaticity feedback (ramp)
- 10 Hz local orbit feedback (store) – tested R. Michnoff et al.

M. Minty et al.
MOPEC029
MOPEC030
MOPEC031

First ramp with simultaneous orbit, tune, coupling and chromaticity feedback (both beams)

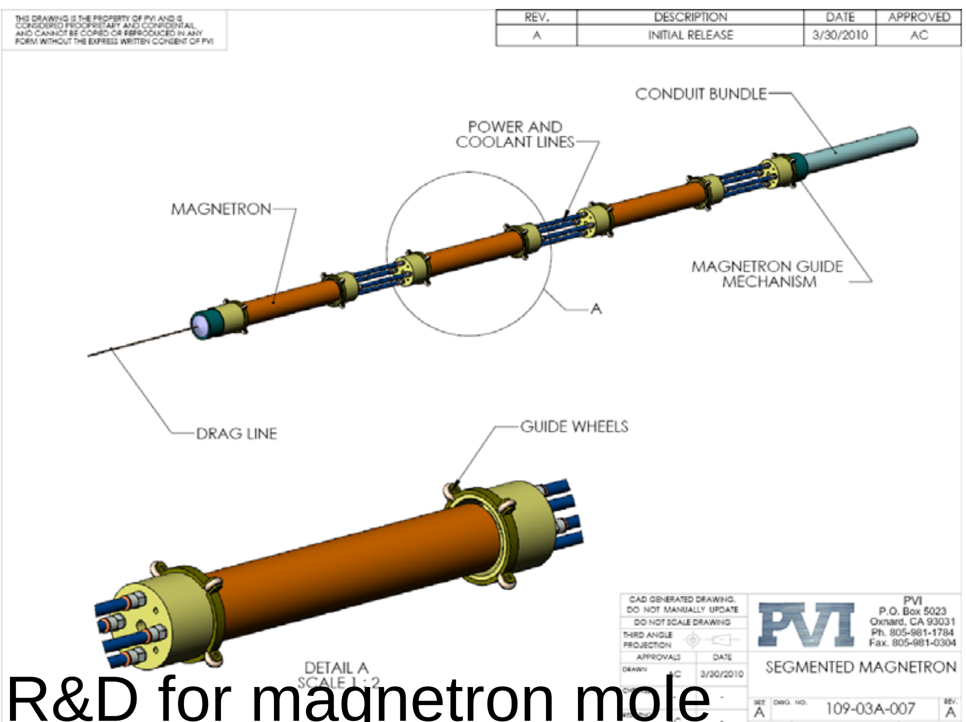


Upgrades for heavy ions and polarized protons – in situ-coating

- Electron clouds limit
  - Ion intensity (through instability at transition)
  - Proton emittance at injection, and intensity
- Warm parts are largely coated with NEG
- Cold arcs are stainless steel, not coated

Need in-situ coating for arcs

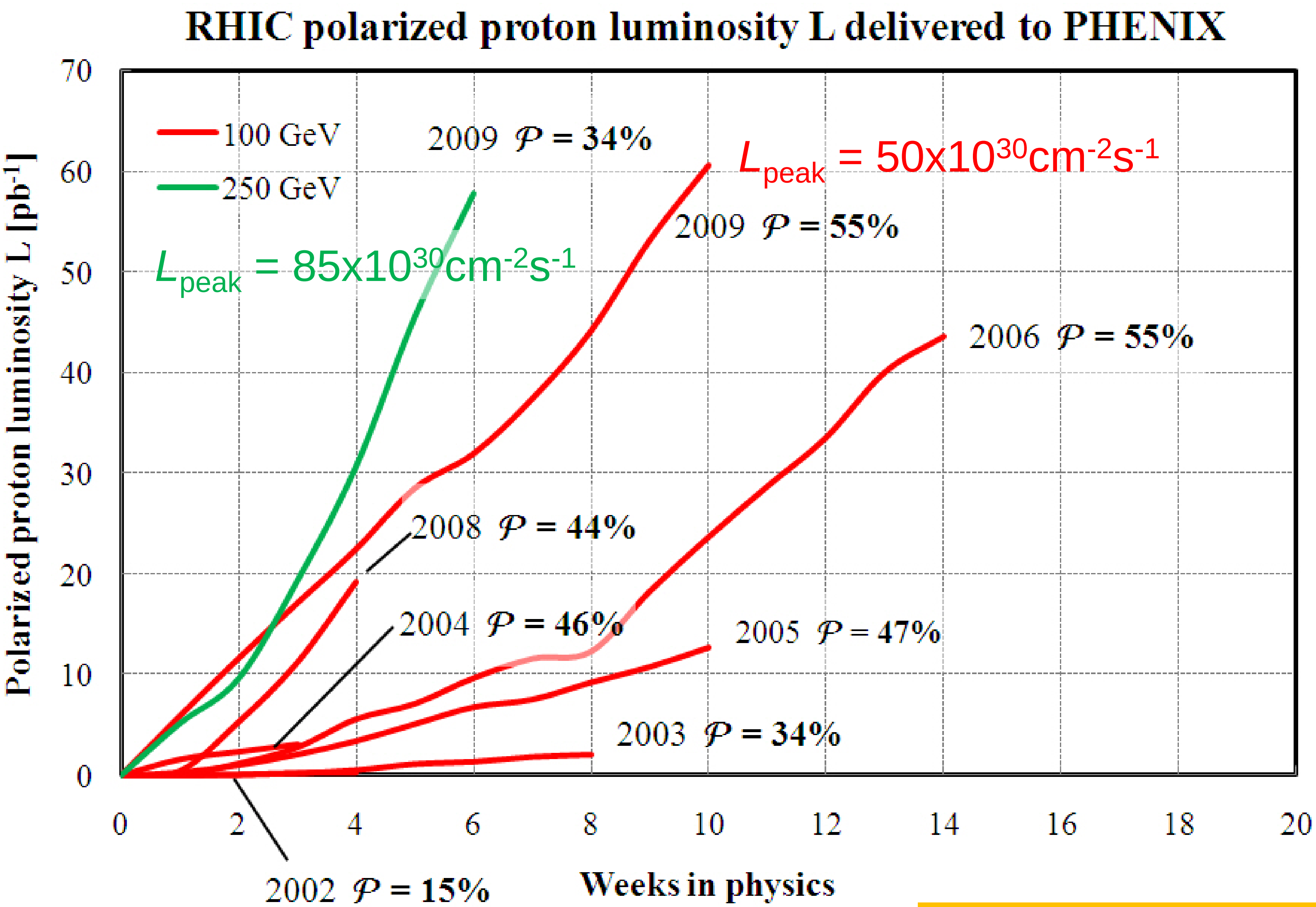
A. Hershkovich et al.
TUPEA082



R&D for magnetron mole

Test tube coated with Cu

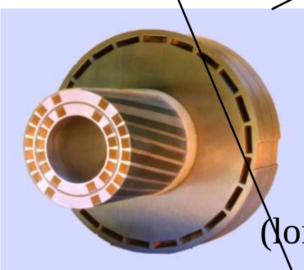
RHIC polarized protons – luminosity and polarization

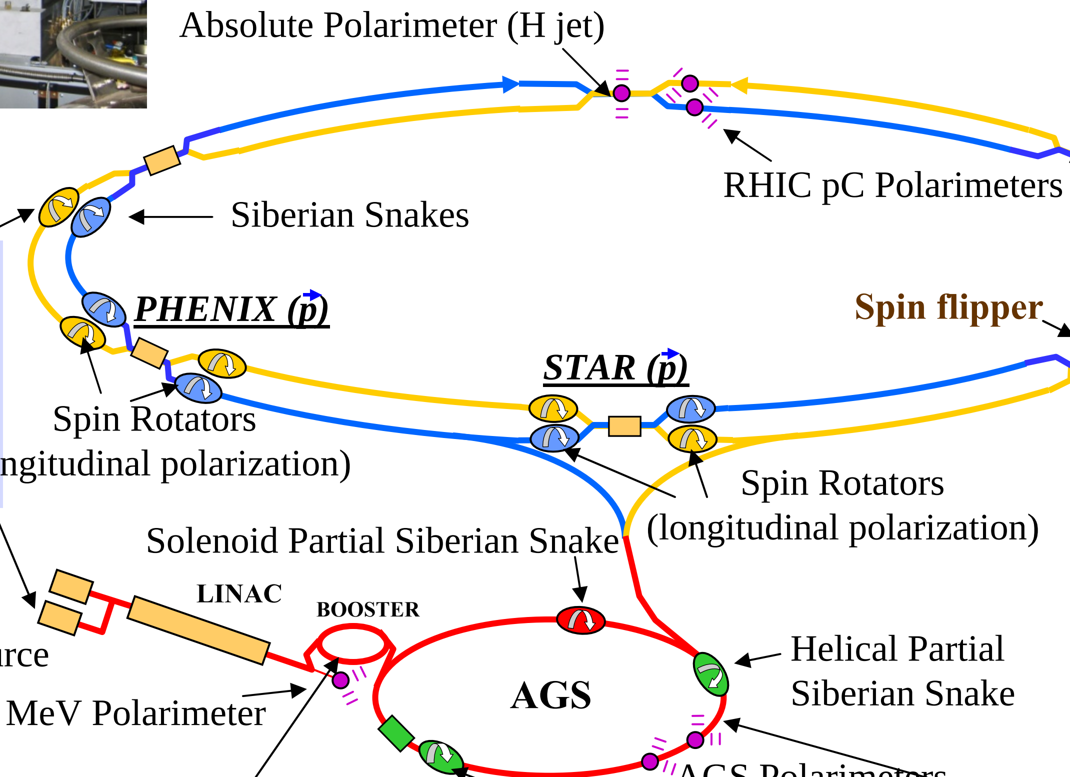


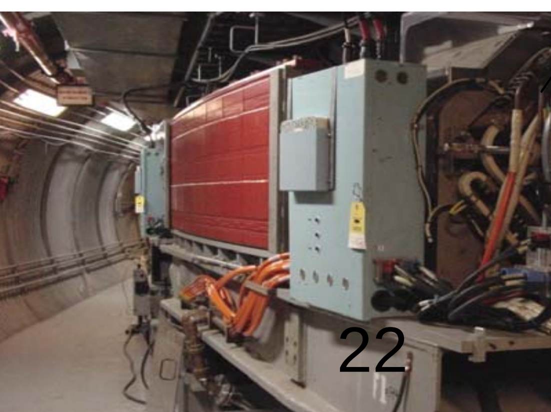
$FOM = LP^4$

(longitudinally polarized beams)

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







RHIC protons – polarization and luminosity limits

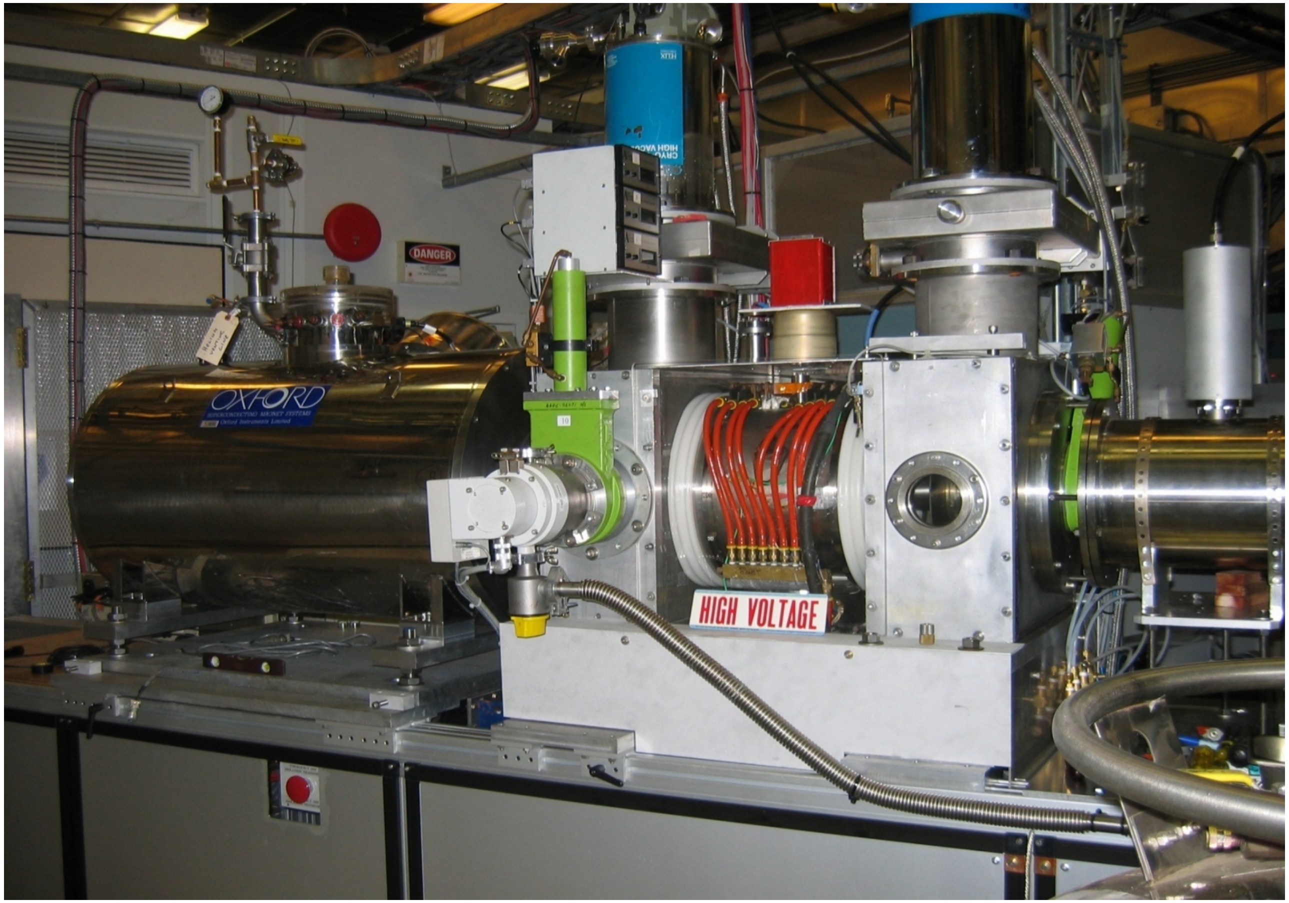
1. **AGS : proton bunches with high intensity, high polarization and low emittance**
   polarized source upgrade (under way)
   AGS horizontal tune jump system (tested in 2009-10)

2. **RHIC: polarization transmission to 250 GeV**
   acceleration near 2/3 resonance (tested in 2010)

3. **RHIC: intensity transmission to 250 GeV**
   beam dump system modifications (thicker beam pipe in dump)
   Yellow ramp transmission (9 MHz rf system)

4. **RHIC: peak luminosity and luminosity lifetime**
   reached lower β^* limit at 100 GeV (not necessarily a problem at 250 GeV)
   electron lenses allow for larger beam-beam parameter

Optically Pumped Polarized H⁻ source at RHIC (A. Zelenski)



RHIC OPPIS produces reliably 0.5-1.0 mA polarized H^- ion current.

Polarization at 200 MeV:
P = 80-85%.

Beam intensity (ion/pulse) routine operation:

Source	- 10^{12} H^-/pulse
Linac	- $5x10^{11}$
AGS	- 1.5-$2.0x10^{11}$
RHIC	- $1.5x10^{11}$/bunch

- 29.2 GHz ECR source used for primary proton beam generation
- source was originally developed for dc operation
- 10x intensity increase was demonstrated in a pulsed operation by using a very high-brightness Fast Atomic Beam Source instead of the ECR source

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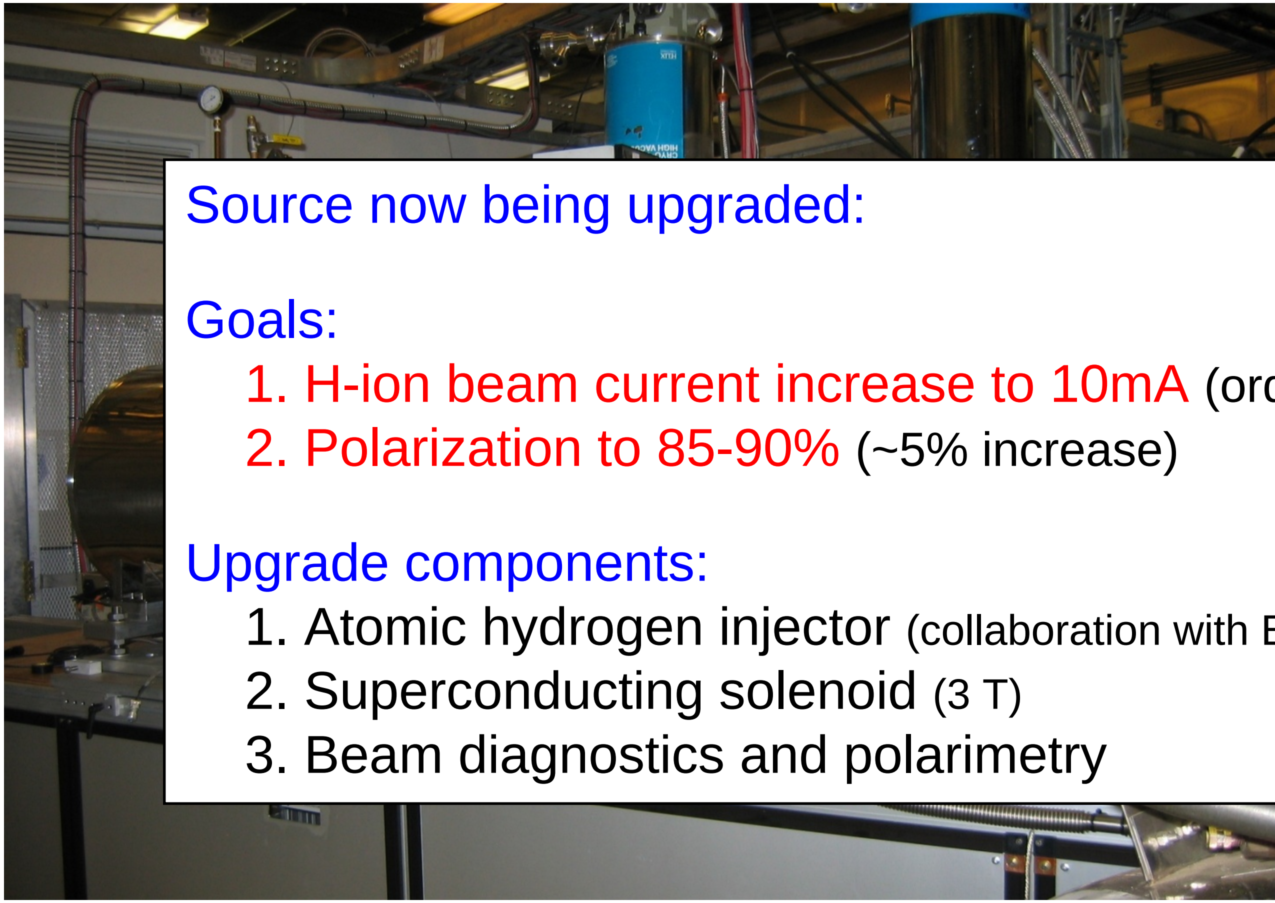
Optically Pumped Polarized H⁻ source at RHIC (A. Zelenski)



Source now being upgraded:

Goals:

1. H-ion 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

RHIC OPPIS produces reliably 0.5-1.0 mA polarized H⁻ ion current.

0 MeV:

n/pulse)

/pulse

0x10^{11}

RHIC - 1.5x10^{11}/bunch

- 29.2 GHz ECR source used for primary proton beam generation
- source was originally developed for dc operation
- 10x intensity increase was demonstrated in a pulsed operation by using a very high-brightness Fast Atomic Beam Source instead of the ECR source

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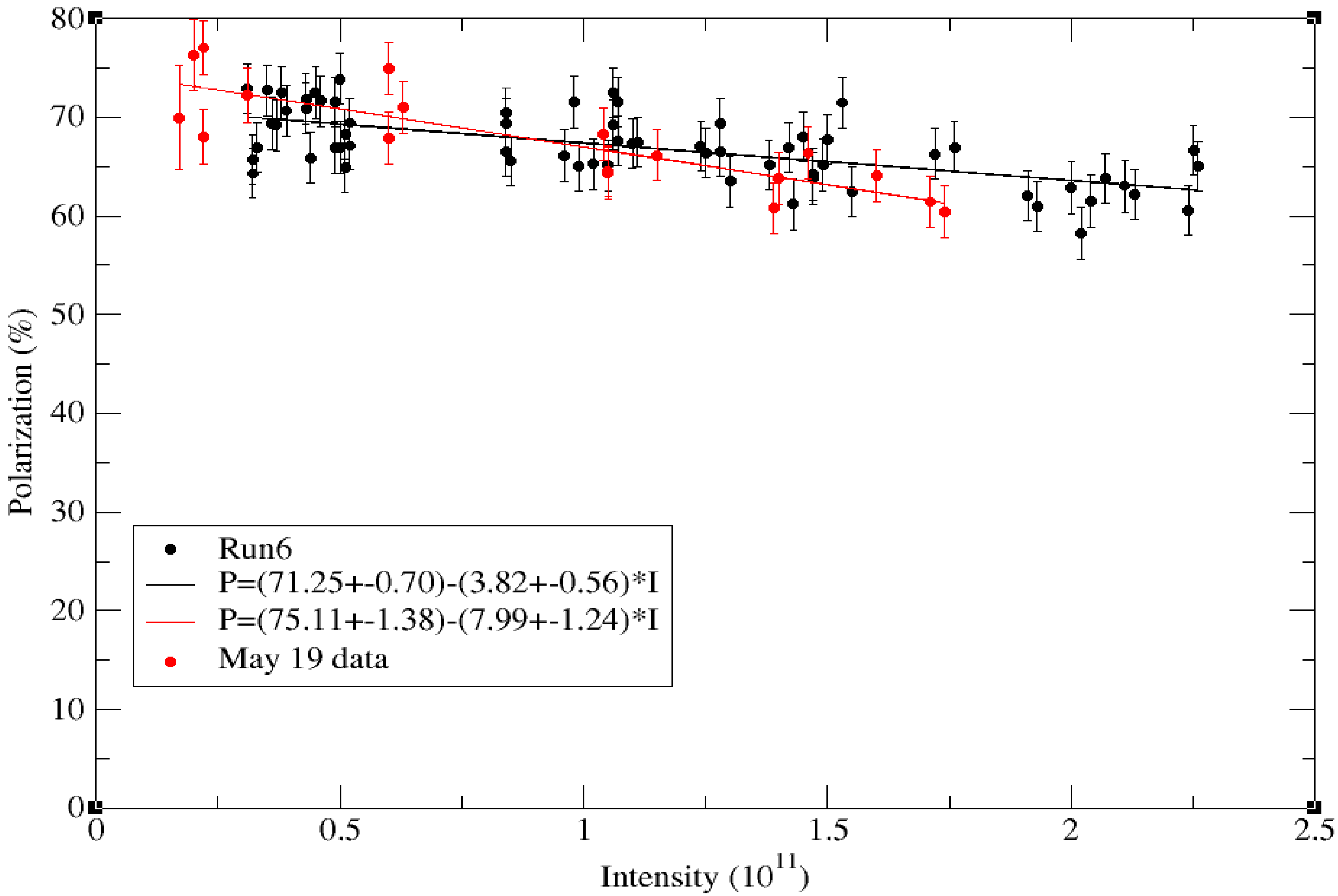
Polarized protons from AGS

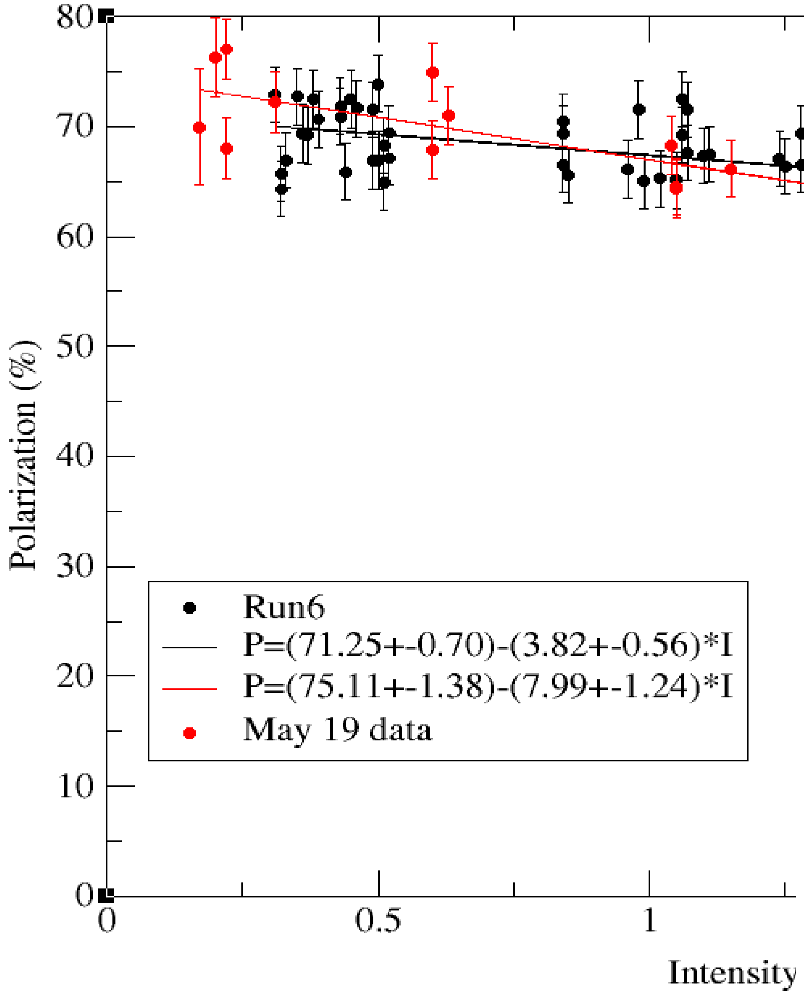
Intensity dependent polarization in AGS in 2006 and 2009



Courtesy H. Huang

Polarized protons from AGS

Intensity dependent polarization in AGS in 2006 and 2009



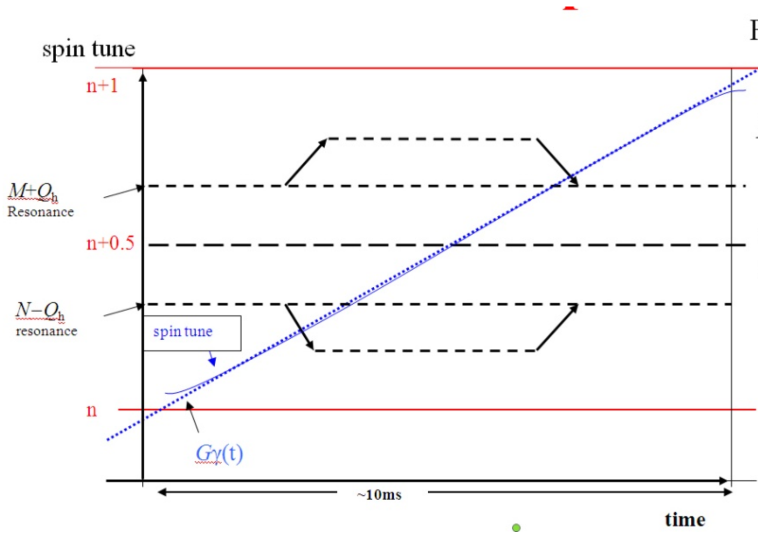
- Partial snakes prevent depolarization from low-order resonances
- With partial snakes stable spin direction is tilted, horizontal resonances can depolarize beam

AGS horizontal tune jump system under commissioning
up to 5% more polarization

Courtesy H. Huang

Horizontal tune jump system in AGS (H. Huang et al.)

- 2 partial snakes prevent depolarization from low-order resonances
- Stable spin direction with partial snakes is off-vertical, horizontal depolarizing resonances appear (82, causing 5% polarization loss)
- Horizontal tune jump system installed in the AGS ($\Delta Q = 0.04$, 100ms)
- Critical for success: jump timing, emittance preservation
- Completed tests:
  - Demonstrated better polarization at $G\gamma=7.5$ (extraction at $G\gamma=45.5$)
  - Polarization maximization with timing scans
  - Demonstrated emittance preservation ($\Delta\varepsilon/\varepsilon$ few percent) with β-beat correction (Q near integer)

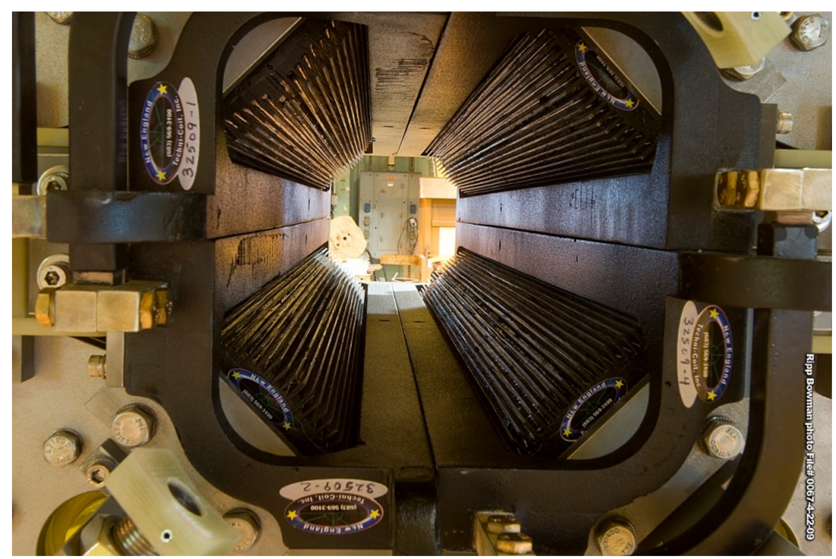


For isolated resonance:

$$P_f = P_0\left(2e^{-\frac{\pi|\varepsilon|^2}{2\alpha}} - 1\right)$$

resonance crossing rate is given by:

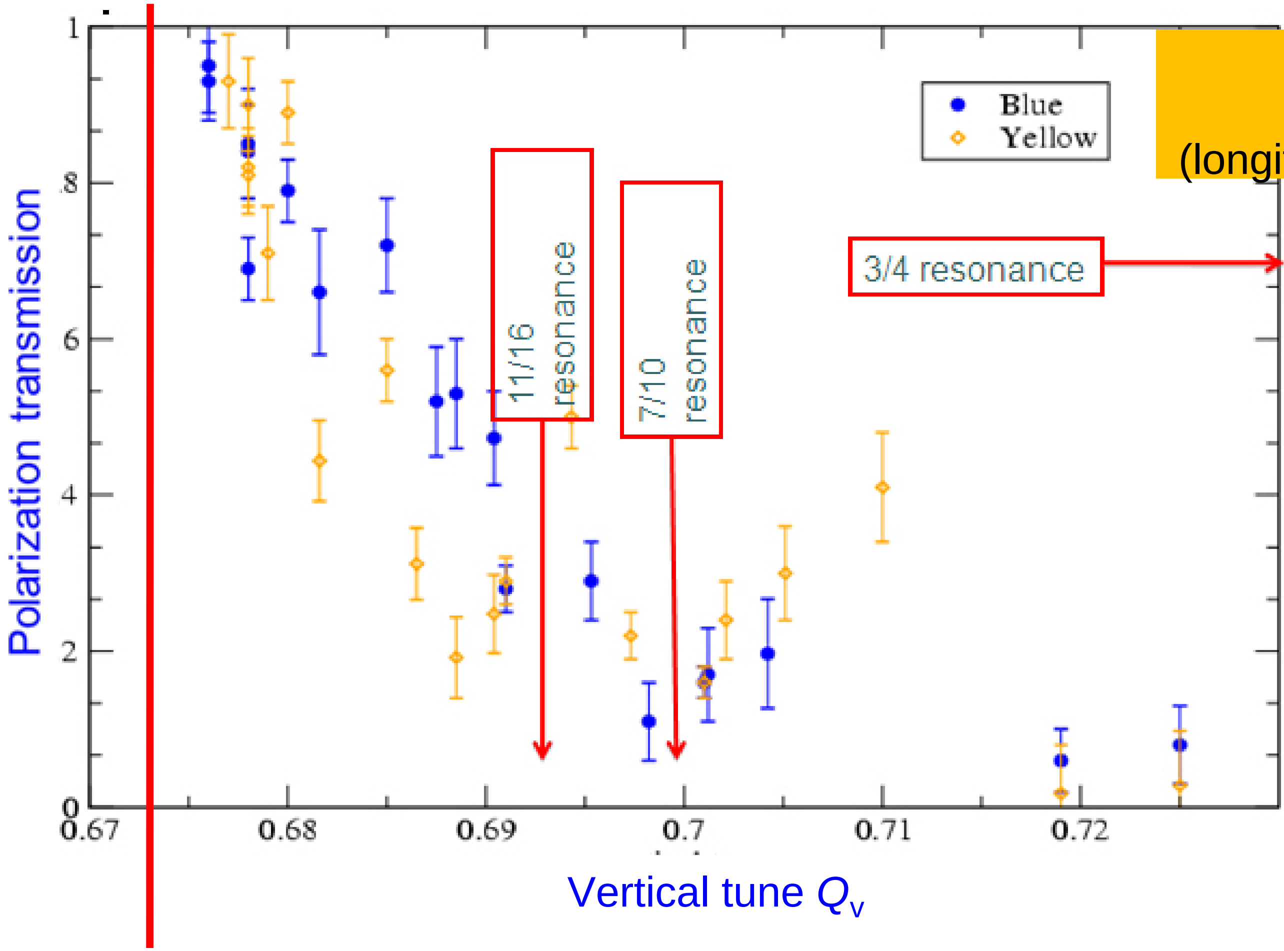
$$\alpha = \frac{dG\gamma}{d\theta} + \frac{d\nu}{d\theta}$$



RHIC polarized protons – acceleration to 250 GeV near Q_v = 2/3

Had only 34% polarization at 250 GeV (57% at 100 GeV)

M. Bai et al.



FOM = LP^4

(longitudinally polarized beams)

Need upgrade to main ps to reduce transients between ramp and flattop supplies (for 2011)

Tested acceleration with intense Au beam with **tune 0.005 away from 2/3**
Simulations (X. Gu, Y. Luo) to compared Au with p lattice DA

RHIC polarized protons – 9 MHz system

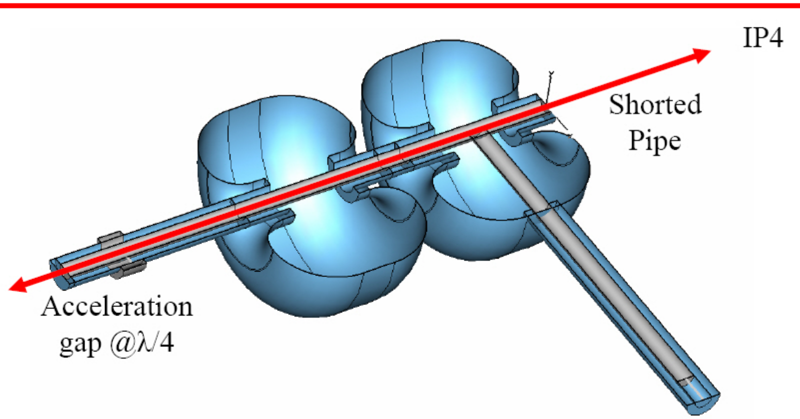
Problem: A. Zaltsman et al.

- **Inject close to and above transition in 28 MHz system (h = 360)**
- **Longitudinally matched bunches are short**
  emittance growth from e-cloud
- **Unmatched bunches have 4x larger longitudinal emittance**
  luminosity loss from hourglass effect and vertex size

Solution:

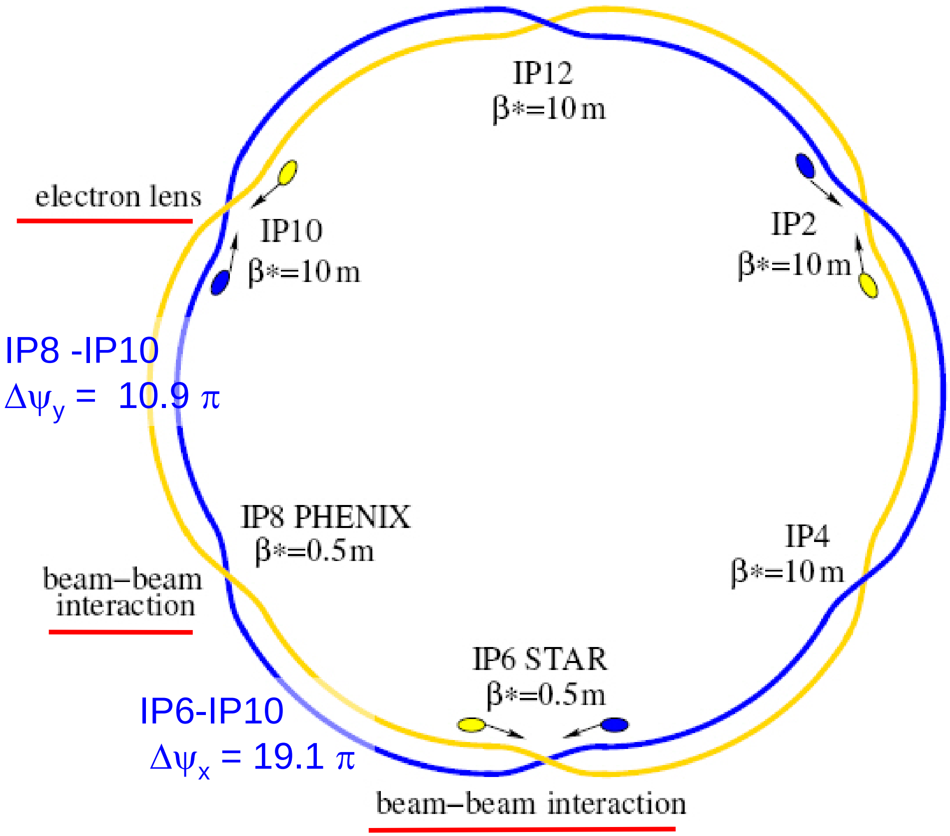
Use a 9 MHz system (h = 120) allows to accelerate long bunches that preserve both the longitudinal and transverse emittance

Cavity Concept:
use the shield inside the common cavities to make a 9 MHz resonator



- common to both beams
- 9 MHz, 25 kV
- tested in 2009
- need independent long. dampers in both beam
- will use again in 2011

Electron lenses in RHIC – under construction



Basic idea:

In addition to 2 beam-beam collisions with **positively** charged beam have another collision with a **negatively** charged beam with the same amplitude dependence.

2 electron lenses installed in Tevatron,
not used for head-on beam-beam compensation

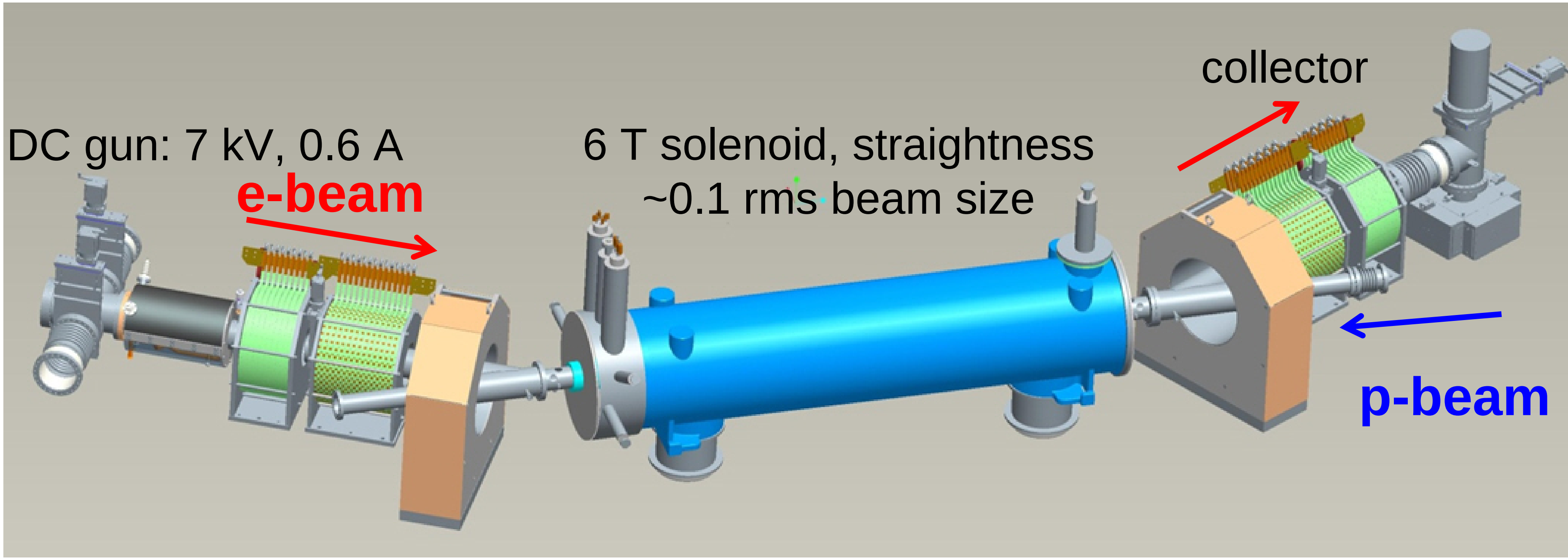
Exact compensation possible for:

- 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

MOPEC026 (overview), THPE100 (long bunches), Y. Luo TUPEC082 (SimTrack), THPE102 (simulations), C. Montag MOPEC035 (beam alignment with bremsstrahlung), C. Montag TUPEB050 (e-lens for e-beam)

Electron lenses in RHIC – under construction



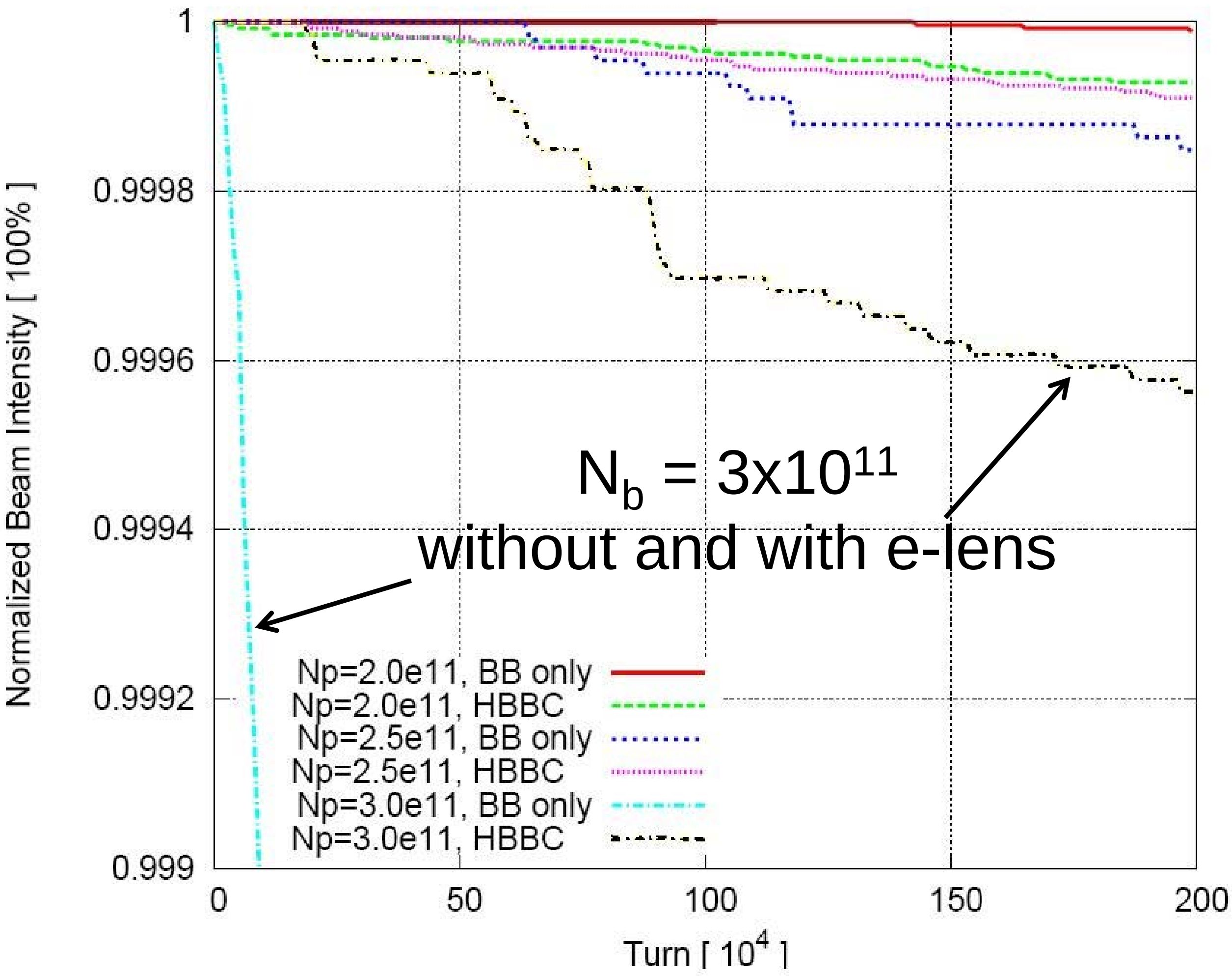
- partial compensation of head-on beam-beam

- goal of 2x luminosity increase together with source upgrade
  (allowing for higher bunch intensity with good polarization)

- critical: relative beam alignment (Tevatron experience)
  requires straight solenoid field lines, good instrumentation
  (bremsstrahlung monitor – C. Montag MOPEC035)

Electron lenses in RHIC – under construction

6D beam lifetime simulation of electron lens (Y. Luo, THPE102)



Beam lifetime simulations are challenging – require good model and supercomputer

Simulations show full benefit of e-lens for $N_b > 2x10^{11}$
(i.e. with source upgrade)

Summary – RHIC luminosity and polarization goals

Parameter	Unit	Achieved	Enhanced design	Next *L* upgrade
Au-Au operation		(2010)		(>=2012)
Energy	GeV/nucleon	100	100	100
No of bunches	…	111	111	111
Bunch intensity	10^9	1.1	1.0	1.0
Average *L*	10^{26}cm^{-2}s^{-1}	**20**	**8**	**40**
p↑- p↑ operation		(2009)	(>=2011/12)	(>=2014)
Energy	GeV	100 / 250	100 / 250	250
No of bunches	…	109	109	109
Bunch intensity	10^{11}	1.3 / 1.1	1.3 / 1.5	2.0
Average *L*	10^{30}cm^{-2}s^{-1}	**24 / 55**	**30 / 150**	**300**
Polarization *P*	%	**55 / 34**	**70**	**70**

Had previously a goal of 60 here – but low luminosity lifetime with low β^*.

RHIC luminosity upgrade program – summary

Heavy ion upgrades

Reached: 100 GeV/nucleon **(design)** <L>=20x10^{26}cm^{-2}s^{-1} **(10x design)**

- 2-3x more luminosity by through
  3D stochastic cooling upgrade, 56 MHz SRF (overcoming IBS)
- New Electron Beam Ion Source (EBIS) (uranium beams)
- Operation below nominal injection energy, electron cooling

Polarized proton upgrades (polarization, beam-beam)

Reached: 250 GeV **(design)** <L>=85x10^{30}cm^{-2}s^{-1} **(0.4x design)** <P>=35% **(0.5x design)**

- New polarized source under construction (10x intensity, 5% polarization)
- AGS upgraded with horizontal tune jump system (5% polarization increase)
- RHIC acceleration near 2/3 vertical resonance (P transmission)
- 9 MHz rf system (longitudinal emittance reduction)
- Electron lenses (reduction of head-on beam-beam effect)

Abstract

The Relativistic Heavy Ion Collider (RHIC) operates with either ions or polarized protons. After increasing the heavy ion luminosity by two orders of magnitude since its commissioning in 2000, the current luminosity upgrade program aims for an increase by another factor of 4 by means of 3D stochastic cooling and a new 56 MHz SRF system. An Electron Beam Ion Source is being commissioned that will allow the use of uranium beams. Electron cooling is considered for collider operation below the current injection energy.
For the polarized proton operation both luminosity and polarization are important. In addition to ongoing improvements in the AGS injector, the construction of a new high-intensity polarized source has started. In RHIC a number of upgrades are under way to increase the intensity and polarization transmission to 250 GeV beam energy. Electron lenses will be installed to partially compensate the head-on beam-beam effect.