RHIC status and upgrade plans

Wolfram Fischer

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Thanks to many at BNL.

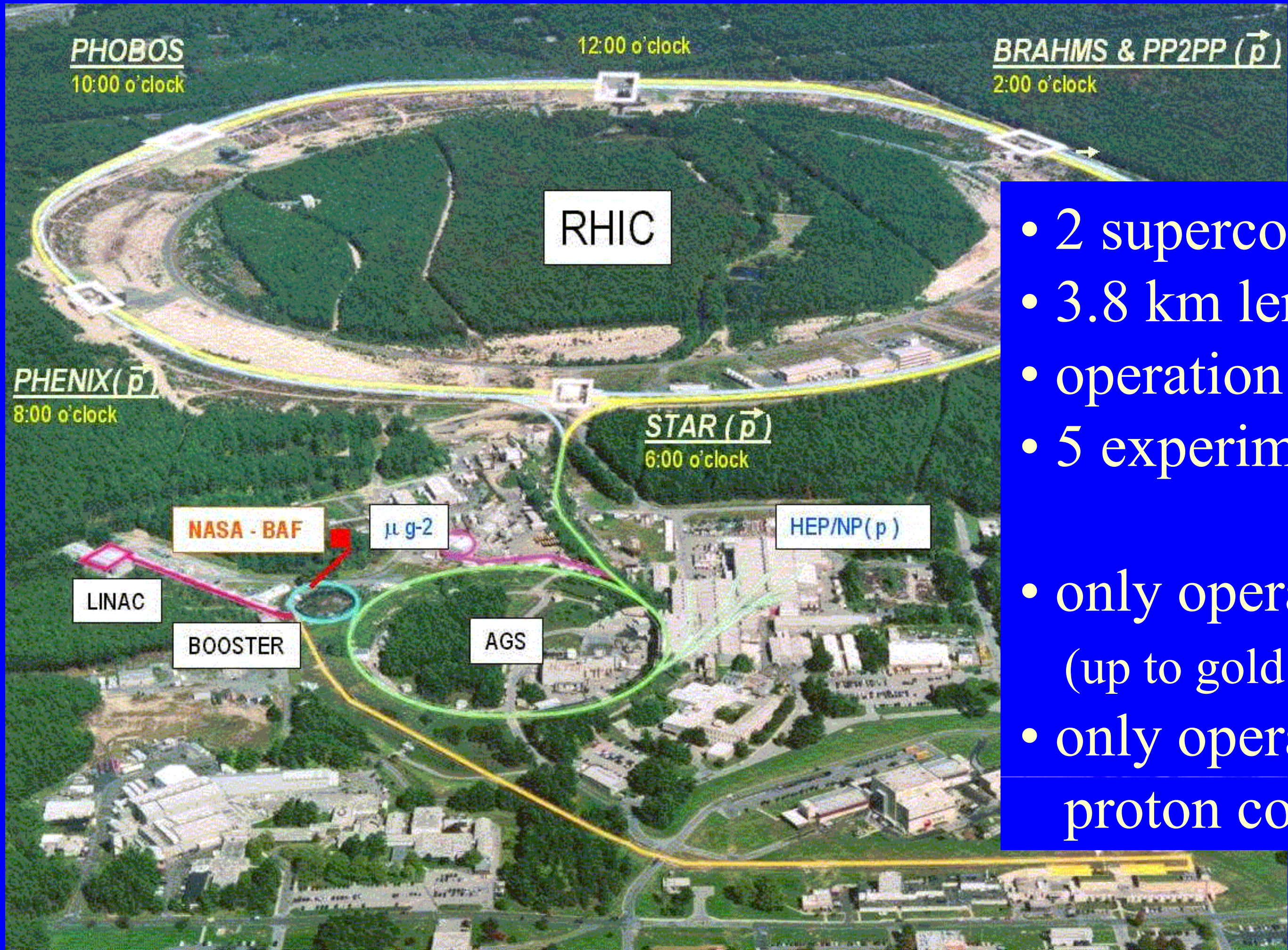
CARE-HHH-APD Workshop BEAM'07, CERN

1 October 2007

Outline

1. Status
   - Achieved performance
   - Performance limits
2. Upgrades
   - Enhanced Design parameters
   - Electron Beam Ion Source (EBIS)
   - Au-Au collisions at very low energies
   - RHIC II (stochastic cooling / electron cooling)
   - eRHIC

Relativistic Heavy Ion Collider



- 2 superconducting rings
- 3.8 km length
- operation since 2000
- 5 experiments so far

- only operating ion collider (up to gold 100 GeV/nucleon)
- only operating polarized proton collider

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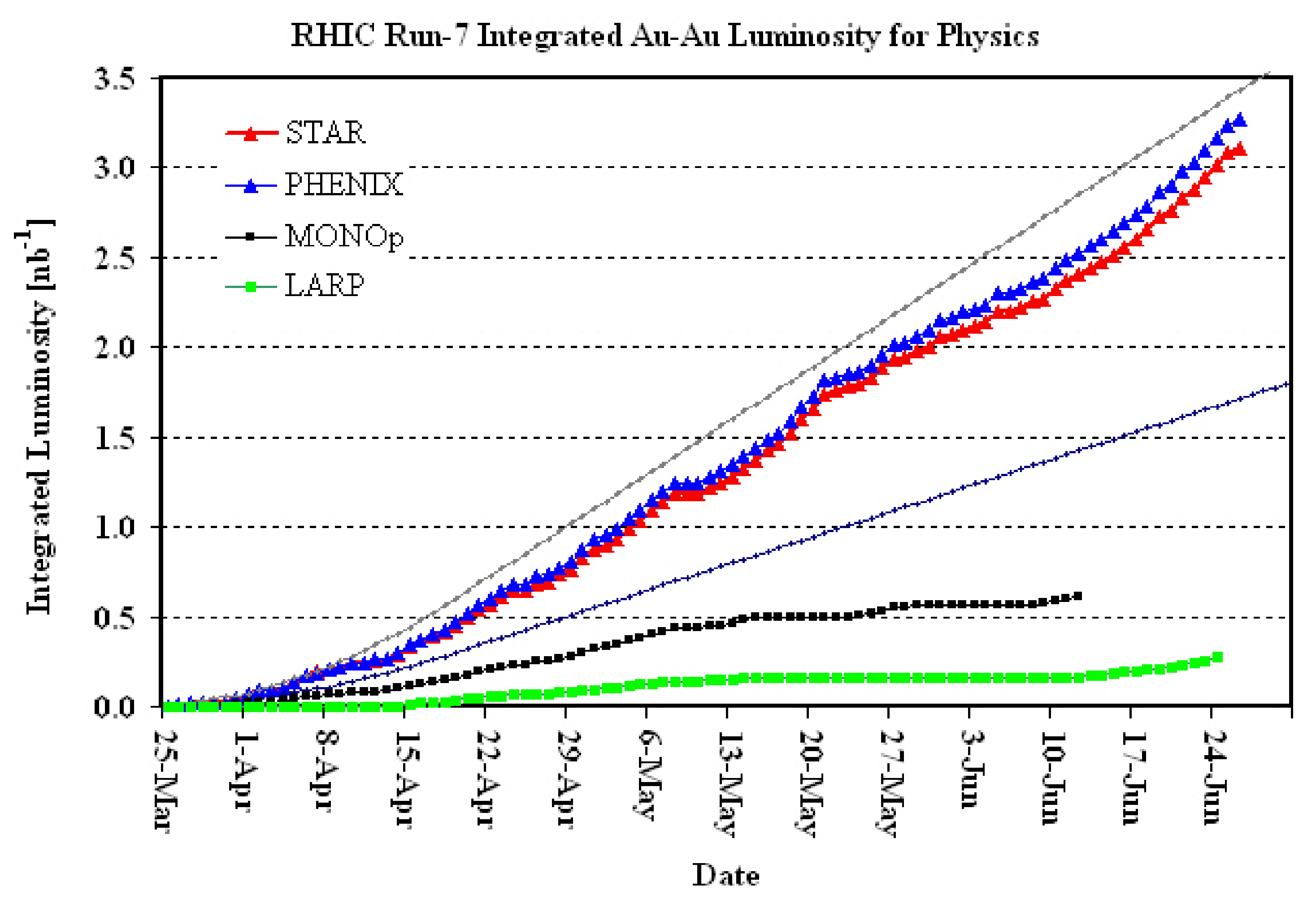
RHIC running modes

- Au–Au 4.6, 10, 28, 31, 65, 100 GeV/n
- d–Au 100 GeV/n ← **Important control experiment in physics program**
- Cu–Cu 11, 31, 100 GeV/n
- polarized p–p 11, 31, 100, 205, 250 GeV

Some modes only for days – fast machine setup essential.

RHIC Run-7 Au-Au

Run Coordinator: A. Drees



Projected maximum

Projected minimum

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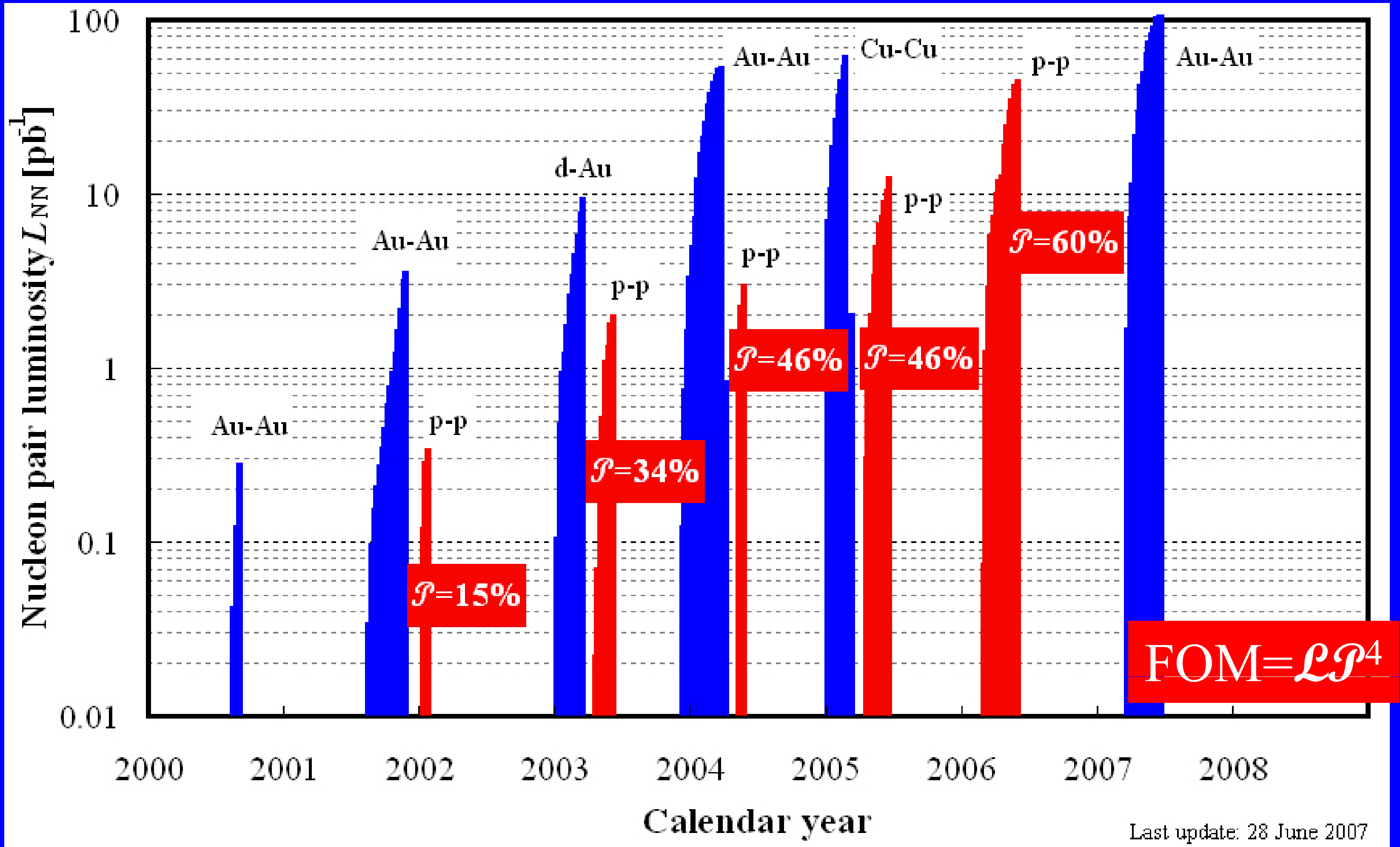
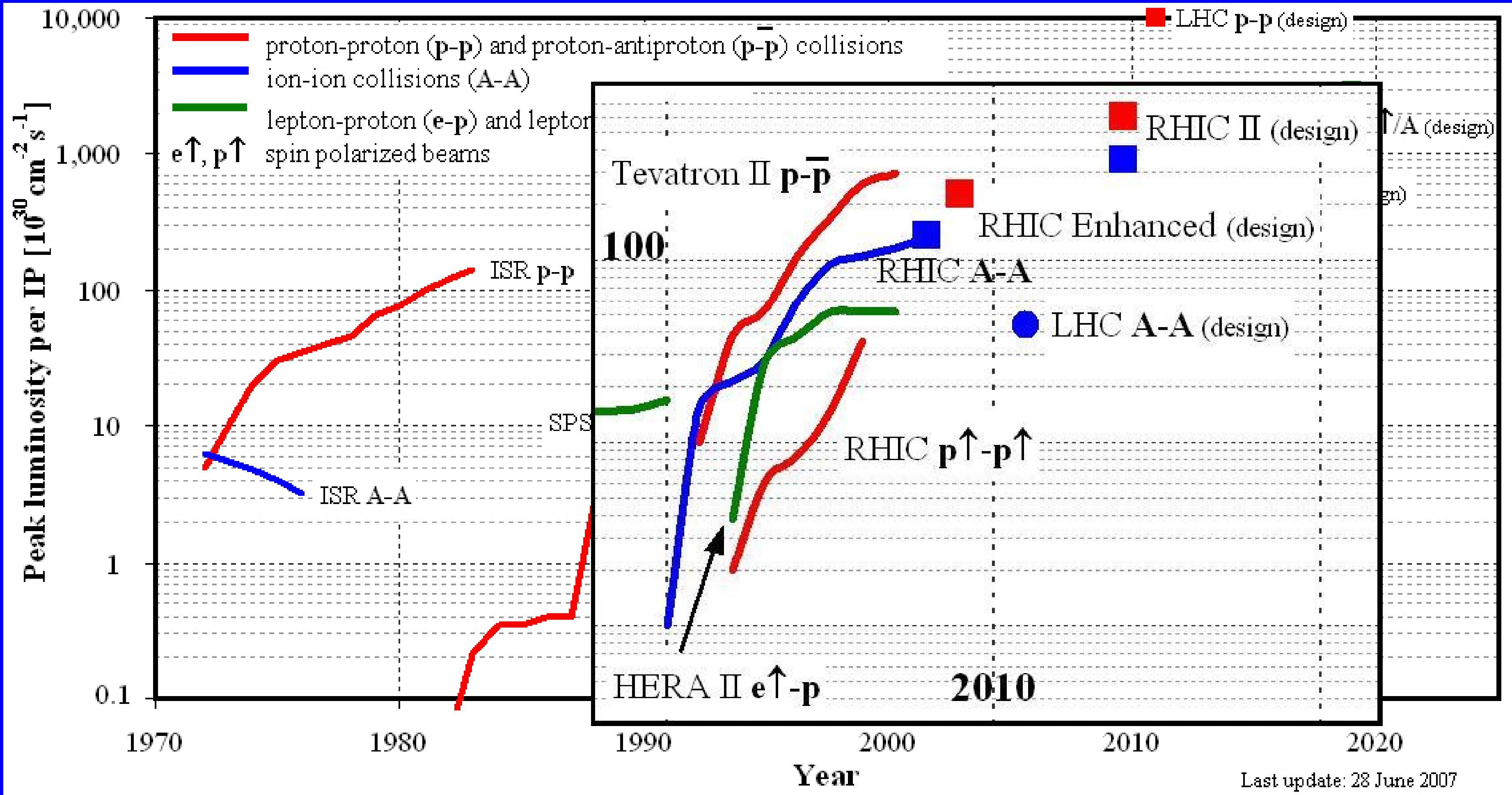
RHIC delivered luminosity

Delivered luminosity increased by >2 orders of magnitude in 5 years.



Delivered to PHENIX, one of RHIC's high-luminosity experiments.

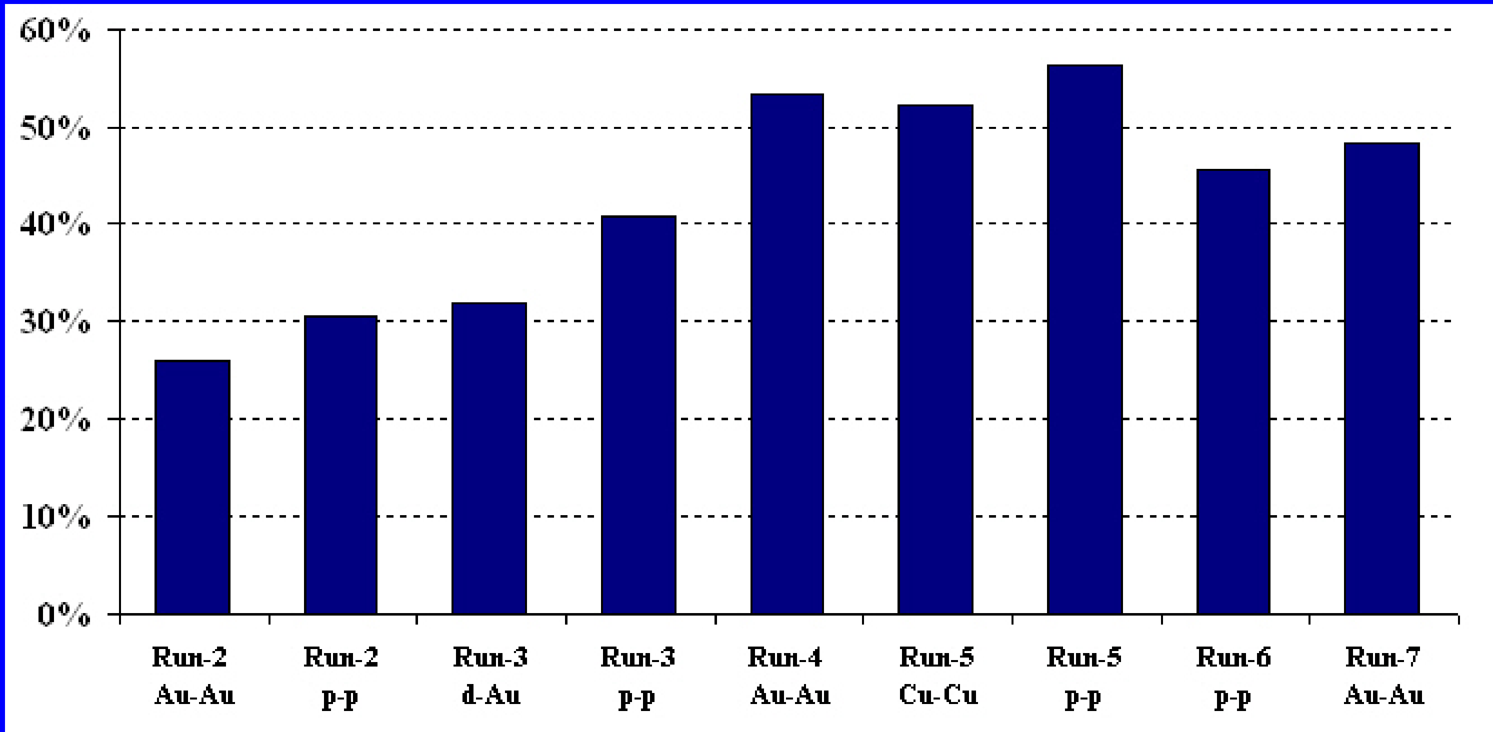
Hadron collider luminosities



Show nucleon-pair luminosity for ions: $\mathcal{L}_{NN}(t) = A_1 A_2 \mathcal{L}(t)$

(can compare different ion species, including protons)

Calendar time in store after setup



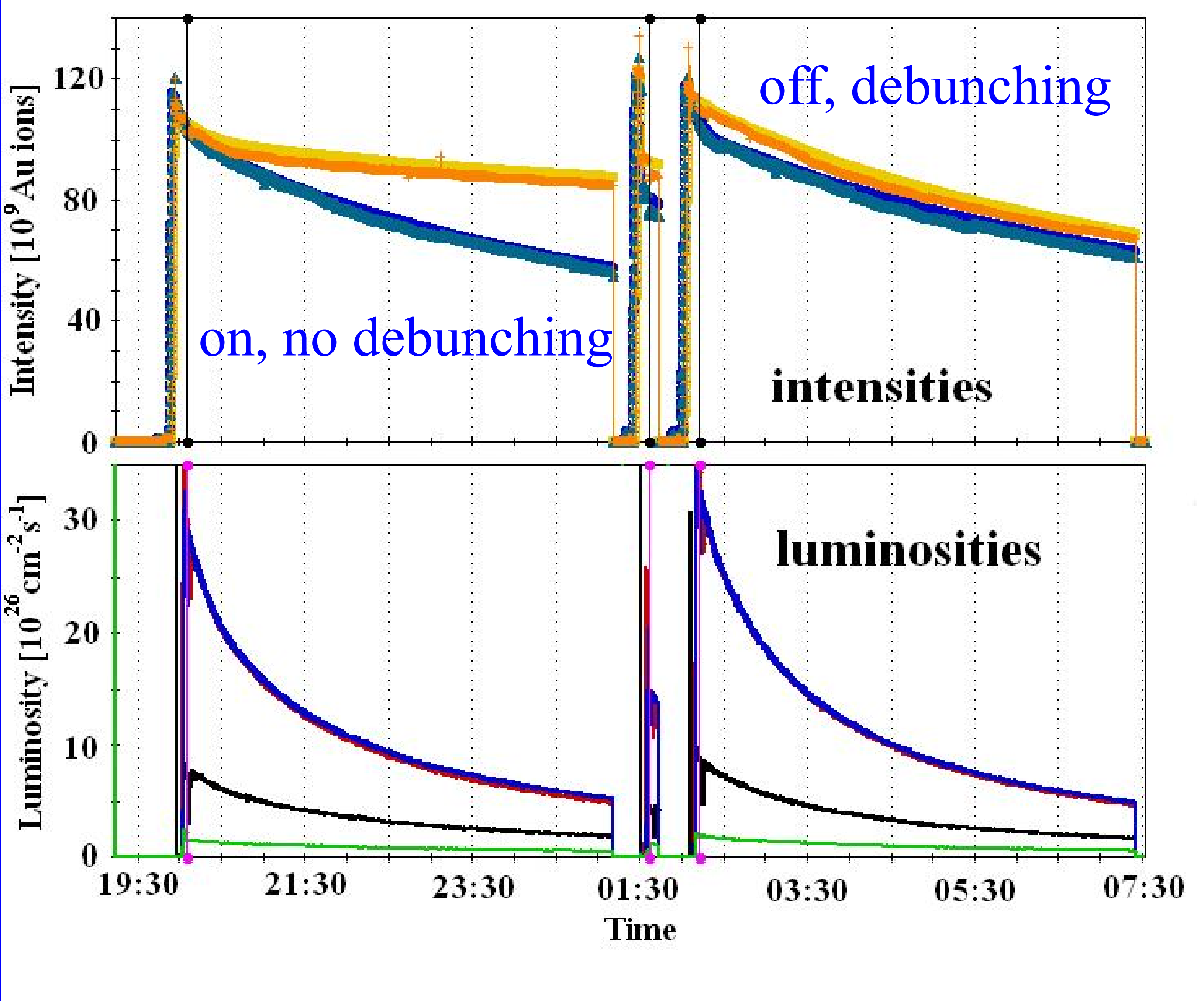
goal 100h/week

No progress with time-in-store in last 2 years.

Rest of the time:
~20% machine tuning/ramping
~15% failures
~10% machine development and accelerator physics experiments

Performance limit: IBS for heavy ions

Longitudinal stochastic cooling in Yellow operational M. Blaskiewicz
M. Brennan



About 20% luminosity gain per ring from stopping debunching

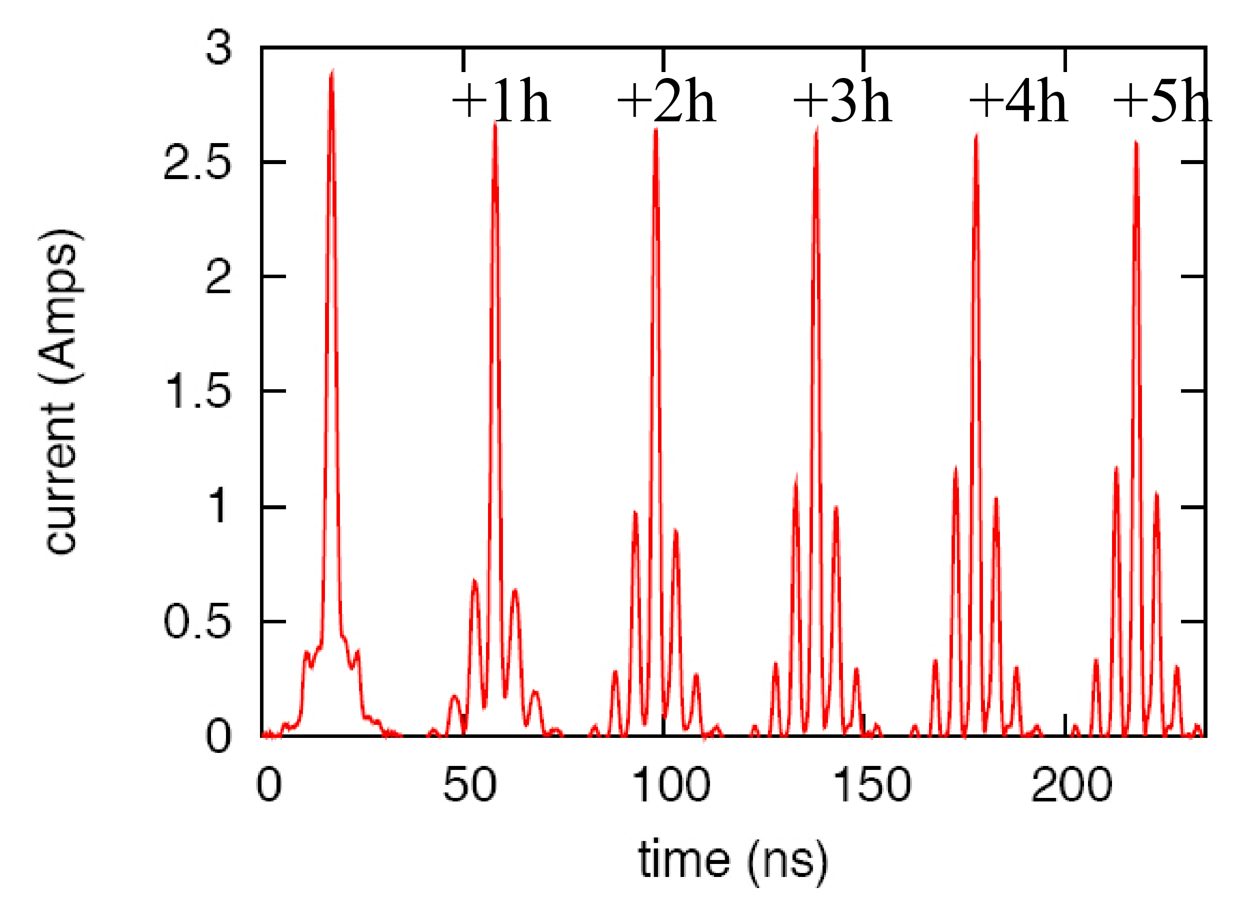
$$\tau^{-1} \propto \frac{Z^4}{A^2} N_b$$

[Factor 10 between Au an p]

Longitudinal stochastic cooling in RHIC

Evolution of longitudinal profiles over 5 hours

M. Blaskiewicz
M. Brennan
COOL'07



Satellites are result of 2 rf harmonics (360 + 7×360)

Performance limit: transition crossing for heavy ions

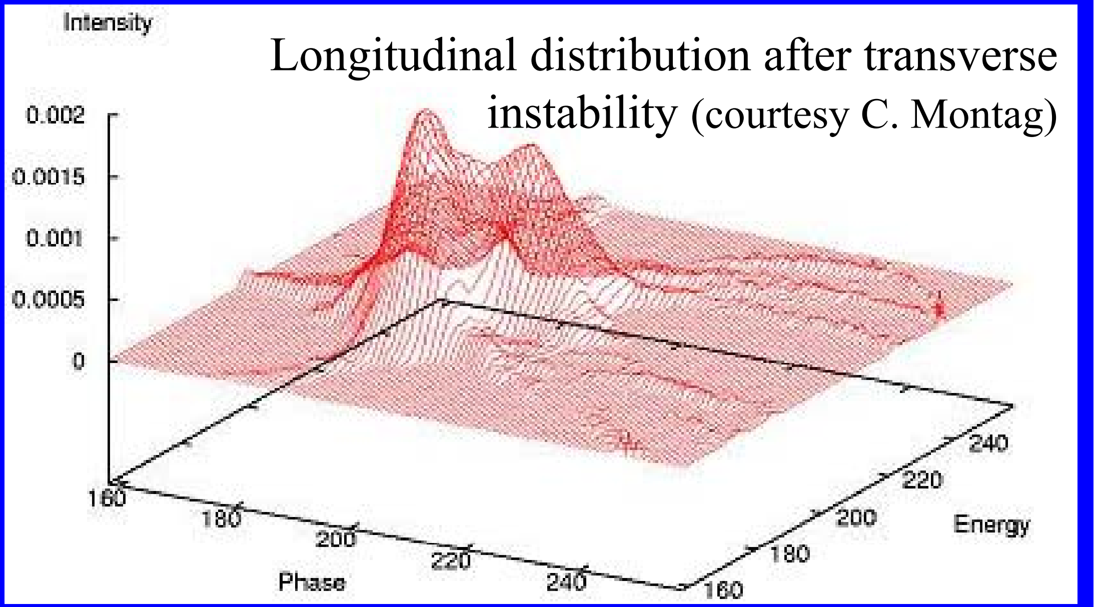
Crossing transition with slowly ramping sc. Magnets
(all ions except protons)

→ Instability limits bunch intensities for ions (~1.5 – 2.0×10^{11} e)

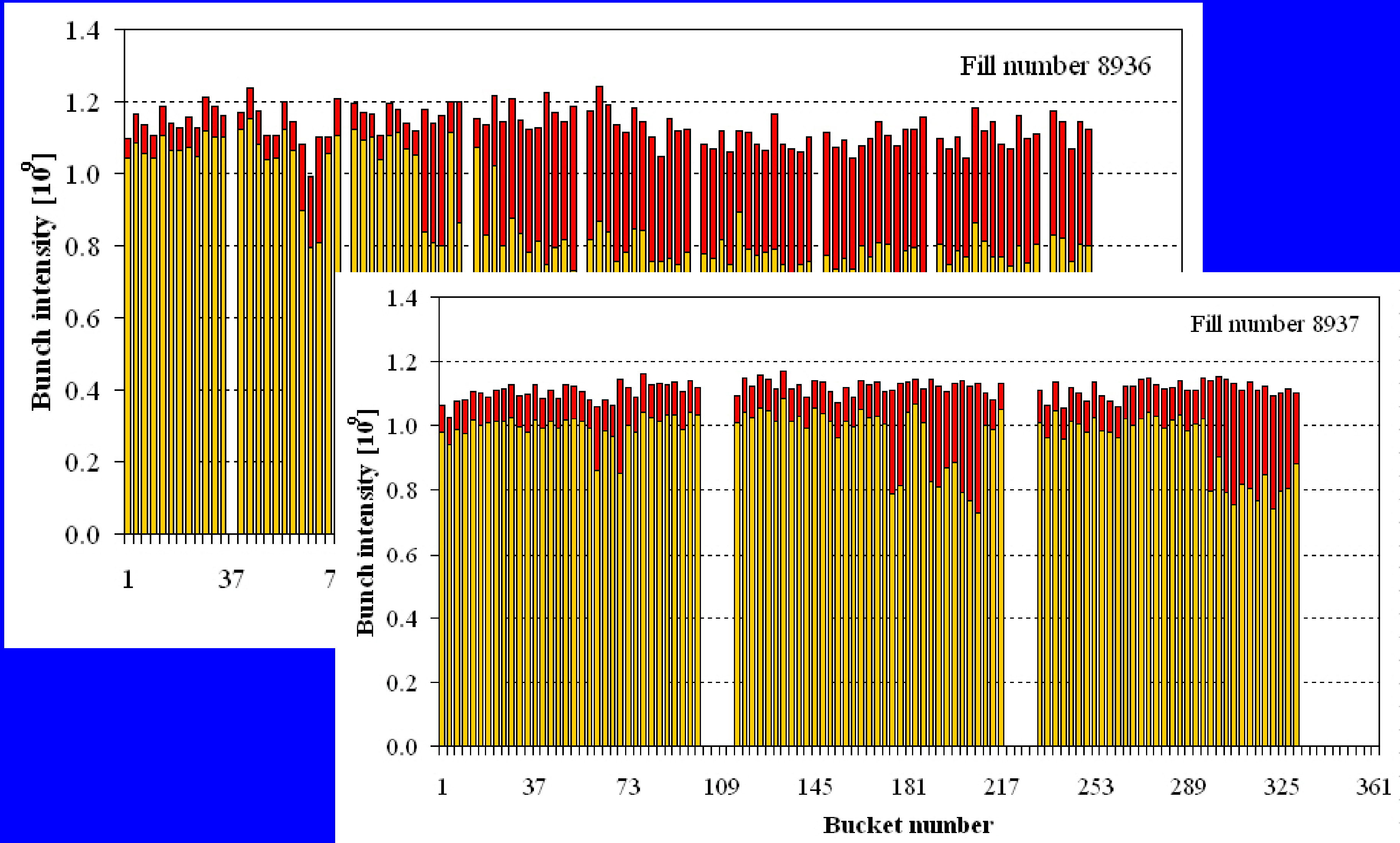
→ Instability is fast (τ =15 ms), transverse, single bunch
(electron clouds can lower stability threshold)

- γ_t-jump implemented
- Octupoles near transition
- Chromaticity control
  (need ξ-jump for higher bunch intensities)

Longitudinal distribution after transverse instability (courtesy C. Montag)



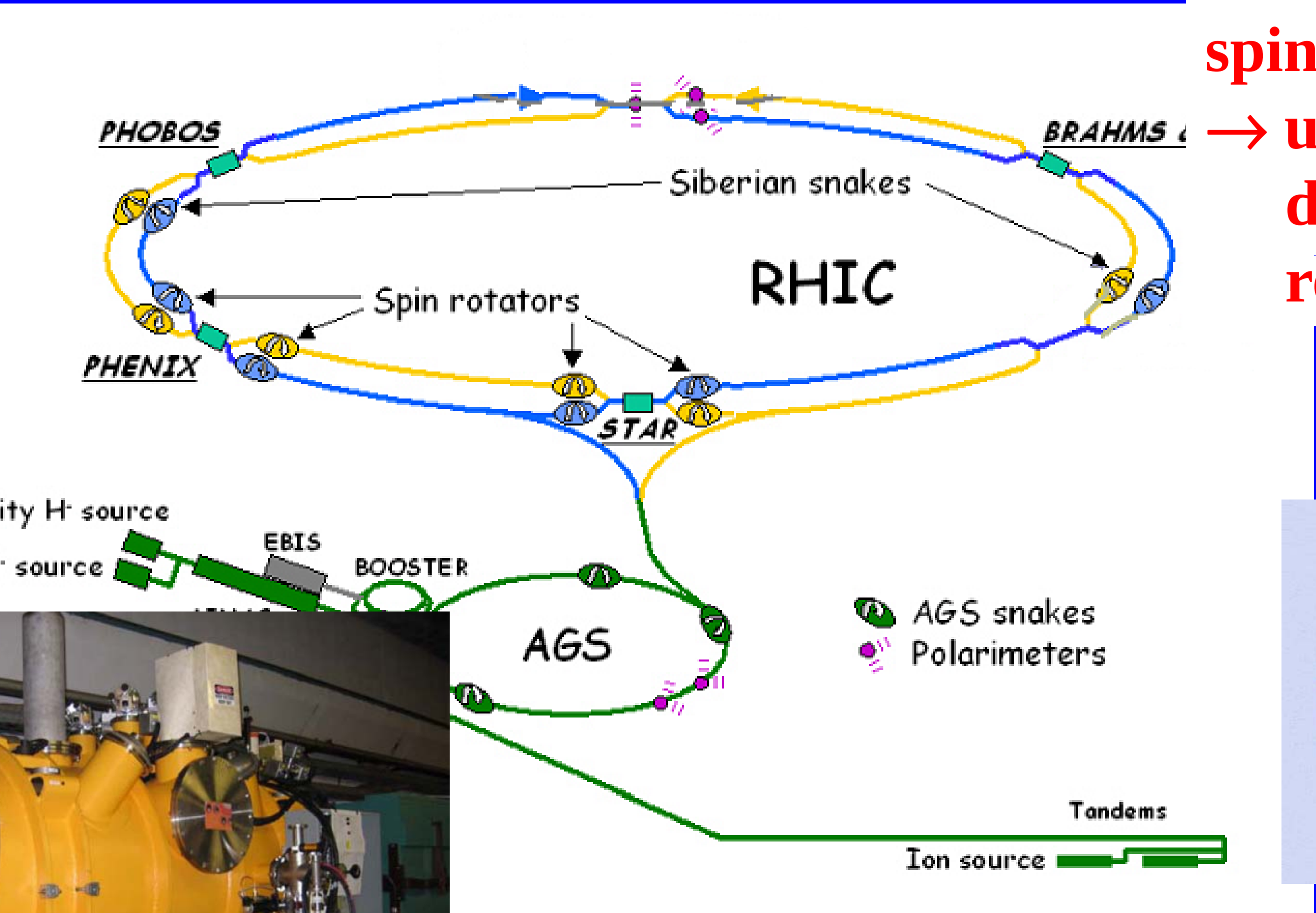
Performance limit: transition crossing for heavy ions



Intensity loss at transition in Yellow, different bunch patterns.

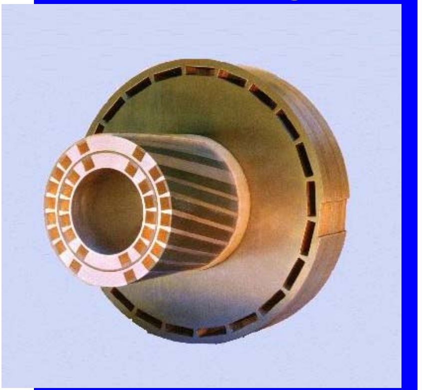
Performance limit: polarization of protons

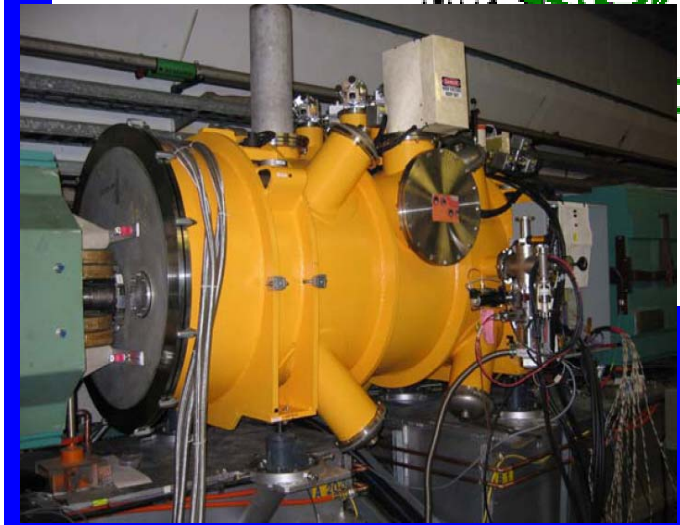
Equipment for polarized beam



Snakes change spin direction → used to avoid depolarizing resonances

RHIC helical magnet





Superconducting helical magnet in AGS – most complex magnet ever built by Superconducting Magnet Division

Performance limit: polarization of protons

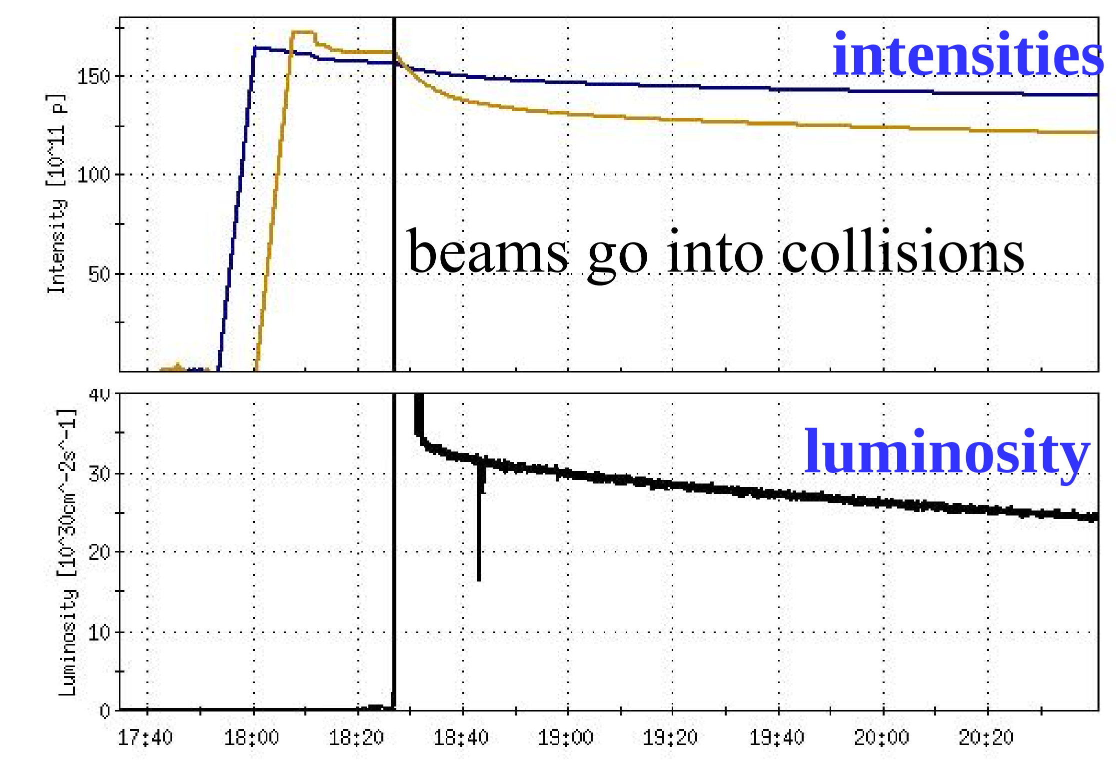
First operational use of AGS cold snake in 2006

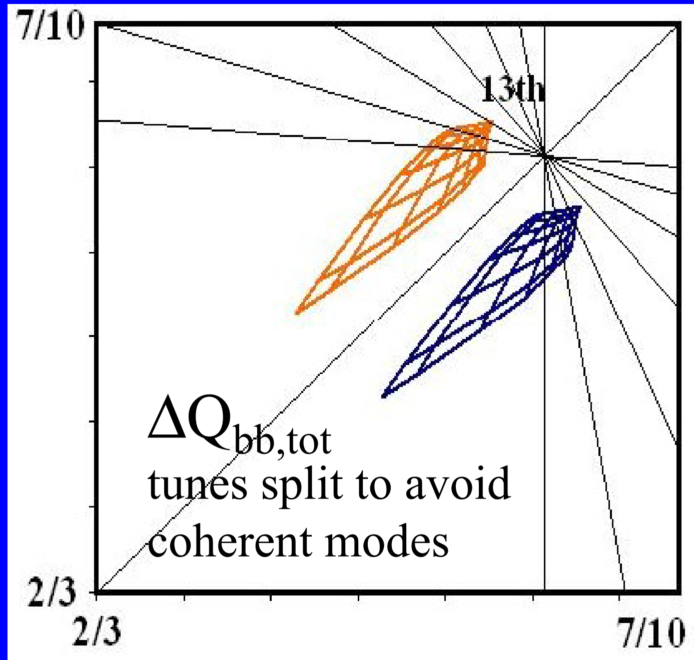
- Raised AGS polarization from 60% to 65%
- Removed intensity dependence of polarization

Polarization by machine

- Source → 85%
- AGS extraction → 65%
- RHIC store
  - 100 GeV (no loss) → 65%
  - 205 GeV (in 2005) → 30% M. Bai et al., PRL 96 174801 (2006).
  - 250 GeV (in 2006) → 47% Blue only, current record energy for p↑

Performance limit: beam-beam for p↑- p↑





- Total beam-beam induced tune spread reached $\Delta Q_{bb,tot} = 0.012$
- Other sources of tune spread: $\Delta Q \approx 0.005$
  - nonlinear chromaticity (correction implemented in 2007)
  - triplet errors (locally corrected)
- Sources for orbit and tune modulation

RHIC upgrades

Upgrade goals

- More luminosity and polarization
- More flexibility and reliability

Main upgrades planned:

1. Enhanced Design parameters
2. Electron Beam Ion Source (EBIS)
3. Au-Au collisions at very low energies
   (down to 1/4 of current injection energy)
4. RHIC II (stochastic cooling / electron cooling)
5. eRHIC

Upgrade 1: Enhanced Design Parameters (~2009*)

Parameter	unit	Achieved	Enhanced design
Au-Au operation			
Energy	GeV/n	100	100
No of bunches	…	103	111
Bunch intensity	10^9	1.1	1.0
Average ℒ	**$10^{26}cm^{-2}s^{-1}$**	**12**	**8**
p↑- p↑ operation			
Energy	GeV	100	100 (250)
No of bunches	…	111	111
Bunch intensity	10^{11}	1.4	2.0
Average ℒ	**$10^{30}cm^{-2}s^{-1}$**	**20**	**60 (150)**
Polarization 𝒫	**%**	**65**	**70**

Exceeded Enhanced Design goal (15-20% from stochastic cooling in Yellow) ← 8

60 (150) ← 3×

70 ← +5%

* First 250 GeV p↑-p↑ physics run currently scheduled for 2009.

Upgrade 1: Enhanced Design Parameters (~2009*)

Measures to increase polarization:

- Increase in source polarization
- Emittance reduction in LEBT
- Emittance reduction at Booster injection
- AGS with warm and cold snake with near integer working point (tune range free of spin resonances)

Measures to increase luminosity (beam-beam limited):

- Nonlinear chromaticity correction
- Orbit feedback at IP (reduction of 10 Hz vibrations effect)
- New 9 MHz cavity (longitudinal matching, reduction of hour-glass effect)
- New working point near integer (one beam in 2008)
- Triplet assembly modification (reduction of 10 Hz vibrations at source)

Upgrade 2: Electron Beam Ion Source (EBIS)

- Current ion pre-injector:
  upgraded Model MP Tandem (electrostatic)
- Plan to replace with:
  Electron Beam Ion Source, RFQ,
  and short linac

→ Can avoid reliability upgrade of Tandem

→ Expect improved reliability at lower cost

→ New species: U, $^{3}He\uparrow$

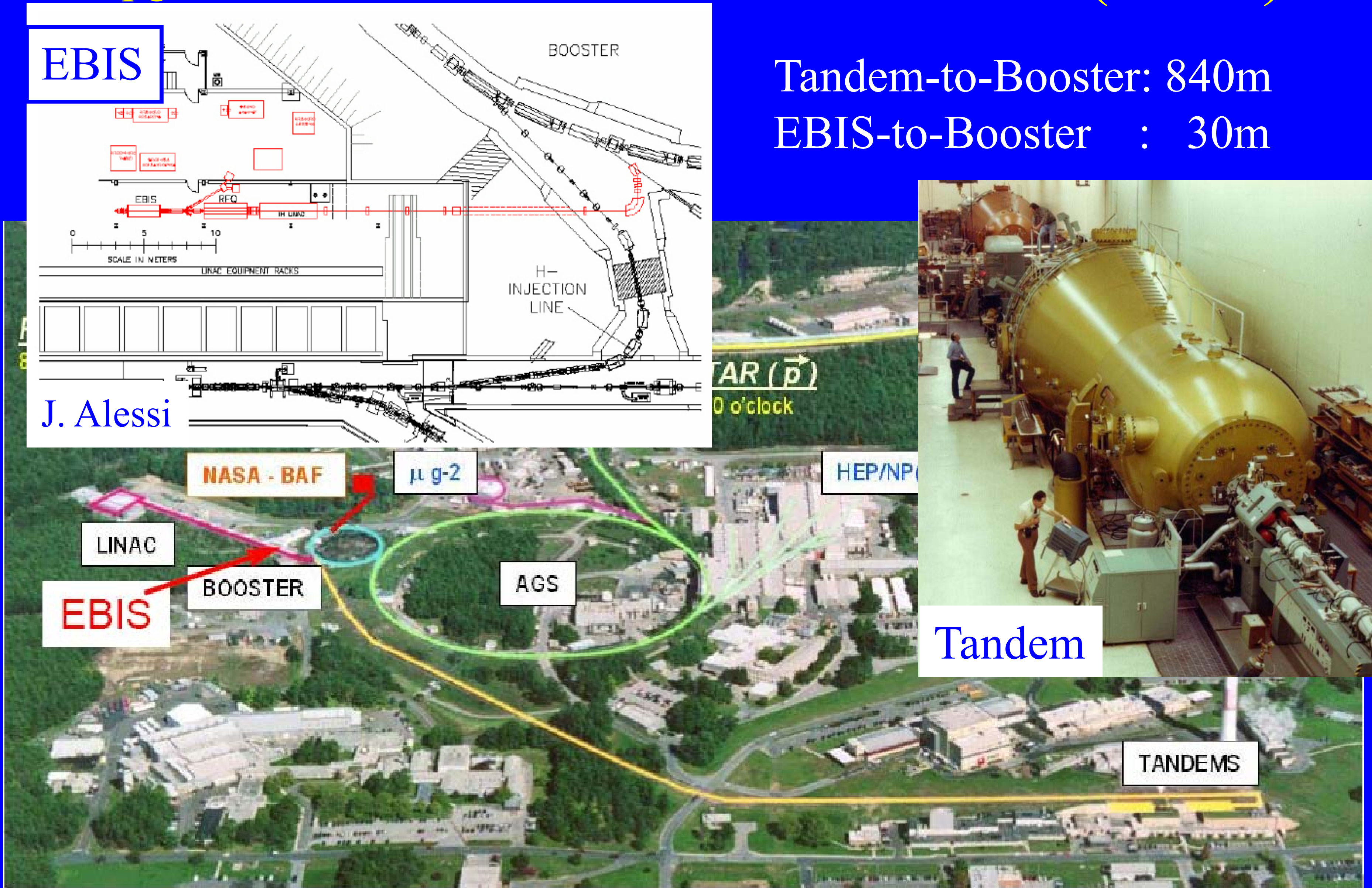
→ Under construction

→ Expect commissioning to begin in 2009

Upgrade 2: Electron Beam Ion Source (EBIS)

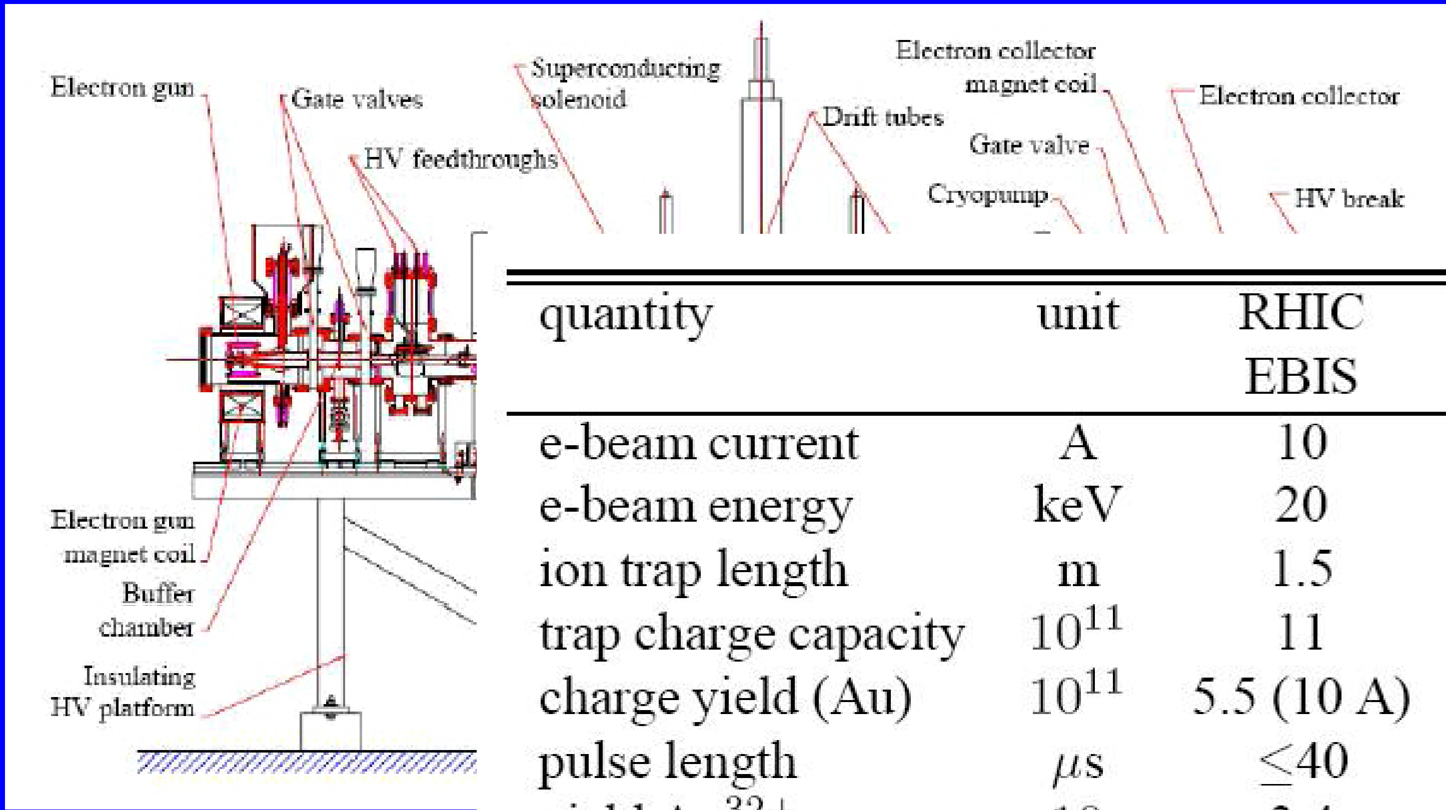
Tandem-to-Booster: 840m

EBIS-to-Booster : 30m



Upgrade 2: Electron Beam Ion Source (2009)

Schematic of RHIC EBIS



quantity	unit	RHIC EBIS	Test EBIS achieved
e-beam current	A	10	10
e-beam energy	keV	20	20
ion trap length	m	1.5	0.7
trap charge capacity	10^{11}	11	5.1
charge yield (Au)	10^{11}	5.5 (10 A)	3.4 (8 A)
pulse length	μs	≤ 40	20
yield Au^{32+}	10	3.4	> 1.5

Test EBIS of ½ length achieved ½ of required yield, yield scales with trap length

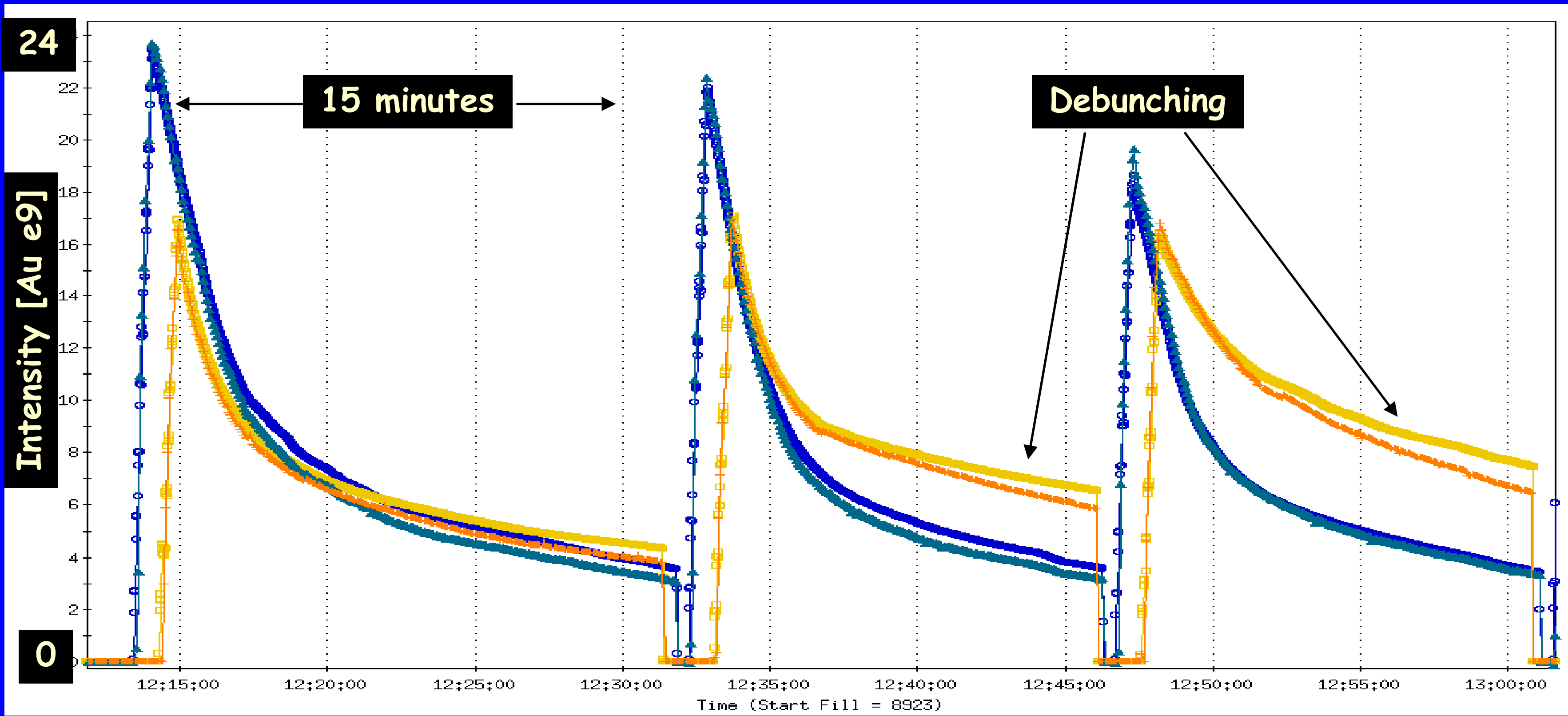
Upgrade 3: Low energy Au-Au operation

← Suspected around half the current RHIC injection energy

Experiment at FAIR
Dubna plans to build machine (in Nuclotron tunnel) high luminosity

Upgrade 3: Low energy Au-Au operation

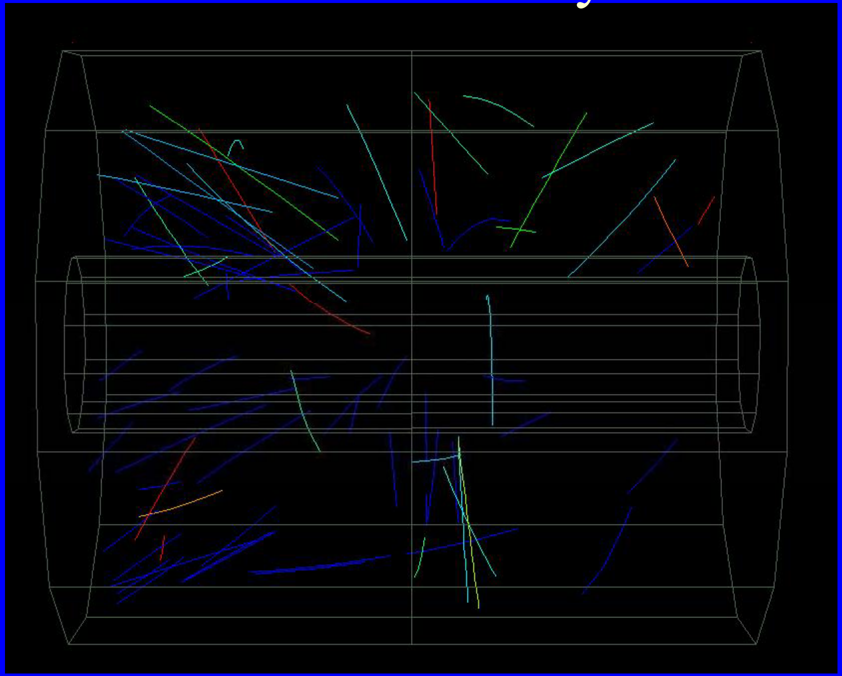
Demonstrated Au-Au collisions
at $\sqrt{s}$ = 9.2 GeV/nucleon T. Satogata et al.

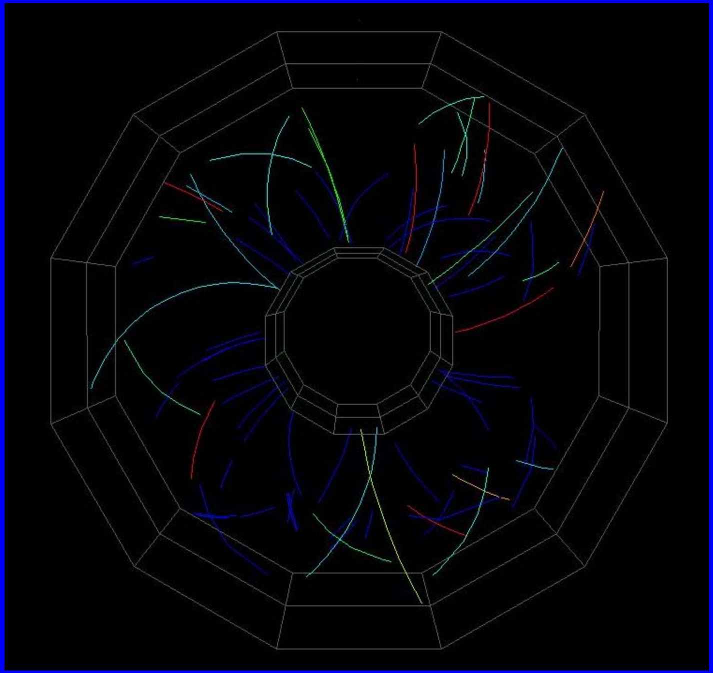


Peak luminosity L = 4×10^{23}cm^{-2}s^{-1}

Upgrade 3: Low energy Au-Au operation

Event seen by the STAR detector.





Low energy operation in principle possible.
Plan to have a physics run in 2009.

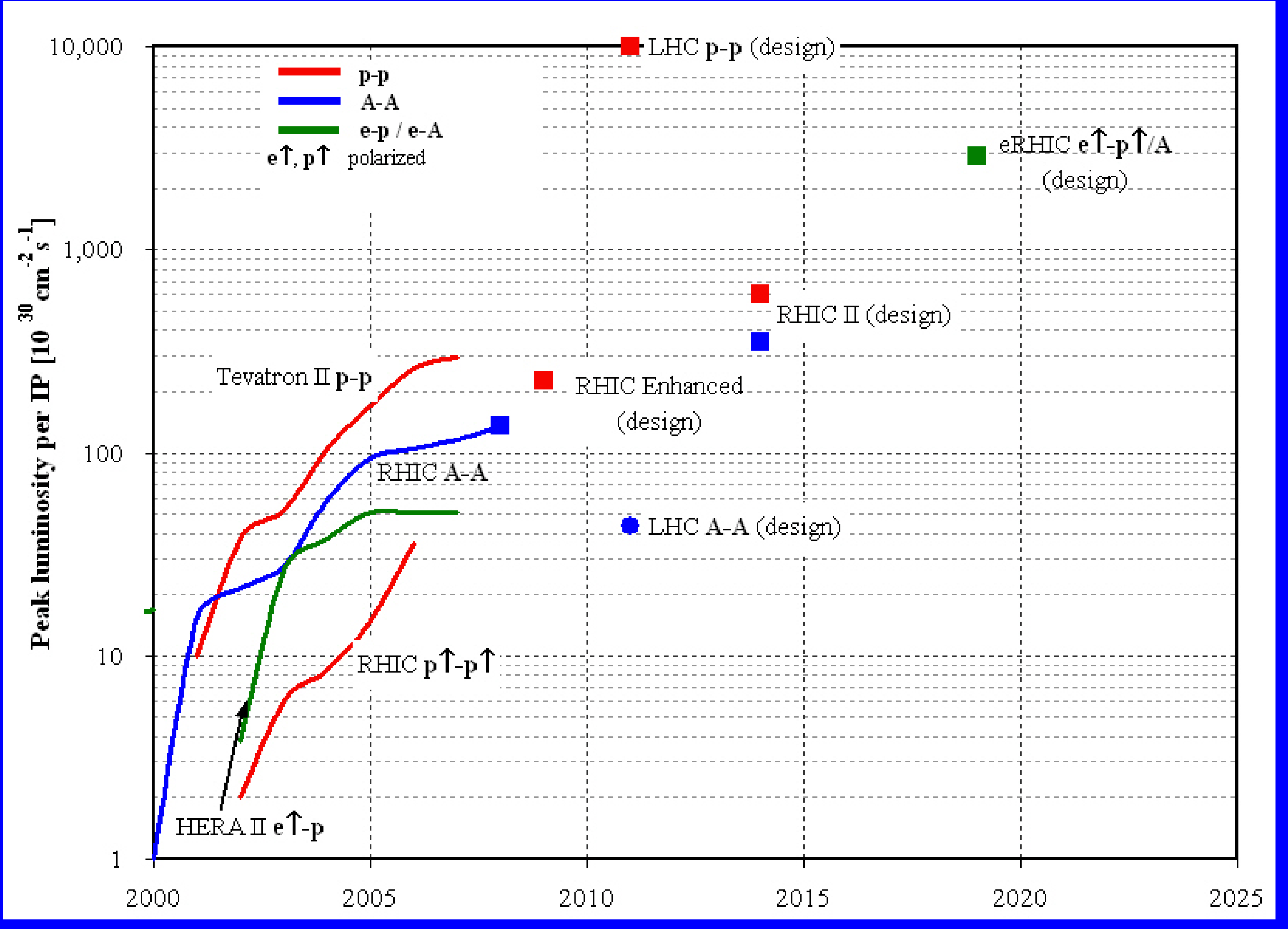
→ Cooling options in AGS/RHIC under investigation to increase luminosity, at even lower energies

(down to 1/4 or normal injection).

Upgrade 4: RHIC II – cooling (≥ 2011)

Parameter	unit	**Achieved/ Enhanced design**	**RHIC II**	
Au-Au operation				
Energy	GeV/n	100	100	
No of bunches	…	103	111	
Bunch intensity	10^9	1.3	1.0	
Average $\mathcal{L}$	**10^{26}cm^{-2}s^{-1}**	**12**	**70**	← **6×**
p↑- p↑ operation				
Energy	GeV	250	250	
No of bunches	…	111	111	
Bunch intensity	10^{11}	2.0	2.0	
Average $\mathcal{L}$	**10^{30}cm^{-2}s^{-1}**	**150**	**400**	← **2.5×**
Polarization $\mathcal{P}$	**%**	**70**	**70**	

Upgrade 4: RHIC II – luminosity goals



Upgrade 4: RHIC II (luminosity + detector upgrade)

Stochastic cooling

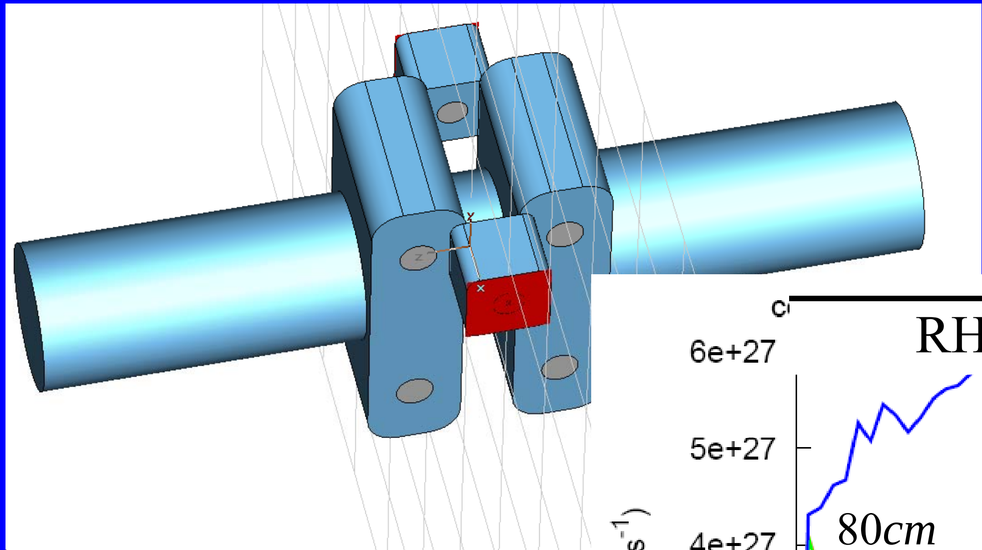
- Plan to have 1st plane of transverse stochastic cooling for Au by end of 2008
- 2nd plane 1 year later
- 2 more planes (if needed) another year later
- New superconducting 56 MHz system (avoids satellites), by 2011
- Limited to Au, and about 10^9 ions/bunch (IBS increases, cooling rate decreases with intensity)

Electron cooling

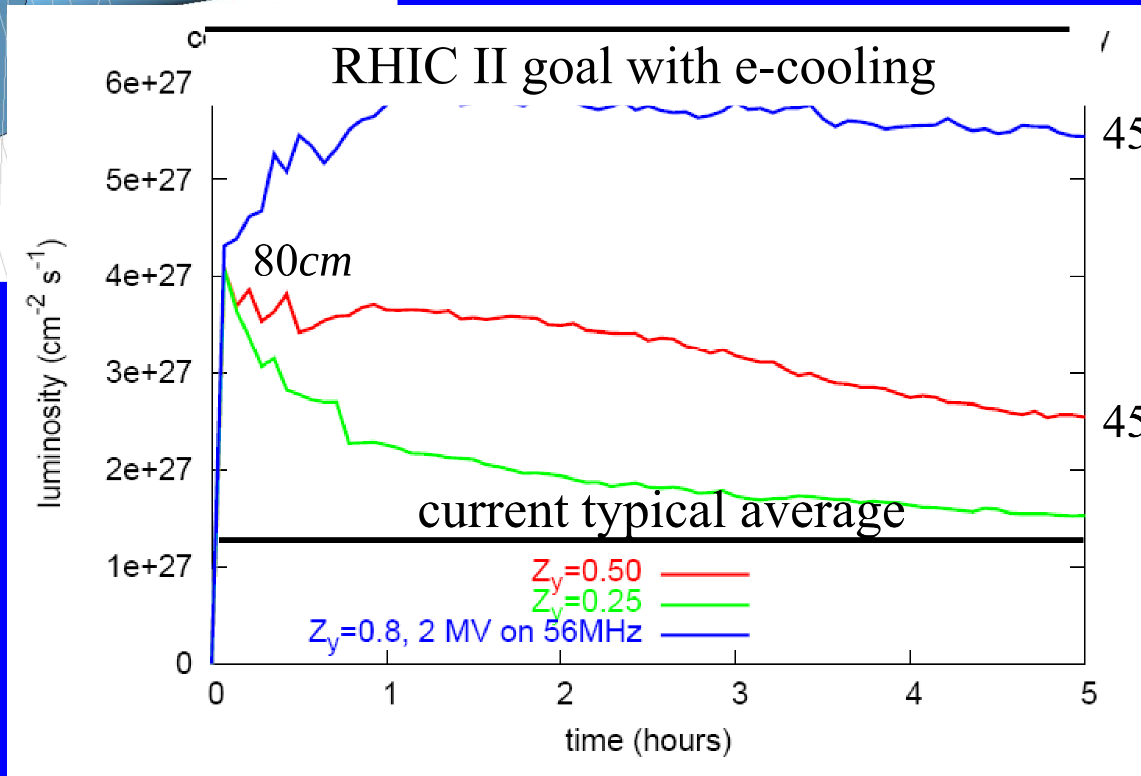
- Can provide another factor 2-4 above stochastic cooling for Au
- Can cool protons at 100 GeV to some extent, and pre-cool protons at lower energies (useful together with e-lens)
- Is needed for eRHIC luminosity goals
- Seen significant cost reduction recently

Upgrade 4: RHIC II – stochastic cooling (Au)

Transverse stochastic cooling appears also possible for heavy ions.



Calculations by M. Blaskiewicz



Frequency : 5-9 GHz
Cooling time: ~ 1 hour

Upgrade 4: RHIC II – electron cooling (≥ 2012)

Use non-magnetized cooling (no solenoidal field)

(demonstrated with 8.9 GeV antiprotons in Fermilab Recycler – Nagaitsev et al.)

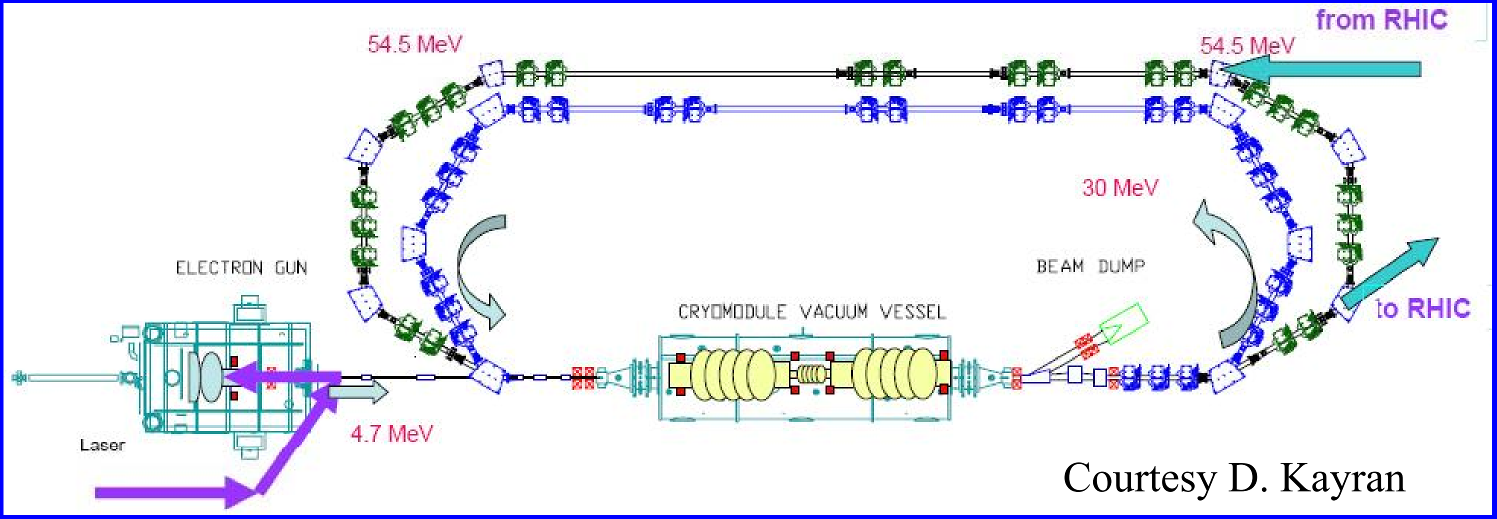
I. Ben-Zvi et al.

For 100 GeV Au beams need:

- 54 MeV electron beam
- 5nC per bunch
- rms emittance < 4 μm

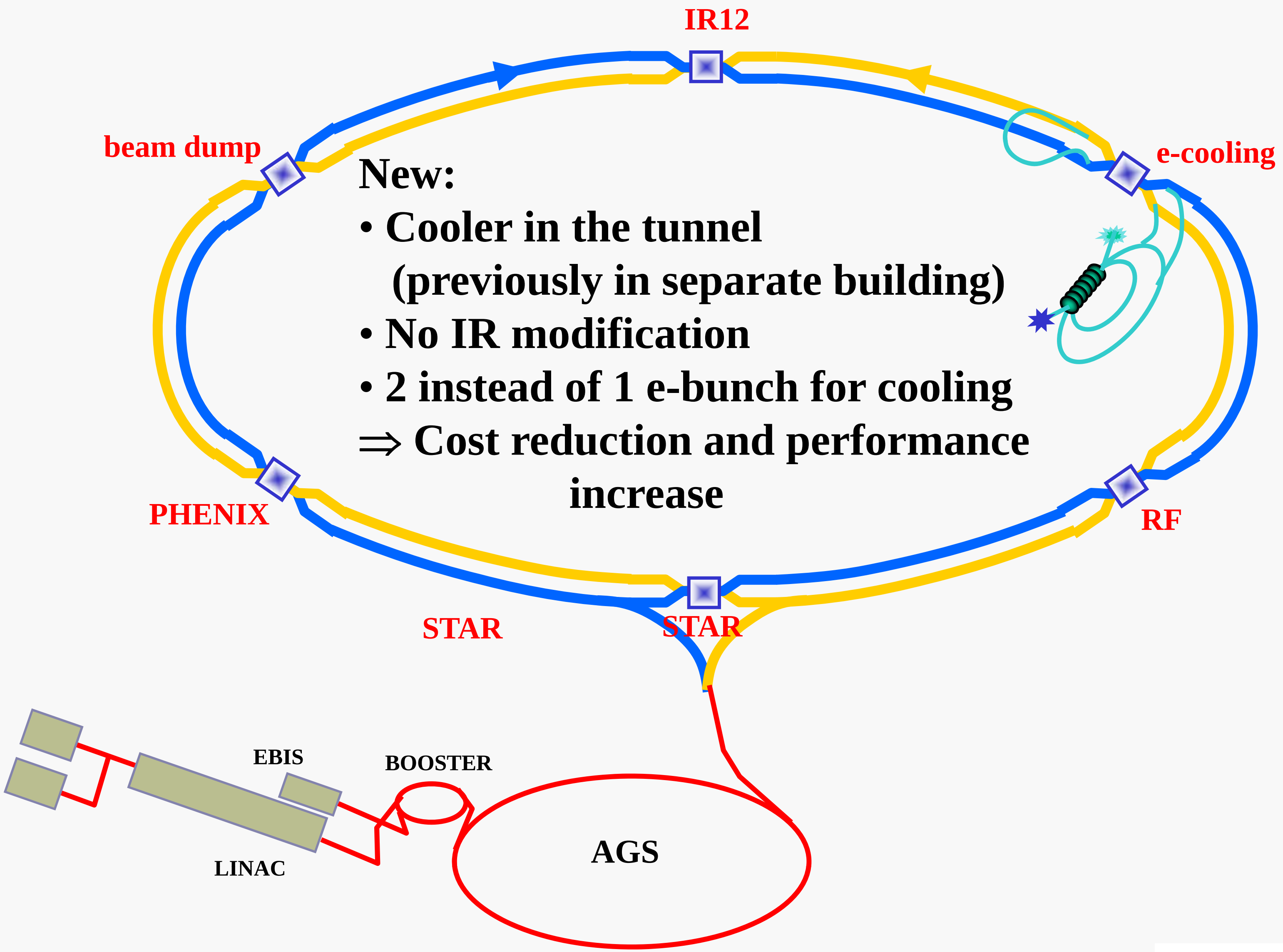
→ 2.7 MW beam power

→ need Energy Recovery Linac (ERL)



Courtesy D. Kayran

Upgrade 4: RHIC II – electron cooling (≥ 2012)



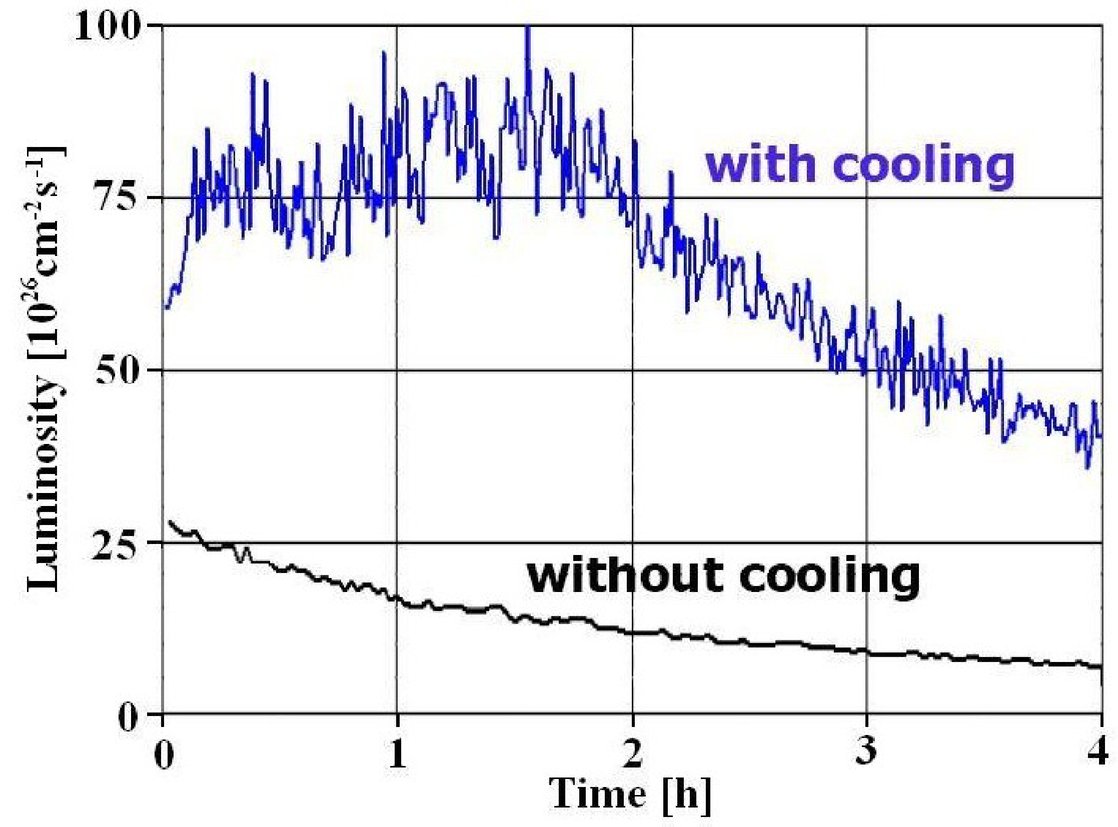
New:

- **Cooler in the tunnel (previously in separate building)**
- **No IR modification**
- **2 instead of 1 e-bunch for cooling**

⇒ Cost reduction and performance increase

Upgrade 4: RHIC II – electron cooling (≥ 2012)

Simulated luminosities (A. Fedotov)



For:

- Beam-loss only from burn-off (luminosity)
- Constant emittance (cooling)

$$\mathcal{L}(t) = \frac{\mathcal{L}(0)}{(1 + t/\tau)^2}$$

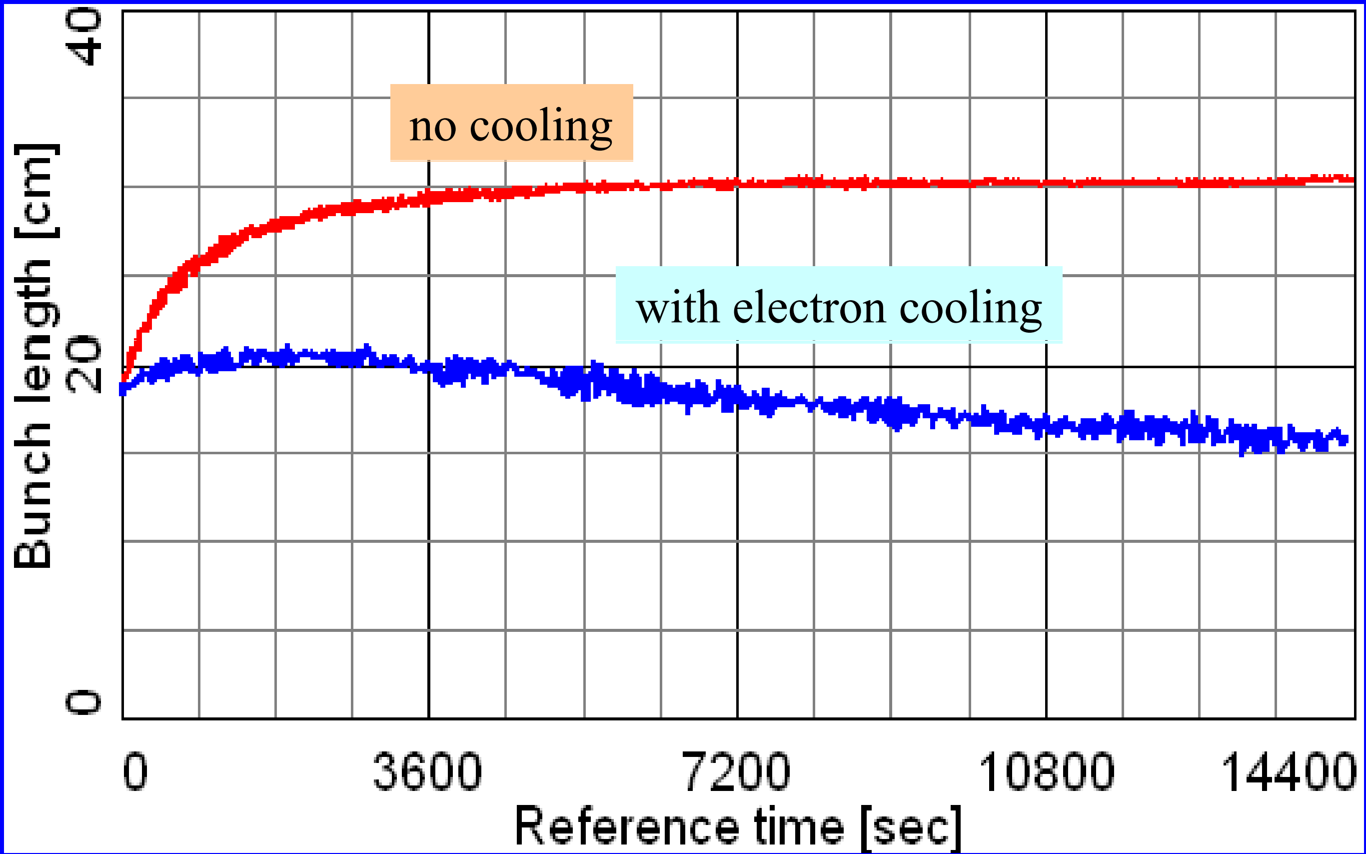
→ $\tau \approx 5$ h for Au-Au

Store length limited by burn-off

Electron cooling can provide another factor 2-4 above stochastic cooling.

RHIC II – electron cooling (≥ 2013)

Bunch length with electron cooling



Can maintain 20 cm rms bunch length.

Shaping of longitudinal distribution is possible.

New idea: Coherent Electron Cooling

V. Litvinenko, Ya. Derbenev
COOL'07

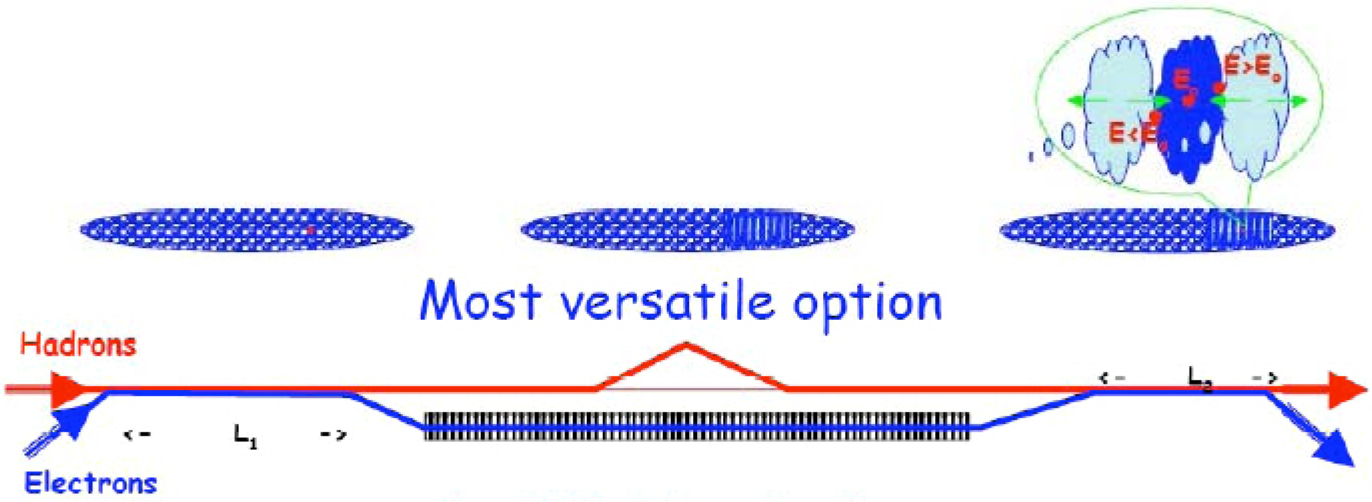


Table 1. Comparison of estimations for various cooling mechanisms in RHIC and LHC colliders.
The sign ∞ is used to indicate helplessly long damping times.

Machine	Species	Energy GeV/n	Synchrotron radiation, hrs	Electron cooling, hrs	CEC, hrs
RHIC	Au	100	20,961 ∞	~ 1	0.03
RHIC	protons	250	40,246 ∞	> 30	0.8
LHC	protons	450	48,489 ∞	> 1,600	0.95
LHC	protons	7,000	13 (energy)/26 (transverse)	∞∞	< 2

To estimate electron cooling in LHC we used an energy scaling $\gamma^{7/2}$ typical for RHIC's electron cooler design [8,9], i.e., cooling protons in LHC at 7 TeV is ~10^{10} harder that cooling antiprotons in the Fermilab recycler [7]. Hence, our usage of ∞∞ in an appropriate column.

Upgrade 5: eRHIC ($\geq$ 2014)

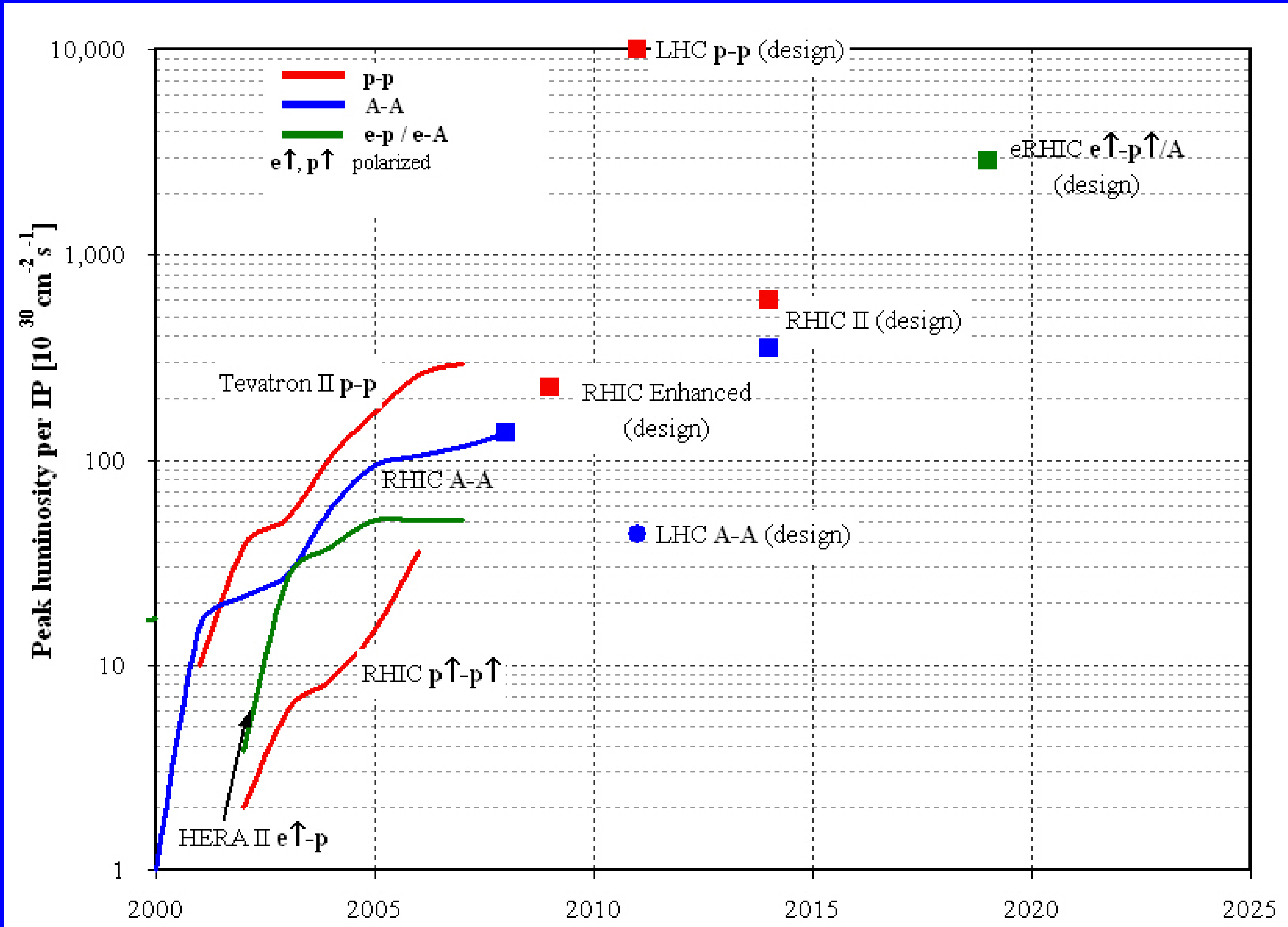
Main features:

V. Litvinenko, V. Ptitsyn

- High-luminosity electron-ion collider
  - 10^{32}-10^{34} cm^{-2}s^{-1} for e↑-p↑
  - 10^{30}-10^{32} cm^{-2}s^{-1} for e↑-A(↑)
- 30-100 GeV center-of-mass energy
- Longitudinally polarized electrons, protons, possibly light ions

- Currently working on
  - Ring-ring option (B-factory like e-ring)
  - Linac-ring option (higher luminosity potential)

Upgrade 5: eRHIC (≥ 2014)



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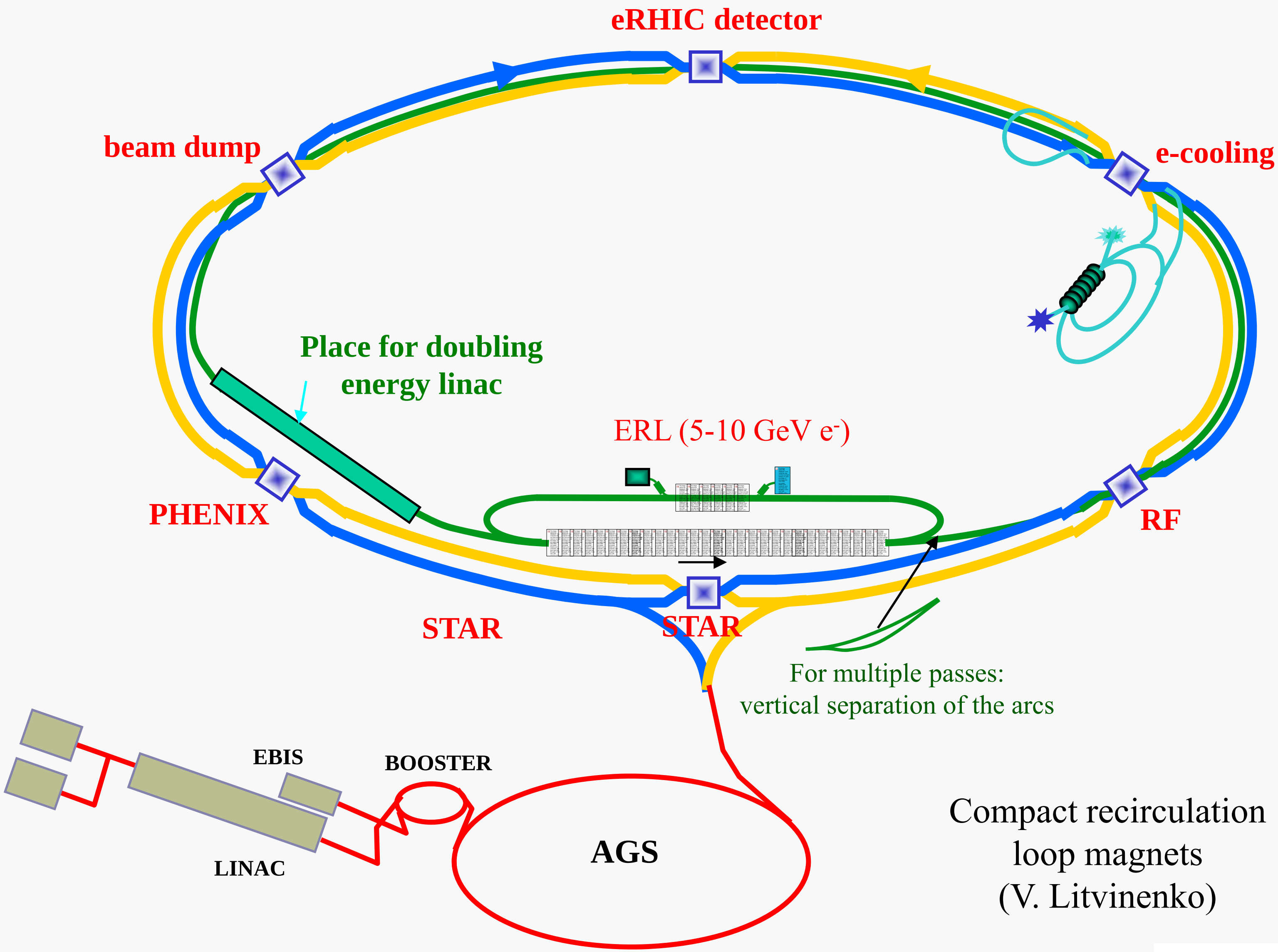
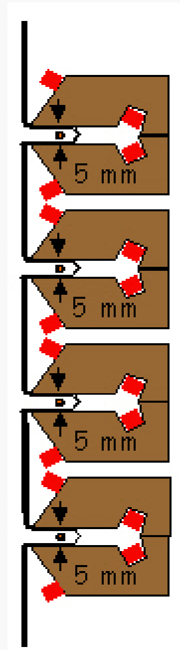
Upgrade 5: eRHIC (≥ 2014)





Compact recirculation loop magnets (V. Litvinenko)

ERL-based eRHIC parameters

	Electron-Proton Collisions				Electron-Au Collisions			
	High energy setup		Low energy setup		High energy setup		Low energy setup	
	p	e	p	e	Au	e	Au	e
Energy, GeV	250	10	50	3	100	10	50	3
Number of bunches	166		166		166		166	
Bunch intensity, 10^{11} (10^{9} for Au)	2.0	1.2	2.0	1.2	1.1	1.2	1.1	1.2
95% normalized emittance, πμm	6	115	6	115	2.4	115	2.4	115
Rms emittance, nm	3.8	1.0	19	3.3	3.7	1.0	7.5	3.3
β*, x/y, cm	26	100	26	150	26	100	26	60
Beam-beam parameters, x/y	0.015	2.3	0.015	2.3	0.015	1.0	0.015	1.0
Rms bunch length, cm	20	1.0	20	1.0	20	1.0	20	1.0
Polarization, %	70	80	70	80	0	0	0	0
Peak Luminosity/n, 1.e33 $cm^{-2}s^{-1}$	**2.6**		**0.53**		**2.9**		**1.5**	
Aver.Luminosity/n, 1.e33 $cm^{-2}s^{-1}$	**0.87**		**0.18**		**1.0**		**0.5**	
Luminosity integral /week, pb^{-1}	**530**		**105**		**580**		**290**	

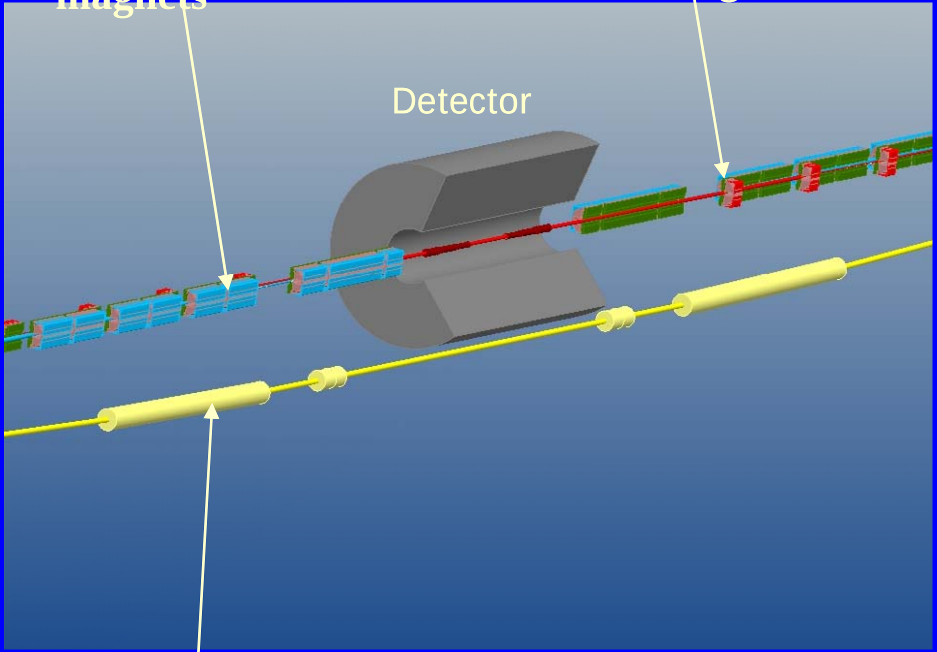
Luminosity of ring-ring version 10× lower

eRHIC interaction region design

C. Montag et al.

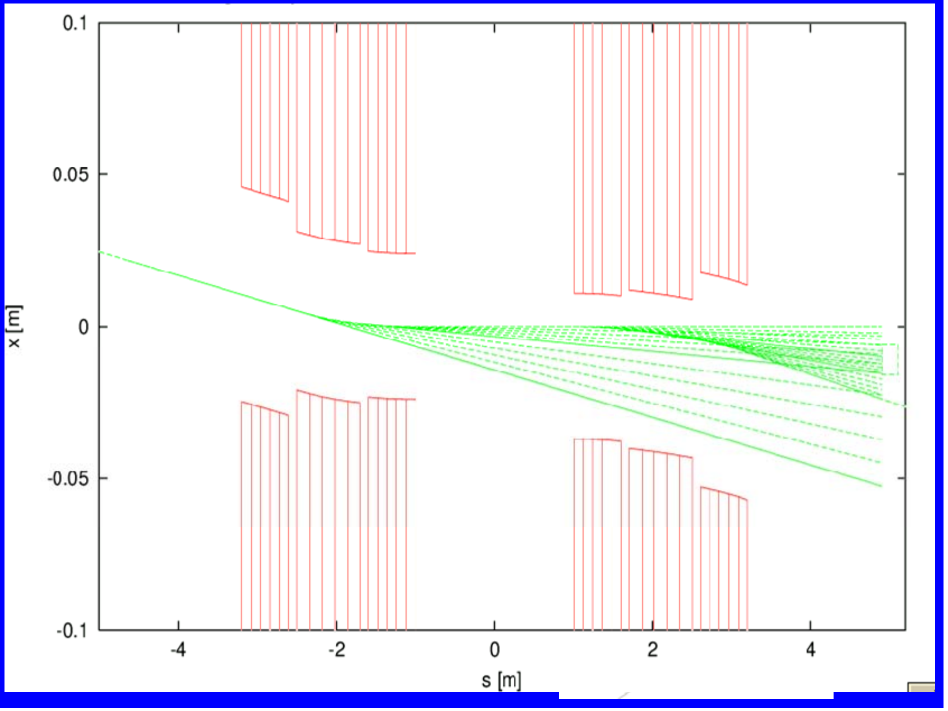
(Blue) ion ring magnets

(Red) electron beam magnets



(Yellow) ion ring magnets

- Yellow ion ring makes 3m vertical excursion.
- Design incorporates both normal and superconducting magnets.
- Fast beam separation. Besides the interaction point no electron-ion collisions allowed.
- Synchrotron radiation emitted by electrons does not hit surfaces of cold magnets



IR Design Schemes

	Distance to nearest magnet from IP	Beam separation	Magnets used	Hor/Ver beam size ratio
Ring-ring, l*=1m	1m	Combined field quadrupoles	Warm and cold	0.5
Ring-ring, l*=3m	3m	Detector integrated dipole	Warm and cold	0.5
Linac-ring	5m	Detector integrated dipole	Warm	1

- No crossing angle at the IP
- Linac-ring: larger electron beta*; relaxed aperture limits ; allows round beam collision geometry (the luminosity gains by a factor of 2.5).
- Detector integrated dipole: dipole field superimposed on detector solenoid.

ERL-based eRHIC R&D items

- High intensity polarized electron source
  → larger cathode surface with existing densities ~50mA/cm^2, good lifetime
- ERL technology for high energy, high current beams
  → R&D ERL under construction at BNL
- Development of compact recirculation loop magnets
  → Design, build and test small gap magnet and vacuum chamber
- Electron-ion beam-beam effects
  → instability and break-up of electron-beam
  → realistic simulations, possibly tests with e-lens
- Polarized ^{3}He production and acceleration
  → EBIS as ionizer of polarized ^{3}He gas
  → depolarizing resonance with anomalous magnetic moment diff. from p

Summary RHIC

Status:

- Since 2000, 4 ion combinations, 8 energies
- Luminosity/year increased by >2 orders of magnitude
- Protons with 65% polarization at 100 GeV

Planned upgrades:

1. Enhanced Design parameters (~2009)
2. EBIS (modern pre-injector, U and ^{3}H↑ 2009)
3. Low energy Au-Au operation (QCD critical point ≥ 2009)
4. RHIC II (order of magnitude increase in Au-Au $\mathcal{L}$ ≥2011)
5. eRHIC (high luminosity electron-ion collider ≥2014)