(RHIC low energy operation) RHIC II, and eRHIC

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RHIC and AGS Annual User's Meeting
22 June 2007

Outline

1. Status, Enhanced Design, EBIS

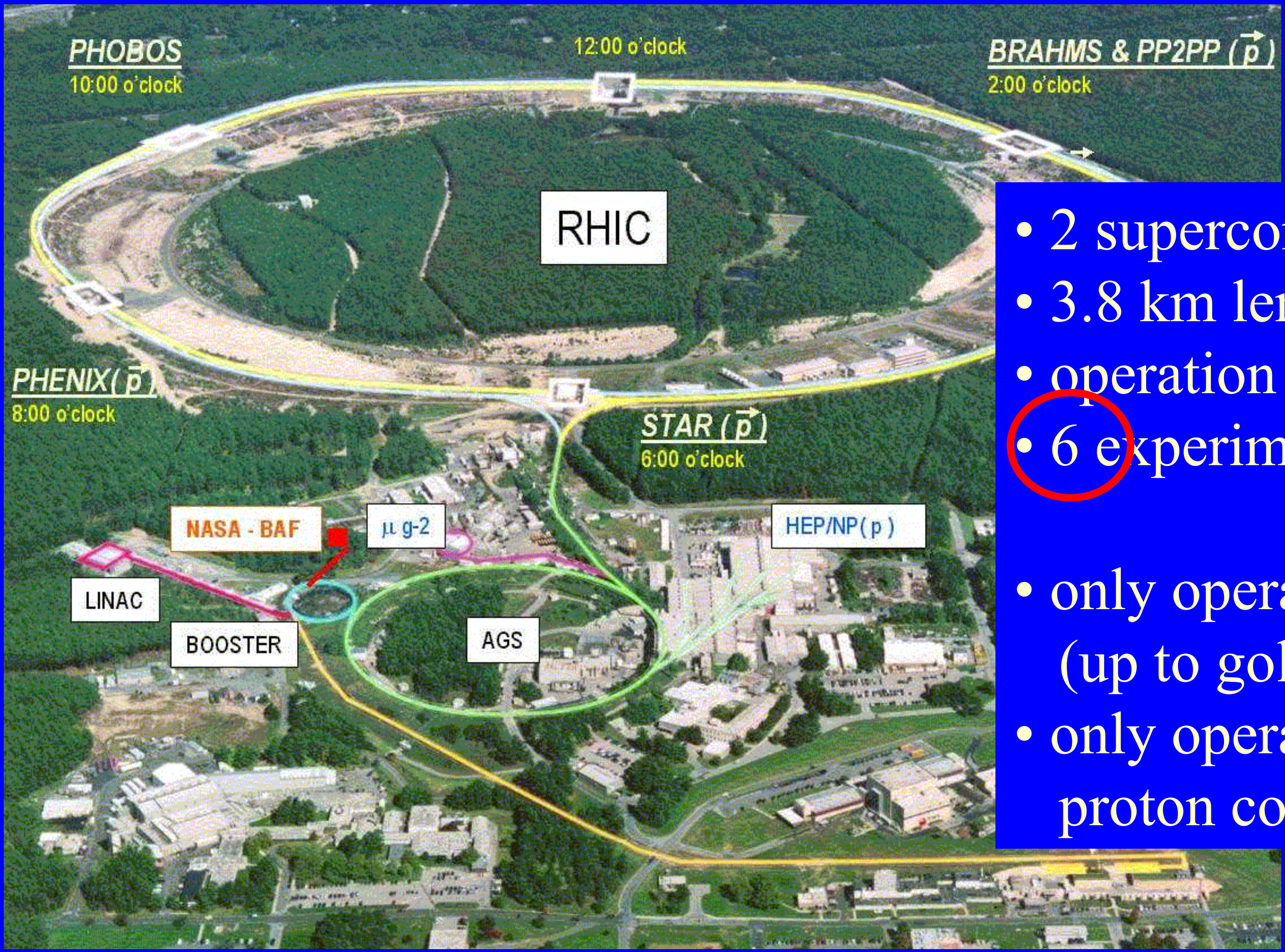
2. (Low energy operation)
   → covered by George Stephans, MIT

3. RHIC II
   → electron cooling

4. Other ideas
   → stochastic cooling, IR modifications, electron lenses

5. eRHIC

Relativistic Heavy Ion Collider



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

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

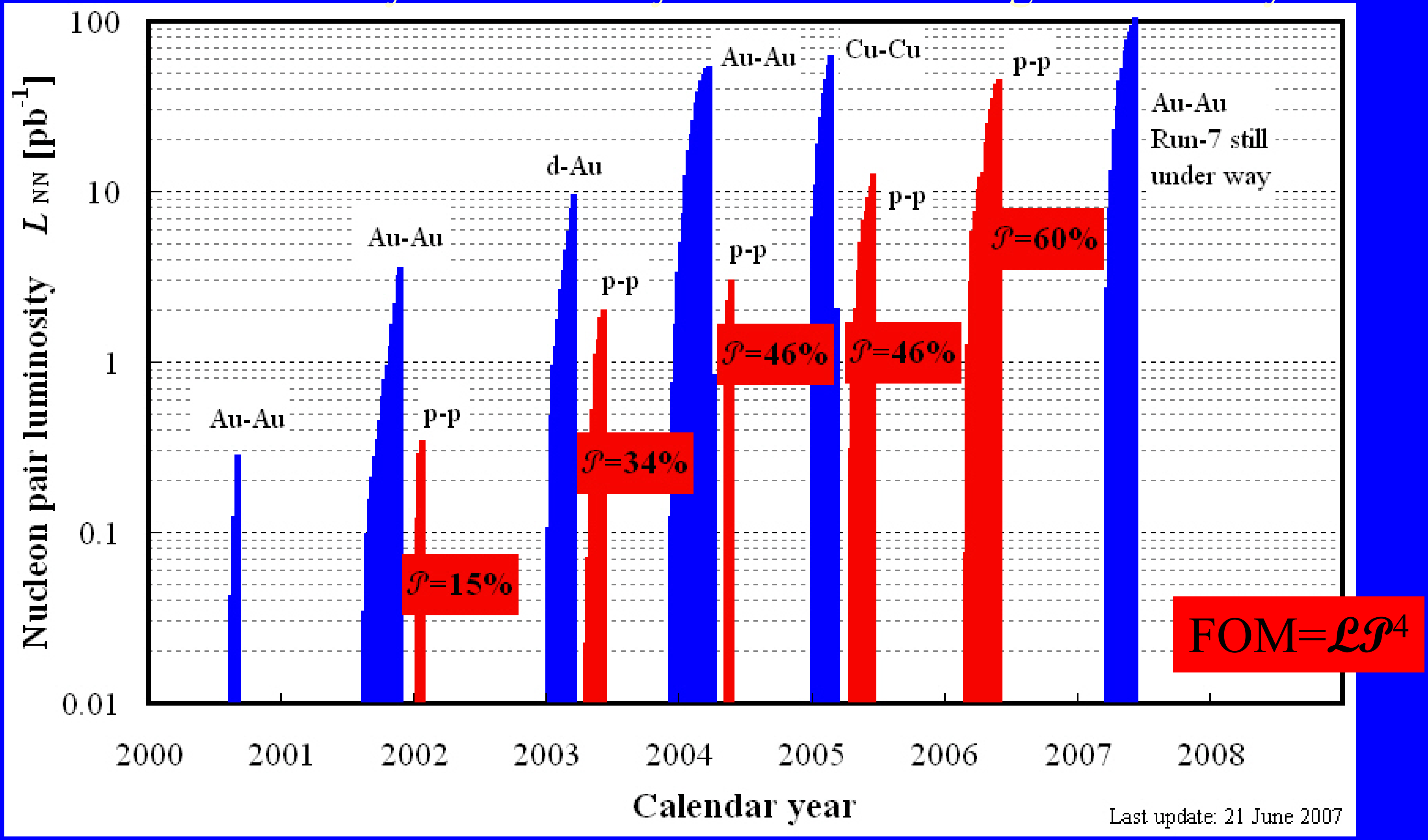
RHIC running modes

- Au–Au 4.6, 10, 28, 31, 65, 100 GeV/nucleon
- d–Au 100 GeV/nucleon
- Cu–Cu 11, 31, 100 GeV/nucleon
- Polarized p–p 11, 31, 100, 205, 250 GeV

Some modes only for days – fast machine setup essential.

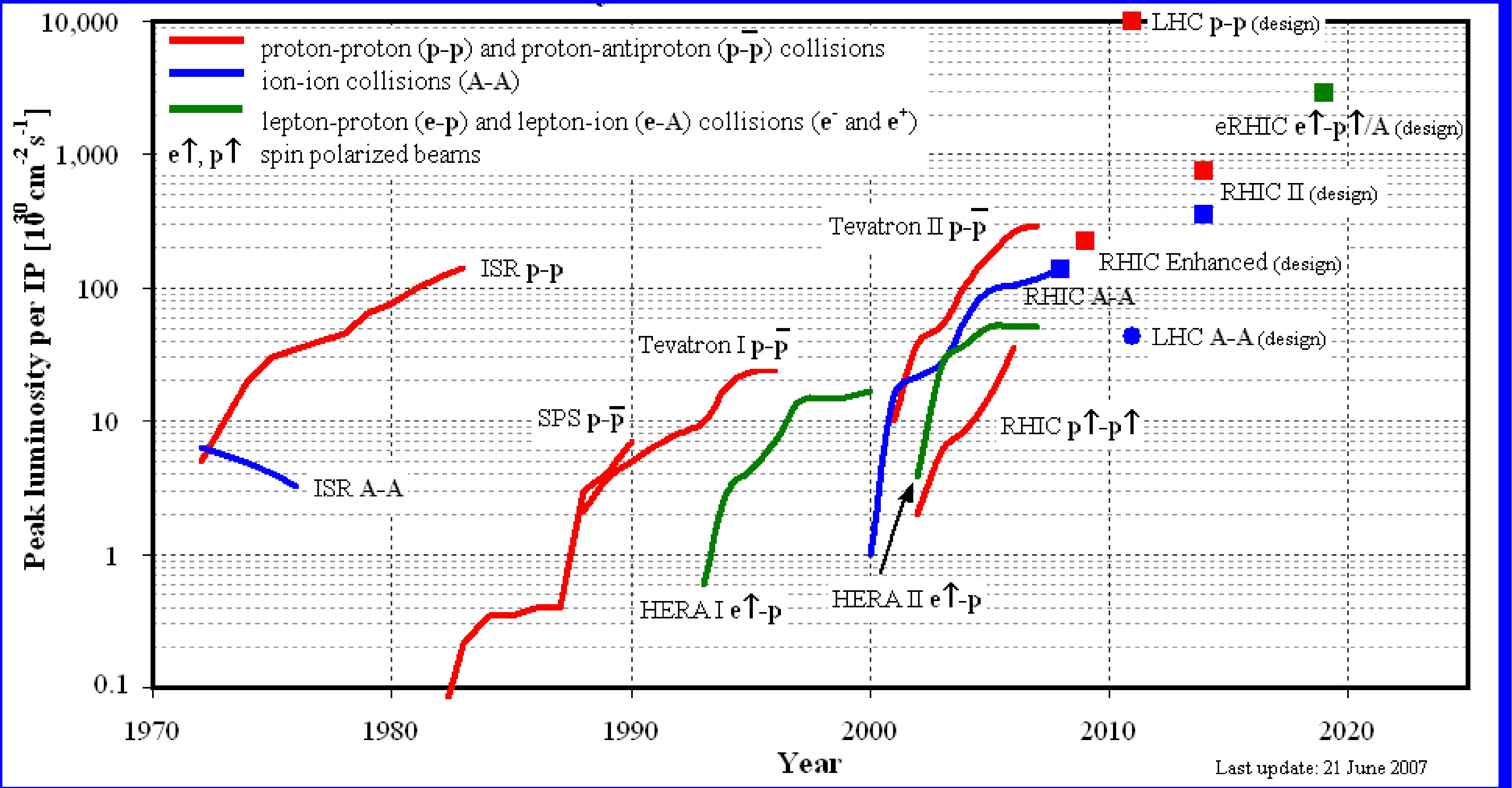
RHIC delivered luminosity

Delivered luminosity increased by >2 orders of magnitude in 7 years.



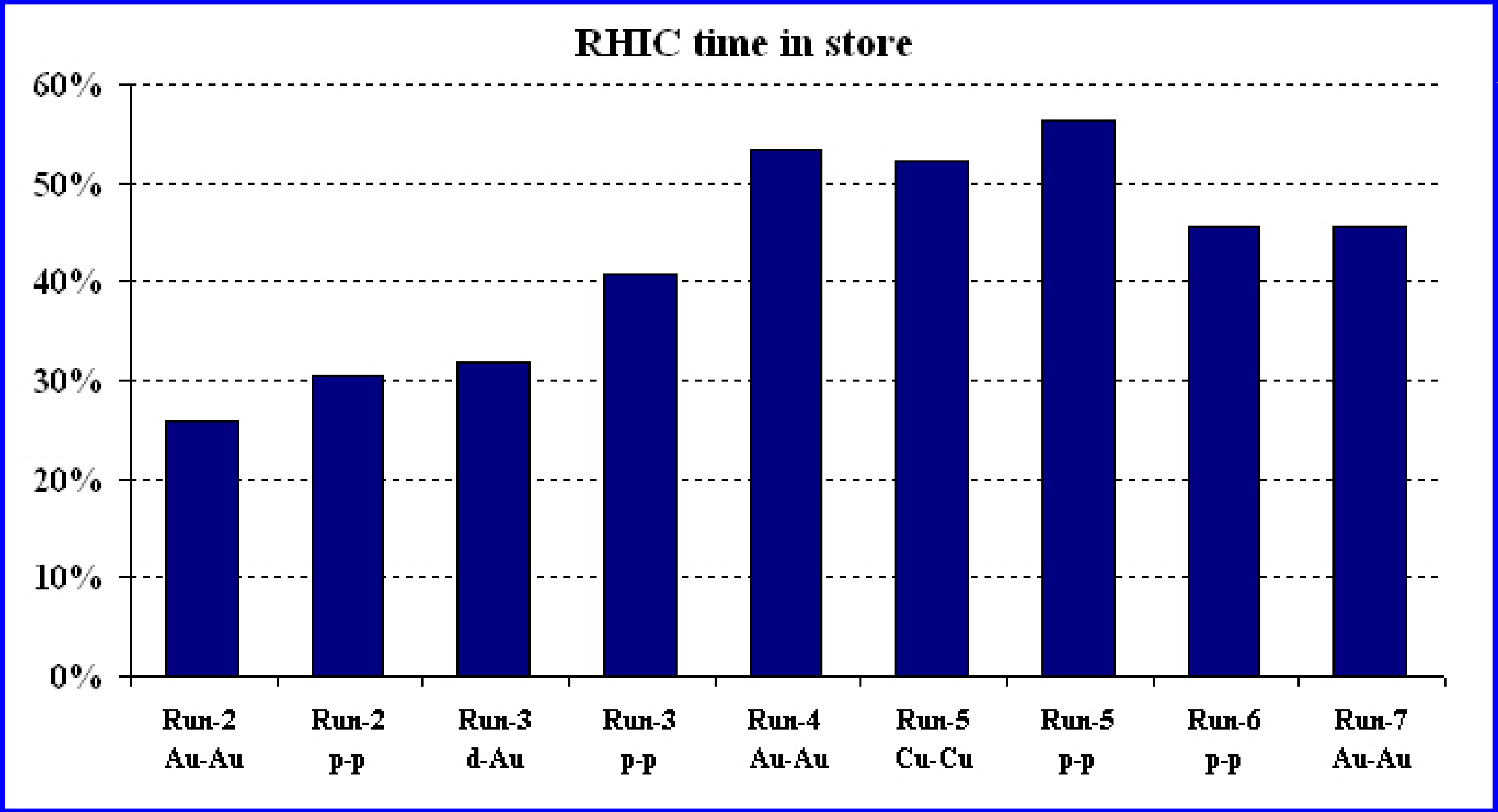
Delivered to PHENIX, one of RHIC's high-luminosity experiments.

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

Setbacks in last 2 years

- set-up times decreased in Run-7 (~1 h/store)
- but failure hours increased significantly

Failures modes are under intense scrutiny

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 $\mathcal{L}$	**10^{26}cm^{-2}s^{-1}**	**14**	**8**
p↑- p↑ operation			
Energy	GeV	100	250
No of bunches	…	111	111
Bunch intensity	10^{11}	1.4	2.0
Average $\mathcal{L}$	**10^{30}cm^{-2}s^{-1}**	**20**	**150**
Polarization $\mathcal{P}$	**%**	**60**	**70**

Exceeded Enhanced Design goal ← (Au-Au Average $\mathcal{L}$)

(15-20% from stochastic cooling in Yellow)

← **7.5×** (p↑- p↑ Average $\mathcal{L}$)

← **+10%** (Polarization)

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

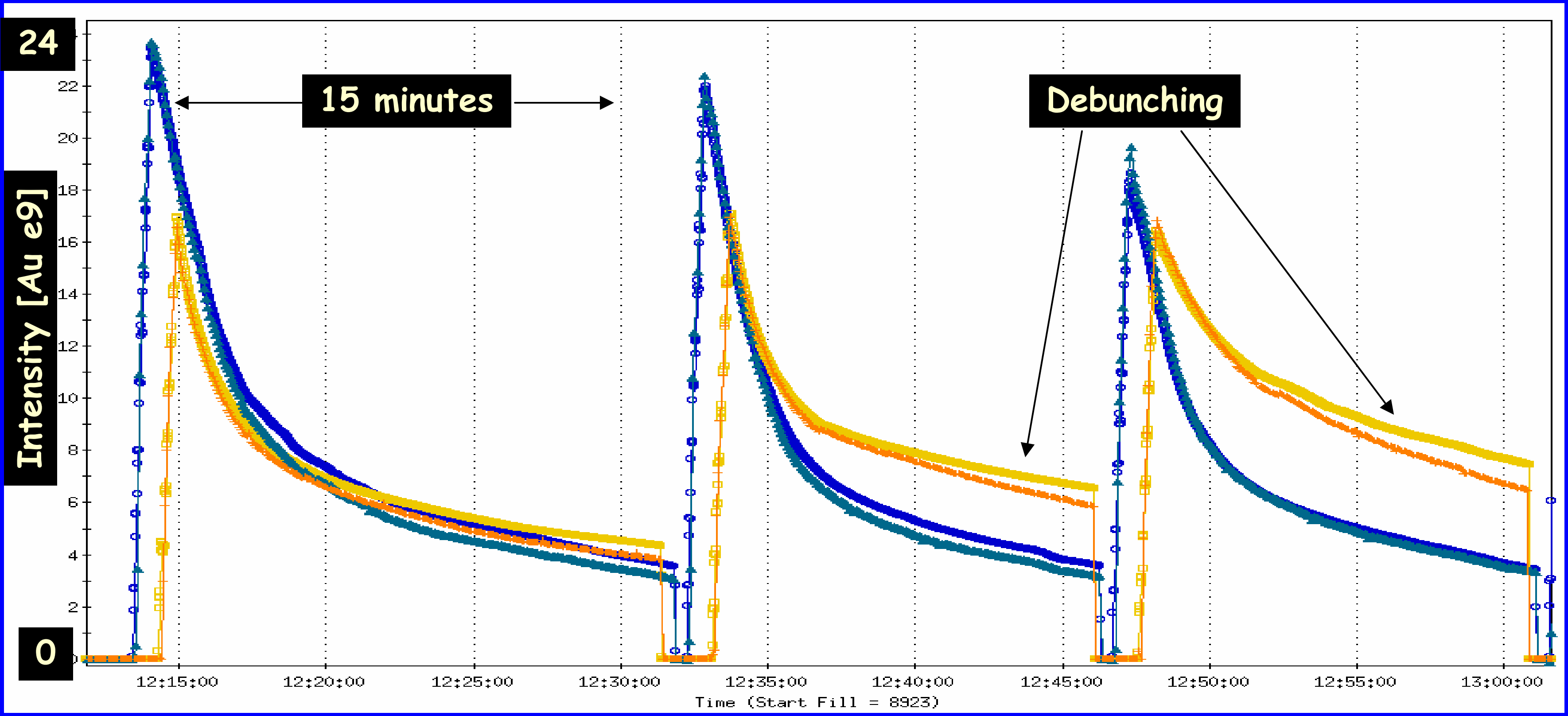
→ New species: U, ^{3}He↑

→ Under construction

→ Expect commissioning to begin in 2009

Low energy Au-Au operation (1)

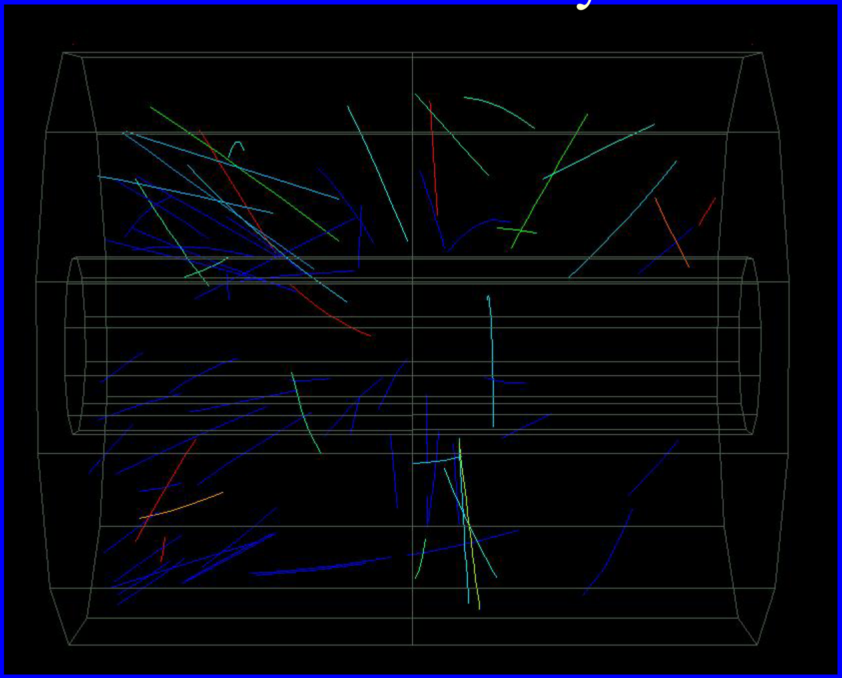
Demonstrated Au-Au collisions
at $\sqrt{s}$ = 9.2 GeV/nucleon T. Satogata et al.

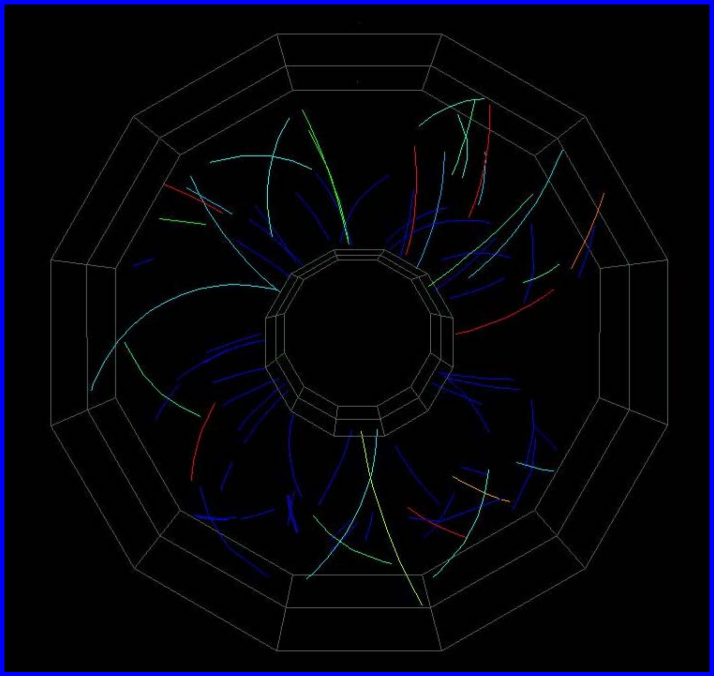


Luminosity not yet analyzed quantitatively.

Low energy Au-Au operation (2)

Event seen by the STAR detector.





Low energy operation in principle possible.

Luminosity of this year's test (1/2 normal injection energy) not yet analyzed quantitatively.

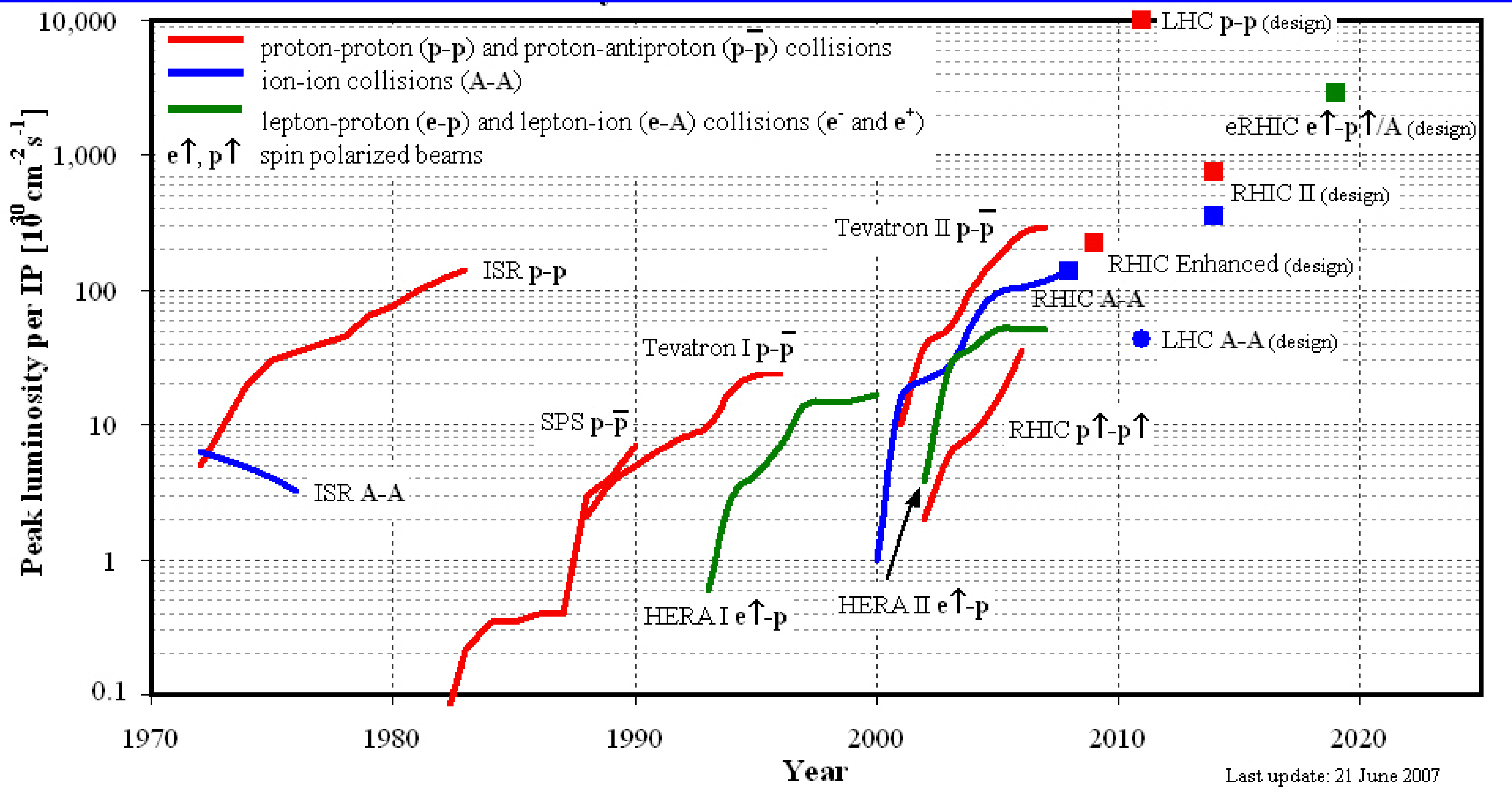
→ Working on e-cooling in AGS for luminosity increase at even lower energies (down to 1/4 or normal injection).

RHIC II – electron cooling (≥ 2013)

Parameter	unit	**Enhanced design (achieved)**	**RHIC II**	
Au-Au operation				
Energy	GeV/n	100	100	
No of bunches	…	111 (103)	111	
Bunch intensity	10^9	1.0 (1.1)	1.0	
Average $\mathcal{L}$	**10^{26}cm^{-2}s^{-1}**	**8 (14)**	**70**	← **9× (5×)**
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**	

RHIC II – electron cooling (≥ 2013)

Hadron collider luminosities



RHIC II – electron cooling (≥ 2013)

Use non-magnetized cooling (no solenoidal field)

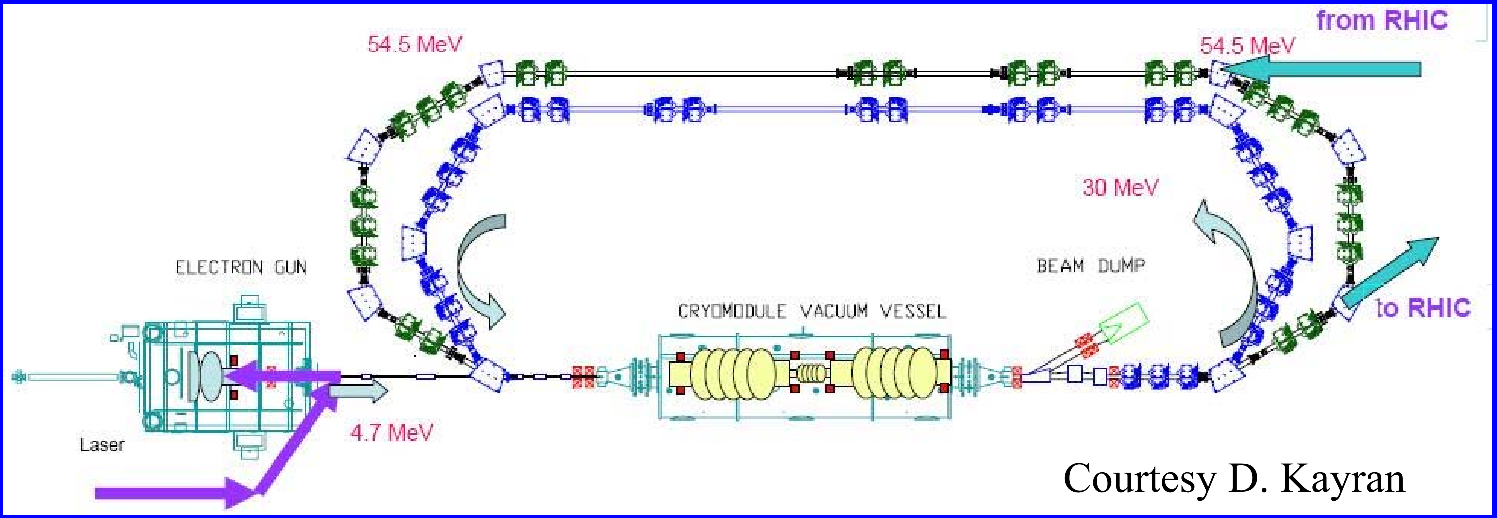
(demonstrated with 8.9 GeV antiprotons in Fermilab Recycler – Nagaitsev et al.)

For 100 GeV/nucleon Au beams need:

- 54 MeV electron beam
- 5nC per bunch
- rms emittance < 4 μm
- rms $\Delta p/p < 5\times10^{-4}$

→ 2.7 MW beam power

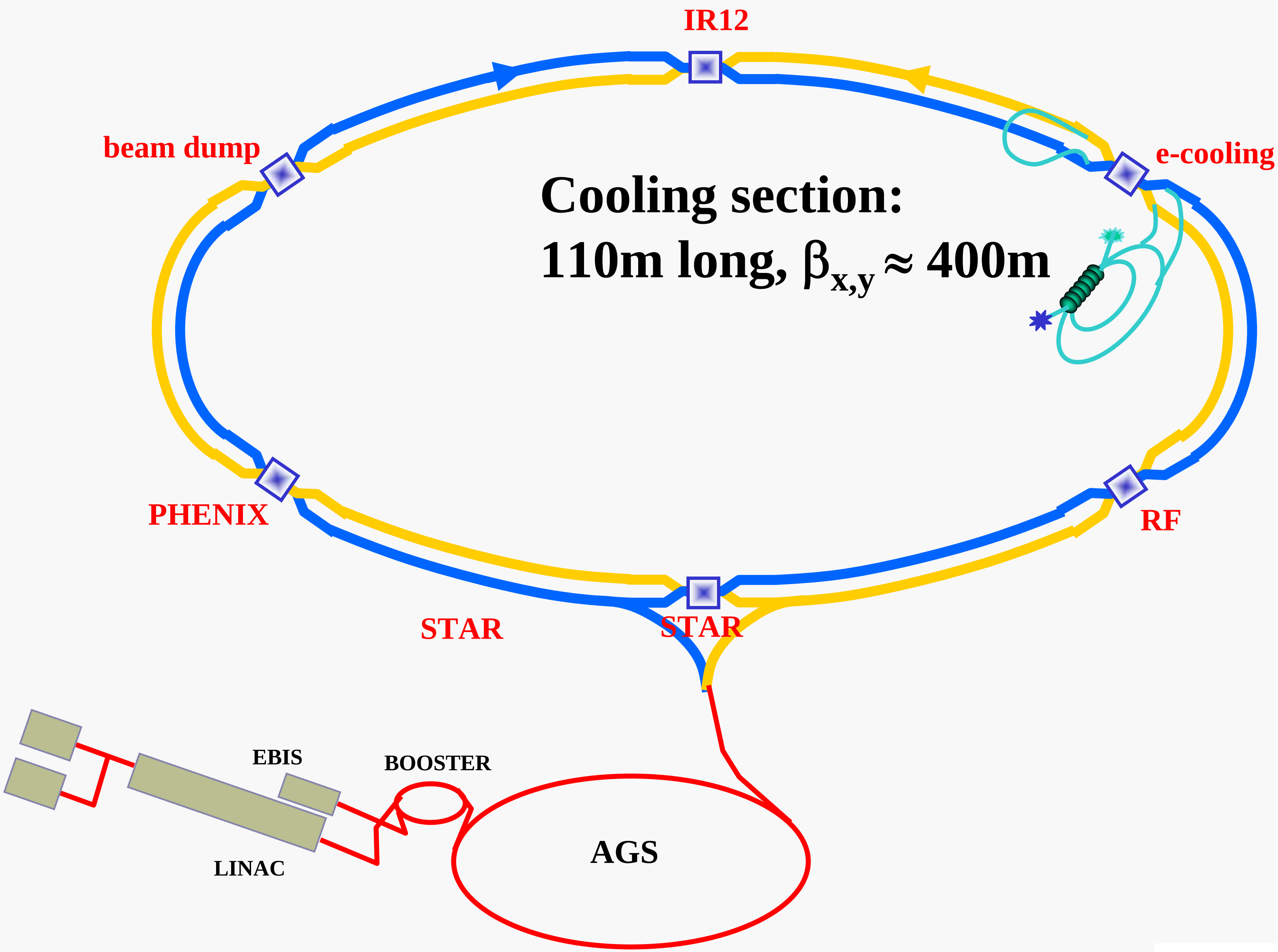
→ need Energy Recovery Linac (ERL)



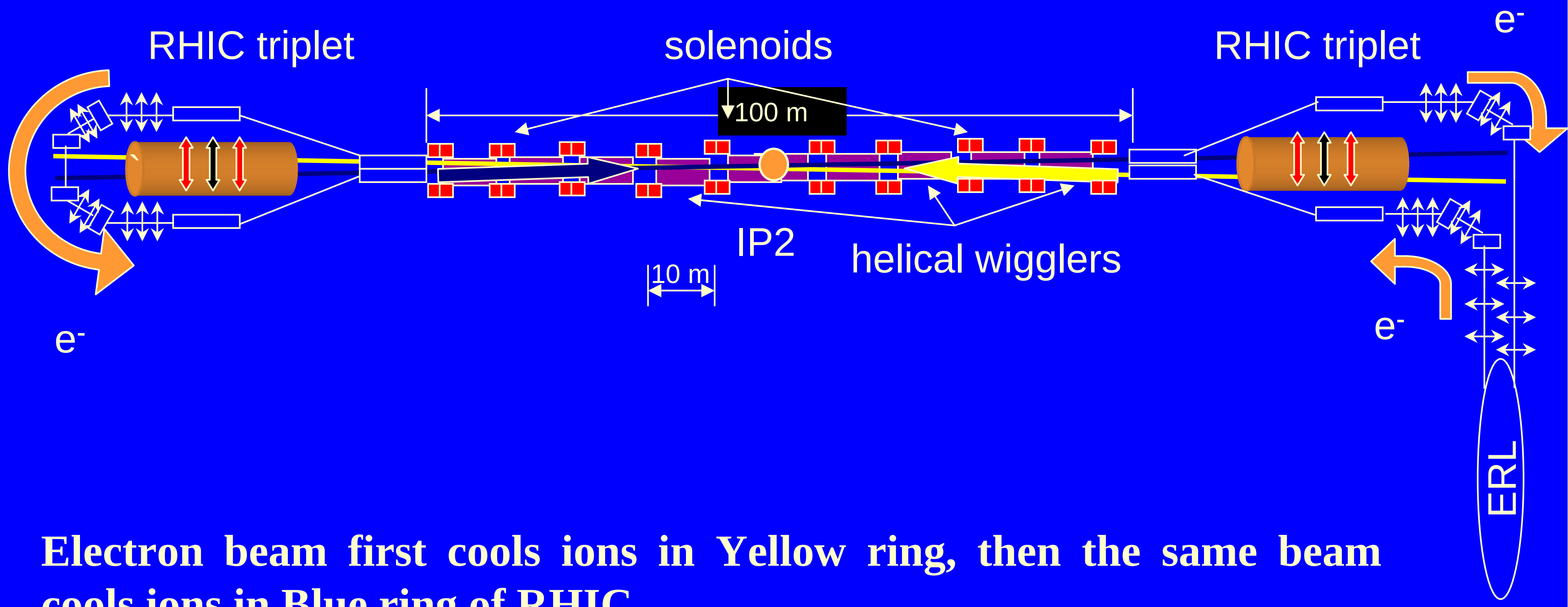
Courtesy D. Kayran

RHIC II – electron cooling (≥ 2013)

Cooling section:
110m long, $\beta_{x,y} \approx 400$m



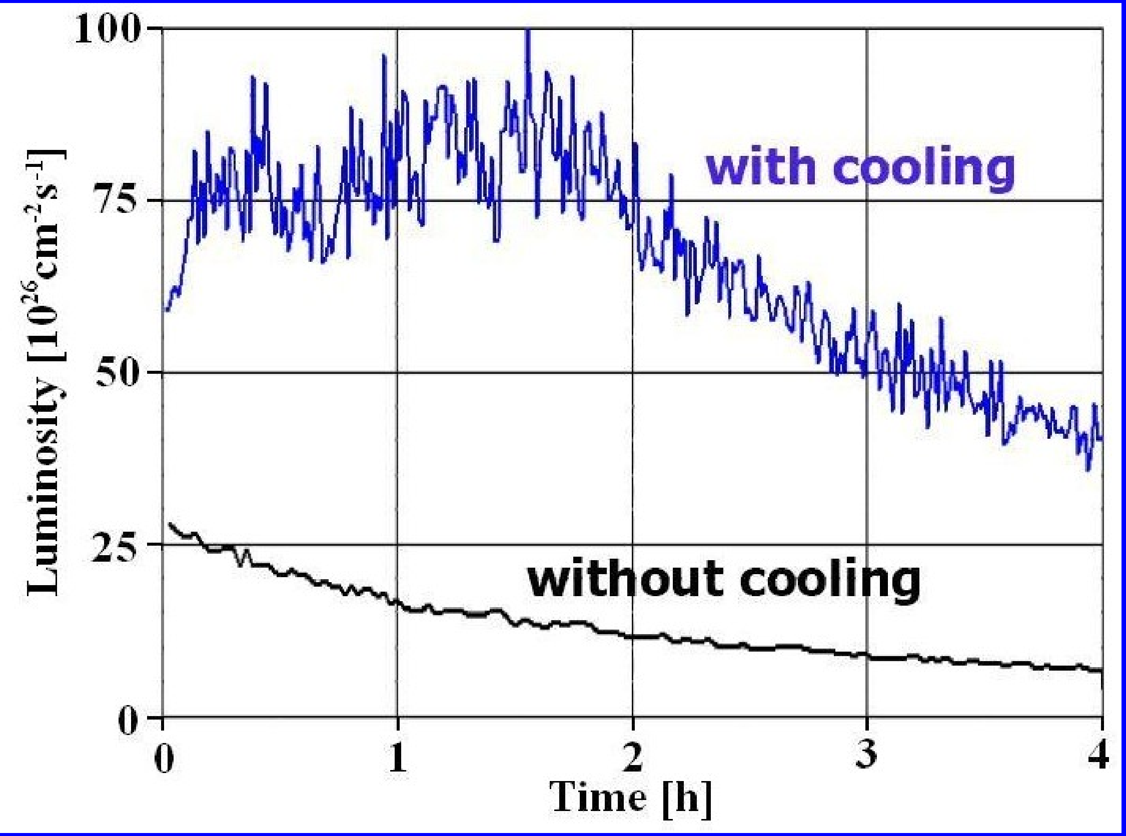
Electron cooling section in IR2



Electron beam first cools ions in Yellow ring, then the same beam cools ions in Blue ring of RHIC.

RHIC II – electron cooling (≥ 2013)

Simulated luminosities (A. Fedotov)



For:

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

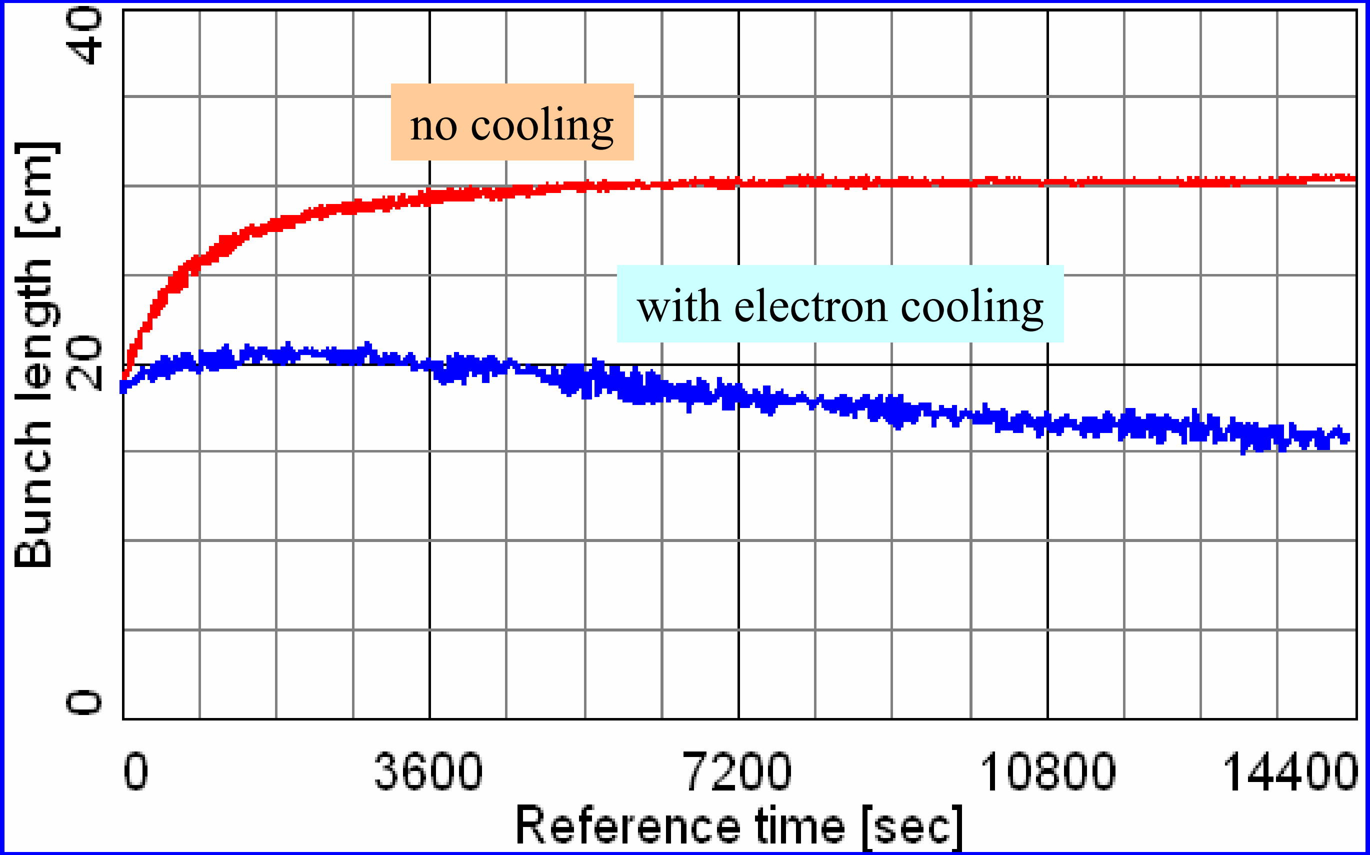
$$\mathcal{L}(t) = \frac{\mathcal{L}(0)}{(1+t/\tau)^2}$$

→ $\tau \approx 5$ h for Au-Au

Store length limited by burn-off

RHIC II – electron cooling (≥ 2013)

Bunch length with electron cooling



Can maintain 20 cm rms bunch length.

Shaping of longitudinal distribution is possible.

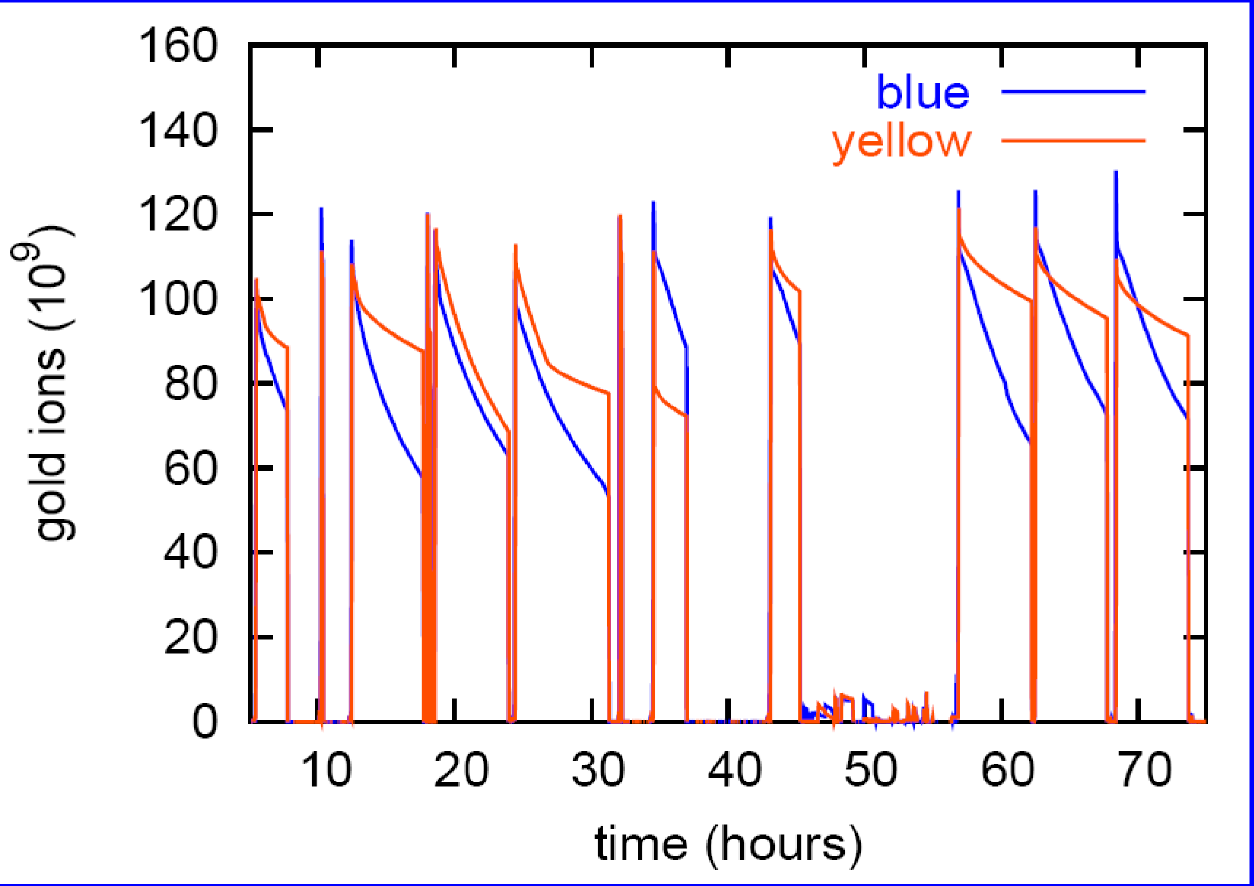
RHIC II – electron cooling (≥ 2013)

E-cooling system under development allows

- Cooling of all species at high bunch intensities
  (stochastic cooling slows down rapidly for $N_b > 10^9$)
- Cooling down to transition energy
- Pre-cooling of protons at lower energies (30 GeV)
  (to emittances corresponding to beam-beam limit ξ_{max})
- Limited cooling of protons at 100 GeV

Other ideas: transverse stochastic cooling (HI)

Longitudinal stochastic cooling operational in Yellow.



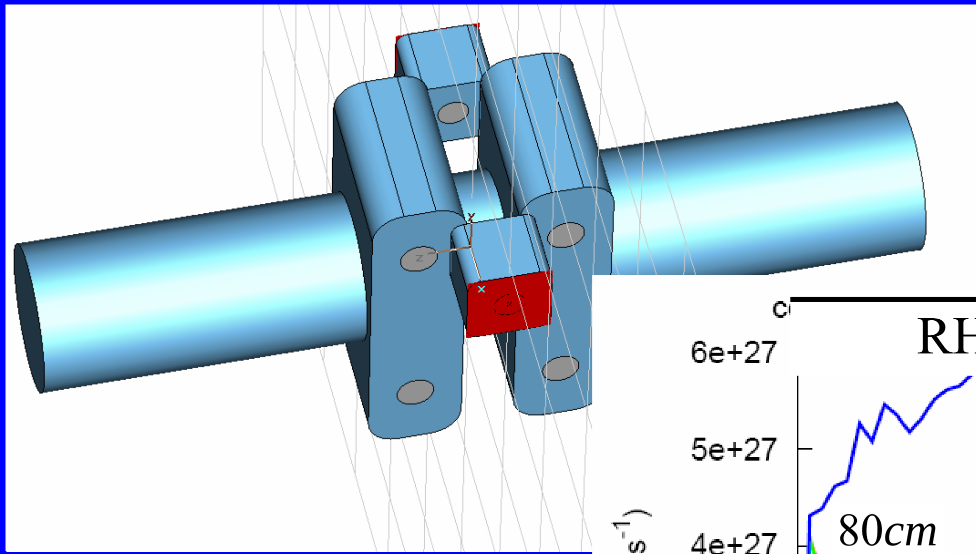
M. Brennan
M. Blaskiewicz

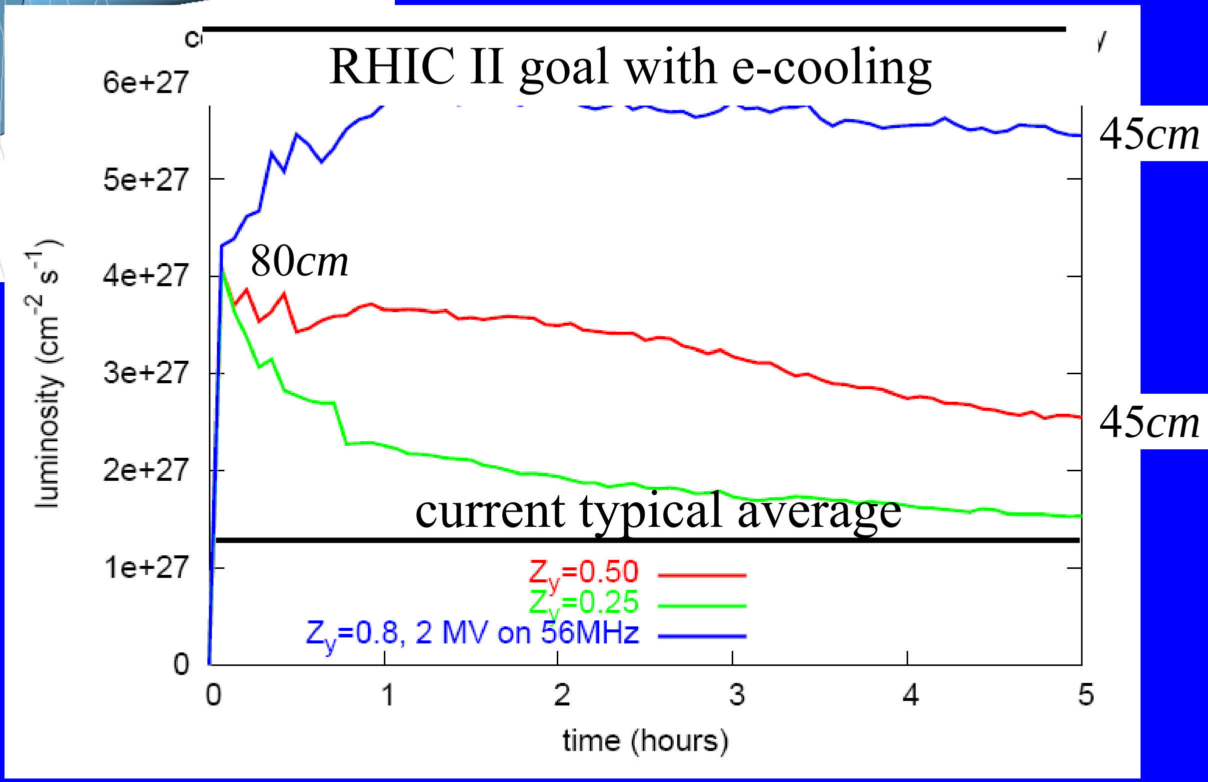
→ 15-20% increase in delivered luminosity.
Expect same improvement with heavy ions in Blue.

Other ideas: transverse stochastic cooling (HI)

Transverse stochastic cooling appears also possible for heavy ions.

Calculations by M. Blaskiewicz





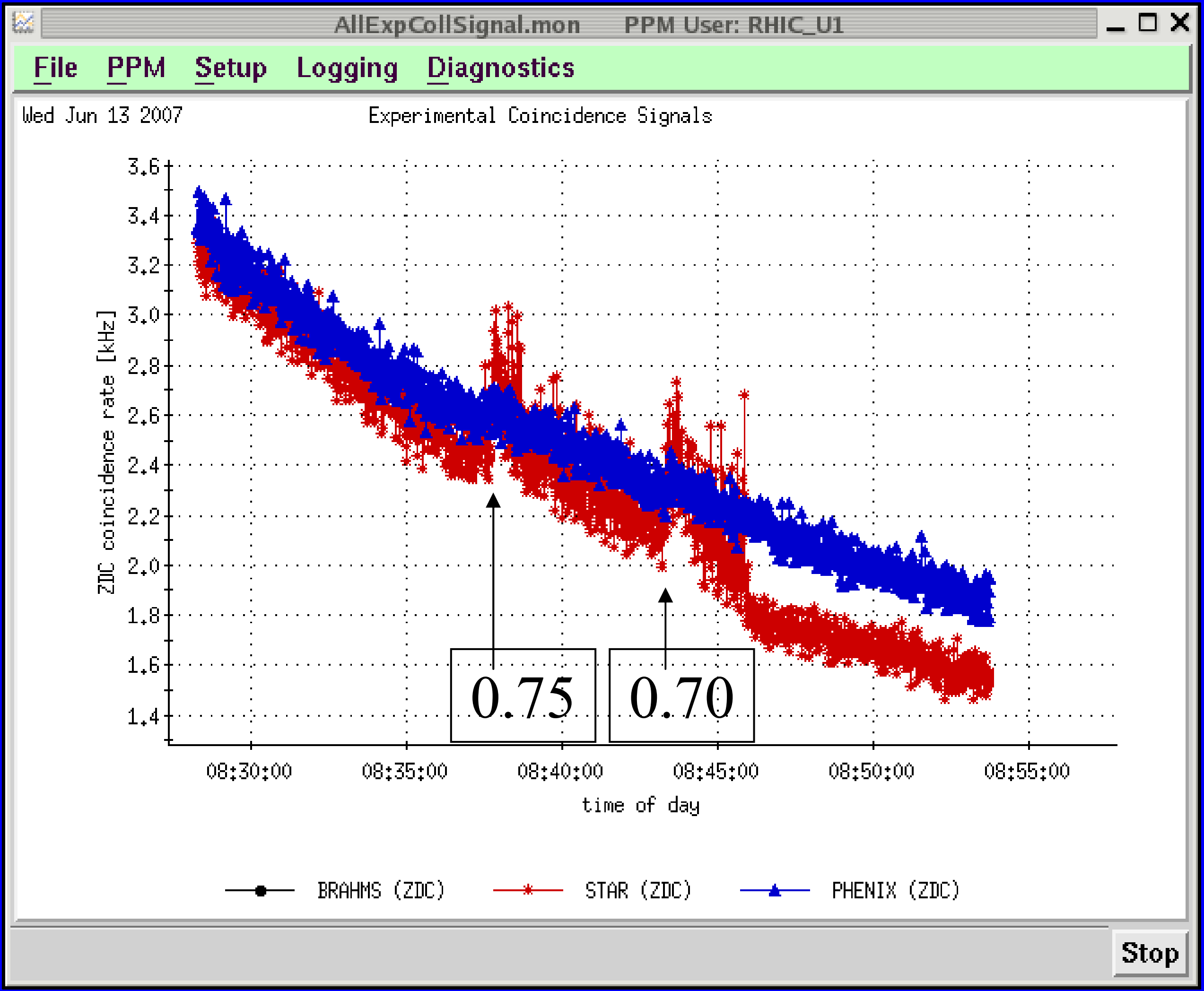
Frequency : 5-9 GHz
Cooling time: ~ 1 hour

Other ideas: lower β* (pp)

D. Trbojevic et al.

- Polarized proton luminosity not limited by burn-off → reduction in β* useful
- Some options:
  - Squeeze more with existing magnets
  - Quadrupole first IR
  - Slim magnets within detectors

Other ideas: lower β* (pp)

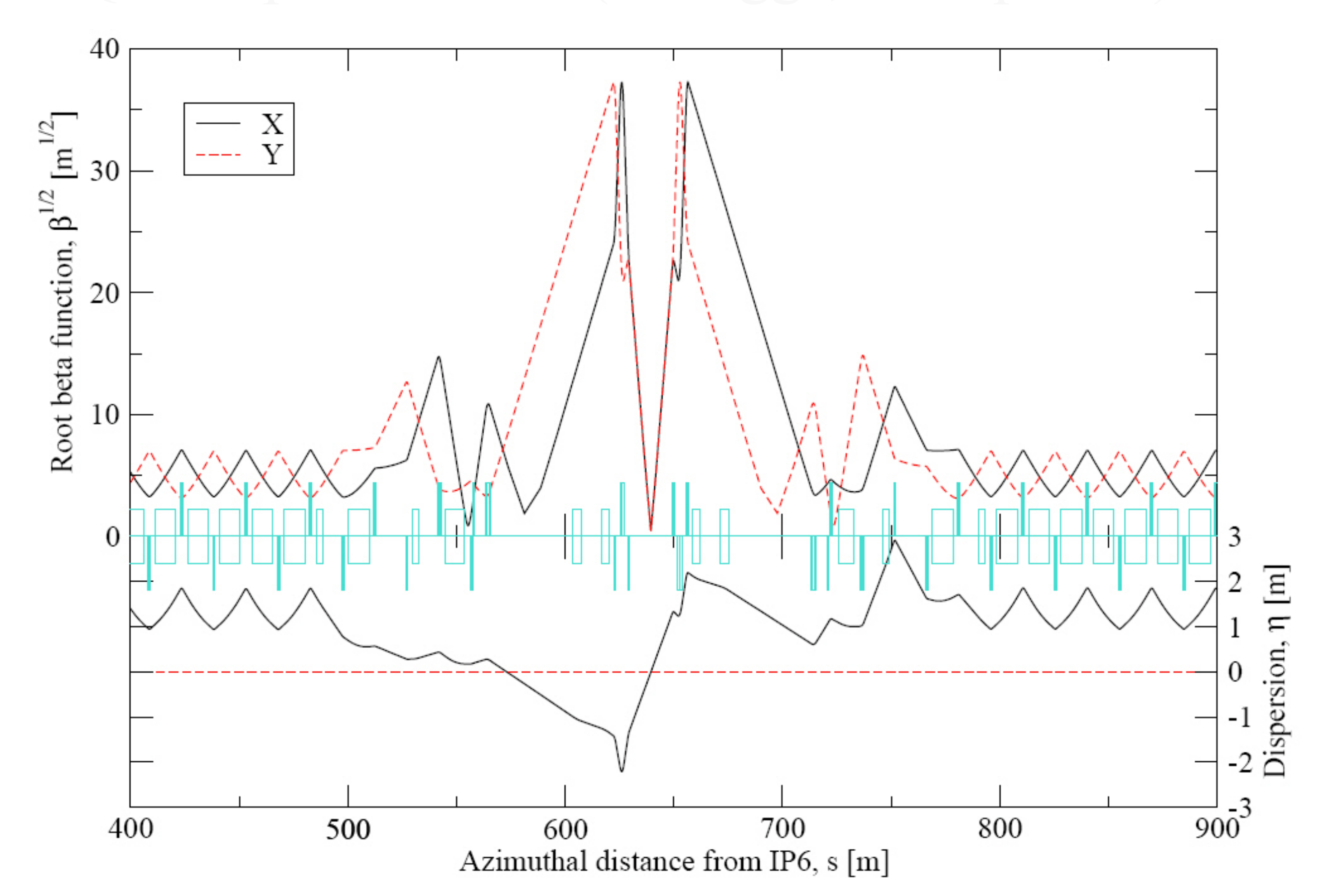


Recent test with Au beams (F. Pilat et al.)

β* lowered from 0.80m to 0.75m to 0.70m

Other ideas: lower β* (pp)

Quadrupole first IR (S. Peggs, S. Tepikian)



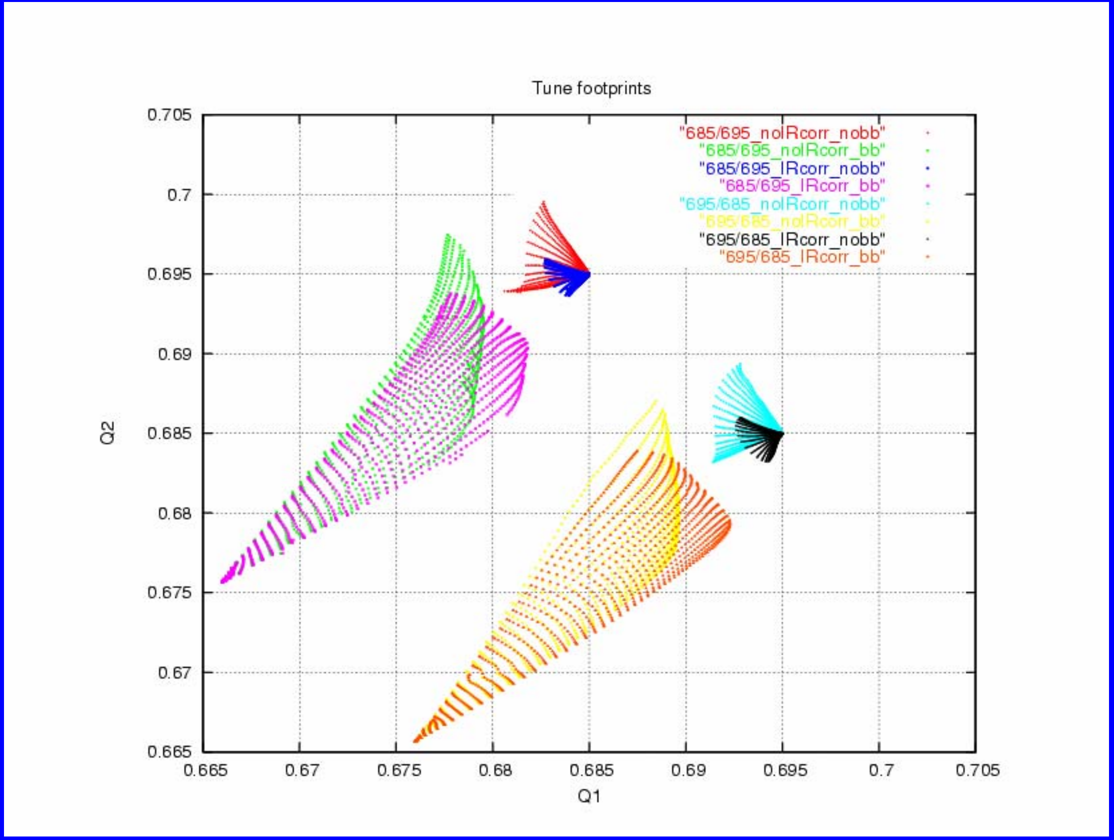
*l** = 10 m and maximum β maintained, **β* = 0.20 m**

However, problems with asymmetric species.

Other ideas: electron lenses (pp)

Why an electron lens?

Y. Luo et al.



This tune spread can only be reduced by an electron lens, not by magnets

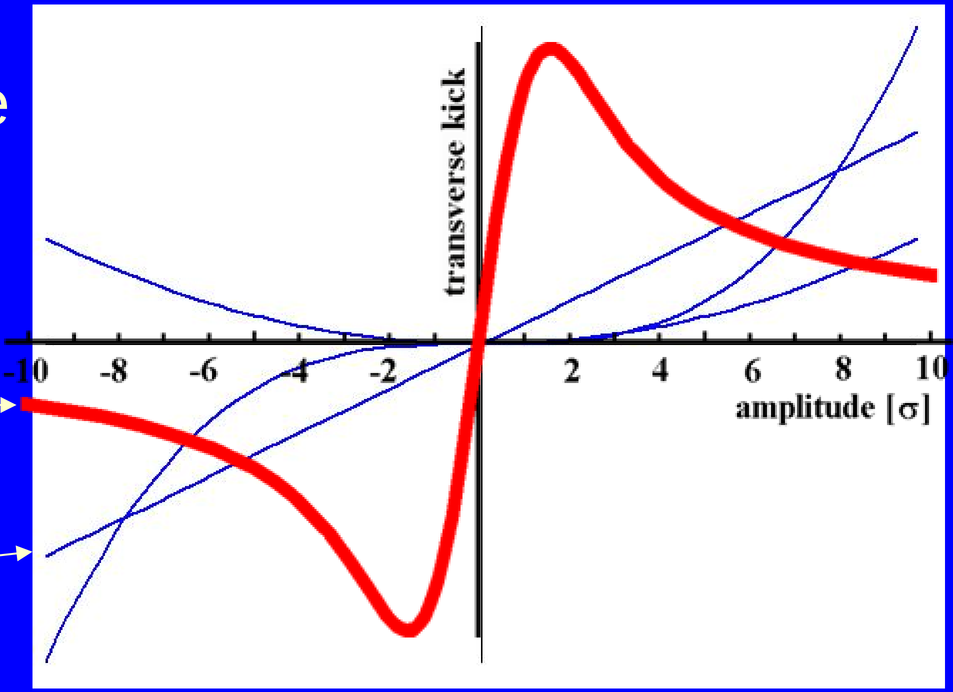
Polarized proton luminosity limited by beam-beam induced tune spread.

Other ideas: electron lenses (pp)

Beam-beam effects cannot be corrected with magnets

beam-beam kick

magnet kicks

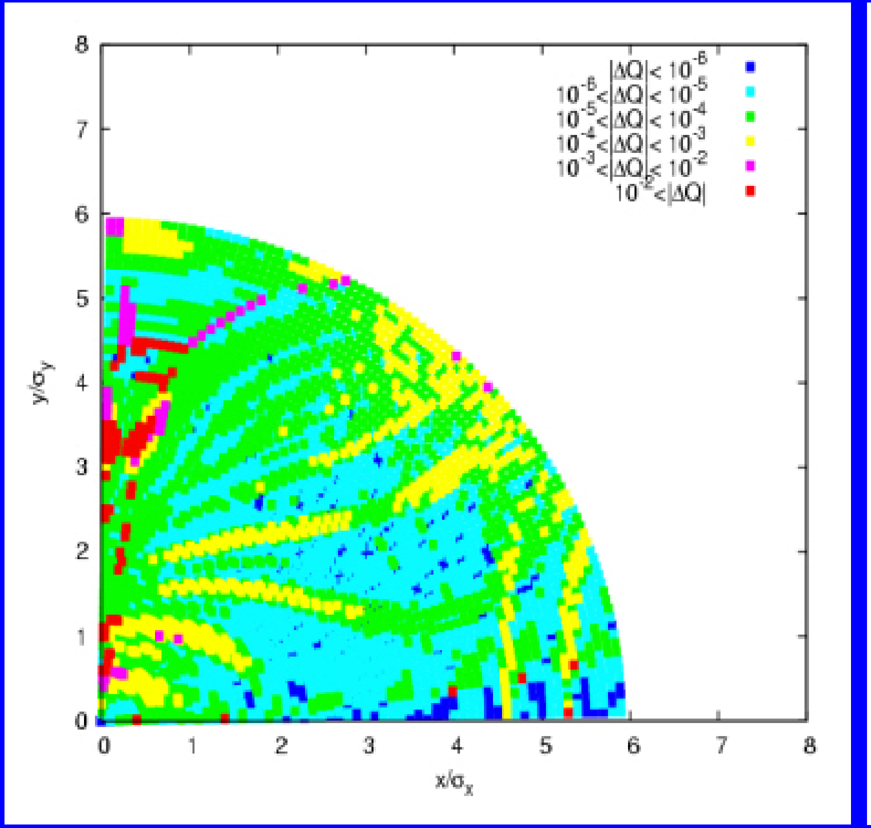


2 e-lenses operate in Tevatron (not for head-on compensation)

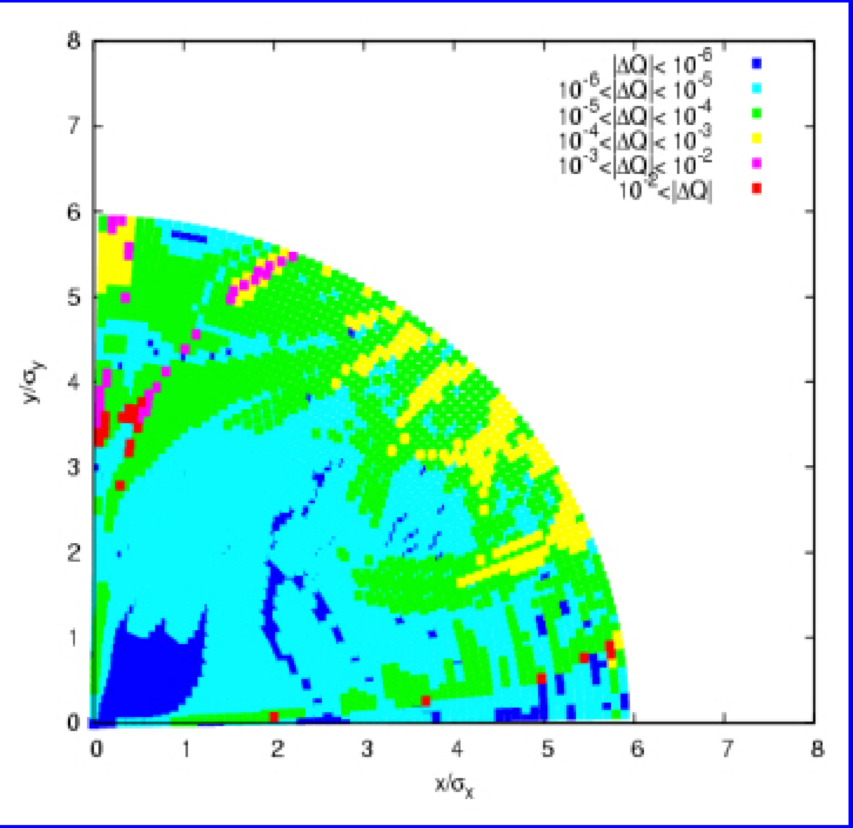
Other ideas: electron lenses (pp)

Simulation by Y. Luo

Tune diffusion w/o e-lens



Tune diffusion w/ e-lens



Electron lens studies under way (~1 year),
Hardware construction (~1 year) only after benefit established.
E-lens technology is similar to EBIS technology.

eRHIC (≥ 2015)

V. Litvinenko
V. Ptitsyn et al.

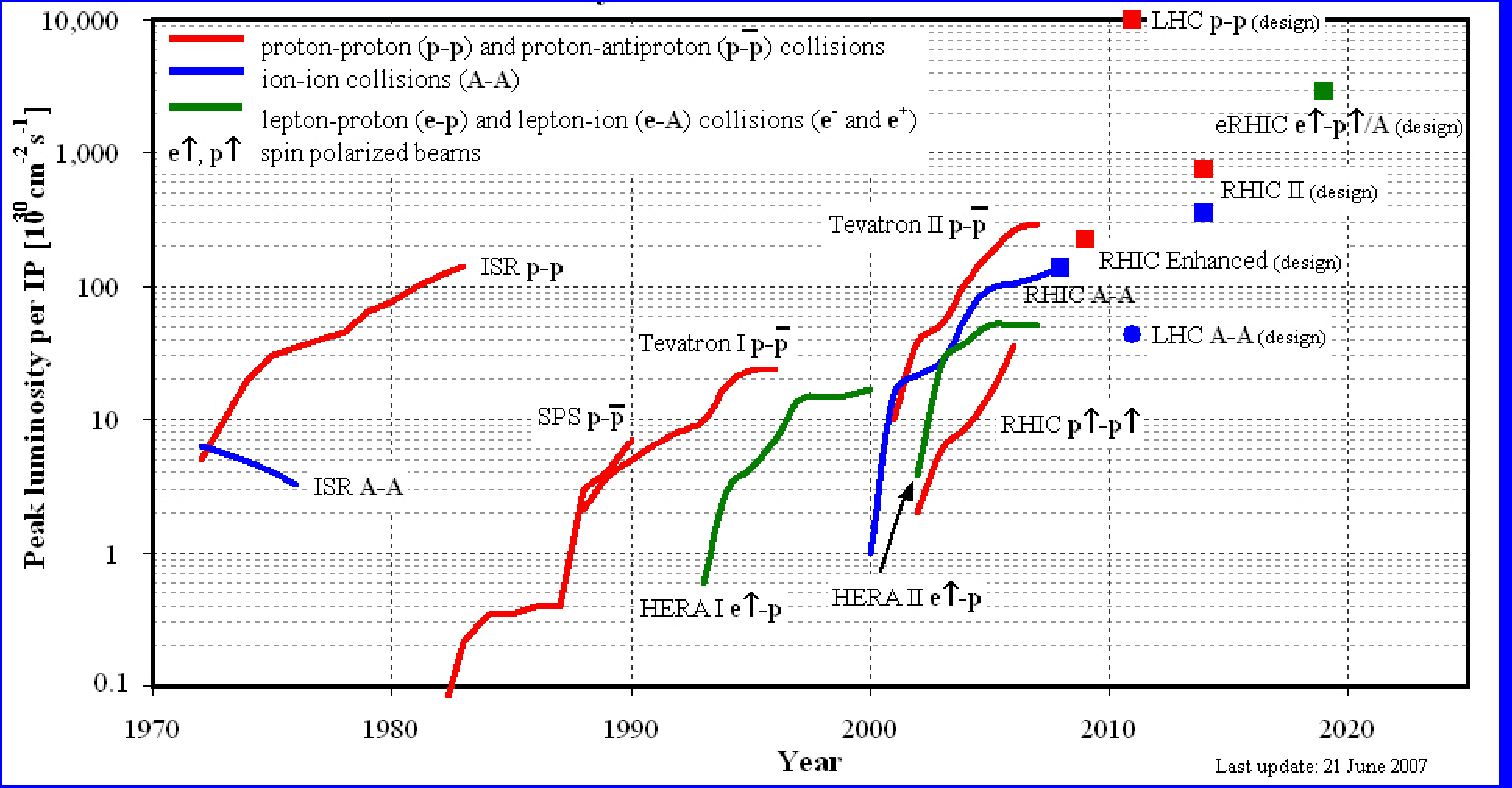
Main features:

- High-luminosity electron-ion collider
  - 10^{32}-10^{33}cm^{-2}s^{-1} average for e↑-p↑
  - 10^{30}-10^{31}cm^{-2}s^{-1} average for e↑-A(↑)
- 10 GeV electron beam (upgrade to 20 GeV)
- Longitudinally polarized electrons, protons, possibly light ions

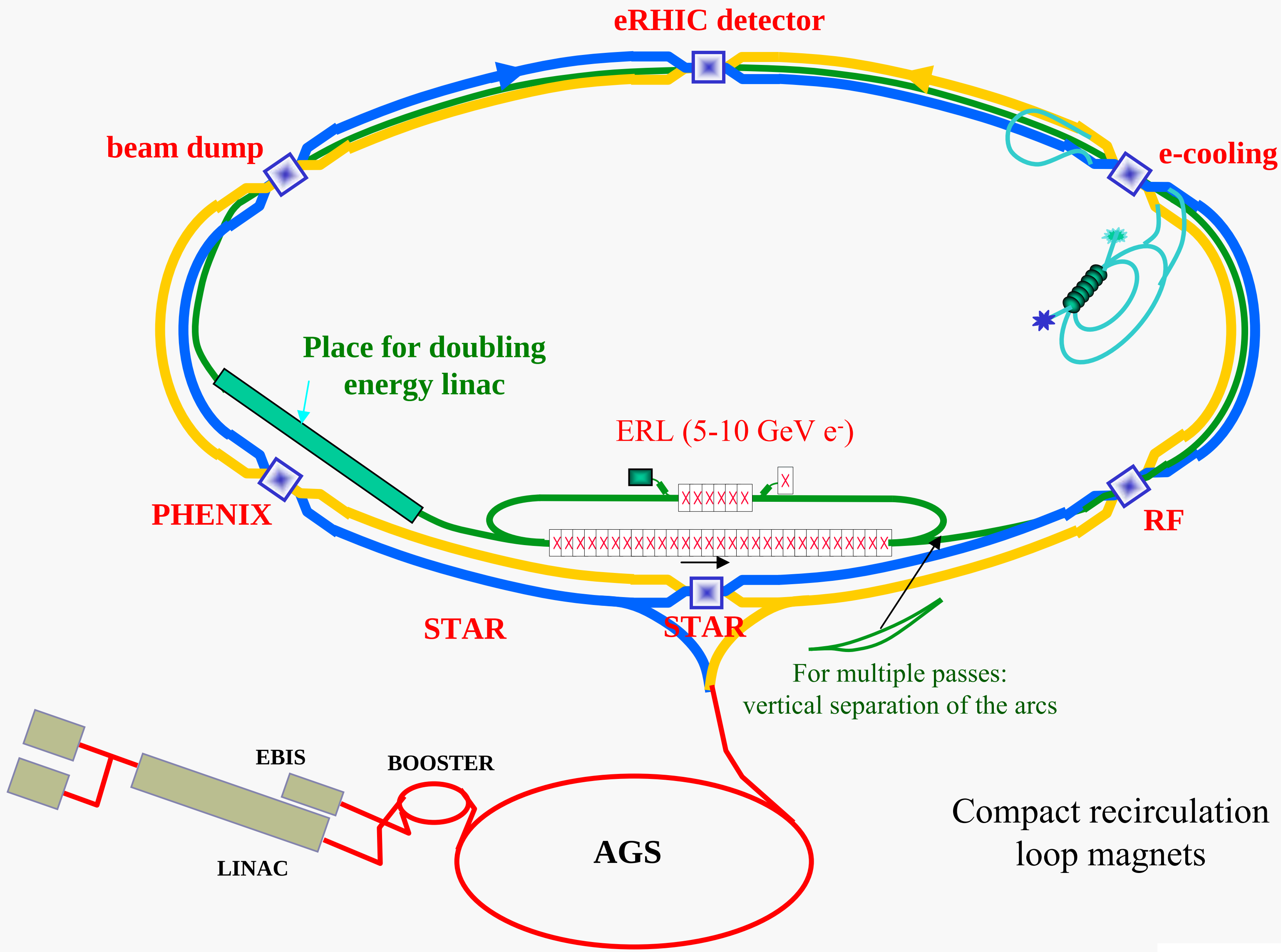
- 2 versions developed
  - Ring-ring option (B-factory like e-ring)
  - Linac-ring option (higher luminosity potential)

eRHIC (≥ 2015)

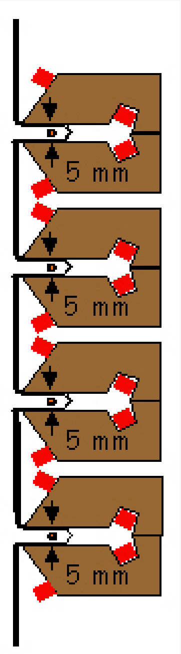
Hadron collider luminosities



eRHIC (≥ 2015)



Compact recirculation
loop magnets

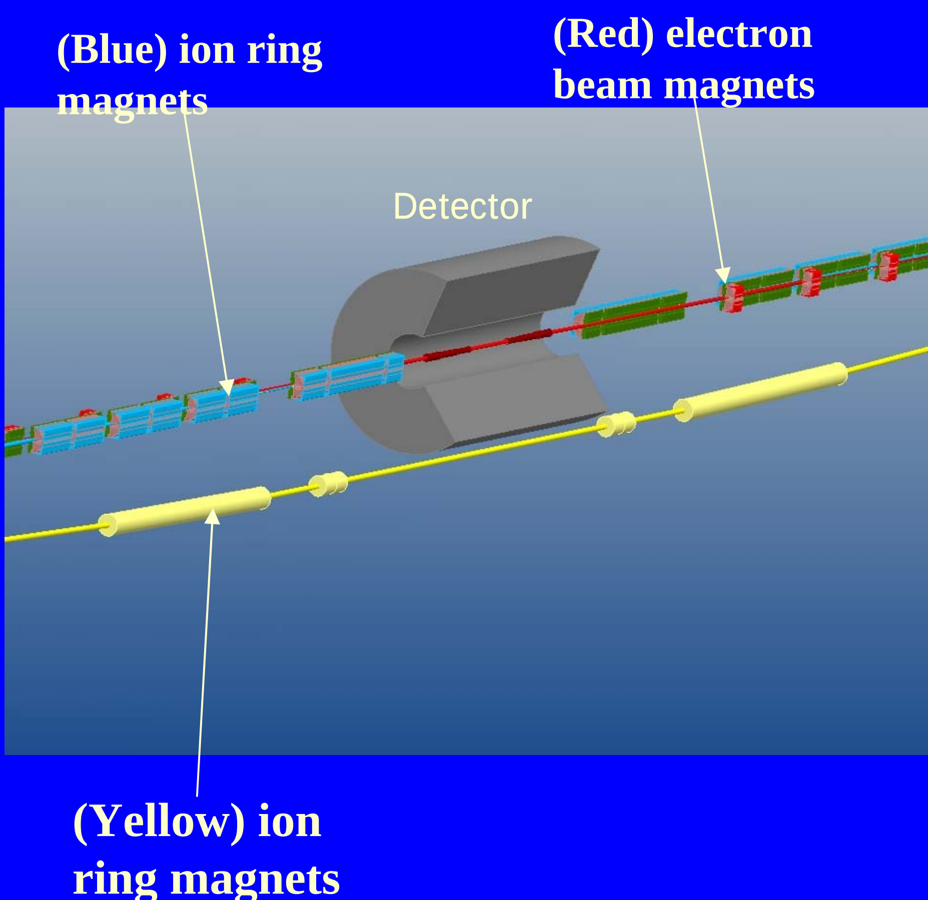


ERL-based eRHIC parameters

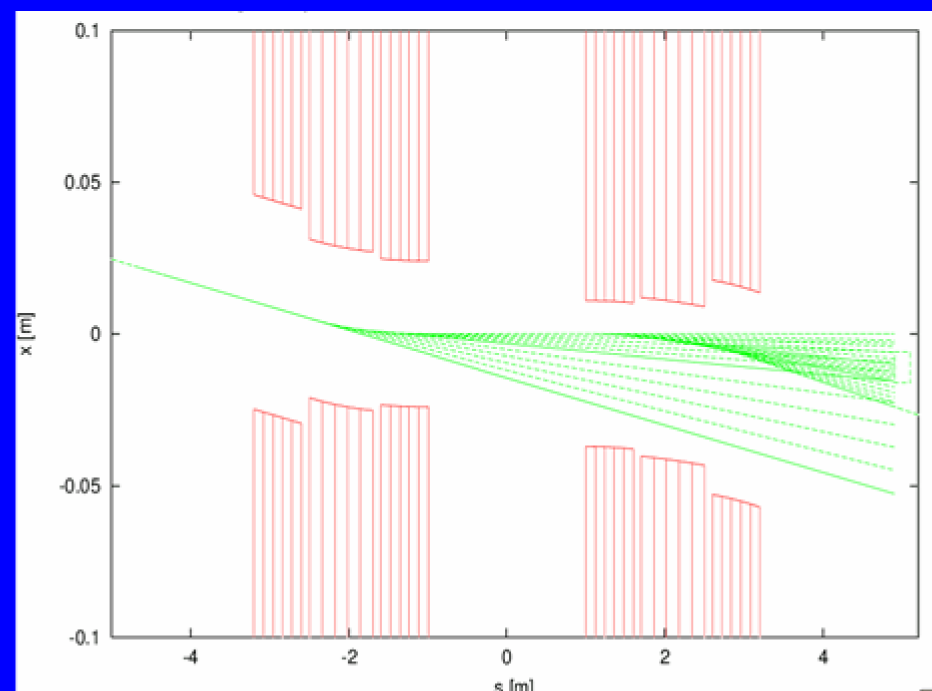
	Electron-Proton Collisions				Electron-Au Collisions			
	High energy setup		Low energy setup		High energy setup		Low energy setup	
	p	e	p	e	Au	e	Au	e
Energy, GeV	250	10	50	3	100	10	50	3
Number of bunches	166		166		166		166	
Bunch intensity, 10^{11} (10^{9} for Au)	2.0	1.2	2.0	1.2	1.1	1.2	1.1	1.2
95% 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



- 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



Wolfram Fischer

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

- Exceeded Enhanced Design goal for Au-Au luminosity in Run-7
  - Time in store only 46% compared to 53% in Run-4 and 60% goal
  - No progress demonstrated with proton $\mathcal{L}$ and $\mathcal{P}$ (no running)
- Demonstrated feasibility of Au-Au operation at E = 9.2 GeV/nucleon cm
  - e-cooling in AGS under investigation for even lower E
- EBIS commissioning expected to begin in 2009 (U, ^{3}He↑)
- RHIC II (based on e-cooling at store)
  - Order of magnitude higher heavy ion luminosity
  - 2-3x higher proton luminosity
- Other ideas under study
  - Transverse stochastic cooling (HI), IR optics (pp), e-lenses (pp)
- eRHIC
  - High luminosity e↑-p↑, e↑-A(↑) collider (ERL-based $\mathcal{L}_{avg}$ **= 10^{33}cm^{-2}s^{-1}**)
  - Several R&D items for ERL version need to be pursued