RHIC Performance Evolution

- Luminosity and polarization evolution
- Plans for luminosity and polarization improvements
- Upgrade projects including ARRA funded projects
- Low energy RHIC running (Critical point search)
- EBIS project status
- Accelerator R&D plans

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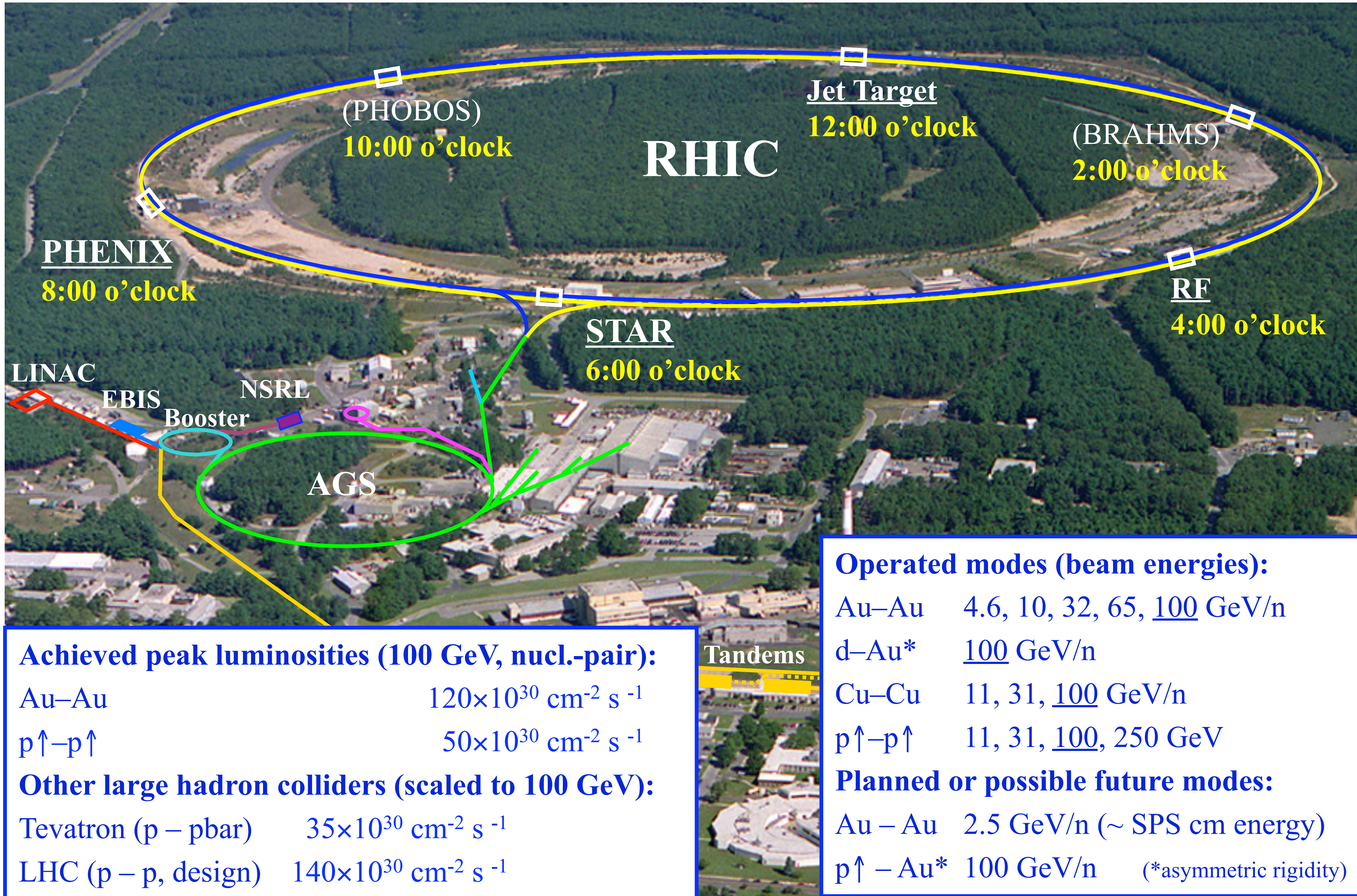
Thomas Roser
RHIC S&T Review
July 22 - 24, 2009

RHIC – a High Luminosity (Polarized) Hadron Collider



Achieved peak luminosities (100 GeV, nucl.-pair):

Au–Au	120×10^{30} cm^{-2} s^{-1}
p↑–p↑	50×10^{30} cm^{-2} s^{-1}

Other large hadron colliders (scaled to 100 GeV):

Tevatron (p – pbar)	35×10^{30} cm^{-2} s^{-1}
LHC (p – p, design)	140×10^{30} cm^{-2} s^{-1}

Operated modes (beam energies):

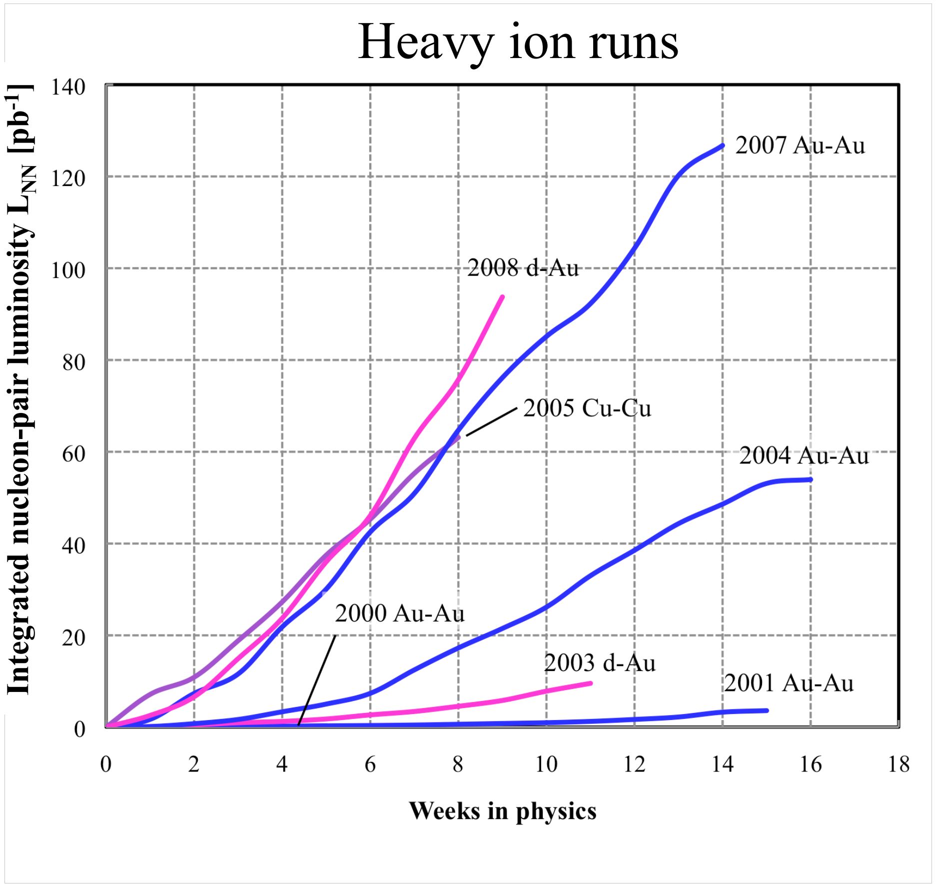
Au–Au	4.6, 10, 32, 65, <u>100</u> GeV/n
d–Au*	<u>100</u> GeV/n
Cu–Cu	11, 31, <u>100</u> GeV/n
p↑–p↑	11, 31, <u>100</u>, 250 GeV

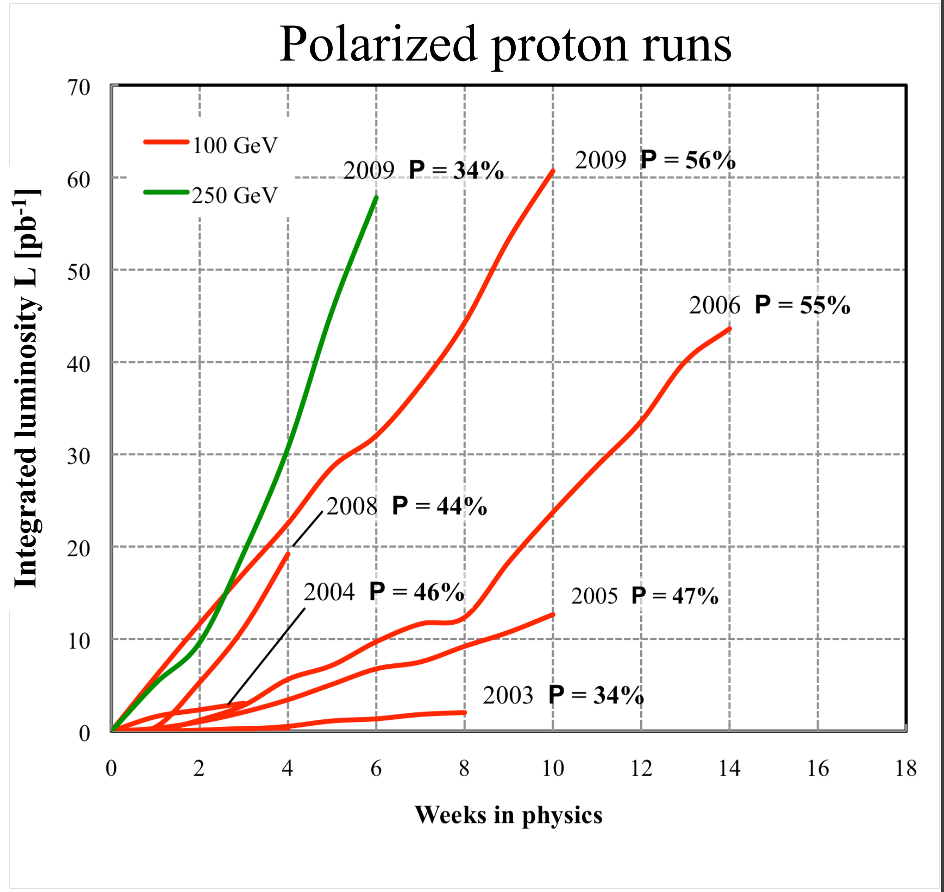
Planned or possible future modes:

Au – Au	2.5 GeV/n (~ SPS cm energy)
p↑ – Au*	100 GeV/n

(*asymmetric rigidity)

Delivered Integrated Luminosity and Polarization





<u>Nucleon-pair luminosity</u>: luminosity calculated with nucleons of nuclei treated independently; allows comparison of luminosities of different species; appropriate quantity for comparison runs.

Luminosity and Polarization Goals

Parameter	unit	Achieved	Enhanced Design	Next L upgrade
Au-Au operation		(2007)		(2012)
Energy	GeV/nucleon	100	100	100
No of bunches	…	103	111	111
Bunch intensity	10^9	1.1	1.0	1.0
Average L	$10^{26}cm^{-2}s^{-1}$	**12**	**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	$10^{30}cm^{-2}s^{-1}$	**28 / 55**	**30 / 150**	**300**
Polarization P	%	**56 / 35**	**70**	**70**

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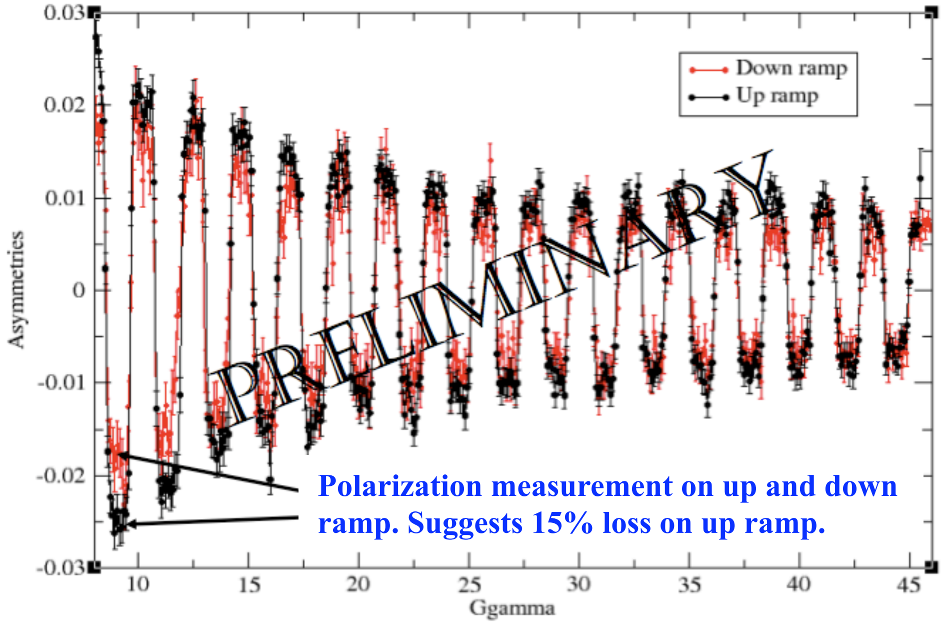
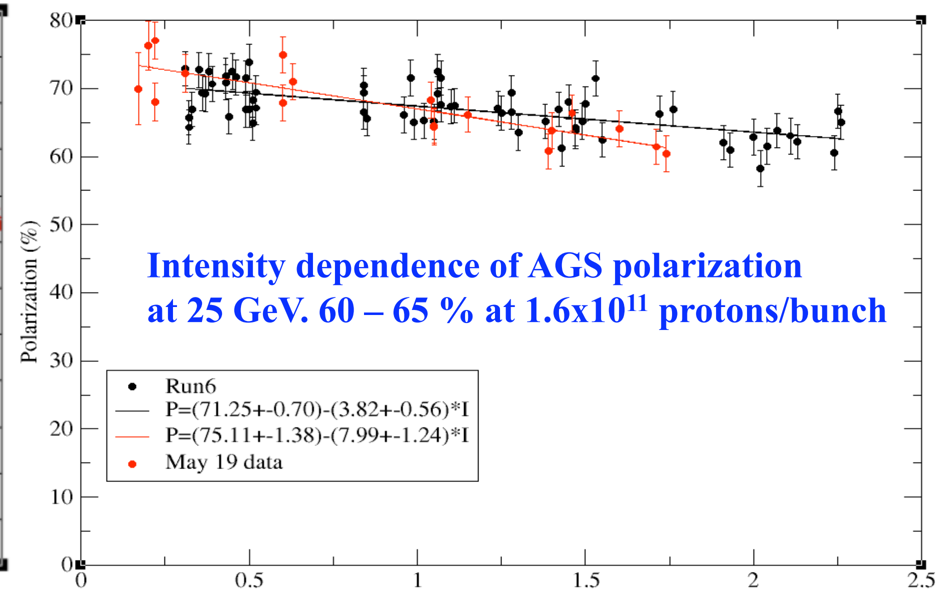
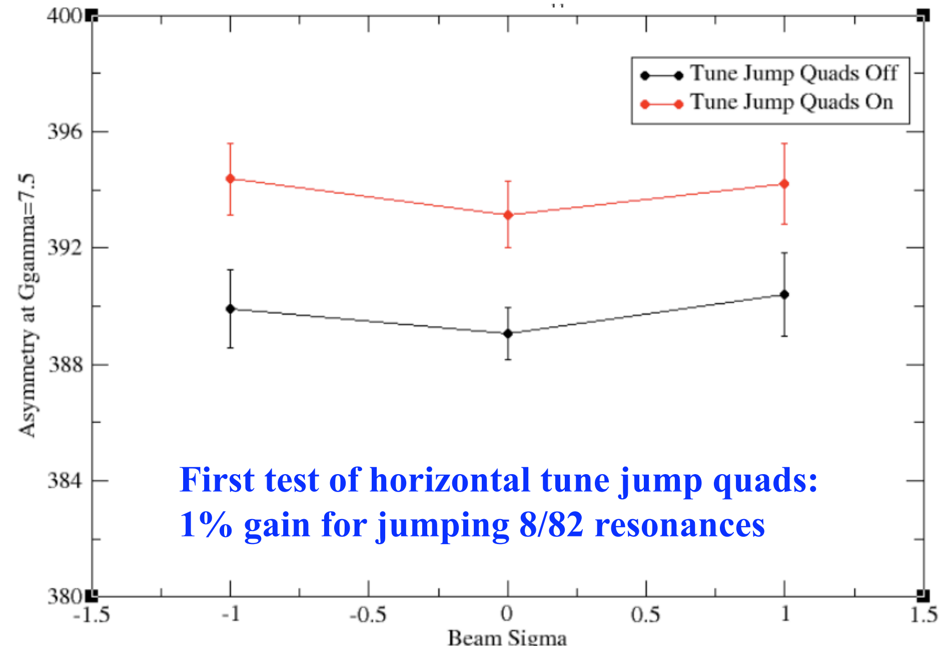
Had previously a goal of 60 here.

AGS Polarization





- Polarized beam acceleration in AGS needs to cross:
  - 40 vertical imperfection resonances
  - 6 vertical intrinsic resonances
  - 82 weak horizontal intrinsic resonances causing emittance dependent pol. loss and horizontal pol. profile
- 2 strong helical partial snakes overcome vertical spin resonances
- New horizontal tune jump quadrupoles used for horizontal resonances.



Polarization Performance (100 GeV)

Main polarization loss from ~ 80 horizontal spin resonances in AGS:

• Source:	P_{center} ~ 80%	$\langle P \rangle$ ~ 80%	
• AGS (25 GeV, high int., A_N?):	P_{center} ~ 65%	$P(\sigma) = \langle P \rangle$ ~ 60%	
• RHIC (100 GeV):	P_{center} ~ 61%	$\langle P \rangle$ ~ 56%	
• Low intensity for pp2pp:		$\langle P \rangle$ ~ 61%	

Upgrades planned and underway:

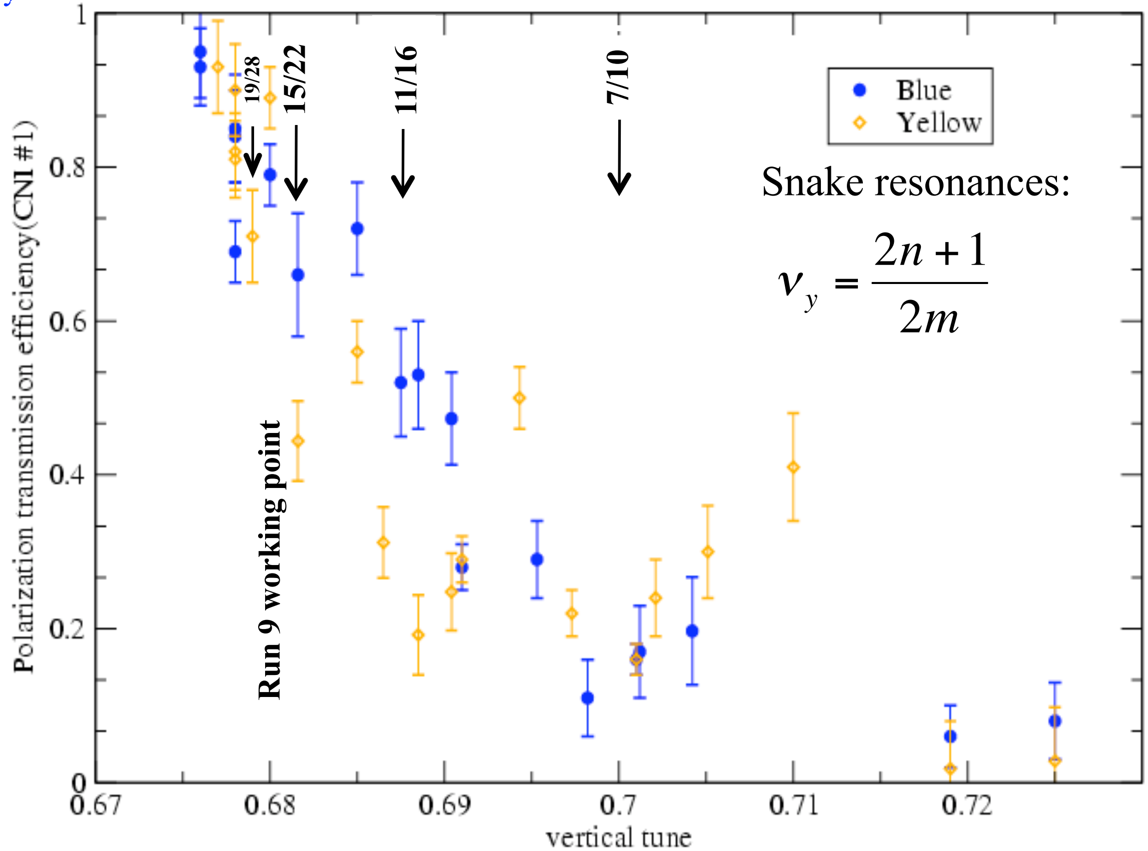
• New OPPIS solenoid:	P_{center} : + 5%;	$\langle P \rangle$: + 5%	(abs.)
• AGS horizontal tune jump quads:	P_{center} : + 5%;	$\langle P \rangle$: + 10%	(abs.)

With both upgrades:

• Source:	P_{center} ~ 85%	$\langle P \rangle$ ~ 85%	
• AGS (25 GeV, high int., A_N?):	P_{center} ~ 75%	$P(\sigma) = \langle P \rangle$ ~ 75%	
• RHIC (100 GeV):	P_{center} ~ 71%	$\langle P \rangle$ ~ 71%	

Polarization Performance (250 GeV)

- Polarization transmission to 250 GeV is strongly tune dependent, as expected.
- RHIC polarization transmission during Run 9 ~ 70% → <P> ~ 35%
- With $\nu_y = 29.677$ polarization transmission > 90% → <P> ~ 50%
- With AGS polarization improvements: <P> ~ 65%
- Plan to accelerate with $\nu_y = 29.675$; need to fix ramp/flattop power supplies glitches!
- Tested near-integer tune $\nu_y = 29.98$: polarization transmission at ~ 80% (?)



Run 9 Luminosity Performance

100 GeV x 100 GeV:

- Peak luminosity increased by 40%
- Average luminosity increased by 20% (last couple of weeks)
- Short luminosity lifetime due to reduced dynamic aperture from (too) small β^* (0.7m), partially compensated by non-linear correctors. Significant machine development time to understand the short luminosity lifetime.
- Yellow bunch intensity limited to 1.4×10^{11} by losses during acceleration possibly due to electron clouds
- Plan:
  - Increase β^* to ~0.85m for improved luminosity lifetime
  - Remove intensity limitation from electron clouds with long bunches using the 9 MHz cavity
  - Increase bunch intensity and beam emittance together to maintain beam-beam parameter with increased luminosity

Run 9 Luminosity Performance

250 GeV x 250 GeV:

- Peak luminosity reached 85×10^{30} cm^{-2} s^{-1}; average luminosity reached 55×10^{30} cm^{-2} s^{-1} with $\beta^* = 0.7$ m and a bunch intensity of 1.1×10^{11}
- At 250 GeV β^* can be reduced to 0.5 m with the same dynamic aperture as $\beta^* = 1.25$ m at 100 GeV
- Design peak luminosity of 200×10^{30} cm^{-2} s^{-1} and average luminosity of 150×10^{30} cm^{-2} s^{-1} can then be reached with a bunch intensity of $\sim 1.5 \times 10^{11}$

RHIC Facility Upgrade Plans

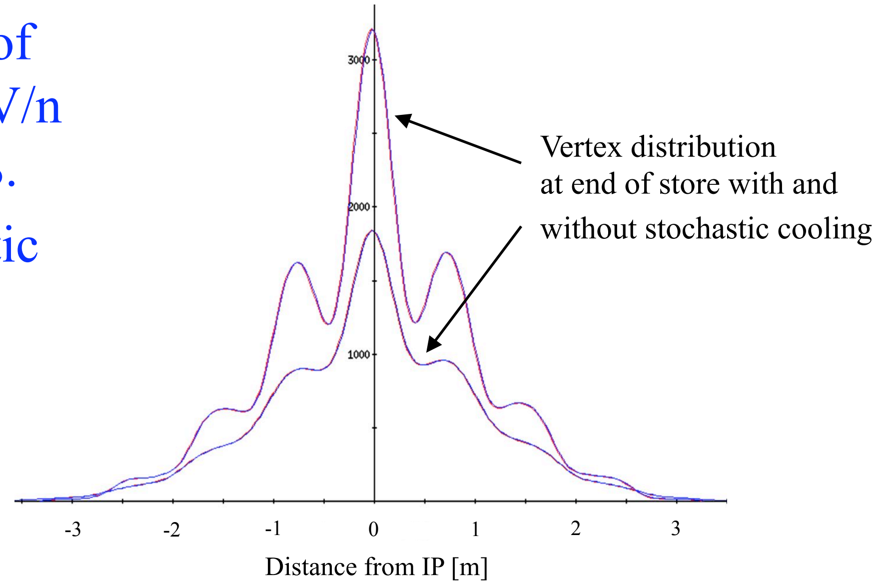
- EBIS (~ 2011) (low maintenance linac-based pre-injector; all species including U and polarized ^3He)
- RHIC luminosity upgrade (~ 2012):
  [Au-Au: 40 × 10^{26} cm^{-2} s^{-1}(× 4); 500 GeV p-p: 1.5 × 10^{32} cm^{-2} s^{-1}]
  - 0.5 m β* for Au – Au and p↑ – p↑ operation
  - Stochastic cooling of Au beams and 56 MHz storage rf system in RHIC
- Further luminosity upgrade for p↑ – p↑ operation (~ 2014):
  [500 GeV p-p: ~ 3× 10^{32} cm^{-2} s^{-1}]
  - 0.3 m β* for 500 GeV p↑ – p↑ operation (× 1.6)
  - Electron lens in RHIC for head-on beam-beam compensation (× 2)
- Low energy ($\sqrt{s}$=5…30 GeV) Au-Au collisions for critical point search
  - ~ 1…5 MeV electron cooling of Au beams at injection (~ 2014)
- eRHIC: high luminosity (≥ 1 × 10^{33} cm^{-2} s^{-1}) eA and pol. ep collider using 4 GeV and later 10 - 20 GeV electron driver, based on an Energy Recovering Linac (ERL), and strong cooling of hadron beams (~ 2020)
  Exploring gluons at extreme density!

Accelerator Improvement Projects FY2008-2014

k$	total	FY2009	FY2010E	FY2011E	FY2012E	FY2013E	FY2014E
RHIC cryo control system upgrade	900	100	450	-	-	-	-
Main Control Room consolidation and upgrade	2,500	175	1,375	-	-	-	-
RHIC SRF (56 MHz)	4,000	1,225	1,475	-	-	-	-
RHIC vertical stochastic cooling, 2nd ring	1,500	1,500	-	-	-	-	-
RHIC hor. stochastic cooling, both rings (ARRA)	4,000	4,000	-	-	-	-	-
RHIC electron lenses (ARRA)	4,000	4,000	-	-	-	-	-
RHIC collimation upgrade	1,000	-	500	500	-	-	-
RHIC low energy electron cooling	4,800	-	-	1,600	2,300	900	-
Motor control center upgrade	1,000	-	-	1,000	-	-	-
Westinghouse stator insulation	800	-	-	800	-	-	-
RHIC abort kicker upgrade	3,000	-	-	-	1,800	1,200	-
RHIC cold beam pipe in-situ coating	4,000	-	-	-	-	2,100	1,900
RHIC stochastic cooling upgrade to 12 GHz	1,250	-	-	-	-	-	1,250
RHIC SRF (56 MHz) 2nd cavity	1,250	-	-	-	-	-	1,250
Total AIP		11,000	3,800	3,900	4,100	4,200	4,400

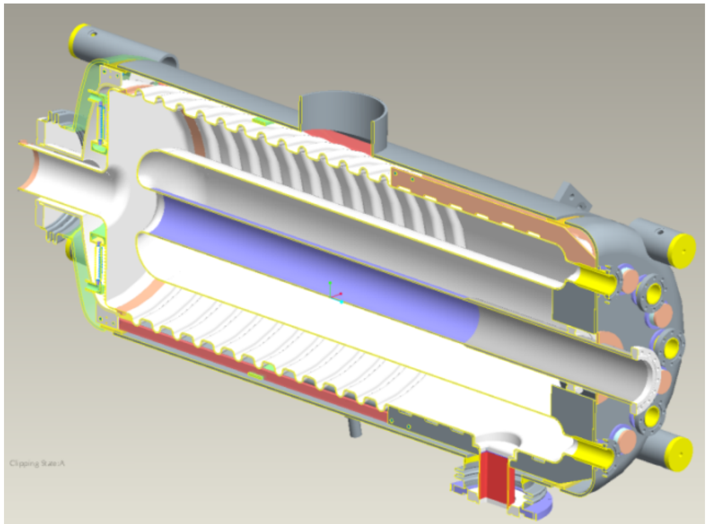
Stochastic Cooling and 56 MHz SRF cavity

- Longitudinal stochastic cooling of core of bunched beam demonstrated at 100 GeV/n in RHIC counteracting longitudinal IBS.
- Full longitudinal and transverse stochastic cooling under construction

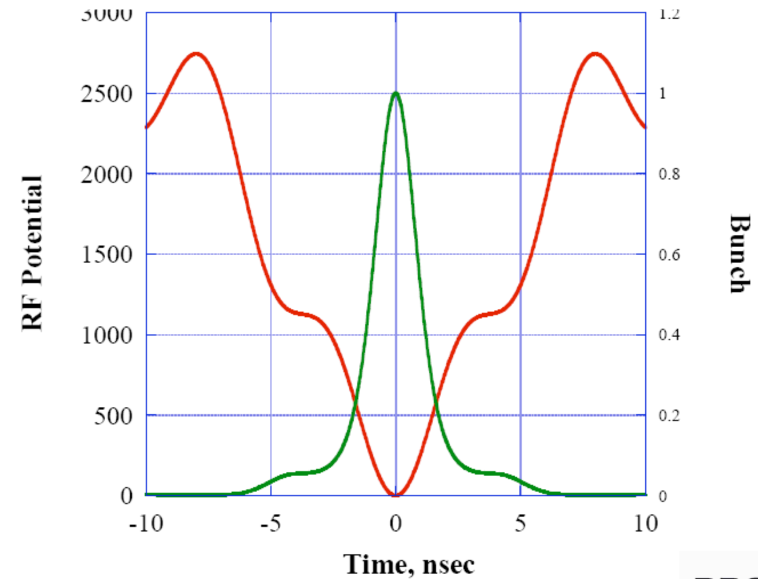


56 MHz SRF storage cavity:

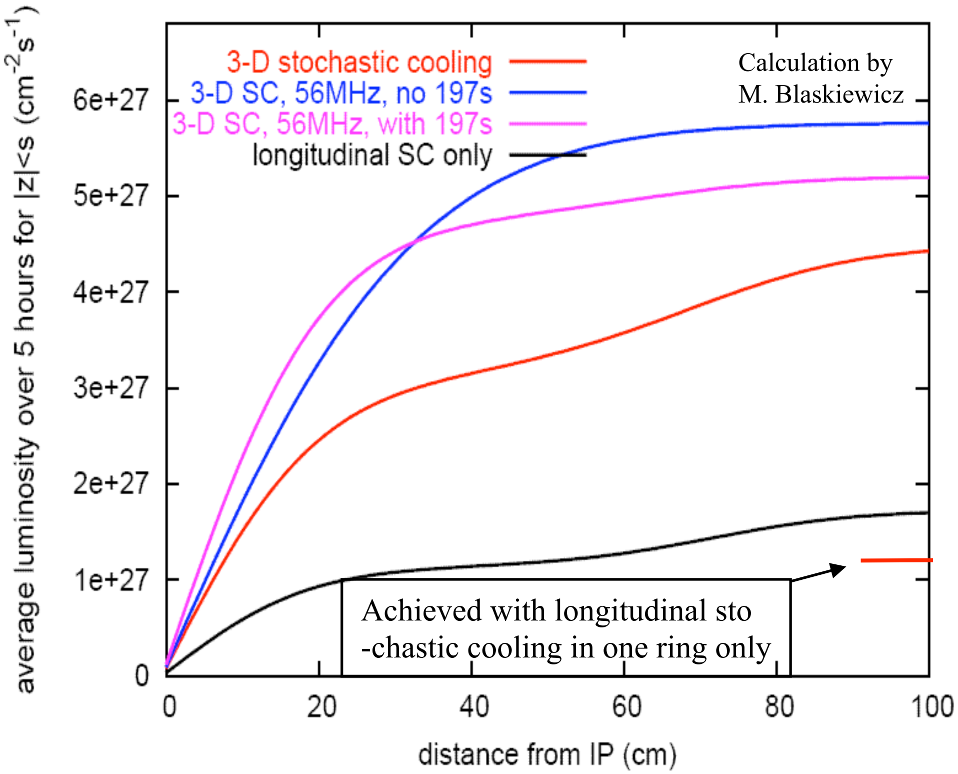
- Greatly reduces satellite bunches
- Re-entrant quarter wave resonator
- Design advanced, review Jan 8-9, 2009
- To be completed for Run 12



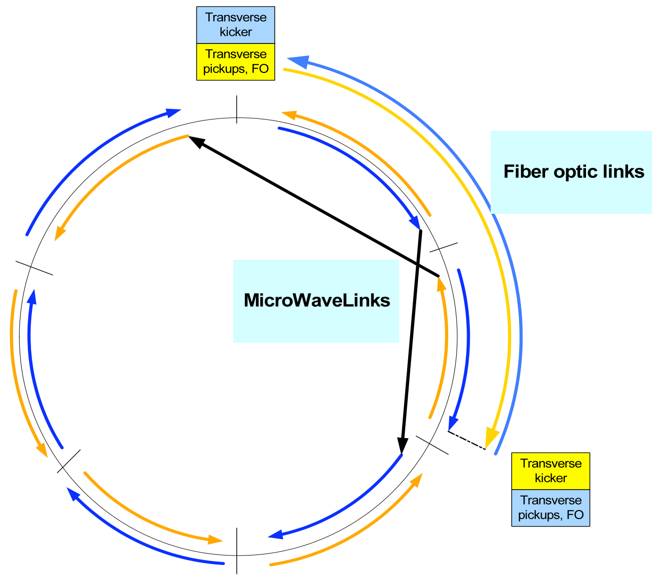
V_{28MHz}= 0.3MV; V_{SRF}= 2 MV; V_{197MHz}= 2 MV

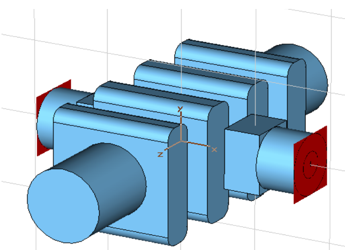


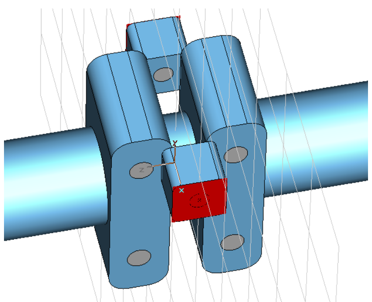
Luminosity Increase with Stochastic Cooling



- Initially vertical stochastic cooling only
- Horizontal plane cooled through x-y coupling
- 5 – 8 GHz bandwidth split up into 16 frequency bands with each frequency having its own cavity kicker
- 6 – 9 GHz bandwidth for longitudinal stochastic cooling using microwave link
- ARRA project: direct stochastic cooling also in horizontal plane
- Further improvement possible:
- 9 – 12 GHz bandwidth for longitudinal stochastic cooling using pick-up in cold section and low aperture kickers







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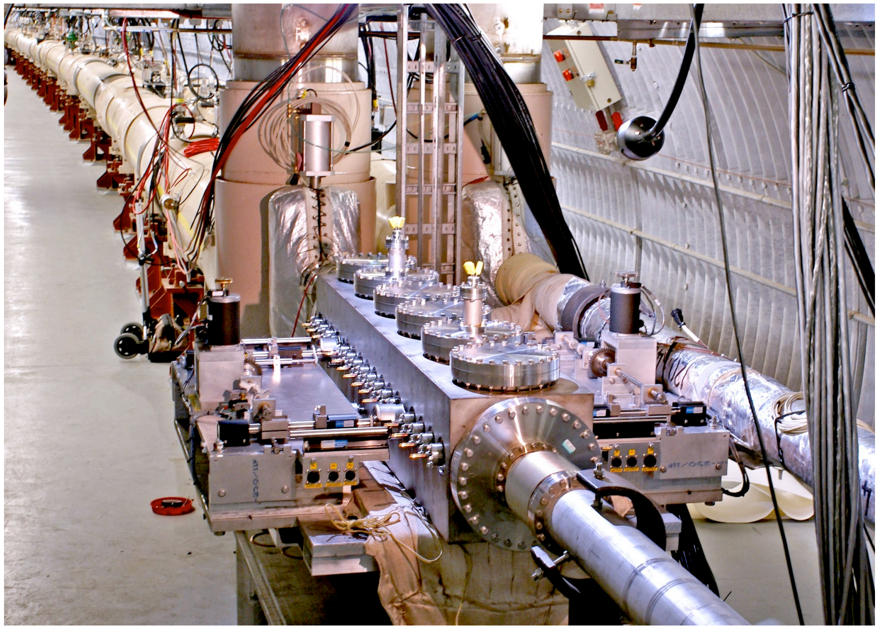
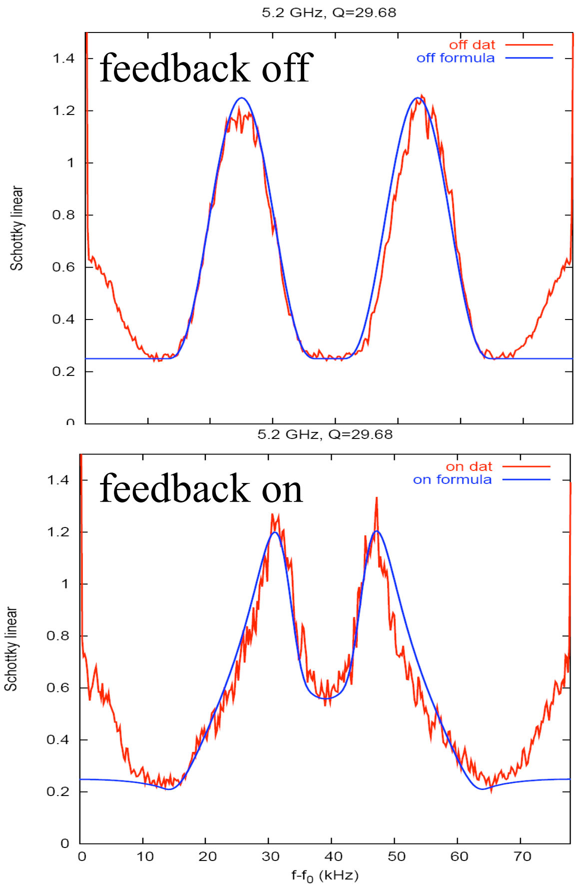
Longitudinal kickers Transverse kickers

Transverse Stochastic Cooling Systems

- Yellow vertical stochastic cooling kicker and pick-up installed, and successfully tested with low intensity proton bunches
- Blue vertical stochastic cooling kicker and pick-up installed for Run 10





- $4M ARRA project: horizontal stochastic cooling kicker and pick-up to be installed in blue and yellow ring for Run 12
- 2 positions opened and filled so far

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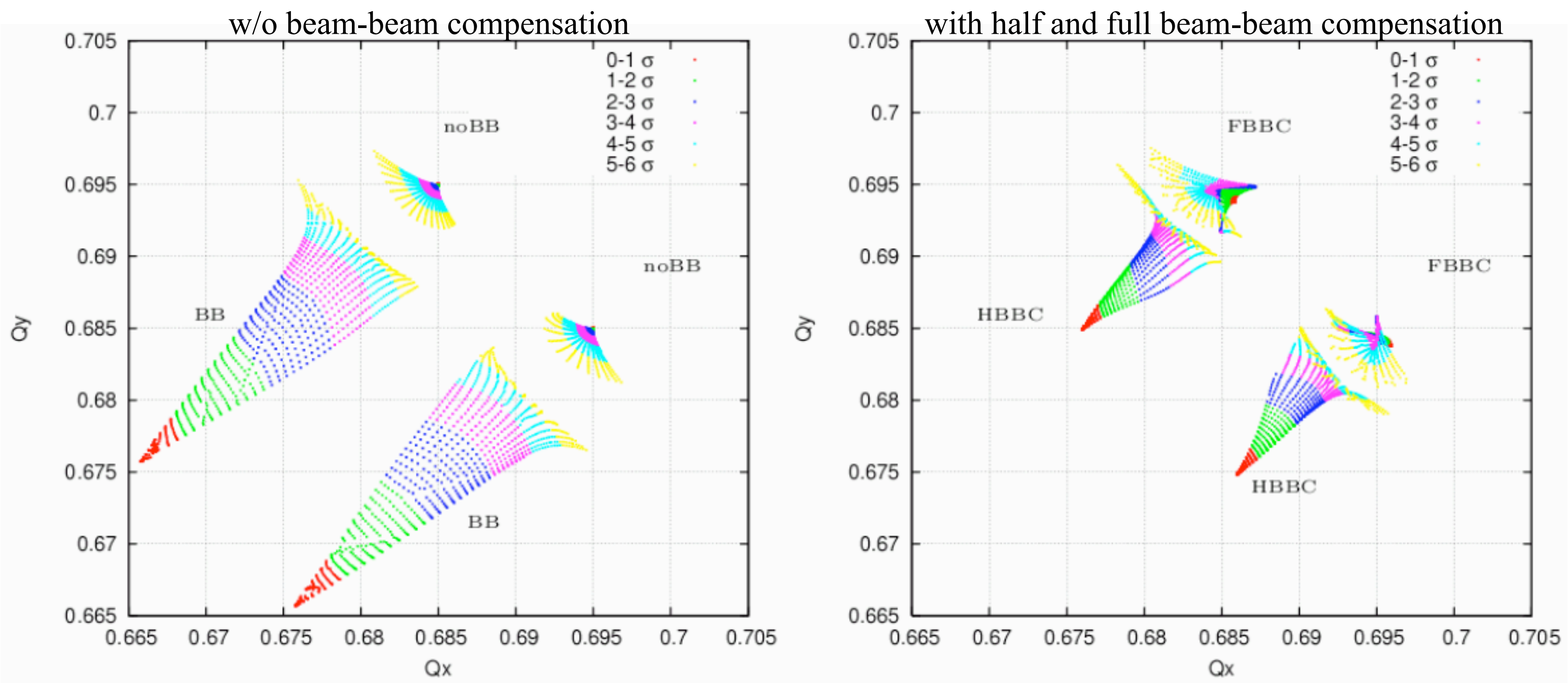
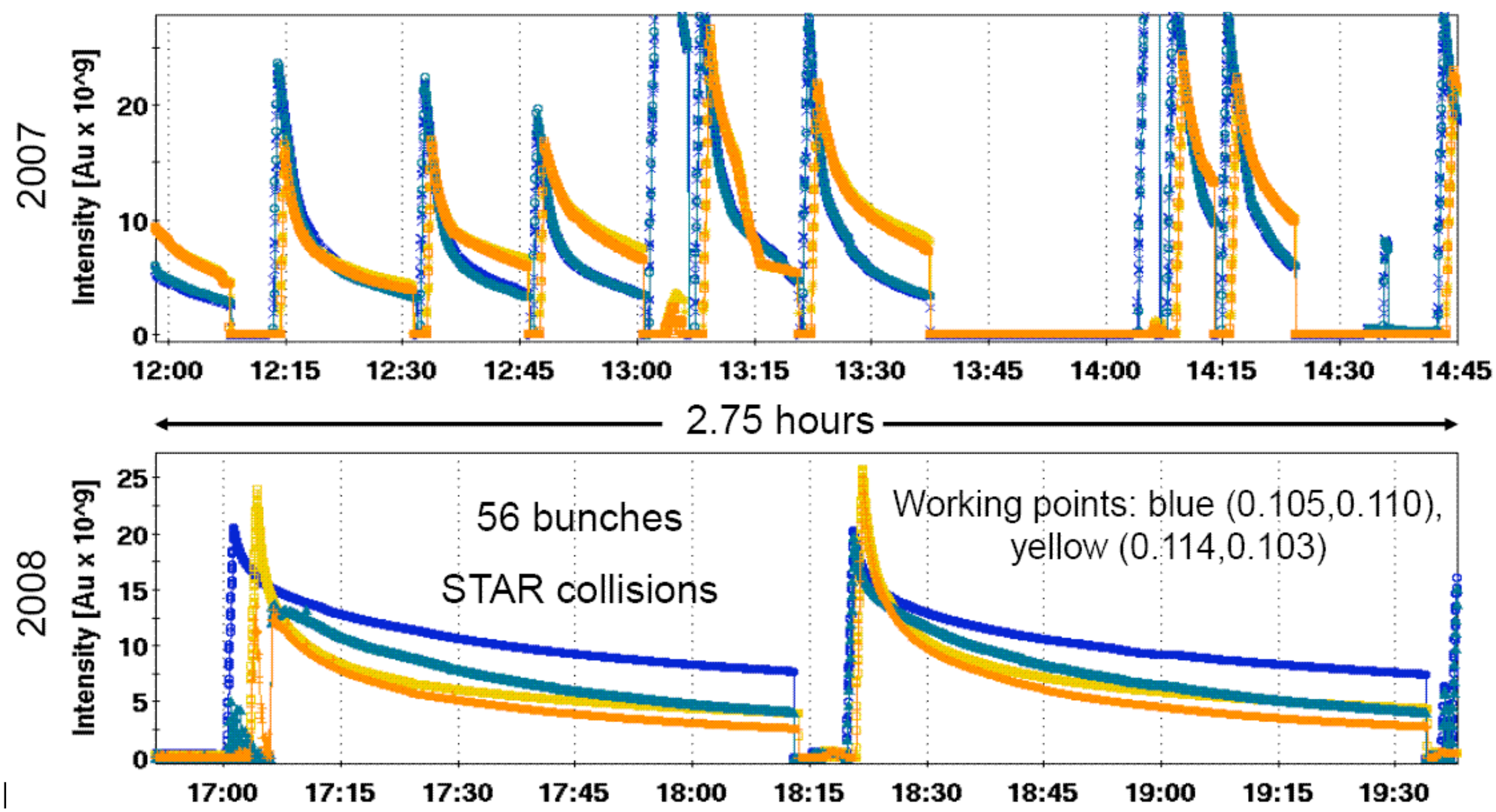
Electron Lenses for pp Operation

- Polarized proton luminosity is limited by beam-beam tune spread
- Low energy electron beam (similar to EBIS) interacting with proton beam can compensate head-on beam-beam tune spread (× 2 luminosity?)
- $4M ARRA project started; 2 positions opened or filled so far.



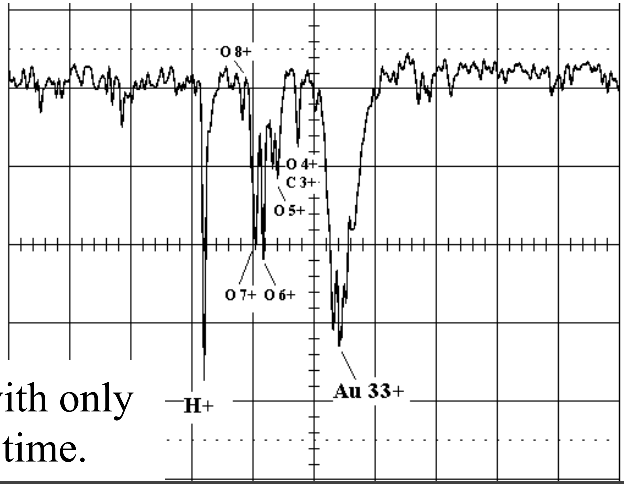
Tests of √s = 9 GeV Au - Au operation in RHIC

- Search for QCD critical point
- Luminosity limited by space charge (space charge limit ΔQsc = 0.05)
- Expect 3-6 times more luminosity when operating at space charge limit
- Electron cooling either with dc beam (Fermilab Pelletron) or with rf beam (56 MHz SRF gun, 703 SRF gun – under construction)



Electron Beam Ion Source (EBIS)

- New high brightness, high charge-state pulsed ion source, ideal as source for RHIC
- Produces beams of all ion species including noble gas ions, uranium (RHIC) and polarized He^3 (eRHIC)
- Achieved 1.7×10^9 Au^{33+} in 20 ms pulse with 8 A electron beam (60% neutralization)
- All major purchases received or placed, installation in track for commissioning 1/10
- Beam tests into Booster by Spring 2010

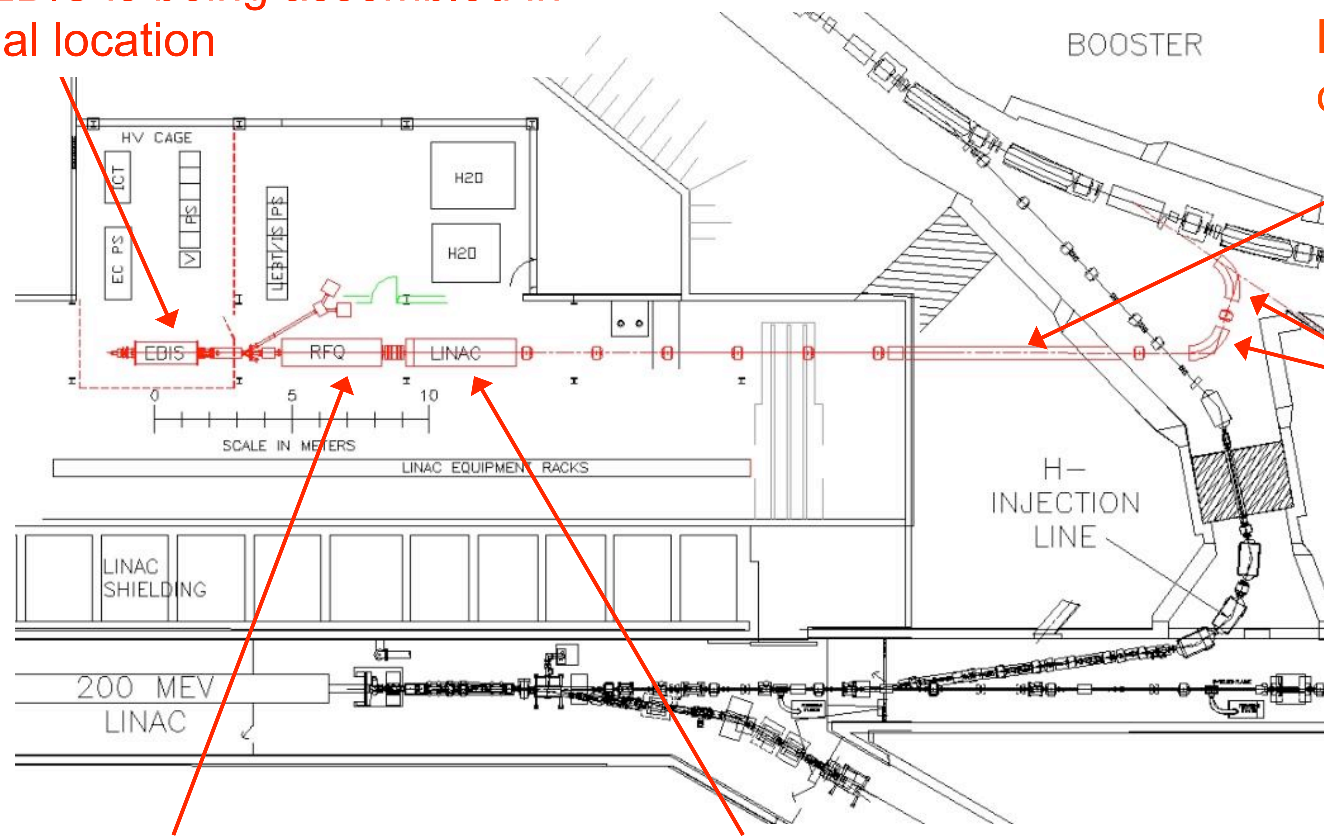


Gold charge state with only 40 ms confinement time.

Status of Major Procurements

EBIS - SC solenoid is installed, and EBIS is being assembled in its final location

Beam port – completed

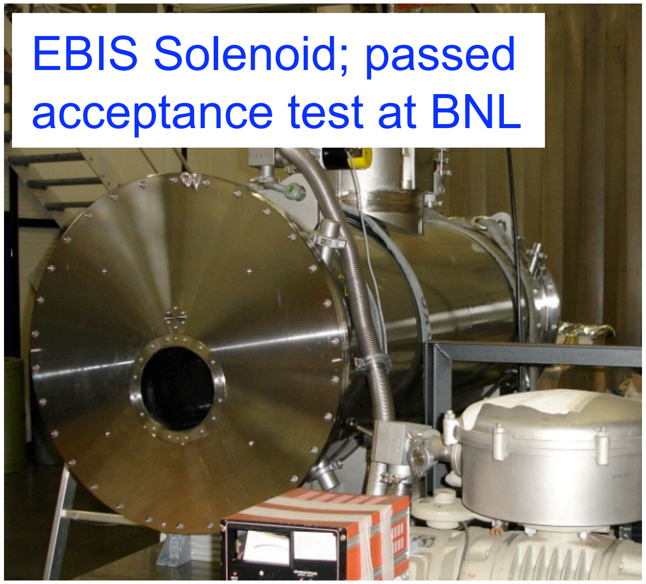


Dipoles – delivered and installed last summer. PS hookup this summer.

RFQ – Frankfurt; delivered, being tested with beam on Test EBIS

Linac – being manufactured (Frankfurt, 10/09 delivery)

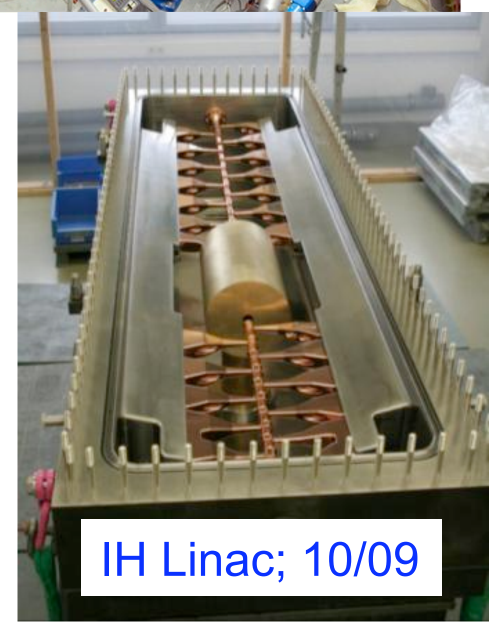
EBIS Hardware


EBIS Solenoid; passed acceptance test at BNL


Dipoles installed in Booster; delivered 7/08


EBIS Drift tubes


RFQ; delivered 9/08


IH Linac; 10/09

Staging of eRHIC (Based on Linac-Ring Option)

MeRHIC: Medium Energy eRHIC

- Both accelerator and detector are located in RHIC at 2 o'clock IR
- 90% reuse of components for eRHIC
- 4 GeV ↑e^- x 250 GeV ↑p (63 GeV c.m.), L ~ 10^{32}-10^{33} cm^{-2} sec^{-1}
- 4 GeV e^- x 100 GeV/n Au (40 GeV c.m.), L/n ~ 10^{32}-10^{33} cm^{-2} sec^{-1}

eRHIC

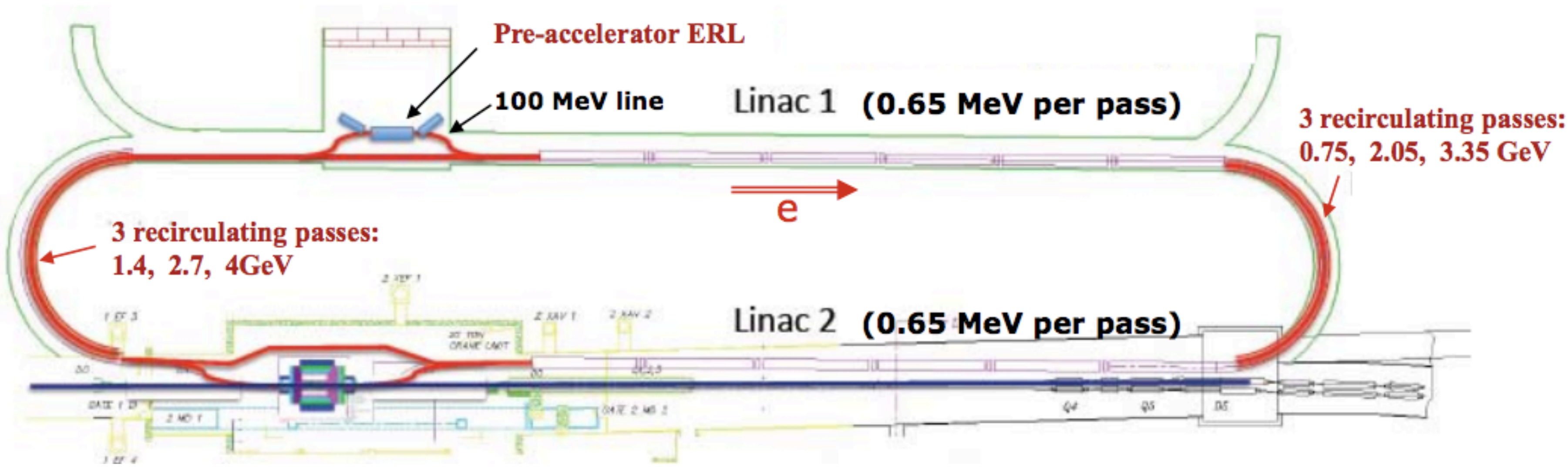
- High energy and luminosity, possibly also inside RHIC tunnel
- 10 (20) GeV ↑e^- x 250 GeV ↑p (140 GeV c.m), L ~ 2.6 x 10^{33} cm^{-2} sec^{-1}
- 10 (20) GeV e^- x 100 GeV/n Au (89 GeV c.m.), L/n ~ 2.9 x 10^{33} cm^{-2} sec^{-1}

Possible eRHIC extensions and upgrades

Higher energy and/or higher luminosity. For example:

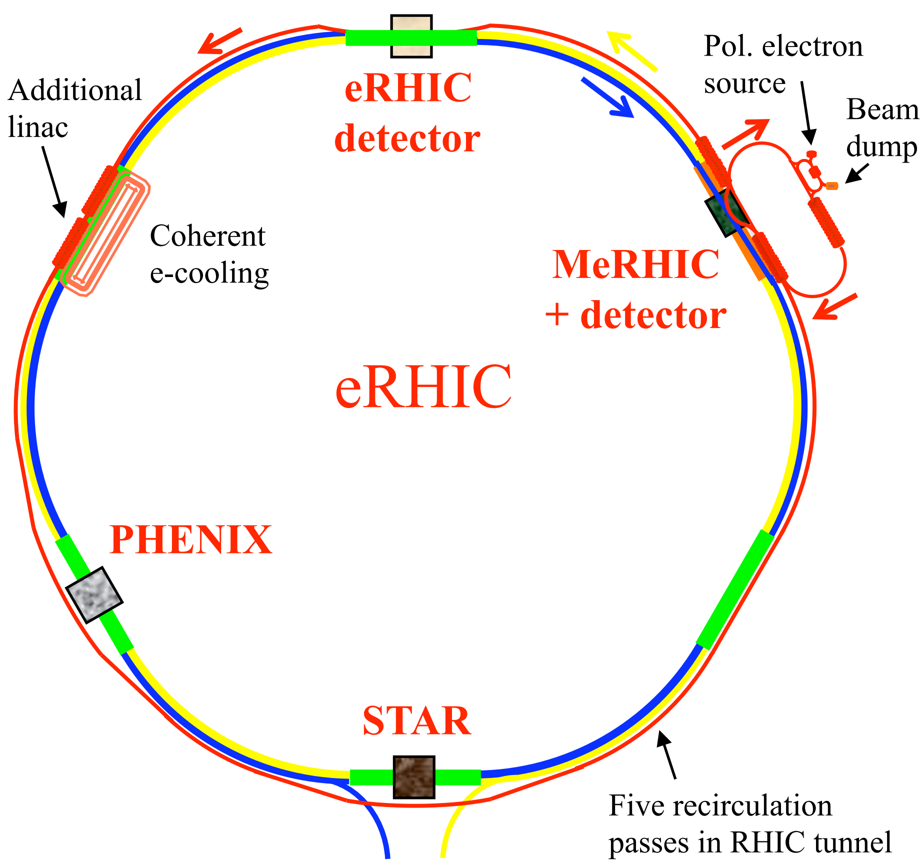
- 10 GeV ↑e^- x 325 GeV ↑p, L ~ 10^{35} cm^{-2} sec^{-1} (high energy proton cooling, high e-beam intensity)
- 30 GeV e^- x 120 GeV/n Au (120 GeV c.m.), L/n ~ 10^{32}-10^{33} cm^{-2} sec^{-1} (extended linac, reduced e-beam intensity to limit synchrotron radiation power)

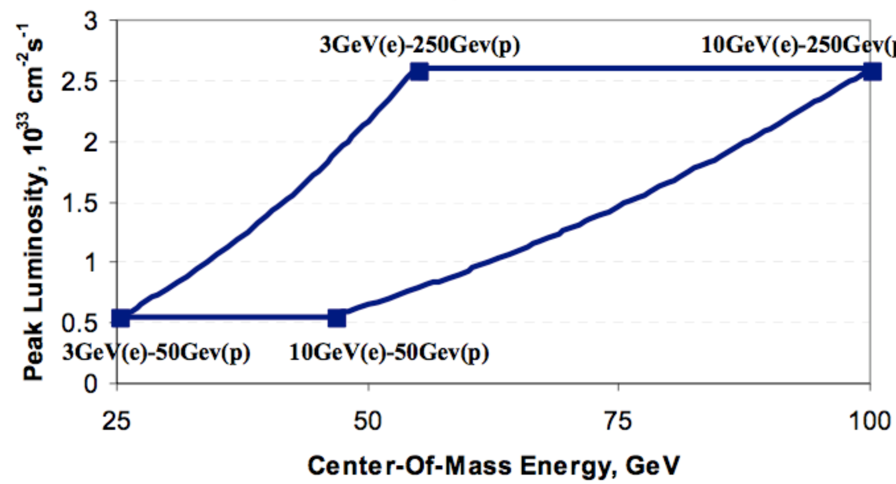
1. stage: Medium Energy eRHIC (MeRHIC)



- 250 GeV p↑ × 4 GeV e ↑ or 100 GeV Au × 4 GeV e
- Peak luminosity: 1×10^{32} cm^{-2} s^{-1}

ERL-based Linac-Ring eRHIC





- Full use of MeRHIC
- 10 GeV electron design energy. Possible upgrade to 20 – 30 GeV.
- Peak luminosity: 3×10^{33} cm^{-2} s^{-1}
- 5 recirculation passes in the RHIC tunnel
- Multiple electron-hadron interaction points and detectors possible
- Full polarization transparency at all energies for the electron beam
- Ability to take full advantage of transverse cooling of the hadron beams
- Possible options to include polarized positrons at lower luminosity: compact storage ring or ILC-type polarized positron source

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Joint EIC R&D plan

Common R&D activities for eRHIC and ELIC

- Polarized 3He production and acceleration (BNL) [5 FTE-yrs; M&S: $ 1.0 M Total: $2M]
- Coherent Electron Cooling (BNL) [15 FTE-yrs; M&S: $ 5.0 M Total: $8M]
- Energy recovery technology for 100 MeV level electron beam. (JLab) [20 FTE-yrs; M&S: $4.5 M Total: $8.5M]
- Crab cavities [8 FTE-yrs; M&S: $1.2M Total: $2.8M]

R&D activities specific to eRHIC

- High current polarized electron source (MIT) [7.5 FTE-yrs; M&S: $ 2.0 M Total: $3.5M]
- Energy recovery technology for high energy and high current beams (BNL) [10 FTE-yrs; M&S: $ 3.0 M Total: $5M]
- Development of eRHIC-type SRF cavity (BNL) [10 FTE-yrs; M&S: $ 2.0 M Total: $4M]

R&D activities specific to ELIC

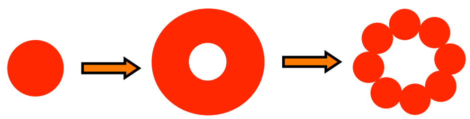
- Ion space charge sim. (JLab in collab. with SNS) [2 FTE-yrs; M&S: $0.5M Total: $0.9M]
- Spin track studies for ELIC (JLab) [8 FTE-yrs; Total: $1.6M]
- Studies traveling focus scheme (JLab) [3 FTE-yrs; Total: $0.6M]
- Simulation studies supporting ELIC project (JLab) [5 FTE-yrs; Total: $1.0M]

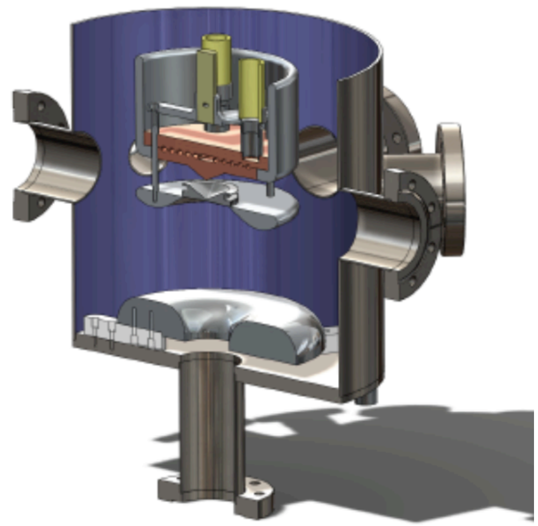
Breakdown between Laboratories

- BNL – $19.0M JLab – $15.4M MIT - $3.5M

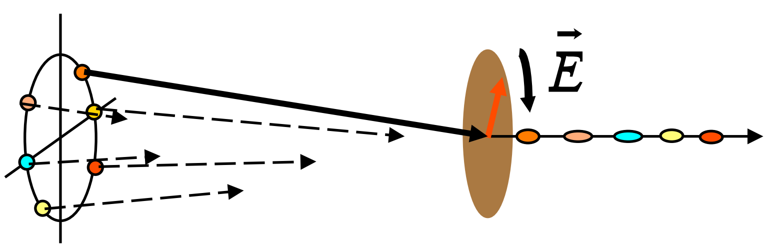
Polarized Electron Gun Development

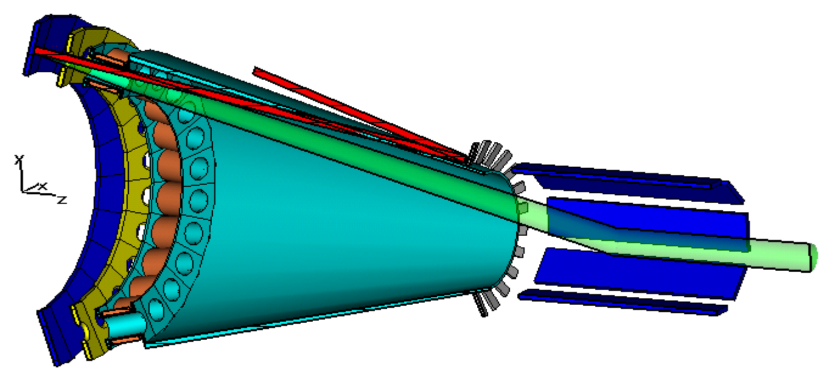
- ERL eRHIC design needs 50 - 250 mA
- 50 mA from large cathode (diameter > 1cm) with ~ 50 mA/cm^2
- Development of a source with large (ring like) cathode area (MIT-Bates, E.Tsentalovich) to minimize ion bombardment damage.





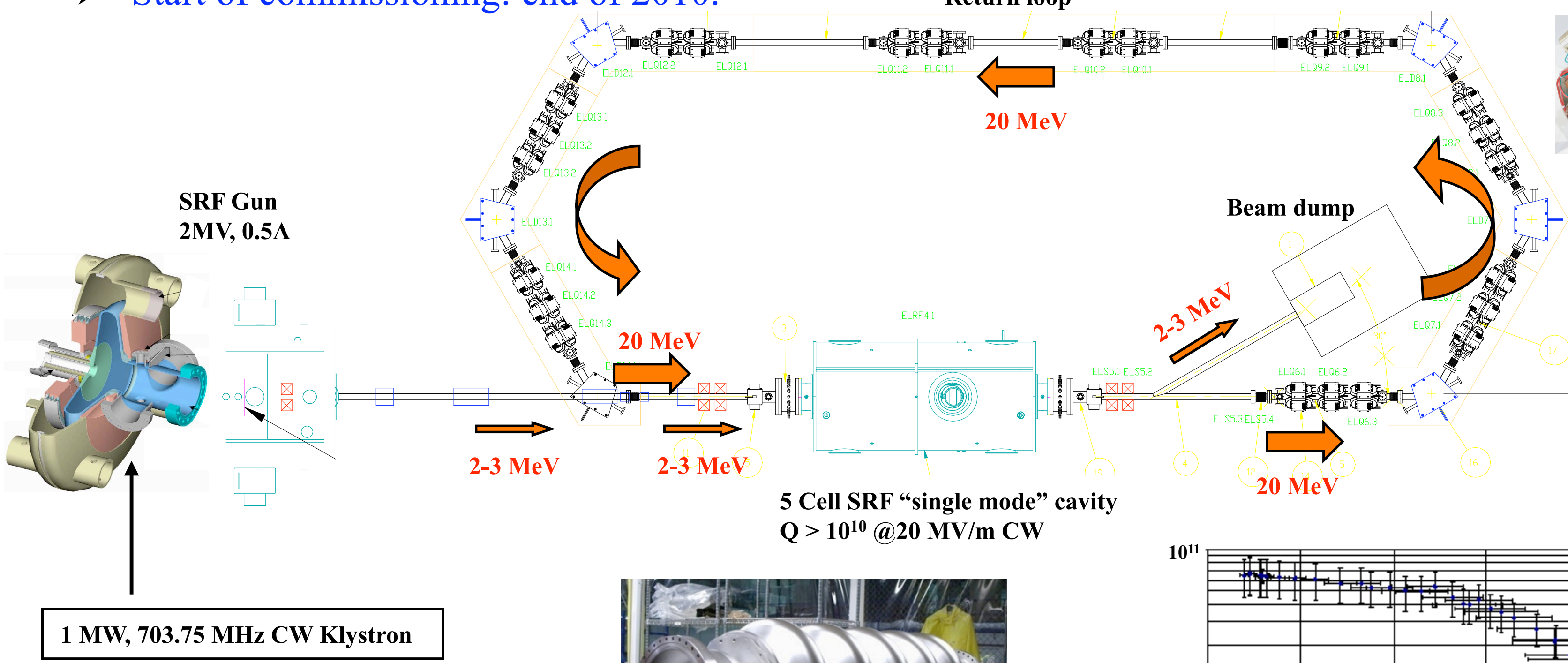
- Multiple guns with rf-combiner to reach 250 mA or 50 mA with 2 mA per cathode:

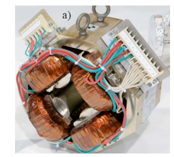


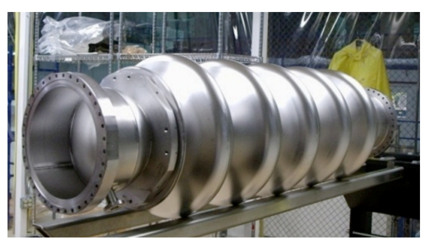


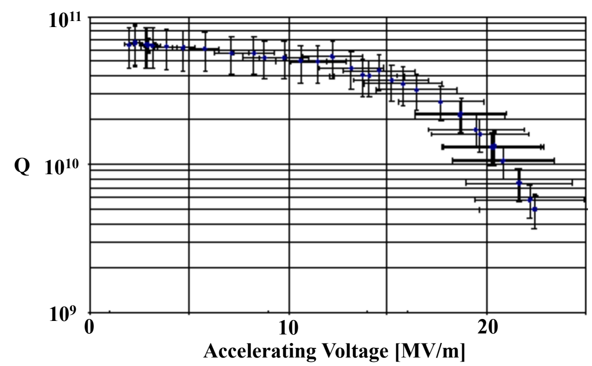
Energy Recovery Linac (ERL) Test Facility

- Test of high current (0.5 A), high brightness ERL operation
- Electron beam for RHIC (coherent) electron cooling (54 MeV, 10 MHz, 5 nC, 4 μm)
- Test for 10 – 20 GeV high intensity ERL for eRHIC
- Test of high current beam stability issues, highly flexible return loop lattice
- Allows for addition of a 2nd recirculation loop
- Start of commissioning: end of 2010.









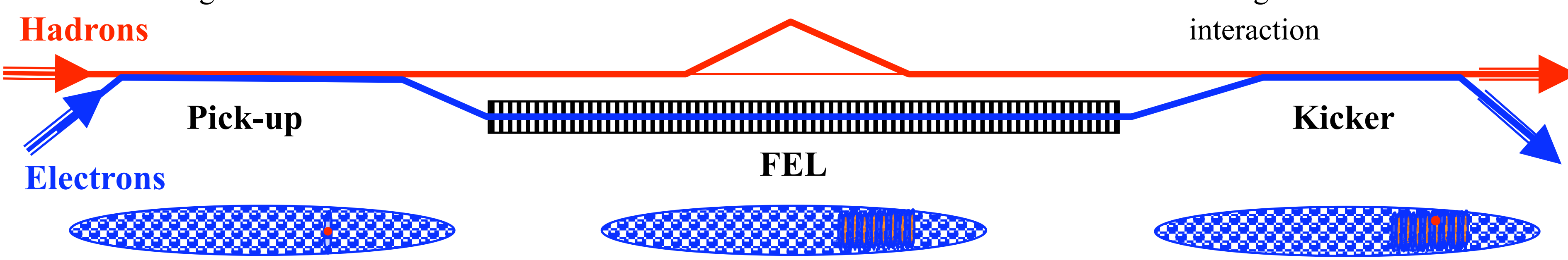
Coherent Electron Cooling

- Idea proposed by Y. Derbenev in 1980, novel scheme with full evaluation developed by V. Litvinenko
- Fast cooling of high energy hadron beams
- Made possible by high brightness electron beams and FEL technology
- ~ 20 minutes cooling time for 250 GeV protons → much reduced electron current, higher eRHIC luminosity
- Proof-of-principle demonstration possible in RHIC using test ERL.

Pick-up: electrostatic imprint of hadron charge distribution onto co -moving electron beam

Amplifier: Free Electron Laser (FEL) with gain of 100 -1000 amplifies density variations of electron beam, energy dependent delay of hadron beam

Kicker: electron beam corrects energy error of co -moving hadron beam through electrostatic interaction



Summary

Successful first 250 x 250 GeV polarized proton collisions (~ 60 pb^{-1})

Long 100 x 100 GeV polarized proton run (~ 60 pb^{-1})

Successful pp2pp run at STAR IR

Future runs / upgrade plans:

- Luminosity upgrade to 40×10^{26} cm^{-2} s^{-1} through high energy beam cooling
- High luminosity 250 x 250 GeV polarized proton run
- Uranium beams from EBIS
- Accelerator R&D for high luminosity polarized electron ion collider – MeRHIC/eRHIC

eRHIC and EIC Accelerator R&D at C-AD

	EIC R&D plan [M$]		Schedule for BNL R&D M&S request [M$]					
	M&S	Total	FY2009	FY2010	FY2011	FY2012	FY2013	Total
pol e gun (MIT)	2.0	3.5	0.5					0.5 *
High intesnity ERL test	3.0	5.0	1.5	1.5				3.0
Polaried HE-3 source	1.0	2.0		0.5	0.5			1.0
Coherent electron cooling test	5.0	8.0		0.4	1.4	1.4	1.8	5.0
eRHIC - type SRF cavity	2.0	4.0			0.5	1.0	0.5	2.0
Total	13.0	22.5	2.0	2.4	2.4	2.4	2.3	11.5
Request through RHIC Ops FWP			2.0	1.0	1.0	1.0	1.0	
Request through EIC R&D				1.4	1.4	1.4	1.3	

* Balance of $3.0M to be requested by MIT

Total C-AD Accelerator R&D

Distribution of FY08-11 Accelerator R&D Investment ($k)									
B&R	**KB0202011**	**Actual FY08**	**FY09 PR**	**FY09 Rev.**	**FY10 Guid.**	**FY11 -5%**	**FY11 flat-flat**	**FY11 +3.5%**	**FY11 Prop.**
Existing Facility									
Machine Development		$2,540	$2,670	$2,670	$2,780	$2,910	$2,910	$2,910	$2,910
TOTAL Existing Facility		**$2,540**	**$2,670**	**$2,670**	**$2,780**	**$2,910**	**$2,910**	**$2,910**	**$2,910**
Next Generation									
Stochastic Cooling									
Labor		$650	$250	$250					
M&S		$1,500	$250	$250					
eRHIC / ERL									
Labor									
	Simulation & Design	$1,890	$1,980	$1,980	$2,060	$2,140	$2,140	$2,140	$2,140
	Production Labor	$1,910	$1,990	$1,990	$2,075	$2,160	$2,160	$2,160	$2,160
M&S		$1,000	$1,500	$1,500	$1,000	$1,000	$1,000	$1,000	$1,000
eRHIC (MIT-Bates)		$300	$690	$440					
EIC R&D Proposals (M&S)					$1,400	$1,400	$1,400	$1,400	$1,400
TOTAL Next Generation		**$7,250**	**$6,660**	**$6,410**	**$6,535**	**$6,700**	**$6,700**	**$6,700**	**$6,700**