RHIC Operations, R&D, and Upgrades

RHIC Operations:

- d-Au and pp operations during Run-3 (FY2003)
- Projections for Run-4 (FY2004)

Accelerator Improvement Projects

Electron Beam Ion Source (EBIS)

RHIC II/eRHIC R&D

- RHIC electron beam cooling
- eRHIC electron ring design

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Office of Science U.S. DEPARTMENT OF ENERGY

Thomas Roser
DOE RHIC program review
July 9 - 11, 2003

Run-3 Achievements

- First asymmetric d-Au collisions with equal-energy injection and acceleration
- Additional bunch merge for deuteron: two Tandem pulses per RHIC bunch
- β^* = 1 meter at both PHEINX and STAR for proton-proton collisions
- Commissioning of eight new spin rotators to give longitudinal polarization at PHENIX and STAR
- 50 % polarization at AGS extraction; 35 % polarization at 100 GeV
- Commissioning of new AGS polarimeter and first polarization measurements during the AGS and RHIC acceleration ramps

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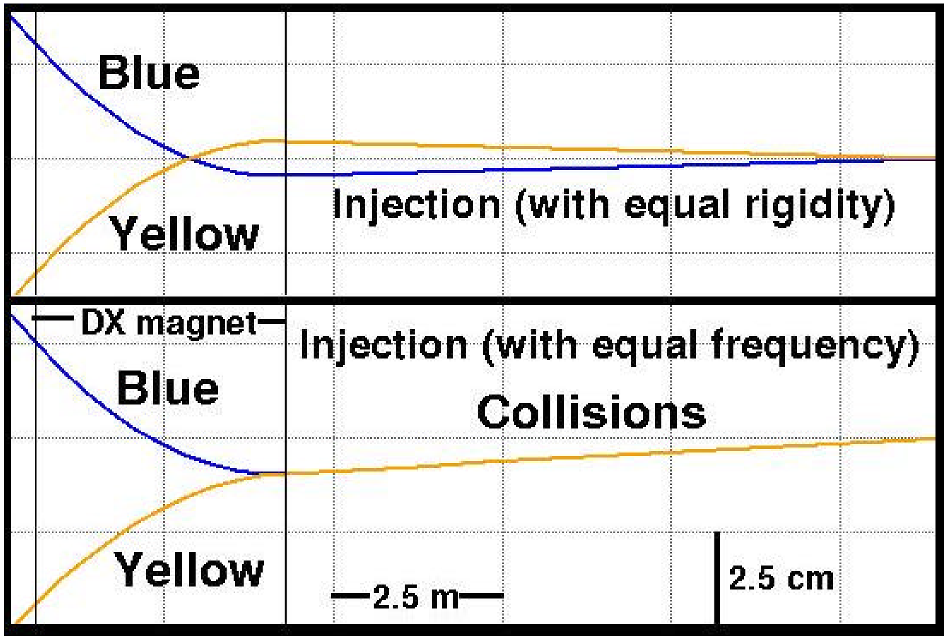
Deuteron-Gold Collisions in RHIC (RUN-3)

- Important comparison measurement: will not produce quark-gluon plasma
- Collisions at 100 GeV/nucleon requires 20% different rigidities
- Use two Tandems; add. bunch merging in Booster:
  1.1×10^{11} d/bunch, $\varepsilon[95\%] = 12\,\pi\,\mu m$; 0.7×10^{9} Au/bunch, $\varepsilon[95\%] = 10\,\pi\,\mu m$
- Initial injection with equal rigidity failed because of beam loss from modulated beam-beam interactions during acceleration ramp
- Injection and acceleration with same energy was successful.



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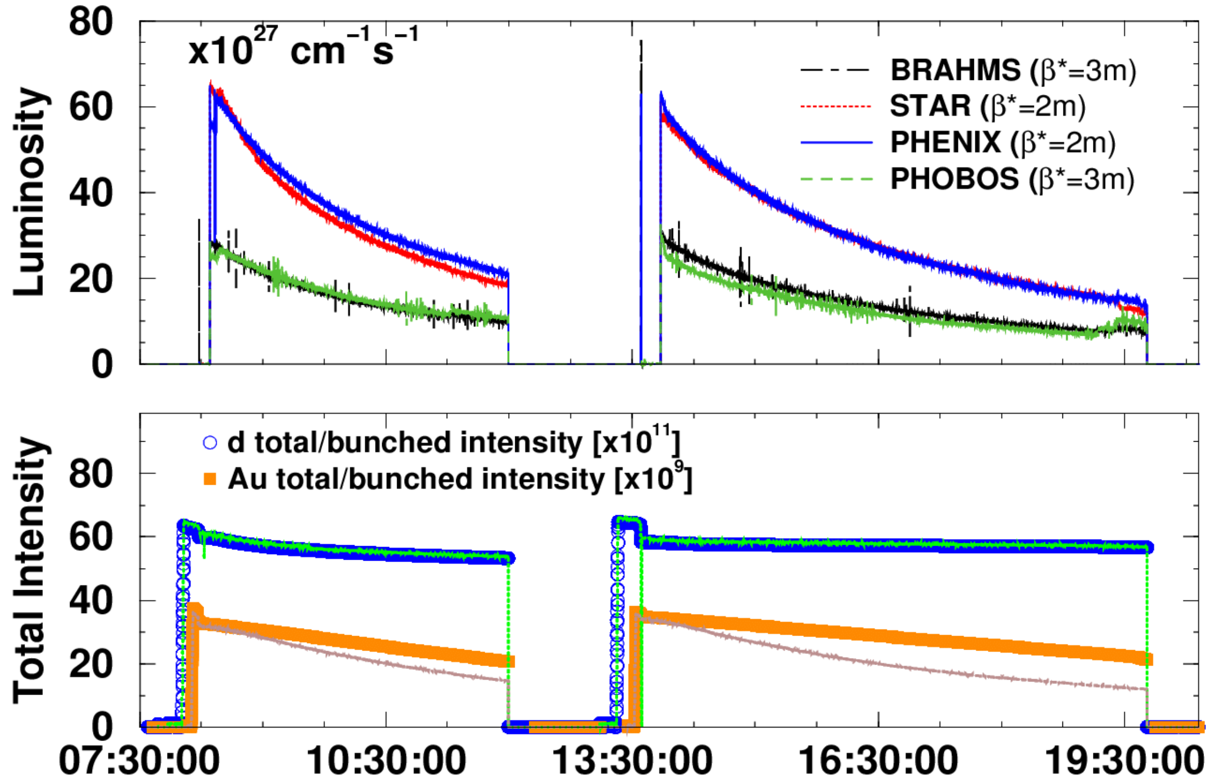
"Typical" Deuteron-Gold Stores

- Vacuum pressure rise limits total charge (both beams) to 10^{13} (~ 56 bunches)
- Transverse instability cured by crossing zero-chromaticity before transition
- Need Landau cavities to avoid coherent longitudinal oscillation during acceleration.
- Fixed noise in 200 MHz system to give good deuteron lifetime
- Intra-beam scattering affects gold beam



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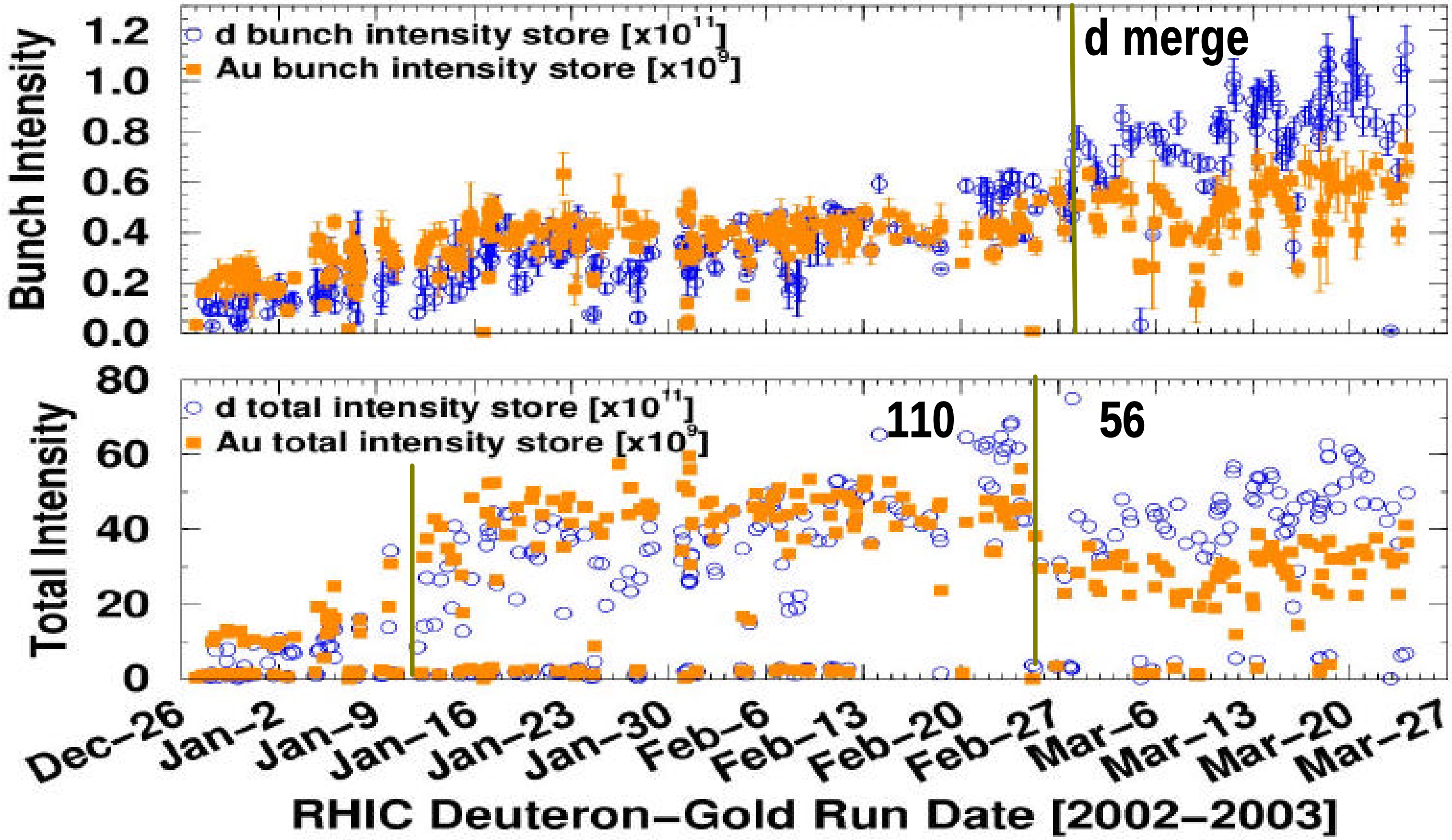
RHIC Deuteron-Gold Intensity Performance



- Injector dAu “mode switch” time usually 3-5 minutes, below goal
- About an even division between 110 and 56 bunch ramping

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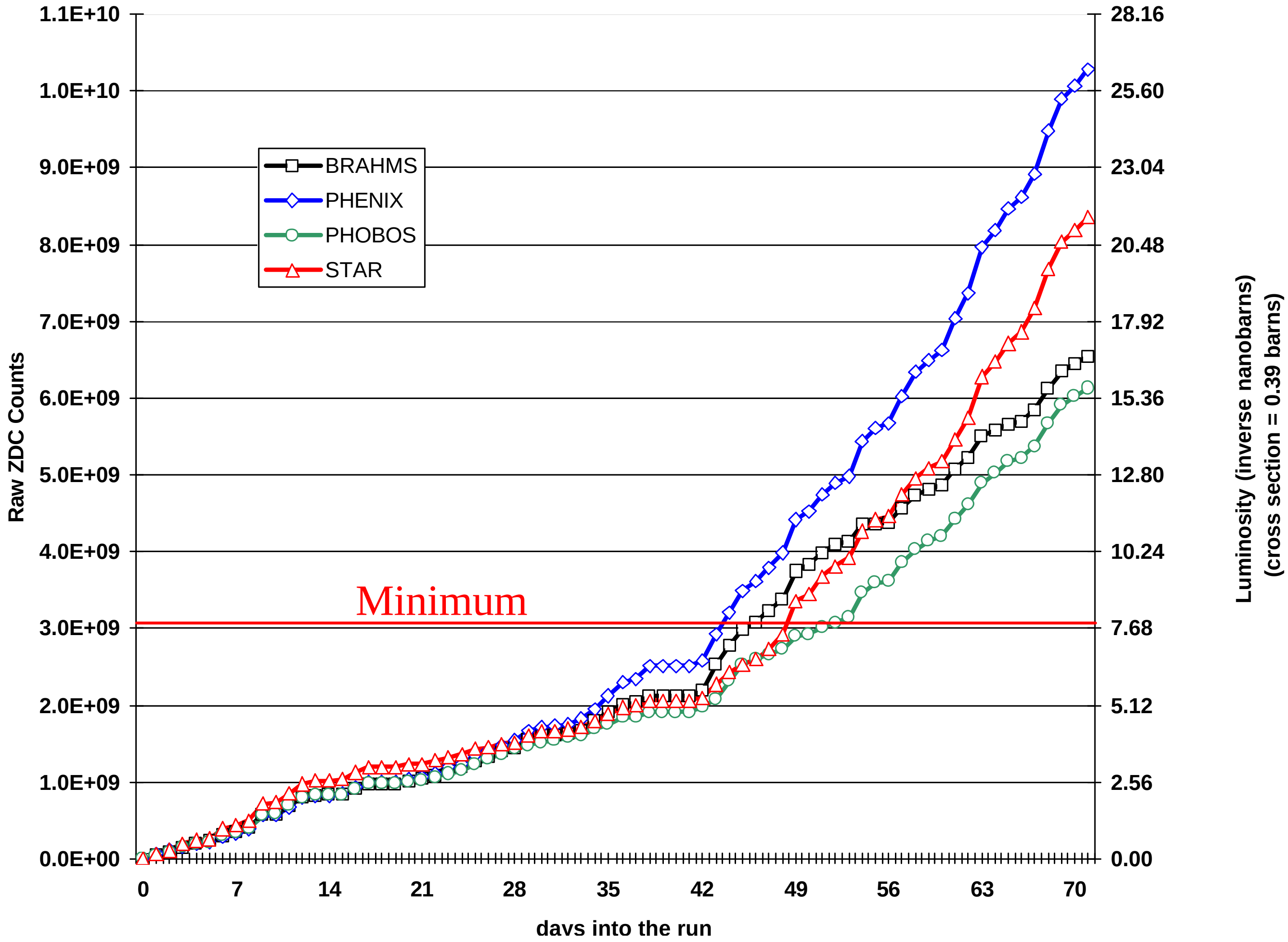
RHIC FY03 Deuteron-Gold Performance

Machine Performance	Max. expect.	achieved
Setup/Ramp-up time [weeks]	2/3	2.5/3 ✓
Storage Energy [GeV/u]	100	100 ✓
Number of bunches	56	56/110 ✓
β* [m]	2	2/3/4 ✓
Diamond length σ [cm]	20	20 ✓
Peak luminosity L [$x10^{28}$ cm^{-2} s^{-1}]	4.0	7.2 ✓
<L>(store) [$x10^{28}$ cm^{-2} s^{-1}]	1.6	2.2 ✓
<L>(week) [nb^{-1}/week]	4.0	4.6 ✓

Storage Parameter	Au, Yellow Ring		d, Blue Ring	
	Max. expect.	Achieved	Max. expect.	Achieved
Intensity/bunch	1.0×10^{9}	0.7×10^{9}	0.8×10^{11}	1.1×10^{11} ✓
Total Intensity (56/100 bunches)	55×10^{9}	$38/60\times10^{9}$ ✓	45×10^{11}	$57/69\times10^{11}$ ✓
Transverse Emittance [95% πμm]	10-40	10-30 ✓	15	12 ✓
Bunch Length [ns] (200 MHz RF)	5	5 ✓	5	5 ✓

Integrated d-Au Luminosity



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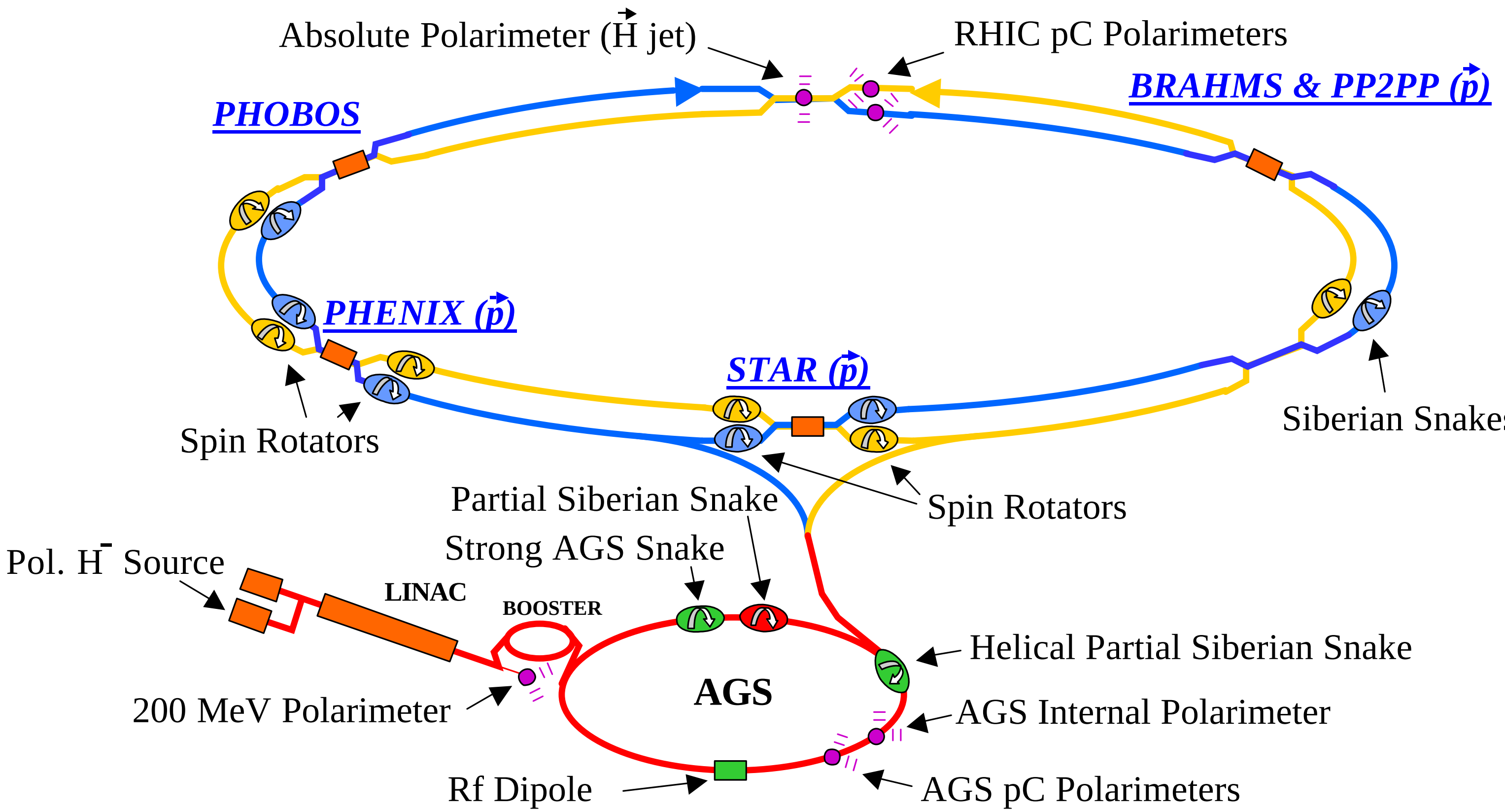
Polarized Proton Collisions in RHIC



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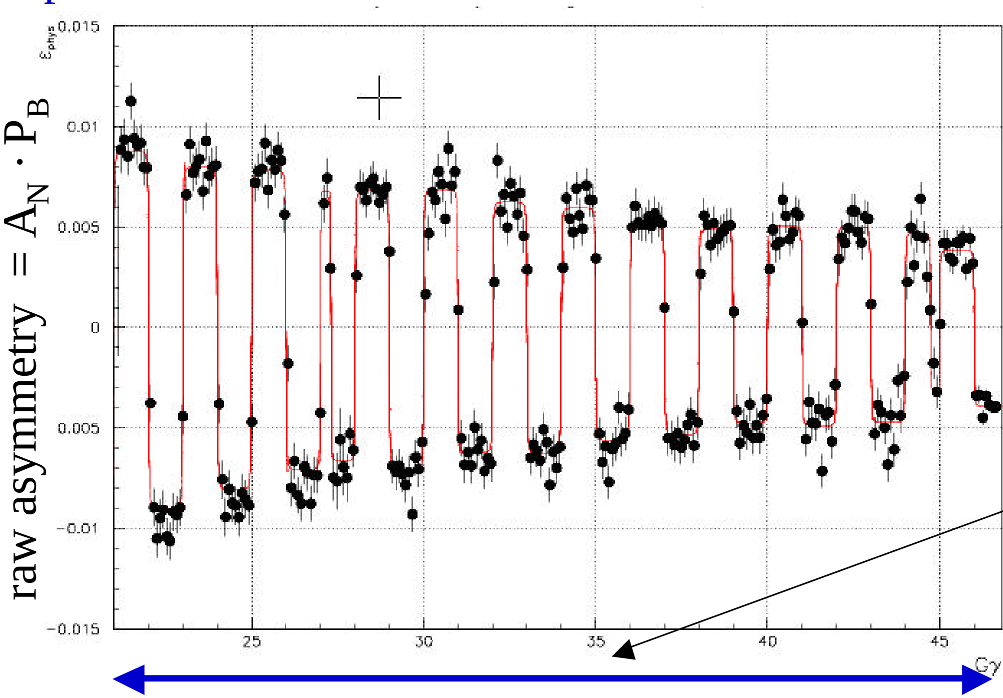
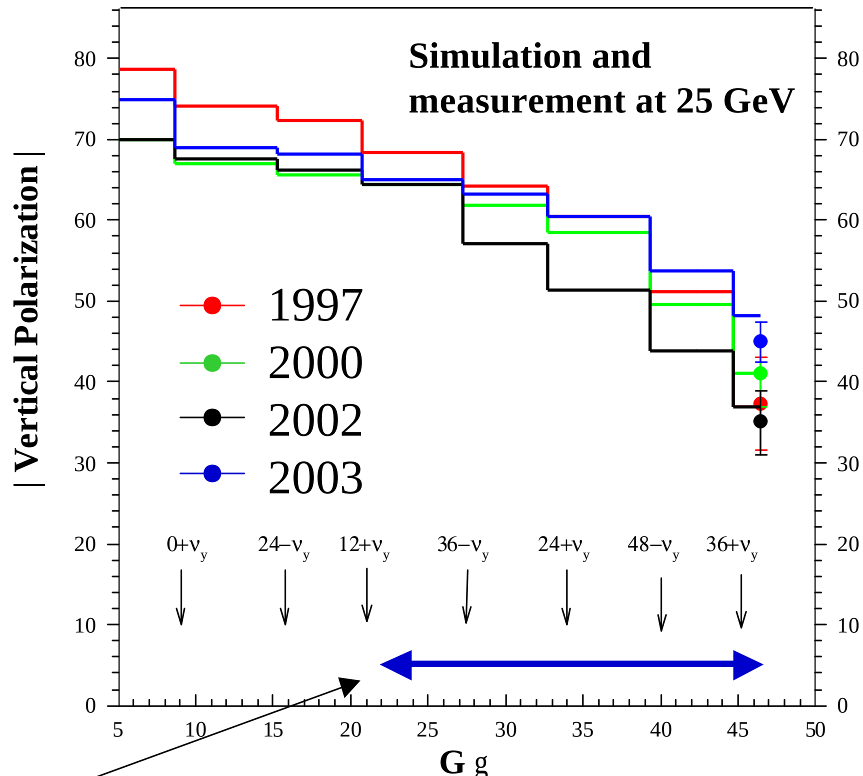
Proton polarization at the AGS

- Full spin flip at all imperfection and strong intrinsic resonances using partial Siberian snake and rf dipole
- Ramp measurement with new AGS pC CNI polarimeter:





- Remaining polarization loss from coupling and weak intrinsic resonances
- New helical partial snake (RIKEN funded) will eliminate coupling res.
- To avoid all depolarization in AGS build strong AGS helical Siberian snake! (Installation: late 2004)

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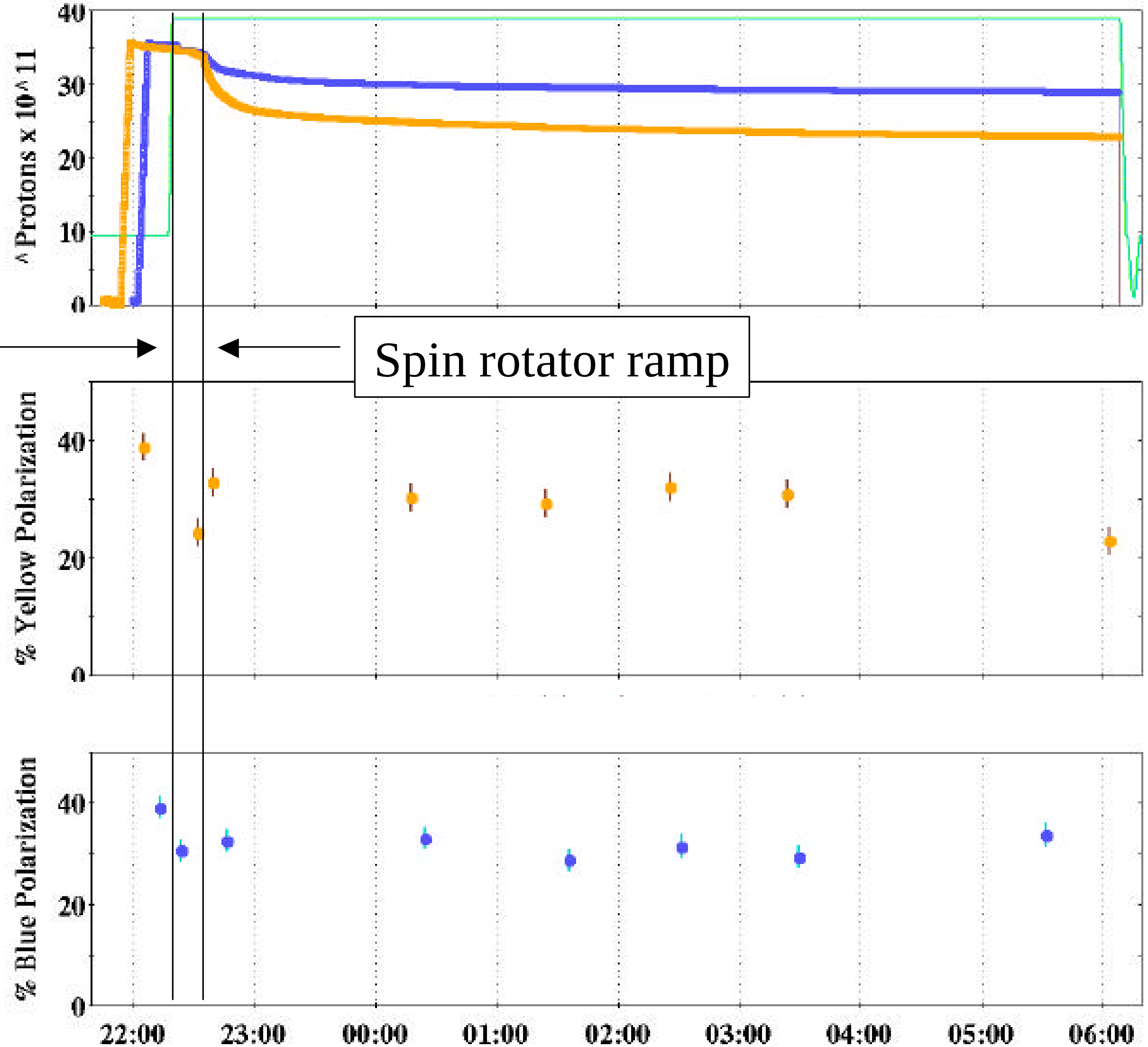
Polarization survival in RHIC (store # 3713)

Acceleration and squeeze ramp

Spin rotator ramp



Some loss during accel/squeeze ramp (Tune too close to ¼)

No loss during spin rotator ramp and during store

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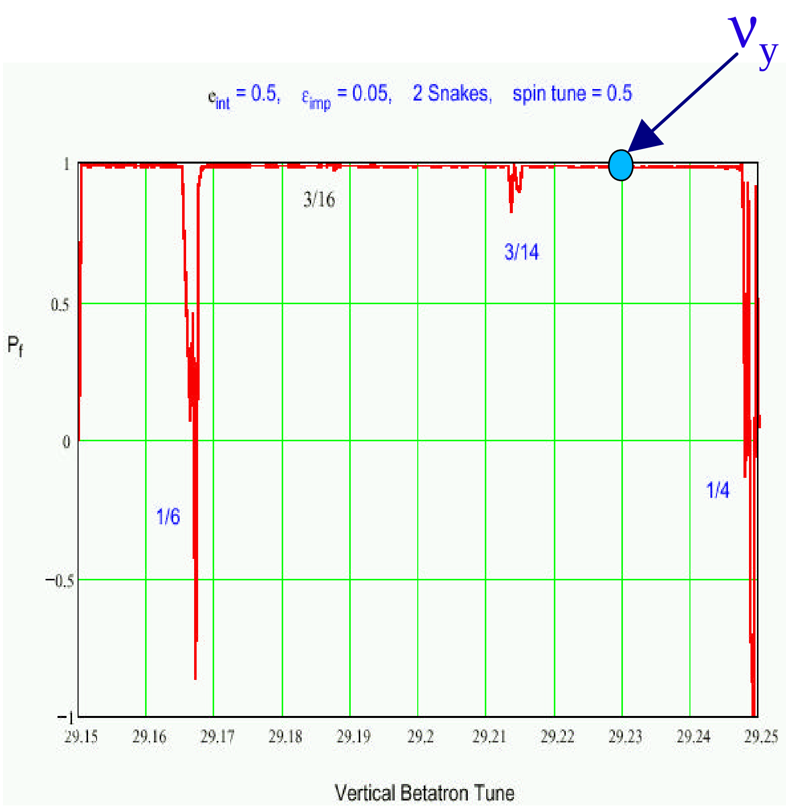
RHIC Polarization Set-up

2 Siberian Snakes per ring hold the spin tune ½ all the way up during the acceleration.

The vertical tune was chosen at 0.23, between 2 high-order spin resonances:

- 1/4=0.25 ; depends on vertical orbit
- 3/14=0.2143; exists even without orbit errors

Need excellent tune control; eventually need tune feed-back.



The special vertical orbit, "really" flat was used as the ideal orbit

- 2002 survey showed up to 5 mm misalignment. Partially realigned for Run-3
- The goal number for vertical orbit correction is 0.5mm rms
- Development of beam based orbit “flattening”

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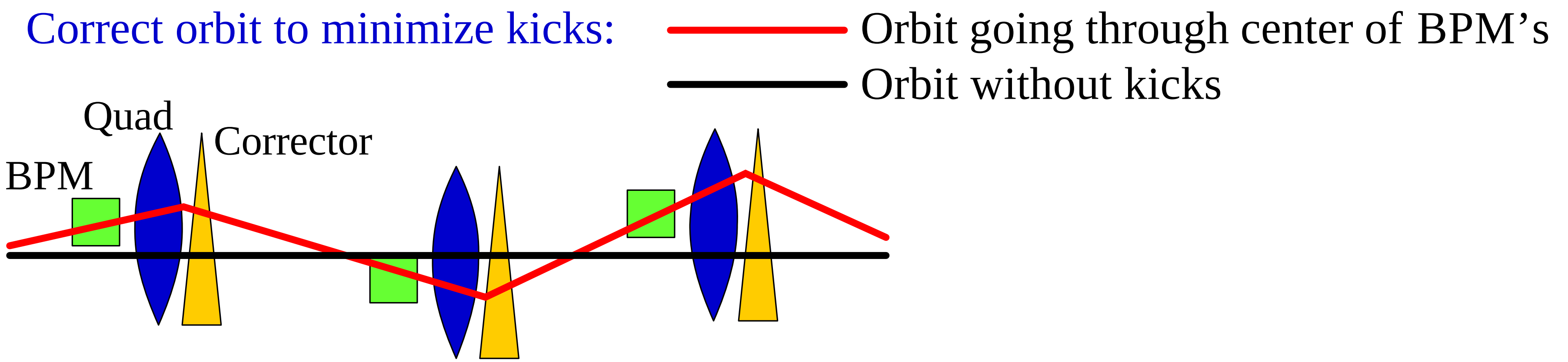
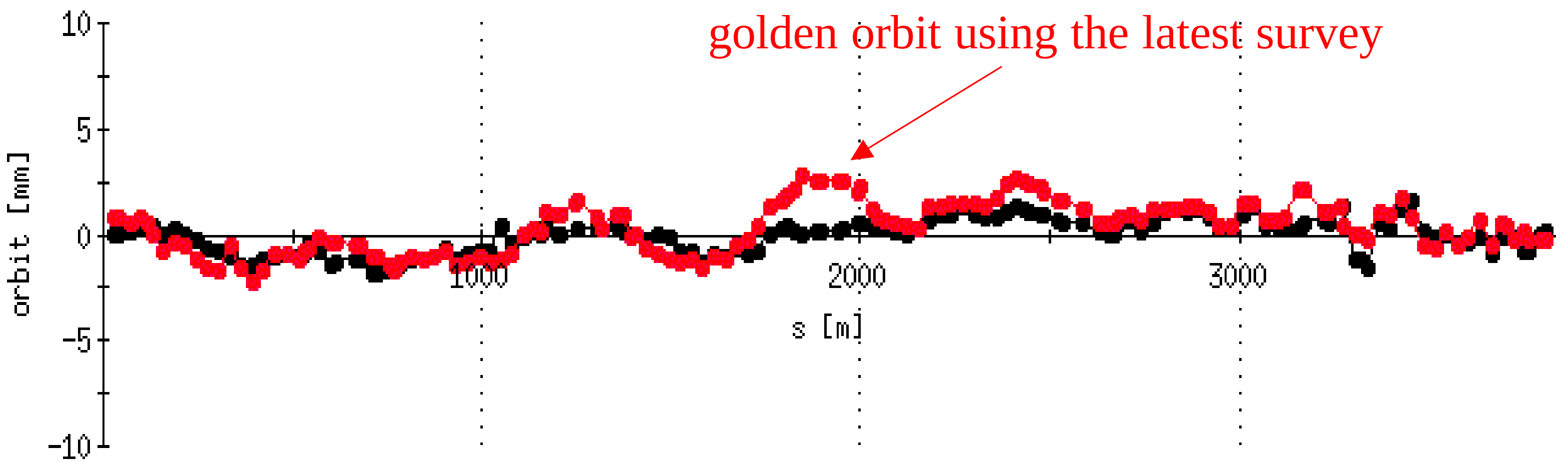
Ideal Orbit for Polarization

Correct orbit to minimize kicks:



Yellow vertical orbit flattened based on survey:



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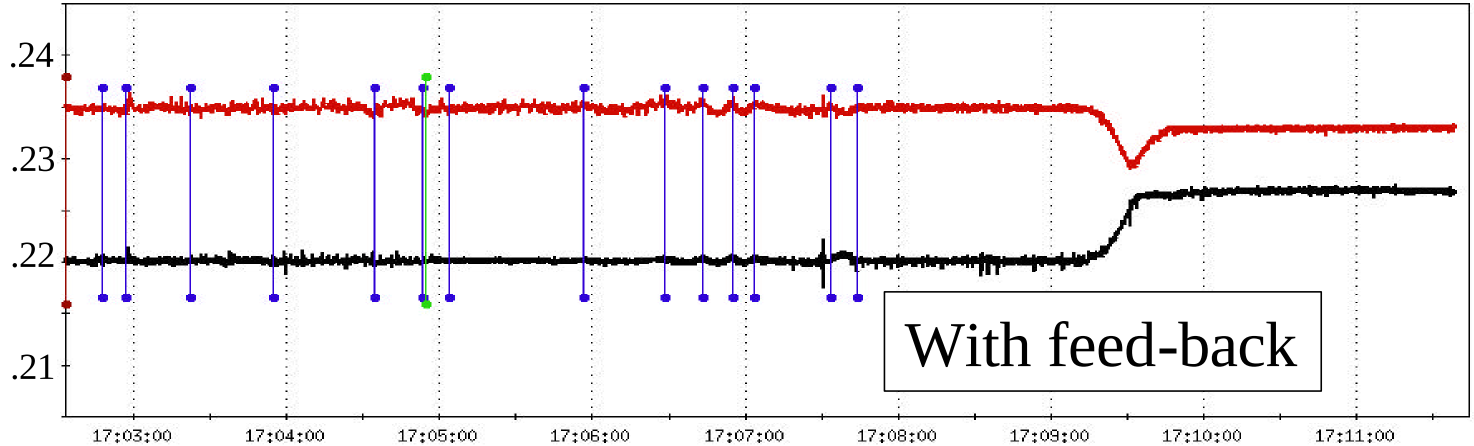
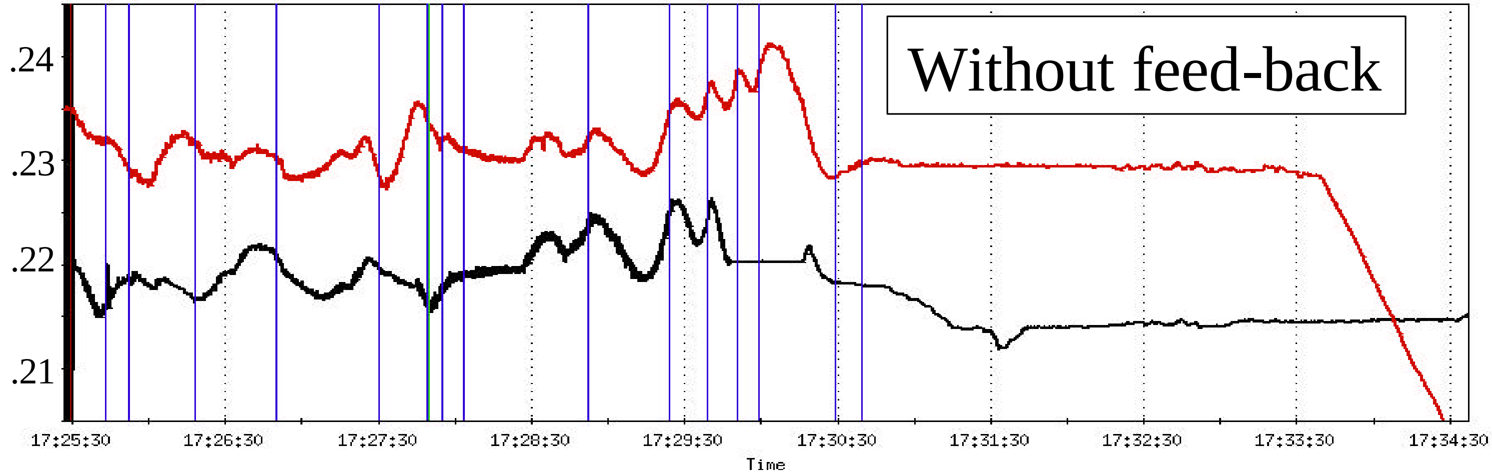
Proton Ramp with Tune Feedback



Tune feed-back using PLL worked but not yet operational.



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Achievements during 9-week p-p run

- Source polarization ~70-75%, it is reasonably stable.
- AGS provided 50% peak and 40% average polarization.
- Spin rotators commissioned successfully. Longitudinal polarization for the first time at IR 6 and 8.
- One helix in 9 o'clock Yellow snake failed. Remaining helices allowed for 88% snake, which was sufficient to maintain polarization.
- Set up six different lattices (!): β^* = 2m for all Irs; β^* = 1m at IR 6 and 8 and 3m for IR 2 and 10; with 88% Yellow snake; with PHEINX spin rotators; with PHENIX and STAR spin rotators; β^* =10m for pp2pp.
- 55 bunches per ring with 0.65 x 10^{11} p↑/bunch, emittance ~15 π, Beam polarization at store: 35% peak, 30% average
- Peak luminosity at beginning of store: ~6×10^{30} cm^{-2} s^{-1} at 100GeV
- Beam life-time affected by beam-beam effect. Needed to reduce number of collisions from 4 to 2. Also working point has to be accurate at 0.001 level.

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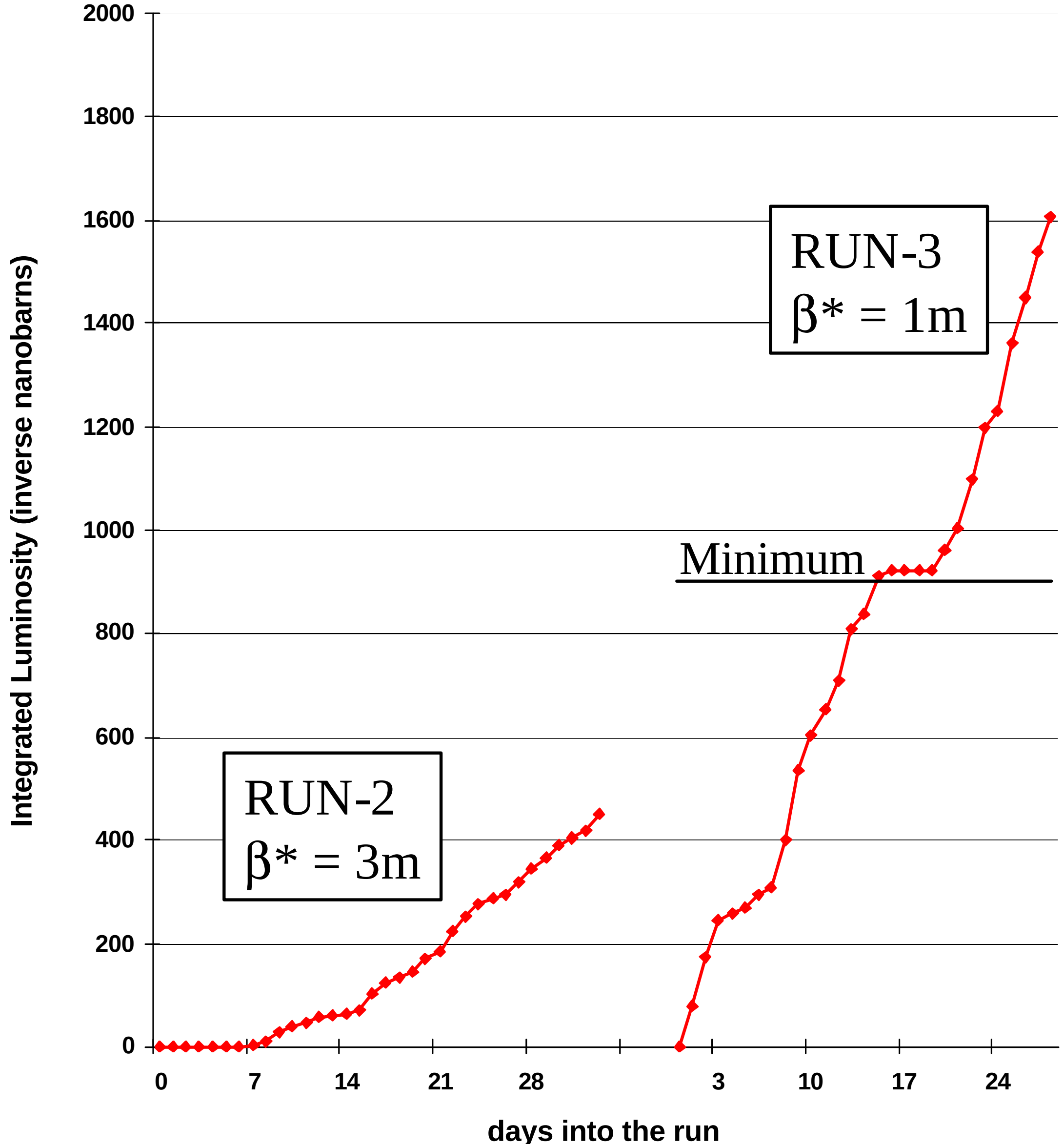
Delivered integrated p-p Luminosity

- Luminosity determined from Zero Degree Calorimeters (ZDC) that were calibrated with Vernier scans.
- Luminosities are similar for STAR and PHENIX with β* = 3m in Run-2 and 1m in Run-3
- Days shown are from start of physics data taking.



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Performance summary

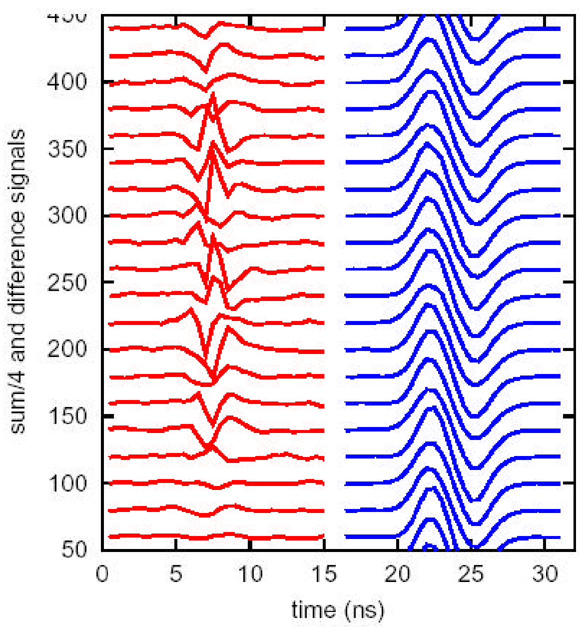
- Energy/beam: 100 GeV/nucl., diamond length: σ = 20 cm, L_{ave}(week)/L_{ave}(store) = 40 %

Mode	# bunches	Ions/bunch [$\times 10^9$]	β^* [m]	Emittance [$\pi\mu$m]	L_{peak} [$cm^{-2}s^{-1}$]	L_{ave}(store) [$cm^{-2}s^{-1}$]	L_{ave} (week) [$week^{-1}$]
Au-Au (*)	55	0.7	1	15 - 40	5×10^{26}	1.5×10^{26}	24 $(\mu b)^{-1}$
d-Au (*)	55	110(d), 0.7(Au)	2	15	6×10^{28}	2.0×10^{28}	4.5 $(nb)^{-1}$
p↑-p↑ (*)	55	70	1	20 - 30	6×10^{30}	3×10^{30}	0.6 $(pb)^{-1}$
d-Au (max. goal)	56	80(d), 1(Au)	2	20	4×10^{28}	1.6×10^{28}	4 $(nb)^{-1}$
p↑-p↑ (max. goal)	112	100	1	25	16×10^{30}	10×10^{30}	2.8$(pb)^{-1}$
Au-Au design	56	1	2	15 - 40	9×10^{26}	2×10^{26}	50 $(\mu b)^{-1}$
p↑-p↑ RHIC spin	112	200	1	20	80×10^{30}	80×10^{30}	20$(pb)^{-1}$

[(*) Best store or last week]

Luminosity Limitations (1)

- Injector performance (routine):
  - Au 0.7 ´ 10^9 /bunch 10 π µm 0.3 eVs
    - additional bunch merge
  - p 0.8 ´ 10^{11} /bunch 10 π µm 0.3 eVs 40%
  - p 2.0 ´ 10^{11} /bunch 20 π µm 0.5 eVs 20% (?)
    - strong AGS partial snake, thinner H^- stripping foil
- Single bunch instabilities around transition:
  - Effect of vacuum chamber impedance, electron cloud (?)
  - Au: < 0.8 ´ 10^9 ions/bunch
    - cross zero-chromaticity before transition (why?)
- Vacuum break-down due to ion desorption (?)
  - Au: < 40 ´ 10^9 ions/ring
    - More baking, scrubbing, NEG coating
- Vacuum problem due to halo scrapping around transition (?)
  - Total accelerated charge in both rings < 10^{13} e
    - More baking, scrubbing, NEG coating



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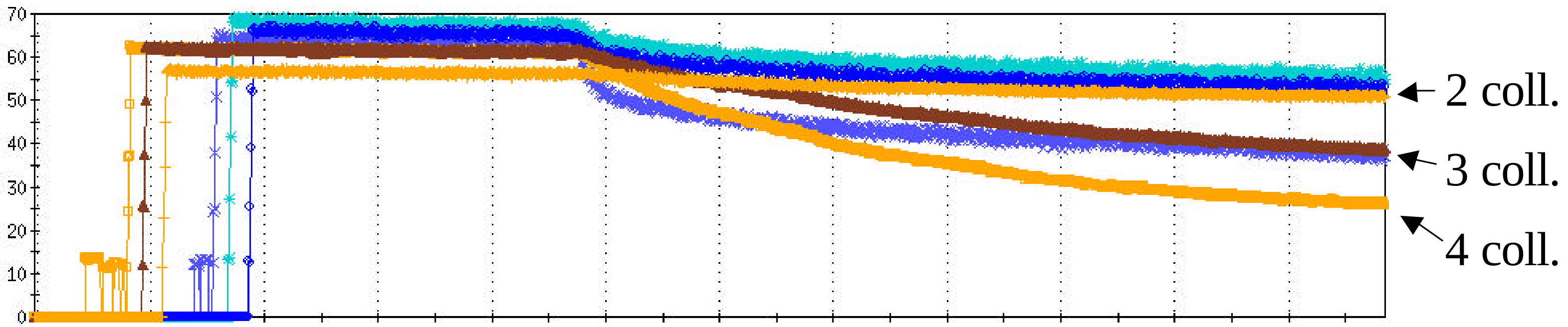
Luminosity Limitations (2)

- Electron multi-pacting (electron cloud)
  - Total charge per ring less than ~ 10^{13} e, worse for 110 bunches
    - Solenoids, scrubbing, NEG coating
- Beam-beam tune shift and spread
  - First strong-strong hadron collider (after ISR)
  - Limits high luminosity pp operation to two IRs
    - Non-linear corrections, better working point



- Intra-Beam Scattering (IBS)
  - Transverse and longitudinal emittance growth
  - Eventually will need electron cooling (see below)

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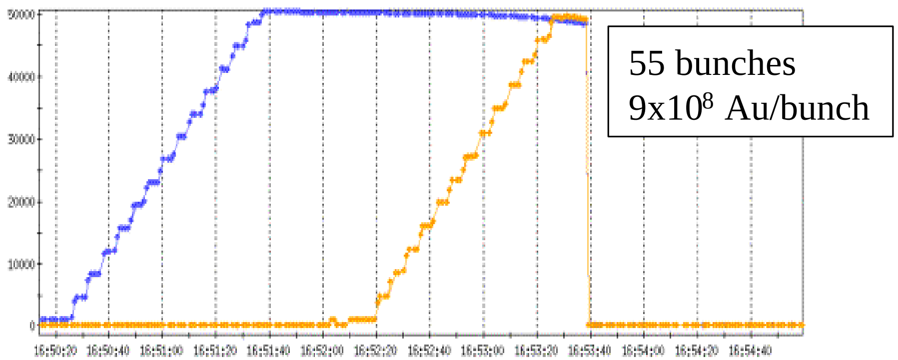
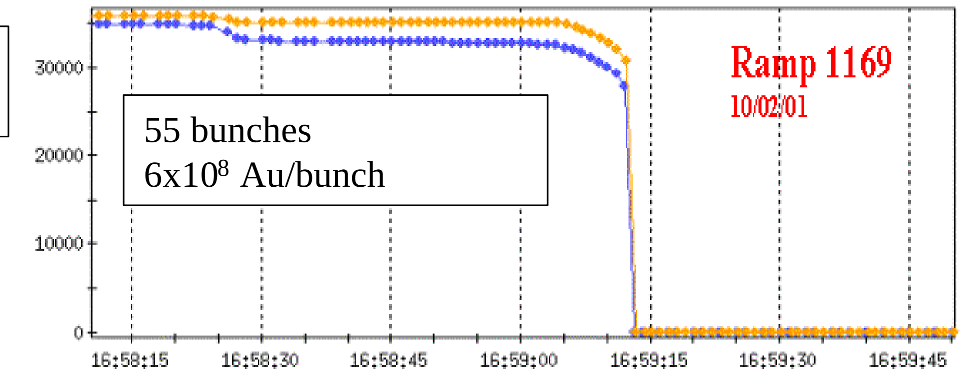
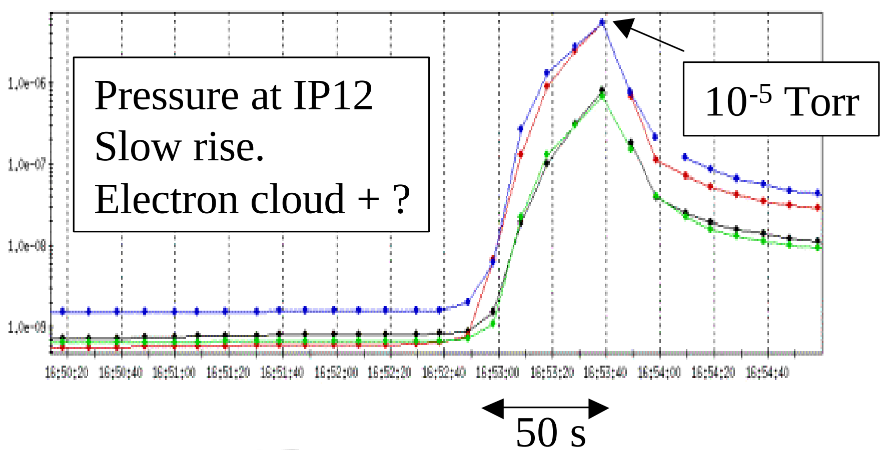
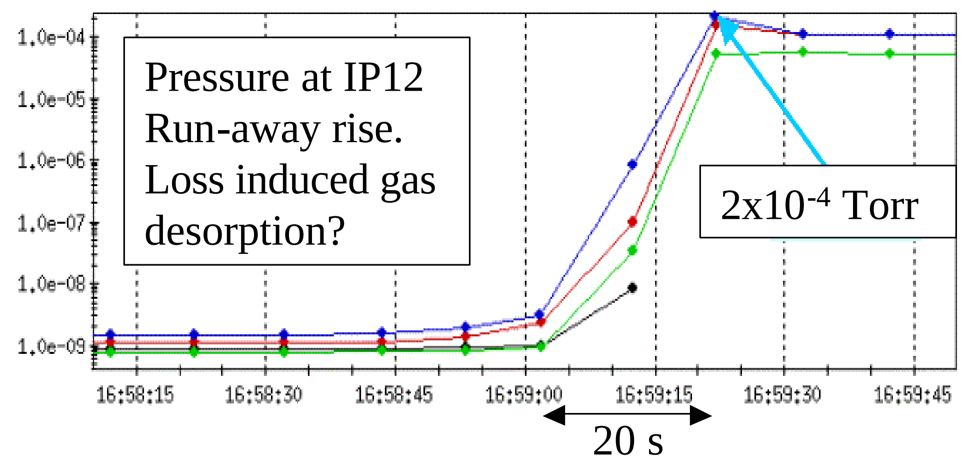
Vacuum break-down

- Mainly in warm sections that didn’t have bake-out; worse with 110 bunches/ring
- Ion desorption, electron desorption, electron multi-pacting, electron cloud
- Installed electron detectors in IP12 and IP2 and solenoids for electron suppression in IP12.
- “scrubbing” with beam, NEG coated vacuum chambers









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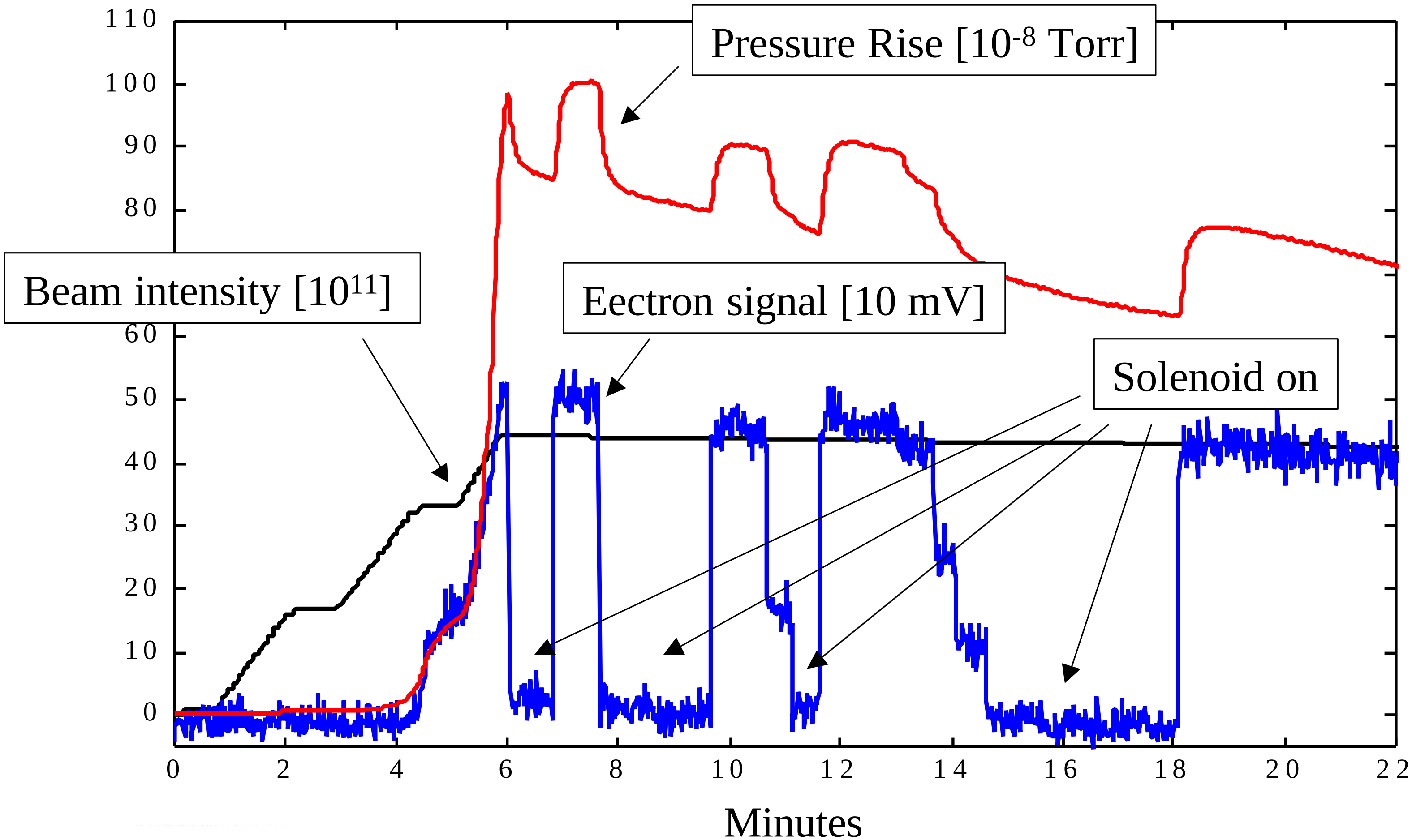
Pressure rise with 100 ns bunch spacing

- Pressure rise coincides with the electron signal.
- Solenoid field reduces electron signal.
- Solenoid field (4 meters) partially reduces pressure rise in the 34 meters long straight section.



NEG coating

- NEG strips first used in TTB(BNL) and LEP
- Non-Evaporable Getter coating: Ti_{30} Zr_{30} V_{40} sputtered ~ 1 μm thick onto walls
- Developed at CERN for LHC warm sections
- Ultimate pressure < 10-12 Torr
- Activation: 1 h @ 250º C, 5 h @ 200º C, 24 h @ 180º C
- Secondary Electron Yield (SEY): 1.1 after activation of 2 h @ 200º C
  Strong suppression of multi-pacting (tested at SPS)
- Electron stimulated gas desorption: ~ 100 times lower than baked SS
- Ion stimulated gas desorption: ~ 10 times lower than SS (tested with 4.2 MeV/n Pb)
- **Test at RHIC: install 60 m of coated pipe, test ion desorption at Tandem**

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Projected Run-4 Luminosities

Achieved:

Mode	# bunches	Ions/bunch [$\times 10^9$]	β^* [m]	Emittance [μm]	L_{peak} [$cm^{-2}s^{-1}$]	L_{ave}(store) [$cm^{-2}s^{-1}$]	L_{ave} (week) [$week^{-1}$]
Au-Au	55	0.6	1	15-40	3.7×10^{26}	1.5×10^{26}	24 $(\mu b)^{-1}$
(p↑-p↑)	55	70	1	20	6.0×10^{30}	3.0×10^{30}	0.6 $(pb)^{-1}$

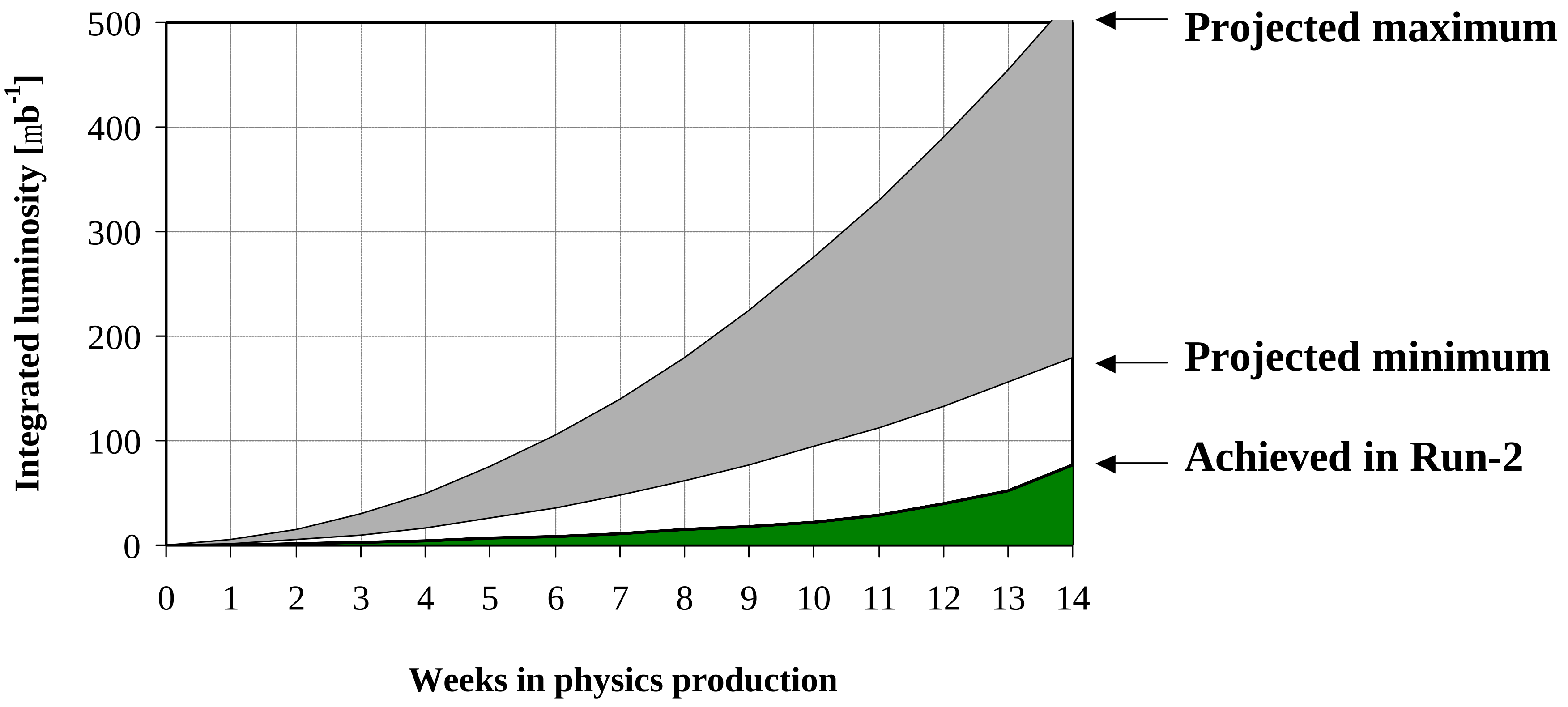
Maximum expectations:

Mode	# bunches	Ions/bunch [$\times 10^9$]	β^* [m]	Emittance [πμm]	L_{peak} [$cm^{-2}s^{-1}$]	L_{ave}(store) [$cm^{-2}s^{-1}$]	L_{ave} (week) [$week^{-1}$]
Au-Au	56	1	1	15-40	14×10^{26}	3×10^{26}	70 $(\mu b)^{-1}$
(p↑-p↑)	56	100	1	20	8×10^{30}	5×10^{30}	1.8 $(pb)^{-1}$
Si-Si	56	7	1	20	5×10^{28}	2×10^{28}	5 $(nb)^{-1}$

Integrated luminosity for 1 or 2 modes:

Mode	Integrated luminosity per mode			
	1 Mode (19 weeks)		2 Modes (7 weeks/mode)	
	Minimum	Maximum	Minimum	Maximum
Au-Au	290 $(\mu b)^{-1}$	840 $(\mu b)^{-1}$	42 $(\mu b)^{-1}$	122 $(\mu b)^{-1}$
(p↑-p↑)	10 $(pb)^{-1}$	24.0 $(pb)^{-1}$	3.2 $(pb)^{-1}$	5.3 $(pb)^{-1}$
Si-Si	?	60 $(nb)^{-1}$	?	9 $(nb)^{-1}$

Projected Run-4 Au-Au Luminosity Evolution



Accelerator Improvement Projects (priority ordered)

- Collider Helium Storage Addition [FY2001/2002] (compl. 9/02) $2.6M
  - On-site He storage during shut-down and > 5 hour refrigerator interruption
- Liquid Nitrogen based shut-down cooling system [FY2002] (compl. 5/03) $2.0M
  - Cost-effective pre-cooler and shut-down cooling system to avoid thermal cycling of RHIC magnets
- AGS MMPS generator field supply upgrade [FY2002/03] (compl. 9/04) $0.6M
  - Repl. of obsolete 30 year-old exciter of Siemens motor-generator
- Eliminate seal gas compressor single point of failure [FY2003] (compl. 9/03) $0.6M
  - Replace present seal gas compressor with redundant system
- **RHIC Secondary Collimator System [FY2003] (compl. 12/04) $1.0M**
  - **Reduce beam halo, facilitate abort gap cleaning**
- **AGS Helical Partial Siberian Snake [FY2003/04] (compl. 12/04) $2.0M**
  - **Eliminate all depolarizing resonances in AGS**
- RHIC Refrigerator Control and Instrumentation Upgrade [FY2004] (compl. 12/04) $1.9M
  - Repl. of 20 year-old compressor and turbine control and instr.
- AGS Main Magnet P. S. Transformer Replacement and Ripple Reduction [FY2005] (compl. 12/05) $3.3M
  - Repl. of 30 year-old main AGS transformer. Single point failure item

Accelerator Improvement Projects

• Westinghouse Generator Cooling System Upgrade	FY2006	$0.3M
▪ Replacement of 40 year-old cooling system		
• Westinghouse Motor Stator Insulation Upgrade	FY2006	$0.4M
▪ Replacement of 40 year-old motor stator insulation		
• AGS Vacuum Control System Upgrade	FY2006	$0.8M
▪ Replacement of 20 year-old controls with PLC-based system		
• Tandem controls and reliability upgrade (if EBIS is not started)	FY2006/07	$5.0M

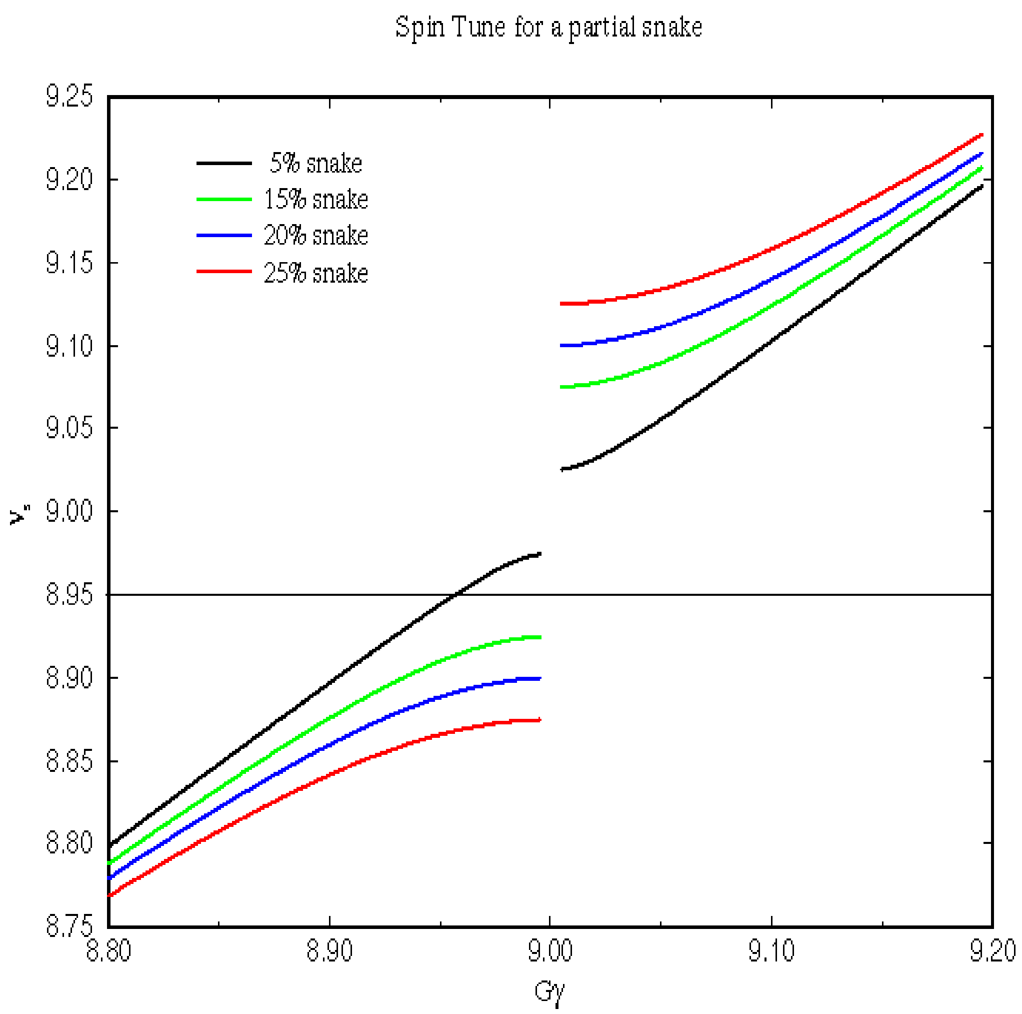
Strong Partial Siberian Snake for AGS

A strong partial Siberian snake generates large spin tune gap for $G\gamma=N$. With strong enough snake gap is large enough to cover both imperfection and intrinsic spin resonances.

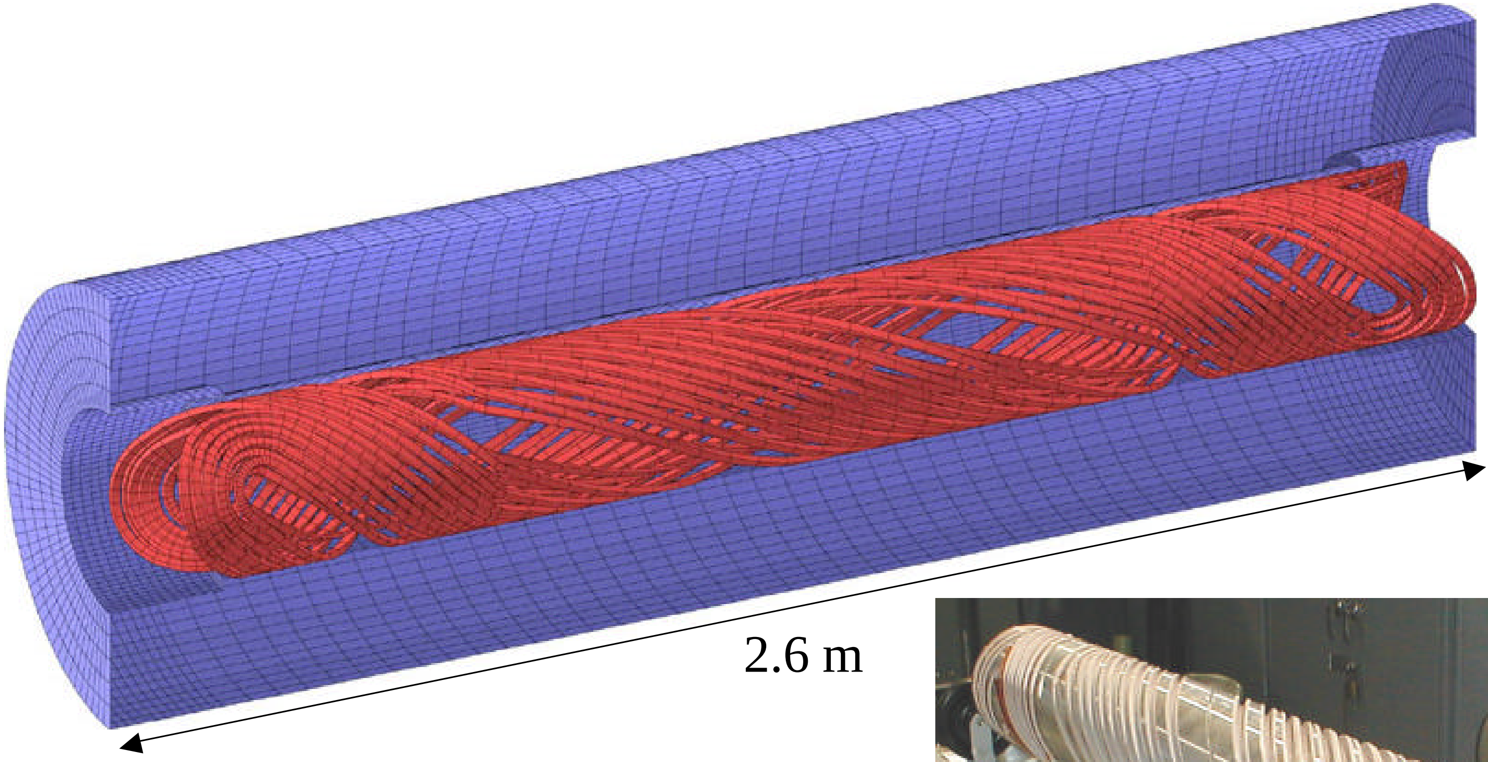
Successfully tested with 10% snake.

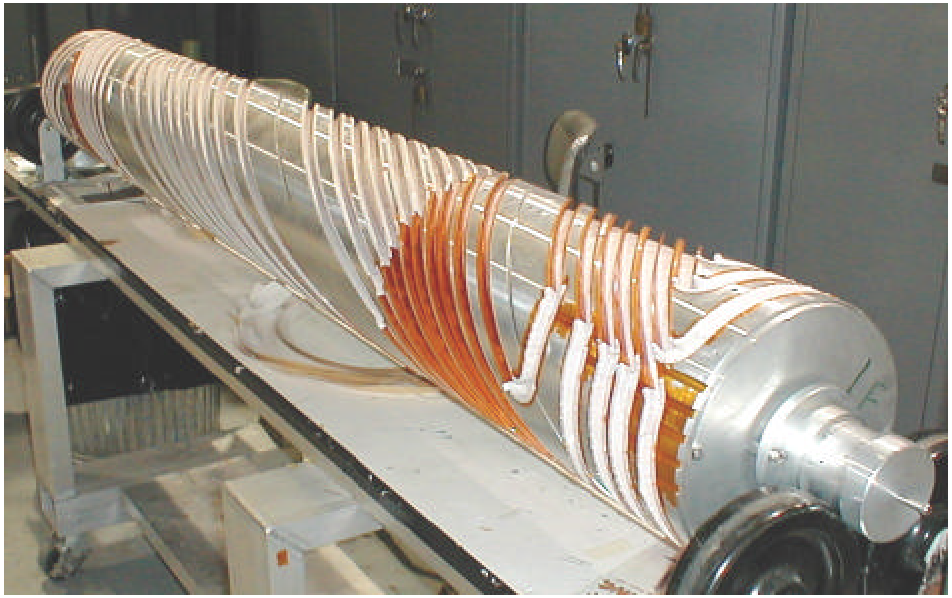
Helical snake will not generate coupling spin resonances

Spin matching at injection and extraction can mostly be achieved with new warm helical 5% snake.



30 % AGS super-conducting helical snake





15 cm warm bore helix with changing pitch
Minimizes orbit excursions

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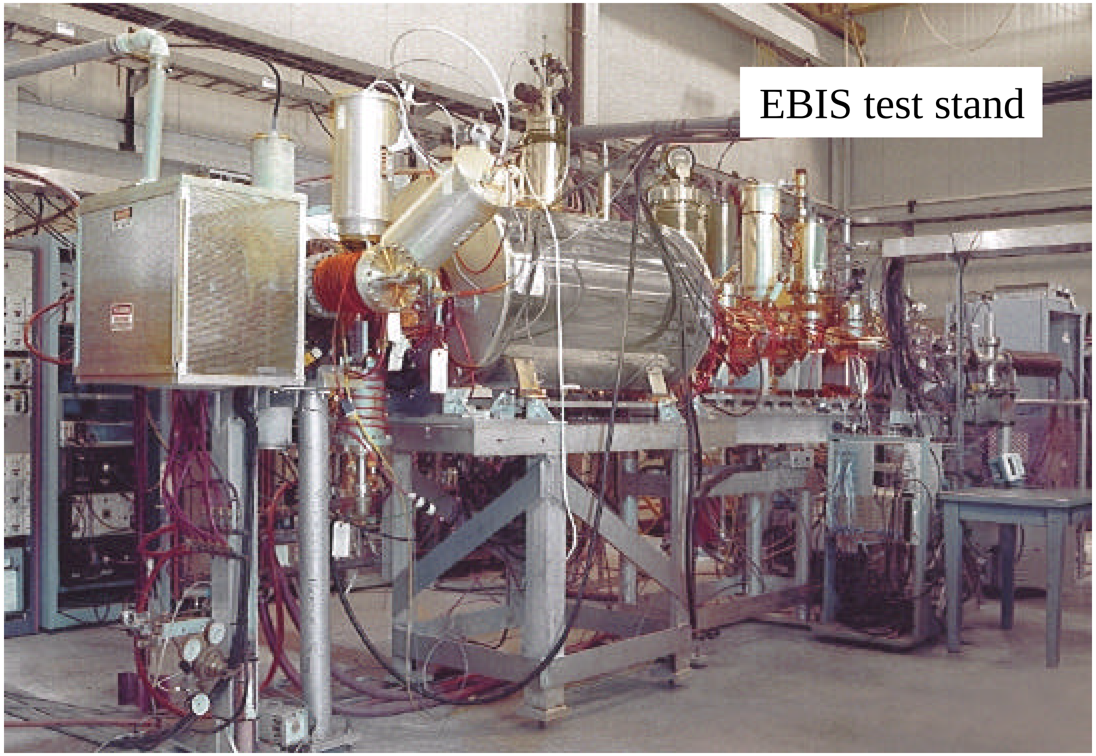
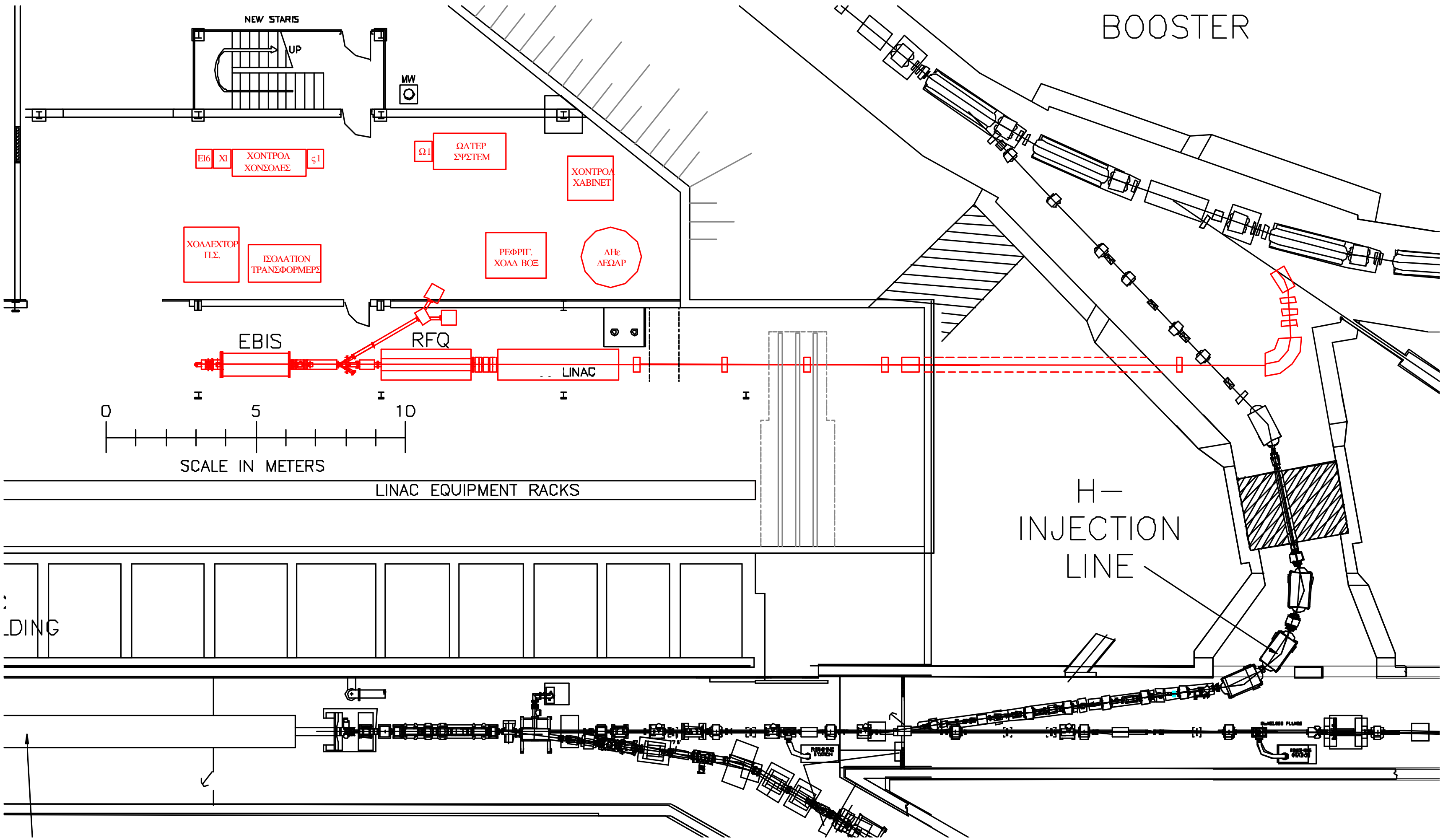
EBIS/Linac RHIC Pre-Injector

- Highly successful development of Electron Beam Ion Source (EBIS) at BNL
- EBIS allows for a reliable, low maintenance Linac-based pre-injector replacing the Tandem Van de Graaffs
- Produces beams of all ion species including Uranium and polarized He^3 (for eRHIC)
- Ready to start construction; Cost: 16.1 M$; Schedule: 2005/6 – 2008/9



EBIS test stand

EBIS layout



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RHIC II luminosity upgrade

- RHIC luminosity is limited by intra-beam scattering $\longrightarrow$ beam cooling at full energy!
- Feasibility study by BINP (V. Parkhomchuk et al.): RHIC luminosity can be increased ten times.
- Bunched electron beam requirements for 100 GeV/u gold beams:
E = 54 MeV, <I> ~ 100 mA, electron beam power: ~ 5 MW!
- Requires high brightness, high power, energy recovering superconducting linac, as demonstrated by JLab for IR FEL. (50 MeV, 5 mA)
- First linac based, bunched electron beam cooling system used at a collider
- First high p_t electron cooler to avoid recombination of e^- and Au^{79+}
- Maintains present bunch spacing (~ 100 ns) and available IR length
- Increased luminosity for pp and other species
- Longitudinal cooling possibly gives shorter diamond length

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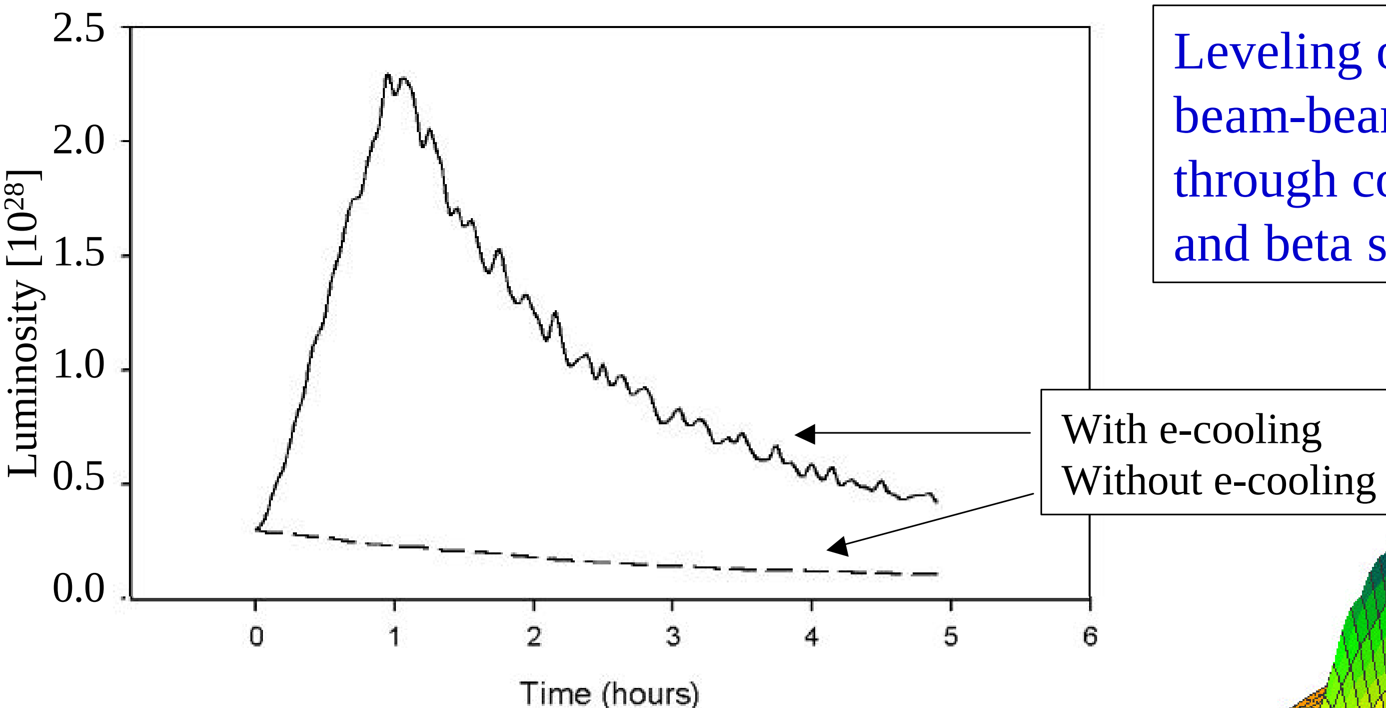
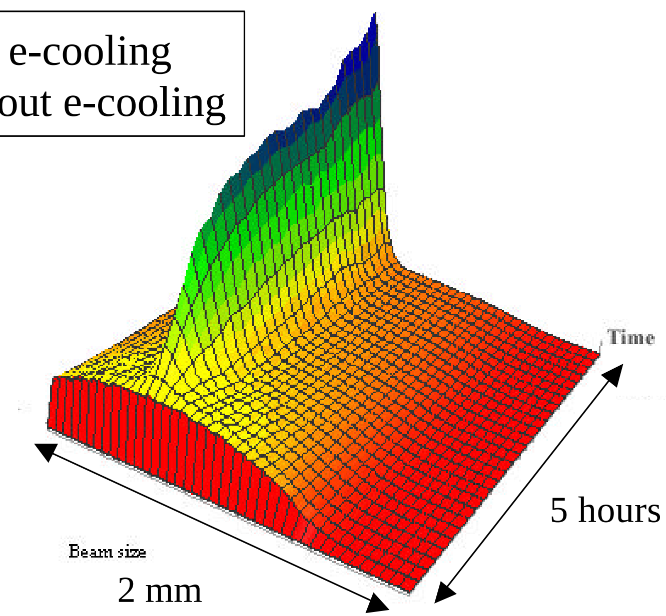
RHIC Luminosity with and without Cooling



Leveling of luminosity and beam-beam interaction through continuous cooling and beta squeeze

Transverse beam profile during store



RHIC II Luminosities with Electron Cooling

Gold collisions (100 GeV/n x 100 GeV/n):	**w/o e-cooling**	**with e-cooling**
Emittance (95%) $\pi\mu m$	$15 \rightarrow 40$	$15 \rightarrow 3$
Beta function at IR [m]	1.0	$1.0 \rightarrow 0.5$
Number of bunches	112	112
Bunch population [10^9]	1	$1 \rightarrow 0.3$
Beam-beam parameter per IR	0.0016	0.004
Peak luminosity [10^{26} cm^{-2} s^{-1}]	32	90
Average luminosity [10^{26} cm^{-2} s^{-1}]	8	70

Pol. Proton Collision (250 GeV x 250 GeV):		
Emittance (95%) $\pi\mu m$	20	12
Beta function at IR [m]	1.0	0.5
Number of bunches	112	112
Bunch population [10^{11}]	2	2
Beam-beam parameter per IR	0.007	0.012
Peak luminosity [10^{32} cm^{-2} s^{-1}]	2.4	8.0

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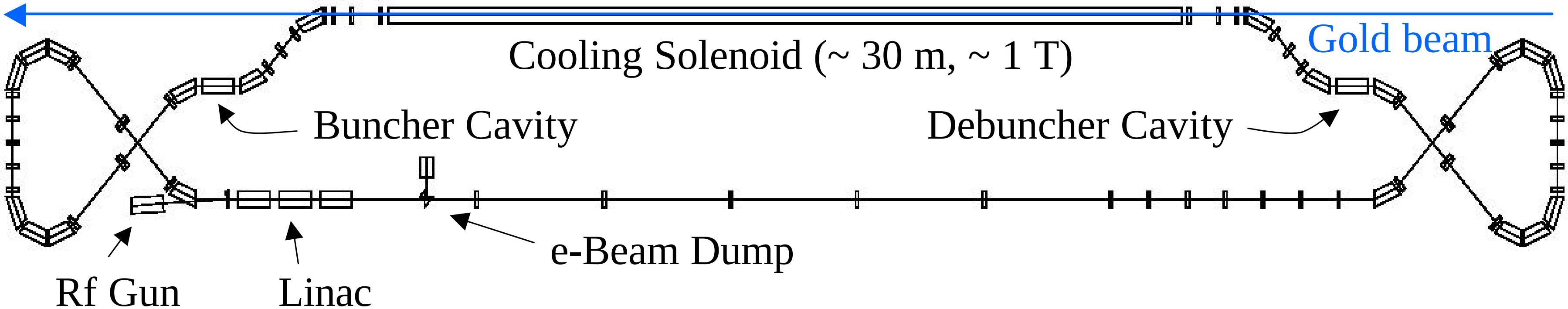
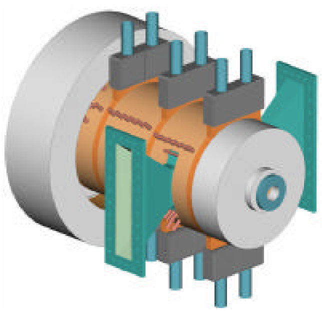
RHIC Electron Cooler R&D

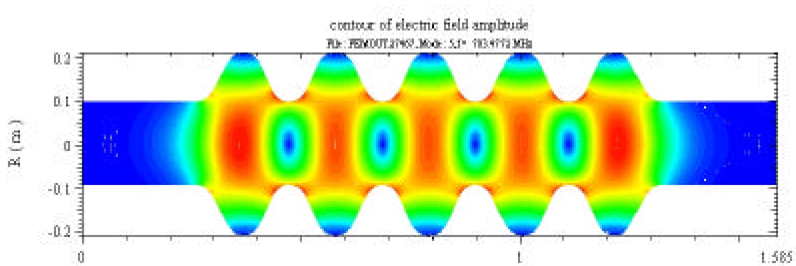


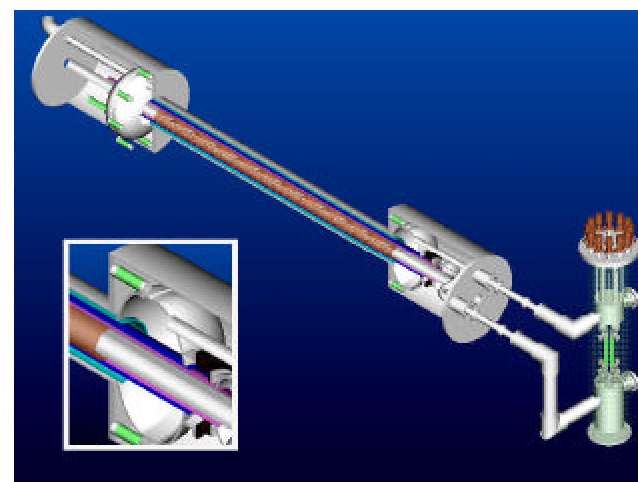


Demonstrate 10 nC, 100 – 300 mA CW rf photo-cathode electron gun:
High power, 700 MHz 2.5 cell cavity (collab. with LANL)

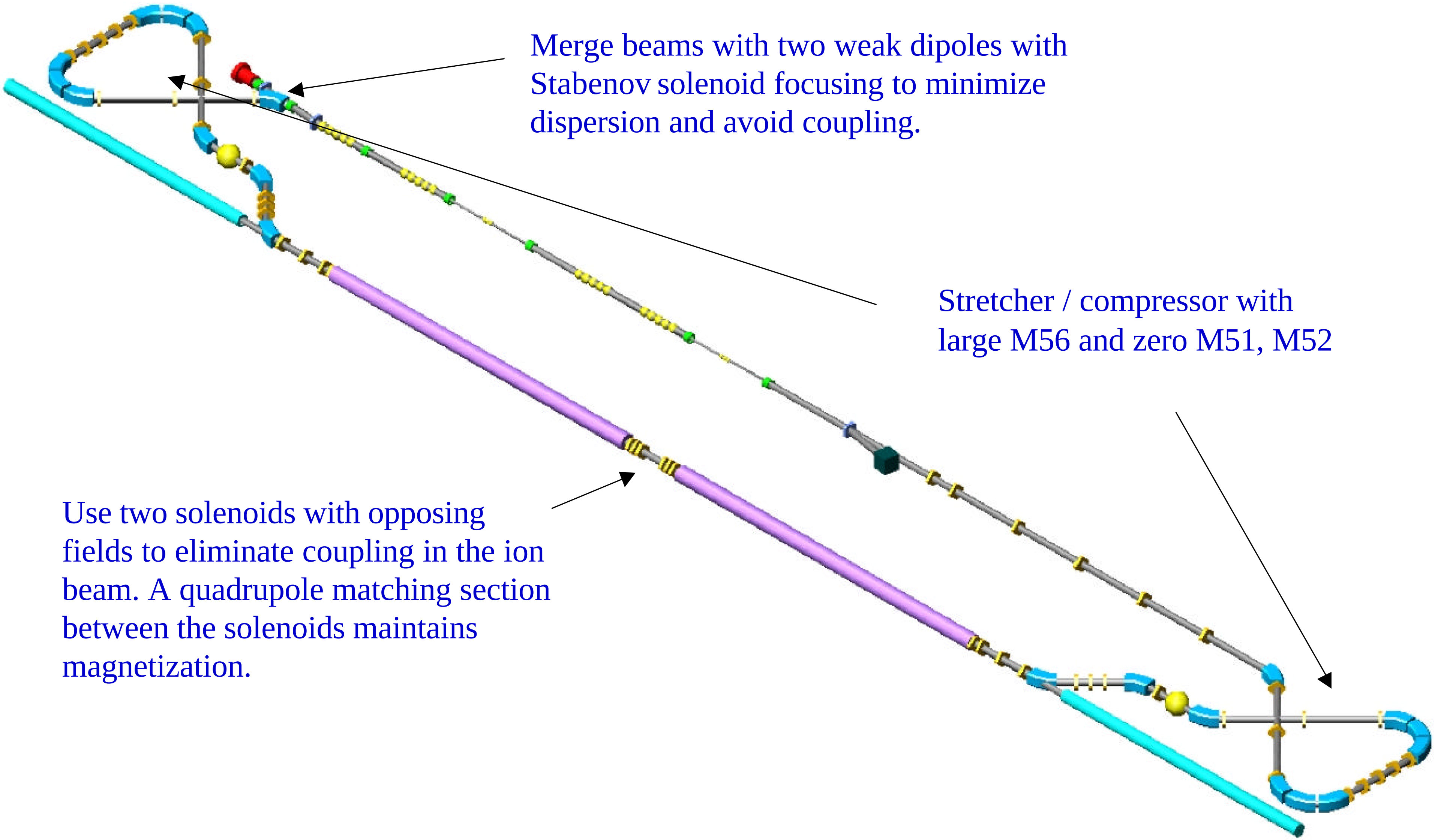
Demonstrate high precision (10 ppm) solenoid

Develop CW s.c. cavity for high intensity beams:
Large bore, 700 MHz cavity with ferrite HOM dampers and high beam break-up threshold (collab. with JLab)





Electron Cooler Beam Dynamics R&D



Merge beams with two weak dipoles with Stabenov solenoid focusing to minimize dispersion and avoid coupling.

Stretcher / compressor with large M56 and zero M51, M52

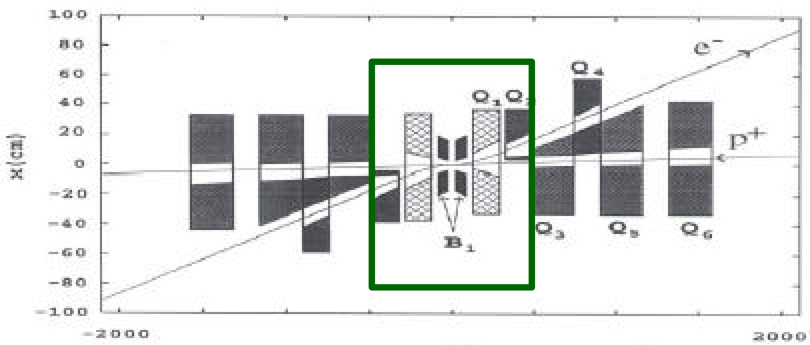
Use two solenoids with opposing fields to eliminate coupling in the ion beam. A quadrupole matching section between the solenoids maintains magnetization.

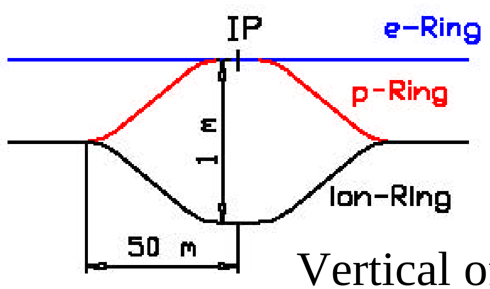
RHIC II beam cooling R&D milestones

Rf gun prototype:	**Date**
Operate laser with super-conducting gun	December 2003
Operate basic beam optical system	June 2004
Demonstrate high-current CW source	April 2005
Solenoid prototype:	**Date**
Magnetic design of solenoid complete	June 2003
Magnetic design of correction coils completed	September 2003
Mechanical design completed	June 2004
Magnet construction completed	September 2005
Magnet testing completed	June 2006
Energy recovery linac prototype:	**Date**
Manufacturing plan complete	September 2003
Cold model delivered to BNL	March 2004
Final Design Review	April 2004
RF tests complete	July 2005
Finish construction of prototype ERL	January 2006
Obtain high-brightness high-current beam	June 2006
Beam dynamics, cooling software and theory:	**Date**
Emittance compensation and magnetized beam	December 2003
Phase I BETACOOL code	August 2003
Benchmarking BETACOOL by ParSEC	December 2003
Phase II BETACOOL (arbitrary ion distribution)	September 2004
Start-to-end beam dynamics of a cooler	December 2004
Benchmarking with cooler ring experiments	September 2005

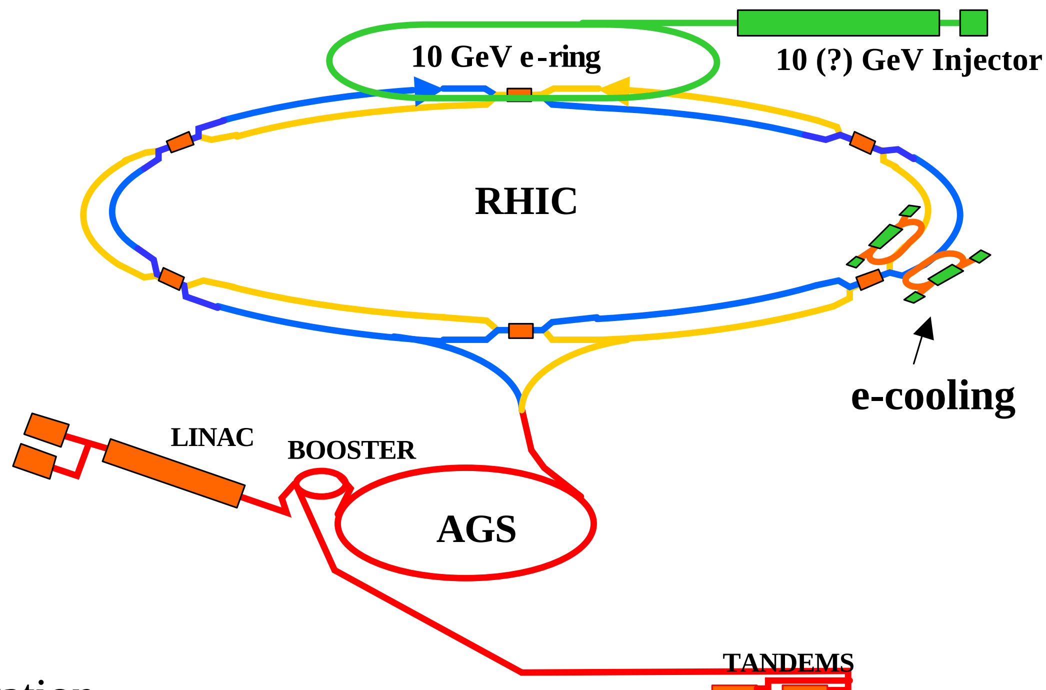
Status of eRHIC design

- 10 GeV, 0.5 A e-ring with ¼ of RHIC circumference (similar to PEP II HER)
- 10 GeV electron beam → $s^{1/2}$ for e-A : 63 GeV/u; $s^{1/2}$ for e-p: 100 GeV
- e-ring with about 15 min. polarization build-up time using super-bends
- Existing RHIC interaction region allows for typical asymmetric detector (similar to HERA or PEP II detectors)
- Luminosity: 0.5 – 1.0 × 10^{33} $cm^{-2}s^{-1}$ per nucleon





Vertical offset
Horizontal separation



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Summary

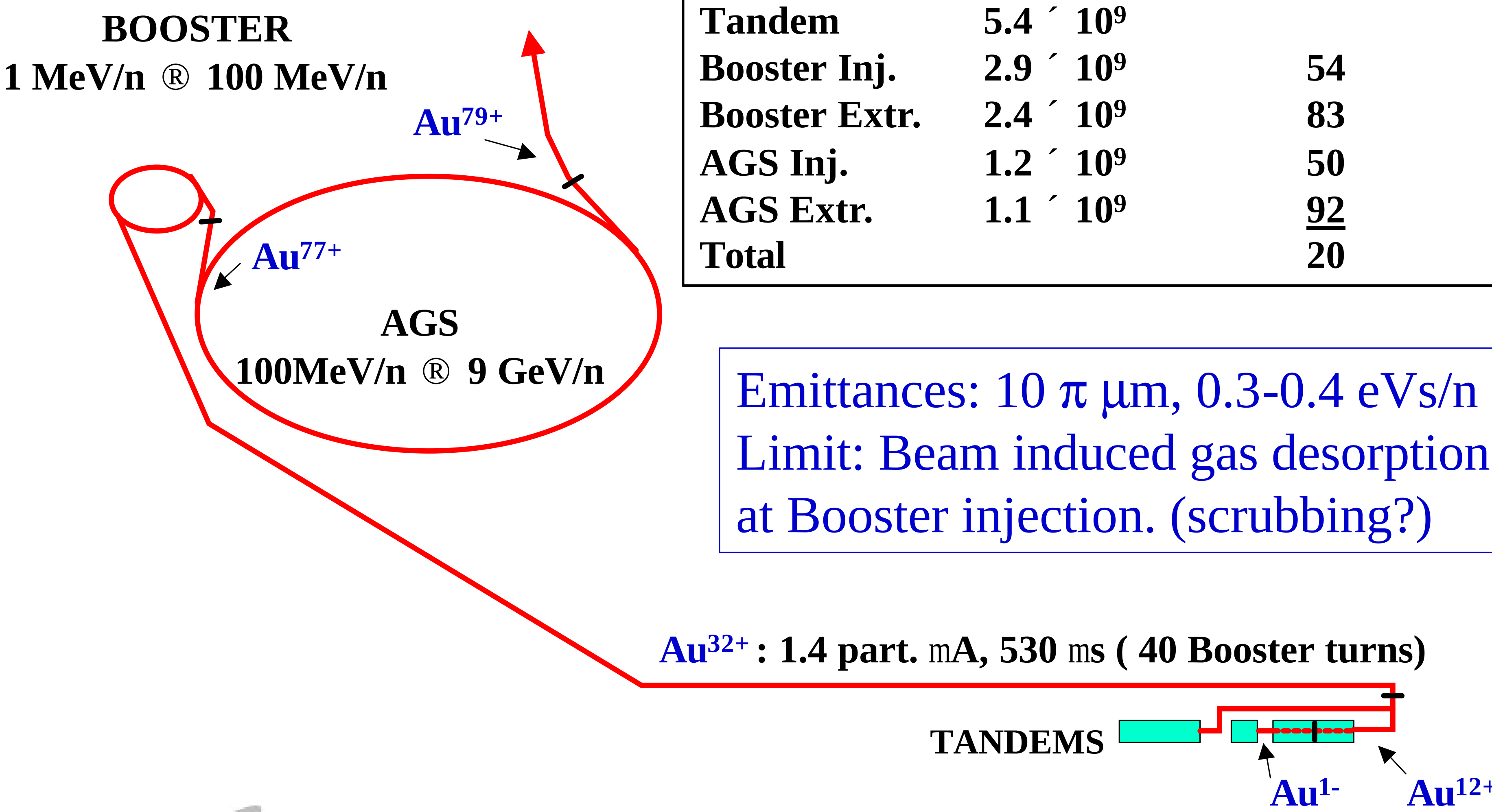
- Successful operation of RHIC with 100 GeV/n beams in three modes:
  - Gold – gold collisions, peak luminosity = 5×10^{26} cm^{-2} s^{-1}
  - Deuteron – gold collsions, peak luminosity = 6×10^{28} cm^{-2} s^{-1}
  - Polarized proton collsions, peak luminosity = 6×10^{30} cm^{-2} s^{-1}
- RHIC Spin data run with 100 GeV on 100 GeV polarized proton collisions and ~ 30 % polarization.
- Full exploitation of the many physics capabilities of RHIC requires extensive, ongoing machine development
- Accelerator Improvement Projects are required to improve performance and maintain and enhance reliability of the RHIC operation
- Successful EBIS R&D allows for the construction of a new Linac-based RHIC pre-injector
- RHIC e-cooling R&D program started for 40 times RHIC Au luminosity upgrade

Supplemental Material

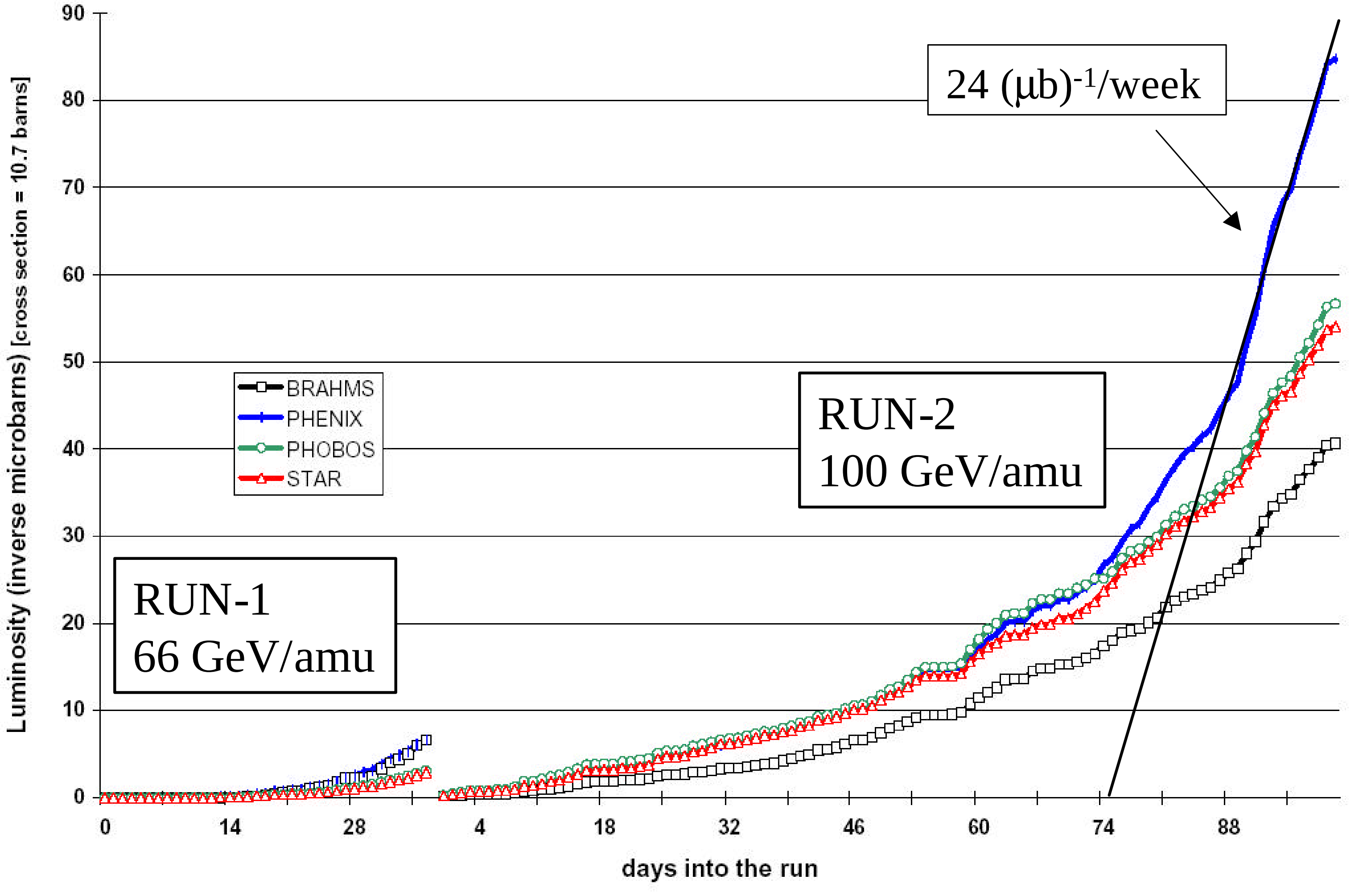
Au Injector Performance

	Intensity/RHIC bunch	Efficiency[%]
Tandem	5.4×10^9	
Booster Inj.	2.9×10^9	54
Booster Extr.	2.4×10^9	83
AGS Inj.	1.2×10^9	50
AGS Extr.	1.1×10^9	92
Total		20

Emittances: 10 π μm, 0.3-0.4 eVs/n
Limit: Beam induced gas desorption at Booster injection. (scrubbing?)



Integrated Au-Au luminosity



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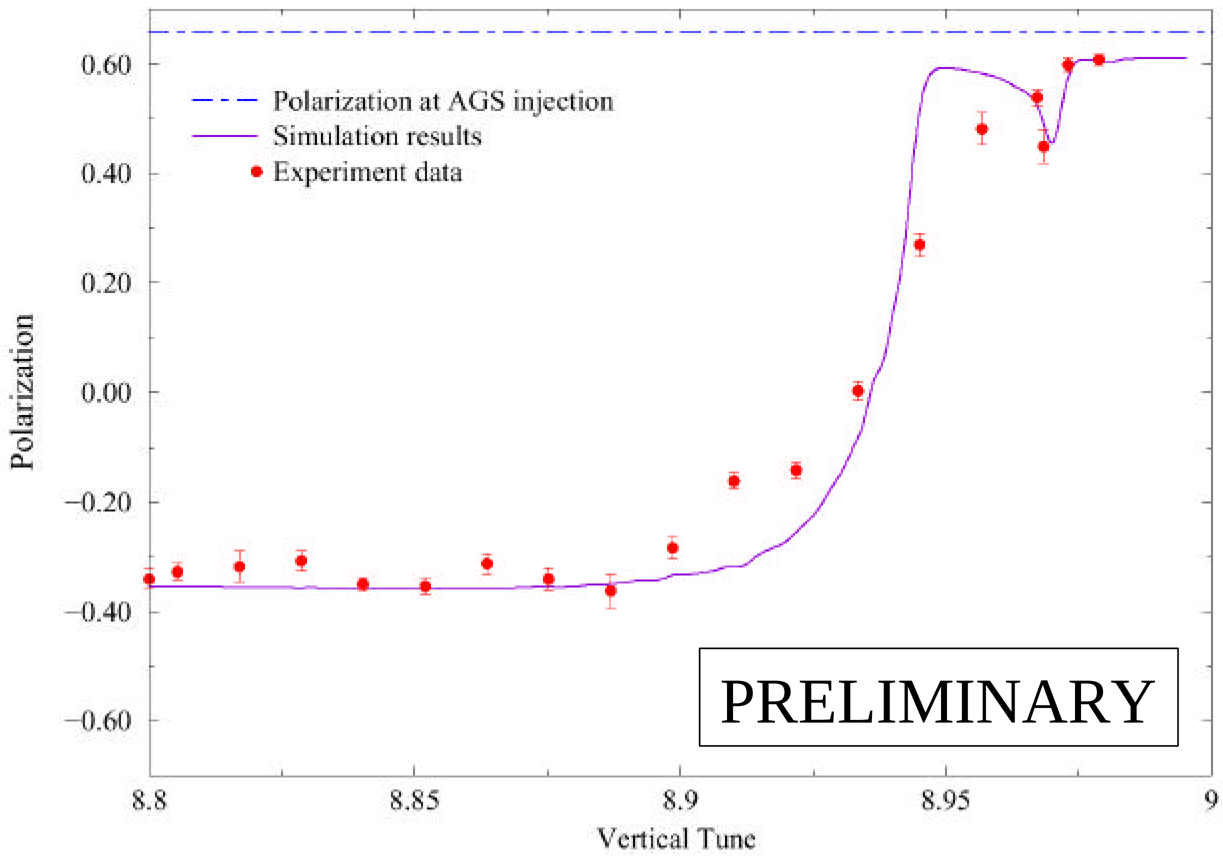
Test results with 10% snake at 0 + n

The difference between the red measurements and blue line is due to the coupling resonance and tilted stable spin direction.

Good agreement with model.



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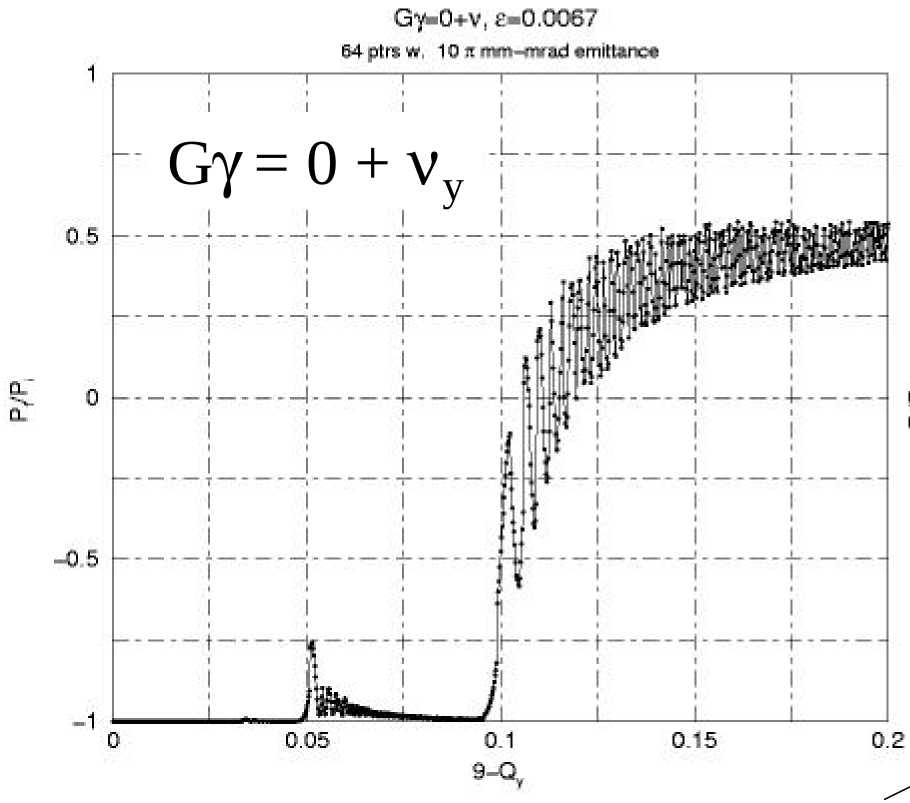
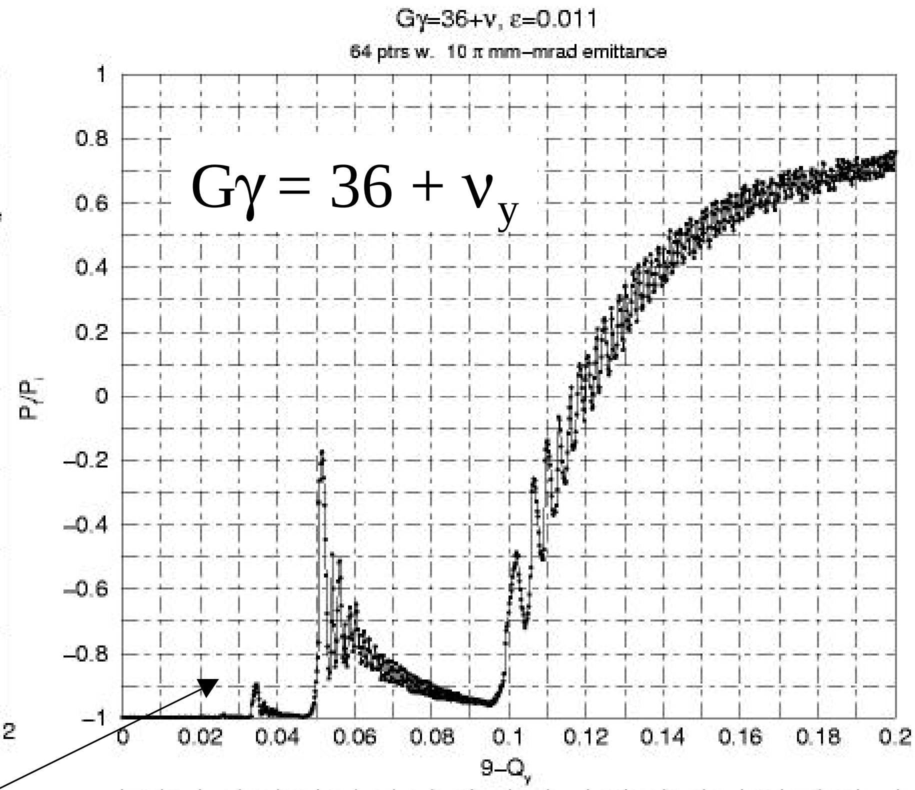
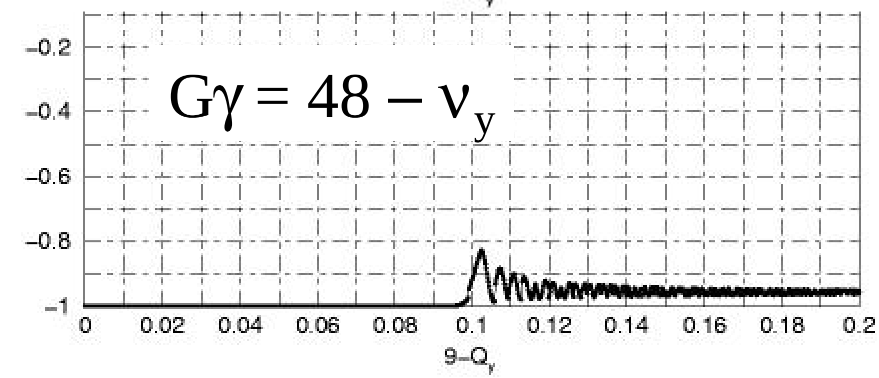
Modeling of AGS resonances with 20% Snake







"Partial Snake Resonances"
if $\nu_{sp} = n\,\nu_y$

(Tracking by M. Bai)

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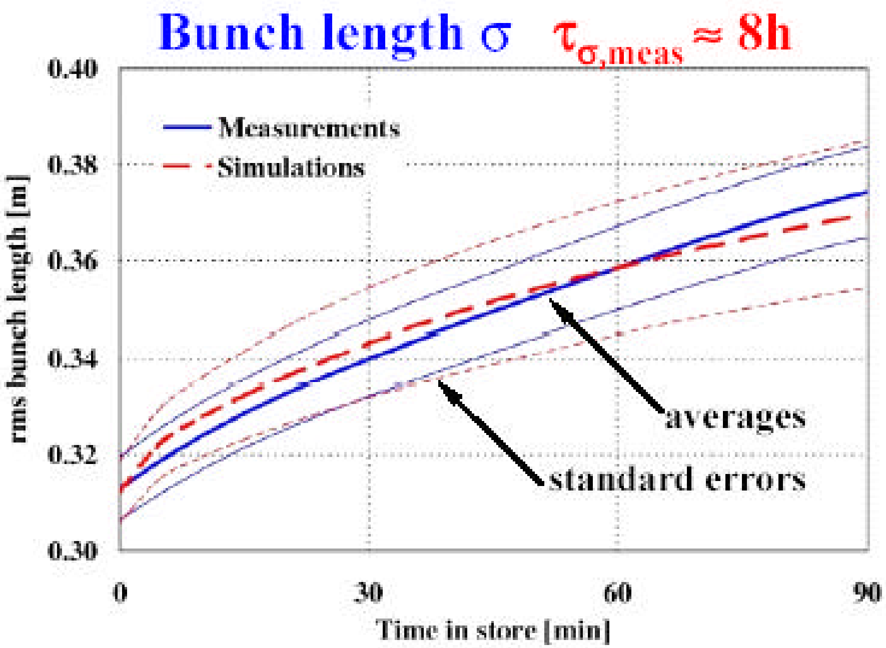
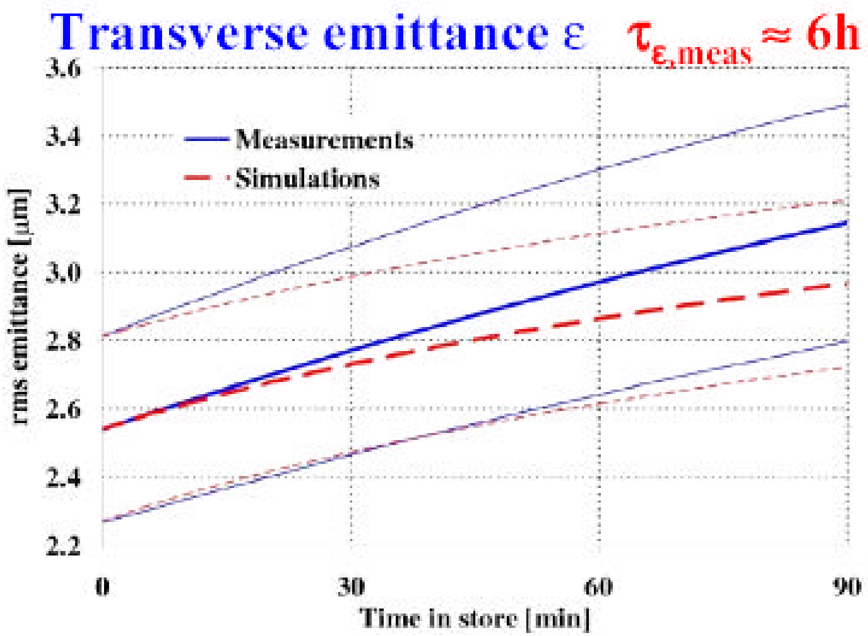
Intra-Beam Scattering (IBS) in RHIC





Longitudinal and transverse emittance growth agrees well with model

Some additional source of transverse emittance growth

IBS determines RHIC Au performance

Eventually will need electron cooling

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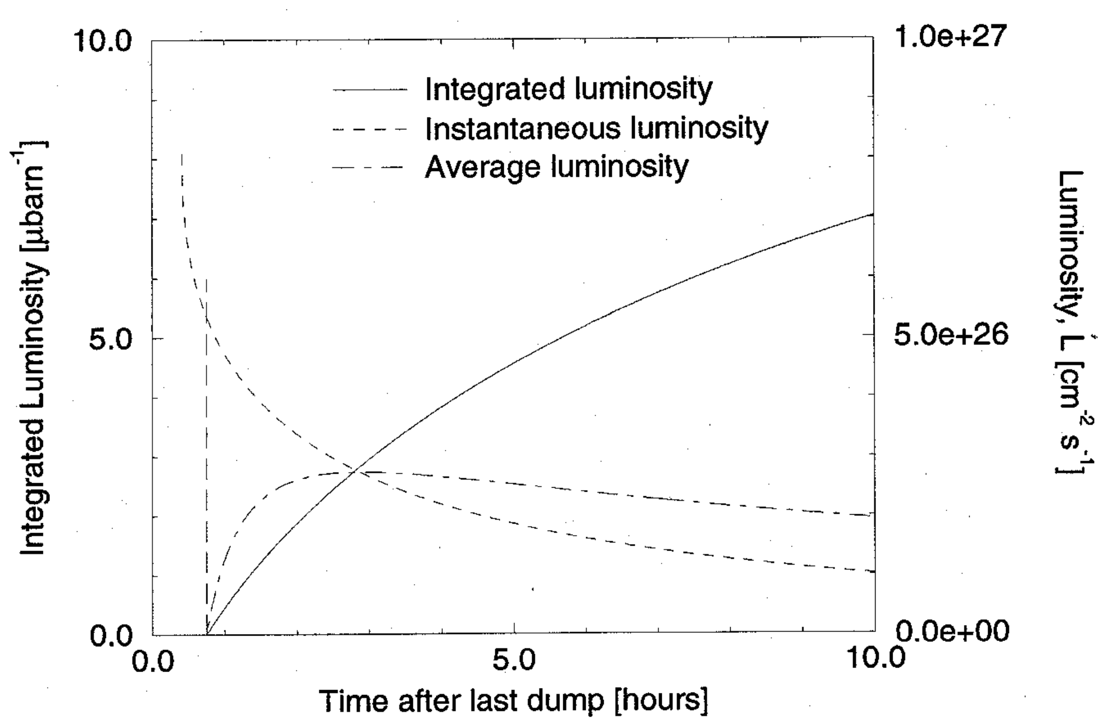
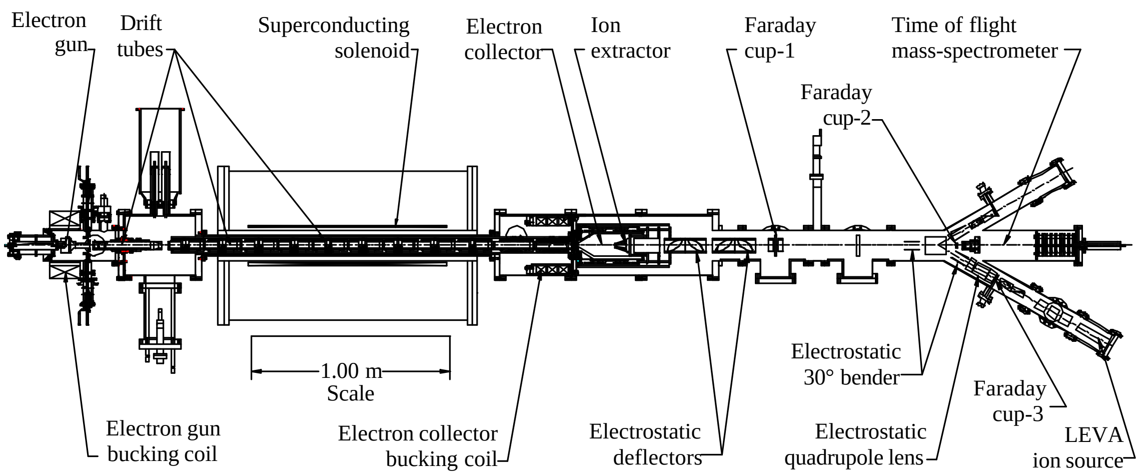
RHIC design luminosity

$$L = \frac{3 f_{rev} g}{2} \frac{N_b N^2}{e b^*} = 9 \text{ to } 1\times10^{26}\,\text{cm}^{-2}\text{s}^{-1} \text{ over 10 hours}$$

$$N_b = 56\,;\; N = 1\times10^9;\, e = 15 \text{ to } 40\text{p}\mu\text{m};\, b^* = 2\text{m}$$



Results from Test EBIS (½ of RHIC EBIS)



	RHIC Requirements	**Achieved**
E-beam current	**10 A**	**10 A**
E-beam energy	**20 keV**	**20 keV**
Yield of pos. charges	**5.5 ´ 10^{11} (Au, 10 A, 1.5m)**	**3.2 ´ 10^{11} (Au, 8 A, 0.7m)**
Pulse length	**£ 40 ms**	**20 ms**
Yield of Au^{33+}	**3.4 ´ 10^{9}**	**~ 1.5 ´ 10^{9}**
Yield of U^{45+}	**2.4 ´ 10^{9}**	

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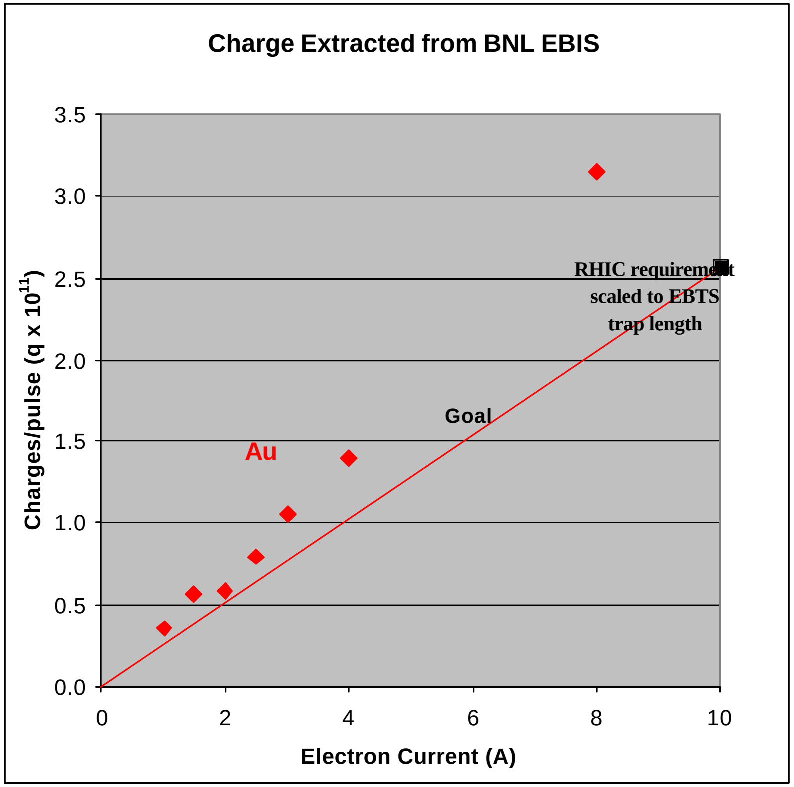
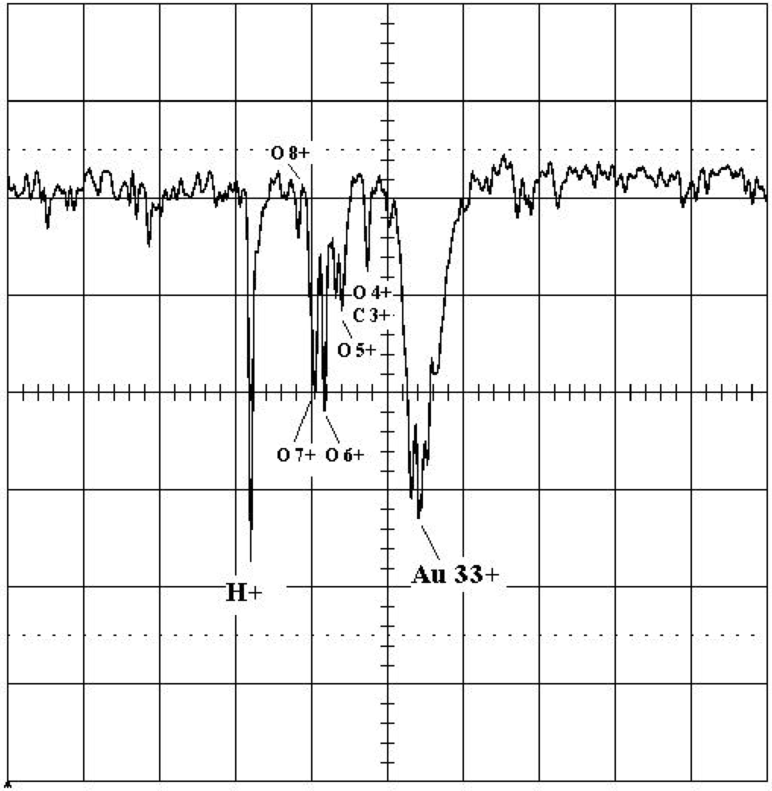


Extracted gold ion yield shows more than 50% neutralization



Gold charge state with only 40 ms confinement time.