Overview of C-AD Accelerator Complex
Motivation for Upgrades

- C-AD Accelerator Complex
- RHIC performance
  - Au-Au operations (W. Fischer)
  - d-Au operations
  - Polarized proton collisions
- RHIC II upgrade plans
- eRHIC
- AGS High Intensity Performance
- AGS intensity upgrade plans and neutrino super-beams

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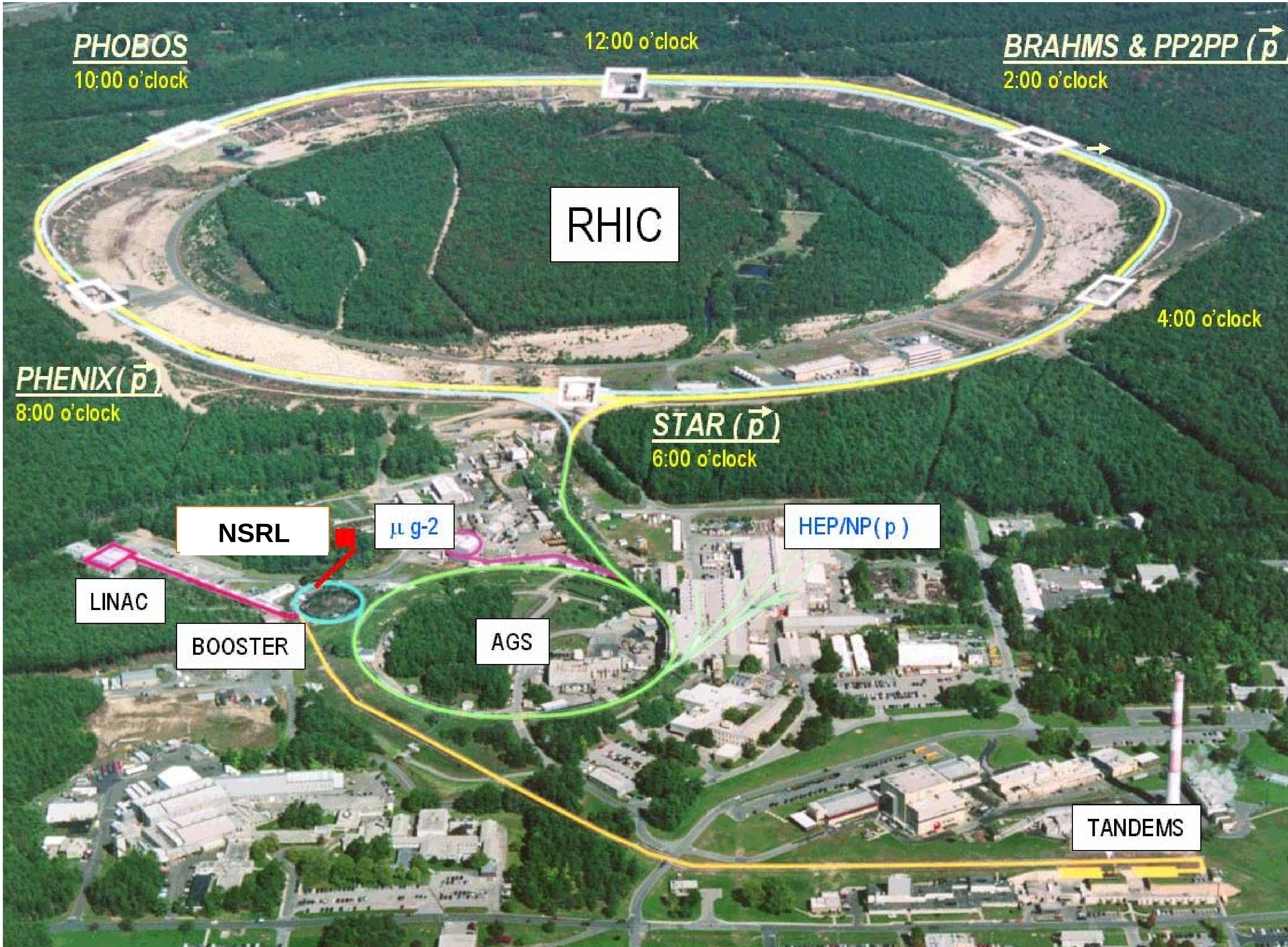
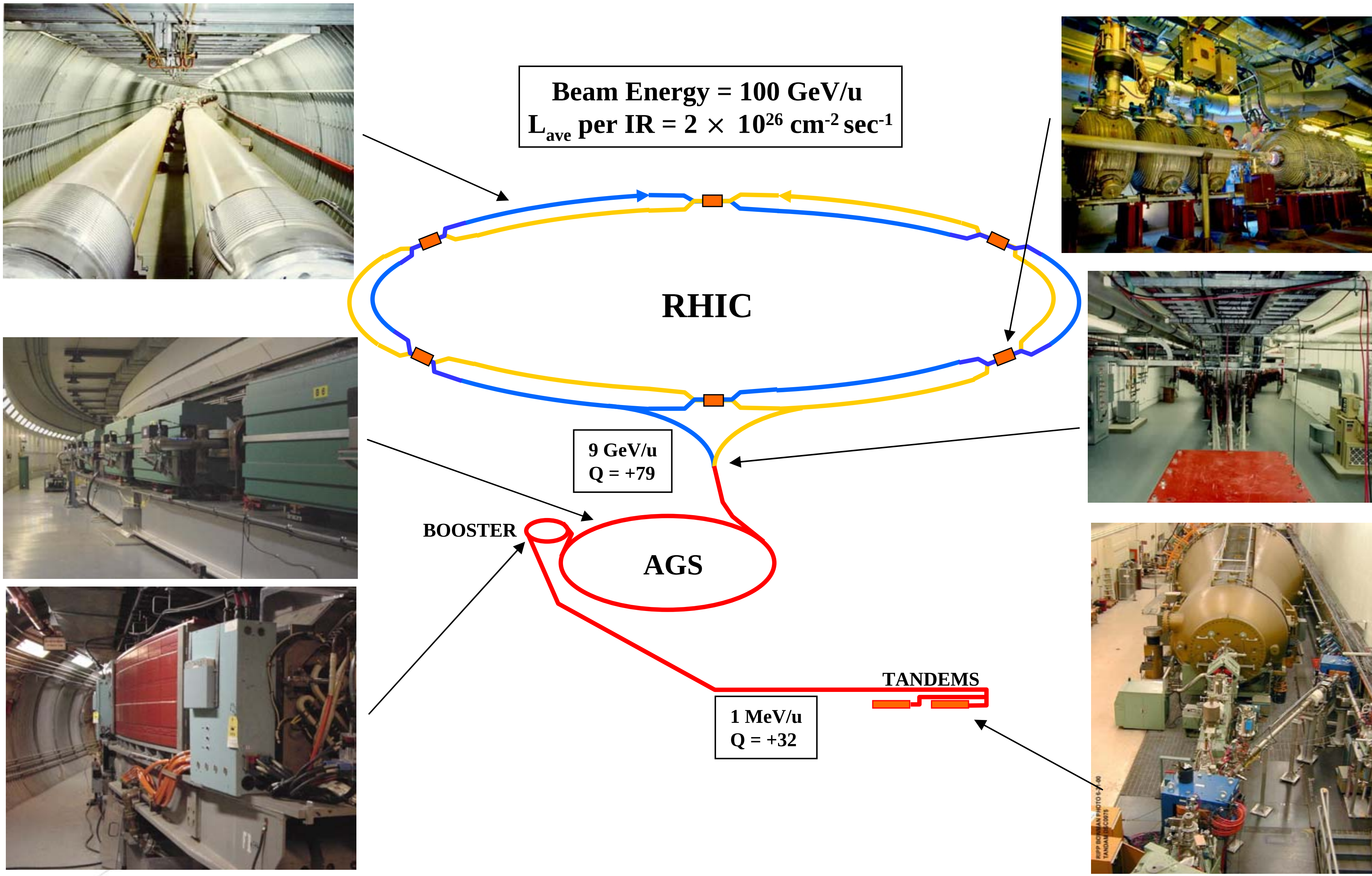
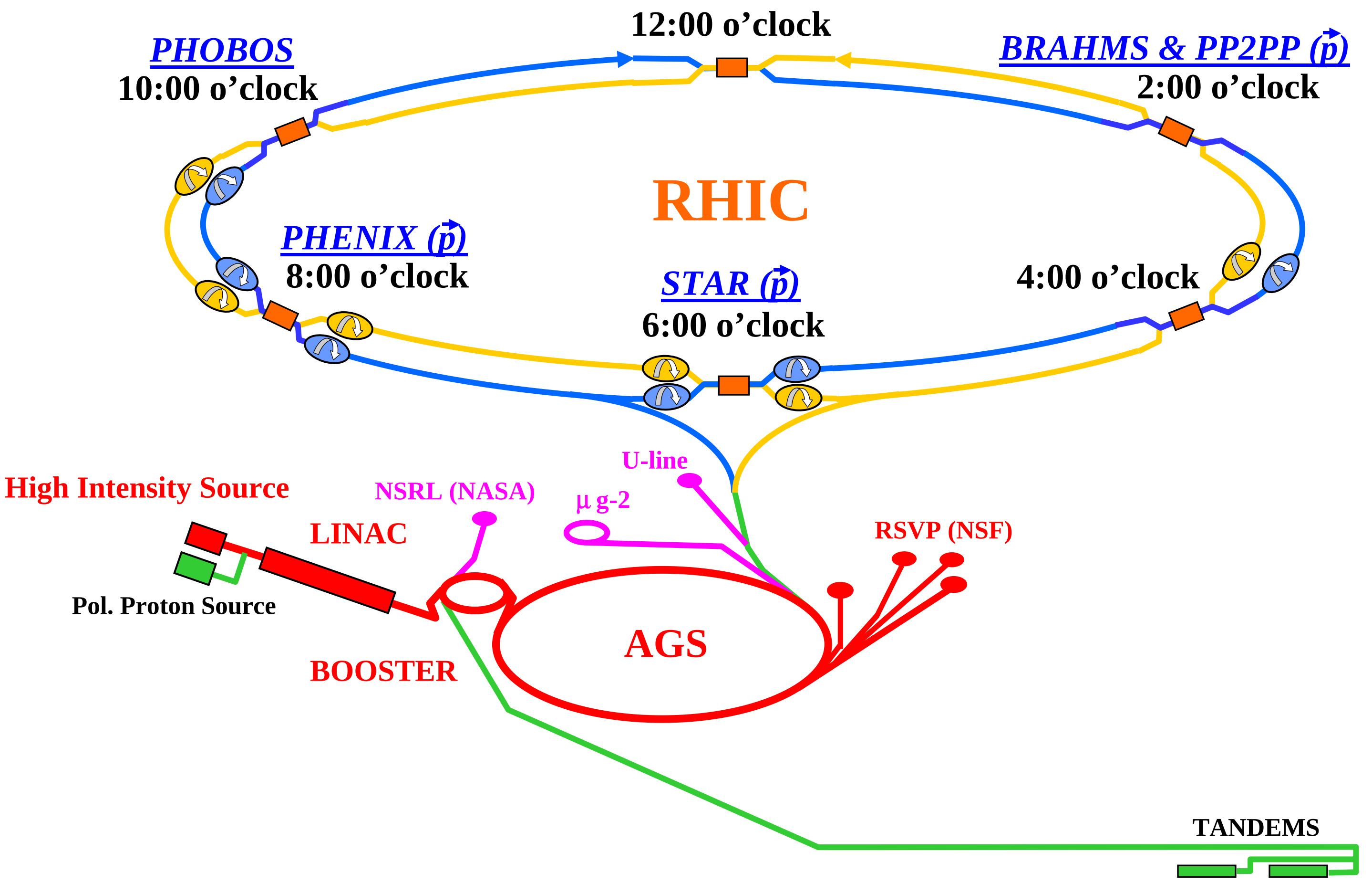
Thomas Roser
C-AD Machine Advisory Committee Meeting
March 10 - 11, 2004


PHOBOS
10:00 o'clock
12:00 o'clock
BRAHMS & PP2PP ($\vec{p}$)
2:00 o'clock
RHIC
4:00 o'clock
PHENIX($\vec{p}$)
8:00 o'clock
STAR ($\vec{p}$)
6:00 o'clock
NSRL
μ g-2
HEP/NP(p)
LINAC
BOOSTER
AGS
TANDEMS

Gold Ion Collisions in RHIC



AGS/RHIC Accelerator Complex



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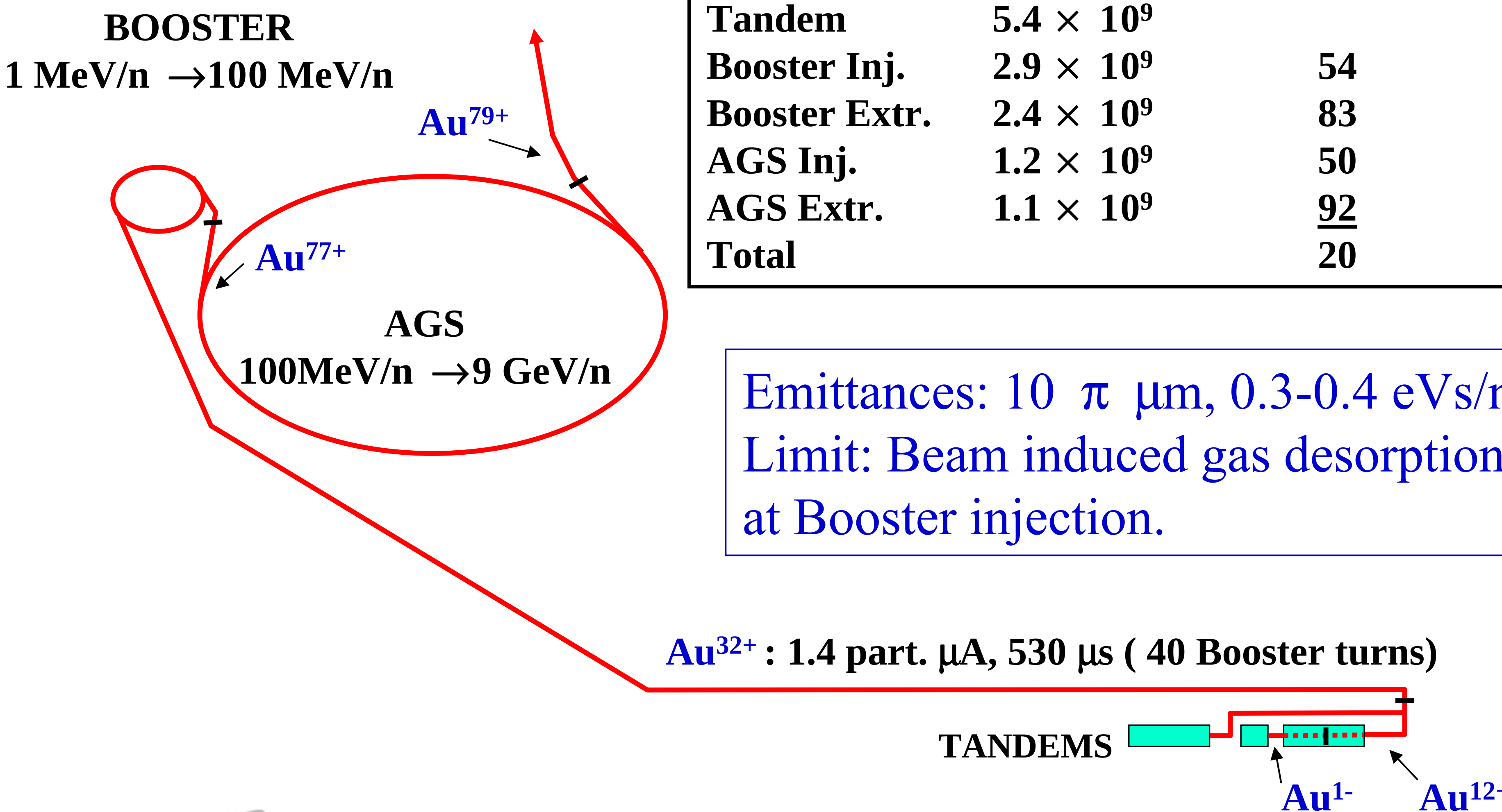
Au Injector Performance

	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: $10\ \pi\ \mu m$, 0.3-0.4 eVs/n
Limit: Beam induced gas desorption at Booster injection.



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: 18 M$; Schedule: FY2006 – 08

	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, 1.5 m)**	**3.2×10^{11} (Au, 8 A, 0.7m)**
Pulse length	**$\leq 40\ \mu s$**	**$20\ \mu s$**
Yield of Au^{33+}	**3.4×10^9**	**$\sim 1.5 \times 10^9$**
Yield of U^{45+}	**2.4×10^9**	

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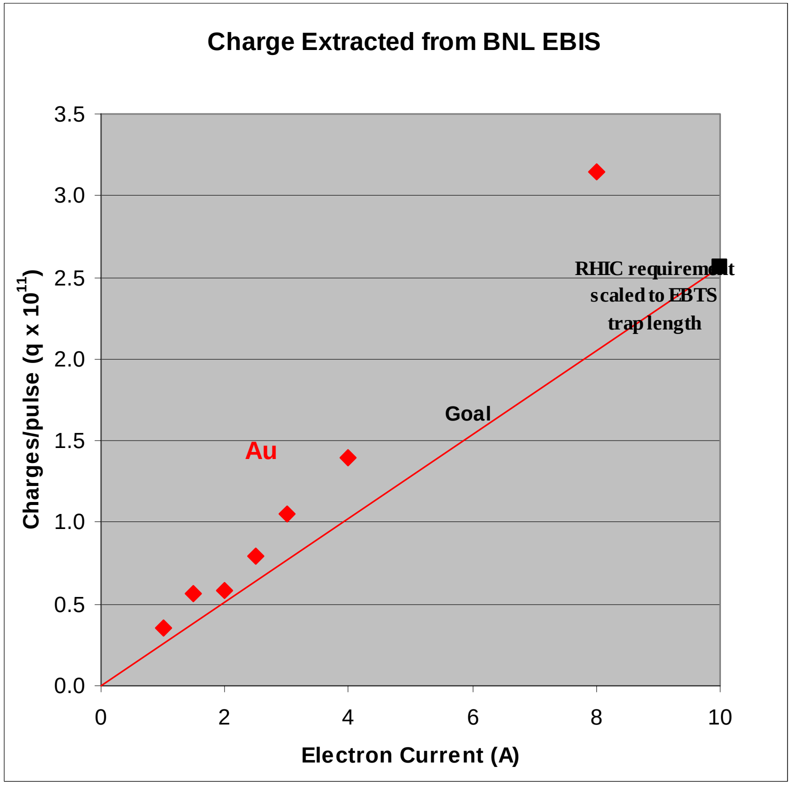
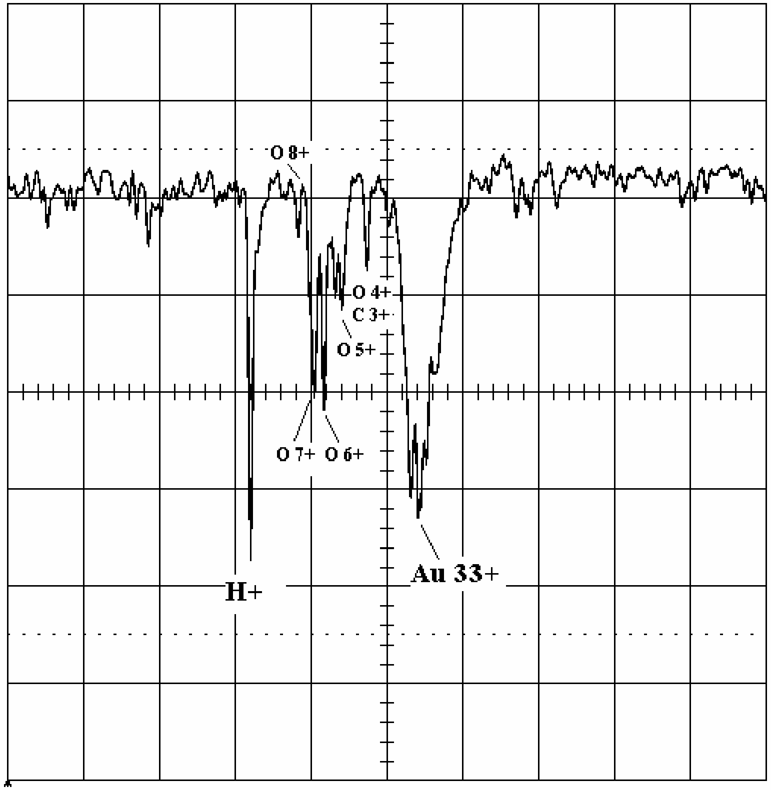
Results from Test EBIS (½ of RHIC EBIS)





Extracted gold ion yield shows more than 50% neutralization

Gold charge state with only 40 ms confinement time.

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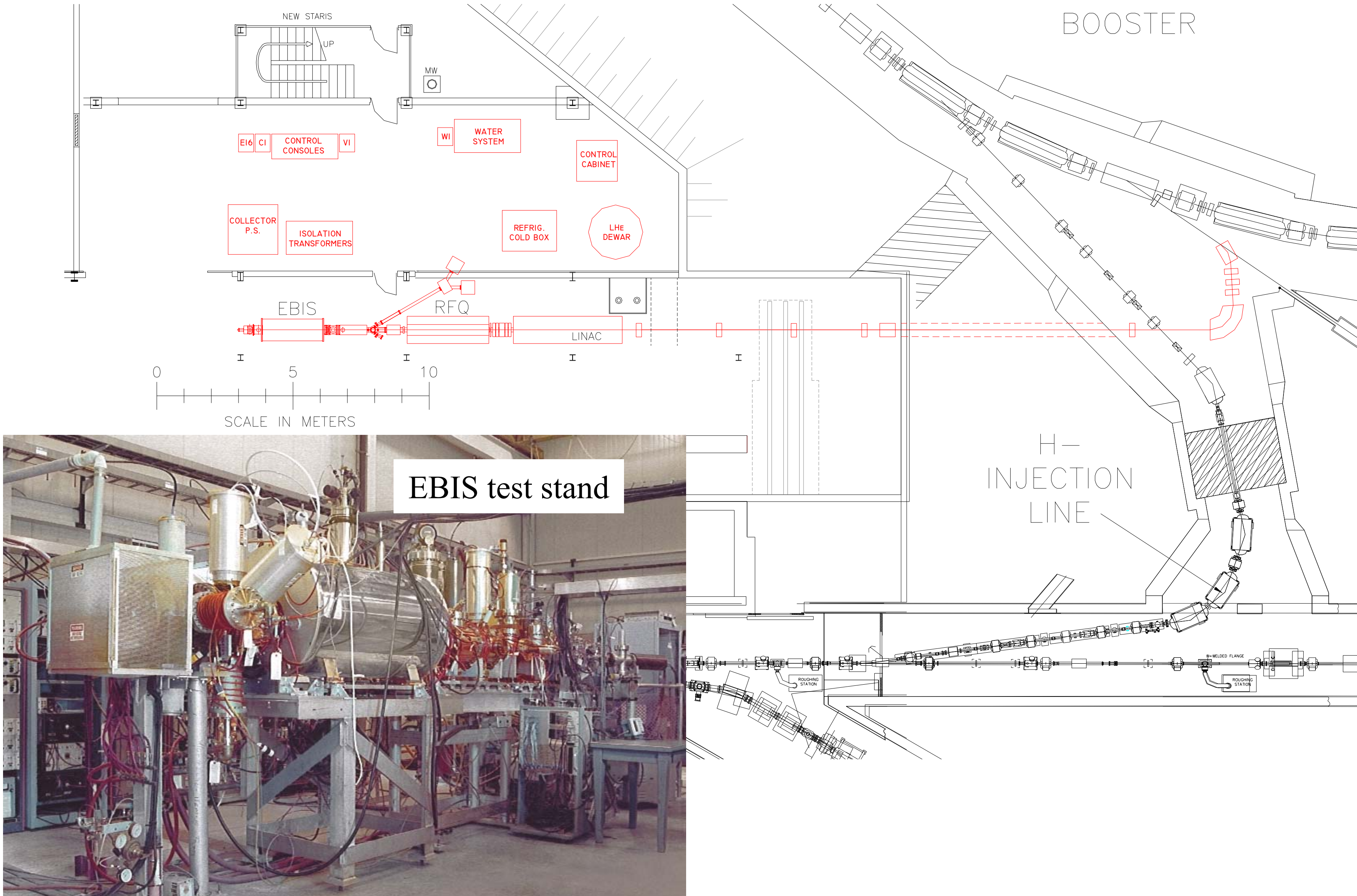
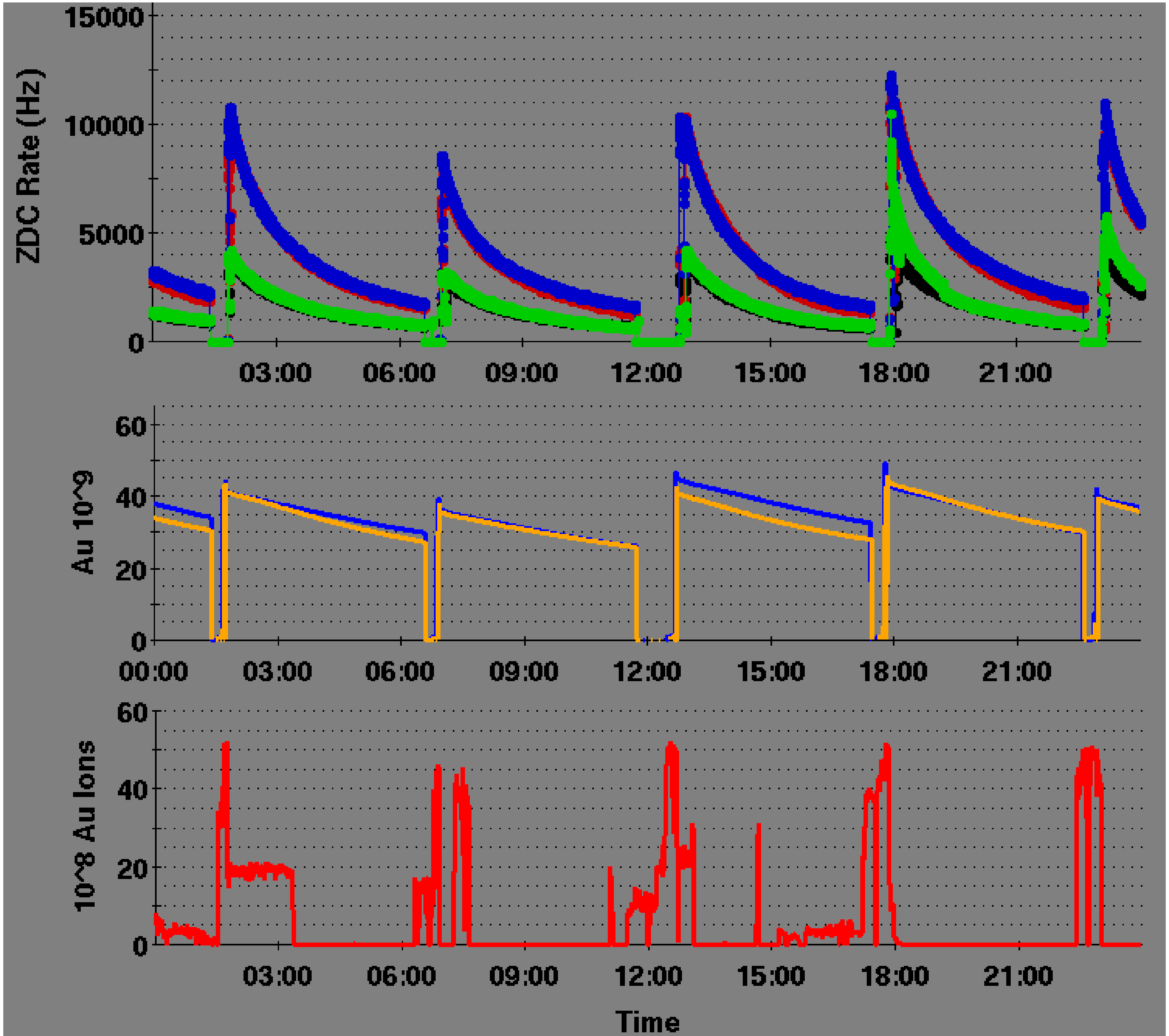
EBIS layout


NEW STARIS
UP
MW
EI6
CI
CONTROL CONSOLES
VI
WI
WATER SYSTEM
CONTROL CABINET
COLLECTOR P.S.
ISOLATION TRANSFORMERS
REFRIG. COLD BOX
LHe DEWAR
EBIS
RFQ
LINAC
0
5
10
SCALE IN METERS
BOOSTER
H–
INJECTION
LINE
EBIS test stand

A recent day of RHIC operations (Feb. 23, 2004)



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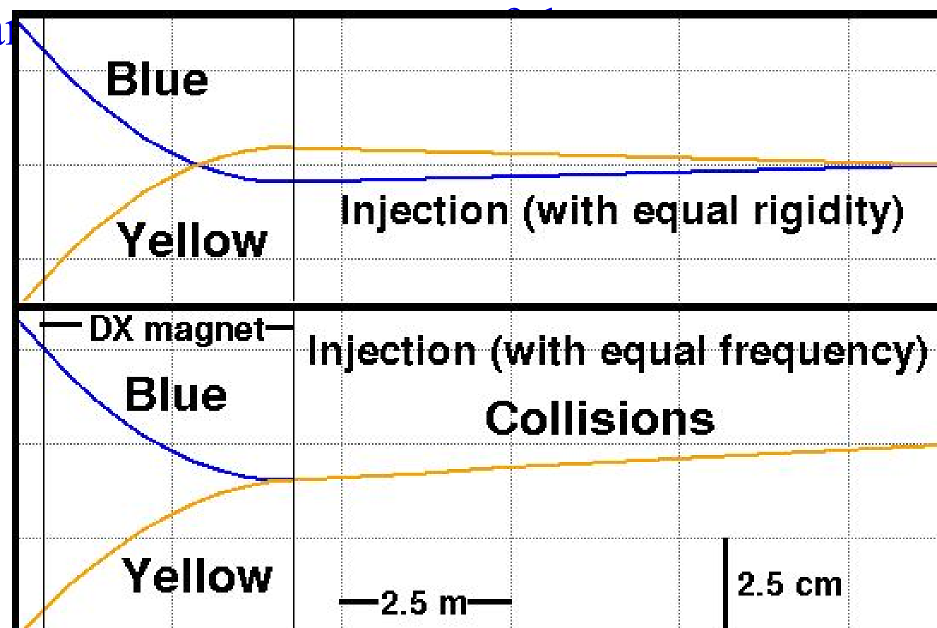
Deuteron-Gold Collisions in RHIC (RUN-3)

- 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 x 10^{11} d/bunch, ε [95%] = 12 π μm; 0.7 x 10^{9} Au/bunch, ε [95%] = 10 π μm
- Initial injection with equal rigidity failed because of beam loss from modulated beam-beam interactions during acceleration ramp
- Injection and acceleration with sa



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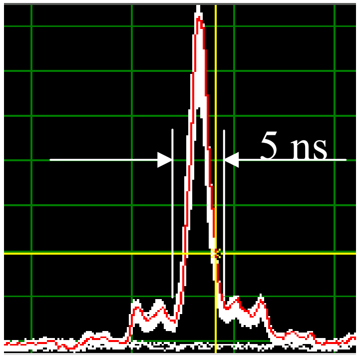
Performance summary



- Energy/beam: 100 GeV/nucl.
- Diamond length: σ = 20 cm

RHIC bunch profile

Mode	# bunches	Ions/bunch [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 (*) [Run-4]	45	1.1	1	15 - 40	14×10^{26}	4×10^{26}	150 $(\mu b)^{-1}$
d-Au (*) [Run-3]	55	110(d), 0.7(Au)	2	15	7×10^{28}	2.0×10^{28}	4.5 $(nb)^{-1}$
p↑ -p↑ (*) [Run-3]	55	70	1	20 - 30	6×10^{30}	3×10^{30}	0.6 $(pb)^{-1}$
Au-Au RHIC design	56	1	2	15 - 40	9×10^{26}	2×10^{26}	50 $(\mu b)^{-1}$
Au-Au enh. lumi.	112	1	1	15 - 40	36×10^{26}	8×10^{26}	200 $(\mu b)^{-1}$
p-p RHIC design	56	100	2	20	5×10^{30}	4×10^{30}	1.2 $(pb)^{-1}$
p↑ -p↑ RHIC spin	112	200	1	20	80×10^{30}	65×10^{30}	20$(pb)^{-1}$

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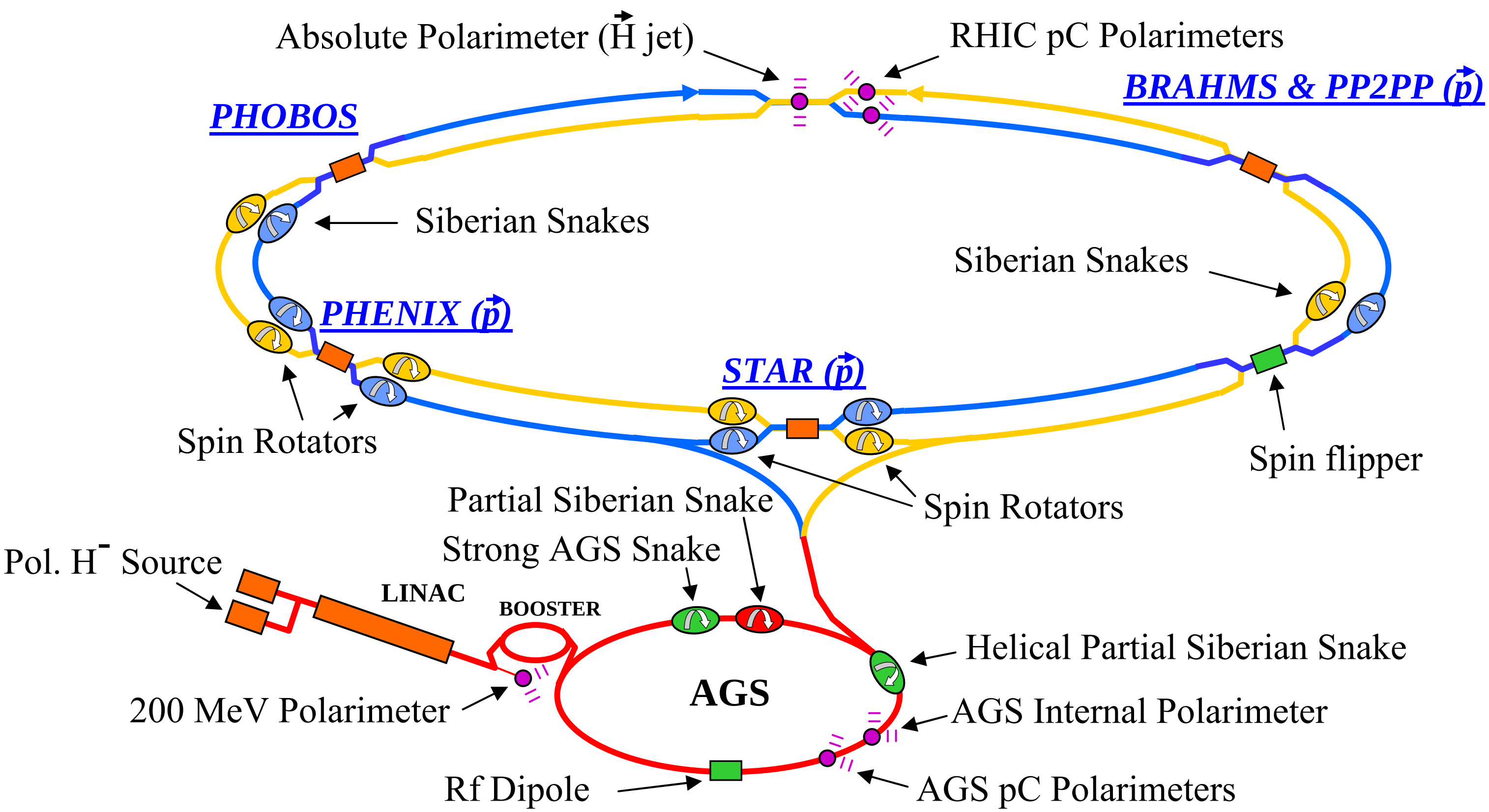
[(*) Best store or week]

Polarized Proton Collisions in RHIC



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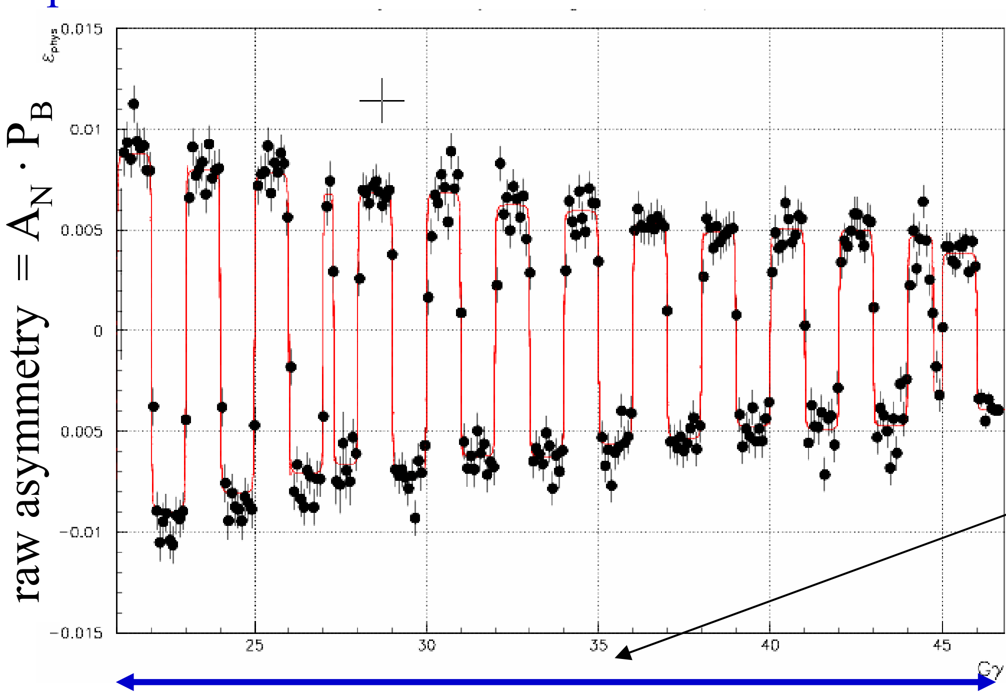
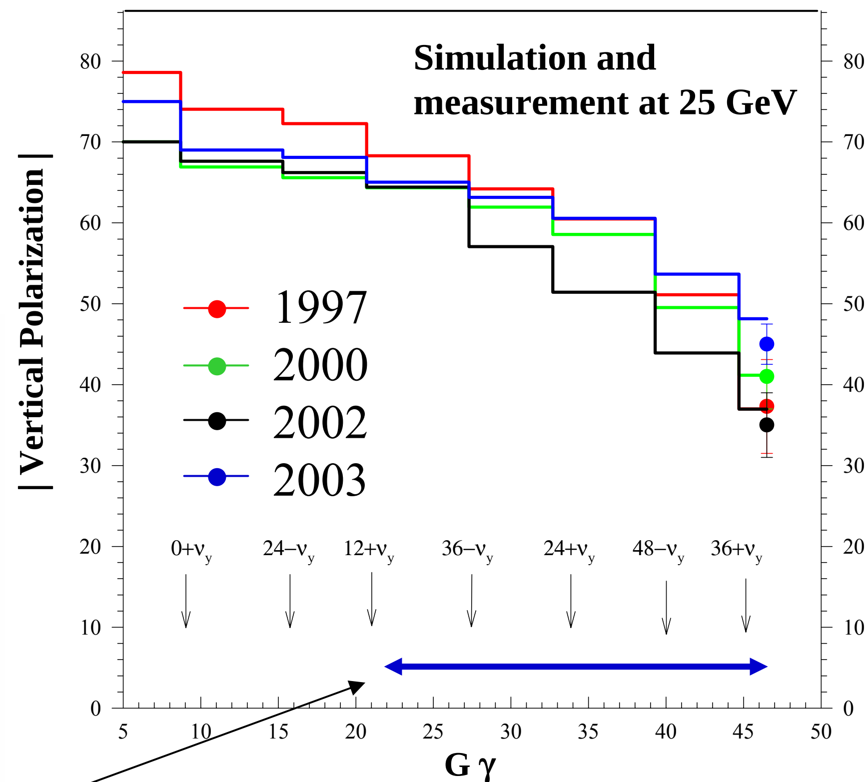
Proton polarization at the AGS

- 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. (Install. 1/04)
- To avoid all depolarization in AGS build strong AGS helical Siberian snake! (Installation: 10/04)

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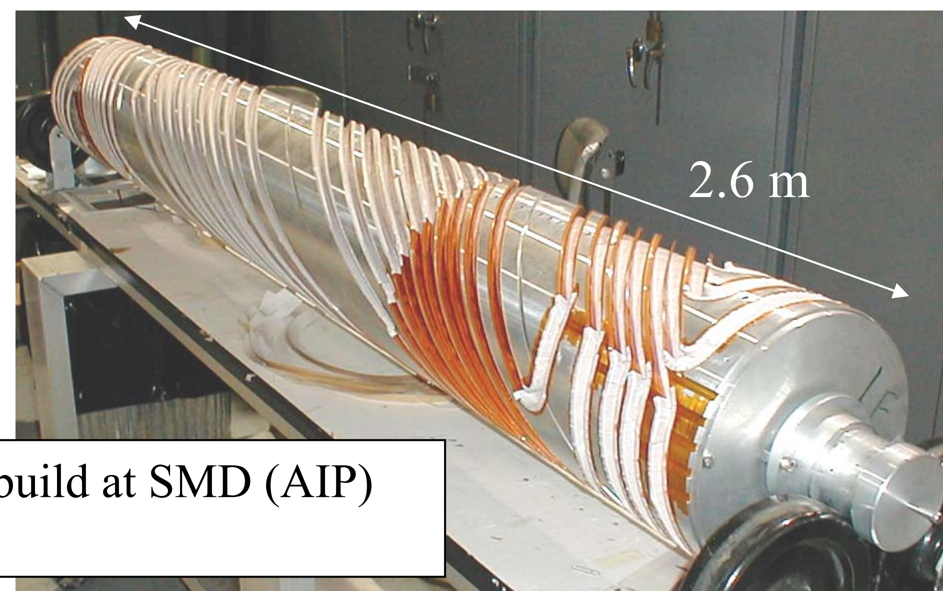
New AGS helical snakes

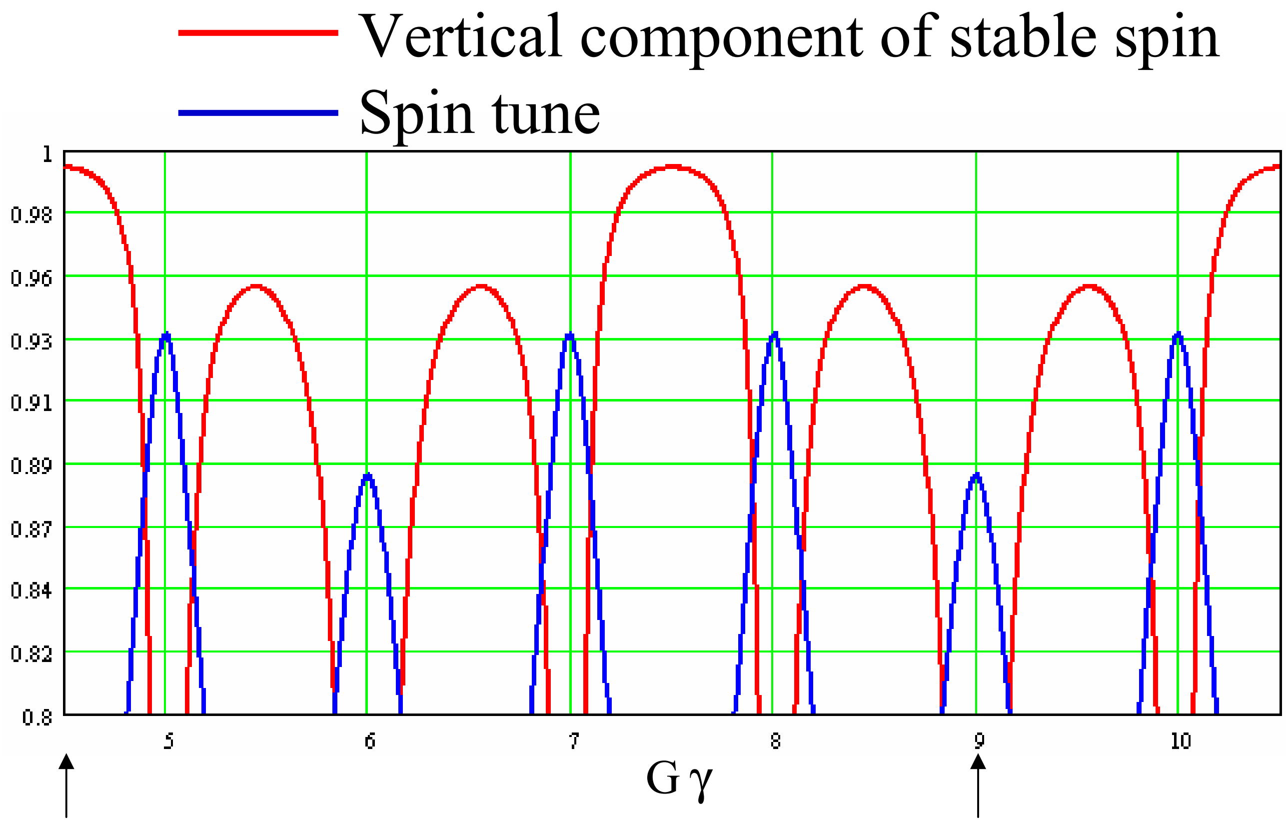
5 % helical snake build at Tokana Industries funded by RIKEN. Installation: Jan. 2004.

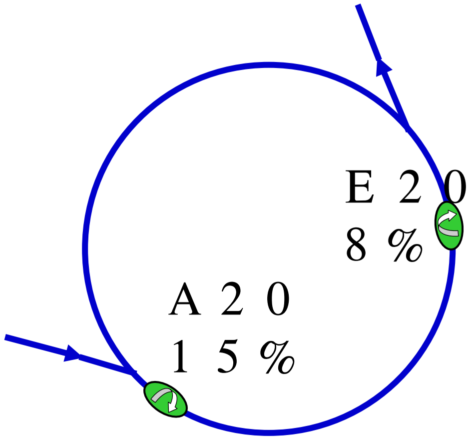
- Cold strong snake eliminates all depolarizing resonances in AGS.
- Warm snake avoids polarization mismatch at AGS injection and extraction.



30% s.c. helical snake build at SMD (AIP)
Installation: Oct. 2005

2 Partial Siberian Snakes in AGS



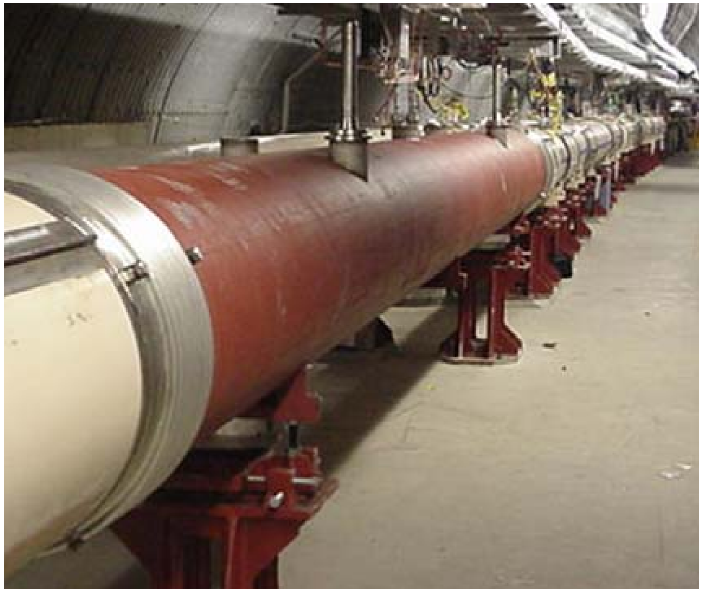


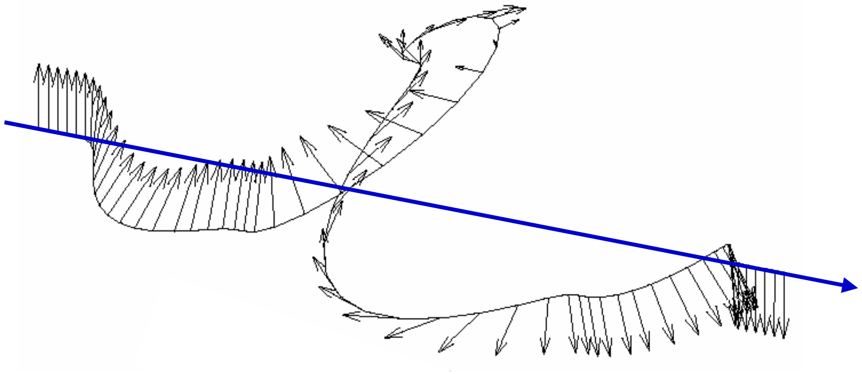
Injection

First intrinsic resonance (0+ν)

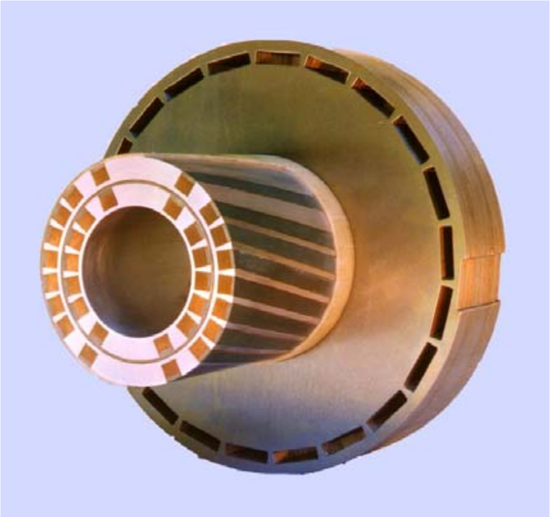
Siberian Snake in RHIC Tunnel

Siberian Snake: 4 superconducting helical dipoles, 4Tesla, 2.4 m long with full 360 ° twist





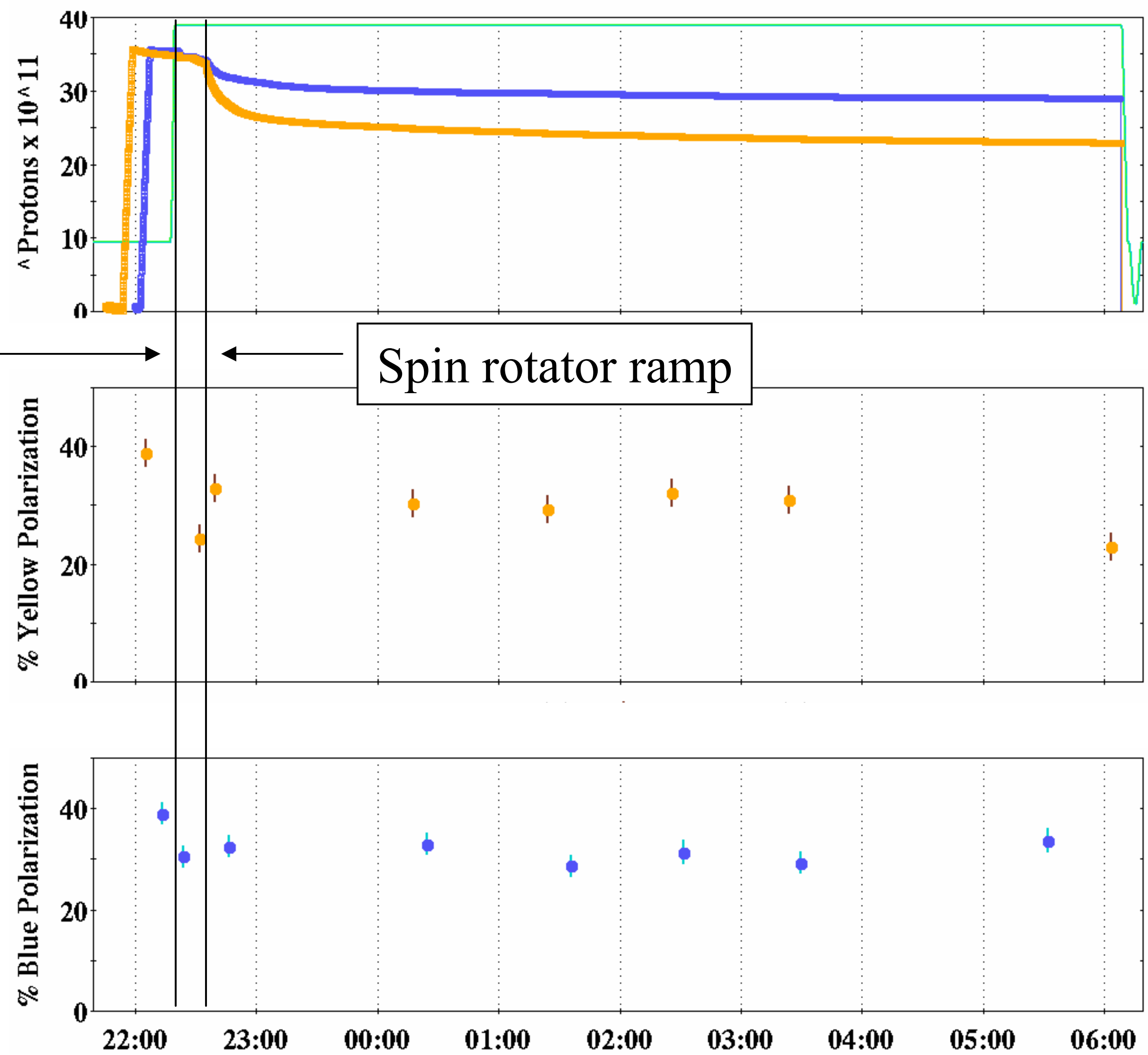
Funded by RIKEN, Japan
Designed and constructed at BNL



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 at ½ during acceleration.

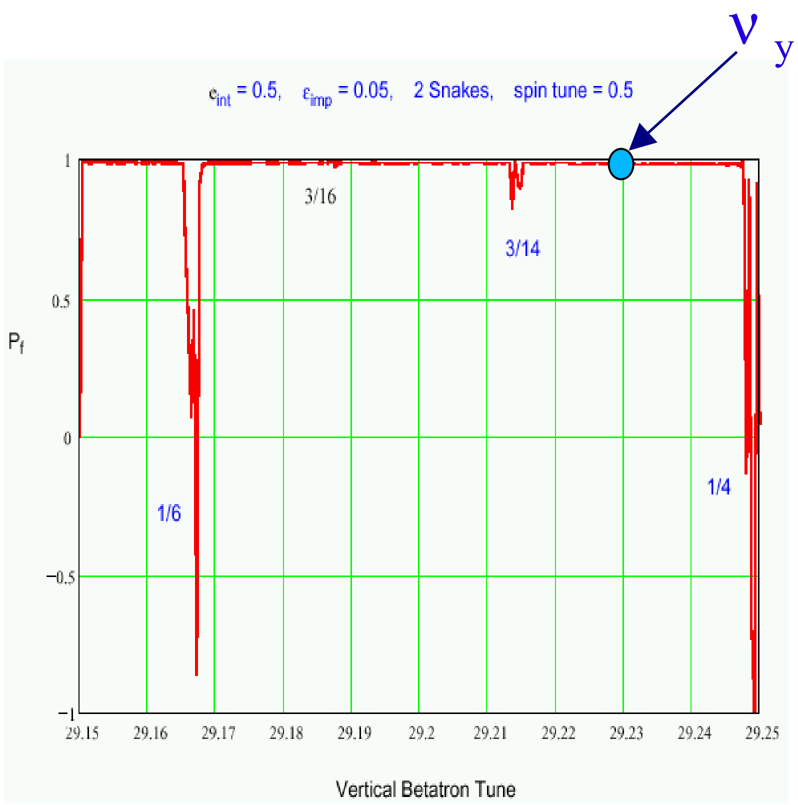
The vertical tune was chosen at 0.23, between 2 high-order spin resonances:

- 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.

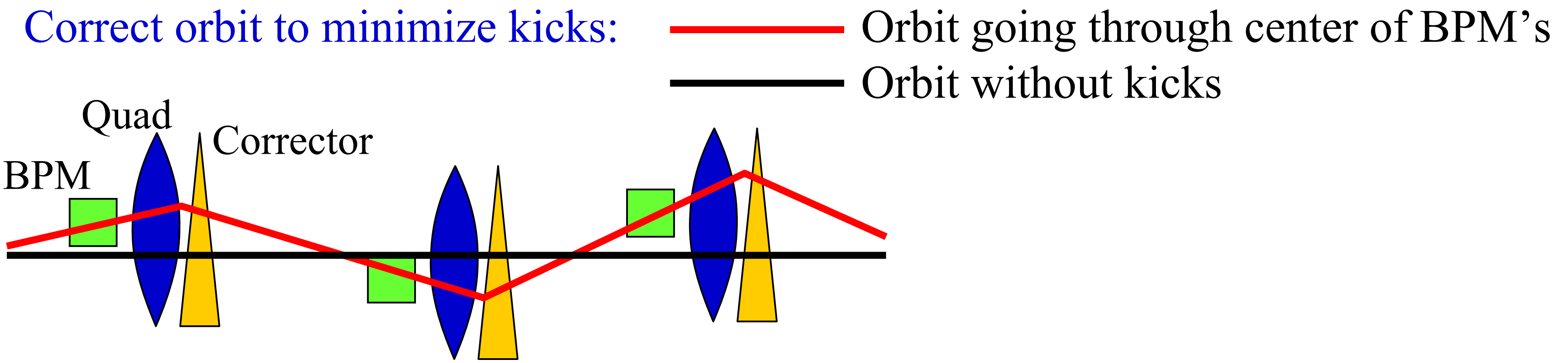
The special vertical orbit, "really" flat was used as the ideal orbit

- 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”

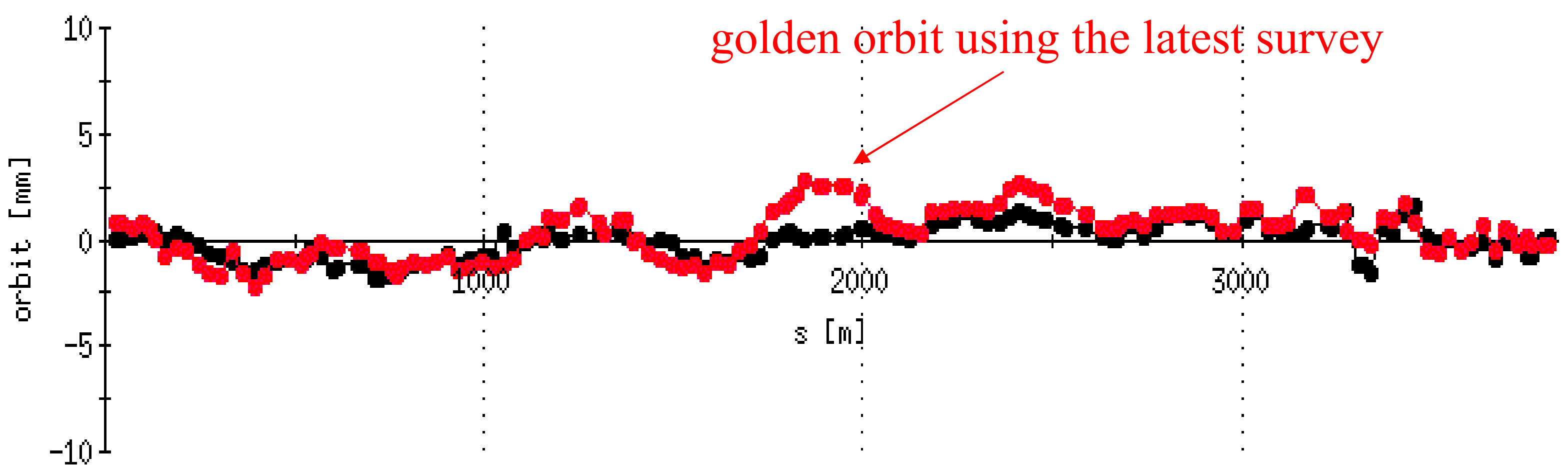


Ideal Orbit for Polarization

Correct orbit to minimize kicks:



Yellow vertical orbit flattened based on survey:



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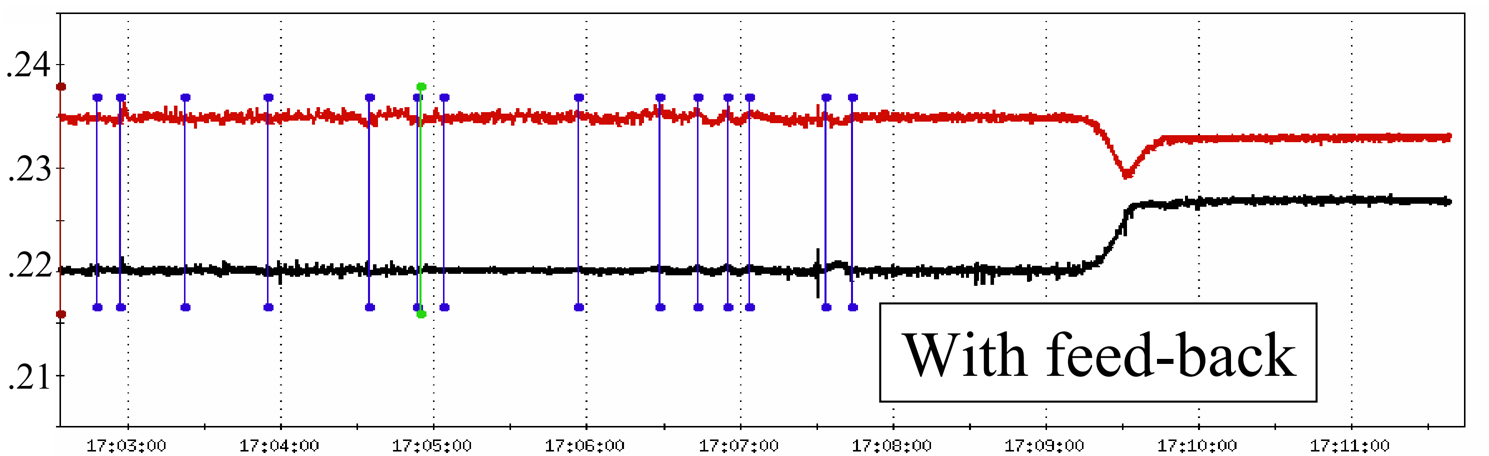
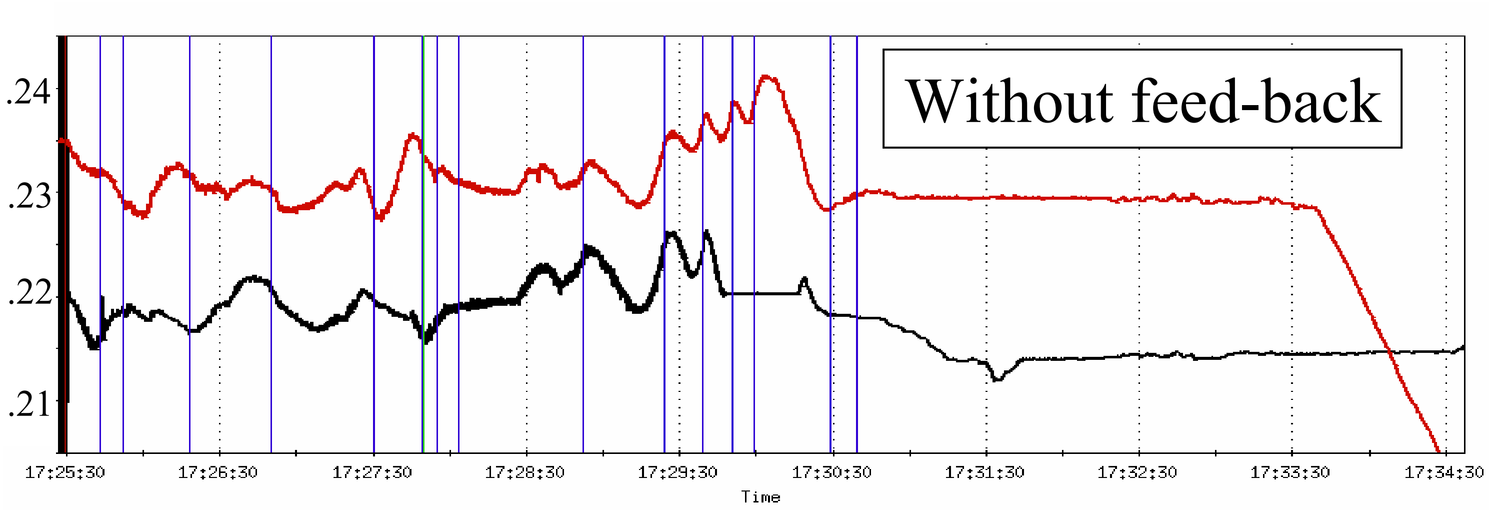
Proton Ramp with Tune Feedback





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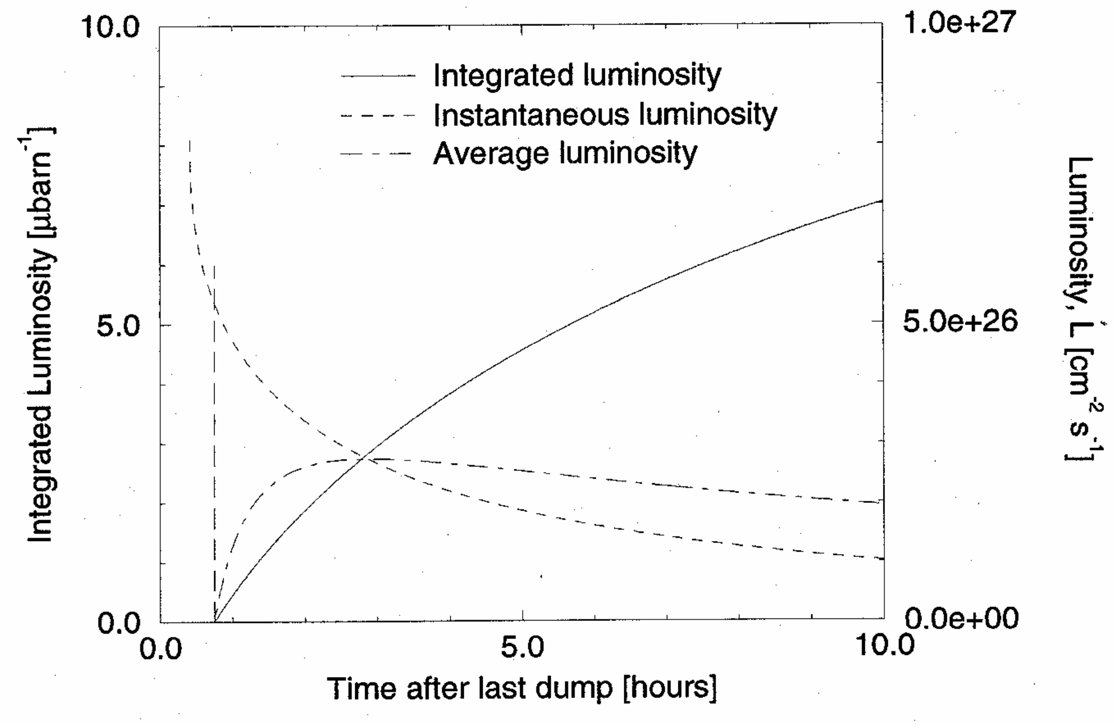
RHIC design luminosity

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

$$N_b = 56\,;\ N = 1\times10^9;\ \varepsilon = 15 \text{ to } 40\pi\mu\text{m};\ \beta^* = 2\text{m}$$



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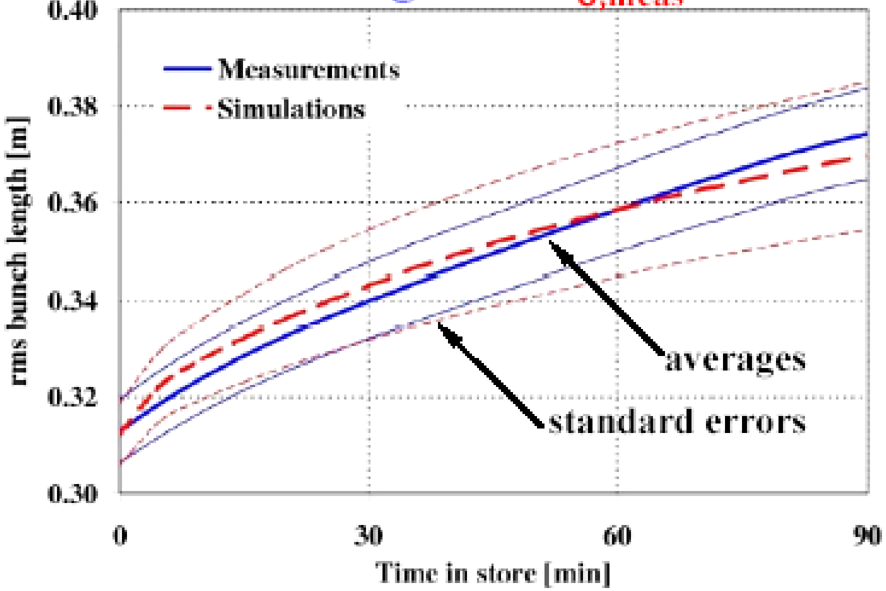
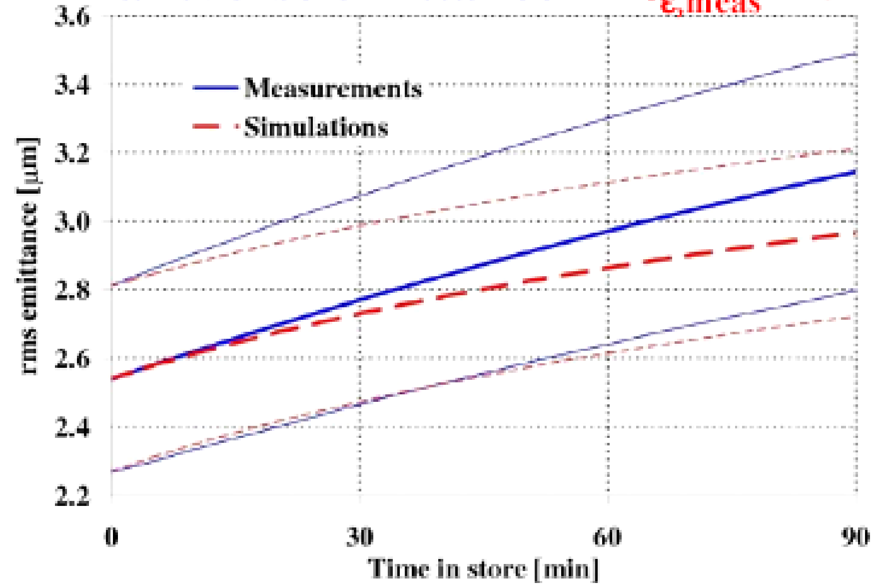
Intra-Beam Scattering (IBS) in RHIC

Bunch length σ $\tau_{\sigma,meas} \approx 8h$



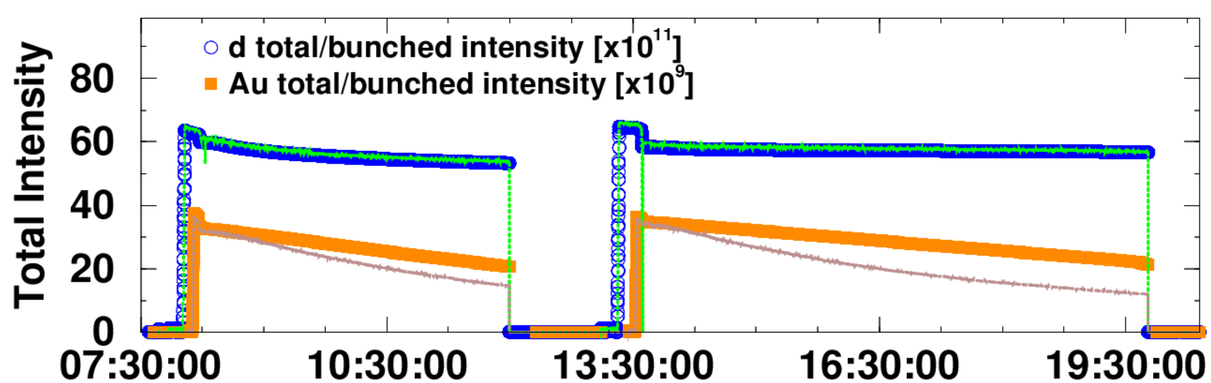
Transverse emittance ε $\tau_{\varepsilon,meas} \approx 6h$



Longitudinal and transverse emittance growth agrees well with model

Some additional source of transverse emittance growth

Deuteron and gold beams are different because of IBS



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RHIC II luminosity upgrade

Eliminate beam blow-up from intra-beam scattering with electron beam cooling at full energy!

What will remain the same:

- 120 bunch pattern
  - 100 ns collision spacing (~ same data acquisition system)
  - Only one beam collision between DX magnets
- 20 m magnet-free space for detectors
  - No "mini-beta" quadrupoles
- Approx. the same bunch intensity
  - No new vacuum or instability issues
  - Background similar as before upgrade

What changes:

- Smaller transverse and longitudinal emittance
  - Smaller vertex region
- Beta squeeze during store to level luminosity
- Store length is limited to ~ 5 hours by "burn-off" due to Au-Au interactions (~ 200 b)

RHIC electron cooling

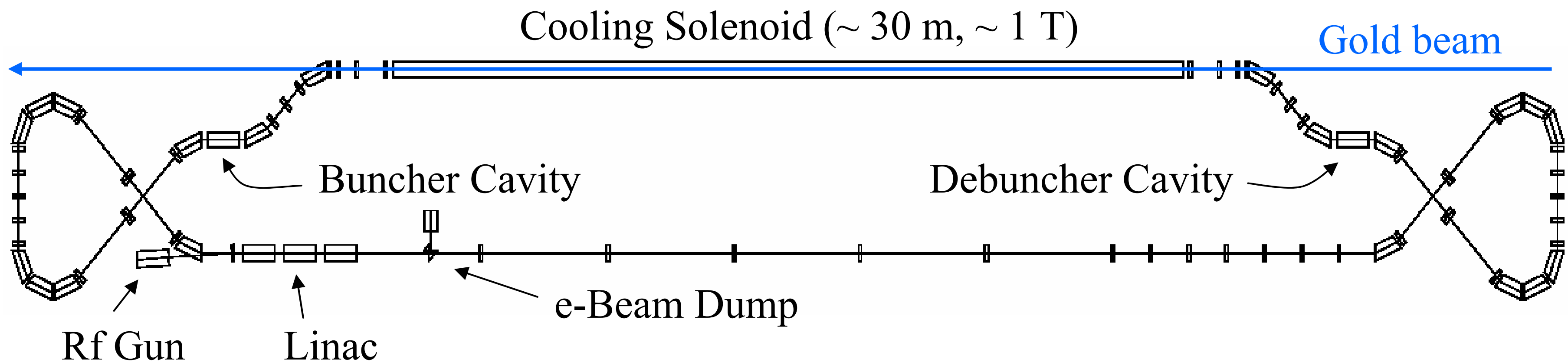
- Au ions in RHIC are 100 times more energetic than in a typical cooler ring. Relativistic factors slow the cooling by a factor of γ^2. Cooling power needs to be a factor of γ^2 higher than typical.

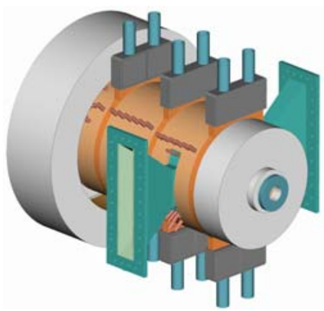
- Bunched electron beam requirements for 100 GeV/u gold beams: E = 54 MeV, <I> ~ 100 mA, electron beam power: ~ 5 MW!

- 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

RHIC Electron Cooler R&D

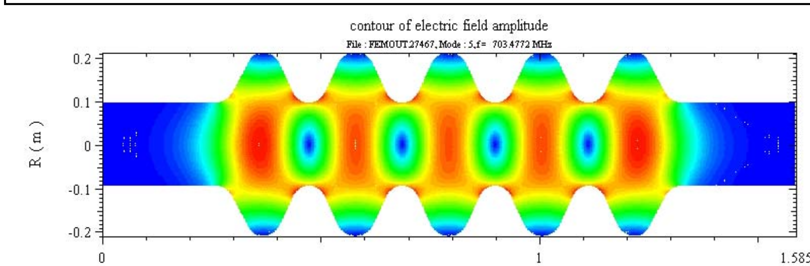


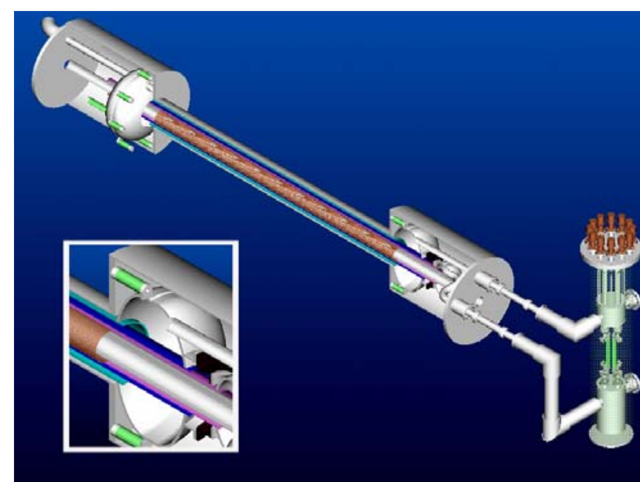


Demonstrate 10 nC, 100 – 300 mA CW rf photo-cathode electron gun:
High power, 700 MHz 2.5 cell cavity (collab. with LANL, AES)

Demonstrate high precision (10 ppm) solenoid

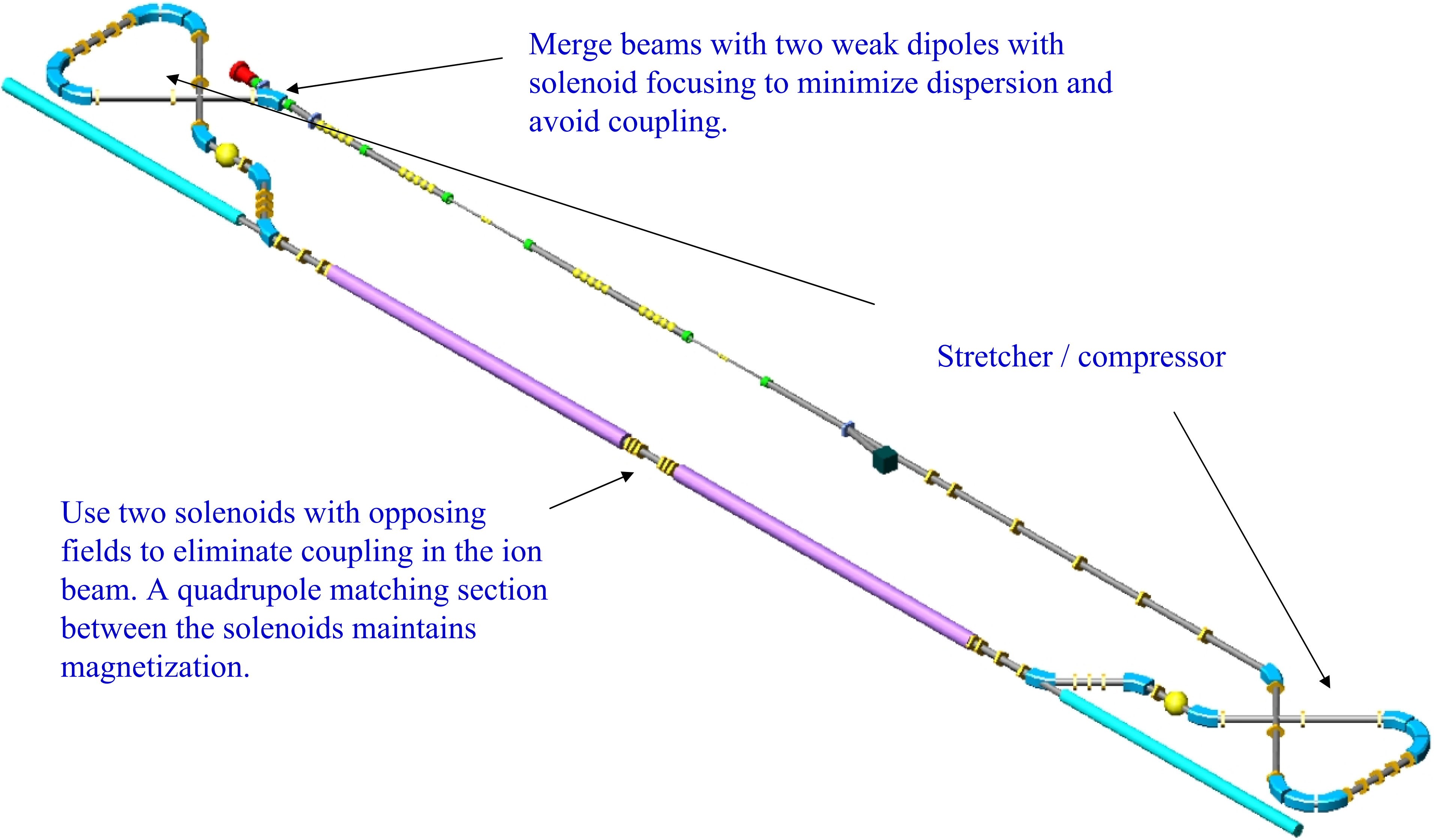
Develop CW s.c. cavity for high intensity beams:
Large bore, 700 MHz cavity with ferrite HOM dampers and high beam break-up threshold (collab. with Jlab, AES)





Electron Cooler Beam Dynamics R&D

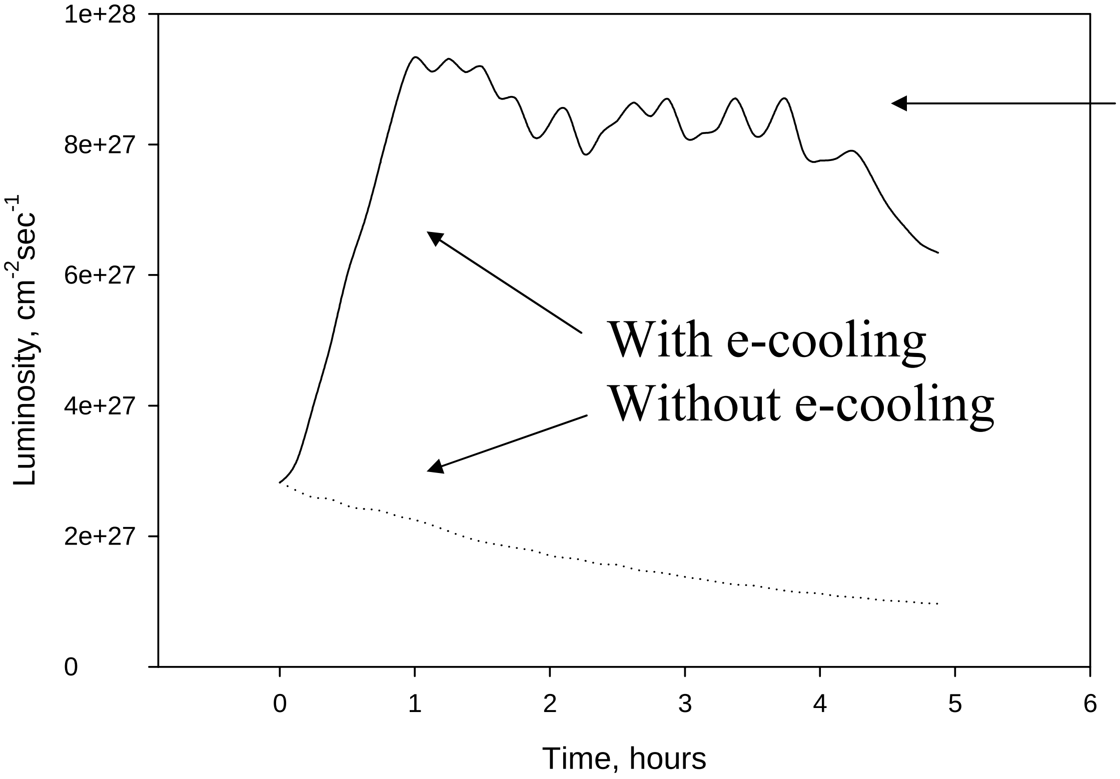
Merge beams with two weak dipoles with solenoid focusing to minimize dispersion and avoid coupling.



Stretcher / compressor

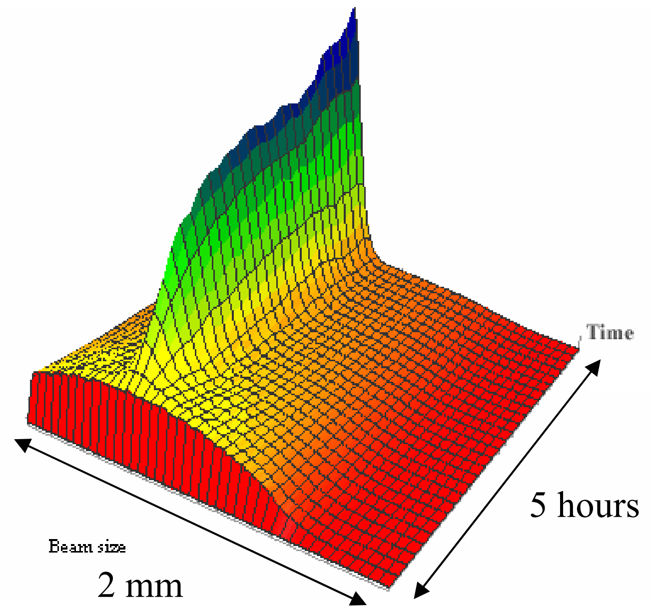
Use two solenoids with opposing fields to eliminate coupling in the ion beam. A quadrupole matching section between the solenoids maintains magnetization.

RHIC Luminosity with and without Cooling



Luminosity leveling through continuous cooling and beta squeeze
Store length limited by "burn-off"

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
Ave. store 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 ?
Ave. store luminosity [10^{32} cm^{-2} s^{-1}]	1.5	5.0

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Stochastic Beam Cooling at RHIC

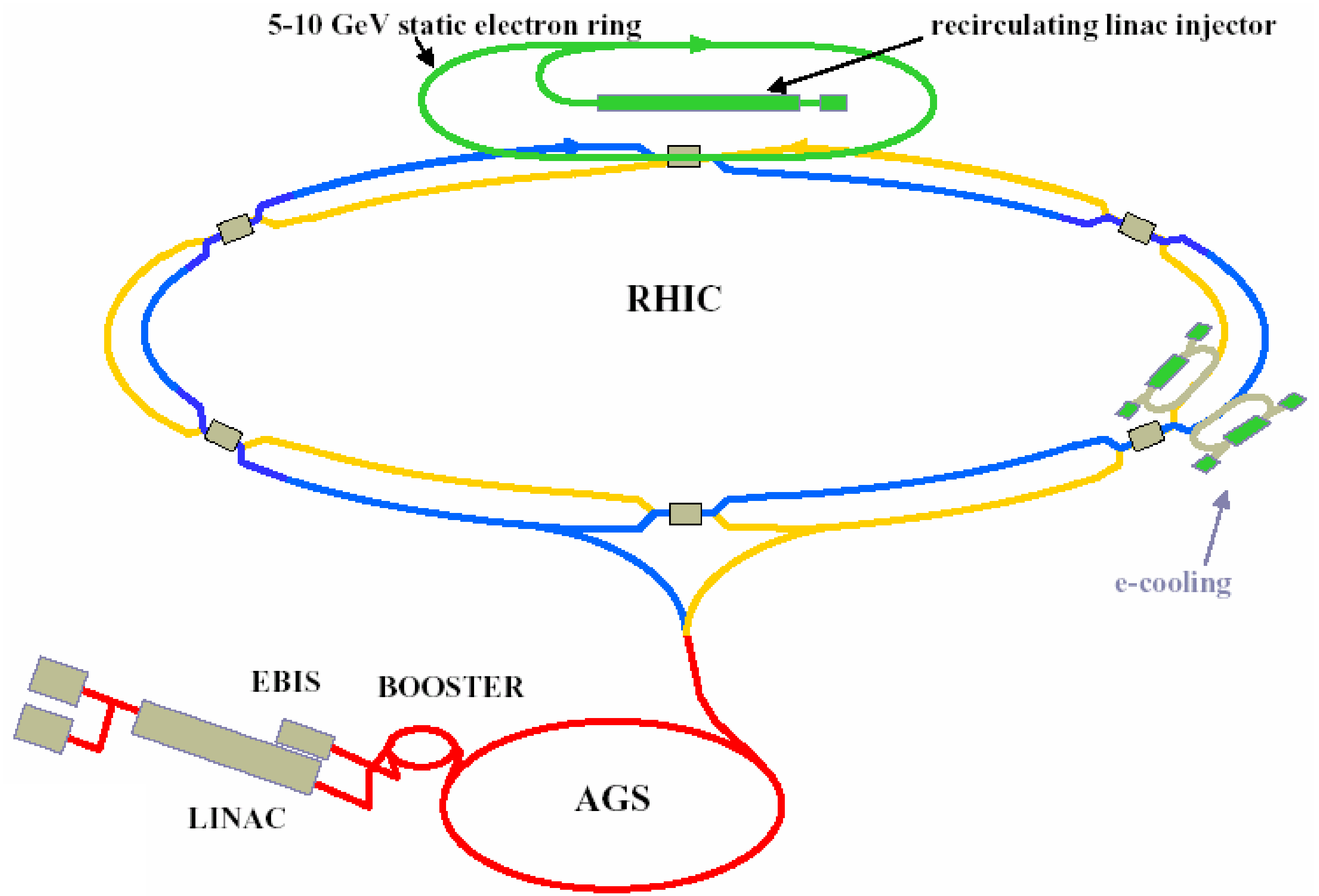
Stochastic cooling is difficult for high intensity, high energy beams, but:

Microwave stochastic cooling (~ 5 GHz) may work for longitudinal cooling and avoid beam debunching during store. Halo cooling in combination with e-cooling.

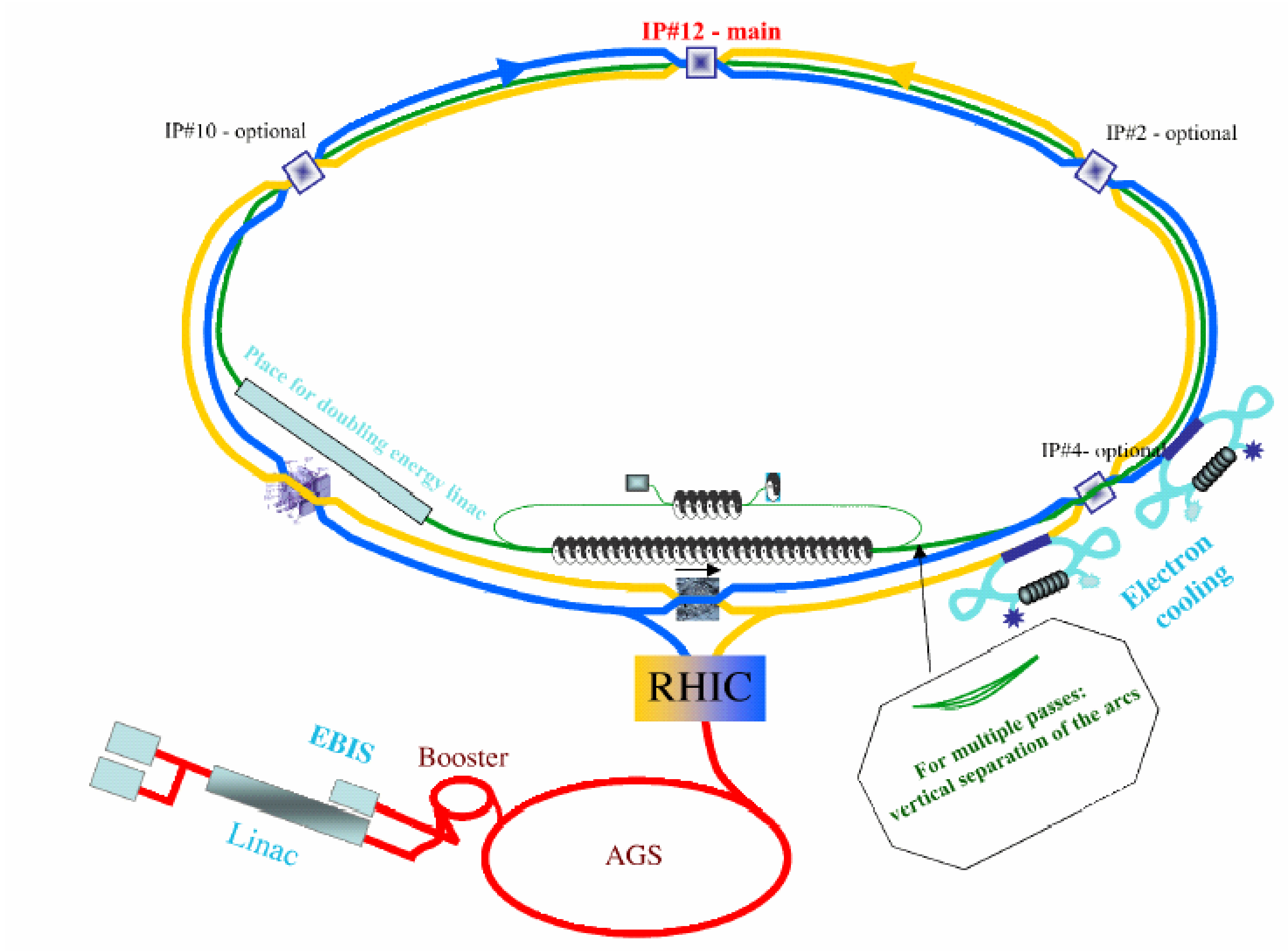
Optical stochastic cooling (~ 30 THz) has great potential for the long term future. Proof-of-principle R&D proceeding

Electron-Ion Collider at RHIC: eRHIC

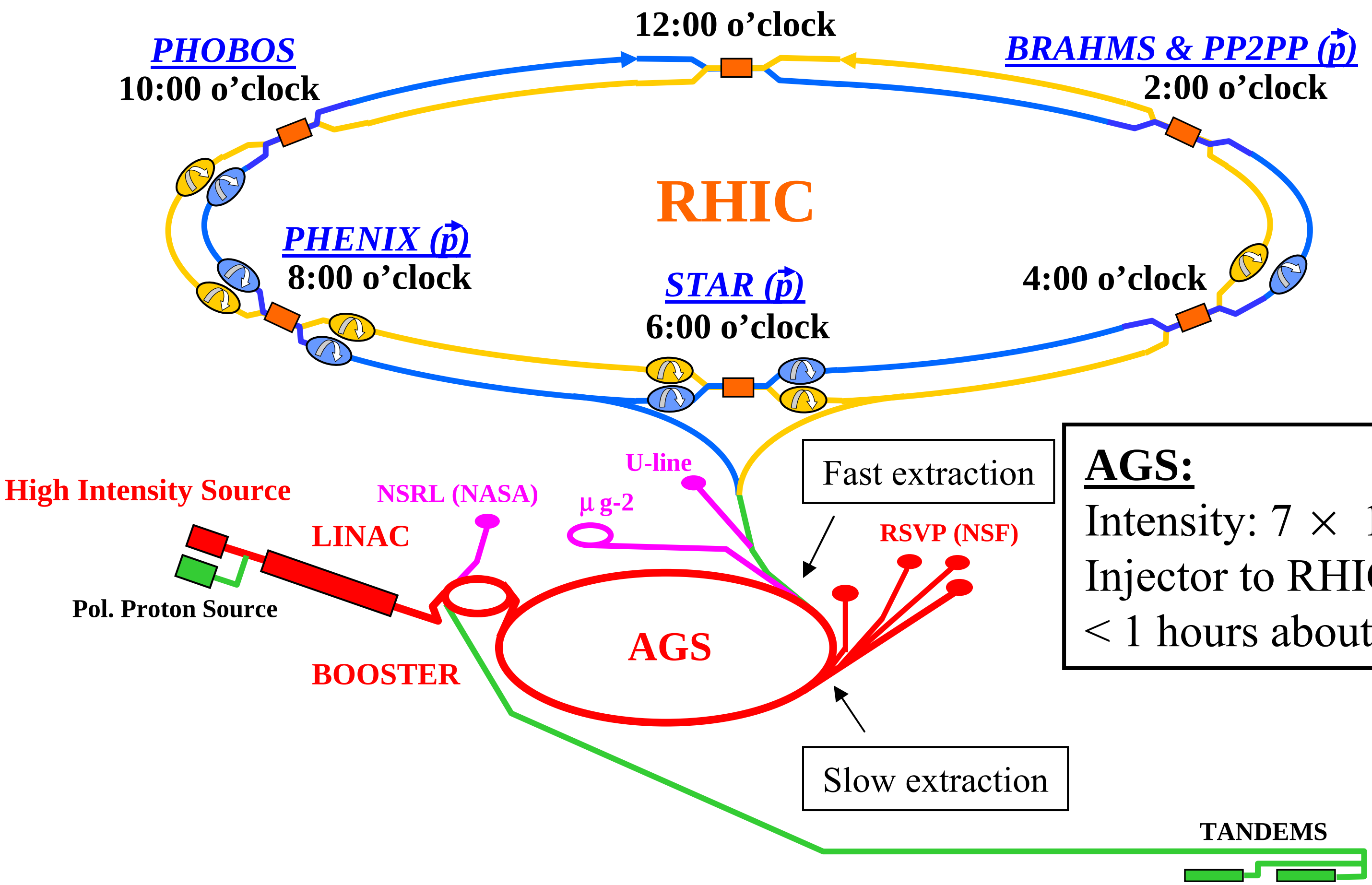
- 10 GeV, 0.5 A e-ring with ¼ of RHIC circumference (similar to PEP II HER)
- 10 GeV electron beam $\rightarrow s^{1/2}$ for e-A : 63 GeV/u; $s^{1/2}$ for e↑ -p↑ : 100 GeV
- Existing RHIC interaction region allows for typical asymmetric detector
- Luminosity: up to 1×10^{33} cm $^{-2}$s^{-1} per nucleon



Linac-ring eRHIC



AGS/RHIC Accelerator Complex



AGS:

Intensity: 7×10^{13} protons/pulse

Injector to RHIC:

< 1 hours about every 4 hours

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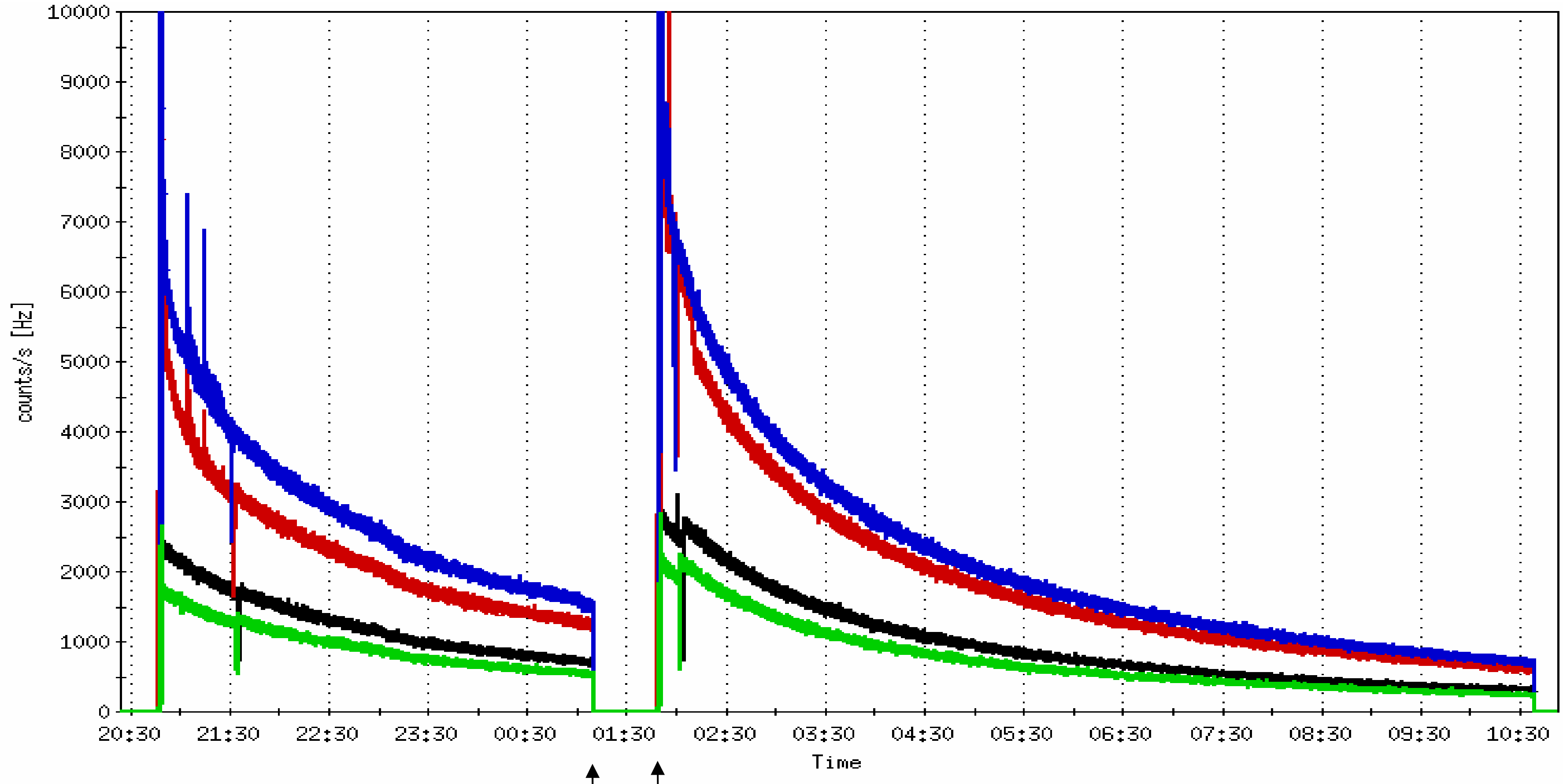
Refill of RHIC

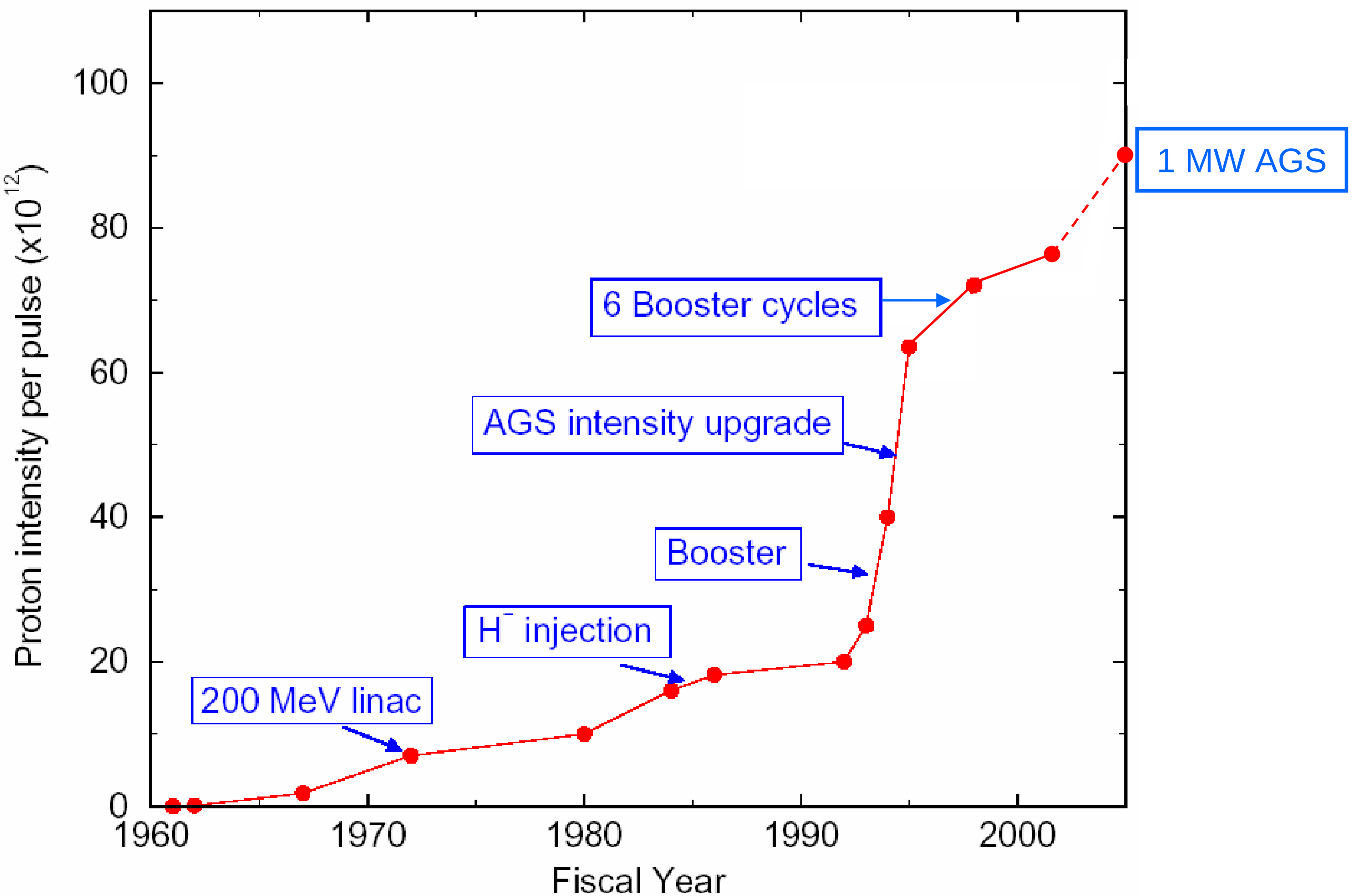


End of store

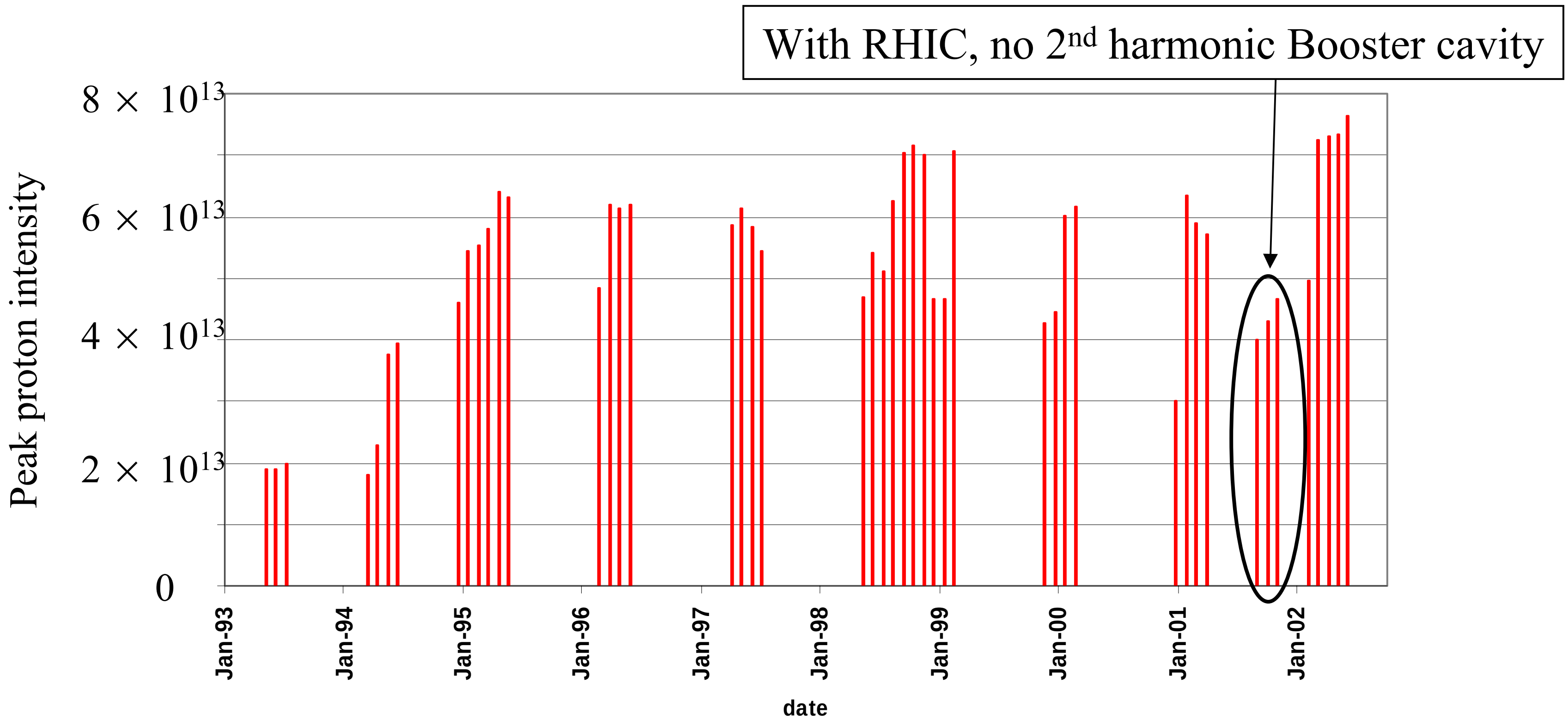
40 min.

Start of store

AGS Intensity History



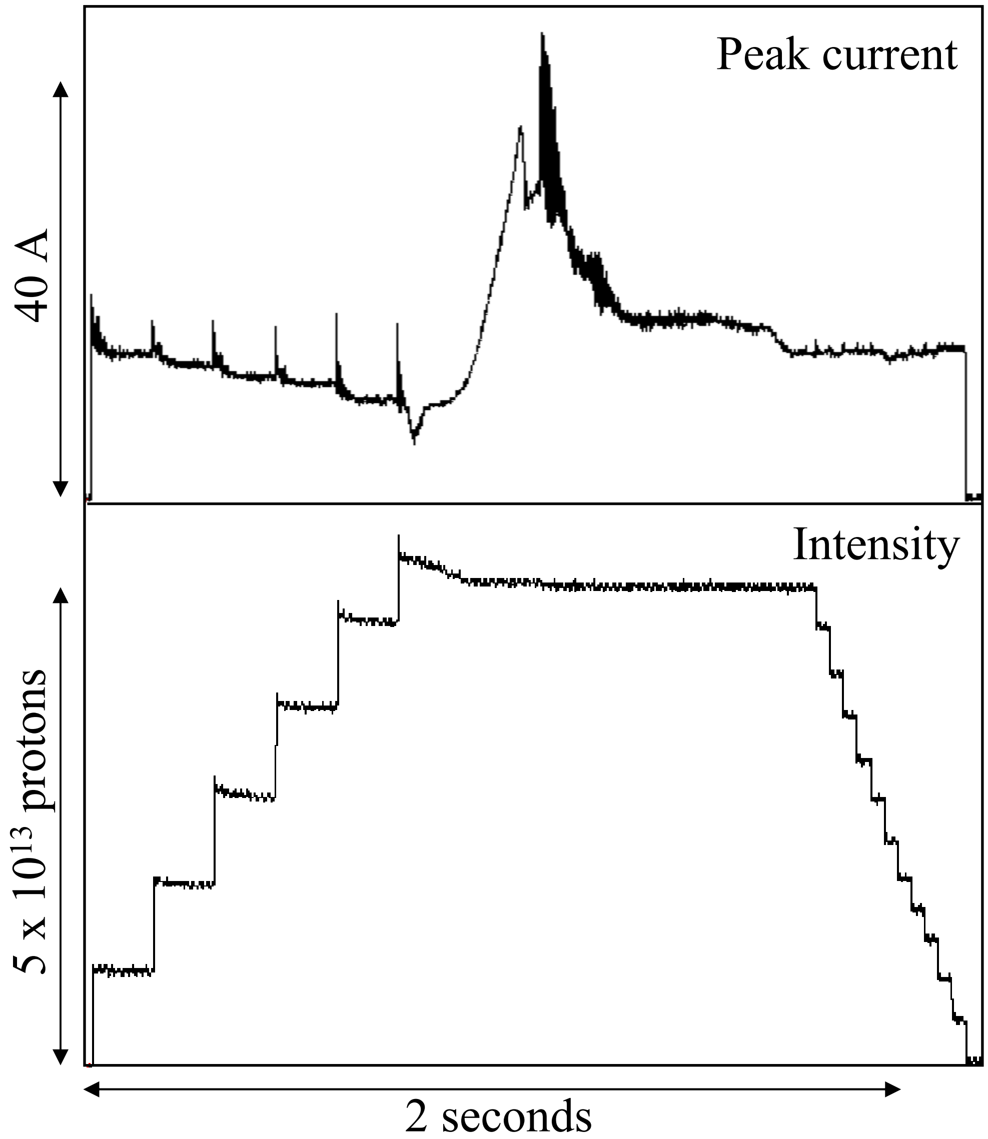
AGS Peak Proton Intensities



World record proton synchrotron intensity!

AGS performance for fast extraction

- 6 single bunch transfers from Booster
- Peak intensity reached: 72×10^{12} ppp (20×10^{12} p/s for 3.6 s cycle)
- Bunch area: 3 eVs at injection
  10 eVs at extraction
- Intensity for g-2 ops: 60×10^{12} ppp (24×10^{12} p/s for 2.5 s cycle)
- Strong space charge effects during accumulation in AGS
- 2nd order transition energy jump limits available momentum aperture.
- Chromatic mismatch at transition causes emittance dilution
- Dilution needed for beam stability



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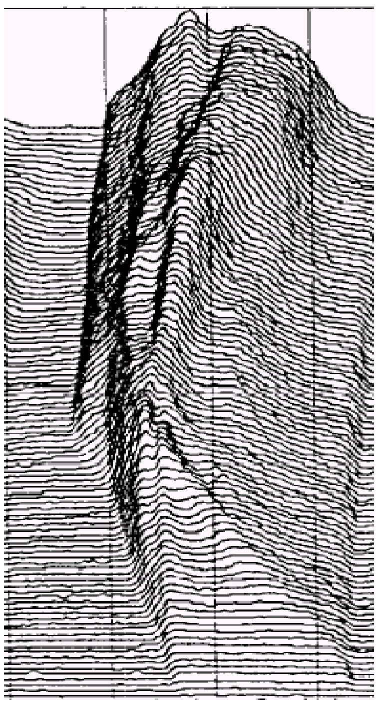
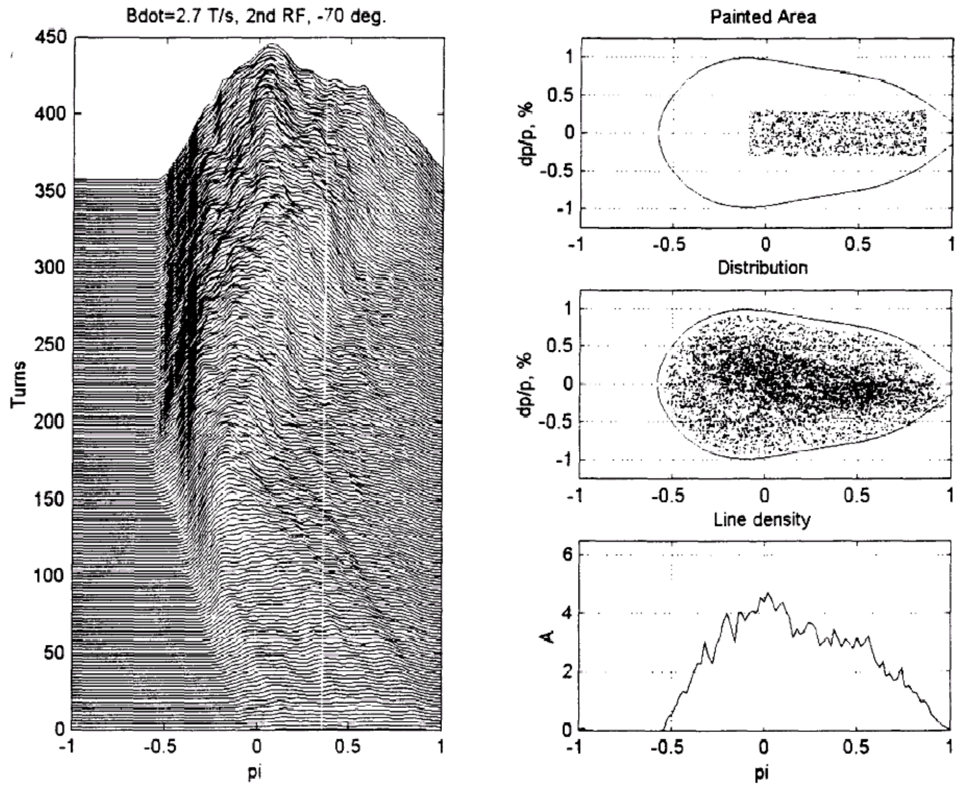
H$^-$ injection into the Booster

Measurement



Simulation



Injected:
23×10^{12} ppb
1.3 eVs
18×10^{12} /eVs

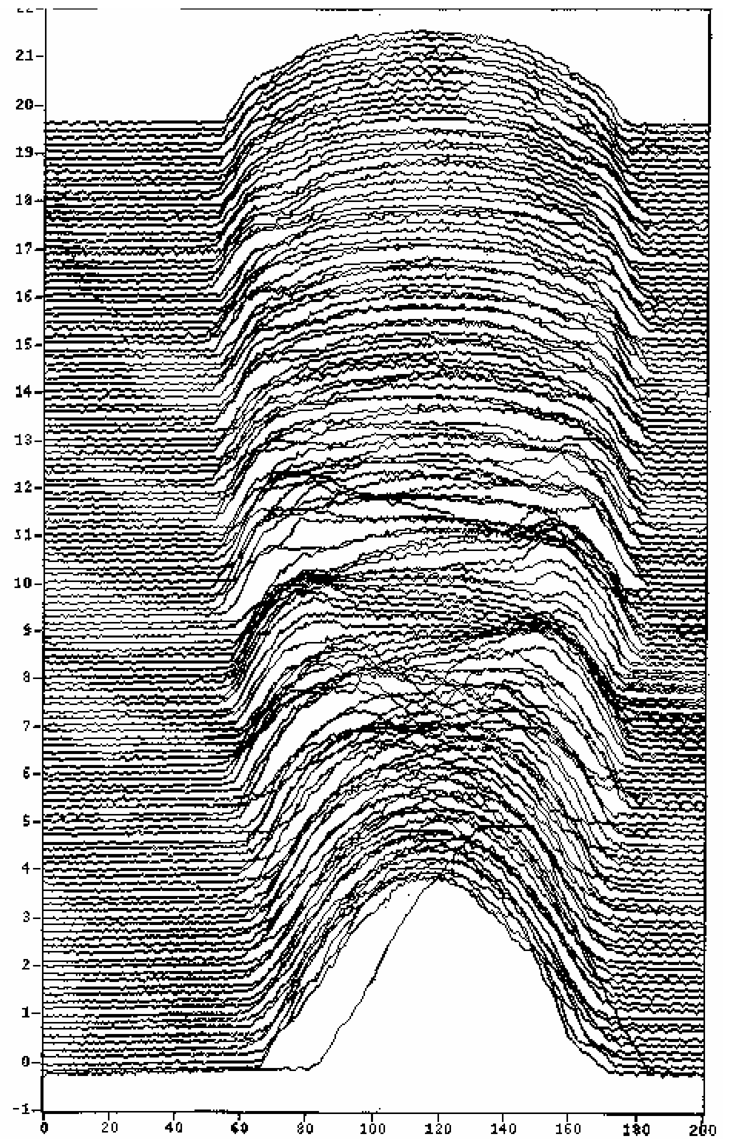
Circulating:
17×10^{12} ppb
3.0 eVs
5×10^{12} /eVs

High B dot gives effective long. phase space painting.
Injection period is approx. equal to synchrotron period.

Controlled dilution at AGS injection

Longitudinal emittance dilution
at AGS injection through mismatch
followed by smoothing with
high frequency (93 MHz) cavity.

Needed to avoid excessive
space charge tune spread and
coupled bunch instabilities.



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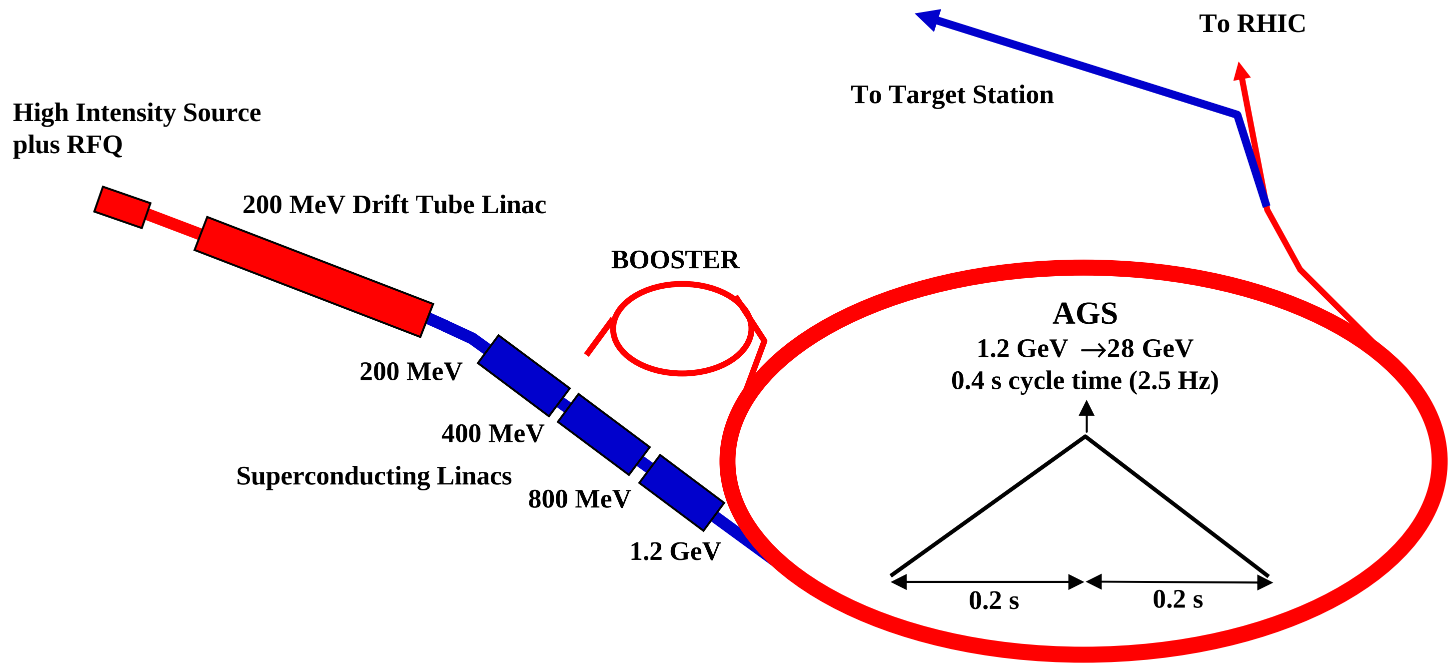
AGS Upgrade to 1 MW



- 1.2 GeV superconducting linac extension for direct injection of $\sim 1 \times 10^{14}$ protons

    low beam loss at injection; high repetition rate possible

    further upgrade to 1.5 GeV and 2×10^{14} protons per pulse possible (x 2)

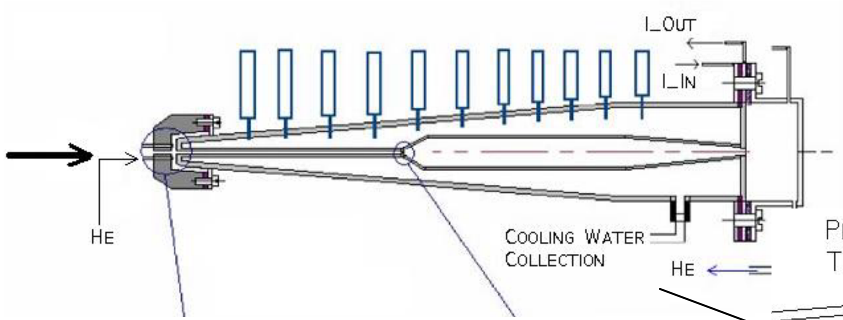
- 2.5 Hz AGS repetition rate

    triple existing main magnet power supply and magnet current feeds

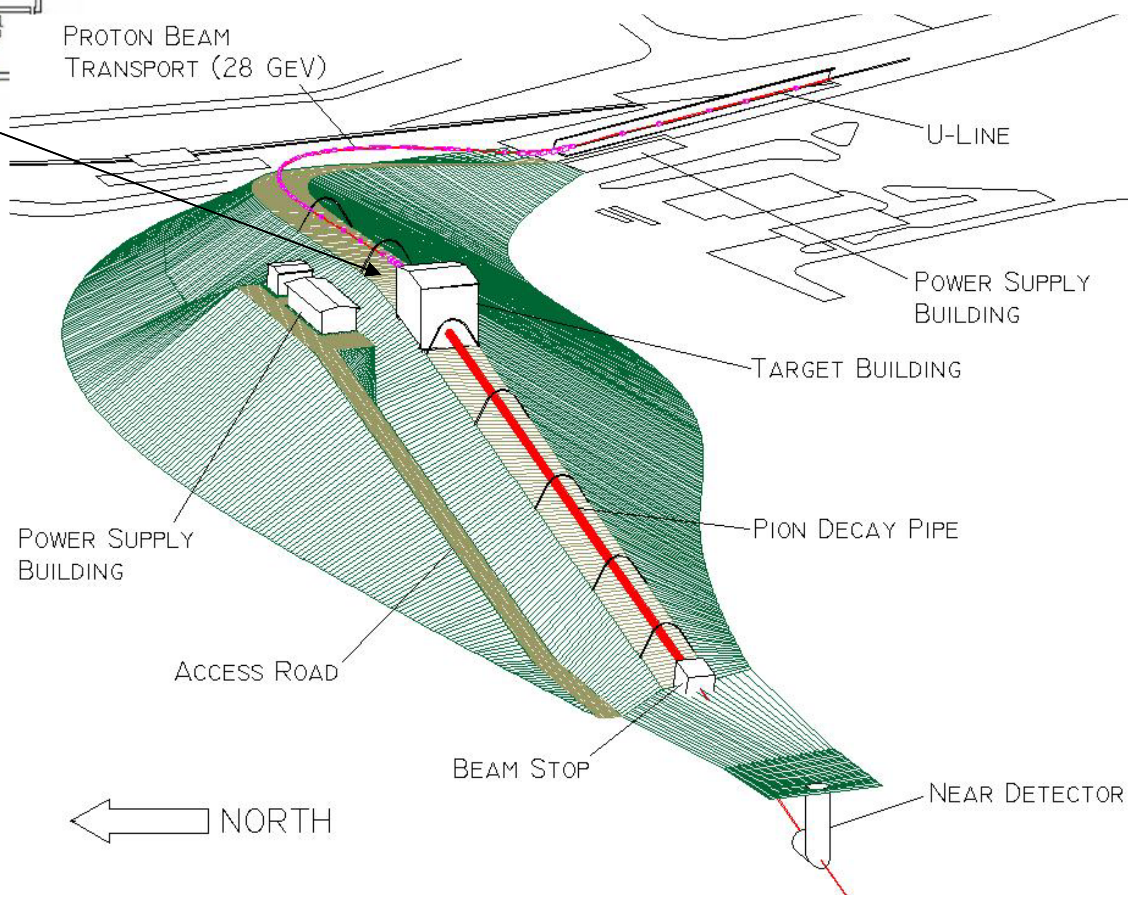
    double rf power and accelerating gradient

    further upgrade to 5 Hz possible (x 2)

Neutrino Beam Production



- 1 MW He gas-cooled Carbon-carbon target
- New horn design
- Target on down-hill slope for long baseline experiment
- Beam dump well above ground water table to avoid activation



Summary

- Successful operation of RHIC with 100 GeV/n beams in three modes:
  - Gold – gold collisions, peak luminosity = 14×10^{26} cm^{-2} s^{-1}
    (Nucleon pair peak luminosity = 54×10^{30} cm^{-2} s^{-1})
    (Proton pair peak luminosity = 9×10^{30} cm^{-2} s^{-1})
  - Deuteron – gold collisions, peak luminosity = 7×10^{28} cm^{-2} s^{-1}
    (Nucleon pair peak luminosity = 28×10^{30} cm^{-2} s^{-1})
    (Proton pair peak luminosity = 6×10^{30} cm^{-2} s^{-1})
  - Polarized proton collisions, peak luminosity = 6×10^{30} cm^{-2} s^{-1}
- RHIC luminosity upgrade (x10) using full energy electron cooling
- With electron cooling $\rightarrow$high luminosity electron-ion collider at RHIC
- Record AGS intensity: 7.6×10^{13} protons per pulse;
  fixed target experiments (RSVP) planned for 2008
- Design for 1 MW AGS for neutrino super-beam, neutrino factory, muon collider, …

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