BNL: 70 Years at the Forefront of Accelerator Technologies

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RHIC & AGS Users Meeting

June 22, 2017

70 YEARS OF DISCOVERY

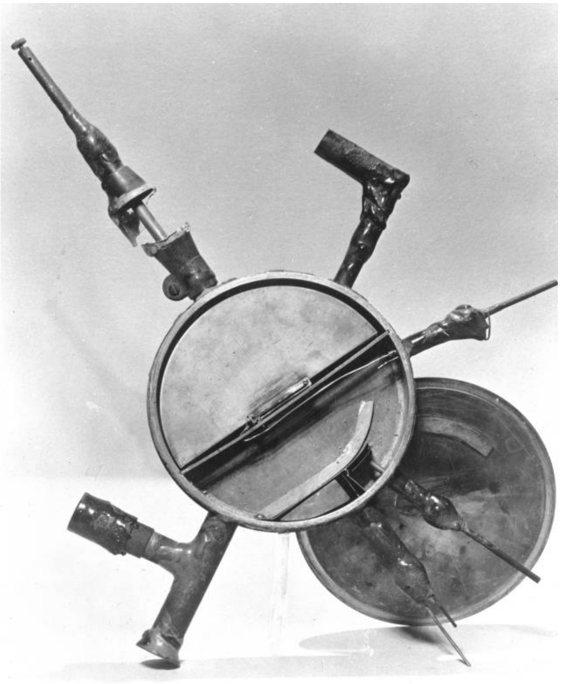
A CENTURY OF SERVICE

U.S. DEPARTMENT OF ENERGY

BROOKHAVEN NATIONAL LABORATORY

Accelerators and Particle Physics

- Progress in accelerator technology is motivated by and has driven advances in particle and nuclear physics
- This started with Ernest Lawrence's first cyclotron (1931) and continues to this day.
- Many of the breakthrough developments took place at BNL



Accelerator Science & Technology at BNL

- Birthplace of modern accelerators:
  - Courant-Snyder strong focusing used for high energy accelerators
  - Chasman-Green low emittance lattice used for synchrotron light sources
  - Palmer’s 2-in-1 magnets used at LHC

- Operation & design of world-leading accelerators:
  - NSLS II: Synchrotron light source with world leading flux and brightness
  - RHIC: only US collider and world's only polarized proton collider
  - eRHIC (EIC @ BNL): very high luminosity polarized electron-ion collider using RHIC accelerators and high intensity electron accelerator

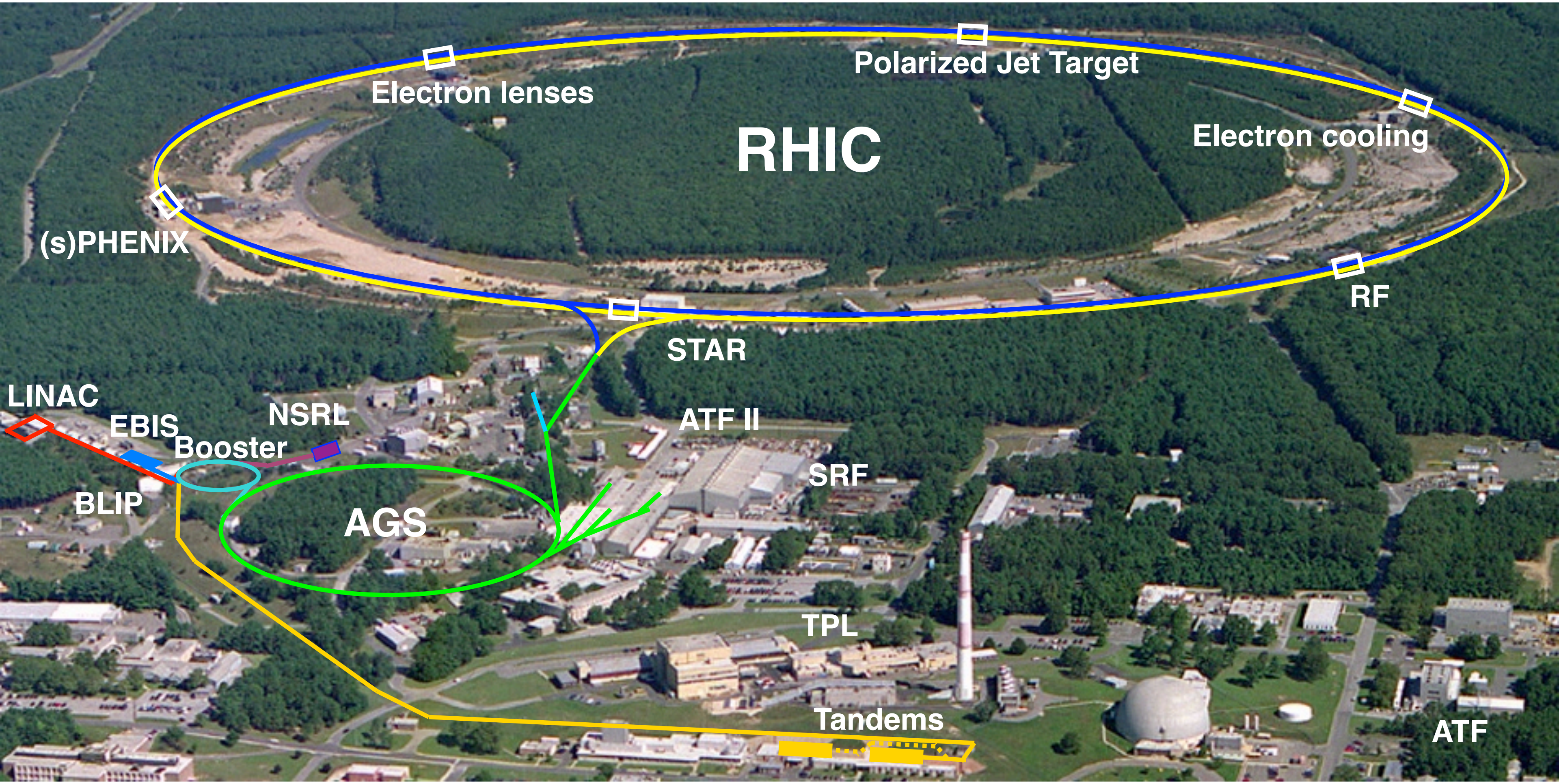
- Accelerator R&D for the next generation accelerators:
  - High brightness, high intensity (polarized) particle sources
  - High intensity Energy Recovery Linacs (ERL)
  - Advanced hadron beam cooling techniques
  - Fast laser interactions with beams (Accelerator Test Facility)
  - Superconducting (incl. HTS) magnet technology

NSLS and NSLS II

- NSLS is first 2nd generation light source using the Chasman-Green low-emittance lattice. Highly successful operation from 1982 to 2014.

- NSLS II is latest 3rd generation light source using double bend achromatic lattice plus damping wigglers to produce x-rays with world leading flux and brightness. Start of operation in 2015.

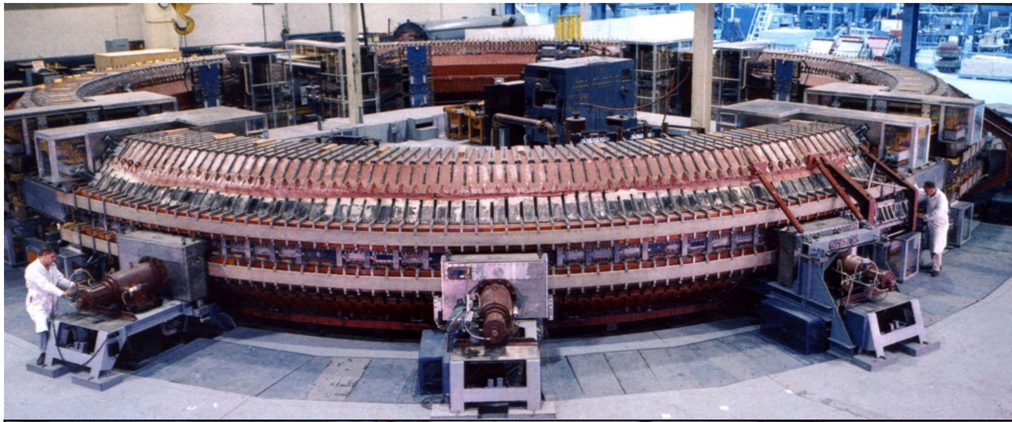
The RHIC Accelerator Complex



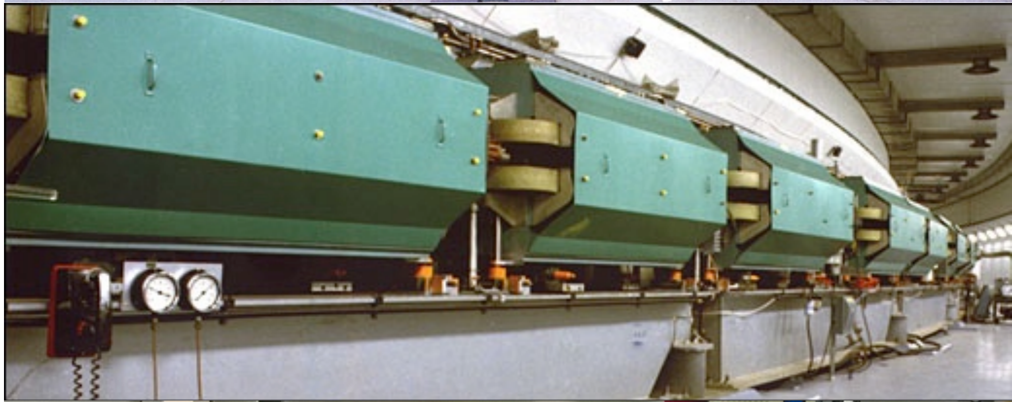
- Highly flexible and only US Hadron Collider exploring the QCD phase diagram and the spin of the proton
- Injectors also provide beams for unique applications: Isotope production (BLIP/TPL); Cosmic radiation simulation (NSRL); Commercial applications (Tandem)

A Hallmark of BNL: Focusing of Particle Beams

- Weak focusing synchrotron
  - 3 GeV Brookhaven Cosmotron
  - Completed in 1952
  - Bending magnetic field provides x and y focusing



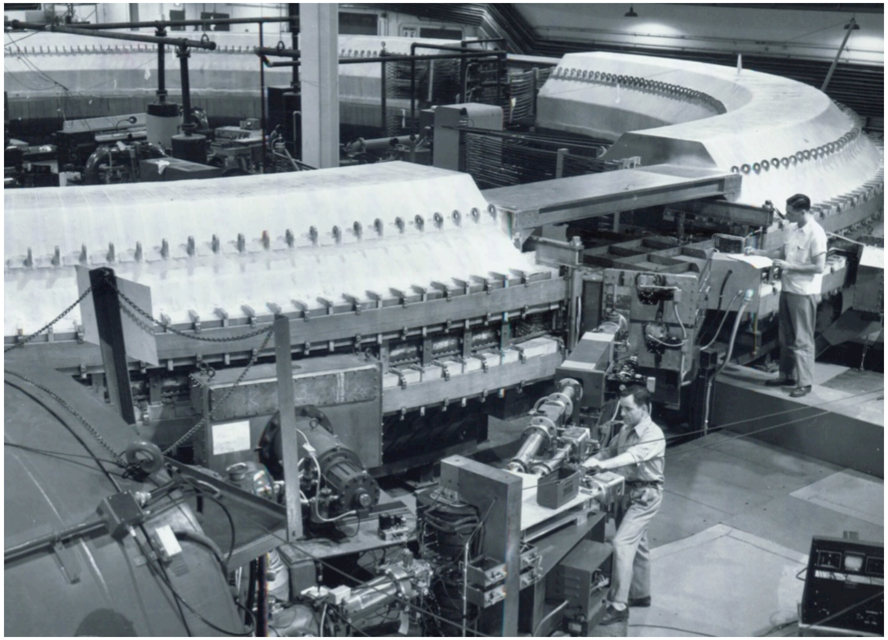
- Strong focusing synchrotron
  - 30 GeV Brookhaven AGS
  - Completed in 1960
  - Strong quadrupoles with alternating gradients



- Very strong focusing
  - CBETA FFAG ERL
  - Many, very strong quadrupoles provide bending and focusing for large energy span

Cosmotron – First Accelerator with Energy above 1 GeV

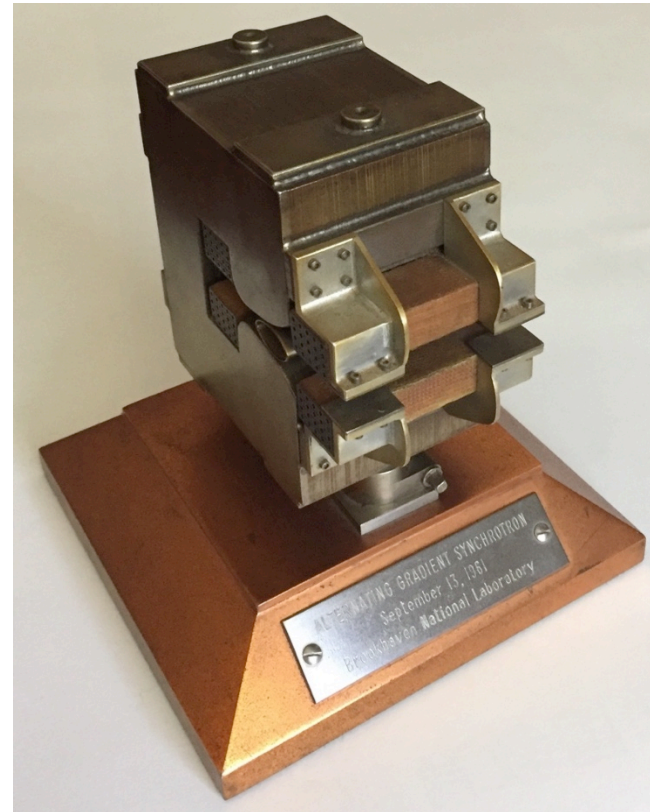
- Synchrotron: pulsed magnetic field to keep particle orbit unchanged [M.O. Oliphant, 1943]
- AEC decided to fund proton synchrotrons at Berkeley and BNL: a smaller 3 GeV synchrotron and a larger one at 6 GeV
- BNL (Leland Haworth) chose the smaller one, hoping to finish it first, but also giving up on a likely discovery of the anti-proton

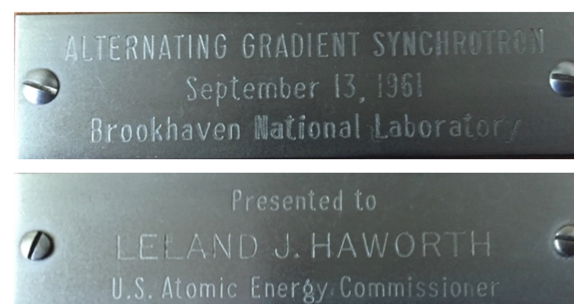


	Birmingham	Cosmotron	Bevatron	Synchrophasotron
Peak energy	1 GeV	3 GeV	6 GeV	10 GeV
Circumference	28 m	70 m	120 m	208 m
Weight of magnet	800 tons	1650 tons	9700 tons	36000 tons
Completion date	1953	1952	1954	1957

AGS – Making High Energy Accelerators Possible

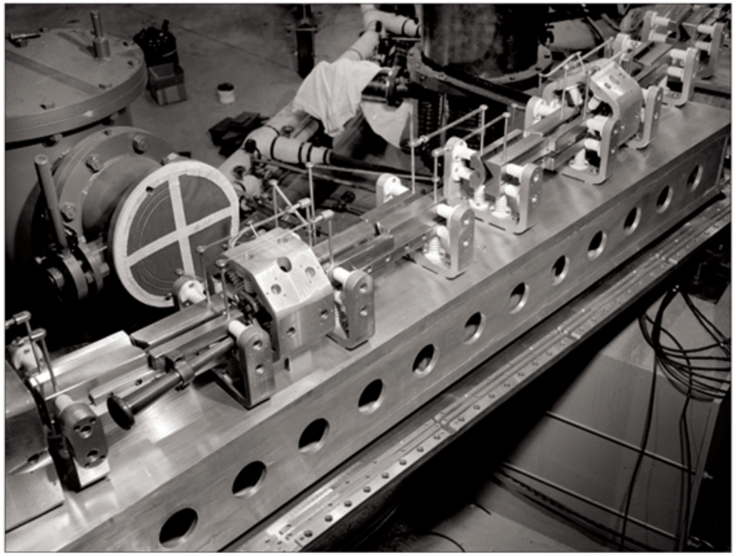
- Quadrupoles with alternating gradients (AG) gives much stronger focusing and smaller beam envelopes
- Reduced size of vacuum chamber and magnetic volume; made high energy accelerators possible
- Below: Ernest Courant and Stanley Livingston comparing AGS and Cosmotron magnet sizes





CERN PS and BNL AGS

- Physicists from the newly formed CERN laboratory visited BNL in 1952 and learned about the AG principle; after returning to Europe it was decided to built an AG synchrotron (PS) instead of a 10 GeV "Cosmotron" as the first accelerator at CERN
- Friendly rivalry between BNL and CERN: who would complete their machine first?
- Both machines would have to cross the transition energy, when the revolution time is independent of particle energy, for the first time. This is a potentially unstable point during the acceleration cycle
- CERN took the risk and started building the machine
- BNL was more risk averse and decided to build an test accelerator – the electron analog
- As result CERN won the race accelerating first beam in the PS in 1959. The BNL AGS followed with first accelerated beam in 1960.

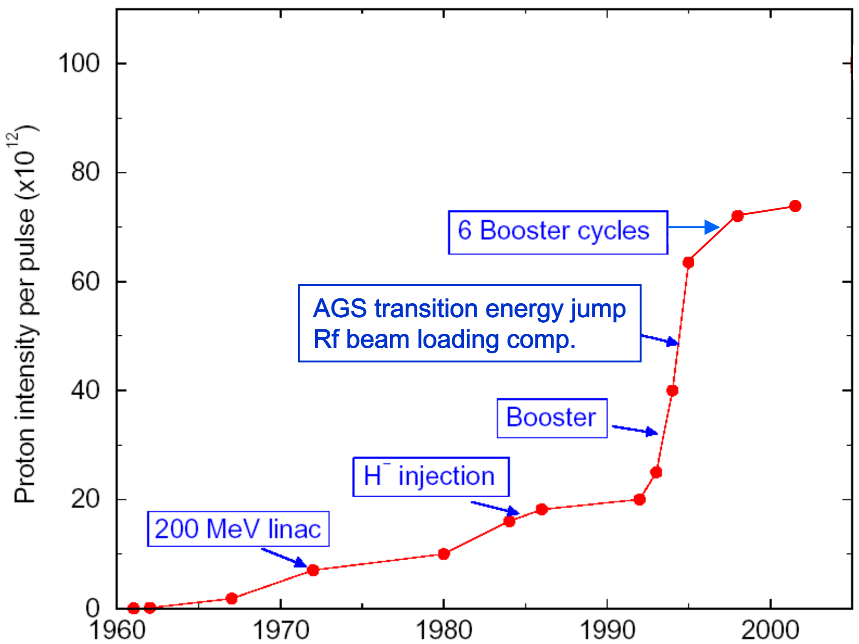


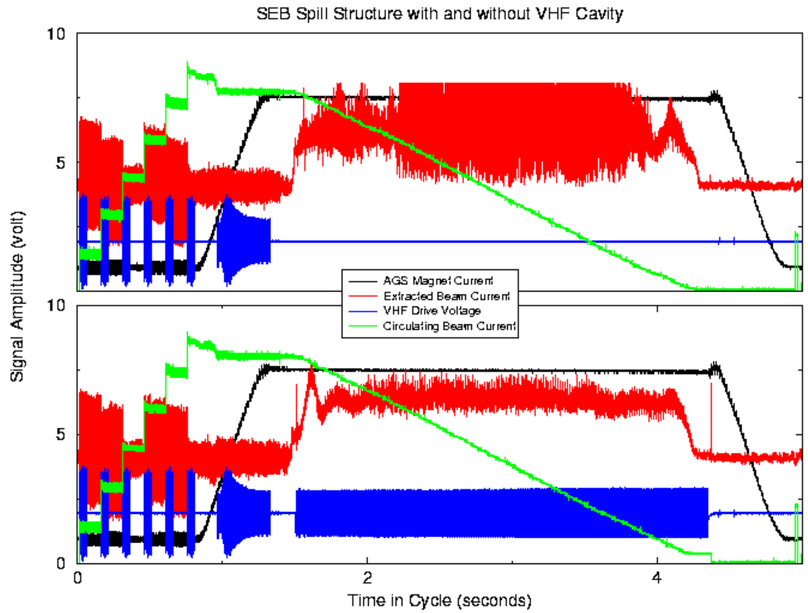
Proton Intensity Evolution at the AGS

- Continuous upgrades led to world record intensities
  - 200 MeV Alvarez Linac
  - H- injection
  - RFQ pre-injector
  - 2 GeV RCS Booster

- Slow extraction of high intensity beam with excellent spill for rare Kaon experiments using 100 MHz RF cavity

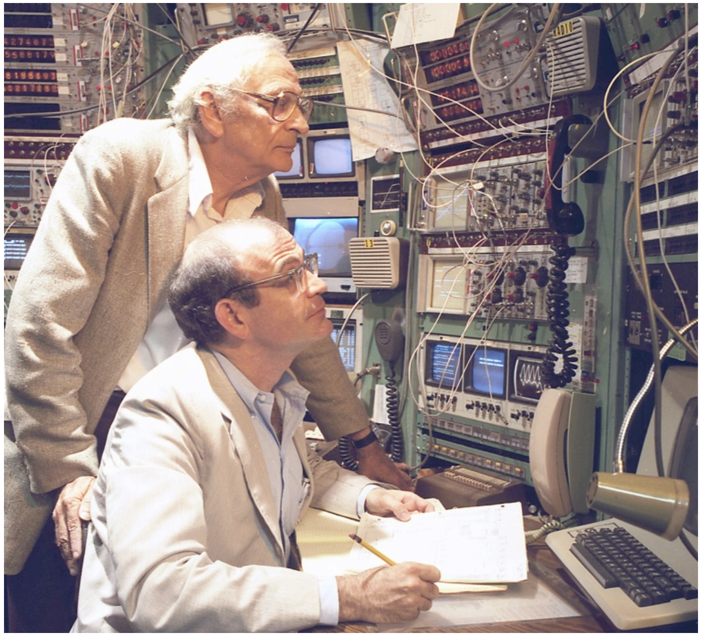
- Peak intensity (slow extraction):
  - 72×10^{12} ppp, ~ 50 kW on target

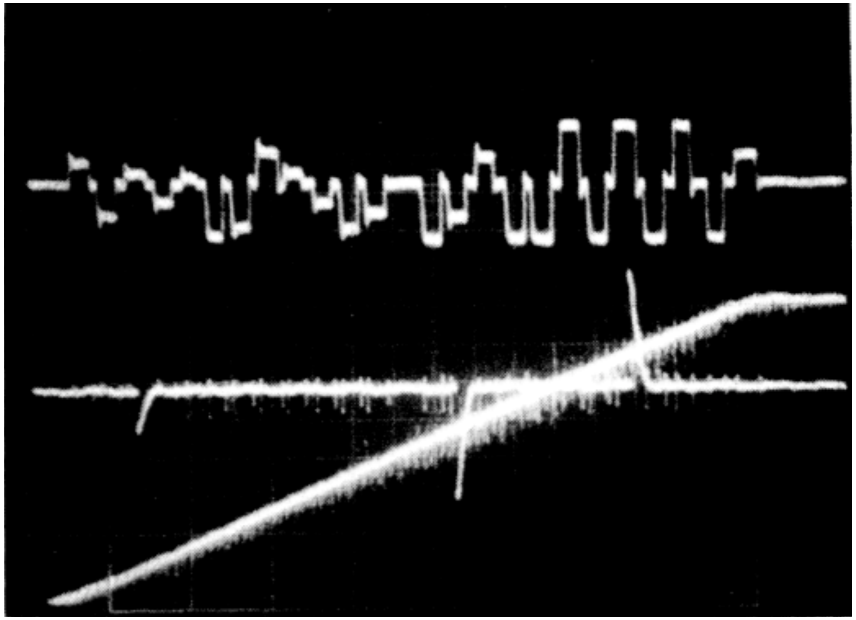




First Polarized Proton Acceleration at the AGS

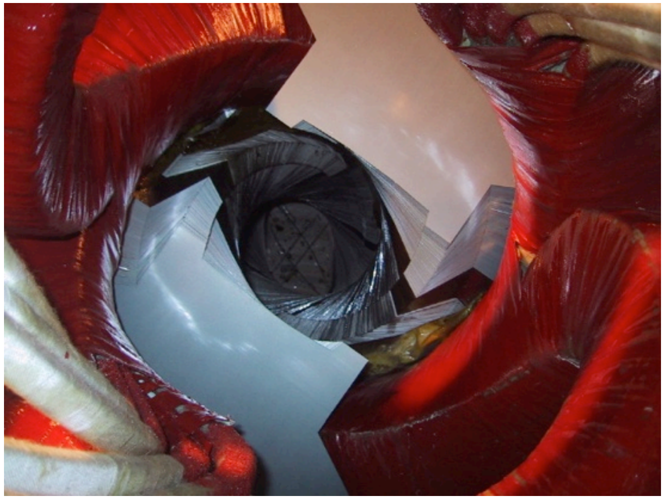
- In the 1980s, after successfully accelerating polarized protons in the Argonne ZGS, Alan Krisch and Larry Ratner led the first effort to polarize the AGS by correcting the approximately 50 depolarizing resonances. This was a truly heroic effort!

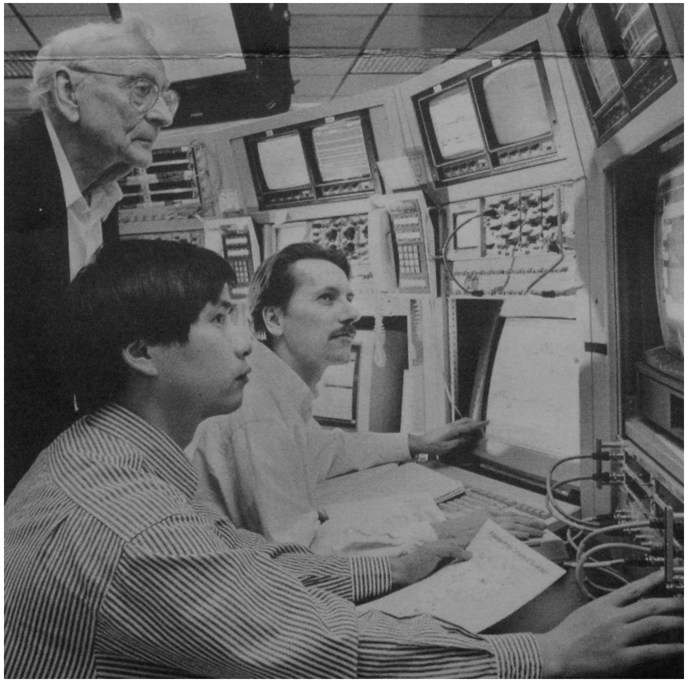




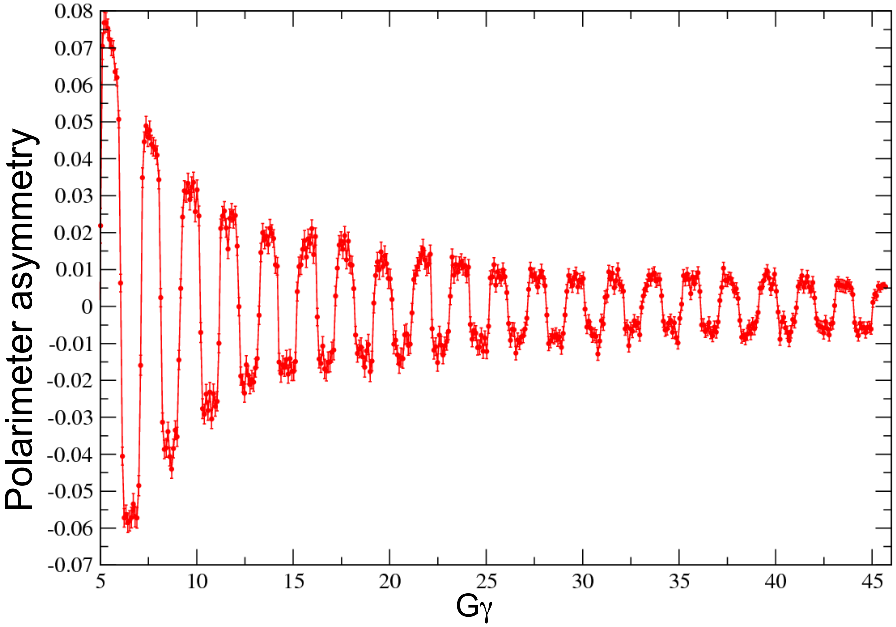
Polarized Protons in the AGS Today

- Two strong partial Siberian snakes using variable-pitch helical dipoles
- Vertical betatron tune at 8.98
- Pulsed quadrupoles to jump across the many weak horizontal spin resonances driven by the partial snakes.



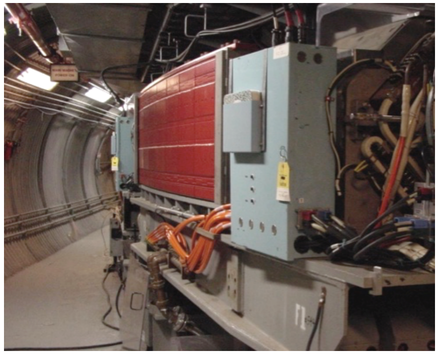


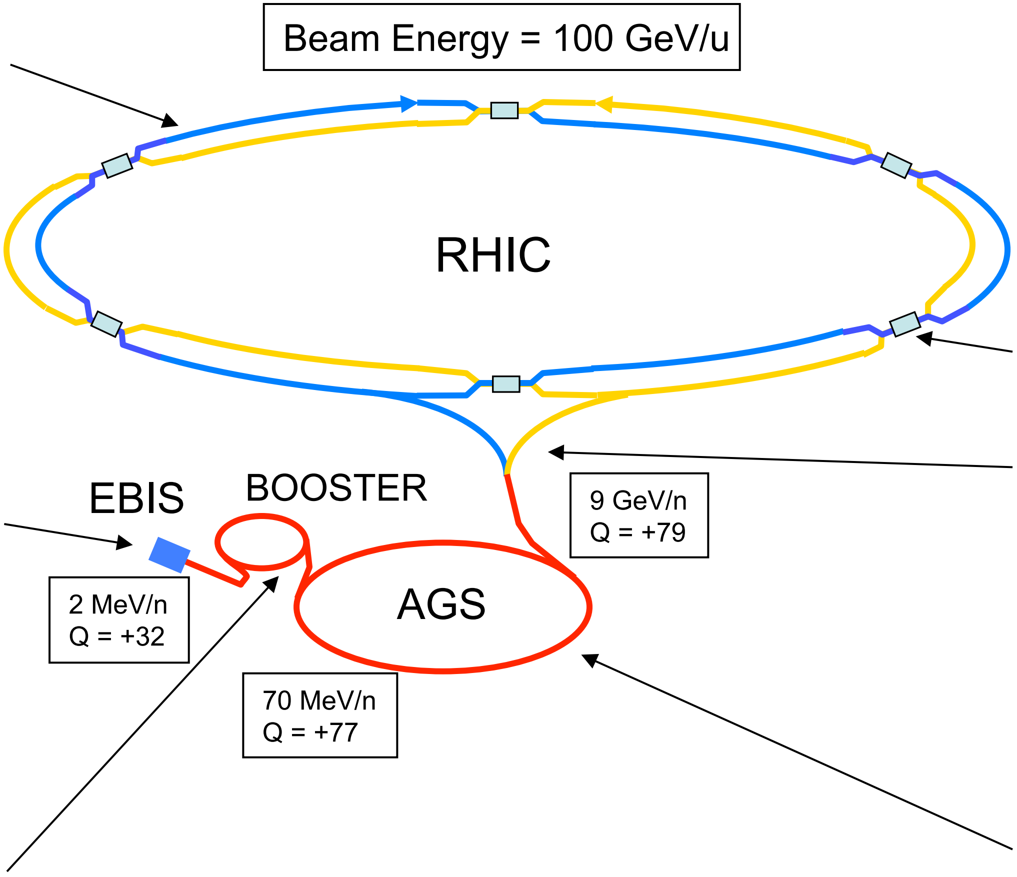
Larry Ratner, Haixin Huang and TR in AGS MCR.

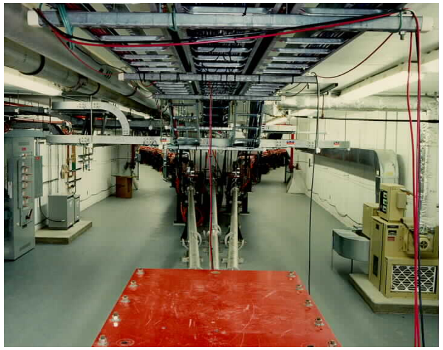


RHIC – First Heavy Ion Collider

- Collisions of fully stripped heavy ions with manageable e^+e^- and neutron production cross sections
- First superconducting accelerator to (slowly) cross transition energy

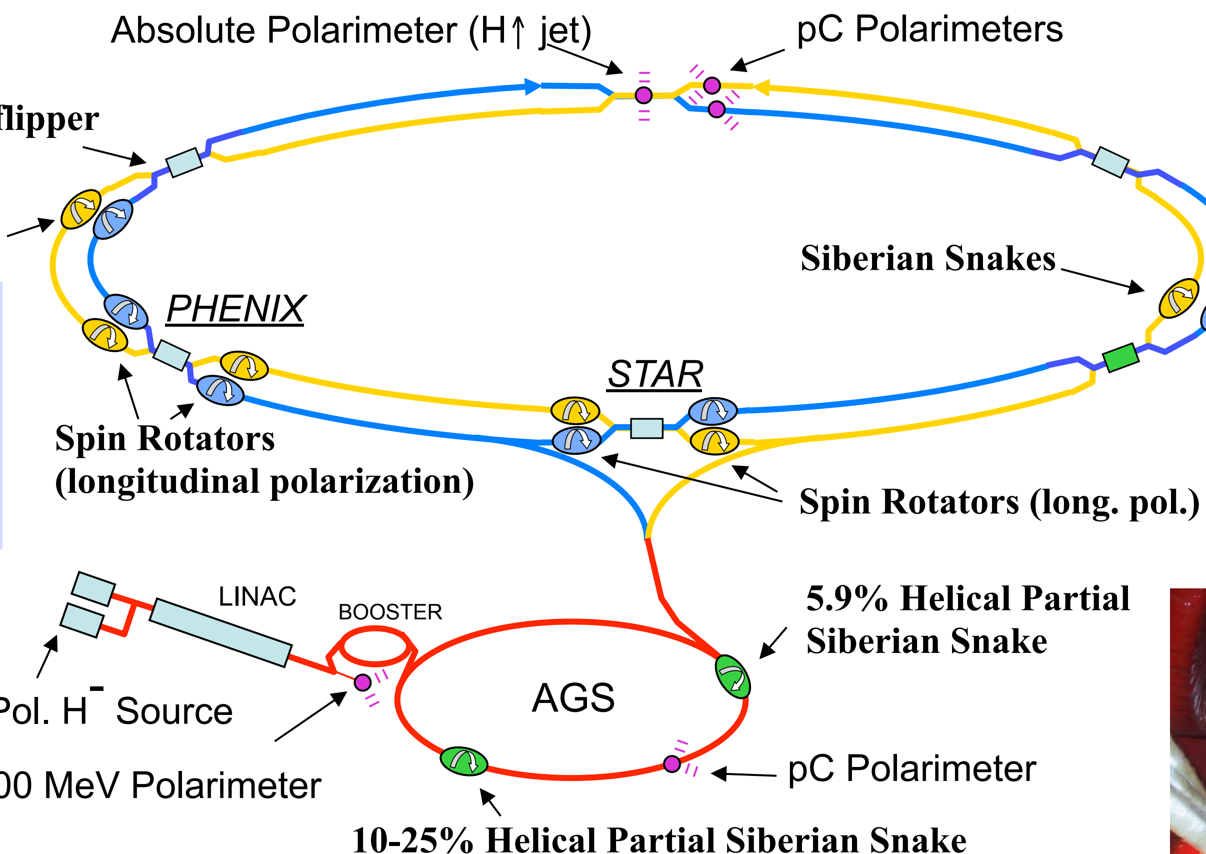


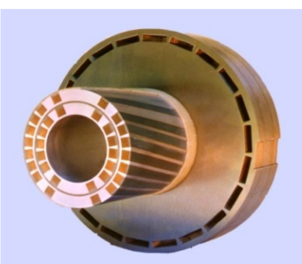




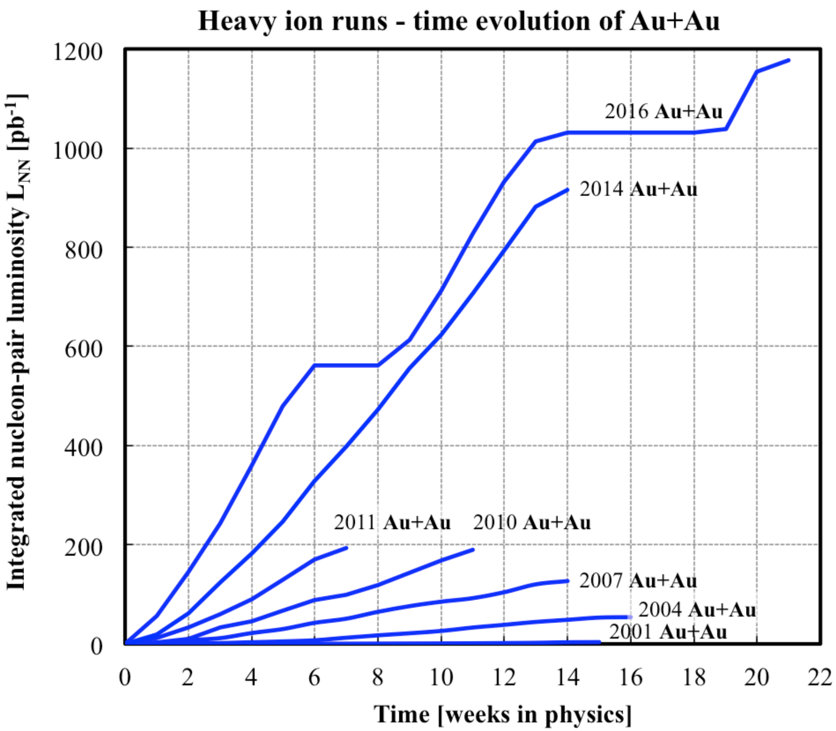
RHIC – First Polarized Hadron Collider

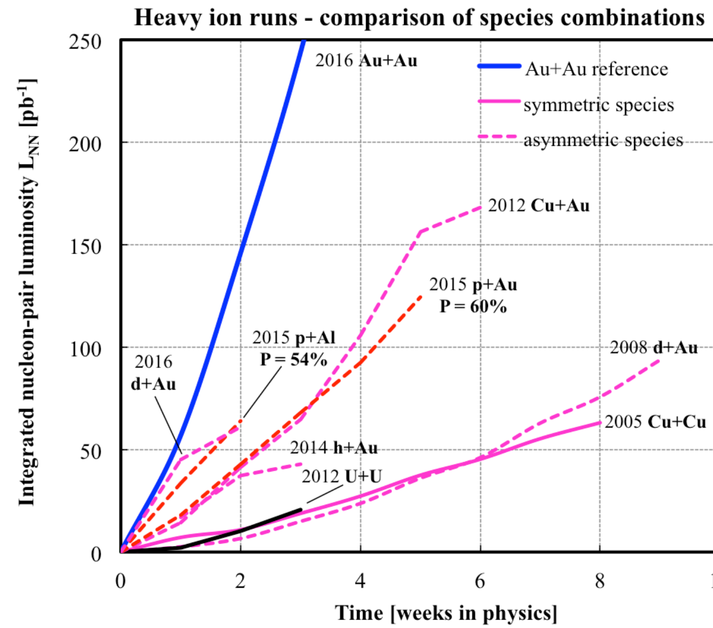
- Two full Siberian snakes per ring preserve proton polarization to 255 GeV
- Spin direction control at detectors with spin rotators
- Minimally invasive polarimeters; also measure polarization profiles
- Absolute polarimeter using world's most intense polarized H jet

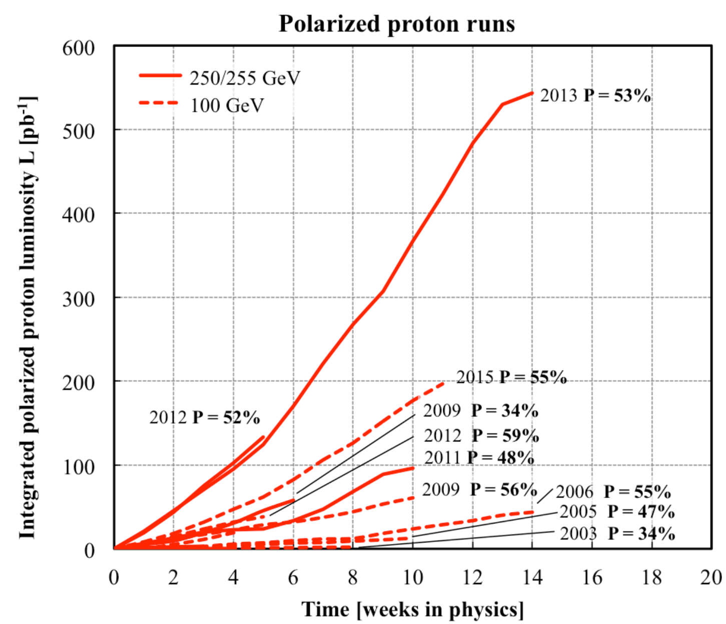




Luminosity and Polarization Evolution at RHIC



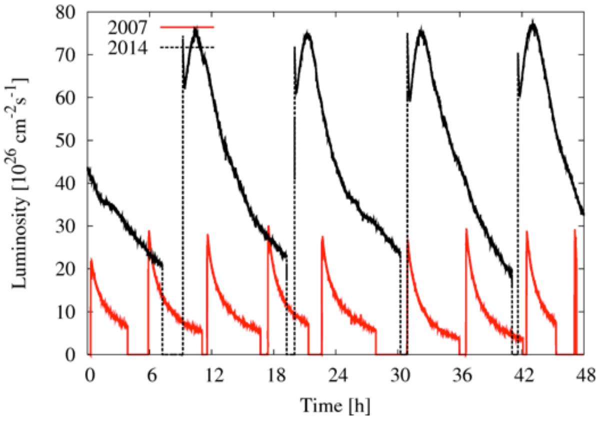




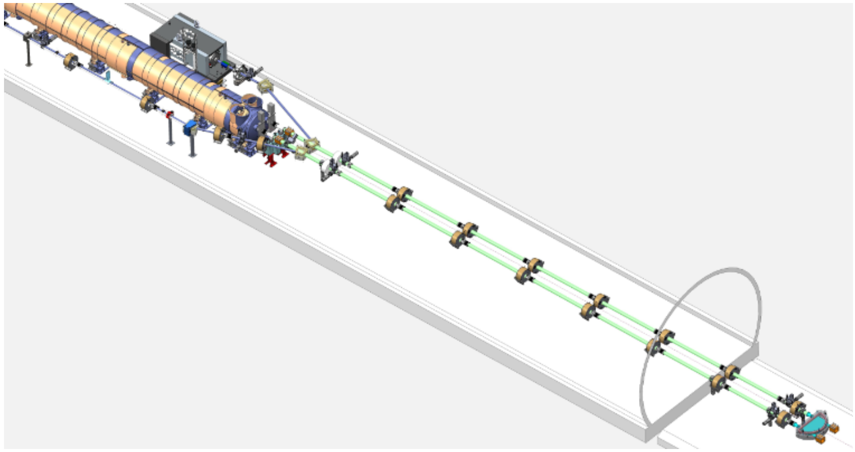
- Dramatic increase in performance as a result of:
  - Accelerator R&D
  - Accelerator Improvement and Capital Projects
  - Replacement of obsolete technology

Advanced Beam Cooling at RHIC

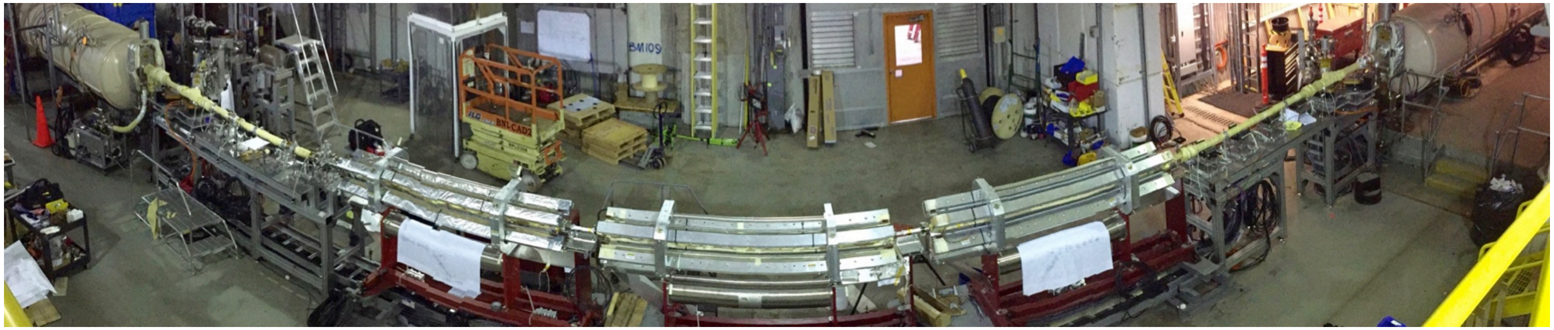
- First high energy, bunched beam stochastic cooling gives record heavy ion collision rates



- Construction of first bunched beam electron cooling for luminosity upgrade of low energy heavy ion collisions

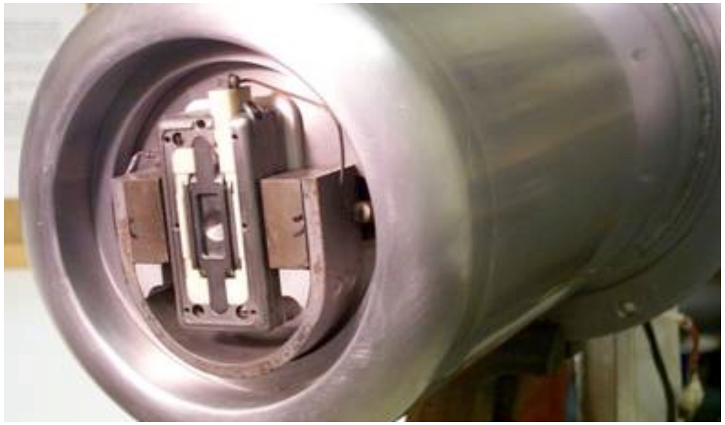


- R&D of Coherent electron Cooling, a combination of stochastic and electron cooling, for fast cooling of high energy hadron beams



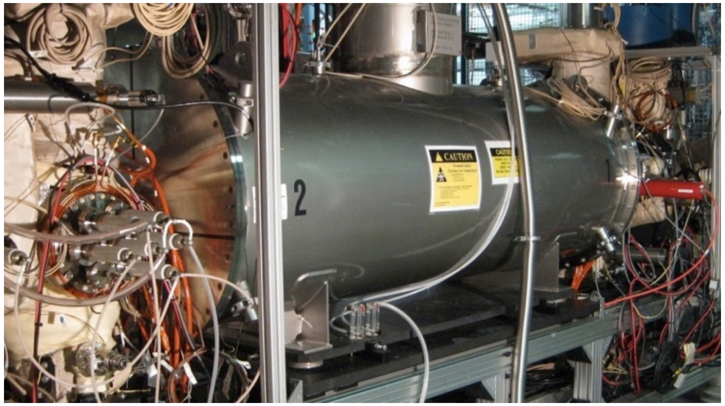
Ion Sources at BNL

- BNL Magnetron H- source
  - Hydrogen plasma interacts with Cs-Mo surface
  - Highest H- peak current (100 mA)



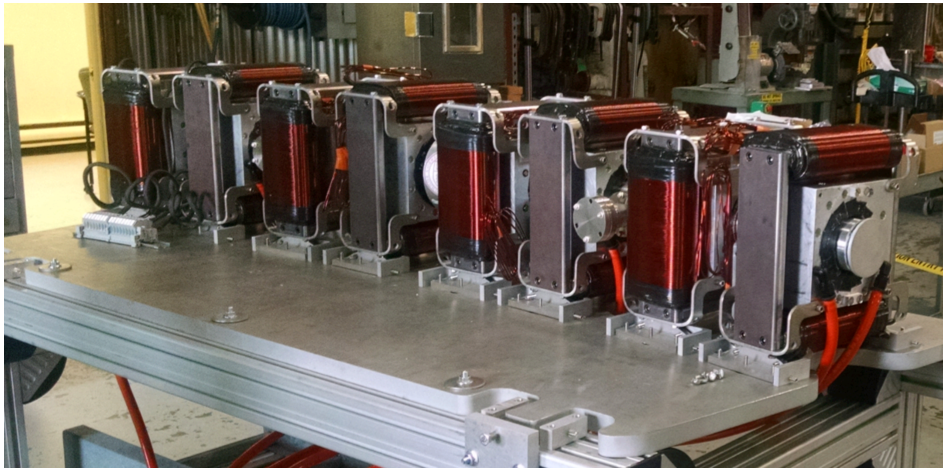
- BNL Optically Pumped Polarized Ion Source (OPPIS)
  - Polarized electrons from optically pumped Rubidium are used to generate polarized H- ions
  - Highest intensity (1 mA) polarized (83%) H- source

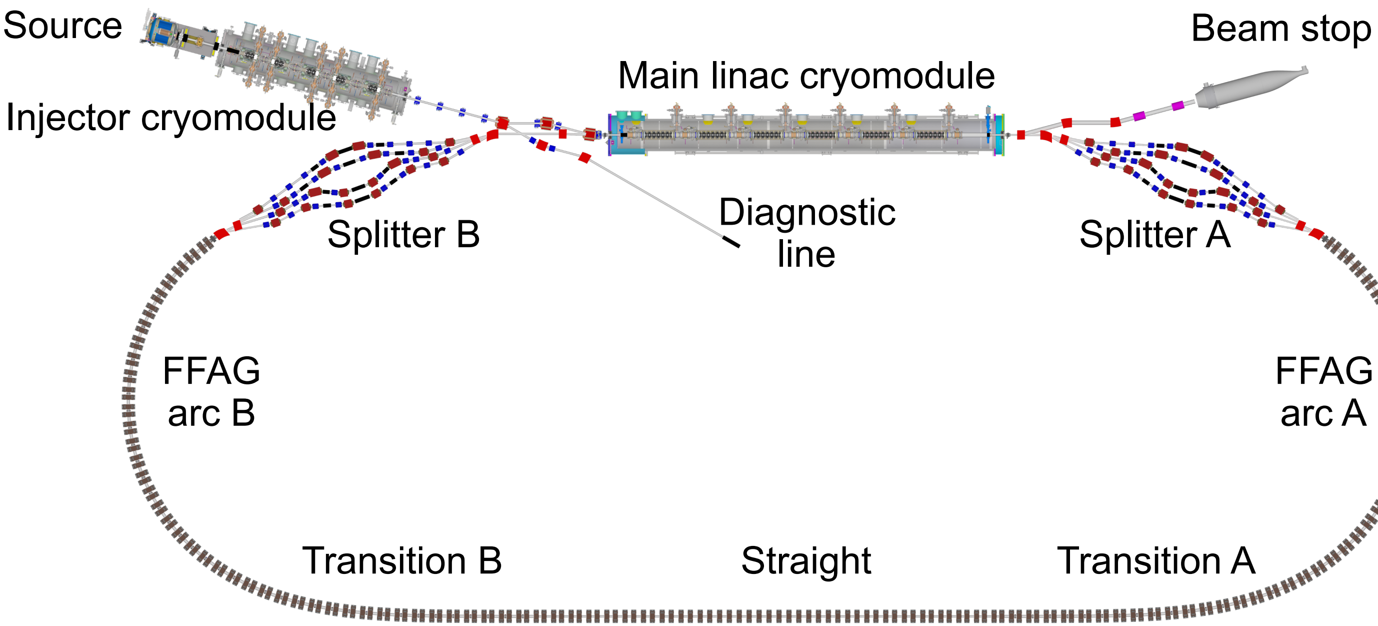
- BNL Electron Beam Ion Source (EBIS)
  - Intense electron beam inside high-field solenoid is used to stepwise ionize heavy ions. Reaches Au^{32+} after about 40 ms.
  - Highest intensity EBIS



CBETA – Multi-pass FFAG Test-ERL

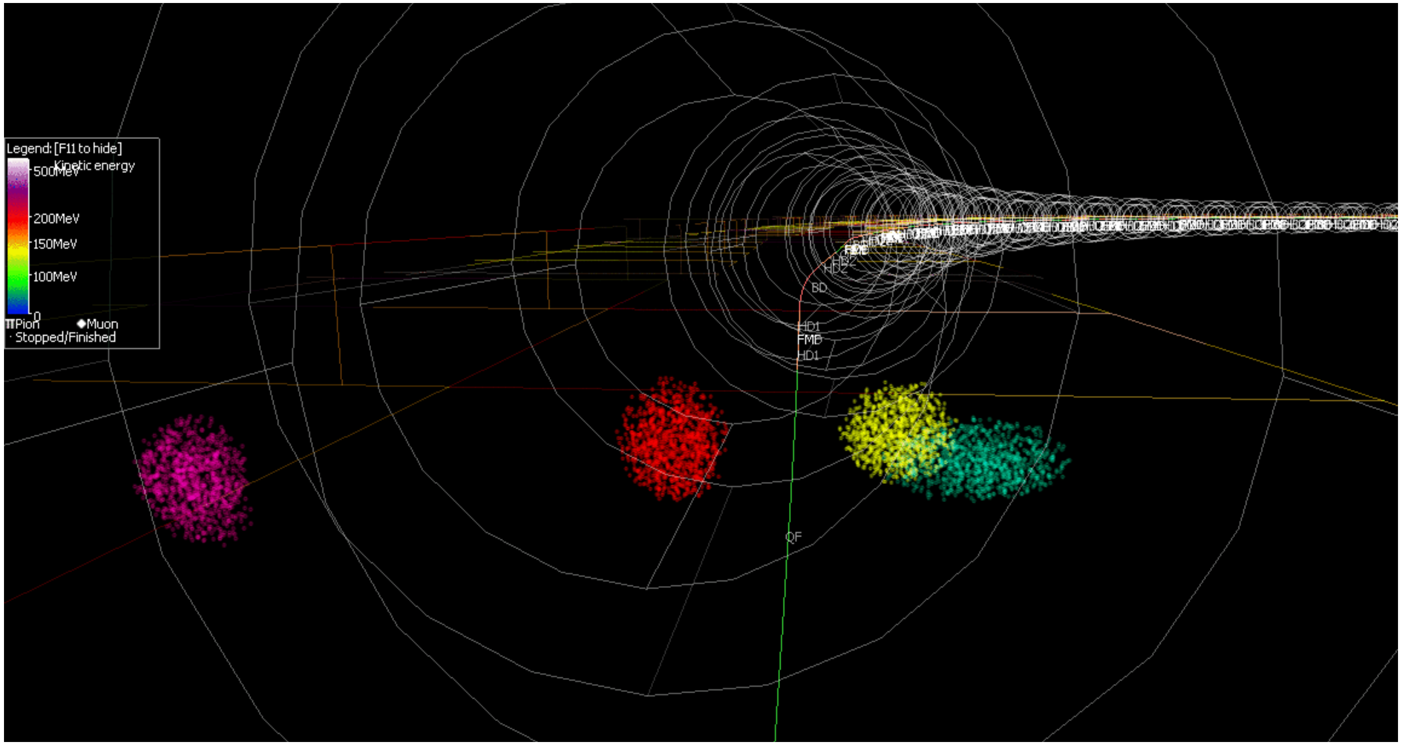
- Uses existing 6 MeV low-emittance and high-current injector and 48.5 MeV CW SRF Linac
- Energy Recovery Linac (ERL) with single four-pass recirculation arc with x4 momentum range
- Permanent magnets used for recirculation arc
- Adiabatic transitions from curved to straight sections





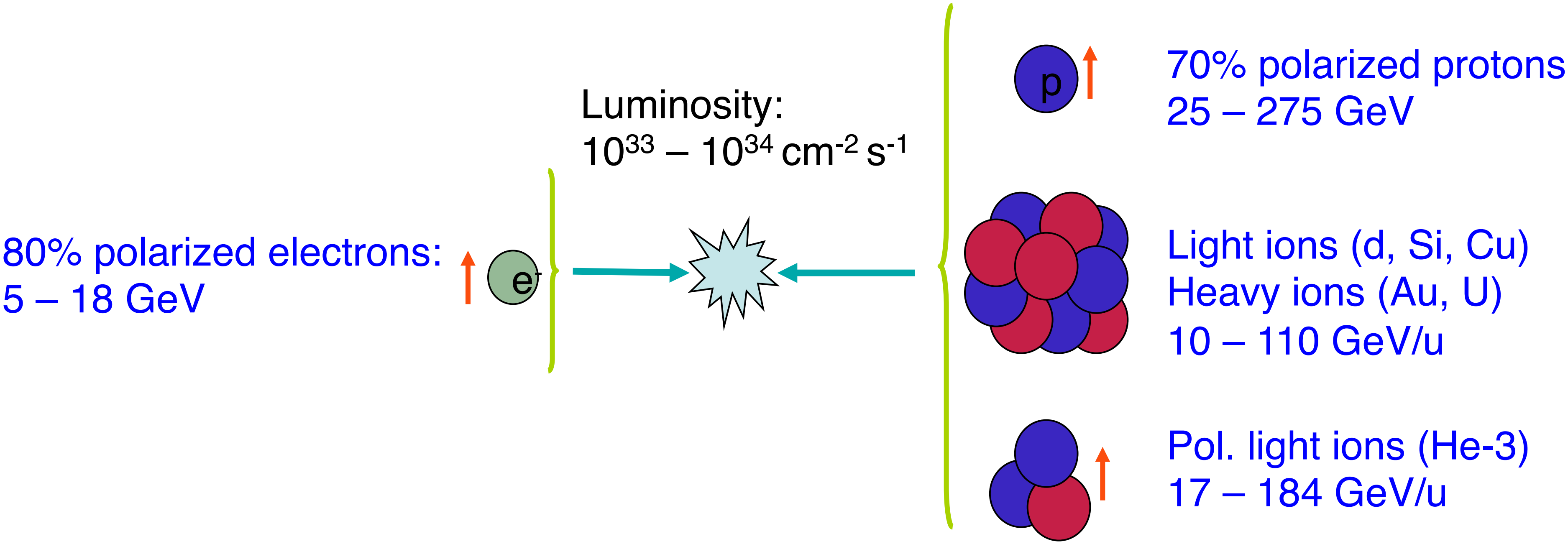
Multi-energy Beam Transport (FFAG Arcs)

- Up to 4 re-circulations of the electron beam through one beam line using novel Fixed Field Alternating Gradient (FFAG) lattice
- Permanent magnet technology is used for the FFAG beam-line magnets eliminating the need for power supplies, power cables and water cooling.

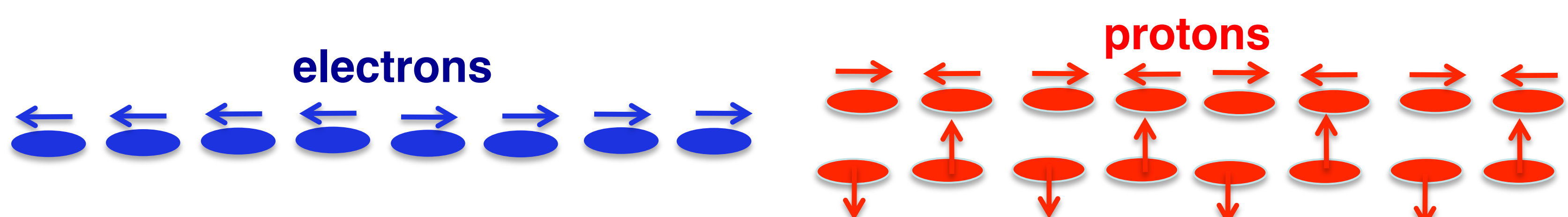


Simulation and animation by Stephen Brooks

eRHIC: Electron Ion Collider at BNL

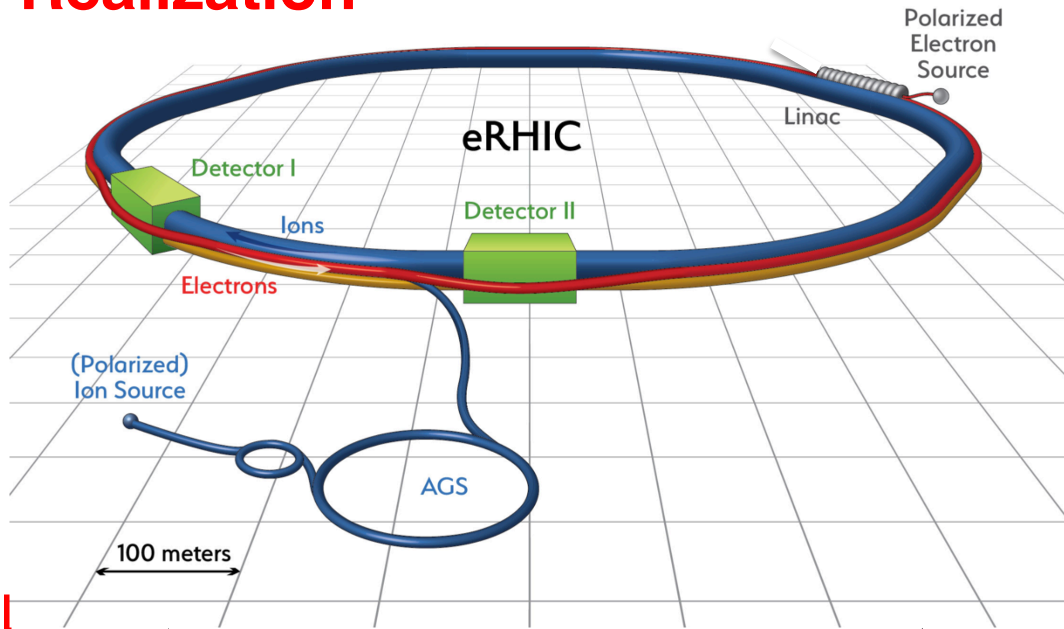


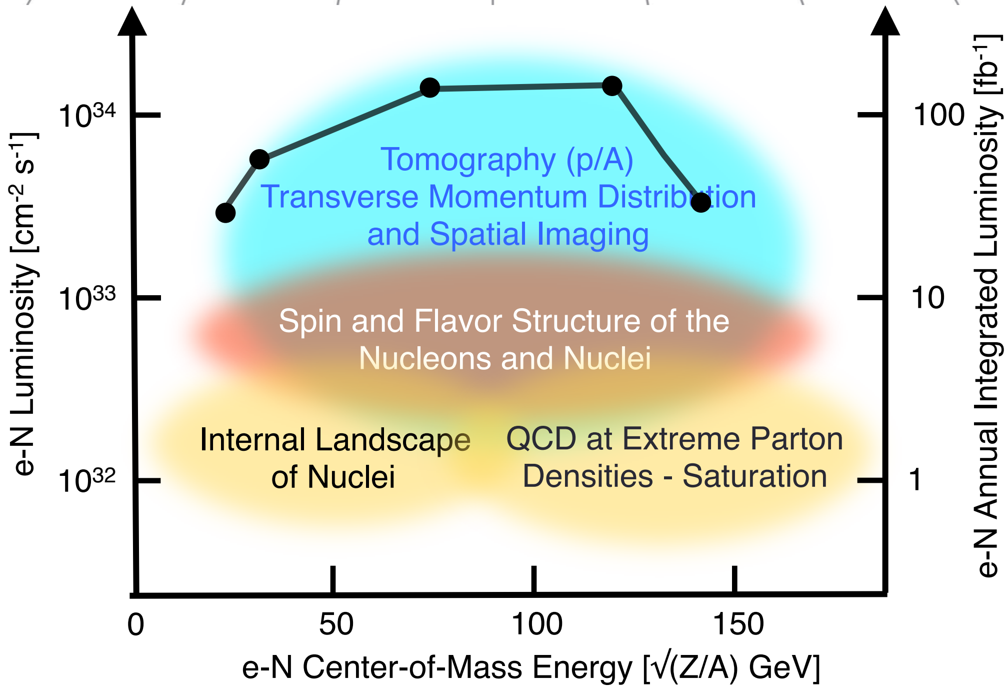
- Center-of-mass energy range: 20 – 140 GeV
- Full electron polarization at all energies
  Full proton and He-3 polarization with six Siberian snakes
- Any polarization direction in electron-hadron collisions:



eRHIC Realization

- **Use existing RHIC**
  - Up to 275 GeV protons
  - Existing: tunnel, detector halls & hadron injector complex
- **Add 18 GeV electron accelerator in the same tunnel**
  - Use either high intensity Electron Storage Ring or Energy Recovery Linac
- **Achieve high luminosity, high energy e-p/A collisions with full acceptance detector**
- **Luminosity and/or energy staging is possibile**





Summary

Brookhaven has a 70-year history and a bright future at the forefront of accelerator science and technology in support of the research needs of the Nation and with many applications for society.