ION COLLIDER PRECISION MEASUREMENTS WITH DIFFERENT SPECIES

Gregory Marr

RHIC FY2018 Run Coordinator

Collider-Accelerator Department

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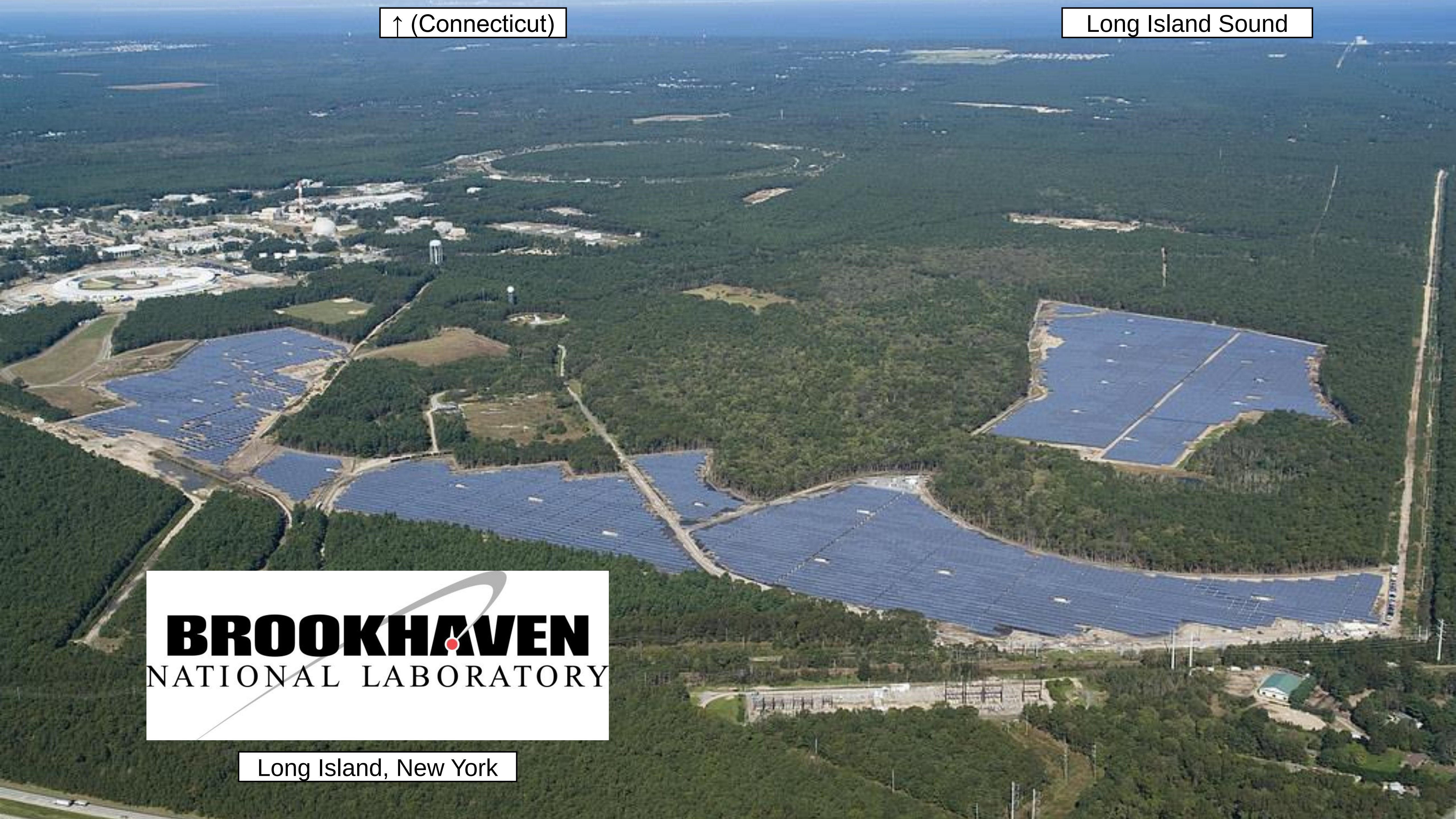

↑ (Connecticut)
Long Island Sound
BROOKHAVEN
NATIONAL LABORATORY
Long Island, New York

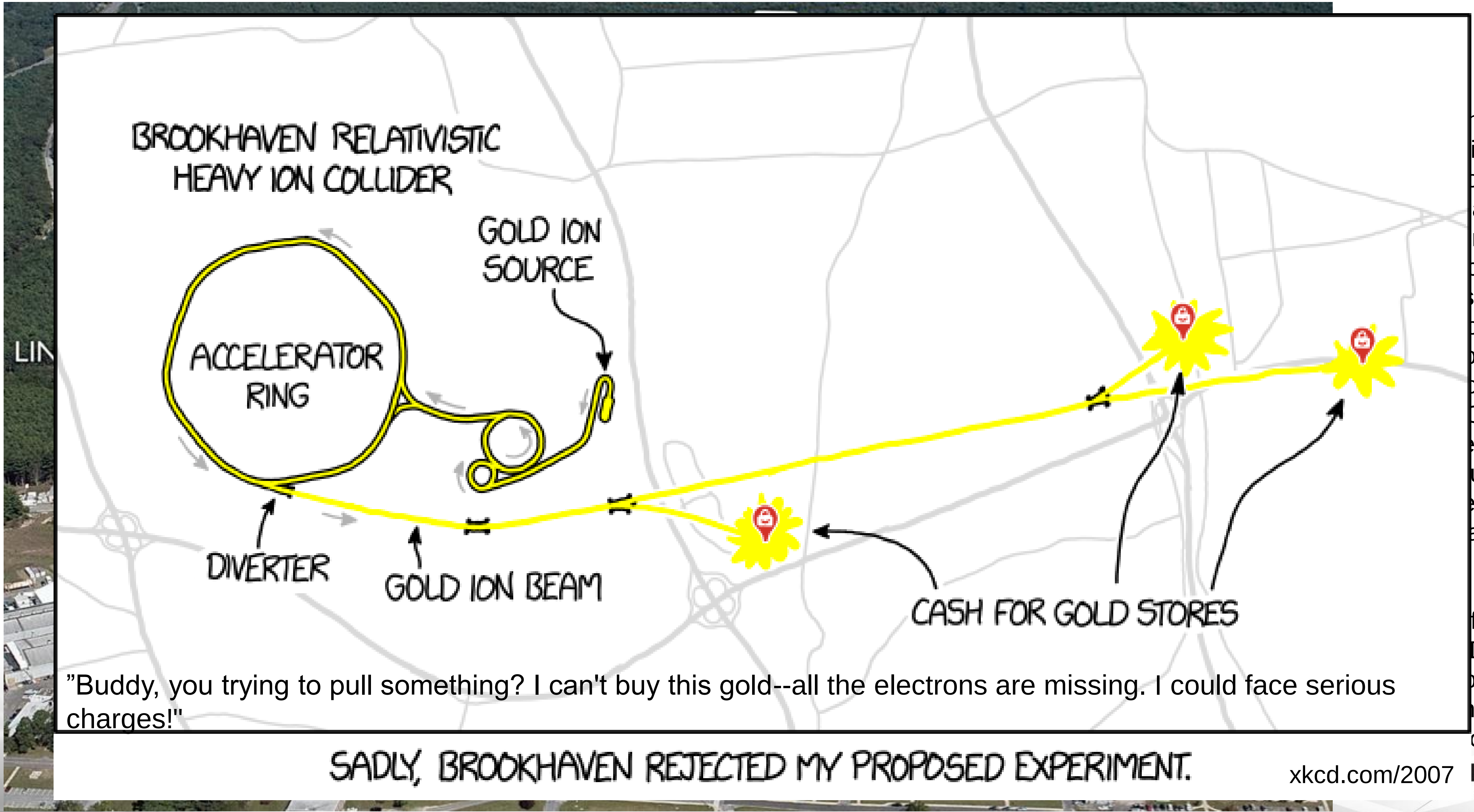
Brookhaven National Laboratory

Many scientific facilities in the disciplines of

- Physics
- Chemistry
- Biology
- Environmental & climate science
- Nanomaterials
- Scientific computing

- Photon Sciences
- High energy and nuclear physics…

The Collider-Accelerator Complex at BNL



"Buddy, you trying to pull something? I can't buy this gold--all the electrons are missing. I could face serious charges!"

xkcd.com/2007

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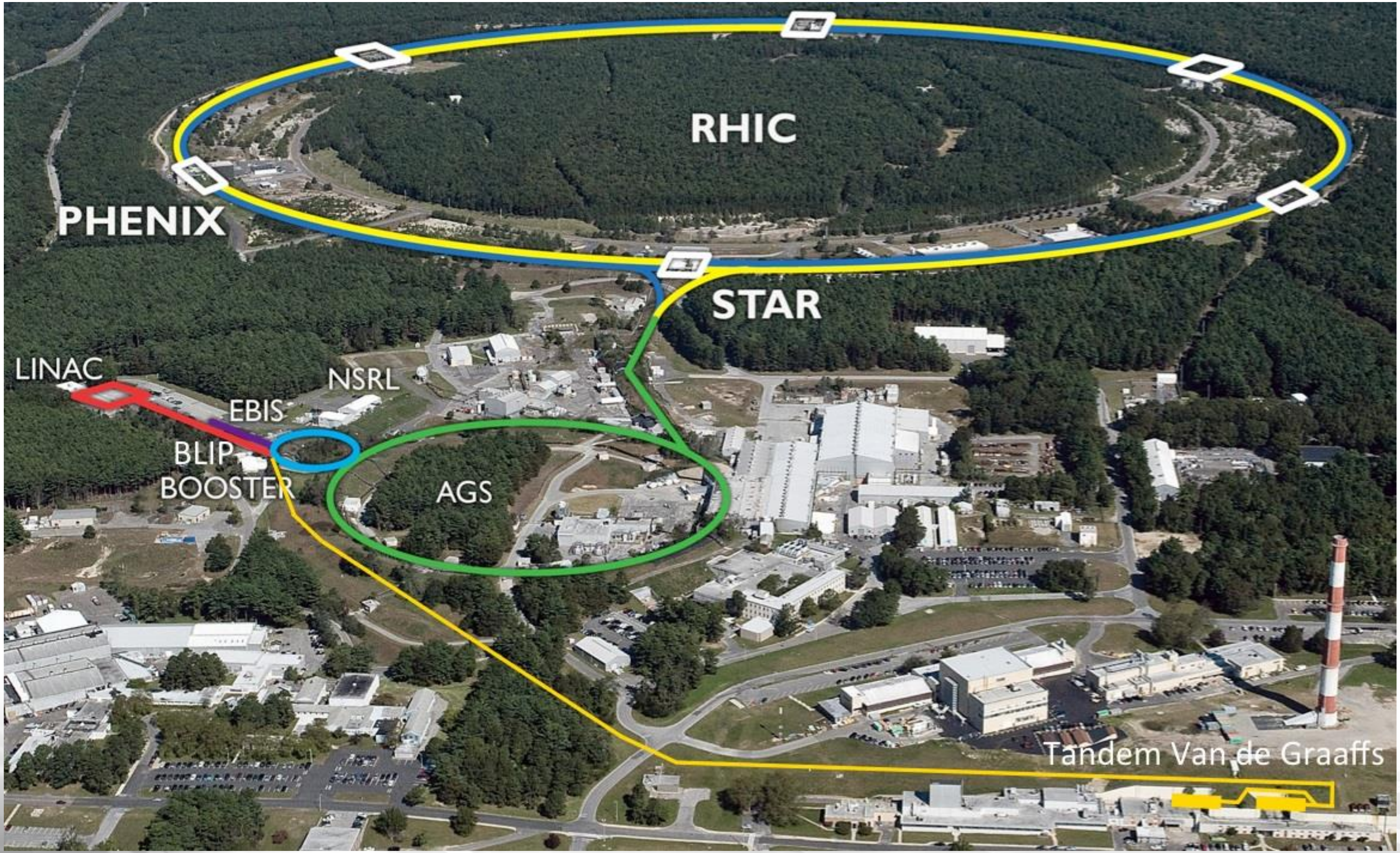

In Operation

- Up to 7 ion sources & 5 electron beams
- 2 linear accelerators
- 2 Tandem Van de Graaf accelerators
- 6+ transfer lines
- 2 electron lines
- 2 injector rings
  - Booster
  - AGS
- 2 collider rings
  - Blue
  - Yellow
- Accelerator Test Facility

Oversight of R&D projects

- Source Development
- Superconducting RF
- Electron-ion collider
- And much more…

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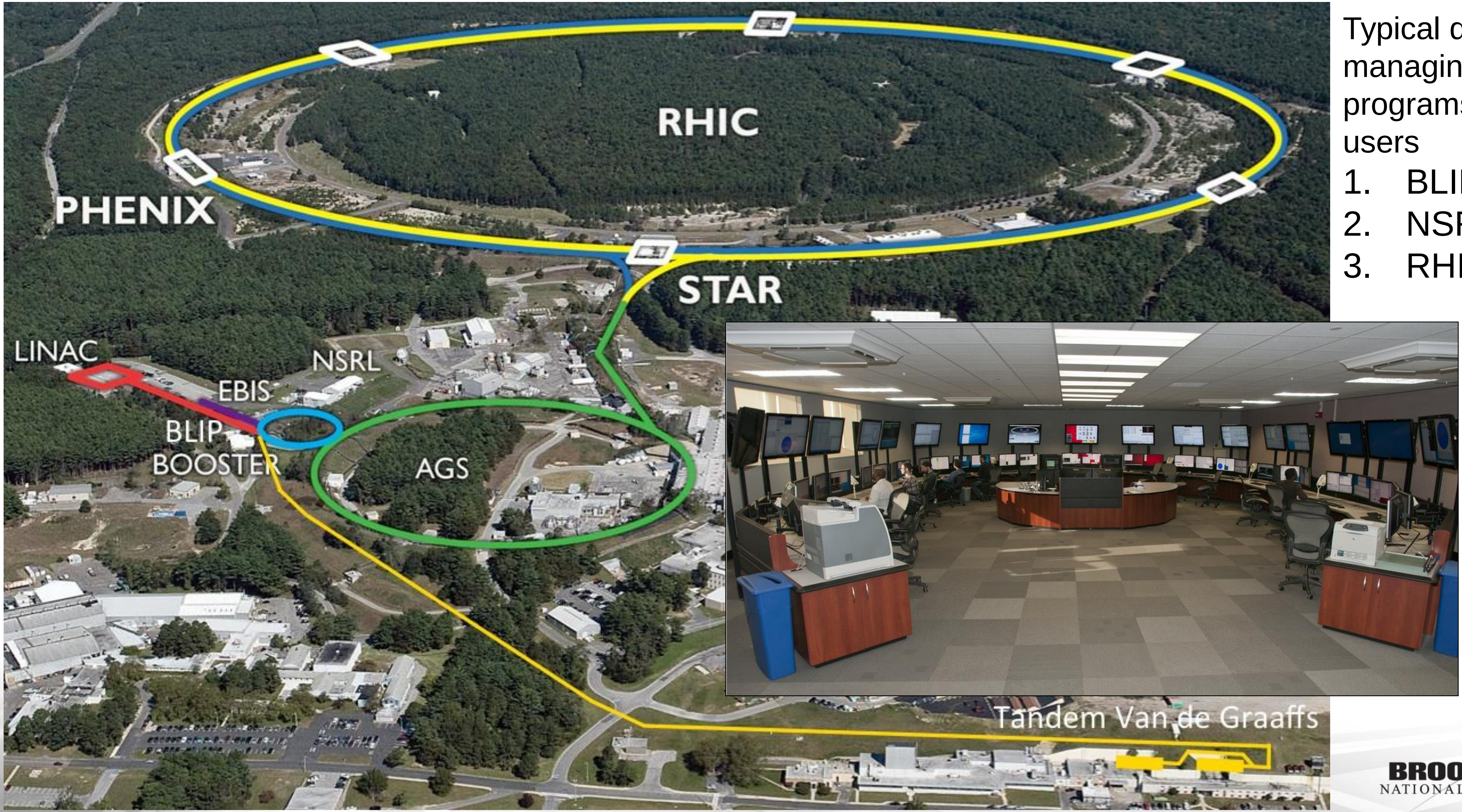
The Collider-Accelerator Complex at BNL



Typical day in MCR: managing 3 programs for end users

1. BLIP
2. NSRL
3. RHIC

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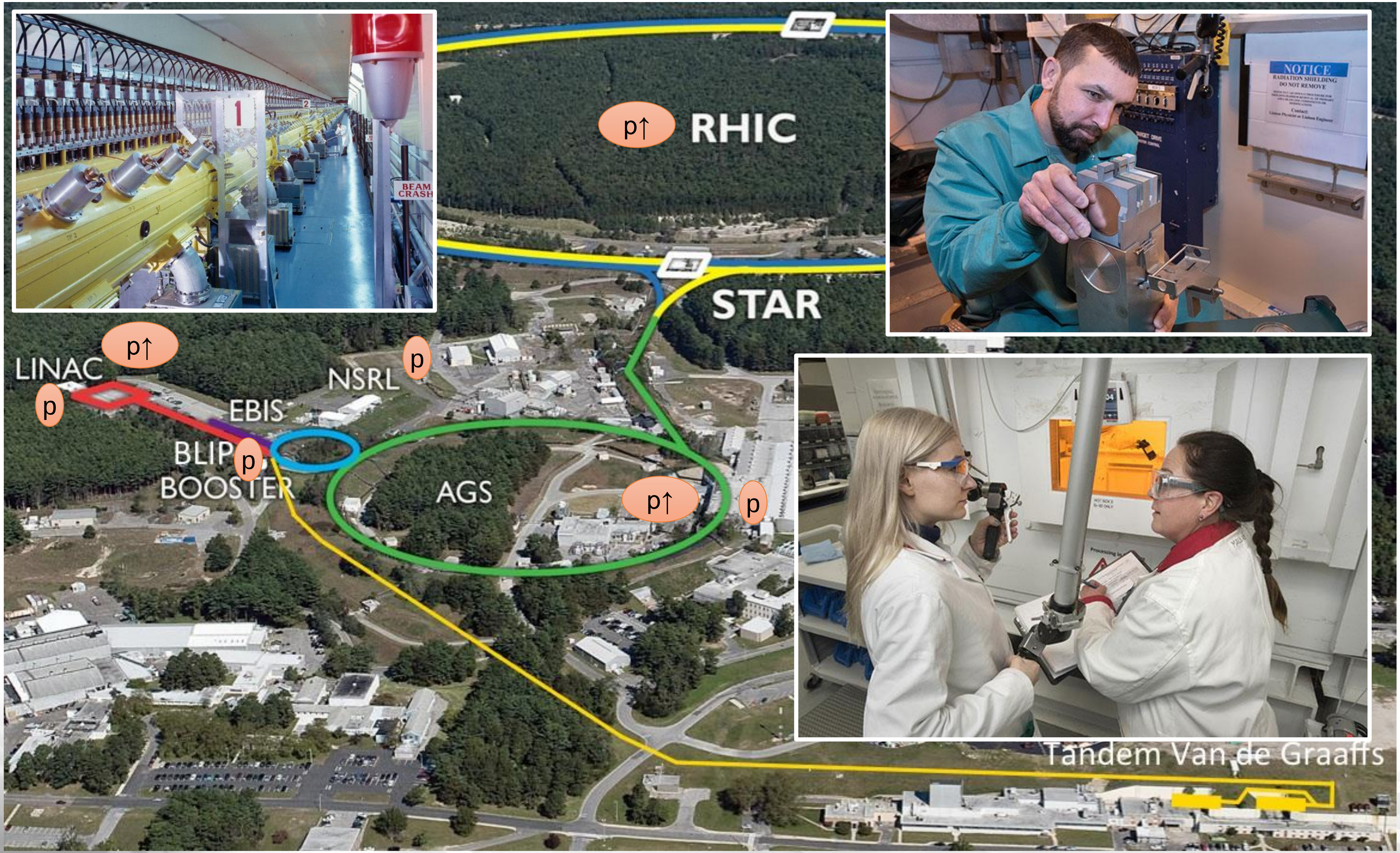
The Collider-Accelerator Complex at BNL



Brookhaven Linac Isotope Producer

- Part of Medical Isotope Research & Production (MIRP) Program
- Target station off of 200 MeV H^- Linac
- Proton source used complex-wide, separate polarized proton source
- *Tuned with various saved setups for multiple energies & intensities*

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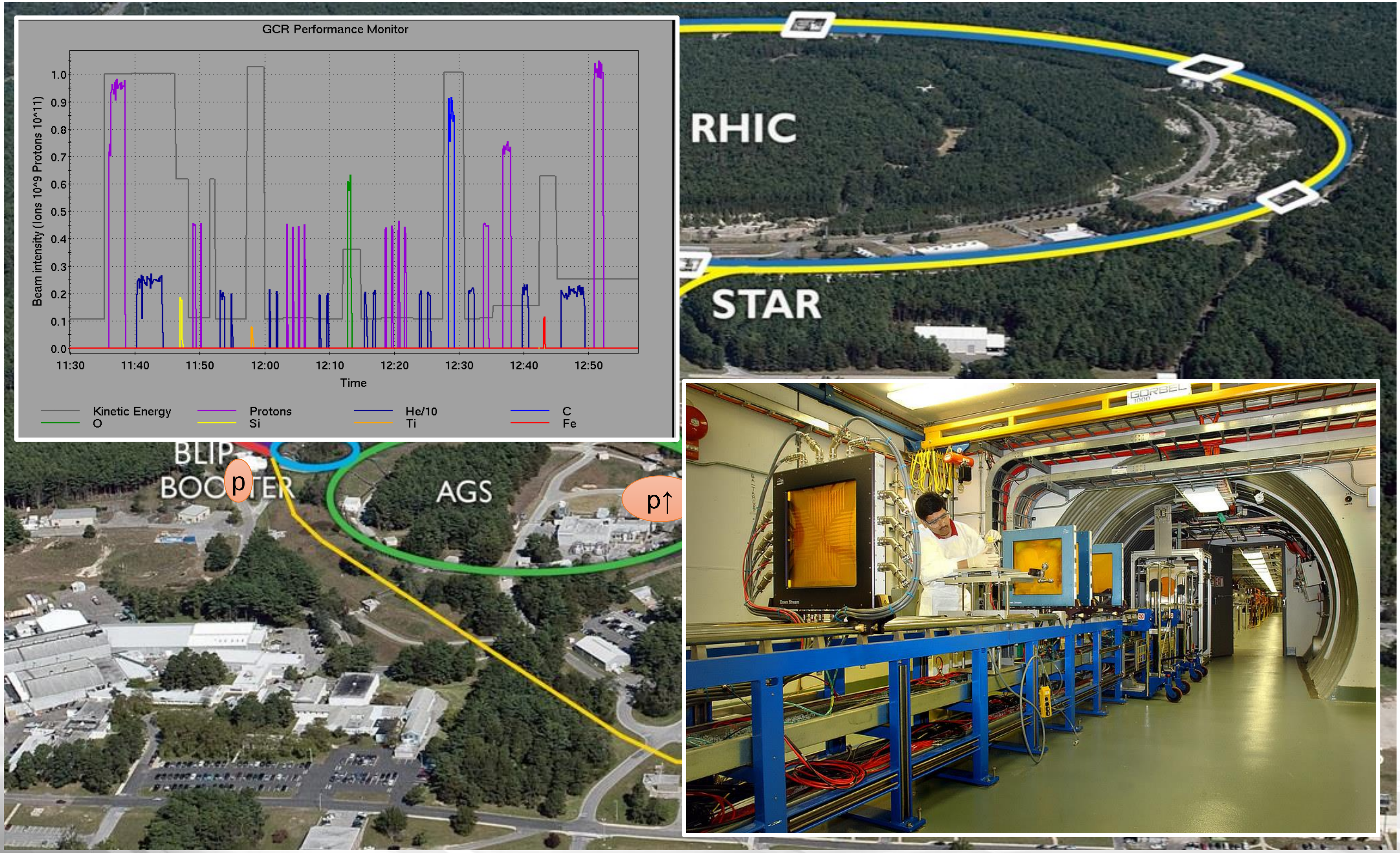
The Collider-Accelerator Complex at BNL



NASA Space Radiation Laboratory

- Fixed target line off of Booster synchrotron
- Uses Linac protons, Tandem ions, EBIS ions, 50-1500MeV
- ***Requires multiple species setups at multiple energies***
- ***Requires rapid switching (~minute) between setups***
- GCR – Galactic Cosmic Ray simulations

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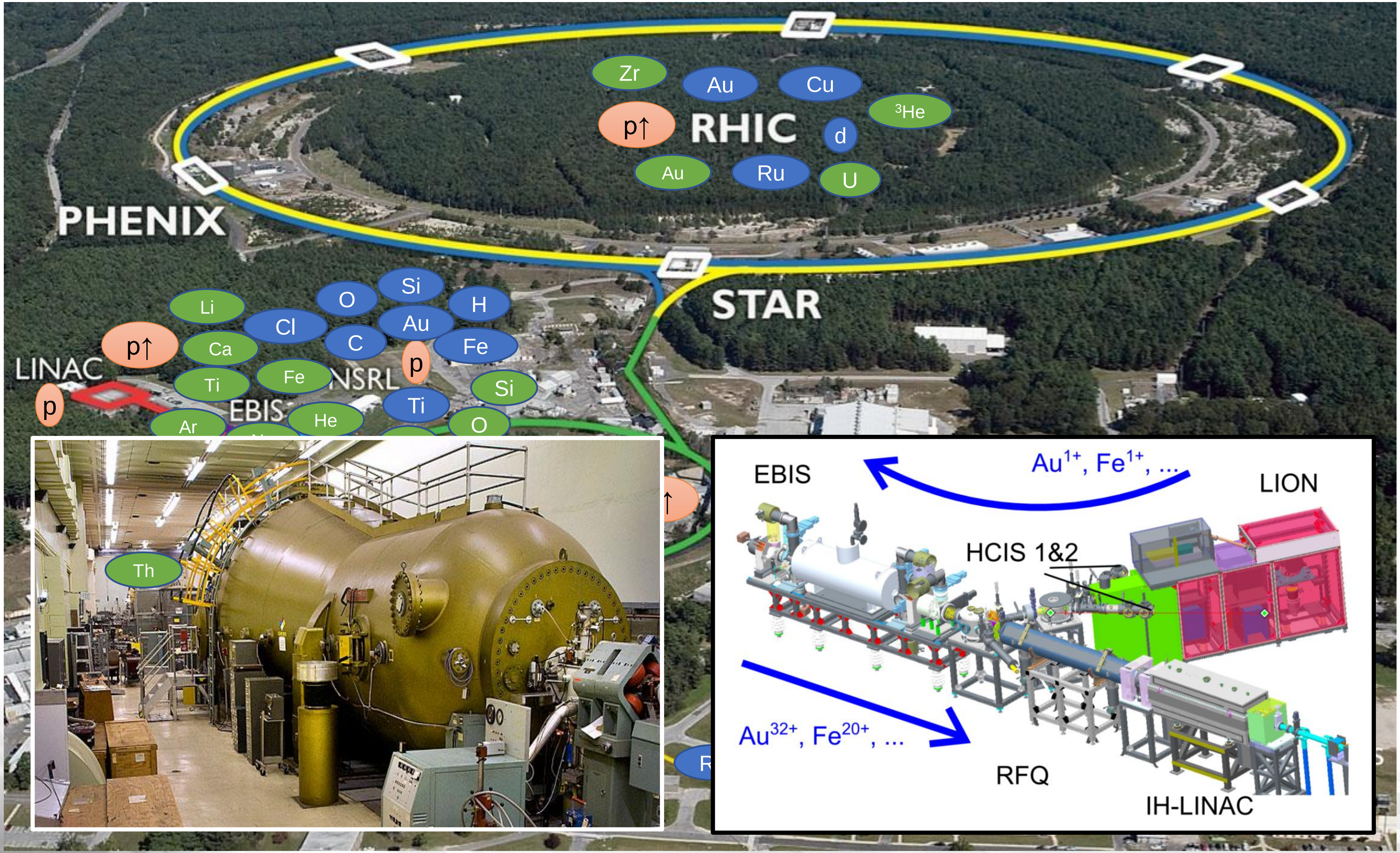
Heavy Ion Sources: History+Progress



Tandems

- 15MV electrostatic accelerators with a long history (1960s) providing various beams for testing and heavy ion physics programs

EBIS

- Electron Beam Ion Source
- 2 Hollow Cathode Sources (HCIS)
- Laser Ion Source (LION) targets allow for selection of many species
- Providing multiple ion species within seconds

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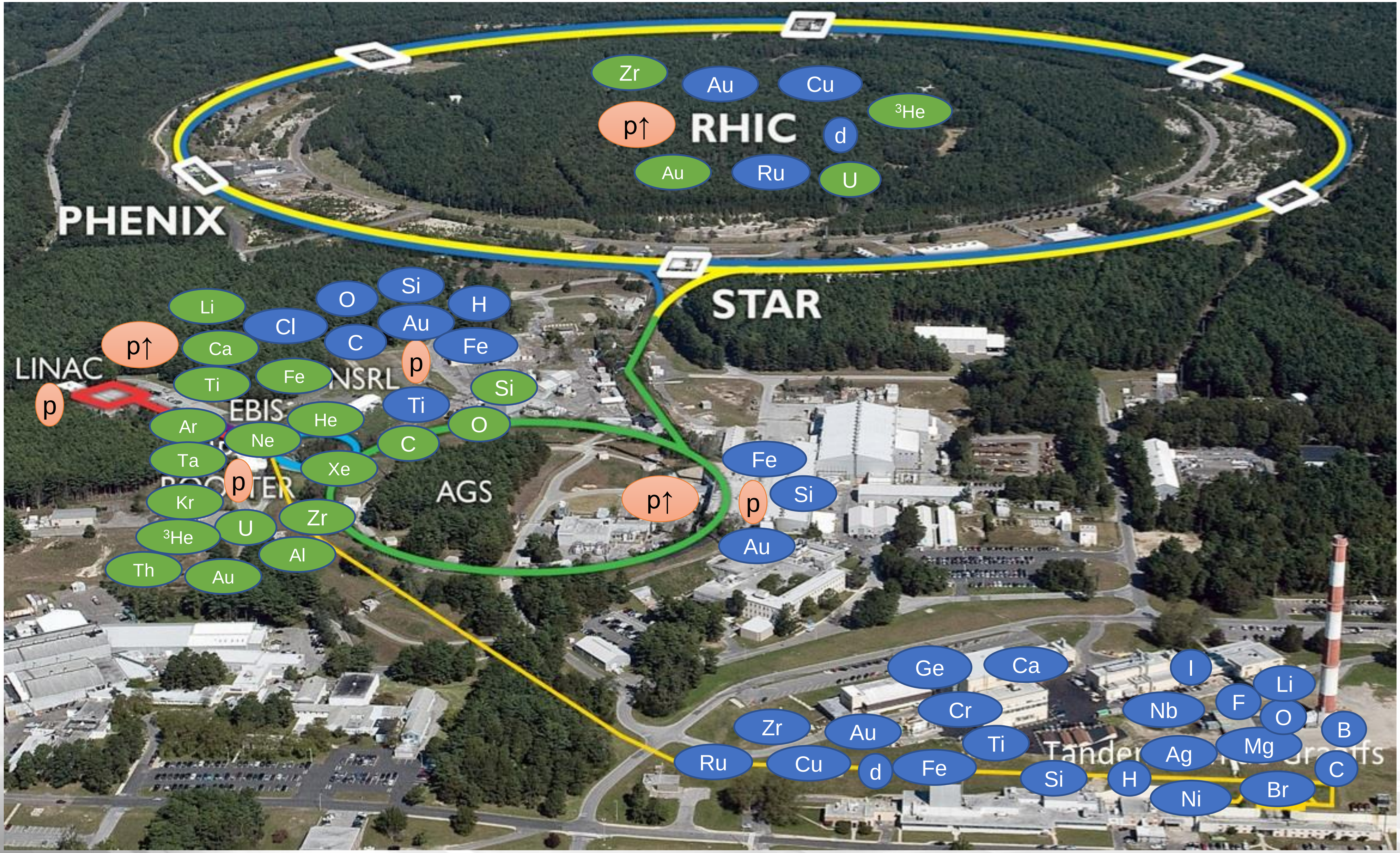
Heavy Ion Sources: History+Progress



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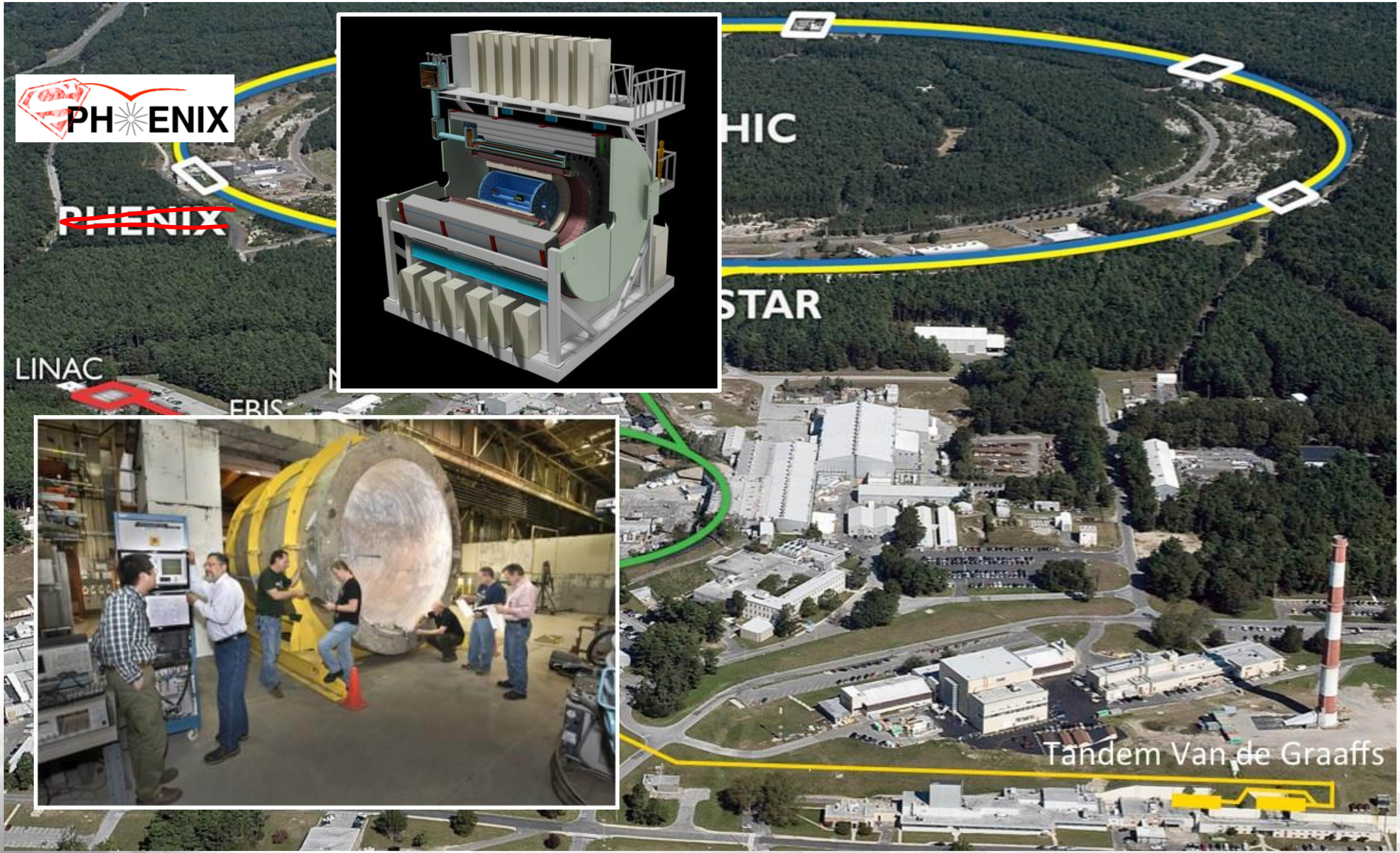
Relativistic Heavy Ion Collider: its 18th year



So far:

- p, d, h, Al, Cu, Au, U, (and now) Ru, Zr ions
- Beam energies 3.85-100 GeV for experiments
- Polarized protons up to 255 GeV

For Run-18

- PHENIX experiment upgrade in progress: superconducting solenoid
- LEReC: Electron cooling of low energy Au beams
    - Commission e$^-$ beam
    - (MOPRB085)
    - (WEPRB103)
    - And more…
- CeC: Coherent electron cooling experiment
    - (TUXXPLS1)
    - (MOPMP050)
    - (TUPTS078)
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- Electron lens: more tests
- **STAR: Solenoidal Tracker At RHIC.**

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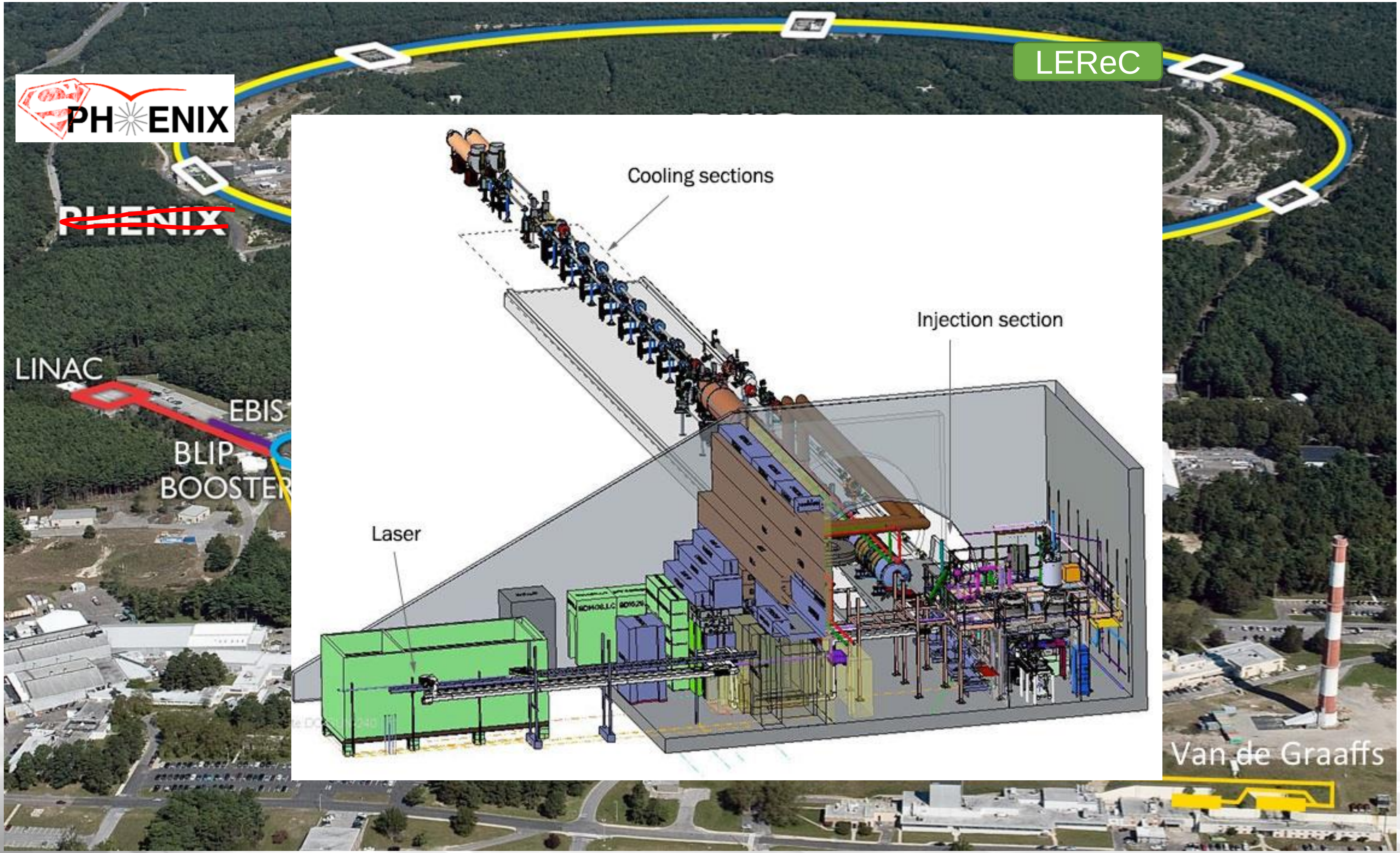

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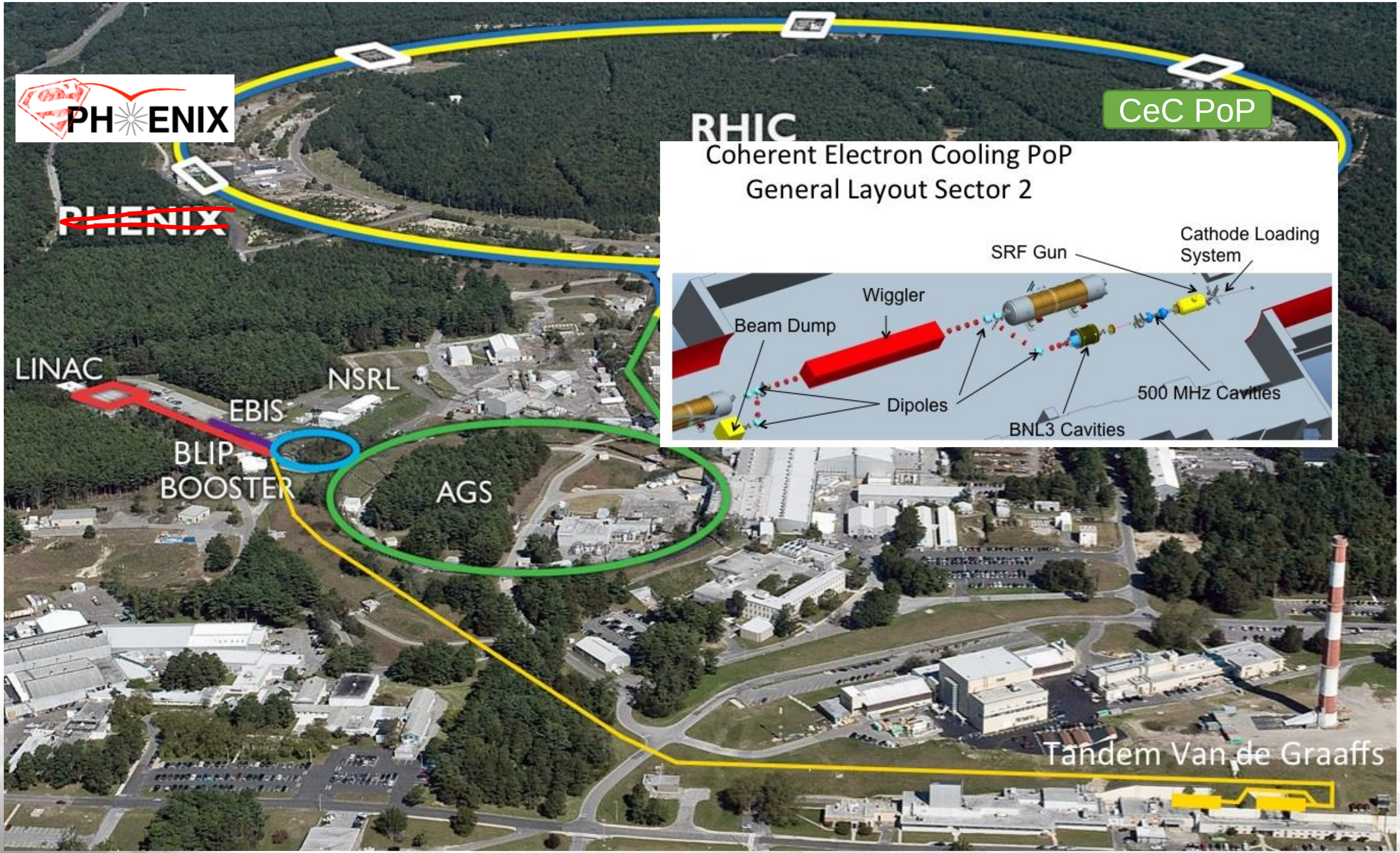

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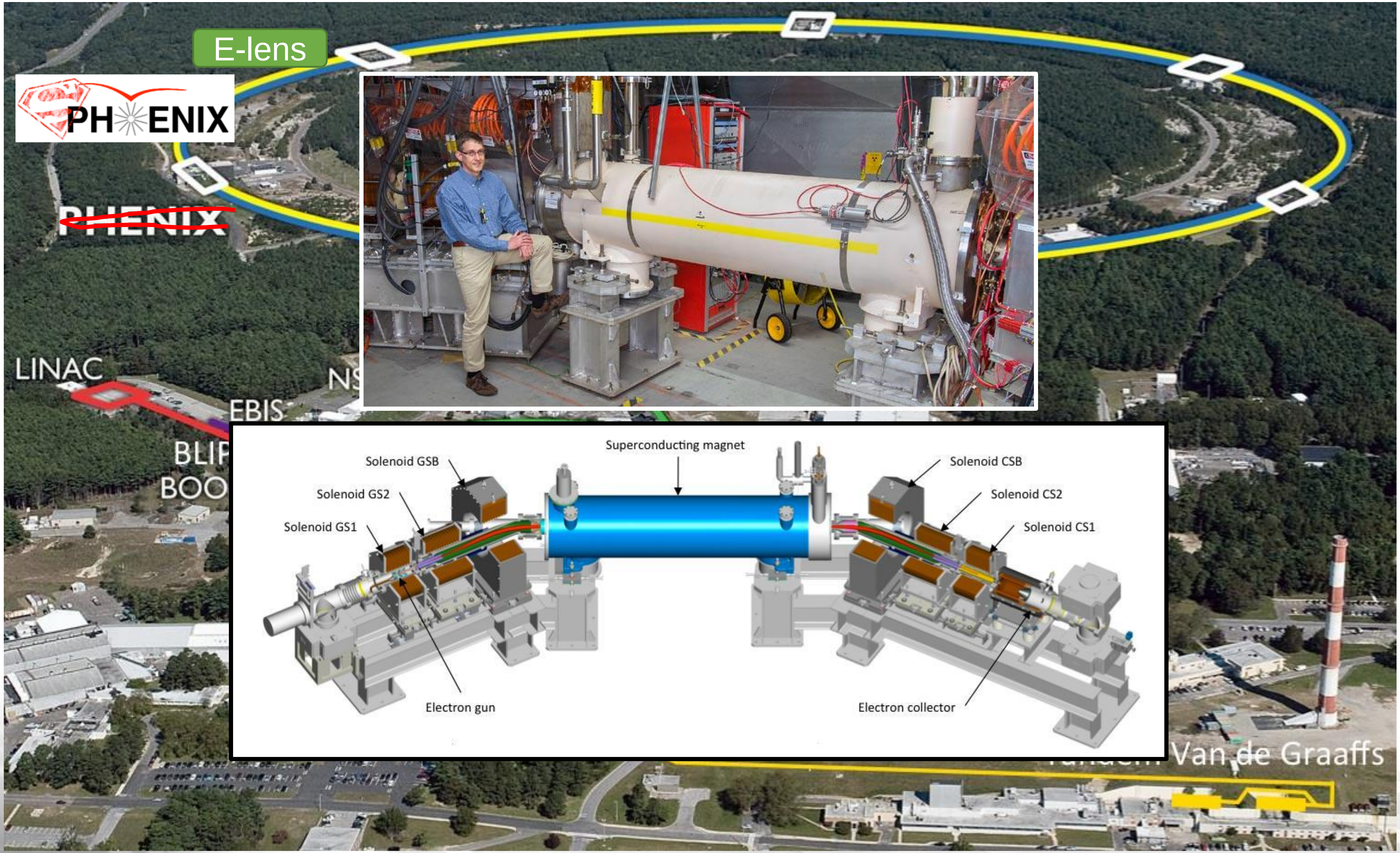

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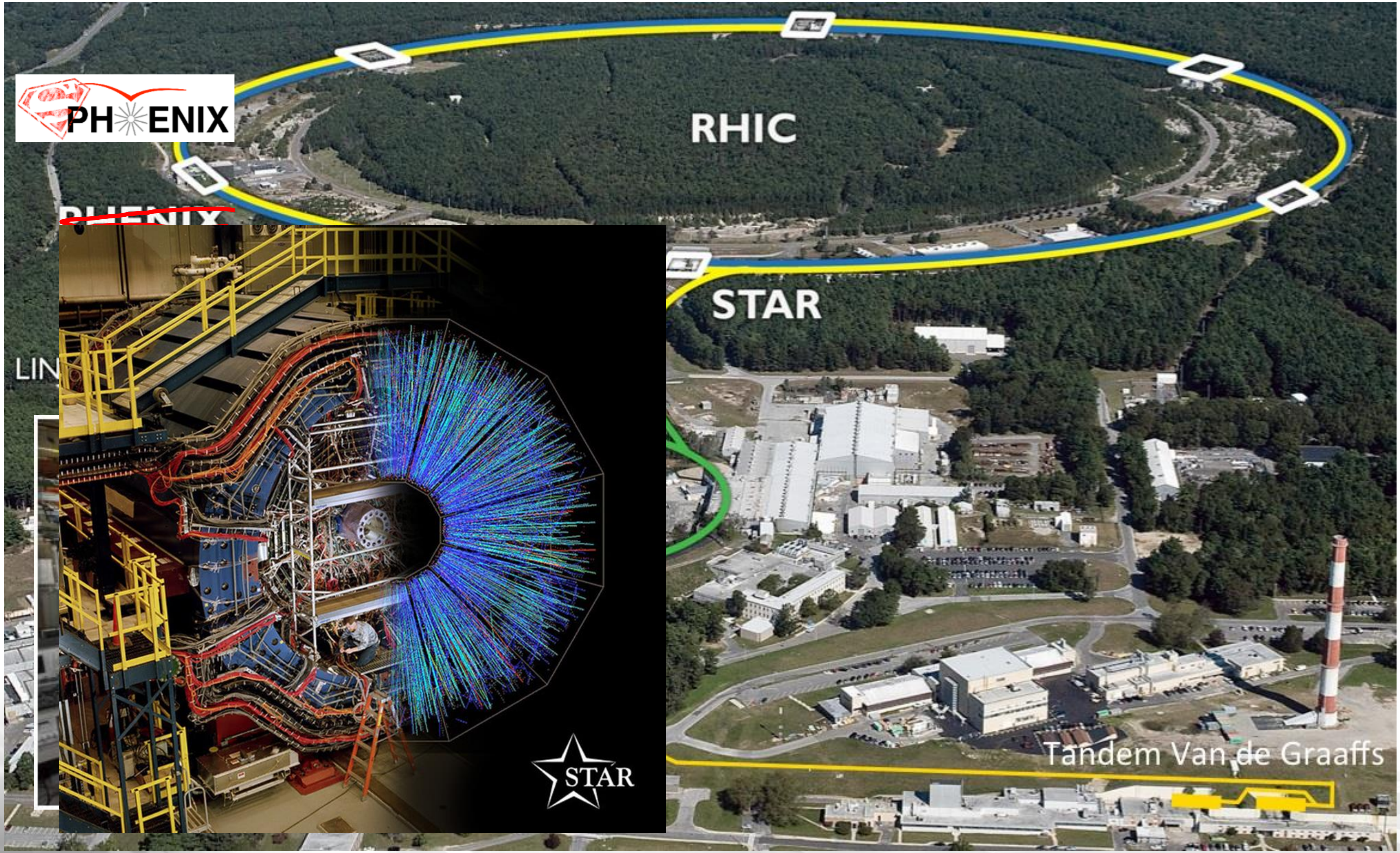

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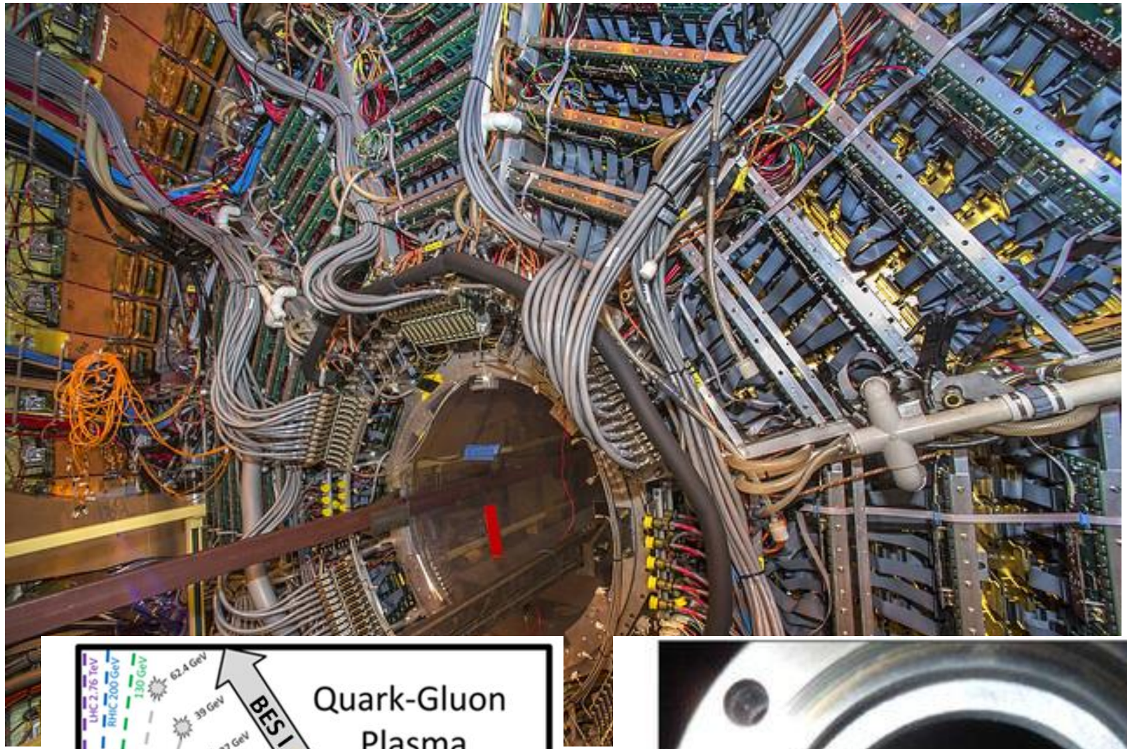
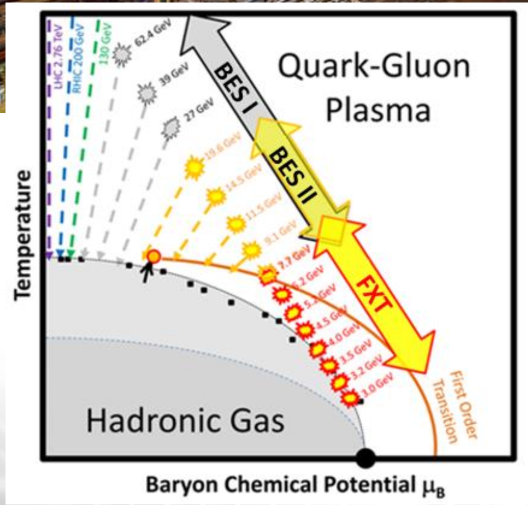
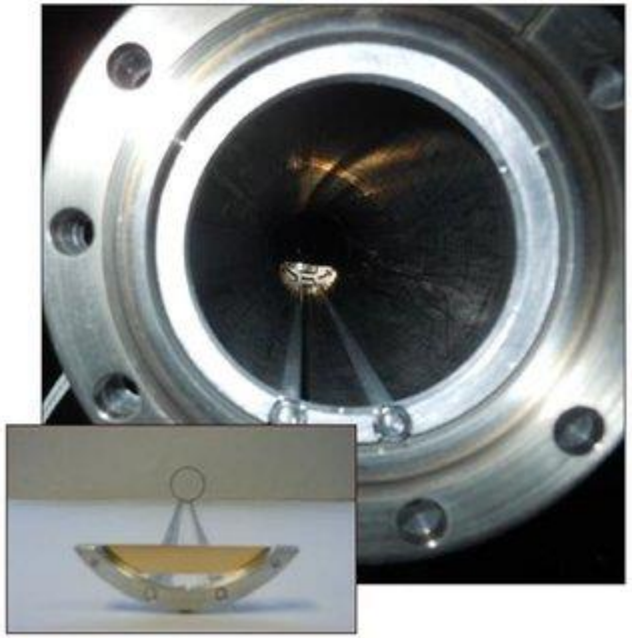
Run-18: STAR experiment proposal





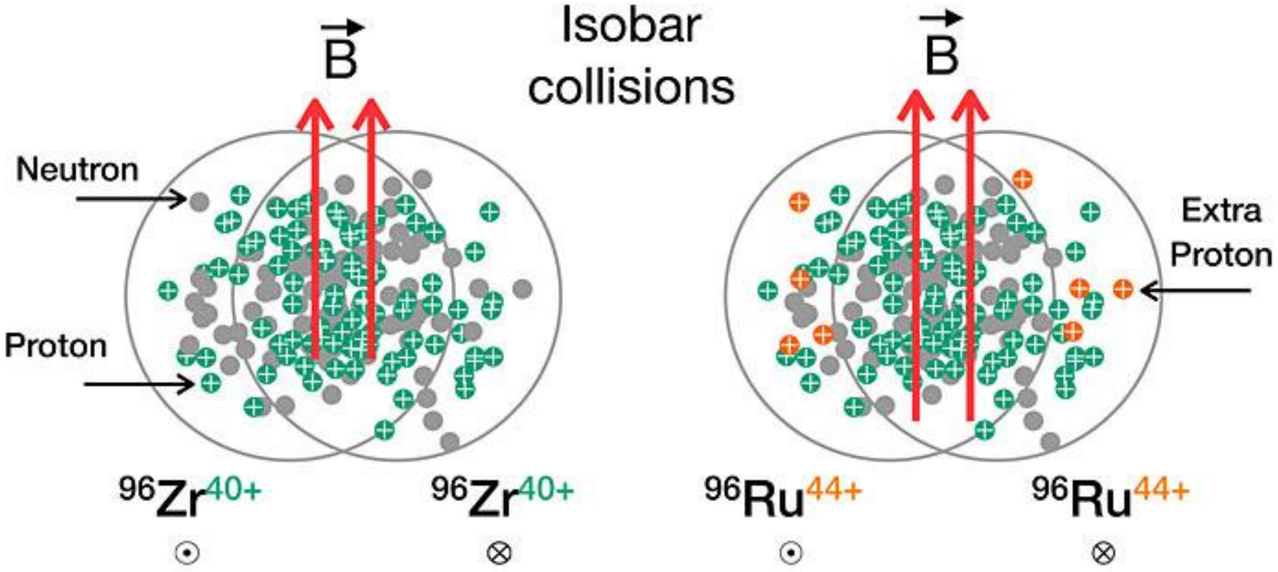


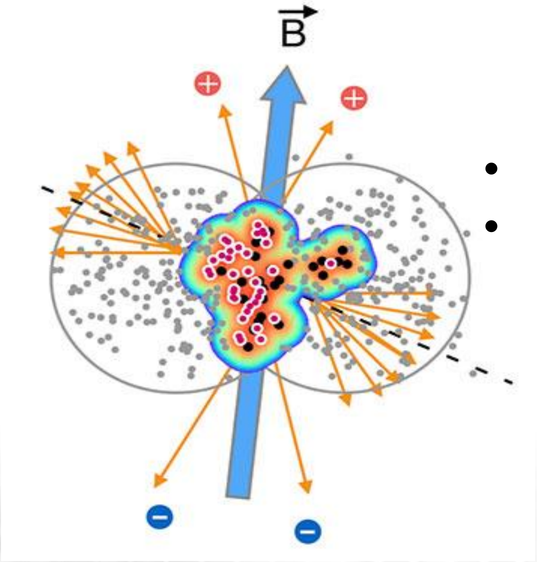
- **“STAR’s highest scientific priority for Run 18 is the successful realization of the isobaric collision program.”**
  - “Collisions of isobaric nuclei, i.e. $^{96}Ru^{44+}$ + $^{96}Ru^{44+}$ and $^{96}Zr^{40+}$ + $^{96}Zr^{40}$, present a unique opportunity to vary the initial magnetic field by a significant amount while keeping everything else almost the same. Therefore, isobaric collisions will play a decisive role in verifying/falsifying the CME.”
- “STAR’s second highest priority for Run 18 is Au+Au collisions at $\sqrt{s_{NN}}$ = 27 GeV…”
- “STAR’s third highest priorities for Run 18 are Au+Au collisions at $\sqrt{s_{NN}}$ = 3.2 GeV in ‘fixed target’ mode.”
- “In Run 19 STAR proposes to initiate the BES-II.” (Beam Energy Scan 2, collisions at lower energies)

STAR Note SN0670, May 15, 2017

Chiral Magnetic Effect (CME)

- A phenomenon in Quark-Gluon Plasma (QGP), affecting subatomic particles with different “handedness” (chirality)
- Electric charge separation occurs along the direction of the strong magnetic field produced by spectator protons.
- Previously investigated at RHIC and LHC: Au+Au, Cu+Cu, U+U, Pb+Pb, others…





- Isobar collisions proposed to disentangle CME from other background effects
- Systematic error concerns raised by STAR experiment
  - Ideally, compare 2 data sets with ONLY 1 difference: 10% charge difference between species – all other collision geometries equal (# of ions, beam size, etc.)
  - Eliminate distortion in detector measurements ~~> constant event rates, & equal between Zr & Ru
  - Detector drift issues – fatigue, temperature, diurnal, seasonal effects…

Run-18 Overview

Run 18 was in many ways a unique and challenging heavy ion run for the Collider. This year involved four different configurations of the Physics program:

- ***100 GeV $^{96}Zr^{40+}$ x 100 GeV $^{96}Zr^{40+}$***
- ***100 GeV $^{96}Ru^{44+}$ x 100 GeV $^{96}Ru^{44+}$***
- ***13.5 GeV $^{197}Au^{79+}$ x 13.5 GeV $^{197}Au^{79+}$***
- ***3.85 GeV $^{197}Au^{79+}$ Fixed Target Operation*** *(Yellow ring only)*

Additionally, we continued support of the coherent electron cooling proof of principle (CeC PoP) experiment with its own configuration:

- ***26.5 GeV $^{197}Au^{79+}$*** *(Yellow ring only)*

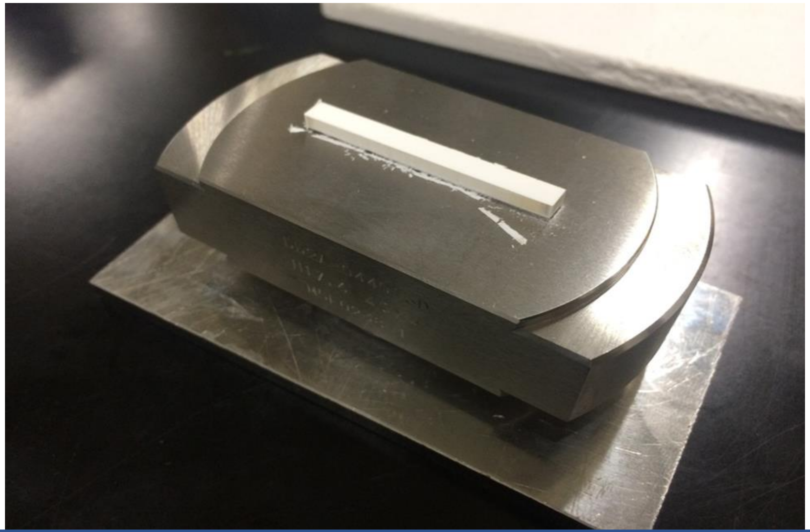
Commissioning of the low energy RHIC electron cooling system (LEReC) also took place.

Zirconium and Ruthenium

- The isobar run required our ion sources produce beams from two rare isotopes:
  - **^{96}Zr** – 2.8% natural abundance
  - **^{96}Ru** – 5.5% natural abundance
- Neither source material (ZrO_2 at EBIS, Ru metal at Tandem) produces sufficient beam intensity (>1x10^9 ions/bunch) as required by the RHIC, unless enriched.
- Complications:
  - Enriched ^{96}Ru was not available in any sufficient quantity.
  - Enriched ^{96}Zr is commercially available, but ZrO_2 powder does not make a good target for EBIS laser ion source.

Zirconium and Ruthenium: more precious than Gold

With assistance from experts at RIKEN, Japan, six enriched ^{96}Zr targets were made, employing their expertise in the sintering process.

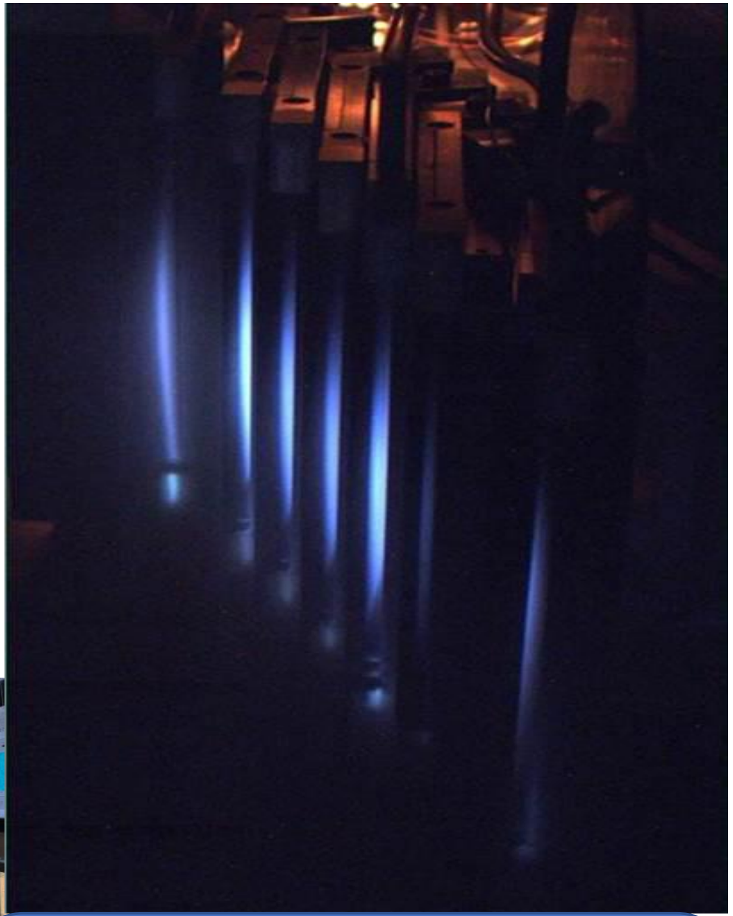


Part of sintering process at RIKEN to form solid ZrO_2 targets for EBIS. Image courtesy of RIKEN

Sidenote: $^{96}Zr^{16+}$ and $^{90}Zr^{15+}$ have the same rigidity in Booster. We could save on enriched material by tuning up EBIS and Booster with a source of natural Zr.

With the facility just coming online, the DOE Isotope Program provided 500mg of ^{96}Ru, with a dedicated production run at the Enriched Stable Isotope Pilot Plant (ESIPP) at Oak Ridge.

At 25% abundance (mixed at Tandem with ^{27}Al), this source produced more than sufficient intensity for the needs of this run.

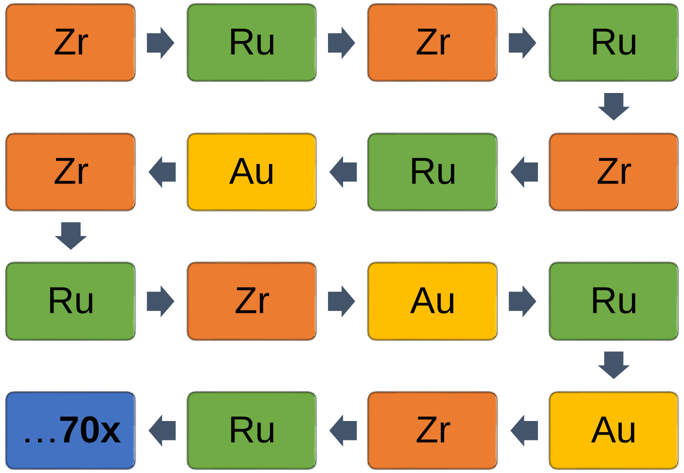


Electromagnetic separation of ^{96}Ru. Image courtesy of ESIPP at ORNL.

Teamwork!

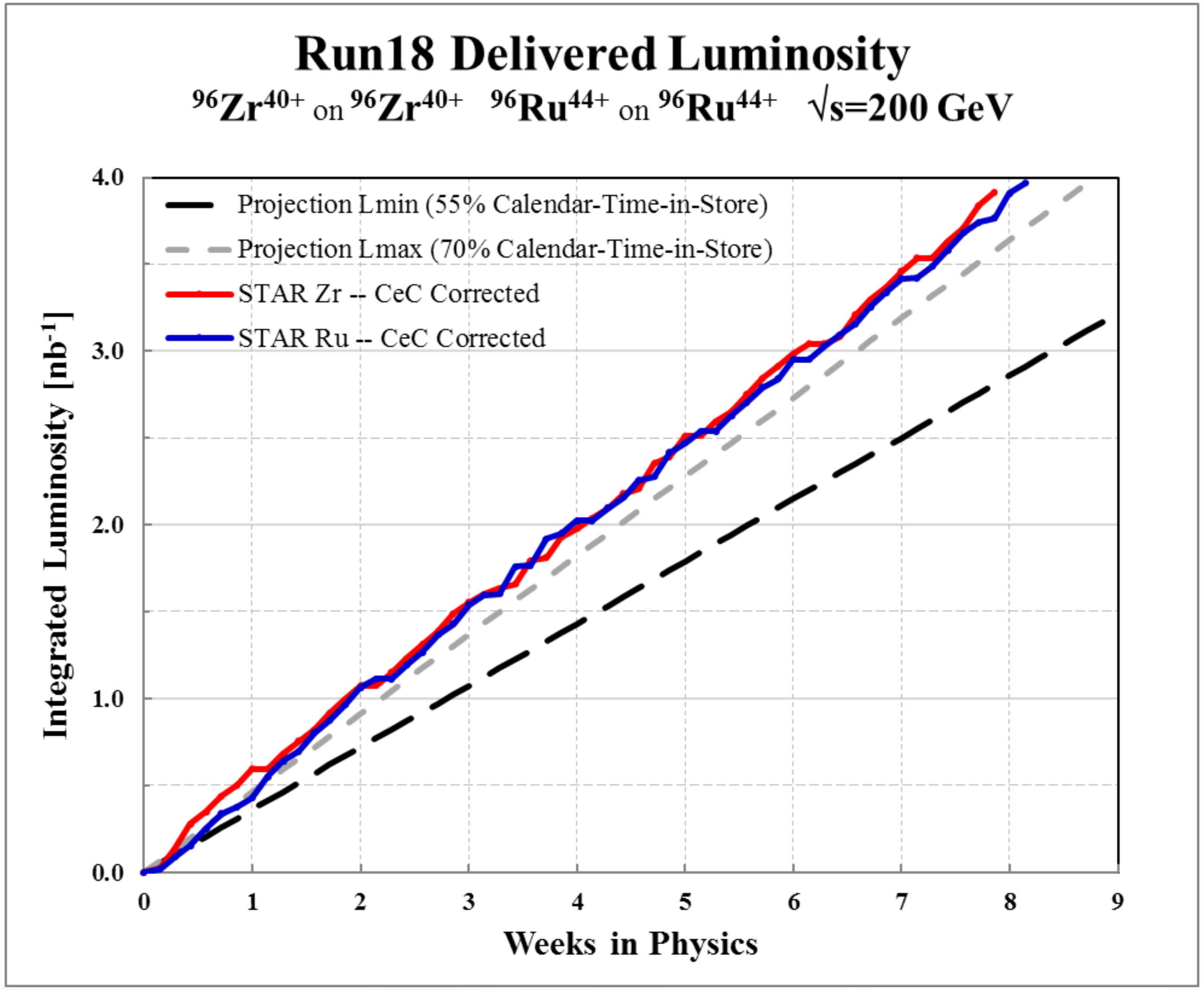
Mode switching

- To further eliminate systematics, the request was made to alternate daily between species.
- There are over a million parameters in our control system
  - It can be difficult to keep track of all that is necessary to change between different RHIC setups
  - It's a time-consuming process to accomplish manually.
- Expanding use of software previously developed to make quick changes to injector setups (GCR), we were able to create sequences to switch the RHIC between Zr, Ru, and Au modes, and identify the relevant parameters to save and reload when changing species.
- With little additional cost in setup and store-to-store time, this was one key to producing high integrated luminosity for Run 18.



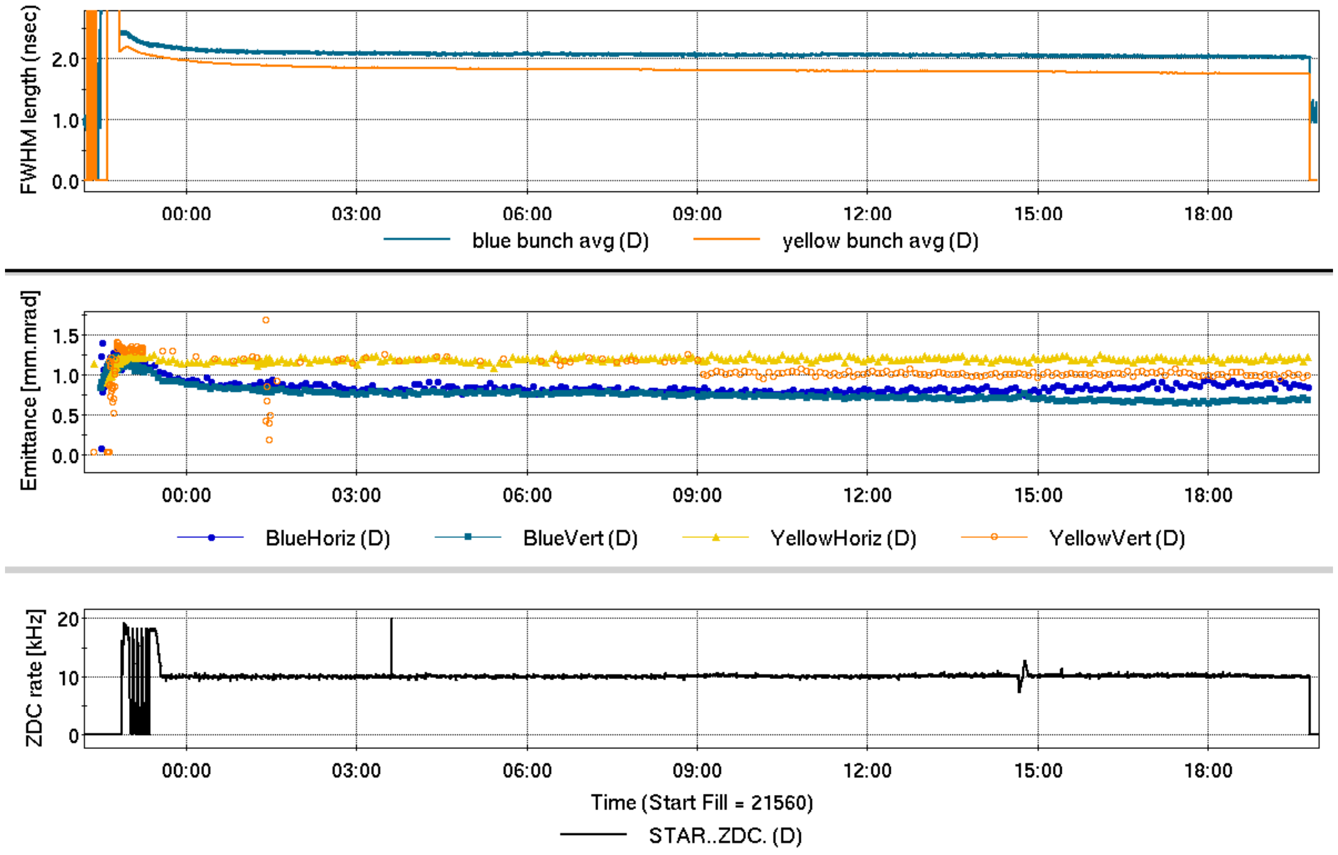
Results: 200 GeV Ru & Zr

- Setup three (Ru, Zr, Au) beams, started physics in 6 days
  - A new record for beam setup (for one beam -- we set up 3)
  - First time RHIC had 3 different species within same 24 hours
  - Includes 2 snowstorms (unscheduled)
- Regular switching incurred minimal delays (~5 min/store)
- Exceeded projected luminosity, which helped STAR accumulate a larger data set than originally planned



Level luminosity

- Pursuant to systematic concerns, the initial request from STAR was to maintain level ZDC rates at 10 kHz, ±5 kHz over the course of a store.
- Other parameters (intensity, emittance, etc.) needed to be as repeatable as possible from store to store as well between Zr and Ru.
- We were able to maintain 10 kHz, ***±0.5 kHz*** for over 20 hours.
  - Initial beam intensity allowed for mis-steering beams, automatically adjusting to maintain collision rates
  - Stochastic cooling applied to maintain beam emittance during store.



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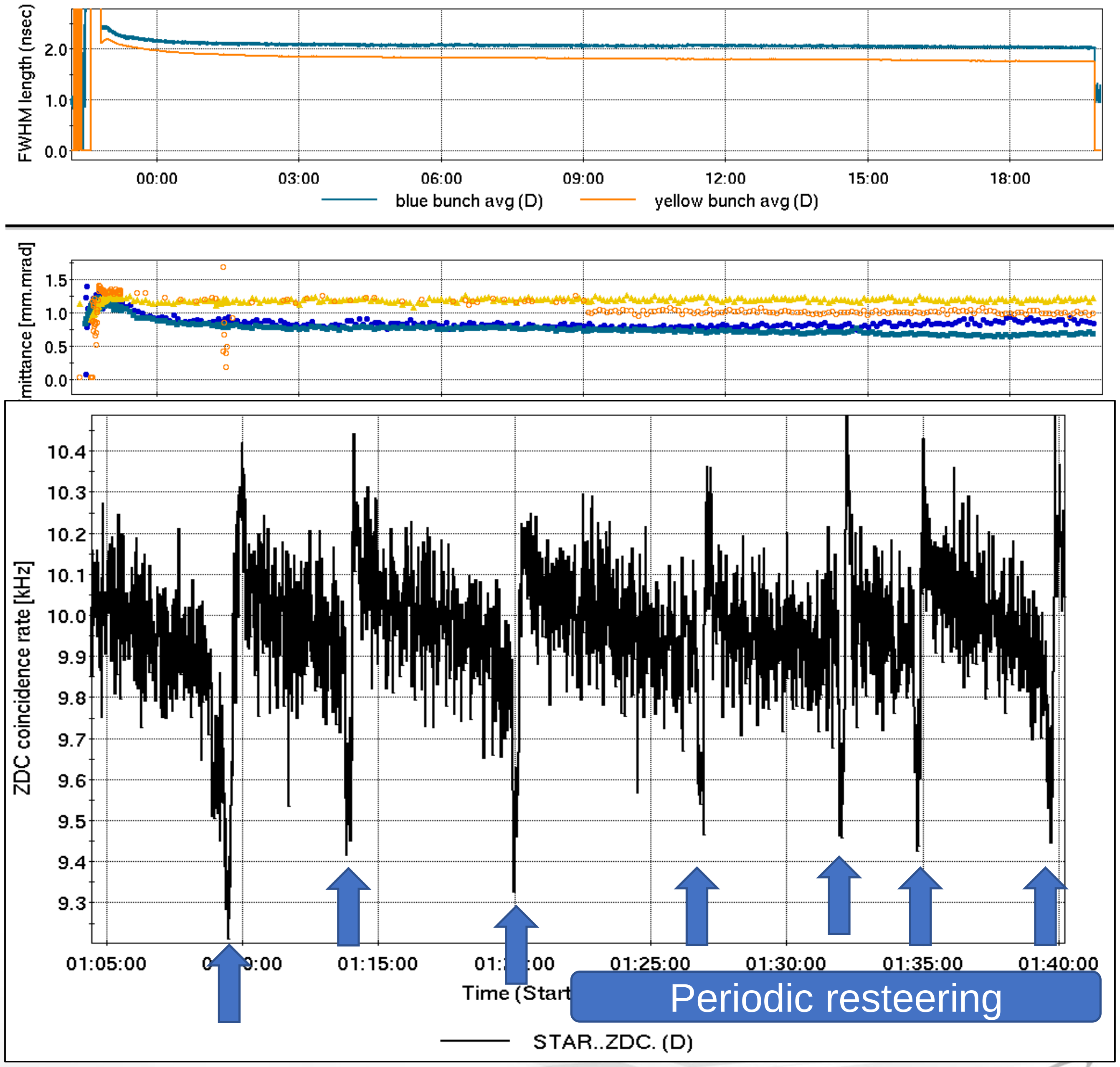
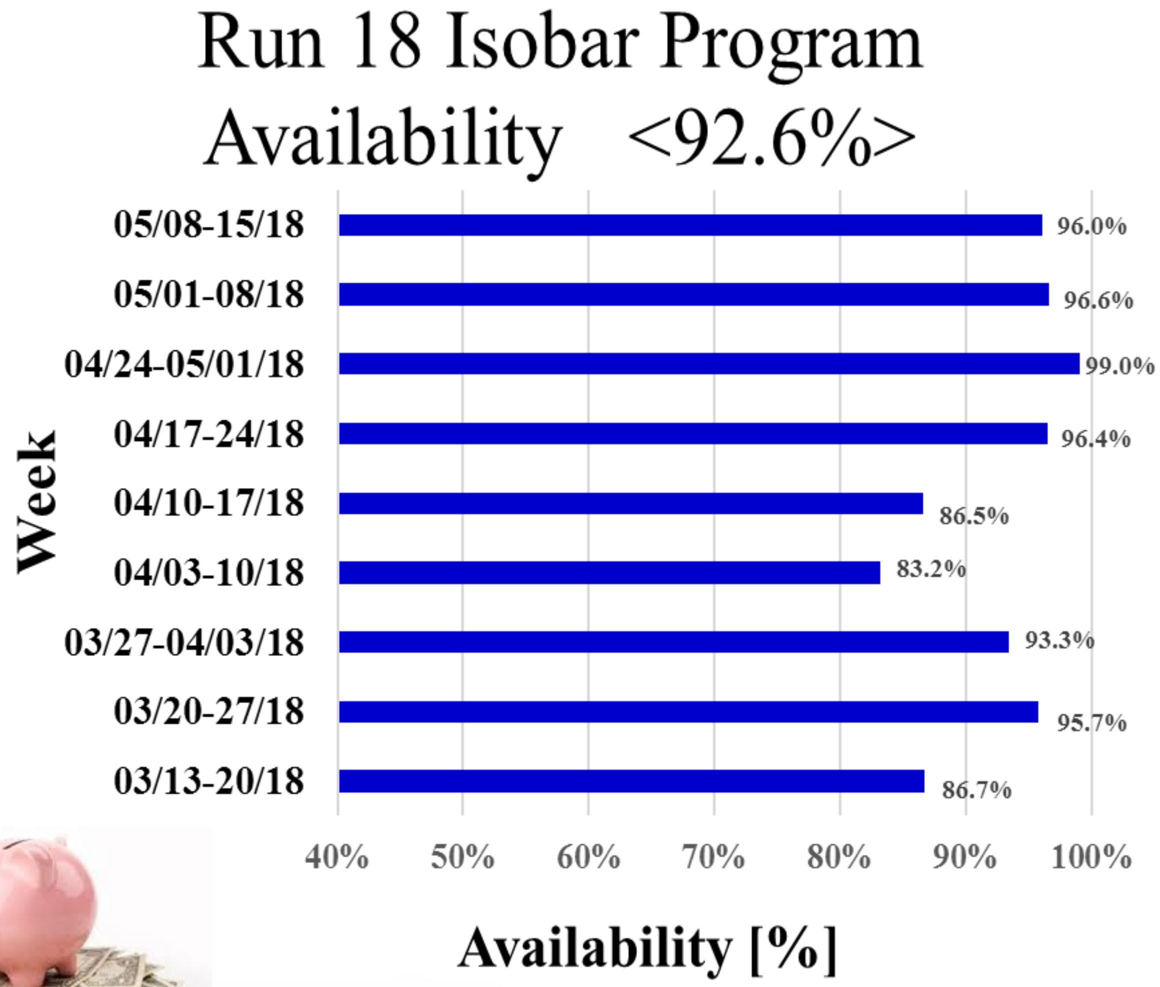


Operational Analysis

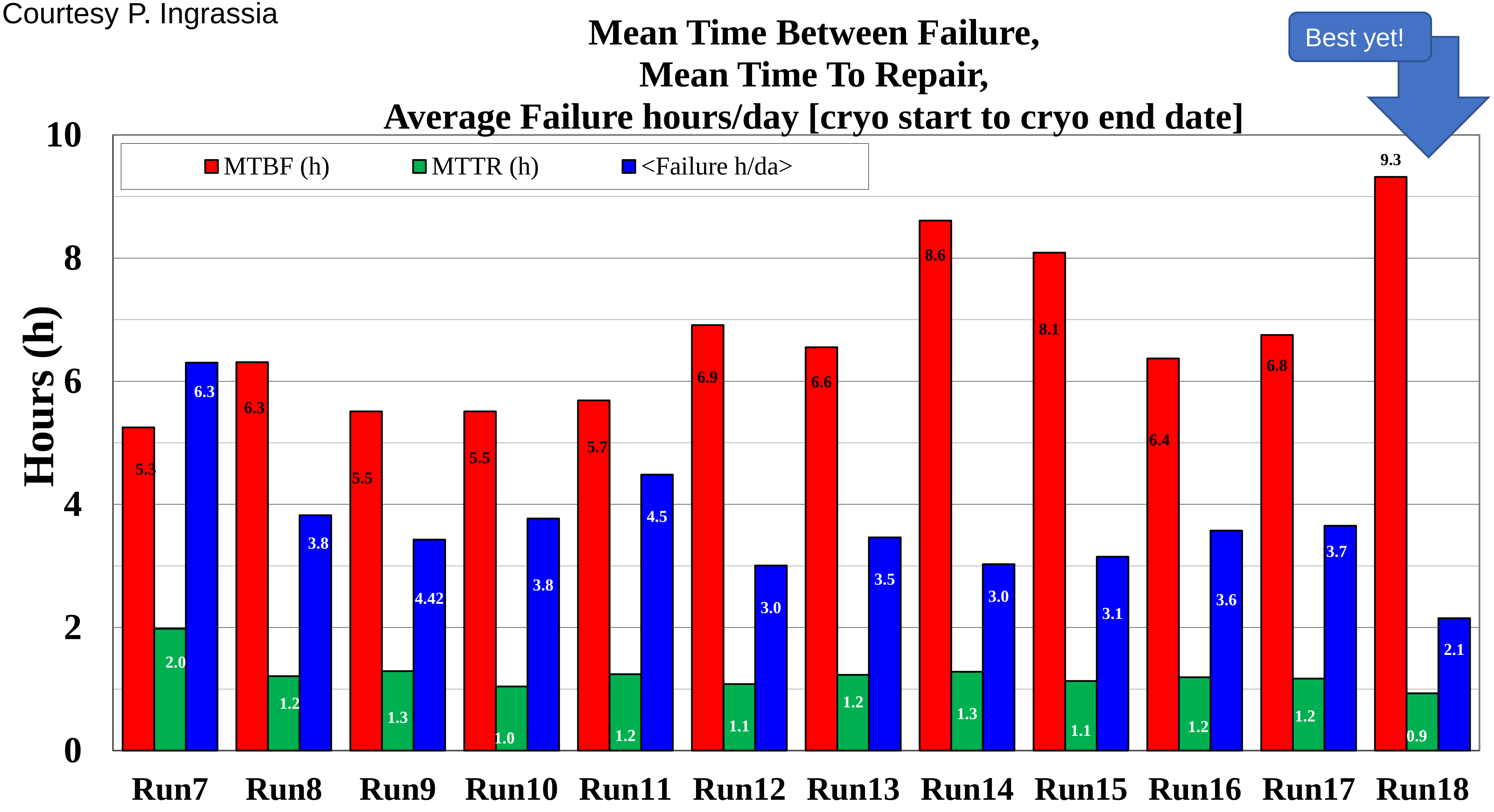
- Availability was high.
  - Rigidity at store energy slightly lower + fewer ramp cycles = less stress on RHIC magnet systems, abort kicker misfires, etc.
  - Low failure rate from most all injector/collider subsystems
  - Reduced secondary beams from ion collisions, lower off-momentum losses, radiation upsets, etc.
- Stores were long.
  - Fewer setup periods to cycle the Collider, a bonus for integrated luminosity
- Stochastic cooling
  - Maintained nearly constant emittance over stores
- Luminosity levelling
  - Constant rates over 20 hours gave better integrated luminosity
- Intensity requirements were low
  - Stochastic cooling more effective
  - Intensity margin allowed for luminosity leveling
  - Less strain on source, injectors
  - One collision point, less beam-beam interactions



Courtesy P. Ingrassia

n.b. We were able to return >90% of the ^{96}Ru. Used ^{96}Zr targets were reprocessed also, to recover material.

Courtesy P. Ingrassia



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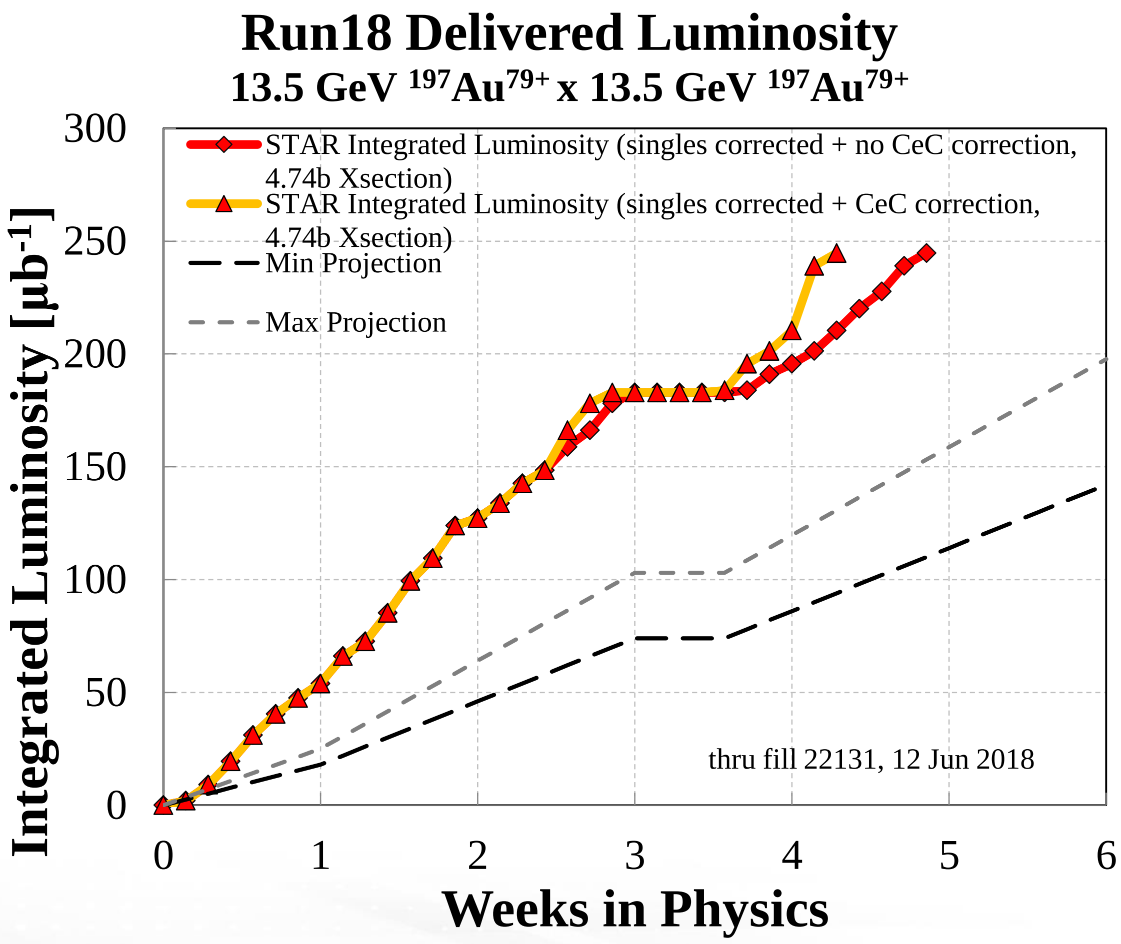
Back to basics: "Medium" energy gold

- In contrast to the isobar program, Au at 13.5 GeV ($\sqrt{s_{NN}} = 27$ GeV) makes use of a previous setup, but required more constant attention
  - Store length down to 1.5 hours
  - No stochastic cooling at this energy
  - No data rate limits from experiment: maximum intensity required
- Explored tune working points near the integer, with mixed results
  - Loss rates at store improved
  - Orbit control issues due to resolution of power supply interface
  - Ramp losses were concentrated in undesirable locations
- Machine time shared with CeC project
  - Second setup used to accelerate beam to 26.5 GeV
  - Concurrently, STAR made use of its fixed target at this energy.

Results: 27 GeV Au

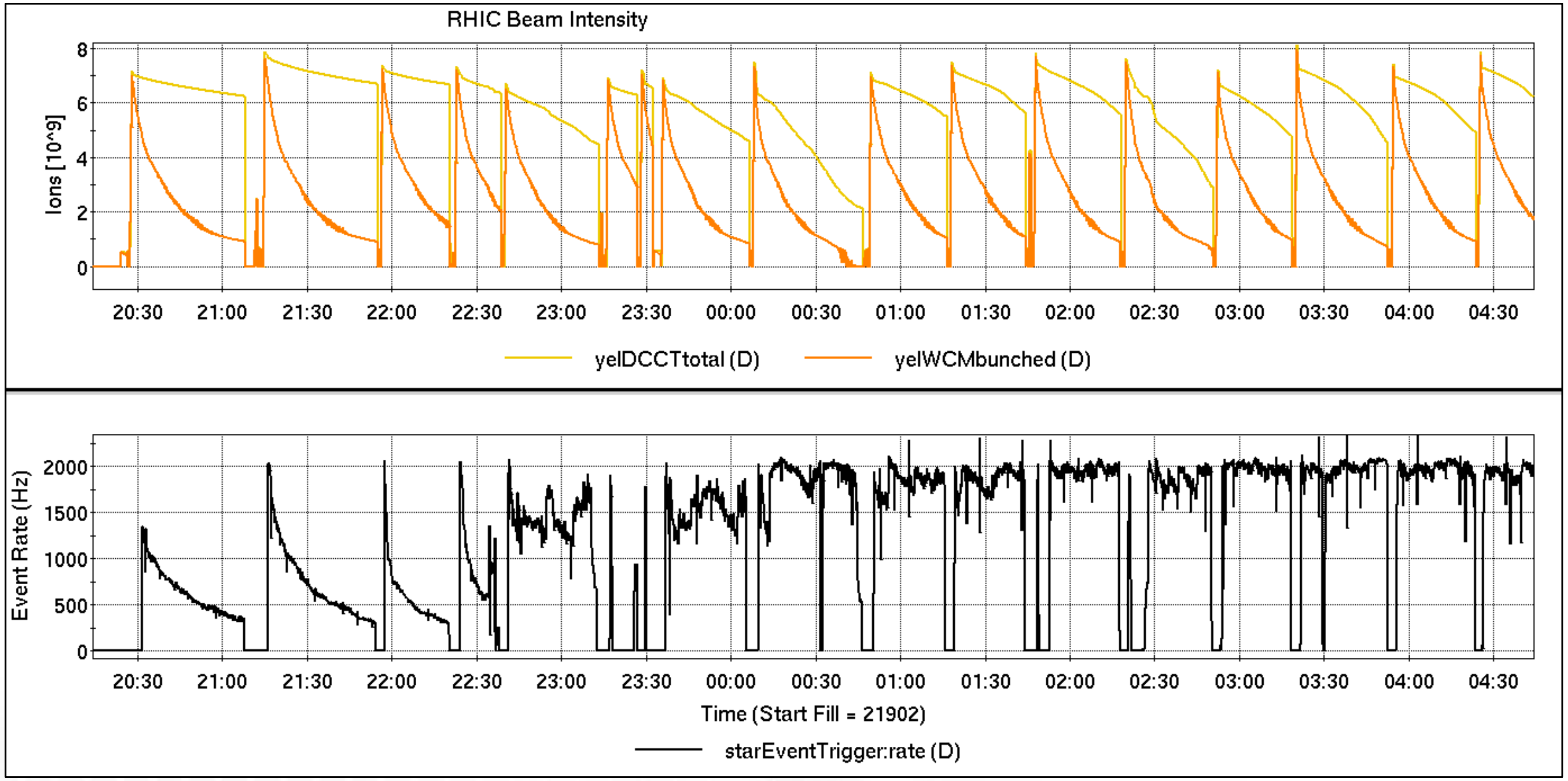
- From setup to physics: 25 hours
- Exceeded projected luminosity goals
- In beginning of run, intensity limited by background rates at STAR
- Later in run, intensity limited by source performance (still, 30-40% above previous run)



Fixed Target

Within the medium energy Au run, the RHIC was reconfigured to run beam at low energy, 3.85 GeV in the Yellow ring only. The circulating beam was moved down vertically to interact with a fixed gold target in the STAR detector.

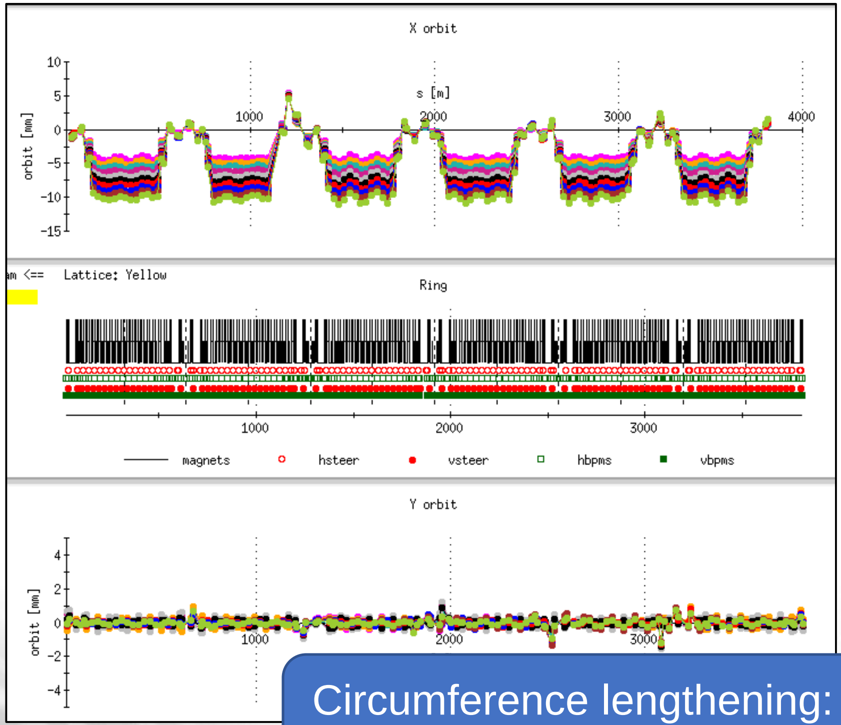
Operators were able to deliver sustained data rates by exciting beam with baseband tune meter (BBQ) kicker.



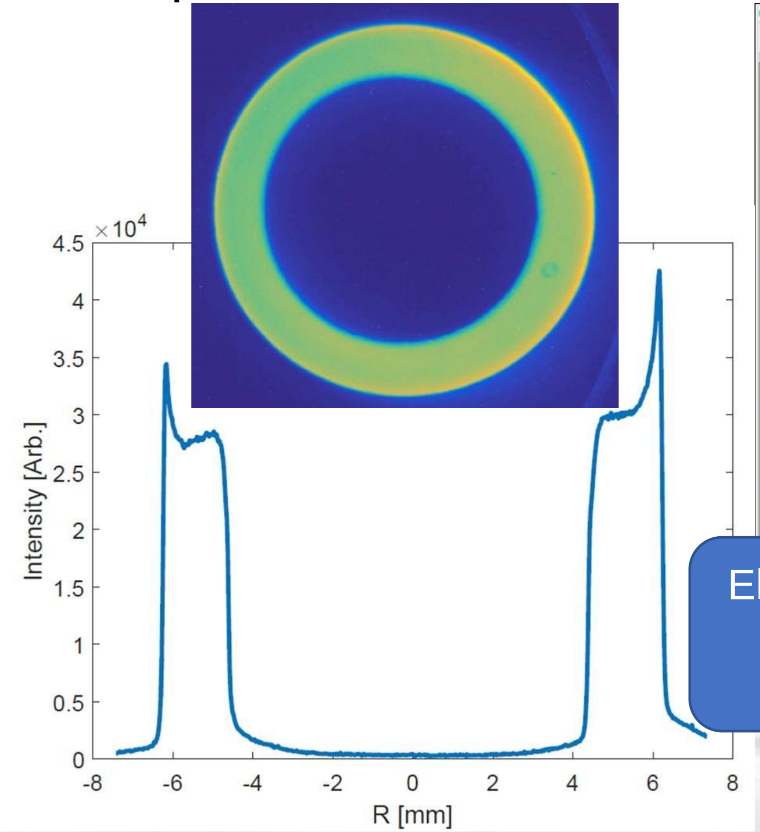
As a result, STAR gained more than 3 times their original event goal.

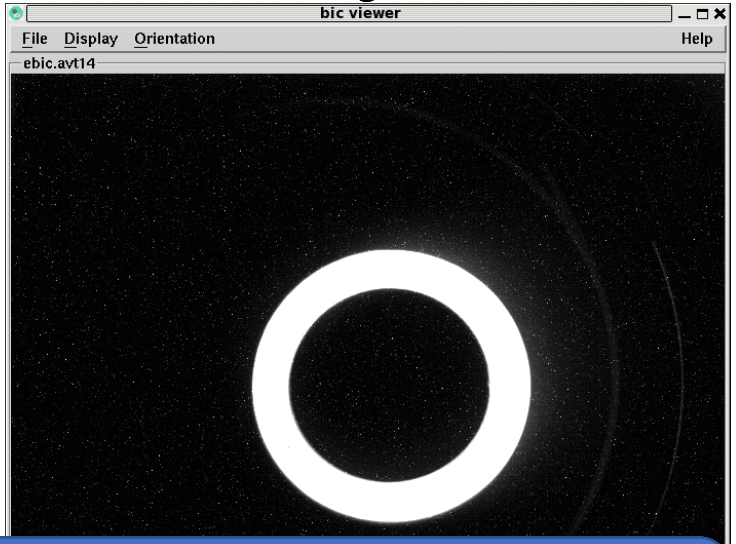
That’s not all: MD and APEX

- In addition to running the Physics program, C-AD uses the collider to conduct Accelerator Physics EXperiments (APEX) and Machine Development (MD)
  - Machine Development is focused to improve the machine conditions in the present or near future.
  - Accelerator Physics Experiments are intended to increase our understanding of the collider and its beam dynamics, and test concepts to be used in future accelerator design.



Circumference lengthening: eRHIC study





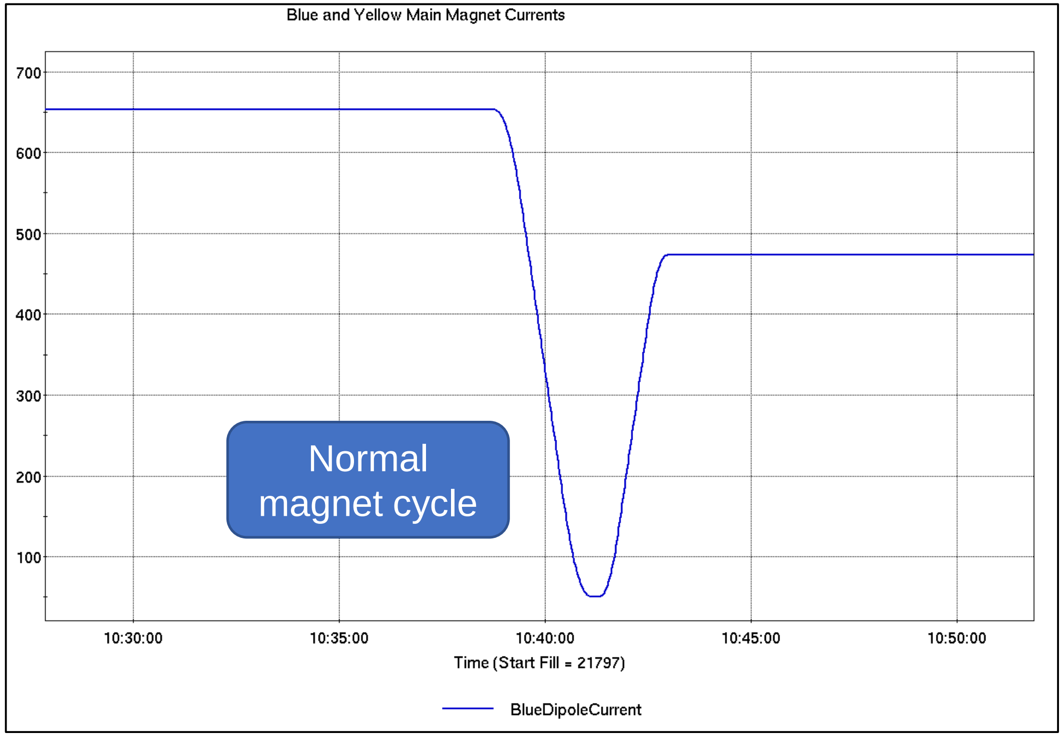
Electron lens collimation study: create hollow electron beam around ion beam

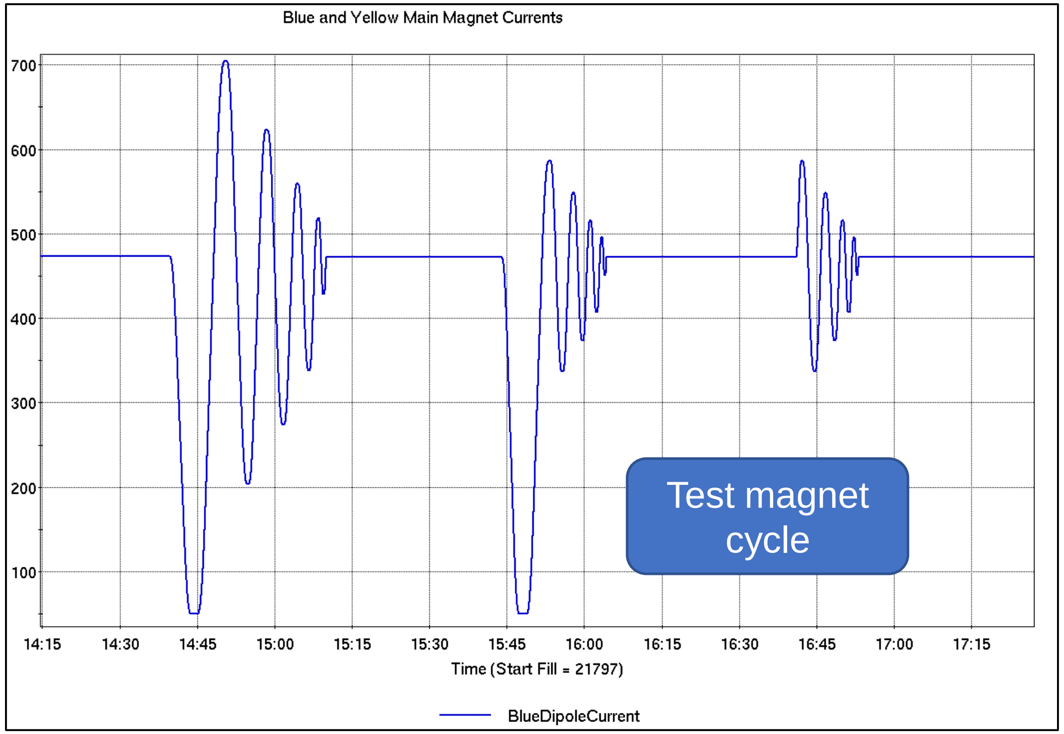
Looking forward: Beam Energy Scan 2 (BES-II) tests

While at low energy during the fixed target portion of Run-18, Machine Development with beam took place to better prepare for upcoming runs at low energy. Other tests took place at normal injection energy.

- As a direct impact, the beam conditions were improved for the remainder of the fixed target run following the MD session (tune, coupling adjustments).
- Experience gained with orbit corrections at low energy and near-integer tunes confirm the need to upgrade power supply interface controls, from 12- to 16-bit resolution.
- New magnet cycles were tested in an attempt to improve reproducibility and reduce harmonic components caused by persistent currents in the dipoles.

Looking forward: BES-II tests





Hysteresis cycles: extra “wiggles” intended to reduce amplitude of persistent current drift, and minimize sextupole component in main dipole magnets

Looking forward: BES-II tests

Injection
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timing, th
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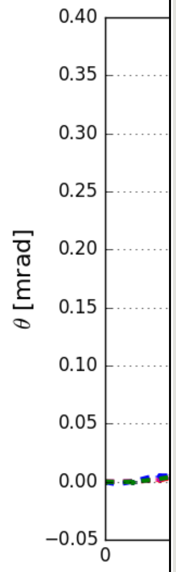

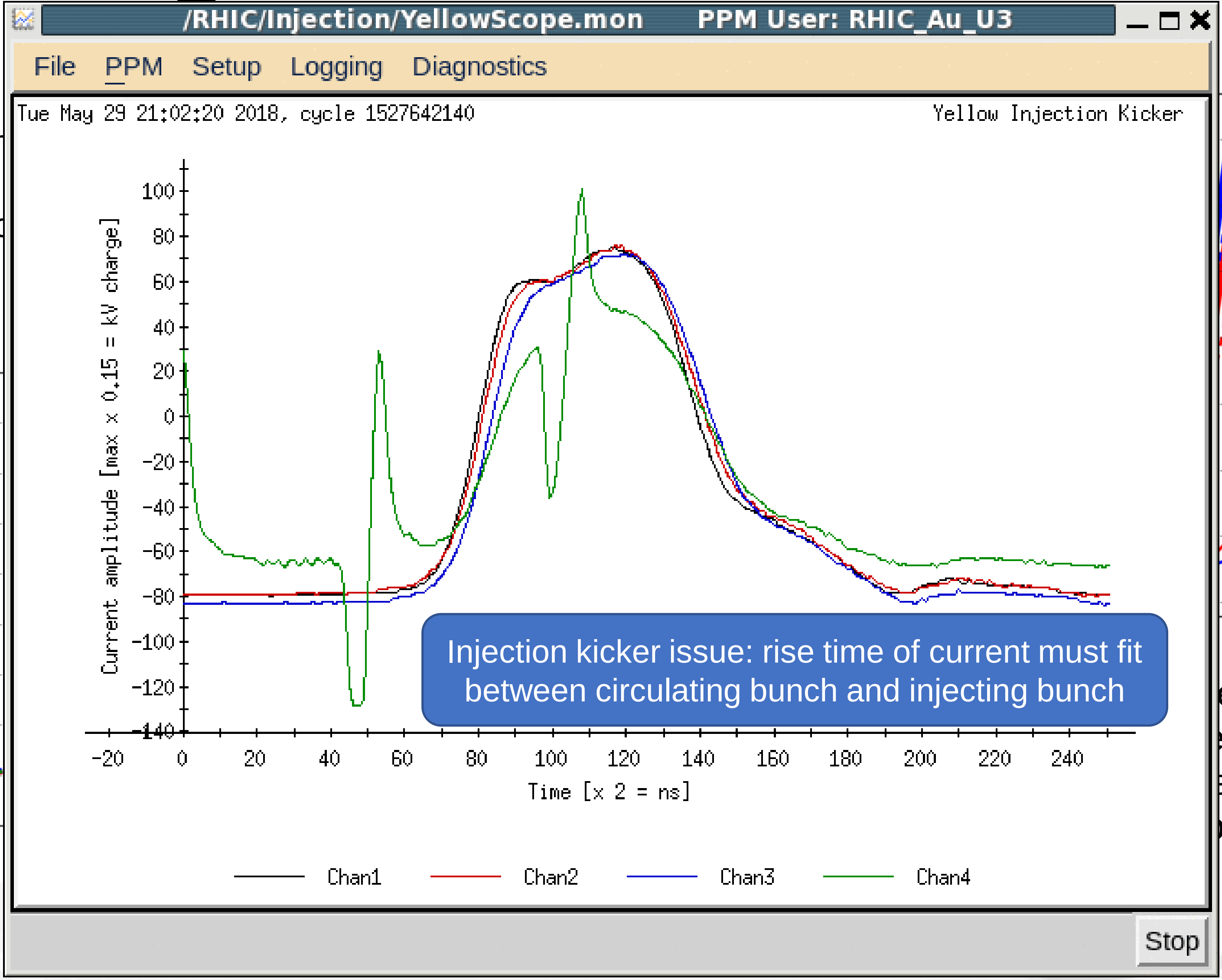

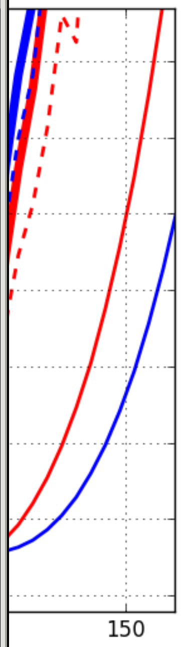

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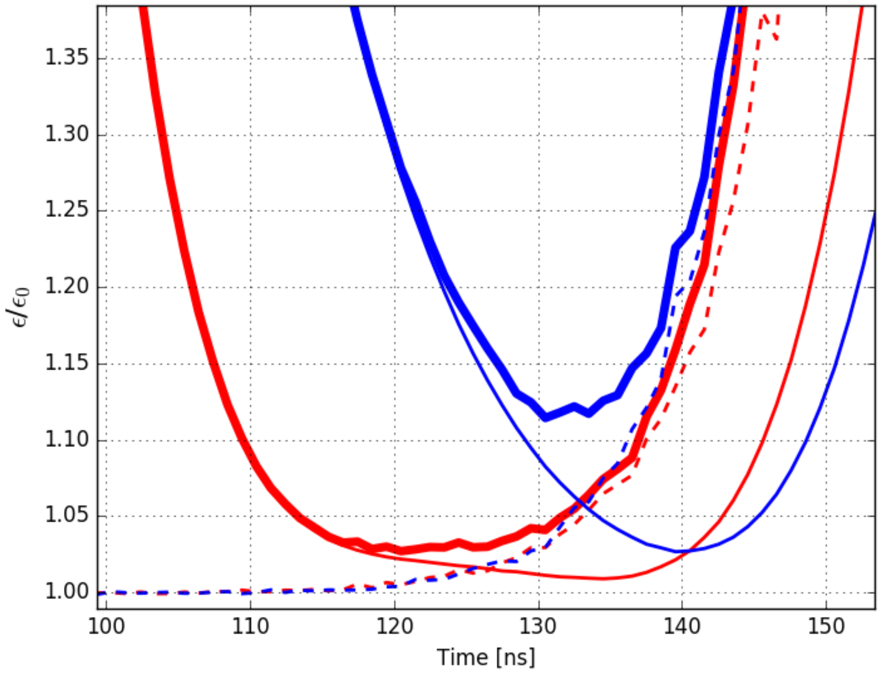
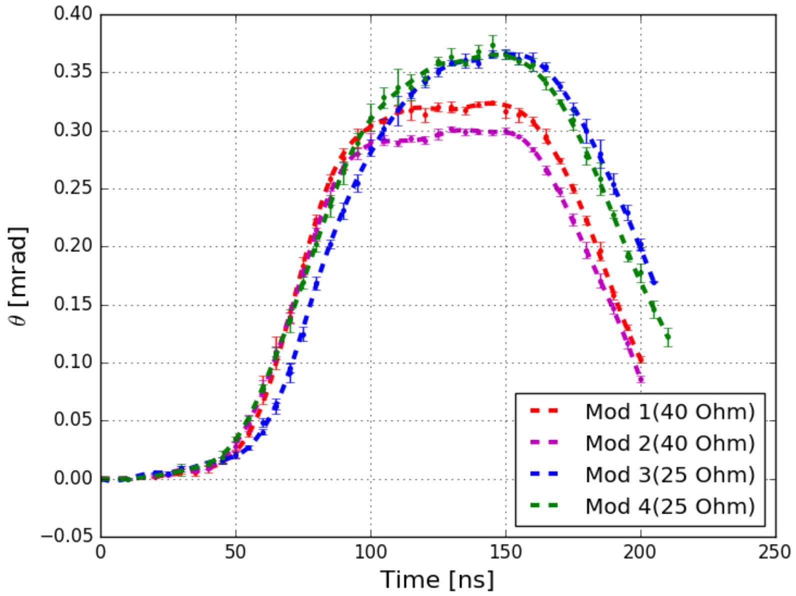
Looking forward: BES-II tests

Injection kicker scans: by measuring deflection of a single turn of beam while scanning kicker timing, the effective kick of each module is mapped out (below). Two different termination resistor configurations were measured.



As a result, one can calculate the vertical emittance growth incurred on a bunch by its own injection, as well as the injection of the subsequent bunch (above).



Courtesy V. Schoefer

BES-II Preparation: LEReC Commissioning

- Following the conclusion of the Physics program for STAR, a sector of the Blue ring continued cryogenic operations for nearly 3 months.
- This allowed the superconducting systems to operate so that electron cooling could begin setup and testing.
- Further commissioning continues, with ion beams, during our FY 2019 run at the RHIC.
- FY 2020: BES-II plans to make use of LEReC for low energy runs at beam energies of 3.85 & 4.5 GeV.

Summary

- Run 18 was a challenging run that required the Collider be more versatile than previous runs. The RHIC again showed that it is adaptable, as that challenge was met or exceeded on nearly all counts.
- Previous experience with multiple setups in the injectors became the engine for switching species in the RHIC on a daily basis – a capability new to any collider. More than five different setups were used in the collider, with dozens of switches between setups.
- The C-AD complex ran with highest availability compared to previous runs, and produced data for the Physics program exceedingly well.
- Time was spent to better prepare for upcoming runs, BES-II and beyond.

Summary

The hard work of the Operations Group and entire C-AD staff made the task of Run Coordinator much more simple.

We are additionally fortunate to have diverse ingenuity and assistance throughout BNL, from across the country, and around the world -- as evidenced by the success of Run 18.

My thanks to all for the effort behind Run 18!