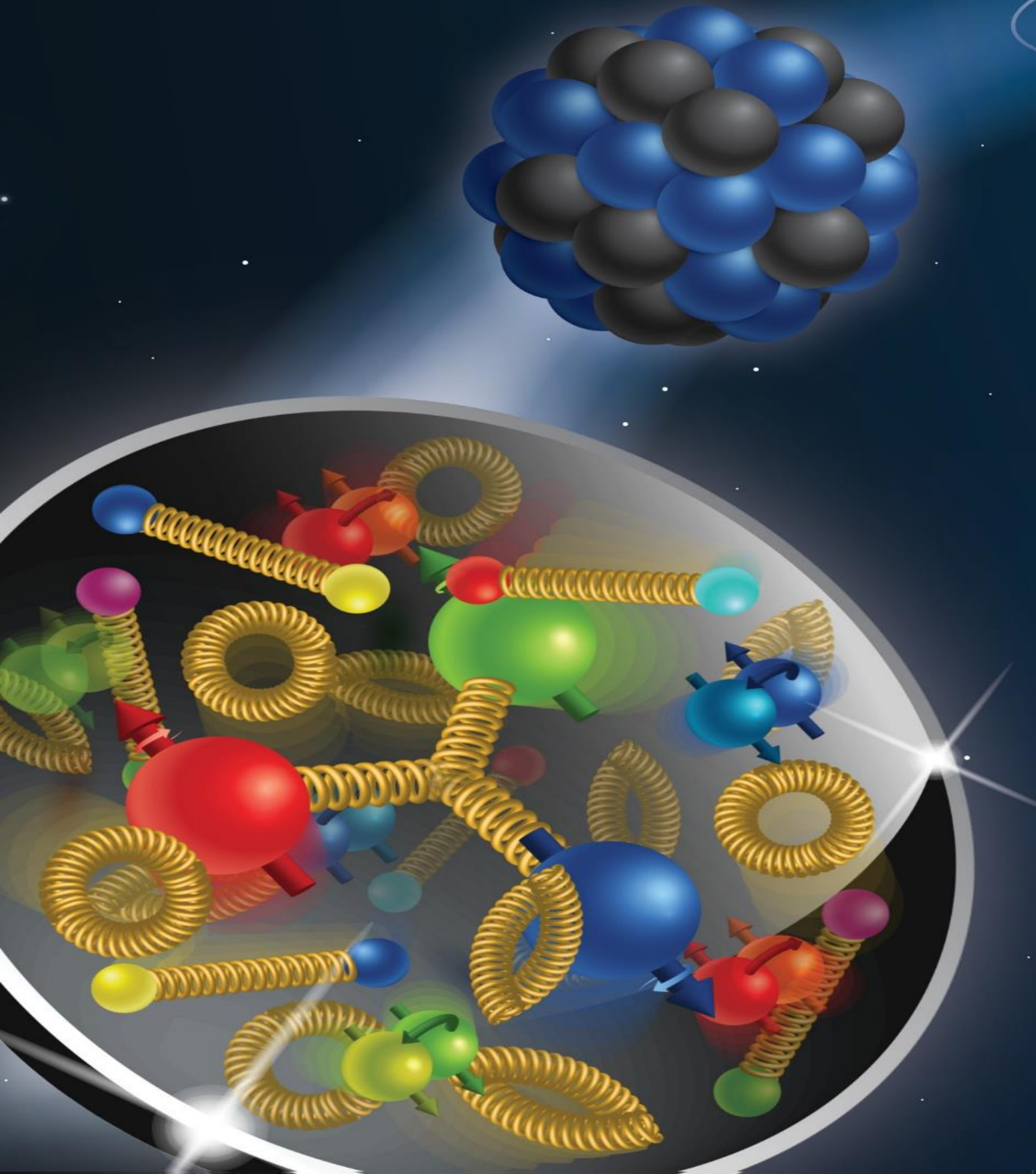


The RHIC Facility and its SBIR/STTR Opportunities

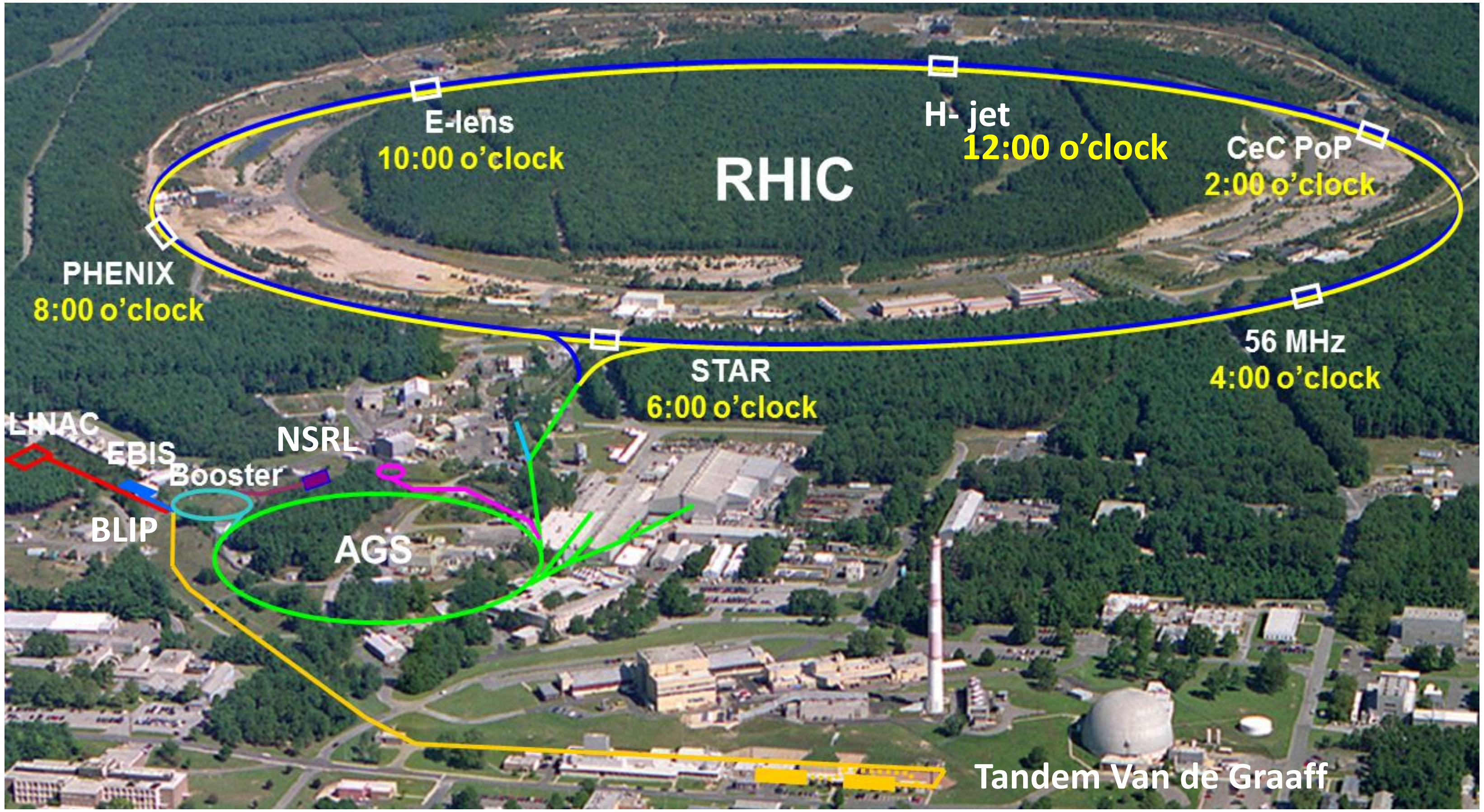
Michiko Minty
Head of Accelerator Operations
Collider-Accelerator Department
Brookhaven National Laboratory

SBIR/STTR Exchange Meeting 2020

BROOKHAVEN NATIONAL LABORATORY

- **Overview of the BNL Hadron Complex**
- Major new accelerator technologies
- The future electron-ion collider, EIC
- Technology developments and NP SBIR/STTR synergies
- Summary

Overview of the BNL Hadron Complex



Hadron-based user and research facilities:

- Linac Isotope Production (BLIP) / Medical Isotope Research and Production Program (MIRP)
- NASA Space Radiation Laboratory (NSRL)
- Tandem van de Graaff accelerators
- Relativistic Heavy Ion Collider (RHIC)

BNL LINAC Isotope Producer (BLIP)

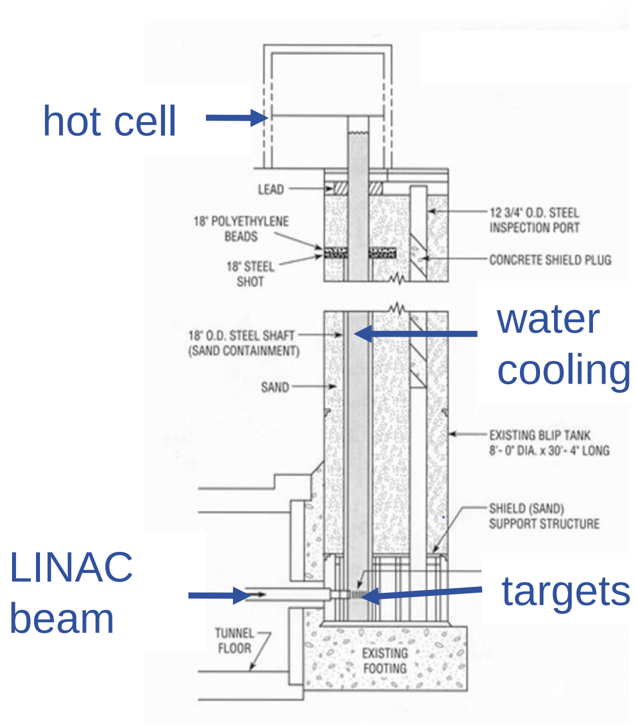
Medical isotope research and production program:

- Priority: preparation of certain commercially unavailable radioisotopes to distribute to the research community (universities and labs), federal agencies and industry.
- Perform research to develop new radioisotopes for nuclear medicine investigators.

Operates generally synergistically with RHIC.

Higher isotope yields afforded by
- linac intensity phase-1 upgrade to 140 μA (2016)
- raster upgrade (2016)
- phase-2 upgrade planned for 250 μA

New (refurbished) cyclotron being commissioned for low energy irradiations.

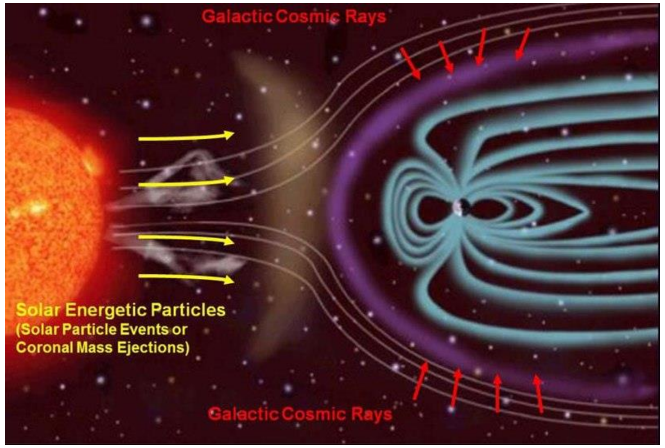


SBIR/STTR developments welcome to overcome beam power limits (target and window survivability)
- accurate component lifetime prediction
- robust multi-MW target component design
- development of new materials to extend lifetimes

BNL NASA Space Radiation Laboratory (NSRL)

Offers:

- Beams of all ions from protons to Uranium.
- Energy range of 50 MeV to 1000 MeV (dependent on ion species).
- User support from BNL's Biosciences and Collider-Accelerator Departments.



Applications include:

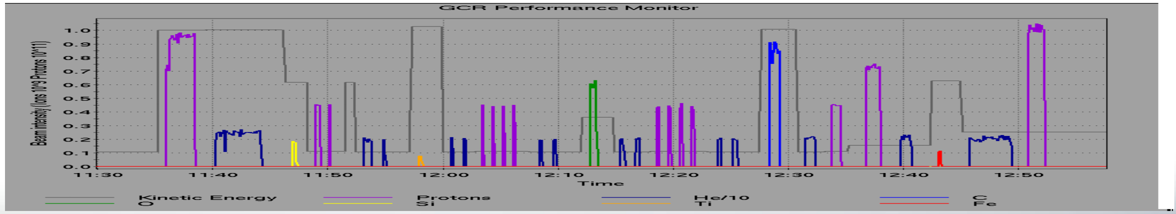
Radiobiology studies with beams simulating cosmic rays.

Industrial material studies on suitability of new materials for space suits and spacecraft shielding.

Testing of electronic components and electronic systems.

Space radiation risk and countermeasure development.

Variable ions and energies delivered in ~ 1 hour upon uniform, large (60 cm by 60 cm) samples.



BNL Tandem Van de Graaff Accelerator Facility

Offers:

- A wide variety of light and heavy ions for industrial and space applications.
- Precisely known and continuously variable energies from a maximum of 28 MeV for protons to 400 MeV for gold ions.
- Accurate dosimetry and user-friendly operation.

Applications include:

Space radiation effect studies of micro-electronic devices.

Micro-pore filter fabrication.

Cell radiobiology investigations at low energies / high stopping powers.

Enhancement of high temperature superconducting wire.

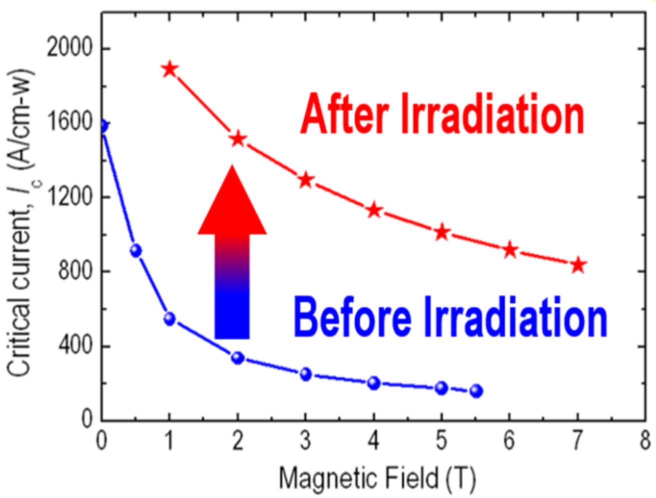
Deep ion implantation for next generation semiconductors.

Active spacecraft shielding studies and flight-instrument calibrations.

Calibrations of instruments for space applications.

Active shielding of spacecraft concept testing by NASA.

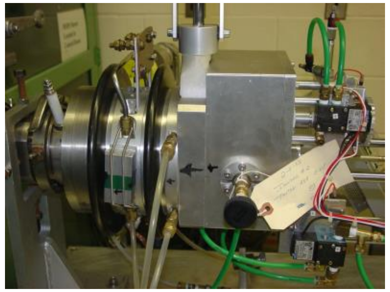
Heated wafer high energy ion implantations (in development, ARPA-E).



BNL Hadron Injectors: state-of-the-art ion sources

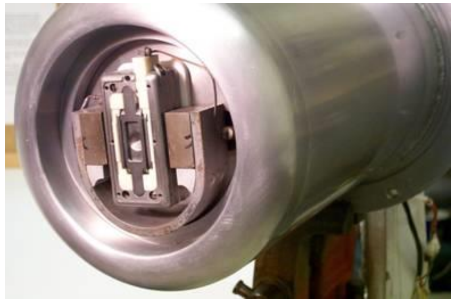
EBIS (for high charge-state heavy ions: He to U), LION

Cs sputter at Tandem (Au, Fe, etc.)



OPPIS, $\vec{H}$- (used with 200 MeV Linac)

Magnetron H- Source (used with 200 MeV linac)



operates with 20 times the intensity of any other EBIS in the world

world’s highest intensity polarized H- source

highest current H- accelerator in the world (SNS, FNAL, ISIS)

Tandem

RHIC

NSRL

BLIP

RHIC history and future

☆ Technologies to be applied in the EIC

- RHIC commissioning era (2000 to 2002)

  first full energy (100 GeV/n) heavy ion runs, first 100 GeV polarized proton run

- RHIC-I era (2003 to 2013)

  first full energy (250 GeV) polarized proton runs

  ☆ **new technology**: stochastic cooling proof-of-principle (2007)

  ☆ **new technology**: high intensity electron beam ion source, EBIS (>2010)

- RHIC-II era (2014 to 2016)

  ☆ **new technology:** 3D stochastic cooling (>2014)

  ☆ **new technology**: high intensity polarized ion source, OPPIS (>2015)

  (☆) **new technology**: electron lenses for head-on beam-beam compensation (>2015)

  ☆ **new technology**: superconducting rf cavity used in hadron operations (>2016)

- RHIC today (2017+)

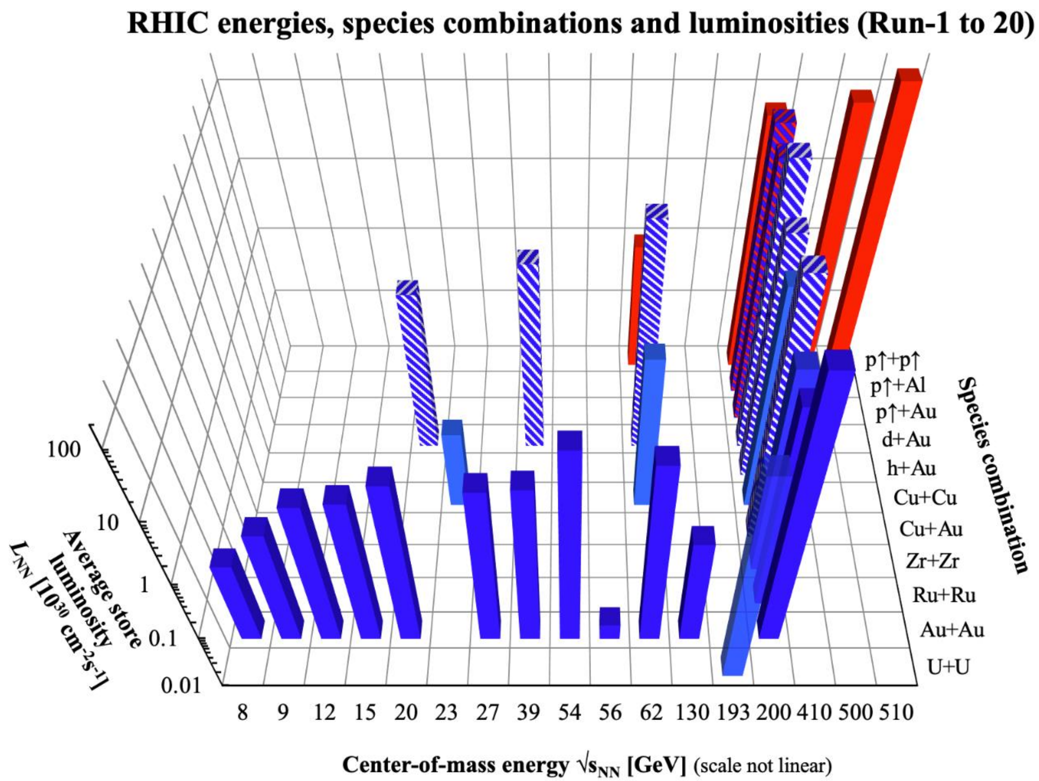
  ☆ **new technology**: bunched-beam electron cooling (2017-2021)

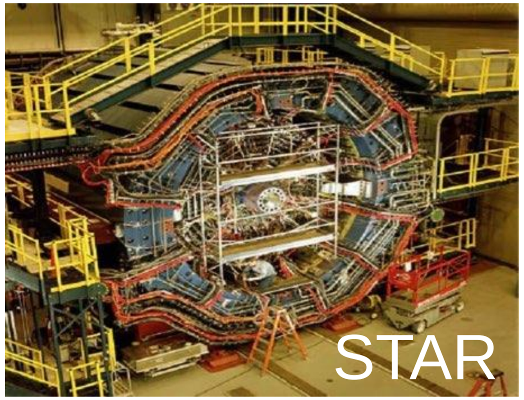
  ☆ **new technology**: extended EBIS (2022), polarized ^{3}He (2023)

  (☆) physics operations with detector upgrade, sPHENIX (>2022)

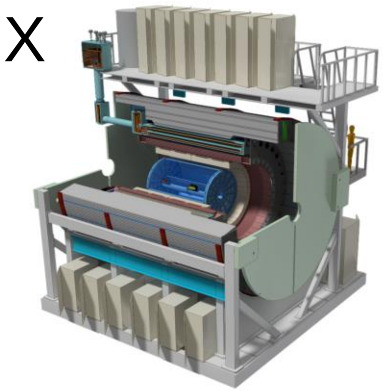
- Future electron-ion collider, EIC

RHIC - the Champion of Versatility





sPHENIX

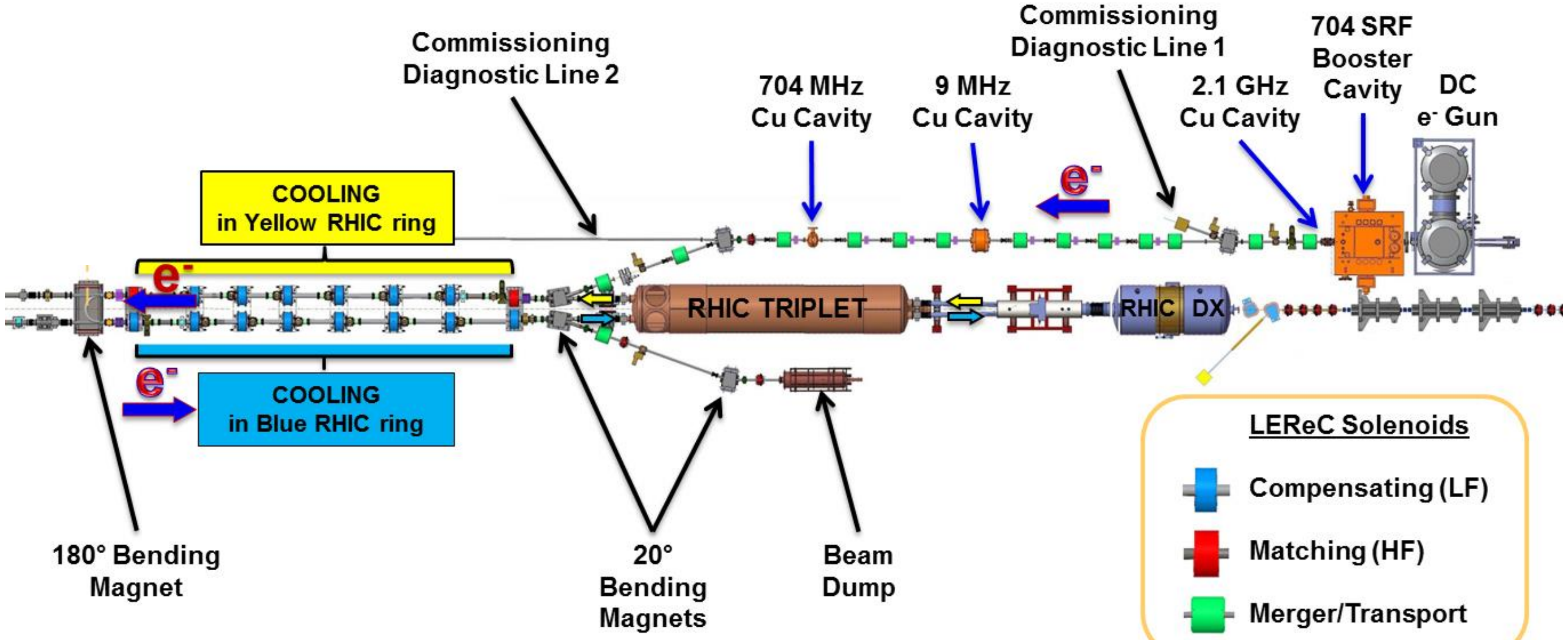


Mission (Collider-Accelerator Department):

- Develop, improve and operate the suite of particle / heavy ion accelerators used to carry out the program of accelerator-based experiments.
- Support the experimental program including design, construction and operation of the beam transports to the experiments plus support of detector and research needs of the experiments.
- Design and construct new accelerator facilities in support of the BNL and national missions.

- Overview of the BNL hadron complex
- Major New Accelerator Technologies
  - stochastic cooling
  - electron lenses
  - superconducting cavities
  - bunched beam electron cooling
  - multi-pass energy recovery linac (CBETA)
- The future electron-ion collider, EIC
- Technology developments and NP SBIR/STTR synergies
- Summary

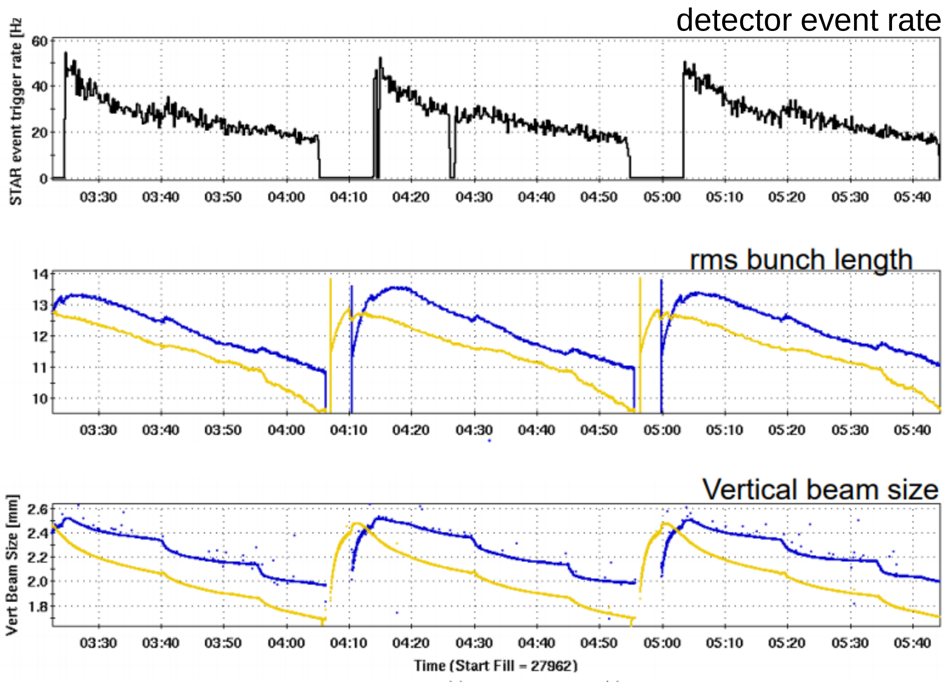
Accelerator Technology:
Bunched-Beam Electron Cooling at RHIC

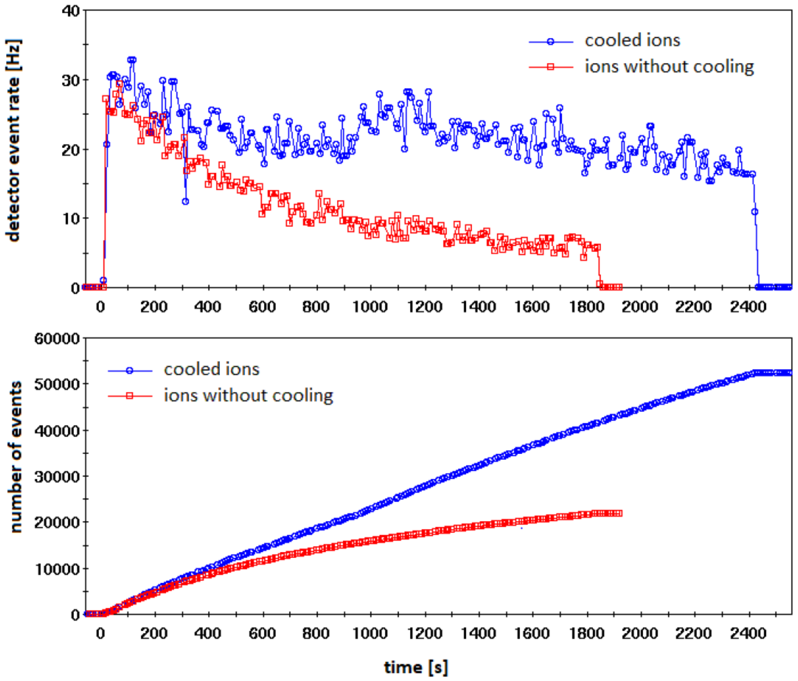


Energies E : 1.6, 2.0 (2.65) MeV
Avg. current I_{avg} : 27 mA
Momentum dp/p : 5×10^{-4}
Luminosity gain : 4×

1st electron cooler using rf-accelerated bunches
planned operation in 2019/2020

Bunched-Beam Electron Cooling at RHIC

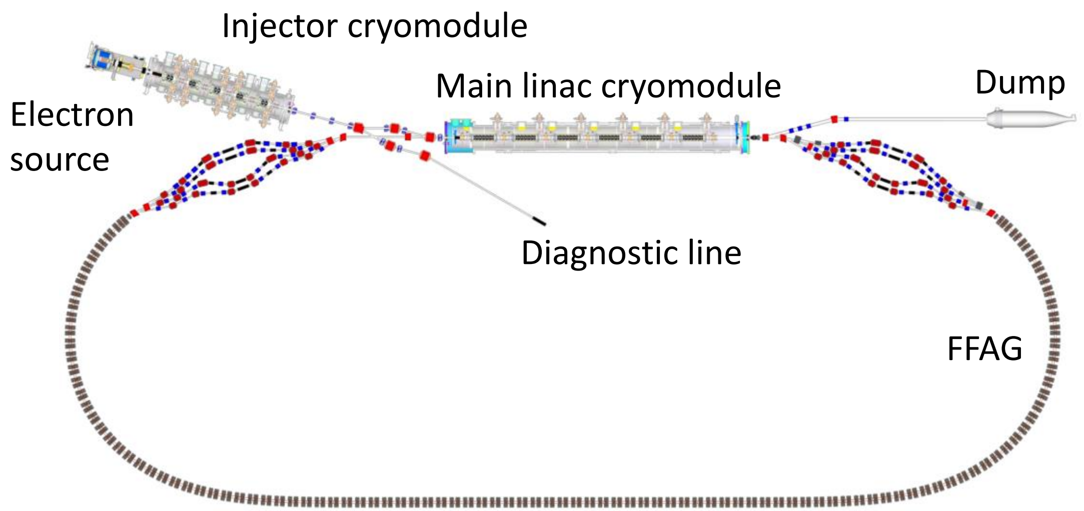




- First electron cooling in a collider.
- Bunched-beam electron cooling used now in routine operation at RHIC in support of the Basic Energy Sciences Program at BNL.
- After the FY21 RHIC Run, facility will be converted for high-current injector studies for the EIC.

A. Fedotov et al, Experimental Demonstration of Hadron Beam Cooling Using Radio-Frequency Accelerated Electron Bunches, Physical Review Letters **124**, 084801 (Feb 2020)

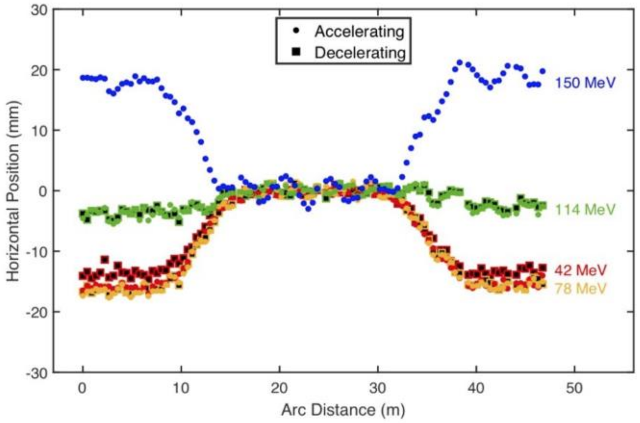
CBETA (Cornell/BNL ERL Test Accelerator)



Features:

- superconducting injector and main linac cryomodules
- permanent magnets in the FFAG arcs
- single vacuum chamber for 4 different energy beams (up to 150 MeV)

Achieved eight passes (4 accelerating, 4 decelerating) with full energy recovery and high-energy efficiency.



A. Bartnik et al, CBETA: First Multipass Superconducting Linear Accelerator with Energy Recovery, Physical Review Letters **125**, 044803 (Jul 2020)

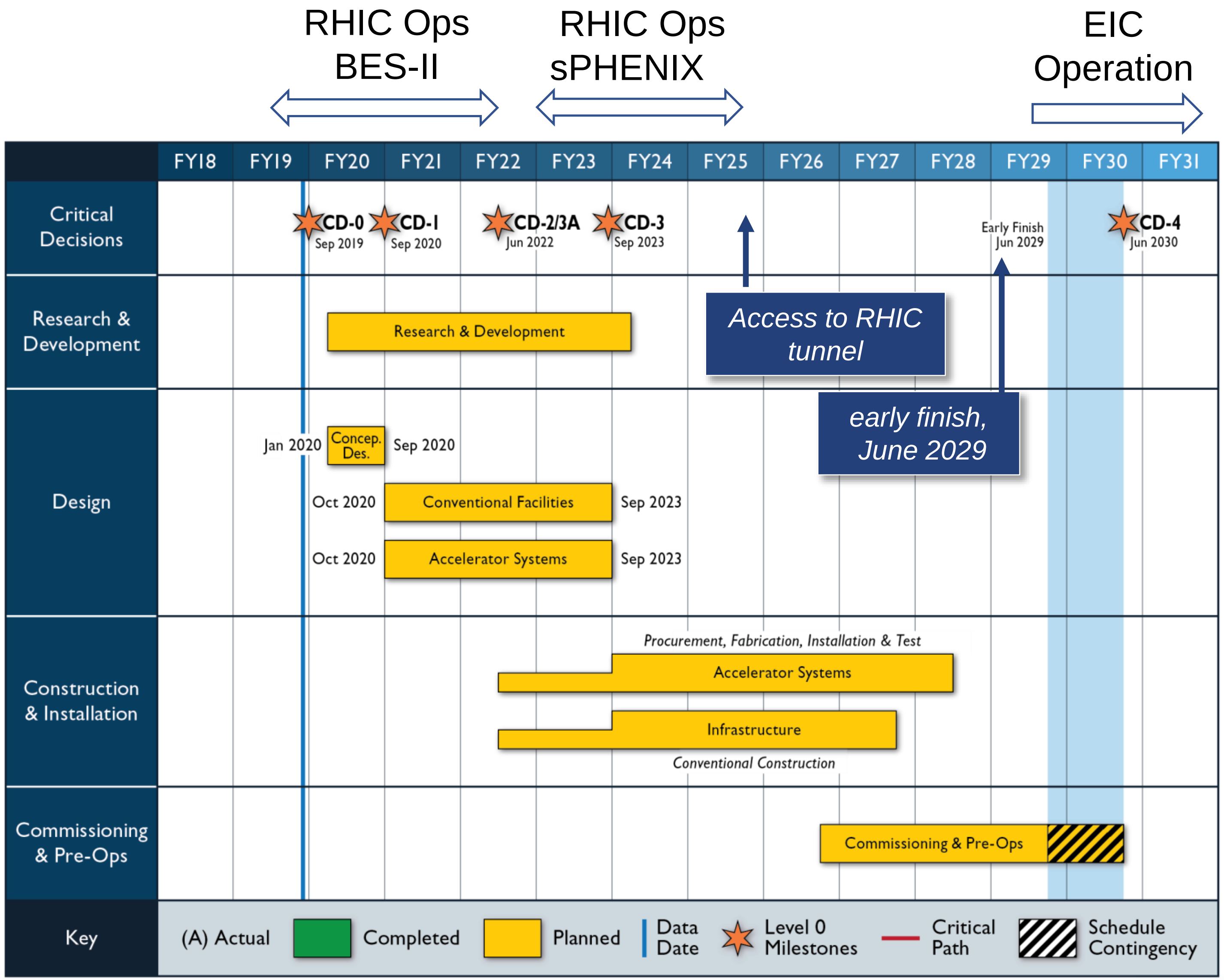
- Overview of the BNL hadron complex
- Major new accelerator technologies
- **The future electron-ion collider, EIC**
    - Timeline, schedule and key parameters
    - How RHIC is transformed into an EIC
- Technology developments and NP SBIR/STTR synergies
- Summary

Timeline of the EIC

2012	EIC White Paper released. Commissioned by BNL and JLab as a follow-up to the 2007 NSAC Long Range Plan.
2015	NSAC Long Range Plan recommended a high-energy, high-luminosity, polarized EIC as the highest priority for a new facility construction following the completion of FRIB.
	………… lots of continued work, pCDR releases and many reviews …………..
Dec 2019	Critical Decision 0 (“mission need”) for an EIC approved by the DOE (enables work to begin on R&D and on the CDR).
Jan 2020	Site decision made by the DOE for hosting the EIC at BNL in strong partnership with Jlab.

EIC Schedule

Draft CDR – Sep 2020
Final CDR – Jan 2021



Key parameters of the EIC

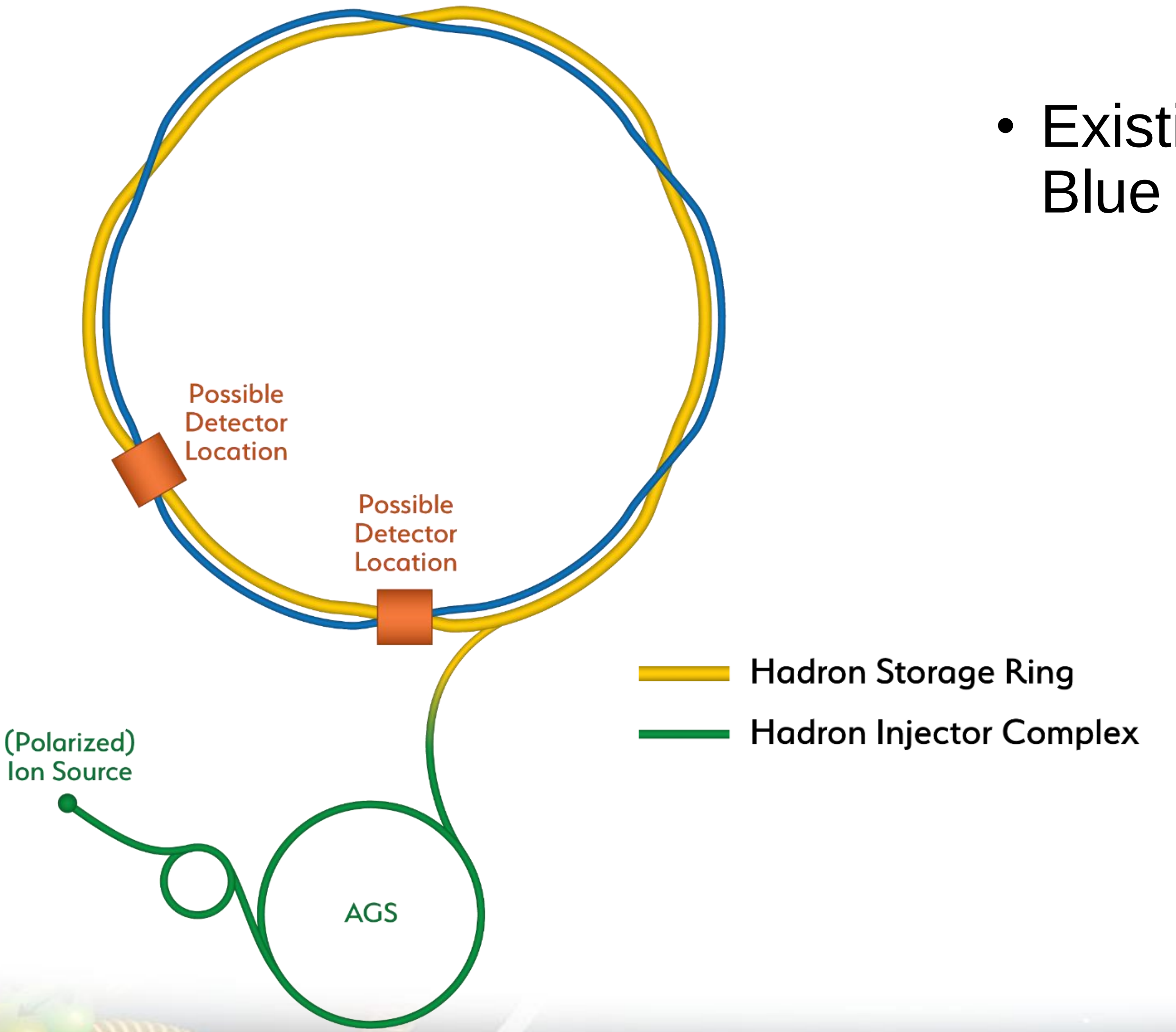
- Highly polarized (70%) electron and light ion beams
- Ion beams from deuterons to the heaviest nuclei (U, Pb)
- Variable center of mass energies from 20 to 100 GeV upgradable to 140 GeV
- High luminosity of 10^{33}-10^{34} $cm^{-2}s^{-1}$
- More than one interaction region possible

Maximum Luminosity ($10^{34}/cm^2s$) Parameters

Parameter	Units	Proton	Electron
Energy	GeV	275	10
Beam Current	Amperes	1.0	2.5
Particles per bunch	10^{10}	6.9	17.2
Number of bunches		1160	1160
Horizontal emittance	nm	11.3	20.0
Vertical emittance	nm	1.0	1.3
Hor/Ver beta at IP	cm	80/7.2	45/5.6
Hor/Ver beam size at IP	μm	95/8.5	95/8.5
Hor/Ver angular spread at IP	μrad	119/119	211/152
Bunch length (rms)	cm	6	2
Hor/Ver beam-beam parameter		0.012/0.012	0.072/0.100
IBS growth time (Long/Hor)	hours	2.9/2.0	[na]

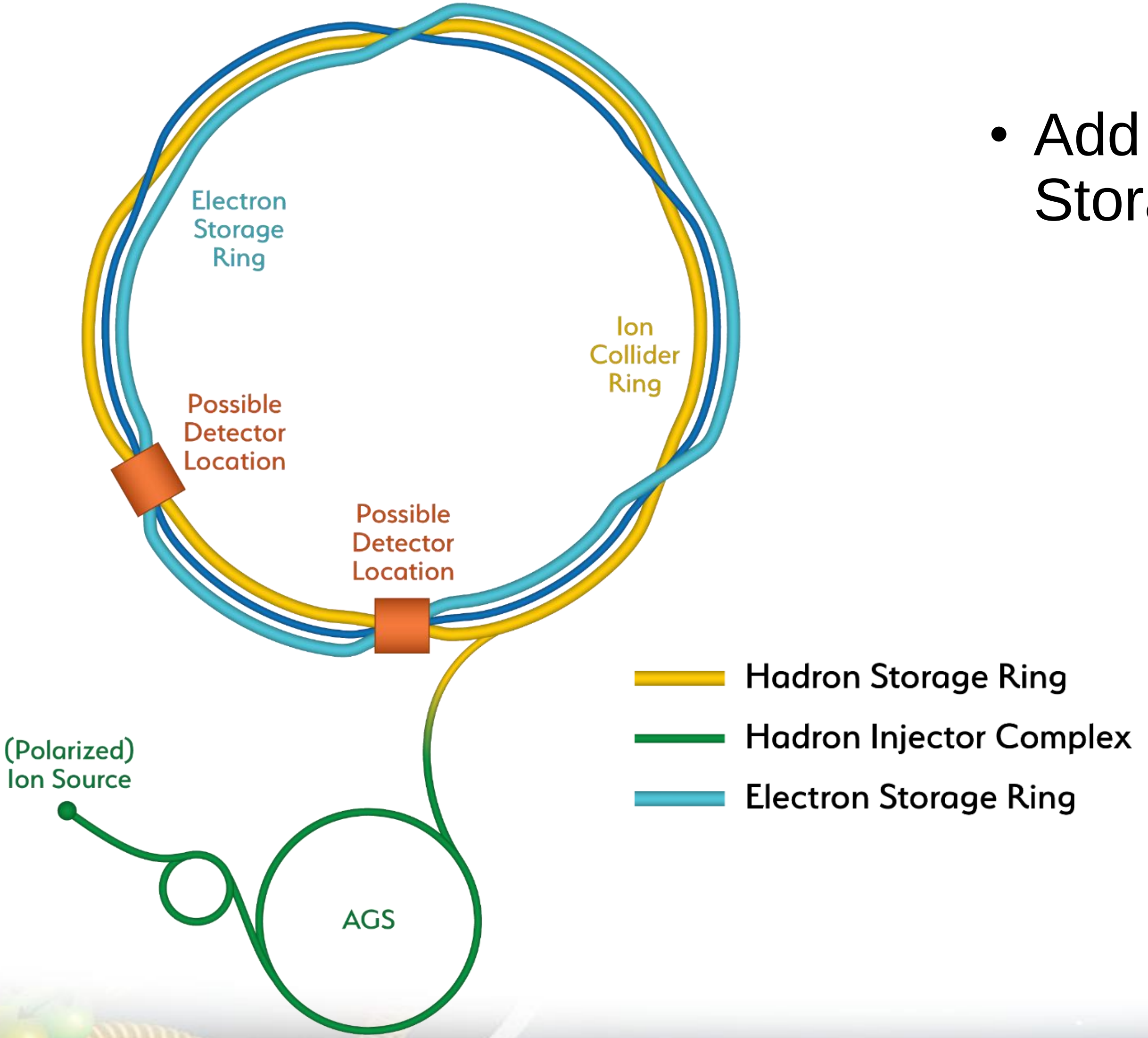
Very dense and closely spaced bunches introduce challenges!

How RHIC is transformed into an EIC



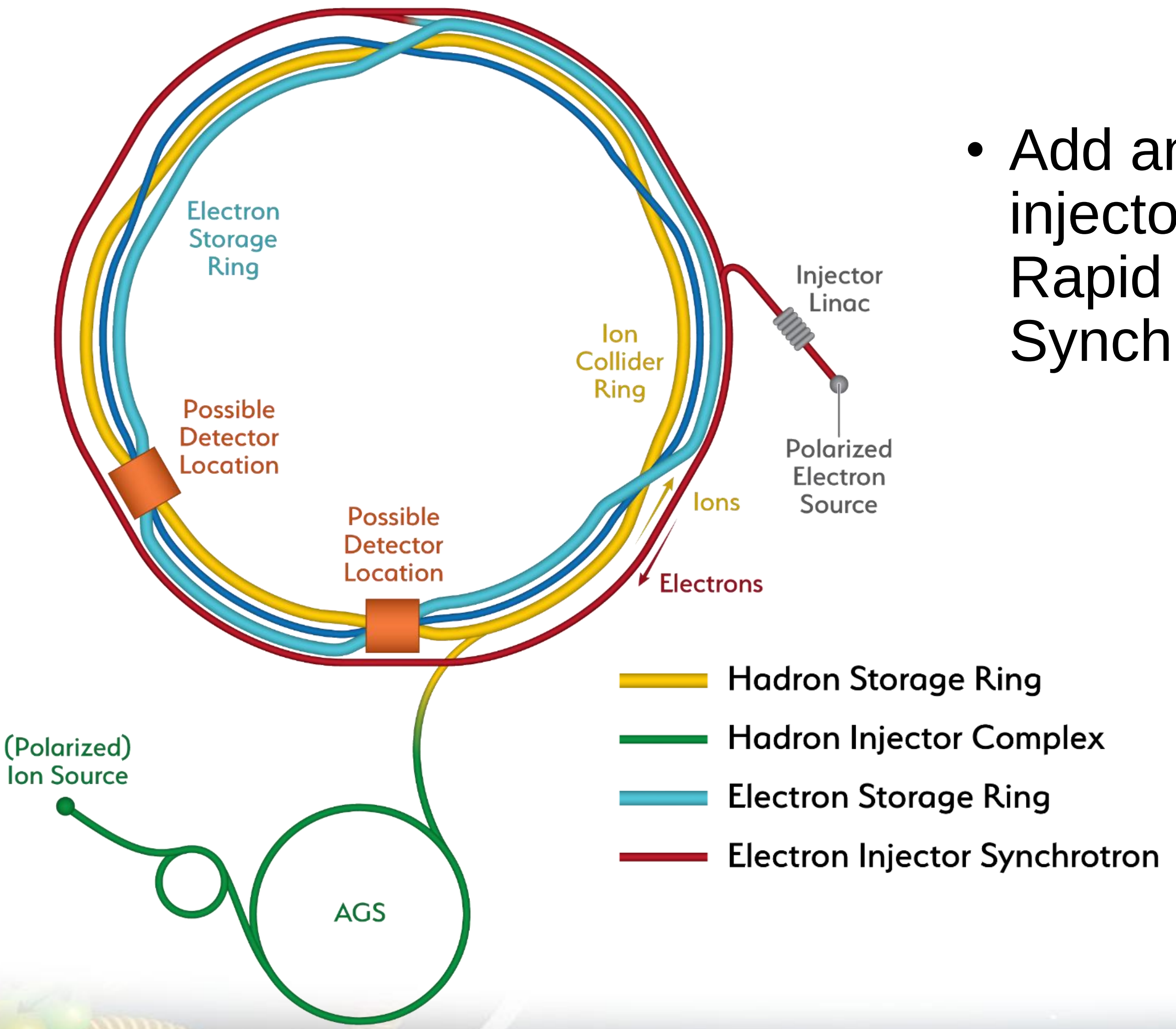
- Existing RHIC with Blue and Yellow rings

How RHIC is transformed into an EIC



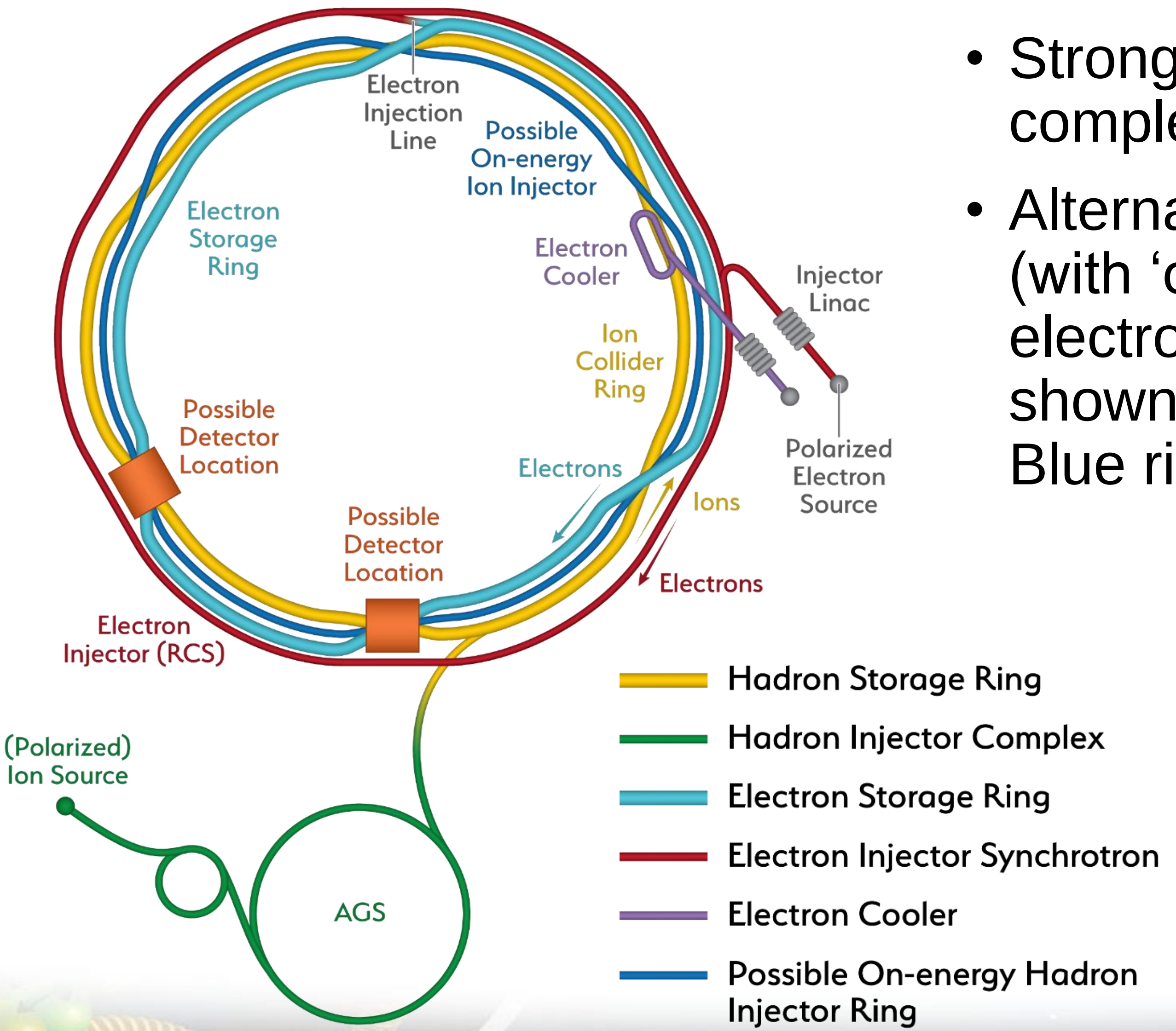
- Add an Electron Storage Ring

How RHIC is transformed into an EIC



- Add an electron injector complex with Rapid Cycling Synchrotron

How RHIC is transformed into an EIC



- Strong hadron cooling completes the facility
- Alternate solution (with ‘conventional’ electron cooling) also shown using RHIC Blue ring

- Overview of the BNL hadron complex
- Major new accelerator technologies
- The future electron-ion collider, EIC
- **Technology Developments and NP SBIR/STTR synergies**
  - Superconducting RF systems
  - Electron guns and photocathodes
  - Beampipe coating
  - Coherent electron cooling
- Summary

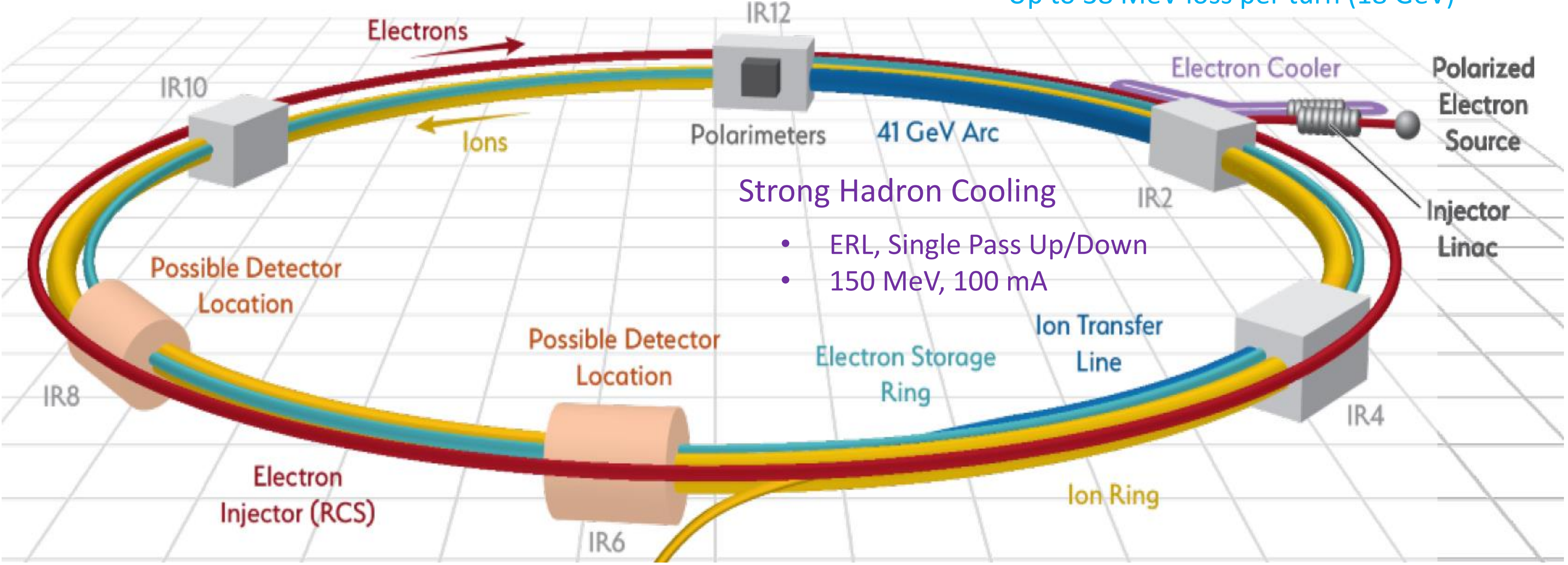
Overview of RF for the EIC

RCS: Rapid Cycling Synchrotron

- 400 MeV – 18 GeV Full Energy e- Injector
- 1 Hz Repetition Rate
- 100 ms ramp
- 28 nC per bunch

eSR: electron Storage Ring

- 5 GeV – 18 GeV
- 2.5 A maximum beam current (10 GeV)
  - 1160 bunches, 28 nC per bunch
- Up to 10 MW synchrotron radiation power
- Up to 38 MeV loss per turn (18 GeV)



Strong Hadron Cooling

- ERL, Single Pass Up/Down
- 150 MeV, 100 mA

Interaction Region Crab Cavities

- 25 mrad crossing angle
- 8x hadron 197 MHz Crab Cavities
- 6x hadron and electron 394 MHz Crab Cavities

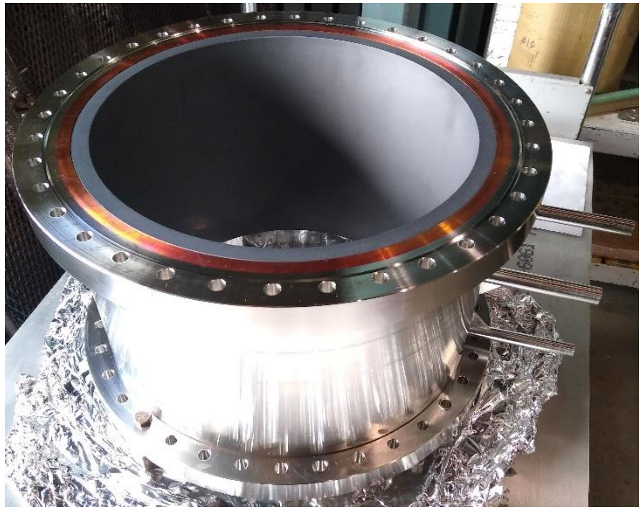
Hadron Ring

- Up to 275 GeV Proton Store Energy
- 1 A maximum beam current
- 1160 bunches, 11 nC per bunch

Technology: RF challenges for the EIC

The two most challenging aspects of the RF systems both result from the very high beam currents in both the Electron Storage Ring (ESR) and the Hadron Storage Ring (HSR):

- Very high power fundamental power couplers for the ESR RF
    - The ESR RF system must provide up to 10MW of RF power to the beam, to replace energy lost to synchrotron radiation.
- Strong and very high power High Order Mode (HOM) damping for the ESR and HSR
    - Beam stability requires HOM impedances to be well controlled via strong HOM coupling and high power HOM absorbers.

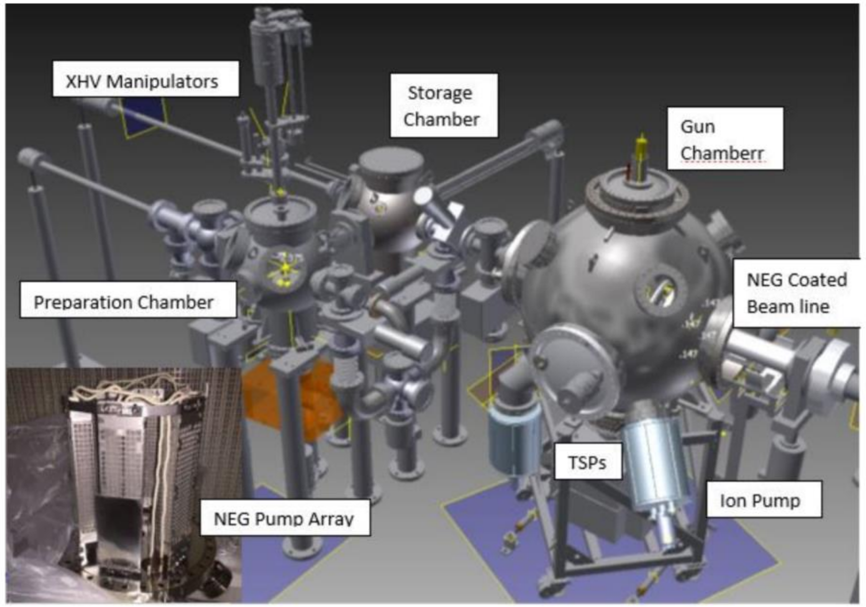


Opportunities for R&D: Improved ceramic materials and fabrication techniques for very high power FPC windows; very high power adjustable couplers; fabrication techniques for large diameter, large area HOM absorbers – solid and tile types.

Technology: Polarized Electron Source

In development at Stony Brook University

- based on the JLAB inverted gun
- 5-10 nC/bunch at 1-2 Hz repetition frequency
- large area cathode (26 mm dia)
- XHV vacuum requirements ($<10^{-12}$ Torr)
- first beams expected Aug 2020



Planned R&D: cathode development and quantum efficiency lifetime studies

Focus areas / opportunities for collaboration:

- photocathode development - both polarized and unpolarized
- superlattice GaAs wafer production
- technologies for XHV and chamber coatings
- simulations

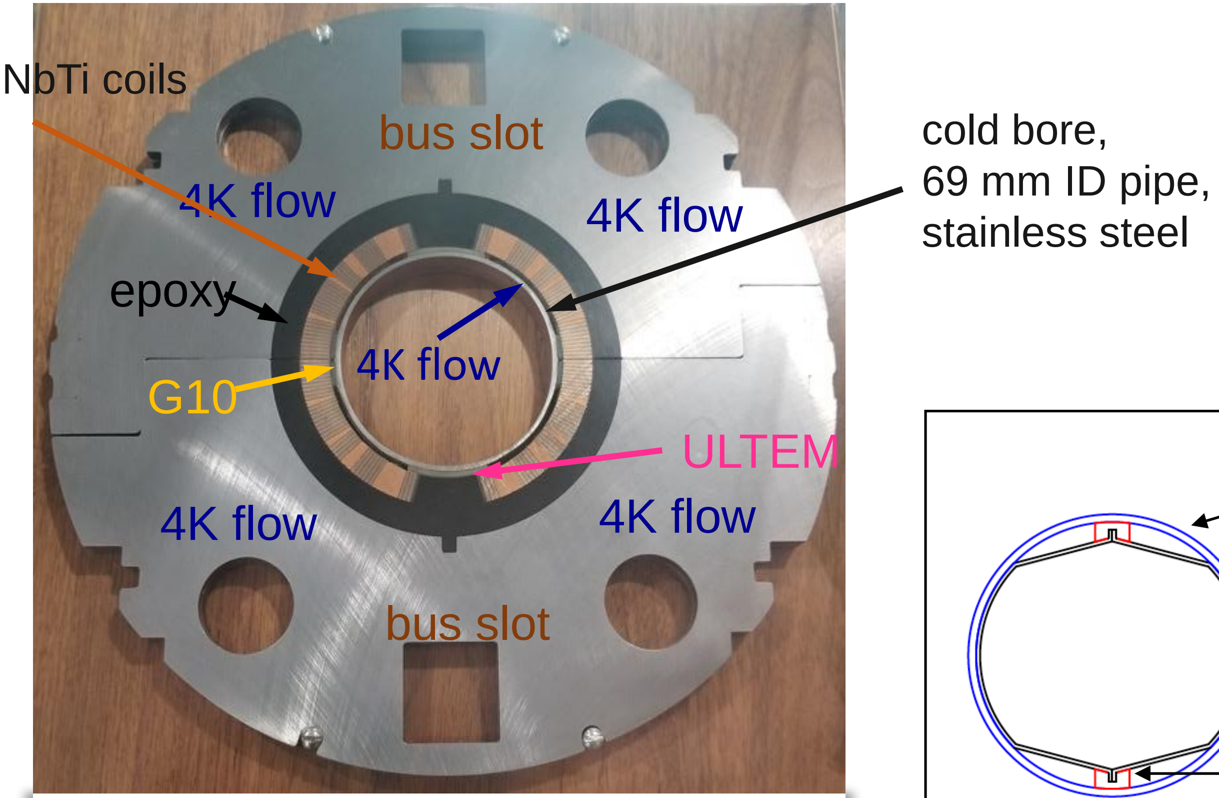
Related - polarimetry:

- for protons with small bunch spacing
- for spin-polarized 3He beams

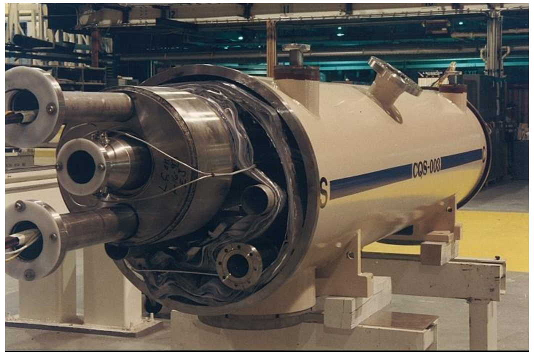
Technology: beam-pipe coating

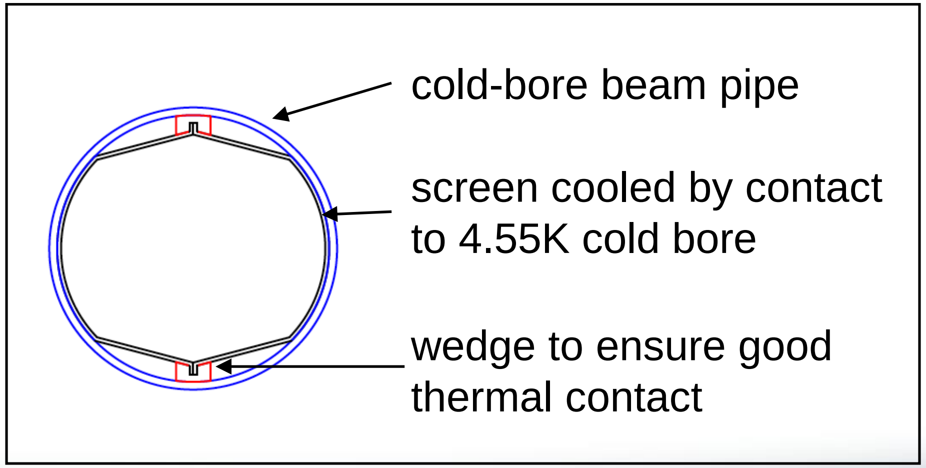
Two main concerns due to short proton bunches and small bunch spacing:

1) Resistive wall heating → stainless-steel screen with co-laminated copper
   RW heating 4.03 W/m → 0.08 W/m
1) Electron cloud generation → apply thin (100 nm) a-C layer (SEY ~ 1.06) on top of copper



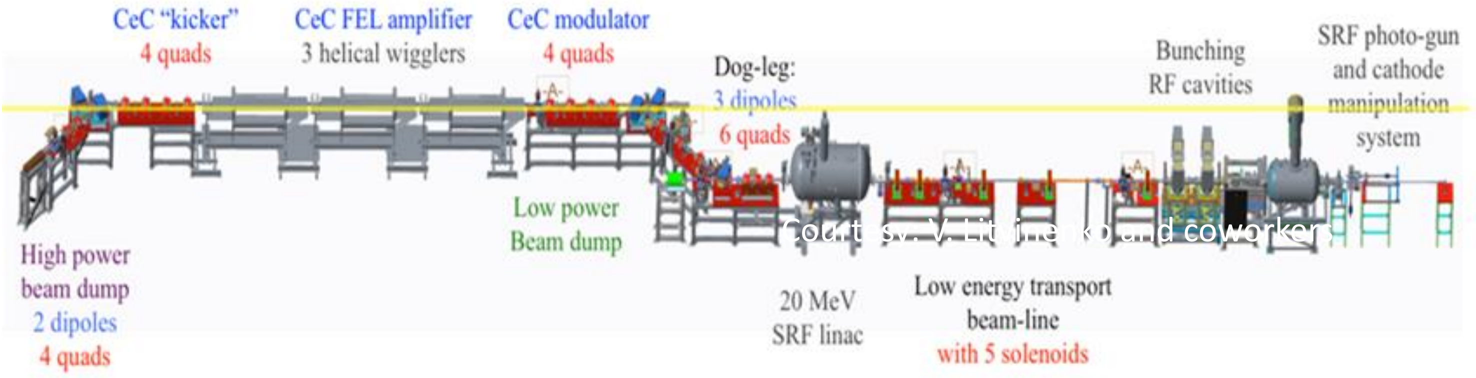
RHIC arc dipole cross section





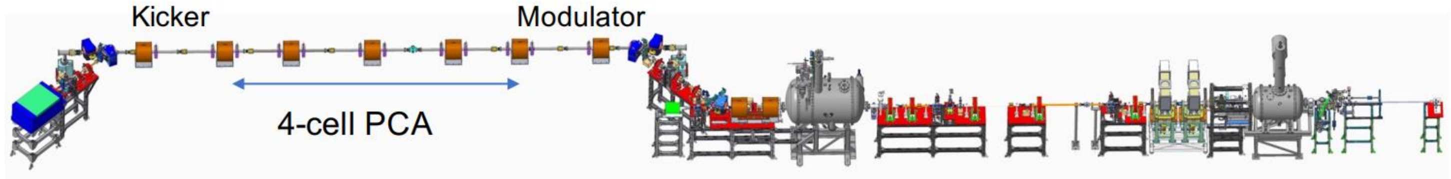
Technology: Coherent electron Cooling

< 2019, Free-electron-laser (FEL) based cooling channel



Courtesy: V. Litvinenko and coworkers

2019+, Plasma-cascade-amplifier (PCA) based cooling channel

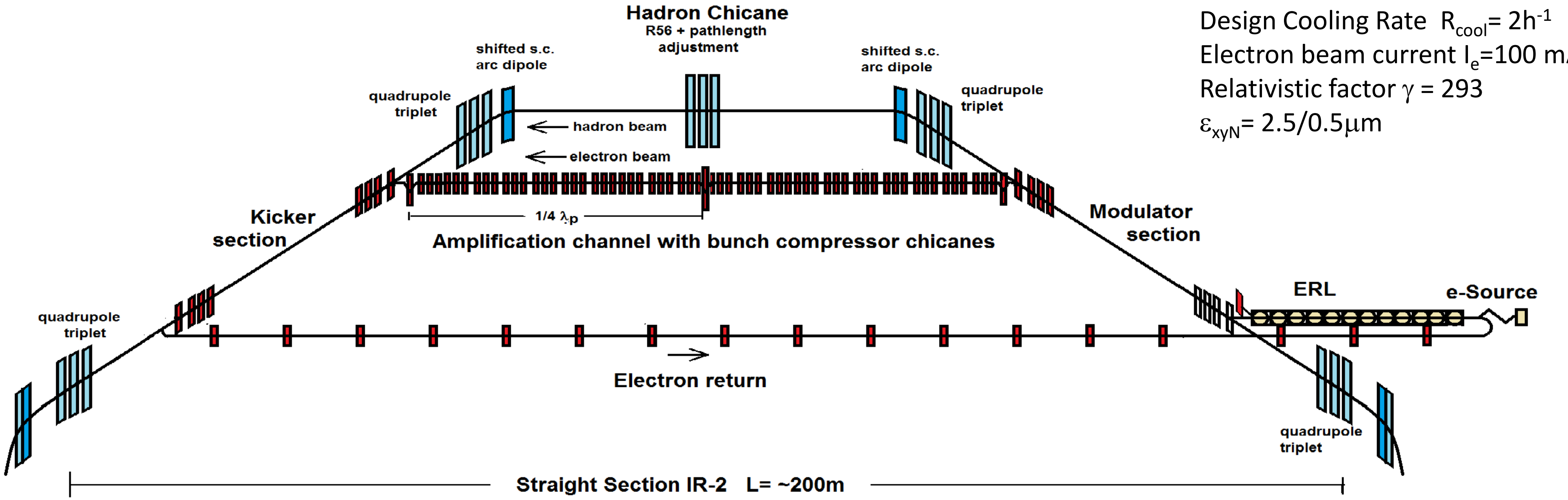


Electron beam (KPP) parameters demonstrated Jul 2020

First amplification by factor ~200 observed Aug 2020 (preliminary)

V. N. Litvinenko, Y.S. Derbenev, Coherent electron Cooling, PRL **102**, 114801 (2009)

Technology: Strong Hadron Cooling



Design Cooling Rate R_{cool}= $2h^{-1}$
Electron beam current I_e=100 mA (1nC/bunch)
Relativistic factor γ = 293
ε_{xyN}= 2.5/0.5μm

Opportunities for collaboration:

- Simulations both for strong hadron and conventional cooling
- RF field control including microphonic mode damping and synchronization methods
- Instrumentation (rad hard, high time resolution, non-invasive, etc.)

Summary

- The RHIC complex serves a wide user base (RHIC experiments, isotope production, industrial and space applications) and is continually upgraded.

- Technology development for the EIC and other BNL programs is necessary for cost reduction and performance upgrades. Current focus is on the electron sources, cavity development with full HOM damping, beampipe shielding and coating methods, the CeC proof-of-principle test at RHIC, magnet development and emerging detector designs.

- The SBIR/STTR program serves an important role in upgrades of existing accelerators and for the EIC.

- Small business companies are encouraged to get in touch with the speaker or others at C-AD to find a match between upgrade and R&D needs for the RHIC complex and EIC developments with their capabilities and ideas.

Acknowledgement and Thanks

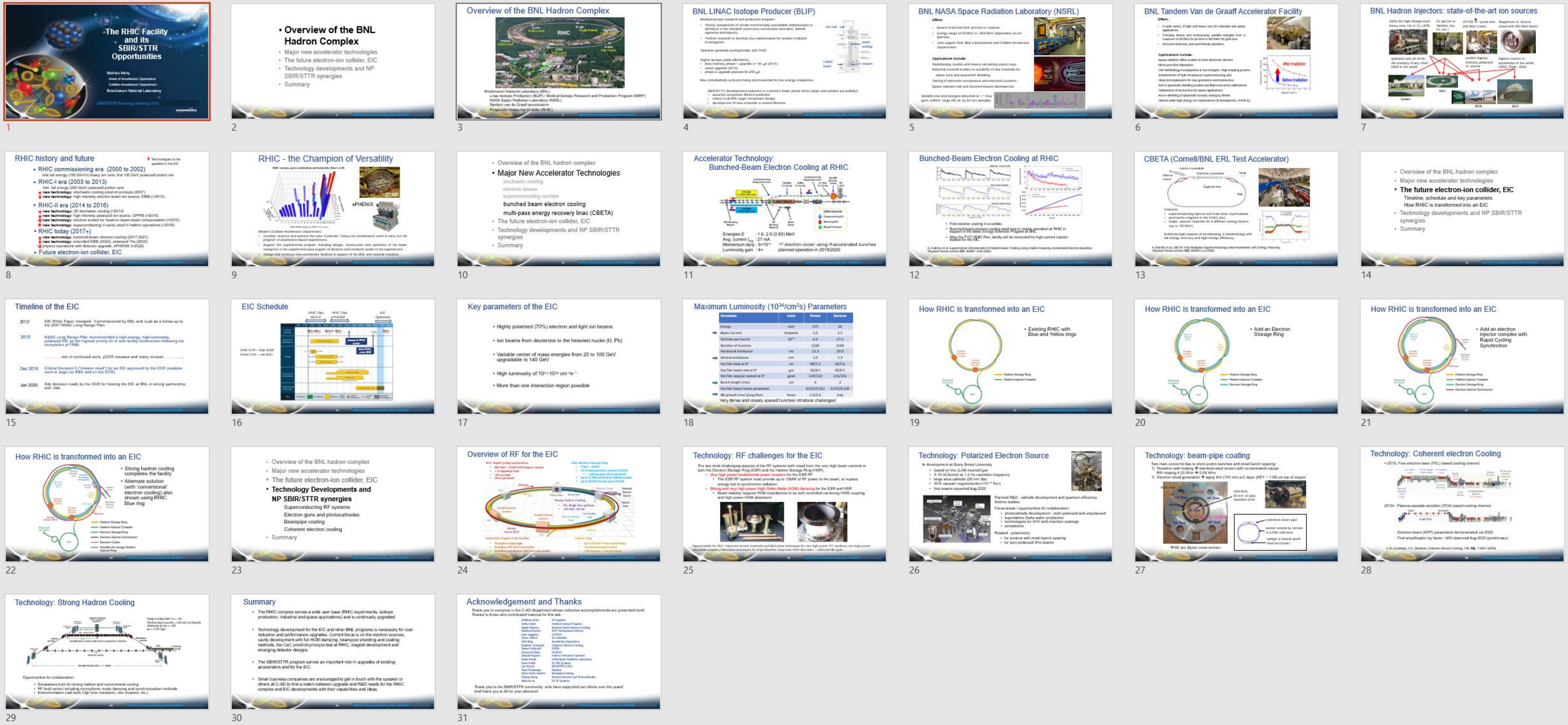
Thank you to everyone in the C-AD department whose collective accomplishments are presented here!
Thanks to those who contributed material for this talk:

Kathleen Amm	SC Magnets
Elke Aschenauer	EIC Detectors
Cathy Cutler	Medical Isotope Program
Alexei Fedotov	Bunched Beam Electron Cooling
Wolfram Fischer	RHIC Performance Metrics
John Haggerty	sPHENIX
Diane Hatton	EIC schedule
Nick Kling	Gallactic Cosmic Ray
Vladimir Litvinenko	Coherent Electron Cooling
Robert Michnoff	CBETA
Edward O'Brien	sPHENIX
Deepak Raparia	Hadron Preinjector Systems
Adam Rusek	NASA Space Radiation Laboratory
Kevin Smith	EIC SRF Systems
Ivar Strand	SBIR/STTR at BNL
Peter Thieberger	Tandem
Sylvia Verdu-Andres	Beampipe Coating
Erdong Wang	Electron Sources and Photocathodes
Wencan Xu	EIC RF Systems

Thank you to the SBIR/STTR community who have supported our efforts over the years!
And thank you to All for your attention!

Ongoing SBIR/STTR collaborations at BNL, Aug 2020

PIQ/Cont#	Sponsor	Title	Dept	SBIR/STTR
NF-18-40	Poole Ventura, Inc. (PVI)	Techniques for Energetic Ion Assisted In-Situ Coating of Long, Small Diameter, Beam Pipes with Compacted Thick Crystalline Copper Film	AD	SBIR
NF-18-42	Advanced Conductor Technologies, LLC	CORC® cable based high field hybrid magnets for future colliders	AM	STTR
NF-18-43	Delaware Diamond Knives, Inc.	Flux Monitoring on an X-ray Refractive Diamond Lens	IO	SBIR
NF-19-45	Spectral Sciences	Compact, High Performance, Drone-Mounted Spectral Imaging System for Ecosystem Carbon-Cycle Characterization and Agricultural Monitoring	EE	SBIR
NF-19-47	Sigray, Inc.	Development of X-ray Nano-focusing System with Tunable Focus Using a Combination of Capillary Mirror Lens with Multlayer Laue Lens (MLL)	PS	SBIR
NF-19-48	RadiaSoft, LLC	Massively-Parralel Magnet Design from a Web Browser - Phase II SBIR	PS	SBIR
NF-19-56	Accelogic LLC	Next-Generation Technology for The Extremely Efficient Storage, Distribution, and Processing Of Nuclear Physics Data	PO	SBIR
NF-19-58	NanoSonic, Inc.	Long-term Radiation Rugged Rotary Vacuum and Water Seals in Heavy-Ion Accelerators	AD	SBIR
NF-20-02	STI Optronics, Inc.	Diamond Electron Amplifier	AD	STTR
NF-20-03	EcoLong LLC	Advanced Peer to Peer Transactive Energy Platform with Predictive Optimization	CC	SBIR
NF-20-08	NanoSonic, Inc.	NSRL User (P-58) NanoSonic, Inc.	AD	SBIR
NF-20-09	NanoSonic, Inc.	NSRL User (P-59) NanoSonic, Inc.	AD	SBIR
NF-20-16	Physical Sciences, Inc.	STTR: Passive Cathode Coatings and Devices for Spacecraft Charge Mitigation	IO	STTR
NF-20-17	Particle Beam Lasers, Inc.	Quench Protectio nfor a Neutron Scattering Magnet	AM	SBIR
NF-20-19	Euclid Techlabs LLC	RF Sputtering Coating of Electron Transparent Materials for Photocathode Encapsulation	AD	SBIR
NF-20-20	Sigray, Inc.	Development of Capillary Optics Optimized for X-ray Fluorescence Microscopy that will Enable 3-Dimensional (3D) Fluorescence Imaging with 250nm Spatial Resolution and Potential Towards 100nm	PS	SBIR
NF-20-37	Sydor Instruments, Inc.	Transparent X-ray Camera	IO	SBIR


The RHIC Facility and its SBIR/STTR Opportunities
Overview of the BNL Hadron Complex
BNL LINAC Isotope Producer (BLIP)
BNL NASA Space Radiation Laboratory (NSRL)
BNL Tandem Van de Graaff Accelerator Facility
BNL Hadron Injectors: state-of-the-art ion sources
RHIC history and future
RHIC - the Champion of Versatility
Accelerator Technology: Bunched-Beam Electron Cooling at RHIC
Bunched-Beam Electron Cooling at RHIC
CBETA (Cornell/BNL ERL Test Accelerator)
Timeline of the EIC
EIC Schedule
Key parameters of the EIC
Maximum Luminosity (10^{34}/cm²s) Parameters
How RHIC is transformed into an EIC
Overview of RF for the EIC
Technology: RF challenges for the EIC
Technology: Polarized Electron Source
Technology: beam-pipe coating
Technology: Coherent electron Cooling
Technology: Strong Hadron Cooling
Summary
Acknowledgement and Thanks
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31