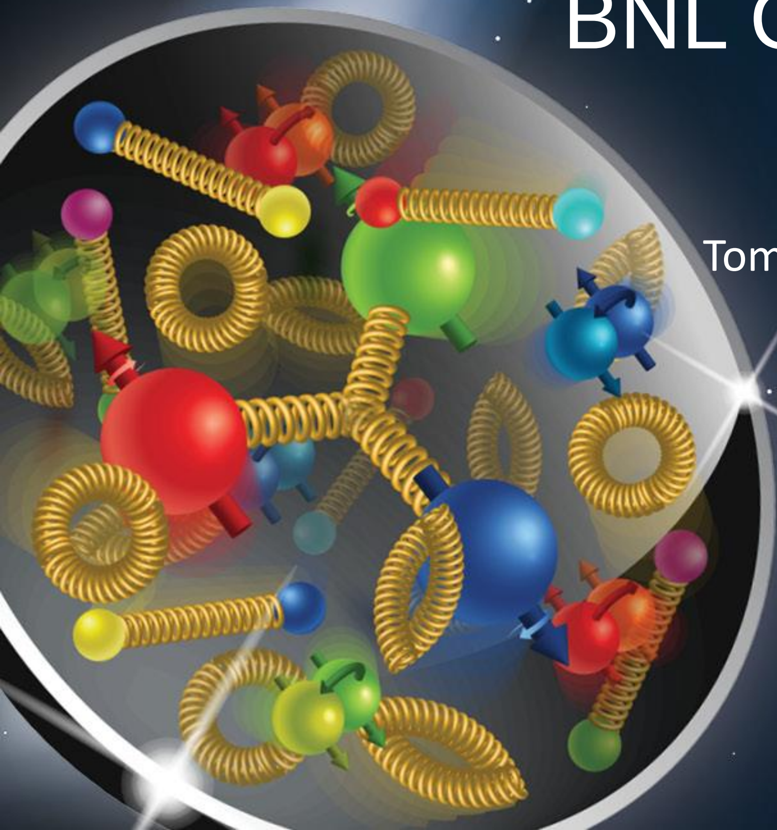
LLRF Operations and Developments at the BNL Collider-Accelerator Complex

Kevin Smith
for the BNL C-AD LLRF Group
Tom Hayes, Kevin Mernick, Geetha Narayan, Freddy Severino



LLRF2017
Low Level Radio Frequency Workshop
BARCELONA
16-19 October
2017
ALBA

Electron Ion Collider – eRHIC

BROOKHAVEN NATIONAL LABORATORY
U.S. DEPARTMENT OF ENERGY | Office of Science

Outline of the Presentation

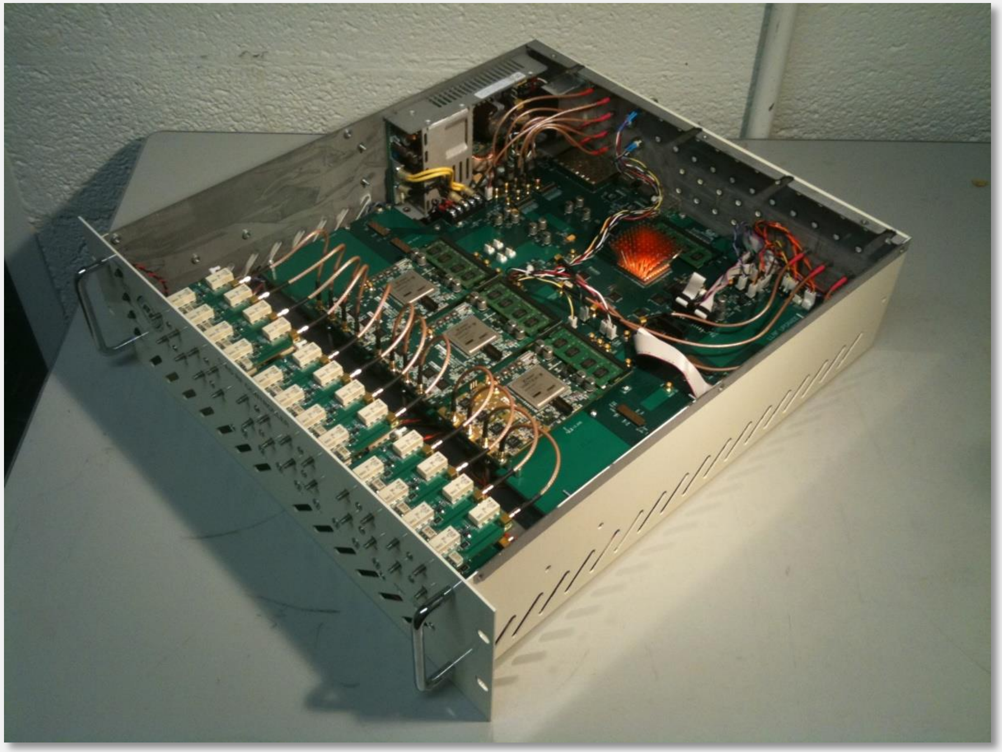
- Brief Review of the RHIC LLRF Upgrade Platform
  - What it is and what we do with it (everything).

- Selected Current LLRF Operational and R&D Efforts
  - 200 MeV High Intensity H- Linac LLRF Upgrade (Poster: F. Severino)
  - LEReC – Low Energy RHIC electron Cooling (Poster: K. Mernick)
  - Active Piezo Compensation of SRF Cavity Microphonics (Poster: F. Severino)

- Toward the Future
  - eRHIC – An Electron-Ion Collider at RHIC

Brief History of the RHIC LLRF Platform

- Architecture described in prior conferences and workshops, PAC 2011, LLRF 2007, LLRF 2011, LLRF 2013.
- A digital LLRF control platform:
  - Extremely flexible, readily scalable and high performance.
- Designed to satisfy every LLRF application across the entire C-AD Complex – known and unknown.
- Concept first described at LLRF 2005.
- Hardware prototyping 2007 and 2008.
  - Prove out lots of new (to us) technologies.
  - Transitioning from Xilinx V4 and PMC to V5 and XMC.
- First operation (10 hours of test in Spring '09):
  - RHIC LLRF Beam Control, Dec. 09 2009 (Run 10).



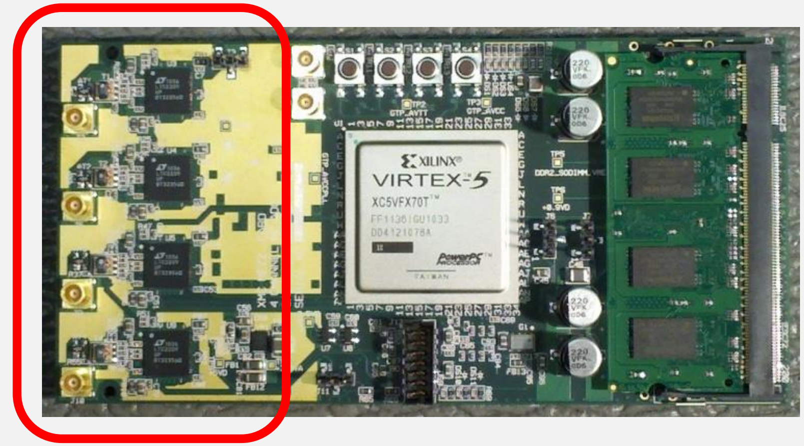
Platform Chassis showing Carrier Board, 2 DAC Daughter Boards and 1 ADC Daughter Board.

ae Dec-09-2009 05:06 (1 edit):cp RF is bailing for the morning.
Basic summary: We achieved our major goal of getting the RF beam control loops closed and stable (phase and radial loops). Found some issues on the way, which are mentioned in this log and ours. But we think we're in pretty good shape.

- LLRF Platform has since been rolled out to every operational machine and is also used for all current projects at C-AD.
- Although based on the now "obsolete" Virtex-5 family, the system has proven incredibly versatile.

RHIC LLRF Platform Sub-Components

- The Platform comprises (for the most part) just five major sub-components.
  - Platform Carrier Board
  - Three XMC Daughter Cards:
    - 4CH High Speed DAC Board=> RF to Analog.
    - 4CH High Speed ADC Board => Analog to RF.
    - "Dawson" Board:
      - Generic-ish DAC/ADC with digital IO.
      - Used primarily as a tuner controller board.



Platform XMC 4CH High Speed ADC Board
Daughter Cards only differ inside RED box

  - "Update Link"
    - Same board used as:
      - Update Link Master Generator
      - "Agglomerator" => Update Link Concentrator.
      - "Deglomerator" = > Update Link Fanout
    - Downstream deterministic (i.e. fixed latency) 2 Gb/s serial link distributing encoded timing and data.
    - Key to ease of system integration, flexibility, scaling and synchronization.

ag·glom·er·ate

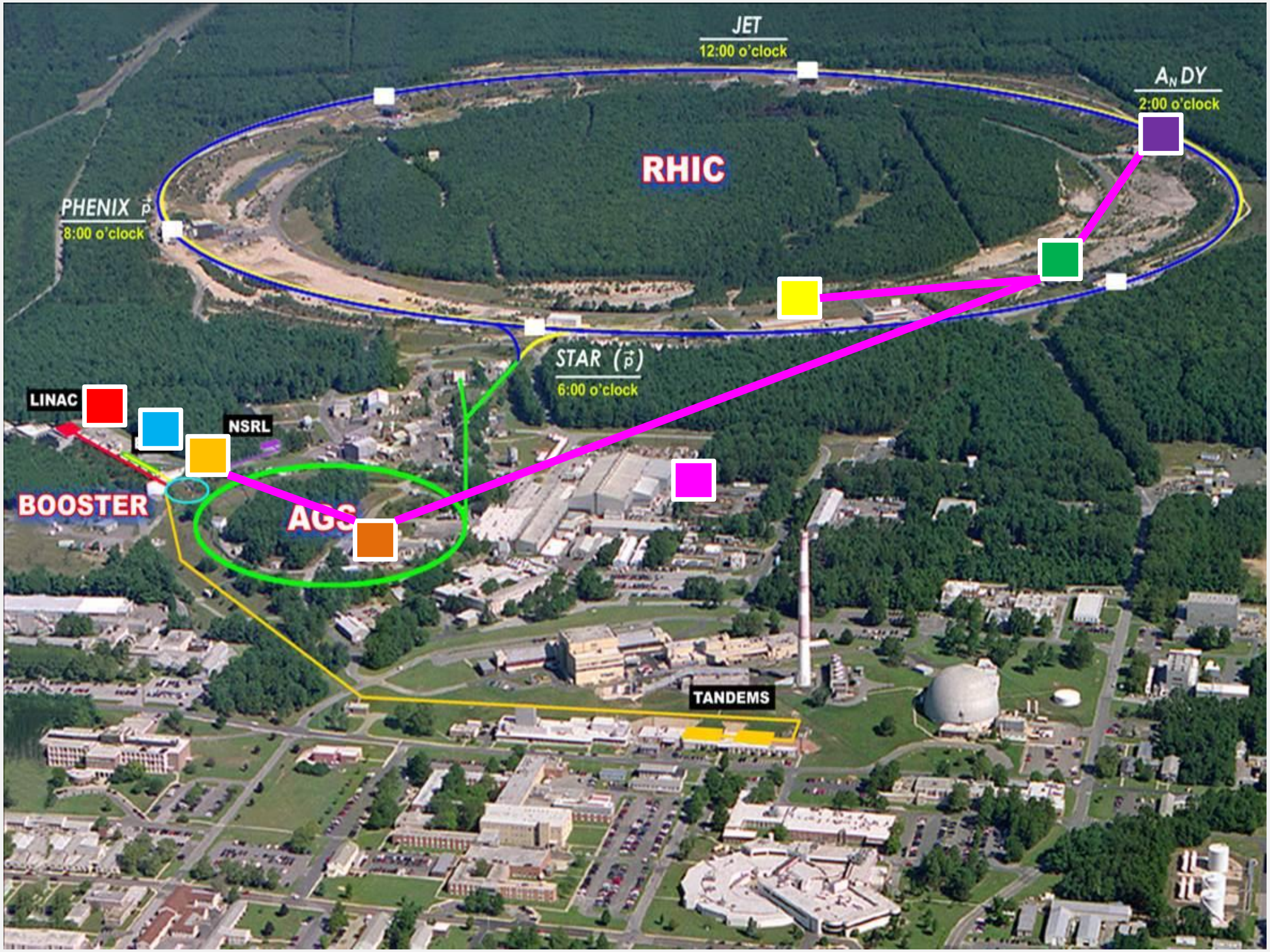
verb

/əˈgläməˌrāt/

1. collect or form into a mass or group.

  - RF Asynchronous Fixed frequency clocking/sampling generally used everywhere.
    - We used fixed almost everywhere because it affords significant advantages for us.
    - RF synchronous clocking used for certain trigger generation applications (e.g. e- gun fiber lasers).
    - Can use fixed, RF synchronous, both or other.

RHIC LLRF Platform Needs a New Name



Systems Linked via Update Link

- LEReC LLRF
- CeC-PoP LLRF
- BBB Long. Damper
- RHIC LLRF
- BBB Trans. Damper
- AGS LLRF
- Booster LLRF

Standalone Systems

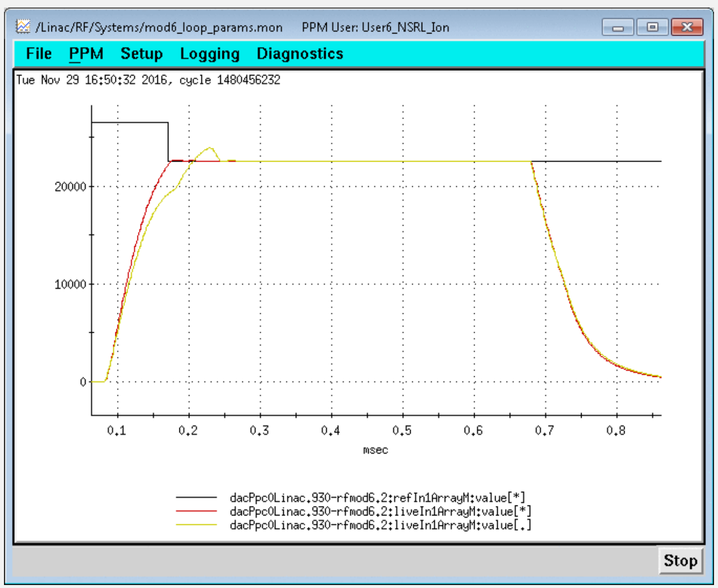
- EBIS LLRF
- H- Linac LLRF
- SRF Test Facility LLRF

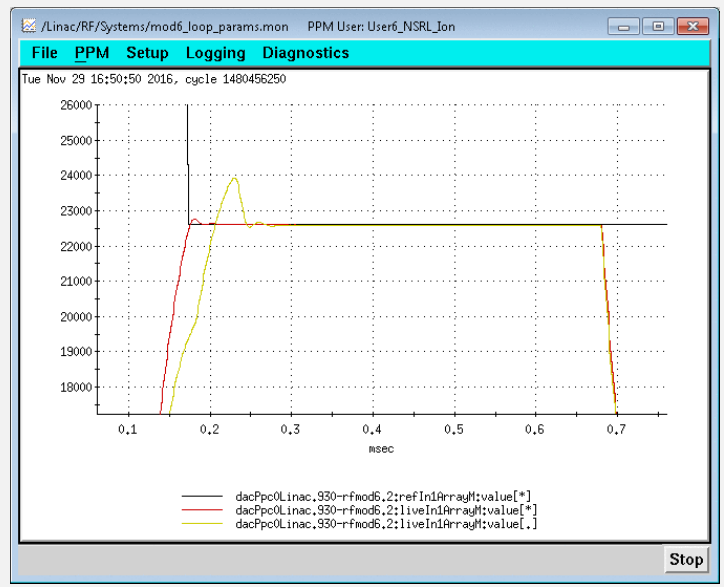
Approximately 73 Controller Chassis in operation.

200 MeV H$^-$ Linac LLRF Upgrade

See Poster, F. Severino "Low Level Upgrade for the BNL 200 MeV H$^-$ Linear Accelerator"

- From a couple of slides back:
  - LLRF Platform has since been rolled out to every operational machine and is also used for all current projects at C-AD.
- The 200 MeV H- Linac was the last major accelerator to be upgraded using the platform.
  - Linac began operation in 1971, when I was 5 ½.
  - 9 DTL tanks + Buncher + RFQ, operating at 201.25 MHz
- Tank Power Amplifiers are 5MW pulsed triodes (7835 - BNL, FNAL, LANL)
  - Phase controlled by the RF Drive signal.
  - Amplitude controlled by modulating the triode plate voltage.





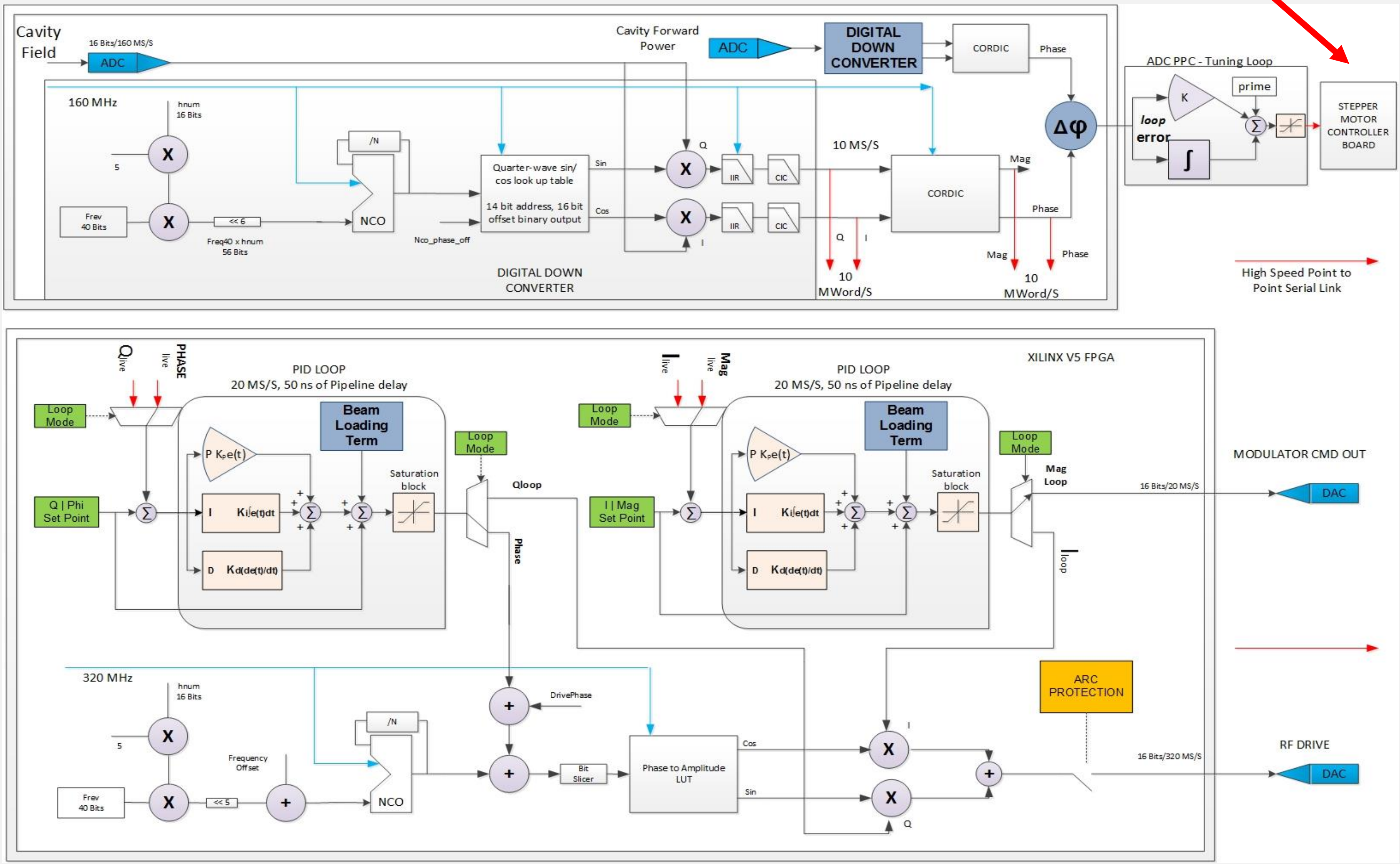
200 MeV H⁻ Linac LLRF Upgrade

See Poster, F. Severino "Low Level Upgrade for the BNL 200 MeV H⁻ Linear Accelerator"

"Dawson" Board

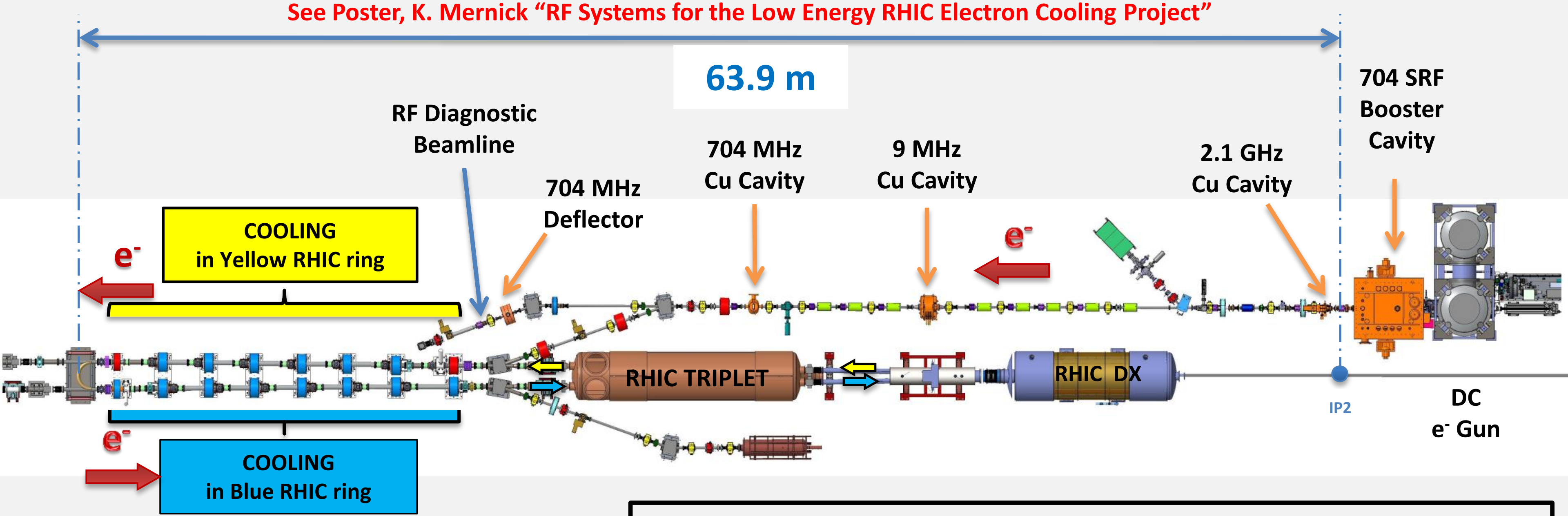
4CH ADC Board

4CH DAC Board



LEReC: Low Energy RHIC electron Cooling

See Poster, K. Mernick "RF Systems for the Low Energy RHIC Electron Cooling Project"



* Layout Not to Scale

- RHIC Beam Energy Scan II
  - Search for the QCD Critical Point.
- Goal is to cool low energy RHIC hadron beams during the RHIC Beam energy Scan II (BES-II) to increase luminosity up to 4x.
- First bunched beam electron cooler in the world.

704 MHz SRF Booster Cavity

Acceleration to desired beam energy.

Produces an energy chirp to stretch the electron bunches (reduce space charge).

2.1 GHz Warm Cavity

Provides RF curvature correction to compensate 704 MHz curvature.

9 MHz Warm Cavity

Provides a bunch by bunch linear energy kick which varies along the macro-pulse bunch train.

Compensates the "linear" periodic transient beam loading, i.e. the discharge of the cavities from the first to the last bunch of a macropulse.

704 MHz Warm Cavity

Removes the energy chirp impressed by the 704 MHz Booster Cavity.

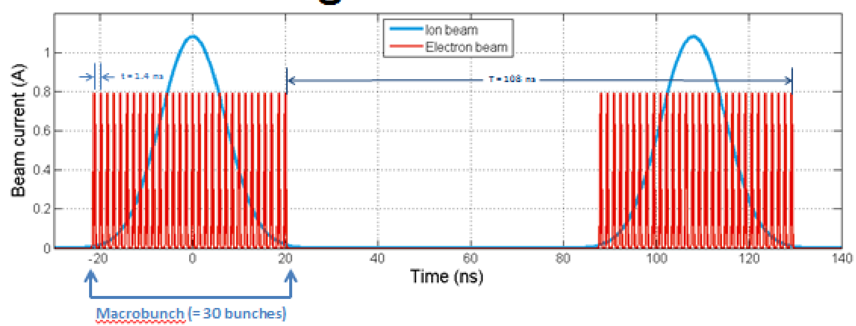
LEReC: Electron Beam Parameters & Stability Requirements

See Poster, K. Mernick "RF Systems for the Low Energy RHIC Electron Cooling Project"

Parameter	Unit	K.E. = 1.6 MeV	K.E. = 2.0 MeV	K.E. = 2.6 MeV
Bunch Charge	pC	130	170	200
Bunches per Macro-Pulse		30	30	24-30
Charge per Macro-Pulse	nC	3.9	5.1	4.8 – 6.0
Average Beam Current	mA	36	47	44 - 55
RMS Energy Spread		< 5E-4	< 5E-4	< 5E-4

- High power, high current, low energy spread, low emittance electron accelerator.
- Macro-Pulse structure generates strong transient beam loading.
- Cavity HOMs and beamline device impedances carefully addressed.

Laser Timing and Bunch Structure



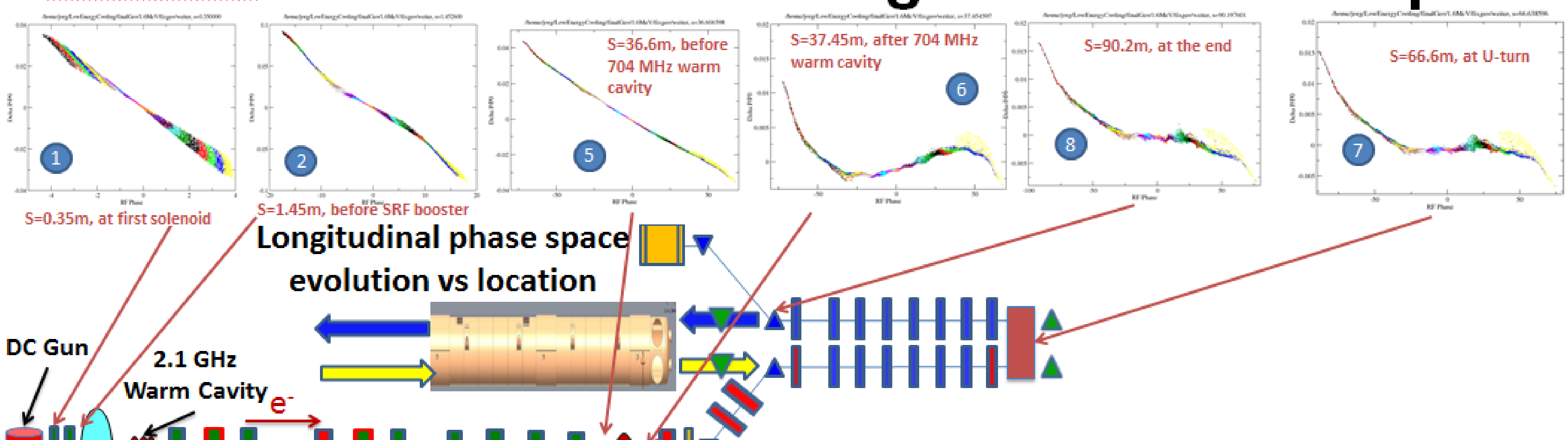
Electron bunches are generated in the DC gun with a repetition rate of 704 MHz. Macrobunches (consisting of ~30 bunches) repeat at the 9 MHz ion bunching frequency. These frequencies are both harmonics of the RHIC ion revolution frequency, but the 704 MHz harmonic is not an integer multiple of the 9 MHz harmonic.

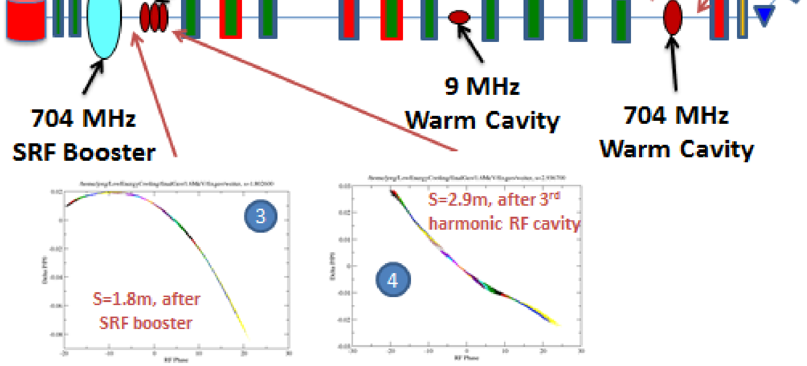
	704 MHz Booster	2.1 GHz Warm	704 MHz Warm	DC Gun	Drive Laser
$\Delta A/A$ (rms)	3×10^{-4}	2.5×10^{-3}	2.5×10^{-3}	5×10^{-4}	–
$\Delta\varphi$ (rms)	0.25°	0.75°	0.25°	–	0.25°

LEReC: Longitudinal Phase Space Evolution

See Poster, K. Mernick "RF Systems for the Low Energy RHIC Electron Cooling Project"

LEReC RF Cavities and Longitudinal Phase Space





704 MHz SRF Booster Cavity
- Acceleration to desired beam energy
- Produces an energy chirp to stretch the electron bunches (to reduce space charge effects)

2.1 GHz Warm Cavity (3rd Harmonic)
- Provides RF curvature correction to compensate 704 MHz curvature

9 MHz Warm Cavity
- Provides a linear energy kick which varies along the macrobunch
- Compensates the "linear" periodic transient beam loading, i.e. the average energy loss from the first to the last bunch of a macrobunch

704 MHz Warm Cavity
- Removes the energy chirp from the 704 MHz Booster Cavity

Active Microphonic Compensation of SRF Cavities at BNL C-AD

See Poster, F. Severino "Possibilities for Active Microphonic Compensation of BNL SRF Cavities"

- The Collider-Accelerator Department has several SRF cavities in operation:
  - RHIC 56 MHz Cavity
    - 4K QWR used to compress the stored ion bunches as well as provide a deeper RF bucket to combat longitudinal beam diffusion via IBS.
  - CeC Proof of Principle Experiment
    - Bunched beam electron cooling experiment aimed at high energy e-cooling.
    - 112 MHz 4K Photocathode Gun
    - 704 MHz 2K 5-Cell Elliptical Linac Cavity
  - LEReC Booster Cavity
    - 2K 704 MHz 0.4 Cell Elliptical Cavity (Converted Gun Cavity)

- The RHIC 56 MHz and CeC 704 MHz cavities are equipped with single piezo stacks in their tuner systems.

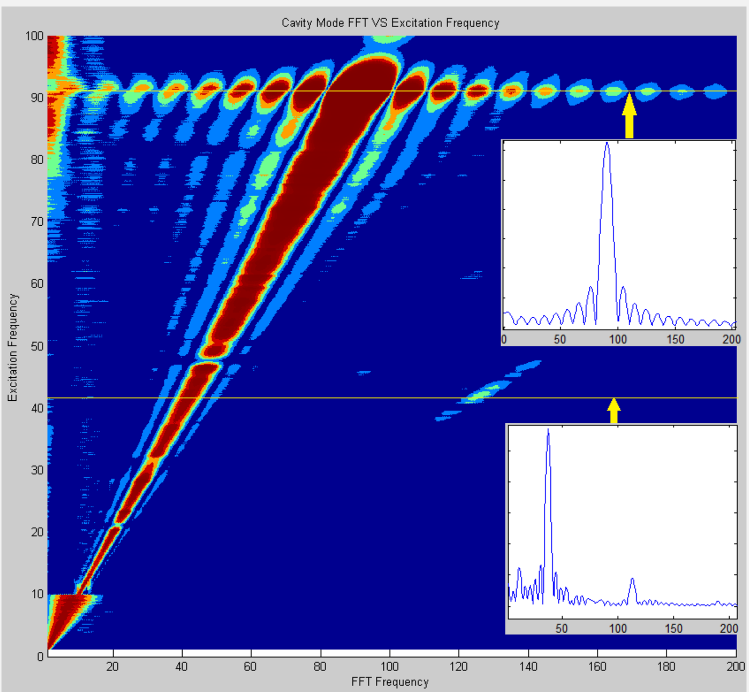
- Just over the past 6 months have we begun to investigate possibilities for active microphonic compensation.

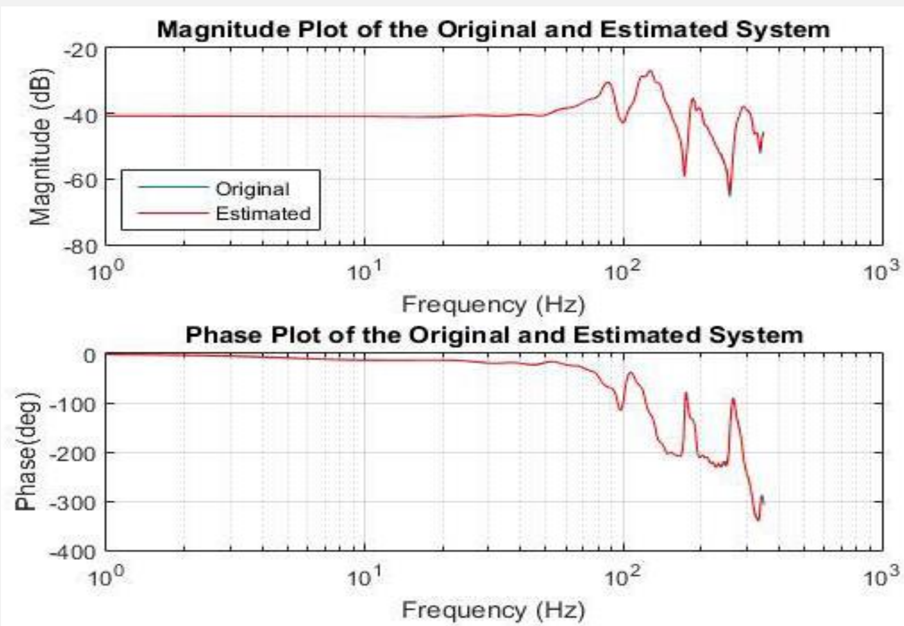
- Effort began with the obvious – characterize the system.
- Developed an accurate transfer function and model.
- Designed and implemented a compensator for the first mode and demonstrate we can at least close a loop.

Active Microphonic Compensation of SRF Cavities at BNL C-AD

See Poster, F. Severino "Possibilities for Active Microphonic Compensation of BNL SRF Cavities"

- Why are we (and many others) interested in this topic?
  - It is well known that SRF cavities are inhabited by small creatures (primarily gnomes) whose only amusement derives from detuning cavities in all manner of ways, leading at best to regulation issues and excess power requirements, and at worst to frequent trips and or cavities which can't operate at spec voltage.
  - Microphonics, if not suppressed by careful cryomodule design and/or some form of active compensation, ultimately dominate the power requirement for high Qext SRF systems => € € € € € …

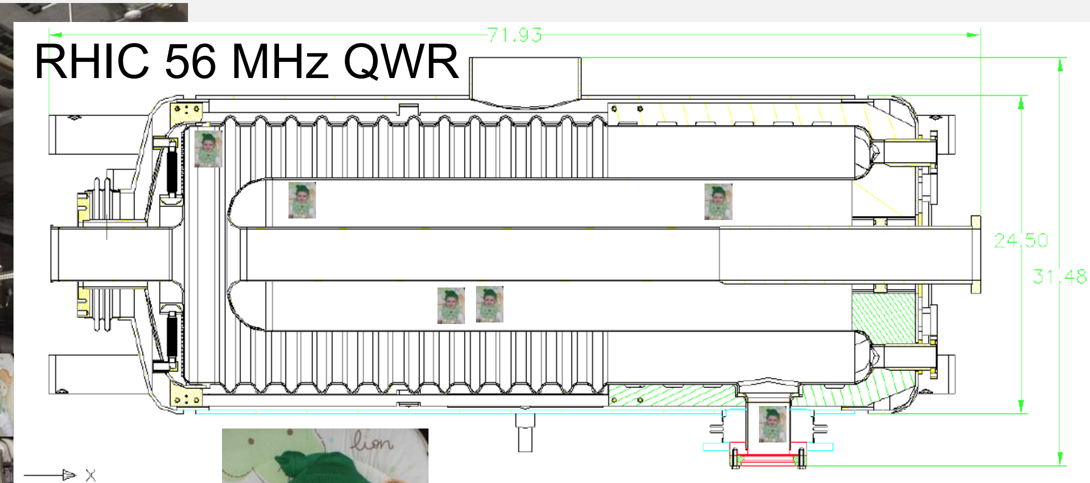


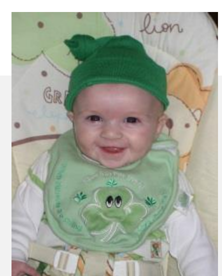


Active Microphonic Compensation of SRF Cavities at BNL C-AD

See Poster, F. Severino "Possibilities for Active Microphonic Compensation of BNL SRF Cavities"

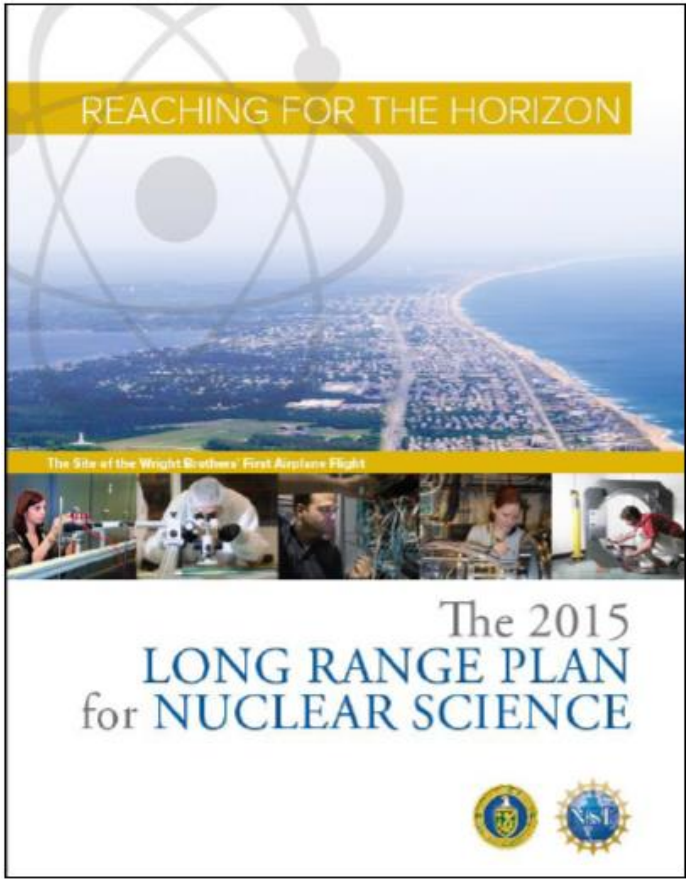
- Why are we (and many others) interested in this topic?
  - It is well known that SRF cavities are inhabited by small creatures (primarily gnomes) whose only amusement derives from detuning cavities in all manner of ways, leading at best to regulation issues and excess power requirements, and at worst to frequent trips and or cavities which can't operate at spec voltage.
  - Microphonics, if not suppressed by careful cryomodule design and/or some form of active compensation, ultimately dominate the power requirement for high Qext SRF systems => € € € € € …





<= Typical Microphonic Gnome

EIC: Electron – Ion Collider



The (US) 2015 Long Range Plan for Nuclear Science recommended to "Construct a high-energy, high luminosity polarized electron-ion collider (EIC) as the highest priority for new construction following completion of FRIB."

THE NATIONAL ACADEMIES OF SCIENCES, ENGINEERING, AND MEDICINE
Division on Engineering and Physical Science
Board on Physics and Astronomy

U.S.-Based Electron Ion Collider Science Assessment

- Assessment began early 2017.
- Report due Spring 2018.

http://www8.nationalacademies.org/cp/projectview.aspx?key=49811

- The EIC pre-conceptual designs are a collaboration between JLAB and BNL.
  - Each lab is developing a pre-conceptual design which leverages off their existing infrastructure and expertise.
  - Each design faces many common challenges.
- Numerous collaborations with US and international labs and universities to solve a number of very challenging technical issues.

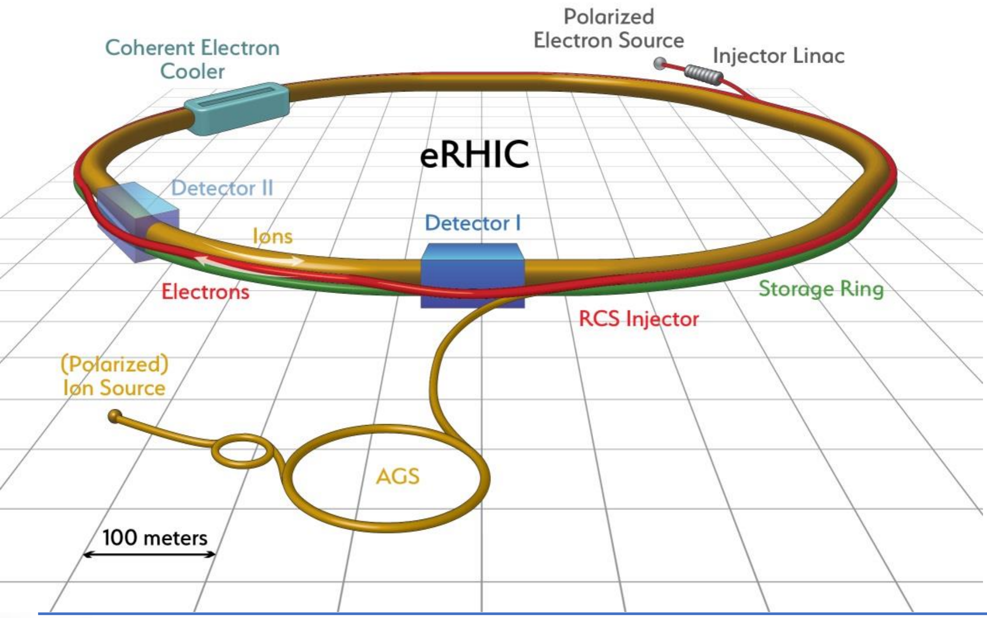
https://indico.bnl.gov/conferenceDisplay.py?confId=3492

EIC Collaboration Meeting 2017
chaired by Ferdinand Willeke (BNL)
from Tuesday, October 10, 2017 at **09:00** to Thursday, October 12, 2017 at **17:10** (US/Eastern)
at **Brookhaven National Laboratory (Bldg 555, Hamilton Seminar Room)**

Jefferson Lab — EXPLORING THE NATURE OF MATTER
BROOKHAVEN NATIONAL LABORATORY

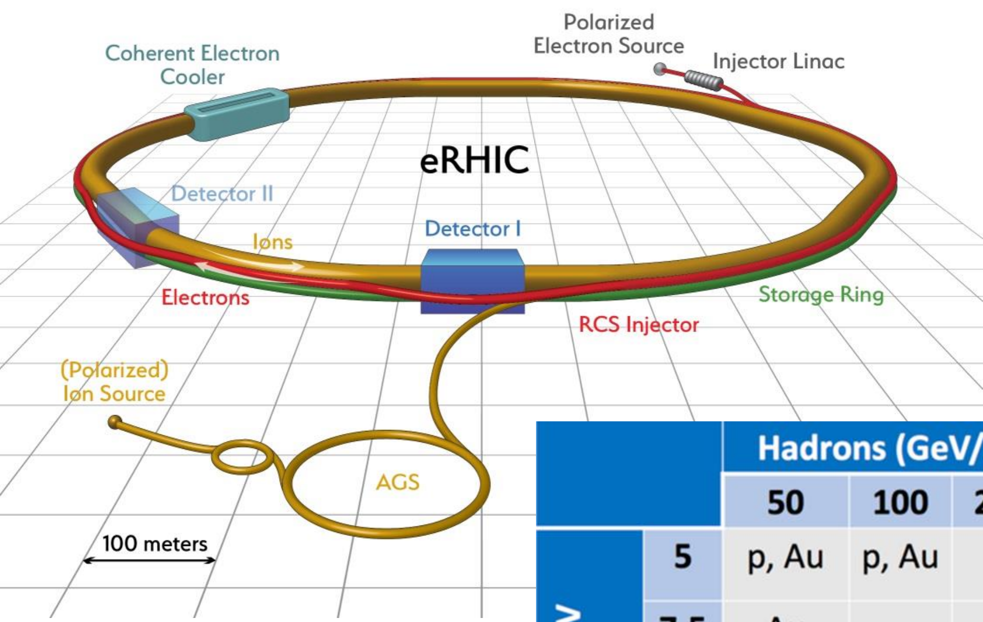
eRHIC: BNL Ring-Ring Design Concept

- High Energy Polarized Proton/Ion – Polarized Electron Collider
- Up to 275 GeV Proton x 18 GeV Electrons
- Peak Luminosity up to $1x10^{34}$ cm^2s^{-1}
  - 100x HERA 2006 (and polarized beams)



- Leverage the existing RHIC hadron infrastructure – with upgrades.
- Electron Storage Ring (5-18 GeV)
  - Up to 2.6 A electron current.
  - 10 MW maximum RF power
    - Into synchrotron radiation
    - Self imposed limit of ~ 4kW / m
- On-Energy Polarized Electron Injector
  - Rapid Cycling Synchrotron
  - 400 MeV to 18 GeV
- Pre-Injector:
  - Polarized electron source and 400 MeV injector linac: 10nC per bunch, 1 Hz

eRHIC: BNL Ring-Ring Design Concept



		Hadrons (GeV/u)		
		50	100	275
Electrons, GeV	5	p, Au	p, Au	
	7.5	Au		
	10		p	p
	15		Au	
	18	Au	Au	p

- Some LLRF Challenges
  - e- Storage Ring
    - 2.6A beam current with up to 10MW synchrotron radiation
    - Transient Beam Loading (10% gap)
    - Long. and Trans. Coupled Bunch Damping
    - 3rd Harmonic Bunch Lengthening
  - Hadron Ring Upgrade
    - 1A average beam current.
    - Transient Beam Loading
    - Bunch Splitting
    - Rebucketing or Adiabatic Squeeze
    - Long. and Trans. Bunch by Bunch Dampers
  - Crab Cavities
    - Very tight stability requirements
  - Hadron Cooling
    - 150 MeV, 50mA (150mA) electron beam
    - Low energy spread (~ 5E-4)
    - Must be an ERL

Alternative approach based on electron ERL accelerator has been thoroughly explored in the past. Technological risks were recognized and are being addressed by R&D. This approach is presently considered as a cost-effective backup and will be presented in the a pCDR Appendix.

CBETA test accelerator under development at Cornell University.
https://www.classe.cornell.edu/Research/CBETA/WebHome.html

Thank You for Your Time and Attention

Thought of the Day: “When you come to a fork in the road, take it.” – Yogi Bera