eRHIC Multi-Pass ERL

- eRHIC – future electron-ion collider at BNL
- Two eRHIC design options
- ERL-based eRHIC design Features
- SRF Linac
- Two variants of recirculation passes
- R&D efforts for polarized electron gun
- Summary

Vadim Ptitsyn
on behalf of eRHIC design team

ERL Workshop, CERN,
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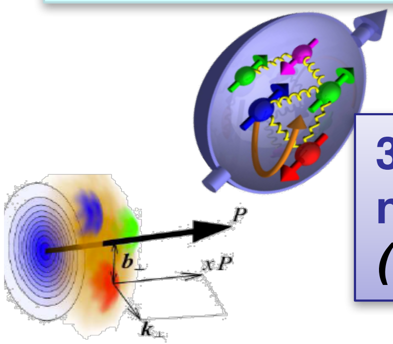
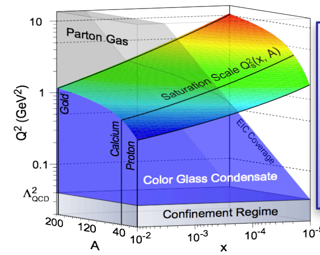
Electron-Ion Collider at BNL, eRHIC

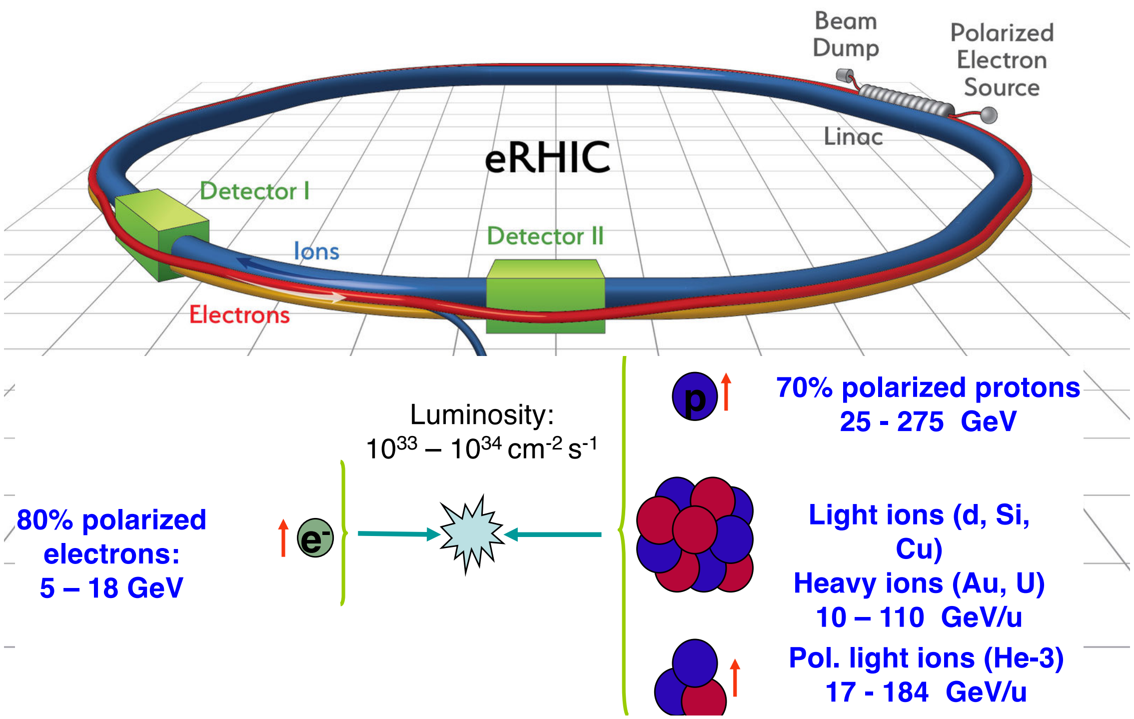
US Nuclear Physics Long Range Plan recommended a high-energy high-luminosity polarized EIC as the highest priority for new NP facility construction.



3D nucleon imaging, nucleon spin origin *(high L, polarized e-p)*



Study of gluon dominated matter, Discovery of color-glass condensate *(high CME , e-A)*

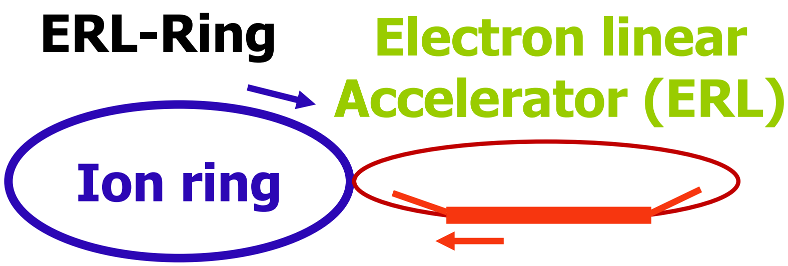


- Add an 18 GeV electron accelerator to the existing **$2.5B** RHIC complex
- In addition to the hadron machine eRHIC will re-use the existing infrastructure: RHIC tunnel and buildings, detector halls and cryo facility
- Take full advantage of existing polarized proton capability
- Take full advantage of existing heavy ion capability and large energy reach for gluon saturation studies

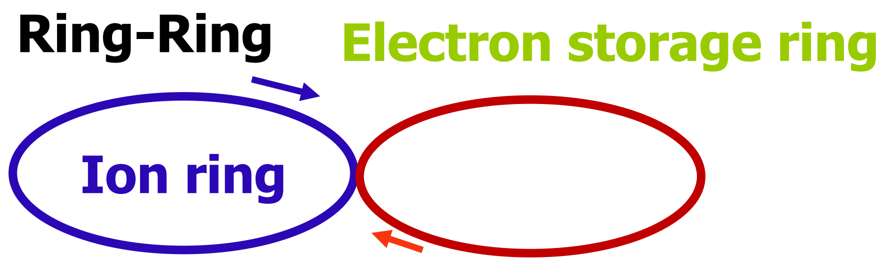
Two eRHIC Design Options

- **Main goals (and challenges) of eRHIC accelerator design:**
  - $L \sim 10^{33}$-10^{34} $cm^{-2}s^{-1}$ (exceeding HERA luminosity by 2 orders of magnitude)
  - High electron and proton polarization (>70%); Realizing complex spin pattern
  - Satisfying large acceptance detector, with detector elements integrated in the accelerator IR for forward particle detection
  - Minimizing the construction and operational cost of accelerator

To realize the goals two design options have been evaluated



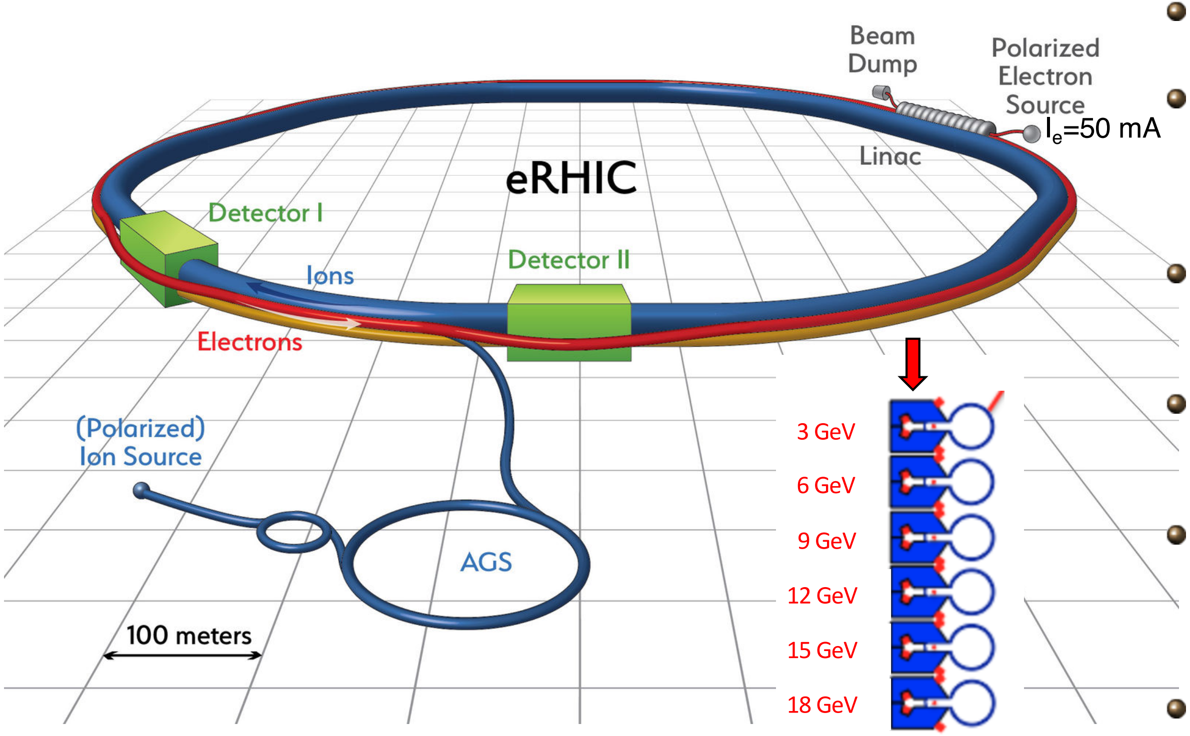
- High luminosity is based on small beam size in IP
- $L \sim E_p$
- Cost efficient; straightforward staging
- Requires some accelerator technology beyond present state-of-the-art
- Main challenge: polarized electron source. Presently addressed by corresponding R&D effort.



- High luminosity is based on high current of electron and proton beams
- $L \sim E_e{*}E_p = 0.5{*}E_{CM}^2$
- Less technological challenges than in ERL-Ring
- Challenges: High electron beam current and synchrotron radiation; Polarization
- Present design efforts are concentrated on this option towards a pre-conceptual design report at middle 2018.

ERL-Ring Design Features

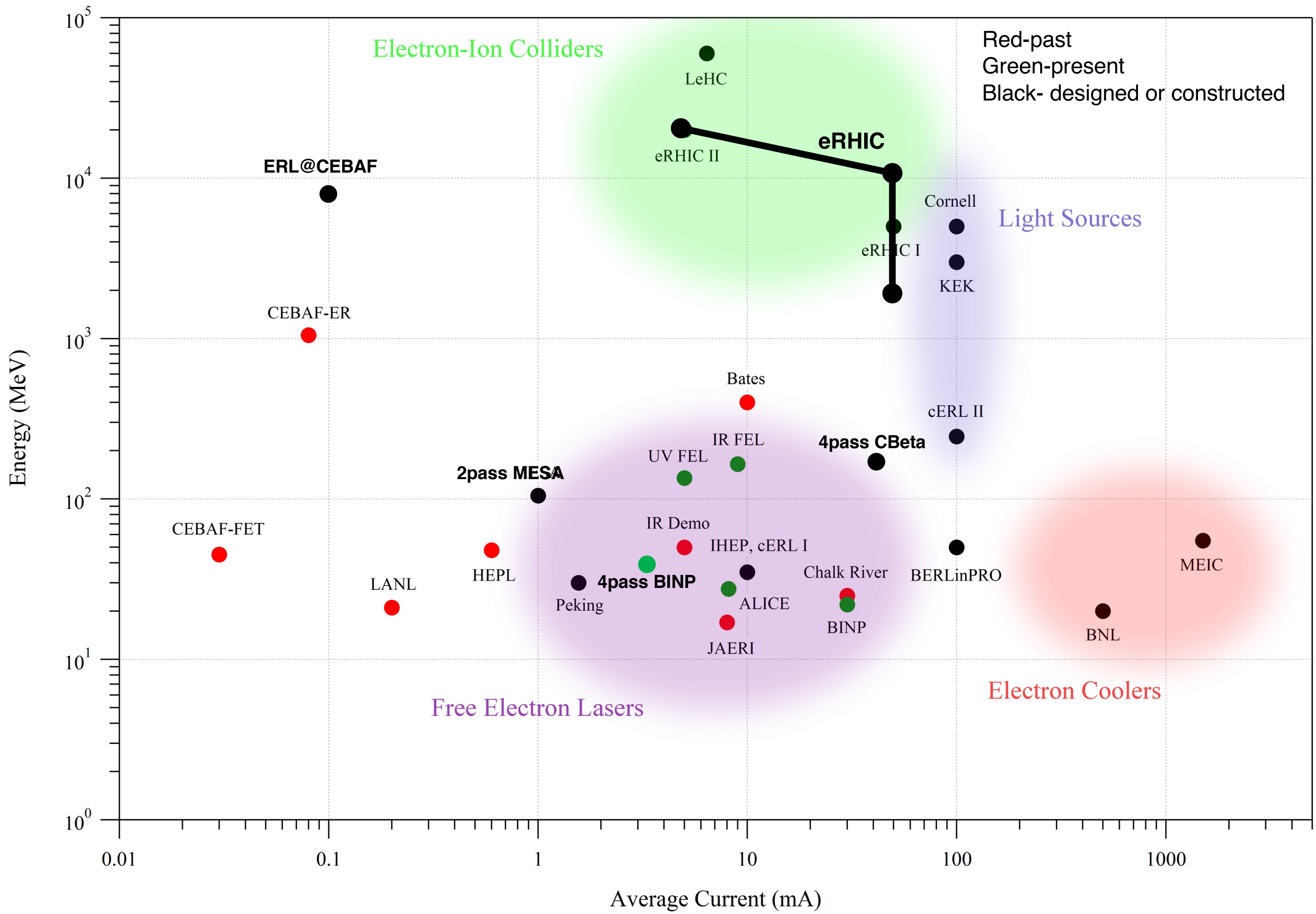
- Based on re-circulaitng electron linac (12 GeV CEBAF) and high current Energy-recovery linac technologies.
- Beyond present state-of-the-art: 50 mA polarized electron source and high-energy high-power ERL.
- Single collision of each electron bunch. No limit of electron beam-beam effect on luminosity.
- Small electron beam emittance.



More in V. Litvinenko's talk on Friday

- Maximum electron energy: 18 GeV
- 50 mA polarized electron source employing merging electron current produced by multiple electron guns
- Main ERL SRF linac(s): 647 MHz cavities, 3 GeV/turn
- Six individual re-circulation beamlines based on electromagnets
- For very high luminosity (~10^{34} cm^{-2} s^{-1}) with hadron cooling system (CeC)
- Interaction region design with crab-crossing satisfying detector acceptance requirements

Energy Recovery Linacs



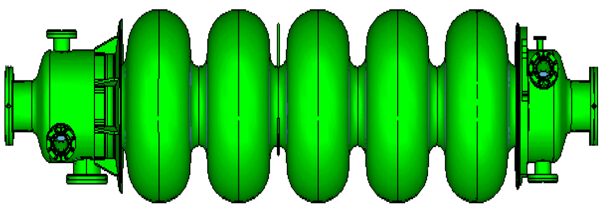
eRHIC ERL: Stepping up in beam current and beam power

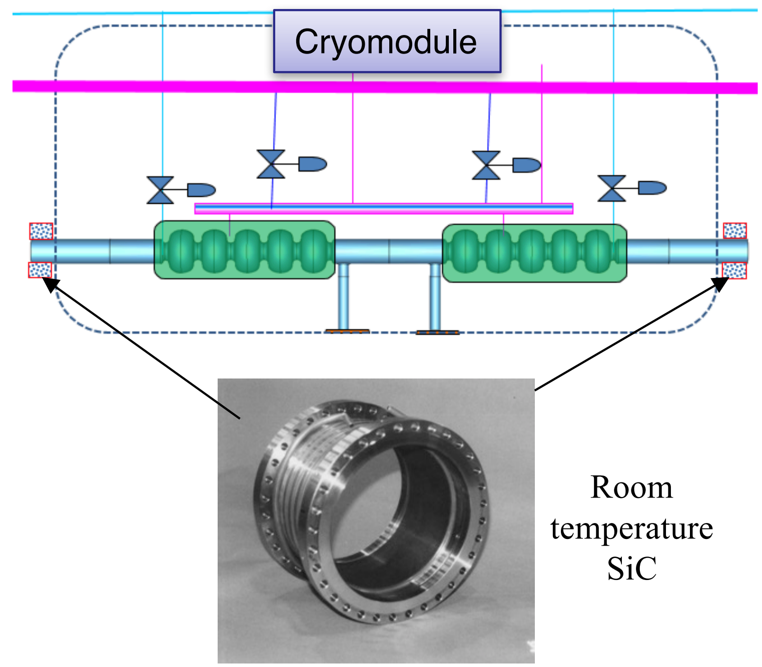
Major issues related with stepping up in the beam current and the beam power:

- Multi-pass Beam Break Up Instability
  - the cavity design and proper HOM damping to minimize HOM impedances
  - straightforward simulations to ensure that the instability threshold is large enough
  - machine lattice incorporating specific tools like betatron phase adjuster, and betatron coupling and/or large chromaticity (if needed)

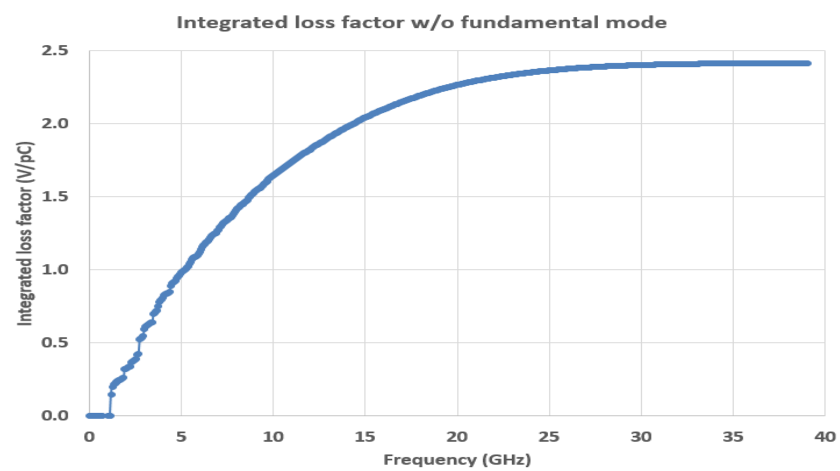
- Beam losses control/prevention:
  - Accounting and evaluating all possible beam halo sources
  - Proper choice of magnet apertures
  - Collimation system
  - Adequate beam current and beam loss diagnostics

Main Linac SRF



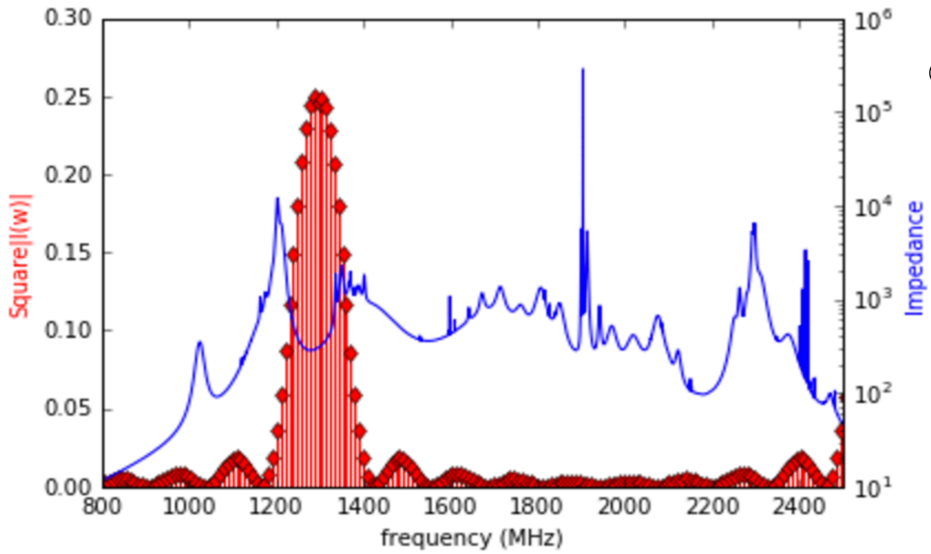


- 647 MHz 5-cell cavity
- Gradient: 18 MV/m@Q0=3e10.
- FPC power: 30 kW, Qext: 1.7e7
- Cooling 1.9K LHe
- Total amount: 144 cavities in 72 cryostats



- Frequency of main linac accelerating cavities is benefitting from the 650 MHz SRF development program for the Fermilab PIP II project.

HOM power



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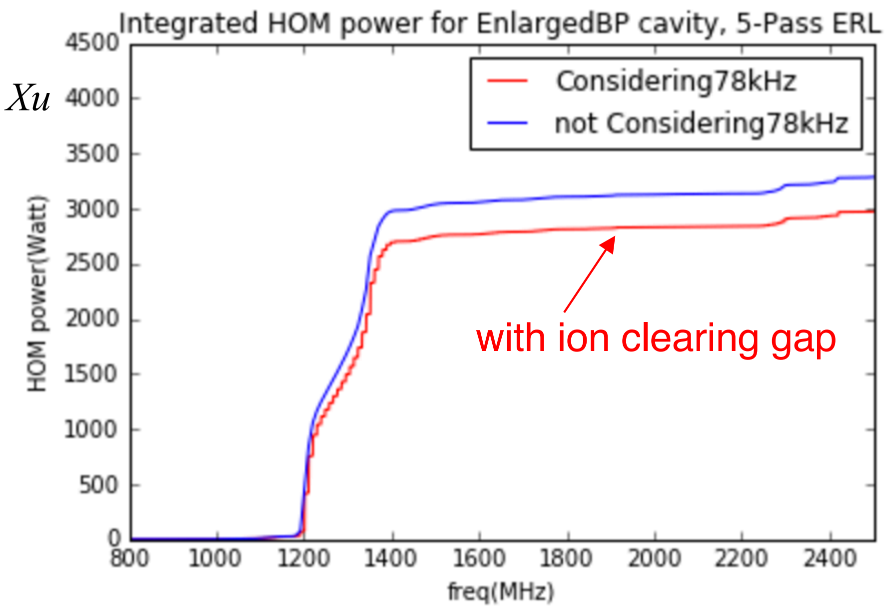


❖This is an example of HOM power calculated with a bunch pattern corresponding to completely interleaved accelerating and decelerating bunches

❖Several hundreds mA of total beam current in the Linac -> HOM power up to 7 kW per cavity.

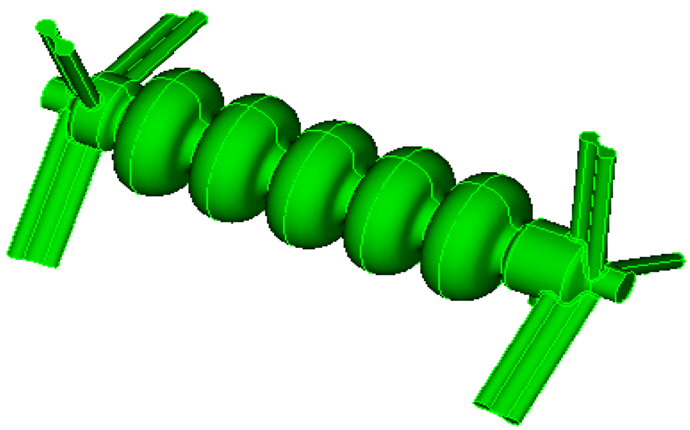
- ❖*This is similar to circulating beam in storage rings at KEKB and Cornell where up to 10 kW of HOM power is absorbed with Ferrite or SiC beam- pipe dampers*

❖Low risk solution: room temperature SiC absorbers

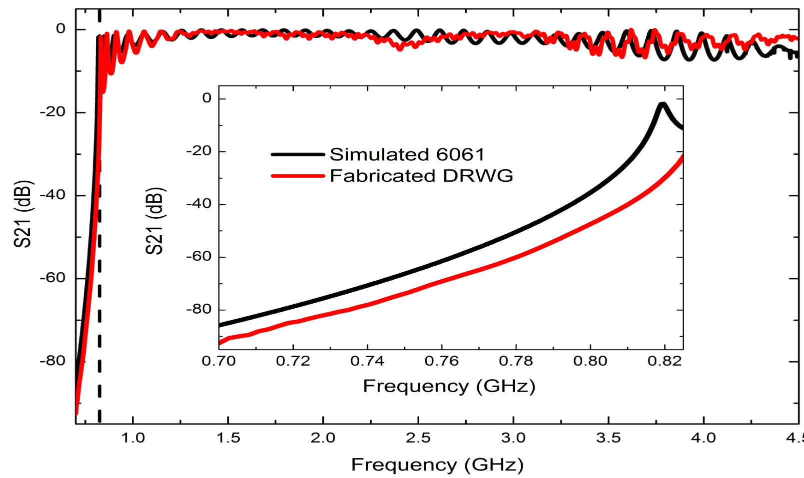
❖Ideal solution: combination of SiC and ridged waveguide absorbers

R&D for 650 MHz Cavity and HOM Damping

- The R&D effort is underway:
  - Copper prototype of 650 MHz 5-cell cavity has been recently fabricated. HOM measurements are ongoing.
  - Superconducting prototype is being fabricated by RI. Expected delivery in fall 2017.
  - HOM damping technology using both ridge waveguide dampers and beam pipe absorbers will be tested with cavity prototypes (2017-2018).



650 MHz cavity with ridge waveguide dampers



Ridge WG is a natural high pass filter with higher bandwidth, smaller size than regular WG.

Dipole HOMs

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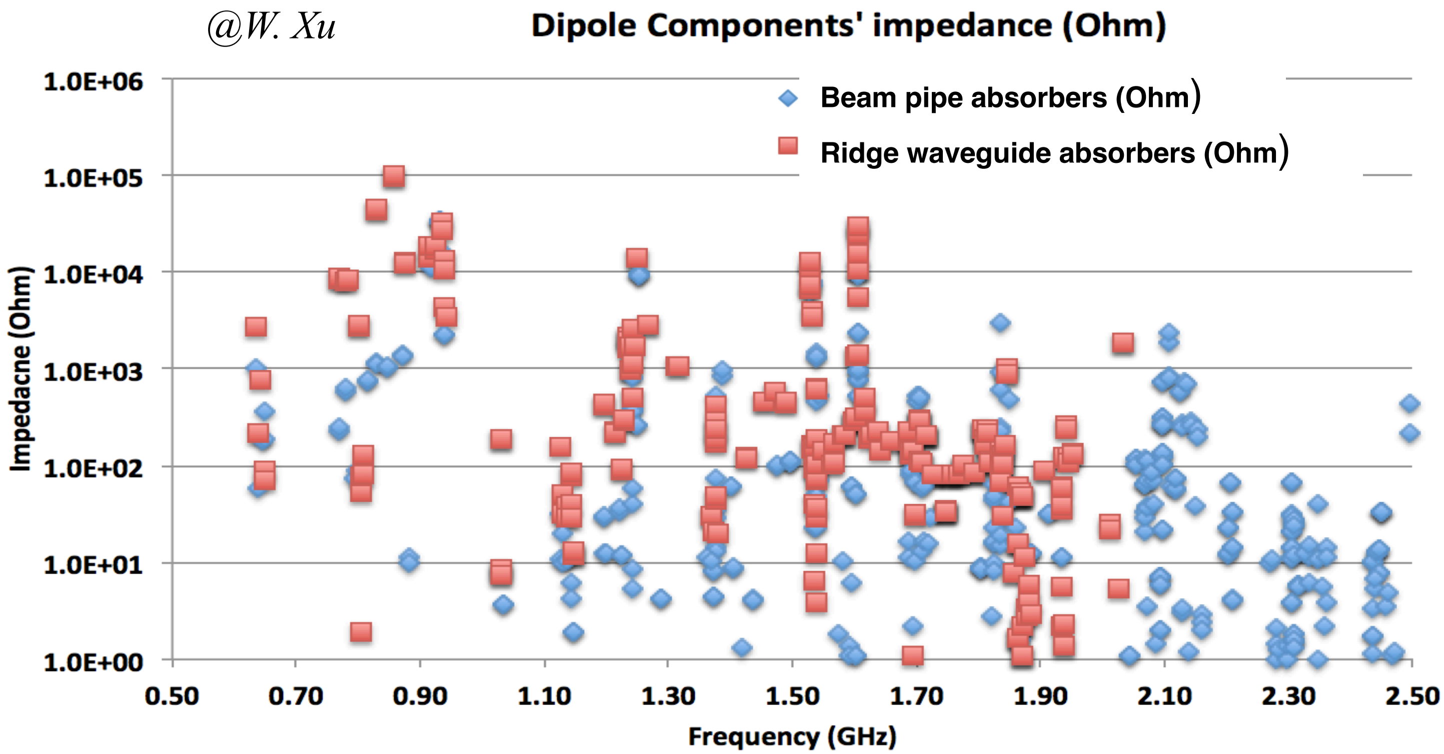


- These data were used as an input to the MBBU simulations
- From simulations with 12-recirculation pass lattice the MBBU threshold is expected to be above 100 mA

Recirculation passes

Two options for recirculating passes have been considered.

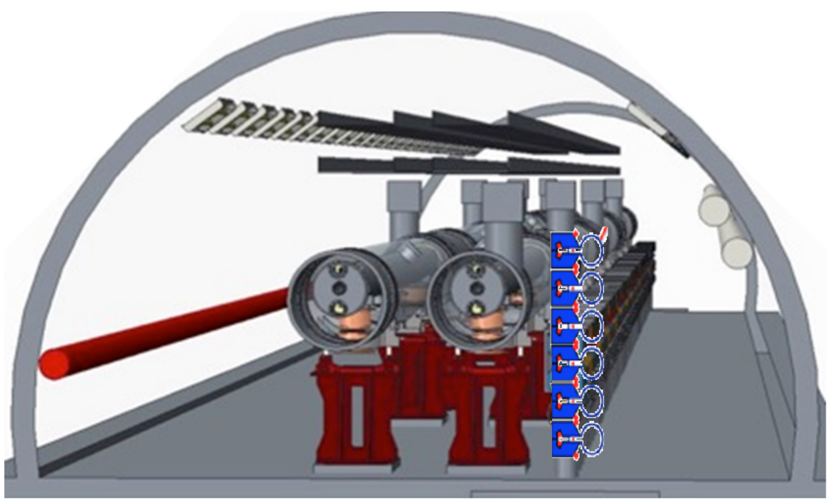
For both options lattice design has been developed.

Standard approach:

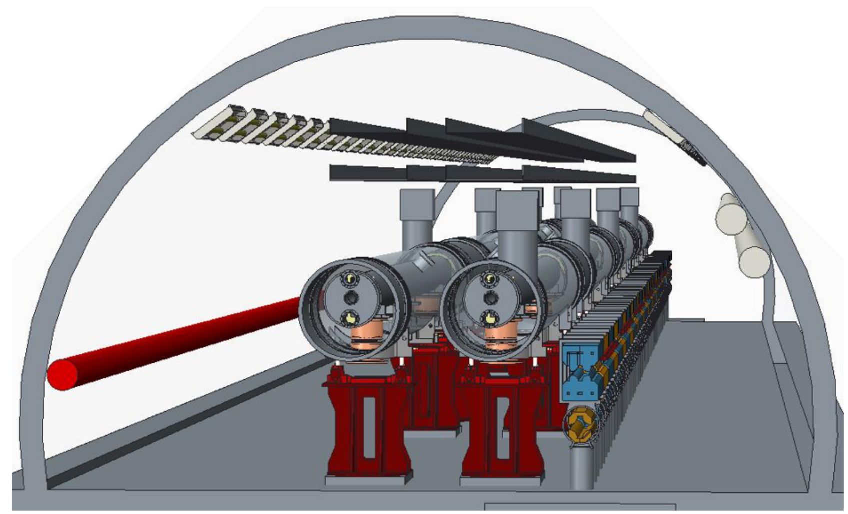
Up to 6 vertically stacked return loops

Novel approach:

Using 2 FFAG beamlines



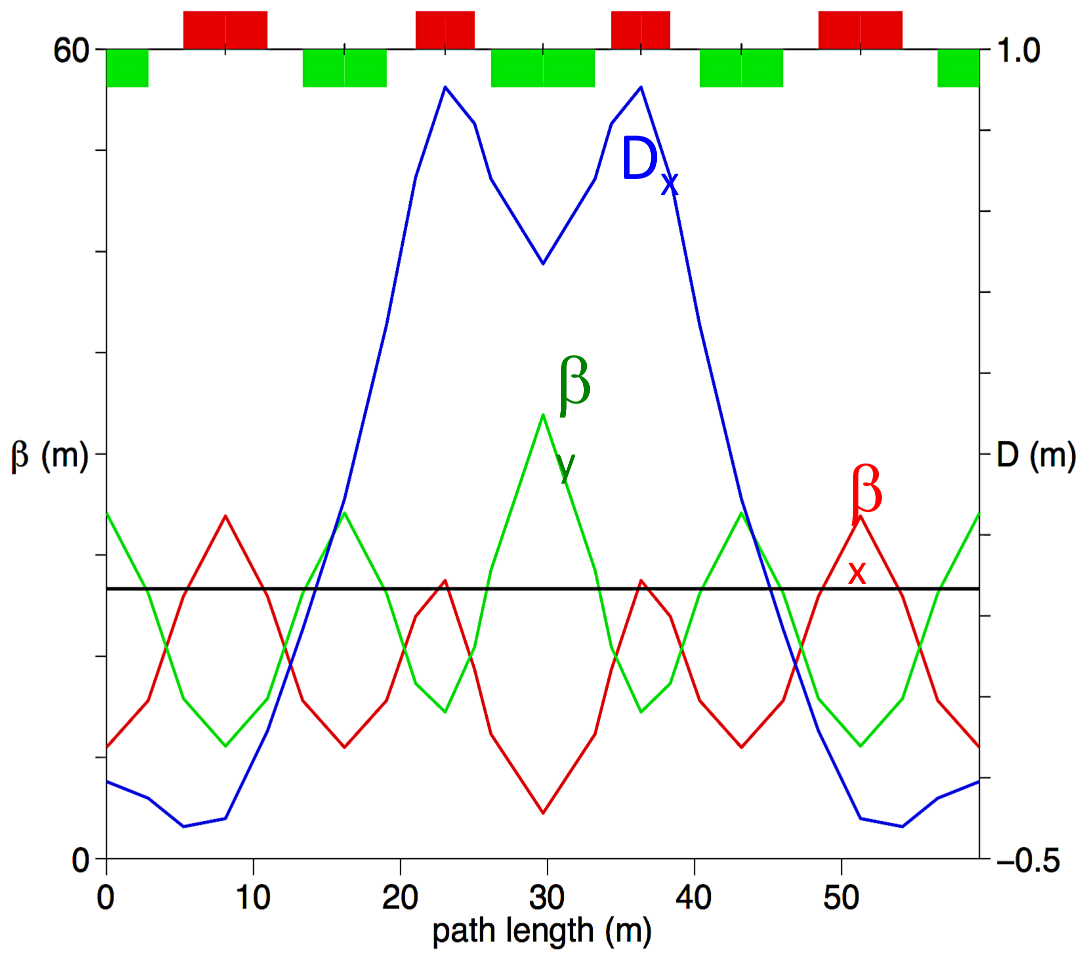
Accelerating up to 18 GeV requires 2 linacs placed in two 200 m straight sections of RHIC tunnel



Accelerating up to 21 GeV requires one linac placed in one 200 m straight section of RHIC tunnel. Up to 16 recirculations are possible. Number of re-circulations is limted by HOM consideration (power and MBBU)

Individual recirculation pass lattice

- The lattice has been optimized to the number of magnets and synchrotron radiation effect.
- Lattice basic cell:
  Isochronous cell based on combined function magnets
- Synchrotron radiation for 12-18 GeV operation with 50 mA current ~1 MW
- R_{56} tuning done by adjusting cell quads.



FFAG Recirculation Passes Based on Permanent Magnets

- FFAG beamline
  - Capable to transport beams in wide energy range (E_f/E_{in} ~3-4)
  - Used mostly for sub-GeV proton accelerators; only one test electron accelerator (EMMA)

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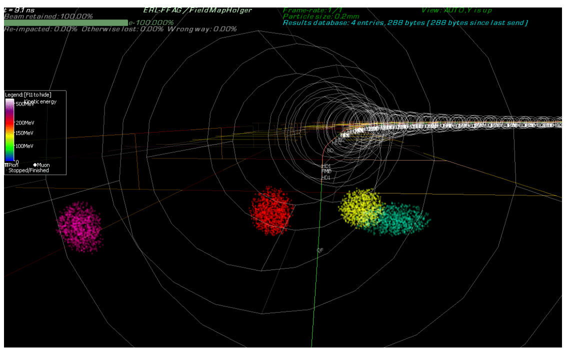
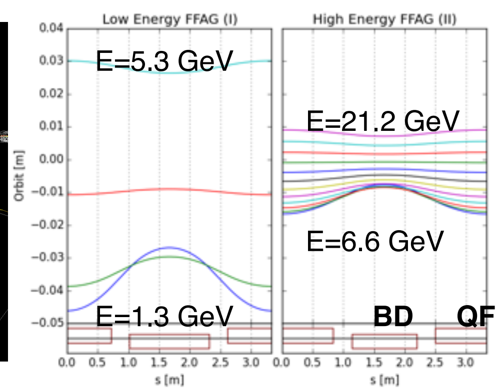
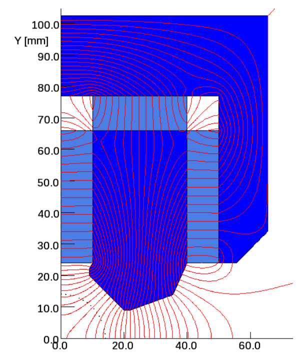
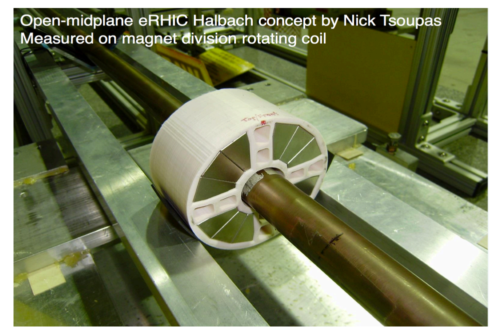




  - Not isochronous; thus spreader/merger is more complex incorporating pathlength and R_{56} correction
  - Considerable cost saving

- Permanent magnets
  - Cost saving: no need for power supplies, cables and cooling.
  - Fermilab has built a permanent magnet based recycler ring.
  - Technological challenges are related with satisfying eRHIC magnet field tolerance requirements and thermal stabilization
  - Permanent magnet prototypes (Hybrid-type and Halbach-type) has been bulit and measured.





CBETA facility, under construction in Cornell University, utilizes the FFAG beamline with permanent magnets for multipass ERL.

Beam dynamic study highlights

Electron beam disruption by proton beam during the collision in the detector

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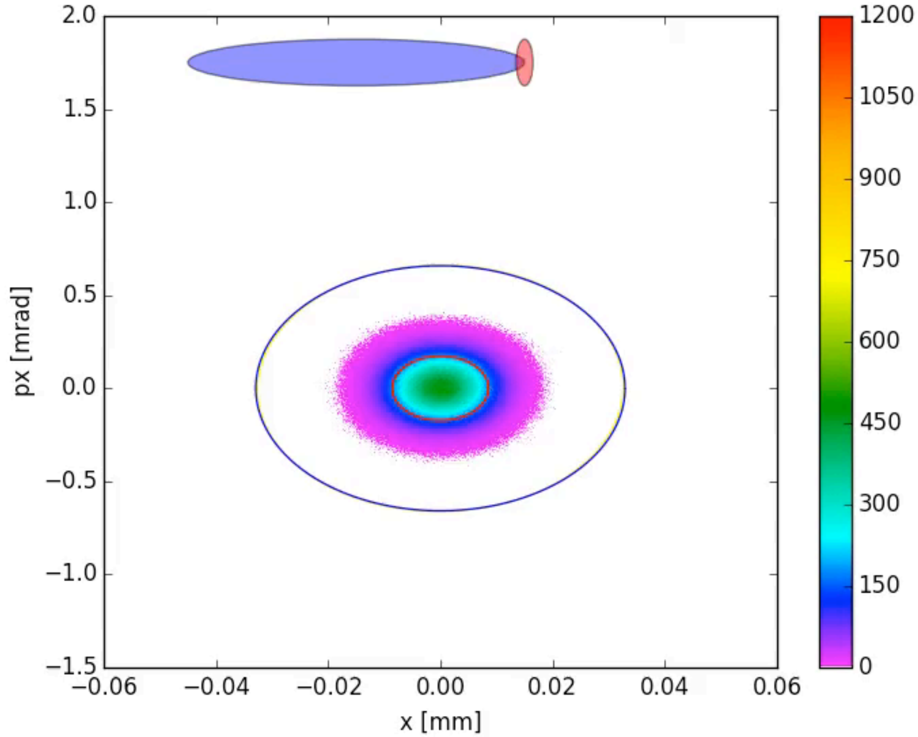

Major source of beam halo in decelerated electron beam.
Simulations helped to define adequate magnet apertures of recirculating loops.

Using gap in electron bunch pattern to facilitate electron beam blow-up by accumulated ions

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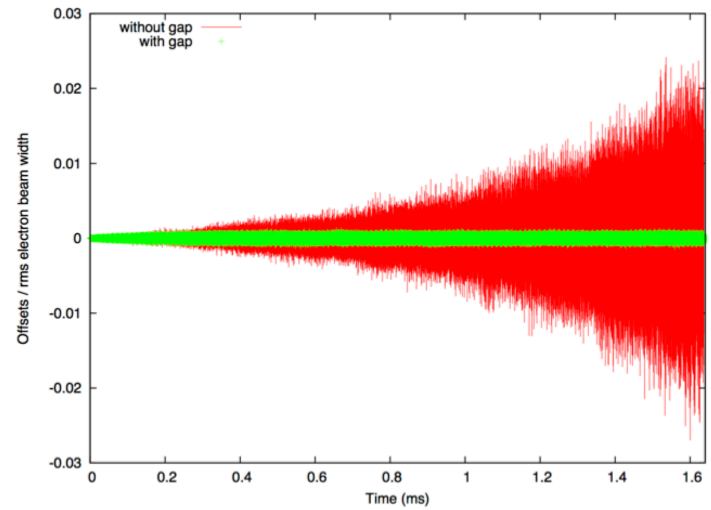
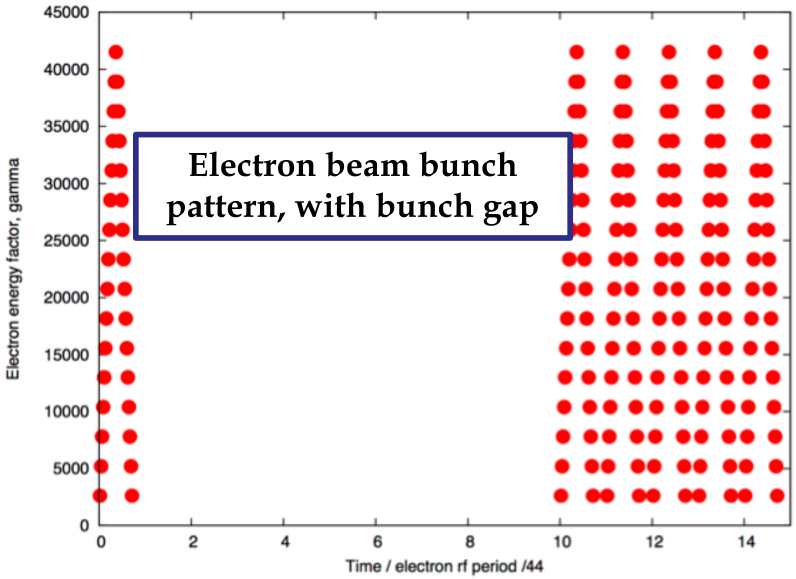
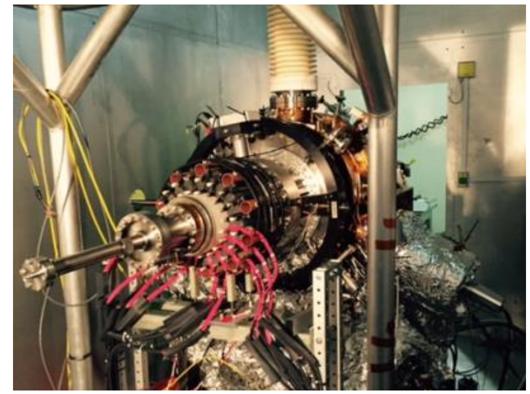


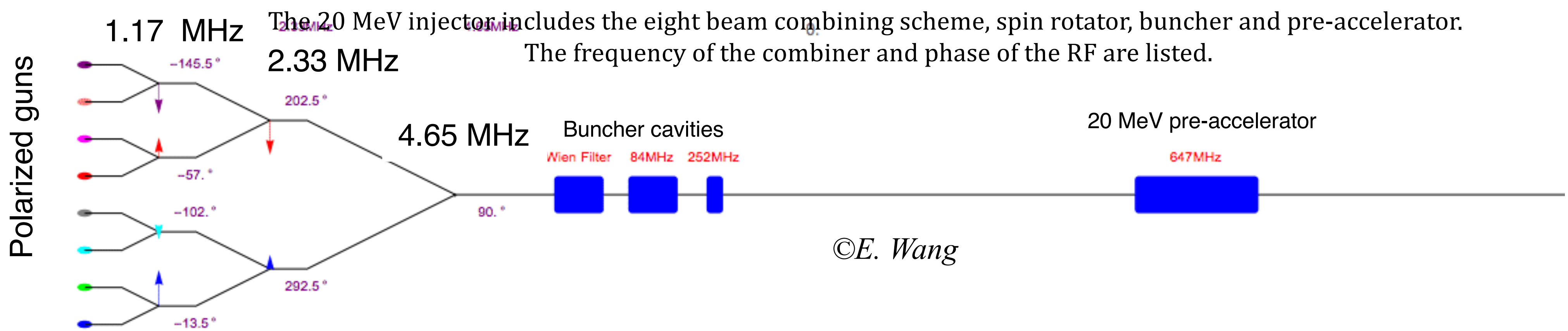


ERL-Ring Polarized Source Using Merging Scheme

- 50 mA polarized electron current required for ERL-based eRHIC
  4 mA polarized electron beam current was demonstrated in dedicated experiments in JLab
  Although the Jlab gun design is not optimal for high bunch charge mA scale operation: small cathode size, no cathode cooling



- R&D is underway for various approaches to high current polarized source:
  - Gatling Gun using multiple cathodes in the same vacuum volume.
    Prototype has been built.
    Studies are underway (BNL- Stony Brook University collaboration).
  - Large cathode gun prototype is being built by BNL (2017-2018)
    Similar gun prototype program is underway in MIT (Boston)
  - Polarized source using longitudinal stacking from multiple guns has been also explored



The 20 MeV injector includes the eight beam combining scheme, spin rotator, buncher and pre-accelerator.
The frequency of the combiner and phase of the RF are listed.

Summary

- ERL-based eRHIC design has been developed to cover the complete EIC White Paper science case and combine high performance with energy efficiency.

- Main design components:
  - Linac(s) based on 647 MHz cavities with strong HOM damping
  - Two possible solutions for recirculating passes:
    - *Return loops for individual energies*
    - *FFAG beam lines capable of multi-energy transport*

- R&D efforts are underway on major technological risk of ERL-based eRHIC, high current polarized electron source, as well as on 647 MHz SRF cavity and its HOM dampers

My acknowledgments to the ERL-based eRHIC design team:

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