Progress of High-Energy Cooling for RHIC

Alexei Fedotov

for Electron Cooling team of

Collider-Accelerator Department, BNL

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RHIC Electron Cooling team: collaborations and multiple support sources

- **BNL Collider-Accelerator Department Electron Cooling group**
  - 10 FTE
  - Matrix support
  - 1 current student
- **Support from**
  - BNL Director's Office
  - DOE ONP
  - DOD / ONR
  - DOD / JTO
  - SBIR (various offices)
- **BNL divisions**
  - Instrumentation, Magnet
- **National Laboratories**
  - Fermilab, JLab, SLAC
- **Universities**
  - Indiana, Stony Brook, UCLA
- **International**
  - BINP, JINR, Uppsala, GSI
- **Industry**
  - AES, Tech-X

Major developments since COOL05

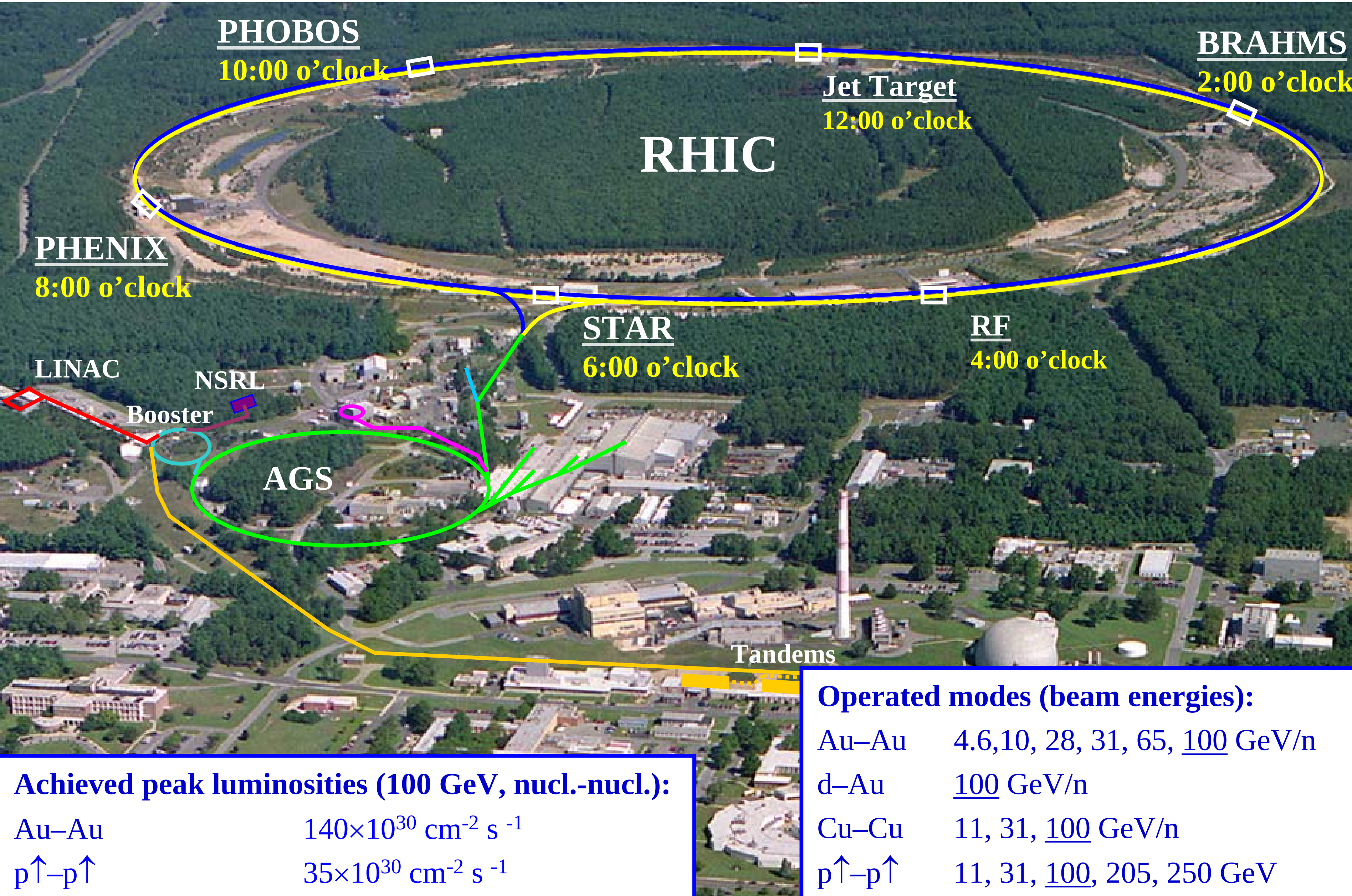
- **Right after COOL05, decision was made to switch design to Non-magnetized cooling.**
- **In January 2006, this decision was reviewed and endorsed by RHIC Machine Advisory Committee (MAC).**
- **In May 2006, Non-magnetized cooling approach for RHIC was reviewed by collaboration Workshop on "eCooling of RHIC".**
- **Detailed cost estimate of new cooler design was performed and reviewed in January 2007.**
- **Feasibility document for new approach was produced in February 2007: http://www.bnl.gov/cad/ecooling**

Recent progress was summarized in

numerous presentations at PAC07:

I. Ben-Zvi, Status of the R&D towards electron cooling of RHIC, WEOCKI03
D. Bruhwiler et al, Scaling VORPAL Electron Cooling Simulations to Larger Domains on >1,000 Processors THPAS018
G.I. Bell et al, Numerical Algorithms for Modeling Electron Cooling in the Presence of External Fields THPAS017
A. Sobol et al, Quantifying Reduction of the Friction Force due to Magnet Imperfections THPAS024
A. Fedotov et al, High-Energy Electron Cooling Based on Realistic Six-Dimensional Distribution of Electrons THPAS093
A. Fedotov, RHIC Plans Towards Higher Luminosity, TUZAKI01
A. Fedotov et al, Electron Cooling in the Presence of Undulator Fields THPAS092.
G. Wang et al, Coherent Instability of RHIC Ion Beam due to Electron Cooling THPAS104
D. Kayran et al, Optics of a Two-Pass ERL as an Electron Source for a Non-Magnetized RHIC-II Electron Cooler THPAS096
J. Kewisch et al, Low Emittance Electron Beams for the RHIC Electron Cooler THPMS087
J. Kewisch et al, Emittance Compensation for Magnetized Beams THPMS088,
V. Ranjbar et al, High-Order Modeling of an ERL for Electron Cooling in the RHIC Luminosity Upgrade FRPMS032
E. Pozdeyev et al, Collective Effects in the RHIC-II Electron Cooler THPAS100
E. Pozdeyev et al. Electron Beam Alignment in the RHIC II Cooling Section FRPMS117
E. Pozdeyev et al. Diagnostics of BNL ERL FRPMS116
X. Chang et al, High Average Current Low Emittance Beam Employing CW Normal Conducting Gun WEPMS090
V.L. Litvinenko et al, Status of R&D Energy Recovery Linac at Brookhaven National Laboratory TUPMS076
D. Kayran et al, Merger System Optimization in BNL's High Current R&D ERL THPAS097
V.L. Litvinenko et al, Unique features in magnet designs for R&D Energy Recovery Linac at BNL MOPAS097
A. M. Todd et al, High-Current Accelerator Development for FELs and ERLs
A. Burrill et al, Challenges Encountered during the Processing of the BNL ERL 5 Cell Accelerating Cavity WEPMS088
A. Burrill et al, Multipacting Analysis of a Quarter Wave Choke Joint Proc WEPMS089
X. Chang et al, Recent Progress on the Diamond Amplified Photo-cathode Experiment WEOCC04
D. Dimitrov et al, 3D Simulations of Secondary Electron Generation & Transport in a Diamond THPAS020
Q. Wu et al, Thermal Emittance Measurement Design for Diamond Secondary Emission TUPMS089
H. Hahn et al, Ferrite-lined HOM Absorber for the e-Cool ERL THPAS095

RHIC – a High Luminosity (Polarized) Hadron Collider



Operated modes (beam energies):

Au–Au	4.6,10, 28, 31, 65, <u>100</u> GeV/n
d–Au	<u>100</u> GeV/n
Cu–Cu	11, 31, <u>100</u> GeV/n
p↑–p↑	11, 31, <u>100</u>, 205, 250 GeV

Achieved peak luminosities (100 GeV, nucl.-nucl.):

Au–Au	140×10^{30} cm^{-2} s^{-1}
p↑–p↑	35×10^{30} cm^{-2} s^{-1}

RHIC design and achieved parameters for 100 GeV/n
(A_1 and A_2 the number of nuclei in the ions of colliding beams)

species	No of bunches	Ions/ bunch [10^9]	β^* [m]	Polarization, average	$L_{store,avg}$ [$cm^{-2}s^{-1}$]	$A_1A_2L_{store, avg}$ [$cm^{-2}s^{-1}$]	$A_1A_2L_{peak}$ [$cm^{-2}s^{-1}$]
Design Parameters (1999)							
Au-Au	56	1.0	2		2×10^{26}	8×10^{30}	31×10^{30}
p-p	56	100	2		4×10^{30}	4×10^{30}	5×10^{30}
Enhanced Design Parameters (by 2009)							
Au-Au	111	1.0	0.9		8×10^{26}	31×10^{30}	140×10^{30}
p↑-p↑	111	200	0.9	70%	60×10^{30}	60×10^{30}	90×10^{30}
Achieved operational values (as of 2007)							
Au-Au	103	1.1	0.8		14×10^{26}	54×10^{30}	140×10^{30}
p↑-p↑	111	130	1	60%	20×10^{30}	20×10^{30}	35×10^{30}
d-Au	55	120/.7	2		2×10^{28}	8×10^{30}	28×10^{30}
Cu-Cu	37	4.5	0.9		80×10^{26}	32×10^{30}	79×10^{30}

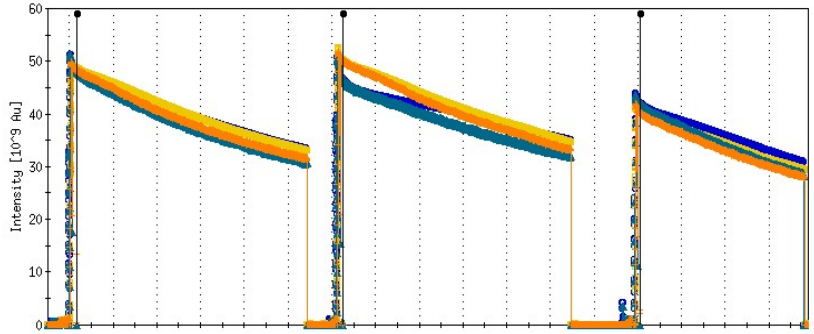
Major planned RHIC upgrades

1. Electron Beam Ion Source (EBIS) – in progress
2. Stochastic cooling – in progress (MOA1I01, WEM2I05)
3. Electron cooling for RHIC-II – this talk
4. Low-energy RHIC operation – FRM2C06
5. Electron-Ion Collider (eRHIC)

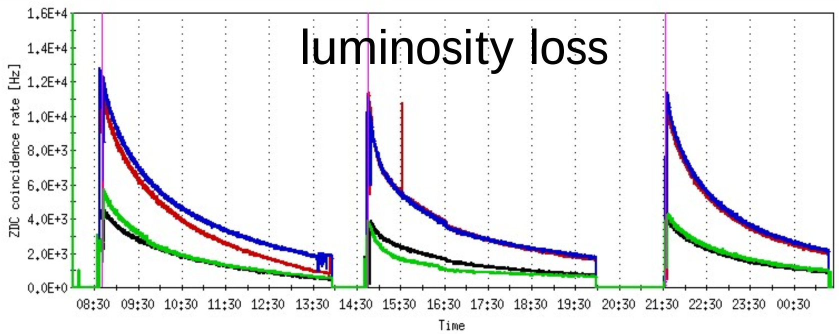
RHIC performance for Au ions

2004 run

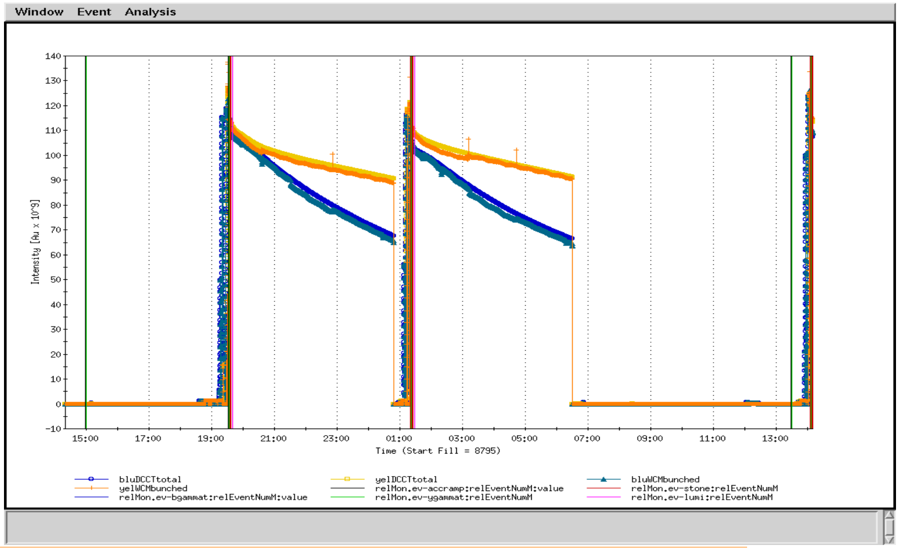
intensity loss



luminosity loss



2007 run
(with longitudinal stochastic cooling in Yellow ring)



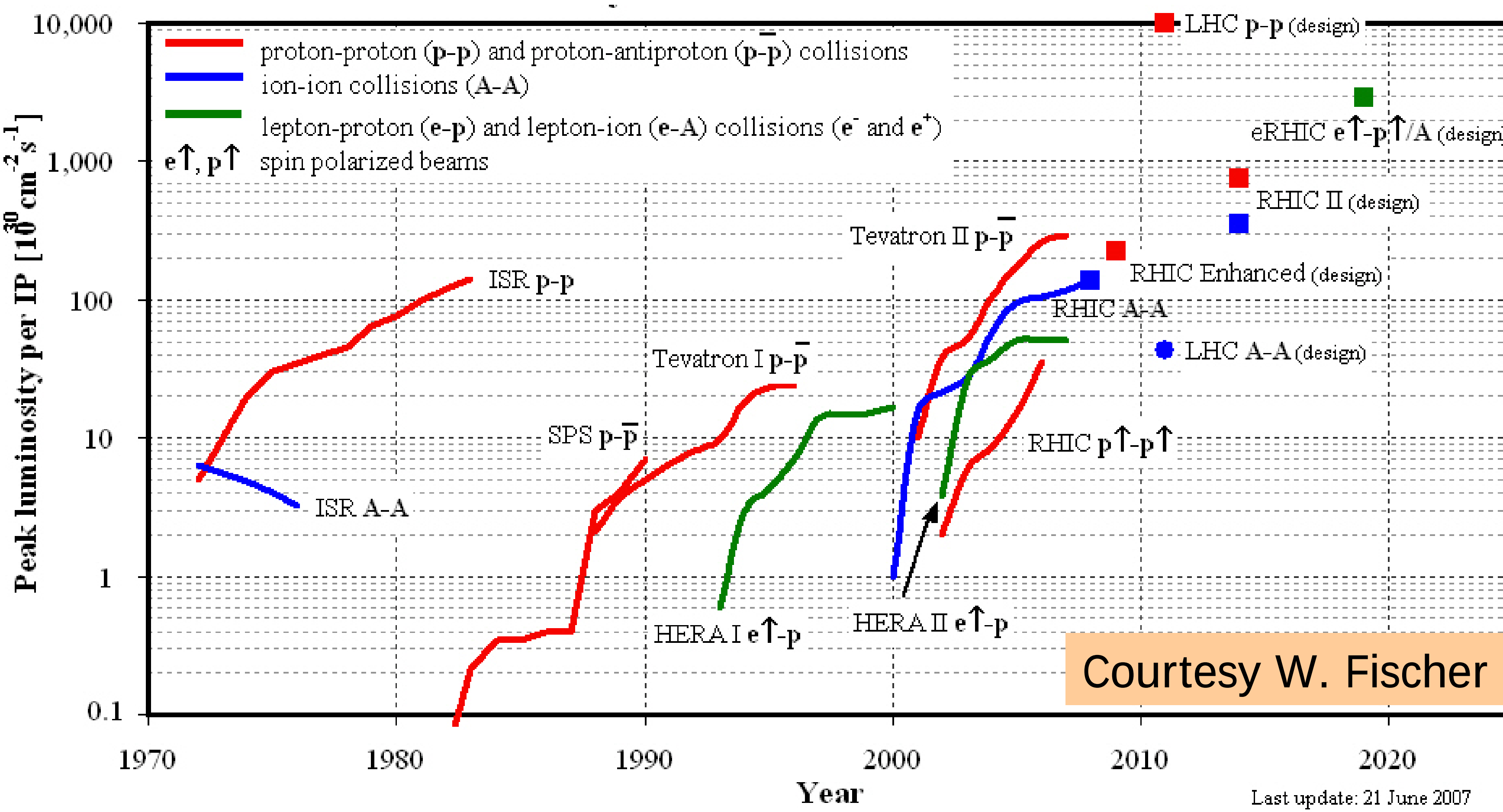
see M. Brennan, M. Blaskiewicz talks MOA1I01, WEM2I05

RHIC II – major luminosity upgrade

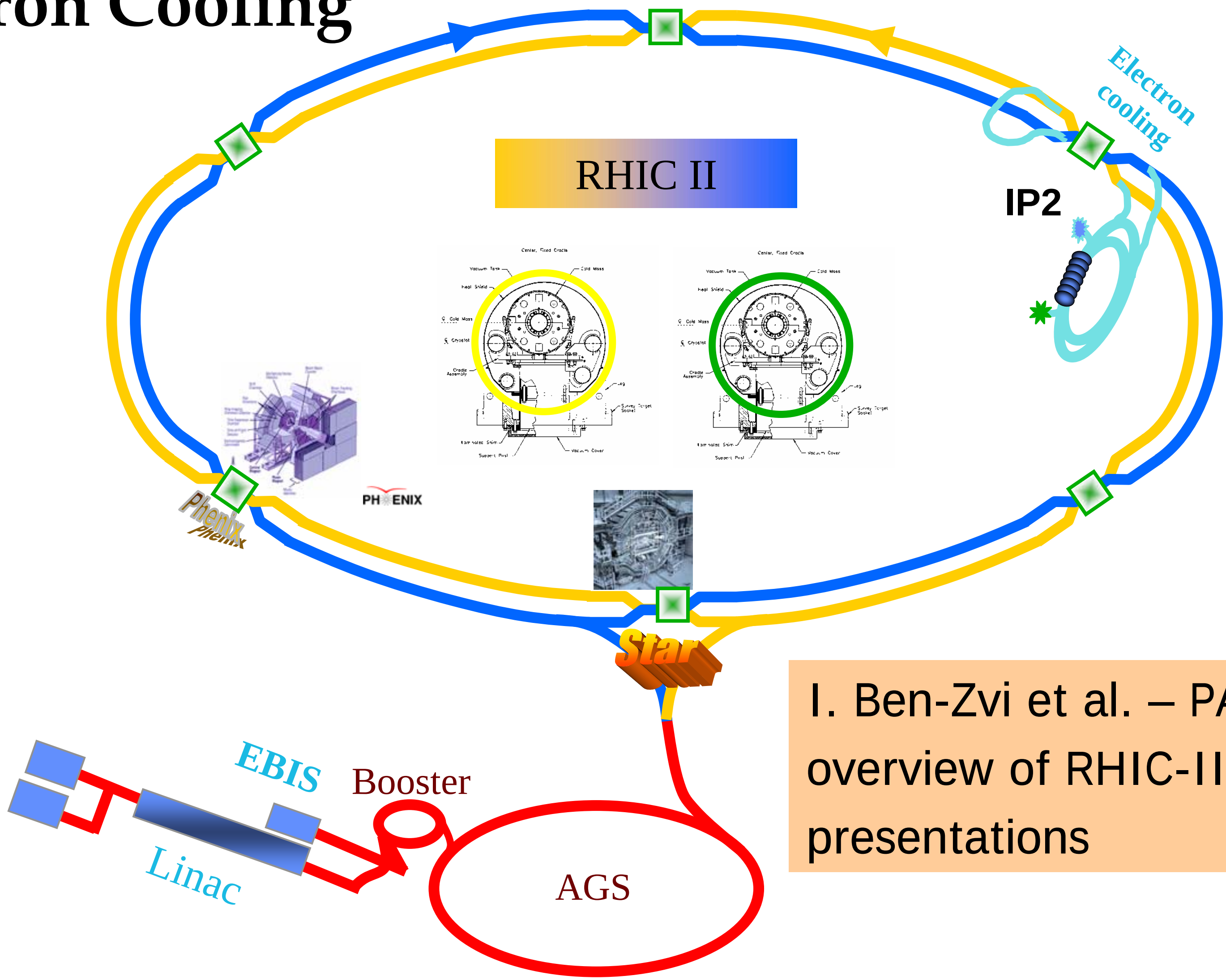
Parameter	unit	Enhanced design	RHIC II
Au-Au operation			
Energy	GeV/n	100	100
No of bunches	…	111	111
Bunch intensity	10^9	1.0	1.0
Average $\mathcal{L}$	10^{26}cm^{-2}s^{-1}	8	70
p↑- p↑ operation			
Energy	GeV	250	250
No of bunches	…	111	111
Bunch intensity	10^{11}	2.0	2.0
Average $\mathcal{L}$	10^{30}cm^{-2}s^{-1}	150	400
Polarization $\mathcal{P}$	%	70	70

Already achieved and exceeded

RHIC II – luminosity (nucleon-pair) projection



Electron Cooling



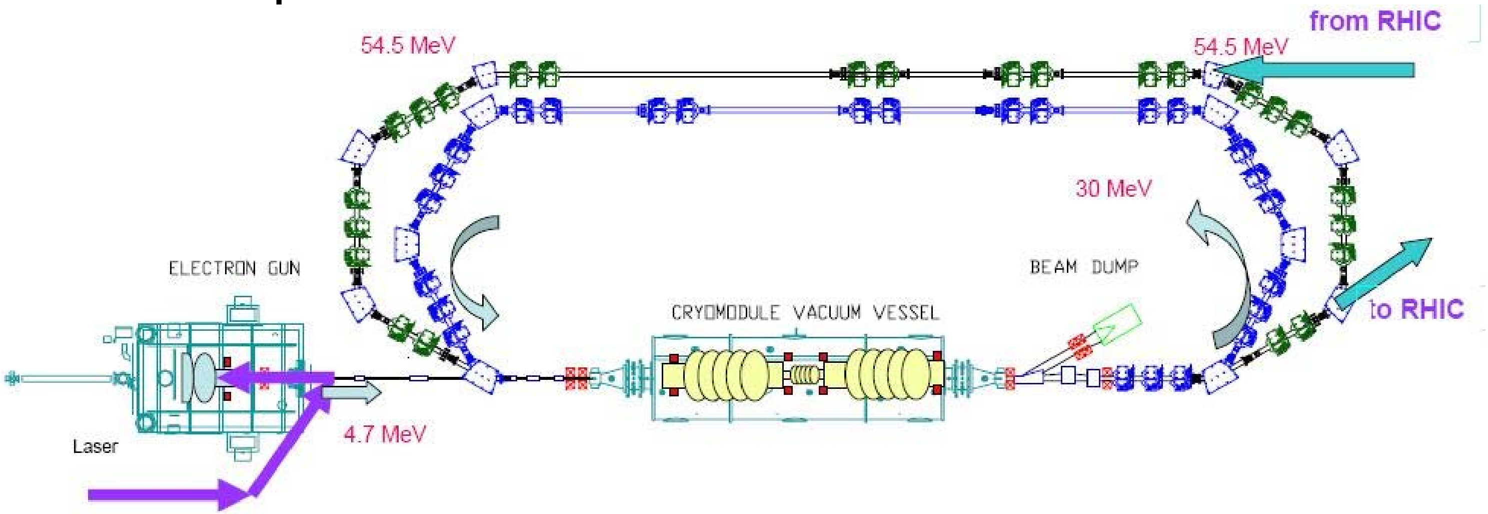
I. Ben-Zvi et al. – PAC07 overview of RHIC-II presentations

Energy Recovery Linac (ERL) for RHIC-II

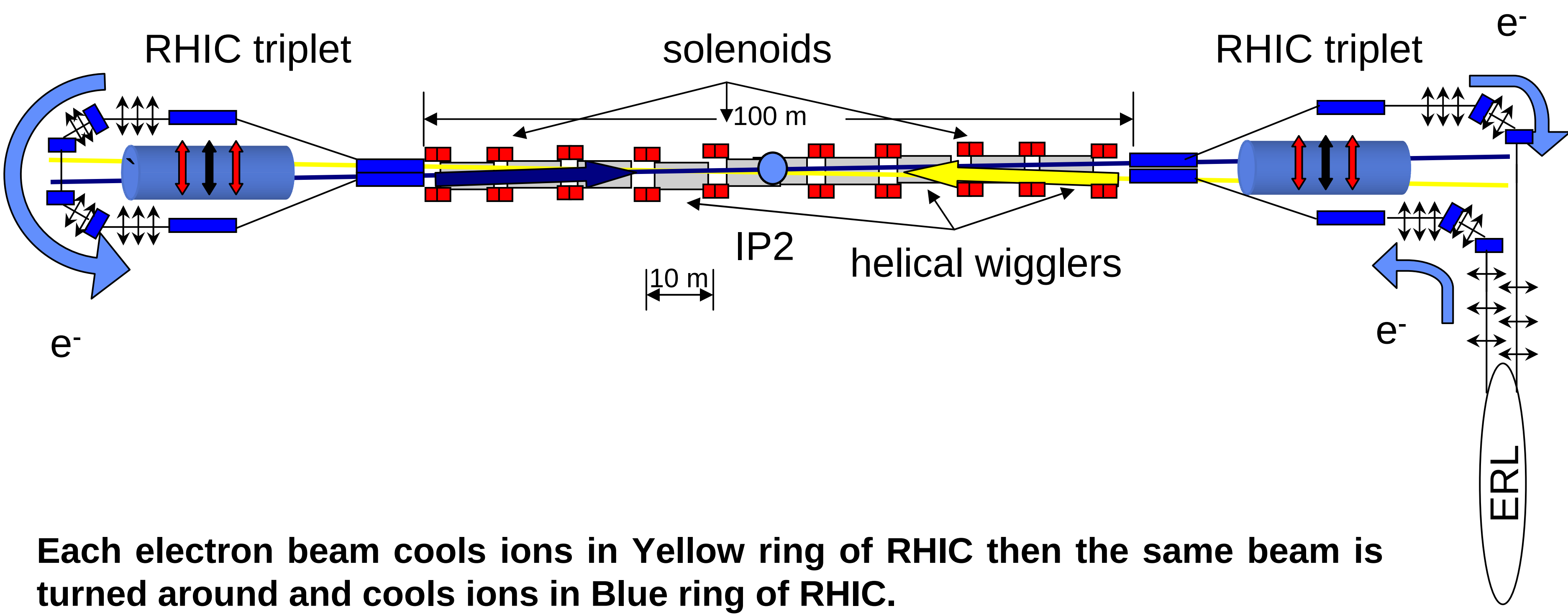
Cooling of Au ions at 100 GeV/n:

- 54.3 MeV electron beam
- 5nC per bunch
- rms normalized emittance < 4 μm
- rms momentum spread < 5×10^{-4}

D. Kayran, PAC07



Electron cooling section at RHIC 2 o'clock IP



Each electron beam cools ions in Yellow ring of RHIC then the same beam is turned around and cools ions in Blue ring of RHIC.

Hardware development

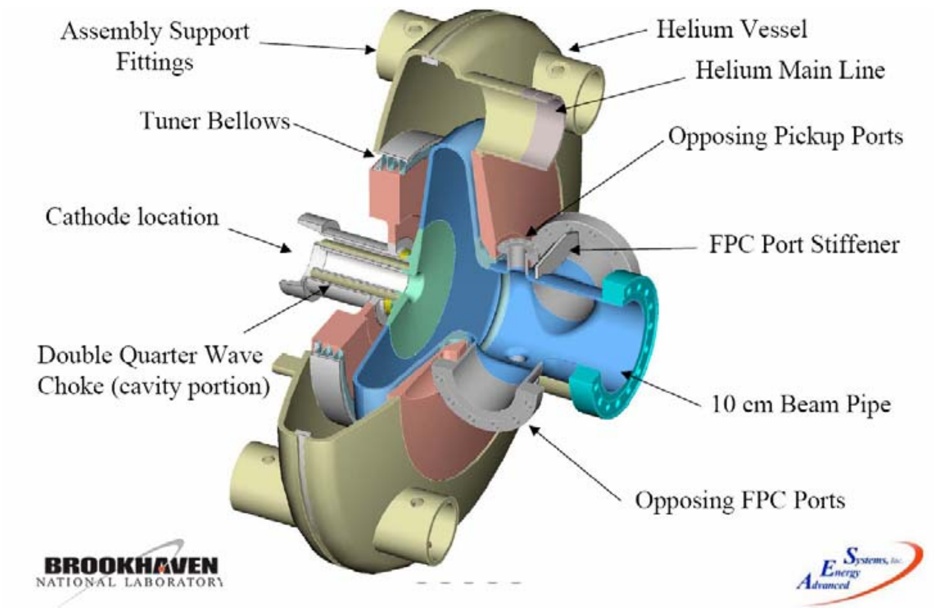
- 5-cell, high-current accelerating cavity
- ½ cell SRF gun
- Photocathode R&D
- R&D ERL

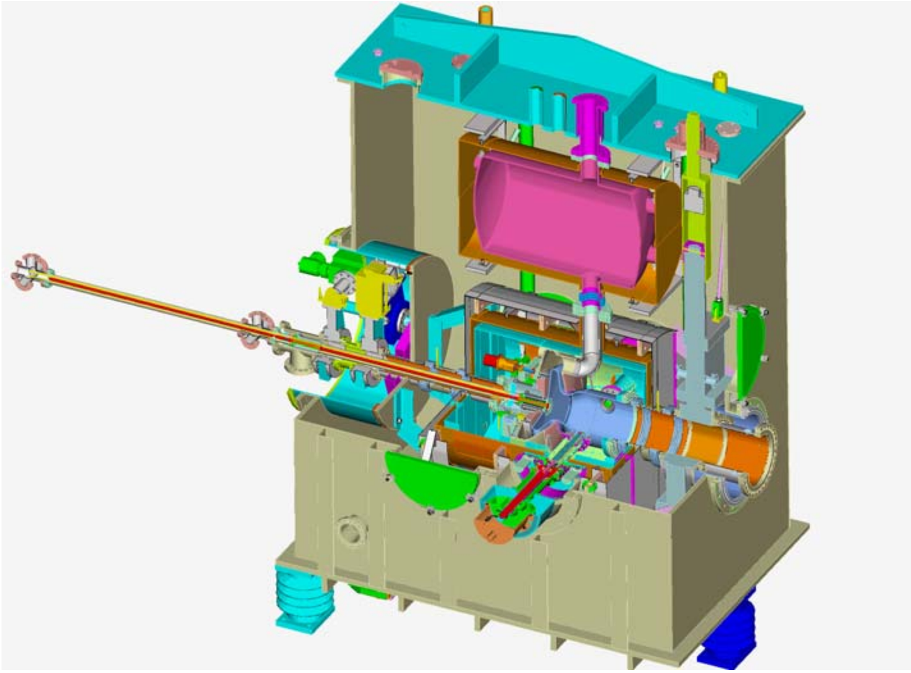
5 cell cavity successfully processed

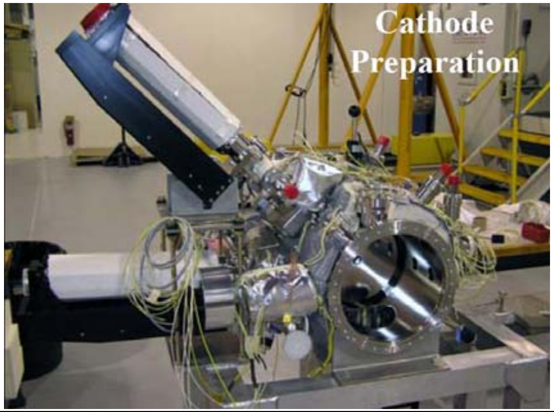
- 703 MHz 5 cell SRF cavity designed by BNL and fabricated by Advanced Energy Systems.

- The cavity has reached its specification of 20 MV/m at a Q of 1×10^{10} .

0.5 ampere SRF gun – under construction by AES



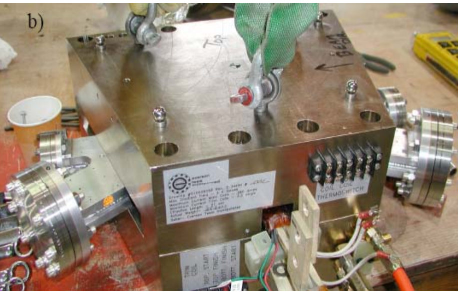


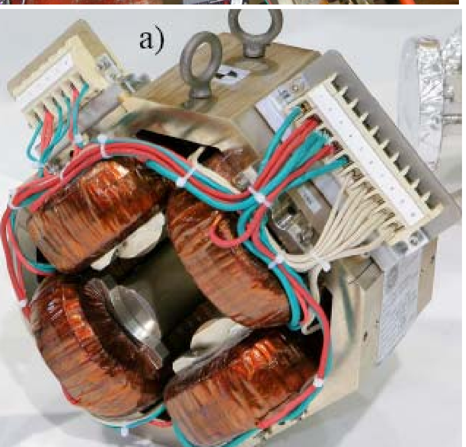


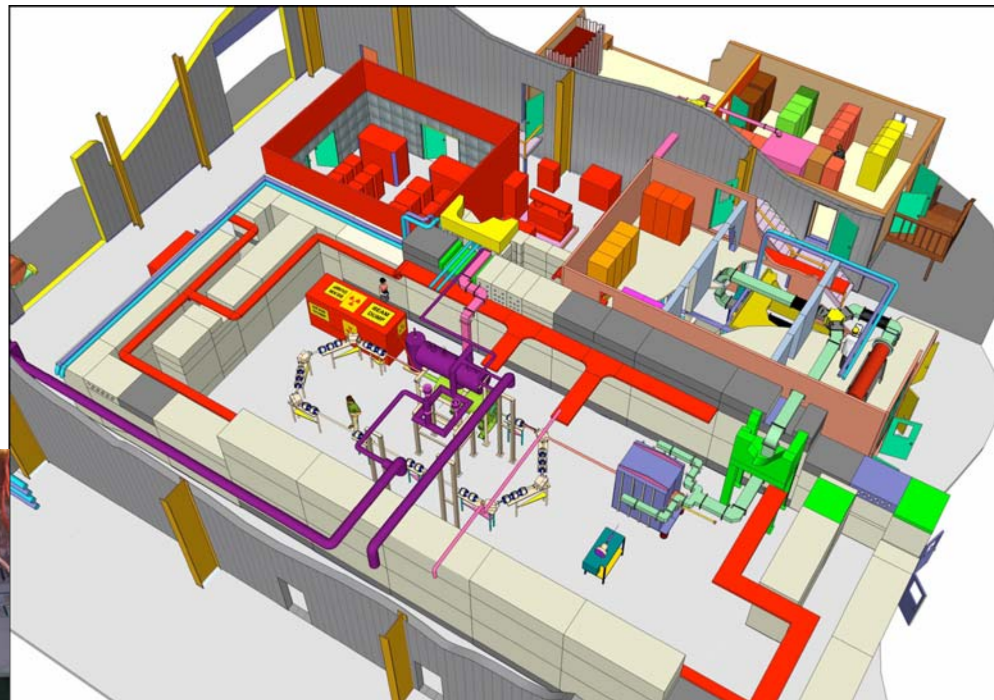
R&D ERL (V. Litvinenko et al.)

Test bed for RHIC-II ecooling and eRHIC

Commissioning starts February 2009







Some of Cooling and Electron beam dynamics tasks studied recently – details on http://www.bnl.gov/cad/ecooling

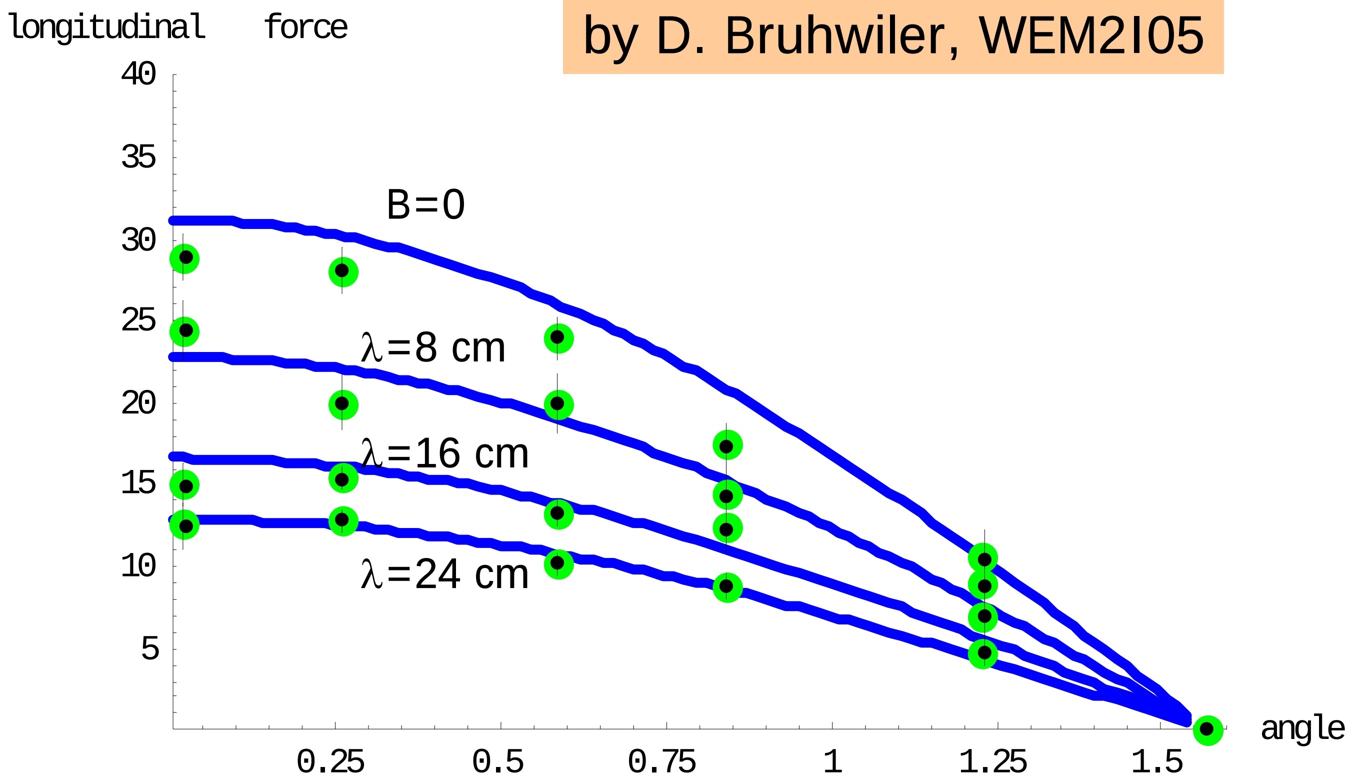
1. Studies of friction force in the presence of undulator fields
2. Measurements at the FNAL cooler; benchmarking of cooling dynamics simulations
3. Development of friction force model based on realistic 6-D electron distribution in BETACOOL and cooling dynamics simulations
4. Development of IBS model for arbitrary distribution in BETACOOL
5. Estimates of various contributions to rms angular spread in the cooling section and cooling dynamics studies
6. Estimates of ion beam stability as a result of electron cooling
7. Studies of recombination suppression and new undulator parameters

Electron beam dynamics:

8. Electron beam collective effects
9. Comparing Space-charge tracking codes
10. Tolerance to errors
11. Development of back-up option gun

Longitudinal force in the presence of undulators fields: (B=10G, λ=8, 16, 24 cm). Curves – numeric evaluation of force integrals, dots – VORPAL simulations (Tech-X, Colorado))

for more details see talk by D. Bruhwiler, WEM2I05



reduction in the force values as expected based on the Logarithm

Wiggler parameters:

B=10 G

λ=8, 16, 24 cm

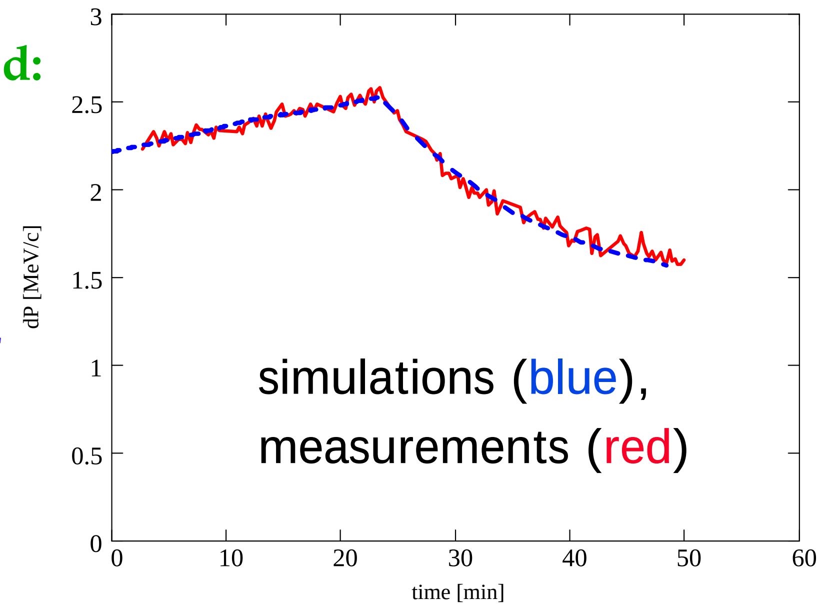
Experimental benchmarking: using Recycler (FNAL) E-cooling

First Non-magnetized cooling was successfully demonstrated:

FNAL – July 2005.

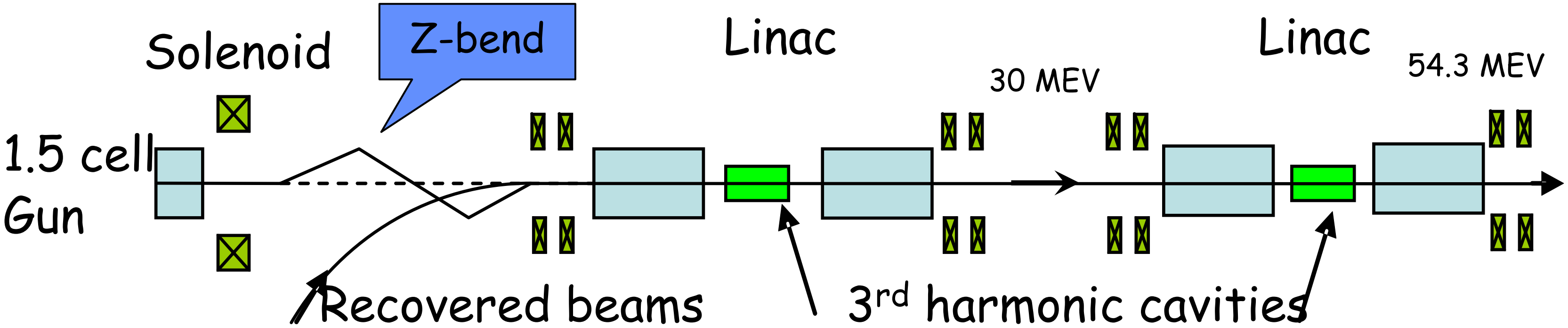
FNAL e-cooling :

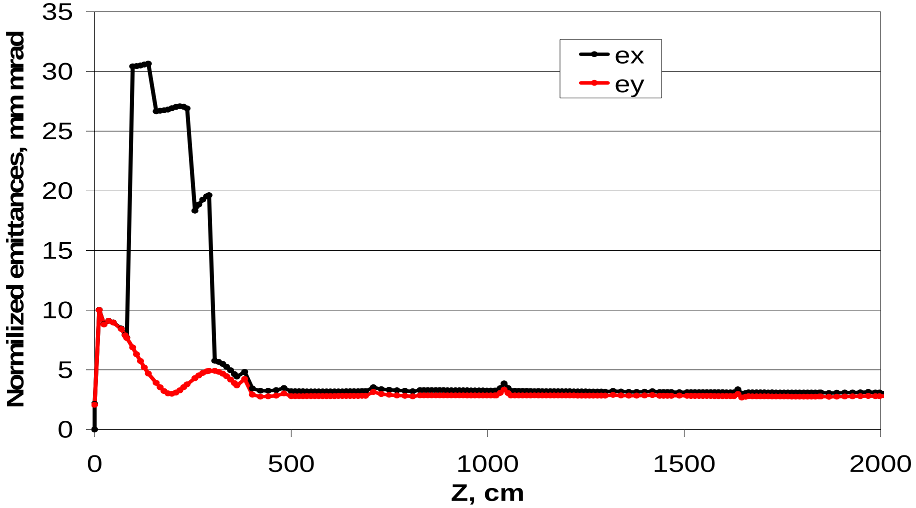
1. Allows to benchmark accuracy of the models for the friction force
2. Allows to study evolution of ion distribution under cooling or during drag rate measurements – requires accurate description of both cooling and diffusion in modeling
3. Allows to study effects of electron cooling together with stochastic cooling (both transverse and longitudinal)



see presentations by
L. Prost, MOA2I06
A. Shemyakin, THAP07

Electron beam dynamics - Evolution of emittance



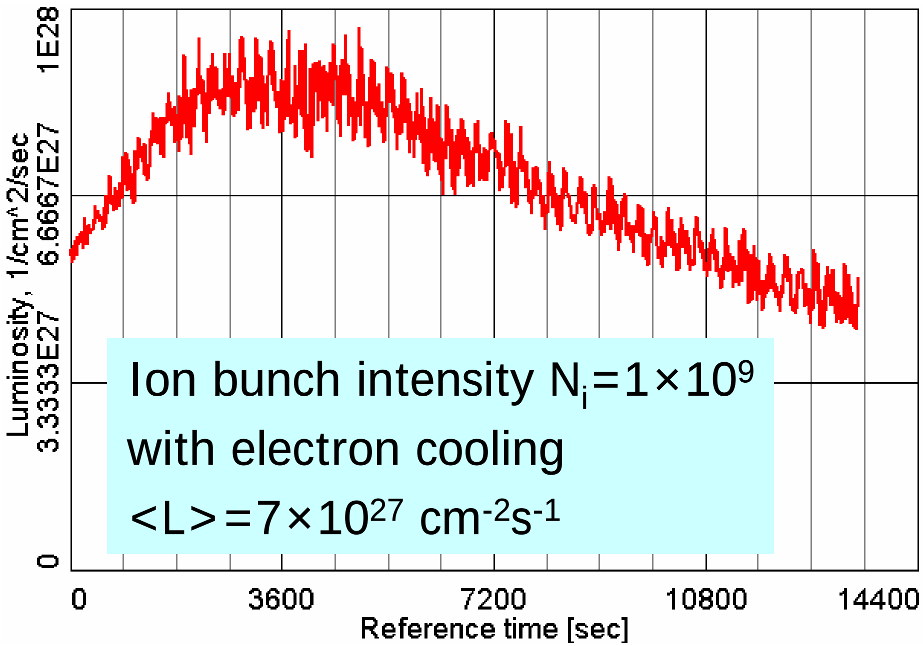


Evolution of the projected normalized transverse emittances rms.
Beer-can distribution, 5nC per bunch: final horizontal emittance black 3.1 mm mrad, vertical emittance red 2.8 mm mrad, D. Kayran et al.

Parameters (2006-2007) of RHIC-II cooler (for cooling of Au ions at 100 GeV/nucleon)

Electron kinetic energy [MeV]	**54.3**
Electron charge per bunch [nC]	**5**
Electron cooler length [m]	**80**
Rms emittance normalized [mm·mrad]	**4**
Electron rms momentum spread	**0.0003**
Rms radius of electron beam [mm]	**4.3**
Electron rms bunch length [mm]	**8**

Cooling of Au ions for RHIC-II (simulations)

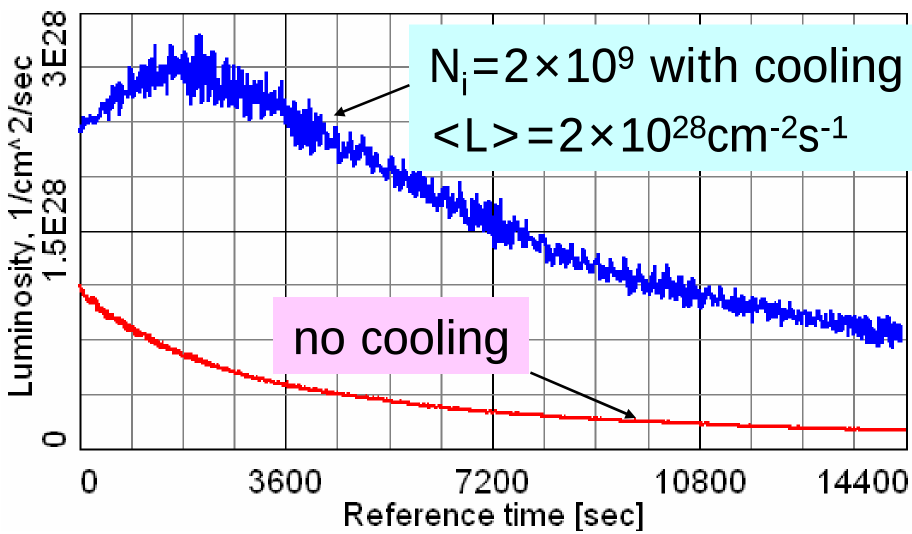


number of bunches: 111

initial $\varepsilon_{95\%,n}$ =15 μm

rms momentum spread 5×10^{-4}

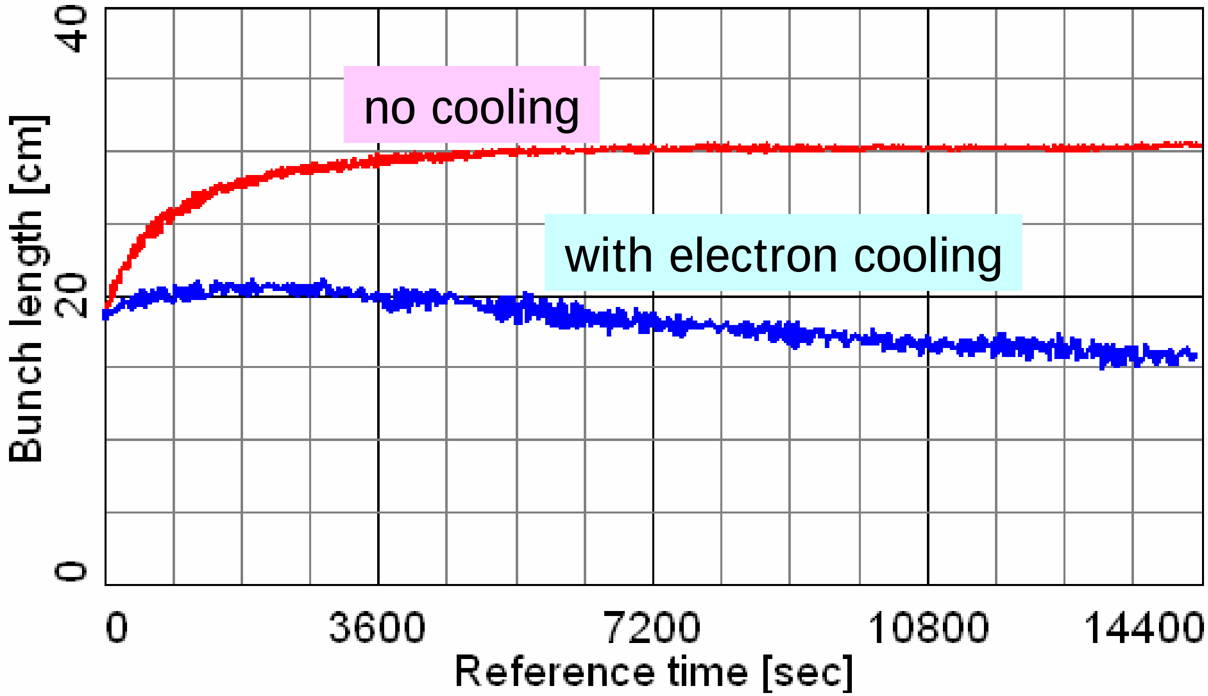
β^*=0.5m



BETACOOL (JINR, Russia) simulation.

included effects: intra-beam scattering, electron cooling, particle loss in collisions ("burn-off"), loss from rf bucket.

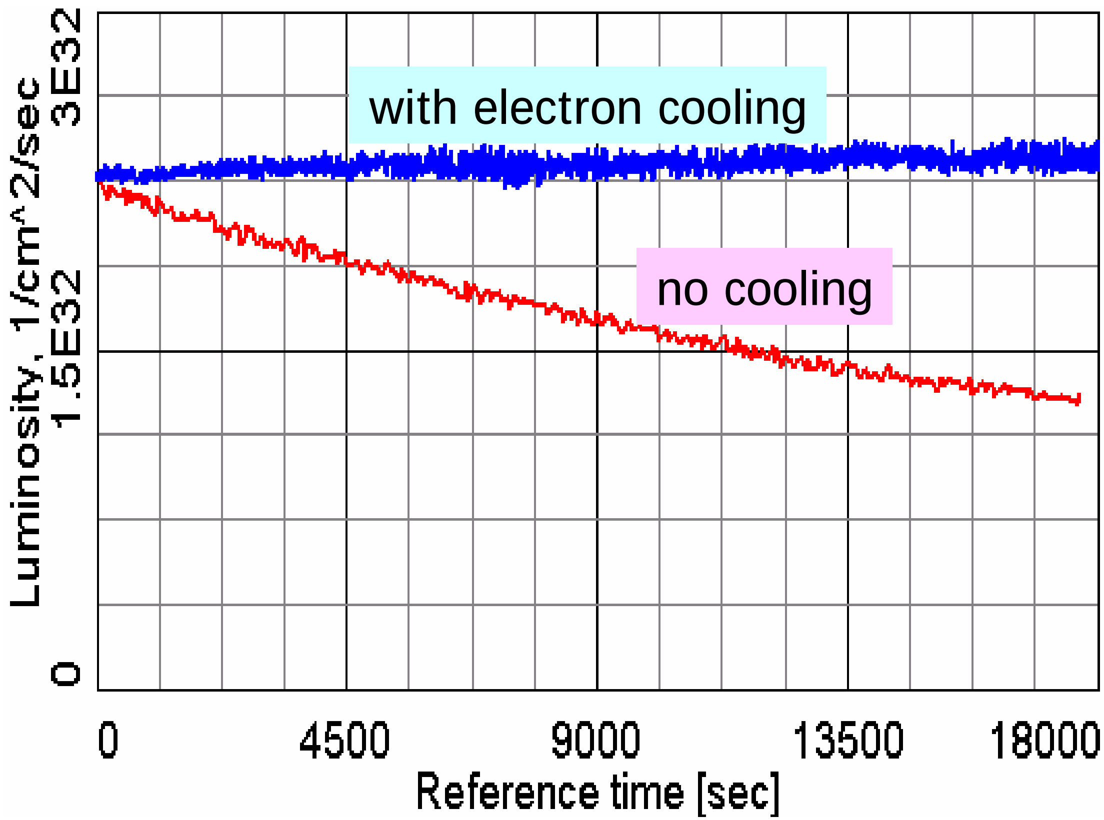
Electron cooling for RHIC-II: bunch length control (simulations)



Maintaining short bunch length.

Also, shaping of the longitudinal distribution is possible.

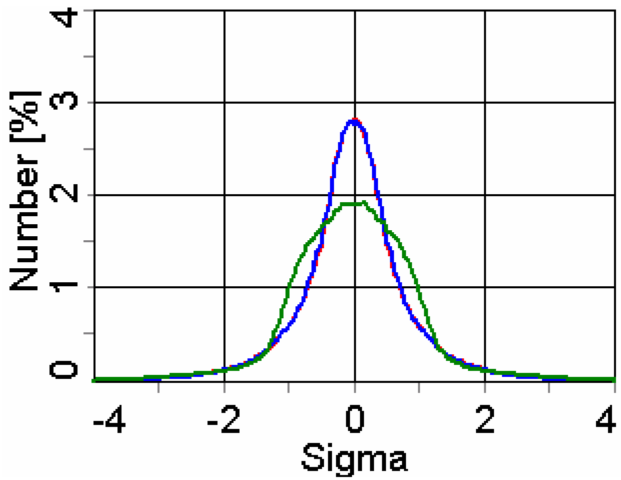
Protons at 100 GeV, Number of protons 2×10^{11}. (using 2 electron bunches/per proton bunch)



bunch profiles:

blue/red – transverse

green - longitudinal



High-energy Electron Cooling system for RHIC-II

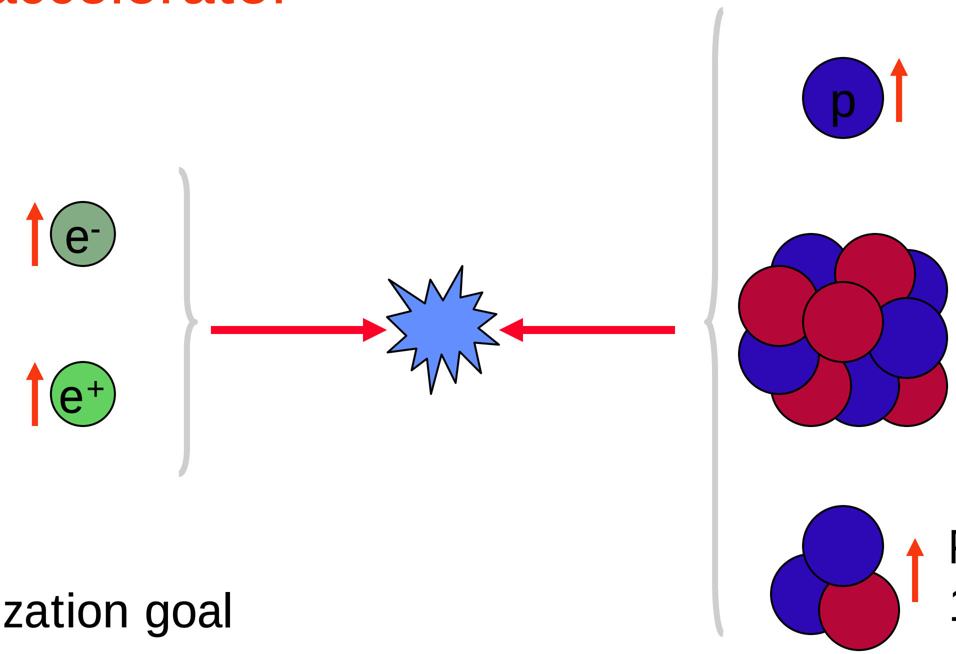
1. **Provides cooling of various ion species at 100 GeV/nucleon.**
2. **Delivers luminosity required by RHIC-II upgrade.**
3. **Maintains short bunch length which is important for detectors.**
4. **Provides pre-cooling of protons (above transition energy) to required transverse and longitudinal emittances.**
5. **Provides cooling of various ion species at other collisions energies in the range of 25-100 GeV/nucleon.**

Electron-Ion collider (eRHIC)

Electron accelerator

RHIC

Polarized leptons
3-20 GeV



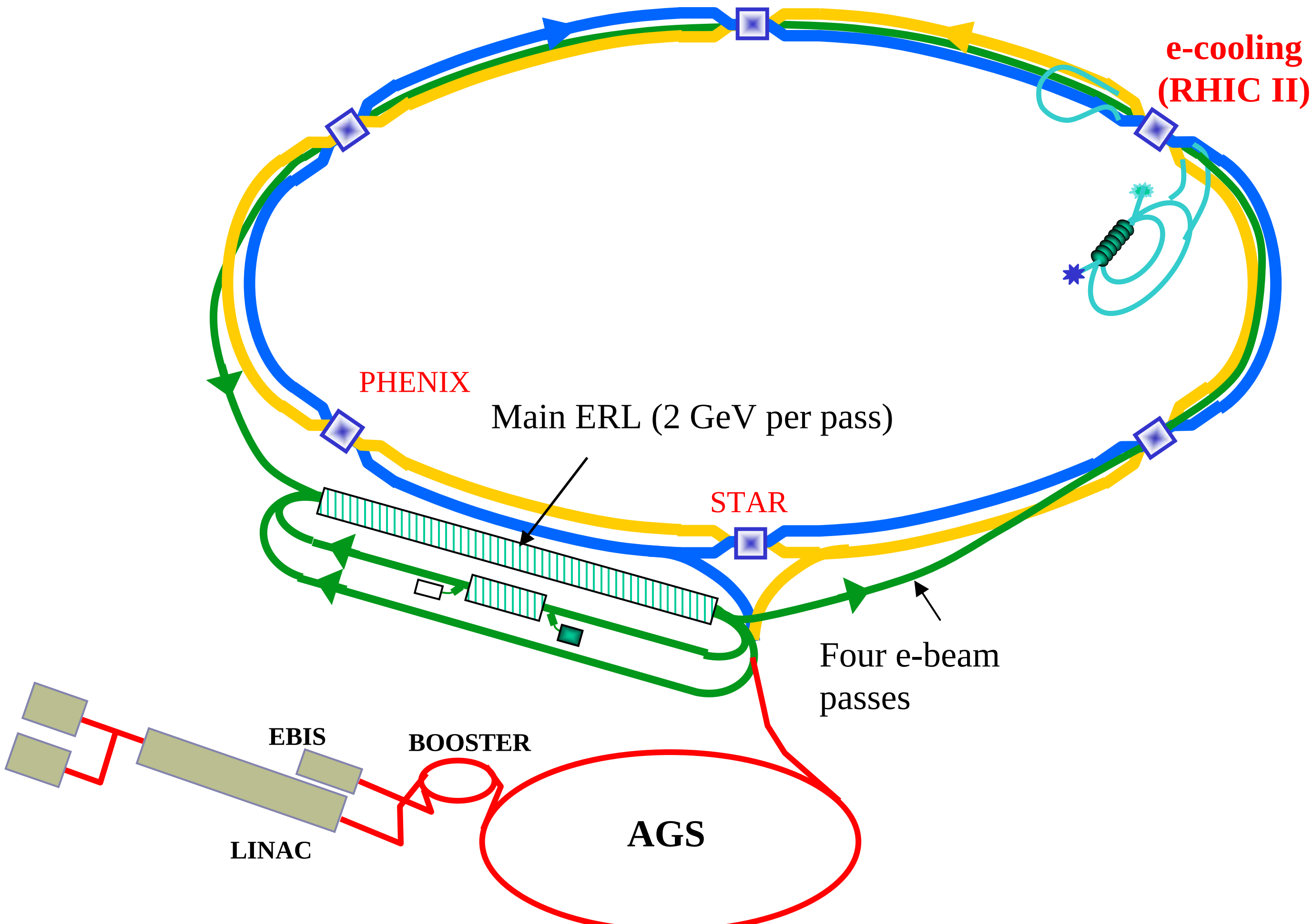
Polarized protons
50-250 GeV

Heavy ions (Au)
50-100 GeV/n

Polarized light ions (He^3)
167 GeV/n

70% beam polarization goal

eRHIC
(Linac-ring schematics: V. Litvinenko et al.)



eRHIC

Present linac-ring luminosities are based on strong pre-cooling of beam emittances both for protons and Au ions.

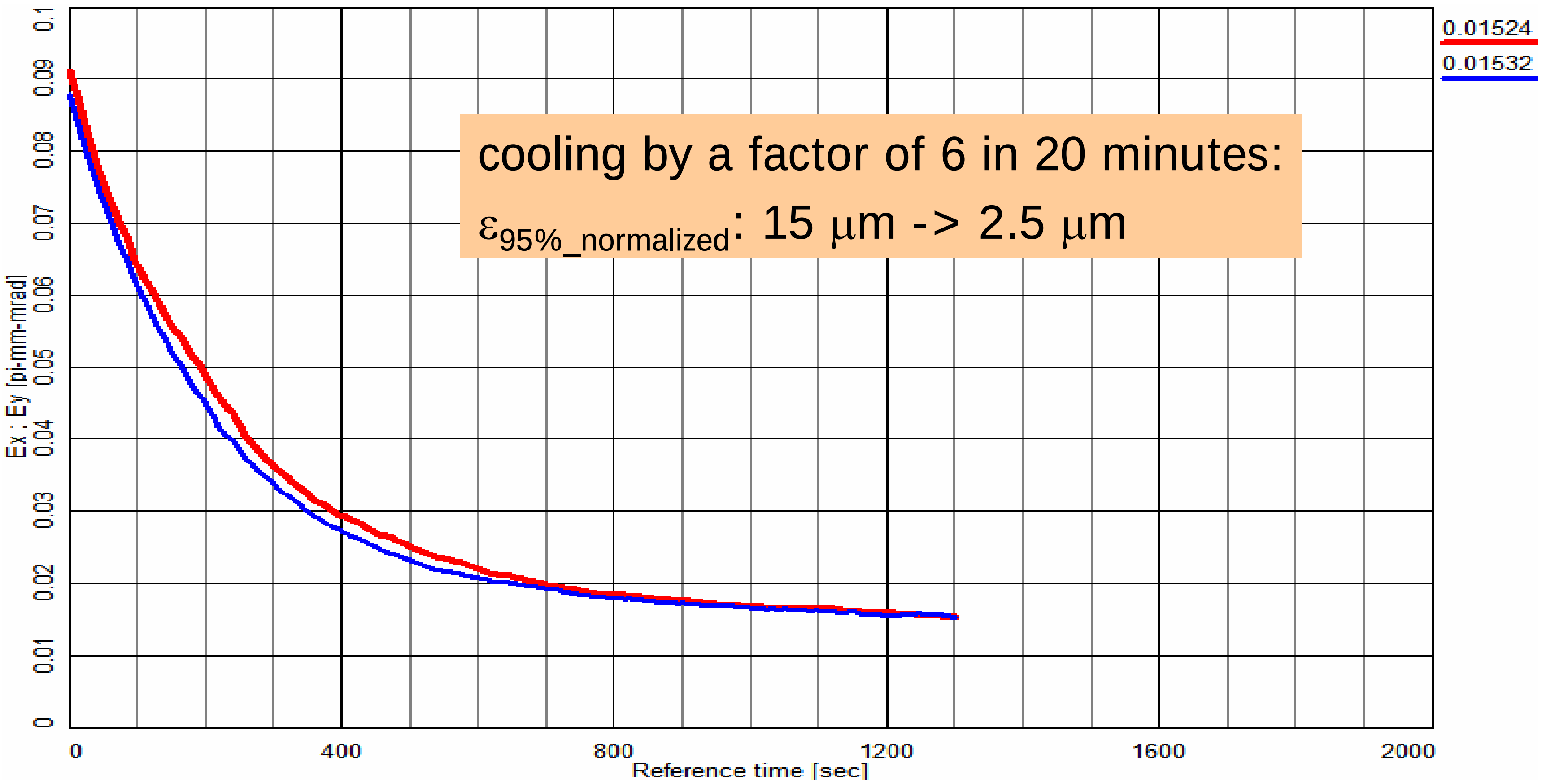
Requires pre-cooling:

Au ions: factor of 6 reduction in initial emittance is needed.

Protons: factor of 3-2 reduction in initial emittance is needed.

E-cooling is needed to achieve eRHIC parameters.

Pre-cooling of Au ions ($N=1\times10^9$) at 25 GeV/n (using several electron bunches per single long ion bunch)



Present developments

1. Presently, work is underway on various modifications of the cooler, such as relocation of ERL inside the RHIC tunnel and employing existing straight section in RHIC without its modification. Such changes promise significant reduction in the cost of the RHIC-II cooler.

   Preliminary evaluation of the new design parameters show that cooler can deliver the same performance as presented in this report.

2. The work has been started on a feasibility study of coherent electron cooling (Ya. Derbenev, 1981) for RHIC. This approach promises very good cooling performance at high energies (V. Litvinenko et al., FEL07 Conference).

Summary: Status of the R&D

- **A lot of information at http://www.bnl.gov/cad/ecooling/**
- **Feasibility was demonstrated through**
  - numerical simulations of the electron cooling process,
  - Benchmarking experiments, and
  - numerical simulations of the electron beam dynamics of the electron cooler.
  - Past year's work refined many of the details.
- **Risk reduction (technical, cost and schedule) R&D on:**
  - Photocathode
  - SRF gun
  - ERL cryomodule
  - ERL beam merging system
  - Demo ERL

} **to be finished in 2009**

Acknowledgements

We thank Collider-Accelerator Department and Accelerator Physics group of RHIC for constant help and support.

We are grateful for FNAL team for providing beam time and experimental measurements for the non-magnetized cooling studies.

Cooling simulation studies are done together with the Dubna group (using BETACOOL code) and Tech-X group (using VORPAL code).

Collaboration on e-cooling with:

BINP, FNAL, JLAB, GSI, Svedberg Lab, Dubna, Tech-X Inc.

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