Electron cooling update

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Electron cooling applications studied recently:

1. Electron Cooling for RHIC-II:

1.1) Feasibility report written – February 2007.

1.2) Detailed cost estimate of the cooler performed.

2. Electron Cooling for eRHIC:

2.1) Pre-cooling at energy just above transition.

2.2) Direct cooling at top energy of protons.

3. Electron Cooling for Low-Energy RHIC (critRHIC):

3.1) Direct cooling in RHIC.

3.2) Pre-cooling in AGS.

4. Coherent Electron Cooling (CEC).

High-energy electron cooling for RHIC-II

RHIC-II electron cooling: 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

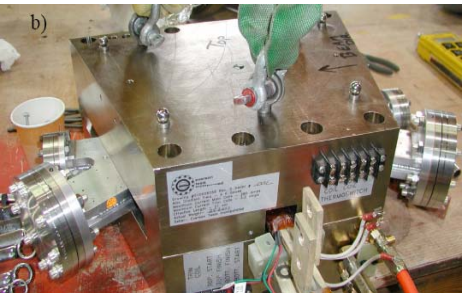
Hardware development

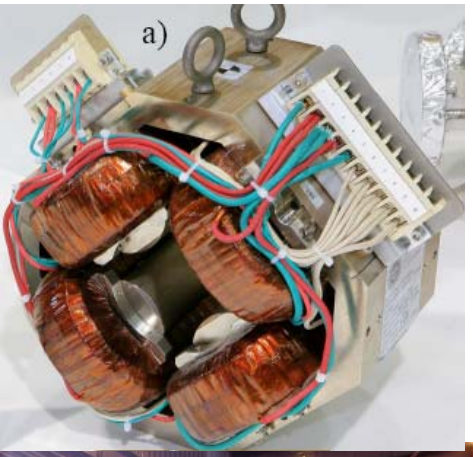
- **5-cell, high-current accelerating cavity**
- **½ cell SRF gun**
- **Photocathode R&D**
- **R&D ERL (prototype of ERL for RHIC-II e-cooler)**

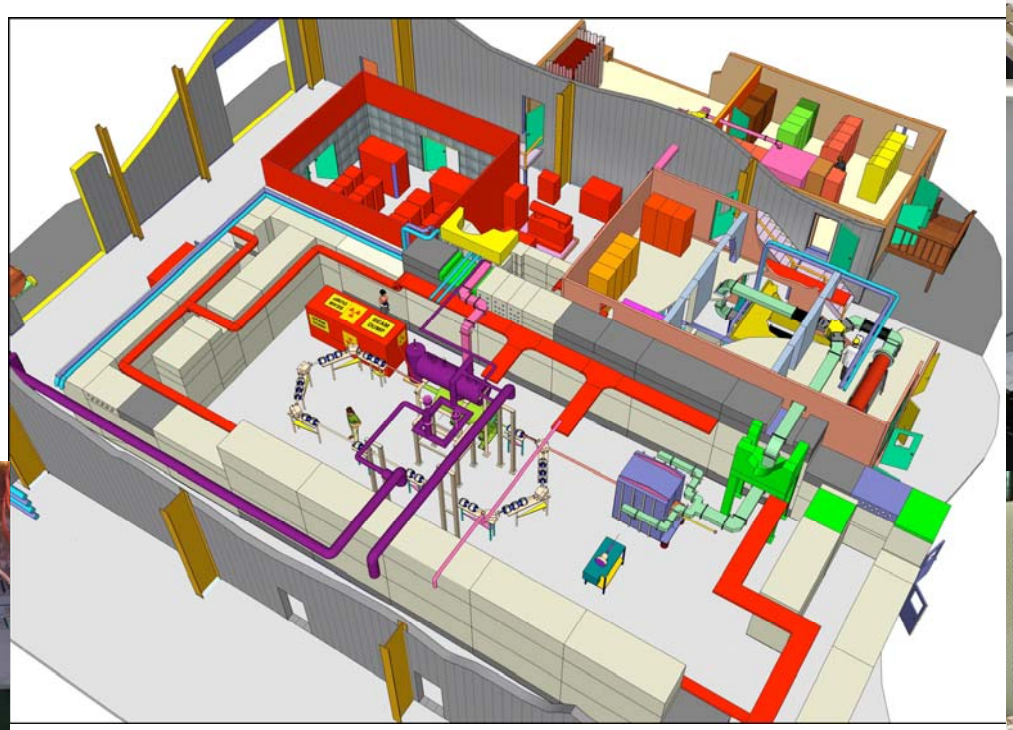
R&D ERL (V. Litvinenko et al.)

Test bed for RHIC-II ecooling and eRHIC

Commissioning starts in 2009







Accelerator Physics Experiments

1. **RHIC APEX experiments on IBS.**

   We also did a lot of measurements to study various aspects of electron cooling in machines equipped with electron coolers. Experimental data was benchmarked with simulations.

2. **Magnetized cooling experiments: CELSIUS, Sweden.**

3. **Non-magnetized cooling experiments: Recycler, FNAL.**

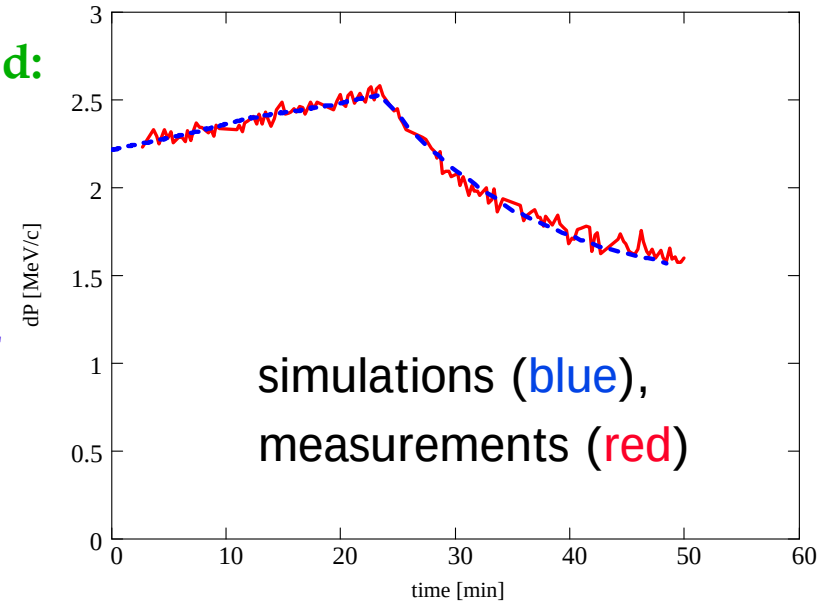
Example of experimental benchmarking using Recycler (FNAL) E-cooling

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)**

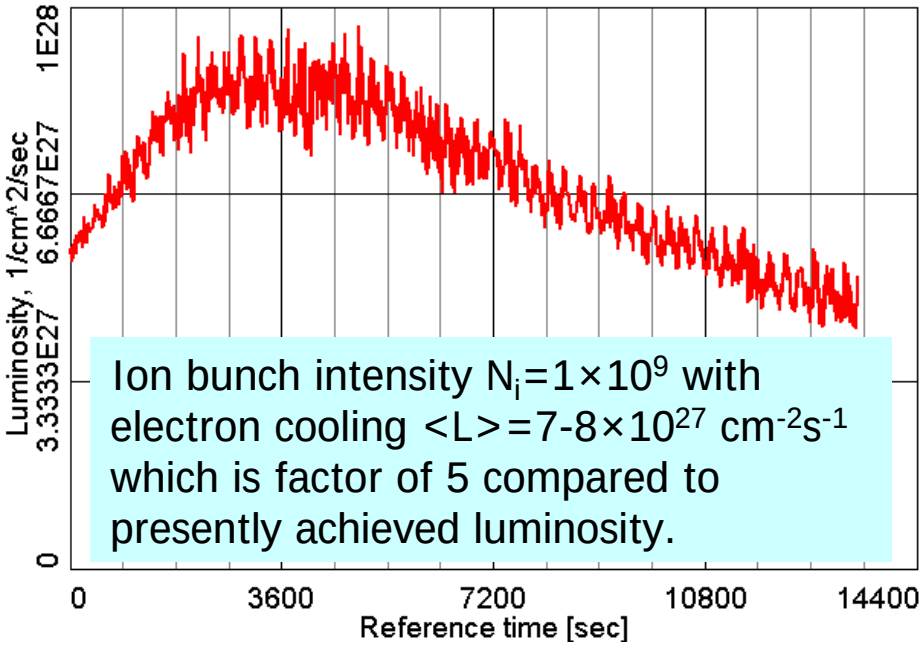


see presentations by

L. Prost et al., COOL07

A. Shemyakin et al., COOL07

E-cooling of Au ions for RHIC-II (simulations)



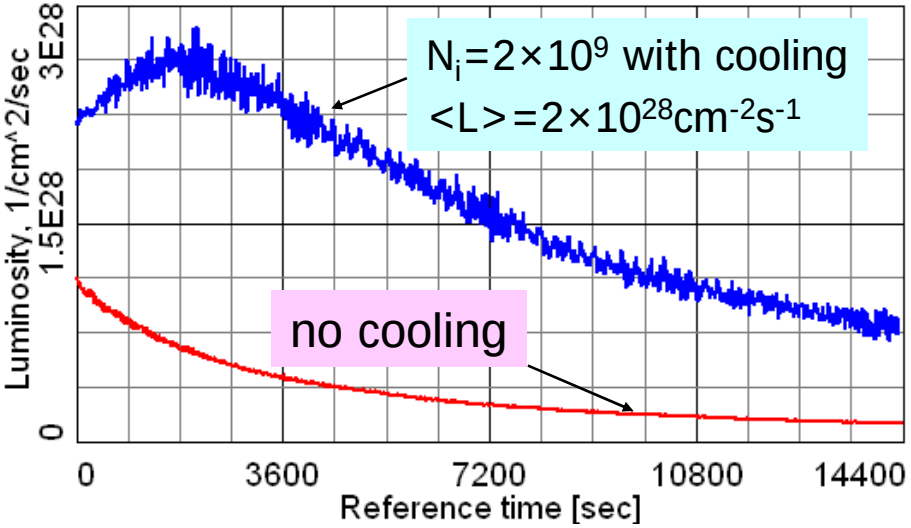
Ion bunch intensity $N_i=1\times10^9$ with electron cooling $\langle L\rangle=7\text{-}8\times10^{27}$ $cm^{-2}s^{-1}$ which is factor of 5 compared to presently achieved luminosity.

number of bunches: 111

initial $\varepsilon_{95\%,n}$ =15 μm

rms momentum spread 5×10^{-4}

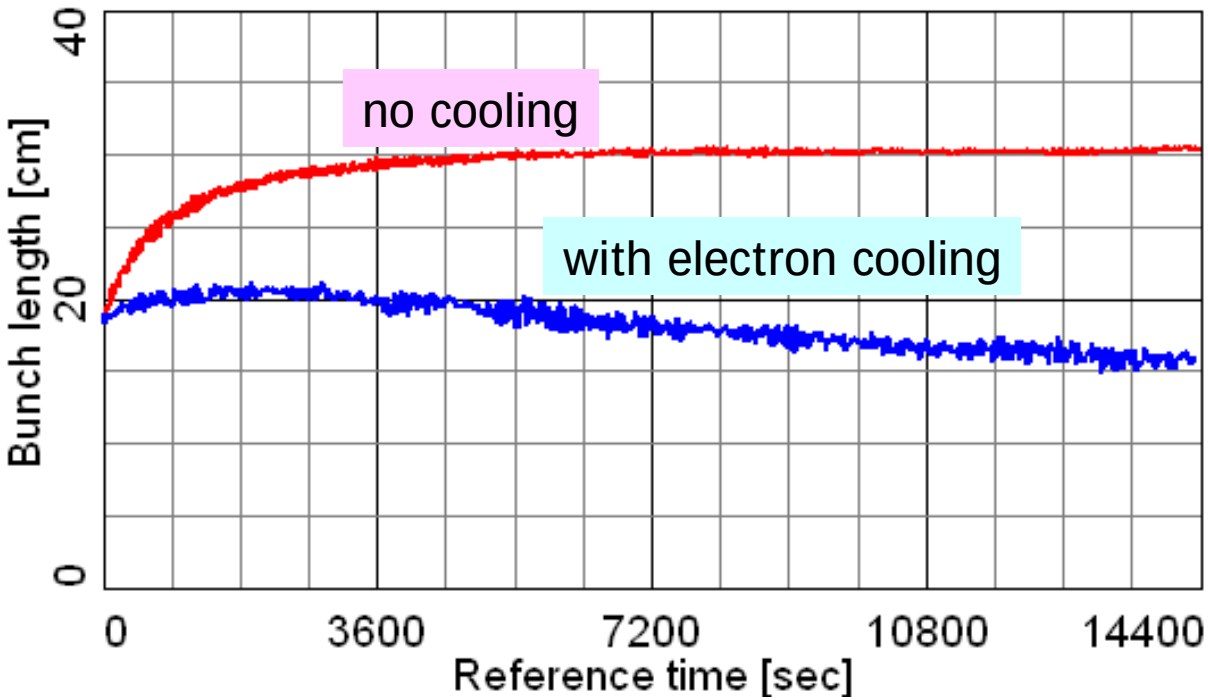
β^*=0.5m



BETACOOL (JINR, Russia) simulation.

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

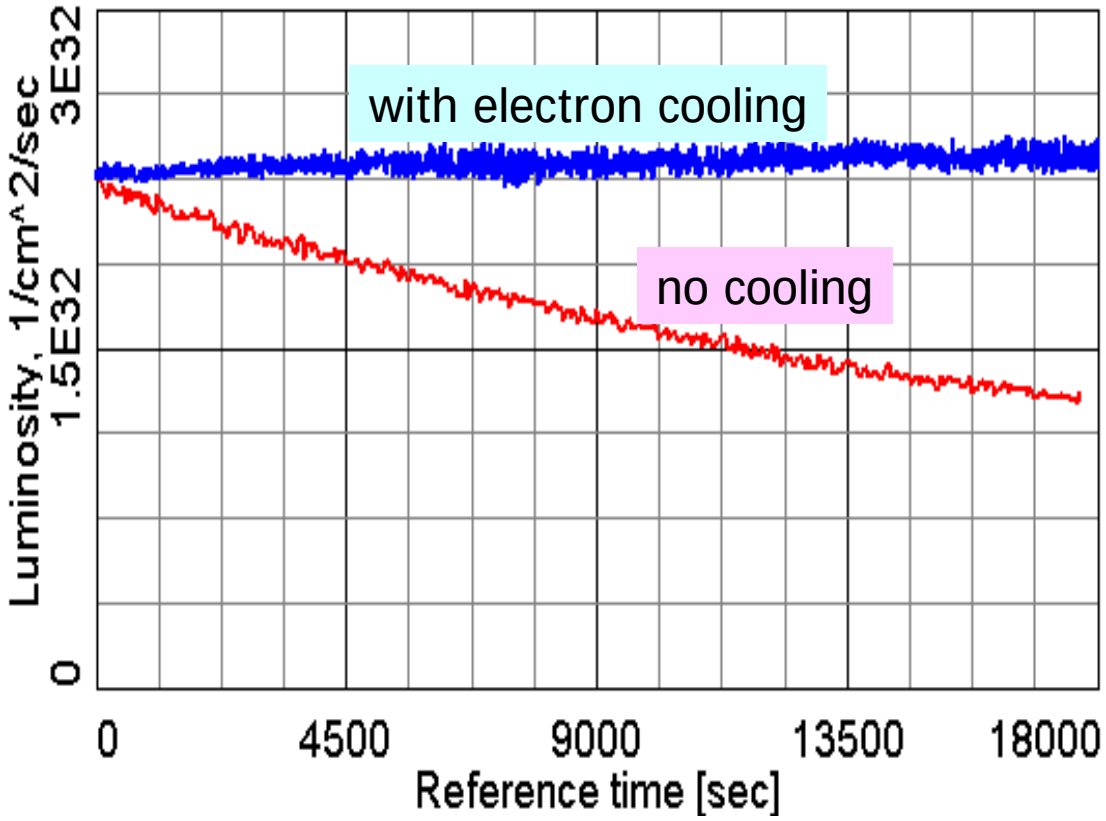
Electron cooling for RHIC-II: bunch length control (simulations)



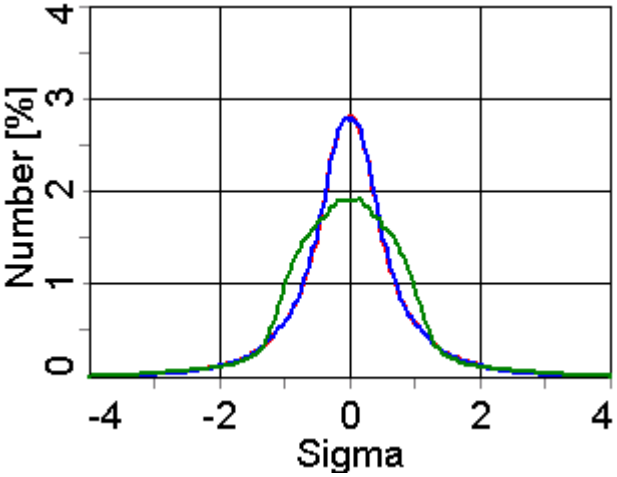
Maintaining short bunch length.

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



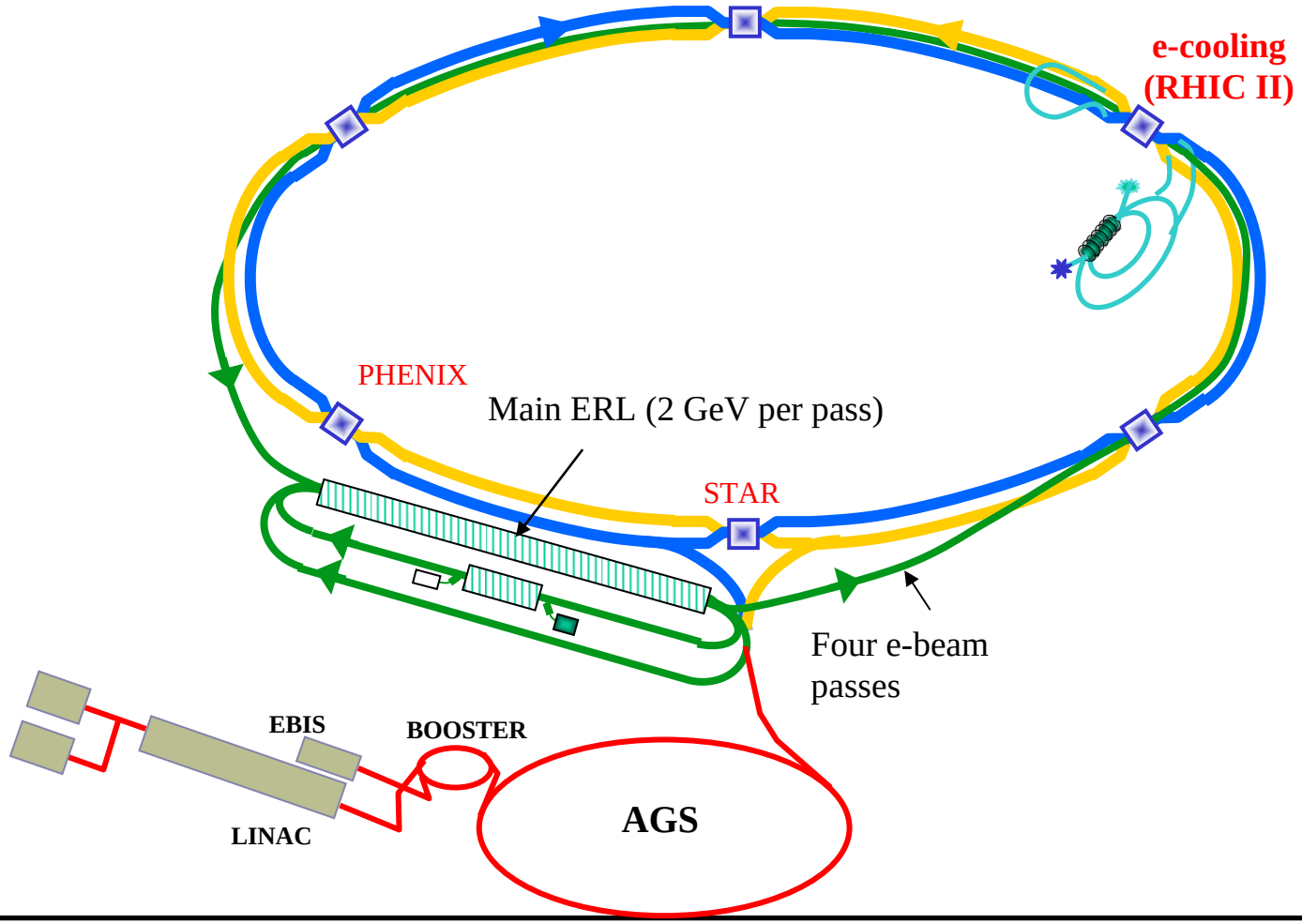
High-energy Electron Cooling system for RHIC-II - summary

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.**

For details see: http://www.bnl.gov/cad/ecooling

Electron cooling for eRHIC

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



eRHIC – electron cooling is required (see Vadim Ptitsyn presentation)

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

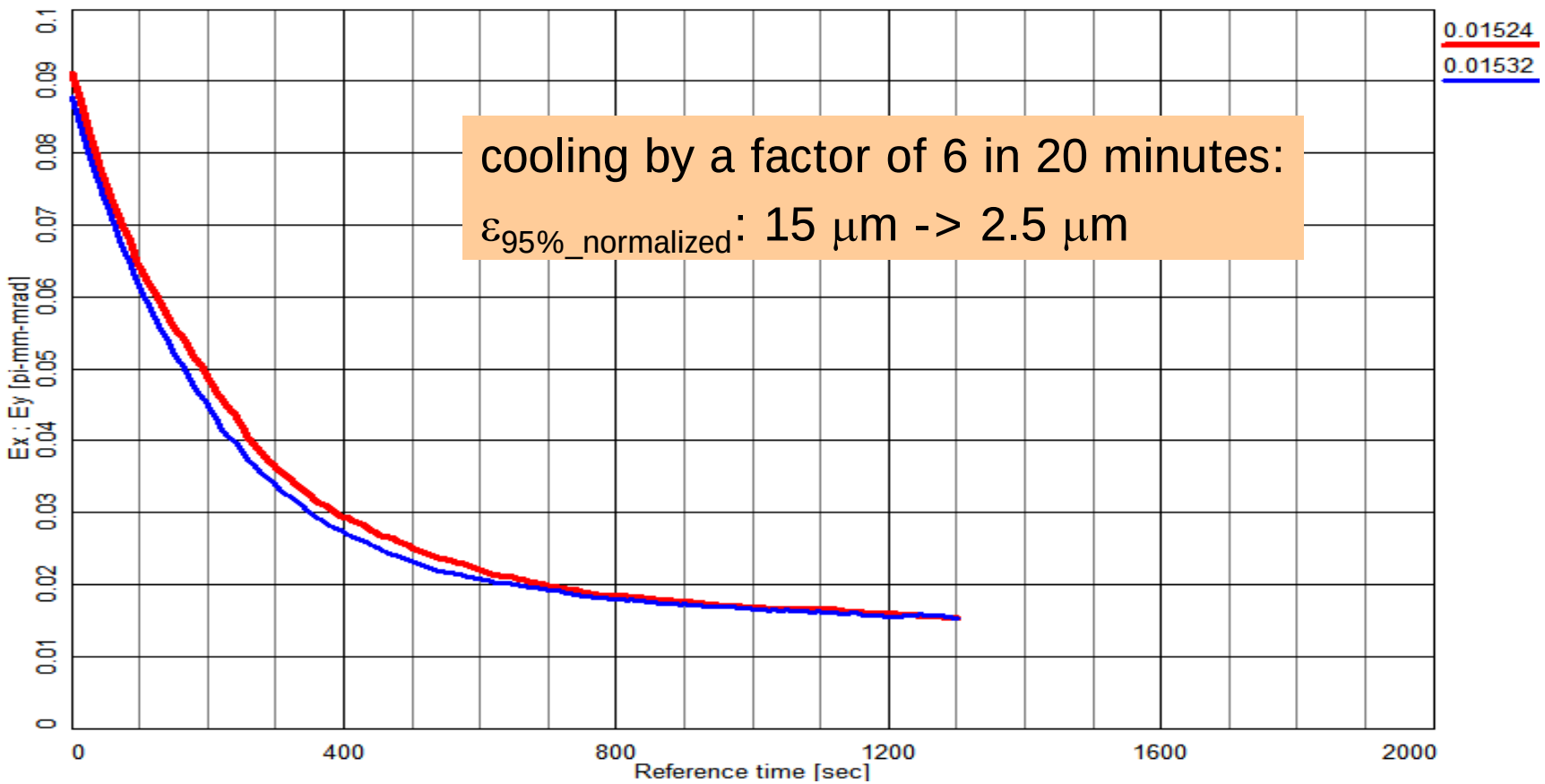
Requires pre-cooling:

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

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

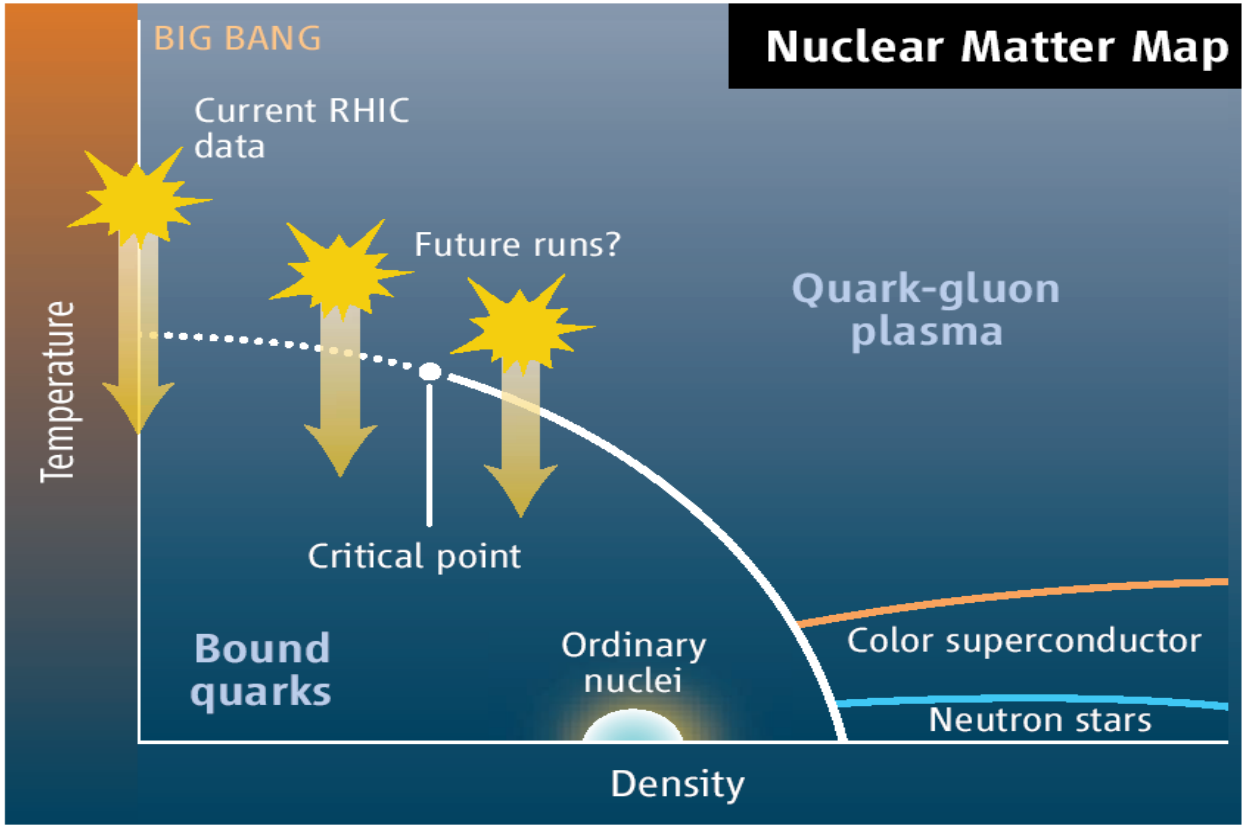
E-cooling is needed to achieve eRHIC parameters.

Pre-cooling of Au ions (N=1×10^9) at 25 GeV/n, using RHIC-II electron cooler (using several electron bunches per single long ion bunch)



Electron cooling for Low-Energy RHIC

Low-energy RHIC operation: 2.5-15 GeV/n



Landmark study. Physicists have seen a smooth transition from bound quarks to quark-gluon plasma (dotted line). They now hope to find the point beyond which the transition becomes violent (white line).

A. Cho, Science, 312 (14 Apr 2006)

Other projects: NICA and FAIR (SIS300)

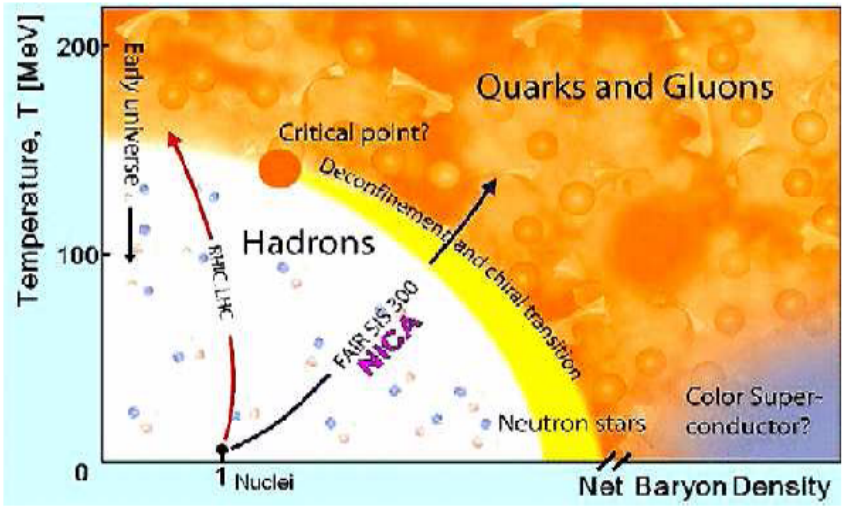
NICA project (Dubna, Russia) – Au-Au collisions in the range of kinetic energies of ions 1.0-3.5 GeV/nucleon. Very high luminosities are essential for physics program. With present (optimistic) design parameters, maybe able to get to luminosities of 10^{27} for highest energy point (3.5 GeV/n).

E-cooling: 1) pre-cooling at injector energy is required (AGS-type) 2) E-cooling (up to 2 MeV) of ions 1.0-3.5 GeV in collider is being considered.

(Design: 2007-09; Construction of components: 2008-11; Assembling: 2011-12; Commissioning: 2013)

At RHIC, for lowest energy point (1.57 GeV/n) without electron cooling one may expect to have average luminosities in the range of $3\text{-}7*10^{22}$.

With direct electron cooling in RHIC, significant boost in luminosity is expected.



Physics:

deconfinement and/or chiral symmetry restoration phase transitions

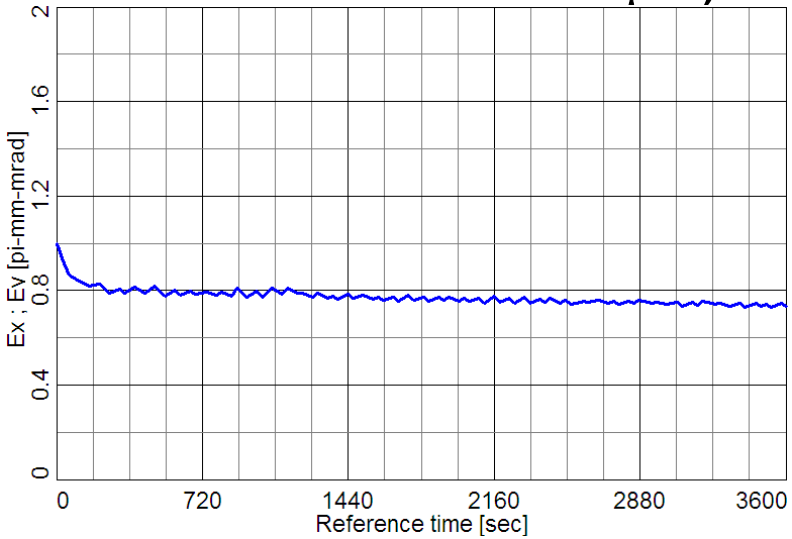
the first stage

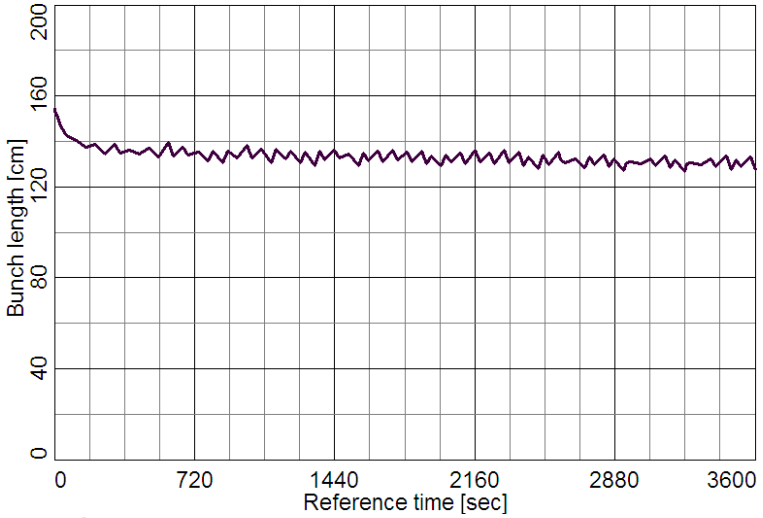
- Multiplicity and global characteristics of identified hadrons including multi-strange particles
- Fluctuations in multiplicity and transverse momenta
- Directed and elliptic flows for various hadrons
- HBT and particle correlations

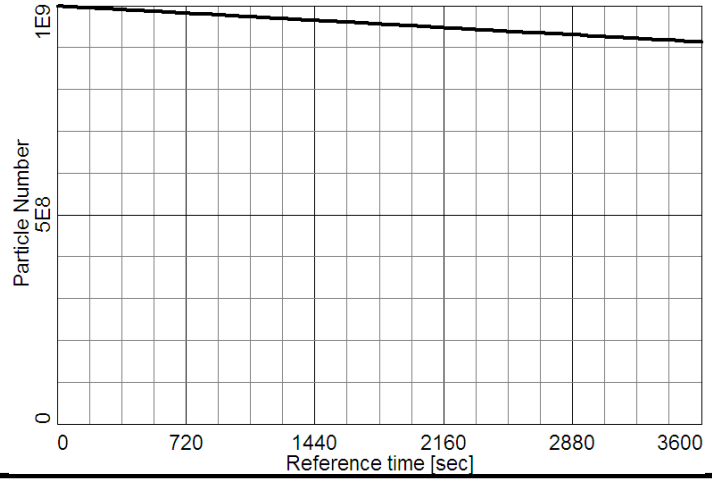
the second stage

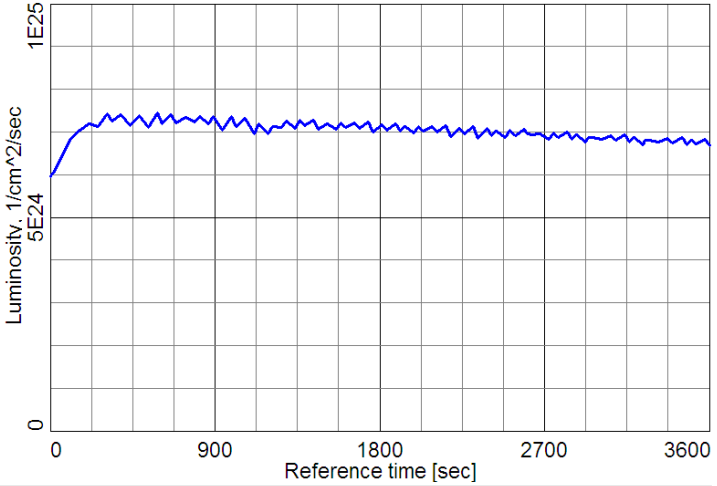
- **Electromagnetic probes (photons and dileptons)**

Simulation – cooling of Au ions in Low-Energy RHIC: γ=2.68 (L=20m, undulator with B=3G, RF gun: q=2nC, electron rms normalized emittance ε=2 μm, rms dp/p=0.0003)









Low-energy RHIC luminosity estimate (given for lowest energy point with γ=2.6)

1. Conservative (no-cooling): beta*=10m, large emittance due to strong transverse IBS, large intensity decrease due to longitudinal IBS and loss from RF bucket, reduced bunch intensity, reduced number of bunches – overall, about $\langle L \rangle = 3\text{-}7 * 10^{22}$ may be expected. But stores are very short – just few minutes.

2. Optimistic (with direct e-cooling in RHIC): beta*=10m, small emittance (15 pi initial), full intensity of 1e9 per bunch, full number of bunches (112) – resulting $\langle L \rangle = 7 * 10^{24}$ - long stores become possible.

This factor of 100 in improvement may be on an optimistic side.

On the other hand, using cooling in RHIC together with additional pre-cooling in AGS, if one can inject higher intensities per bunch (2e9?), or pre-cool transverse emittance even higher luminosities may be possible.

Since no design of such cooling systems exists, cooling performance presented here should be treated as a rough estimate only!

AGS pre-cooling

- For typical RHIC operation longitudinal emittance of Au ion beam injected in RHIC is 0.2-0.3 eV-s.
- For lowest energy point (γ=2.68) RF bucket acceptance is only 0.08 eV-s (at 300 kV). Injecting large emittance in such a bucket would result in a dramatic loss in peak luminosity.

- For June 2007 test run, injected longitudinal emittance was estimated to be only 0.14 eV-s (T. Satogata et al., PAC07) which resulted in nearly perfect longitudinal injection at γ=4.9.
- The source of emittance growth in AGS is presently under investigation (E. Pozdeyev et al.).
- If found necessary, longitudinal emittance of Au beam can be cooled in AGS before injecting into RHIC. AGS pre-cooling was studied in simulations (COOL07).

Low-Energy RHIC - Future Plans

1. A low-energy run in RHIC which should scan 6-7 energies was proposed for 2009-2010 run.
2. Feasibility of pre-cooling in AGS is presently under investigation (E. Pozdeyev et al.).
3. A test run (T. Satogata et al.) at lowest energy of interest 1.6 GeV/n kinetic beam energy has been proposed for 2007-2008 run. It will help to determine luminosity lifetime, evaluate need for AGS pre-cooling, allow more accurate prediction for luminosity gain with direct cooling in RHIC.
4. Various design options of electron cooler in RHIC at these low energies are being considered – about factor of 100 improvement in luminosity looks feasible.

Coherent Electron Cooling

Ya. Derbenev (COOL07 presentation Sept. 2007): Coherent electron cooling (CEC) was proposed 27 years ago

- General idea: amplify response of e-beam to an ion by a micro-wave instability of the beam
- A few instabilities have been shown
- CEC advantages/disadvantages compared to:

EC : Gain in cooling rate

Complicate BT

SC : Very large FB (30 GHz – optics)

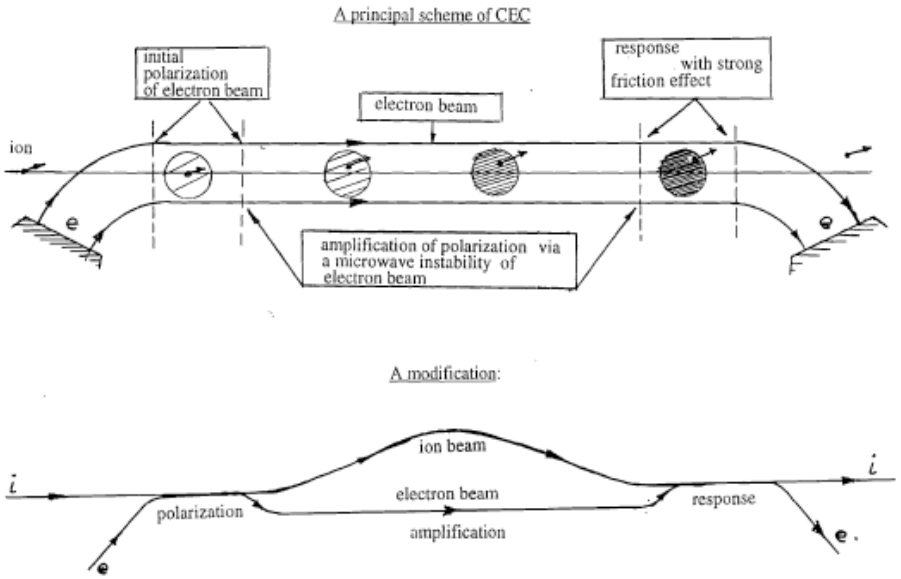
Precise phasing required

OSC : Effective in a wide energy range

Small signal delay

Intense e-beam required

Signal gain is limited



What changed in recent years?

- **Relativistic DC EC realized (FNAL)**
- **ERL realized (JLab)**
- **SASE FEL realized (UCLA - DESY)**
- **ERL-based HEEC on the way (BNL)**

And more…

V. Litvinenko (FEL07 presentation, August, 2007): Estimate of CEC for hadron beams

Machine	Species	Energy GeV/n	Synchrotron radiation, hrs	Electron cooling, hrs	CEC, hrs
RHIC	Au	100	20,961 ∞	~ 1	0.03
RHIC	protons	250	40,246 ∞	> 30	0.8
LHC	protons	450	48,489 ∞	> 1,600	0.95
LHC	protons	7,000	13/26	∞ ∞	< 2

Coherent Electron Cooling

The work started on a feasibility study of coherent electron cooling (suggested by Ya. Derbenev, 1980) for RHIC. This approach promises very good cooling performance at high energies (V. Litvinenko and Ya. Derbenev, FEL07 Conference).

Towards:

1. **Proof of principle experiment using 20 MeV R&D ERL to cool Au ions longitudinally at 40 GeV/n.**
2. **Design of full scale cooling system for direct cooling of protons at 250 GeV/n for eRHIC.**

APEX related studies

1. **IBS studies in RHIC – was very instrumental in testing our simulations and e-cooler design.**
2. **IBS reduced lattice – see Vladimir Litvinenko presentation.**
3. **Study of longitudinal emittance growth in AGS – needed to understand the need of AGS pre-cooling for low-energy RHIC program.**
4. **Experiments with high-intensity beam – transition instability. Electron cooling can cool 2e9 bunch intensity providing up to <L>=2e28 per store, if such intensities can be delivered to store.**

THANK YOU