The RHIC Electron Cooling Project

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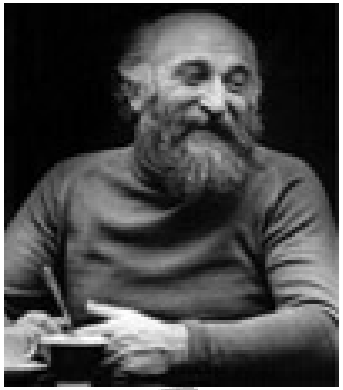

G. I. Budker, the inventor of electron cooling.

First electron cooler:
NAP-M, 1974
68 MeV protons

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RDM Parameters and Upgrade Values

Parameter	Units	Value ⇒ upgrade
Gold energy, E_{Au}	[GeV/u]	100
Particles per bunch		10^9
Interaction Point β^*	[m]	2 ⇒ **1**
Number of bunches		60 ⇒ **120**
95% emittance	[μm]	15 ⇒ **6**
Average luminosity	$cm^{-2}sec^{-1}$	0.2 ⇒ **8** $\times 10^{27}$

About an order of magnitude of luminosity increase through two mechanisms with similar contributions:

1) Reduction of the equilibrium emittance.
2) Extension of the luminosity lifetime.

How does electron cooling work?

- We produce a bunch of ‘cold’ (low emittance) electrons, accelerate it and introduce it into the ring at the ion’s γ.
- The electrons move at the same speed as the ions and thus are at rest in the co-moving frame. However, the ions have thermal motion (emittance) and oscillate in the bucket relative to the electrons.
- Ions scatter (Rutherford) off the electrons and energy is transferred to the electrons. This energy transfer appears as a friction force acting on the ions. The ions slow down and are thus ‘cooled’. The electrons are renewed.

Additional details (life is never simple)

- The electrons must be plentiful (high average current) and cold (high brightness). This requires a high-performance electron source.
- The high-current and energy of the electrons calls for energy recovery for the electron beam.
- To help with the transverse electron emittance, cooling is done in a strong magnetic field. This requires a very high-precision solenoid.
- All of the above points have been addressed. Electron cooling is a well known and proven technique.
- Cooling time:

$$\tau = \frac{\gamma^2 A}{4\pi r_p r_e Z^2 n \eta c \Lambda_c} \left(\frac{\varepsilon_n \beta \gamma}{\beta^{*c}} \right)^{3/2}$$

So what is so special about the RHIC Cooler?

- High energy cooling, ~50 MeV electron energy: We need a linear electron accelerator with some form of energy recovery. That has not been done so far.
- By-product: Discontinuous solenoid field, magnetized electron transport (as is being done in FNAL recycler electron cooler)
- Cooling of a collider: Collision noise, beam-beam parameters, bunched beam. All of these never done.
- Electron – ion Recombination. Consequence: Cooling with relatively ‘hot’ electrons, large solenoid field.
- Beam disintegration (the best way to lose beam, but a limit nevertheless).

Beam Disintegration

- This loss is dominated by bound electron-positron production and Coulomb dissociation in Au–Au collisions. At energies of 100 GeV/nucleon the cross section has been estimated[1] to be

  $\sigma=\sigma_{pair}+\sigma_{dis}=212\pm10$ b

  Leading to a luminosity decline:

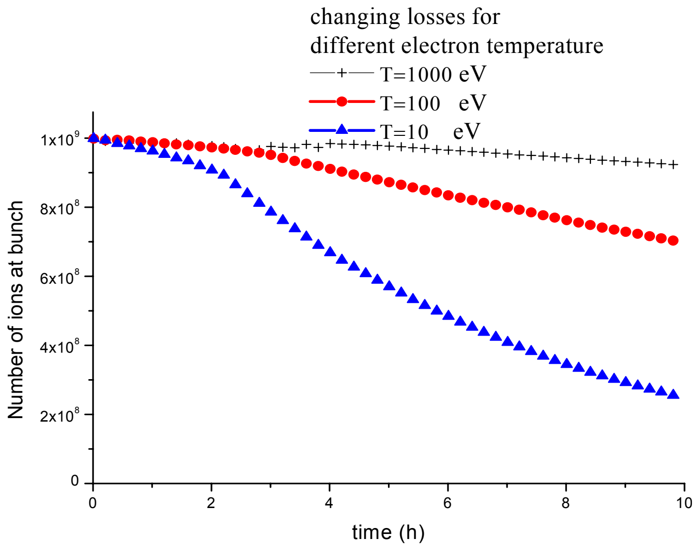
$$\langle L \rangle = \frac{L_0}{1 + \frac{n_i L_0 \sigma}{M N_0} t}.$$

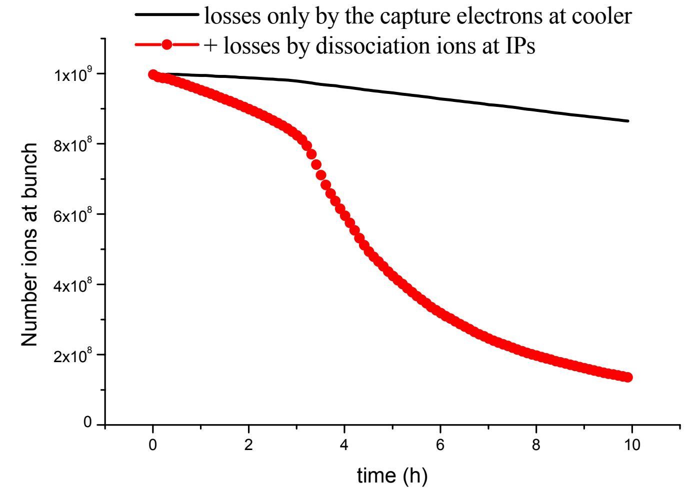
n_i= number of IPs, M= number of bunches

N_0= number of ions per bunch

1. A. J. Baltz, M. J. Rhoades-Brown, and J. Weneser, Phys. Rev. E **54**, 4233 (1996).

Electron – Ion Recombination





Particle loss due to recombination vs. electron temperature (left), comparison of recombination with dissociation (right)

$$\alpha_{rec} = 3.02 \times 10^{-13} \frac{Z_i^2}{\sqrt{T_e}} \left[\ln\left(\frac{11.32 Z_i}{\sqrt{T_e}} \right) + 0.14 \left(\frac{T_e}{Z_i^2} \right)^{1/3} \right]$$

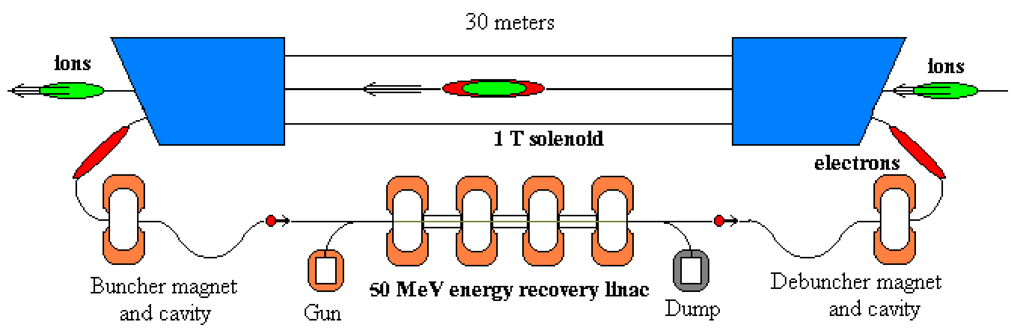
M.Bell, J.S.Bell Particle Accelerator 12 p.49 (1982)

The Bell formula was verified in various experiments on NAP-M (protons) and SIS (Bi^{+67}).

$$\tau_{rec} = \frac{\gamma^2}{n \alpha_{rec} \eta}$$

Schematic of the RHIC Cooler

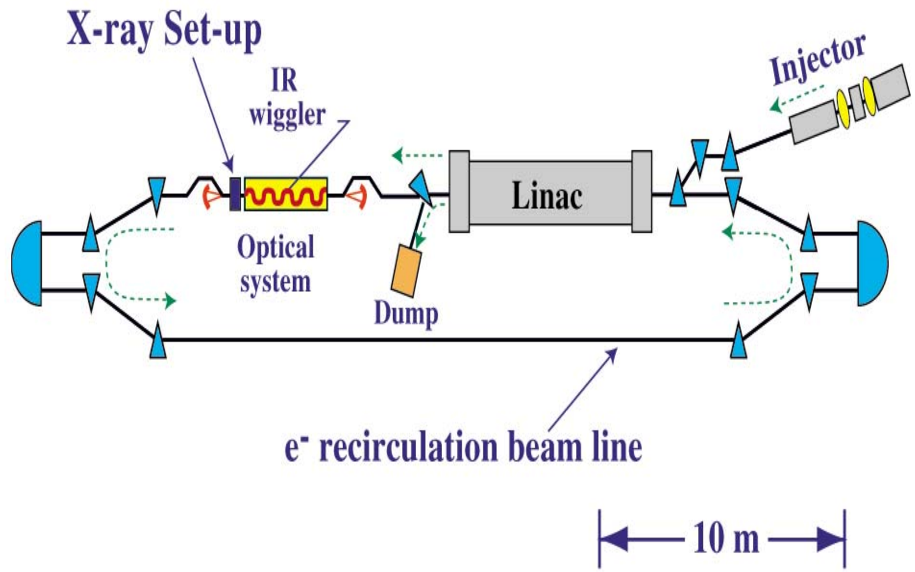
- Energy Recovery Linac
- Buncher - debuncher



> x10 increase in the integrated luminosity of RHIC, as well as better accumulation of rare species.

Energy Recovering Linac – the ticket to high-current

- JLab 50 MeV ERL

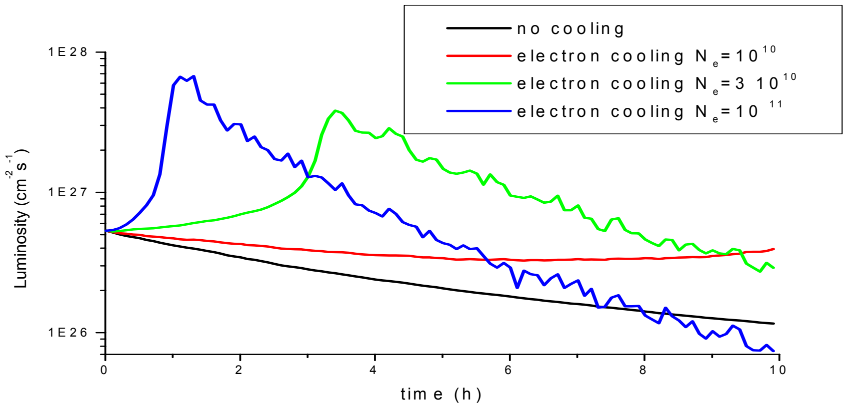


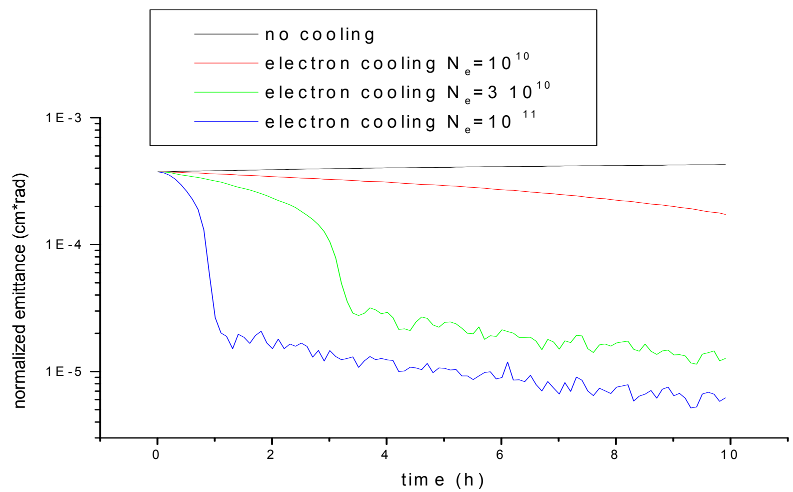
- Linac energy recovery extremely good (loss < 0.02%)
- 5 mA average current, limit – e-gun.
- ~200 mA is believed to be possible **without feedback**, well over 200 mA with B-factory style feedback.

Photoinjector Properties

- Laser control of electron bunch parameters: Charge, bunch size and distribution.
- Low energy spread and low emittance due to rapid acceleration.
- Bunch starts out short, no need for complicated low-energy bunching system, which degrade brightness.
- Boeing 433 MHz gun: 26 MV/m on cathode, duty factor 25%, 7 nC, 27 MHz PRF, emittance 10 mm-mrad, energy spread 100 KeV, bunch length 50 ps.

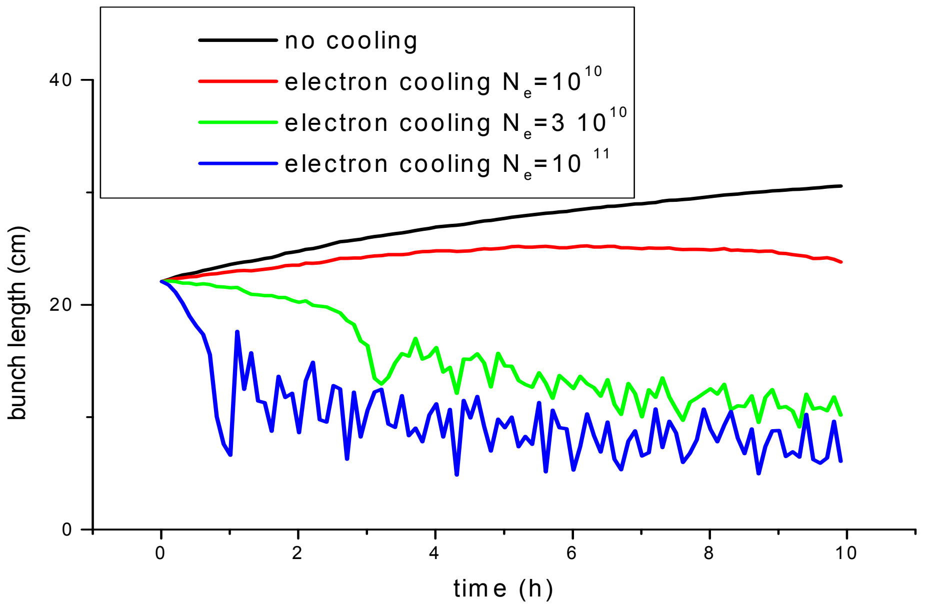
Luminosity and emittance for various cooling currents





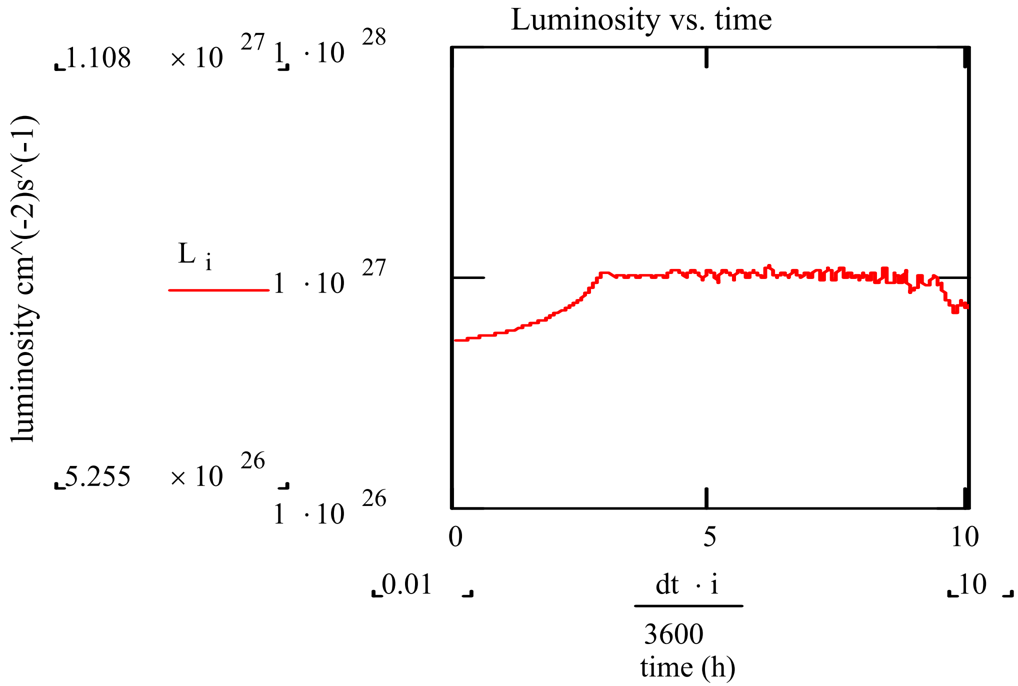
Some results from The BINP-BNL investigation of an electron cooler for RHIC. Here one sees the evolution of the luminosity (above) and emittance (below) as a function of store time.

Bunch length vs. time for various electron currents



Here one sees the evolution bunch Length as a function of store time.

Simple control of cooling rate to stabilize luminosity



By controlling the cooling rate one can stabilize the luminosity over long periods of time.

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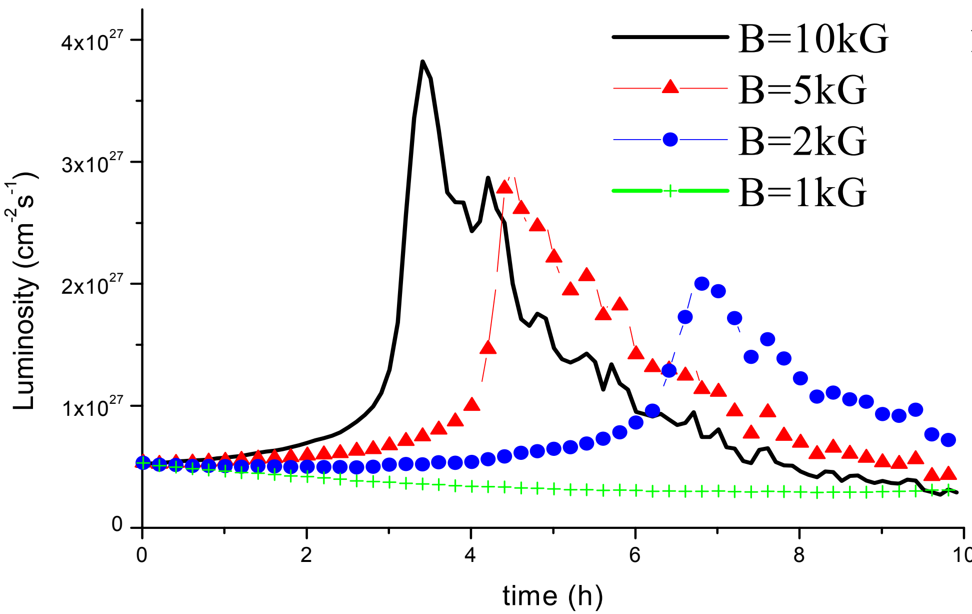
RHIC Retreat, March 2002

Cooling with Hot Electrons Requires a High Magnetic Field



A demonstration of the role of the solenoid: luminosity as a function of time, using 1 keV electrons, as a function of solenoid field.

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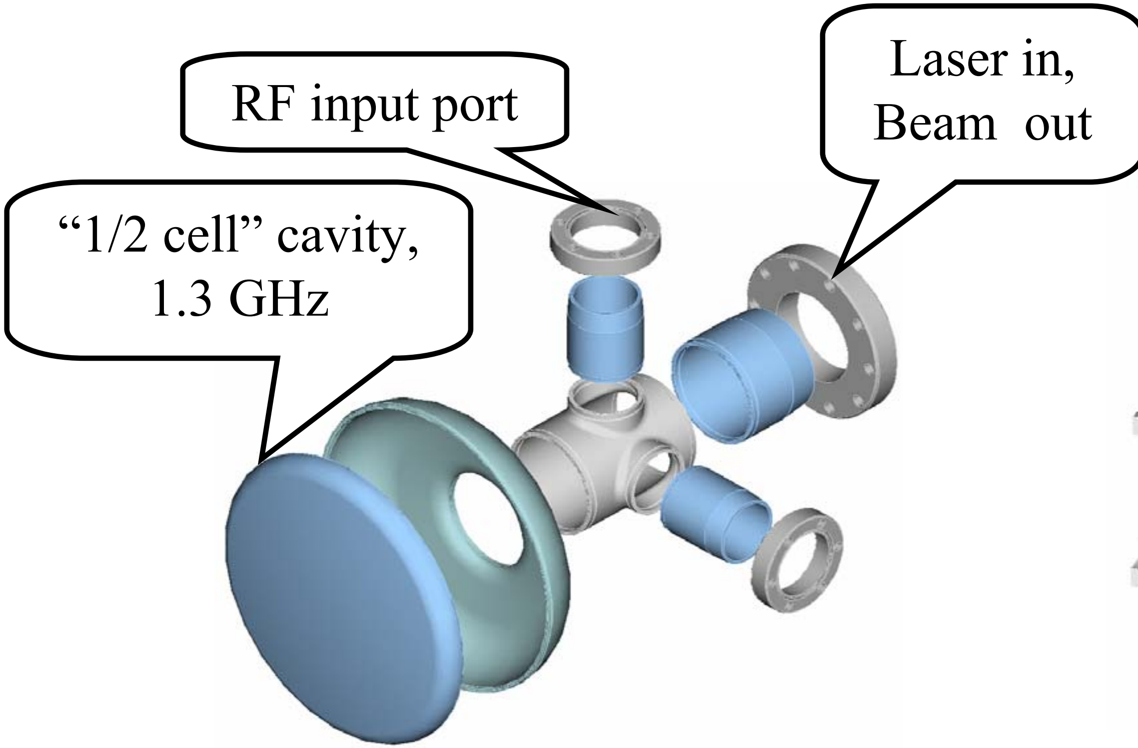
R&D plan.

- Carry out theoretical studies of the specific issues of the RHIC cooler.
  - Collaboration with the Budker Institute, report developed (Electron Cooling for RHIC, C-A/AP/47)
  - Software from JINR Dubna, Tech-X SBIR, beam dynamics…
- Carry out some key experiments (cooling with hot electrons, recombination, bunched beam) as feasible in existing coolers.
- Develop the new electron technology: The Electron Cooling Test Facility, photoinjector development.
- Develop the superconducting solenoid (SC Magnet Division)

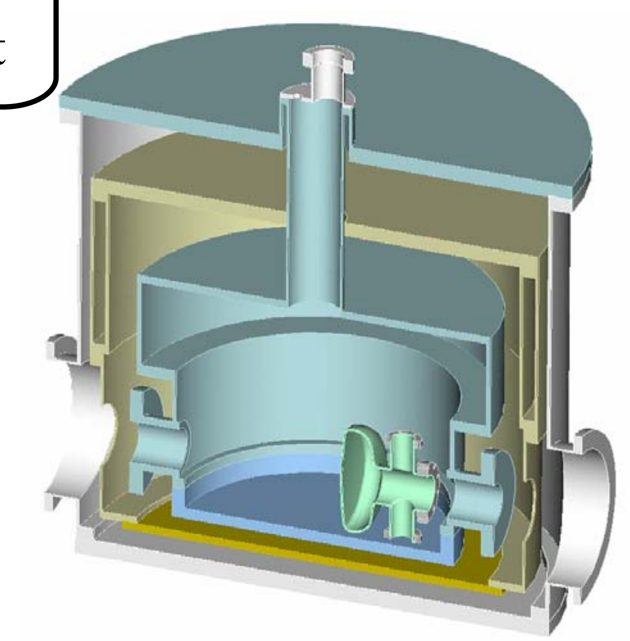
The Electron Cooling Test Facility

- Building 939 (Neural Beam Test Facility)
- Laser Photocathode Electron guns from AES SBIRs (superconducting / normalconducting guns)
- Superconducting linac sections from DESY
- Energy recovery at high current
- Debunching / rebunching of the beam to match longitudinal phase space
- High precision superconducting solenoid (SMD)

Superconducting photoinjector: Get started. (With JLAB and AES)



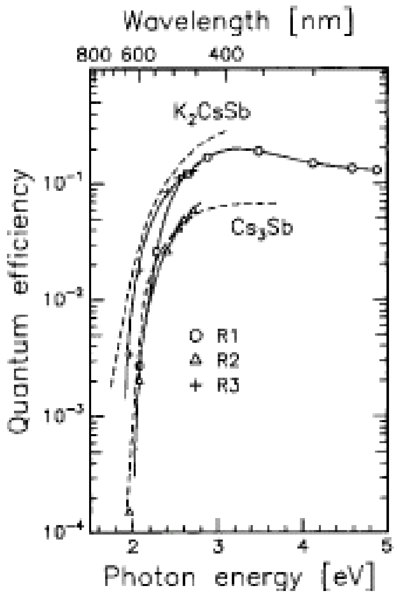
Exploded view of all-niobium photoinjector

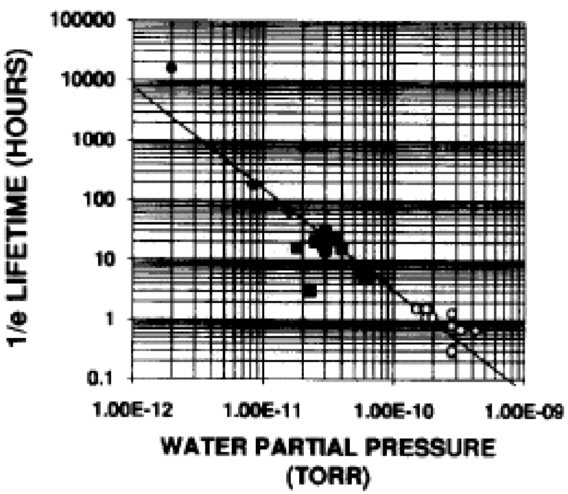


Gun assembled in cryostat

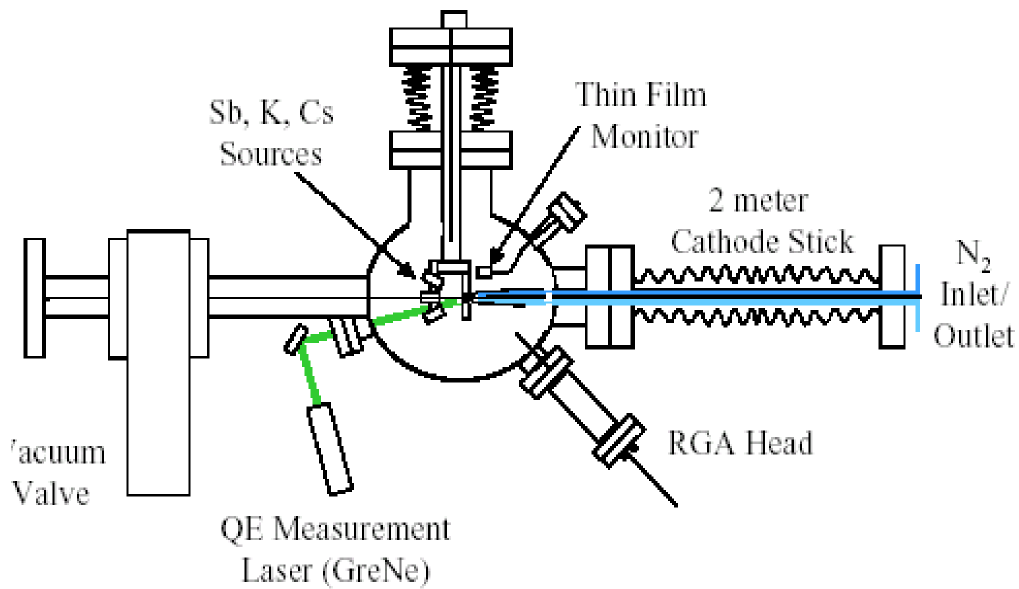
This SBIR AES project will provide us with the laser and CW electron beam to get started in the Cooling Test Facility.

Photocathode development
(T. Srinivasan-Rao, Q. Zhao)





Photocathode Fabrication Chamber

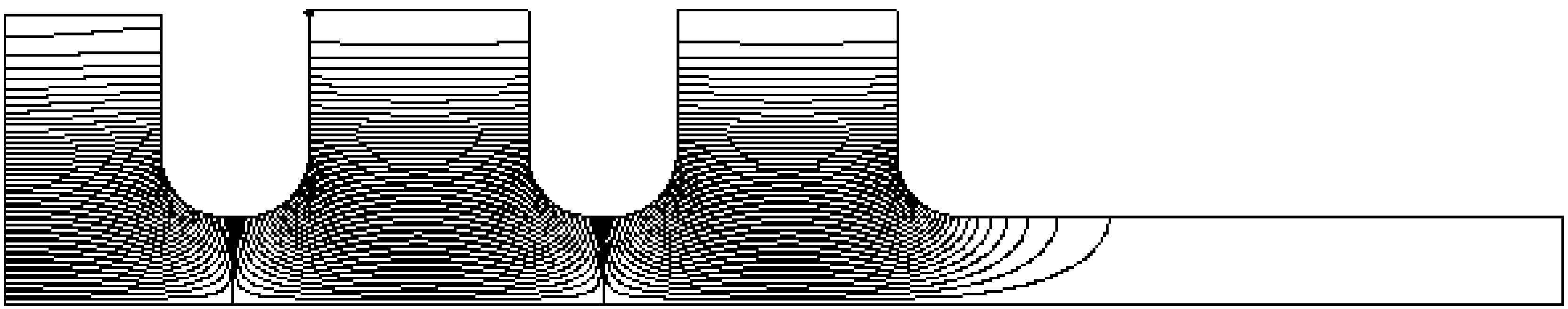


Objective: Develop BNL experience in multi-alkaline cathodes, study lifetime issues, complement AES SBIR. Finally, provide cathodes for the RHIC electron cooler.

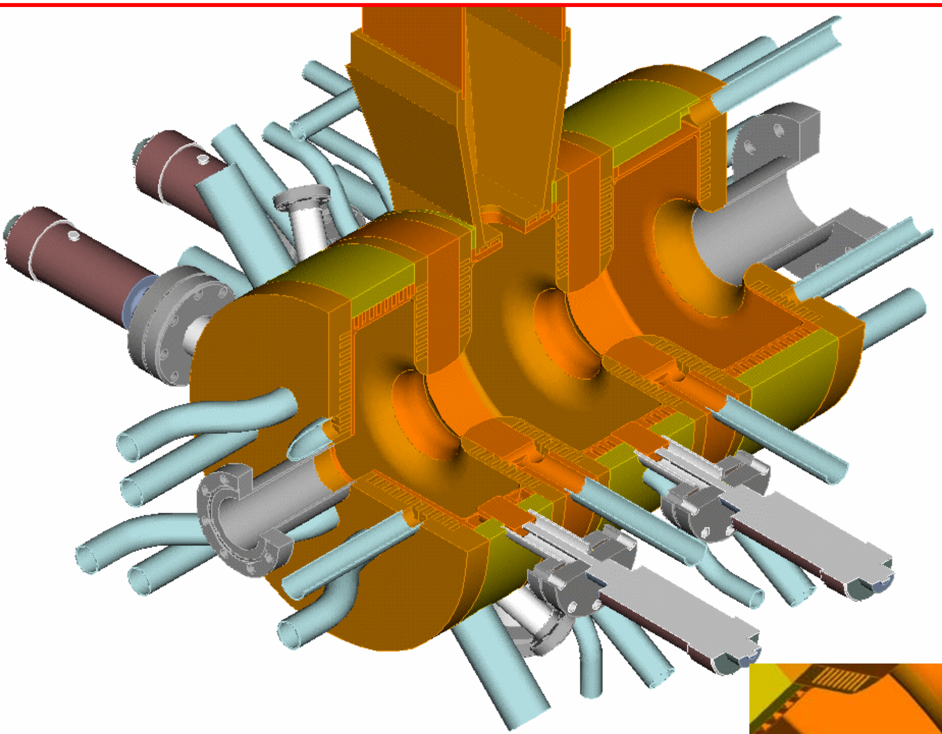
CW Photoinjector developed in collaboration with AES, funded by an SBIR

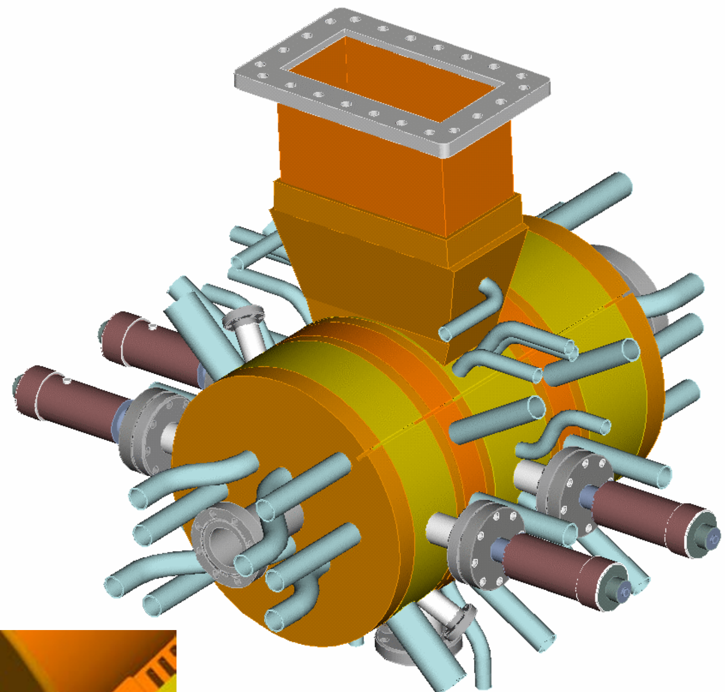
Frequency	1300.33052 MHz
Cathode field	15 MV/m
Stored energy	1.7838250 Joules
Total Power	817.69 kW
Maximum segment power density	376 W/cm^2
Q	17824

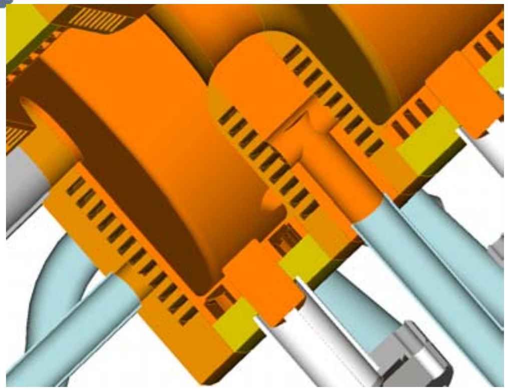
This is the SUPERFISH simulation of the photoinjector being designed In collaboration between AES and C-AD.



AES Photoinjector Design







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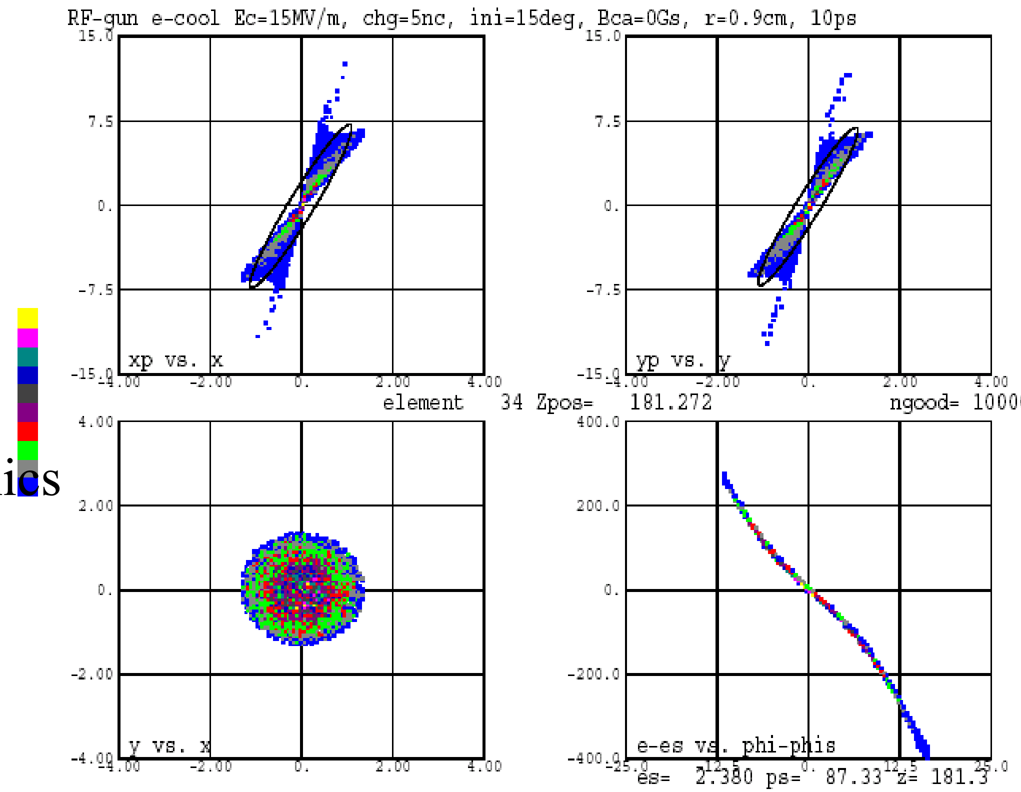
Beam dynamics calculations

In this example, one sees the results of PARMELA simulations for the Photoinjector, part of the ongoing work aimed at A start-to-end beam dynamics Simulation of the facility.



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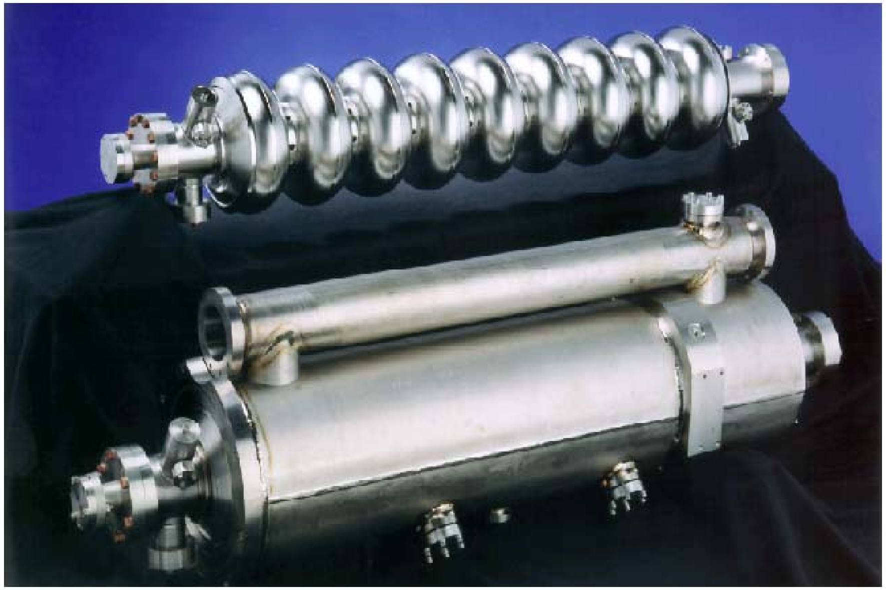
Superconducting linac

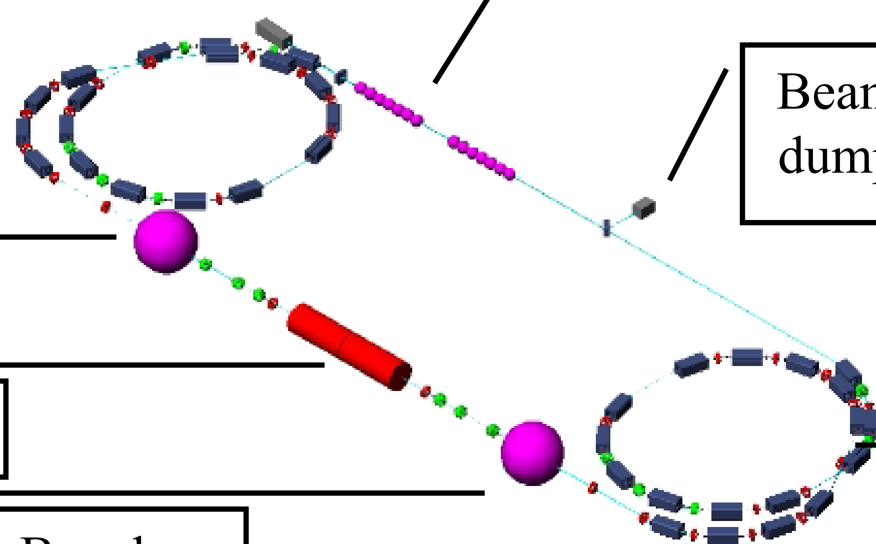
- Cavities: TESLA design, demonstrated >25 MV/m.
- Commercial technology, ~20k$/MV
- Refrigeration ~26 W / cavity at 2K, 20 MV/m assuming Q_0~$1.5x10^{10}$, + standing loss.
- Agreement with DESY pending for production of catities for test facility.



Electron Cooling Facility beam optics design (Joerg Kewisch)

Phased approach:

- Gun
- Linac
- Energy recovery
- Debunching
- Magnetized electrons



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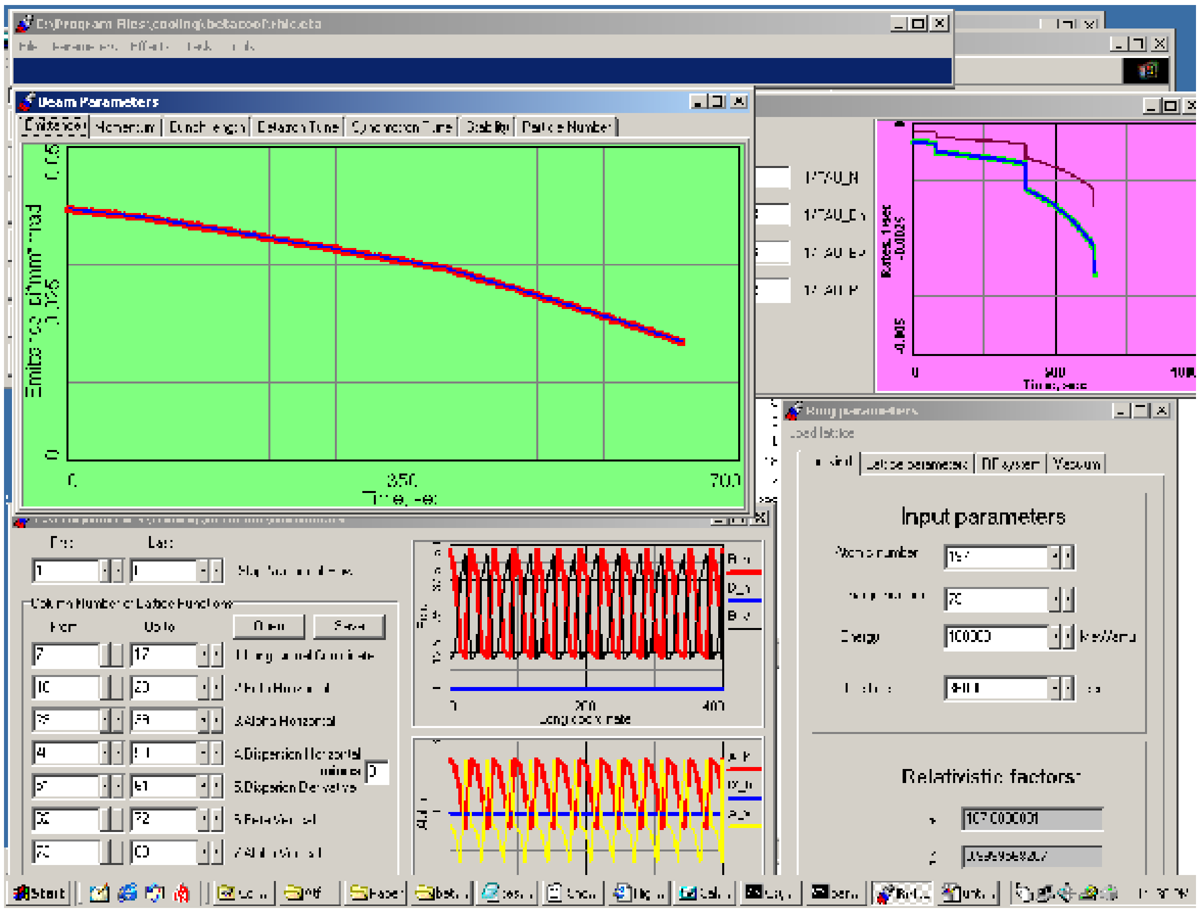
E-Cooling Software

BETACOOL, JINR Dubna (Control interface display)



SBIR with Tech-X: Develop a 3-D simulation code that can model electron cooling physics through direct Coulomb interactions.

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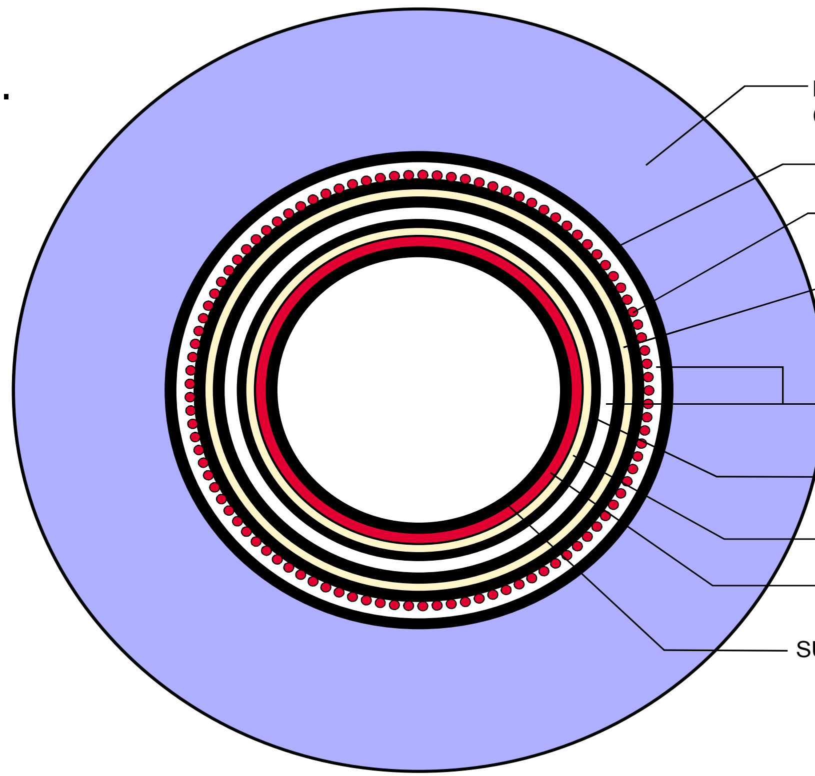
High Solenoid Precision Required (Superconducting Magnet Division)

$$\Delta\theta := \sqrt{\frac{\varepsilon\ ni}{\beta \cdot \gamma \cdot \beta\ cool}}$$

$$\Delta\theta = 1.25 \times 10^{-5}$$

- Superconductor:
  - RHIC/SSC cable:
    - ~5 kA, 2 layers.
    - Low inductance, larger errors.
  - "Wire-like" cable at < 1kA:
    - Winding errors average out.
    - Higher inductance.
- Axis straightening:
  - Initial precision (short solenoids).
  - mechanical adjustments (long).
  - Final straightening by correctors.
  - Full length tilt of axis by 1 mrad.



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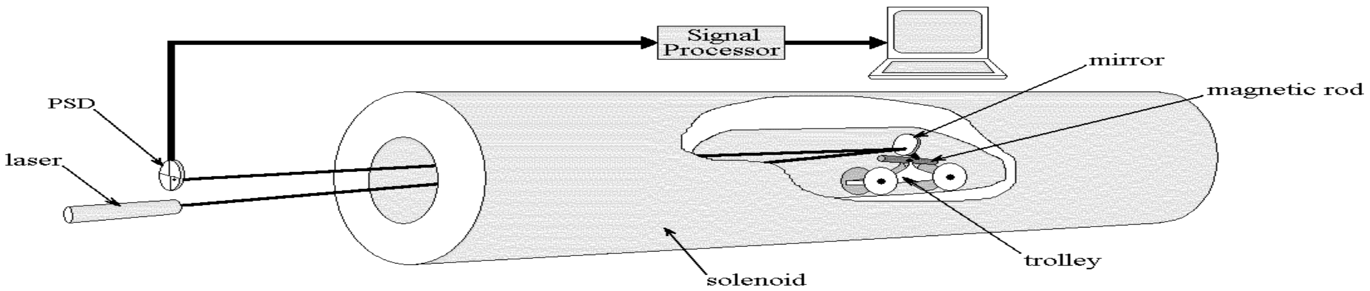
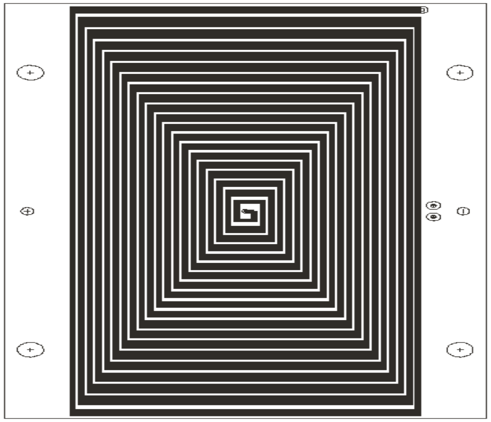
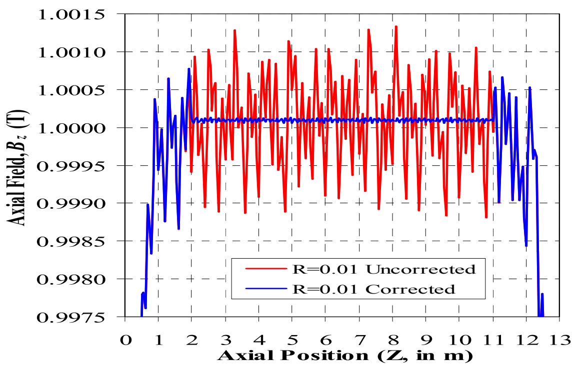
Measurement and correction (Animesh Jain)

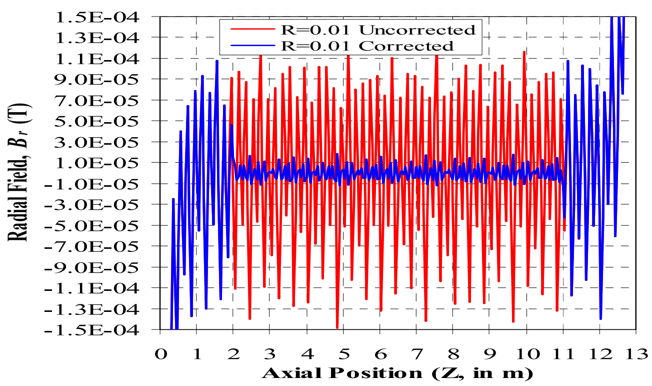
Use BINP/FNAL method:





Simulated correction – axial (left) and radial (right)





Horizontal and vertical PC double-sided dipole layers, 2A, 10^{-3} Tesla on LN2 wall

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Summary

- High energy electron cooling of the RHIC collider is being pursued.
- Outstanding research issues:
  - Optimize the design, carry out start-to-end simulations.
  - Detailed design of the electron source.
  - Demonstrate energy recovery at ~100 mA average current.
  - Demonstrate the magnetized electron transport
  - Debunching and rebunching, demonstrate beam quality.
  - Design, prototype and build the solenoid.
  - Verify cooling with 1 KeV electrons.