THE ERL HIGH-ENERGY e-COOLER FOR RHIC

EPAC'06

Presented on behalf of the many people who contribute
to the electron cooling R&D effort by
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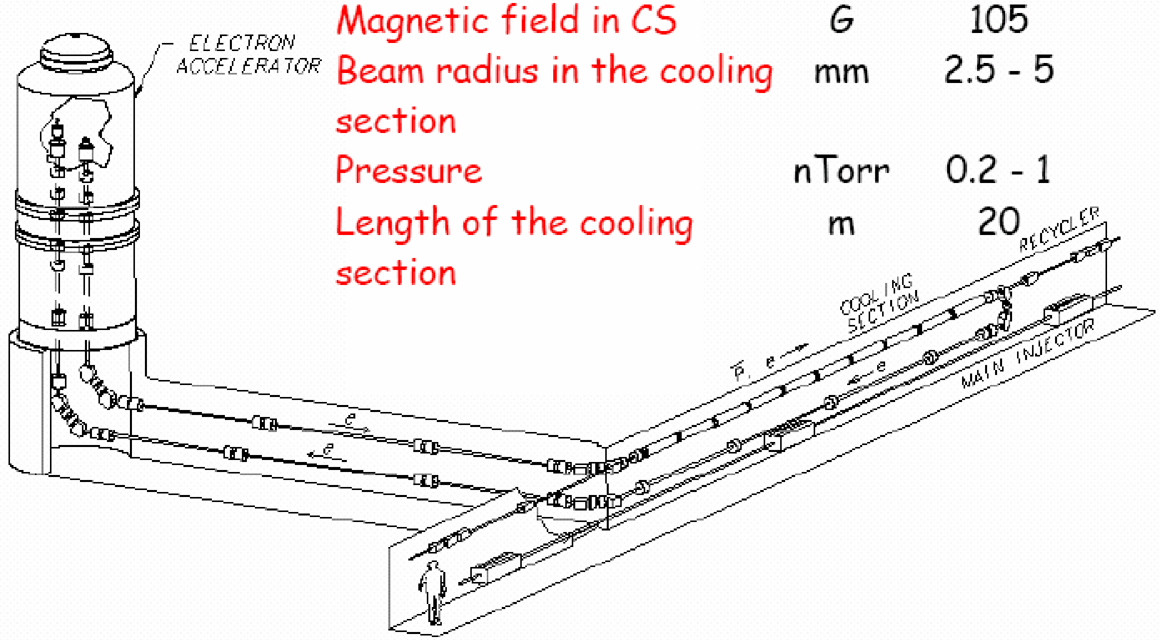
The High-Energy Electron Cooling era got started at Fermilab

- Electrostatic accelerator (Pelletron) working in the energy recovery mode
- DC electron beam
- 100 G longitudinal magnetic field in the cooling section
- Lumped focusing outside the cooling section
- The first cooling has been demonstrated in July 2005 and is routinely used in operation since then
- Outstanding achievement!

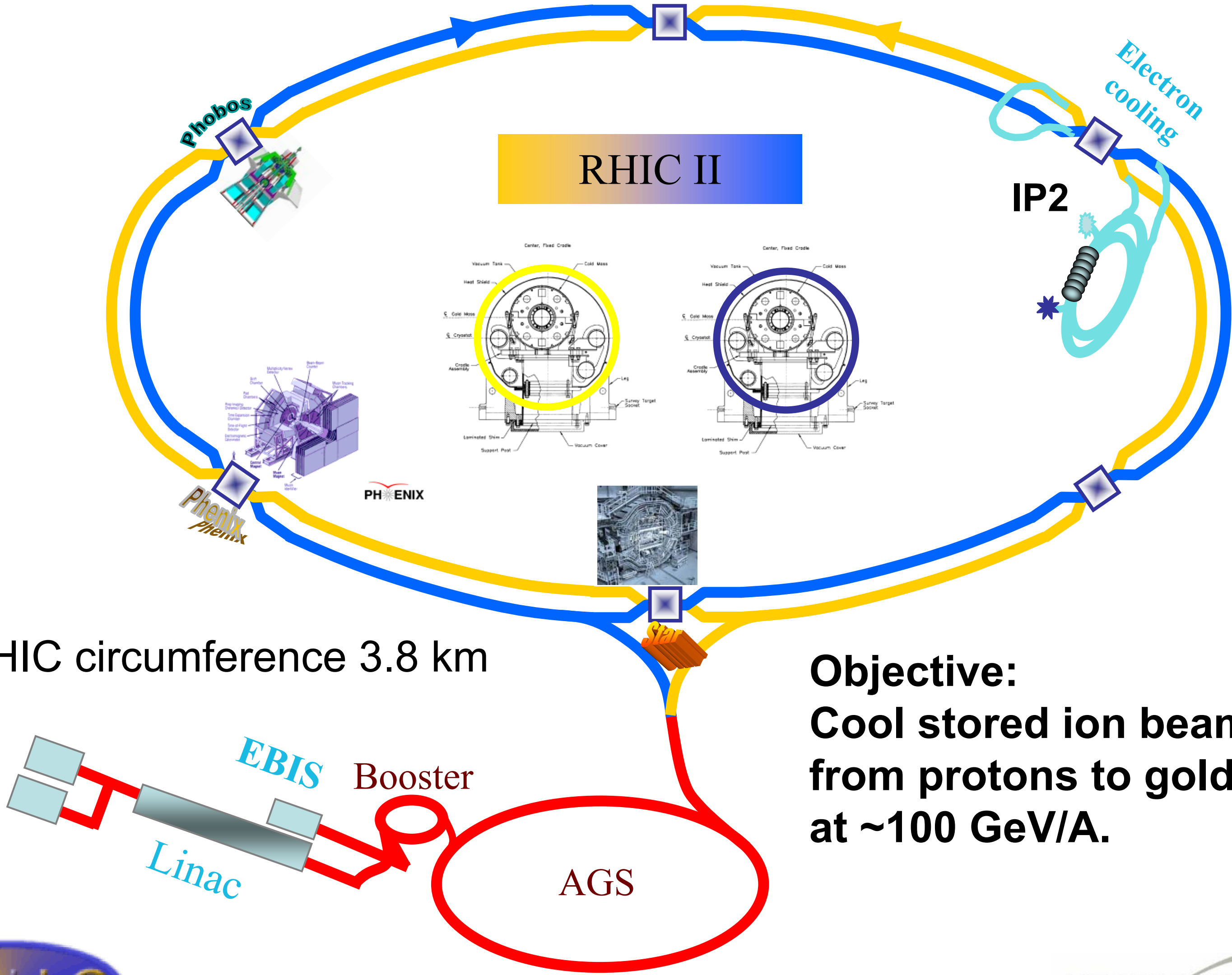
Electron energy	MeV	4.338
Beam current used for cooling	A	0.05 - 0.5
Magnetic field in CS	G	105
Beam radius in the cooling section	mm	2.5 - 5
Pressure	nTorr	0.2 - 1
Length of the cooling section	m	20



The RHIC II Upgrade

- Evolution of RHIC to a QCD laboratory calls for a luminosity increase.
- A significant part of the luminosity increase will be through electron cooling.
- Electron cooling is also important for the eRHIC – a high-energy, high-luminosity lepton-hadron collider based on RHIC.
- The energy range is yet another order of magnitude increase past the FNAL cooler.

Schematic Layout of RHIC with an electron cooler at IP2



RHIC circumference 3.8 km

Objective:
Cool stored ion beams, from protons to gold, at ~100 GeV/A.

The objectives and challenges

- Electron cooling will increase RHIC luminosity: For various ions from P to Au at 100 GeV/A
- Reduce background due to beam loss
- Maintain smaller vertex

- Cooling rate slows in proportion to $\sim\gamma^{5/2}$
- Energy of electrons 54 MeV, well above DC accelerators
- Need high electron bunch charge (5 nC) and low emittance ($\leq 4\mu$m)
- For gold, we must deal with recombination and burn-off

RHIC

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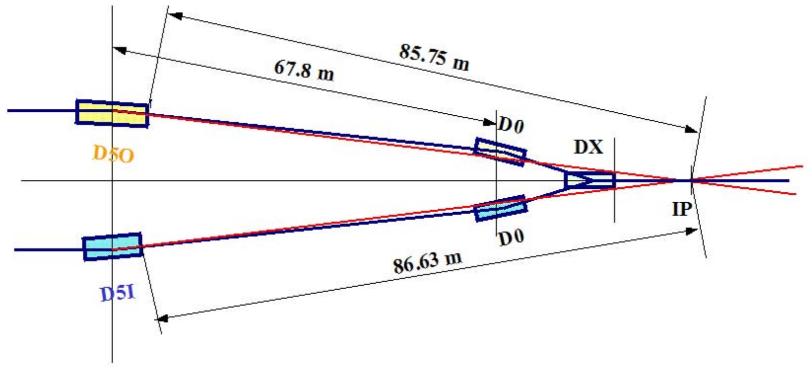
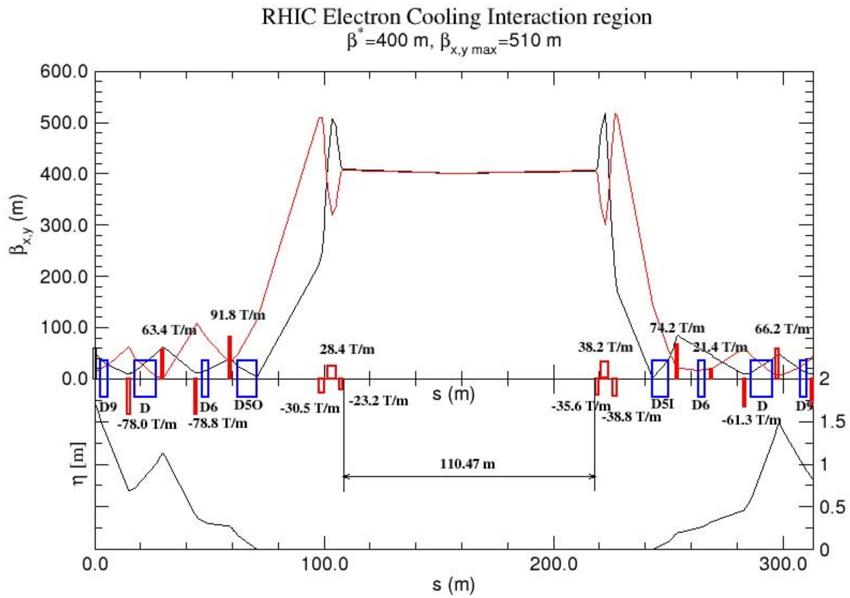
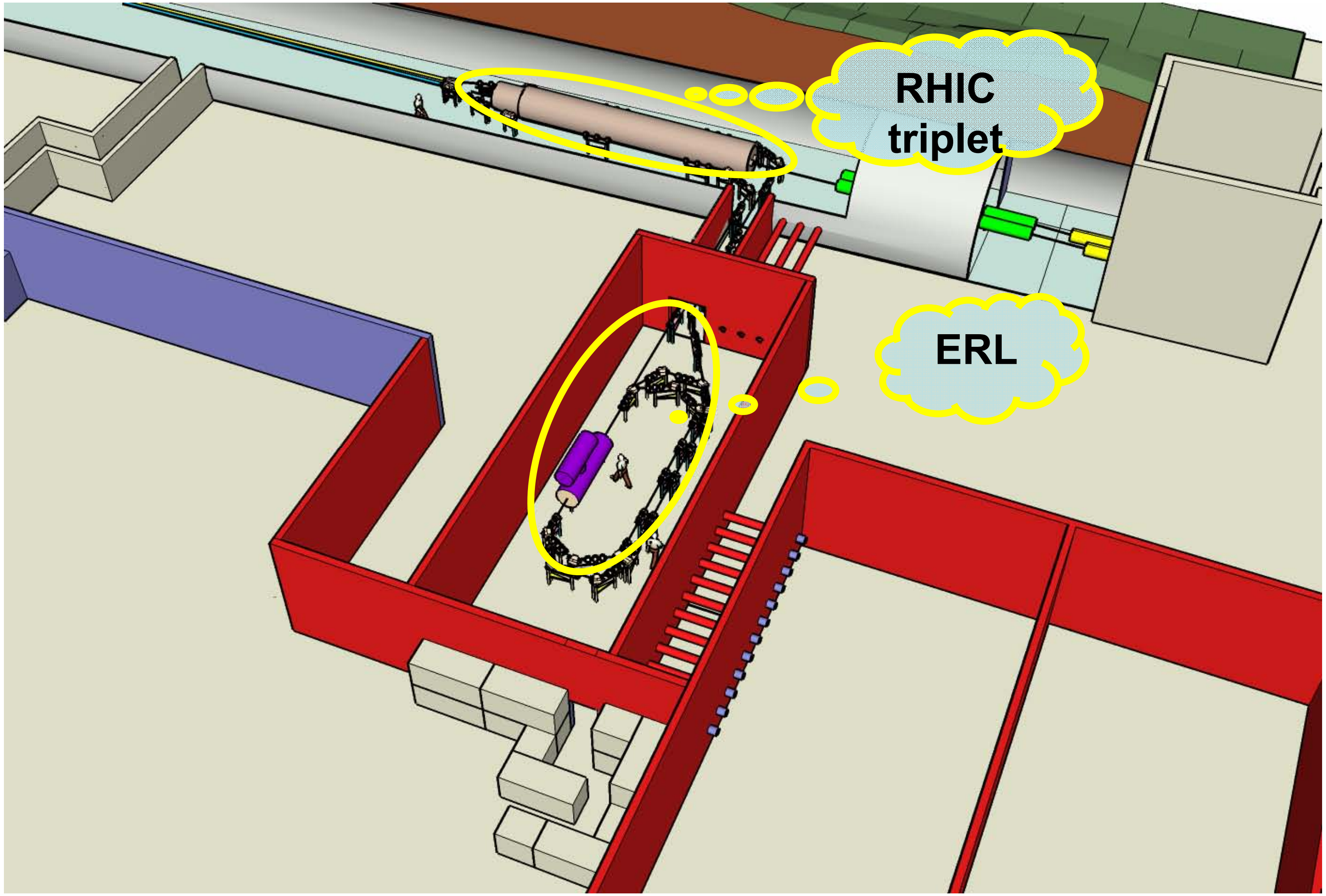
Modification of the RHIC lattice

- See D. Trbojevic, et al, MOPCH102
- A number of solutions are possible.
- One can accommodate a dispersion free, large β (400 m) long section (110 m) for cooling.

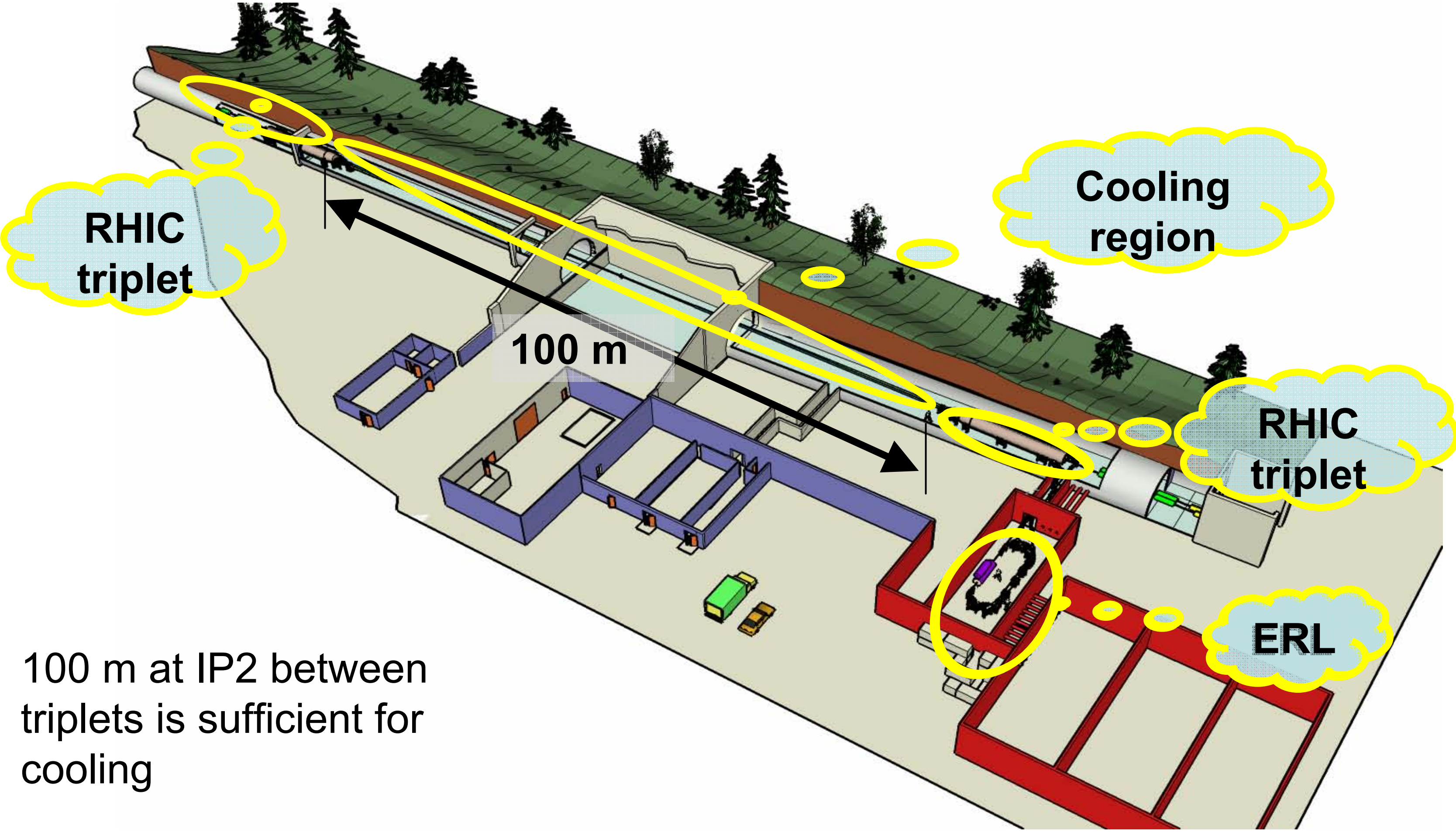




E-cooler ERL matched to RHIC



The RHIC electron cooler at IP2.



100 m at IP2 between triplets is sufficient for cooling

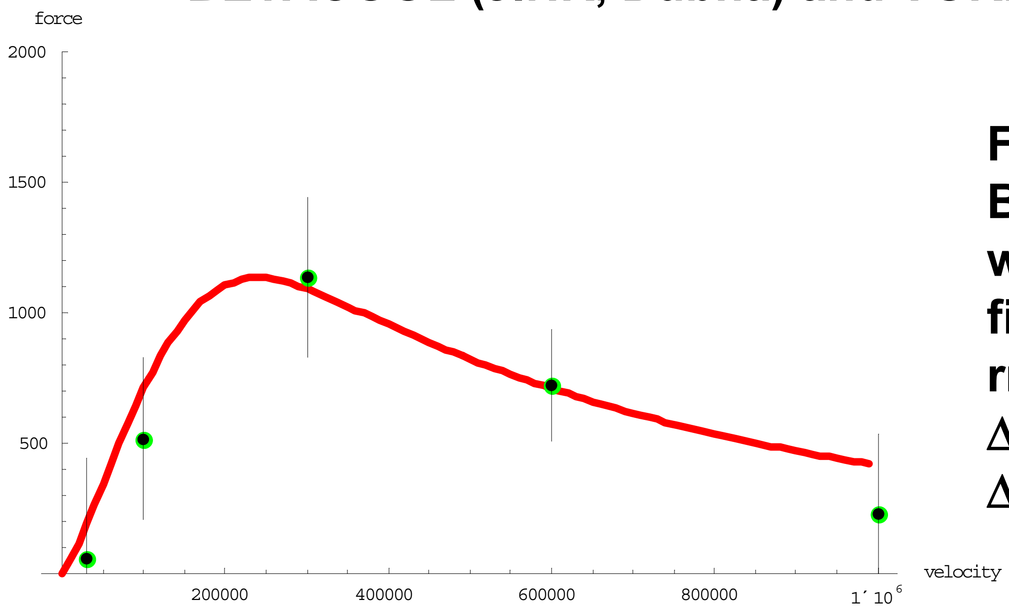
R&D issues

- Understanding the cooling physics in a new regime to reduce uncertainty
  - cooling dynamics simulations with some precision
    - **IBS**, recombination, disintegration
    - benchmarking experiments
    - stability issues
- Developing a high current, energetic, low emittance electron beam
  - Photoinjector (inc. photocathode, laser, etc.) 5 nC, 4μm
  - Energy Recovery Linac, at x10 of state-of-the-art current
    - Preservation of high-charge, low emittance beam
    - Wakes, CSR, space-charge

The cooling “friction” force and dynamics of cooling

$$\vec{F} = -\frac{4\pi n_e e^4 Z^2}{m} \int L \frac{\vec{V}_i - \vec{v}_e}{\left|\vec{V}_i - \vec{v}_e\right|^3} f(v_e) d^3 v_e$$

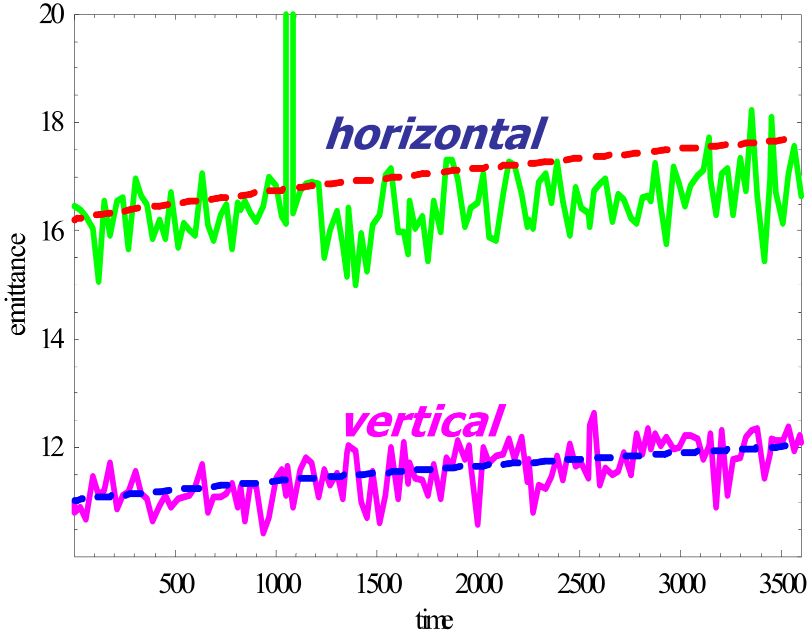
BETACOOL (JINR, Dubna) and VORPAL (Tech-X, Colorado)



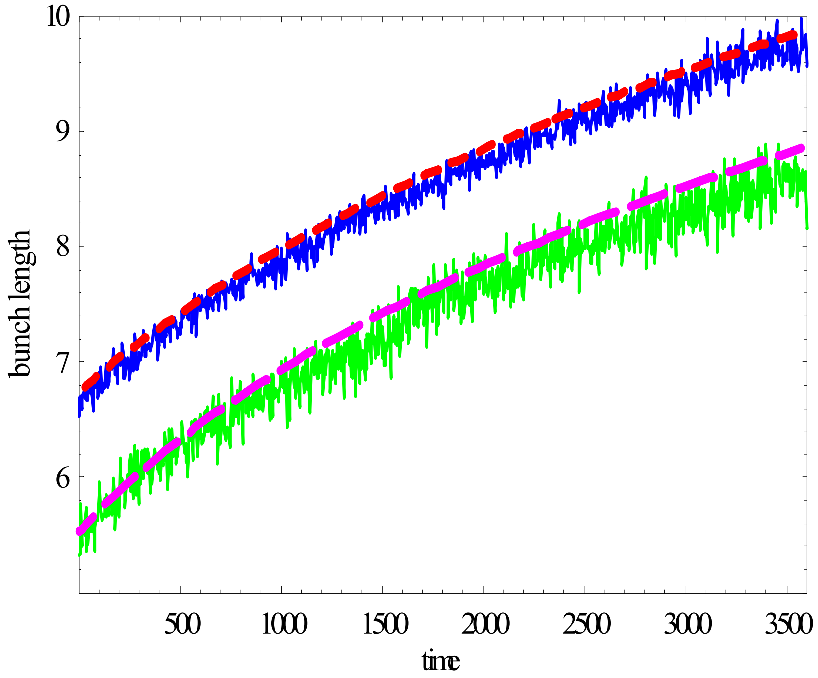
Formula integration in BETACOOL compared with VORPAL simulation from first principles.
rms electron velocities
Δ|| = 1.0e5 m/s
Δ⊥ = 4.2e5 m/s

IBS in RHIC – measurements vs. theory Example of 2005 data with Cu ions.

Simulations – Martini's model of IBS for exact designed lattice of RHIC, including derivatives of the lattice functions.



Growth of 95% normalized emittance [μm] for bunch with intensity N=2.9·10^9



FWHM [ns] bunch length growth for intensities N=2.9·10^9 and 1.4·10^9

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Experimental benchmarking: using Recycler (FNAL) E-cooling

FNAL uses classical electron cooling (the weak solenoid is used only for guiding the electron beam)

FNAL e-cooling allows us to:

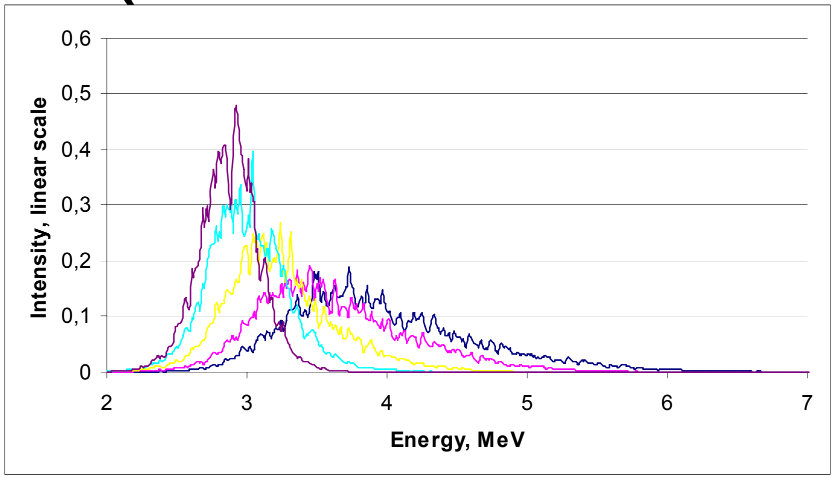
1. Benchmark the models for the friction force
2. Study evolution of ion distribution under cooling
3. Study electron cooling together with stochastic cooling
4. See presentations by the FNAL team:
    1. TUPCH098 D. Broemmelsiek et al, Antiproton Momentum Distributions as a Measure of Electron Cooling Force at the Fermilab Recycler
    2. TUPLS007 S. Nagaitsev et al, Fermilab Recycler Performance with a Dual Cooling System
    3. TUPLS069 A. Shemyakin et al, Performance of Fermilab's 4.3 MeV Electron Cooler

Benchmarking of distribution evolution (500 mA, 2 keV HV step)

FNAL

Measurement 10/31/05

L. Prost

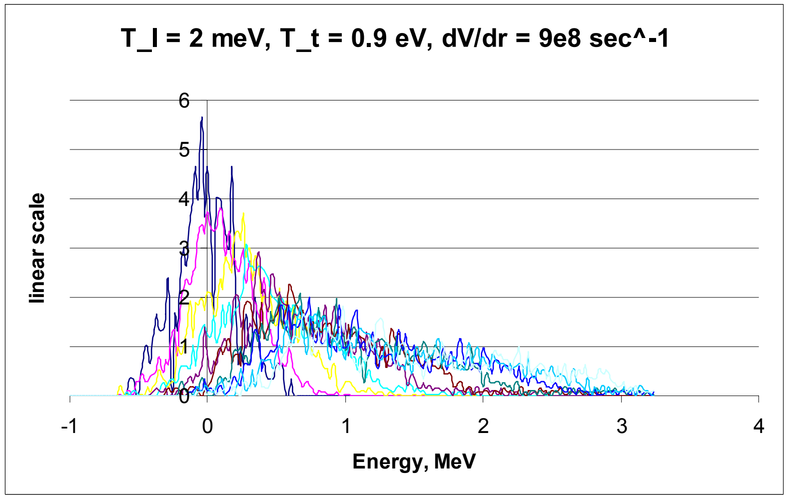


BETACOOL

Simulation

12/03/05

A. Sidorin

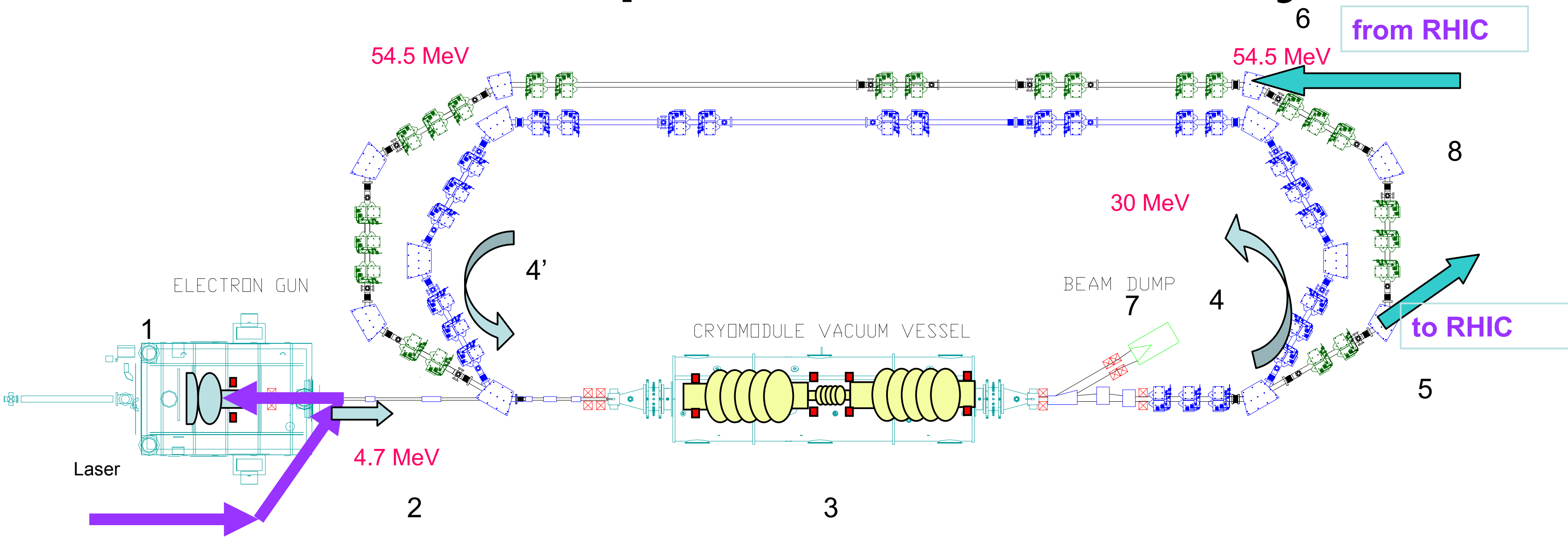


Beam dynamics of the RHIC e-cooling injector

Requirements:

- RF frequency: 703.5 MHz
- Charge: 5 nC/bunch
- Emittance: ≤ 4 μm (rms, normalized)
- Repetition frequency: 9.4 MHz
- Average current: ~50 mA
- Energy after gun: 5 MeV
- Energy after ERL: 54 MeV

E-cooler: 2 passes ERL layout



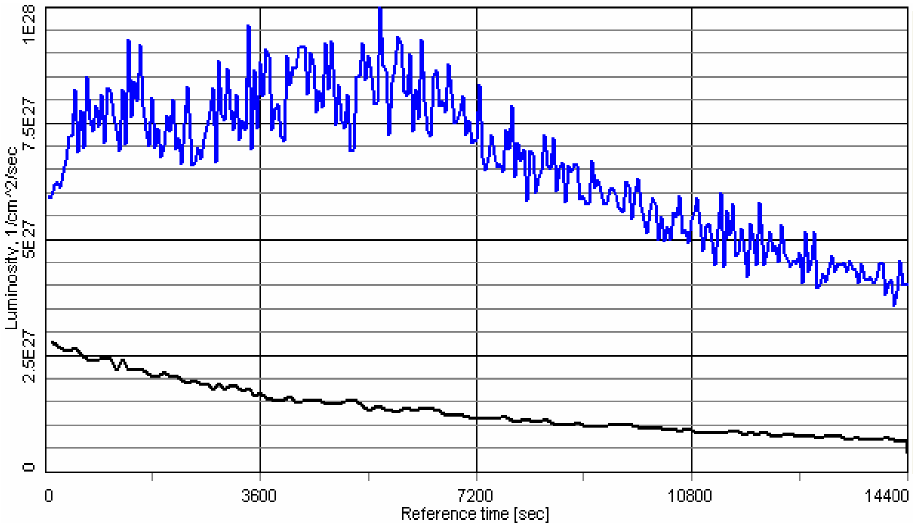
1. SRF Gun,
2. Injection merger line
3. SRF Linac two 5-cell cavities and 3rd harmonic cavity

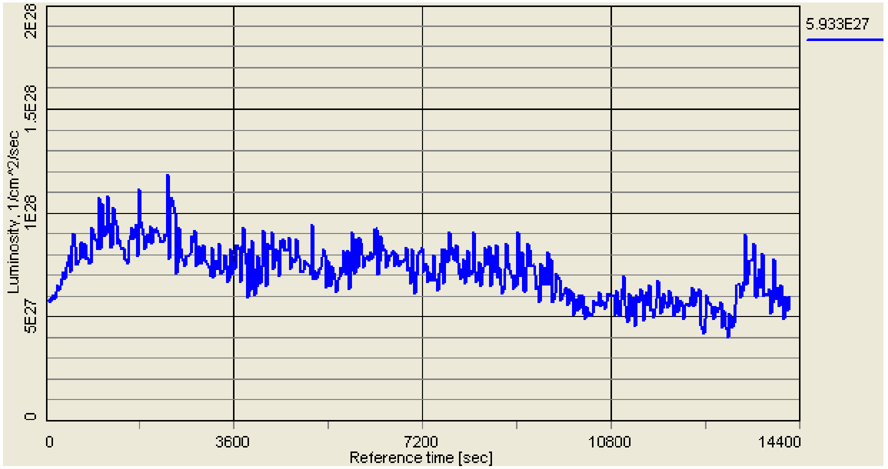
4, 4'. 180° achromatic turns

5, 6. Transport lines to and from RHIC,

7. Ejection line and beam dump
8. Short-cut for independent run of the ERL.

Au ions ($N=10^9$)
Electrons: 5nC, 4 μm emittance



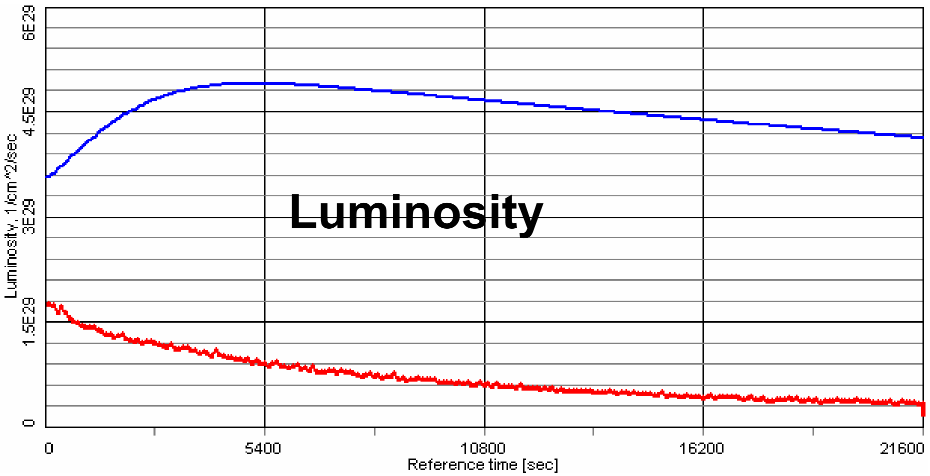


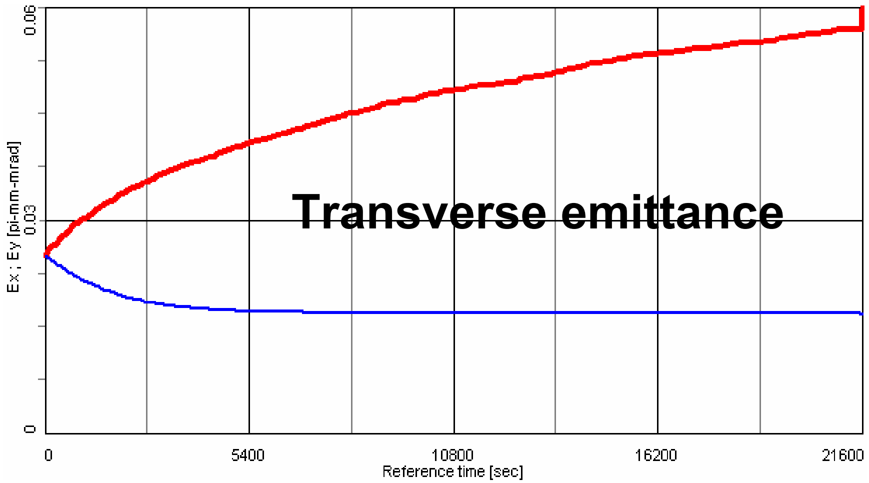
Luminosity with and without cooling (modeled beam approach) over 4 hours

Same as on left, but with (coarse) control of cooling rate

$\langle L \rangle = 6.9 \times 10^{27}$

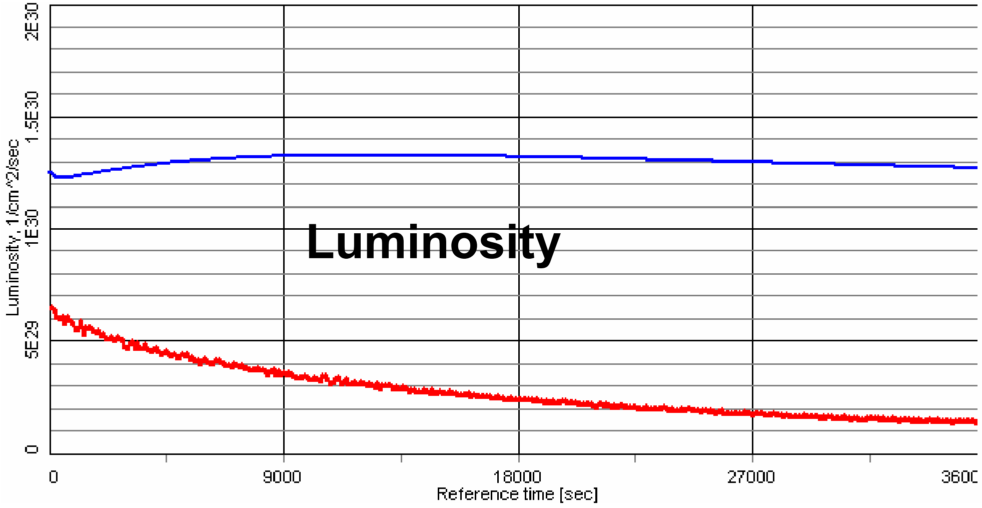
N=8x10^9 Cu ions with and without cooling

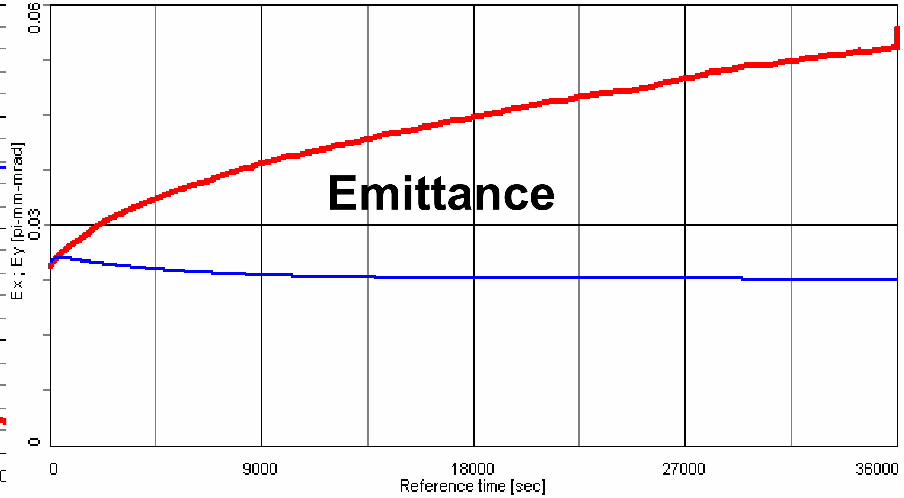




Electron beam 8nC,
4 μm emittance,
6 hour store:
<L> (cooling)/<L>(without)=6.4

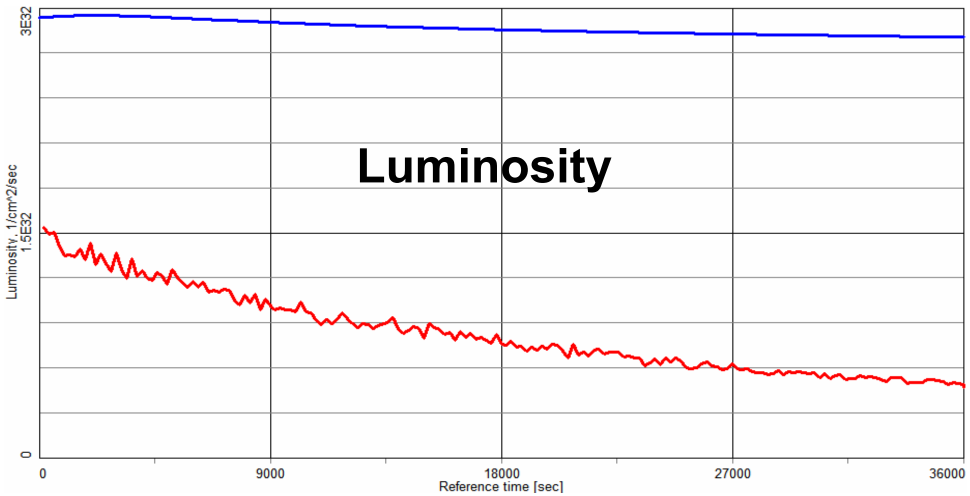
$N=1.5x10^{10}$ Si ions – Luminosity with and without cooling

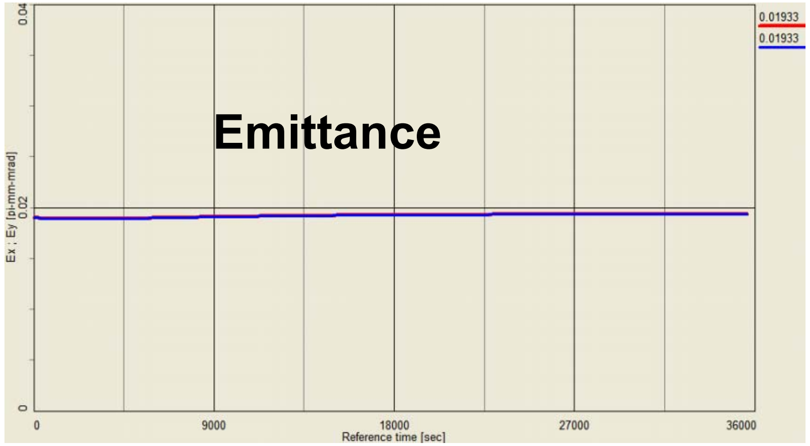




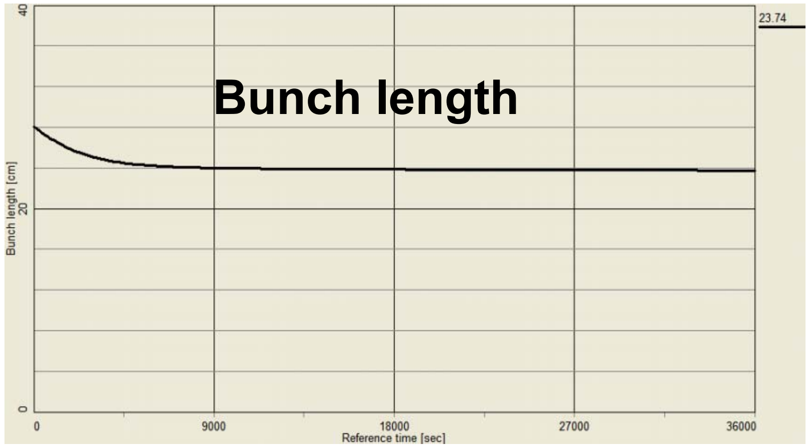
<L>(w/cooling)/<L>(without)=5,
during 10 hour store

P @100 GeV emittance w/ cooling Electron beam 5 nC 4μm





Cooling protons at 100GeV with initial 95% normalized emittance 12 um.
<L> (w/cooling)/<L> (without)=3.5, during 10 hour store

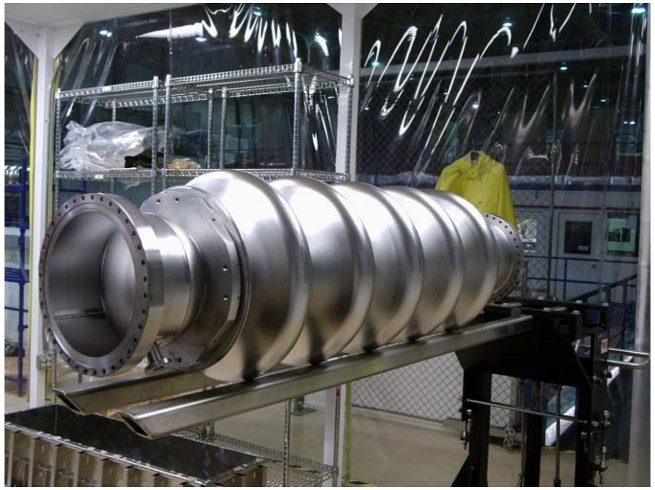


Hardware development

- Photocathodes, including diamond amplified photocathodes
- Superconducting RF gun
- Energy Recovery Linac (ERL) cavity
- New optical elements (merger)
- Full ERL demonstration

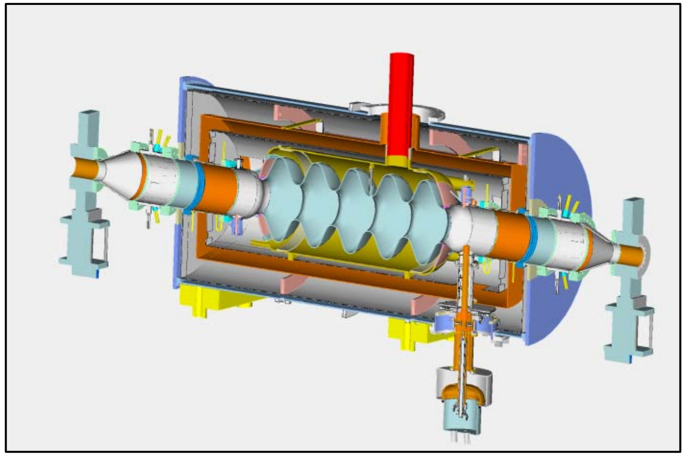
BNL ERL original developments

SRF ERL cavity for ampere-class current.

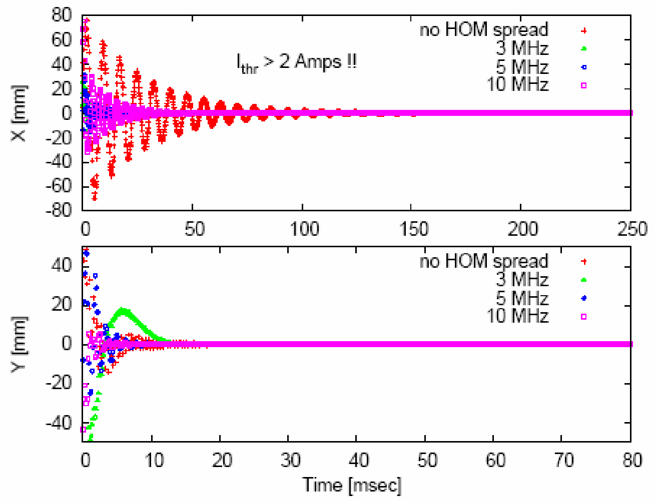


"Single mode":
All HOMs damped.

Multi ampere rating.



TDBBU



Advanced Energy Systems, Inc.

RHIC

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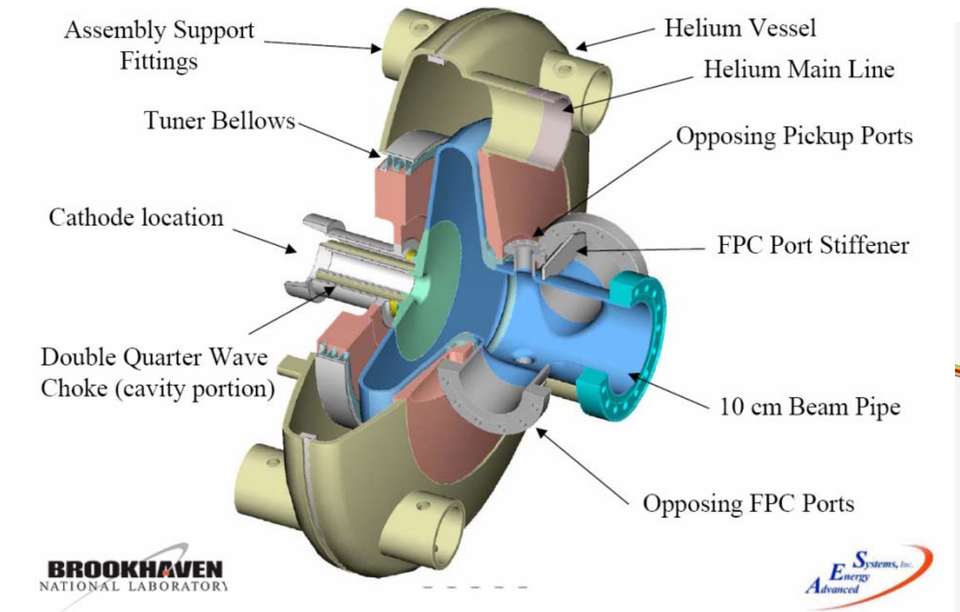
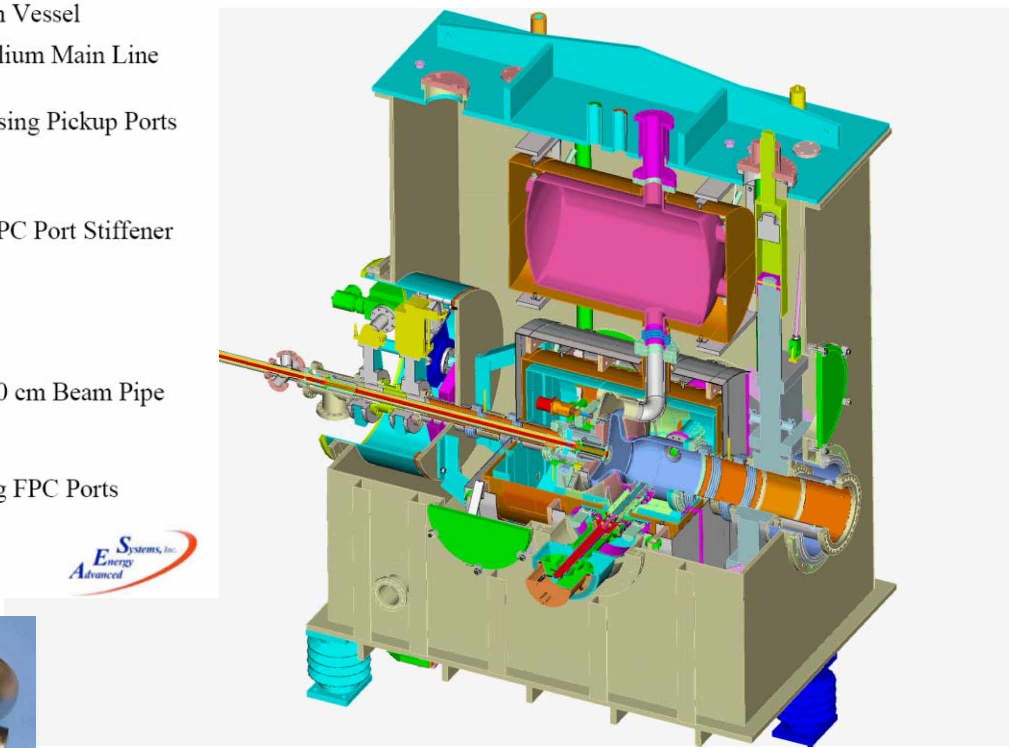
BNL ERL original developments

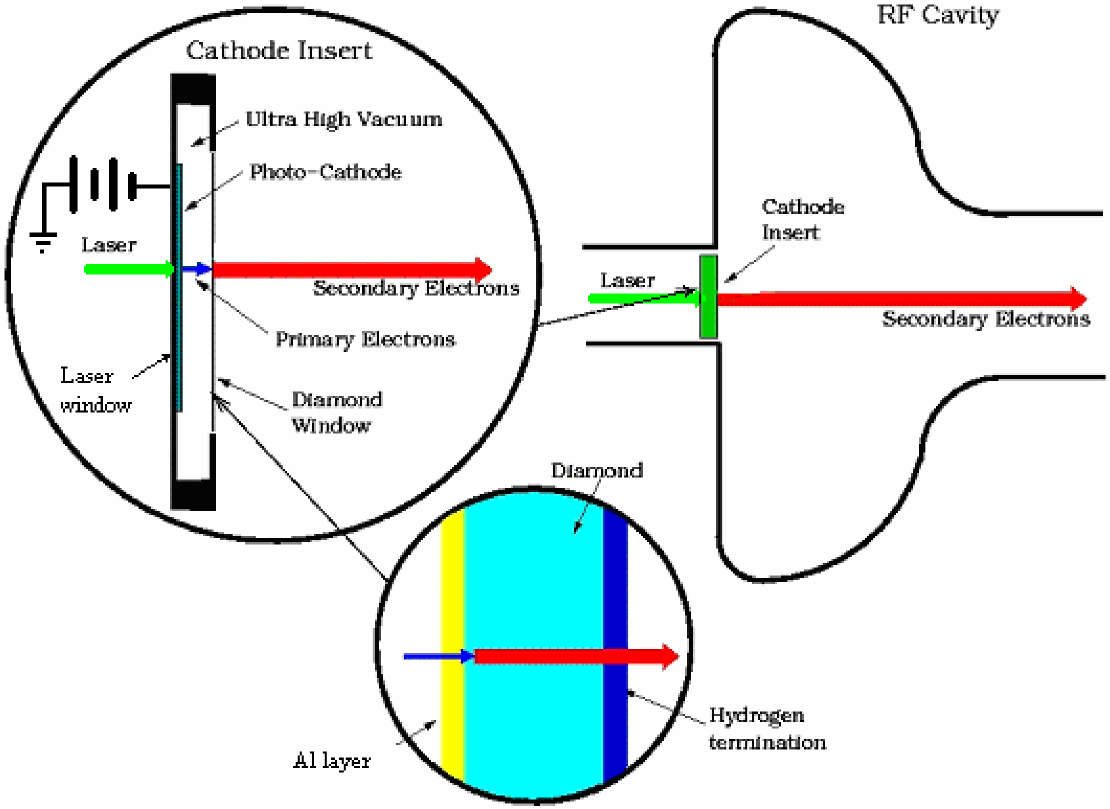
Ampere-class superconducting RF gun

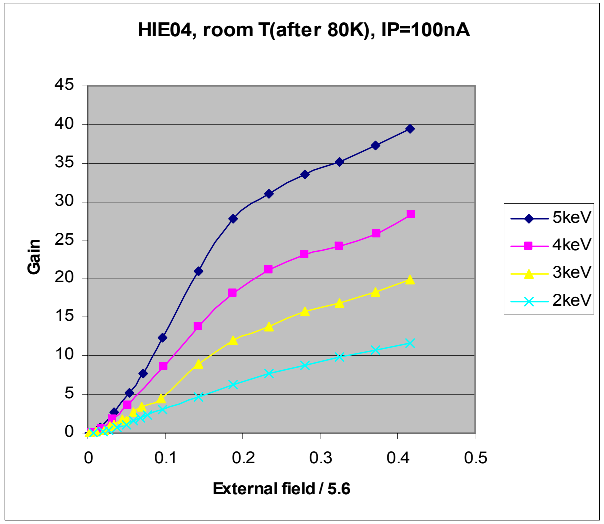




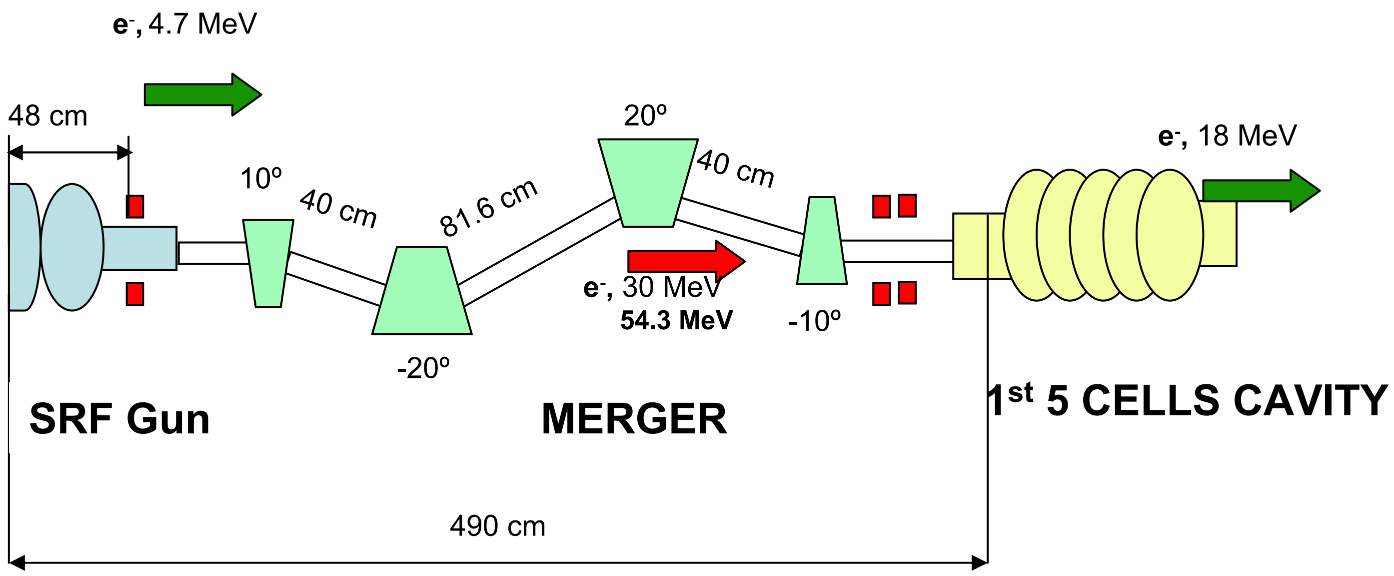
BNL ERL original developments

Diamond amplified photocathode

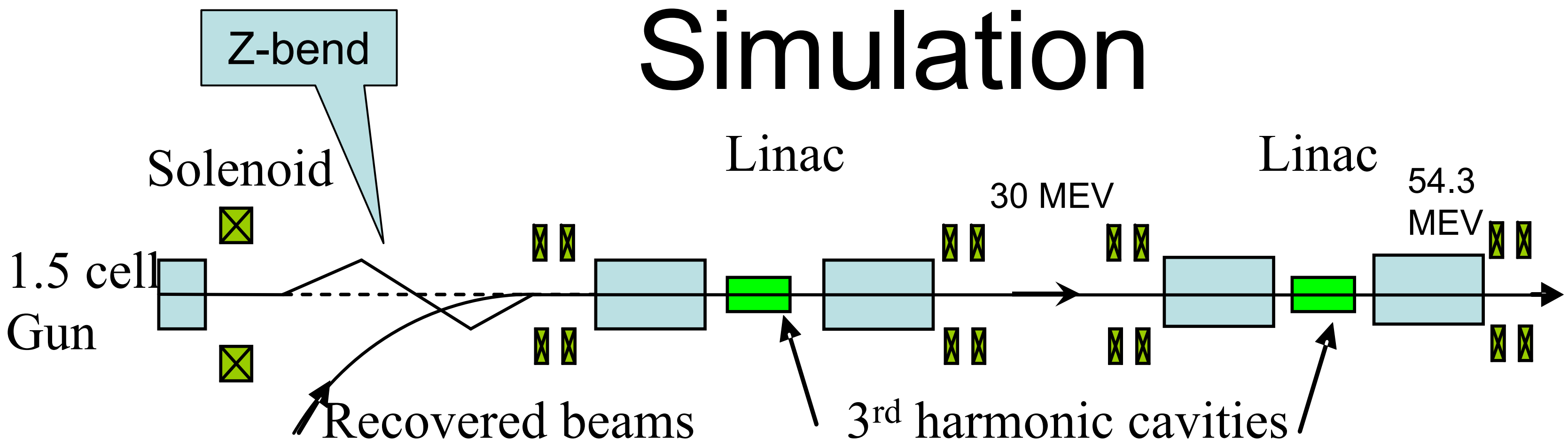


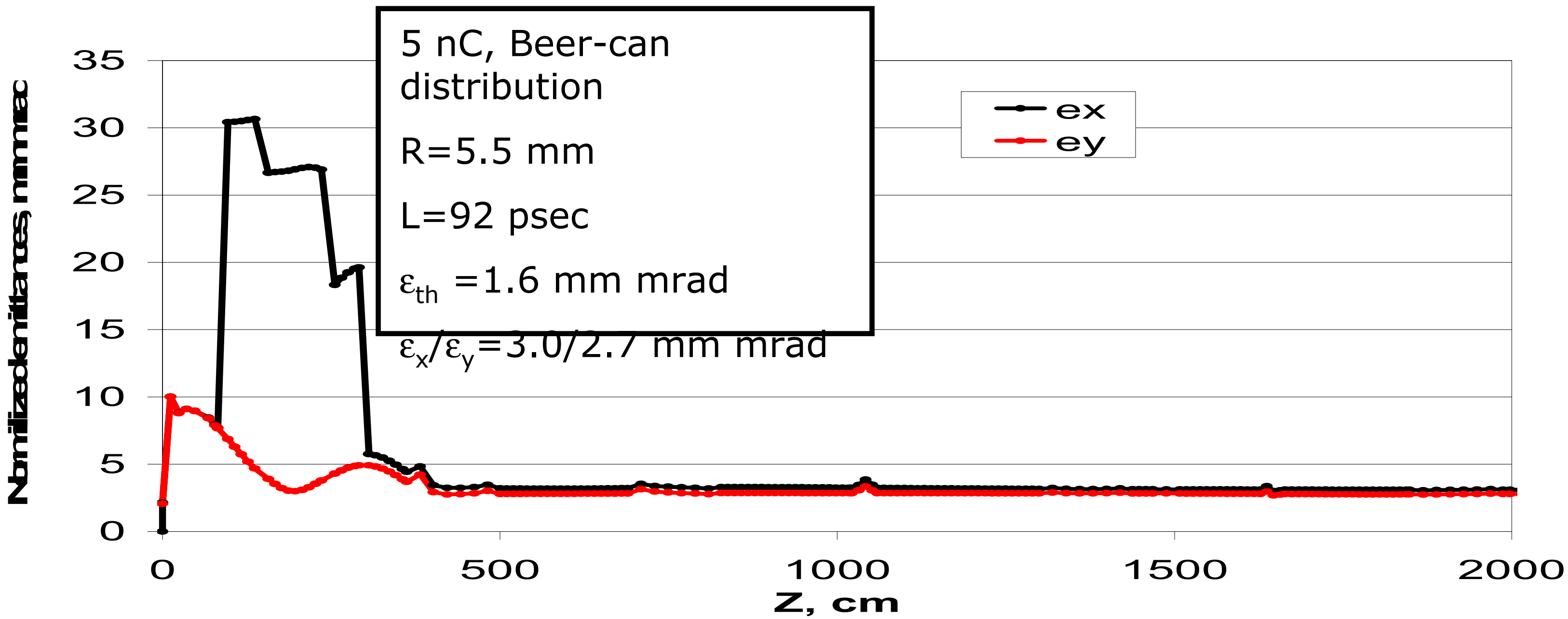


BNL ERL original developments Vertical Z-bend injection

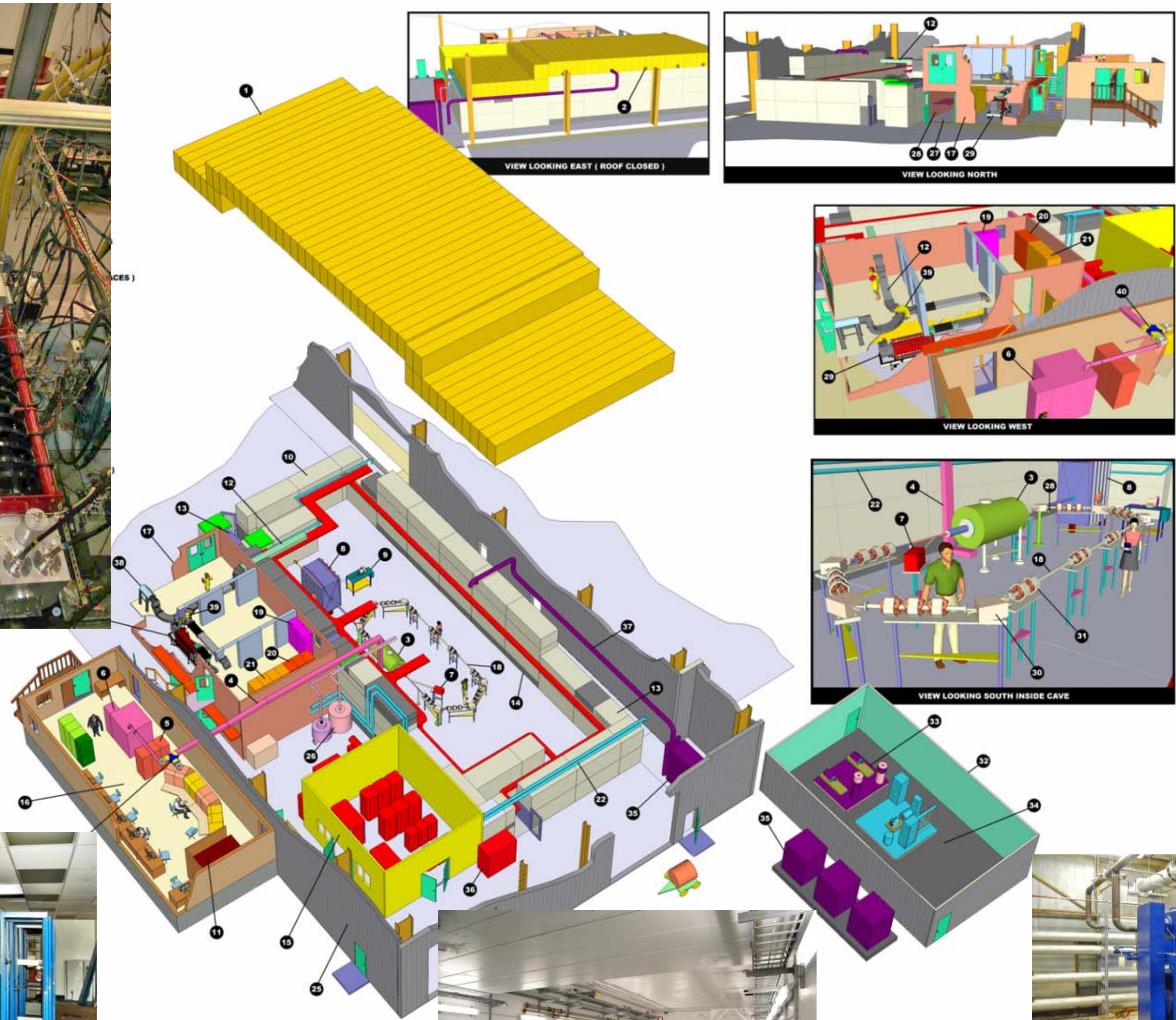


Simulation


Z-bend
Solenoid
1.5 cell
Gun
Linac
30 MEV
Linac
54.3
MEV
Recovered beams
3rd harmonic cavities


5 nC, Beer-can
distribution
R=5.5 mm
L=92 psec
ε_{th} =1.6 mm mrad
$\varepsilon_x/\varepsilon_y$=3.0/2.7 mm mrad
ex
ey
35
30
25
20
15
10
5
0
0
500
1000
1500
2000
Z, cm

R&D ERL: To be completed 2008



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Thank you for your attention