High-current ERL-based electron cooling system for RHIC

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The objectives and challenges

- Increase RHIC luminosity: For Au-Au at 100 GeV/A by ~10, from ~7 10^{26}.
- Cool polarized p at injection.
- Reduce background due to beam loss
- Allow smaller vertex

- Cooling rate slows in proportion to $\gamma^{7/2}$.
- Energy of electrons 54 MeV, well above DC accelerators, requires bunched e.
- Need exceptionally high electron bunch charge and low emittance.

R&D issues: Theory

- A good estimate of the luminosity gain is essential.
- We must understand cooling physics in a new regime:
  - understanding IBS, recombination, disintegration
  - binary collision simulations for benchmarking

Detailed Studies of Electron Cooling Friction Force, A. Fedotov, yesterday

Simulations of dynamical friction including spatially-varying magnetic fields, D. Bruhwiler, yesterday

  - cooling dynamics simulations with some precision

Numerical results of beam dynamics simulation using BETACOOL code, A.V. Smirnov et al, poster

  - benchmarking experiments

Experimental Benchmarking of the Magnetized Friction Force, A. Fedotov et al, today

  - stability issues

Coherent Dipole Instability In RHIC Electron Cooling Section, G. Wang, poster

R&D issues: Electron beam

- Developing a high current, energetic, magnetized, cold electron beam. Not done before
  - Photoinjector (inc. photocathode, laser, etc.)
  - ERL, at high current and very low emittance
  - Diagnostics

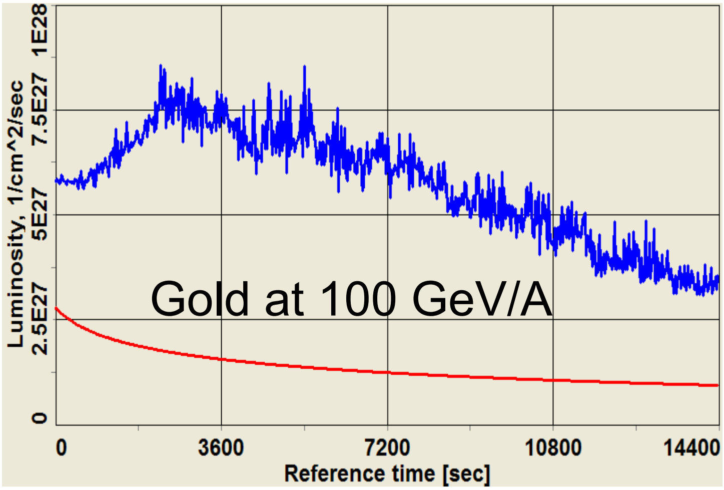
Diagnostics for the Brookhaven Energy Recovery Linac, P. Cameron, poster

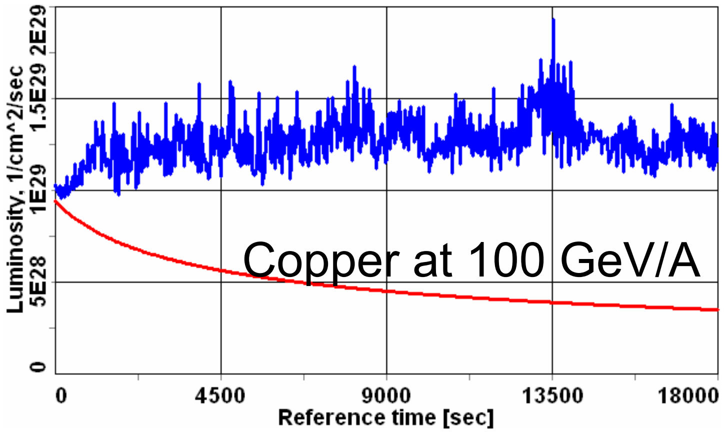
  - Beam dynamics issues

Magnetized e-cooling of RHIC

"COOLING DYNAMICS STUDIES AND SCENARIOS FOR THE RHIC COOLER", "SIMULATIONS OF HIGH-ENERGY ELECTRON COOLING", A. Fedotov et al, proceedings PAC'05,

- An order of magnitude luminosity increase (from 7×10^{26} to about 7×10^{27}) can be achieved for various ion species and at various energies
- Solenoids=2x40=80m, B=5T, electrons q=20nC, emittance 50μm, energy spread 3×10^{-4}.
- The integrated luminosity under cooling is calculated from the percentage of the beam burned during 4 hours, for 3 IPs, 112 bunches, beta*=0.5 meters
- The limitation may be either beam disintegration (gold) or beam-beam parameter (copper).

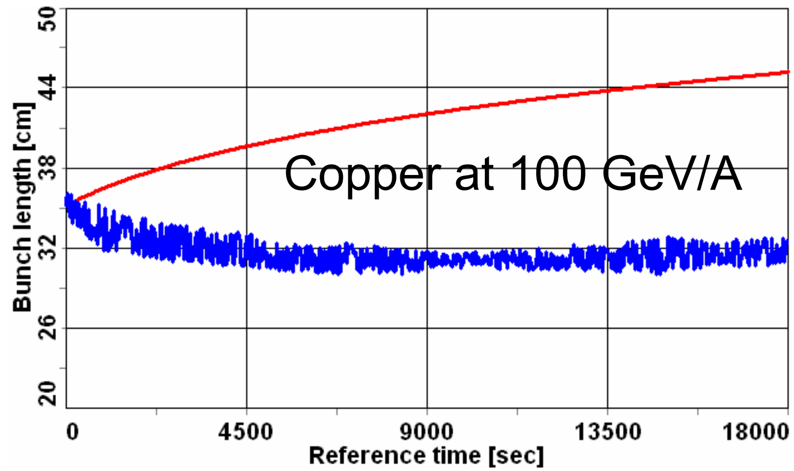


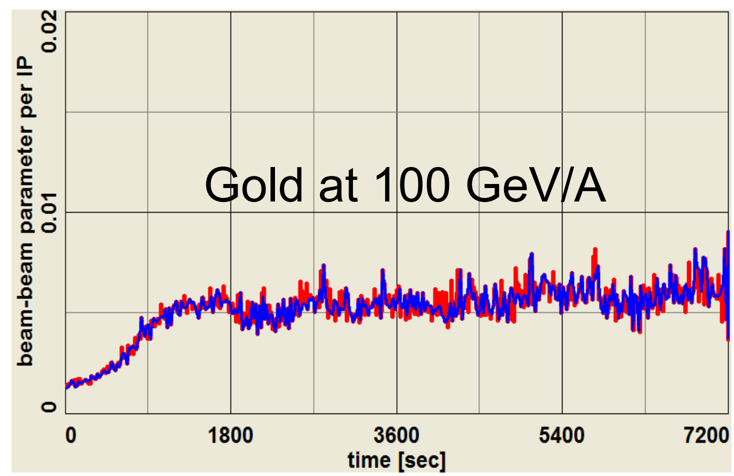


Luminosities per IP in $cm^{-2}sec^{-1}$ vs. time in seconds

Beam-beam, bunch length

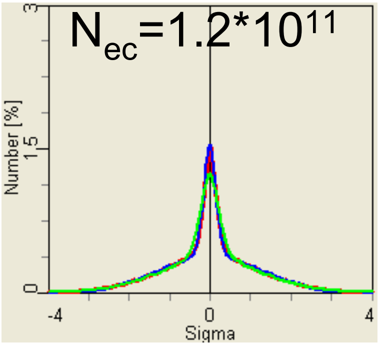
- The bunch length and beam-beam parameter can be controlled.
- Cooling can be done also below the critical number.

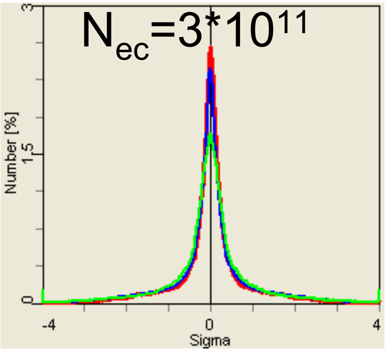




Challenge in the electron beam

- Magnetized cooling is not easy:
- Total solenoid length 30 to 60 m.
- Solenoid error limits benefits!
- The electron beam is very challenging: 20 nC with strong magnetization (2 T mm^2 to 5 T mm^2)

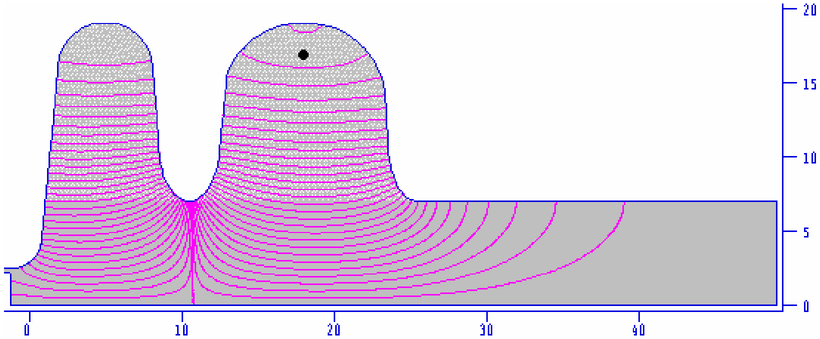




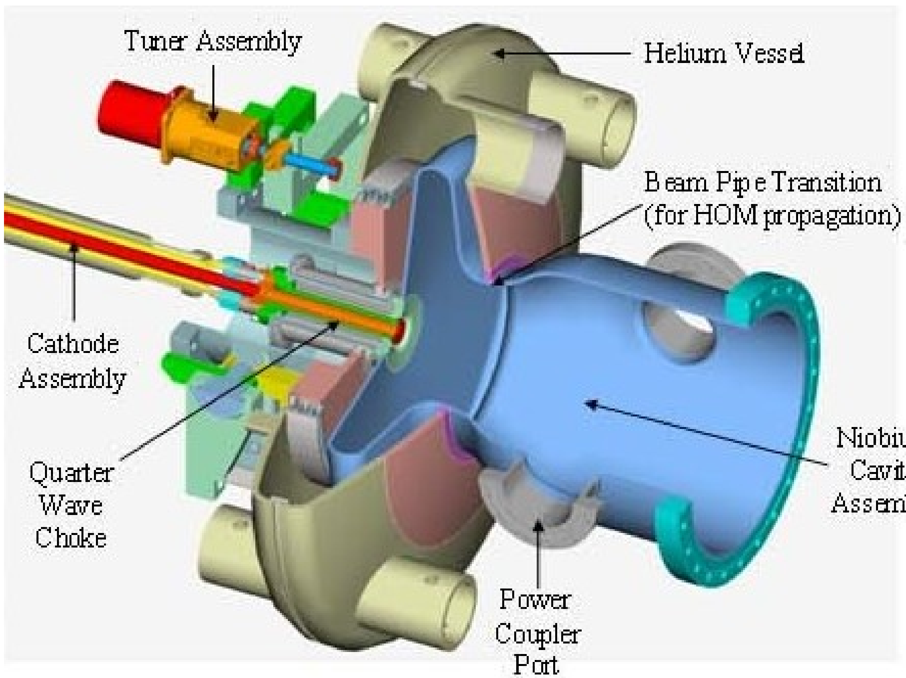
$$N_{ec} \approx \frac{r_i}{r_e}\frac{N_i}{\eta}\frac{\Lambda_{ibs}}{\Lambda_c}\frac{1}{g_f}, \qquad g_f = \left(\frac{v_{longitud.}}{v_{tranverse}}\right)^2 = \frac{\sigma_p^2}{\gamma^2(\varepsilon/\beta_a)}.$$

Taking the following parameters of RHIC: $N_i=10^9$, $\eta=0.0078$, $\Lambda_{ibs}=20$, $g_f=0.2$, and assuming that the cooler will have magnetized cooling logarithm $\Lambda_c=2$ one gets critical number of electrons about $N_{ec}=1\text{-}3*10^{11}$, depending on expressions Used to describe IBS and friction force.

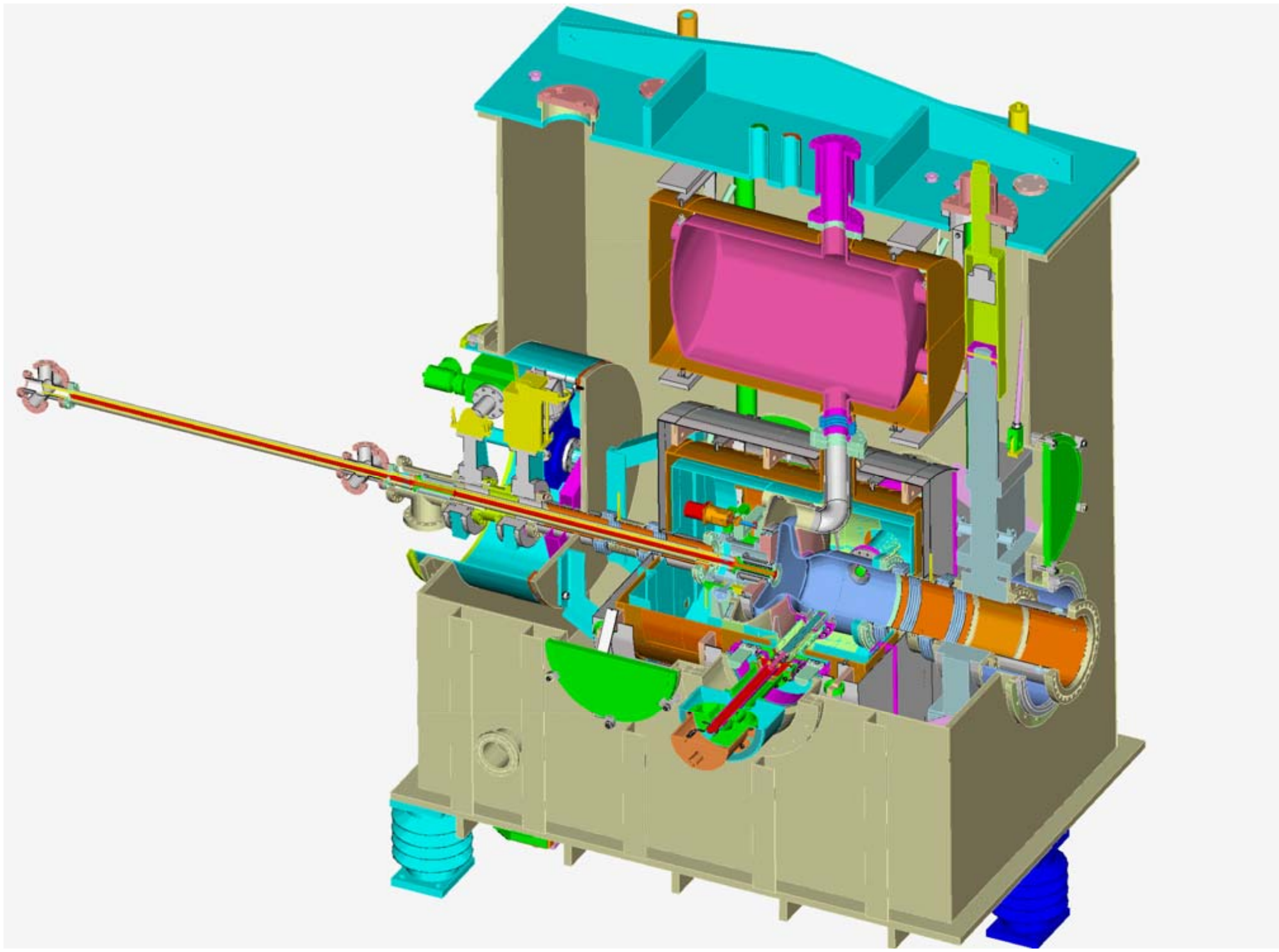
Laser photocathode RF gun: Key to performance



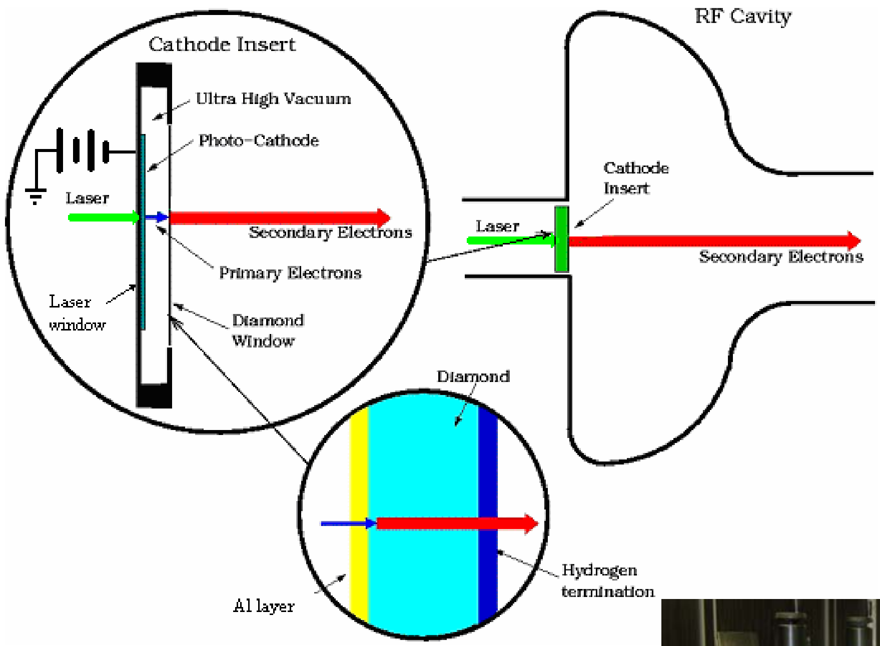
Left: 1 ½ cell gun designed for cooler.
Below: ½ cell gun prototype which is
Under construction.

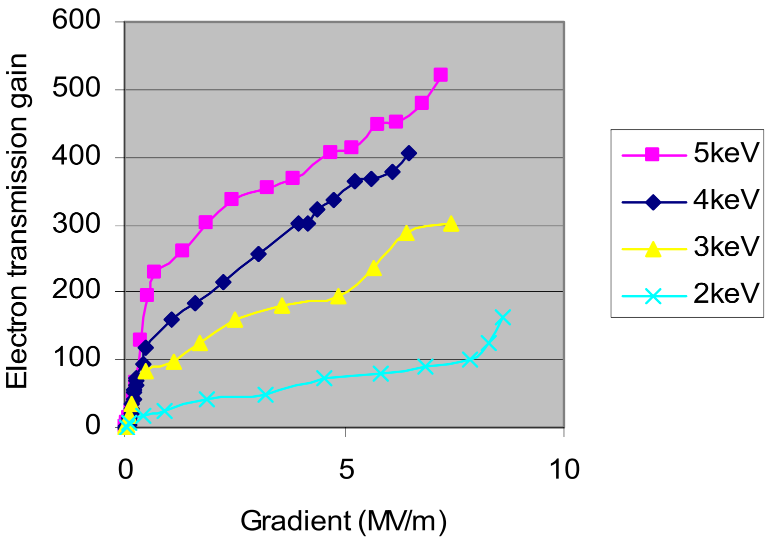


Ampere-class SRF gun



Diamond amplified photocathode

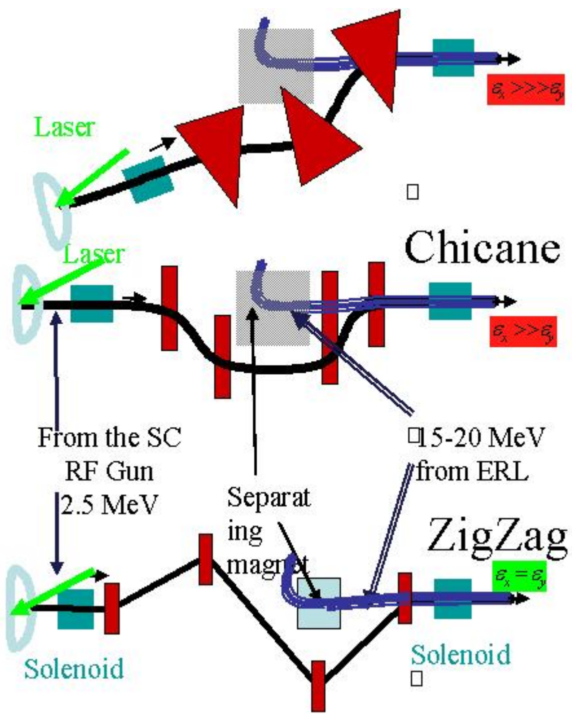


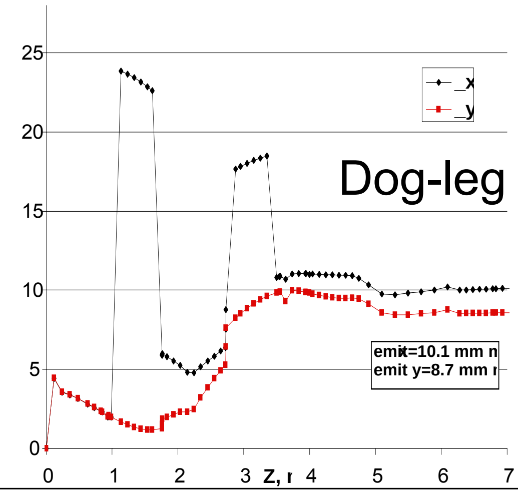


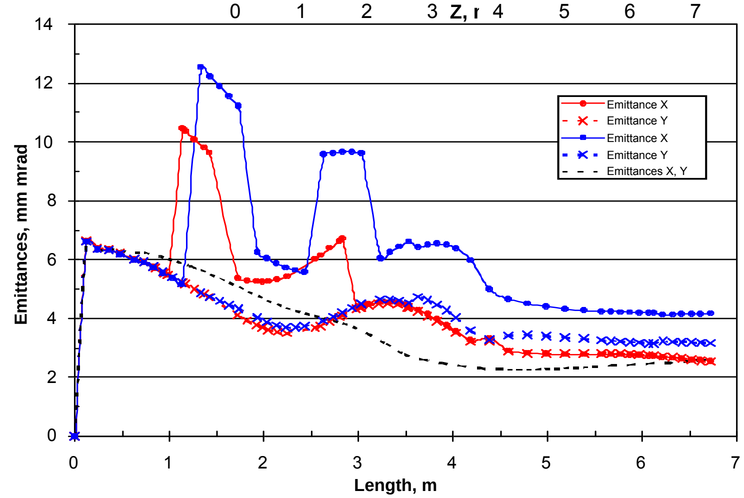
Photocathode fabrication chamber

Z-bend merging optics for ERL: Emittance conserved

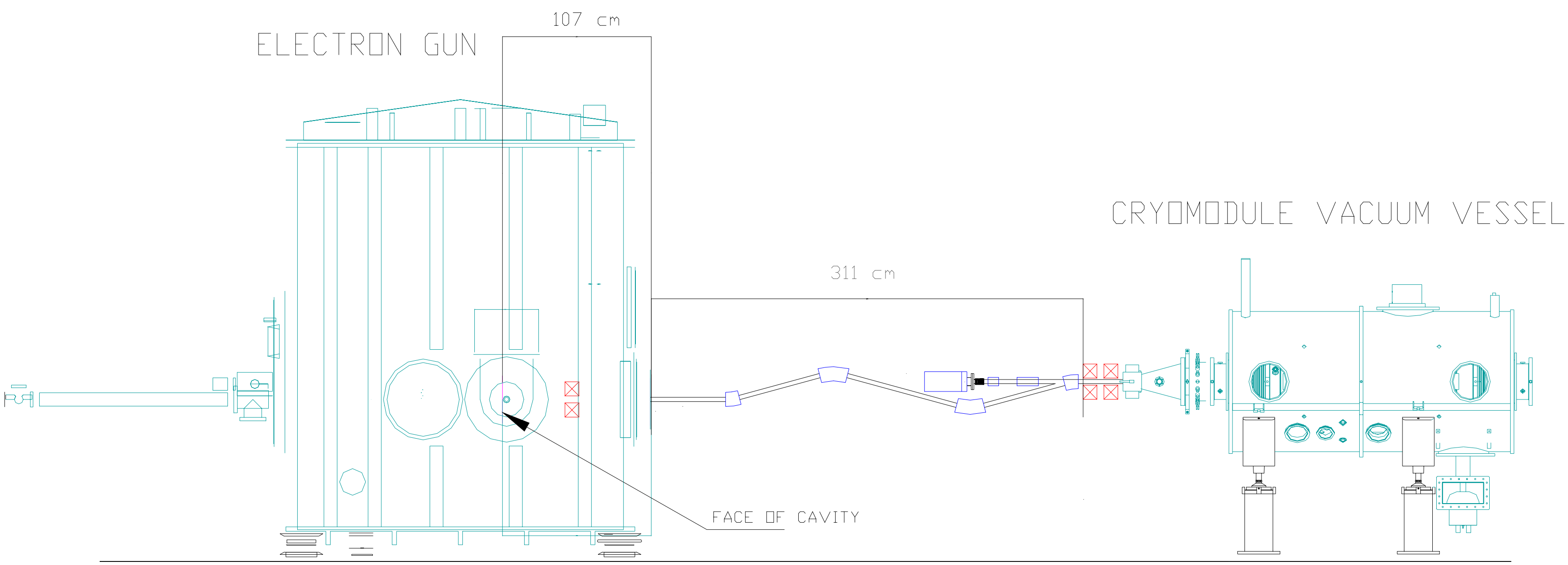
Z-bend compared to dog-leg and chicane:



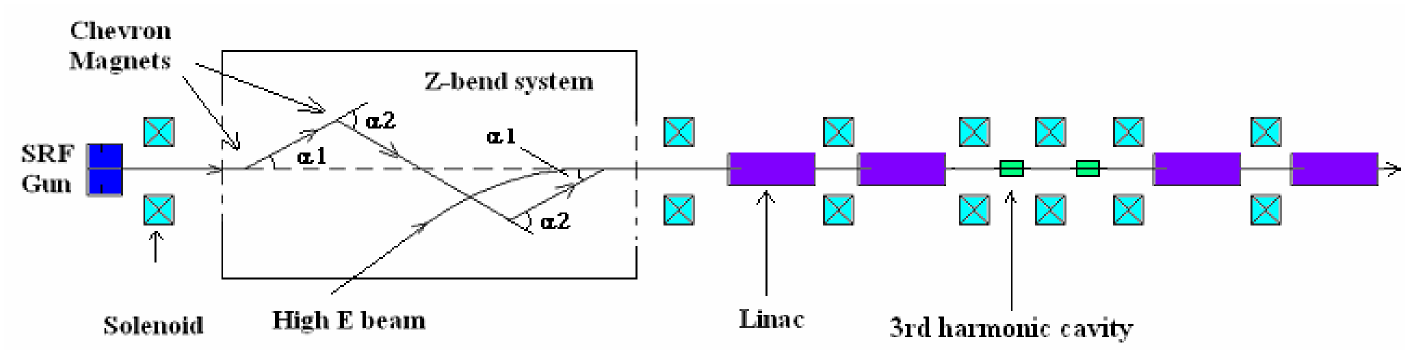


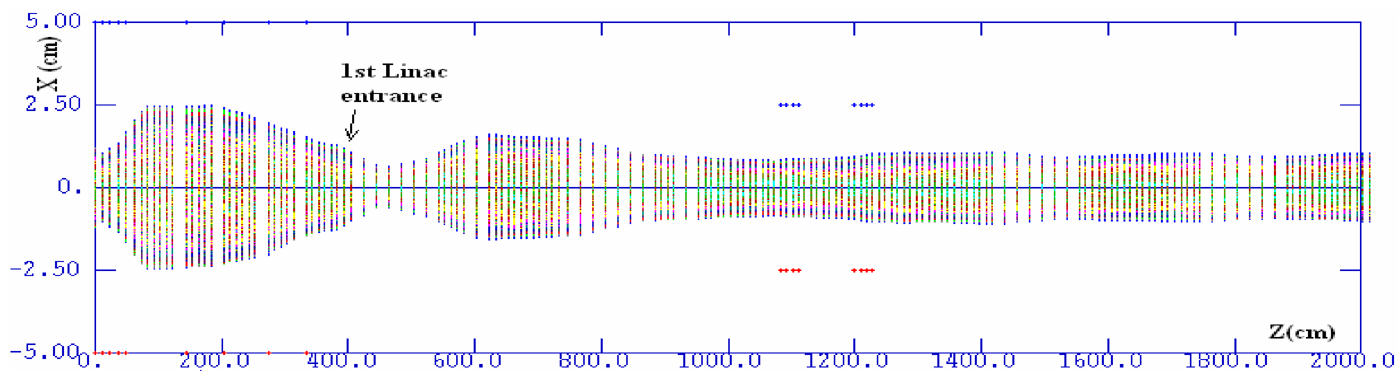


Layout of the injection system



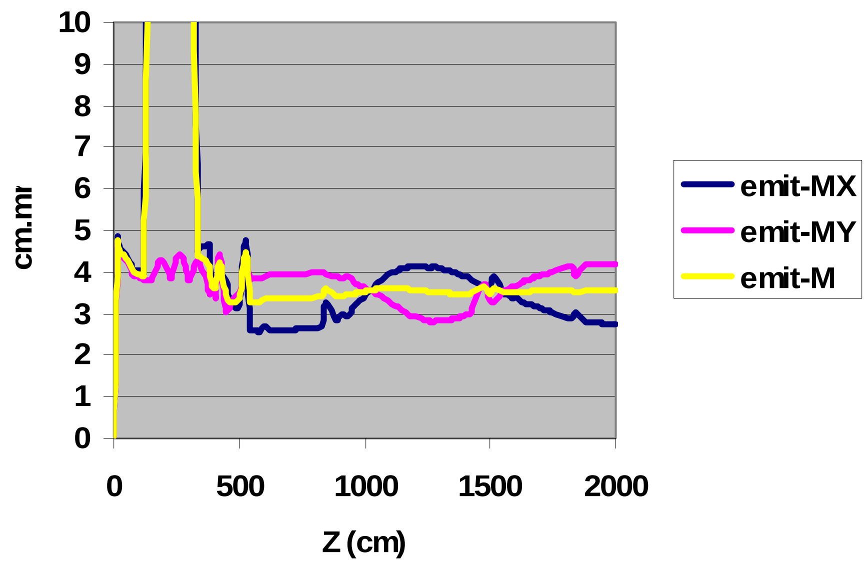
Performance out of linac

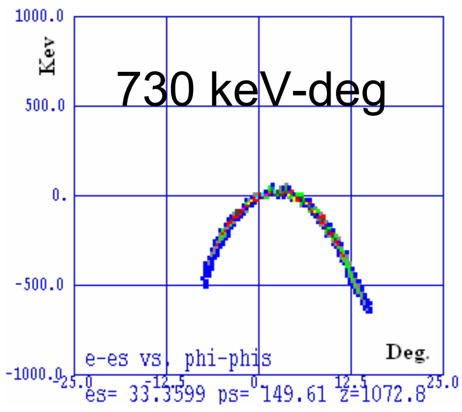


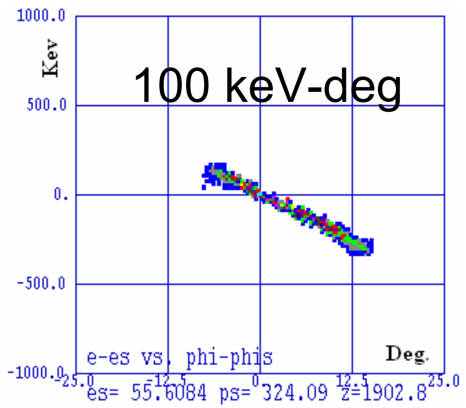


Parameters for magnetized beam

Charge	20nC
Radius (Transverse uniform distribution)	12mm
Magnetization	380mm.mr
Longitudinal Gaussian distribution	4degrees, 16ps
Maximum field on axis of gun cavity	30MV/m
Initial phase	30deg.
Energy at gun exit	4.7MeV
Energy spread at gun exit	rms 1.87%
Bend angle	10degrees
Energy at linac exit	55MeV
Final emittance (normalized rms)	35mm.mr
Final longitudinal emittance	100deg.keV

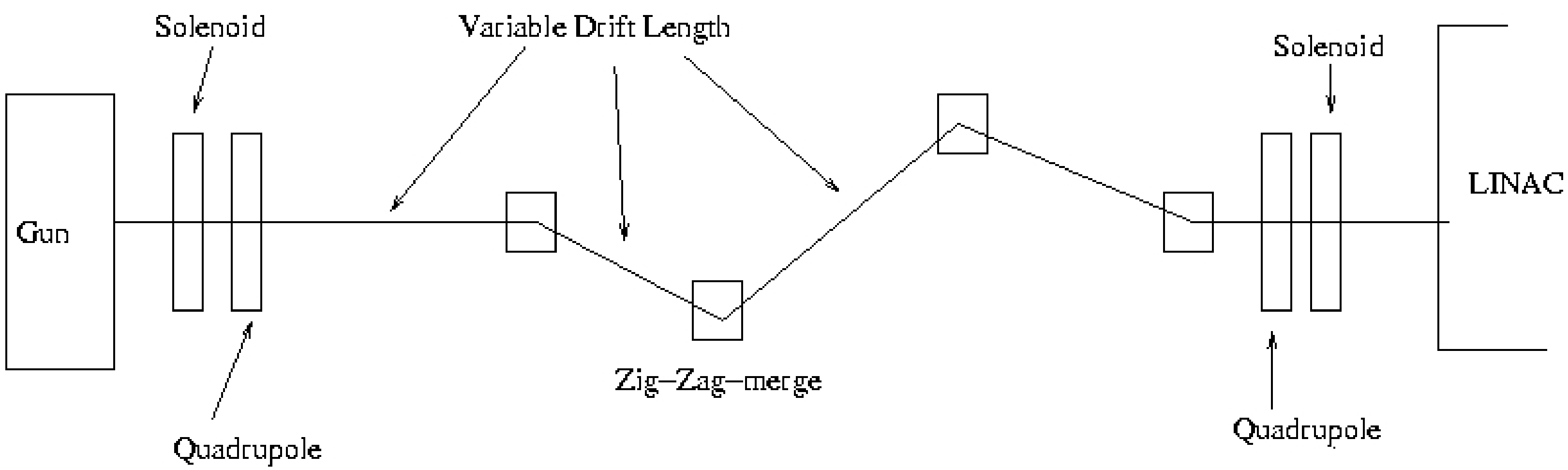






Injector Optimization

- Start point: Beam envelope close to the invariant envelope, chromaticity compensated using time dependent RF fields. 4-D emittance: 35 μm
- C++ Optimizing with 7 parameters uses Powell method or Simplex method and PARMELA. 4-D emittance: 28.5 μm

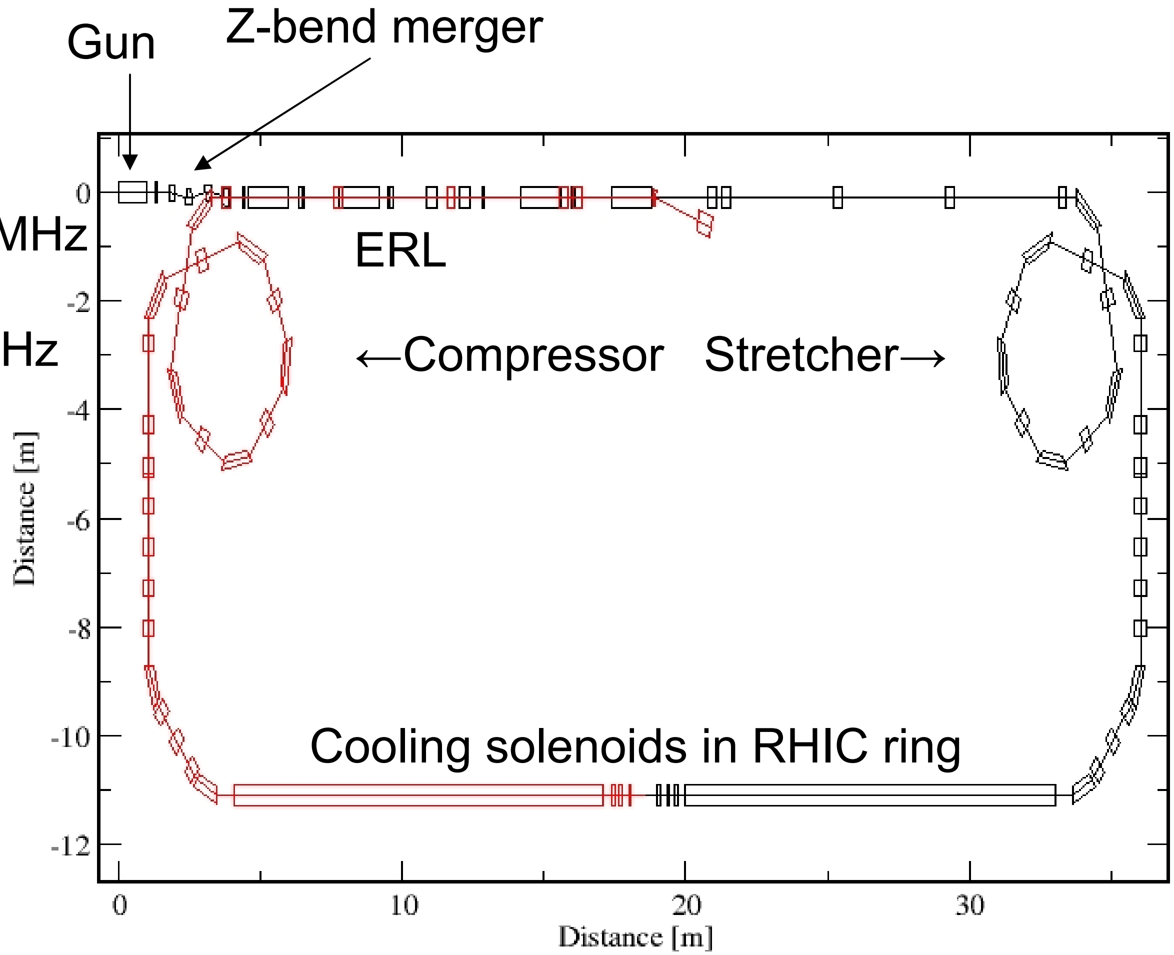


Lattice for magnetized beam

RF frequency: 703.5 MHz
Charge: 20nC/bunch
Repetition rate: 9.4 MHz

$$B_S \sigma_S^2 = 500G\left(10mm\right)^2$$

$$\mathcal{M} \sim 380\text{mm.mr}$$



The possibility of non-magnetized electron cooling for RHIC

- Sufficient cooling rates can be achieved with non-magnetized cooling.
- At high γ, achievable solenoid error limit fast magnetized cooling.
- Recombination is small enough
  - Reduced charge
  - Larger beam size
- Helical undulator can further reduce recombination*

*Suggested by Derbenev, and independently by Litvinenko

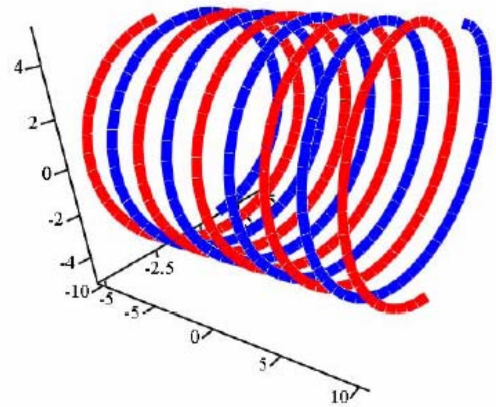
The use of a helical undulator

- Large coherent velocity can be achieved to reduce recombination.
- Small circle radius can be made with low field
- Undulator provides focusing of the electron beam

$$\theta = \frac{K}{\gamma} \approx \frac{93.4 B\lambda}{\gamma}$$

$$r_0 = \frac{\theta\lambda}{2\pi} \qquad L = \ln\frac{\rho_{max}}{r_0}$$

Take λ=5cm, B=20 Gauss, R=5 cm, I=72 Amp
Then r_0=0.7 μm, β_w=180 m



25 hours recombination Lifetime:
More than enough

Non magnetized cooling

Rms momentum spread of electrons =0.1%

Rms normalized emittance: 2.5 microns

Rms radius of electron beam in cooling section: 2 mm

Rms bunch length: 5 cm

Charge per bunch: 5nC

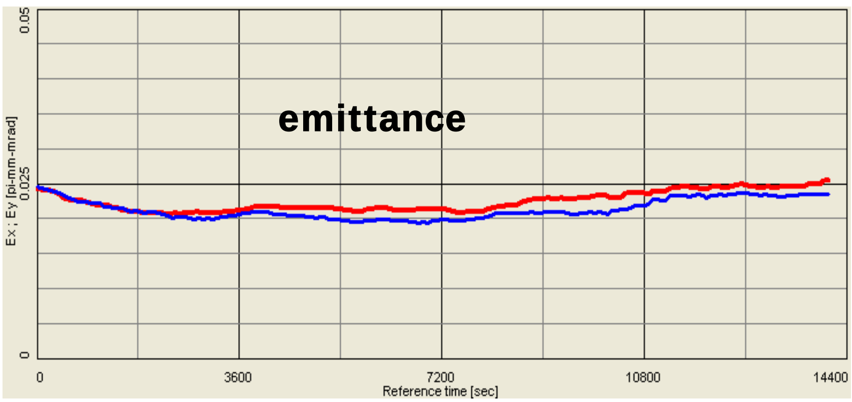
Cooling sections: 2x30 m

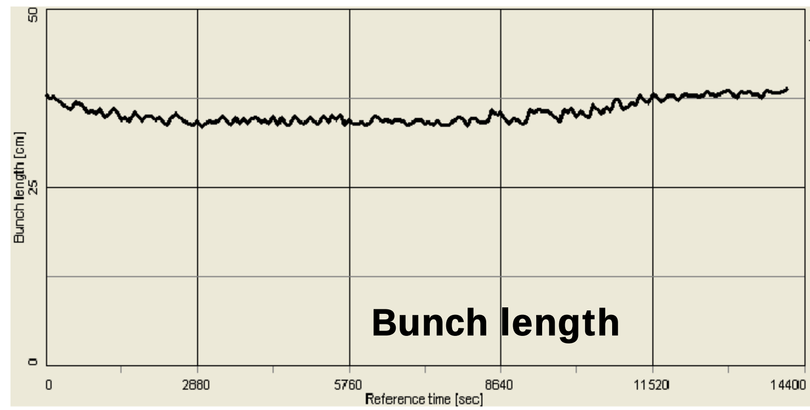
Ion beta-function in cooling section: 200 m

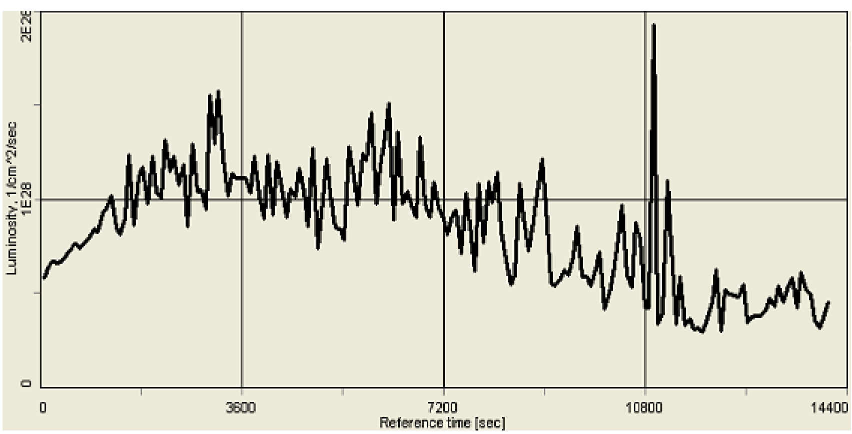
IBS: Martini's model for exact RHIC lattice

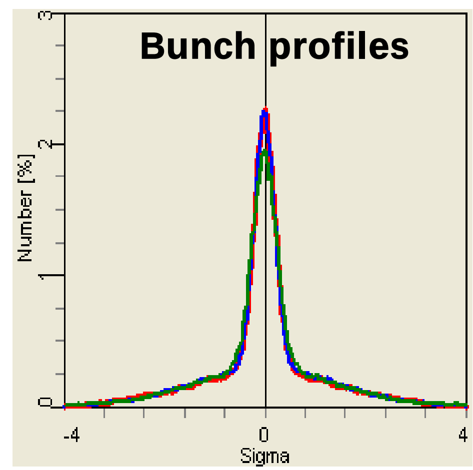
Friction force given by: $$\vec{F} = -\frac{4\pi n_e e^4 Z^2}{m} \int L \frac{\vec{V}_i - \vec{v}_e}{\left|\vec{V}_i - \vec{v}_e\right|^3} f(v_e) d^3 v_e$$

Non-magnetized cooling of gold at 100 GeV/A

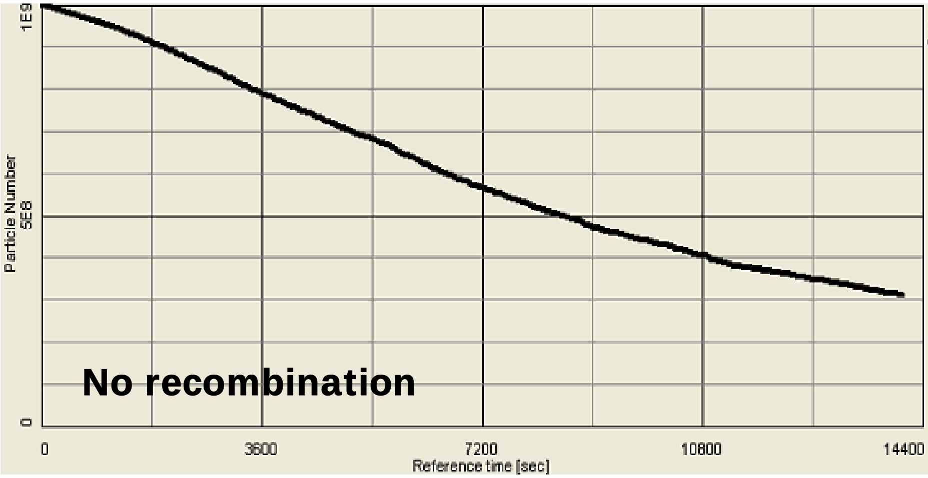


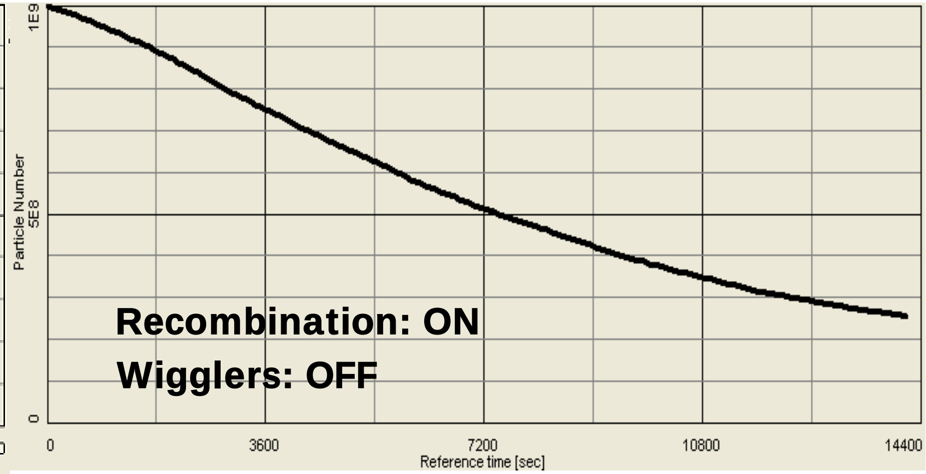


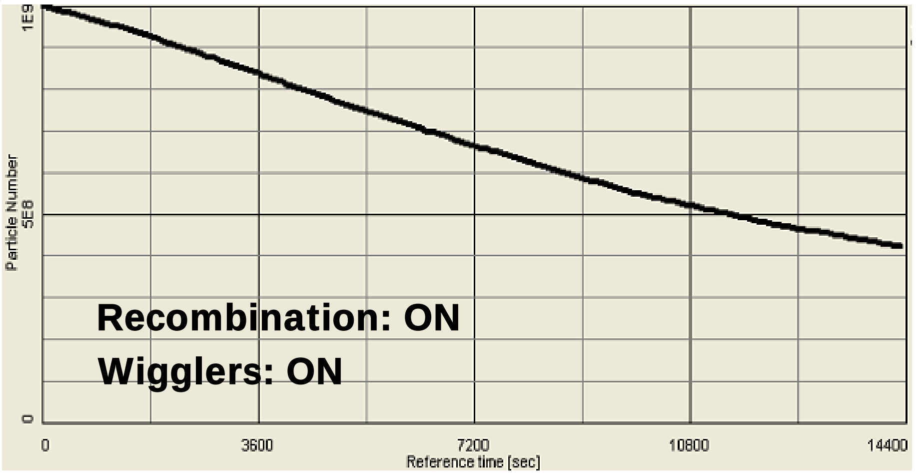




Beam loss

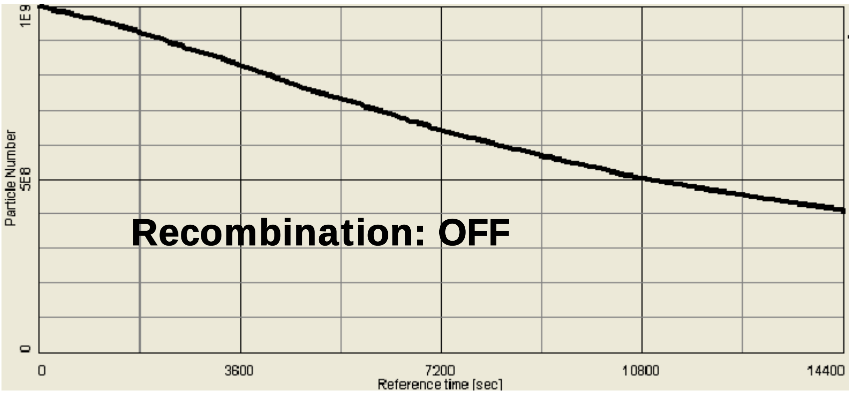


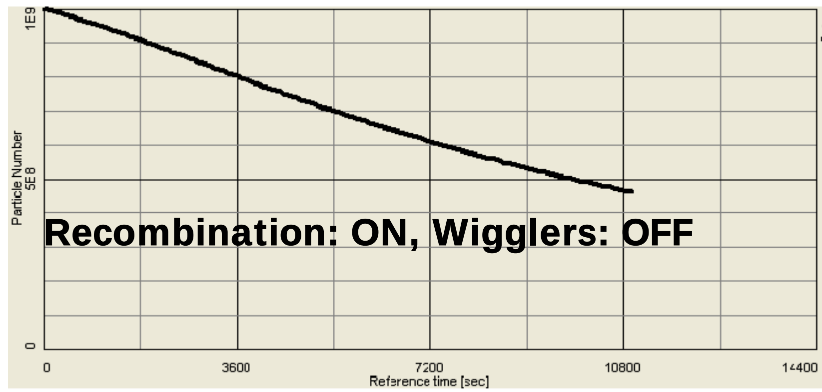


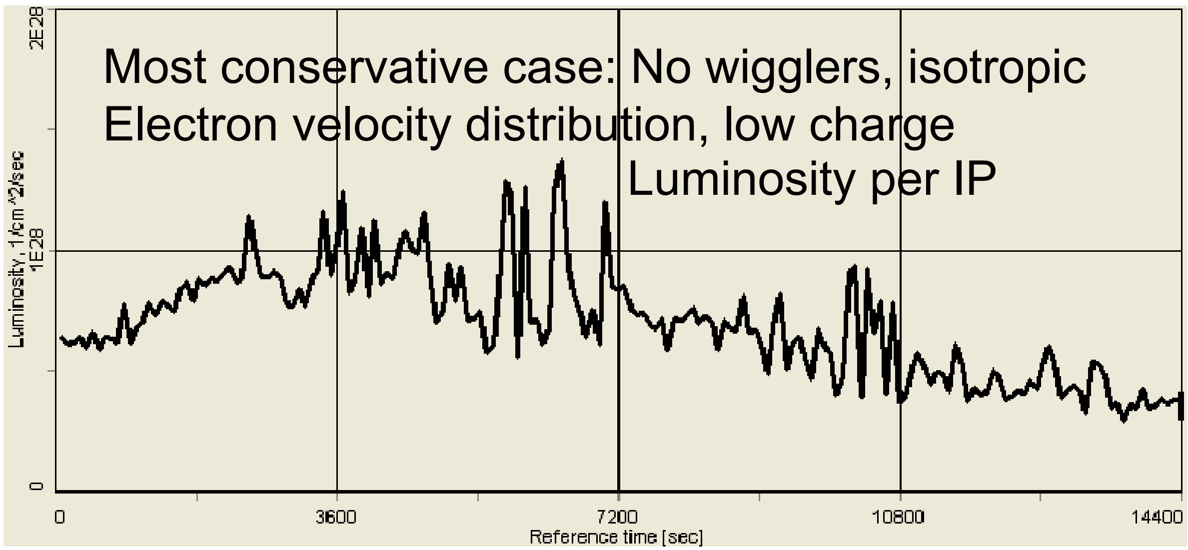


Wiggler parameters:
50 Gauss, 5 cm period,
Radius of rotation 1.7 μm

Cooling at 2.5 nC and 2 μm using isotropic velocity distribution







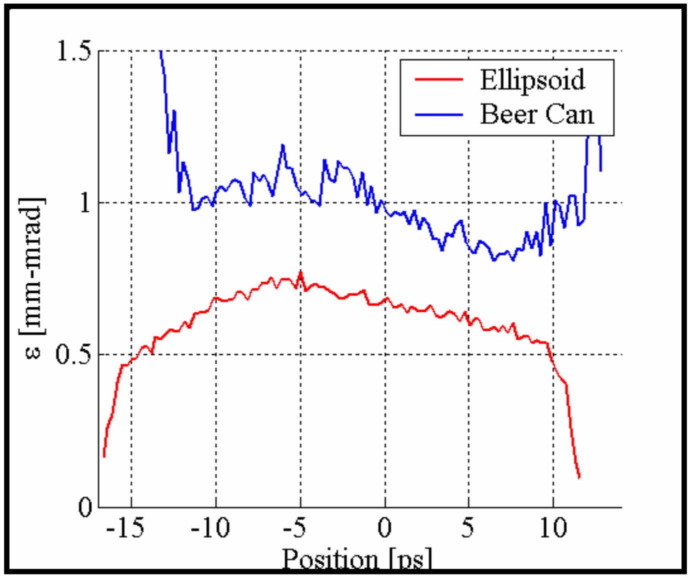
The electron machine R&D

- Beam dynamics
- Photocathodes, including diamond amplified photocathodes
- Superconducting RF gun
- Energy Recovery Linac (ERL) cavity
- ERL demonstration

Ellipsoid bunch shape

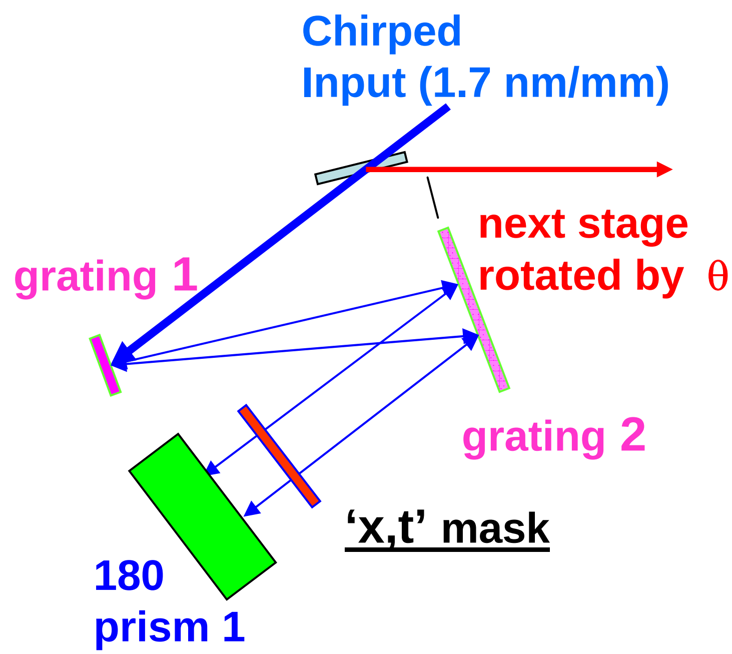
Cecile Limborg-Deprey, Proc. 2005 FEL Conference.

TTF2 gun: 40 MV/m , 1nC ,
$\varepsilon_{thermal}$ = 0.43 mm-mrad /mm



$\varepsilon_{projected}$ = 1.13 mm-mrad
$\varepsilon_{projected}$ = 0.67 mm-mrad

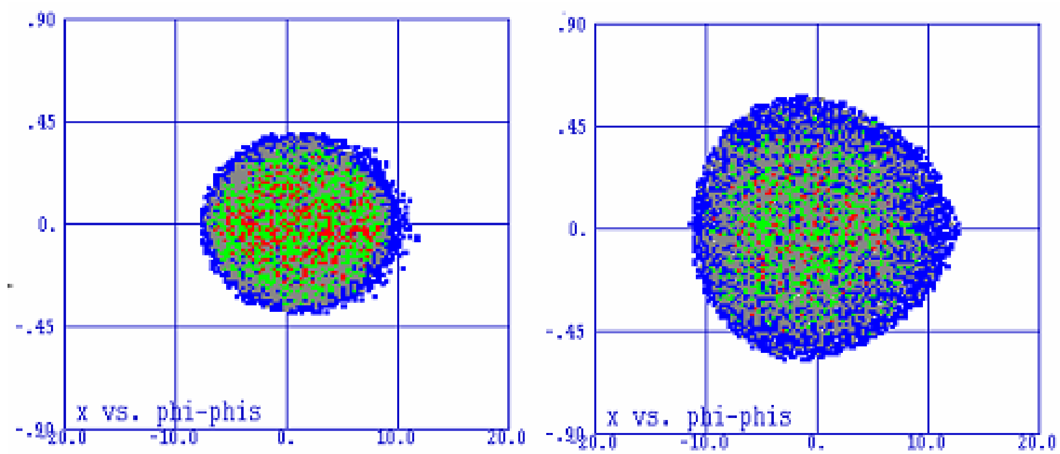
Elliptic bunch generating stage



2 stages OK, 4 very good.

Non-magnetized beam

- The combined use of ellipsoid bunch, high electric field and no magnetization results a good emittance



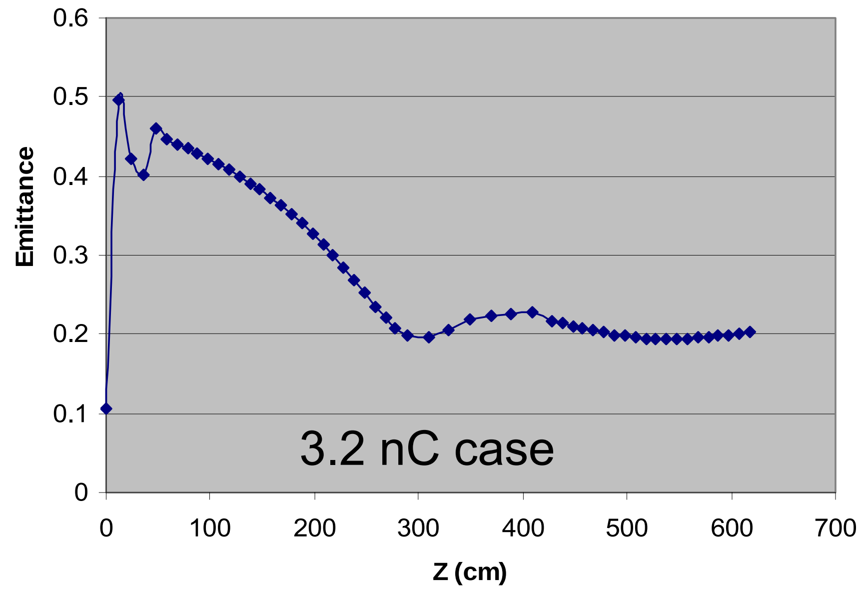
Laser profile on cathode and bunch out of cathode

Charge/bunch (nC)	Maximum radius (mm)	rms radius (mm)
2.5	4	1.77
3.2	4	1.77
5	6	2.65

Bunch length: 16degrees (63ps) from head to tail.
Lunch phase: about 35deg.
Maximum field on axis: 30MV/m
Energy out of gun 4.7 MeV

Emittance results

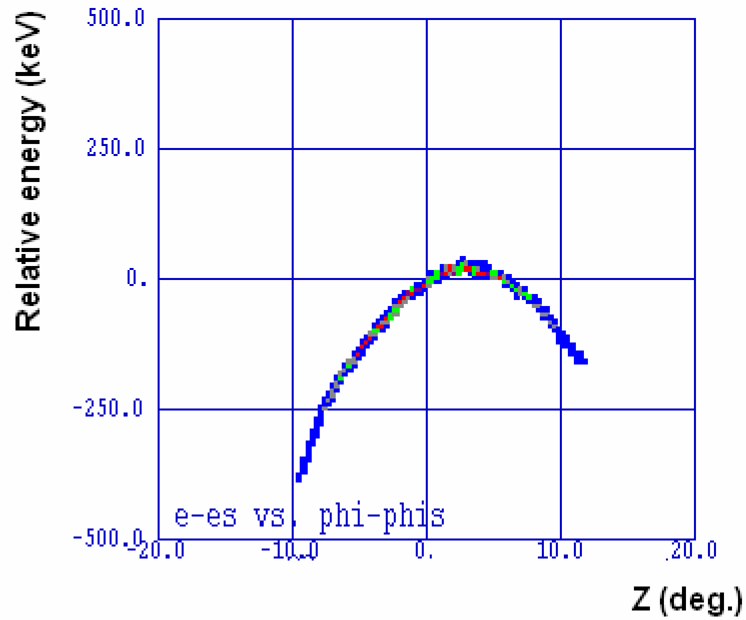
- Much room for further optimization.
- Performance satisfactory for non-magnetized cooling.



Charge/ bunch (nC)	RMS normalized emittance after linac μm
2.5	1.7
3.2	2.0
5	2.9

Longitudinal emittance

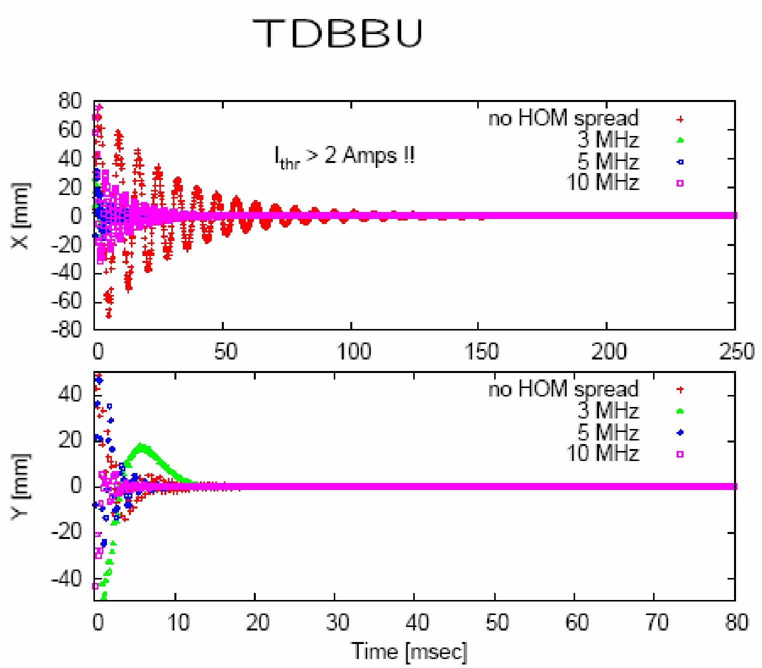
- The longitudinal emittance is 300 degree*keV
- 3rd harmonic correction reduces it to less than 50 degree*keV or about $7*10^{-5}$

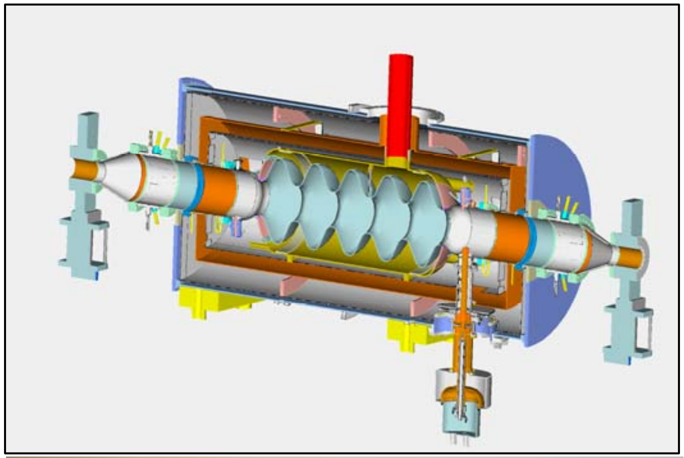


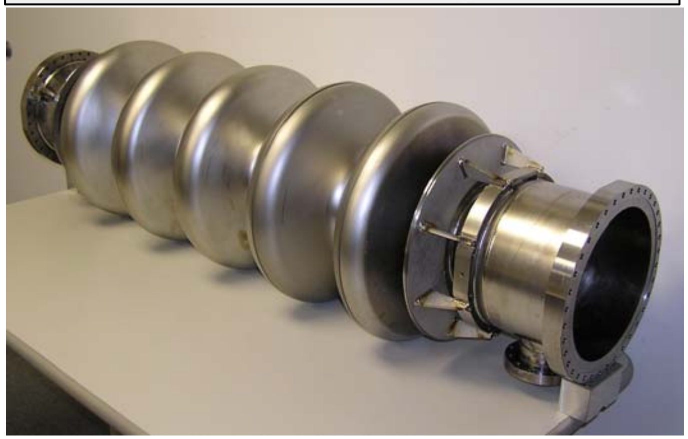
R&D ERL under construction

To study the issues of high-brightness, high-current electron beams as needed for RHIC II and eRHIC.

SRF cavity for ampere current.







Acknowledgments

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* Reference: Dave Sutter.