Invited Talk at SRF 2007, Beijing, China

Electron Cooling and Electron-Ion Colliders at BNL

Ilan Ben-Zvi
Collider-Accelerator Department
Brookhaven National Laboratory

Presented with sincere thanks to my many colleagues at BNL, AES, JLab and elsewhere

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Accelerators at the Collider-Accelerator Department at BNL

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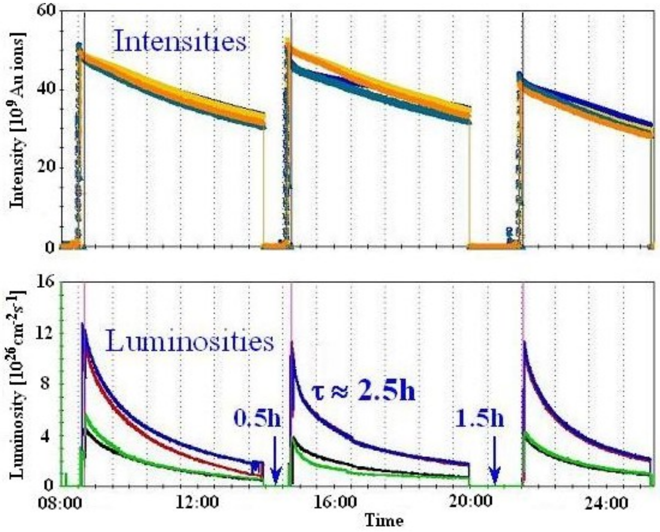
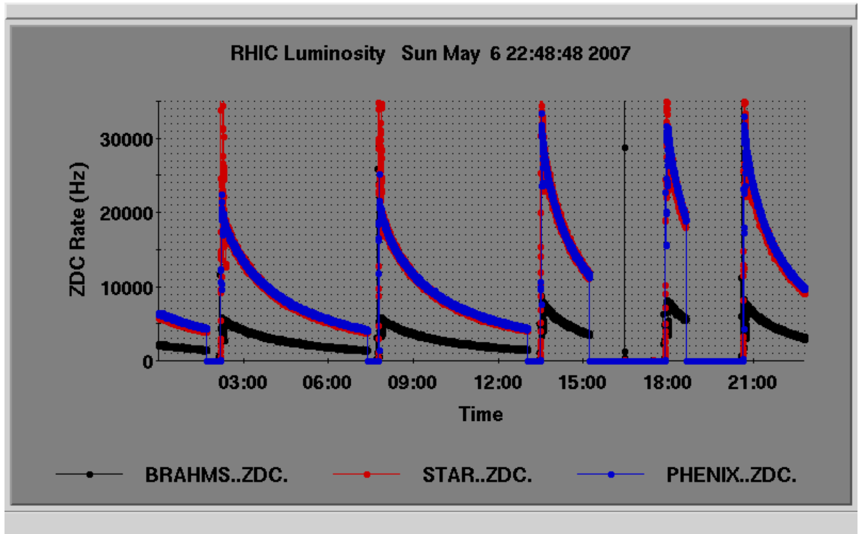
Measure of Performance in colliders: Luminosity measured in cm^{-2} sec^{-1}

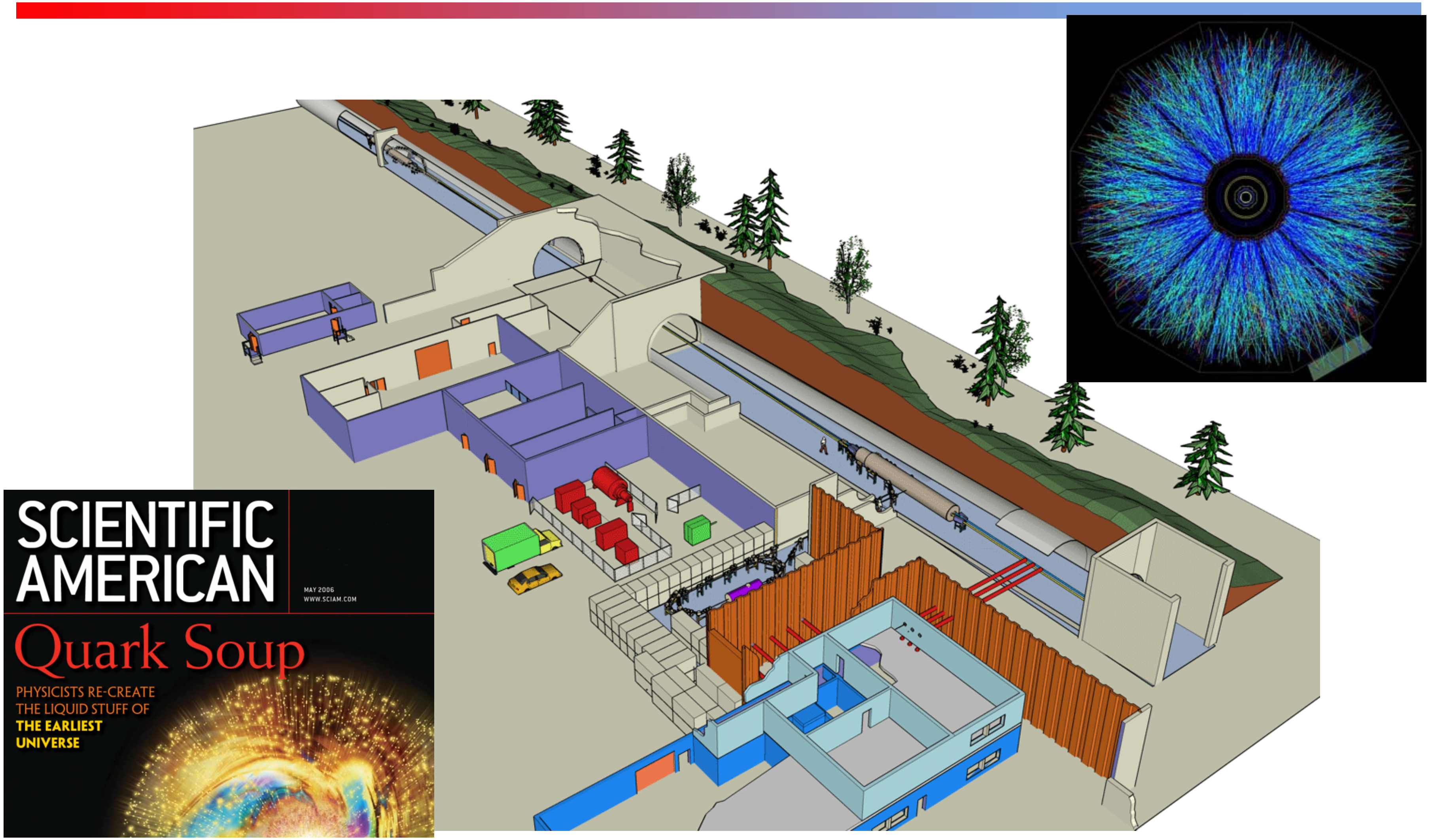
$$\frac{\partial}{\partial t} N_{events} = \sigma_{A \to B} \cdot L \qquad L = \frac{f_{coll} \cdot N_1 \cdot N_2}{4\pi\beta^* \varepsilon}$$

Main sources of luminosity reduction - emittance growth and loss of particles



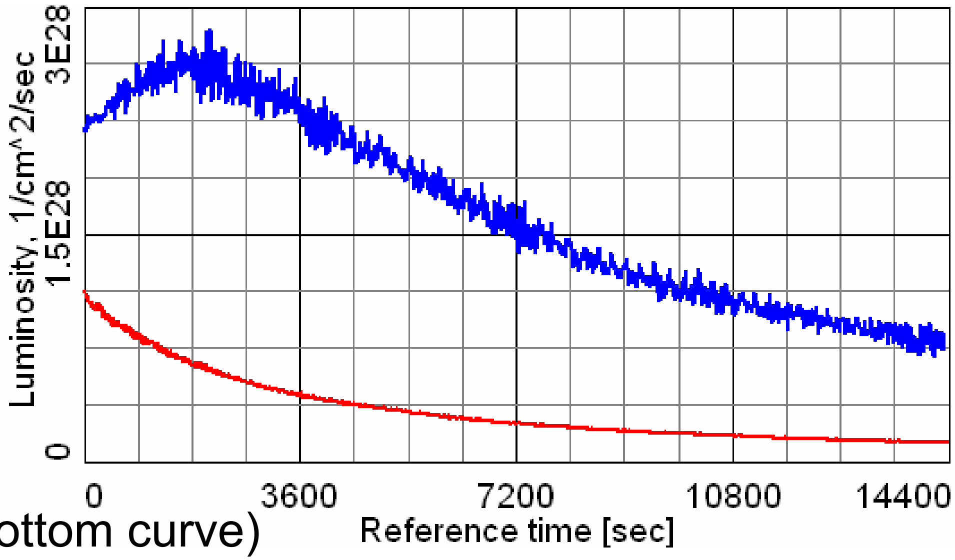


RHIC II: Electron cooling of RHIC



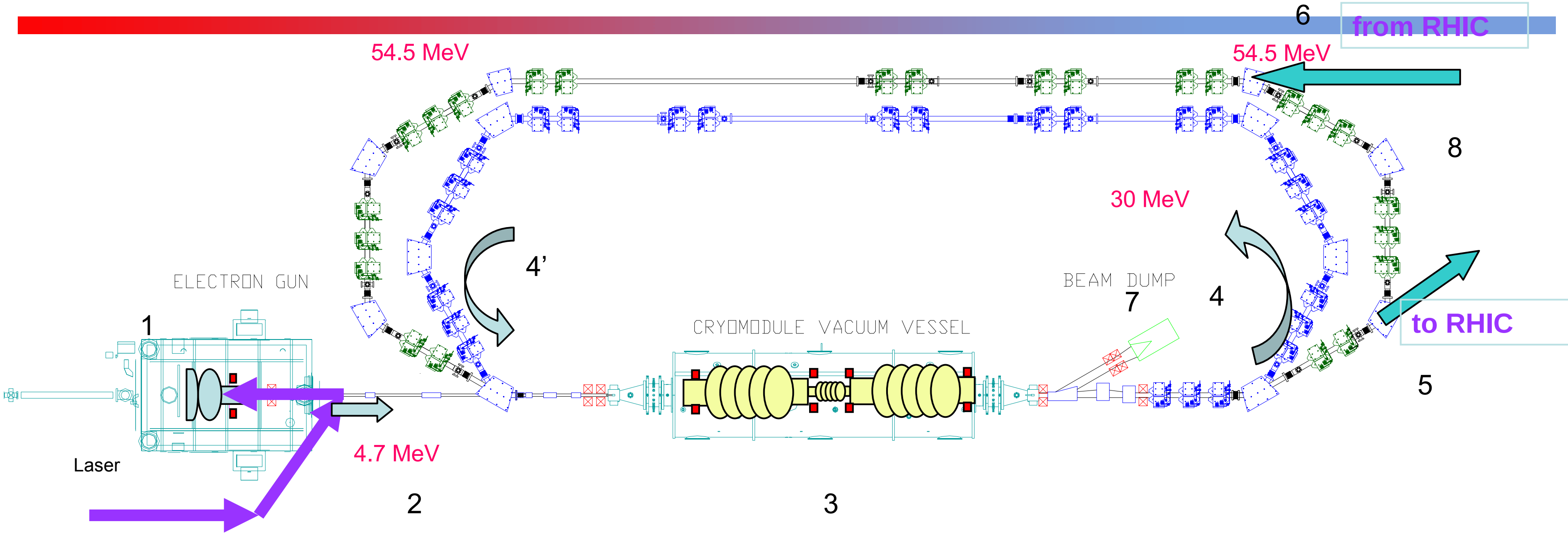
Potential performance of RHIC II

- Requirements:
  - RF frequency: 703.5 MHz
  - Charge: **2x5 nC/bunch**
  - Emittance: **≤ 3 μm** (rms,normalized)
  - Repetition frequency: 9.4 MHz
  - Average current: ~ 100 mA
  - Energy after gun: 5 MeV
  - Energy after ERL: 54 MeV



Simulation of Au-Au luminosity for ion bunch intensity 2×10^9 and 111 bunches using two 5nC electron bunches per single ion bunch with (blue top curve) and without (red bottom curve) electron cooling, taking b*=0.5 m and 1 m, respectively.

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.

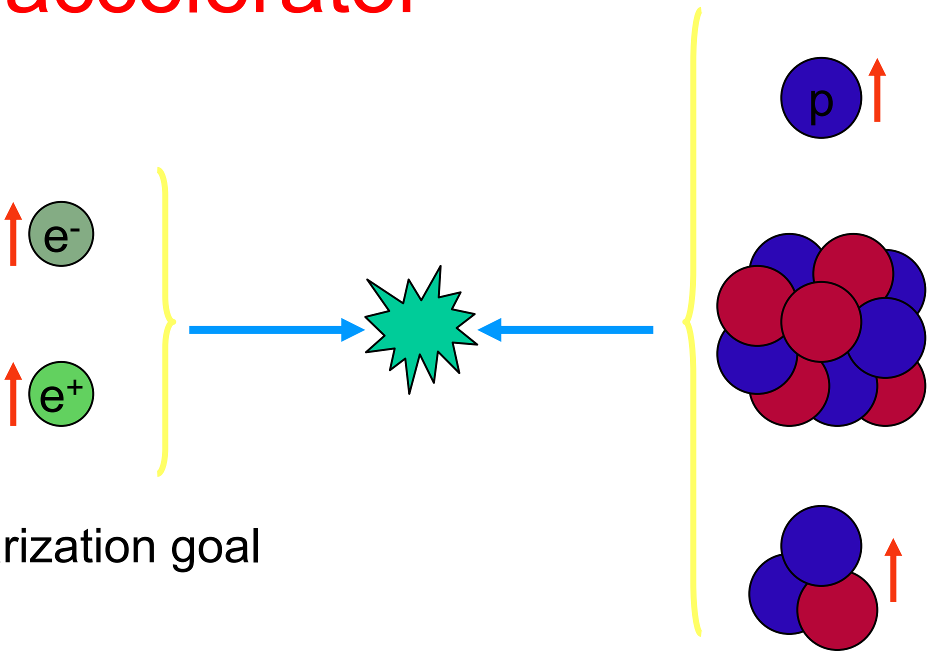
54 MeV, 2x5 nC at 9.4 MHz. RF 703.75 MHz. Gun 5 MeV

eRHIC scope: QCD Factory

Electron accelerator

RHIC

Polarized leptons
$_{2}\downarrow$5-10$\uparrow^{20}$ GeV



Polarized protons
$_{25}\downarrow$ 50-250 GeV

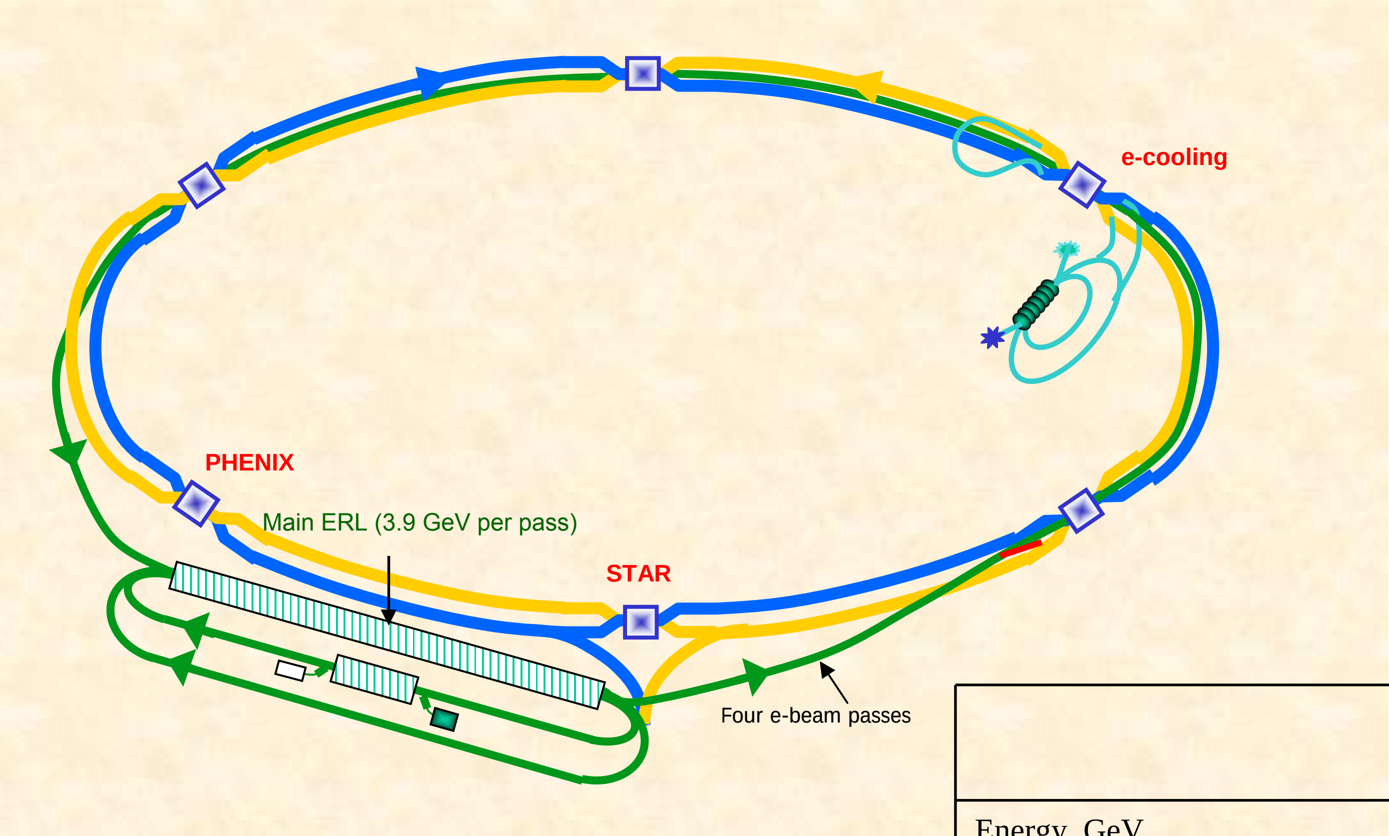
Heavy ions (Au)
50-100 GeV/u

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

70% beam polarization goal

Center mass energy range: 15-100 GeV

eRHIC: ERL based eRHIC



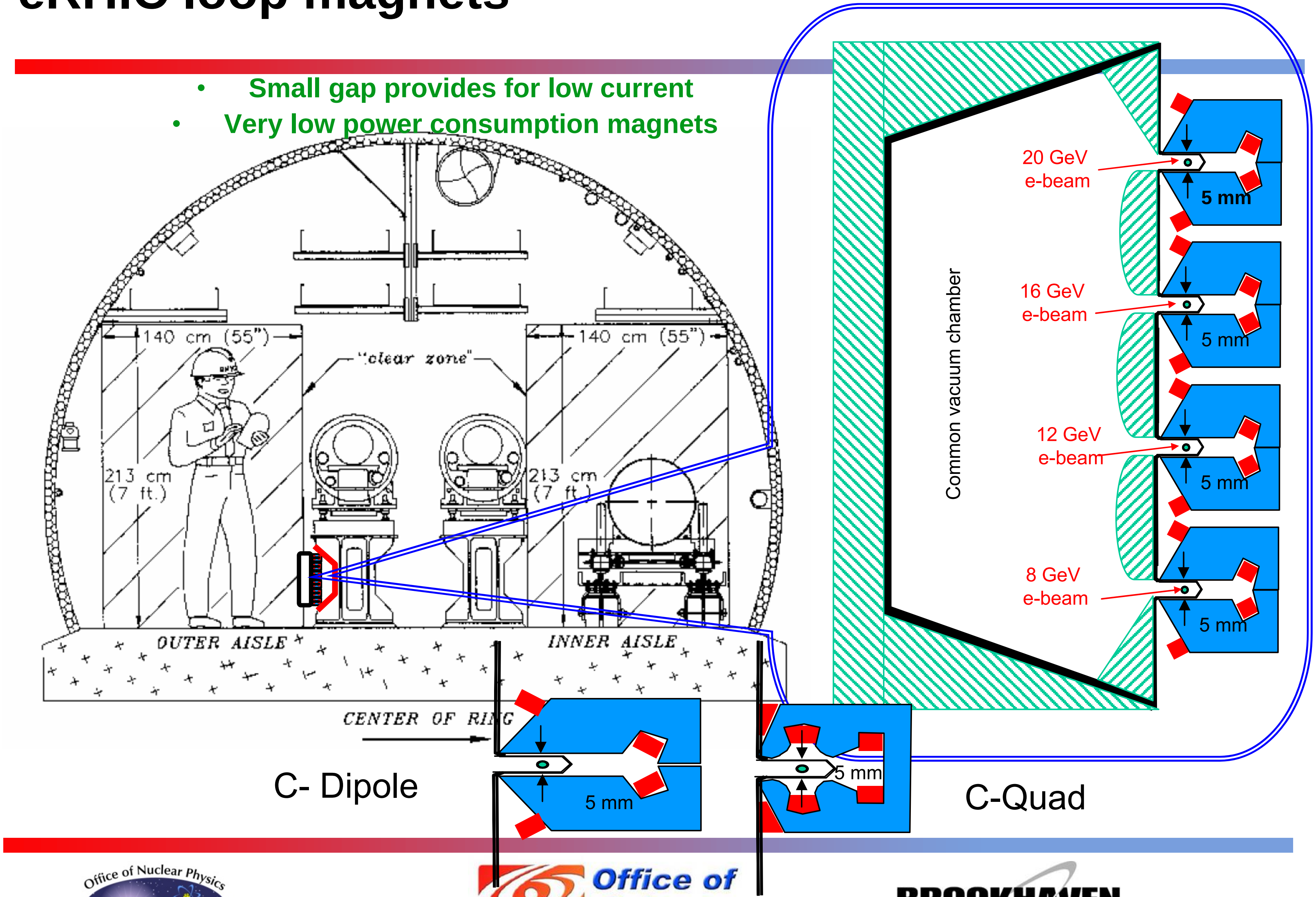
High current
AND
High charge

	High energy setup	
	p	e
Energy, GeV	250	20
Bunch intensity, 10^{11}	2	1.2
Beam current, mA	420	260
Peak Luminosity, 1.e33 $cm^{-2}s^{-1}$	2.6	

Courtesy Vladimir Litvinenko

eRHIC loop magnets

- **Small gap provides for low current**
- **Very low power consumption magnets**



Other applications

- ERL storage rings
  - 0.1 ampere (or higher) current
  - ~0.1 nC bunch charge
  - Emittance as good as possible (sub micron)
- ILC polarized electrons
  - 3.2 nC
  - Flat beam
  - 0.4 micron 4-D emittance
- Other objectives (FELs, Compton sources, THz sources, more)

Objectives and challenges of high-current ERL cavities

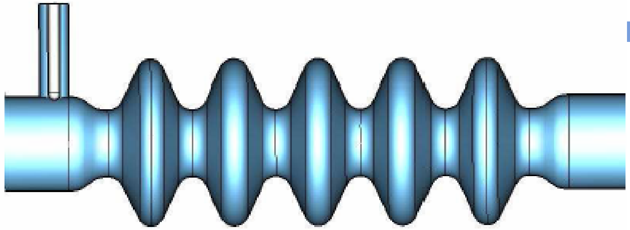
- Accelerate a high current in an ERL avoiding Beam-Breakup
- Disposing safely high power of HOMs
- Reduce wake impedance to preserve beam density
- Reduce cryogenic losses
- Be capable of a reasonably good gradient
- Reduce sensitivity to acoustics

- Need single-mode cavity
- Need good conduit for the HOM power
- Need large apertures
- Need low frequency
- Optimum cavity shape

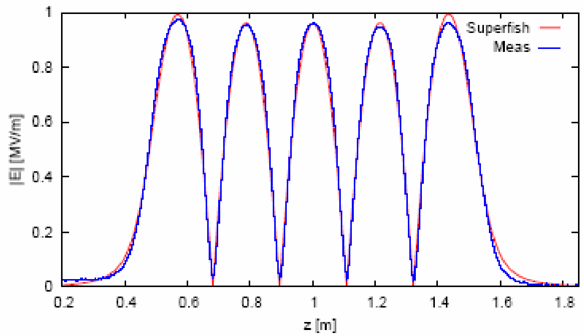
BNL Cavity

Main Parameters:

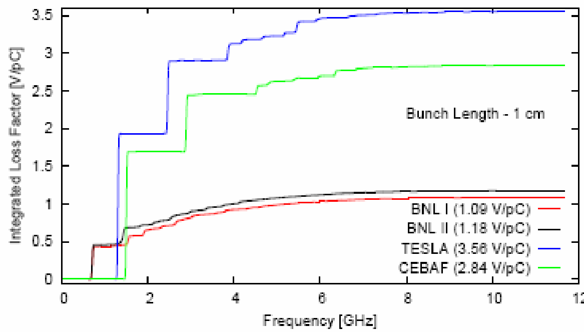
Frequency	703.75 [MHz]
RHIC Harmonic	25
Number of cells	5
Active cavity length	1.52 [m]
Iris Diameter	17 [cm]
Beam Pipe Diameter	24 [cm]
G (Ω)	225
R/Q	403.5 [Ω]
Q BCS @ 2K	4.5×10^{10}
Q_{ext}	3×10^{7}
E_p/E_a	1.97
H_p/E_a	5.78 [$mT/MV/m$]
cell to cell coupling	3%
Sensitivity Factor ($\frac{N^2}{\beta}$)	833
Field Flatness	96.5 %
Lorentz Detuning Coeff	1.2 [$Hz/(MV/m)^2$]
Lowest Mech. Resonance	96 [Hz]
$k_{\|\|}$ ($\sigma_z - 1cm$)	1.1 [V/pC]
$k_{\perp}$ ($\sigma_z - 1cm$)	3.1 [V/pC/m]
HOM Power (10-20 nC)	0.5-2.3 [kW]



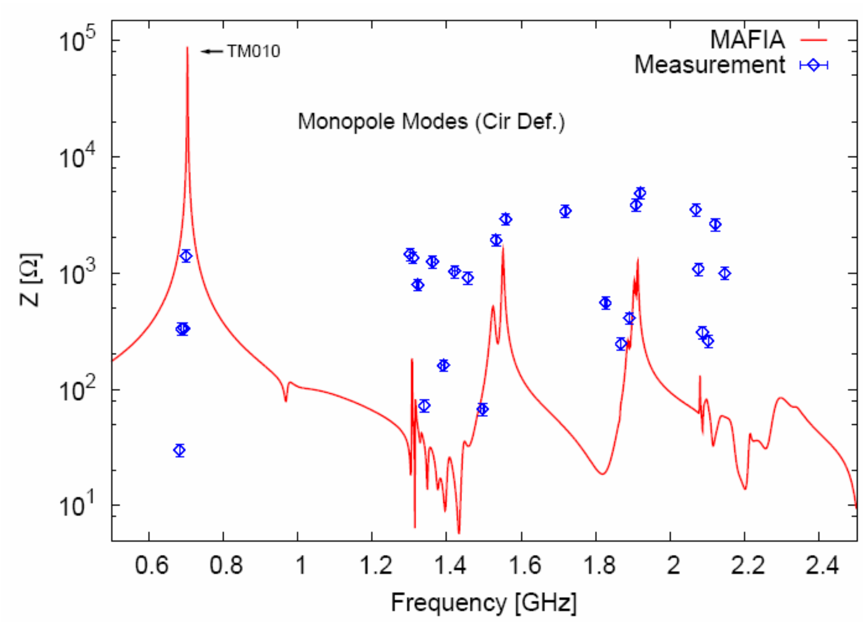
Field Flatness

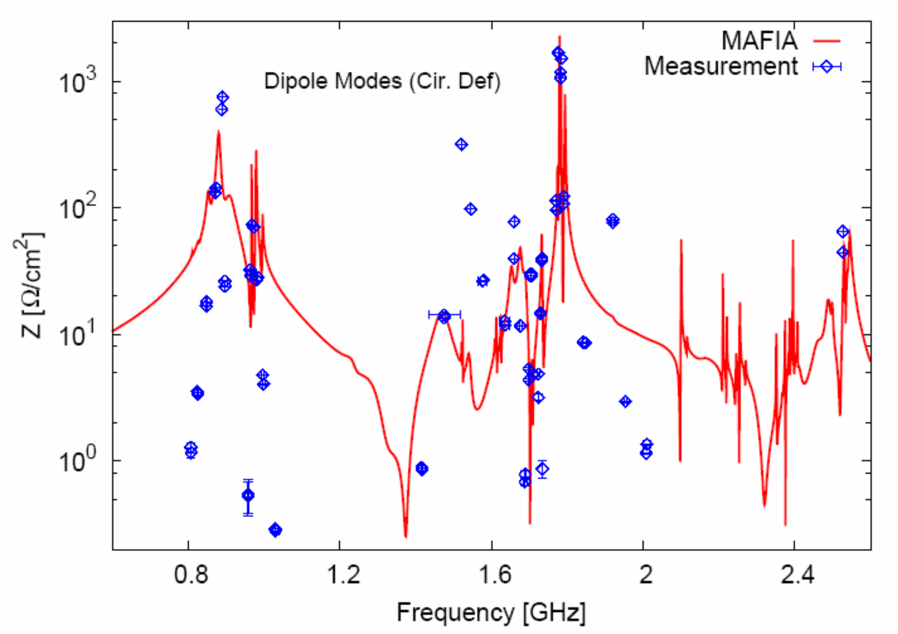


Integrated Loss Factor



Courtesy Ram Calaga





Red line – MAFIA simulation. Blue points - measured

BNL 5-cell impedance – lower than any other cavity

Courtesy Ram Calaga

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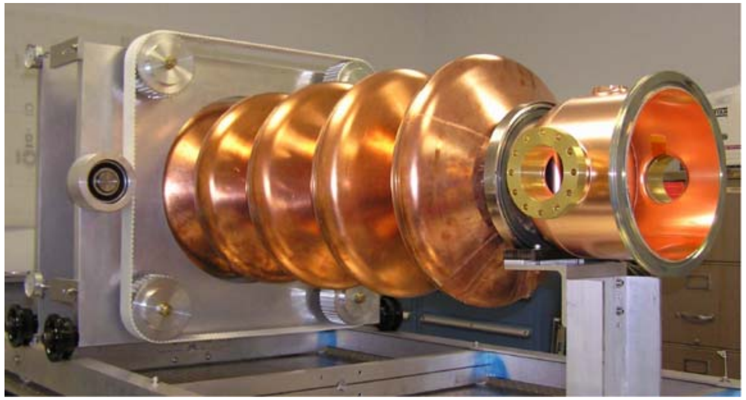
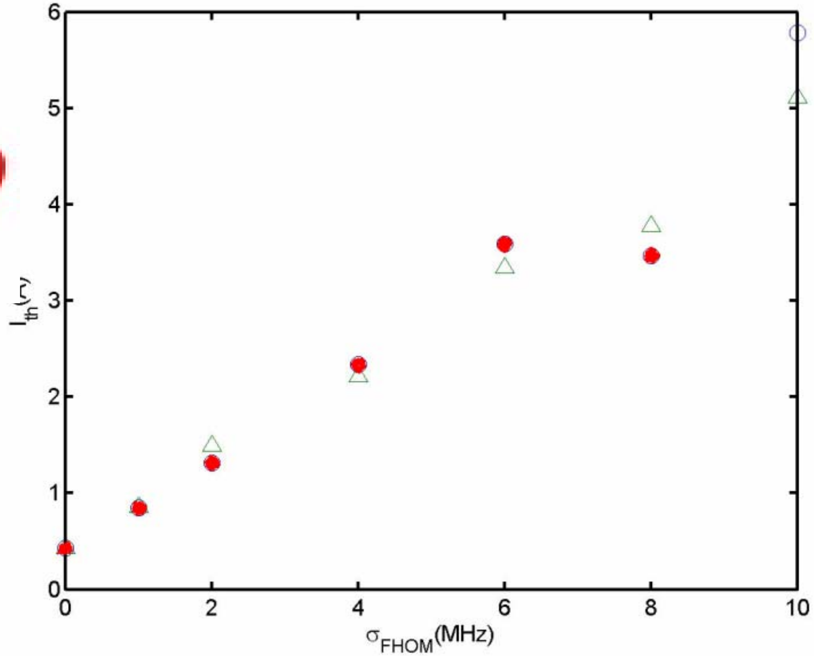
ERL High-Current Cavity



Fully damped "single mode" cavity at 703.75 MHz
Allows ~ampere in 3 pass eRHIC.
Also used for electron cooler.

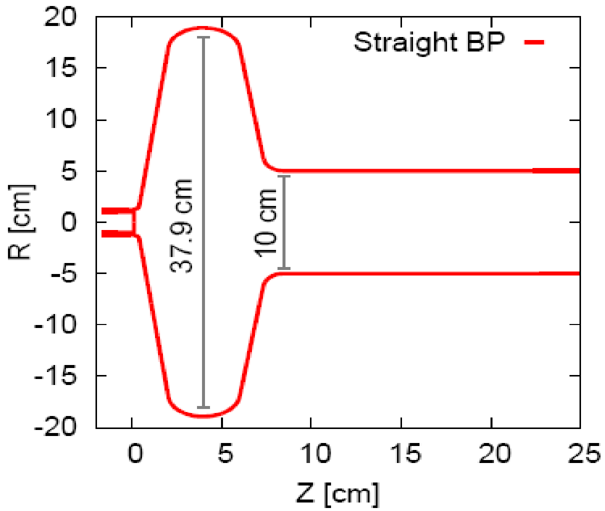
E. Pozdeyev

Advanced Energy Systems, Inc.



200 16MeV/pass cavities,
measured Cu-model HOM spectrum
50 foc. and 50 defoc. quadrupoles,
G=1.262 T/m
3 acel.-decel. passes,
each is 1.3 km long
28 MHz bunch rep.rate

Parameters of the High-Current SRF Photoinjector

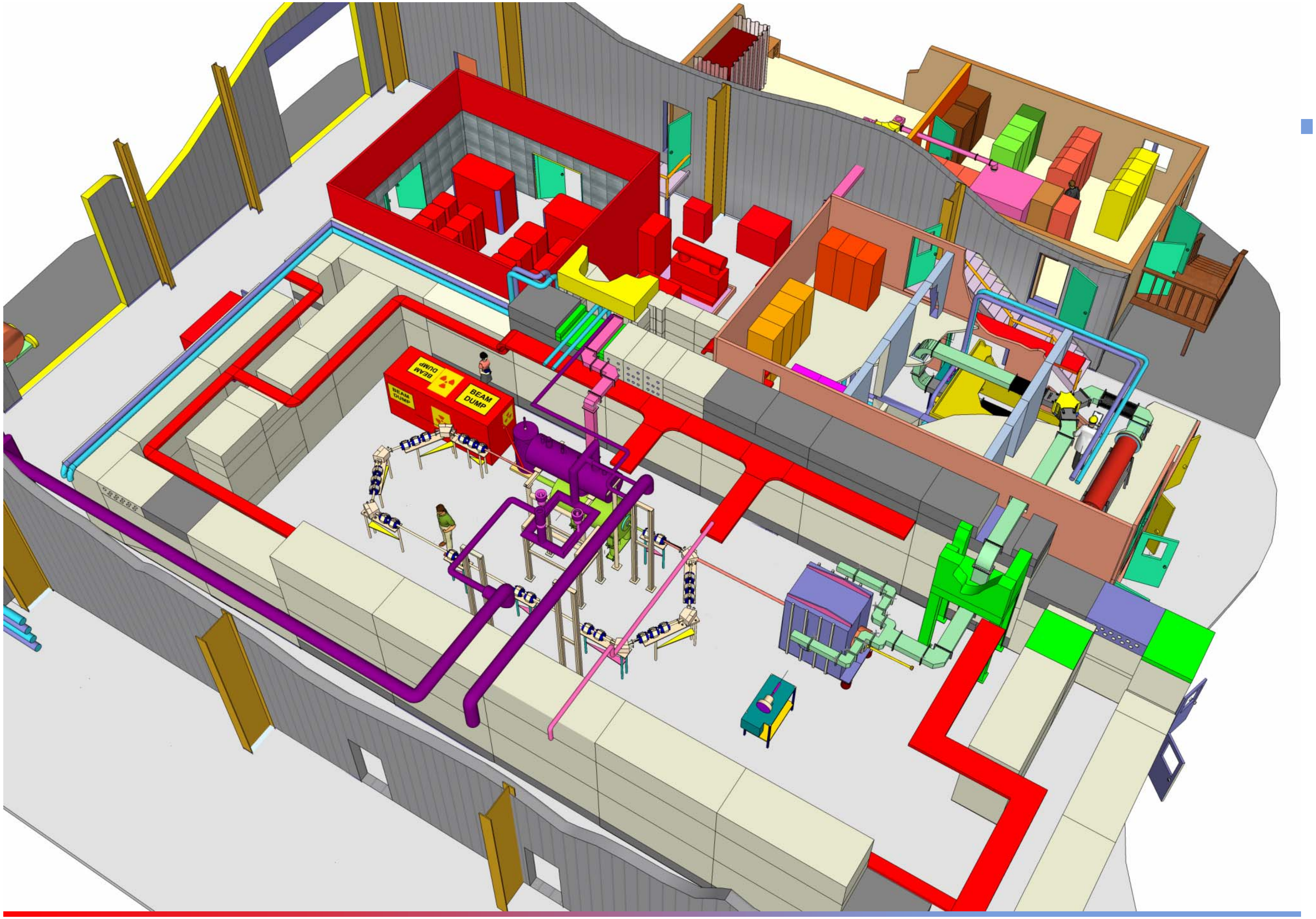


Parameter	Units	Value
Frequency	MHz	703.75
Iris radius	cm	5
Equator Diameter	cm	37.9
Beam kinetic energy	MeV	2
Peak electric field	MV/m	35.7
Peak magnetic field	A/m	58740
Stored energy	Joule	8.37
QR_s (geometry factor)	Ω	3.52
R/Q	Ω	96
Q_e (external Q)		37000
Input power	kW	1000
Longitudinal loss factor	V/pC	0.7
Transverse loss factor	V/pC/m	32

Courtesy Ram Calaga

The BNL High-Current R&D ERL

- Aimed at needed current for electron cooling (~100 mA) or eRHIC (a few 100’s mA)
- Testing of novel components and techniques:
  - Superconducting electron gun
  - High current photocathodes
  - Z-bend ERL beam merging
  - High-current SRF cavity at 703.75 MHz
  - Diagnostics and more.


BEAM DUMP
BEAM DUMP
BEAM DUMP

Some of the equipment

Bellow: 1 MW CW klystron for the electron gun

Above: Work on the cryo system

Above: The klystron power supply

RHIC 56 MHz SRF Storage Cavity

- Adiabatic rebucketing from 28 MHz cavity
- Huge bucket – keeps ions in one bucket, reduce loss and background
- Help stochastic cooling by eliminating satellite bunches
- SRF cavities are stable and reliable
- SRF cavities provide good vacuum (pressure rise)
- Large voltage : 2.5 MV conservatively from single cavity
- Somewhat lower RHIC impedance (fewer cavities)
- Reduce the effect of the abort gap

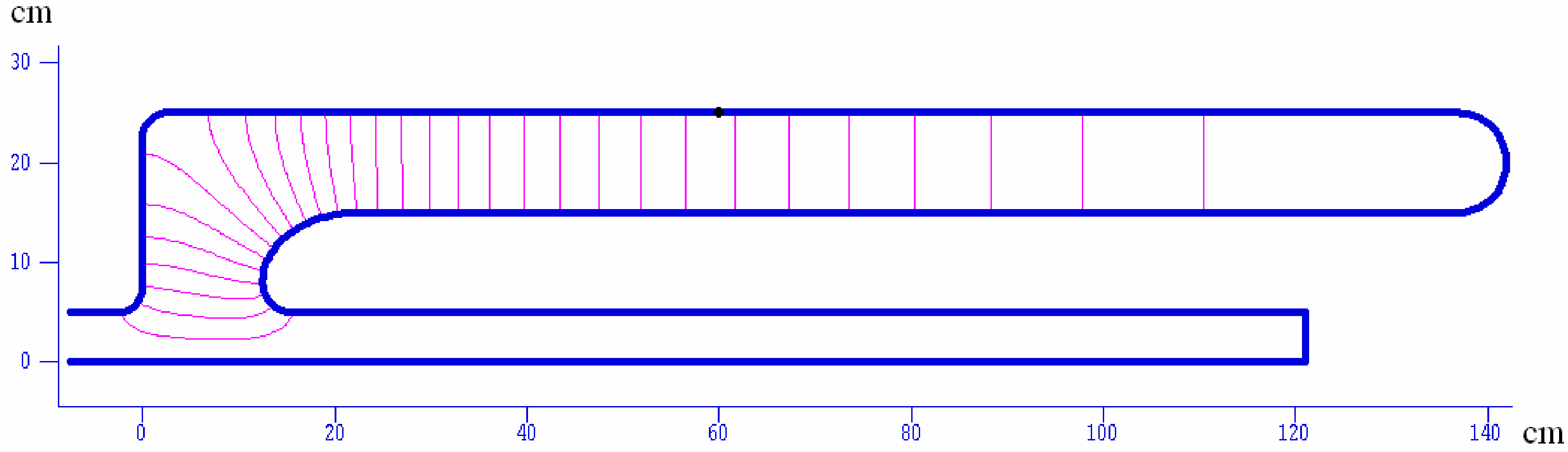
$$\delta f = \frac{1}{2}\frac{R}{Q} f \frac{I_B}{V}\cos(\phi_B) = 448\,\mathrm{Hz}$$

$$\Delta\phi_M = 2\pi\delta f T_g = 3\times10^{-3}\,\mathrm{radians}$$

Operating conditions for stability

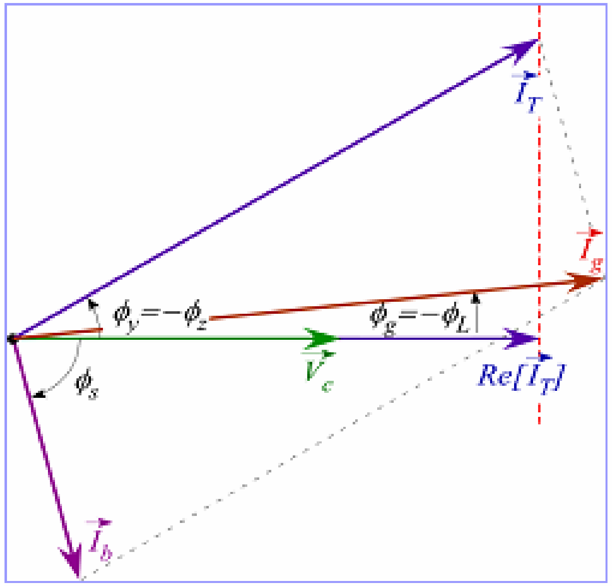
- Robinson stability conditions: Both will be fulfilled if the cavity's resonance frequency is bellow the RF frequency (above transition).
- Therefore the design of the cavity is to be resonant somewhat below the beam frequency harmonic at store.
- However, at injection, the beam frequency is lower than the cavity's resonance frequency.
- That means that during acceleration the beam will go through the cavity's resonance.
- At such time, the cavity must be heavily damped!

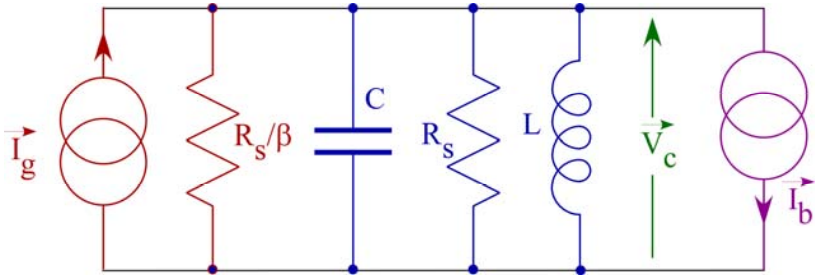
Resonator of choice: the Quarter Wave Resonator



Frequency	= 56 MHz
Stored energy (at 2.4 MV voltage)	= 207 Joules
Operating temperature	~ 4.2 K
Power at LHe (assume 10 nΩ Rr)	= 41 W
Q quality factor (assume 10 nΩ R_r)	= 1.8E+9
Geometry factor Rs*Q	= 20 Ω
r/Q	= 80 Ω
Maximum H (at Z,R = 137.0,15.0)	= 82 kA/m, 3.8 mW/cm^2
Maximum E (at Z,R = 14.2,11.9)	= 38.9 MV/m

From the equivalent circuit:





$$Y_L = \frac{\vec{I}_T}{\vec{V}_c} = \frac{1+\beta}{R_L} + j\left(\omega C - \frac{1}{\omega L}\right) \qquad I_g = \frac{2V_{FWD}}{n Z_0} = \sqrt{\frac{8\beta P_{FWD}}{R_s}}$$

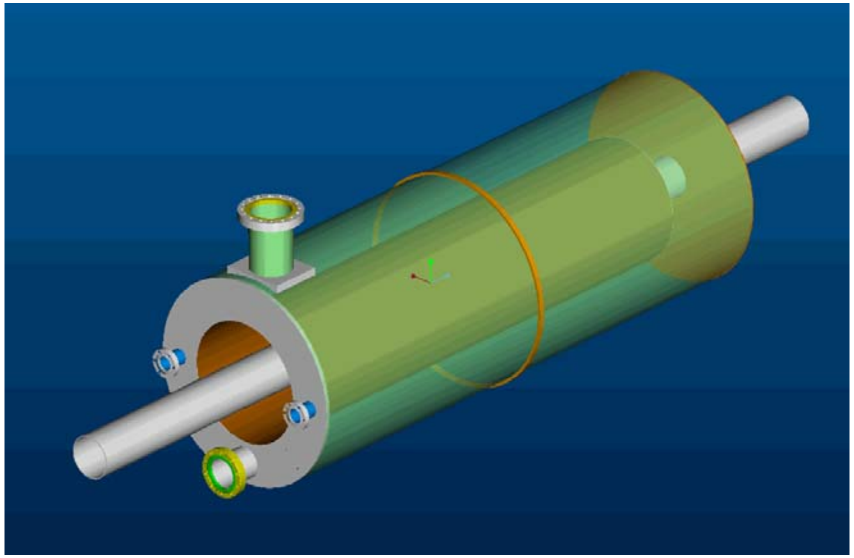
$$I_b \approx \frac{2q}{T_b}; \quad \phi_b = \phi_s$$

$$\frac{R}{Q} = \frac{V^2}{2\omega U} \qquad L = \frac{R/Q}{\omega} \qquad C = \frac{1}{\omega R/Q} \qquad \frac{V\delta}{R/Q} = -I_B \sin(\phi_s) \qquad \phi_s = -\frac{\pi}{2}$$

$$\delta \sim 2\frac{\Delta f}{f} = \frac{R}{Q}\frac{I_B}{V}$$

For example, I_B=0.5A, V=2.5 MV, R/Q=80
Then $\delta=1.6\times10^{-5}$, $\Delta f/f=8\times10^{-6}$, Δf=448 Hz

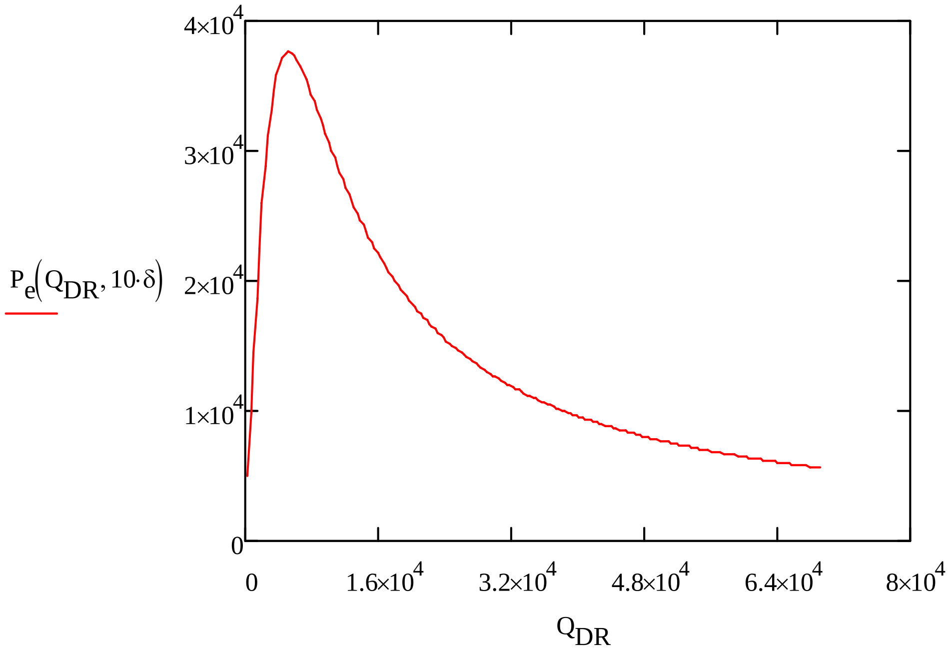
The damper probe must be extracted quickly



$U_D := \frac{P_e(Q_D, 0) \cdot Q_D}{\omega}$ $\quad V_D := \sqrt{\frac{2 \cdot U_D}{Cap}}$ $\quad Q_{DR} := 350$

$U_D = 4.934 \times 10^{-3}$ $\quad V_D = 1.667 \times 10^{4}$ $\quad P_e(Q_D, 0) = 5.013 \times 10^{3}$

$Q_{DR} := Q_D, 2 \cdot Q_D .. 200\, Q_D$ $\quad \delta = 1.925 \times 10^{-5}$ $\quad P_e(Q_D, 10 \cdot \delta) = 4.991 \times 10^{3}$



The power into a damping loop with Q_D of 350 at maximum coupling as a function of the strength of the coupling, assuming a detuning of 2×10^{-4} during the extraction.

Polarized Electron SRF gun. See D. Holmes, WEP02

- RF electron guns may be able to provide electron beams for the ILC without the need for a damping ring.
- Attempts for polarized electrons from RF guns were not successful, mostly due to poor vacuum conditions.
- SRF gun are more promising thanks to cryogenic pumping even of hydrogen (at 2K), it may be possible to maintain a vacuum close to 10^{-12} torr.
- Of concern would be in this case contamination of the gun cavity by evaporating cathode material.
- Work at BNL in collaboration with AES, FNAL and MIT, aims at demonstrating a successful operation of a GaAs:Cs in a 1.3 GHz SRF gun.

Towards a polarized electron gun

- Potential source for ILC or eRHIC.
- ILC emittance and charge directly from SRF gun! $\varepsilon_{4D} = \sqrt{\varepsilon_x \cdot \varepsilon_y} = 0.4\mu$
- RF gun have an order of magnitude less ions impacting cathode

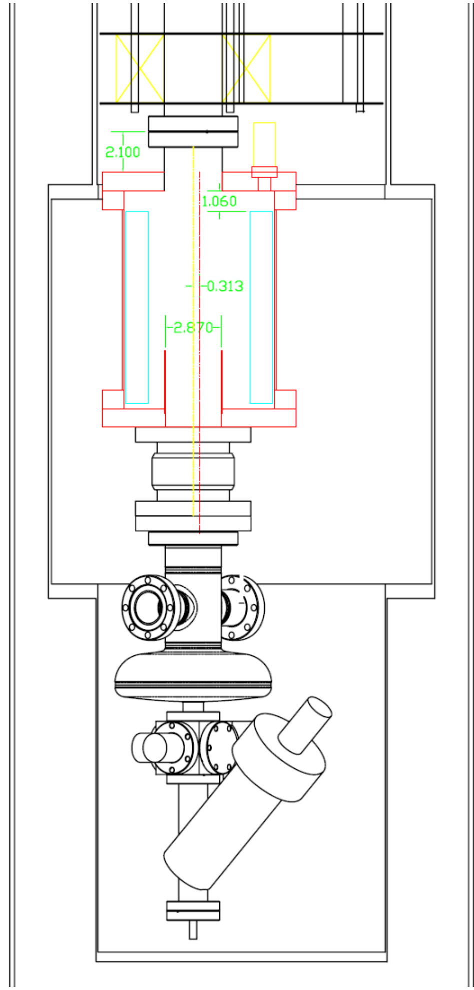
$$\varepsilon_{eff}^2 = \varepsilon_{4D}^2 + L^2 \qquad L \equiv \frac{M}{2} = \frac{q \cdot B \cdot r_{cath}^2}{2m_e c}$$

$$M = \beta\gamma(<x \cdot y'> - <y \cdot x'>)$$

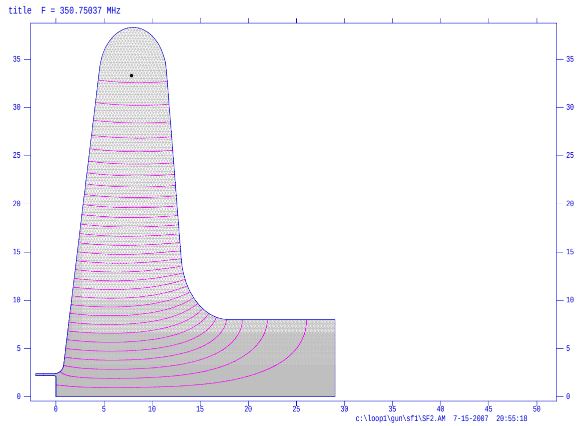
$$\varepsilon_x = \varepsilon_{eff} + L \approx M + \frac{2\varepsilon_{4D}^2}{M}$$

$$M = \varepsilon_x - \varepsilon_y = 8\mu$$

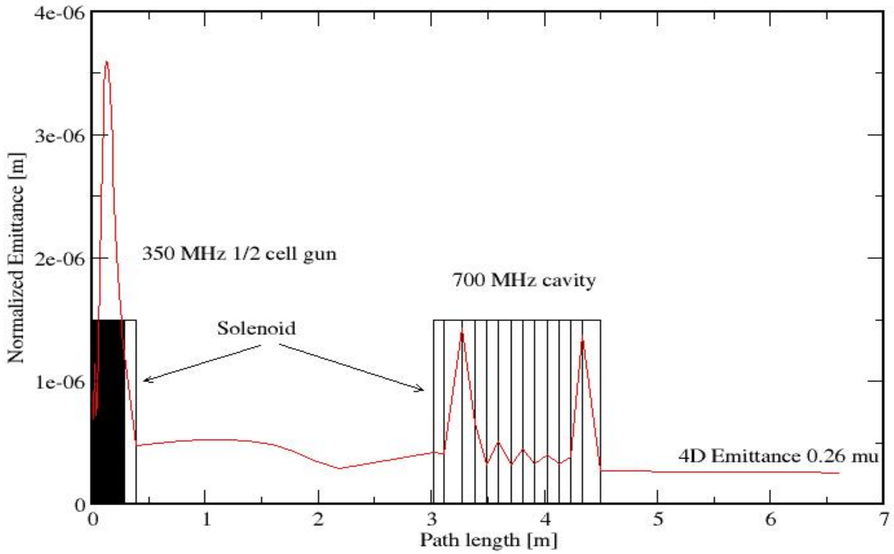
$$\varepsilon_y = \varepsilon_{eff} - L \approx \frac{\varepsilon_{4D}^2}{M}$$



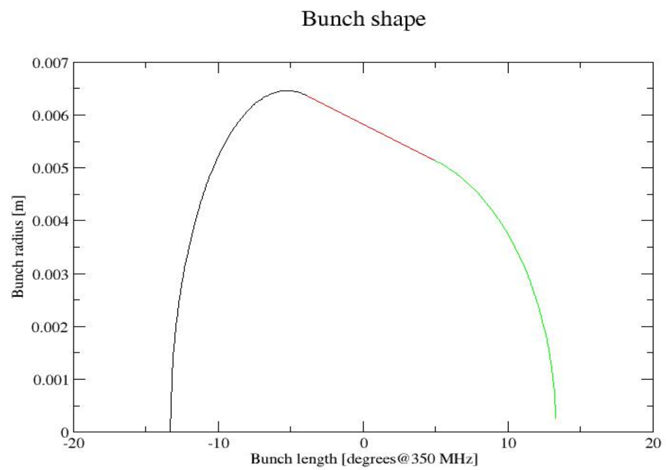
Emittance after acceleration: Best so far 0.26 μm



Gun frequency: 350 MHz
Bunch length: ± 13.3 degrees
Cathode radius: 6.3 mm
kT out of cathode: 0.03 eV
Field on the cathode: 11.2 Gauss
Magnetization 5 μ (will use 8 μ)
Energy out of the gun: 5 MeV

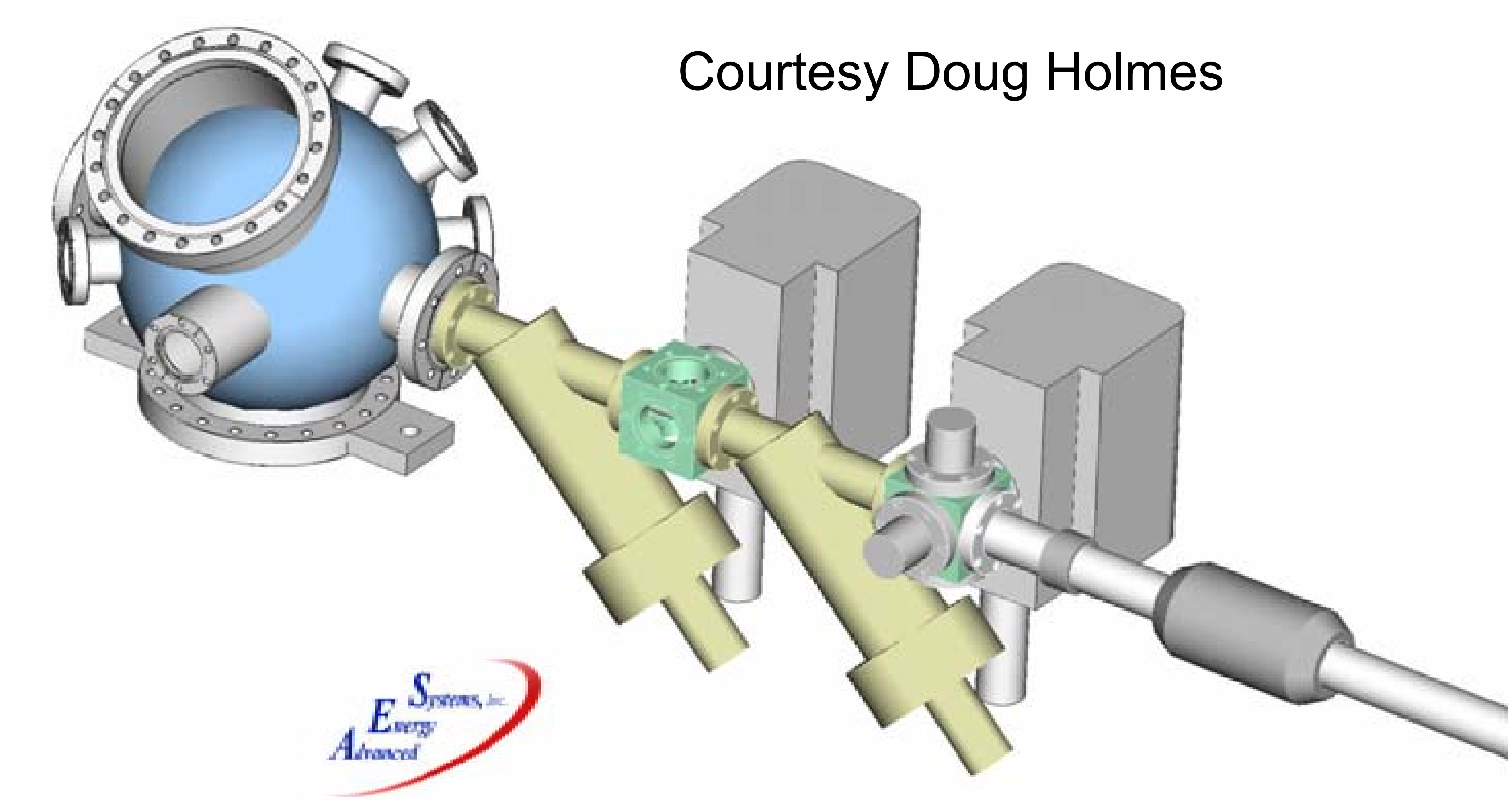


Courtesy Jorg Kewisch

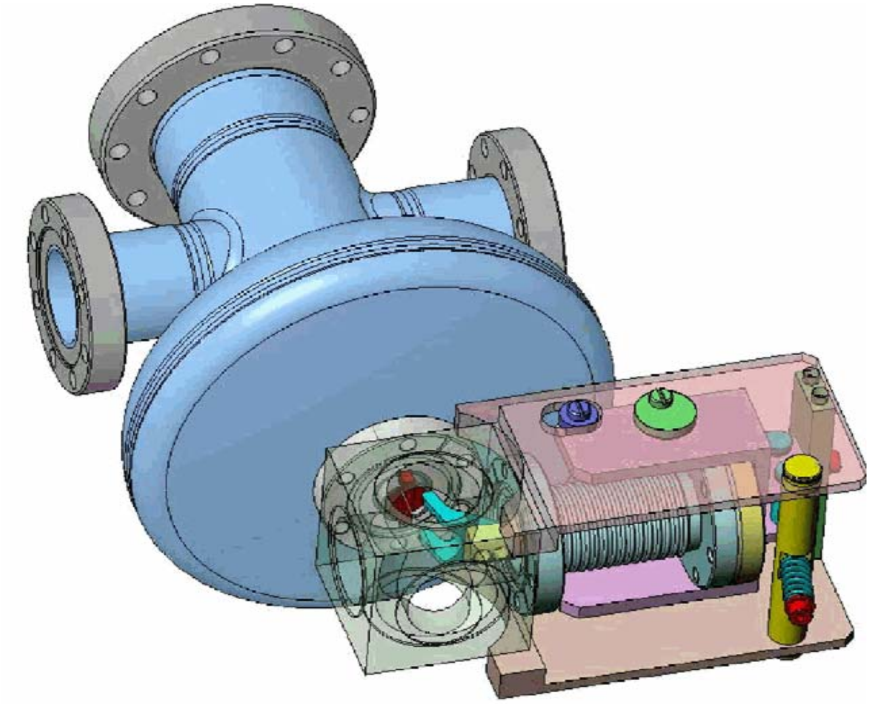


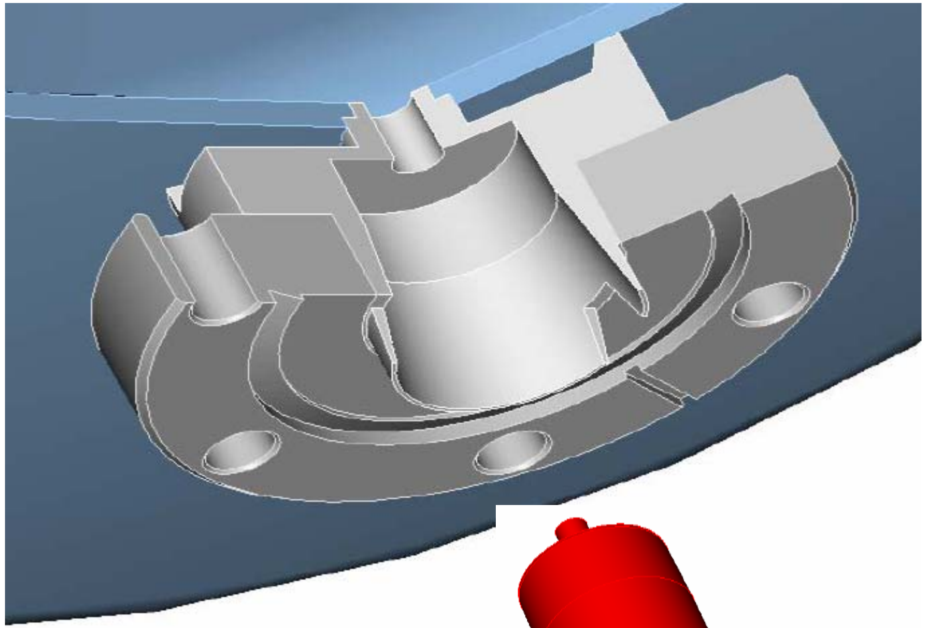
Cathode transporter clamped to cathode preparation chamber

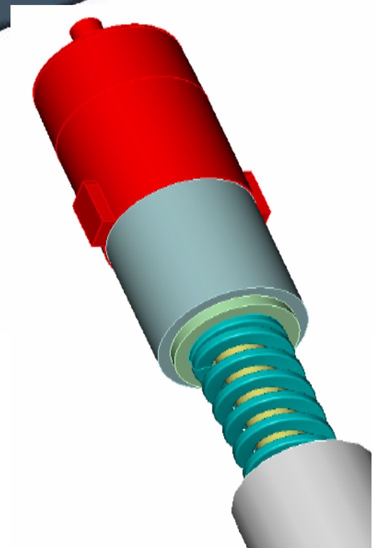
Courtesy Doug Holmes



Plug cathode insertion will be used for the test







Courtesy Doug Holmes

Acknowledgements

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Thanks due to many colleagues at BNL, AES, JLab and other places, too many to be named here.

Thank you for listening