Energy Recovery Linac Development at Brookhaven National Laboratory

Presented at

Workshop to Explore Physics Opportunities with Intense, Polarized Electron Beams up to 300 MeV

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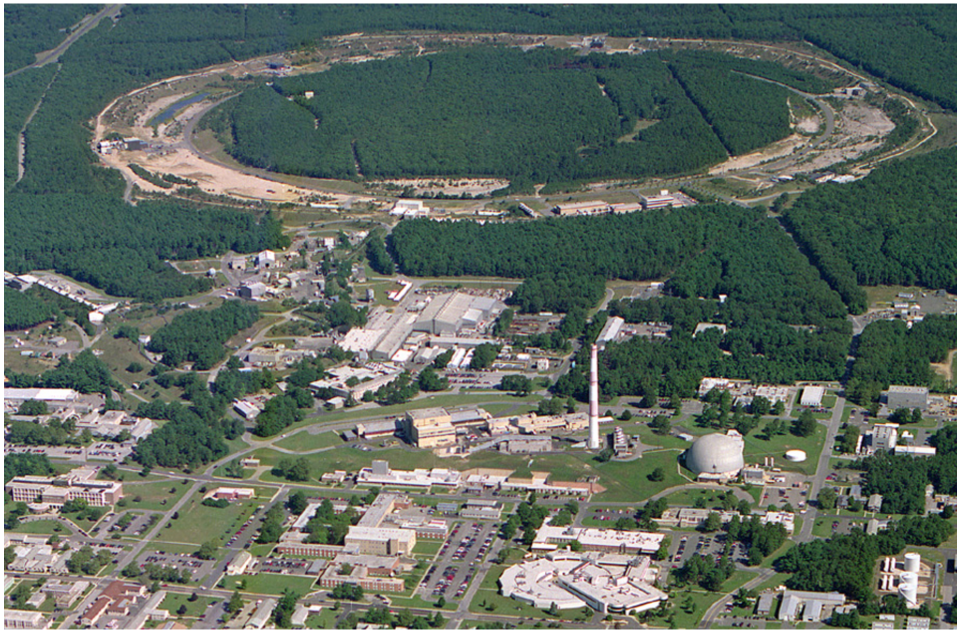

RHIC:
Discovery of a "perfect" liquid of strongly interacting quarks and gluons.
Deep mystery:
"missing" proton spin

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What is an Energy Recovery Linac?

1. In a linear accelerator (or LINAC), beam is injected into a series of radio frequency (RF) cavities which accelerate the beam using the cavities' electric field. The accelerated beam is used and dumped at full energy.
2. In a superconducting RF (SRF) linac, the cavities are superconducting, enabling CW operation at a good accelerating voltage.
3. In a multi-pass linac, the accelerated beam may be returned to the linac <u>in phase,</u> for further acceleration. This process may be repeated a few times, leading to cost savings (CEBAF is a good example).
4. In an <u>Energy Recovery Linac</u> (ERL), the high-energy beam, following its use, is returned to the linac in <u>opposite RF phase</u> to be decelerated back to about the injection energy. The beam is dumped at a low energy.
5. An analogy to this process is a hybrid car, which uses stored energy in a battery for acceleration, and returns some of this energy while braking.

What are the advantages of an ERL?

- **Relative to a linac:**
  - Higher beam current possible (RF power limit removed)
  - Reduced power bill (RF power recovered)
  - Reduced cost of RF amplifiers (smaller RF power amplifiers)
  - Reduced beam power and energy in beam dump (less shielding / activation issues)
- **Relative to a storage ring:**
  - Better beam quality (emittance, polarization – maintain non-equilibrium state due to short dwell time)
  - Easier to upgrade (add linac section or recirculation passes)
  - Tolerate more “damage” to the beam from collisions with a beam or a target (the beam is dumped soon after)

eRHIC: polarized electron ERL colliding with RHIC beams

Single pass allows for large collision disruption of electron bunch and high luminosity ($L \sim 10^{34}\ cm^{-2}\ s^{-1}$) and full electron polarization transparency

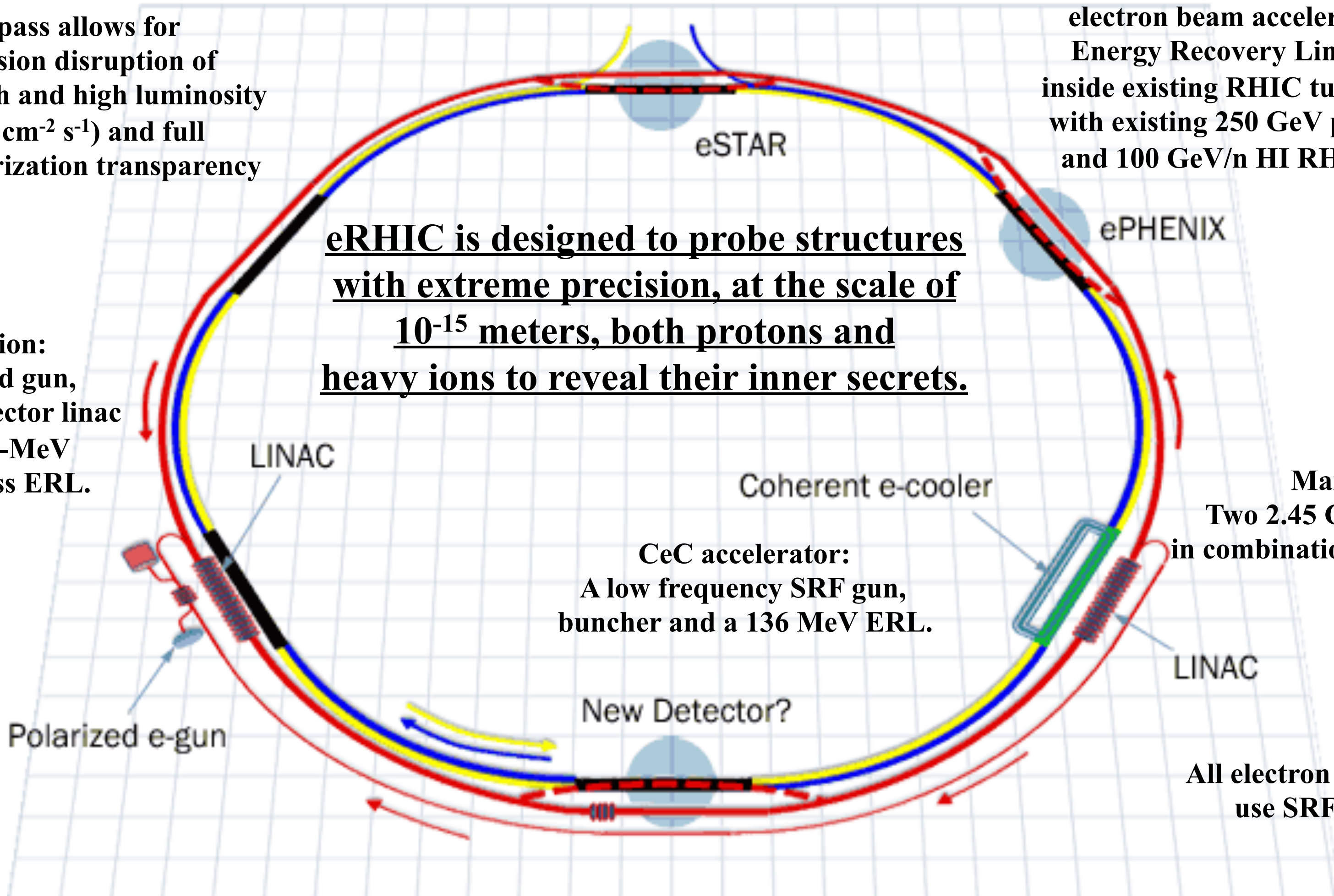
eRHIC: 5 – 30 GeV electron beam accelerated with Energy Recovery Linac (ERL) inside existing RHIC tunnel collides with existing 250 GeV pol. protons and 100 GeV/n HI RHIC beams

eRHIC is designed to probe structures with extreme precision, at the scale of 10^{-15} meters, both protons and heavy ions to reveal their inner secrets.

Injection: Polarized gun, 10 MeV injector linac and 600-MeV single-pass ERL.

Main ERL: Two 2.45 GeV SRF linacs in combination with six passes.

CeC accelerator: A low frequency SRF gun, buncher and a 136 MeV ERL.



All electron accelerators use SRF cavities

Not shown: Energy loss and energy spread compensation linacs, crab cavities for electrons and ions.

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Accelerator R&D at the Collider-Accelerator Department

- eRHIC machine design
  - Lattice design
  - Wake fields and losses
  - Kink instability
  - IP design
  - Crab crossing
  - Small gap magnets
- Multi-pass high average current ERL
  - ERL highly-damped accelerating cavities
  - SRF photocathode gun
  - R&D ERL for 300 mA average current
- High current (50 mA) polarized electron gun
- Coherent electron cooling of hadron beam
- Misc. items: ERL BBU, photocathode R&D

Innovative approach: Use an Energy Recovery Linac for the electron machine

Double QWR crab cavity

Funneling for the gun,

Diamond Amplified Photocathode, chromaticity suppression of BBU

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704 MHz 5-cell niobium cavity for high-current ERL

- **Total HOM power to extract is 7.3 kW per cavity at eRHIC 3.5 nC, 50 mA, 6 passes up + 6 passes down energy (loss factor 3.5 V/pC).**

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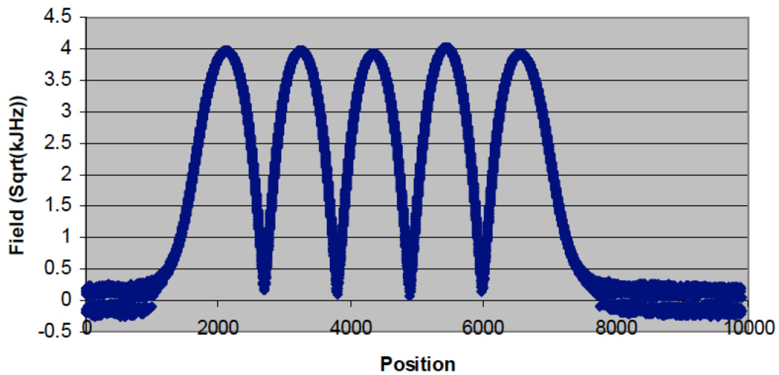
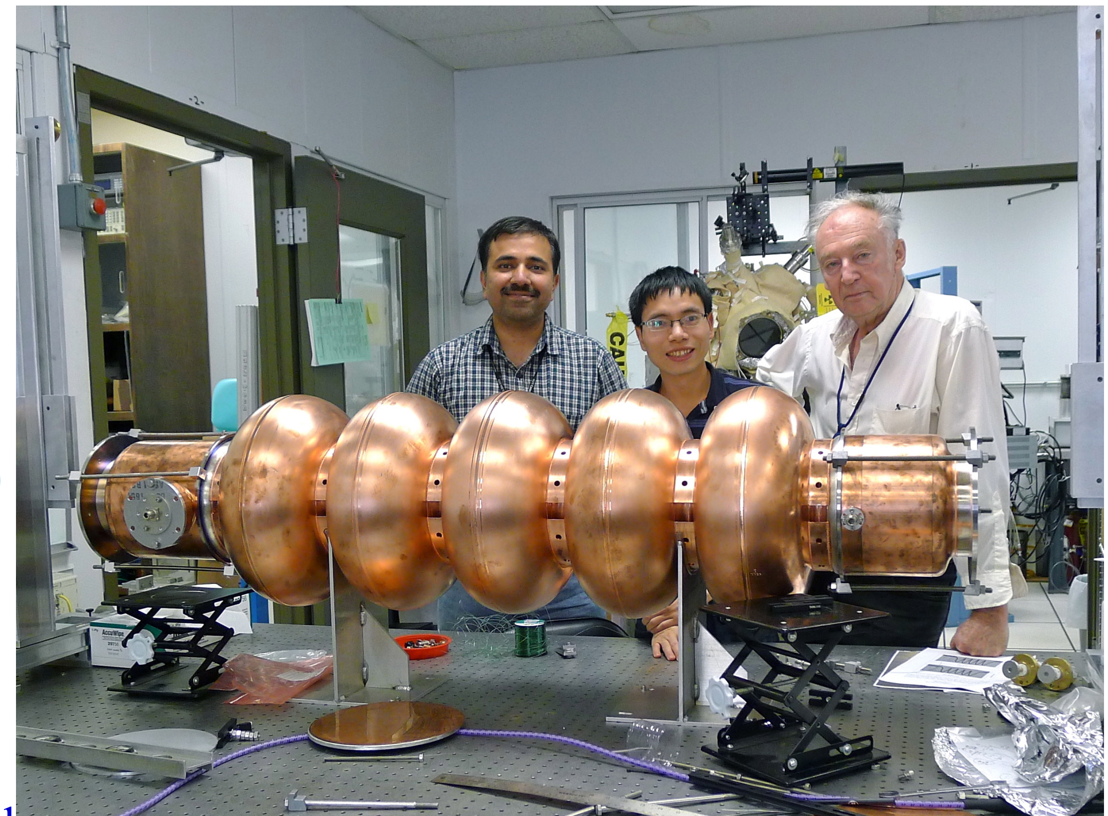
The copper cavity prototype





Cavity was fabricated by AES.

Tuned to specs (98.5% field flatness).

Acceptance measurements are finished.

Detailed HOM studies done.

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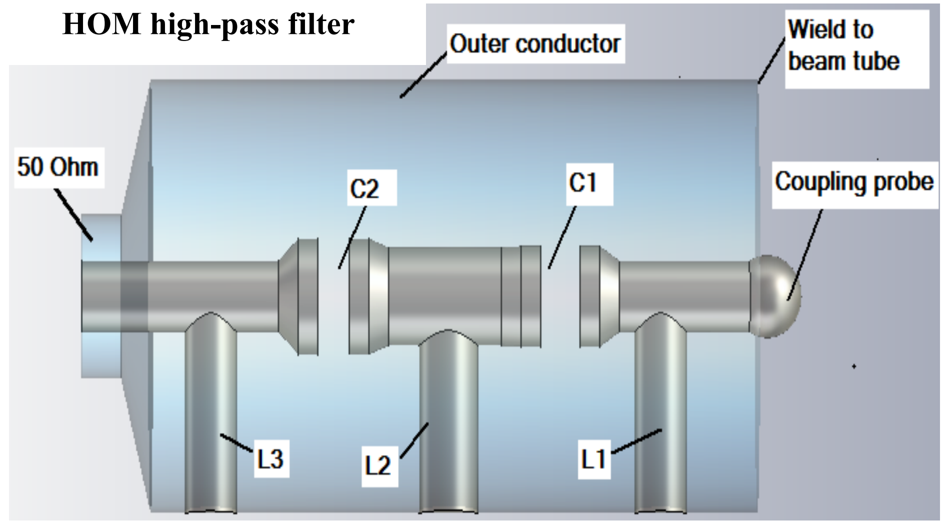
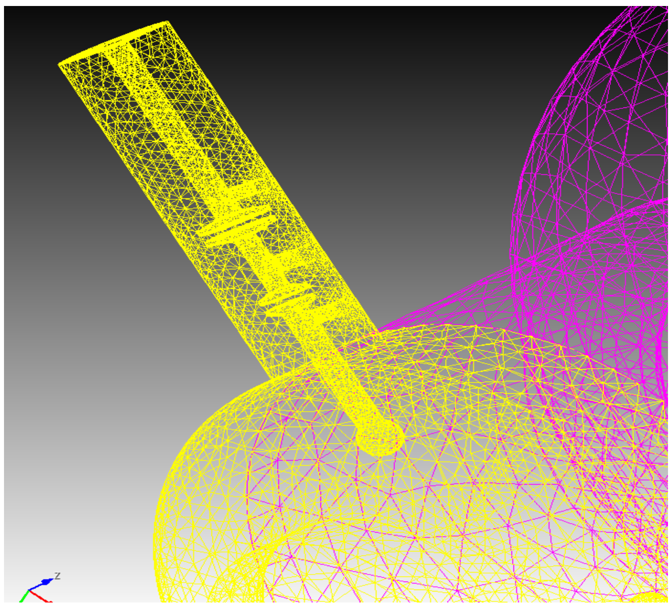
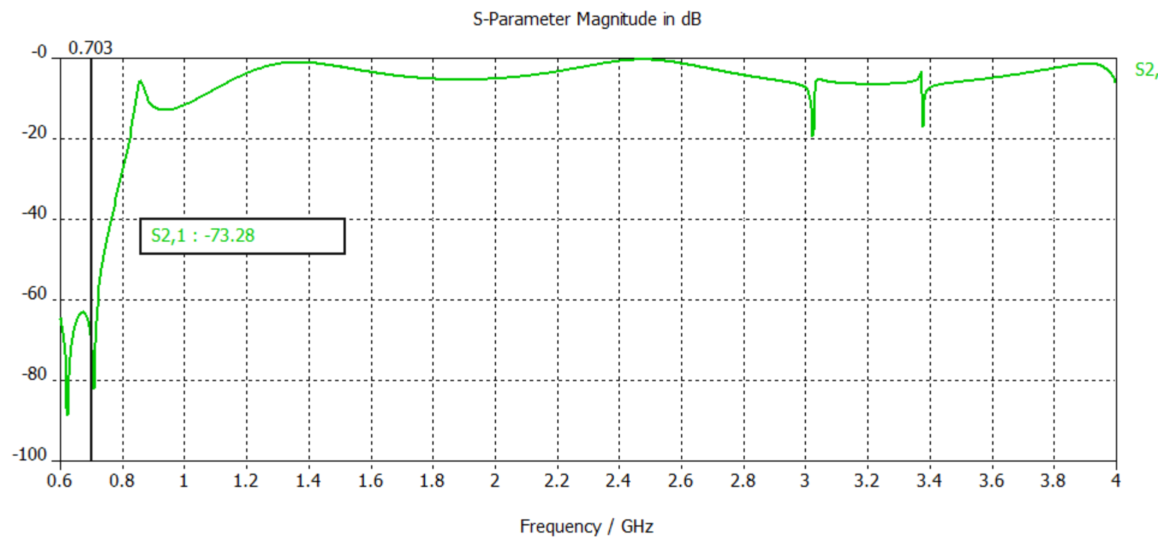
HOM damping with antenna-type couplers

- **A two-stage high-pass filter rejects fundamental frequency, but allows propagation of HOMs toward an RF load.**
  - **1st HOM is at 0.82 GHz.**

HOM high-pass filter







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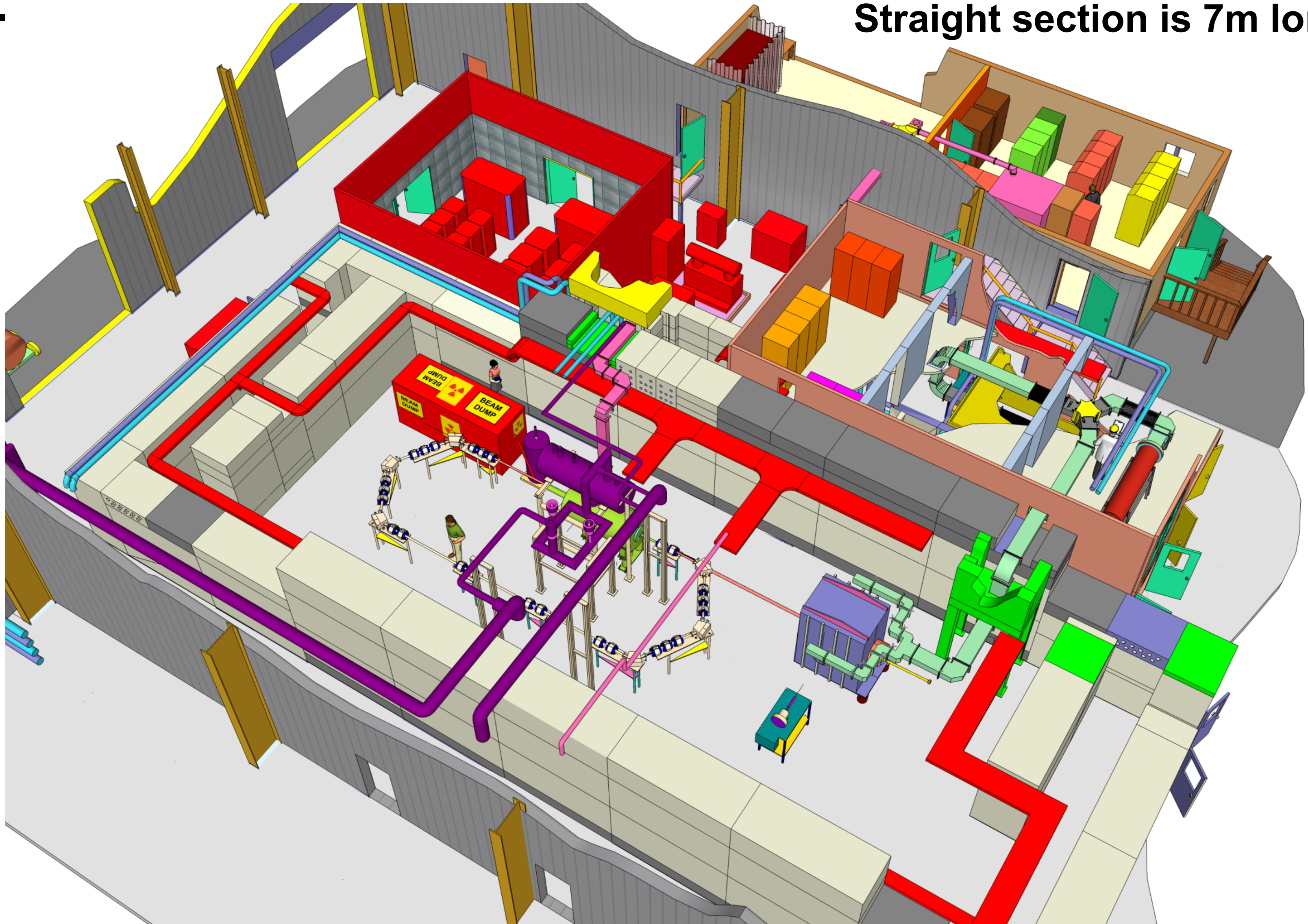
ERL layout.
Straight section is 7m long



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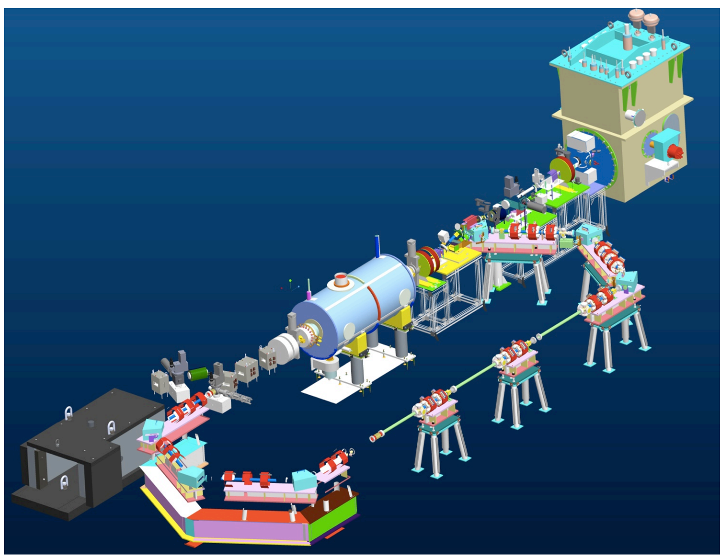
R&D ERL, target: 300 mA at 20 MeV

- **Test the key components of the High Current SRF ERL**
- **Test the beam current stability criteria for CW beam currents**
  - measure beam quality
  - measure halo
  - measure spurious radiations



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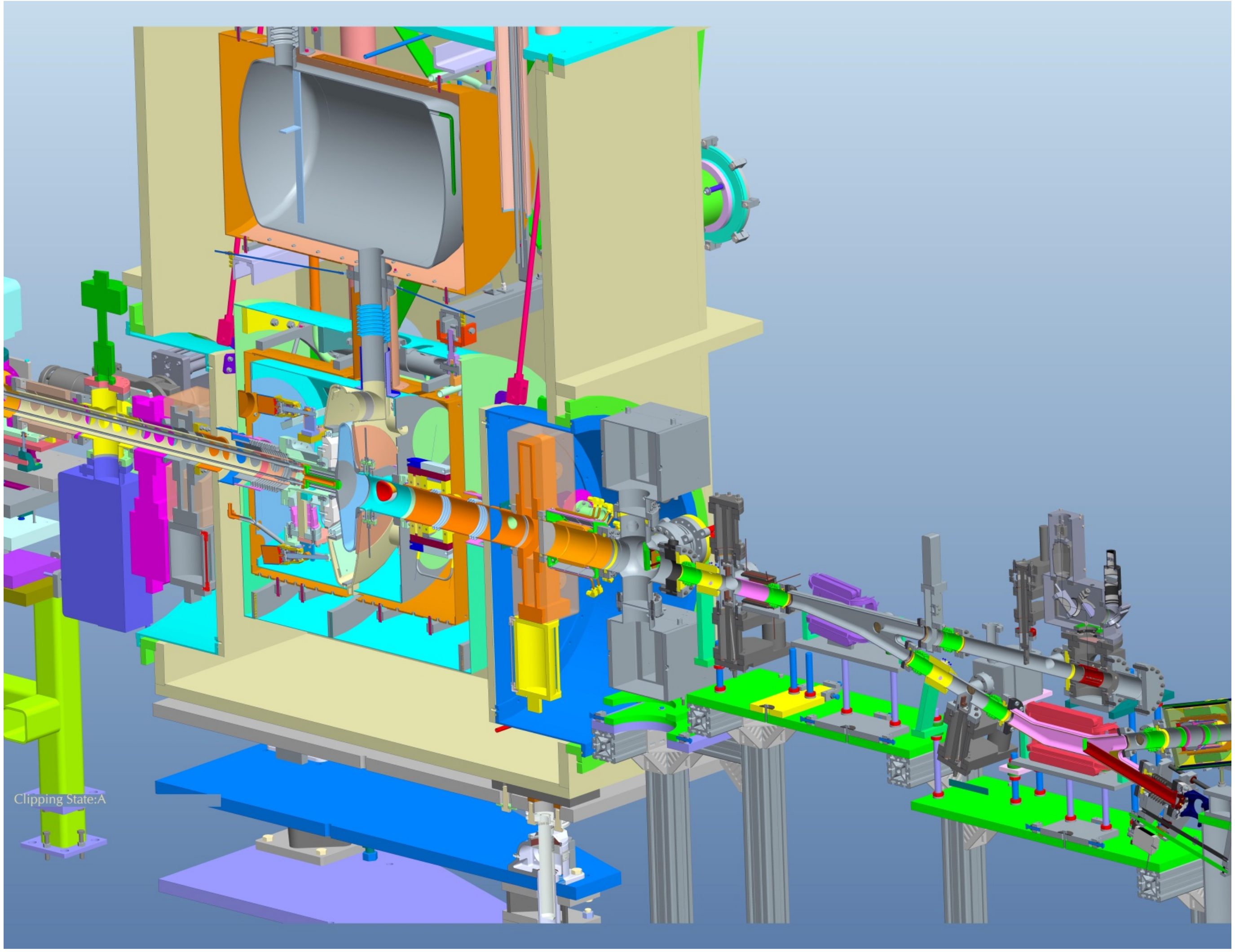
SRF Photocathode RF gun

Cut-away view of the 704 MHz elliptical half-cell SRF gun.

Photocathode injection is on the left, beam transport is on the right.



SRF Photocathode RF gun

- The 704 half-cell elliptical shape SRF gun has two Fundamental input Power Couplers (FPCs) allowing to deliver 1 MW of RF power to 0.5 A - 2 MeV electron beam.
- HOM damping is provided by an external beam-line ferrite load with ceramic break.

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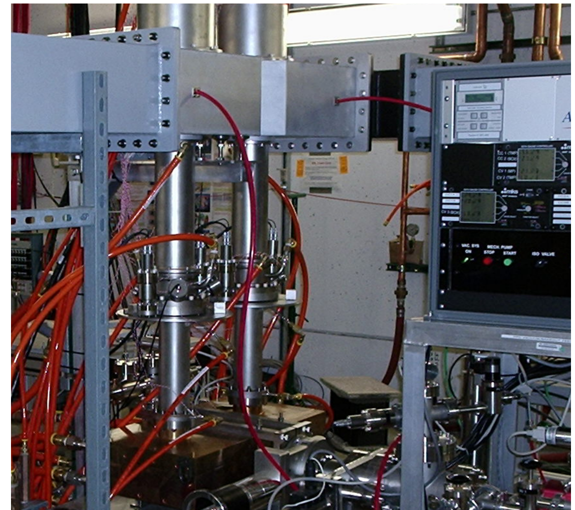
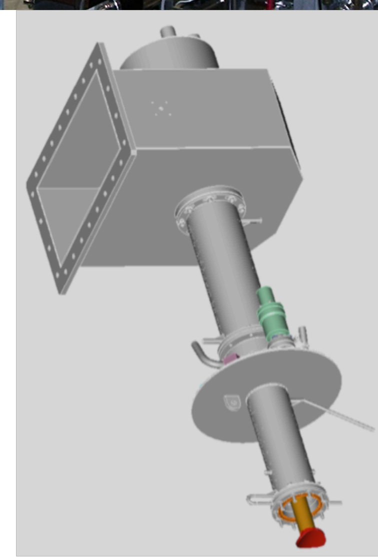
Fundamental Power Coupler



2X 500 kW RF couplers built for 703 MHz injector

- Conditioning couplers at BNL using 1 MW klystron done



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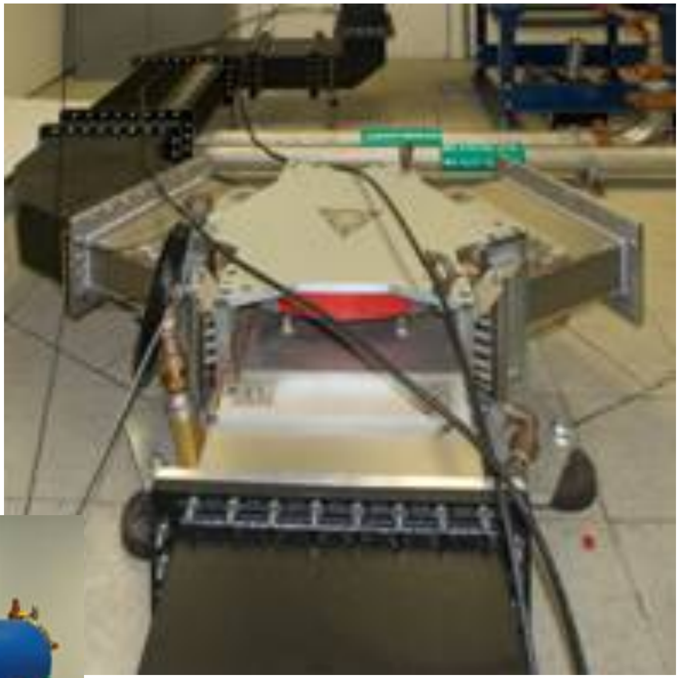
RF components



1 MW CW klystron
92kV at 17A
380 gpm of water

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Power supply for a 1 MW klystron
(as needed for 10 MeV at 100 mA)

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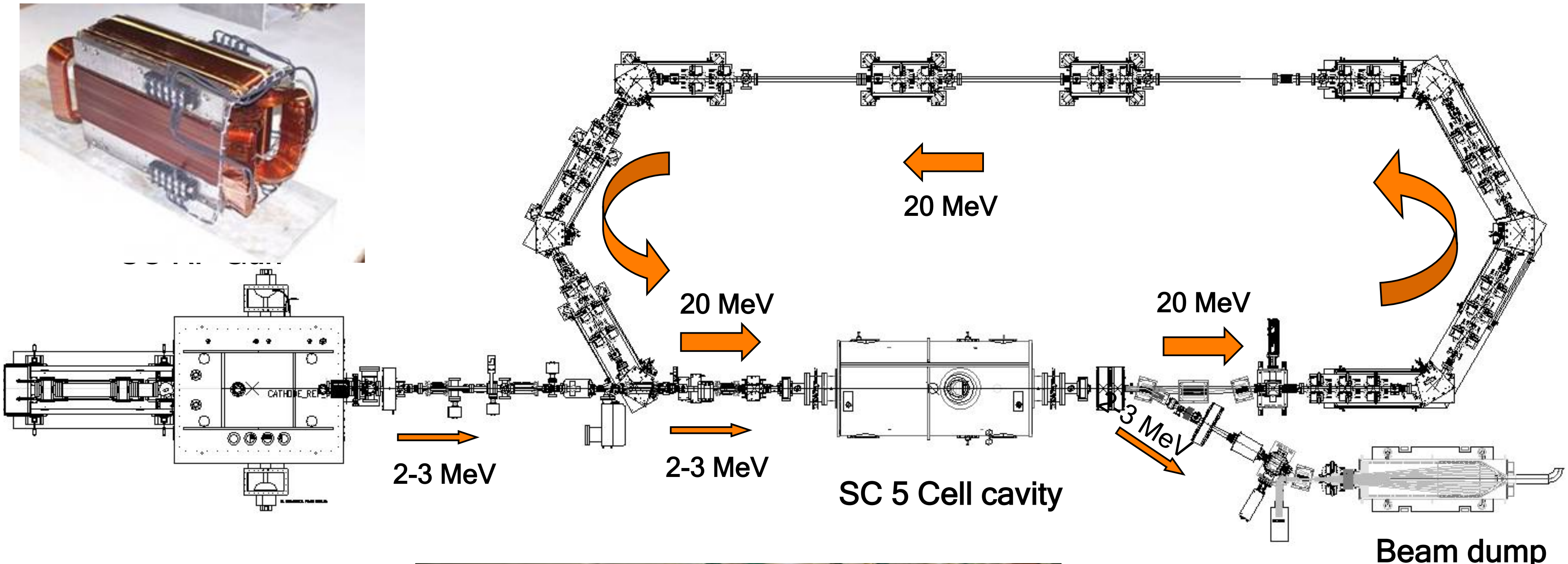
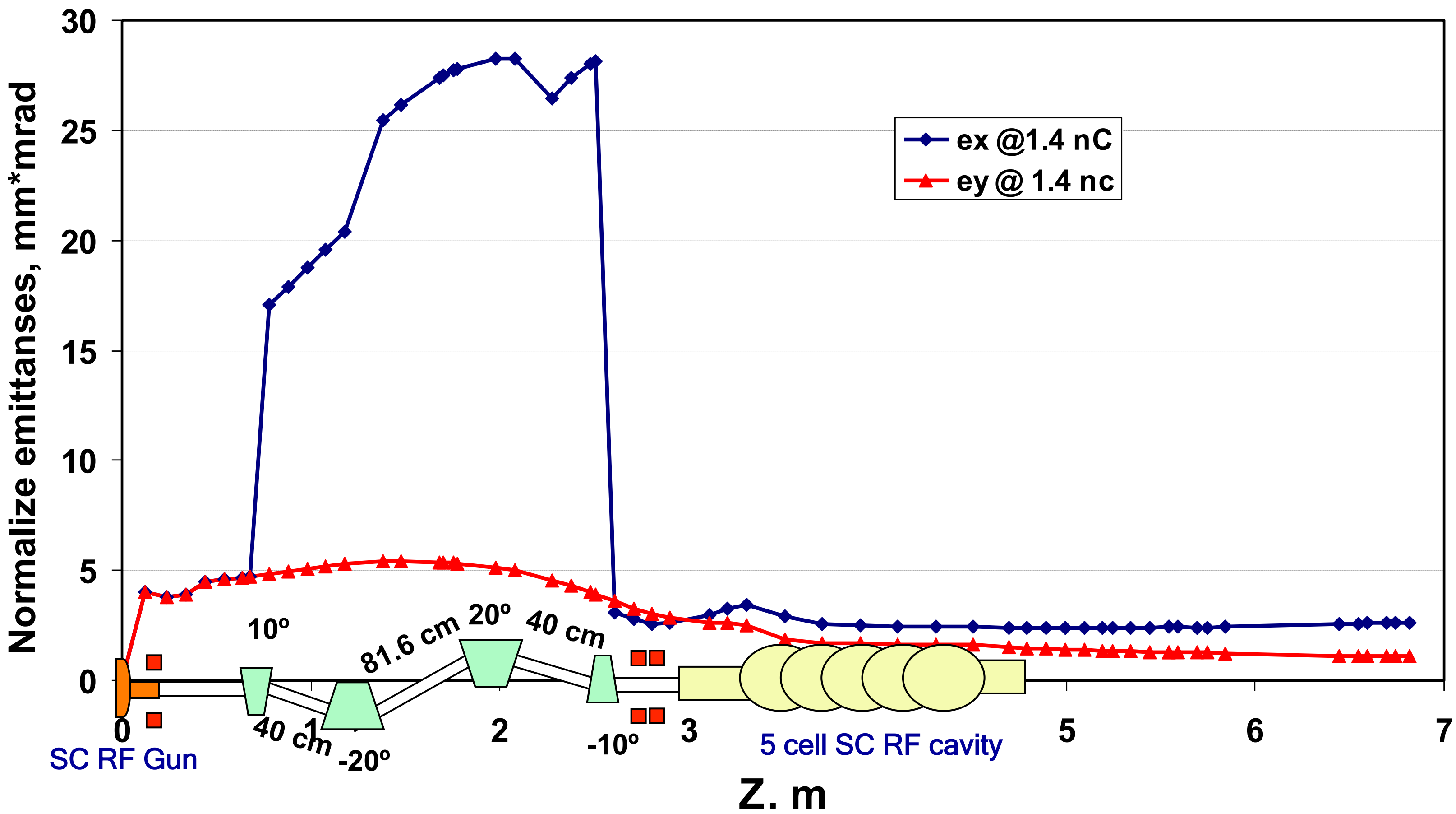
ERL layout



20 MeV
20 MeV
20 MeV
2-3 MeV
2-3 MeV
3 MeV
SC 5 Cell cavity
Beam dump

Emittance - at the end of the linac



Emittances as a function of path length from the cathode to the end of the linac.

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PARMELA simulation results in two operating regimes

	High Current	High charge
Charge per bunch, nC	0.5	5
Numbers of passes	1	1
Energy maximum/injection, MeV	20/2.5	20/3.0
Bunch rep-rate, MHz	700	9.383
Average current, mA	350	50
Injected/ejected beam power, MW	1.0	0.15
R.m.s. Normalized emittances ex/ey, mm*mrad	1.4/1.4	4.8/5.3
R.m.s. Energy spread, $\delta E/E$	3.5×10^{-3}	1×10^{-2}
R.m.s. Bunch length, ps	18	31

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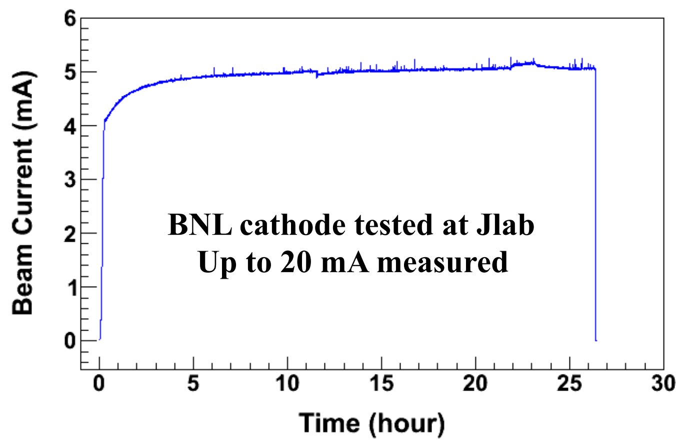
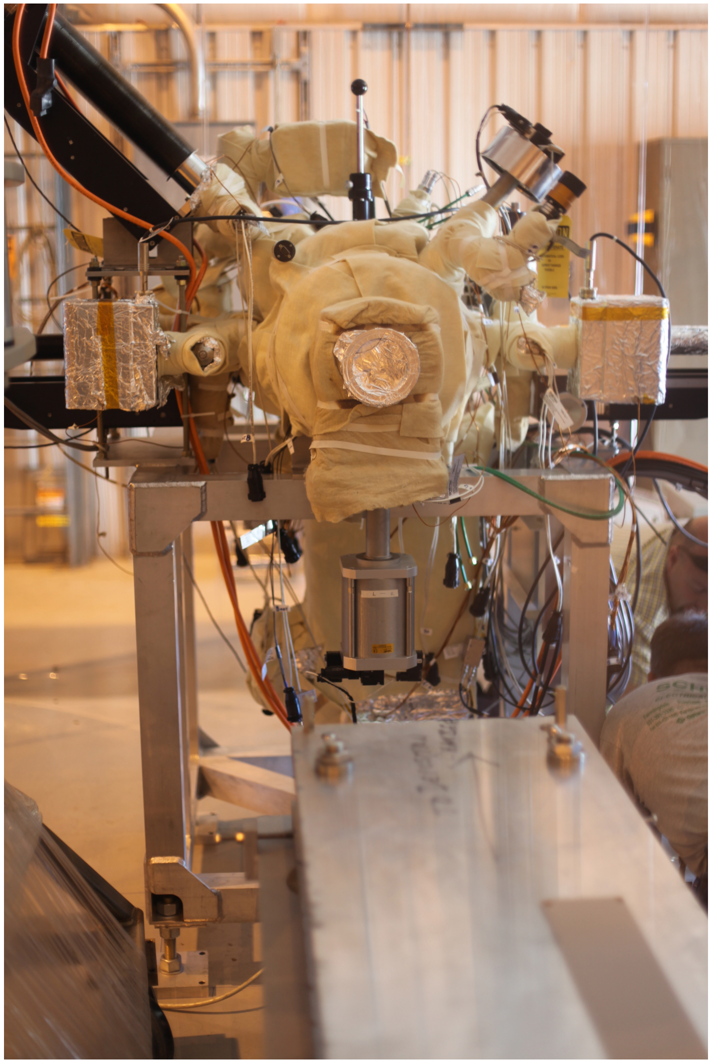
High QE Photocathode for RF gun

Deposition System

- Base pressure 1x10^{-10} Torr
- System designed to eliminate cross contamination of sources
- Robust CsK2Sb photocathode, high QE (8%) and low thermal emittance (0.37 microns / mm-rms) at a wavelength of 543 nm.





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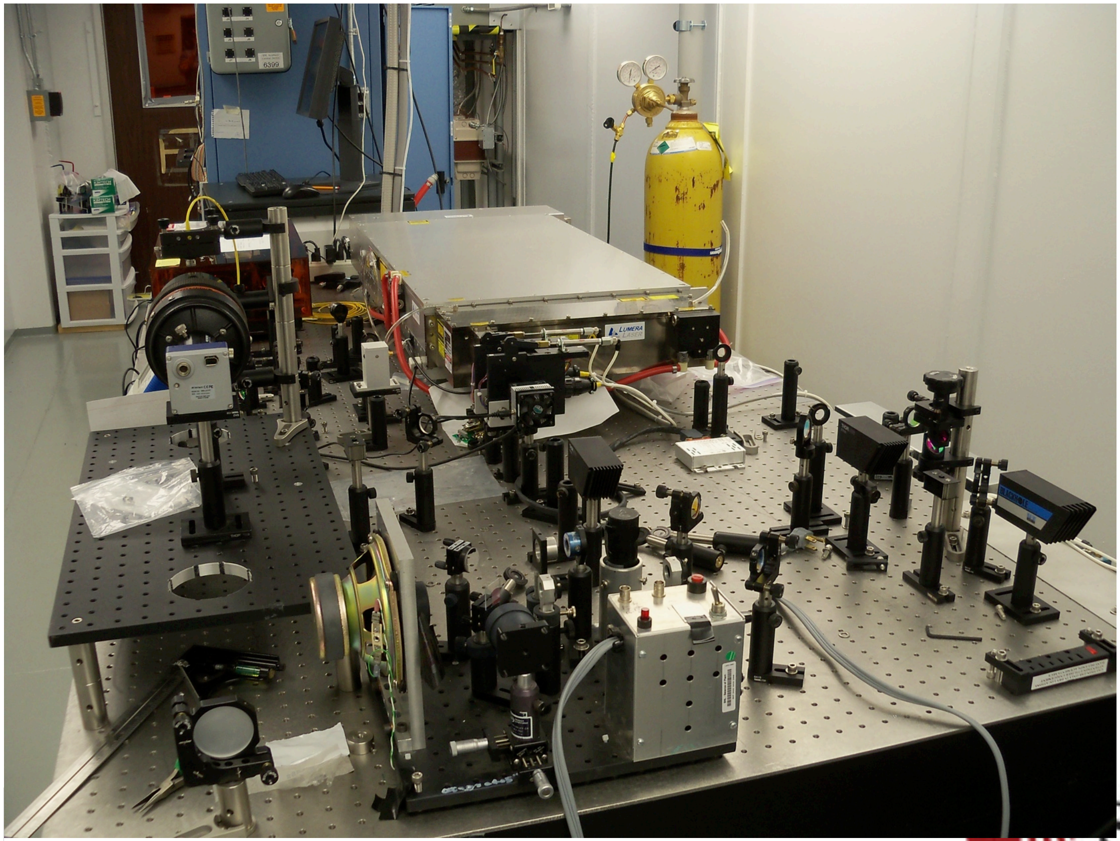
Photocathode laser

- Lumera 5 W, 355 nm, 10 ps, 9.38 MHz laser system
- Will be operated at 532nm, 355nm, and 266nm
- Climate controlled, 1C/hour, Humidity +/- 2%/hour HEPA Filters



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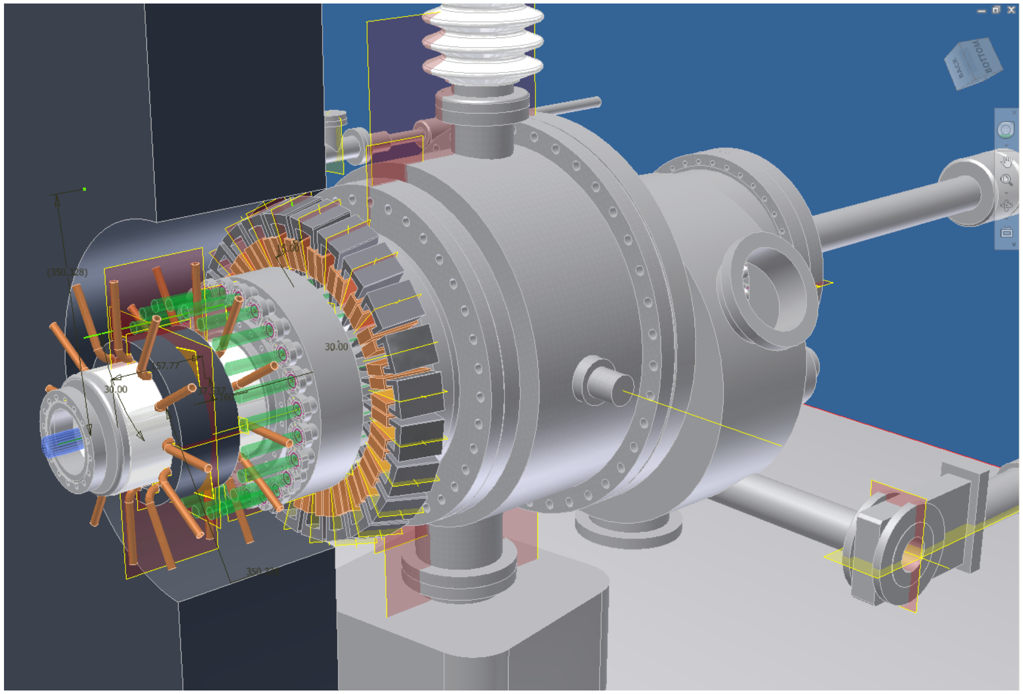
20 cathode funneling polarized electron gun "Gatling Gun"

A current of a few mA has been demonstrated by the Jefferson Laboratory group with good charge lifetimes. While this performance is expected to improve with additional research, can we multiply the number of cathodes to get a large increase in the charge-lifetime?

The "Gatling Gun" R&D program is set to examine this question in a 20-cathode funneling system. The key question is the "cross-talk" due to the common vacuum system in an otherwise independent cathodes.



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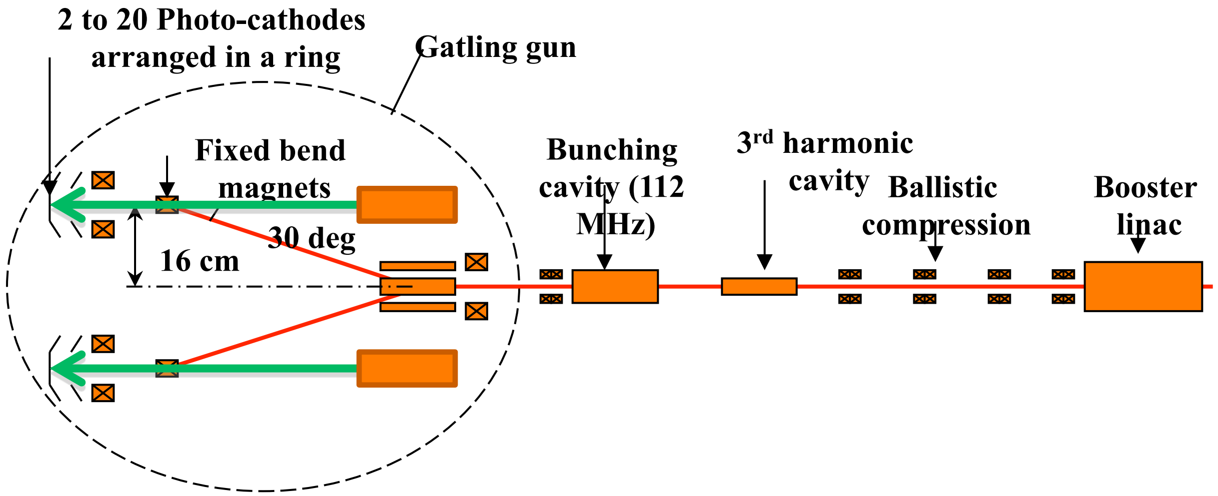
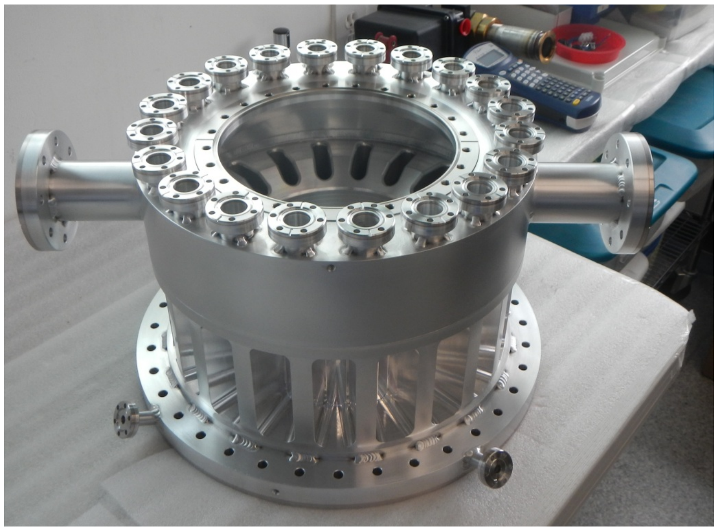
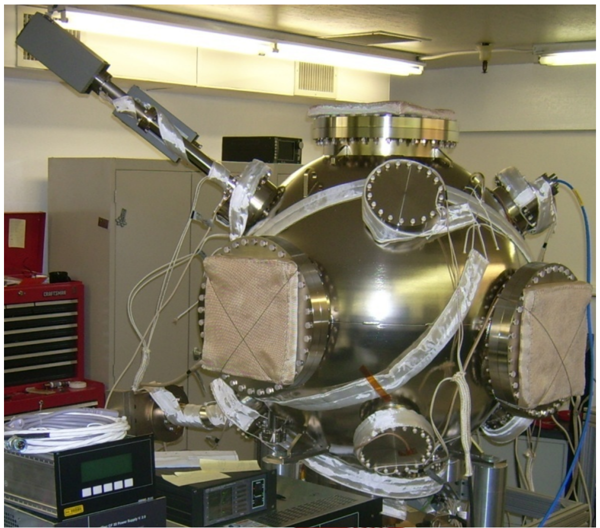
20 cathode funneling polarized electron gun ("Gatling Gun")







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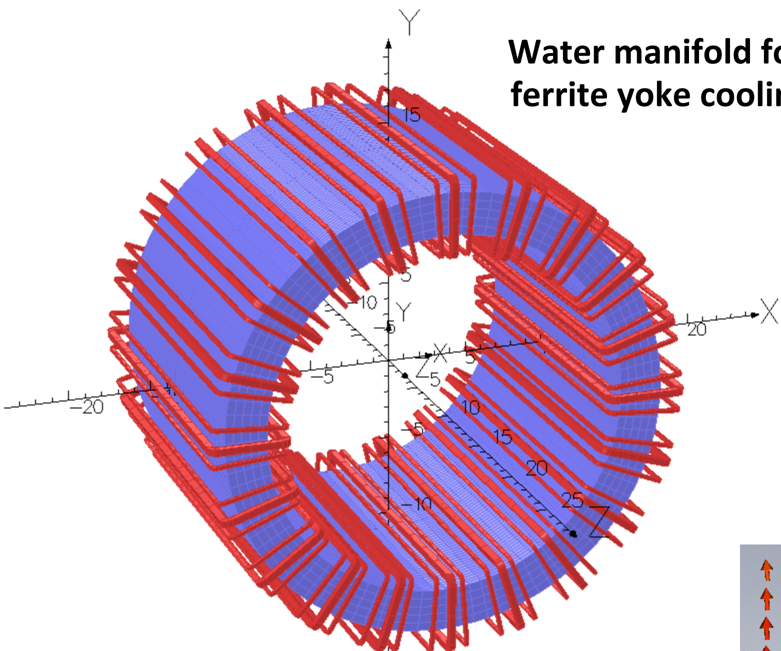
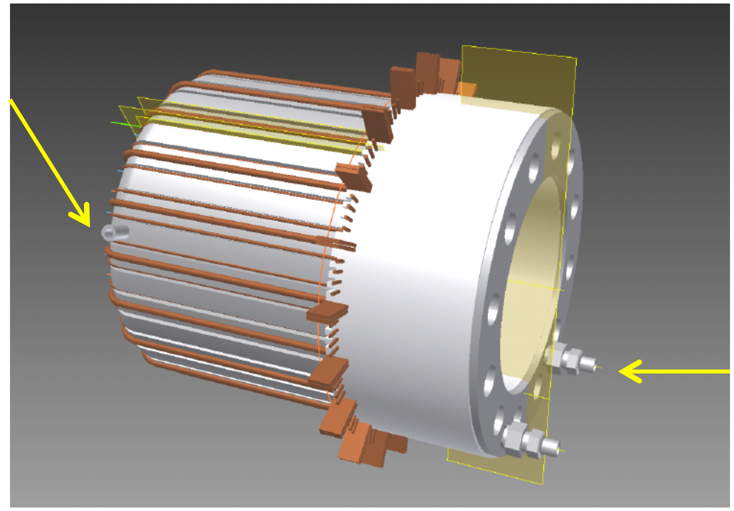
Beam Combiner

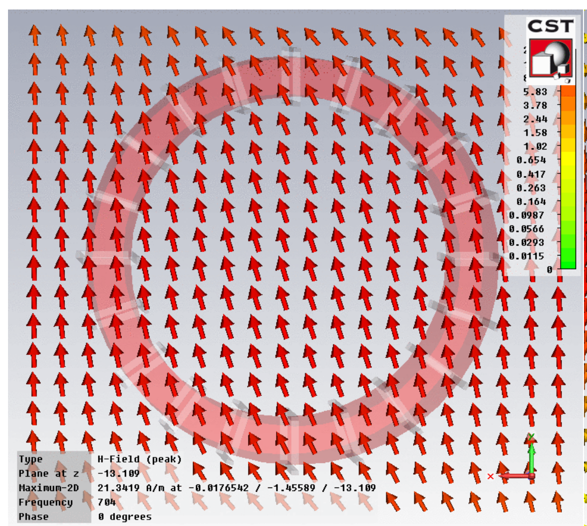


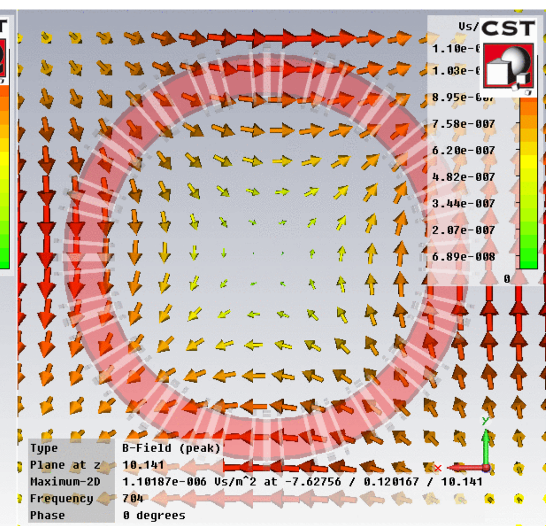
Water manifold for ferrite yoke cooling



Water manifold for coil cooling

•Bending the beam by dipole
•Equalize the focusing by quadrupole
•Parameters:
$I(t)=I_{od}*\cos(\omega t+\phi)$ where I_{od}=70.7A
$I(t)=I_{oq}*\cos2(\omega t+\phi)$ where I_{oq}=1.54A
B(0,0,0)=25.04G
Freq=704kHz
Bending angle=29 degrees





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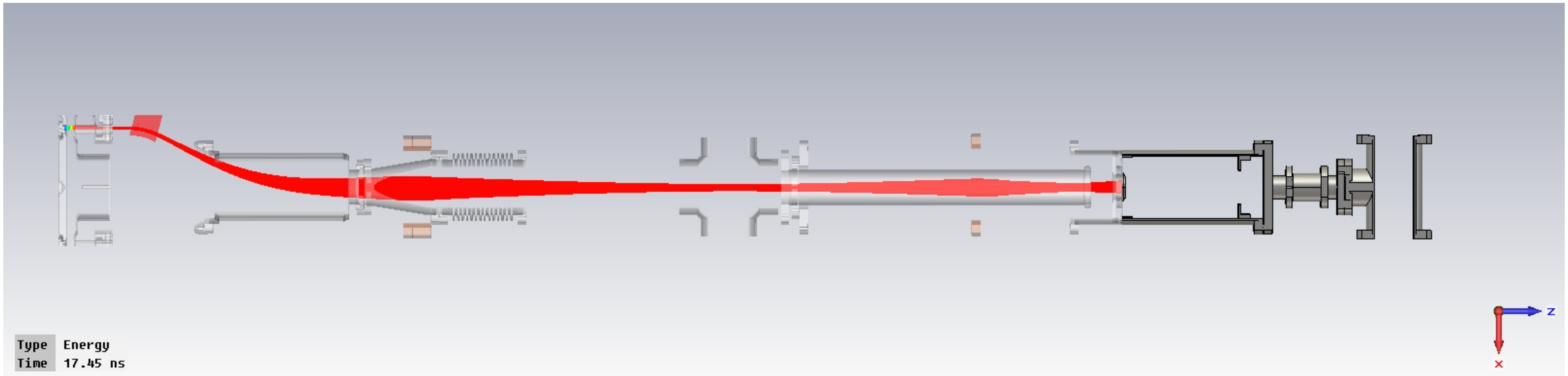
Tracking with space charge the entire beam line



Particle tracking with space charge.
On diagnostic :
•Divergence angle: X'/Y'=23.6mrad/25.1mrad
•Beam profile: X/Y=15.0mm/15.2mm
•$\varepsilon_{n,x}$/ $\varepsilon_{n,y}$ =20.5mm-mrad/20.1mm-mrad

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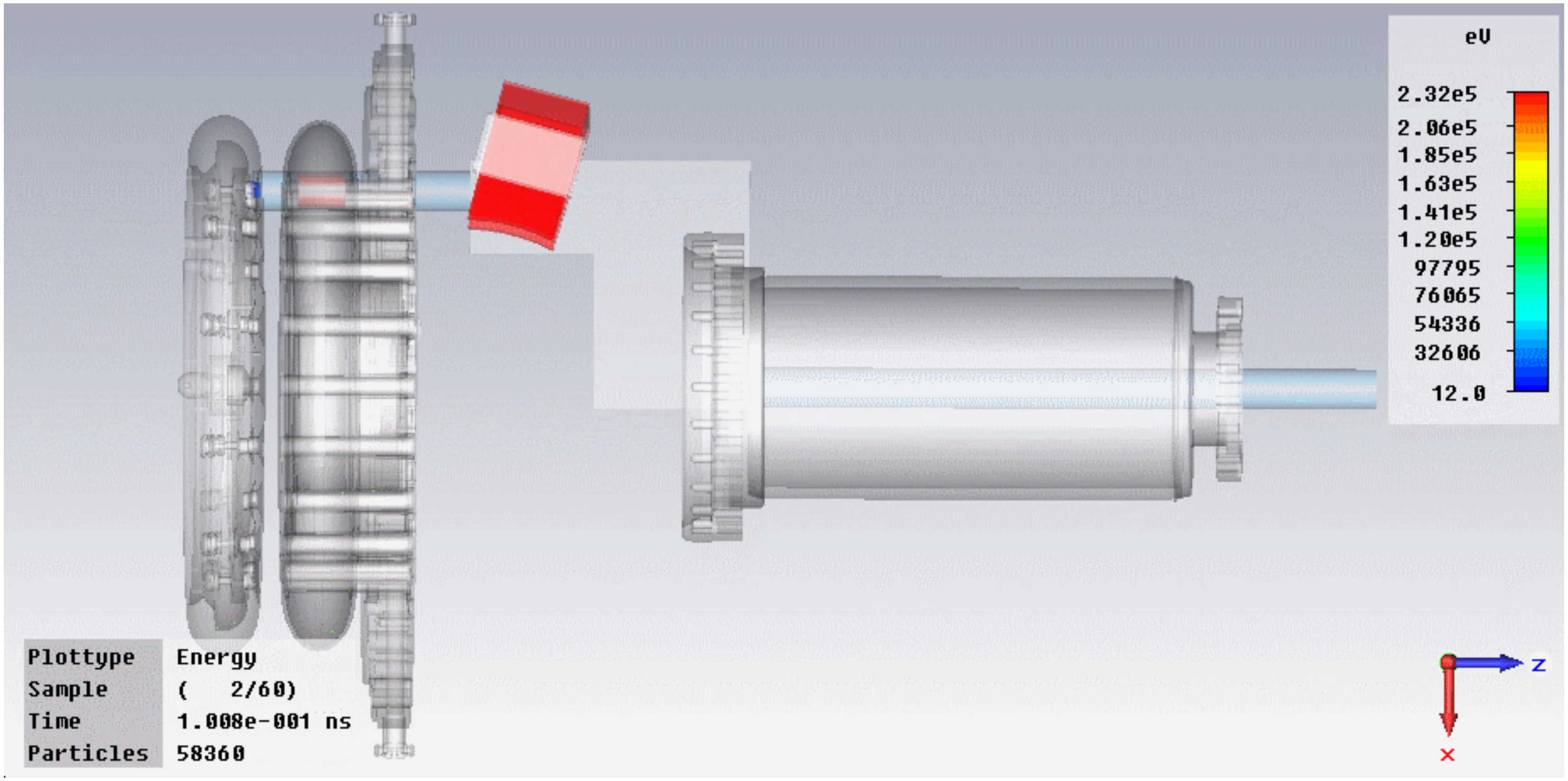
Beam motion by 3-D Particle In Cell code



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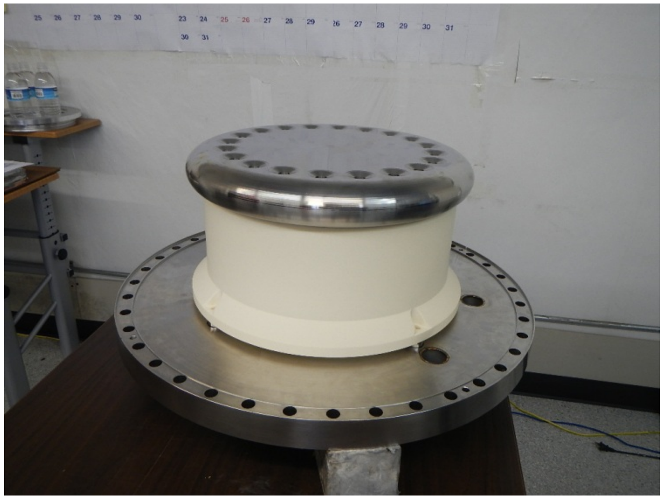
XHV vessels 10^{-12} Torr scale vacuum achieved

Left: Cathode preparation chamber; Right: Main gun vessel

20 cathode XHV stainless steel shroud assembly



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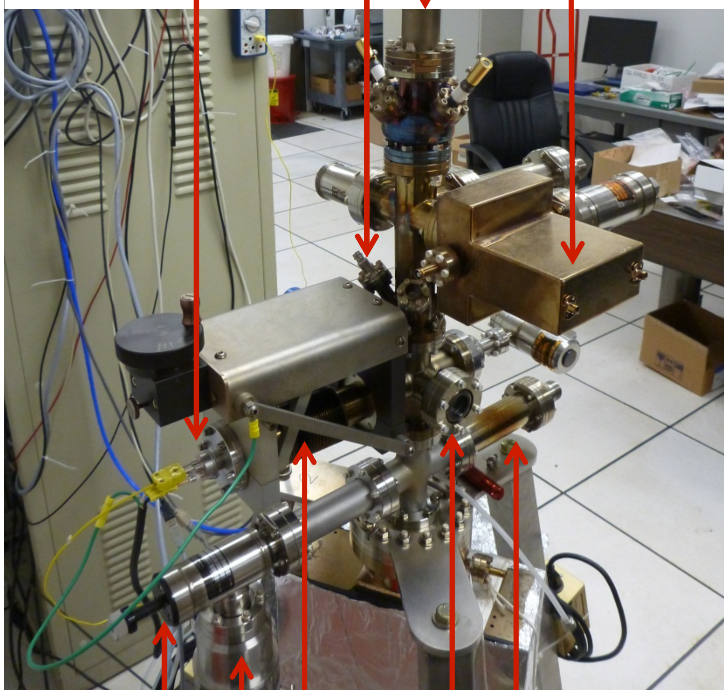
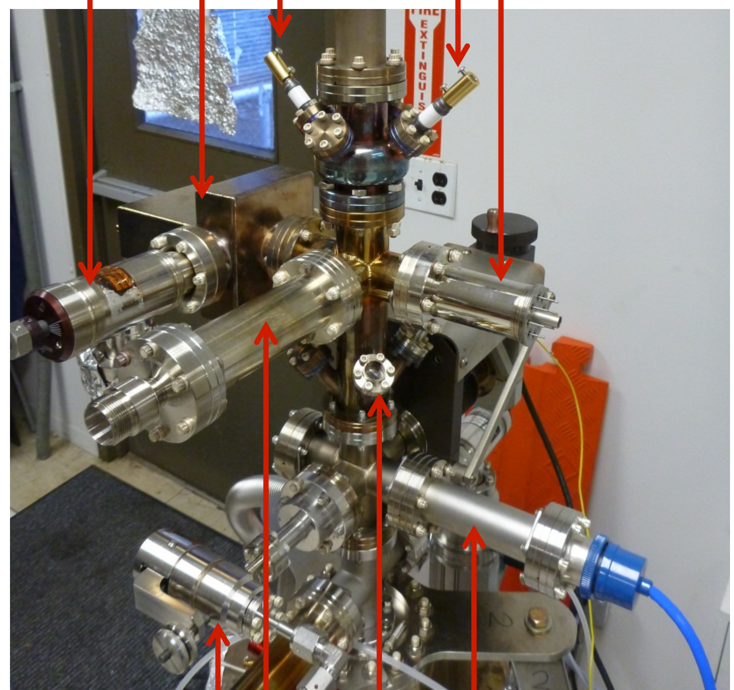
Setup for single cathode tests





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Summary

- R&D is currently carried out on the eRHIC collider design, including various elements of the ERL, some of which are:
  - The 50 mA polarized electron gun
  - A 300 mA 20 MeV R&D ERL
  - Highly-damped 704 MHz 5-cell ERL cavities
- This research is highly relevant to a high-current, high-polarization and high-brightness medium energy ERL.

Backup slides

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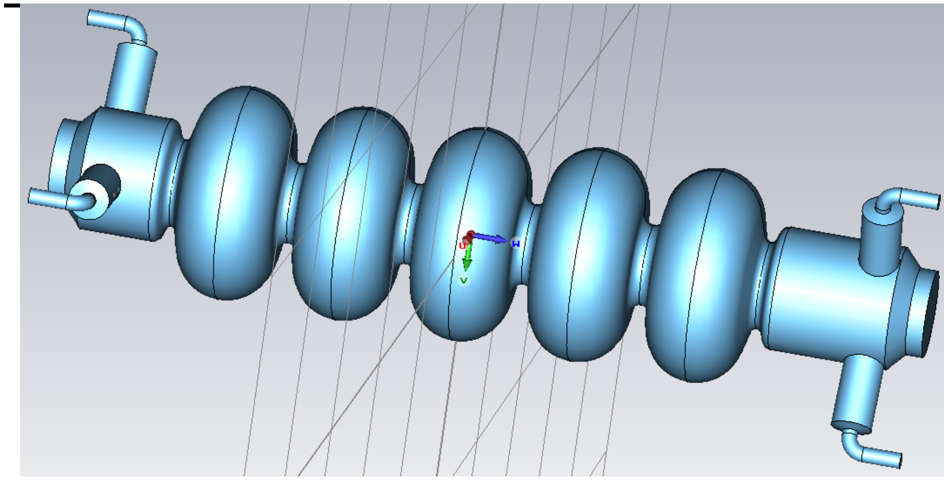
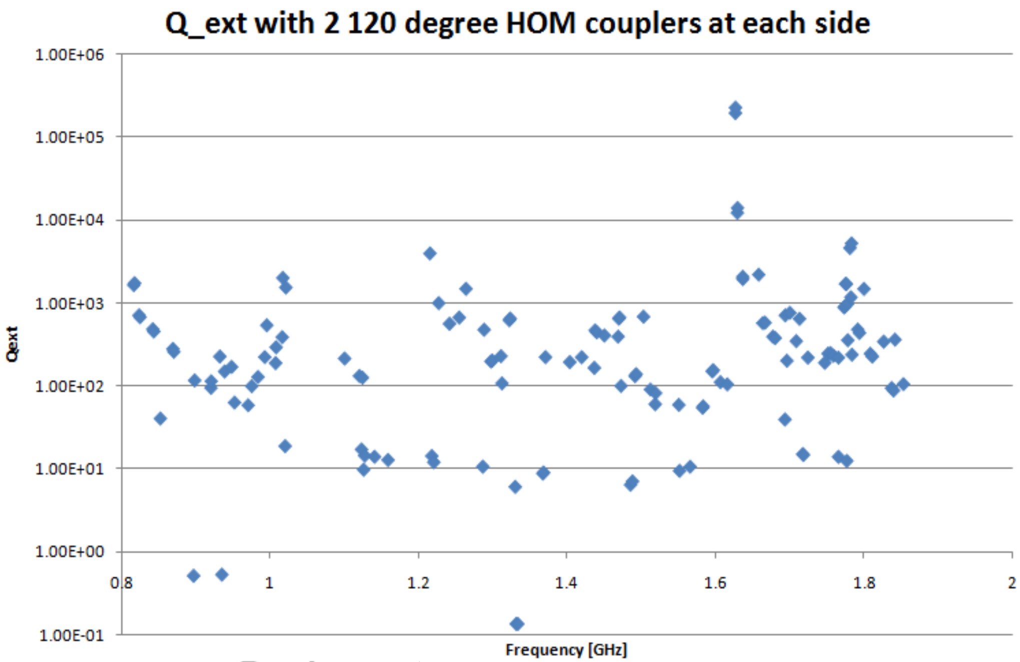
HOM damping





- Damping of dipole modes has been considered important to avoid beam breakup (BBU).
- We simulated a model with just two HOM couplers per side using CST MWS, showing excellent damping.
  - Modes at 1.62 GHz have R/Q of ~0.1 Ohm.
- Recent work by Vladimir Litvinenko points to a method of avoiding BBU by using the chromaticity in the ERL. See presentation MOPB034 in this conference.

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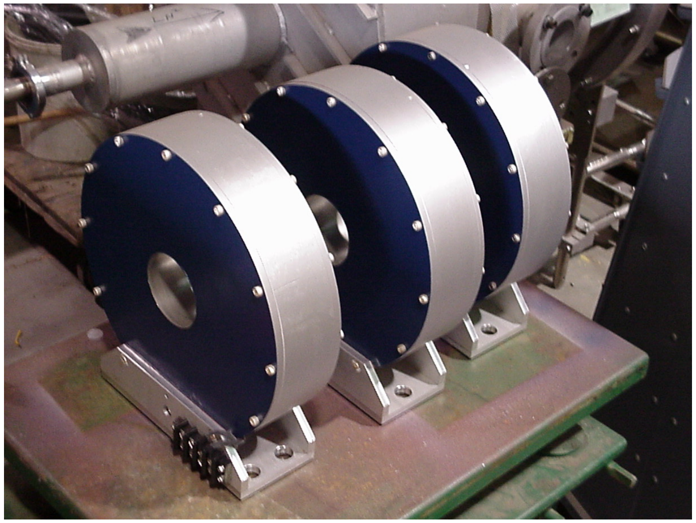
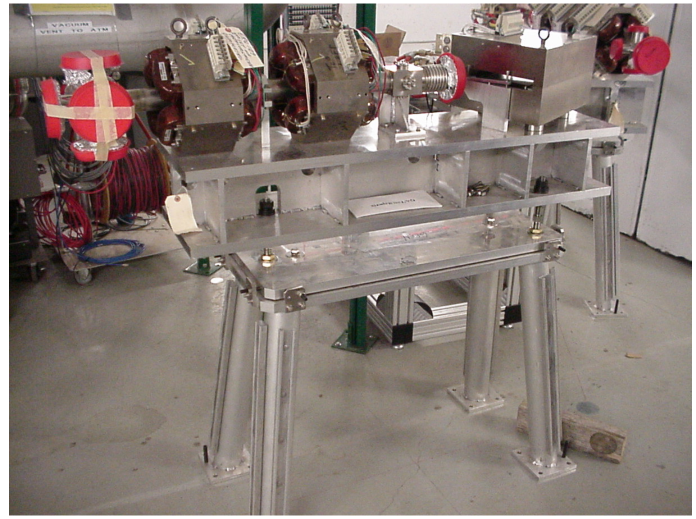
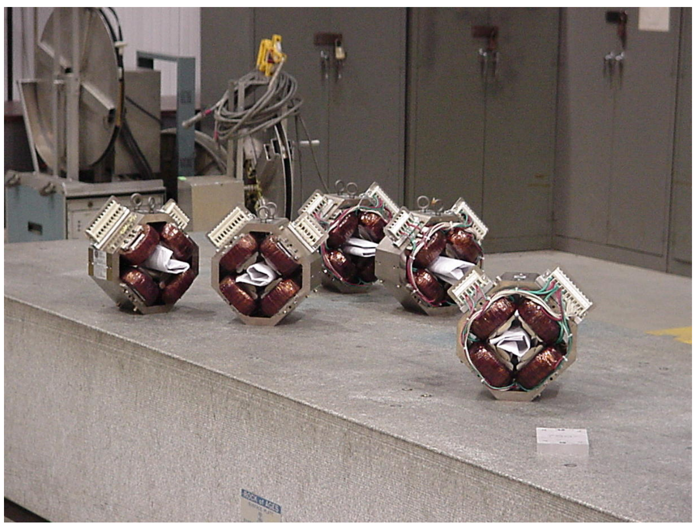
Magnets and stands







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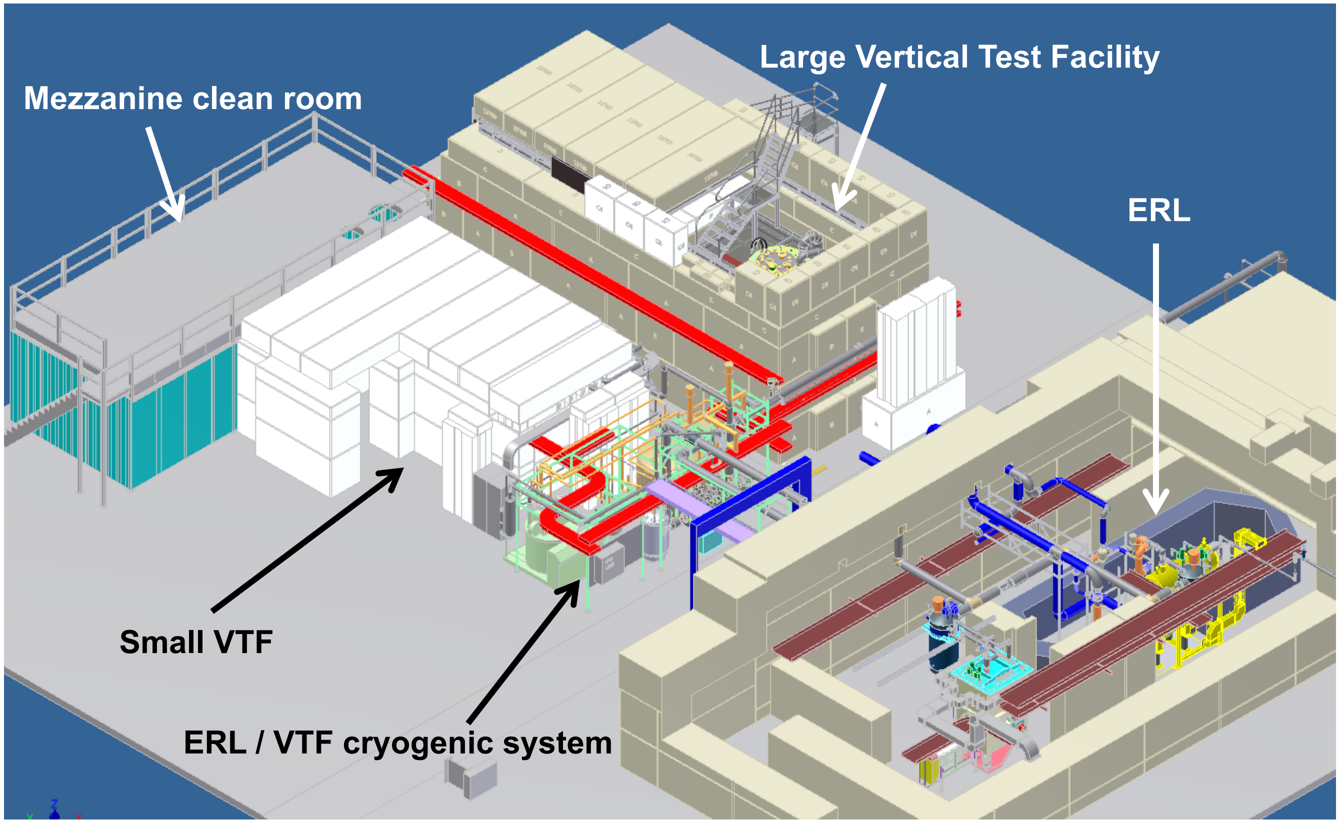
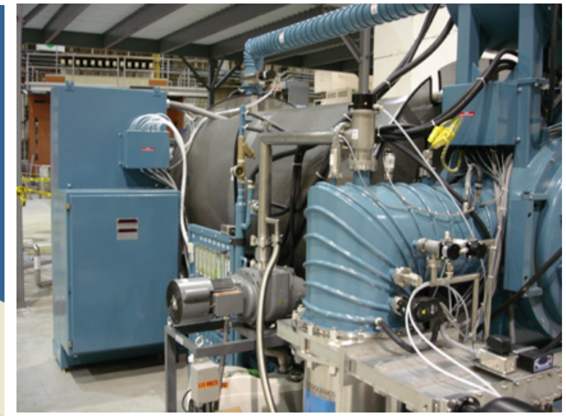
SRF test facilities in building 912



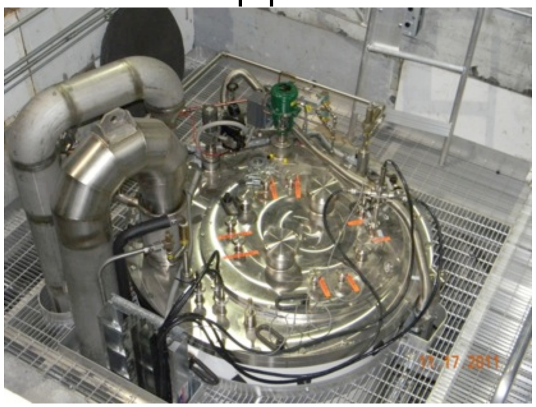
800°C vacuum oven for cavity baking



Mezzanine clean room

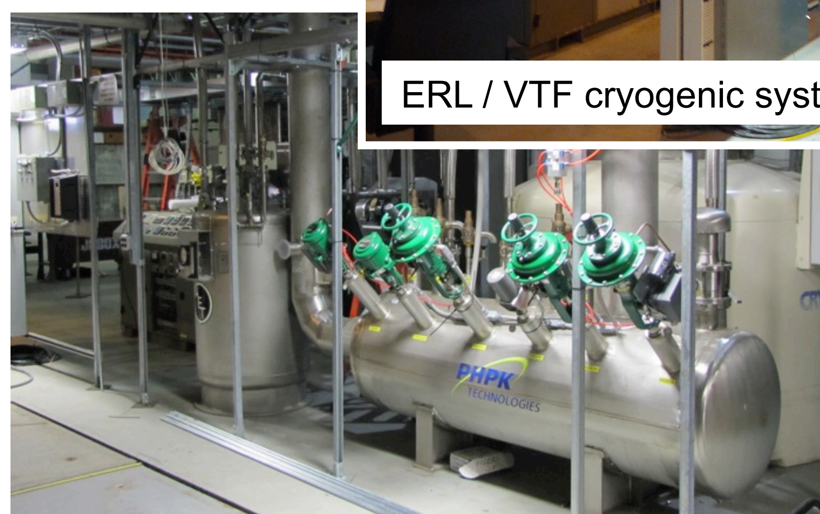
SRF test facilities in building 912 (cont'd)

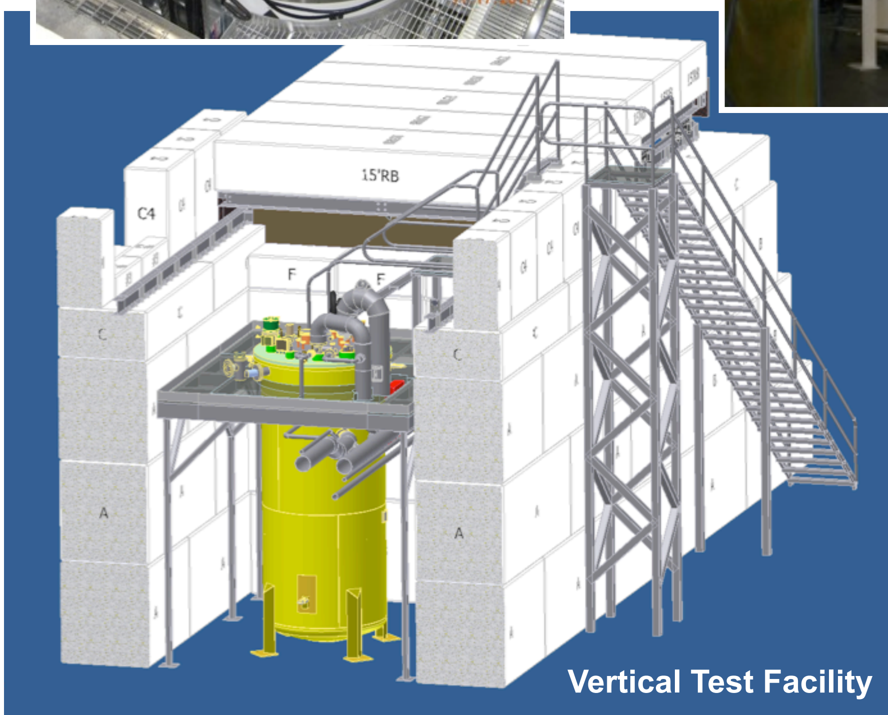
VTF dewar top plate



VTF Dewar

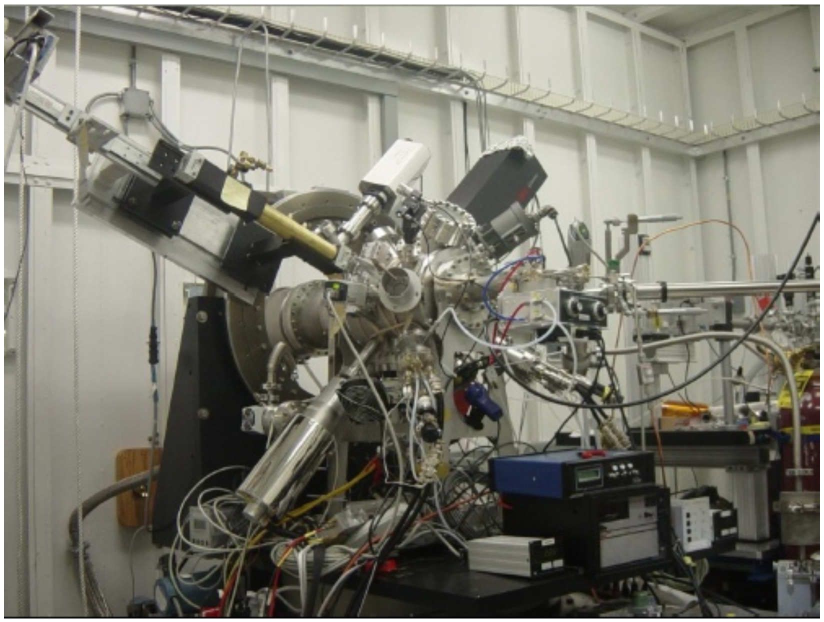
ERL / VTF cryogenic system





Vertical Test Facility

Deposition with *In Situ* Analysis



UHV system w/ Load Lock
Sb Line Source (evaporation)
Sb Sputtering
K and Cs Alvasources
SAES Getter Sources
Heat Cathode to 800C
Gas cooling
QE Measurement with 532 nm
Residual Gas Analyzer, Quartz FTM

In-Situ Diagnostics (during growth):
XRD for grain size and orientation in plane and reflection geometry
X-ray fluorescence for stoichiometry and contamination
Reflection high energy electron diffraction

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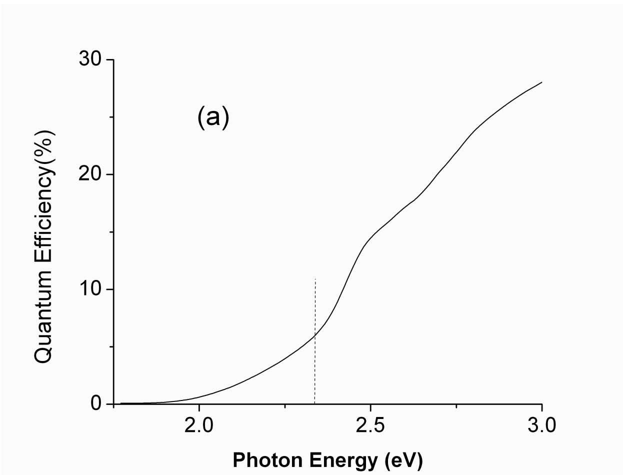
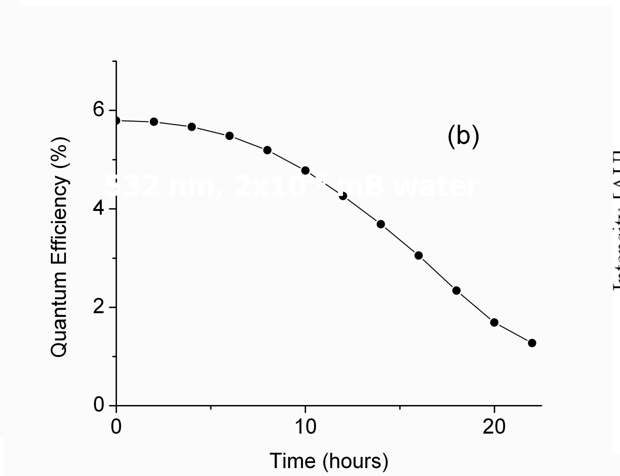
Some CsK2Sb photocathode results

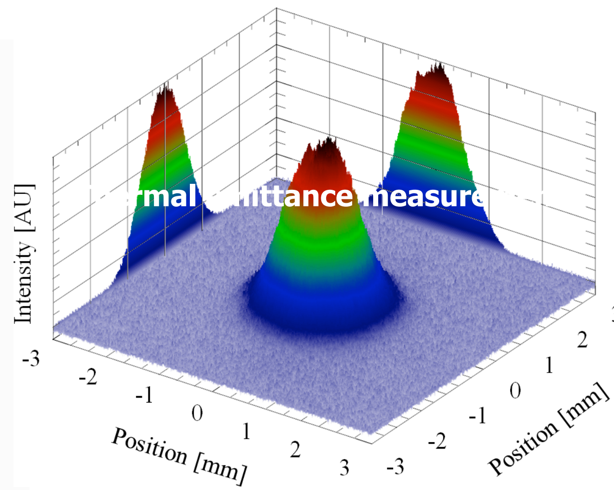
Robust CsK2Sb photocathode, high QE and low thermal emittance of 0.37 microns / mm-rms at a wavelength of 543 nm.

On-line thermal emittance measurement

Test of lifetime under various vacuum conditions







A Low Emittance and High Efficiency Visible Light Photocathode for High Brightness Accelerator-Based X-ray Light Sources, T. Vecchione, et al, Appl. Phys. Lett. 99, 034103 (2011)

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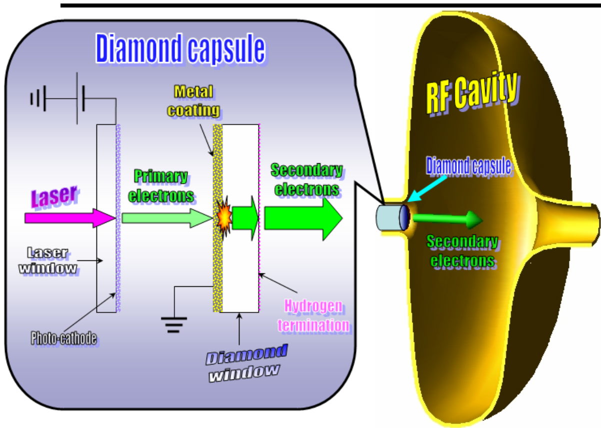
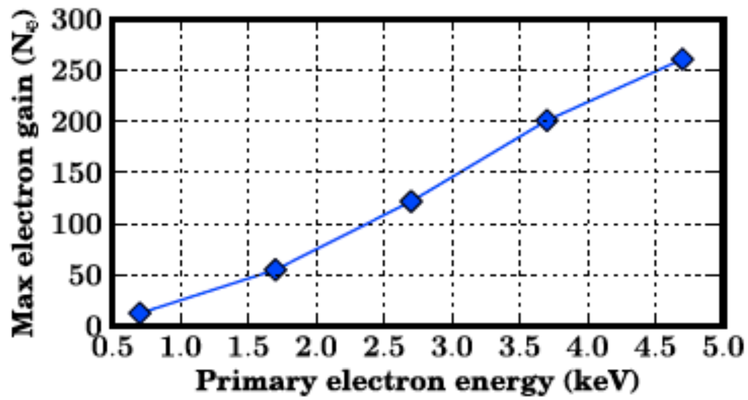
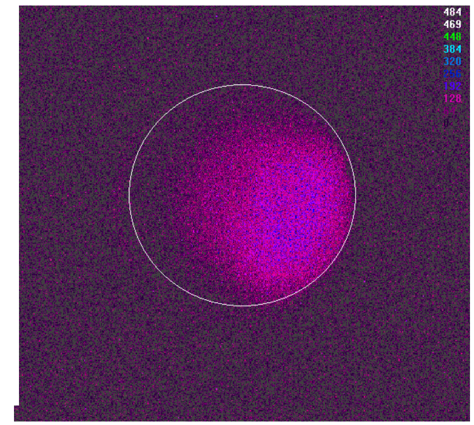
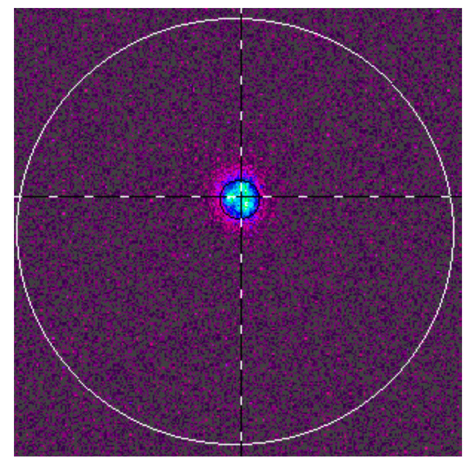
Diamond Amplifier









- **Routine diamond amplifiers with high gain into vacuum**
- **Large current density generated**
- **Samples are extremely robust**
- **Detailed simulations by Tech-X**
- **Preparation for tests in SRF gun under way**
- **PRL, PRST-AB, JAP publications**

5 nC/cm^2
Xiangyun Chang, et al,
Electron Beam Emission from a Diamond-Amplifier Cathode
PRL 105, 164801 (2010)

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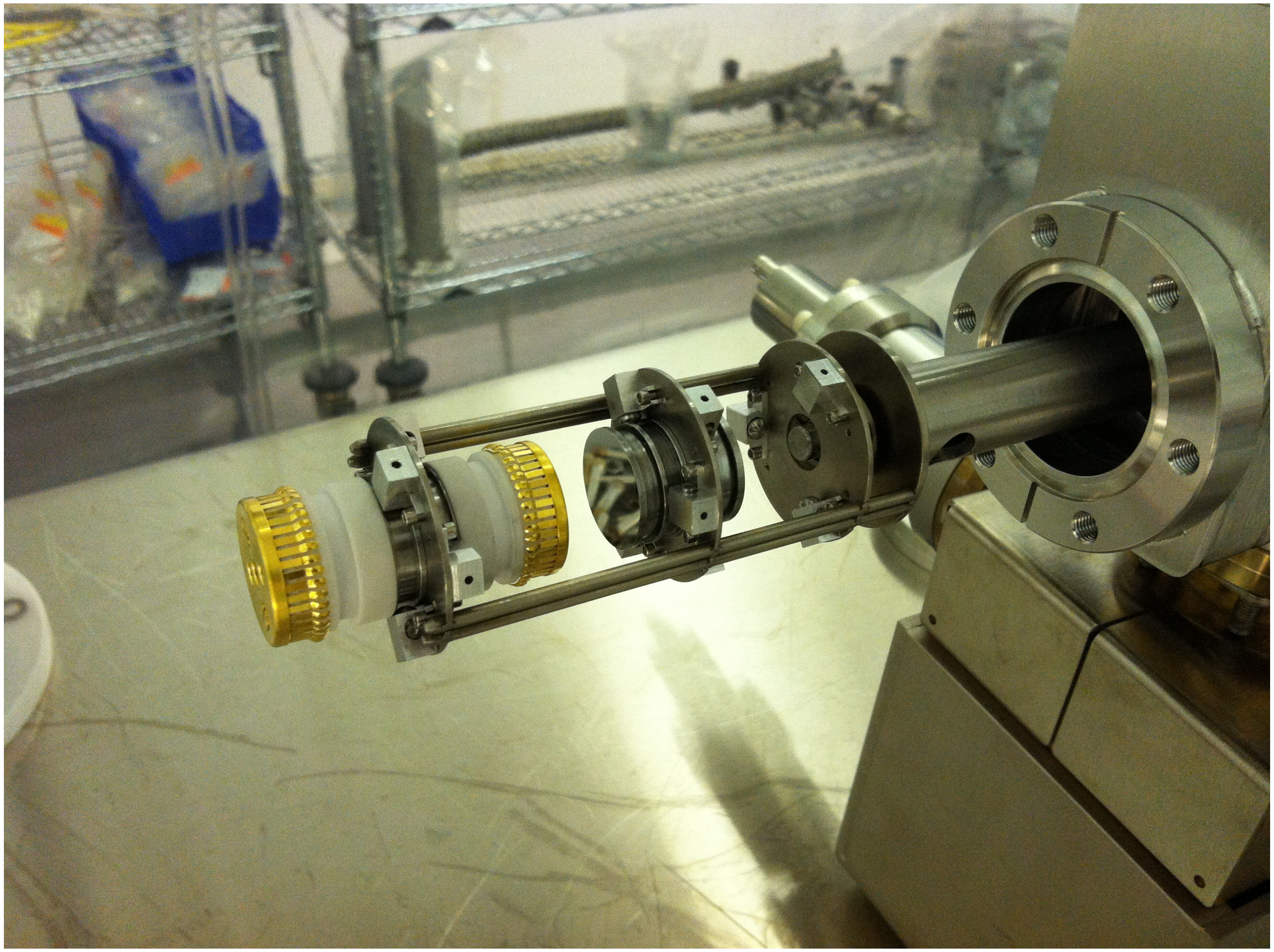
Load-lock transport for diamond amplifiers and CsK2Sb



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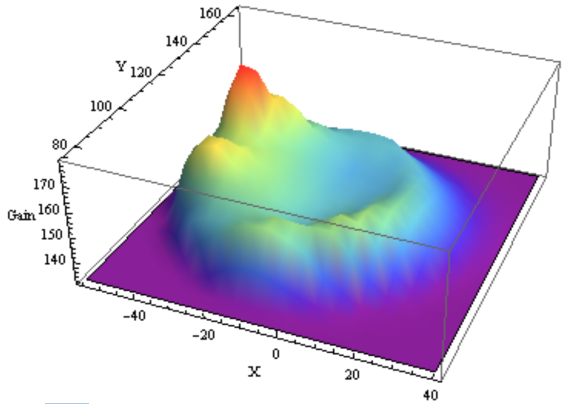
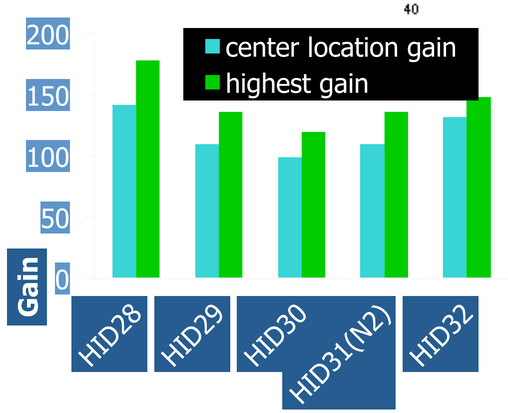
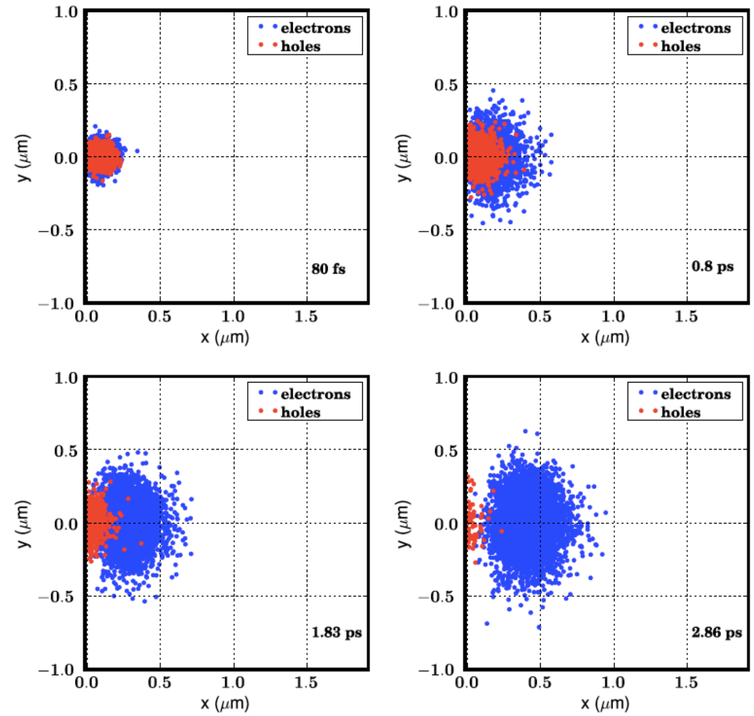
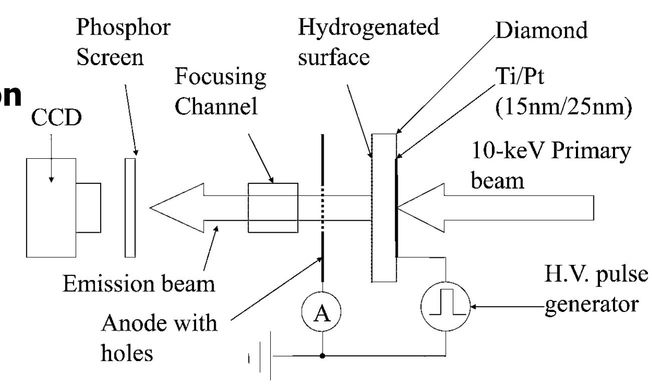
Various results from diamond amplifier R&D









Systematic study of hydrogenation in a diamond amplifier
Erdong Wang, et al
Phys. Rev. ST Accel. Beams
14, 061302 (2011)

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D. A. Dimitrov, et al,
Multiscale three-dimensional simulations of charge gain and transport in diamond,
JOURNAL OF APPLIED PHYSICS
108, 073712 (2010)

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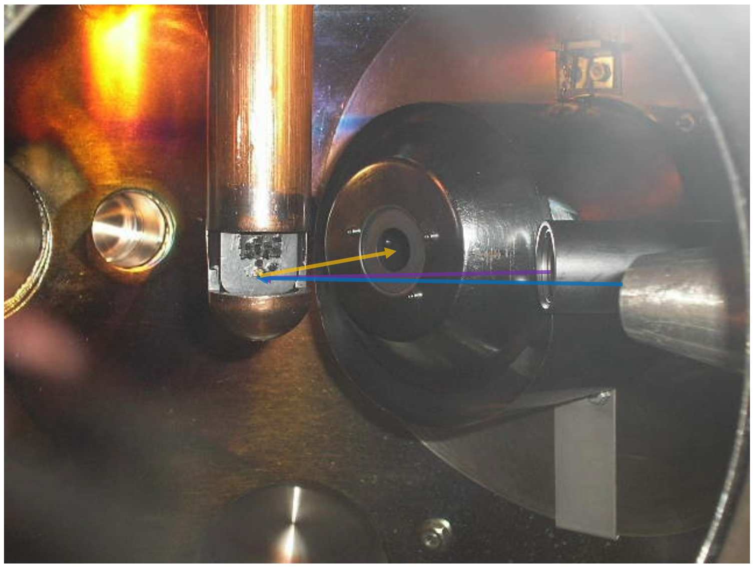
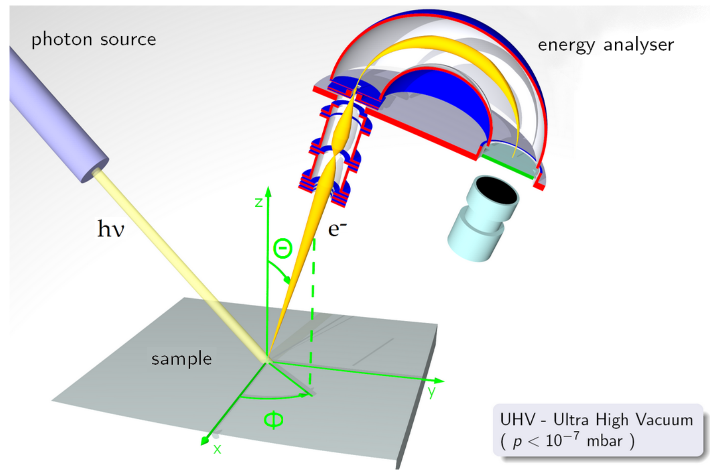
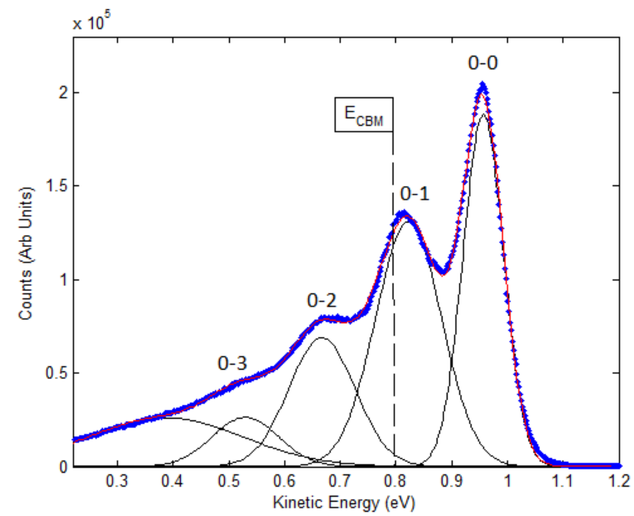
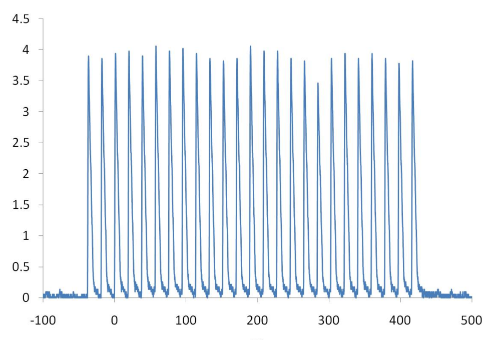
Angle Resolved Photoemission Spectroscopy (ARPES)





Beamline U13 at the National Synchrotron Light Source
hemispherical electron spectrometer
(<10 meV resolution)
Capability to heat diamond to 400C, cool to 77K





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