BNL R&D ERL program

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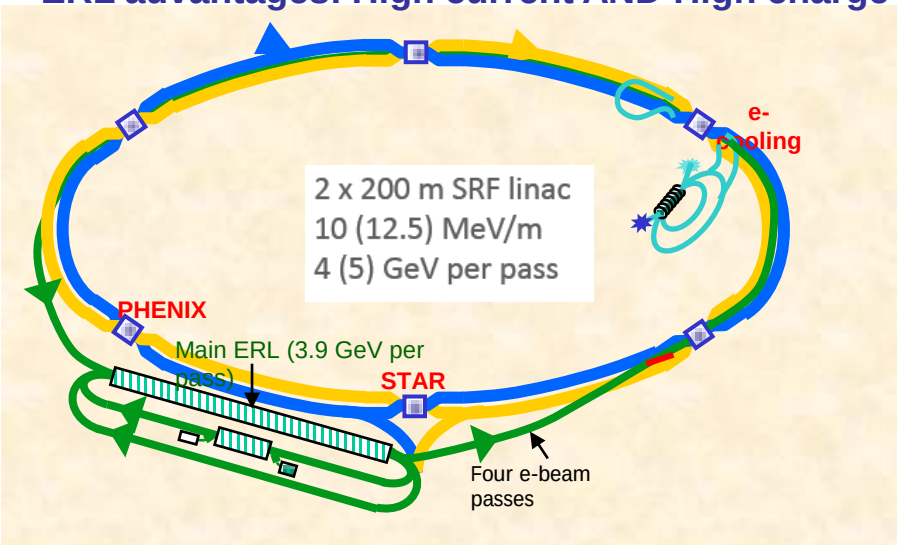
for ERL team

Outline

- Introduction
- R&D ERL
  - general layout,
  - parameters
  - main components status
- G5 test
- Plans & Conclusions

ERL based eRHIC

ERL advantages: High current AND High charge



MeRHIC: Medium Energy eRHIC

-4GeV e^- x 250 GeV p

- Linac e-current 300mA

- Luminosity ~10^{32}-10^{33} cm^{-2} sec^{-1}

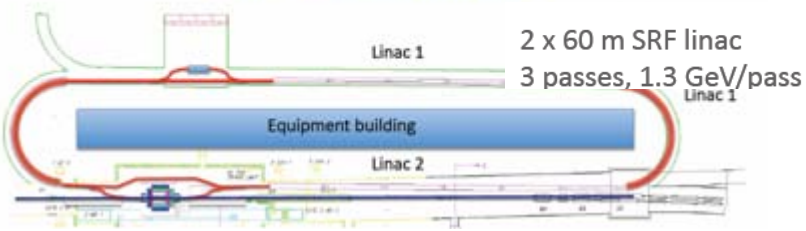
eRHIC, High energy and luminosity

-Polarized 20 GeV e^- x 325 GeV p,

-Linac e-current 500mA

- Luminosity: ~ 10^{33}-10^{34} cm^{-2} sec^{-1}

MeRHIC at 2 o'clock IR at RHIC



Demonstration proof of principal coherent electron cooling RHIC

Energy 21.7 MeV

Charge per bunch 5nC (4x1.4nC),

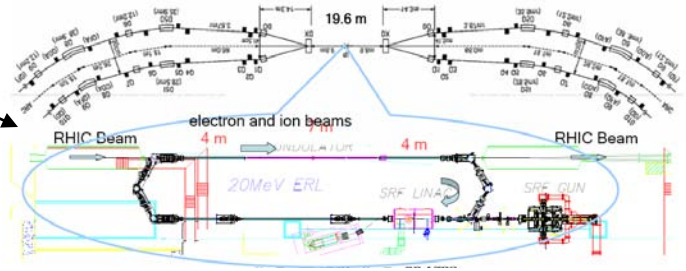
Normalized emittance 5 mm-mrad

Energy Spread 0.15 %

Ion energy 40 GeV/nucl./ Au bunch intensity 10^9

Estimated IBS 9 min, Cooling time 3 min

Possible RHIC IR for proof-of-principle for CEC



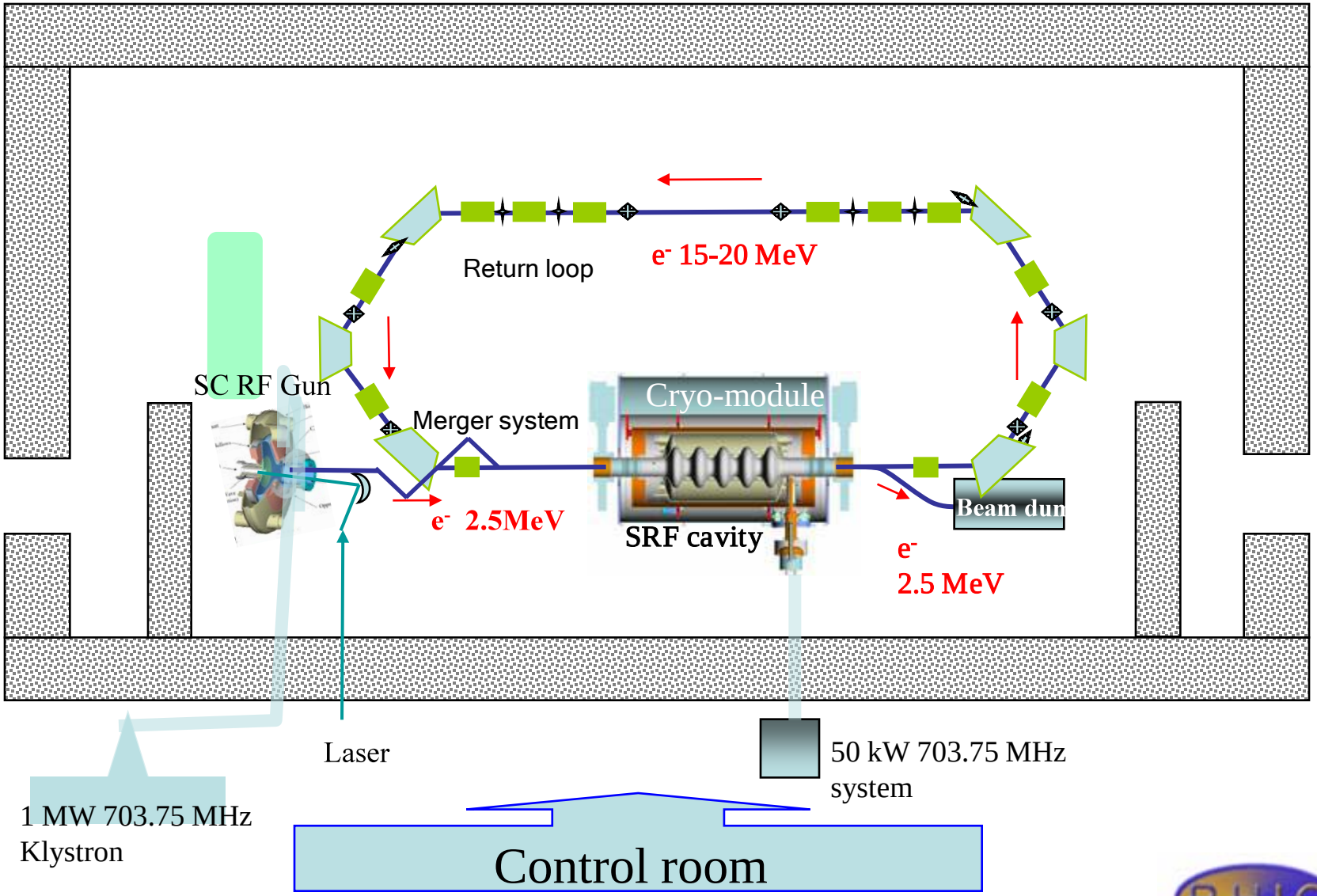
BNL R&D ERL issues to be addressed

- R&D ERL will serve as a test-bed for future RHIC projects
- eRHIC/MeRHIC:
  - very high average current
    - SRF injector
    - BBU,
    - e-dump
- Proof of principal of coherent e-cooling / conventional pre-cooling
  - High charge per bunch
  - Low energy spread and emittances (3rd harmonic is needed)
  - Conservation of beam parameter in merger (Z-bend test will give an answer)
  - Ion bunch much longer then electron one (703.75 MHz train of e-bunches helps, will split laser beam to 2/4/8)
- For all projects

  Stability criteria for CW beam current

  Halo/losses control
  - G5 test will give us more information,
    - First, halo study (scrapers)
    - then collimators at low energy in injection line will be installed

Schematic Layout of the BNL ERL

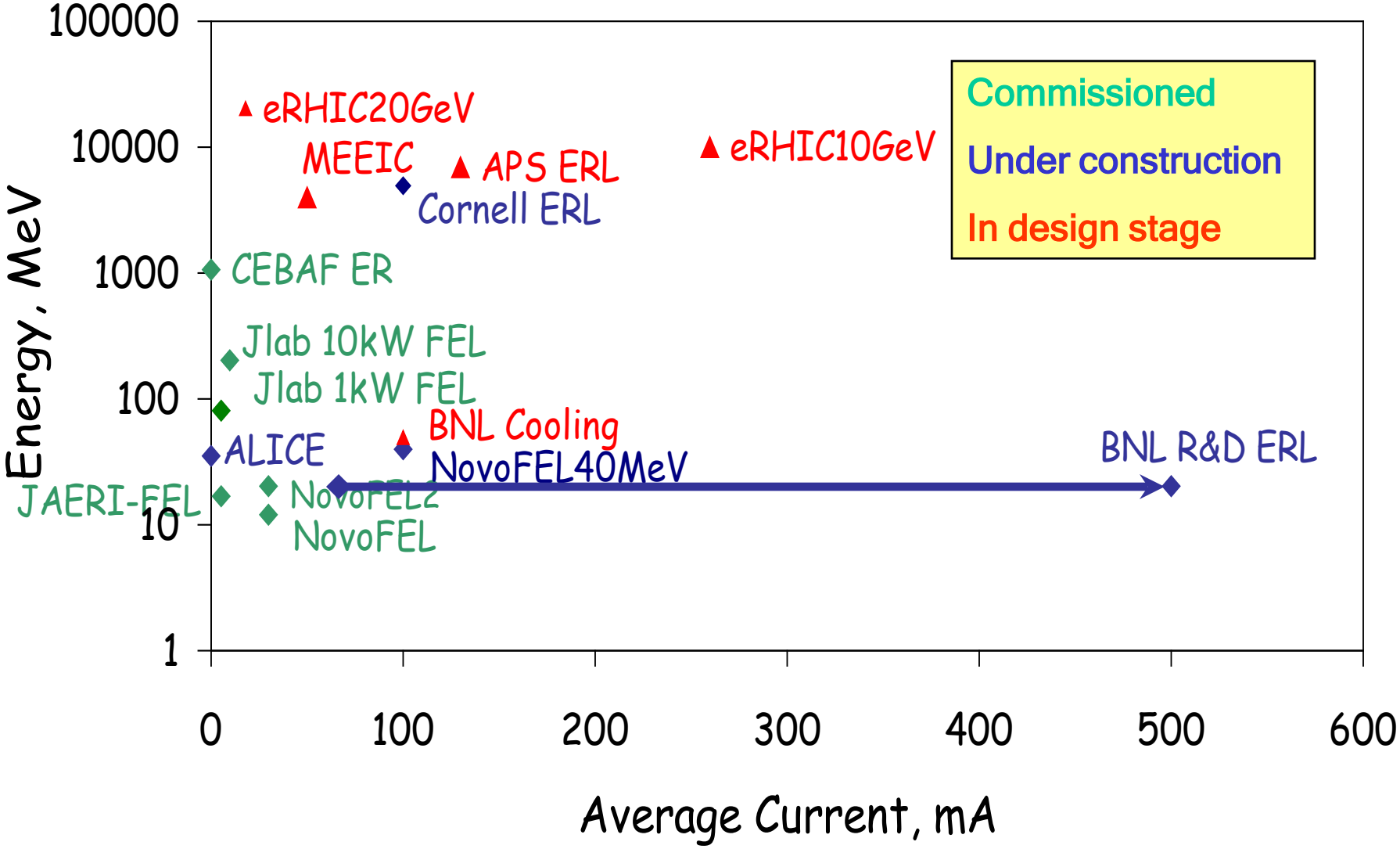


ERLs beam parameters

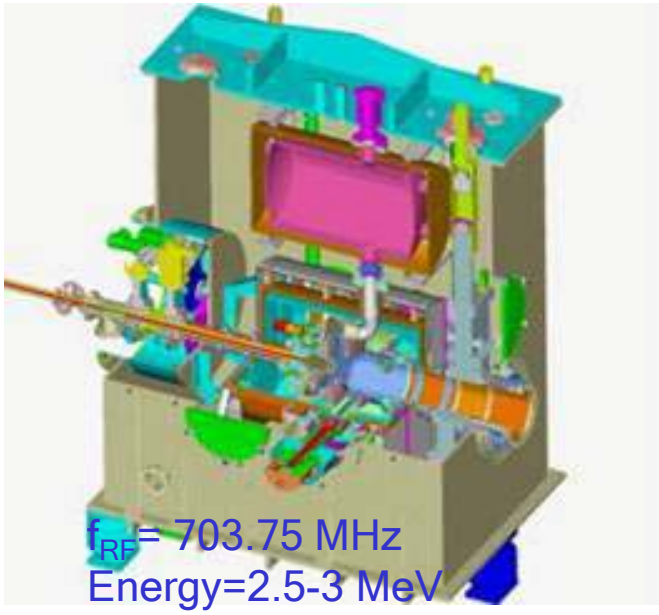
	R&D ERL design		BNL ERL projects requirements				
	High Current	High charge	PoP CeC Test *)		Pre-cooling @ 40GeV	MEeRHIC	eRHIC 10/20
Charge per bunch, nC	**0.7**	**5**	**5**	**5**	**14 (9x1.56)**	**5**	**18/3.5**
Energy maximum/injection, MeV	20/2.5	20/3.0	21/3	21/3	21/3	4000/5	10000/5 20000/5
R.m.s. Normalized emittances ex/ey, mm*mrad	**1.4/1.4**	**4.8/5.3**	**5**	**5**	**3**	**7-73**	**77**
R.m.s. Energy spread, $\delta E/E$	3.5×10^{-3}	1×10^{-2}	1.5×10^{-3}	1.5×10^{-3}	$8\ 10^{-4}$	2×10^{-3}	1×10^{-3}
R.m.s. Bunch length, ps	18	31	30	30	30	6.7	30
Bunch rep-rate, MHz	700	9.383	0.078	9.383	9.383	9.383	14.1
Gun/dumped avrg. current, mA	500	50	0.4	50	130	50	260/50
Linac average current, mA	**500**	**50**	**0.4**	**0.4/50**	**130**	**300**	**2600/500**
Injected/ejected beam power, MW	1.0	0.150	0.0012	0.15	0.390	0.250	1.3/0.250
Numbers of passes	1	1	1	1	1	3	5

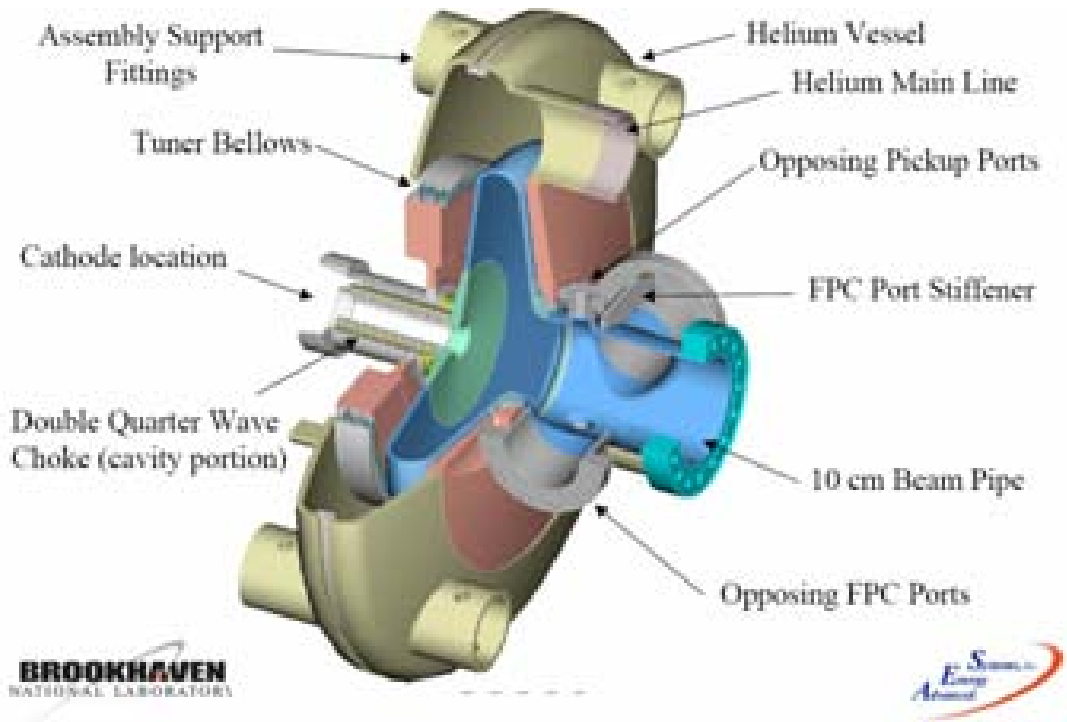
*) To demonstrate 3 min cooling time for proof pf principal of Coh. eCooling for single Au bunch at injection energy 40GeV/nucl (above transition) with 1e09 particles 66cm length energy recovery may not be necessary. To improve energy spread 3rd harmonic cavity and increase injection energy will help

High Power ERL landscape

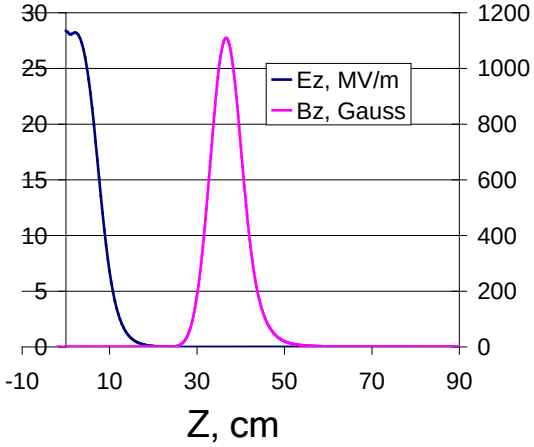


SRF Injector





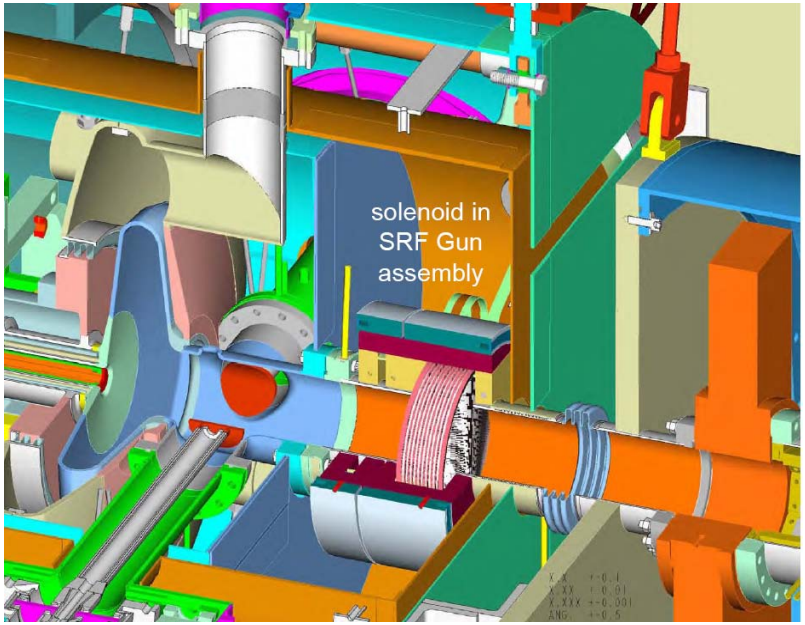
Average Current: 0.5 A
Two fundamental
power couplers: 0.5 MW each



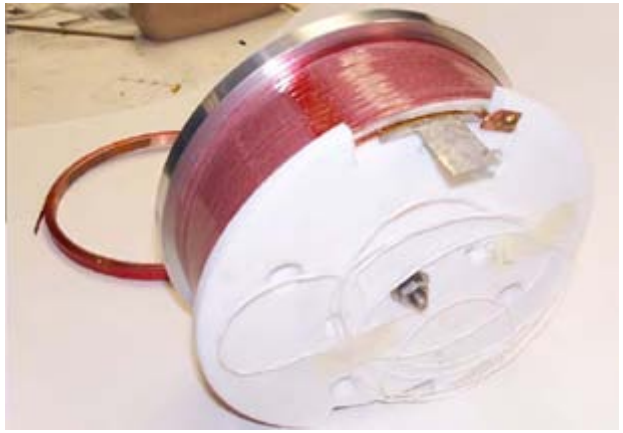
Built by AES
Will process at JLAB
Plan to have it at BNL March 2010

High Temperature SC solenoid with proper shielding field from SC cavity surface makes emittance compensation schema work

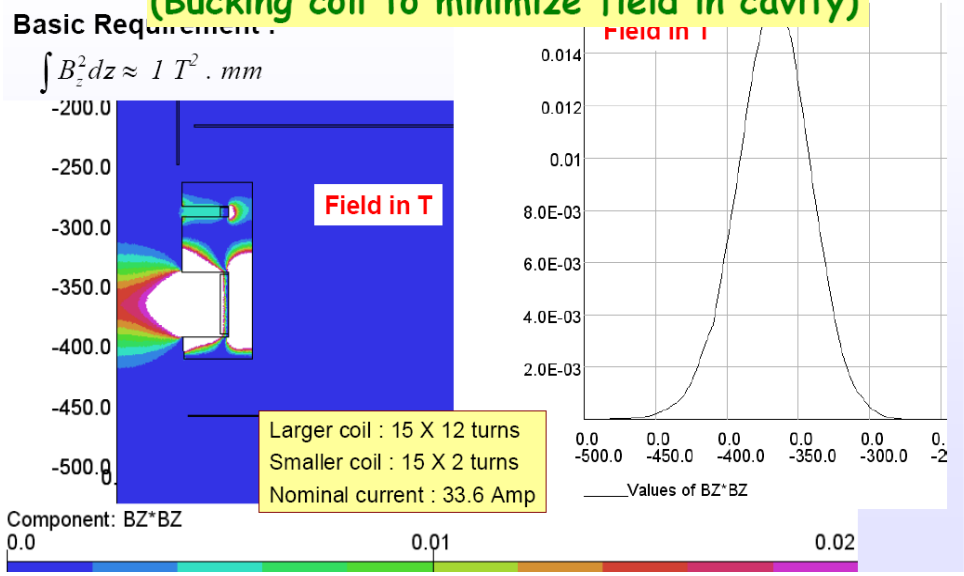
High Temperature Superconductive Solenoid



HTS Solenoid Coils



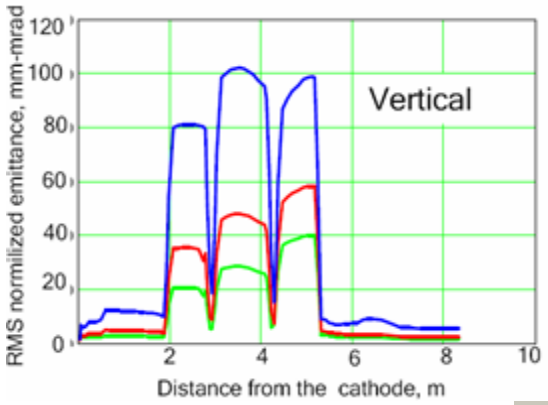
Focusing in the Current Solenoid Design
(Bucking coil to minimize field in cavity)

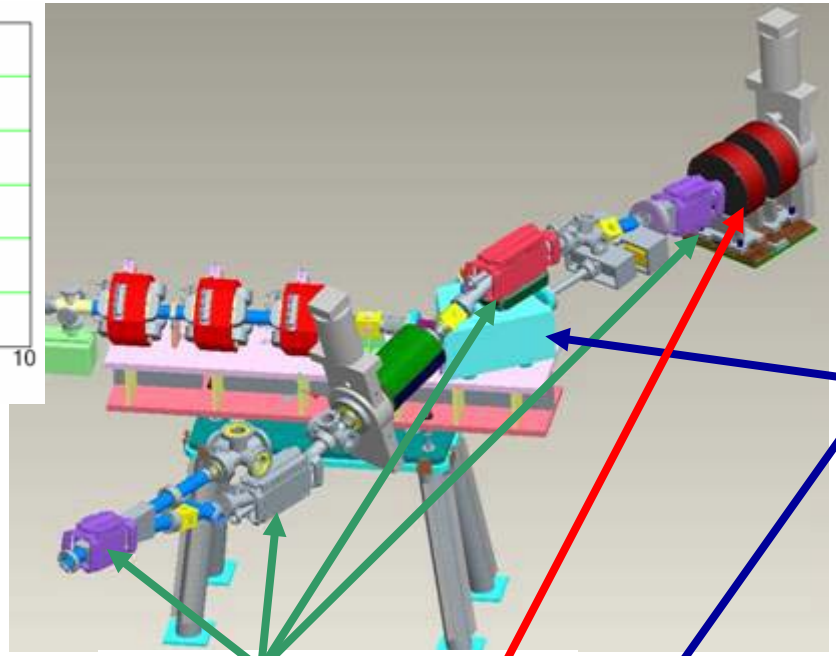


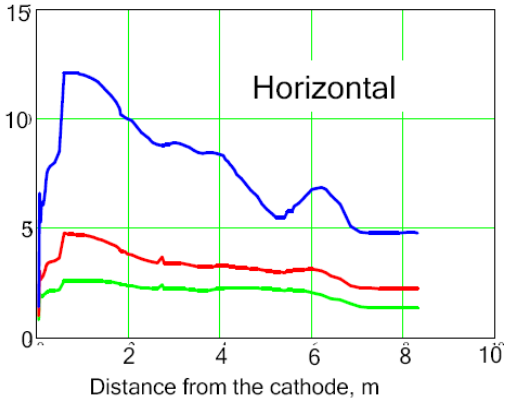
The solenoid coils tested at 77K.
Will be operate at 5 K.

Solenoid is assembled and will be tested in real shielding environment in fall 2009.

BNL R&D ERL SRF Injector layout







ERL Loop

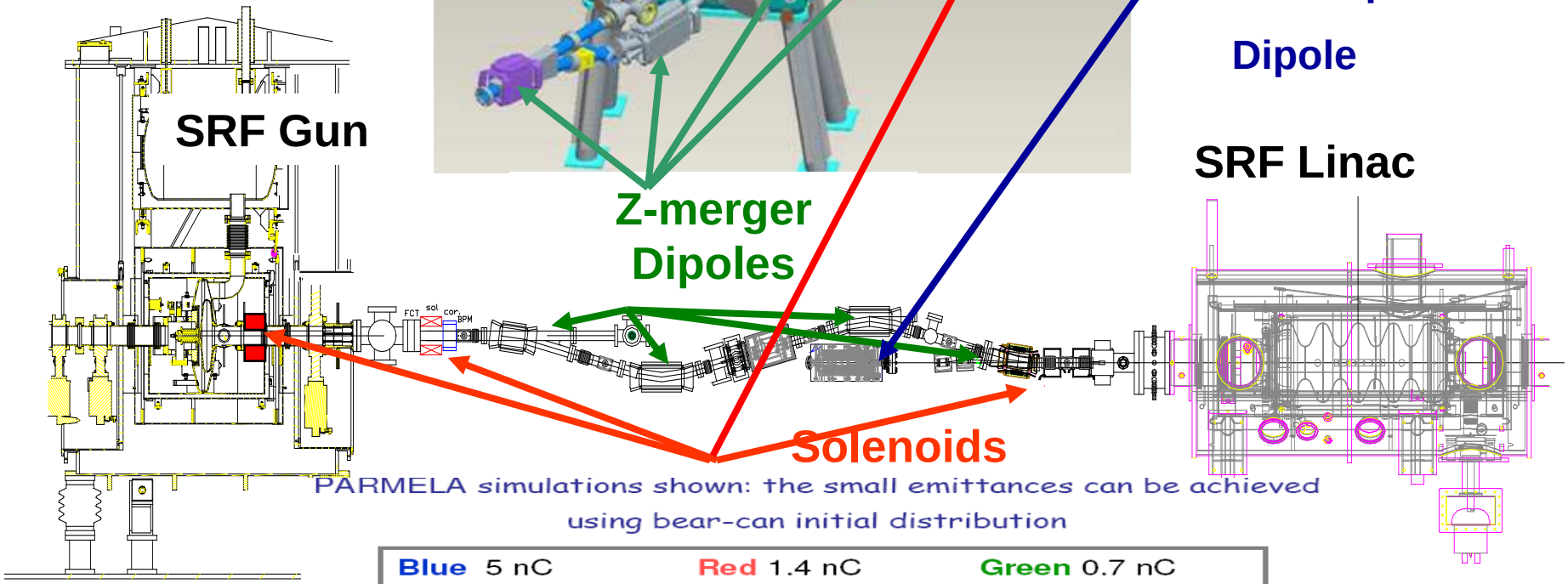
Dipole

SRF Gun

SRF Linac

Z-merger

Dipoles



Solenoids

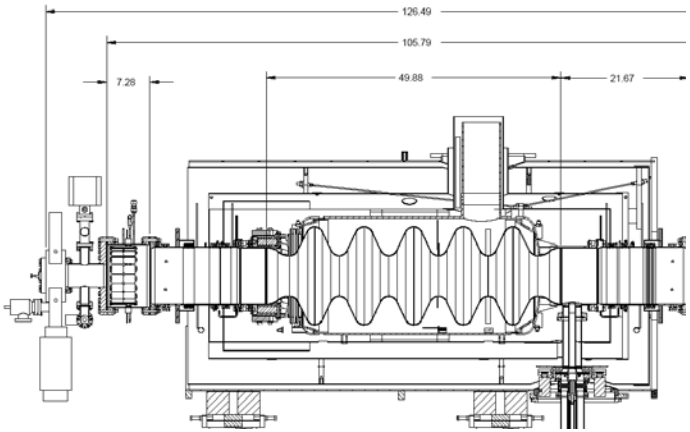
PARMELA simulations shown: the small emittances can be achieved using bear-can initial distribution

Blue 5 nC	**Red** 1.4 nC	**Green** 0.7 nC
4.8/5.3 um	2.2/2.3 um	1.4/1.4um

BNL 5 Cell SRF Linac

F = 703.75 MHz, δE = 20 MeV
$Q_0 \sim 10^{10}$, $Q_{HOM} \sim 10^3$

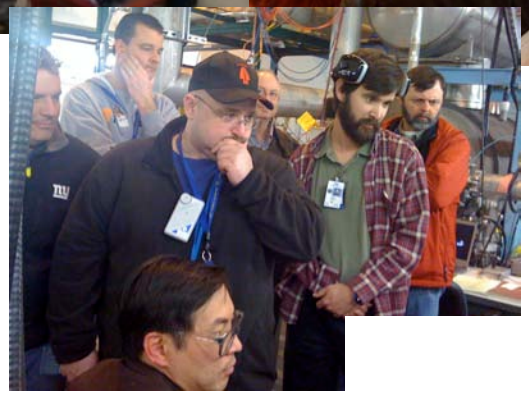
5 Cell SRF Cavity inside the cryomodule in ERL cave

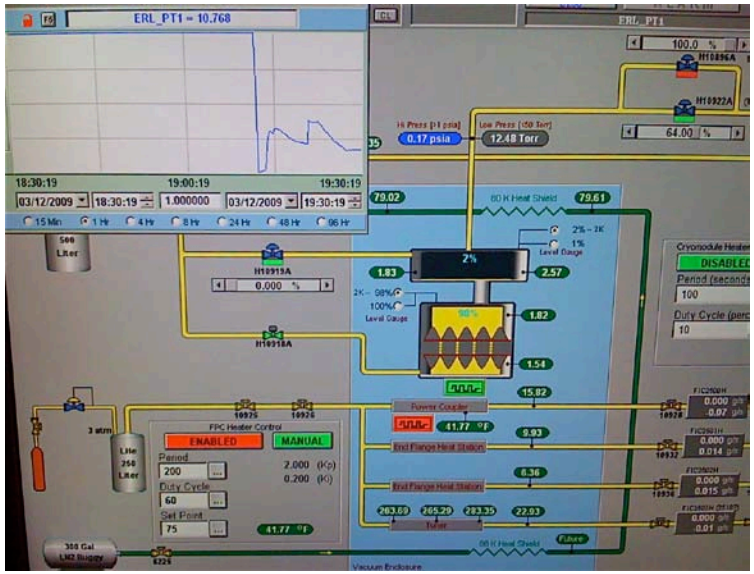


- The 5-cell cavity was specifically designed for high current, high bunch charge applications such as eRHIC and high energy electron cooling.
- The loss factor of the cavity was minimized.
- The number of cells was limited to 5 to avoid HOM trapping.
- Additionally, HOM power is effectively evacuated from the cavity via an enlarged beam pipe piece 24 cm diameter.
- **The simulated BBU threshold is of the order of 20 A**
- **First horizontal test in April 2009 gradient > 20 MV/m**
- **All system works (Cryo, RF, Vacuum, rad monitors, control)**
- Measured HOMs

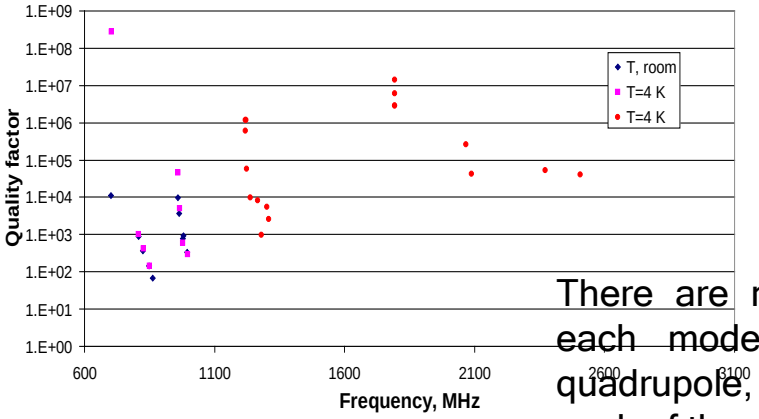
Build: AES
Processed: JLAB
Will be used: BNL

First cool-down (no RF involved) of the 5-cell SRF linac to 1.8K, March, 12 2009



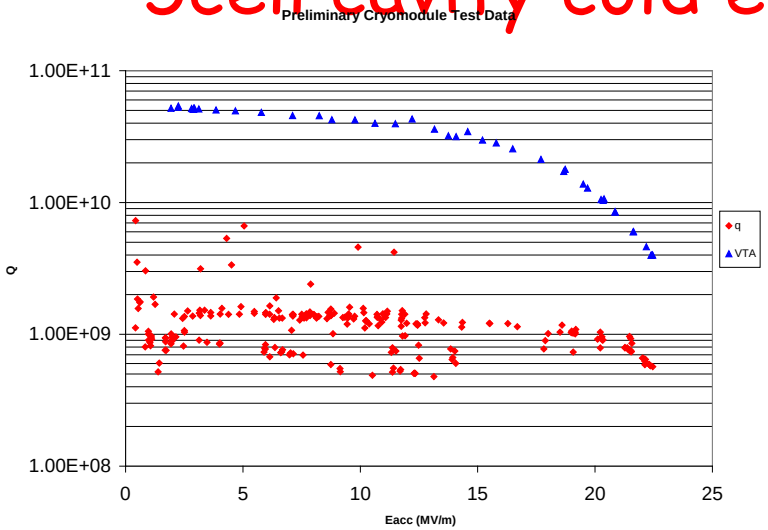


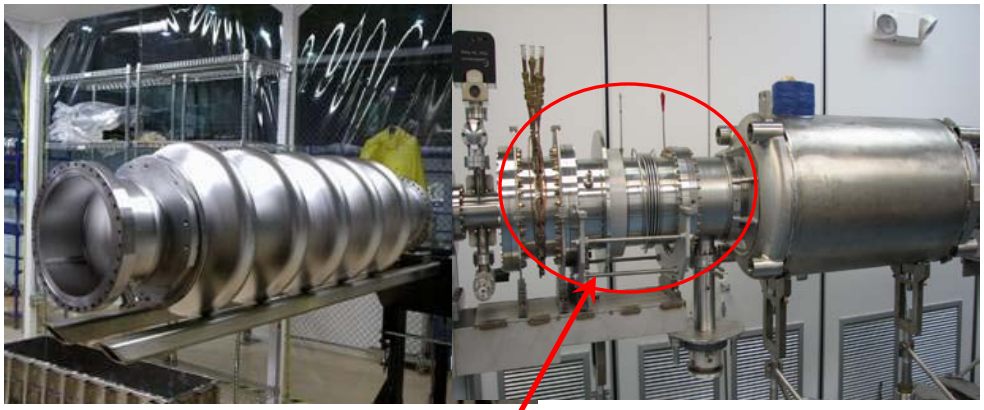
High Order Modes Measurements

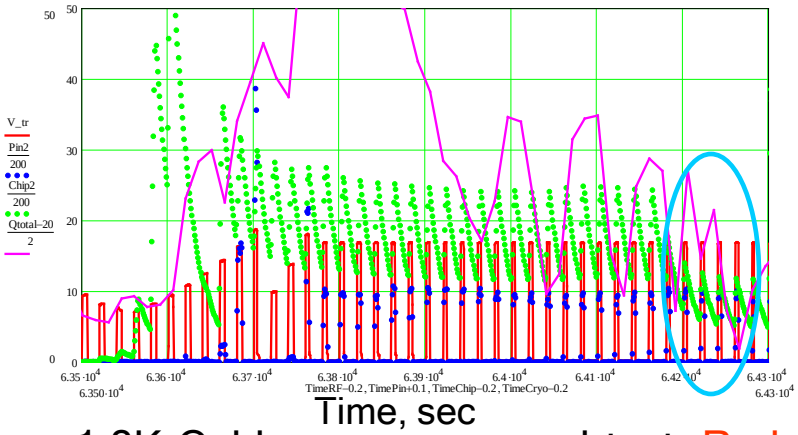


There are more HOM data available now and each mode needs to be indentified (dipole, quadrupole, monopole) and what are R/Q for each of them

5cell cavity cold emission test (April, 23 2009)







Cavity processed at JLab.
Vertical Test results – 20 MV/m reached.
$Q=1*10^{10}$
First Cold Emission Test full string shown
20 MV/m $Q=1*10^{9}$
Low field $Q=1.6*10^{9}$,in well agreement with SUPERFISH simulation whole string assembly

1.8K Cold emission pulsed test: Red electric field 17 MV/m, Green Chipmunk signal near the cavity, blue pin-diodes signal, magenta cavity losses from cryo data.

The cavity conditioning effect is observed. Using the lowest radiation and the loweest power losses data the Quality factor estimation $1.3x10^{10}$

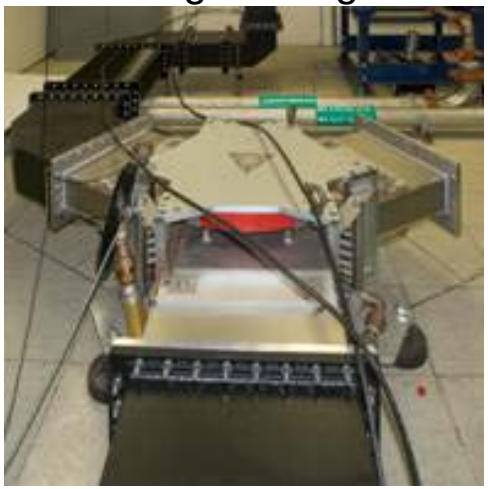
RF power supplies

1 MW Klystron tested at its full output power of 1MW CW at 703.75 MHz. With the dummy load

50 kW Transmitter tested operational

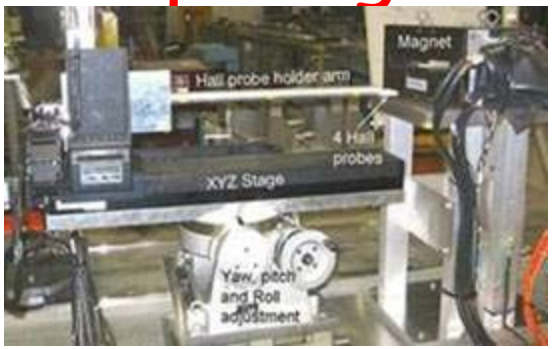
Drive 5cell SRFcavity

As part of system testing, one port of the AFT circulator was shorted, which directed all the power into the CML Engineering water cooled load. Both of these components performed as specified.

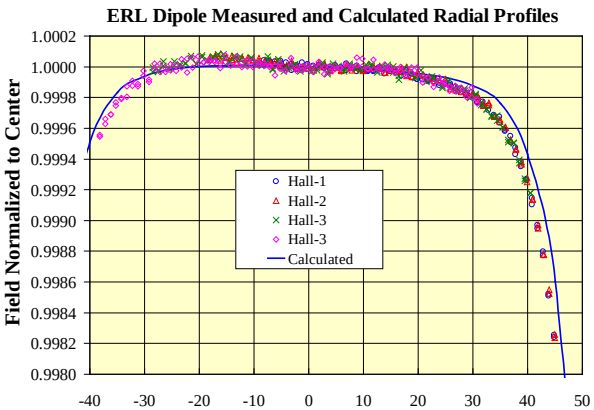


Loop Magnets

ERL 60 dipoles with vacuum chamber assembly



Measurement setup



Agreement between the measurements and simulations

Dipoles: the R&D ERL 60° dipole magnets have a rather small bending radius of 20 cm.
15° edges are used to split very strong focusing evenly between the horizontal and vertical planes (so-called chevron-magnet);
Magnetic measurements of the ERL magnets employs both rotating coil and Hall probe array mapping

Quadrupoles: The requirements on field quality of the loop's quadrupoles had been determined by the requirement to preserve a very low normalized transverse slice emittance of electron beam ($\varepsilon n \sim$ 1mm-mrad).

We used direct tracking of a sample electron beam to verify a high degree of the emittance preservation. Each quadrupole is equipped with a dipole trim coil, which can be also used to excite a sextupole component, if required, for emittance preservation of e-beam with a large energy spread.

W.Meng et al., "**Unique Features in Magnet Designs for R&D Energy Recovery Linac at BNL**",PAC2007

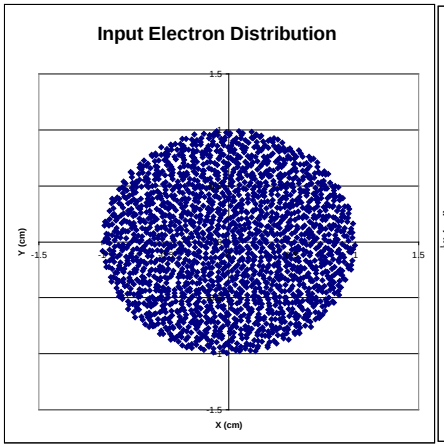
Injection combine function magnets

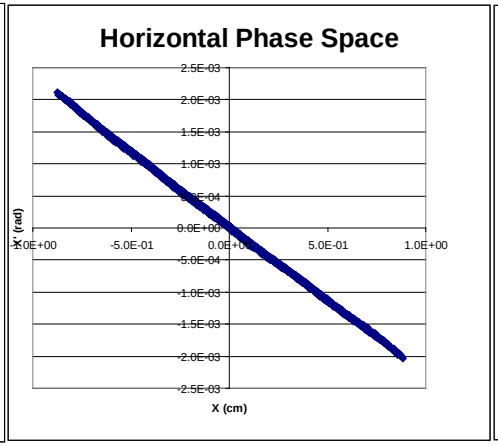
Window-frame dipole for Z-bend

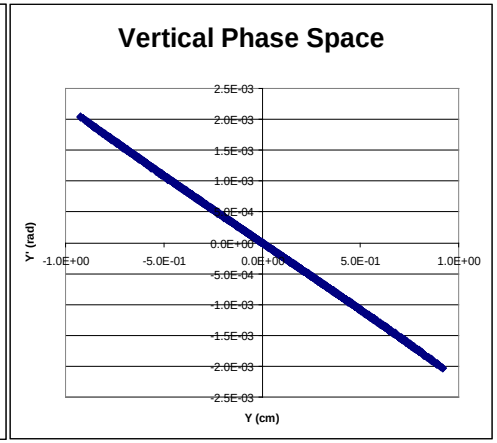
Due to very small real estate and large beam size: each magnet includes 4 sets of coils: 1) vertical bend, 2) quadrupole focusing, 3) sextupole correction and 4) horizontal steering.

The quadrupole coil is used to split focusing equally between the planes

The amount of the sextupole component is controlled by the gap between the yoke and the main dipole coil. A small additional coil in the corners is a sextupole trim coil, intended for use if sextupole component needs to be adjusted to reduce emittance growth







initial emittances 0

After tracking emittances:

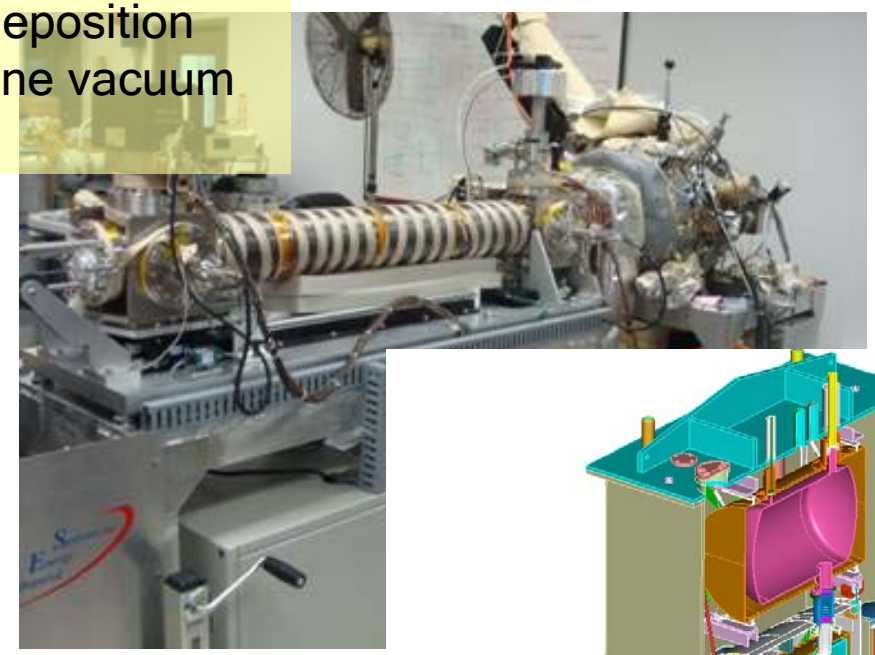
εxn=0.6 mm-mrad

εyn=0.6 mm-mrad

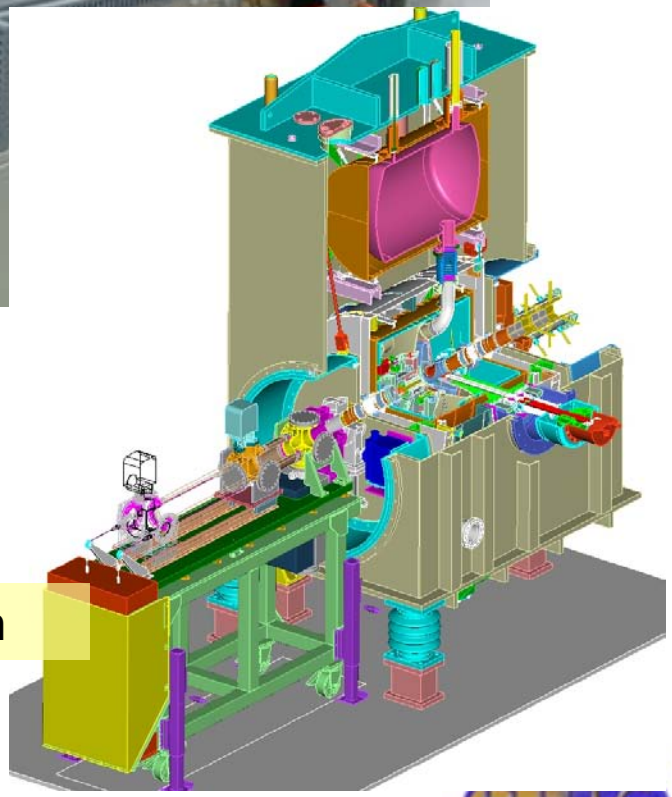
Analysis predicts that the influence of various field components on the emittance growth are complicated by the fact that the beam trajectory bends significantly in the fringe fields. Hence, direct tracking in the calculated fields extracted from Opera3d was used of test beam to evaluate and to minimize influence of magnetic field on the beam emittance

Transport car and deposition system

Transport car engaged in the deposition system. After baking the baseline vacuum is $1*10^{-9}$ torr



Deposition system inside view. The baseline vacuum is $1*10^{-10}$ torr



Transport car engaged in the SRF Gun

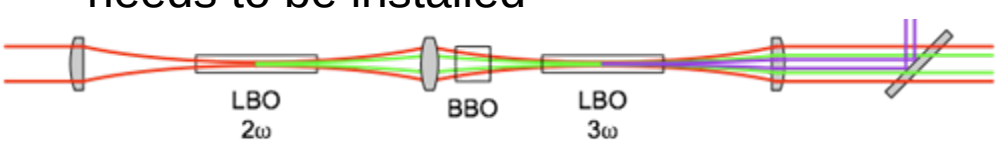
Injector Drive Laser

Main Specs

Wavelength:	1064, 532, 355 and 266 nm
Power:	20 W, 10 W, 5 W and ~ 1 W
Pulse duration:	~ 10 ps/50-70 ps
Repetition rate:	single pulse to 9.383 MHz
Synchronization:	Synchronized to master clock

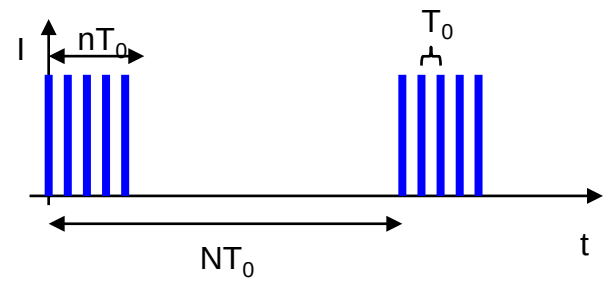
Status

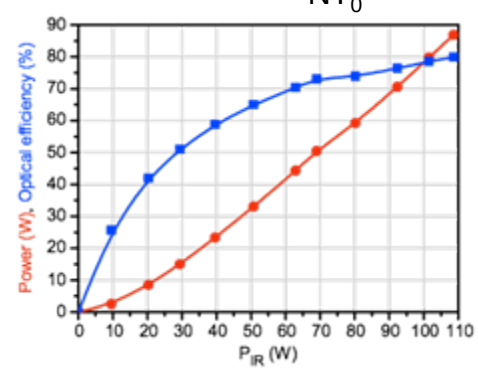
- Installed in the ERL Laser Room **(May 2009)**
- Measured the power and beam profile using Lumera detectors meet the specifications
- Laser to gun transport line is designed, needs to be installed

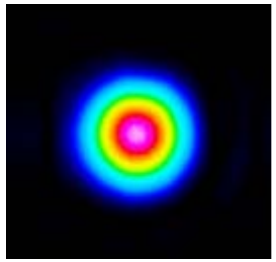


Pulse train capability

Pulse train period is adjustable and given by NT_0, where T_0 is the period between laser pulses, $T0$=1/9.383 MHz^{-1}, and N is an integer in the range between 10^4 and 10^7, corresponding to 1Hz-1kHz train rep. rate (for G5 test 100 Hz)



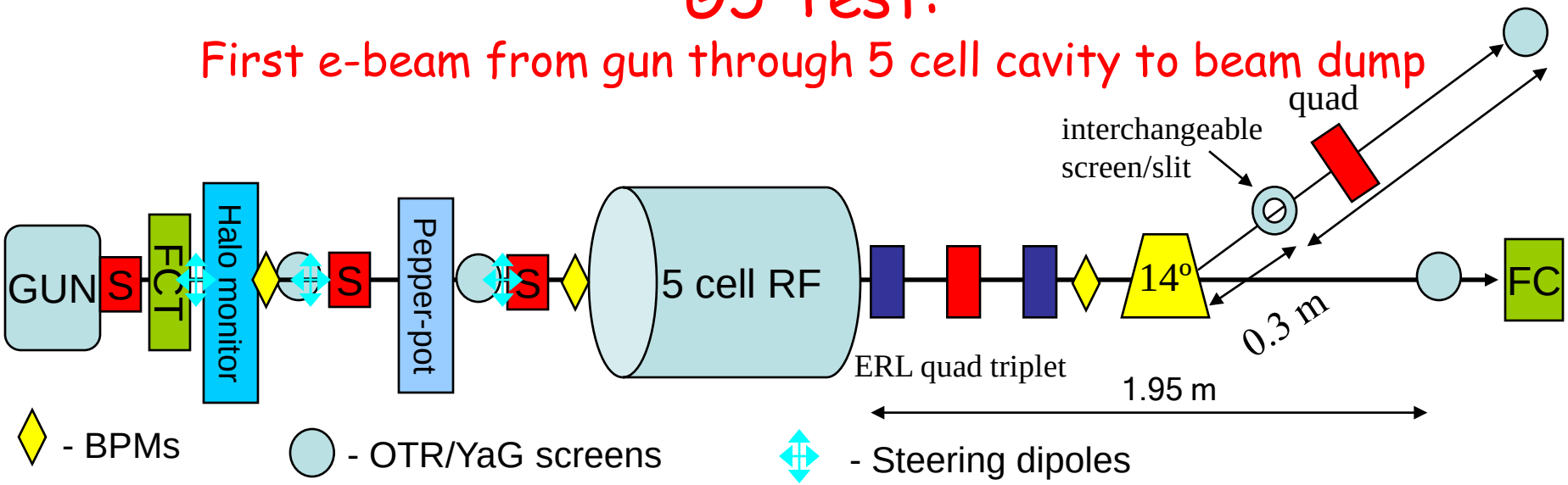




Courtesy Lumera Laser

G5 Test:

First e-beam from gun through 5 cell cavity to beam dump



Baseline parameters

Charge per Bunch: 0.05-5 nC
Gun Energy: 2.5 -3 MeV
Maximum Energy: 20 MeV
Max. Average current: 1μA
Max. Rep Rate: 100 Hz
Average Power: < 20 Watts
Trains mode operation

Plan to do at low energy

- Cathode QE and
- Cathode lifetime in SRF gun
- Slice emittance
- Projected emittance
- Halo studies

At 20MeV two operational modes:

1. Straight ahead
   - projected emittance
   - transverse halo
2. With the bend
   - bunch length / long. halo /energy spread
   - slice emittance

BNL R&D ERL Status: complete

✓ Design of major ERL components is completed. Hardware components are being manufactured and/or procured.

- ERL Enclosure (Vault) was constructed (2005)
- 50 kW (for 5 cell 20 MeV SRF linac) installed, tested
- Recirculation loop magnets and injection line magnets have arrived and measured.
- Dipole and quadrupole magnets power supplies were delivered, installation has been started (June 2009).
- 1 MW Gun klystron (for SRF gun) including circulators and dummy loads installed, tested for full power 1MW (Summer 2008)
- ERL control room is finished (August 2008)
- PASS and Machine protection system is installed, tested well perform during the CET.
- 5cell cavity cryogenic system installed and fully functional (First cool-down T=2K, March 2009).
- The preparation chamber and the cathode transport car ready to use (AES designed, built, BNL processing, March 2009)
- 5-cell Cavity is being processed and tested at JLAB, installed at 912. Cold Emission Test April 2009 20MV/m demonstrated.
- Radiation diagnostic tested during the CET (chipmunks, ionization chambers, Pin diodes, PMTs)
- Gun drive laser installed and tested (May, 2009)
- Loop vacuum system components are on hand
- RF control will be based on the new digital RHIC LLRF. The LLRF system is currently under development. 5cell cavity CET and FPC conditioning were done using PLL based LLRF.

Commisionnig plan: in progress

✓We started commissioning of the R&D ERL components

- ✓5cell SRF cavity cold emission test
  - •first cool-down March, 14, 2009
  - •20 MV/m in CET April, 23 2009
- •Next CET scheduled for August 2009,
  - •Will apply helium conditioning
  - •Up-grated LLRF will be used, will try to tune the cavity during the test

•Refrigeration system will be installed March 2010, will be used for ERL and for VTF

•All magnets, diagnostics and vacuum components for G5test will be installed

•Half cell SRF gun will arrive in March 2010.

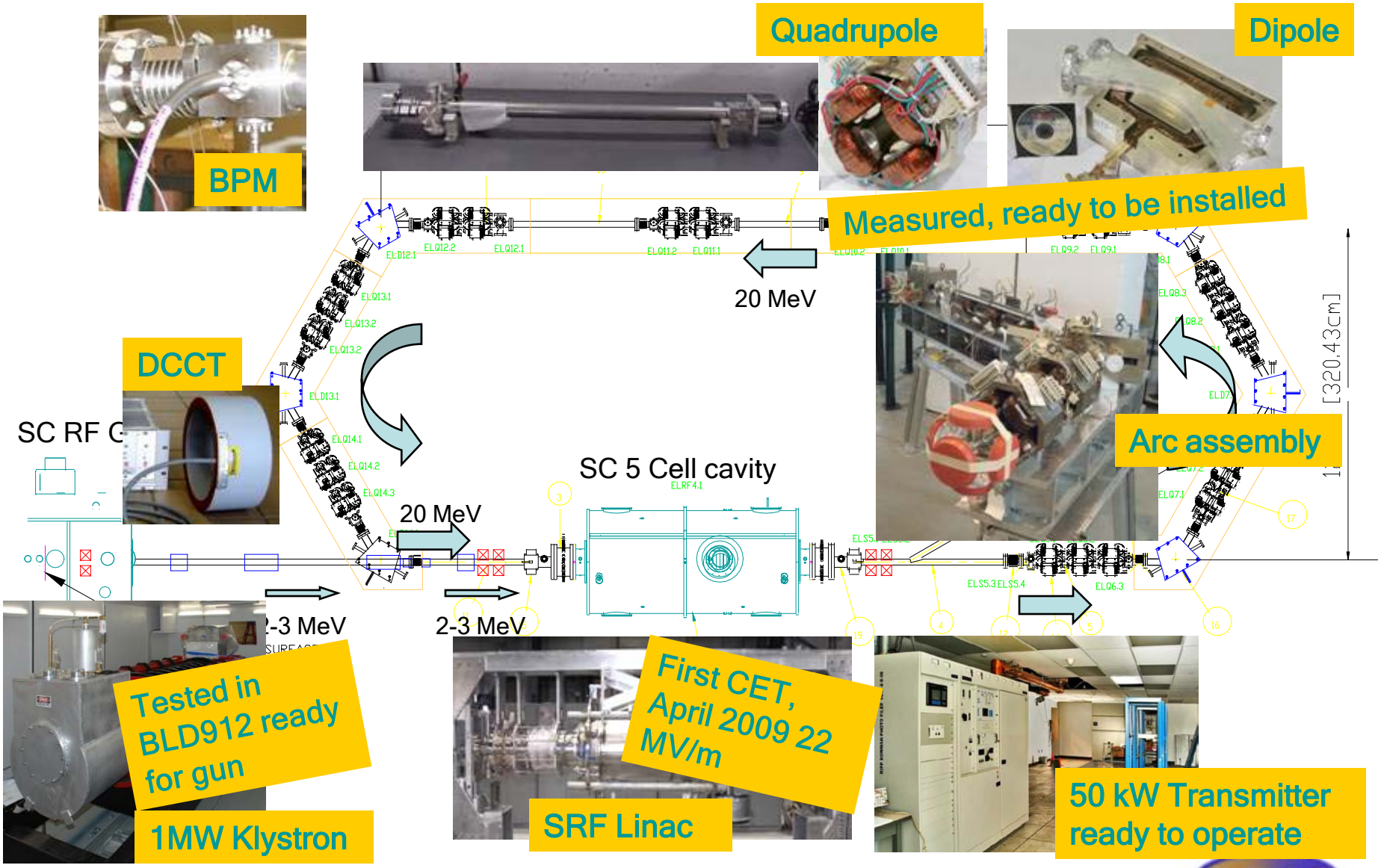
•LLRF based on new digital RHIC LLRF will be available for G5 test

•Control system for ERL needs to be completed

Commisionnig plan: ERL fully operational in 2011

✓**G5 test (low average current) work in progress**

- First, the straight pass (gun - 5 cell cavity - beam stop) test for the SRF Gun performance studies. (October 2010)
  - #Metal cathode (low charge per bunch)
  - #Multi-Alkaline Cathode (up to 5nC per bunch)
- Next, a novel concept of emittance preservation in a beam merger at the lower energy will be tested (end of 2010)

- After recirculation loop and extraction line (under design right now) completed, demonstrate energy recovery of high charge and high current beam. The prototype will serve as a test bed for studying issues relevant for very high current ERLs (2011)
- **Proof of principle coherent electron cooling ions in RHIC at ~ 40 GeV/n is feasible with existing R&D ERL parameters with some modifications (ERL available around 2012)**

BNL R&D ERL commissioning is going on