R&D Efforts for ERLs

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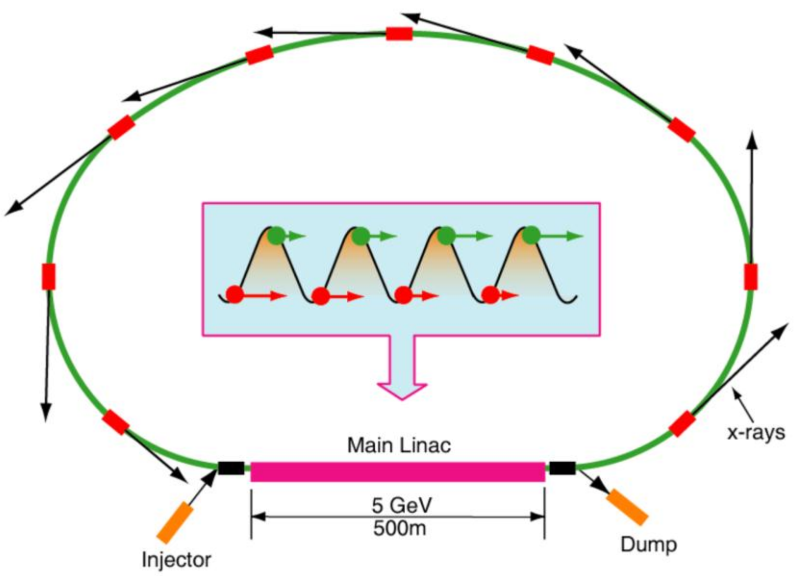
The ERL idea

A Possible Apparatus for Electron Clashing-Beam Experiments (*).

M. TIGNER

Laboratory of Nuclear Studies, Cornell University - Ithaca, N. Y.

(ricevuto il 2 Febbraio 1965)



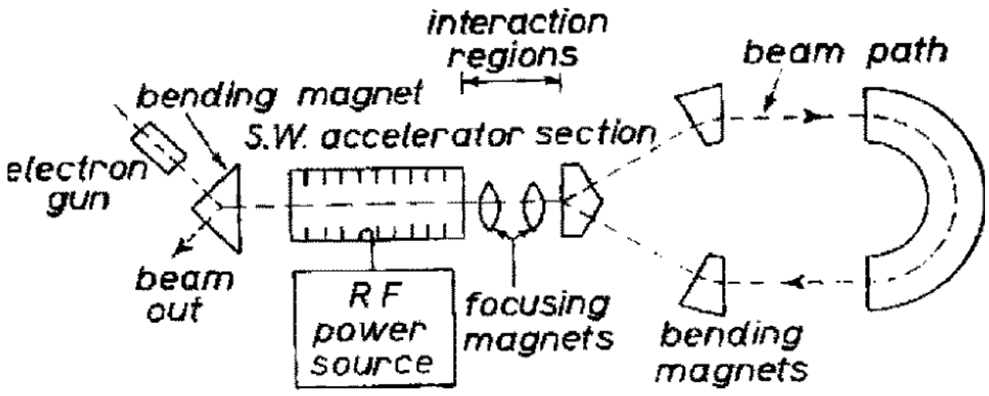


Fig. 3.

What are ERLs good for?

Storage Ring

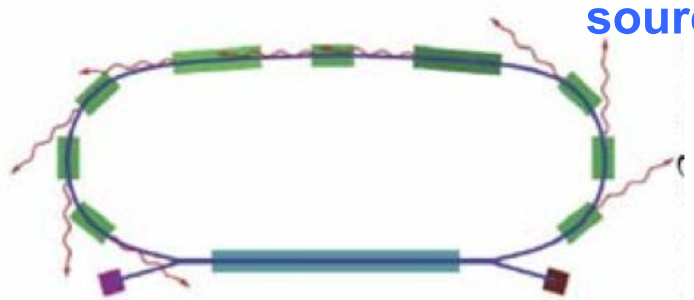
High repetition rates (1000 MHz)
High current (100+ mA)

Many user stations

Fixed energy spread (10^{-3} relative)

Bunch durations (20 ps)

Emittance determined by the ring



Flexible optics
Flexible bunch structure

Linac

Low repetition rates (120 Hz, 1 MHz)
Low average current (10^{-4} mA)
(but very high peak current)
Few user stations

Excellent energy spread (10^{-4} relative)
Drive XFEL-Os
Short bunch durations (0.1 – 2 ps)

Emittance determined by the source

Worldwide efforts on ERLs

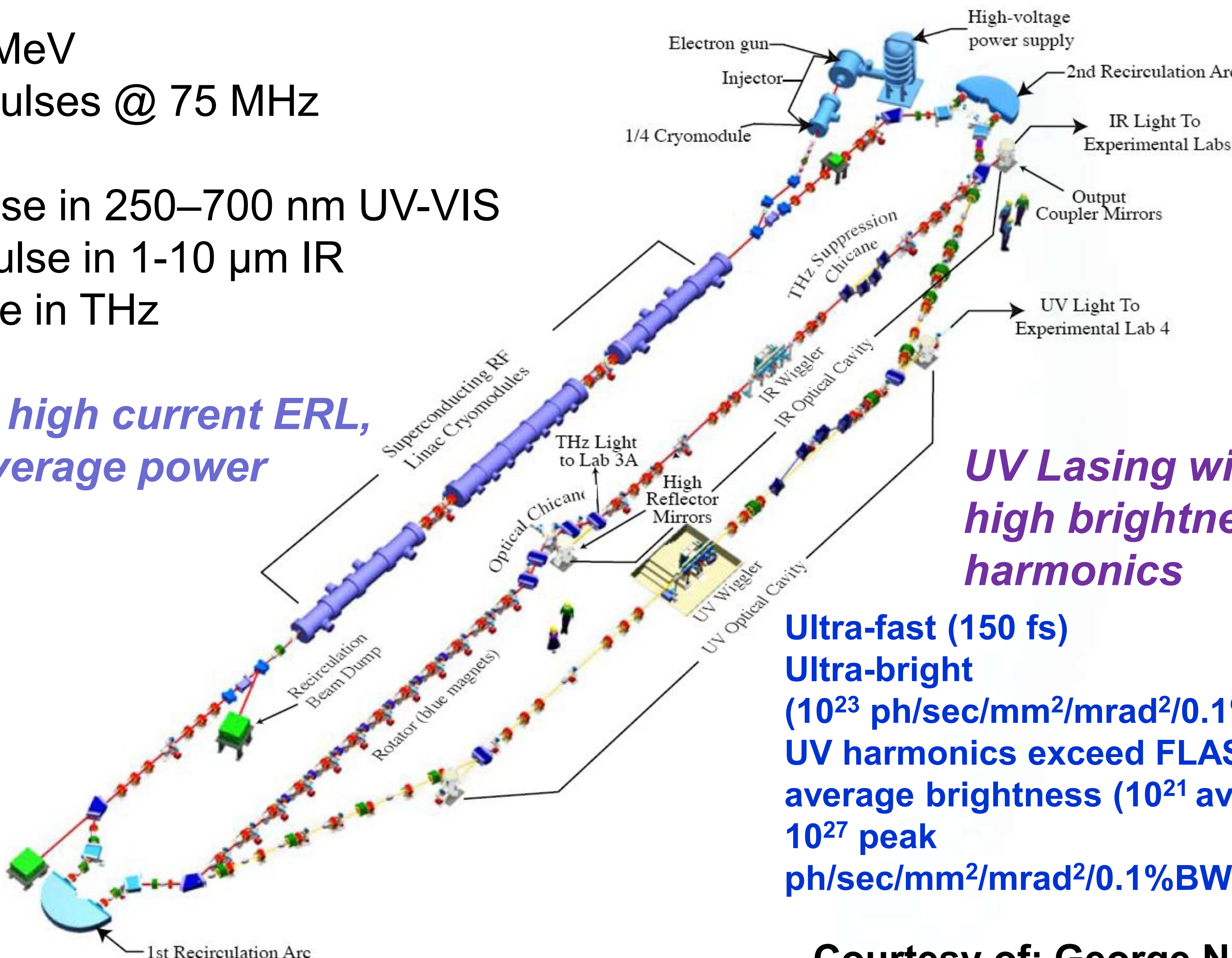
- Facilities existing or planed
  - Jlab FEL/ ERL
  - ERL @ Budker
  - Alice @ Daresbury
  - IHEP ERL test facility
  - ERL facility @ BNL
  - cERL @ KEK
  - bERLinPro
  - Mesa @ U of Mainz
  - LHeC ERL
  - Cornell ERL R&D program

JLab IR/UV ERL Light Source

E = 135 MeV
135 pC pulses @ 75 MHz

20 µJ/pulse in 250–700 nm UV-VIS
120 µJ/pulse in 1-10 µm IR
1 µJ/pulse in THz

The first high current ERL, 14 kW average power in IR



UV Lasing with high brightness harmonics

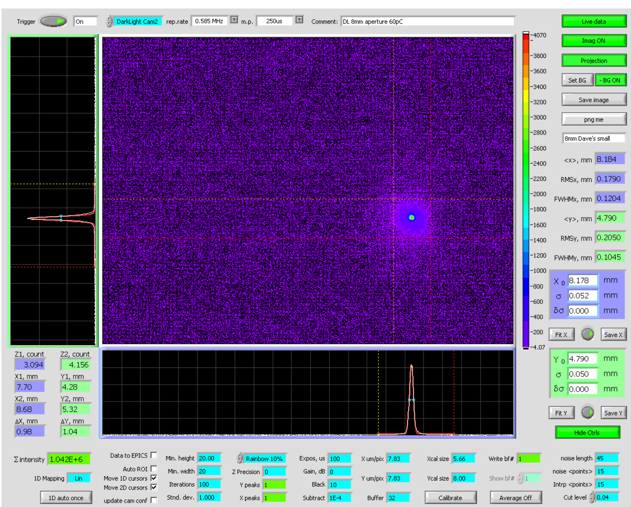
Ultra-fast (150 fs)
Ultra-bright (10^{23} ph/sec/mm^2/mrad^2/0.1%BW)
UV harmonics exceed FLASH average brightness (10^{21} average, 10^{27} peak ph/sec/mm^2/mrad^2/0.1%BW)

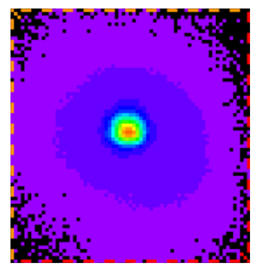
Courtesy of: George Neil

Dark Light Feasibility test

Goal

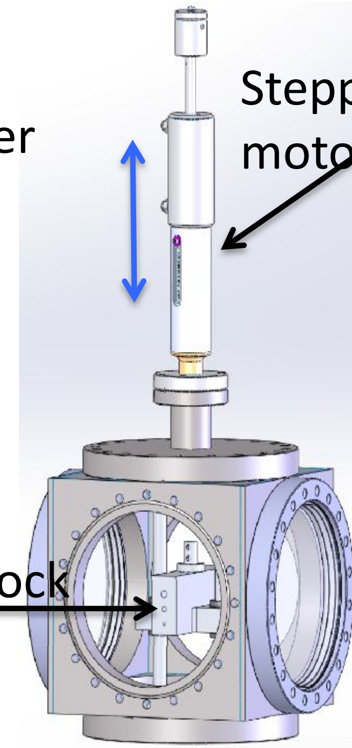
Simulate high-power ERL operation with an internal gas target controlling power deposition from beam loss and impedance/wake effects from both beam core and halo components through a 12.5 cm long small aperture (6, 4, or 2 mm diameter)





Area: 1 mm x 1 mm;

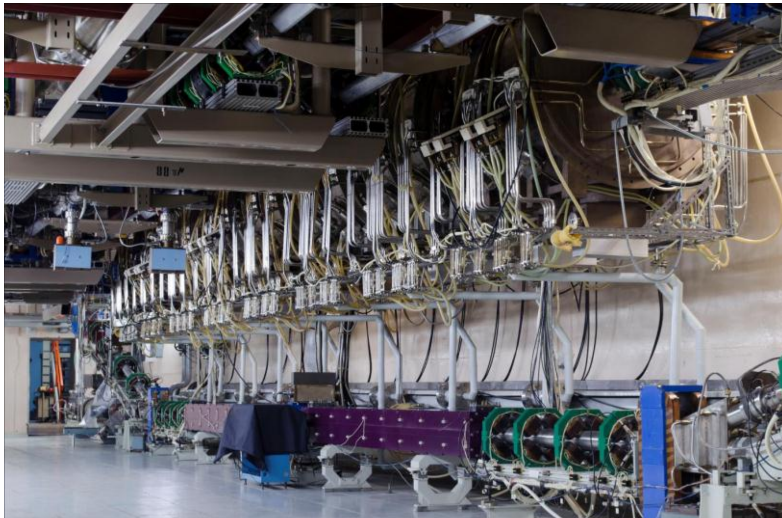
Best Gaussian: fit σ_x=50 µm; σ_y=52µm

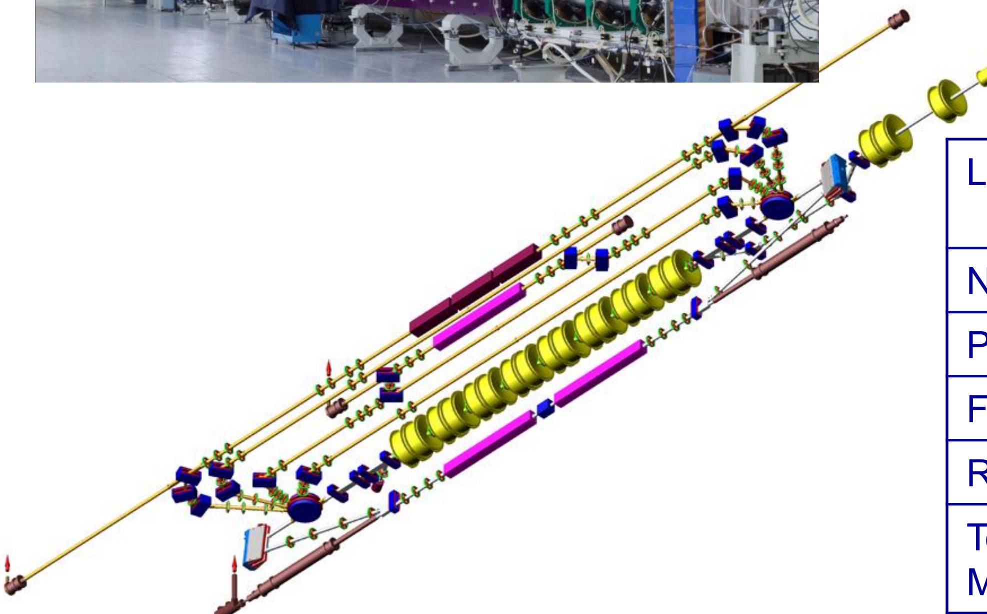


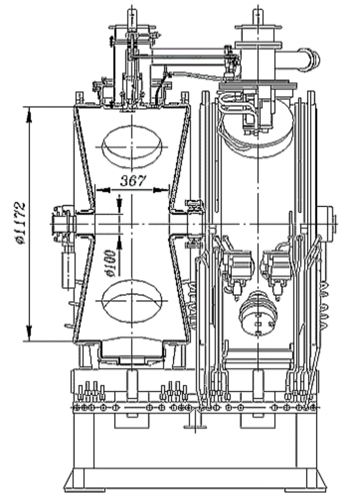
Designed and constructed by MIT-Bates R&E Center in collaboration with JLab FEL staff

Courtesy of: George Neil

ERL @ Budker





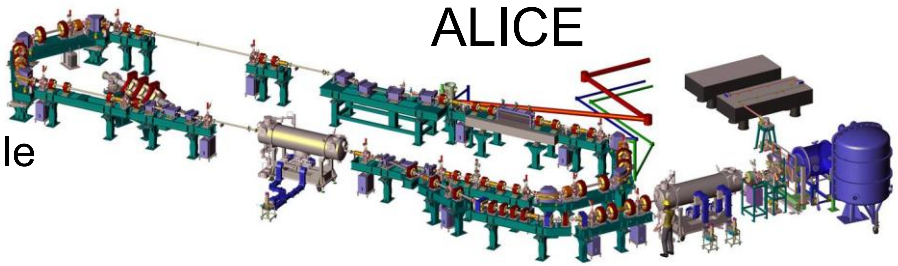


Linac	Normal conducting, independent cavities, CW
Number of cavities	16
Phase advance, rad	π
Frequency, MHz	180.4
RF quality	40000
Total RF power, MW	1
Maximum energy gain, MeV	12

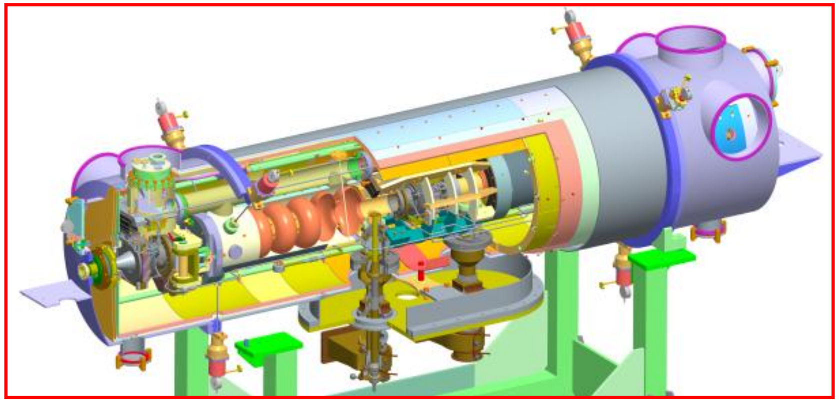
Courtesy of: Nikolay Vinokurov

International ERL Cryomodule on ALICE

- Collaboration formulated in early 2005
- Objective to design and fabricate new CW cryomodule and validate it with beam
- Dimensioned to fit on the ALICE ERL facility at Daresbury:
  - Same cryomodule footprint
  - Same cryo/RF interconnects
  - 'Plug Compatible' with existing cryomodule



Parameter	Target
Frequency (GHz)	1.3
No. of cavities	2
No. of Cells per Cavity	7
E_{acc} (MV/m)	>20
Q_o	$>10^{10}$
Q_{ext}	4×10^6 - 10^8

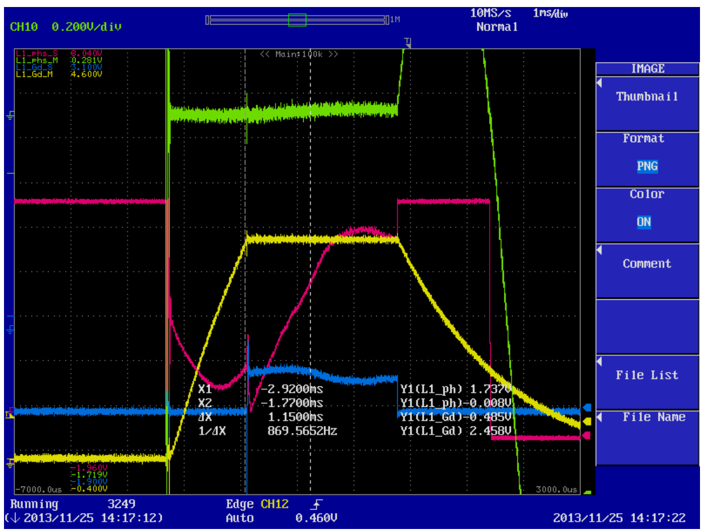


TRIUMF DESY HZDR

Courtesy of: Alan Wheelhouse

Cryomodule Evaluation

- Initial conditioning performed:-
- Gradients reached:
  - LC1 – 10.8MV/m
  - LC2 – 12.5MV/m
- No FE radiation observed
- Microphonic issues discovered



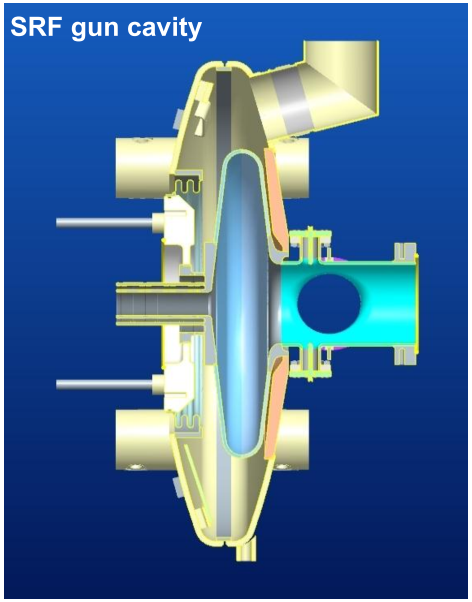
Pink – Phase set
Green – Phase measure
Blue – Grdient set
Yellow – Gradient measure

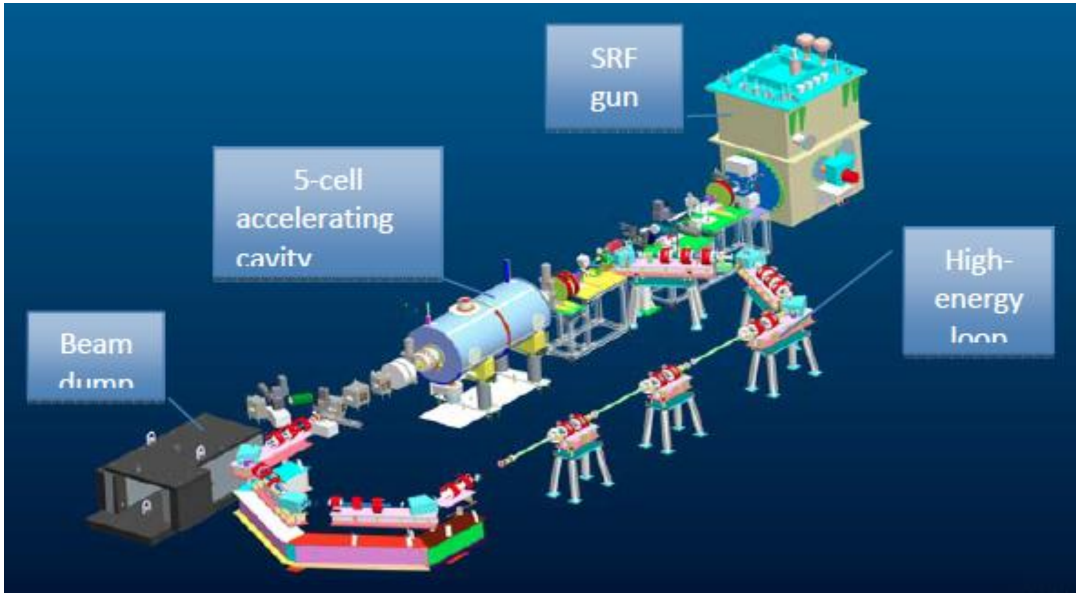
Future Plans:-

- Microphonics investigation
- Establish full gradient and Q_0
- Measure Lorentz force detuning at high gradient
- Performance measurements with piezo tuners
- Determine DLLRF control limitations wrt Q_{ext}
- Evaluate the effect of beam loading with DLLRF
- Characterise cavities in CW mode at high gradient

Courtesy of: Alan Wheelhouse

R&D ERL facility at BNL

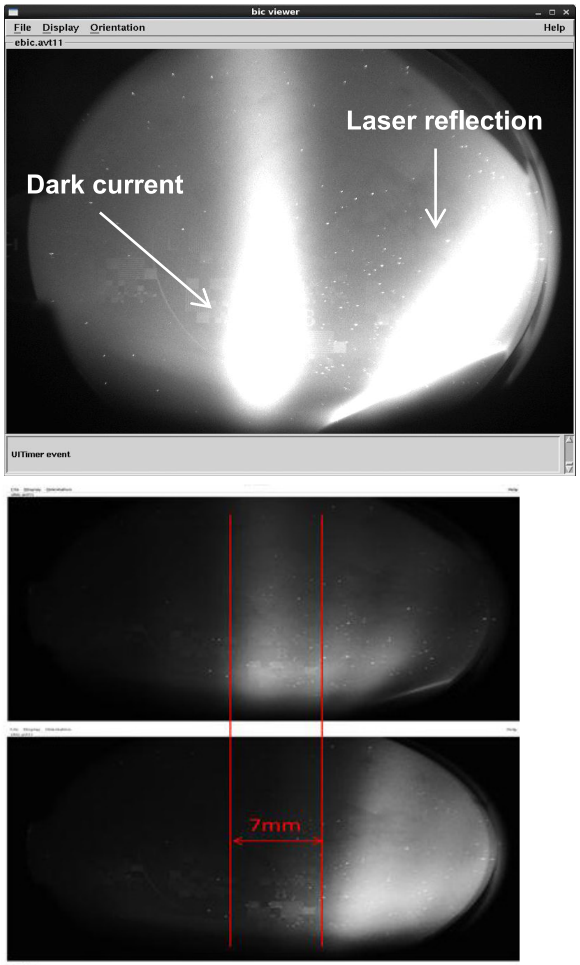




- An ampere class 20 MeV superconducting ERL (R&D ERL) is under commissioning at BNL.
- This facility enables testing of concepts relevant for high-energy coherent electron cooling, electron-ion colliders, and high repetition rate Free Electron Lasers.
- The machine consists of an SRF photoemission injector, an SRF accelerating cryomodule, a recirculating loop, and a beam dump.

Courtesy of: Sergey Belomestnykh

First beam commissioning at BNL



Dark current image taken at beam profile monitor during energy measurement at gun voltage settings 1.2 MV. Corrector current top 0.5 A, bottom 1 A. 7mm shift due to 0.5 A corrector change corresponds to beam energy of 1.2 MeV

- For the first beam test, a Cs3Sb cathode was fabricated and QE has been measured at 0.25% in the deposition chamber.
- During the cathode insertion into the gun and initial start of RF power, there were several instances of vacuum spiking to 1e-8 Torr range. These significantly reduced QE of the cathode to the level, where it became impossible to measure the photoemission current.
- However, a dark current was observed on a YAG screen and measured by the Faraday cup (1.4 uA at a cathode field of 15 MV/m). Gun has been running with 40 msec pulses with 1 second interval during the dark current measurements. Measurements of the dark current energy agree with RF gun voltage calibration.
- The low power beam testing will continue in September after some improvements are mad to the cathode deposition chamber and transport cart.
- The ERL 1 MW beam dump is installed. Extraction line magnets vacuum components are installed as well. We plan to start the gun to beam dump test later this fall.
- After the recirculation loop is complete, we will be able to demonstrate energy recovery with high charge per bunch and high beam current. These experiments are planned for 2015.

Courtesy of: Sergey Belomestnykh

Compact ERL @ KEK

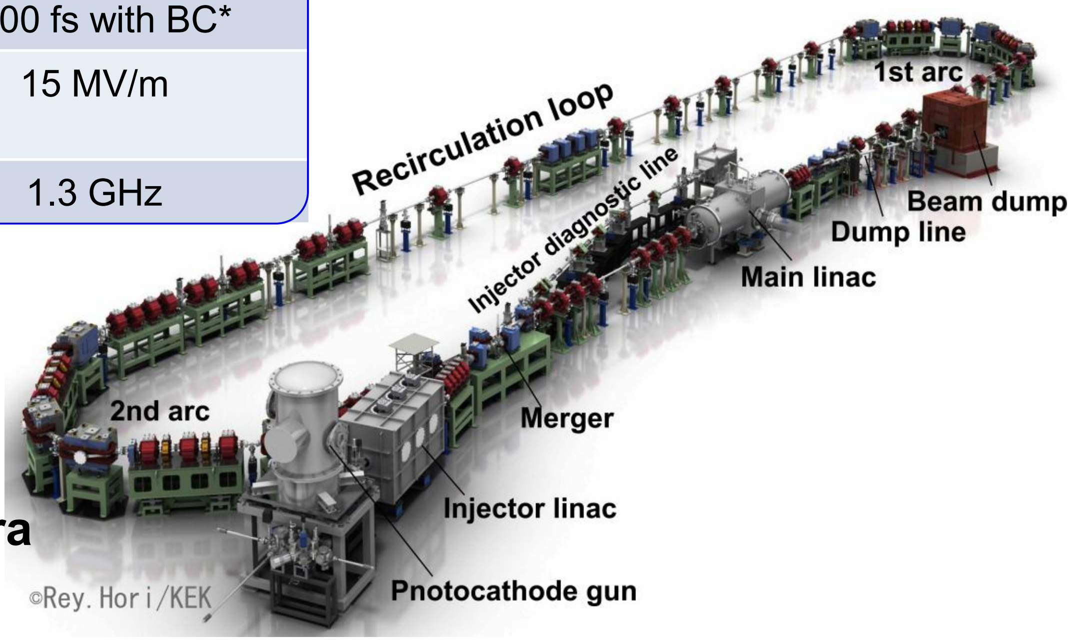
Design Parameters of cERL

Maximum beam energy	35 MeV (upgradable to 125 MeV)
Injector energy	5 MeV (10 MeV in future)
Beam current (initial goal) (long-term goal)	10 mA 100 mA
Normalized emittance @bunch charge	0.3 mm·mrad @7.7 pC 1 mm·mrad @77 pC
Bunch length (rms)	1 - 3 ps ~100 fs with BC*
Accelerating gradient (main linac)	15 MV/m
RF frequency	1.3 GHz

*BC : bunch compression

Purpose of the Compact ERL

- To demonstrate the generation and recirculation of ultra-low emittance beams
- To demonstrate reliable operations of our ERL components (photocathode gun, SC cavities, ...)
- Initial goal: 1 mm·mrad @7.7pC/bunch(10mA)



Courtesy of: Norio Nakamura

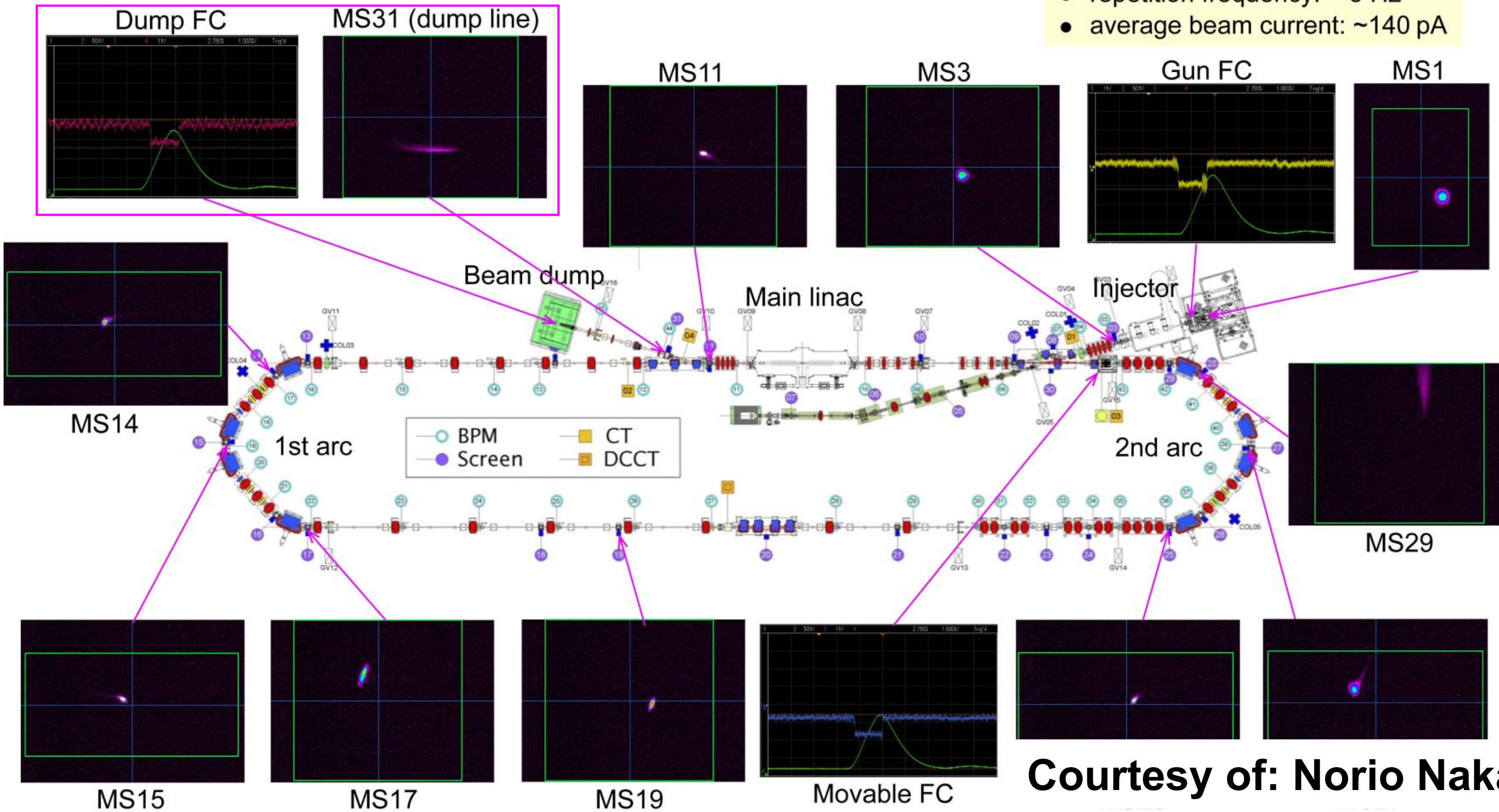
Beam Recirculation & Energy Recovery

Beam was successfully transported to the beam dump in Feb. 6, 2014.

Beam energy
- Injector: 2.9 MeV
- Recirculation loop: 19.9 MeV

Acceleration parameters
- Gun voltage: 390 kV Buncher: OFF
- Injector cavities: E_{acc} = (3.3, 3.3, 3.1) MV/m
- Main-Linac cavities: Vc = (8.57, 8.57) MV

Beam parameters
- peak current: ~24 μA
- macropulse width: 1.2 μs
- repetition of bunches: 1.3 GHz
- repetition frequency: 5 Hz
- average beam current: ~140 pA

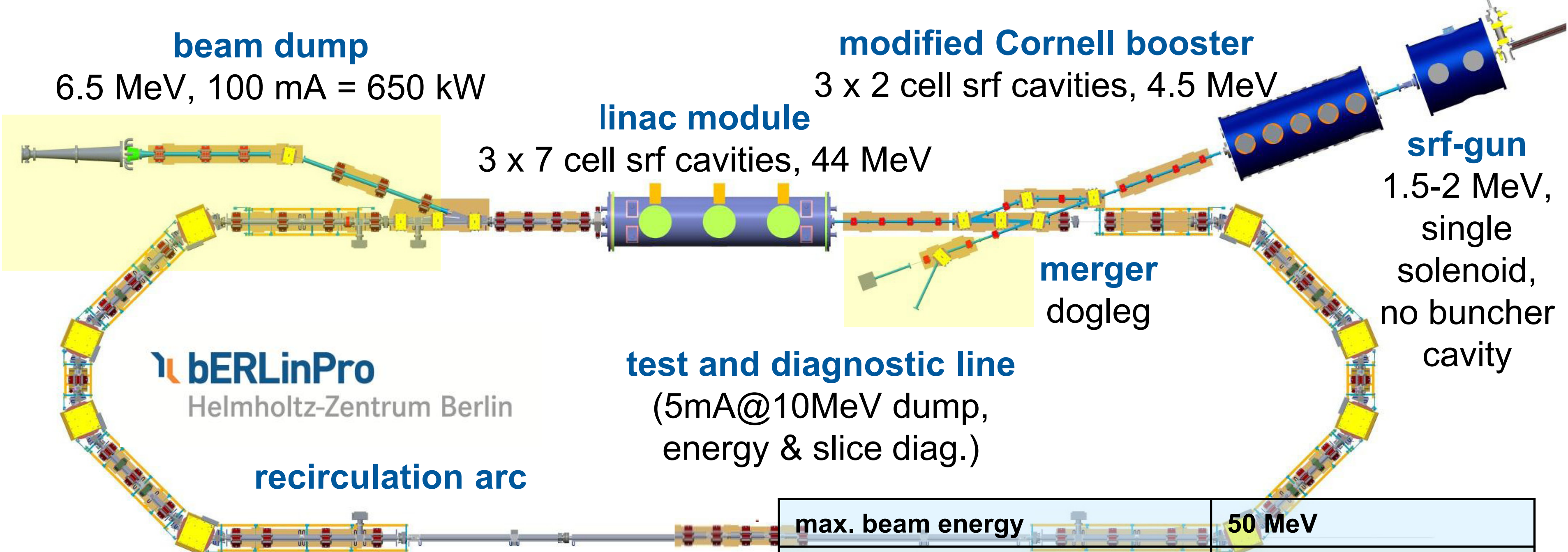


Courtesy of: Norio Nakamura

bERLinPro

bERLinPro = Berlin Energy Recovery Linac Project (project phase 2011-2019, fully funded)

100 mA / low emittance technology demonstrator (covering key aspects of large scale ERL)



max. beam energy	50 MeV
max. current	100 mA (77 pC/bunch)
normalized emittance	1 μm (0.5 μm)
bunch length (straight)	2 ps or smaller (100 fs)
rep. rate	1.3 GHz
losses	< 10^{-5}

- **cw srf technology for high current injectors and linacs**
- **explore parameter space of ERLs**
- **first operation of srf gun 2011**
- **building ready 2016**
- **first electrons 2017**
- **first recirculation + recovery 2019**

Courtesy of: Andreas Jankowiak

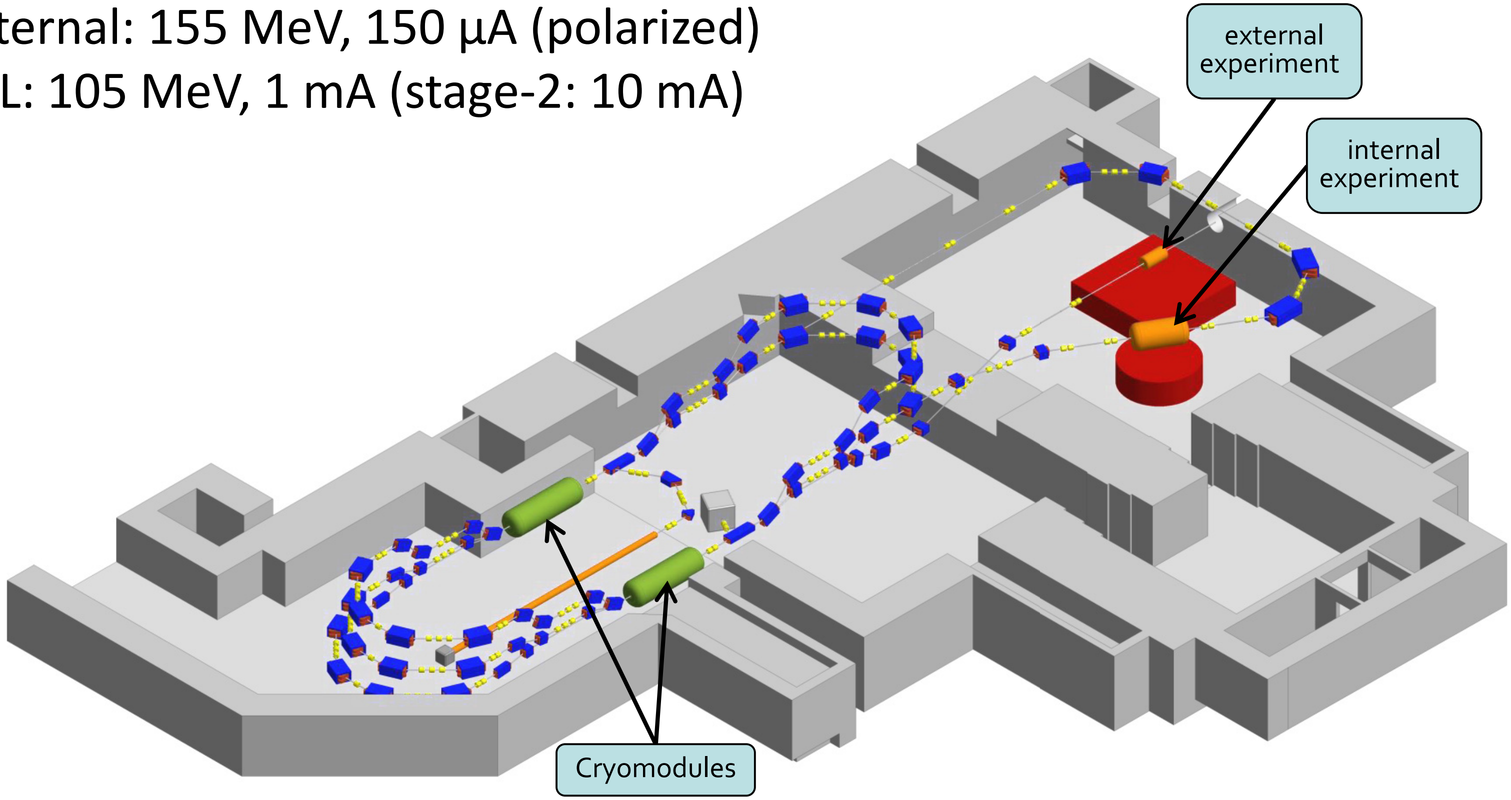
MESA @ U of Mainz

MESA – Parameters:

CW electron beam

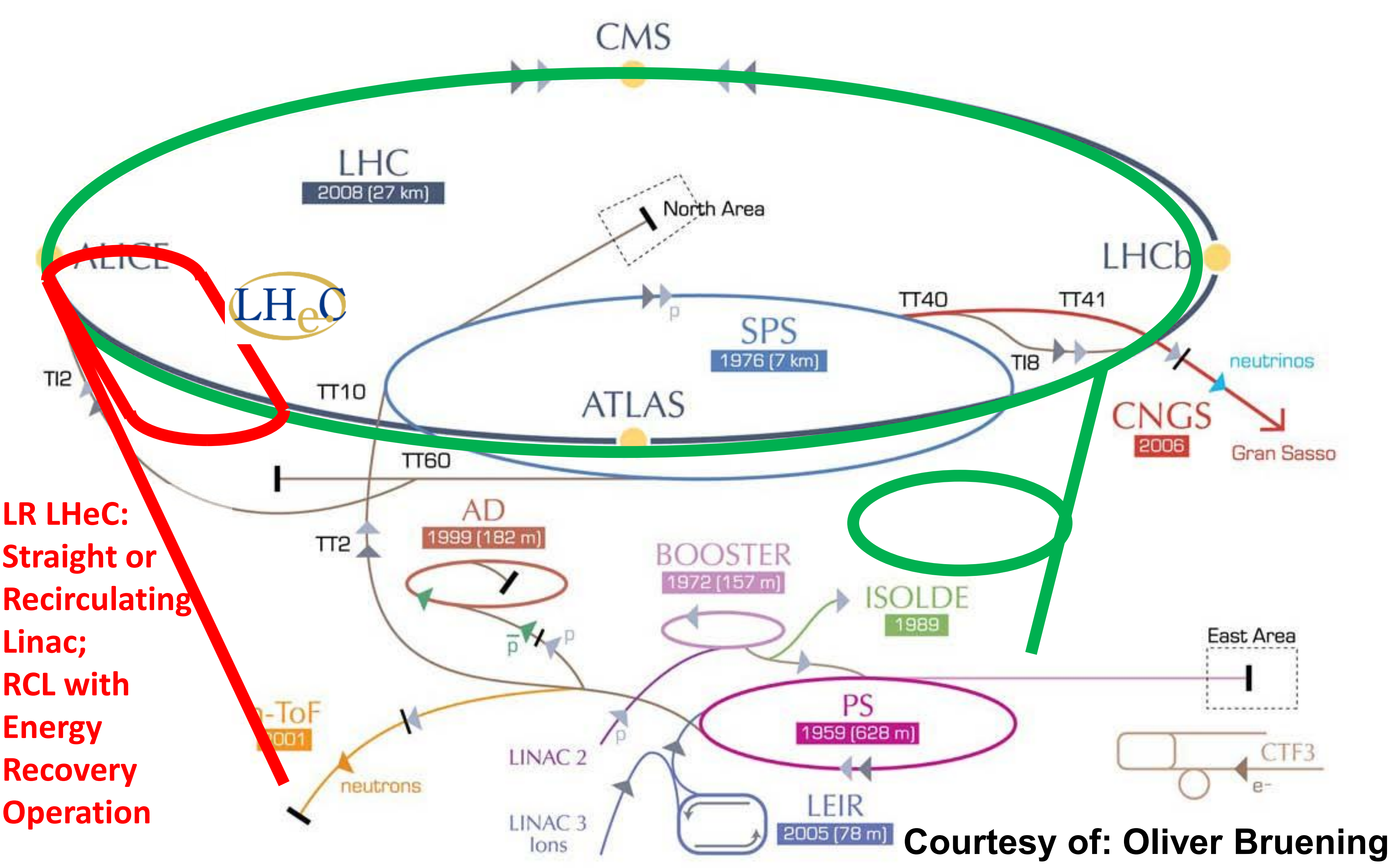
External: 155 MeV, 150 µA (polarized)

ERL: 105 MeV, 1 mA (stage-2: 10 mA)



Courtesy of: Robert Heine

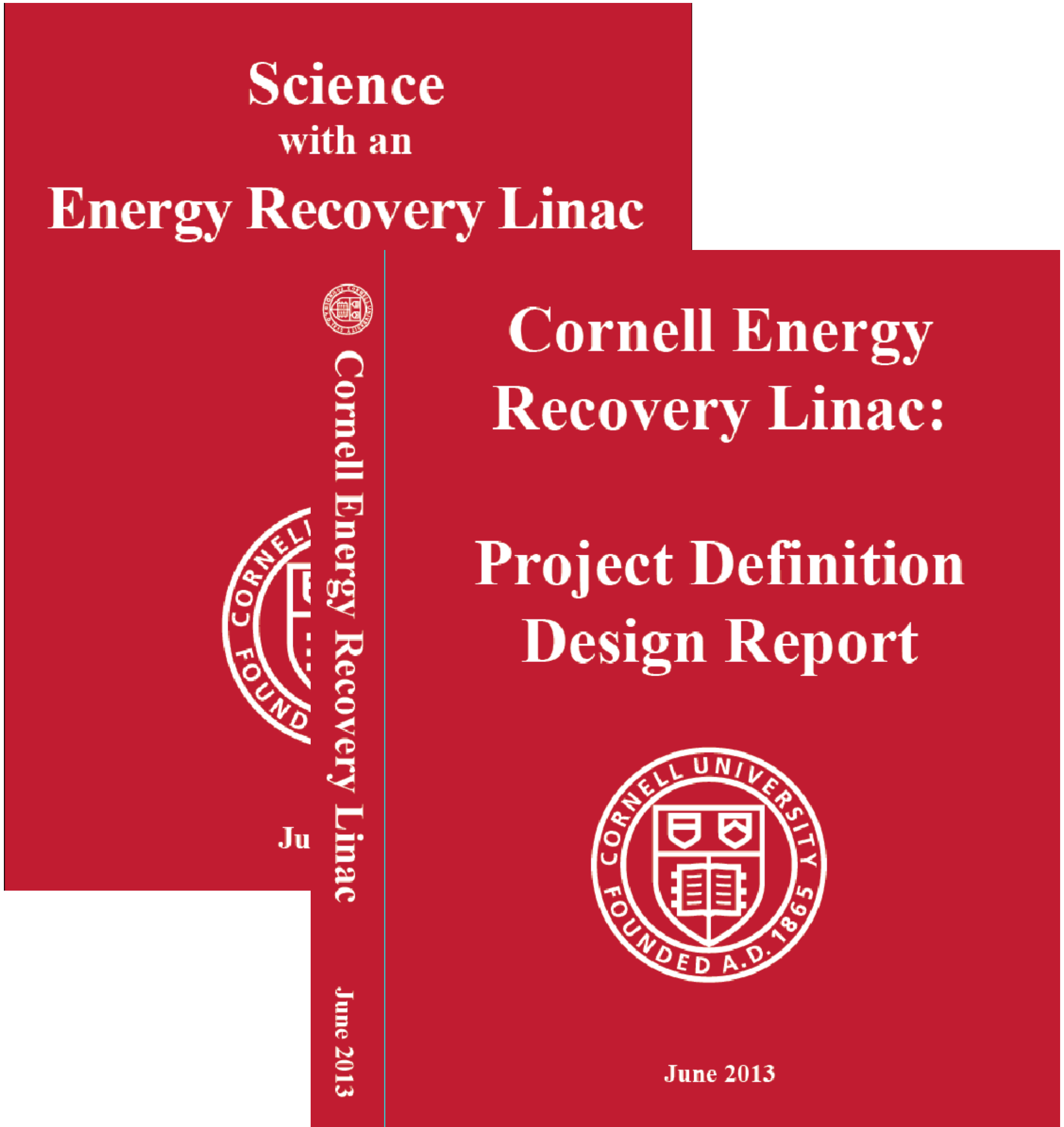
LHeC ERL Option



LR LHeC: Straight or Recirculating Linac; RCL with Energy Recovery Operation

Courtesy of: Oliver Bruening

Cornell ERL documentation: (1) Science, (2) Generic design



- Science case gathered in international workshops
- Design report
  - 530 pages between conceptual design and engineering design
  - Access at

www.classe.cornell.edu/ERL/PDDR

Cornell ERL Parameter

- 5 GeV, 100 mA CW beam
  - 8 pm emittance, 2 ps bunch length
- Stable operation
  - Strong HOMs can cause beam breakup
  - ~200 W HOM power in beamline loads/cavity
- CW operation
  - Q(1.8 K) = 2×10^{10} @ 16.2 MV/m
    - 10 W cryogenic loss from fundamental/cavity
    - ~4 MW wall power

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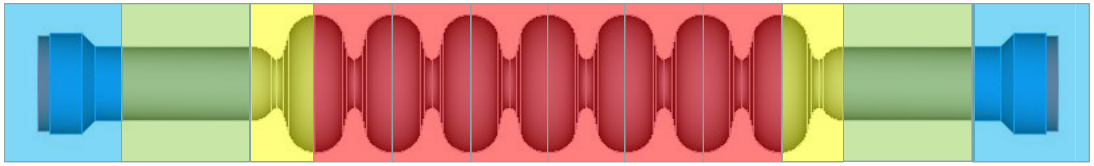
ERL Cavity Shape Design



Goal: Maximize I_{th} > 100 mA (under constraints)

Center cells

- Geometries are (nominally) identical
- Responsible for general properties of HOM spectrum
  - Controls frequencies of HOM passbands and dispersion relations
  - Determines cell-to-cell coupling and how sensitive HOM spectrum is to variation in cell shape

End cells

- Asymmetric design helps prevent trapped modes
- Responsible for coupling HOMs to HOM absorber
  - Directly controls quality factors of HOMs

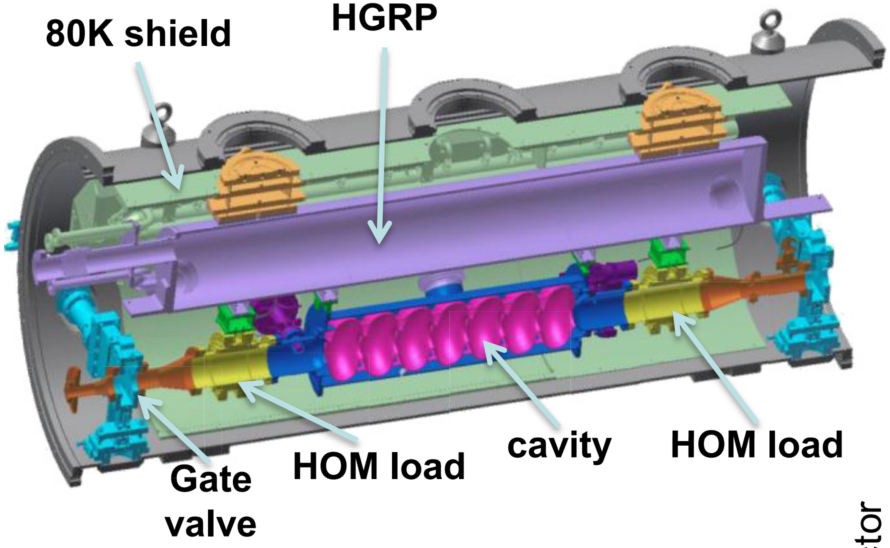
Beam Pipe

- Should be short to improve linac fill factor but long enough to avoid dissipating too much power from the fundamental mode

HOM load

- Absorber material properties determine specific mode losses.
- Also serves as bellows connecting cavities

Horizontal Test Results (2013)



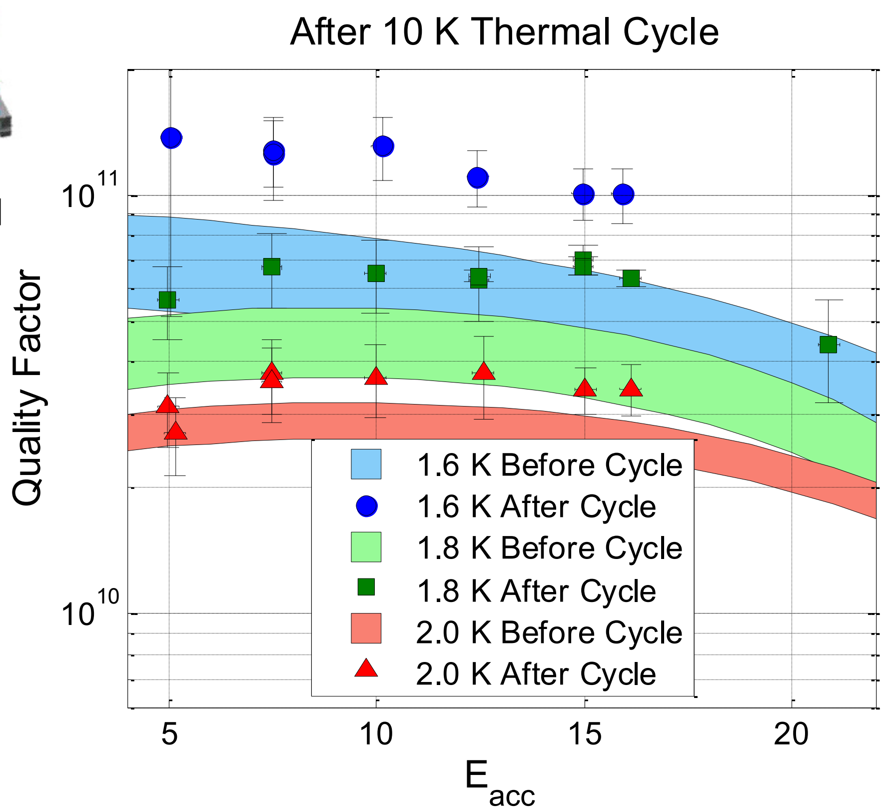
Horizontal Test Cryostat:

(@16MV/m, 1.8K):

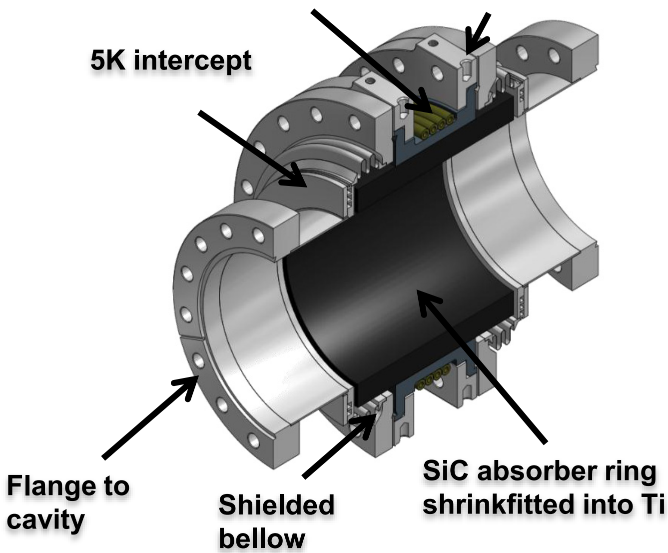
Q0 = 3.5E10 without coupler

Q0 = 2.E10 with couplers

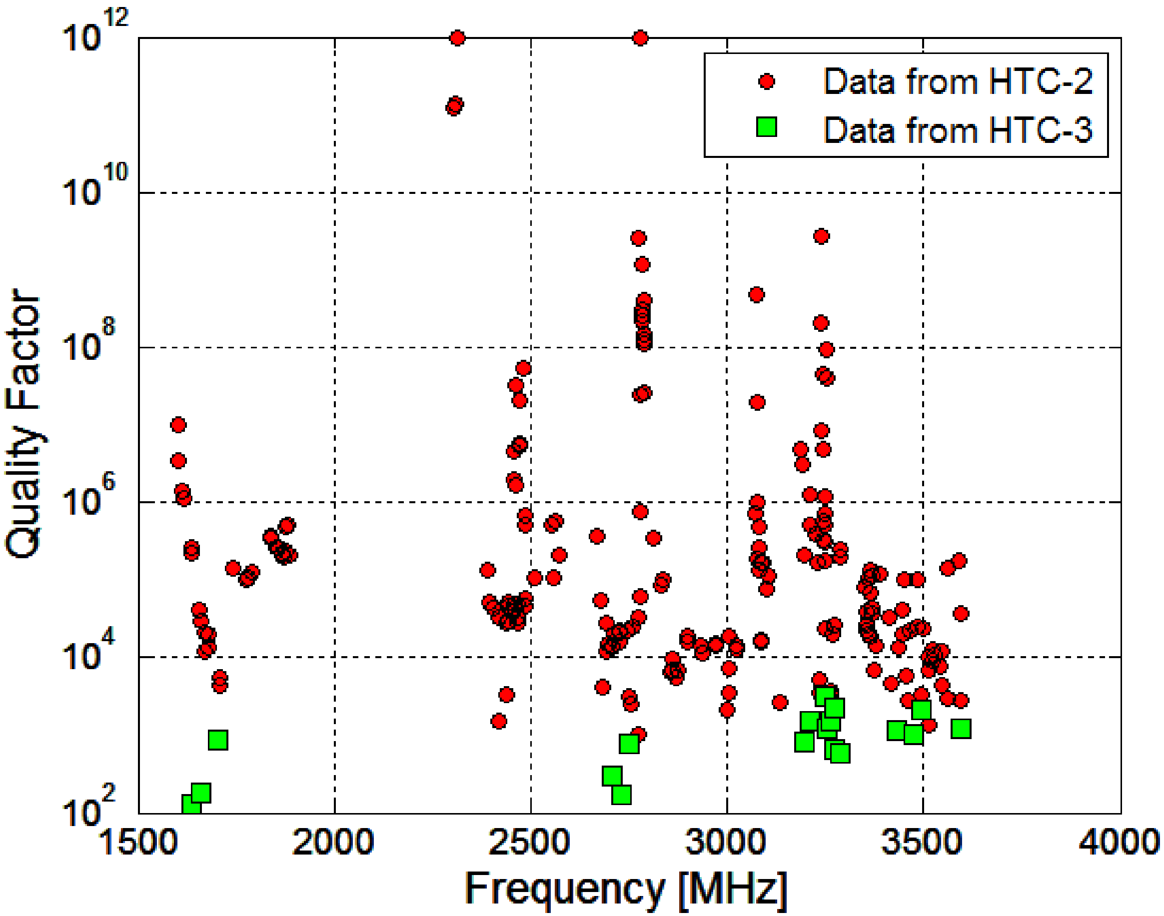
Q0 = 6E10 with coupler and HOM absorbers



HOM Damping in the HTC



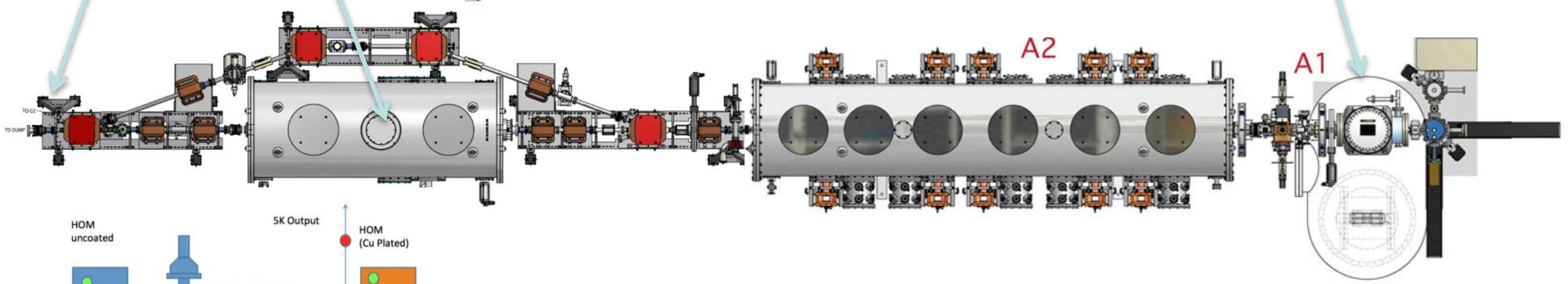
HTC-2: No HOM Absorbers
HTC-3: With HOM Absorbers

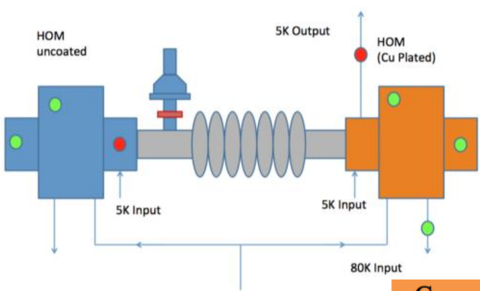


Beamline HOM absorbers strongly damp dipole HOMs to under Q ~ 10^4

Cavity beam test @ 40 mA

BPM 7-cell cavity in cryostat gun

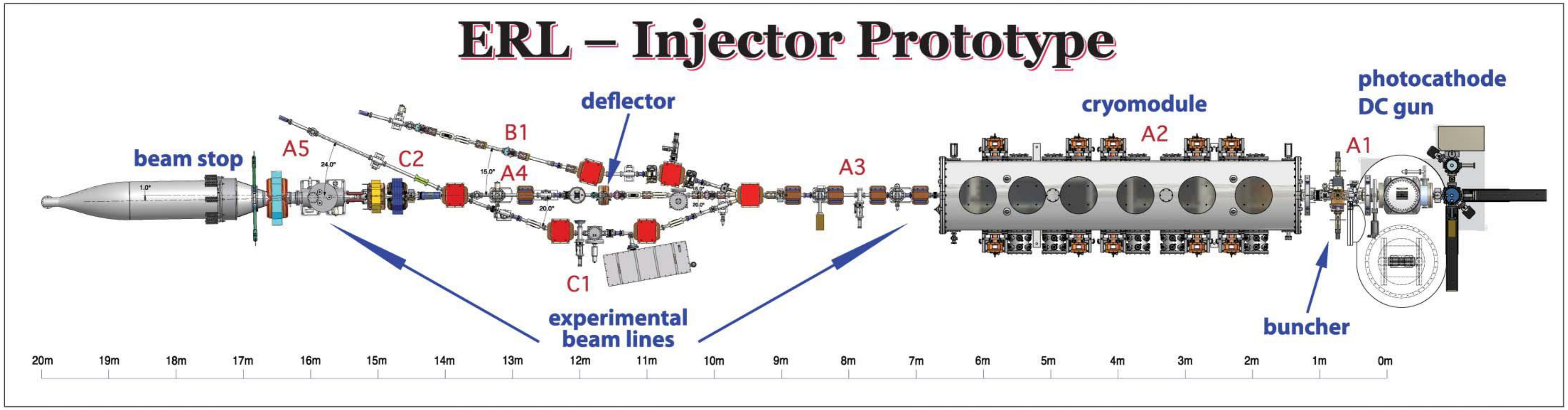


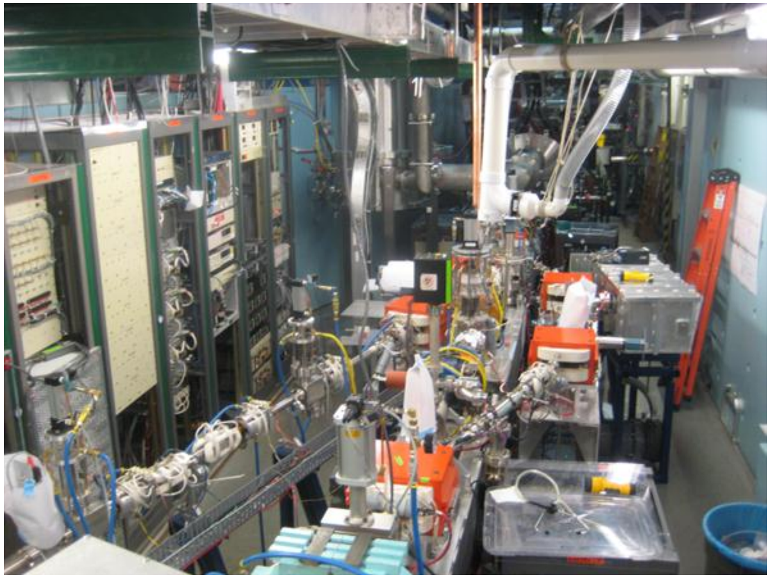


Current, bunch length	ΔT (beam pipe behind Abs.) coated/uncoated	ΔT (80K gas temp) coated/uncoated	ΔT (80K absorber temp) coated/uncoated	ΔT (5K flange next to cavity) coated	ΔT, beam pipe to cavity coated/uncoated
25 mA, 3.0 ps	0.075/0.075	1.14/0.82	1.02/0.975	0.007	0.076/-.005
40 mA, 3.4 ps	0.2475/0.335	2.95/2.16	2.72/2.53	0.021	0.179/0.009
40 mA, 2.7 ps	0.2975/0.425	3.00/2.22	2.772/2.63	0.027	0.203/0.014

- No charge-up of the HOM ceramics observed
- HOM heating was less than expected

Cornell ERL Injector

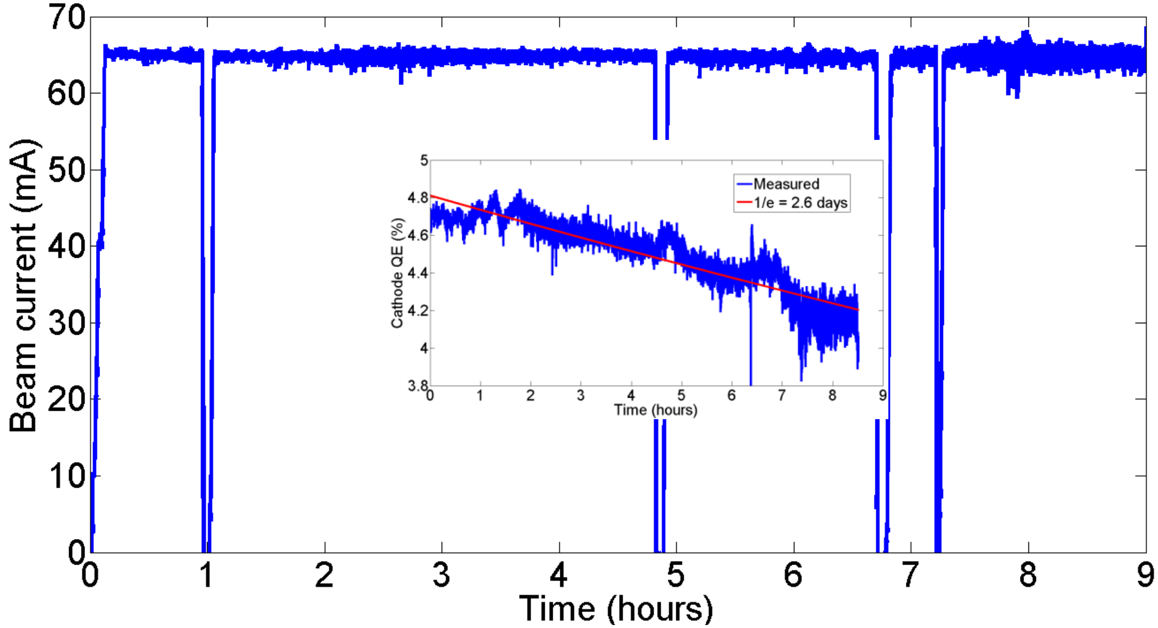




ERL Injector Prototype: Achievements to date (last high current run Sept'13):

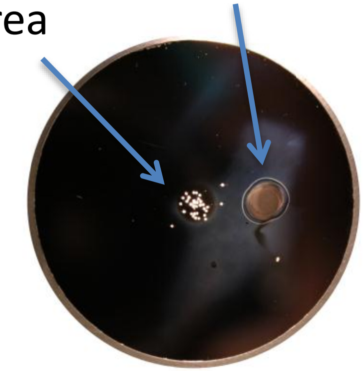
- *75 mA average current @ 4 MeV*
- *0.3 μm emittance @ 77 pC, 8 MeV*

High Currents – Na2KSb



Ion damage limited to the central area

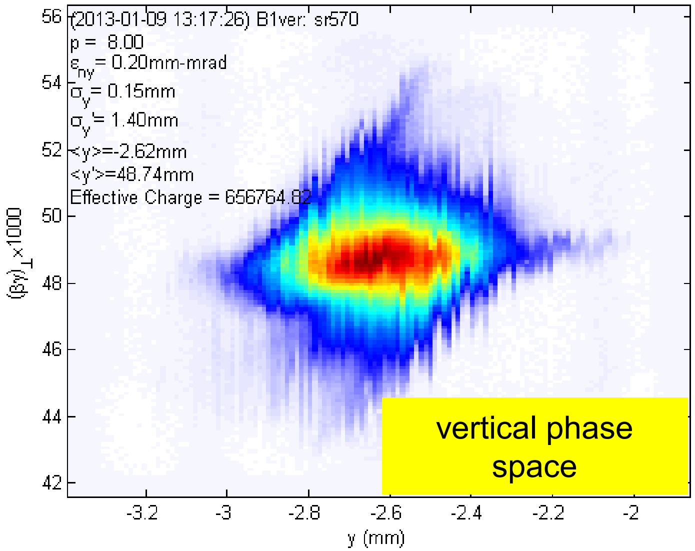
Active area is offset from the center

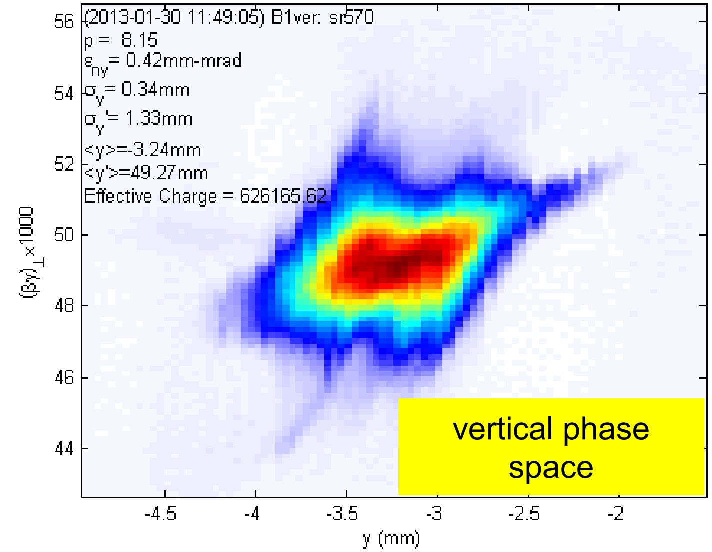


Front surface of the cathode (CsK_2Sb on Si) after use.

Using a Na_2KSb photocathode, ran over 8 hours at 65 mA (2000 C) with a 2.6 day 1/e cathode lifetime.
Reached as high as 75 mA for a short time.

Beam brightness





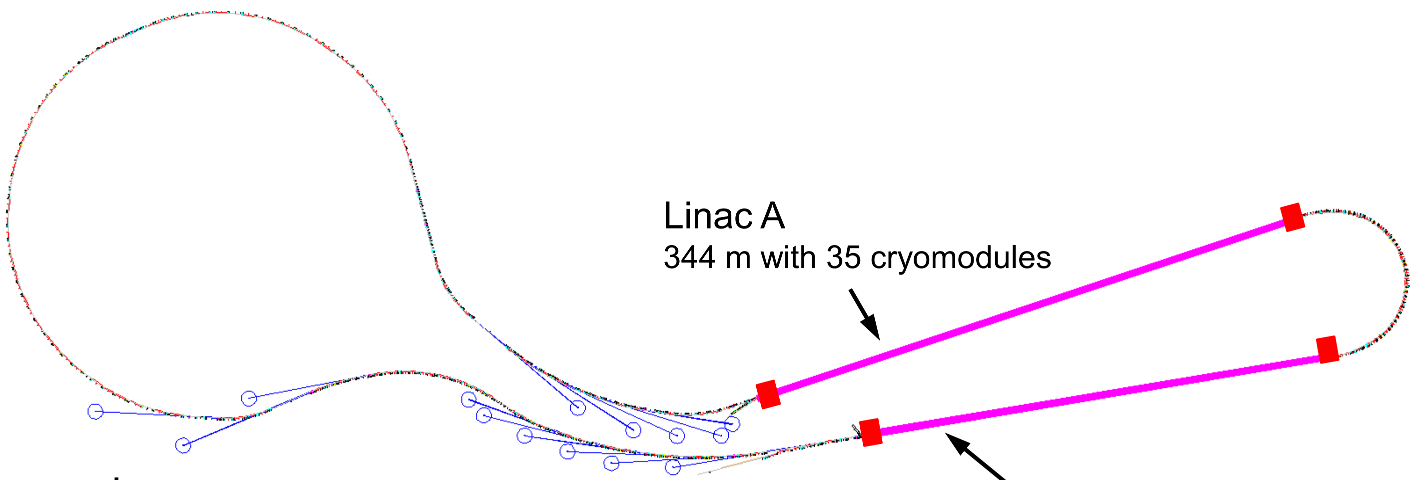
20 pC/bunch	80 pC/bunch
Normalized rms emittance (horizontal/vertical) 90% beam, E ~ 8 MeV, 2-3 ps	
0.23/0.14 mm-mrad	0.51/0.29 mm-mrad
Normalized rms core* emittance (horizontal/vertical) @ core fraction (%)	
0.14/0.09 mm-mrad @ 68%	0.24/0.18 mm-mrad @ 61%

9 pm at 5 GeV, diffraction limited for 12 keV photons

**Phys. Rev. ST-AB 15 (2012) 050703*

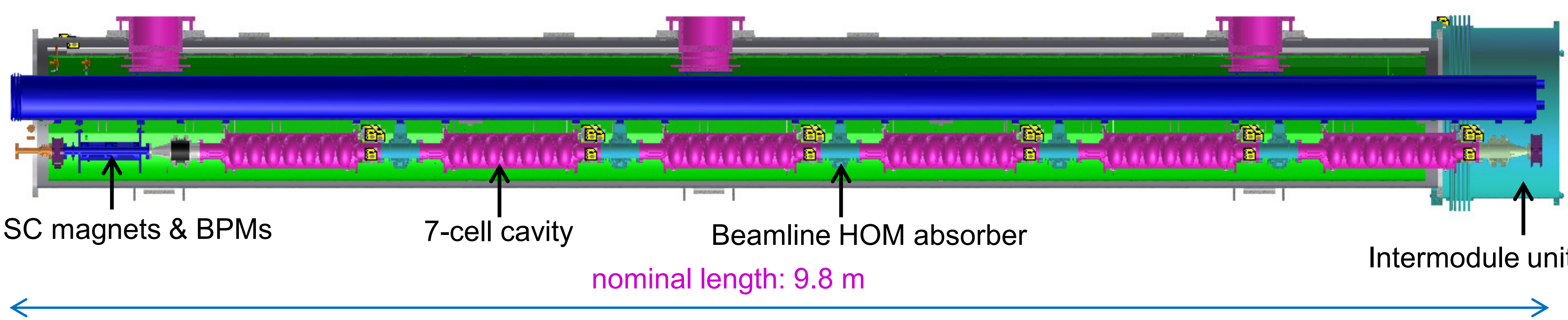
✓ At 5 GeV this gives 20x the world's highest brightness (Petra-III)

Linac cryomodule for the ERL (MLC)

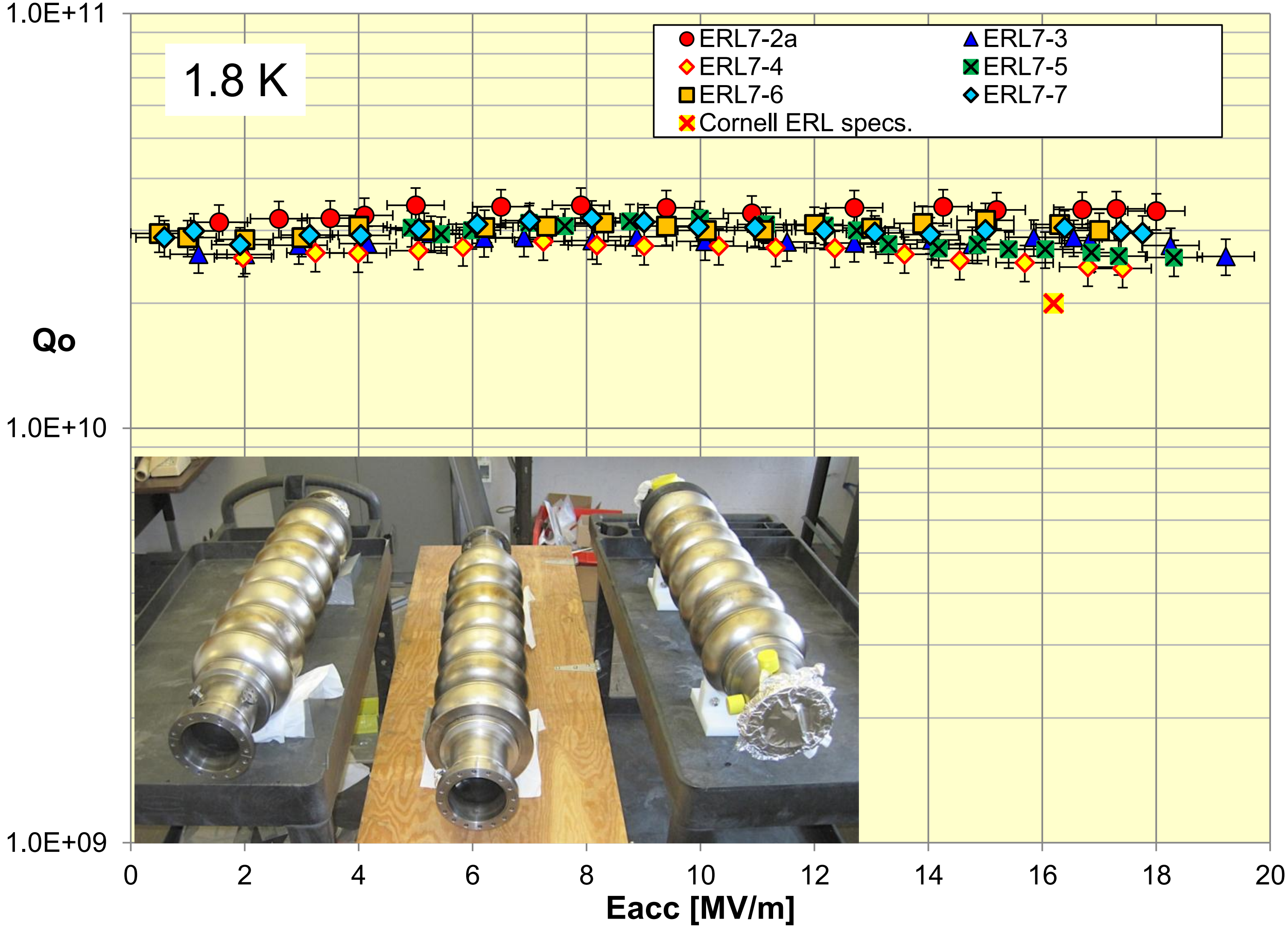


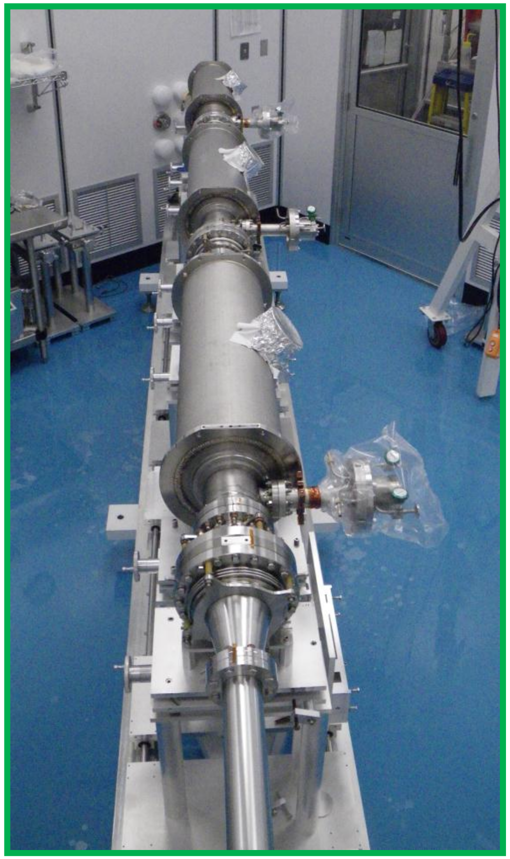
Total 64 cryomodules, each:

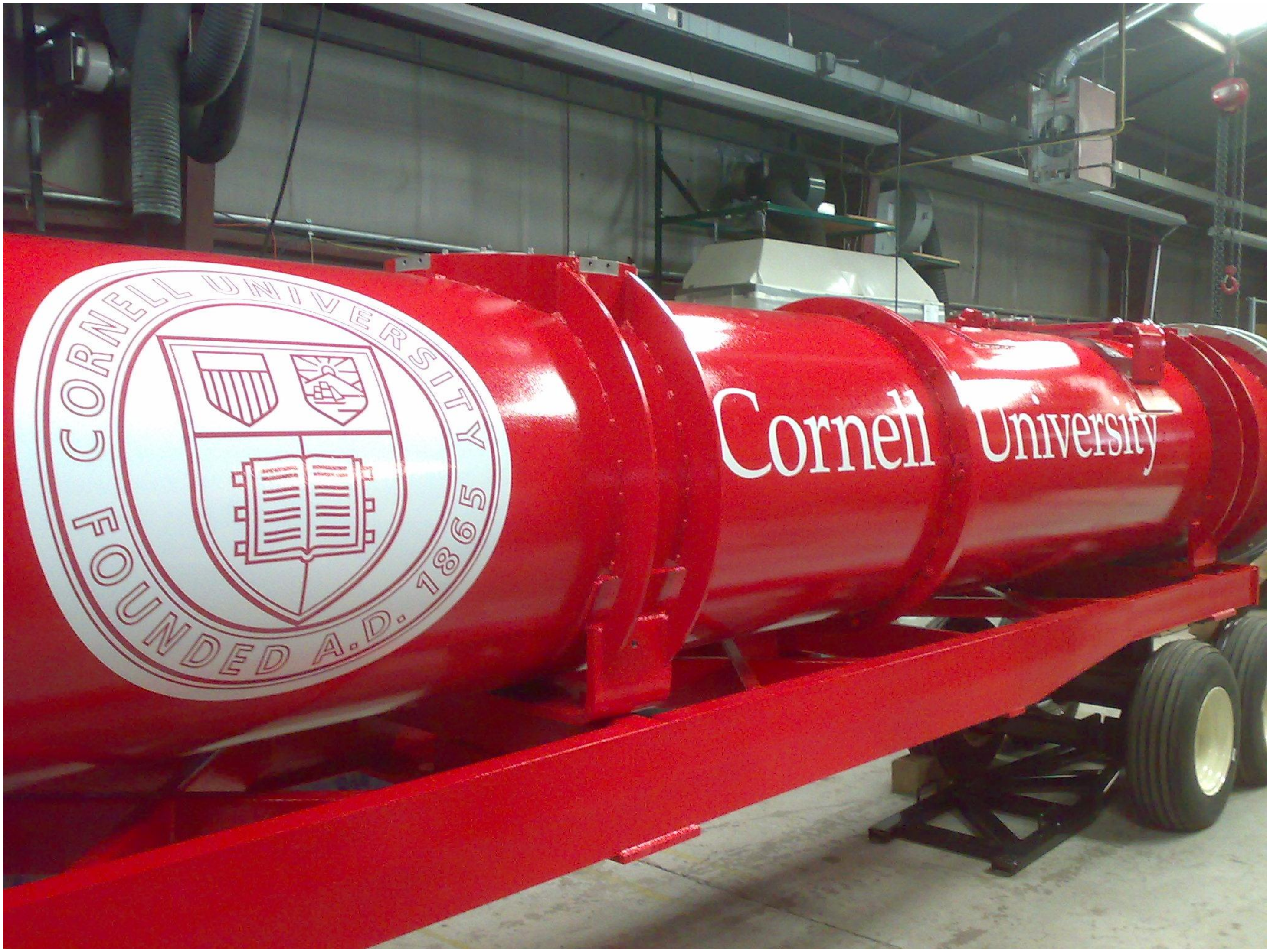
- six packages of 7-cell cavity/Coupler/tuner
- a SC magnets/BPMs package
- five regular HOMs/two taper HOMs



ERL Cavity test results



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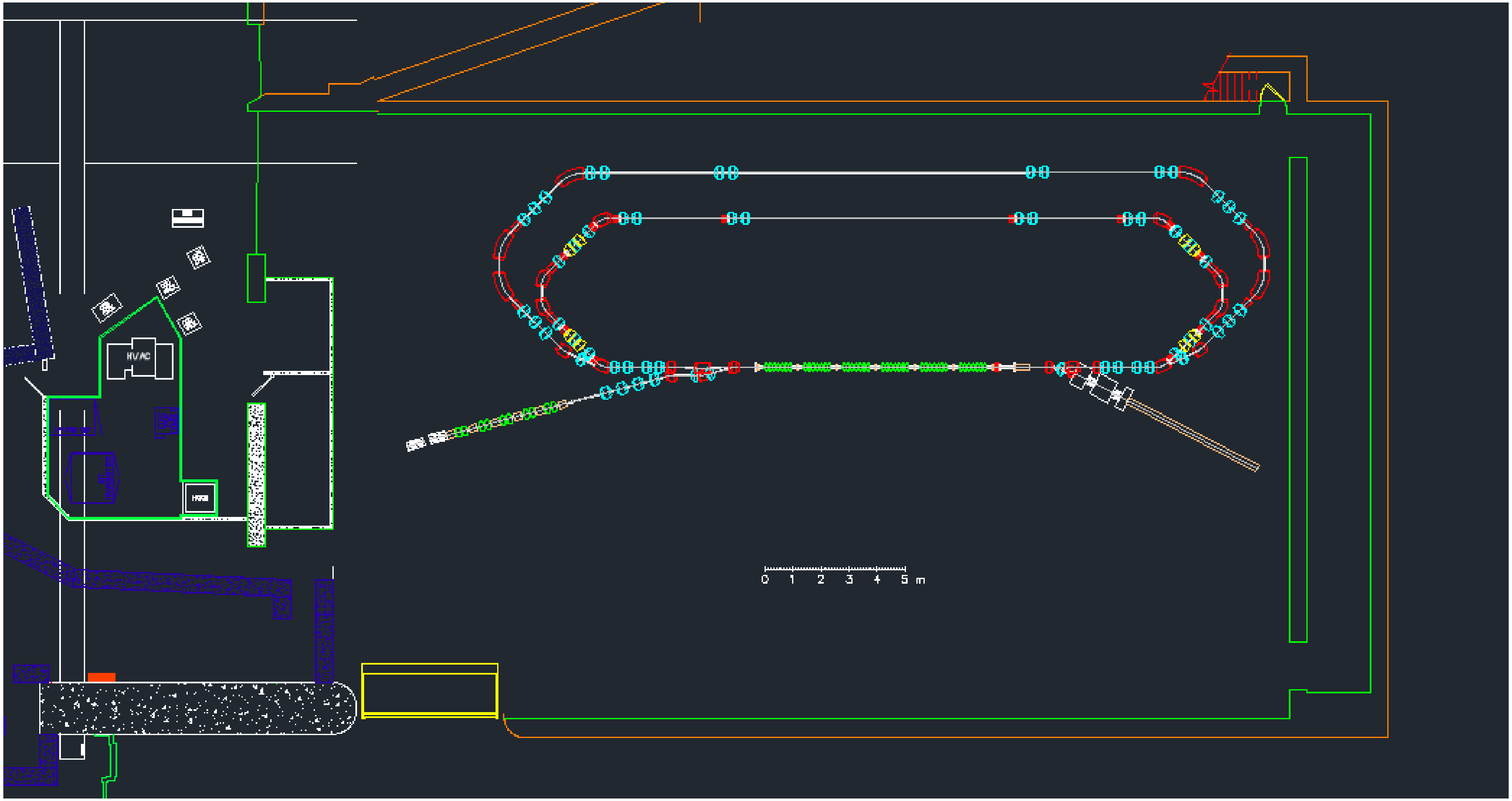
Where do we stand?

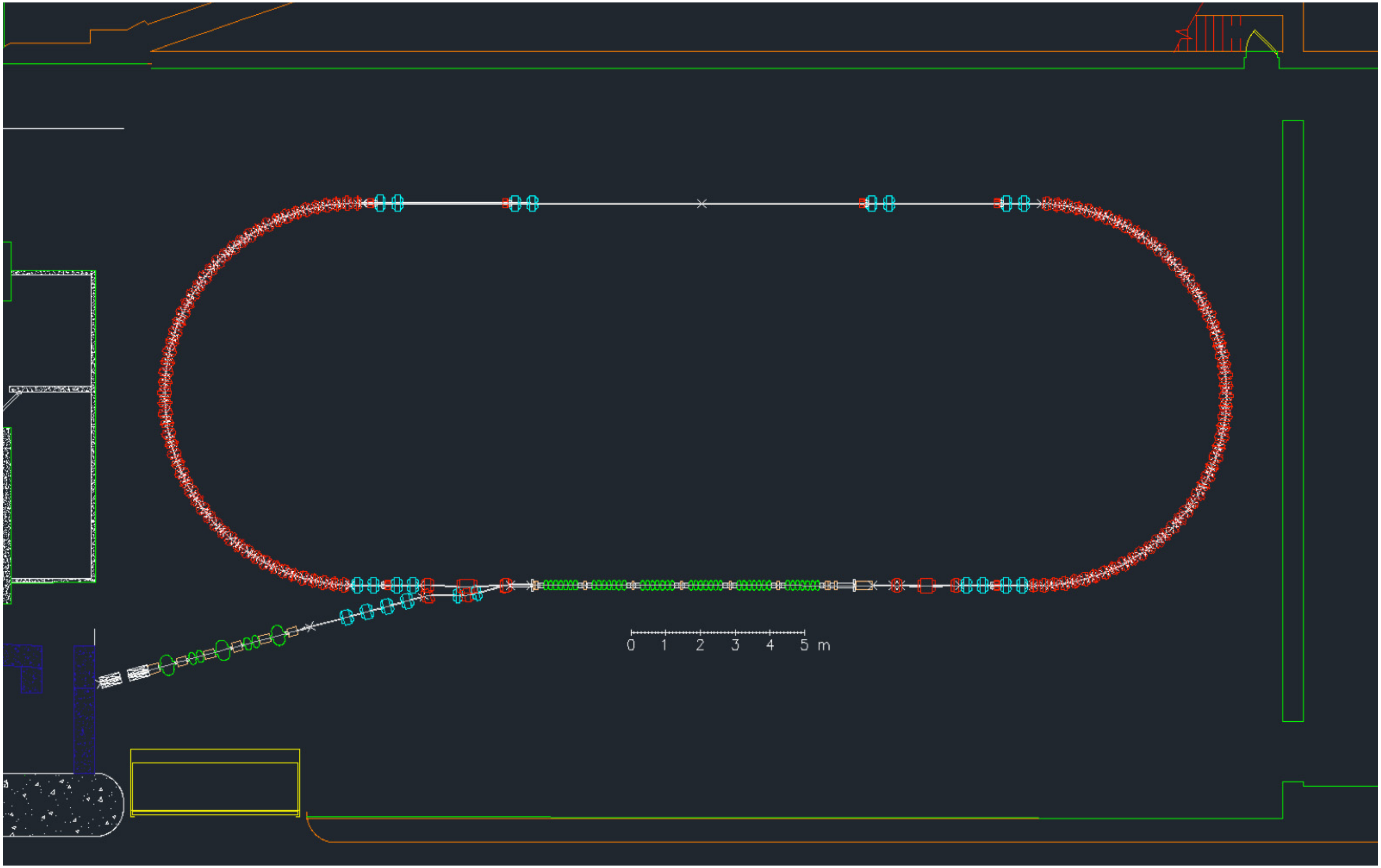
- In HTC, we reached a Q of $6*10^{10}$ at 1.8 K with a fully dressed cavity
- We measured sufficient HOM damping
- We built a photo-injector, currently achieving 75 mA
- We reached our emittance goals
- A full, 6 cavity cryomodule is under assembly and will be finished by the end of this year

- So, what might come next?

Ready to propose: Cornell recirculation loop



ERL/ FFAG ring option



The Cornell ERL team