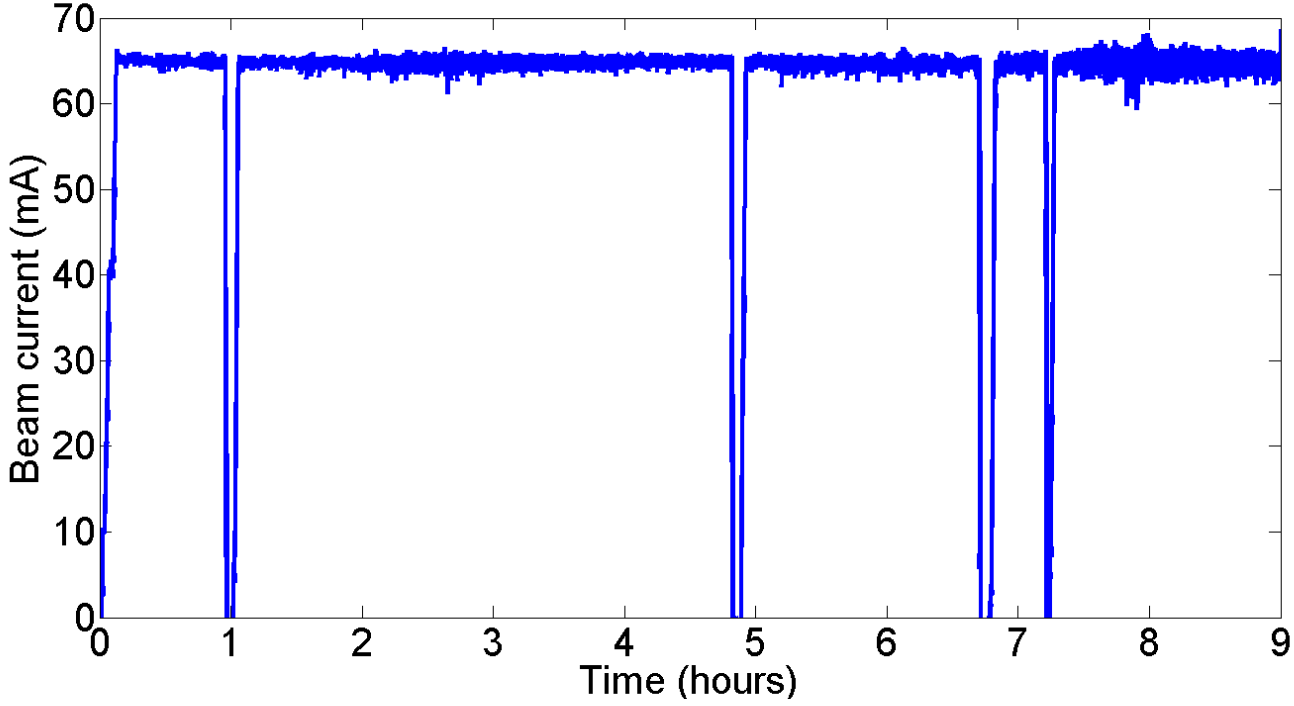
Recent advances in Energy Recovery Linacs



Christopher Mayes – June 20, 2014

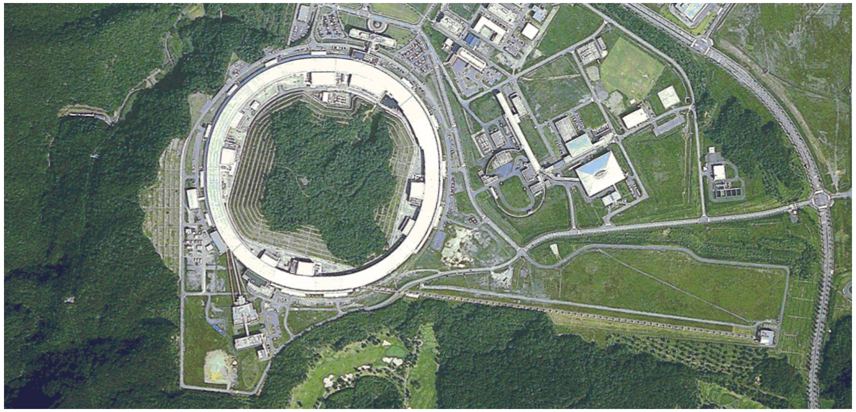
Existing High-Energy, High-Current machines

ESRF - France (1994 -)
844 m, 6 GeV, 200 mA

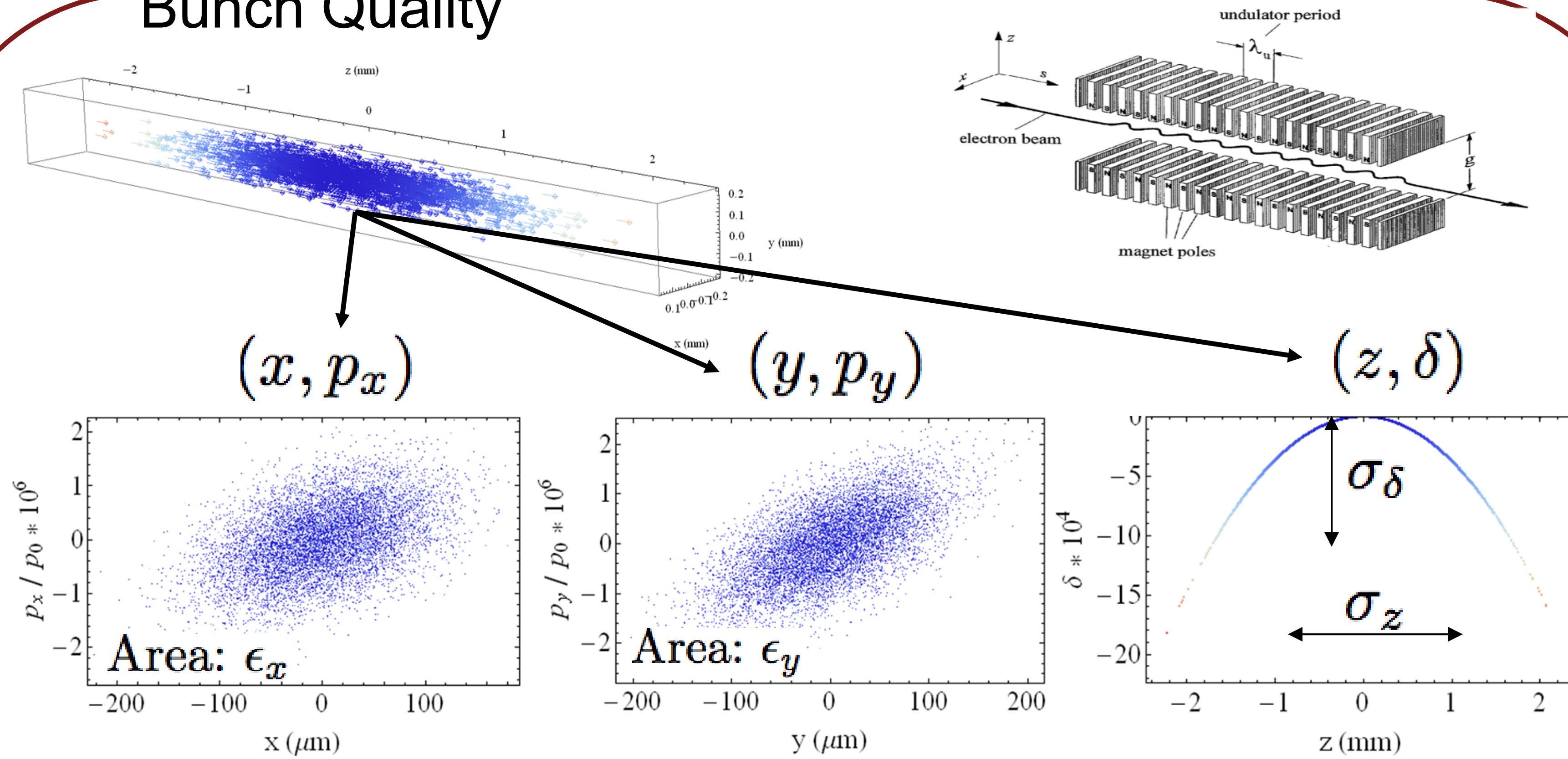
Petra III - Germany (2009 -)
2304 m, 6 GeV, 100 mA

APS - United States (1996 -)
1104 m, 7 GeV, 100 mA

SPring8 - Japan (1997 -)
1438 m, 8 GeV, 100 mA



Bunch Quality



Lightsource

Flux $\mathcal{F} \propto I_{\mathrm{av}} \cdot N_{\mathrm{u}} \cdot f_n(\lambda_{\mathrm{u}}, B_{\mathrm{u}})$

Brilliance $\mathcal{B} \propto \dfrac{I_{\mathrm{av}}}{\epsilon_x \, \epsilon_y}$

Peak Brilliance $\hat{\mathcal{B}} \propto \dfrac{I_{\mathrm{av}}}{\epsilon_x \, \epsilon_y \, \sigma_z \, \sigma_\delta}$

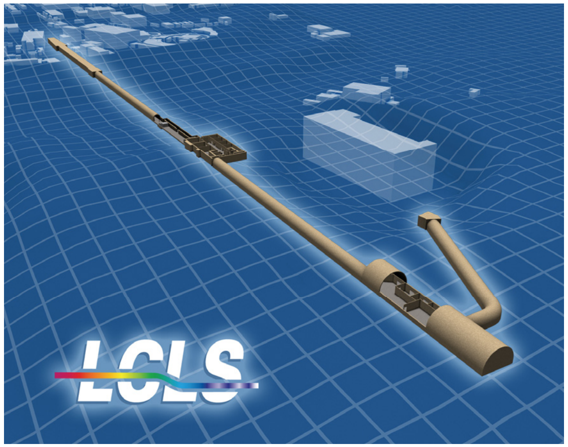
Collider

Luminosity $\mathcal{L} \propto \dfrac{I_{\mathrm{av}}}{\sigma_x \sigma_y}$

$$\propto \frac{I_{\mathrm{av}}}{\sqrt{\beta_x \, \epsilon_x \, \beta_y \, \epsilon_y}}$$

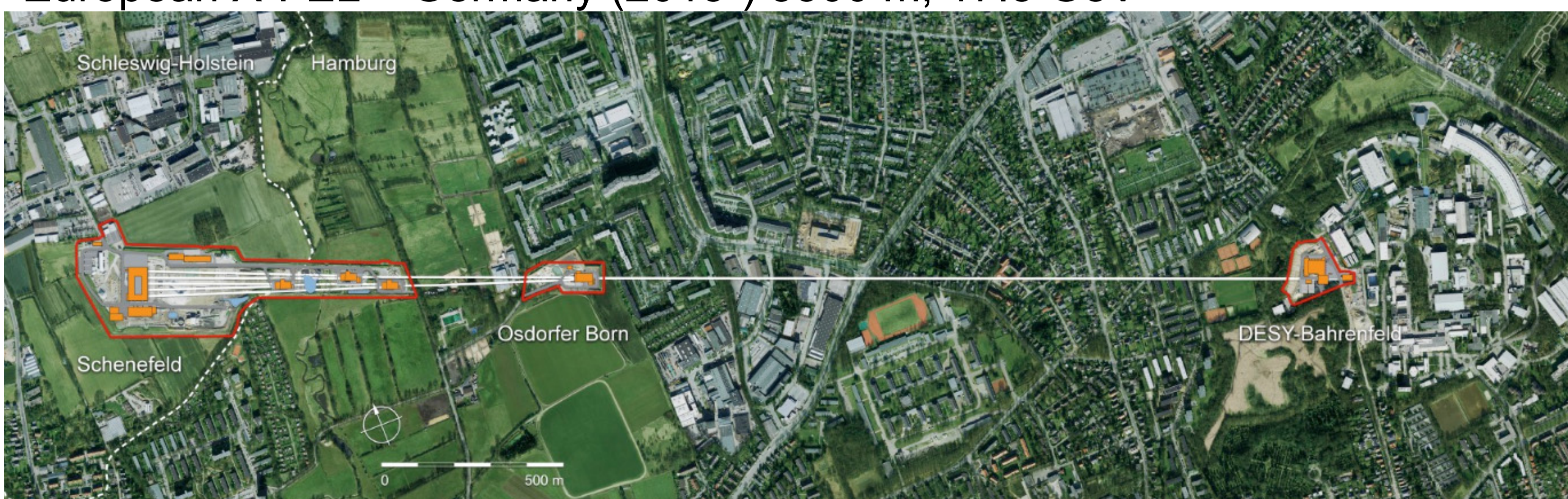
High-Energy, High-Quality machines: Linacs

LCLS - United States (2009-)
3000 m, 14.3 GeV
Planning: LCLS2 4 GeV SRF



SACLA – Japan (2011-)
750 m, 6-8 GeV

European X-FEL – Germany (2015-) 3500 m, 17.5 GeV



But not High-Current, because

$$P_{\text{linac}} = 1\,\text{MW}\left(\frac{I_{\text{av}}}{\text{mA}}\right)\left(\frac{\Delta\mathcal{E}}{\text{GeV}}\right)$$

[Nine Mile Point Nuclear Power Plant, Oswego, NY]

Storage Ring

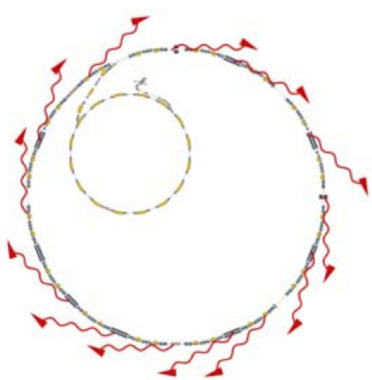
High repetition rates (100+ MHz)
High current (100+ mA)

Many user stations

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

Bunch durations (20 ps)

Emittance determined by the ring



Linac

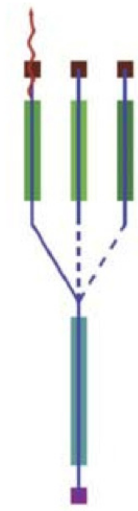
Low repetition rates (120 Hz, 17 kHz)
Low average current (10^{-4} mA)
(but very high peak current)
Few user stations

Excellent energy spread (10^{-4} relative)

Drive FELs

Short bunch durations (0.01 – 2 ps)

Emittance deter the source



Energy Recovery Linac

~~Storage Ring~~

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

Many user stations

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

Bunch durations (20 ps)

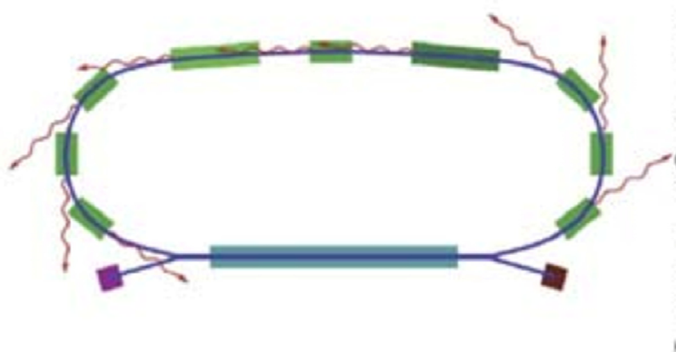
Emittance determined by the ring

~~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



Can also be operated as linac

Flexible optics
Flexible bunch structure

ERL Concept (1965)

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

M. TIGNER

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

(ricevuto il 2 Febbraio 1965)

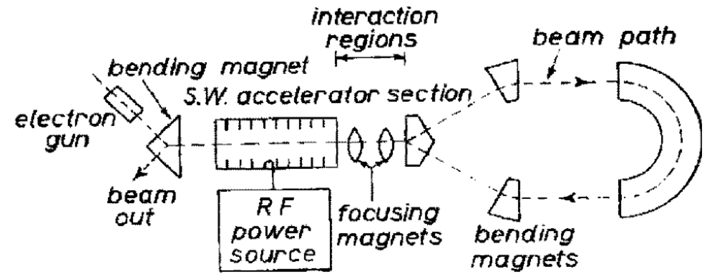
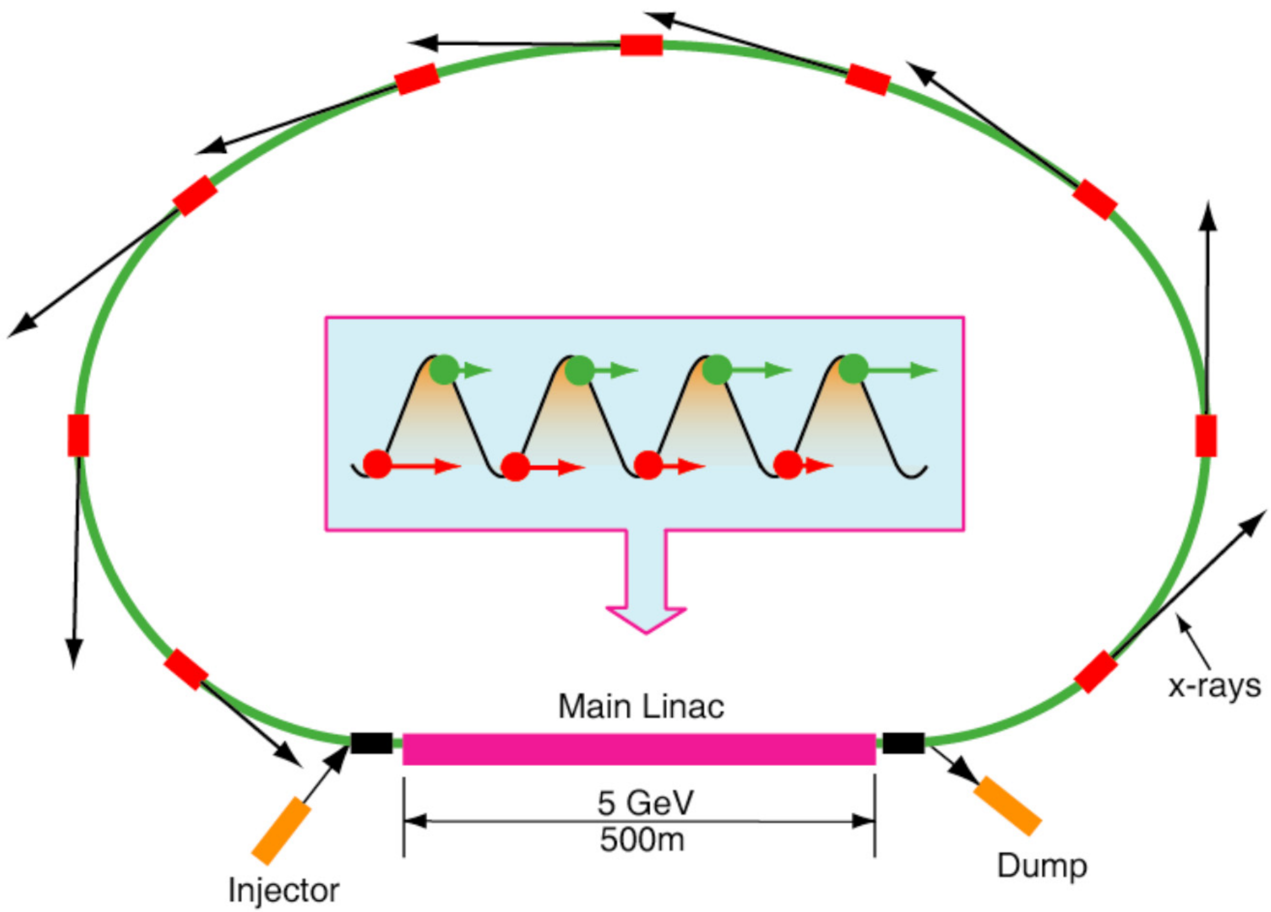
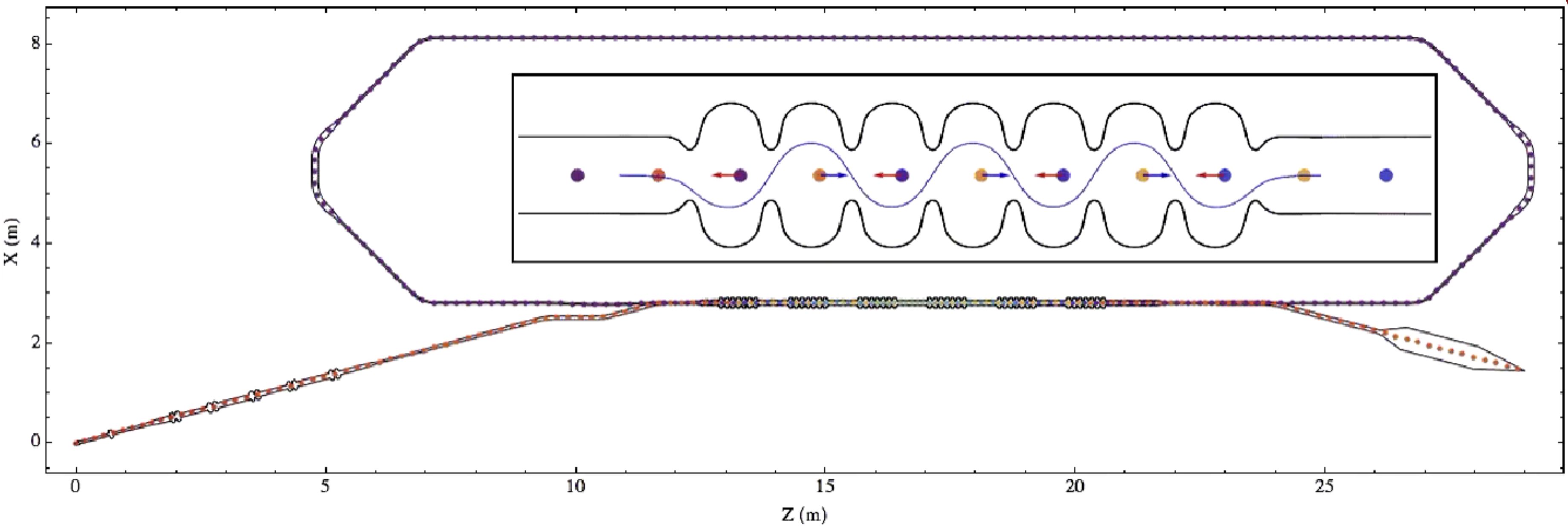


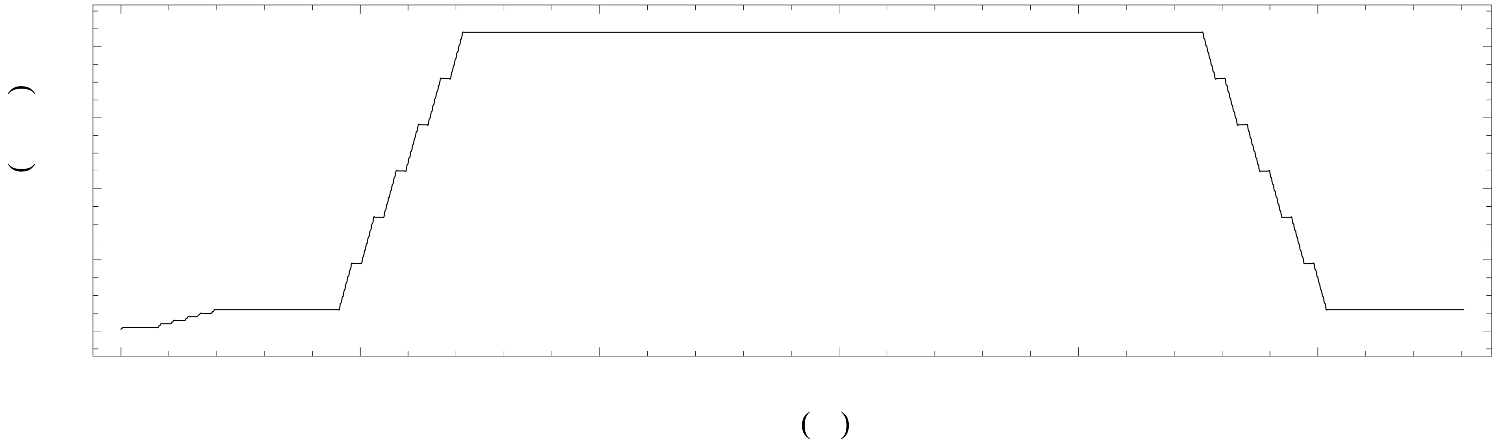
Fig. 3.

Cornell ERL Study (2001)



ERL Concept





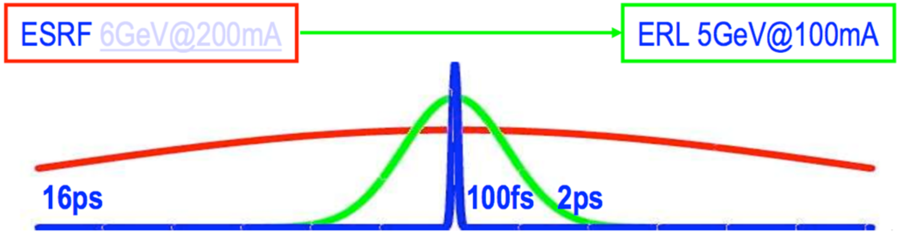
http://www.lepp.cornell.edu/~cem52/Movies/ERL_animation.mov

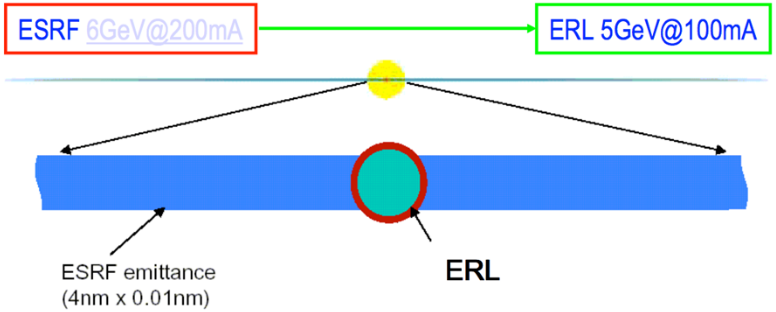
Baseline ERL Lightsource parameters

	Energy recovered modes			One pass	
Modes:	(A) Flux	(B) Coherence	(C) Short-Pulse	(D) High charge	Units
Energy	5	5	5	5	GeV
Current	100	25	100	0.1	mA
Bunch charge	77	19	77	1000	pC
Repetition rate	1300	1300	1300	0.1	MHz
Norm. emittance	0.3	0.08	1	5.0	mm mrad
Geom. emittance	31	8.2	103	1022	pm
Rms bunch length	2000	2000	100	50	fs
Relative energy spread	0.2	0.2	1	3	10^{-3}
Beam power	500	125	500	0.5	MW

Advantages of ERL Beams

Name	Energy (GeV)	Current (mA)	Emittance (pm)	Duration (ps)
APS	6	100	3100	34
ESRF	6	200	4000	13
SPring-8	8	100	2800	17
APS MBA Upgrade	6	200	50	50
ESRF MBA Upgrade	6	200	160	11
SPring-8 MBA Upgrade	6	100	110	5
CERL mode A	5	100	31	2
mode B	5	25	8	2
mode C	5	1	511	0.1





First successful ERLs

VOLUME 84, NUMBER 4 PHYSICAL REVIEW LETTERS 24 JANUARY 2000

Sustained Kilowatt Lasing in a Free-Electron Laser with Same-Cell Energy Recovery

G.R. Neil,* C.L. Bohn, S.V. Benson, G. Biallas, D. Douglas, H.F. Dylla, R. Evans, J. Fugitt, A. Grippo, J. Gubeli, R. Hill, K. Jordan, R. Li, L. Merminga, P. Piot, J. Preble, M. Shinn, T. Siggins, R. Walker, and B. Yunn

Thomas Jefferson National Accelerator Facility, Newport News, Virginia 23606

(Received 3 September 1999)

ELSEVIER Nuclear Instruments and Methods in Physics Research A 557 (2006) 23–27 Section A

www.elsevier.com/locate/nima

Status of the Novosibirsk energy recovery linac

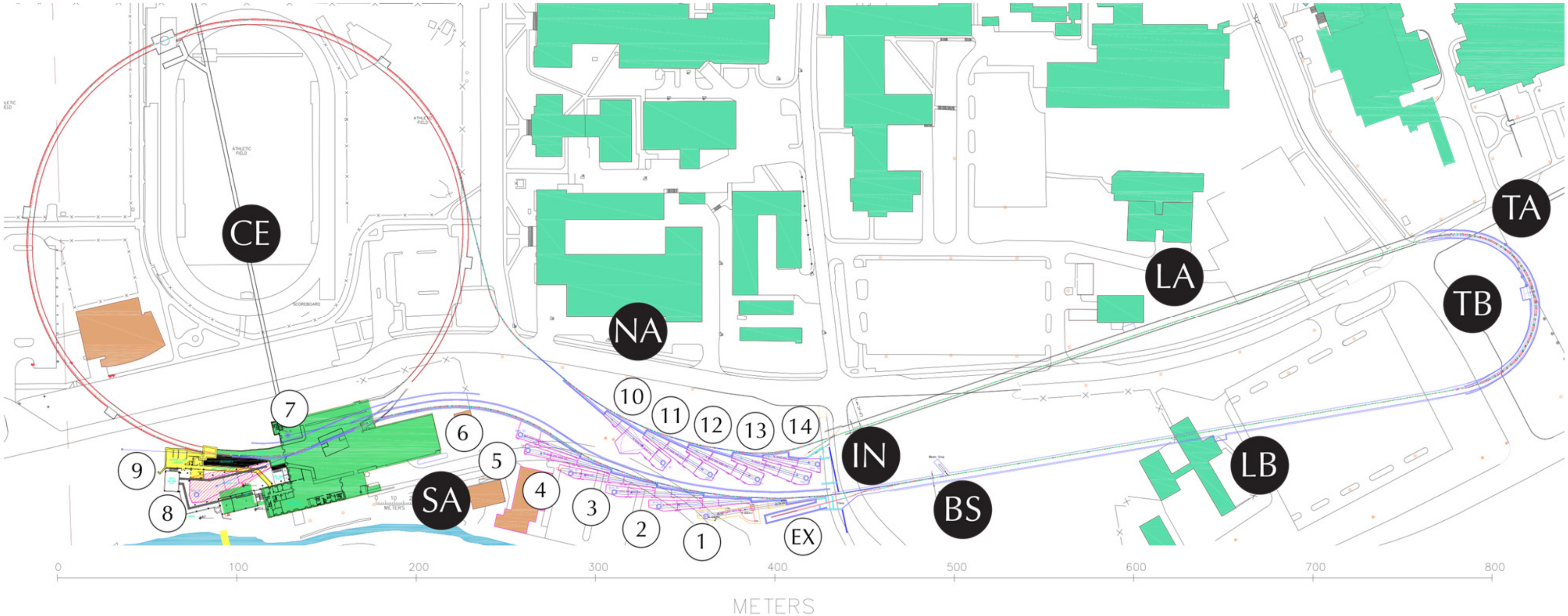
V.P. Bolotin, N.A. Vinokurov*, N.G. Gavrilov, D.A. Kayran, B.A. Knyazev, E.I. Kolobanov, V.V. Kotenkov, V.V. Kubarev, G.N. Kulipanov, A.N. Matveenko, L.E. Medvedev, S.V. Miginsky, L.A. Mironenko, A.D. Oreshkov, V.K. Ovchar, V.M. Popik, T.V. Salikova, S.S. Serednyakov, A.N. Skrinsky, O.A. Shevchenko, M.A. Scheglov, V.G. Tcheskidov

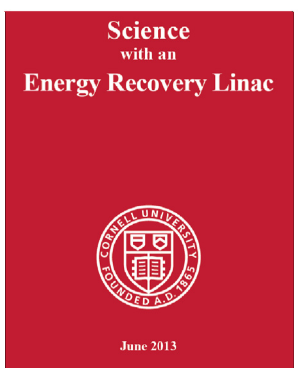
Budker Institute of Nuclear Physics, 11 Lavrentyev Prospect, Novosibirsk 630090, Russia

Available online 15 November 2005

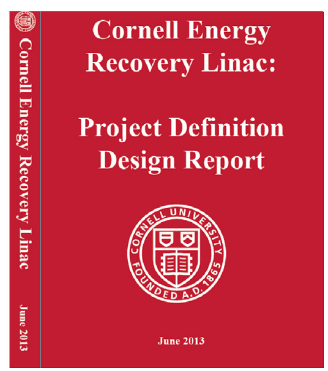
Large ERL Facilities

ERL lightsources: Cornell ERL





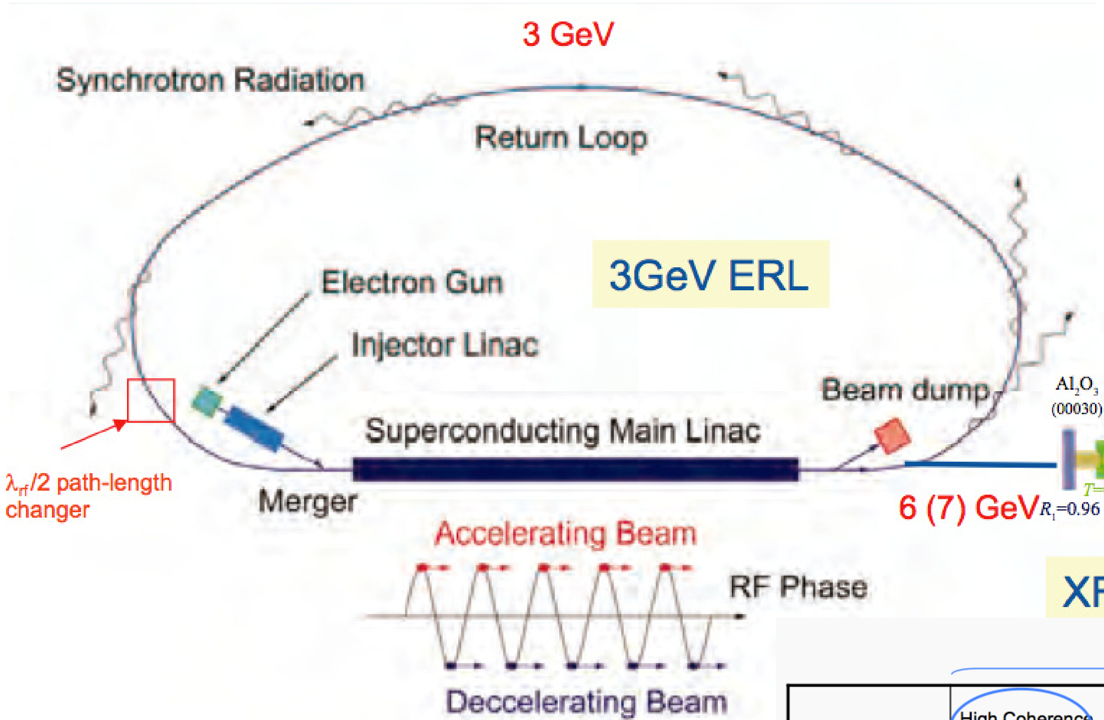
Science case gathered in international workshops

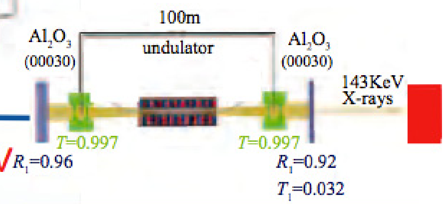


530 page PDDR

Cornell ERL
Project Definition Design Report
(PDDR)
http://www.classe.cornell.edu/ERL

ERL lightsources: KEK





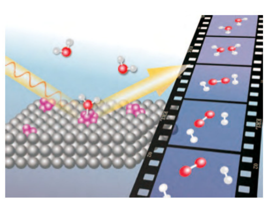
PEARL Photon Factory

次世代放射光源
Energy Recovery Linac

XFEL-O in 2nd stage

	3 GeV ERL				XFEL-O
	High Coherence (HC) mode	High Flux (HF) mode	Ultimate (UL) mode	Ultra-Short Pulse (US) mode	XFELO mode
Beam Energy	3 GeV				6 - 7 GeV
Beam Current	10 mA	100 mA	100 mA	77 μA (typ.)	10 μA
Bunch Charge	7.7 pC	77 pC	77 pC	77 pC	10 pC
Repetition Rate	1.3 GHz	1.3 GHz	1.3 GHz	1 MHz	1 MHz
Norm. Emittance	0.1 mm·mrad	1 mm·mrad	0.1 mm·mrad	-	0.2 mm·mrad
Emittance	17 pm·rad	170 pm·rad	17 pm·rad	-	15 pm·rad
Energy Spread	2×10^{-4}	2×10^{-4}	2×10^{-4}	-	5×10^{-5}
Bunch Length	2 ps	2 ps	2 ps	≤ 100 fs	1 ps

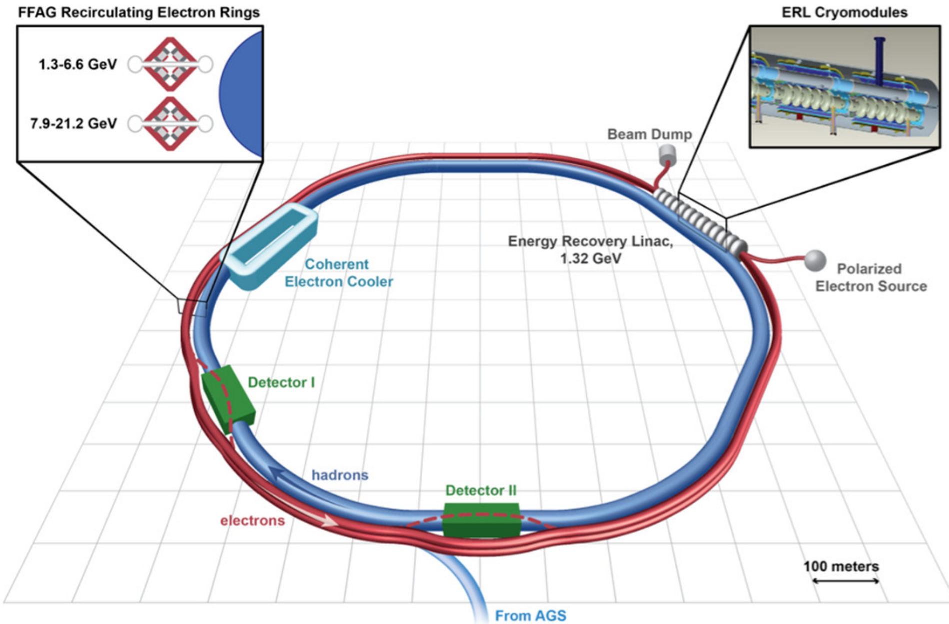
Energy Recovery Linac
Conceptual Design Report



KEK ERL CDR (2012)

N. Nakamura IPAC12 talk

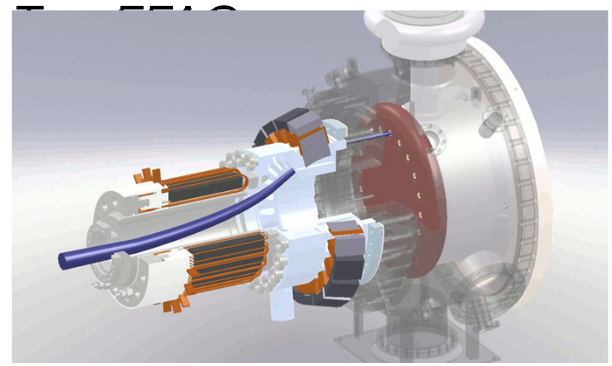
ERLs for Nuclear Physics - eRHIC



	e	p	$^{2}He^{3}$	$^{79}Au^{197}$
Energy, GeV	15.9	250	167	100
CM energy, GeV		122.5	81.7	63.2
Bunch frequency, MHz	9.4	9.4	9.4	9.4
Bunch intensity (nucleons), 10^{11}	0.33	0.3	0.6	0.6
Bunch charge, nC	5.3	4.8	6.4	3.9
Beam current, mA	50	42	55	33
Hadron rms normalized emittance, 10^{-6} m		0.27	0.20	0.20
Electron rms normalized emittance, 10^{-6} m		31.6	34.7	57.9
β^*, cm (both planes)	5	5	5	5
Hadron beam-beam parameter		0.015	0.014	0.008
Electron beam disruption		2.8	5.2	1.9
Space charge parameter		0.006	0.016	0.016
rms bunch length, cm	0.4	5	5	5
Polarization, %	70	70	70	none
Peak luminosity, 10^{33} $cm^{-2}s^{-1}$		1.5	2.8	1.7

21.2 GeV (16 passes) : 18 mA
15.9 GeV (12 passes) : 50 mA
=> 12 MW SR power

Linac: 1.32 GeV
422 MHz cavities
120 m cold length
no quadrupoles
1.2 A total current



[courtesy of V. Litvinenko]

ERLs for High-Energy Physics - LHeC

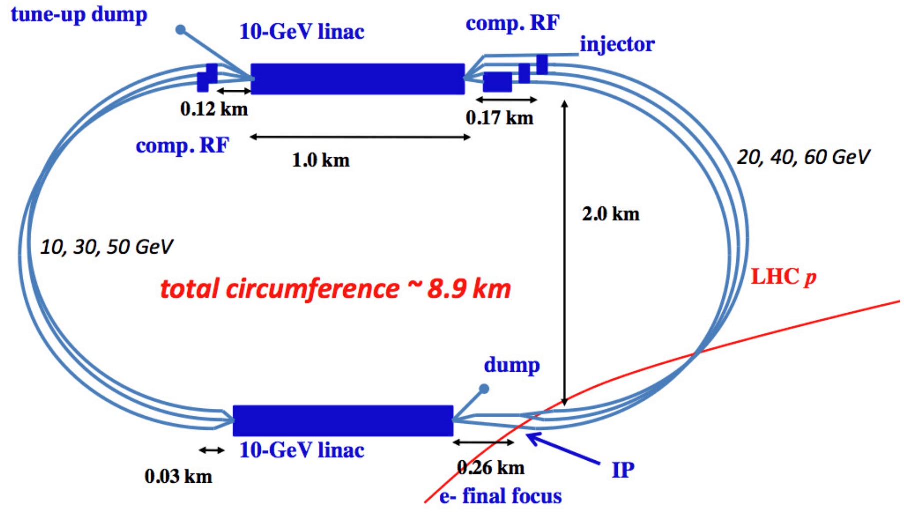
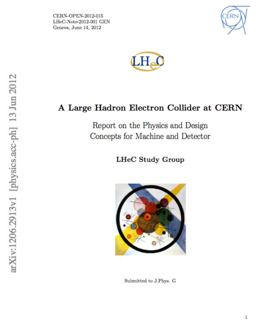


Figure 7.5: LHeC ERL layout including dimensions.

LINAC Parameters for the Linac-Ring Option		
Operation mode	**CW**	**Pulsed**
Beam Energy [GeV]	60	140
Peak Luminosity [$cm^{-2}s^{-1}$]	10^{33}	$4x10^{31}$
Cavity gradient [MV/m]	20	32
RF Power Loss [W/cavity]	13-37	11
W per W (1.8K to RT)	700	700
Cavity Q_0	$2.5x10^{10}$	$2.5x10^{10}$
Power loss/GeV	0.51-1.44	0.24
RF length [km]	2	7.9
Total length [km]	9	7.9
Beam current [mA]	6.4	0.27
Repetition rate	-	10 Hz
Pulse length	-	5ms

Bruening – IPAC13 MOZB201

Designed for 100 MW wall-plug power
6.4 mA, but could be raised 12+ mA



A Large Hadron Electron Collider at CERN: Report on the Physics and Design Concepts for Machine and Detector - J. L. Fernandez et al.

ERL-Ring and Ring-Ring studies - 600 pages
http://arxiv.org/abs/1206.2913

January 2014 workshop

Critical Components

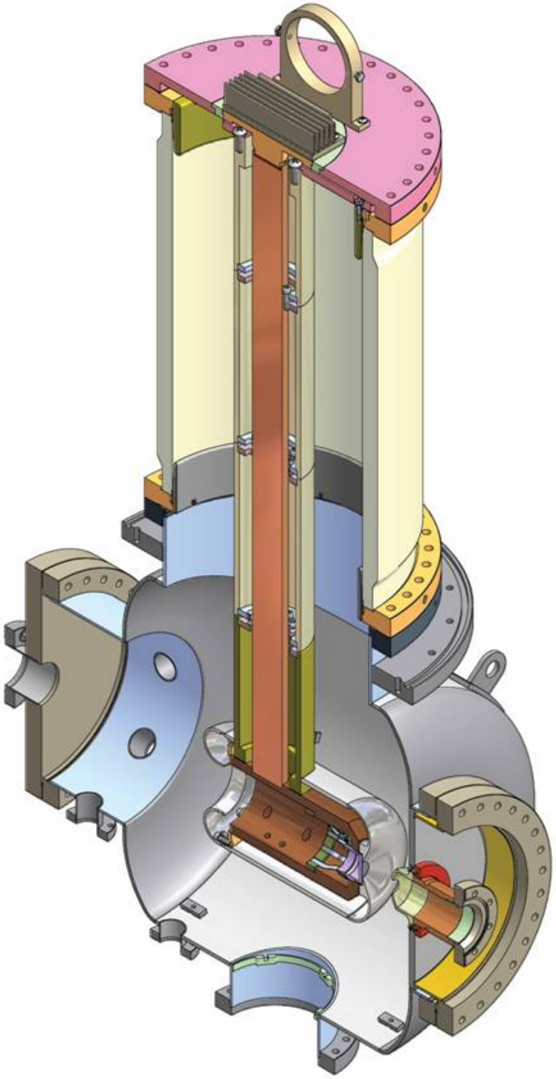
Source

Injector

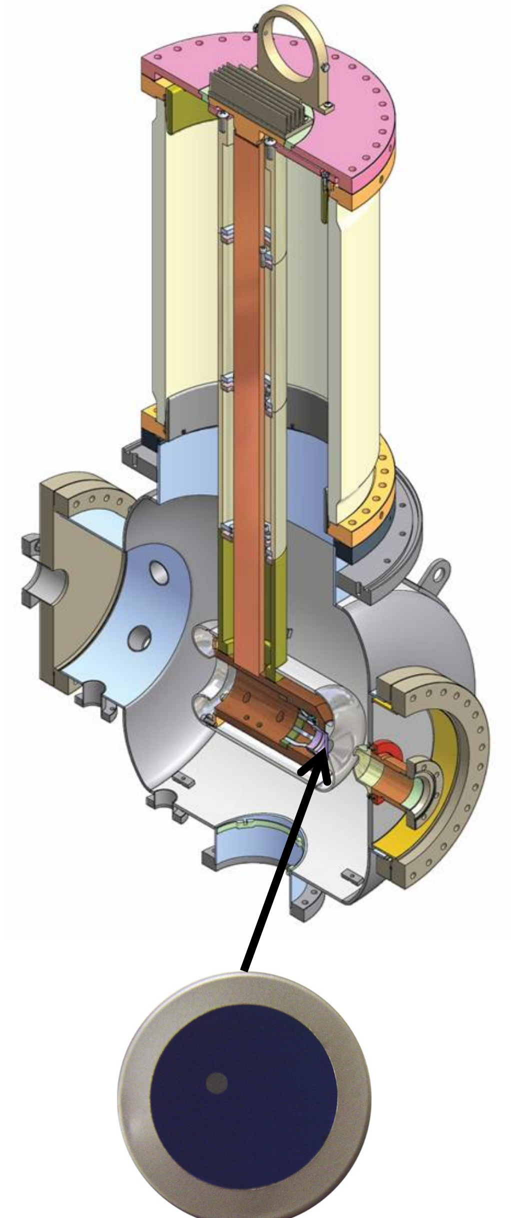
Linac

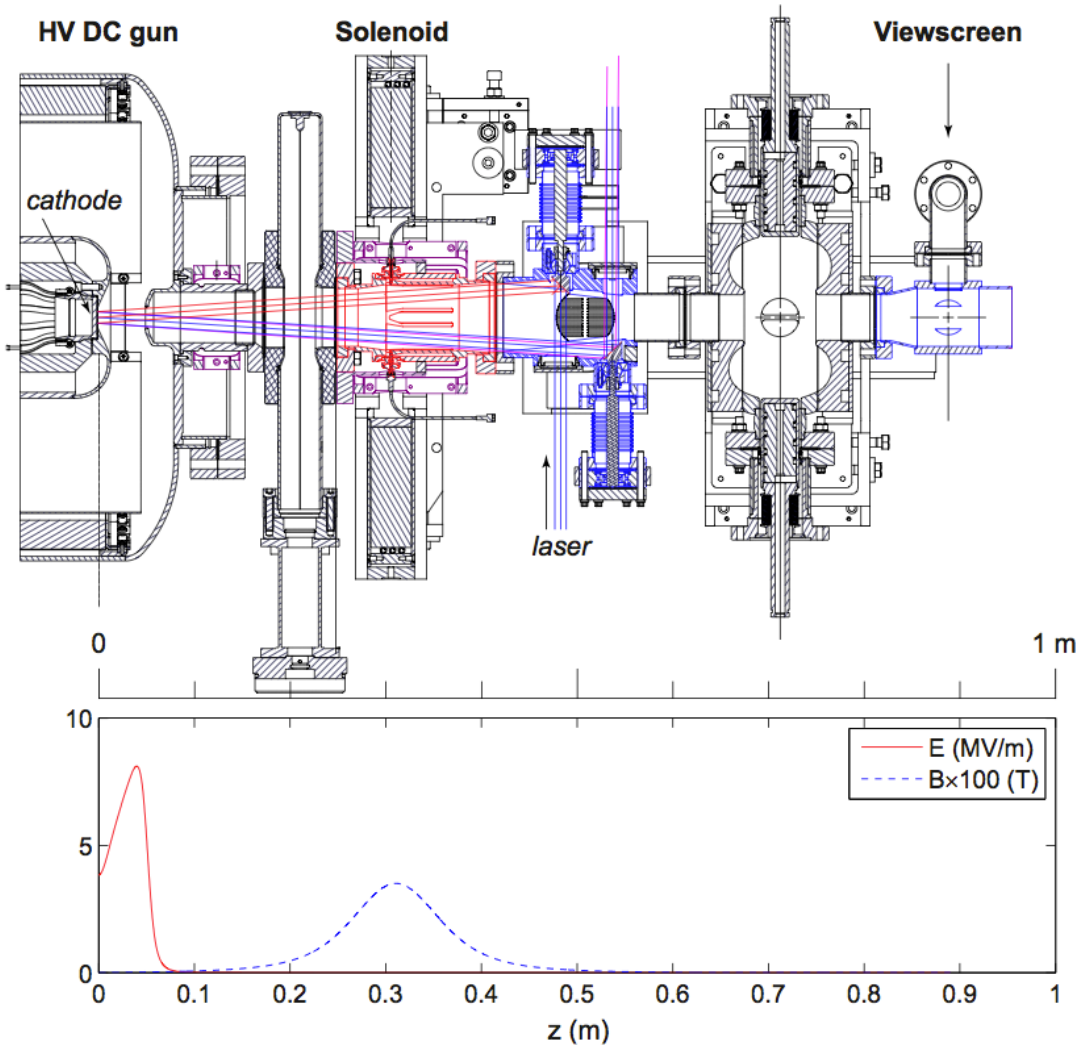
Beam Transport

Insertion Devices

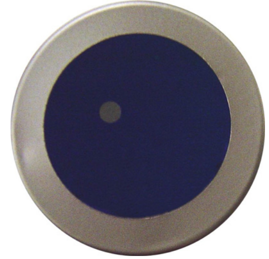


Source: Cathode and Gun





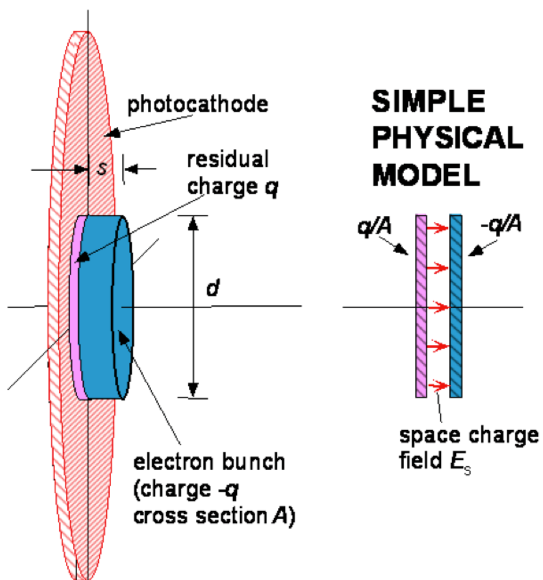
Cathode



Highest Charge

$$\frac{Q_{\text{bunch}}}{A_{\text{spot}}} \lesssim \epsilon_0 E_z$$

Uniform disk: $A_{\text{spot}} \approx 4\pi\sigma_x^2$



$$\sigma_z \ll \sigma_x, \sigma_y$$

$$Q_{\text{bunch}} \lesssim 9\ \text{pC}\ \frac{E_z}{\text{MV/m}}\ \frac{A_{\text{spot}}}{\text{mm}^2}$$

Lowest Emittance

$$\epsilon_{x,\text{n}} = \sigma_x \sqrt{\frac{\mathcal{E}_{\text{thermal}}}{m_e c^2}}$$

Mean transverse kinetic energy, determined by the cathode material and laser wavelength

$$\epsilon_{x,\text{n}} \gtrsim \sqrt{\frac{Q_{\text{bunch}}}{4\pi\epsilon_0\, E_z}\ \frac{\mathcal{E}_{\text{thermal}}}{m_e c^2}}$$

$$\epsilon_{x,\text{n}} \gtrsim .13\ \mu\text{m}\sqrt{\frac{Q_{\text{bunch}}}{100\ \text{pC}}\ \frac{10\ \text{MV/m}}{E_z}\ \frac{\mathcal{E}_{\text{thermal}}}{100\ \text{meV}}}$$

[Bazarov et al., PRL 102, 104801 (2009)]

Cathode Engineering

L. Cultrerea, IPAC14: MOZB0

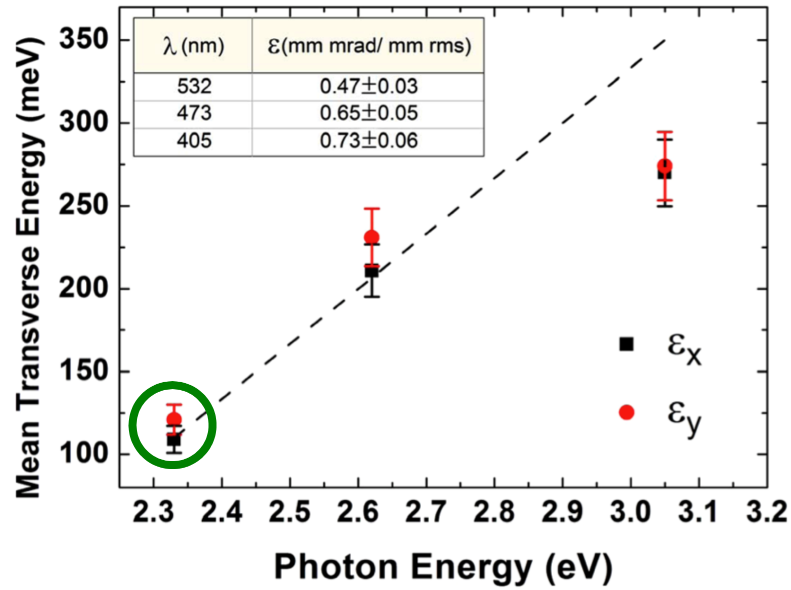
Want:
Low $\mathcal{E}_{\text{thermal}}$
Good Quantum Efficiency (> 1%)
(QE: electron yield per photon)
Long lifetime (many hours)

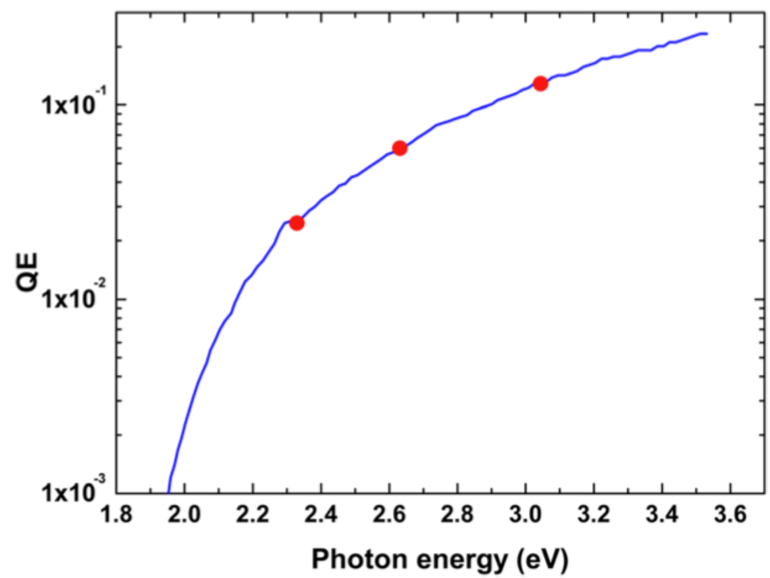
GaAs
lowest thermal energy of any known cathode
25 meV at 800 nm (IR), QE 1%
120 meV at 520 nm (green), QE 10%
(also can produce polarized electrons)

Alkalai antimonide: CsK_2Sb, NaKSb
widely used in photomultiplier devices
100's meV in visible, QE of a few %
Robust
Record sustained currents (65 mA)

NaKSb Measurement

$\mathcal{E}_{\text{thermal}}$

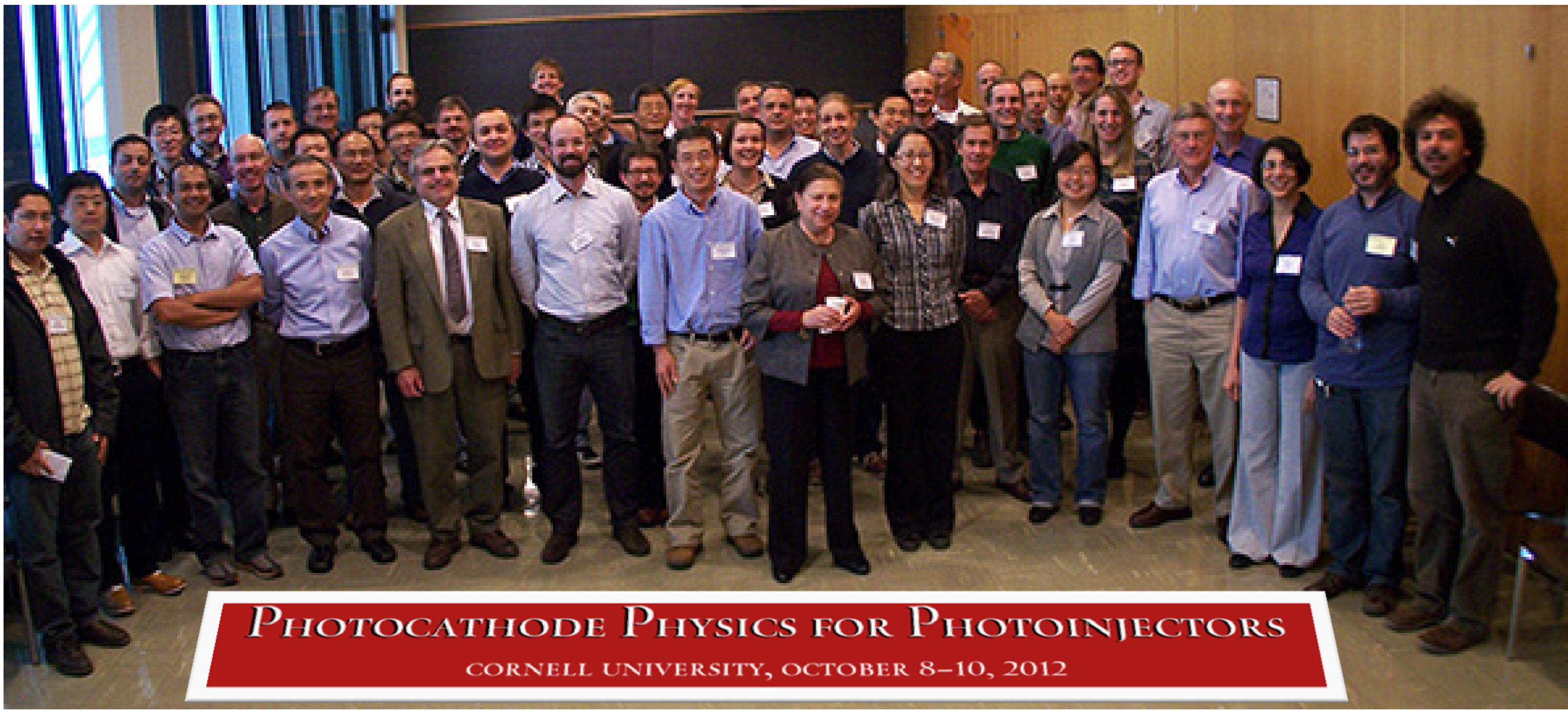




Cultrera et al., Appl. Phys. Lett. **103**, 103504 (2013)

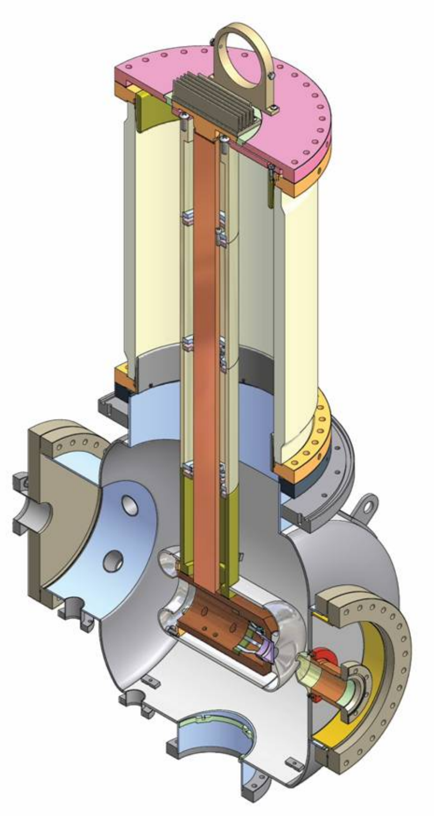
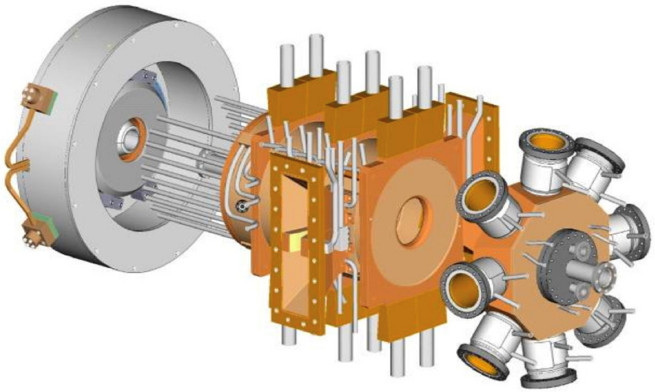
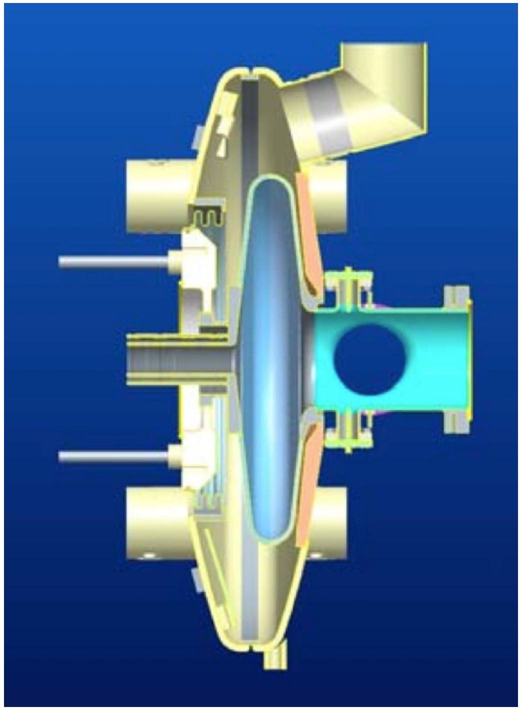
Photocathode Wiki

P3 workshop at Cornell (Oct 2012), wiki website for photocathodes, fostering national and international collaborations on theory/modeling and MBE grown samples, and more…



http://photocathodes.chess.cornell.edu/wiki/Main_Page

High-Current, low emittance Guns

DC	NCRF	SRF
		
Cornell 500 kV DC Gun	LANL 700 MHz NCRF Gun	BNL 704 MHz SRF Gun

Superconducting RF (SRF) Guns

J. Teichert, IPAC14: MOZB01

SRF

High fields on cathode (10-20 MV/m)
(but bunch must be accelerated off-crest, 30 degrees)
-> higher charge/area

High net accelerating voltage
(+2 to +9 MeV, dependent on the number of cells)

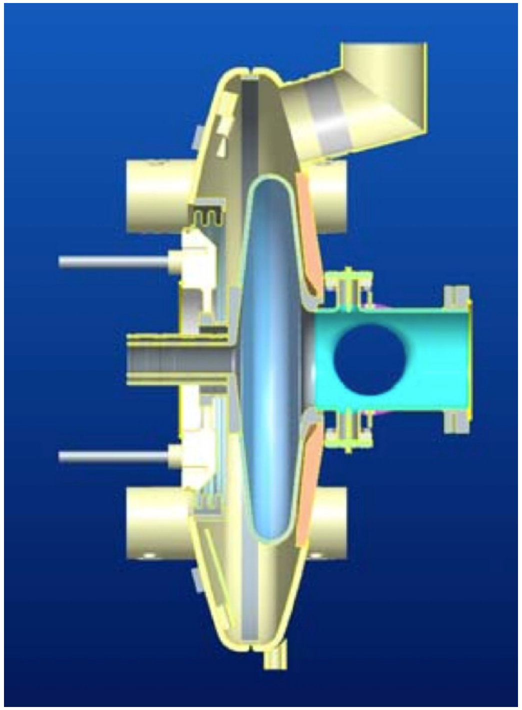
Can suffer from field emission
(contamination from cathode insertion)

Difficulty pumping in RF power for high currents

Record: 0.4 mA at Rossendorf

Developed for:

- eRHIC (BNL) (300 mA)
- BERlinPro (HZB) (100 mA)
- ELBA (Rossendorf) (<10 mA)
- PKU (8 mA)



BNL 704 MHz SRF Gun

Normal-Conducting RF Guns (NCRF)

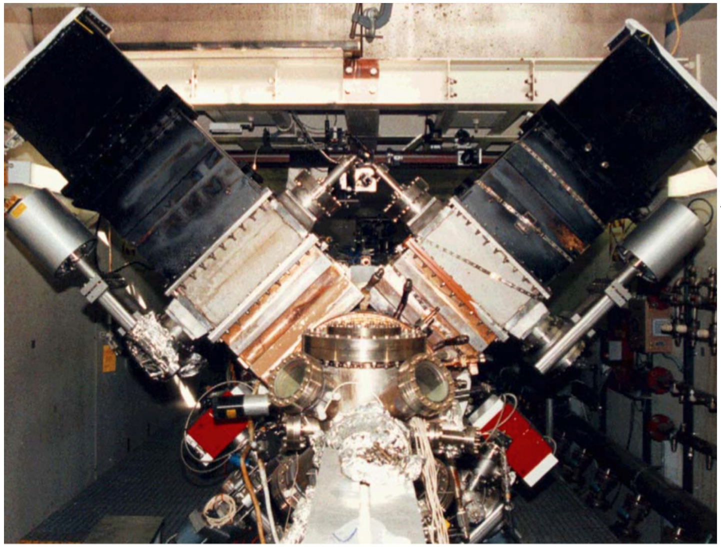
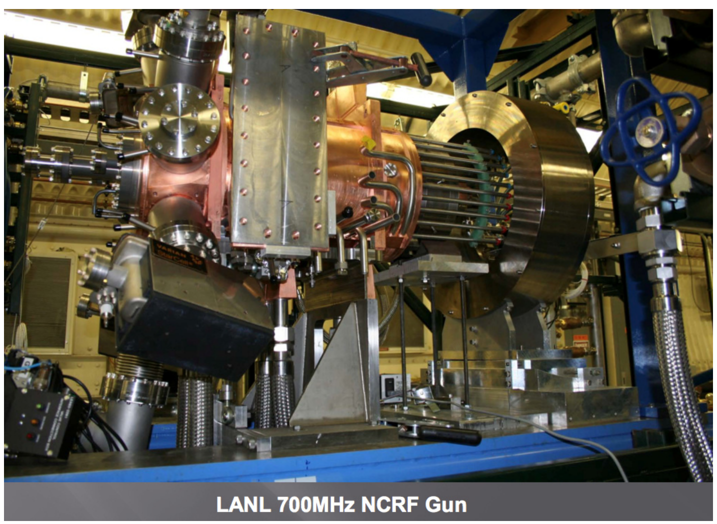


Fig. 1. Photograph of the Boeing/LANL 433 MHz NCRF gun in the test vault.

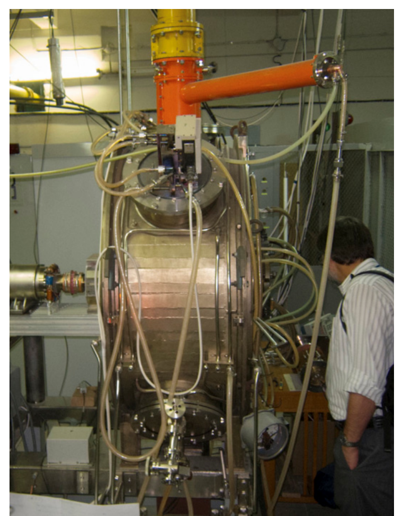
Dowell et al., Appl. Phys. Lett. 63, 2035 (1993)

Boeing/LANL 433 MHz gun held
record 32 mA at 5 MeV in 1993

Very high-field on cathode for pulsed operation:
>100 MV/m LCLS gun
Moderate fields for CW operation:
10 MV/m for the LANL/AES gun
Difficulty cooling at CW
Limited to alkali cathodes because of poor vacuum



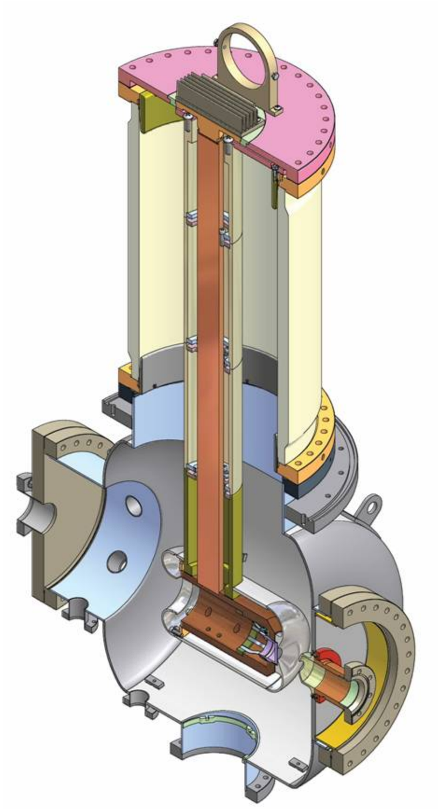
LANL 700 MHz NCRF Gun



BINP (Novosibirsk) 130 MHz Gun

Developed at:
- BINP (30 mA)
- LANL
- Berkeley (1 mA)

Direct-Current (DC) Guns



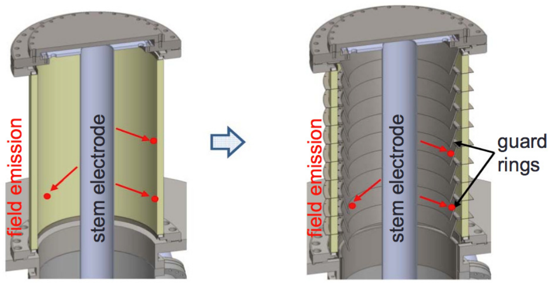
Moderate fields on cathode (4-7 MV/m)
Compatible with any type of cathode
Any repetition rate
Any average current
Bunch charges < a few hundred pC
Reliable, proven design (developed at SLAC, Jlab)

Relatively inexpensive

Potential problems with insulator at high voltages
newer guns use guard rings

New current record-holder …

<u>Improvements</u>



<u>Used and developed at:</u>
Cornell
JLab
KEK
JAEA
ALICE (Daresbury)
IHEP (Beijing)

Critical Components

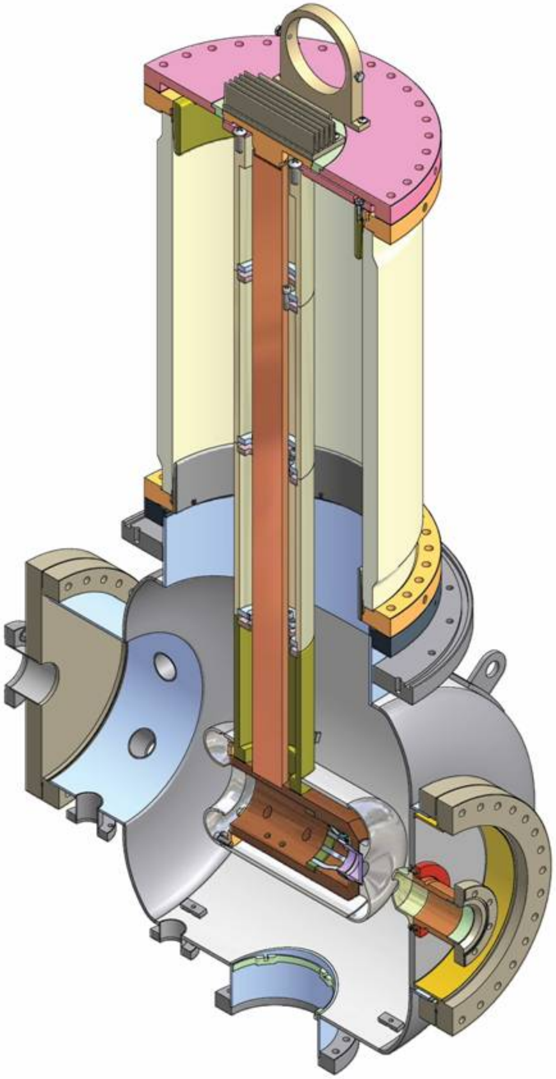
Source

Injector

Linac

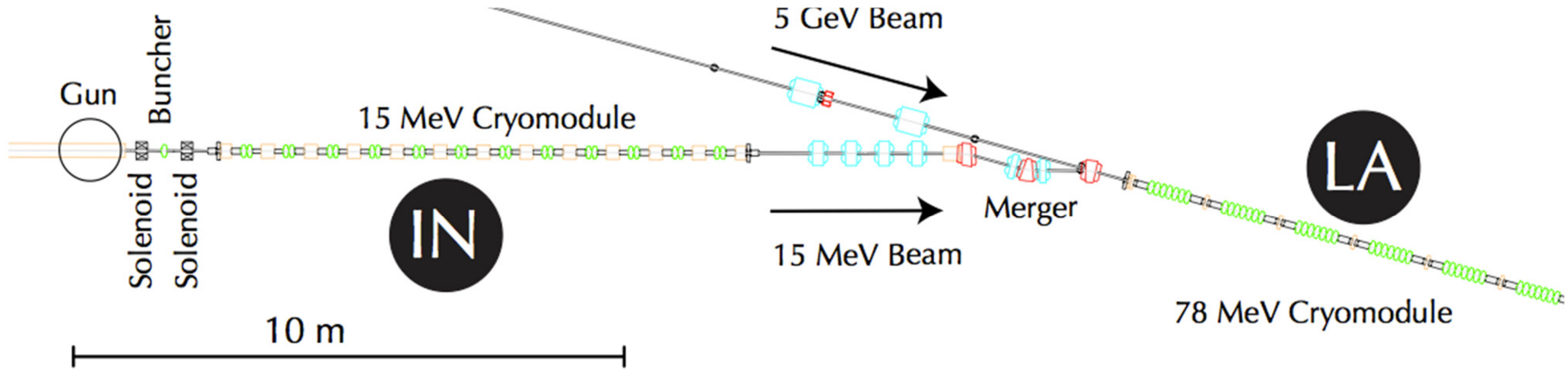
Beam Transport

Insertion Devices

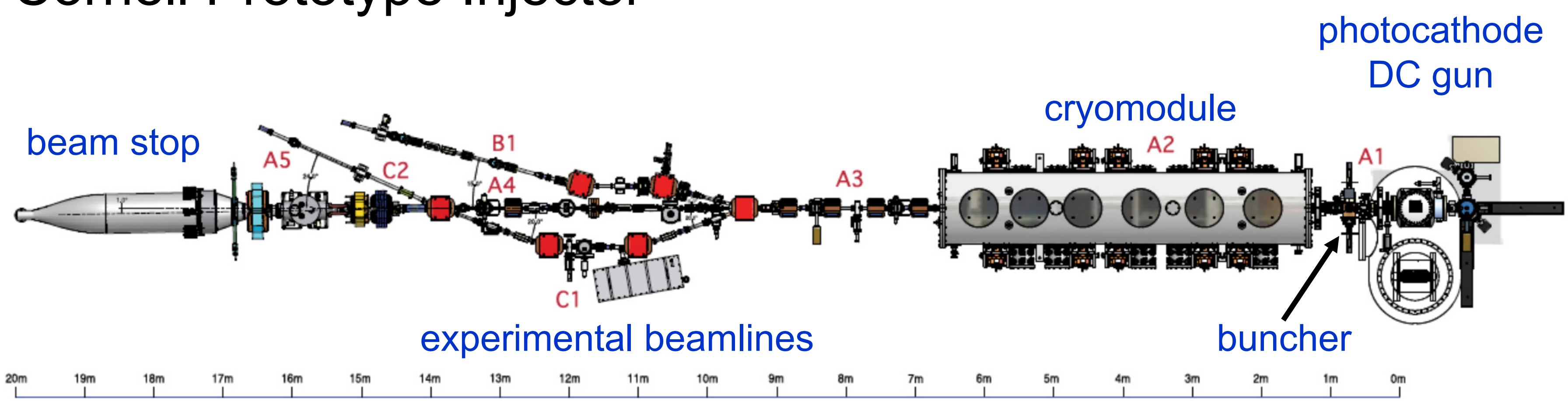


Injector

Cornell ERL

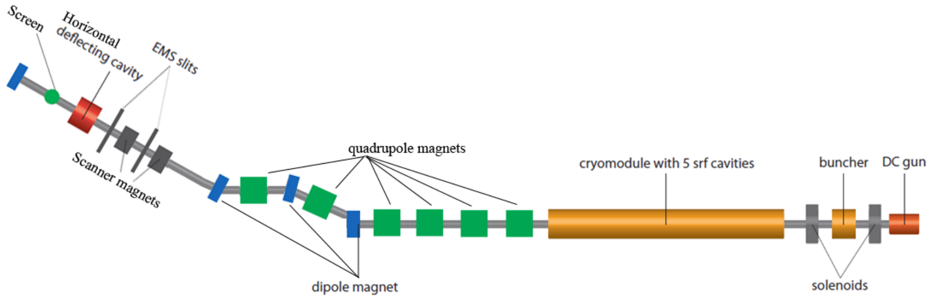


Cornell Prototype Injector

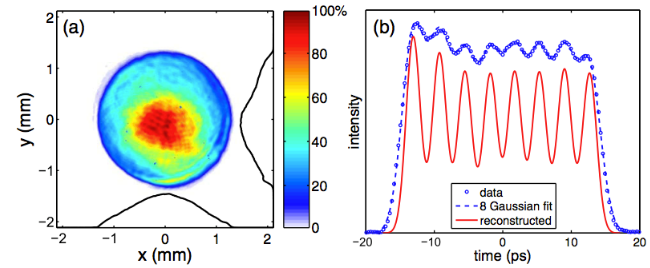


Injector: emittance preservation

Model



Shape your laser pulse



Understand your fields

Gun

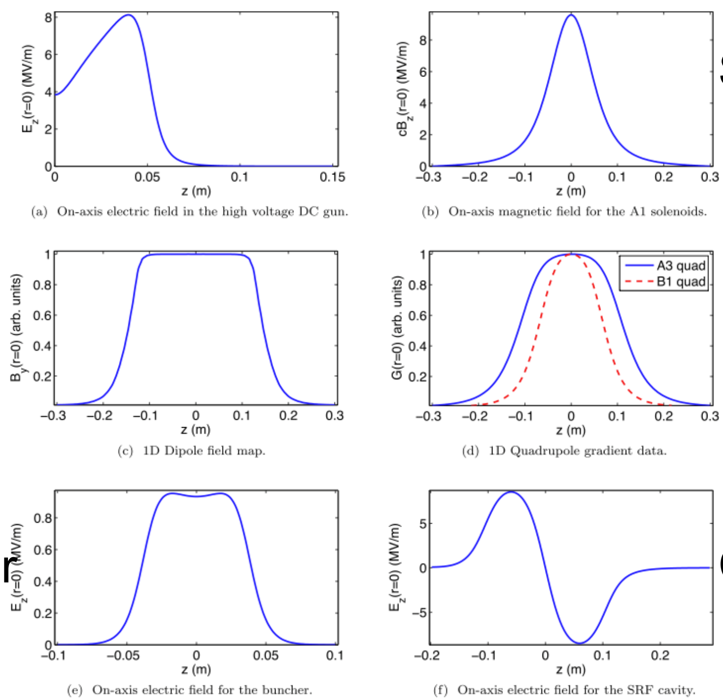
Solenoid

Dipole

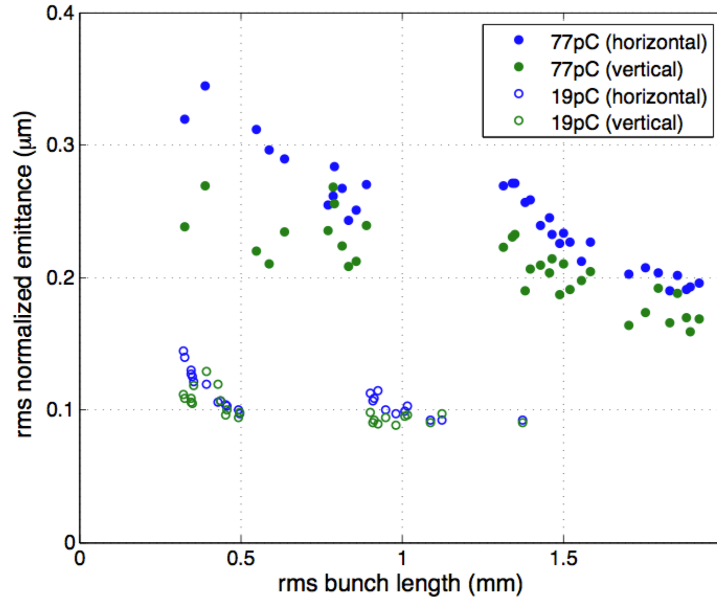
Quad.

Buncher

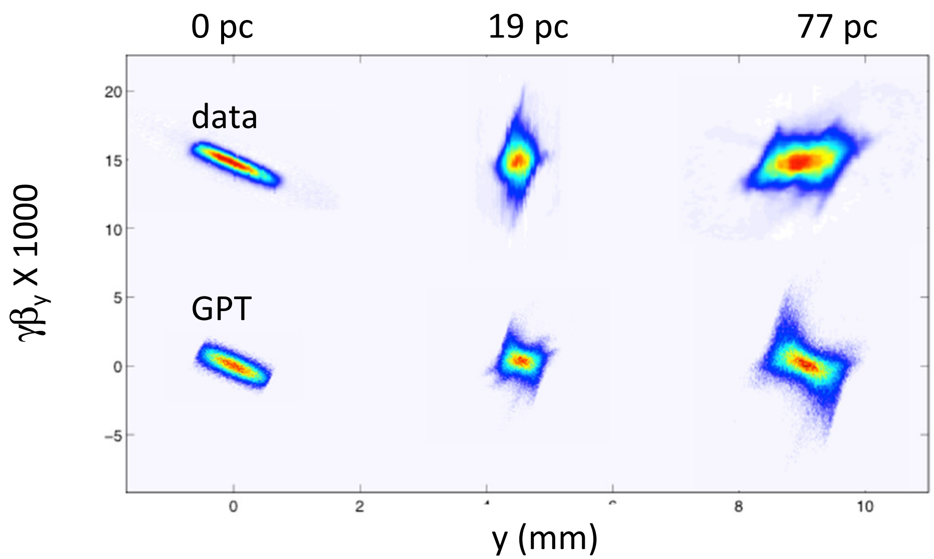
Cavity

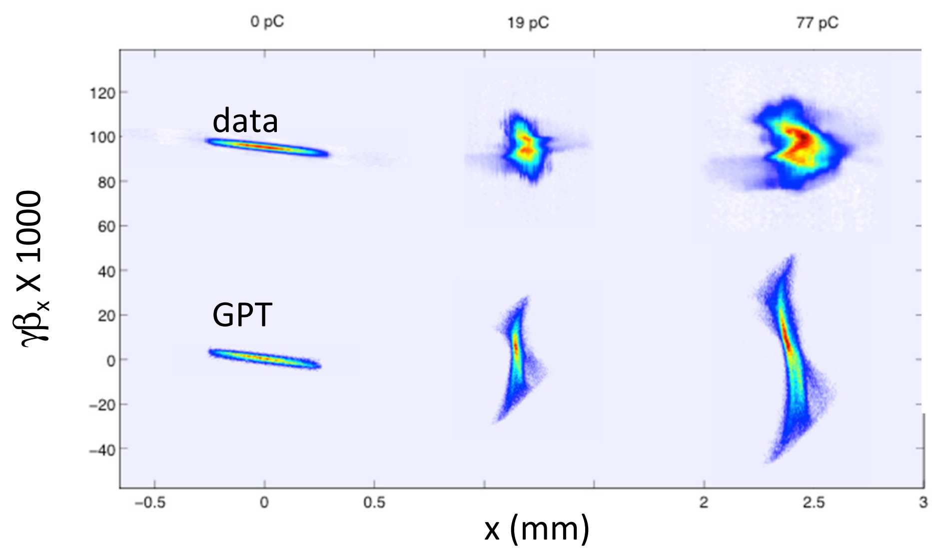


Optimize



Phase space measurements and simulation





Projected Emittance for 19 (77) pC at 8 MeV:

$$(y, p_y)$$

Data Type	enorm(100%) [mm-mrad]	enorm(90%) [mm-mrad]
Projected (EMS)	0.20 (0.40)	0.14 (0.29)
GPT	0.16 (0.37)	0.11 (0.25)

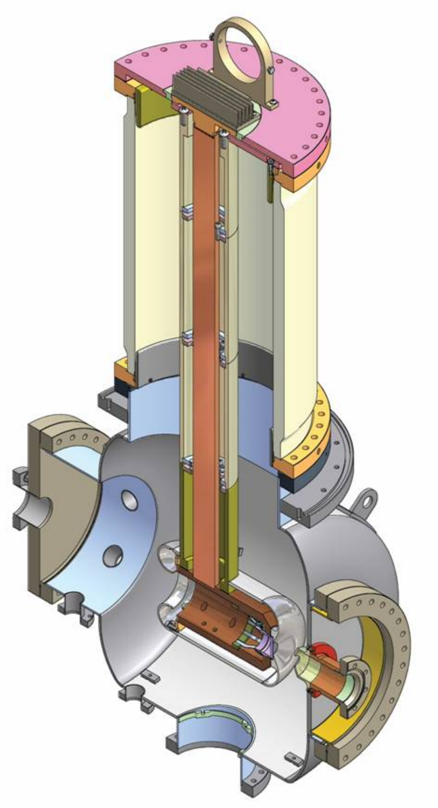
$$(x, p_x)$$

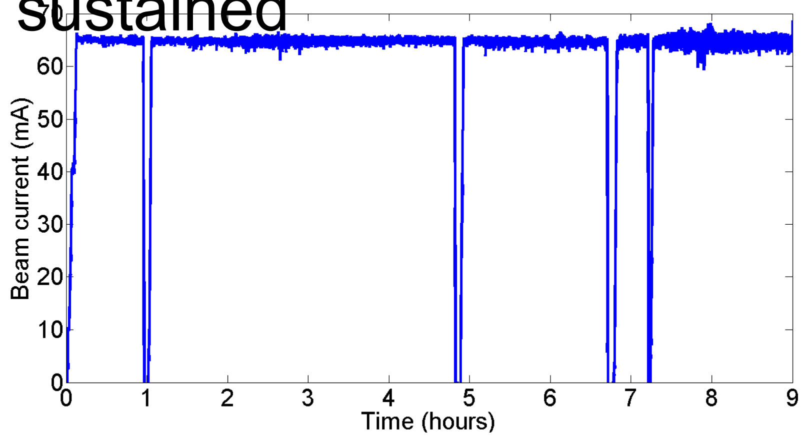
Data Type	enorm(100%) [mm-mrad]	enorm(90%) [mm-mrad]
Projected (EMS)	0.33 (0.69)	0.23 (0.51)
GPT	0.31 (0.72)	0.19 (0.44)

Gulliford et al., Phys. Rev. ST Accel. Beams 16, 073401 (2013)

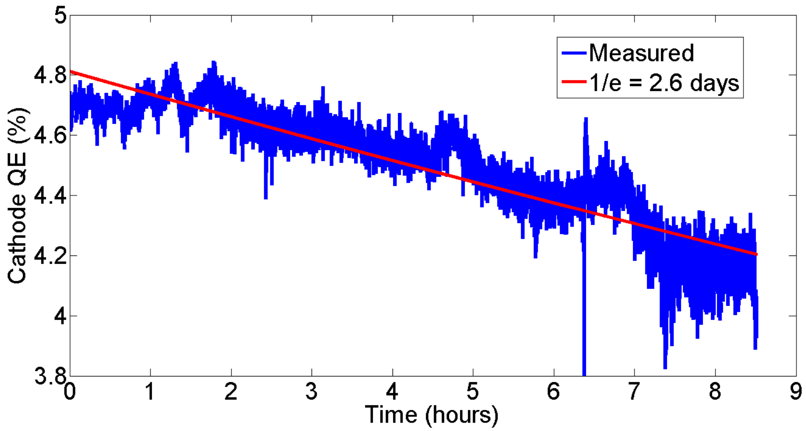
Cornell Injector Record Current at 4 MeV

Highest current ever NaK_2Sb Cathode: 75 mA, 65 mA sustained





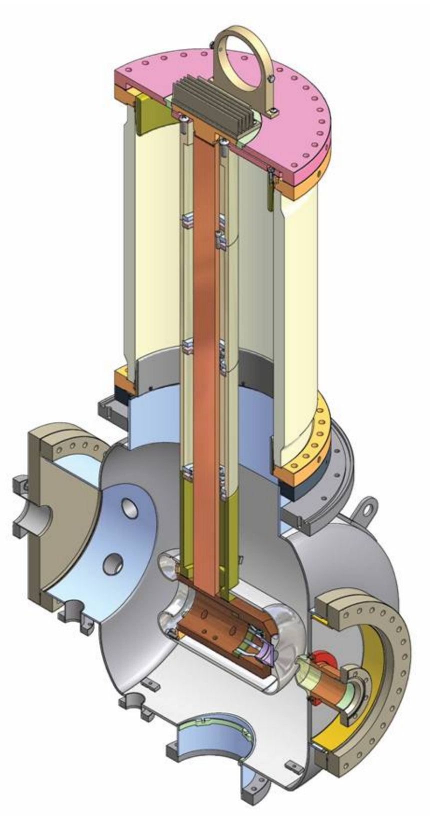
May 24, 2013



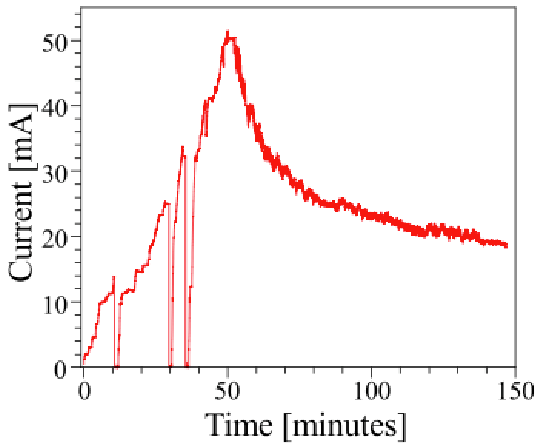
Dunham et al., Appl. Phys. Lett., 102, 034105 (2013)

Cornell Injector Record Current at 4 MeV

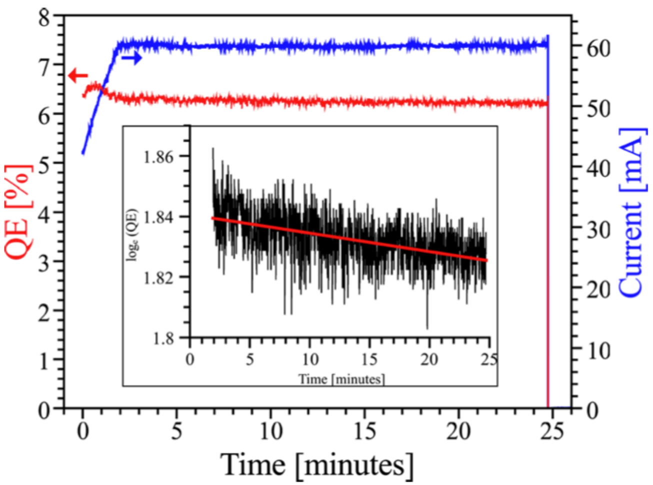
More records:



GaAs: 52 mA



CsK_2Sb: 60 mA



[Dunham et al., Appl. Phys. Lett., 102, 034105 (2013)]

Critical Components

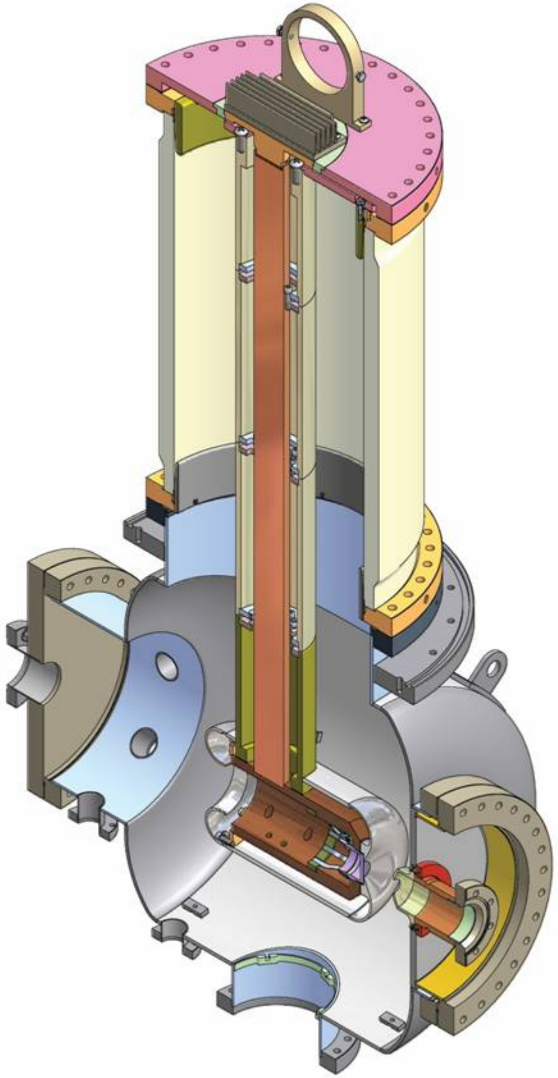
Source

Injector

Linac

Beam Transport

Insertion Devices



AC power optimization per unit length

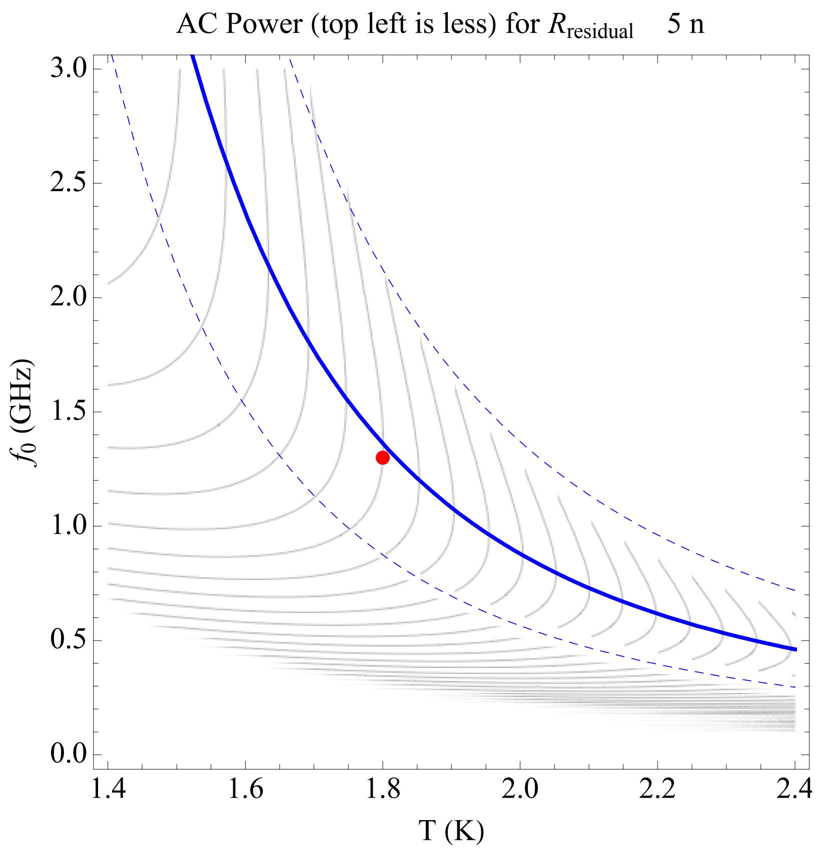
$$P_{\mathrm{AC}} \propto \frac{1}{f\,T}\left[R_{\mathrm{res}} + R_{\mathrm{BCS}}(f,T)\right]$$

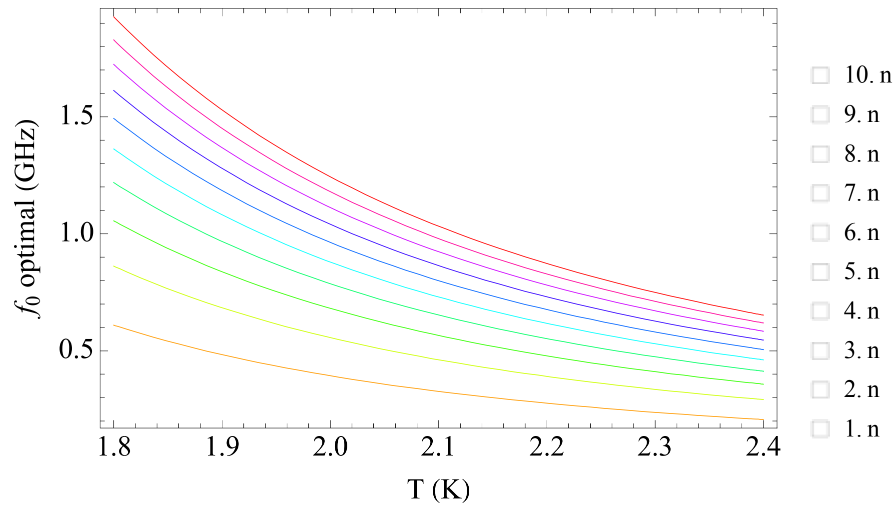
SRF Surface Resistance

$$R_{\mathrm{surface}} = R_{\mathrm{residual}} + \underbrace{A\,(2\pi f)^2\,\frac{\exp\left(-\Delta/k_B T\right)}{T}}_{R_{\mathrm{BCS}}(f,T)}$$

$$A = 2.26\,\mu\Omega\,\mathrm{K}/\mathrm{GHz}^2$$
$$\Delta/k_B = 17.67\,\mathrm{K}$$

Valles et al., SRF2009-tuppo072





$$400\ \mathrm{MHz} \lesssim f_0 \lesssim 1500\ \mathrm{MHz}$$

Frequency choice $400\ \mathrm{MHz} \lesssim f_0 \lesssim 1500\ \mathrm{MHz}$

Less RF losses, if BCS resistance dominates

Lower wakefields
(beam is smaller relative to the cavity)

Fewer cells per cavity, so less likely to have trapped modes

Lower HOM excitation for same offset (therefore higher BBU threshold)

eRHIC, LHeC

Lower Power/Length

Lower surface area:
- contamination less likely
- less material costs
- smaller components in general

Thinner walls (less expensive)

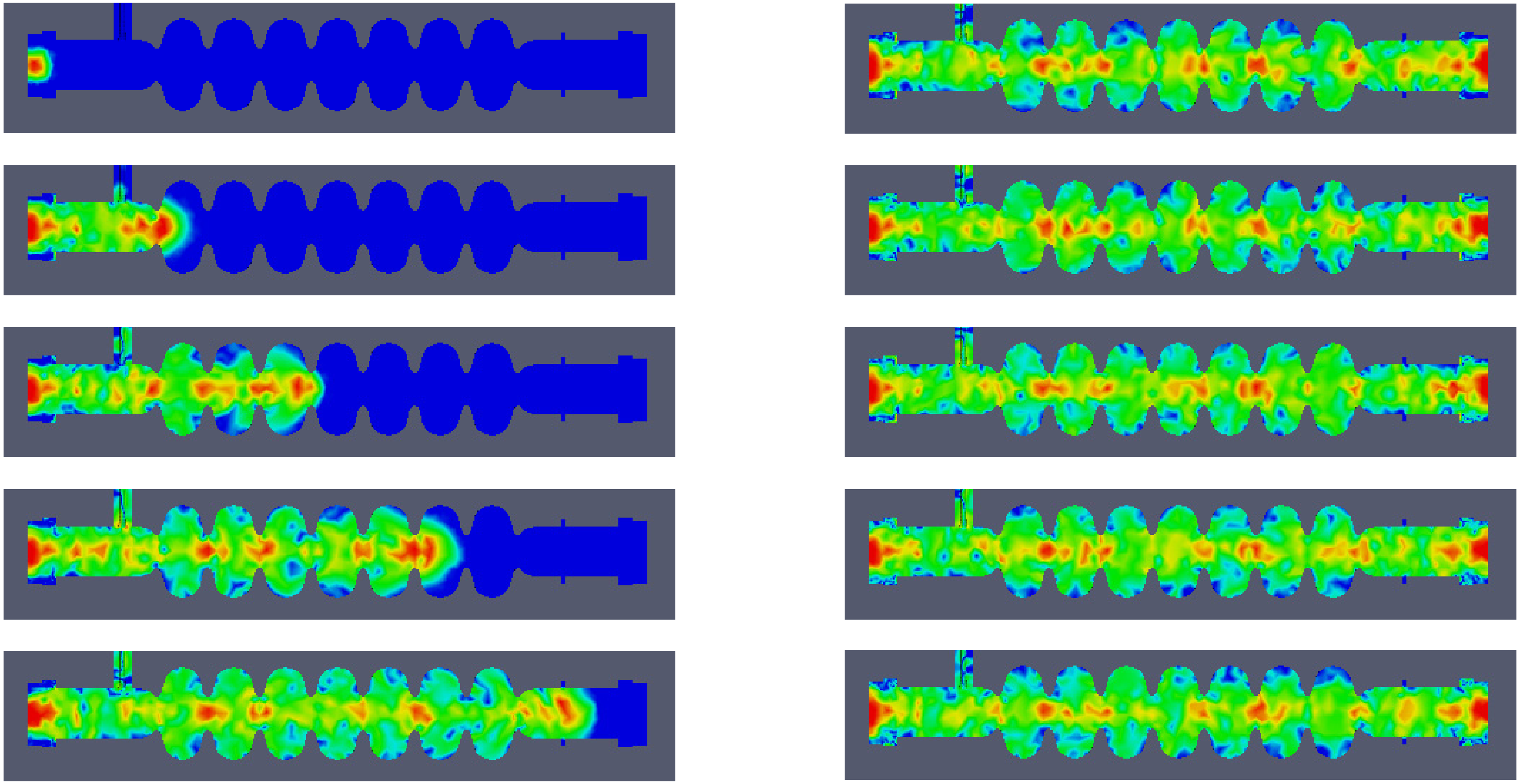
Higher frequencies better for lightsources

Established technology at 1.3 and 1.5 GHz

ILC, European X-FEL, CEBAF, LCLS2

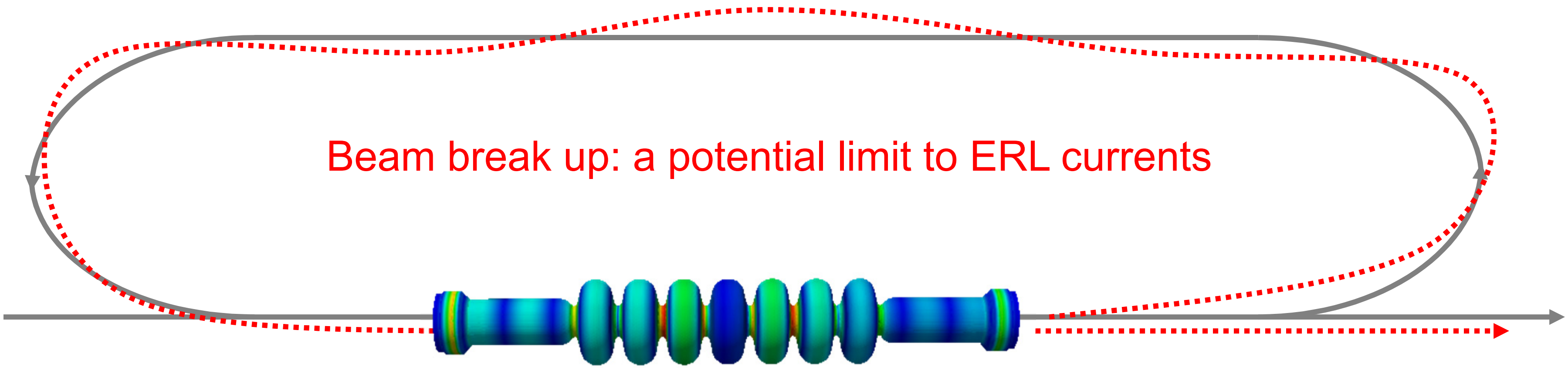
More than the fundamental…

Wakefields excite Higher Order Modes (HOMs)
Color scale is logarithmic
Cavity with higher order mode absorbers



Gaussian bunch passing through with average length 15 mm

Beam Breakup (BBU) instability



For a single Higher Order Mode (HOM) in a single cavity, the maximum sustainable current is:

$$I_{\text{threshold}} = -\frac{2c^2}{e(R/Q)_\lambda\, Q_\lambda\, \omega_\lambda}\,\frac{1}{T_{12}\sin\omega_\lambda t_{\text{return}}}$$

First observed in 1981

UNIQUE BEAM PROPERTIES OF THE STANFORD 300 MeV SUPERCONDUCTING RECYCLOTRON*

C. M. Lyneis, M. S. McAshan, R. E. Rand, H. A. Schwettman, T. I. Smith and J. P. Turneaure

High Energy Physics Laboratory
Stanford University
Stanford, California 94305

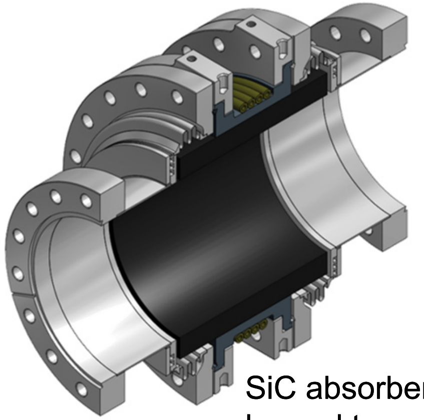
$$x_{\text{pass 2}} = T_{12}\, x'_{\text{pass 1}}$$

Hoffstaetter & Bazarov, PRST-AB 7, 054401 (2004)

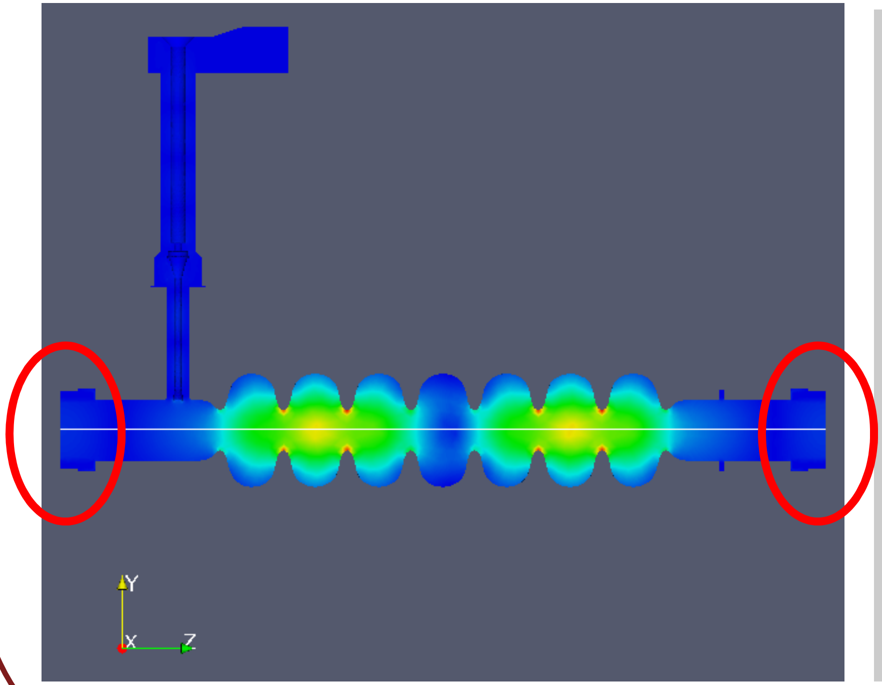
Add HOM Absorbers

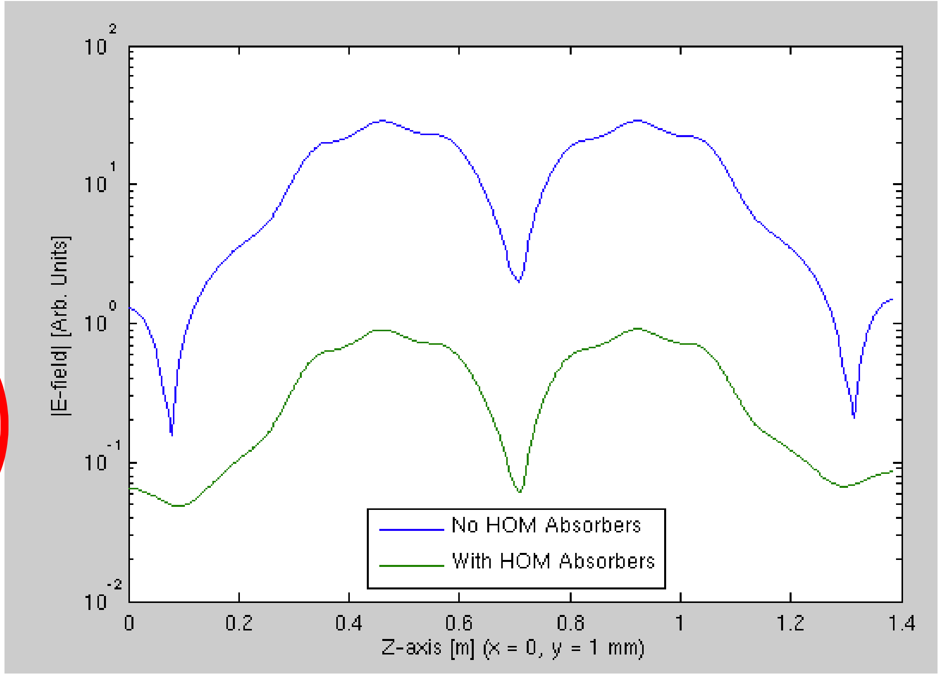
Example HOM at 1612.4604 Hz
Q without absorber: $Q = 5.49 \times 10^6$
Q with absorber: 5.38×10^3

Other methods: HOM antennas
(BNL, KEK)



SiC absorber ring
brazed to metal ring





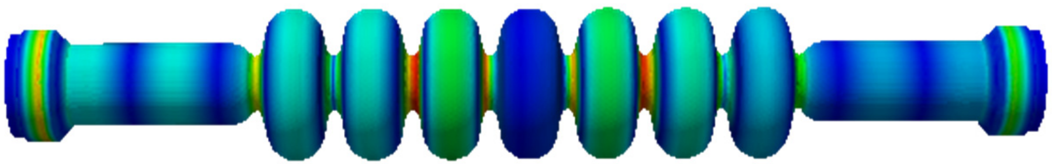
[Courtesy of N. Valles]

Cavity Design: shape optimization

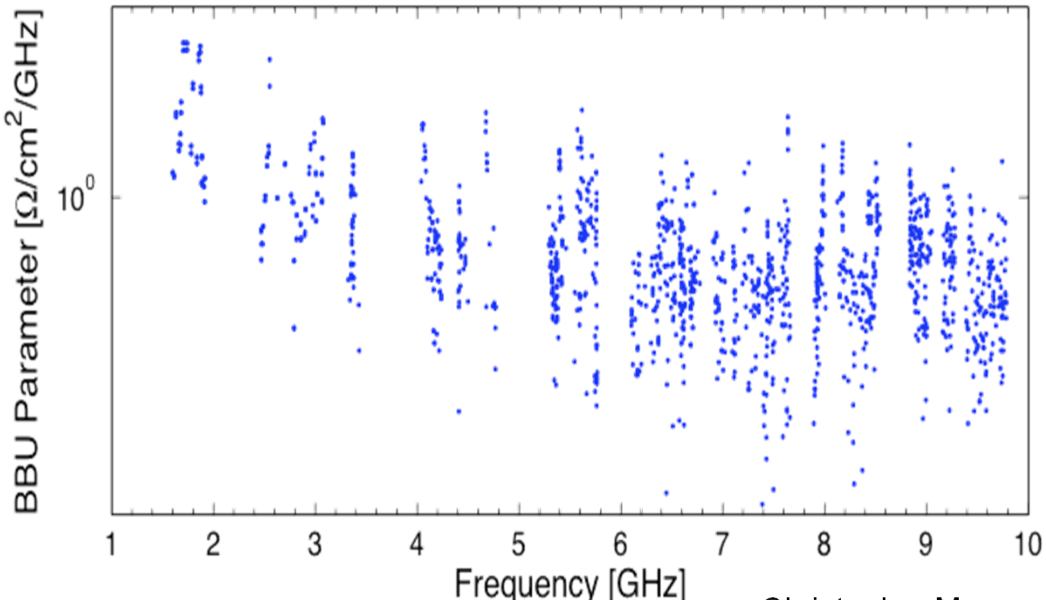
$$I_{\text{threshold}} = -\frac{2c^2}{e(R/Q)_\lambda\, Q_\lambda\, \omega_\lambda} \frac{1}{T_{12} \sin \omega_\lambda t_{\text{return}}}$$

BBU parameter

Optimize the cavity shape with about 20 free parameters

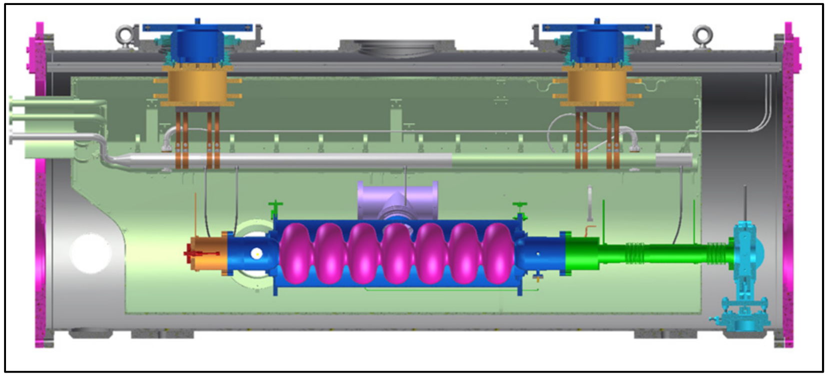


Dipole HOM damping calculated up to 10 GHz with realistic RF absorbers

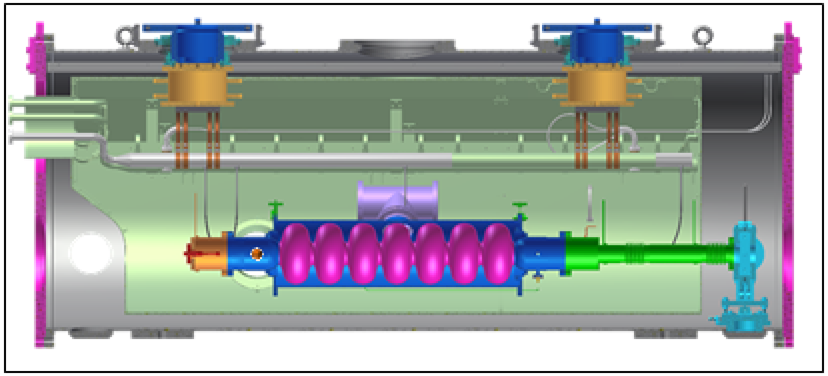


Cornell Horizontal Test Cryomodule (HTC)

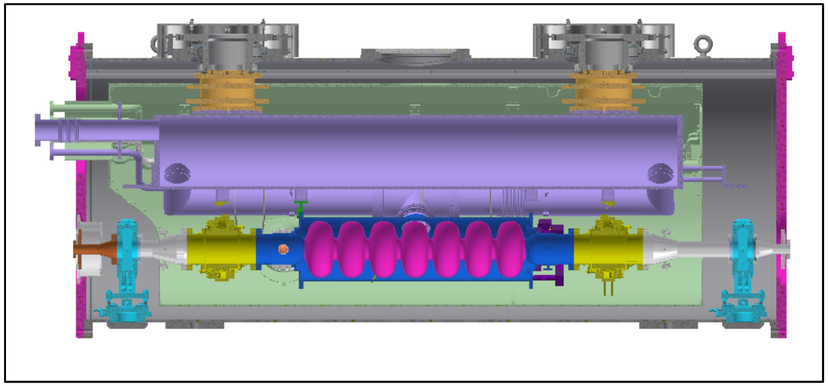
- HTC-1: Follow vertical assembly procedure as closely as possible



- HTC-2: Include side mounted, High-power input coupler

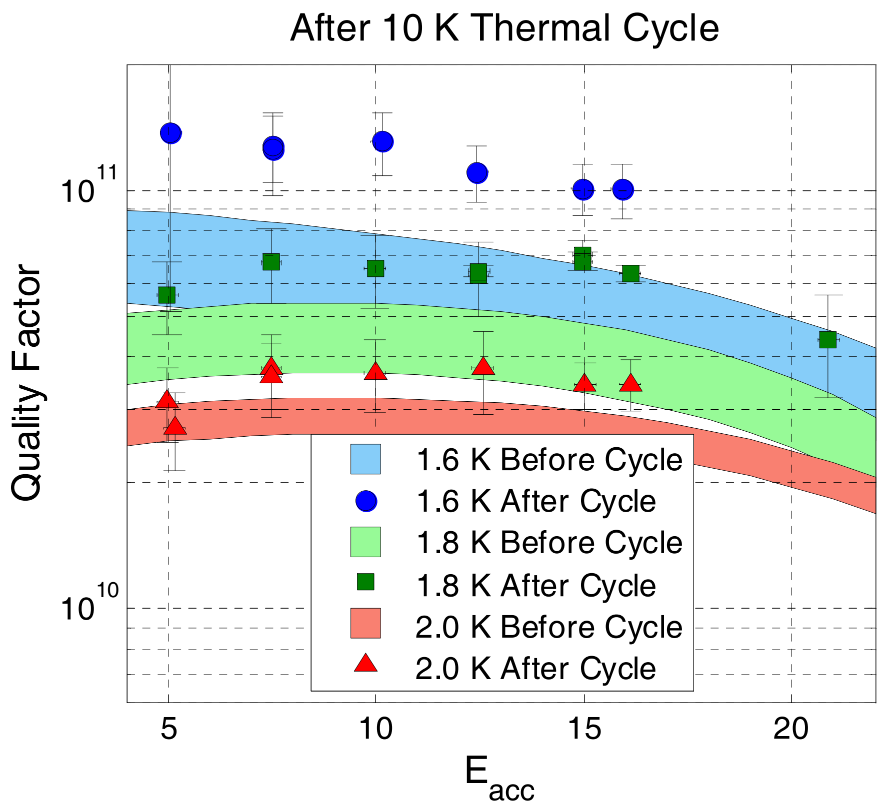


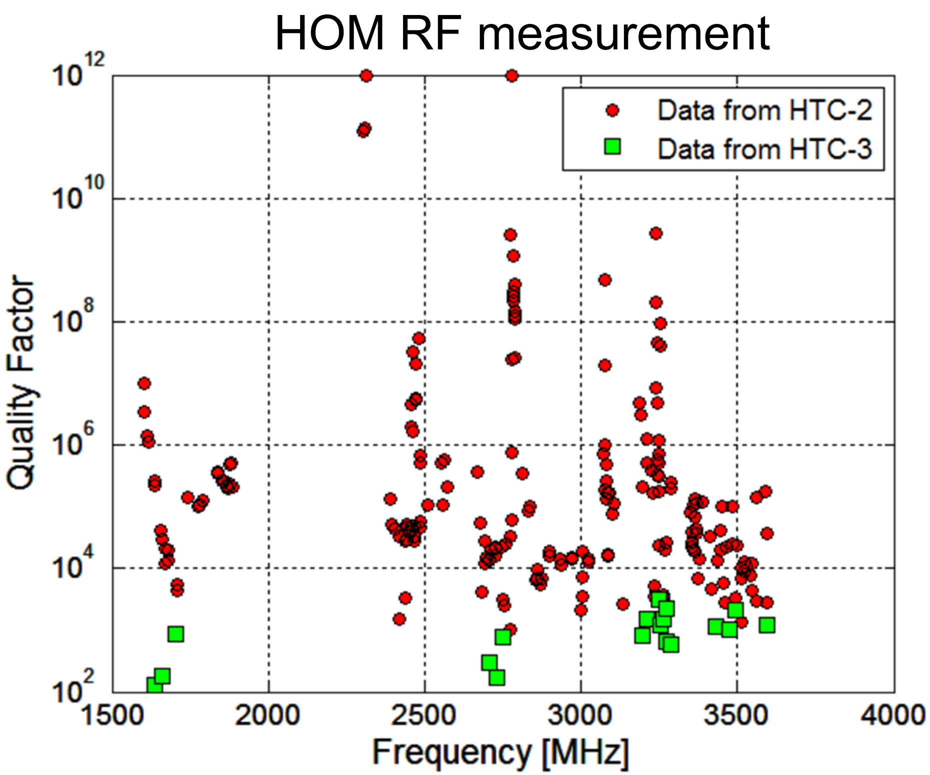
- HTC-3: Full cryomodule assembly-high power RF input coupler and HOM absorbers



HTC-3: Cavity + Coupler + HOM Absorbers

New Record in a horizontal cryomodule:
$Q_0 > 10^{11}$ (at 16.2 MV/m, 1.6 K)

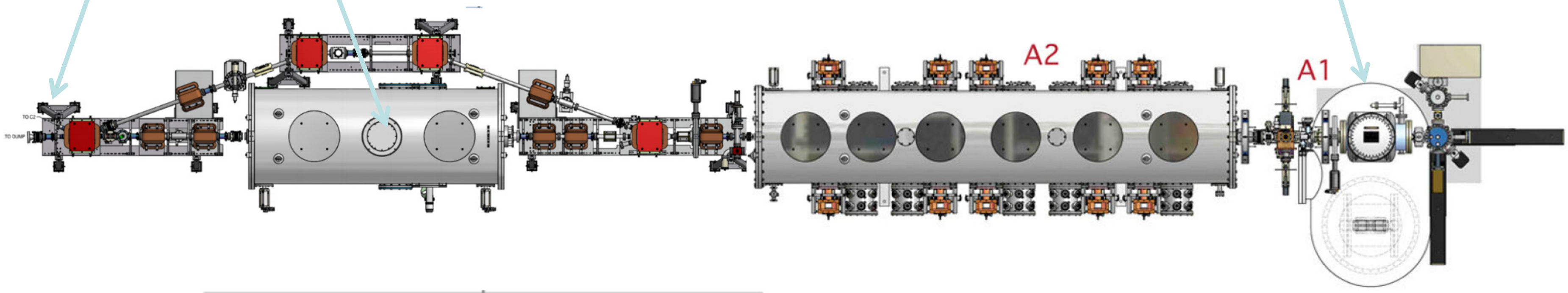


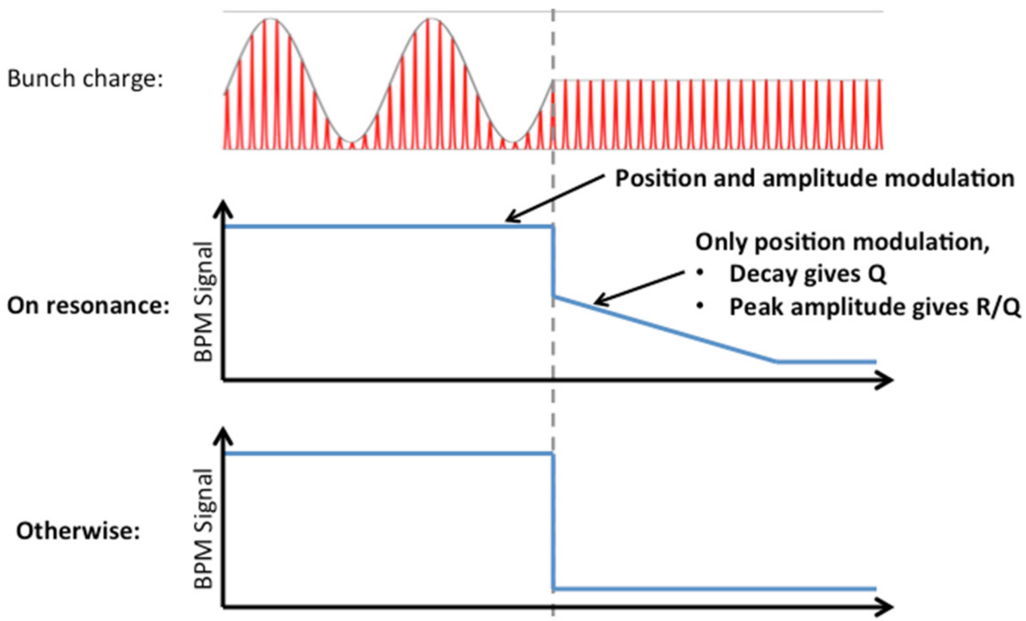


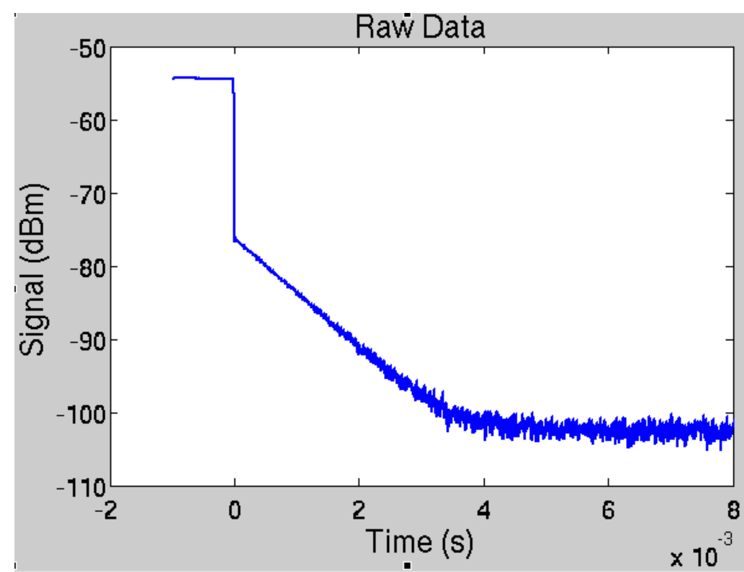
HTC HOM measurement with beam

D. Hall, IPAC14: MOPRO113

BPM **7-cell cavity in cryostat** **gun**



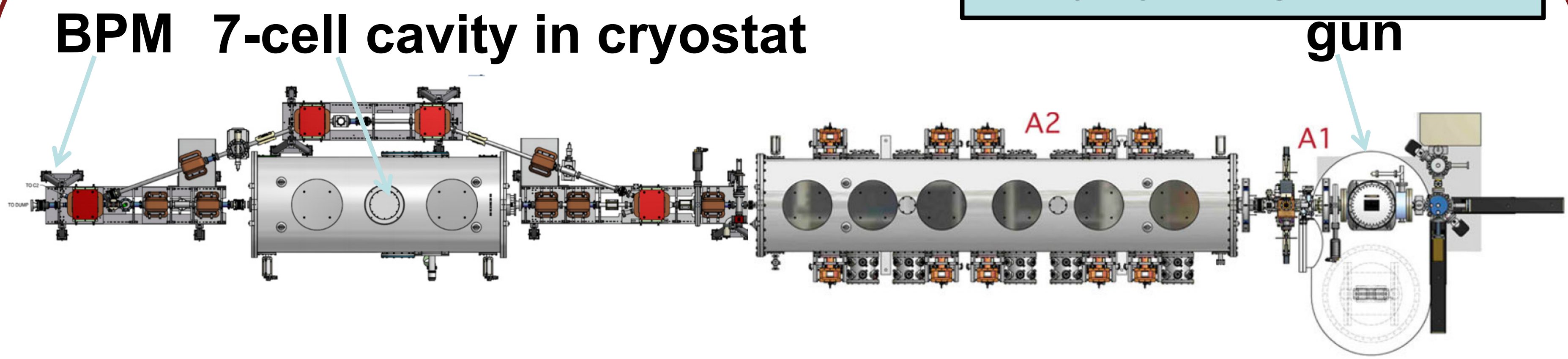




Data was taken December 2013, currently being analyzed…

HTC High current tests with beam (40 mA)

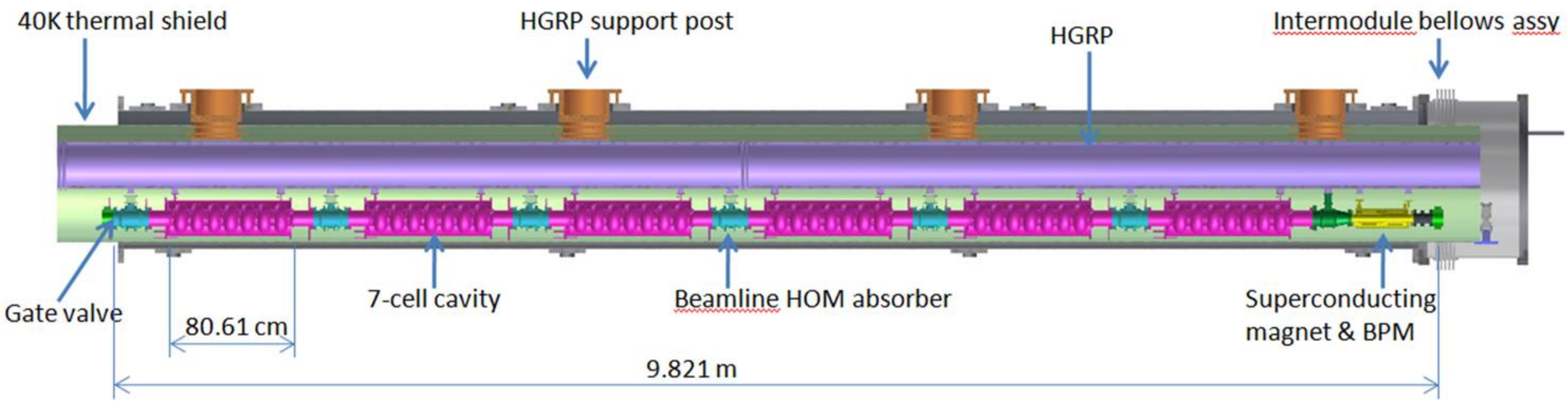
R. Eichhorn IPAC14: THPRI111



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

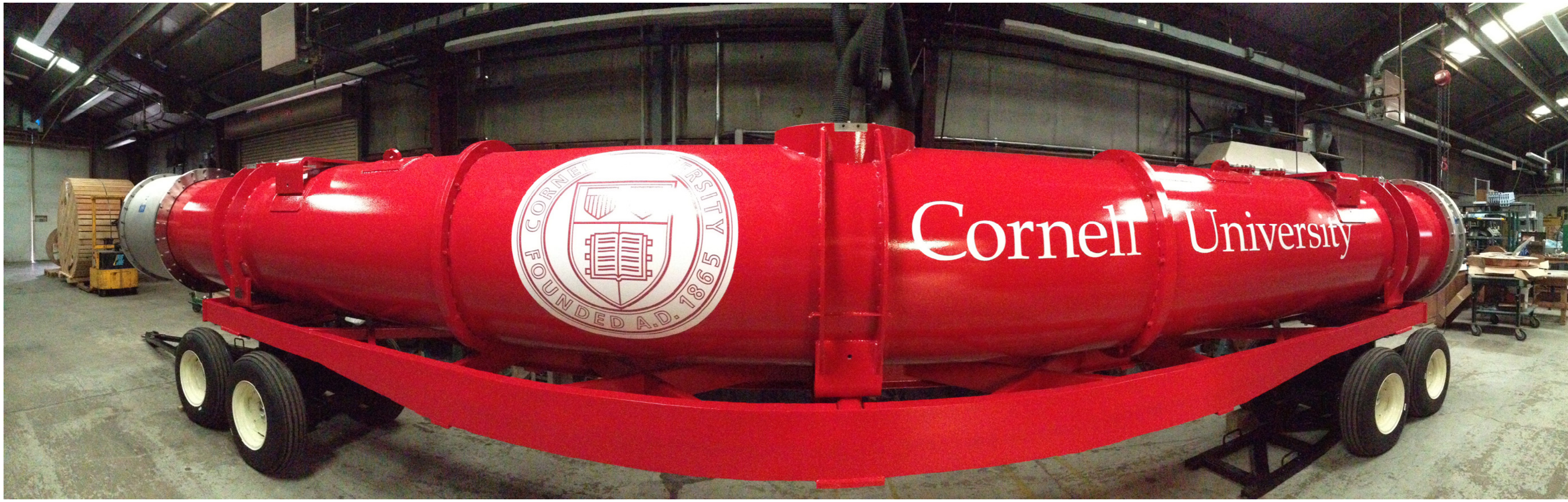
Cornell ERL Main Linac Cryomodule (MLC) Prototype

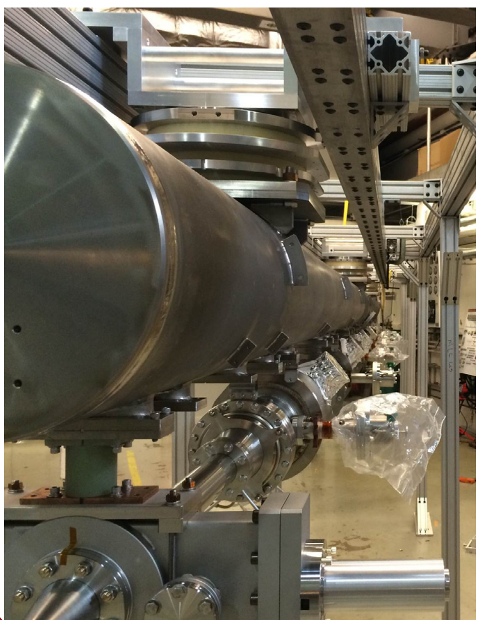


- Completed fabrication and RF test of 6 main linac SRF cavities
  - Statistics of high Q_0 cavity preparation
- Fabrication of full ERL main linac prototype cryomodule
  - Fabrication of input couplers, tuners, beamline HOM absorbers, cryomodule components…
  - January 2014: Started string assembly
  - June 2014: Start cold mass assembly June
  - End 2014: completion

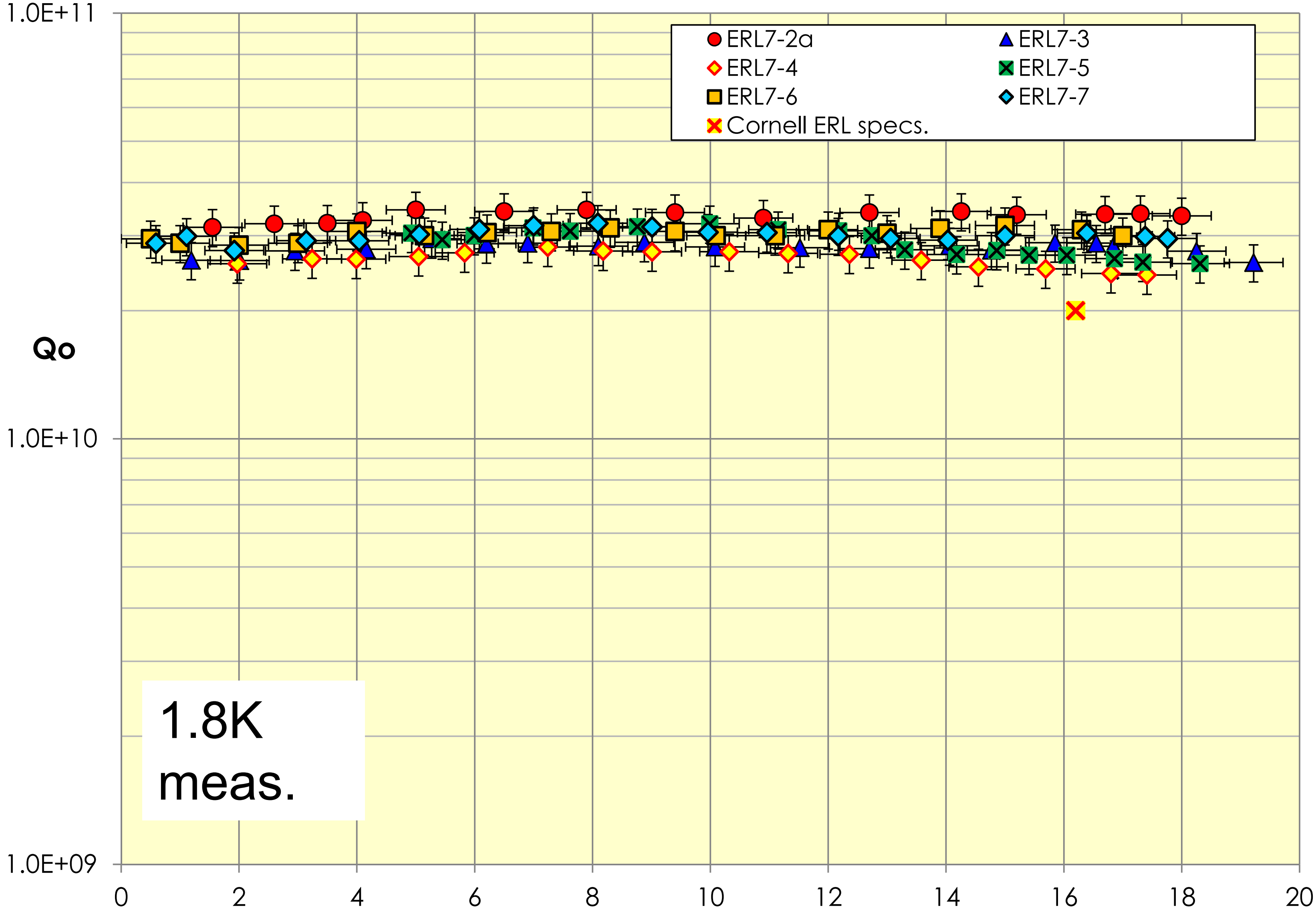
First high current (>100 mA), CW SRF linac cryomodule worldwide!

Main Linac Cryomodule (MLC) Prototype





Cornell Main Cryomodule cavity tests (Vertical)



Critical Components

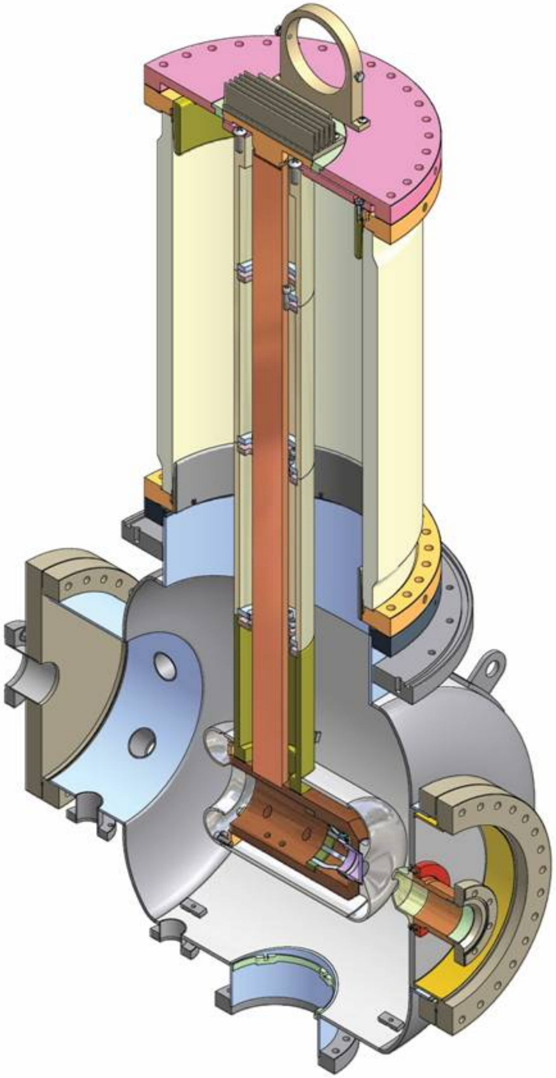
Source

Injector

Linac

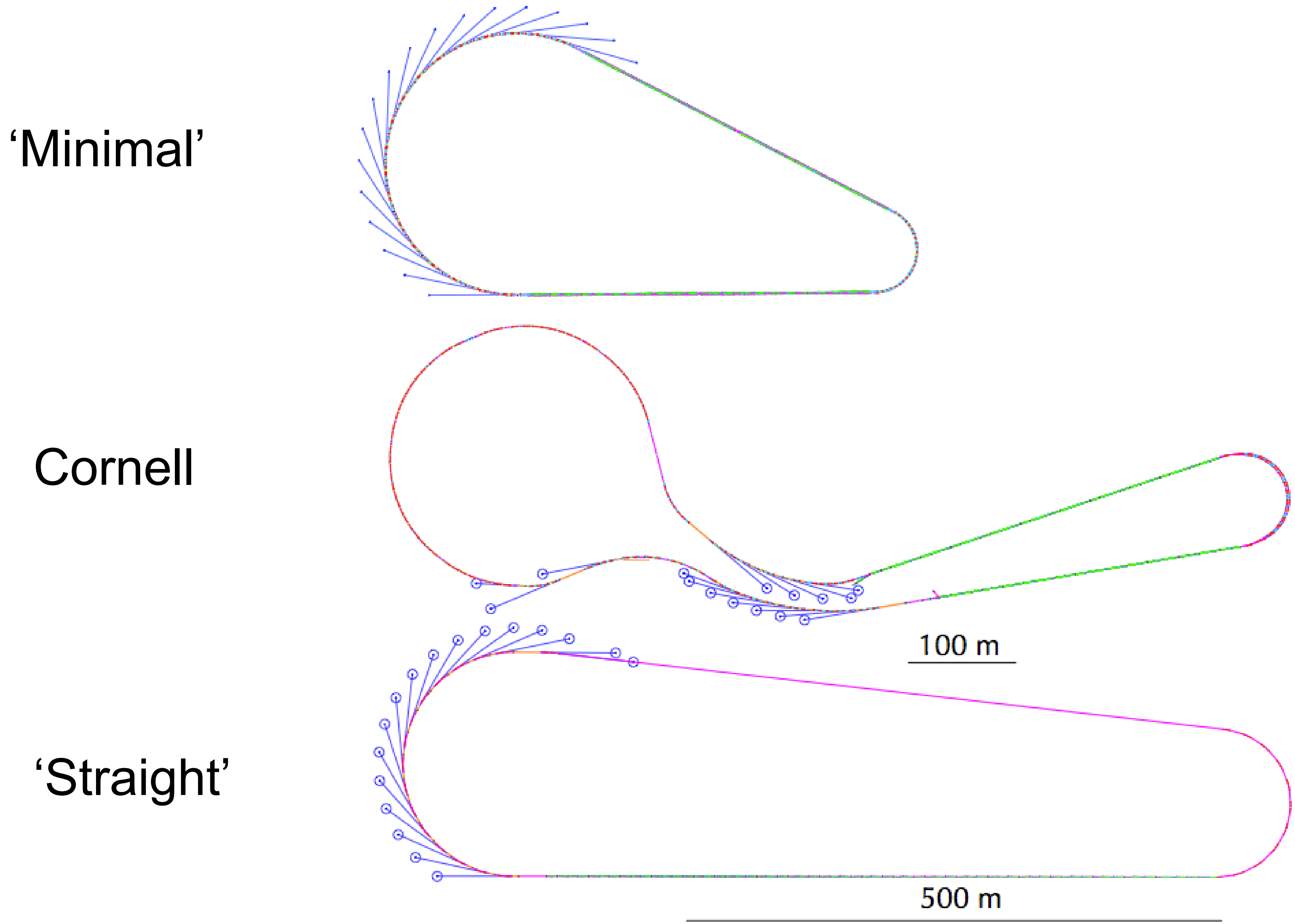
Beam Transport

Insertion Devices

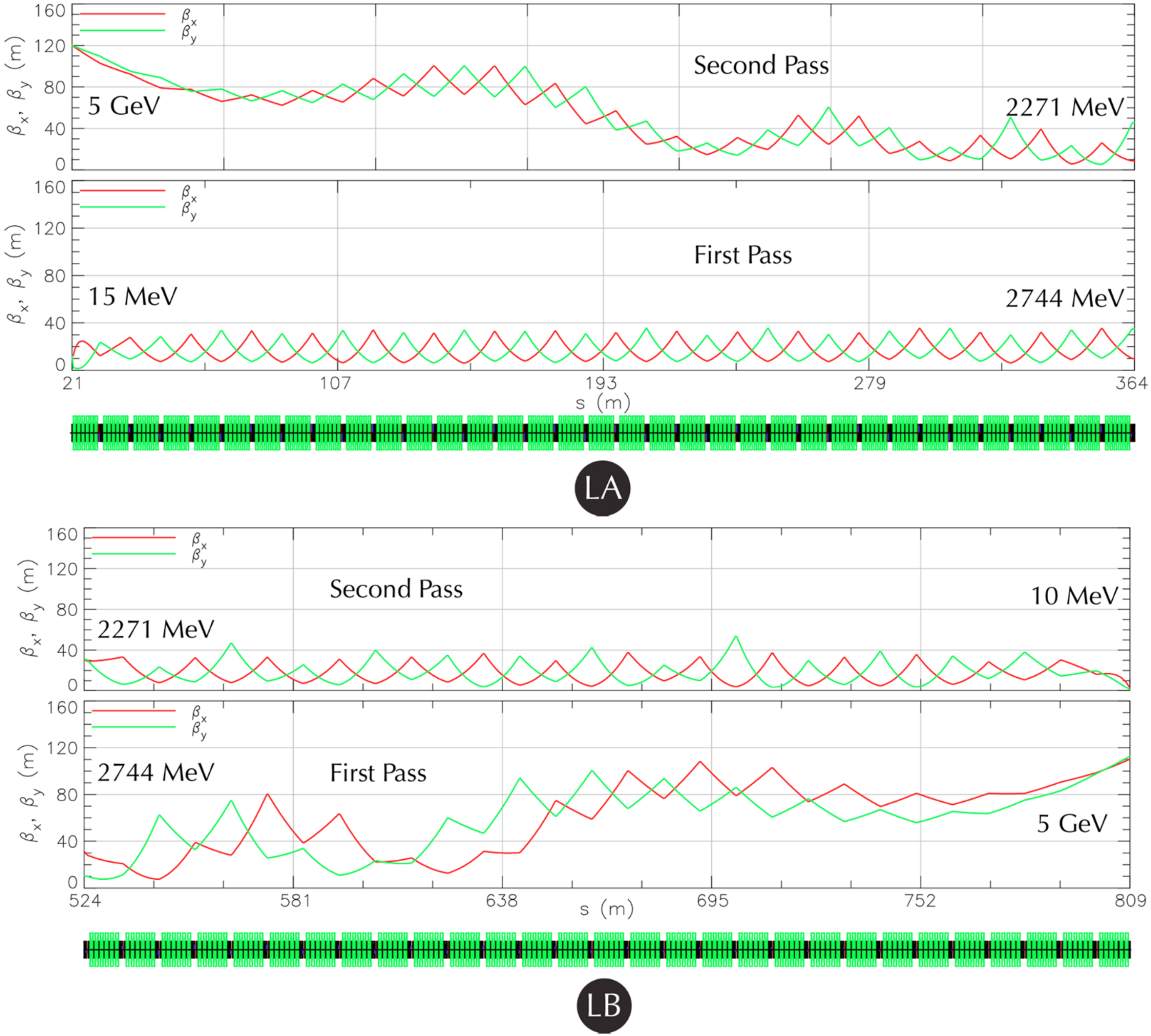


Layouts

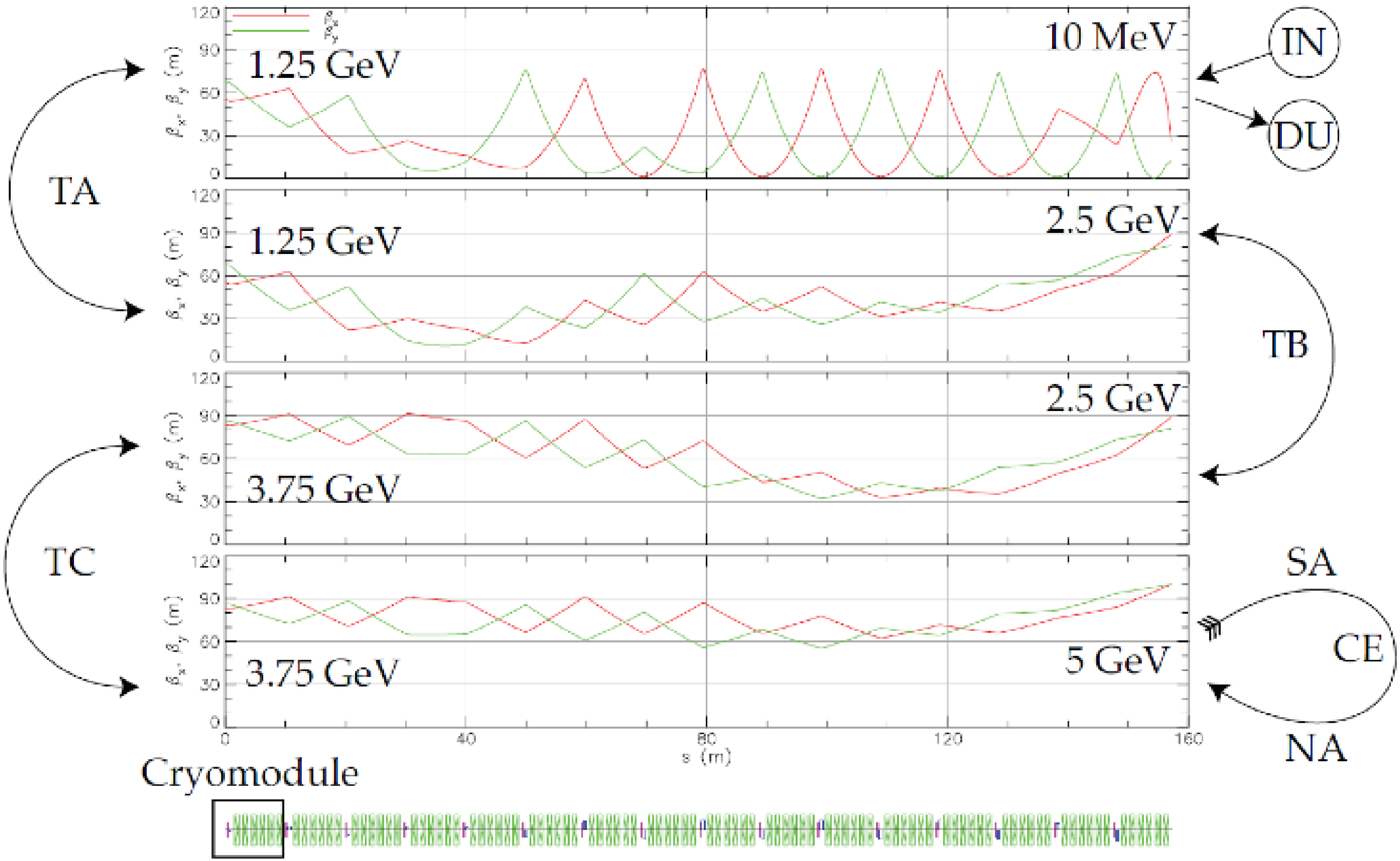
5 GeV , single pass ERLs



Split Linac Optics

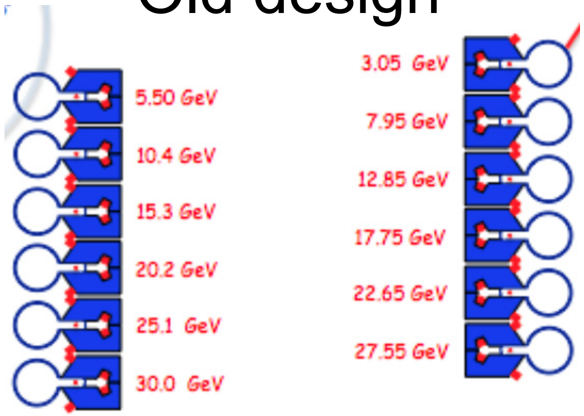


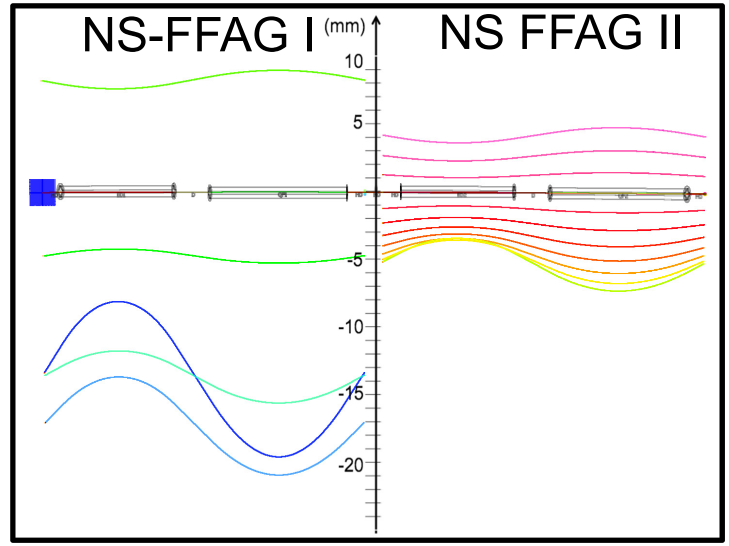
Four Pass Linac Optics



Novel Arc design: eRHIC non-scaling FFAG

Old design



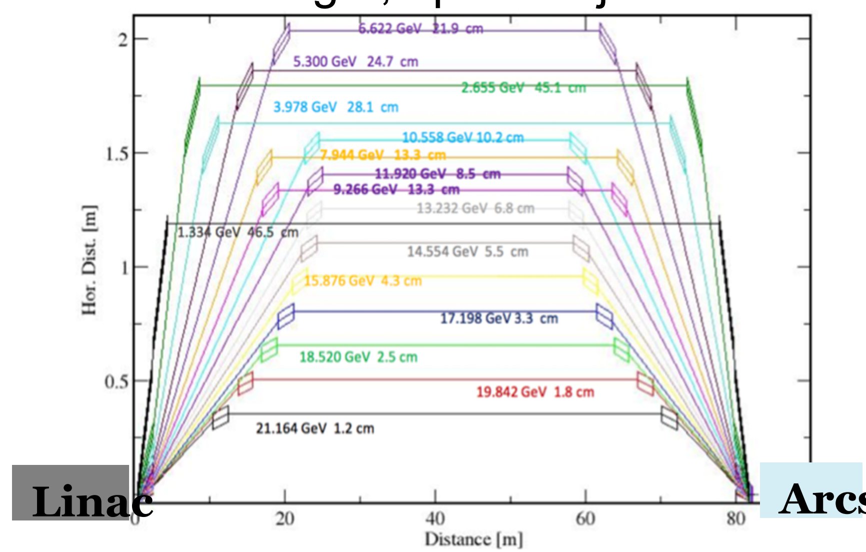


12 MeV injection
1.32 GeV linac, no quadrupoles

NS-FFAG I
5 orbits for 1.3, 6.6 GeV

NS-FFAG II
11 orbits for 7.9, …, 21.2 GeV
All kept within 10 mm

Separated for path length, time of flight, optics adjustment



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Injector

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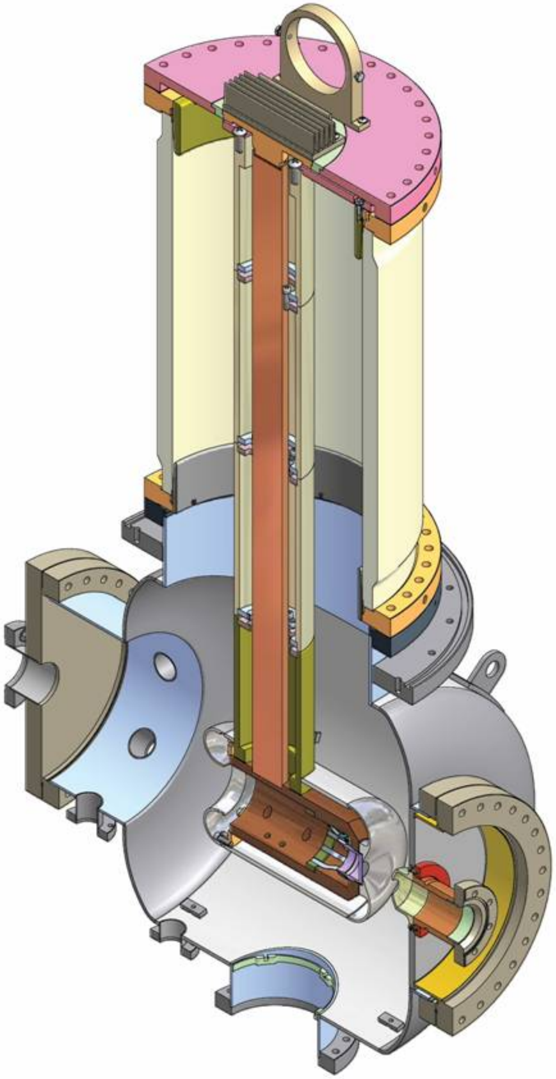
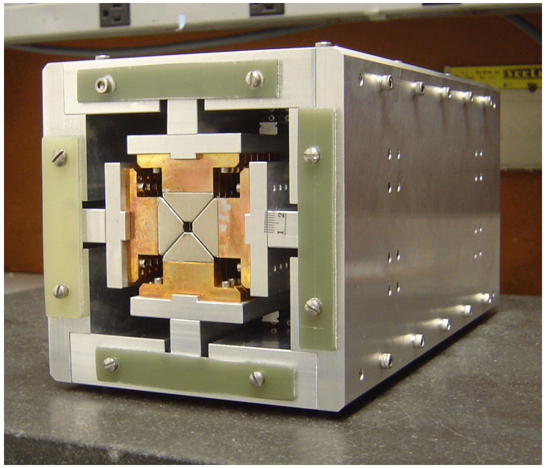
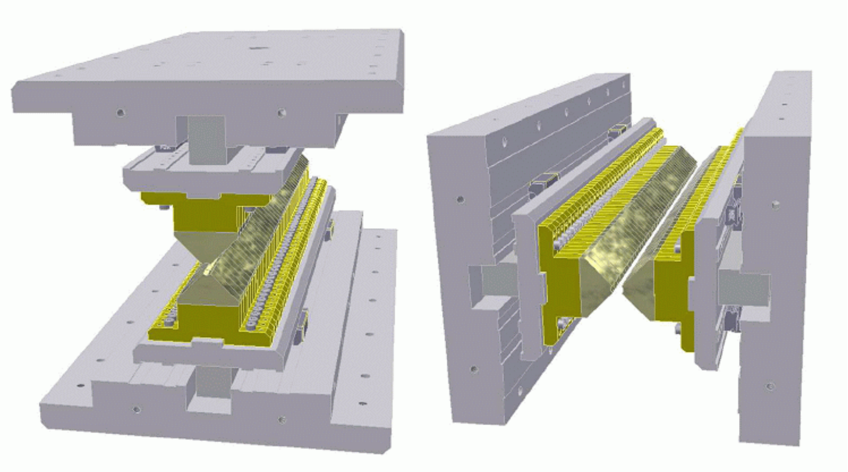


Delta Undulator





- Developed to take advantage of the ERL's round beams
- Full polarization control
- Strong fields (1.4 T)
- Very compact
- Tested ATF at BNL late 2009
- A planar version is to be used in CESR
- SLAC is building a 3.2 m version for LCLS

[A. Temnykh, PRST-AB 11, 120702 (2008)]

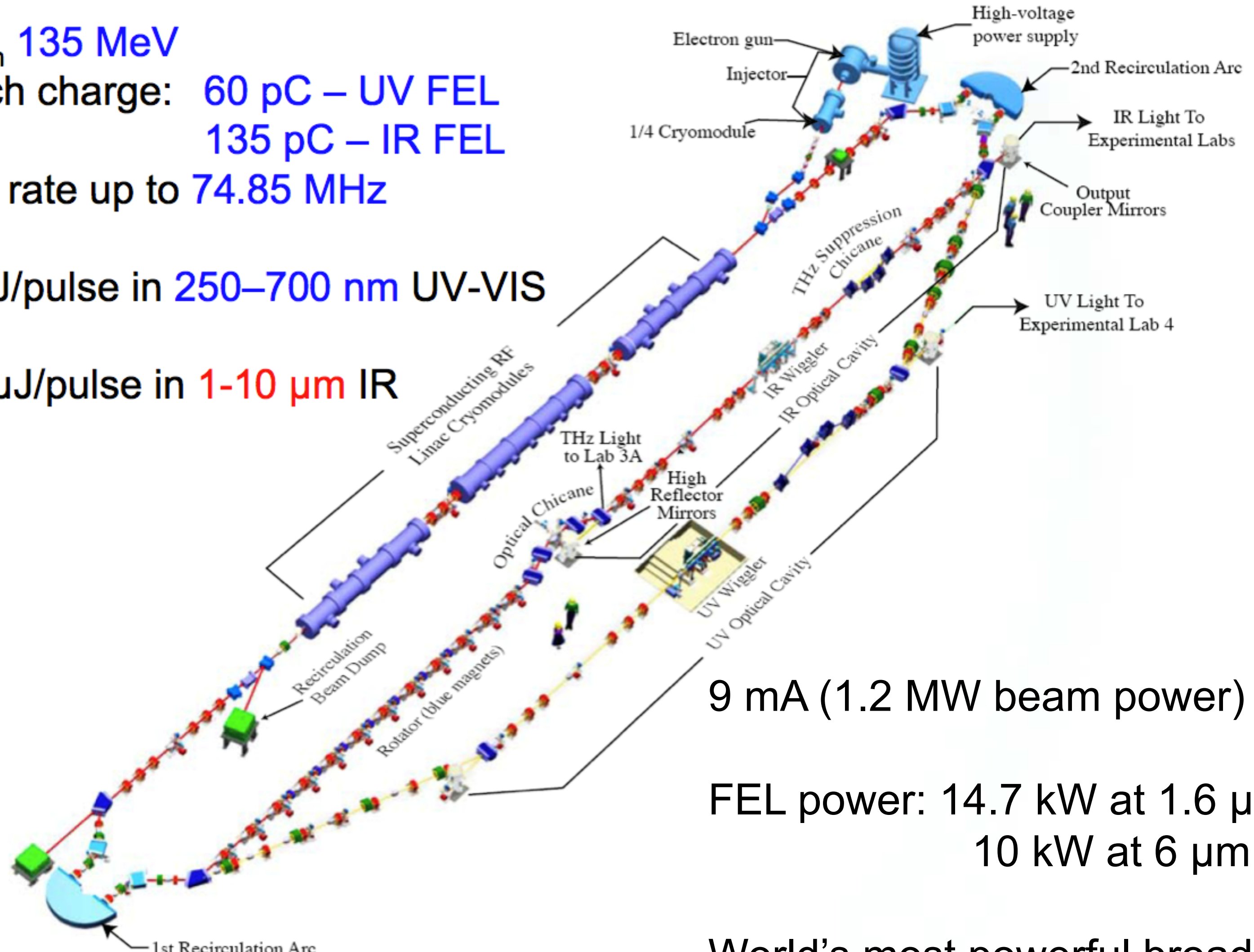
Existing ERL Facilities

UV/IR FEL (JLab)

E_{beam} 135 MeV
Bunch charge: 60 pC – UV FEL
135 pC – IR FEL
Rep. rate up to 74.85 MHz

25 μJ/pulse in 250–700 nm UV-VIS

120 μJ/pulse in 1-10 μm IR



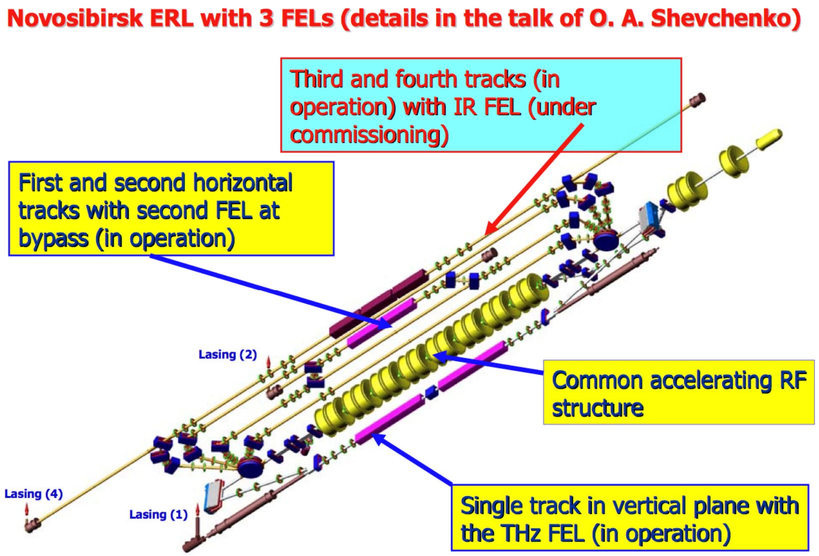
9 mA (1.2 MW beam power)

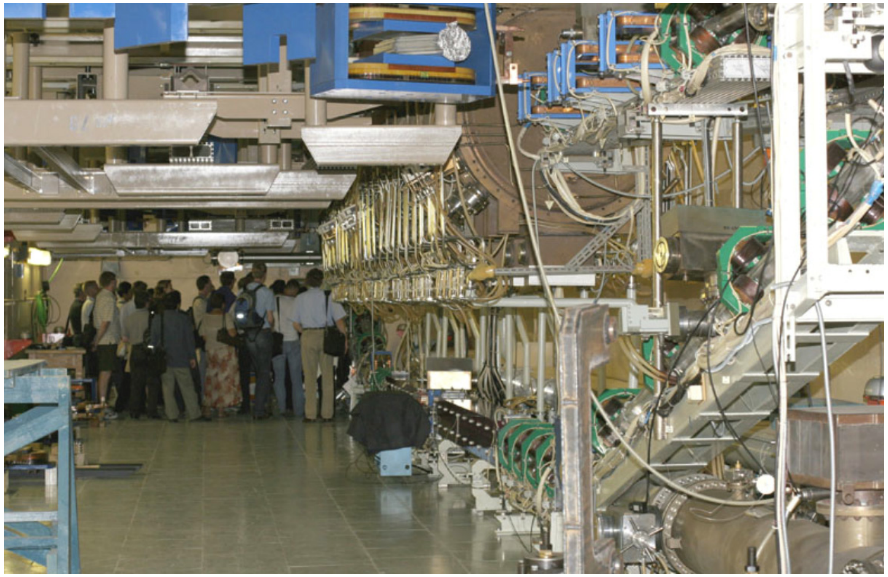
FEL power: 14.7 kW at 1.6 μm
10 kW at 6 μm

World's most powerful broadband THz source, 100 W

[Neil et al., NIM-A 557 1 9–15 (2006)]

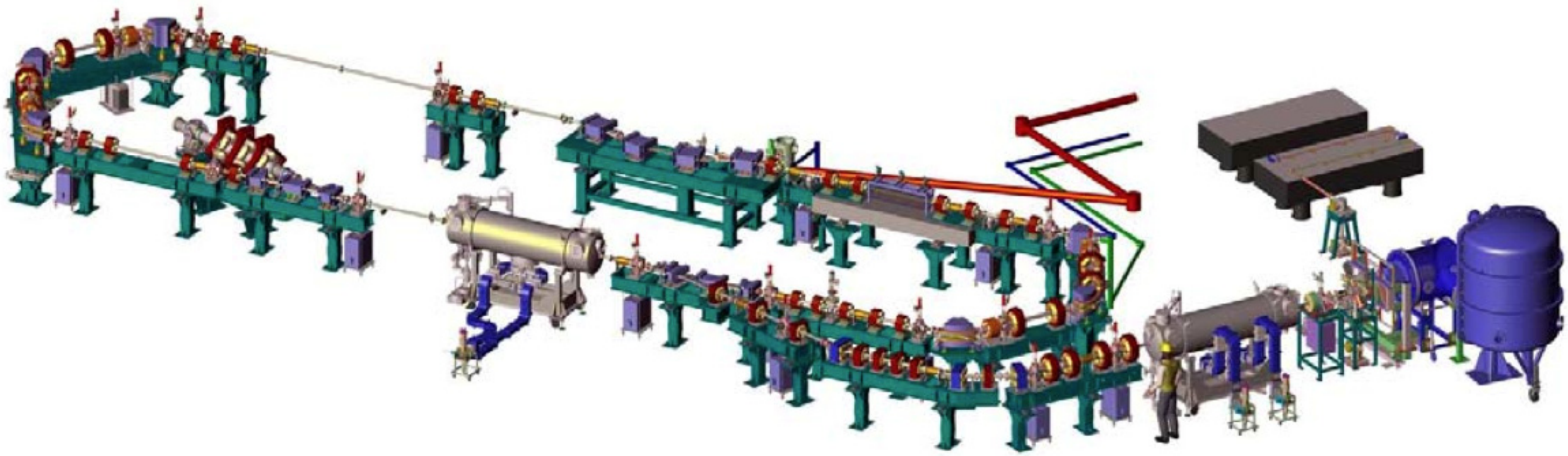
Novosibirsk ERL-FEL

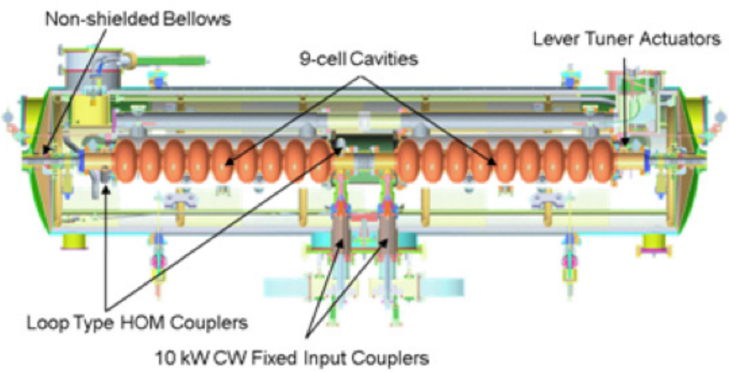




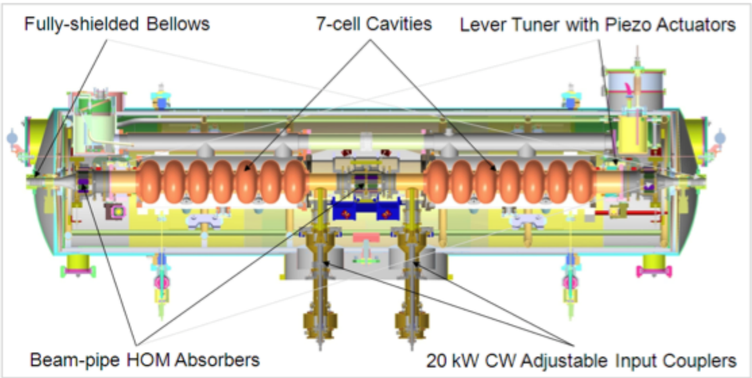
NovoFEL ERL13 presentation

ALICE (Daresbury)





Existing Cryomodule on ALICE



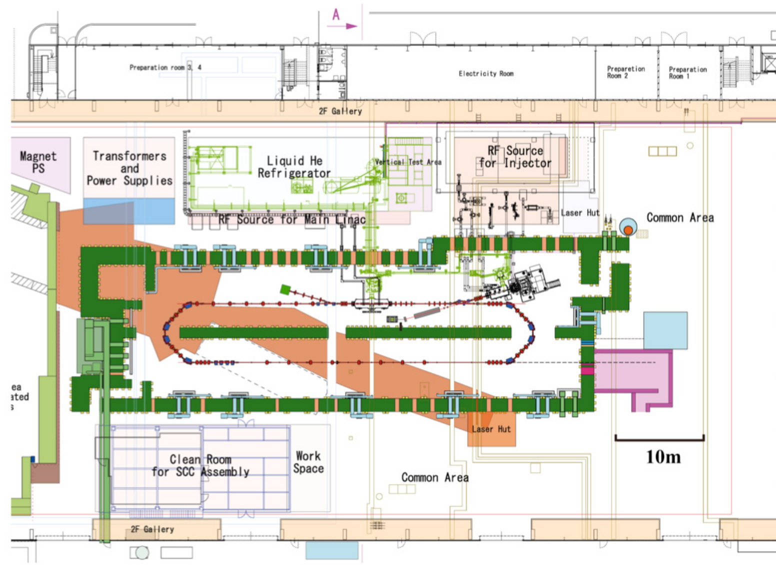
CW-ERL Cryomodule

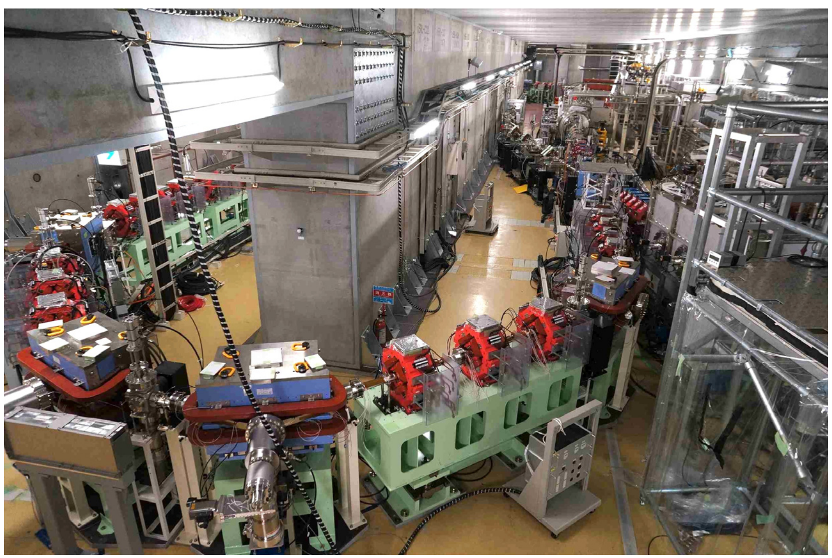
Jones et al., AIP Conf. Proc. 1149, 1084 (2009)

New ERL Facilities

Compact ERL (KEK)

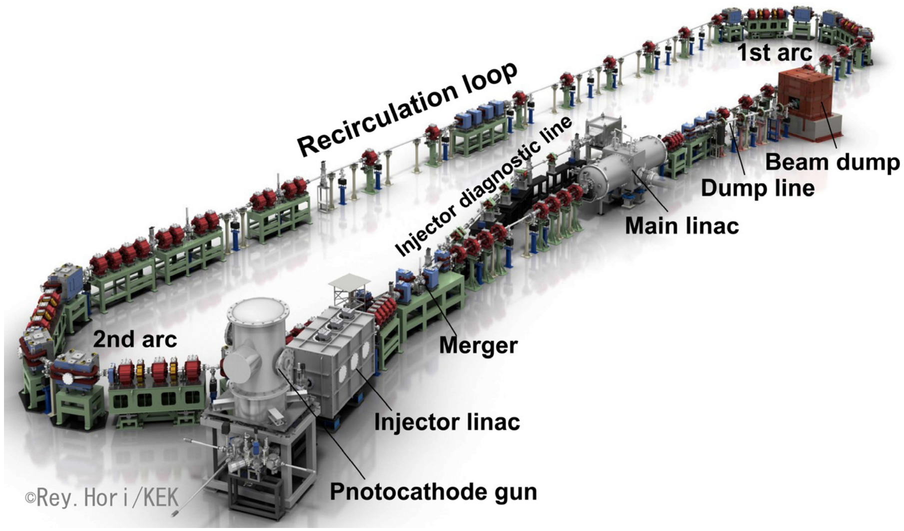
Beam energy	35 - 125 MeV (single loop) 245 MeV (double loop)
Injection energy	5 MeV
Average current	10 mA (100 mA in future)
Acc. gradient	15 MV/m
Normalized emittance	0.1 mm·mrad (7.7 pC) 1 mm·mrad (77 pC)
Bunch length	1 - 3 ps 100 fs (with bunch compression)
RF frequency	1.3 GHz





Nakamura IPAC12 - TUXB02

Compact ERL (KEK)



Purpose

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

Achievements

Commissioning of the entire cERL was started in Dec. 16, 2013.

So far achieved:

acceleration of beams up to 20 MeV

beam recirculation and energy recovery without significant beam loss

maximum current of 6.5 μA in CW operation

Optics tuning and beam quality improvement are in progress.

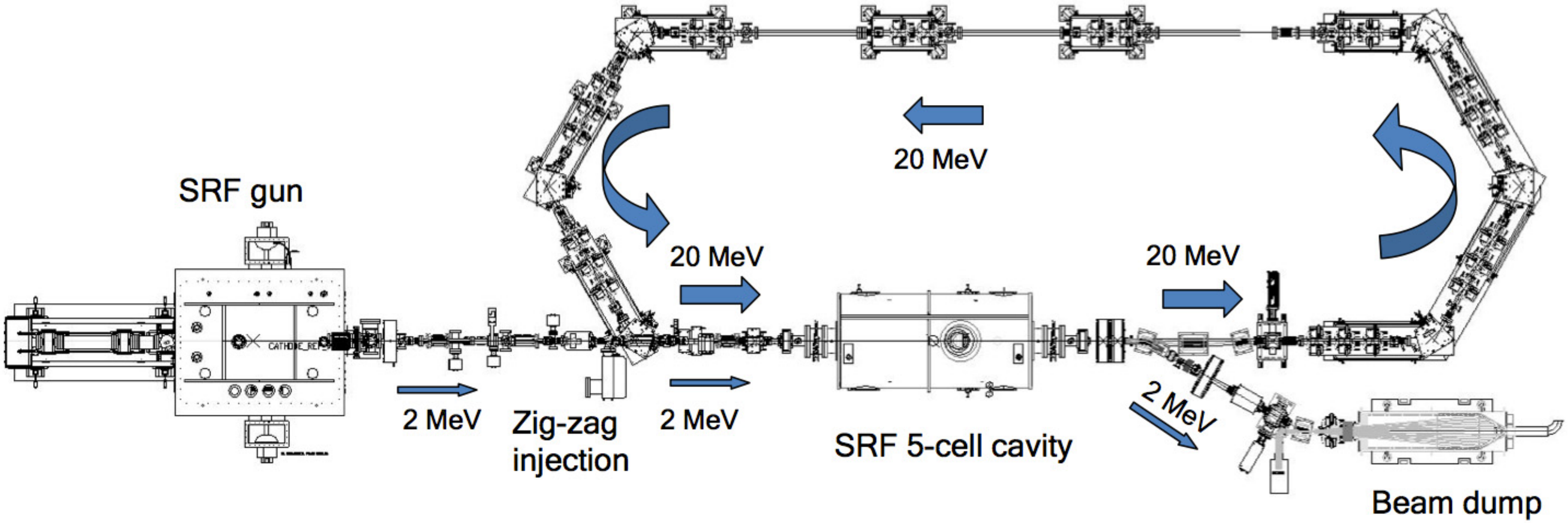
Future developments

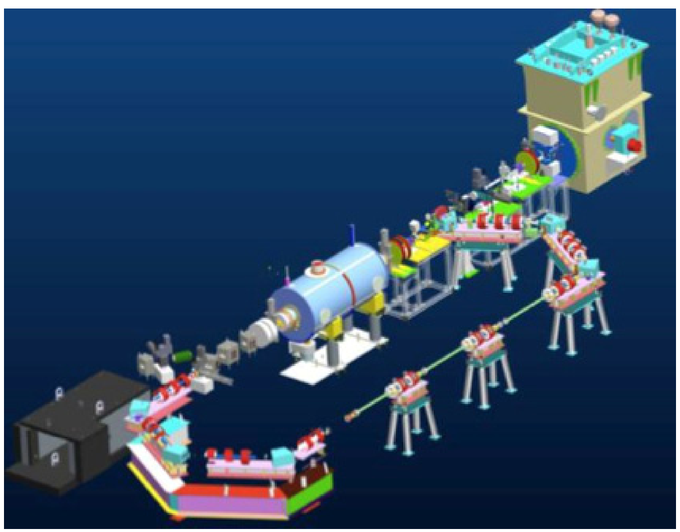
Generation of Laser Compton Scattering (LCS) X-rays is scheduled at the end of FY2014.

Generation of THz coherent radiation is planned in FY2015.

[Slide courtesy of N. Nakamura]

BNL Test ERL





✓The main goal of BNL R&D ERL project is to serve as a test-bed to demonstrate the main electron beam parameters for future RHIC upgrade projects:

- ERL-based coherent electron cooling;
- 10-to-20 GeV ERL for lepton-ion collider eRHIC.

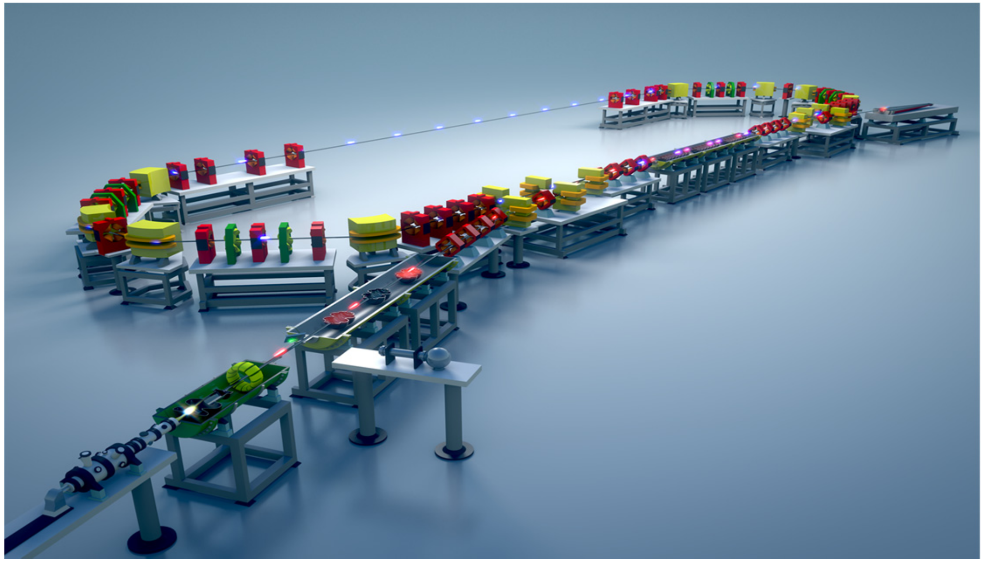
✓Test the key components of a high current ERL based solely on SRF technology

- SRF photoinjector test with 300 mA: preservation of high-charge, low emittance beam;
- High current 5-cell SRF linac test with HOM absorbers: single turn, 300 mA;
- Stability criteria for CW beam current;
- Attainable ranges of electron beam parameters in an SRF ERL.

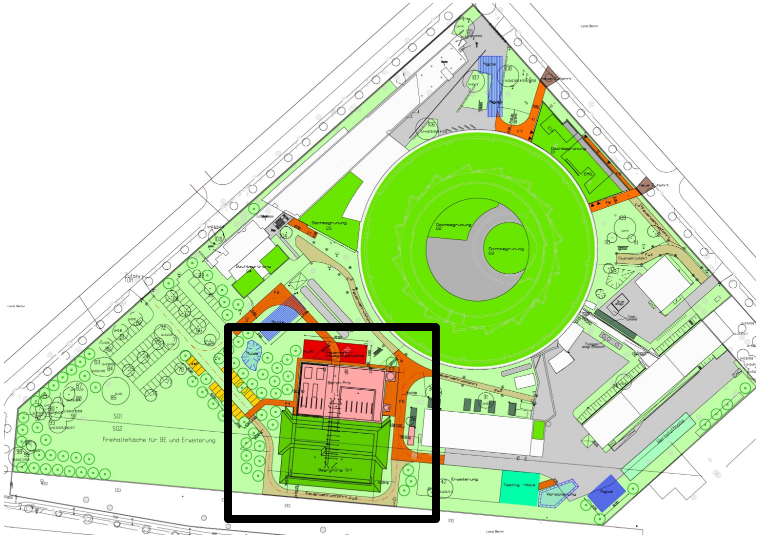
9/10/13 Wencan Xu: SRF system for BNL's R&D ERL 5

ERL13 Presentation

bERLinPro - Helmholtz Zentrum Berlin (HZB)



Parameter	Value	Unit
Beam energy	50	MeV
Beam current @ 1.3 GHz	100	mA
Bunch charge	77	pC
Bunch length	< 2	ps
Energy spread	0.5%	-
Emittance	< 1	mm mrad
Beam loss	$< 10^{-5}$	-



Groundbreaking late 2014

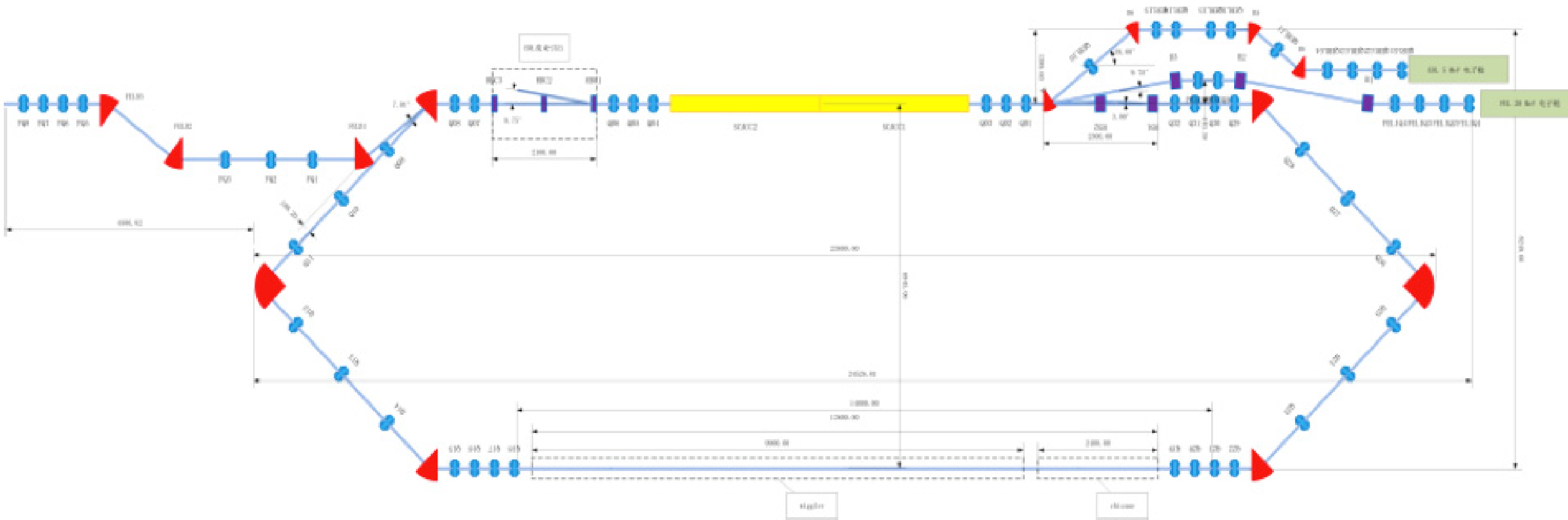
Operational
Cathode prep system

Fabricated
SRF gun
SRF booster cavities (in fabrication)

Ordered
All magnets
Gun cryomodule parts (some delivered)
Klystrons and SS amplifiers
Beam stop

Designed
Vacuum components
Linac (being designed)

IHEP ERL Test Facility (Beijing)

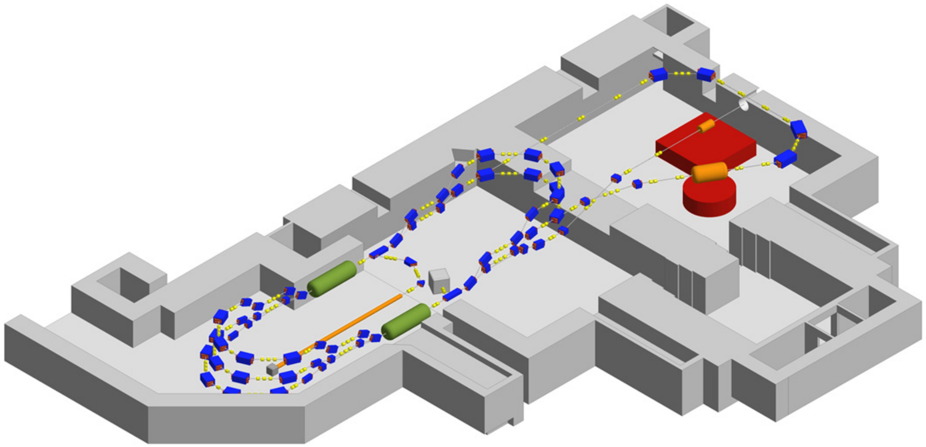


Parameter	Value
Beam energy (MeV)	35
Beam current (mA)	10
Bunch charge (pC)	77 (or 7.7)
Normalized emittance (mm.mrad)	1.0-2.0
Rms bunch length (ps)	2.0-4.0
Rms energy spread (%)	0.2-1.0
Bunch frequency (MHz)	130 (or 1300)
RF frequency (MHz)	1300

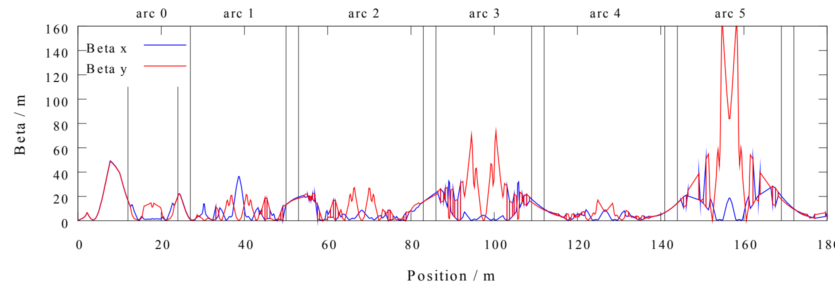
Yi and Ou-Zheng - Beam dynamics studies of the photo-injector in low-charge operation mode for the ERL test facility at IHEP
http://arxiv.org/abs/1308.0383

MESA (Mainz)

R. Heine, IPAC14: MOPRO108



Parameter	stage-1 (EB/ERL)	stage-2 (EB/ERL)
Beam energy, MeV	155/105	205/105
Bunch charge, pC	0.15/0.77	0.15/7.7
norm. emittance, μm	0.1 / <1	0.2/< 1
Beam polarization, %	>0.85/n.a.	>0.85/n.a.
Recirculations	2	3
Beam power at exp., kW	22.5/100	31/1000

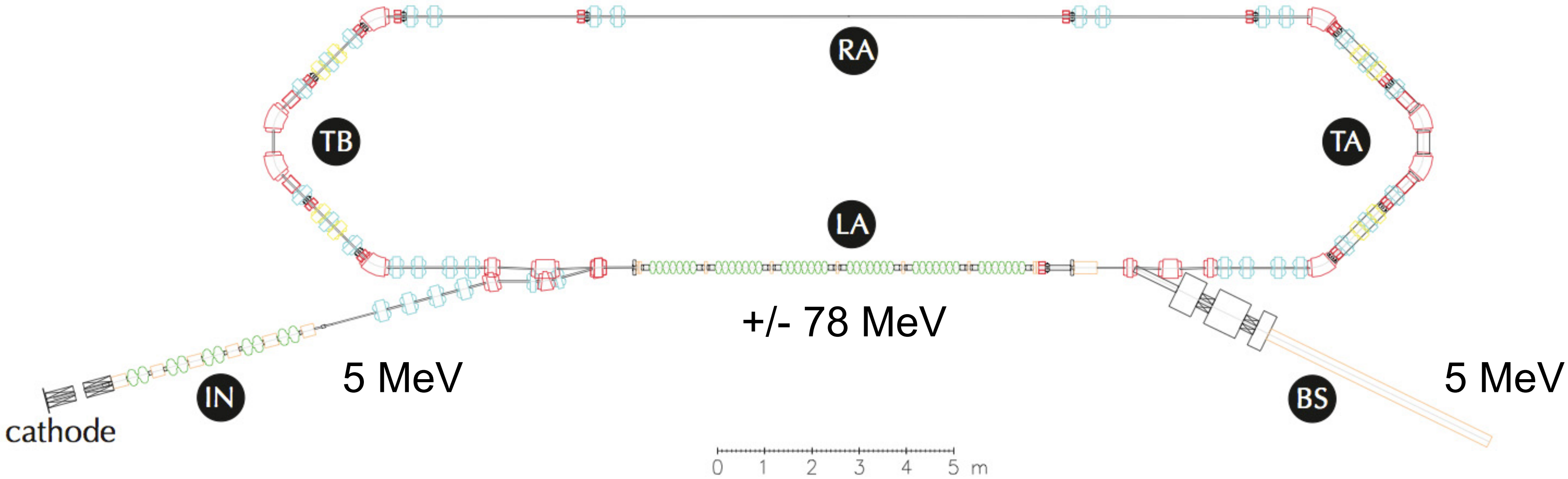


- one normal conducting injector linac with an extraction energy of 5 MeV
- two superconducting linac modules with an energy gain of 25 MeV each
- four spreader sections for vertically separating and recombining the beam
- five 180° arcs for the beam recirculation
- two chicanes for the injection and extraction of the 5 MeV beam
- one 180° bypass arc for energy recovery mode incorporating the internal experiment
- one beam line to the external experiment

Aiming for beam in 2017

[K. Aulenbacher, AIP Conf. Proc. 1563, 5-12 (2013)]

Cornell High-power recirculation loop (preliminary design)

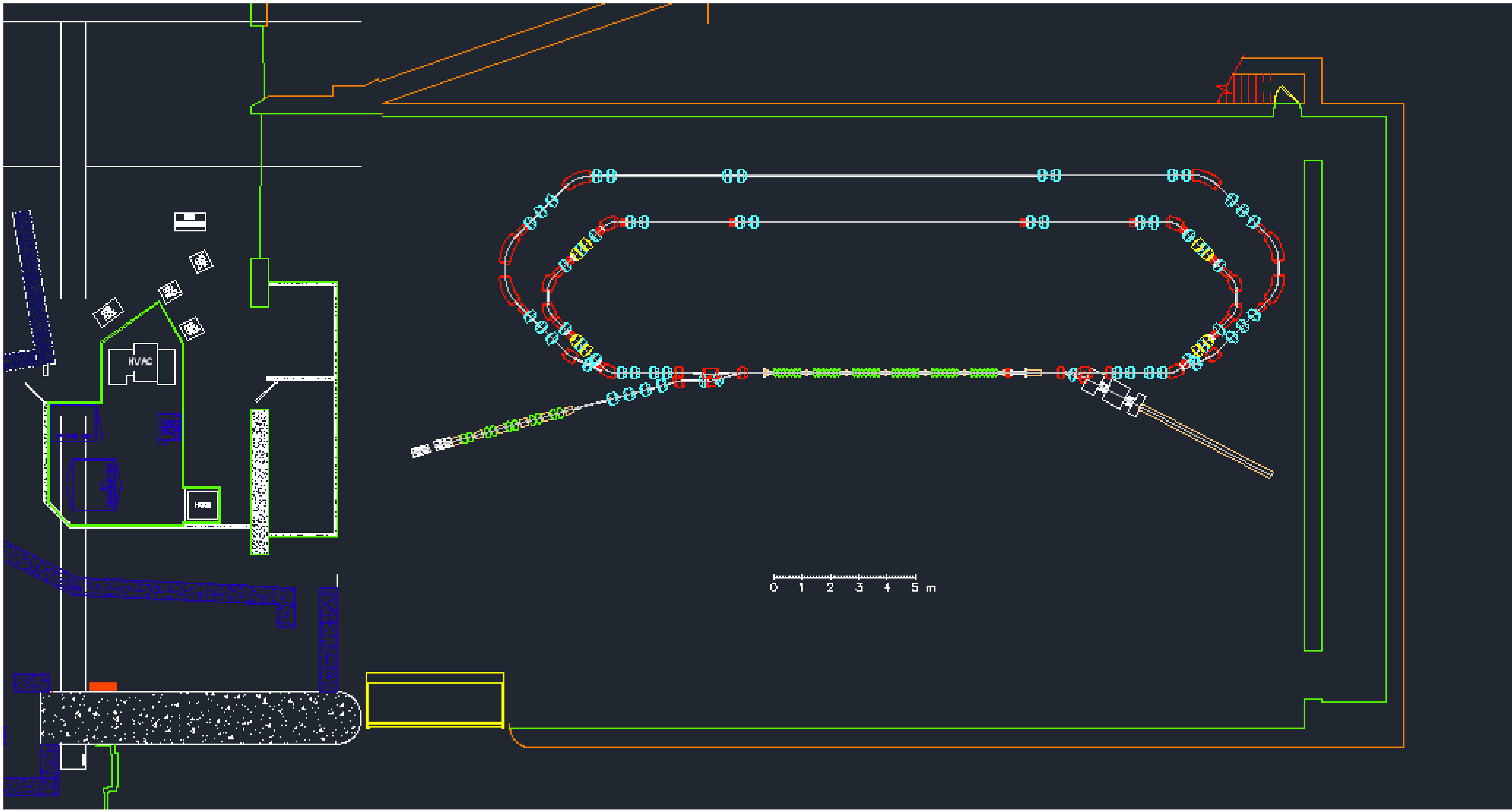


Energy	83	MeV
Current	100	mA
Emittance x, y	0.3	mm-mrad
Frequency	1.3	GHz
Bunch charge	77	pC

Mayes ERL13 Presentation

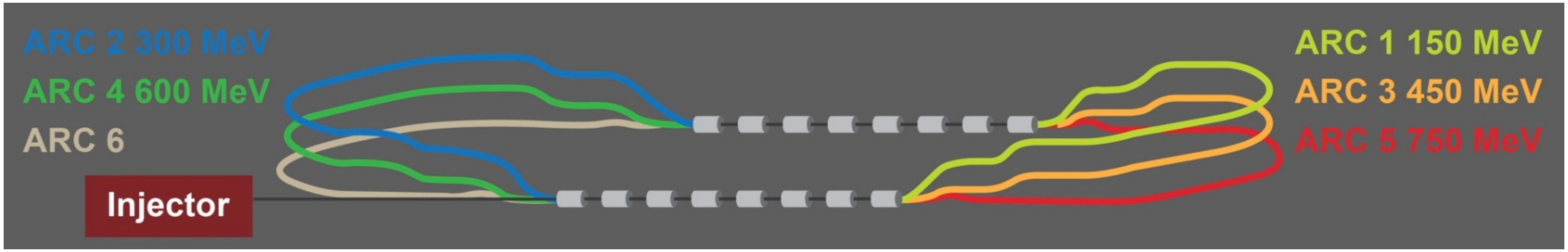
Cornell High-power recirculation loop

CESR's L0E hall



CERN ERL Test Facility

E. Jensen IPAC14: TUOBA02



Parameter	Value	
injection energy	5 *MeV*	
RF *f*	801.59 *MHz*	
acc. voltage per cavity	18.7 *MV*	
# cells per cavity	5	
cavity length	≈1.2 *m*	
# cavities per cryomodule	4	
RF power per cryomodule	≤50 *kW*	
# cryomodules	4 *)	
acceleration per pass	299.4 *MeV* *)	
bunch repetition *f*	40.079 *MHz*	
Normalized emittance	50 μm	
injected beam current	<13 *mA*	
nominal bunch charge	320 *pC*=2·10⁹ *e*	
number of passes *)	2	3
top energy *)	604 *MeV*	903 *MeV*
total circulating current *)	52 *mA*	78 *mA*
duty factor	CW	

Jensen – IPAC14 Presentation

CERN Mandate: 5 main points

The mandate for the technology development **includes studies and prototyping of the following key technical components**:

•Superconducting RF system for CW operation in an Energy Recovery Linac (high Q_0 for efficient energy recovery) S

•Superconducting magnet development of the insertion regions of the LHeC with three beams. The studies require the design and construction of short magnet models

•Studies related to the experimental beam pipes with large beam acceptance in a high synchrotron radiation environment

•The design and specification of an ERL test facility for the LHeC.

•The finalization of the ERL design for the LHeC including a finalization of the optics design, beam dynamics studies and identificationof potential performance limitations

The above technological developments require close collaboration between the relevant technical groups at CERN and external collaborators.

Given the rather tight personnel resource conditions at CERN **the above studies should exploit where possible synergies with existing CERN studies.**

Bruening - ERL13 Presentation

2009 BES Report

In addition to the demonstration of energy recovery on a quantitative scale, the development of an X-ray ERL, as well as the realization of FEL designs with megahertz pulse rates, is also hindered by the lack of technical developments as far as gun performance is concerned. ***Today's guns cannot yet deliver the bunch charges, emittances, and repetition rates required for the full ERL or FEL designs outlined above****. Guns capable of delivering a few mA average current are available, but for an ERL to deliver a flux comparable to a storage ring, the average current has to be on the order of 100 mA. However, both these technological goals are quite well defined and within range.* ***Once these are achieved. there will be a very bright future for accelerator-based X-ray sources.***

BES Subcomittee report - Next Generation Photon Sources - May 2009

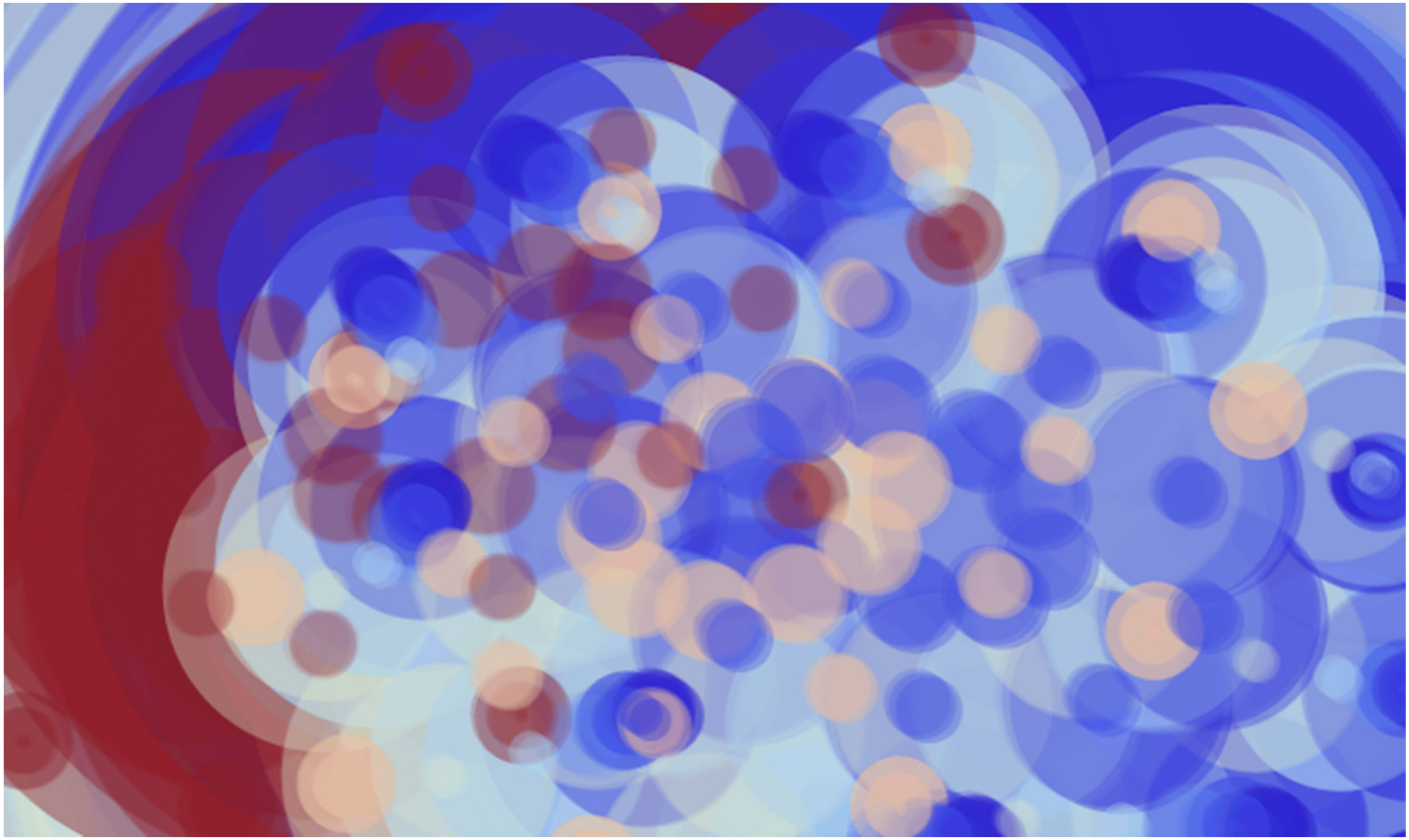
ERL Technology Readiness

Shovel Ready

Key ERL challenges have been overcome

- Photocathode lifetime
- High current
- Low emittance
- Emittance preservation through merger between photoinjector and linac
- High Q_0 superconducting RF accelerating structures

Large-scale ERL construction could begin soon



End