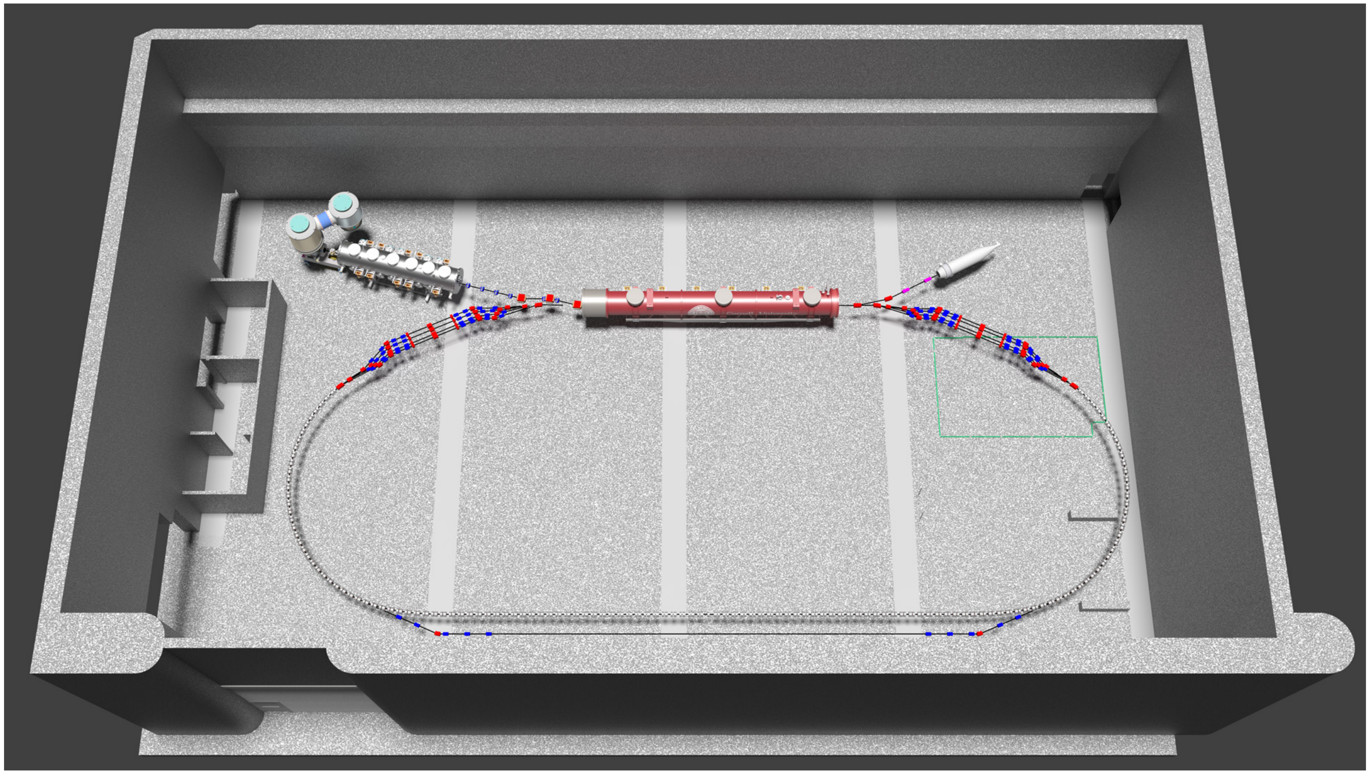
High Intensity ERL Developments

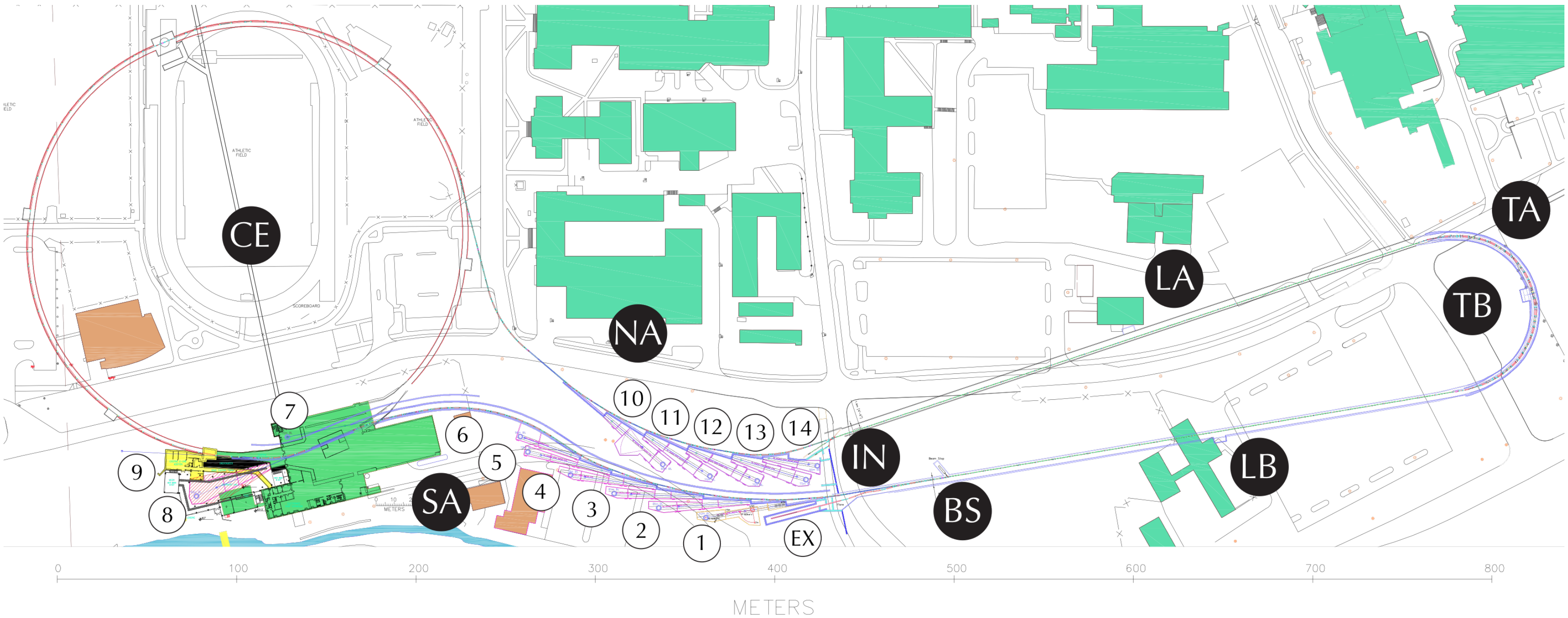


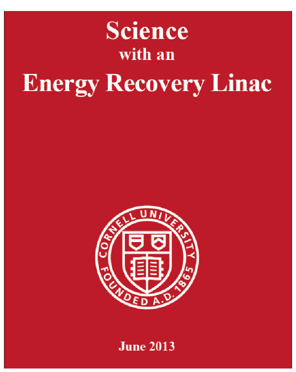
Christopher Mayes – June 25, 2015

Outline

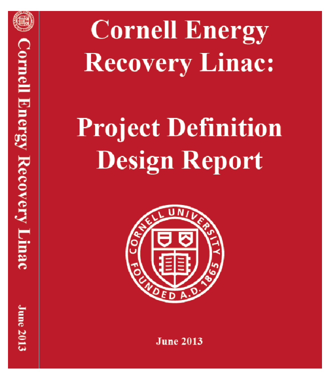
- History
- Prototype ERL Injector
- SRF cavity design & testing
- Prototype ERL Cryomodule
- Cornell-BNL ERL-FFAG Test Accelerator

Cornell ERL





Science case gathered in international workshops



530 page PDDR

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

Cornell ERL Timeline

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

M. Tigner

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

(ricevuto il 2 Febbraio 1965)

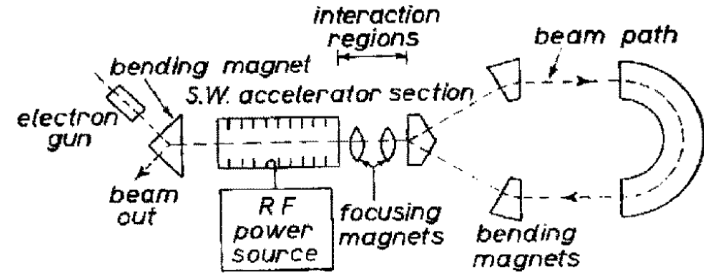


Fig. 3.

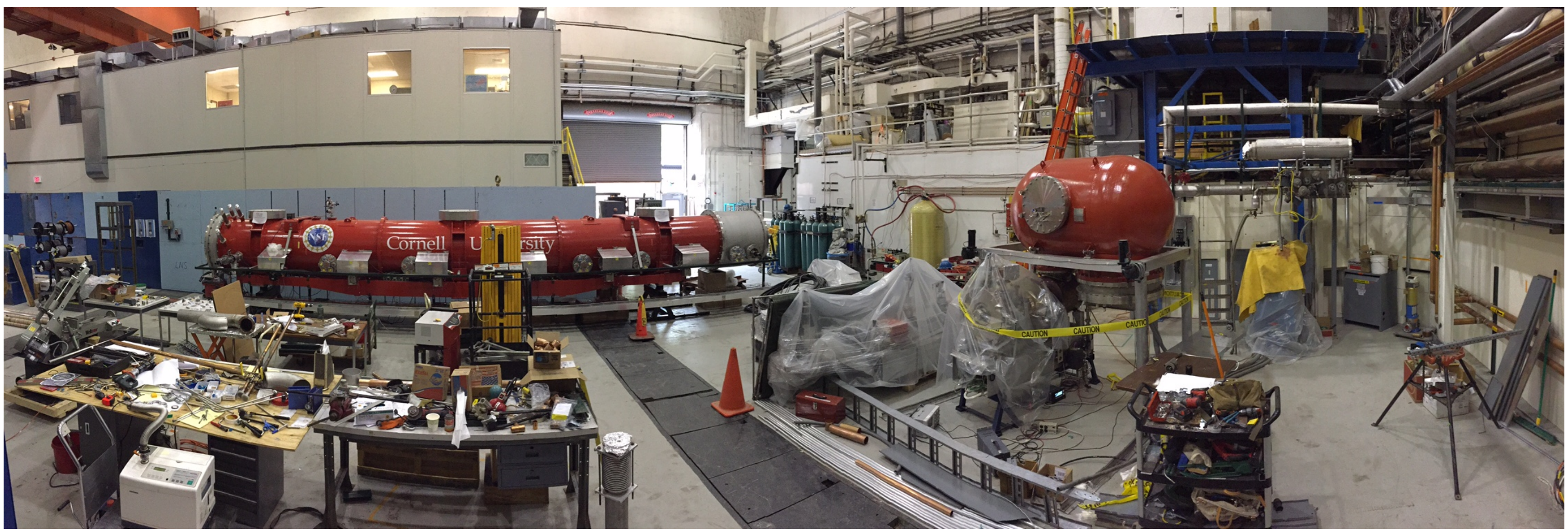
1999: Tigner suggests a coherent hard x-ray ERL light source is feasible.
2000: First x-ray Science Workshop for an ERL at Cornell
NSF encourages proposal
2001: Cornell & JLab ERL `white' paper. Phase 1a proposed.
2005: **NSF funds Phase1a**: 5-yr R&D on injector, linac modules, machine issues.
2006: Six x-ray Science Workshops for an Energy Recovery Linac at Cornell
2006: Conceptual engineering studies for Phase II (**NY State + CU support**)
2008: NSF Light Source Panel recommends that the NSF
should build & steward a coherent light source.
2010: **NSF funds Phase 1b**: 4 year continued R&D).
ERL civil construction design study completed.
2011: XDL-2011 Workshops completed.
ERL technical design report (PDDR) completed, reviewed.
ERL draft Environmental Impact Statement ready for submission.
2012: Critical ERL Phase 1b milestones achieved

Cornell ERL Timeline

2013: Record 75 mA, 65 mA sustained from DC gun
Achieved emittance goals for the Cornell ERL
Started collaboration with **SLAC for LCLS2**:
SRF cavities, injector emittance measurements, beam dynamics

2014: Main Linac Cryomodule (MLC) prototype completed
Achieved emittance specifications for LCLS2
Started collaboration with BNL for an ERL-FFAG test accelerator
High bunch charge (2 nC) studies (**DOE**)

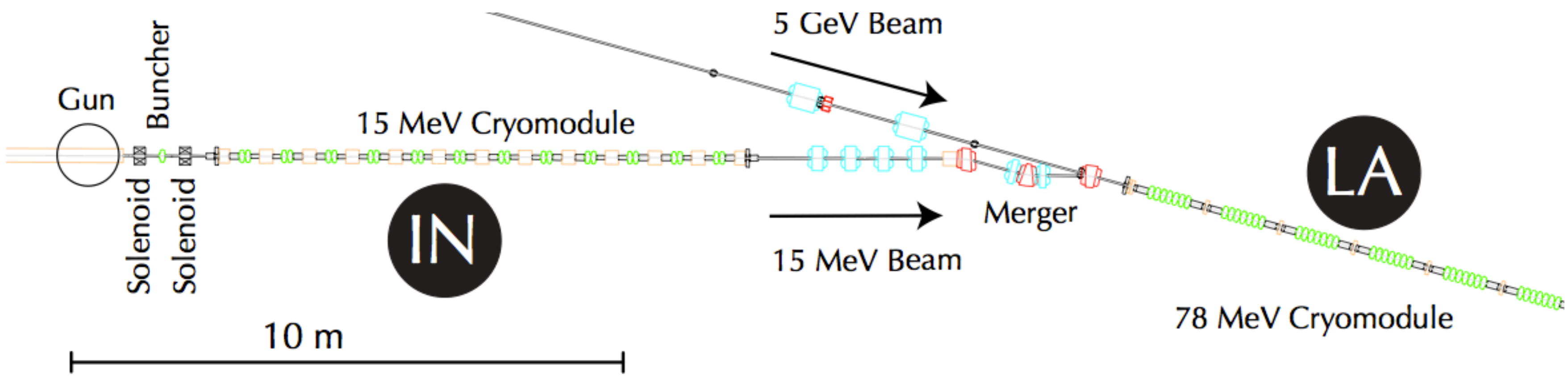
2015: DC Gun and MLC moved to L0E hall
Intense electron beams workshop



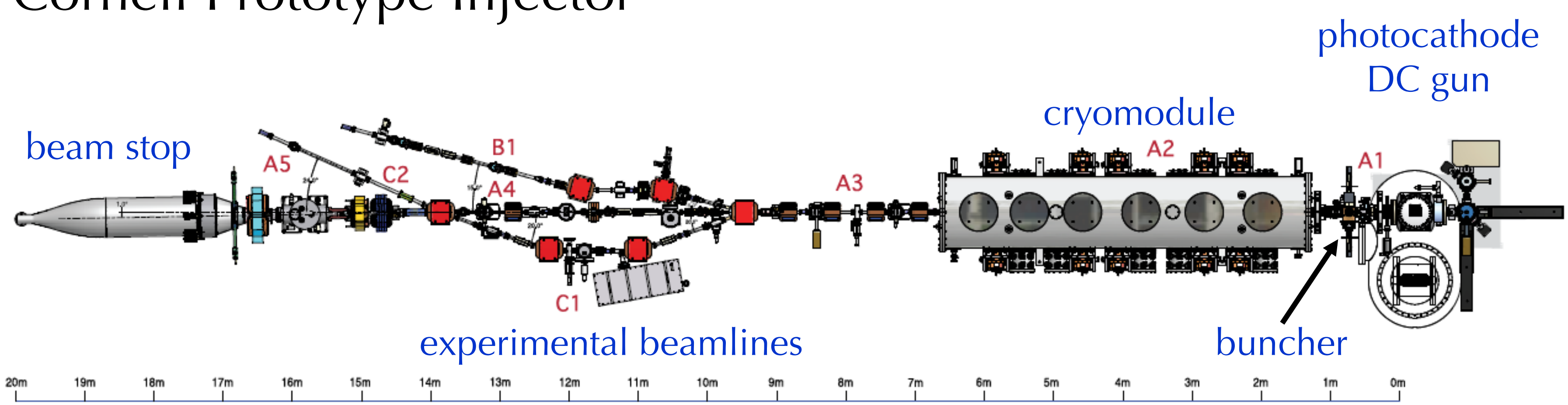
Prototype Injector

Injector

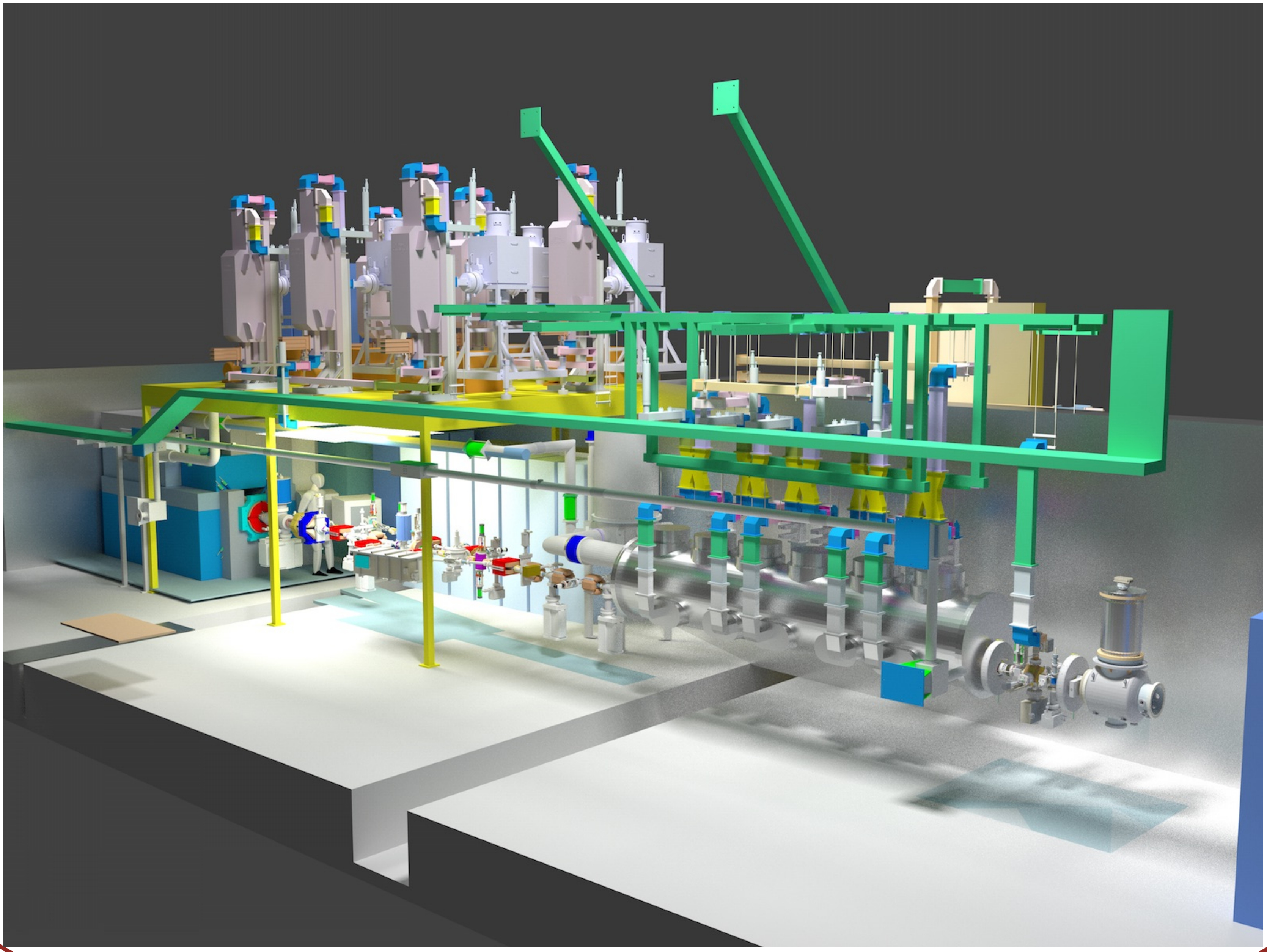
Cornell ERL



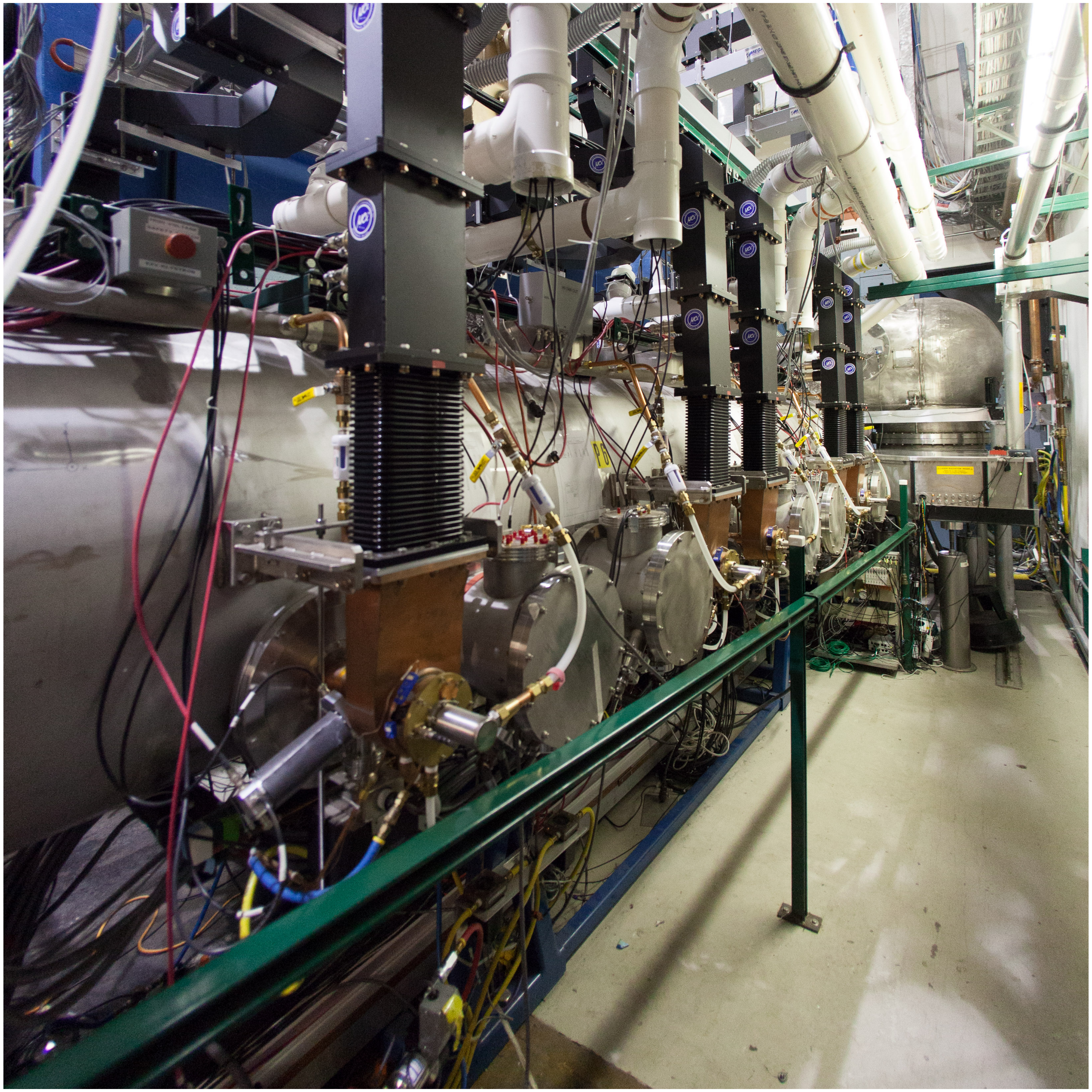
Cornell Prototype Injector



Cornell ERL prototype injector

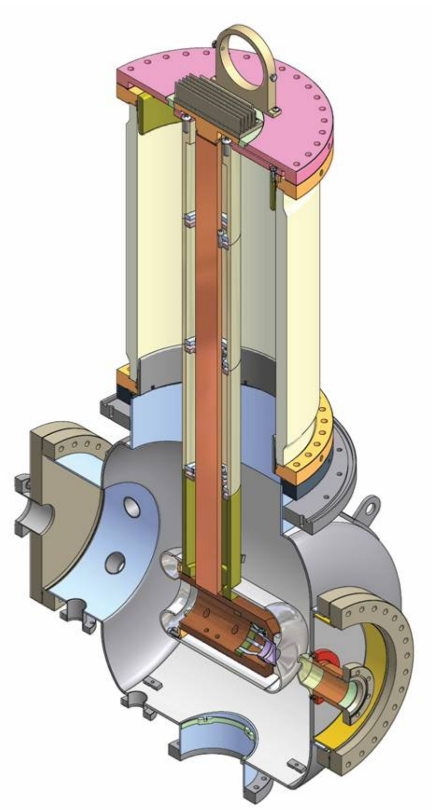


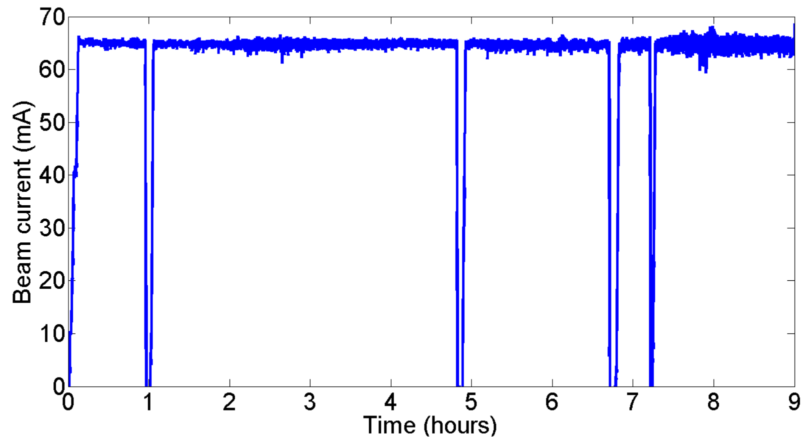
Cornell ERL prototype injector



Cornell Injector Record Current at 4 MeV

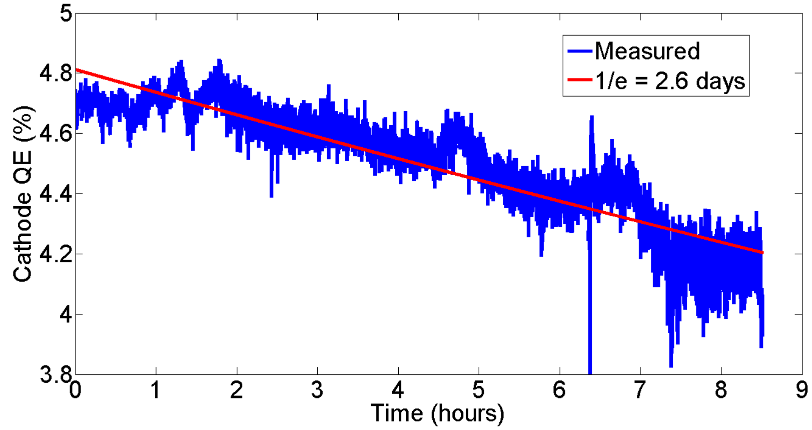
Highest current ever NaK_2Sb Cathode: 75 mA, 65 mA sustained





May 24, 2013

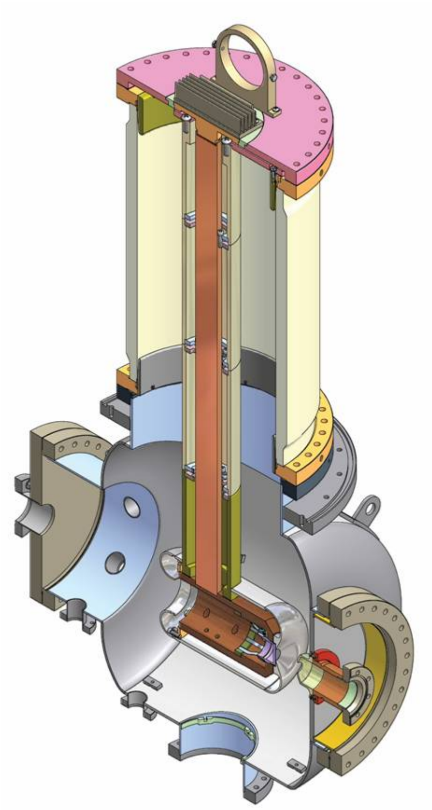
5W laser power,
20W available



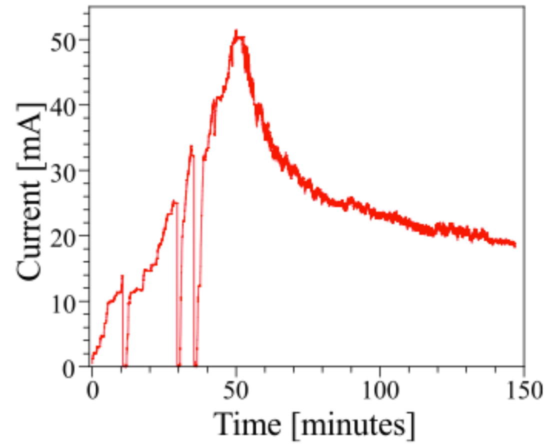
[Dunham et al., Appl. Phys. Lett., 102, 034105 (2013)]

Cornell Injector Record Current at 4 MeV

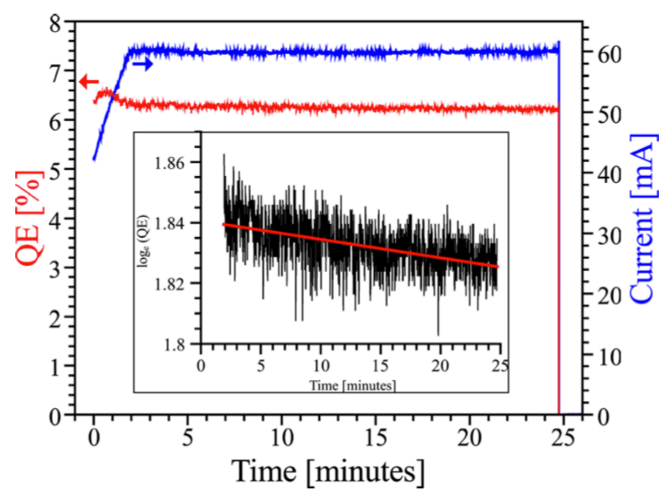
More records:



GaAs: 52 mA



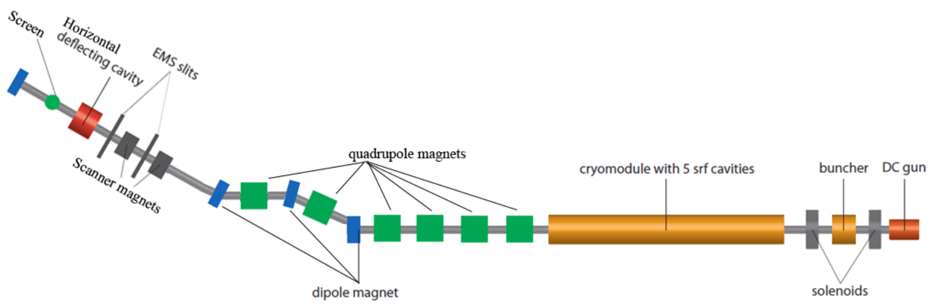
CsK_2Sb: 60 mA



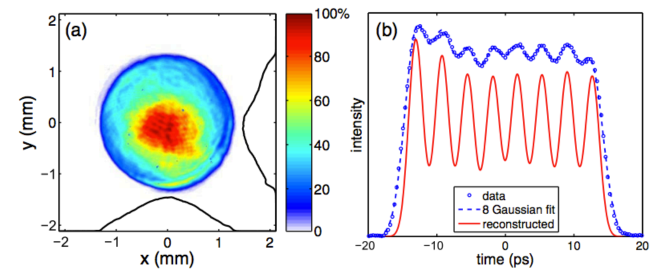
Dunham et al., Appl. Phys. Lett., 102, 034105 (2013)

Injector: emittance preservation through merger

Model



Laser shaping



Understand the fields

Gun

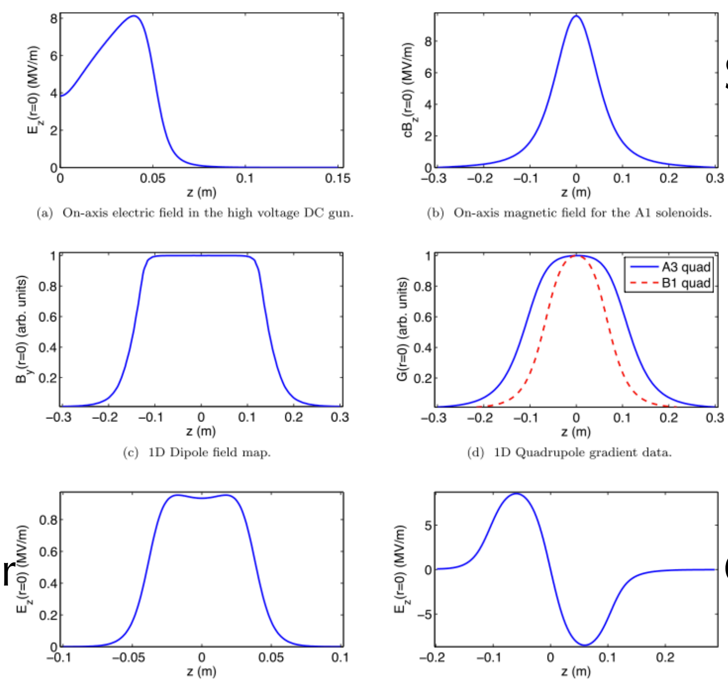
Solenoid

Dipole

Quad.

Buncher

Cavity



(a) On-axis electric field in the high voltage DC gun.

(b) On-axis magnetic field for the A1 solenoids.

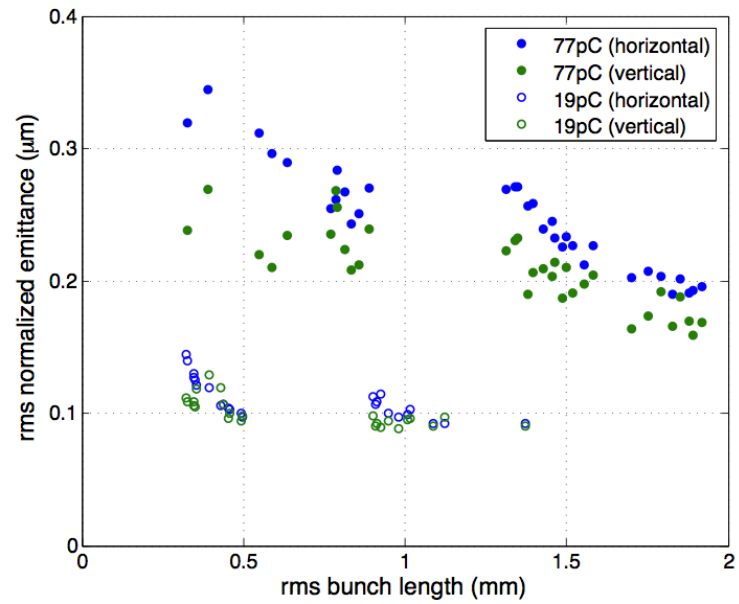
(c) 1D Dipole field map.

(d) 1D Quadrupole gradient data.

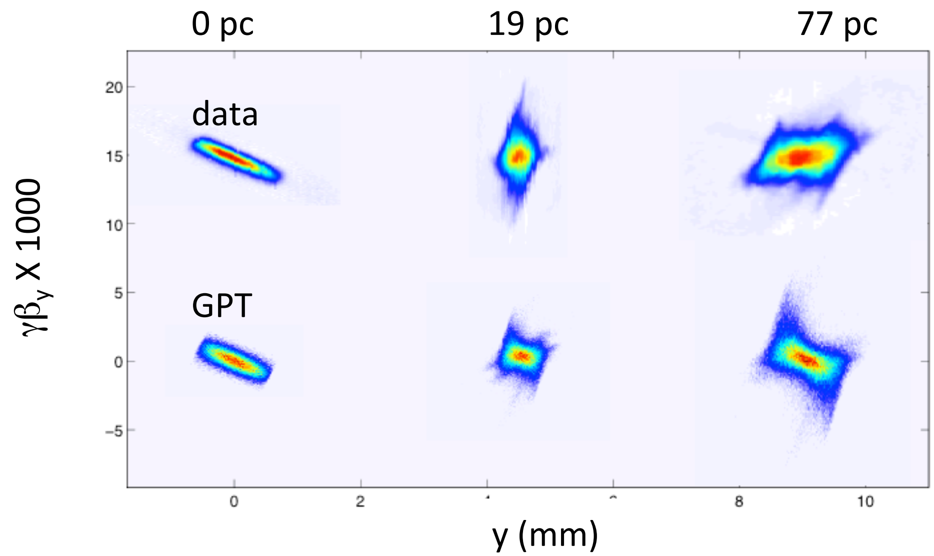
(e) On-axis electric field for the buncher.

(f) On-axis electric field for the SRF cavity.

Optimize



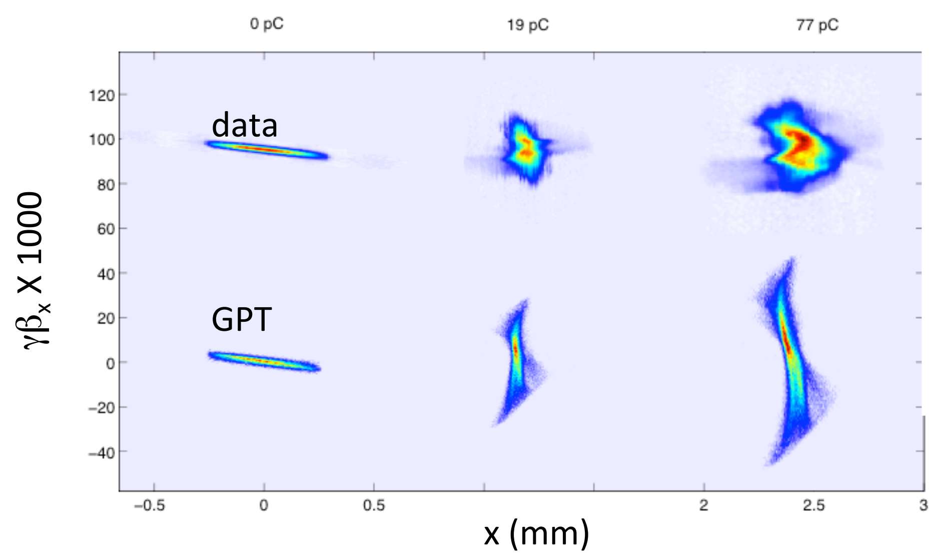
Phase space measurements and simulation



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)

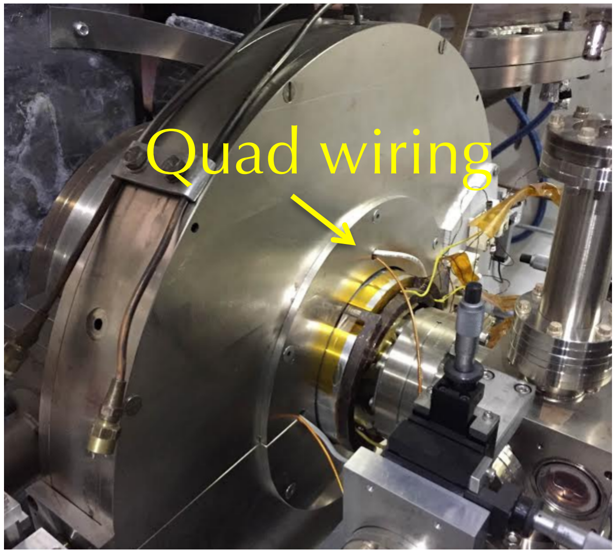


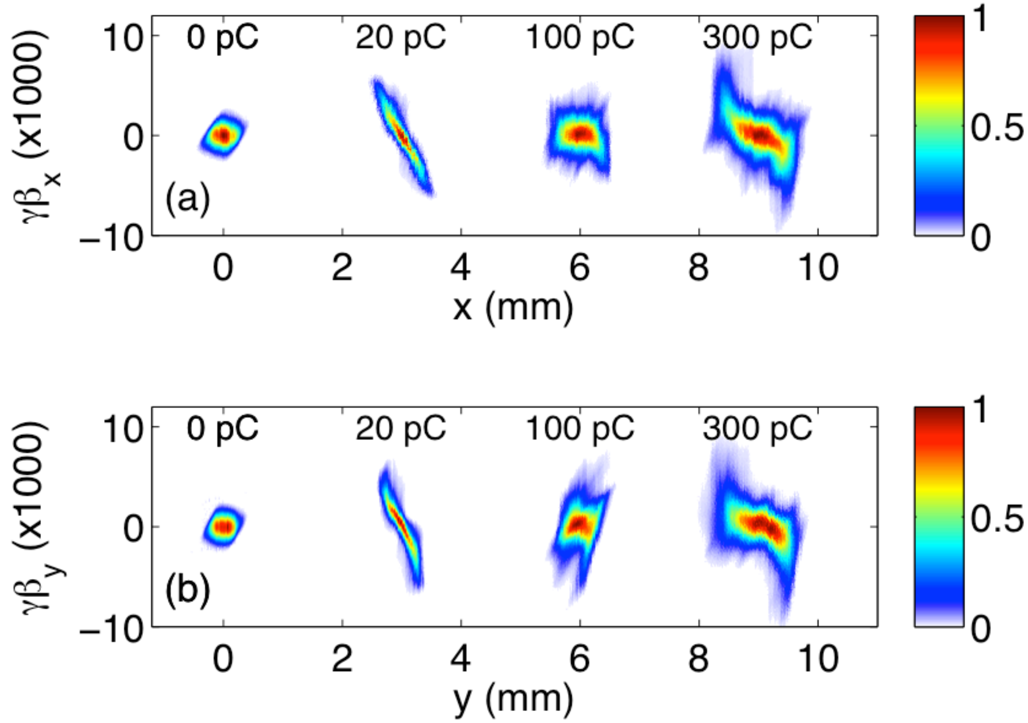
$$(x, p_x)$$

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)

LCLS-II specifications achieved (at 9.5 MeV)



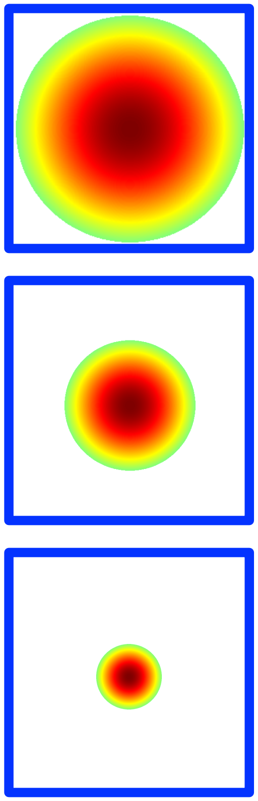


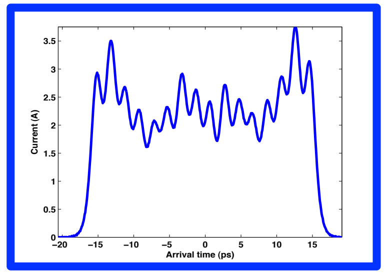
- Wired quad correction on solenoid
- Emittance asymmetry is gone
- Met spec at all charges
- Same SRF settings for all charges

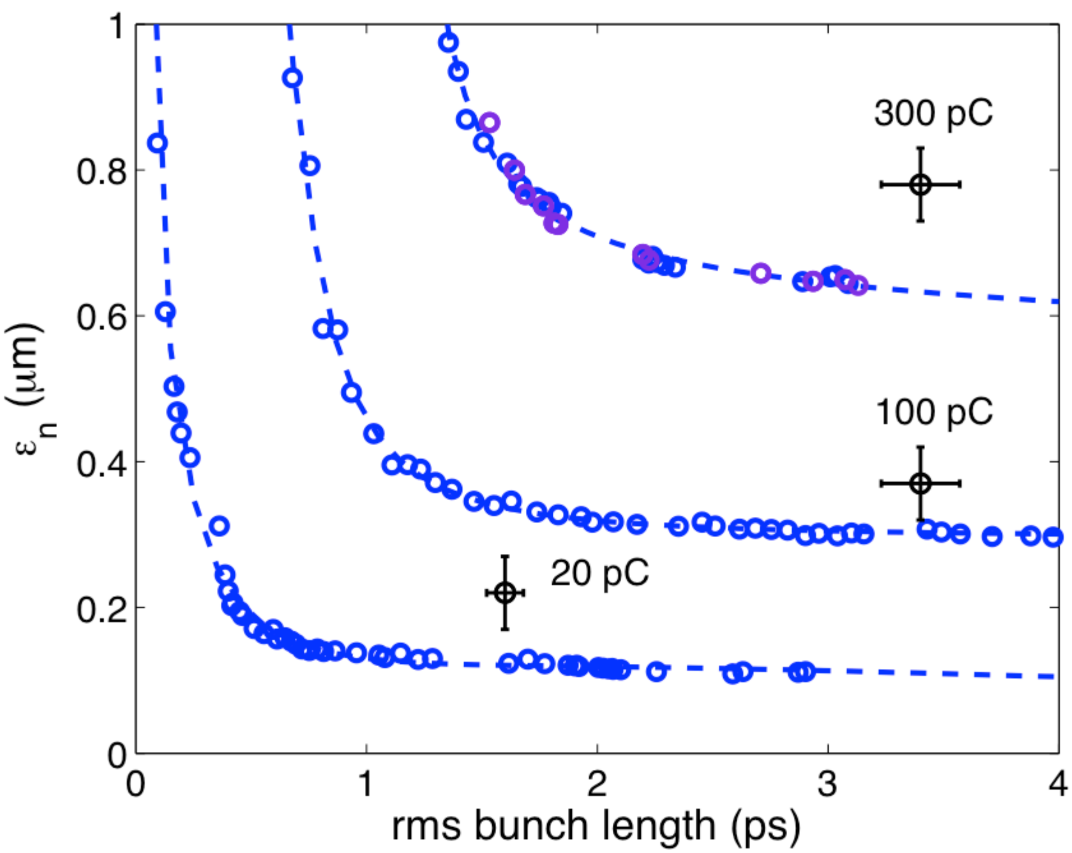
Q (pC)	I_{peak} Target (A)	I_{peak} (A)	ε_n Target (95%) (mm-mrad)	ε_n (95%) (mm-mrad)
20	5	**5**	0.25	**H: 0.18, V: 0.19**
100	10	**11.5**	0.40	**H: 0.32, V: 0.30**
300	30	**32**	0.60	**H: 0.62, V: 0.60**

Best possible emittance

Ideal Shape

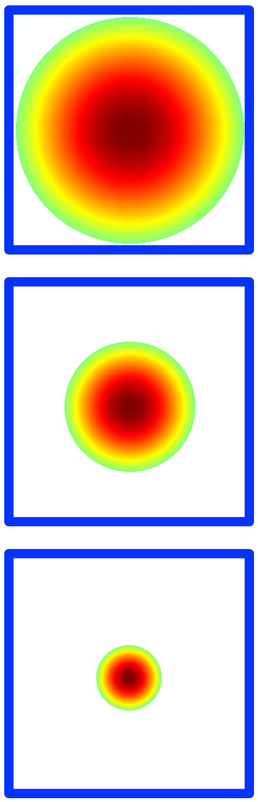


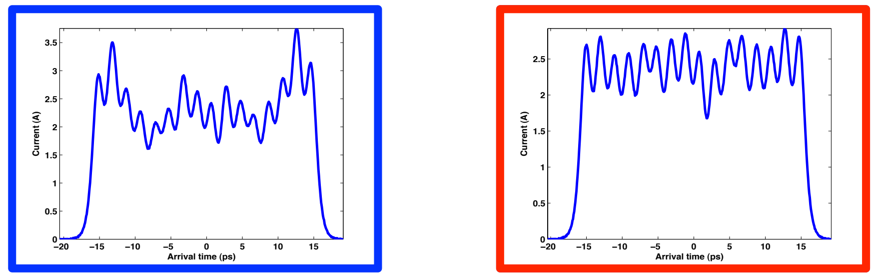


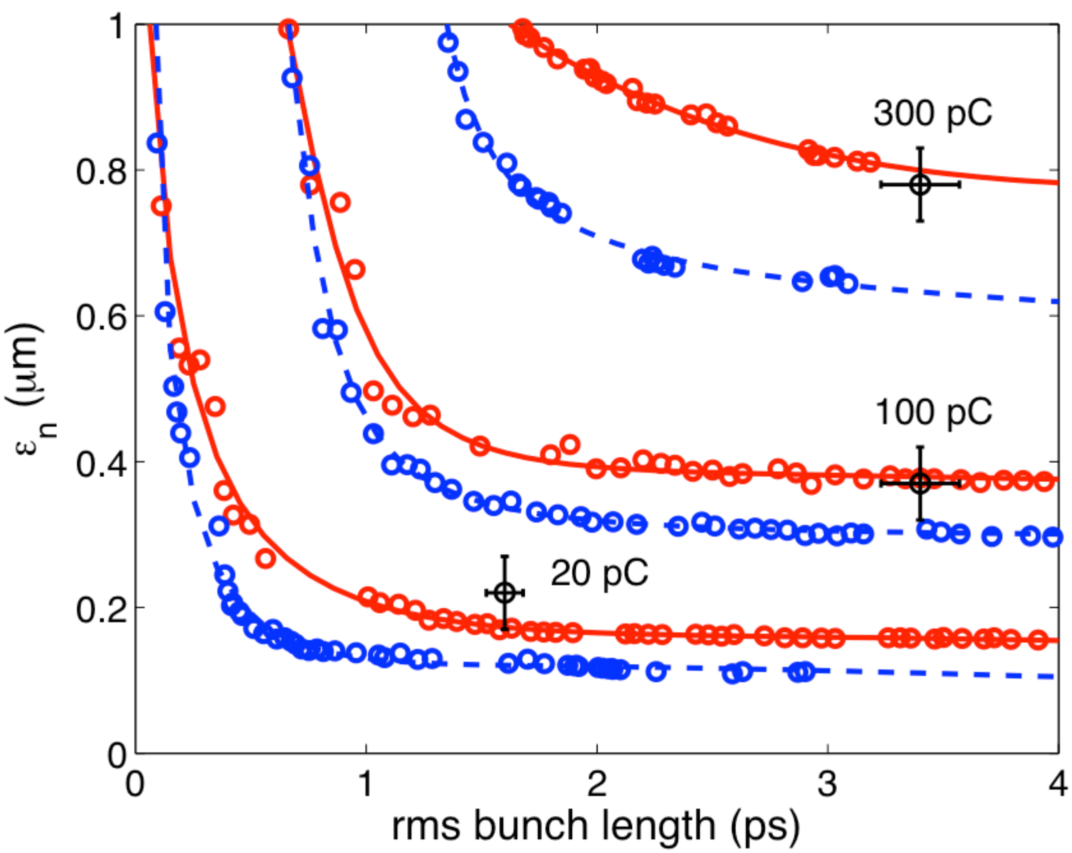


Best possible emittance

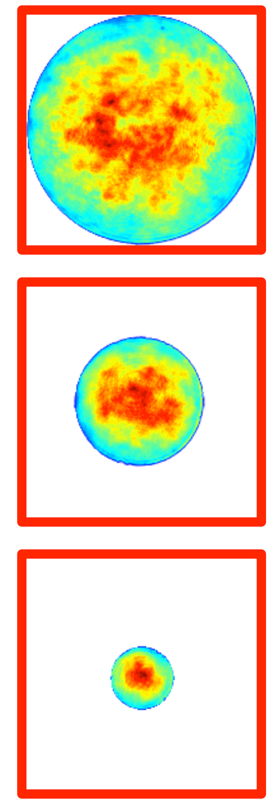
Ideal Shape



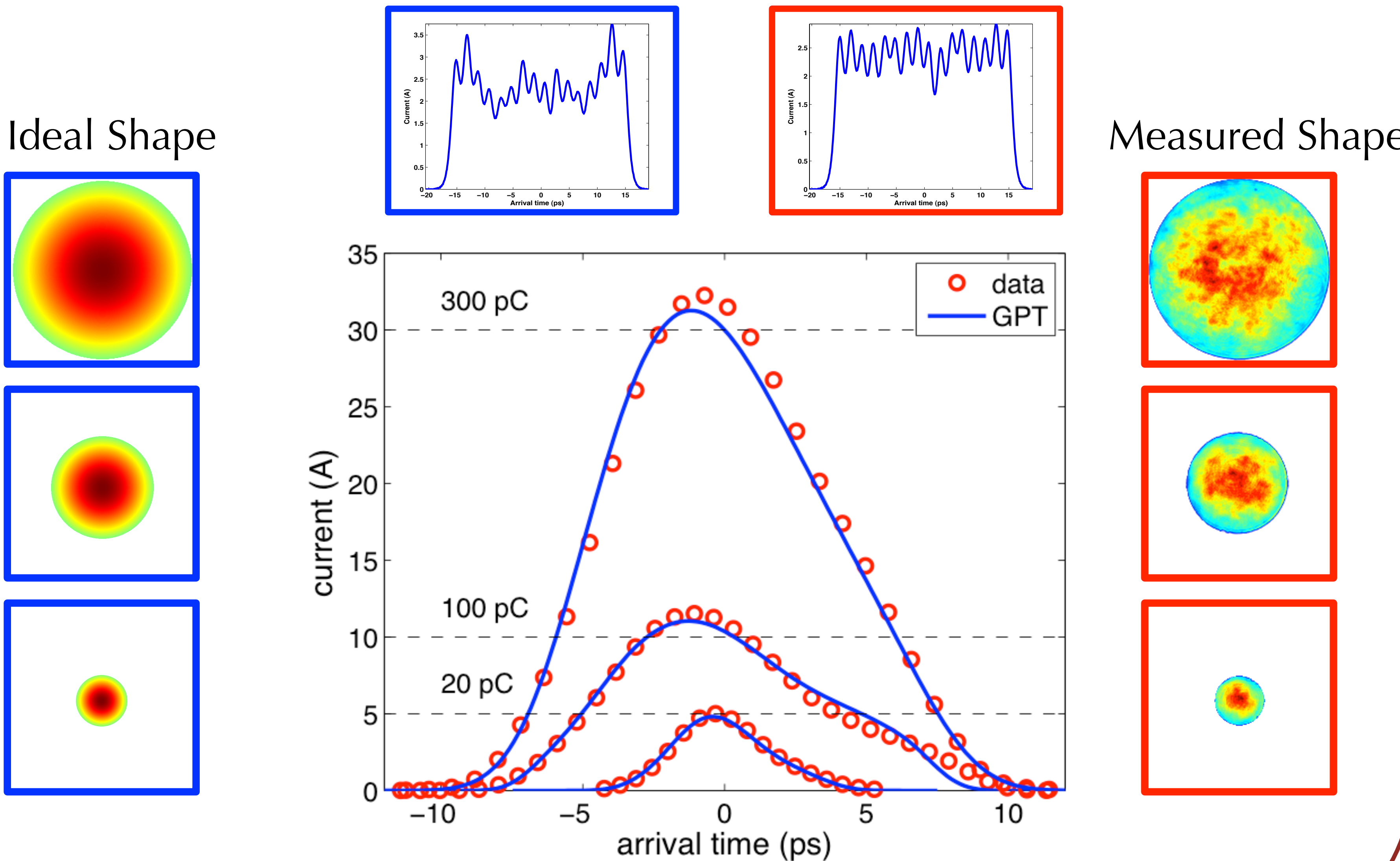




Measured Shape



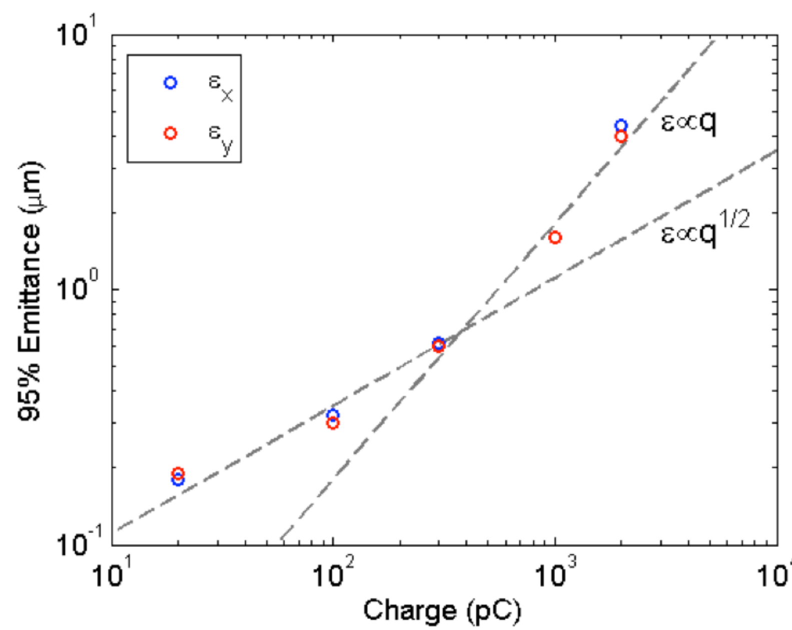
Best possible emittance



High Charges

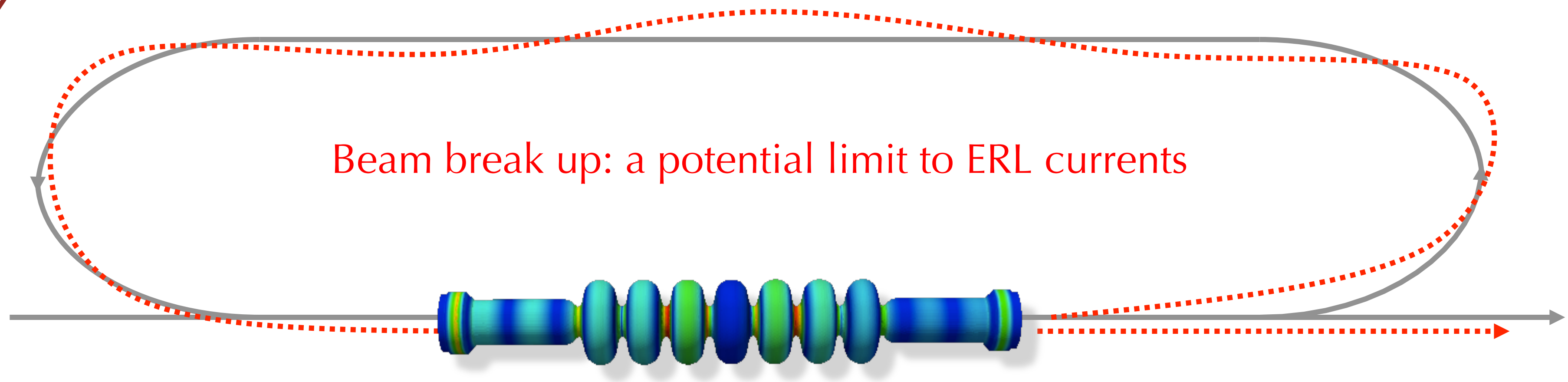
- Below 300 pC, emittance scales roughly as $\sqrt{q}$
- Above 300 pC, emittance scales roughly as q
- Best emittance requires careful control of transverse laser profile
- Need diagnostics to detect unexpected stray fields, and ability to counter them

Q (pC)	**Peak Current (A)**	**Emittance (95%) (mm-mrad)**
20	5	H: 0.18 V: 0.19
100	11.5	H: 0.32 V: 0.30
300	32	H: 0.62 V: 0.60
1000	50	H: 1.6 V: 1.6
2000	56	H: 4.4 V: 4.0



SRF Cavity Design & Testing

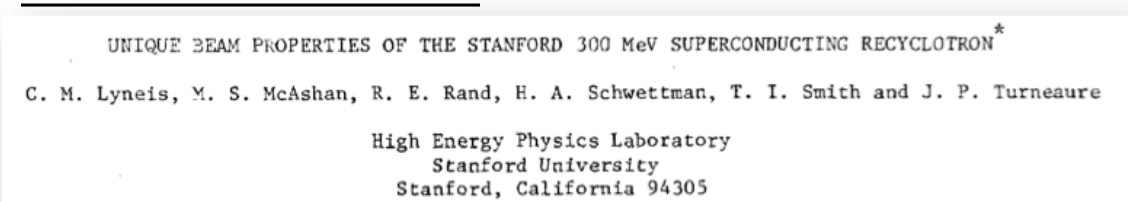
Beam Breakup (BBU) instability



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

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

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

$$x_{\mathrm{pass\ 2}} = T_{12}\, p_{x\ \mathrm{pass\ 1}}$$

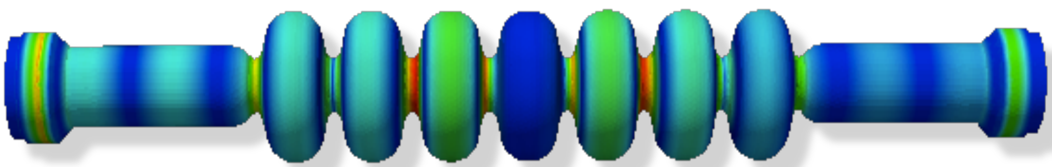
Hoffstaetter & Bazarov, PRST-AB 7, 054401 (2004)

Cavity Design: shape optimization

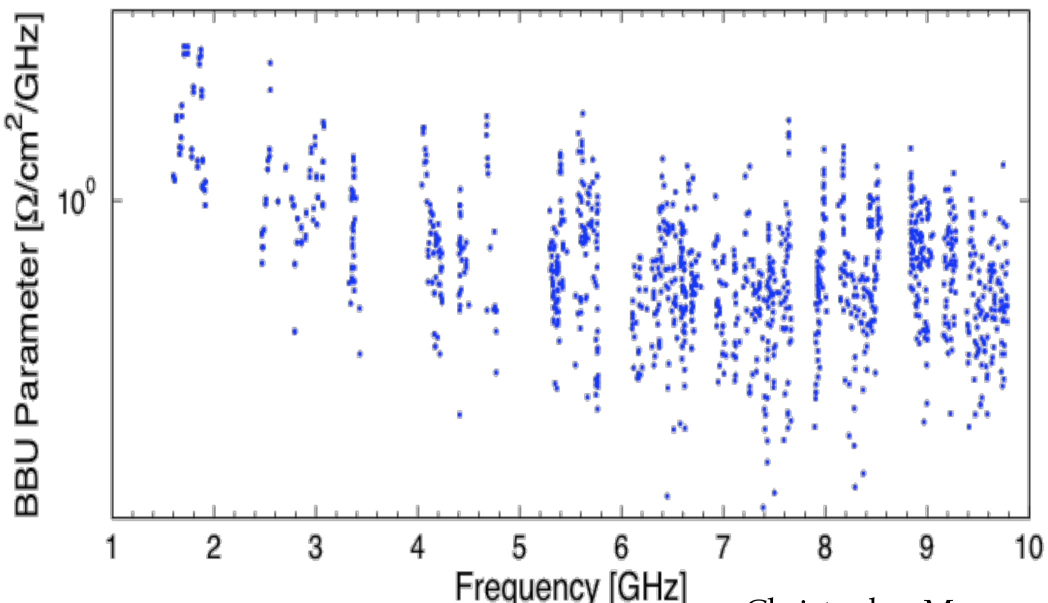
$$I_{\text{threshold}} = -\frac{2c^2}{e(R/Q)_\lambda \, Q_\lambda \, \omega_\lambda} \frac{1}{T_{12} \sin \omega_\lambda t_{\text{return}}}$$

BBU parameter

Optimize the cavity shape with about 20 free parameters



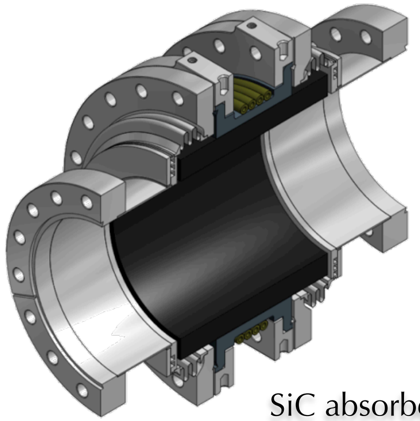
Dipole HOM damping calculated up to 10 GHz
with realistic RF absorbers



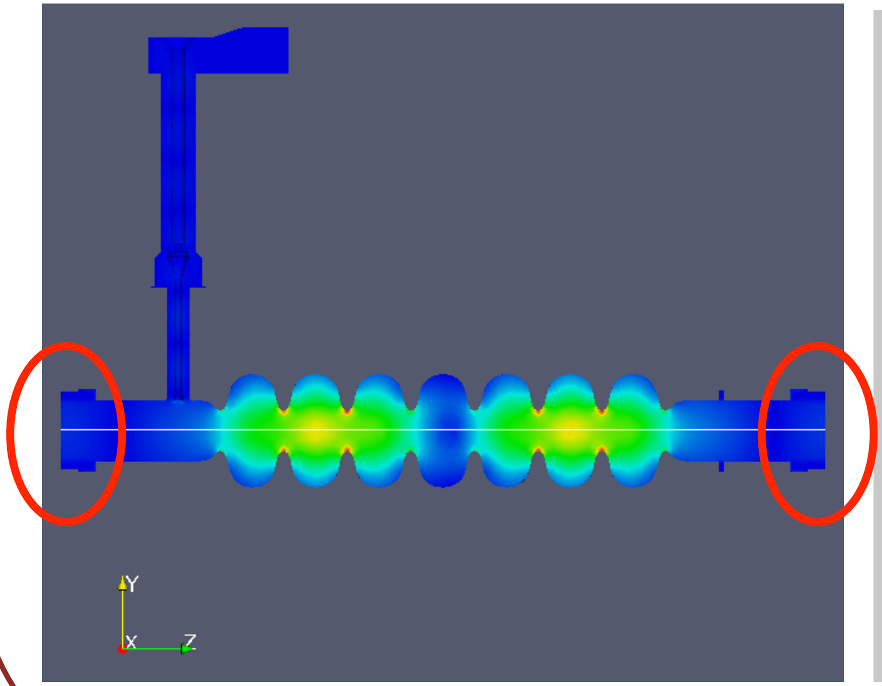
Add HOM Absorbers

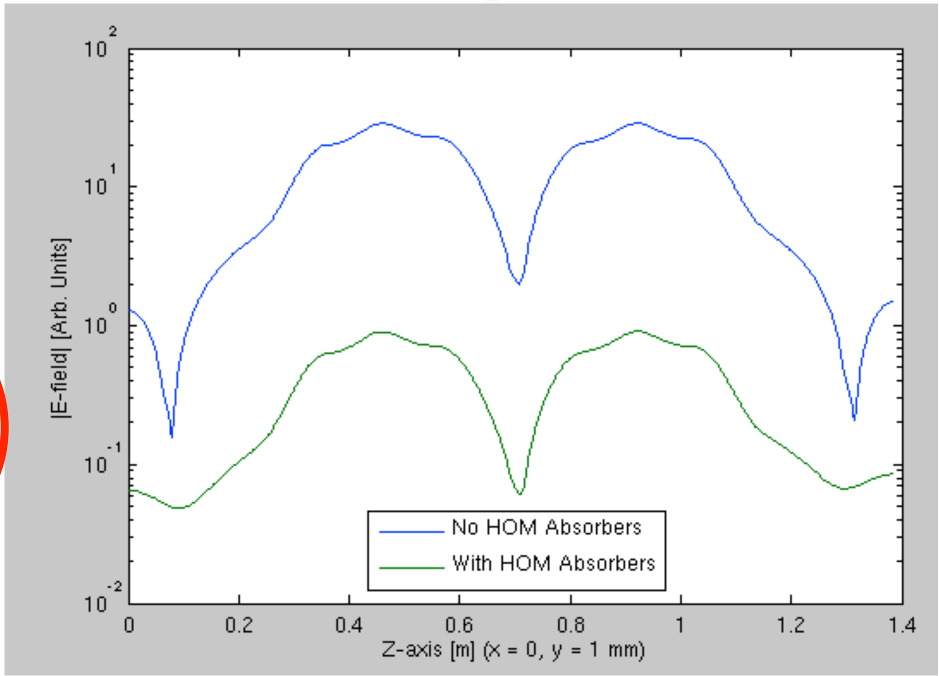
Example HOM at 1612.4604 Hz
Q without absorber: $Q = 5.49 \times 10^6$
Q with absorber: 5.38×10^3

Other methods: HOM antennas
(BNL, KEK)



SiC absorber ring
brazed to metal ring

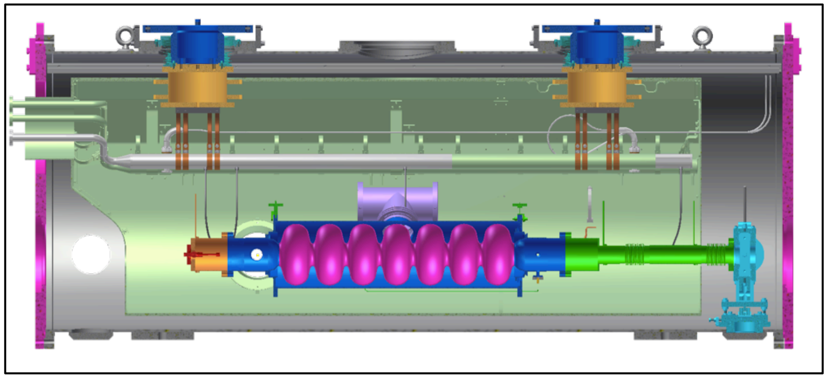




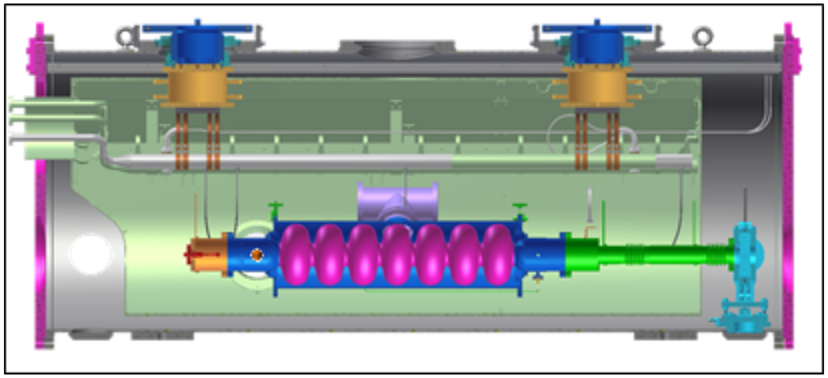
[Courtesy of N. Valles]

Cornell Horizontal Test Cryomodule (HTC)

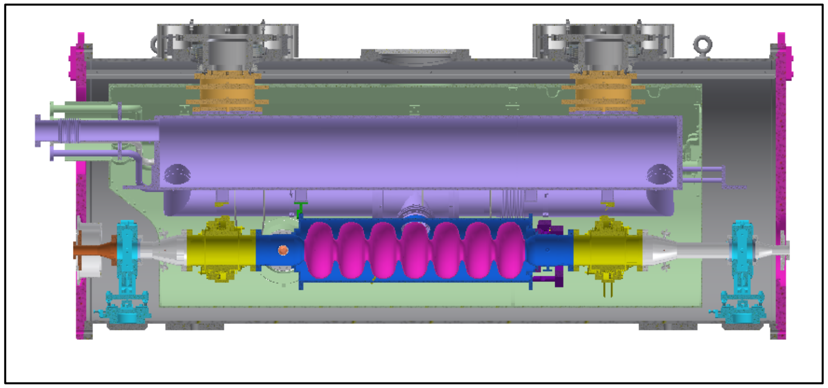
- HTC-1: Follow vertical assembly procedure as closely as possible



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

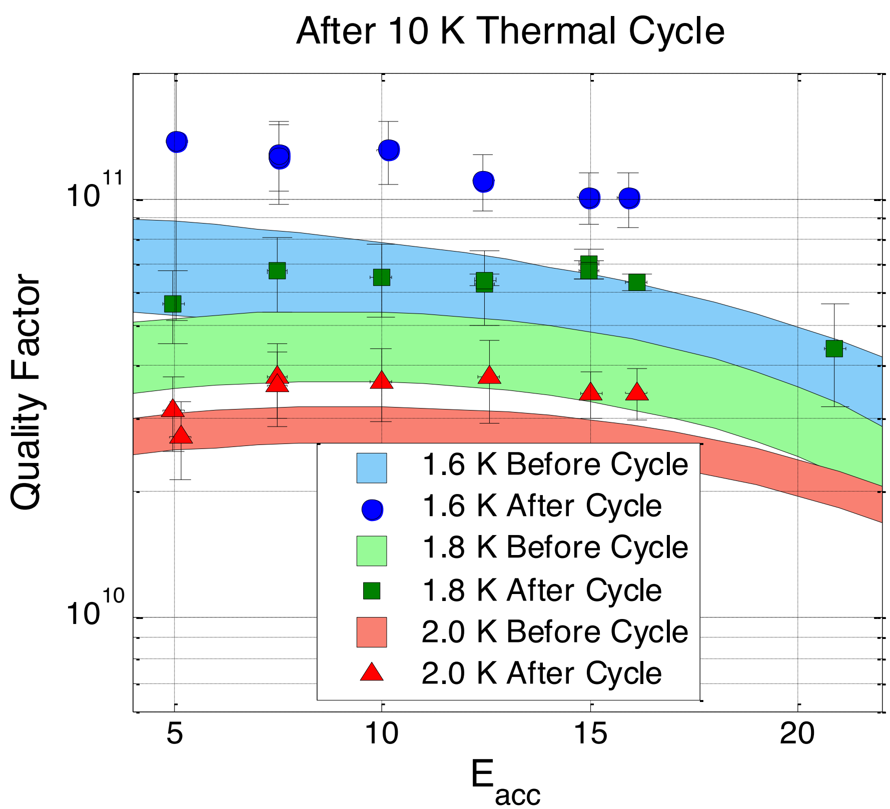


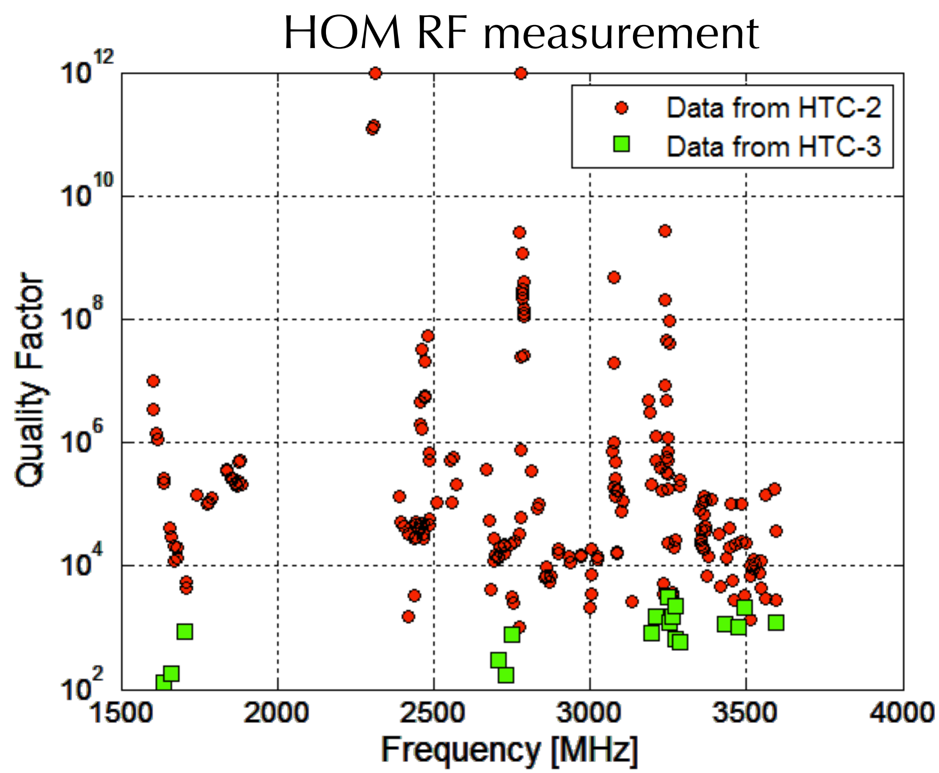
- HTC-3: Full cryomodule assembly-high power RF input coupler and HOM absorbers



HTC-3: Cavity + Coupler + HOM Absorbers

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

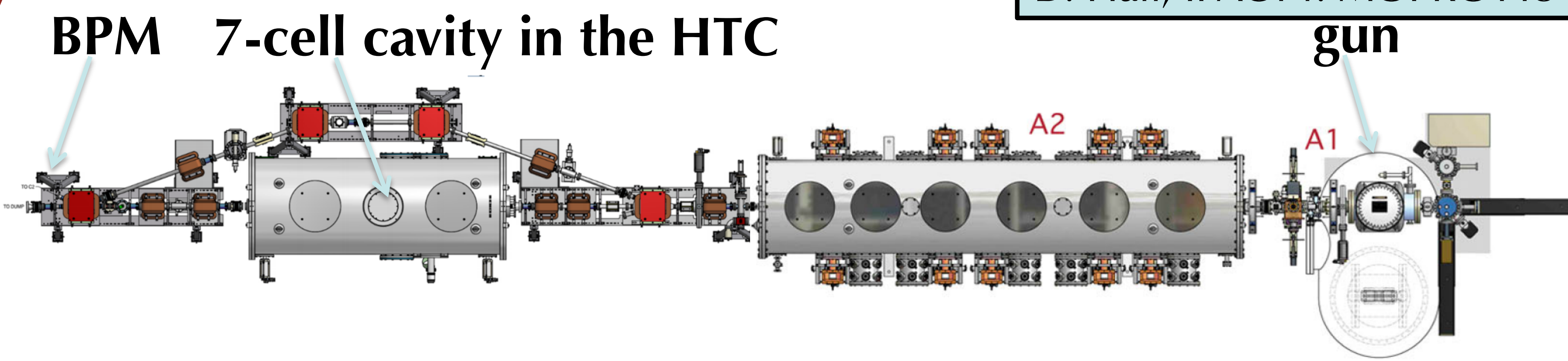


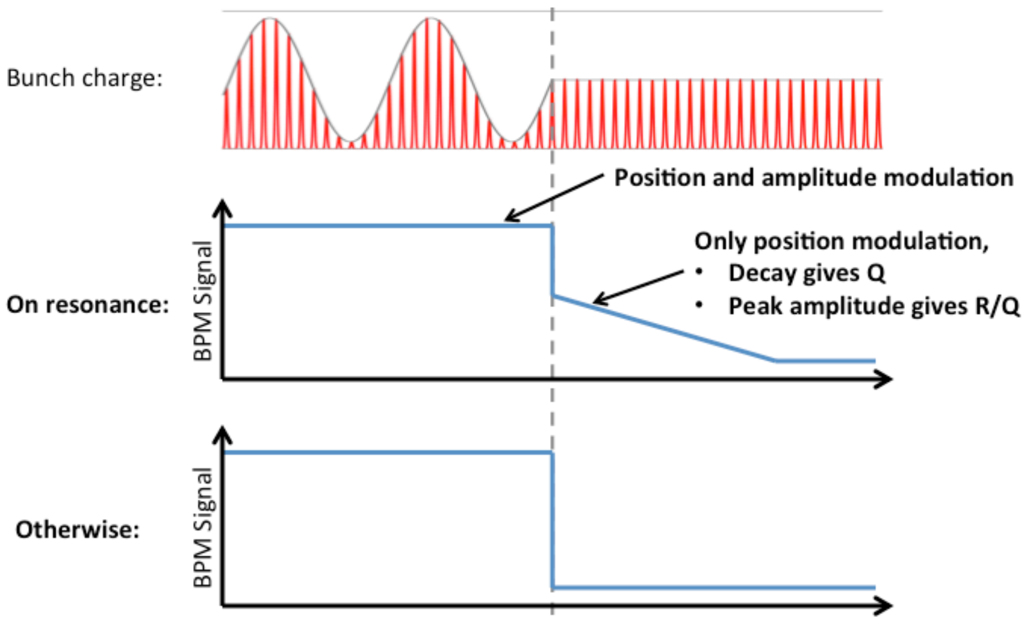


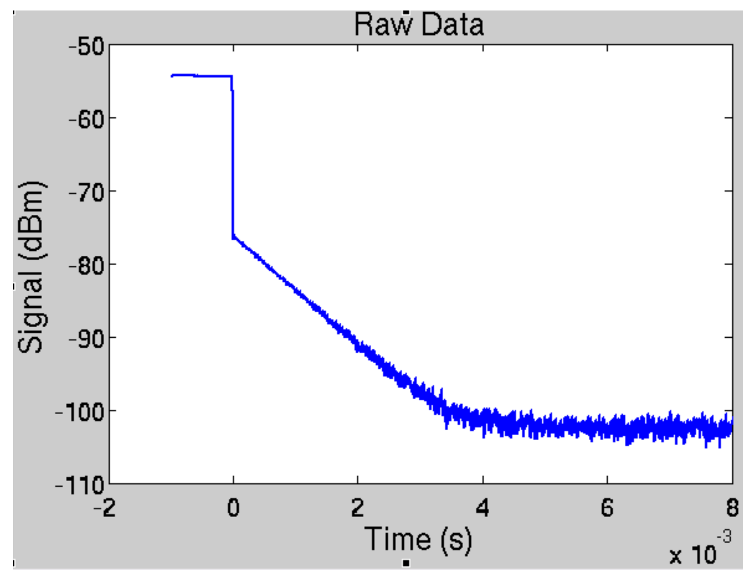
Eichhorn et al., SRF2013

HTC HOM measurement with beam

D. Hall, IPAC14: MOPRO113



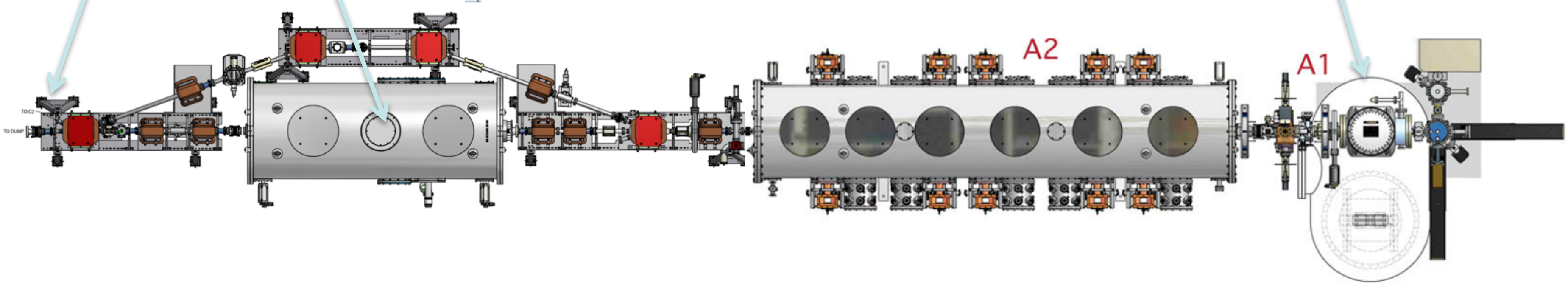




Data was taken December 2013, currently being analyzed…

HTC High current tests with beam (40 mA)

R. Eichhorn IPAC14: THPRI111

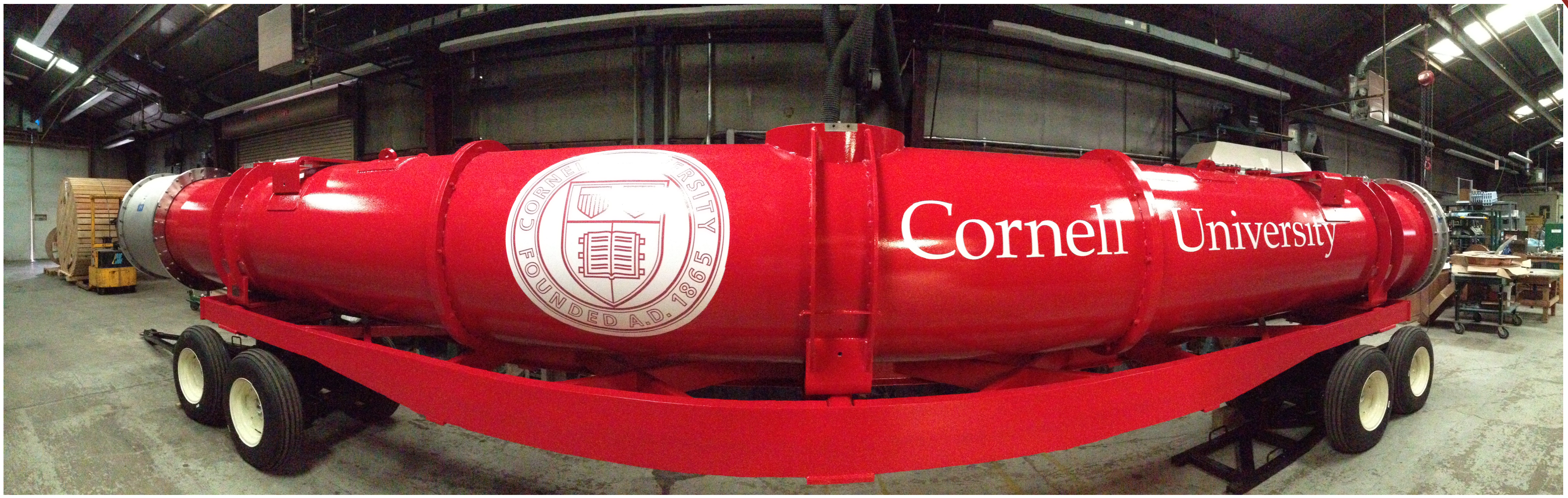


Current, bunch length	ΔT (beam pipe behind Abs.) coated/uncoated	ΔT (80K gas temp) coated/uncoated	ΔT (80K absorber temp) coated/uncoated	ΔT (5K flange next to cavity) coated	ΔT, beam pipe to cavity coated/uncoated
25 mA, 3.0 ps	0.075/0.075	1.14/0.82	1.02/0.975	0.007	0.076/-.005
40 mA, 3.4 ps	0.2475/0.335	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

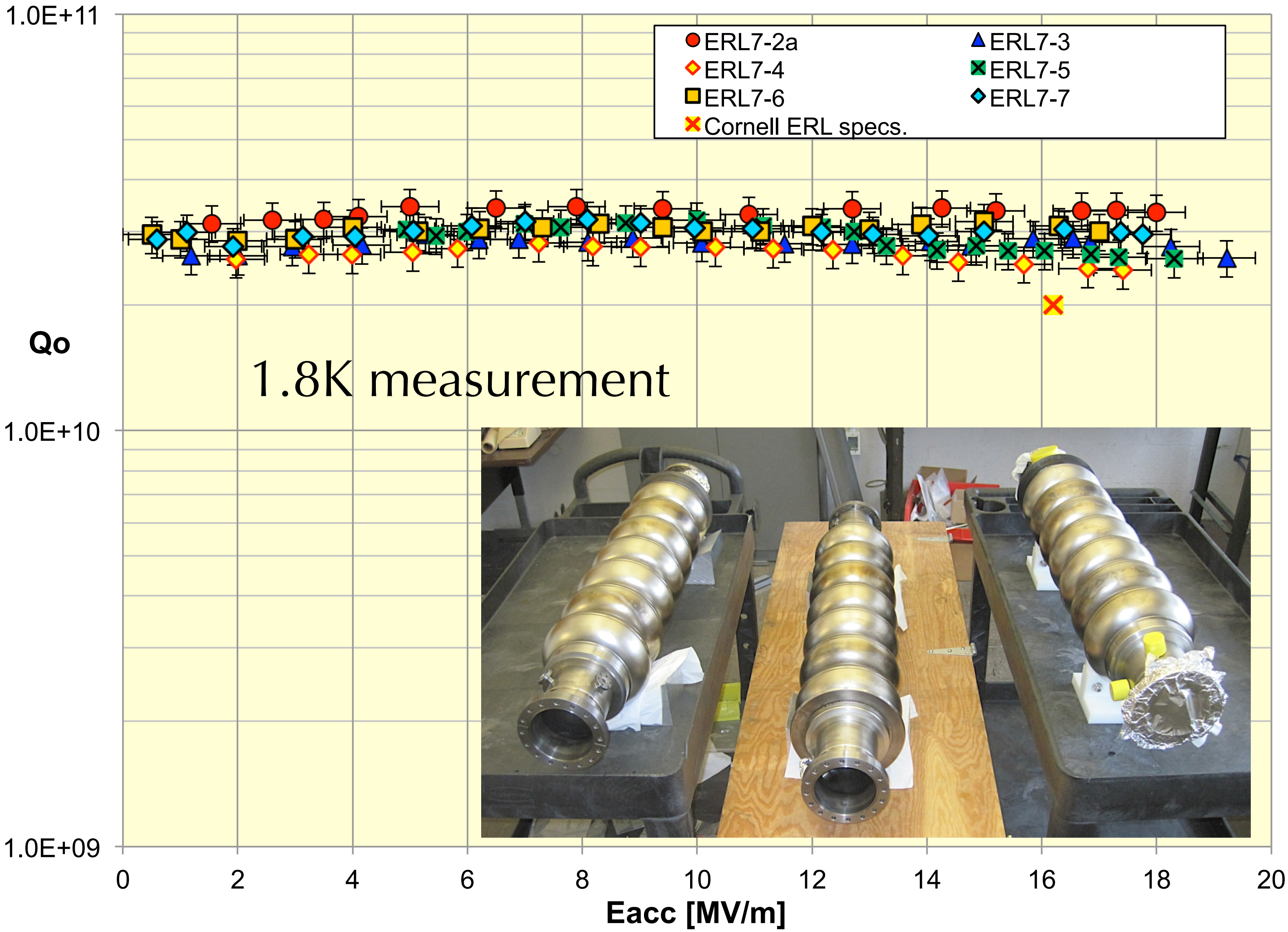
- No charge-up of the HOM ceramics observed
- HOM heating was less than expected

Prototype Main Linac Cryomodule

Main Linac Cryomodule (MLC) Prototype



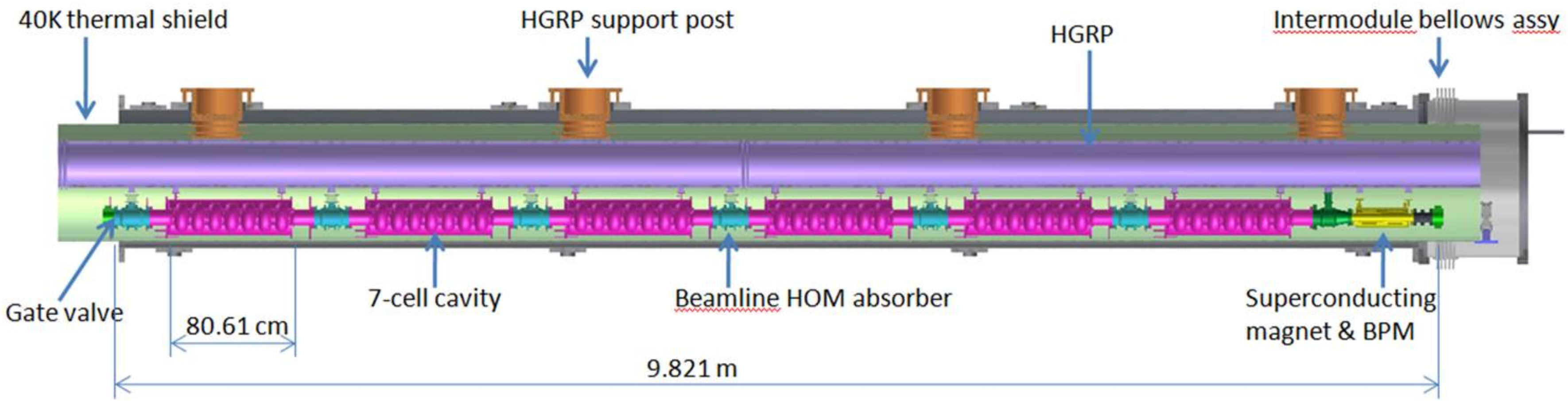
Cornell Main Cryomodule cavity tests (Vertical)



Eichhorn et al., IPAC2014

Main Linac Cryomodule (MLC) Prototype

Cornell ERL Main Linac Cryomodule (MLC) Prototype

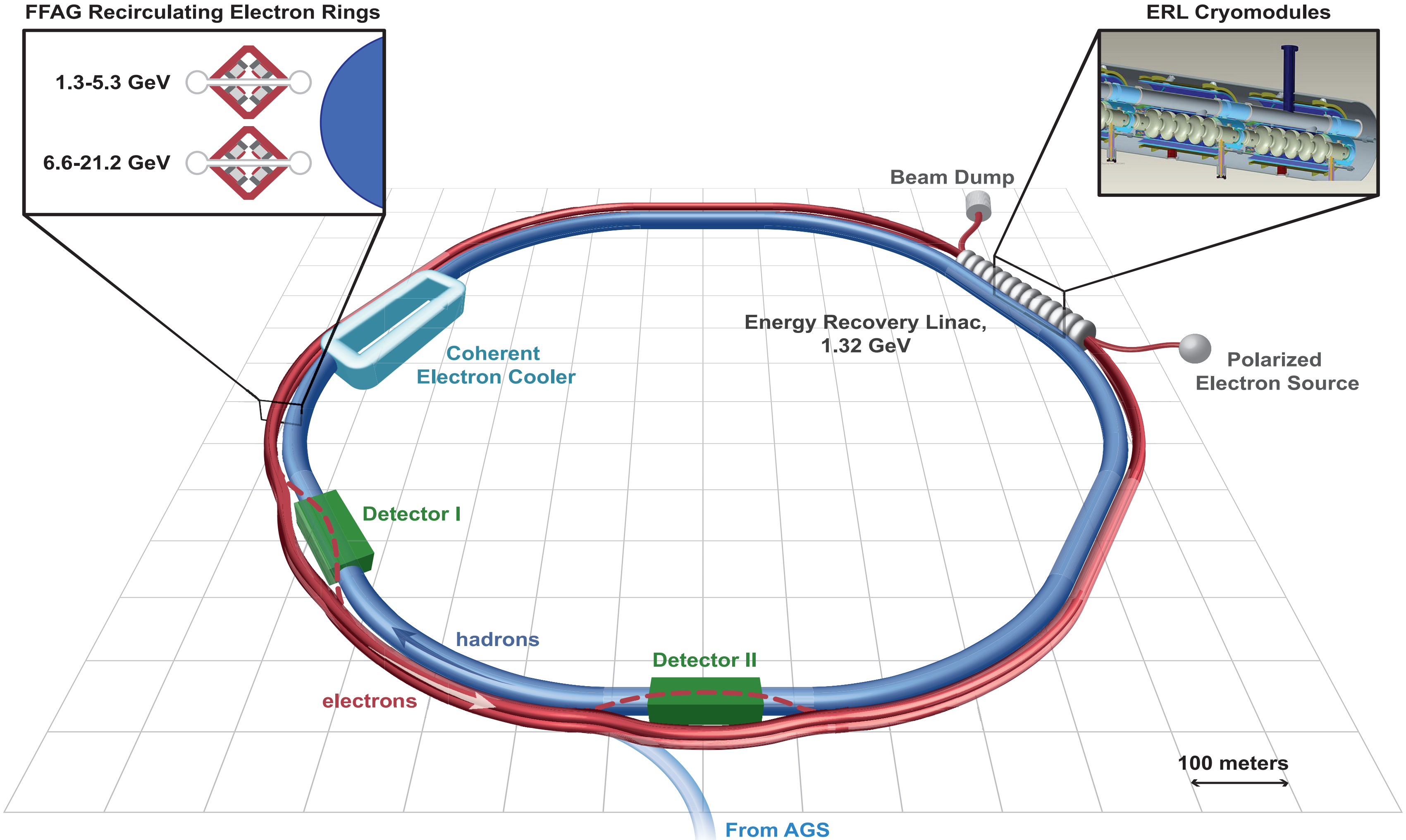


- Completed fabrication and RF test of 6 main linac SRF cavities
  - Statistics of high Q_0 cavity preparation
- Fabrication of full ERL main linac prototype cryomodule
  - 2013: Fabrication of input couplers, tuners, beamline HOM absorbers, cryomodule components
  - January 2014: Started string assembly
  - June 2014: Start cold mass assembly June
  - November 2014: completion
- Testing starting this summer
  - July (Mid) 2015: First cooldown
  - August 2015: RF tests (Q vs. E)

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

Cornell-BNL ERL-FFAG Test Accelerator

Collaboration with BNL for eRHIC



arxiv.org/abs/1409.1633

Cβ White Paper

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The Cornell-BNL FFAG-ERL Test Accelerator

White Paper

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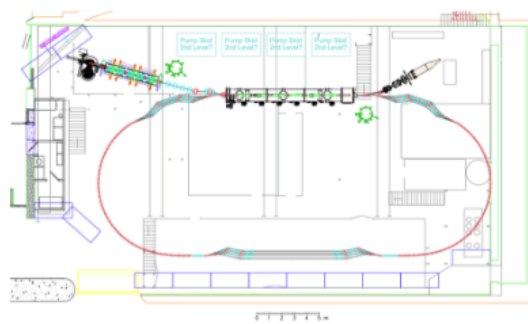
Brookhaven National Laboratory, Upton NY



December 16, 2014

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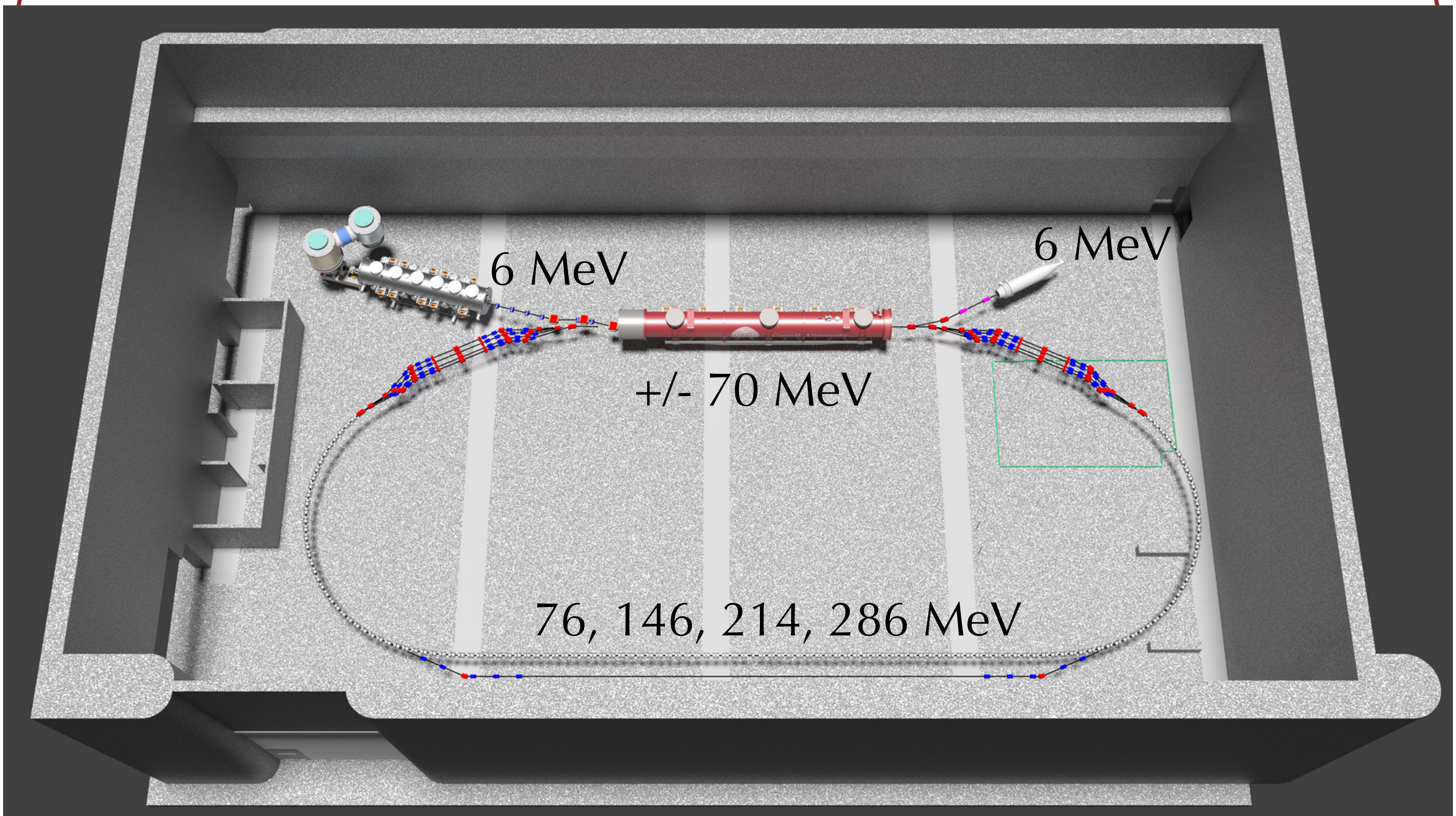
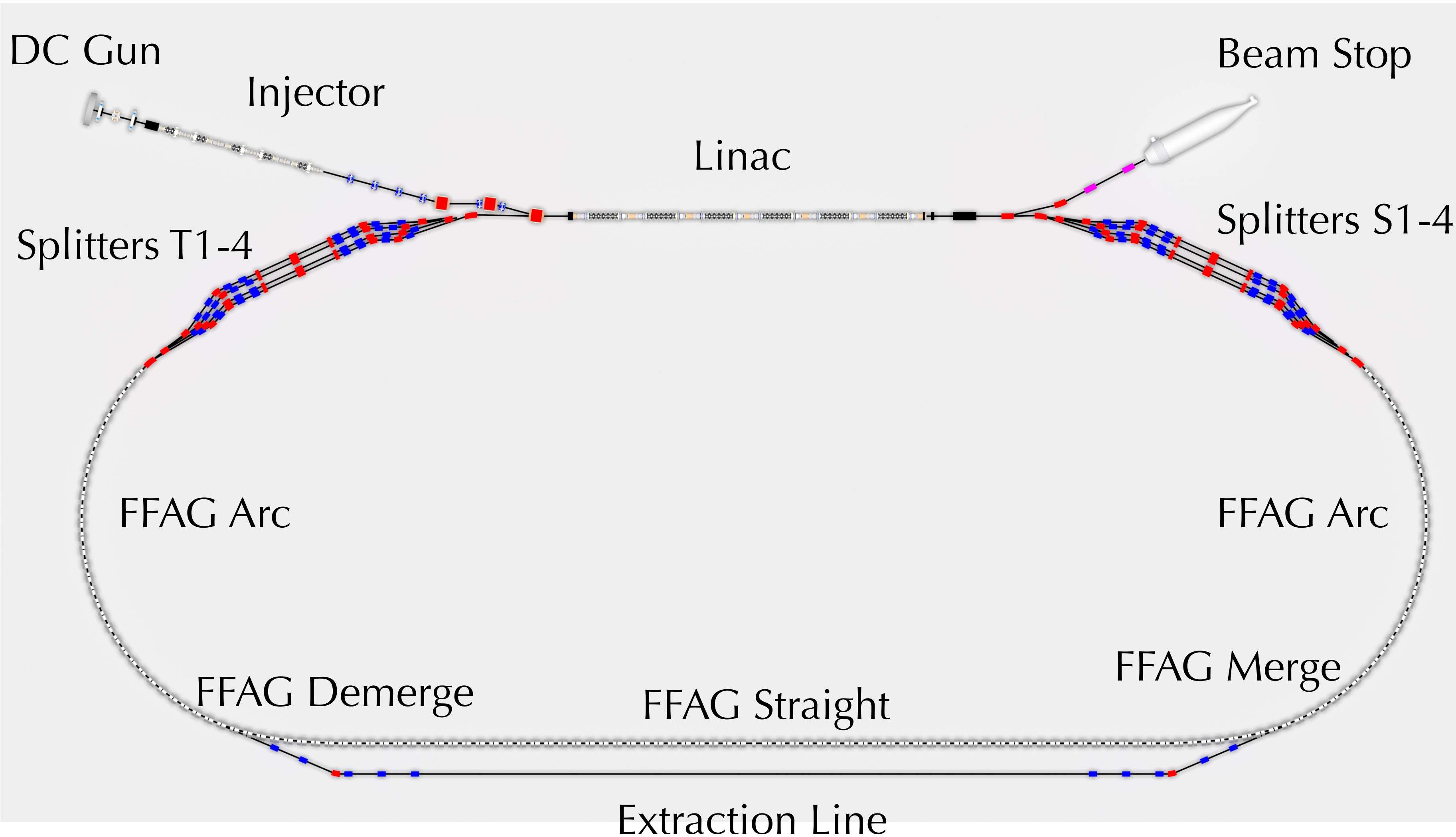
arxiv.org/abs/1504.00588

Cβ: Cornell-BNL ERL-FFAG Test Accelerator

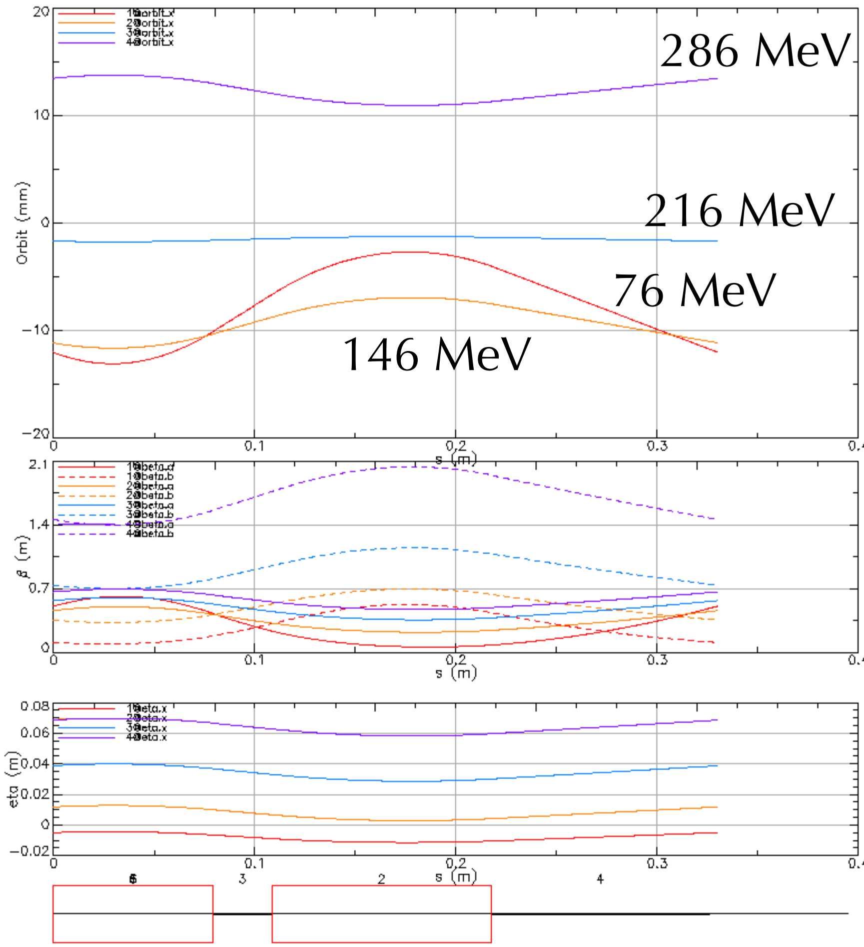


Layout


DC Gun
Injector
Linac
Beam Stop
Splitters T1-4
Splitters S1-4
FFAG Arc
FFAG Arc
FFAG Merge
FFAG Demerge
FFAG Straight
Extraction Line

FFAG Optics

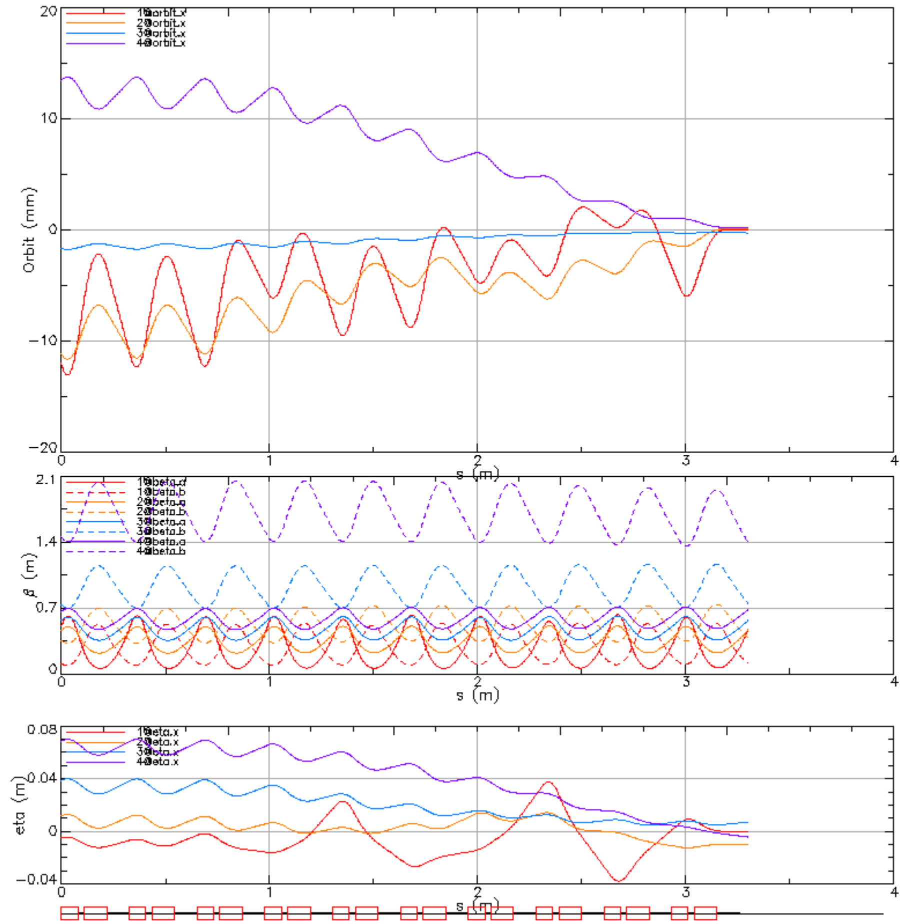
Cell

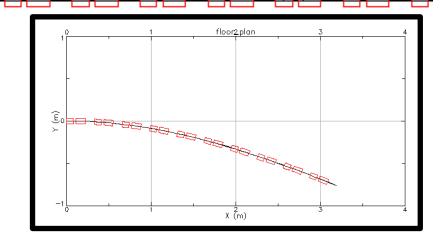


3.6 deg

8 cm	11 cm
42.5 T/m	-27.5 T/m
-0.104 T	0.5044 T

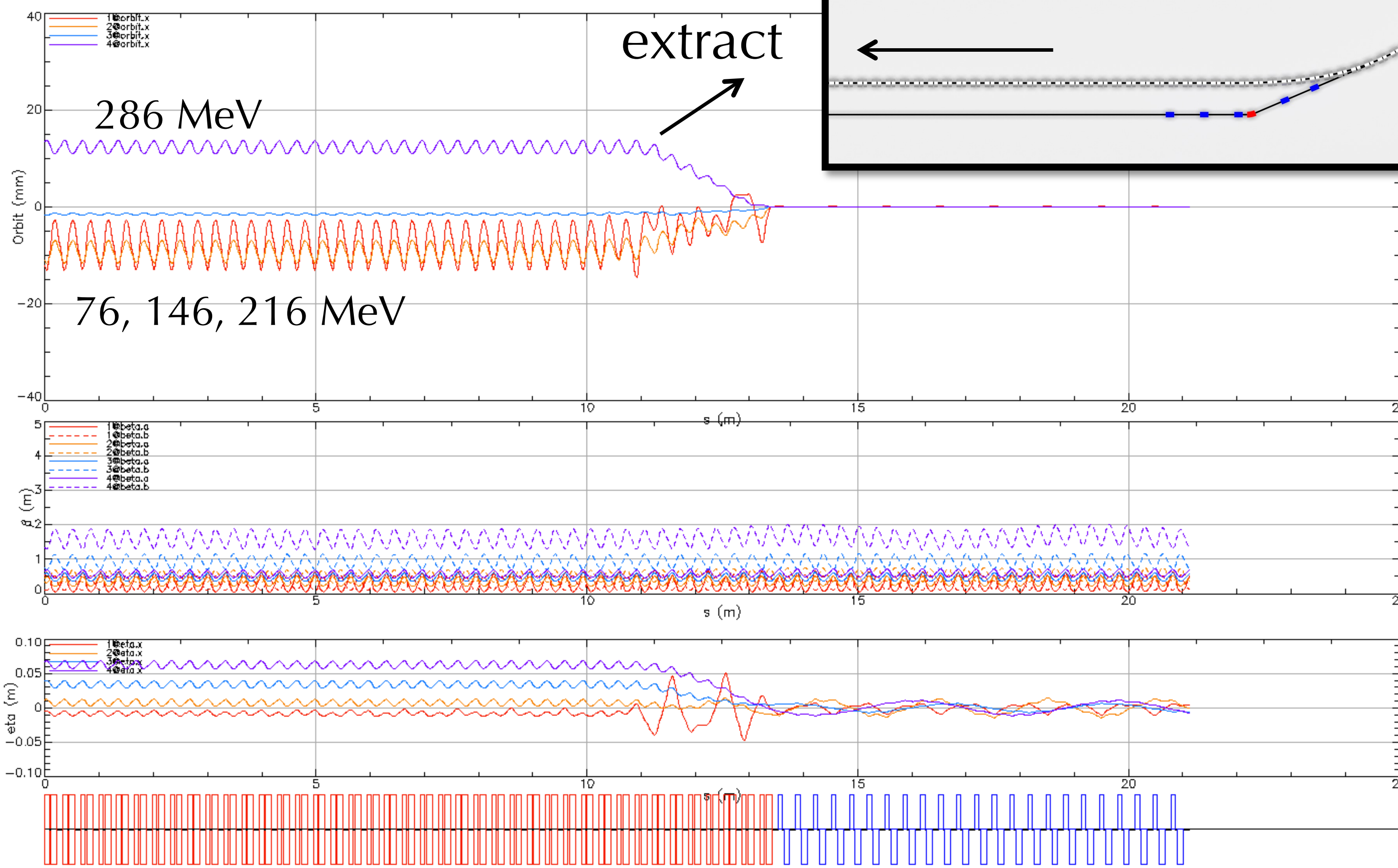
Merge (10 cells)

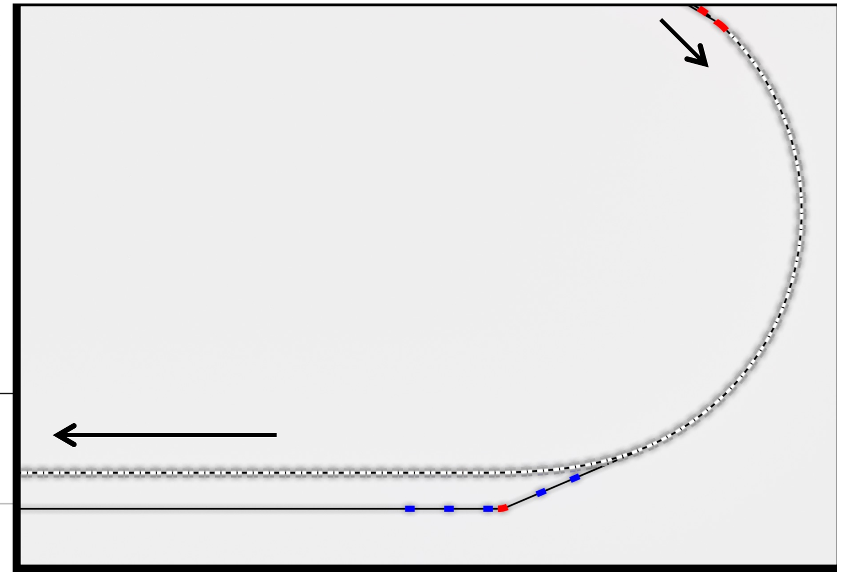




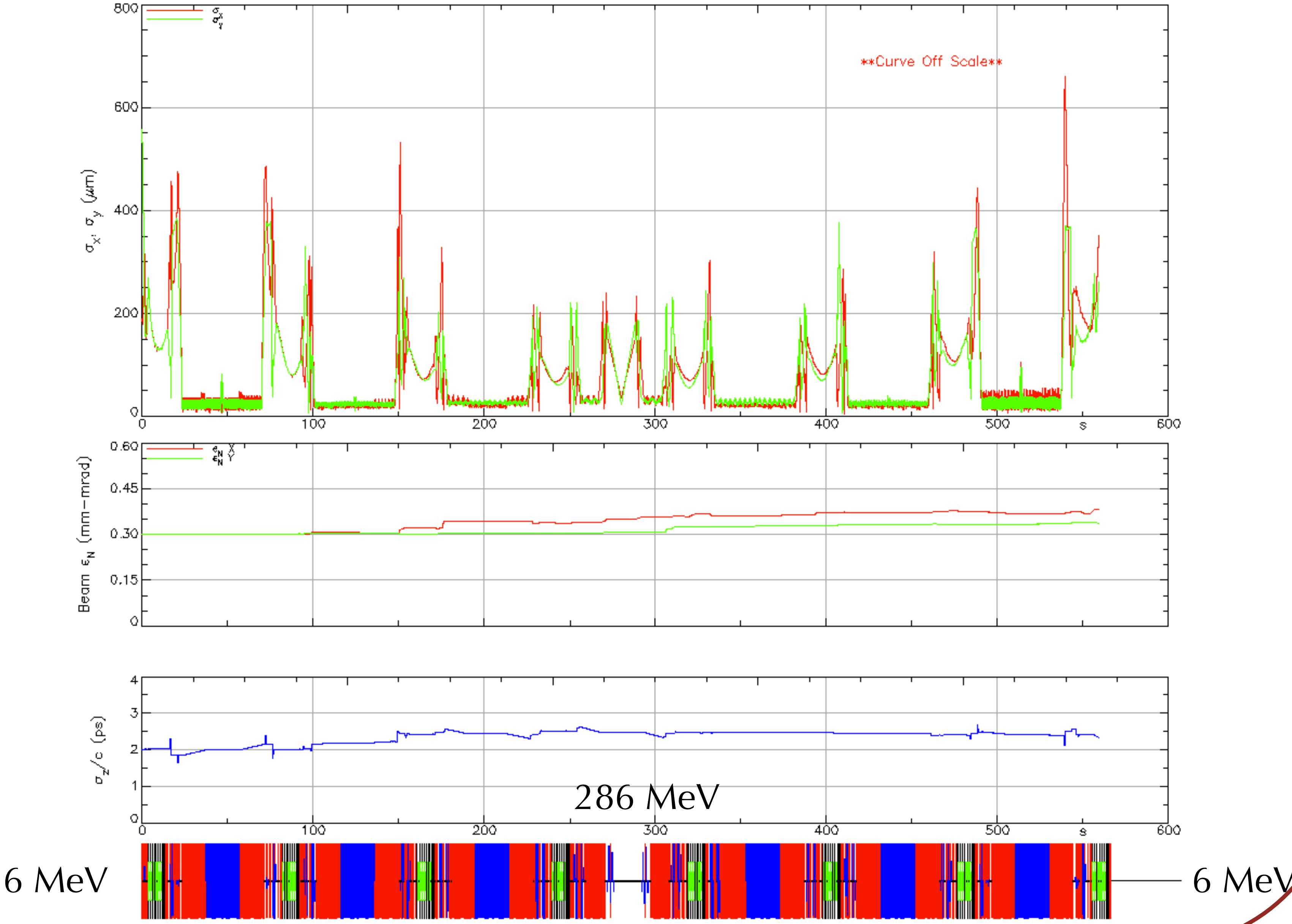
22 deg

FFAG Arc, Merge, Straight





Complete optics & bunch tracking



Cβ: Cornell-BNL ERL-FFAG Test Accelerator

Will be the first accelerator with:

- 4-pass SRF ERL
- ERL using FFAG recirculating arcs
- FFAG with momentum range of 4x
- Adiabatic transition from curved to straight FFAG
- Permanent magnets (PMs) in an FFAG
- PMs in ERL return arc

It will utilize existing components at Cornell:

- DC electron gun
- low-emittance and high-current injector linac
- ERL-merger
- 10 m long CW SRF cryomodule
- 600 kW beam stop

Cβ: Cornell-BNL ERL-FFAG Test Accelerator

Multi-turn ERL risk items:

- BBU limits
- HOM damping
- LLRF controls
- ERL startup from a low-power beam
- Precision, reproducibility, alignment of FFAG magnets
- Stability in a radiation environment of permanent magnets
- Matching and correction of simultaneous orbits
- Matching and correction of simultaneous optics
- Path length control for all orbits
- Emittance control
- Longitudinal phase space control

Important eRHIC-ERL prototyping results can be available before 2018

Summary

Cornell has been funded for ERL R&D since 2005, and has designed and built:

Prototype high-power ERL injector & beam stop

- Record current peak 75 mA, and 65 mA sustained for 8 hours
- Emittance through merger meets Cornell ERL specifications
- Emittance straight meets LCLS-II specifications

Horizontal Test Cryomodule (HTC)

- First ERL cavity achieved Q_0 of $6x10^{10}$ @ 16 MV/m, 1.8K
- (with couplers and HOM absorbers) (3 times spec.)
- Tested with 40 mA in the injector

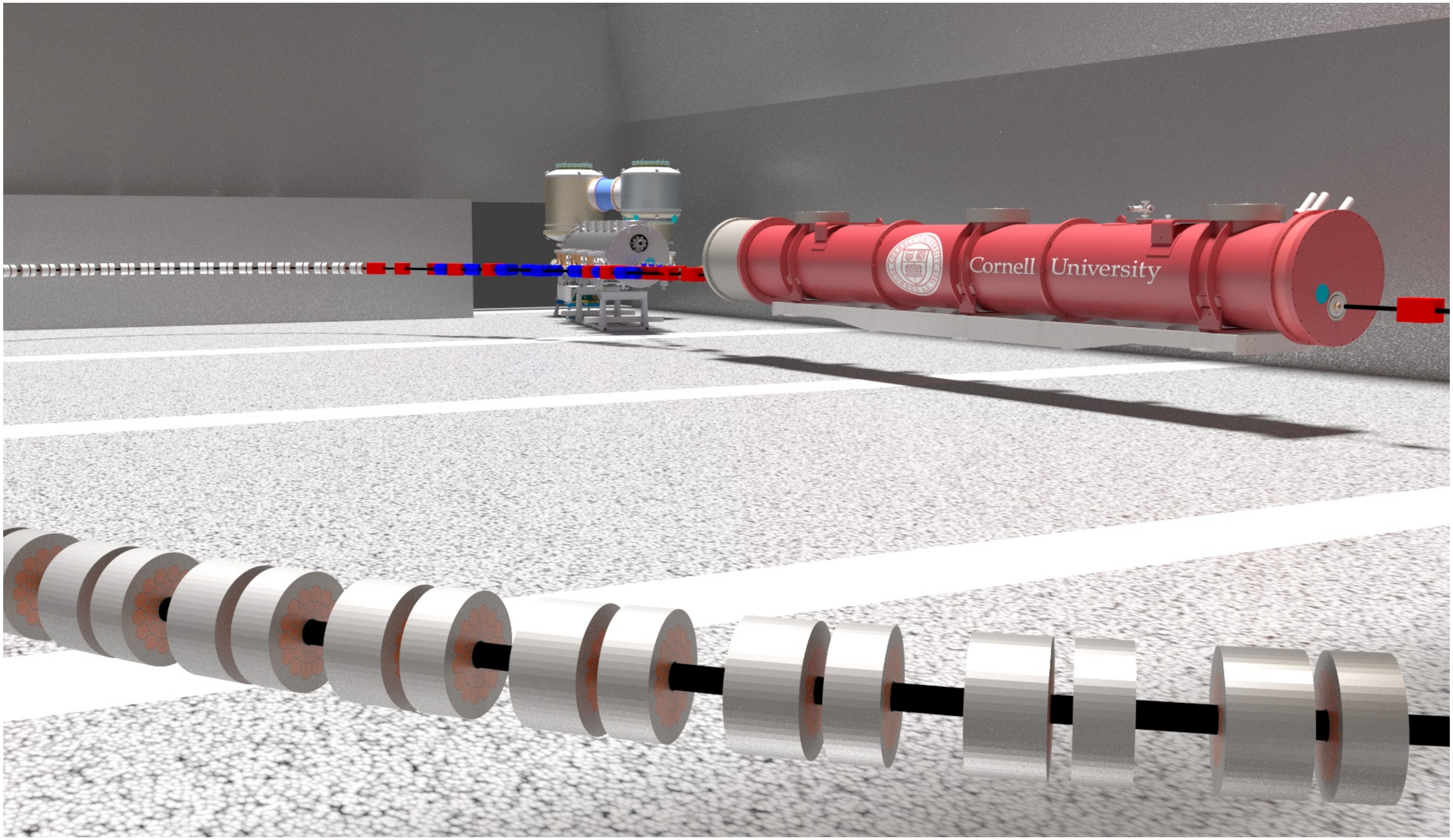
Prototype Main Linac Cryomodule (MLC)

- 6 cavities completely built and tested (vertical) in-house
- Assembly completed in November 2014
- Cooldown and testing begins in July

Cornell-BNL FFAG-ERL Test Accelerator (Cβ)

- Currently designing in collaboration with BNL
- Uses injector, MLC, and beam stop in Cornell's L0E hall
- Injector and MLC recently moved to L0E

Cβ: Cornell-BNL ERL-FFAG Test Accelerator

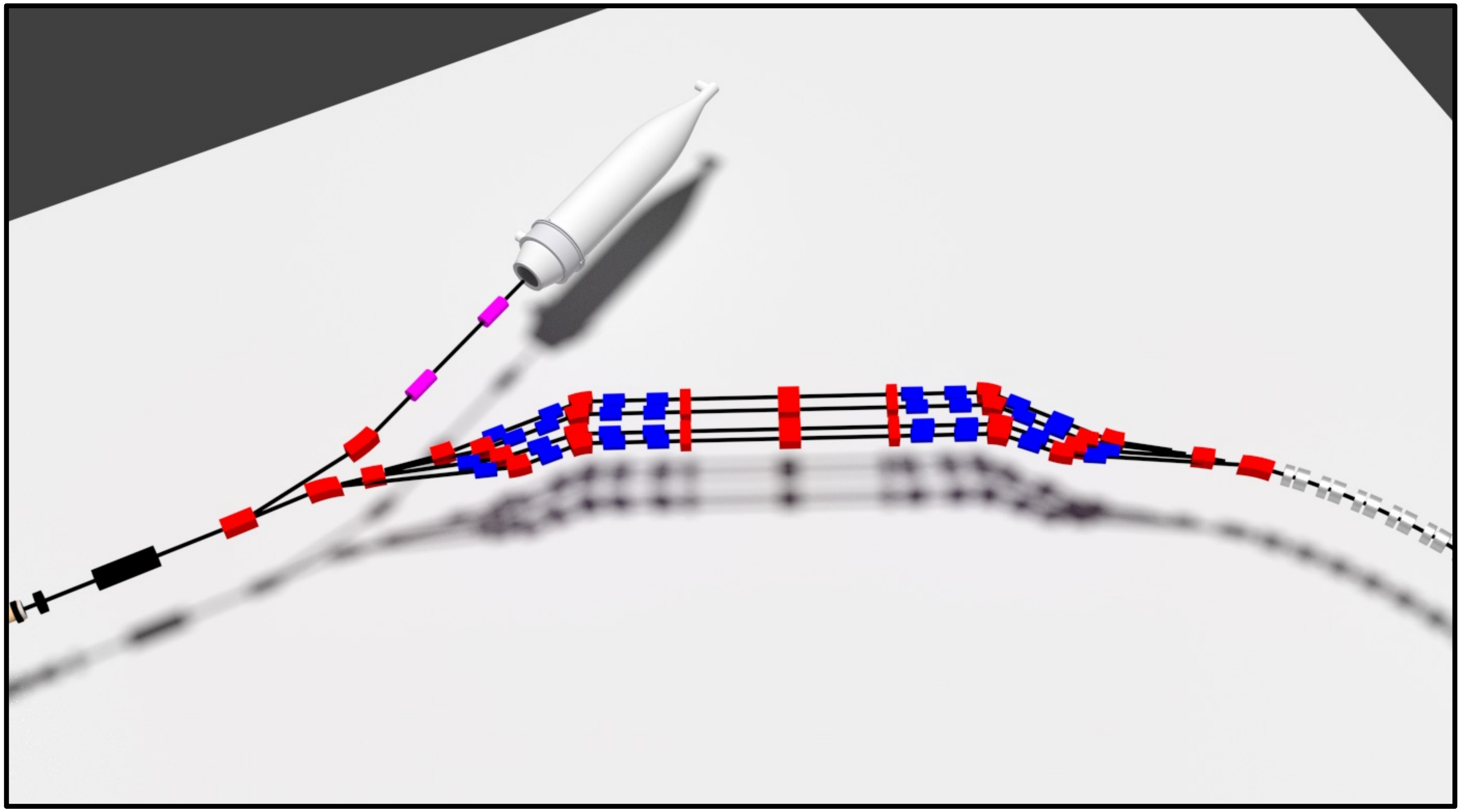


End

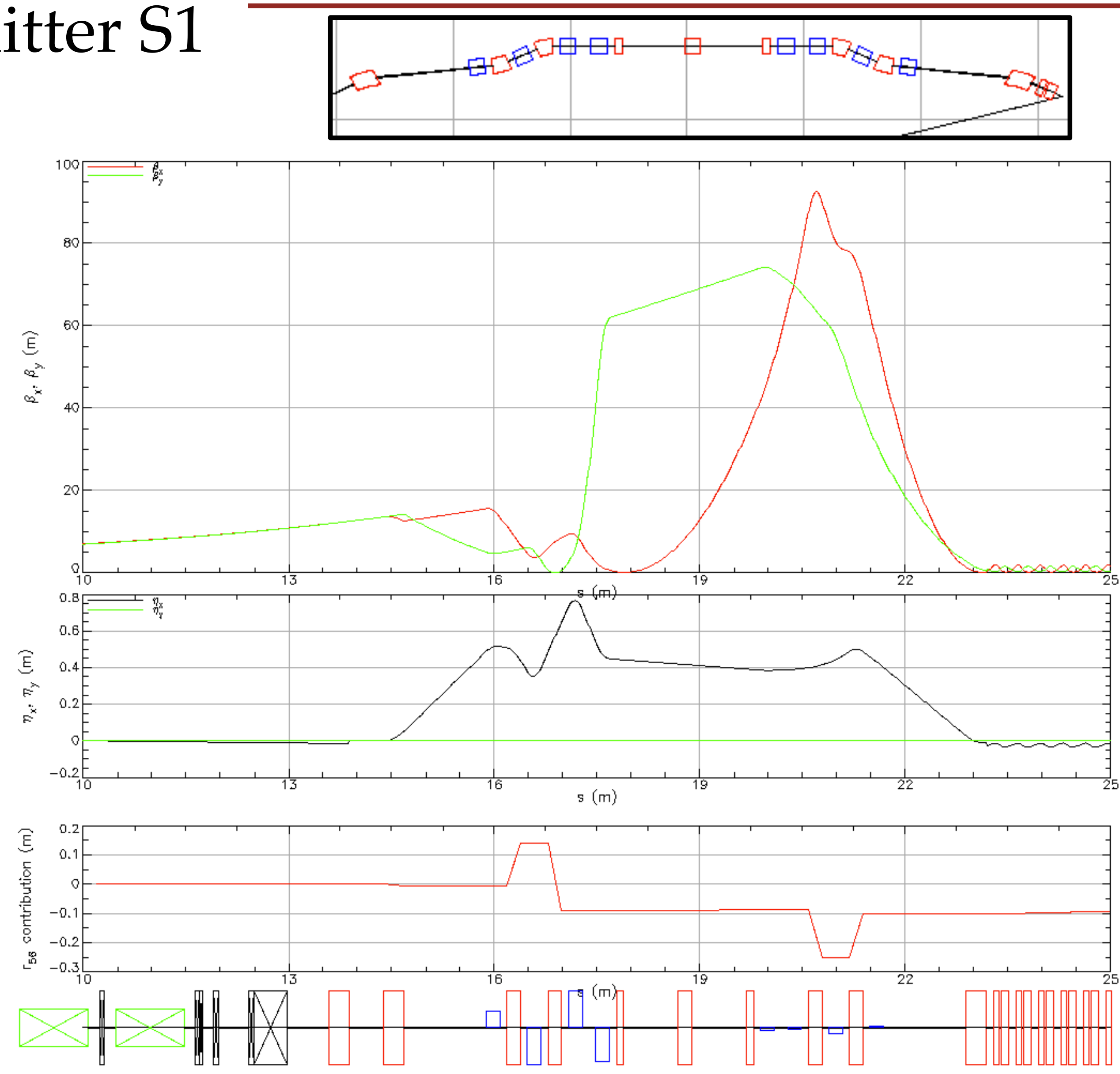
Extra

Splitters S1-4

- Accept large beams from Linac
- Steer onto FFAG closed orbits
- Match to FFAG optics
- r_{56} adjustment
- Path length adjustment via vertical chicanes
- Total path lengths close to ideal for ERL operation



Splitter S1



r_{56}

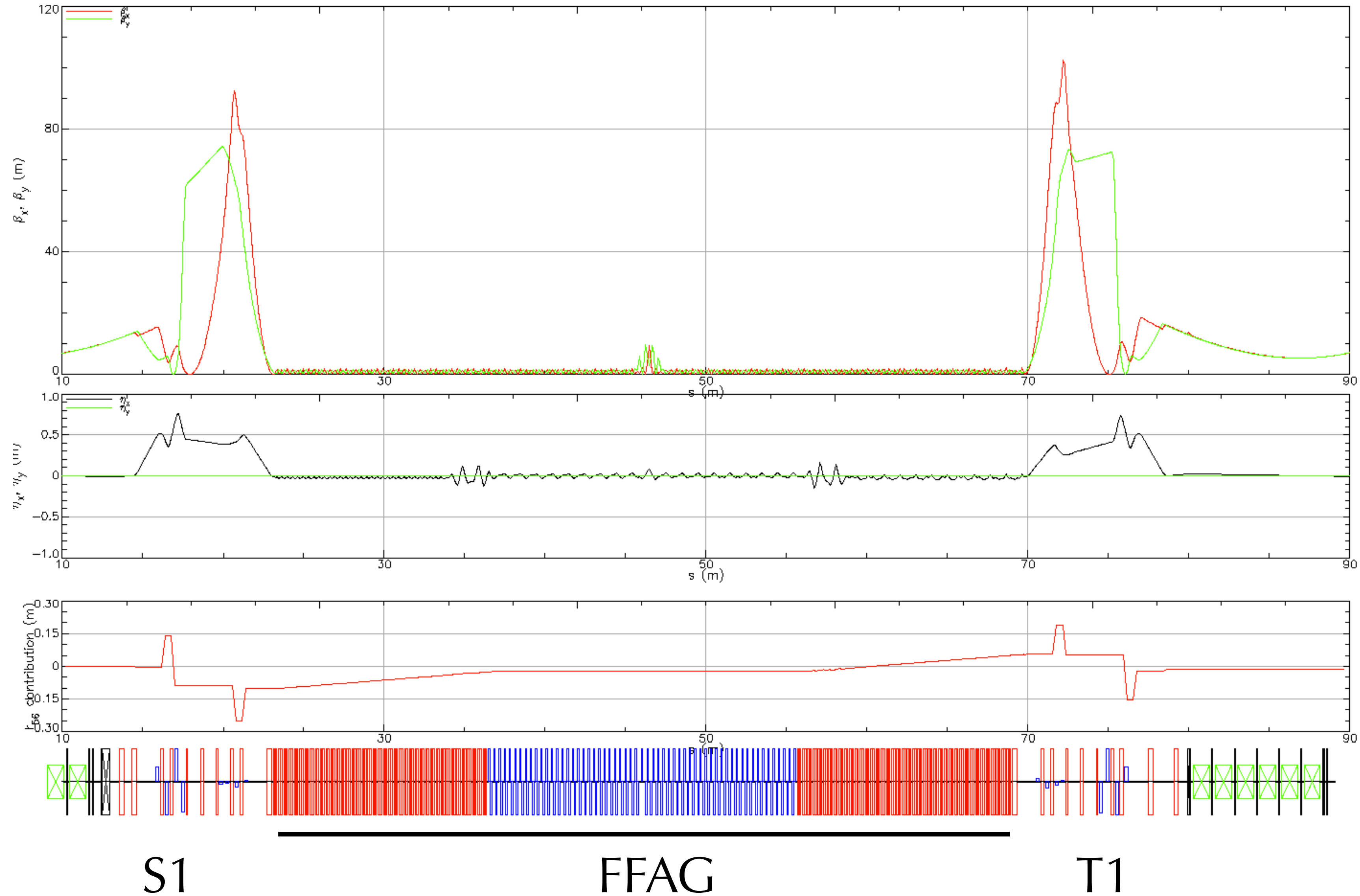
Linac

Vertical chicane

FFAG

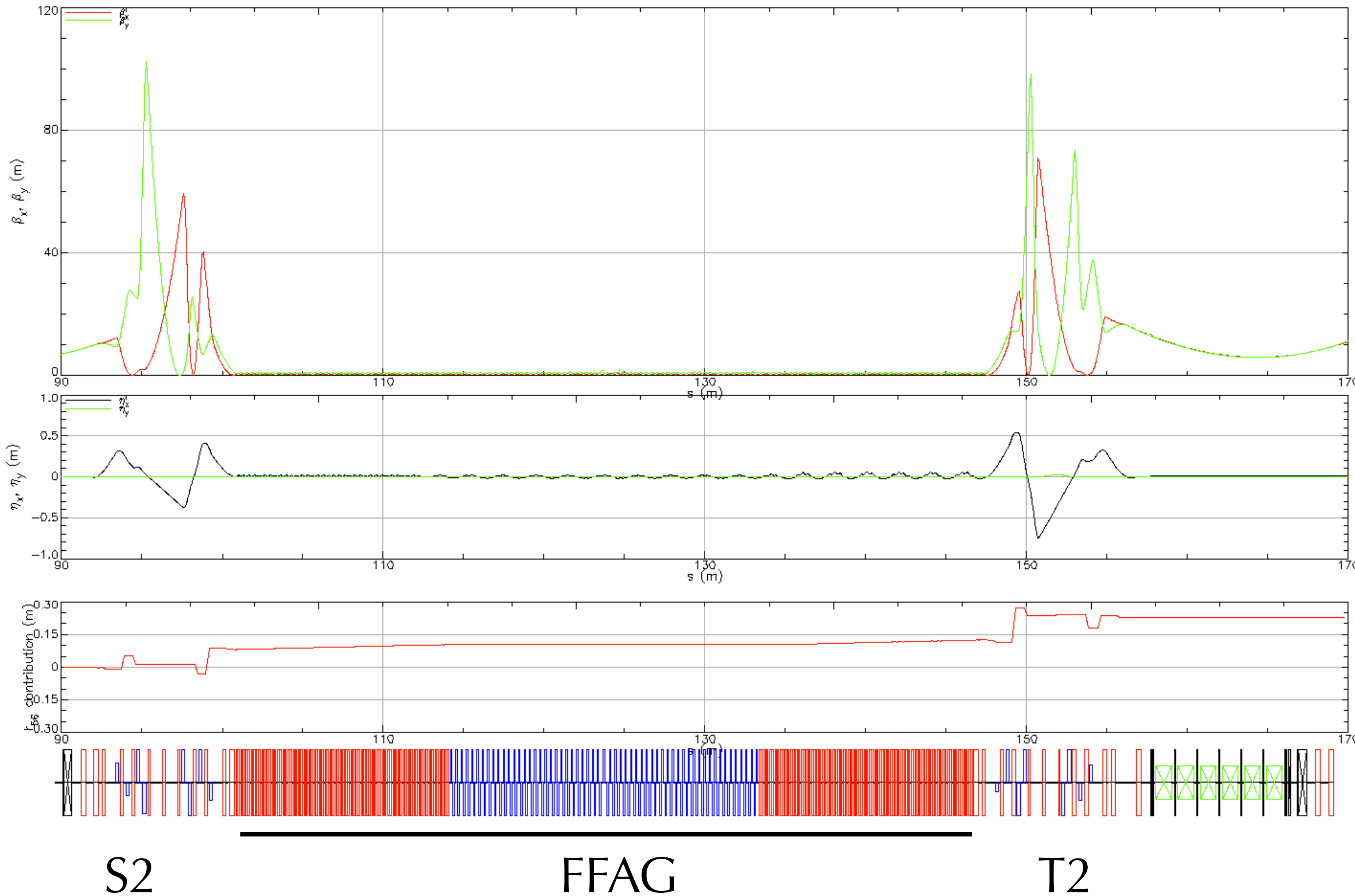
Pass 1 optics

76 MeV to 146 MeV



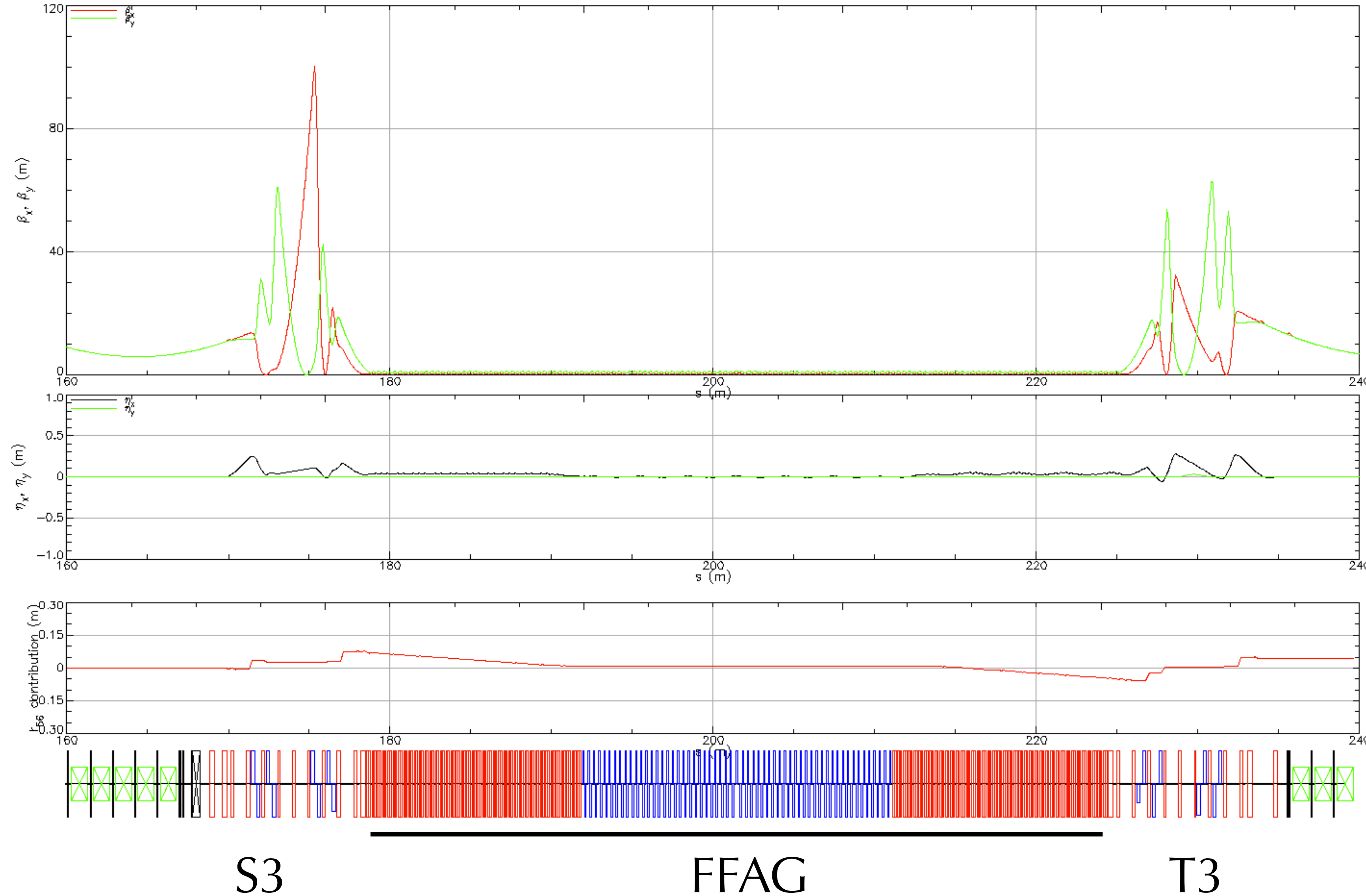
Pass 2 optics

146 MeV to 216 MeV



Pass 3 optics

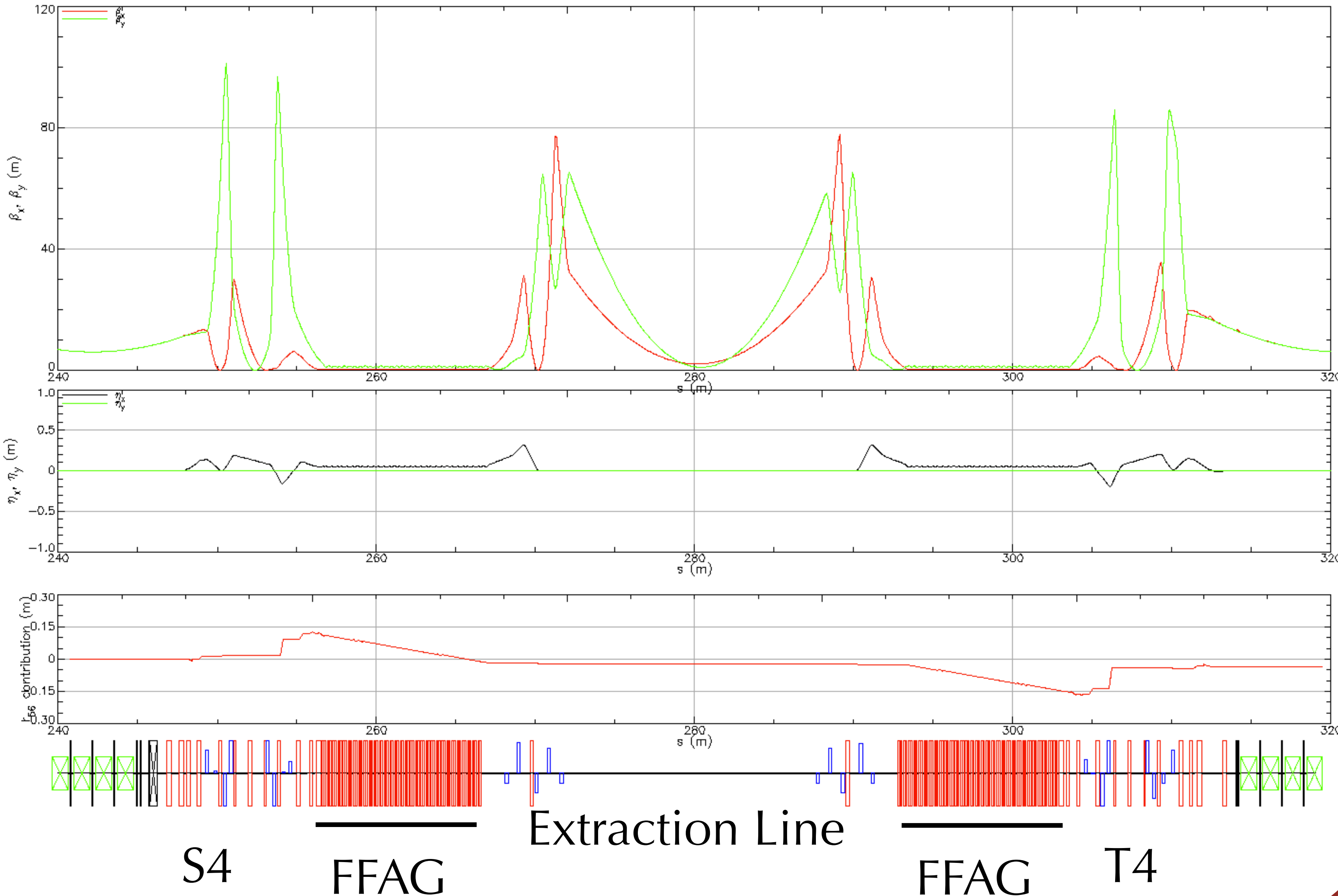
216 MeV to 286 MeV



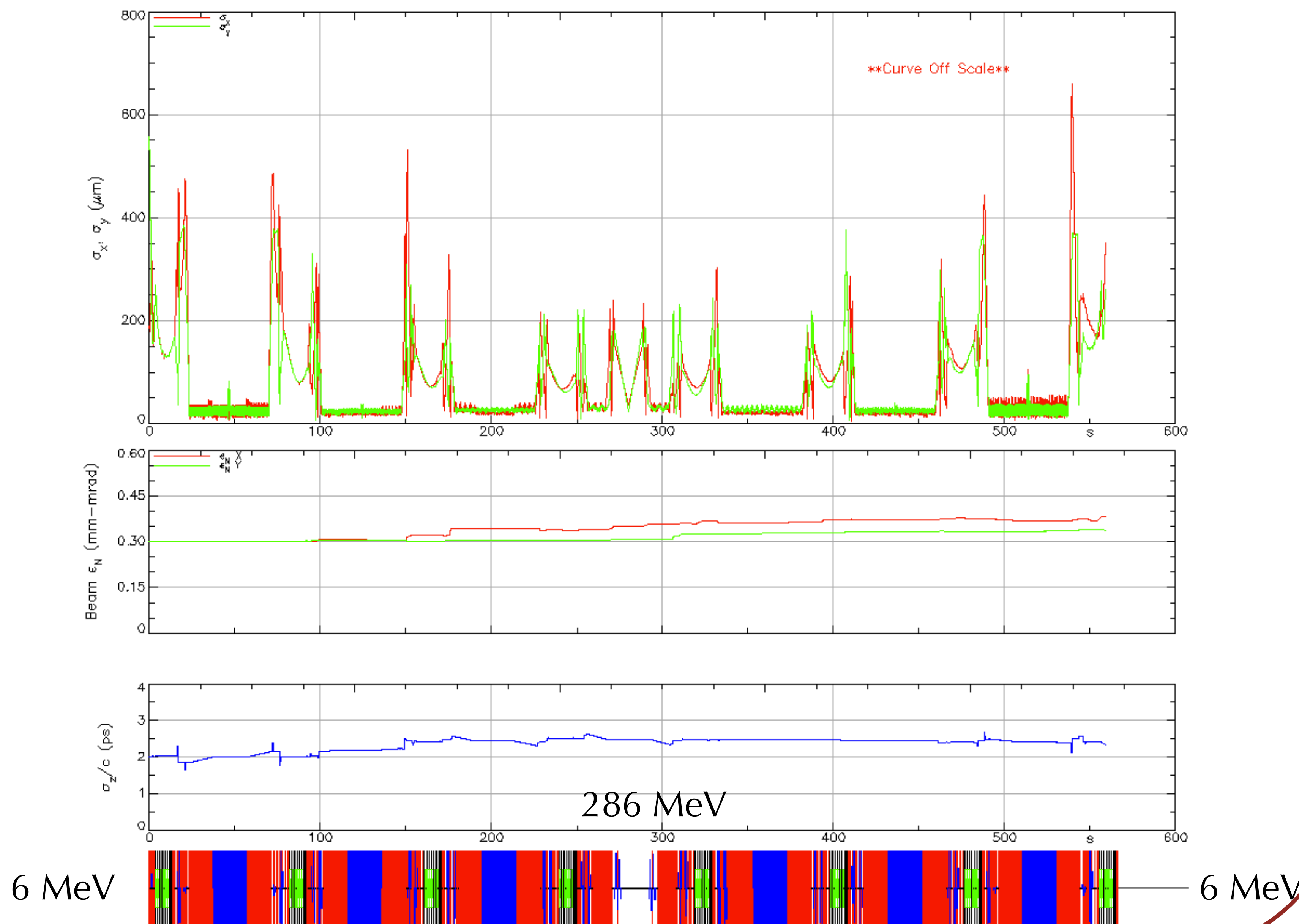
Pass 4 optics

286 MeV

Decelerate to 216 MeV

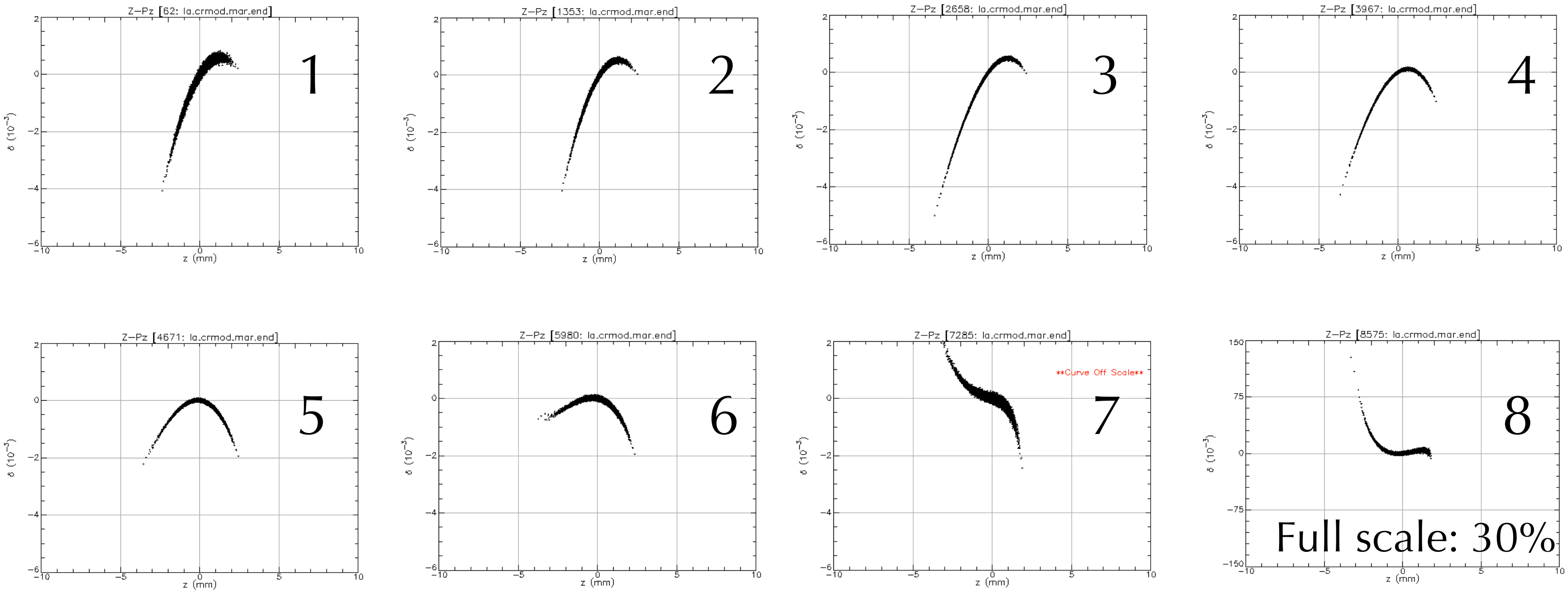


Full ERL bunch tracking



Longitudinal Phase Space

end of the Linac for pass (full scale 8%)



Longitudinal Phase Space

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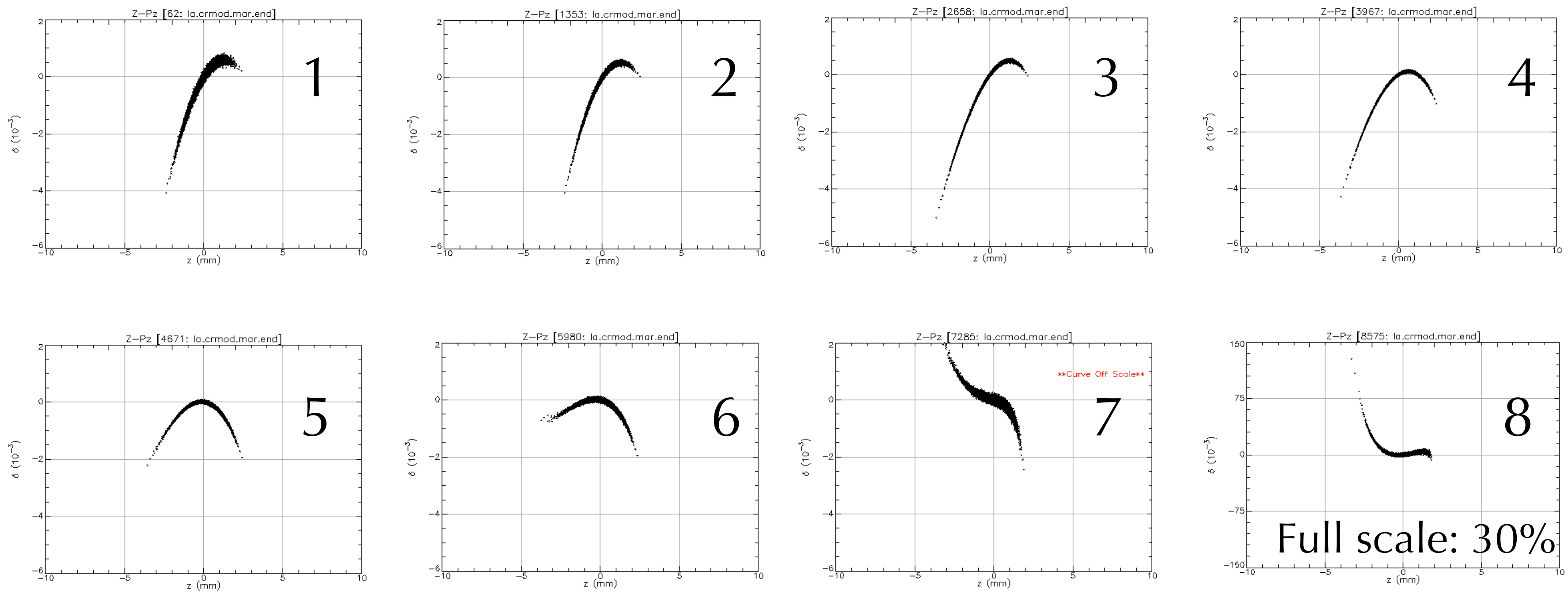
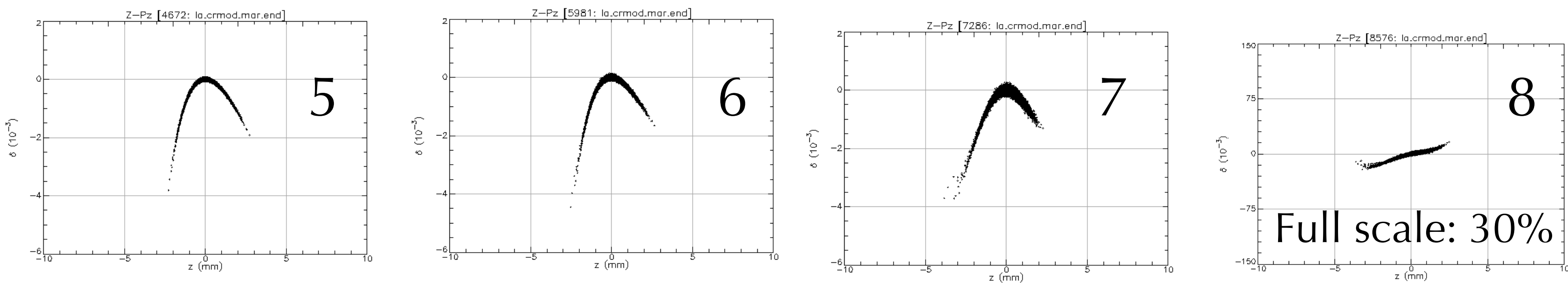
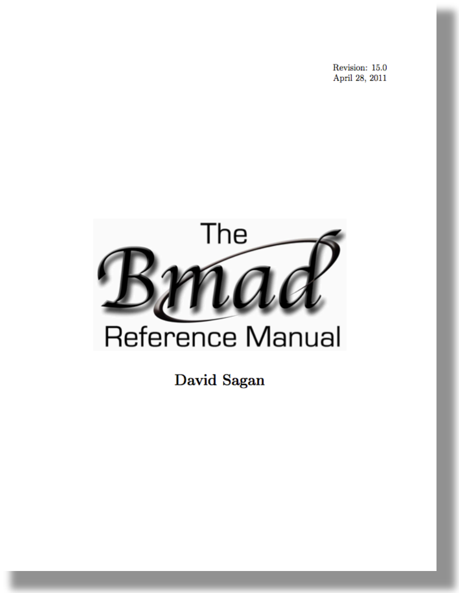


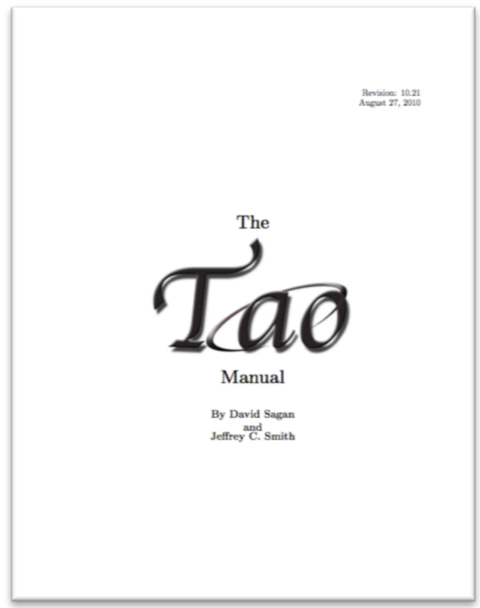


r_{56} adjusted on pass 4

Simulation Software

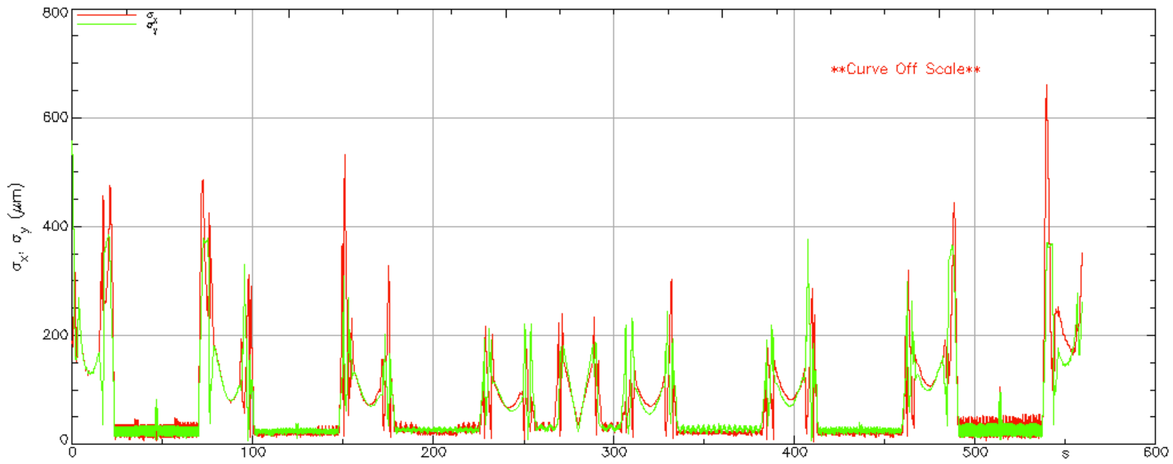
Bmad & Tao (Cornell)





www.lns.cornell.edu/~dcs/bmad

Next steps

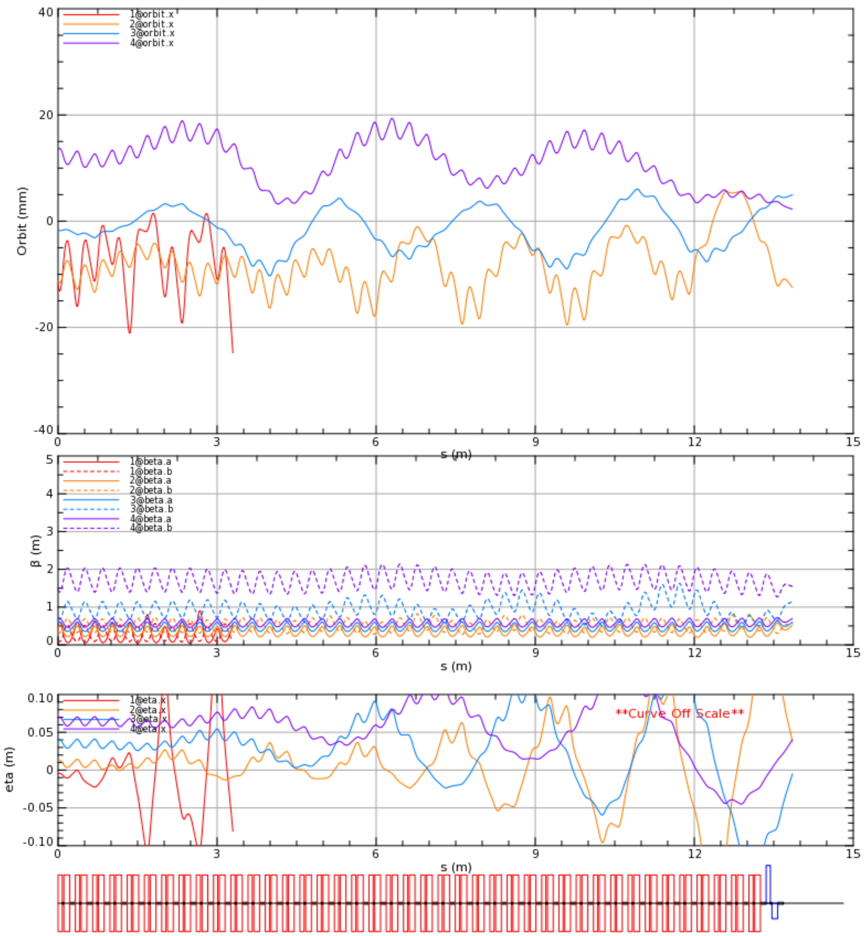


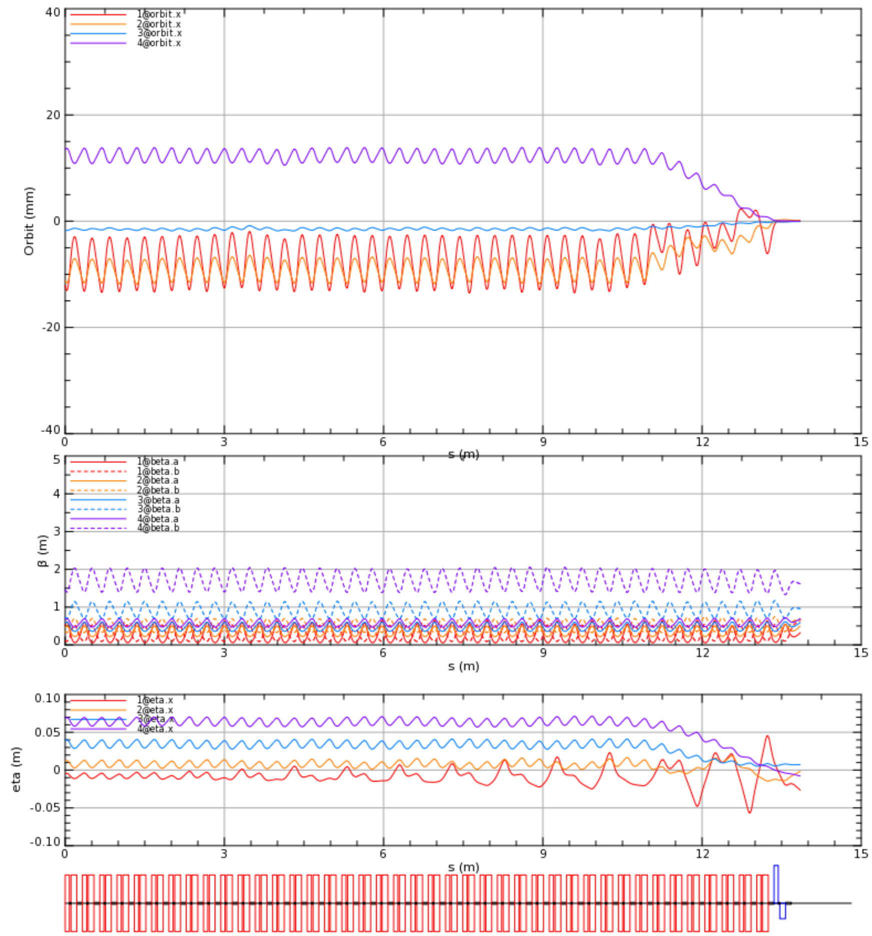
- Real fieldmaps (FFAG magnets, cavities, …)
- Wakefields (CSR, resistive wall, …)
- Injector + Linac space charge optimization
- Touschek scattering
- Dark current tracking & collimation
- BBU
- Ion trapping
- Orbit and optics correction
- Tolerance & stability analysis

FFAG orbit correction simulation

500 um rms x offset errors

SVD correction given BPM readings for separate beams and correction coils on every other dipole



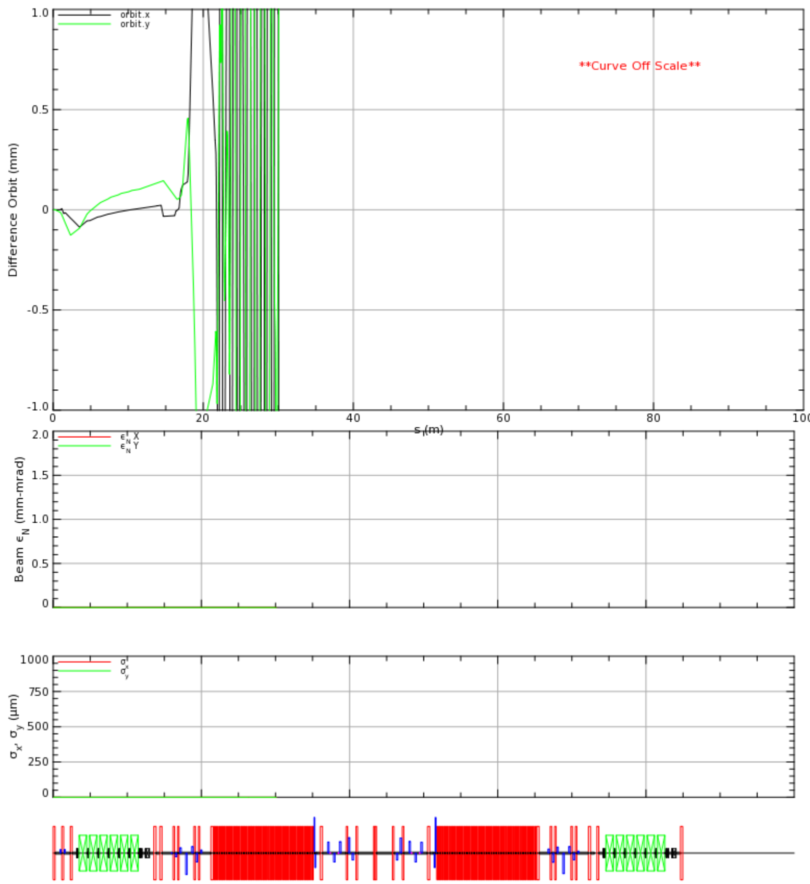


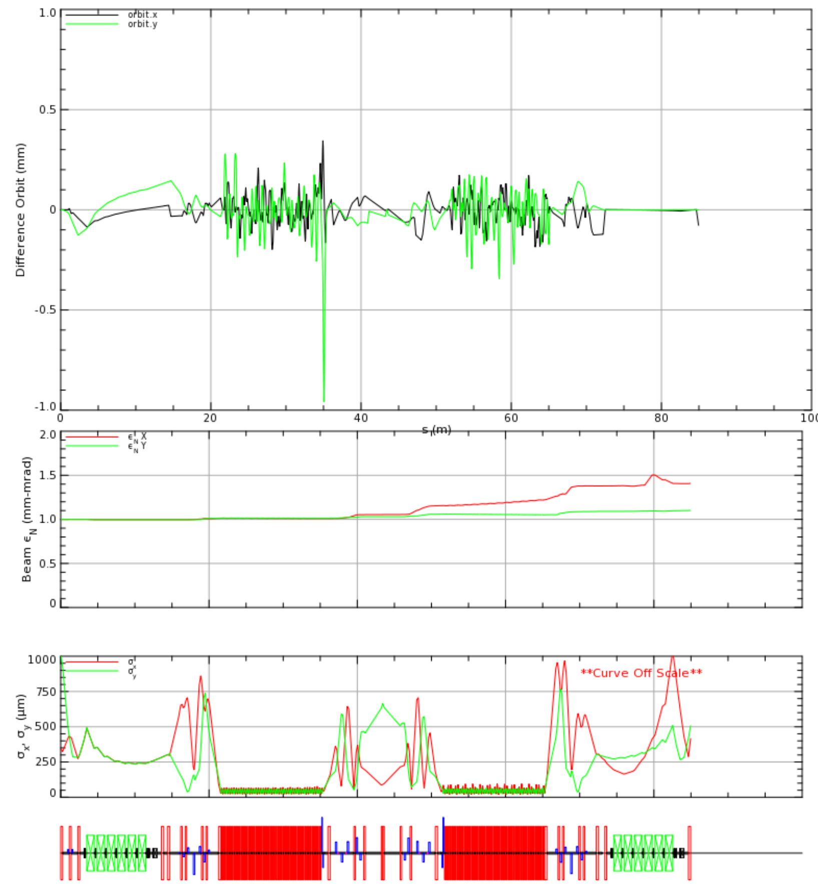
FFAG Arc

Example errors, correction, and bunch tracking

Variety of errors

SVD correction given BPM readings for separate beams and correction coils on every other FFAG dipole and all quadrupoles





1-pass ERL-FFAG (early design)