ELECTRONS FOR THE LHC

Chavannes de Bogis, Confédération des Helvètes, 24-25 octobre 2019

CBETA

F. Méot

Collider-Accelerator Department

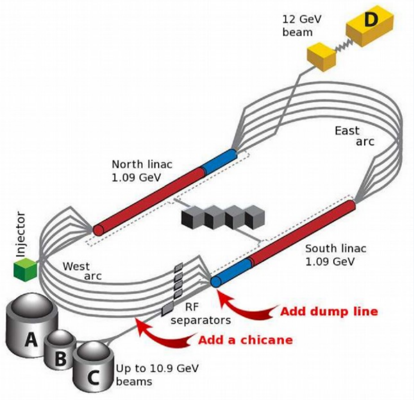
Brookhaven National Laboratory

With numerous slides from a number of earlier presentations, by S. Brooks, G. Hoffstaetter, R. Mishnoff, D. Trbojevic & others

All details about CBETA, here:

https://arxiv.org/pdf/1706.04245.pdf

And a communication:
7 GeV ER@CEBAF
latest news



All details about ER@CEBAF, here:

https://technotes.bnl.gov/PDF?publicationId=40234

Origins of CBETA prototyping

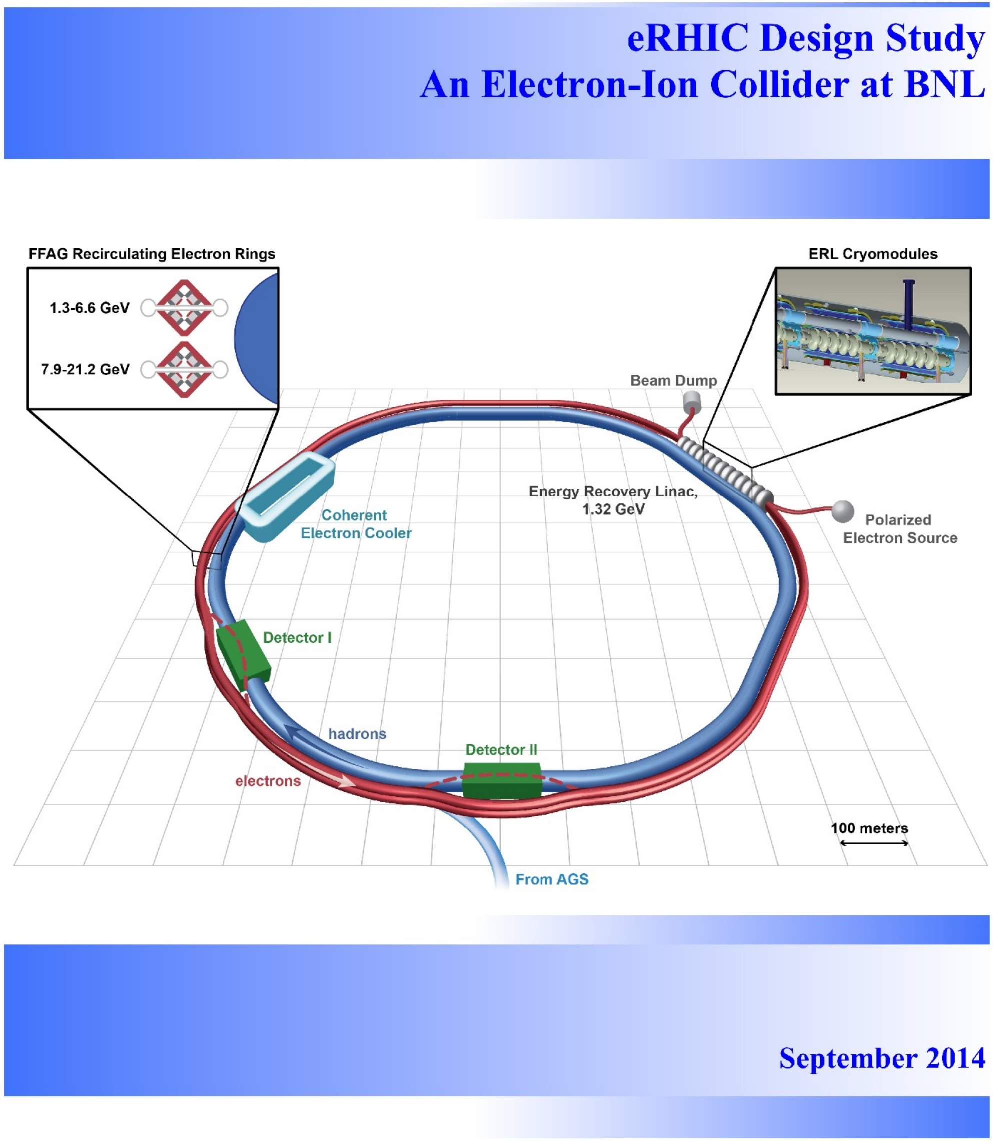
The FFLAG (Fixed Field Linear Alternating Gradient) single-arc concept has been developed as part of the **Linac-Ring** design of the eRHIC EIC project at BNL.

Why an ERL for an EIC:

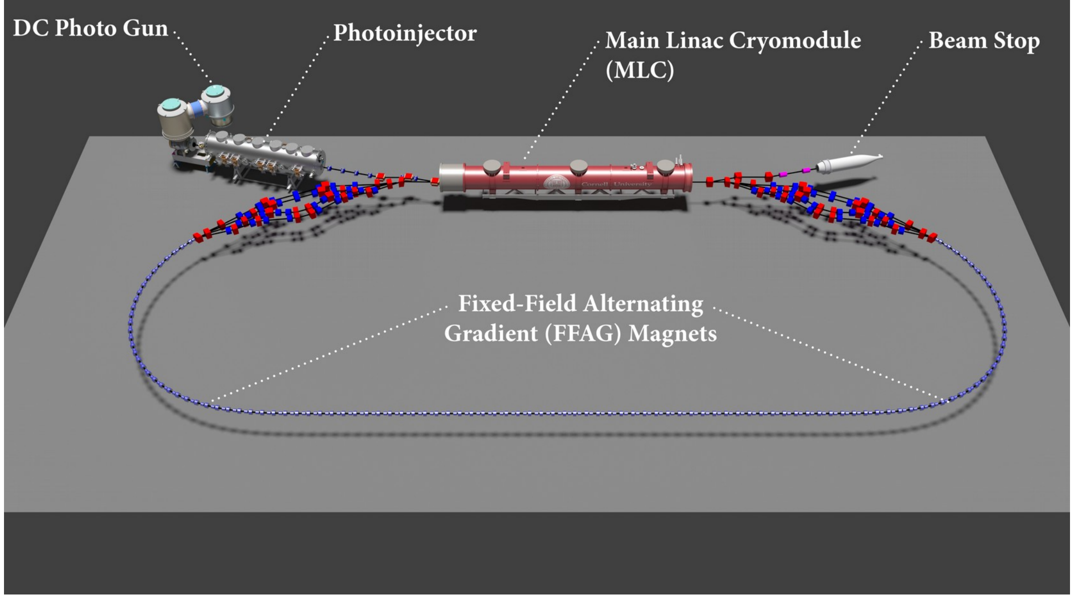
- Single e-bunch collision == no consideration of beam-beam on e-beam == greater tolerance on disruption of e-bunch == lower operating and building cost == energy recovery == beam dumped at injection energy

Why an FFAG channel for an ERL:

a single beam line for many energies.



CBETA objectives



- First 4-turn SRF ERL
- Large (x4) momentum aperture.
  Only one linear FFAG so far: EMMA ring at Daresbury, achieved x1.7 energy range
- Halbach-style magnet channel (cheap)
- Largest electron beam power in an ERL (40 mA @ 150MeV)

- Constructed & operated by a Cornell-BNL collaboration, at Cornell
- Commissioned with world-wide support, including JLAB, KEK, , ASTEC, HZ-Berlin, TU-Darmstadt, etc.

Genesis, brief recall

2005 - Start construction of DC photo-emitter gun; world record current (75mA).

2012 - Pre-Design on a hard x-ray 5GeV Cornell ERL.

2013 - Cornell's 6 MeV injector achieves world record brightness.

2014 - 75MeV SC linac completed.

2000-on - Linear FFAG R&D: NuFact design, EMMA prototype.

2010s - eRHIC ERL design. CBETA design. Halbach quads design and tests.

2016 - prototype CBETA-style FFAG arc test at BNL ATF, 20-80MeV energy range.

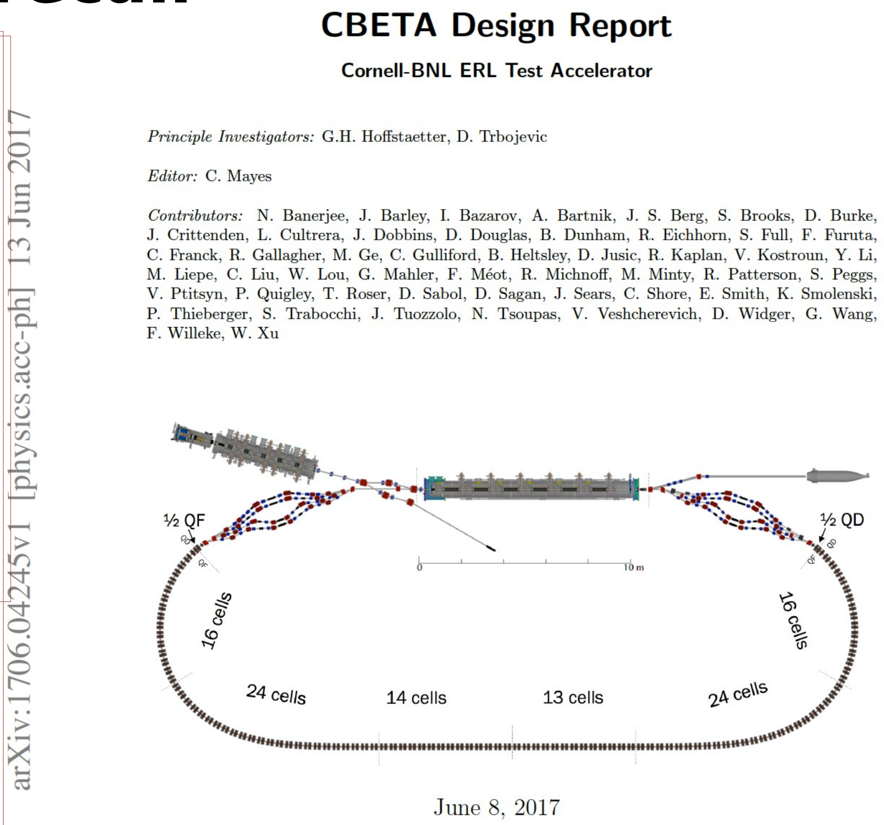
2014- White paper by Cornell - BNL collaboration.

2016 - Construction funding by New York State NYSERDA

2017 - CBETA Design Report

2018 - Fractional arc test: 1st beam through SRF chain, S1 spreader line and 4-cell FFLAG.

2019 - 1st energy recovery, 1 recirculation, 42 MeV.



CBETA Design Report

Cornell-BNL ERL Test Accelerator

Principle Investigators: G.H. Hoffstaetter, D. Trbojevic

Editor: C. Mayes

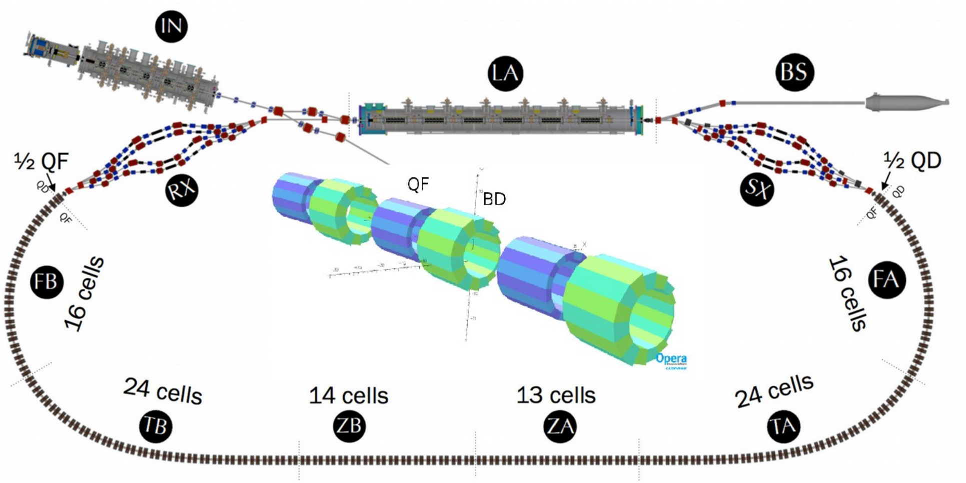
Contributors: N. Banerjee, J. Barley, I. Bazarov, A. Bartnik, J. S. Berg, S. Brooks, D. Burke, J. Crittenden, L. Cultrera, J. Dobbins, D. Douglas, B. Dunham, R. Eichhorn, S. Full, F. Furuta, C. Franck, R. Gallagher, M. Ge, C. Gulliford, B. Heltsley, D. Jusic, R. Kaplan, V. Kostroun, Y. Li, M. Liepe, C. Liu, W. Lou, G. Mahler, F. Méot, R. Michnoff, M. Minty, R. Patterson, S. Peggs, V. Ptitsyn, P. Quigley, T. Roser, D. Sabol, D. Sagan, J. Sears, C. Shore, E. Smith, K. Smolenski, P. Thieberger, S. Trabocchi, J. Tuozzolo, N. Tsoupas, V. Veshcherevich, D. Widger, G. Wang, F. Willeke, W. Xu

June 8, 2017

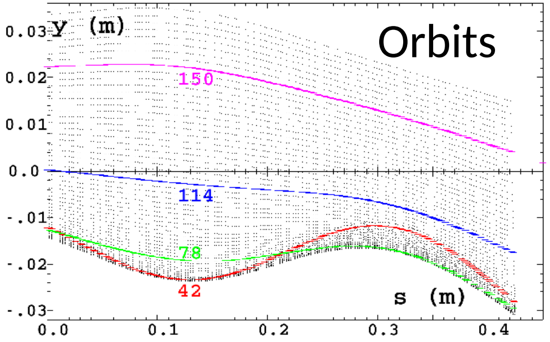
Starting in 2020, CBETA will be available for R&D on high power beams.

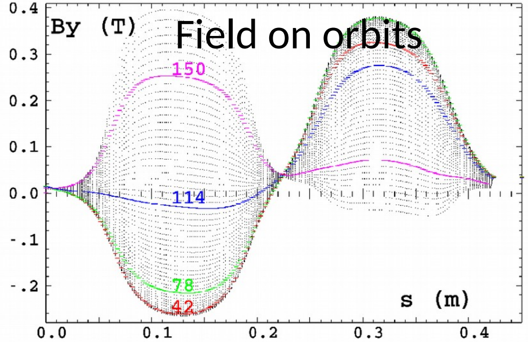
FFLAG lattice design,
magnet prototyping stages

Return-arc FFLAG cell parameters are obtained from magnet modeling in OPERA



Advantage: tracking includes all field and kinematic non-linearities





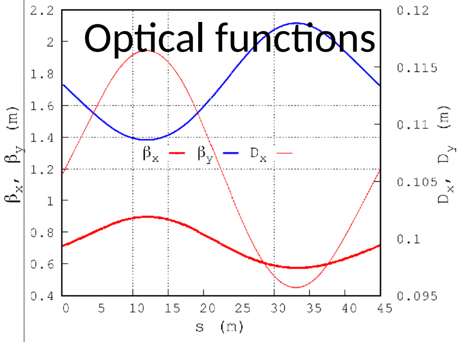
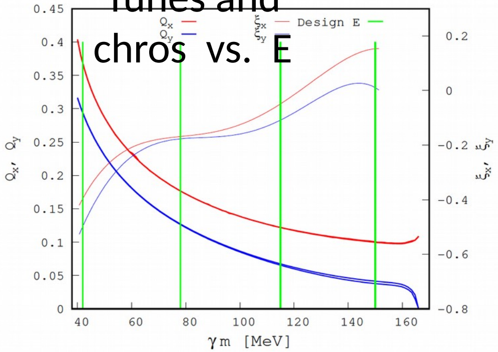
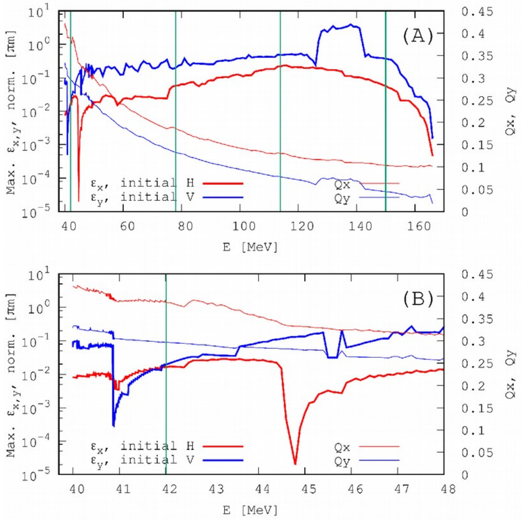


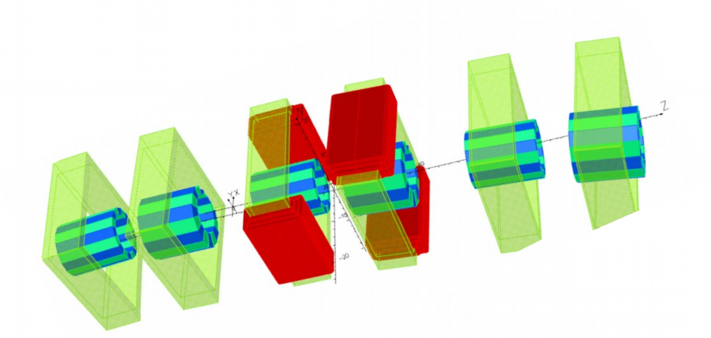
Figure 7: Optical functions along the cell, 150 MeV case.

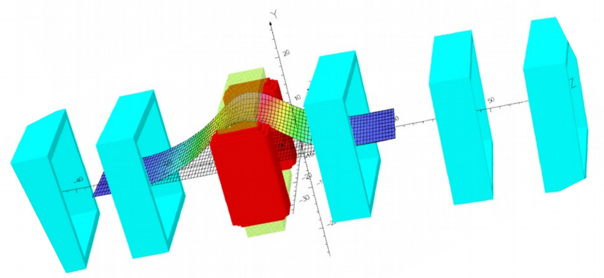


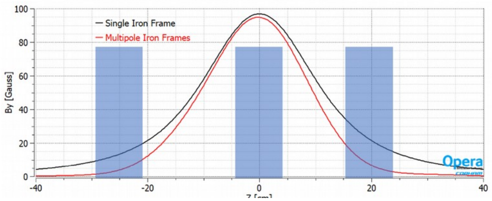
DA vs. E



- Field map approach allows to prove that linear superposition hypothesis does hold.
- This makes field contribution by any individual magnet a free knob in the design optimizations, in spite of substantial field overlapping between neighbor magnets.







- This results from

  (i) PMs' μ~1.03,

  (ii) only weak corrector-to-corrector cross-talk

Eventually,
CBETA arc cell parameters

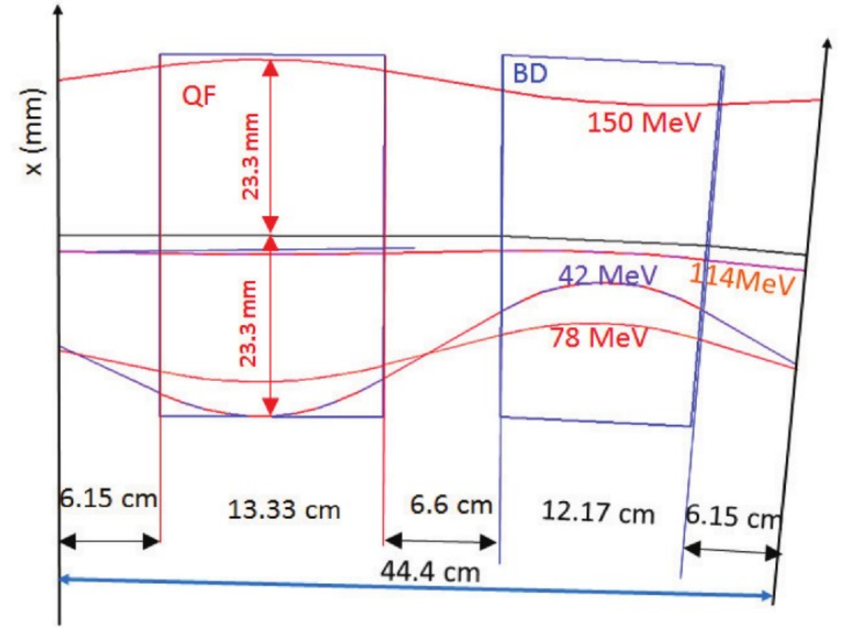


Figure 2: A schematic diagram of the FFAG doublet cell

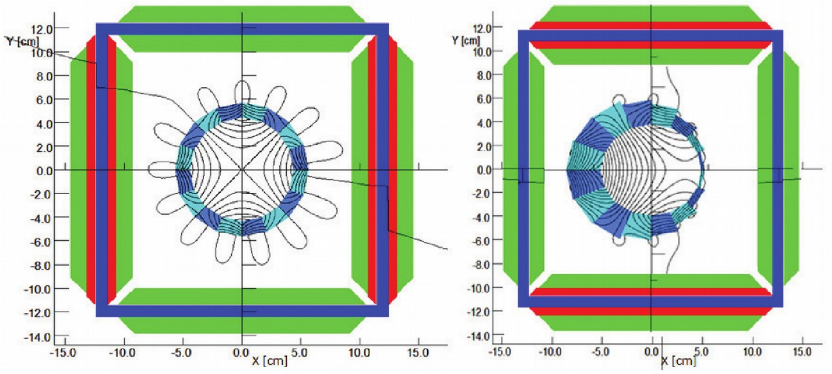
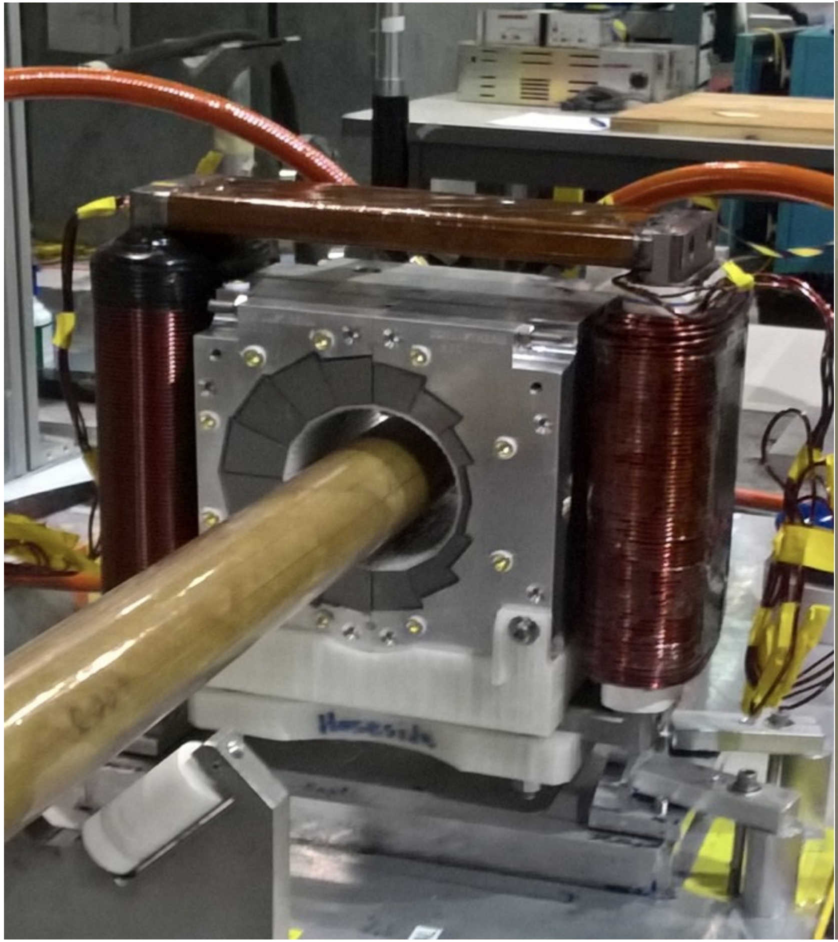


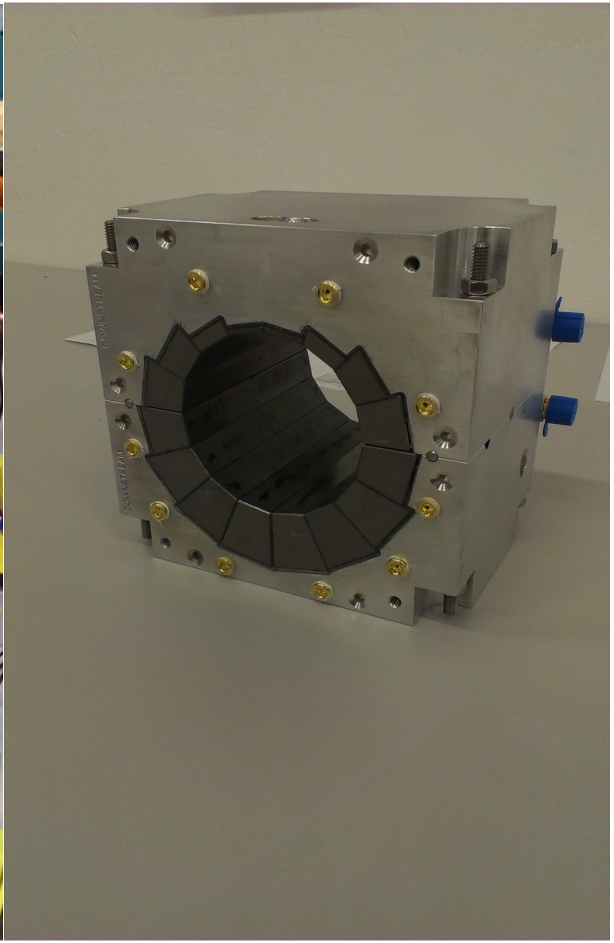
Figure 3: The cross sections of the (QF) a pure focusing Halbach magnet (left), and the (BD) a defocusing quadrupole

Table 2: Parameters for the arc cell

BPM block length (mm)	42
Pipe length (mm)	402
Magnet offset from BPM block (mm)	12
Focusing quadrupole length (mm)	133
Defocusing magnet length (mm)	122
Single cell horizontal tune, 42 MeV	0.368
Single cell vertical tune, 150 MeV	0.042
Integrated focusing magnet strength (T)	−1.528
Integrated defocusing magnet strength (T)	+1.351
Integrated field on axis, defocusing (T m)	−0.03736

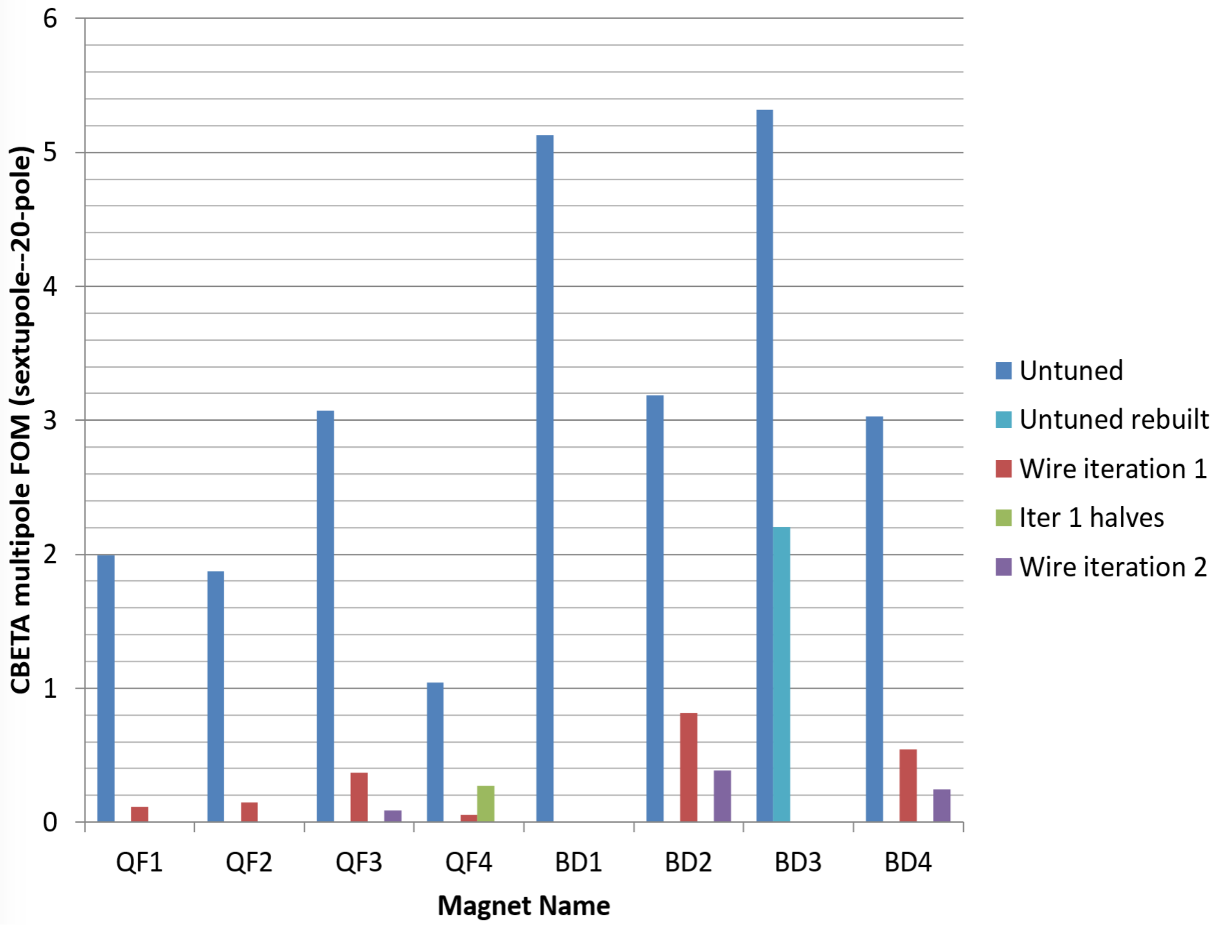
Halbach magnet prototyping and measurements at BNL.
Vertical correction coils in place here.





12 proof-of-principle magnets
(6 QF, 6 BD)
built as part of CBETA R&D.
Iron wire shimming applied on
3 QFs and 6 BDs with good results.

Iron Wire Shimming



All multipoles of the Halbach magnets can be corrected as required.

12 CBETA prototype permanent magnets assembled in an FFAG Arc Test at BNL, total bending 40o.

Successful operation at ATF, 2017.

Electron energies in the experiment:
18, 24, 36, 54, and 72 MeV

$$Electron\ p_{max} = 18\ MeV/c \qquad \frac{\Delta p}{p} = -60\%$$

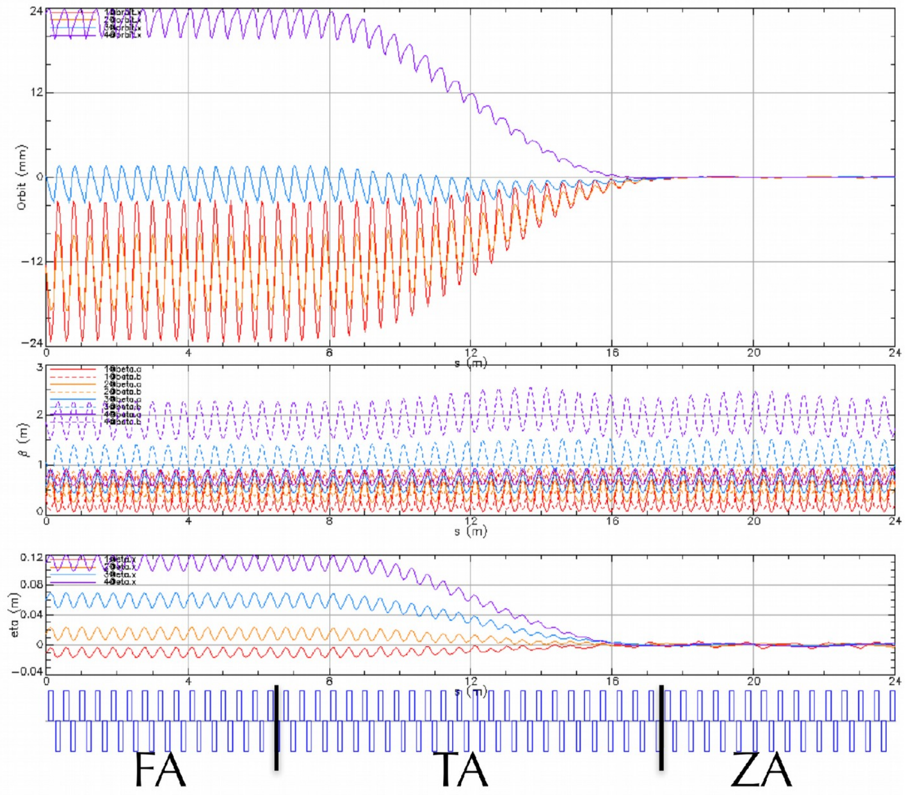
$$Electron\ p_{cent} = 45\ MeV/c$$

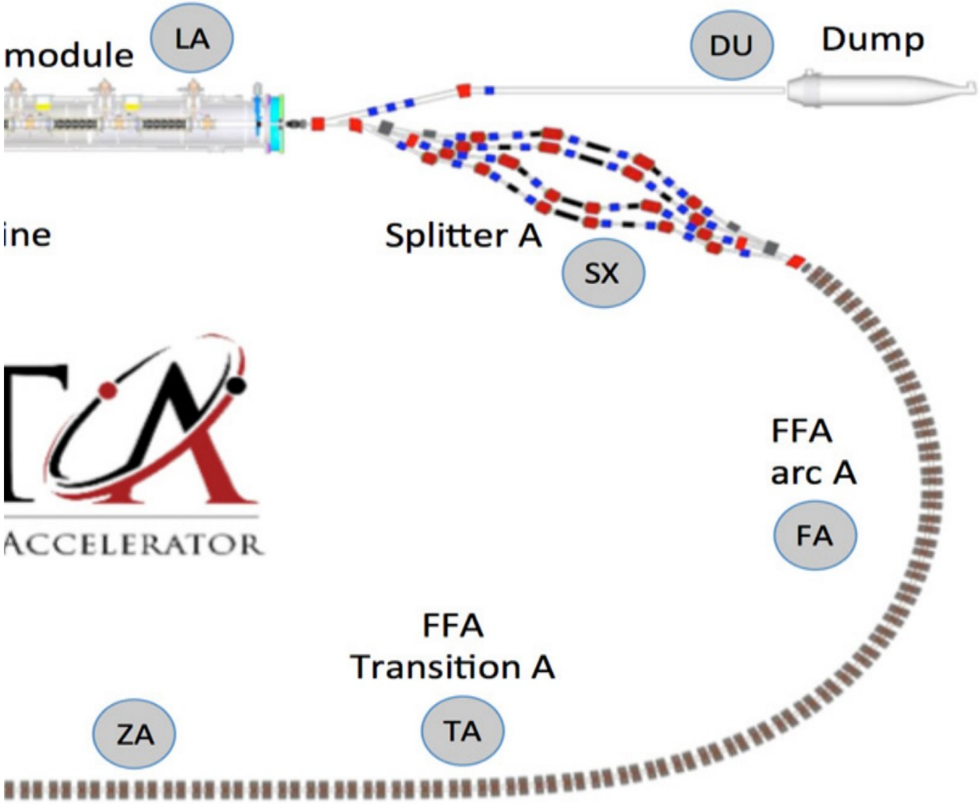
$$Electron\ p_{min} = 72\ MeV/c \qquad \frac{\Delta p}{p} = +60\%$$

After Dejan Trbojevic, ERL2019 Helmholtz Zentrum Berlin

More Halbach lattice: dispersion suppressor,

adiabatically merge 4 orbits from arc to common long straight axis.





Progressive transition from arc to long straight includes: expanding cell lengths, zeroing the D/F magnet offset, zeroing the reltaive D/F tilt.

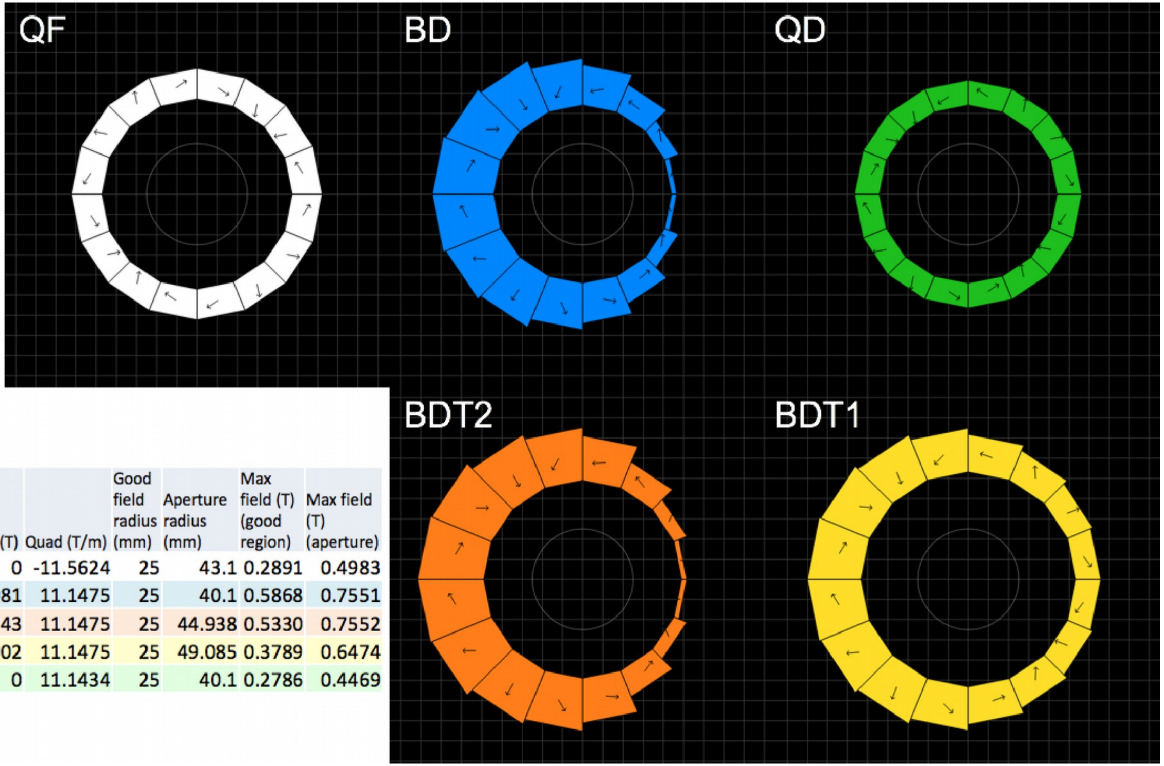
The FFLAG return loop ends up featuring 5 different Halbach permanent magnet cross-sections:

- the same QF throughout

- a single BD in the arcs

- a single QD in the long straight

- BDT1, BDT2 in the two transitions

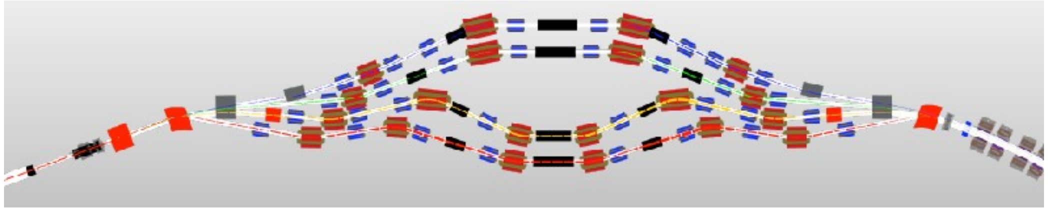


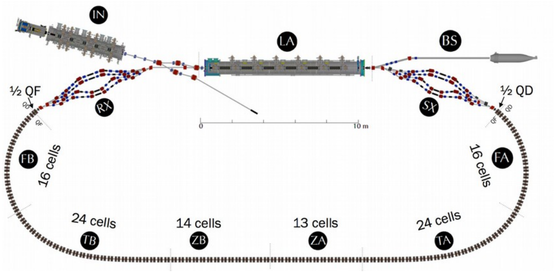
Magnet	Dipole (T)	Quad (T/m)	Good field radius (mm)	Aperture radius (mm)	Max field (T) (good region)	Max field (T) (aperture)
QF	0	-11.5624	25	43.1	0.2891	0.4983
BD	-0.3081	11.1475	25	40.1	0.5868	0.7551
BDT2	-0.2543	11.1475	25	44.938	0.5330	0.7552
BDT1	-0.1002	11.1475	25	49.085	0.3789	0.6474
QD	0	11.1434	25	40.1	0.2786	0.4469

Permanent magnet and corrector tally

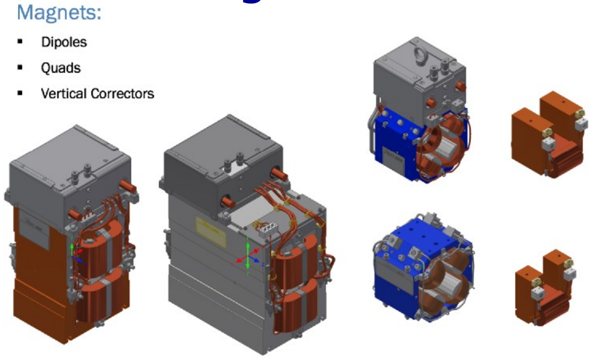
subsection	Focusing (F) Quad	Defocusing (D) Quad	BPM	Corrector (H)	Corrector (V)
FA	16	17	16	16	16
TA	24	24	24	24	24
ZA+ZB	27	27	27	27	27
TB	24	24	24	12	12
FB	17	16	16	16	16
Total	108	108	107	107	107

More lattice: conventional SX and RX design

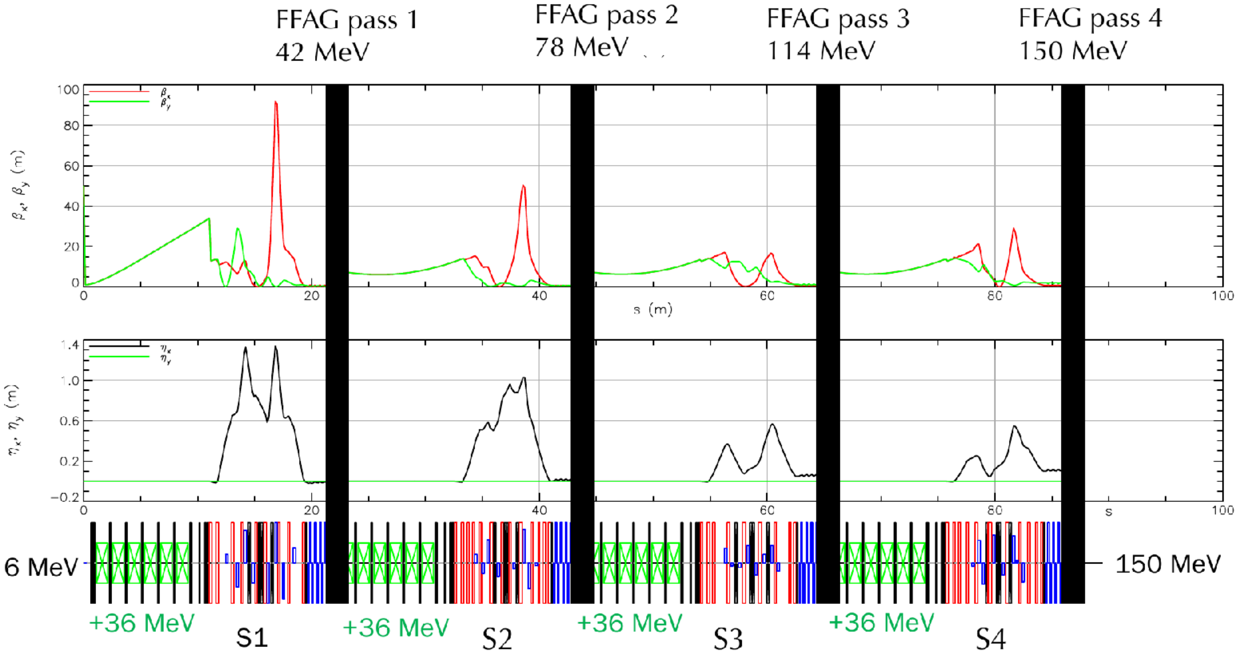




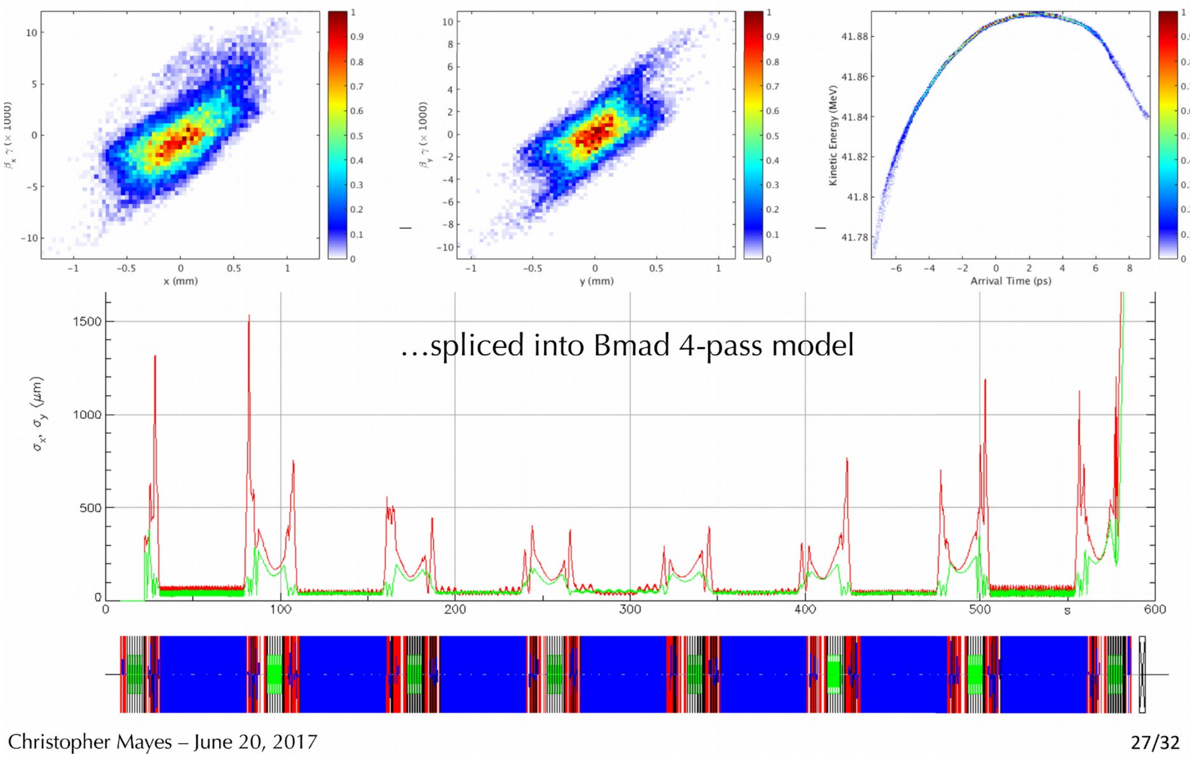
- Splitter/combiner design uses conventional electromagnets

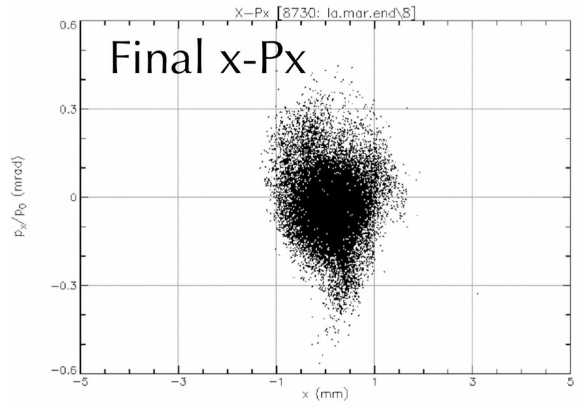


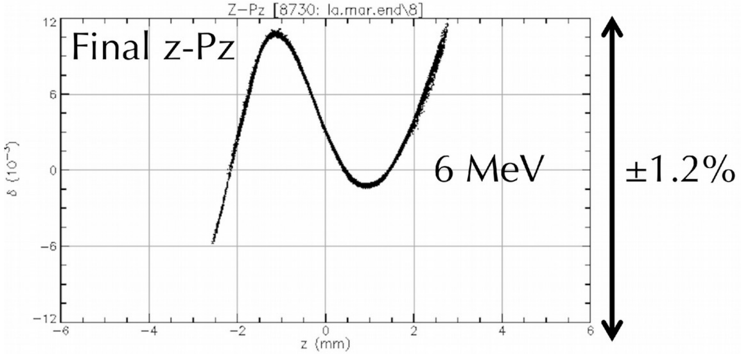
- includes a TOF-adjustment chicane, remote-command.



Campaigns of start-to-end tracking studies support design options



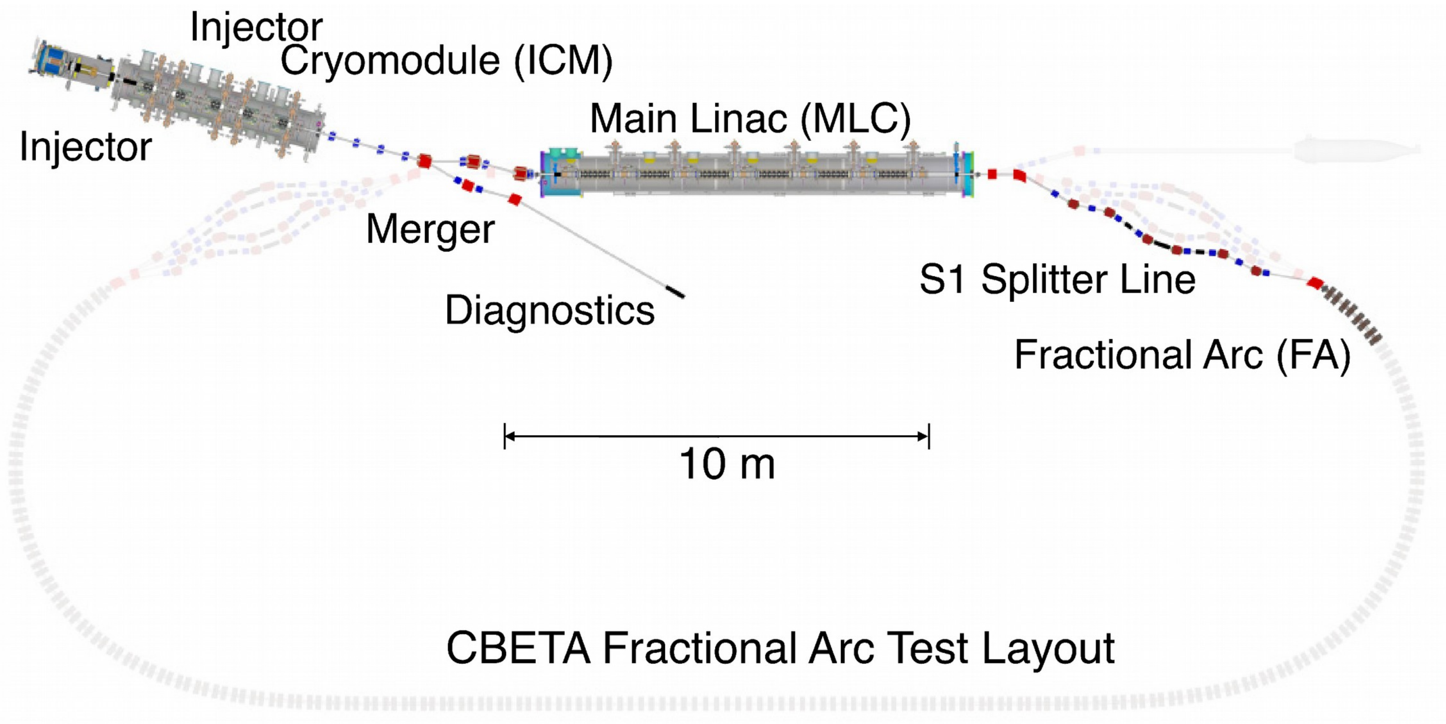




Let’s conclude - CBETA design parameters:

Parameter	Value	Unit
Top energy	150	MeV
Injector energy	6	MeV
Energy gain	36	MeV
Injector current	$\leq$40	mA
Linac passes	4 accel. + 4 decel.	
Arc energies	42, 78, 114, 150,	
	114, 78, 42	MeV
RF frequency	1300	MHz
Bunch frequency	$\leq$325	MHz
Harmonic number	343	
Rms x/y emittances	2	μm
Bunch length	3	ps
Typical arc $\beta_{x/y}$	0.4	m
Typical splitter $\beta_{x/y}$	50	m
Rms bunch size	52 to 2806	μm
Bunch charge (min)	1 to 123	pC

CBETA construction at Cornell (1/3) Towards “Fractional Arc Test”



CBETA Fractional Arc Test Layout

Hall L0E before CBETA

L0E contained approximately 7,000 square feet of Lab and Shop space until 2014

Spring 2015

70% of the existing technical-use space was emptied for the initial phase

Magnet work at BNL, then transport to Cornell

2017

S1 and
4-cell
FFLAG arc
are
ready for
FAT

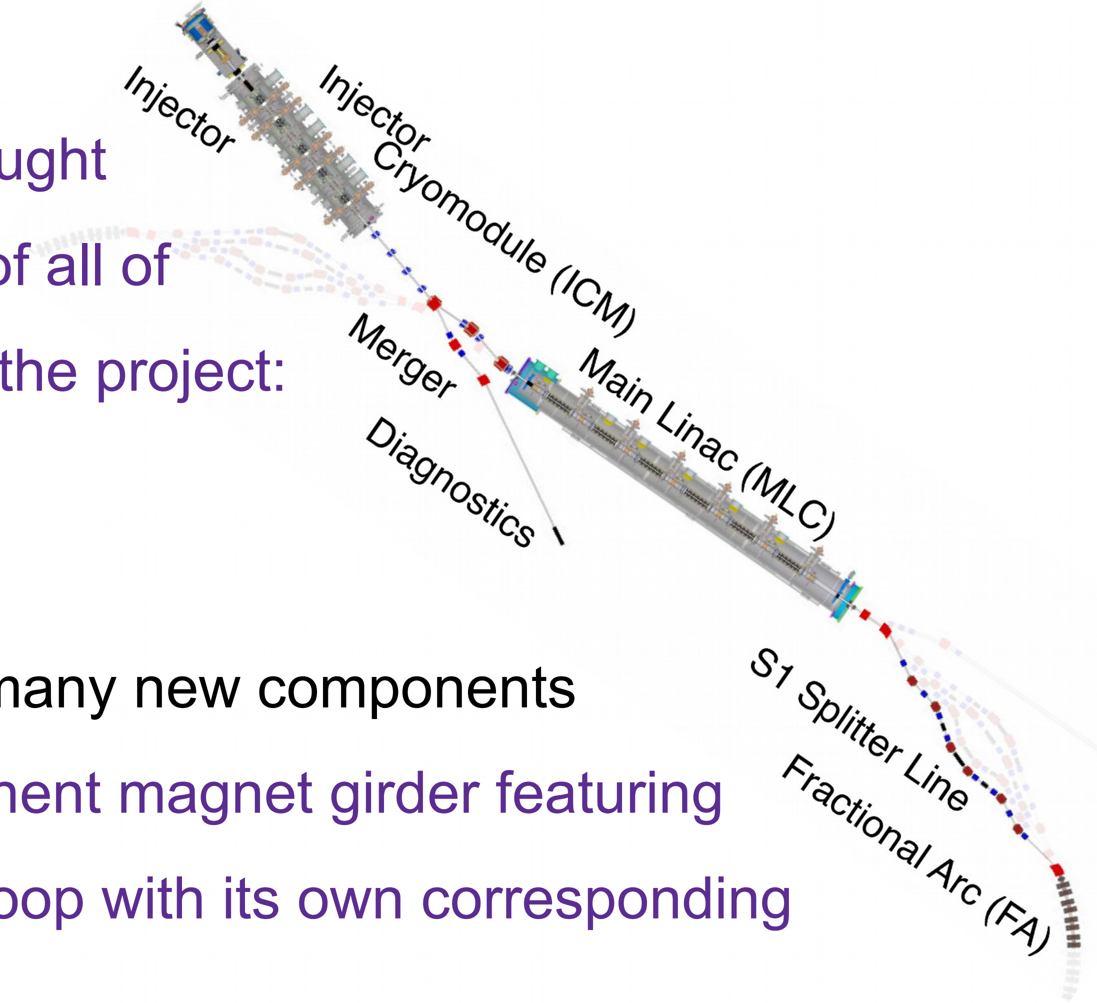
First beam to FFLAG arc: FAT

- Fractional Arc Test -

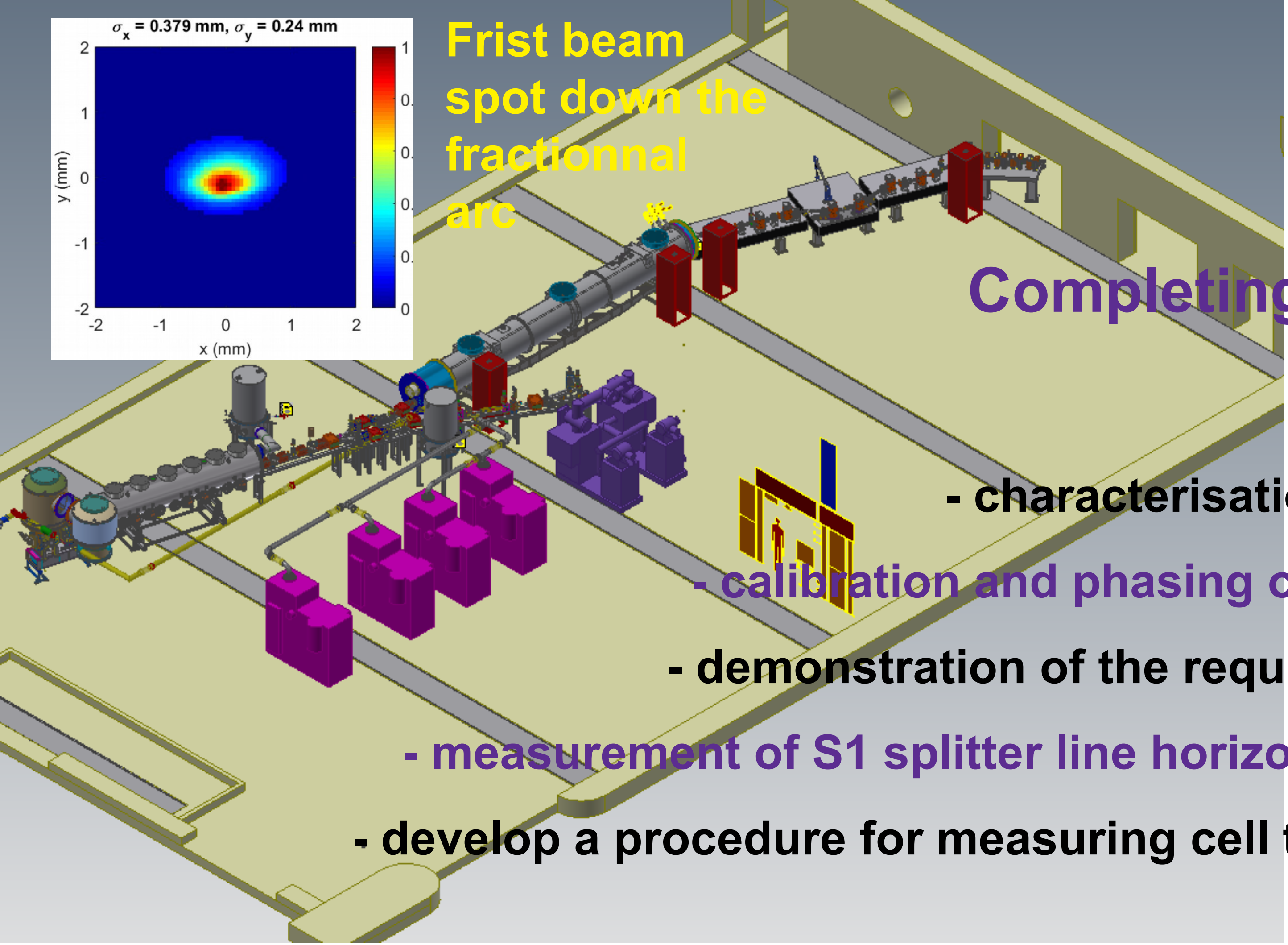
April-May last year

The CBETA **Fractional Arc Test** brought together for the first time elements of all of the critical subsystems required for the project:

- Injector
- Main Linac Cryomodule (MLC)
- Low energy (S1) splitter line with many new components
- A first prototype production permanent magnet girder featuring 4 cells (8 quads) of the FFA return loop with its own corresponding vacuum system and BPM design



RESULTS FROM THE CBETA FRACTIONAL ARC TEST, C.~Gulliford et als., IPAC2019.

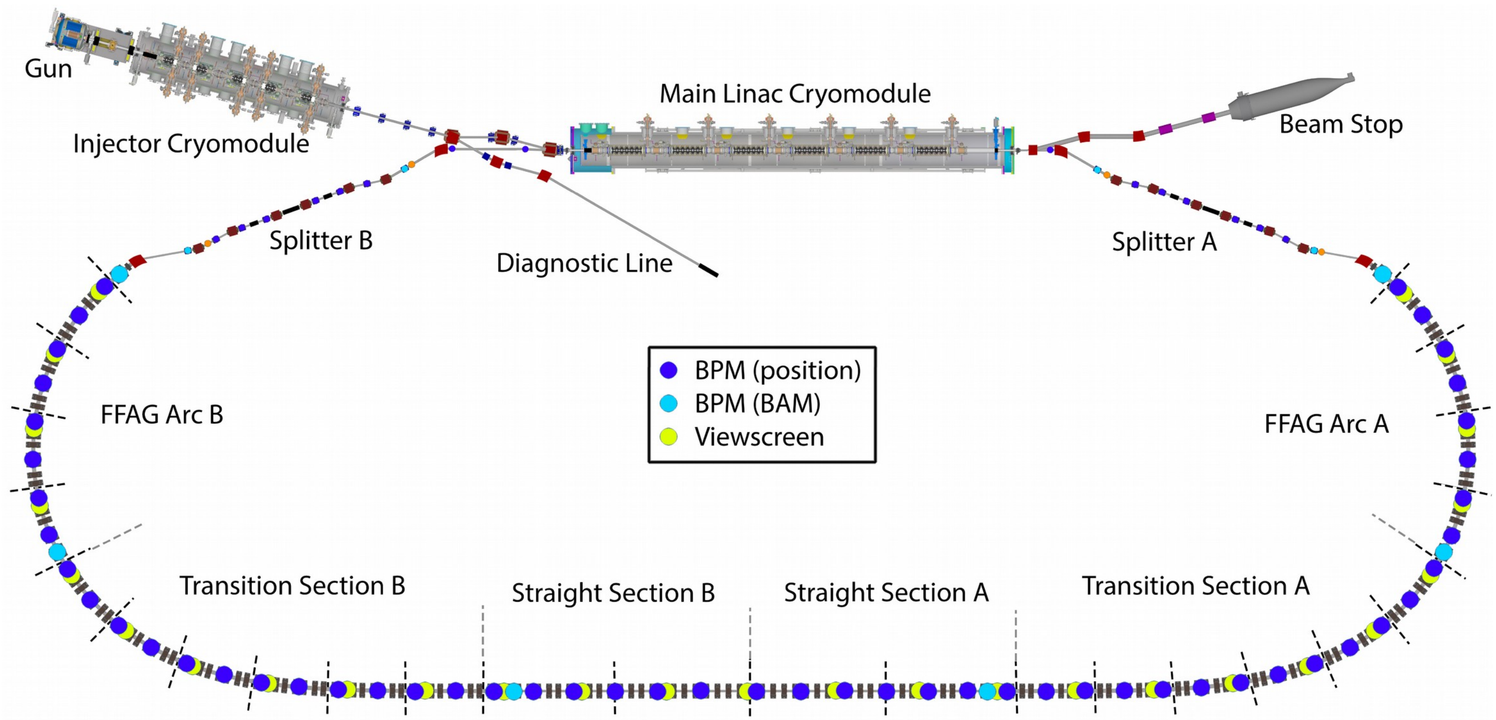


Frist beam spot down the fractionnal arc

Completing the test required:

- characterisation of the injection beam
- calibration and phasing of the main linac cavities
- demonstration of the required 36 MeV energy gain
- measurement of S1 splitter line horizontal dispersion and R56
- develop a procedure for measuring cell tune in the 4-cell FFLAG

CBETA construction (2/3)
Towards 1-pass ER



CBETA, February 2019

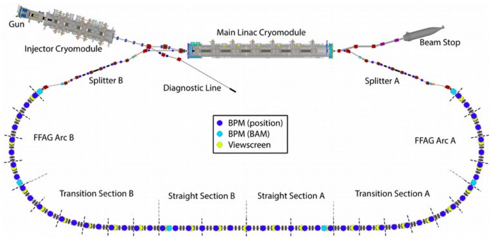
February 2019

First ER’ed beam:

1 pass up to 42 MeV /
1-pass down to 6 MeV and dump

March-June 2019

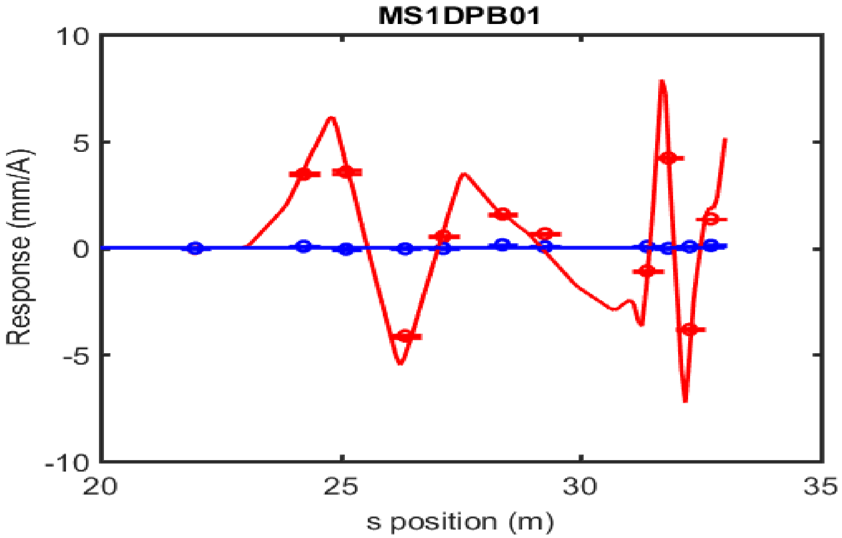
Optics measurements



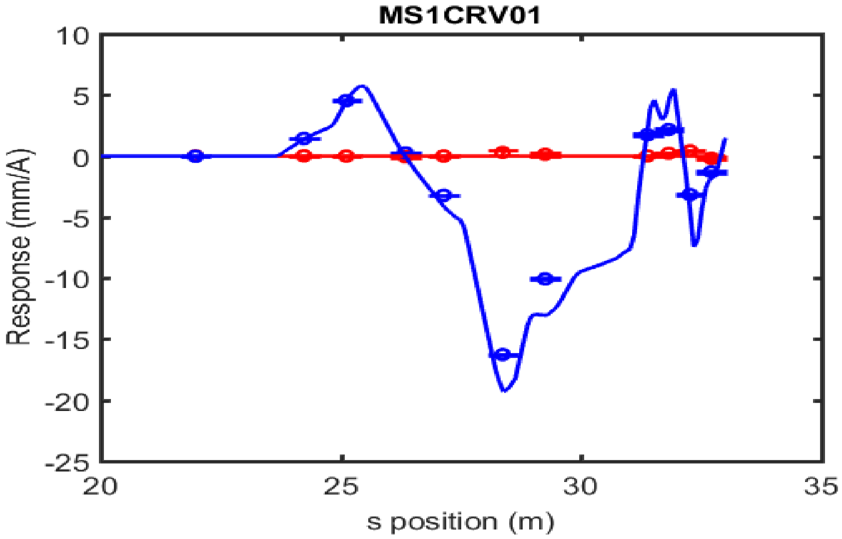
Orbit Response. Here at 42 MeV, along S1:

- Response data served live using the on-line model “CBETA-V”
- Detailed measurements help refine the model off-line

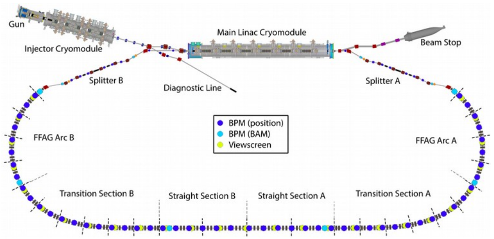
Example: First horizontal dipole kick



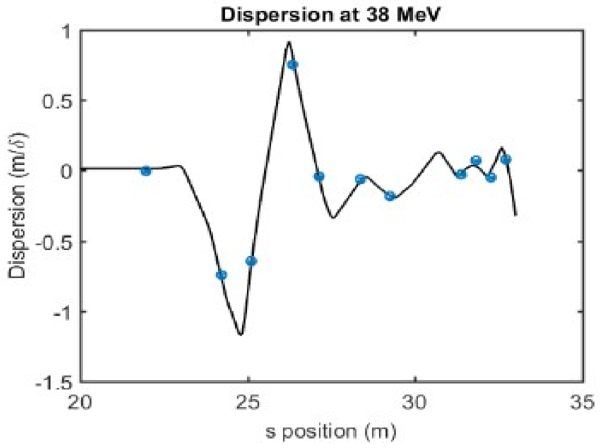
Example: First vertical dipole kick

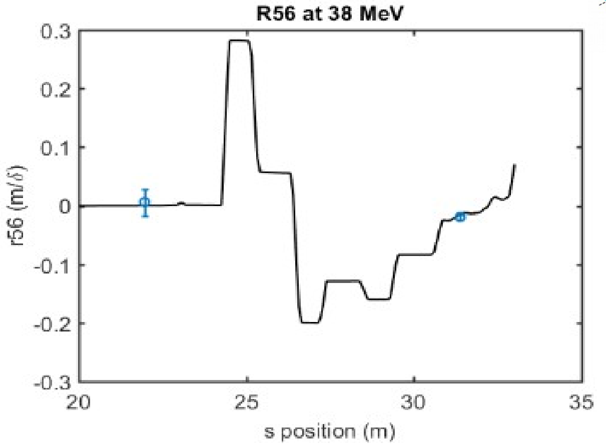


Dispersion and R56 along S1, from an energy scan (last MLC cavity).

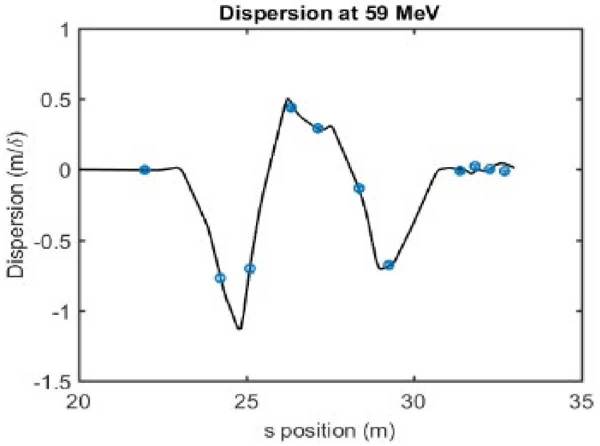


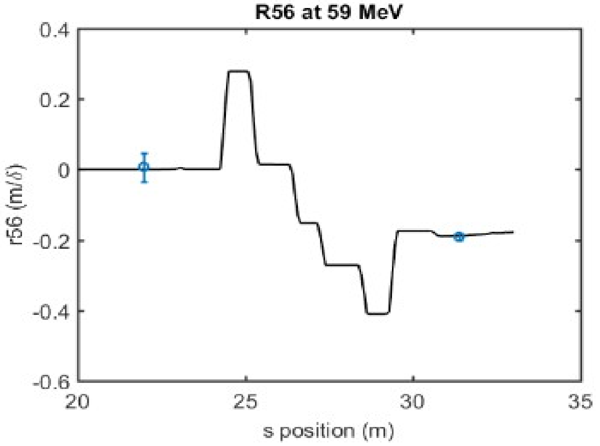
38 MeV



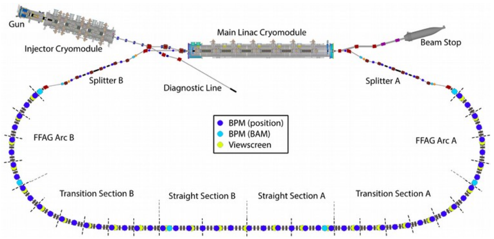


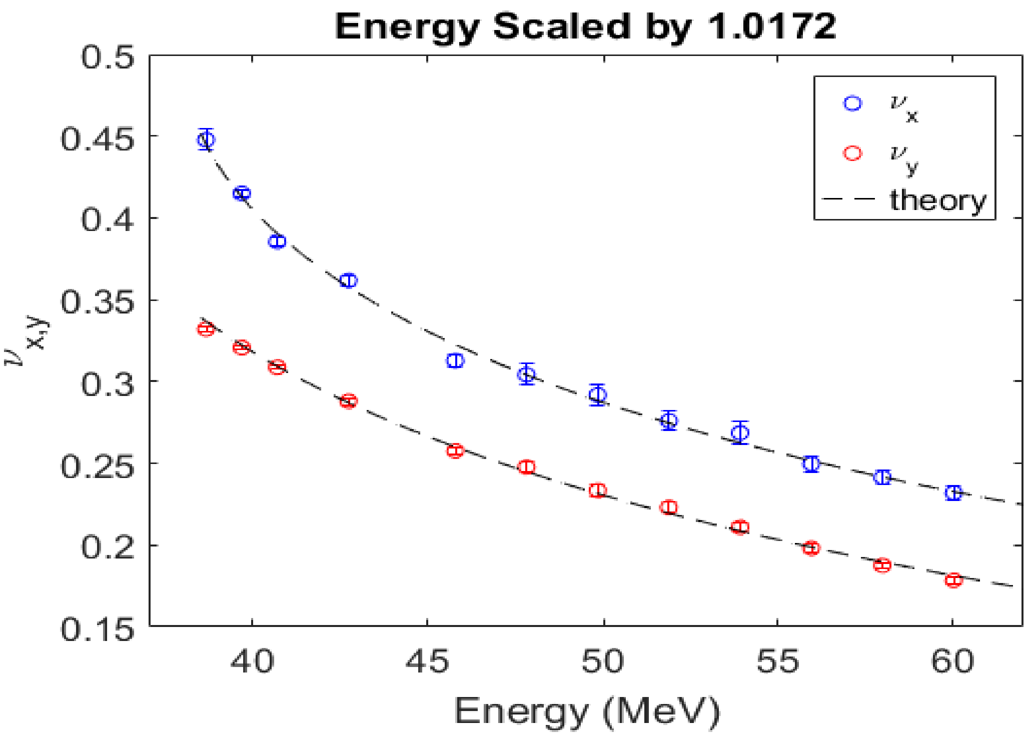
59 MeV



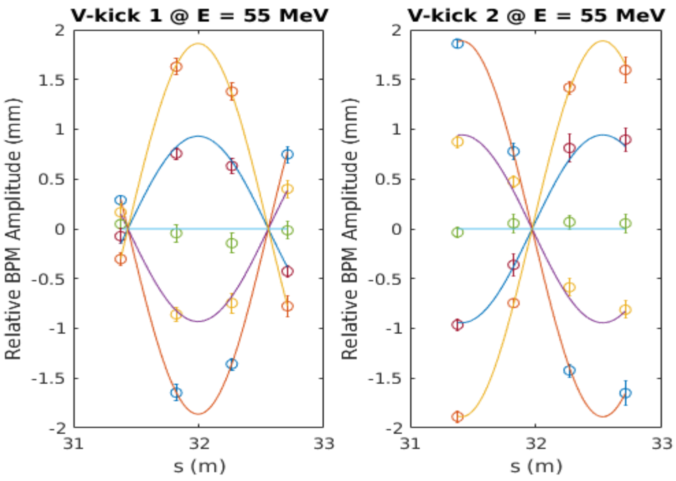


Tune Measurements vs. Energy, in FFLAG





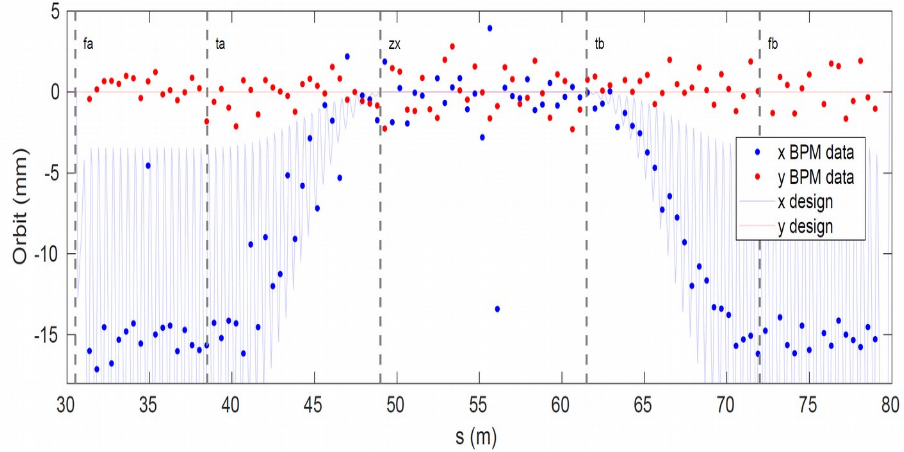
Tunes (left) are derived from interpolation of kick-induced betatron oscillation by analytical transport model

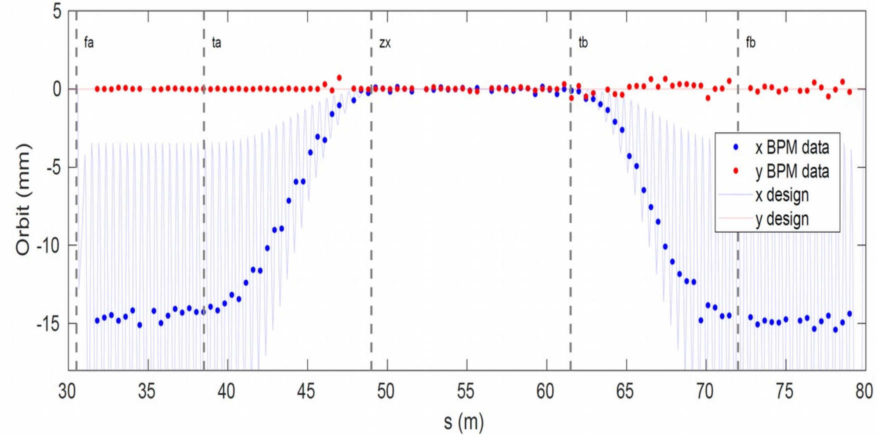


Orbit Correction, along FFLAG

- Orbit correction uses response matrix and SVD solver

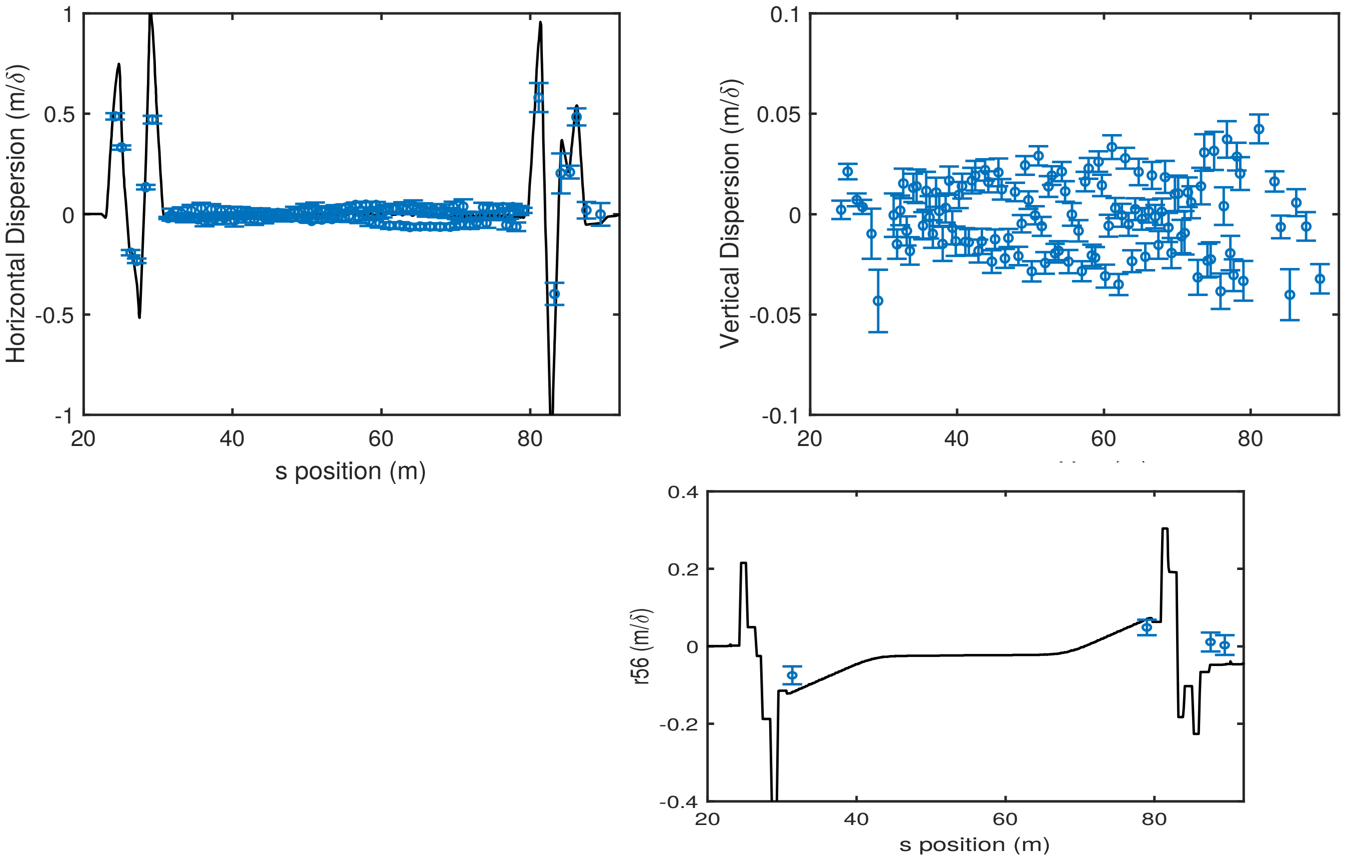
Horizontal and vertical positions on BPMs through the FFLAG arc for initial orbit (left) and corrected orbit (right).
Note: beam makes it throughout, even w/o correction.





Dispersion and R56, complete loop

Measure and compare with CBETA-V virtual machine simulation

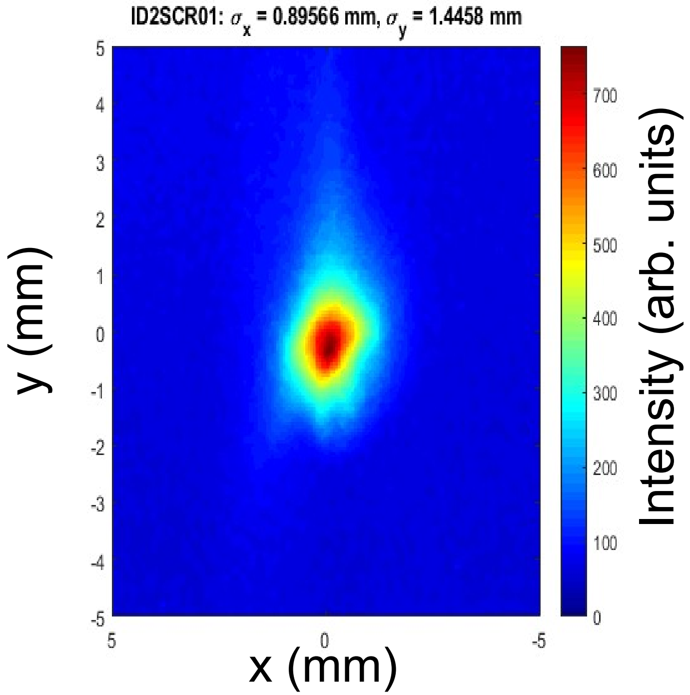


High acceptance lattice

- Permanent magnet region is very clean - beam losses are hardly measurable, by far dominated by other regions.

First Recirculation

- June 2019, first circulated beam, acceleration to 42 MeV, back to 6 MeV through the MLC into the beam stop



Beam on first viewscreen in dump line: first energy-recovered beam spot @CBETA ,June 24th, 2019

1-pass energy Recovery

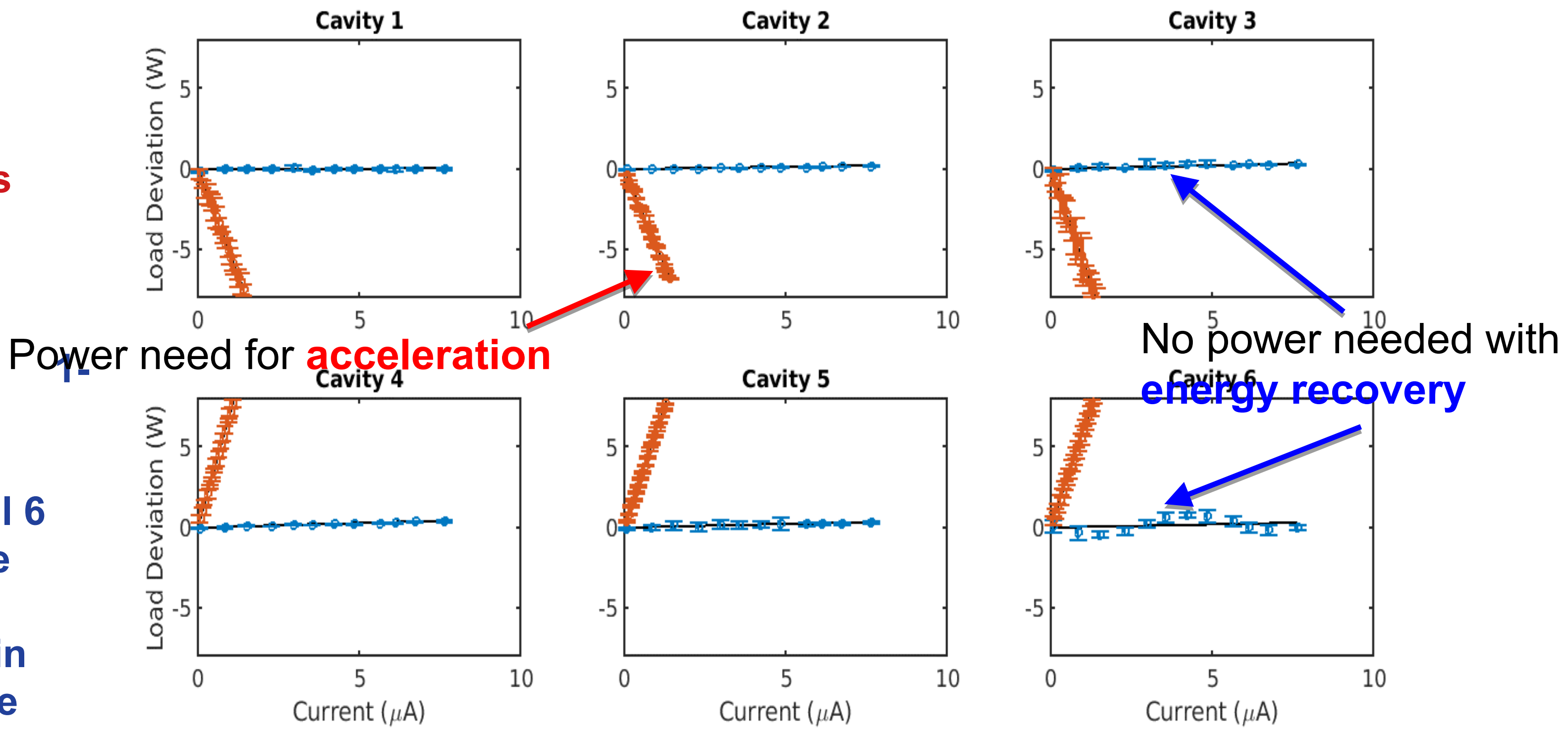
- Transmission 99.6 ± 0.1% ; energy recovery > 99.8%
- Measured up to 8 μA
- Each cavity accelerates beam without receiving external power

Experiment #1:

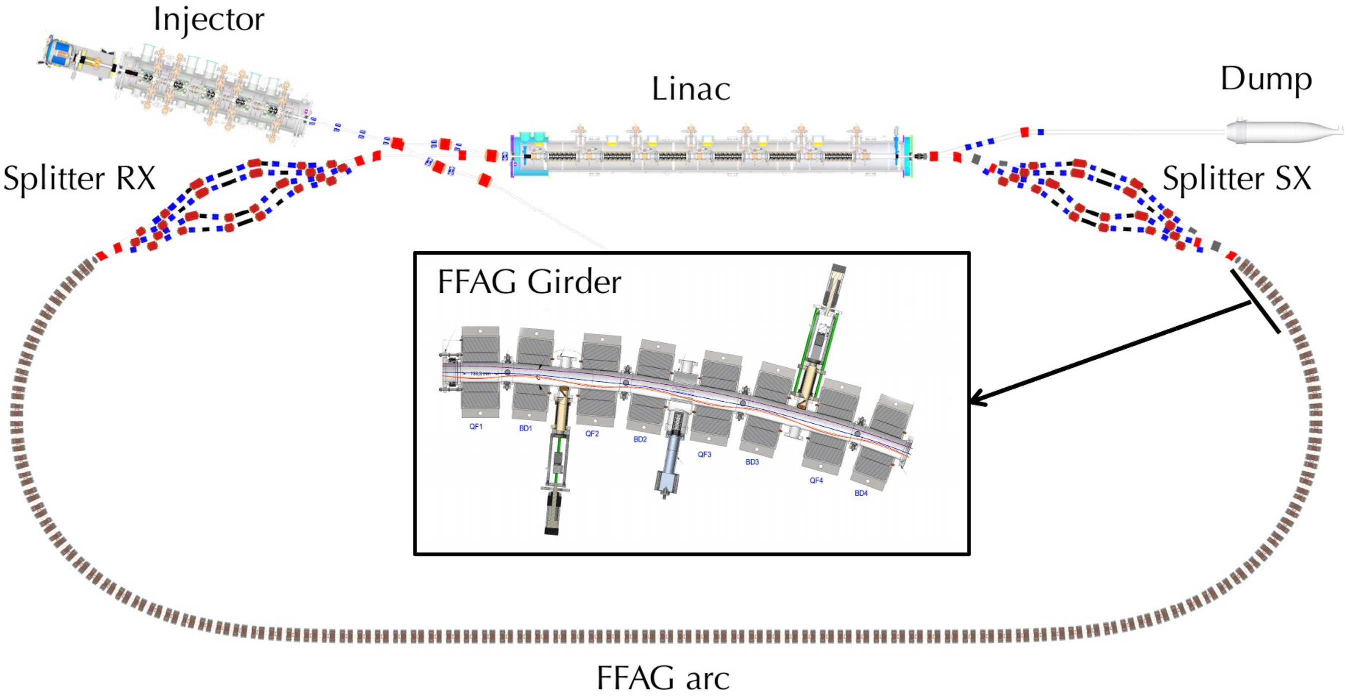
- first 3 cavities accelerate
- second 3 cavities decelerate

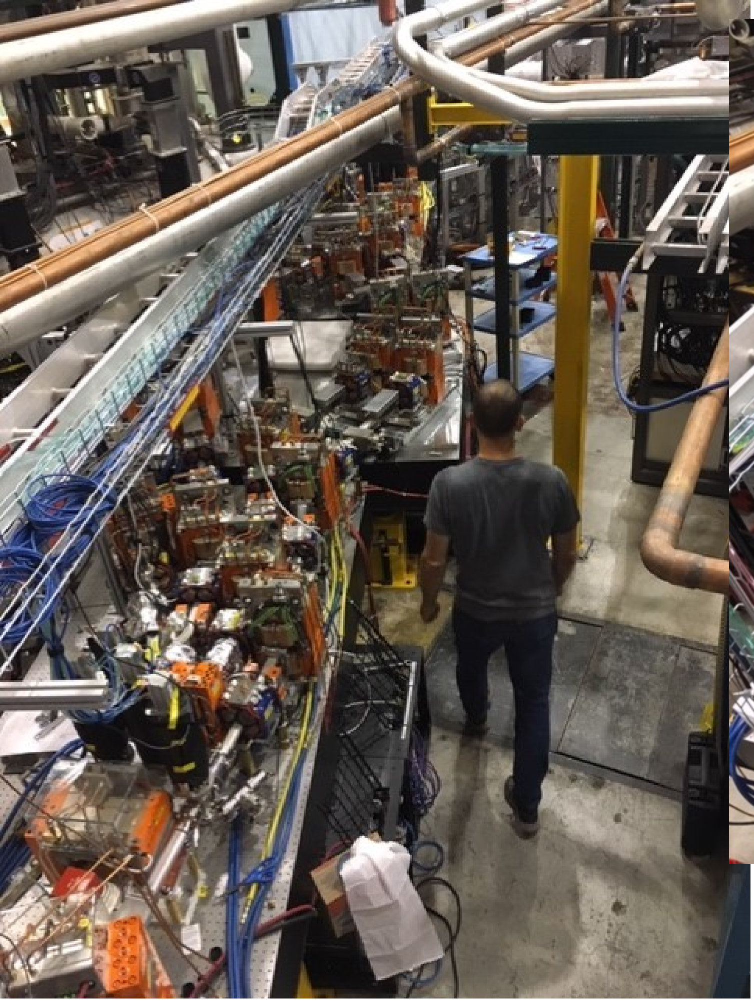
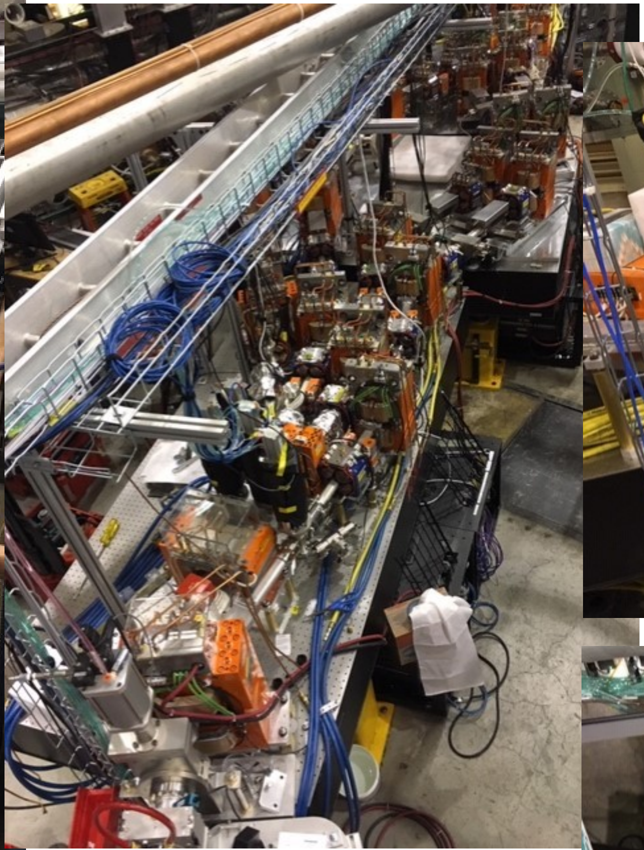
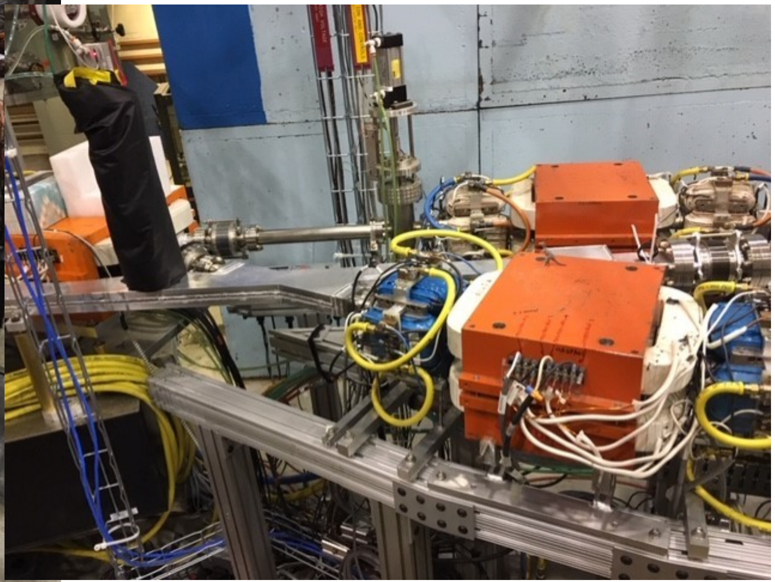
Experiment #2:
1-pass ER

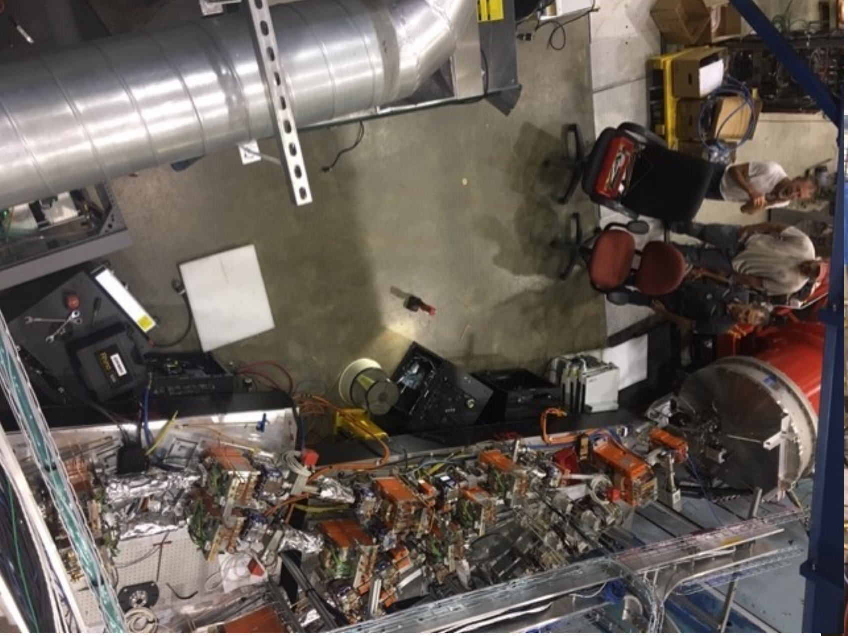
- 1st linac pass: all 6 cavities accelerate
- 2nd linac pass is in decelerating phase

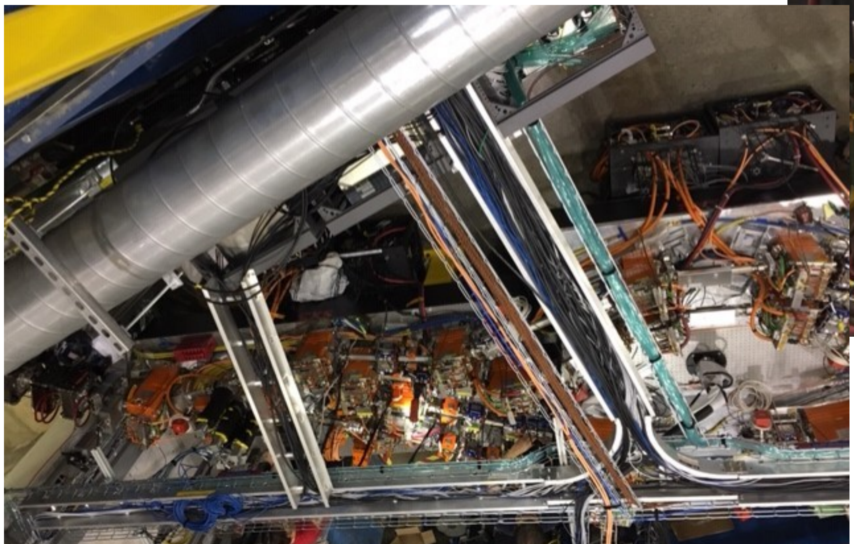


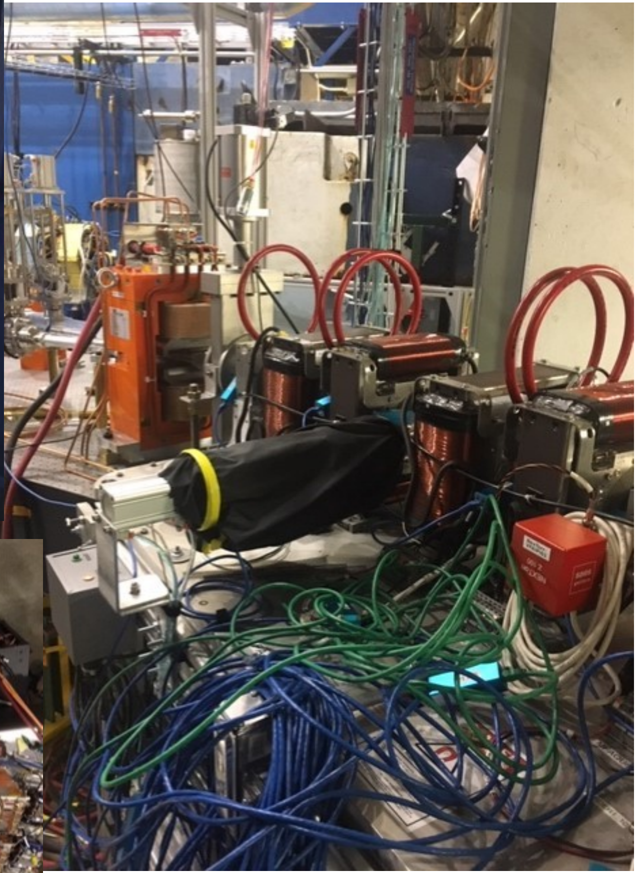
CBETA construction (3/3)
Toward 4-pass ER
Was this summer: July-September

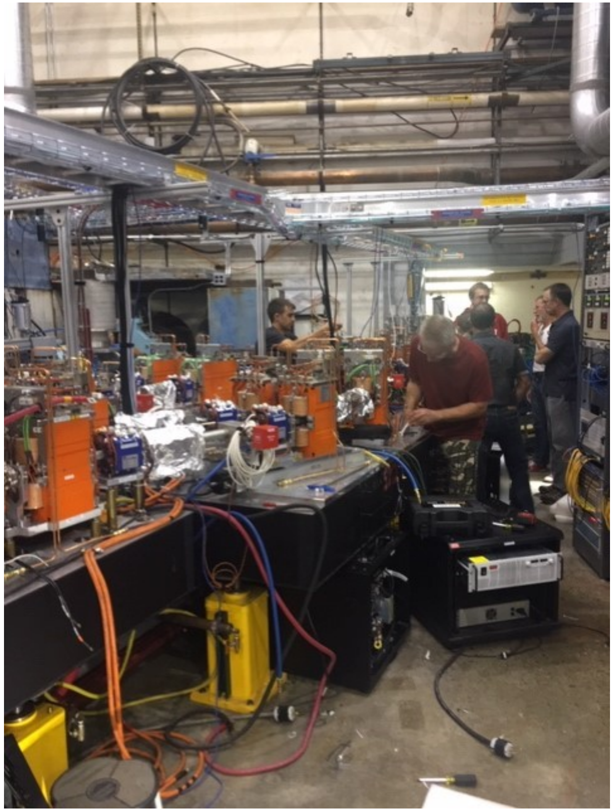


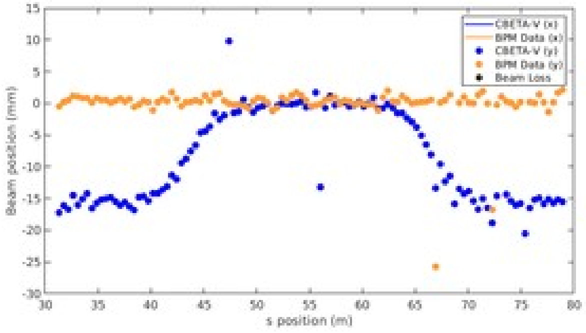






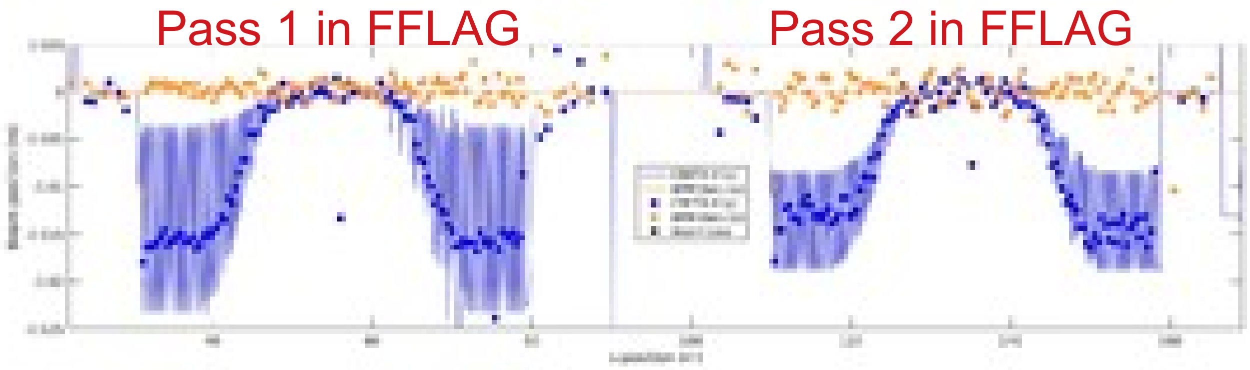
¿ Where is the beam (today) ?

10/09/2019: MLC Initial RF Turn On



10/14/2019: MLC successfully brought to 36 MeV.
Beam makes it through to entrance to R1.

10/23/2019: Got beam around FFLAG loop on 2nd pass



CONCLUSION

The way is open for CBETA program completion

#	Milestone	Baseline	Actual
	Funding start date		Oct-16
1	Engineering design documentation complete	Jan-17	
2	Prototype girder assembled	Apr-17	
3	Magnet production approved	Jun-17	
4	**Beam through Main Linac Cryomodule**	**Aug-17**	
5	First production hybrid magnet tested	Dec-17	
6	**Fractional Arc Test: beam through MLC & girder**	**Apr-18**	
7	Girder production run complete	Nov-18	
8	Final assembly & pre-beam commissioning complete	Feb-19	
9	**Single pass beam with factor of 2 energy scan**	Jun-19	
10	**Single pass beam with energy recovery**	Jun-19	
11	**Four pass beam with energy recovery (low current)**	Dec-19	
12	Project complete	Apr-20	

ER@CEBAF

Most recent news,

and they are very positive...

ER@CEBAF: 7 GeV, 10-pass, ER experiment proposal, as part of LR-eRHIC EIC R&D

(ERL2017, CERN – WEIACC003.pdf)

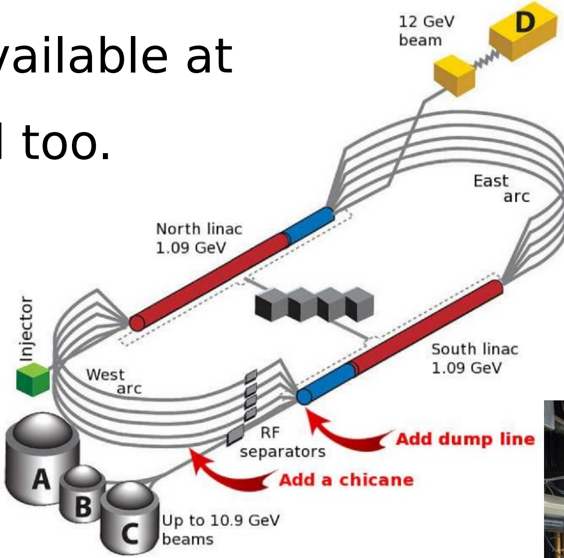
- Four main dipoles from Cornell light source upgrade save ~$300k on cost! Will be installed as Arc10 chicane, plan is **May 2020**.
- A spare beam dump is available at CEBAF, will be installed too.
- Demo requires
  - < 1 week of beam
- ***We're soon there!***

Machine/Lattice Parameters of ER@CEBAF

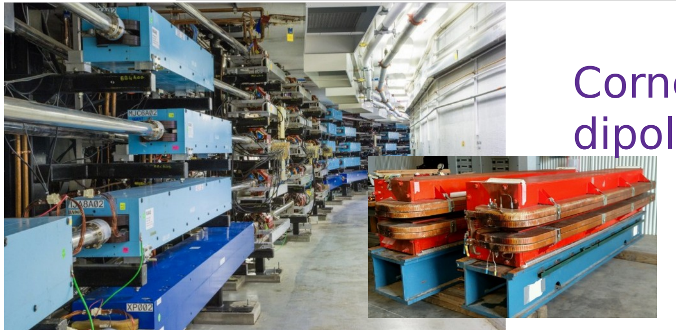
f_{RF}	1497	MHz	RF frequency
E_{linac}	700	MeV	Gain per linac (baseline)
E_{inj}	79	MeV	$= E_{\mathrm{linac}} \times 123/1090$
ϕ_{FODO}	60	deg	Per cell, at first NL pass and last SL pass
M_{56}	<90	cm	Compression, Arc A
Extraction	8	deg	Angle to dump line
Dump power	20	kW	
$\Delta\phi_{\mathrm{tol}}$	0.25	deg	Req$^{\mathrm{cd}}$ path-length control

Beam Parameters

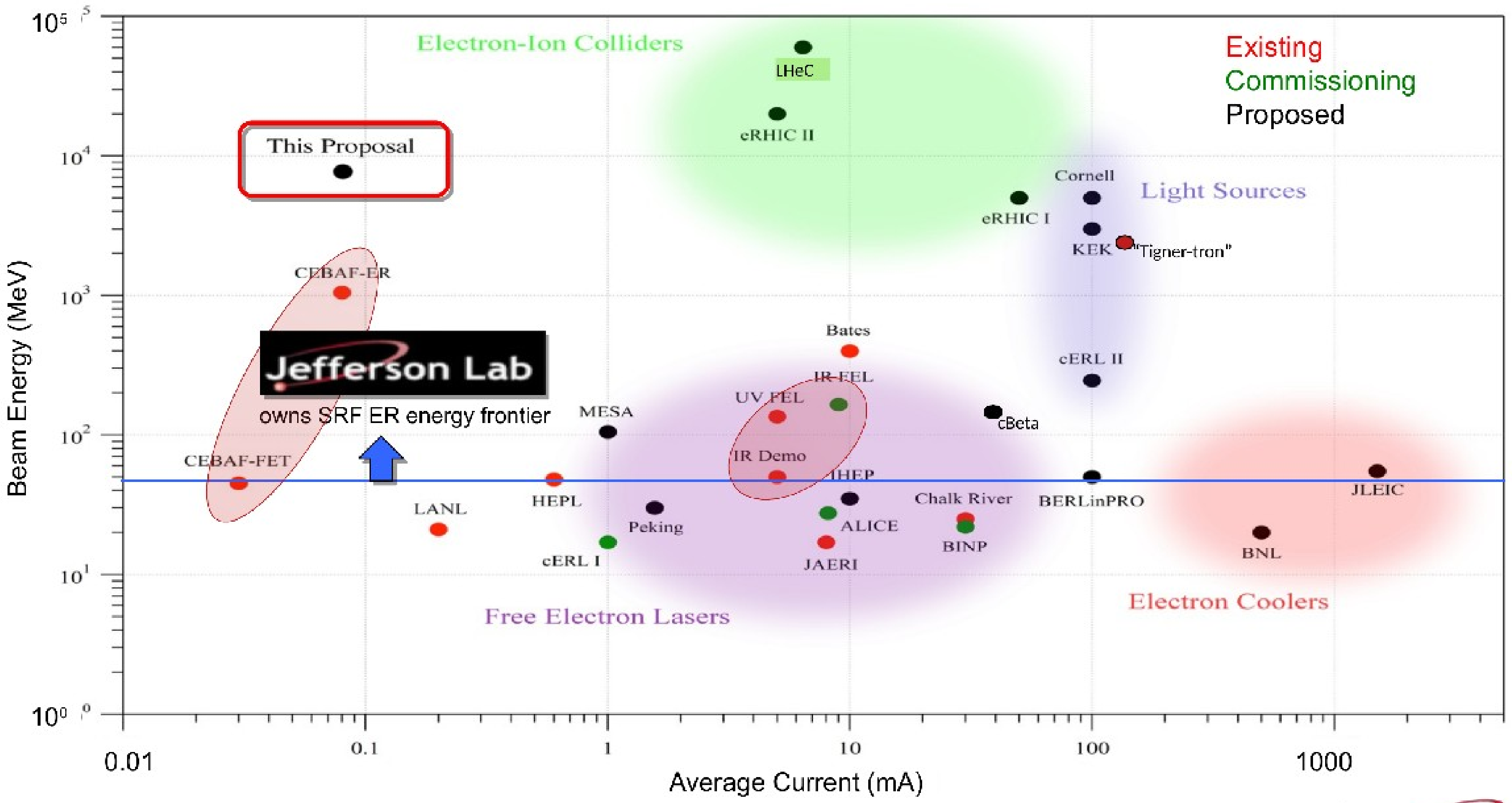
f_{beam}	31 - 499	MHz	Bunch rep. freq., CW
	7.485	MHz	Bunch rep. freq., tune mode
I_{beam}	100	μA	Max. CW beam current
q_{bunch}	0.2	pC	Bunch charge at 100 μA
σ_l	90 - 150	μm	Bunch length, high energy
σ_t	0.3 - 0.5	ps	
$\epsilon_{x,y}$	$\sim 10^{-8}$	m	Geom. emitt. at injection
dp/p	$< 10^{-4}$		Energy spread at injection
$\epsilon_{x,y}$	$\mathcal{O}(10^{-8})$	m	Geom. emitt., after ER
dp/p	2-3	%	At extraction



Detailed project report & costing: https://technotes.bnl.gov/PDF?publicationId=40234



Cornell dipoles

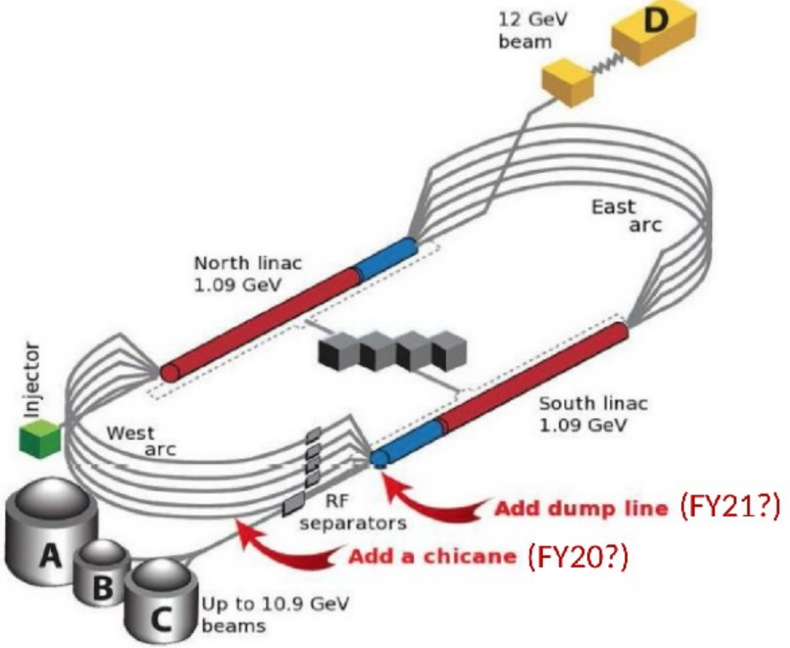


Jefferson Lab

CEBAF Energy Recovery Experiment: ER@CEBAF

T. Satogata

for the ER@CEBAF collaboration



Jefferson Lab Accelerator Advisory Committee Review

October 22 – 24, 2019

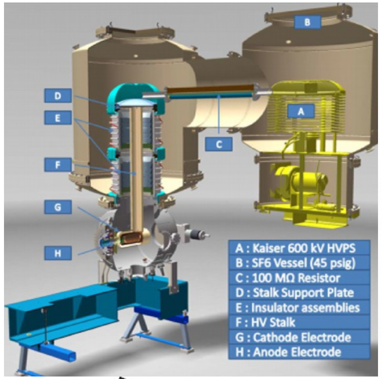
Jefferson Lab

U.S. DEPARTMENT OF ENERGY | Office of Science

JSA

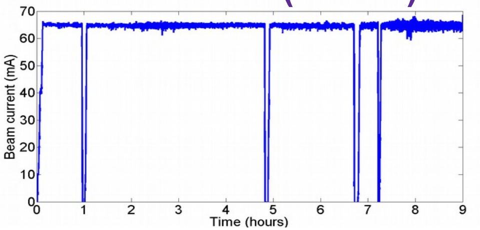
THANK YOU FOR YOUR ATTENTION

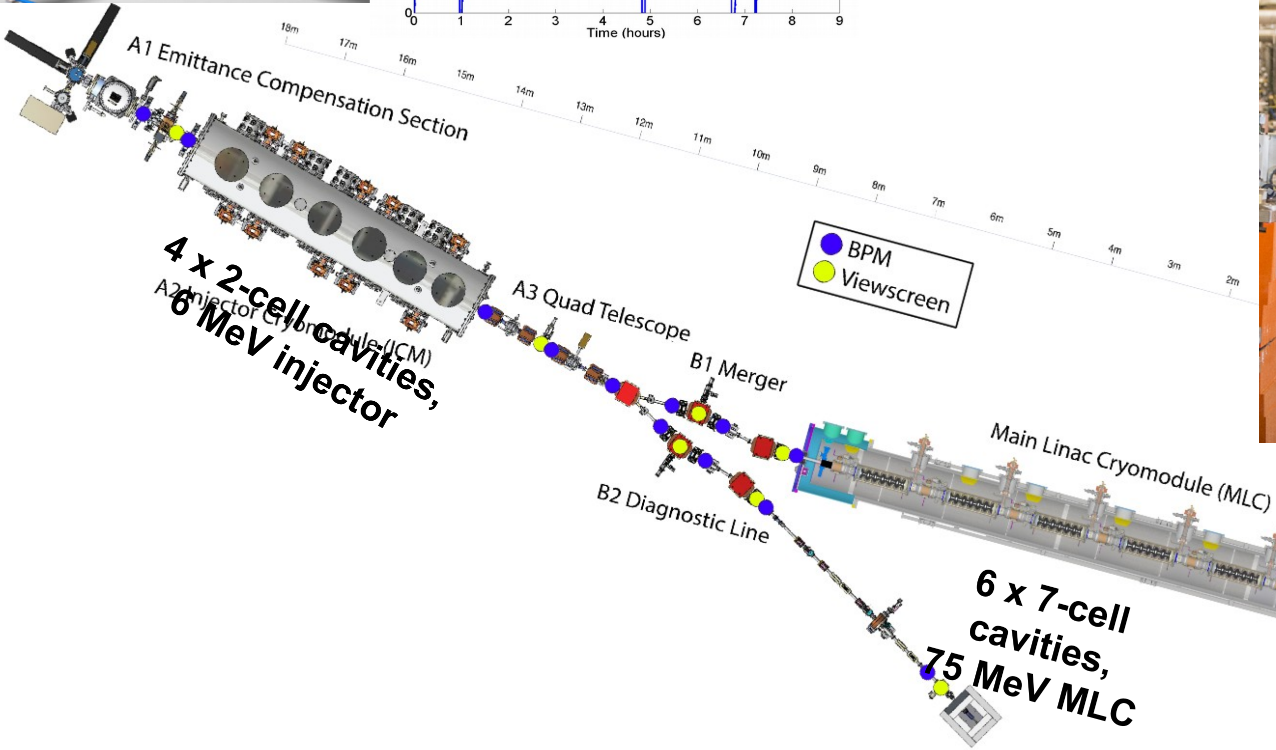
Backup slides



Cutaway view of the DC photoemission gun.

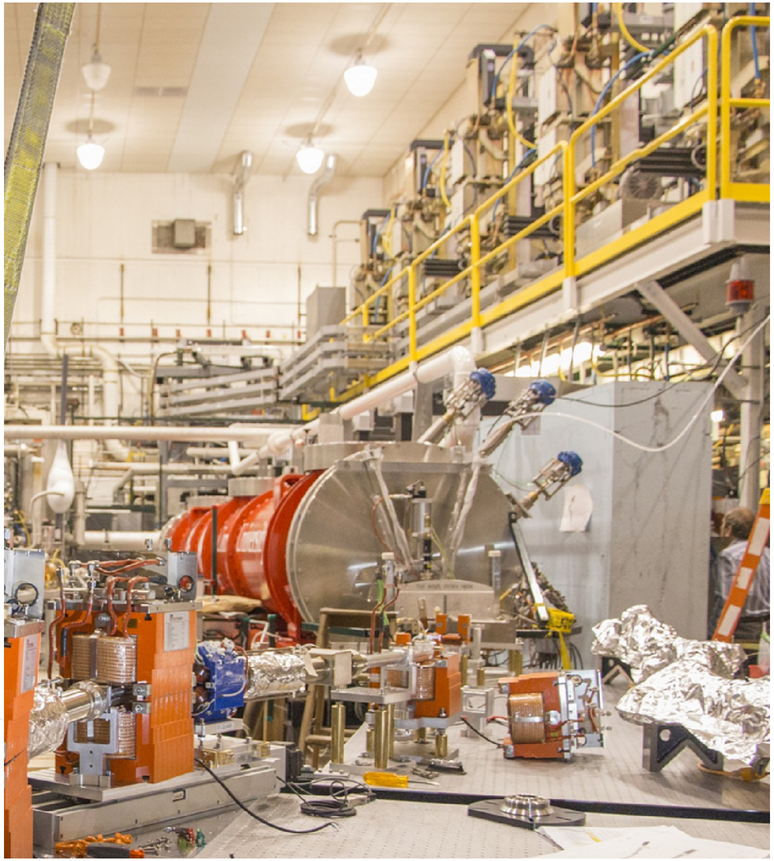
CW operation at 350kV fulfills CBETA needs (40 mA)





4 x 2-cell cavities, 6 MeV injector

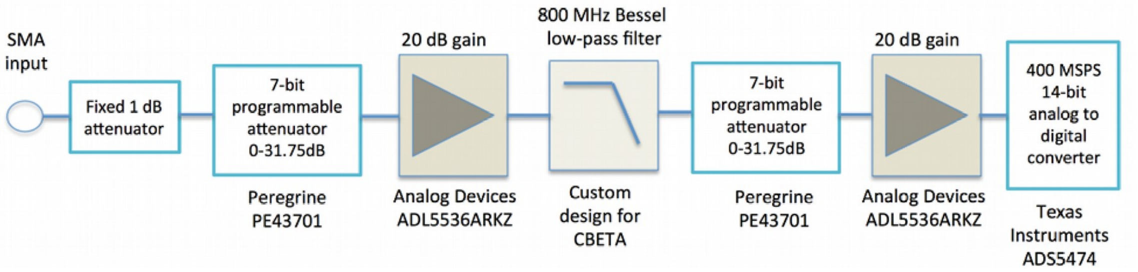
6 x 7-cell cavities, 75 MeV MLC



75MeV Main Linac Cryomodule (MLC) and its solid-state amplifier cabinets (under injector bench of klystrons).

BPMs

- 160 BPMs / 12 VME chassis
- Based on BNL design VME-based “V301 BPM board”



- A single beam/energy is measured at a time by triggering acquisition on peak of bunch, through energies.

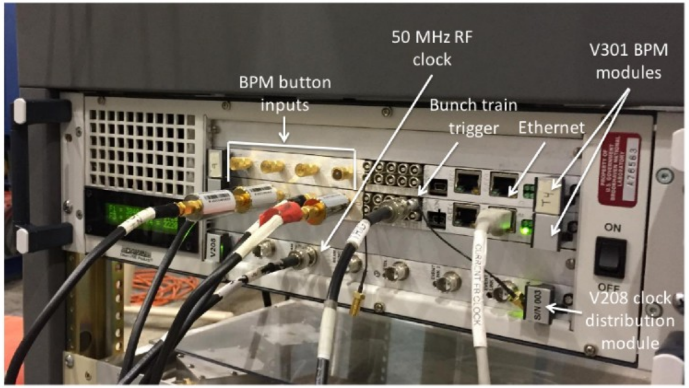
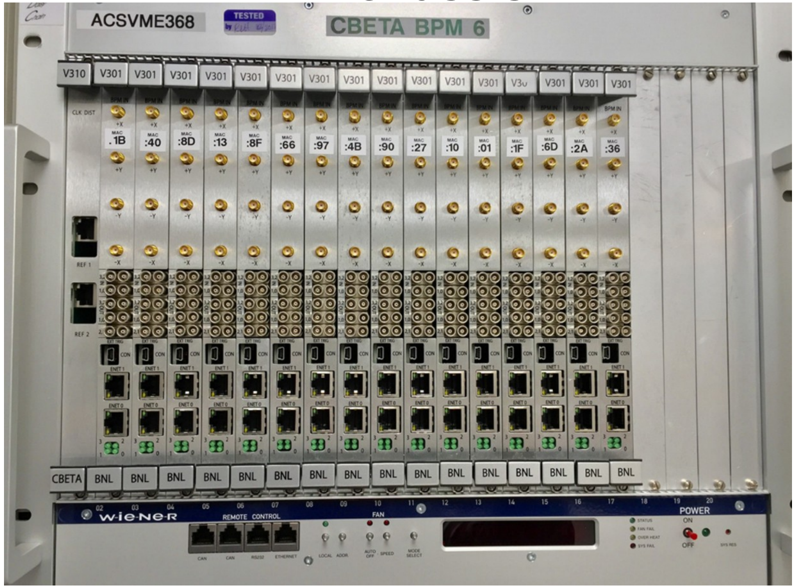


Figure 0.2.2: Fractional Arc Test: Technique for measuring beam positions at the peak of each bunch

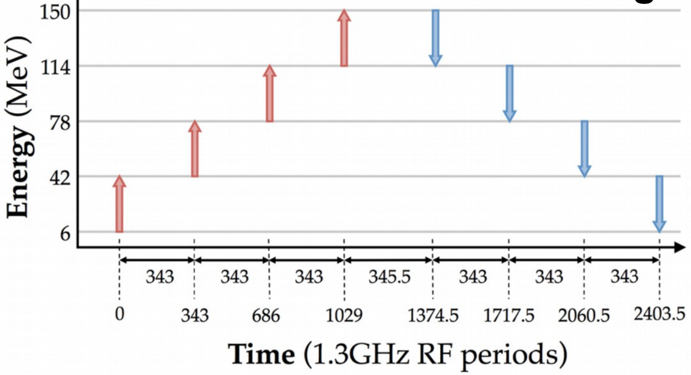
VME chassis



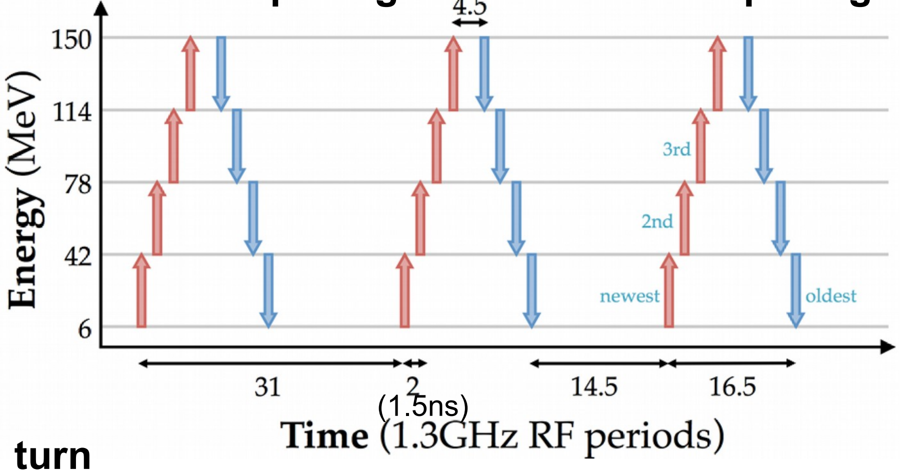
BPMs - CBETA bunch pattern

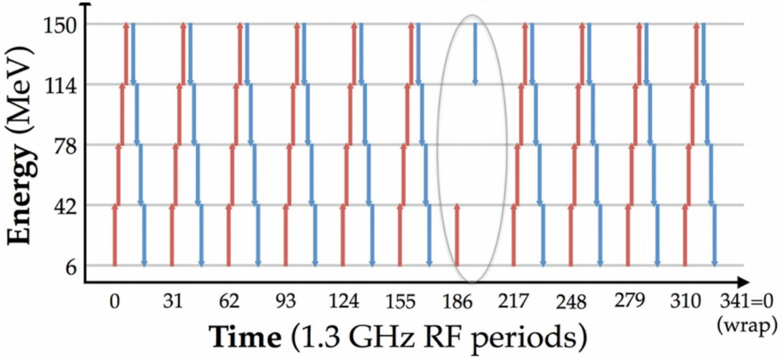
Up to 8 different energies (4 accelerating, 4 decelerating) must be independently measured.

Inject a bunch every 31 of 1.3GHz RF periods, a rep. Rate of 42MHz (and 11 bunches injected / turn). Distance between turns for a single bunch:



A bunch train is a sequence of 4 accel. and 4 decel. bunches. Bunch spacing and bunch train spacing:





One full turn of 11 bunch trains, including a probe 2-bunch train

The 2 probe bunches are 8.1 ns distant, allowing for BPM resolution

Parameter	Unit	KPP	UPP
Electron beam energy	MeV	150 42	150
Electron bunch charge	pC		123
Gun current	mA	1	40
Bunch rep. rate	MHz	42	325
RF frequency	MHz	1300	1300
Injector energy	MeV	6	6
# of turns		1	4
Energy aperture of arc		2	4