Cornell-BNL ERL Test Accelerator CBETA

Status & opportunities

Steve Peggs, Project Director,
for the CBETA collaboration

Acknowledgements

Thanks for material created by many people:

Cornell: Adam Bartnik, David Burke, John Dobbins, Rihc Gallagher, Colwyn Gulliford, Georg Hoffstaetter, Yulin Li, Peter Quigley, Karl Smolenski.

BNL: Scott Berg, Stephen Brooks, Khianne Jackson, George Mahler, Rob Michnoff, Steven Trabocchi, Dejan Trbojevic, Joe Tuozzolo.

Jefferson Lab: Steve Benson, Dave Douglas.

Oxford: Adam Steinberg.

SLAC: Chris Mayes (ex-Cornell).

Why an ERL?
Why BNL+Cornell ?

Energy Recovery – a new regime

Synchrotron: Repetitive acceleration, low repetition rate
high energy, low current, relatively large beam size.

Storage ring: Occasional fills, long-time storage.
Requires very low loss rates.
high energy, high current, relatively large beam size.

Linac: Single pass energy limited by the length.
Average_current*Energy limited by wall-plug power.
moderate energy, low current, small beam size.

ERL: Linear deceleration recaptures spent beam energy.
"No" wall-plug power limit on average beam current.
Very low loss rates + new accelerator physics regime !
moderate energy, high currents, small beam size.

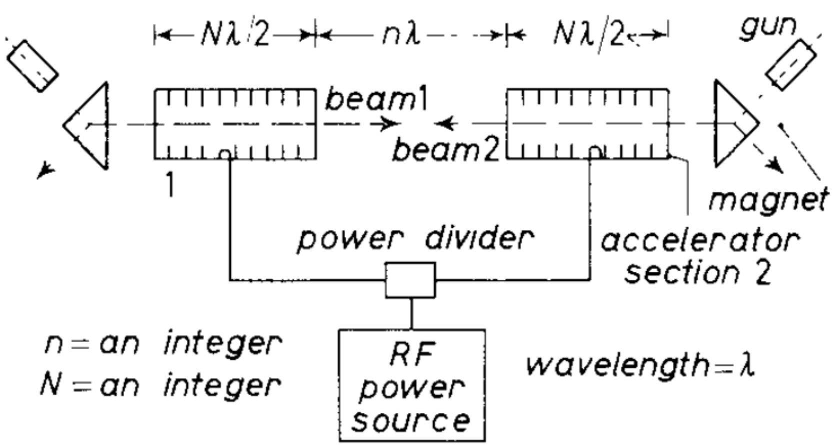
Cornell concept: Tigner 1965

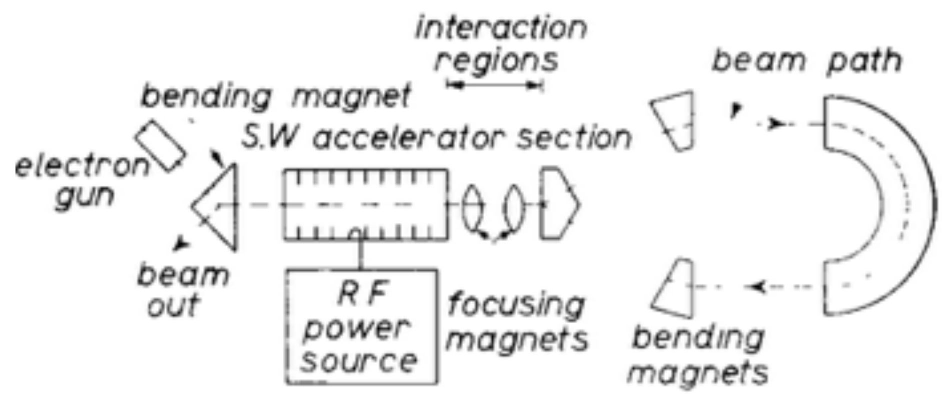
A Possible Apparatus for Electron Clashing-Beam Experiments (*).

M. Tigner

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

(ricevuto il 2 Febbraio 1965)





Energy recovery needs continuous waveform RF fields

- Normal conducting high field cavities waste energy.
- Superconducting cavities used to have too low fields.

Accelerators at Cornell

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1934 Livingston: first non-Berkeley cyclotron (2 MeV p)

1949 Wilson: first stored beam in synchrotron (300 MeV e)

1954 Wilson: first strong focusing synchrotron (1.1 GeV e)

1979 Cornell Electron Storage Ring CESR (up to 8 GeV)

1990's World's highest luminosity for a decade

2017 CESR operation & upgrade as light source CHESS

CESR as a storage/damping ring test facility

ERL prototyping facility (eg for proposed FEL)

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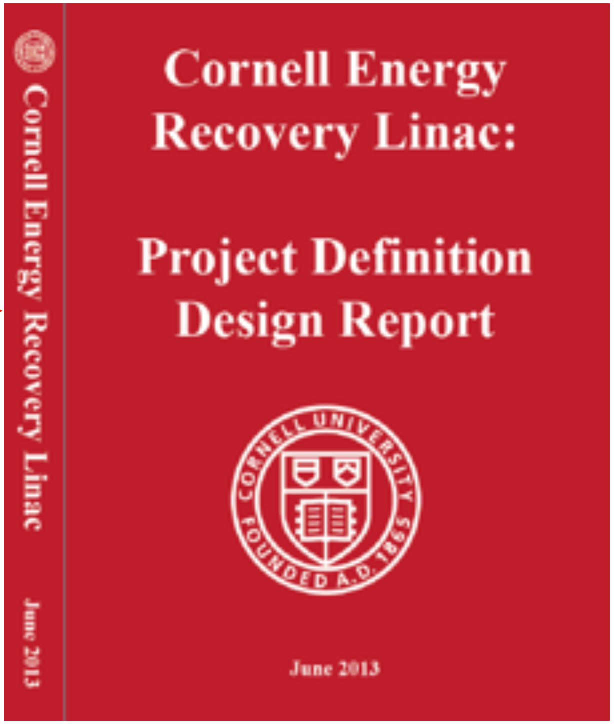

Federal & state funds

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2015 DOE Nuclear Science Advisory Committee Long Range Plan Recommendation III

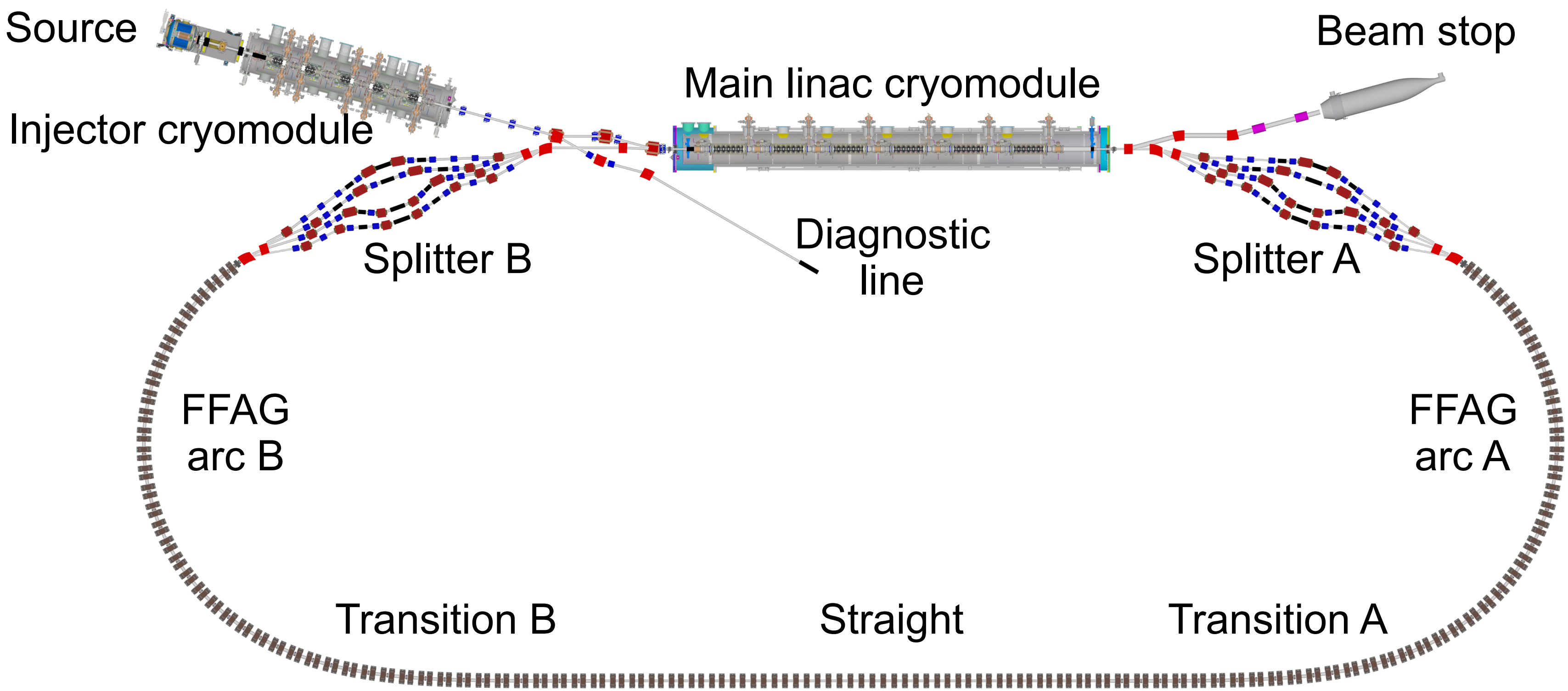
"We recommend a high-energy, high-luminosity polarized Electron Ion Collider as the highest priority for new facility construction following the completion of FRIB."

New York State Energy R&D Agency (NYSERDA) contract

"Successful demonstration [of CBETA] will ensure that the electric power requirements of the eRHIC design are within acceptable limits, with respect to operating costs and reuse of existing power infrastructure at BNL."

CBETA basics

CBETA layout

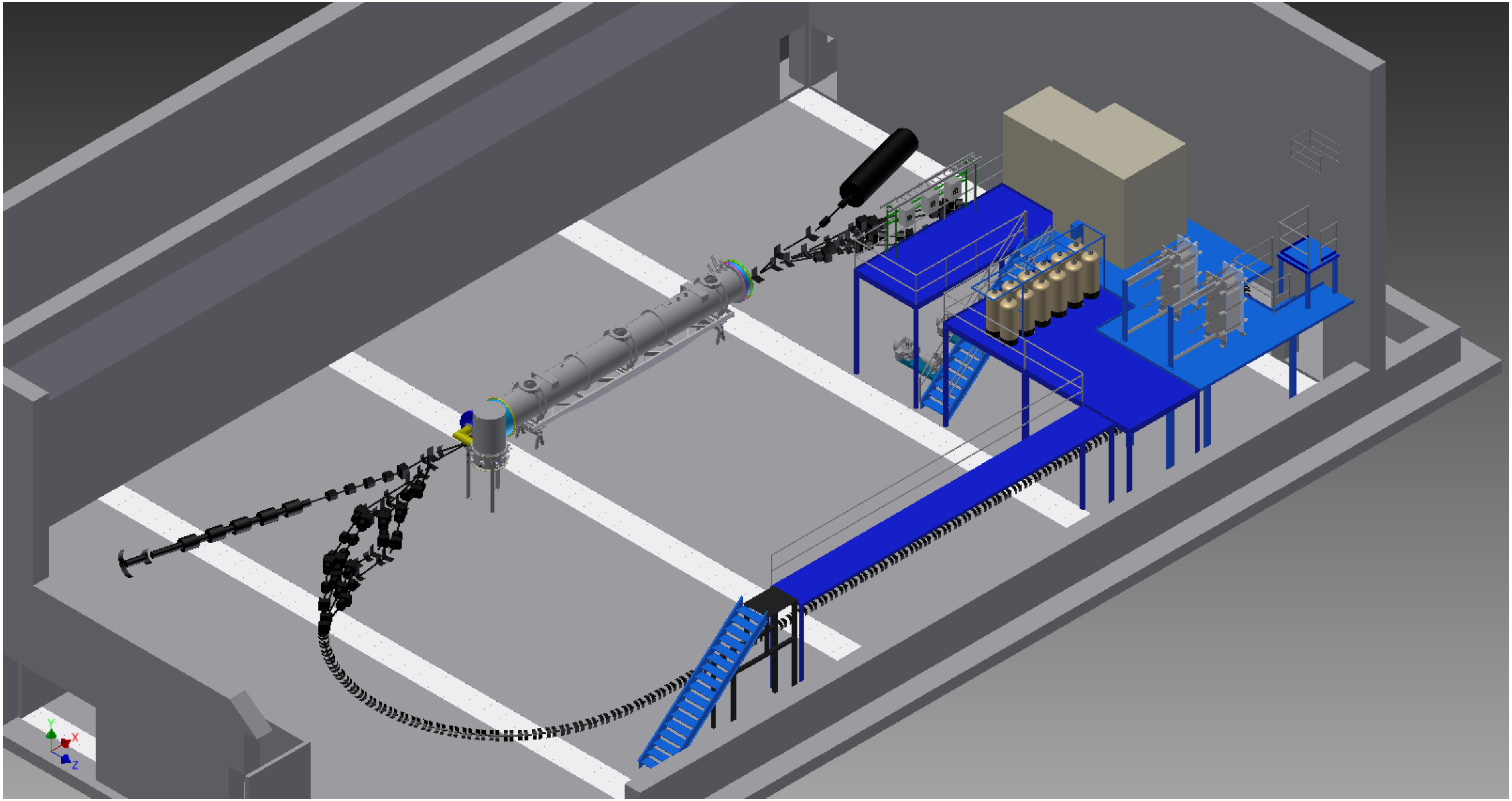


Much equipment & infrastructure exists — 32 M$

Major new equipment:

- 2 splitters (electromagnets & tables)
- Halbach (permanent) magnets in return arc
- Diagnostics, power supplies etc.

Experimental hall L0E



Circumference = 70.100 m

Four key features

4 key technical features …

1. 4 pass up, 4 pass down, energy recovery
2. Superconducting RF (1.3 GHz)
3. Very strong focusing single aperture optics
4. Halbach permanent magnets

… have been individually demonstrated elsewhere, but CBETA is first to put them all together.

The optics are unique in demonstrating no-symmetry adiabatic transitions from FFAG arc to straight.

These technologies could be used in a next generation EIC, e.g. eRHIC at BNL.

eRHIC topics at CBETA

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Very strong focusing return loop:

- Momentum aperture factor of 4
- Precision, reproducibility, alignment (production/installation).
- Stability of magnetic fields in a radiation environment.
- Matching & correction of 4 simultaneous orbits & optics
- Independent path length control for all orbits.

Multi-turn ERL operation:

- Higher Order Mode damping.
- Beam Break Up limits.
- Low Level RF control and microphonics.
- ERL startup from low-power beam.

Contract parameters

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Key Performance Parameters are 1-pass, with 4-pass capability fully installed.

Design parameters are stretch goals — with challenges / opportunities for post-NYSERDA collaboration

Parameter	Unit	KPP	Design
Electron beam energy	MeV		150
Electron bunch charge	pC		123
Gun current	mA	1	40
Bunch repetition rate (gun)	MHz		325
RF frequency	MHz	1300	1300
Injector energy	MeV		6
RF operation mode			CW
Number of ERL turns		1	4
Energy aperture of arc		2	4

Contract scope

BNL collaborate with Cornell University, to test & develop a 4 pass Energy Recovery Linac using a single aperture return loop with an energy acceptance factor of up to 4.

Relocate:

- Source gun with its laser system
- Injector Cryo-Module & Main Linac Cryomodule (MLC)
- High-power beam stop

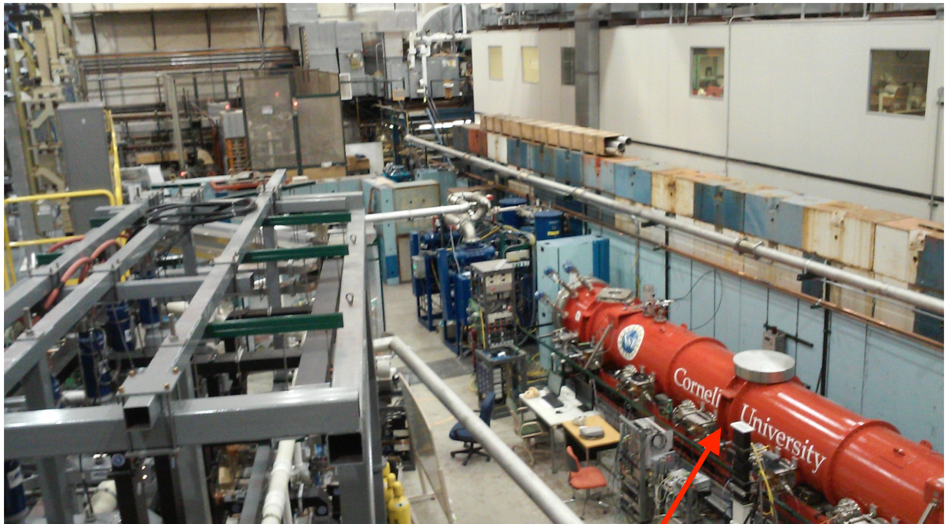
Install:

- Return loop with a single aperture accepting 4 discrete energies
- Splitters to connect the arc to the MLC.

Commission & operate with 1 mA, increasing towards 40 mA.

Visible evolution

January 2017



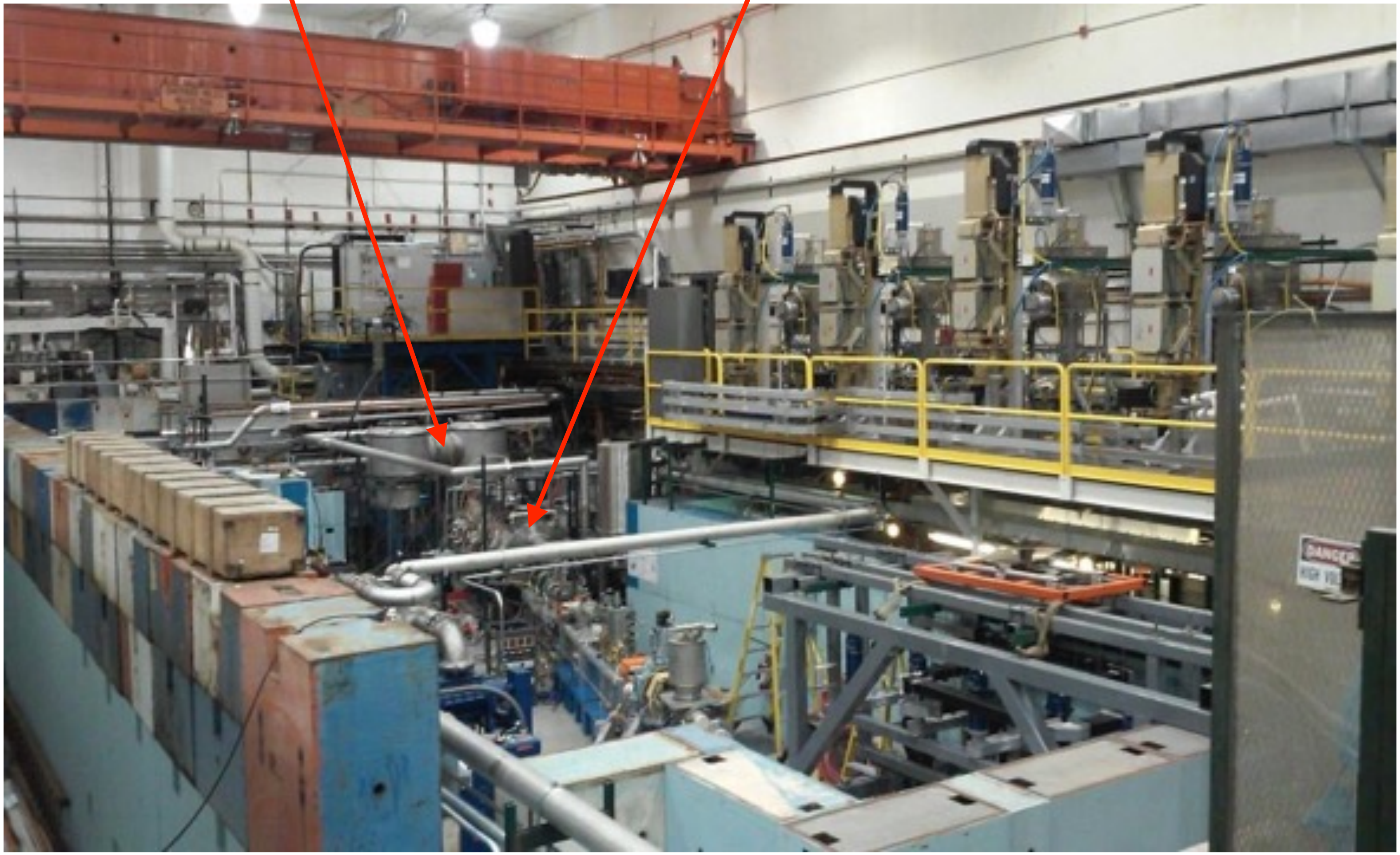
6-cavity
Main Linac Cryomodule (MLC)
in non-beam test location

Miscellaneous stuff
under a 30 ton crane

Spring 2017

High voltage
source gun
~400 kV

Injection
CryoModule
6 MeV



November 2017 — source

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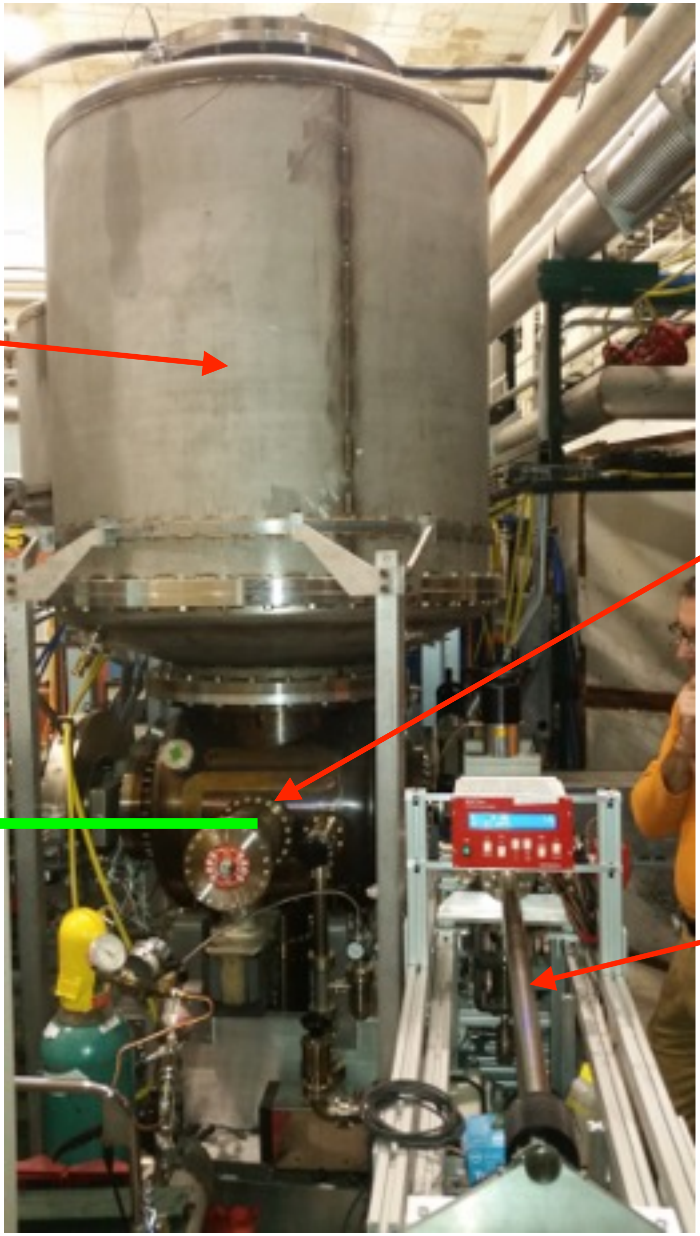
~400 kV DC



75mA photocathode

Electron beam

e^-

Translation stage to change photocathode pucks

Source

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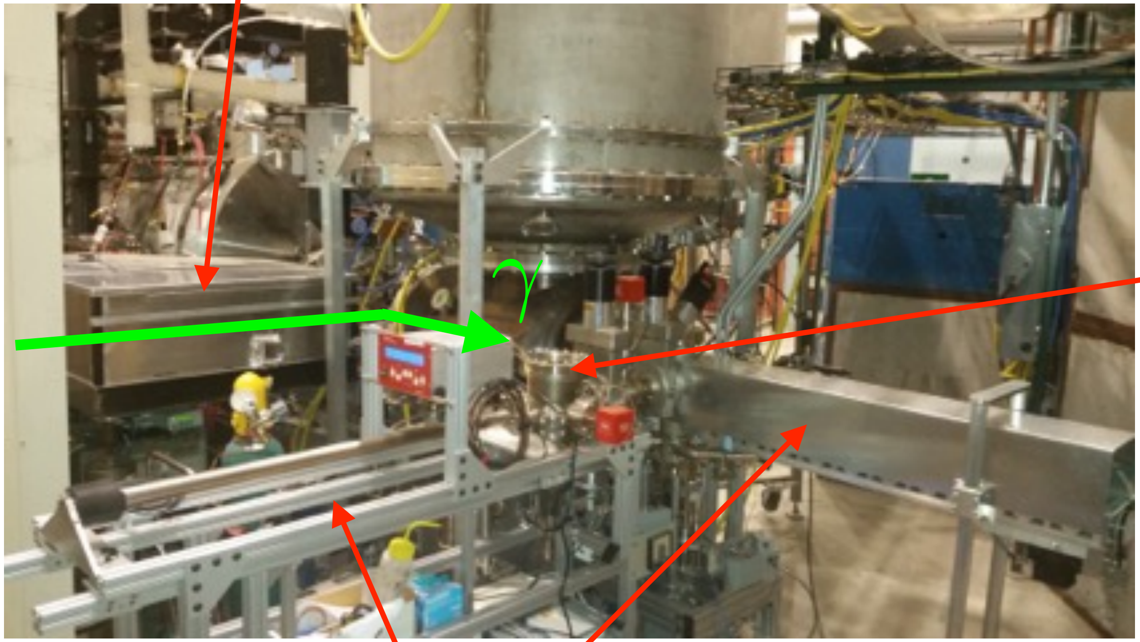
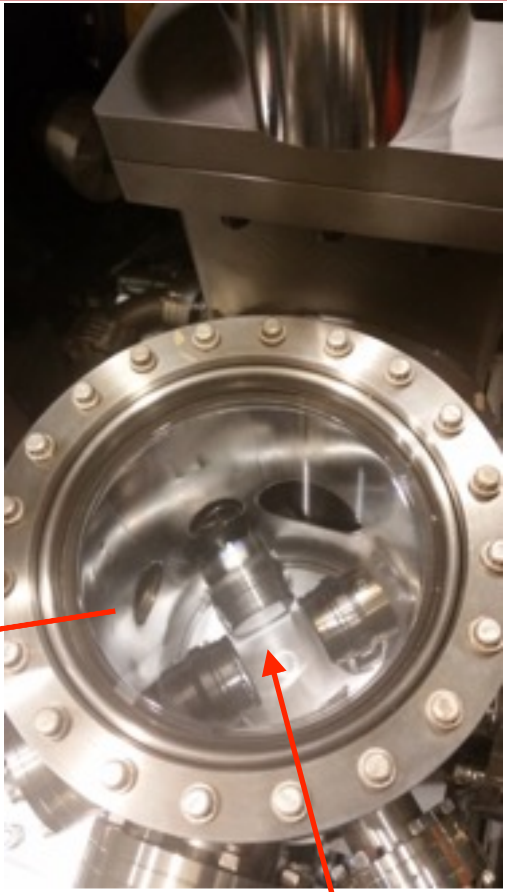
Laser table





Photocathode "pucks"

Translation stages

MLC in place for beam

September — FFAG17

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ILC, MLC, & diagnostic beamline

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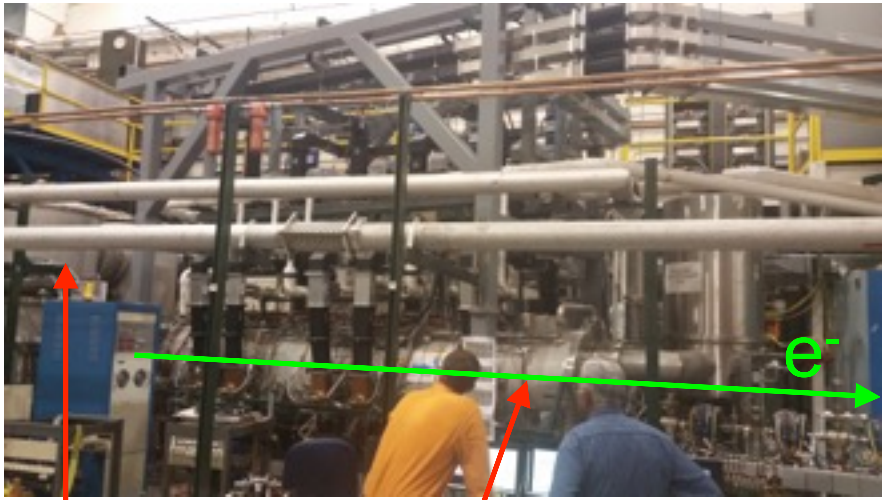

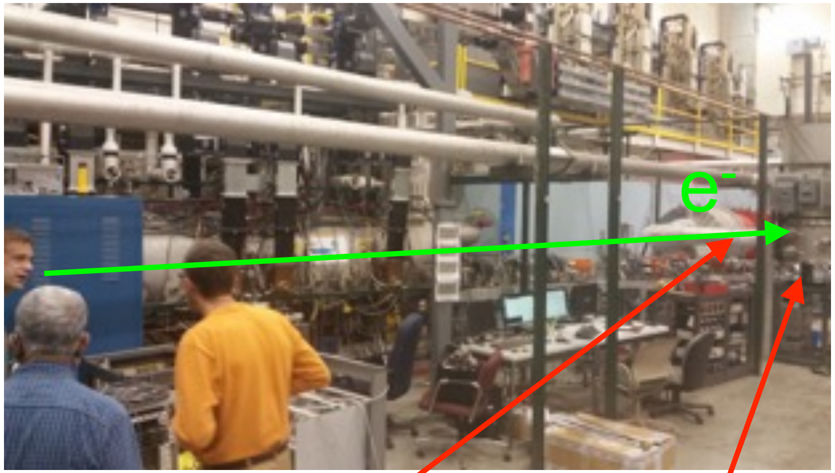

400 kV cans

Injection Cryomodule ICM

Main Linac Cryomodule

Diagnostic beamline

Beam commissioning

Schedule

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The 2-month timeline breaks down into 3 approximate phases:

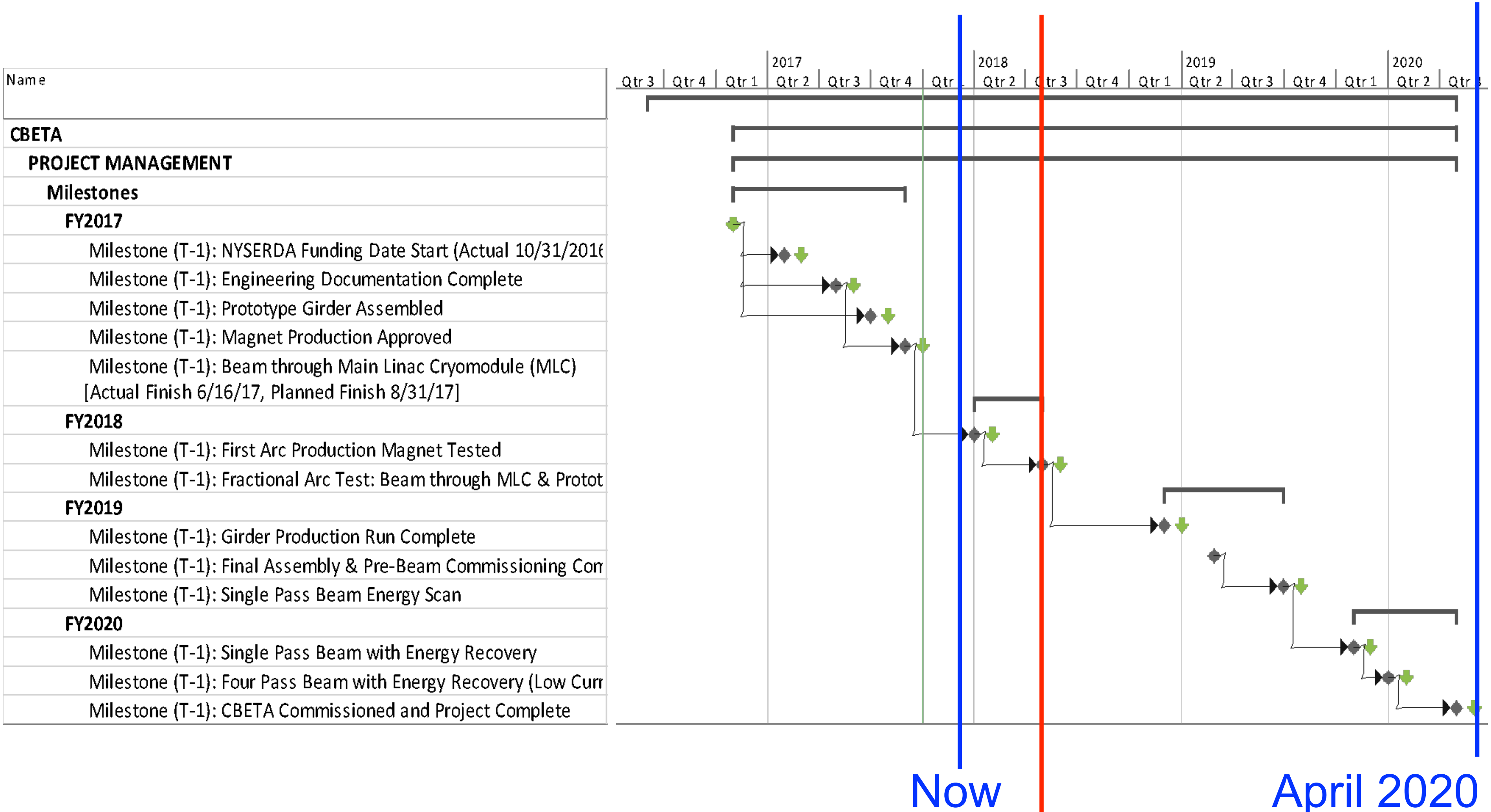
1. Design and Construction (months 1 to 24)
2. Installation (months 25 to 30)
3. Commissioning (months 31 to 42)

The first 4 technical milestones have been met on schedule or early.

Go/
no-go

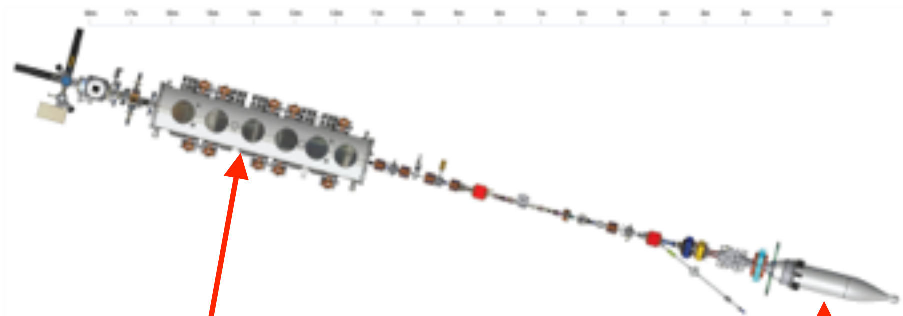
#	NYSERDA milestone	Baseline	Actual	Forecast
	NYSERDA funding start date		31-Oct-16	
1	Engineering design documentation complete	31-Jan-17	31-Jan-17	31-Jan-17
2	Prototype girder assembled	30-Apr-17	30-Apr-17	30-Apr-17
3	Magnet production approved	30-Jun-17	23-Jun-17	30-Jun-17
4	**Beam through Main Linac Cryomodule**	**31-Aug-17**	**16-Jun-17**	**31-Aug-17**
5	First production hybrid magnet tested	31-Dec-17		31-Dec-17
6	**Fractional Arc Test: beam through MLC & girder**	**30-Apr-18**		**30-Apr-18**
7	Girder production run complete	30-Nov-18		30-Nov-18
8	Final assembly & pre-beam commissioning complete	28-Feb-19		28-Feb-19
9	Single pass beam with factor of 2 energy scan	30-Jun-19		30-Jun-19
10	Single pass beam with energy recovery	31-Oct-19		31-Oct-19
11	Four pass beam with energy recovery (low current)	31-Dec-19		31-Dec-19
12	Project complete	30-Apr-20		30-Apr-20

Go/no-go 2



Fractional Arc Test = go/no-go 2

2016: Pre-CBETA



Injector CryoModule
(ICM) 6 MeV

Beam dump

May 2017: MLC first beam

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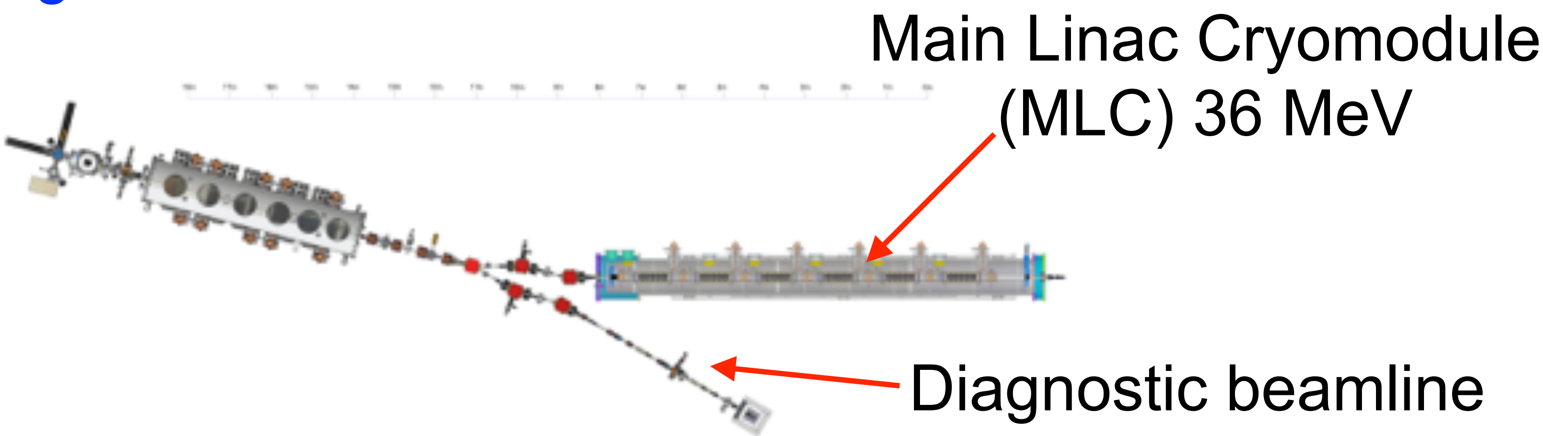
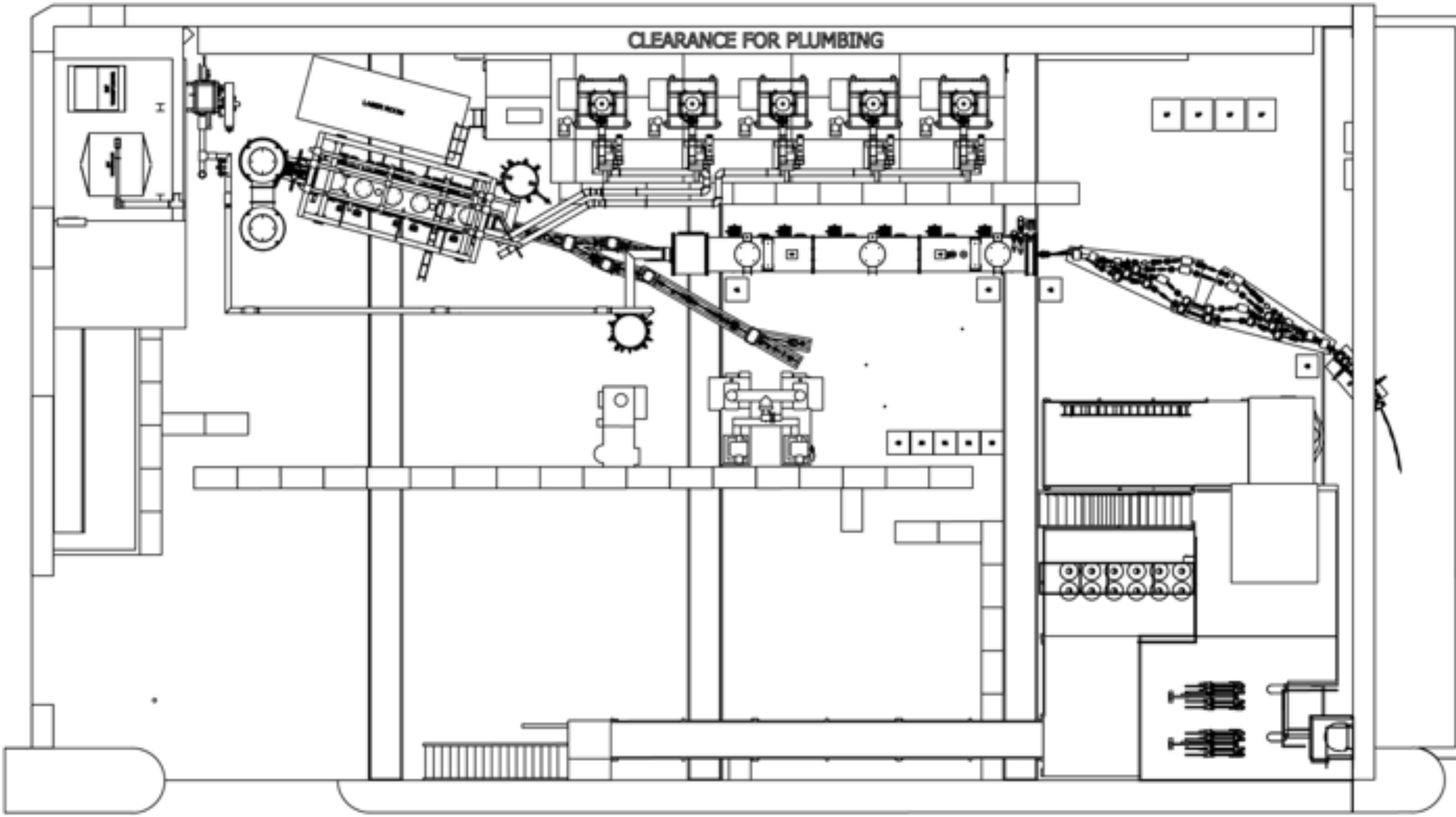
Go/no-go milestone 1



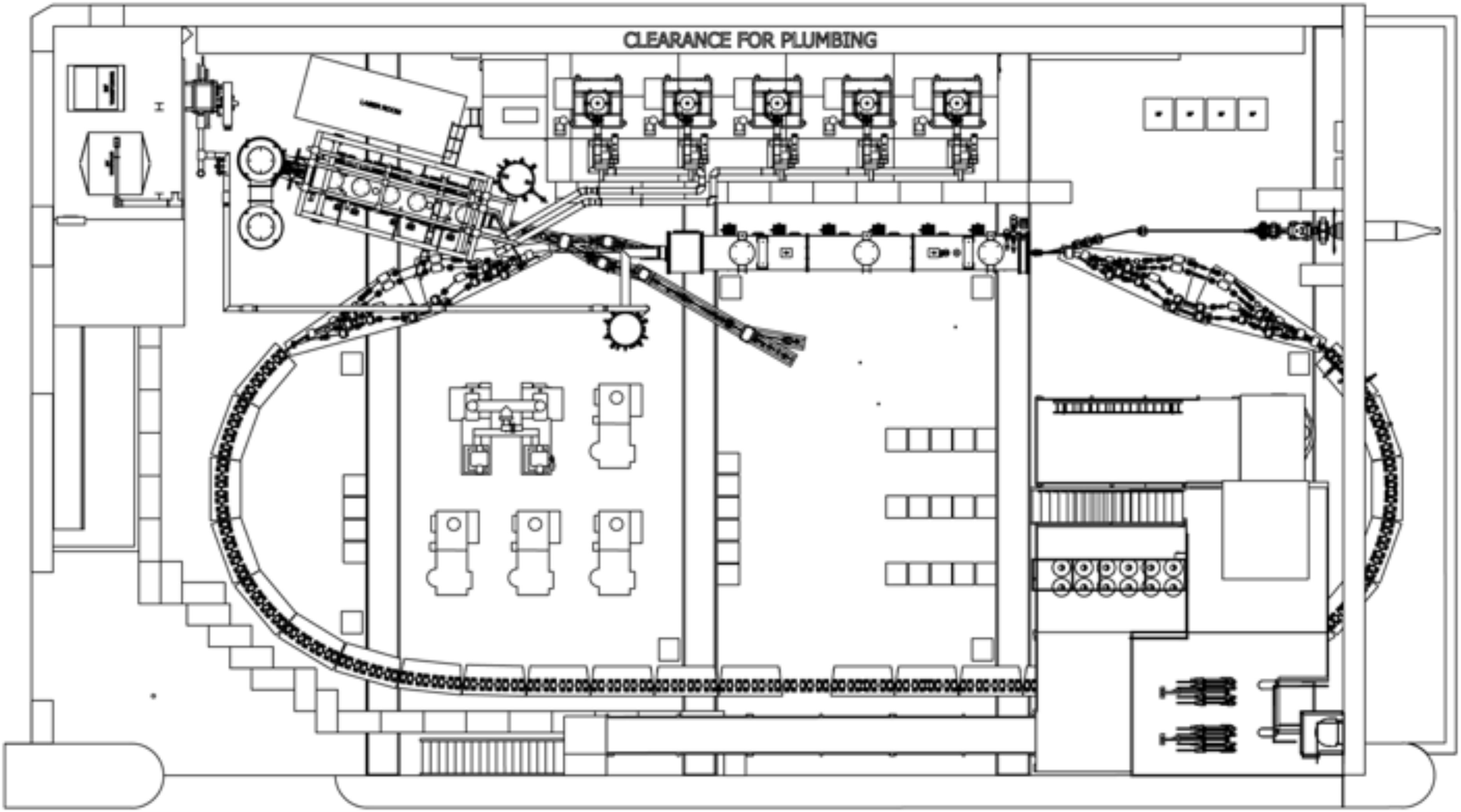
April 2018: Fractional Arc Test

CBETA



Go/no-go milestone 2: MUST DO ON TIME !

August 2019: 1-pass up, 1 down



Push toward 4-pass ERL operation until April 2020

Project management

New York State Energy Research and Development

Laboratory Director: Doon Gibbs

Advisory Committee
Chair: Mike Harrison.
Sergey Belomestnykh, Oliver Bruning,
Wolfram Fischer, Shinji Machida,
Dave Rubin

Oversight Board
Chair: Berndt Mueller (BNL), Emmanuel Giannelis (CU),
Ritchie Patterson (CU), Thomas Roser (BNL)

Project Office
Project Director: Steve Peggs (BNL),
Project Manager: Rob Michnoff (BNL), **Deputy PM:** Karl Smolenski (CU)
Principal Investigators: Georg Hoffstaetter (CU), Dejan Trbojevic (BNL)
Resource Manager: Stephanie LaMontagne (BNL)
Financial Services: Katie Jacoby (CU), Ann Lamberti (BNL), Chris Manalo (BNL)

Baseline Control Board
Chair: Ivan Bazarov (CU),
Georg Hoffstaetter (CU),
Rob Michnoff (BNL),
Steve Peggs (BNL),
Vadim Ptitsyn (BNL),
Karl Smolenski (CU),
Dejan Trbojevic (BNL)

Work Breakdown Structure (Level 2)

1.1	**Project management**	Rob Michnoff (BNL)
1.2	**Accelerator physics**	Georg Hoffstaetter (CU)
1.3	**DC gun/injector**	Colwyn Gulliford(CU)
1.4	**RF systems**	Fumio Furuta (CU)
1.5	**Halbach magnets & girders**	Joe Tuozzolo (BNL)
1.6	**Splitters**	David Burke (CU)
1.7	**Power supplies**	John Barley (CU)
1.8	**Controls**	John Dobbins (CU)
1.9	**Instrumentation**	John Dobbins (CU)
1.10	**Vacuum system & beam stop**	Yulin Li (CU)
1.11	**System integration**	Rich Gallagher (CU)
1.12	**Beam commissioning**	Adam Bartnik (CU)
1.13	**Safety**	Dwight Widger (CU)

WBS	WBS/System Name	Funding ($M)	BNL Total ($M)	CU Total ($M)
A1.01	PROJECT MANAGEMENT	3.4	2.0	1.4
A1.02	ACCELERATOR DESIGN	1.3	0.2	1.1
A1.03	DC GUN/INJECTOR	0.6	-	0.6
A1.04	RF SYSTEMS & CRYOGENICS	2.8	-	2.8
A1.05	FFAG MAGNETS & GIRDERS	4.4	4.4	-
A1.06	SPLITTER	2.0	-	2.0
A1.07	POWER SUPPLIES	0.9	-	0.9
A1.08	CONTROLS	0.8	0.2	0.6
A1.09	INSTRUMENTATION	2.0	1.2	0.8
A1.10	VACUUM & BEAM STOP	1.3	-	1.3
A1.11	SYSTEM INTEGRATION	3.5	-	3.5
A1.12	BEAM COMMISSIONING	1.2	-	1.2
A1.13	SAFETY	0.8	-	0.8
TOTALS	CBETA	25.0	8.0	17.0

The BNL/CU total split is $8.0M / $17.0M (includes labor).

PM, AP, Instrumentation, Beam Commissioning: collaborative.

The other WBS activities are mostly – or completely – the responsibility of one partner or the other.

Procurements

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At Cornell, almost all procurements have been issued: RF amplifiers, vacuum pump skids, splitter magnets, vacuum pumps, vacuum gate valves, and power supplies.

- The largest outstanding construction cost is for two penetrations in the east wall of the experimental hall.

At BNL, Halbach magnets and girders are being purchased through four major procurements: permanent magnet material, magnet assembly, dipole correctors, & girder plates.

- Halbach magnet & girder costs will be accurately known when all bids are received, around December 2017.

Very strong focusing

Straight line arc cell geometry

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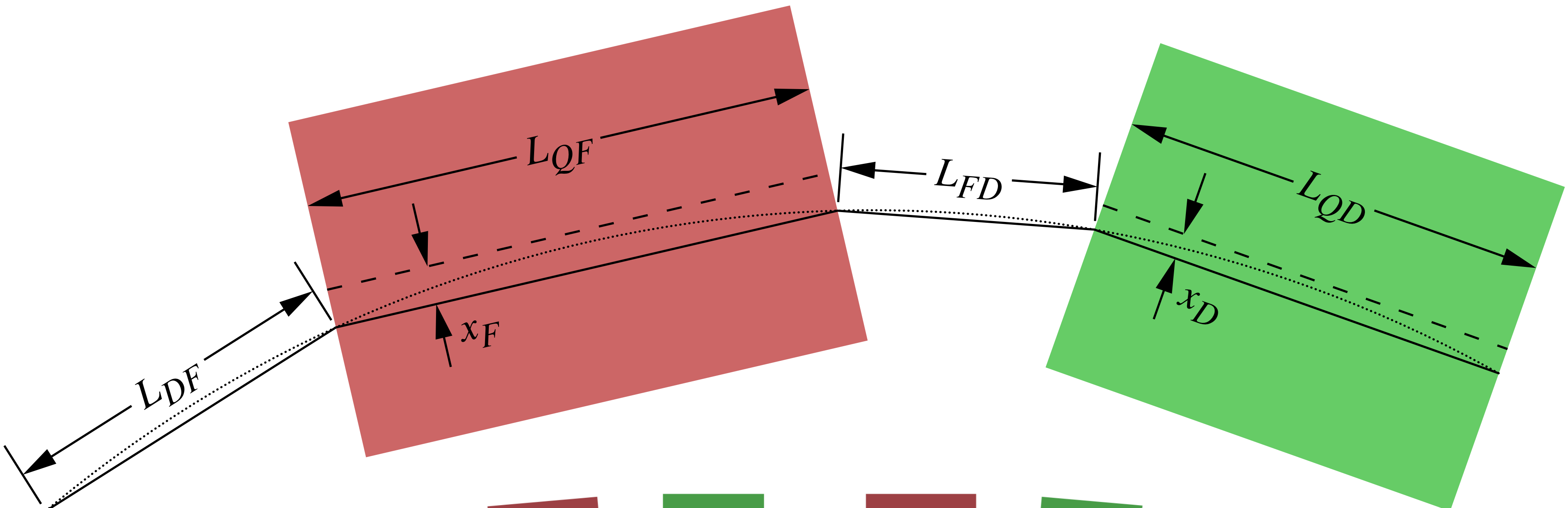
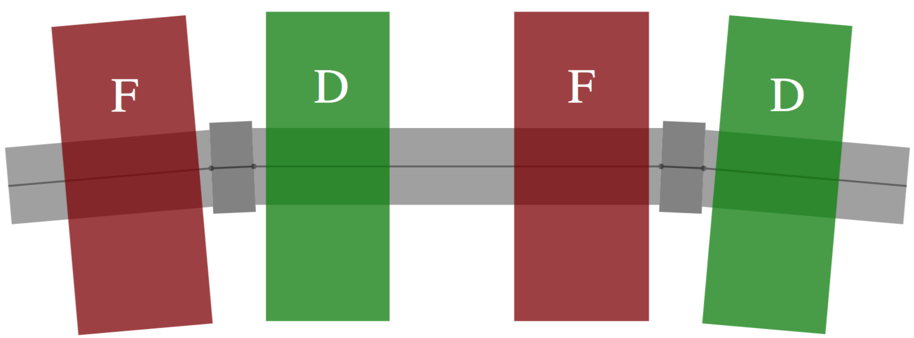
As in EMMA, displaced quadrupoles in arc FODO cells act as "combined function magnets"





Orbits in arc cells

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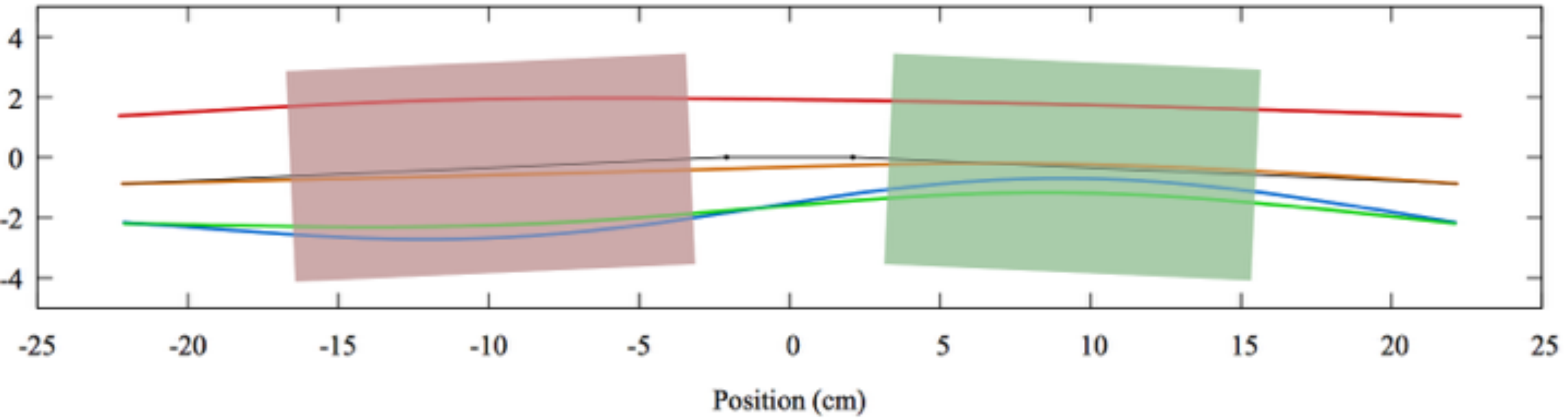

Periodic orbits at 4 design energies — 42, 78, 114, 150 MeV — are displaced over about 50 mm

Short magnets, large apertures: field maps !

"Long" drifts (12 cm) for Beam Position Monitors et cetera.

Tune per arc cell

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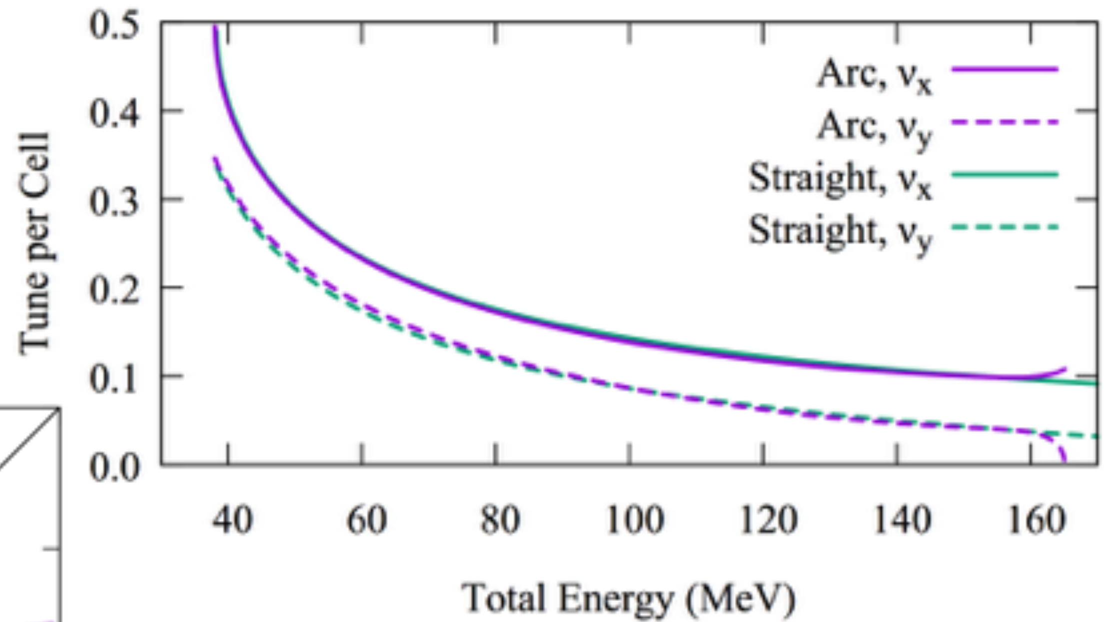
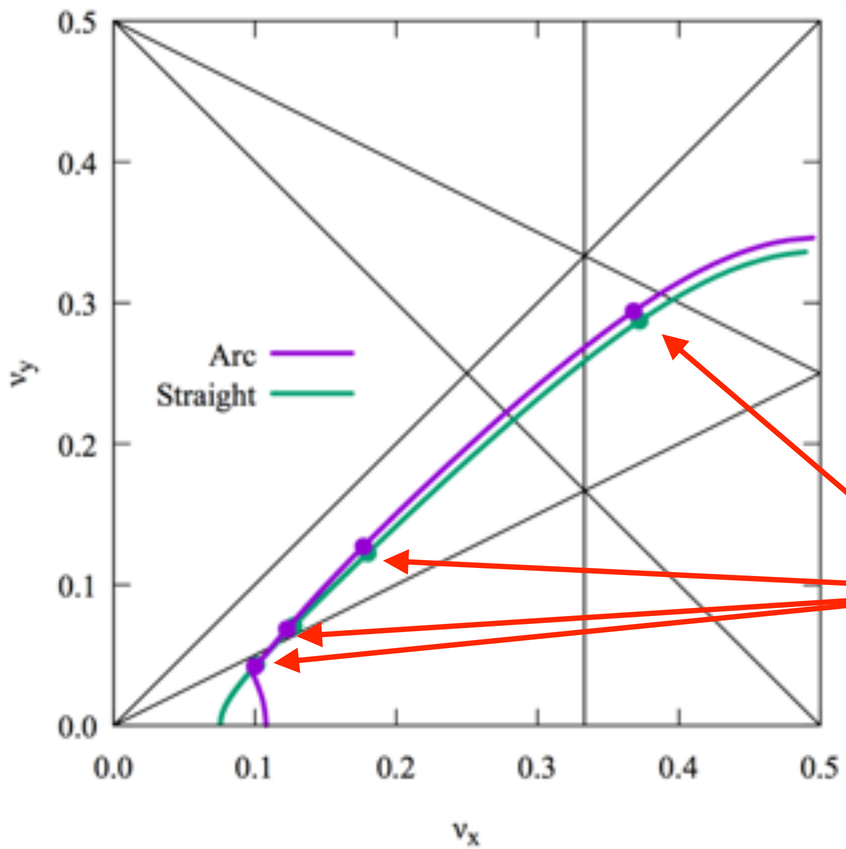
FODO cell stability
limits energy range





Tunes at 4 discrete energies
must avoid resonance lines !

Almost no layout symmetry

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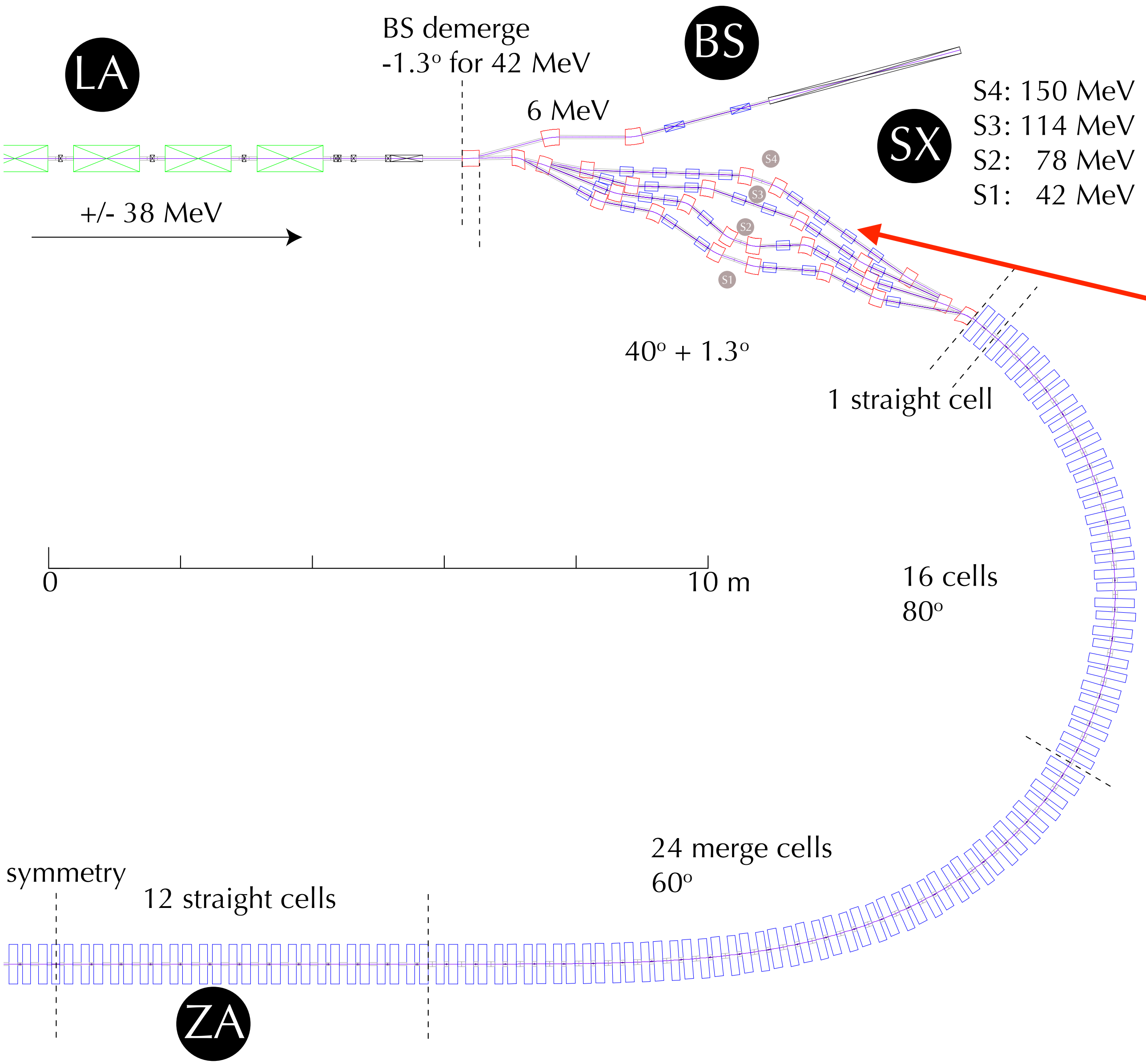
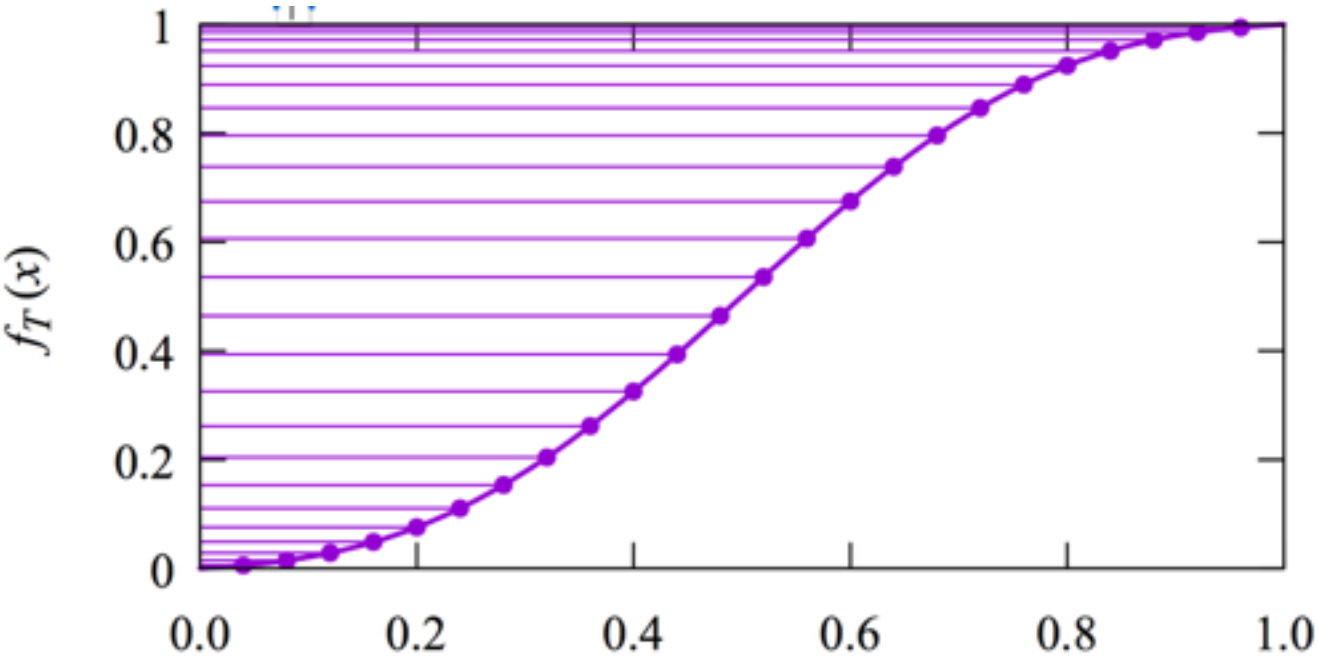


Independently tunable splitter beamlines (electromagnets)

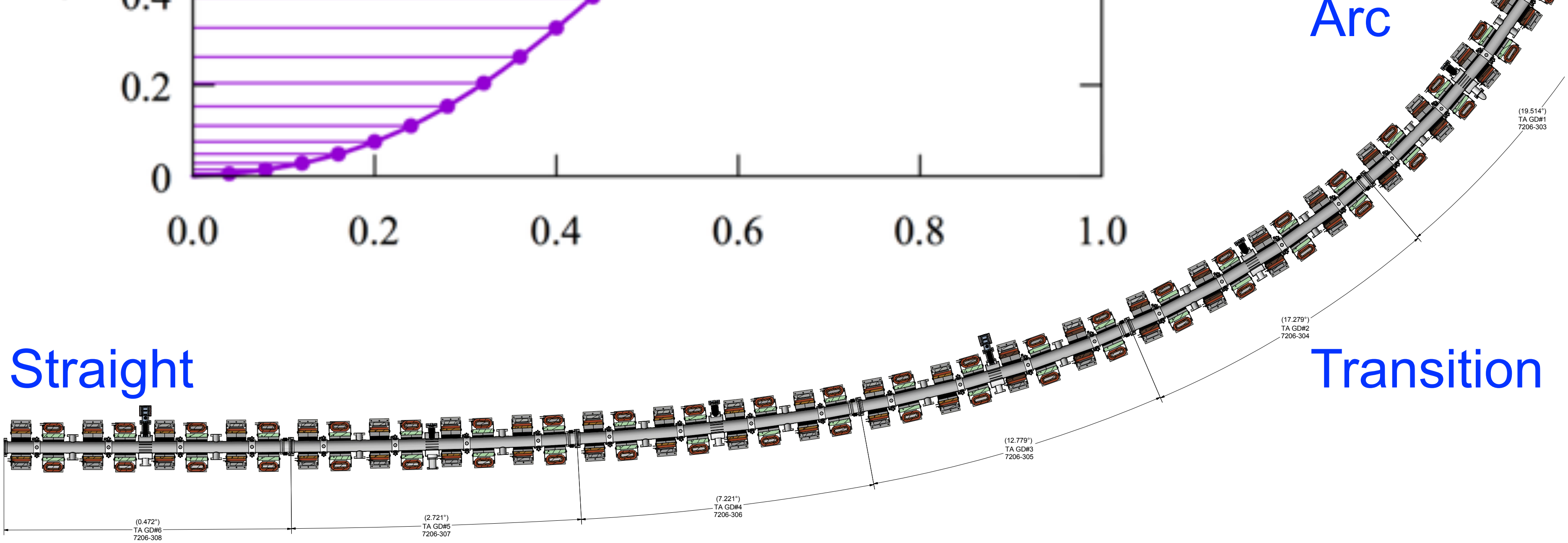
Unlike EMMA, break the high rotational symmetry, to include straights, splitters & utilities!

Adiabatic transitions

Parameters (drift length, angle, dipole component, offsets …) follow an adiabatic function in the transitions



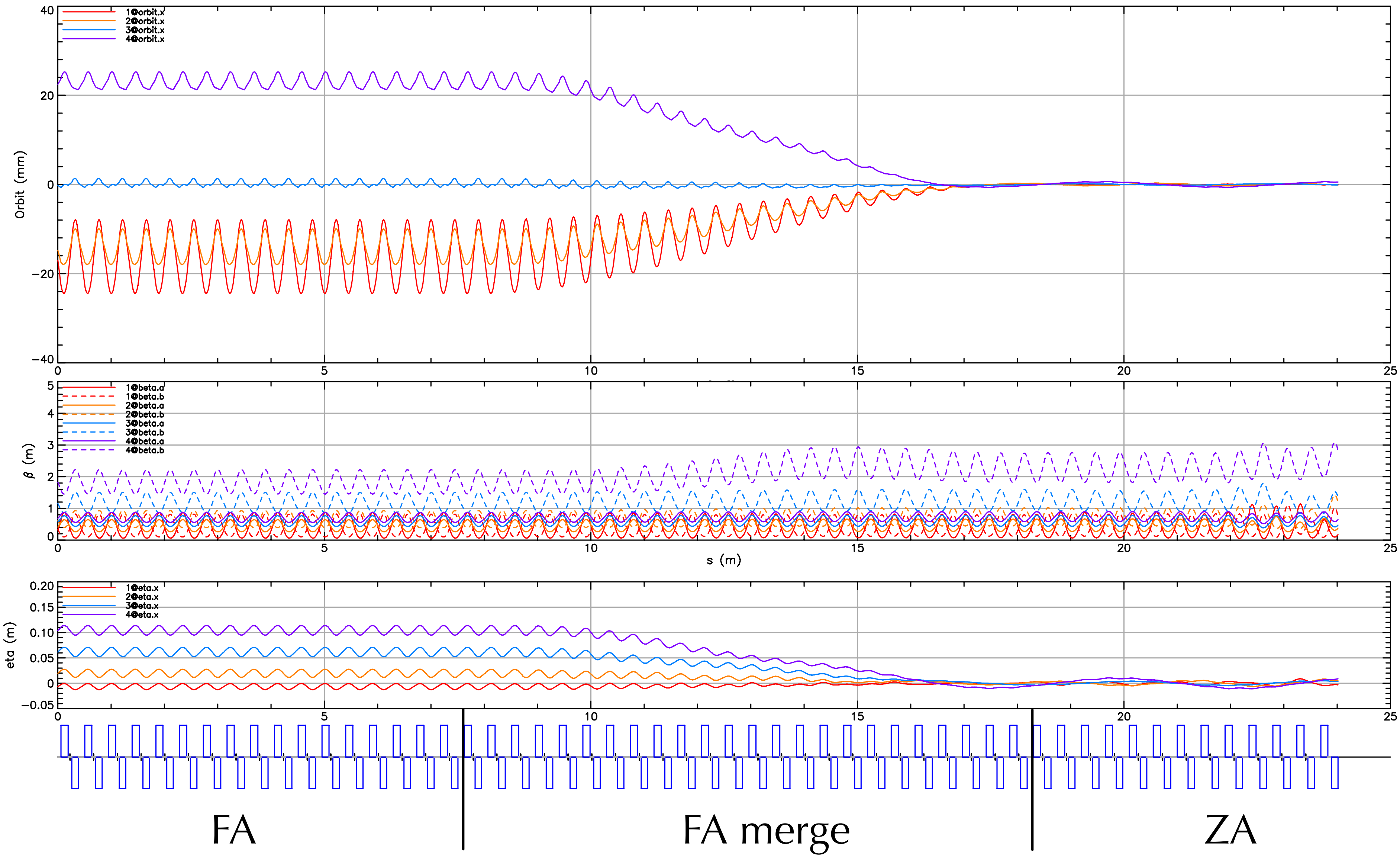
Arc



Straight

Transition

Return arc optics



Linac & splitter optics

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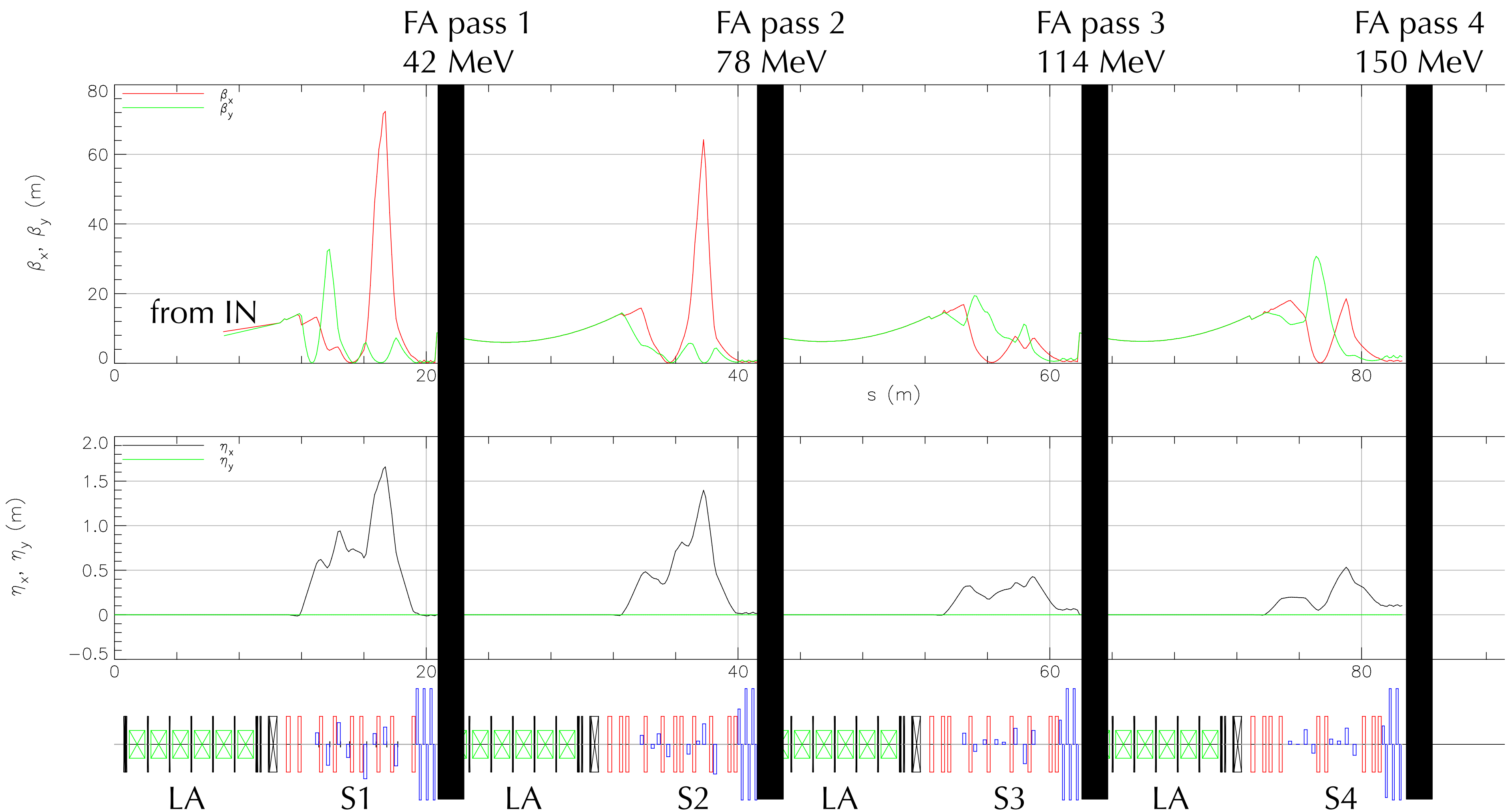

Halbach magnets

Halbach (permanent) magnets

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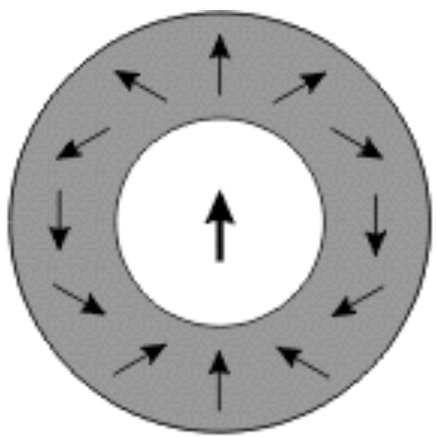
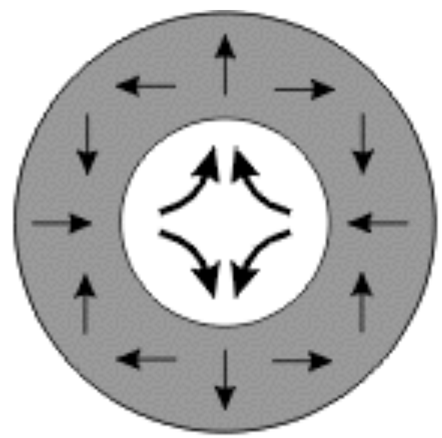
Permanent magnet blocks



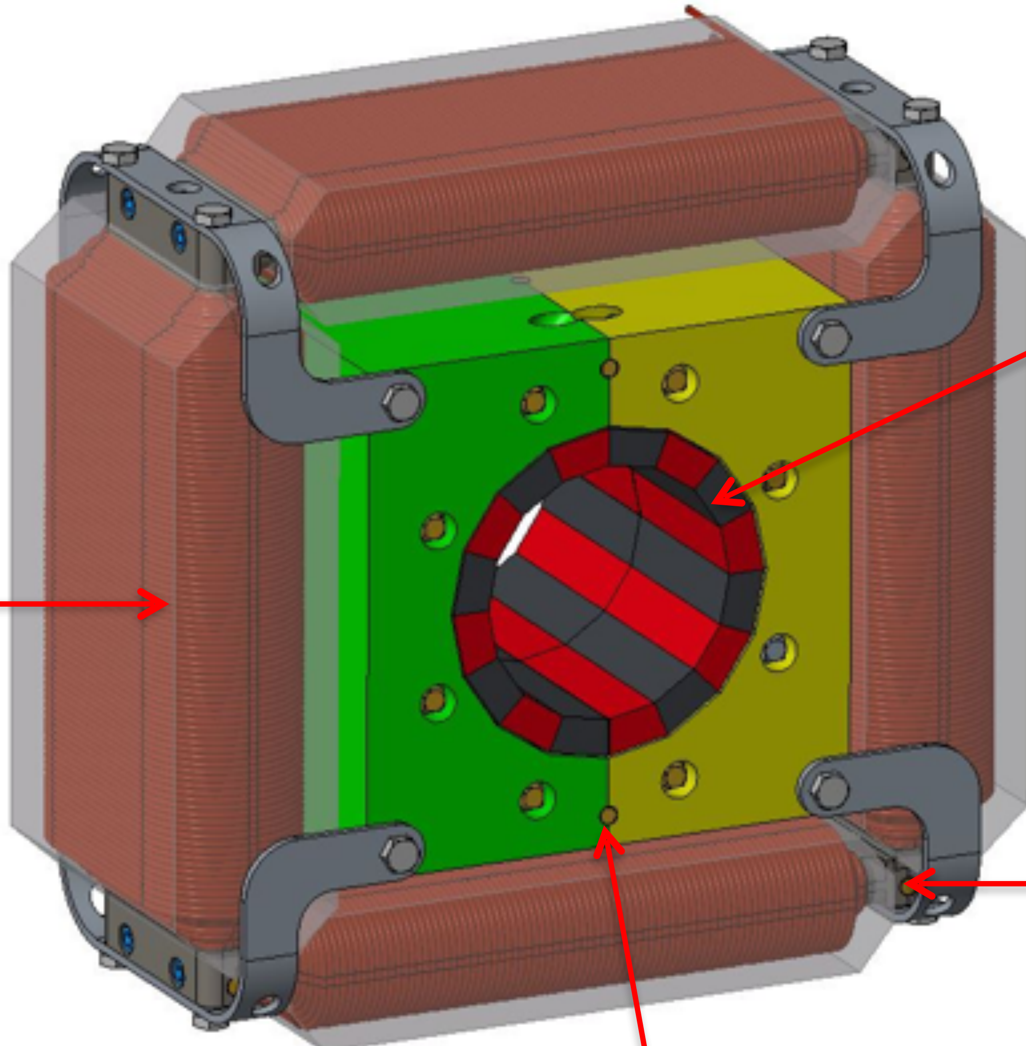
k=2



k=3

Halbach magnet + weak corrector

Horizontal or vertical dipole corrector allows vertical Halbach split.



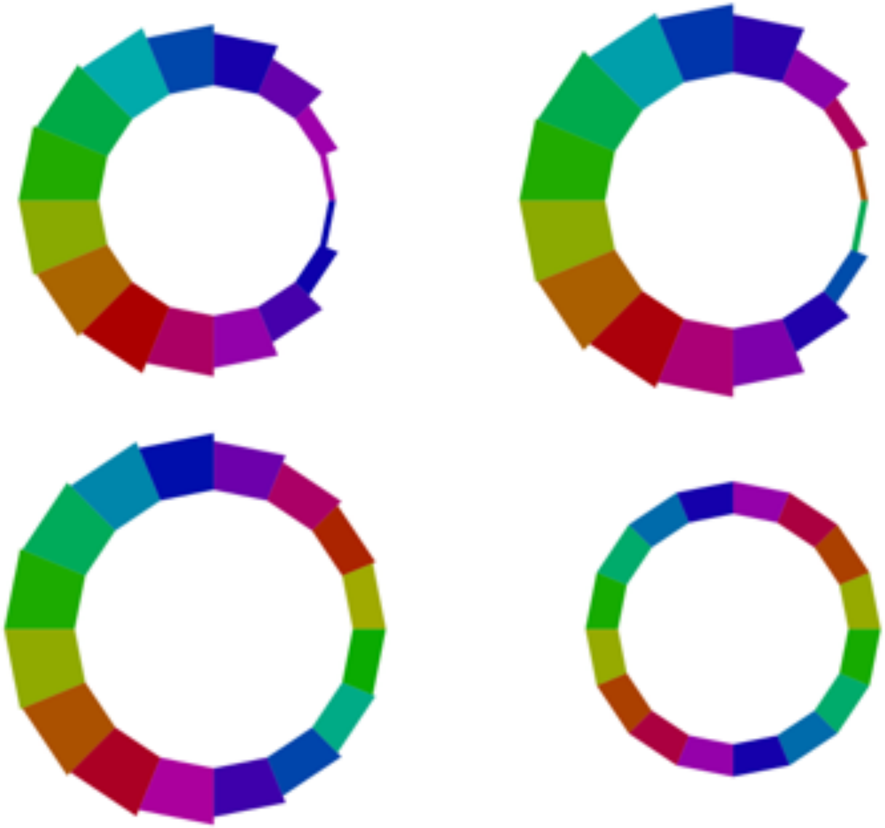
Permanent magnet blocks glued in place inside a machined aluminum frame.

Alignment pins for repeatable corrector assembly.

Alignment pins for repeatable Halbach assembly

CBETA quads & arc cells

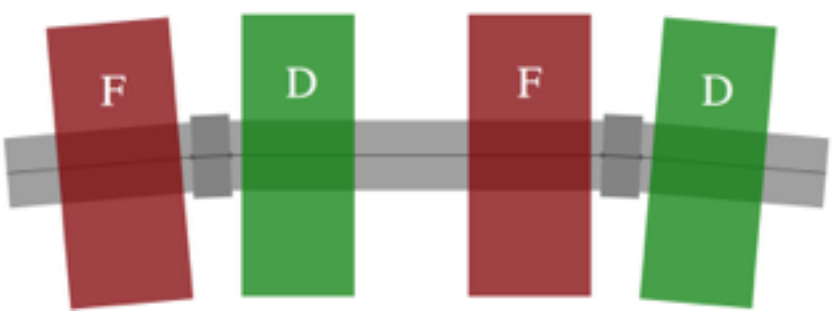
Halbach permanent magnet quadrupoles with offset centers: multiple styles of combined function magnets.



Design questions, physics vs engineering:

Q1: How many different magnet styles?

Q2: How many girder styles?



Magnets styles & girders

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Halbach Styles (S. Berg, S. Brooks)				171113
Style name	**Length**	**Int B.dl**	**Int G.dl**	**Radial aperture**
	m	T.m	T	mm
QF	0.133	0.00000	-1.5378	43.1
BD	0.122	-0.03759	1.3600	40.1
BDT1	0.122	-0.01223	1.3600	49.085
BDT2	0.122	-0.03102	1.3600	44.938
QD	0.122	0.00000	1.3595	40.1
QFH	0.0665	0.00000	-0.7692	43.1
BDH	0.061	-0.01881	0.6804	40.1

A: 7 magnet styles

QFH & BDH are half length one-offs.

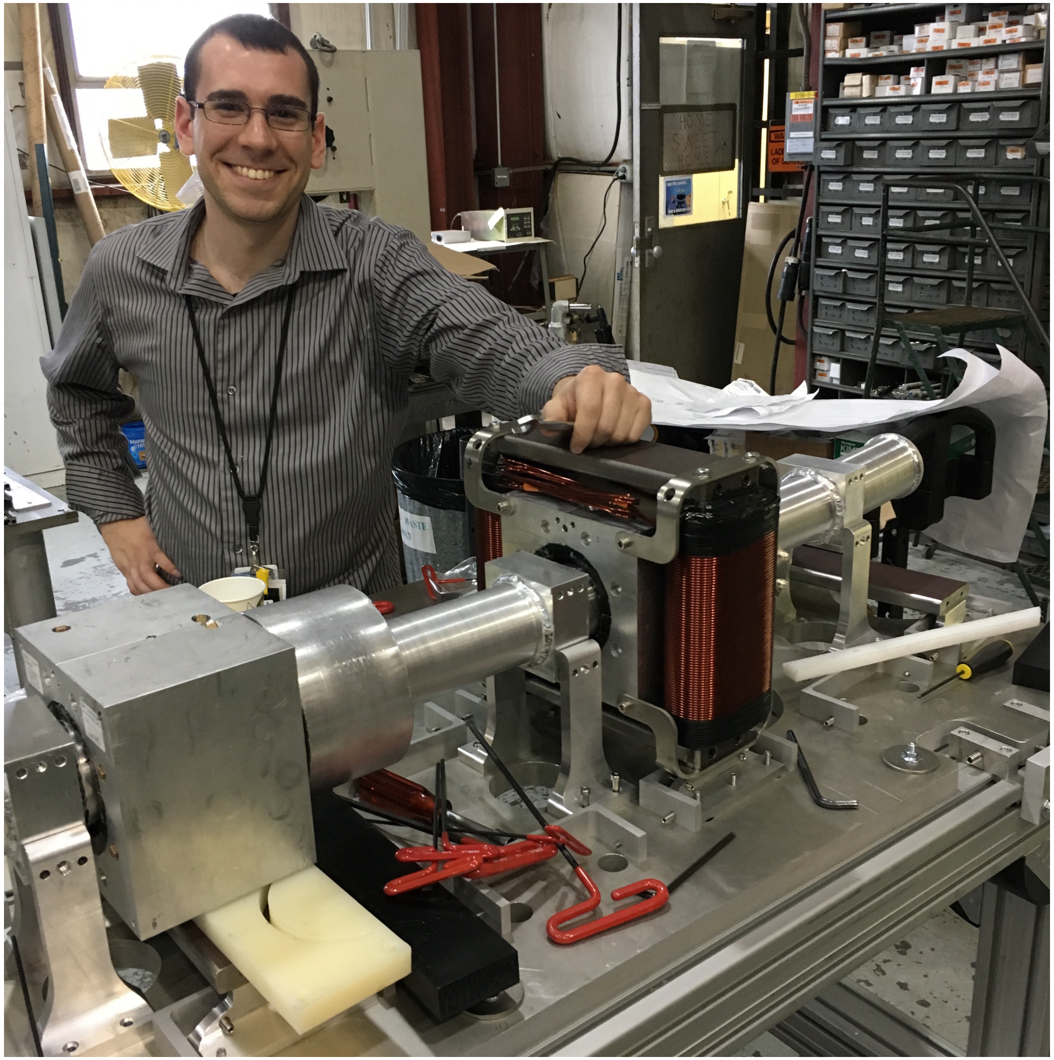
8 magnets per girder,

with an evolving mix

(Note broken symmetry!)

Girder	QF	BD	BDT2	BDT1	QD	QFH	BDH
GFA1	4	4					1
GFX	4	4					
GFX	4	4					
GFX	4	4					
GTA1	4		4				
GTA2	4		4				
GTA3	4		2	2			
GTA4	4			4			
GTA5	4			4			
GTA6	4			4			
GZX	4				4		
GZX	4				4		
GZX	4				4		
GZ1	3				3		
GZX	4				4		
GZX	4				4		
GZX	4				4		
GTB1	4			4			
GTB2	4			4			
GTB3	4			4			
GTB4	4		2	2			
GTB5	4		4				
GTB6	4		4				
GFX	4	4					
GFX	4	4					
GFX	4	4					
GFB1	4	4				1	
	107	32	20	28	27	1	1

Magnet & girder construction



Pre-production girder (April 2017)

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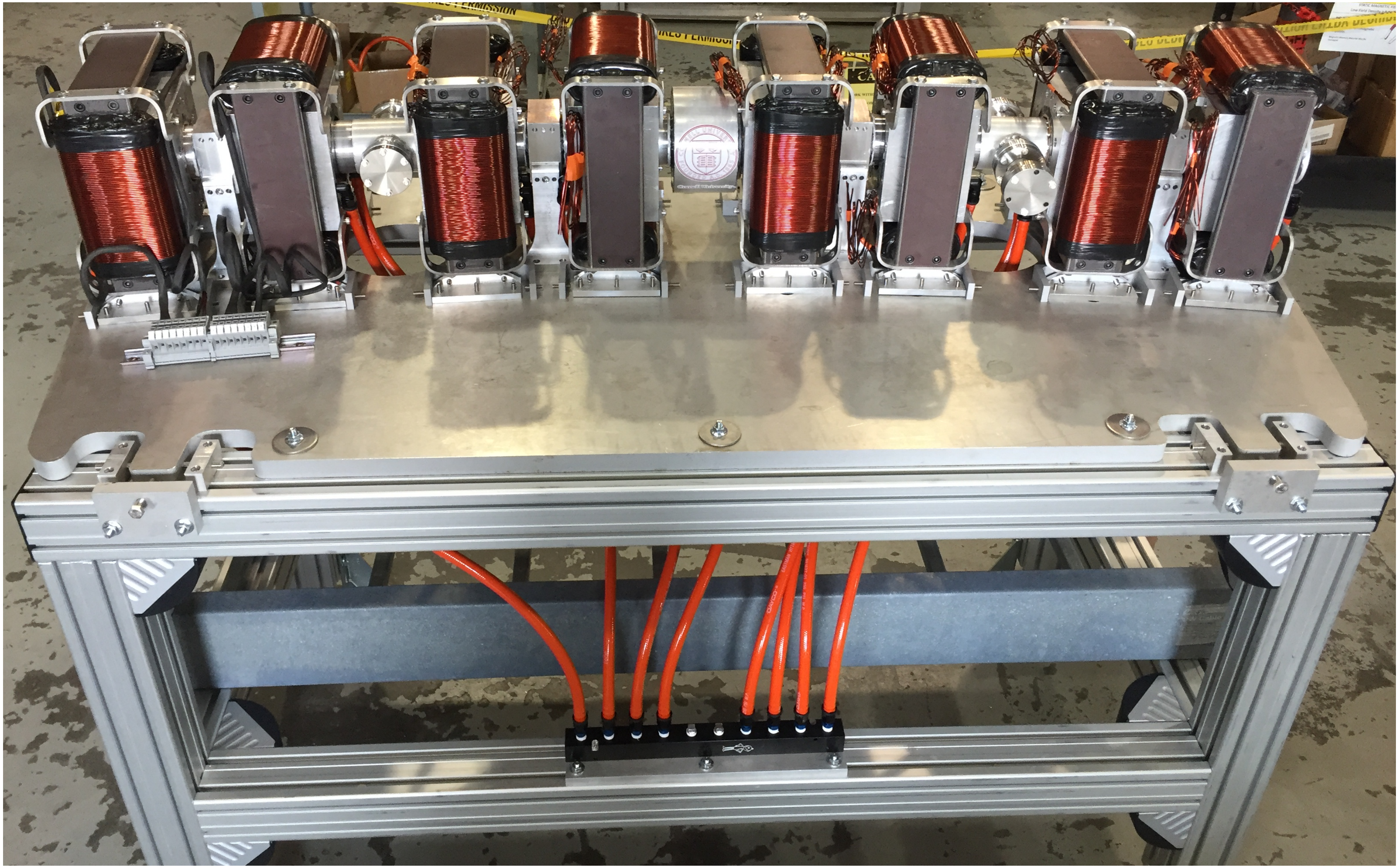
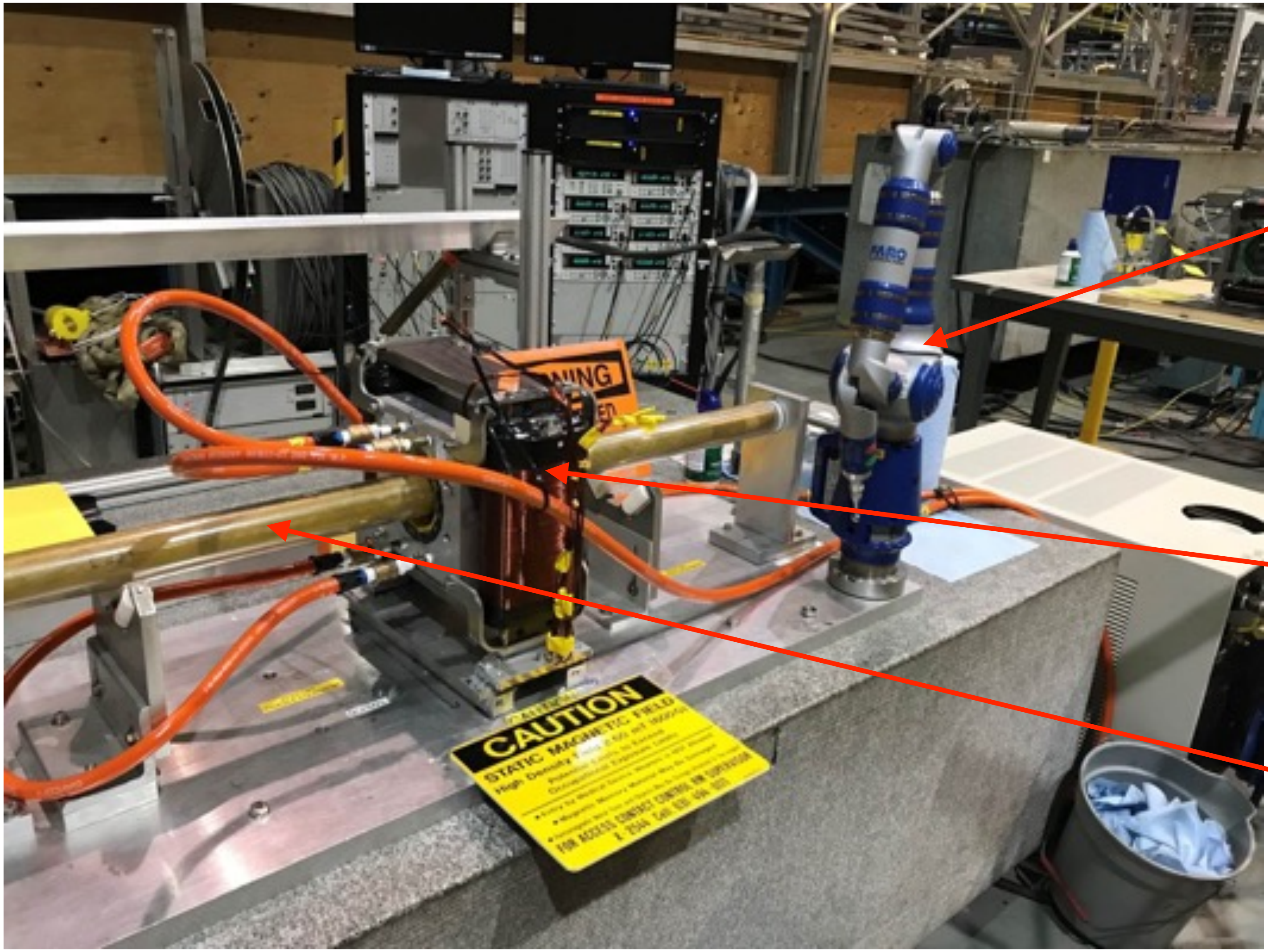


Integrated test stand: field + survey

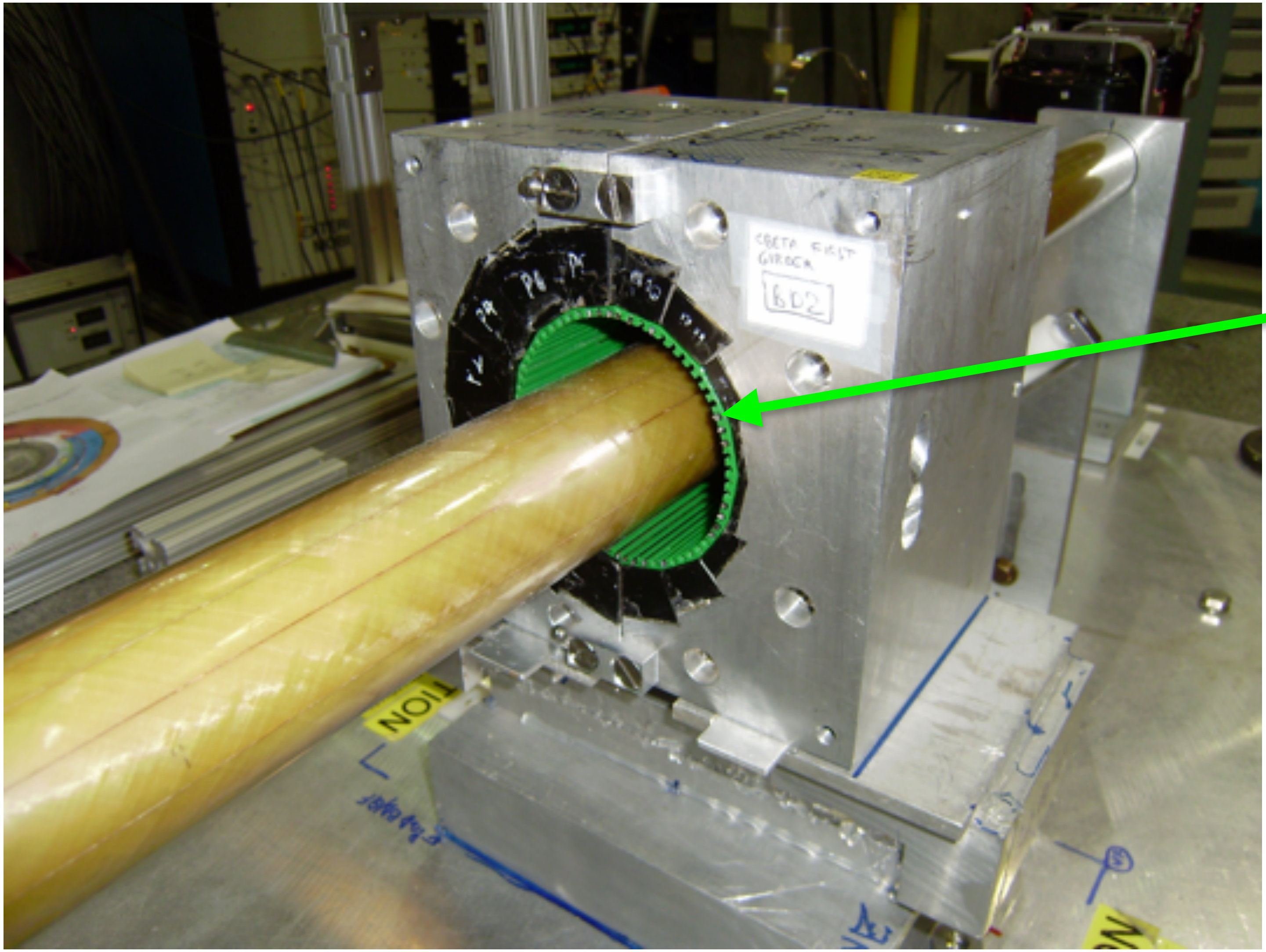


FARO arm
(survey)

Magnet with
corrector

Rotating coil
(field quality)

Rotating coil test stand



Green ring holds variable length iron tuning wires for harmonic reduction — "tuning"

Iron wire field quality tuning

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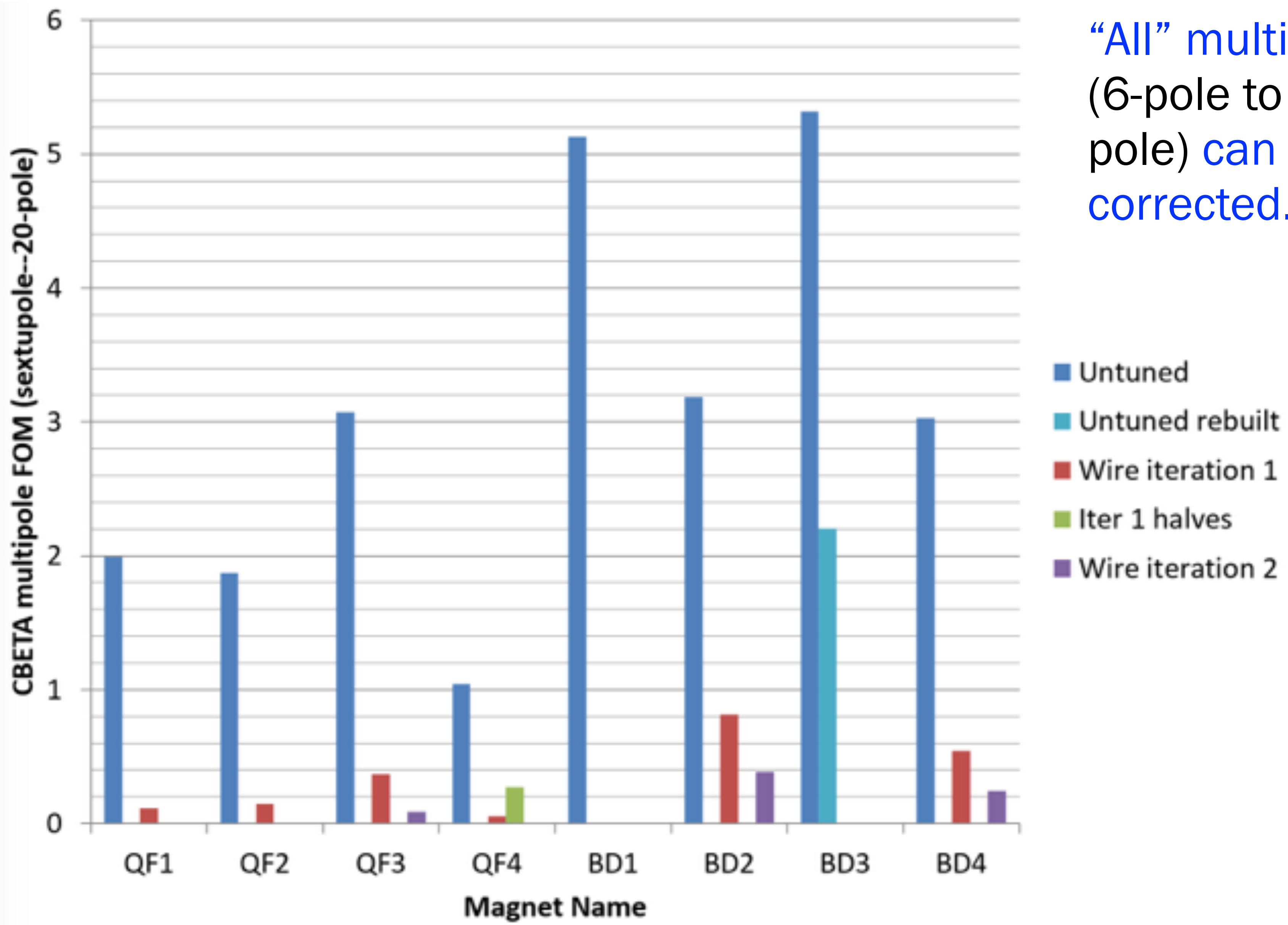
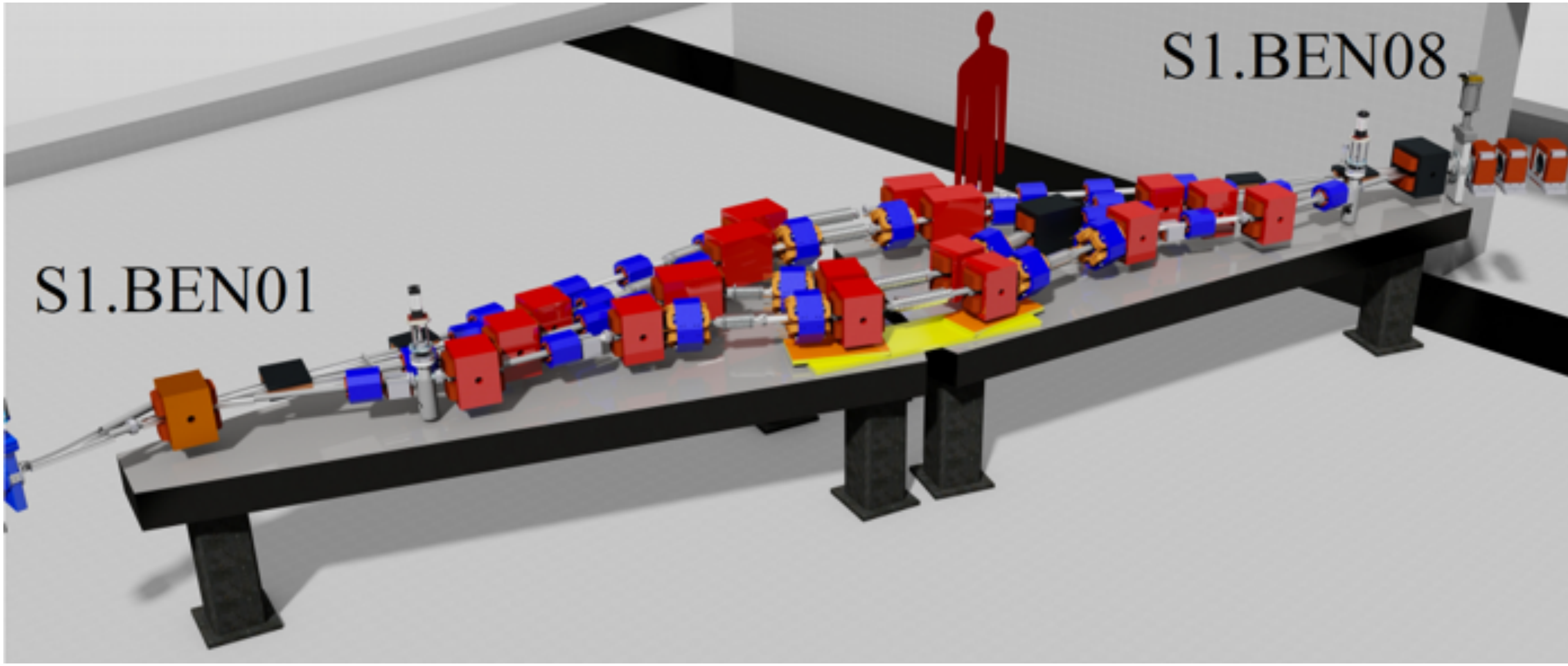


"All" multipoles (6-pole to 20-pole) can be corrected.

Splitters

Splitter tables

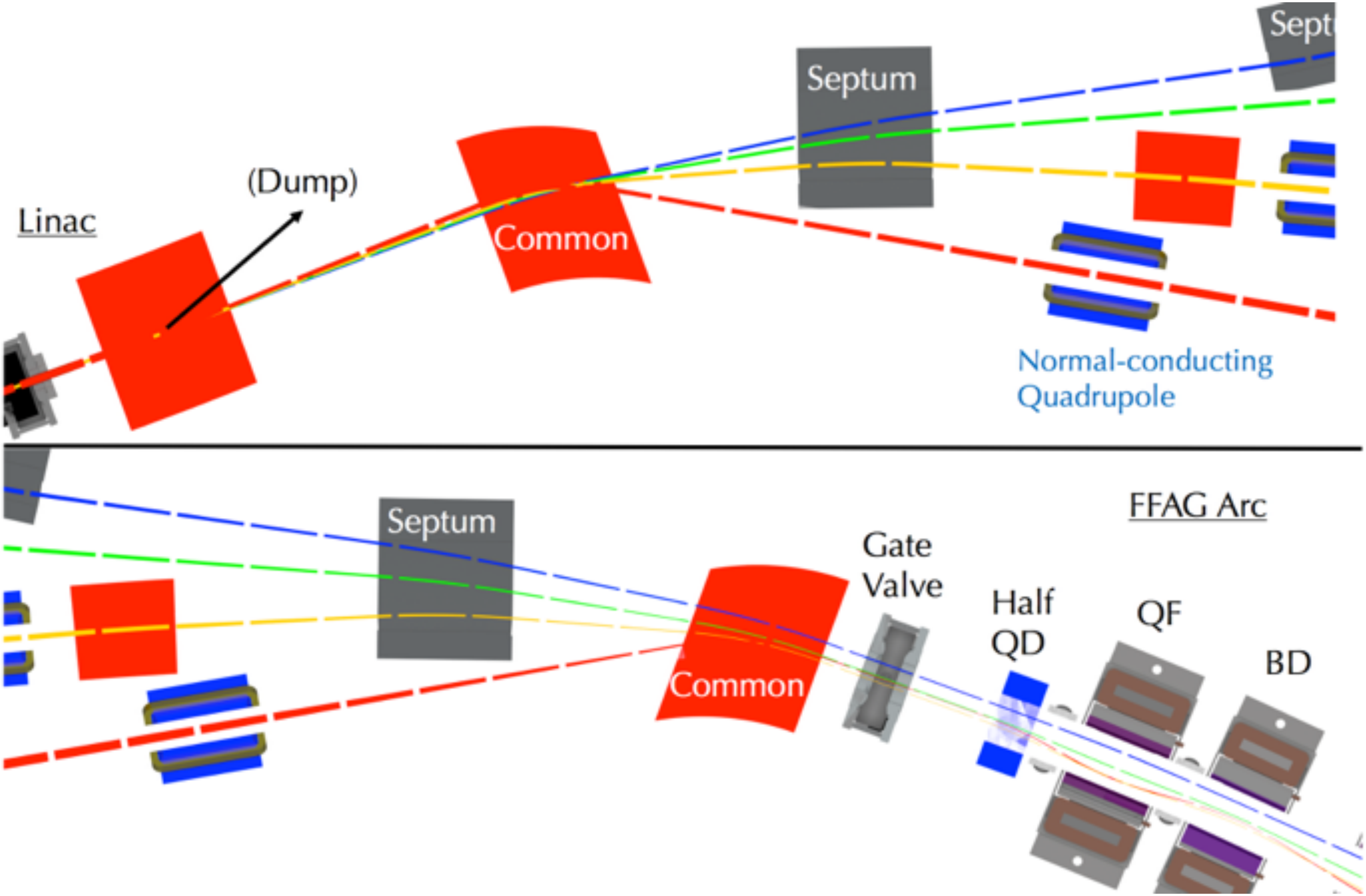


Splitters enable individual control of 4 beams, with tunable electro-magnets.

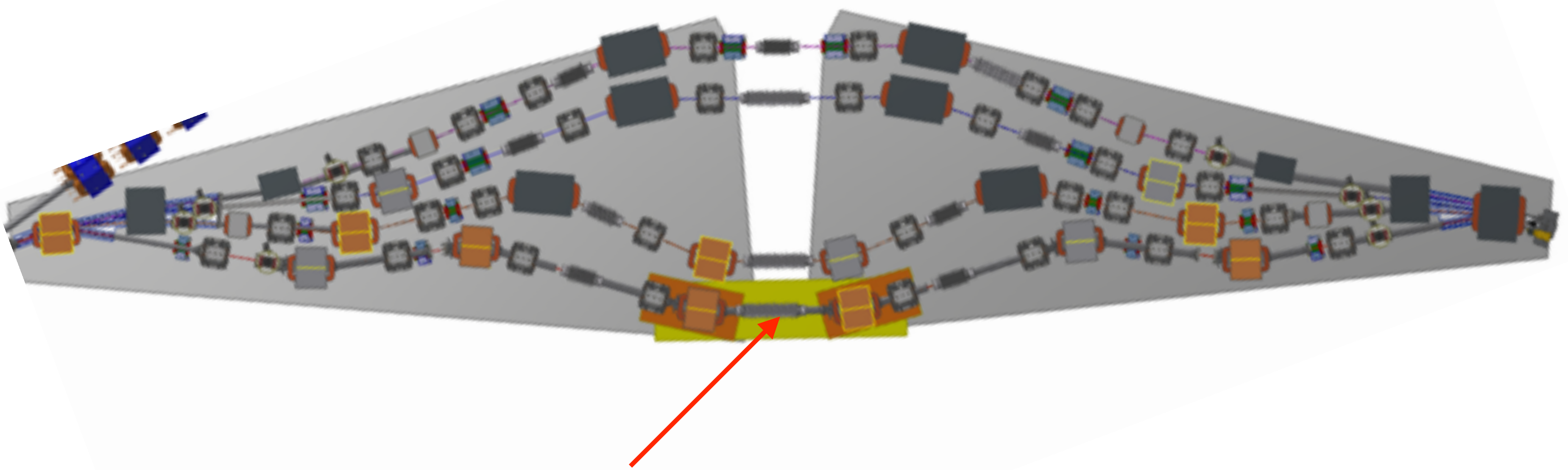
"Common" magnets are ordered, septum magnets are in design.

Common magnets & septa

CBETA



Adjustable path lengths



Adjustable path lengths on enable energy recovery with 1, 2, 3, or 4 acceleration (and deceleration) passes

Changing configurations is time consuming …

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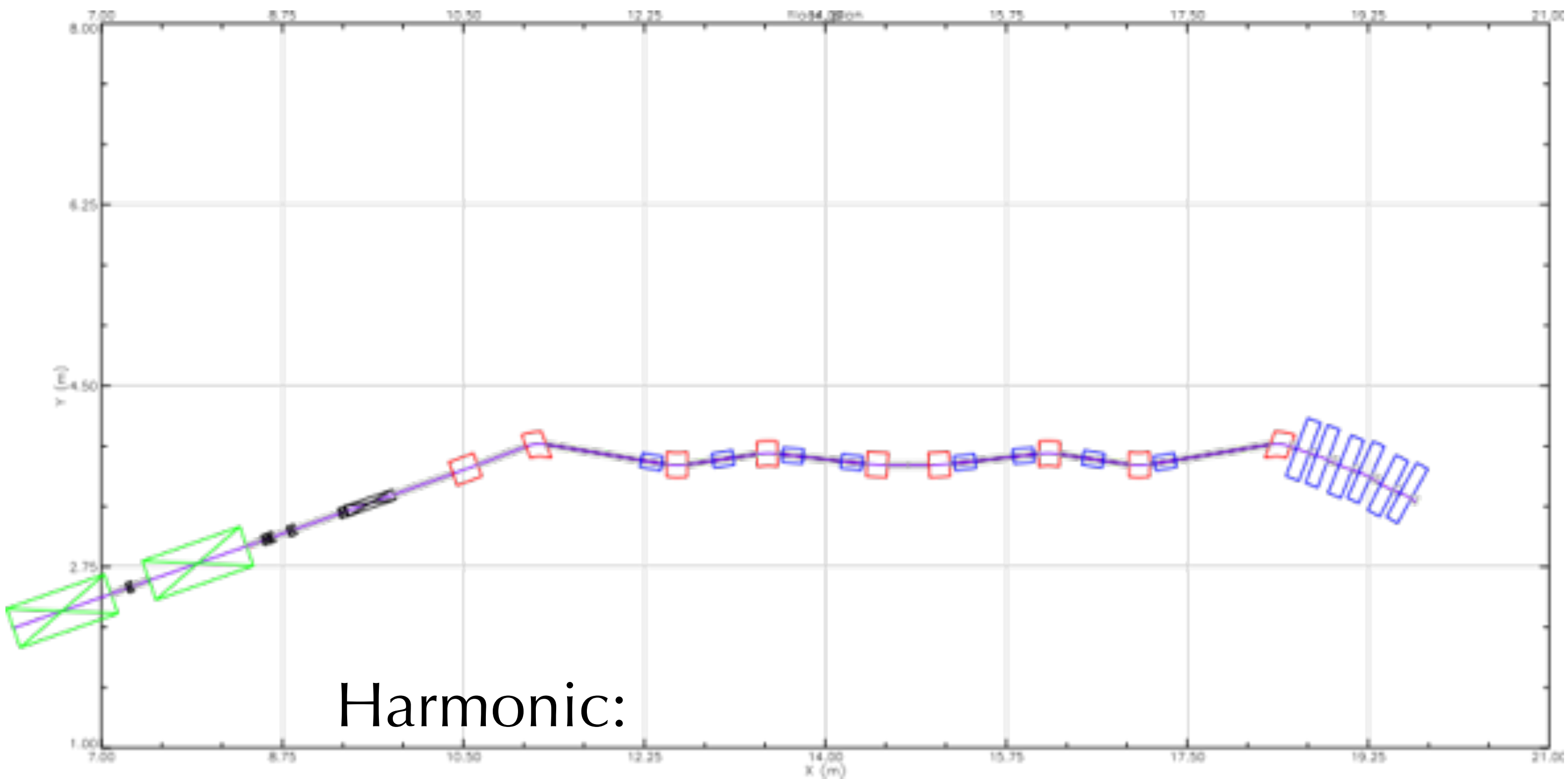
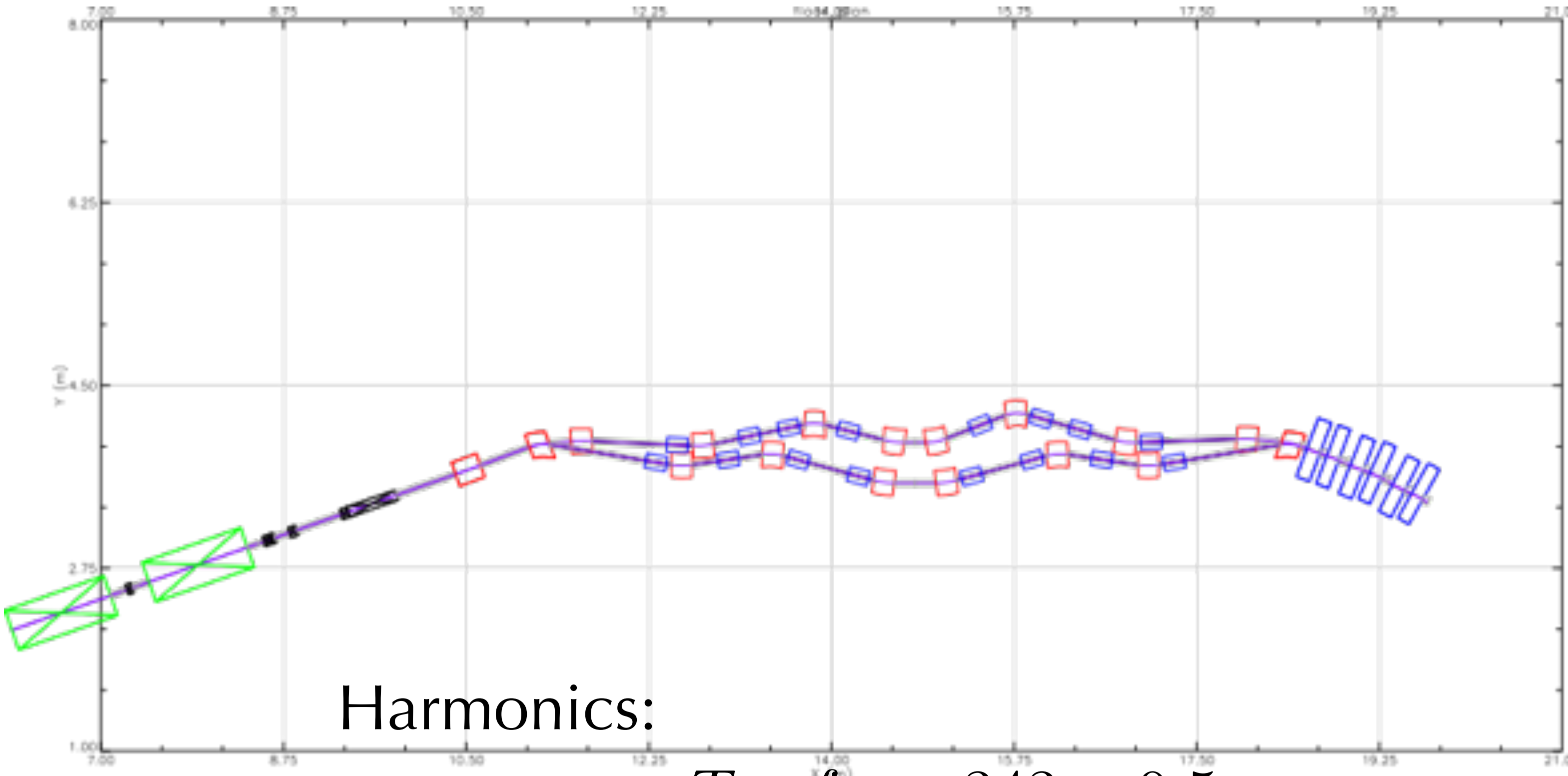


Harmonic:

$$T_1 \cdot f_{\mathrm{rf}} = 343 - 0.5$$

2-pass Energy Recovery



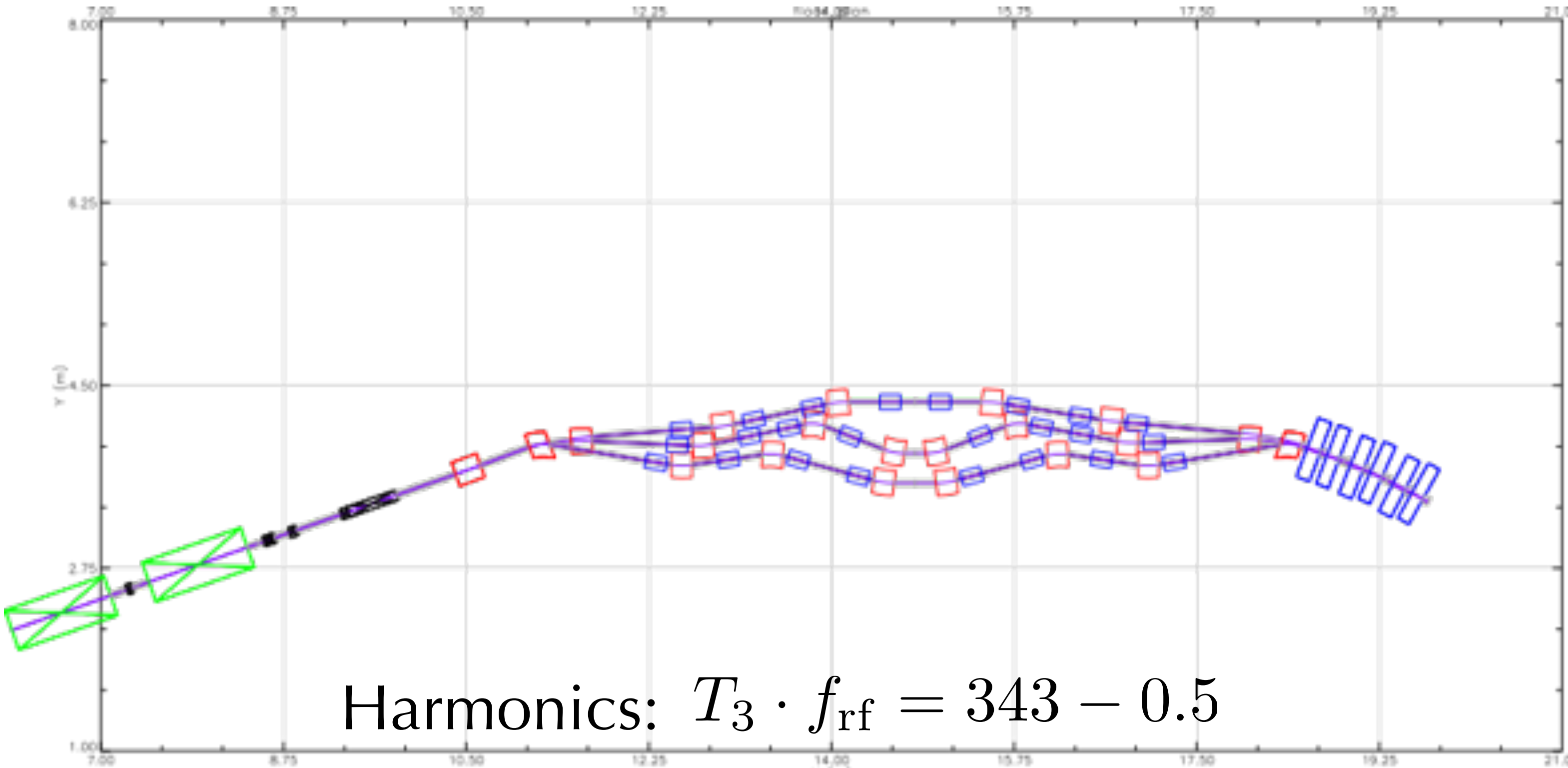
Harmonics:

$$T_2 \cdot f_{\mathrm{rf}} = 343 - 0.5$$

$$T_1 \cdot f_{\mathrm{rf}} = 343$$

3-pass Energy Recovery

CBETA

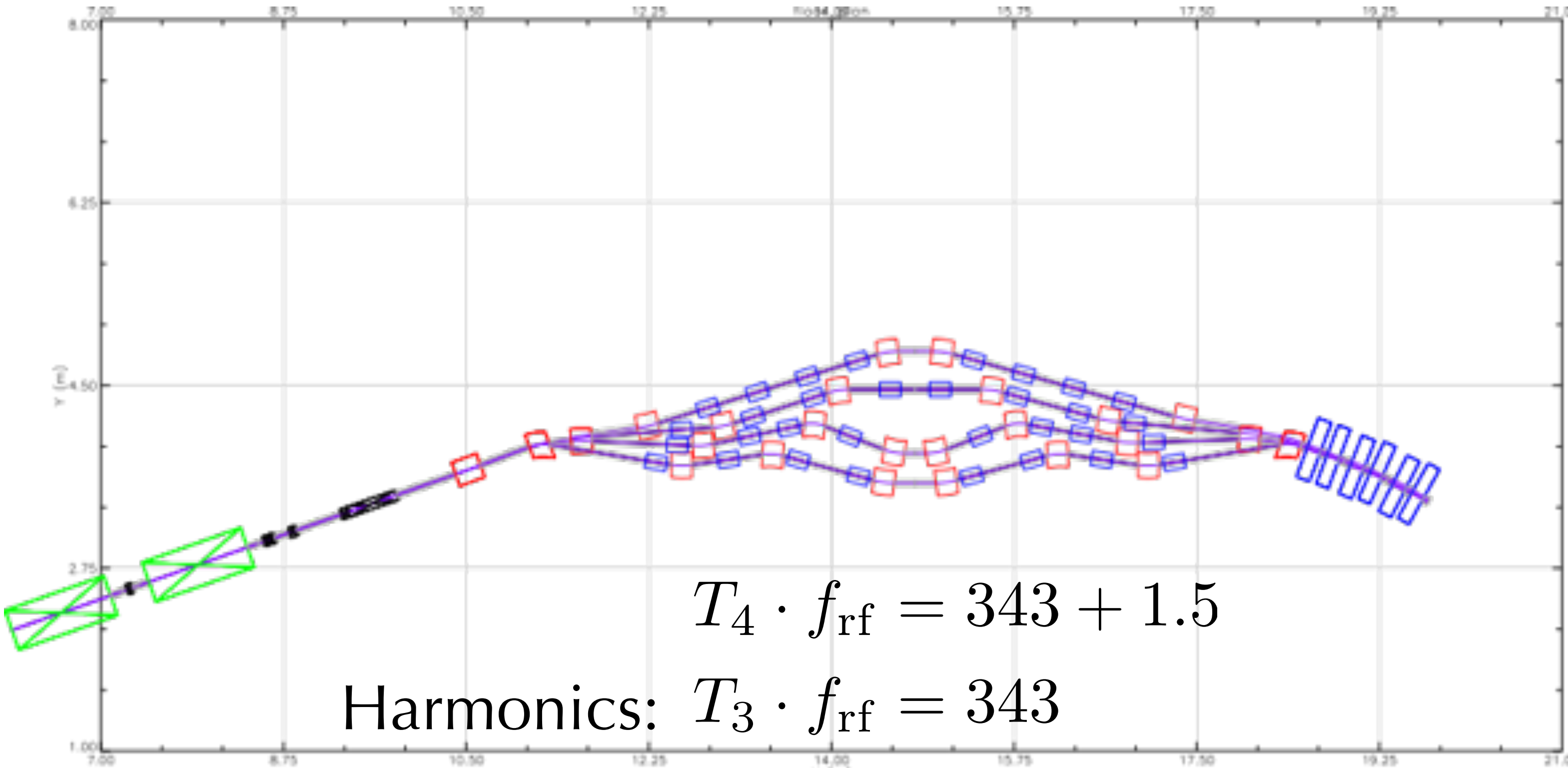


$$\text{Harmonics: } T_3 \cdot f_{\mathrm{rf}} = 343 - 0.5$$

$$T_2 \cdot f_{\mathrm{rf}} = 343$$

$$T_1 \cdot f_{\mathrm{rf}} = 343$$

4-pass Energy Recovery



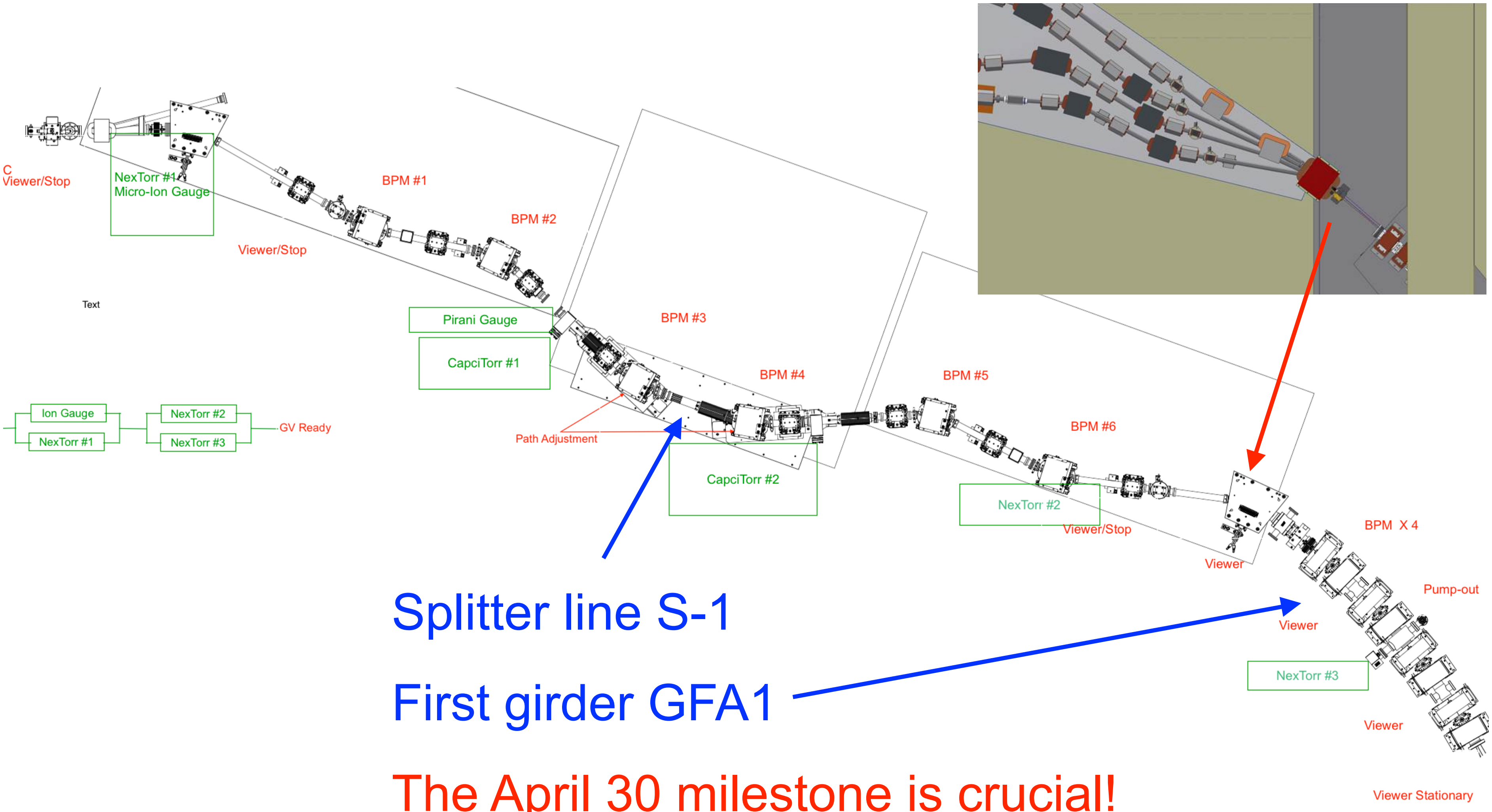
$$T_4 \cdot f_{\mathrm{rf}} = 343 + 1.5$$

Harmonics: $T_3 \cdot f_{\mathrm{rf}} = 343$

$$T_2 \cdot f_{\mathrm{rf}} = 343$$

$$T_1 \cdot f_{\mathrm{rf}} = 343$$

Fractional Arc Test configuration



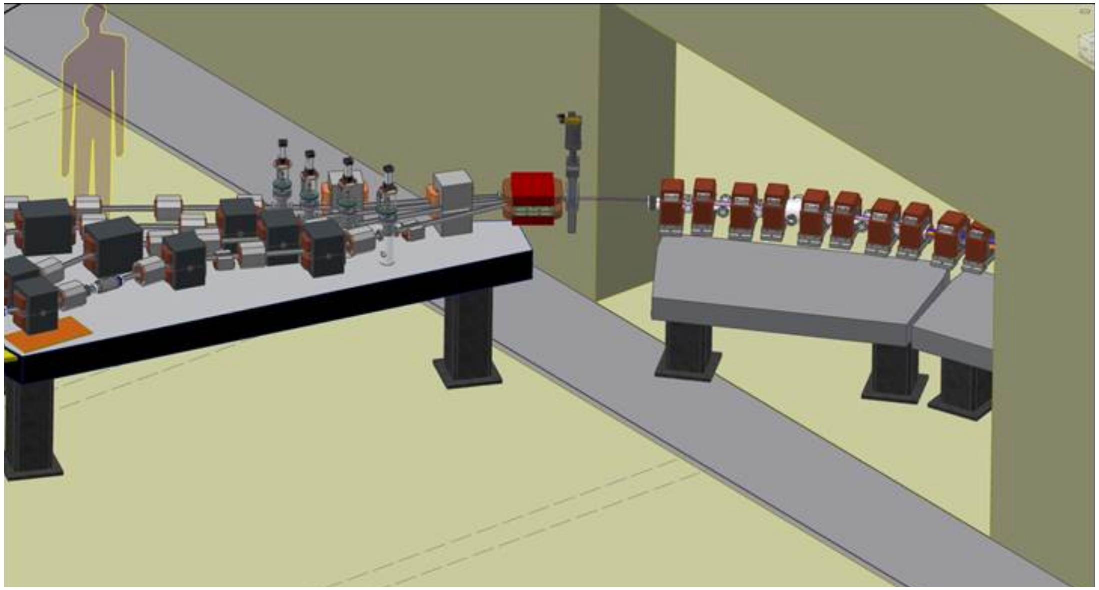
Splitter line S-1

First girder GFA1

The April 30 milestone is crucial!

Holes-in-the-wall

CBETA



Holes are being cut in the east concrete wall for the beam stop & first arc girder.

There are geometric challenges to squeezing a 70.1 m circumference machine into L0E.

Implications for future flexibility & upgrades!

Nov 30, 2017

Holes-in-the-wall (2)

Beam stop penetration

December 6: The wall has not fallen down, so far.

Risks could occur anytime …

Top ten:

1. Halbach magnets: schedule slip would delay CBETA.
2. Main Linac & Injection CryoModules: complex to repair
3. DC gun: like MLC & ICM, repairs could take months.
4. RF amplifiers: schedule, custom built, infant mortality.
5. East wall penetrations: tight schedule for FAT.
6. Splitter magnets: timely delivery
7. Beam halo & losses: additional shielding costs
8. Magnetic field fluctuations: e.g. power supply ripple
9. Septum magnets, power supplies: technical challenge
10. Key staff loss & availability: limited resources.

After NYSERDA: expanded collaboration

Towards an Electron Ion Collider

CBETA

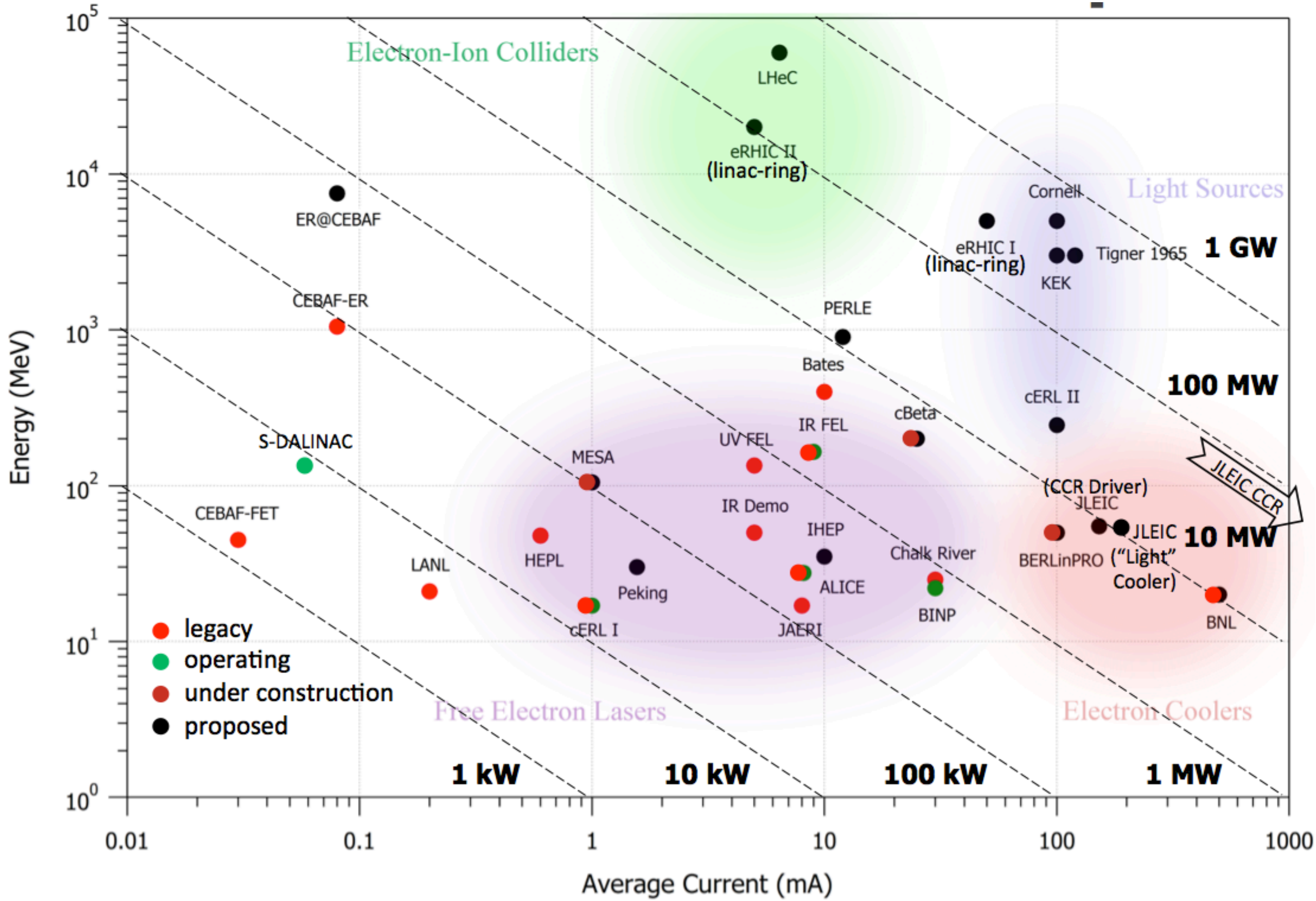
An ERL is necessary for beam-cooling, to reach the highest EIC luminosities in any scenario:

- JLEIC or eRHIC,
- ring-ring or linac-ring
- conventional or coherent electron cooling

CBETA is a prime platform for Strong Electron Cooling R&D (see presentations by Benson, Douglas & Zhang at https://www.bnl.gov/eiccm2017/)

CBETA can also be considered to be a high current RF cryomodule test stand (eg 650 MHz cavities for eRHIC).

ERL landscape (Douglas)



Technical readiness levels

Dave Douglas:

What we have (Mosquito) … vs … what we need (F-22 Raptor)

Stealth by wood & canvas or by composites?

Electron cooling R&D parameters

CBETA

Parameter	Unit	State-of-the-art	CBETA	Required
Bunch charge	nC	0.1	0.125	3
Beam current	A	0.01	0.04	0.1 to 1.0
Beam power	MW	1	6	10 to 100
Rep. rate	MHz		31 to 325	43.3

Although there is a long way to go to practical parameters, many high bunch current, beam quality & optics issues can be addressed in the configuration as-built by NYSERDA:

1. microbunching,
2. coherent synchrotron radiation,
3. space charge,
4. higher order modes,
5. beam break-up, …

Multi-pass beam dynamics issues

CBETA

1. High current effects
    a) Space charge
    b) Halo dynamics
    c) HOM heating
    d) Intra-Beam Scattering
    e) Touschek scattering
    f) Gas scattering
    g) Ion accumulation

2. Beam quality
    a) Emittance matching
    b) Time-of-flight control
    c) Wakefield interactions
    d) Micro-bunching instability
    e) Coherent Synch. Radiation

3. Transport of damaged beam
    a) Phase space rotation
    b) Large 6-D phase-space optics

4. Recovery topics
    a) Energy spread growth during deceleration.
    b) Transverse halo growth during deceleration.
    c) Recirculative Beam Breakup
    d) Ion instabilities
    e) Simultaneous control of multiple beams

Other potential applications (cf Cornell)

DarkLight – an experiment to find dark matter particles

Compact Compton backscattering for hard x-rays

THz laser – complementing CHESS

Beam for time-resolved electron diffraction from 1 to 6 MeV

Beam for Plasma Wakefield Acceleration

ASML medical isotope cavity testing with beam

Preparations for PERLE & LHeC

Permanent magnet & very strong focusing optics test bed

Goals & opportunities

CBETA

1. NYSERDA funding Construct a high performance CBETA, commission to modest KPPs, e.g. 1 mA.
   - opportunities for participation in commissioning
2. DOE Nuclear Physics funding ? EIC R&D @ CBETA commissioning towards ultimate parameters, e.g. 40 mA.
   - BNL + Cornell + JLab + …
3. ?? funding Add a high energy CBETA beamline(s) for cooling &/or other experiments & applications
   - e.g. DarkLight (MIT) proposal, …
4. "Zero" funding? Networking on common physics and engineering topics. ARIES?
   - bERLinPro, MESA, PERLE, UK-XFEL, …

Summary

Challenges & opportunities

The project is 29% complete (out of 3.5 years & $25M)

“Risks could occur at any time”, but consider next steps in commissioning a state-of-the-art ERL:

1. 4 pass up, 4 pass down
2. Superconducting RF (1.3 GHz)
3. Very strong focusing single aperture optics
4. Halbach permanent magnet return arc

Next: perform challenging R&D with world-beating performance without additional capital expenditures

Capital expenditures, later, would enable much more, e.g. high-energy beamline, EIC cavity prototyping, etc.

Collaboration

We (BNL & Cornell) seek DIRECT collaboration in CBETA:

- individual beam commissioners in 2018
- students & post-docs
- JLab on EIC R&D
- potential “users” e.g. MIT

We also seek enhanced INDIRECT collaboration on topics of mutual interest with other ERL projects:

- bERLinPro, MESA, PERLE, UK-XFEL …

Near-term calendar

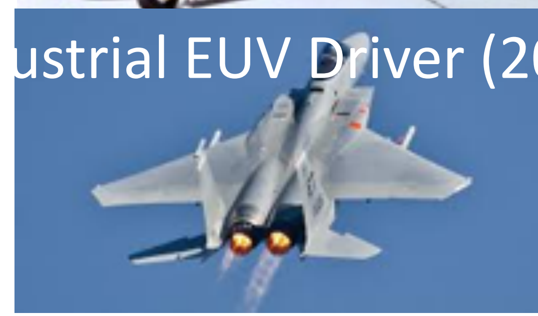
CBETA

	Technical Milestone	
2017		
Dec 19		Oversight Board meeting
Dec 31	5	"First arc production magnet tested"
2018		
Jan 15-17		PERLE collaboration meeting, Daresbury
Feb 12		Shift training begins (Bartnik)
Feb 12		Dario Pellegrini arrives at CU
Feb NN ?		FAT shifts begin
Feb 22-23		Advisory Committee meeting, CU
Mar NN ?		Cost, schedule & management review, BNL
April 30	6	"Fractional Arc Test"
Nov 30	7	"Girder production run complete"

Backup slides

History of ERLs (Dave Douglas)

CBETA



Notes

CERN Courier article

Advisory Committee topics

Wencan slides

Adam slides