Abstract:

The Future of CEBAF

The CEBAF accelerator at Jefferson Lab has been providing polarized electrons for high-impact nuclear and particle physics experiments for almost three decades. Accelerator upgrades providing polarization of the beam, increasing the beam energy, and increasing number of experimental end stations have paved the way to many new and successful experiments conducted at the lab. Studies are underway of potential future upgrades for the accelerator and the physics they would make possible. The considered upgrades include exciting topics such as doubling the luminosity of the accelerator, doubling the energy reach, and providing positron beams with a high degree of spin polarization. In this presentation I will discuss recent efforts to improve and expand the capabilities of CEBAF, highlighting some of the innovative ideas proposed while mentioning the challenges remaining to be solved.

The Future of CEBAF

WG6: Future Experiments
Tue 3/5/22

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Operations
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DIS2022:

XXIX International Workshop on Deep-Inelastic Scattering (DIS) and Related Subjects May 2 – 6, 2022

Jefferson Lab

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JSA

Outline

- Introduction to CEBAF

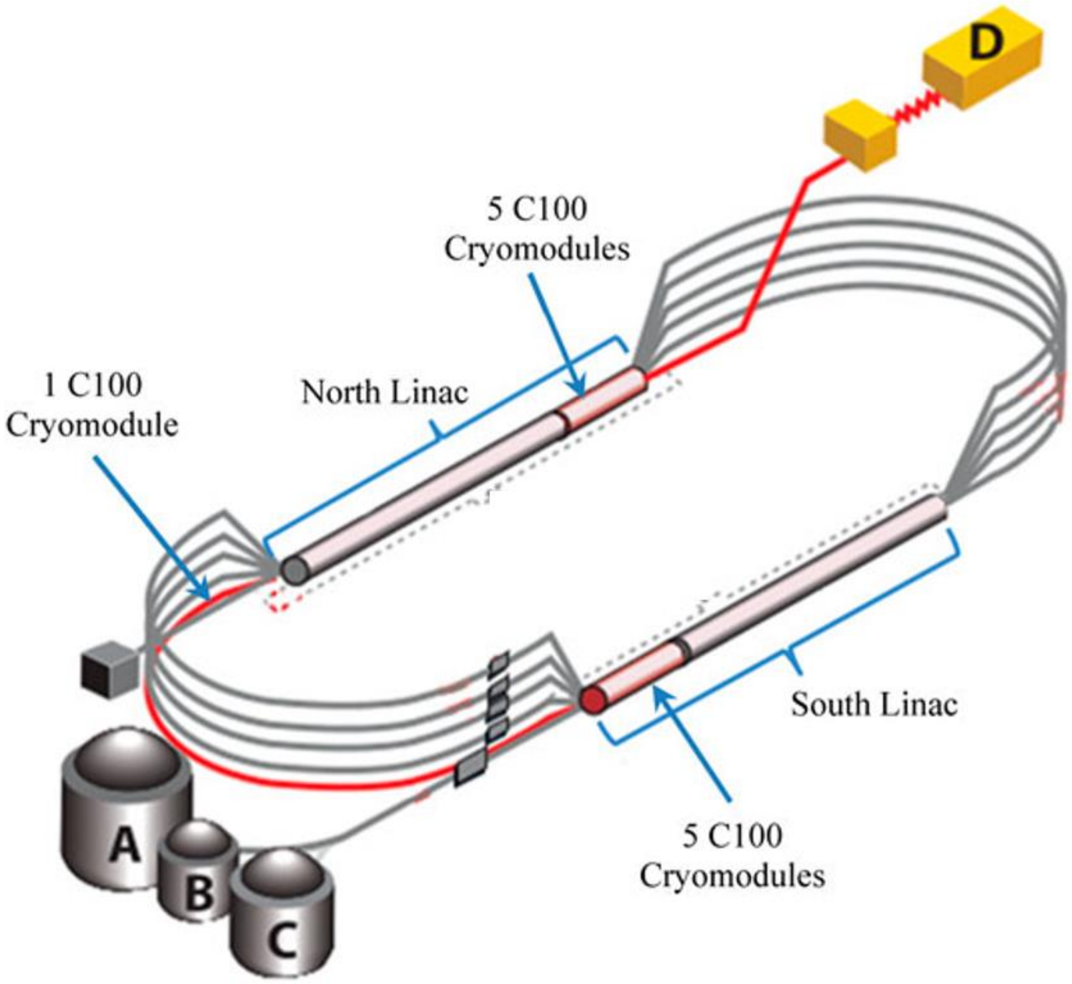
- The Future CEBAF upgrades being considered for 2030 and beyond:

    - Luminosity increase
    - Positron beam addition
    - Energy increase

Introduction to CEBAF Accelerator

- **High duty factor / CW beam**
- **1.1 GeV design per Linac** (FY22 1.05 GeV)
- **Recirculating Up to 5 Passes** (5.5 to Hall D)
- **Lower pass extraction possible**

Current (design)	Up to 85μA @11GeV Hall A + Hall C total Max 82 μA each
Energy (design)	11 GeV to A, B, or C 12 GeV to D

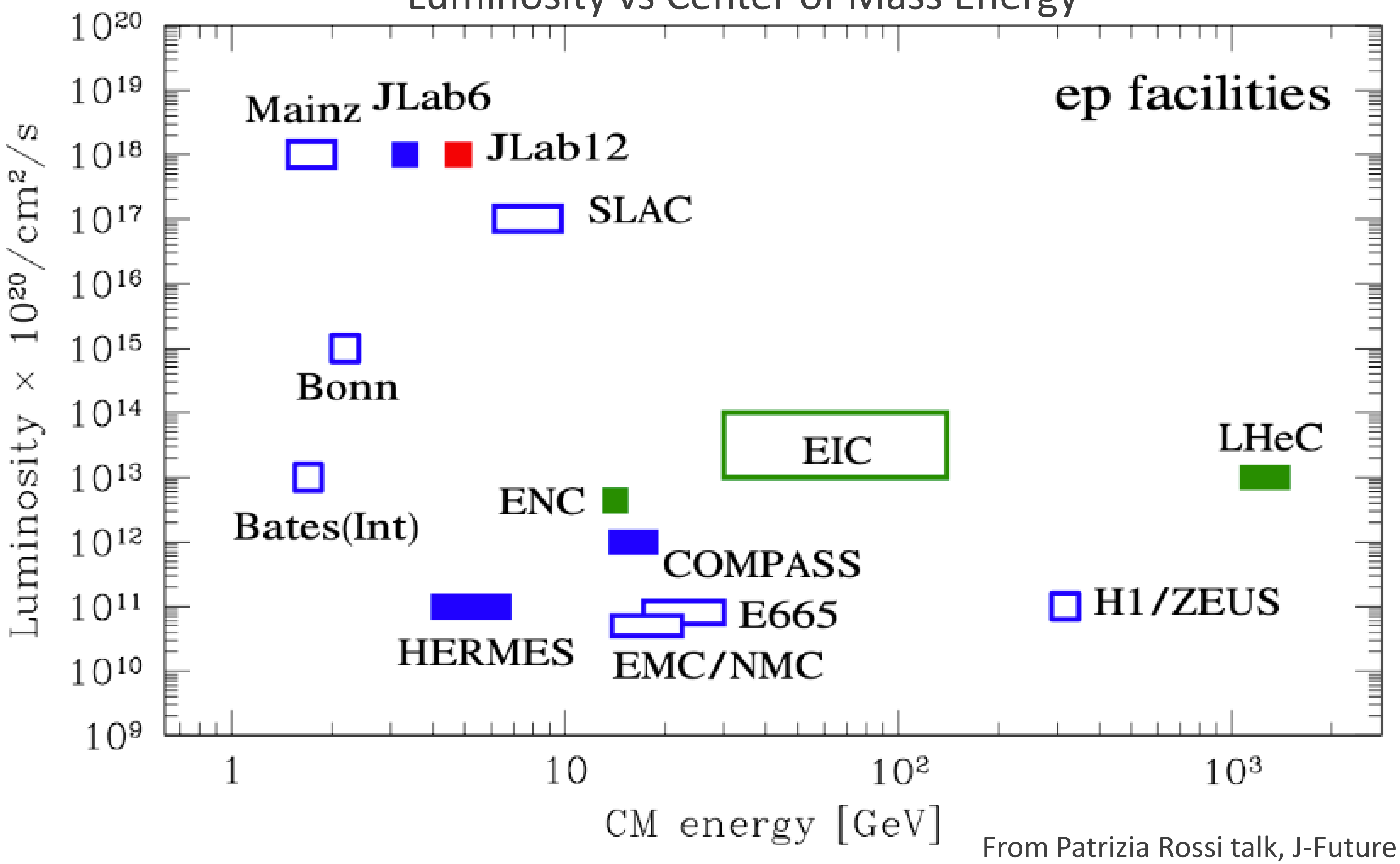


Introduction

CEBAF will remain the prime facility
for fixed target electron scattering at the luminosity frontier parameters.

But we also need to look in to the future especially beyond 2030.

Luminosity vs Center of Mass Energy



From Patrizia Rossi talk, J-Future March, 2022, Messina, Italy

Luminosity Increase

Key Points

- Present safety documentation limits operation to 1 MW total to all halls

  $\Rightarrow$86uA total at highest energy

  This documentation will be updated to 1.2 MW by Oct without changes.

- Halls A/C beam dump cooling limits operation to ~1.1 MW combined

- Beam Breakup instability (BBU) depends on beam current, impact to be investigated.

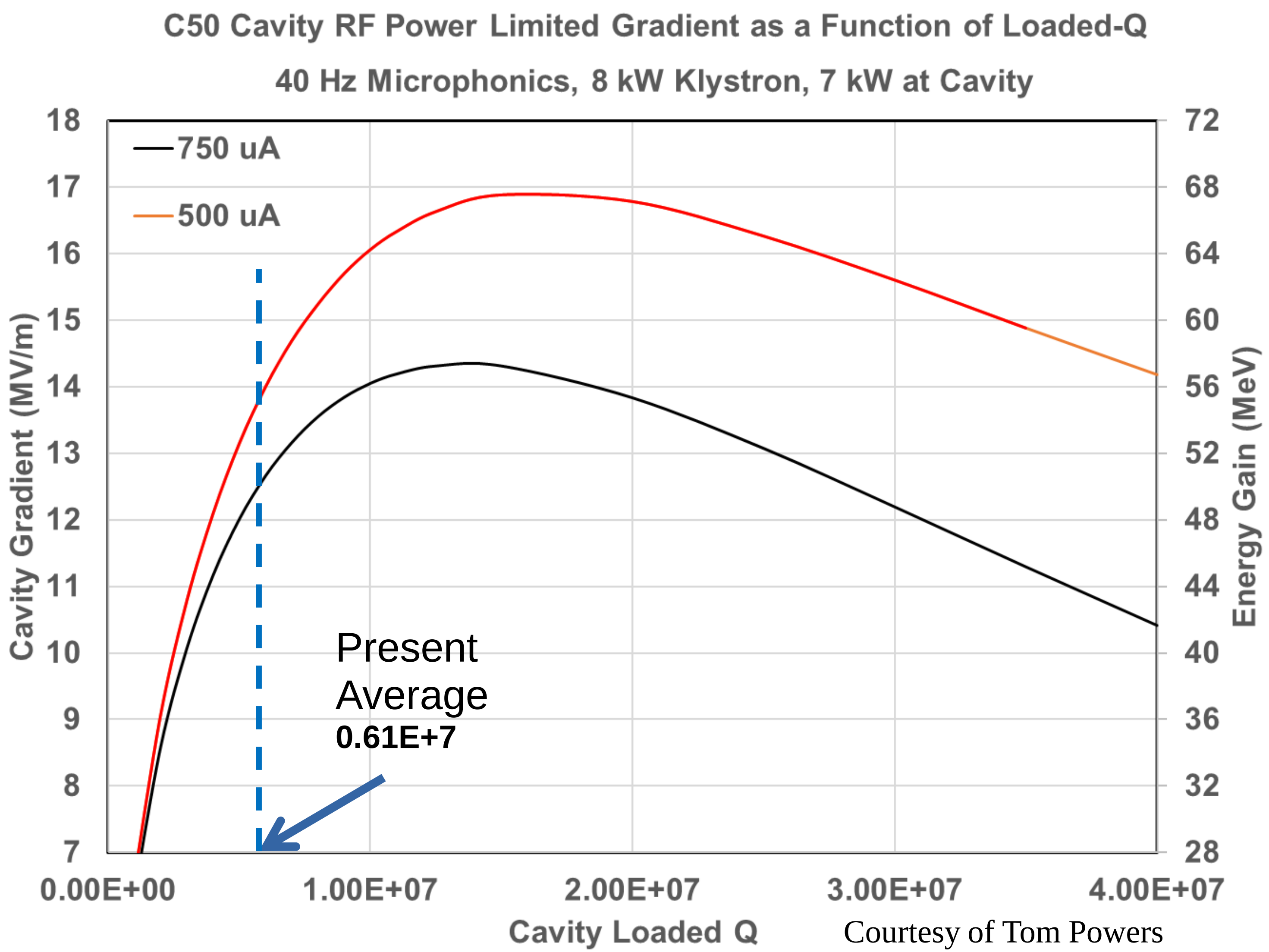
Luminosity Increase

Assuming existing klystron power, What Can We Do?

We can gain luminosity by optimizing the *Loaded Q* of cavities without klystron upgrade.

Luminosity Increase

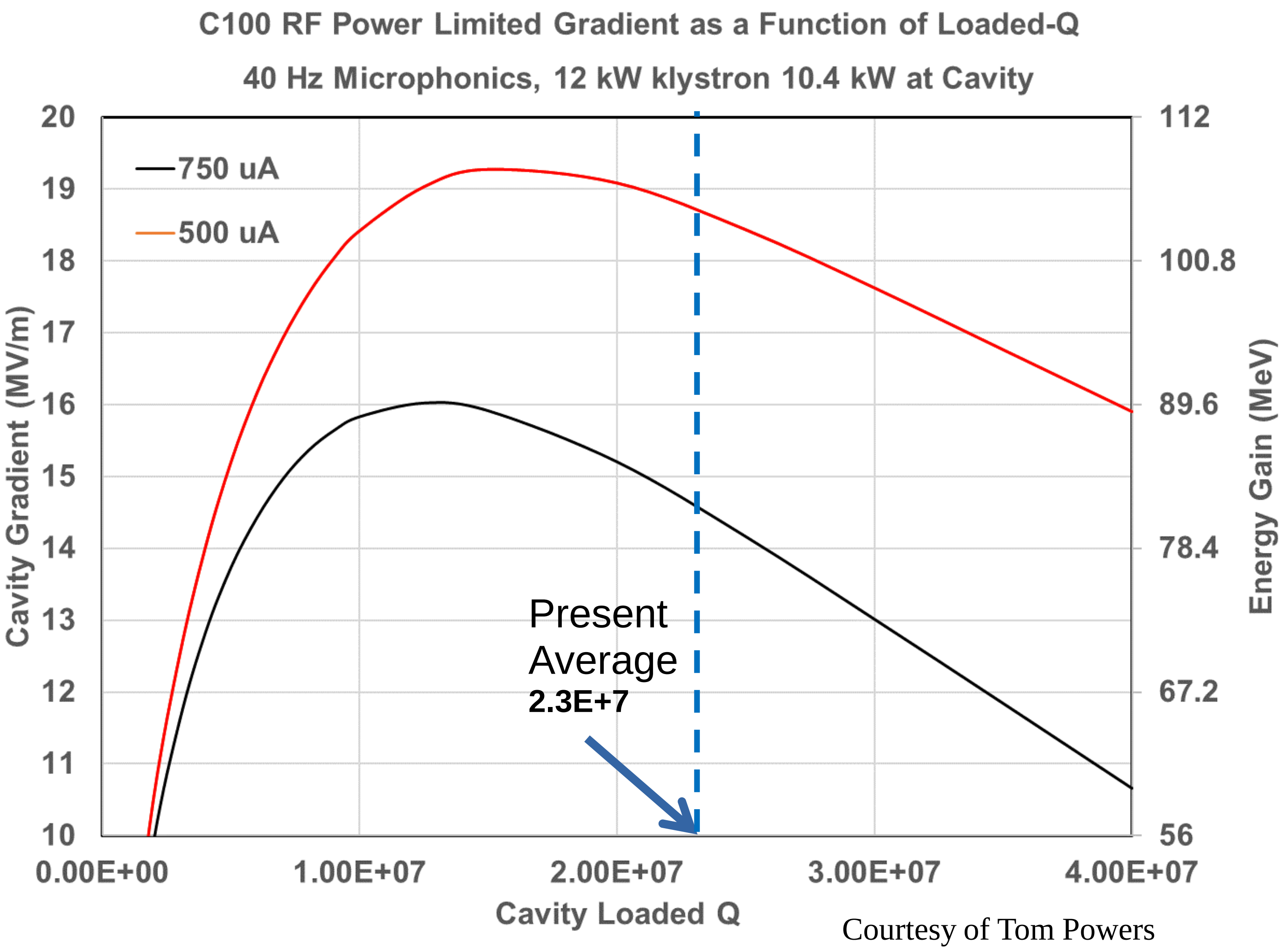
The Loaded Q generally needs to be moved higher for C25/C50 cavities
(For both currents)



Courtesy of Tom Powers

Luminosity Increase

The Loaded Q generally needs to be moved Lower for C100 cavities
(For both currents)



Courtesy of Tom Powers

Luminosity Increase

How much increase?

- Delivering up to 140 uA total to Halls A and C (70 uA each) at 11 GeV, may be possible with existing klystron power, after optimizing loaded Q.
- Includes 25 kW to B and 60 kW to D.
- The total beam power would be up to 1.625 MW.
- This requires an upgrade to the LCW cooling for the A and C dumps and beam testing for possible BBU instability in the cavities.
- Physics motivates an increase only up to 1.1 MW at this time.

Ce+BAF : Positron Beams at Jefferson Lab

The interest is there:

- Physics side
  - Positron physics workshops at JLab in 1999, 2009 and 2017
  - Recent EPJA issue dedicated to e+ physics at Jefferson Lab
  - Today, two conditionally approved PAC (Program Advisory Comm) proposals exist

- Accelerator side
  - PEPPo experiment
  - JLAAC recommendations (JLab Accel Advisory Comm)
  - Positron LDRD (Laboratory Directed Research & Development)

* Physics interest in e+ limited to 12 GeV

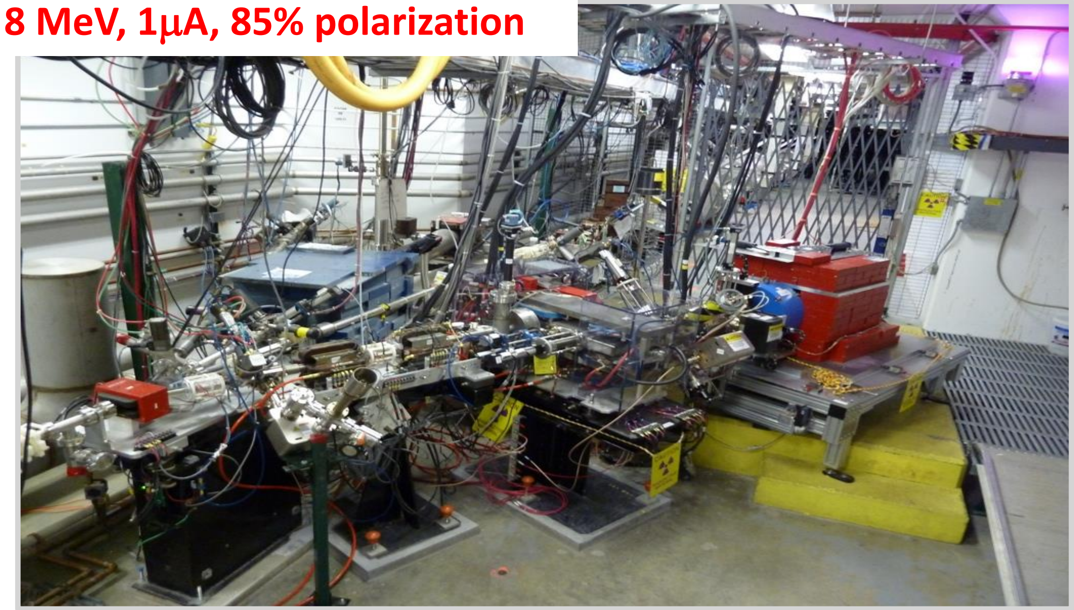
Ce+BAF: PEPPo Experiment

PEPPo @ CEBAF

PEPPo (**P**olarized **E**lectrons for **P**olarized **Po**sitrons) => ***demonstrate feasibility*** of using bremsstrahlung radiation of **MeV energy Polarized Electrons** for production of **Polarized Positrons**.

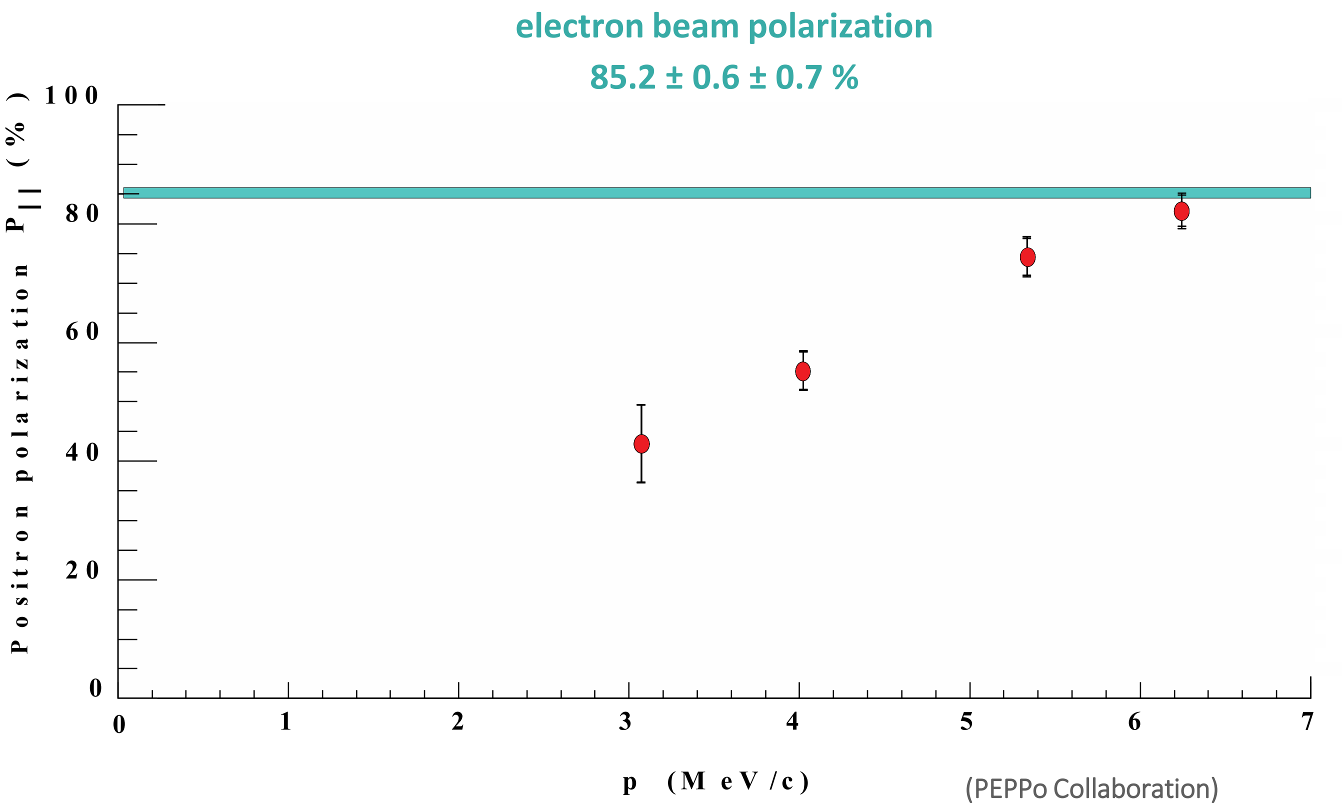
W (1mm)
<10 W beam

8 MeV, 1μA, 85% polarization

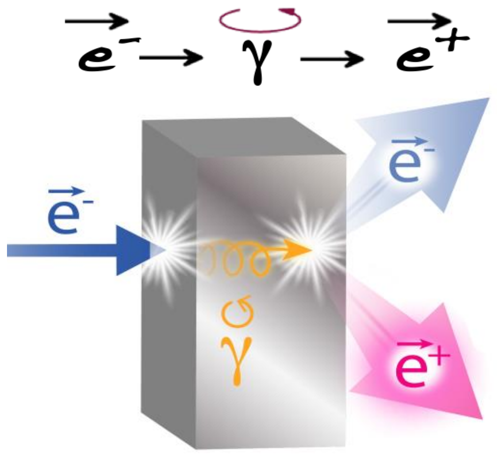


Polarized Positron Production

PEPPo demonstrated **efficient polarization transfer** of **8.2 MeV/c polarized electrons** to **positrons**, expanding polarized positron production using **MeV electron beam.**



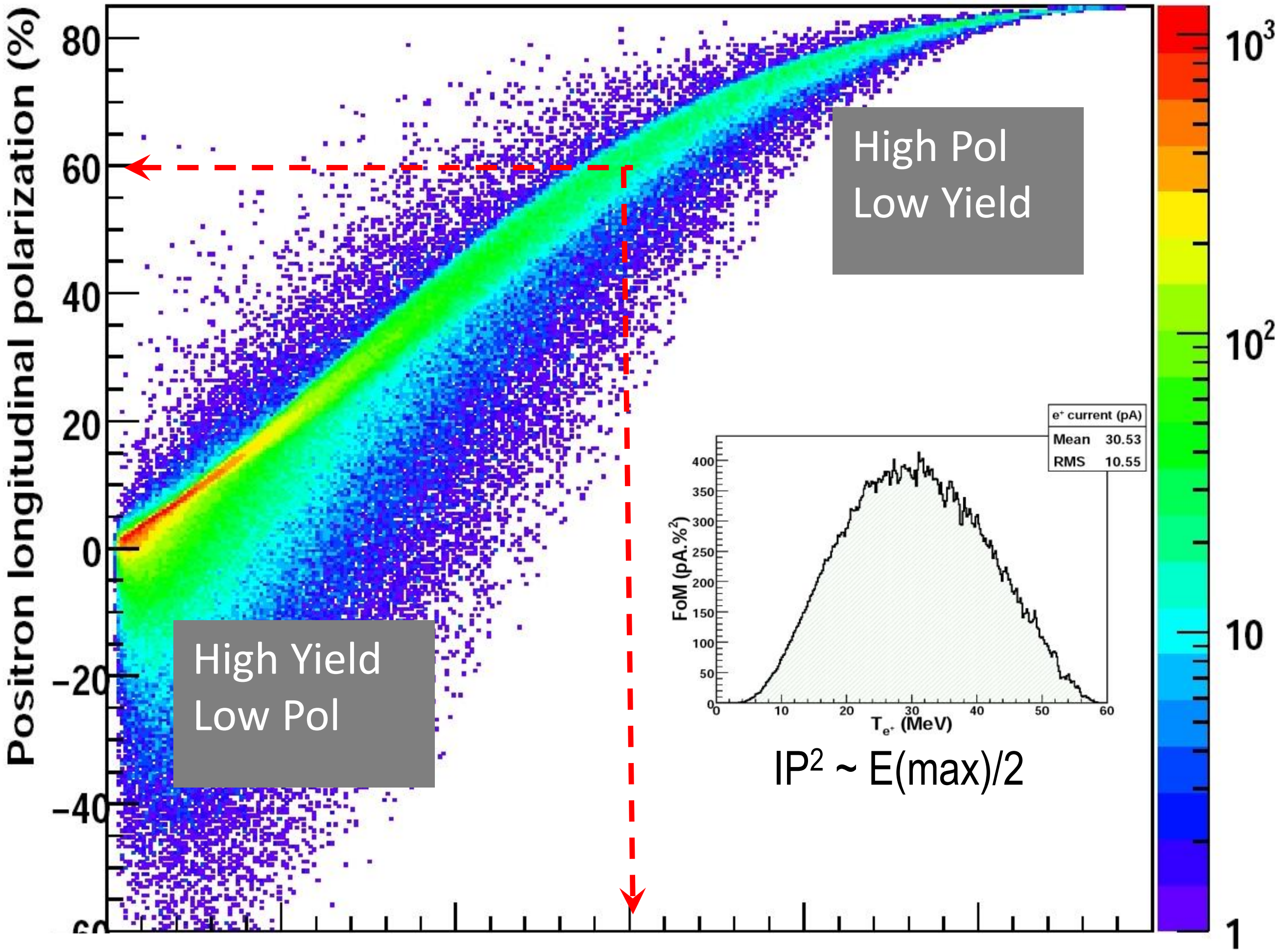
(PEPPo Collaboration)
D. Abbott et al. , Phys. Rev. Lett. 116 (2016) 214801



Whenever producing e^+ from e^-, polarization transfer efficiency is almost 100% at highest momentum transfer.

Ce+BAF

Polarization and Intensity Trade Off



Yield scales with Beam Power

0

e+ energy

$E_{(max)}$=7, 123, 1090, etc

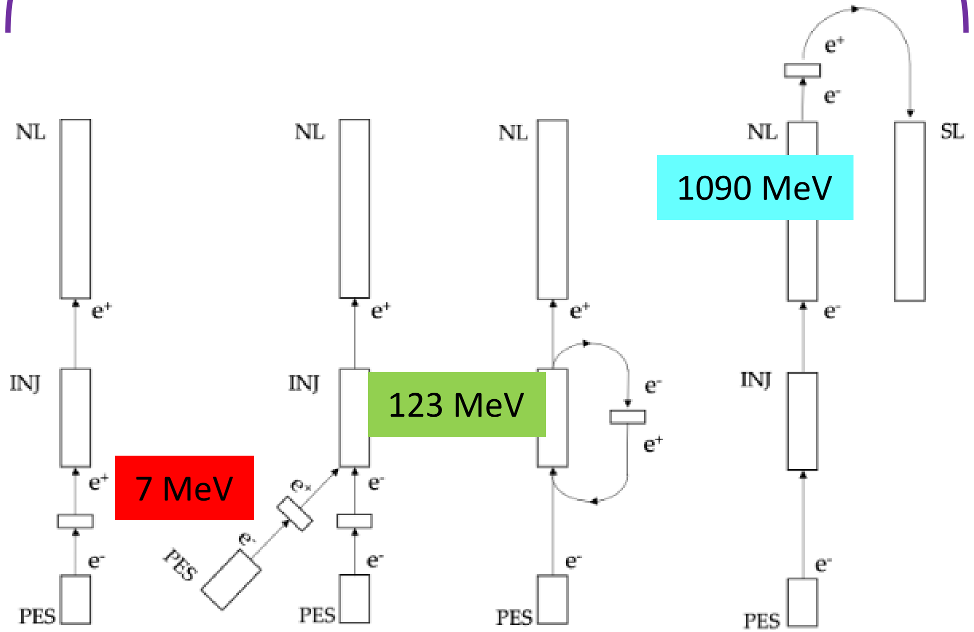
The **Yield** (e+/e-) depends on the beam power

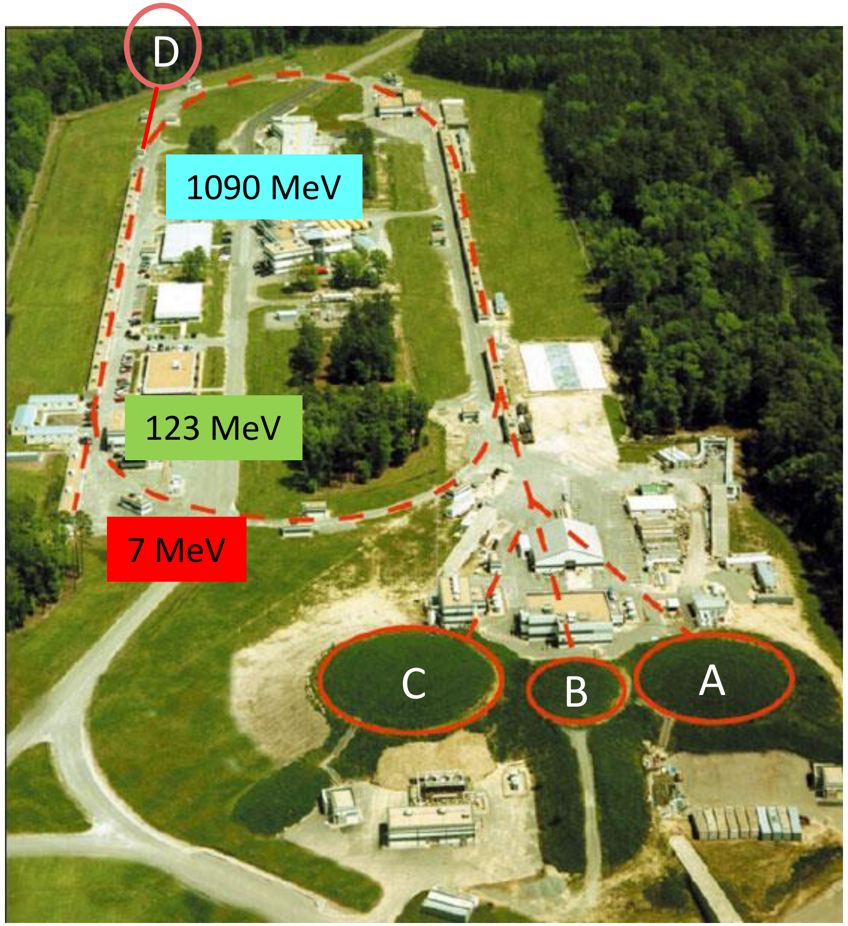
Beam Energy x Beam Current

Polarization transfer curve is universal whether the electron beam is 10 MeV, 100 MeV, 1 GeV, etc…

3 Possible Configurations for e+ Production

Today’s 12 GeV e- energies





PEPPo approach is a new approach vs. others

”Conventional” unpolarized bremsstrahlung positron sources

- SLAC – Stanford Linear Accelerator Center (US)
- HERA – Hadron Electron Ring Accelerator (Germany)
- BELLE/KEK – National Laboratory for High Energy Physics (Japan)
- CESR – Cornell Electron Storage Ring (US)
- VEPP – Budker Institute of Nuclear Physics (Russia)
- BEPCII – Beijing Electron Positron Collider (China)

PEPPo builds upon this

- e+ polarization/intensity configurable
- CW (all prior machines are pulsed)
- Milliamp polarized e- source
- Integrates to 12 GeV CEBAF…

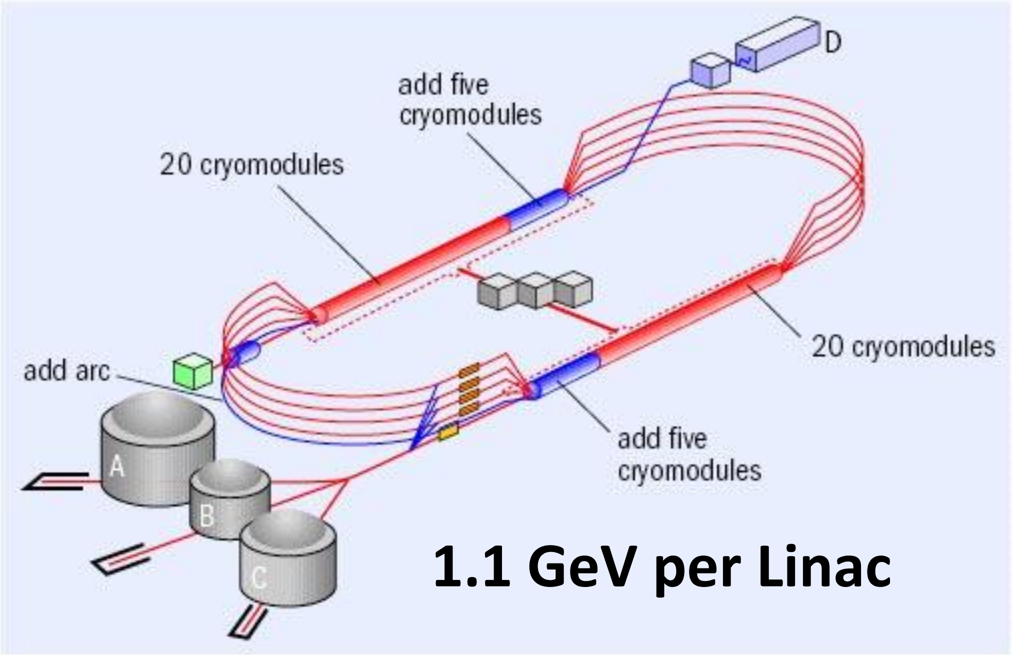
We consider building an e+ source prototype

- 350 kV polarized electron gun with 1000 C lifetime
- 8 MeV, 1 mA electron beam
- Optics model of the positron source including especially the positron distribution downstream of target and capture/bunching sections
- e- and e+ beamline layout
- Positron production target that can take >10 kW
- Solenoid magnet, >0.5 T, positron spatial capture
- RF cavity, positron temporal capture
- e+ diagnostic beamline (Low current)

Goal: >100 nA unpolarized or >10 nA polarized positron beams

Energy Increase

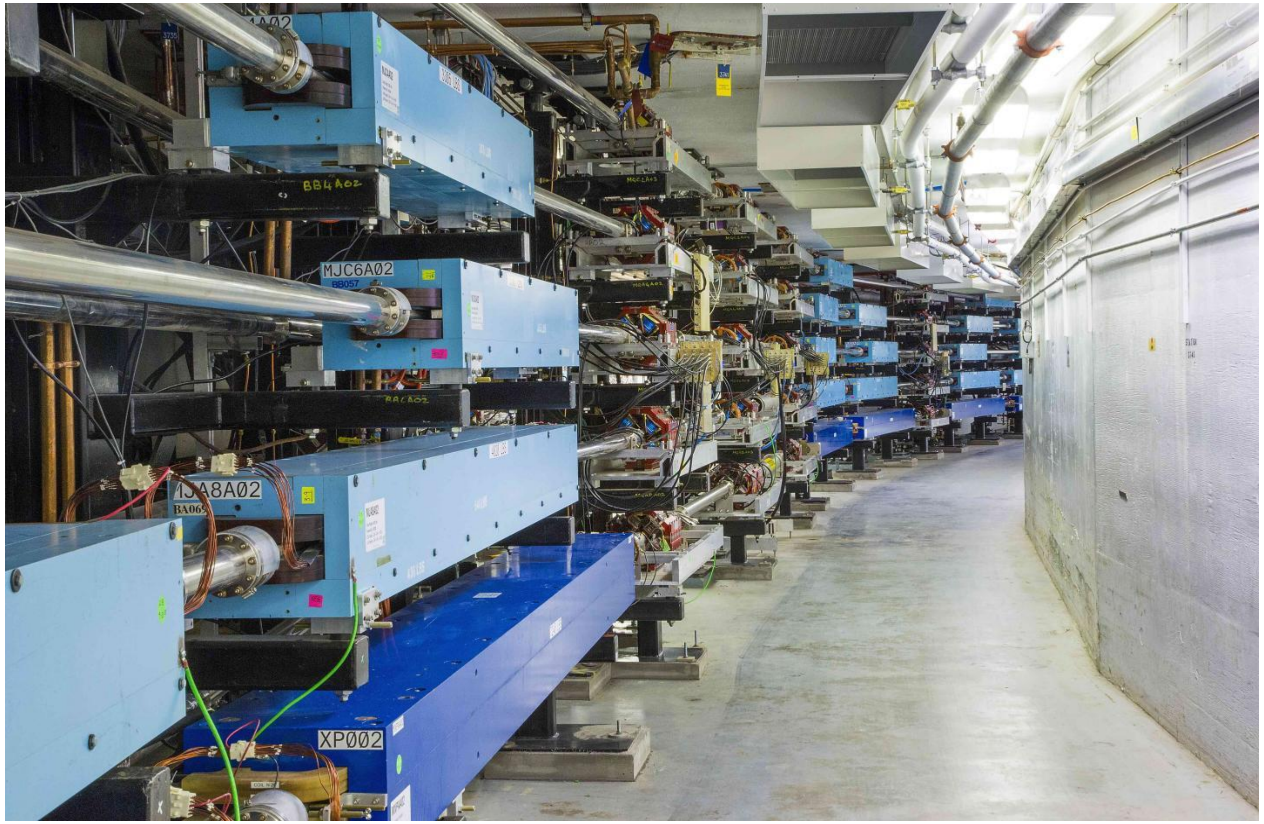
- How did we increase energy reach last time? By adding more accelerating RF cryomodules to the ends of the two Linacs.



- Adding more cryomodules is not an option any more. Costly and no more room.

Energy

- How about more recirculation through the Linacs?
- The recirculating arcs are already from ceiling to floor.

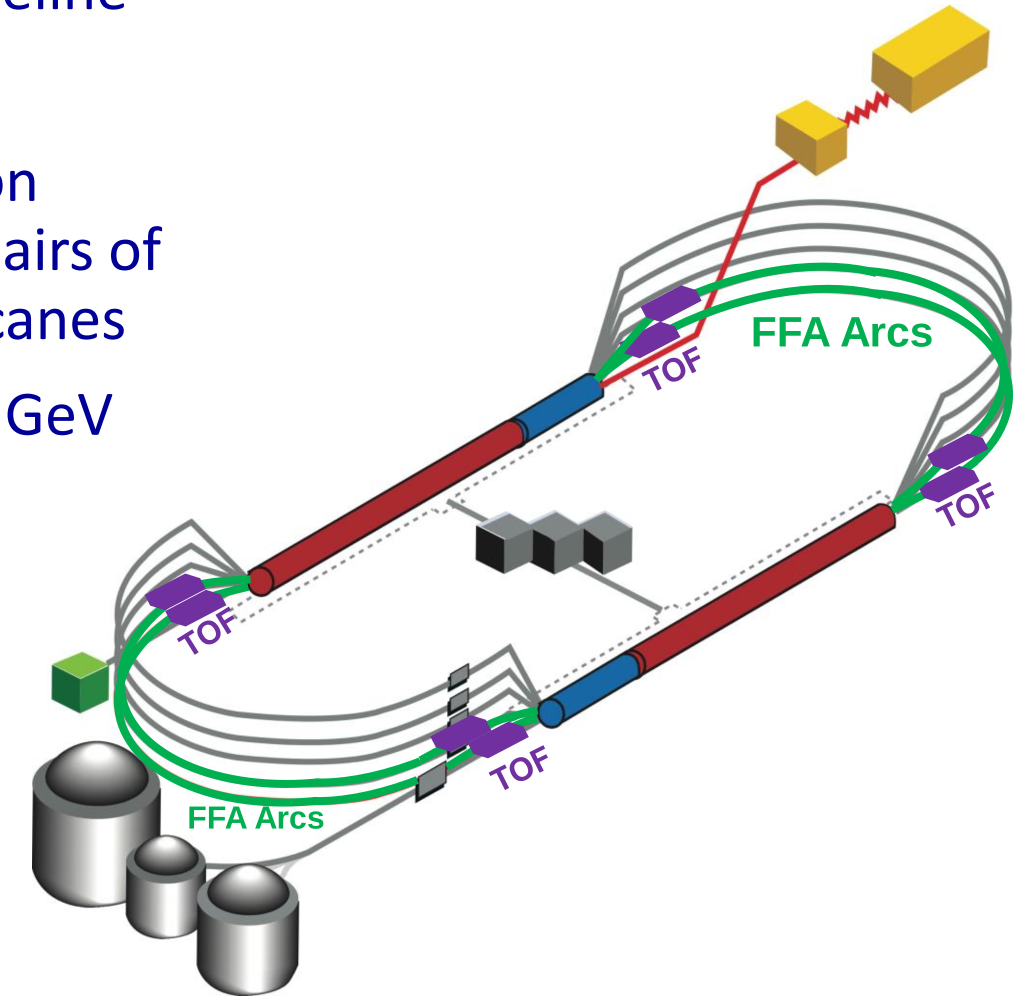


Solution: Recirculate more in the same beam pipe using FFA Permanent magnets.

*FFA (Fixed Field Alternating-Gradient)

Energy: CEBAF FFA Upgrade – ‘Big Picture’

- Starting with 12 GeV CEBAF as a baseline
- NO new SRF (1.1 GeV per Linac)
- Remove the highest two recirculation passes and replace them with two pairs of FFA arcs including time-of-flight chicanes
- Recirculate 11 times to get to 22-24 GeV



3 passes through EM arcs

4 passes through 1st FFA arcs

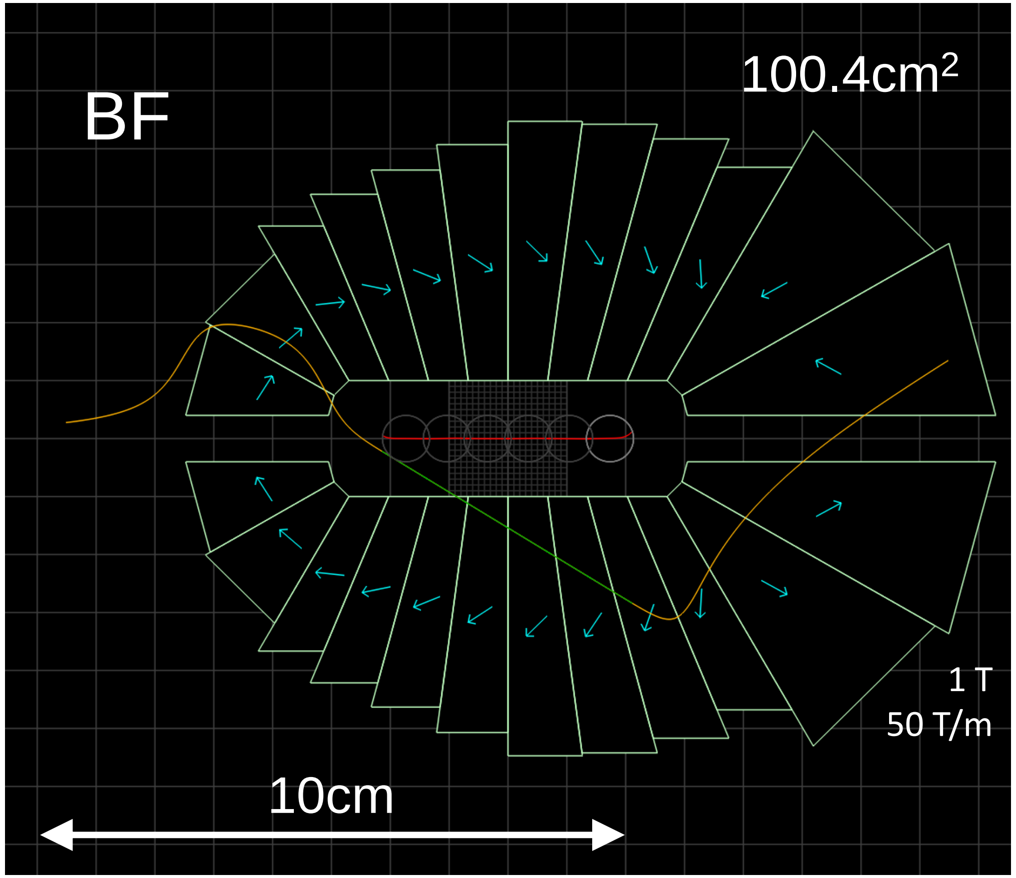
4 passes through 2nd FFA arcs

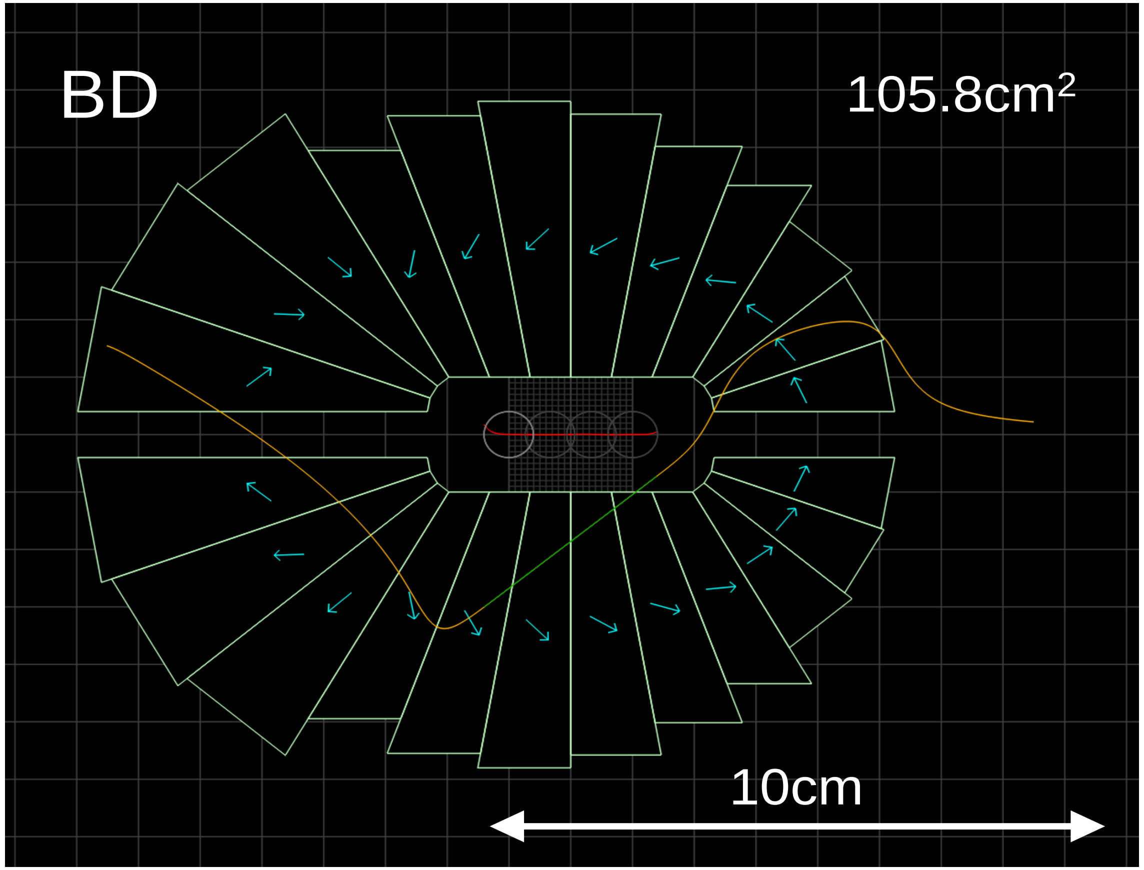
1 (pass 1)
1 (pass 2)
1 (pass 3)
4 (passes 4,5,6,7)
4 (passes 8,9,10,11)

Total = 11 passes

Energy: How Does FFA Work? Compact FODO Cell

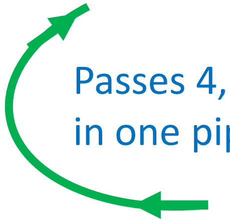
Large momentum acceptance FFA cell, configured with combined function magnets capable of transporting multiple energy beams through the same string of permanent magnets (beams with energies spanning a factor of two)





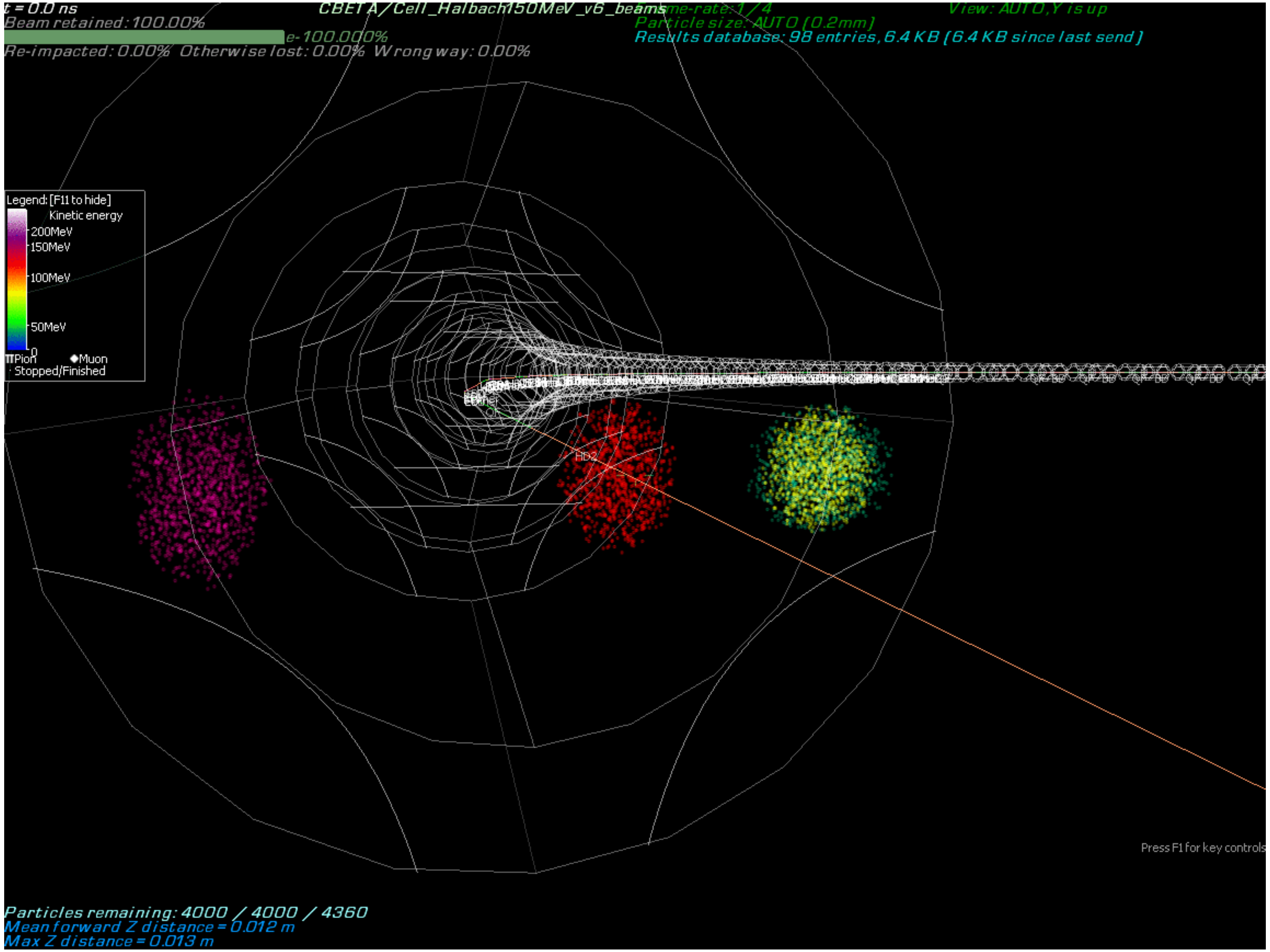
Energy: Four Different Energy Beams Bending in One FFA Line

Four beams from different passes Bending in the Arc through one FFA beamline.



Passes 4,5,6, and 7 in one pipe

FFA Arc



Courtesy Stephen Brooks

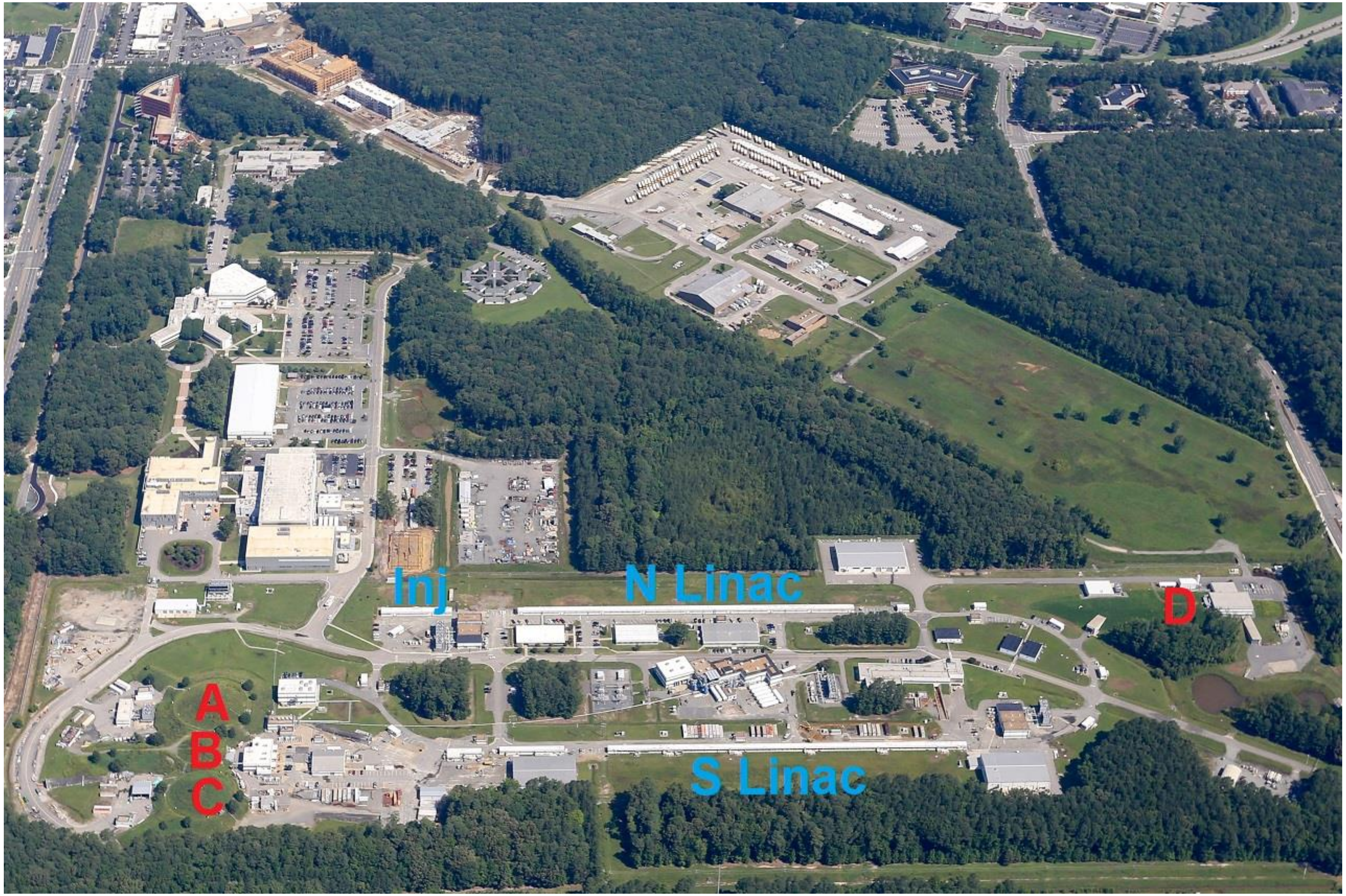
Recap

	Present Design	Possible	Challenges
Luminosity increase	Hall A & C @11GeV Total < 85 μA (< 82 μA Each dump limit)	Hall A & C @11GeV Total < 140 μA (< 82 μA Each dump limit)	▪ RF Beam Loading ▪ Dump Cooling ▪ BBU Instability
Positron option	Not Yet an Option	>100 nA Unpolarized Or >10 nA Polarized e+	▪ Target Design ▪ e+ Collection ▪ Beam dynamics, Injector and Main ▪ High Intensity e- Beam (~1 mA) Need ▪ Production Energy Choice and Design ▪ Gaining Experience
Energy increase	Up to 11 GeV to A, B, or C 12 GeV to D	20 – 24 GeV	▪ Scaling Up FFA Optics to Several GeVs ▪ Dump Cooling & Enviro. Evaluation ▪ Injector Energy increase ~ factor 4. ▪ BBU instability

Some Final Thoughts

- CEBAF accelerator offers unique advantage in terms of luminosity among the Nuclear Physics machines even beyond 2030.
- Very active R&D is underway on three different fronts: Luminosity, Energy reach and Positron capability.
- In some of these fronts, we are ready to develop prototypes or make incremental advances.
- I mentioned some of the Challenges we face in every front.
- These efforts also depend on the level of funding, prioritization of projects and scheduling the upgrades with busy nuclear physics use of the accelerator.
- Project prioritization will be driven by physics motivation.

Thank You!



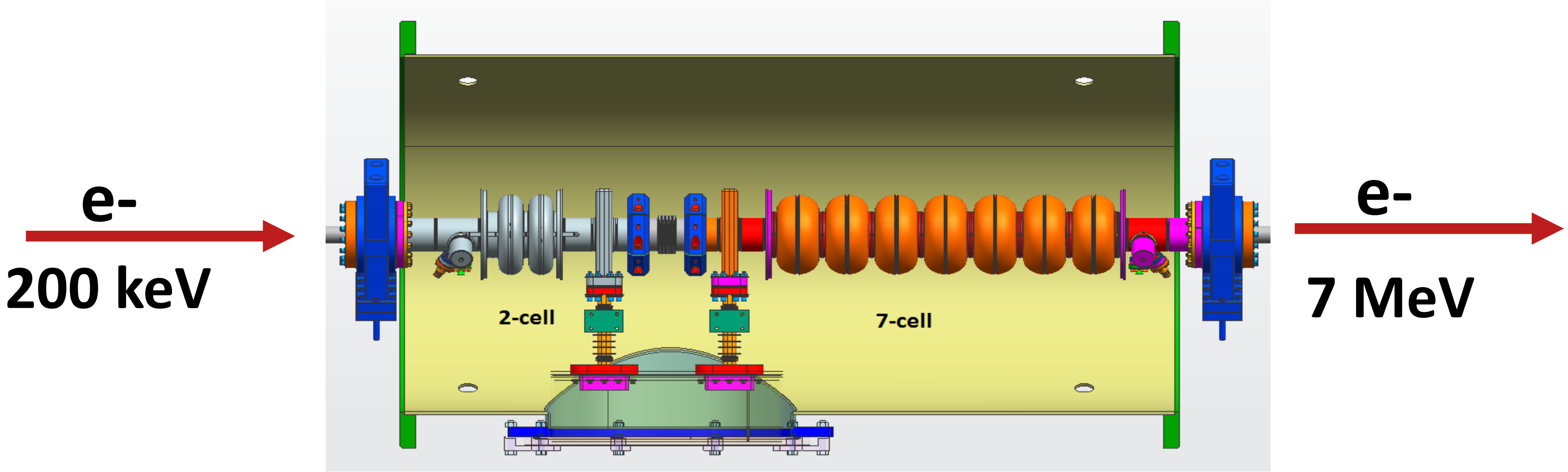
Thank You.

If time allows,

Announcing the ongoing Injector upgrade and getting ready for MOLLER experiment

An Important Upgrade for Injector Next Year

- We are upgrading the front end of the CEBAF injector to achieve a more controled uniform bunching and acceleration process. This gives us better Adiabatic Damping.
- Adiabatic damping in the injector is important for lowering helicity-correlated beam asymmetries at experimental halls.
- The most significant part is next year's installation of a new RF booster cavity.



Jefferson Lab

Why Is Asymmetry Important? Look at Parity Violation Experiments at CEBAF

Experiment	Energy (GeV)	Pol (%)	I (μA)	Target	A_{pv} (ppb)	Charge Asym (ppb)	Position Diff (nm)	Angle Diff (nrad)	Size Asym (δσ/σ)
HAPPEx-I 1998 – 1999	3.3	38.8 68.8	100 40	^{1}H (15 cm)	15,050	200	12	3	
G0-Forward 2003 – 2004	3.0	73.7	40	^{1}H (20 cm)	3,000-40,000	300±300	7±4	3±1	
HAPPEx-II 2004 – 2005	3.0	87.1	55	^{1}H (20 cm)	1,580	400	2	0.25	
HAPPEx-III 2009	3.484	89.4	100	^{1}H (25 cm)	23,800	200±10	3	0.5±0.1	10^{-3}
PREx-I 2010	1.056	89.2	70	^{208}Pb (0.5 mm)	657±60	85±1	4	1	10^{-4}
QWeak 2010 – 2012	1.162	88.7	180	^{1}H (30 cm)	226.5±9.3	20.5±1.7	-2.3±0.1	-0.07±0.01	$<10^{-4}$
PREx-II 2019	0.953	89.7	70	^{208}Pb (0.5 mm)	550±18	20.7±0.2	1.1	0.28	$<10^{-5}$
CREx 2019-2020	2.1825	87.1	150	^{48}Ca (5 mm)	2659± 113	<100	<10	<2	$<10^{-4}$
MOLLER	11	90	65	^{1}H (125 cm)	35.6±0.74	<10	<0.6	<0.12	$<10^{-5}$

Helicity-correlated Beam Asymmetries

	MOLLER	Previously achieved	PREx-II
Charge Asymmetry	<10 ppb	30 ppb (QWeak)	20.7 ± 0.2 ppb
Energy Asymmetry	<0.7 ppb	0.2 ppb (HAPPEx-II)	0.6 ± 0.6 ppb
Position Difference	<0.6 nm	2 nm (HAPPEx-II)	1.1 ± 1.1 nm
Angle Differences	<0.12 nrad	0.25 nrad (HAPPEx-II)	0.28 ± 0.28 nrad
Beam Spot Size Asymmetry	$<1x10^{-5}$	$<1x10^{-4}$ (PREx-I, QWeak)	$<10^{-5}$

- Path to achieve these requirements on helicity-correlated beam asymmetries:
  - Smaller beam asymmetries from Injector
  - Feedbacks
  - Slow Reversals
  - Adiabatic damping

Getting Ready for MOLLER

Backup

Luminosity Increase

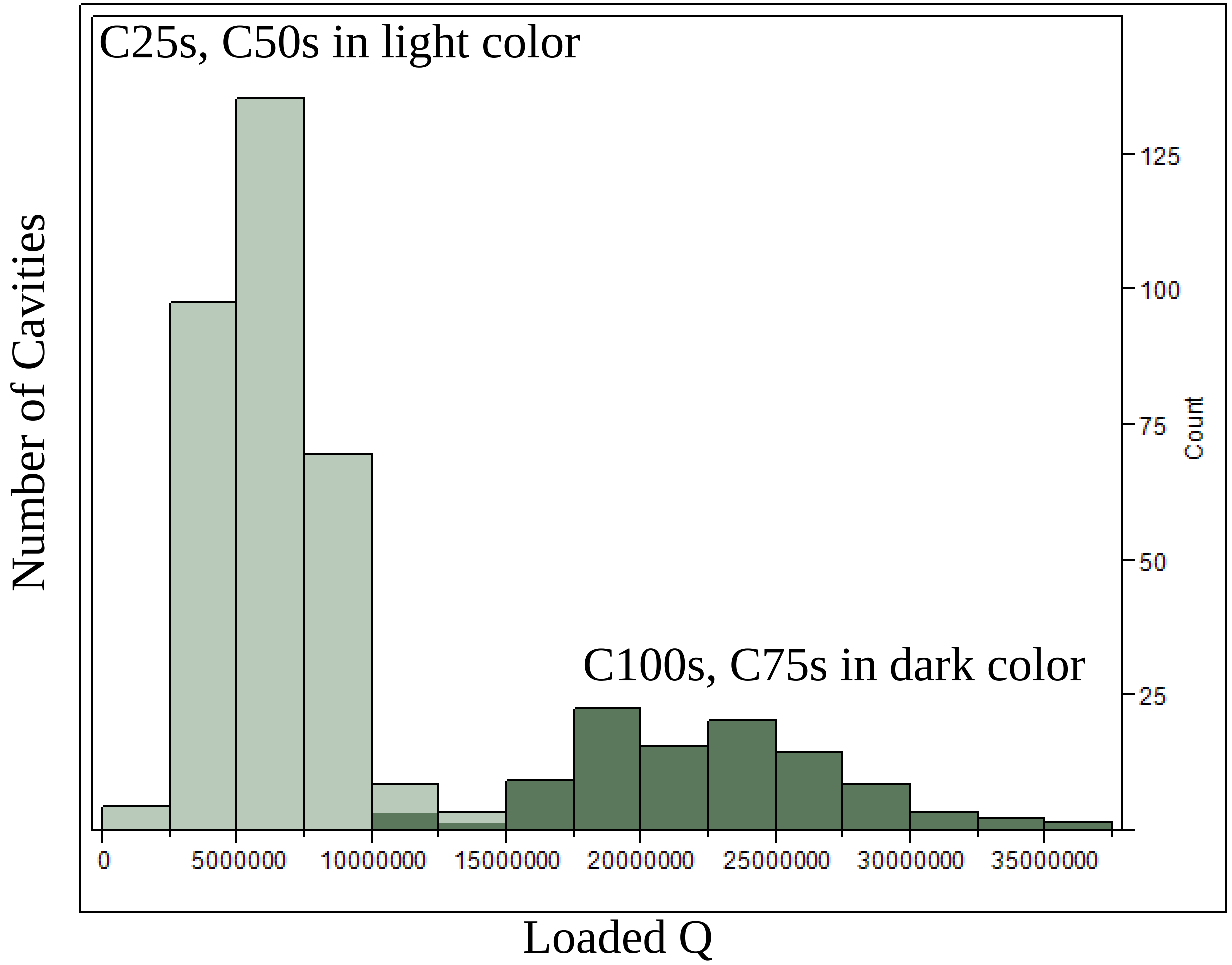
History

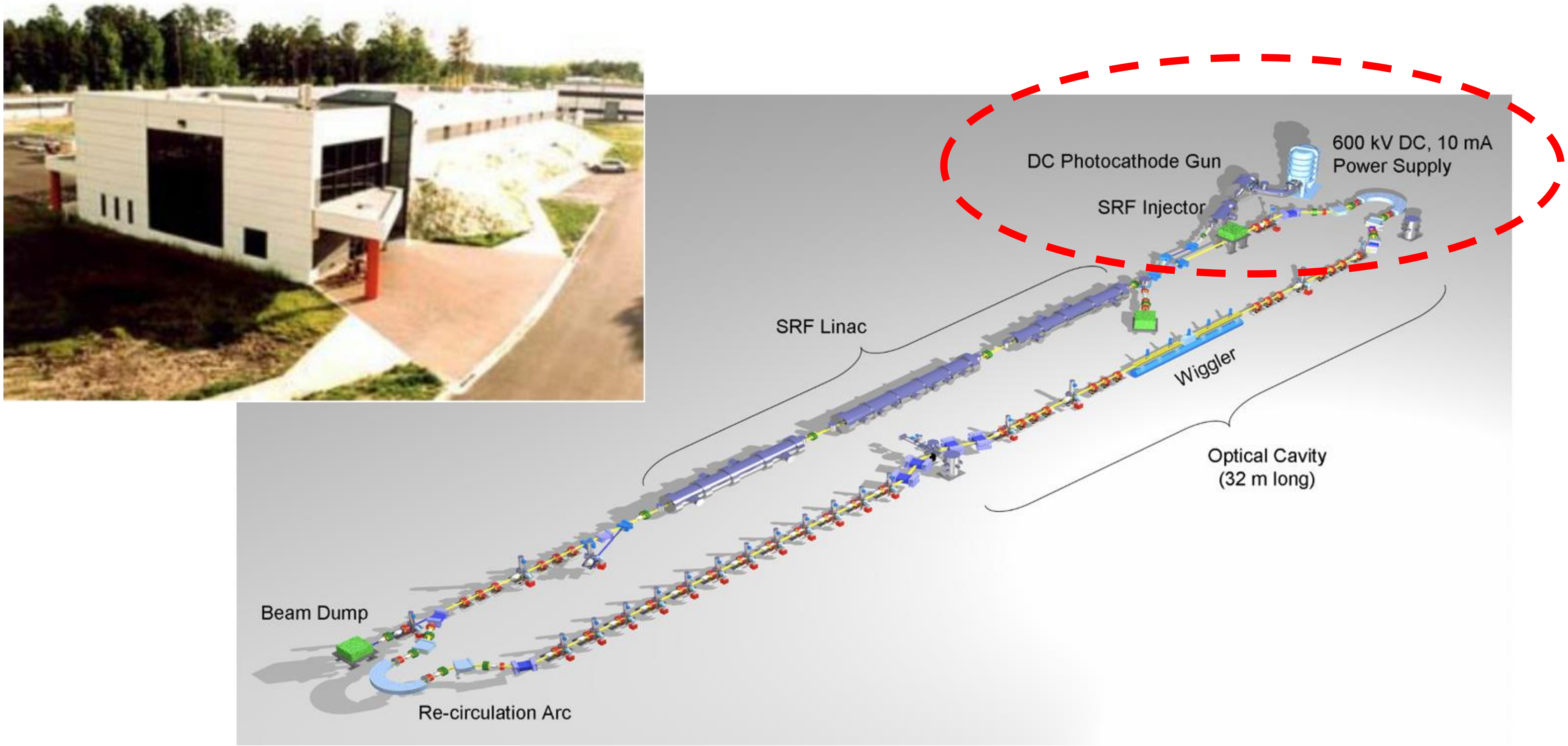
- 1986: 4 GeV CEBAF specification 200*5 µA, 1 mA through cavities and maximum 1 MW at the beam dump.
- 1998: Preliminary 12 GeV specification assumed original 1 MW Environmental Assessment beam power limit would remain
- 2005: Cavity cell shape defined assuming 460 µA {5*86 (A+C) +6*5(D)} with 13 kW klystrons plus a factor of two safety margin for dipole beam breakup (BBU) instability. TN-05-044
- 2007: Environmental Assessment allowed 1 MW each to Halls A and C. 12 GeV Project retained the original 1 MW beam power limit.
- 2017: C75 cavity specification retained 460 µA assumption. TN-17-055

Design choices from current limit

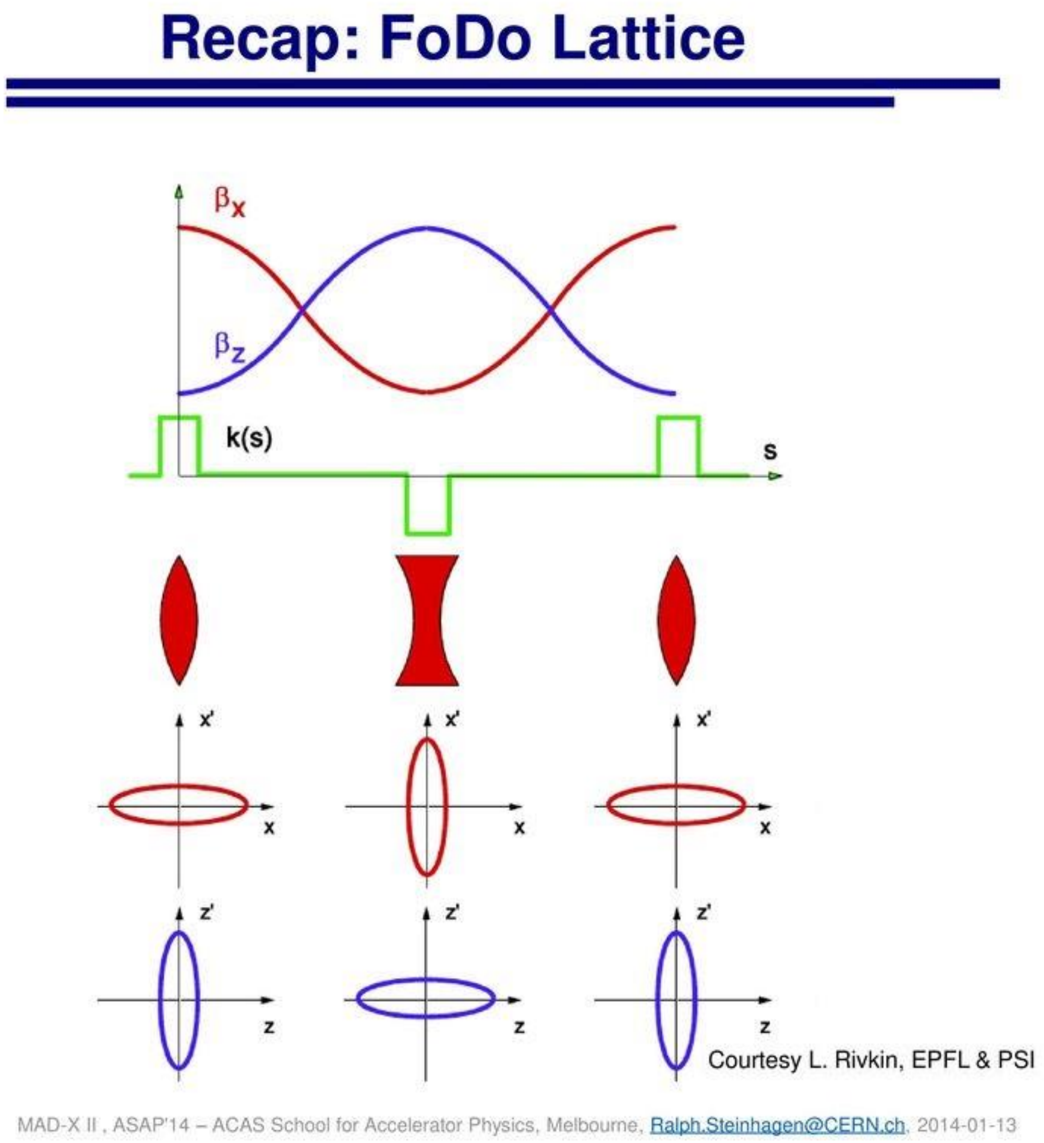
- Simplifying, required klystron power **P = V2/R + RI^2 +noise**
- R is proportional to Loaded Q and klystron power is fixed.
- Therefore different values of Loaded Q change the relationship between maximum current and maximum voltage that can be achieved.
- We can change the Loaded Q using stub tuners.

Luminosity Increase



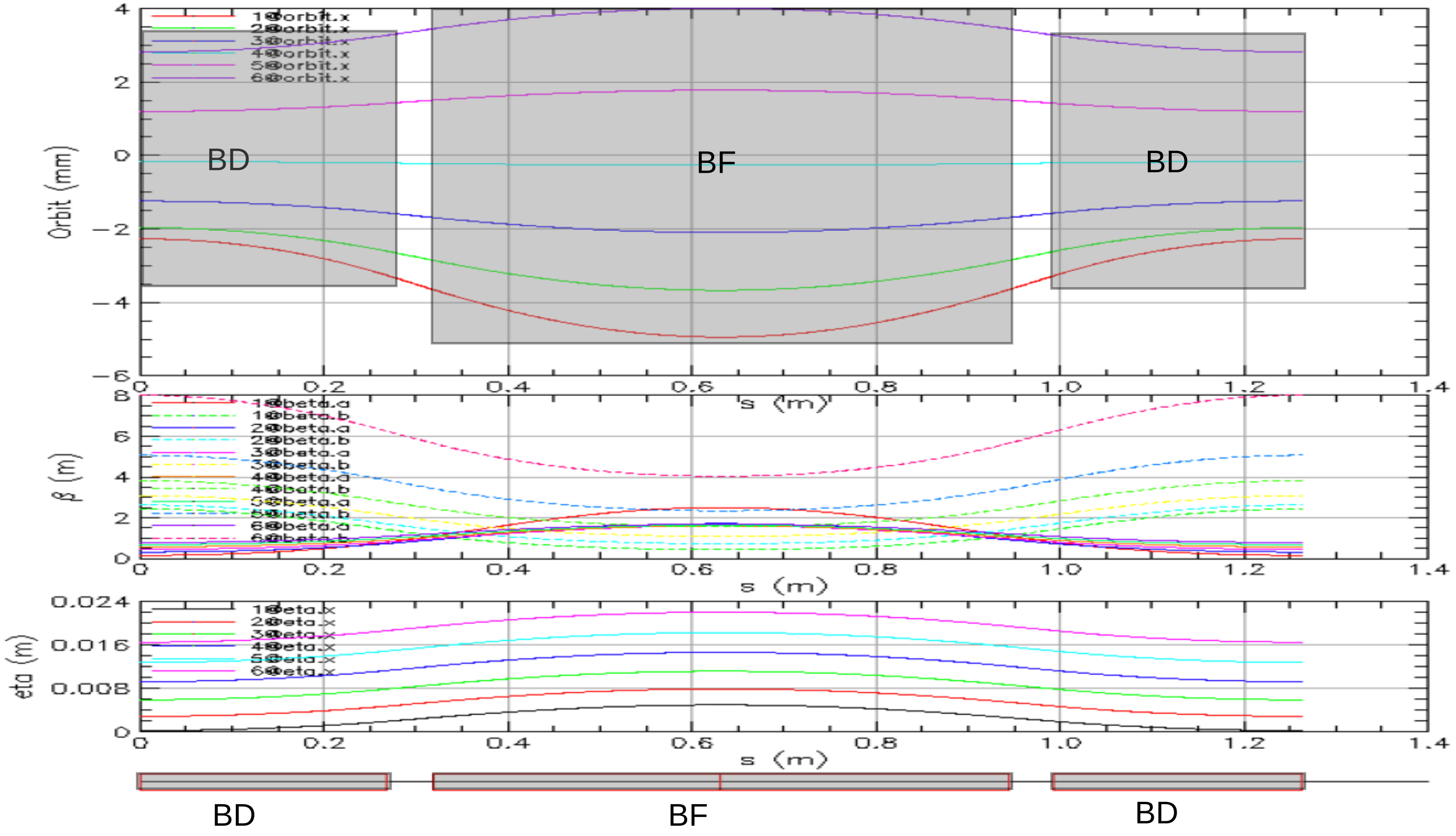

DC Photocathode Gun
600 kV DC, 10 mA
Power Supply
SRF Injector
SRF Linac
Wiggler
Optical Cavity
(32 m long)
Beam Dump
Re-circulation Arc

Energy: Focusing Defocusing Lattice (FoDo)



Energy: How Does FFA Work? Compact Combined Function Permanent Magnets

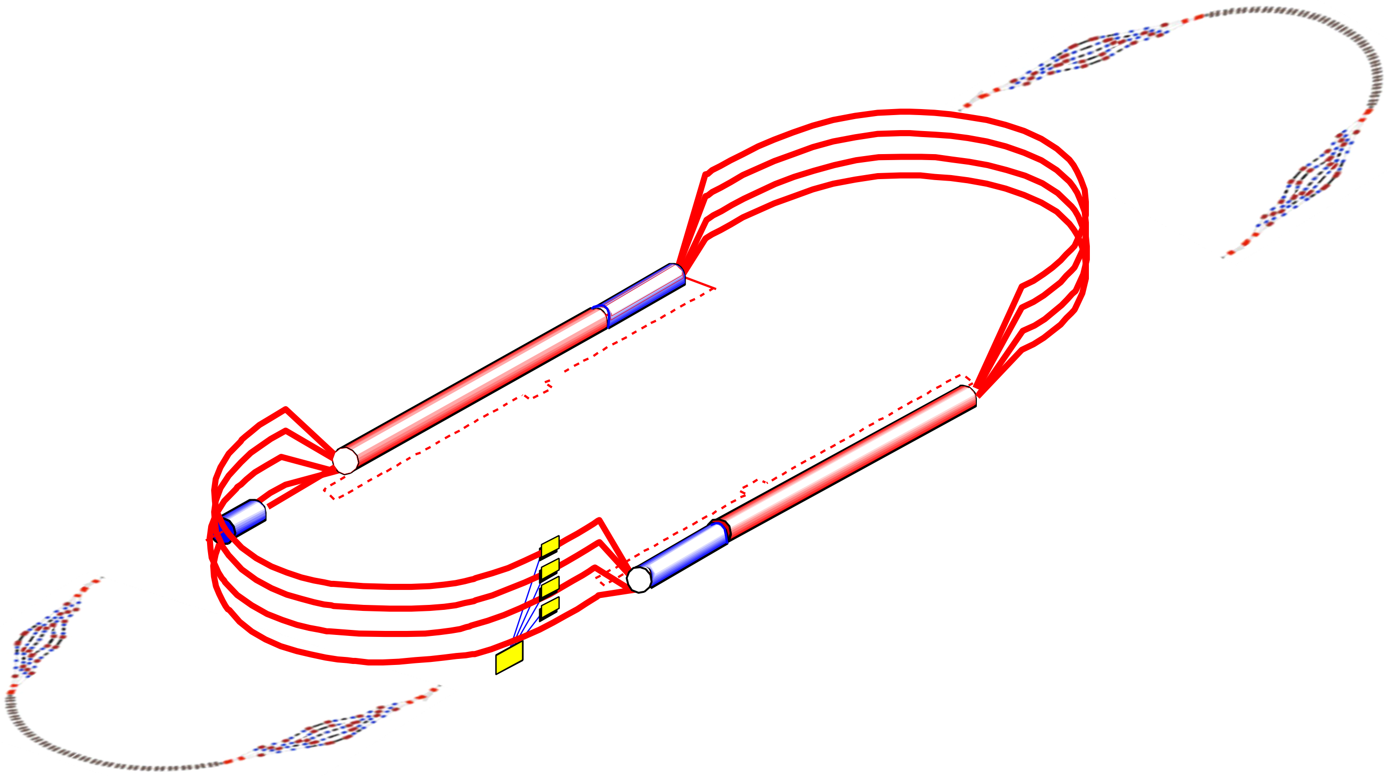
Large momentum acceptance FFA cell, configured with combined function magnets capable of transporting multiple energy beams through the same string of permanent magnets (beams with energies spanning a factor of two)



CBETA 6 Beam + Energy Recovery

CBETA - Cornell University Brookhaven National Laboratory electron energy recovery test accelerator

FFA CEBAF with CBETA-like Arcs



Energy Upgrade: Another Version 3x(1 pass EM) + 4 pass FFA + 3 pass FFA

Energy Range

Linac pass	Linac	Energy (MeV)	SR (MeV)	Line
0	injector	649	0.00	injector
1	North-1	1749	0.01	EM1E
2	South-1	2849	0.10	EM1W
3	North-2	3949	0.36	EM2E
4	South-2	5049	0.97	EM2W
5	North-3	6148	2.14	EM3E
6	South-3	7245	4.14	EM3W
7	North-4	8341	5.06	FFA1-1E
8	South-4	9436	5.76	FFA1-1W
9	North-5	10530	7.27	FFA1-2E
10	South-5	11623	11.00	FFA1-2W
11	North-6	12712	19.16	FFA1-3E
12	South-6	13793	34.63	FFA1-3W
13	North-7	14858	61.06	FFA1-4E
14	South-7	15897	101.93	FFA1-4W
15	North-8	16895	54.73	FFA2-1E
16	South-8	17941	63.24	FFA2-1W
17	North-9	18977	75.64	FFA2-2E
18	South-9	20002	93.36	FFA2-2W
19	North-10	21008	118.38	FFA2-3E
20	South-10	21990		Hall B
		21920	70.00	Halls A, C

Linac energy assumed 1100 MeV.

Three electromagnetic passes retained. Two FFAs used to limit energy range to 2.3:1 in each so peak is less than 1.6T in the good field region.

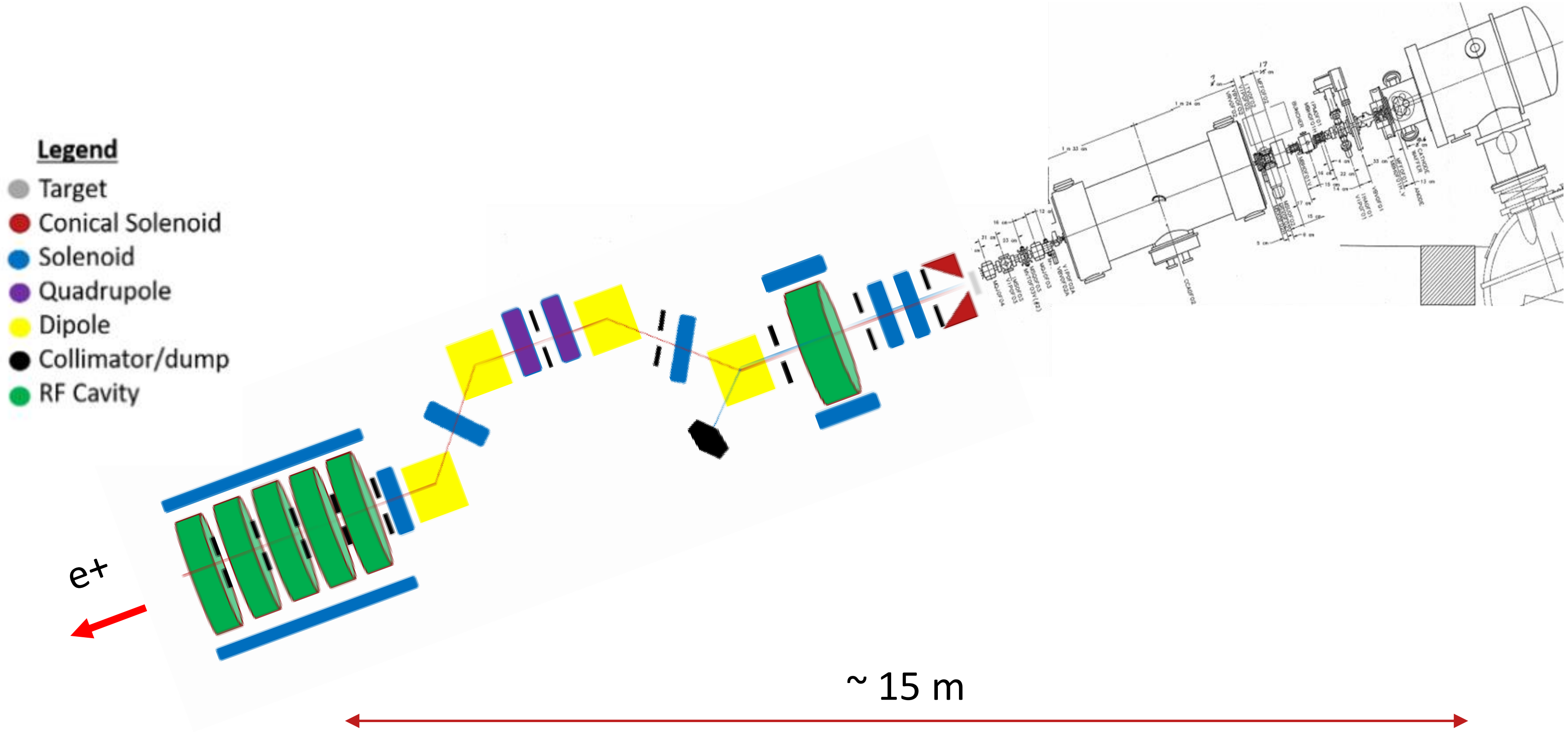
Final energy 22 GeV limited by feasible Hall line arc dipoles. TN-21-051.

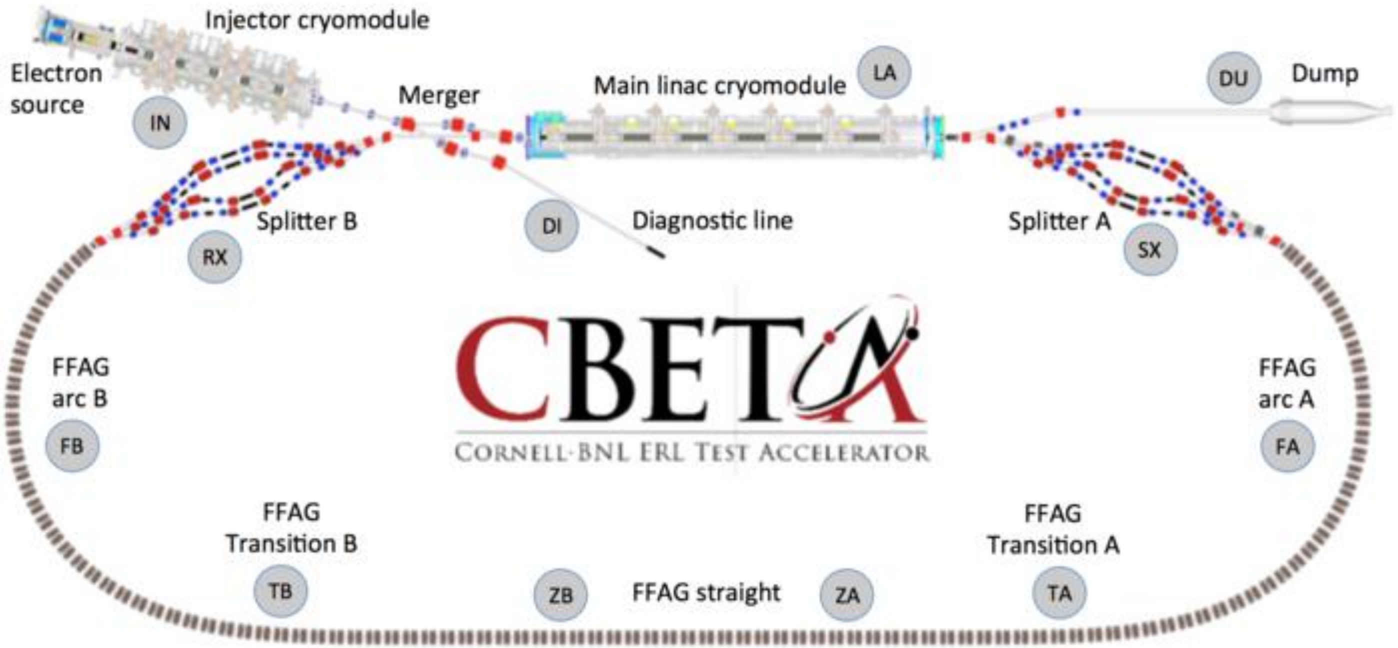
HT Stephen Brooks

Ce+BAF

We are designing a compact e+ source concept which could be installed at LERF at Jlab.

(Low Energy Recirculator Facility / the old FEL building)

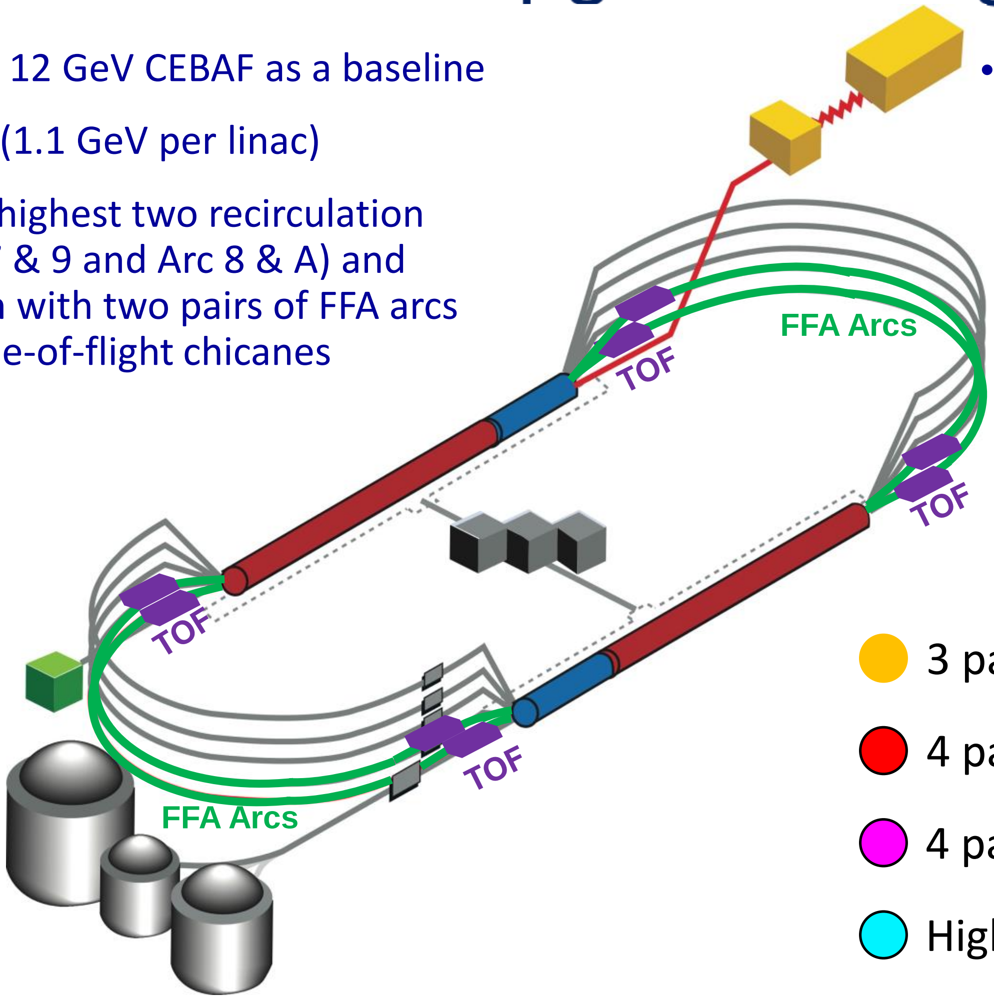



Injector cryomodule
Electron source
IN
Merger
Main linac cryomodule
LA
DU
Dump
Splitter B
RX
DI
Diagnostic line
Splitter A
SX
CBETA
CORNELL-BNL ERL TEST ACCELERATOR
FFAG arc B
FB
FFAG arc A
FA
FFAG Transition B
TB
ZB
FFAG straight
ZA
FFAG Transition A
TA

Energy Increase

CEBAF FFA Upgrade – ‘Big Picture’

- Starting with 12 GeV CEBAF as a baseline
- NO new SRF (1.1 GeV per linac)
- Remove the highest two recirculation passes (Arc 7 & 9 and Arc 8 & A) and replace them with two pairs of FFA arcs including time-of-flight chicanes

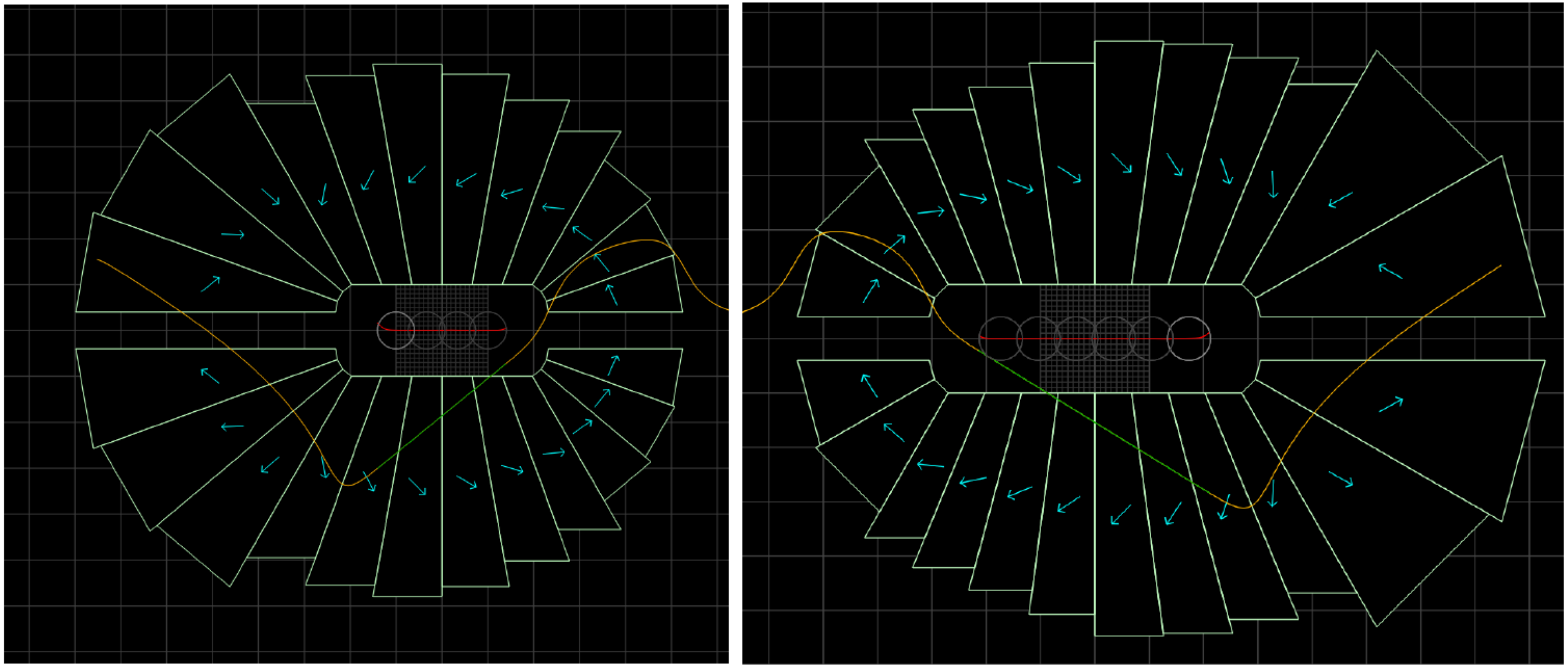


- Recirculate 11 times to get to 22-24 GeV:
  - 3 passes with the current CEBAF (Arcs 1-6)
  - 8 passes through a pair non-scaling FFAs (4 + 4)
  - CBETA -proven architecture
  - Novel permanent magnet CBETA technology used for power and cost savings

- 3 passes through EM arcs
- 4 passes through 1st FFA arc
- 4 passes through 2nd FFA arc
- Highest pass to halls

Energy Upgrade: FFA Magnet Cross-section

Permanent magnets (S. Brooks)



Left BD 105.8 cm² of permanent magnet material. Right BF 100.4 cm² Squares span 1 cm.

Luminosity Increase

Another Constraint

- Beam dumps have to be cooled. Halls A and C beam dumps are rated at 1 MW each.
- But the intermediate heat exchanger (IHX) which interfaces between their radioactive LCW systems and the cooling towers is rated at 1.1 MW.
- JLab Facilities group has been asked to begin planning for an upgrade to 2 MW, funding permitting. Two years required after funding.