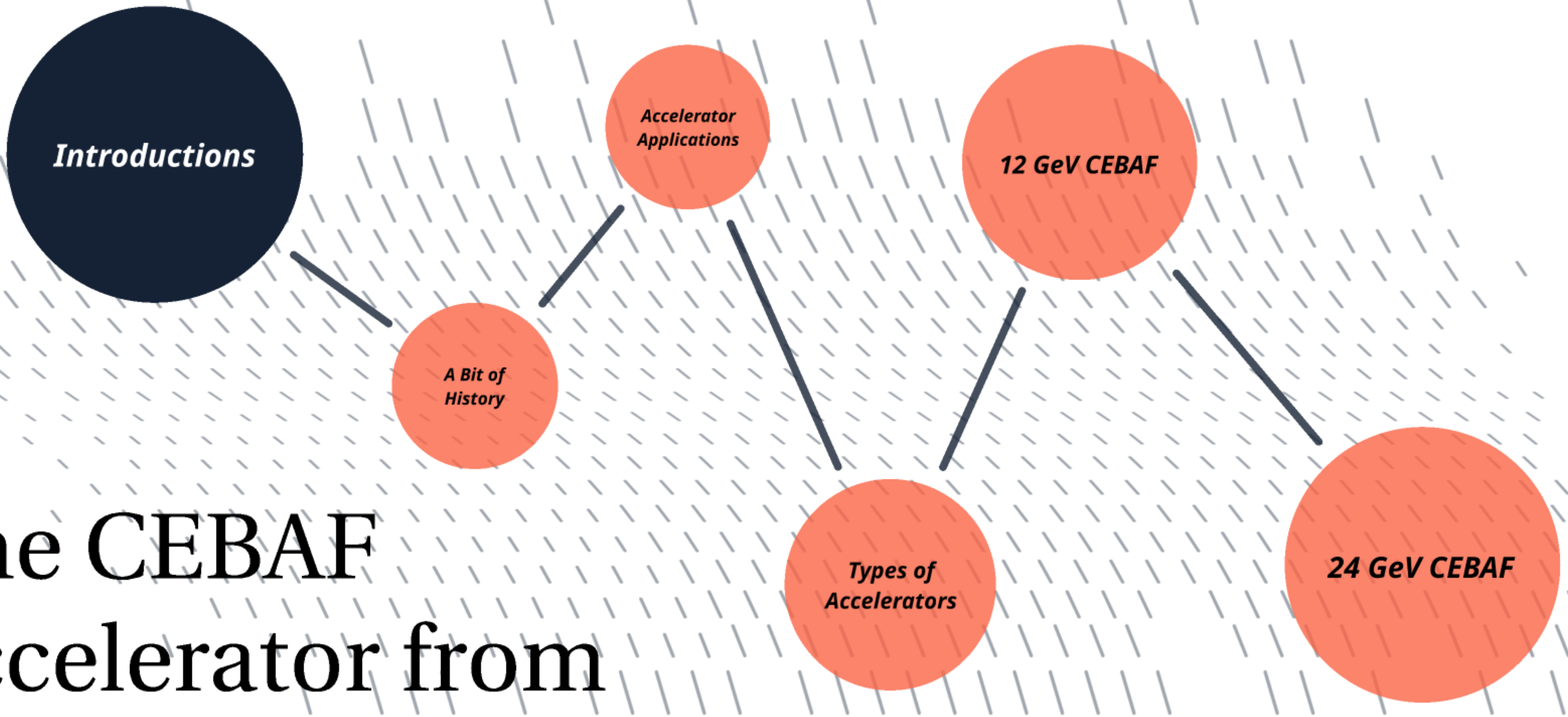


The CEBAF Accelerator from 12 to 22 GeV

Ryan Bodenstein

Brief Introduction

Who am I?
What have I done?
What do I do?
Caveats!

Who am I?

What have I done?

What do I do?

Caveats!

Ryan Bodenstein

- Originally from rural Vermont
- Lived in 5 countries on 3 continents
- Husband and father of two young kids
- Undergrad at Mary Washington (Fredericksburg)
- PHD at UVA/Jefferson Lab in Accelerator Physics

Brief Introduction

Who am I?
What have I done?
What do I do?
Caveats!

Who am I?

What have I done?

What do I do?

Caveats!

Accelerator Physicist

1. Research Fellow at Rare Isotope Science Project (RISP) in Daejeon, South Korea
   - Design electrostatic Low Energy Beam Transport (LEBT) for RAON rare isotope accelerator

2. Postdoc at University of Oxford in Oxford, UK
   - Beam Delivery System simulations for Compact Linear Collider and International Linear Collider
   - Feedback system tests at KEK in Japan
   - Teaching Accelerator Physics, as well as undergraduate physics

3. Project Associate at CERN in Meyrin, Switzerland
   - More BDS simulation work, as well as post-collision line studies for CLIC

4. Beam Optics Expert for the MYRRHA Project at SCK-CEN in Mol, Belgium
   - Design and oversight for High Energy Beam Transport (HEBT) for target facilities and accelerator-driven system (ADS)

5. Staff Scientist at the Center for Advanced Study of Accelerators at Jefferson Lab
   - FFA@CEBAF is my main work
   - Operations support
   - Etc…

Brief Introduction

Who am I?
What have I done?
What do I do?
Caveats!

Who am I?

What have I done?

What do I do?

Caveats!

What do I do?

- Main expertise is in beam dynamics and optics of particle beams
  - Also have worked in/with Superconducting RF, Operations, Education, and Outreach
- I consider myself an accelerator science generalist
- Majority of my current work is on the FFA@CEBAF Upgrade
  - Working on some design
  - Managing an LDRD grant

Brief Introduction

Who am I?
What have I done?
What do I do?
Caveats!

Who am I?

What have I done?

What do I do?

Caveats!

All I know is that I don't know...

~Operation Ivy

- Over 19 years of experience
  - The field is very broad and interdisciplinary
  - I absolutely *DON'T* know it all - and I'll be sure to tell you that
- I plan to keep this talk mostly non-technical

Brief Introduction

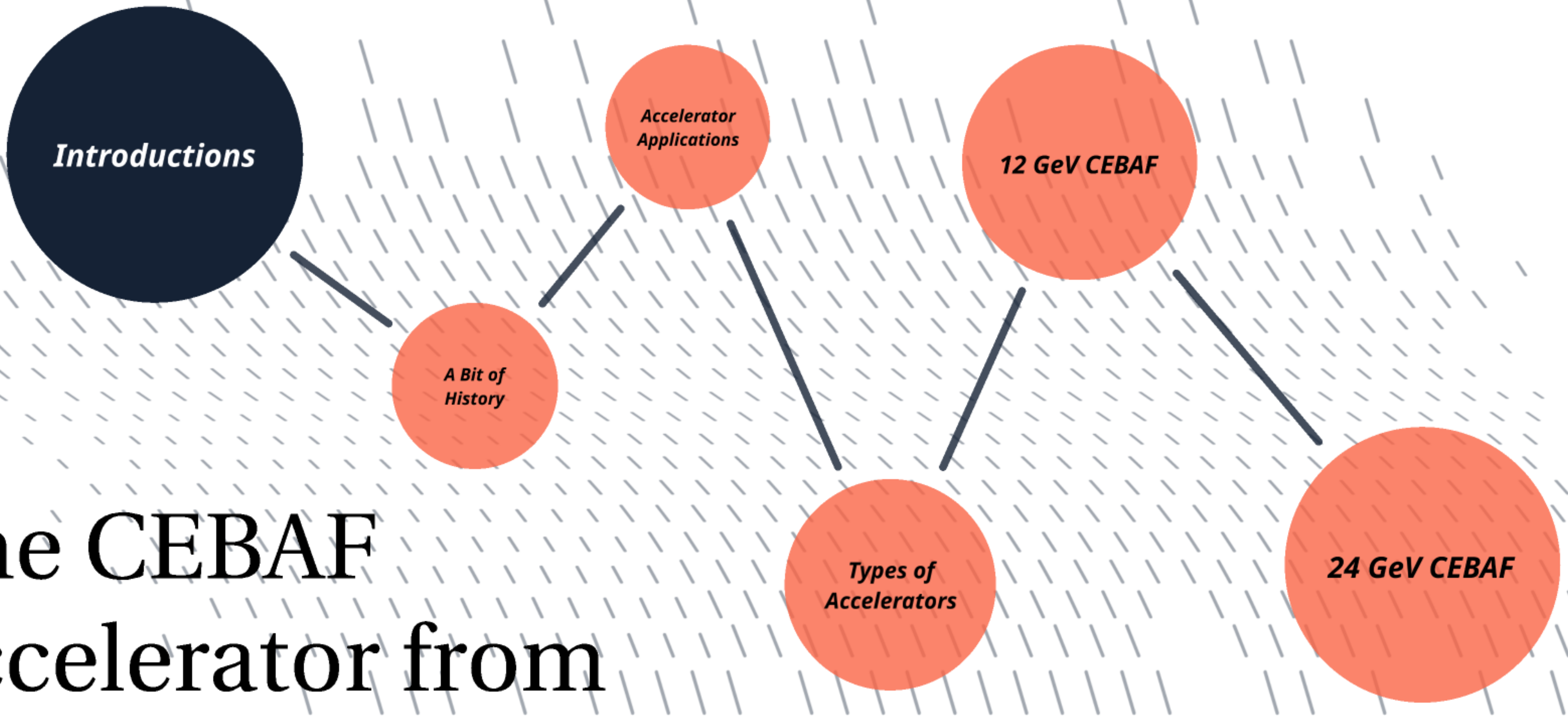
Who am I?
What have I done?
What do I do?
Caveats!

Who am I?

What have I done?

What do I do?

Caveats!



The CEBAF Accelerator from 12 to 22 GeV

Ryan Bodenstein

Some historical background...

Please note, some of these slides are taken from and/or inspired by Associate Professor Suzie Sheehy's work.

https://www.suziesheehy.com/

Her book,
The Matter of Everything:

Similarly, some these slides are taken from and/or inspired by Dr. Todd Satogata's work.

http://www.toddsatogata.net/

His book,
Introduction to
Accelerator Dynamics:

The First Accelerators

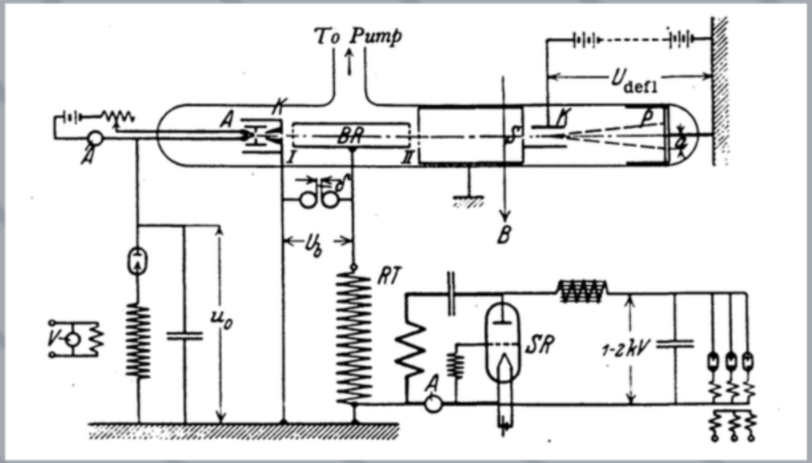
Rapid Progress

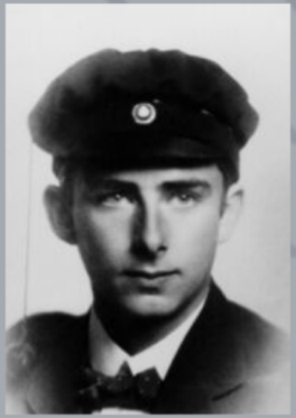
Modern Era

Early Accelerators

- In the 1920s, electricity increasingly started powering household items

- Rolf Widerøe, 1924
- His PhD thesis was to realise a single drift tube with 2 gaps. 25kV, 1MHz AC voltage produced a 50keV kinetic energy beam.
- First resonant accelerator (patented)





The linear accelerator & it's AC powering circuit

Historical note: He was influenced by Gustav Ising's work, which was never realised in practise as Ising didn't use an AC source.
Ising, Gustav. ***Arkiv Fuer Matematik, Astronomi Och Fysik* 18** (4), 1928

Slide from S. Sheehy

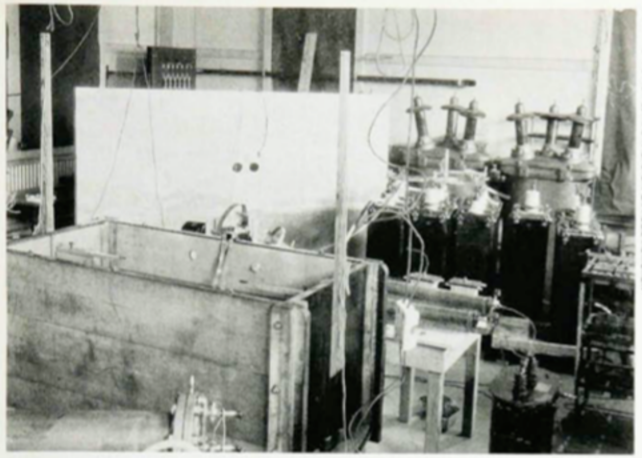
Electrostatic Accelerators

In the 1920s, electricity increasingly started powering household items

In the late 1920s, managed to get to 15 MV

Attempts at Electrostatic Accelerators

Tesla Coil

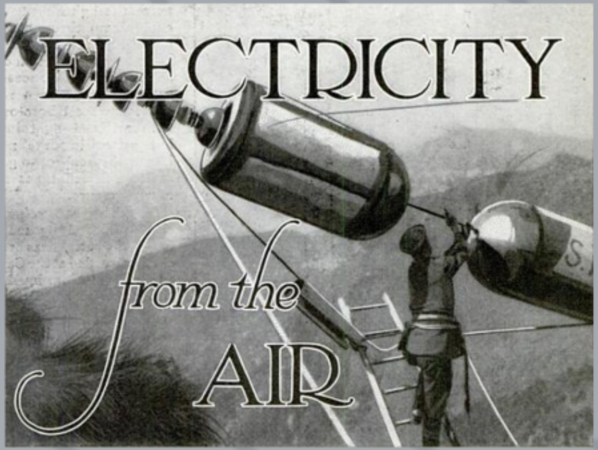


Early version of the Tesla apparatus at the Carnegie Institution's Department of Terrestrial Magnetism in March 1927. By immersing the Tesla coil in a wooden tank filled with oil, Tuve and Gregory Breit succeeded in producing 3 million volts.

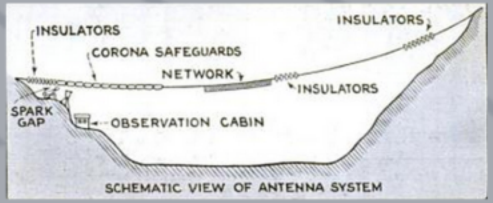
Thomas D. Cornell, Physics Today 41, 1, 57 (1988)

Merle Tuve – Carnegie – 3MV Tesla Coil. Allibone also at Cambridge.

Lightning



Arno Brasch, Fritz Lange, Kurt Urban, in Italian Alps 1927-28



http://lateralscience.blogspot.com/2012/10/alpine-air-to-produce-30-million-volts.html?m=0

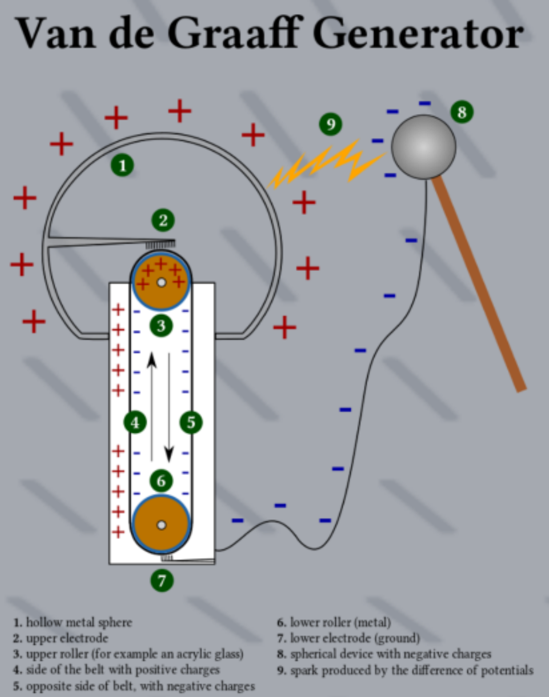
Slide from S. Sheehy

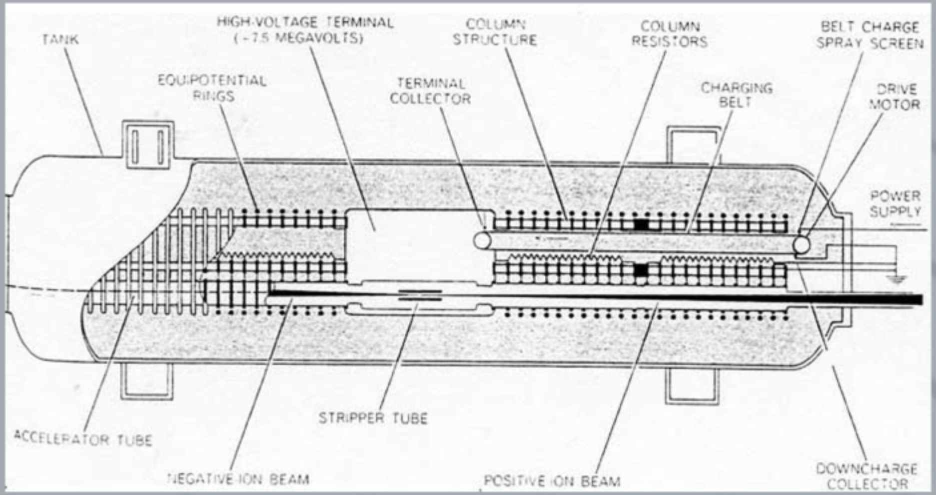
Electrostatic Accelerators

- Enter the Van de Graaff

1930

1933 – 7MV



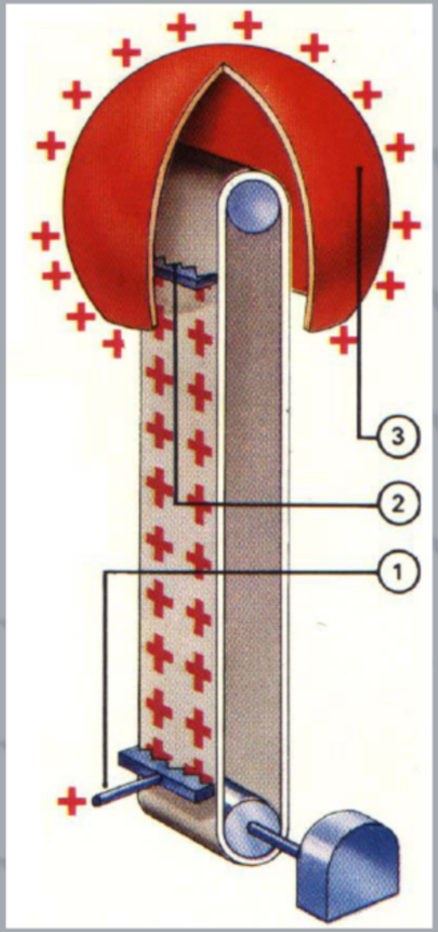


http://chem.ch.huji.ac.il/~eugeniik/history/graaff.html

Slide from S. Sheehy

Electrostatic Accelerators

DC Accelerating Gaps: Van de Graaff



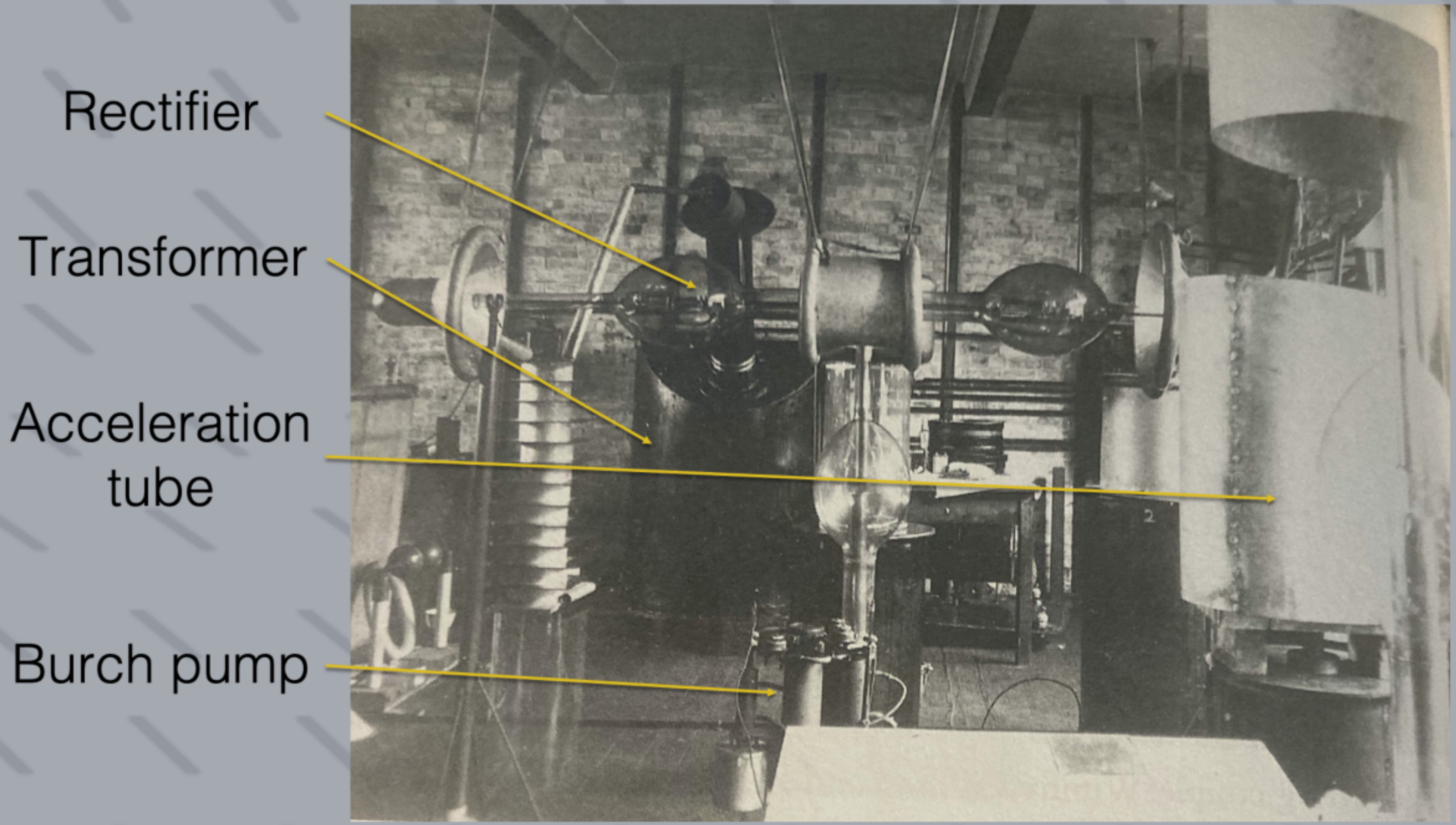
- How to increase voltage?
  - R.J. Van de Graaff: charge transport
  - Electrode (1) sprays HV charge onto insulated belt
  - Carried up to spherical Faraday cage
  - Removed by second electrode and distributed over sphere
- Limited by discharge breakdown
  - ~2MV in air
  - Up to 20+ MV in SF_6!
  - Ancestors of Pelletrons (chains)/Laddertrons (stripes)

Slide from T. Satogata

Electrostatic Accelerators

1930 - the first accelerator at Cambridge
Pushed to 200 kV

The first accelerator at Cambridge



Electrostatic Accelerators

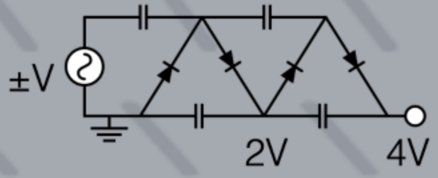
1930 - the first accelerator at Cambridge
Pushed to 200 kV

2 years later - CW accelerator

Cockcroft-Walton accelerator: 1932

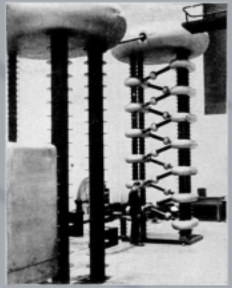
Walton and the machine used to "split the atom"

Cavendish Lab, Cambridge



Voltage multiplier circuit

https://www.youtube.com/watch?v=ep3D_LC2UzU



15

1.2 MV 6 stage Cockcroft-Walton accelerator at Clarendon Lab, Oxford University in 1948.

ATOM TORN APART, YIELDING 60% MORE ENERGY THAN USED

But Two British Scientists Succeed Only Once in Each 10,000,000 Bombarded.

BATTERED WITH PROTONS

Hydrogen Atoms Are Thus Transmuted Into Helium—Conservation Theory Seen Upset.

TESTS MADE FOR 3 YEARS

Dr. J. D. Cockroft and Dr. E. T. S. Walton of Cavendish Laboratory, Cambridge, Explain Work.

NEW YORK TIMES, May 2, 1932

Science context

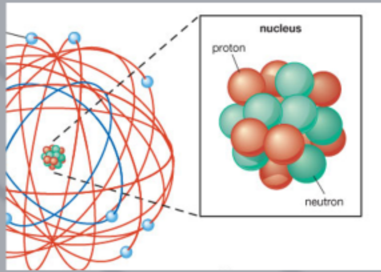
JEFFERSON CITY POST-TRIBUNE

Monday, May 2, 1932

SCIENTIST SPLITS UP THE ATOM, HAILED AS GREAT ACHIEVEMENT

LONDON, May 2.—(AP)—Two young scientists of Cambridge University were hailed today as having achieved a goal physicists have sought to reach for years. They have broken the atom.

In announcing details of what he called "a discovery of great scientific importance," Lord Rutherford, noted scientist, said Drs. J. D. Cockroft and E. T. S. Walton accomplished the feat after several years of work with apparatus erected under his supervision.



• Image: http://ck12.org.uk

Proton: 1909(?) Rutherford
Neutron: 1932, Chadwick

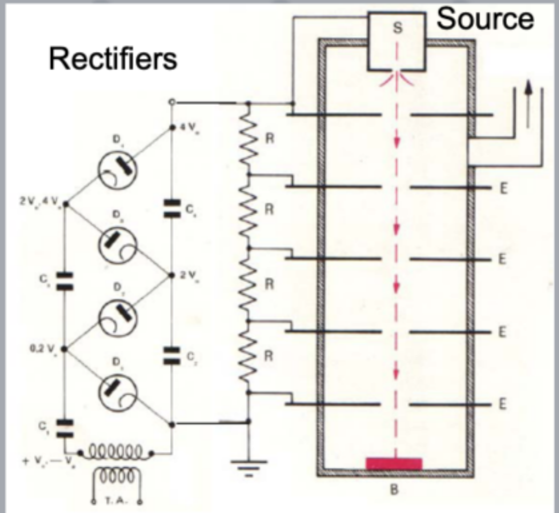
Splitting the atom was announced at same meeting!

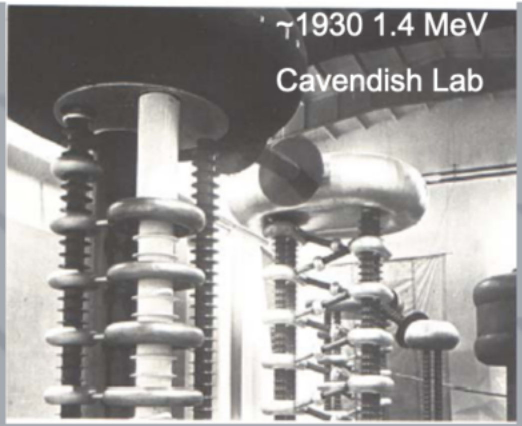
Slides from S. Sheehy

Electrostatic Accelerators

DC Accelerating Gaps: Cockcroft-Walton

- Accelerates ions through successive electrostatic voltages
  - First to get protons to >MeV
  - Continuous HV applied through intermediate electrodes
  - Rectifier-multipliers (voltage dividers)
  - Limited by HV sparking/breakdown
  - FNAL still uses a 750 kV C-W
- Also example of early ion source
  - H gas ionized with HV current
  - Provides high current DC beam





Slide from T. Satogata

Cyclotron

- Along comes Ernest Lawrence
- Inspired by Widerøe's paper
- Didn't know that relativistic mass would break this equality

Ernest Orlando Lawrence

Centrifugal force = magnetic force

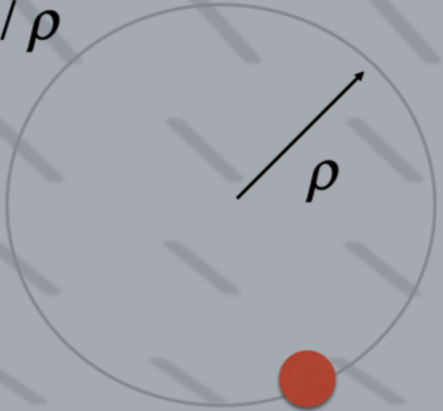
$$\frac{mv_\theta^2}{\rho} = qv_\theta B_z$$

Revolution frequency $\omega_0 = v_\theta / \rho$

Cancelling out rho gives:

$$\omega_0 = qB_z / m$$

$$\rho = mv / qB_z$$



Lawrence: "R cancels R!"

ie. for constant charge q and mass m, and a uniform magnetic field B, the angular frequency is constant. ie. the rf frequency can be constant. The orbit radius is proportional to speed, v.

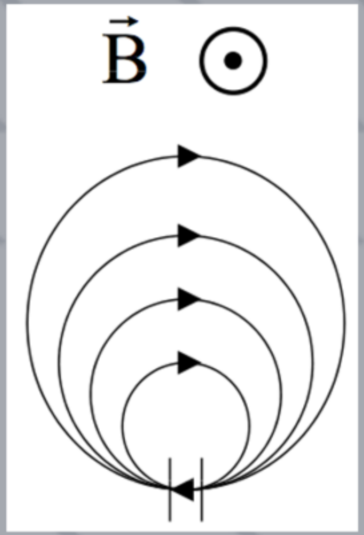
Cyclotron

Along comes Ernest Lawrence

Inspired by Widerøe's paper

Didn't know that relativistic mass would break this equality

- Can we repeatedly spiral and accelerate particles through the same potential gap?

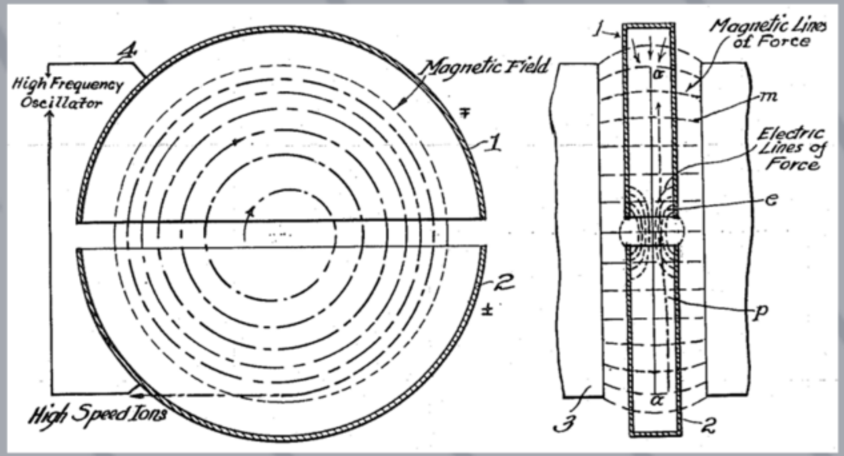


Accelerating gap $\Delta\Phi$

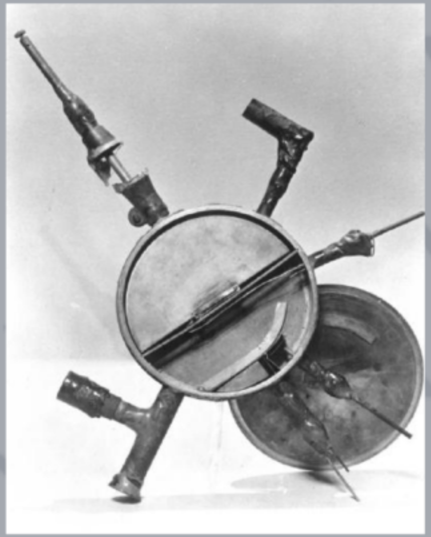
Slide from T. Satogata

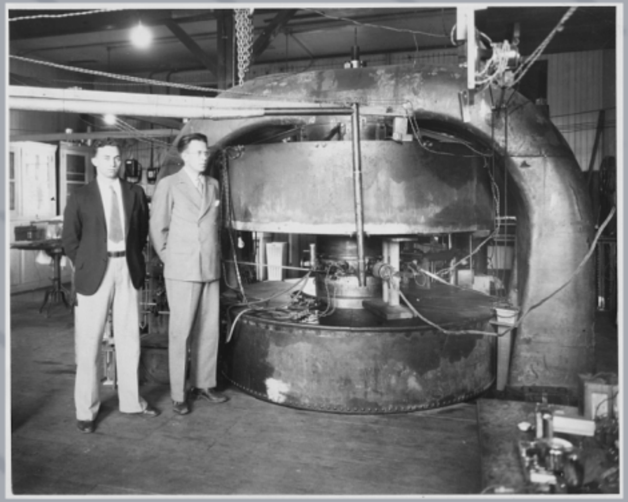
Cyclotron

This version has two accelerating gaps per turn



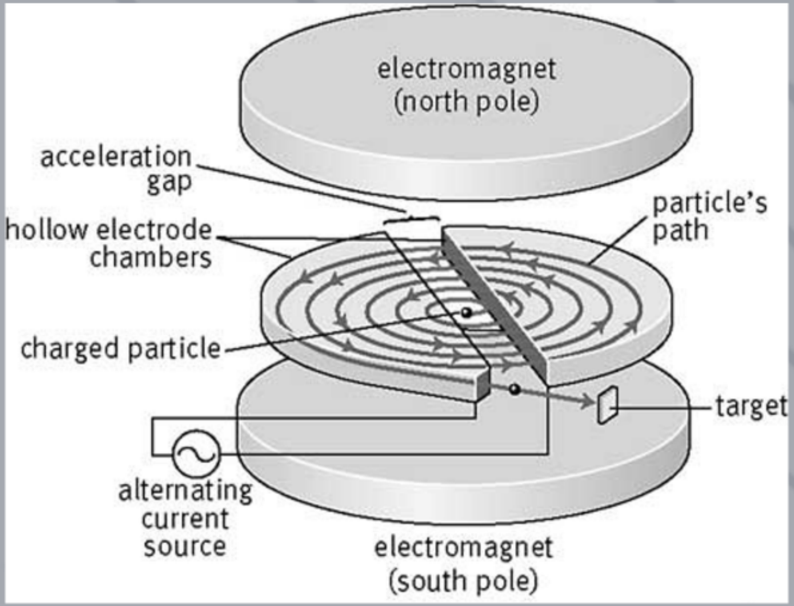
The Cyclotron, from E. Lawrence's 1934 patent





E. Lawrence & M. Stanley Livingston

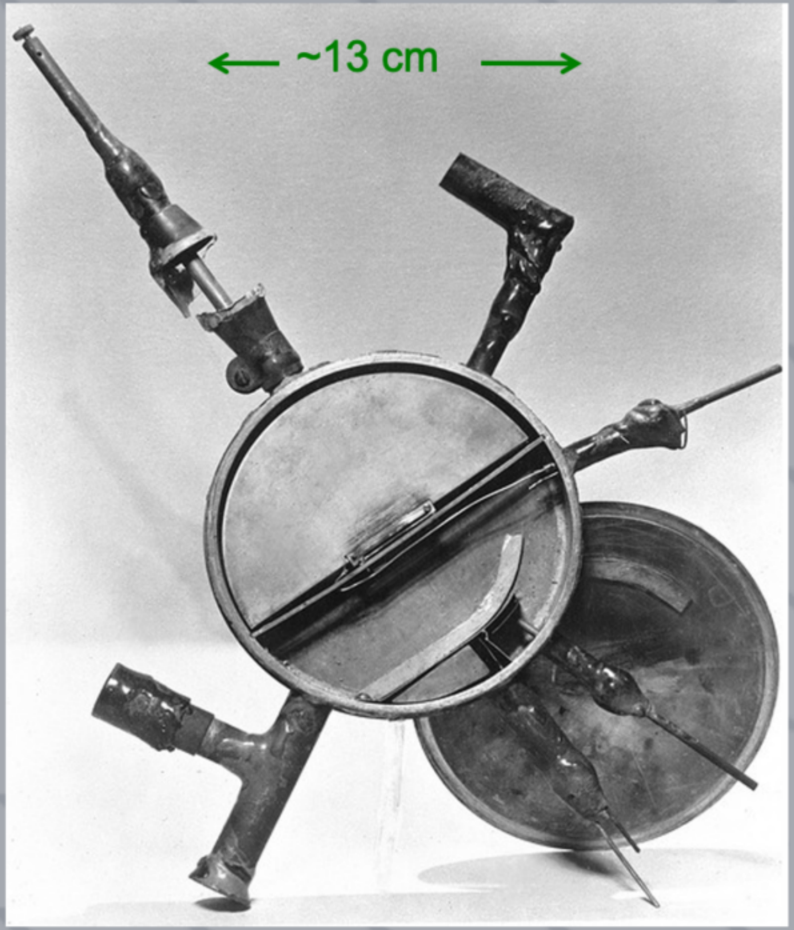
Cyclotron



All The Fundamentals of an Accelerator

- Large static magnetic fields for guiding (~1T)
  - But no vertical focusing
- HV RF electric fields for accelerating
  - (No phase focusing)
  - (Precise f control)
- p/H source, injection, extraction, vacuum
- 13 cm: 80 keV
- 28 cm: 1 MeV
- 69 cm: ~5 MeV
- … 223 cm: ~55 MeV

(Berkeley)



Slides from T. Satogata

Some historical background...

Please note, some of these slides are taken from and/or inspired by Associate Professor Suzie Sheehy's work.

https://www.suziesheehy.com/

Her book,
The Matter of Everything:

Similarly, some these slides are taken from and/or inspired by Dr. Todd Satogata's work.

http://www.toddsatogata.net/

His book,
Introduction to
Accelerator Dynamics:

The First Accelerators

Rapid Progress

Modern Era

The Betatron (1940)

Betatron

D.W. Kerst, Phys. Rev. 58, 841 (1940)

- Like a transformer with the beam as a secondary coil
- Usually used for relativistic electrons (so different from a cyclotron).
- Max energy achieved 300 MeV
- Accelerating field produced by a changing magnetic field that also serves to maintains electrons in a circular orbit of fixed radius as they are accelerated

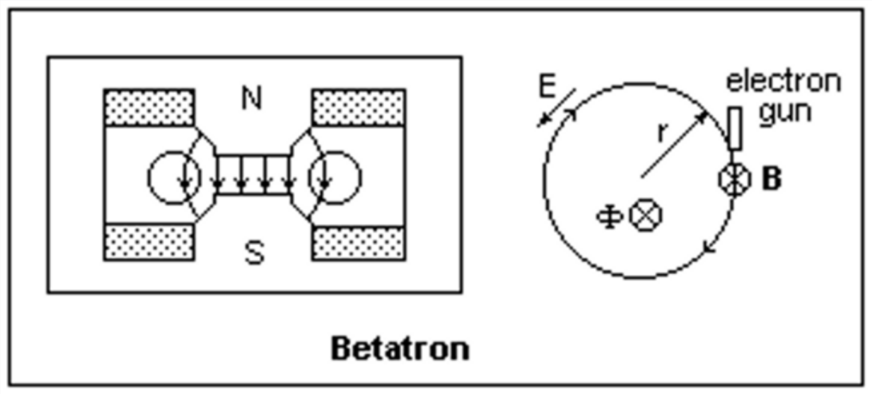


Image: http://mysite.du.edu/~jcalvert/phys/partelec.htm#Tron

Equate Faradays law on induction & Lorentz force law gives…

$$B_{orbit} = \frac{\Phi}{2\pi r^2} \rightarrow B_{orbit} = \frac{\bar{B}}{2}$$

since $\bar{B} = \frac{\Phi}{\pi r^2}$

http://physics.princeton.edu/~mcdonald/examples/betatron.pdf

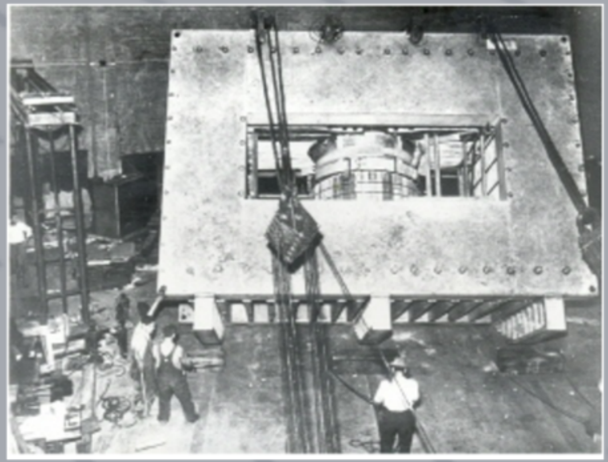
The Betatron (1940)

$I(t)=I_0 \cos(2\pi\omega_I t)$

- Apply Faraday's law with time-varying current in coils
- Beam sees time-varying electric field – accelerate half the time!
- Early proofs of stability: focusing and betatron motion

Donald Kerst
UIUC 2.5 MeV
Betatron, 1940

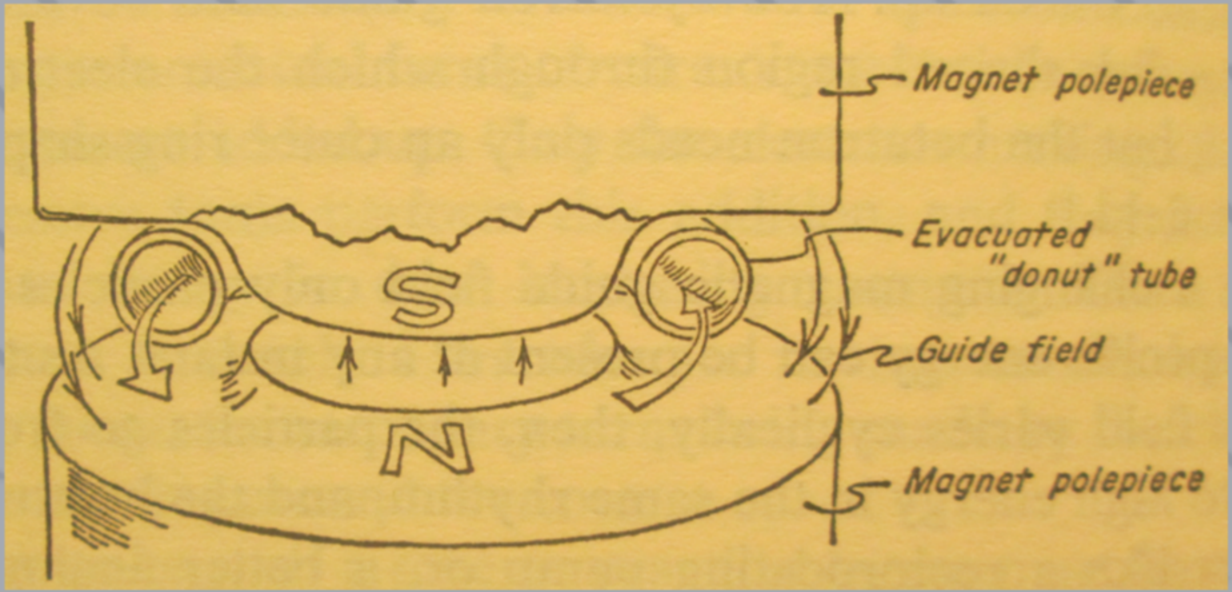
Don't try this at home!!

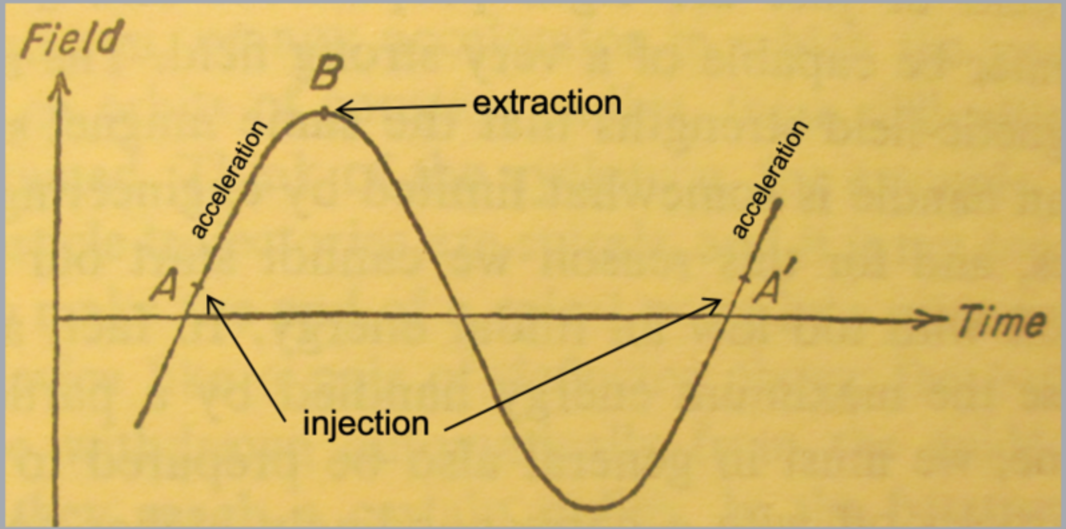


Really don't try this at home!!

UIUC 312 MeV
betatron, 1949

The Betatron (1940)



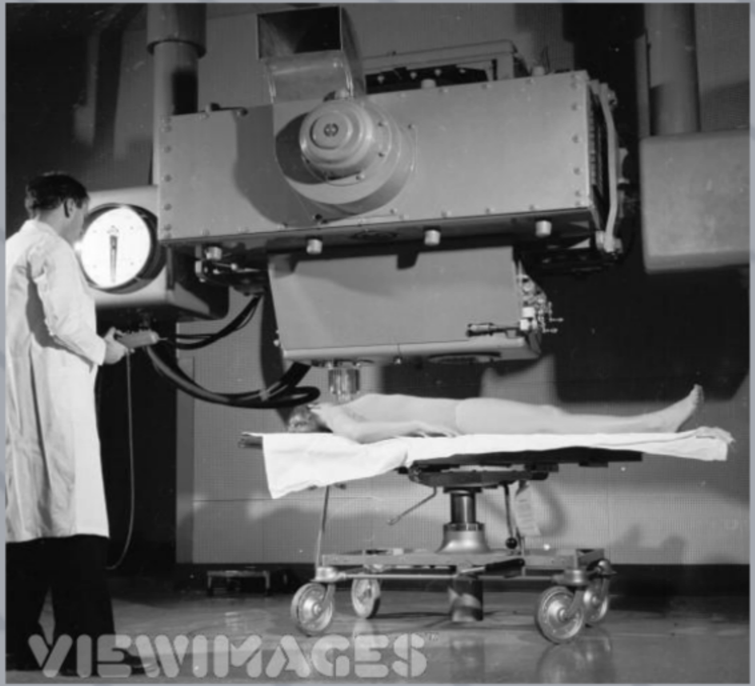


Wilson and Littauer: "Accelerators, Machines of Nuclear Physics", 1960

Slide from T. Satogata

The Betatron (1940)

- Betatrons produced electrons up to 300+ MeV
  - Early materials and medical research
  - Also produced medical hard X-rays and gamma rays
- Betatrons have their challenges
  - Linear aperture scaling
  - Large stored energy/impedance
  - Synchrotron radiation losses
  - Quarter duty cycle
  - Ramping magnetic field quality



This will only hurt a bit…

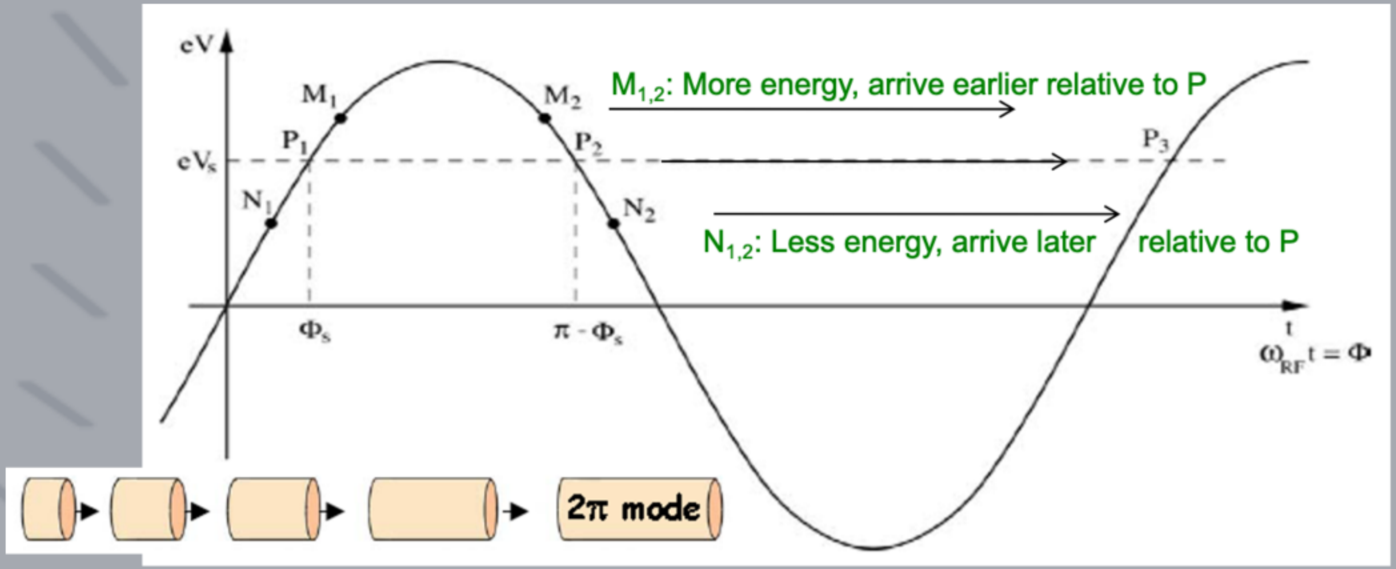
Slide from T. Satogata

Synchrotrons - Phase Stability

- A particle at M1/2 arrives early, sees a higher voltage, goes to a larger orbit, and arrives later next time around.

- A particle at N1/2 arrives late, sees a lower voltage, goes to a smaller orbit, and arrives earlier next time around.

- A particle at P1/2 is synchronous.

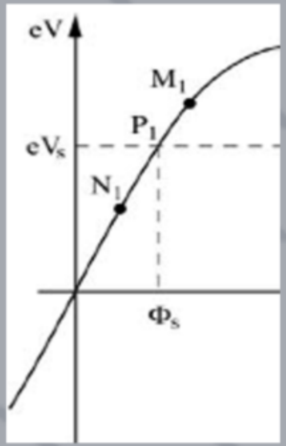


- Consider a series of accelerating gaps (or a ring with one gap)
  - **By design** there is a synchronous phase Φ_s that gains just enough energy to hit phase Φ_s in the next gap
  - $P_{1,2}$ are fixed points: they "ride the wave" exactly in phase
- If increased energy means increased velocity ("below transition")
  - M_1,N_1 will move towards P_1 (local stability) => **phase stability**
  - M_2,N_2 will move away from P_2 (local instability)

Slide from T. Satogata

Synchrotrons - Phase Stability

Phase Stability Implies Transverse Instability



$$\frac{\partial V}{\partial t} > 0 \quad \Rightarrow \quad \frac{\partial E_z}{\partial z} < 0$$

- For phase stability, longitudinal electric field must have a negative gradient. But then (source-free) Maxwell says

$$\vec{\nabla} \cdot \vec{E} = 0 \quad \Rightarrow \quad \frac{\partial E_x}{\partial x} + \frac{\partial E_y}{\partial y} + \frac{\partial E_z}{\partial z} = 0 \quad \Rightarrow \quad \frac{\partial E_x}{\partial x} + \frac{\partial E_y}{\partial y} > 0$$

There must be some transverse defocusing/diverging force!

Any accelerator with RF phase stability (longitudinal focusing) needs transverse focusing! (solenoids, quads…)

Slide from T. Satogata

Synchrotrons

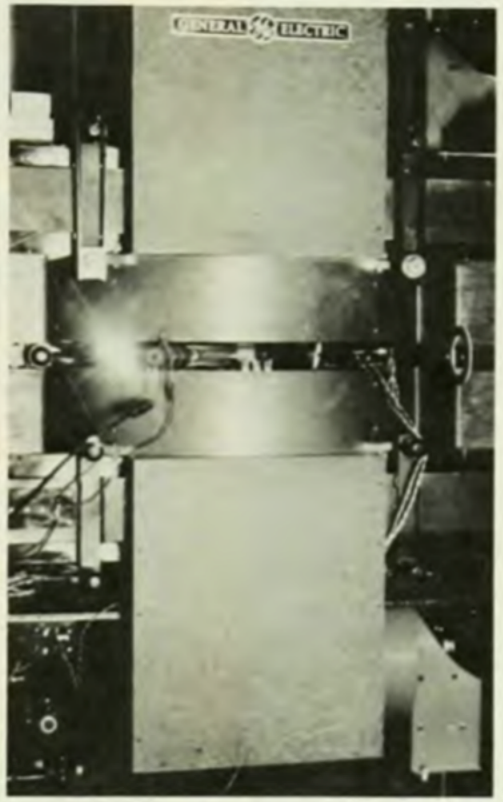
Discovery of Synchrotron Light

GE, 1947

Astrophysical relevance: majority of radio sources in the universe emit via synchrotron processes!

NB. GE team were beaten to 'first synchrotron' by a month:

Goward and Barnes (UK) converted a small betatron into an 8 MeV electron synchrotron

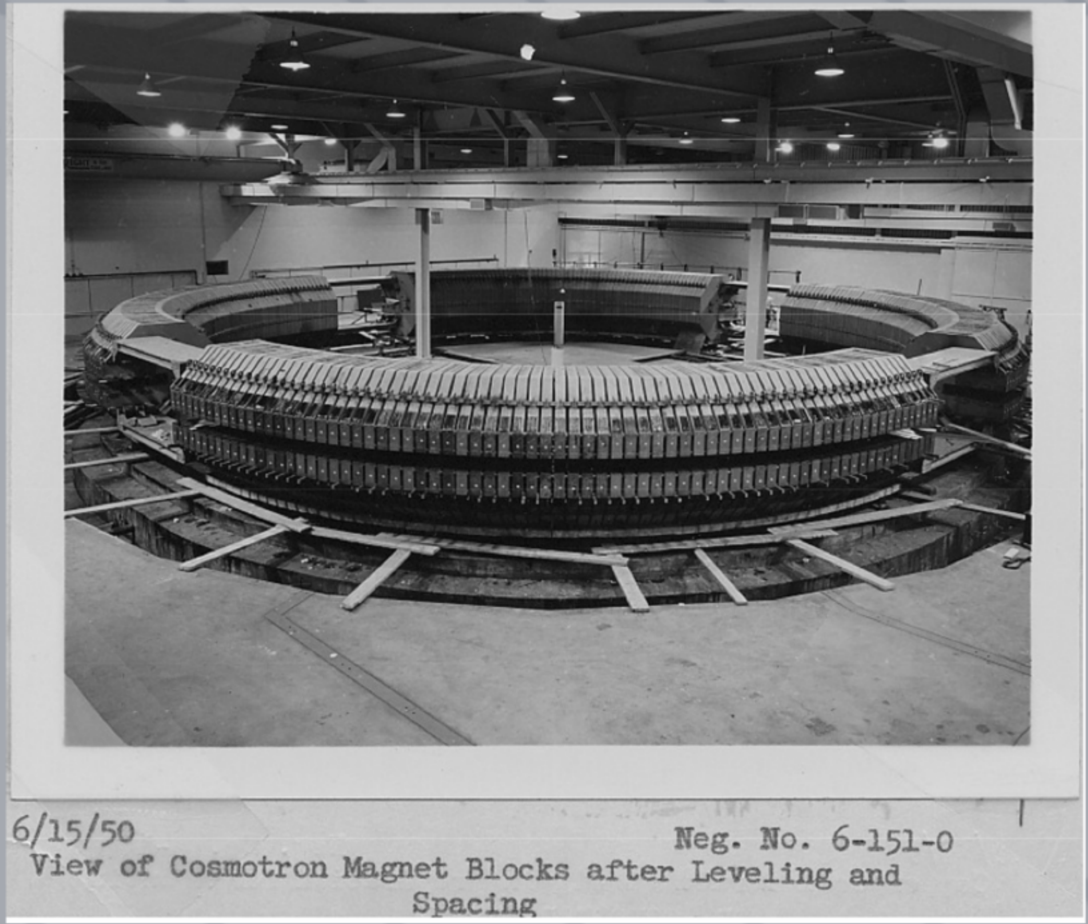


Synchrotron radiation from 70-MeV machine at General Electric Research Laboratory where it was first discovered in 1947.

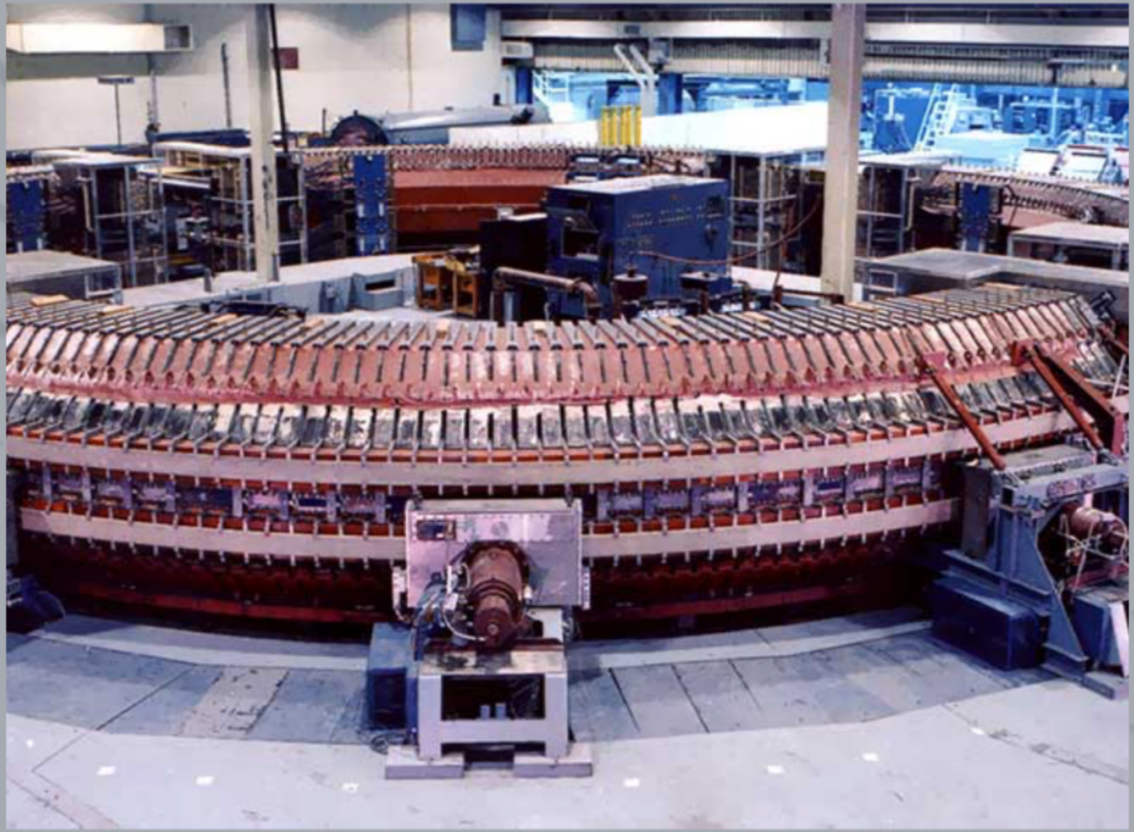
Slide from S. Sheehy

Proton Synchrotrons

BNL Cosmotron



National Academy of Sciences, Biographical Memoir of M. Stanley Livingston by Ernest D. Courant



Up to 3 GeV beam energy

Slide from T. Satogata

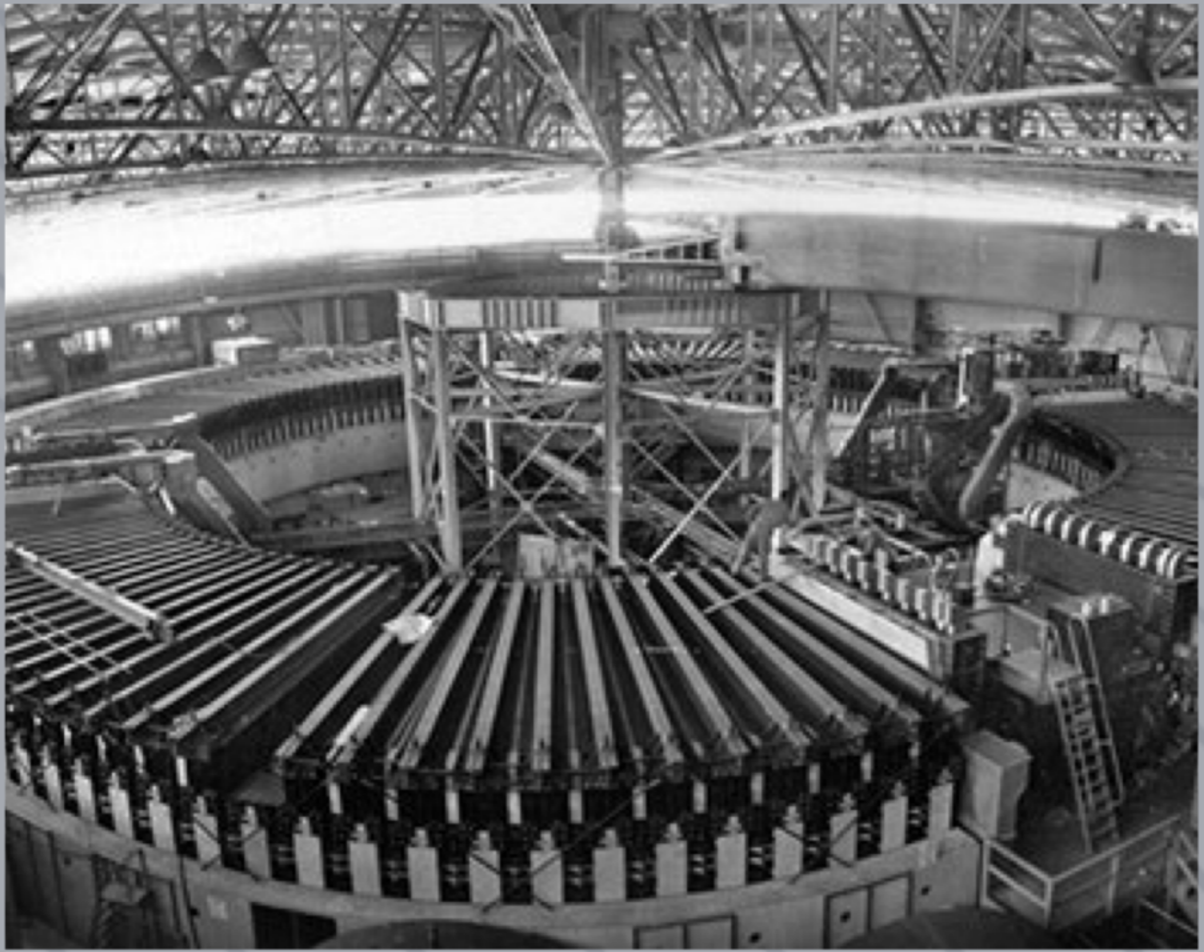
Slide from S. Sheehy

Proton Synchrotrons

LBL Bevatron

- Last and largest weak-focusing proton synchrotron
- 1954, Beam aperture about 4' square!, beam energy to 6.2 GeV
- Discovered antiproton 1955, 1959 Nobel for Segre/Chamberlain

(Became Bevelac, decommissioned 1993, demolished recently)



Slide from T. Satogata

Slide from S. Sheehy

Proton Synchrotrons

Two Serious Problems

- These machines were getting way too big
  - Bevatron magnet was 10,000 tons
  - Apertures scale linearly with machine size, energy

    (Length/circumference scales linearly with energy at fixed field strength too…)

- Fixed target energy scaling is painful
  - Available CM energy only scales with $\sqrt{E_{beam}}$

- Accelerator size grew with the square of desired CM energy
  - Something had to be done!!!

    Strong Focusing (1952) and Colliders (1958-62ish) to the rescue!!!

Slide from T. Satogata

Strong Focusing

Brookhaven, 1952, Livingston: Can we turn around some Cosmotron magnets?

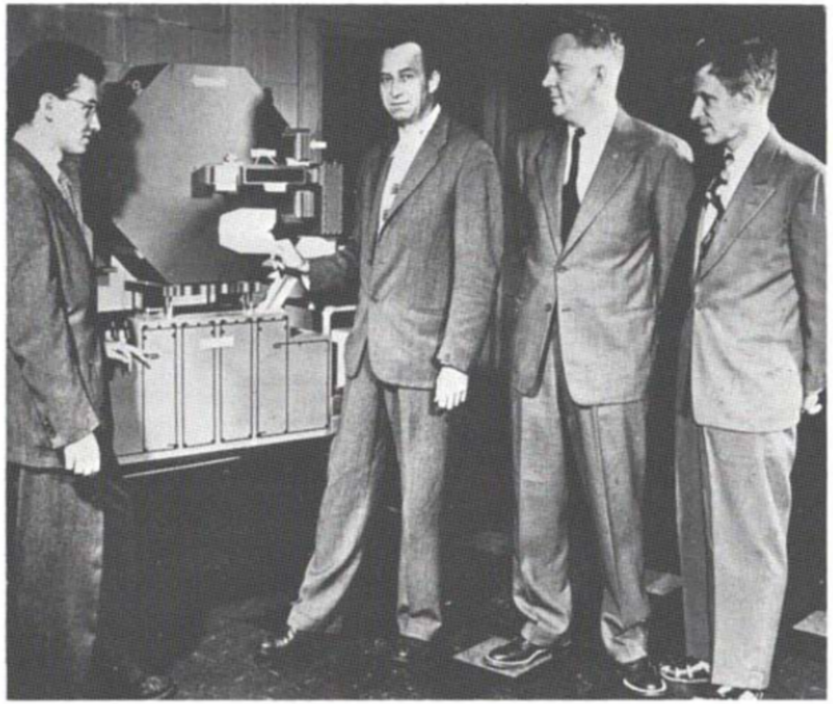
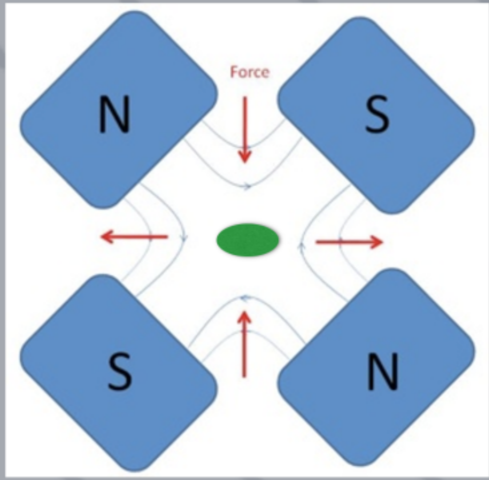


FIG. 27. E. D. Courant, M. S. Livingston, H. S. Snyder, and J. P. Blewett demonstrating the relative cross sections of the cosmotron magnet and a speculative alternating-gradient magnet of very large gradient.

E. Courant & H. Snyder worked out the theory…



It turned out Nikolas Christophilos (Greek engineer) had got there first and patented the idea: they later hired him.

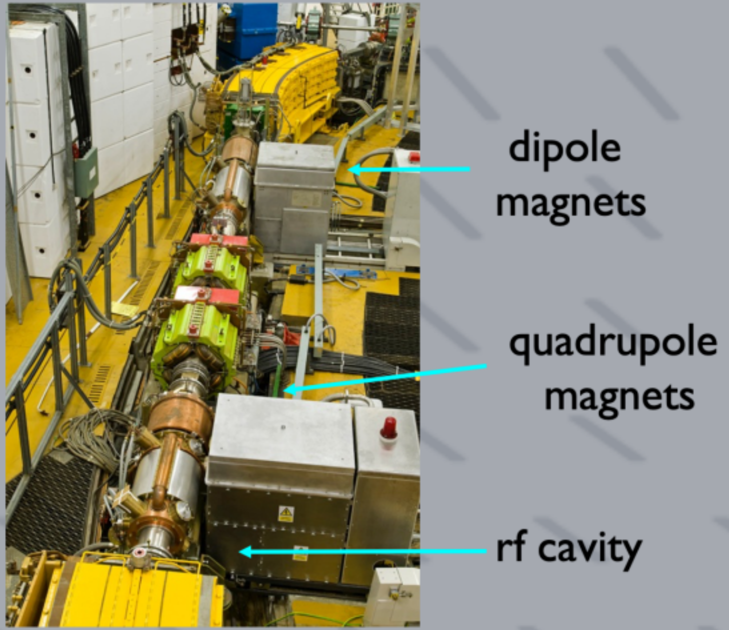
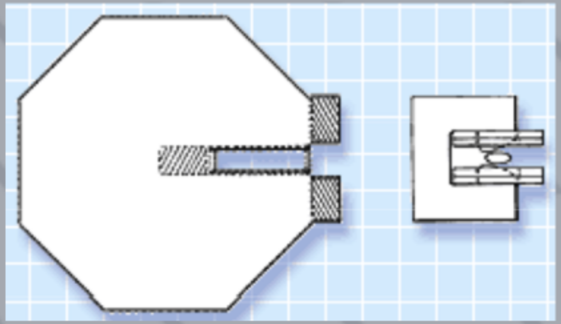


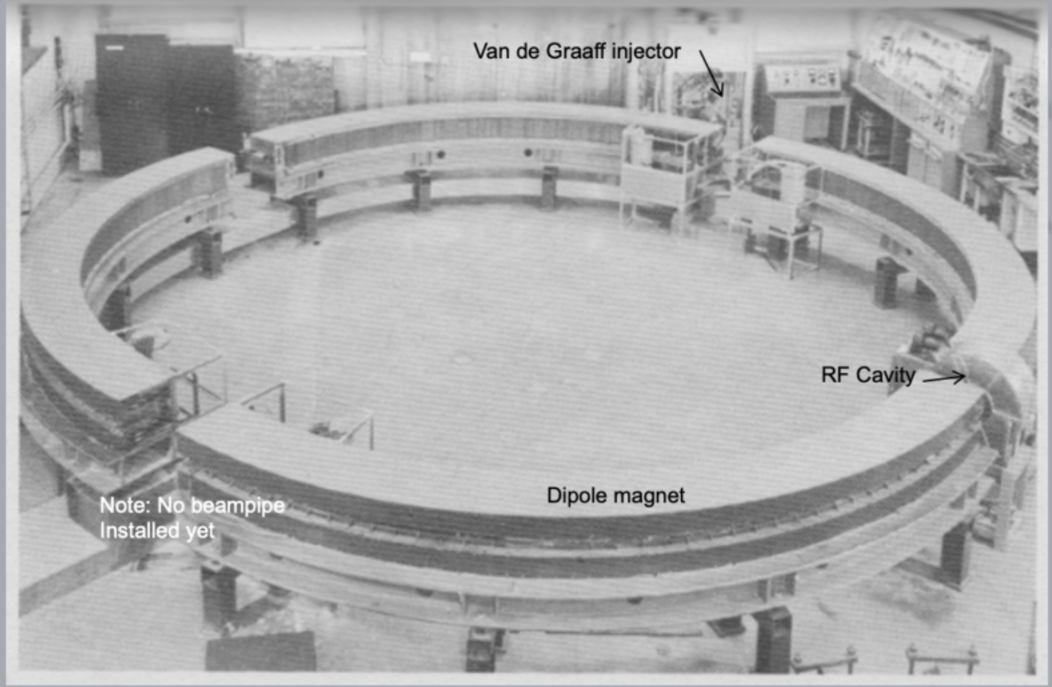
Image courtesy of ISIS, STFC



Slide from S. Sheehy

Strong Focusing

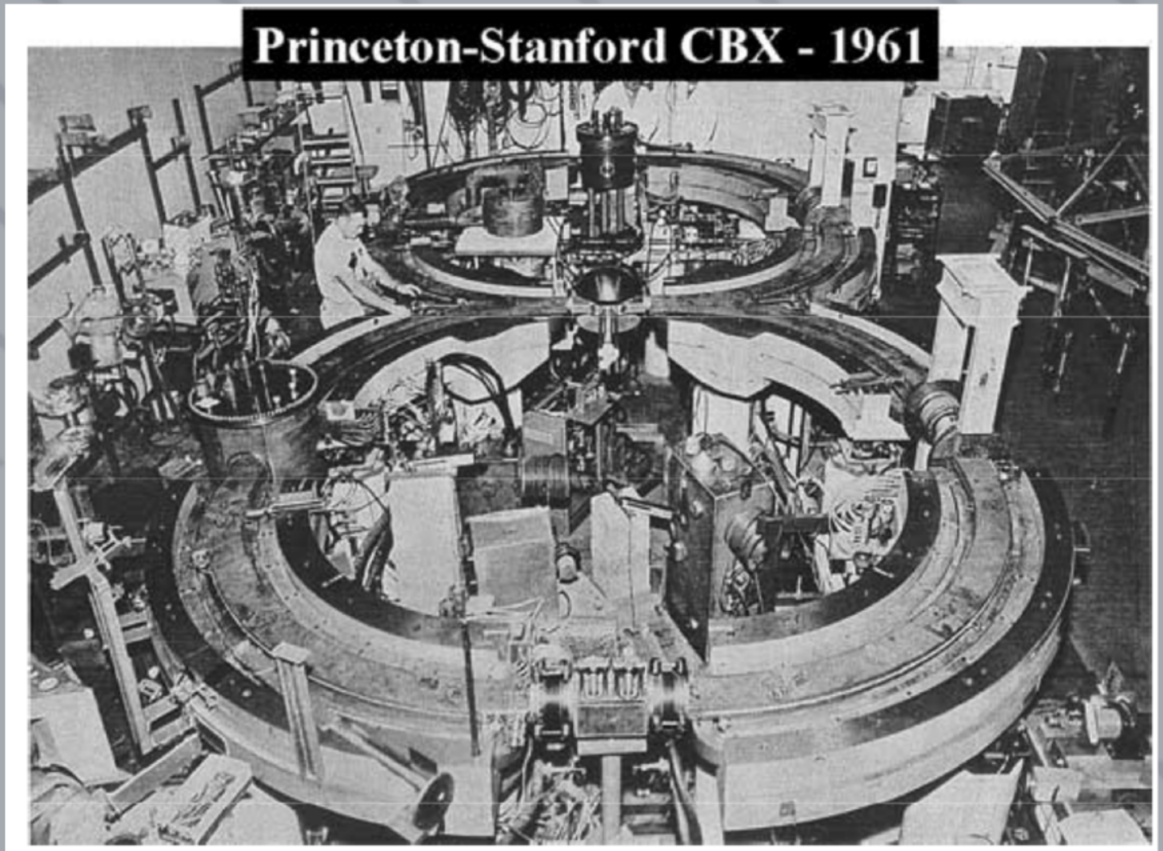
Cornell Electron Synchrotron (1954)



- 1.3 “BeV” (GeV) with van de Graaff injector
  - First strong focusing synchrotron, 16 tons of magnets, 4 cm beam pipe

Accelerators: Machines of Nuclear Physics (Wilson/Littauer 1960)

First Electron Collider



Slides from T. Satogata

Some historical background...

Please note, some of these slides are taken from and/or inspired by Associate Professor Suzie Sheehy's work.

https://www.suziesheehy.com/

Her book,
The Matter of Everything:

Similarly, some these slides are taken from and/or inspired by Dr. Todd Satogata's work.

http://www.toddsatogata.net/

His book,
Introduction to
Accelerator Dynamics:

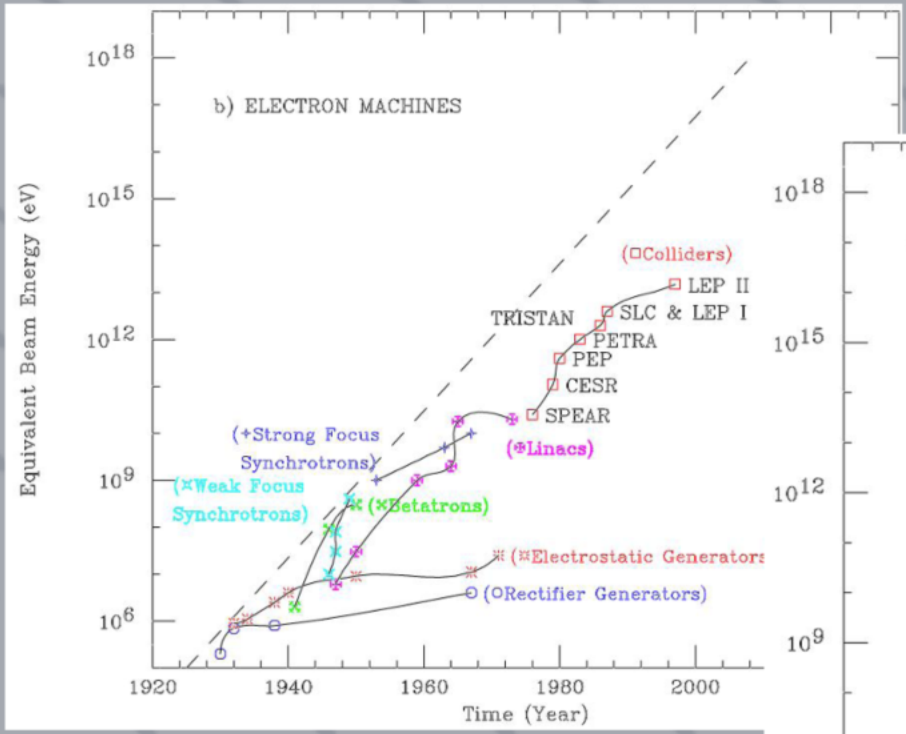
The First Accelerators

Rapid Progress

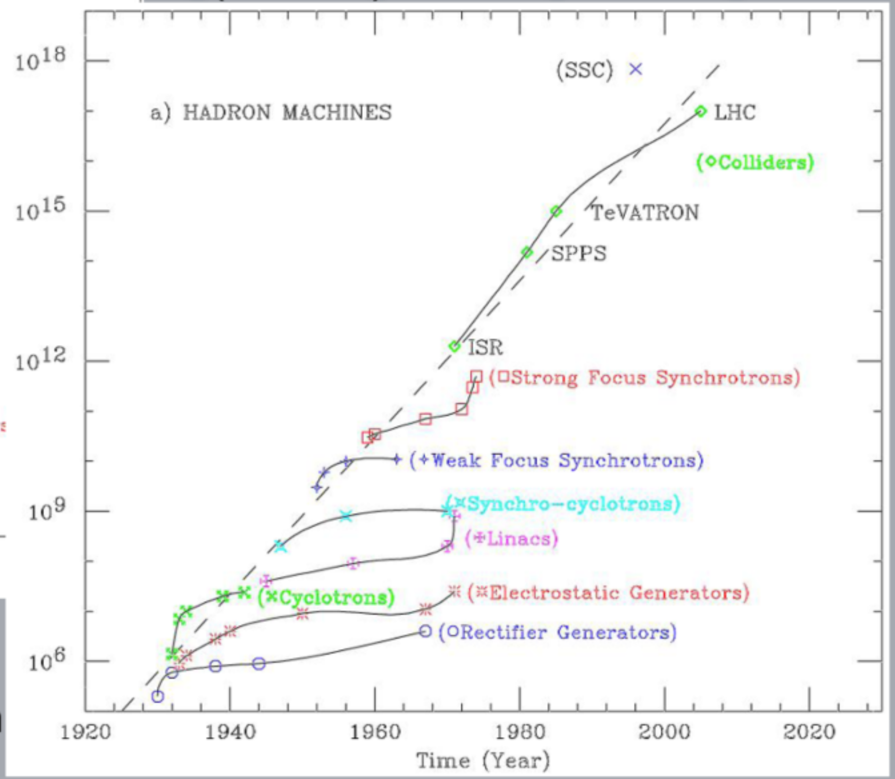
Modern Era

Progress in Leaps and Bounds

Livingston Plots



Livingston observed that accelerator energy was growing exponentially (in 1950!)



Still holds true over 60 years (!!!) later

Technologies tend to saturate then new technologies are introduced

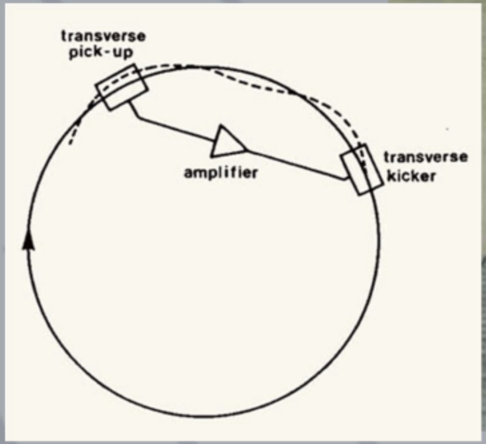
Slide from T. Satogata

(G. Hoffstaetter, Cornell)

Progress in Leaps and Bounds

ISR – first hadron collider

1971 to 1984,
CoM energy
62GeV



Also: stochastic cooling invented by Simon Van de Meer

Progress in Leaps and Bounds

The Tevatron & superconducting magnets

Alvin Tollestrup

THE TEVATRON ENERGY DOUBLER:
A Superconducting Accelerator

Helen T. Edwards

Fermi National Accelerator Laboratory,[1] Batavia, Illinois 60510

Helen Edwards

“Tevatron”= 1 TeV beam energy

Slide from S. Sheehy

Progress in Leaps and Bounds

Superconducting Radio Frequency Technology (SRF)

- Much of the pioneering efforts made at Cornell in the 1970s and 1980s
- Jefferson Lab brought this into the limelight as the first major large-scale SRF accelerator in the world
  - This has now become relatively "standard" in the LINAC world

Some historical background...

Please note, some of these slides are taken from and/or inspired by Associate Professor Suzie Sheehy's work.

https://www.suziesheehy.com/

Her book,
The Matter of Everything:

Similarly, some these slides are taken from and/or inspired by Dr. Todd Satogata's work.

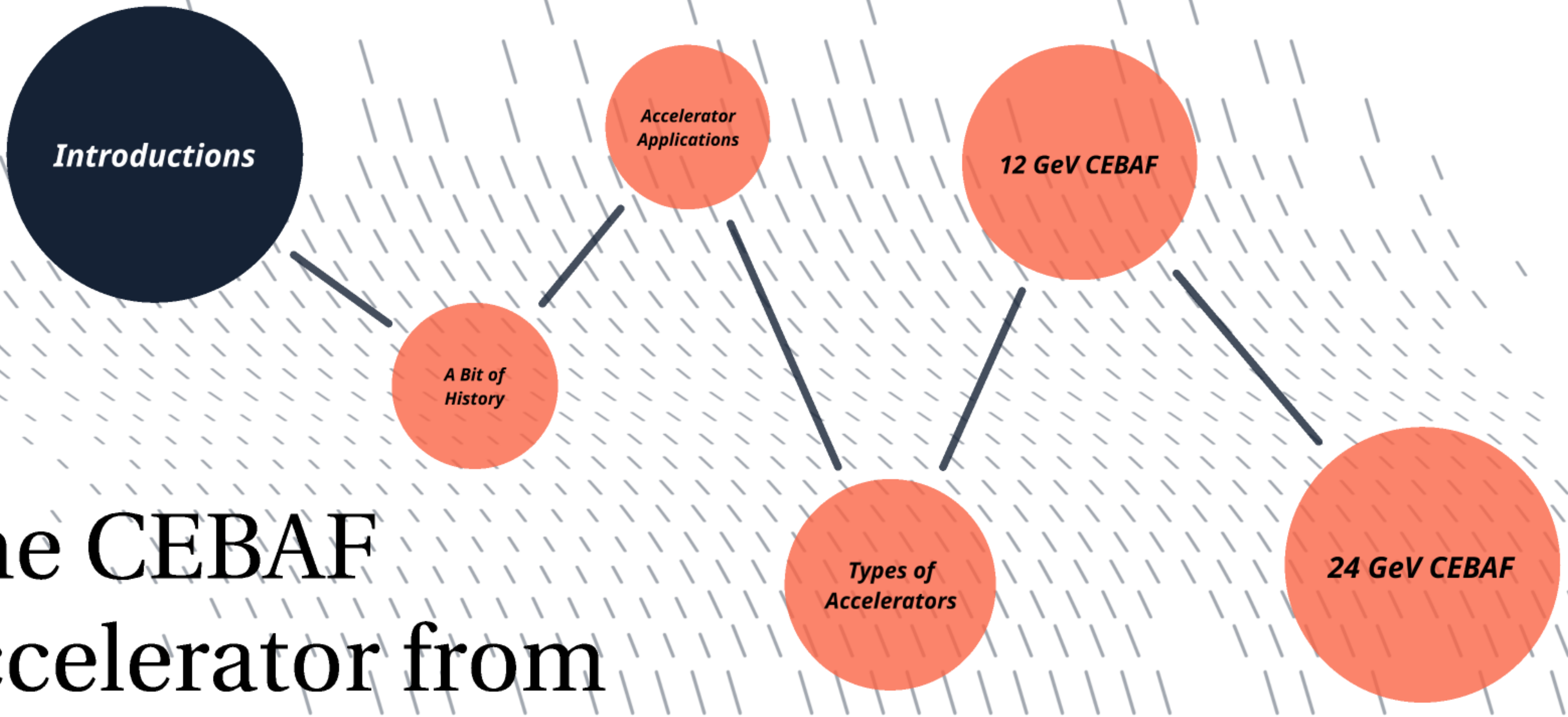
http://www.toddsatogata.net/

His book,
Introduction to
Accelerator Dynamics:

The First Accelerators

Rapid Progress

Modern Era



The CEBAF Accelerator from 12 to 22 GeV

Ryan Bodenstein

But what are they for?

It's not just particle/nuclear physics.

In fact, let's ignore particle/nuclear physics altogether for the time being.

Please note, some slides are again influenced/borrowed from Suzie Sheehy.

Some slides are from the work of Dr. Tessa Charles.
https://www.liverpool.ac.uk/physics/staff/tessa-charles/

Medicine

Industry

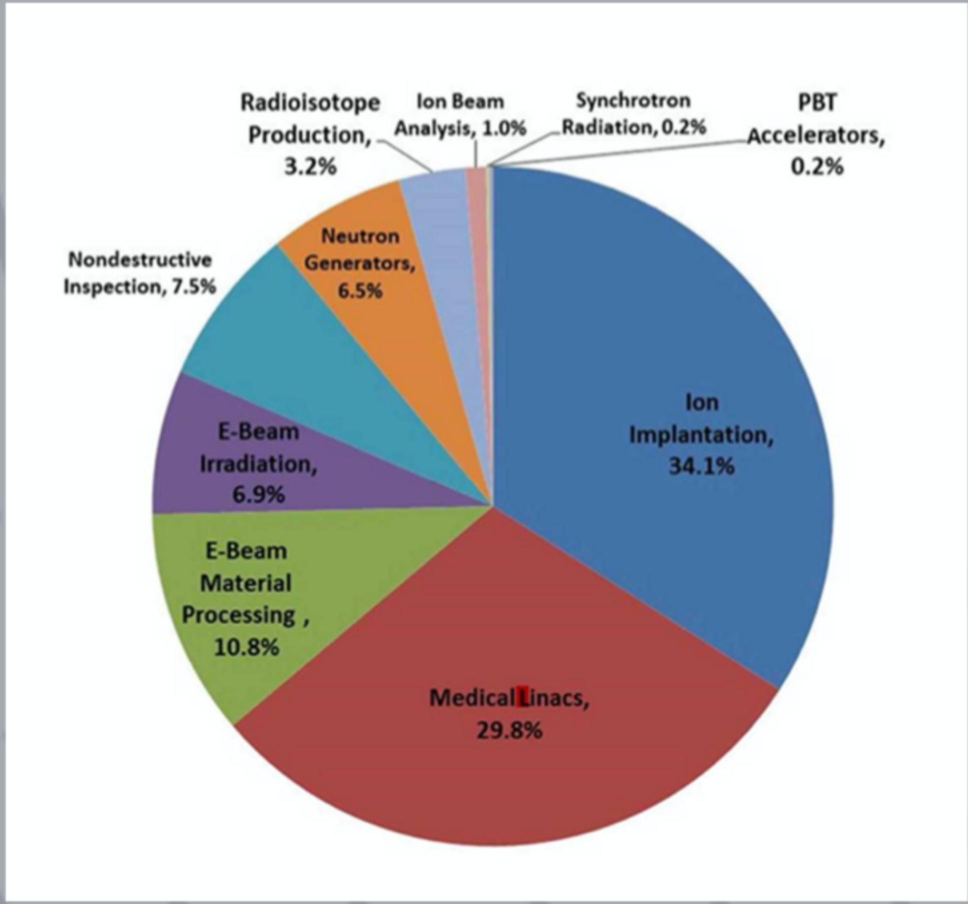
Environment

History/Culture

Before we begin…

"A beam of particles is a very useful tool…"

"A beam of the right particles with the right energy at the right intensity can shrink a tumor, produce cleaner energy, spot suspicious cargo, make a better radial tire, clean up dirty drinking water, map a protein, study a nuclear explosion, design a new drug, make a heat-resistant automotive cable, diagnose a disease, reduce nuclear waste, detect an art forgery, implant ions in a semiconductor, prospect for oil, date an archaeological find, package a Thanksgiving turkey or… discover the secrets of the universe."
~Accelerators for America's Future

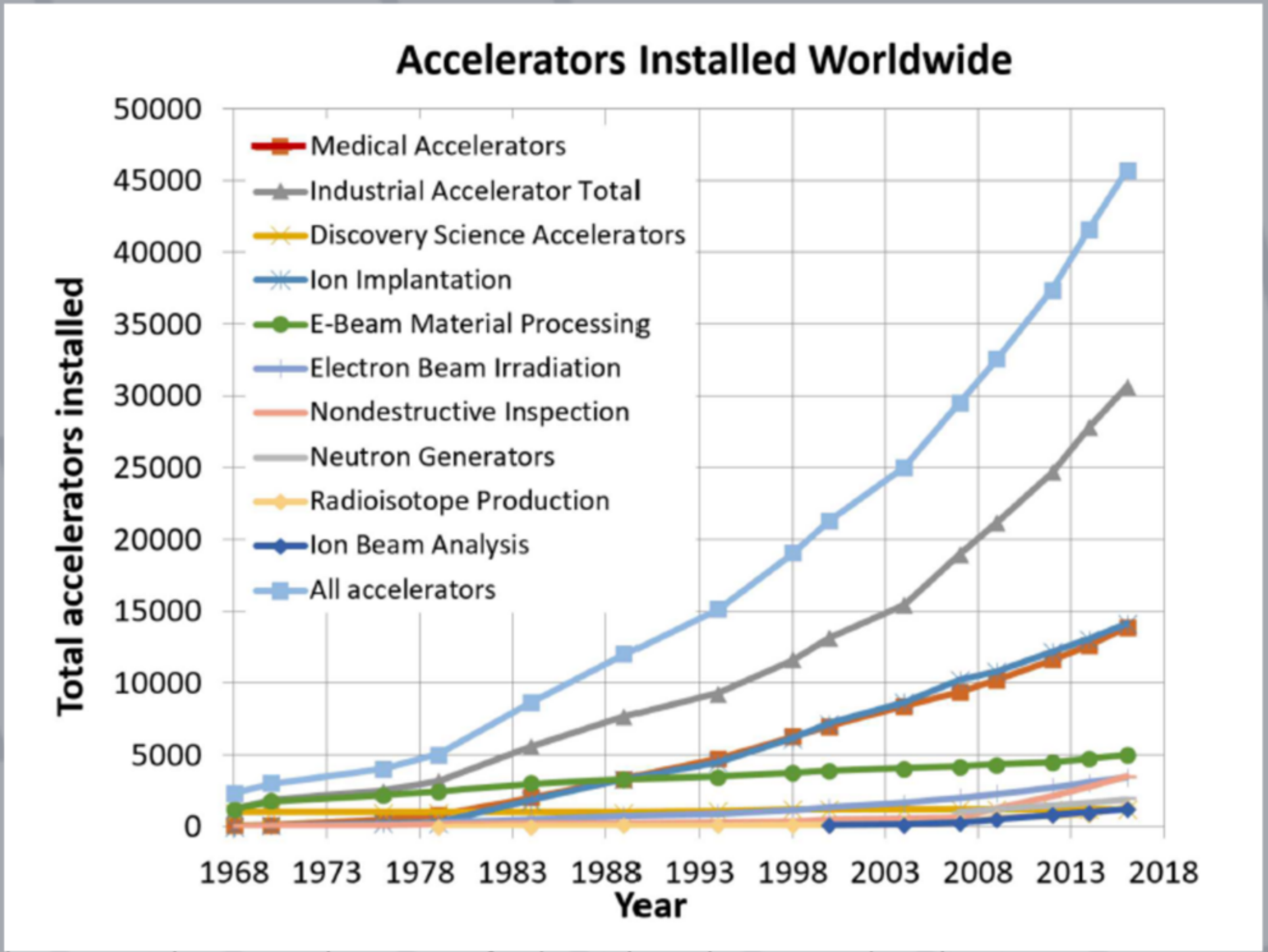


Slide from S. Sheehy

Doyle, McDaniel, Hamm, *The Future of Industrial Accelerators and Applications, SAND2018-5903B*

Before we begin…

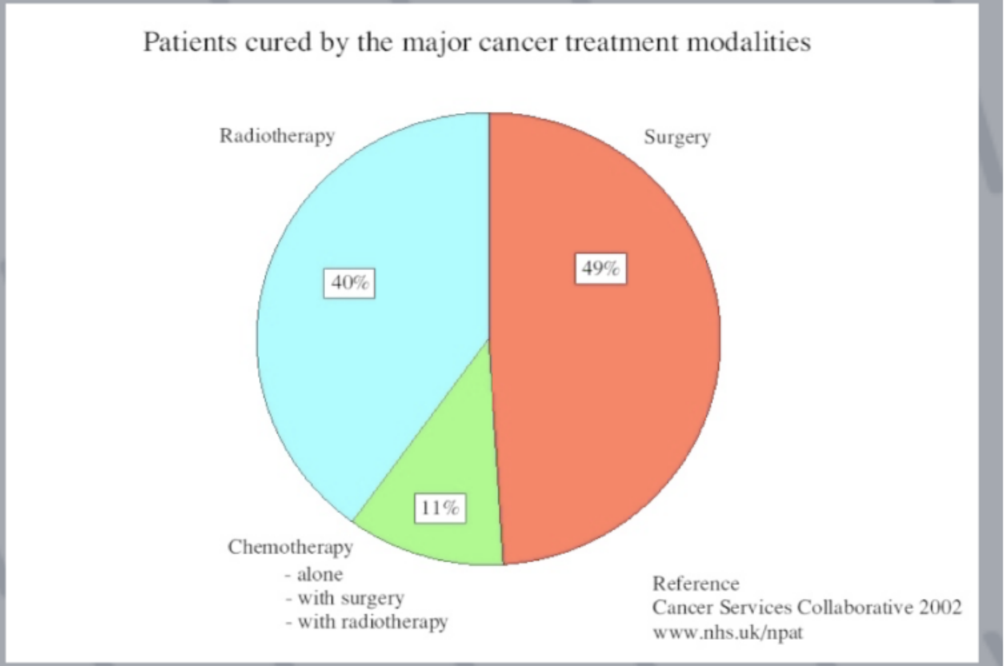
“The annual market for all medical and industrial accelerators described is estimated to now be — US$5.0 Billion/year and growing at —4% per year over the past decade, even during the recession” [2018]

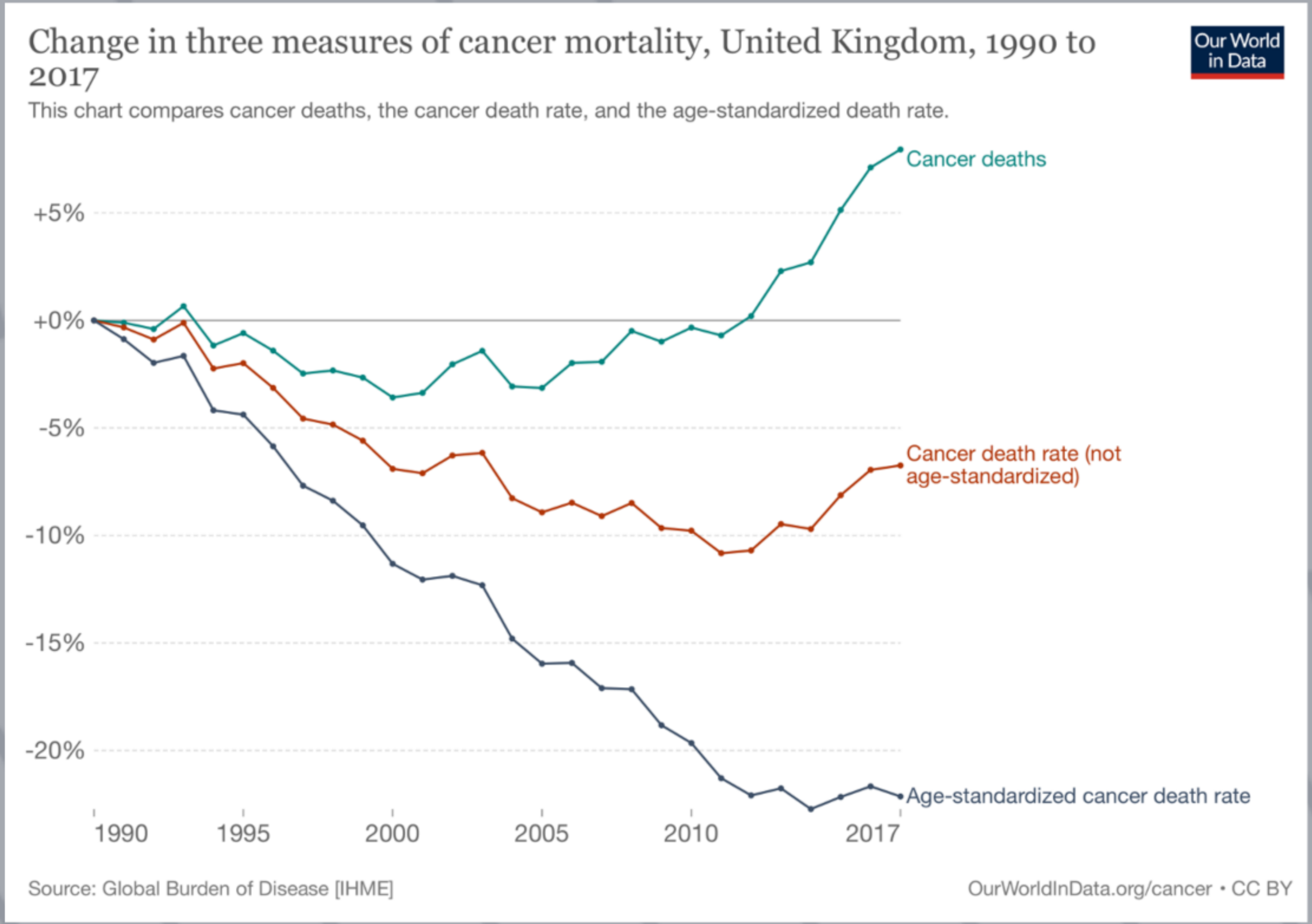


Doyle, McDaniel, Hamm, *The Future of Industrial Accelerators and Applications, SAND2018-5903B*

Slide from S. Sheehy

Let's start with cancer





Slides from S. Sheehy

Treating cancer

X-ray Radiotherapy (RT)

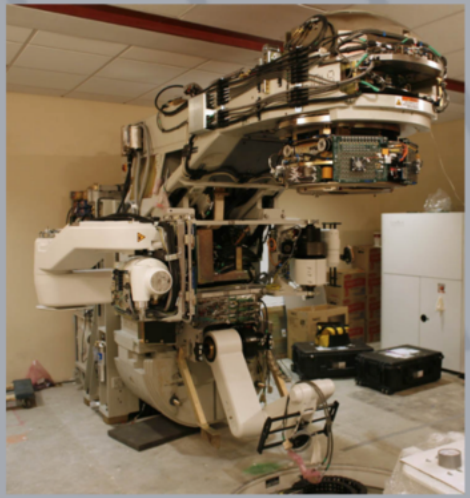
Around **<u>half of all cancer patients</u>** in HICs benefit from RT

Linac (S-band)

Achromatic Bend

Foil to produce x-rays

Collimation system



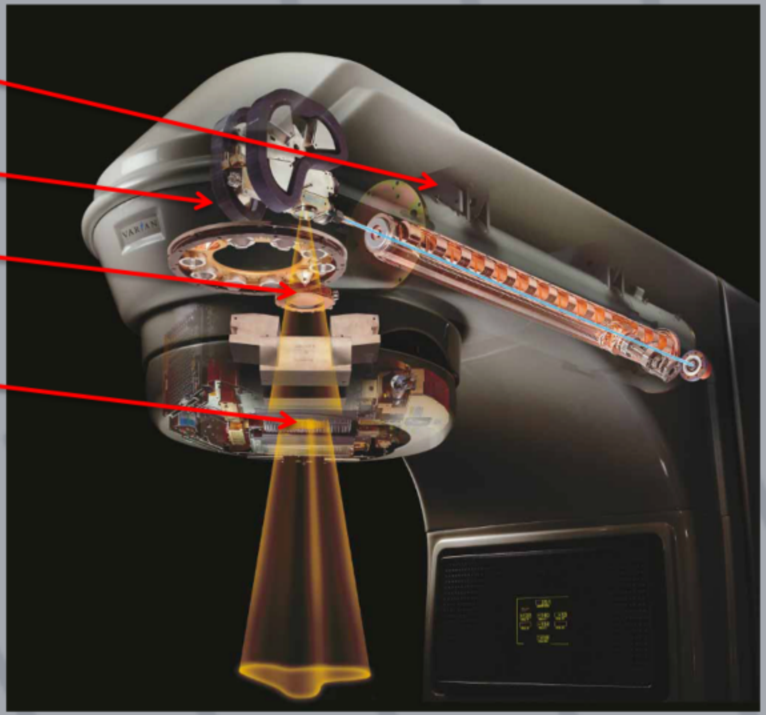
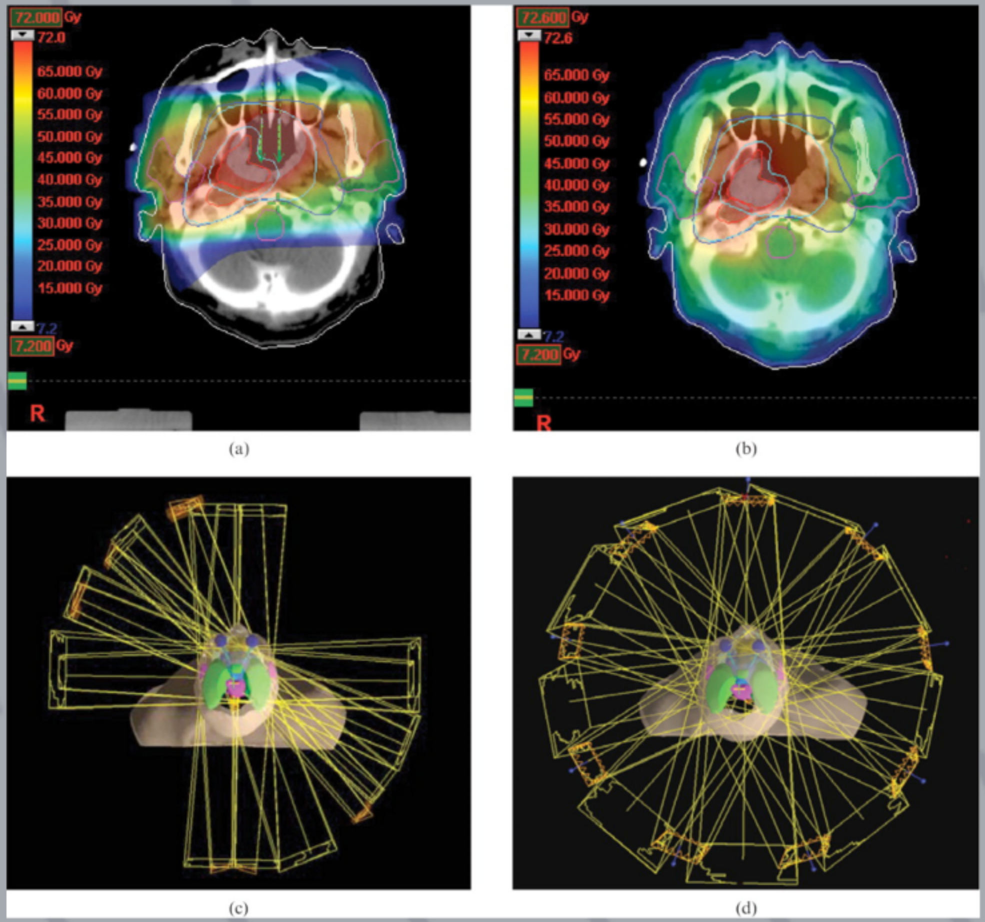


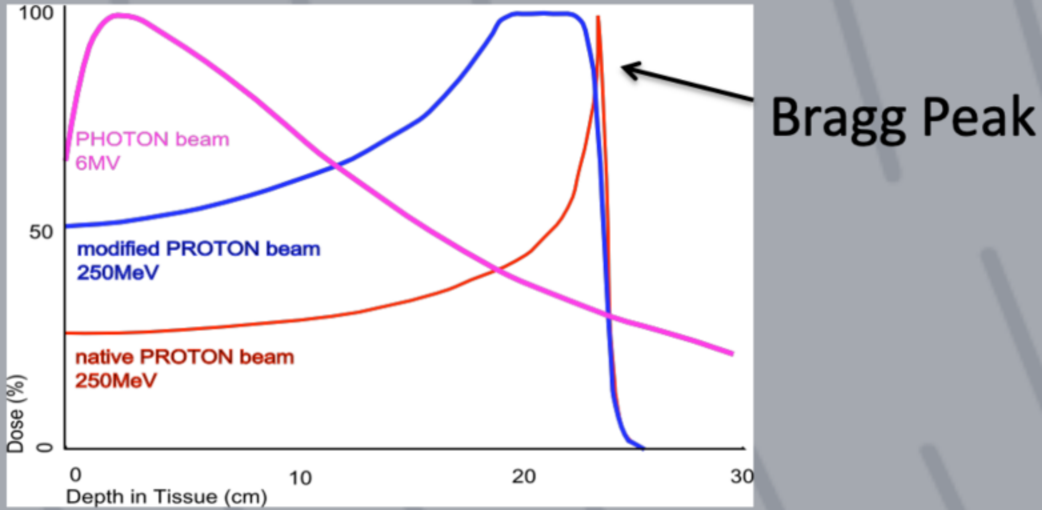
Image: copyright Varian medical systems



Slides from S. Sheehy

Treating cancer

Charged Particle Therapy

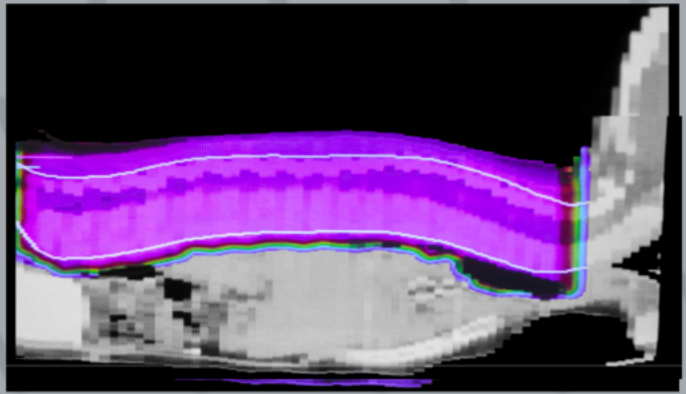


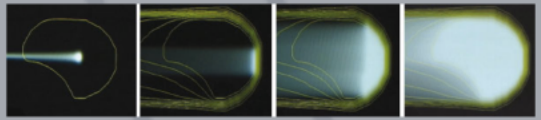
- Greater dose where needed
- Less morbidity for healthy tissue
- Less damage to vital organs

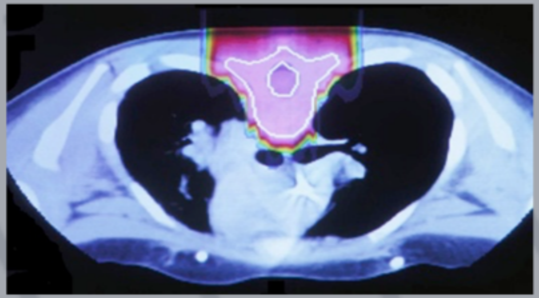
Proton & Ion therapy

"Hadron therapy" = Protons and light ions

- Used to treat localised cancers
- Less morbidity for healthy tissue
- Less damage to vital organs
- Particularly for childhood cancers







Slides from S. Sheehy

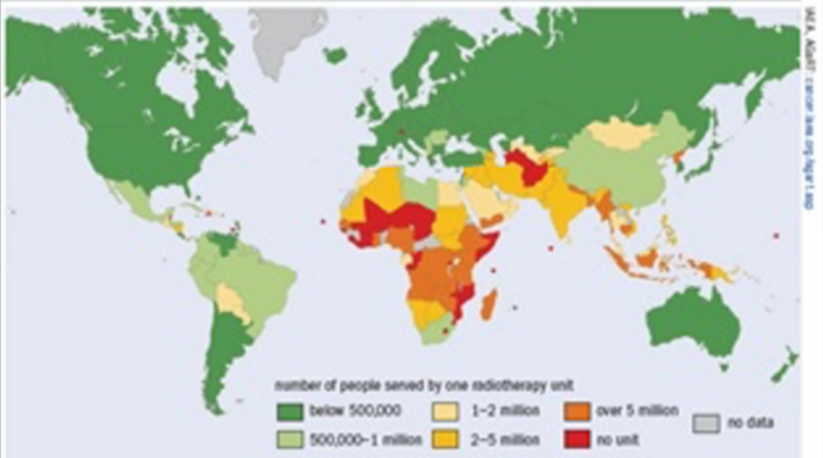
A quick aside...

Not everyone has access to the same treatment technology!

Efforts are being made to increase access to this life-saving technology.

A Global Challenge in Healthcare:

- By 2035, 75% of cancer deaths worldwide will be in LMICs
- Severe shortfall of LINACs & issues with machine failures

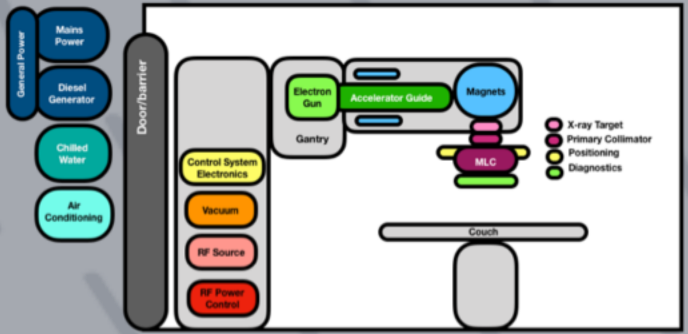


International Cancer Expert Corps
Partnering to transform global cancer care

UKRI Science and Technology Facilities Council

CERN

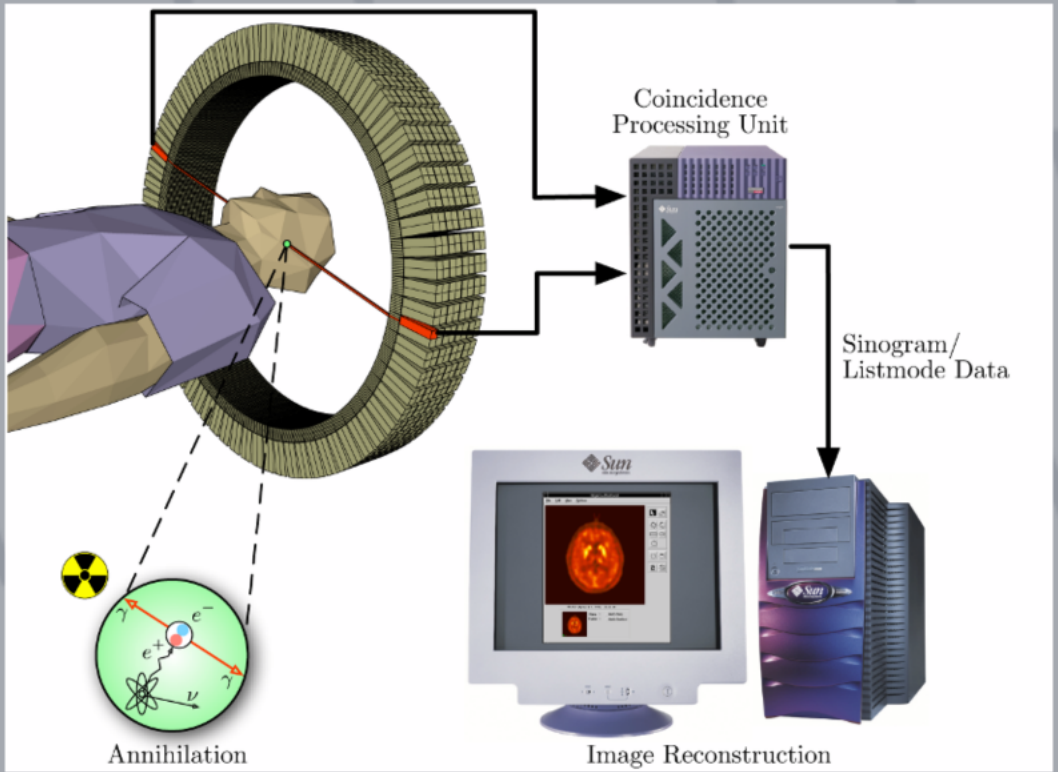
STELLA Collaboration Formed to Address this Issue



Slide from S. Sheehy

Radioisotope production

- Accelerators (compact cyclotrons or linacs) are used to produce radio-isotopes for medical imaging.
- 7-11MeV protons for short-lived isotopes for imaging
- 70-100MeV or higher for longer lived isotopes



- Positron emission tomography (PET) uses Fluorine-18, half life of ~110 min

Slides from S. Sheehy

But what are they for?

It's not just particle/nuclear physics.

In fact, let's ignore particle/nuclear physics altogether for the time being.

Please note, some slides are again influenced/borrowed from Suzie Sheehy.

Some slides are from the work of Dr. Tessa Charles.
https://www.liverpool.ac.uk/physics/staff/tessa-charles/

Medicine

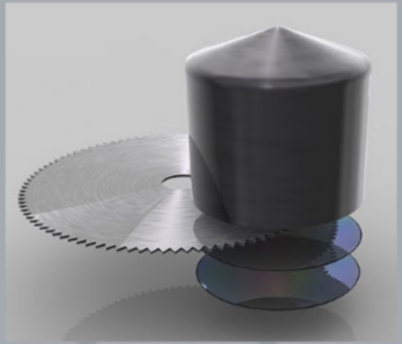
Industry

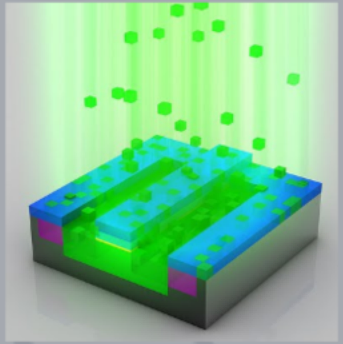
Environment

History/Culture

A few industrial uses…

- Ion Implantation





Images courtesy of Intel

- Accelerators keV->MeV are used to deposit ions in semiconductors.

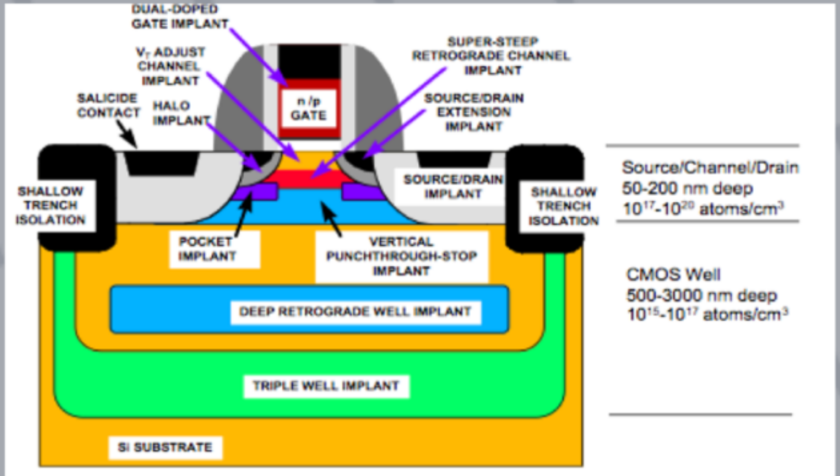


Figure 2: Sketch of major doped regions for a planar CMOS transistor.

Image: https://accelconf.web.cern.ch/pac2013/papers/weyb2.pdf

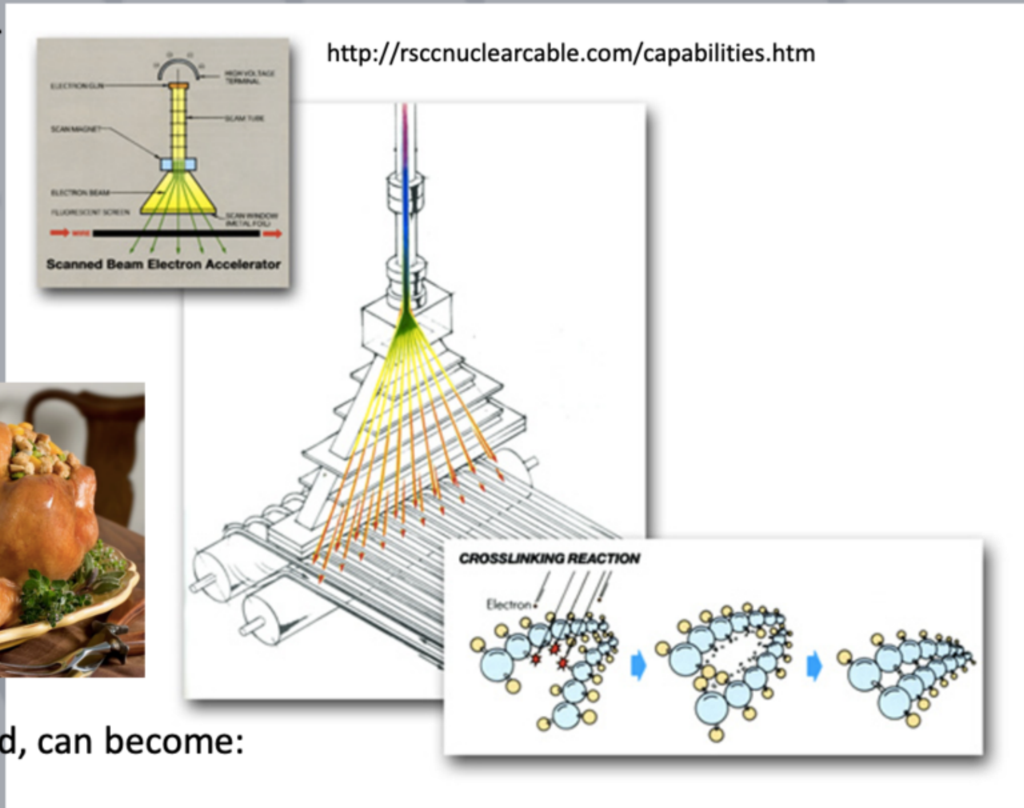
Slide from S. Sheehy

A few industrial uses…

- Ion Implantation
- Electron Beam Processing

In the US, potential markets for industrial electron beams total $50 billion per year.

33% Wire cable tubing
32% Ink curing
17% shrink film
7% service
5% tires
6% other



When polymers are cross-linked, can become:

- stable against heat
- increased tensile strength, resistance to cracking
- heat shrinking properties etc

Slide from S. Sheehy

A few industrial uses…

- Ion Implantation
- Electron Beam Processing
- Equipment Sterilization

Manufacturers of medical disposables have to kill every germ on syringes, bandages, surgical tools and other gear, without altering the material itself.

E-beam sterilization works best on simple, low density products.

Advantages: takes only a few seconds (gamma irradiation can take hours)

Disadvantages: limited penetration depth, works best on simple, low density products (syringes)

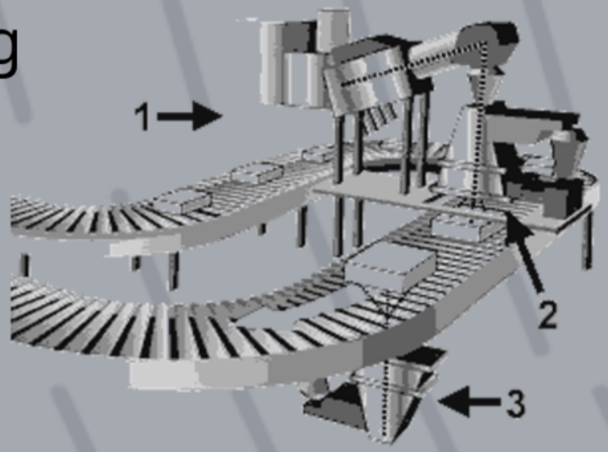
40-50% of all disposable medical products manufactured in North America are currently radiation sterilized, primarily at 60Co irradiation facilities. – Hamm & Doyle, 2018

The IBA rhodotron – a commercial accelerator used for e-beam sterilization

Slide from S. Sheehy

A few industrial uses...

- Ion Implantation
- Electron Beam Processing
- Equipment Sterilization
- Food Irradiation



'Cold pasteurization' or 'electronic pasteurization'
Uses electrons (from an accelerator) or X-rays produced using an accelerator.

The words 'irradiated' or 'treated with ionizing radiation' must appear on the label packaging.

In the US all irradiated foods have this symbol

Foods authorized for irradiation in the EU:

Lower dose → Higher dose

Slide from S. Sheehy

A few industrial uses…

- Ion Implantation
- Electron Beam Processing
- Equipment Sterilization
- Food Irradiation
- Gemstone Irradiation

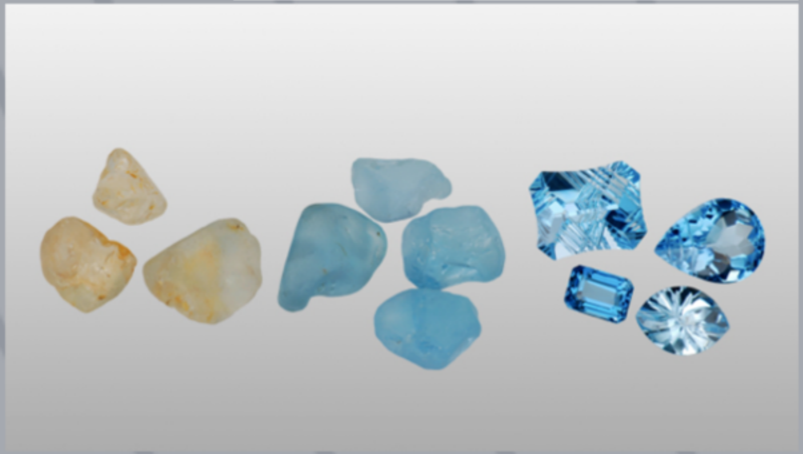


TABLE 2. Effects of irradiation treatment on various gem materials.[a]

Material	Starting color	Ending color
Beryl	Colorless	Yellow
	Blue	Green
Maxixe-type	Pale or colorless	Blue
Corundum	Colorless	Yellow
	Pink	Padparadscha
Diamond	Colorless or pale to yellow and brown	Green or blue (with heating, turns yellow, orange, brown, pink, red)
Fluorite	Colorless	Various colors
Pearl	Light colors	Gray, brown, "blue," "black"
Quartz	Colorless to yellow or pale green	Brown, amethyst, "smoky," rose
Scapolite[b]	Colorless, "straw," pink, or light blue	Blue, lavender, amethyst, red
Spodumene	Colorless to pink	Orange, yellow, green, pink[c]
Topaz	Yellow, orange	Intensify colors
	Colorless, pale blue	Brown, blue (may require heat to turn blue), green
Tourmaline	Colorless to pale colors	Yellow, brown, pink, red, bicolor green-red
	Blue	Purple
Zircon	Colorless	Brown to red

[a] *Adapted from Nassau (1984).*
[b] *Charles Key, pers. comm., 1988.*
[c] *George Drake, pers. comm., 1988.*

http://www.nrc.gov/reading-rm/doc-collections/fact-sheets/irradiated-gemstones.html

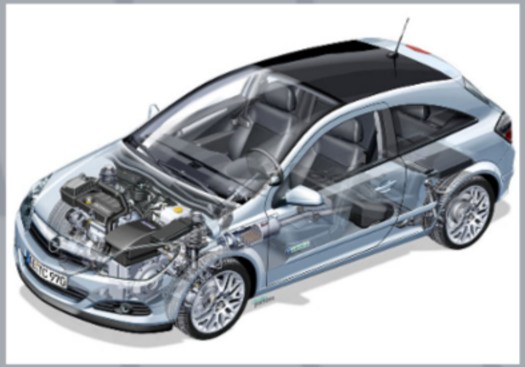
http://www.symmetrymagazine.org/article/october-2009/cleaner-living-through-electrons

'Irradation and Radioactivity', Gems and Gemology, 1988

Slide from S. Sheehy

A few industrial uses…

- Ion Implantation
- Electron Beam Processing
- Equipment Sterilization
- Food Irradiation
- Gemstone Irradiation
- Non-destructive testing (weld integrity, etc…)
- Hardening surfaces of artificial joints
- Scratch resistant furniture
- Hardening of tarmac
- Etc…



http://www.accelerators-for-society.org/case-studies/case-study-car.php

Image: https://www.mistrasgroup.com

Slide from S. Sheehy

But what are they for?

It's not just particle/nuclear physics.

In fact, let's ignore particle/nuclear physics altogether for the time being.

Please note, some slides are again influenced/borrowed from Suzie Sheehy.

Some slides are from the work of Dr. Tessa Charles.
https://www.liverpool.ac.uk/physics/staff/tessa-charles/

Medicine

Industry

Environment

History/Culture

Environment you say?

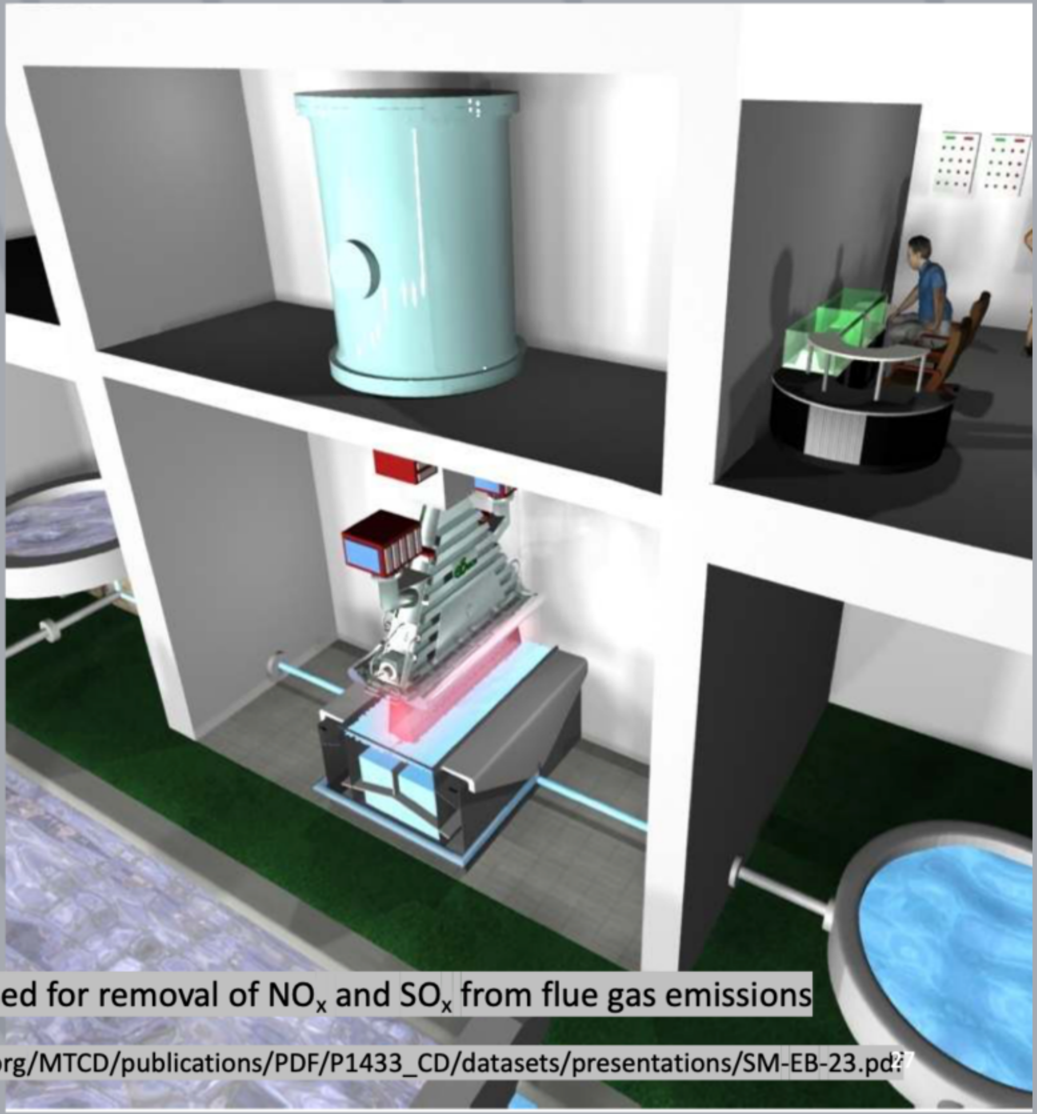
- Wastewater Treatment

Remove organic compounds and disinfect wastewater.

Can be used to treat/reclaim:

- Textile Dyeing
- Pharmaceutical
- Petrochemical
- Municipal Wastewater
- Contaminated Underground Water

1 MeV, High Current, scanning system



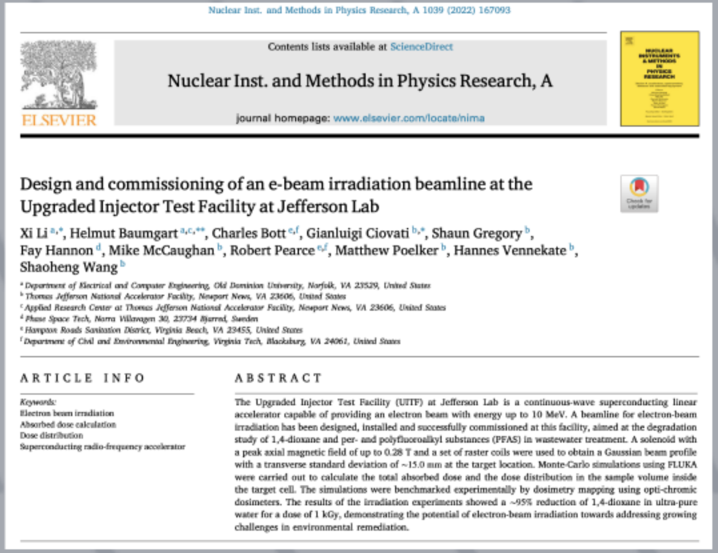
Slide from S. Sheehy

Also used for removal of NO_x and SO_x from flue gas emissions

https://www-pub.iaea.org/MTCD/publications/PDF/P1433_CD/datasets/presentations/SM-EB-23.pdf

Environment you say?

- Wastewater Treatment


Nuclear Inst. and Methods in Physics Research, A 1039 (2022) 167093

Contents lists available at ScienceDirect

Nuclear Inst. and Methods in Physics Research, A

journal homepage: www.elsevier.com/locate/nima

Design and commissioning of an e-beam irradiation beamline at the Upgraded Injector Test Facility at Jefferson Lab

Xi Li[a,*], Helmut Baumgart[a,c,**], Charles Bott[e,f], Gianluigi Ciovati[b,*], Shaun Gregory[b], Fay Hannon[d], Mike McCaughan[b], Robert Pearce[e,f], Matthew Poelker[b], Hannes Vennekate[b], Shaoheng Wang[b]

[a] Department of Electrical and Computer Engineering, Old Dominion University, Norfolk, VA 23529, United States
[b] Thomas Jefferson National Accelerator Facility, Newport News, VA 23606, United States
[c] Applied Research Center at Thomas Jefferson National Accelerator Facility, Newport News, VA 23606, United States
[d] Phase Space Tech, Norra Villavagen 30, 23734 Bjarred, Sweden
[e] Hampton Roads Sanitation District, Virginia Beach, VA 23455, United States
[f] Department of Civil and Environmental Engineering, Virginia Tech, Blacksburg, VA 24061, United States

ARTICLE INFO

Keywords:
Electron beam irradiation
Absorbed dose calculation
Dose distribution
Superconducting radio-frequency accelerator

ABSTRACT

The Upgraded Injector Test Facility (UITF) at Jefferson Lab is a continuous-wave superconducting linear accelerator capable of providing an electron beam with energy up to 10 MeV. A beamline for electron-beam irradiation has been designed, installed and successfully commissioned at this facility, aimed at the degradation study of 1,4-dioxane and per- and polyfluoroalkyl substances (PFAS) in wastewater treatment. A solenoid with a peak axial magnetic field of up to 0.28 T and a set of raster coils were used to obtain a Gaussian beam profile with a transverse standard deviation of ~15.0 mm at the target location. Monte-Carlo simulations using FLUKA were carried out to calculate the total absorbed dose and the dose distribution in the sample volume inside the target cell. The simulations were benchmarked experimentally by dosimetry mapping using opti-chromic dosimeters. The results of the irradiation experiments showed a ~95% reduction of 1,4-dioxane in ultra-pure water for a dose of 1 kGy, demonstrating the potential of electron-beam irradiation towards addressing growing challenges in environmental remediation.

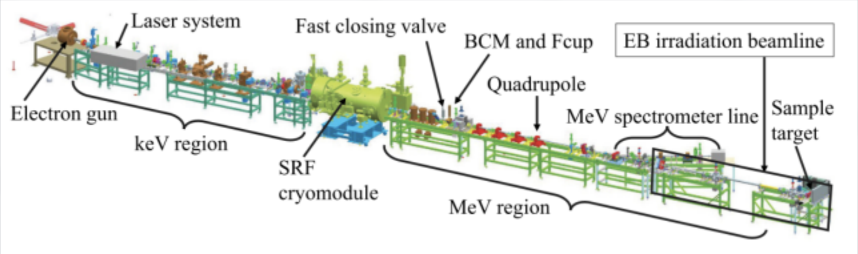


Fig. 1. Schematic layout of the UITF at Jefferson Lab. (BCM -- beam current monitor; Fcup -- Faraday cup.)

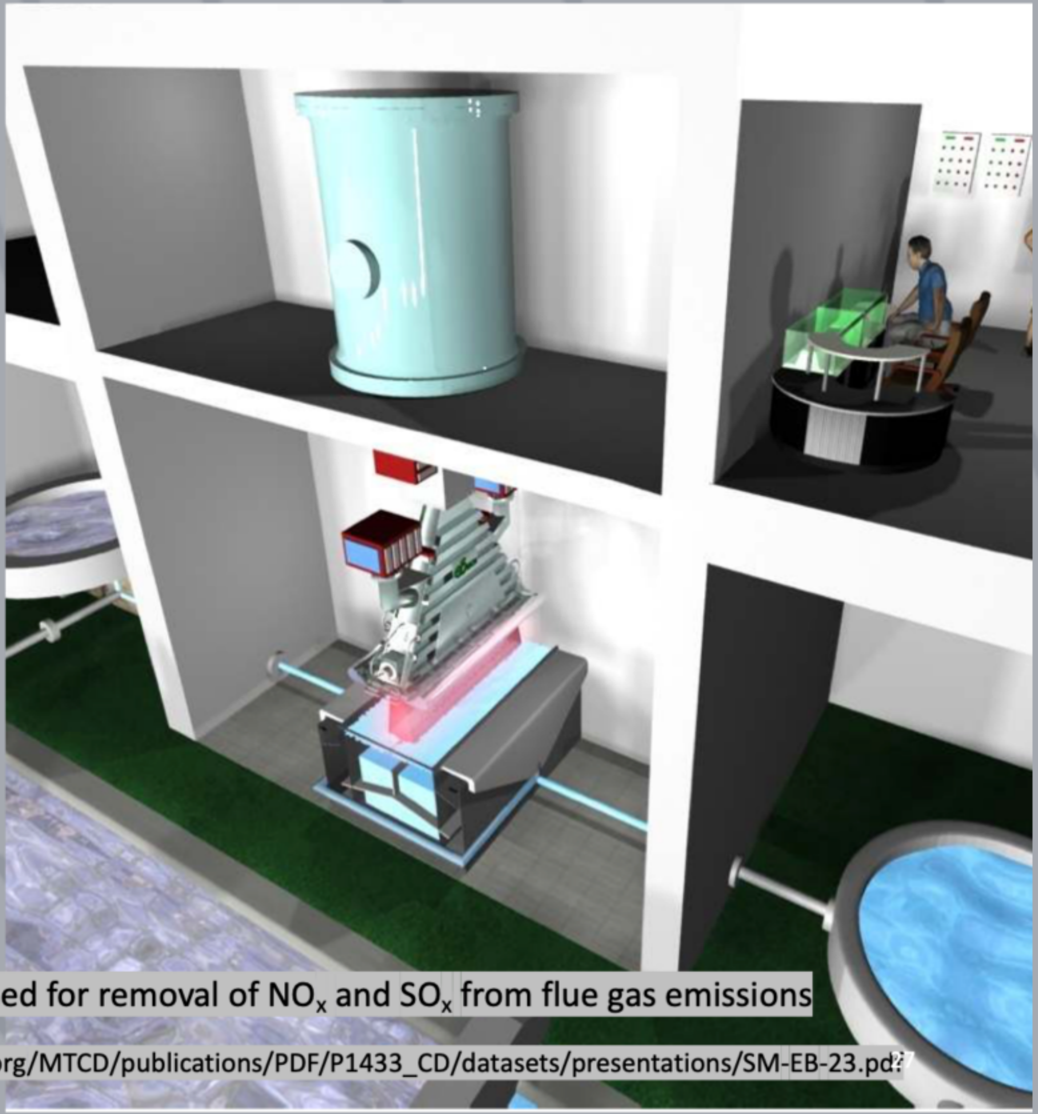
https://doi.org/10.1016/j.nima.2022.167093

Remove organic compounds and disinfect wastewater.

Can be used to treat/reclaim:

- Textile Dyeing
- Pharmaceutical
- Petrochemical
- Municipal Wastewater
- Contaminated Underground Water

1 MeV, High Current, scanning system



Slide from S. Sheehy

Also used for removal of NO_x and SO_x from flue gas emissions

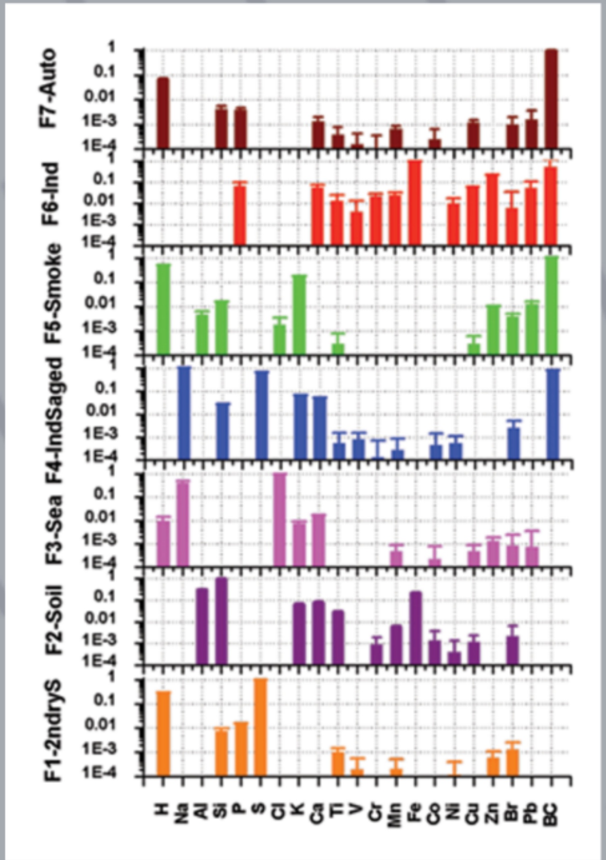
https://www-pub.iaea.org/MTCD/publications/PDF/P1433_CD/datasets/presentations/SM-EB-23.pdf

27

Environment you say?

- Wastewater Treatment
- Aerosols/Pollutants

"Using ion beam analysis methods, it is possible to not only determine the number of minute quantities of pollutants in the air but also to identify their sources," - David Cohen, ANSTO



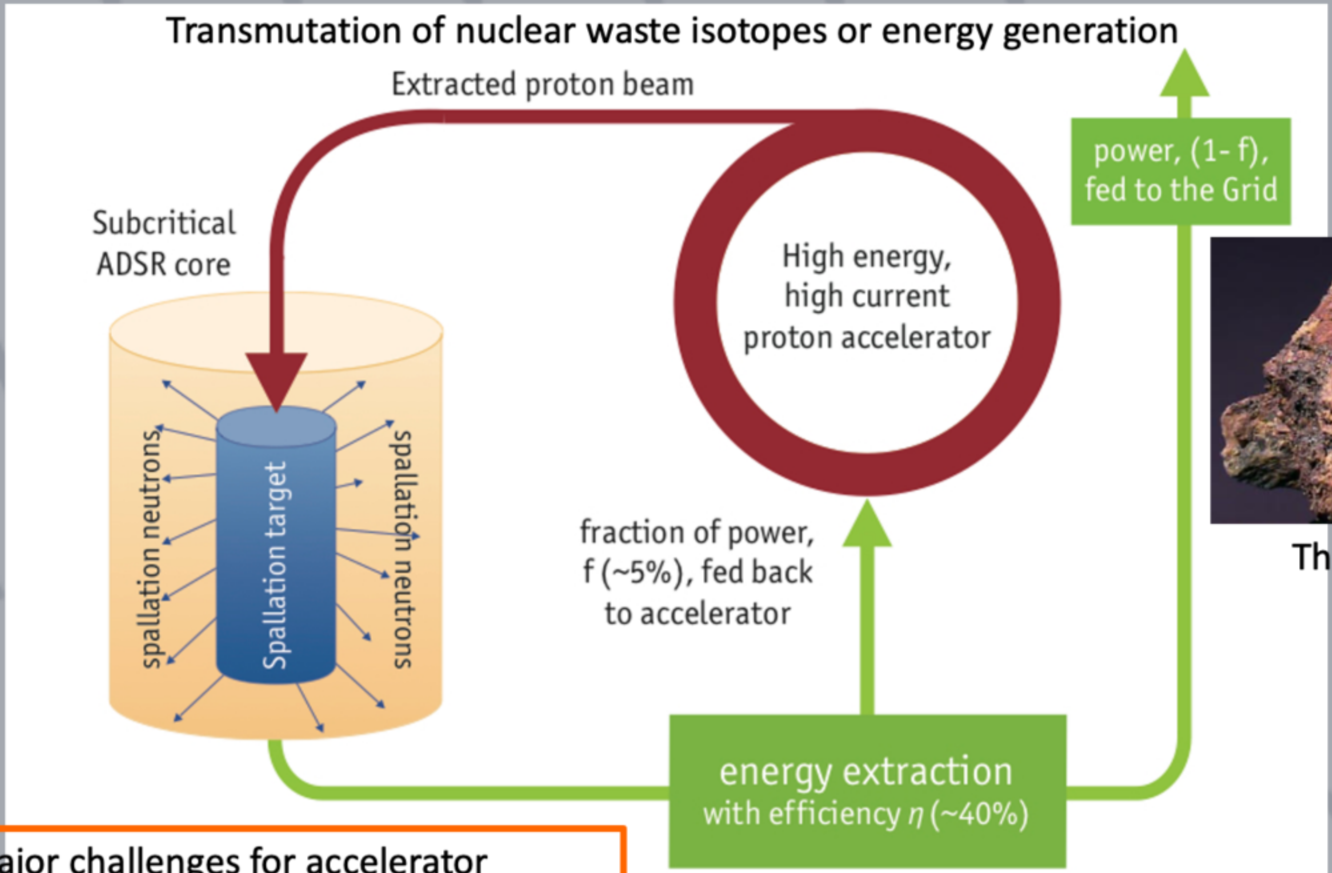
"up to half of the total sulfate air pollution in the greater Sydney region can be attributed to emissions from NSW's eight coal-fired power stations" - ANSTO

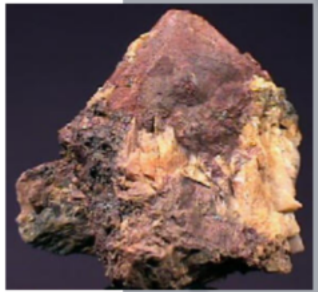
https://www.ansto.gov.au/our-science/projects/aerosol-sampling-program/highlights-aerosol-sampling

Slide from S. Sheehy

Environment you say?

- Wastewater Treatment
- Aerosols/Pollutants
- Accelerator-Driven Systems





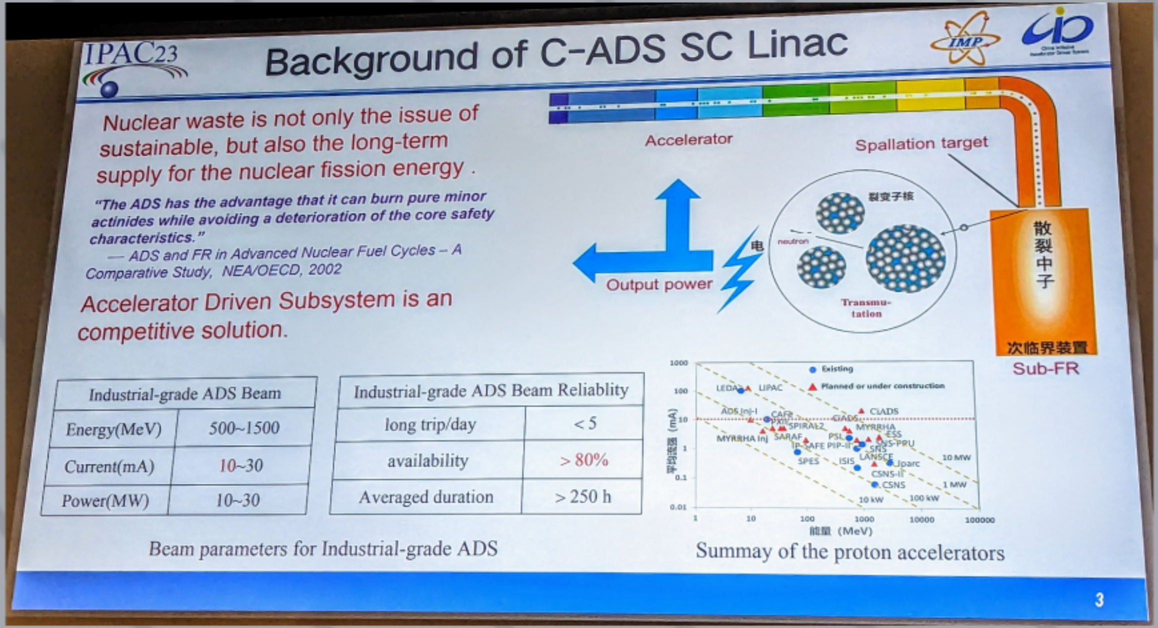
Thorium

Major challenges for accelerator technology in terms of beam power (>10MW) and reliability

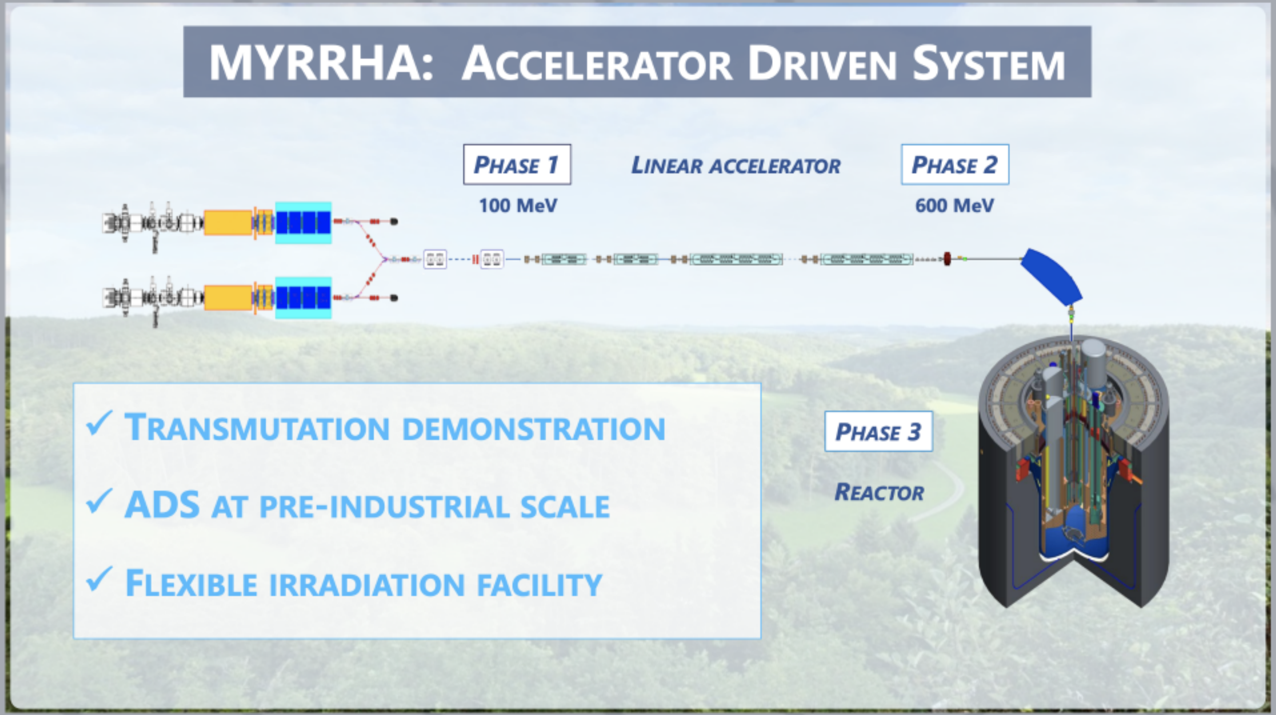
Slide from S. Sheehy

Environment you say?

- Wastewater Treatment
- Aerosols/Pollutants
- Accelerator-Driven System



From IPAC23 proceedings: The Beam Commissioning of 10 mA, 100 kW CW Proton Beam at CAFe



https://esfr-smart.eu/wp-content/uploads/2021/04/S51_2_Didier_De_Bruyn_The_MYRRHA_Project_ESFR_SMART_Summer_School_V3.pdf

Another quick aside...

- Large scale accelerators tend to be very power hungry, and not especially "green" by their very nature.
- The last few years have seen a major change in approaching future accelerators and upgrades, with aims to reduce the carbon footprints and make these machines more environmentally responsible.
  - For example, the recent International Particle Accelerator Conference (IPAC23) had several invited and contributed talks focused on these sorts of improvements.

- There's still a LONG way to go.
  - Concrete tends to be one of the major impacting factors, along with power usage.

But what are they for?

It's not just particle/nuclear physics.

In fact, let's ignore particle/nuclear physics altogether for the time being.

Please note, some slides are again influenced/borrowed from Suzie Sheehy.

Some slides are from the work of Dr. Tessa Charles.
https://www.liverpool.ac.uk/physics/staff/tessa-charles/

Medicine

Industry

Environment

History/Culture

Studies of art

New AGLAE (Accélérateur Grand Louvre d'analyse élémentaire) Facility

AGLAE is a 2 MeV electrostatic pelletron accelerator.

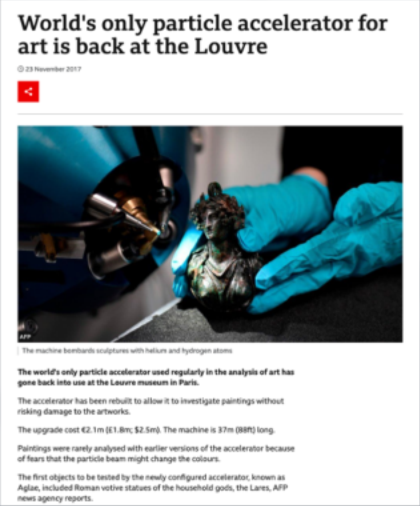
100% dedicated to the study of Cultural Heritage (CH).

Ion Beam Analysis (IBA) techniques used:

- PIXE: Particle Induced X-ray Emission
- PIGE: Particle Induced γ-ray Emission
- RBS: (Rutherford) Backscattering Spectroscopy

Slide from T. Charles

Studies of art



World's only particle accelerator for art is back at the Louvre

23 November 2017

The machine bombards sculptures with helium and hydrogen atoms

The world's only particle accelerator used regularly in the analysis of art has gone back into use at the Louvre museum in Paris.

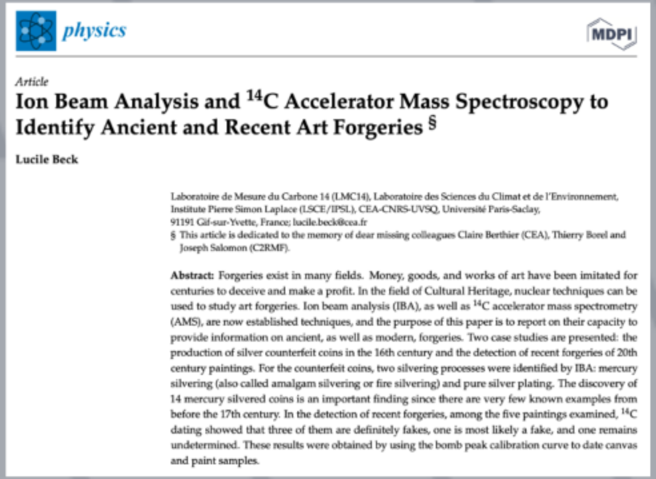
The accelerator has been rebuilt to allow it to investigate paintings without risking damage to the artworks.

The upgrade cost €2.1m (£1.8m; $2.5m). The machine is 37m (88ft) long.

Paintings were rarely analysed with earlier versions of the accelerator because of fears that the particle beam might change the colours.

The first objects to be tested by the newly configured accelerator, known as Aglae, included Roman votive statues of the household gods, the Lares, AFP news agency reports.

https://www.bbc.com/news/world-europe-42094003



physics MDPI

Article

Ion Beam Analysis and ^{14}C Accelerator Mass Spectroscopy to Identify Ancient and Recent Art Forgeries §

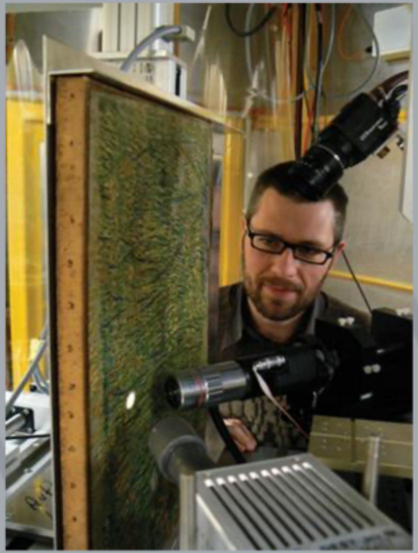
Lucile Beck

Laboratoire de Mesure du Carbone 14 (LMC14), Laboratoire des Sciences du Climat et de l'Environnement, Institute Pierre Simon Laplace (LSCE/IPSL), CEA-CNRS-UVSQ, Université Paris-Saclay, 91191 Gif-sur-Yvette, France; lucile.beck@cea.fr

§ This article is dedicated to the memory of dear missing colleagues Claire Berthier (CEA), Thierry Borel and Joseph Salomon (C2RMF).

Abstract: Forgeries exist in many fields. Money, goods, and works of art have been imitated for centuries to deceive and make a profit. In the field of Cultural Heritage, nuclear techniques can be used to study art forgeries. Ion beam analysis (IBA), as well as ^{14}C accelerator mass spectrometry (AMS), are now established techniques, and the purpose of this paper is to report on their capacity to provide information on ancient, as well as modern, forgeries. Two case studies are presented: the production of silver counterfeit coins in the 16th century and the detection of recent forgeries of 20th century paintings. For the counterfeit coins, two silvering processes were identified by IBA: mercury silvering (also called amalgam silvering or fire silvering) and pure silver plating. The discovery of 14 mercury silvered coins is an important finding since there are very few known examples from before the 17th century. In the detection of recent forgeries, among the five paintings examined, ^{14}C dating showed that three of them are definitely fakes, one is most likely a fake, and one remains undetermined. These results were obtained by using the bomb peak calibration curve to date canvas and paint samples.

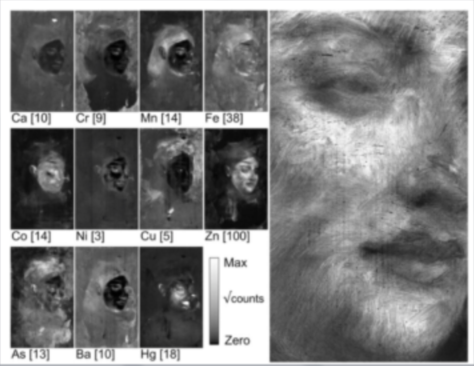
Beck, L. Ion Beam Analysis and 14C Accelerator Mass Spectroscopy to Identify Ancient and Recent Art Forgeries. *Physics* **2022**, *4*, 462–472.
https://doi.org/10.3390/physics4020031



Vincent van Gogh, "Patch of Grass", Apr-June 1887

J. Dik et al Anal. Chem. 2008, 80, 6436–6442

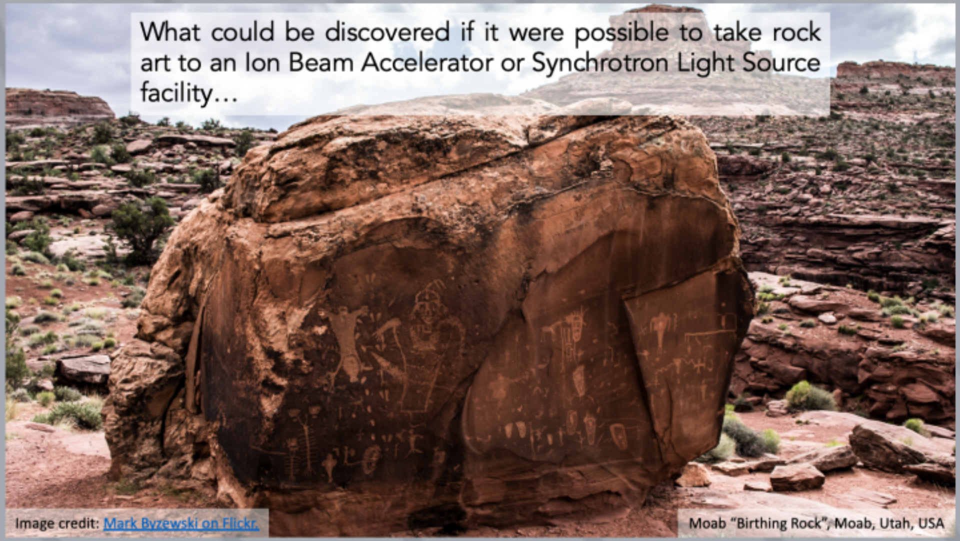
Edgar Degas' 1876 *Portrait of a Woman*



D. Thurrowgood et al Scientific Reports | 6:29594 | DOI: 10.1038/srep29594

Slides from T. Charles

Cultural Heritage



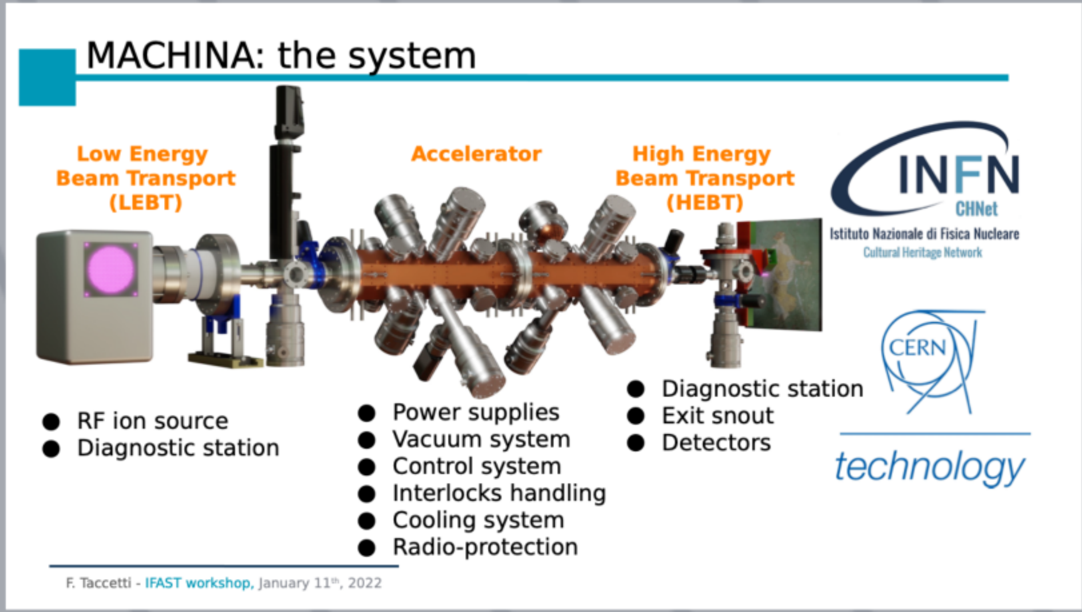
INFN portable alpha-PIXE

- Consists of a polonium source emitting alpha particles of 5 MeV energy.
- It is based on an annular geometry and it is coupled to a 25 mm² SDD detector with a high energy resolution of 125 eV at 5.9 keV.
- Beam spot = 18 mm diameter
- Has been used to detect forgeries in coins.

Photo credit: Paolo Romano

Slide from Francesco Taccetti, LABEC laboratory

Movable Accelerator for Cultural Heritage In-situ Non-destructive Analysis.



Movable Accelerator for Cultural Heritage In-situ Non-destructive Analysis

Need for Portable Accelerators in Cultural Heritage

Tessa Charles, *University of Liverpool and Cockcroft Institute*
Alejandro Castilla, *Lancaster University and CERN*
Ryan Bodenstein, *Thomas Jefferson National Accelerator Facility*

Slides from T. Charles

And so much more!

But what are they for?

It's not just particle/nuclear physics.

In fact, let's ignore particle/nuclear physics altogether for the time being.

Please note, some slides are again influenced/borrowed from Suzie Sheehy.

Some slides are from the work of Dr. Tessa Charles.
https://www.liverpool.ac.uk/physics/staff/tessa-charles/

Medicine

Industry

Environment

History/Culture

Introductions

Accelerator Applications

12 GeV CEBAF

A Bit of History

Types of Accelerators

24 GeV CEBAF

The CEBAF Accelerator from 12 to 22 GeV

Ryan Bodenstein

Some of the basics

There are *lots* of other types, and lots of important details, but we'll stick to the basics here.

Rings

LINACs

A few more...

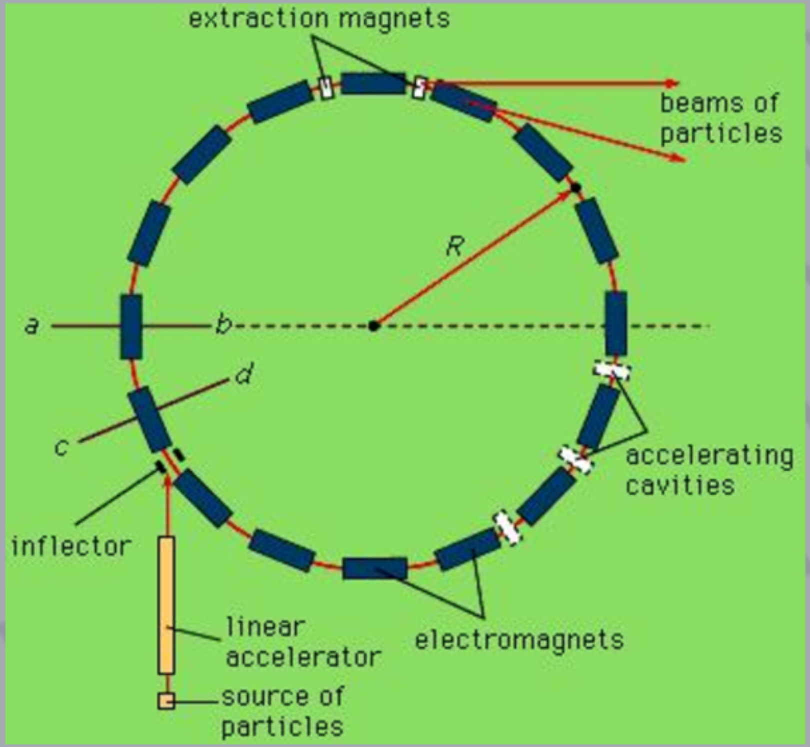
Put a ring on it...

- First thing to realize about ring-based accelerators: they're mostly magnets, with a bit of accelerating components
  - For example, the LHC at CERN is 27 km around, and only has 16 Superconducting Radio Frequency (SRF) cavities split into 4 cryomodules.
  - Meanwhile, it has 1232 superconducting dipoles (15 m in length), 392 quadrupoles (5-7 m in length), plus correctors, interaction region magnets, etc...
    - This makes ~18.48 km of dipoles alone

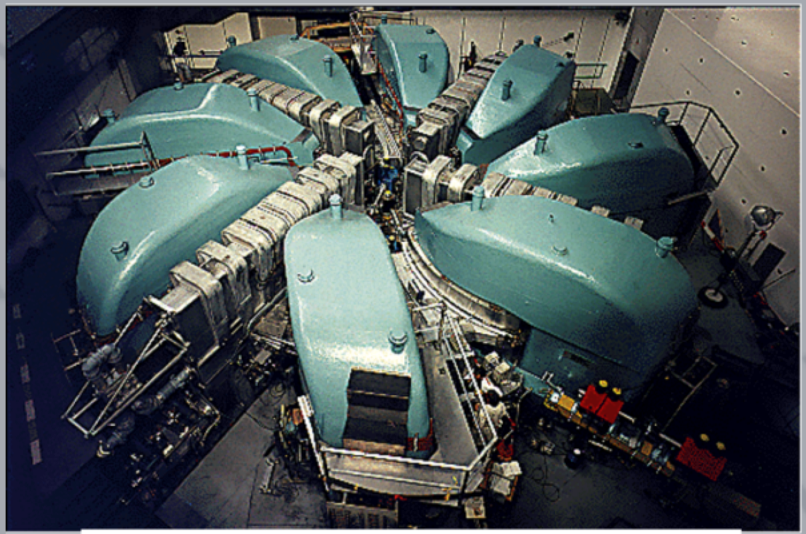
LHC Spare Cryomodule

LHC Spare Dipoles

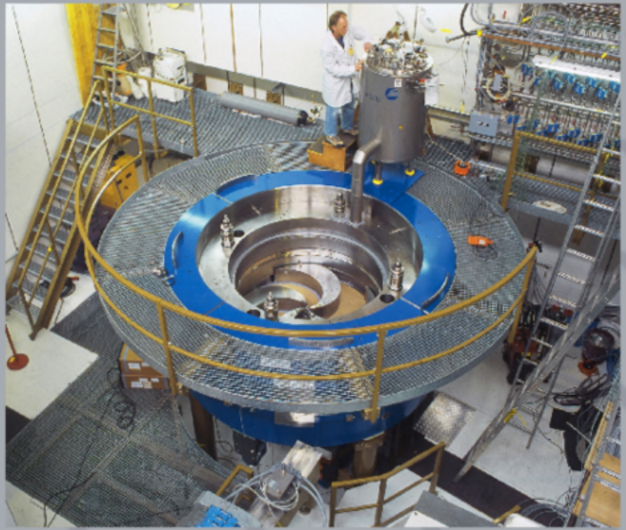
A few types of rings



Synchrotron



590 MeV PSI Isochronous Cyclotron (1974)



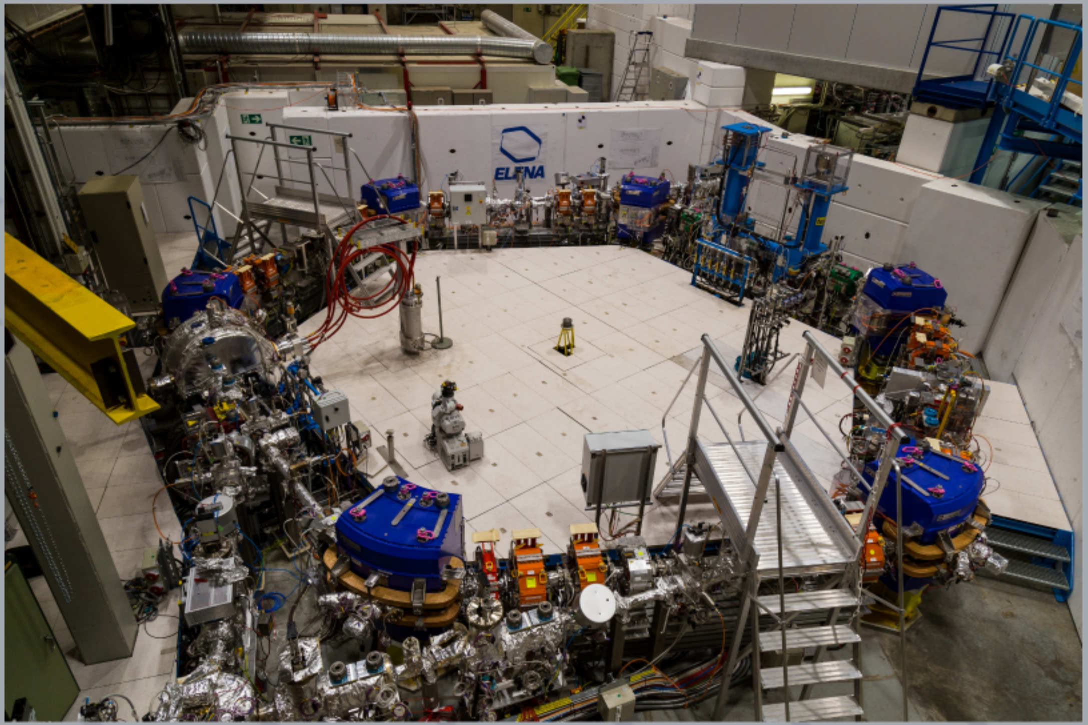
250 MeV PSI Isochronous Cyclotron (2004)

IBA Medical Cyclotron

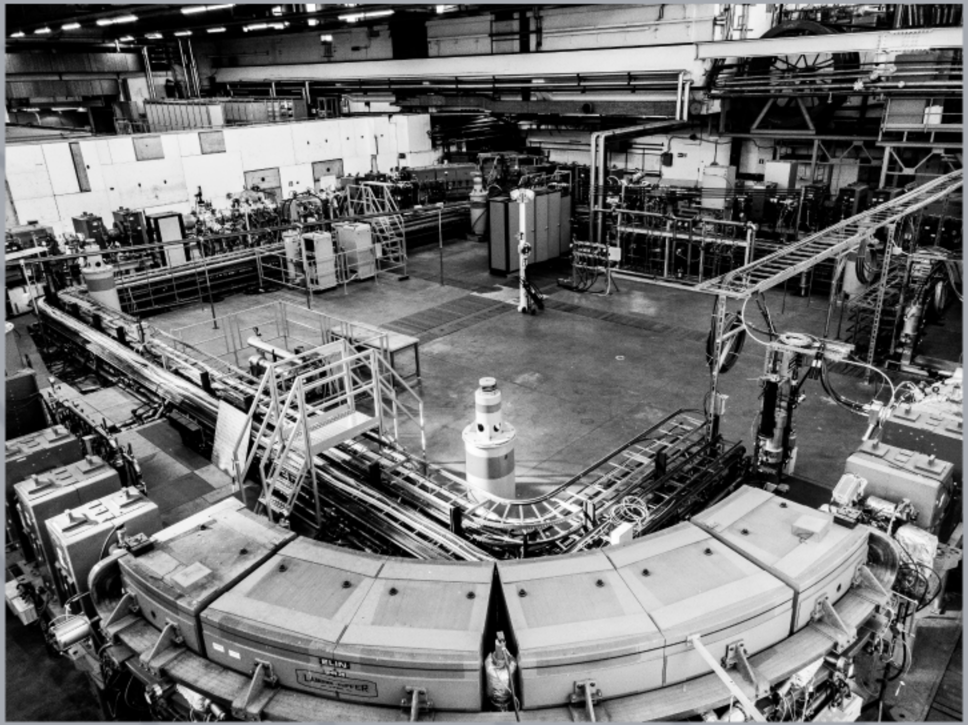
A few types of rings

Swiss Light Source (SLS)

A few types of rings

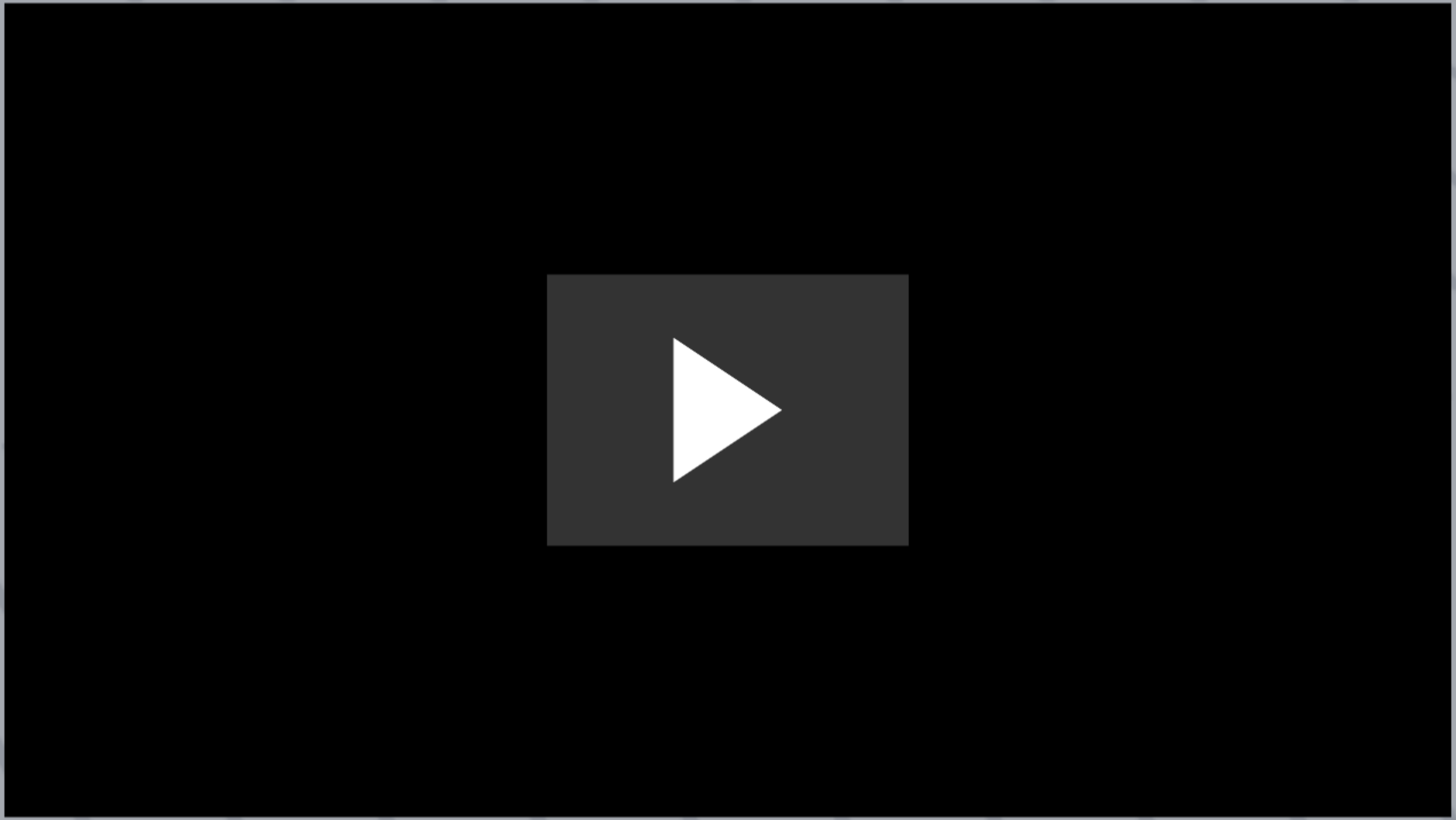


Extra Low ENergy Antiproton ring
(ELENA)



Low Energy Ion Ring
(LEIR)

A few types of rings



Compact Linear Collider (CLIC) Delay Loop and Combiner Ring

https://videos.cern.ch/record/2688466

A few more points

- Ring optics are designed to meet a periodic condition which allows the beam to recirculate many times
- Often, LINACs are used for getting particles "up to speed" for injection into a ring
  - When the particle velocity is non-relativistic, the accelerating structures must vary with the v/c
  - Once the velocity is relativistic, it can be more efficient to use a synchrotron
- Electrons are relativistic in the keV range, and as they gain momentum, they emit synchrotron radiation
  - This can reach a point of diminishing returns

Some of the basics

There are *lots* of other types, and lots of important details, but we'll stick to the basics here.

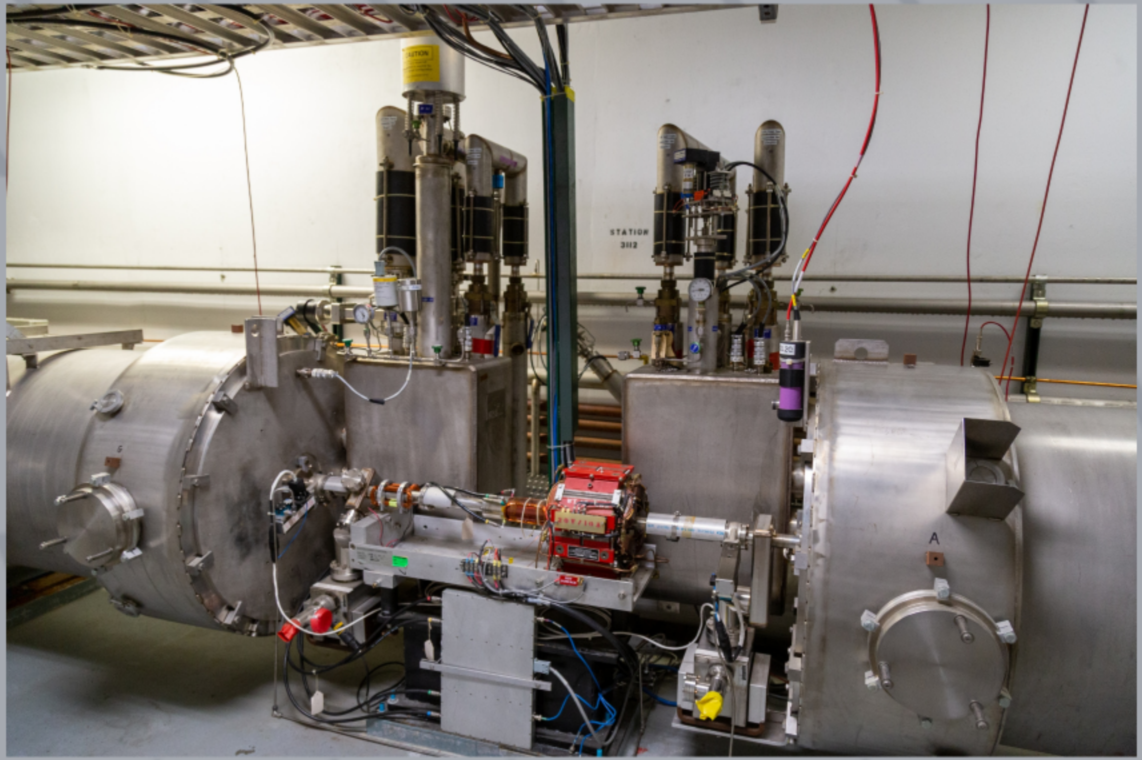
Rings

LINACs

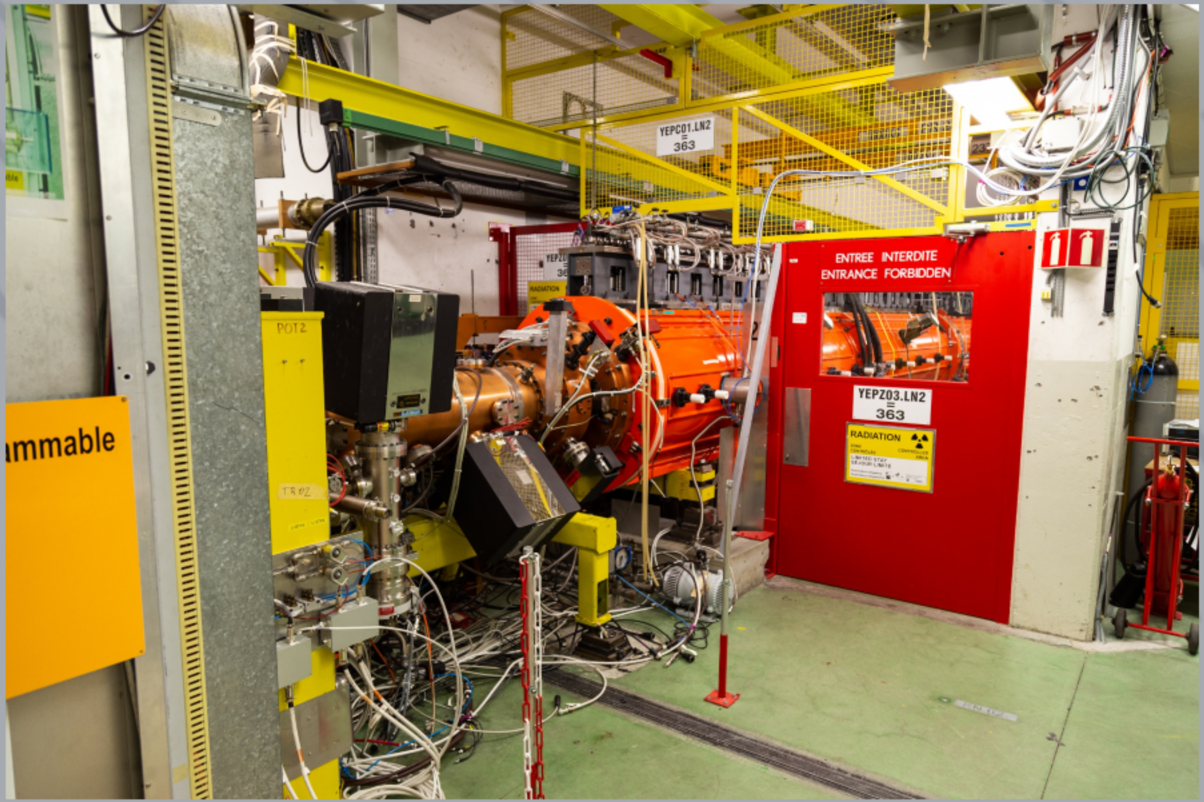
A few more...

Get in line…

- Contrary to ring-based accelerators, LINACs are mostly made of accelerating components, with magnets used to control the beam dynamics
    - Looking below, you'll see that JLab's LINACs are almost all SRF cavities, with some magnets sprinkled in
    - Beamlines are another story…more on that later



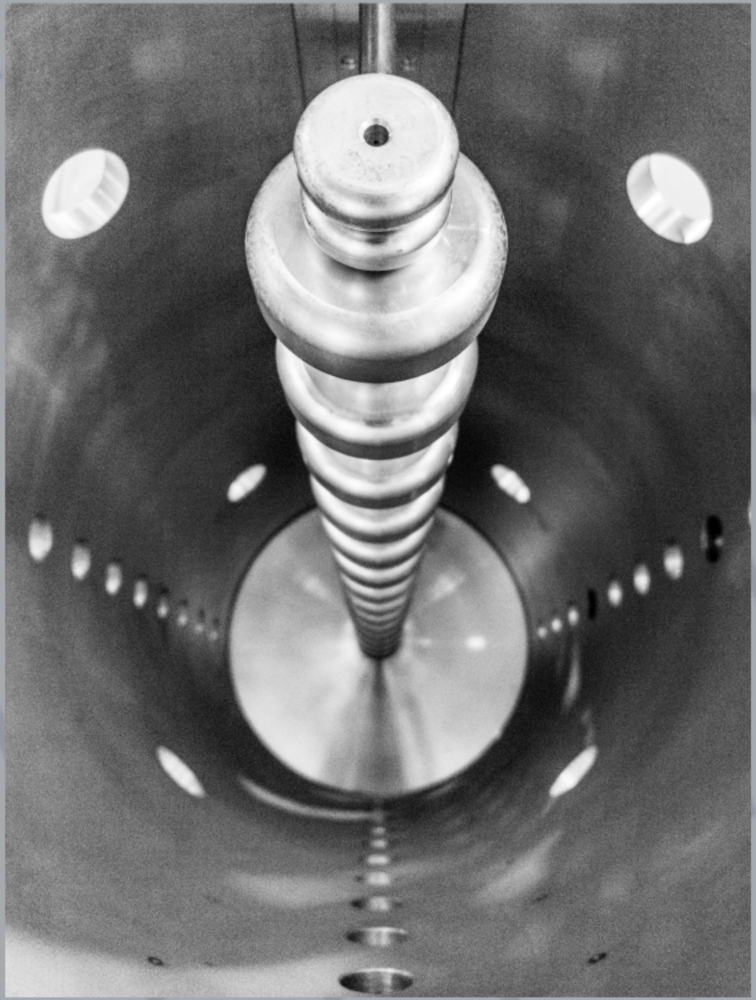
A few types of LINACs



LINAC2 at CERN

LEBT RFQ at SCK-CEN

A few types of LINACs

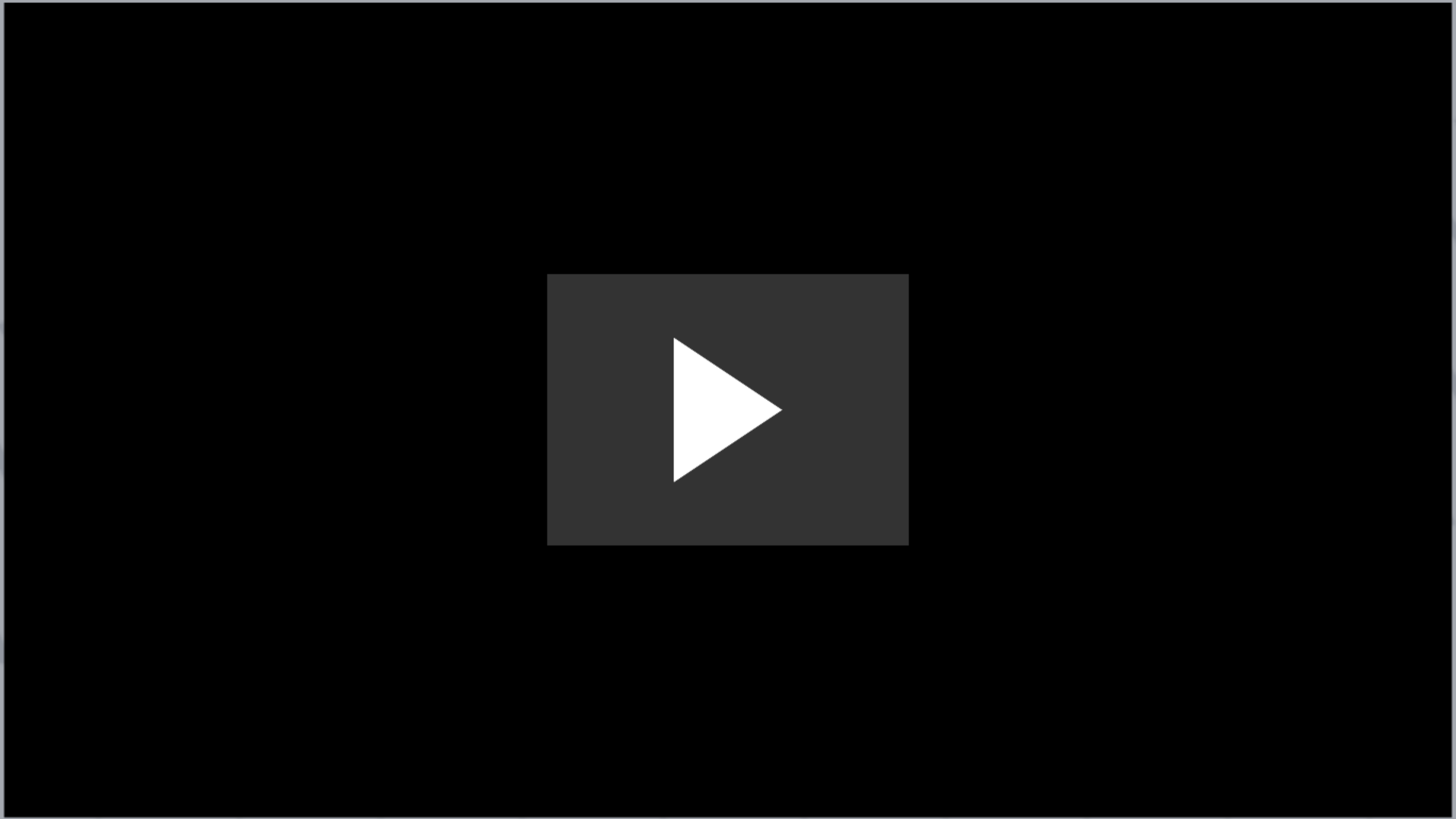


Drift Tube LINAC

XFEL at DESY

https://www.xfel.eu/sites/sites_custom/site_xfel/content/e35165/e35166/e50702/2016-11-14_001_1020x380_eng.jpg

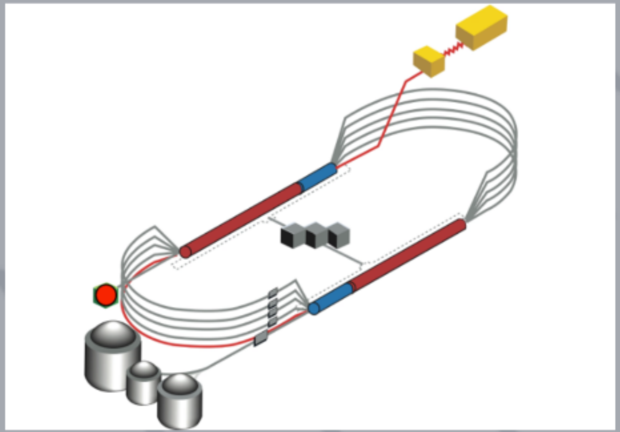
A few types of LINACs



Compact Linear Collider

https://videos.cern.ch/record/2688462

And of course!



JLab's Recirculating LINAC

A few more points

LINAC optics are NOT designed to meet a periodic condition which allows the beam to recirculate many times, but rather meet other specific needs

LINACs tend to be great for high-energy electrons, since they minimize synchrotron radiation

  However, they're inefficient for heavier, relativistic particles

The so-called Twiss Parameters are mathematically identical to those of rings, but represent the beam itself, rather than being defined by the lattice

Some of the basics

There are *lots* of other types, and lots of important details, but we'll stick to the basics here.

Rings

LINACs

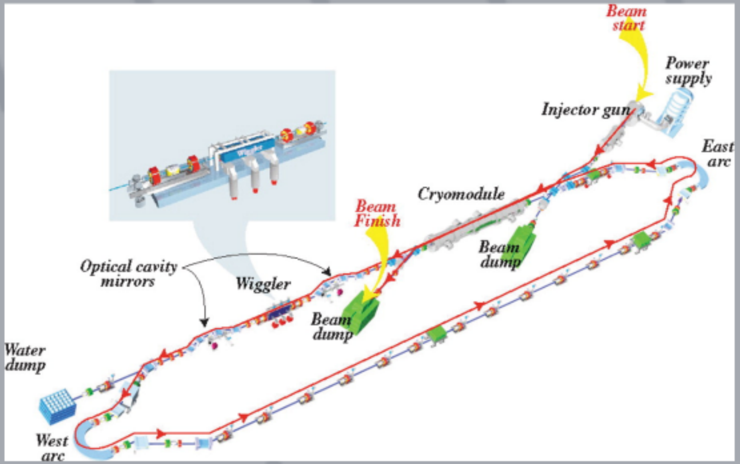
A few more...

There are MANY more types

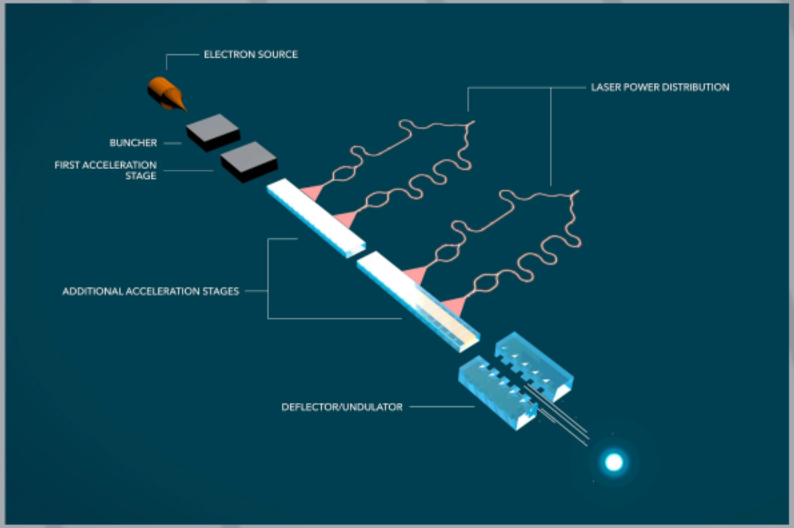
- Mainly, they're either ring, LINAC, or hybrid based
- Newer technology is looking into shrinking accelerators:
    - Plasma Wakefield
    - Dielectric
    - Drive beams
    - Energy Recovery LINACs
    - etc...

Type of acceleration	Experiments
Laser wakefield acceleration	BELLA, TREX, CLF, LUX
Plasma wakefield acceleration using electrons	FACET, FACET II, DESY FLASHForward
Plasma wakefield acceleration using positrons	FACET, FACET II
Plasma wakefield acceleration using protons	AWAKE

https://www.symmetrymagazine.org/article/the-potential-of-plasma-wakefield-acceleration



https://doi.org/10.1146/annurev.nucl.53.041002.110456

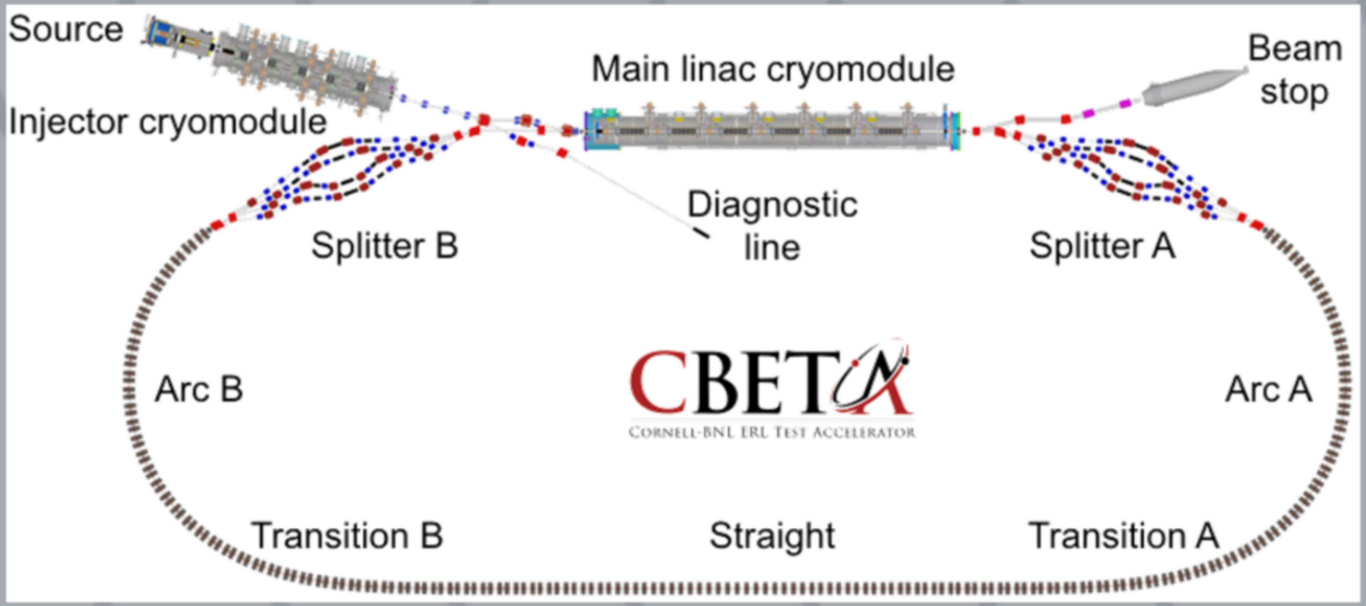


https://achip.stanford.edu/research-highlights

But we MUST mention FFAs

- FFA = **F**ixed **F**ield **A**lternating gradient accelerator
    - Uses fixed magnetic fields (or permanent magnets)
    - Alternating magnets have opposite bending fields
- Allows for multiple passes in same arc
- PMs mean no power draw

This is what we want for 22 GeV!



https://www.bnl.gov/newsroom/news.php?a=216719

Some of the basics

There are *lots* of other types, and lots of important details, but we'll stick to the basics here.

Rings

LINACs

A few more...

The CEBAF Accelerator from 12 to 22 GeV

Ryan Bodenstein

Introductions

A Bit of History

Accelerator Applications

Types of Accelerators

12 GeV CEBAF

24 GeV CEBAF

Continuous Electron Beam Accelerator Facility - CEBAF at 12 GeV

Please note, some slides taken from or inspired by Dr. Yves Roblin.

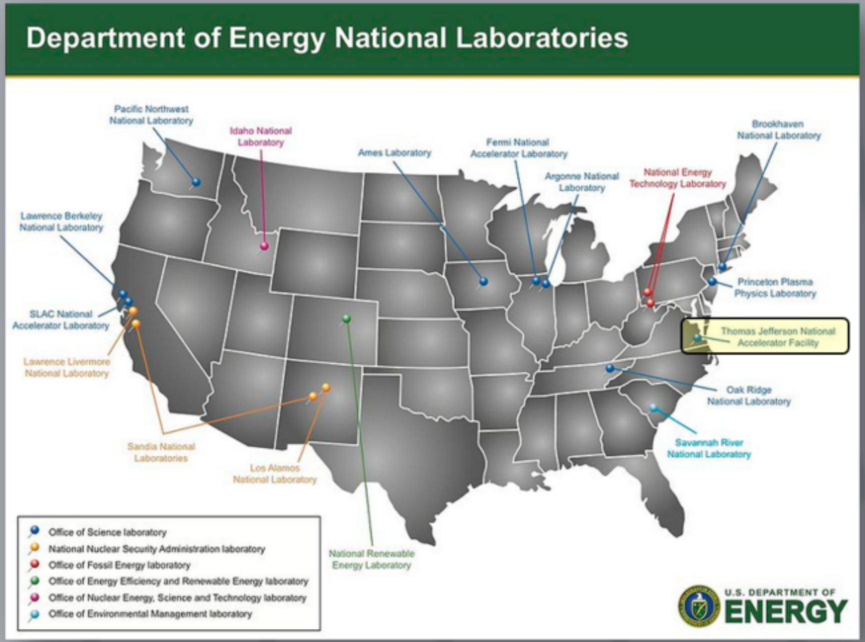
Overview

Injector & LINACs

Arcs & Extraction

Jefferson Lab Overview

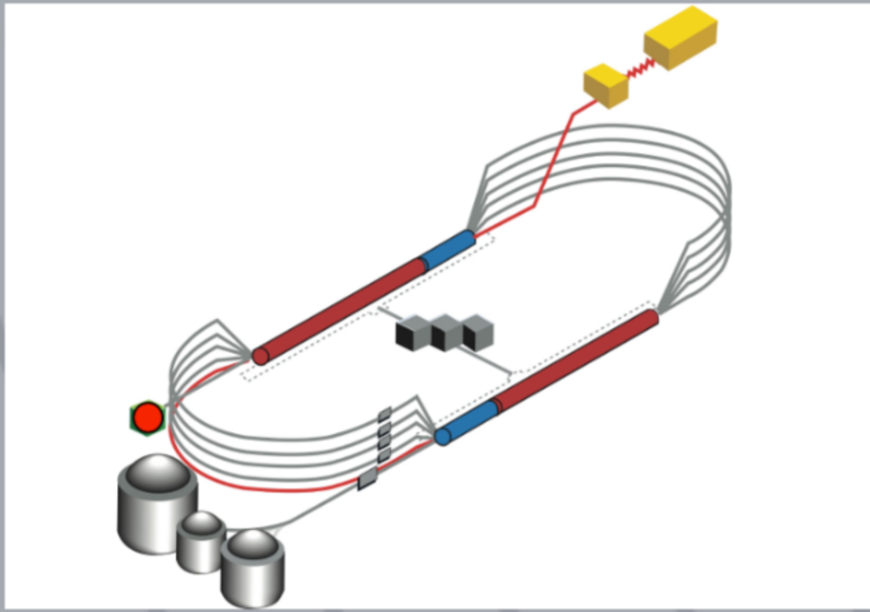
- 180 M$ annual operating budget
- 759 Full Time Employees
- >1600 Active Users
- Produces ~1/3 of US PhDs in Nuclear Physics
- 169 acres and 80 buildings and trailers

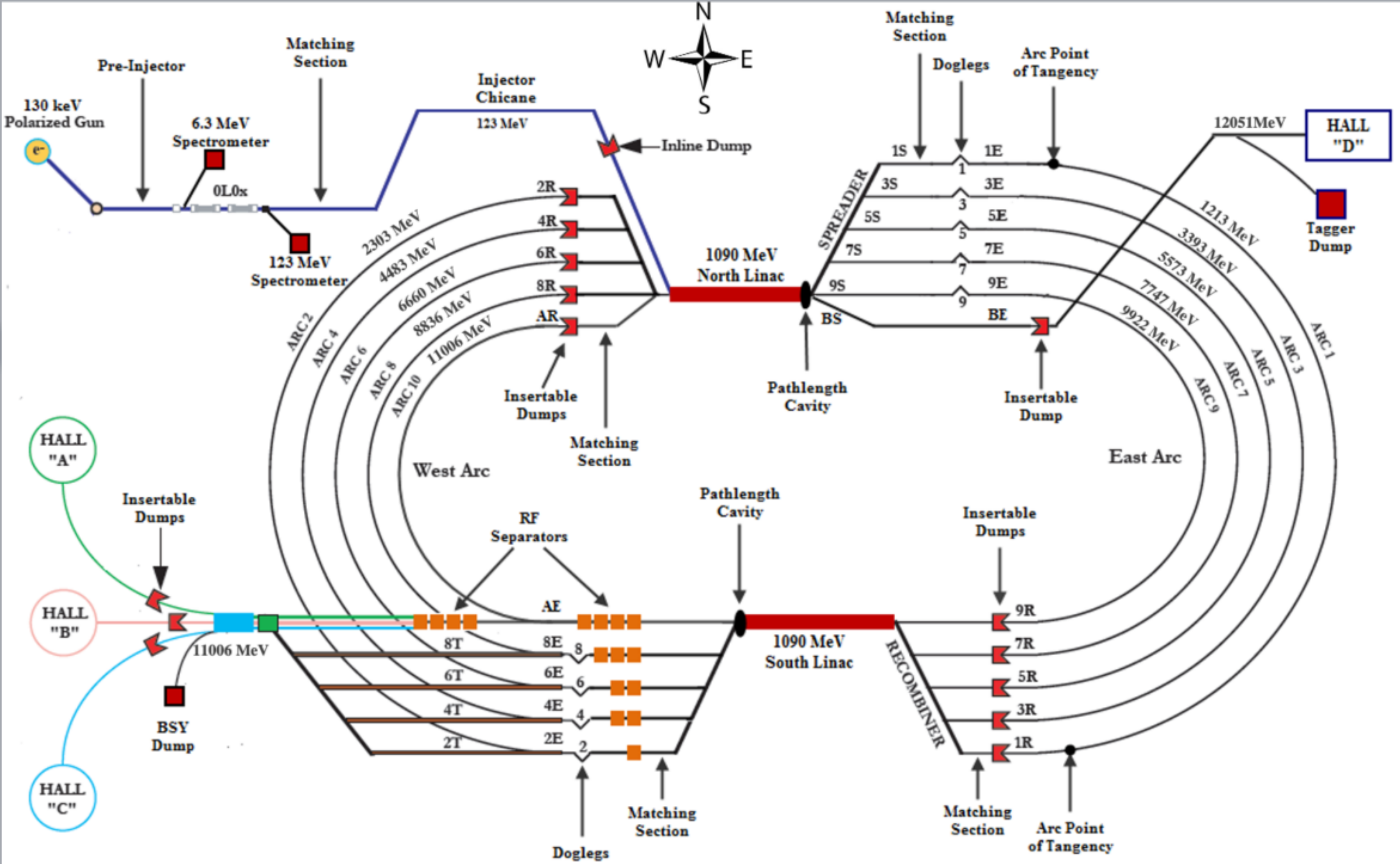


- **Core Competencies**
  - Nuclear Physics Research
  - SRF Technology Leadership
  - Polarized Electron Sources
  - Cryogenics Research and Development
  - Accelerator Physics and Diagnostics Development

Slide from Y. Roblin

Jefferson Lab Overview





Slide from Y. Roblin

Continuous Electron Beam Accelerator Facility - CEBAF at 12 GeV

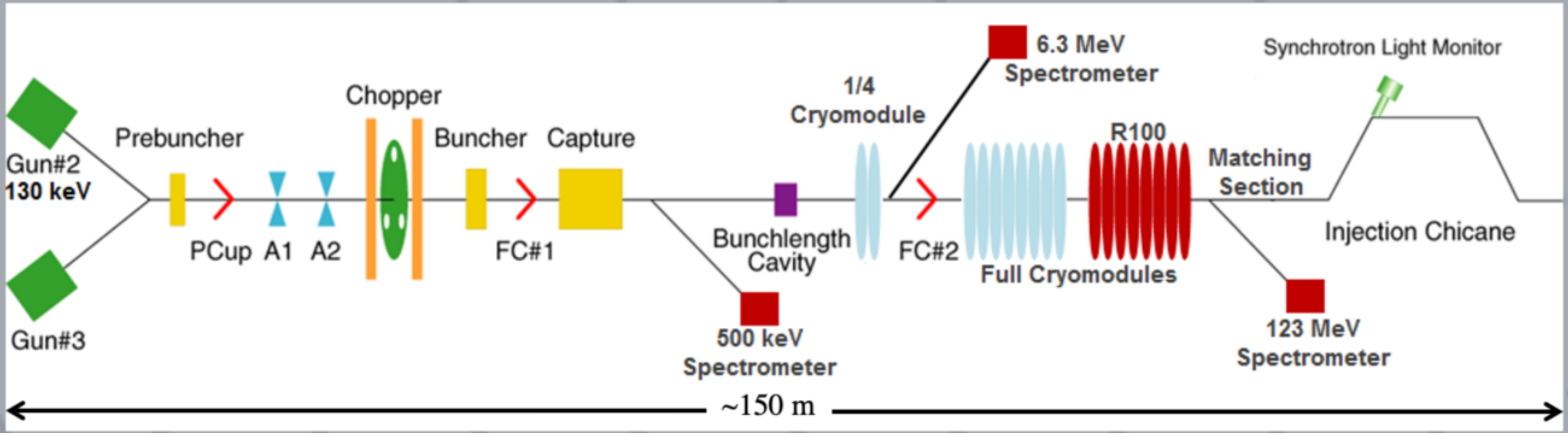
Please note, some slides taken from or inspired by Dr. Yves Roblin.

Overview

Injector & LINACs

Arcs & Extraction

The Injector

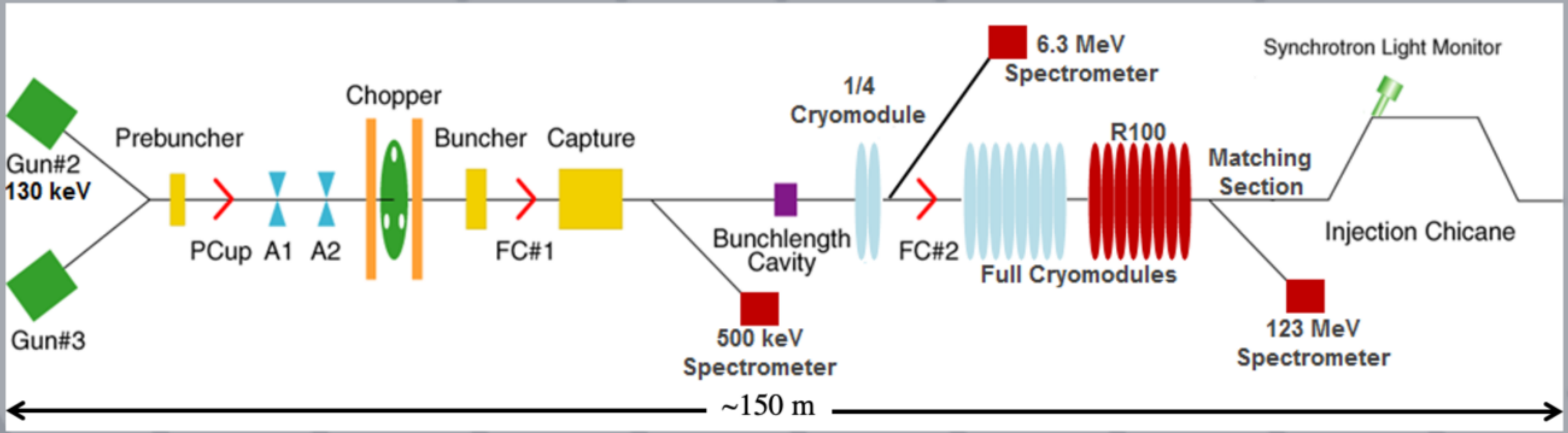


- Source provides ~90% polarized electrons with variable bunch charge
- Interleaved micro-bunch structure at 499 MHz or 249.5 MHz depending on physics program
- Bunching cavities to control longitudinal size of beam
- Faraday cups to measure beam current
- Aperture A1 and A2 to collimate the beam and minimize transverse phase space extent
- Chopper system to independently control beam intensity for each experiment
- Capture RF system to transition to relativistic energy
- 18 SRF cavities accelerate beam to 123 MeV beam for injection into the North Linac
- Spectrometers to measure energy of the electron beam

Slide from Y. Roblin

The Injector

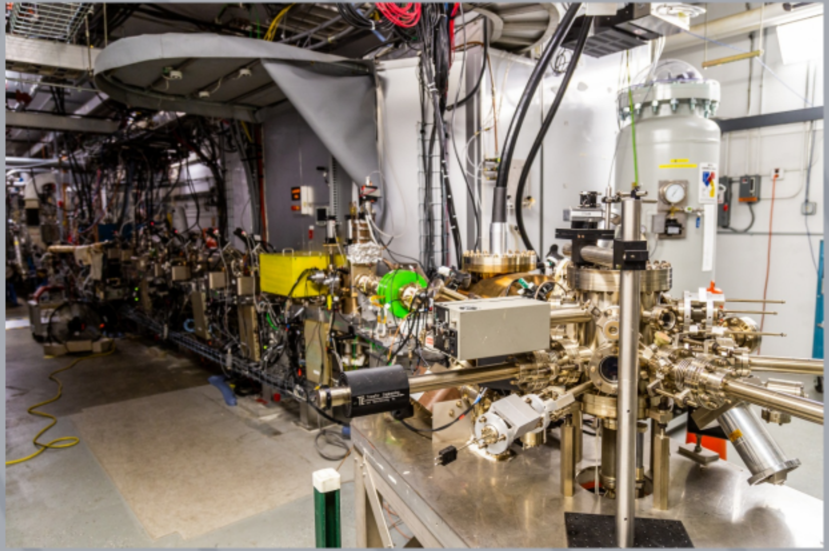
This *was* the injector
Replacing 1/4 cryo
Upgrade gun
Upgrade components

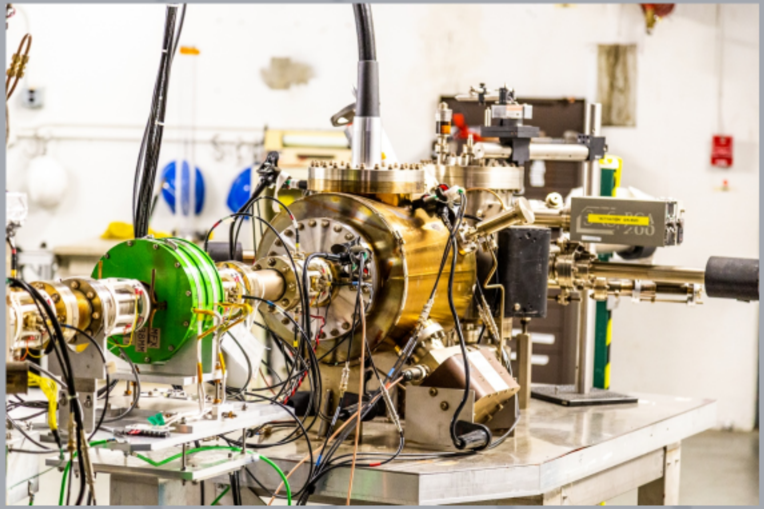


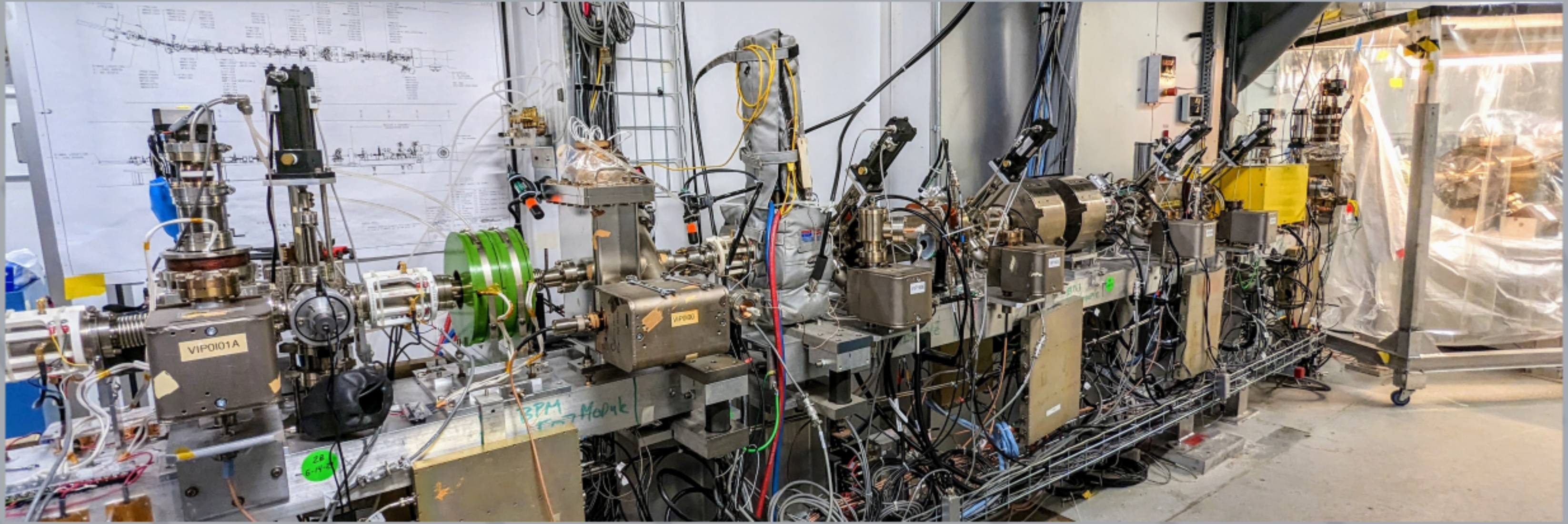
- Source provides ~90% polarized electrons with variable bunch charge
- Interleaved micro-bunch structure at 499 MHz or 249.5 MHz depending on physics program
- Bunching cavities to control longitudinal size of beam
- Faraday cups to measure beam current
- Aperture A1 and A2 to collimate the beam and minimize transverse phase space extent
- Chopper system to independently control beam intensity for each experiment
- Capture RF system to transition to relativistic energy
- 18 SRF cavities accelerate beam to 123 MeV beam for injection into the North Linac
- Spectrometers to measure energy of the electron beam

Slide from Y. Roblin

The Injector

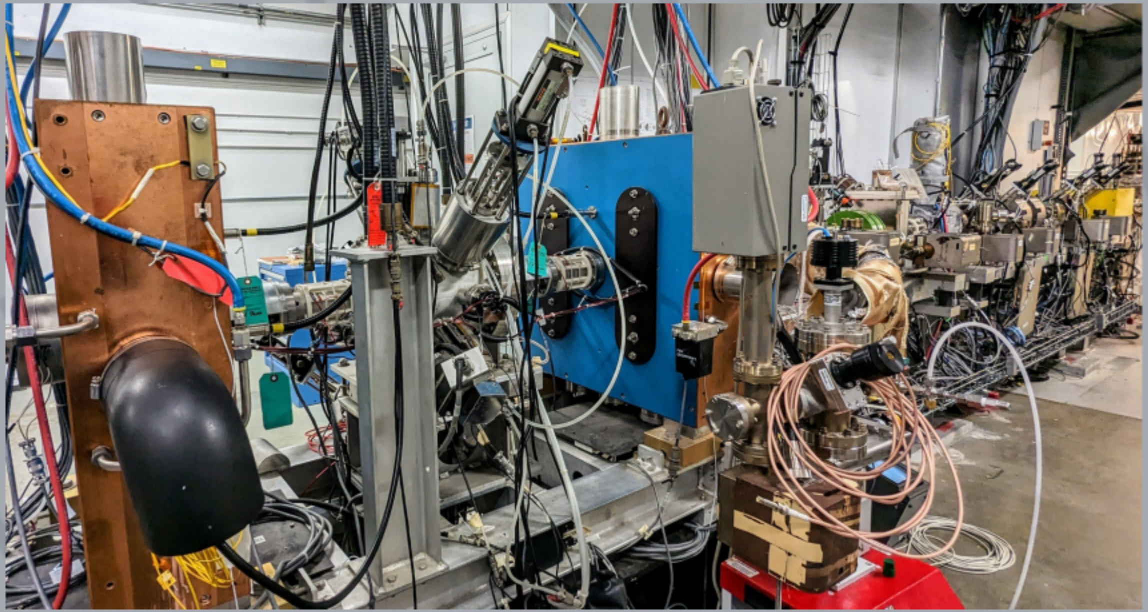


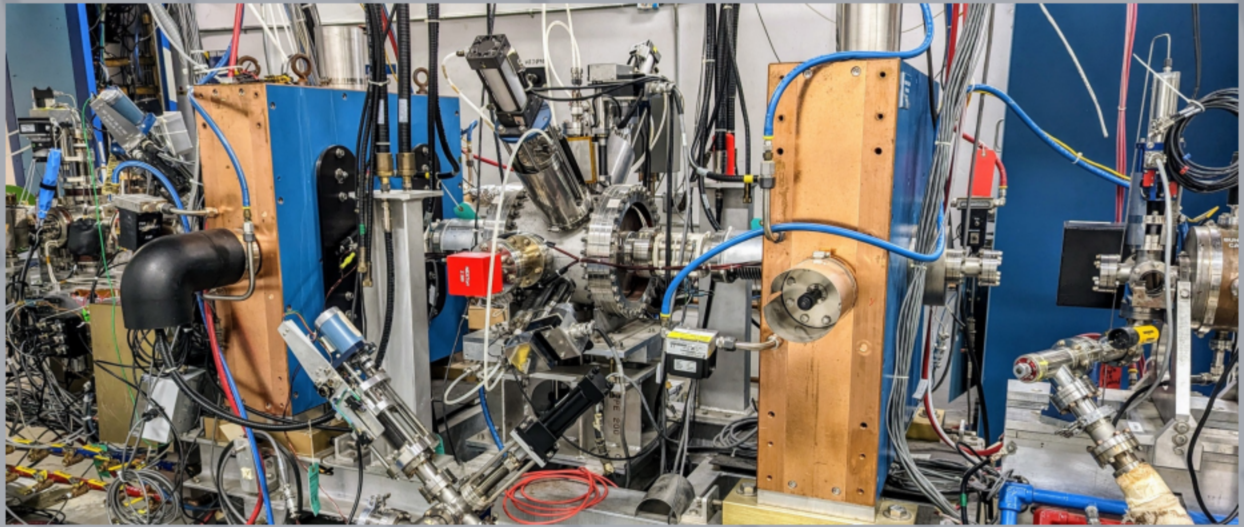




Four laser pulses come from the room labeled with the laser sign. They travel to the chamber, striking a target and giving off electrons. The electrons then travel up to the Wien filters and solenoids, which give 4π control over polarization.

The Injector - THE CHOPPER!





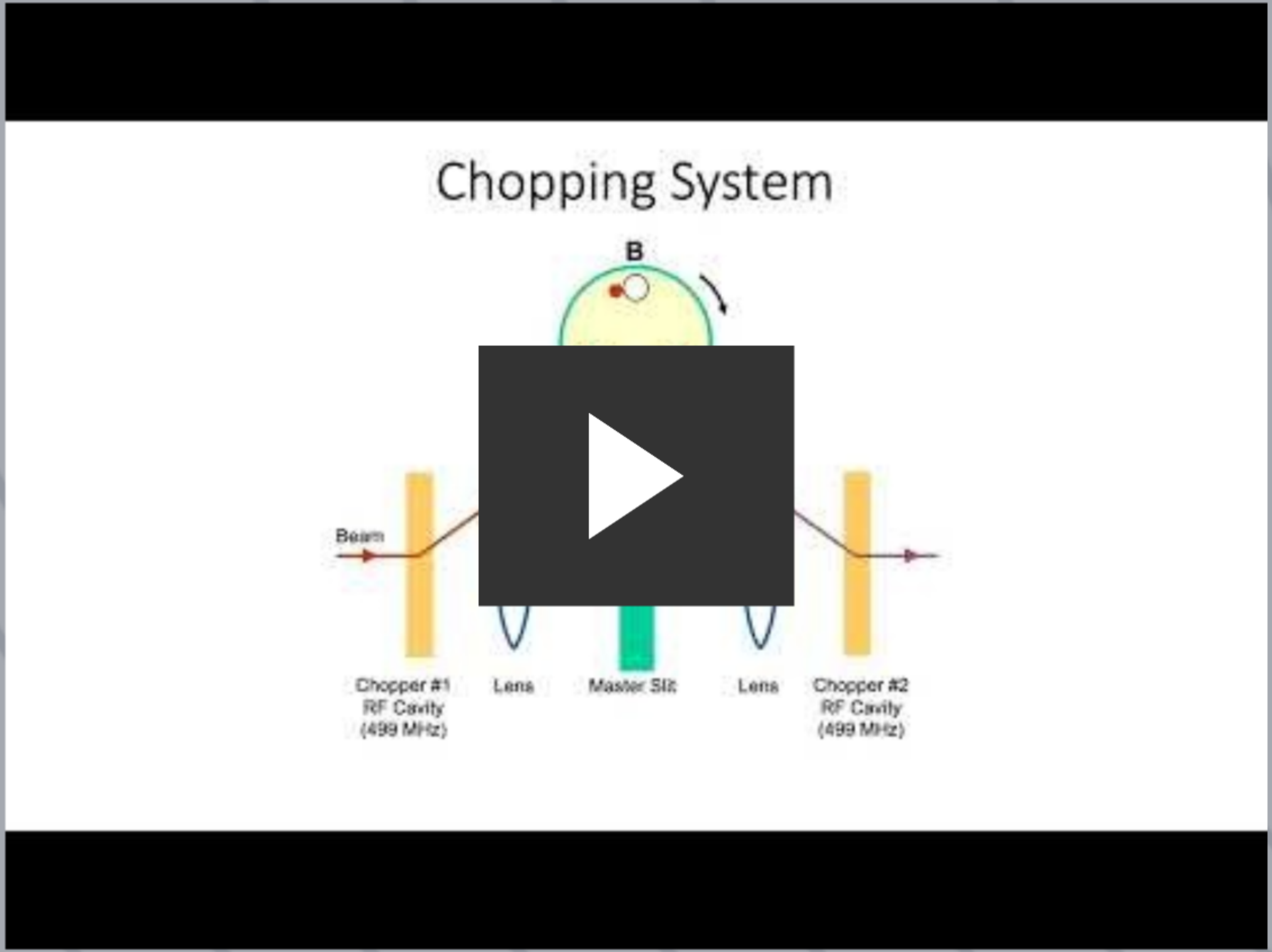
Beam Direction

Beam Direction

From there, the beam passes through some optics, a buncher cavity, diagnostics, and into THE CHOPPER. Interestingly, we have 4 experimental halls, but only 3 slits in the chopper. If all 4 are running, two have to share!

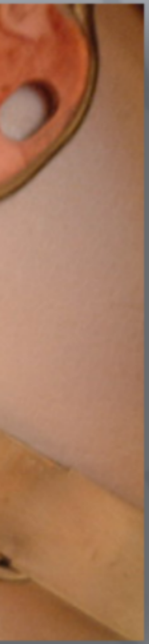
The Injector

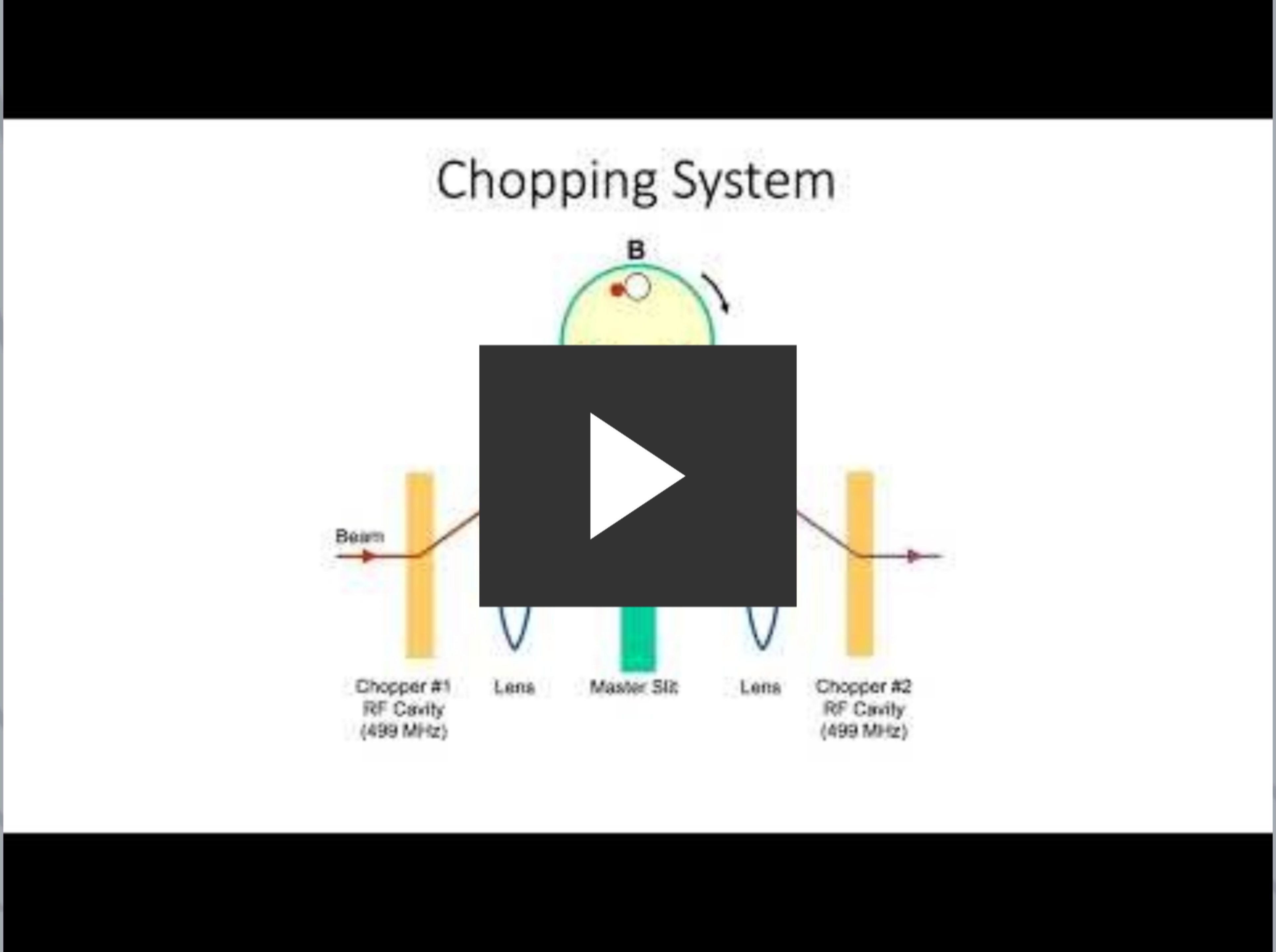
- This video shows the basics



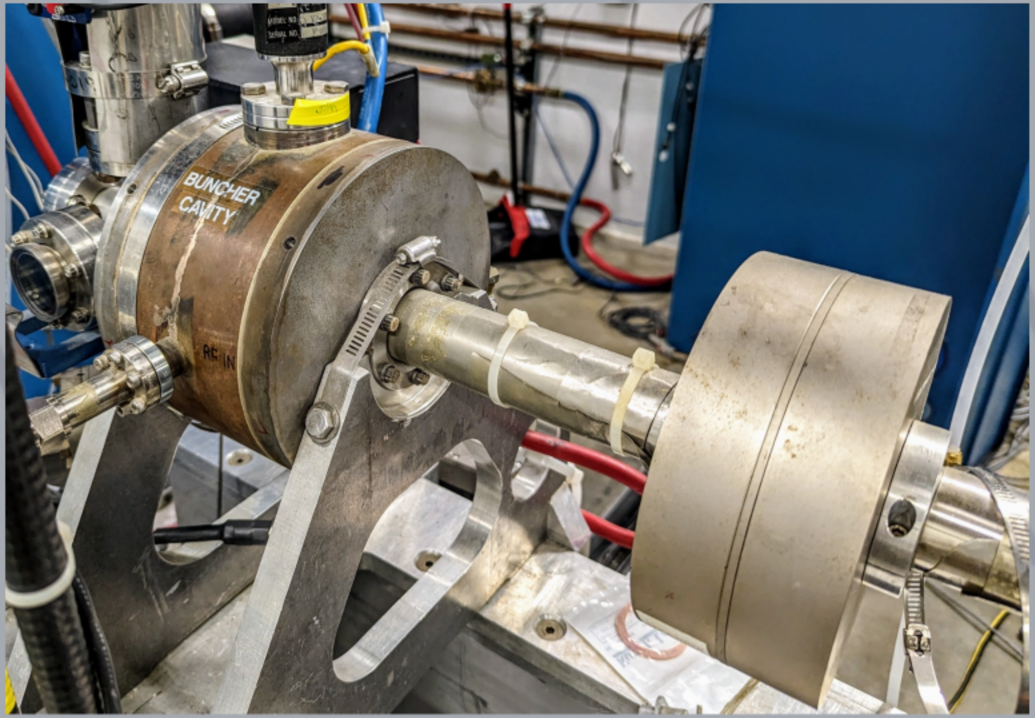
Slide from Y. Roblin

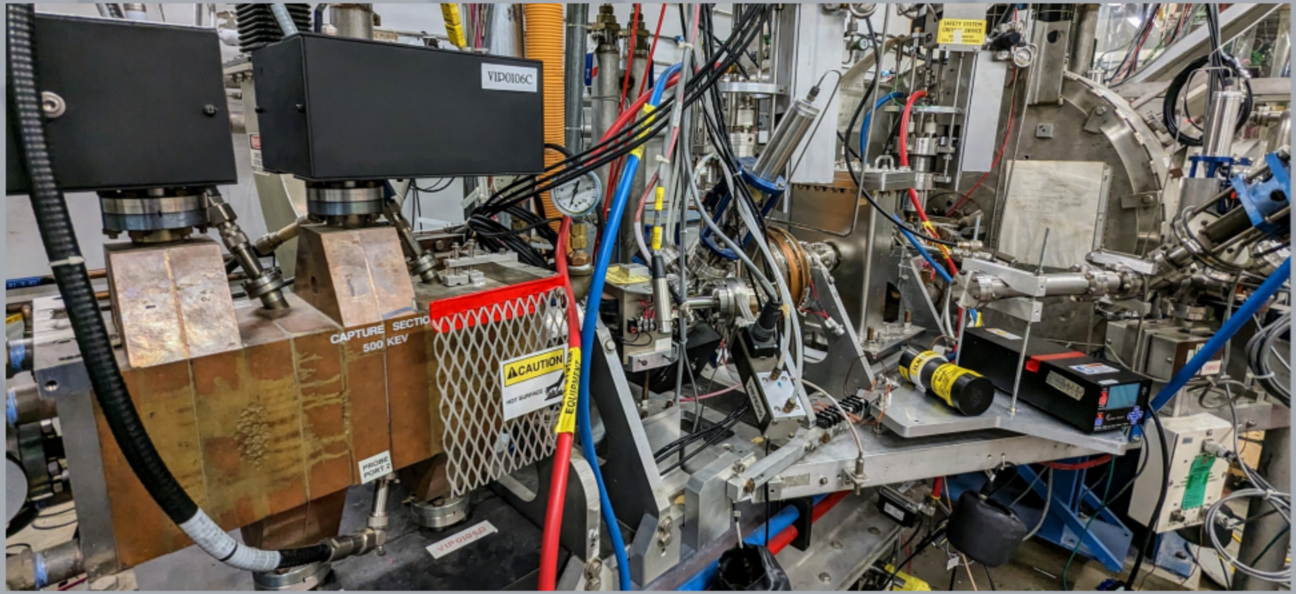
asics




Chopping System
B
Beam
Chopper #1
RF Cavity
(499 MHz)
Lens
Master Slit
Lens
Chopper #2
RF Cavity
(499 MHz)

The Injector



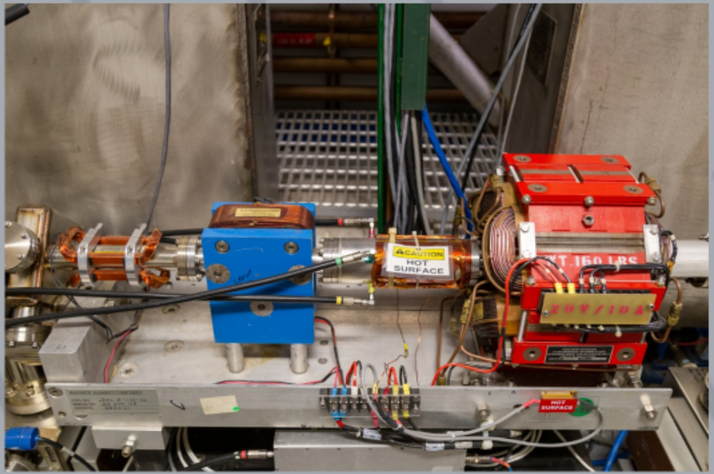


Beam Direction

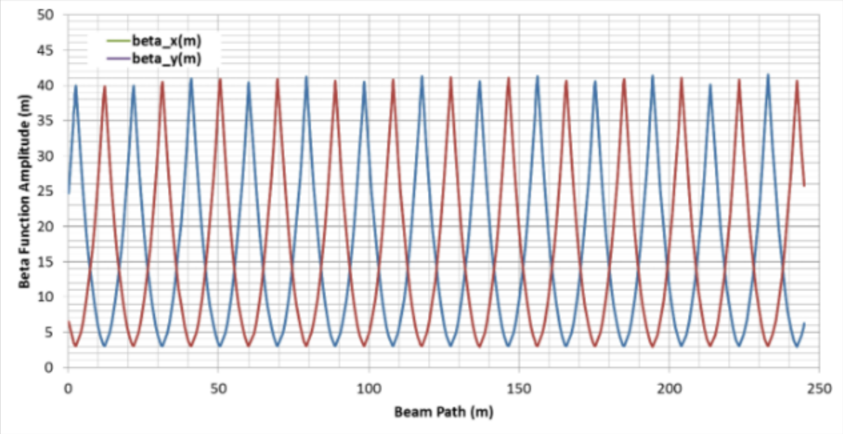
Beam Direction

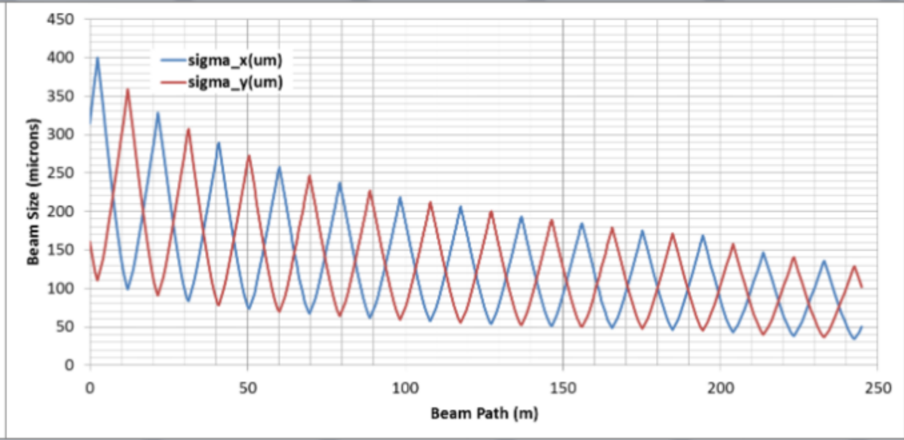
After the chopper, it's another buncher, and a small 500 keV cavity to up the energy a bit. Then diagnostics and a quarter cryomodule. This is currently being upgraded: farewell to the capture section - it's all in the new module!

The LINACs



- North and South Linac Optics:
  - 9.6 m FODO channel with cryomodules between quadrupoles.
  - Beam injected with large spot size and damps as the beam is accelerated.
  - Skew quads in lattice around C20 and C50 cryomodules to correct for skew moment in cavity fields.
  - C100s have no skew moment.
  - Designed to provide 1090 MeV for a 12 GeV CEBAF



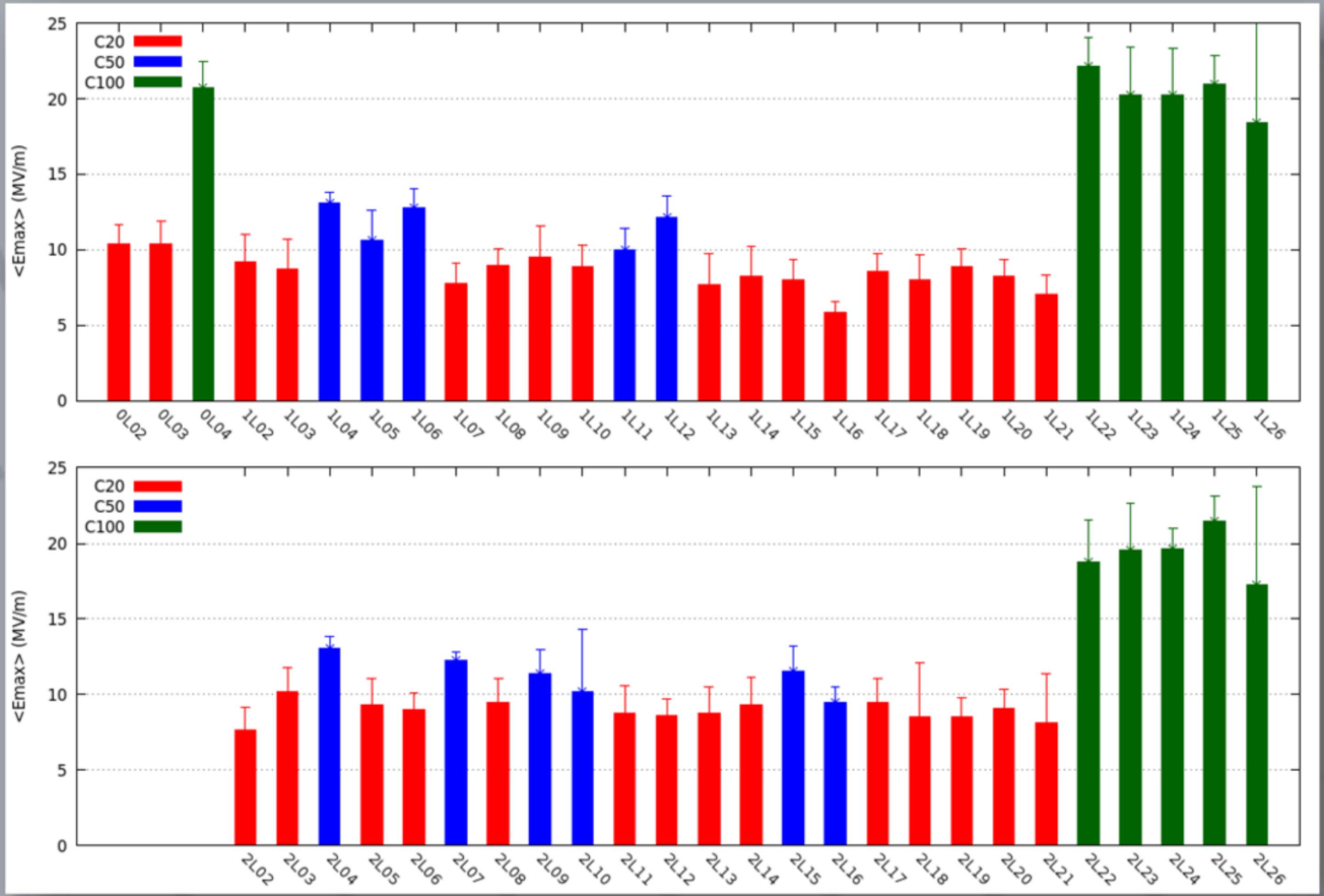


Slide from Y. Roblin

The LINACs

Average Cavity Gradient

- There are 418 SRF cavities in CEBAF



Slide from Y. Roblin

Continuous Electron Beam Accelerator Facility - CEBAF at 12 GeV

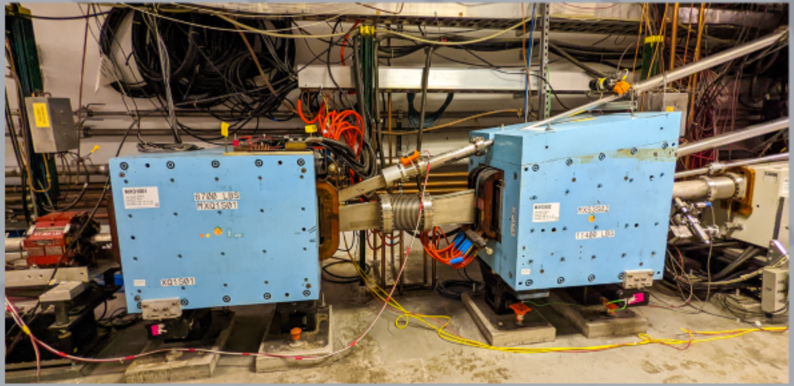
Please note, some slides taken from or inspired by Dr. Yves Roblin.

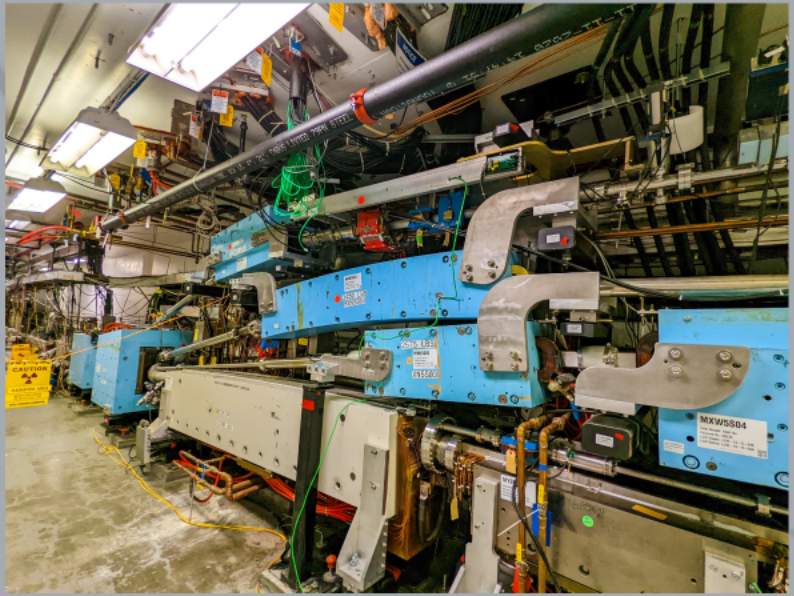
Overview

Injector & LINACs

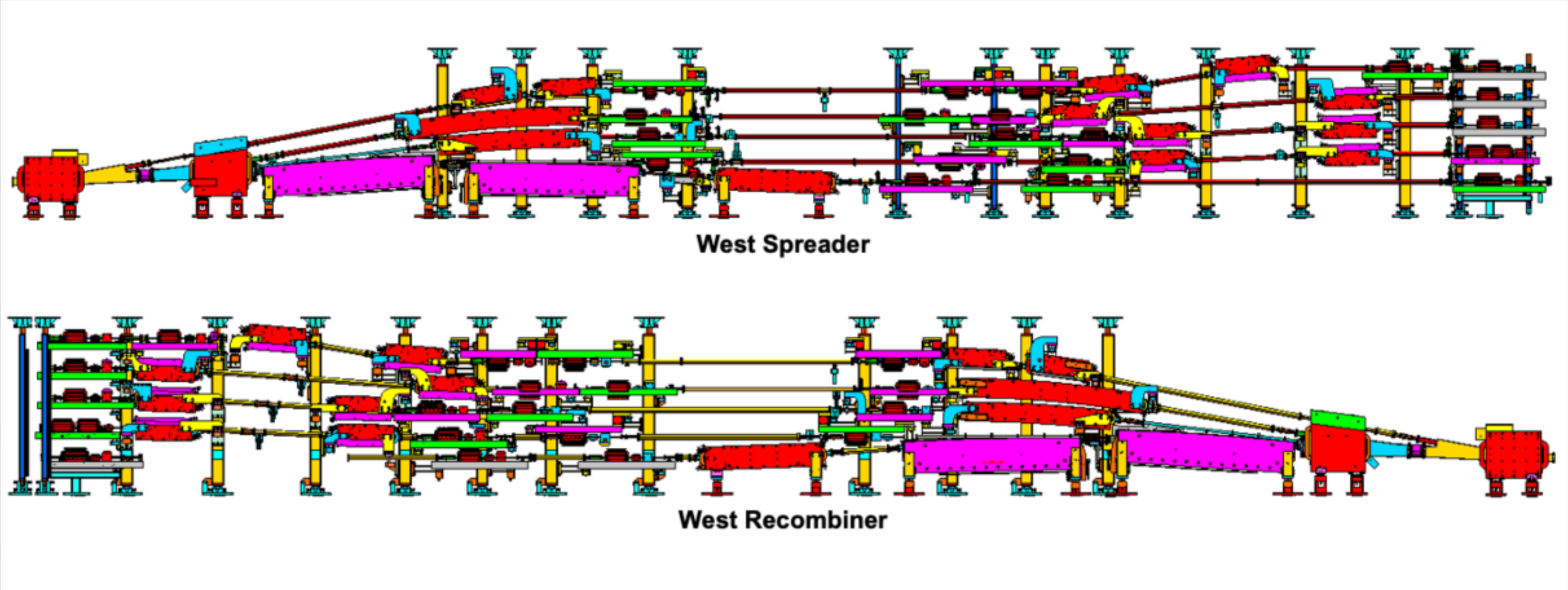
Arcs & Extraction

Spreaders and Recombiners





- Spreader/Recombiner layout:
  - Vertically achromatic system designed to accept broad range of multi-pass input parameters for recirculation transport.
  - Final step heights in ½ meter increments above lowest pass.
  - Quads in step control the vertical dispersion.
  - Recombiner is mirror-symmetric to the Spreader.

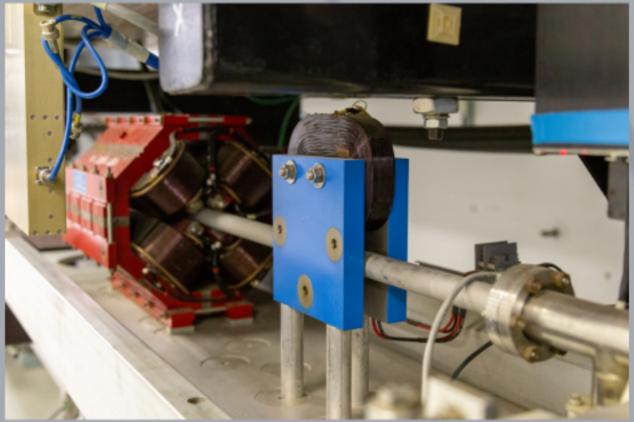


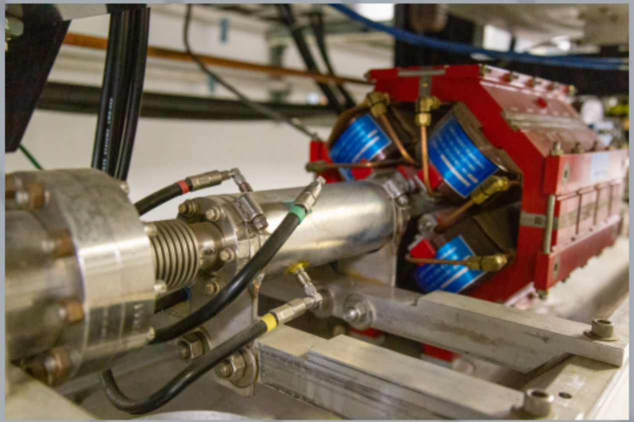
Slide from Y. Roblin

Recirculation Arcs

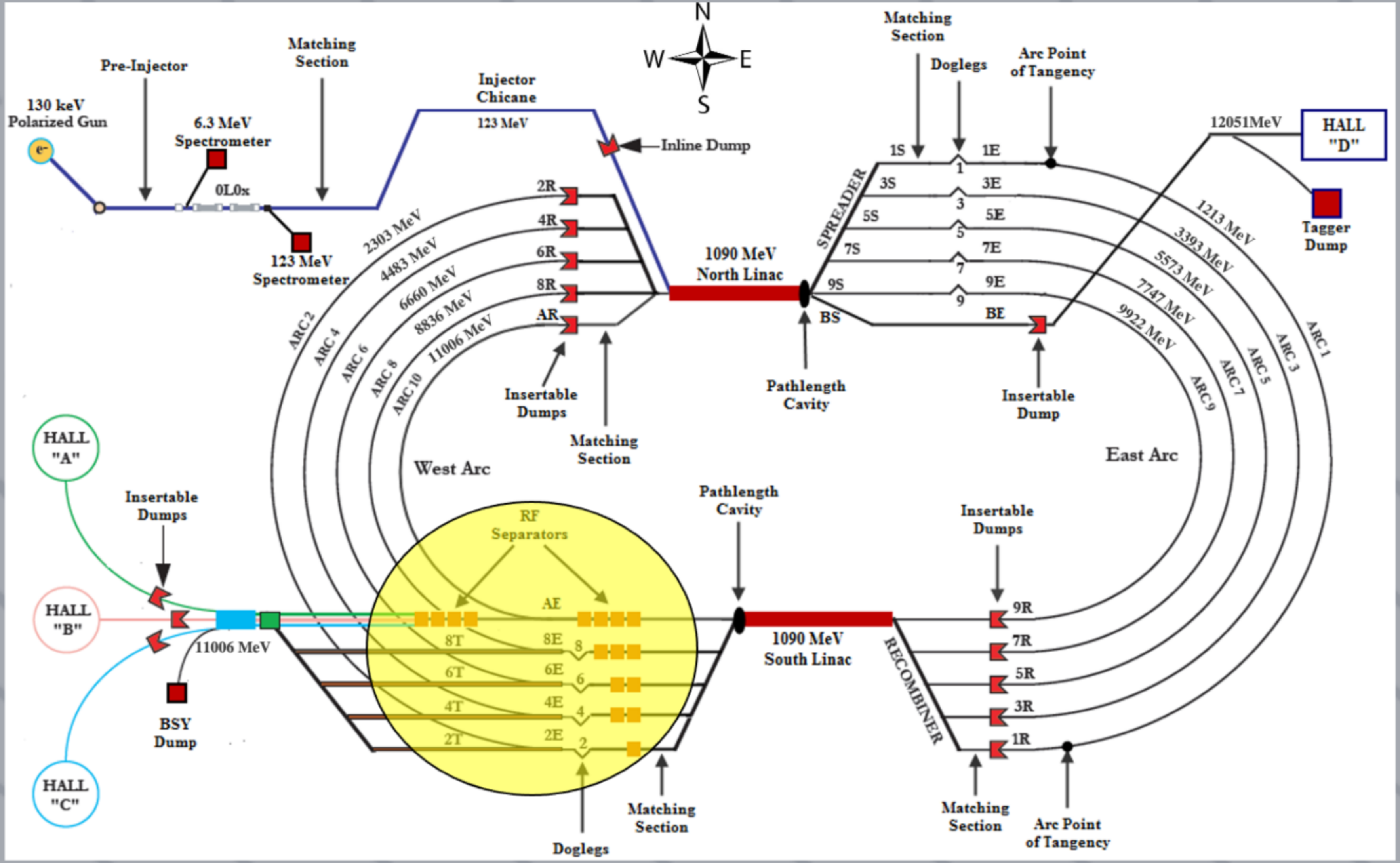
- Arc layout:
  - Sixteen dipoles for Arc 1 and Arc 2 and thirty-two dipoles for Arc 3-10.
  - The recirculating Pi bends are at a radius of 80 m.
  - Each Arc has 32 quadrupole girders grouped in 4 families to control achromaticity, momentum compaction and the betatron tune.
  - Beam Position Monitors at the entrance of quadrupoles.
  - Horizontal and vertical correctors throughout to control the beam orbit.

Slide from Y. Roblin





Extraction

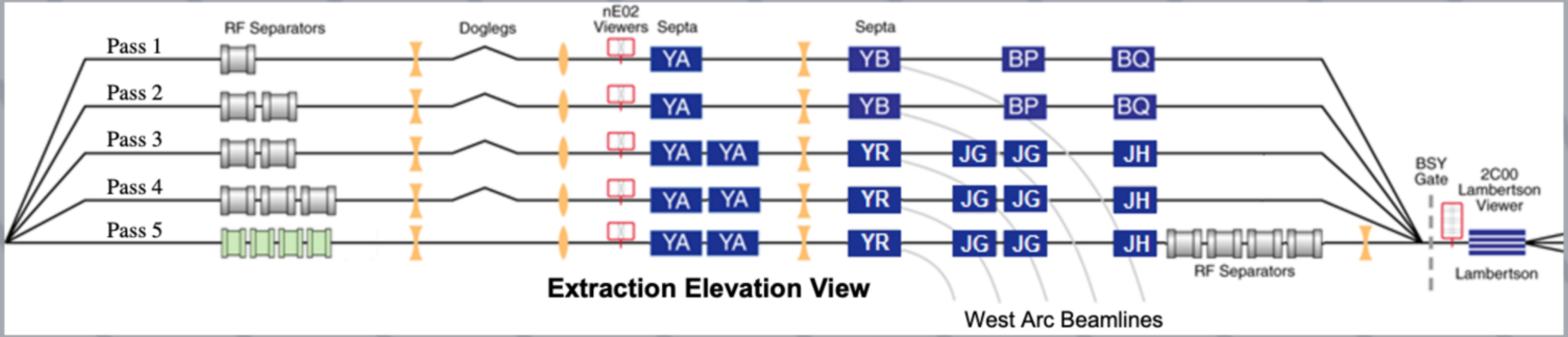


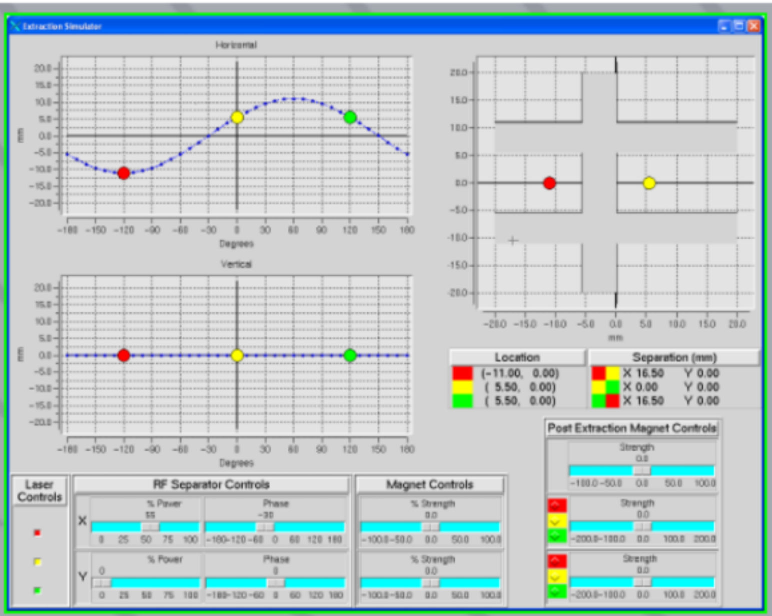
Slide from Y. Roblin

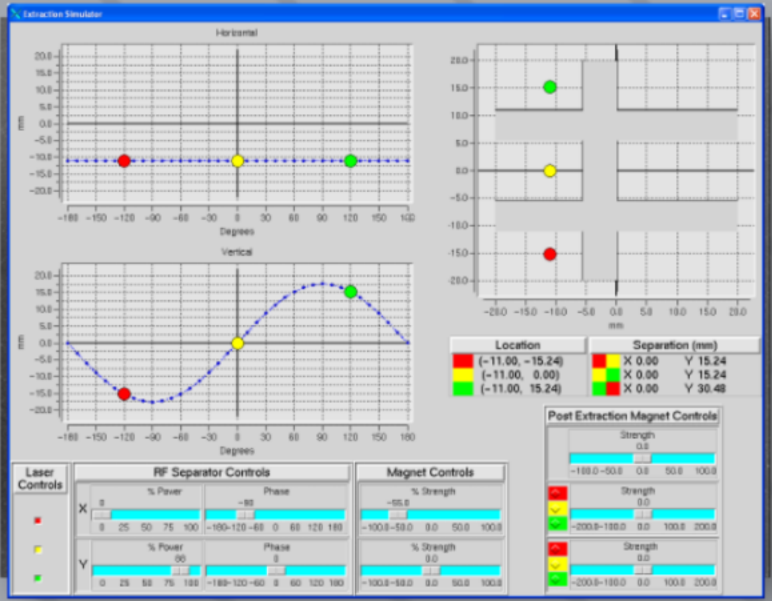
Extraction System

Overall configuration:

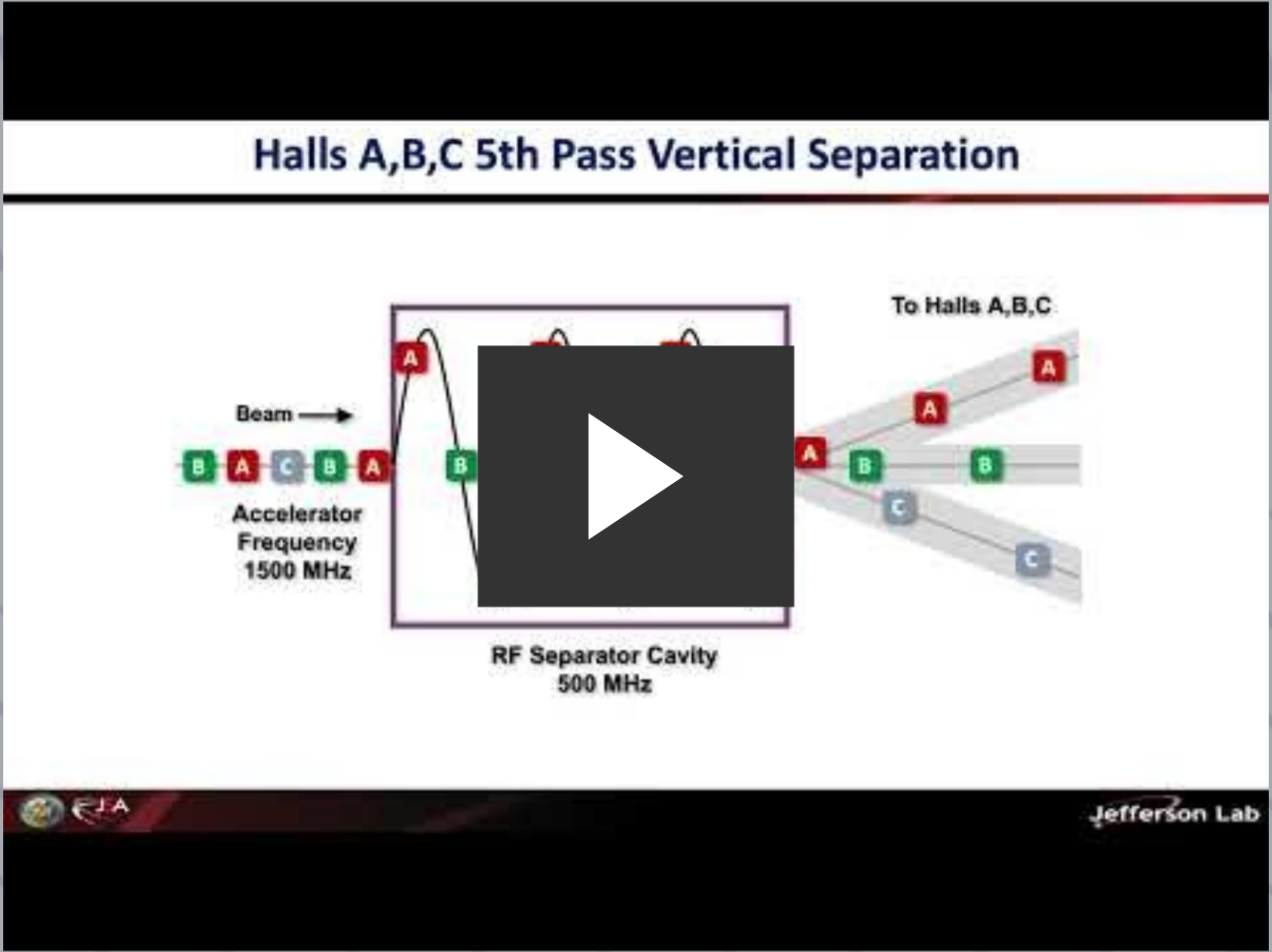
- Horizontal extraction systems at 500 MHz for 1st through 4th pass
- Vertical extraction system at 500 MHz for 5th pass
- New horizontal extraction system at 750 MHz for 5th pass





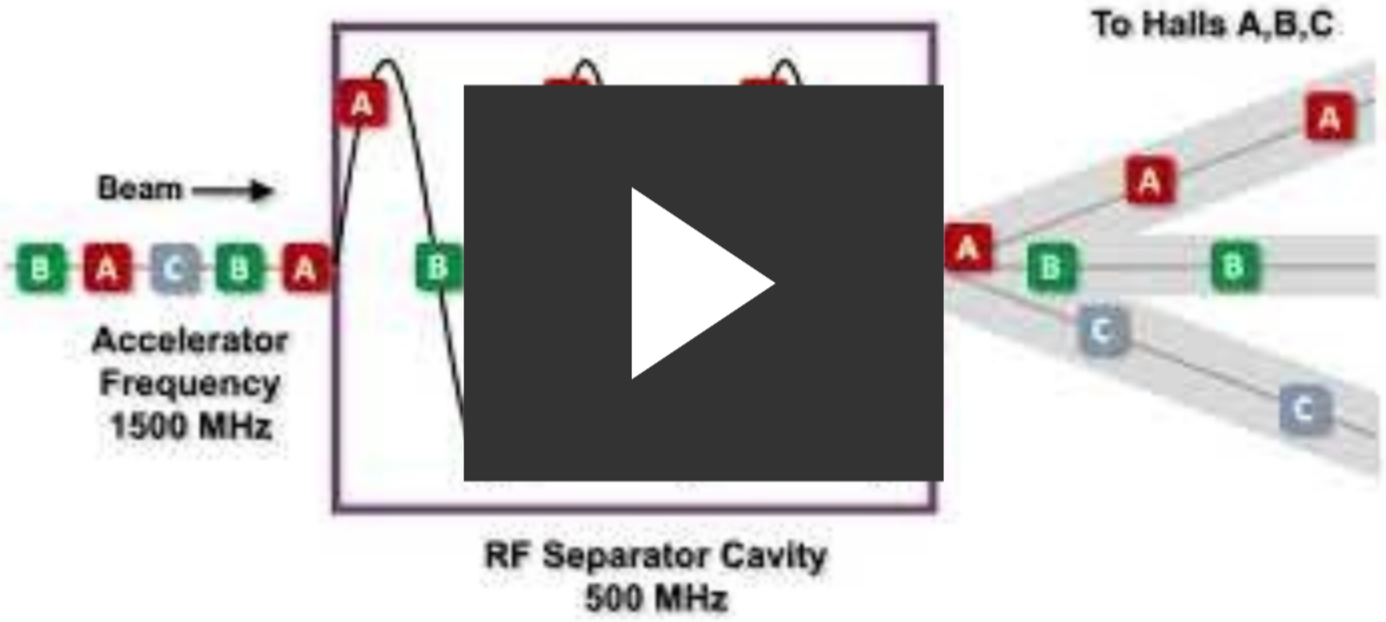


Slide from Y. Roblin



Slide from Y. Roblin

Halls A,B,C 5th Pass Vertical Separation

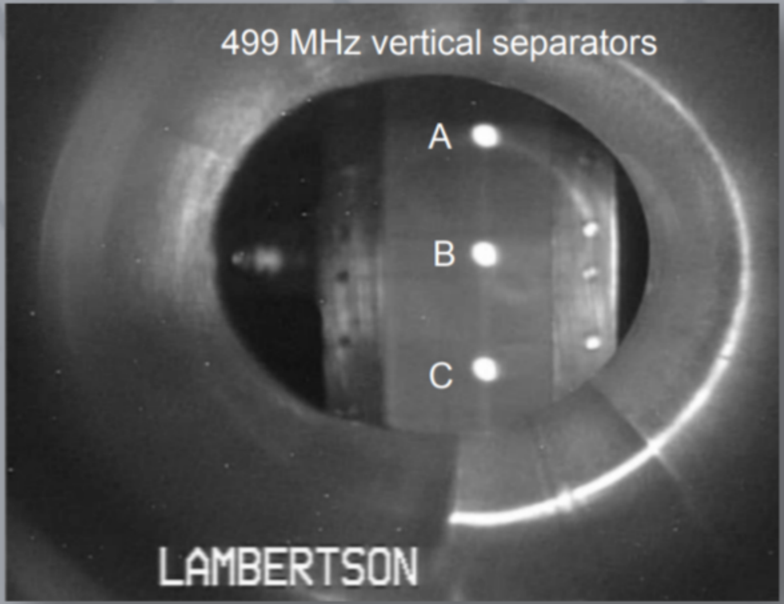


Extraction

Simultaneous Four-Hall Capability

- 5^{th} Pass Horizontal Extraction at 750 MHz with three beams left and one beam right
- 5^{th} Pass Vertical Extraction at 500 MHz showing A, B, C beams

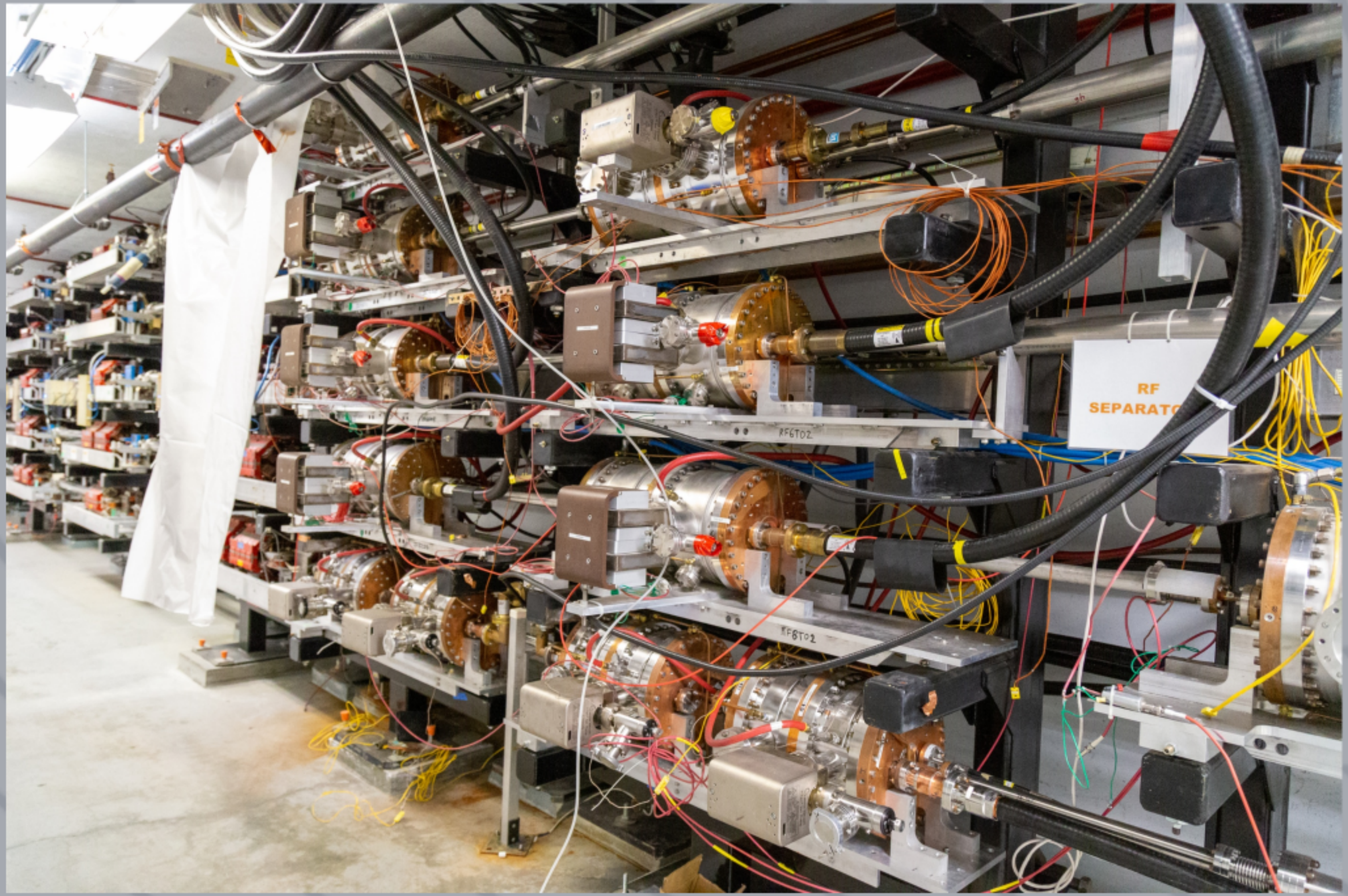
Viewer at Entrance of Extraction Septum

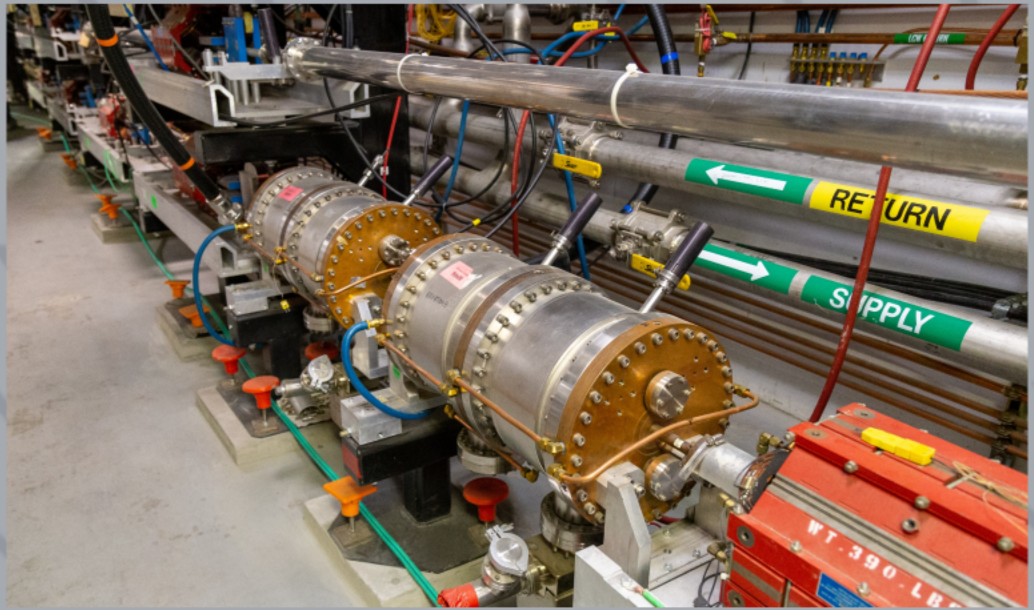


Viewer at Entrance of Beam Switchyard

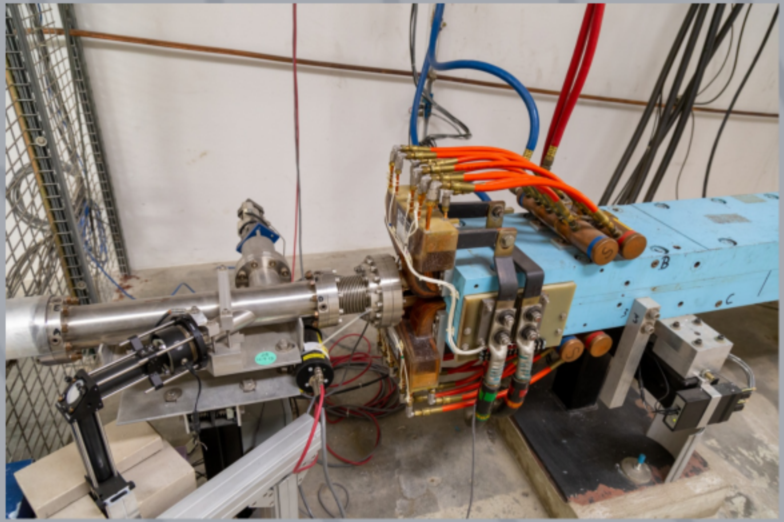
Slide from Y. Roblin

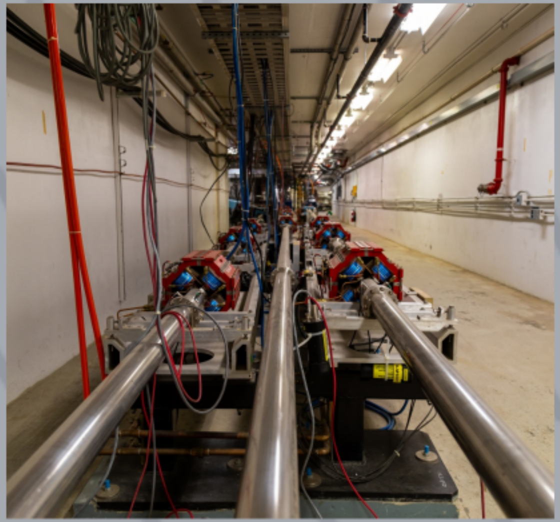
Extraction





To the Halls!






To the Halls! (Even Hall D)

Continuous Electron Beam Accelerator Facility - CEBAF at 12 GeV

Please note, some slides taken from or inspired by Dr. Yves Roblin.

Overview

Injector & LINACs

Arcs & Extraction

The CEBAF Accelerator from 12 to 22 GeV

Ryan Bodenstein

Introductions

A Bit of History

Accelerator Applications

Types of Accelerators

12 GeV CEBAF

24 GeV CEBAF

Upgrading to 22 GeV

Images and slides in this section are often taken from the work of our collaboration.

Motivation

Current Status

Challenges

Future

Jefferson Lab's Future

There's only about a decade or so left "in the queue" for experiments at the lab.

- Once these wrap up, we hope to run a positron program for a bit
- But after that, what is next for the lab?

Jefferson Lab's Future

- What if we increased the energy?
  - We could upgrade our LINACs and all the infrastructure
    - That's not cheap, nor "green"
  - What if we could use the current LINACs, but increase the number of passes?
    - No room in the recirculating arcs...

Jefferson Lab's Future

What if we increased the energy?

- We could upgrade our LINACs and all the infrastructure
  - That's not cheap, nor "green"
- What if we could use the current LINACs, but increase the number of passes?
  - No room in the recirculating arcs...

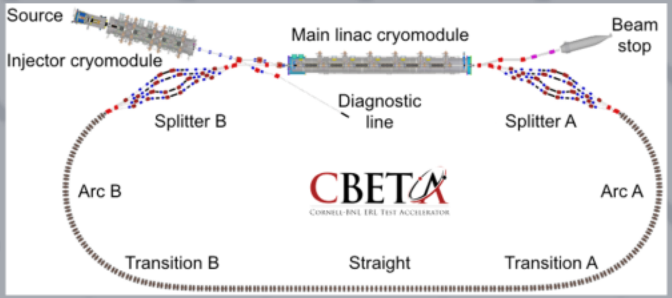
...or IS THERE?

Remember FFAs?

But we MUST mention FFAs

- FFA = **F**ixed **F**ield **A**lternating gradient accelerator
  - Uses fixed magnetic fields (or permanent magnets)
  - Alternating magnets have opposite bending fields
- Allows for multiple passes in same arc
- PMs mean no power draw

This is what we want for 22 GeV!



Remember FFAs?

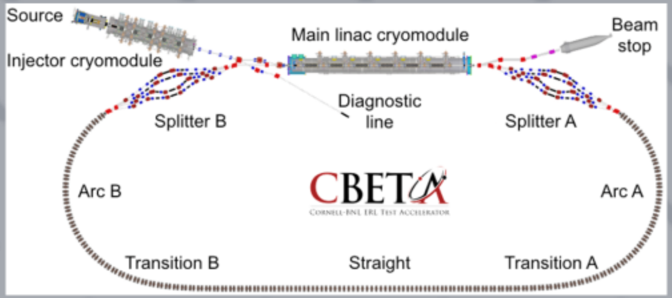
But we MUST mention FFAs

FFA = **F**ixed **F**ield **A**lternating gradient accelerator
- Uses fixed magnetic fields (or permanent magnets)
- Alternating magnets have opposite bending fields

Allows for multiple passes in same arc

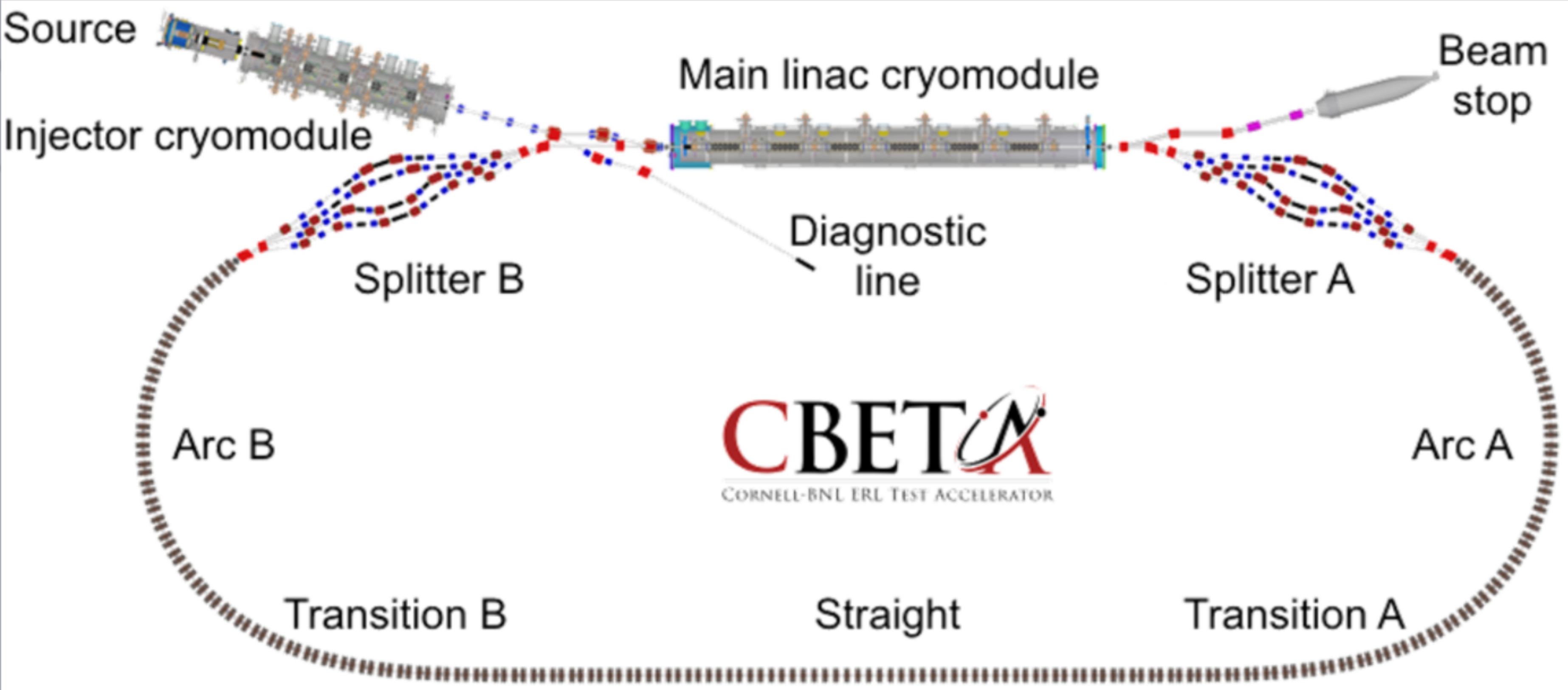
PMs mean no power draw

This is what we want for 22 GeV!



Allows for multiple passes in the same arc!

CBETA - An ERL FFA

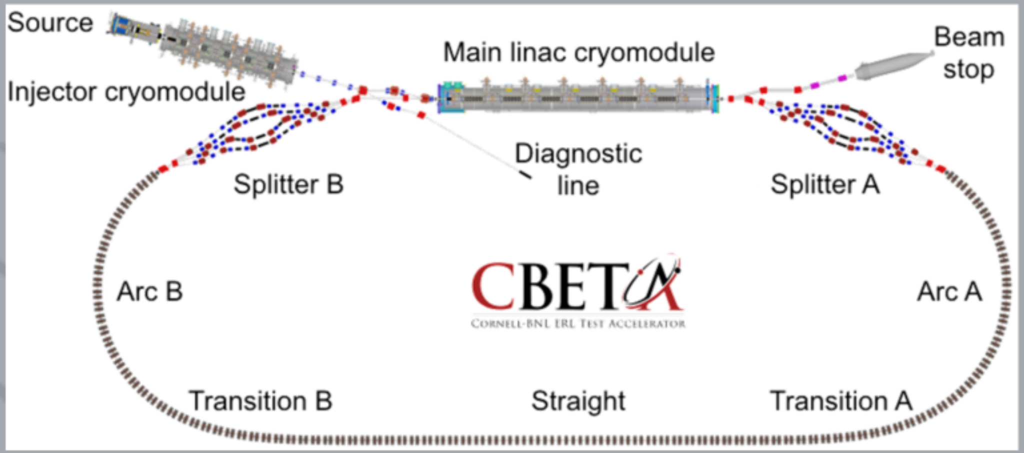


CBETA - An ERL FFA

Demonstrated muli-pass operation
- 4 acceleration
- 4 deceleration

Uses permanent magnets for arcs

1 mA, 150 MeV electron beam



Read all about it! https://wiki.classe.cornell.edu/pub/CBETA/WebHome/CBETA_final_report_revB-V3f.pdf

Can JLab use this technology?

Could we use permanent magnet FFA arcs to recirculate more times through our pair of LINACs?

Could we do this in a manner which minimizes impact on the current infrastructure?

Can FFAs handle beams up to 10s of GeV?

Can JLab use this technology?

Could we use permanent magnet FFA arcs to recirculate more times through our pair of LINACs?

Could we do this in a manner which minimizes impact on the current infrastructure?

Can FFAs handle beams up to 10s of GeV?

We think so!

Upgrading to 22 GeV

Images and slides in this section are often taken from the work of our collaboration.

Motivation

Current Status

Challenges

Future

The quick rundown

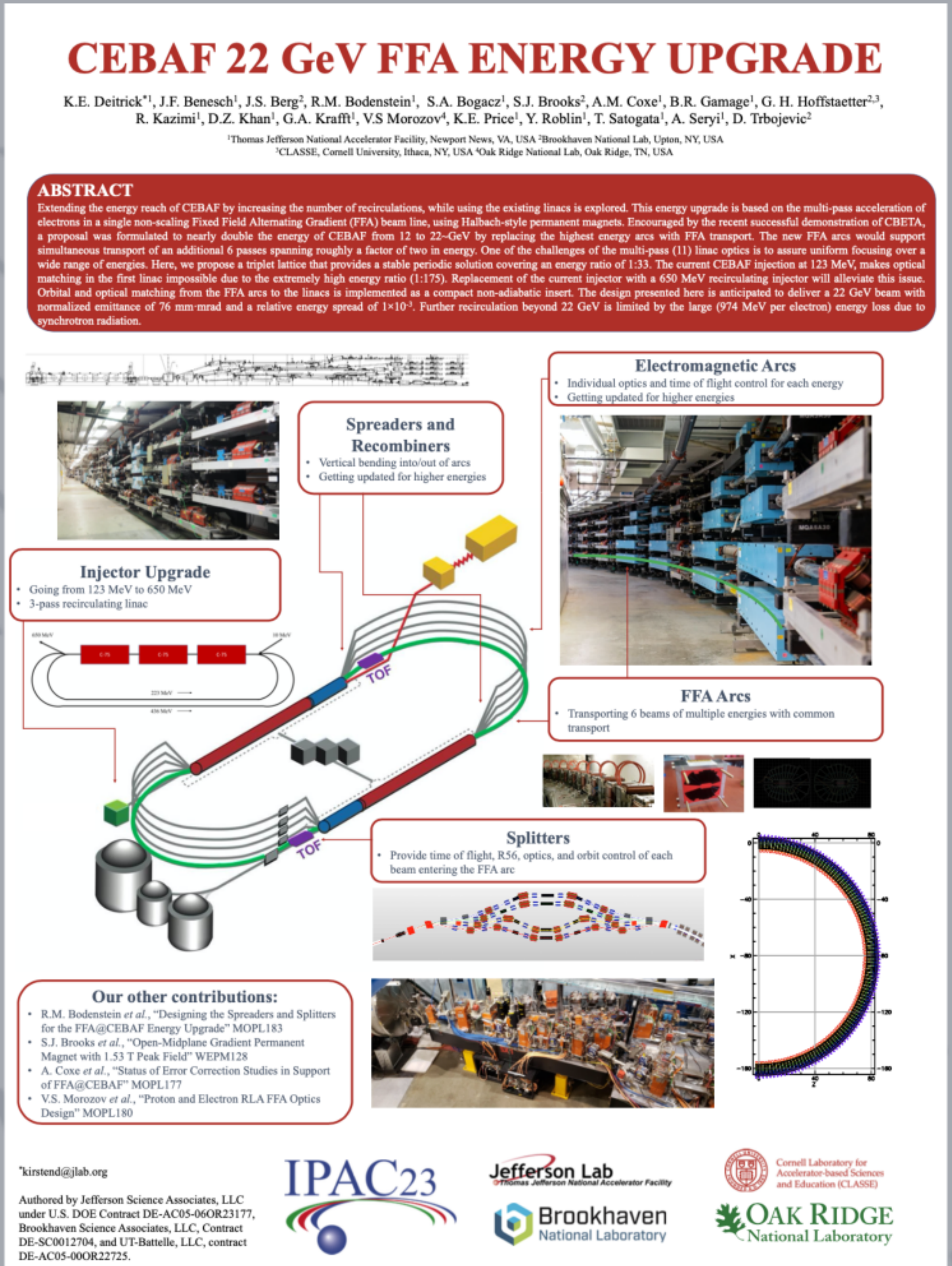
The collaboration has been working on this for just over 2 years.

CEBAF 22 GeV FFA ENERGY UPGRADE[*]

K.E. Deitrick[†], J.F. Benesch, R.M. Bodenstein, S.A. Bogacz, A.M. Coxe, B.R. Gamage,
R. Kazimi, D.Z. Khan, G.A. Krafft, K.E. Price, Y. Roblin, A. Seryi, T. Satogata,
Thomas Jefferson National Accelerator Facility, Newport News, VA, USA
J.S. Berg, S.J. Brooks, D. Trbojevic, Brookhaven National Lab, Upton, NY, USA
V.S Morozov, Oak Ridge National Lab, Oak Ridge, TN, USA
G. H. Hoffstaetter[1], CLASSE, Cornell University, Ithaca, NY, USA
[1] also at Brookhaven National Laboratory, Upton, New York, USA

The quick rundown

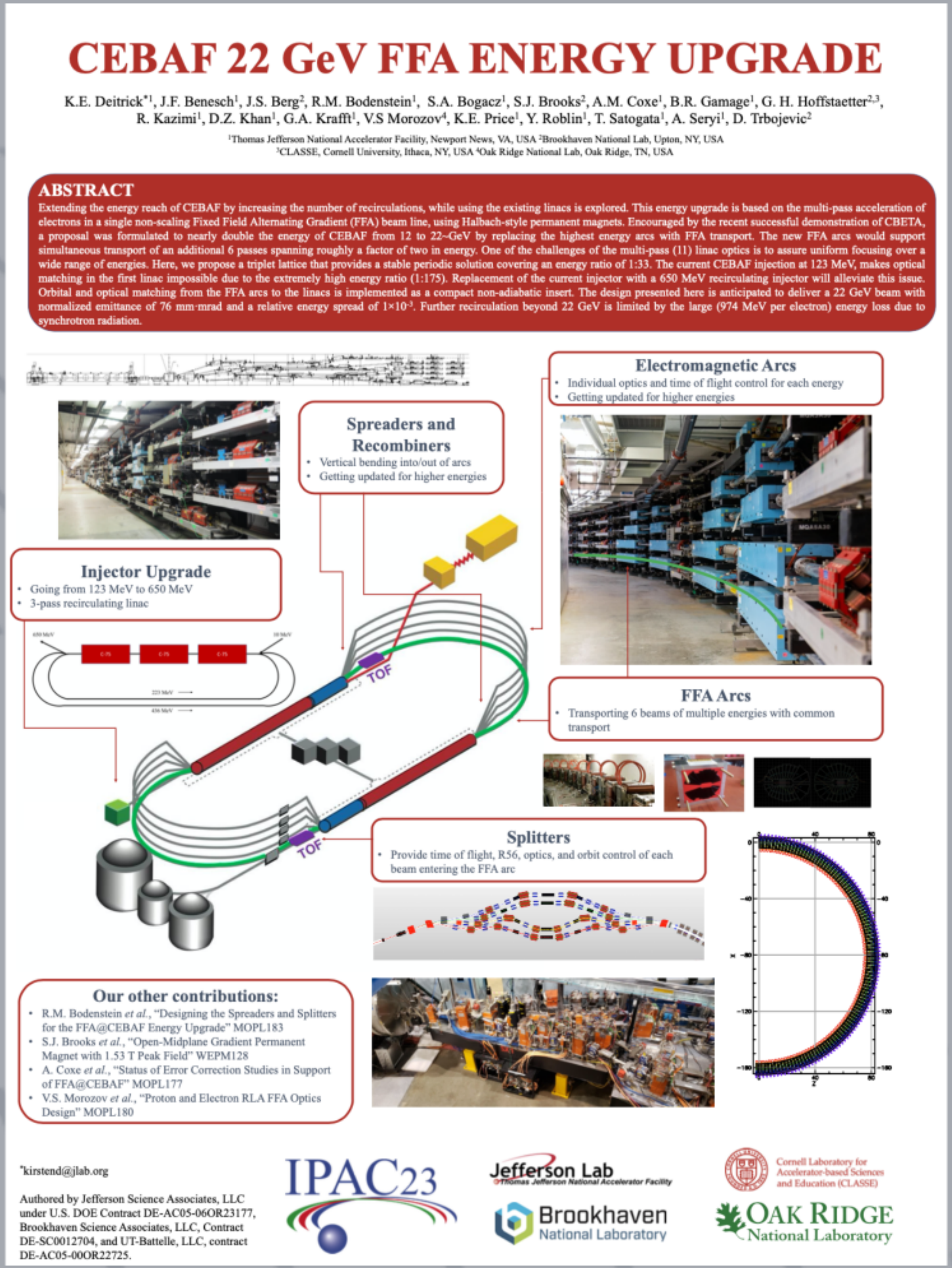
We've come a very long way!



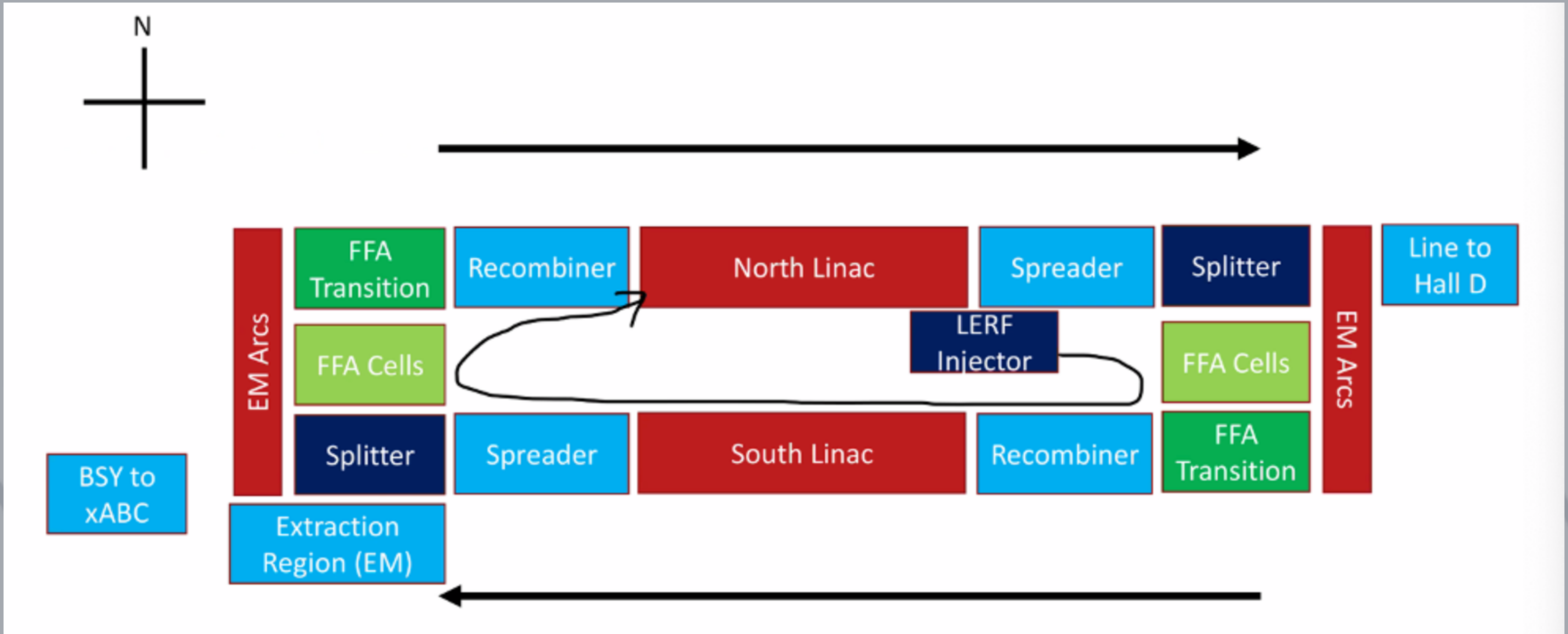
The quick rundown

We've come a very long way!

And there's still a lot of work left!

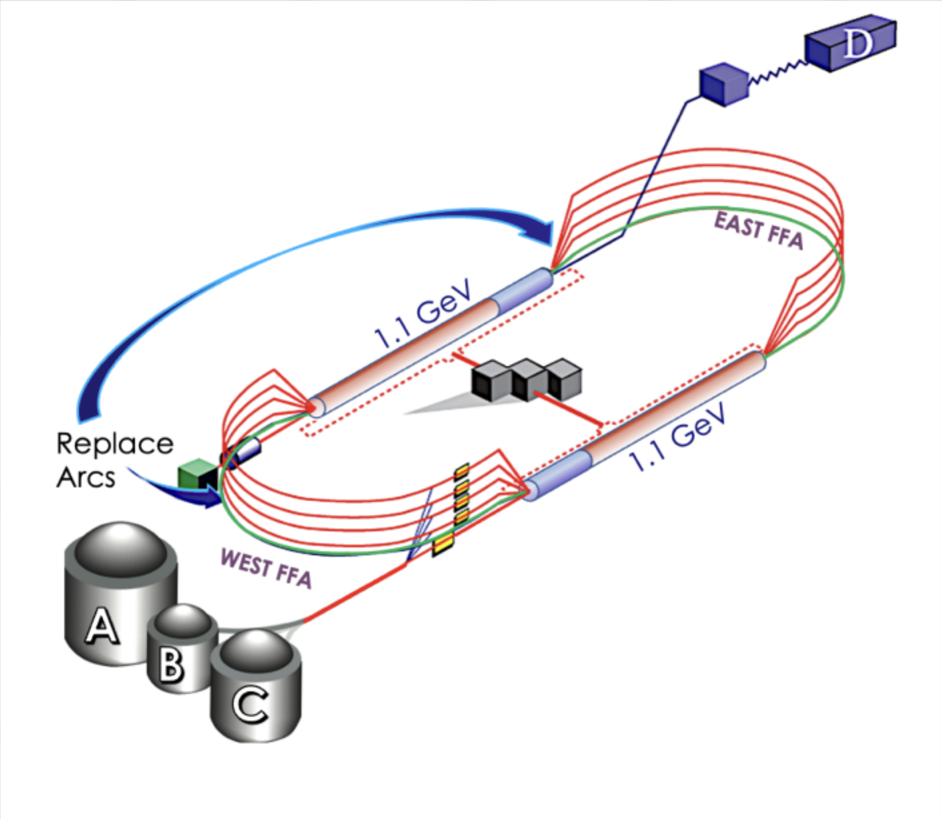


Let's review the current baseline



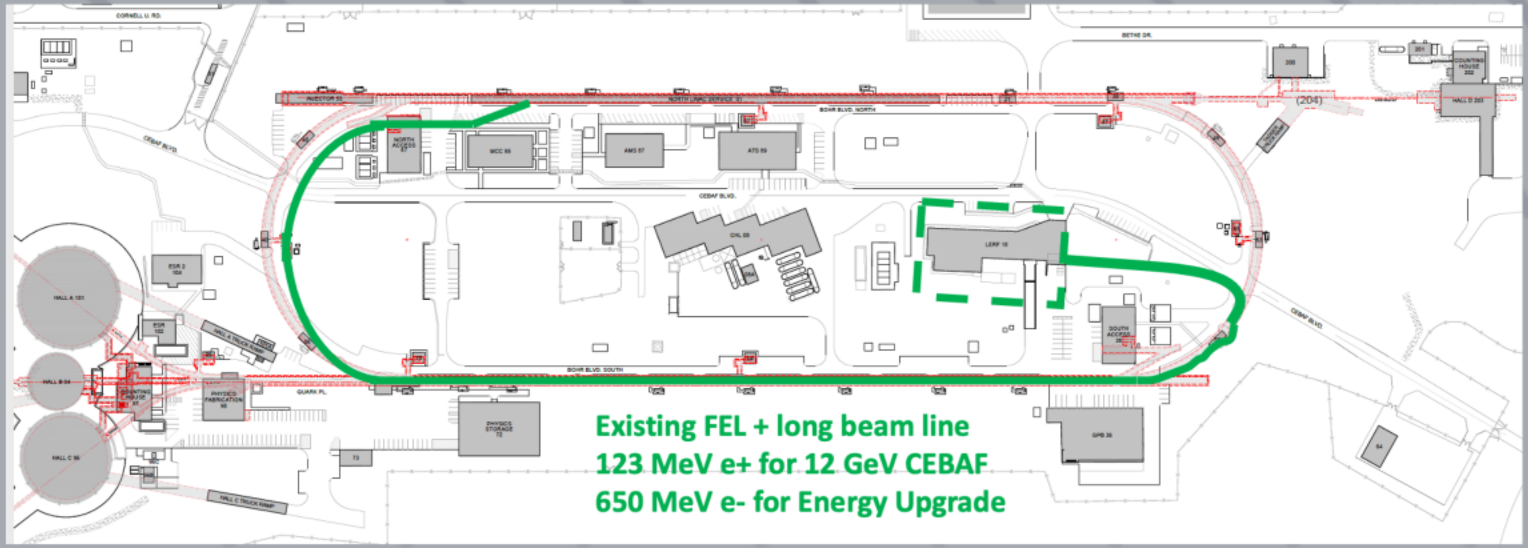
FFA Arcs

We currently envision replacing the highest-energy EM arcs on each side of the machine with 6-pass capable, permanent magnet FFA arcs.



Upgraded Injector + LINAC Optics

If we just upgrade the arcs, there will be a large range of energies in the LINACs (ratio of ~ 1:175). The optics cannot handle that range. To address this, we propose a new, 650 MeV injector (up from 123 MeV) to be placed in the current LERF vault, and a quadrupole triplet scheme for the LINAC optics.



Location	Pass Number	Energy (GeV)
Northeast	1	1.750
	3	3.950
	5	6.150
	7	8.350
	9	**10.550**
	11	**12.750**
	13	**14.950**
	15	**17.150**
	17	**19.350**
	19	**21.550**
Southwest	2	2.850
	4	5.050
	6	7.250
	8	9.450
	10	**11.650**
	12	**13.850**
	14	**16.050**
	16	**18.250**
	18	**20.450**
	20	**22.650**

Upgraded Injector + LINAC Optics

The new LINAC optics maintains adequate control over the lowest-energy passes, but appears as a drift to the higher-energy passes.

However, with the new injection energy comes a new energy ration that must pass through the spreaders and recombiners. They needed updating as well.

Updated Spreaders

Designing the Spreaders and Splitters for the FFA@CEBAF Energy Upgrade

R.M. Bodenstein*, J.F. Benesch, S.A. Bogacz, A.M. Coxe, K.E. Deitrick, B.R. Gamage, D.Z. Khan,
K.E. Price, A. Seryi, Jefferson Lab, Newport News, VA, USA
J.S. Berg, S.J. Brooks, D. Trbojevic, Brookhaven National Lab, Upton, NY, USA
V.S. Morozov, Oak Ridge National Lab, Oak Ridge, TN, USA

IPAC23

Abstract

The FFA@CEBAF energy upgrade study aims to approximately double the final energy of the electron beam at the Continuous Electron Beam Accelerator Facility (CEBAF). It will do this by replacing the highest-energy recirculating arcs with fixed-field alternating gradient (FFA) arcs, allowing for several more passes to circulate through the machine. This upgrade necessitates the re-design of the vertical spreader sections, which separate each pass into different recirculation arcs. Additionally, the FFA arcs will need horizontal splitter lines to correct for time of flight and R56 . This work will present the current state of the spreader re-design and splitter design.

Current CEBAF Spreader Layout

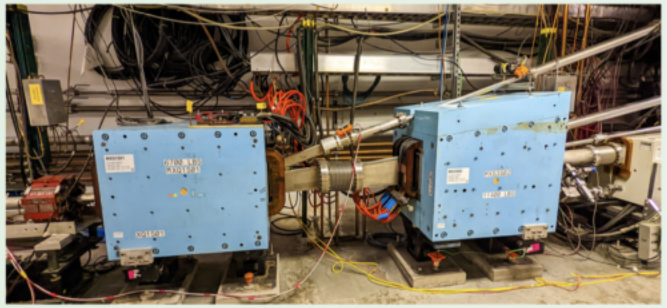
Spreaders downstream of linacs, recombiners are mirror images upstream of linacs.

The two common dipoles separate the passes by energy, with the lowest energy beam being bent upward the furthest. Each successive pass will be bent less. They then follow a two-step elevation rise, which allows for achromaticity in the main Arc.

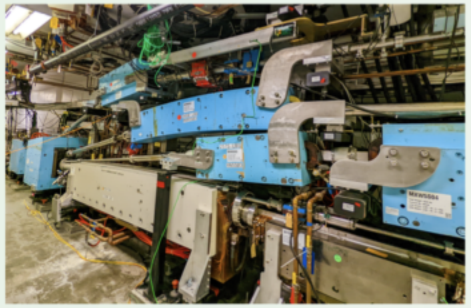
Redesigned CEBAF Spreader Layout

Lengthened first common dipole, changed ratios of step elevations, added/strengthened diploles/quadrupoles to accomodate higher energies. Upgraded septa used to separate six FFA passes from EM passes. FFA passes recombined at LINAC height.

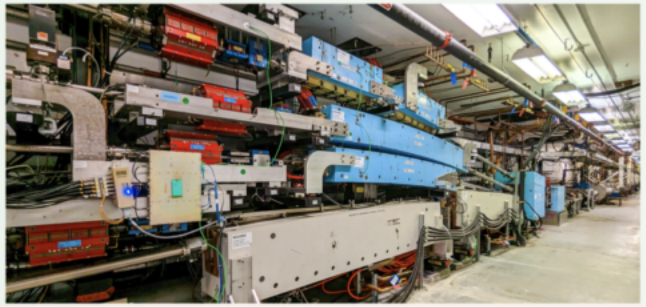
Common Dipoles Into Spreader



First Step of Spreader



Recombiner

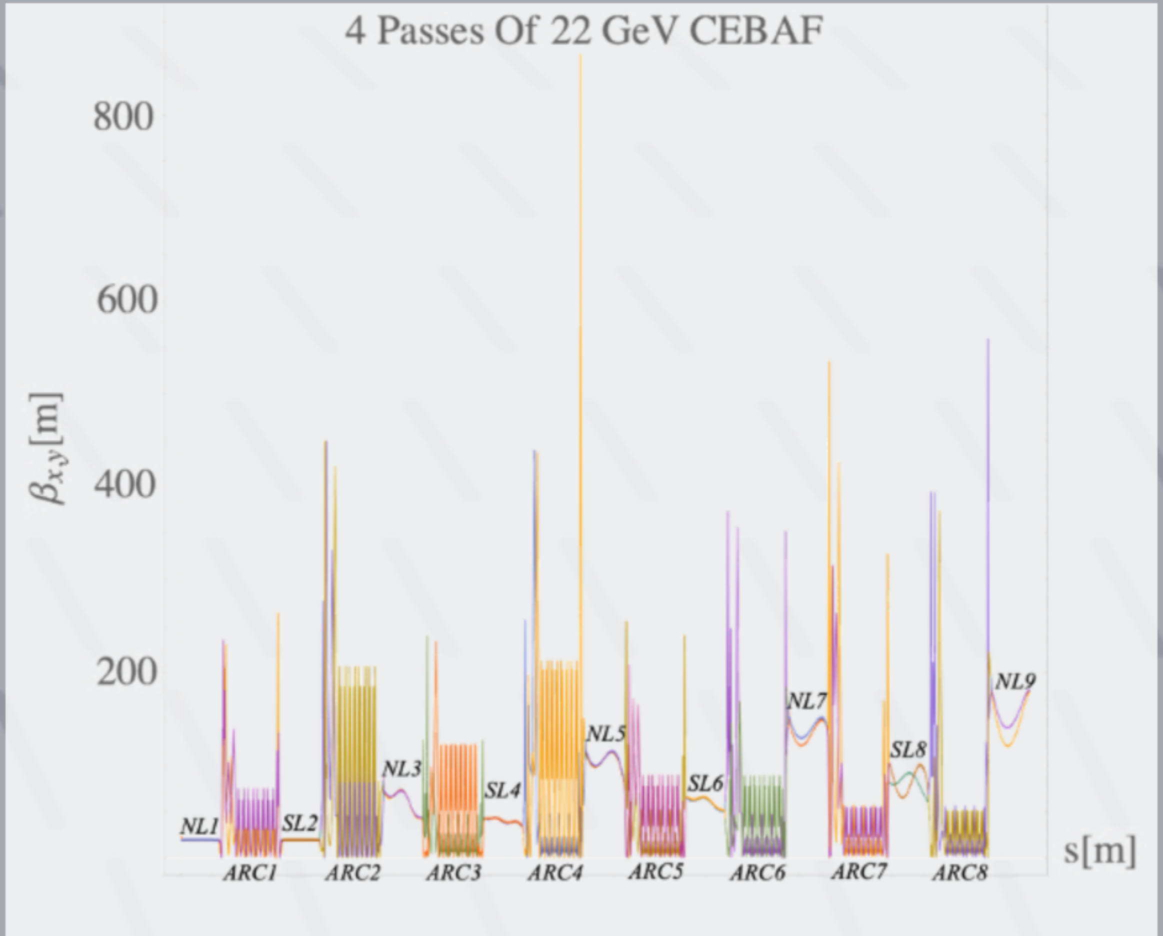


Updated EM Arcs

It turns out, the upgraded injection energy also caused the beam in the EM arcs to be too high energy for the current magnets. The solution was to "promote" each line "upward" and rematch the optics.

Concatenating the EM CEBAF

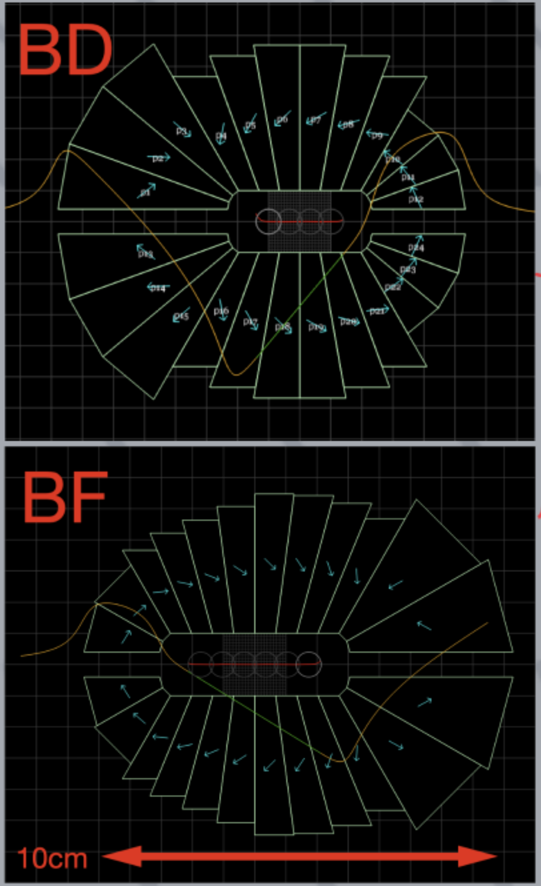
Next, we put together all the updated pieces to make sure they work. Error analysis is still ongoing, but the 4-Pass CEBAF is looking pretty good!

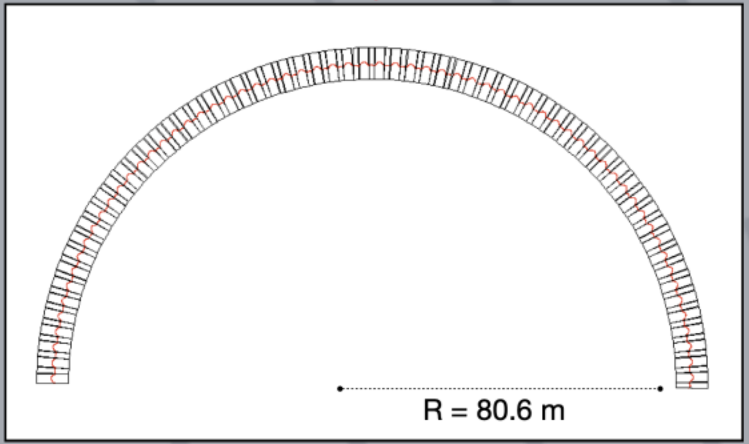


Slide from Donish Khan

Designing the FFA Arcs

Once the magnets were designed to handle the energies, they were turned into a lattice that would fit in the current tunnel footprint.

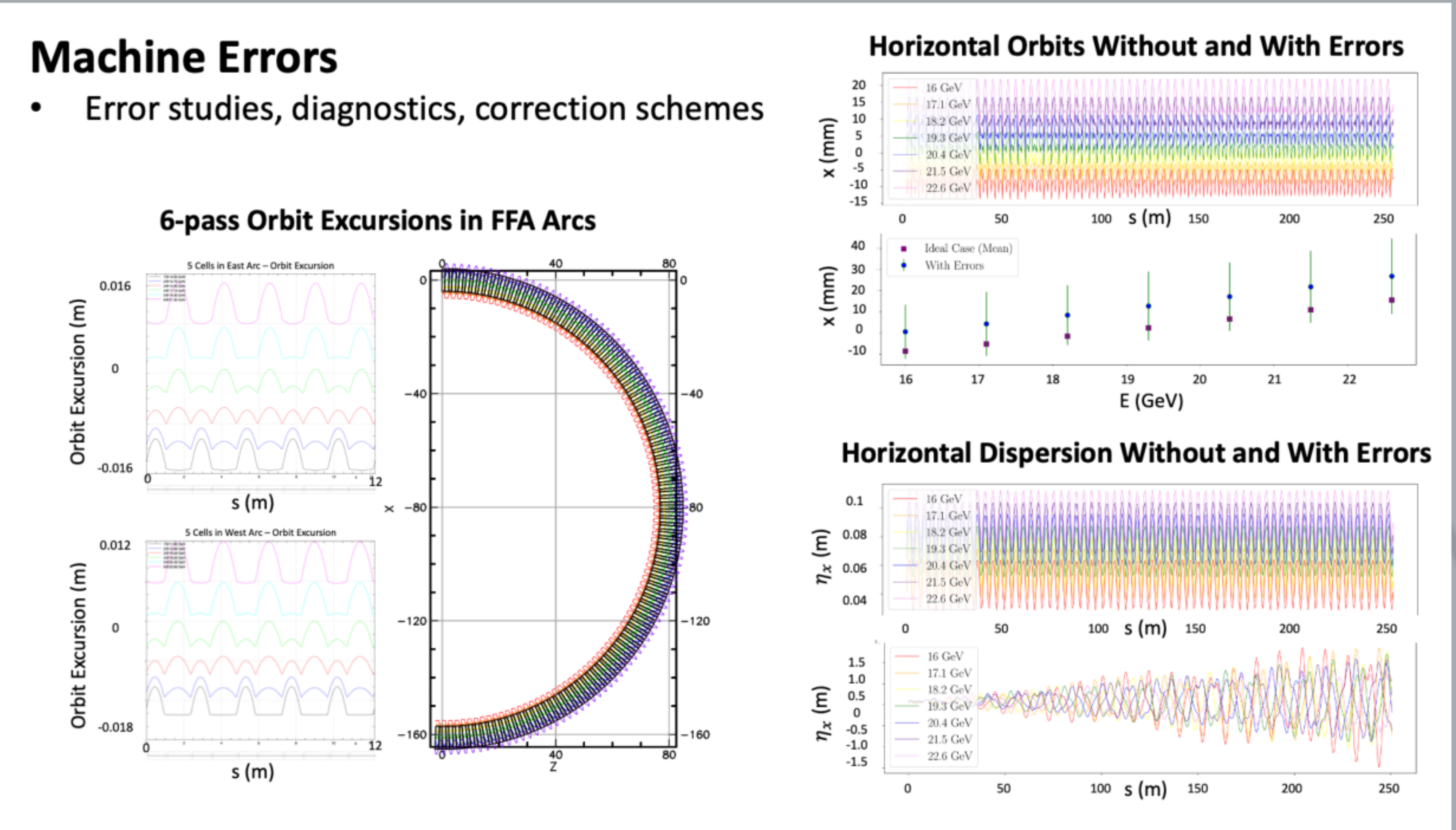




Slides from S. Brooks and A. Coxe

Simulating the FFA Arcs

The FFA arcs are currently undergoing detailed error studies, as well as the development of a correction scheme.



Slide from A. Coxe

Not bad for ~2 years of work!

But there's a lot more to do.

Upgrading to 22 GeV

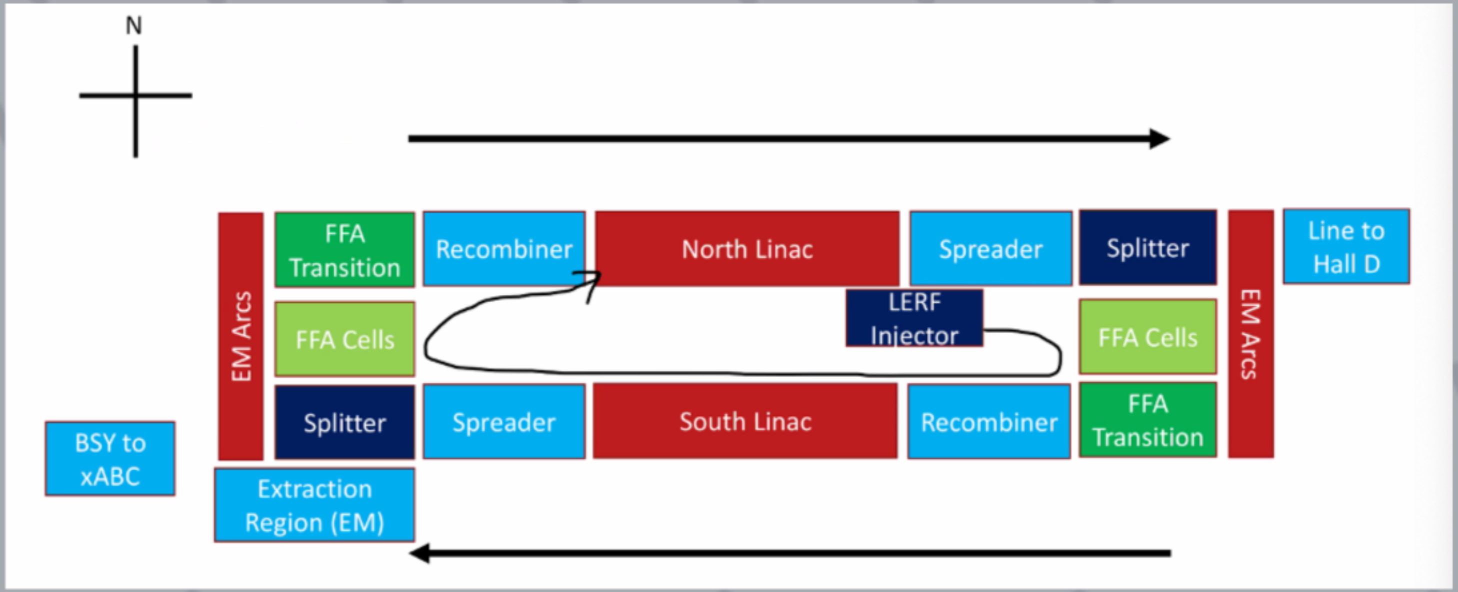
Images and slides in this section are often taken from the work of our collaboration.

- Motivation
- Current Status
- Challenges
- Future

So what's the problem?

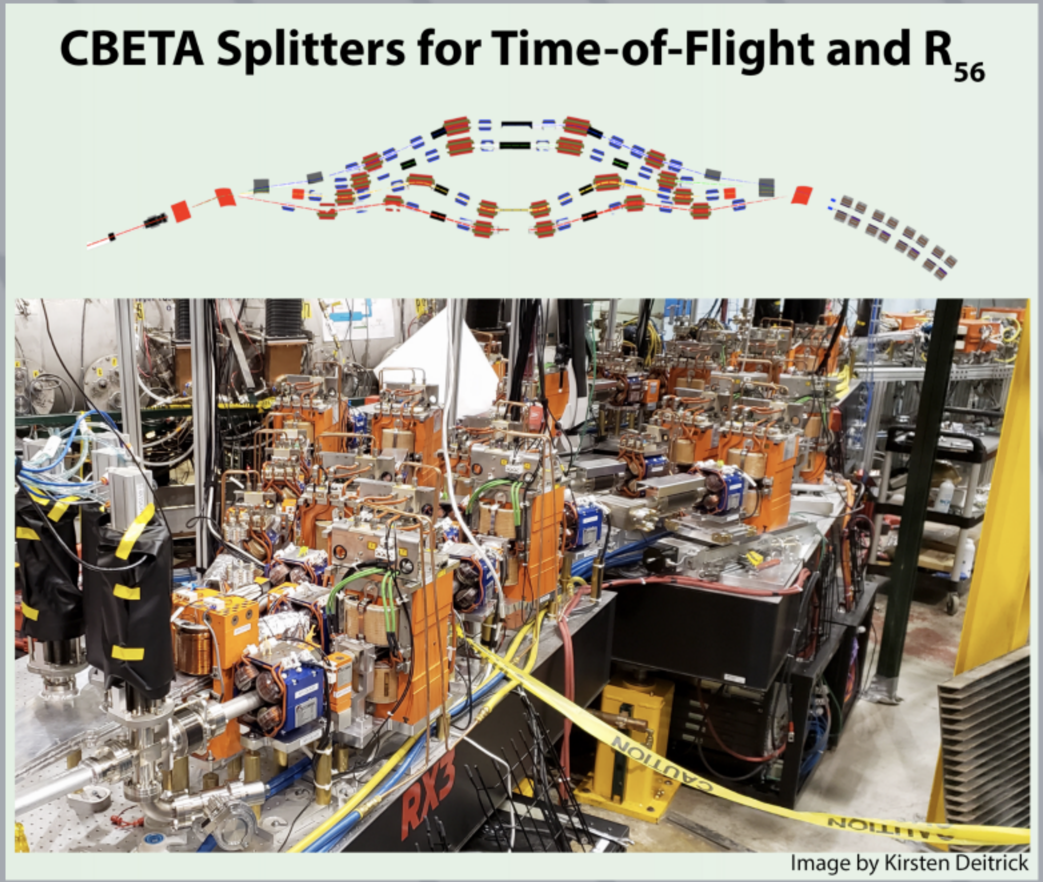
Currently, the highest priority challenges are:

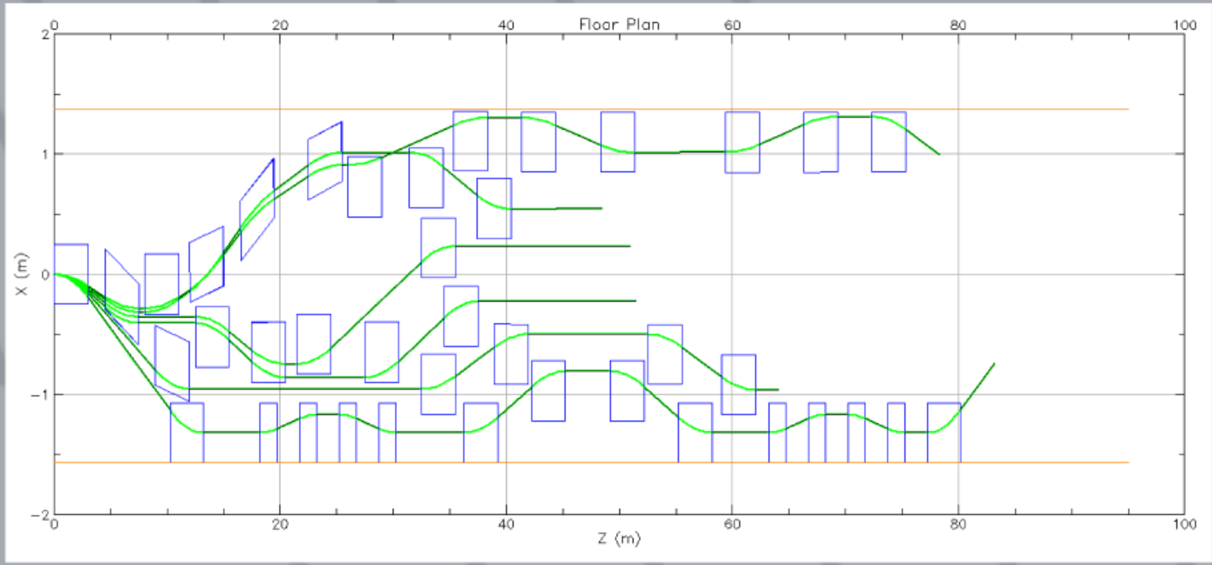
- splitter design
- extraction of FFA passes
- FFA transition design
- new injection line



Splitter Design (and extraction)

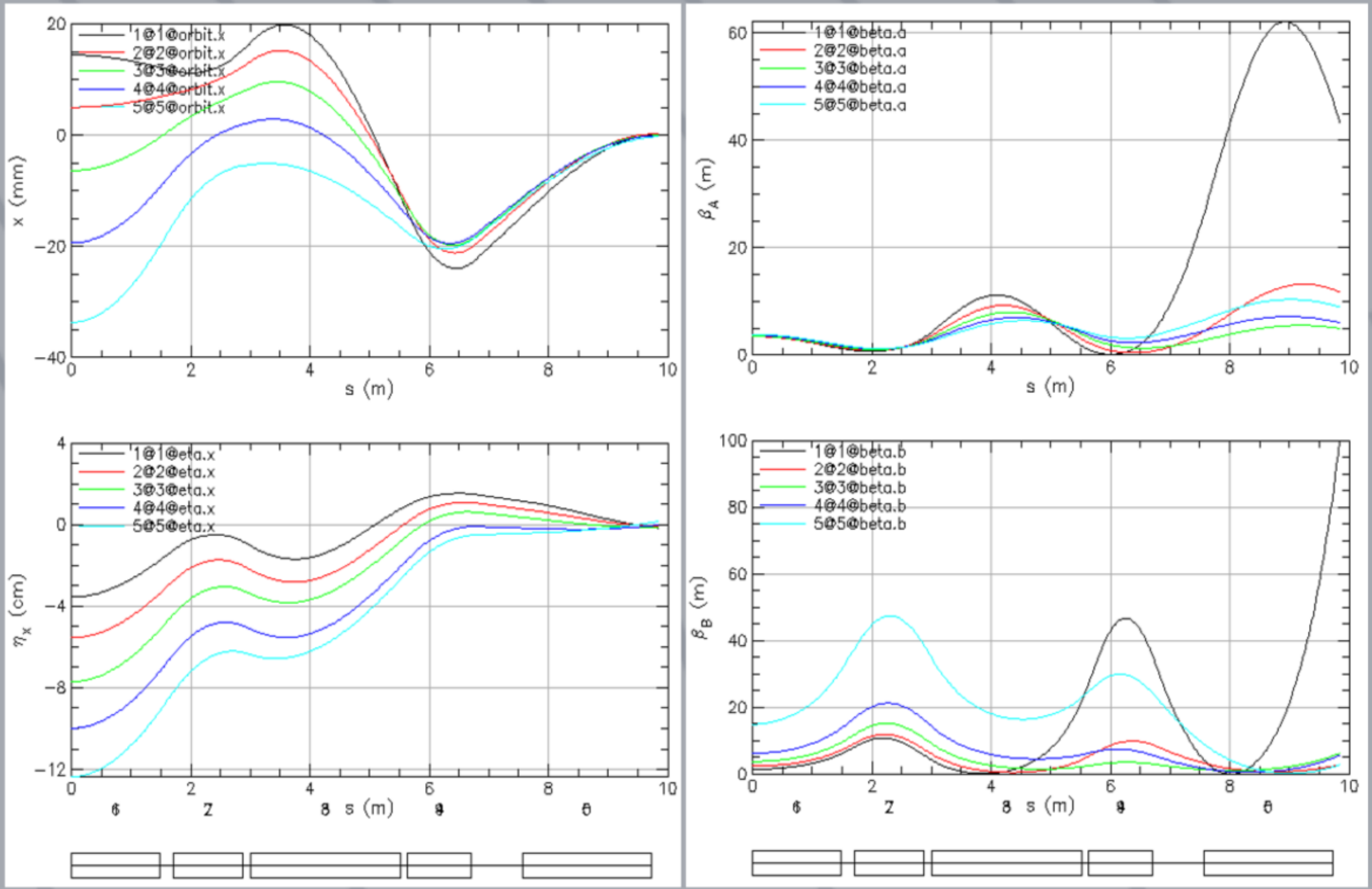
Splitters are used to control time of flight, R56, optics, and orbits before the beams enter the FFA arc.





FFA Transition Lattice Design

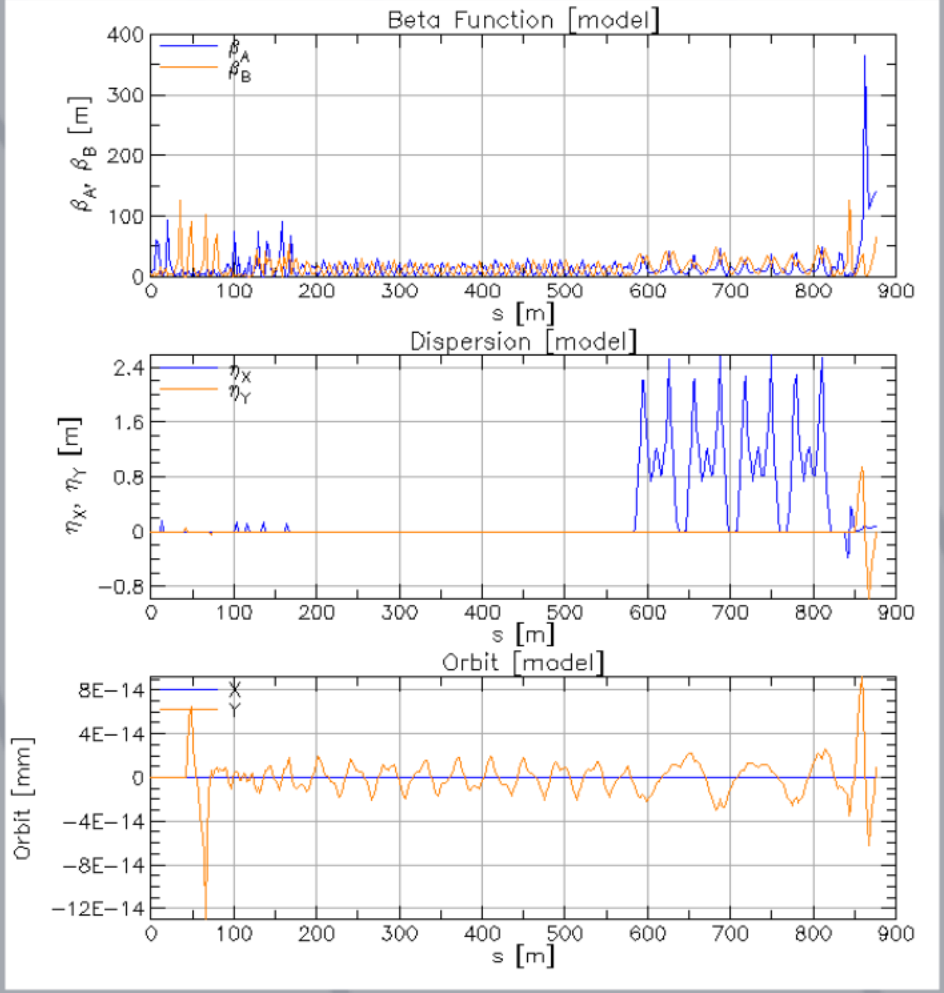
This section brings the FFA passes back together prior to the recombiner and LINAC.



Work by V. Morozov and R. Gamage

LERF Injection into CEBAF

The design for the new injection line is progressing nicely.



Work by Y. Roblin and D. Turner

Upgrading to 22 GeV

Images and slides in this section are often taken from the work of our collaboration.

Motivation

Current Status

Challenges

Future

What's on deck?

- Currently wrapping up an LDRD study on Start-to-End simulations
- Submitting a new LDRD to test magnet degradation due to radiation exposure
- Continue refining design

Upgrading to 22 GeV

Images and slides in this section are often taken from the work of our collaboration.

Motivation

Current Status

Challenges

Future

The CEBAF Accelerator from 12 to 22 GeV

Ryan Bodenstein

- ***Introductions***
- ***A Bit of History***
- ***Accelerator Applications***
- ***Types of Accelerators***
- ***12 GeV CEBAF***
- ***24 GeV CEBAF***