Fermilab

Managed by Fermi Research Alliance, LLC for the U.S. Department of Energy Office of Science

Accelerator Physics at Fermilab

Jeffrey Eldred

Summer Lecture Series

May 30, 2024

Applications of Particle Accelerators (Science)

Particle & Nuclear Physics

Fundamental Physics

- Fermilab long-baseline neutrino program
  - -> origin of matter & antimatter in the universe.
- CERN LHC in Switzerland/France
  - -> higgs boson, and beyond the standard model.
- MSU FRIB in Michigan
  - -> new elements and isotopes.

Radiation & Neutron Physics

Science to do Science

- SLAC LCLS-II in California, powerful coherent x-ray source.
- SNS in Oak Ridge TN, powerful spallation neutron source.

Applications of Particle Accelerators (Technology)

Medical Accelerators

- proton therapy to target cancerous tumors.
- medical radioisotope production.

Industrial Processes

- Ion implantation for radiation-hardened electronics.
- Electron-beam welding.
- Large-scale metal 3D-printing.

Emerging Applications

- Imaging of sensitive archeological materials.
- EUV Light Source for microchip lithography.
- Irradiation for treatment of wastewater and food pathogens.
- Identification and inspection of radiological materials.
- Transmutation of nuclear waste / subcritical nuclear reactor.

Learn more at US Particle Accelerator School

I will have another summer lecture on in-depth accelerator mechanics.

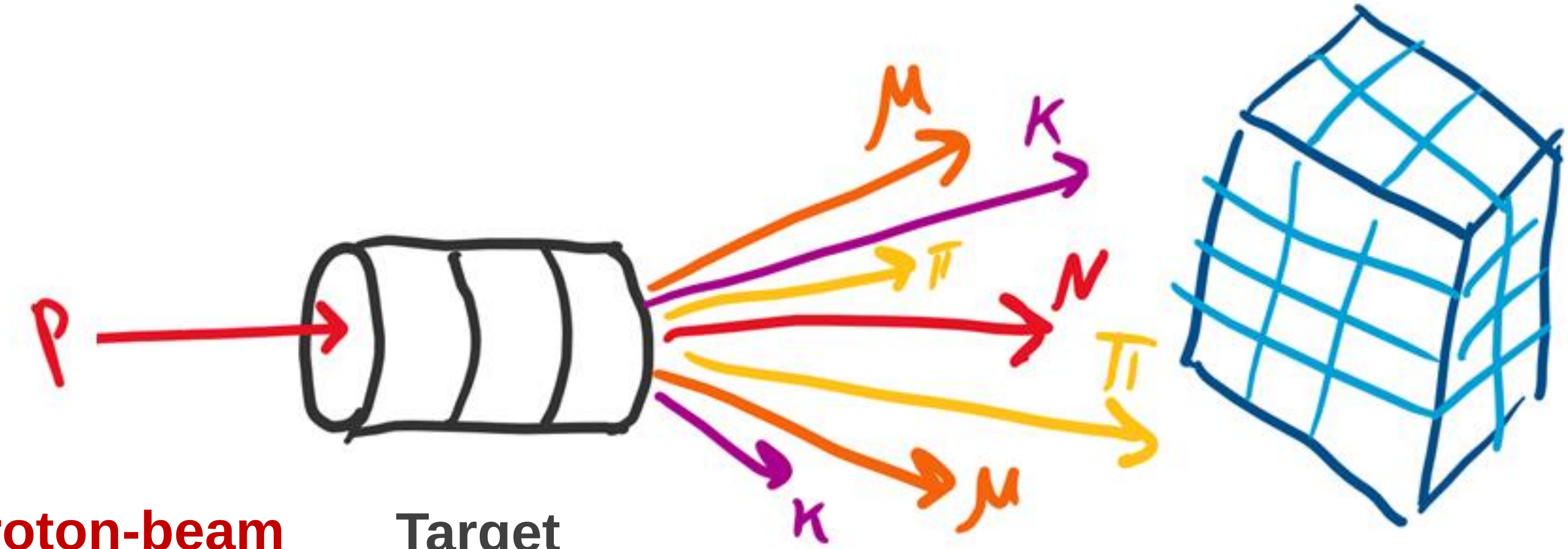
Free Recorded Classes:
- Eric Prebys' online course: "Fundamentals of Accelerator Physics"
- Huang & I's online course: "Mechanics & Electromagnetism for Accelerator Physics"

Sign up for Live USPAS classes: website
- Two-week full-time sessions usually June and January.
- Equivalent to graduate-level college-semester course!

I took many USPAS classes as a graduate student, and now I regularly teach at USPAS.

Fermilab Accelerators

Cartoon of Particle Accelerator Experiments



J. Eldred

Proton-beam **Target**

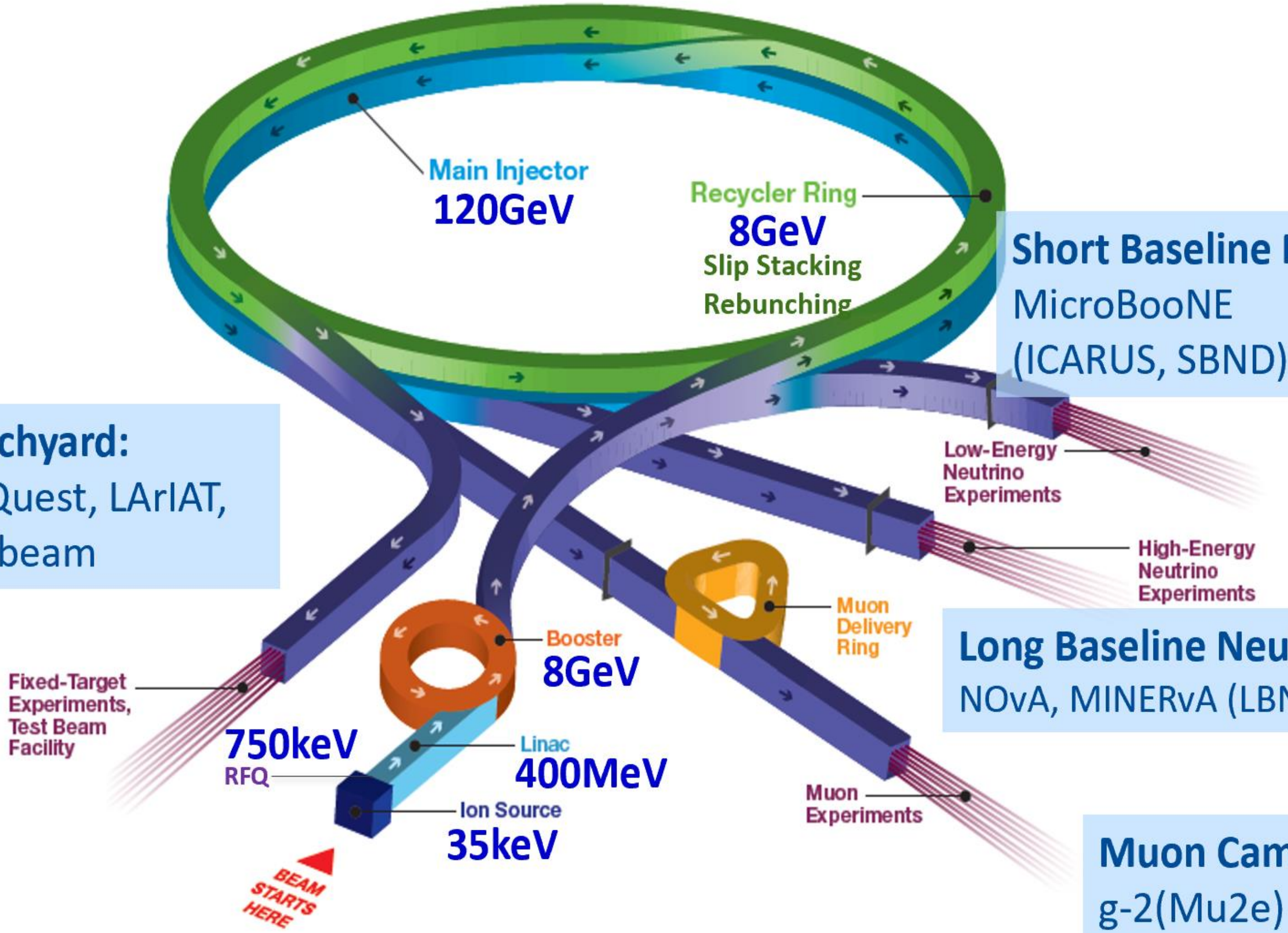
Detector

Secondary Particles

The Fermilab Accelerator Complex is optimized to deliver intense proton beams at a variety of GeV-scale energies.

Fermilab

Fermilab Accelerator Complex and Experiments



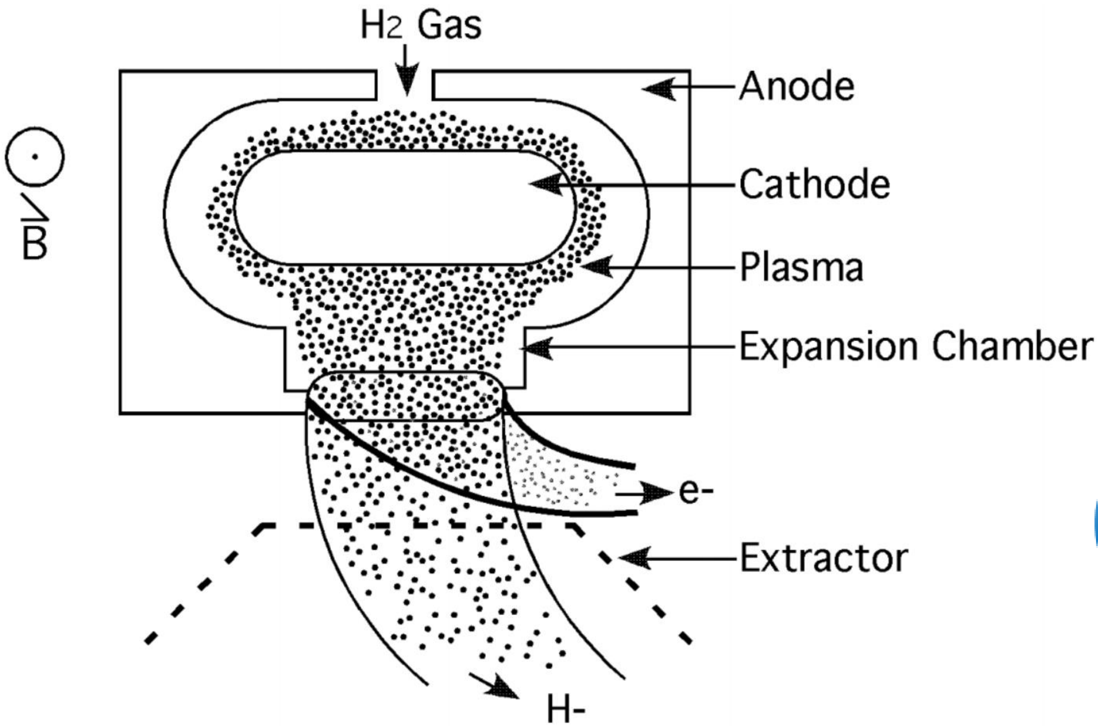
Short Baseline Neutrino:
MicroBooNE
(ICARUS, SBND)

Switchyard:
SeaQuest, LArIAT,
test beam

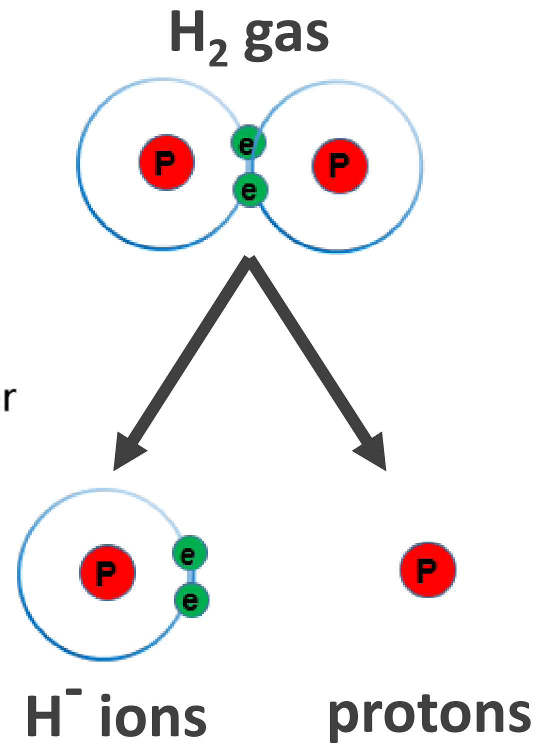
Long Baseline Neutrino:
NOvA, MINERvA (LBNF/DUNE)

Muon Campus:
g-2(Mu2e)

Magnetron H$^-$ Source



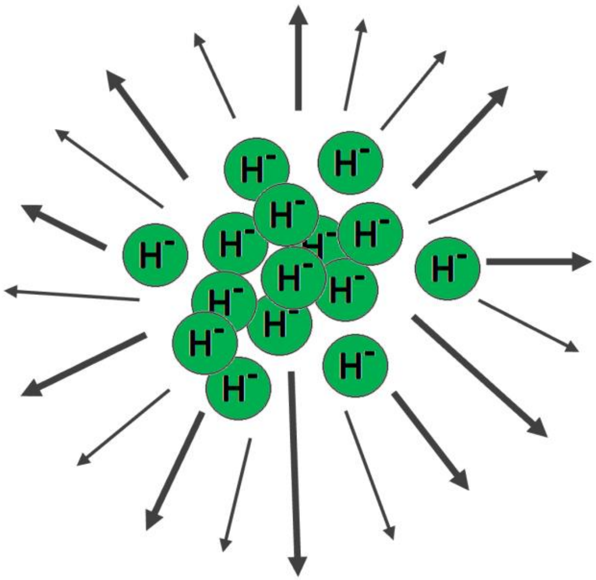
B. Worthel et al., Linac Rookie Book



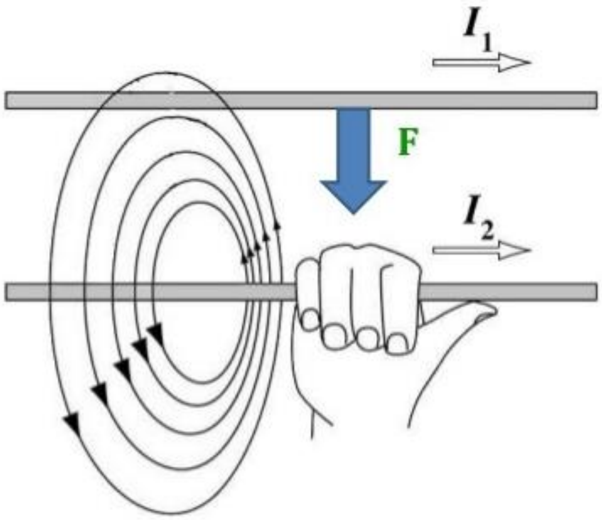
The particle beam starts as a H_2 gas, which is bombarded with electrons to ionize it, and the H$^-$ ions are extracted.

Acceleration for Beam Stability

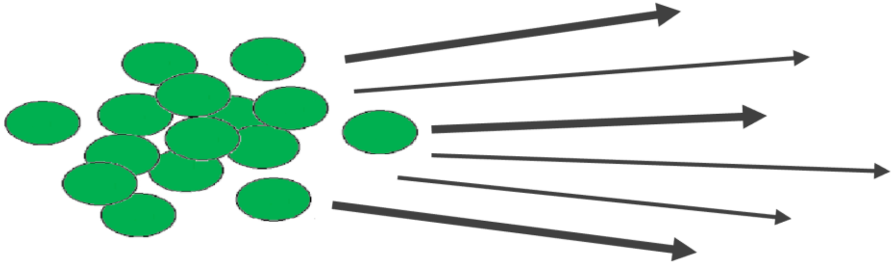
Electric Repulsion:



Magnetic Attraction:



Weakened Repulsion with Acceleration:



$$\vec{E}_\perp = \gamma E'_\perp$$

$$\vec{B}_\perp c = \beta(\hat{z} \times \vec{E}_\perp)$$

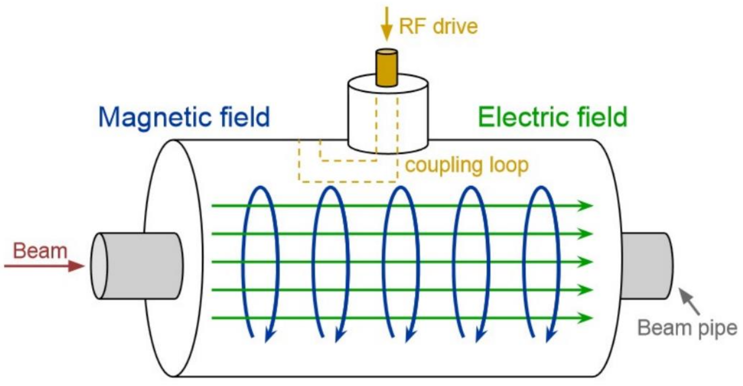
$$\vec{F}_\perp = q(E + v \times B)_\perp$$

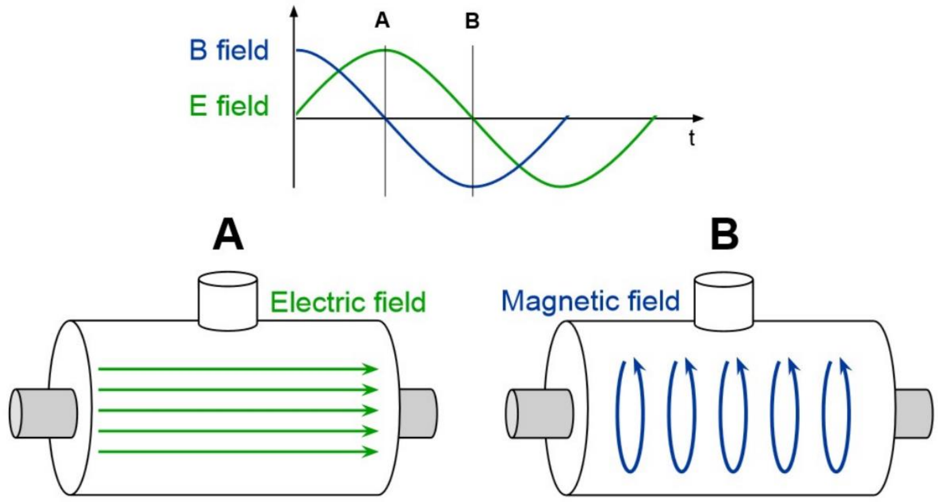
$$\vec{F}_\perp = q(1 - \beta^2)E_\perp = \frac{q}{\gamma^2}E_\perp$$

Fermilab

RF Accelerating Cavity

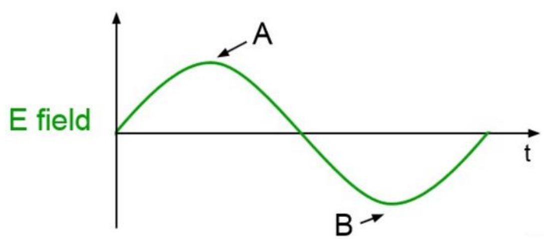
We use resonating radiofrequency (RF) cavities to efficiently trap an electromagnetic wave which accelerates the beam.

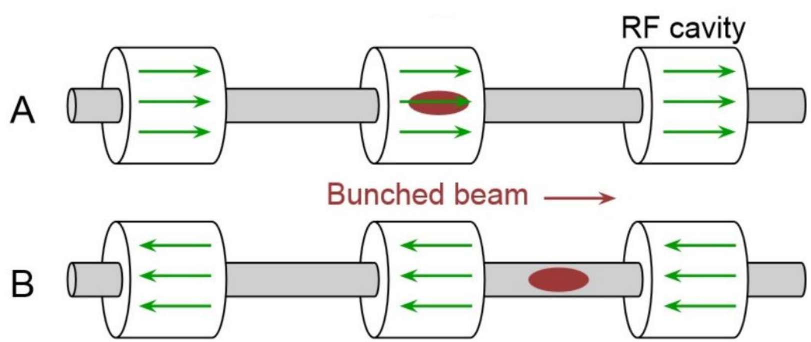




A. Watts, Concepts Rookie Book

The beam must arrive in synchronized bunches to be accelerated.

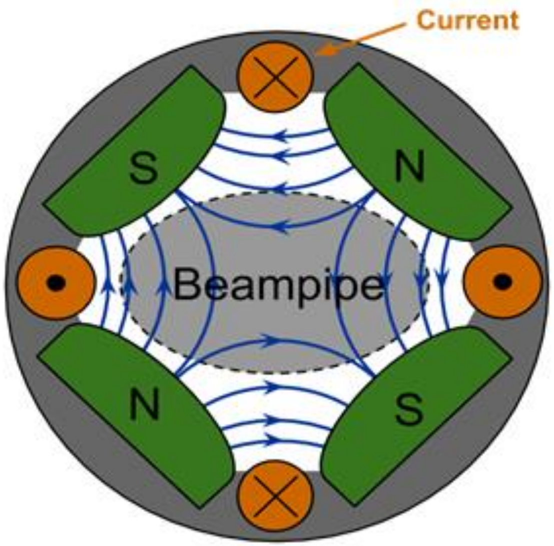




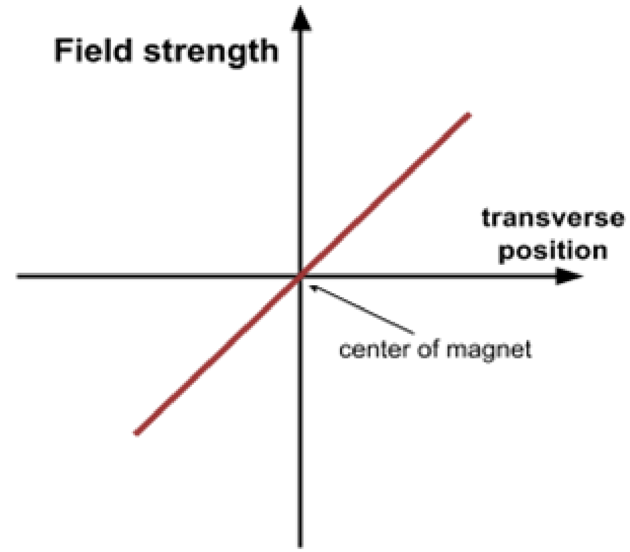
Fermilab

Focusing for Beam Stability

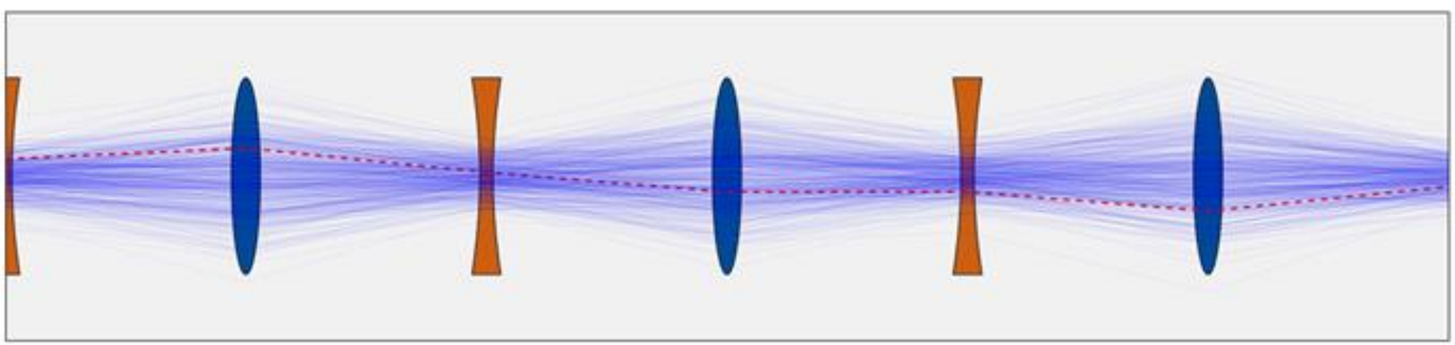
Quadrupole Magnet:



Linear Restoring Force:



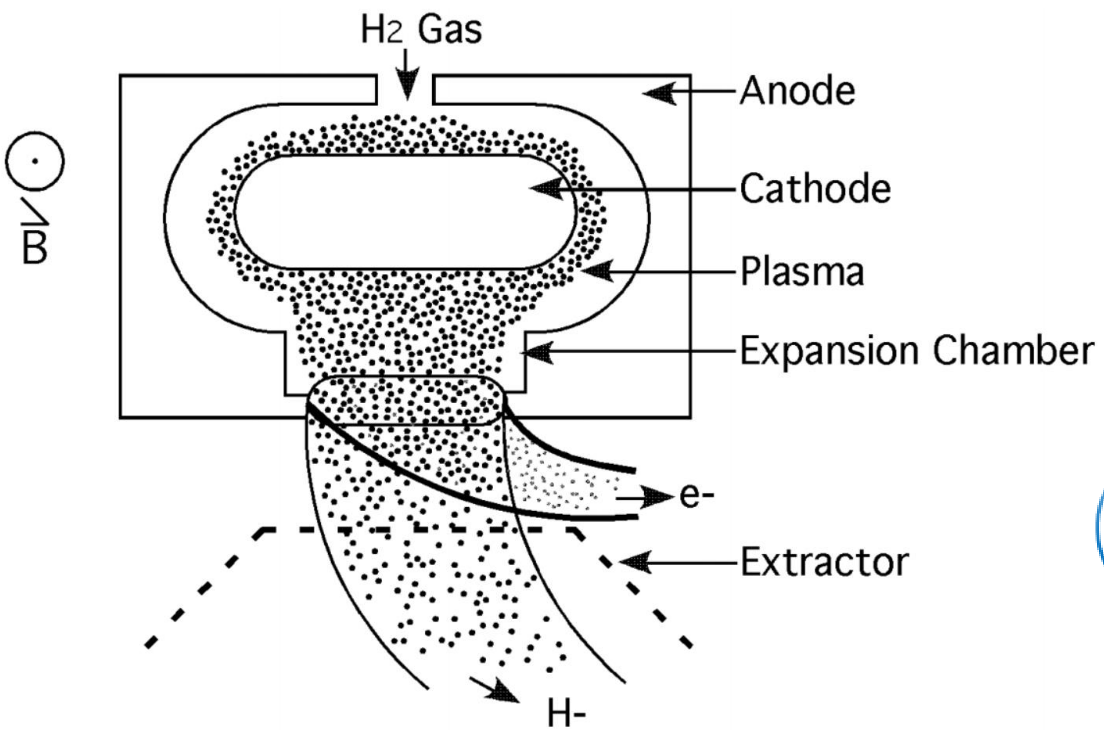
Alternating Focusing Magnets:

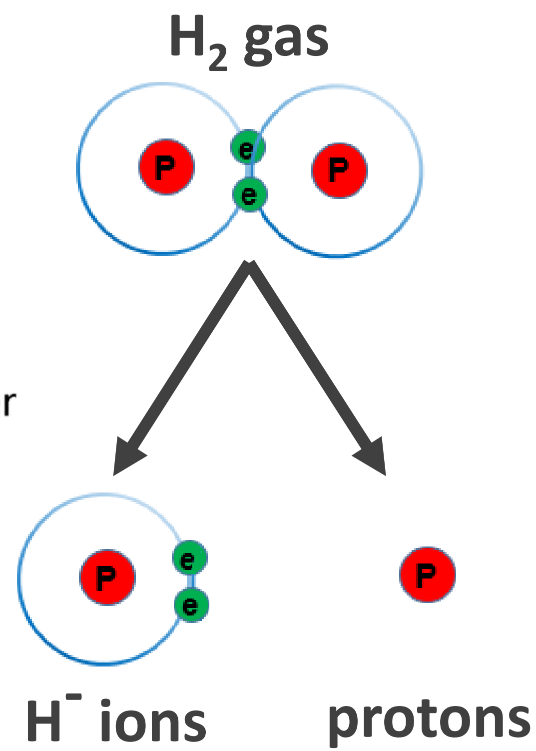


D. Barak, B. Harrison, A. Watts, Concepts Rookie Book, special thanks A. Watts

Magnetron H^- Source

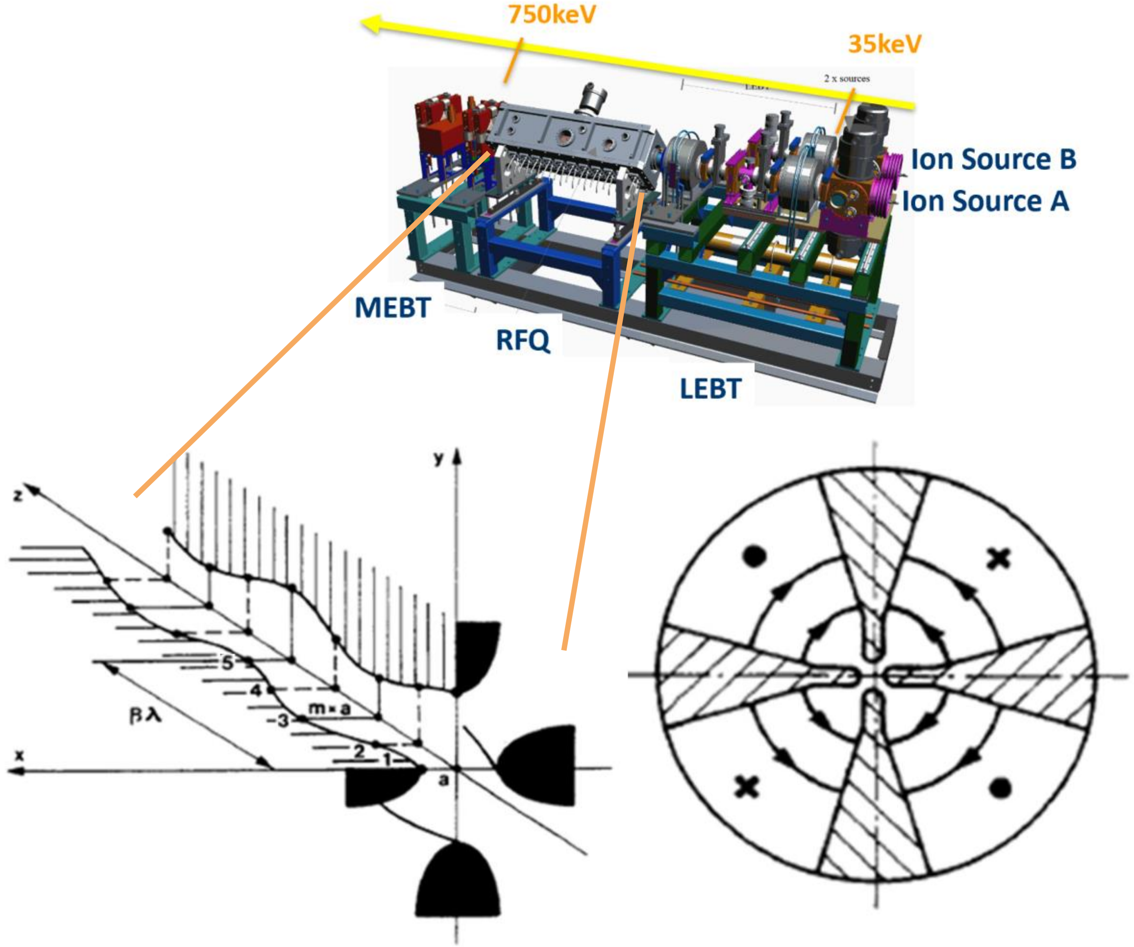
B. Worthel et al., Linac Rookie Book





The particle beam starts as a H_2 gas, which is bombarded with electrons to ionize it, and the H^- ions are extracted.

RFQ = Radiofrequency Quadrupole



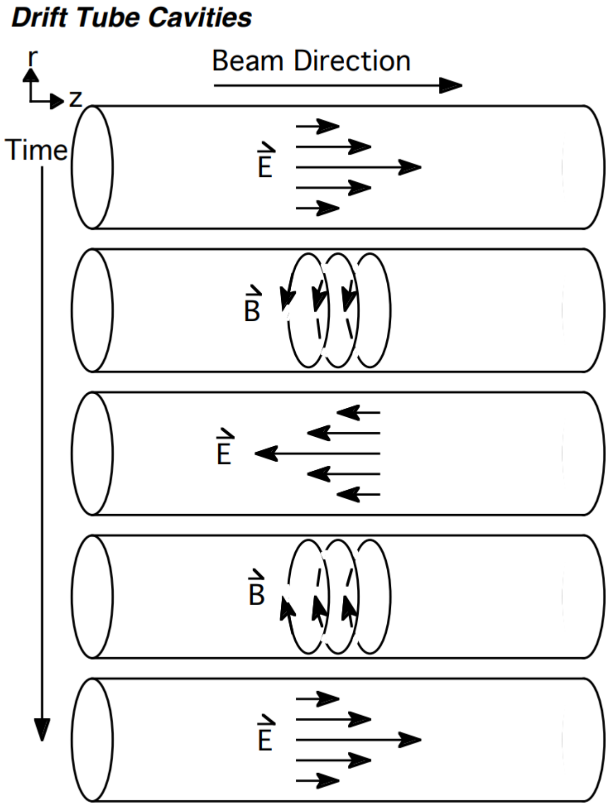
K. Seiya, NuFACT19

Italian INFN-LNL

The RFQ accelerates and focuses the beam simultaneously.

Linac = Linear Accelerator

B. Worthel et al., Linac Rookie Book

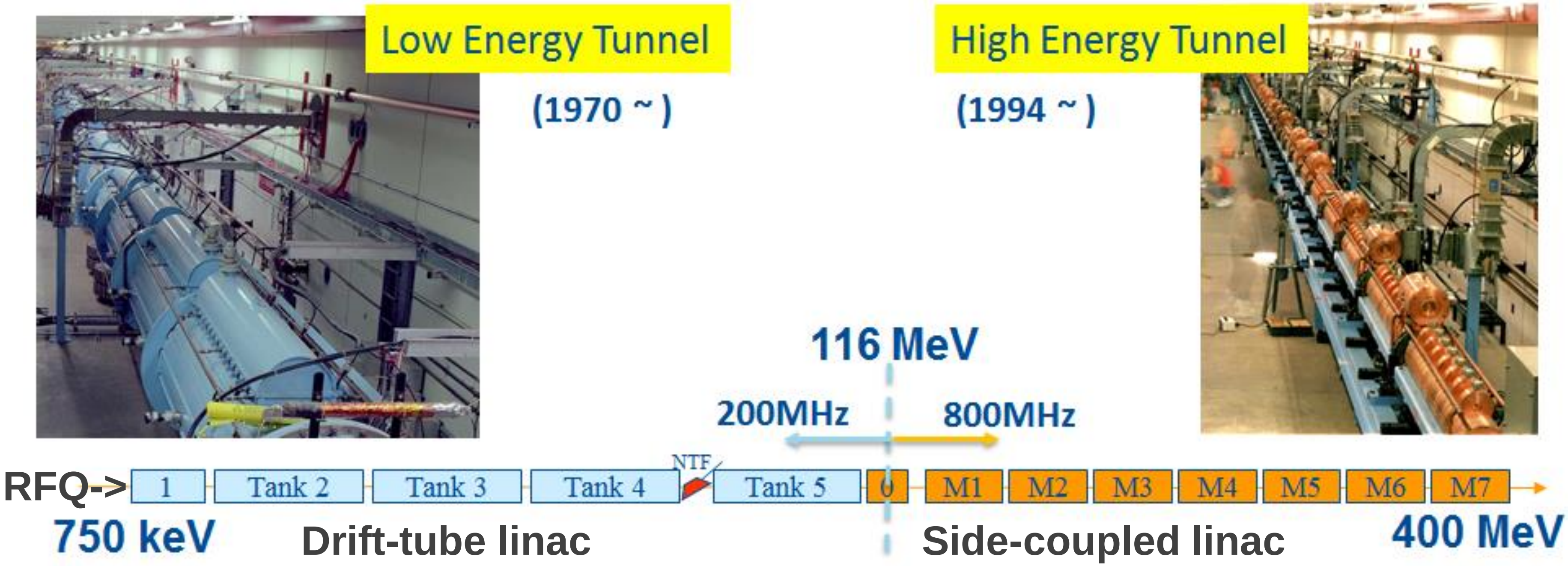


D. Barak, B. Harrison, A. Watts, Concepts Rookie Book

The Linac is a powerful single-pass accelerator design to get the H^- particles to relativistic energy very quickly.

Fermilab

Fermilab Linac – 400 MeV



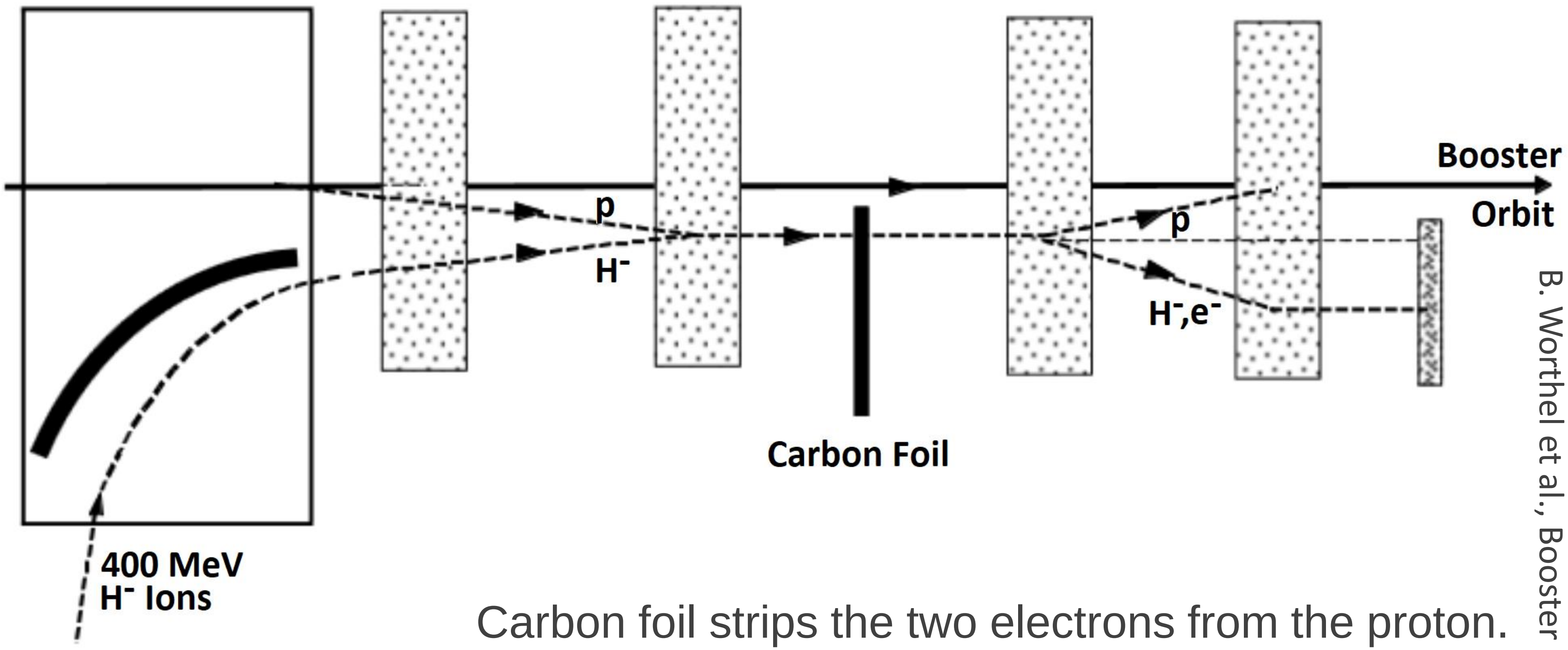
K. Seiya, NuFACT19

Status
Linac output: 25mA
Pulse length: 35 µsec
Efficiency: 96%

The length, frequency, and design of the RF cavities change as the beam accelerates.

Ultimately 400 MeV H- ions are delivered.

H^- Injection through Carbon foil into Booster



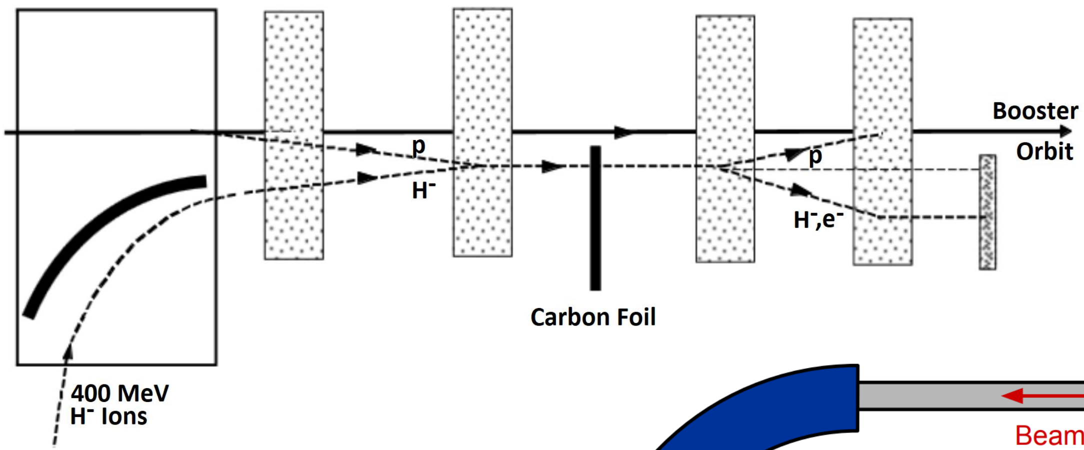
B. Worthel et al., Booster Rookie Book

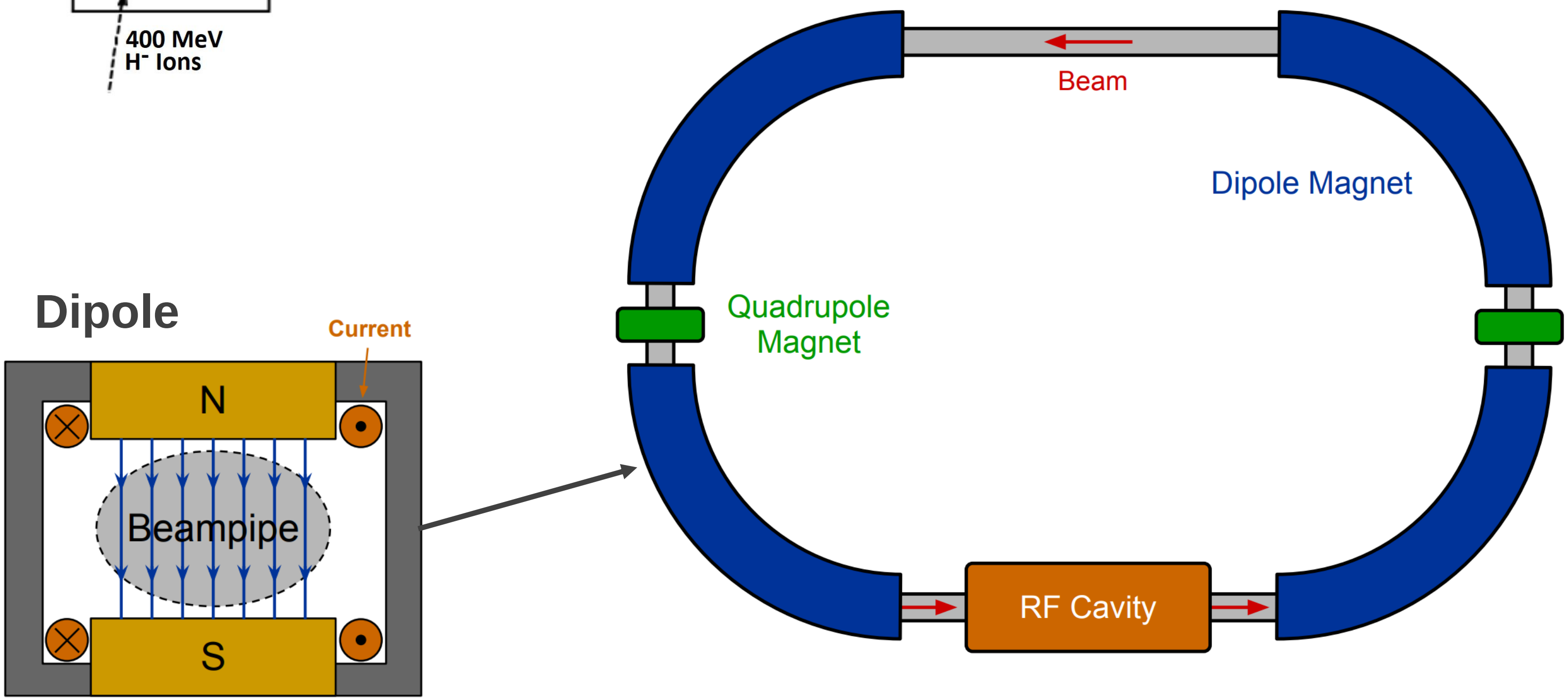
Carbon foil strips the two electrons from the proton.

Proton beam accumulates in the Booster ring.

Unstripped H- ions are sent to an absorber.

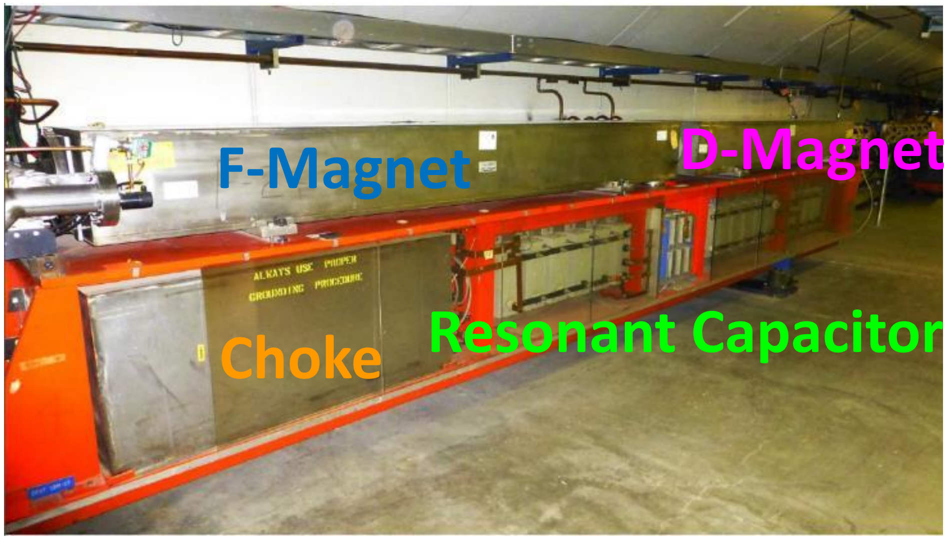
Simplified Diagram of a Synchrotron





B. Worthel et al., Booster Rookie Book
D. Barak, B. Harrison, A. Watts, Concepts Rookie Book

Fermilab Booster – 8 GeV

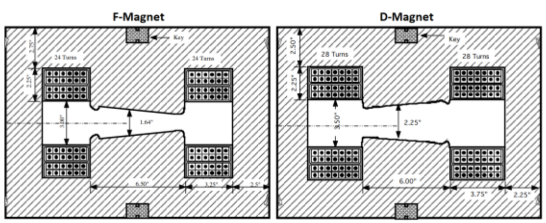


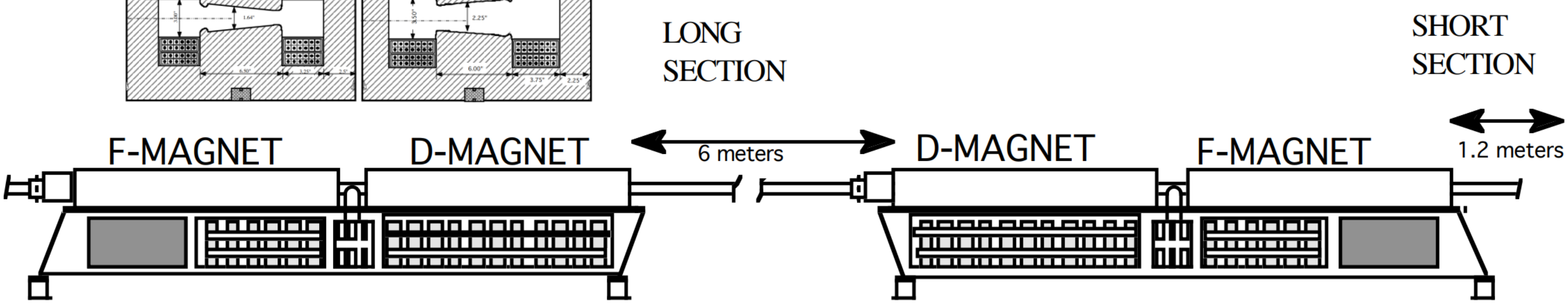
15Hz Resonant circuit synchrotron

Accelerating protons from 400MeV to 8GeV in 33.33msecDF

Status
Intensity: 4.5e12 protons
Efficiency: 94%
Number of protons per hour: 2.3e17 pph

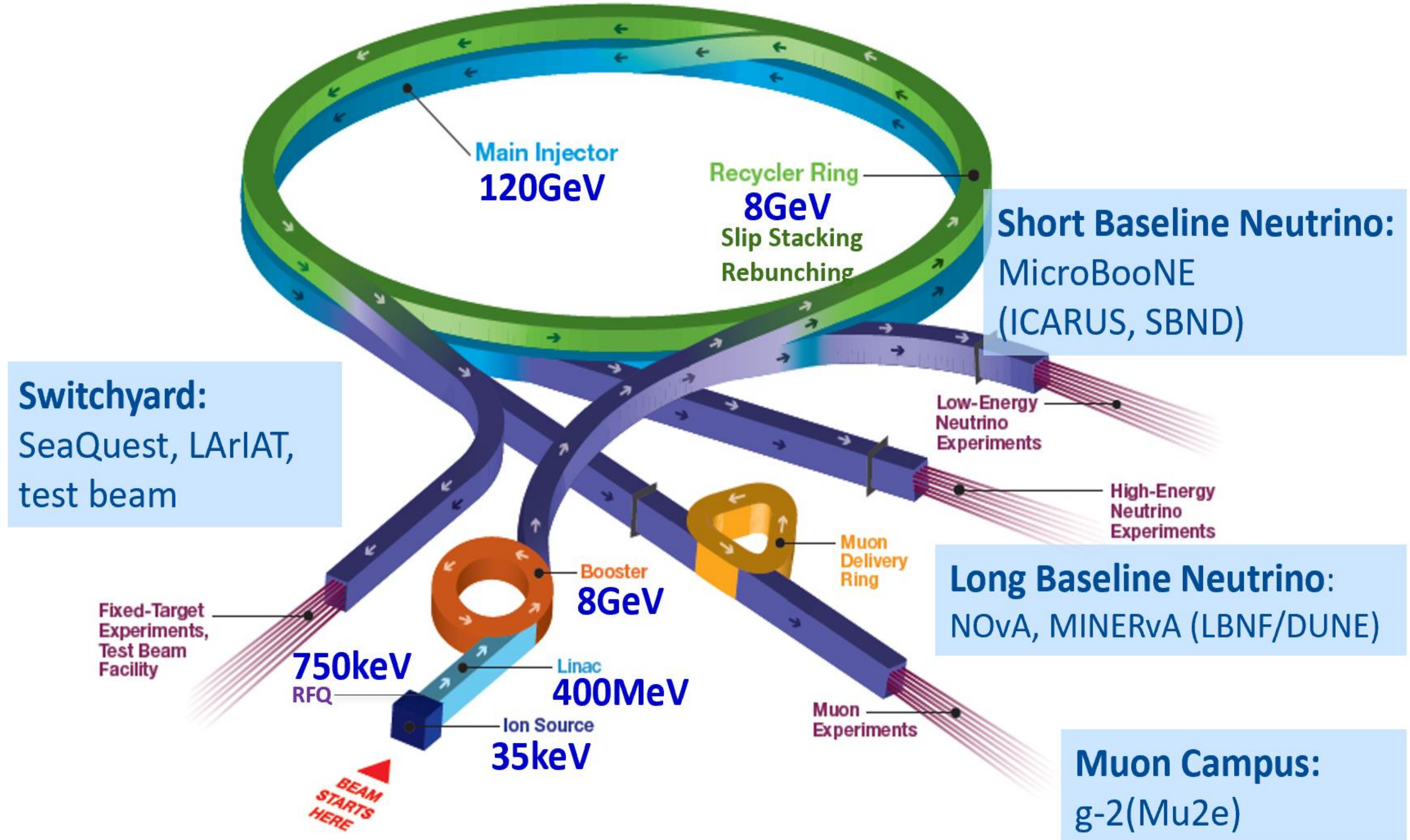
Record flux:	**>2.5e17 pph in FY18**
Operational:	**2.3e17 pph**
Goal:	**2.7e17 pph in FY22**



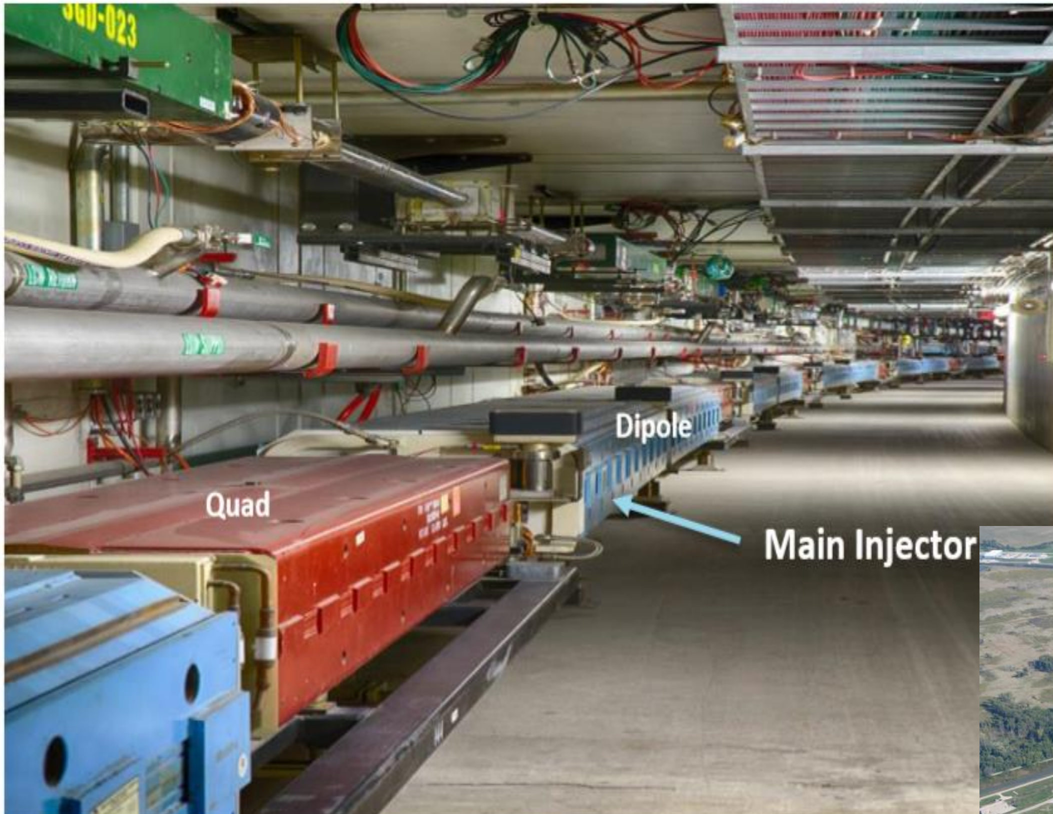


K. Seiya, NUFACT19, B. Worthel et al., Booster Rookie Book

Fermilab Accelerator Complex and Experiments



Main Injector – 120 GeV



Recycler (RR):

8GeV fixed energy storage ring with permanent magnets.

Main Injector (MI):

8GeV –120GeV Synchrotron

I. Kourbanis, K. Seiya, NUFACT19

Status	
Intensity:	53e12 protons
Energy Loss:	1 kJ
Cycle time:	1.333 s

Filling the Main Injector

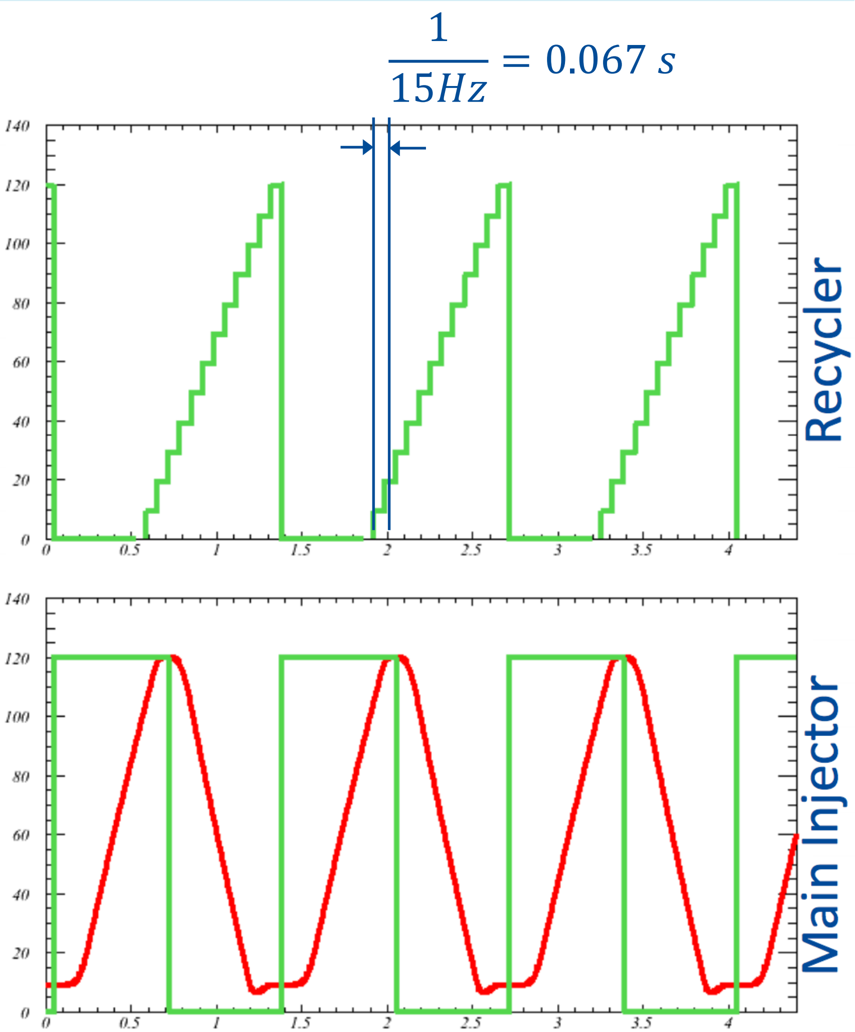
Every Main Injector cycle, the Booster extracted twelve pulses (called “batches”).

Each batch is stored in the Fermilab Recyler.
- Actually the Recycler is only 7 times the circumference of the Booster, so the 12 batches have to be overlapped using a two beam technique called slip-stacking.

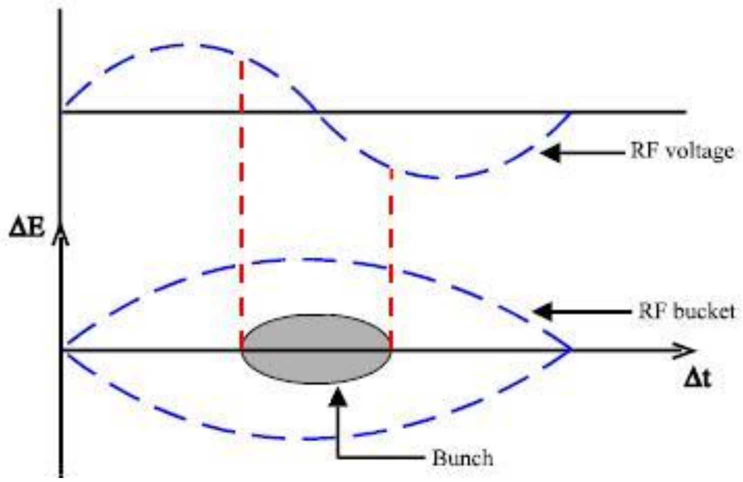
After accumulation in the Recycler, the beam is transferred to Main Injector to accelerate to 120 GeV.

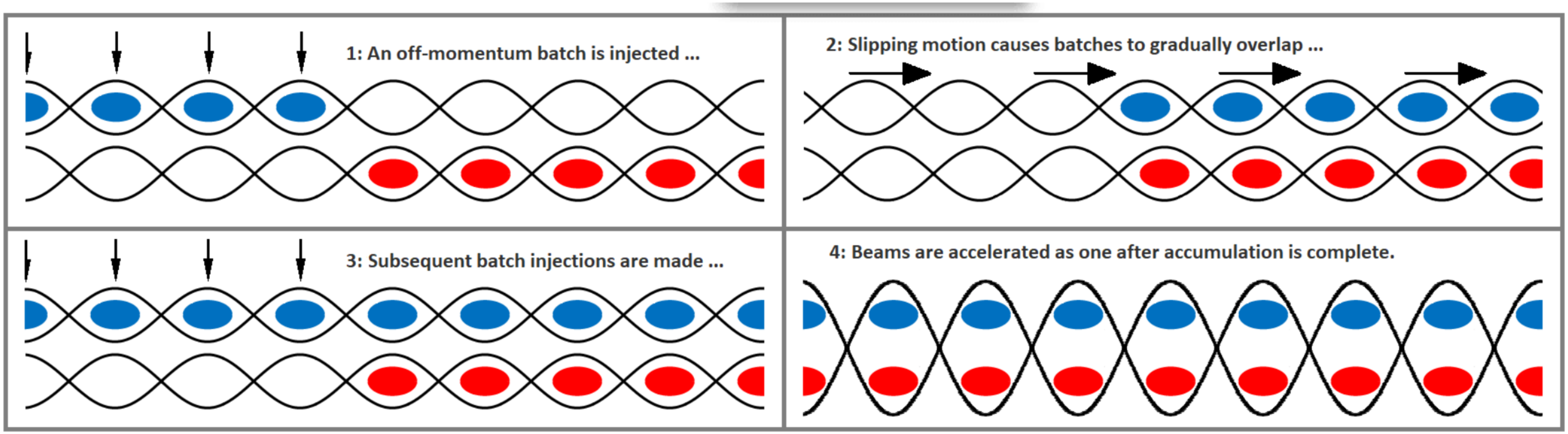
While the MI magnets ramp back down, the Recycler is already accumulating the next pulse.

It takes ~1.2s for the MI to ramp, and ~0.8s for the Recycler to accumulate.

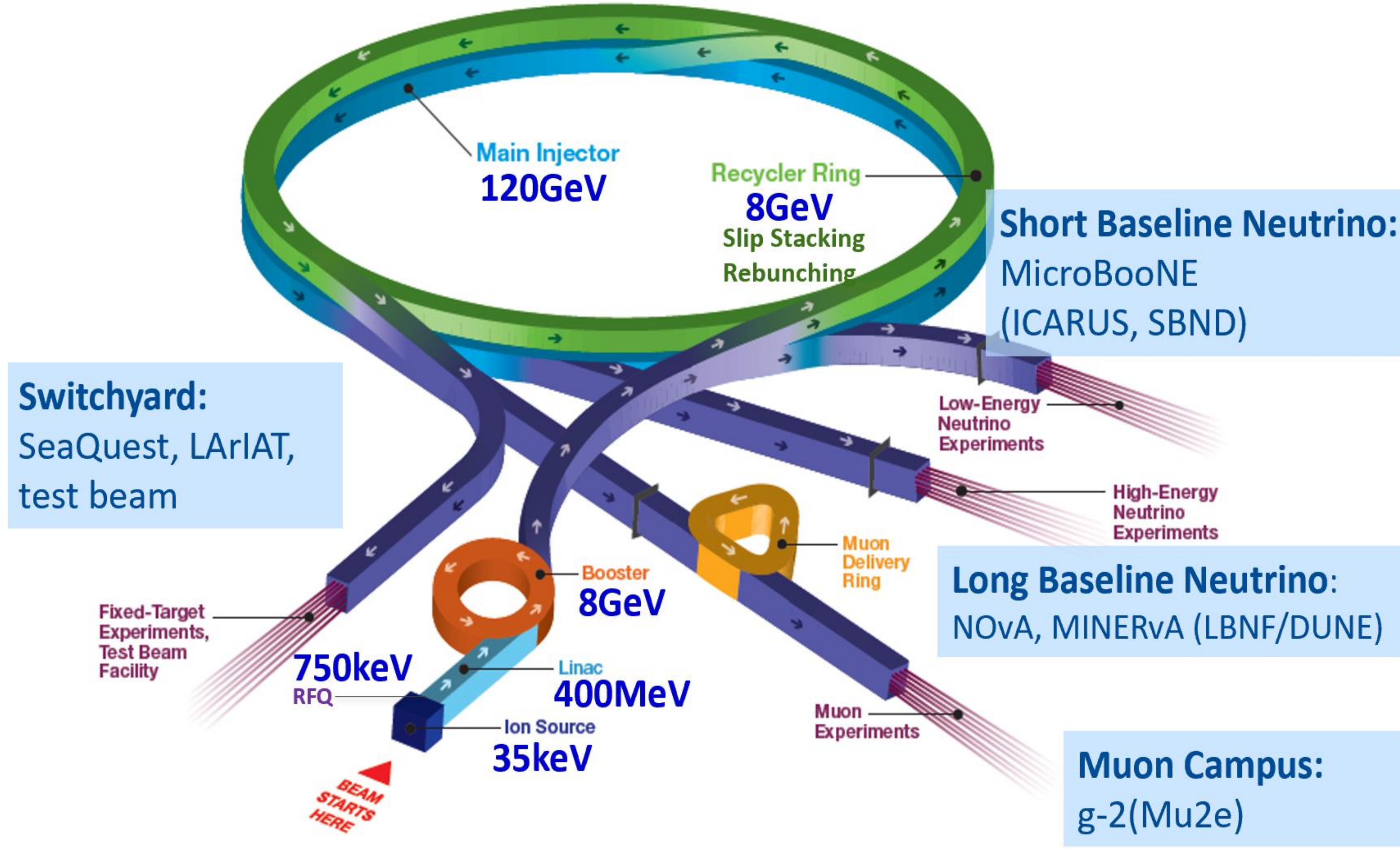


Slip-stacking

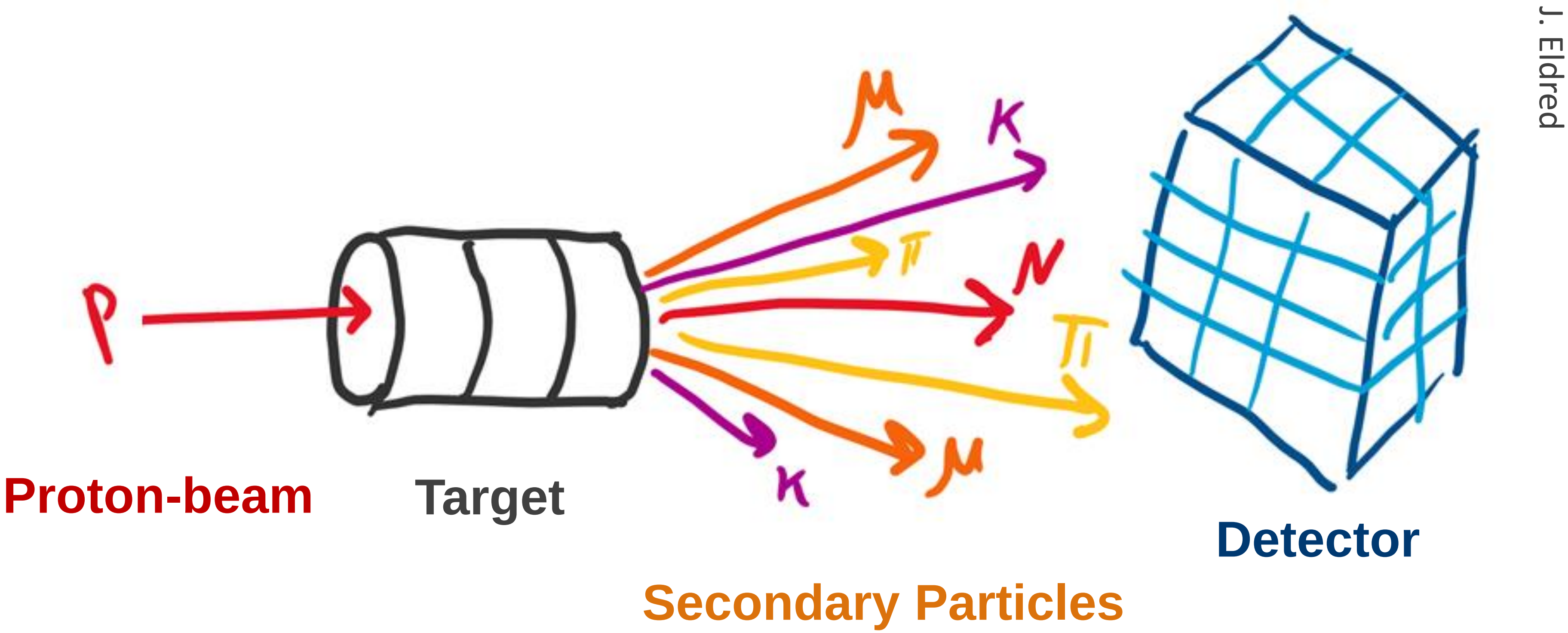




Fermilab Accelerator Complex and Experiments

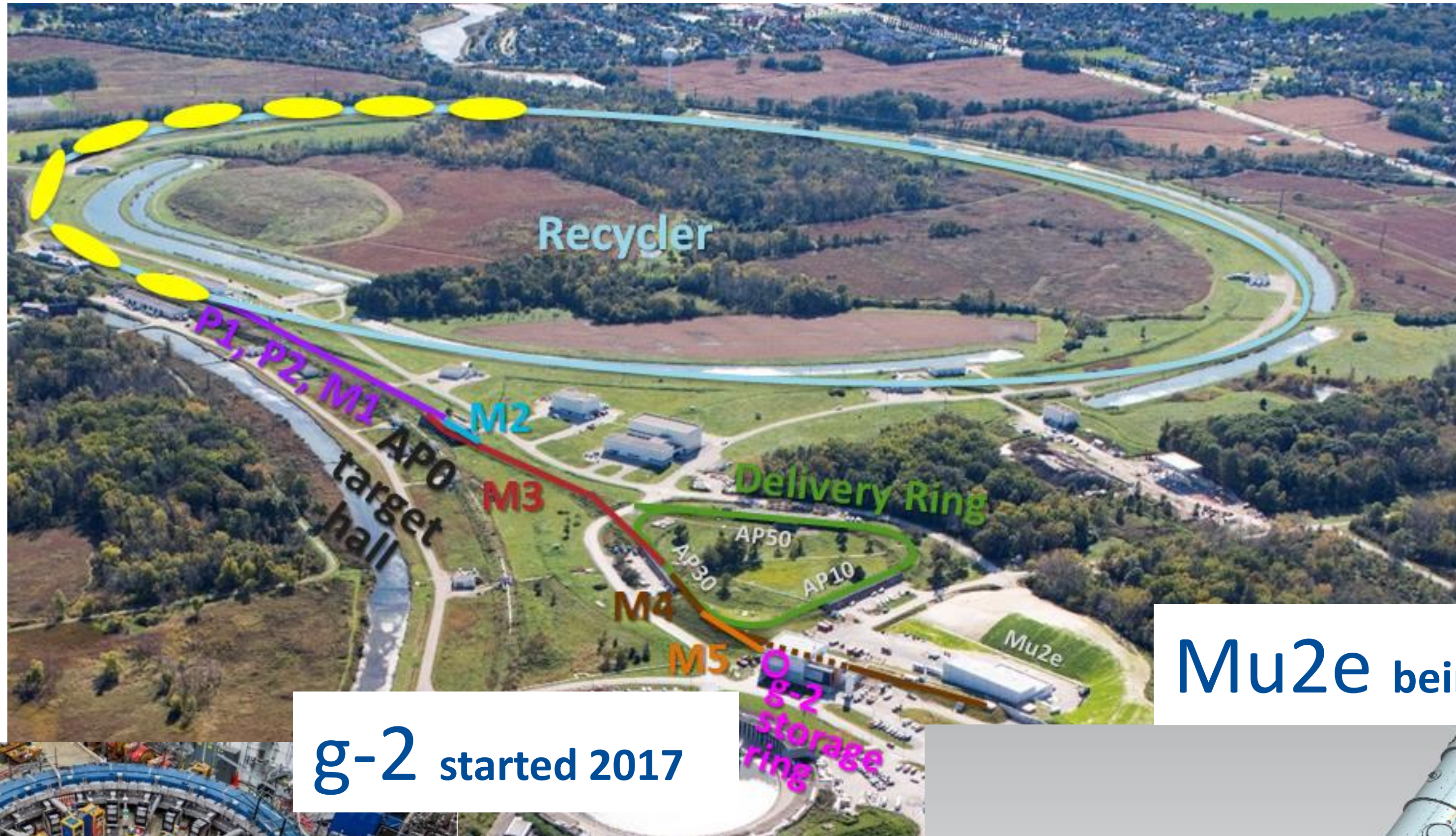


Cartoon of Particle Accelerator Experiments



The Fermilab Accelerator Complex is optimized to deliver intense proton beams at a variety of GeV-scale energies.

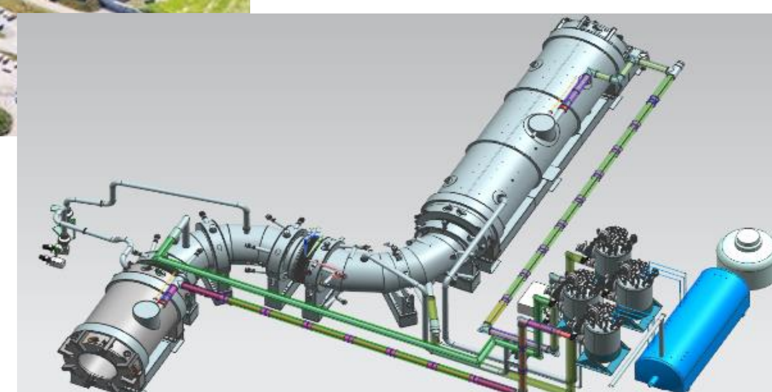
Delivery Ring & Muon Campus



K. Seiya, NUFACT19

g-2 **started 2017**

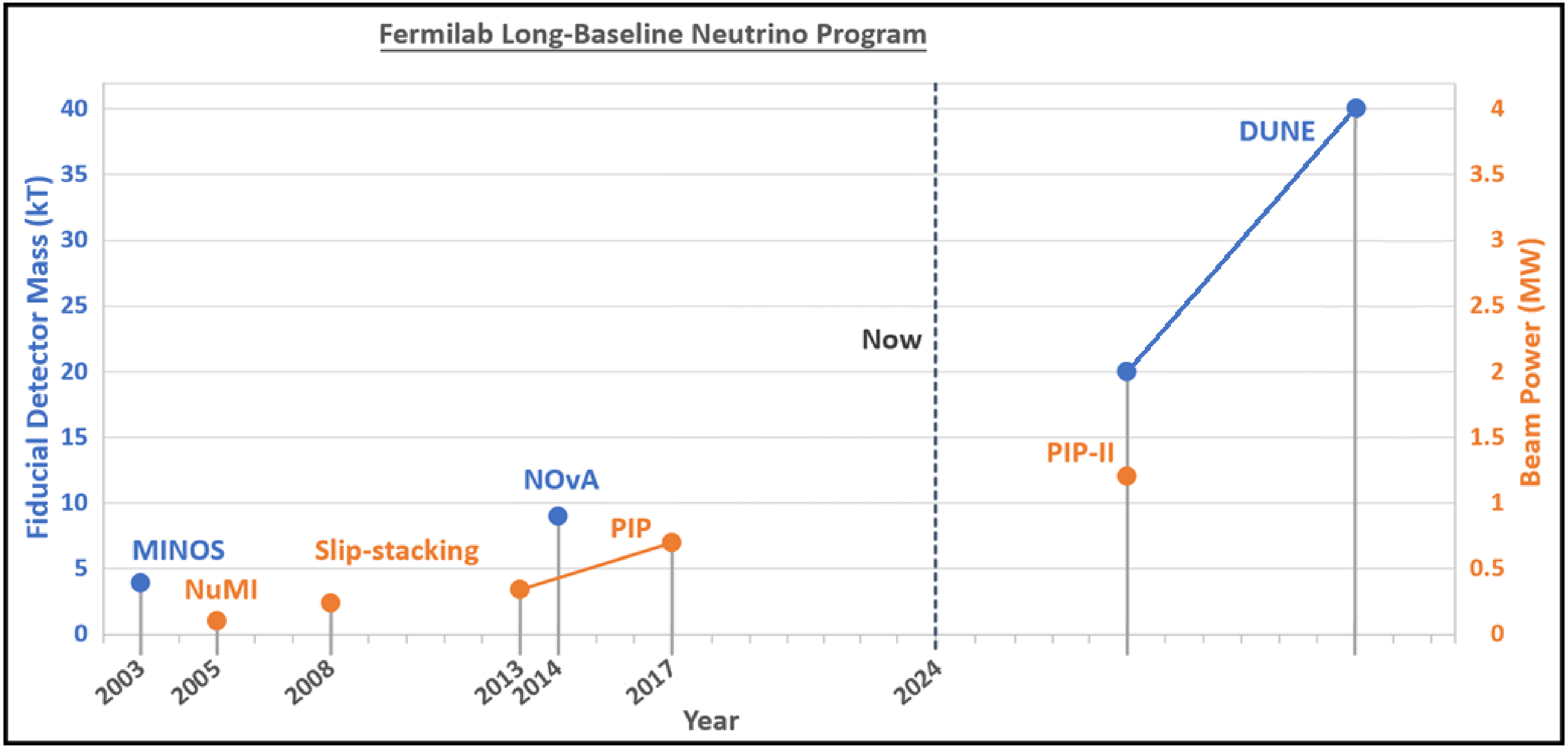
Mu2e **being built**



Future Proton Complex

Beam Power and Detector Size

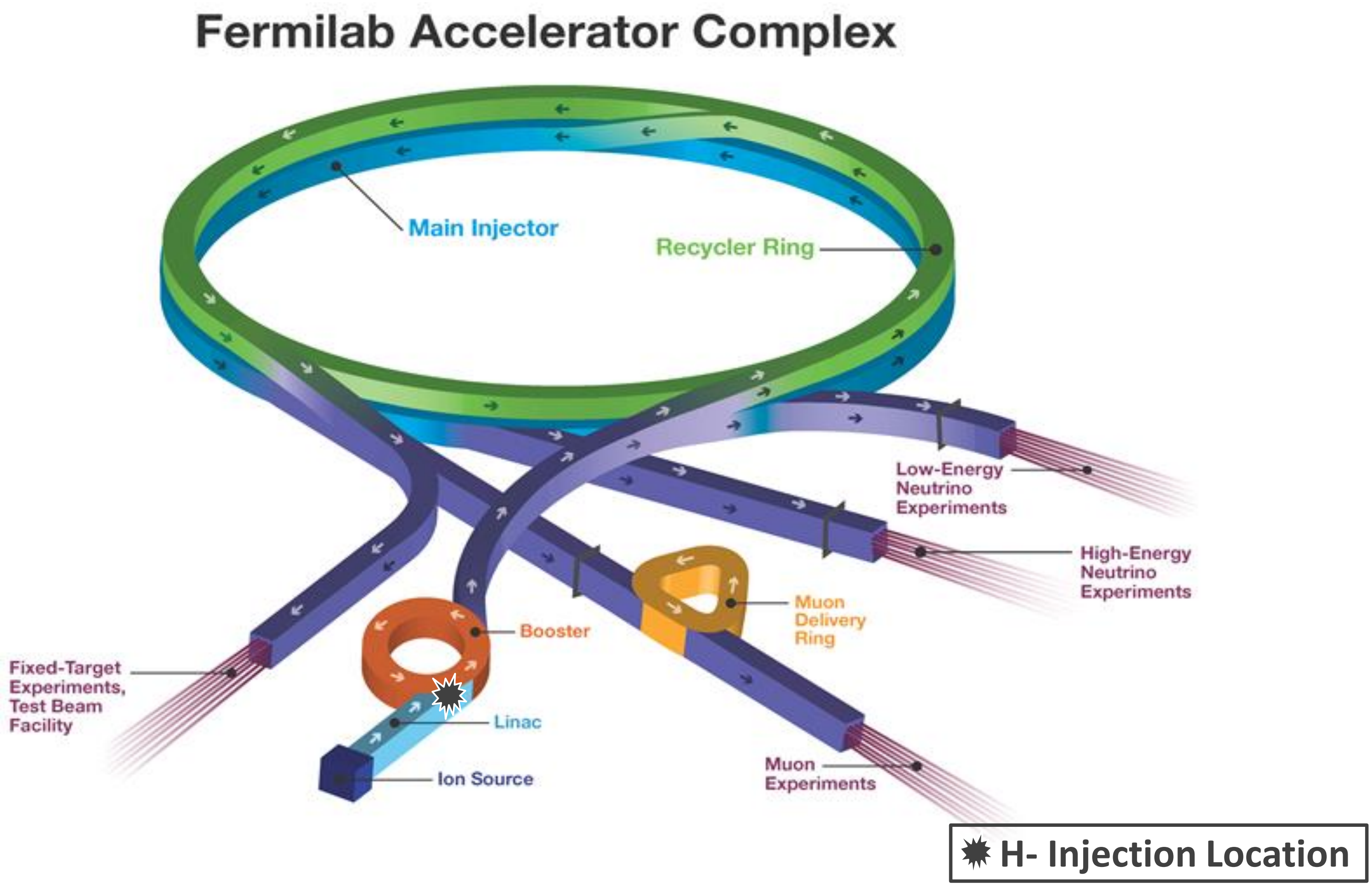
DUNE long-baseline neutrino program calls for **2.4 MW**



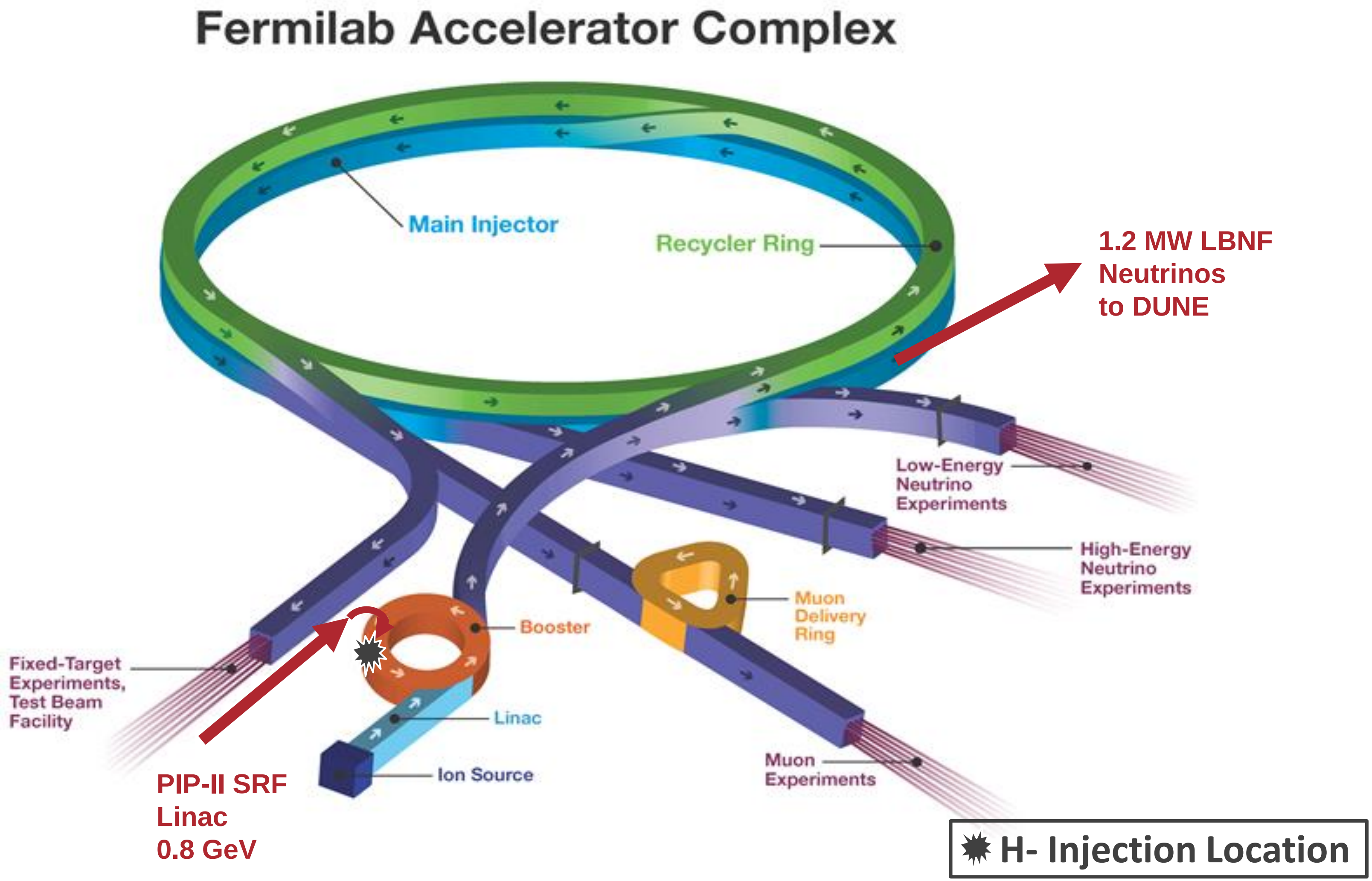
J. Eldred, JINST 2019

Fermilab

Fermilab Upcoming Upgrades 700-900 kW

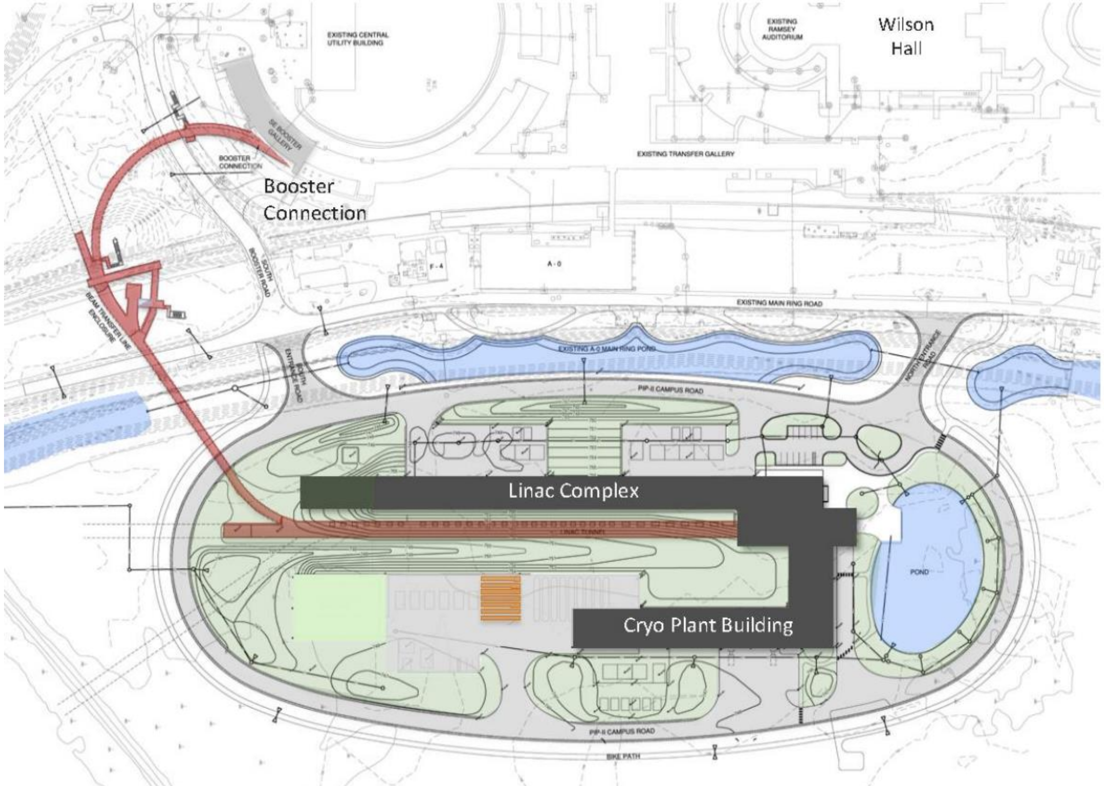


Fermilab Upcoming Upgrades PIP-II 1.2MW



New SRF linac raises Booster injection energy, new LBNF beamline.

PIP-II Linac & Upgrade



800 MeV H− linac
- Warm Front End
- SRF section

Linac-to-Booster transfer line
- 3-way beam split

Upgraded Booster
- 20 Hz, 800 MeV injection
- New injection area

Upgraded Recycler & Main Injector
- RF in both rings

Conventional facilities
- Site preparation
- Cryoplant Building
- Linac Complex
- Booster Connection

E. Pozdeyev, SpaceCharge19

Fermilab

PIP-II Timeline

2018 | 2019 | 2020 | 2021 | 2022 | 2023 | 2024 | 2025 | 2026 | 2027 | 2028

Mar 2018
Approve Alternative Selection (CD-1)

Mar 2019
Linac Complex Ground-Breaking

Jul 2020
Cryoplant Bldg. Construction Approved

Dec 2020
Approve Scope, Cost, Schedule (CD-2)

Mar 2021
Approve Long-Lead Procurements (CD-3a)

Apr 2022
Approve Technical Construction (CD-3)

Sep 2024
Linac Tunnel Occupancy

Oct 2026
Shutdown Complex Operations For Booster Connection

Jan 2027
SRF Linac Comm. Begins

Dec 2028
Project Completion
Start of Operations
(Early CD-4)

Fermilab

What's next? P5 Report offer clues

Over the last three years, the entire US physics community got together to discuss new physics experiments, priorities, and planning.

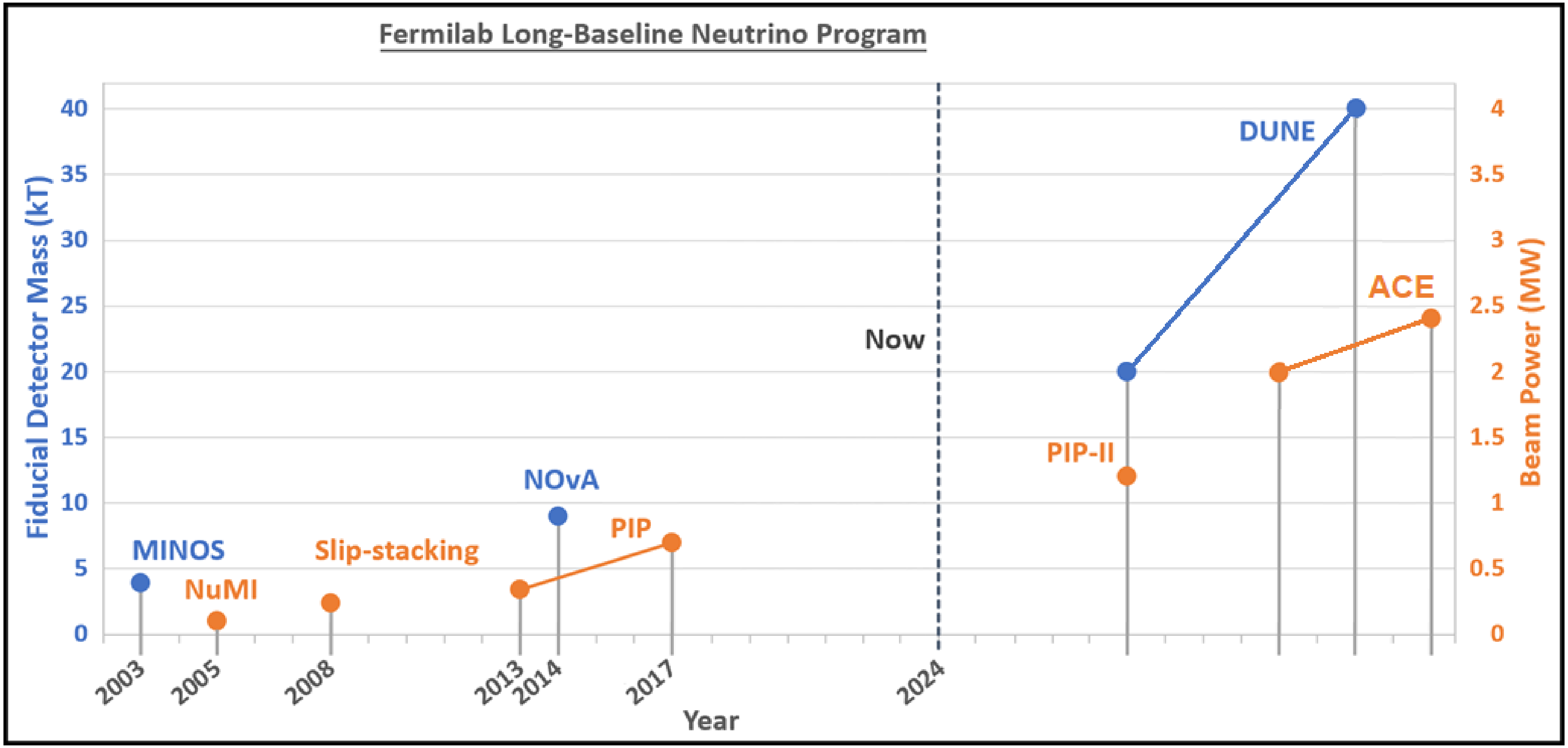
This is called Snowmass and culminated in the **P5 Report**

A couple of Fermilab related recommendations

- Affirms support for Fermilab's **DUNE** program and **PIP-I**I upgrade.
- Supports a newly proposed upgrade called **ACE-MIRT** which includes
  - Reducing the Main Injector ramp rate from 1.2s to 0.65s.
  - Material R&D and new designs for high-power neutrino targets.
  - Improve the reliability and infrastructure of the entire complex.
- Assess the Fermilab **Booster reliability**, and take measures.
- More **accelerator R&D**, in particular for new collider ideas.
- Develop a **20-year strategic plan** for future Fermilab proton complex.
  - What is after DUNE? What is after neutrino program?
  - Should we start to build a **muon collider?**

Beam Power and Detector Size (with ACE)

DUNE long-baseline neutrino program calls for **2.4 MW**



J. Eldred, JINST 2019

Fermilab

ACE MIRT – Main Injector Ramp & Targetry

Make the Main Injector ramp faster, rather than increasing intensity. Better for machine performance and better for targets.

To shorten the MI cycle 1.2 to 0.65s, the ramp needs to be twice as fast!

Requires more voltage and electrical power

- Power supplies, transformers, feeders, service building size, additional tunnel penetrations, additional cooling

RF accelerating system

- Replace cavities with newer design (more volts per cavity) or add cavities of current design

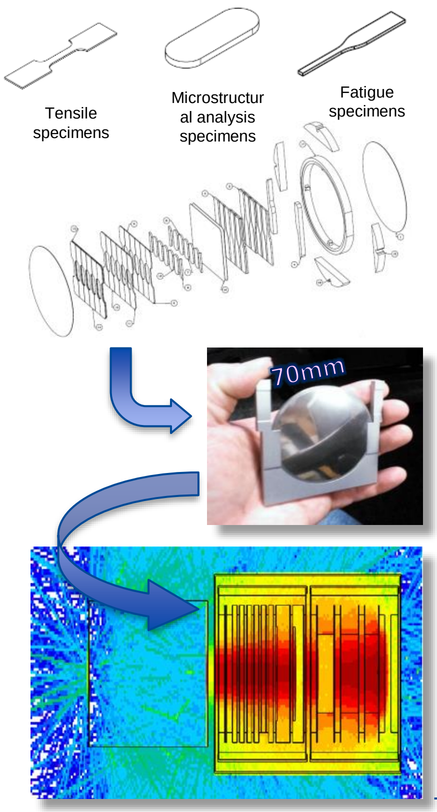
Regulation, control & instrumentation

- New low-level RF, new power supply regulation/control system

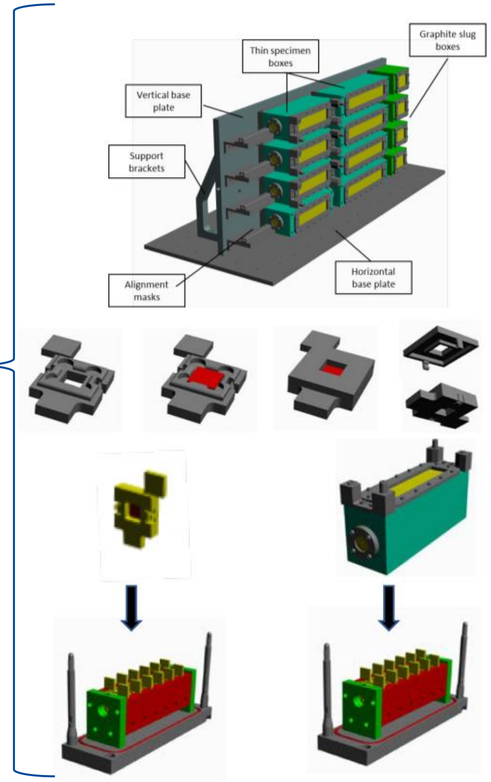
Beam dynamics, losses and shielding

- Upgrade MI collimators, upgrade abort line

Target materials R&D on critical path to 2+ MW target

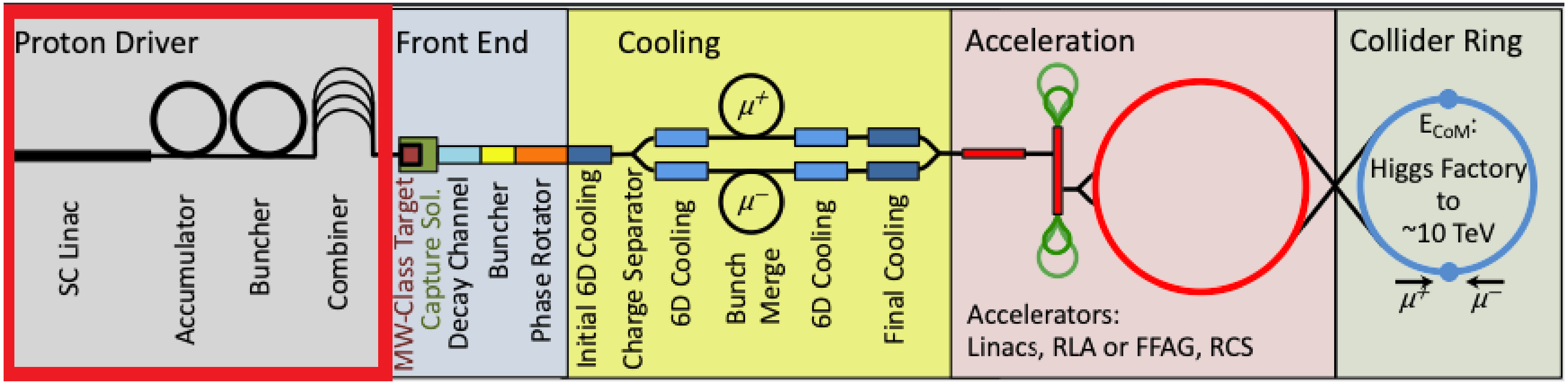


1. Identify candidate materials
2. High-energy proton irradiation of material specimens to reach expected radiation damage
3. Pulsed-beam experiments of irradiated specimens to duplicate loading conditions of beam interactions
4. Non-beam PIE (Post-Irradiation Examination) of specimens
   – Material properties
   – Microscopic structural changes
   – High-cycle fatigue testing



Five-year cycle needs to start ASAP

Muon Collider



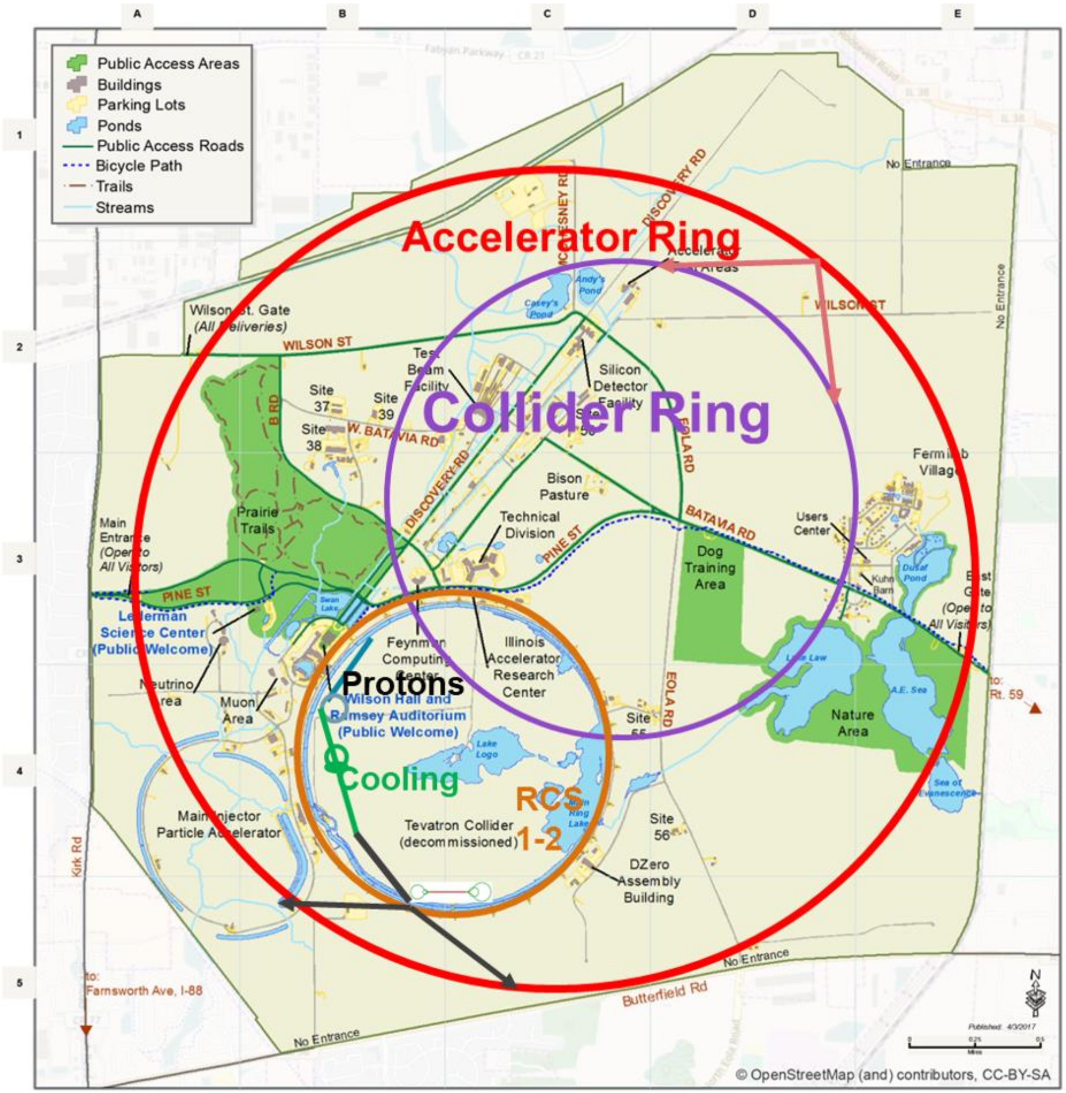
A complex chain of accelerators each of which needs R&D!

- Generate muons by concentrating 1-4MW protons on a target.
- Use a high-power targer and power solenoid to capture the muons.
- Cool those muons to collect them into a dense muon bunch.
- Rapidly accelerate the muons to 5 TeV before they all decay.
- Collide muons and anti-muons while managing intense decay radiation.

If the CERN LHC is like the first man on the Moon,

Muon Collider is the first person on Mars...

Muon Collider – 5+5 TeV on Fermilab Site

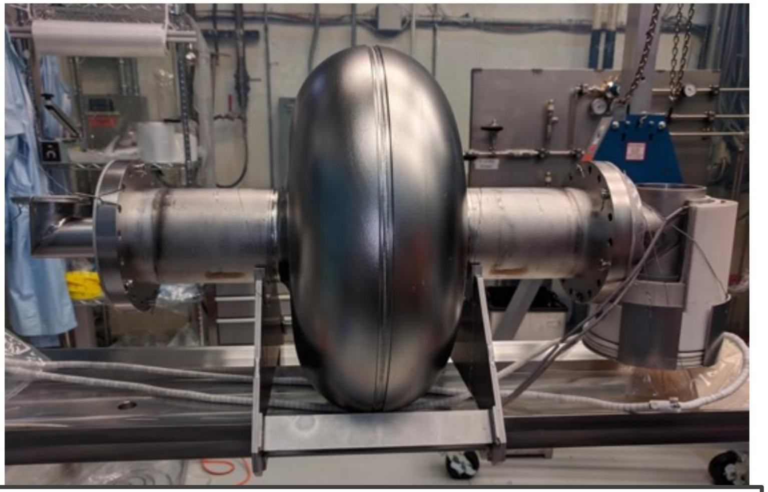


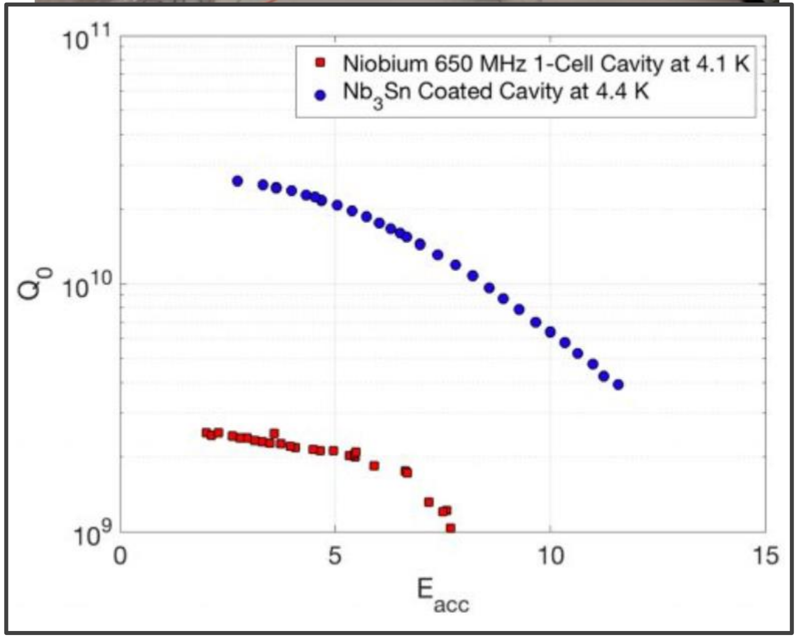
Fermilab

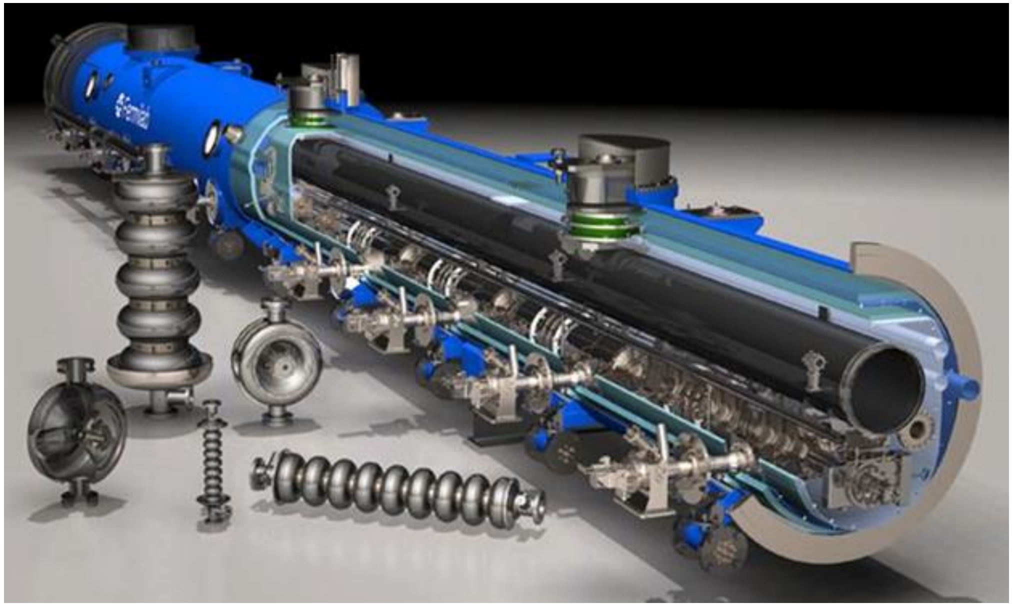
Accelerator R&D Facilities

Superconducting RF at Fermilab Technology Division

S. Posen, 2018



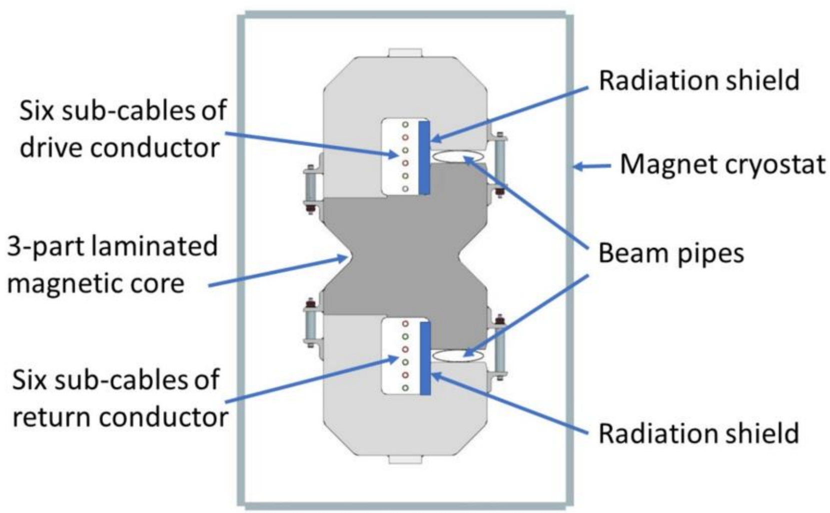




Fermilab has a cutting-edge superconducting RF R&D program to make accelerators more powerful, more efficient, and more affordable.

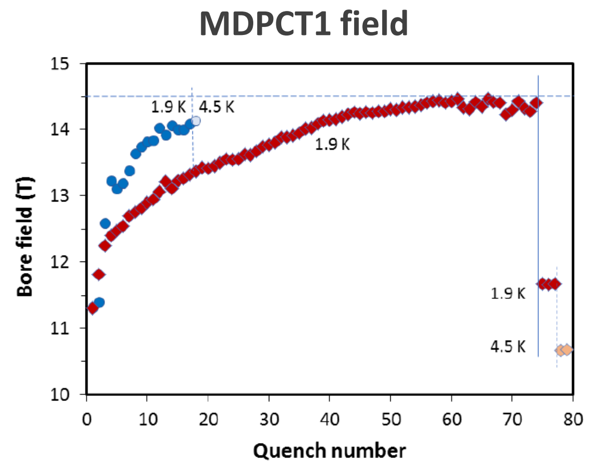
Superconducting Magnets at Fermilab TD

Highest field superconducting *Nb_3Sn* accelerator magnet!



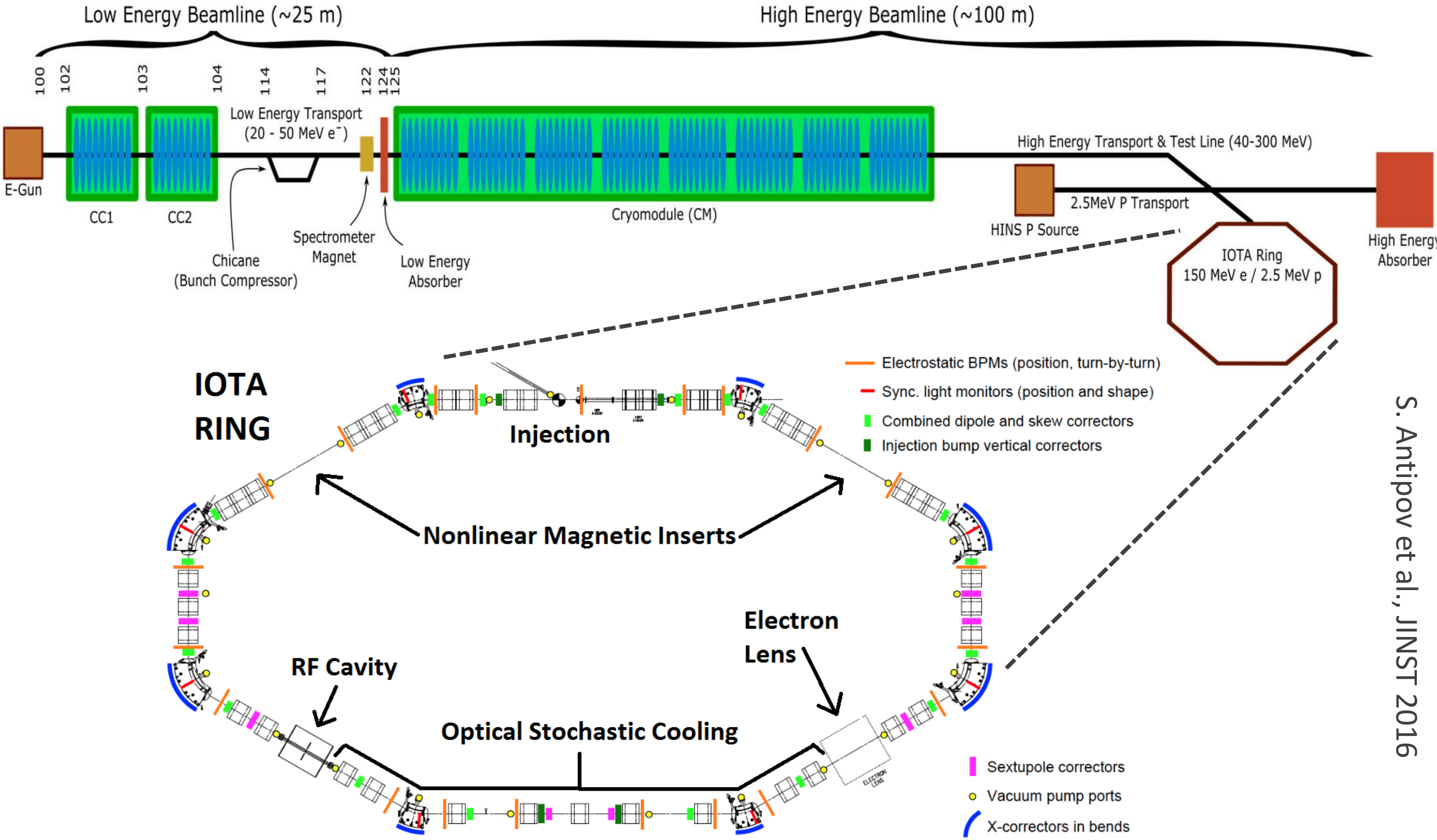
The field levels achieved in dipole model MDPCT1 at 4.5 K and 1.9 K set ***new world records for accelerator magnets***

B_{max}=14.5 T @1.9 K



Fastest-ramping superconducting *REBCO* accelerator magnet!

FAST/IOTA – Accelerator R&D Facility at Fermilab



S. Antipov et al., JINST 2016

Research + Operations at the Proton Complex

Linac
- Next-generation particle sources.
- Reliabilty and ML tuning.

Booster
- Extreme space-charge.
- PIP-II era H- injection design.

Delivery Ring / Muon Campus
- Resonant slow-extraction and beam quality.

Recycler / Main Injector
- Understanding collective instabilities, particle resonances.
- Dynamics of slip-stacking beams.

Beamlines & Targets
- Material reliability in high-radiation environments.
- Optimal capture/focusing for experiments.

Thank you!
Any Questions?