



Introduction to Accelerator Physics Concepts

Kevin Lynch, Division Lead AD/TSD
FNAL Saturday Morning Physics
2026-10-3

What we'll cover...

- Introductions
- Accelerators
- Fundamentals
- Fermilab Accelerator Complex
 - I am from Fermilab, after all....

Who the heck are you?

No, really ... who am I talking to, and why are you here?

Who the heck am I?

- FNAL Senior Scientist (2022-present)
 - Lead, TSD (2023-present)
- CUNY Professor of Physics (2010-2022)
- Education
 - Boston University (PDRA/ResProf 2002-2010)
 - Boston University (MA/PhD Physics 1996-2002)
 - MIT (SB Physics 1992-1996)
- Technical Experience
 - Experimental Muon Physics (2002-present)
 - MuLan, MuCap, MuD, MuFuse, Muon g-2, Mu2e, Muon Tomography
 - Large Scale Simulations (Geant4, FLUKA), Data Acquisition Hardware/Software, Timing, Targets
 - Engineering Failure Analysis (1993-2004)
 - MEMS



What are accelerators?

- *accelerator* first attested in English ~1610 “a hastener”
 - *accelerare*: Latin verb “to hasten”
 - Ad + Celerare: “to” + “hasten”
 - *celer*: Latin adjective “swift, quick, rapid, fast”
 - *kel-: PIE “to drive”
 - Cognate with “hold” and “exalt”, believe it or not
- Merriam-Webster says
 - “a device, substance, or program that increases the speed or rate of a process, action, or physical movement”
- In physics, an accelerator is a “device that uses electromagnetic fields to propel charged particles”

What do we do with accelerators?

- Experimental High-Energy and Nuclear Physics
- Medical
 - Direct Cancer treatment
 - Isotope production
 - X-ray production
- Material Science
 - Study structure of materials
 - Radiation damage
 - Neutron production
- Industry
 - Galvanization
 - Sterilization
 - Semiconductor manufacturing
- Many, many other applications!



Let's talk about fundamentals

- Accelerator physics is highly complicated and technical
- I am not really an accelerator physicist ... but all you need to know to understand how accelerators work is basic E&M
- There's math here to help tell the story; I don't expect you to memorize it!

The fundamental question for this talk

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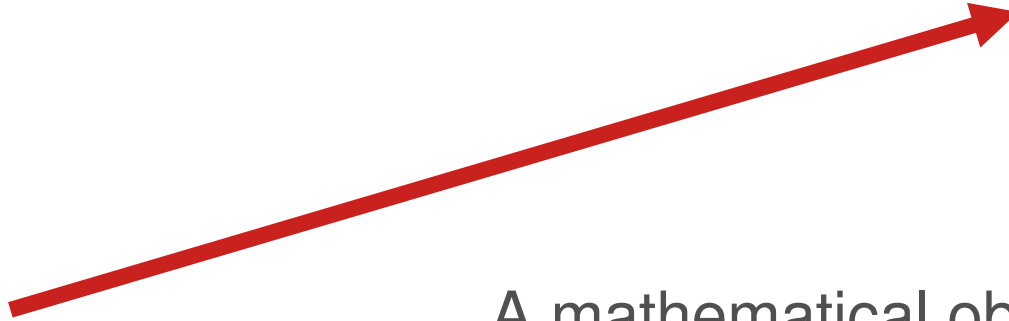
How do I get a particle to go
where I want it to go?

Let's start with vectors

Let's start with vectors



Let's start with vectors



A mathematical object that
has a *magnitude* and a
direction

Let's start with vectors



$$\vec{r}(t)$$

$$\vec{v}(t)$$

$$\vec{a}(t)$$

Let's start with vectors



$$\vec{r}(t)$$

$$\vec{\theta}(t)$$

$$\vec{v}(t)$$

$$\vec{\omega}(t)$$

$$\vec{a}(t)$$

$$\vec{\alpha}(t)$$

Let's start with vectors



$$\vec{r}(t)$$

$$\vec{\theta}(t)$$

$$\vec{v}(t)$$

$$\vec{\omega}(t)$$

$$\vec{p}(t) = m\vec{v}(t)$$

$$\vec{a}(t)$$

$$\vec{\alpha}(t)$$

To get a particle to go where I want, I have to push on it!

$$\vec{F}(\vec{r}, t) = \frac{d}{dt}\vec{p}(t)$$

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$$\vec{F}(\vec{r}, t) = \frac{d}{dt}\vec{p}(t)$$

$$\vec{F} = \frac{d\vec{p}}{dt}$$

$$F = ma$$

So, how do I push on a charged particle? The Lorentz Force

$$\vec{F} = \frac{d\vec{p}}{dt} = q\vec{E} + q\vec{v} \times \vec{B}$$

What the heck are E and B?

Electric and Magnetic *Fields*

A *field* has a magnitude and direction at every point in space and time: wind velocity field

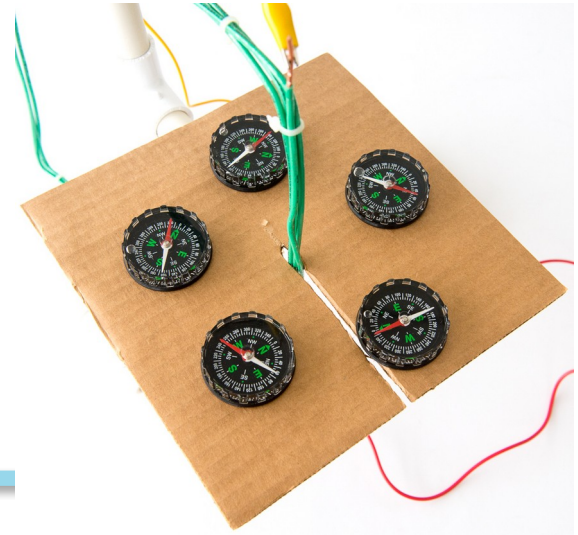
Electric and Magnetic *Fields*

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$$\vec{E}(\vec{r}, t)$$



$$\vec{B}(\vec{r}, t)$$



What can I ask (mathematically) about fields?

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How fast is it
changing?

$$\frac{d}{dt} \vec{E}(\vec{r}, t)$$

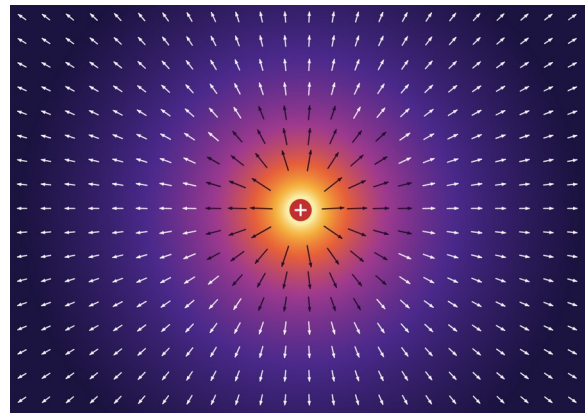
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Is there a source
generating the field?

$$\nabla \cdot \vec{E}(\vec{r}, t)$$



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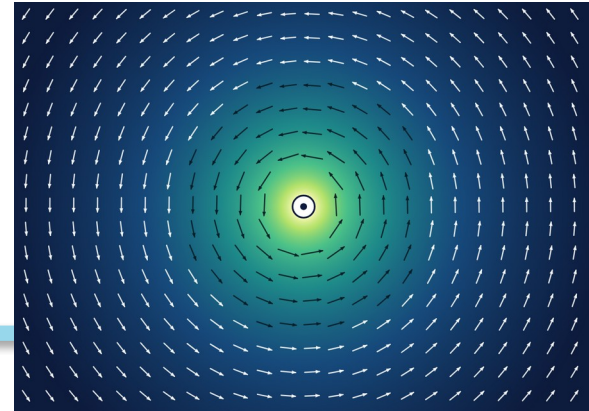
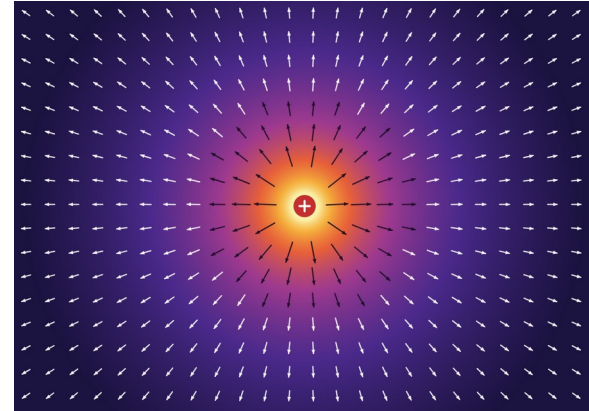
$$\frac{d}{dt} \vec{E}(\vec{r}, t)$$

Is there a source
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$$\nabla \cdot \vec{E}(\vec{r}, t)$$

Is it wrapping around?

$$\nabla \times \vec{E}(\vec{r}, t)$$



What can I ask (mathematically) about fields?

How fast is it
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Time derivative

Is there a source
generating the field?

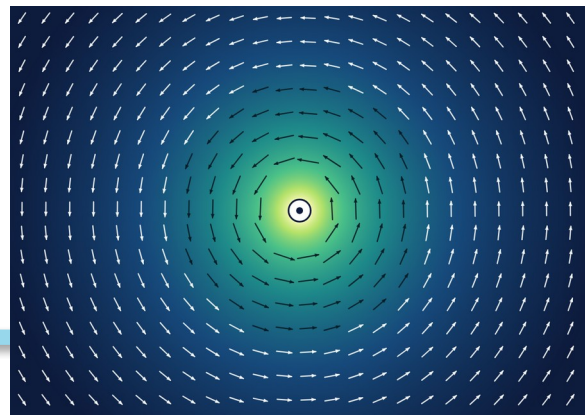
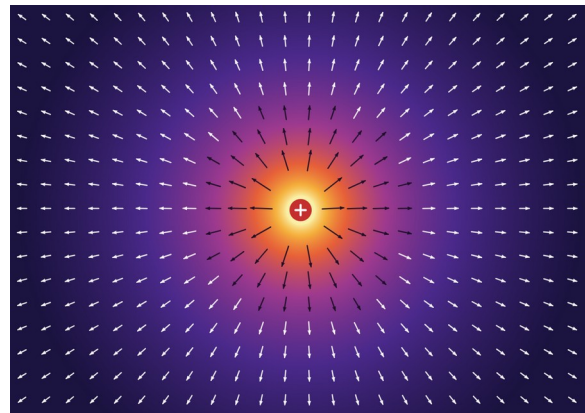
$$\nabla \cdot \vec{E}(\vec{r}, t)$$

Divergence

Is it wrapping around?

$$\nabla \times \vec{E}(\vec{r}, t)$$

Curl



Why do we care about divergence and curl?

The Helmholtz Decomposition theorem tells you how to reconstruct a field if you know both the divergence and curl everywhere!

Why do we care about divergence and curl?

The Helmholtz Decomposition theorem tells you how to reconstruct a field if you know both the divergence and curl everywhere!

And there's no way that I'm going to show you that formula here, but you can find it on Wikipedia

Maxwell tells us how to determine those properties!

$$\nabla \cdot \vec{E} = \frac{\rho}{\epsilon_0}$$

$$\nabla \cdot \vec{B} = 0$$

$$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}$$

$$\nabla \times \vec{B} = \mu_0 \vec{J} + \mu_0 \epsilon_0 \frac{\partial \vec{E}}{\partial t}$$

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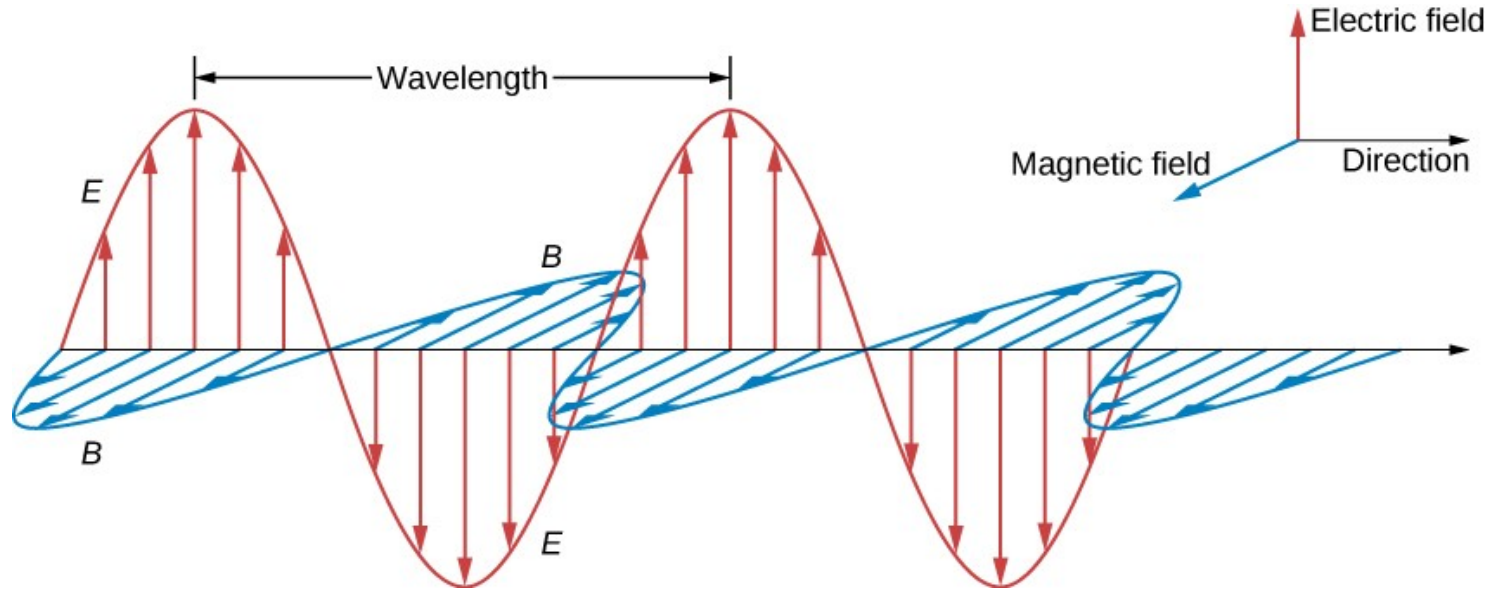
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Let's talk about these a little

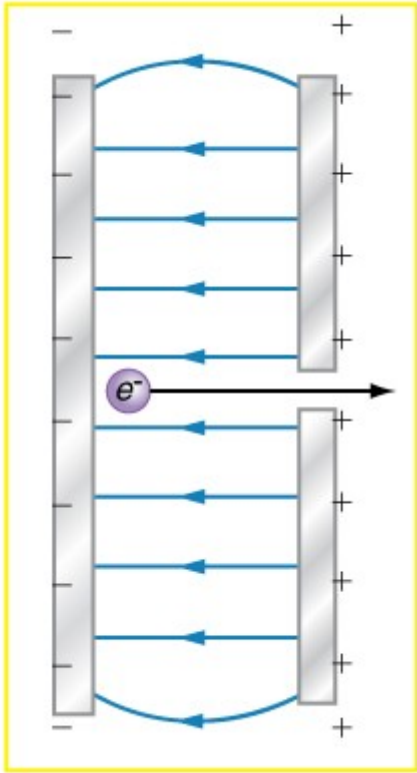
Electromagnetic waves!

$$\frac{\partial^2}{\partial t^2} \vec{E} = c^2 \nabla^2 \vec{E}$$



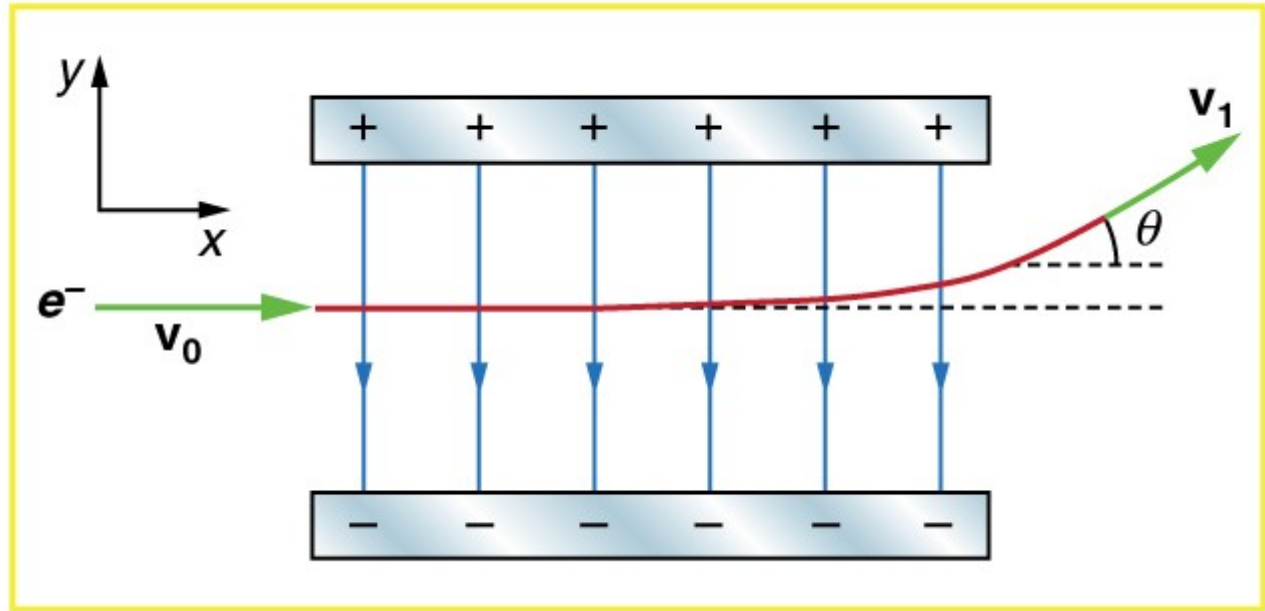
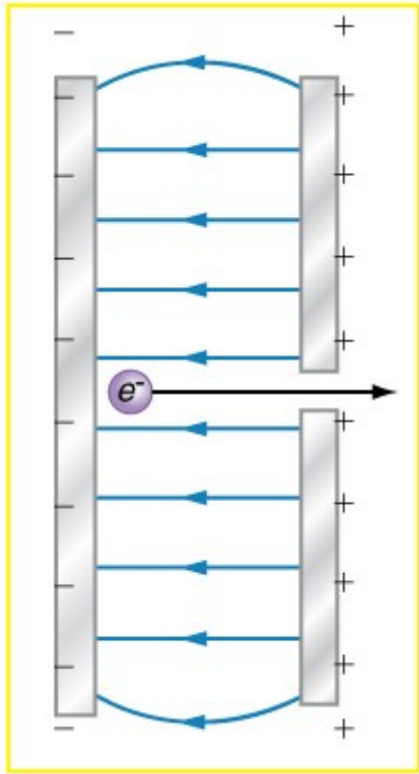
Moving particles in an accelerator – electrostatics!

$$\vec{F}_E = q\vec{E}$$



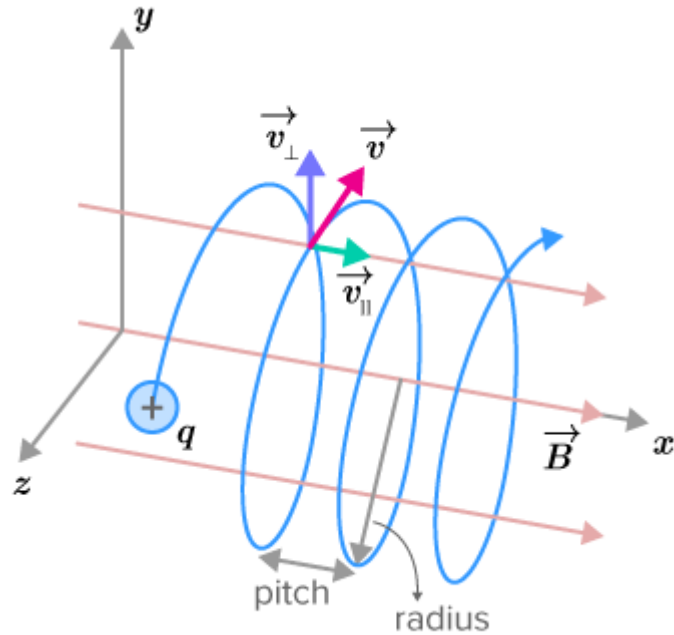
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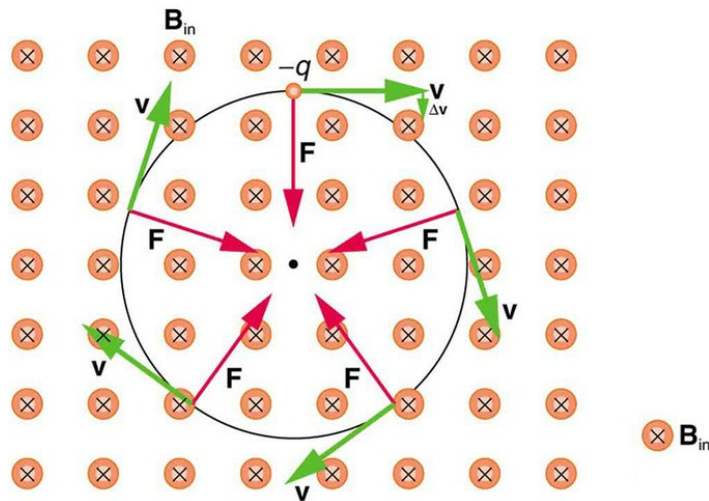
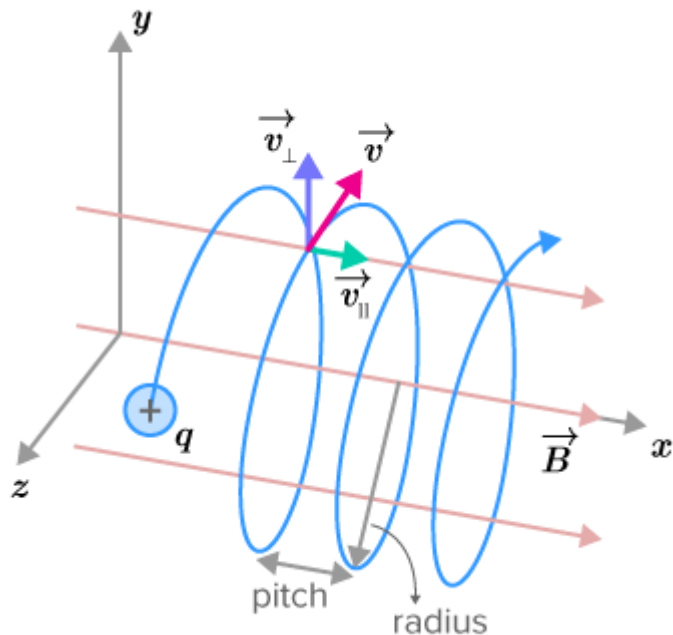
Moving particles in an accelerator – magnetostatics!

$$\vec{F}_B = q\vec{v} \times \vec{B}$$



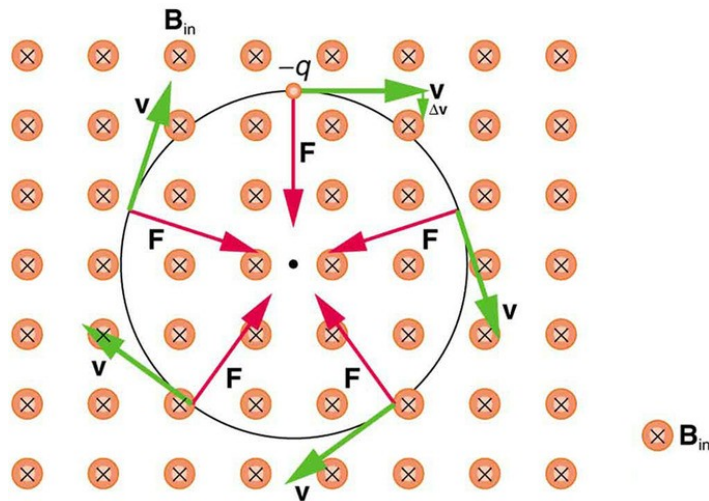
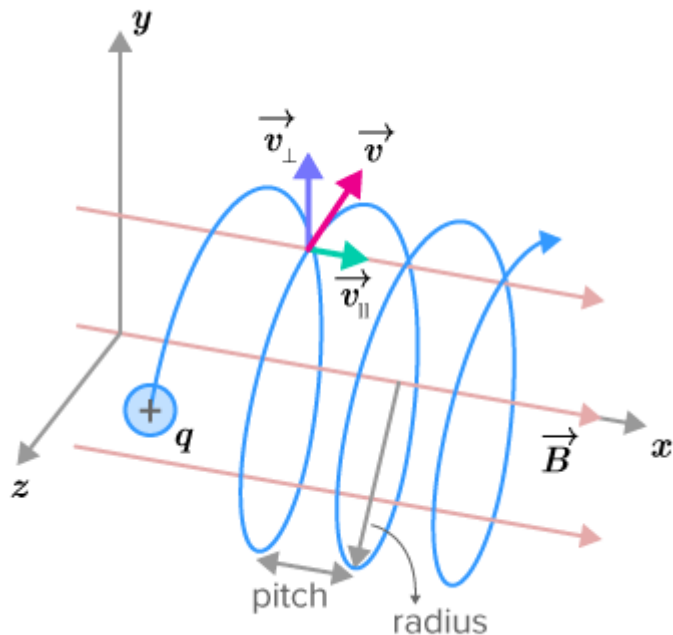
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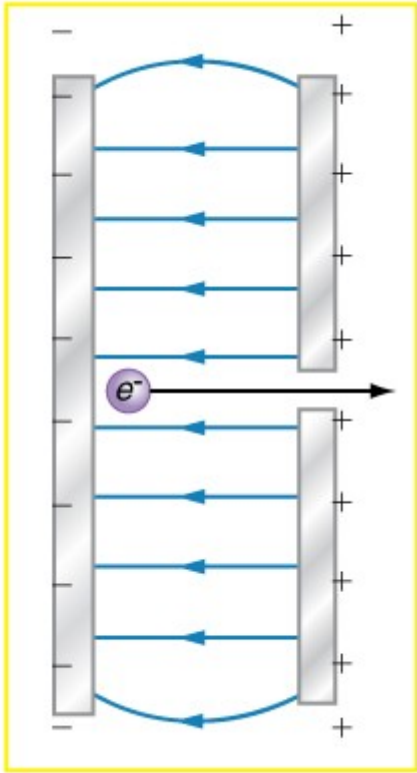
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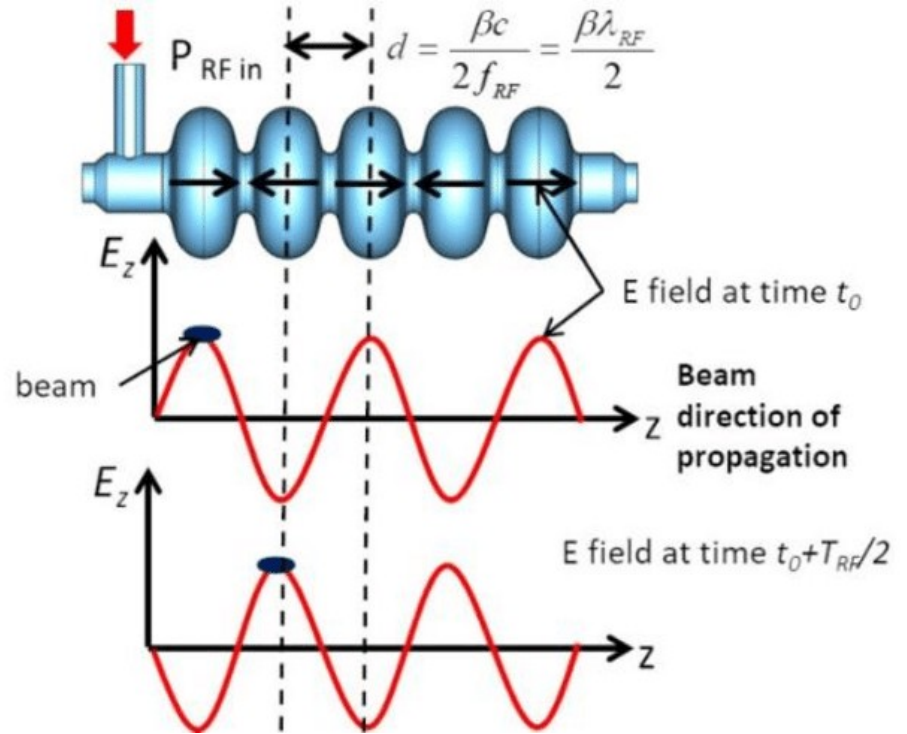
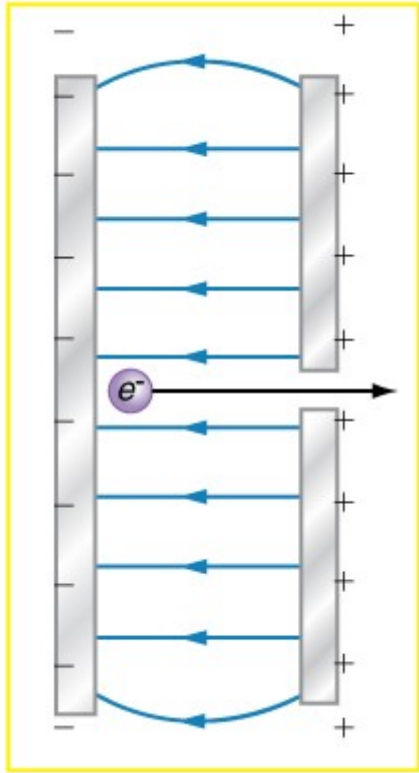
$$R = \frac{p}{qB}$$

Cyclotron
radius

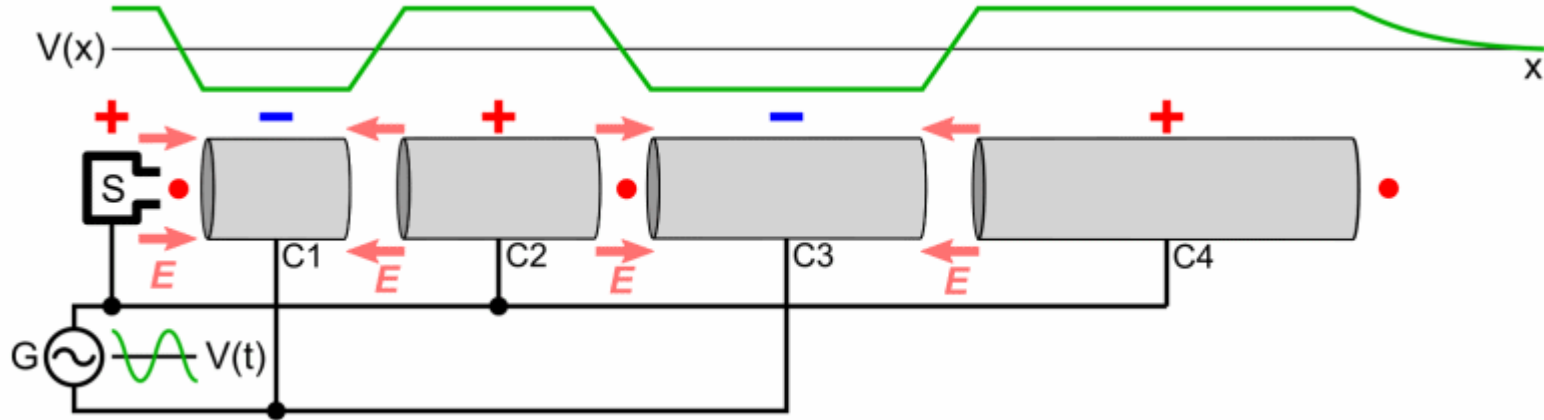
Electrostatic acceleration is inefficient: RF cavities fix the problem



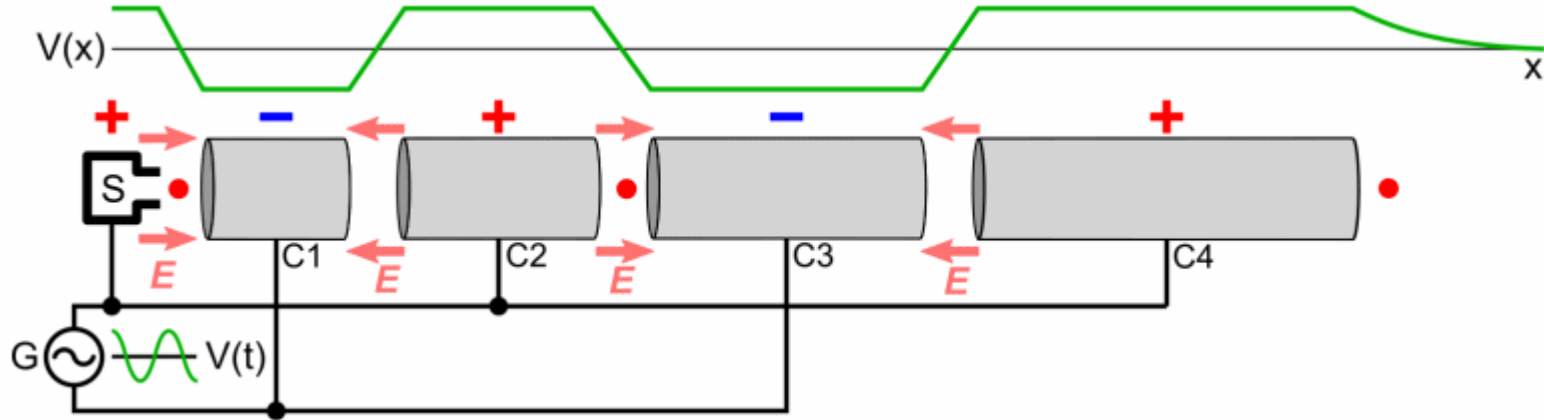
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How RF cavities work



How RF cavities work

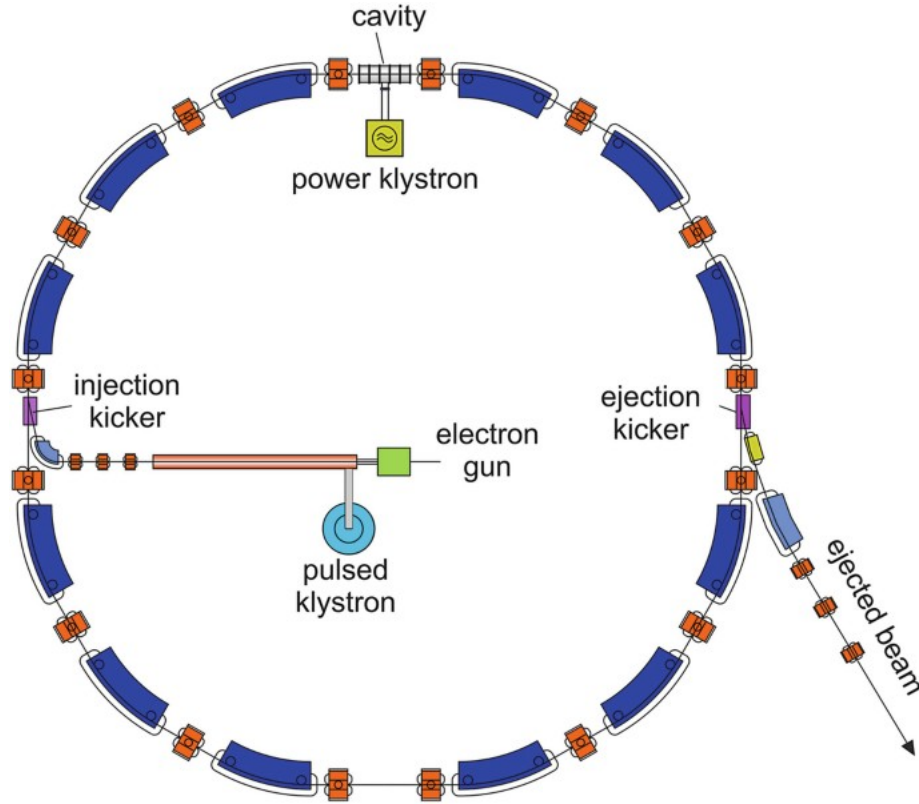


This naturally results in discrete, time separated *beam bunches*, not continuous beam!

Linear accelerators



Linacs take up a lot of space: multipass accelerators



Multipass accelerators



Key complications with circular machines

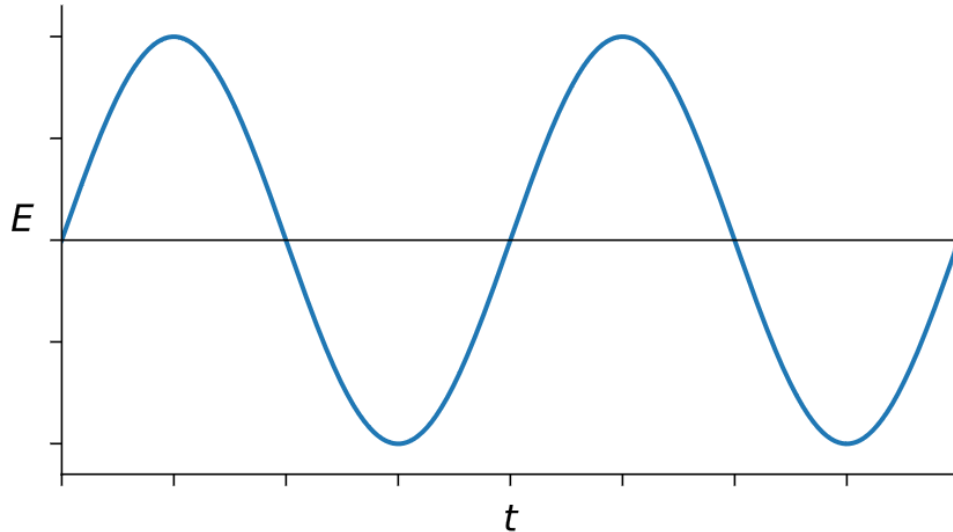
- Large vacuum volumes!
- As the particle momentum increases, so must the magnetic field to contain the particle inside the machine
$$R = \frac{p}{qB}$$
- *RF frequency* has to change as speed increases so the peaks match for a particle that has run around the circumference – that's surprisingly hard to accomplish
- Particles that don't stay near the middle of the *RF bucket* will be *lost*
- Lost particles result in large *radiation doses* if not shielded, so we put machines underground in *tunnels*, with lots of rules to protect people that have to enter to do maintenance and troubleshooting

It's time to talk about RF buckets

- If you don't do something, particles in a bunch will spread out around the circumference of a machine, filling in those gaps you need
- In addition to accelerating particles, RF cavities can *maintain* or *rebunch* those spreading bunches

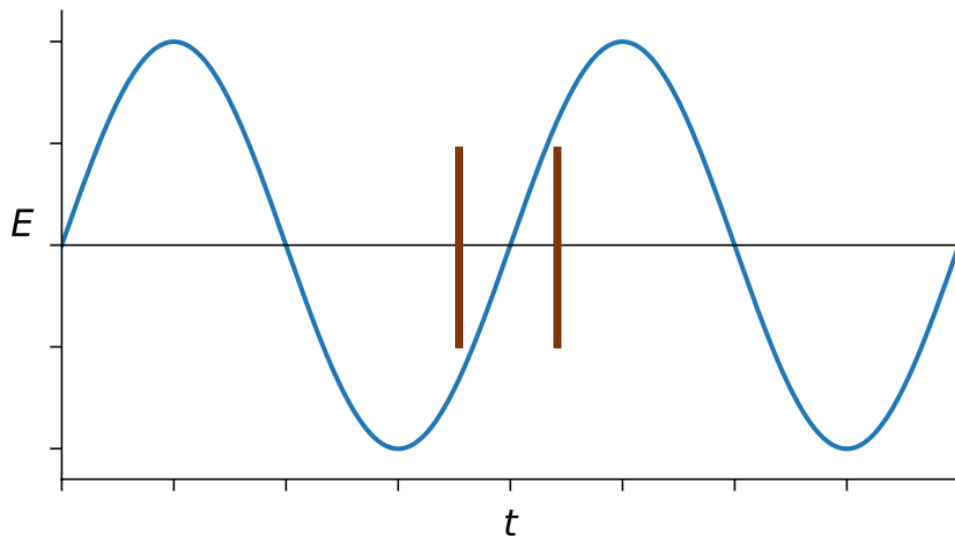
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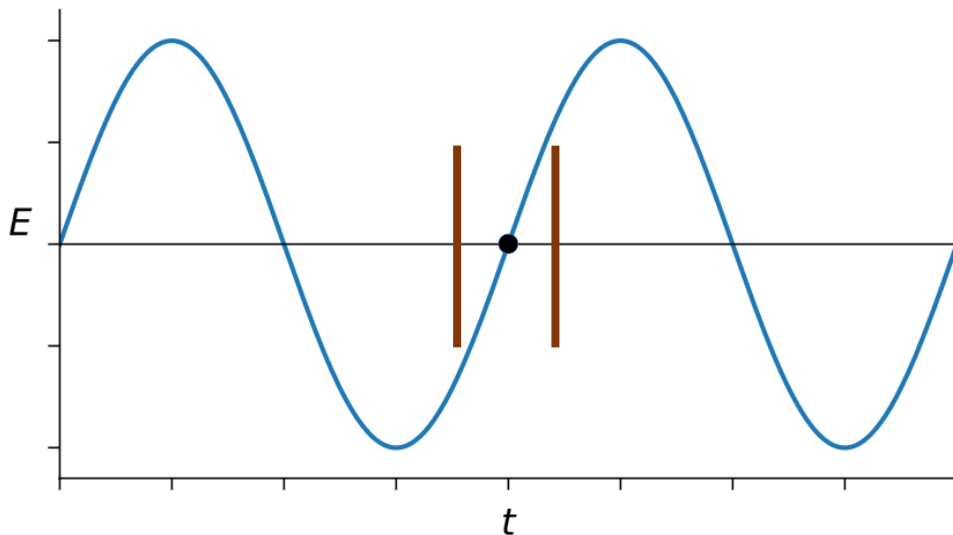
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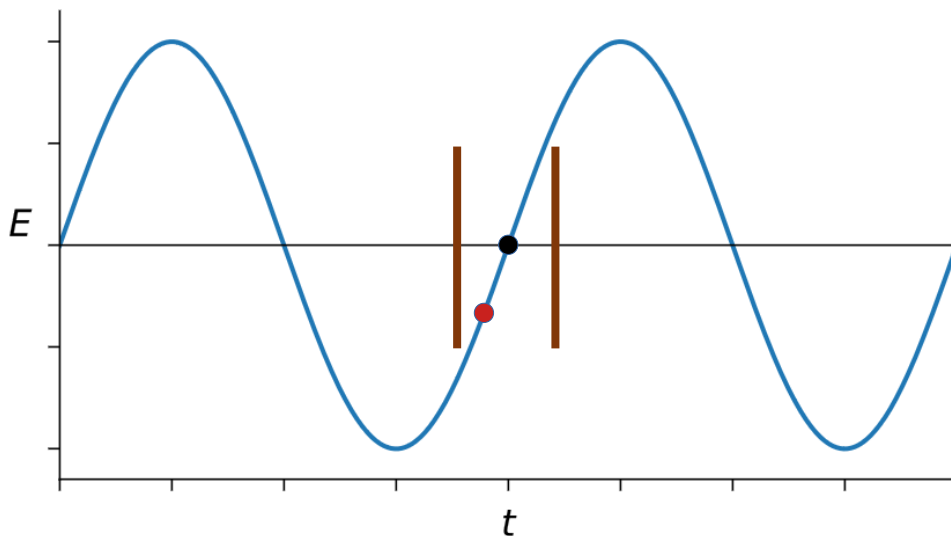
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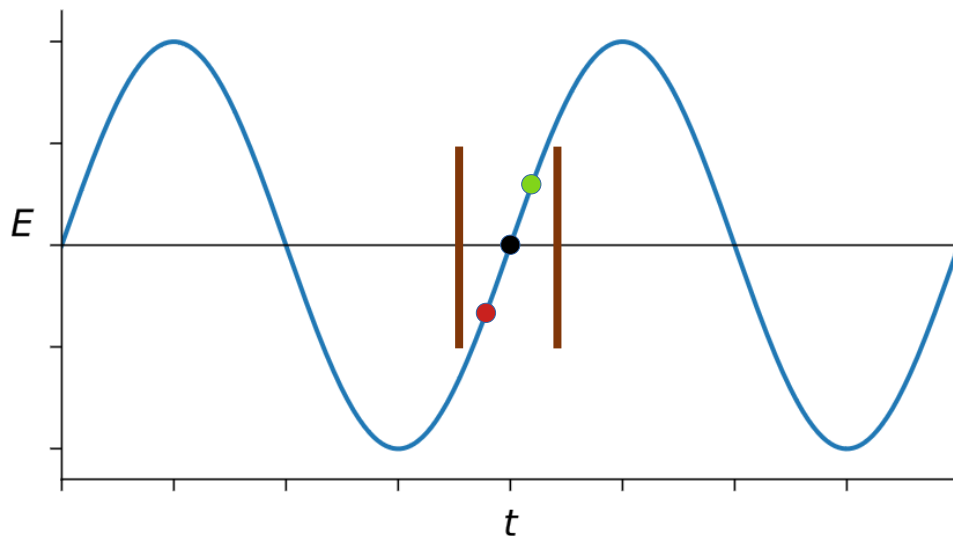
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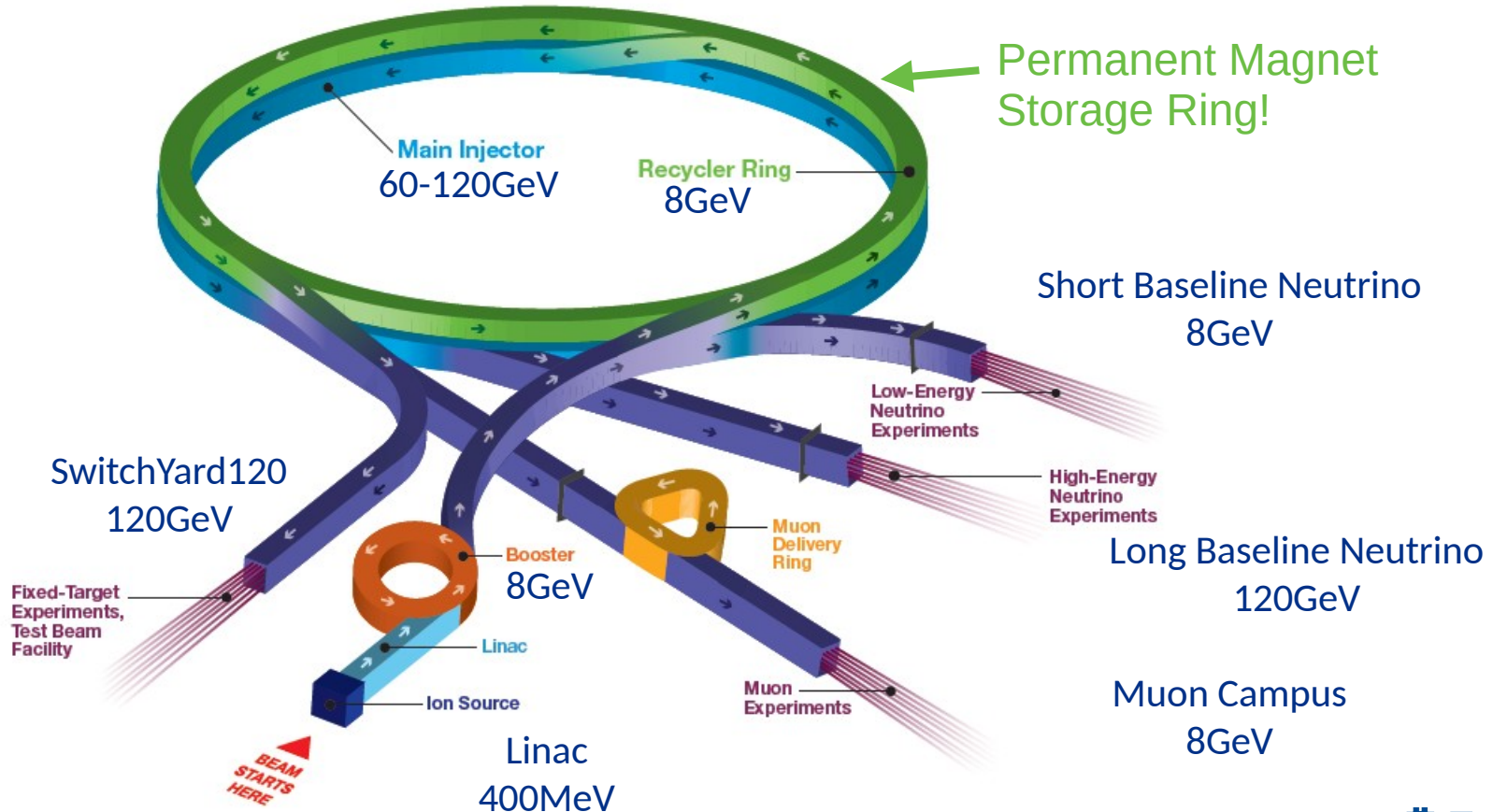


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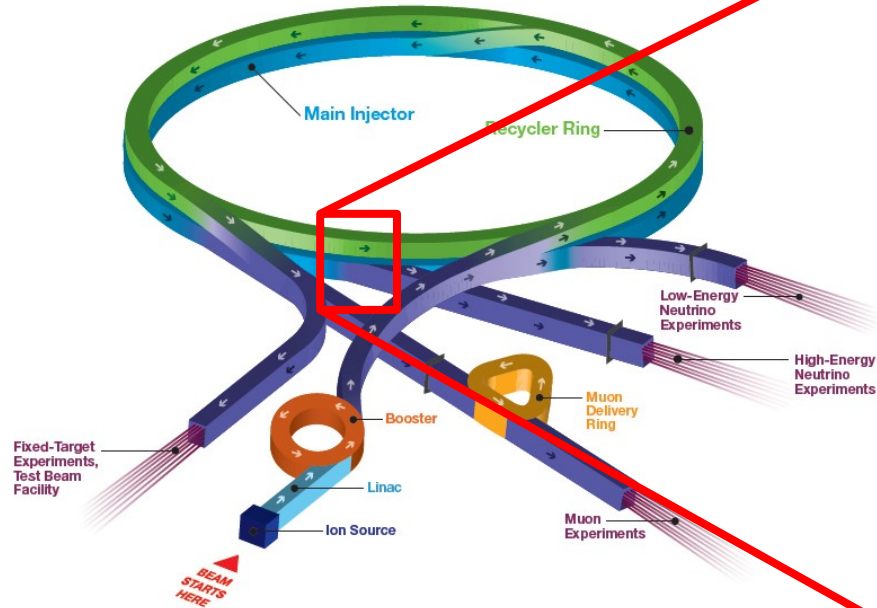
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Fermilab accelerator complex as an example of real machines



Reminder that these cartoons hide a wealth of complex and interesting science and engineering

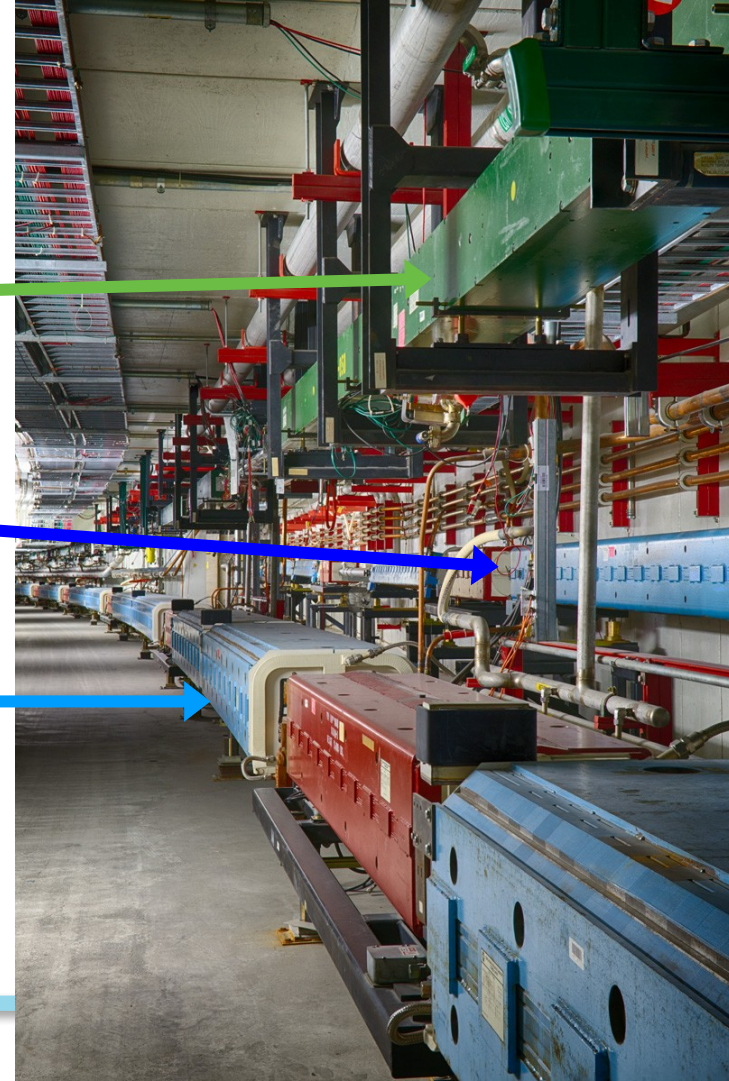


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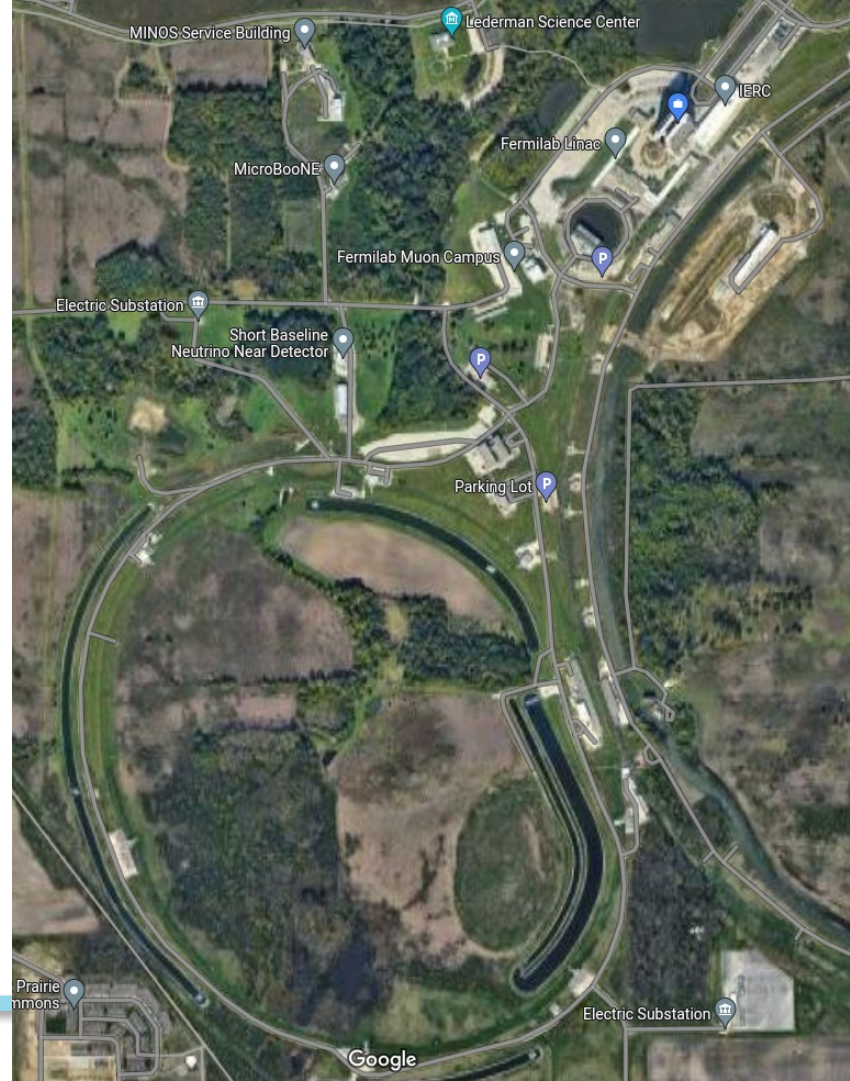
Recycler Ring

NuMI Extraction Line

Main Injector



They also hide a vast hierarchy of scales!

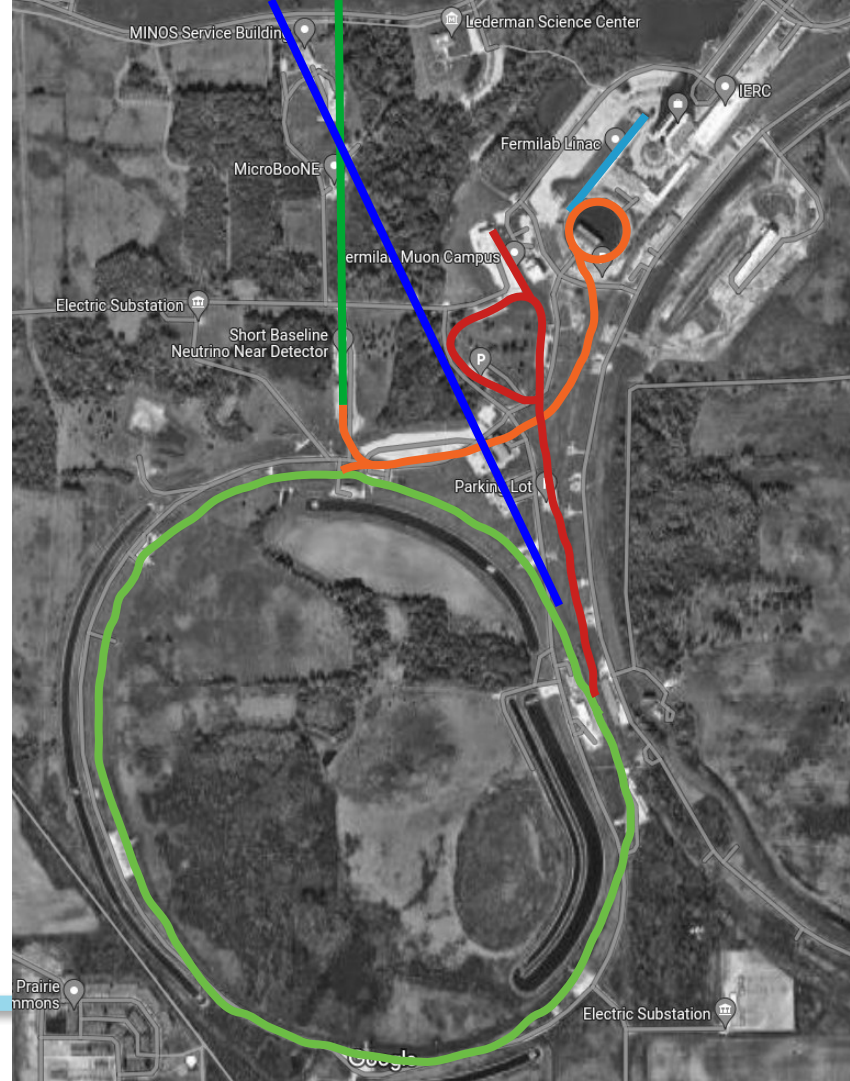


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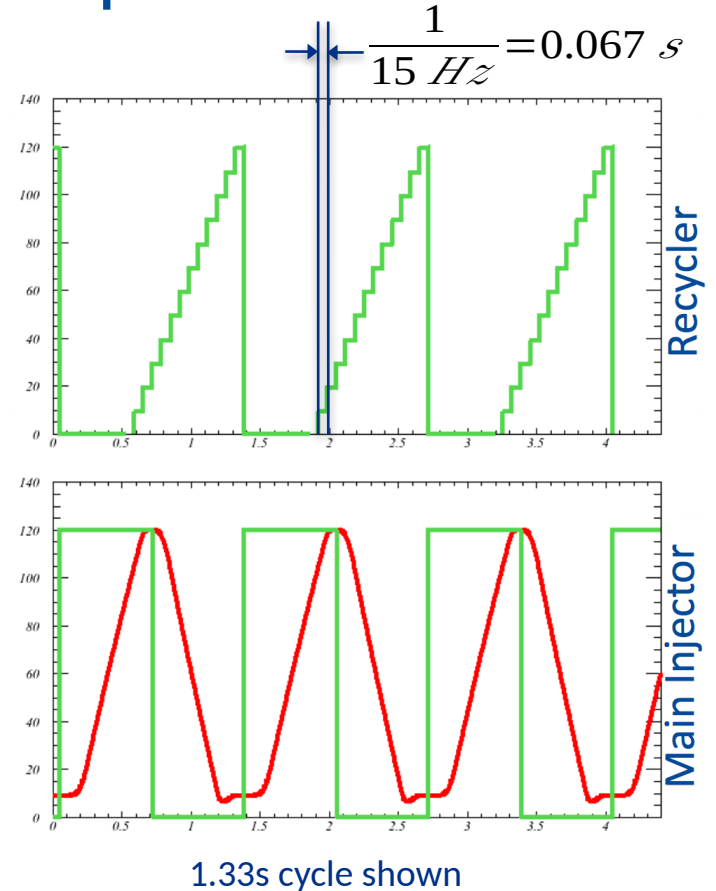
They also hide a vast hierarchy of scales!

- Linac (400MeV)
- Booster (8GeV)
- RR/MI (8GeV/120GeV)
- Muon Campus (3.094GeV/8GeV)
- BNB (8GeV)
- NuMI (120GeV)



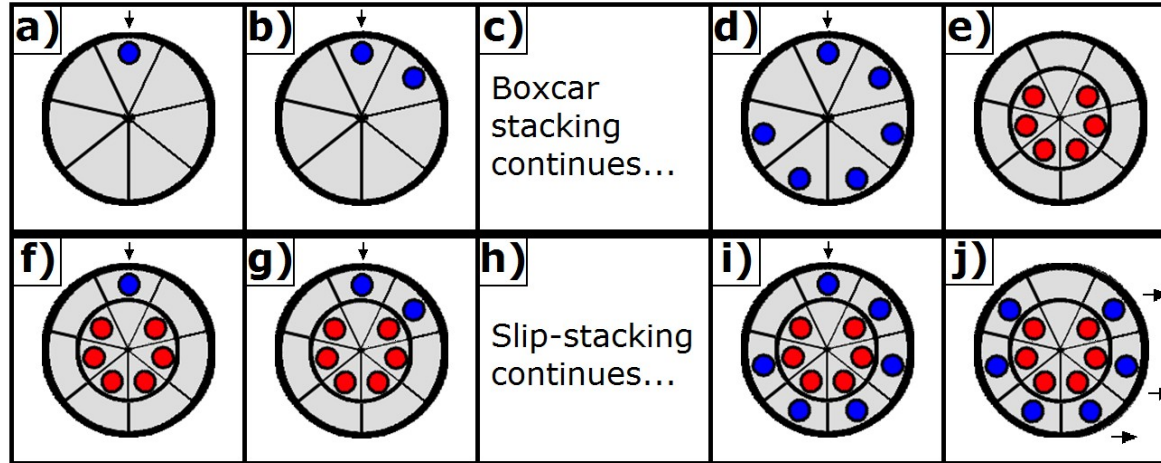
Let's talk about how we get protons to typical experiments

- H- linac (1970, 1993, 2012)
 - 400 MeV linac ~20mA
- Booster synchrotron (1970)
 - H- stripping injection (1978)
 - 16 turns to $\sim 4.7 \times 10^{12}$ p per pulse
 - Resonant Ramp from 0.4 to 8 GeV at 15 Hz
- Recycler (1998)
 - 3.3 km permanent magnet 8 GeV ring
 - Slip-stacking 12 Booster batches, $\sim 56 \times 10^{12}$ p
 - Also re-bunches beam for Muon Campus
- Main Injector (1998, but!)
 - 8 to 120 GeV ramp, cycle time ~ 1 s



Stacking beam in the Recycler is the key timeline constraint

- Slip stacking is a method of injecting multiple beams at different momenta into the same circular machine.
 - We combine slip stacking with boxcar stacking to stuff beam into the Recycler



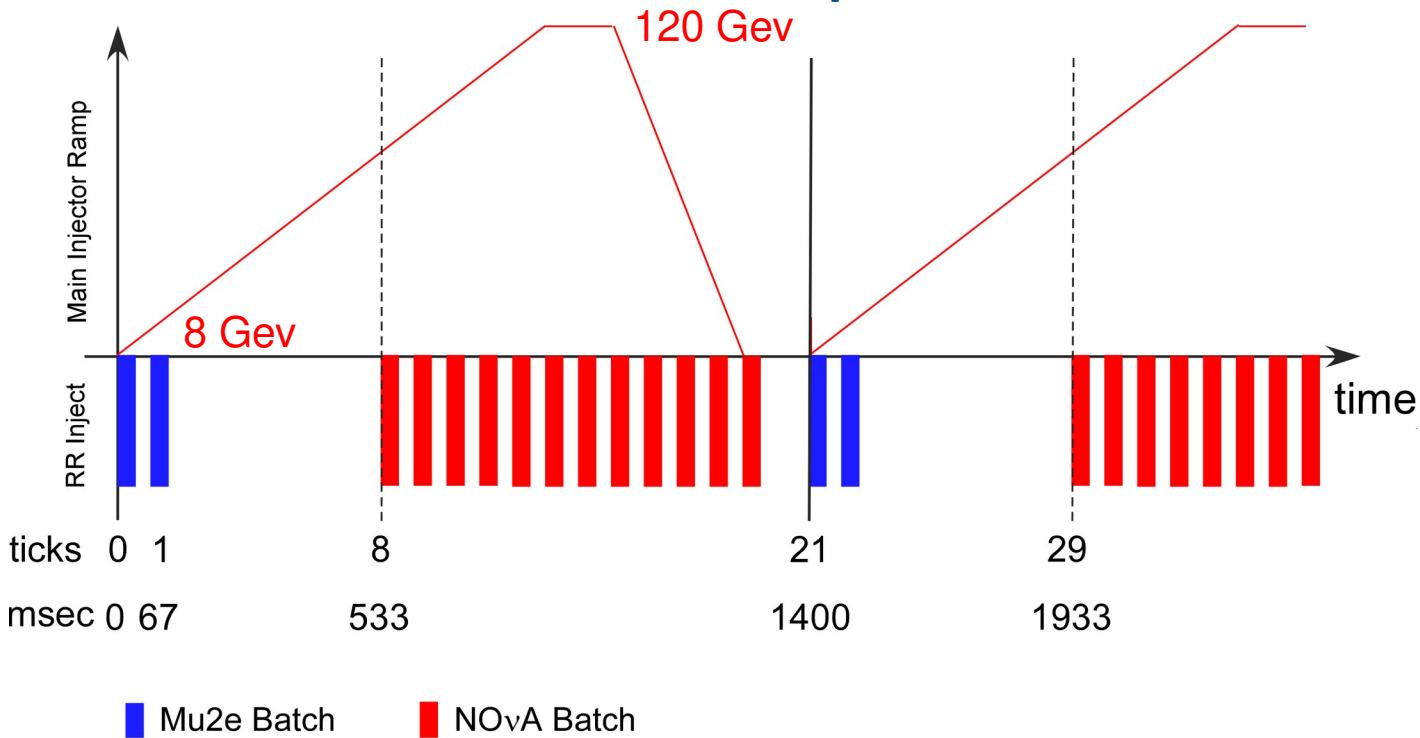
7x as many
53MHz RF
buckets in RR/MI
as in Booster
(588/84) ... 81
filled buckets per
transfer

- These manipulations require 13 ticks of the Booster clock
 - 12 for injection, one for extraction

RF buckets maintain bunch stability in the machine

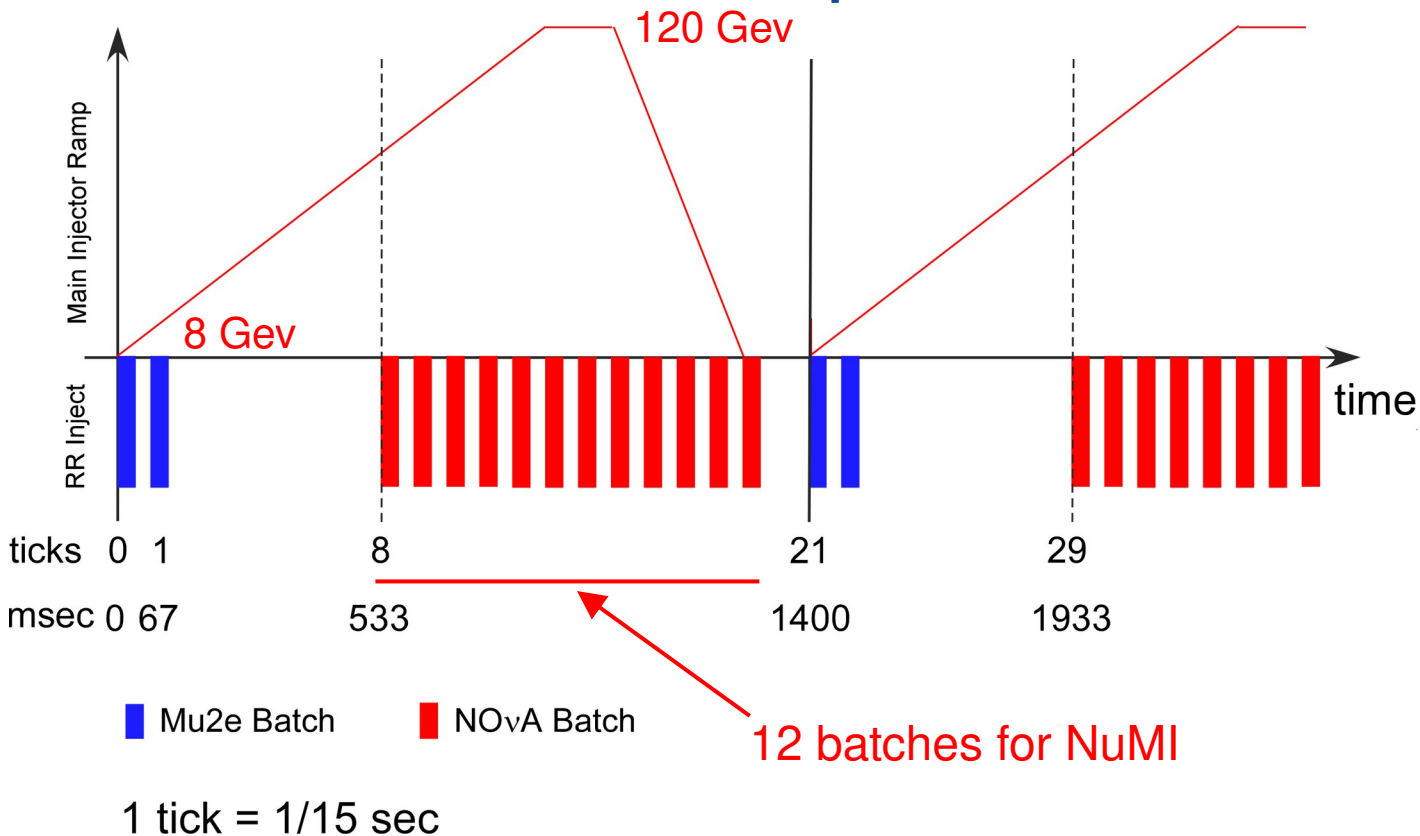
- Bunches have to align with the bucket on each revolution
 - Machine circumference has to be an integer multiple of bucket length
- Buckets have to align between machines
 - RF phase between different machines have to be actively adjusted and controlled

All our machine timelines are built around moving 12 successive Booster batches to the MI – but we have lots of experiments!

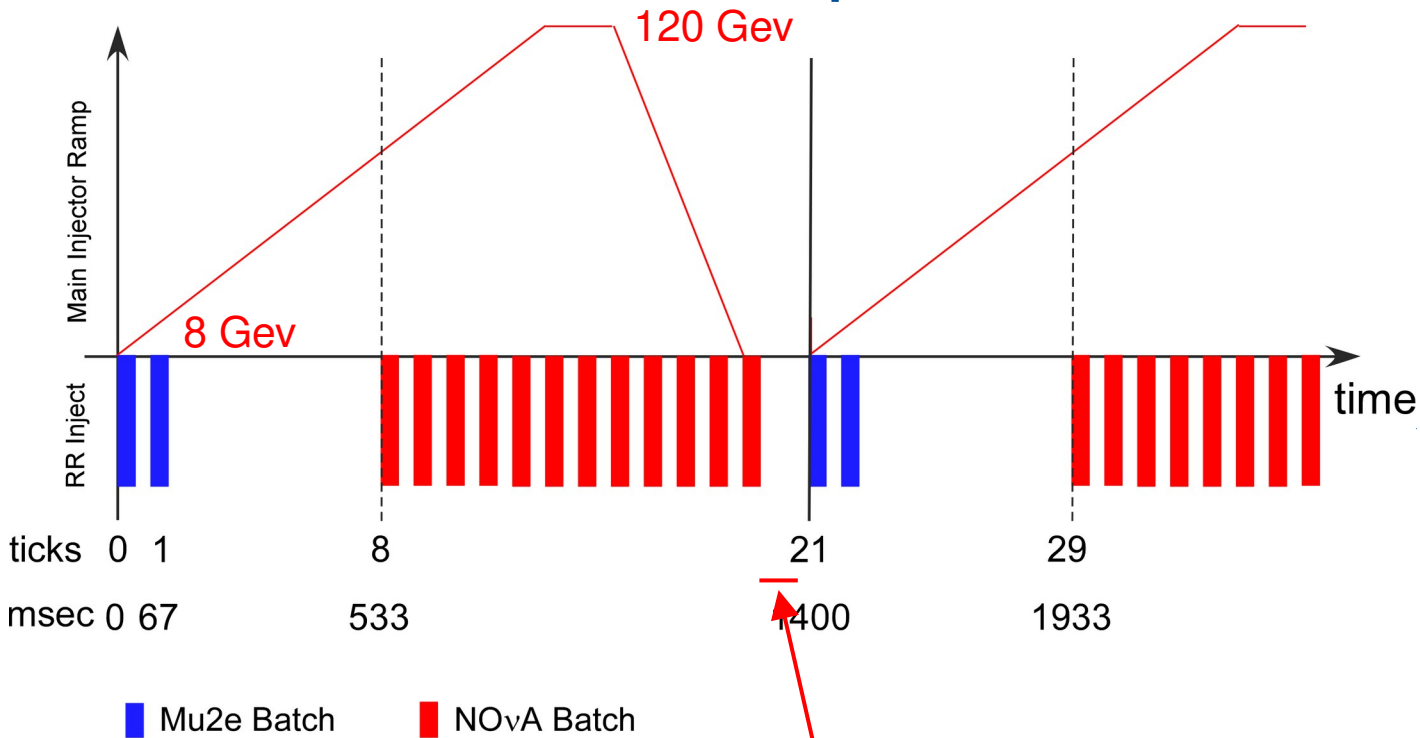


1 tick = 1/15 sec

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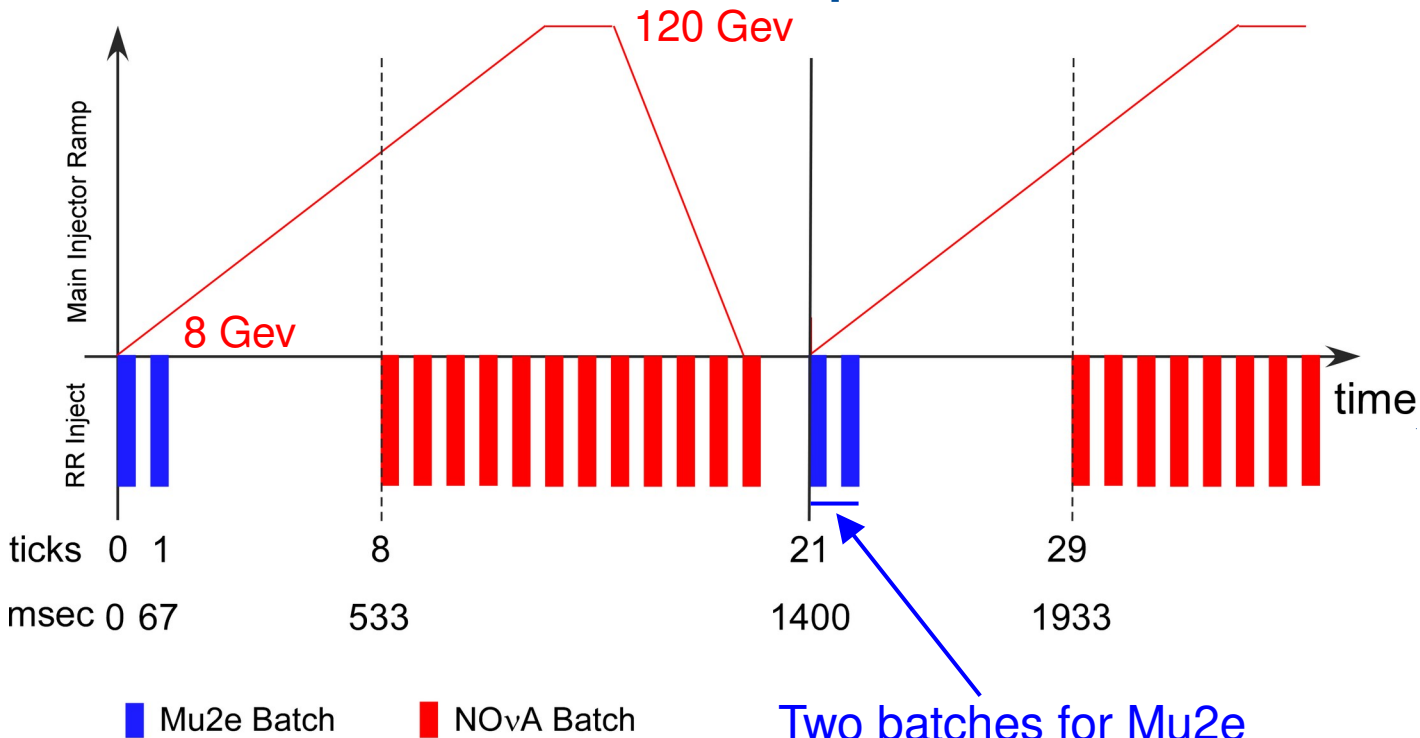


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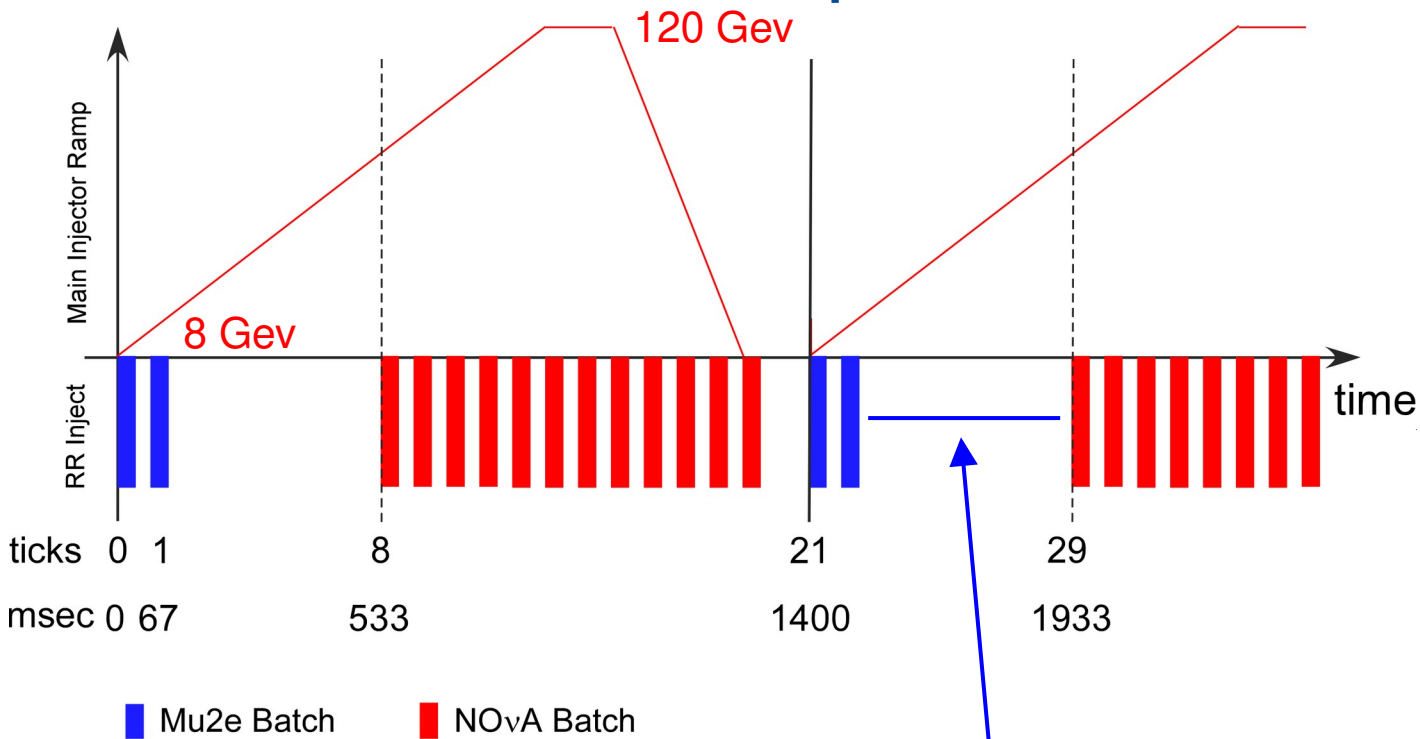
One tick for RR → MI transfer

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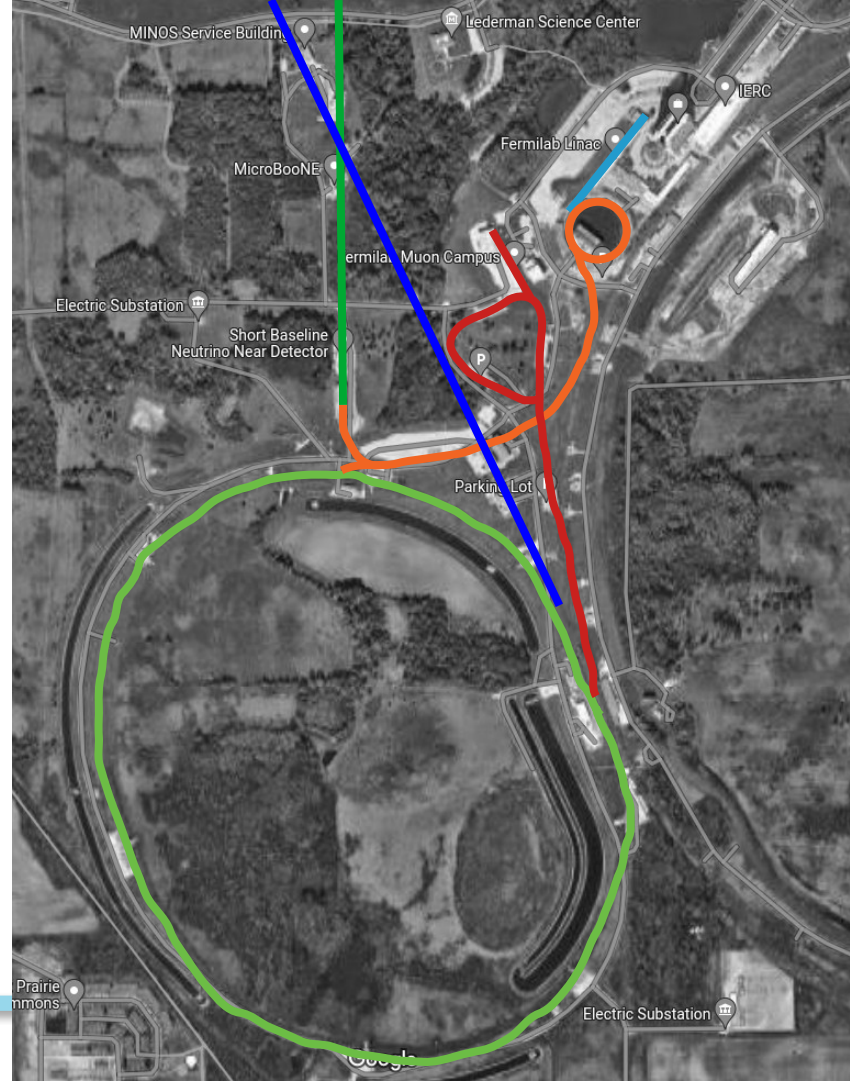


1 tick = 1/15 sec

Rebunching and transfer to DR
81x2 53MHz → 1x8 2.5MHz

And that's just one possible timeline!

- We have lots of different facilities running at the same time, and they have to share the available protons
 - NuMI
 - BNB
 - Mu2e
 - Switchyard
 - Testing and tuning



There are lots and lots of fun things I haven't talked about

- Focusing lattices
- Resonances
- Beam losses
- Dispersion
- Chromatic aberration
- Beam abort and absorbers
- Targets
- Radiological protection and shielding
-

Thanks for your attention and interest!