Accelerating Structures and Linear Machines

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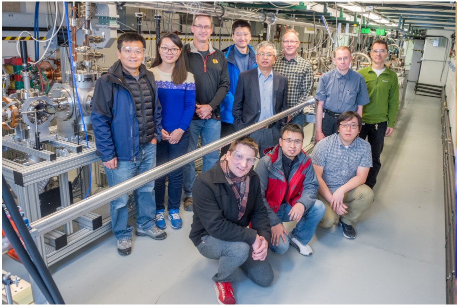
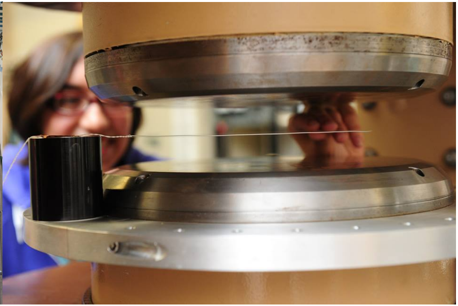
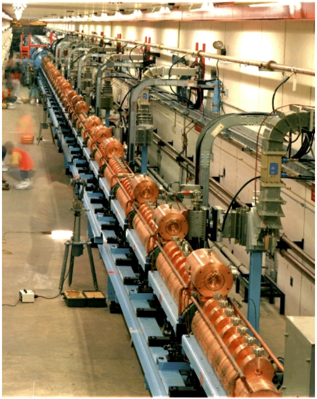
About me...

- 20013: BS Electrical Engineering, University of Houston
- 2013-2018: PhD Student, Illinois Institute of Technology
  - Thesis work on beam line design
  - Part of the Argonne Wakefield Accelerator Group (ANL)
  - Lots of simulation work
  - Comparison to experimental measurements

Outline

- Linacs
  - Types of Linacs
- Waveguides
  - Rectangular Waveguides
  - Circular Waveguides
- Accelerating Structures
  - Common Structures
- Power and Energy in Cavities
  - Energy Calculation
- Energy Measurements
  - Experimental



Source: Fermilab Media

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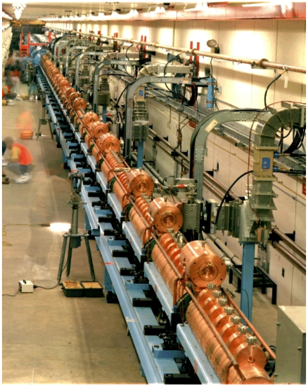
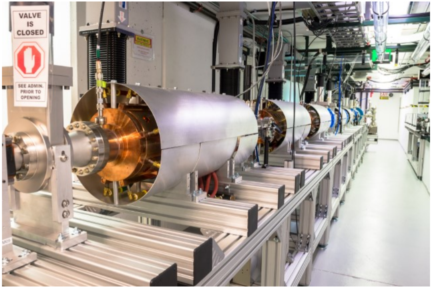


Linear Accelerators (Linacs)

Goals for this talk:

- What is a linac?
- Why do we need them?
- How do they work (conceptually)?



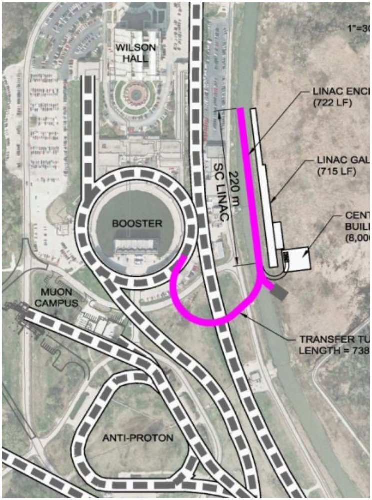
Source: AWA-ANL

Note: It's a general overview of some common machine types and techniques. Not a complete and thorough review of all machines!

Some Uses for Linacs

- Colliders
- Injectors for circular machines
- Light sources to produce x-rays for experiments:
  - Chemistry, Biology, Material Science, Engineering, etc.
- Medical accelerators
  - Cancer therapy
  - Isotope production
- Semiconductor industry

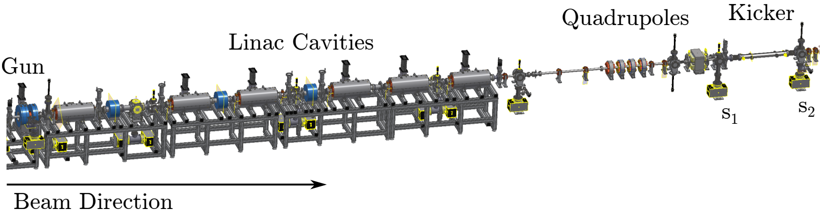
Proton Improvement Plan (PIP-II)



Source: Fermilab, E. Prebys

Electron Linacs

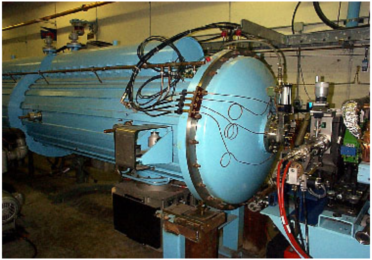
- Usually the speed of light after gun (large β)
- Commonly use copper and superconducting cavities
- Usually less radiation compared to protons/ions
- Used for light sources (synchrotrons, FEL)
- FEL = Free Electron Laser



Source: AWA-ANL

Proton/Ion Linacs

- Low β
- Copper and superconducting
- FRIB - here at MSU



Low energy Fermi proton linac.

Inside of Fermi proton linac.

Source: Fermilab, E. Preybs

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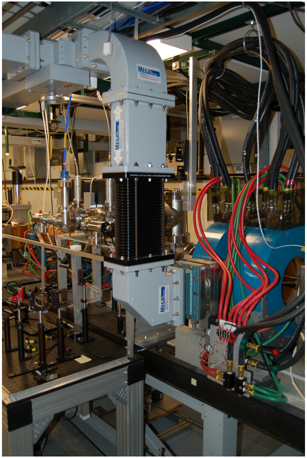


Some terms that might be useful...

- Radio Frequency (RF): 3Hz - 3 THz
- Microwaves: 300 MHz to 300 GHz
  - L band: 1-3 GHz
  - S band: 2-4 GHz
  - C band: 4-8 GHz
  - X band: 8-12 GHz
  - Waveguide: used for high power transmission to cavities

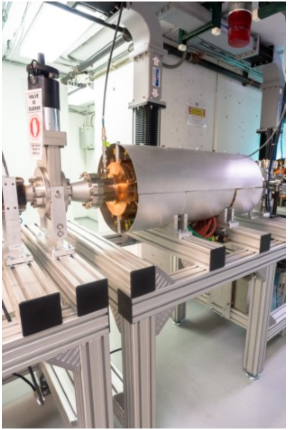
Most electron copper or superconducting linacs operate in L and S band (in my experience).

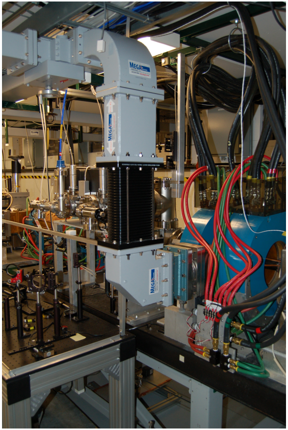
https://en.wikipedia.org/wiki/Radio_spectrum
https://en.wikipedia.org/wiki/Microwave

Source: AWA-ANL

Waveguides in real life...

The power cable for cavities! Why not use cable (coax)?





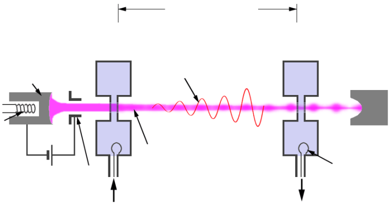
More waveguides...

We use L band, 1.3 GHz klystrons.
This is the roof of the AWA-ANL bunker.

Source: AWA-ANL

Klystrons

Mini accelerators that generate high power RF waves.

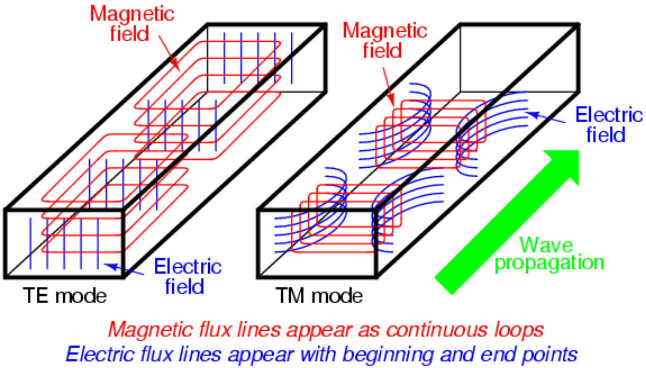


Video of how klystrons work:

https://www.youtube.com/watch?v=TsBTI3tO5-8

Source: https://en.wikipedia.org/wiki/Klystron , E. Prebys

Rectangular Waveguide

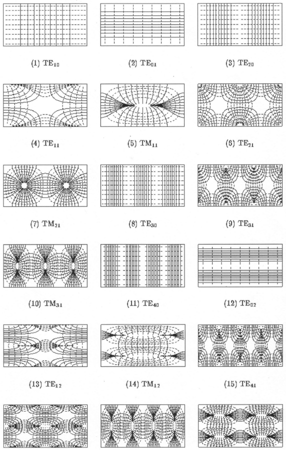


Source: L. Spentzouris, and...
http://www.kathrynindiana.com/pages/science/Physics/waveguides.html

Rectangular Waveguide

The waves that propagate inside the waveguide depend on the size, shape, and filling material. Some waveguides are pumped with gas to prevent electric breakdown.

- TE_{nm} = Transverse electric field
- TM_{nm} = Transverse magnetic field
- Several modes can propagate at a time (usually not good)



Source: L. Spentzouris

Rectangular Waveguide Derivation

Start with plane waves (electric and magnetic):

$$\vec{E}(x, y, z, t) = \vec{E}(x, y)\ e^{j(kz - \omega t)} \tag{1}$$

$$\vec{B}(x, y, z, t) = \vec{B}(x, y)\ e^{j(kz - \omega t)} \tag{2}$$

These equations can be written

$$\vec{B}(x, y, z, t) = X(x)\, Y(y)\ e^{j(kz - \omega t)} \tag{3}$$

Get the wave equation from Maxwell's equations...

$$\left(\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + k_c^2\right) B_z(x, y) = 0 \tag{4}$$

TE Boundary Conditions

Due to metallic walls:

$$B_x(x=0,y) = B_x(x=a,y) = 0 \quad (5)$$

$$B_y(x,y=0) = B_y(x,y=b) = 0 \quad (6)$$

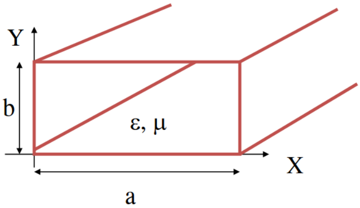


Figure and derivation of resulting fields here:
`http://uspas.fnal.gov/materials/10MIT/Lecture5.pdf`

Cutoff Frequencies

Cut off frequencies tell us what waves will propagate in the waveguides. Derived from Maxwell's equations and boundary conditions.

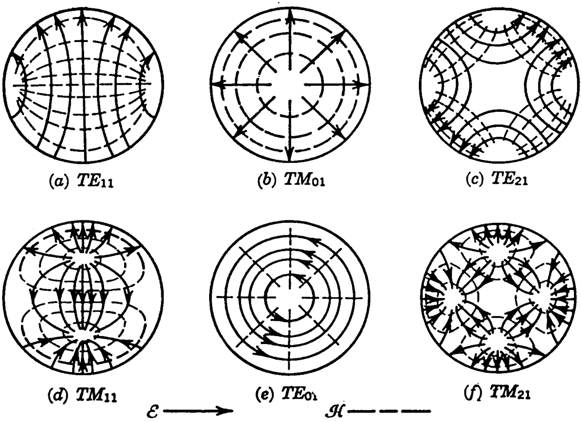
$$f_{nm} = \frac{1}{2\sqrt{\mu_0 \epsilon_0}} \sqrt{\left(\frac{n}{a}\right)^2 + \left(\frac{m}{b}\right)^2} \tag{7}$$

In class exercise:

1. Calculate the cutoff frequencies for the following modes: a=0.02, b=0.06
   - f_{01}, f_{10}, f_{20}, f_{11}
2. In what frequency range is only one mode propagating?
3. In what frequency range are three modes propagating?
4. Is it good or bad to have more than one mode propagating?

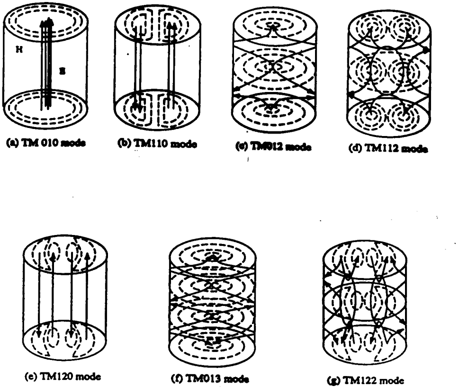
Alireza Nassiri and Geoff Waldschmidt

This theory applies to circular geometries too.



Alireza Nassiri and Geoff Waldschmidt

Coaxial (coax) cables are a commonly used example of this.



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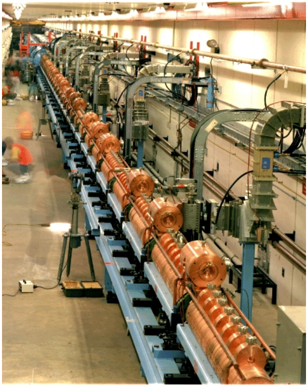


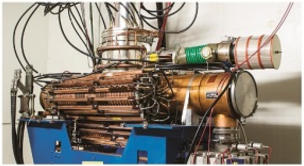
Accelerating Structures

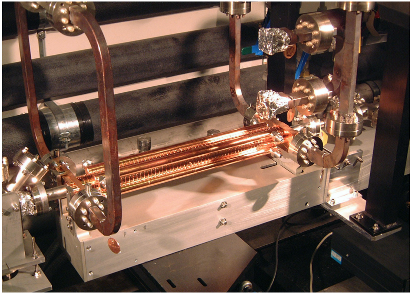
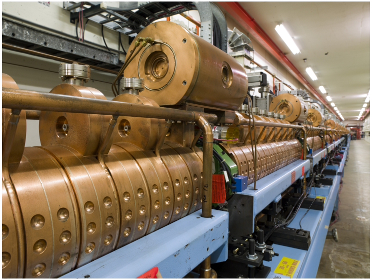
Shape and material of acc. structures depends heavily on:

- particle type (electron, proton, ions)
- Beta, β after source
  - large β for electrons
  - low β for protons/ions
- Final energy requirement
- Continuous or pulsed operation?
  - This determines superconducting or not!
  - SC saves power, but cryoplant is expensive.

Source: Fermilab, E. Harms

Normal Conducting

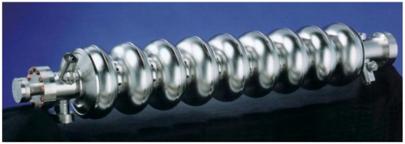


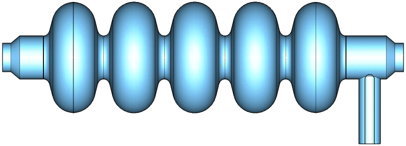



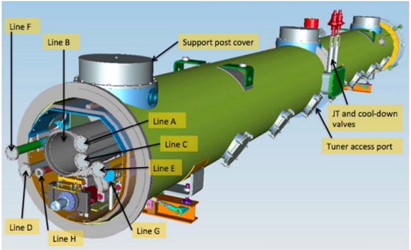
Source: Fermilab, SLAC

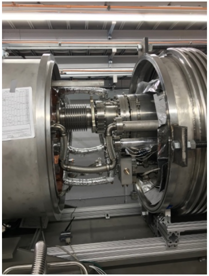
Superconducting

LCLS-II, Fermilab, Jlab, Europe, Japan, etc...





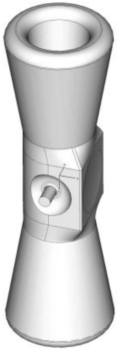




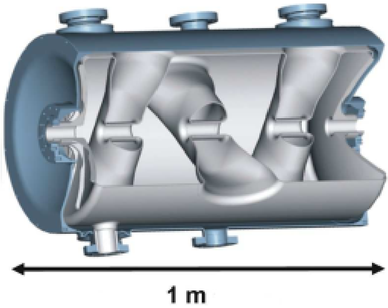
Sources: Fermilab, E. Harms, E. Prebys

Proton, Ion

Spoke cavities used for low Beta (β) particles:



Half-wave resonator

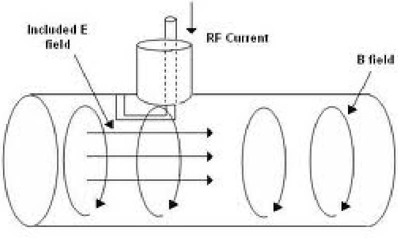


(Triple) spoke resonator

Source: E. Prebys

Pillbox Cavity

Source: T. Wangler, E. Prebys



$$\vec{E} = \vec{E}(r,t)\,\hat{z} \quad (8)$$

$$\vec{B} = \vec{B}(r,t)\,\hat{\phi} \quad (9)$$

$$E_z = E(r)\,e^{i\omega t} \quad (10)$$

Boundary conditions +
Using Maxwell's and a wave equation again:

$$\frac{\partial^2 E_z}{\partial r^2} + \frac{1}{r}\frac{\partial E_z}{\partial r} = \frac{1}{c^2}\frac{\partial^2 E_z}{\partial t^2} \quad (11)$$

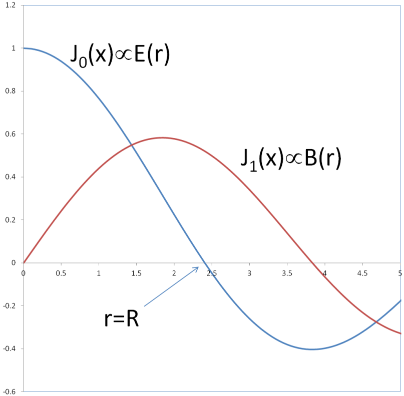
Assume Ez is the form of eq. 10 to solve PDE in eq. 11.

Bessel Functions

Source: T. Wangler, E. Prebys

Solutions include Bessel functions.

0th order gives the first mode of the cavity.



$$E_z(r) = E_0 J_0\left(\frac{\omega}{c} r\right) \quad (12)$$

First zero at J(2.405):

$$f_0 = 2.405 \frac{c}{2\pi R} \quad (13)$$

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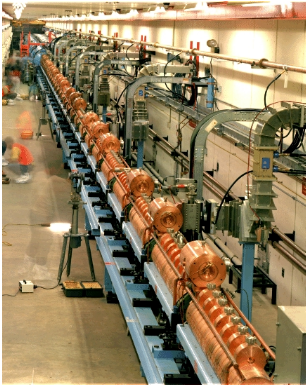


Quality Factor

A measure of how fast power is dissipated. High Q means slower power loss, i.e. oscillations in resonator die out more slowly.
https://en.wikipedia.org/wiki/Q_factor

$$Q = \frac{\omega U}{P} \tag{14}$$

- Q = quality factor
- ω = frequency of cavity
- U = stored energy in the cavity

Source: Chp. 2, "RF Linear Accelerators", T. Wangler

Gradient

The electric field strength (*on axis) in a cavity due to an externally applied power is:

$$E_z^2 = \frac{P\omega}{v_g}\frac{R}{Q} \tag{15}$$

- E = electric field on axis
  - This field contributes to the gradient of a cavity.
- P = power supplied to cavity
- v_g = group velocity
- R = Shunt impedance
- Q = Quality factor of cavity

Energy Gain

Given a gradient based on the information in the last slides... Calculating the expected energy gain is proportional to the gradient and length of the accelerating structure.

$$\Delta W = qE_z TL\, cos\phi \tag{16}$$

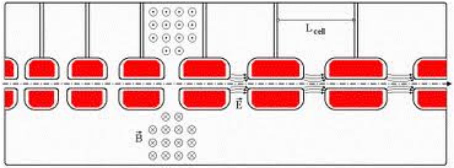
- ΔW = change in beam energy (also ΔE sometimes)
  - "on crest": $\phi = 0$
- q = charge of particles
- $E_z T$ = accelerating gradient
- L = length of accelerating structure or cell

Source: Chp. 2, "RF Linear Accelerators", T. Wangler

Transit Factor (T) - Protons/Ions

- Need to account for this in drift tube linacs (protons, ions), etc.
- Usually not an issue for high β electron machines
  - Energy gain equation reduces to: $\Delta W = qE_z L$
  - On crest energy gain

http://uspas.fnal.gov/materials/09VU/Lecture4.pdf

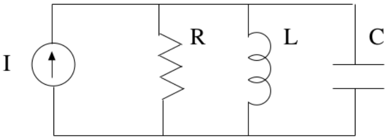


$$d = \frac{v}{f} \tag{17}$$

Let's watch a gif!

Source: Chp. 2, "RF Linear Accelerators", T. Wangler

RLC Circuit Model of Cavity



We can model a resonant (accelerating) cavity as a RLC circuit. Circuit analysis tells us the impedance (similar to resistance) is:

$$Z = \left| \frac{V_0}{I_0} \right| = \frac{1}{\sqrt{\left(\frac{1}{R}\right)^2 + \left(\omega C - \frac{1}{\omega L}\right)}} \tag{18}$$

In class practice problem: R=8, L=0.2, C=0.8

What does a plot of $\left| \frac{V_0}{I_0} \right|$ vs. ω look like? What does this mean?

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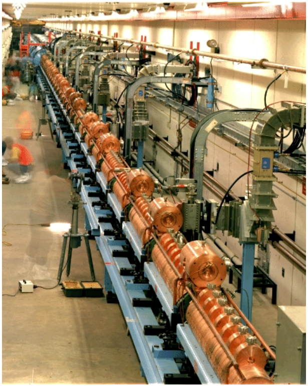


Energy Measurements

Trajectory of a beam through a dipole is proportional to it's energy:

$$B\rho = 0.2998\,\beta\,E\,[GeV] \tag{19}$$

- $B =$ magnetic field in Tesla
- $\rho =$ bending radius through magnet in meters
- $\beta =$ velocity of beam
- $E =$ energy of beam in GeV

Reminder from Monday:
$B\rho$ is called "beam rigidity"

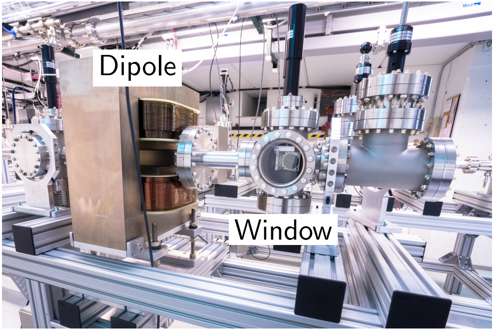
Source: "Particle Accelerator Physics", H. Wiedemann

Energy Measurements

Hardware needed to do measurement:

- Dipole
- Imaging screen(s)
- Actuators
- Current monitors

Actuator



Source Picture: AWA-ANL

Summary

- Linacs
- Rectangular waveguides
- Accelerating Structures
- Q, gradient, and energy calculations
- Klystron $\rightarrow$ waveguide $\rightarrow$ cavity $\rightarrow$ beam

Thanks for your attention!