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RF Devices – Why and How

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USPAS – Applied Electromagnetism Lecture 1

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First, Sources and Recommendations

- Much thanks to Tom Wangler whom I've taken many, very useful images from.
- Recommended Literature:
 - RF Linear Accelerators – T. Wangler
 - RF and Beam Optics for Linear Machines
 - Extensive history with NC structures at Los Alamos
 - RF Superconductivity for Accelerators – H. Padamsee
 - Formative figure in Superconducting RF
 - Lots of SRF theory and application, including cavity processing and limitations
 - Microwave Electronics – J.C. Slater
 - Head of the MIT Rad Lab and Bell Laboratories (!)
 - Difficult to find, but outstandingly written and understandable

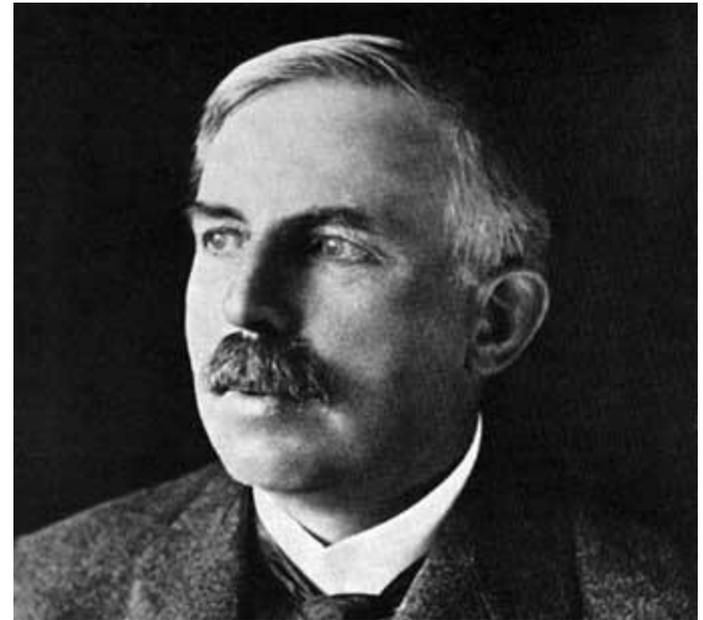
Course Outlook

- My goal is to give you the tools you need to work with (around/in connection with) RF systems
- The class will be roughly an equal mix of:
 - EM Theory (Analytical calculations, scaling, derivations)
 - Practical Concerns (Implementation, design, and limitations)
- Start with RF Basics
 - Maxwell Equations, Helmholtz Equations
 - Standard Transmission Line/Cavity Geometries
 - Figures of Merit and Optimization
- Move to Real Design
 - Practical Concerns and Implications (fabrication, cleaning, etc.)
 - Many Examples of RF structures in use today

Quick Introduction

Rutherford's Desire

- Ernest Rutherford's discovery of the structure of the nucleus in 1909 opened new fields of experimentation
 - Nuclear Physics
 - Eventually, High Energy Physics, Light Sources, etc.
- These fields (and eventually others) require particle “accelerators”
 - Rutherford expressed a long-standing “ambition to have available for study a copious supply of atoms and electrons which have individual energy far transcending that of the alpha and beta particles” available from natural sources.
 - This desire has led to a century of accelerator physics research



High Energy Particles

- What does the science want?
 - More Energy!
 - Different science available
 - Controllable/Tunable Energy!
 - Dynamic behavior studies
 - Fine structure investigations like resonances
 - More Intensity!
 - Take data faster
 - Study rare processes
 - Rare isotopes
 - Neutrinos
 - Rare particle decays
 - Variety of Particle Beams!
 - The ability to create and use beams of any element/isotopes

- What do they REALLY want?

Wall power



Desired Beam

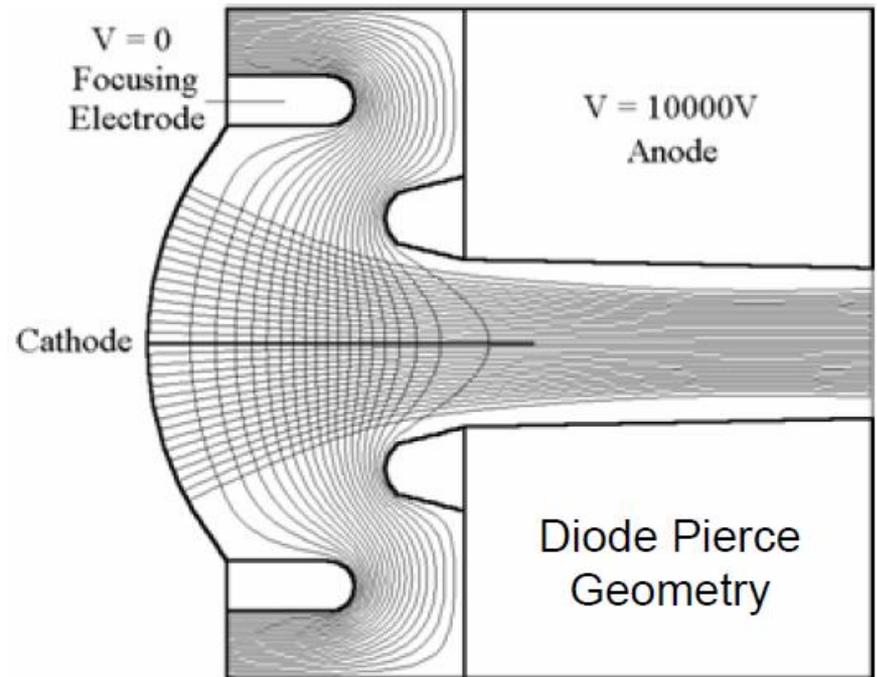
What force to use?

- Strong
 - Weak
 - Electromagnetic
 - Gravity
-
- Radioactive decay
 - Limited Natural Sources (some artificial sources, not much better)
 - Limited Intensity
 - Very specific energies
 - Limited set of available beams
 - Extremely weak
 - Using the Sun's gravity well, you could get a proton up to ~22 MeV
 - No comments on the practicality
 - Electric Fields!
 - Magnetic fields can't do work
 - $\Delta E = F \cdot \Delta x = (q\vec{v} \times \vec{B}) \cdot \vec{v}\Delta t = 0$

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

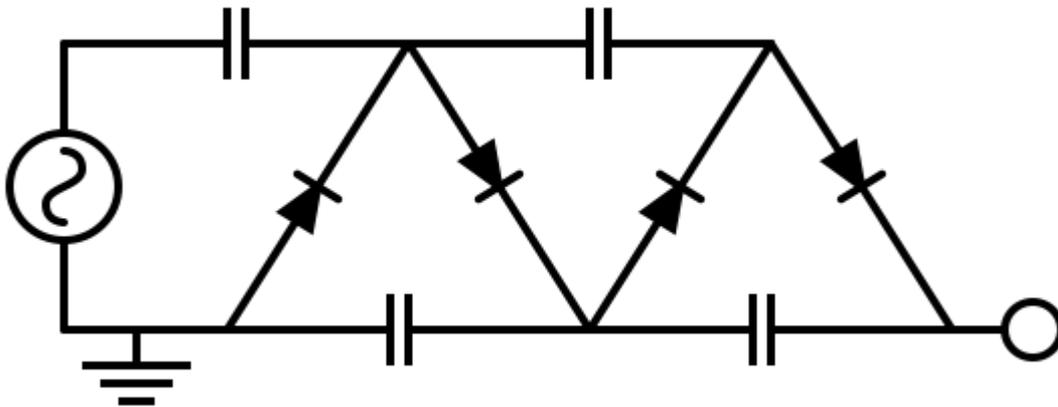
Most Simple Accelerator

- We don't want Magnetic Fields
 - Steering should be left to the magnets (most of the time), we're just talking about energy gain
 - If you assume $B = 0$, then we only get *static* electric fields
 - We want only longitudinal electric fields, strong in the desired direction



Static Electric Fields

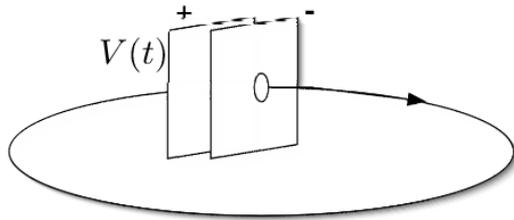
- Electrostatic Accelerators
 - Limited energy gain ($60 \text{ MeV}/q$)
 - Can accelerate DC beams (used often for particle sources)
- Tandem Accelerators
 - By changing the particle charge from negative to positive, twice the energy can be achieved (limited current)



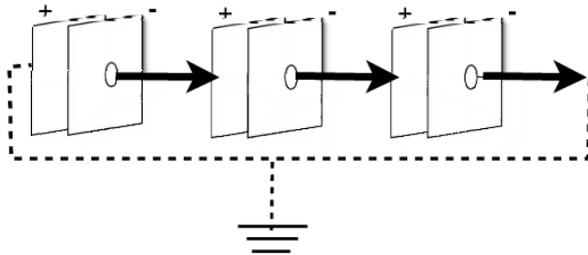
The Benefits of RF Fields

■ The Need for AC Systems

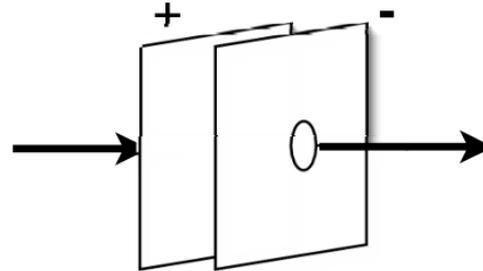
Circular Accelerator



Linear Accelerator



$$\text{energy gain} = q \cdot V$$



DC systems limited to a few MV

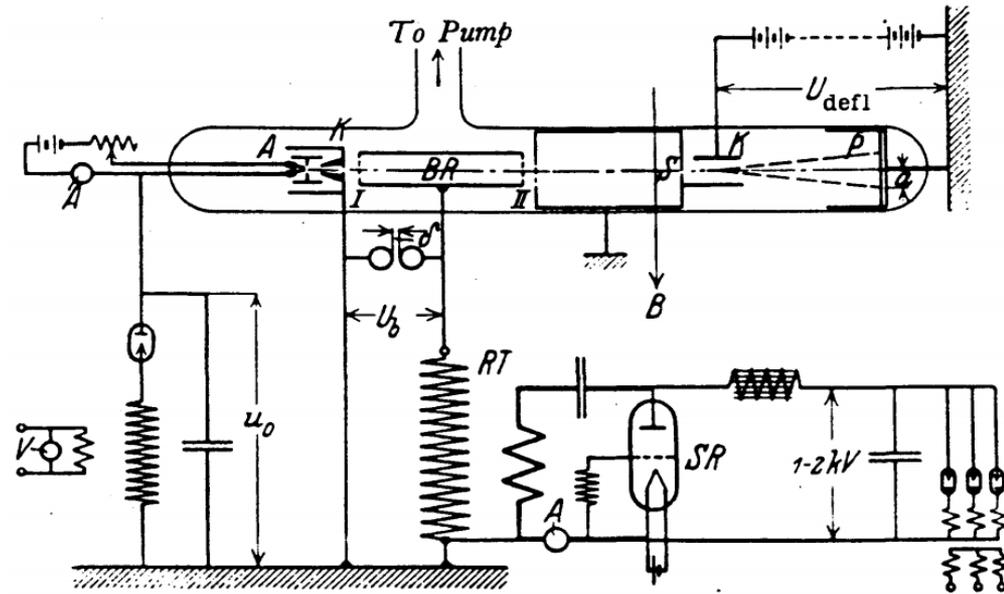
$$\oint (q\vec{E}) \cdot d\vec{s} = \text{work} = \Delta(\text{energy})$$

To gain energy, a time-varying field is required:

$$\oint \vec{E} \cdot d\vec{s} = -\frac{\partial}{\partial t} \oint \vec{B} \cdot d\vec{A}$$

Wideroe Drift Tube Linac

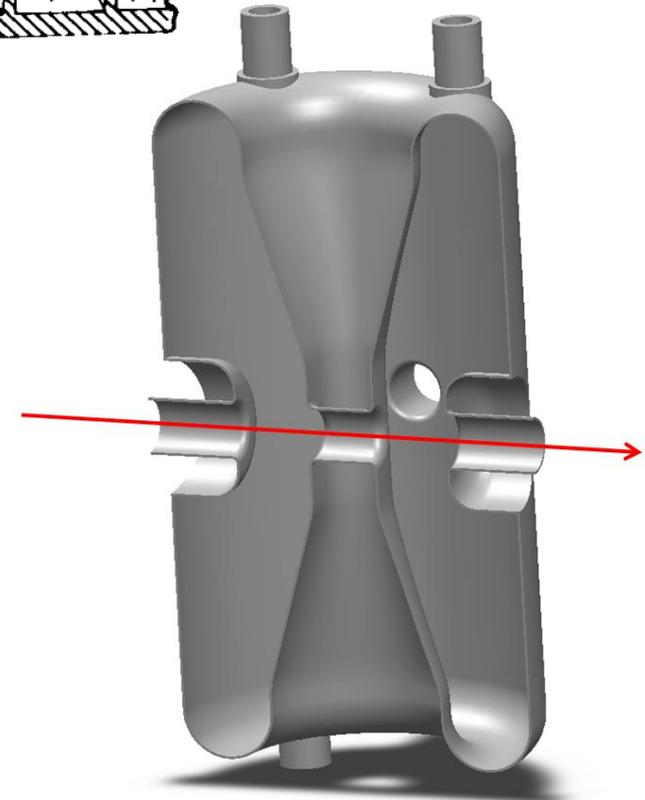
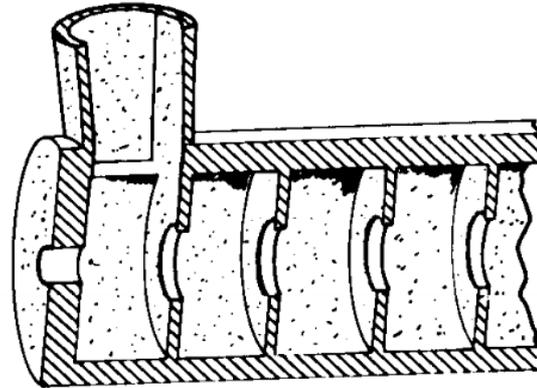
- First RF accelerator conceived and demonstrated by Wideroe in 1927 in Aachen, Germany
- RF voltage of 25 kV from 1 MHz oscillator was applied to single electrode between two ground planes
- Accelerated potassium ions to 50 keV, two gaps for twice the voltage
- Sloan and Lawrence built one of these style linacs with 30 electrodes, applying 42 kV to get mercury ions up to 1.36 MeV



Wideroe's Device (from his thesis)

How do we create $V(t)$?

- What do we need?
 - Correct Frequency
 - Accelerating fields that are easy to access
 - “Clean” accelerating field distribution
 - Reasonable mechanical properties
 - Efficiency energy storage
- Coaxial Waveguide Modes!
- Cylindrical Waveguide Modes!
 - Everything else is just topological adjustments of these



How are these cavities judged?

$$\Delta W = q \times V_0 \times TTF(\beta) \times \cos(\phi)$$

Charge

Maximum
Accelerating
Voltage

Transit Time
Factor

Longitudinal
Focusing Term

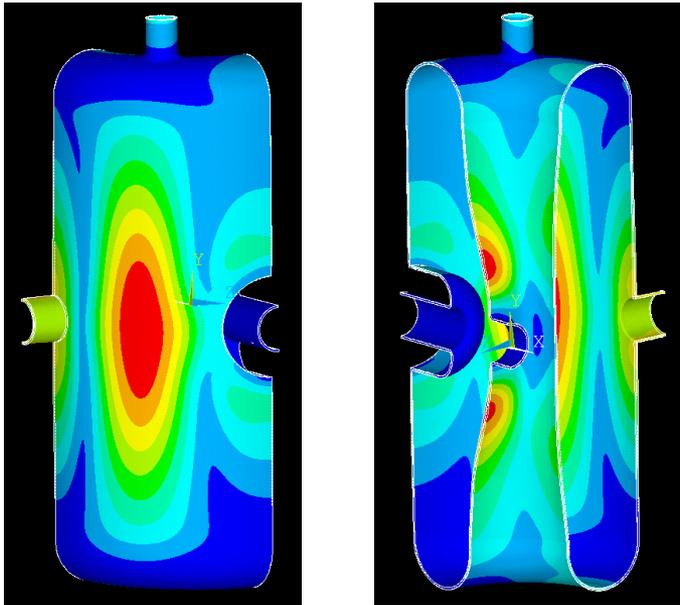
- R/Q
 - Measure efficiency of transferring energy to the beam
- Geometry Factor
 - Measure of efficiency of energy storage in the cavity

$$R/Q = \frac{V_{acc}^2}{\omega U}$$

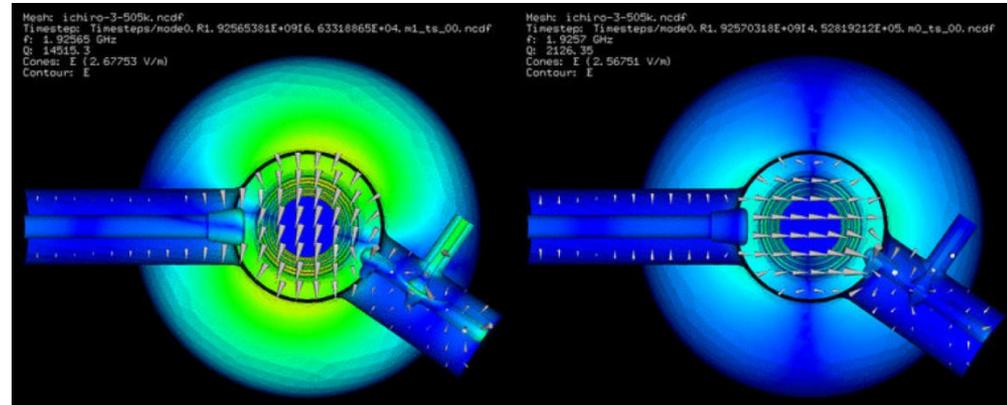
$$G = \frac{\omega U}{P_d/R_s}$$

Other Design Considerations

- Mechanical Issues
 - In operation, a cavity is exposed to many different pressures that deform the cavity
 - How this deformation changes the cavity frequency and performance must be well understood

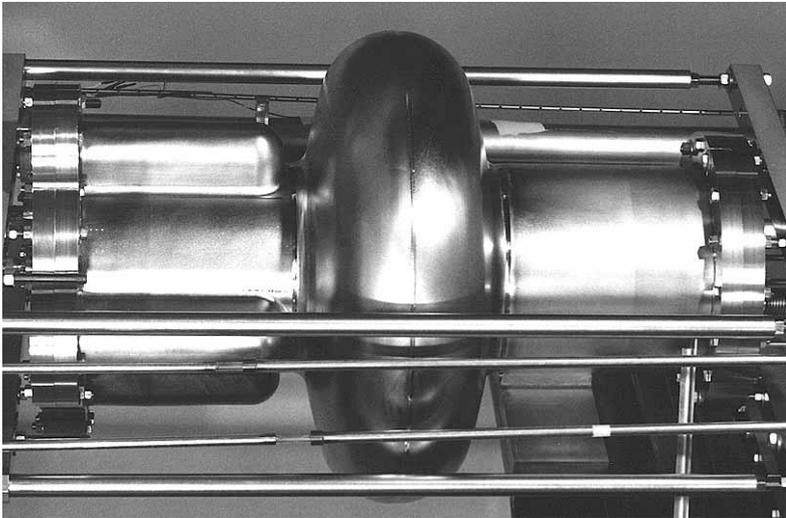


- Higher Order Modes
 - As the beam passes through the cavity, it can excite ALL cavity modes
 - Strong beam asymmetry or offset increases the strength of this coupling
 - These modes must be strongly damped or they can cause emittance growth or beam breakup



Cavity Design for Different Accelerators

- Synchrotrons (Ring Machines)
 - The beam sees the cavity MANY times, low gradient is typical
 - Field must be very clean and stable
 - Very heavy higher order mode damping
 - Very large aperture
 - Acceleration and bunching
- Linacs (Linear Accelerators)
 - Single (or low #) pass machine
 - High Gradient is KEY (reduces # of cavities needed, therefore \$\$\$)
 - Reliability and ease of fabrication is very important (many cavities)
 - Efficiency of operation also important



Summary by Tom Wangler (RF Linear Accelerators)

- In DC accelerators the energy gain is limited by the maximum applied voltage, which is limited by electric breakdown.
- In RF accelerators (linacs, synchrotrons, cyclotrons) the final energy can exceed the maximum applied voltage, which is applied repeatedly to the beam. **The final energy is limited only by economics.**
- Synchrotrons are limited to low beam currents by beam instabilities associated with the repetitive cycling of the beam from turn to turn through unavoidable focusing lattice errors.
- Cyclotrons are not pulsed but are limited to low beam currents by weak focusing and same inherent circular machine instabilities.
- Linacs can deliver high beam currents because they can provide strong focusing to confine the beam and are not subject to circular-machine repetitive instabilities.

Maxwell to Helmholtz

Basic Equations

- Maxwell's Equations are very general, govern all classical electromagnetic interactions

$$\vec{\nabla} \cdot \vec{D} = \rho$$

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

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

$$\vec{\nabla} \times \vec{H} = \vec{J} + \frac{\partial \vec{D}}{\partial t}$$

- Lorentz Force
- Stored Energy density in EM fields
- Poynting Vector is useful conceptual tool (direction of energy flow in EM fields)

Where $\vec{D} = \epsilon_0 \vec{E}$ and $\vec{B} = \mu_0 \vec{H}$

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

$$u = \frac{1}{2} \left(\epsilon_0 \vec{E}^2 + \frac{1}{\mu_0} \vec{B}^2 \right) \text{ in vacuum}$$

$$\vec{S} = \frac{1}{\mu_0} \vec{E} \times \vec{B} \text{ in vacuum}$$

Helmholtz Equation

Any solution to the wave equation with a time-independent form can be represented by the Helmholtz Equation

The solutions we want for RF applications are sinusoidal in time with frequency ω .

Particles will generally be accelerated in vacuum, so we can assume $\rho = \vec{j} = \epsilon_r = \mu_r = 0, c^2 \mu_0 \epsilon_0 = 1$

- Starting from $\left(c^2 \nabla^2 - \frac{\partial^2}{\partial t^2}\right) \vec{E}(\vec{r}, t) = 0$
- Assume $\vec{E}(\vec{r}, t) = \vec{E}_s(\vec{r})T(t)$
- Gives $\frac{\nabla^2 \vec{E}_s}{\vec{E}_s} = \frac{1}{c^2 T} \frac{d^2 T}{dt^2}$
- Assume both sides equal to a constant $-k^2$
- Gives:
- $(\nabla^2 + k^2)\vec{E}_s = 0$
- $\left(\frac{d^2}{dt^2} + \omega^2\right)T = 0$
- We want: $T = e^{i\omega t}$

Good!

Bring it all together - Free Space and Beyond

- Plugging this back into Maxwell's Equations, we get: $\omega = kc$
- Solving for $\vec{E} = \vec{E}_0 e^{-i\vec{k}\cdot\vec{r}-i\omega t}$
- Note that the magnetic field is specified: $\vec{B} = \frac{i}{\omega} \vec{k} \times \vec{E}$
- While we've solved for one frequency, we don't have to only work in one frequency
- If required we can solve for as many frequencies as required and add using Fourier Superposition to give the full, final field distribution
- Now, we have a powerful tool, just solve the Helmholtz Equation with whatever boundary conditions are appropriate to give us the RF fields in a structure of our choosing!

Boundary Conditions

Boundary Conditions

- For most of this class, we'll only be considering surface boundary conditions
- For magnet design, it's often important to simulate the device plus its surroundings because those fields (can) penetrate through materials, significantly complicating simulation
- For RF, metallic walls serves as an effectively perfect shield with very small (negligible) penetration depth
- Additionally, RF transmission will be bounded and well behaved, not free travel of plane waves
- Free propagation and interaction with EM fields and charges, like in a Free-Electron Laser are significantly more complex and will not be covered here (See G. Stupakov's class at USPAS)

Perfect Conductor Boundary Conditions

- Gauss'/Faraday's Laws applied to a pillbox/loop on the metallic surface gives two conditions:
 - $D_{n1} - D_{n2} = \rho_s$
 - $E_{t1} - E_{t2} = 0$
 - Any field in the metal (2) will drive currents, so the only stable configuration is with $D_{n2} = E_{t2} = 0$.
- Gauss'/Ampere's Laws applied to a pillbox/loop on the metallic surface gives two conditions:
 - $B_{n1} - B_{n2} = 0$
 - $H_{t1} - H_{t2} = J_s$
 - Again, surface currents are fine, but not inside the material, so $B_{n2} = H_{t2} = 0$.

Electric Metallic Boundary Condition:

$$E_{\text{transverse}} = 0$$

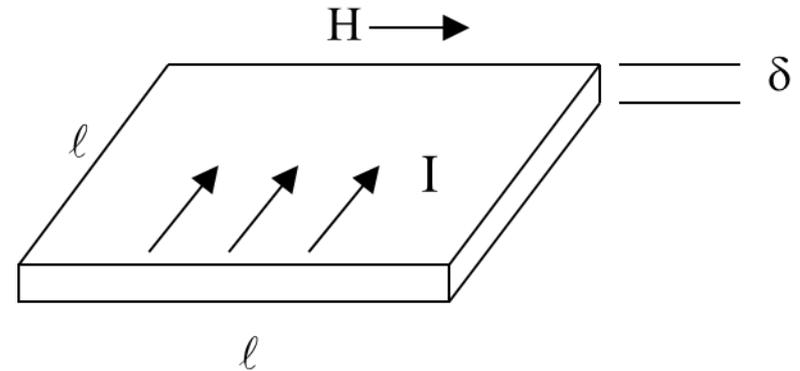
Magnetic Metallic Boundary Condition:

$$H_{\text{normal}} = 0$$

Normal Conducting Materials – Skin Depth

- The charge/current density at the surface isn't infinite.
- Fields do penetrate into the material some amount.
- Fortunately, the generalized Helmholtz equation still applies, and gives
- $\delta^{-1} = \sqrt{\pi f \mu_0 \sigma}$
- We will get to losses later

For copper at 1 GHz, this gives a 2 μ m skin depth. This perturbation on the very small for most applications. (Also, very simulation intensive)



Magnetic fields drive surface currents in a thin layer near the surface to oppose the fields penetrating the metal

Additional Boundaries - In ComputerLand™

The boundary conditions given are for real materials and will always represent the physical boundaries of your device.

Additional types of boundaries are used to reduce the size of the simulation or represent an interface with the outside world.

I'll talk about losses later.

- Symmetry Boundaries
 - In 2D sims - rotational symmetry
 - In 3D sims - used to reduce size of the simulation and generally takes one of the following forms:
 - Electric – just like metallic wall
 - Magnetic - opposite conditions of electric B.C.
 - Periodic – Fields must be related at two planes
 - Ports to the outside – Places for power to flow into or out of your structure
 - More complex B.C. that are defined in software.

Basic RF Design Process – So Far

1. Define closed boundary that has all the features you want to simulate.
2. Choose appropriate boundary conditions, including fixed frequency or eigenmode solver?
3. Use software to solve the Helmholtz Equation for the system
4. Repeat. Many times.
 - So, now the question becomes what geometries should we use?
 - In the next section, we'll cover the most common geometries, play with them a while, then start to torture them into the most unreasonable geometries we can think of and see what's useful.