HTE - UKO

INTRODUCTION: ELECTRODYNAMICS

Gökhan Ünel / UC Irvine

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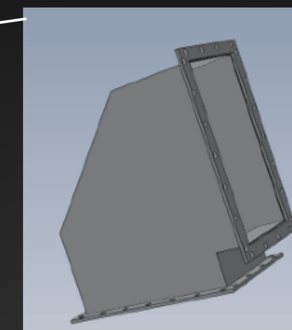
An accelerator lab

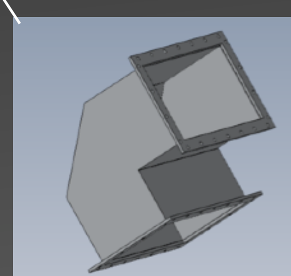
rectangular wave-guides



H-bend

accelerating cavity

ion source



E-bend

RF Power Supply

1 page recall

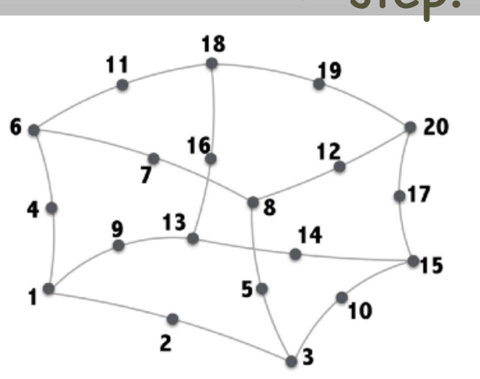
ohm-m

Material	Resistivity
Conductors:	
Silver	1.59×10^{-8}
Copper	1.68×10^{-8}
Gold	2.21×10^{-8}
Aluminum	2.65×10^{-8}
Iron	9.61×10^{-8}
Mercury	9.61×10^{-7}
Nichrome	1.08×10^{-6}
Manganese	1.44×10^{-6}
Graphite	1.6×10^{-5}

- Equations
  - $F_c = k.q_1.q_2 / r^2$ -- Coulomb equation
  - $F_{total} = F_1+F_2+F_3+\ldots$ -- linearity of EM
- Notation
  - j : current density : I =j.Volume
  - σ : conductivity --- 0: perfect insulator
  - ρ : resistivity --- 0: perfect conductor
  - R = ρ.A/L -> A: cond. area, L: cond. length R: Resistance
  - V : potential wrt some referance point, usually earth.
  - E : Electric field & B : Magnetic field both vector fields
- Current and Power
  - V = I R --> Ohm Equation
  - P = I V --> Power Equation

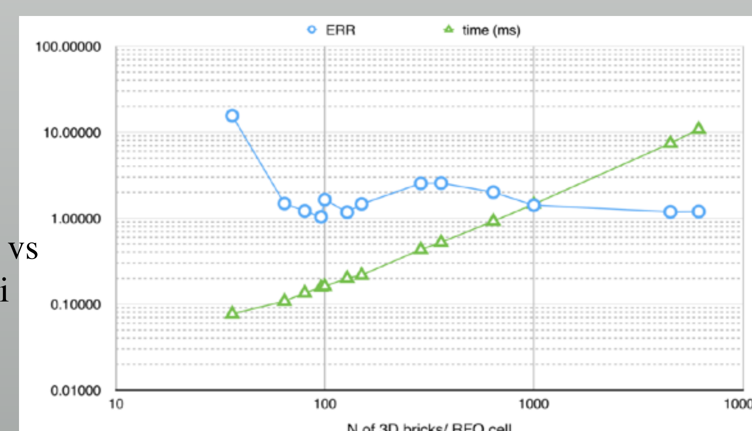
Moving particles

- F = m.a as usual but F = q (E + v x B)
  - F is Lorentz force. The relativistic version: $F_L = \gamma^3 m \frac{dv}{dt}$
- If you know electric and magnetic field vectors and if you have computational means you can simulate & predict
  - CST lecture (generic), Demirci (RFQ) and RhodoSim (Rhodotron) presentations
- The computational method - PIC: particle in a cell
  - create a mesh out of your geometry - usually 3D (FET)
    - grid size - to be optimized
  - compute the fields at mesh points & move particles
    - various methods for "mover" - LeapFrog, RG, Boris method,...
    - step: position or time - to be optimized



3D meshing unit with a 20 node isoparametric solid brick element

computational error vs meshsize in Demirci



Experiments & Laws: gauss & co

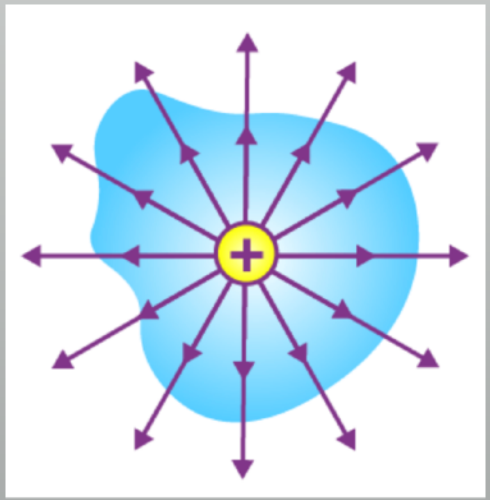
- By many: Lagrange (1760-70), Gauss(1813), Green(1825)…
  - divergence theorem, more math than phys.
  - charge conservation, mass conservation, hydrodynamics…

Gauss

It can be summarized as:

$$\nabla \cdot \mathbf{E} = \frac{\rho}{\varepsilon_0}$$

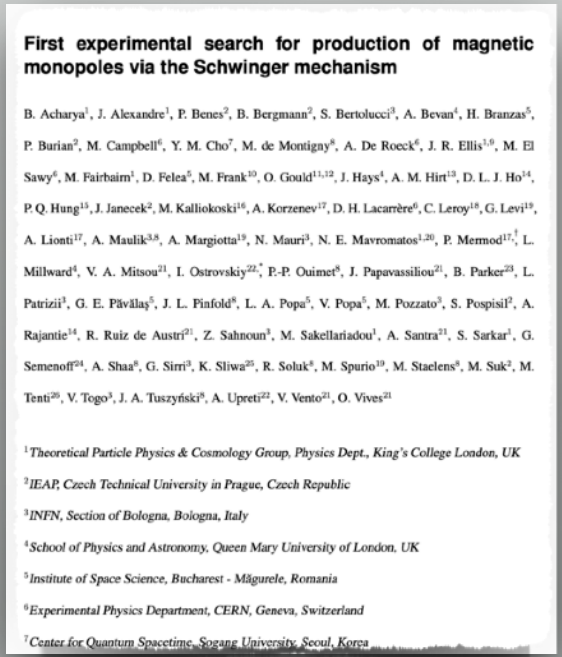
static electric charge creates E



since AFAWK there are not magnetic charges

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

no static magnetic charge, no B



First experimental search for production of magnetic monopoles via the Schwinger mechanism

B. Acharya[1], J. Alexandre[1], P. Benes[2], B. Bergmann[2], S. Bertolucci[3], A. Bevan[4], H. Branzas[5], P. Burian[2], M. Campbell[6], Y. M. Cho[7], M. de Montigny[8], A. De Roeck[6], J. R. Ellis[1,9], M. El Sawy[6], M. Fairbairn[1], D. Felea[5], M. Frank[10], O. Gould[11,12], J. Hays[4], A. M. Hirt[13], D. L. J. Ho[14], P. Q. Hung[15], J. Janecek[2], M. Kalliokoski[16], A. Korzenev[17], D. H. Lacarrère[6], C. Leroy[18], G. Levi[19], A. Lionti[17], A. Maulik[3,8], A. Margiotta[19], N. Mauri[3], N. E. Mavromatos[1,20], P. Mermod[17,†], L. Millward[4], V. A. Mitsou[21], I. Ostrovskiy[22,*], P.-P. Ouimet[8], J. Papavassiliou[21], B. Parker[23], L. Patrizii[3], G. E. Păvălaş[5], J. L. Pinfold[8], L. A. Popa[5], V. Popa[5], M. Pozzato[3], S. Pospisil[2], A. Rajantie[14], R. Ruiz de Austri[21], Z. Sahnoun[3], M. Sakellariadou[1], A. Santra[21], S. Sarkar[1], G. Semenoff[24], A. Shaa[8], G. Sirri[3], K. Sliwa[25], R. Soluk[8], M. Spurio[19], M. Staelens[8], M. Suk[2], M. Tenti[26], V. Togo[3], J. A. Tuszyński[8], A. Upreti[22], V. Vento[21], O. Vives[21]

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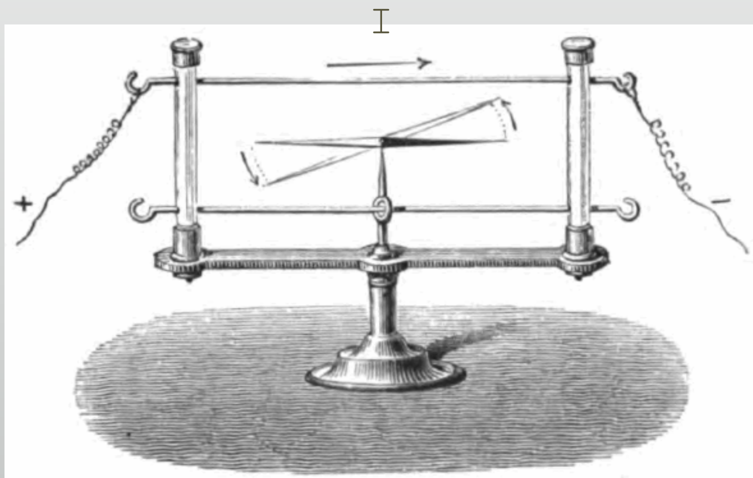
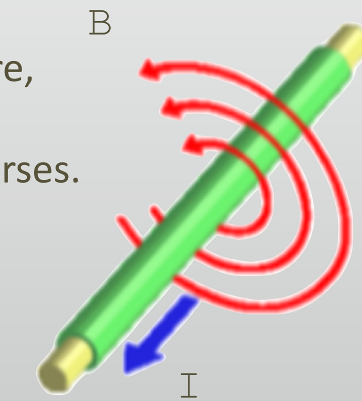
Experiments & Laws: ørsted-Ampere-maxwell

- **Original Experimenter: Ørsted @1820 - E & B related.**
  - a current on a wire induces a magnetic field
  - Ampere improved the experiment with multiple wires

Ampere



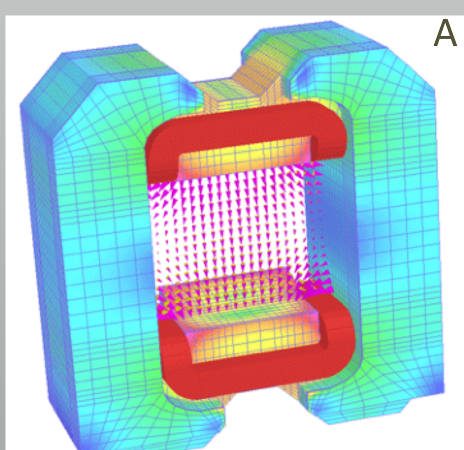
- The B field lines encircle the wire, always perpendiculary.
- If I is reversed, B direction reverses.
- The strength of B ~ I.
- The strength of B(r) ~1/r.



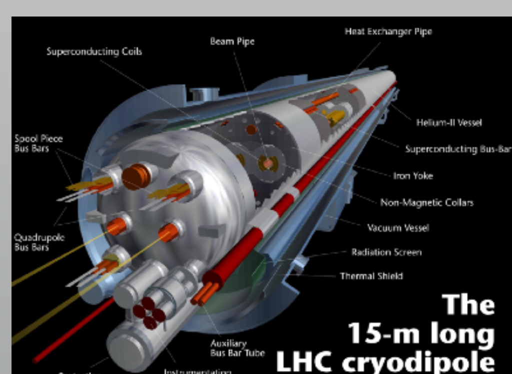
The results can be summarized as:

moving charges produce B $\nabla \times \mathbf{B} = \mu_0 \mathbf{J}$

maxwell's addition: changing electric field also produces B $\nabla \times \mathbf{B} = \mu_0 \left(\mathbf{J} + \varepsilon_0 \frac{\partial \mathbf{E}}{\partial t} \right)$



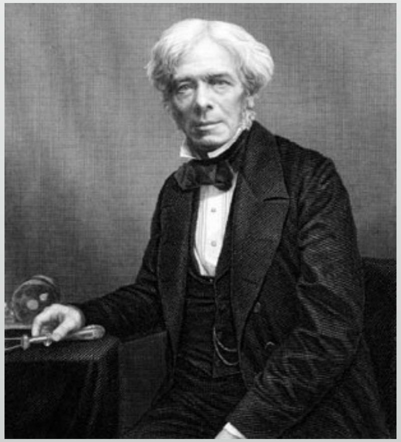
A bending magnet



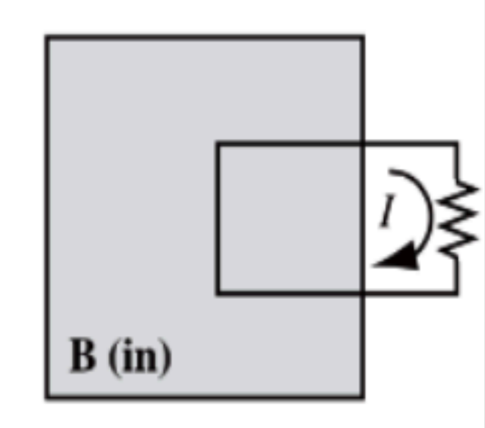
This is how we build magnets! see superfish lecture.

Experiments & Laws: Faraday-Maxwell

- Faraday 1831 also independently by Henry 1832
  - an iron core couples magnets. motors, transformers, detectors…



Faraday



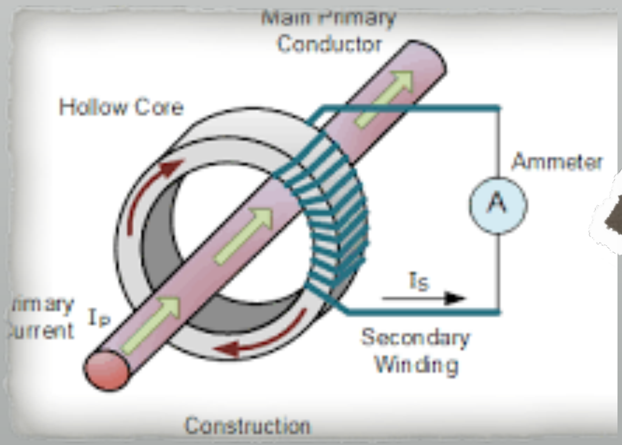
Constant B field, static circuit, no current. I=0.
change B --> I induced.
move circuit --> I induced.
move magnet producing B --> I induced

The results can be summarized with multiple equations

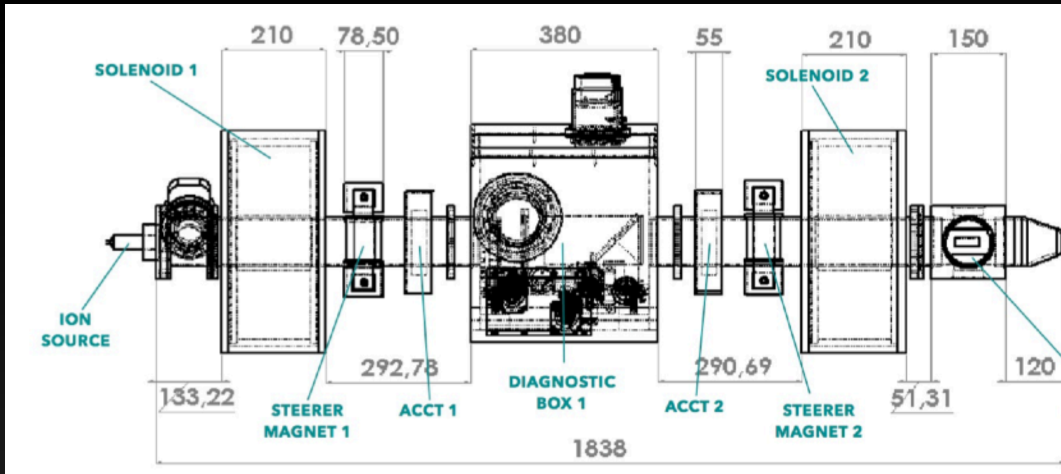
Define magnetic flux $$\Phi_B = \int_\Sigma \mathbf{B} \cdot d\mathbf{A}$$

change in magnetic flux defines an electromotrice force. $$\mathcal{E} = -N \frac{d\Phi_B}{dt}$$

EMF originates from an electric field. Maxwell-Faraday eqn $$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$



AC Current transformer for beam measurements



Pulsed Beam Tests at the SANAEM RFQ Beamline

G Turemen[1,2], Y Akgun[1], A Alacakir[1], I Kilic[1], B Yasatekin[1,2], E Ergenlik[3], S Ogur[3], E Sunar[3], V Yildiz[3], F Ahiska[4], E Cicek[5] and G Unel[6]

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Abstract. A proton beamline consisting of an inductively coupled plasma (ICP) source, two solenoid magnets, two steerer magnets and a radio frequency quadrupole (RFQ) is developed at the Turkish Atomic Energy Authority's (TAEA) Saraykoy Nuclear Research and Training Center (SNRTC-SANAEM) in Ankara. In Q4 of 2016, the RFQ was installed in the beamline. The high power tests of the RF power supply and the RF transmission line were done successfully. The high power RF conditioning of the RFQ was performed recently. The 13.56 MHz ICP source was tested in two different conditions, CW and pulsed. The characterization of the proton beam was done with ACCTs, Faraday cups and a pepper-pot emittance meter. Beam transverse emittance was measured in between the two solenoids of the LEBT. The measured beam is then reconstructed at the entrance of the RFQ by using computer simulations to determine the optimum solenoid currents for acceptance matching of the beam. This paper will introduce the pulsed beam test results at the SANAEM RFQ beamline. In addition, the high power RF conditioning of the RFQ will be discussed.

1. Introduction

SANAEM is finalizing the construction of a proton beamline to be used for training and educational purposes. All of the components were designed and produced locally to train accelerator physicists and engineers on the job. The full proton beamline, which is designed for pulsed beam operation, composed of an ion source, a low energy beam transport and an RFQ operating at 352.21 MHz, together with the RF components was designed and installed. This note summarizes the ongoing commissioning work of both the proton beamline and the RF power supply unit (PSU).

2. SANAEM RFQ Beamline

The beamline of the SANAEM RFQ consists of an ion source, a LEBT (Low Energy Beam Transport) line, a 1.3 MeV RFQ and an energy spectrometer. The drawing and a view of the LEBT line and the RFQ cavity is shown in Fig.1. The ion source and the LEBT line components

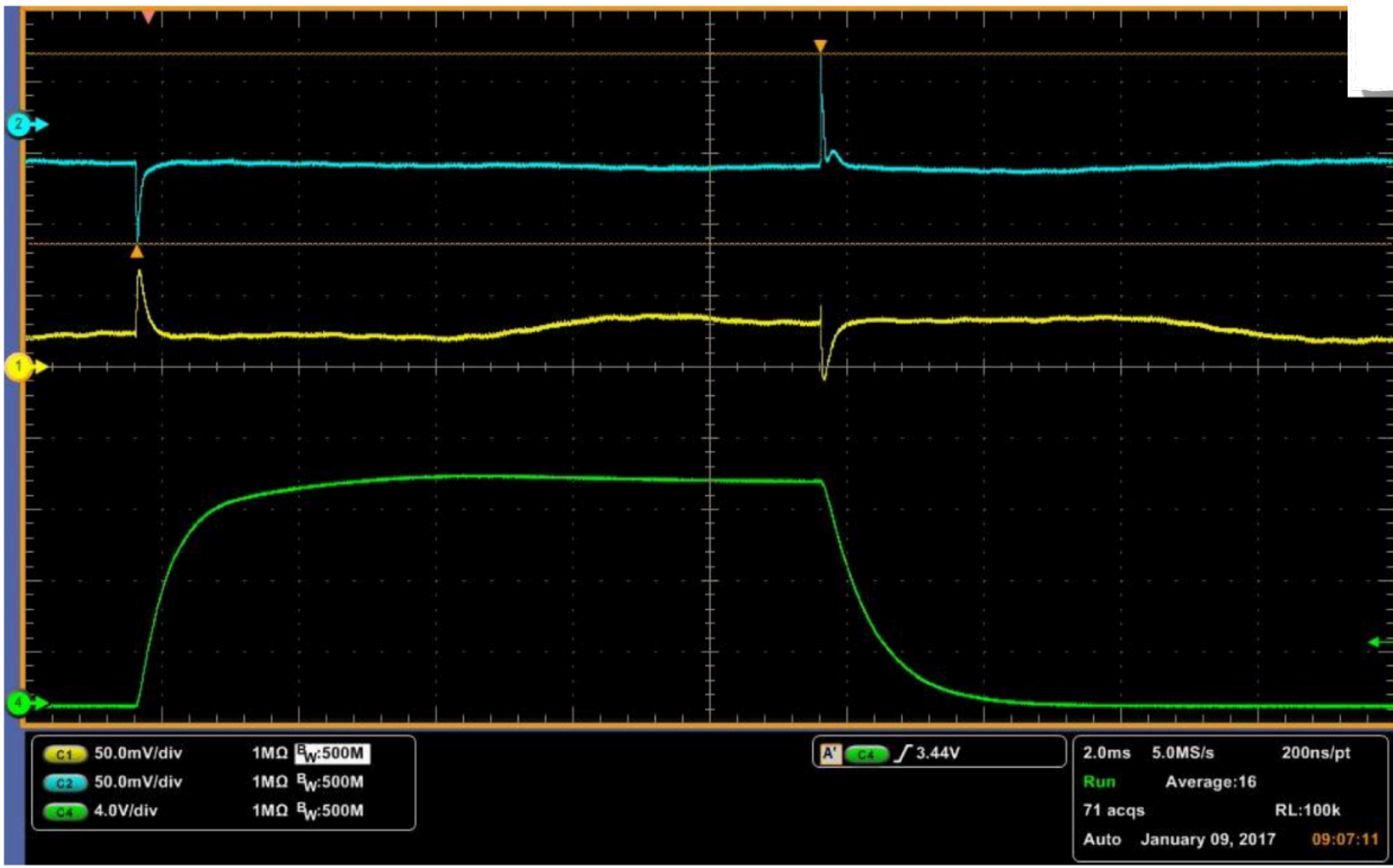
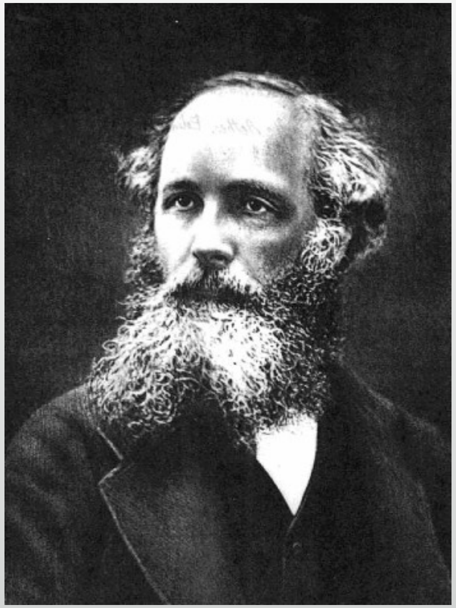


Figure 5: Beam current measurements on the LEBT line. Green: Faraday cup, yellow and blue: ACCT signals.

Laws summary by Maxwell-Heaviside



James Clerk Maxwell

$$\nabla \cdot \mathbf{E} = \frac{\rho}{\varepsilon_0}$$

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

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

$$\nabla \times \mathbf{B} = \mu_0 \left(\mathbf{J} + \varepsilon_0 \frac{\partial \mathbf{E}}{\partial t} \right)$$

- $\mathbf{E}$ electric field
- $\mathbf{B}$ magnetic field
- $\mathbf{J}$ current density
- ρ charge density
- ε_0 vacuum permittivity
- μ_0 vacuum permeability

Remember two identities

$$\nabla \cdot (\nabla \times \mathbf{A}) = 0$$

div. of curl of a vector field is zero

what if $B = \nabla \times A$?

$$\nabla \times (\nabla \times \mathbf{A}) = \nabla(\nabla \cdot \mathbf{A}) - \nabla^2 \mathbf{A}$$

curl of curl of a vector field is ~div²

$$\nabla^2 \mathbf{A} = (\nabla^2 A_x, \nabla^2 A_y, \nabla^2 A_z),$$

EM waves 1

IF no electric no magnetic charges. equations simplify...

$$\nabla \cdot \mathbf{E} = 0, \qquad \nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t},$$
$$\nabla \cdot \mathbf{B} = 0, \qquad \nabla \times \mathbf{B} = \mu_0 \varepsilon_0 \frac{\partial \mathbf{E}}{\partial t}.$$

use identity-2

$$\mu_0 \varepsilon_0 \frac{\partial^2 \mathbf{E}}{\partial t^2} - \nabla^2 \mathbf{E} = 0,$$
$$\mu_0 \varepsilon_0 \frac{\partial^2 \mathbf{B}}{\partial t^2} - \nabla^2 \mathbf{B} = 0.$$

if we assume $c = (\mu_0 \varepsilon_0)^{-1/2}$ it looks like the wave equation

$$\frac{\partial^2 u}{\partial t^2} = c^2 \left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2} \right)$$

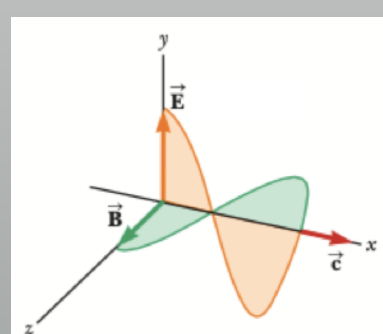
$\omega = 2\pi f \quad \lambda = c/f$

$$E = E_{\max} \cos(kx - \omega t)$$
$$B = B_{\max} \cos(kx - \omega t)$$

recall

$$\frac{\partial E}{\partial x} = -\frac{\partial B}{\partial t}$$

E & B fields are not independent.



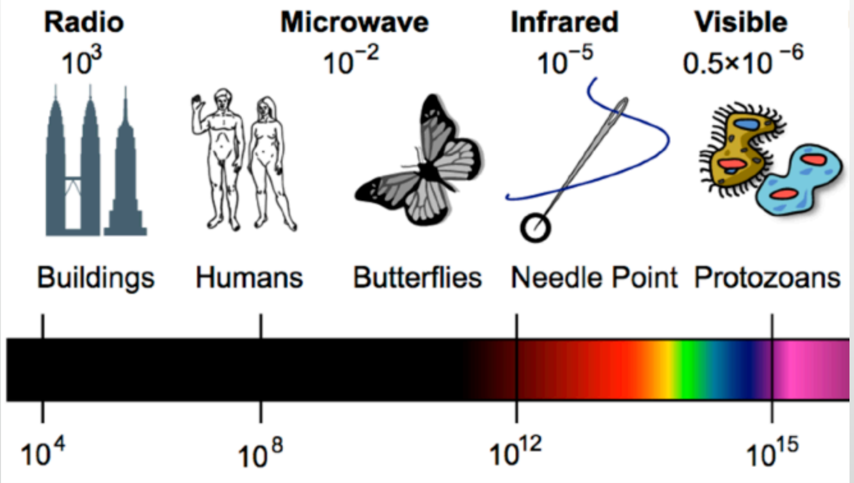
so EM waves move at the speed of light
or light is an EM wave!

EM waves 2

wavelength (m)

object at typical wavelength

Frequency (Hz)



In accelerator & detector physics, we typically use MHz and GHz EM waves: RF or microwave

What is the relation between E and B?

$$\frac{\partial E}{\partial x} = -\frac{\partial B}{\partial t}$$

$$E = E_{\max} \cos(kx - \omega t)$$
$$B = B_{\max} \cos(kx - \omega t)$$

$$\frac{\partial E}{\partial x} = -kE_{\max} \sin(kx - \omega t)$$
$$\frac{\partial B}{\partial t} = \omega B_{\max} \sin(kx - \omega t)$$

$$\frac{E_{\max}}{B_{\max}} = \frac{\omega}{k} = c$$

E & B fields are not independent, in fact this is a single wave with two components.

What kind of energy this wave carries?

energy ~ $(\text{field})^2$

power = energy / unit-time

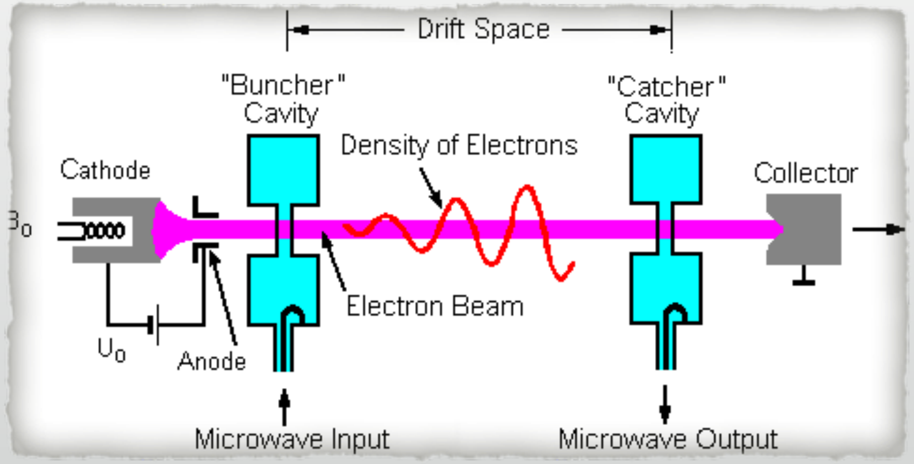
correcting for units:

$$S = \frac{E^2}{\mu_0 c} = \frac{cB^2}{\mu_0}$$

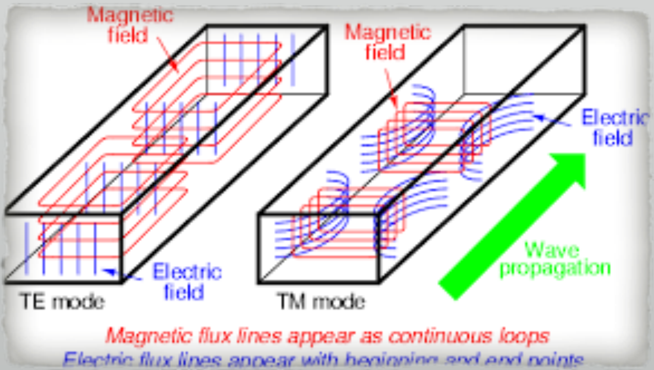
power per area that EM wave crosses

RF structures

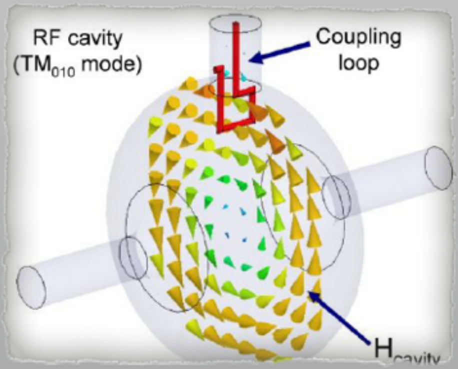
- power supply

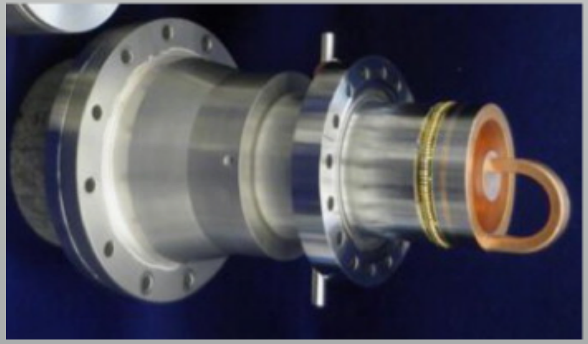


- power transmission



- power coupling





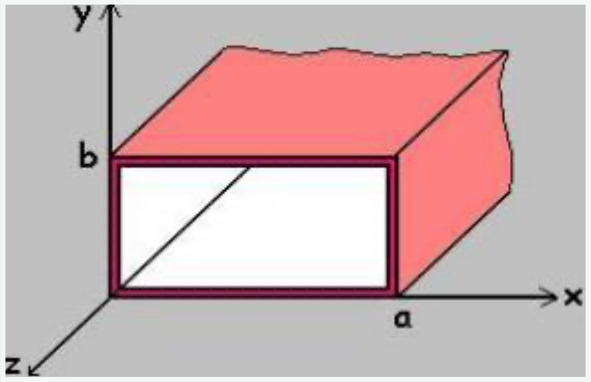
power transmission

$$\frac{\partial^2 u}{\partial t^2} = c^2 \left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2} \right)$$

choose the direction of motion as *z*

$$\left[\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + (\omega/c)^2 - k^2 \right] E_z = 0,$$
$$\left[\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + (\omega/c)^2 - k^2 \right] B_z = 0.$$

coupled equations, as before
 if E_z=0 --> Transverse Electric - T E
 if B_z=0 --> Transverse Magnetic - T M



Lets work with TE mode in a rectangular wave guide

E_z=0

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$
$$\frac{\partial E_y}{\partial x} - \frac{\partial E_x}{\partial y} = -\frac{\partial B_z}{\partial t}$$

assume B_z = F(x).G(y)

at the WG boundary, there must be a special case
 --> E_x and E_y must be 0
 --> all power must be carried by B field
 --> B field must "fit" as a sin (or cos) wave

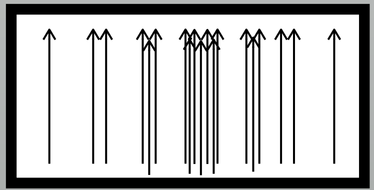
lets try:

$$B_z = B_0 \cos\left(\frac{m\pi}{a}x\right) \cos\left(\frac{n\pi}{b}y\right)$$

Electric Field induced a the borders:~ sine

should vanish on th metal

cos(0)= 1
cos(π)= -1



Efield

why this?
wave that fits m and n cosine with maxima at the boundaries
 integers m and n define the TE wave.
 TE00: does not exist- no wave
 TE10: fundamental mode

power transmission