Universidade de São Paulo
Instituto de Física

Aceleradores de íons: Princípios e Aplicações

Manfredo H. Tabacniks
2019

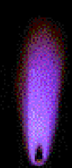
~450 AC, na Grécia antiga, Empédocles classificou a matéria em quatro elementos:

terra, água , ar e fogo

Esses 4 elementos eram envoltos por: amor e **ódio**. O amor une os elementos. O ódio os separa. A mistura dos elementos cria todas as coisas.

http://perso.club-internet.fr/molaire1/e_plan.html

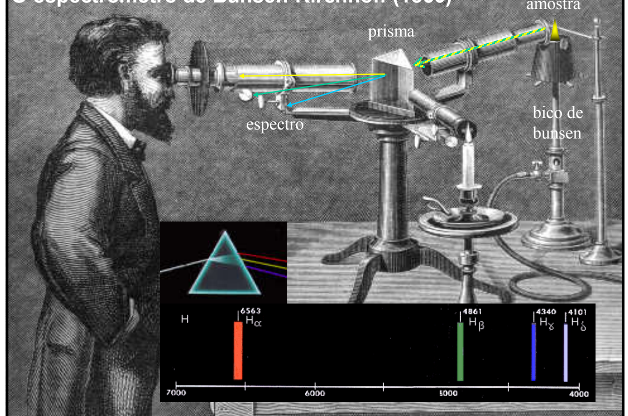
No século 18, a cor da chama dos materiais indicava os elementos.



césio - Cs

lítio - Li sódio - Na cobre - Cu

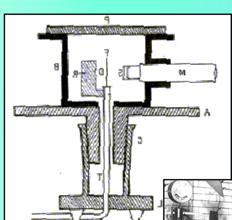
O espectrômetro de Bunsen-Kirchhoff (1860)

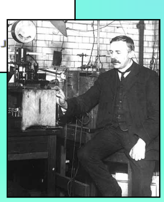


http://physics.kenyon.edu/EarlyApparatus/Optics/Spectrometers/Bunsen_Spectrometer.JPG

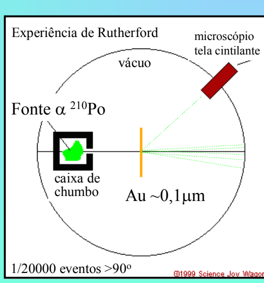
Tudo começou com a experiência de Rutherford (1909)

Atirando alfas em finas folhas de ouro (0,086 μm)





Ernest Rutherford. Premio Nobel de química 1908



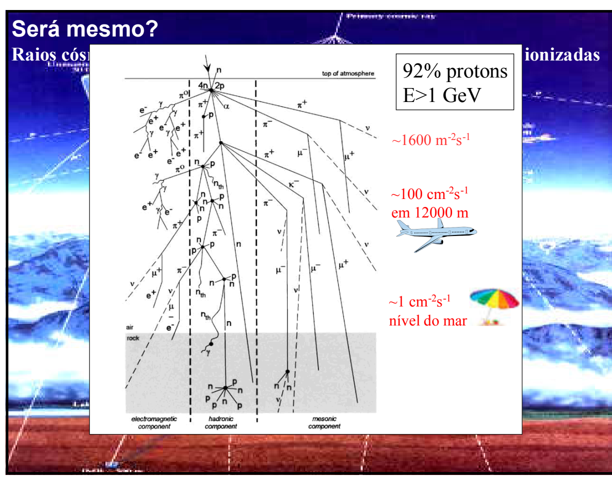
http://myweb.usf.edu/~mhight/goldfoil.html

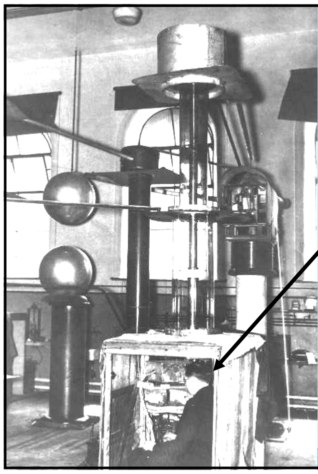
Marsden e Geiger em 1909: ~1:20000 "refletiam" em ângulo maior que 90º

http://dbhs.wvusd.k12.ca.us/AtomicStructure/Rutherford-Model.html

Será mesmo?

Raios cós... ionizadas





1931 - 300 kV

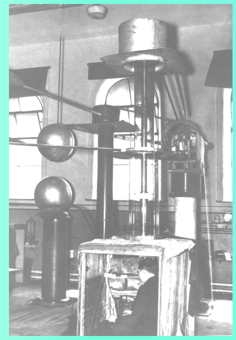
Acelerador Eletrostático DC Cockcroft-Walton

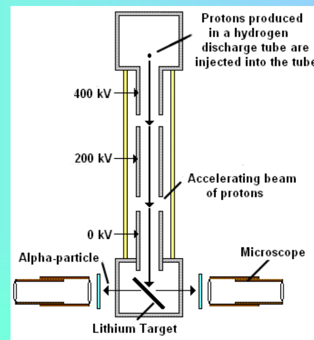
Gamov, em 1928, mostra que uma partícula alfa com baixa energia pode tunelar a barreira coulombiana e penetrar no núcleo.

Walton

Um microscópio focado numa pequena tela cintilante é operado pelo próprio Ernest Walton, 28 revelando a primeira evidência de uma desintegração artificial: $^{7}Li(p,\alpha)^{4}He$

Acelerador Cockcroft-Walton de 280kV (1931)

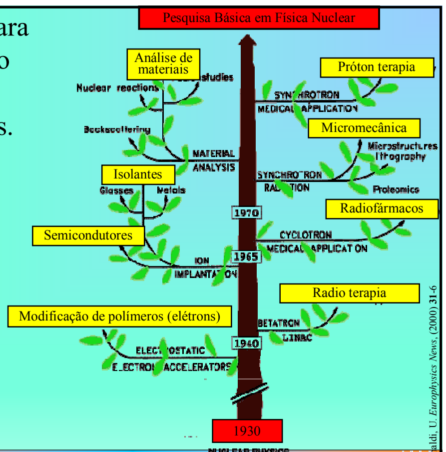




$$^{7}_{3}Li + ^{1}_{1}H \rightarrow ^{4}_{2}He + ^{4}_{2}He + Energy$$

http://homepage.eircom.net/~louiseboylan

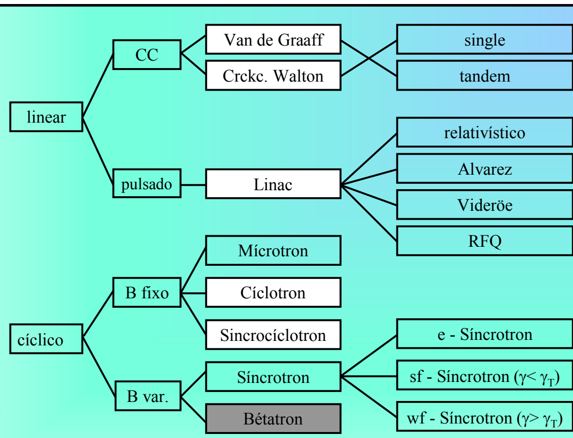
Aceleradores para estudar o núcleo atômico e sua aplicações.



Amaldi, U. *Europhysics News*, (2000) 31-6

Aceleradores em ciência tecnologia

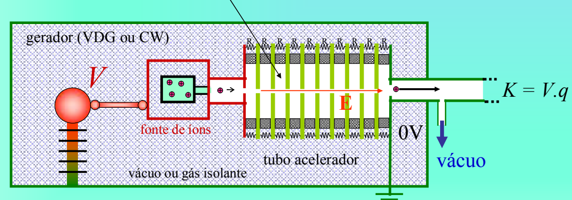
- **Militar**
  - Armas, segurança, inspecção (γ e neutrons)
- **Pesquisa e Análise de Materiais**
  - Análise de materiais com feixes iônicos (RBS, PIXE, PIGE, NRA, ERDA, AMS, MALDI..)
  - Datação
  - Luz Síncrotron
    Matéria Condensada, Microbiologia, Proteômica, Morfologia Molecular
  - Implantação de íons. Quantum dots.
- **Tratamento e diagnóstico médico**
  - Radioterapia (e^-, H, γ, X..), dosimetria, dano em DNA..
  - Radiofármacos, marcadores isótopicos
  - Radiodiagnóstico - tomografia
- **Aplicações Tecnológicas**
  - Polimerização e reticulação (embalagens, pneus, tintas..)
  - Implantação de íons (semicondutores, superfícies biologicamente ativas..)
  - Análises estruturais, μLitografia, micromecânica
  - Esterilização (alimentos, embalagens, eq. médico)
- **Geração de energia**
  - Reatores nucleares, ADS...



Adaptado de E. Michaelis

Um acelerador eletrostático de íons

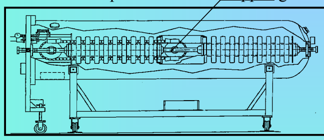
- Fonte de íons (ou de elétrons)
- Fonte de alta tensão (VDG ou CW)
- Estrutura em vácuo para transporte do feixe (íons ou elétrons)

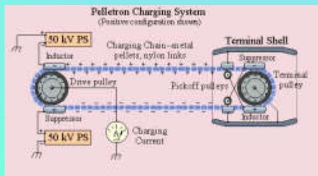


Aceleradores

Acelerador Pelletron tipo tandem com *stripper* gasoso

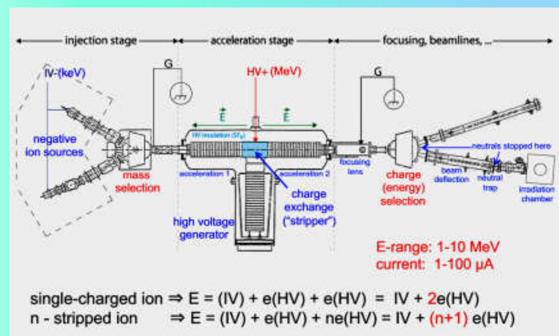
- **Van de Graaff**
- CW
- Linac...
- Ciclotron
- Sincrociclotron
- Bétatron





- Tensão máxima 25MV (tandem)
- 74+ Pelletrons construídos (~35 anos) 60 U < 5MV
- 300+ aceleradores VDG da HVE

Acelerador Van de Graaff para pesquisa

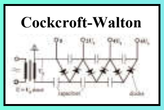


G. Lulli, CNR Institute for Microelectronics and Microsystems, IMM, Bologna

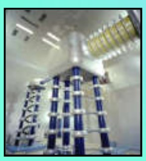
Aceleradores

- Van de Graaff
- **CW**
- Linac...
- Ciclotron
- Sincrociclotron
- Bétatron

Cockcroft-Walton

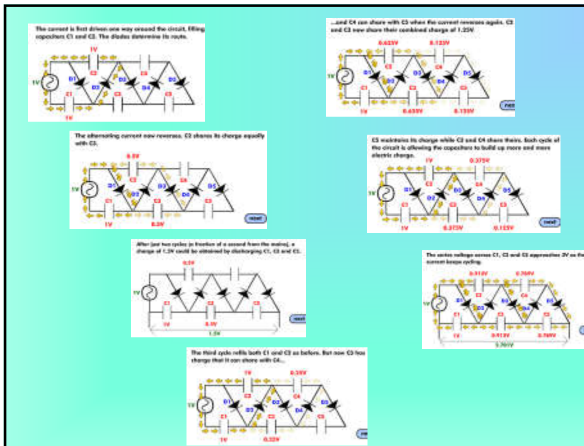


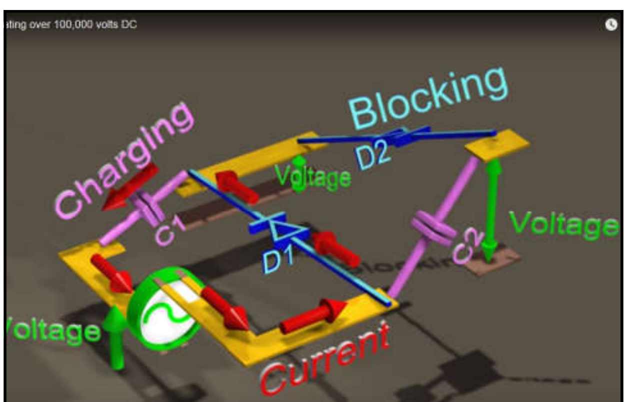
Cockcroft-Walton (1932)
- Carrega em paralelo CA e descarrega em série
- É a fonte em qualquer televisão
- V x I hiperbólica: baixa corrente em alta tensão
- *Ripple* alto (α I/f) => f alta
- Oferece tensões intermediárias. (polarização de dinodos, fotomultiplicadoras, etc.)



Injetor de prótons do Fermilab (750 kV)

Fonte de AT do implantador de íons do IFUSP (400 kV)

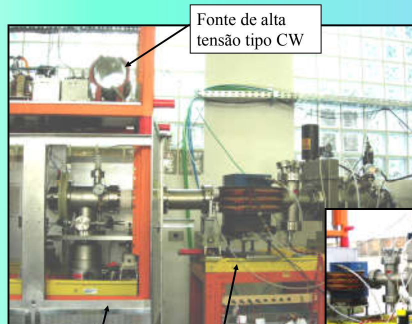




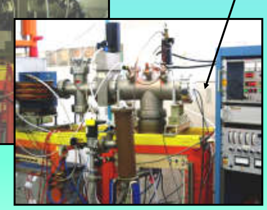
https://www.youtube.com/watch?v=DI8Yt1AQrH8

Implantador de íons 70kV IFUSP

Fonte de alta tensão tipo CW



Porta amostras

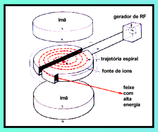


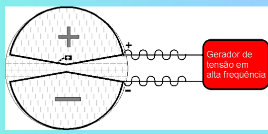
Fonte de íons e plataforma de 70kV

Imã analisador

Cíclotron

Van de Graaff
CW
Linac...
Cíclotron
Sincrocíclotron
Bétatron





$$r = \frac{mv}{qB} \qquad f = \frac{1}{2\pi}\frac{qB}{m}$$

Freqüência ciclotrônica **constante.**

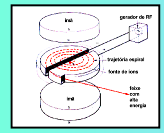
Limitado para cerca de 10 MeV de prótons. Acima dessa energia, é necessário considerar o incremento de massa dos prótons (γm).

$$f_{RF} = \frac{1}{2\pi}\frac{qB}{\gamma m}$$

O maior sincrocíclotron em operação (Gatchina, St. Petesburgo) acelera prótons até 1 GeV. Pesa 10000 t. As peças polares têm 6 m de diâmetro.

Cíclotron

Van de Graaff
CW
Linac...
Cíclotron
Sincrocíclotron
Bétatron



$$r = \frac{m\,\mathrm{v}}{qB} \qquad f = \frac{1}{2\pi}\frac{qB}{m}$$

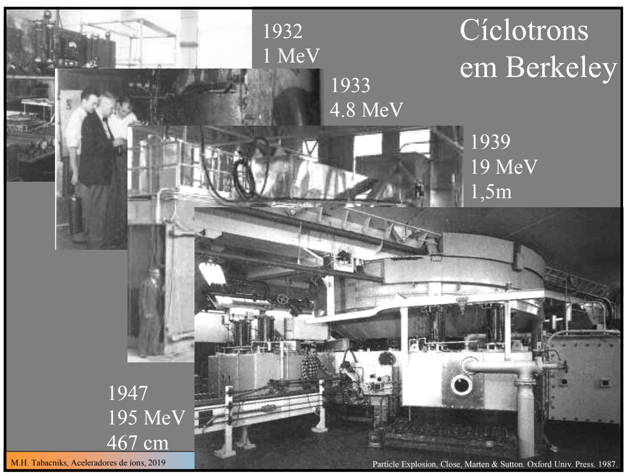
Freqüência ciclotrônica **constante.**

Variando o *gap* entre as peças polares (1960) foi possivel reprojetar os imãs "*sector focused cyclotron*" para compensar a perda de velocidade devido ao incremento de massa, aumentar a energia e manter constante a freqüência da fonte de RF.

D. Robin. Michigan State University (2007)

O maior cíclotron focado é o de Vancouver. Gera feixe de H^- com 600 MeV

Cíclotrons em Berkeley



1932
1 MeV

1933
4.8 MeV

1939
19 MeV
1,5m

1947
195 MeV
467 cm

Particle Explosion, Close, Marten & Sutton. Oxford Univ. Press. 1987.

Moderno cíclotron para produção de radioisótopos

Ciclotron de 30 MeV do IPEN, em São Paulo, para fabricação de radioisótopos: ^{18}F para PET, ^{13}N, ^{15}O, ^{123}I, ^{67}Ga, ^{201}Tl.

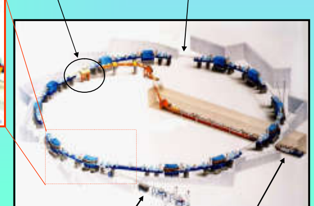
Aceleradores

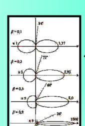
- linear
  - CC
    - Van de Graaff
    - Crckc. Walton
  - pulsado
    - Linac
- cíclico
  - B fixo
    - Mícrotron
    - Cíclotron
    - Sincrocíclotron
  - B var.
    - Síncrotron
    - Bétatron

Adaptado de E. Michaelis

Anéis de armazenamento (Acelerador Síncrotron)

O feixe (de elétrons ou íons) é injetado num anel com imãs e órbita fixa. A energia do feixe é aumentada (em seção aceleradora tipo cavidade ressonante de um acelerador linear), ao mesmo tempo em que se aumenta o campo magnético dos imãs que confinam o feixe em sua órbita.



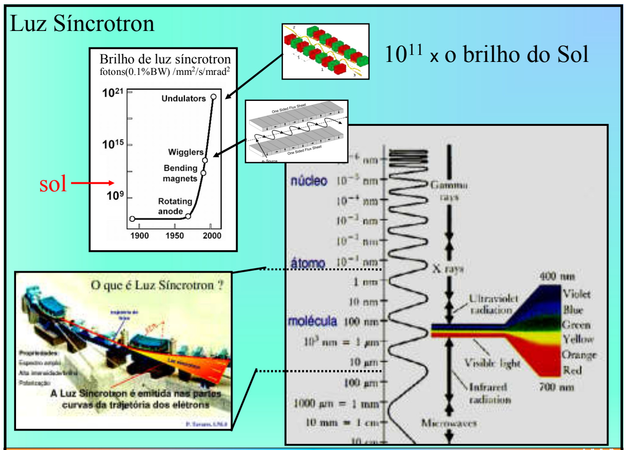


O estreito feixe de luz é um efeito relativístico.

Uma das muitas estações experimentais

Ac. linear 100 MeV

Luz Síncrotron



Acelerador Sírius (LNLS - Campinas).

CERN: Large Hadron Collider, (50 + 50) GeV

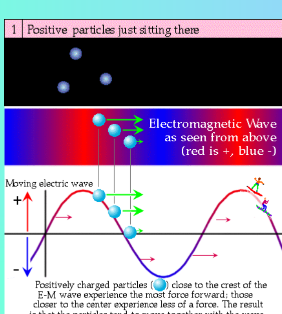
Aceleradores

- linear
  - CC
    - Van de Graaff
    - Crckc. Walton
  - pulsado
    - Linac
- cíclico
  - B fixo
    - Microtron
    - Cíclotron
    - Sincrocíclotron
  - B var.
    - Síncrotron
    - Bétatron

Adaptado de E. Michaelis

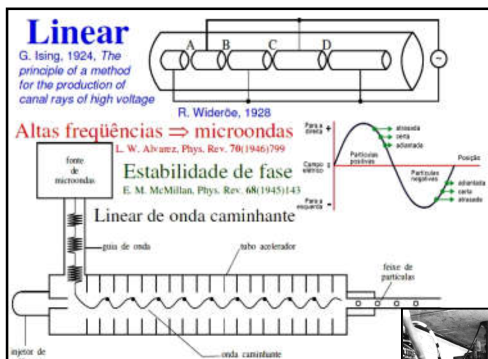
e se linearizarmos o ciclotron ? → acelerador linear

íons surfam numa onda caminhante

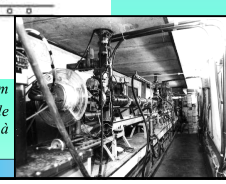


http://www.particleadventure.org/accel_ani.html

Linear



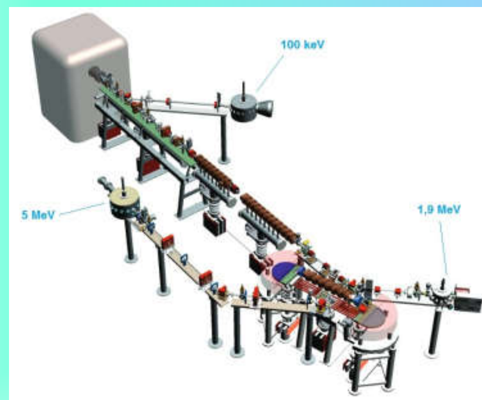
Acelerador linear *de elétrons, de 70MeV instalado em 1967 pelo Prof. Goldemberg no IFUSP. Doado pela U. de Stanford, funcionou até meados de 1980. No canto à esquerda vê-se o injetor de elétrons.*

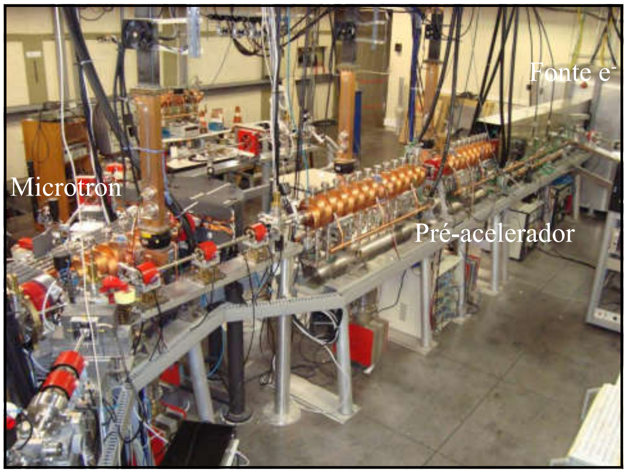


Acelerador linear injetor do Bevatron, Lawrence - Berkeley, EUA

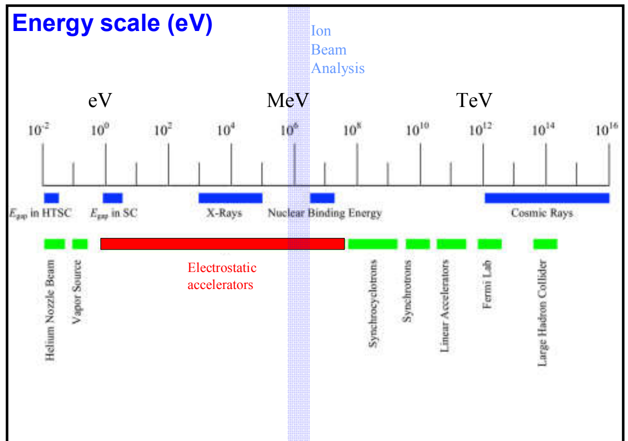
Particle Explosion, Close, Marten & Sutton. Oxford Univ. Press. 1987.

Microtron - IFUSP

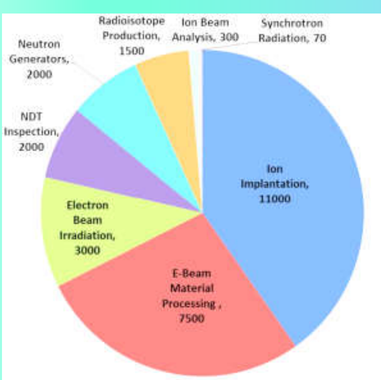




Energy scale (eV)



Aceleradores no mundo (2013)



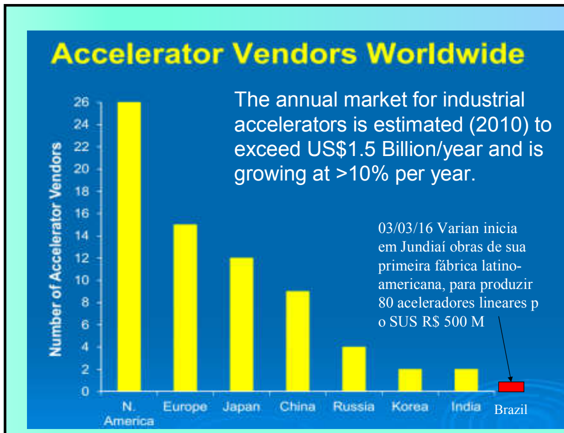
>27,000 systems have been sold.

>20,000 are still in operation.

>Accelerator business: 70 vendors worldwide .

Annual value of processed, treated or inspected products: +US$500B (2010.

R.W. Hamm. R&M Technical Enterprises, Inc. (2013)



R.W. Hamm. 2013. R&M Technical Enterprises, Inc.

Ion Implantation Applications 40%

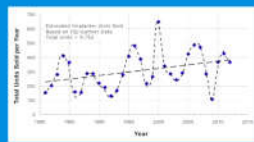
S. Felch – WEYB2

Semiconductors
- CMOS transistor fab for essentially all IC devices.
- CCD & CMOS imagers for cell phones & digital cameras.
- Cleaving silicon for producing photovoltaic solar cells.

Metals
- Harden cutting tools.
- Reduce friction in metal parts.
- Biomaterials for implants.

Ceramics & Glasses
- Harden surfaces.
- Modify optics.

All digital electronics are dependent on ion implantation. A typical IC has 30-40 implants during fabrication.



R&M Technical Enterprises, Inc.

Electron Beam Irradiator Applications 38%

S. Sabharwal – WEYB03

- Cross linking of materials (largest application)
  - Wire & cable insulation – heat resistant
  - Heat shrink tubing
  - Heat shrinkable food packaging films
  - Closed cell polyethylene foams – auto & medical p…
  - Tire components
  - Curing of inks, coatings & adhesives – paper, wood, metals & plastics
  - Hydrogels for wound dressings
  - Sterilization of medical products (growing application) Syringes, catheters, gloves, surgical gowns and drapes, towels, bandages, tubing, fluid bags, labware, tubing, and absorbent
- Decontamination of food & medical device packaging
- Food and waste irradiation (largest potential applications)

Cross linking by industry

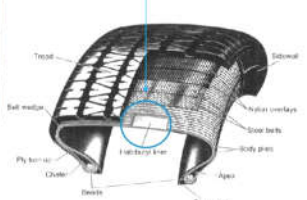
Total of $50 billion per year

Curetron (150-300kV)

R&M Technical Enterprises, Inc.

Most of modern tires are e-beam irradiated

300kV down-fire low energy electron beam system for crosslinking wear liner of automotive tires.



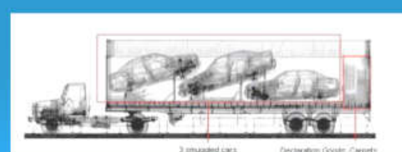
2016 SAE EBEAM TECHNOLOGIES

M.H. Tabacniks, Aceleradores de íons, 2019

High Energy X-Ray Inspection Applications

H. Chen – WEYB4

- Radiography of large castings – Original application that led to development of systems.
- Examination of rocket motors and munitions – Includes CT examinations systems.
- Port examination of containers & semi-trailers – Started as a security application and is now an import/export control tool.



7%

Used by many countries for manifest verification.

R&M Technical Enterprises, Inc.

Neutron Generator Applications 7%

- **Geophysical Exploration** – Mineral detection and oil well borehole logging.
- **Bulk material analysis** – Includes gold, coal, cement and scrap metal on-line monitoring.
- **Gauging & radiography** – Materials inspection.
- **Neutron activation analysis** – Trace elements in biological and environmental areas.
- **Security** – Detection of contraband, high explosives, fissionable materials and chemical weapons agents.
- Now replacing many radioactive sources due to new US regulations on control of these sources.

Oil well logging is largest industrial application of these systems.

R&M Technical Enterprises, Inc.

Radioisotope Applications 5.5%

S. Lapi – THYBB2

- **Industrial – Gauging & Calibration**
  - Thickness monitoring
  - Moisture content determination
- **Medical – Diagnostics & Treatment**
  - Single Photon Emission CT: ^{123}I & ^{111}In (^{99m}Tc ??)
  - PET (Positron Emission Tomography): ^{18}F, ^{11}C, ^{15}O, ^{13}N, ^{64}Cu & ^{124}I
  - Brachytherapy: ^{125}I & ^{103}Pd

>50 accelerator-produced radioisotopes in routine use.

R&M Technical Enterprises, Inc.

Ion Beam Analysis Applications 1%

Application Techniques – All were adapted from nuclear physics measurements

- Rutherford Back Scattering (RBS)
- Elastic Recoil Detection Analysis (ERDA)
- Nuclear Reaction Analysis (NRA)
- Particle Induced X-ray Emission (PIXE)
- Particle Induced Gamma ray Emission (PIGE)
- Nuclear Resonance Reaction Analysis (NRRA)
- Resonant Scattering Analysis (RSA)
- Charged Particle Activation Analysis (CPAA)
- Accelerator Mass Spectrometry (AMS)

Applications

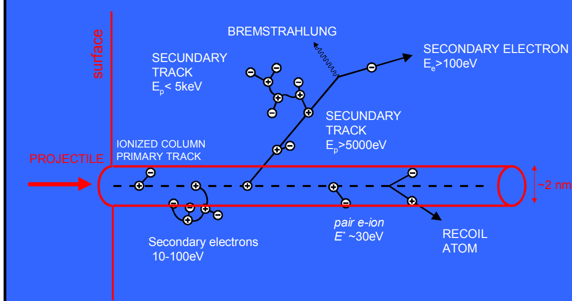
- ✓ Semiconductor quality
- ✓ Environmental monitoring
- ✓ Geological studies
- ✓ Oceanography studies
- ✓ Biomedical science
- ✓ Renewable energy

These applications are still widely used at many research labs.

R&M Technical Enterprises, Inc.

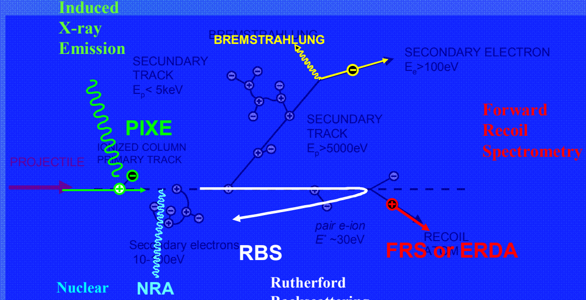
When an energetic ion (~MeV) penetrates a solid...

$M >> m_e$

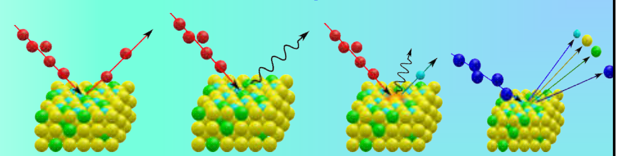


Adapted from Choppin, Liljenzin e Rydberg, Radiochemistry and Nuclear Chemistry, 2002

... the interactions can be used for material analysis



Métodos da Física Nuclear para análise de materiais



RBS: *Rutherford Back-scattering Spectrometry*
Na colisão entre íons e átomos da amostra, a massa dos átomos da amostra determina a velocidade do íon retro-espalhado.

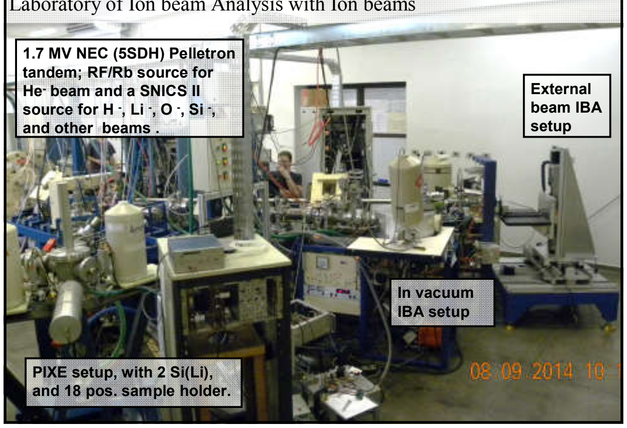
PIXE: *Particle Induced X-ray Emission*
Medem-se os raios-X característicos emitidos pela amostra quando irradiada com feixes de íons.

NRA: *Nuclear Reaction Analysis*
Reações nucleares bem conhecidas são usadas para medir elementos específicos.

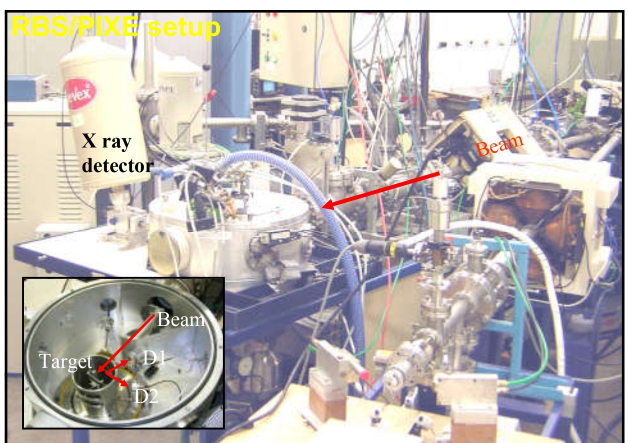
FRS: *Forward Recoil Spectrometry*
Um dos únicos métodos para a medida de hidrogênio elementar. No espalhamento frontal, tomos da própria amostra são ejetados na colisão com íons do feixe incidente.

Figuras: Tiago Fiorini da Silva e Cleber Rodrigues

LAMFI Laboratório para Análise de Materiais por Feixes Iônicos
Laboratory of Ion beam Analysis with Ion beams

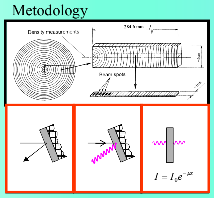


RBS/PIXE setup

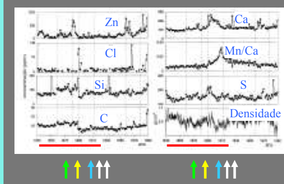


Tree ring analysis (1830 – 1990: 150 y)

Metodology



Time series



Rubber exploitation (1827-1920)
Krakatoa eruption (1883)
Foreign maritime commerce (1866)
Manaus port construction (1901)
Intense drawness (1911, 1926)

Martins, J.V.; Artaxo, P. A.; Ferraz, E. S. B.; Tabacniks, M.. H. Chronological studies of tree-rings from the Amazon Basin using thick target PIXE and proton backscattering analysis. NIM - B150 (1999) 240-247

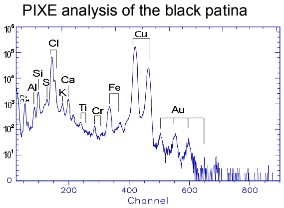
Ion Beam Analysis of an archaeological artifact

Mochican rattle (1AC-7DC)

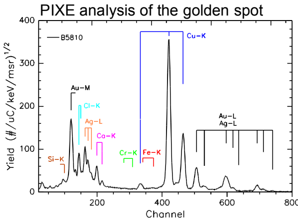
Plasma cleaned artifact found in the King of Sipan tomb by Walter Alva (1987).

Saettone, E; Matta, JA Sevidanes; Alva, W; Chubaci, JDD; Fantini, MCA; Galvão, RMO; Kiyohara, P; Tabacniks, MH. Journal of Physics - D (Applied Physics) 36 (2003) 842-848.

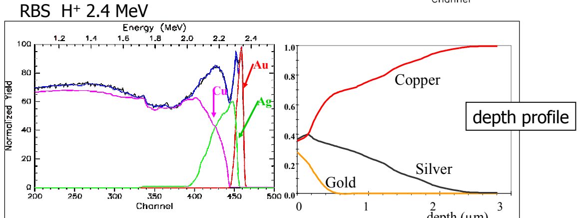
PIXE analysis of the black patina



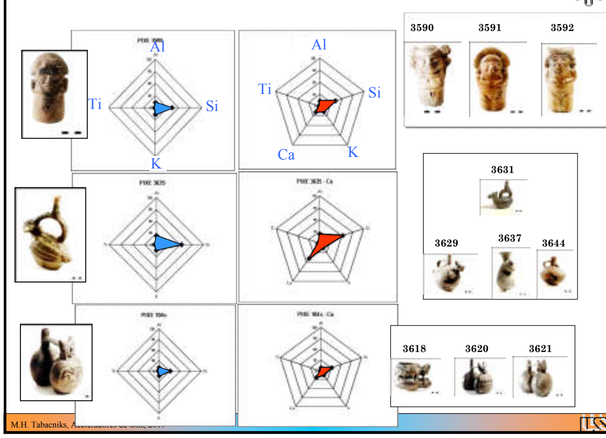
PIXE analysis of the golden spot



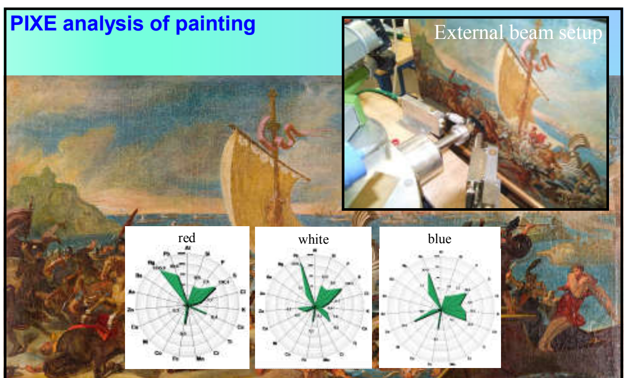
RBS H+ 2.4 MeV



PIXE analysis of historical remains (with MAE USP)



PIXE analysis of painting

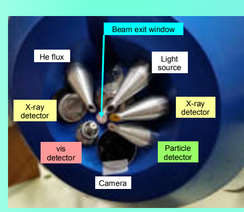


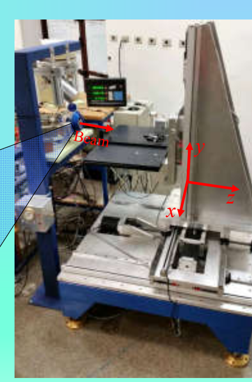
Desembarque e combate, Brazil, unknown author, end of XVIII

A Painting Studied with Integrated PIXE and Image Analysis,
E. Kajiya1, M. A. Rizzutto, V. Pagliaro, S.I. Finazzo, P. R. Pascholati

External beam at LAMFI: The rastering machine

The sample scans the beam:
3D 60cm± 5μm
Machine vision autofocus (0,05 mm)
Submilimeter beam size
PIXE elemental maps
3D 0,5mm pixel scan





Paleontology studies – Fossil maps

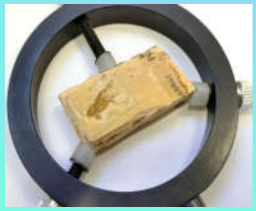
Fossil preservation suppose the action of micro-organisms.

Fossils are formed at the bottom of lakes (low concentration of oxygen and high concentration of minerals)

The organic material is replaced by elements like Fe, Cu and Zn. The matrix where the fossil is fixed on is made of calcite.

In collaboration with the Paleontology Group of the University of São Paulo.

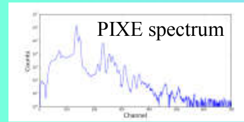
Fossil sample ready for analysis at the external beam



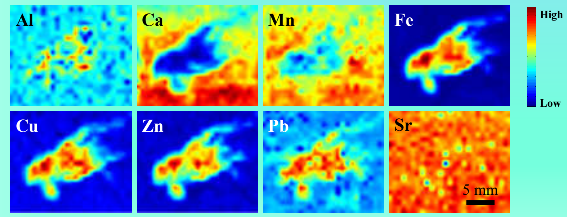
Gabriel Osés
Prof. Setembrino Petri
Prof. Mírian Liza Alves Forancelli Pacheco

Hyper-spectral images

GEOCIÊNCIAS

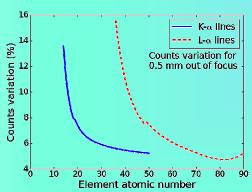


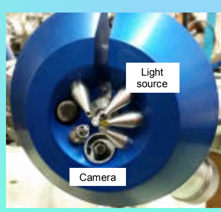
The organic material is replaced by elements like Fe, Cu and Zn. The matrix where the fossil is fixed on is made of calcite.

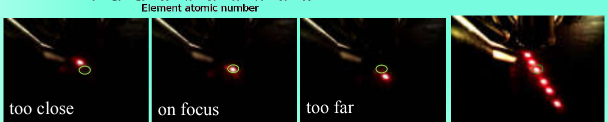


External beam – Auto focus

Machine vision controls the sample position for surface irregularities.
As a bonus, the sample surface can be digitally reconstructed.



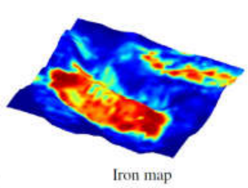




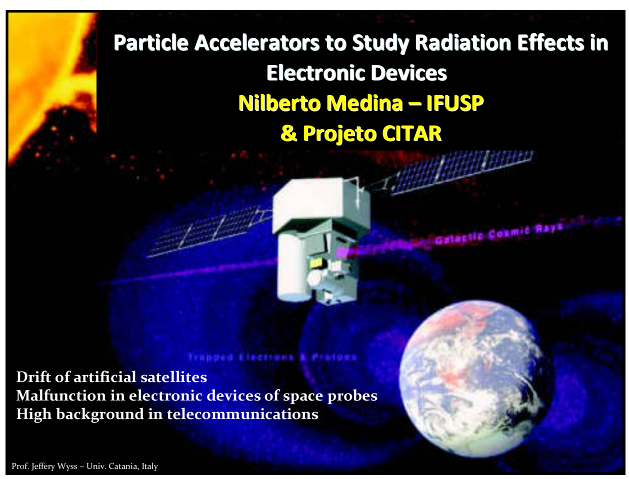
External beam auto-focus is a 3D micro-scanner

Hyper-spectral images

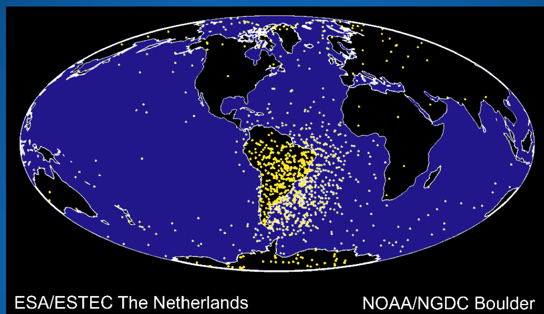
Surface reconstruction



Iron map



Interrupções na eletrônica de um satélite (U Surrey)



https://www.ngdc.noaa.gov/stp/satellite/anomaly/satelliteanomaly.html

All the Electronic Devices May Suffer from Radiation Effects

Particle and electromagnetic radiation
Ionizing and non-ionizing

Degradation of:
Micro-electronics, micro-processors,
solar cells, optical components, semiconductor detectors,
front-end electronics, cabling, etc

Causing: System shutdowns
Circuit damage
Data corruption, etc

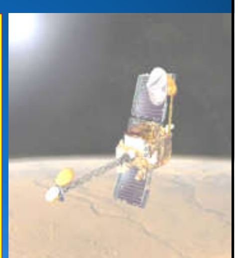
Radiation Effects are a headache for the designers of electronic boards for space missions

Cassini Mission (1997) – Some information was lost because of MBUs. End of the mission: September 15th 2017

Deep Space 1 Mission (1998) – A SEU caused a solar panel to stop opening out

Mars Odyssey (2001) – Two weeks after the launch, alarms went off because some errors lately attributed to a SEU.

GPS satellite network – One of the satellites is out of work, probably because of a latch-up.



B.E. Pritchard, IEEE NSREC 2002 Data Workshop Proceedings, pp 7-17, 2002

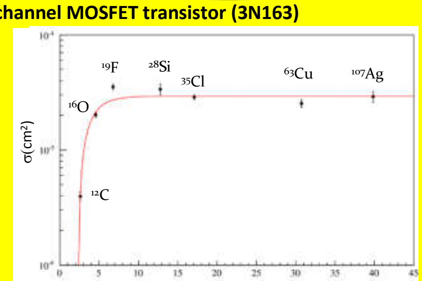
SAFIIRA SYSTEM @ LAFN-USP

SistemA de Feixes Iônicos para IRradiações e Aplicações

First SEU measurement with heavy ions in Brazil

Single Event Upset

p-channel MOSFET transistor (3N163)



$$\sigma_{SEE} = \frac{events}{\Phi}$$

$$\Phi = \frac{particles}{cm^2}$$

Weibull Function

$$\sigma = \sigma_{sat}\left[1 - e^{\left(\frac{LET - LET_{th}}{W}\right)^s}\right]$$

σ_{sat} = 294(10)10^{-5} cm²
LET_{th} = 2.35(36) MeV/mg/cm²
W= 1.06(11) MeV/mg/cm²
S = 0.62(10)

N.H. Medina et al., Proc. 2014 IEEE Radiation Effects Data Workshop, Paris, France, pg 272

obrigado pela atenção
tabacniks@if.usp.br

FAPESP CAPES CNPq FINEP USP