Applications of Particle Accelerators

Carsten P. Welsch

Accelerators everywhere

Particle Colliders

Waste Transmutation

Accelerator-Driven Subcritical Reactors

Food Processing

Lithography

Medical Accelerators

Material Irradiation

Antimatter ‚Factories'

Exotic Ions

Spallation Sources

Light Sources

Recap: What makes an accelerator ?

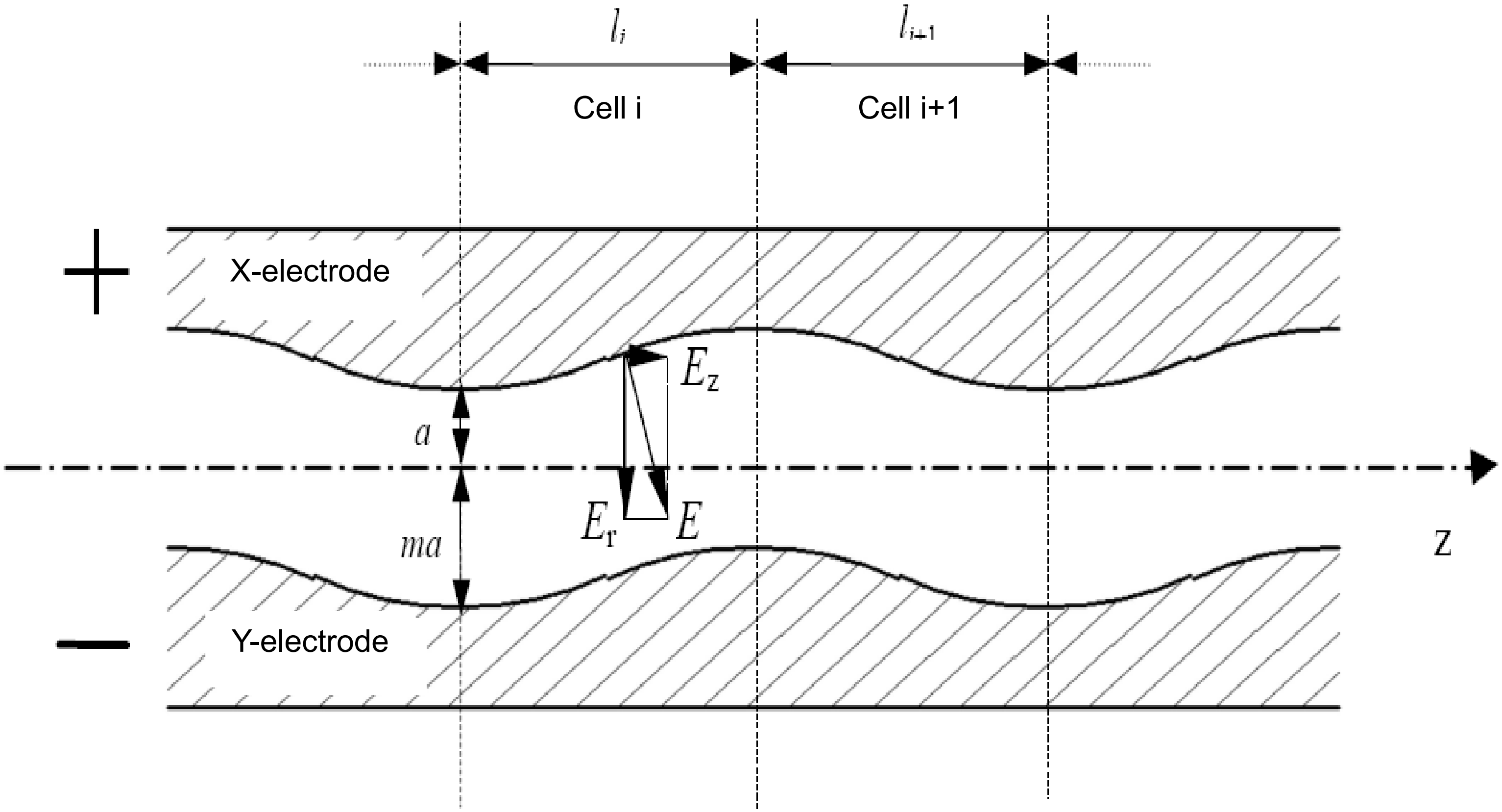
- Accelerate beam
- Focus / modulate

Important

- Preserve emittance;
- Maximize transmission.

- All-in-one: Radiofrequency Quadrupole (Rfq)

Acceleration in an Rfq



Beam Dynamics in an Rfq

Focusing Strength *B*:

$$B = \left(\frac{q}{m_0}\right)\left(\frac{V}{a}\right)\left(\frac{1}{f^2}\right)\left(\frac{1}{a}\right)\left(\frac{I_0(ka)+I_0(mka)}{m^2 I_0(ka)+I_0(mka)}\right)$$

ion type | sparking limit | Transverse field distortion due to modulation of electrodes (=1 for unmodulated)

Accelerating Efficiency E_0T:

$$E_0T = \frac{m^2-1}{m^2 I_0(ka)+I_0(mka)} \cdot V \frac{2}{\beta\lambda}\frac{\pi}{4}$$

fraction of the field in longitudinal direction (=0 for unmodulated) | cell length

...are related via

$$\left(\frac{I_0(ka)+I_0(mka)}{m^2 I_0(ka)+I_0(mka)}\right)+\left(\frac{m^2-1}{m^2 I_0(ka)+I_0(mka)}\right)\cdot I_0(ka)=1$$

Focusing strength — Accelerating efficiency

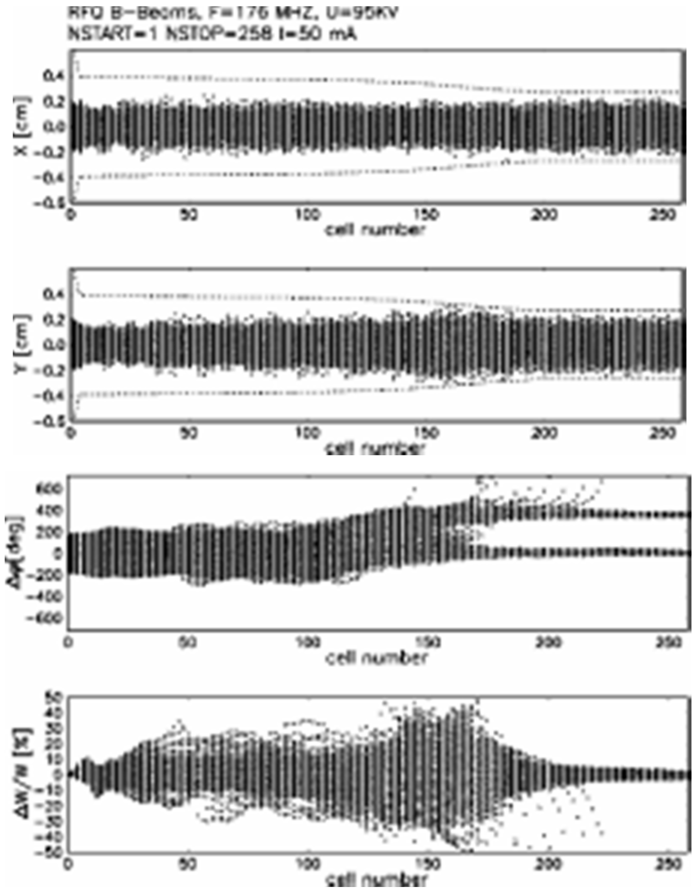
a=bore radius, β,γ=relativistic parameters, c=speed of light, f= rf frequency, I_0= zero order Bessel function, k=wave number, λ=wavelength, m=electrode modulation, m_0=rest mass, q=charge, r=average transverse beam dimension, r_0=average bore radius, V=vane voltage

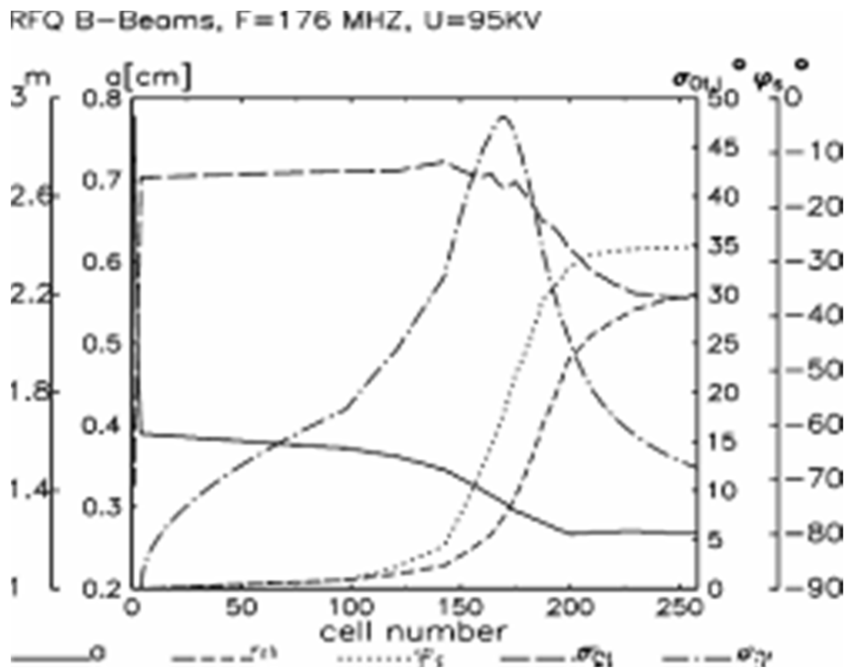
Design Considerations

- Aperture: Focusing Strength & acceptance
- Depth of modulation: Field-% for acceleration
- $\Delta_{max\text{-}min}$: Synchronicity between field and particles.

1st step: Determine values along the structure.

Overall Design

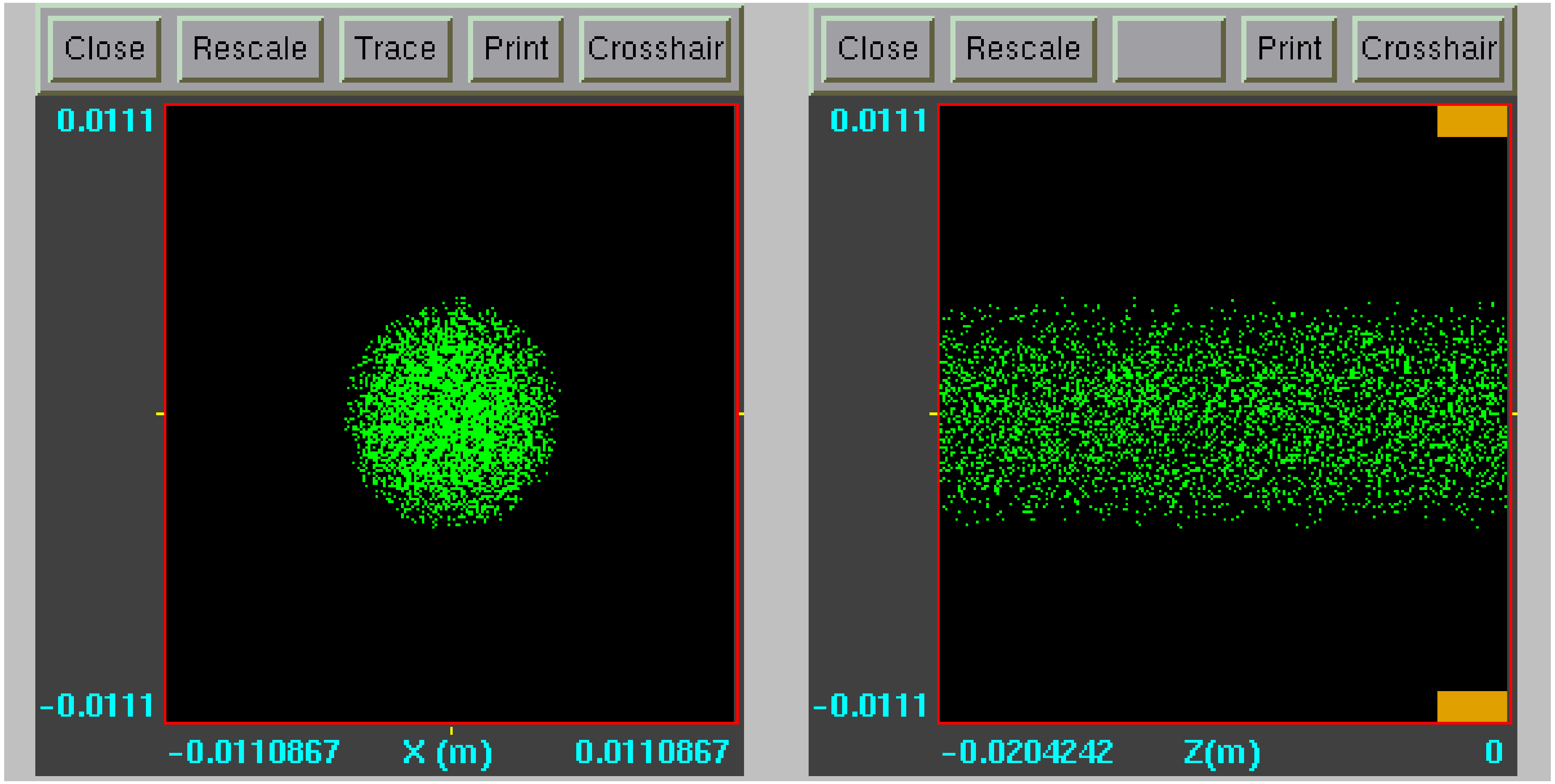




Rfq Sections

Radial matching to adapt the beam to a time-varying focusing system		
		aperture smoothly brought to average value
Shaping to give the beam a longitudinal structure		
Taper phase to –80°,-60°	Start modulation	aperture such that focusing is constant
Bunching to bunch and begin acceleration		
Taper phase to –30°,-20°	Max. modulation	aperture such that focusing is constant
Acceleration to bring the beam to the final energy		
Constant Phase	Constant modulation	Constant aperture
Output matching to adapt the beam to the downstream user's need.		

RFQ - an Illustration



R. Duperrier

RFQ Applications

- Element of most injector chains;
- Solves problem of beam transfer between source and drift tube linac !
- Excellent transmission rate;
- Preserves emittance.

- Ion implantation applications,
- High intensity beams.

...off the beaten track

Diamond detection

CA 2198990 C

ABSTRACT

The invention concerns a method of detecting the presence of diamond in a body. In method the body is irradiated with a fast neutron beam modulated between first and second, distinct energy levels which are respectively resonant and non-resonant energy levels for diamond. Corresponding first and second absorption images are obtained for the body and from these images, a third absorption image is derived in which absorption effects attributable to the presence of non-diamond material in the body are eliminated or at least reduced. The resulting image is then analysed for the presence of diamond in the body. The energy modulated fast neutron beam is produced by nuclear reaction between an energy modulated particle beam and a target. The energy modulated particle beam itself is produced by a procedure in which a particle beam is passed sequentially through first and second particle accelerators in series. Modulation is achieved by operating the second particle accelerator alternately in first and second modes to produce, from the particle beam delivered by the first particle accelerator, a particle beam which is modulated between relatively high and relatively low energy levels.

Publication number	CA2198990 C
Publication type	Grant
Application number	CA 2198990
Publication date	Jun 5, 2007
Filing date	Mar 3, 1997
Priority date	Mar 4, 1996
Also published as	CA2198990A1
Inventors	Ulf Anders Staffan Tapper, Robert Hamm
Applicant	Ulf Anders Staffan Tapper, Robert Hamm, De Beers Consolidated Mines Limited
Export Citation	BiBTeX, EndNote, RefMan

Classifications (6), Legal Events (2)

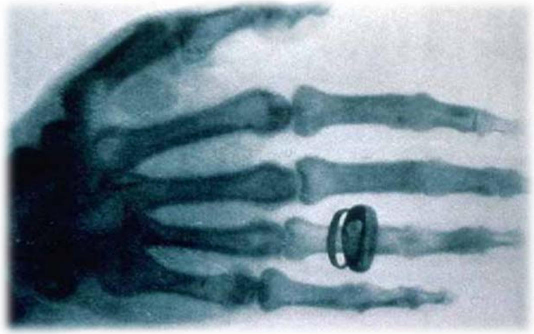
External Links: CIPO, Espacenet

Medical Accelerators

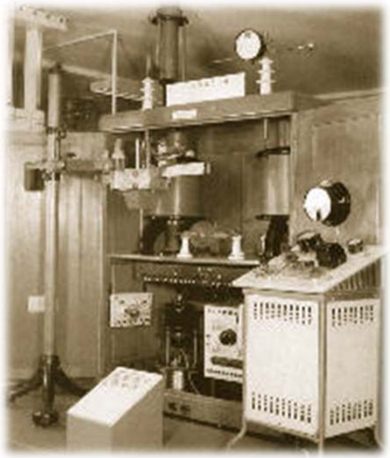
...thanks to Andreas Peters, HIT.

History of Medical Accelerators

- 1895 Wilhelm Conrad Röntgen (1845 –1923) discovers the X-rays
- 1896 Röntgen showed a photograph of the hand of Albert von Kolliker
- 1897 First treatments of tissue with X-rays in Vienna
- 1901 Physics Nobel prize for Röntgen



- 1899 First X-ray treatment of carcinoma in Sweden
- 1913/4 Invention of part-and full-rotation radiation instrumentation
- 1920´s Industrially manufactured X-ray apparatus; voltage of up to 150 kV – without shielding!
- 1930 linear accelerator invented by Rolf Wideroe
- 1949 Newberry developed first linear accelerator for therapy in England



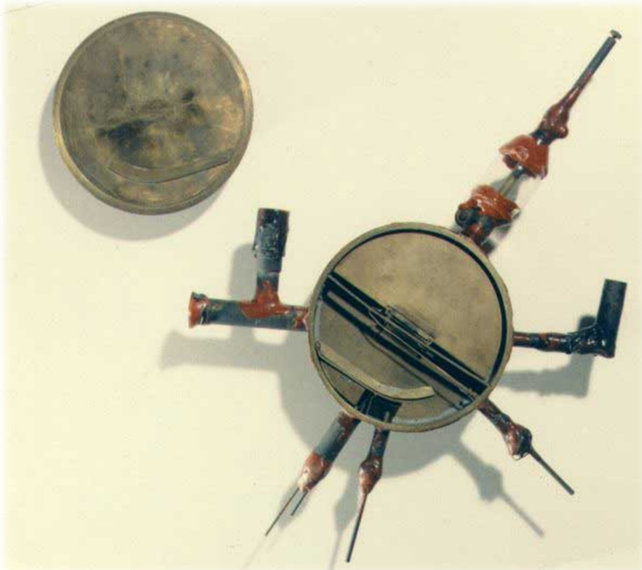
- Since 1950´s: Development of compact linear accelerators by Siemens, Varian, Elekta, etc.

Varian

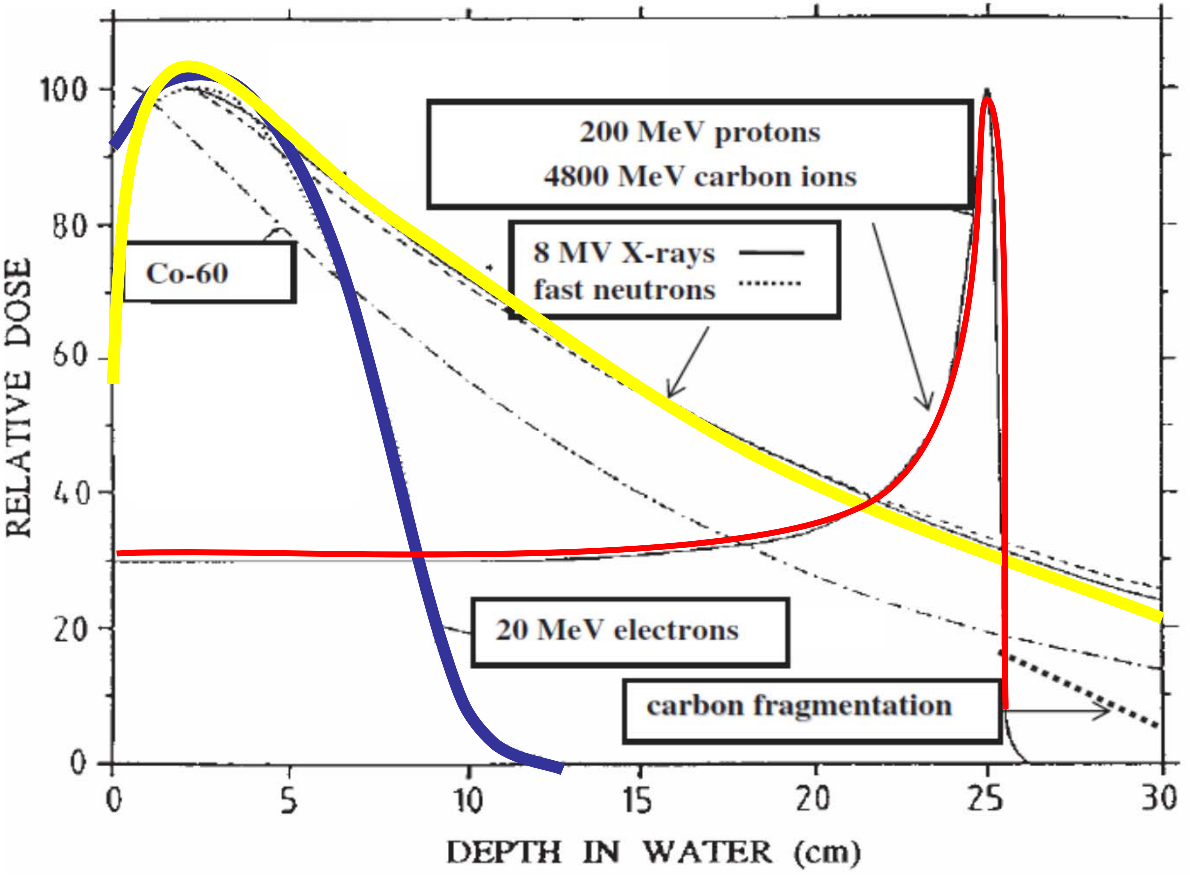
Siemens

History of Ion Beam Treatment

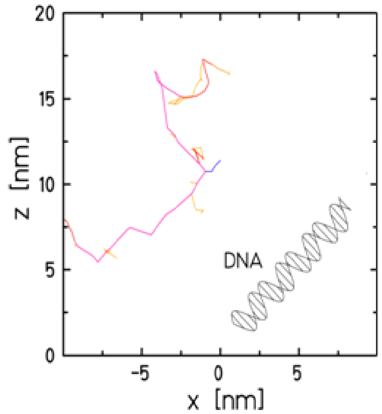
- 1929 Invention of cyclotron by Ernest Lawrence
- 1930´s Experimental neutron therapy
- 1946 R.R. Wilson proposed proton & ion therapy
- 1950's Proton therapy in Berkeley
- 1975 Begin of carbon therapy at Bevalac Synchrotron (Berkeley)

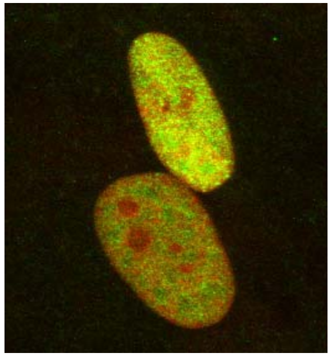


Ion Therapy – Energy Deposition



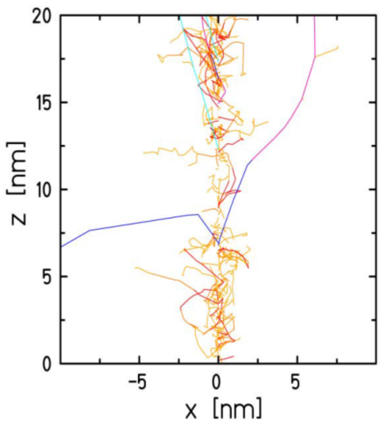
Cell Damage – Linear Energy Transfer

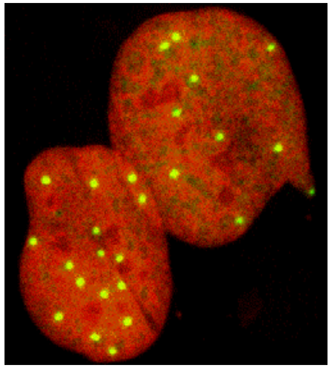




- Low LET

  Homogeneous deposition of dose



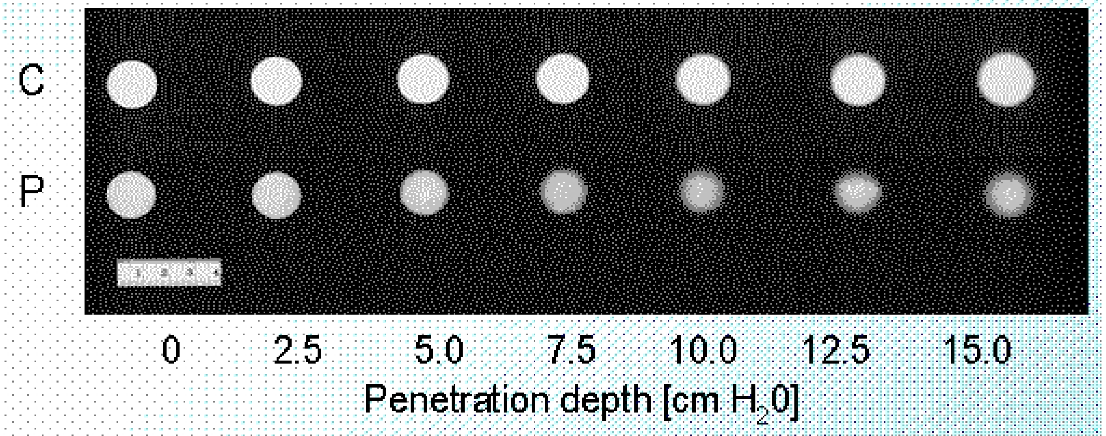


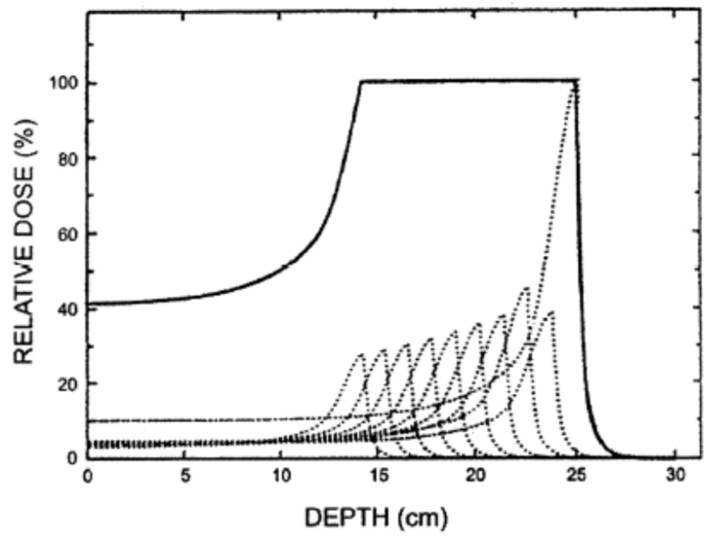
- High LET

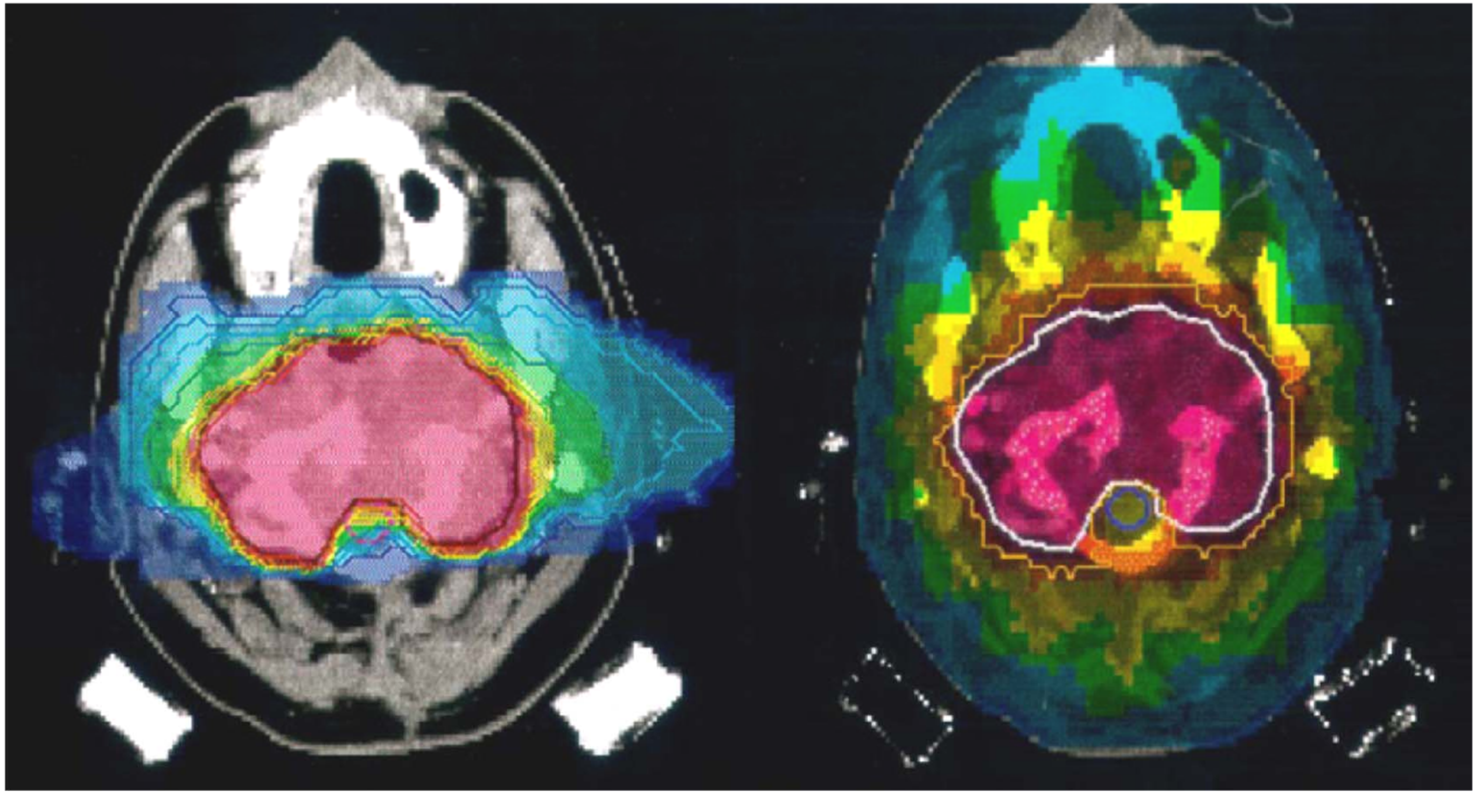
  Local deposition of high doses

Ion Therapy – Tumor Painting

- Higher local precision with carbon ions for deep-seated tumour treatment
- Energy for deep-seated tumors (25 cm)
  - 200 MeV (protons)
  - 4,800 MeV (Carbon ions)







Comparison of treatment plans with 2 fields of carbon ions (IMPT - left panel) and with 9 fields of x-rays (IMRT - right panel). In both cases the conformity to the target volume is good but for carbon ions the dose to the normal tissues is much smaller.

*Amaldi, U. and Kraft, G.: **Radiotherapy with beams of carbon ions**, Rep. Prog. Phys. 68 (2005) 1861–1882*

Ion Beam Production

Cyclotrons

- Advantages:
  - Easy Operation;
  - Continuous beam for active beam scanning;
  - Compact design.
- Disadvantages:
  - Fixed energy;
  - Limited access to structure;
  - Superconducting design still has open questions.

Synchrotrons

- Advantages:
  - Well-known techniques;
  - Variable energy.
- Disadvantages:
  - Costly injector;
  - Sophisticated control system;
  - Large machine dimensions.

Gantry – HUGE for Heavy Ions

- isocentricion gantry
- Ø= 13m; 25m long
- 600 tons weight (!!!)
- 0.5 mm max. deformation

News !!

HESSEN

Startseite > Einigung mit Rhön-Klinikum erzielt: Partikeltherapie-Anlage in Marburg wird betrieben

Wissenschaftsminister Boris Rhein:

Einigung mit Rhön-Klinikum erzielt: Partikeltherapie-Anlage in Marburg wird betrieben

24.09.2014
Pressestelle: Hessisches Ministerium für Wissenschaft und Kunst [1]

Positives Signal für die Krebsbehandlung in Hessen – alle Verträge wurden am Montag gezeichnet

Industrial Applications

With material from Y. Joungen, IBA

e^- beam and X-ray Industrial Applications

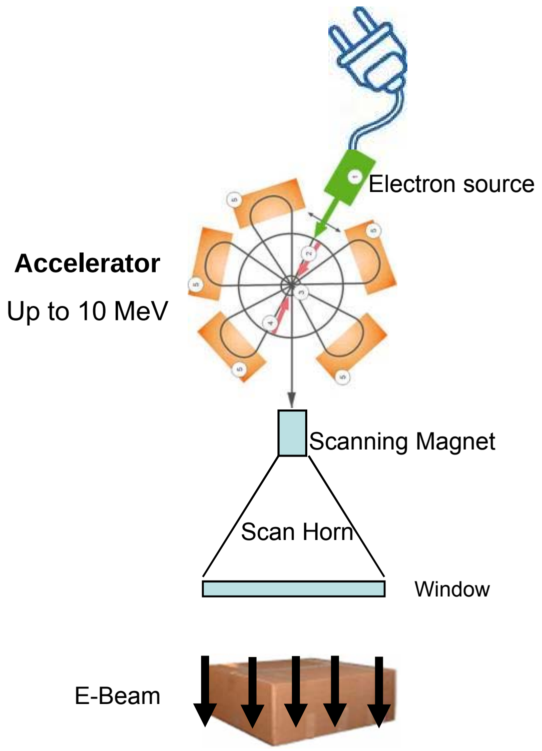
- Sterilization
  - Sterilization of Medical Devices
  - Surface Sterilization
  - Food Pasteurization
- e^- beam induced chemistry
  - Reticulation of Polymers
  - Curing of composites
  - Environment remediation
- e^- beam induced crystal defects
  - Modification of Semiconductors
  - Coloring of Gemstones

Sterilization of Medical Devices

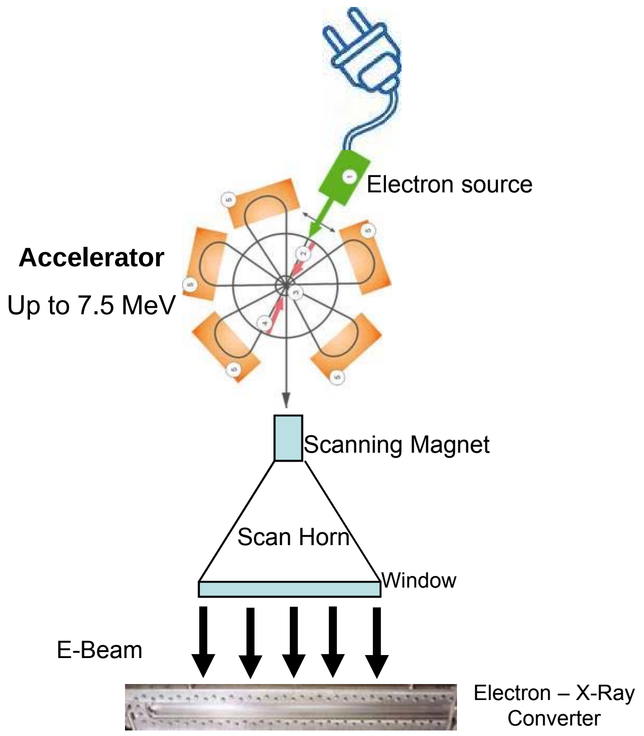
- Steam (incompatible with most polymers)
- Ethylene Oxide
  - Inexpensive
  - EtO is explosive, toxic and harmful to the environment
  - EtO sterilization may leave harmful residues
- Irradiation
  - Cobalt
  - Electron beam
  - X-rays

Sterilization by Irradiation

E-beam

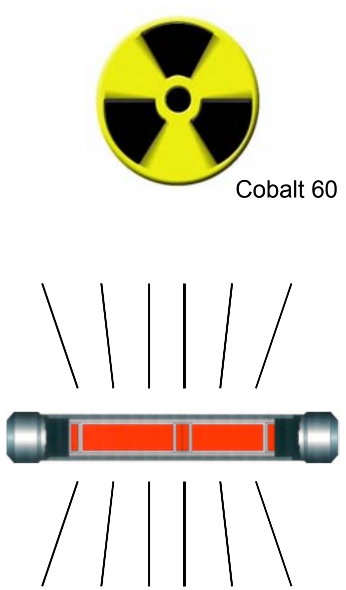


X-ray



X-rays

Gamma



Gamma Rays

Sterilization by Irradiation

- Gammas from Co_{60}
  - Low investment cost, specially for low capacities
  - Simple and reliable, scalable from 100 kCu to 6 MCu
  - Pallet irradiation, but low dose rate > slow process
  - Absolutely no activation
  - Cannot be turned OFF > inefficient if not used 24/7
  - Security: Cobalt could be used to make dirty bombs
- Electron beams
  - Directed radiation > Efficient use
  - Lowest cost of sterilization for large capacities
  - Can be turned OFF > safer
  - Short range (4.5 g/cm^2 at 10 MeV) > 2-sided irradiation of boxes
  - More complex dose mapping
  - Minimal, hardly measurable, but non zero activation

Sterilization by Irradiation

- X-Rays from electron beams
  - Excellent penetration
  - Simple dose mapping
  - Pallet irradiation
  - Directed radiation > Efficient use
  - Loss of a factor 10 in energy in conversion
  - Cost of sterilization higher than electrons and
  - generally higher by X-Rays than Cobalt if used 24/7, excepted for very large capacities
  - Can be turned OFF > safer
  - Minimal, hardly measurable, but non-zero activation

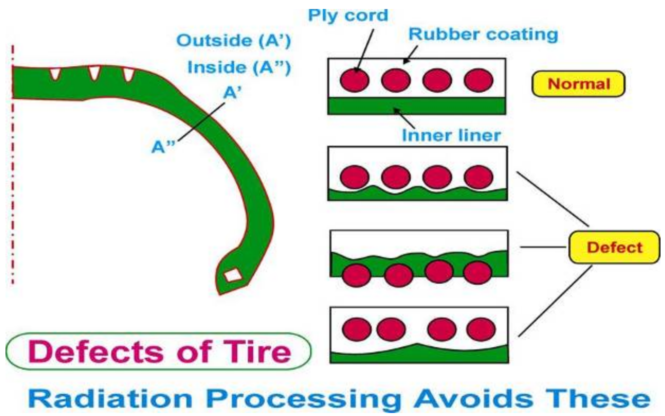
Food Irradiation Applications

- Low Dose Applications (< 1kGy)
  - **Phytosanitary** Insect disinfection for grains, fruits
  - **Sprouting Inhibition** for potatoes, onions, garlic
  - **Delaying of Maturation**, parasite disinfection.
- Medium Dose Applications (1 – 10 kGy)
  - **Control of Foodborne Pathogens** for beef, eggs, oysters...
  - **Shelf-life Extension** for chicken and pork, low fat fish,...
  - **Spice Irradiation**

- High Dose Applications (> 10 kGy)
  - **Food sterilization** of meat, poultry and some seafood for hospitalized patients or astronauts.

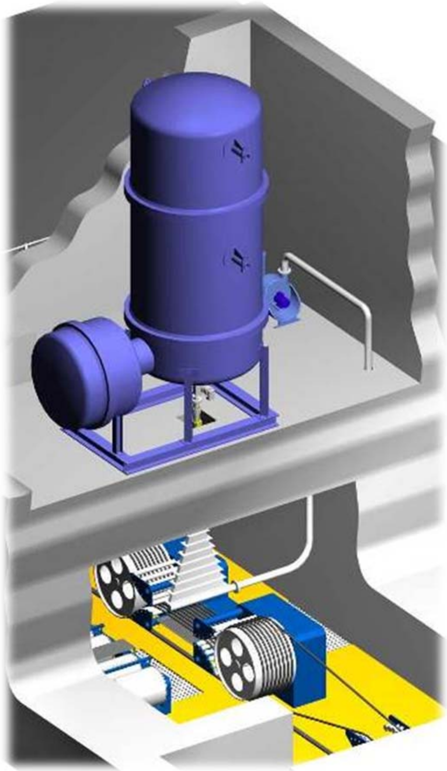
Electron Beam Treatment of Tires

- Reduction in material hence in the weight of the tire
- Relatively low cost synthetic rubber can be used instead of costly natural rubber without a loss in strength
- The radiation pre-vulcanization of body ply is achieved by simply passing the body ply sheet under the scan horn of an electron accelerator to expose the sheet to high-energy electrons
- Higher production rates
- Construction of green tires
- Reduction of production defects



Polymer Cross-Linking

- Wires stand higher temperature after irradiation
- Pipes for central heating and plumbing
- Heatshrink elastomers are given a memory



Flue gas treatment

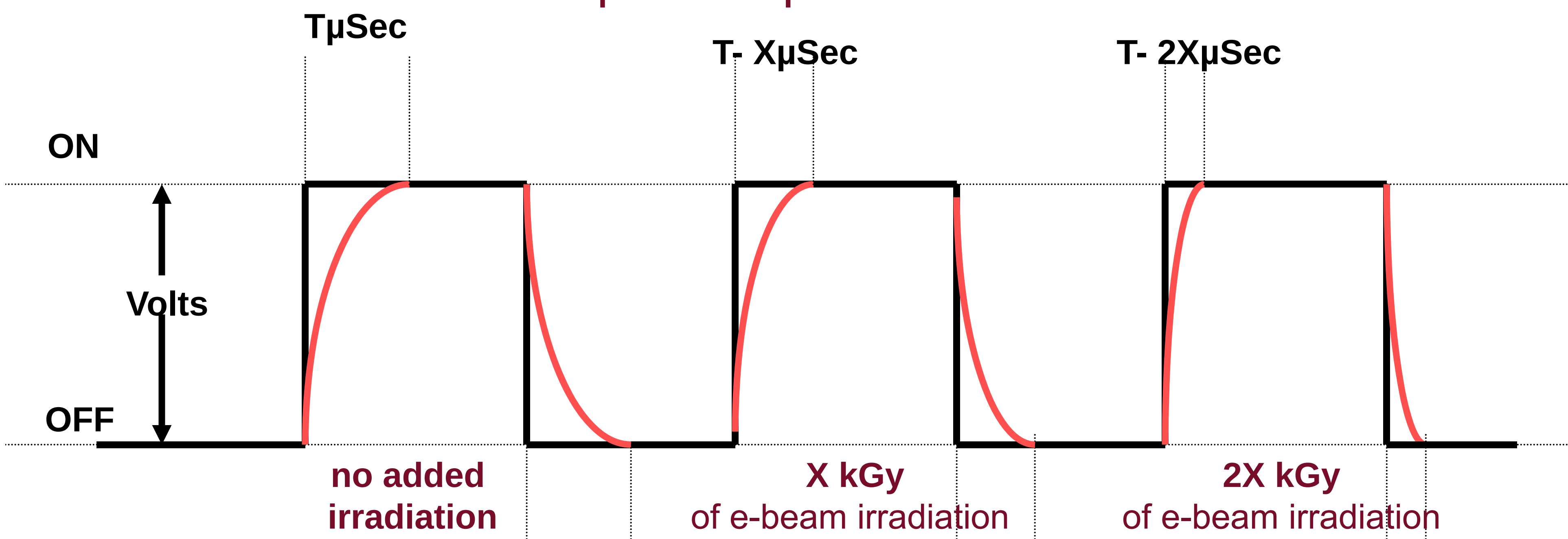
Liquid effluents treatment

Production of Viscose

Gemstones

Improving the color of glass and gemstones

Electron beam irradiation for semiconductor switching speed improvement

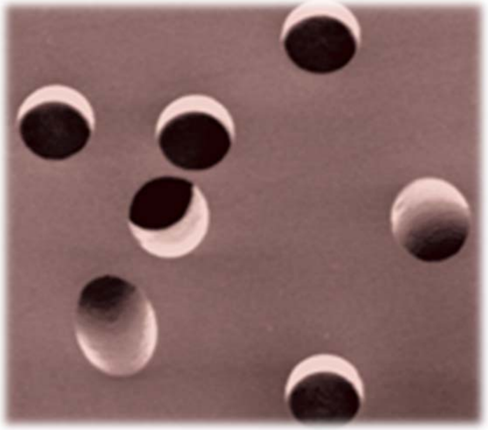


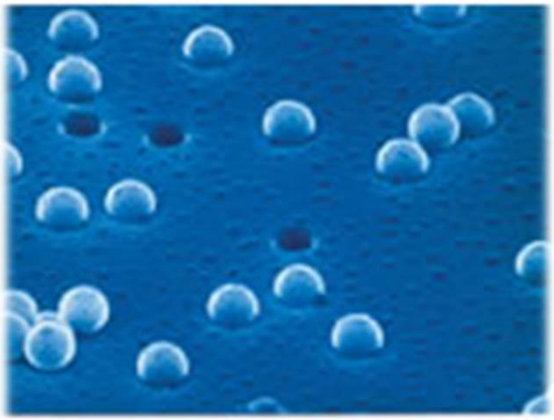
Typical semiconductors:

- fast recovery diodes
- power diodes
- Bipolar power transistors
- power MOSFETs
- power rectifiers
- thyristors
- silicon-controlled rectifiers

Microfiltration membranes by heavy ions

- Heavy ion beams are used to produce track-etched microfiltration membranes, commercialized e.g. under the brand name “Cyclopore”
- In these membranes, tracks of slow, heavy ions crossing a sheet of polymer are chemically etched, giving cylindrical pores of very accurate diameter

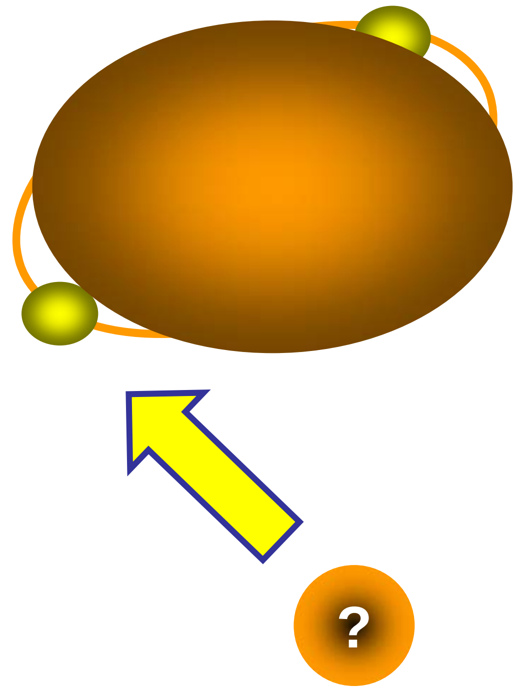




Antimatter

How to analyze Quantum Systems ?

Few-body-Problem: interaction with „clean" projectile.

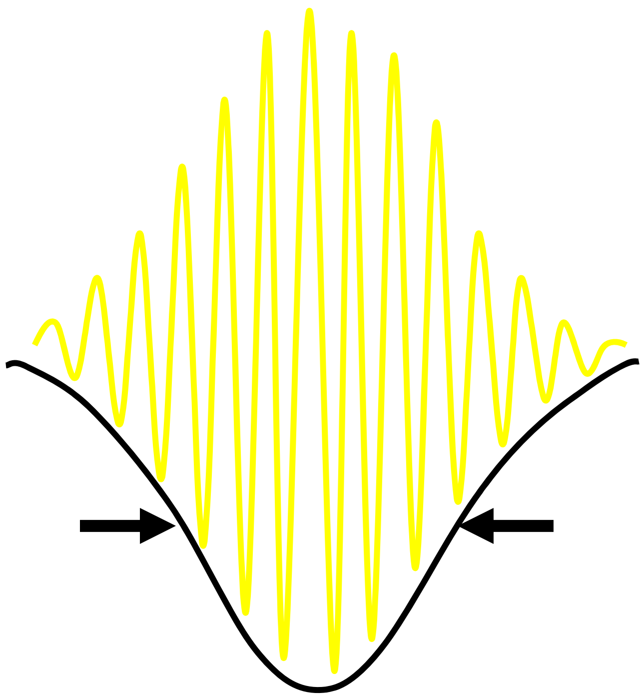


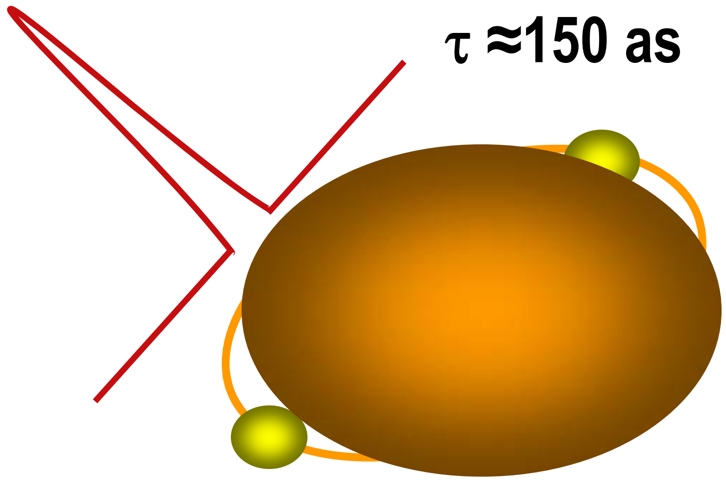
Important:

- No (or few) add. reaction channels,
- Possibility to control perturbation Z/v,
- Vary interaction time as -> fs.

Laser

Why Antiprotons ?





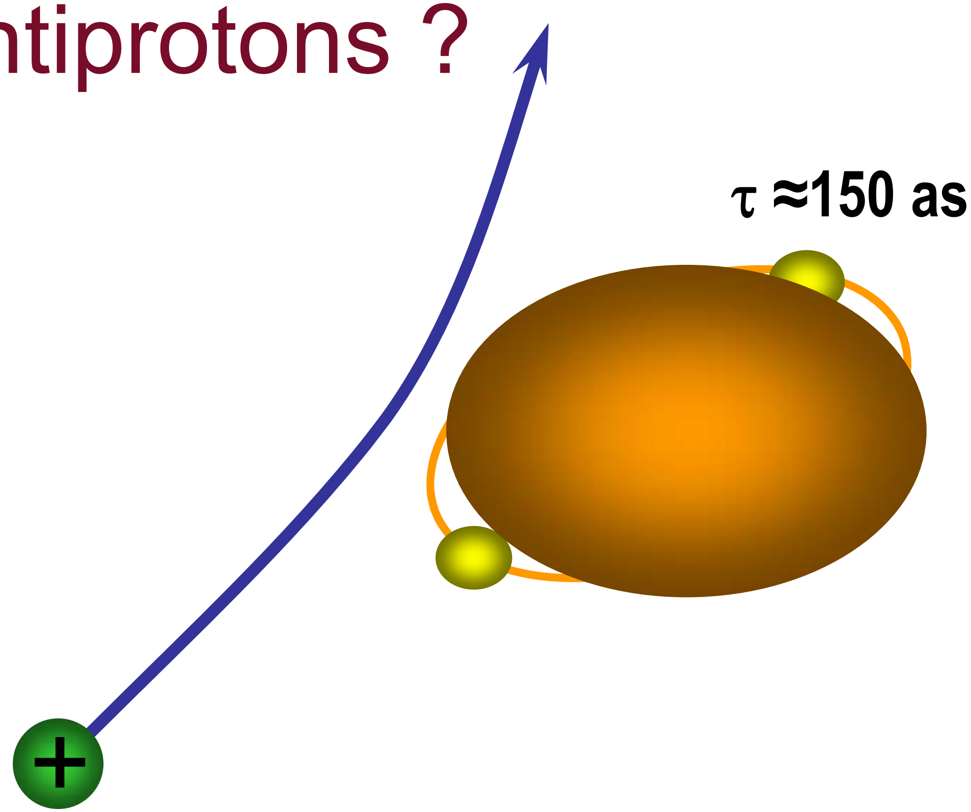
$t = 30 \ldots 6 \ldots 3.5$ fs

$I \geq 10^{15}$ W/cm^2

Why Antiprotons ?

~~Laser~~

~~Pos. Ions~~



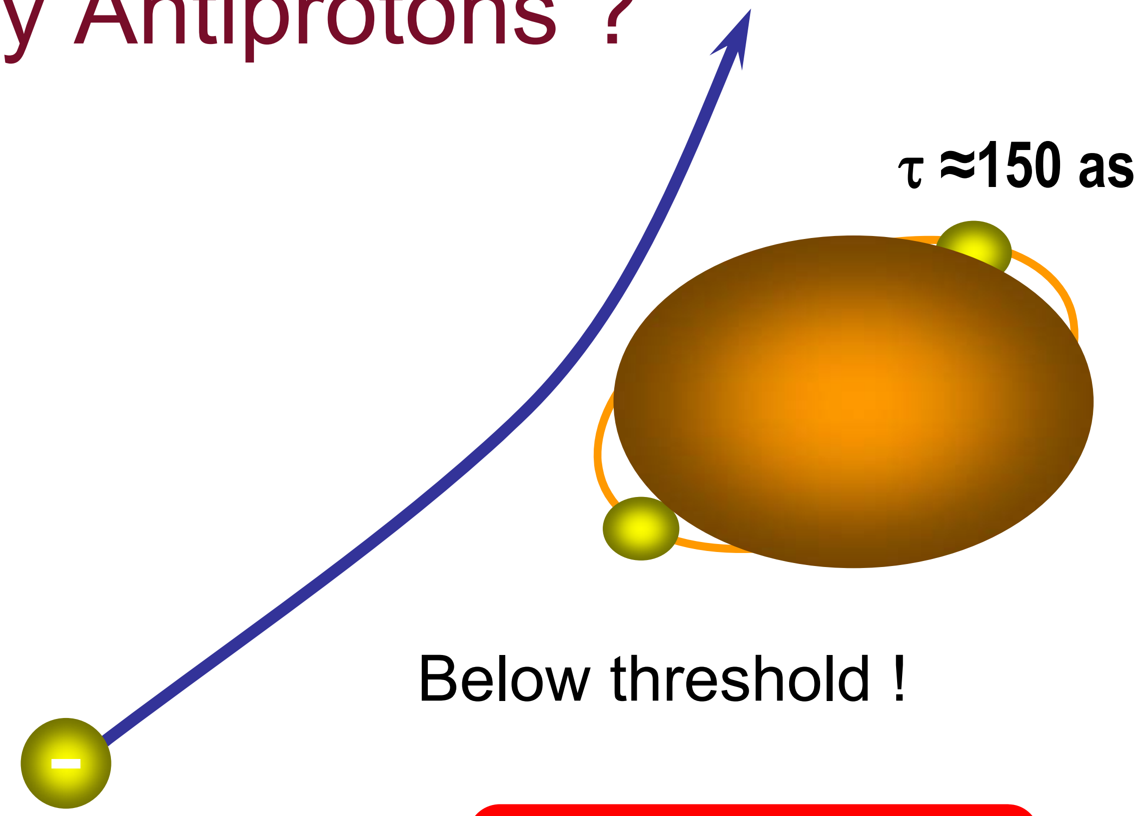
Dominated by capture-channels !

Why Antiprotons ?

~~Laser~~

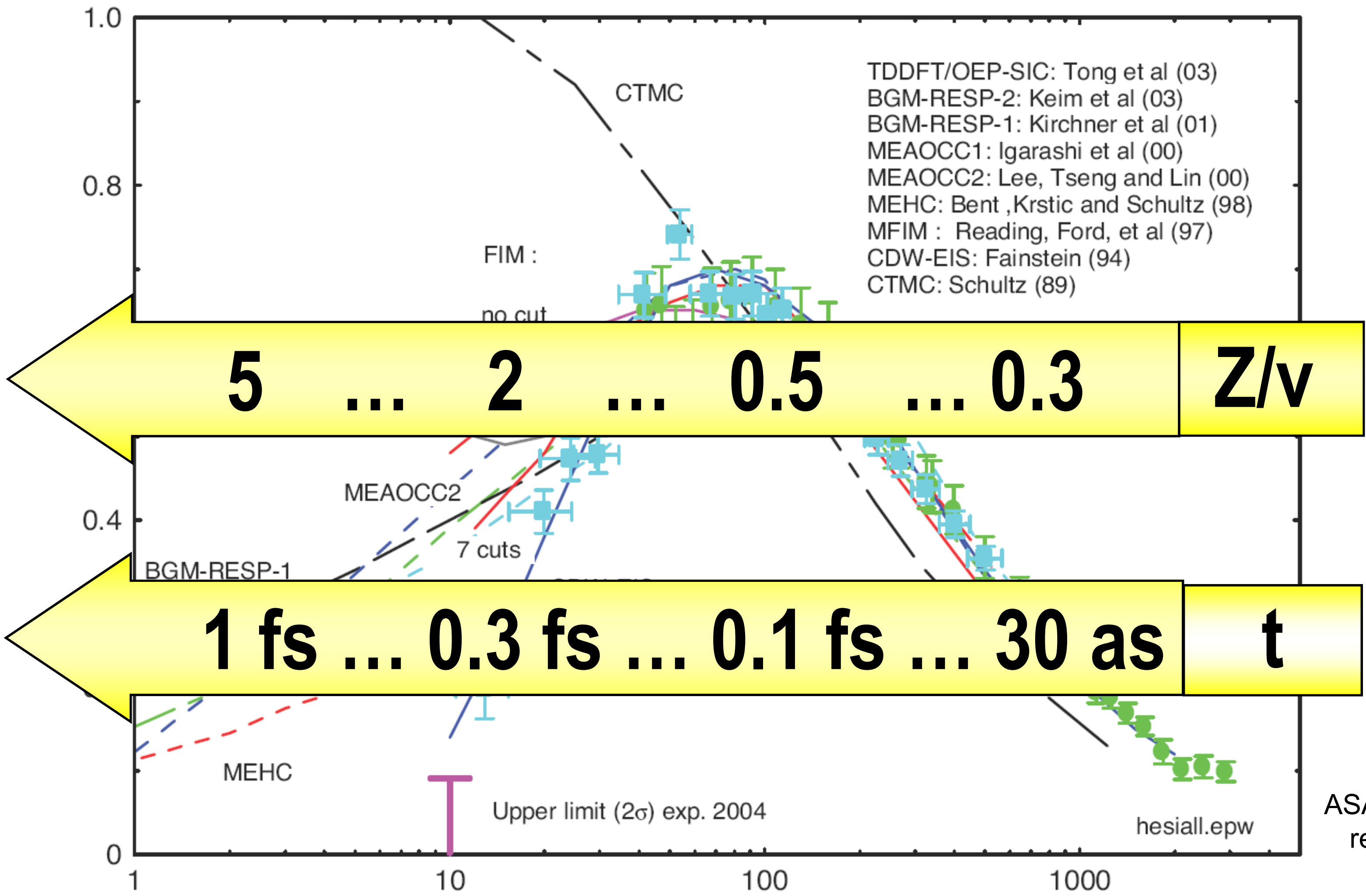
~~Pos. Ions~~

~~Electrons~~



Below threshold !

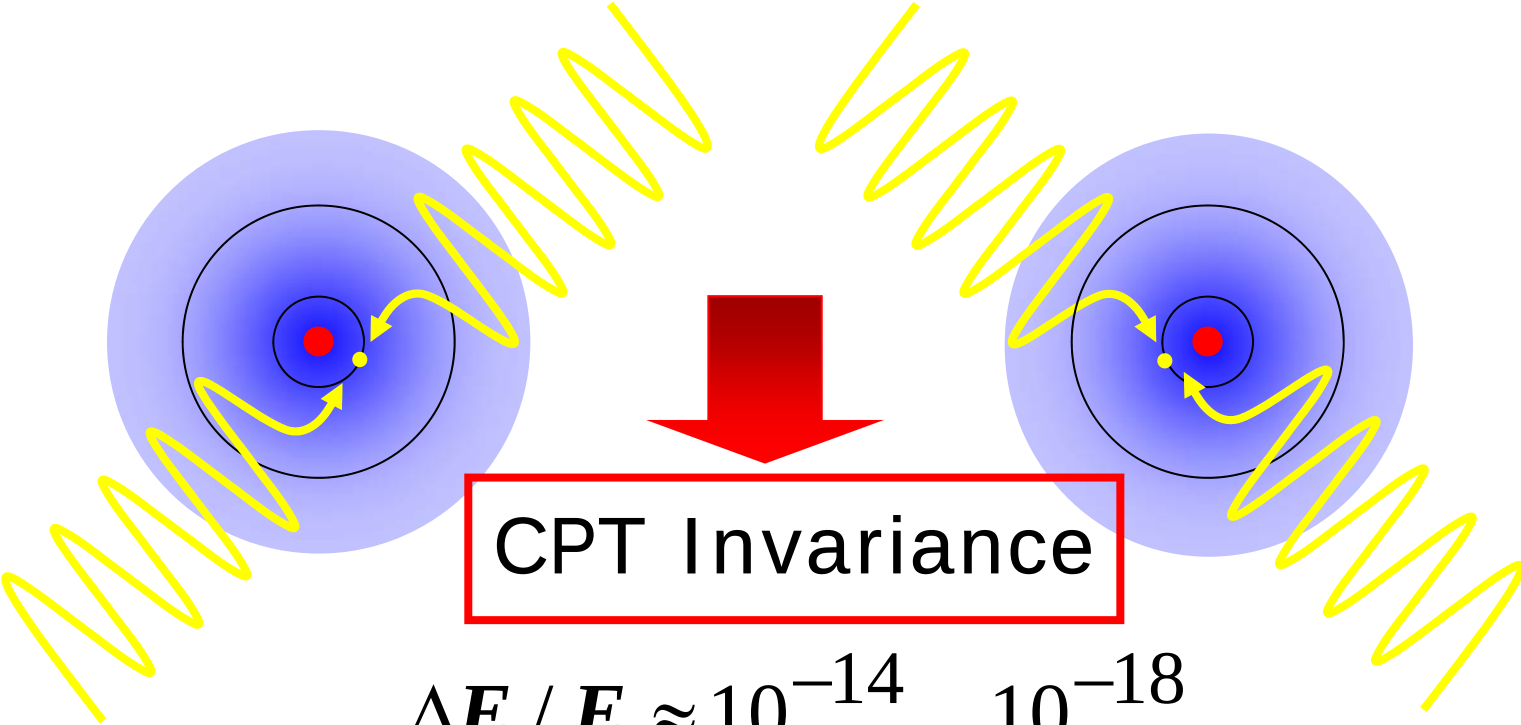
➡ **Antiprotons !!!**



ASACUSA results

Same Structure ?

Hydrogen **Anti-Hydrogen**

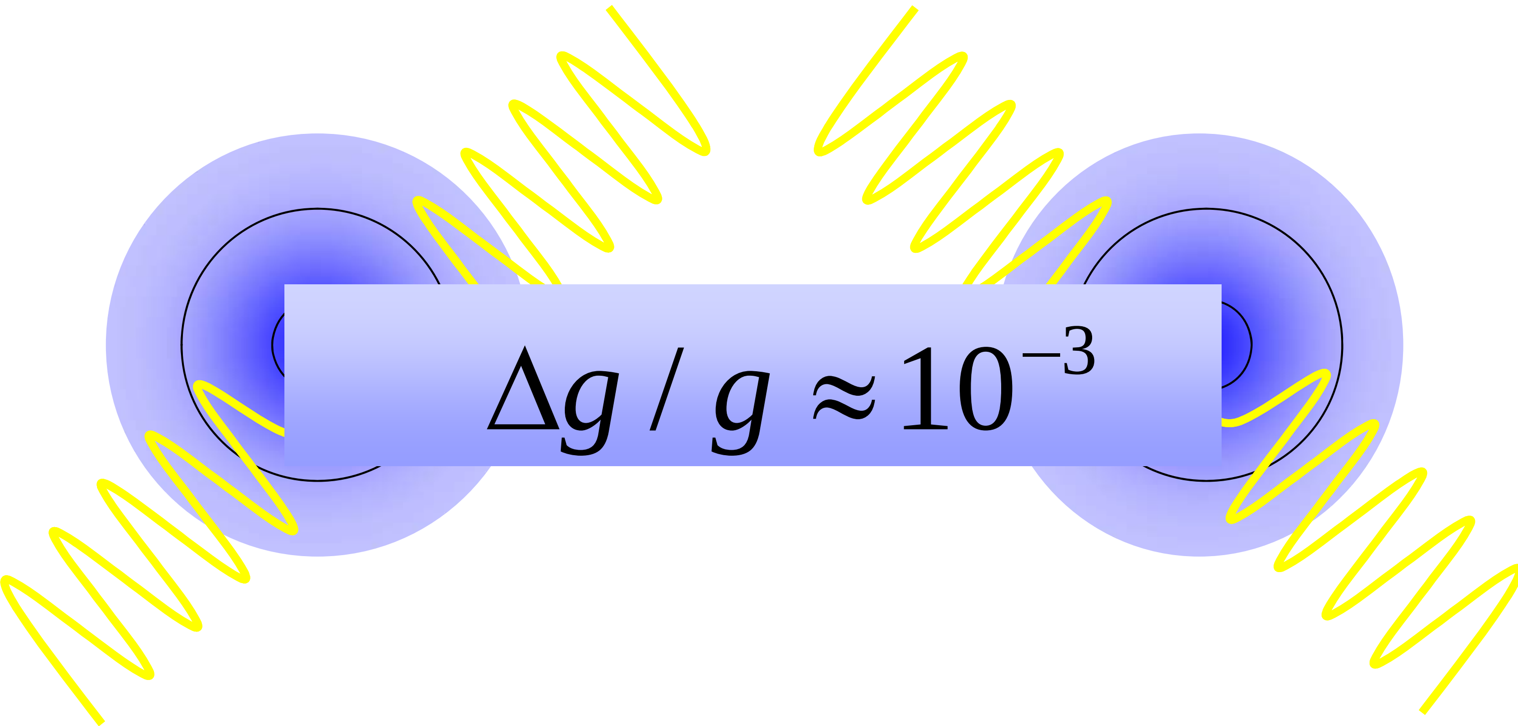


CPT Invariance

$$\Delta E / E \approx 10^{-14} \ldots 10^{-18}$$

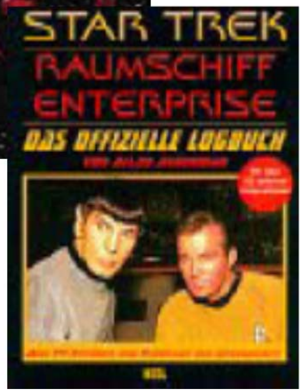
Same Weight ?

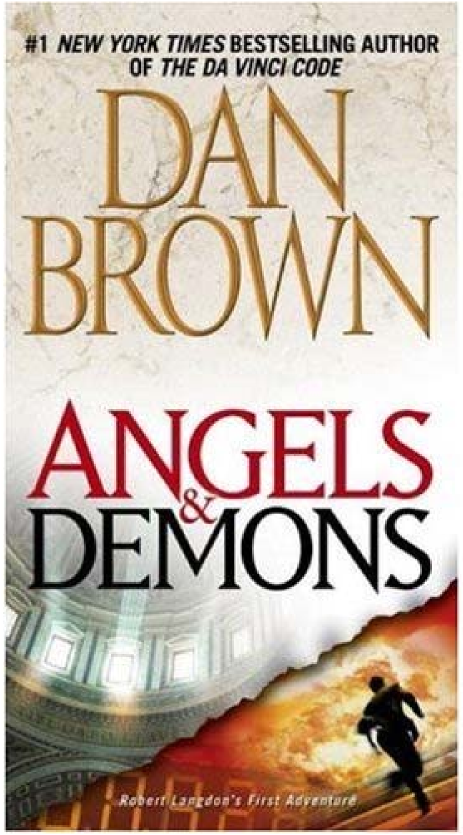
Hydrogen **Anti-Hydrogen**



$$\Delta g / g \approx 10^{-3}$$

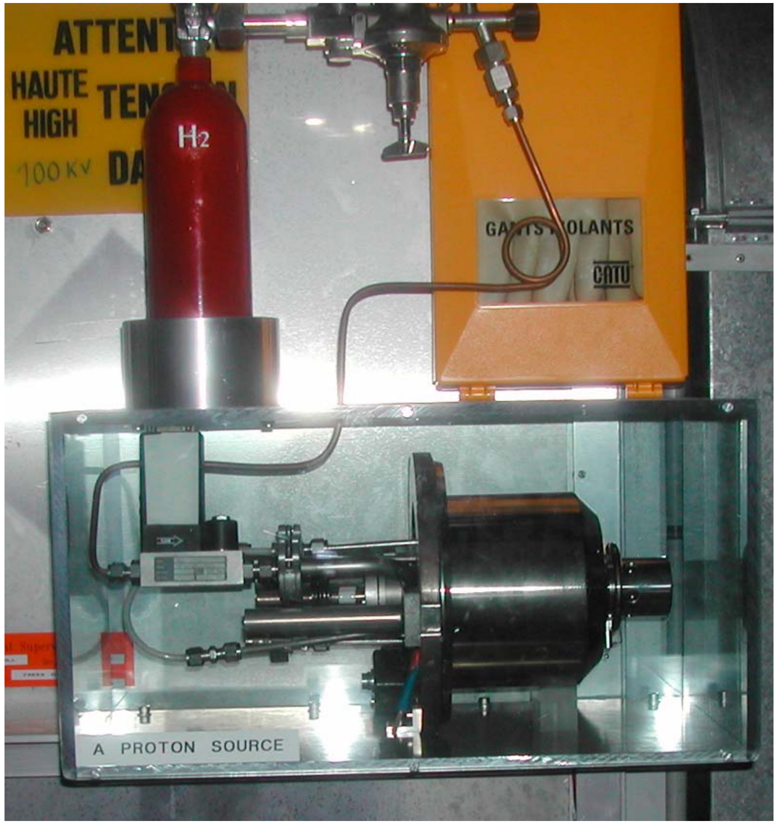
Antimatter: Where from ?



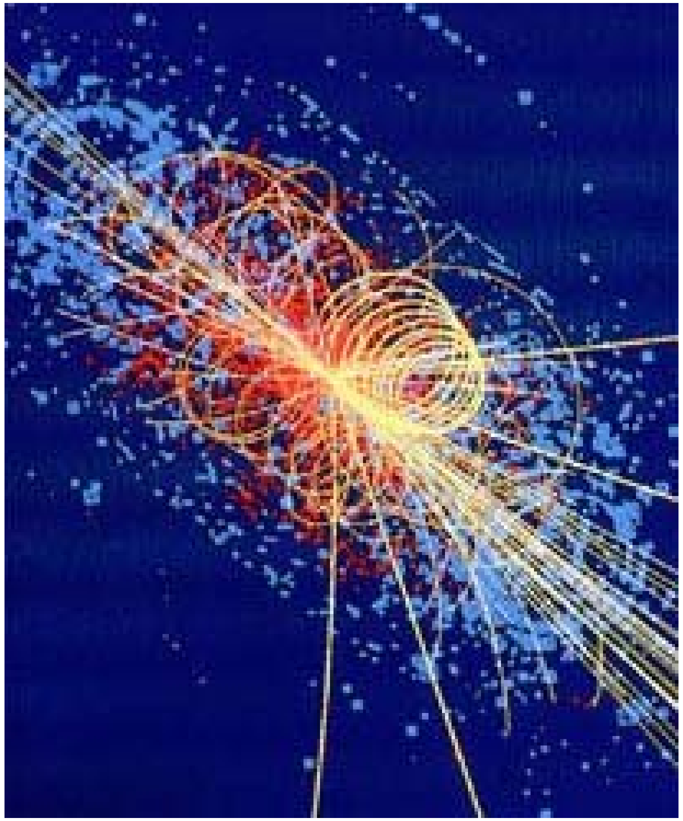


How to get...

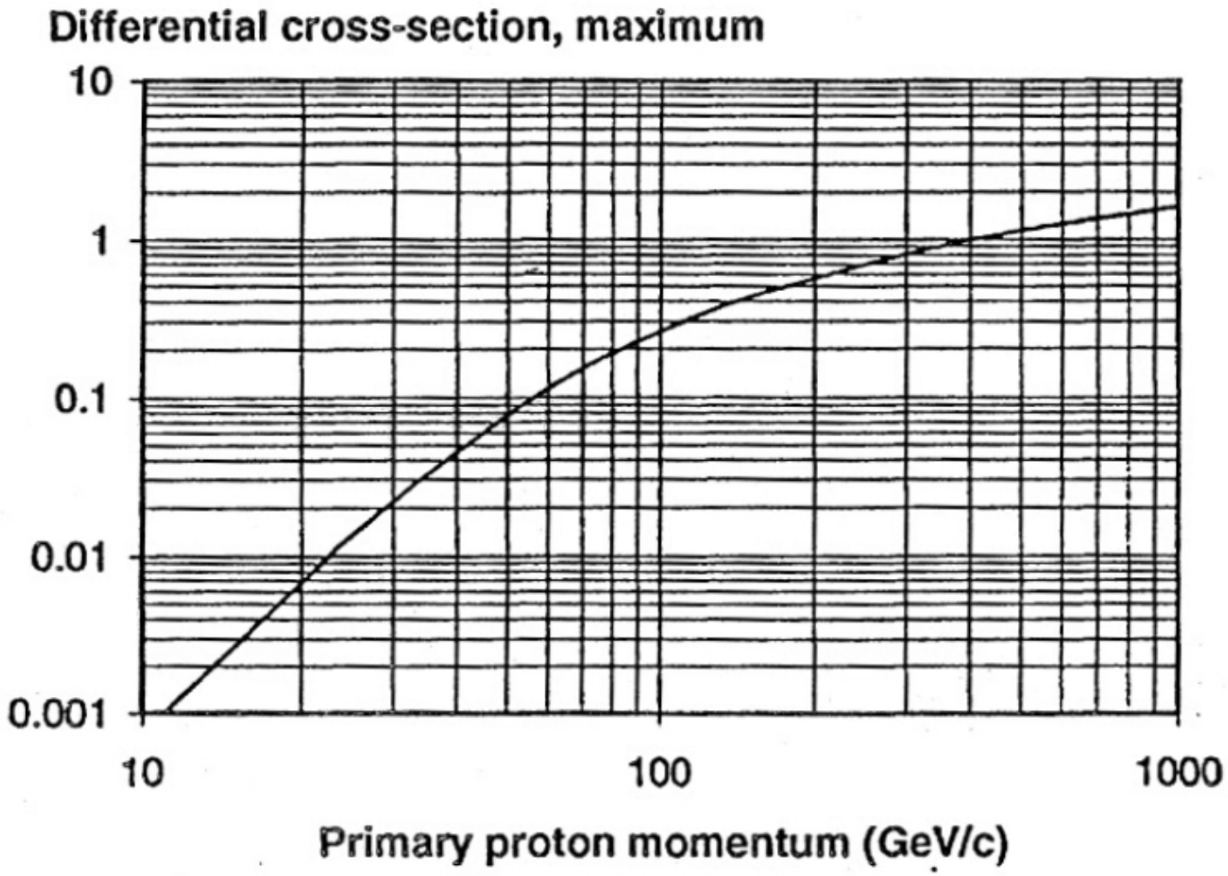
From:



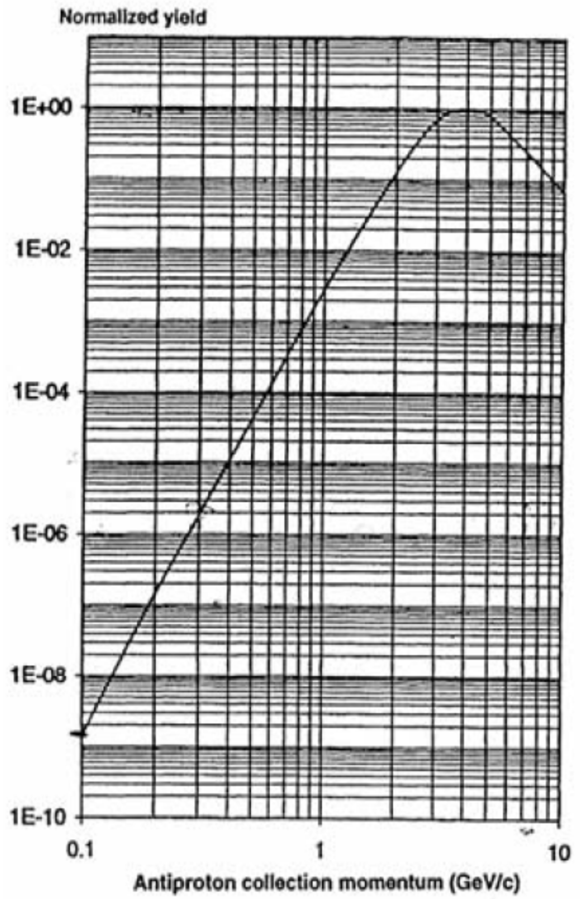
To:



Energy Dependence



Antiprotons from 26 GeV protons (PS)

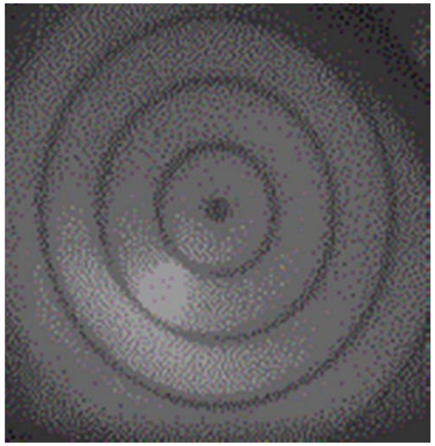


- Max. at 4 GeV/c
- At 100 MeV 9 orders of magnitude less !!!
- True yield depends on collection system and acceptance of antiproton channel.

Receipe

- Use intense beam of protons;
- Go to high energies;
- Shoot on target;
- Capture antiprotons;
- Cool, Decelerate....go for experiments !

The Target Area



<u>Goal</u>: Maximize number of antiprotons.

<u>Avoid</u>: Melting the target.

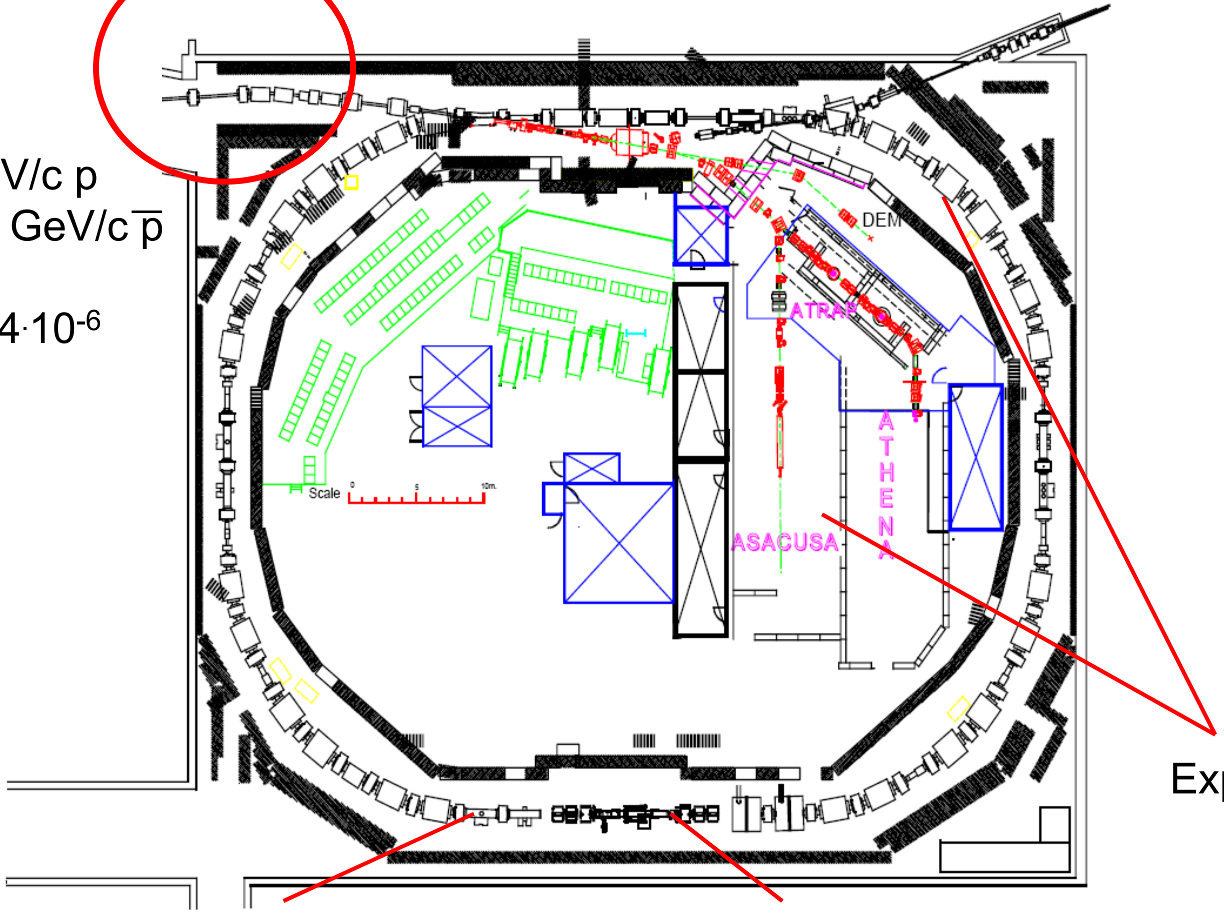
Present Situation: AD @ CERN

p

Target

26 GeV/c p
→ 3.57 GeV/c $\bar{p}$

Yield: $4 \cdot 10^{-6}$

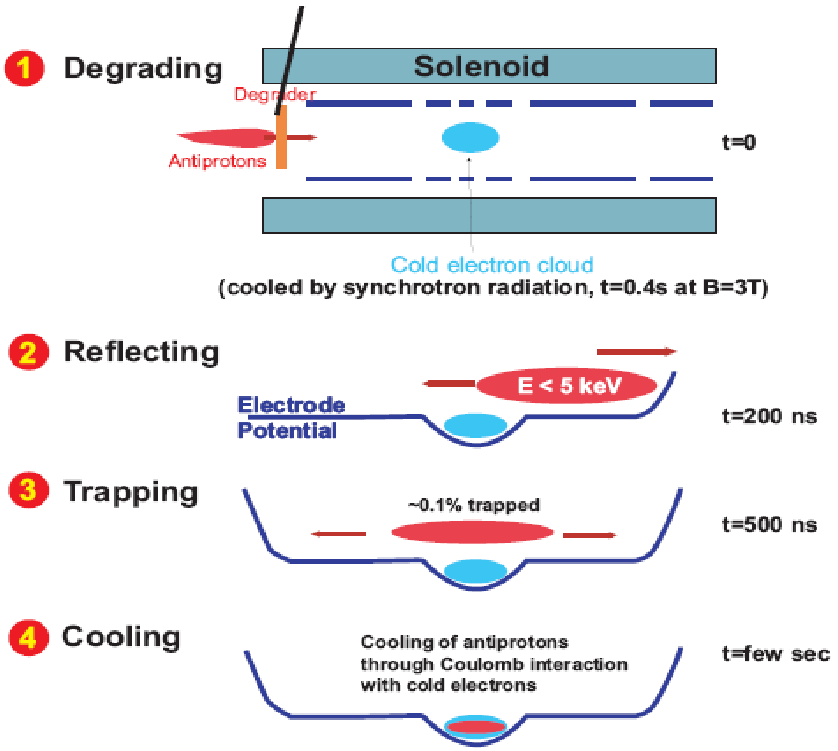


Experiments

Stoch. Cooling

e^- Cooler

Problem: 5 MeV too high for trapping !



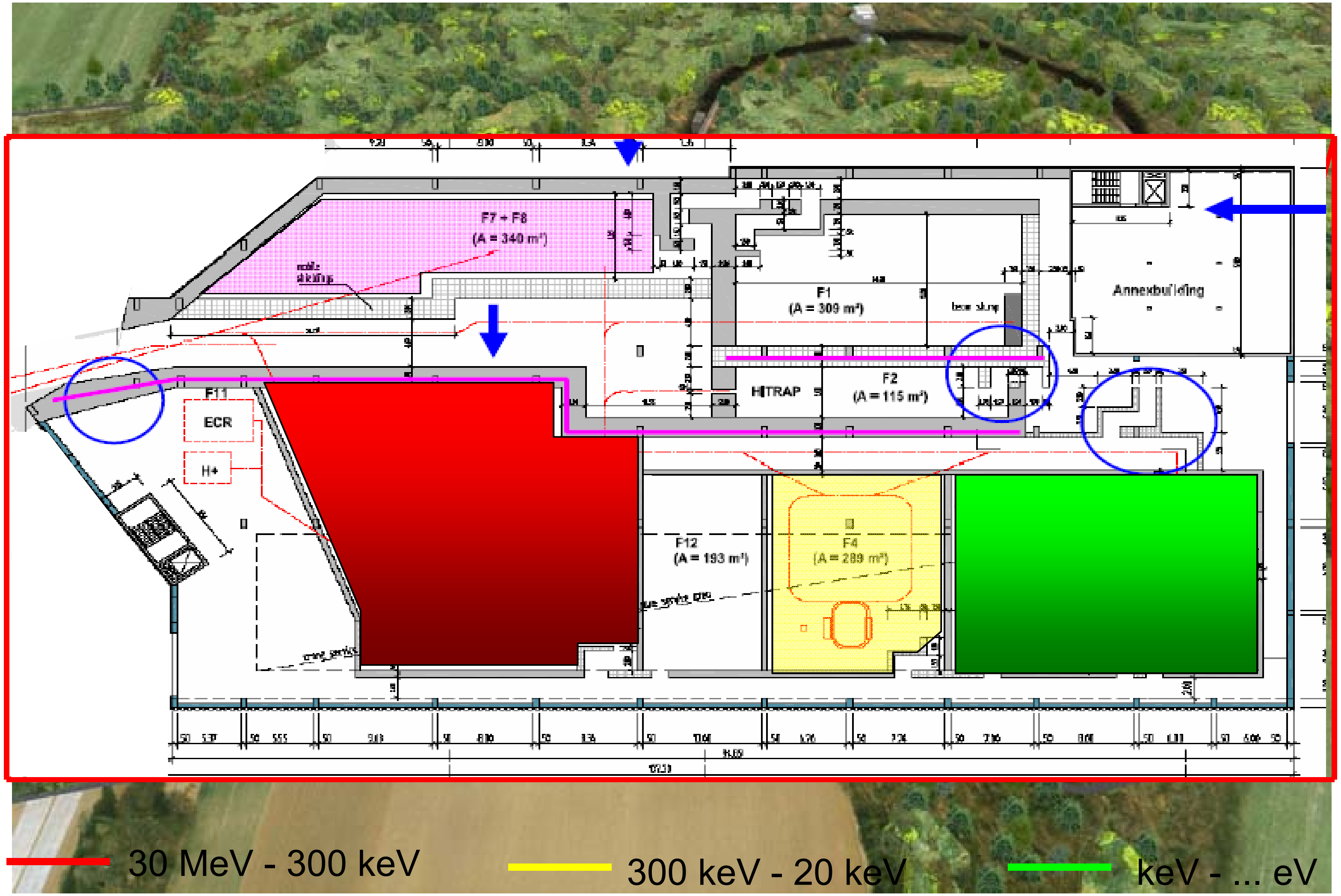
- > 99.9 % of pbars lost in degrader.
- ~ 10.000 pbars/shot

- ASACUSA: RFQ-D

  ~ 2.000.000 pbars/shot

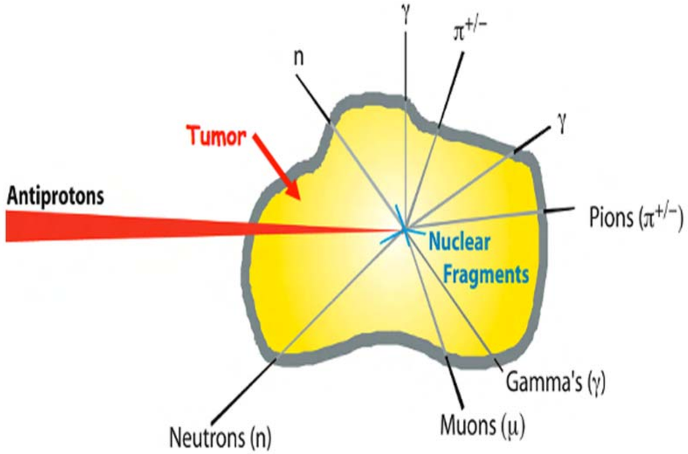
- BUT: $\Delta E/E$, $\varepsilon_{x,y}$

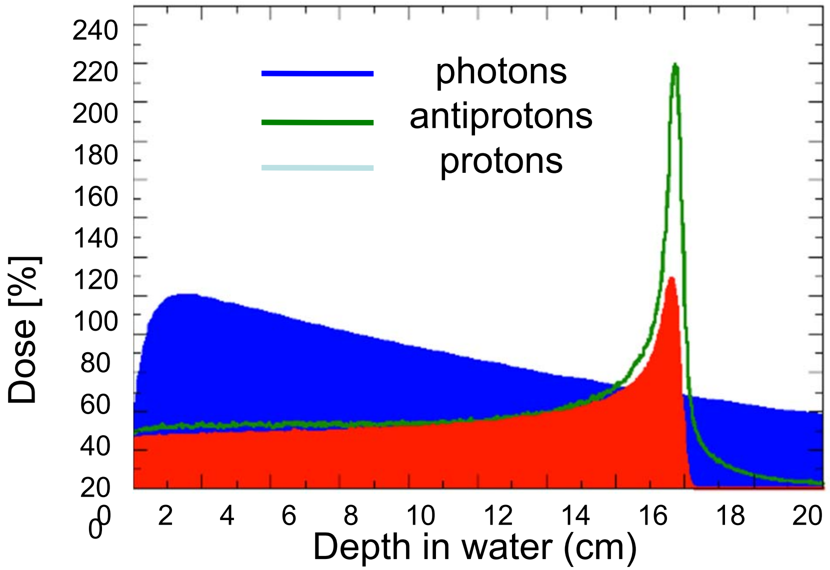
LA³NET

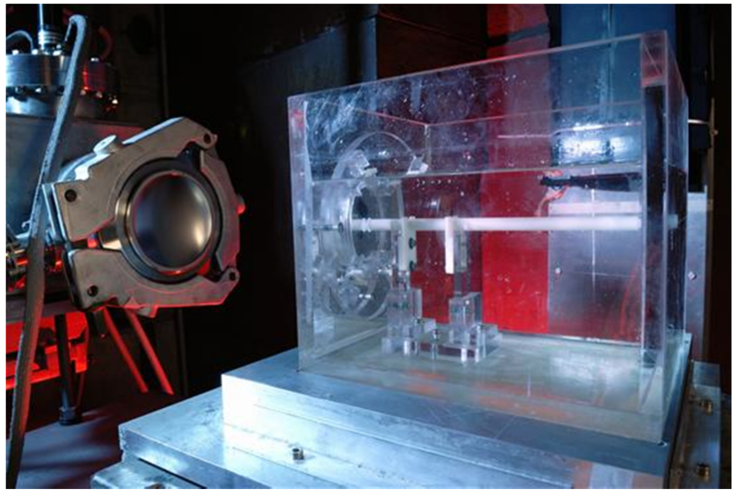


30 MeV - 300 keV
300 keV - 20 keV
keV - ... eV

ACE: **A**ntiproton **C**ell **E**xperiment

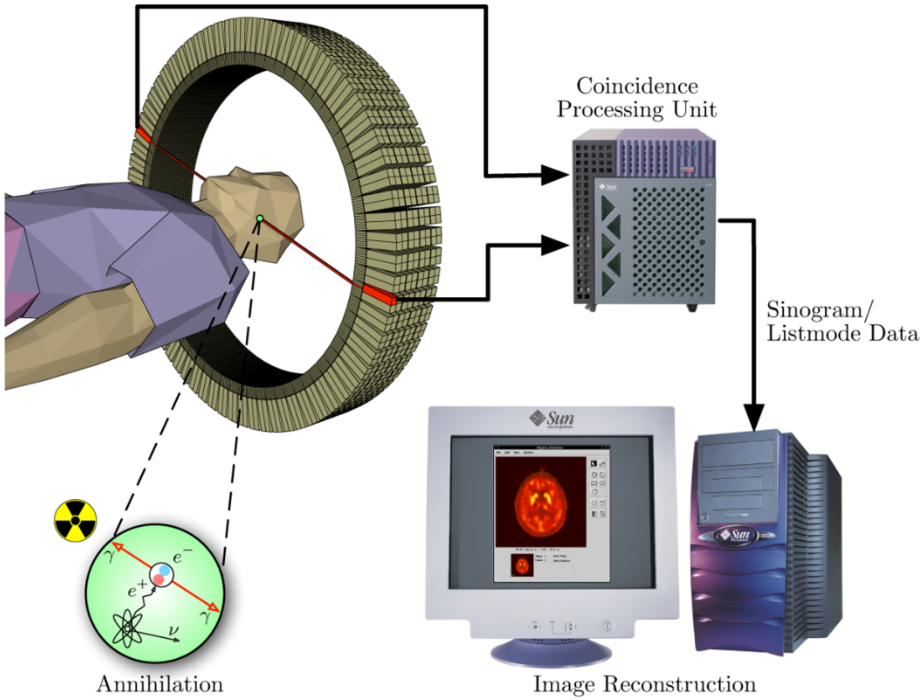




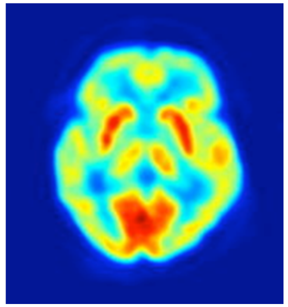


We already use Antimatter routinely

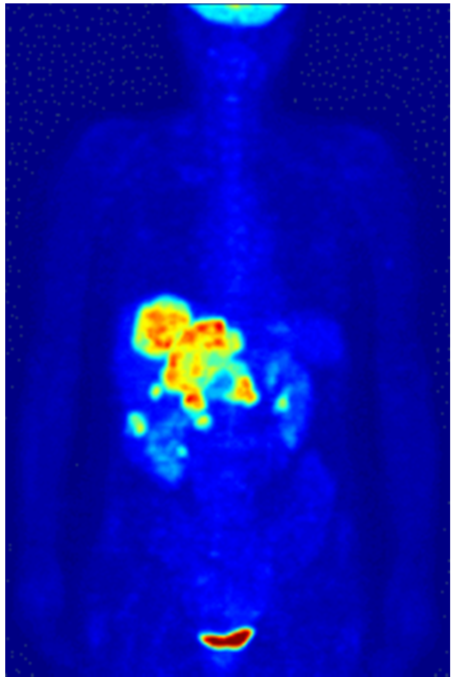
- Production of β^+ emitter
- Annihilation e^+/e^-
- Detector looks for 2 coincident 511 keV photons escaping back-to-back



Physiological information on biological processes



Combination of PET with CT (Computer Tomography) and MRI (Magnetic Resonance Imaging)



Conclusion & Outlook

- More than 30,000 accelerators in operation.
- < 1% at high energy end, however,...
- 50% of ESFRI roadmap linked to accelerator-based infrastructures;
- 44% for radiotherapy and 41% for ion implantation;
- Next technology break-through ?
  - (dielectric) laser acceleration
  - Plasma wakefield acceleration