Introduction

Spring, 2021

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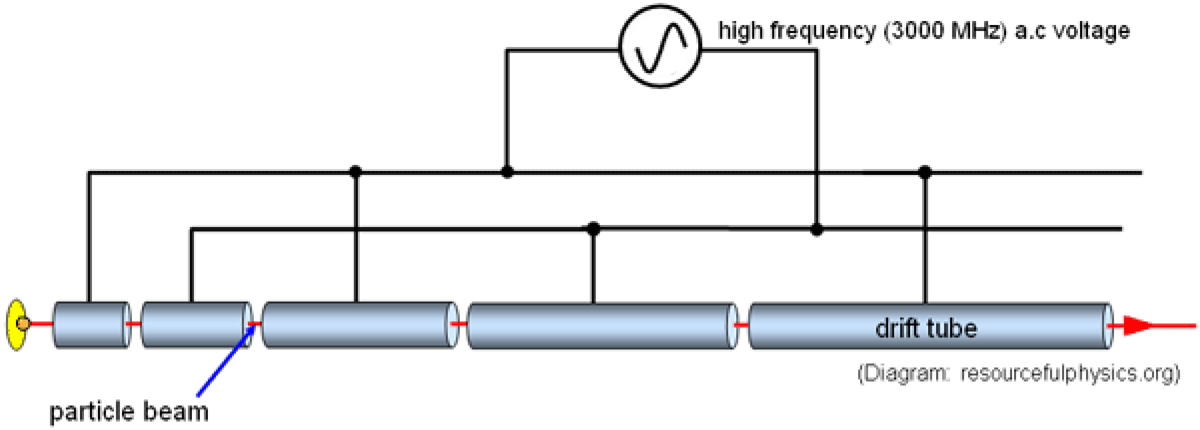
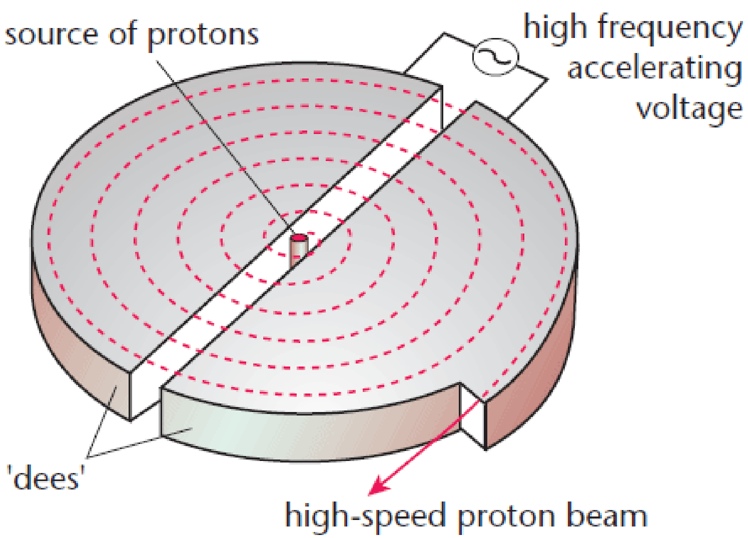
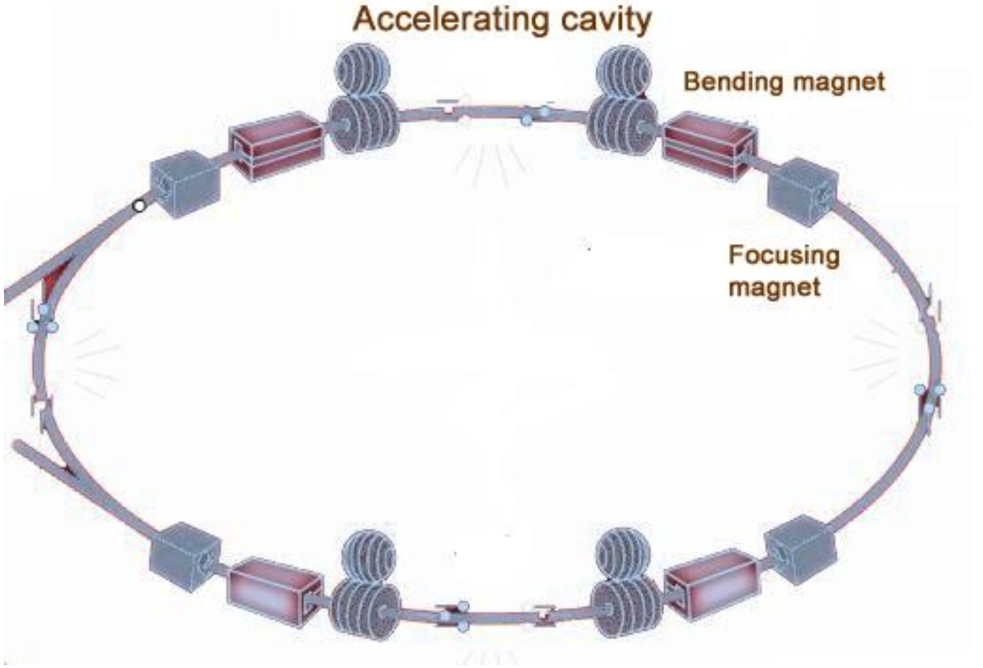
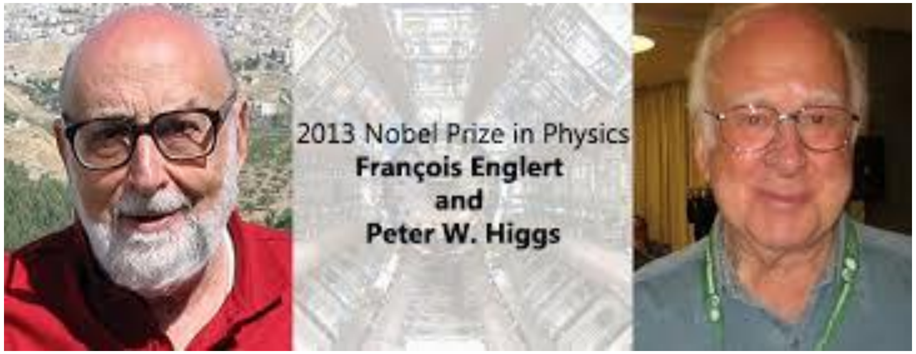
Various particle accelerators

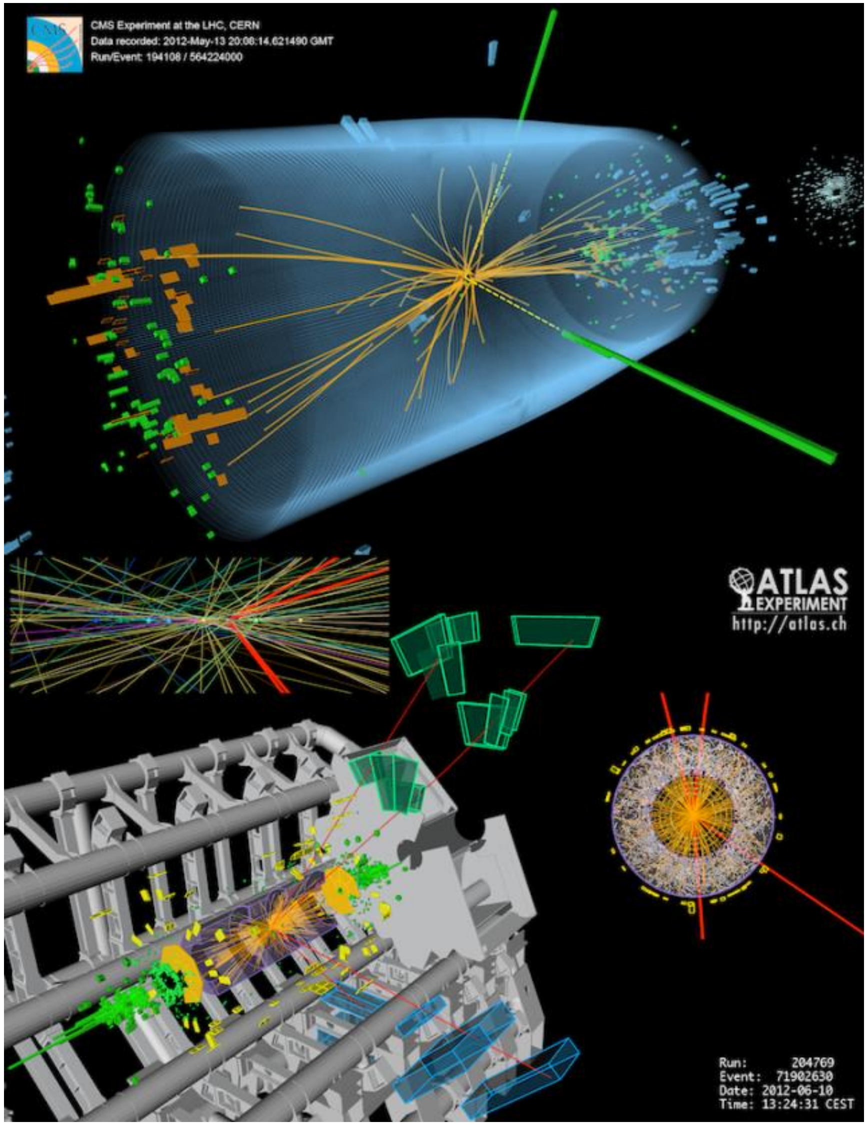






LHC (Large Hadron Collider)





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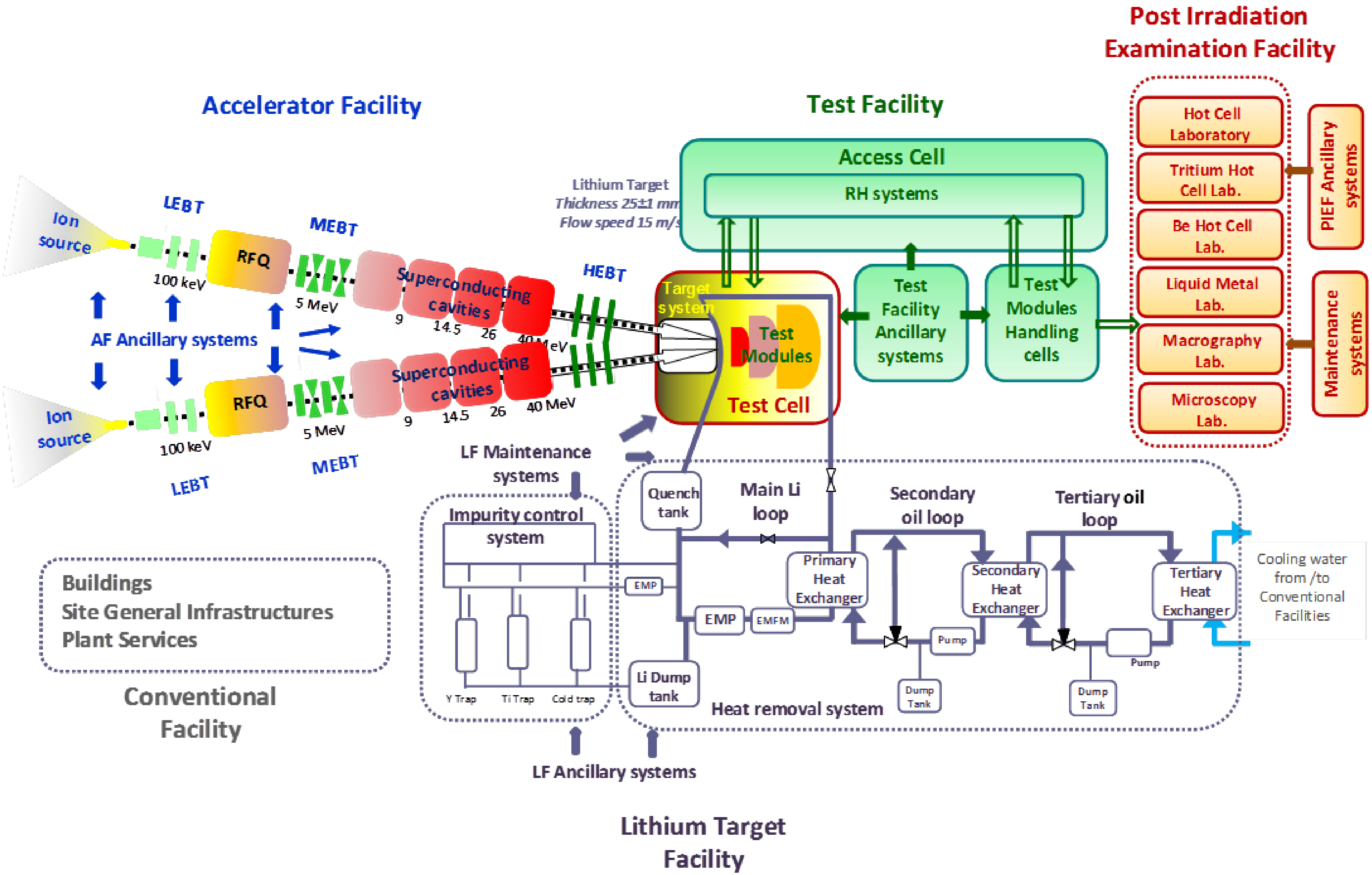
SNS (Spallation Neutron Source)

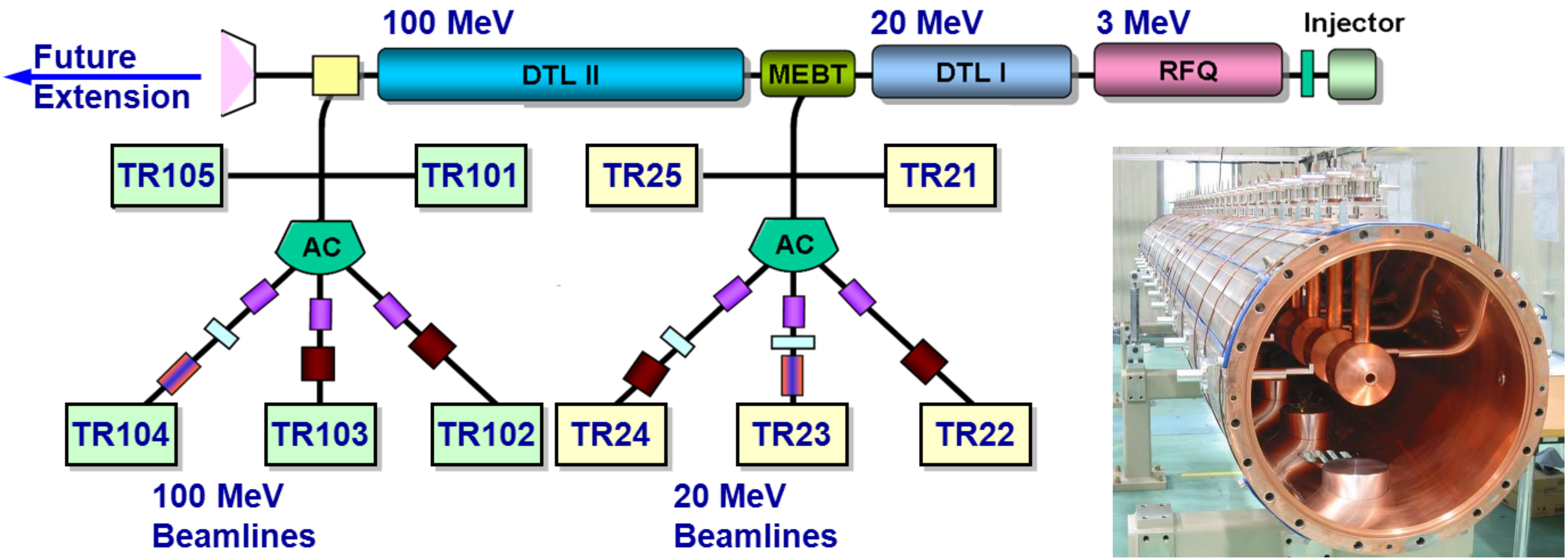
IFMIF (International Fusion Material Irradiation Facility)



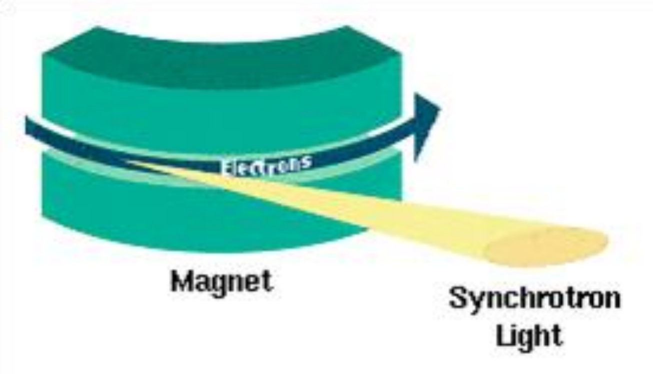
KOMAC (proton accelerator)

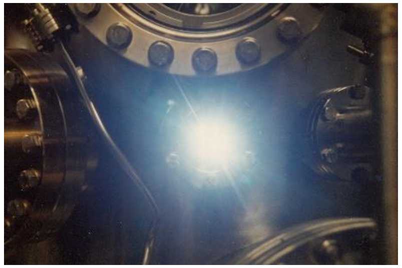
Features of KOMAC 100MeV linac
50-keV Injector (Ion source + LEBT)
3-MeV RFQ (4-vane type)
20 & 100-MeV DTL
RF Frequency : 350 MHz
Beam Extractions at 20 or 100 MeV
5 Beamlines for 20 MeV & 100 MeV

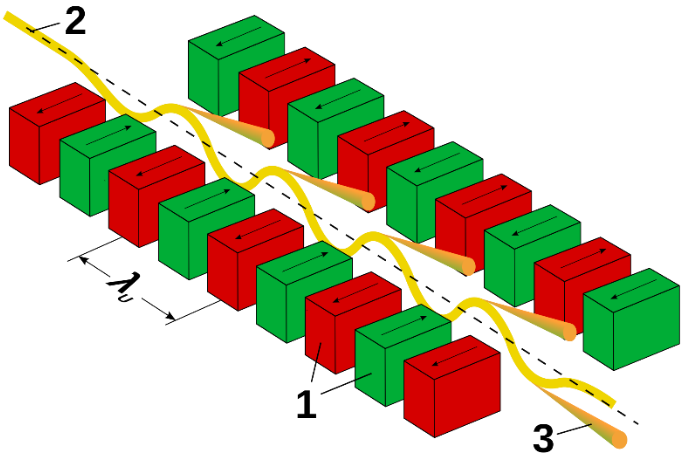
Output Energy (MeV)	20	100
Max. Peak Beam Current (mA)	1 ~ 20	1 ~ 20
Max. Beam Duty (%)	24	8
Avg. Beam Current (mA)	0.1 ~ 4.8	0.1 ~ 1.6
Pulse Length (ms)	0.1 ~ 2	0.1 ~ 1.33
Max. Repetition Rate (Hz)	120	60
Max. Avg. Beam Power (kW)	96	160



PAL (light source)

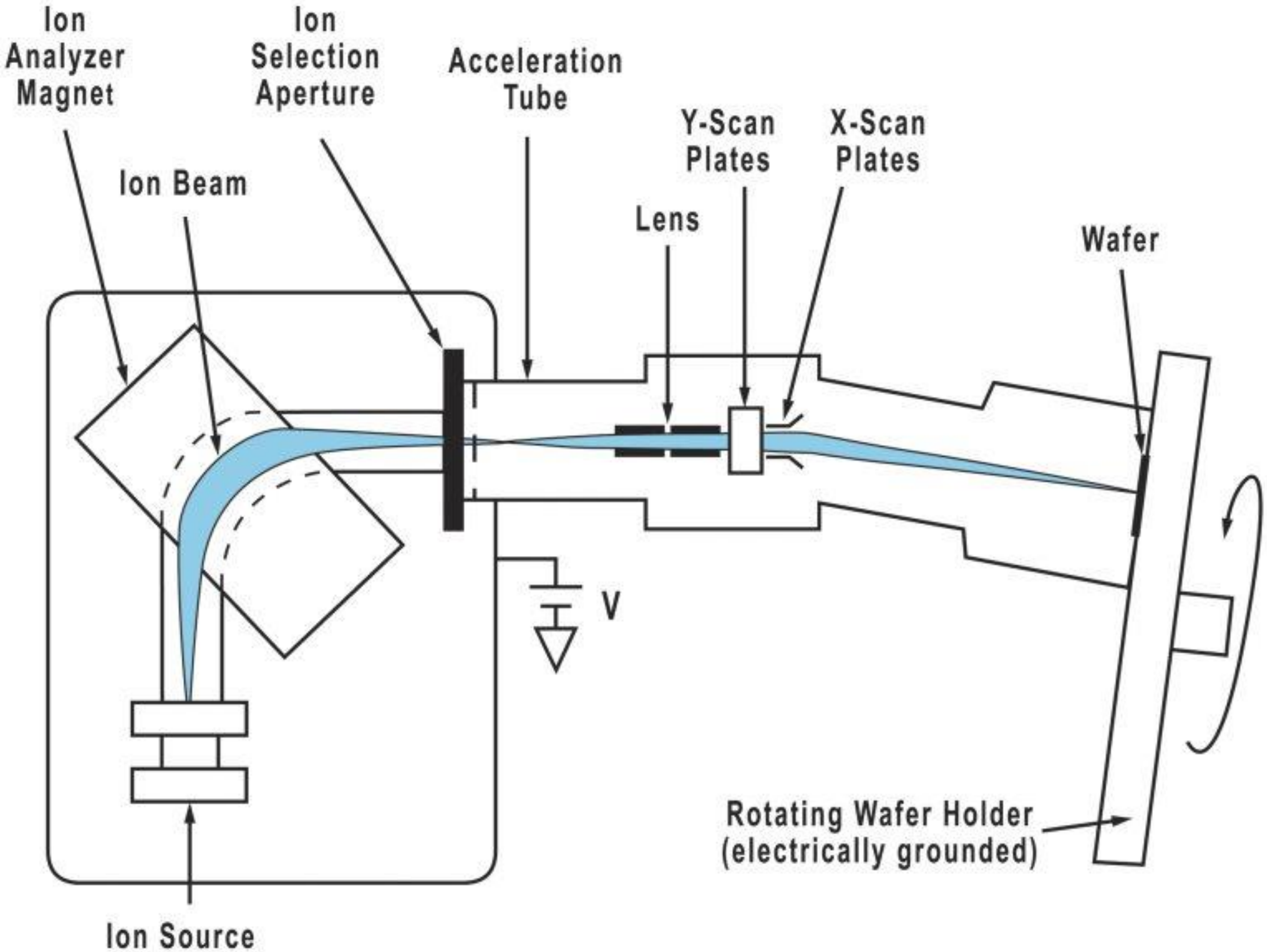






Accelerators for semiconductor industry

- Ion implanter for B^+, P^+, As^+ doping



Industrial applications

Accelerators: Essential Tools in Industry

Ion Implantation

- Accelerators can precisely deposit ions modifying materials and electrical properties

Semi Conductors

- CMOS transistor fabrication of essentially all IC's
- CCD & CMOS imagers for digital cameras
- Cleaving silicon for photovoltaic solar cells
- Typical IC may have 25 implant steps

Metals

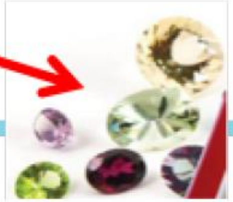
- Harden cutting tools
- Reducing friction
- Biomaterials for implants

Ceramics and Glasses

- Harden surfaces
- Modify optics
- Color in Gem stones!

Applied Materials, Inc.

N2 ions reduce wear and corrosion in this artificial femur



5 APT seminar, RDK, Nov 2014

Fermilab *(courtesy R. Kephart)*

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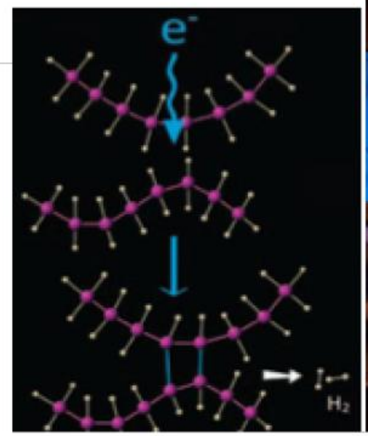
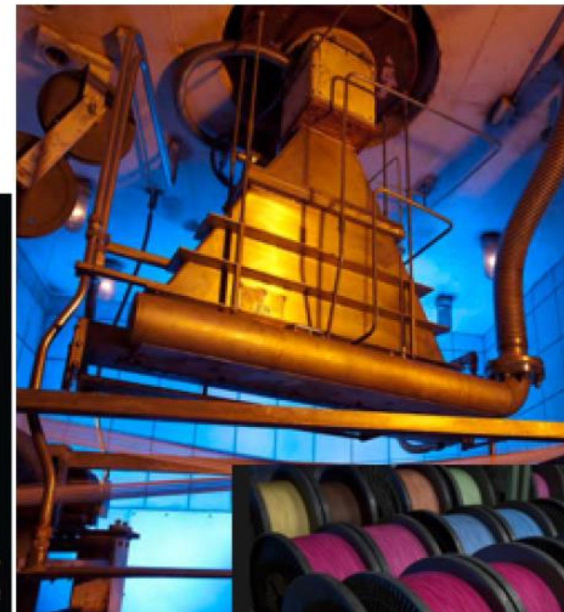
Industrial applications

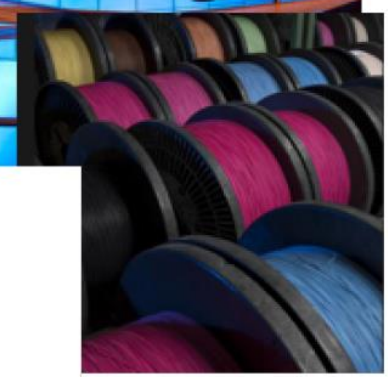
Accelerators: Essential Tools in Industry

A wide-range of industrial applications makes use of low-energy beams of electrons to drive chemistry

- 0.1-10 MeV up to MW beam power electrostatic, linac, betatron accelerators







Electron Beam Irradiation

Improved heat resistance of coatings, wire and cable, crosslinking polymers, radial tires, etc)

1500 dedicated facilities worldwide

Fermilab

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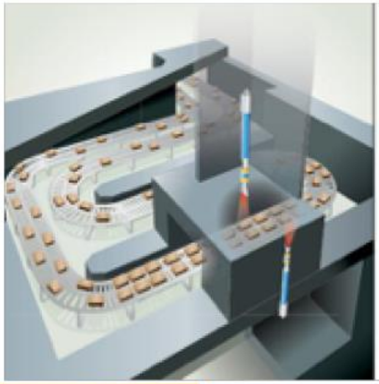
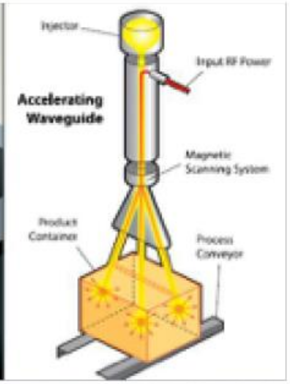
Industrial applications

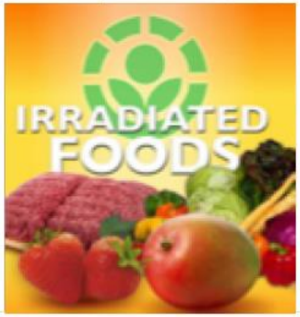
Accelerators: Food Preservation

Low-energy beams of electrons can help beat food-borne Illness

- ~6000 people/week are sickened, and ~100/week die from food-borne illness in the U.S.
- Food poisoning is estimated to cost the US $152 billion a year.
- Electron beams and/or X-rays can kill bacteria like E. coli, Salmonella, and Listeria.
- Currently in use for: Spices, fruit, lettuce, ground beef, milk, juice, military rations…
- Many more opportunities exist
- Barriers = cost & public acceptance







Fermilab

9 APT seminar, RDK, Nov 2014

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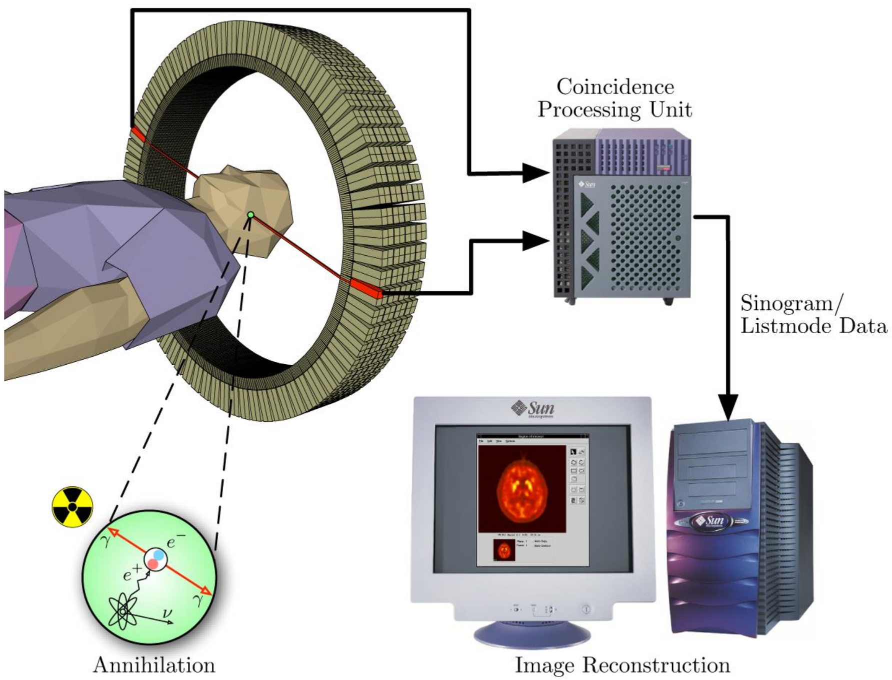
PET (positron emission tomography)

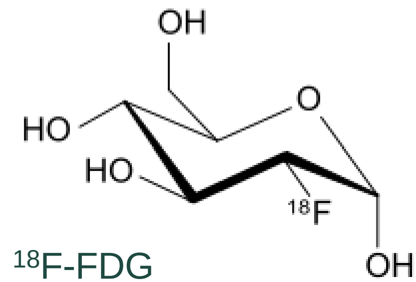
- The system detects pairs of gamma rays emitted indirectly by a positron-emitting radionuclide, most commonly fluorine-18. which is introduced into the body on a biologically active molecule called a radioactive tracer.

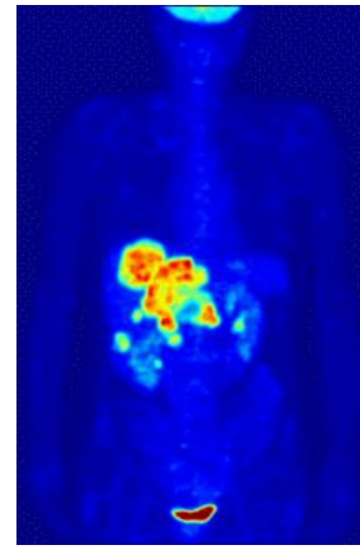
O-18 $\xrightarrow{p}$ F-18 $\xrightarrow[110\text{ m}]{\beta^+}$ O-18

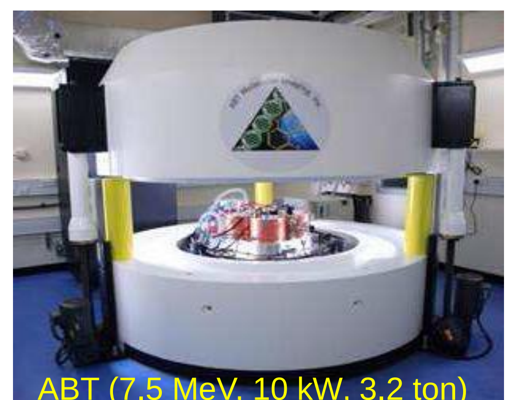
Cyclotron

$$e^+ + e^- \rightarrow 2\gamma$$







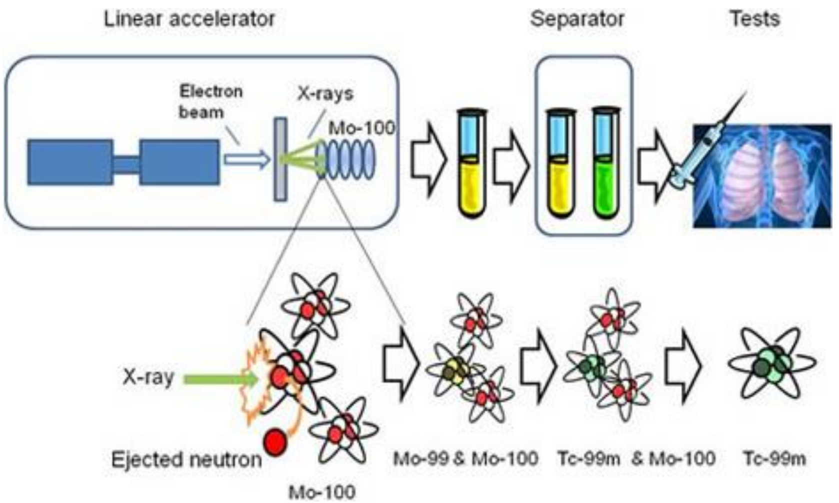


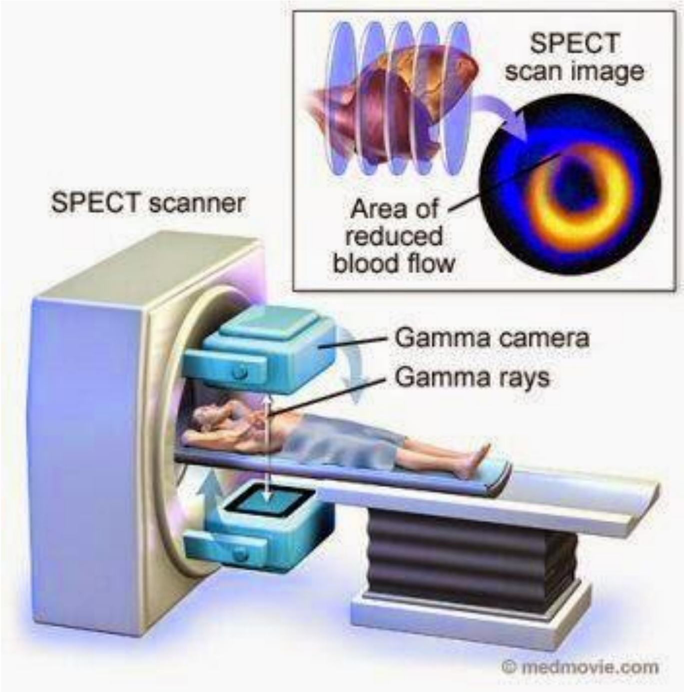
SPECT (single-photon emission computed tomography)

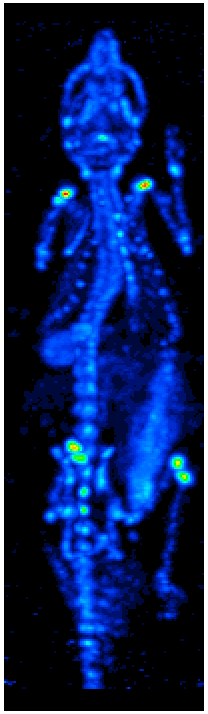
- SPECT is a nuclear medicine tomographic imaging technique using gamma rays. It is similar to PET in its use of radioactive tracer material and detection of gamma rays. In contrast with PET, however, the tracers used in SPECT emit gamma radiation that is measured directly.

$$\text{Mo-98} \xrightarrow{\text{n (Reactor)}} \text{Mo-99} \xrightarrow[66\text{ h}]{\beta^-} \text{Tc-99m}$$

$$^{99m}_{43}\mathrm{Tc} \xrightarrow[6\text{ h}]{\gamma\ 141\text{ keV}} {}^{99}_{43}\mathrm{Tc} \xrightarrow[211{,}000\text{ y}]{\beta^-\ 249\text{ keV}} \overbrace{^{99}_{44}\mathrm{Ru}}^{\text{ruthenium}-99}\ (\text{stable})$$



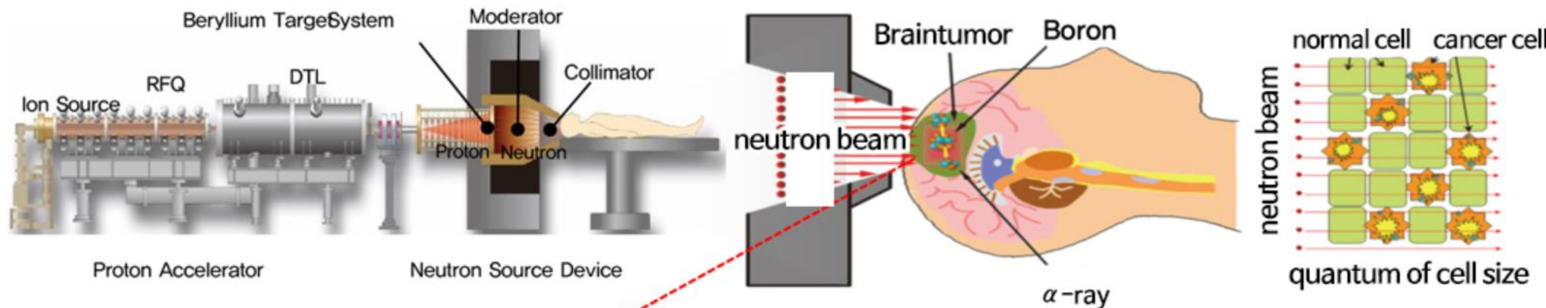




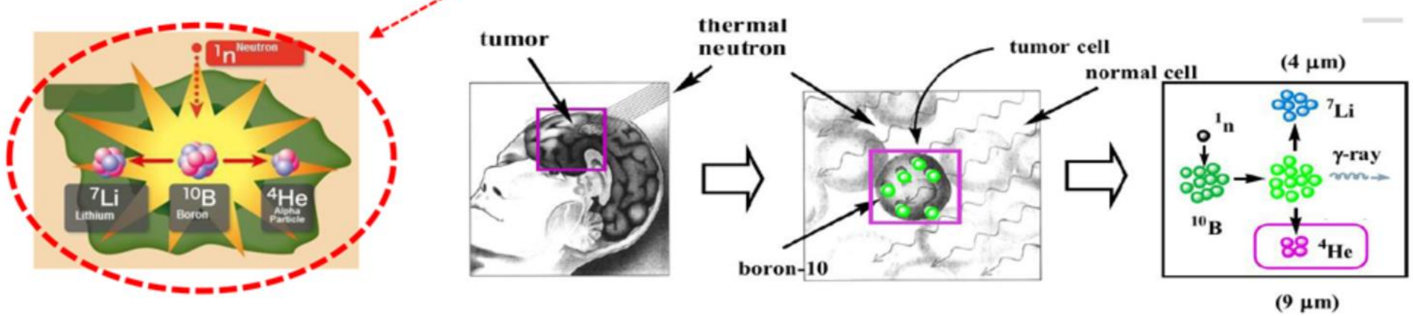
BNCT (boron neutron capture therapy)

- Two-step procedure:
  ① The patient is injected with a tumor-localizing drug containing the non-radioactive isotope boron-10 (^{10}B) that has a high cross section to capture slow neutrons.

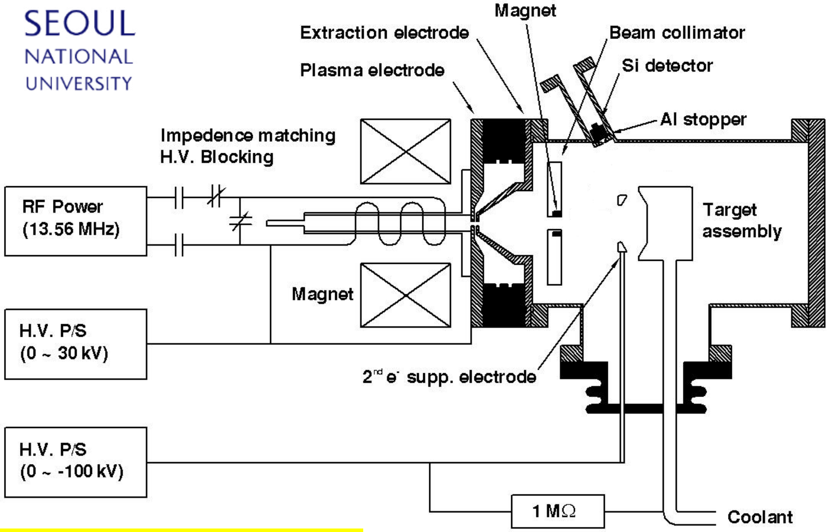
  ② The patient is radiated with epithermal neutrons, the source of which is either a nuclear reactor or, more recently, an accelerator.



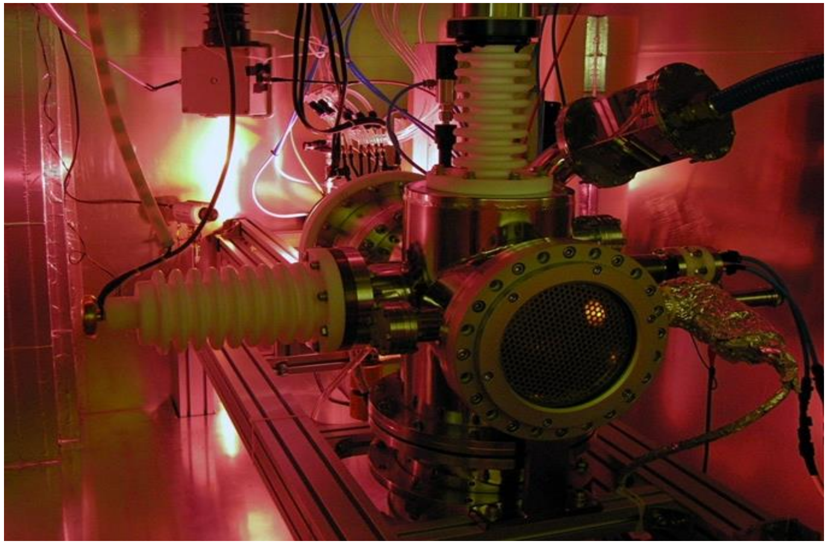
$^{10}B + n_{th} \rightarrow [^{11}B]^{*} \rightarrow \alpha + {}^{7}Li + 2.31$ MeV



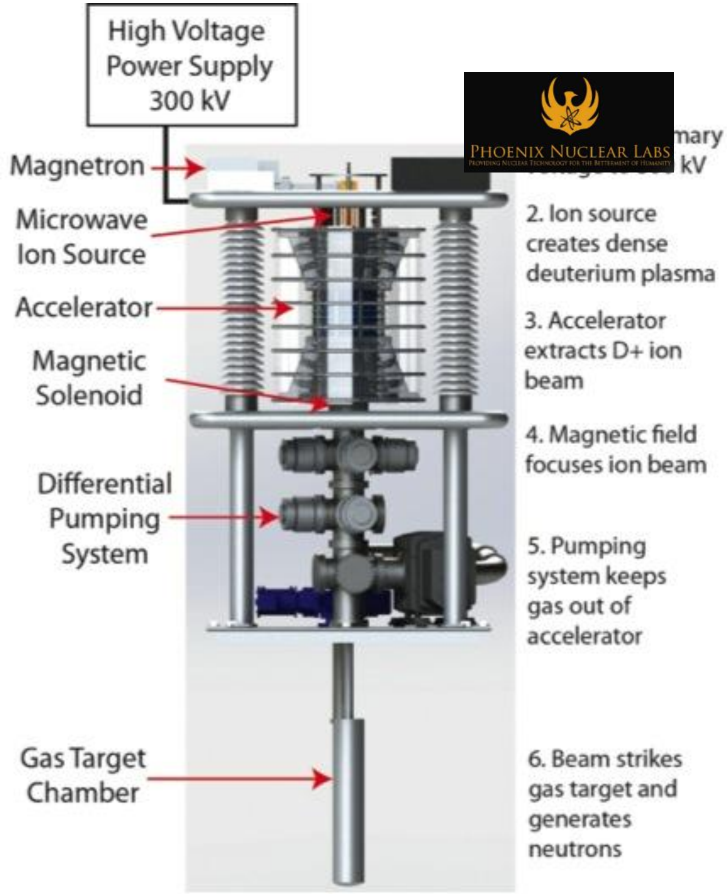
D-D of D-T neutron generators



2x10^8 n/s @97keV, 8mA



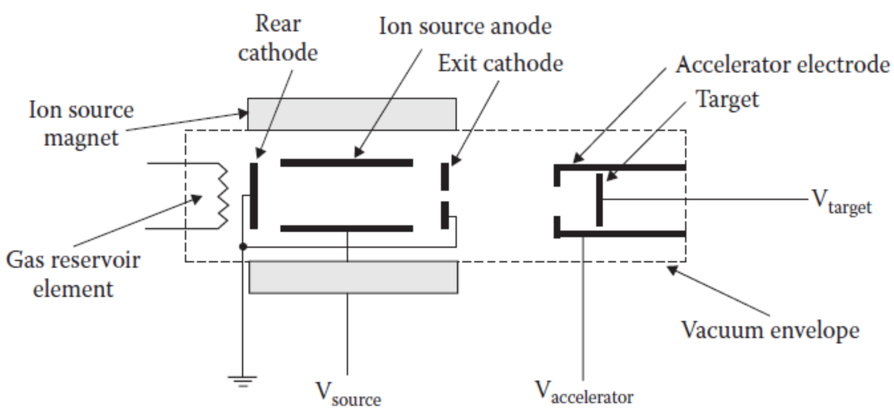
$$D + D \rightarrow {}^3He(0.82) + n(2.45)$$



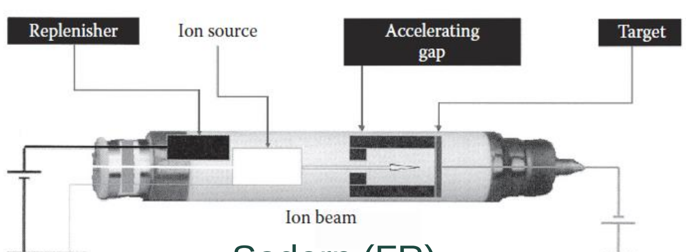
3x10^11 n/s @300keV, 50mA

Neutron tube

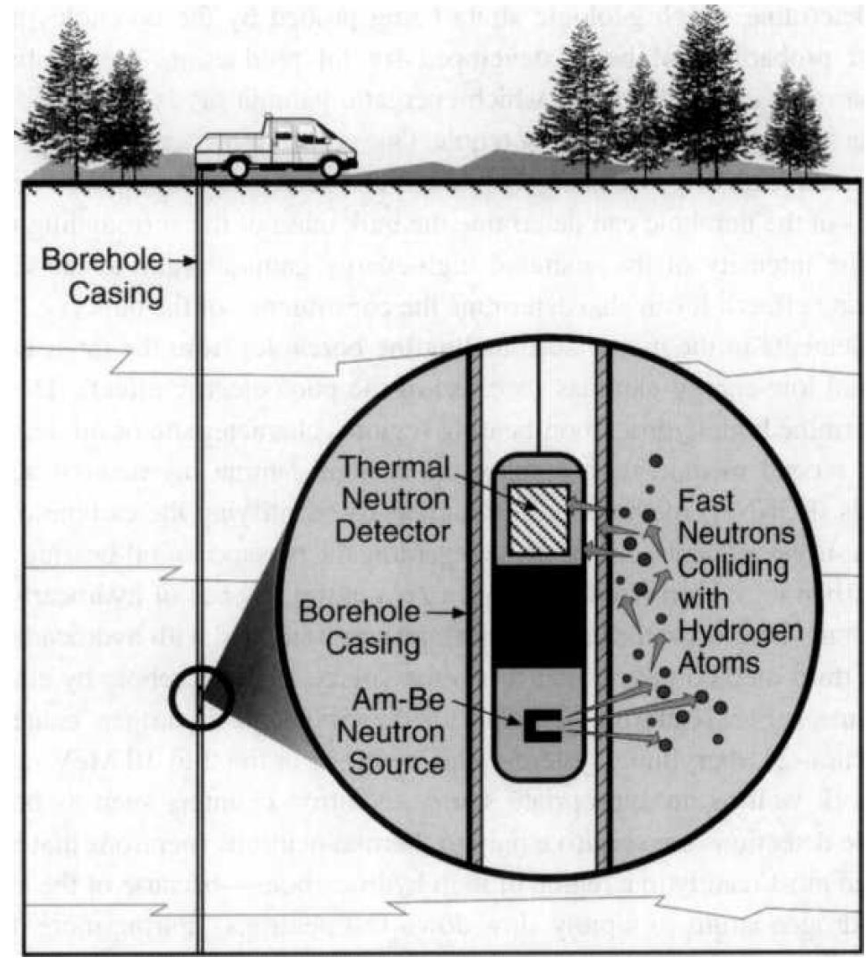
- **Sealed-tube neutron generators**: Some accelerator-based neutron generators induce fusion between beams of deuterium and/or tritium ions and metal hydride targets which also contain these isotopes.



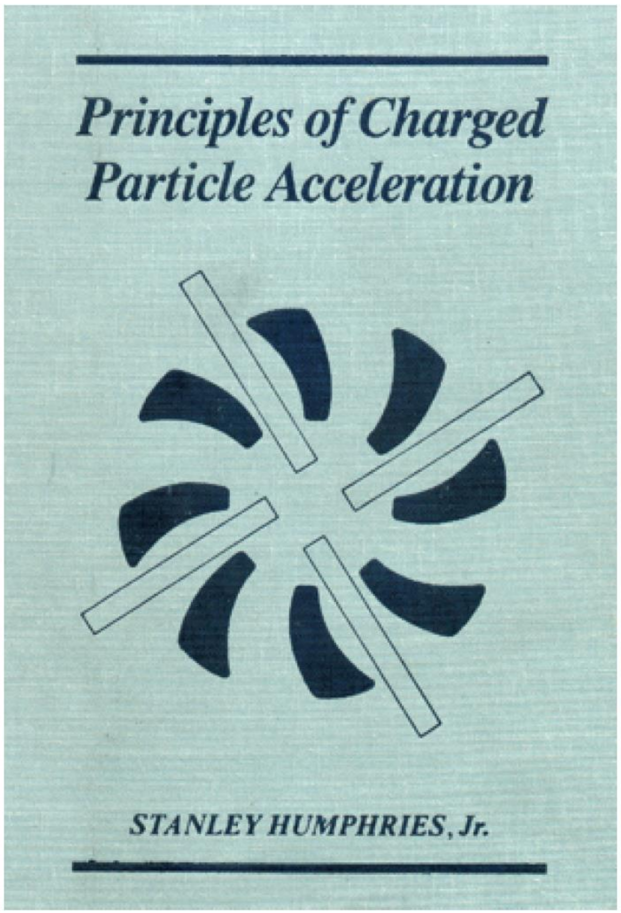
VNIIA (RF)



Sodern (FR)



Textbook



Principles of Charged Particle Acceleration

Stanley Humphries, Jr.
Department of Electrical and Computer Engineering
University of New Mexico
Albuquerque, New Mexico

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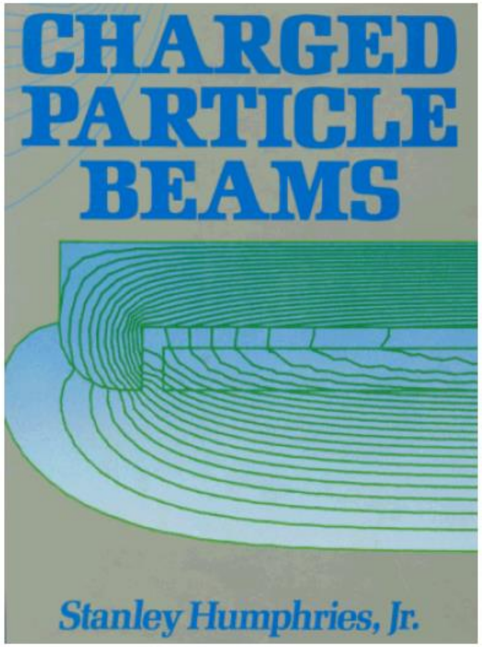
Textbook



Charged Particle Beams

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University of New Mexico
Albuquerque, New Mexico

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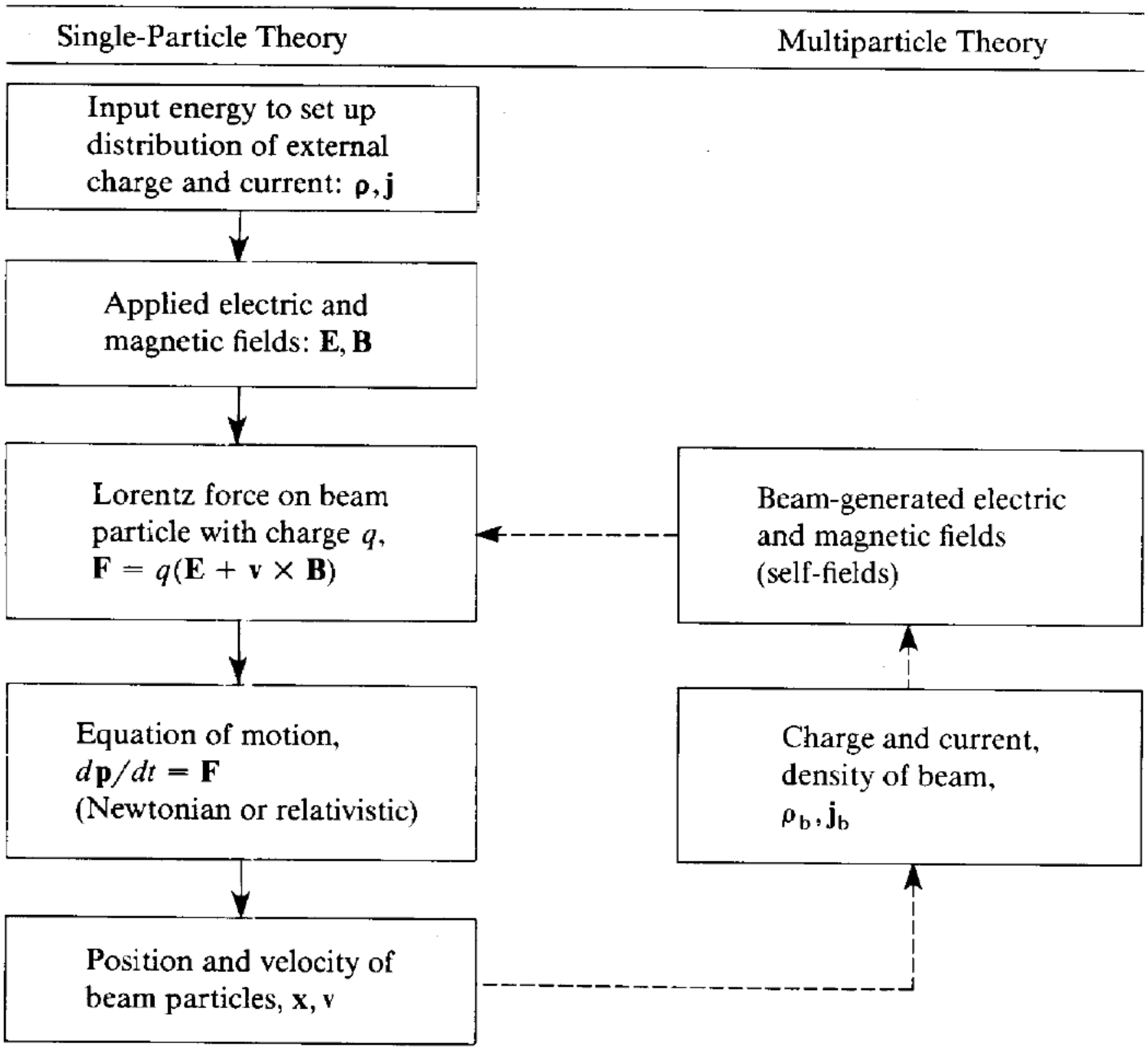
Basic definitions

- A charged particle is an elementary particle or a macroparticle which contains an excess of positive or negative charge. Its motion is determined mainly by interaction with electromagnetic forces.
- Charged particle acceleration is the transfer of kinetic energy to a particle by the application of an electric field.
- A charged particle beam is a collection of particles distinguished by three characteristics: (1) beam particles have high kinetic energy compared to thermal energies, (2) the particles have a small spread in kinetic energy, and (3) beam particles move approximately in one direction. In most circumstances, a beam has a limited extent in the direction transverse to the average motion. The antithesis of a beam is an assortment of particles in thermodynamic equilibrium.
- Most applications of charged particle accelerators depend on the fact that beam particles have high energy and good directionality. Directionality is usually referred to as coherence. Beam coherence determines, among other things, (1) the applied force needed to maintain a certain beam radius, (2) the maximum beam propagation distance, (3) the minimum focal spot size, and (4) the properties of an electromagnetic wave required to trap particles and accelerate them to high energy.

Beam acceleration process



Beam acceleration process

- In accelerator theory, particles are separated into two groups: (1) particles in the beam and (2) charged particles that are distributed on or in surrounding materials. The latter group is called the external charge.
- Energy is required to set up distributions of external charge; this energy is transferred to the beam particles via electromagnetic forces.
- For example, a power supply can generate a voltage difference between metal plates by subtracting negative charge from one plate and moving it to the other. A beam particle that moves between the plates is accelerated by attraction to the charge on one plate and repulsion from the charge on the other.
- Applied forces are usually resolved into those aligned along the average direction of the beam and those that act transversely.
- The axial forces are acceleration forces; they increase or decrease the beam energy.
- The transverse forces are confinement forces. They keep the beam contained to a specific cross-sectional area or bend the beam in a desired direction.
- Magnetic forces are always perpendicular to the velocity of a particle; therefore, magnetic fields cannot affect the particle's kinetic energy. Magnetic forces are confinement forces. Electric forces can serve both functions.

Applications and organization of topics

- Production of short-lived radioisotopes for medical diagnosis
- Intense ion beams to drive inertial fusion reactors
- Electron beam welding
- Pulsed neutron sources for uranium borehole logging
- Cathode ray tubes and fast digitizers
- Electronuclear breeding of fissile fuels
- Measurement of cross sections for atomic physics
- Processing of semi-conductor circuits
- Secondary ion mass spectroscopy
- Generation of synchrotron radiation for solid-state physics research
- Diagnostics of rock formations in oil and natural gas wells
- Elementary particle physics
- Electron microscopy
- Materials testing for controlled thermonuclear fusion reactors
- Drivers for gas lasers and free electron lasers
- Cross-linking of thermoplastics
- Image intensifiers and fast streak tubes
- Pulsed X-ray radiography
- Surface modification of materials by ion implantation
- Nuclear structure studies
- Plasma heating for fusion reactors
- Assay of nuclear materials for safeguard applications
- Sterilization of food products
- Studies of transuranic elements
- Intense pulsed neutron sources for radiography and materials studies
- Generation of X rays and pions for radiation therapy
- Electron and ion surface microprobes
- Analysis of trace elements for biology and archeology
- Calibration of radiation detectors
- Studies of radiation damage in fission reactors