

Introduction

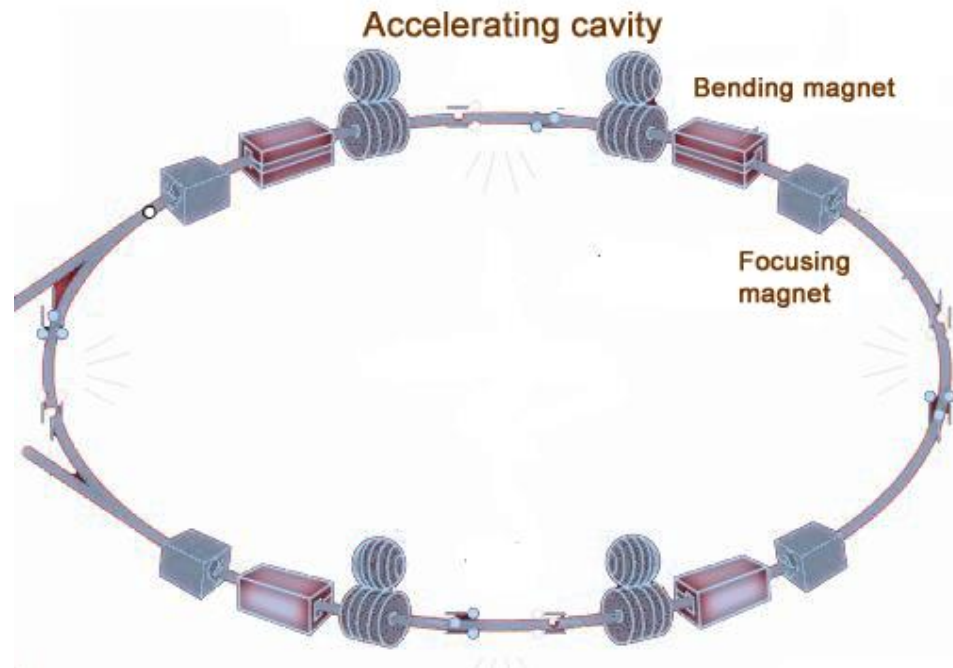
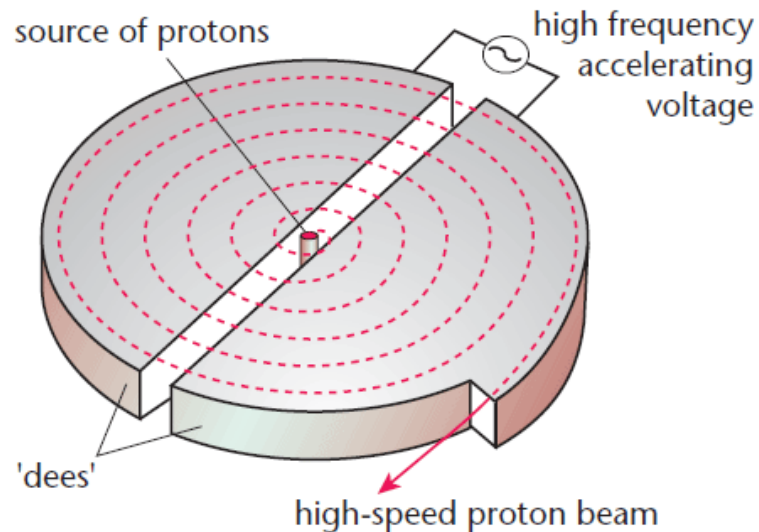
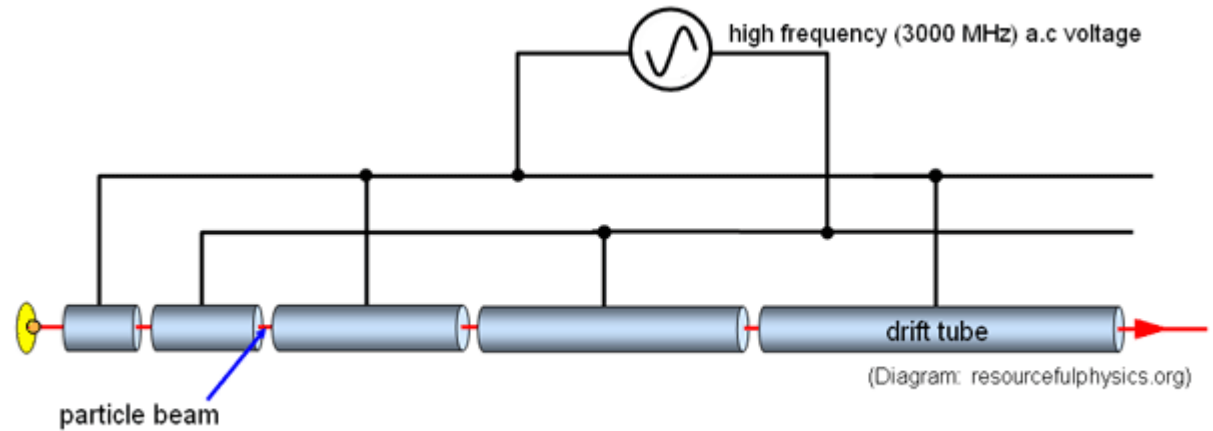
Spring, 2021

Kyoung-Jae Chung

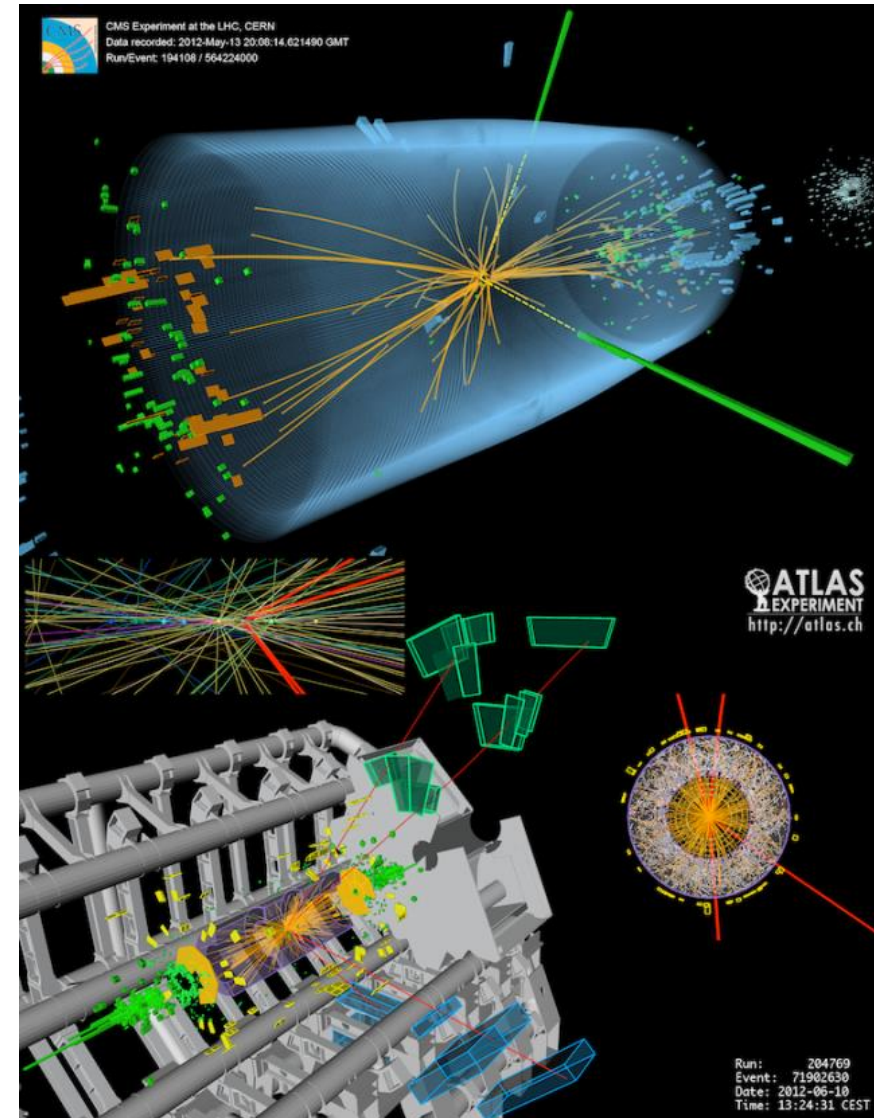
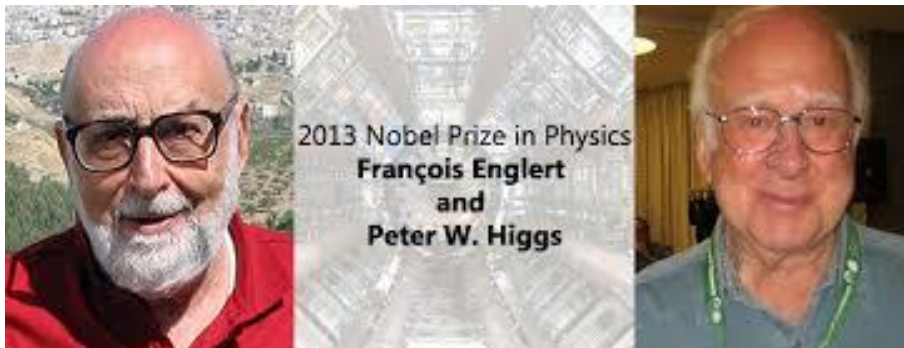
Department of Nuclear Engineering

Seoul National University

Various particle accelerators



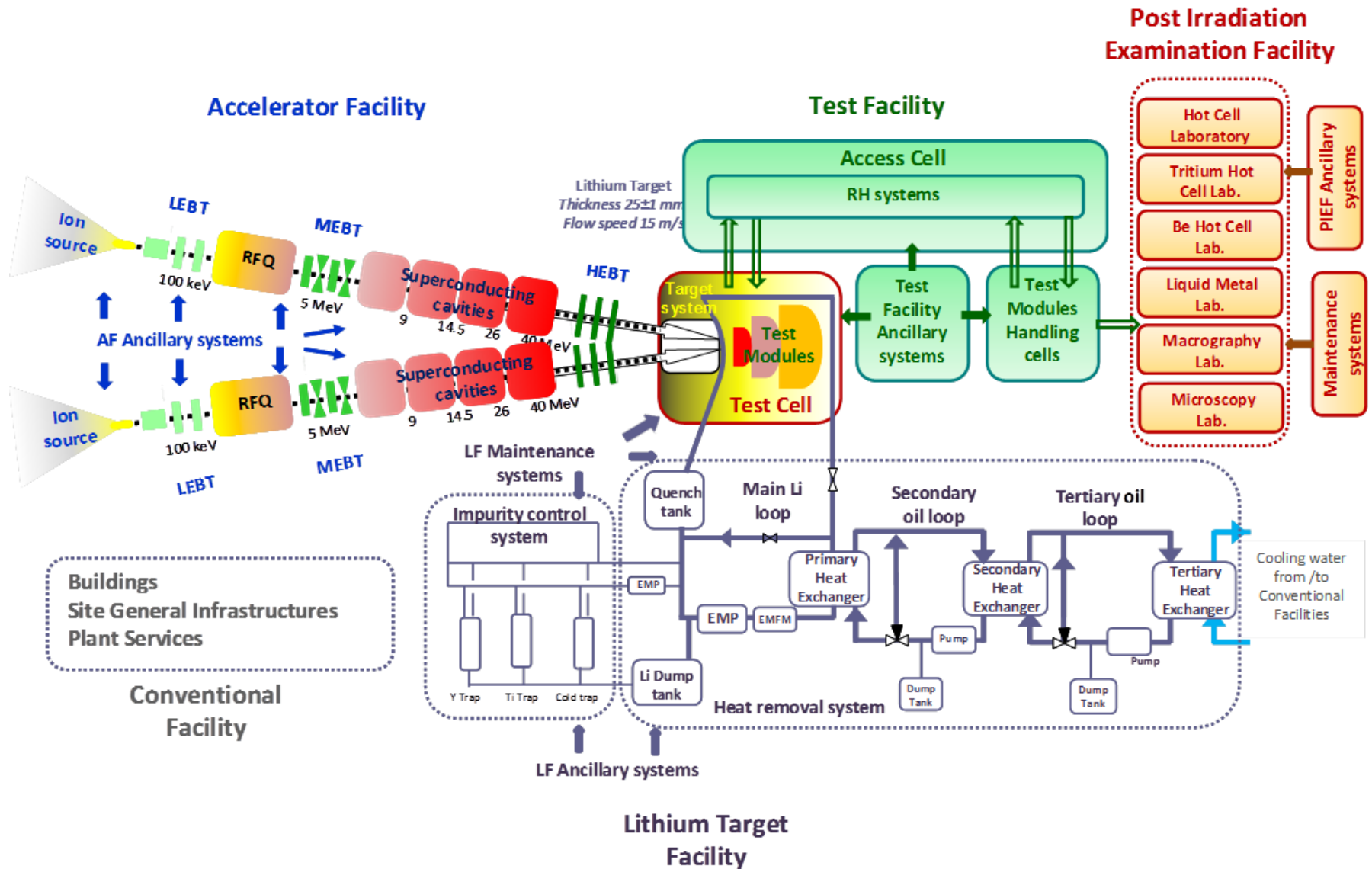
LHC (Large Hadron Collider)



SNS (Spallation Neutron Source)



IFMIF (International Fusion Material Irradiation Facility)

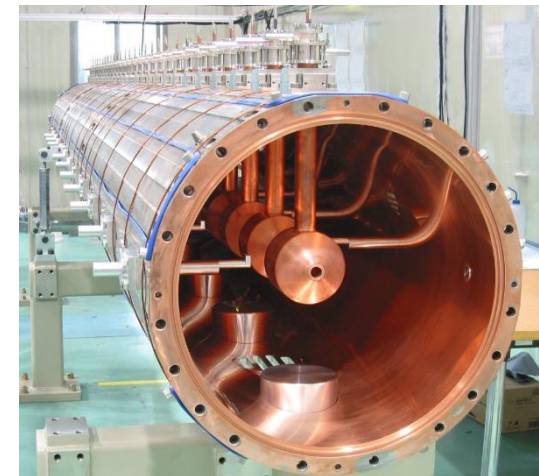
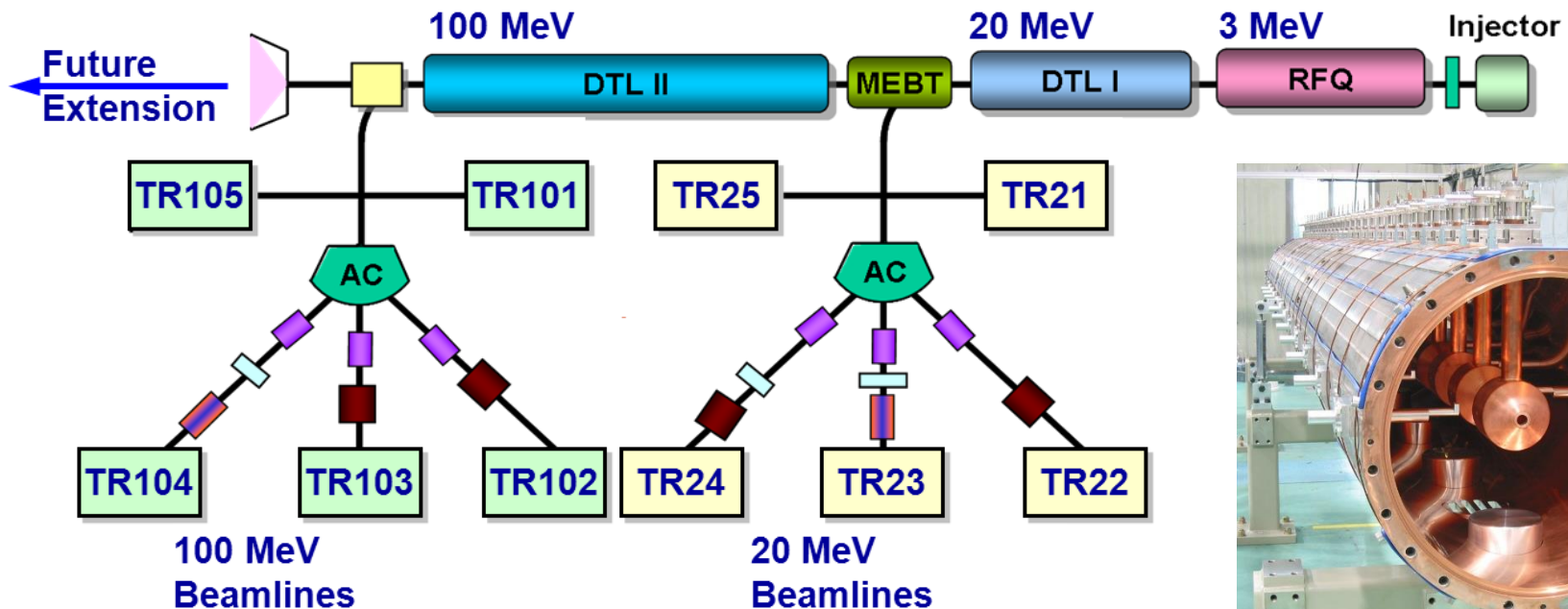


KOMAC (proton accelerator)

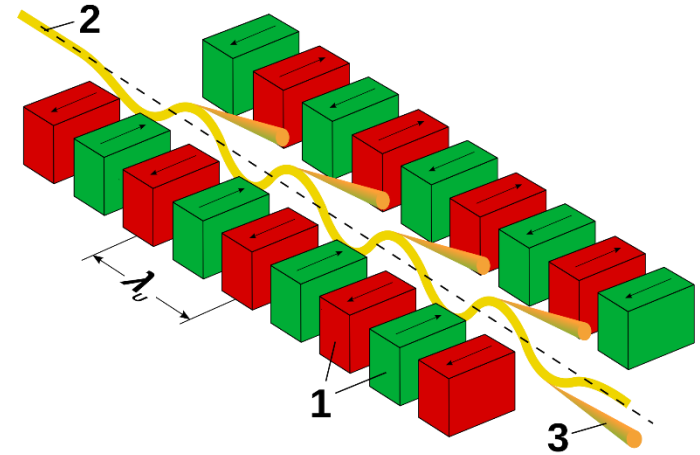
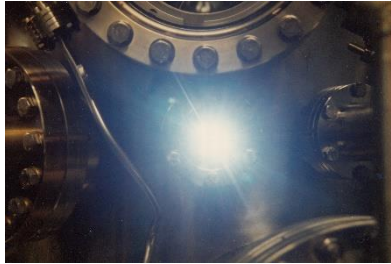
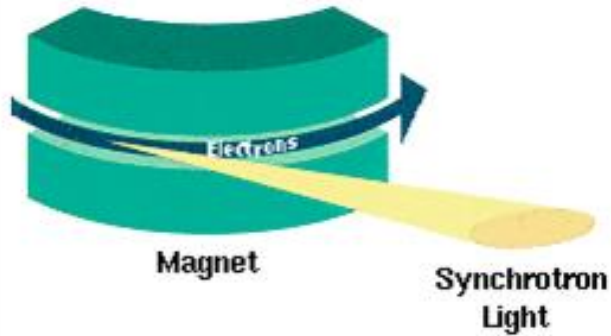
Features of KOMAC 100MeV linac

- 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

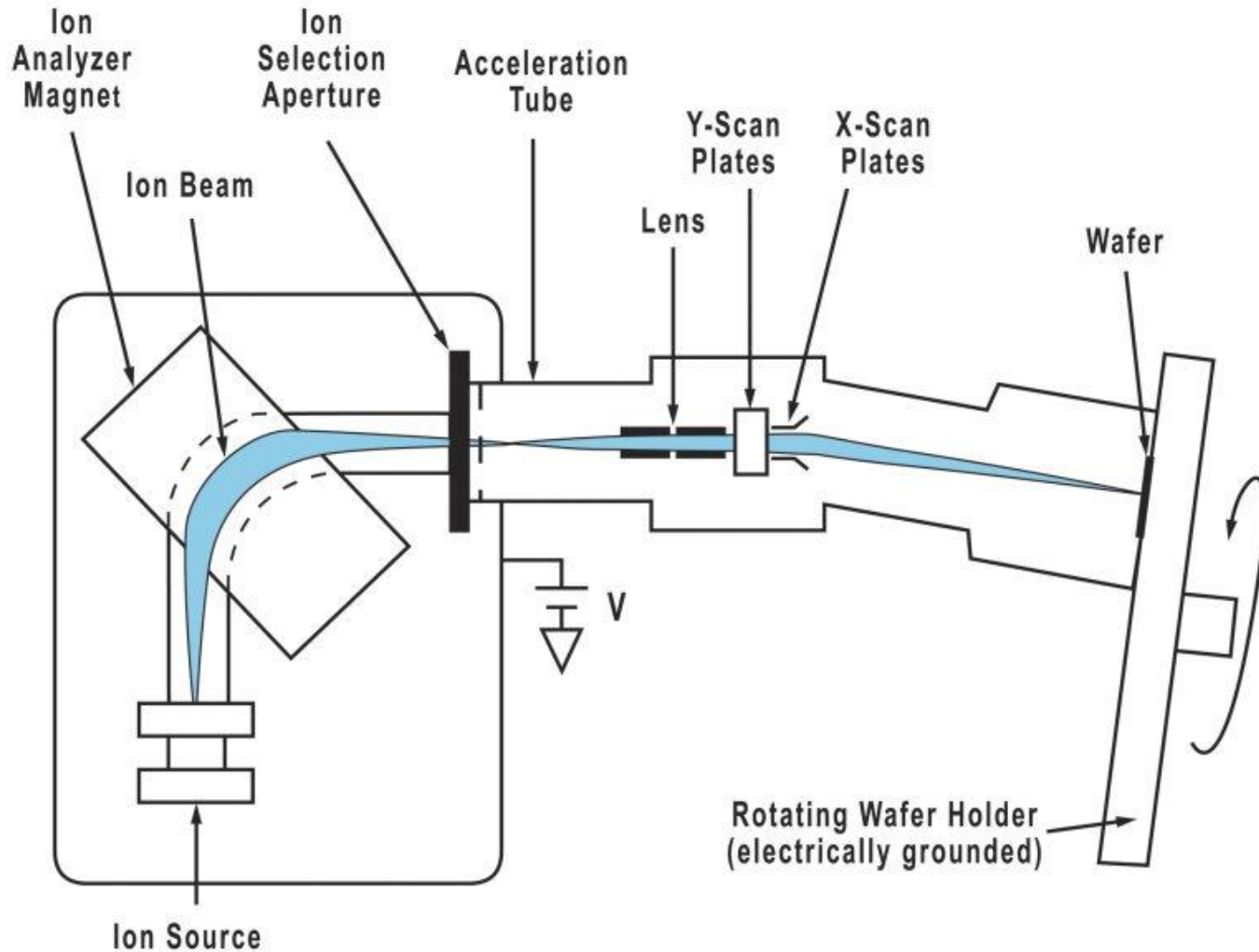


PAL (light source)



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

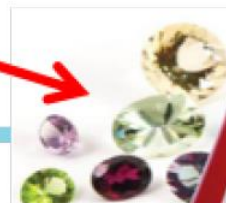
- Harden cutting tools
- Reducing friction
- Biomaterials for implants

Ceramics and Glasses

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



N₂ ions reduce wear and corrosion in this artificial femur



 Fermilab

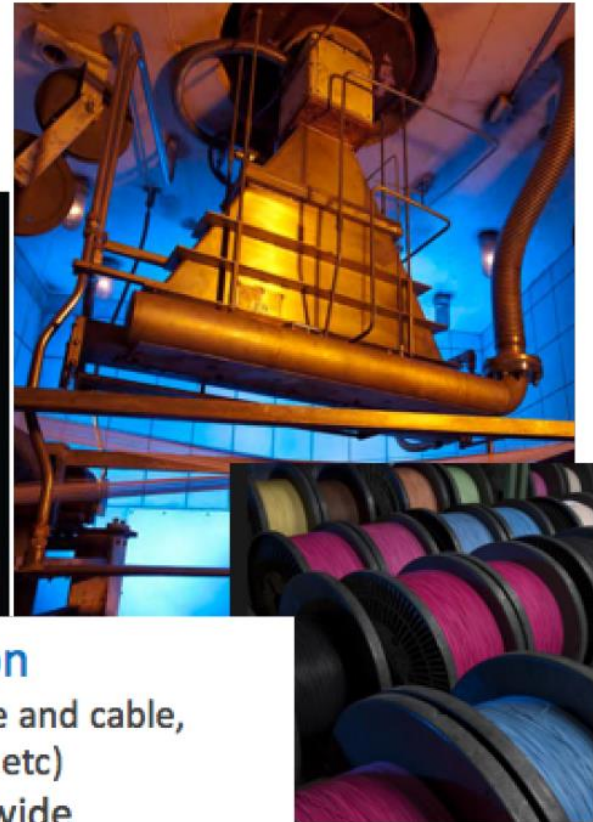
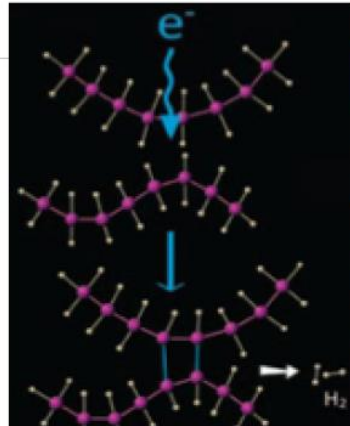
(courtesy R. Kephart)

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

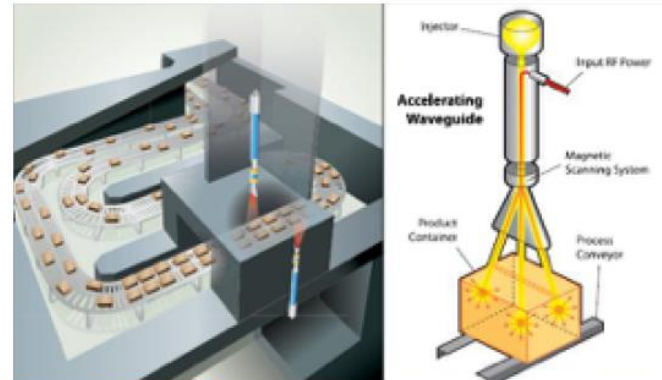
Improved heat resistance of coatings, wire and cable,
crosslinking polymers, radial tires, etc)
1500 dedicated facilities worldwide

 Fermilab

Accelerators: Food Preservation

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

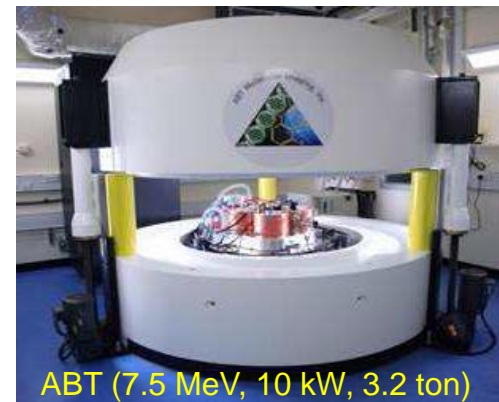
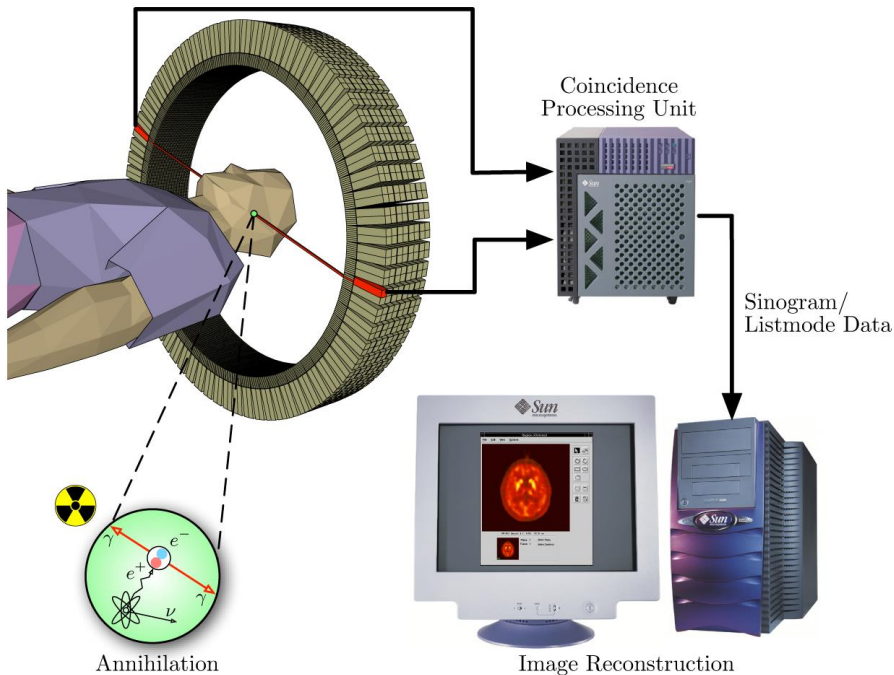
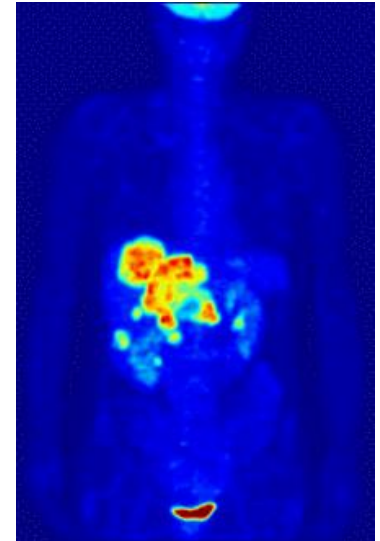
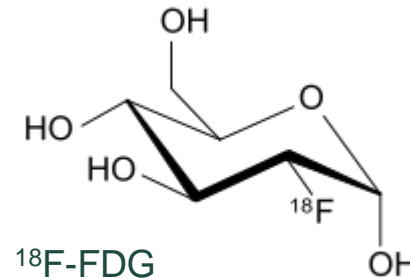
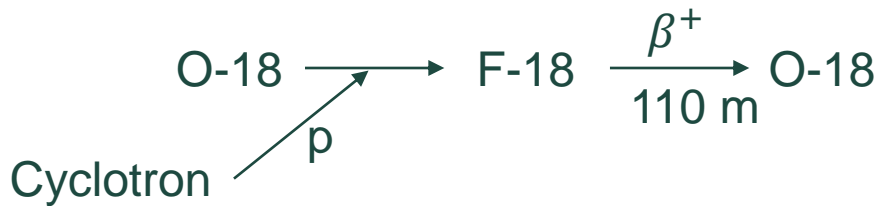
- ~6000 people/week are sickened, and ~100/week die from food-borne illness in the U.S.
- Food poisoning is estimated to cost the US \$152 billion a year.
- Electron beams and/or X-rays can kill bacteria like E. coli, Salmonella, and Listeria.
- Currently in use for: Spices, fruit, lettuce, ground beef,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



 **Fermilab**

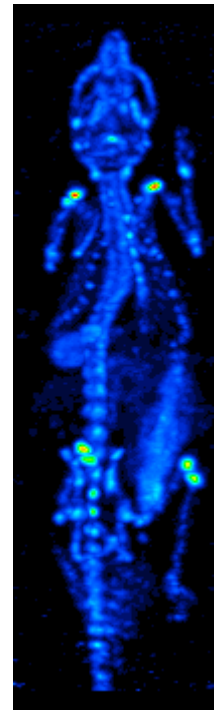
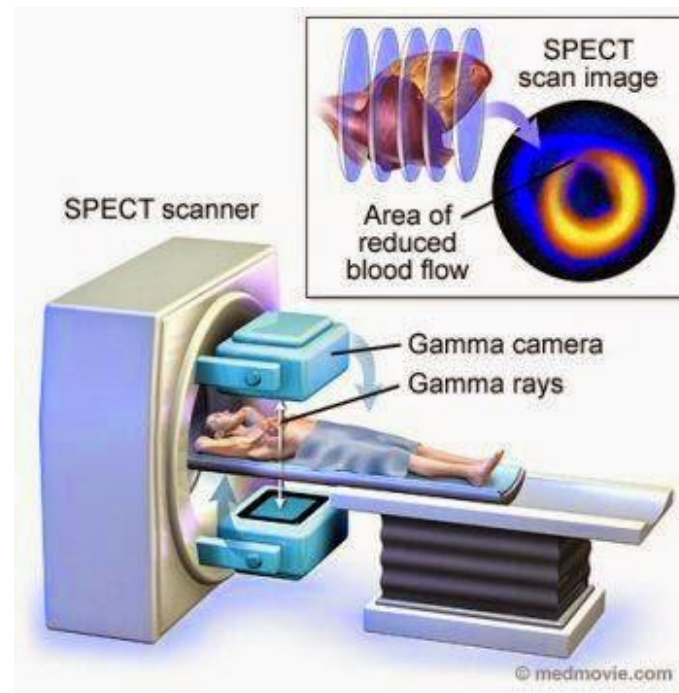
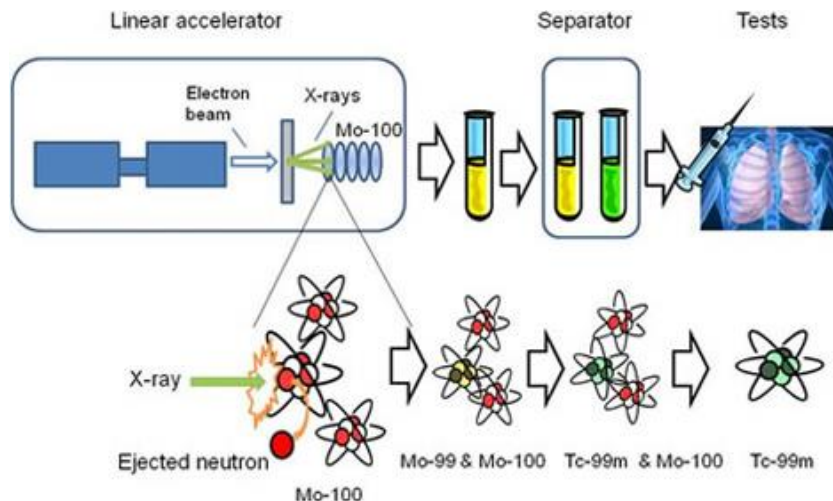
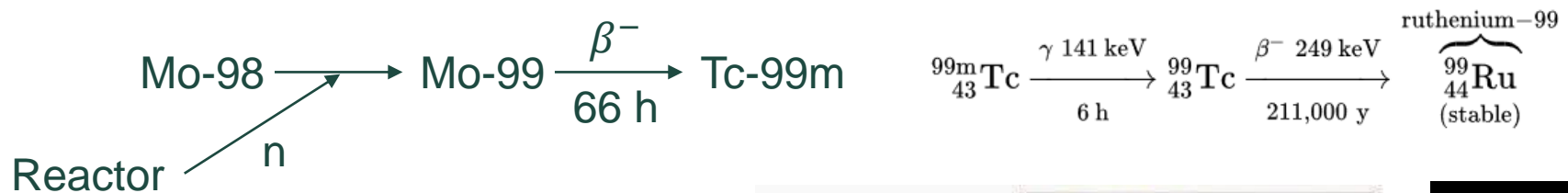
PET (positron emission tomography)

- 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.



SPECT (single-photon emission computed tomography)

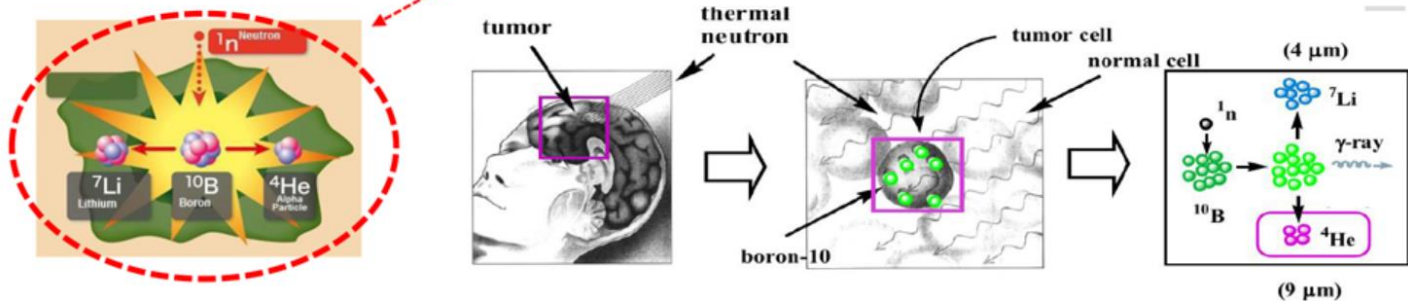
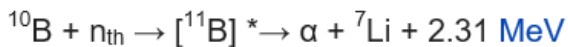
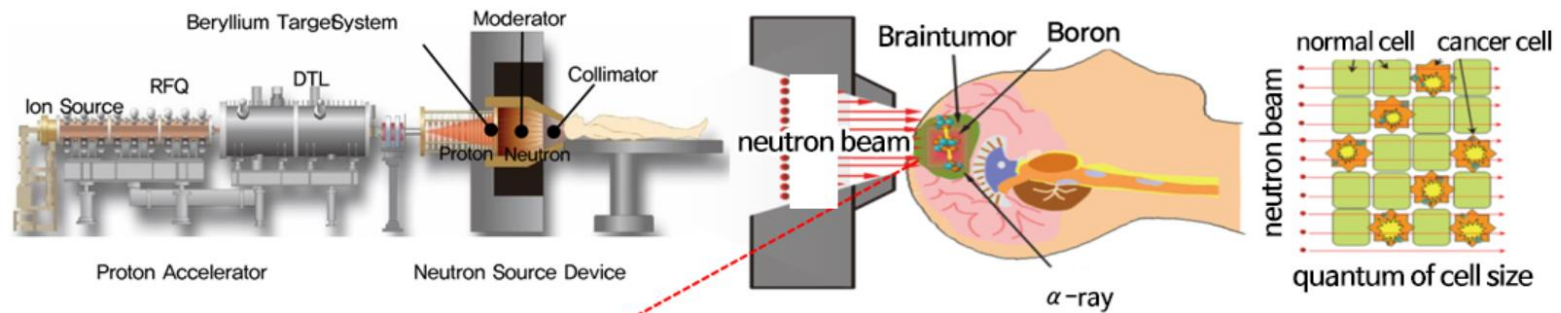
- SPECT is a nuclear medicine tomographic imaging technique using gamma rays. It is similar to PET in its use of radioactive tracer material and detection of gamma rays. In contrast with PET, however, the tracers used in SPECT emit gamma radiation that is measured directly.



BNCT (boron neutron capture therapy)

- Two-step procedure:

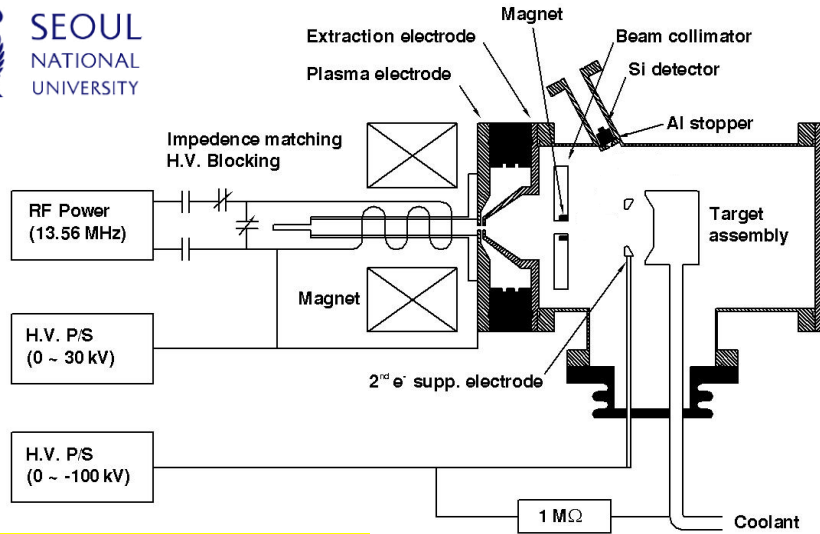
- ① The patient is injected with a tumor-localizing drug containing the non-radioactive isotope boron-10 (^{10}B) that has a high cross section to capture slow neutrons.
- ② The patient is radiated with epithermal neutrons, the source of which is either a nuclear reactor or, more recently, an accelerator.



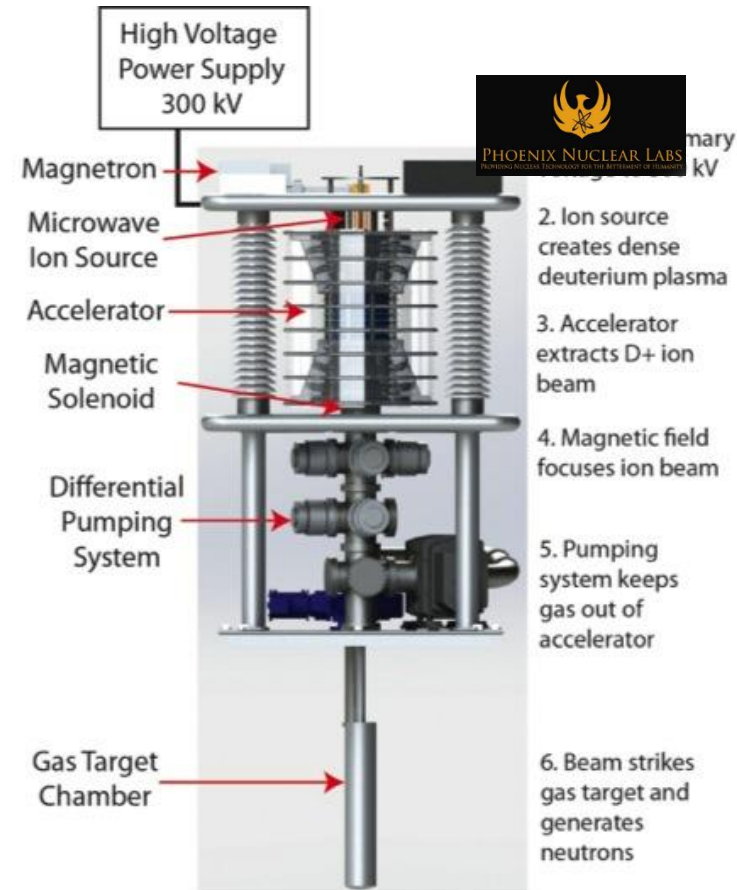
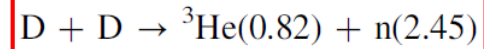
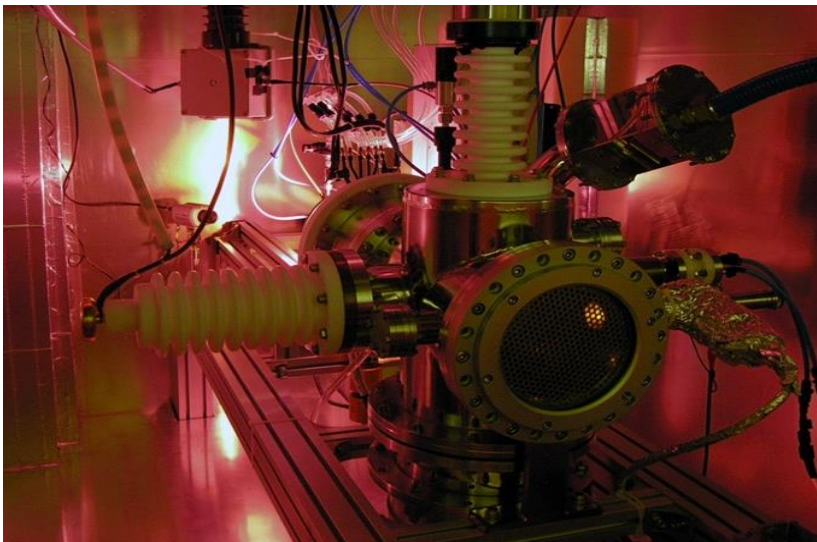
D-D of D-T neutron generators



SEOUL
NATIONAL
UNIVERSITY



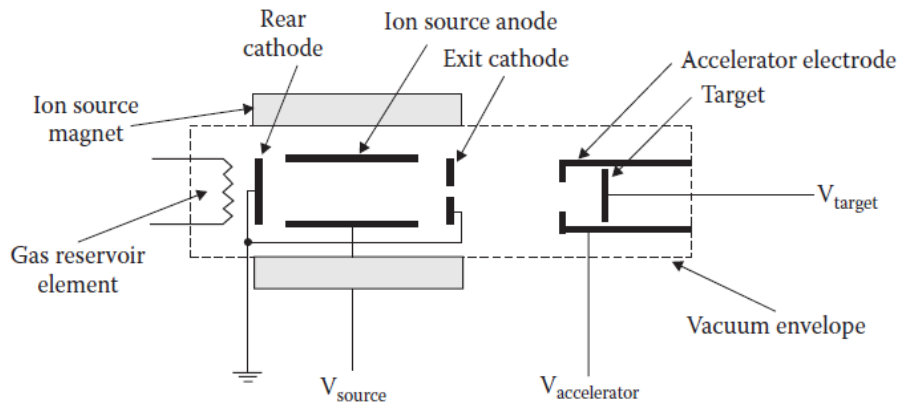
2×10^8 n/s @97keV, 8mA



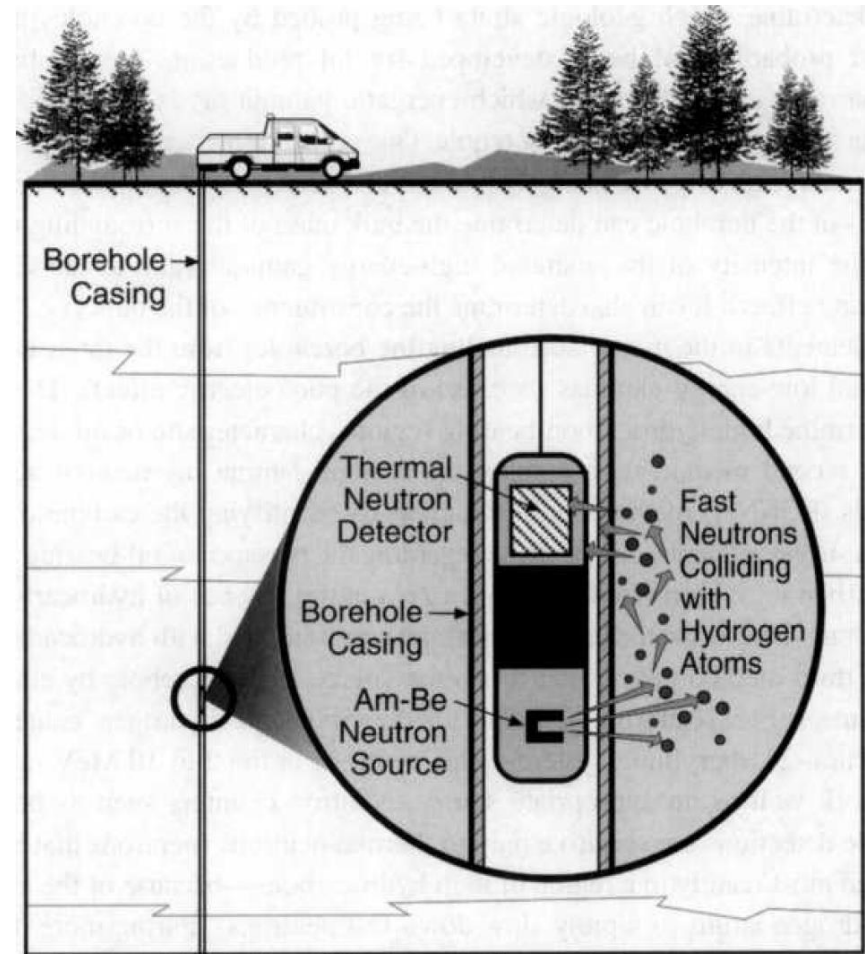
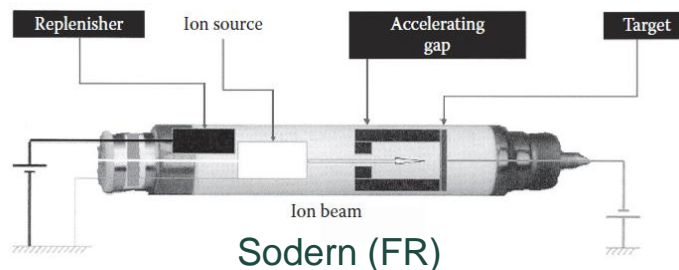
3×10^{11} n/s @300keV, 50mA

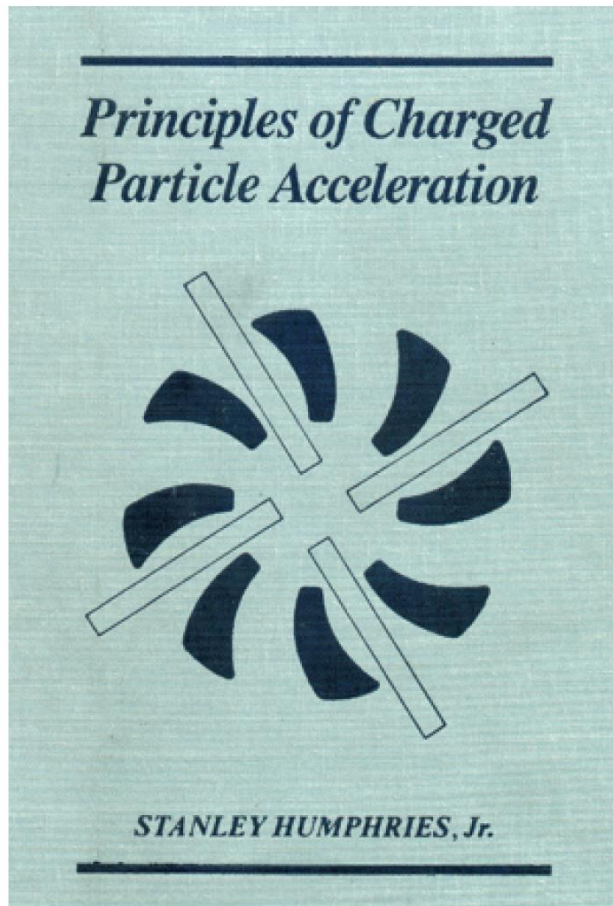
Neutron tube

- **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)





Principles of Charged Particle Acceleration

Stanley Humphries, Jr.

Department of Electrical and Computer Engineering

University of New Mexico
Albuquerque, New Mexico

(Originally published by John Wiley and Sons.
Copyright ©1999 by Stanley Humphries, Jr.
All rights reserved. Reproduction of translation
of any part of this work beyond that permitted by
Section 107 or 108 of the 1976 United States
Copyright Act without the permission of the
copyright owner is unlawful. Requests for
permission or further information should be
addressed to Stanley Humphries, Field Precision,
PO Box 13595, Albuquerque, NM 87192
(humphriess@fieldp.com).

QC787.P3H86 1986 ISBN 0-471-87878-2

Contents

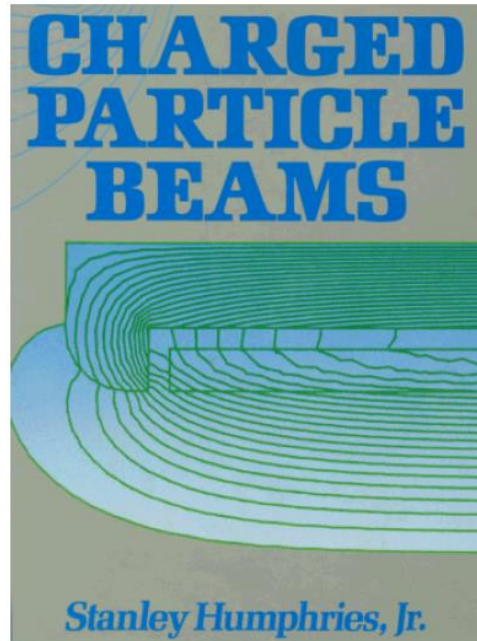
Contents

1. Introduction	1
2. Particle Dynamics	8
2.1. Charged Particle Properties	9
2.2. Newton's Laws of Motion	10
2.3. Kinetic Energy	12
2.4. Galilean Transformations	13
2.5. Postulates of Relativity	15
2.6. Time Dilation	16
2.7. Lorentz Contraction	18
2.8. Lorentz Transformations	20
2.9. Relativistic Formulas	22
2.10. Non-relativistic Approximation for Transverse Motion	23
3. Electric and Magnetic Forces	26
3.1. Forces between Charges and Currents	27
3.2. The Field Description and the Lorentz Force	29
3.3. The Maxwell Equations	33
3.4. Electrostatic and Vector Potentials	34
3.5. Inductive Voltage and Displacement Current	37
3.6. Relativistic Particle Motion in Cylindrical Coordinates	40
3.7. Motion of Charged Particles in a Uniform Magnetic Field	43
4. Steady-State Electric and Magnetic Fields	45
4.1. Static Field Equations with No Sources	46
4.2. Numerical Solutions to the Laplace Equation	53
4.3. Analog Methods to Solve the Laplace Equation	58
4.4. Electrostatic Quadrupole Field	61
4.5. Static Electric Fields with Space Charge	64
4.6. Magnetic Fields in Simple Geometries	67
4.7. Magnetic Potentials	70

5. Modification of Electric and Magnetic Fields by Materials	76
5.1. Dielectrics	77
5.2. Boundary Conditions at Dielectric Surfaces	83
5.3. Ferromagnetic Materials	87
5.4. Static Hysteresis Curve for Ferromagnetic Materials	91
5.5. Magnetic Poles	95
5.6. Energy Density of Electric and Magnetic Fields	97
5.7. Magnetic Circuits	99
5.8. Permanent Magnet Circuits	103
6. Electric and Magnetic Field Lenses	108
6.1. Transverse Beam Control	109
6.2. Paraxial Approximation for Electric and Magnetic Fields	110
6.3. Focusing Properties of Linear Fields	113
6.4. Lens Properties	115
6.5. Electrostatic Aperture Lens	119
6.6. Electrostatic Immersion Lens	121
6.7. Solenoidal Magnetic Lens	125
6.8. Magnetic Sector Lens	127
6.9. Edge Focusing	132
6.10. Magnetic Quadrupole Lens	134
7. Calculation of Particle Orbits in Focusing Fields	137
7.1. Transverse Orbits in a Continuous Linear Focusing Force	138
7.2. Acceptance and P of a Focusing Channel	140
7.3. Betatron Oscillations	145
7.4. Azimuthal Motion of Particles in Cylindrical Beams	151
7.5. The Paraxial Ray Equation	154
7.6. Numerical Solutions of Particle Orbits	157
8. Transfer Matrices and Periodic Focusing Systems	165
8.1. Transfer Matrix of the Quadrupole Lens	166
8.2. Transfer Matrices for Common Optical Elements	168
8.3. Combining Optical Elements	173
8.4. Quadrupole Doublet and Triplet Lenses	176
8.5. Focusing in a Thin-Lens Array	179
8.6. Raising a Matrix to a Power	193
8.7. Quadrupole Focusing Channels	187

Contents

9. Electrostatic Accelerators and Pulsed High Voltage	196	12.8. Waveguides	386
9.1. Resistors, Capacitors, and Inductors	197	12.9. Slow-Wave Structures	393
9.2. High-Voltage Supplies	204	12.10. Dispersion Relationship for the Iris-Loaded Waveguide	399
9.3. Insulation	211	13. Phase Dynamics	408
9.4. Van de Graaff Accelerator	221	13.1. Synchronous Particles and Phase Stability	410
9.5. Vacuum Breakdown	227	13.2. The Phase Equations	414
9.6. LRC Circuits	231	13.3. Approximate Solution to the Phase Equations	418
9.7. Impulse Generators	236	13.4. Compression of Phase Oscillations	424
9.8. Transmission Line Equations in the Time Domain	240	13.5. Longitudinal Dynamics of Ions in a Linear Induction Accelerator	426
9.9. Transmission Lines as Pulsed Power Modulators	246	13.6. Phase Dynamics of Relativistic Particles	430
9.10. Series Transmission Line Circuits	250	14. Radio-Frequency Linear Accelerators	437
9.11. Pulse-Forming Networks	254	14.1. Electron Linear Accelerators	440
9.12. Pulsed Power Compression	258	14.2. Linear Ion Accelerator Configurations	452
9.13. Pulsed Power Switching by Saturable Core Inductors	263	14.3. Coupled Cavity Linear Accelerators	459
9.14. Diagnostics for Pulsed Voltages and Current	267	14.4. Transit-Time Factor, Gap Coefficient and Radial Defocusing	473
10. Linear Induction Accelerators	283	14.5. Vacuum Breakdown in rf Accelerators	478
10.1. Simple Induction Cavity	284	14.6. Radio-Frequency Quadrupole	482
10.2. Time-Dependent Response of Ferromagnetic Materials	291	14.7. Racetrack Microtron	493
10.3. Voltage Multiplication Geometries	300	15. Cyclotrons and Synchrotrons	500
10.4. Core Saturation and Flux Forcing	304	15.1. Principles of the Uniform-Field Cyclotron	504
10.5. Core Reset and Compensation Circuits	307	15.2. Longitudinal Dynamics of the Uniform-Field Cyclotron	509
10.6. Induction Cavity Design: Field Stress and Average Gradient	313	15.3. Focusing by Azimuthally Varying Fields (AVF)	513
10.7. Coreless Induction Accelerators	317	15.4. The Synchrocyclotron and the AVF Cyclotron	523
11. Betatrons	326	15.5. Principles of the Synchrotron	531
11.1. Principles of the Betatron	327	15.6. Longitudinal Dynamics of Synchrotrons	544
11.2. Equilibrium of the Main Betatron Orbit	332	15.7. Strong Focusing	550
11.3. Motion of the Instantaneous Circle	334	Bibliography	556
11.4. Reversible Compression of Transverse Particle Orbits	336	Index	
11.5. Betatron Oscillations	342		
11.6. Electron Injection and Extraction	343		
11.7. Betatron Magnets and Acceleration Cycles	348		
12. Resonant Cavities and Waveguides	356		
12.1. Complex Exponential Notation and Impedance	357		
12.2. Lumped Circuit Element Analogy for a Resonant Cavity	362		
12.3. Resonant Modes of a Cylindrical Cavity	367		
12.4. Properties of the Cylindrical Resonant Cavity	371		
12.5. Power Exchange with Resonant Cavities	376		
12.6. Transmission Lines in the Frequency Domain	380		
12.7. Transmission Line Treatment of the Resonant Cavity	384		



Charged Particle Beams

Stanley Humphries, Jr.

Department of Electrical and Computer
Engineering
University of New Mexico
Albuquerque, New Mexico

Originally published in 1990 by John Wiley and Sons (QC786.H86 1990, ISBN 0-471-60014-8). Copyright ©2002 by Stanley Humphries, Jr. All rights reserved. Reproduction of translation of any part of this work beyond that permitted by Section 107 or 108 of the 1976 United States Copyright Act without the permission of the copyright owner is unlawful. Requests for permission or further information should be addressed to Field Precision, Attn: Stanley Humphries, PO Box 13595, Albuquerque, NM 87192.

Contents

Contents

1. Introduction	1	3. Introduction to beam emittance	79
1.1. Charged particle beams	1	3.1. Laminar and non-laminar beams	80
1.2. Methods and organization	6	3.2. Emittance	87
1.3. Single-particle dynamics	9	3.3. Measurement of emittance	93
2. Phase space description of charged particle beams	20	3.4. Coupled beam distributions, longitudinal emittance, normalized emittance, and brightness	101
2.1. Particle trajectories in phase space	22	3.5. Emittance force	107
2.2. Distribution functions	28	3.6. Non-laminar beams in drift regions	109
2.3. Numerical calculation of particle orbits with beam-generated forces	32	3.7. Non-laminar beams in linear focusing systems	113
2.4. Conservation of phase space volume	36	3.8. Compression and expansion of non-laminar beams	128
2.5. Density and average velocity	46	4. Beam emittance - advanced topics	133
2.6. Maxwell distribution	49	4.1. Linear transformations of elliptical distributions	134
2.7. Collisionless Boltzmann equation	52	4.2. Transport parameters from particle orbit theory	145
2.8. Charge and current density	56	4.3. Beam matching	150
2.9. Computer simulations	60	4.4. Non-linear focusing systems	157
2.10. Moment equations	65	4.5. Emittance in storage rings	167
2.11. Pressure force in collisionless distributions	71	4.6. Beam cooling	174
2.12. Relativistic particle distributions	76	5. Introduction to beam-generated forces	187
		5.1. Electric and magnetic fields of beams	188
		5.2. One-dimensional Child law for non-relativistic particles	195
		5.3. Longitudinal transport limits for a magnetically-confined electron beams	204
		5.4. Space-charge expansion of a drifting beam	211
		5.5. Transverse forces in relativistic beams	216

Contents

6. Beam-generated forces - advanced topics	224		
6.1. Space-charge-limited flow with an initial injection energy	225		
6.2. Space-charge-limited flow from a thermionic cathode	227		
6.3. Space-charge-limited flow in spherical geometry	232		
6.4. Bipolar flow	239		
6.5. Space-charge-limited flow of relativistic electrons	242		
6.6. One-dimensional self-consistent equilibrium	246		
6.7. KV distribution	256		
7. Electron and ion guns	262		
7.1. Pierce method for gun design	263		
7.2. Medium perveance guns	271		
7.3. High perveance guns and ray tracing codes	277		
7.4. High current electron sources	283		
7.5. Extraction of ions at a free plasma boundary	289		
7.6. Plasma ion sources	300		
7.7. Charged-particle extraction from grid-controlled plasmas	315		
7.8. Ion extractors	322		
8. High power pulsed electron and ion diodes	328		
8.1. Motion of electrons in crossed electric and magnetic fields	329		
8.2. Pinched electron beam diodes	337		
8.3. Electron diodes with strong applied magnetic fields	346		
8.4. Magnetic insulation of high power transmission lines	351		
8.5. Plasma erosion	356		
8.6. Reflex triode	364		
8.7. Low-impedance reflex triode	370		
8.8. Magnetically-insulated ion diode	377		
		8.9. Ion flow enhancement in magnetically-insulated diodes	388
		9. Paraxial beam transport with space-charge	395
		9.1. Envelope equation for sheet beams	396
		9.2. Paraxial ray equation	400
		9.3. Envelope equation in a quadrupole lens array	407
		9.4. Limiting current for paraxial beams	412
		9.5. Multi-beam ion transport	419
		9.6. Longitudinal space-charge limits in RF accelerators and induction linacs	423
		10. High current electron beam transport under vacuum	432
		10.1. Motion of electrons through a magnetic cusp	433
		10.2. Propagation of beams from an immersed cathode	439
		10.3. Brillouin equilibrium of a cylindrical electron beam	445
		10.4. Interaction of electrons with matter	451
		10.5. Foil focusing of relativistic electron beams	457
		10.6. Wall-charge and return-current for a beam in a pipe	470
		10.7. Drifts of electron beams in a solenoidal field	477
		10.8. Guiding electron beams with solenoidal fields	482
		10.9. Electron beam transport in magnetic cusps	490
		11. Ion beam neutralization	501
		11.1. Neutralization by comoving electrons	502
		11.2. Transverse neutralization	511
		11.3. Current neutralization in vacuum	517
		11.4. Focal limits for neutralized ion beams	522
		11.5. Acceleration and transport of neutralized ion beams	528

Contents

12. Electron beams in plasmas	535
12.1. Space-charge neutralization in equilibrium plasmas	536
12.2. Oscillations of an un-magnetized plasma	540
12.3. Oscillations of a neutralized electron beam	546
12.4. Injection of a pulsed electron beam into a plasma	552
12.5. Magnetic skin depth	563
12.6. Return current in a resistive plasma	569
12.7. Limiting current for neutralized electron beams	577
12.8. Bennett equilibrium	583
12.9. Propagation in low-density plasmas and weakly-ionized gases	587
13. Transverse instabilities	592
13.1. Instabilities of space-charge-dominated beams in periodic focusing systems	594
13.2. Betatron waves on a filamentary beam	610
13.3. Frictional forces and phase mixing	615
13.4. Transverse resonant modes	622
13.5. Beam breakup instability	631
13.6. Transverse resistive wall instability	640
13.7. Hose instability of an electron beam in an ion channel	645
13.8. Resistive hose instability	655
13.9. Filamentation instability of neutralized electron beams	664
14. Longitudinal instabilities	674
14.1. Two-stream instability	675
14.2. Beam-generated axial electric fields	687
14.3. Negative mass instability	697
14.4. Longitudinal resistive wall instability	704

15. Generation of radiation with electron beams	720
15.1. Inverse diode	722
15.2. Driving resonant cavities with electron beams	736
15.3. Longitudinal beam bunching	749
15.4. Klystron	762
15.5. Traveling wave tube	772
15.6. Magnetron	781
15.7. Mechanism of the free-electron laser	796
15.8. Phase dynamics in the free-electron laser	803

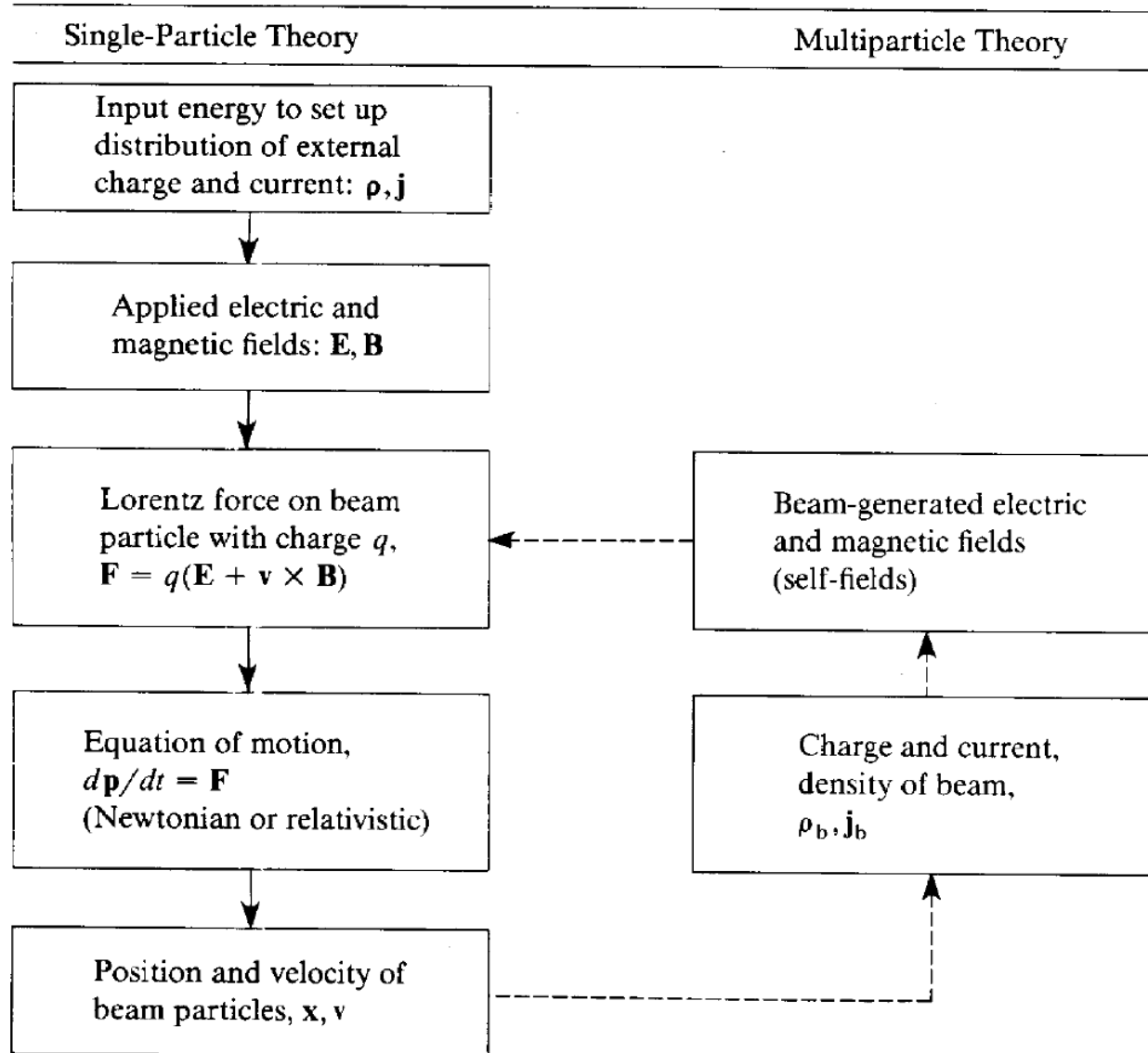
Bibliography

Index

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 semiconductor 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

