Radiation Source Technology

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Charged particle properties

Particle	Charge (coulomb)	Mass (kg)	Rest Energy (MeV)	A	Z	Z^*
Electron (β particle)	-1.60×10^{-19}	9.11×10^{-31}	$\boxed{0.511}$	—	—	—
Proton	$+1.60 \times 10^{-19}$	1.67×10^{-27}	$\boxed{938}$	1	1	1
Deuteron	$+1.60 \times 10^{-19}$	3.34×10^{-27}	1875	2	1	1
Triton	$+1.60 \times 10^{-19}$	5.00×10^{-27}	2809	3	1	1
He^{+}	$+1.60 \times 10^{-19}$	6.64×10^{-27}	3728	4	2	1
He^{++} (α particle)	$+3.20 \times 10^{-19}$	6.64×10^{-27}	3728	4	2	2
C^{+}	$+1.6 \times 10^{-19}$	1.99×10^{-26}	1.12×10^{4}	12	6	1
U^{+}	$+1.6 \times 10^{-19}$	3.95×10^{-25}	2.22×10^{5}	238	92	1

1 eV = 1.6×10^{-19} J = 1,240 nm = 241.8 THz

Particle momentum and energy

- The special theory of relativity states that the inertia of a particle observed in a frame of reference depends on the magnitude of its speed in that frame.

$$\gamma = \frac{1}{\sqrt{1-(v/c)^2}} = \frac{1}{\sqrt{1-\beta^2}}$$

Lorentz factor

- The inertia of a particle is proportional to γ. The apparent mass is $m = \gamma m_0$.
- The particle momentum, a vector quantity, equals $\boldsymbol{p} = \gamma m_0 \boldsymbol{v}$.
- The equation of motion:

$$\frac{d\boldsymbol{p}}{dt} = \frac{d(\gamma m_0 \boldsymbol{v})}{dt} = \boldsymbol{F}$$

- The kinetic energy equals the total energy minus the rest energy:

$$E = \gamma m_0 c^2 \qquad\qquad T = (\gamma - 1) m_0 c^2$$

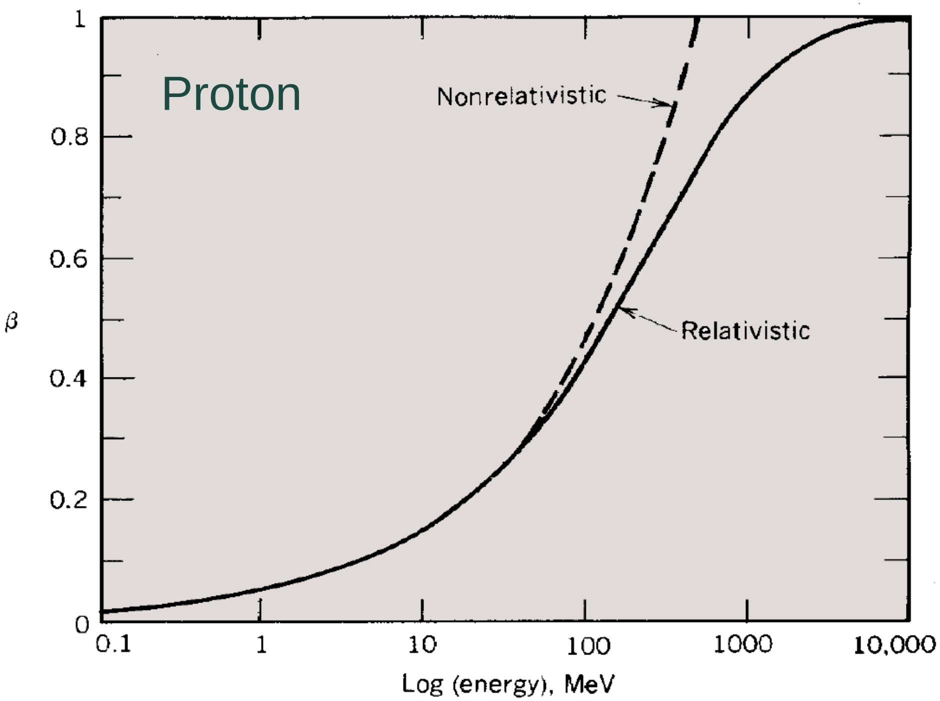
- Newtonian dynamics describes the motion of low-energy particles when $T \ll m_0 c^2$.

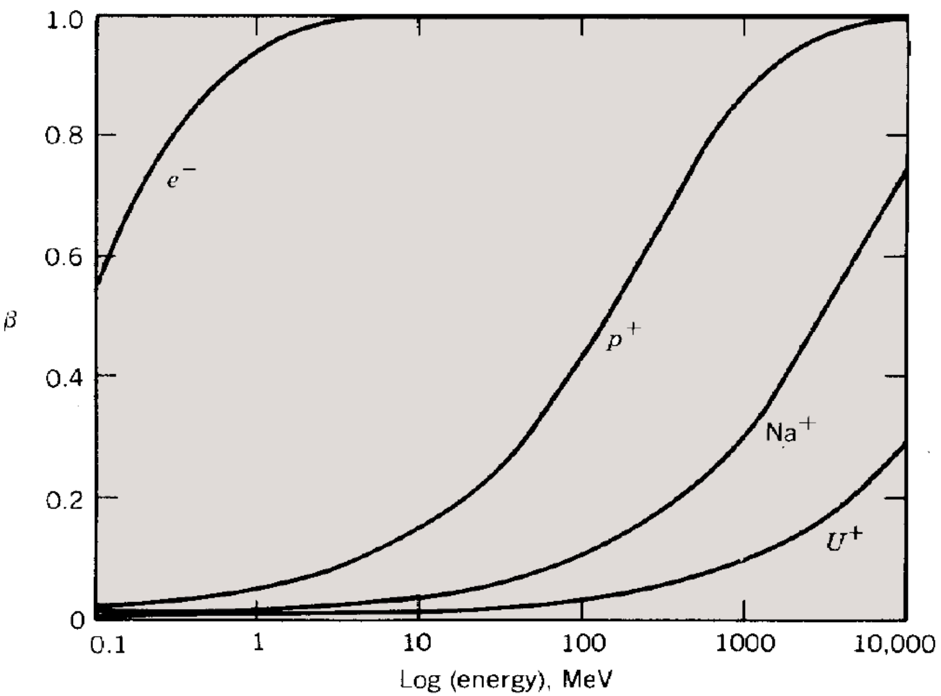
$$T = \frac{1}{2} m_0 v^2$$

$$(1+x)^{-1/2} \approx 1 - \frac{1}{2}x + \cdots$$

β for particles as a function of kinetic energy

$$\beta = \frac{v}{c}$$





Maxwell's equations

$$\boxed{\begin{gathered}\boldsymbol{\nabla}\cdot\boldsymbol{E}=\rho/\epsilon_0\\ \boldsymbol{\nabla}\cdot\boldsymbol{B}=0\\ \boldsymbol{\nabla}\times\boldsymbol{E}=-\frac{\partial\boldsymbol{B}}{\partial t}\\ \boldsymbol{\nabla}\times\boldsymbol{B}=\mu_0\epsilon_0\frac{\partial\boldsymbol{E}}{\partial t}+\mu_0\boldsymbol{J}\end{gathered}}$$

- Gauss's law
- Gauss's law for magnetism
- Faraday's law of induction
- Ampere's law with Maxwell's addition

$$\boxed{\begin{gathered}\rho=e(Zn_i-n_e)\\ \boldsymbol{J}=e(Zn_i\boldsymbol{u}_i-n_e\boldsymbol{u}_e)\end{gathered}}$$

- Constitutive relation

$$\boxed{\frac{\partial\rho}{\partial t}+\boldsymbol{\nabla}\cdot\boldsymbol{J}=0}$$

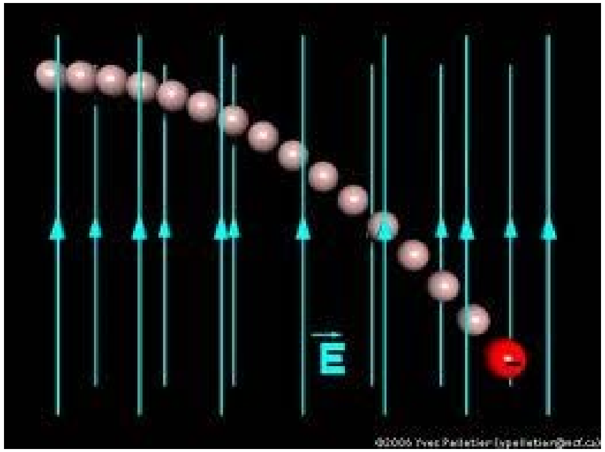
- Charge continuity equation

Motions in uniform electric field

- Equation of motion of a charged particle in fields

$$m\frac{d\boldsymbol{v}}{dt} = q[\boldsymbol{E}(\boldsymbol{r},t) + \boldsymbol{v} \times \boldsymbol{B}(\boldsymbol{r},t)], \qquad \frac{d\boldsymbol{r}}{dt} = \boldsymbol{v}(t)$$

- Motion in constant electric field



✓ For a constant electric field $\boldsymbol{E} = \boldsymbol{E_0}$ with $\boldsymbol{B} = 0$,

$$\boldsymbol{r}(t) = \boldsymbol{r_0} + \boldsymbol{v_0}t + \frac{q\boldsymbol{E_0}}{2m}t^2$$

✓ Electrons are easily accelerated by electric field due to their smaller mass than ions.

✓ Electrons (Ions) move against (along) the electric field direction.

✓ The charged particles get kinetic energies.

Motions in uniform magnetic field

- Motion in constant magnetic field

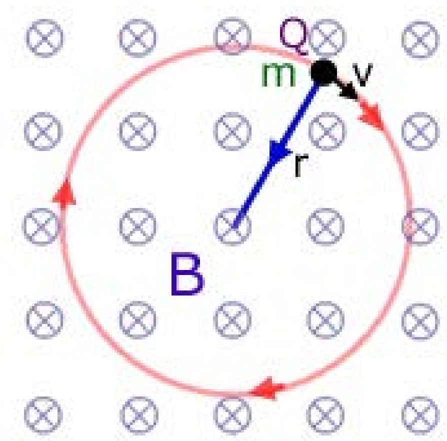
$$m\frac{d\boldsymbol{v}}{dt} = q\boldsymbol{v} \times \boldsymbol{B}$$

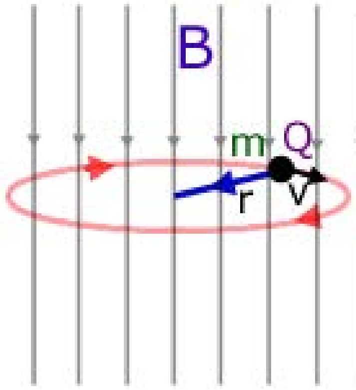
- For a constant magnetic field $\boldsymbol{B} = B_0\boldsymbol{z}$ with $\boldsymbol{E} = 0$,

$$m\frac{dv_x}{dt} = qB_0v_y$$

$$m\frac{dv_y}{dt} = -qB_0v_x$$

$$m\frac{dv_z}{dt} = 0$$





- Cyclotron (gyration) frequency

$$\frac{d^2v_x}{dt^2} = -\omega_c^2 v_x$$

$$\boxed{\omega_c = \frac{|q|B_0}{m}}$$

Motions in uniform magnetic field

- Particle velocity

$$v_x = v_\perp \cos(\omega_c t + \phi_0)$$
$$v_y = -v_\perp \sin(\omega_c t + \phi_0)$$
$$v_z = v_{z0}$$

- Particle position

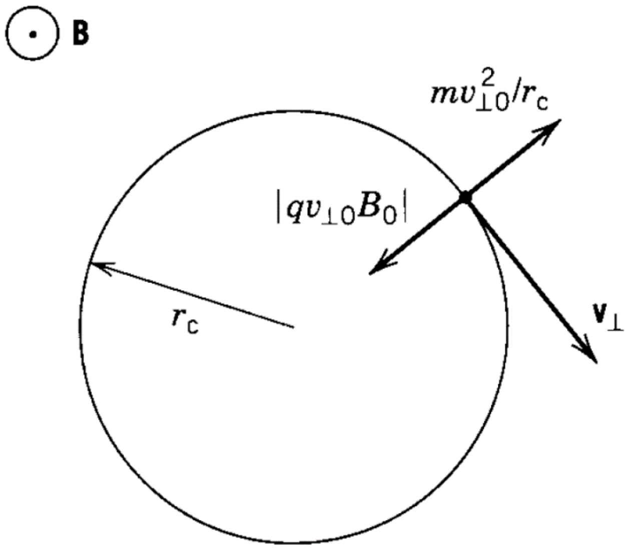
$$x = r_c \sin(\omega_c t + \phi_0) + (x_0 - r_c \sin\phi_0)$$
$$y = r_c \cos(\omega_c t + \phi_0) + (y_0 - r_c \cos\phi_0)$$
$$z = z_0 + v_{z0} t$$

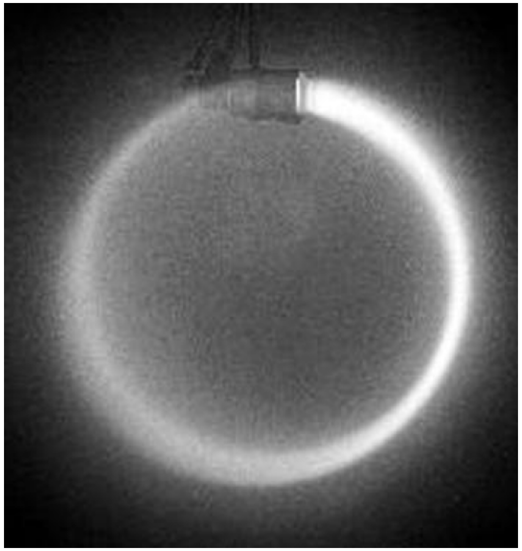
- Guiding center

$$(x_0, y_0, z_0 + v_{z0} t\ )$$

- Larmor (gyration) radius

$$\boxed{r_c = \frac{v_\perp}{\omega_c} = \frac{m v_\perp}{|q| B_0}}$$





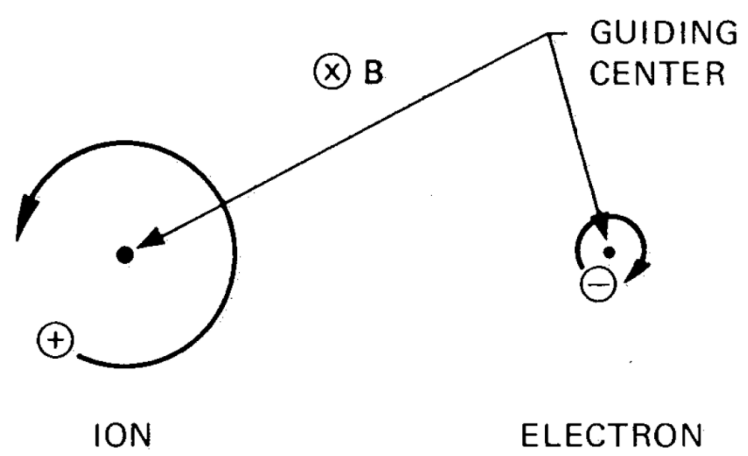
Gyro-frequency and radius

- The direction of gyration is always such that the magnetic field generated by the charged particle is opposite to the externally imposed field. → diamagnetic

- For electrons

$$f_{ce} = 2.80 \times 10^6\ B_0\ [\mathrm{Hz}] \quad (B_0 \text{ in gauss})$$

$$r_{ce} = \frac{3.37\sqrt{E}}{B_0}\ [\mathrm{cm}] \quad (E \text{ in volts})$$



- For singly charged ions

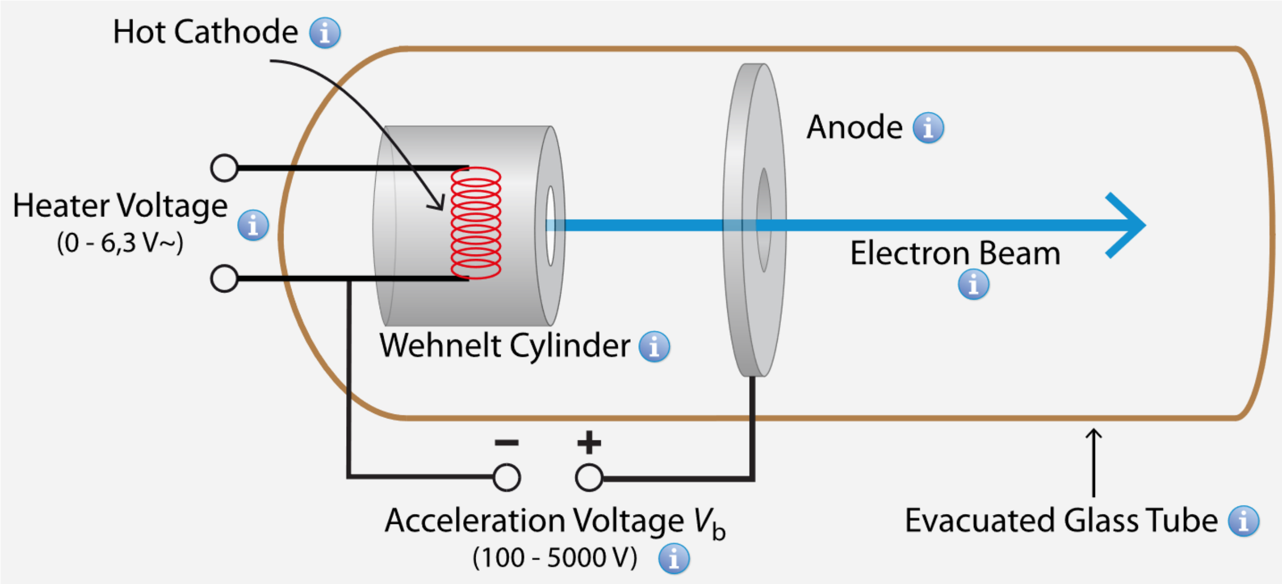
$$f_{ci} = 1.52 \times 10^3\ B_0/M_A\ [\mathrm{Hz}] \quad (B_0 \text{ in gauss})$$

$$r_{ci} = \frac{144\sqrt{EM_A}}{B_0}\ [\mathrm{cm}] \quad (E \text{ in volts}, M_A \text{ in amu})$$

- Energy gain?

Electron beam sources

- Typical schematic diagram of electron beam sources

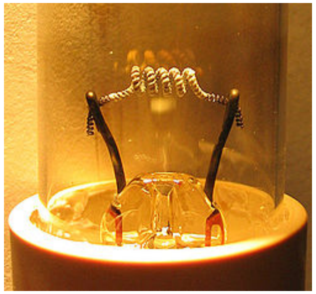


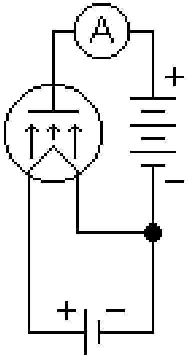
- Electron emission from solid
  - Thermionic emission
  - Field emission
  - Photoelectric emission
  - Secondary electron emission by ion or electron impact
  - Auger electron emission

Thermionic emission

- Thermionic emission (hot emission) is the heat-induced flow of charge carriers from a surface or over a potential-energy barrier.
- This occurs because the thermal energy given to the carrier overcomes the binding potential, also known as work function of the metal.
- Richardson-Dushman law (1901)

$$J = AT^2 \exp\left(-\frac{W}{kT}\right)$$



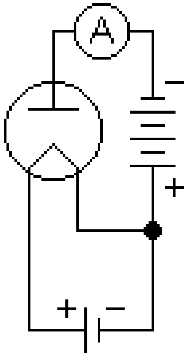


Electron flow

- Schottky effect: field-enhanced thermionic emission
- Work function: the minimum energy (usually measured in electron volts) needed to remove an electron from a solid to a point immediately outside the solid surface (or energy needed to move an electron from the Fermi level into vacuum)

Elements	Work function (eV)
C	~ 5
Al	4.06 ~ 4.26
Fe	4.67 ~ 4.81
Ni	5.04 ~ 5.35
Cu	4.53 ~ 5.1
Mo	4.36 ~ 4.95
Ba	2.52 ~ 2.7
W	4.32 ~ 5.22

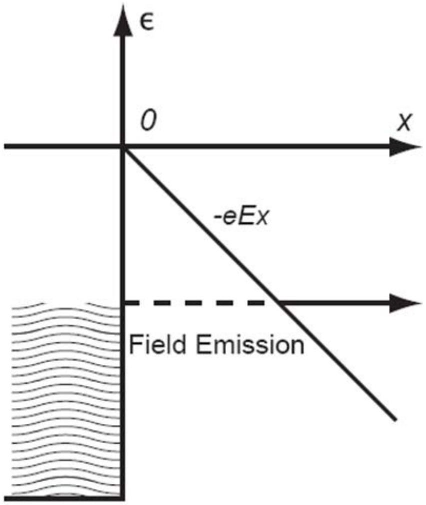
$W/ThO_2 \sim 2.5$



No current

Field emission

- Field emission (cold emission) involves the extraction of electrons from a solid by tunneling through the surface potential barrier. The emitted current depends directly on the local electric field at the emitting surface, E, and on its work function, W.



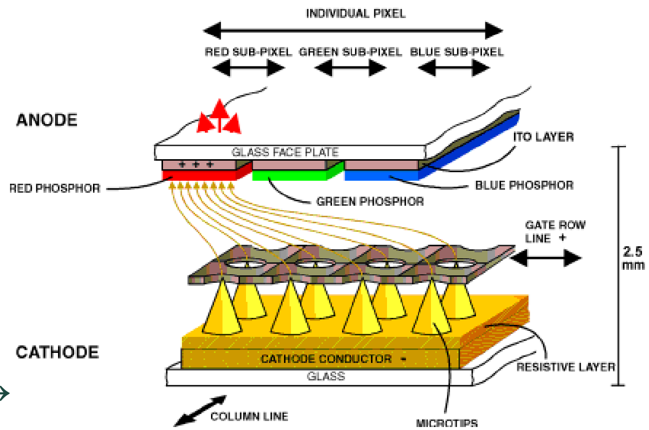
- Fowler-Nordheim model

$$J = C\frac{E^2}{W}\exp\left(-D\frac{W^{3/2}}{E}\right)$$

- A small variation of the shape or surrounding of the emitter (geometric field enhancement) and/or the chemical state of the surface has a strong impact on the emitted current.

- It is most commonly an undesirable primary source of vacuum breakdown and electrical discharge phenomena.

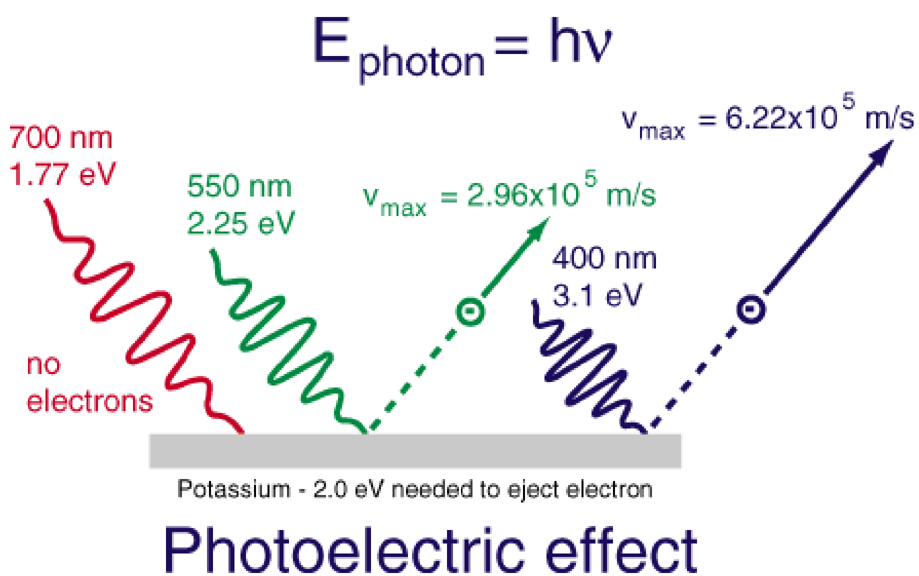
Field emission display →

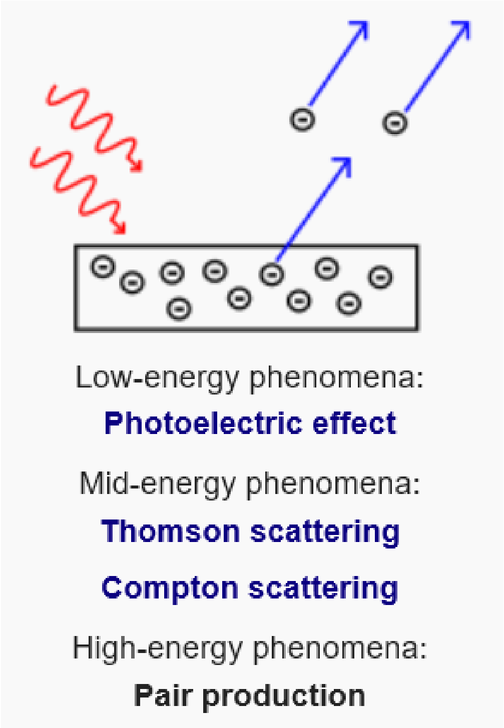


Photoelectric emission

- In the photoelectric effect, electrons are emitted from matter as a consequence of their absorption of energy from electromagnetic radiation of very short wavelength, such as visible or ultraviolet light.
- First observed by Heinrich Hertz in 1887
- Einstein's explanation (1905)

$$K_{max} = h\nu - W$$



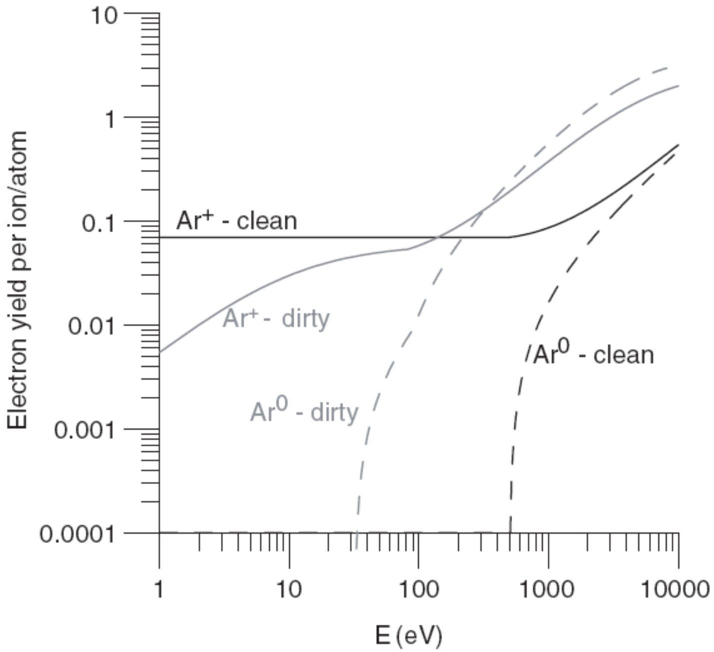


Secondary electron emission by ion impact

- The field of ion approaching a surface to within a distance of atomic dimensions transforms a potential well on the surface into a potential barrier. The barrier is low and narrow because the field is tremendously strong. An electron from the metal immediately tunnels into the ion and neutralizes it.
- If the energy released is greater than W, it may be spent on ejecting another electron.
- SEE coefficient by ion impact

$$\gamma_i = \frac{No.of\ emitted\ electrons}{No.of\ incident\ ions}$$

- γ_i depends greatly on the kinetic energy of ions impinging on the solid surface.
- This process plays an important role in breakdown process for DC discharge.

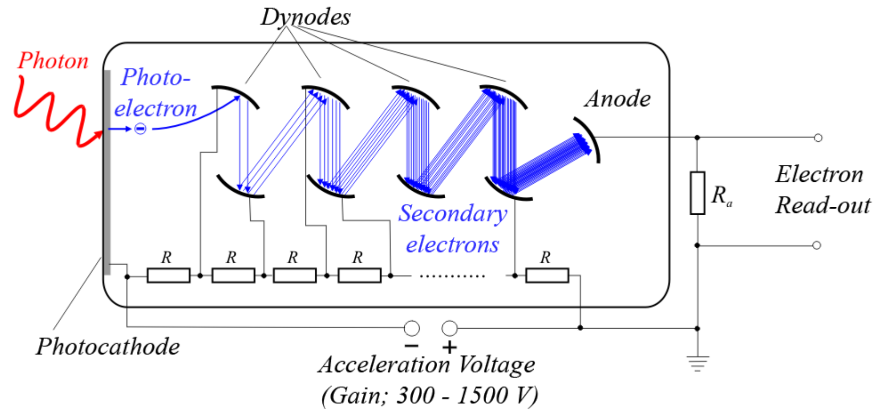


Secondary electron emission by electron impact

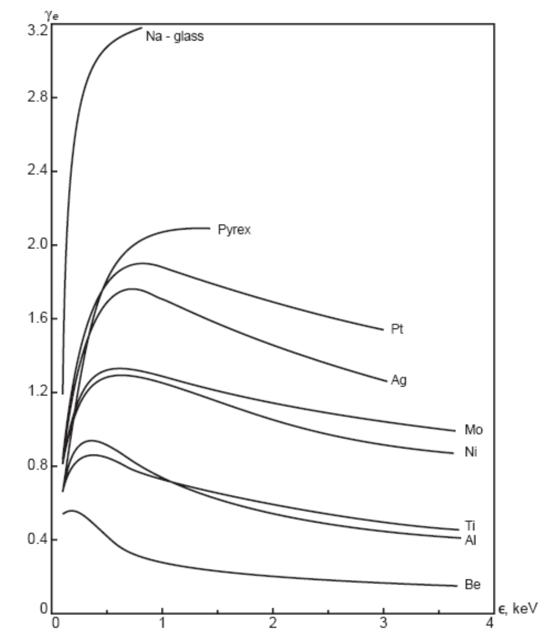
- The electron emission from a solid surface induced by electron impact.
- SEE coefficient by electron impact

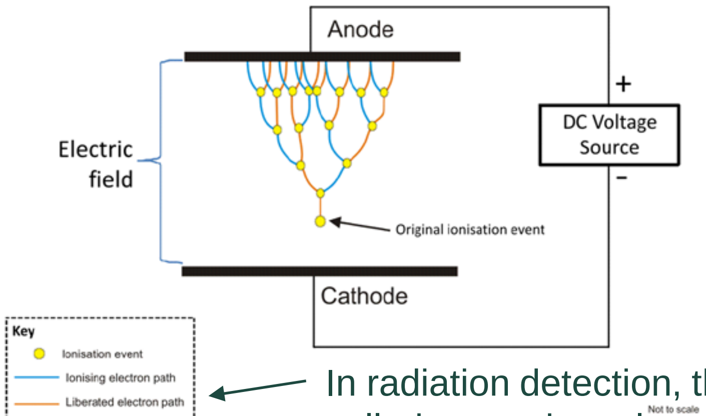
$$\gamma_e = \frac{No.\,of\ emitted\ electrons}{No.\,of\ incident\ electrons}$$

- Photomultiplier tube (PMT)



- This process plays an important role in vacuum breakdown by high frequency fields: the oscillating electron strikes the gap walls alternatingly, on after the other.

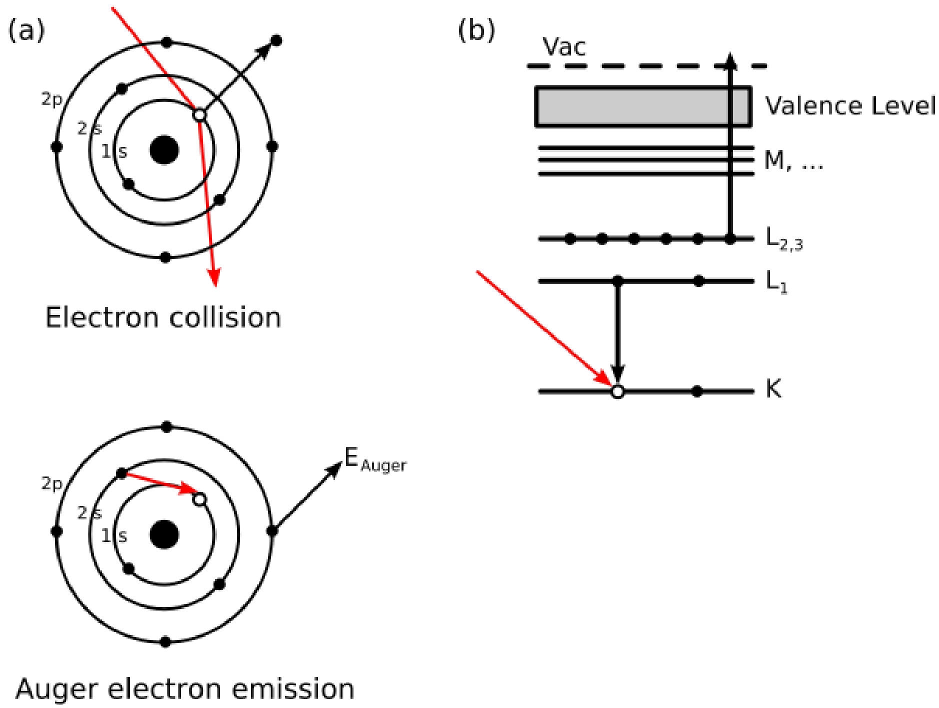




In radiation detection, these electrons are also called secondary electrons.

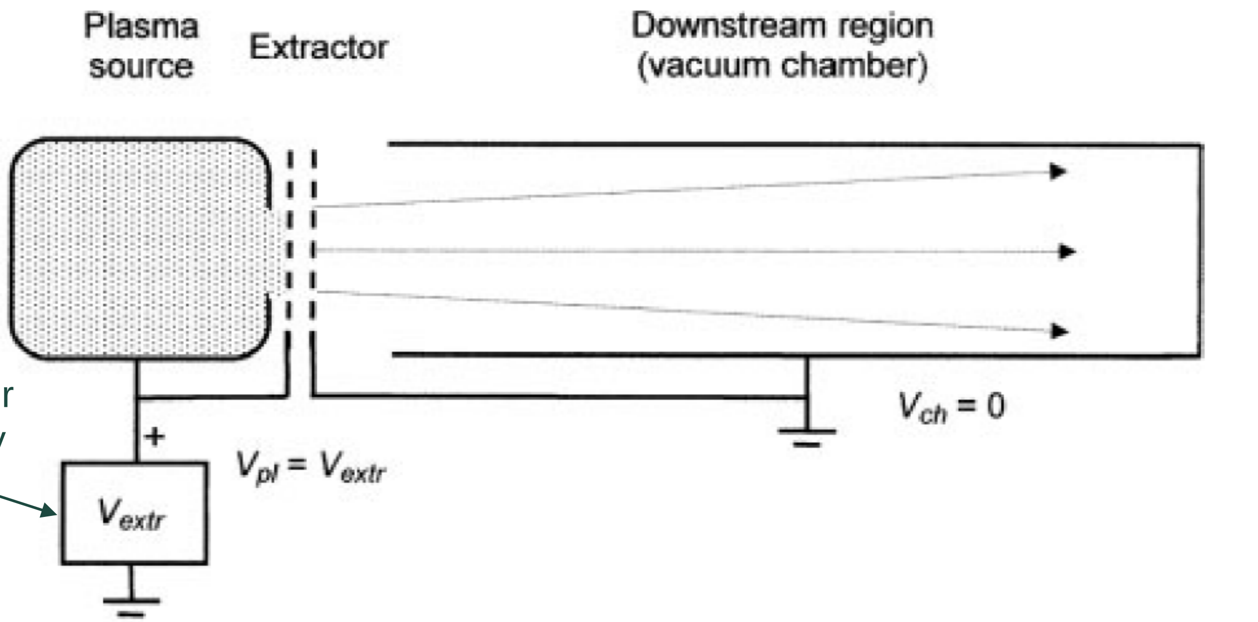
Auger electron emission

- The Auger effect is a physical phenomenon in which the transition of an electron in an atom filling in an inner-shell vacancy causes the emission of another electron.
- When a core electron is removed, leaving a vacancy, an electron from a higher energy level may fall into the vacancy, resulting in a release of energy. This energy can be transferred to another electron, which is ejected from the atom.



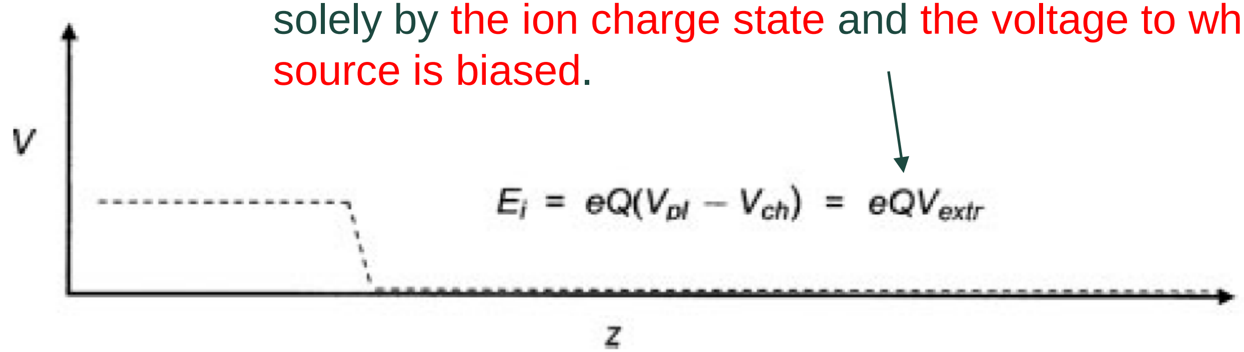
Ion beam sources

- Most ion sources consist of a plasma source and an extractor



Extractor supply or accelerator supply

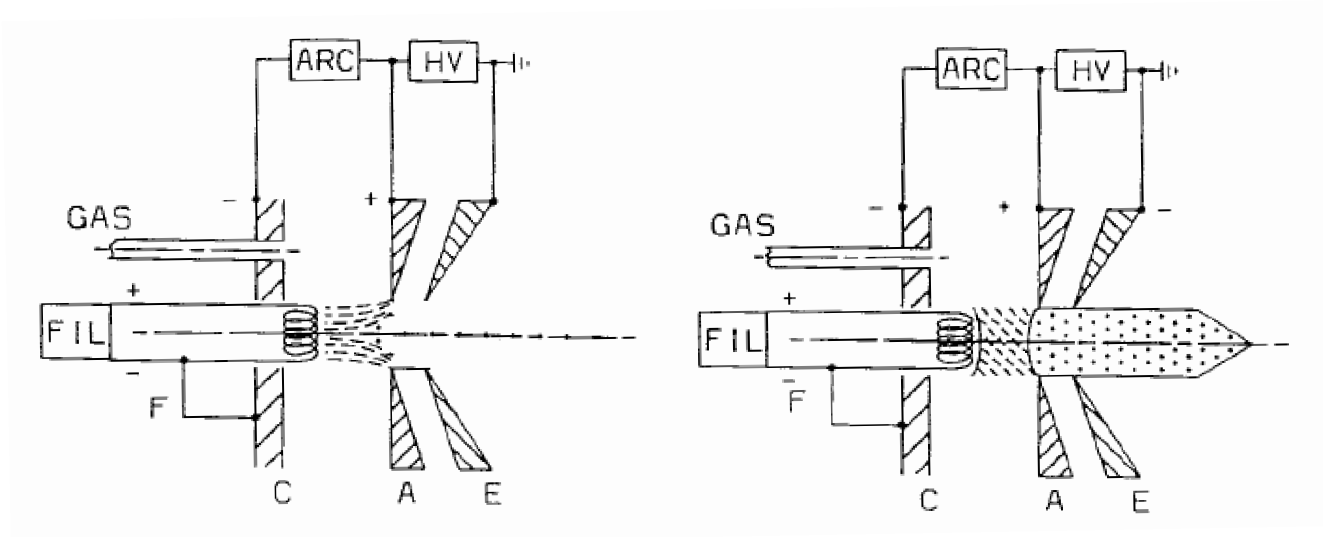
The ion beam energy (energy of the ions in the beam) is determined solely by the ion charge state and the voltage to which the plasma source is biased.



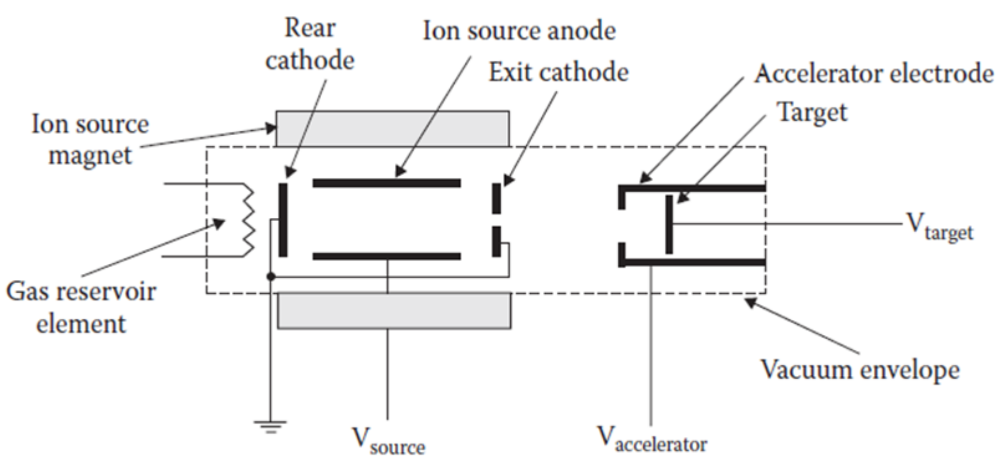
$$E_i = eQ(V_{pl} - V_{ch}) = eQV_{extr}$$

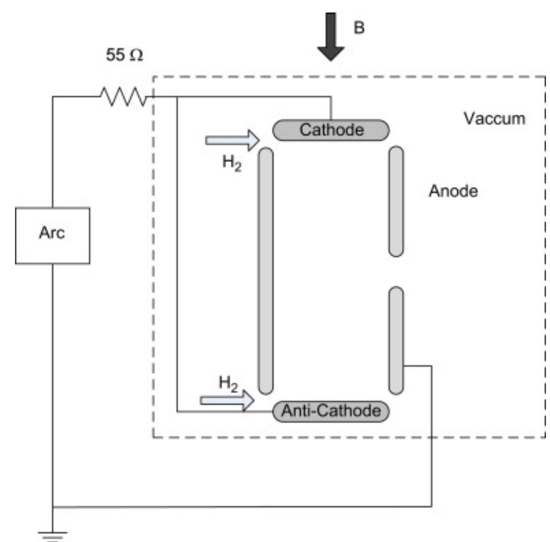
Various ion sources

- DC sources (glow or arc)



- DC sources (glow or arc) with magnetic field





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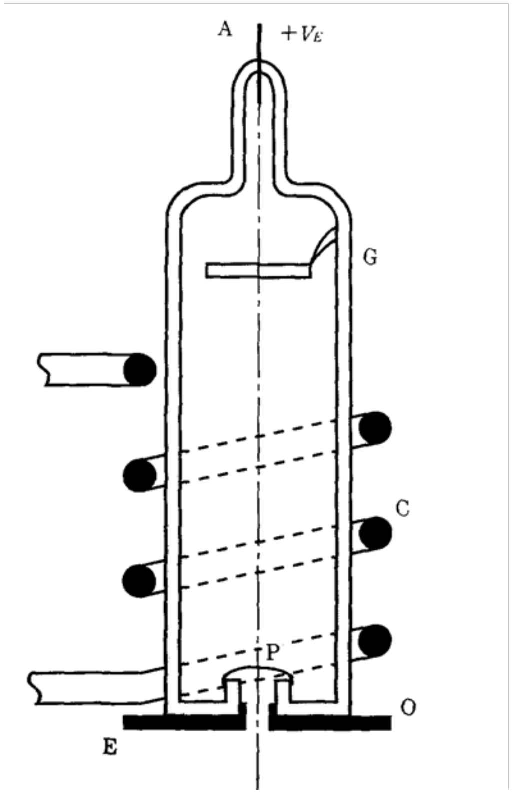
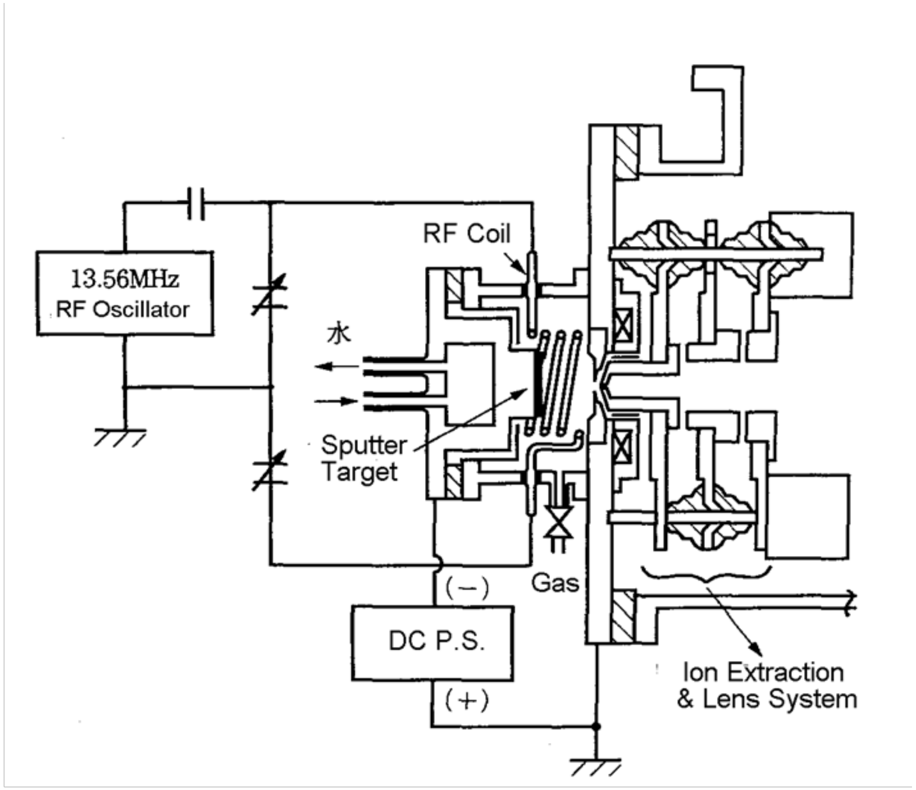
Various ion sources

- RF sources (13.56 MHz is widely used)



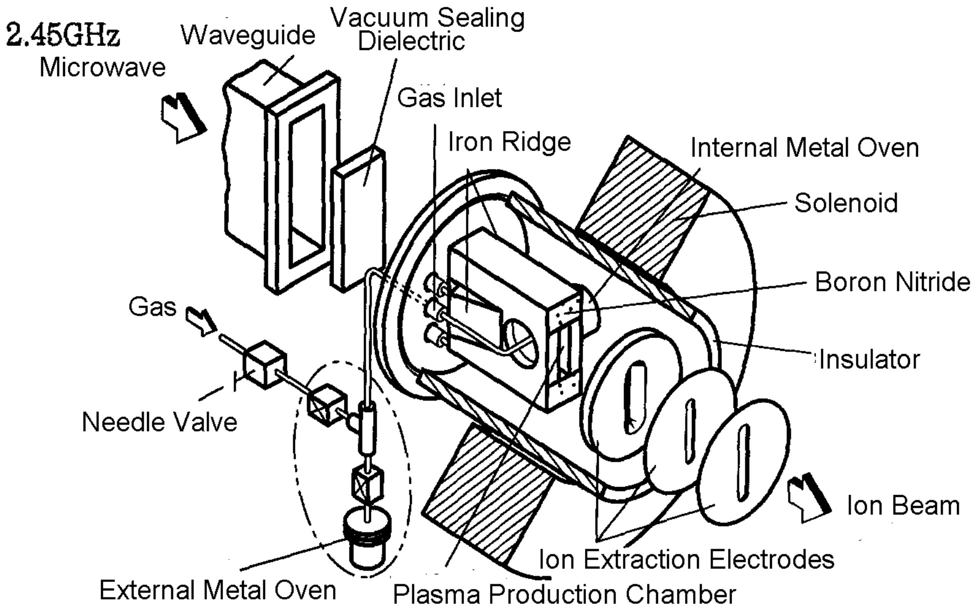
External antenna

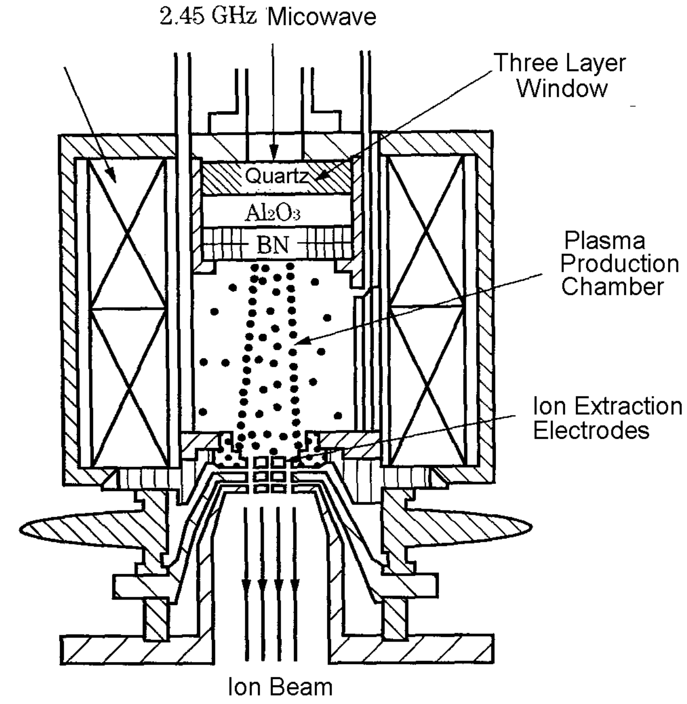


Internal antenna

Various ion sources

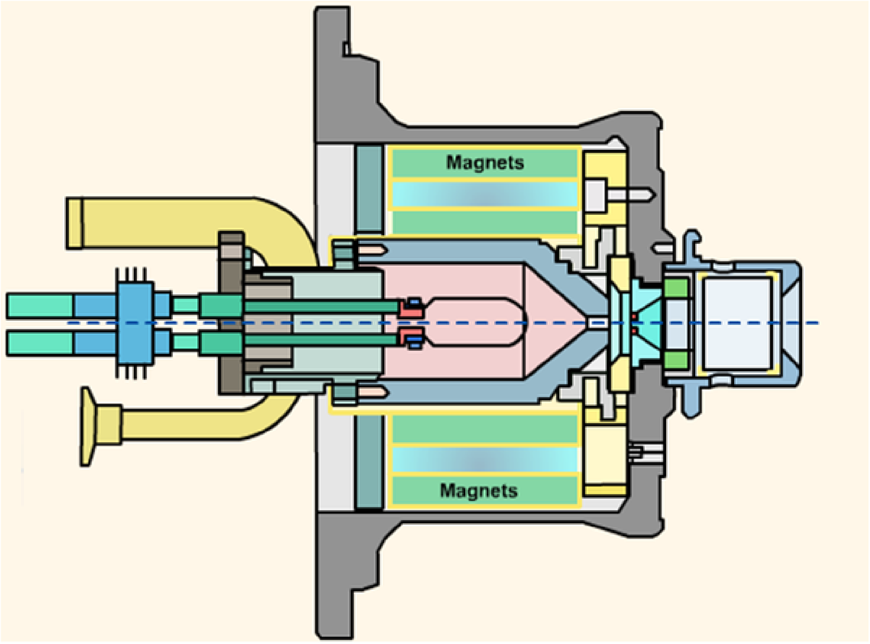
- MW sources (2.45 GHz is widely used)





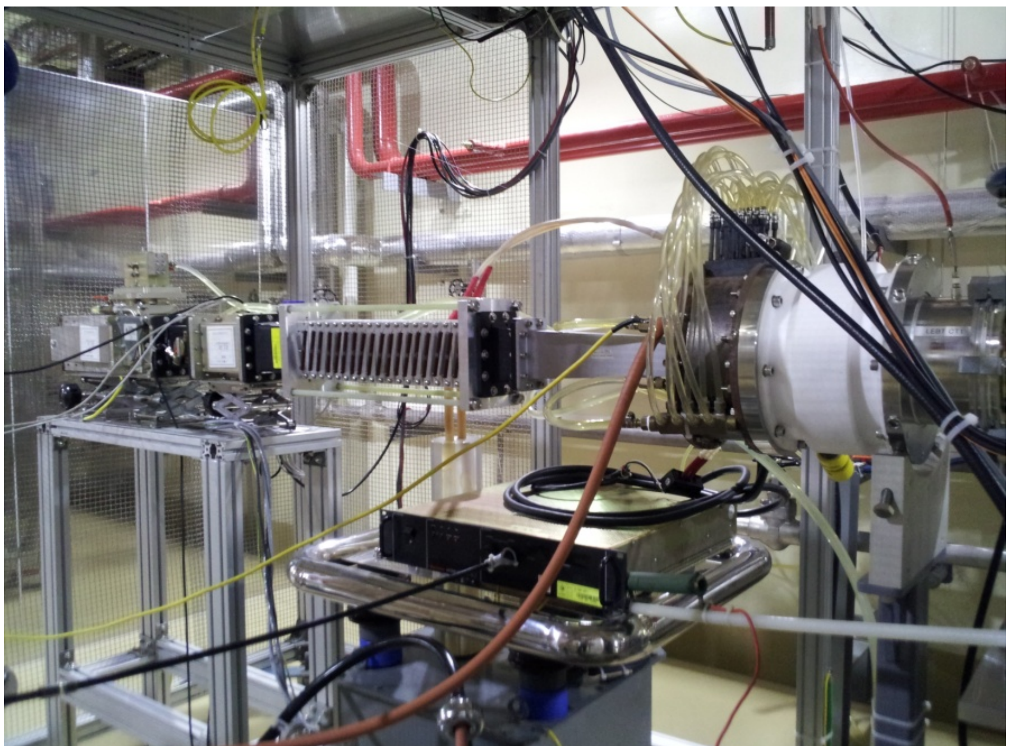
Example of ion sources

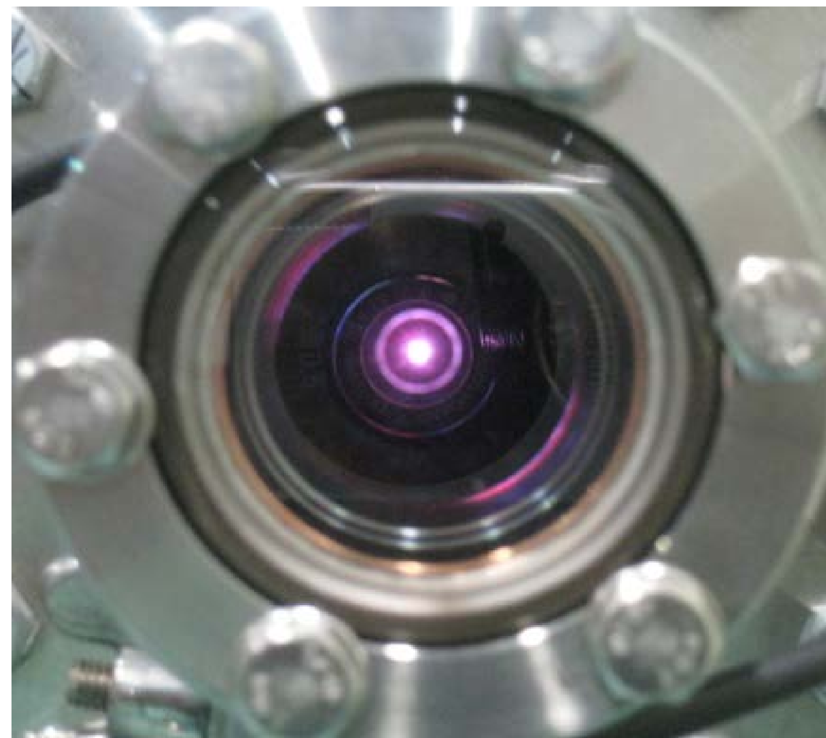
- LHC (Large Hadron Collider): Duoplasmatron



Example of ion sources

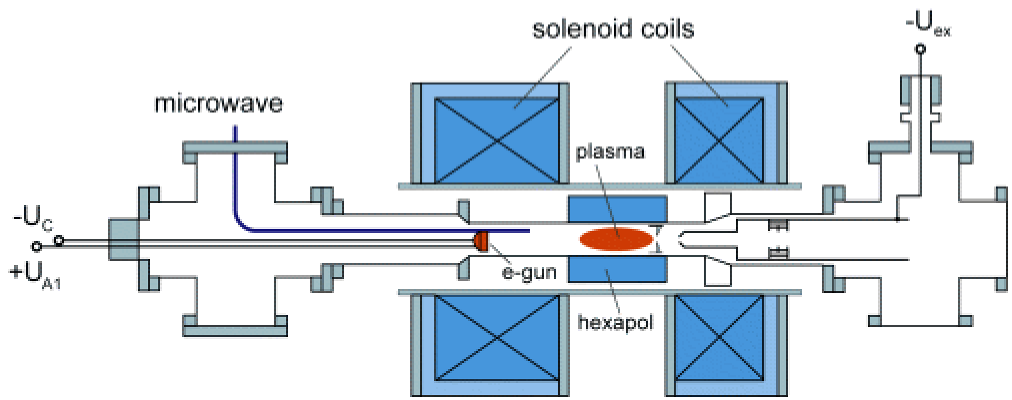
- KOMAC (Korea Multipurpose Accelerator Complex): MW ion source
  - Hydrogen discharge using 2.45 GHz magnetron
  - Pulsed proton beam extraction: 50 keV, 20 mA, 2 ms pulse beam

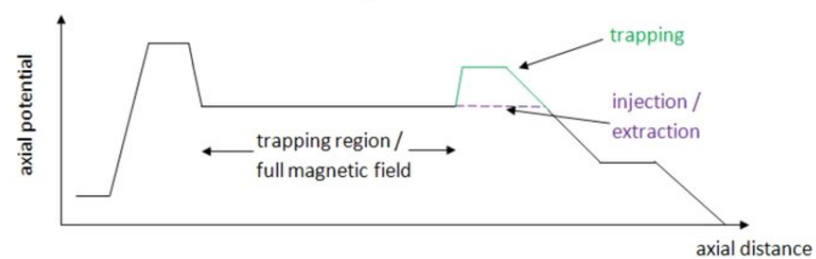


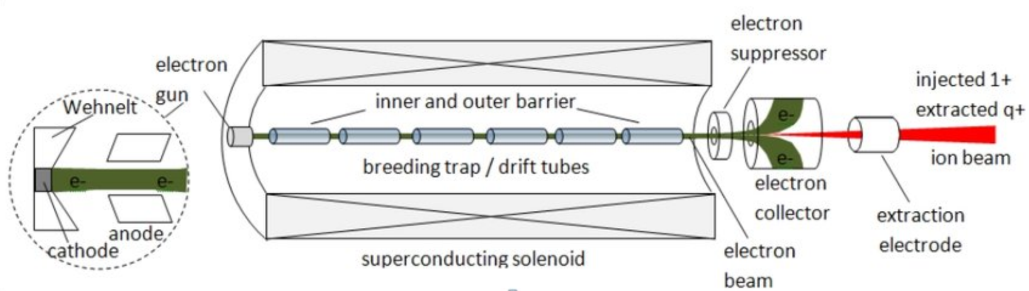


Example of ion sources

- Highly charged ion sources: Superconducting ECR, EBIS



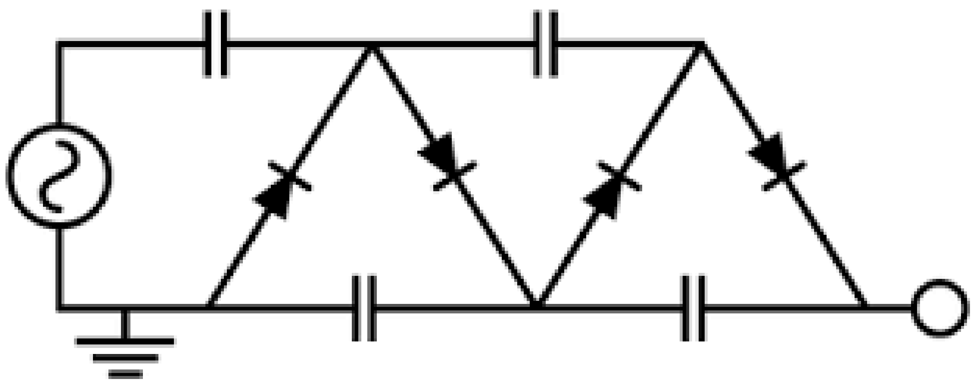


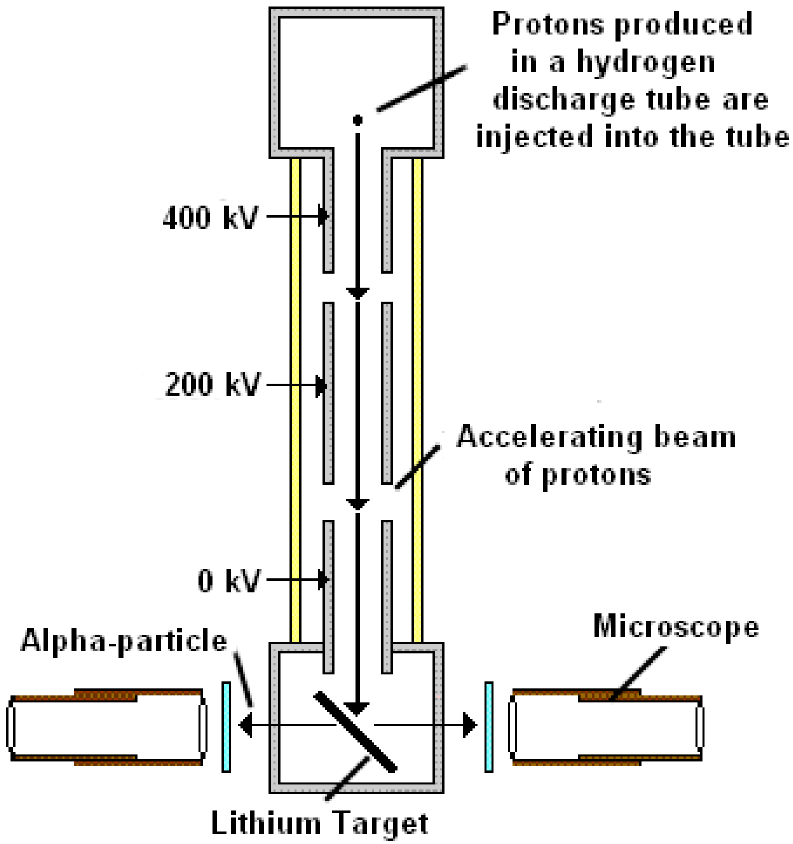


Cockcroft-Walton's voltage multiplier

- The first nuclear disintegration by nuclear projectiles artificially produced in a man-made accelerator (1932).

$$^{7}\text{Li} + {}^{1}\text{H} \rightarrow {}^{4}\text{He} + {}^{4}\text{He}\ (+17.3\ \text{MeV})$$



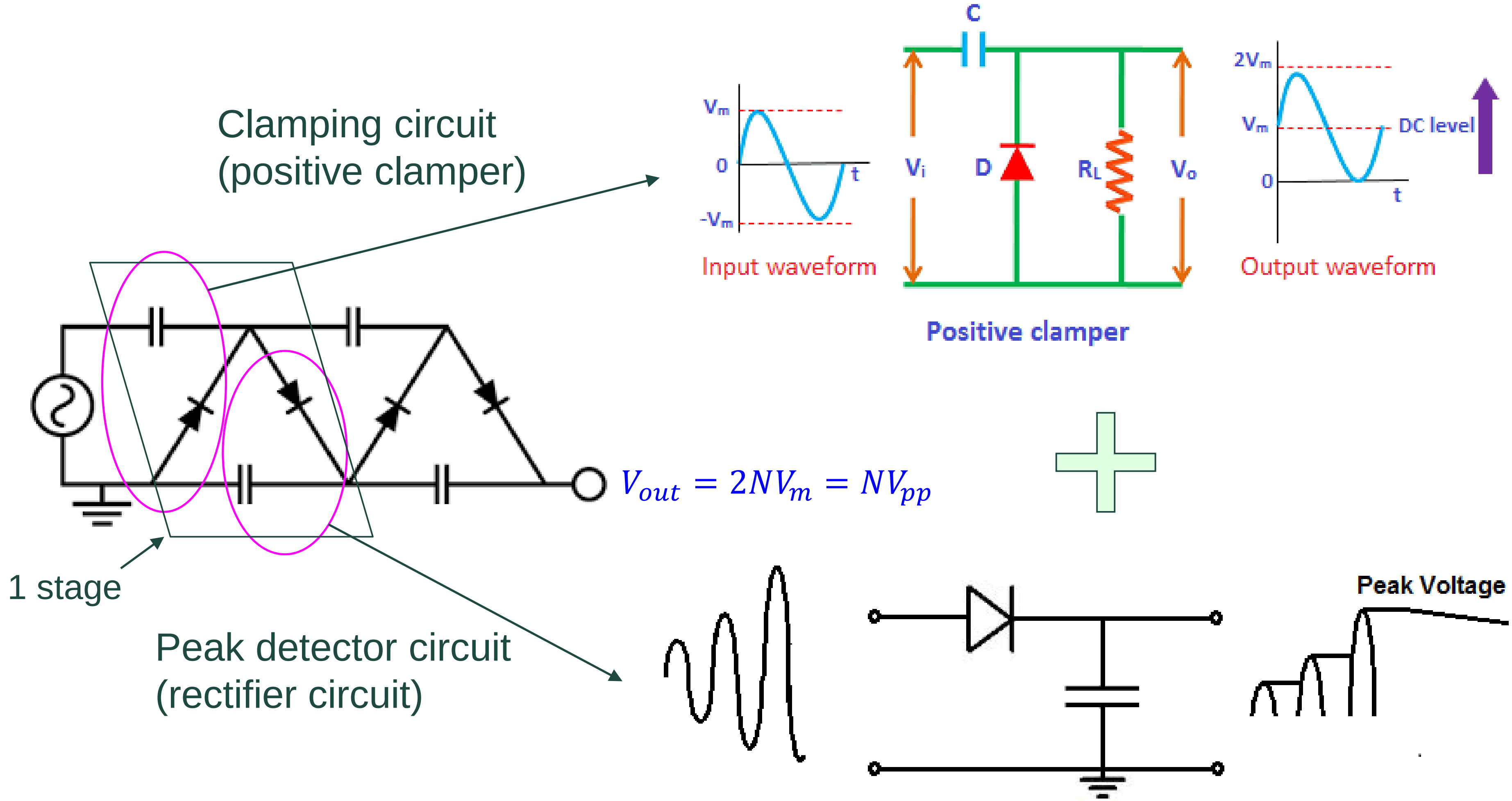


- [H/W] Find the angle between the two alpha particles?

Cockcroft and Walton, Proc. Roy. Soc. A136, 619 (1932)
Cockcroft and Walton, Proc. Roy. Soc. A137, 229 (1932)

Analysis of Cockcroft-Walton's voltage multiplier circuit

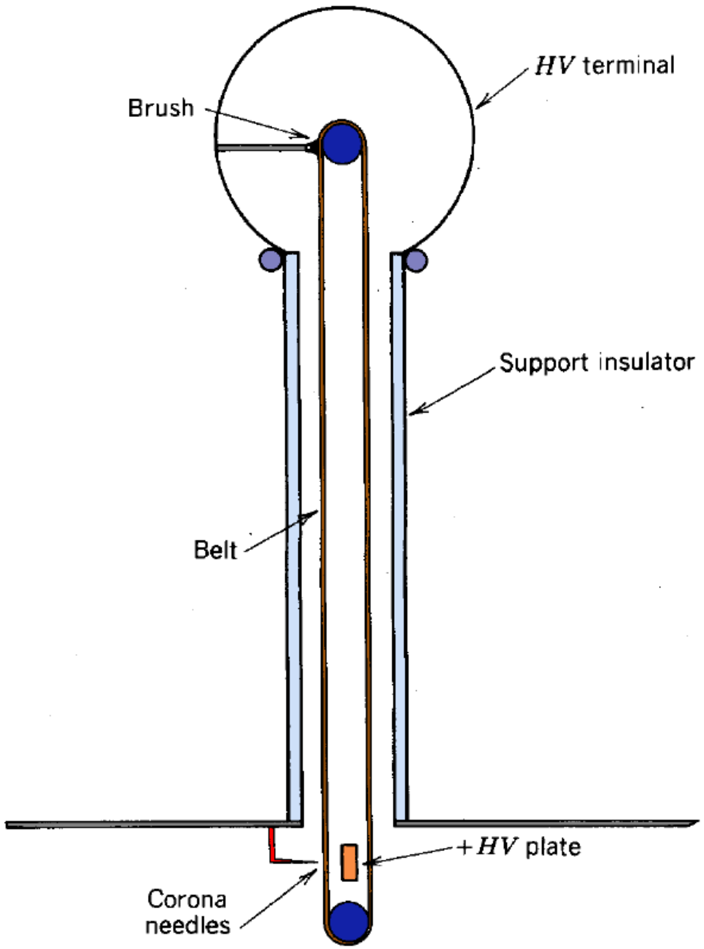
- The voltage multiplier circuit is a combination of a clamping circuit and a peak detector circuit (rectifier circuit).



$$V_{out} = 2NV_m = NV_{pp}$$

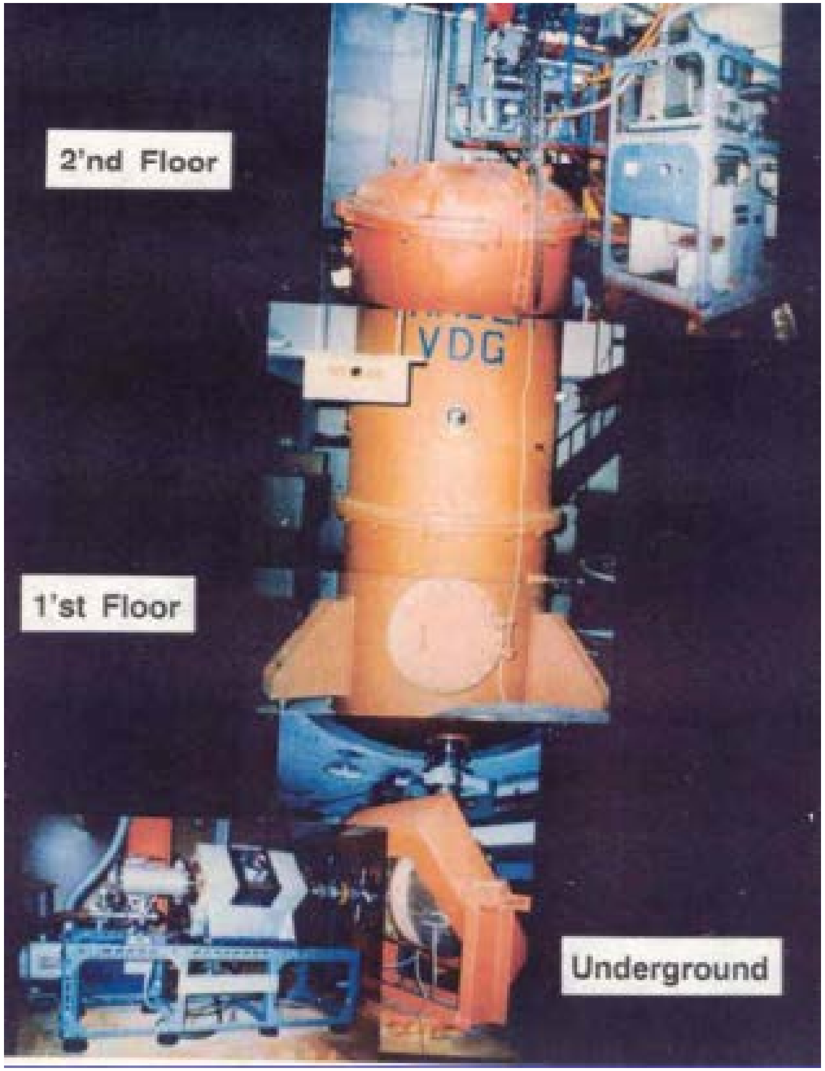
Van de Graaff accelerator

- A Van de Graaff [R. J. Van de Graaff, Phys. Rev. 38, 1919 (1931)] accelerator is a low-current electrostatic MeV-range high-voltage generator using corona discharge from an array of needles in gas.
- The electrons drift toward the positive electrode and are deposited on a moving belt. The belt composed of an insulating material with high dielectric strength, is immersed in insulating gas at high pressure. The attached charge is carried mechanically against the potential gradient into a high-voltage metal terminal.
- The terminal acts as a Faraday cage; there is no electric field inside the terminal other than that from the charge on the belt. The charge flows off the belt when it comes in contact with a metal brush and is deposited on the terminal.



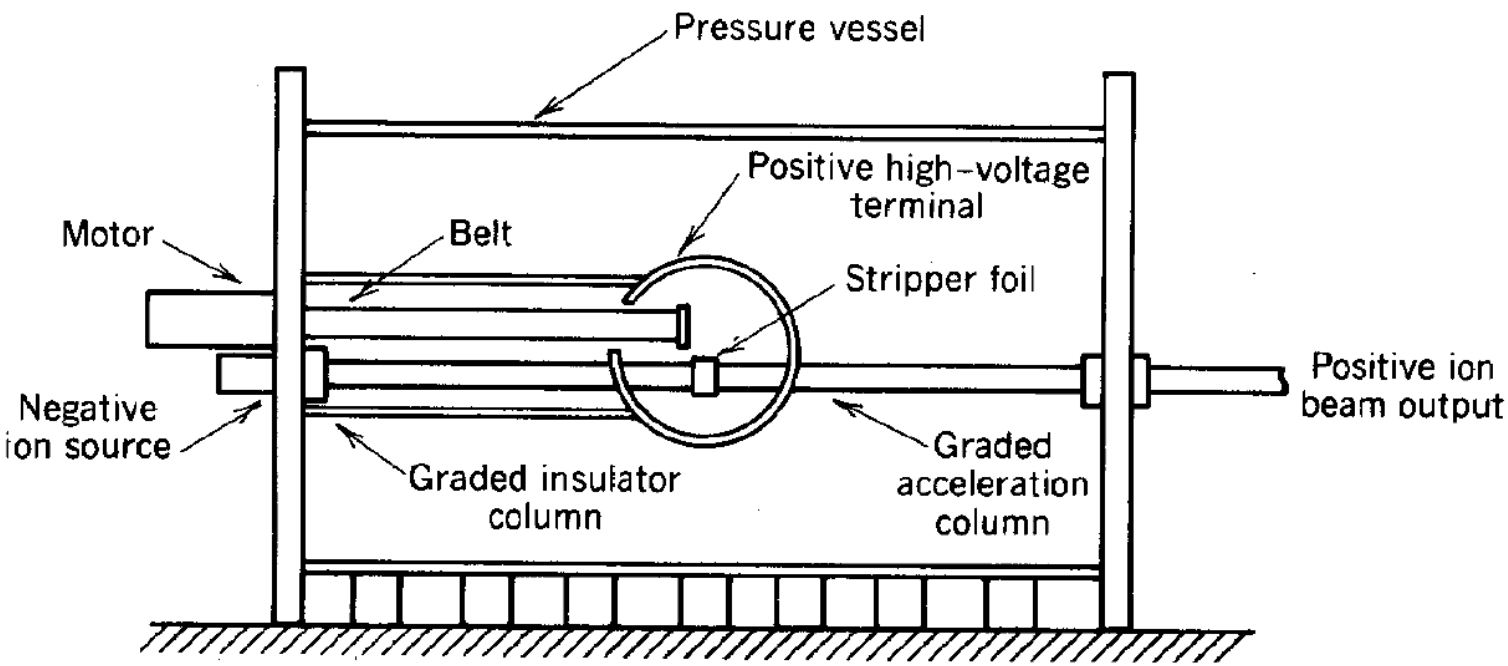
LANL 7 MeV VDG, as injector for 24.5 MeV tandem VDG

1.5 MeV SNU Van de Graaff accelerator



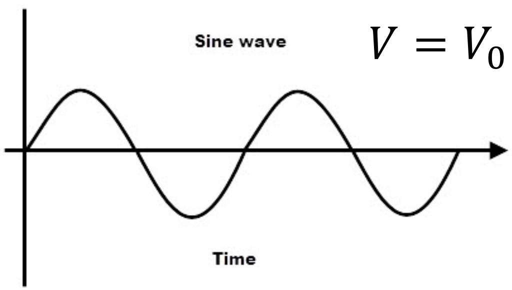
Tandem Van de Graaff accelerator

- The output beam energy of a Van de Graaff accelerator can be extended a factor of 2 through the tandem configuration.
- Negative ions produced by a source at ground potential are accelerated to a positive high-voltage terminal and pass through a stripping cell. Collisions in the cell remove electrons, and some of the initial negative ions are converted to positive ions. They are further accelerated traveling from the high-voltage terminal back to ground.

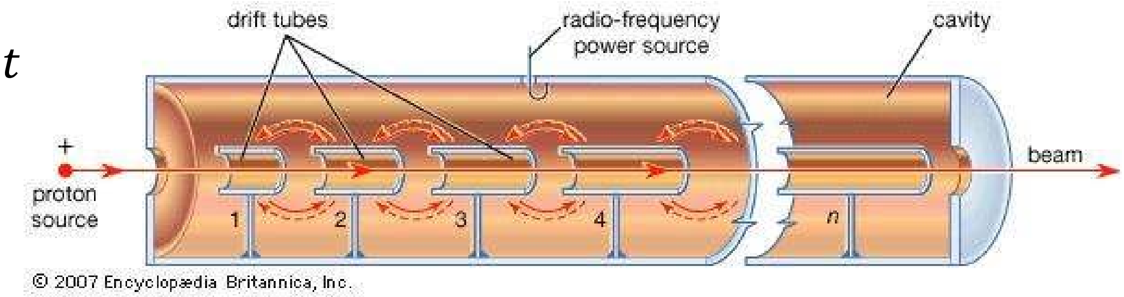


Linear RF (radio-frequency) accelerator

- The particles travelling from the source are subjected to an accelerating electric field when travelling between one cavity and the next, and the electric field is reversed by the time the particles reach the following gap.



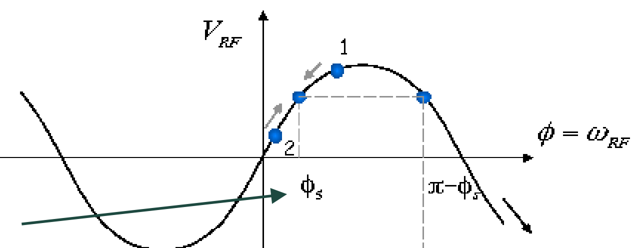
$$V = V_0 \sin \omega t$$

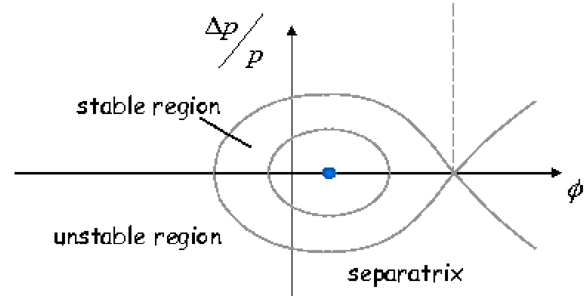


- The particles are shielded from seeing the decelerating field whilst travelling within the cavities, so that the energy acquired after n cavities is:

$$E_n = n \times q \times V_0 \sin \phi_s$$

Synchronous phase angle between the particle and the RF



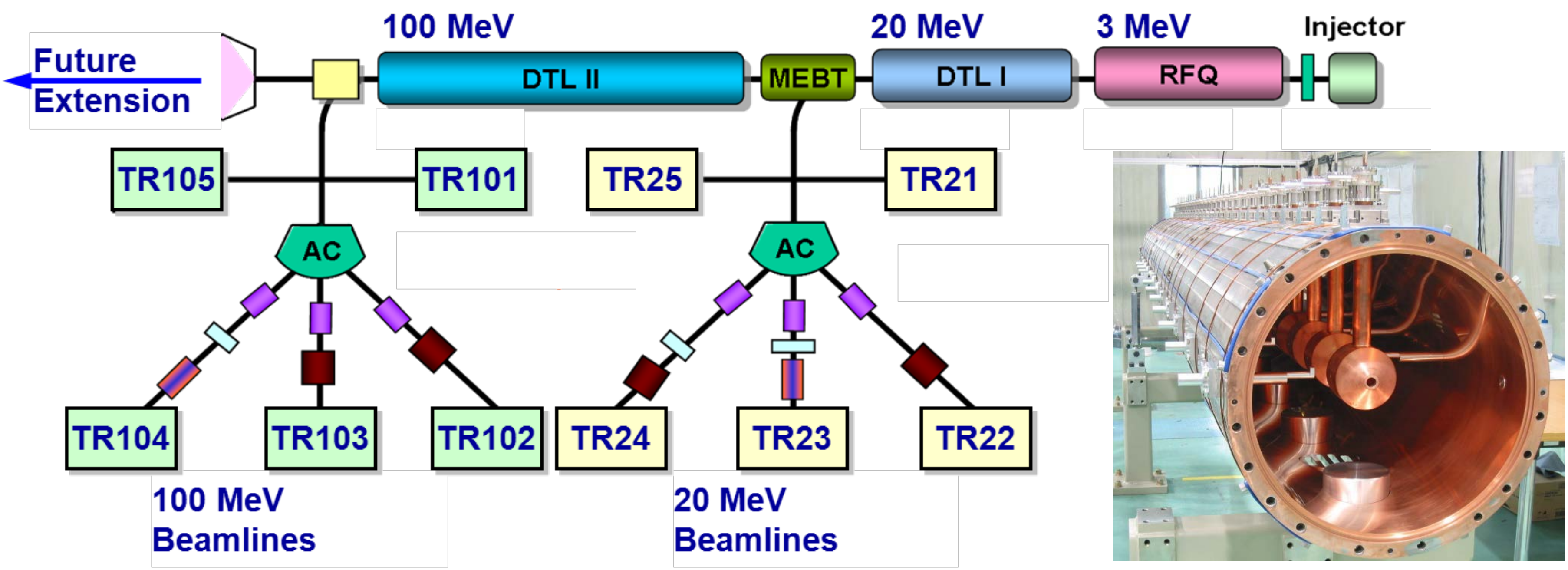


Q1. Why is the length of the cavities changed?
Q2. How to determine the synchronous phase angle?

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



Betatron: circular induction accelerator

- The betatron [D. W. Kerst, Phys. Rev. 58, 841 (1940)] is a circular induction accelerator used for electron acceleration.

$$\boldsymbol{\nabla} \times \boldsymbol{E} = -\frac{\partial \boldsymbol{B}}{\partial t} \quad \Rightarrow \quad \oint \boldsymbol{E} \cdot \boldsymbol{dl} = -\frac{\partial}{\partial t} \oiint \boldsymbol{B} \cdot \boldsymbol{da}$$

- The vertical field at R, i.e. $B_z(R)$ is related with R by

$$R = \frac{\gamma m_e v_\theta}{e B_z(R)} = \frac{p_\theta}{e B_z(R)}$$

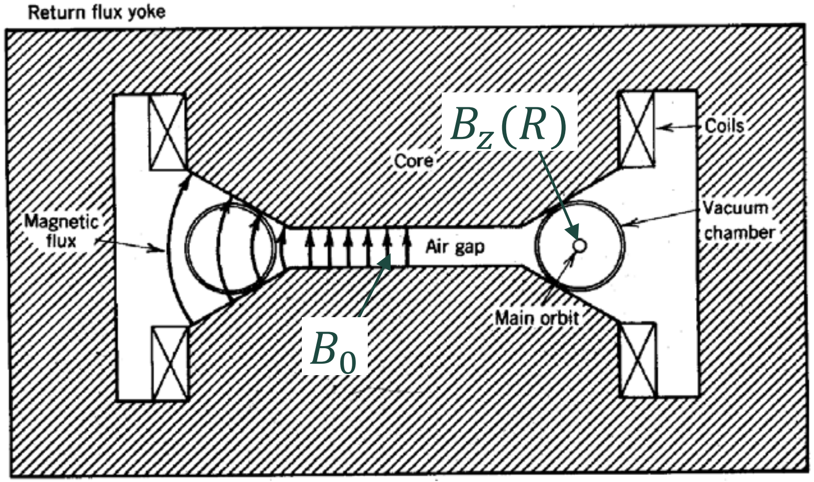
- Particle motion on the main orbit is described by the Faraday induction law:

$$\frac{dp_\theta}{dt} = eE_0 = \frac{e}{2\pi R}\frac{d\Phi}{dt}$$

$$\Rightarrow \quad p_\theta = \frac{e[\Phi(t) - \Phi(0)]}{2\pi R} = \frac{e}{2\pi R}\Delta\Phi$$

- Betatron condition:

$$B_z(R) = \frac{\Delta\Phi}{2\pi R^2} \approx \frac{B_0 \cdot \pi R^2}{2\pi R^2} = \frac{B_0}{2}$$



Cyclotron: circular RF accelerator with constant ω_{RF} and B

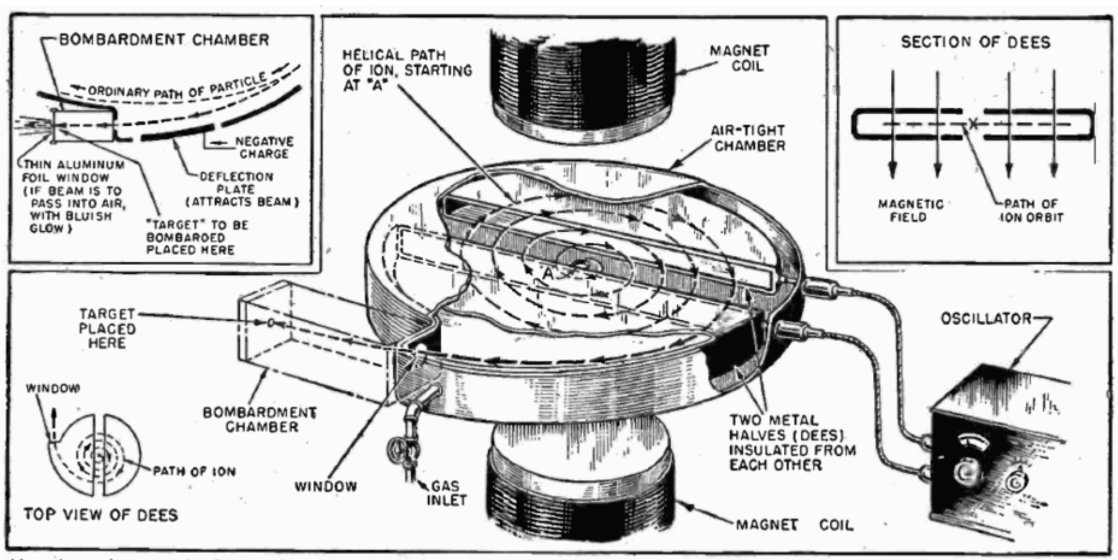
- The operation of the uniform-field cyclotron [E. O. Lawrence, Science 72, 376 (1930)] is based on the fact that the gyro-frequency for non-relativistic ions is independent of kinetic energy. Resonance between the orbital motion and an accelerating electric field can be achieved for ion kinetic energy that is small compared to the rest energy.

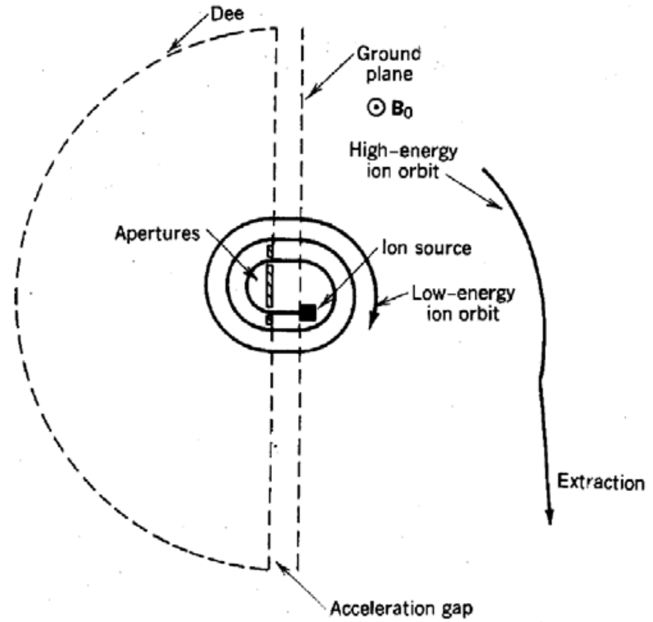
constant

$$\omega_c = \frac{qB}{\gamma m}$$

$$r_L = \frac{\gamma m v_\perp}{qB}$$

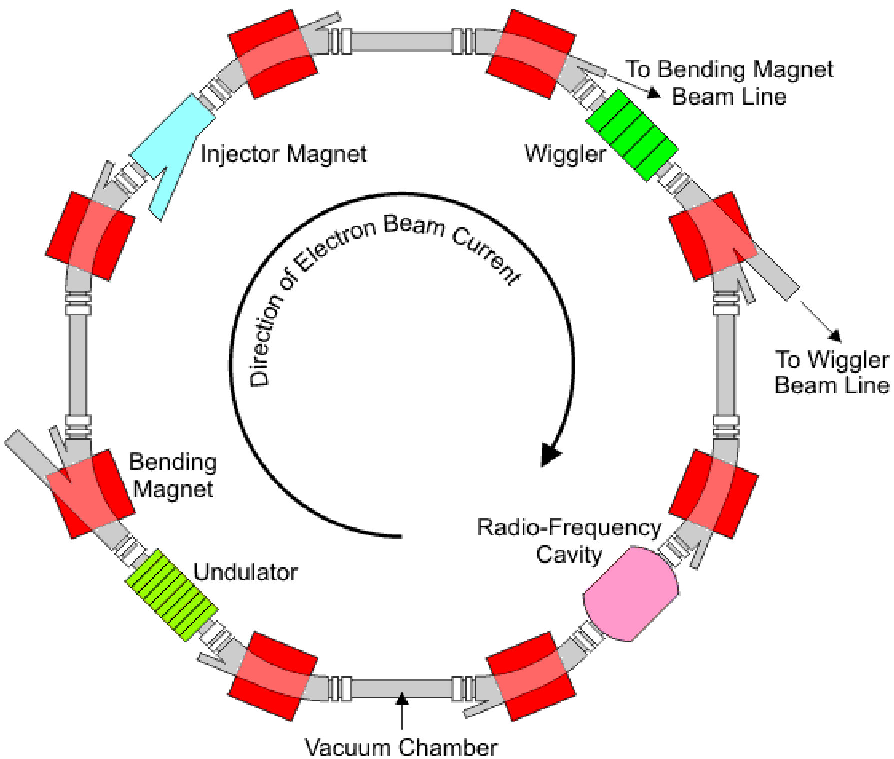
$$\boxed{E = \frac{1}{2}mv^2 = \frac{q^2B^2R^2}{2m}}$$





Synchrotron

- Synchrotrons are resonant circular particle accelerators in which both the magnitude of the bending magnetic field and the rf frequency are cycled. An additional feature of most modern synchrotrons is that focusing forces are adjustable independent of the bending field.



$$\omega_c = \frac{qB}{\gamma m}$$

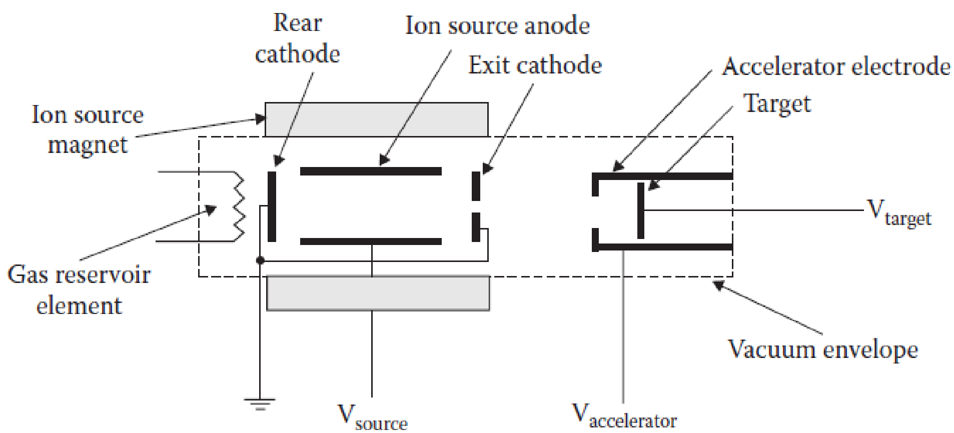
constant

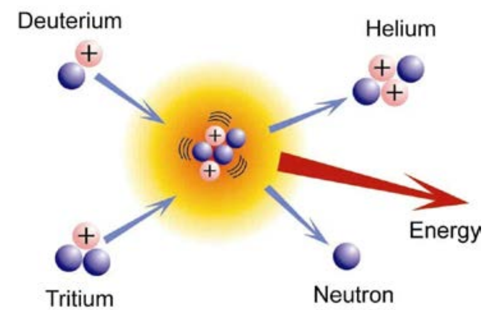
$$r_L = \frac{\gamma m v_\perp}{qB}$$

Pohang Light Source

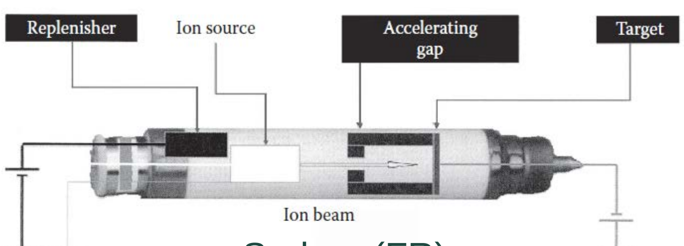
Neutron sources

- **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)

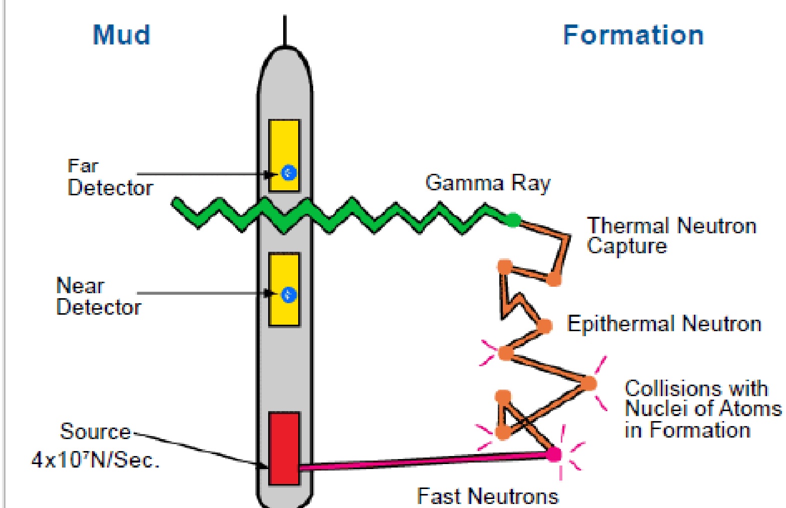
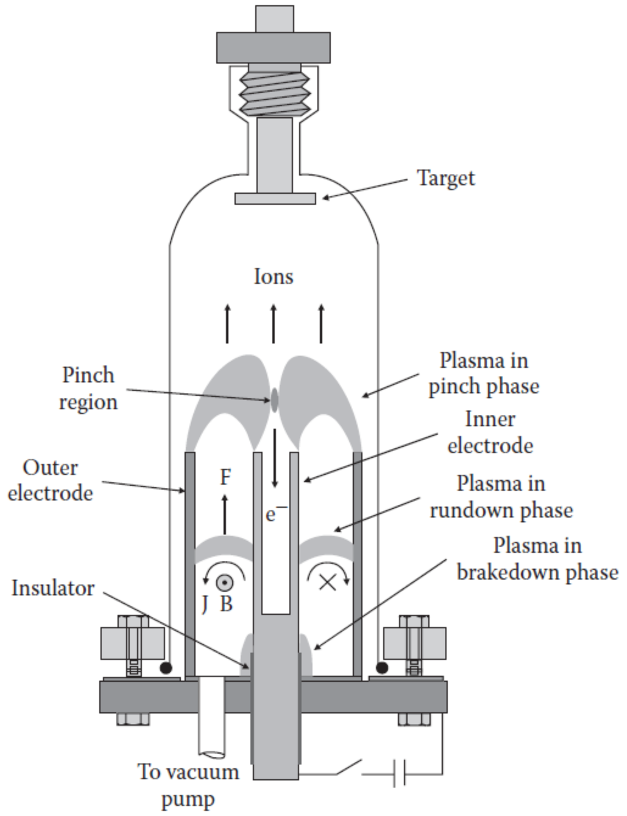
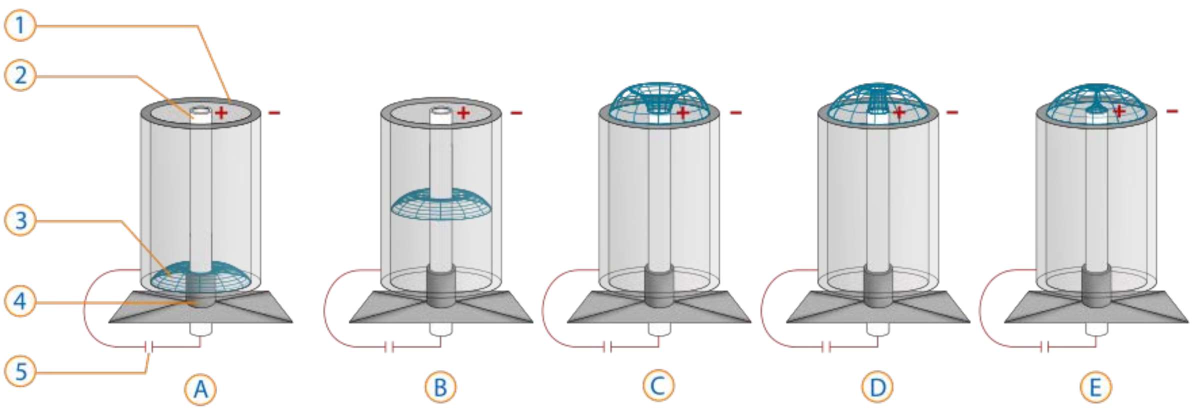


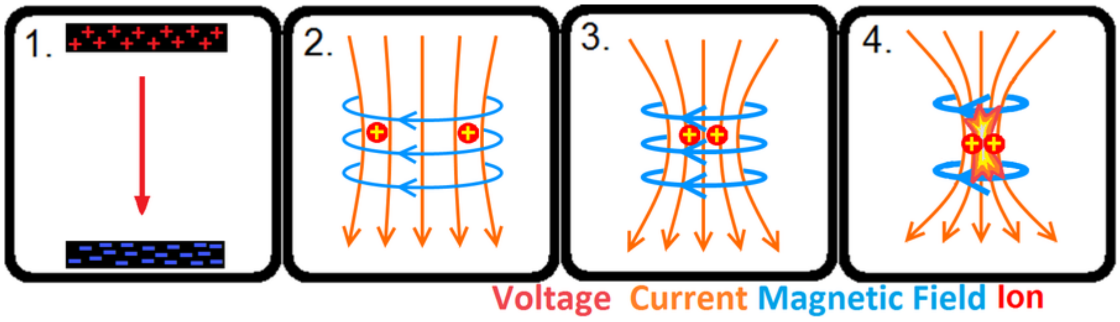
Figure 6: Generalized Neutron Logging Tool illustrates a typical neutron logging tool (Schlumberger, 2010).

Neutron sources

- **Plasma focus and plasma pinch devices**: The dense plasma focus neutron source produces controlled nuclear fusion by creating a dense plasma within which heats ionized D and/or T gas to temperatures sufficient for creating fusion.

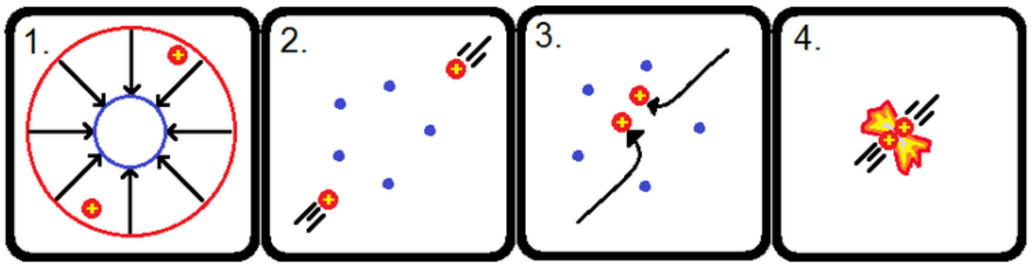


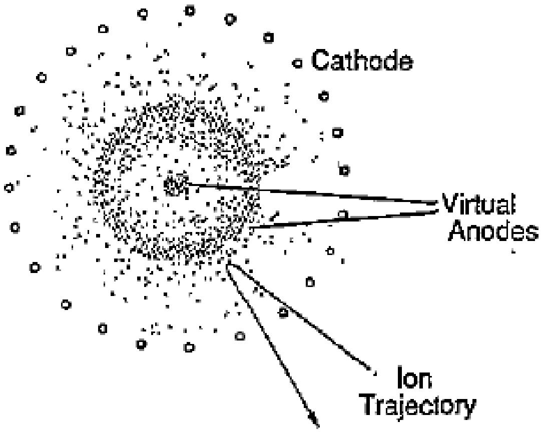


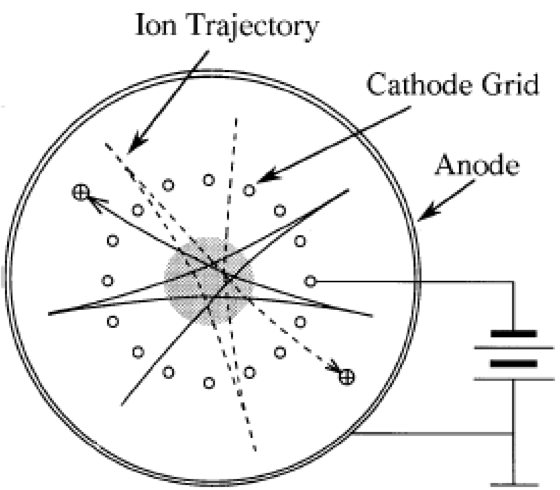


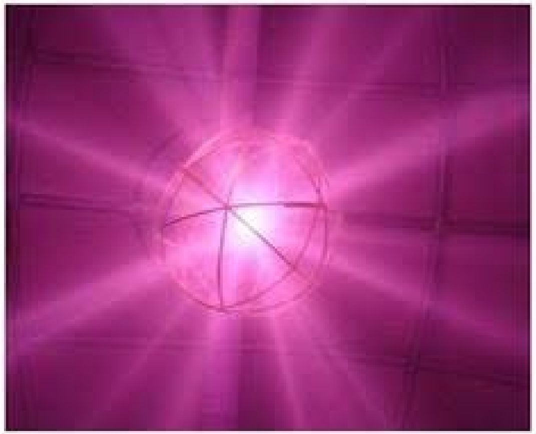
Neutron sources

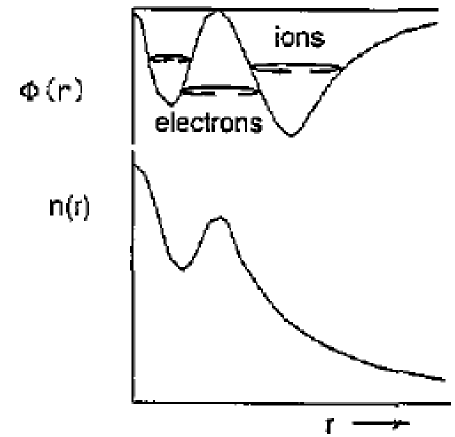
- **Inertial electrostatic confinement (IEC)**: Inertial electrostatic confinement devices such as the Farnsworth-Hirsch fusor use an electric field to heat a plasma to fusion conditions and produce neutrons. The ions are believed to be confined in the electrostatic potential well.





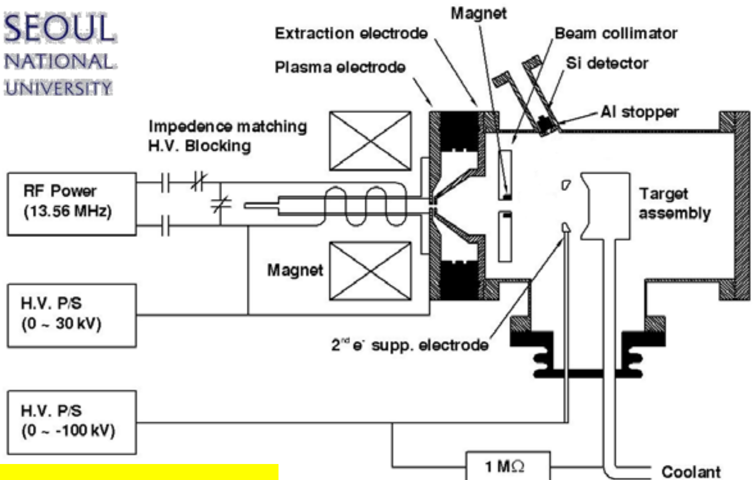




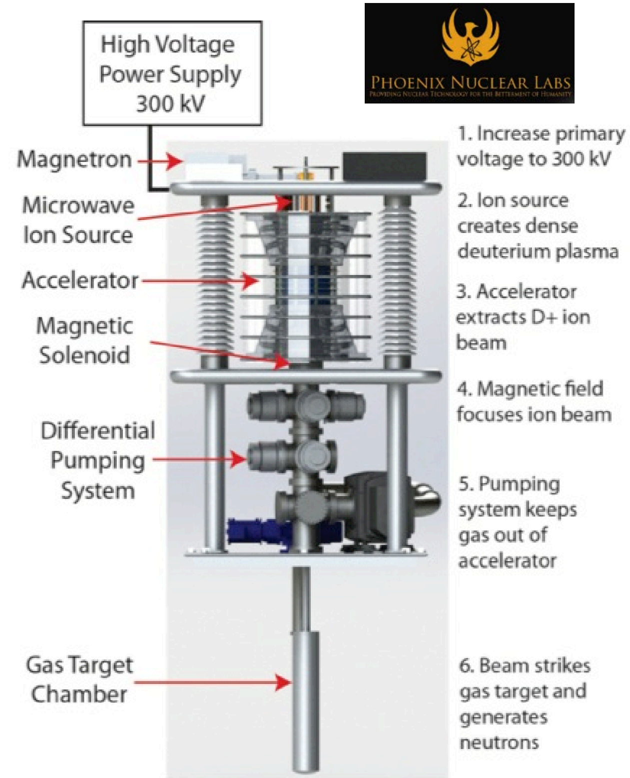


Neutron sources

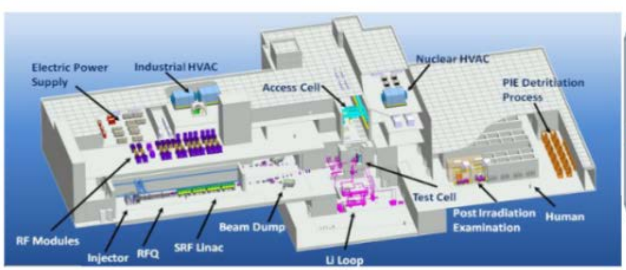
- **Light ion accelerators**: Traditional particle accelerators with hydrogen (H), deuterium (D), or tritium (T) ion sources may be used to produce neutrons using targets of deuterium, tritium, lithium, beryllium, and other low-Z materials.



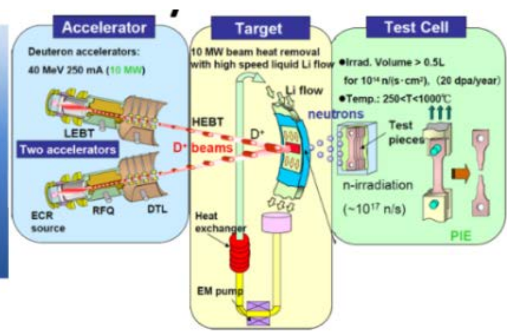
2x10⁸ n/s @97keV, 8mA



3x10¹¹ n/s @300keV, 50mA



IFMIF artist's view



IFMIF utilizes liquid Li as a target

Neutron sources

- **Nuclear fission reactors**: Fission reactor sources rely on a neutron-propagated chain reaction in the fuel (usually ^{235}U). Power reactors are optimized for heat extraction and efficient use of fuel, so they have quite a different design from research reactors that are optimized for high (external) thermal neutron flux.

$$^{235}\mathrm{U} + \mathrm{n} \rightarrow \mathrm{X} + \mathrm{Y} + 2.5\,\mathrm{n}\,,$$

$$(\sim 200\,\mathrm{MeV}\ \text{total energy release}, \sim 2\,\mathrm{MeV}\ \ \text{per neutron})$$

- In a typical research reactor design, one of the neutrons produced per fission is needed to sustain the chain reaction, ~0.5 is lost, and one is available for external use (i.e., ~200 MeV of heat is produced for each available neutron).

Table 2.1 Existing medium- and high-flux reactor sources and their respective parameters

Country	United States	United States	Canada	France	France	Germany	Germany	Australia	Korea	Japan
Neutron source	HFIR	NBSR	NRU	HFR	ORPHEE	BENSC	FRM-II	OPAL	HANARO	JRR-3 M
Organization	Oak Ridge National Laboratory	National Institute of Standards and Technology	Atomic Energy of Canada Limited	Institut Laue-Langevin	Laboratoire Léon Brillouin	Helmholtz-Zentrum Berlin	Technische Universitat Munchen	Australian Nuclear Science and Technology Organization	Korea Atomic Energy Research Institute	Japan Atomic Energy Agency
Power (MW)	85	20	120	58	14	10	20	20	24 (present) 30 (designed)	20
Flux ($\mathrm{n \cdot cm^{-2} \cdot s^{-1}}$)	1.5×10^{15}	3×10^{14}	3×10^{14}	1.5×10^{15}	3×10^{14}	2×10^{14}	8×10^{14}	3×10^{14}	2×10^{14}	3×10^{14}
Number of cold/hot sources	1/0	1/0	0/0	2/1	1/1	1/0	1/1	1/0	1(planned)/0	1/0
Number of instruments	9(present) + 6 (planned by 2012)	24	5	26	22	22	20 (present) + 10 (under construction)	6	6	24
Existing neutron imaging instrument		BT-2 [14]			[15]	CONRAD [16]	ANTARES [17]		NR-port [18]	TNRF [19] And TNRF-2 [20]
Facility operating since	1967	1970	1957	1972 (refurbished 1993)	1980	1973	2004	2006	1997	1990

HFIR: High-Flux Isotope Reactor [21]; NBSR: National Bureau of Standards Reactor [22]; NRU: National Research Universal Reactor, Chalk River, Canada [23]; HFR: High-Flux Reactor at ILL [1, 2]; ORPHEE: reactor at LLB [24]; BENSC: Berlin Neutron Scattering Centre [25]; FRM-II: Forschungsneutronenquelle Heinz Maier-Leibnitz [5]; OPAL: Open Pool Australian Light-water Reactor [6]; HANARO: High-flux Advanced Application Reactor [4]; JRR-3 M: Japan Research Reactor No. 3 Modified [3]. Consult the web sites for these facilities to obtain additional information and current details. A number of smaller research reactors, primarily at universities, are not listed here.

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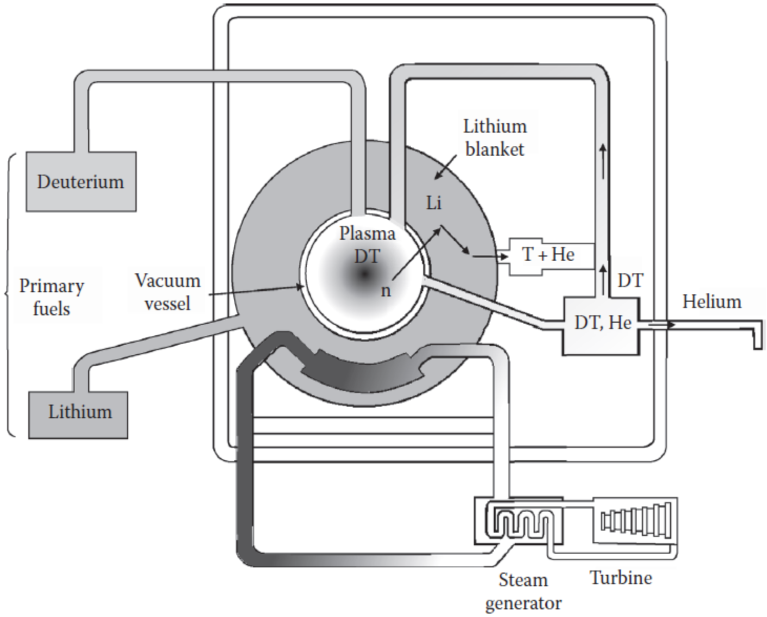
Neutron sources

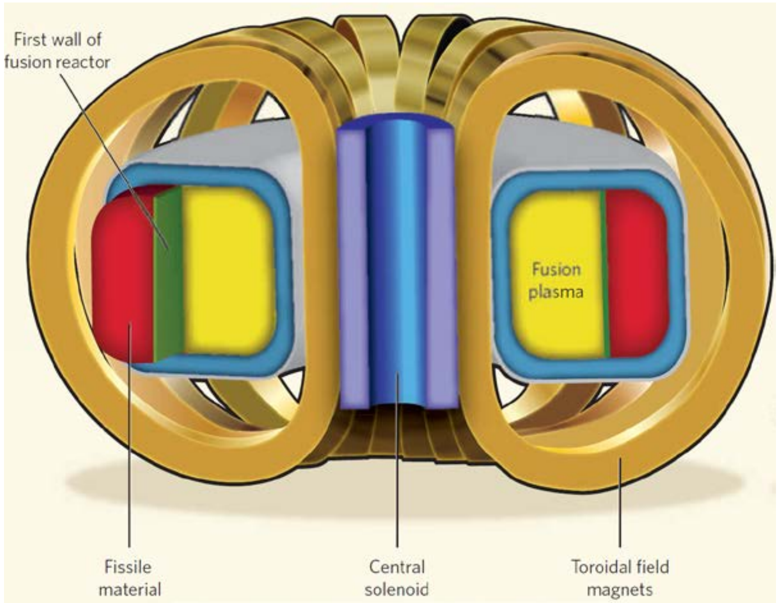
- **Thermonuclear fusion reactors**: A number of experiments around the world have verified the principles of d + t fusion; however, it still has to be demonstrated that a gain in energy can be achieved.

$$d + t \rightarrow \alpha\,(3.5\ \text{MeV}) + n\,(14\ \text{MeV}).$$

- In hybrid reactors, high-energy neutrons generated by fusion reactions drive fission in the surrounding blanket of fissile material, burning up long-lived radioactive by-products produced by the fission process.



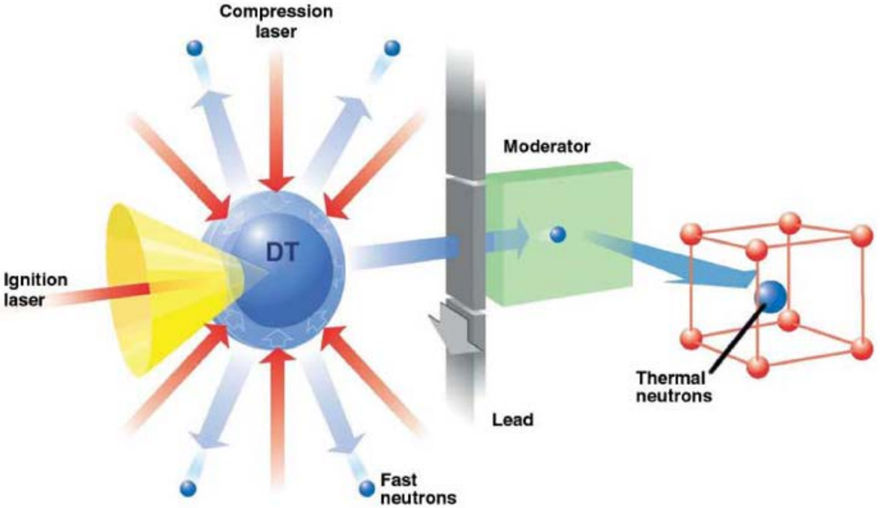
D-T fusion reactor

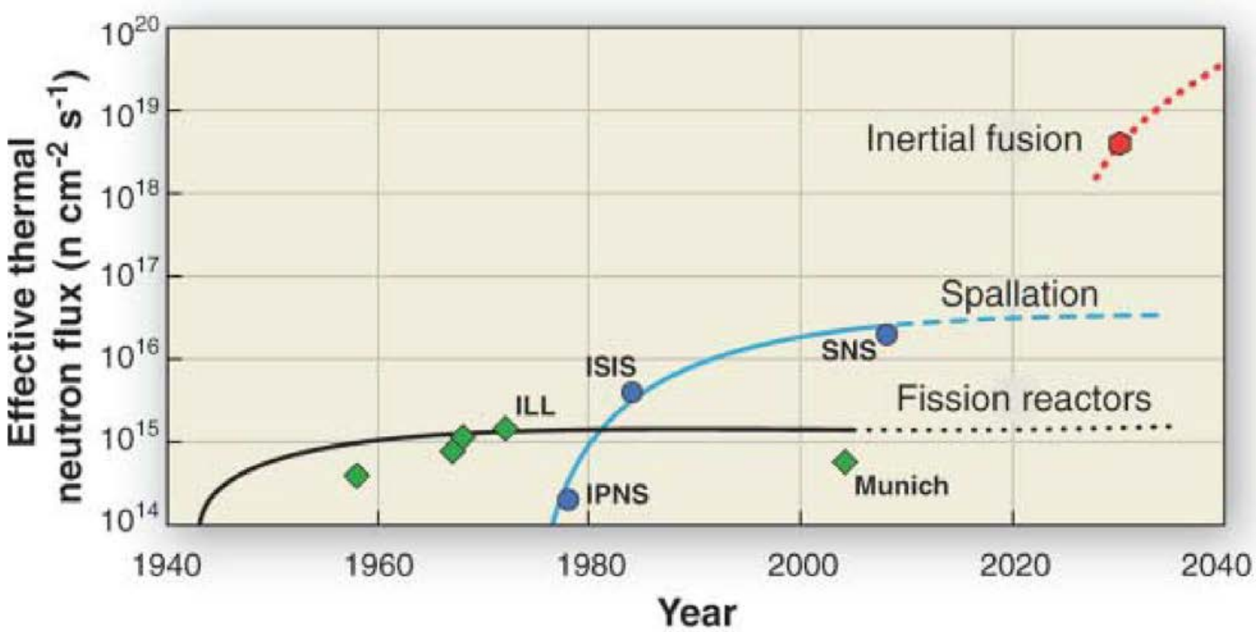


Fusion-fission hybrid reactor

Neutron sources

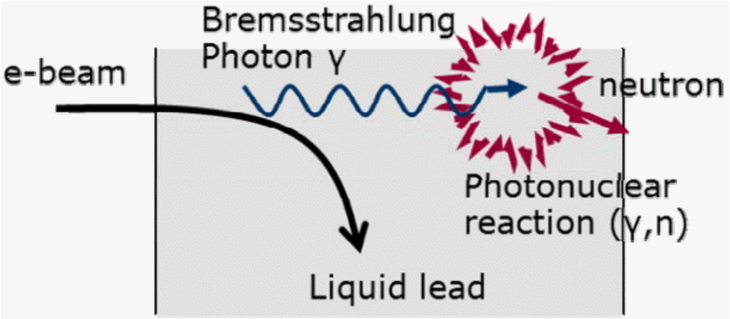
- **Inertial confinement fusion reactors**: Compression laser beams are focused on the millimeter-diameter Deuterium-Tritium capsule. The ignition short-pulse beam enters ~10 ns later via a gold cone through the compressed plasma.

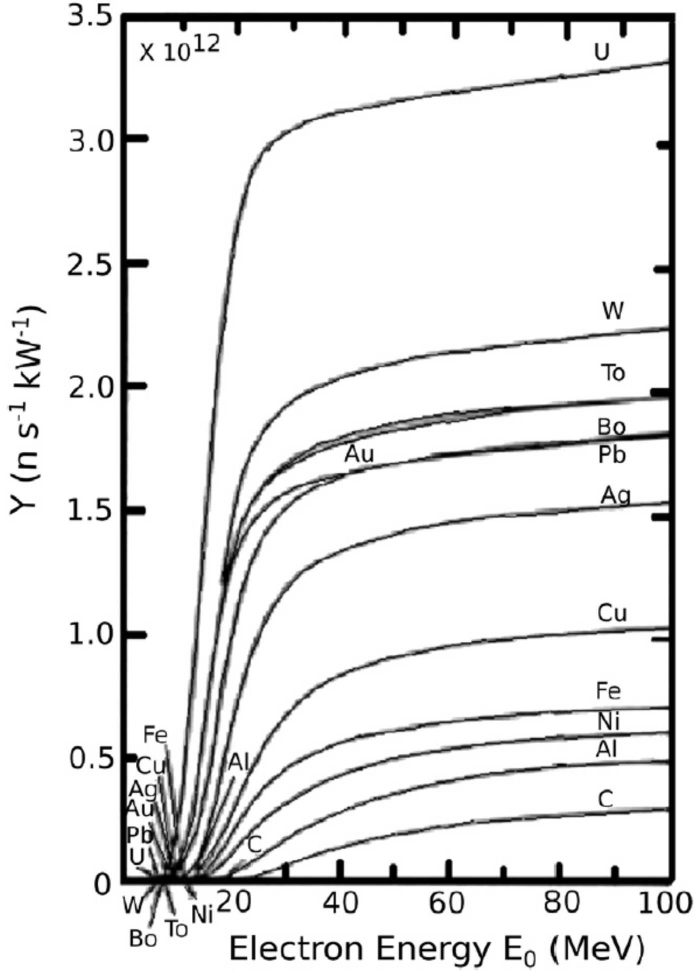




Neutron sources

- **Electron beam neutron sources**: Energetic electrons striking high-mass targets slow down to emit bremsstrahlung (e,γ) photons. Photons proceed to interact with target nuclei to produce (γ,n) photoneutrons.
- Early work at accelerator-driven sources was based on cyclotrons and pulsed electron-linac-driven bremsstrahlung photoneutron sources.
- The e-linac-driven sources soon reached a power limit of about 50 kW, imposed by heat transfer engineering constraints on target design which is subjected to about 2000-MeV heating per neutron production.





Neutron sources

- **Spallation neutron sources**: Spallation is a violent reaction in which a target is bombarded by very high-energy particles. The incident particle, such as a proton, disintegrates the nucleus through inelastic nuclear reactions. The result is the emission of protons, neutrons, α-particles, and other particles.
- Threshold energy of spallation reaction by protons in heavy nuclei is ~100 MeV.
- It shows excellent neutron production efficiency compared with other techniques. For example, a 1-GeV proton on tungsten (A = 184) produces 18 neutrons and deposits ~30 MeV of heat per neutron.

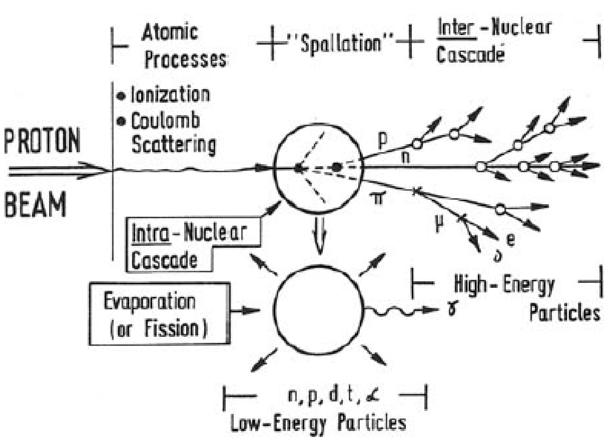


Table 2.2 Past, existing, and future spallation source and their respective parameters

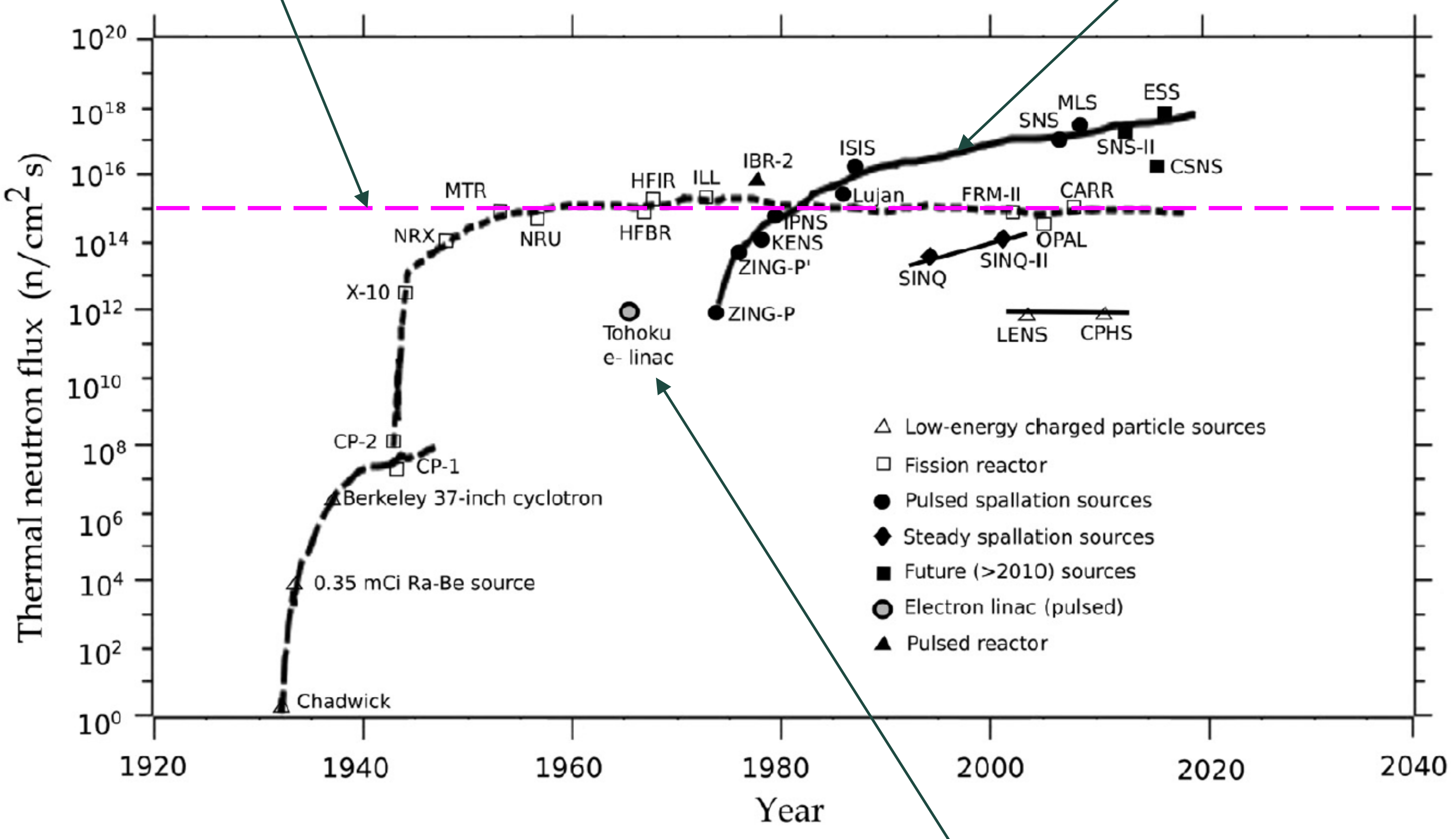
Country	United States	United States	United States	U.K.	Switzerland	China	Europe	Japan	Japan
Neutron source	IPNS	LANSCE	SNS	ISIS	SINQ	CSNS	ESS	KENS	JSNS
Organization	Argonne National Laboratory	Los Alamos National Laboratory	Oak Ridge National Laboratory	Rutherford Appleton Laboratory	Paul Scherrer Institute	Institute of High Energy Physics	Undecided	High Energy Accelerator Research Organization	Japan Atomic Energy Agency
Proton energy (MeV)/ Current (μA)	450/15	800/70	1000/1400	800/200	590/1500	1600	1333/7500	500/9	3000/333
Proton beam power	7 kW	56 kW	1.4 MW	160 kW	1 MW	100 kW	5 MW	4.5 kW	1 MW
Repetition rate (Hz)	30	20	60	50/10 (2 targets)	Continuous	25	16 (long pulse)	20	25
Target material	Depleted Uranium	Tungsten	Mercury	Tantalum	Zircaloy	Tungsten	Mercury	Tungsten	Mercury
Moderator	S-CH_4/L-CH_4	L-H_2/H_2O	L-H_2/H_2O	L-H_2/L-CH_4/H_2O	L-D_2/D_2O	H_2OL-CH_4L-H_2	L-H_2	S-CH_4/H_2O	L-H_2
Number of instruments	12	7	24 (beam ports)	22 (TS1) 7 (TS2)	15		20 (beam ports)	15	23 (beam ports)
Existing neutron imaging instrument					NEUTRA [30] and ICON [31]				
Facility operating since or planned to operate in	1981 (closed 2008)	1983	2006	1985 (TS1) 2008 (TS2)	1996	2014	Under planning	1980 (closed 2005)	2008

IPNS: Intense Pulsed Neutron Source [32]; LANSCE: Los Alamos Neutron Science Center [33]; SNS: Spallation Neutron Source [8, 9]; ISIS: [34, 35]; SINQ: Swiss Spallation Neutron Source [36, 37]; CSNS: Chinese Spallation Neutron Source [10, 11]; ESS: European Spallation Source [38, 39]; KENS: Koh-Energy-ken Neutron Source [40, 41]; JSNS: Japanese Spallation Neutron Source [8, 9]. Consult the websites for these facilities to obtain additional information and current details.

History of flagship neutron facilities

Limitation of fission reactors (~200 MeV / neutron)

Spallation sources (~30 MeV / neutron)



Electron-linac-driven photoneutron source (~2000 MeV / neutron)