PAL 포항가속기연구소 POHANG ACCELERATOR LABORATORY

UNIST ULSAN NATIONAL INSTITUTE OF SCIENCE AND TECHNOLOGY

2022 ATE accelerator school

입자가속기의 종류와 원리 개론: Part 1

UNIST
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2022.08.08~2022.08.12

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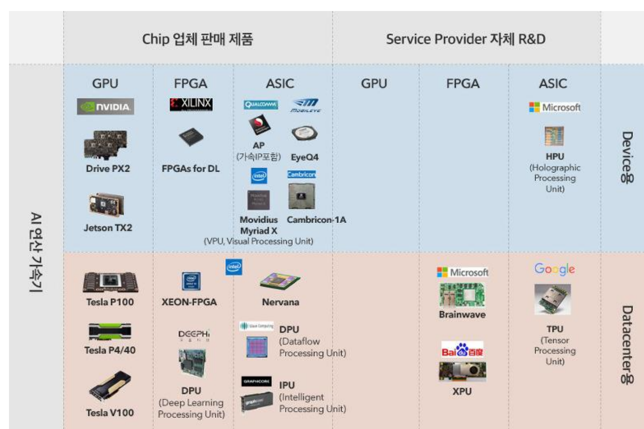
What is the Accelerator?

What is the Accelerator?

가속기
(加速器) =

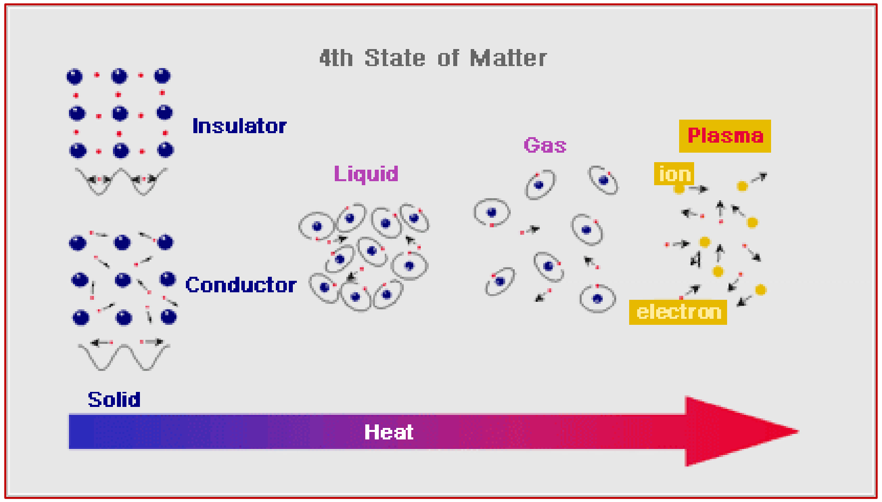
Ultrasonic humidifier
가습기(加湿器)

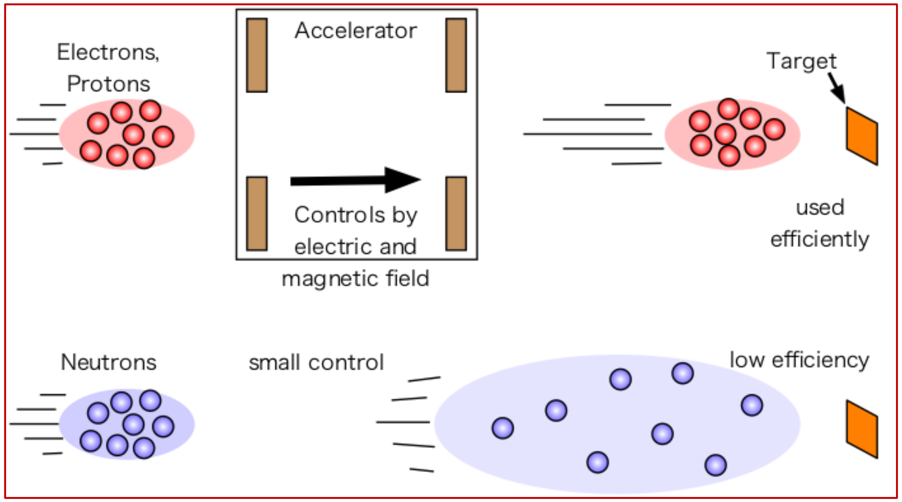
Accelerator pedal



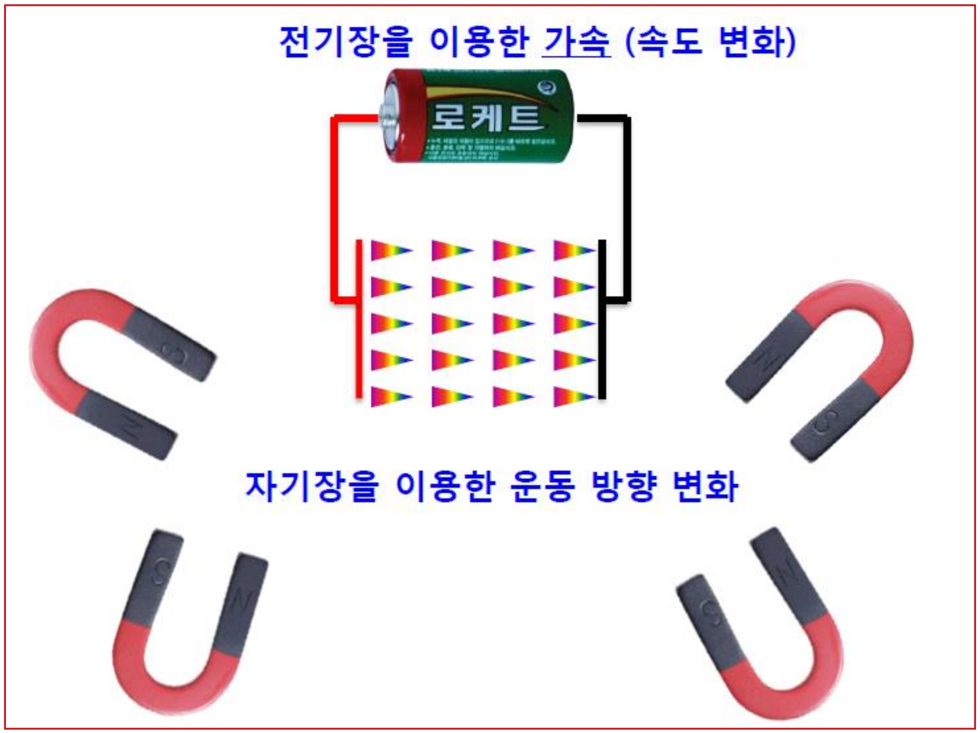
AI Accelerator
(AI 알고리즘을 빨리 처리하기 위해 설계된 chip)

Accelerator = Particle source + E/B fields



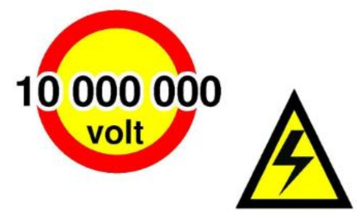


Accelerator = Particle source + E/B fields



DC

Cockcroft-Walton accelerator

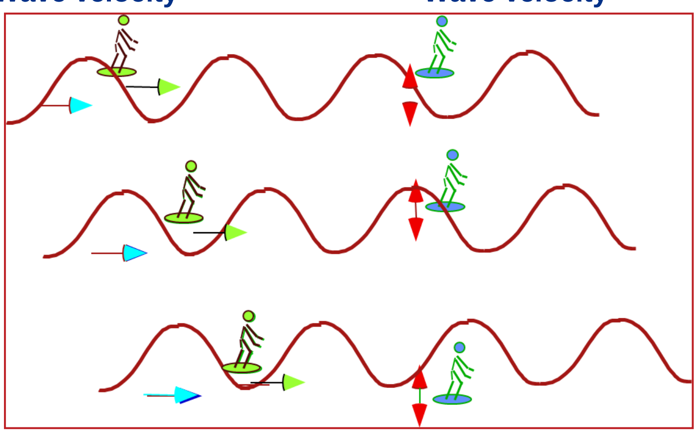


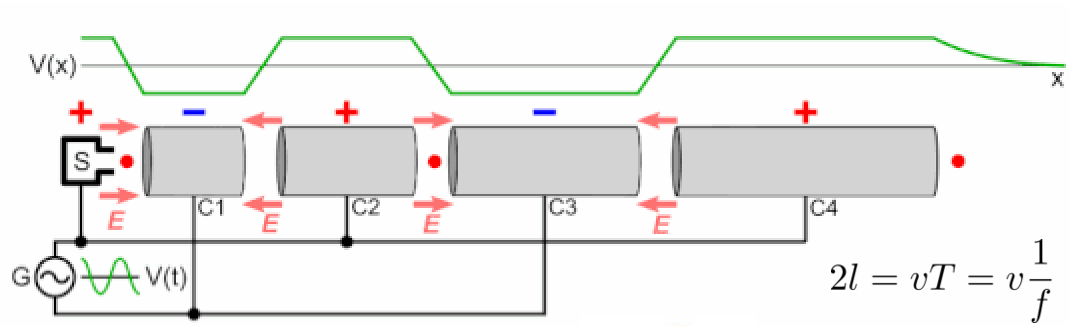
<3 MV/m
(DC Kilpatrick criteria)

RF Acceleration

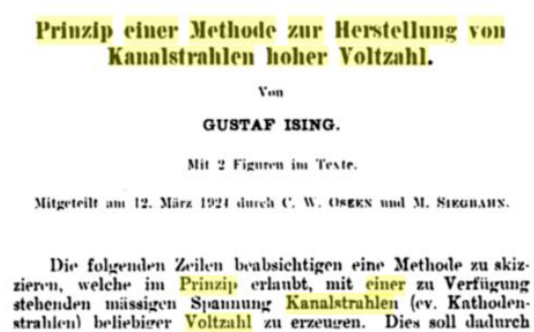
Particle velocity
~Wave velocity

Particle velocity
<< Wave velocity





$$2l = vT = v\frac{1}{f}$$



Prinzip einer Methode zur Herstellung von Kanalstrahlen hoher Voltzahl.

Von

GUSTAF ISING.

Mit 2 Figuren im Texte.

Mitgeteilt am 12. März 1924 durch C. W. Oseen und M. Siegbahn.

Die folgenden Zeilen beabsichtigen eine Methode zu skizzieren, welche im Prinzip erlaubt, mit einer zu Verfügung stehenden mässigen Spannung Kanalstrahlen (ev. Kathodenstrahlen) beliebiger Voltzahl zu erzeugen. Dies soll dadurch

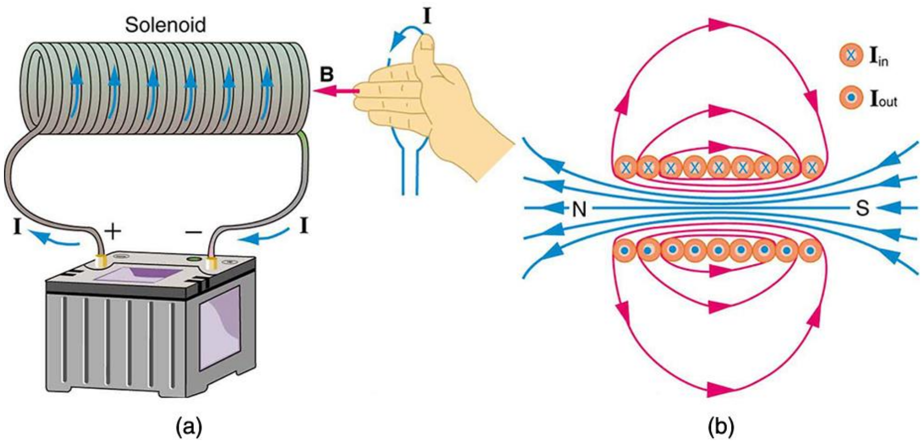
Wideröe
(1928)

The **Rolf Wideroe Prize** is awarded every third year by the Accelerator Group of the European Physical Society (EPS), in memory of Rolf Widerøe, to individuals in recognition of outstanding work in the field of accelerator physics.[1]

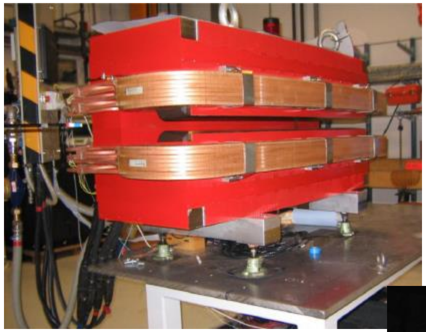
Electromagnet

→ Permanent magnet
(ex, undulator, very strong field gradient)

→ Electromagnet
(most popular)



→Dipole: Changing direction



→Quadrupole: Focusing

→Sextupole: Control chromatic aberration

→ Superconducting magnet (ex, Tevatron/LHC dipoles)

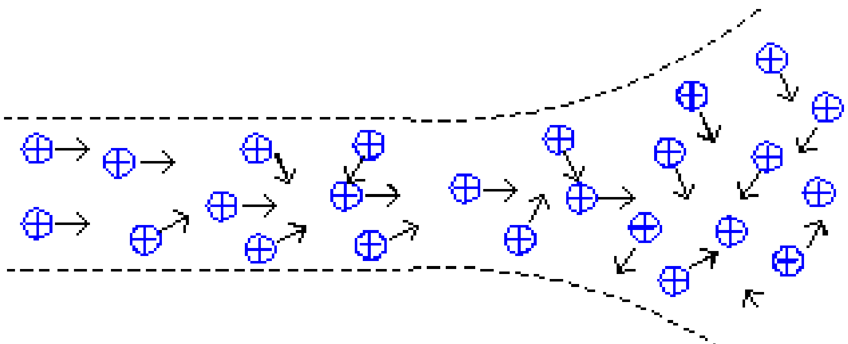
Self Ac(De)celeration and (De)Focusing

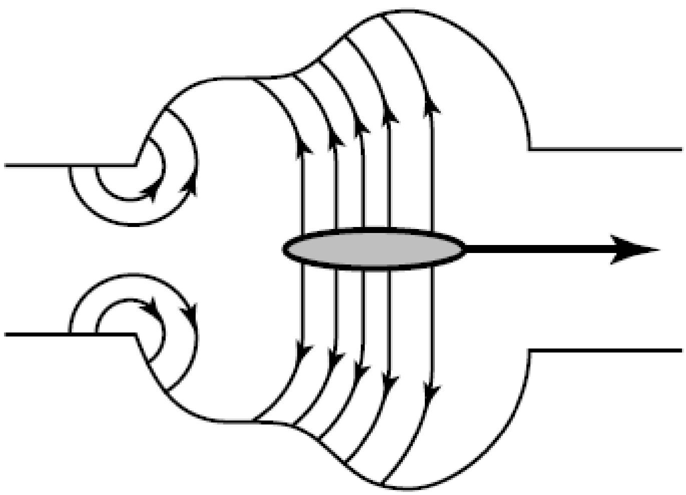
Dominant for low energy

Space charge effects ⇨ Nonlinearity, resonance, coupling

Dominant for high energy

Pipe with Structure ⇨ Wakefields

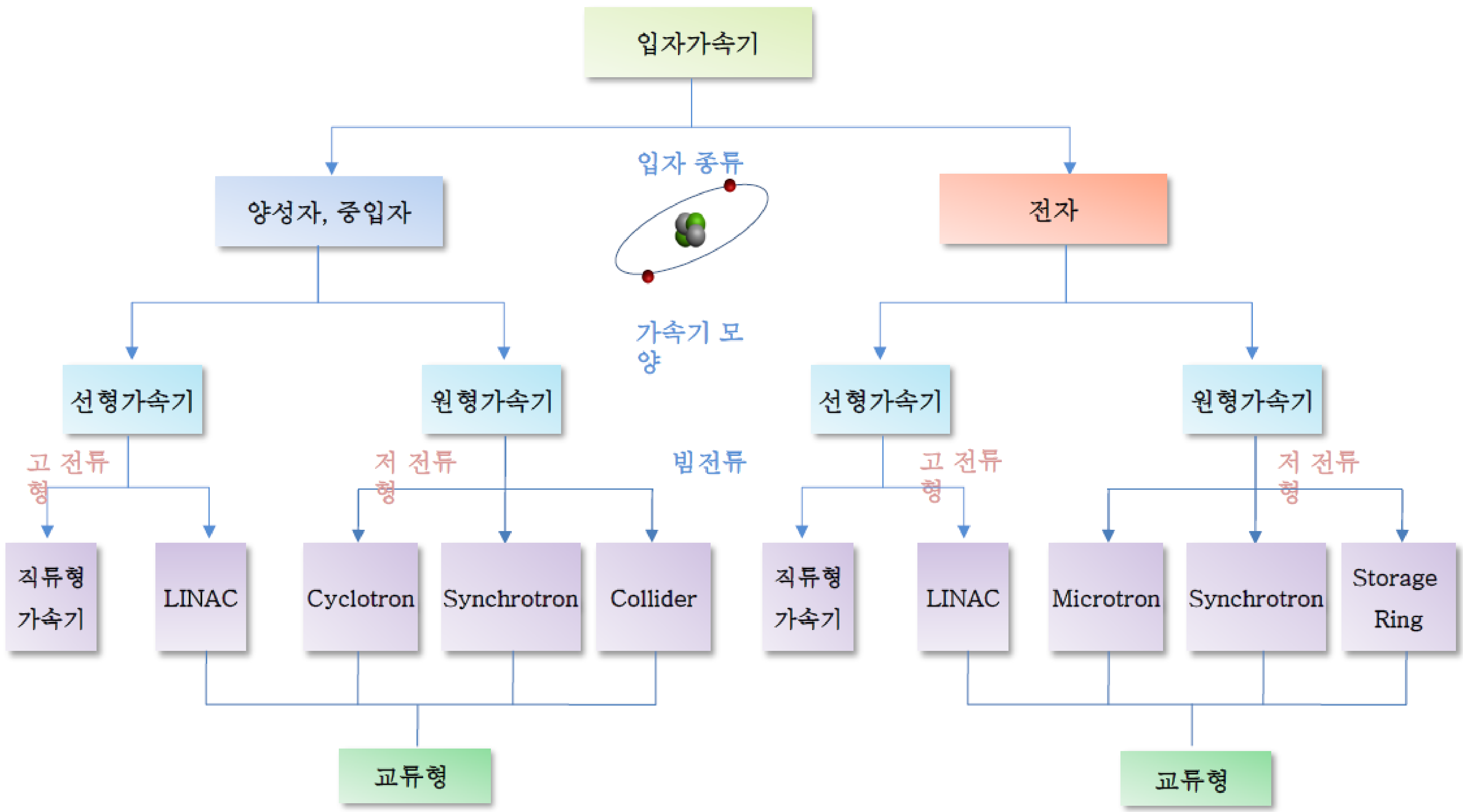




(cf., scattering effect)

(cf., plasma wakefield)

Zoo of Accelerators



[From KOMAC]

Pros VS Cons of Accelerators

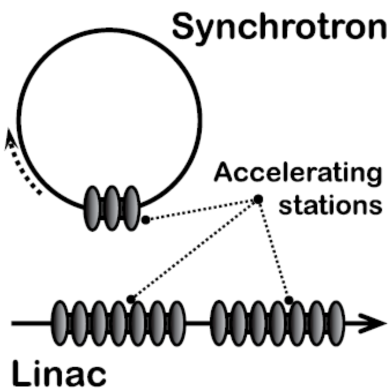


FIGURE 5.6
Synchrotron and linac.

$$B\rho = \frac{p}{q}$$

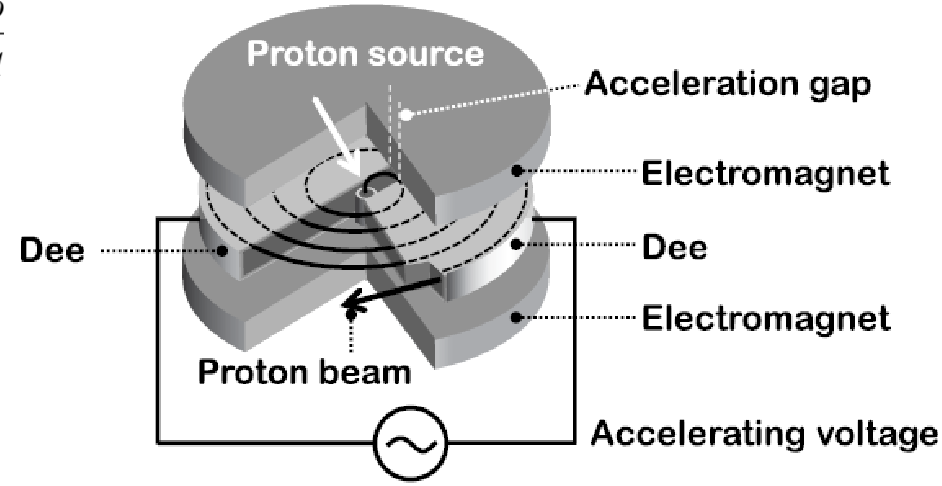


FIGURE 9.7
Schematic of a cyclotron.

[From A. Seryi]

형태 분류	장 점	단 점
선형가속기	연속적인 형태로 가속하기 때문에 대 전류 입자 가속이 가능 (= 입자의 개수 늘릴 수 있음)	에너지를 높일 수록 가속관이 점점 더 길어짐
싱크로트론	입자를 반복 가속할 수 있어 에너지를 높이는데 유리함 (CERN의 LHC 는 약 7 TeV/u)	같은 궤도를 돌며 가속하기 때문에 연속적이지 못하여 대 전류 입자 가속이 불가능
사이클로트론	• 대 전류 입자 가속 가능 • 입자의 반복 가속 가능	제작 가능한 전자석 크기의 기술적 제한으로 에너지를 높이기 어려움

[From KOMAC]

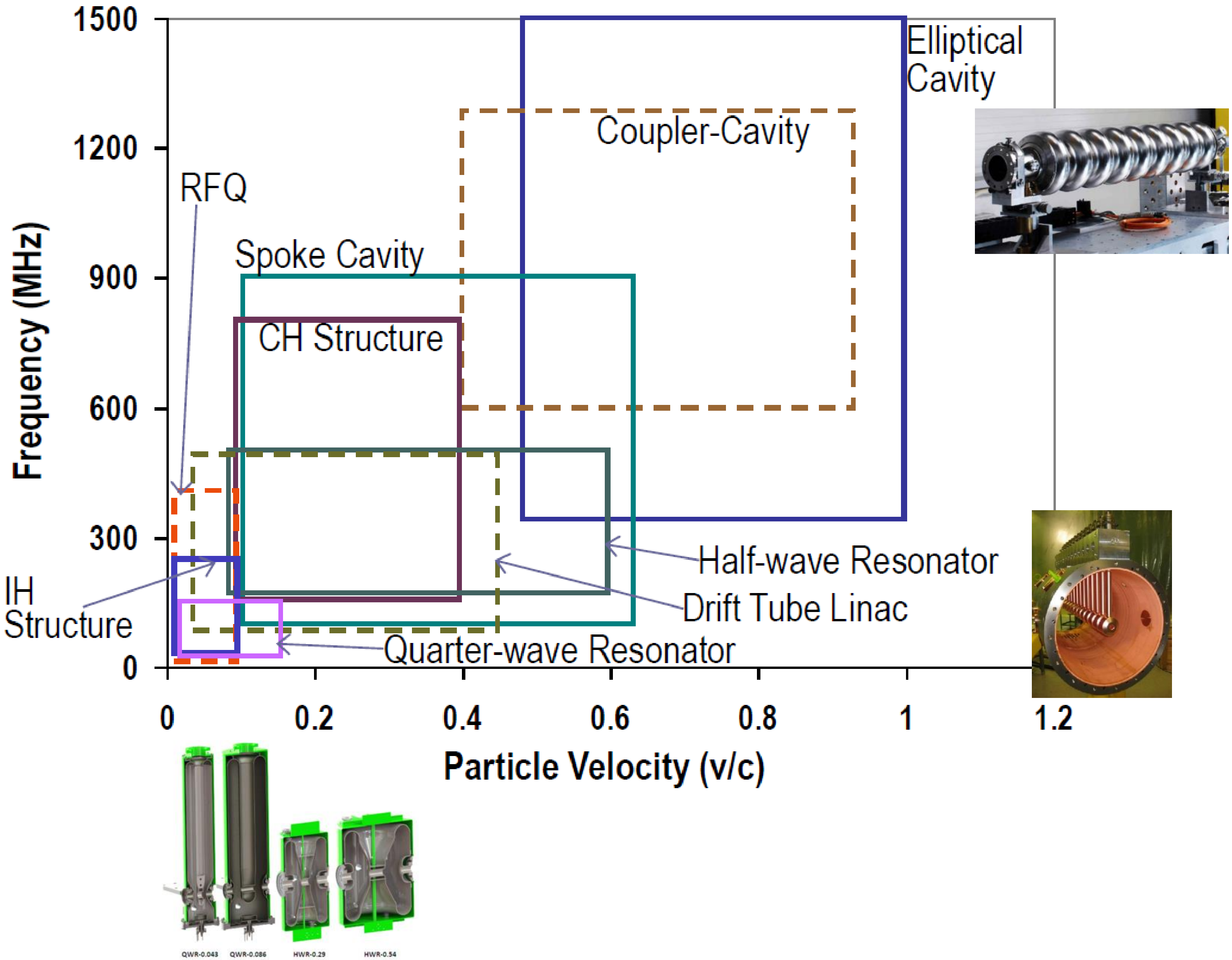
Comparison between Circular Machines

- Isochronous: Arriving at the same time
- Weak transverse focusing
- Essentially no longitudinal focusing
- AG: Alternating Gradient

	bending radius **vs. time**	bending field vs. time	bending field vs. radius	RF frequency vs. time	operation mode (pulsed/CW)	
betatron	→	↗	↘		pulsed	induction
microtron	↗	→	→	→	CW	varying *h*
classical cyclotron	↗	→	→ / ↘ (dashed)	→	CW	simple, but limited E_k
isochronous cyclotron	↗	→	↗	→	CW	suited for high power!
synchro-cyclotron	↗	→	→ / ↘ (dashed)	↘	pulsed	higher E_k, but low P
FFAG	↗ (dashed) / →	→	↗	↗	pulsed	strong focusing!
a.g. synchrotron	→	↗	↑	↗ (dashed) / →	pulsed	high E_k, strong focus

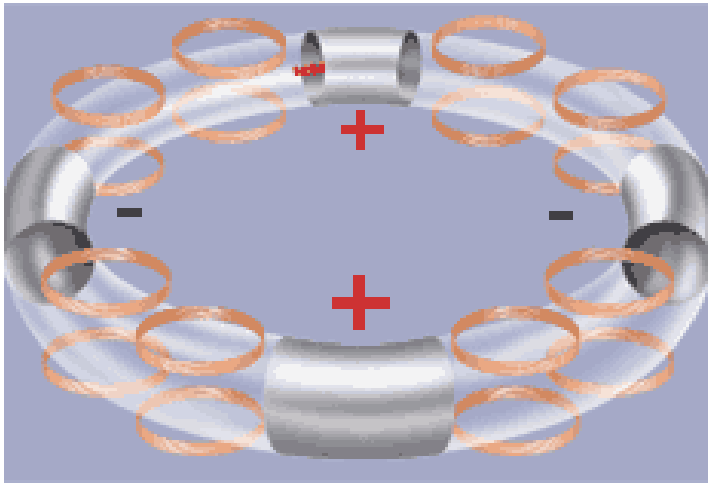
[From PSI]

Comparison between Linac Sturctures



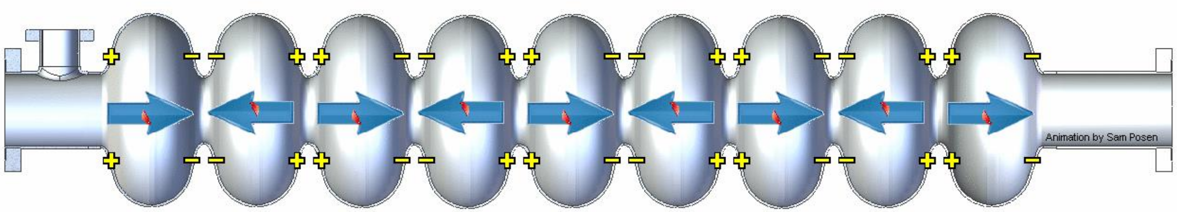
Cartoons Might Be Better!

Harmonic number h = 2



The voltages are swapped to make sure that the positive protons are always leaving a positive electrode. The coils provide a magnetic field that keeps the particles in orbit. Field increases as energy increases.

[From STFC]



- Blue: Electric fields
- Red: Magnetic fields
- Yellow: Charges
- Orange: Beam bunches

Various Actions of Accelerated Beams

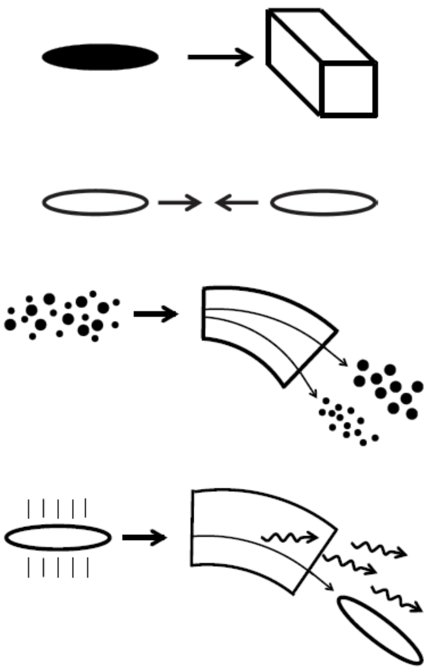


FIGURE 1.4
Uses of accelerated beams — sending to target, colliding with another beam, characterization of the beam or separation into species, generation of useful radiation.

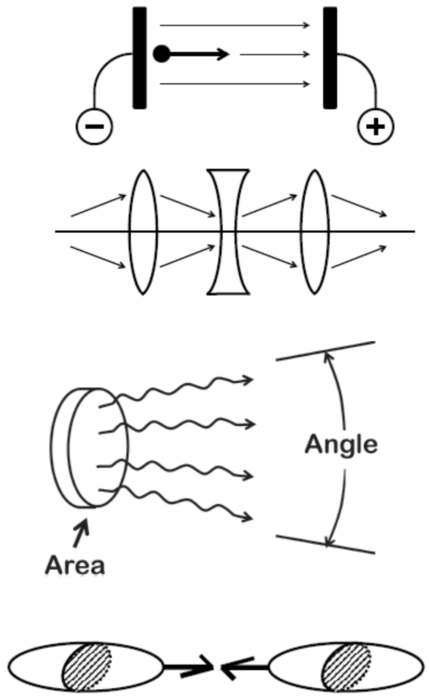


FIGURE 1.5
Actions on accelerated beams — acceleration, focusing, generation of radiation, colliding.

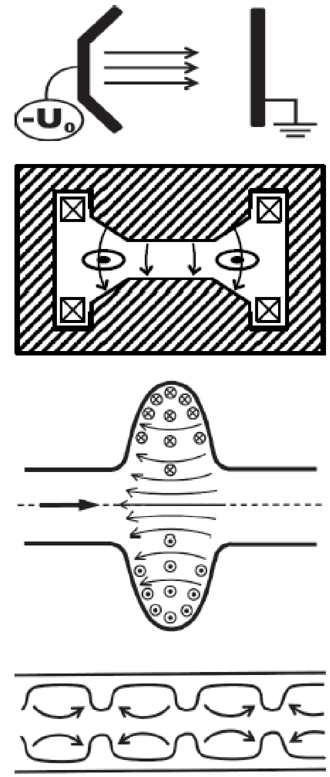


FIGURE 4.13
Electrostatic and betatron acceleration. RF cavity and RF structure.

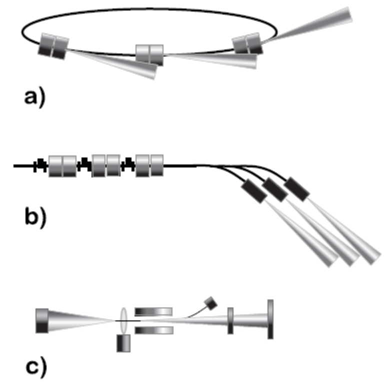


FIGURE 6.19
Light sources' evolution.

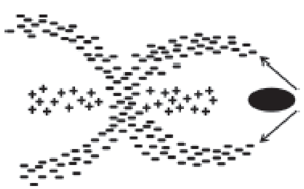


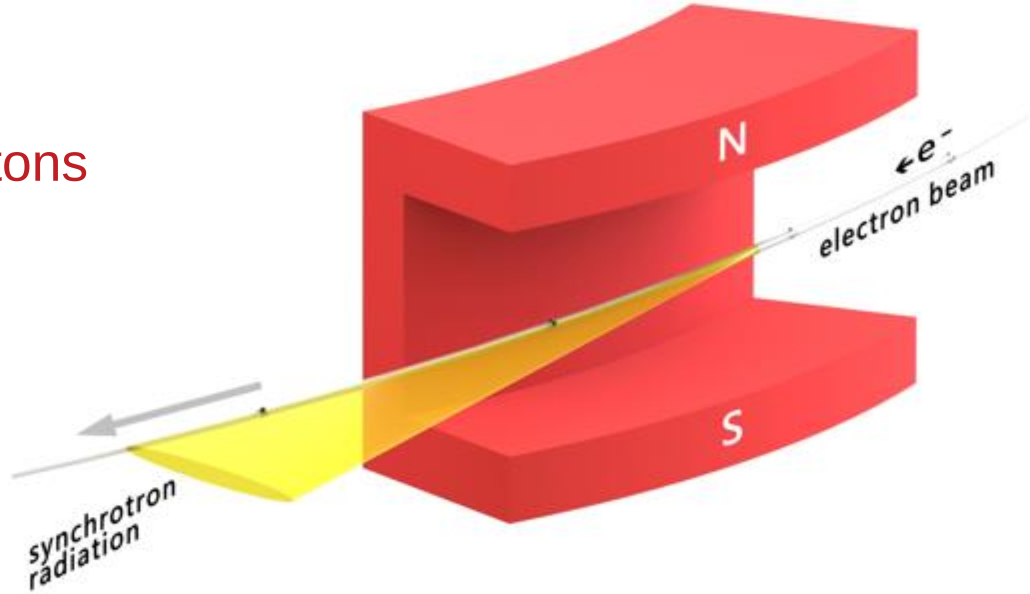
FIGURE 1.15
Plasma acceleration concept.

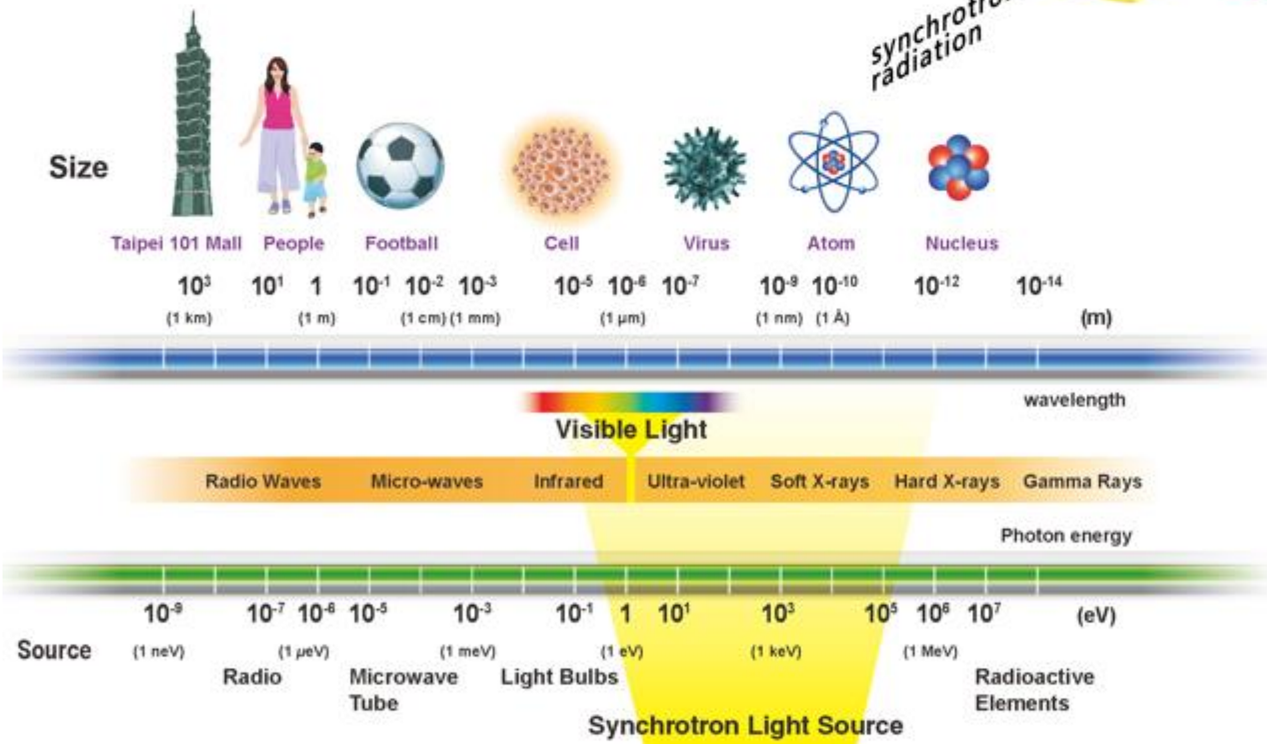
[From "*Unifying Physics of Accelerators, Lasers and Plasma*"]

What can the Accelerator do for us?

What Accelerators Can Do

→ Electron accelerator → Photons

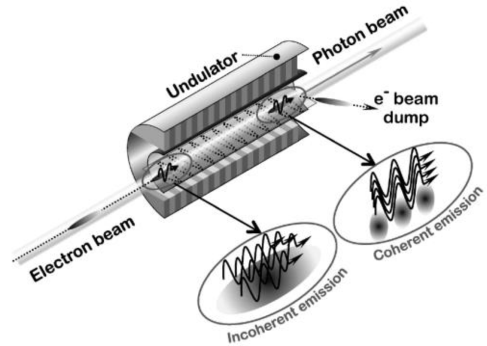


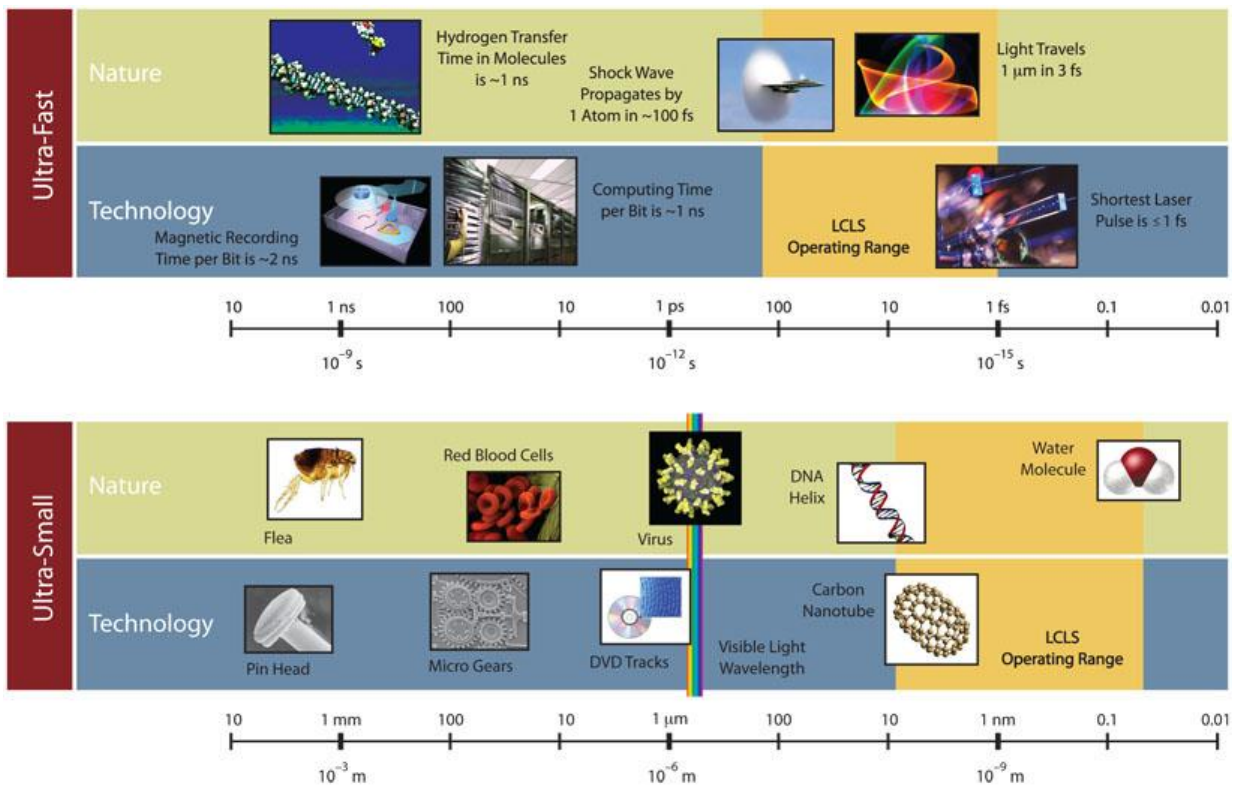


[From NSRRC]

X-ray

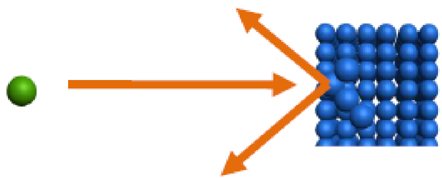
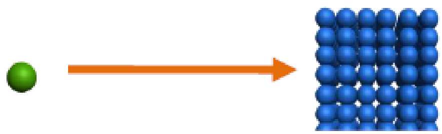
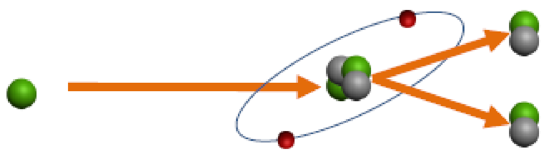
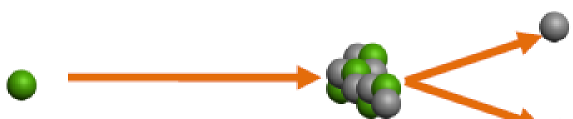
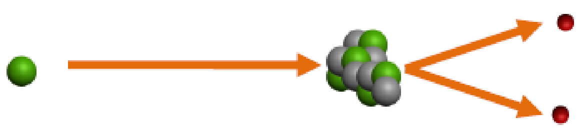
First medical X-ray
by Röntgen in 1895





What Accelerators Can Do

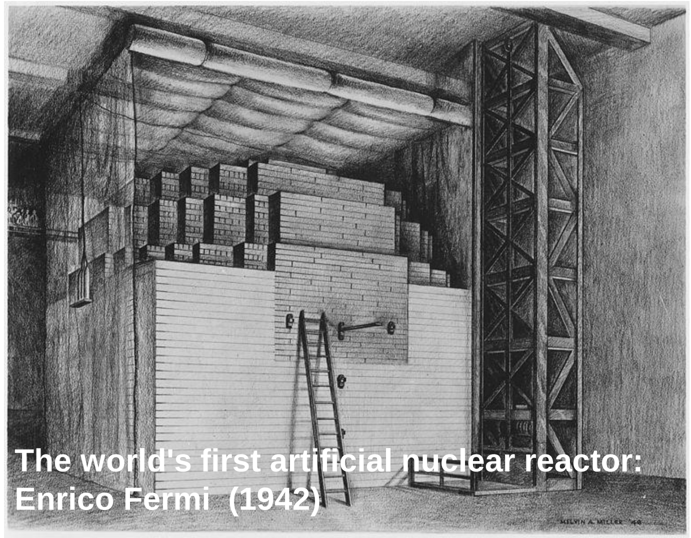
→ Proton / Heavy ion accelerator → Neutron / Secondary particles

입자에너지		기본반응	주요연구
~ 1KeV		**Sputtering** 물질표면의 원자를 낱개로 분리	박막가공 나노가공
~ 10KeV		**Implantation** 물질 속에 투여하여 물질구조와 성질변화	표면 개질 나노결정 반도체 도핑
~ 100MeV		**Nuclear Reaction** 물질의 원자핵과 반응하여 새로운 원소 생성	신종 유전자원 RI 생산 방사선 치료기기
~ 10GeV		**Spallation** 무거운 원자핵을 쪼개서 가벼운 원자 또는 중성자 생성	중성자원 신종 RI 생산
~ 100GeV		**소립자 연구** 원자핵 속의 양성자 중성자를 쪼개 소립자 생성	신종 소립자 탐색 핵 및 고에너지 물리

[From KOMAC]

Neutron

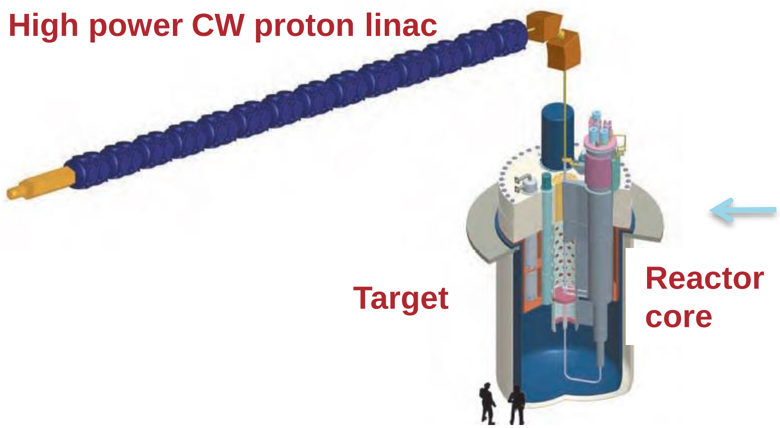
Reactor:

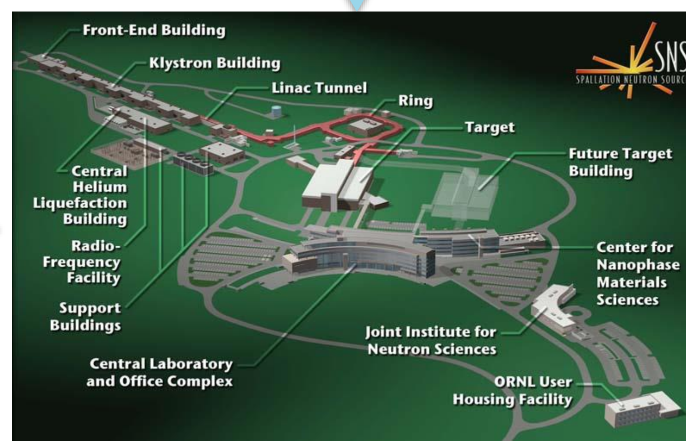


The world's first artificial nuclear reactor: Enrico Fermi (1942)

Neutron scattering: Clifford G. Shull, Bertram N. Brockhouse

Accelerator:





→ Subcritical nuclear reactor

→ Intense pulsed neutron source

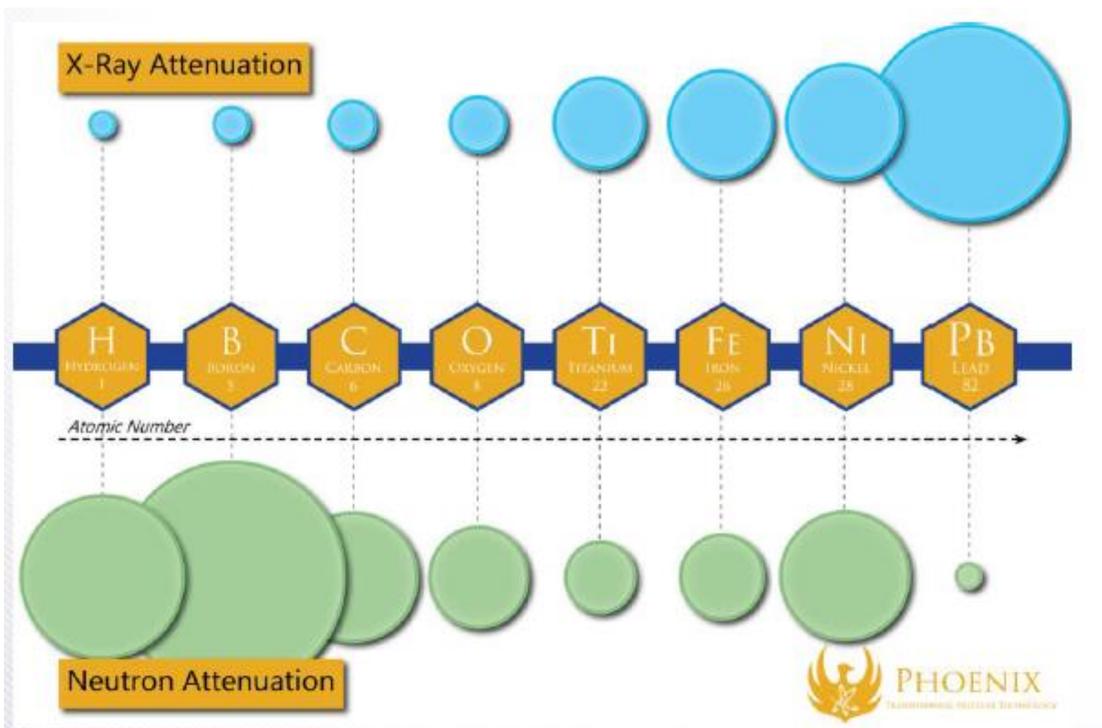
X-ray VS Neutron

방사광 (X-ray)

- 방사광가속기에서 발생하는 X-ray는 단백질 같은 생체 물질을 투과할 때 원자구조를 손상시킴
- 단백질 구조분석 시 X-ray는 수소원자를 투과하여 수소원자 위치를 찾기가 어려움

중성자

- 원자구조를 손상시키지 않음 → 백신개발을 위한 손상되지 않은 바이러스 구조분석에 매우 유용
- 방사광가속기의 X-ray보다 단백질내부의 수소원자의 위치를 더욱 정확하게 찾아줌
- 방사광가속기와 중성자빔 이용시설은 실험결과의 신뢰도를 높이기 위한 상호 보완적이 시설



[From KOMAC]

What Accelerators Can Do

Phys. Perspect. 13 (2011) 146–160
© 2011 Springer Basel AG (outside the USA)
1422-6944/11/020146-15
DOI 10.1007/s00016-010-0049-y

Physics in Perspective

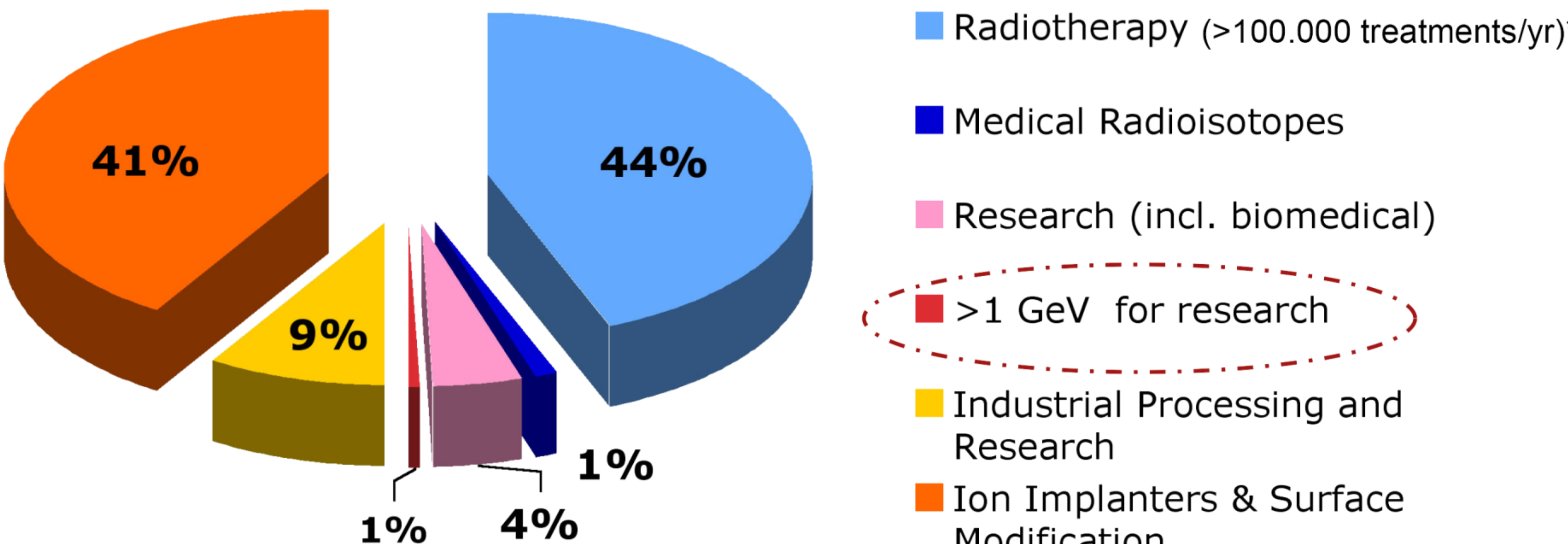
The Influence of Accelerator Science on Physics Research

Enzo F. Haussecker and Alexander W. Chao*

"It is estimated that accelerator science has influenced almost 1/3 of physicists and physics studies, and on average contributed to physics Nobel Prize-winning research every 2.9 years."

What Accelerators Can Do

Number of accelerators worldwide ~ 26,000



Annual growth is several percent

Sales >3.5 B$/yr

Value of treated good > 50 B$/yr **

Why You Can't Live Without A Particle Accelerator

TECHNOLOGY

10 Reasons Why You Can't Live Without A Particle Accelerator

Particle accelerators can make you healthy and wealthy.

BY LINA ZELDOVICH   MAY 30, 2014Illustrations By James Walton

https://nautil.us/10-reasons-why-you-cant-live-without-a-particle-accelerator-2047/

1. Is your milk carton sealed? An accelerator did it.

2. A lot of natural gas is wasted. Accelerators can fix that problem.

3. Want your spinach *E. coli* free? Accelerators may have cleaned it.

4. Can coal be a clean fuel? Yes, if you attach an accelerator to the smokestack.

5. Antibiotics harm fish? Accelerators can turn pharmaceuticals into fertilizer.

6. Your new computer has arrived. Thank an accelerator for building it.

7. Accelerators make us live longer. They kill cancer.

8. Can nuclear reactors be accident-proof? Yes, if particle accelerators control them.

9. The world still runs on oil. Accelerators can find it.

10. Accelerators keep watch for weapons of mass destruction.

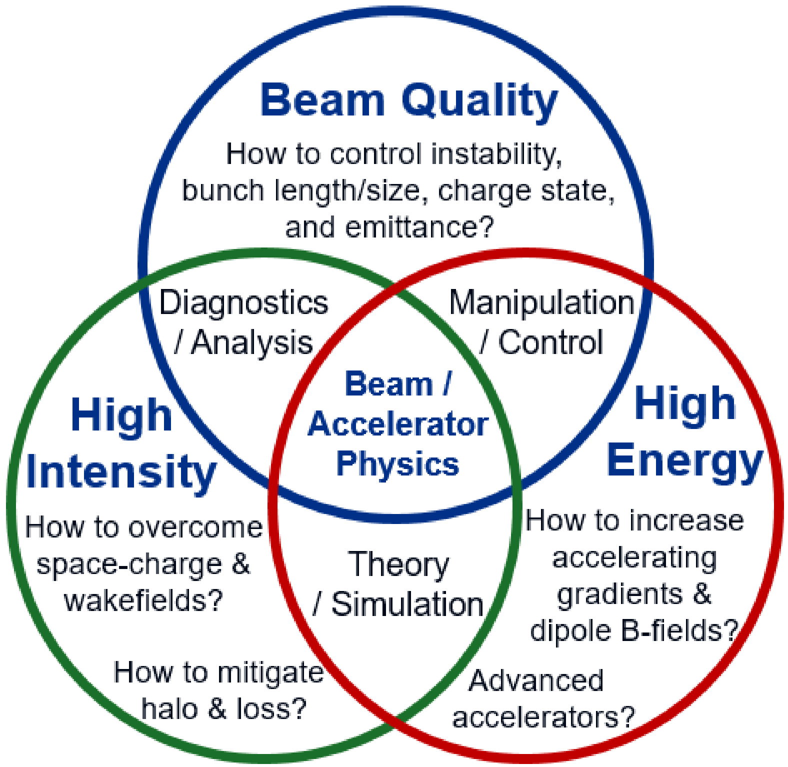
What are the frontiers of the accelerator?

Frontiers of Accelerators

→ Science goals/Society needs push limits of accelerator performance

Driving comfort/ Option

Capacity



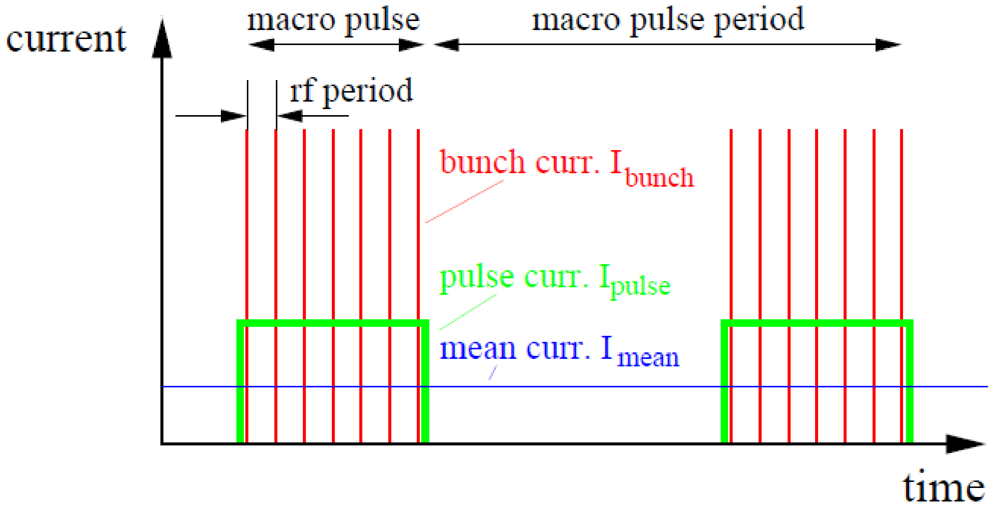
Speed

Important Figures of Merit

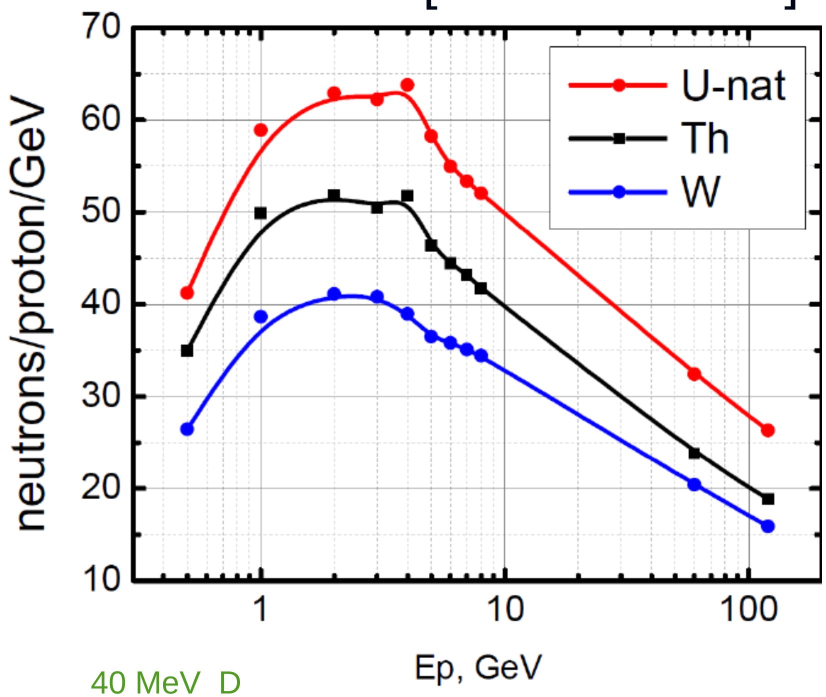
- Neutron source: Power

$$P[\mathrm{MW}] = I_{\mathrm{pulse}}[\mathrm{mA}] \times E[\mathrm{GeV}] \times \mathrm{Duty}[\%]$$

$$\mathrm{Duty} = f_{\mathrm{rep}} T_{\mathrm{pulse}}$$



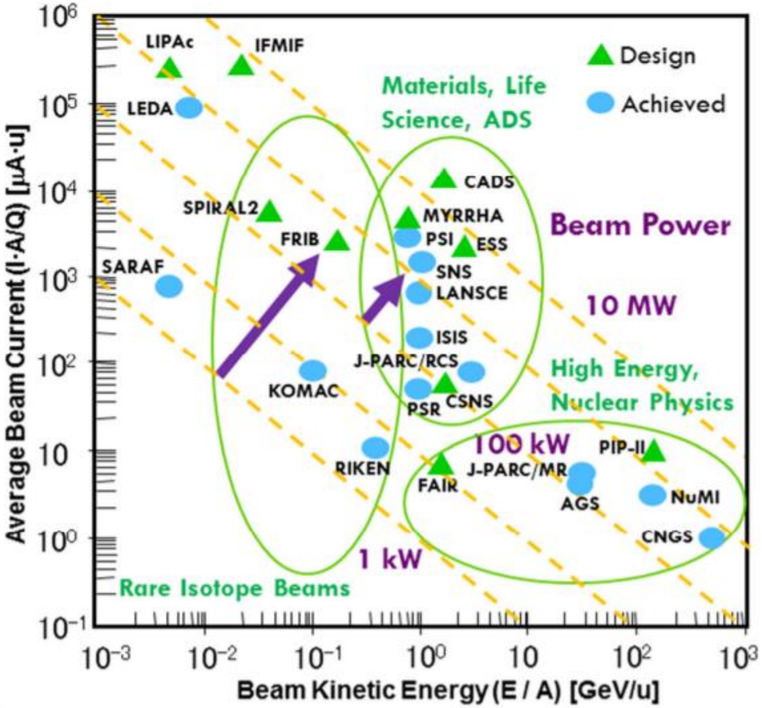
[From Fermilab]

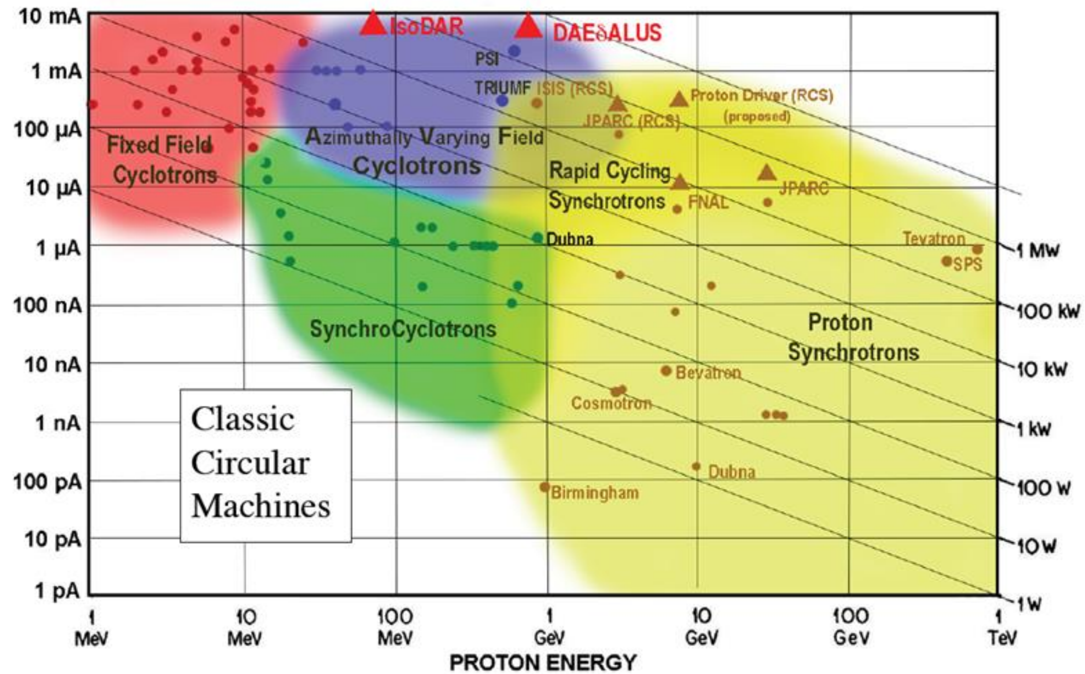


40 MeV D
for fusion neutron spectrum

Power

Space charge issues: ≤10 mA for cyclotron

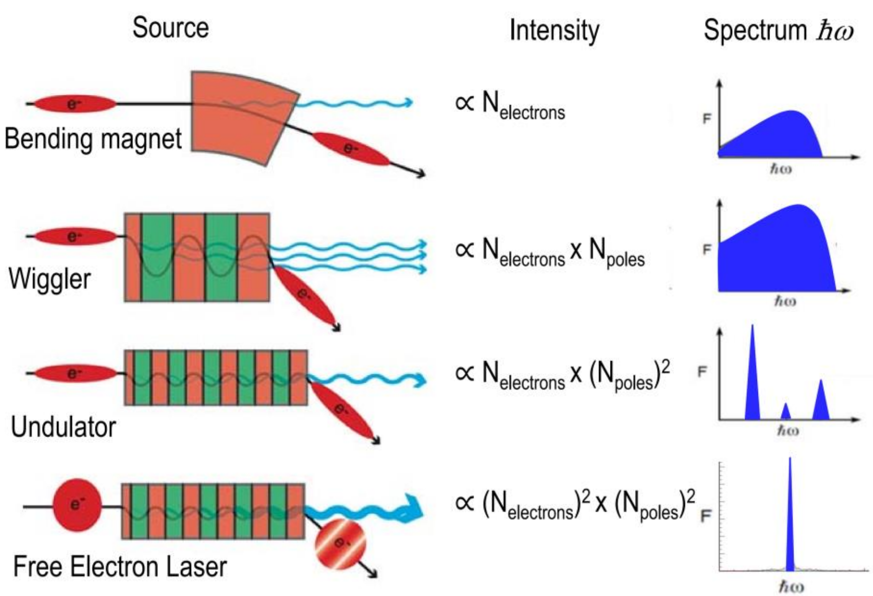


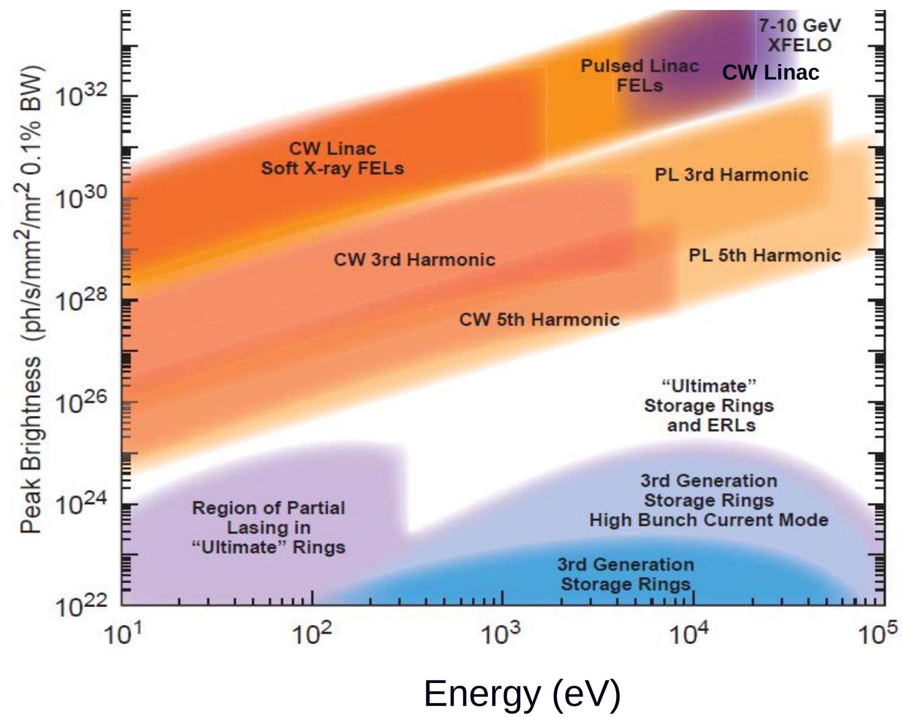


Important Figures of Merit

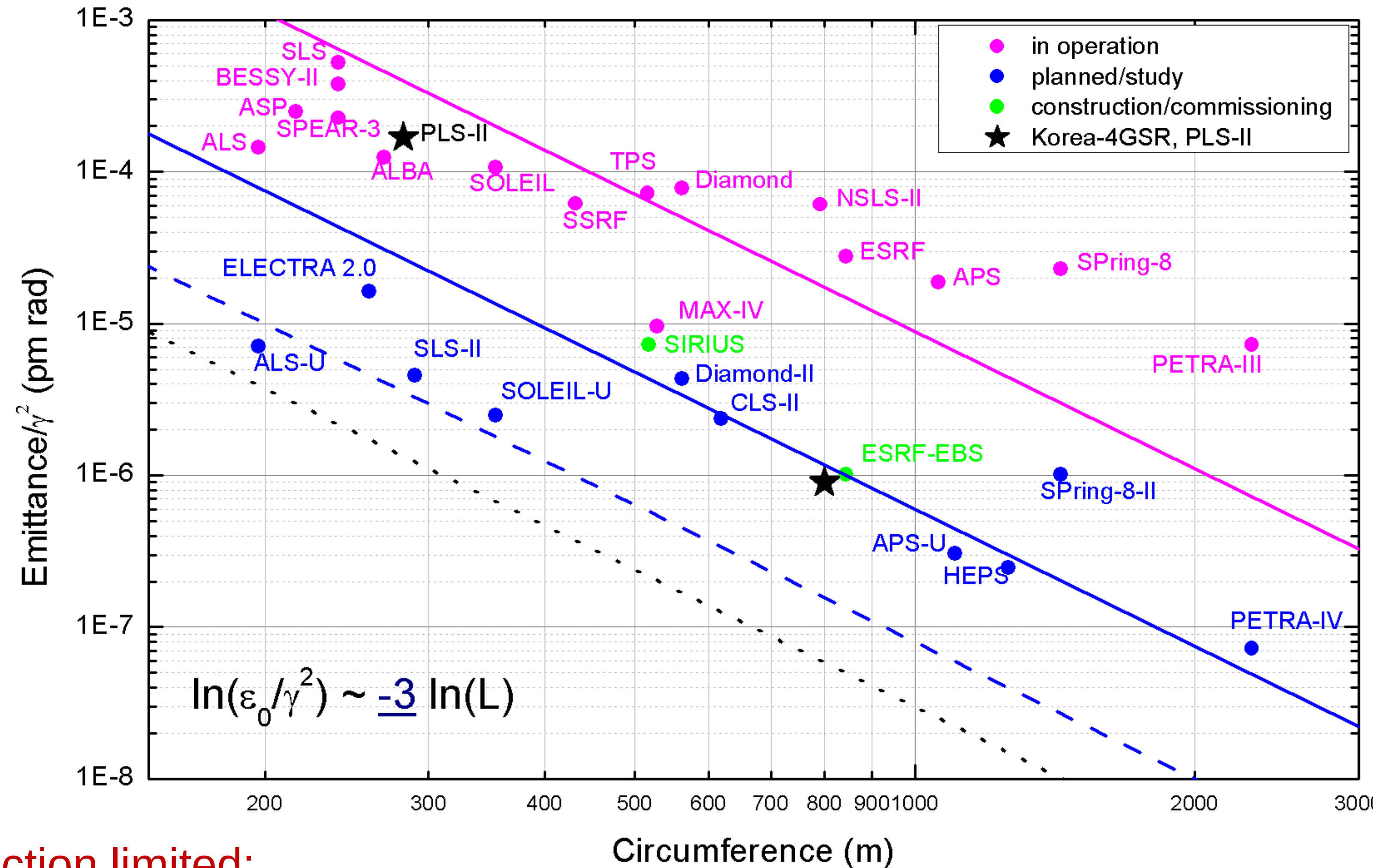
- Light source: Brightness (Brillance)

$$B[\#/\mathrm{s}/\mathrm{mm}^2/\mathrm{mr}^2/0.1\%\mathrm{BW}] = \frac{d^4 N_{photon}}{dtdSd\Omega(d\lambda/\lambda)} \propto \frac{N_{beam}}{\epsilon_x \epsilon_y}$$





Emittance



Diffraction limited:

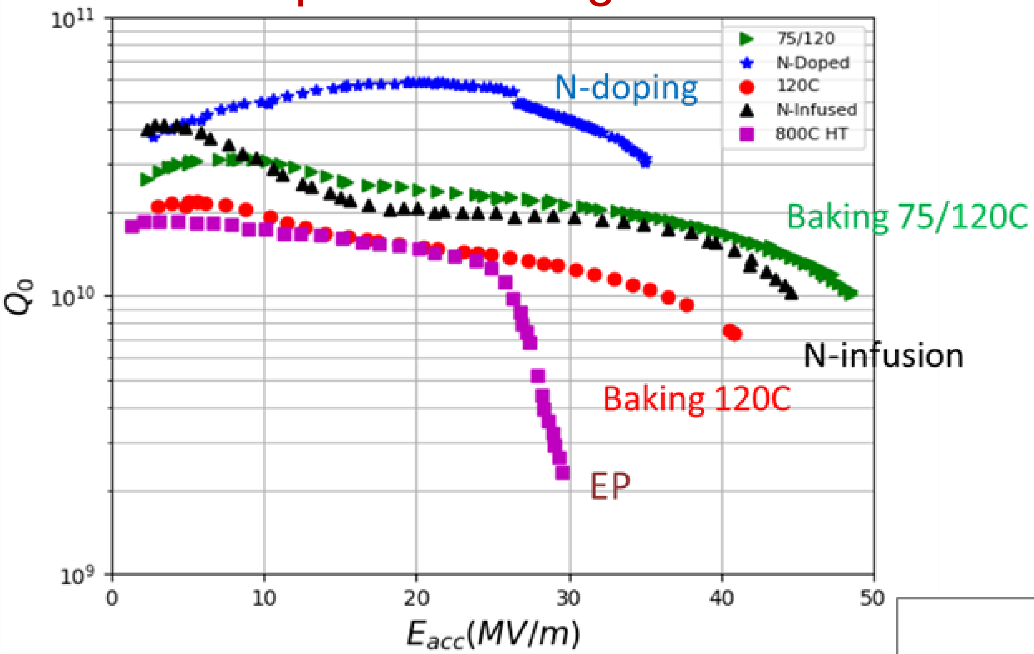
$$\epsilon_y \leq \epsilon_x \approx \frac{\lambda}{4\pi}$$

Quantum excitation + Dispersion
~ Radiation damping

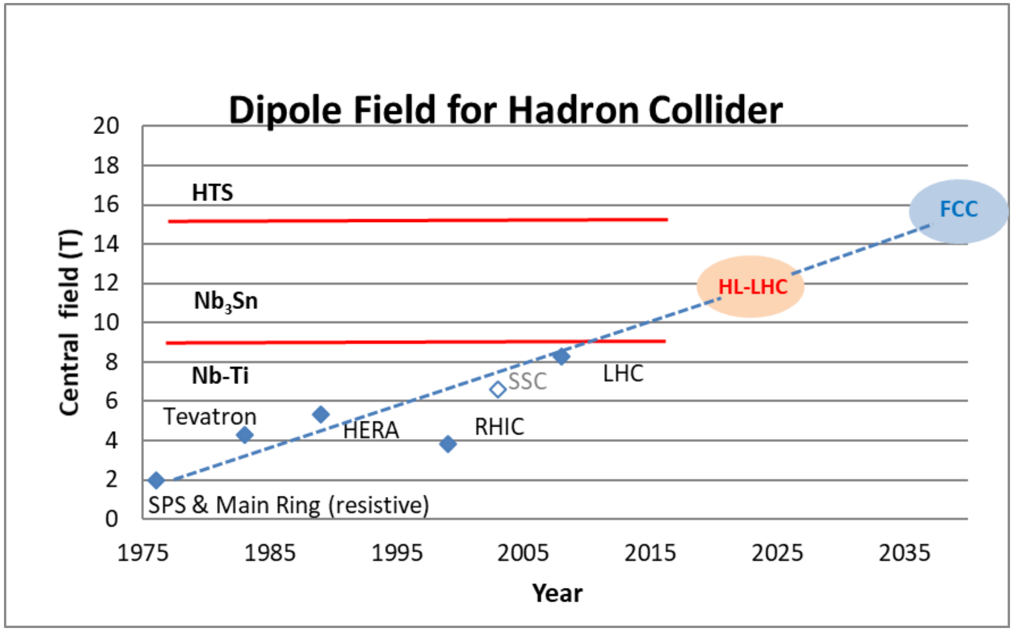
[From PAL]

Technology

Superconducing RF



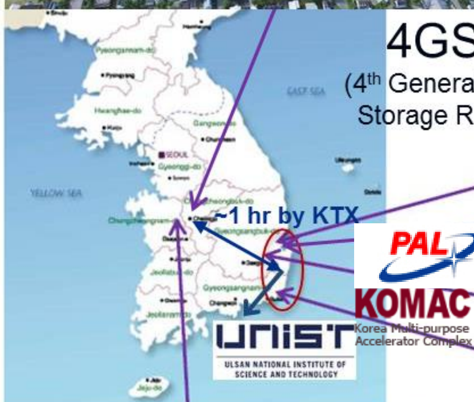
Superconducing Magnet



Large Accelerators in Korea

4GSR

(4th Generation Storage Ring)



2.5 → 3 GeV
NC → SC

PLS II

(Pohang Light Source)

PAL XFEL

(Pohang Accelerator Lab. X-ray Free Electron Laser)

RISP

(Rare Isotope Science Project)

SGCC-HITS

(SNUH Gijang Cancer Center of Heavy Ion Therapy and Study)

KOMAC

(Korea Multi-purpose Accelerator Complex)

Large Accelerators in Korea

Parameter	PLS-II	KOMAC	PAL-XFEL	RAON
Species	Electron	Proton	Electron	Proton ~ Heavy ion
Energy	3 GeV	100 MeV	10 GeV	200 MeV/u for U^{79+}
Beam current	400 mA	20 mA (1.33 ms)	3 kA (0.2 nC/100 fs)	8 pμA U^{79+}
Rep. Rate	499.973 MHz (ring)	60 Hz	120 Hz	CW
Accelerating Structure	NC S-band (linac) SCRF (ring)	Vane-type RFQ 350 MHz DTL	3 Bunch Compressor 2.856 GHz (S-band)	SCRF: QWR (81.25 MHz), HWR (162.5 MHz), SSR (325 MHz)
Research Areas	Condensed matter, Surface/Cluster, Material science, Chemistry/Biology, Energy/Medicine	Nano, Bio, IT, Space, Radiation, Medical etc.	Atomic/Molecular, Condensed matter, Surface/cluster, Material science, Chemistry/Biology, Non-equilibrium plasma, Warm-dense plasma	Nuclear physics, Bio-medical science, Material science, Neutron science
	~Typical 3GSR	~ front end of SNS/ORNL	~ LCLS/SLAC	~ FRIB/MSU

What is accelerator physics?

Accelerator Physics from Wikipedia

Accelerator physics

From Wikipedia, the free encyclopedia

> This article includes a list of general references, but it remains largely unverified because **it lacks sufficient corresponding inline citations.** Please help to improve this article by introducing more precise citations. *(January 2020) (Learn how and when to remove this template message)*

Accelerator physics is a branch of applied physics, concerned with designing, building and operating particle accelerators. As such, it can be described as the study of motion, manipulation and observation of relativistic charged particle beams and their interaction with accelerator structures by electromagnetic fields.

It is also related to other fields:

- Microwave engineering (for acceleration/deflection structures in the radio frequency range).
- Optics with an emphasis on geometrical optics (beam focusing and bending) and laser physics (laser-particle interaction).
- Computer technology with an emphasis on digital signal processing; e.g., for automated manipulation of the particle beam.

The experiments conducted with particle accelerators are not regarded as part of accelerator physics, but belong (according to the objectives of the experiments) to, e.g., particle physics, nuclear physics, condensed matter physics or materials physics. The types of experiments done at a particular accelerator facility are determined by characteristics of the generated particle beam such as average energy, particle type, intensity, and dimensions.

Accelerator VS Plasma Physics

To a large degree, accelerator physics and plasma physics are quite similar. Both involve nonlinear dynamics (single-particle effects) and collective instabilities (multiparticle effects). However, there is an important difference,

$$\text{beam self fields} > \text{external applied fields} \qquad \text{(plasma)}\,,$$
$$\text{beam self fields} \ll \text{external applied fields} \qquad \text{(accelerators)}\,.$$

This difference means *perturbation techniques* are applicable to accelerators with

$$\text{unperturbed motion} = \text{external fields (magnets, RFcavities)},$$
$$\text{perturbation} = \text{self fields, wakefields}\,.$$

In fact, in accelerator physics, a first order perturbation often suffices. This makes accelerators much cleaner physical system to study compared to typical plasma systems, although the mathematics and physics tools are quite similar.

[From A. Chao]

Publish or Perish

The Nobel Prize in Physics 1984
Carlo Rubbia, Simon van der Meer

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Simon van der Meer - Facts

Simon van der Meer

Born: 24 November 1925, the Hague, the Netherlands

Died: 4 March 2011, Geneva, Switzerland

Affiliation at the time of the award: CERN, Geneva, Switzerland

Prize motivation: "for their decisive contributions to the large project, which led to the discovery of the field particles W and Z, communicators of weak interaction"

Field: experimental particle physics

Prize share: 1/2

Discovered the W and Z Particles

According to modern physics, there are four fundamental forces in nature. The weak interaction, responsible for e.g. the beta-decay of nuclei is one of them. According to the theory forces are mediated by particles: the weak interaction by the so called heavy bosons W, Z, about 100 times more massive than the proton. Simon van der Meer developed a method to accumulate a large number of energetic antiprotons in an accelerator ring. These were used in experiment where antiprotons and protons of high energy were brought to collide. In these experiments W and Z particles were discovered in 1983.

"Accelerator physics—a field where often work of the highest quality is buried in lost technical notes or even not published;
one has only to think of Simon van der Meer's Nobel prize work on stochastic cooling — unpublished in any refereed journal."

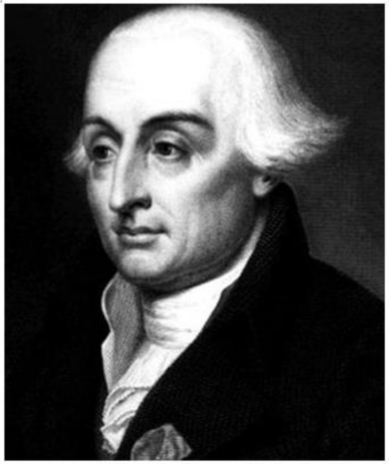
attitude at some laboratories:

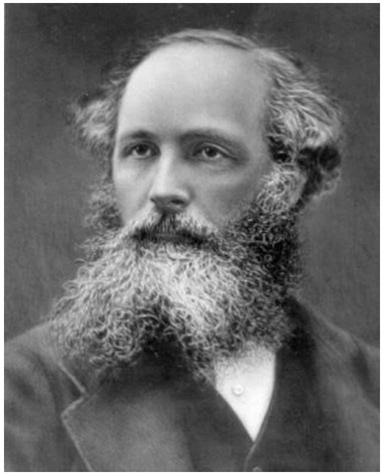
"... if you have time to write papers you do not have enough real work to do..."

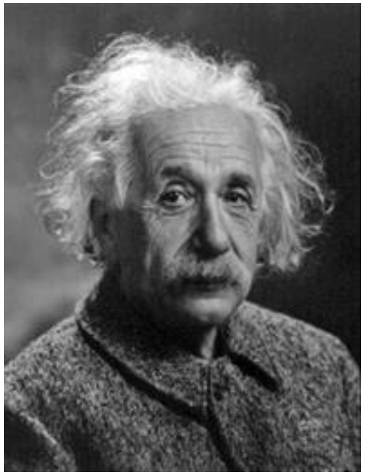
"We publish in concrete and steel!", John B. Adams

(CERN director)


My downfall
was
Newton's
inspiration!



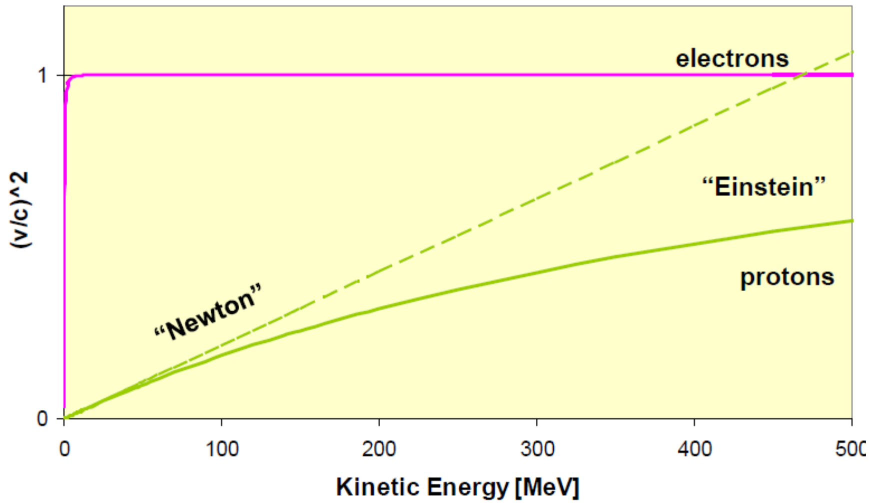




Main Results of Special Relativity

- Relativistic parameters: Don't be confused with Twiss parameters.

$$\beta = \frac{v}{c}, \quad \gamma = \frac{1}{\sqrt{1-\beta^2}} \approx 1 + \frac{1}{2}\beta^2, \quad \beta = \sqrt{1-\frac{1}{\gamma^2}} \approx 1 - \frac{1}{2\gamma^2}$$



- The total energy, mechanical momentum, and kinetic energy of a rest mass m:

$$U = \gamma m c^2, \quad p = \gamma m \beta c, \quad W = (\gamma - 1) m c^2 \longrightarrow \frac{1}{2} m v^2$$

- The relation between total energy and momentum in the absence of EM fields:

$$U = \sqrt{p^2c^2 + (mc^2)^2}, \quad \text{or} \quad \gamma^2 = (\beta\gamma)^2 + 1$$

Energy and Mass Units

- To describe the energy of individual particles, we use the eV, the energy that a unit charge

$$e = 1.6 \times 10^{-19} \text{ Coulomb}$$

gains when it falls through a potential, $\Delta\phi$ = 1 volt.

$$1 \text{ eV} = 1.6 \times 10^{-19} \text{ Joule}$$

- We can use Einstein's relation to convert rest mass to energy units.

$$E = mc^2$$

- For electrons,

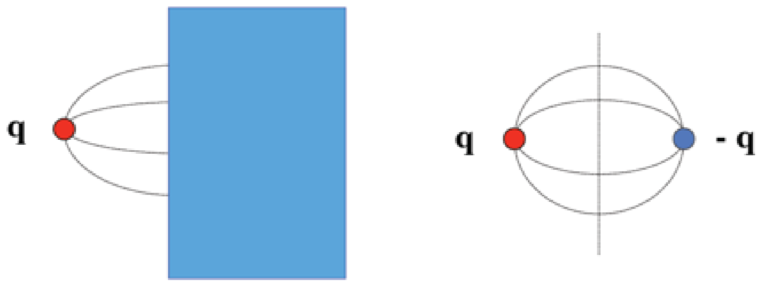
$$E = (9.11 \times 10^{-31} \text{ kg}) \times (3 \times 10^8 \text{ m/s})^2 = 0.512 \text{ MeV}$$

- For protons,

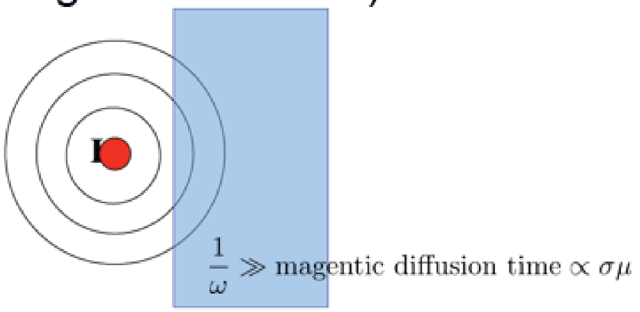
$$E = (1.67 \times 10^{-27} \text{ kg}) \times (3 \times 10^8 \text{ m/s})^2 = 938 \text{ MeV}$$

Boundary Conditions

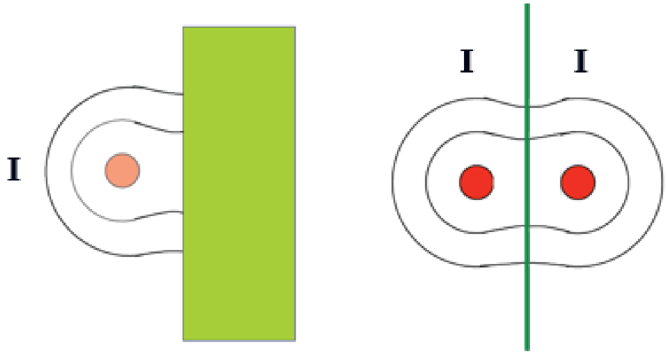
- Electric field near a good conductor:



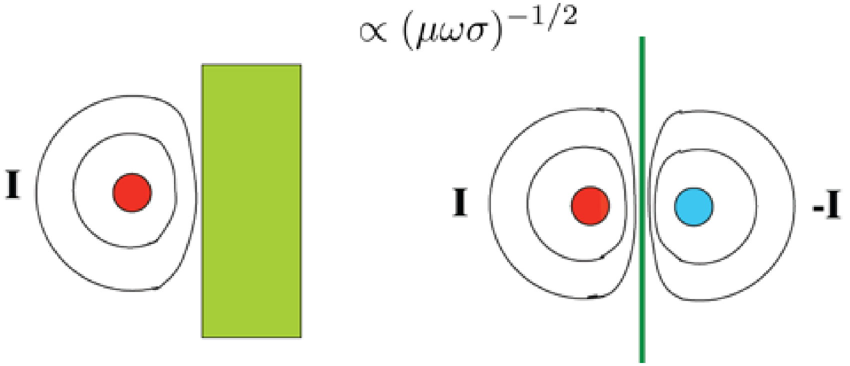
- Static magnetic field near $\mu_r \approx 1$(even in the case of a good conductor)



- Static magnetic field near $\mu_r \gg 1$(i.e., ferromagnetic material)



- Time-varying magnetic field near a good conductor (i.e., small skin depth):



Q: 다음은 한국원자력연구원 양성자가속기의 파라미터입니다. 최대 빔파워는 얼마일까요?

Parameters	Value
Output energy (MeV)	100
Macro pulse current (mA)	0.1 ~ 20
Macro pulse width (ms)	0.05 ~ 1.33
Maximum repetition rate (Hz)	60