입자 가속기와 과학기술의 발전:
전자부터 빅데이터까지

박 향 규
고려대학교 세종캠퍼스 가속기과학과

2026 가속기스쿨, 고대세종캠퍼스

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천사와 악마 (2009년 개봉)

CERN에서 실바노 신부와 비토리아 베트라 박사는 반물질 용기 3개를 만든다. 실바노가 살해되고 용기 중 하나가 도난을 당한다. 가톨릭교회는 교황 비오 16세의 갑작스러운 죽음을 애도하고 바티칸 시국의 후임자를 선출하기 위한 교황청 콘클라베를 준비를 한다. 궁무처장인 패트릭 맥케나 신부가 바티칸을 장악한다. 교황 후보 프리페리티 4명은 일루미나티를 대표한다고 주장하는 한 남자에게 납치당한다.

https://www.youtube.com/watch?v=ZhbuaN40CfA

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- 용기 1개당 1그램의 반물질
  - CERN 가속기로 10^5/s 반양성자 생성가능
  - 10^5/s x 3.16×10^7 s/year = 3.16×10^{12}/year

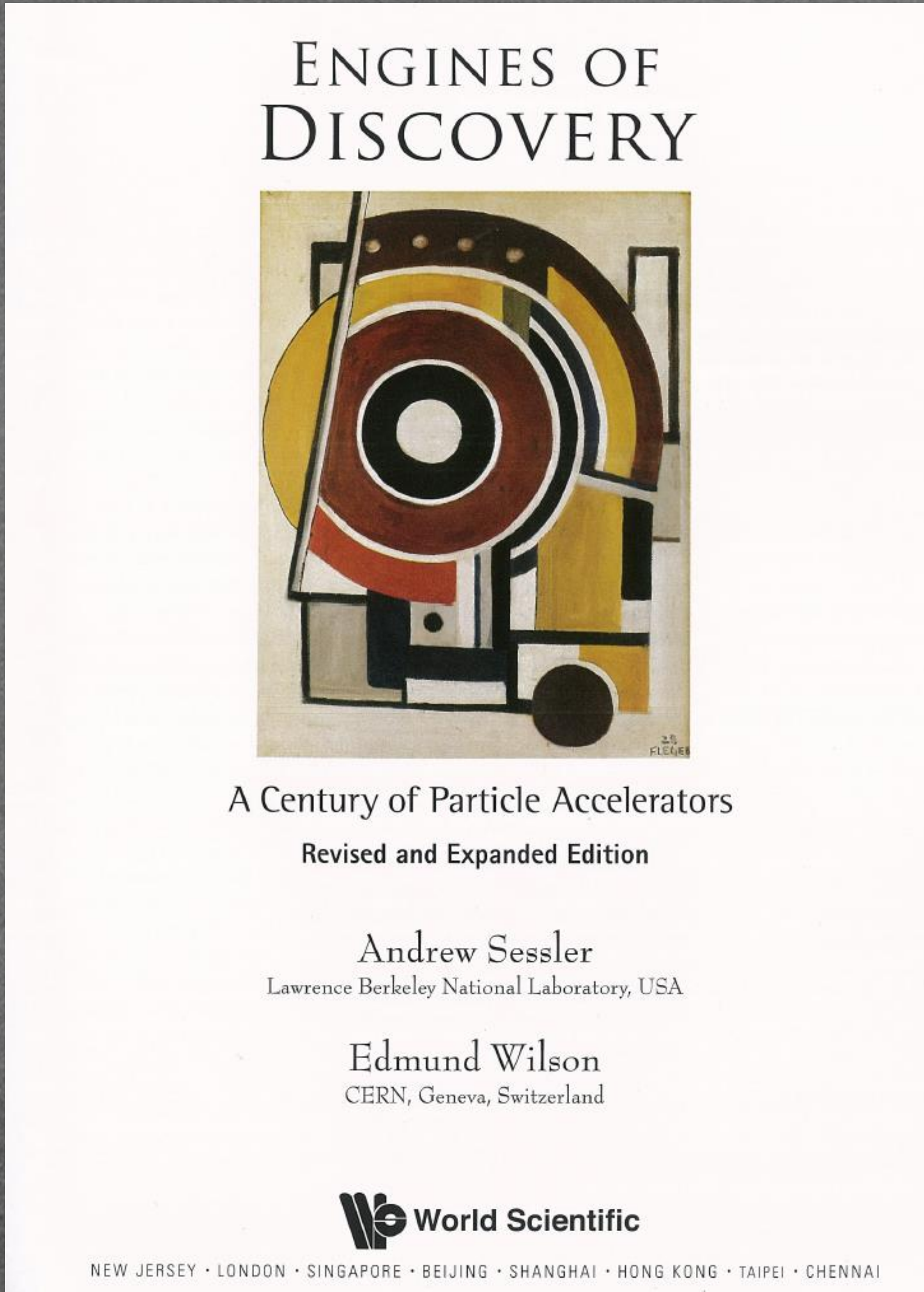
$$\frac{6.02\times10^{23}\ \text{반양성자/g}}{3.16\times10^{12}/\text{year}} \approx 2 \times 10^{11}\ \text{year/g}$$

우주의 나이: 1.38×10^{10} year

가속기 활용분야

전세계 약 40,000여대: ~80(3)대(국내)

연구		6 %
	Particle Physics	0,5%
	Nuclear Physics, solid state, materials	0.2 – 0.9%
	Biology, Material Science, Chemistry, etc.	5%
의료		35%
	Diagnostics/treatment with X-ray or electrons	33%
	Radio-isotope production	2%
	Proton or ion treatment	0.1%
산업		<60%
	Ion implantation	34%
	Cutting and welding with electron beams	16%
	Polymerization	7%
	Neutron testing	3.5%
	Non destructive testing	2.3%

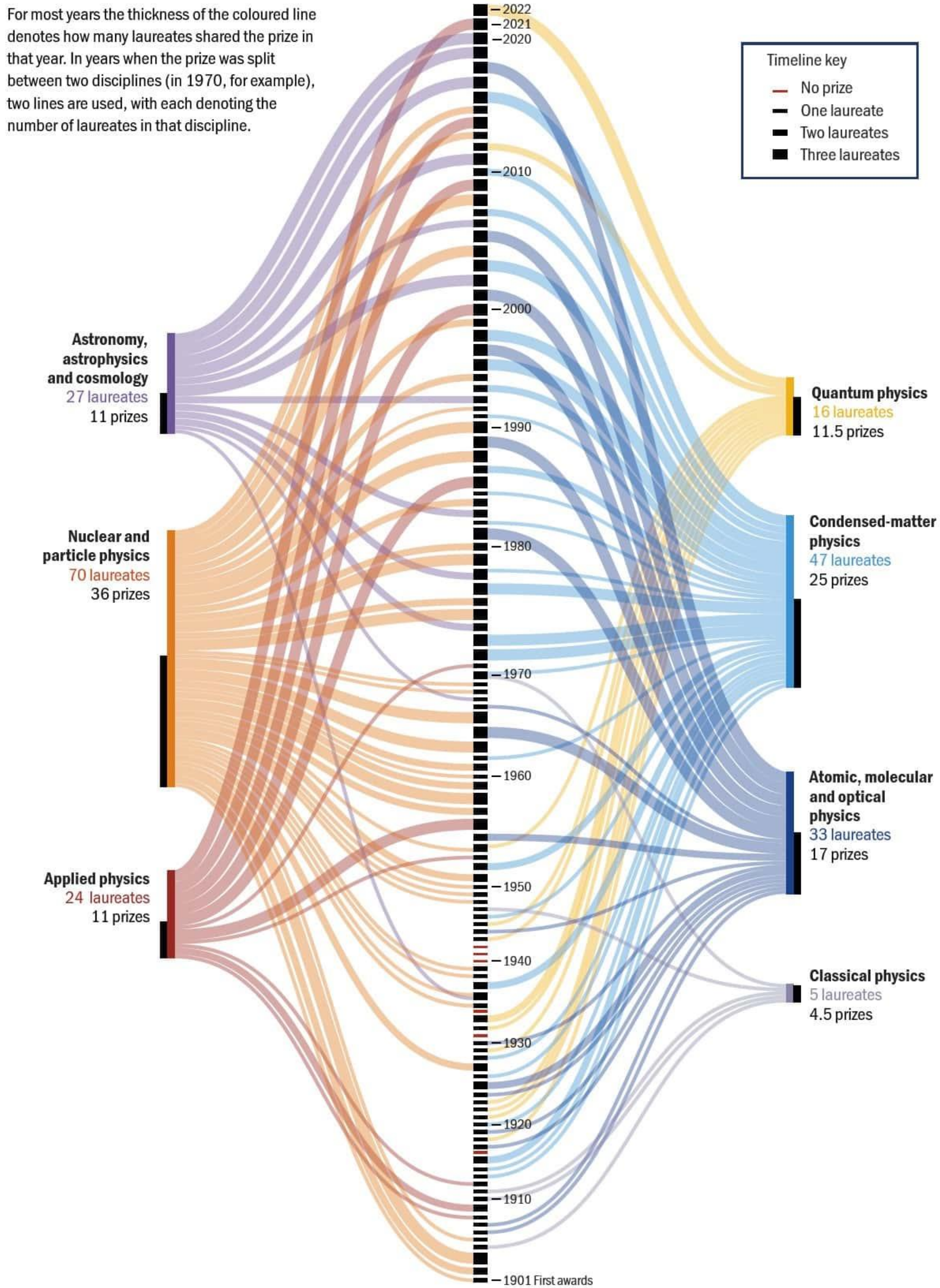


발표 개요

- 입자 가속기의 발전
- 입자 물리학
- 방사광 가속기
- 의료용 가속기

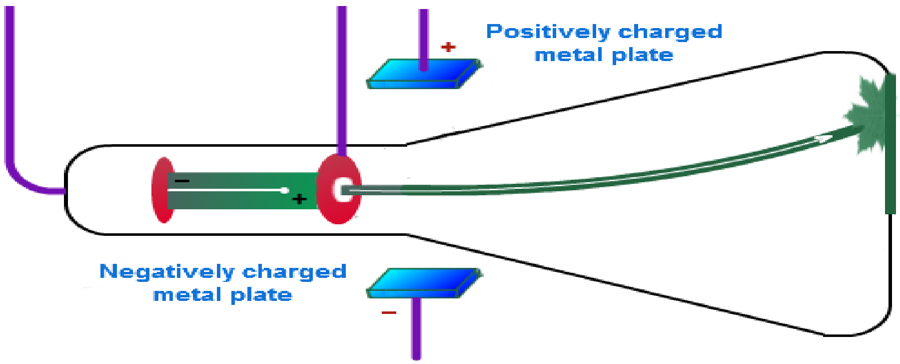
1901년~2022년 노벨 물리학상

분야	비율(%)
핵·입자	31.5
고체	21.2
원자	14.9
천체	12.2
응용	10.8
양자	7.2
고전	2.3



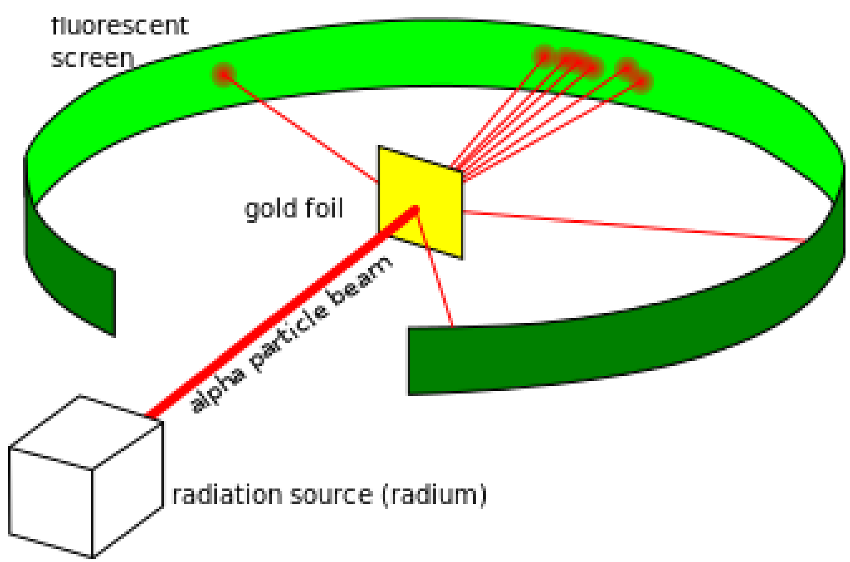
전자및 원자핵의 발견

- 전자: J.J. Thompson (1897년)



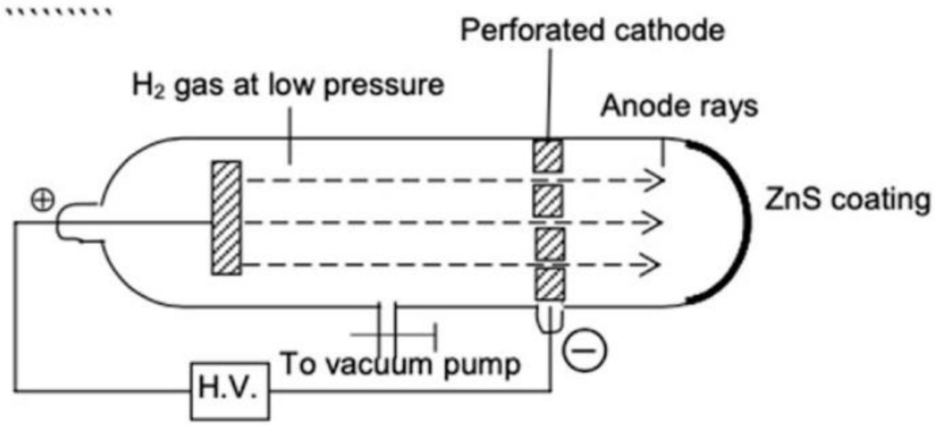
m_e = 9.109 x 10^{-31} kg
= 0.511 MeV/c^2
전하량 = -1.602x10^{-19} C

- 원자핵: Ernest Rutherford (1908년~1913년)



양성자의 발견

- Eugen Goldstein 실험 (1886년): positively charged particle



Production of anode rays

- Ernest Rutherford 실험 (1917년):

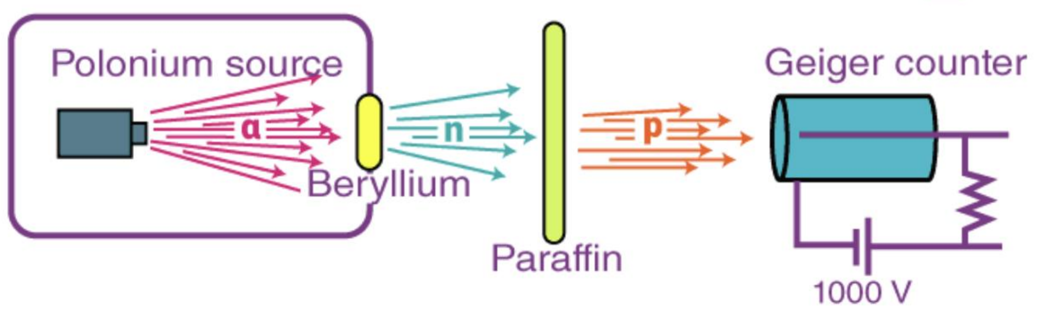
Reaction: α N(공기) → O p

m_p = 1.673 x 10^{-27} kg
= 938.272 MeV/c^2

전하량 = + 1.602 x 10^{-19} C

중성자의 발견

- Rutherford 양성자 발견 후 원자핵은 양성자로 생각
  -> 문제점: $m_{He} \approx 2\ m_H$ (실제 $m_{He} \approx 4\ m_H$)
  -> 중성자 존재 제안 ($m_n \approx m_p$)
- James Chadwick 1932년 실험적으로 중성자 발견

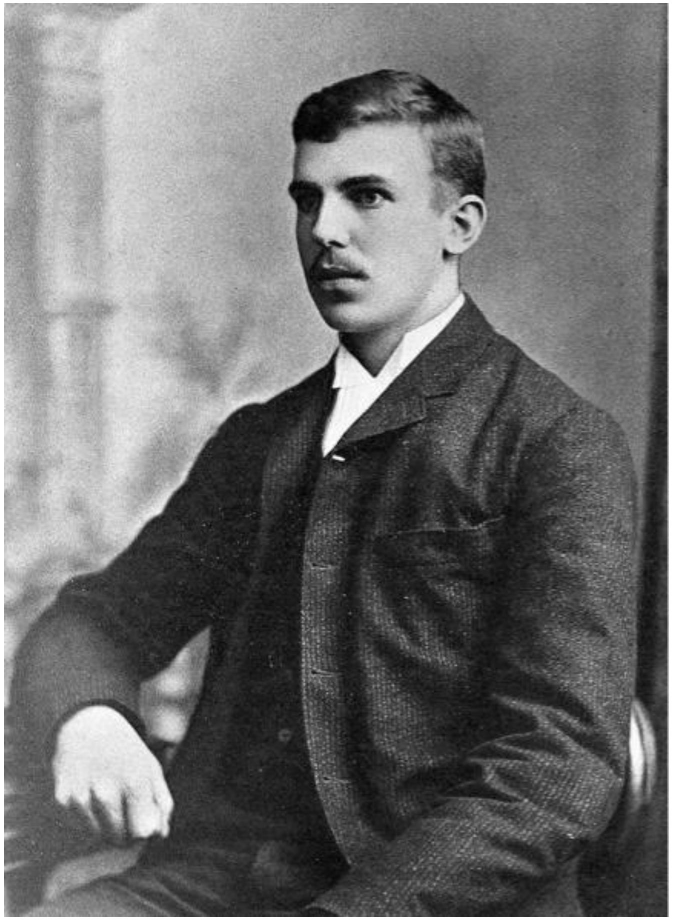


Discovery of neutron

m_n = 1.675 x 10^{-27} kg
= 939.565 MeV/c^2

전하량 = 0

Mean lifetime(수명): 879.4(6) s (free neutron)



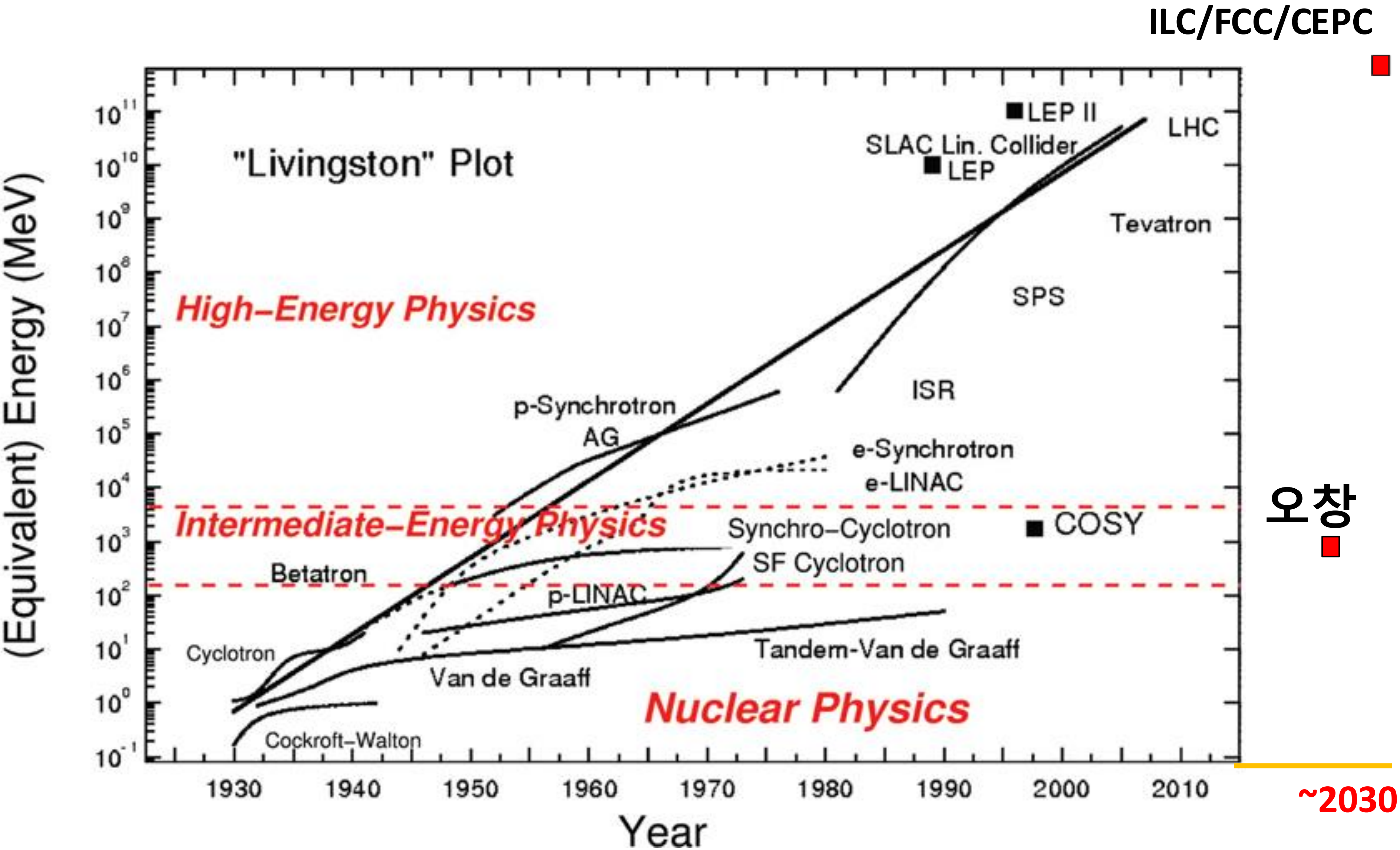
"it has long been my ambition to have available for study a copious supply of atoms and electrons which have an individual energy far transcending that of the alpha- and beta-particles from radioactive bodies"

Ernest Rutherford

Address to the Royal Society, 1927

방사선 물질 붕괴에 의한 알파 또는 베타입자보다 에너지가 더높은 전자 또는 이온의 필요성

History of Particle Accelerator

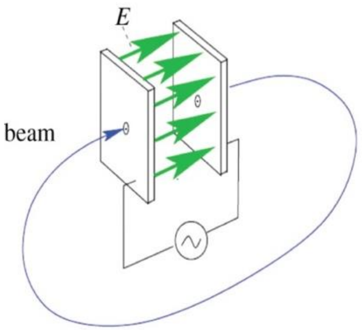


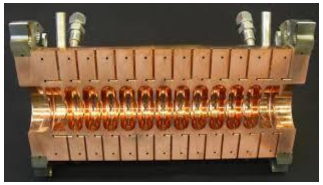
입자 가속 및 제어

$$\frac{d\vec{p}}{dt} = q\left(\vec{E} + \vec{v} \times \vec{B}\right)$$

ACCELERATION

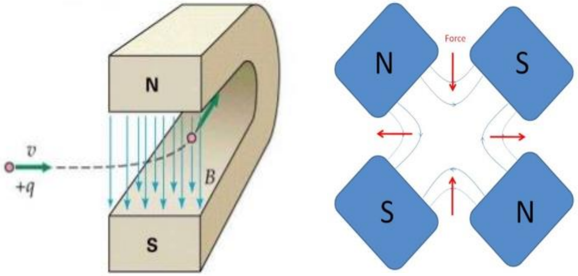
전기력

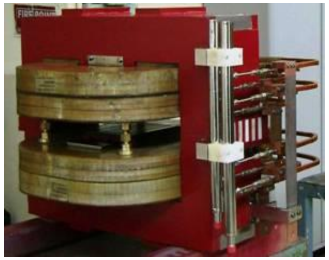


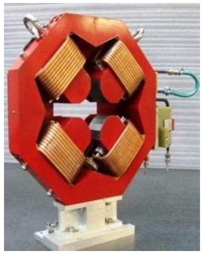


BENDING AND FOCUSING

자기력







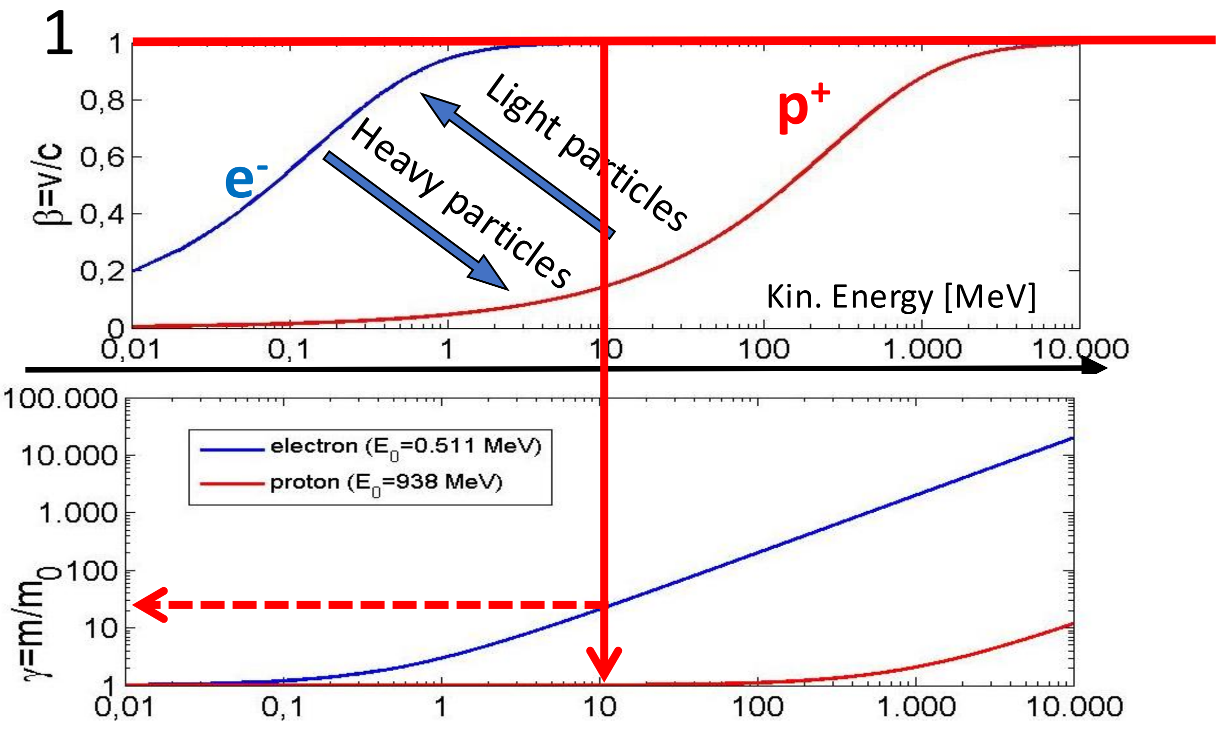
가속하려면 입자는 전하를 띠어야 한다.

입자의 속도 및 에너지

- **전자 질량: 0.511 MeV/c²**
- **양성자 질량: 938.3 MeV/c²**

$$E = m_0c^2 + K.E. = \gamma m_0 c^2$$

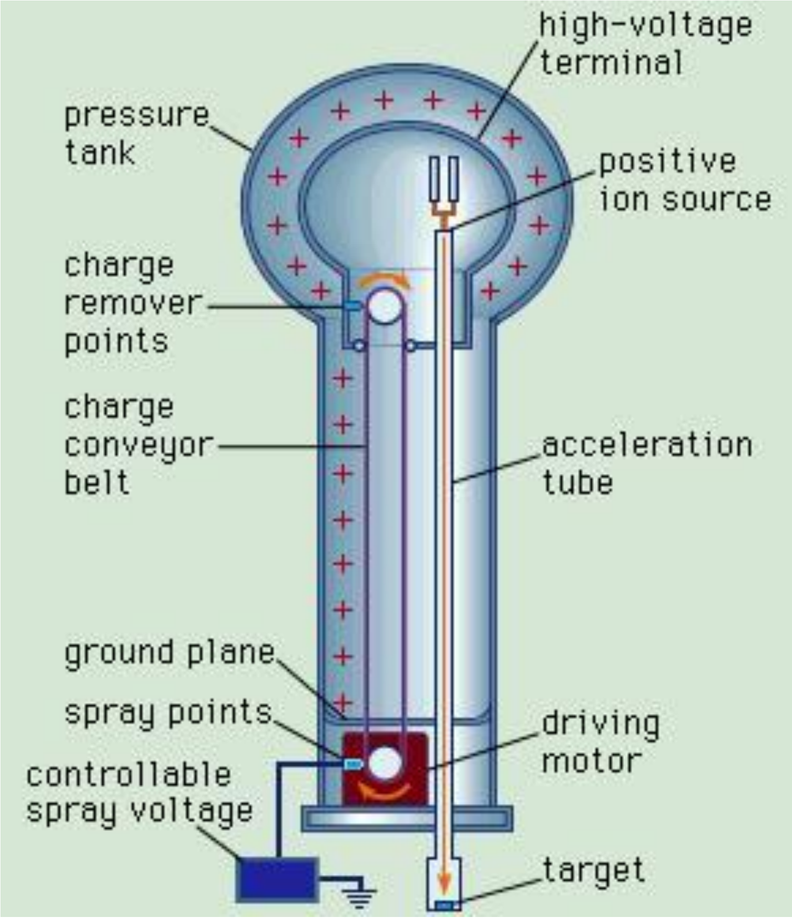
$$\gamma = \frac{1}{\sqrt{1-\frac{v^2}{c^2}}}, \quad v=\text{입자의 속도}$$



Kinetic Energy [MeV]

정전형 가속기(Electrostatic Accelerator)

- **Van de Graaff Accelerator**



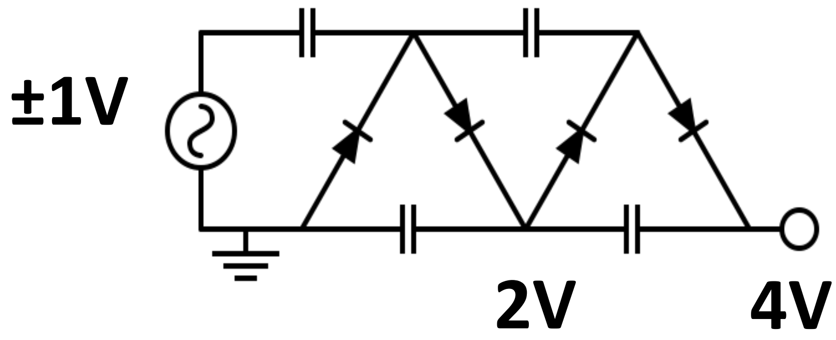
1933 – DC 7 MV

E = 7 MeV

정전형 가속기(Electrostatic Accelerator)

- **Cockcroft-Walton accelerator:**

Voltage multiplier circuit



750 kV Cockcroft-Walton injector at CERN from 1978 to 1992.

정전형 가속기의 한계

- 좋은 절연체를 이용해도 전기 방전(breakdown) 때문에 기술적으로 가능한 DC voltage:
  ~10 MV -> E~10 MeV

- 10 MeV 이상 가속하기 위해 새로운 방법 필요
  - Cyclotron
  - Linear Accelerator
  - Syncrotron

RF(Radio Frequency): 마이크로 웨이브

- 진동수가 약 300 MHz ~ 300 GHz 범위 전자기파

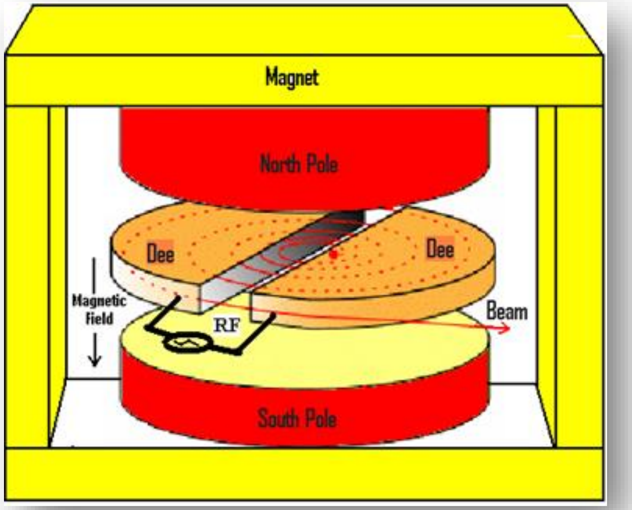
밴드(Band)	진동수(GHz)	파장(cm)
UHF	300 MHz ~ 3 GHz	100 ~ 10
L-band	1 ~ 2	30 ~ 15
S-band	2 ~ 4	15 ~ 7.5
C-band	4 ~ 8	7.5 ~ 3.75
X-band	8 ~ 12	3.75 ~ 2.5

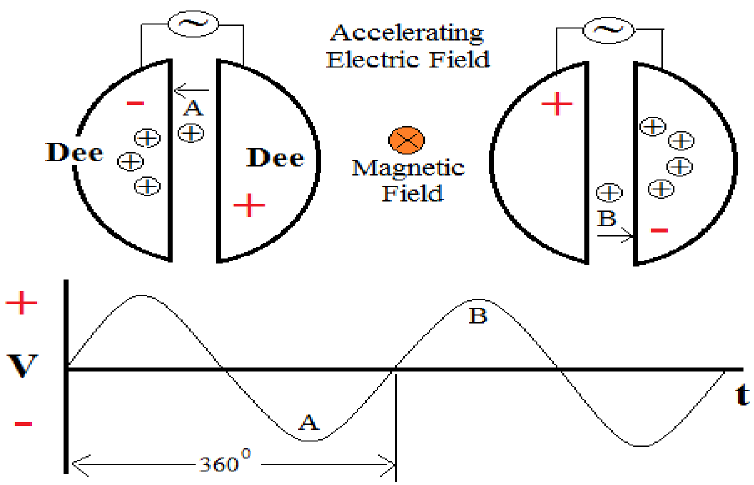
WiFi: 2 ~ 6 GHz

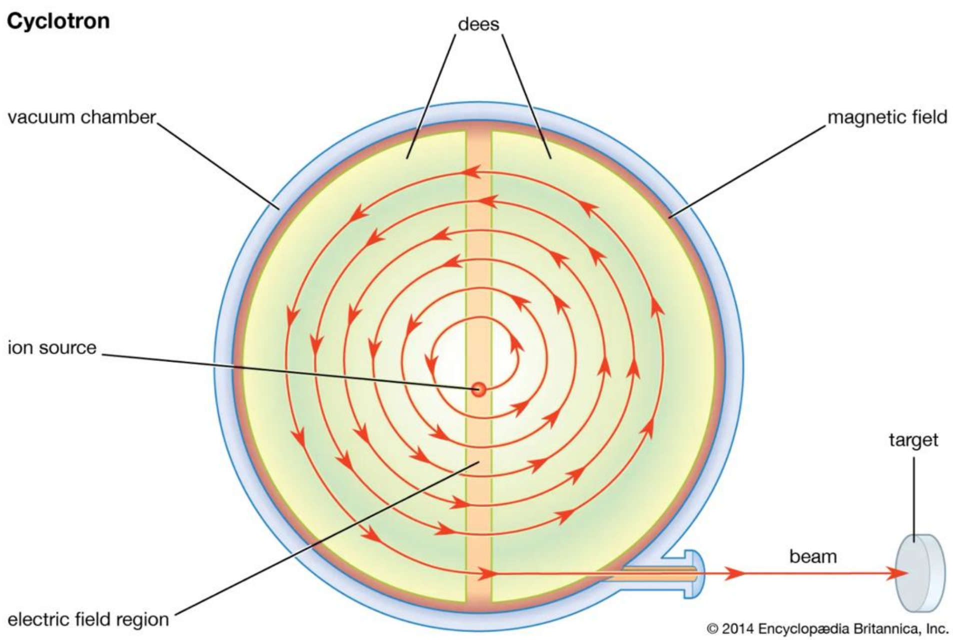
전자레인지: 2.45 GHz

Cyclotron(I)

- 주로 양성자 또는 중양성자 가속: 수십 MeV ~ 수백 MeV







Cyclotron(II)

- E. Lawrence invented in 1929.

The first cyclotron

11 inch cyclotron

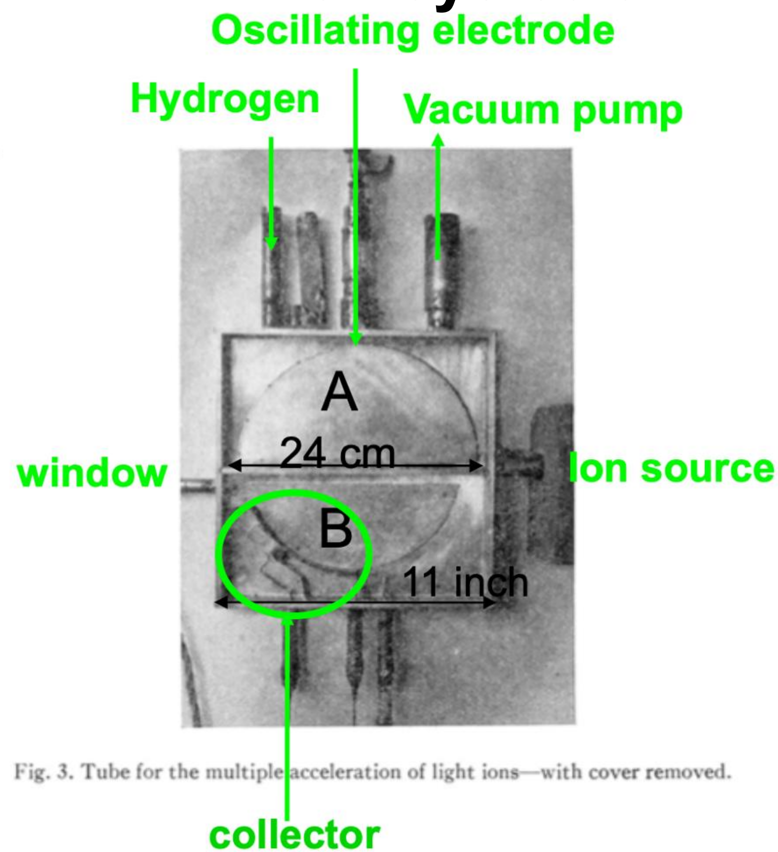
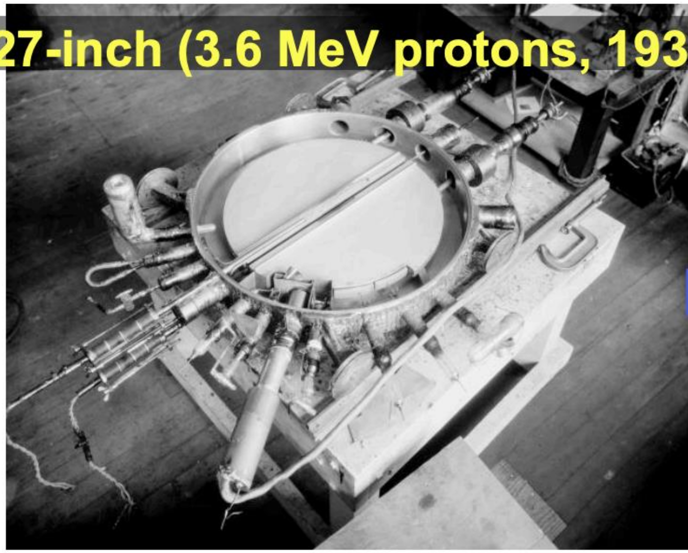


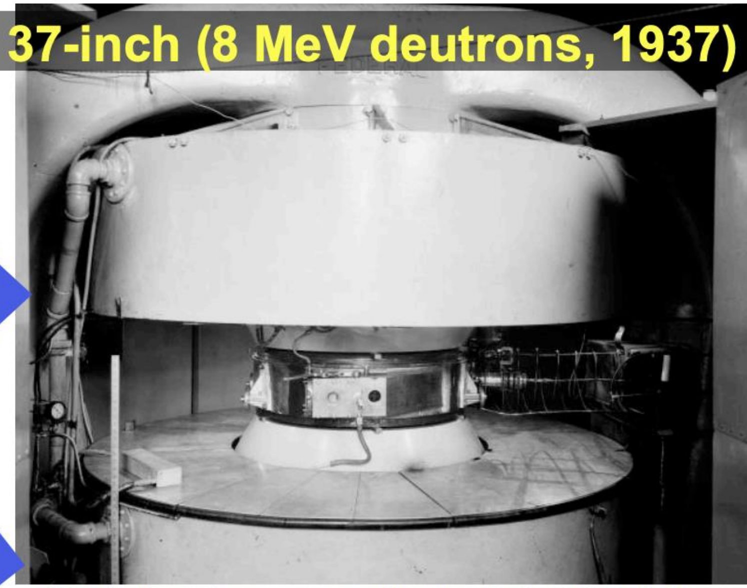
Fig. 3. Tube for the multiple acceleration of light ions—with cover removed.

Protons spiral around 150 times
→ 300 increments of energy
→ Acquire 1.2 MeV

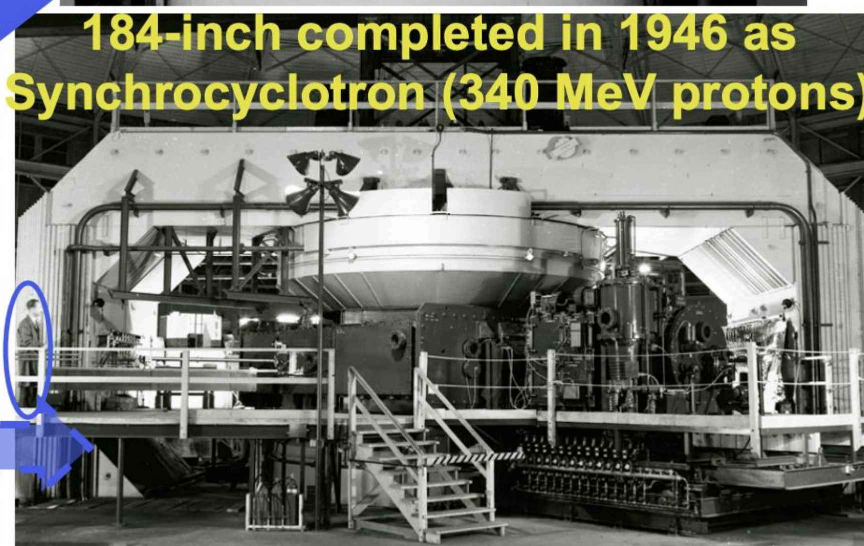
Cyclotron(III)

- **Bigger…**


27-inch (3.6 MeV protons, 1932)

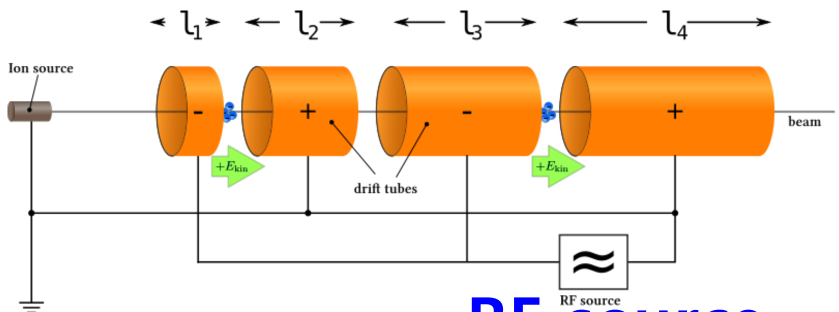

37-inch (8 MeV deutrons, 1937)


60-inch (16 MeV deutrons, 1939)


184-inch completed in 1946 as Synchrocyclotron (340 MeV protons)

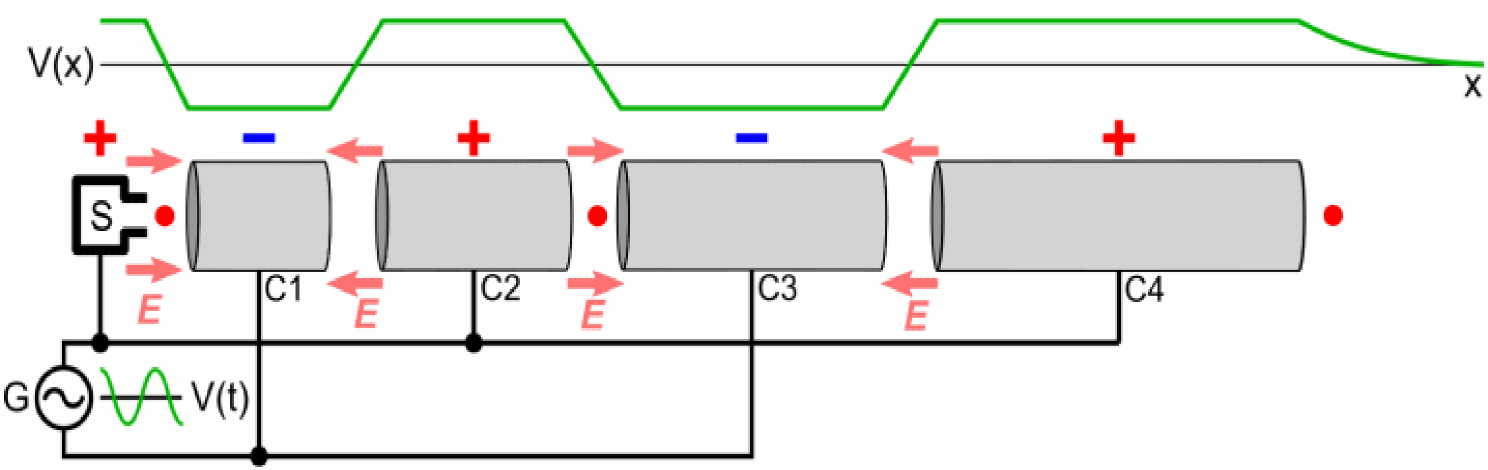
선형가속기(Linear Accelerator, LINAC)

- **Drift Tube LINAC (DTL) by Rolf Wideroe (1927) : proton & Ions 가속**



$$L = \beta\lambda$$

RF source



선형가속기(Linear Accelerator, LINAC)

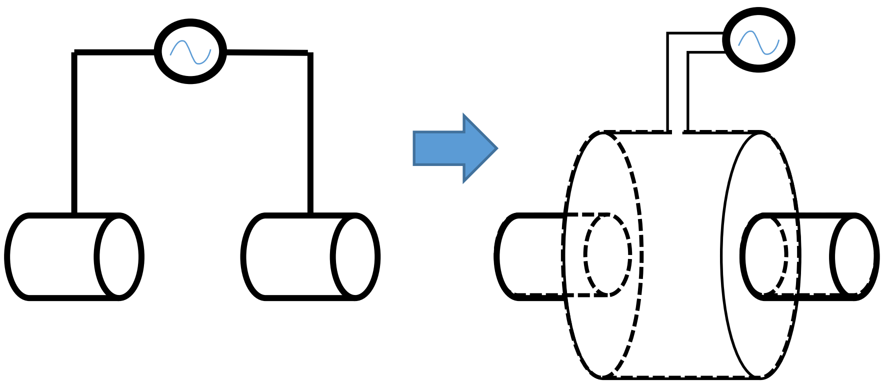
- **CERN LINAC 2 (Drift Tube LINAC):**
  - 200 MHz
  - 7 m x 3 tanks, 1 m diameter
  - final energy 50 MeV.

Acceleration with RF Cavity

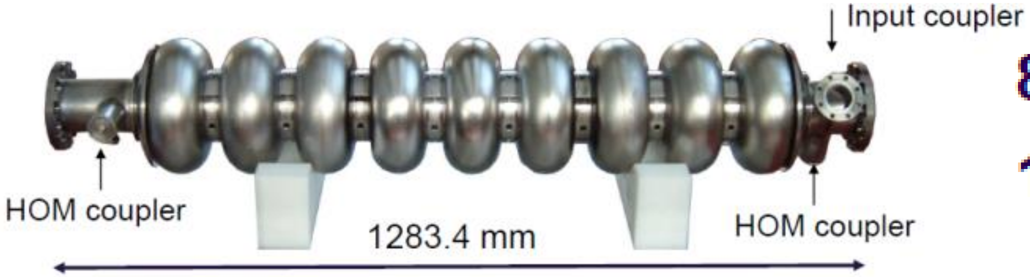
- 입자의 속도가 높아지면 가속이 효율적이지 않음.
- 각 Cavity에 독립적으로 RF 파워 공급

DTL

RF Cavity
(가속관)



European XFEL (Desy): electrons



800 accelerating cavities

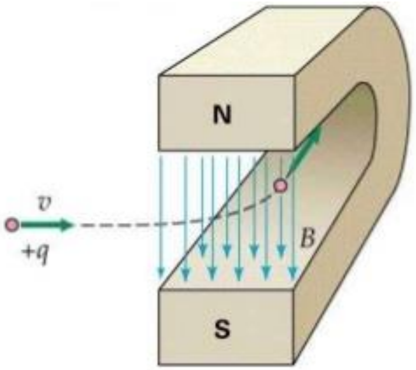
1.3 GHz / 23.6 MV/m

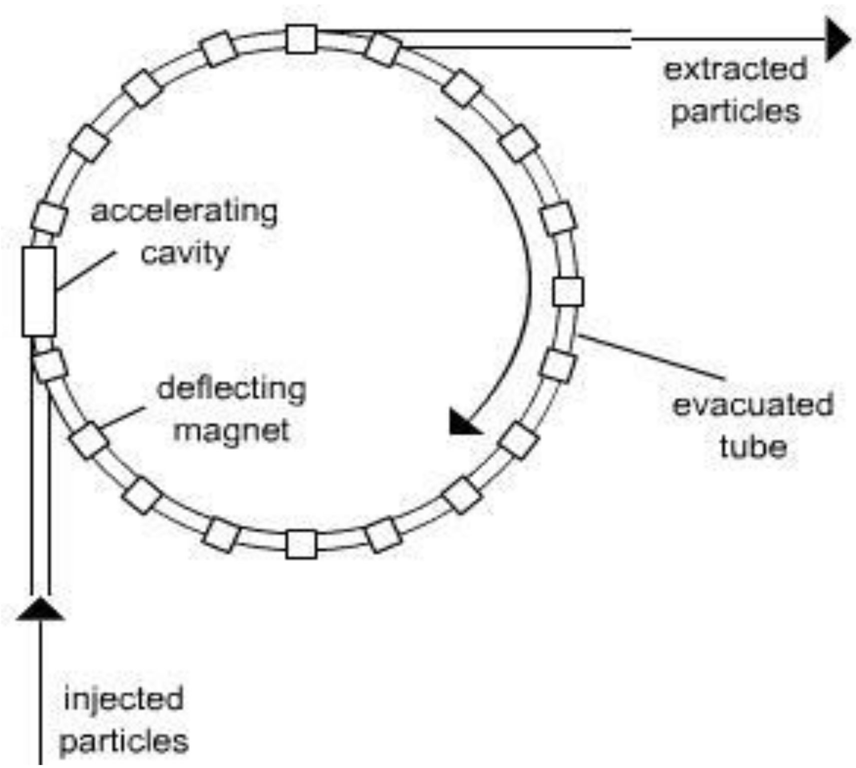
Stanford Linear Accelerator (SLAC):

- **20 GeV 전자 선형가속기 (1966년): 3.2 km 길이**
- **양성자 내부에 쿼크의 존재 발견**

원형가속기: Synchrotron

- 입자의 에너지는 ring을 돌면서 증가.
- Ring안에서 원운동을 유지하기 위해서 자석의 자기장 크기는 에너지에따라 변함.: 에너지증가 -> 자기장 증가

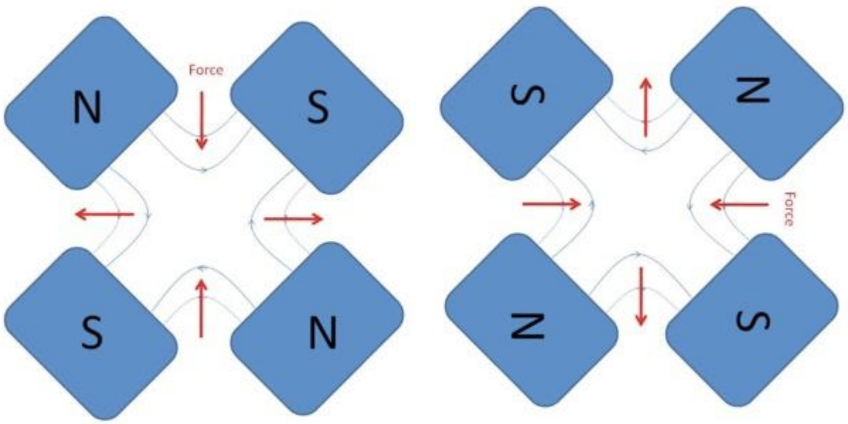


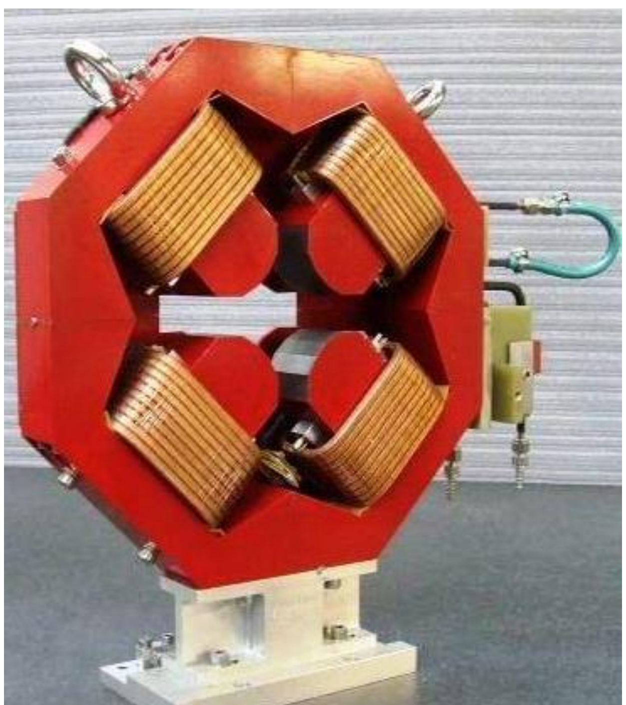


The Bevatron, Berkeley:
6.2 GeV 양성자(둘레:약 471 m), 1954년
Discovered the antiproton(반양성자)

Weak focusing (대형자석 사용)

Strong Focusing Synchrotrons





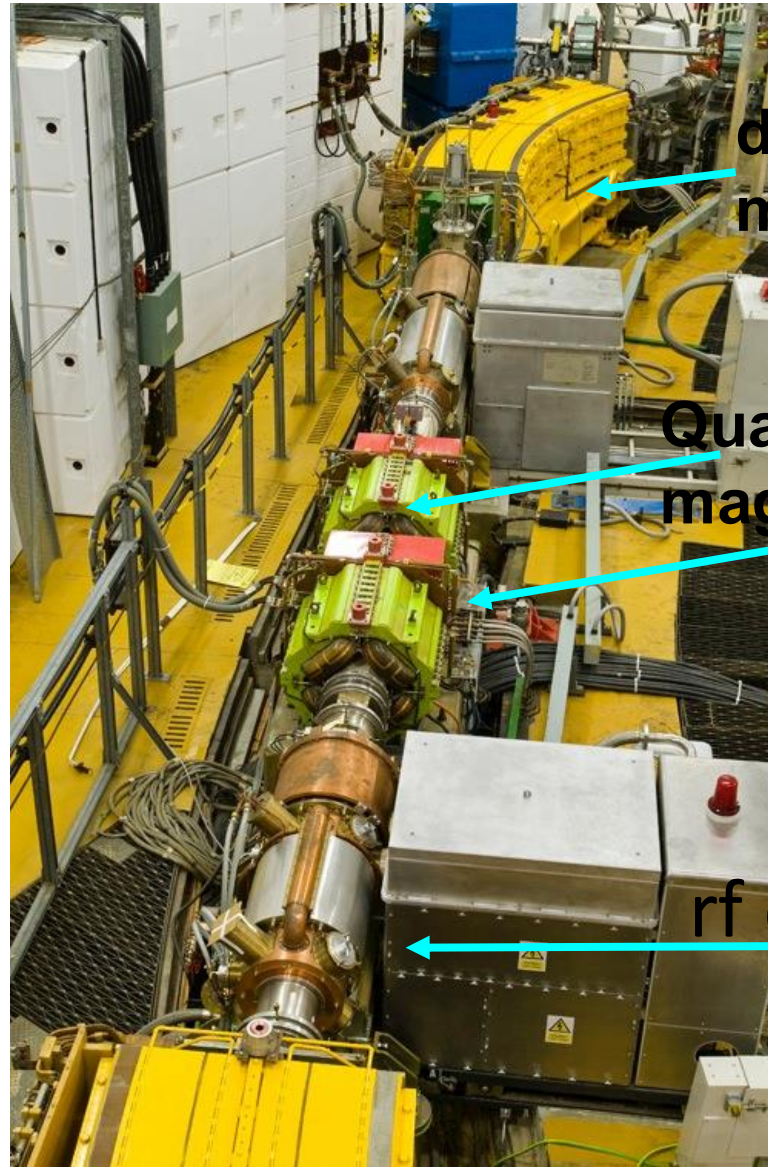
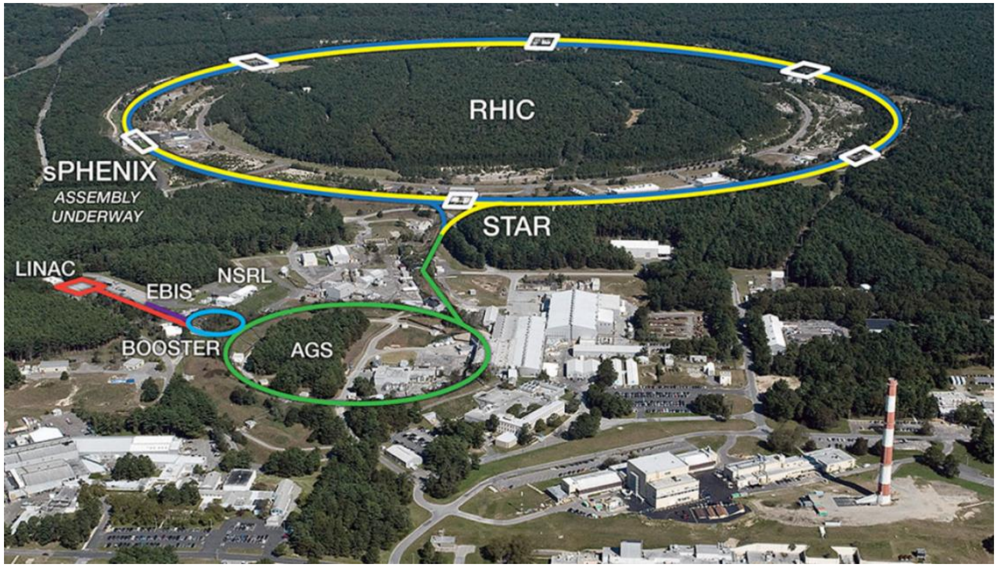


Image courtesy of ISIS, STFC

Strong Focusing Synchrotrons

- CERN Proton Synchrotron (PS) (1959년) -> LEP, LHC로 발전
  - 28 GeV 양성자 (둘레: 약 628 m)
- Alternating Gradient Synchrotron (AGS) at BNL (1960년).
  - 33 GeV 양성자 (둘레: 약 807 m)
  - 현재 RHIC의 전단 가속기(Injector)

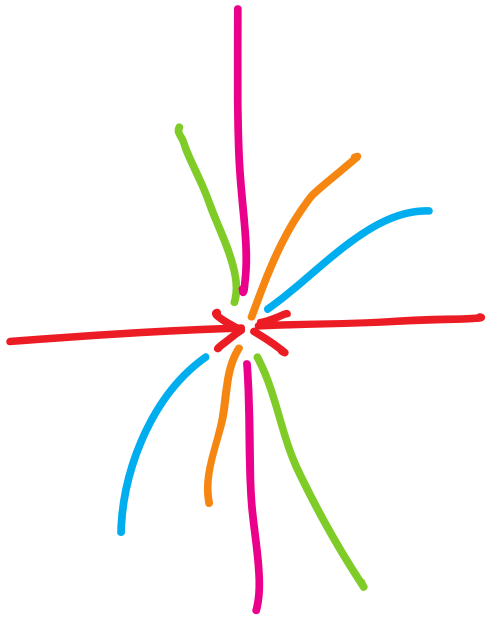


- 중성 Kaon 붕괴를 통해 CP violation 발견
- 뮤온 중성미자 발견
- Charm 쿼크 발견

Collider Accelerator (I)

- Collider VS. Fixed target experiment

Collider experiment

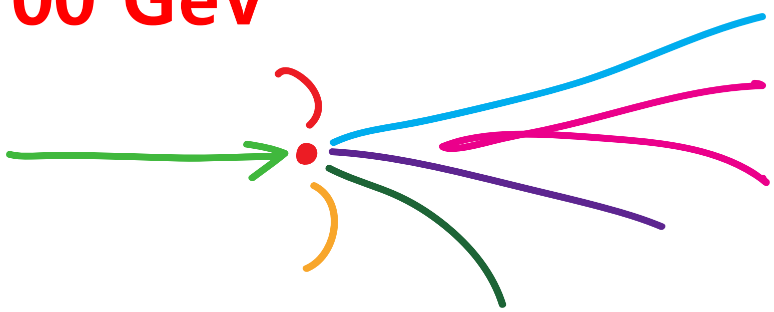


$$E_{CM} \simeq 2E_{beam}$$

~ 200 GeV

E_{beam}=100 GeV

Fixed Target experiment

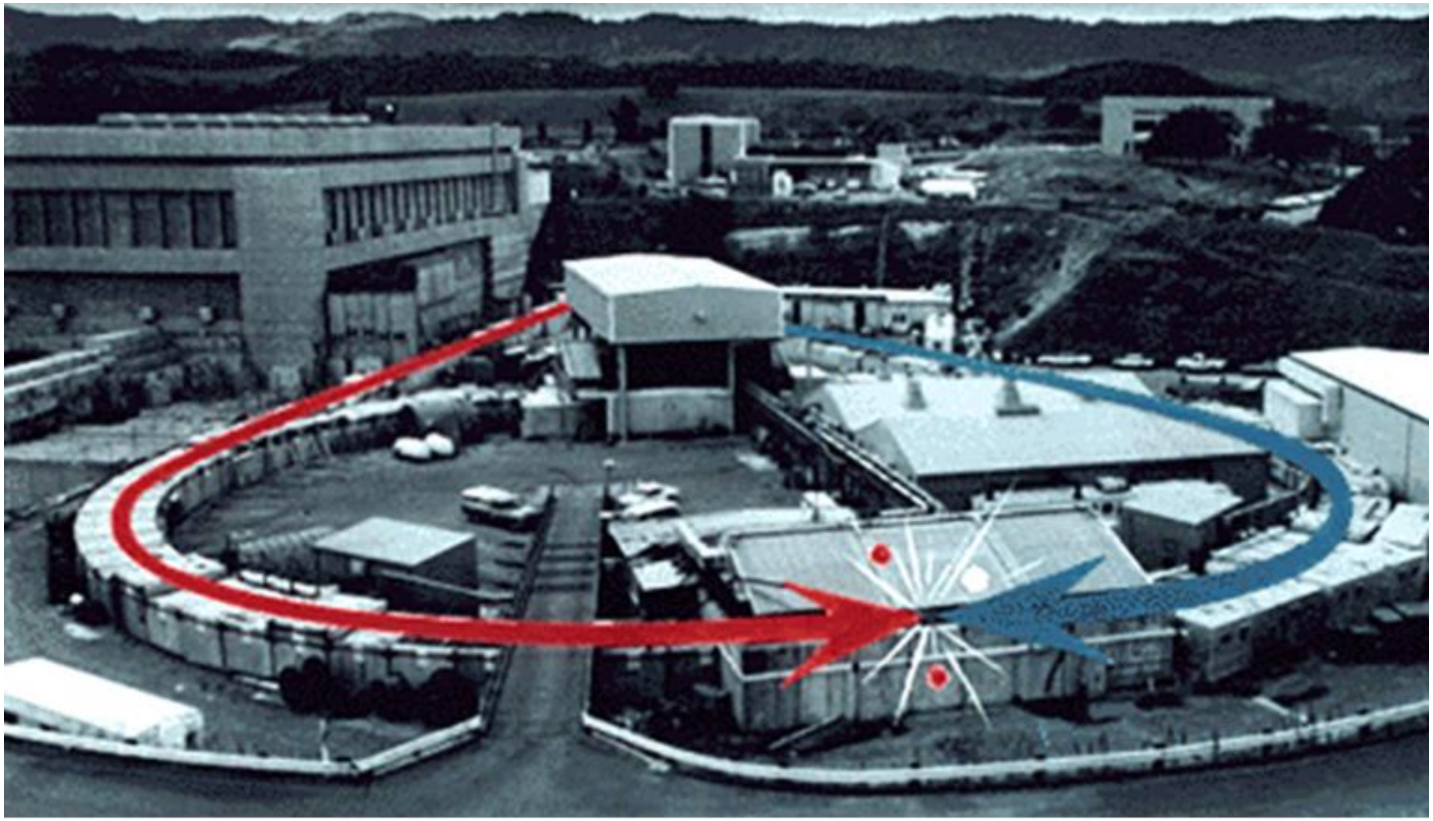


$$E_{CM} \simeq \sqrt{2ME_{beam}}$$

~14 GeV

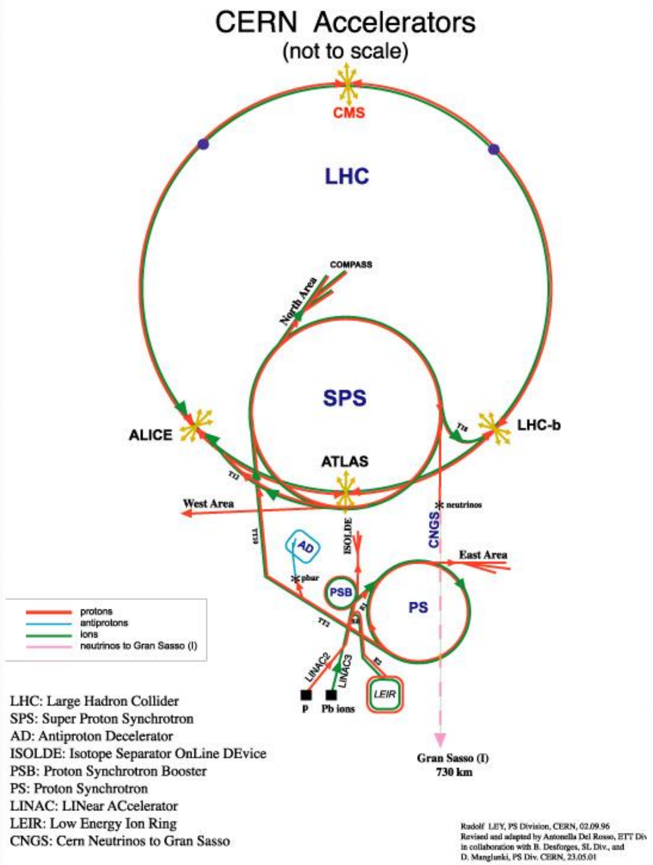
Collider Accelerator (II)

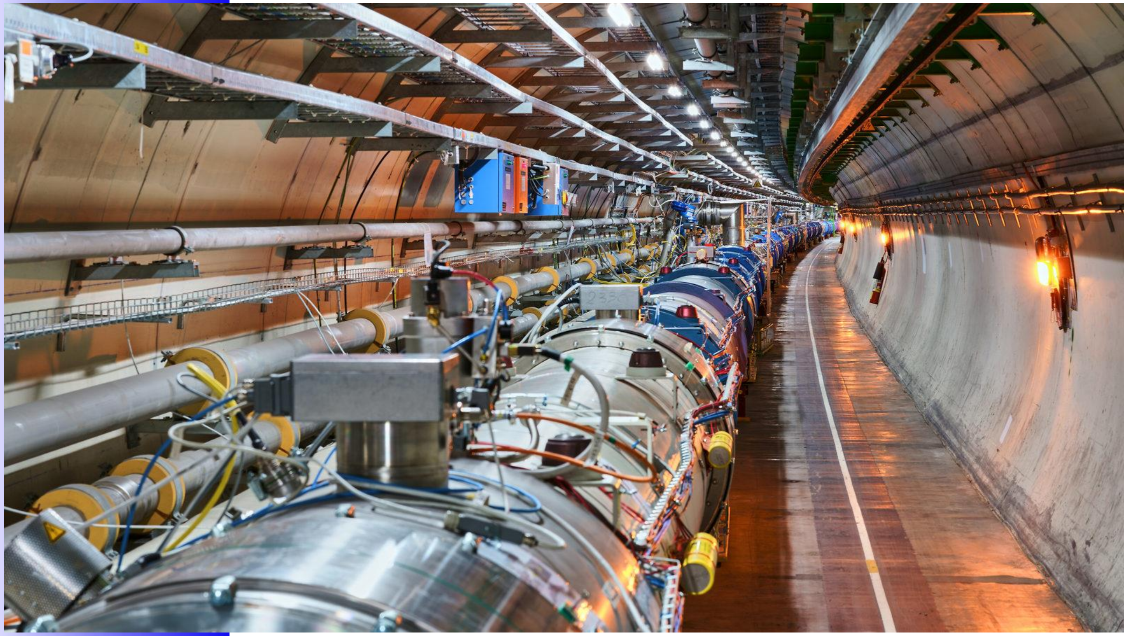
- **SPEAR (Stanford Positron-Electron Asymmetric Ring)**
  - e^+ e^- collider (1972년): 3 ~ 4 GeV, 둘레: 약 234 m
  - Charm 쿼크 발견 (1974년)
  - Tau 렙톤 발견 (1975년)



Collider Accelerator (III)

- **LHC (Large Hadron Collider) at CERN**
  - proton-proton collider (2008년~):
  7 TeV + 7 TeV, 둘레: 약 27 km
  - Higgs 입자 발견 (2012년)



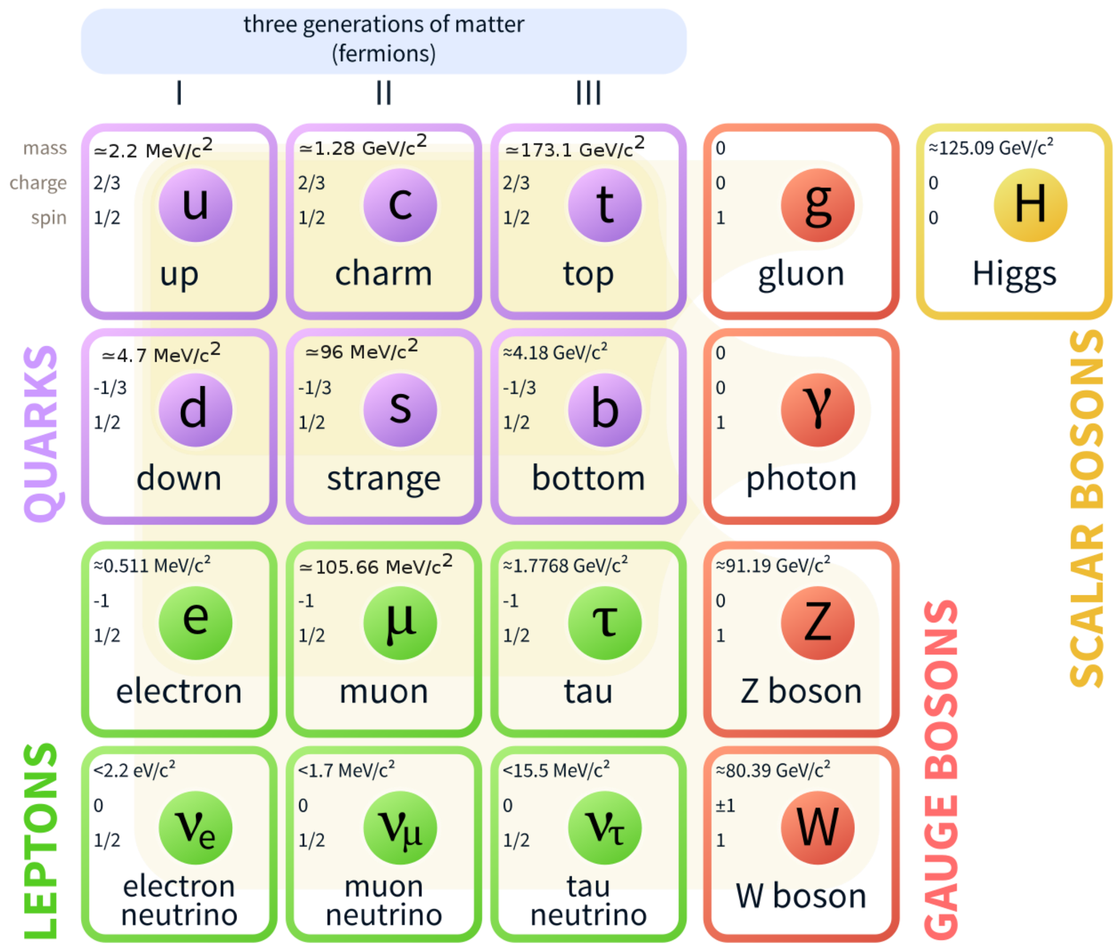


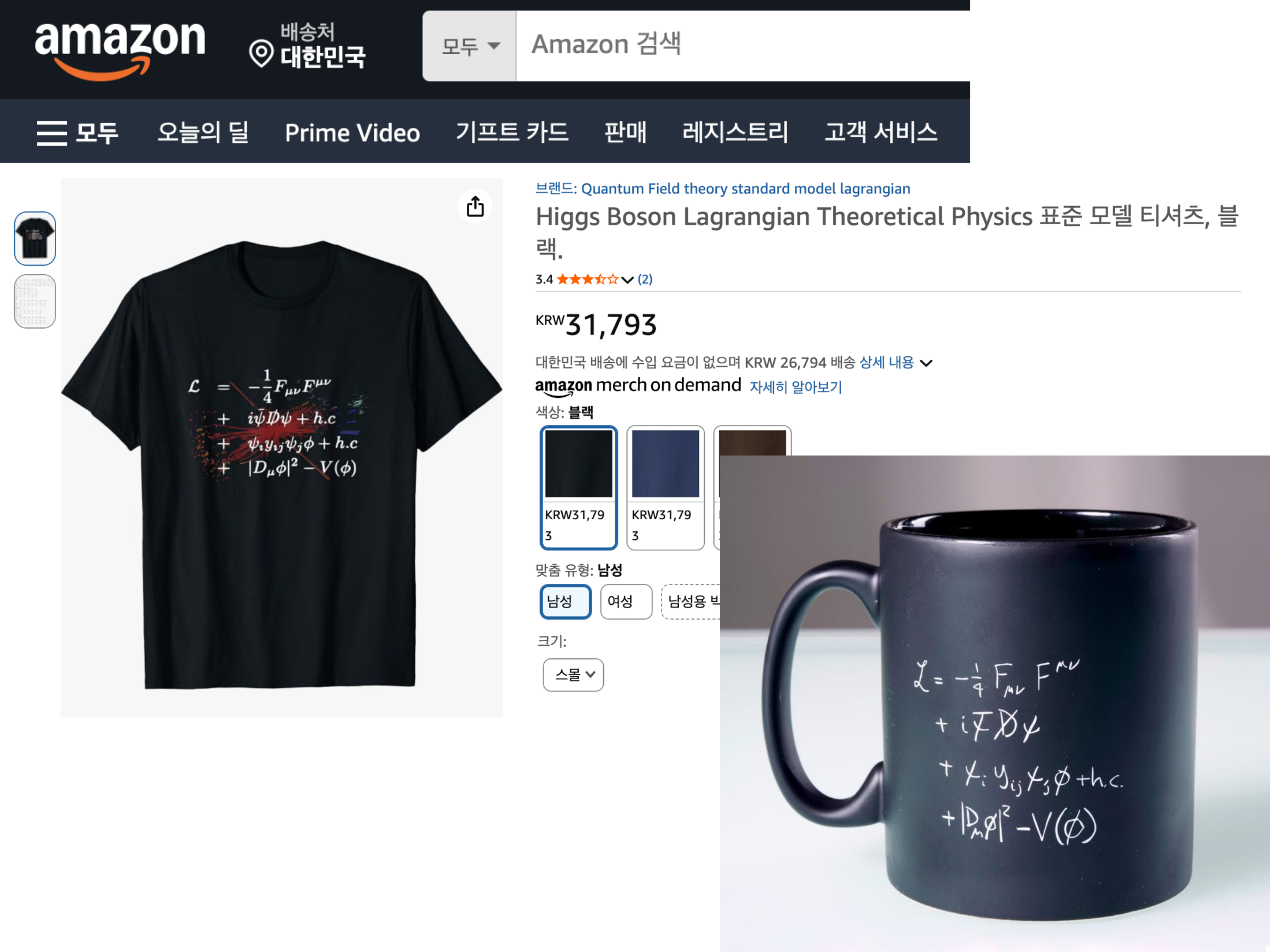
27km circumference underground tunnel (cross-section diameter 4m)

입자물리 표준모형

- 1897년 전자의 발견 → 약 100년 가속기 이용 실험
→ 마침내 완성(2012년)

Standard Model of Elementary Particles




amazon
배송처
대한민국
모두
Amazon 검색
모두
오늘의 딜
Prime Video
기프트 카드
판매
레지스트리
고객 서비스
$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu}$
$+ i\bar{\psi}D\!\!\!/\psi + h.c$
$+ \psi_i y_{ij}\psi_j\phi + h.c$
$+ |D_\mu\phi|^2 - V(\phi)$
브랜드: Quantum Field theory standard model lagrangian
Higgs Boson Lagrangian Theoretical Physics 표준 모델 티셔츠, 블랙.
3.4 (2)
KRW31,793
대한민국 배송에 수입 요금이 없으며 KRW 26,794 배송 상세 내용
amazon merch on demand 자세히 알아보기
색상: 블랙
KRW31,793
KRW31,793
맞춤 유형: 남성
남성
여성
크기:
스몰
$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu}$
$+ i\bar{\psi}D\!\!\!/\psi$
$+ \psi_i y_{ij}\psi_j\phi + h.c.$
$+ |D_\mu\phi|^2 - V(\phi)$

입자물리 표준모형은 아주 정확하다

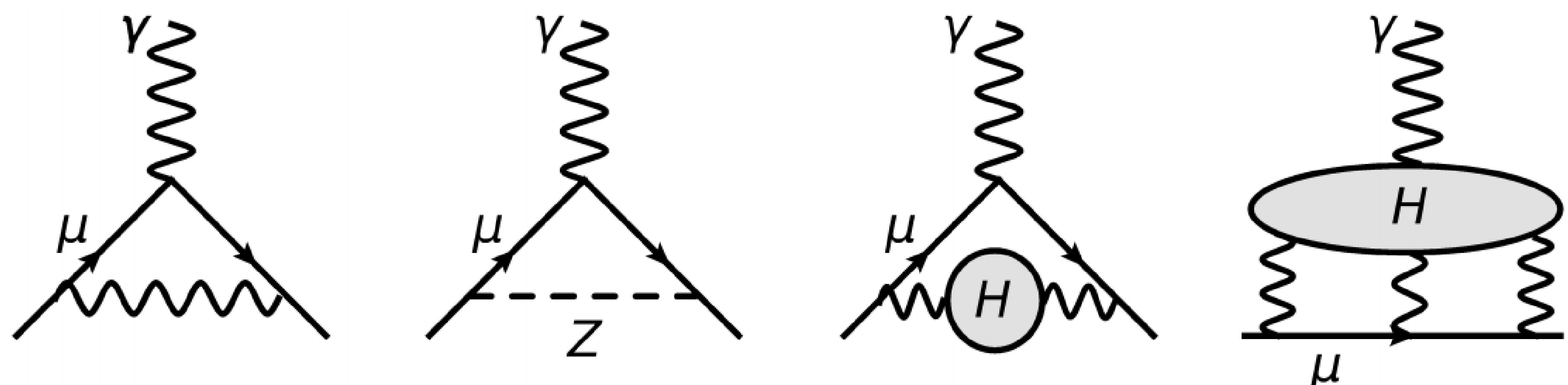
Muon magnetic moment:

$$\boxed{\vec{\mu} = g\left(\frac{e}{2m}\right)\vec{S}}$$

g = 2 for spin ½ particle (from Dirac's eq.)

$$\boxed{\frac{g-2}{2} \equiv a_\mu}$$

"anomalous" magnetic moment (due to radiative corrections)



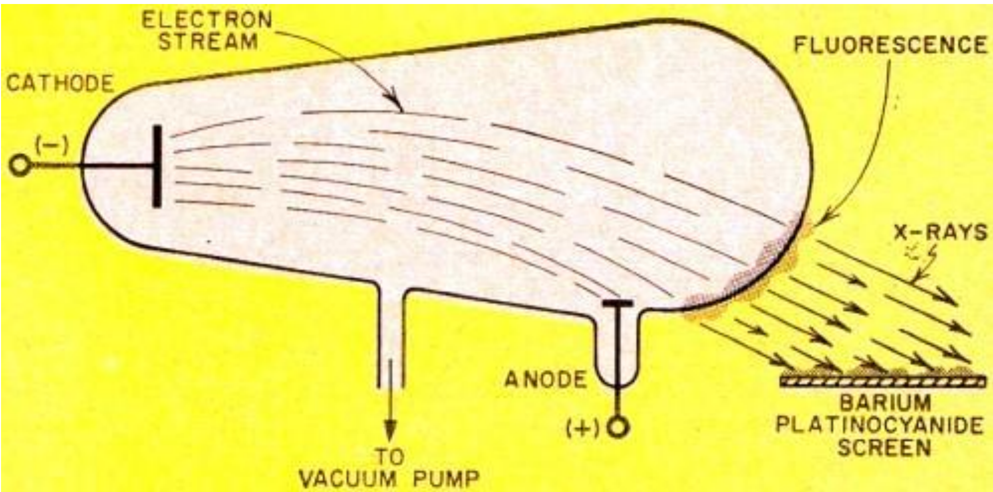
a_μ (SM) = a_μ(QED) + a_μ(Electroweak) + a_μ(HVP) + a_μ(HLbL)

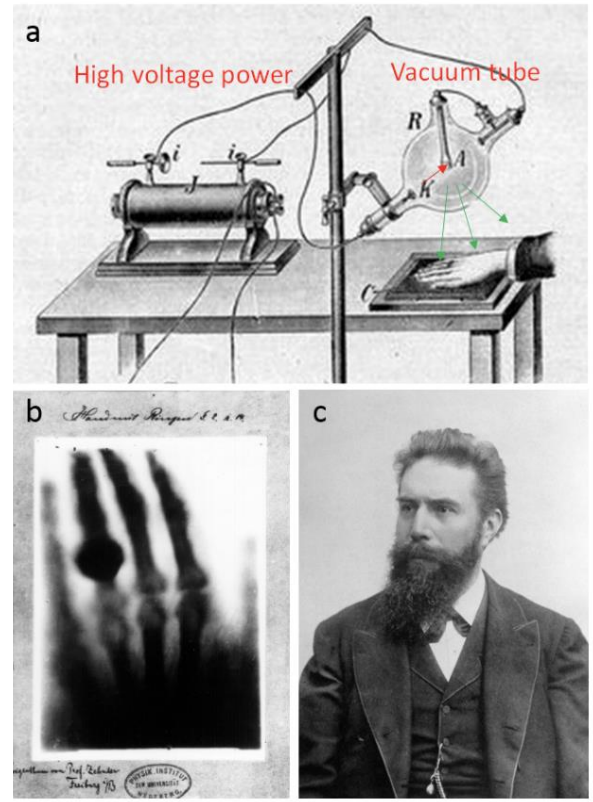
Calculation: $a_\mu = (116591840 \pm 59) \times 10^{-11}$

$$\boxed{a_\mu\,(\mathrm{EXP}) - a_\mu\,(\mathrm{SM}) = (286 \pm 80) \times 10^{-11}}$$

X-ray의 발견

- Röntgen(렌트겐)이 Crookes튜브 실험 통해 1895년 발견

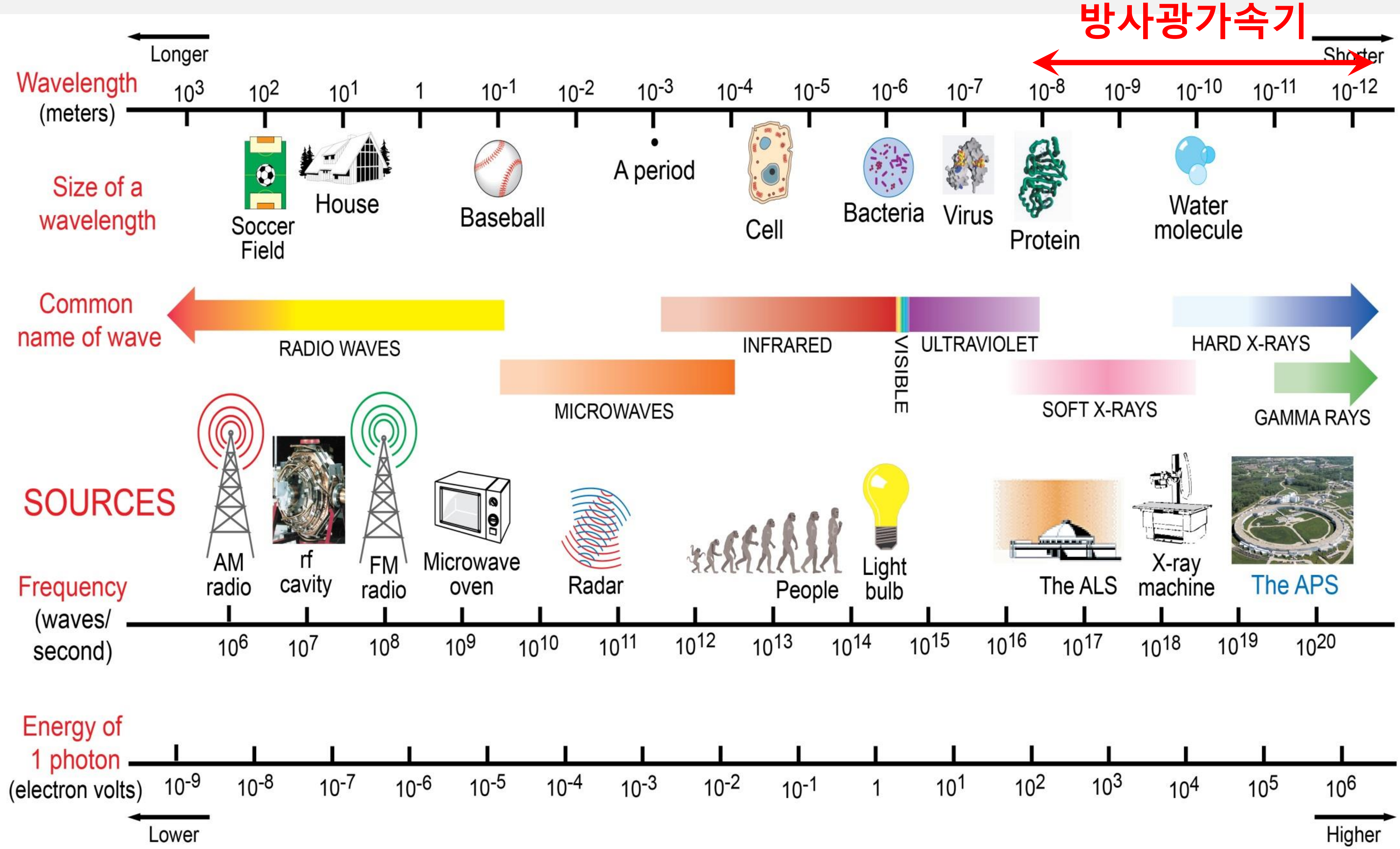




- X-ray의 활용
  - 의료분야 필수 진단 장비
  - 기초과학 및 공학(분자 구조 이해): 방사광 가속기
  - 공항 · 항만 위험물 탐지

Synchrotron Radiation Light Sources (방사광 가속기)

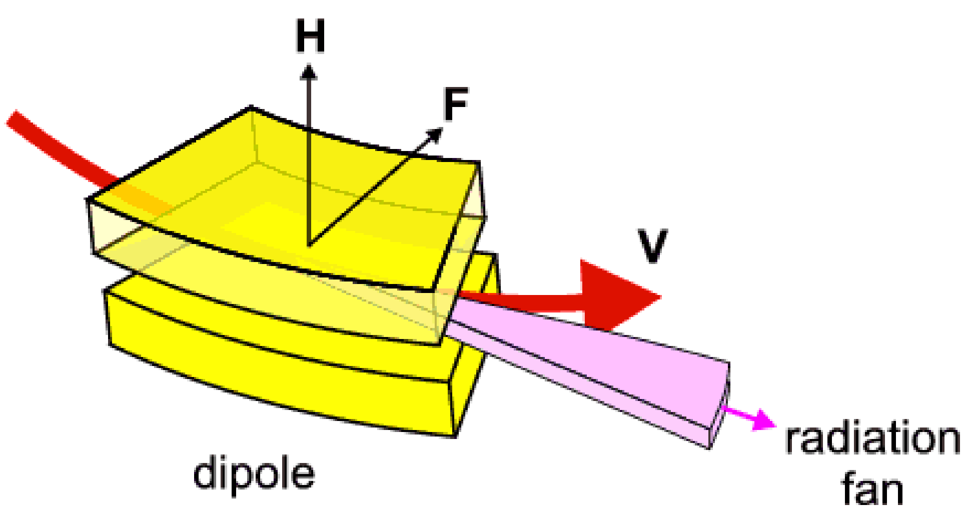
전자기파 에너지 스펙트럼

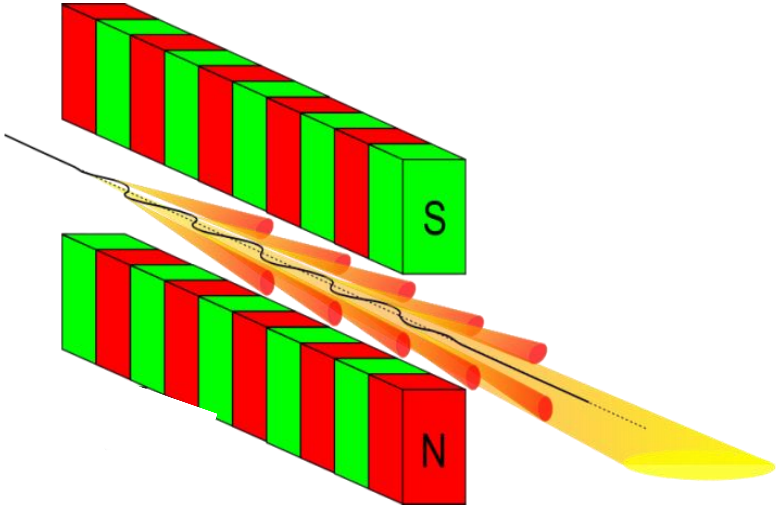


What is Synchrotron Radiation?

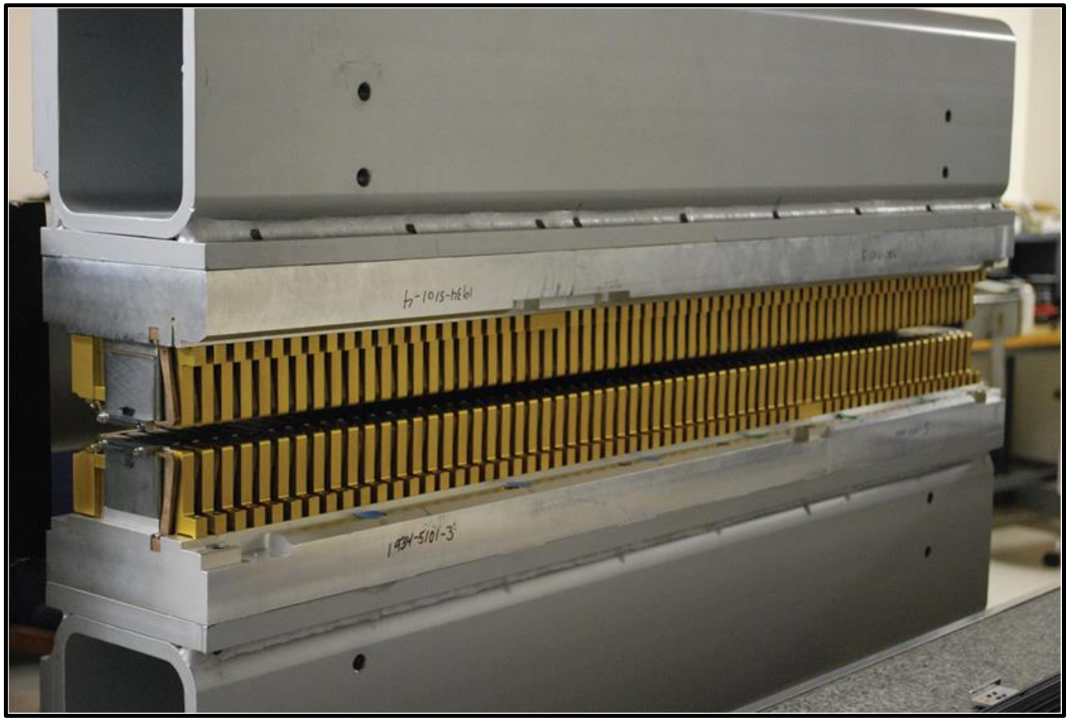
- Synchrotron Radiation은 자기장 속에서 방향이 바뀌는 전하 입자가(예: 전자) 방출하는 전자기파이다.
  (전자기학: 가속 운동하는 전하입자는 전자기파 방출)

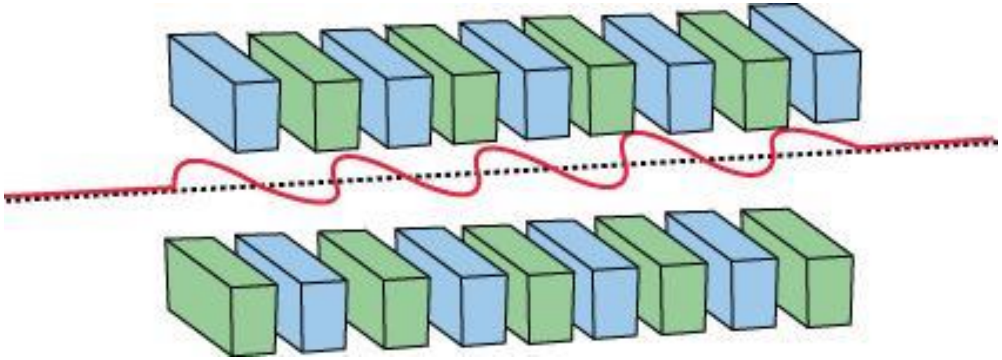
- 입자의 경로를 휘게 하는 자석이용:
  - Bending magnet
  - Wiggler or Undulator





Wigglers and Undulators



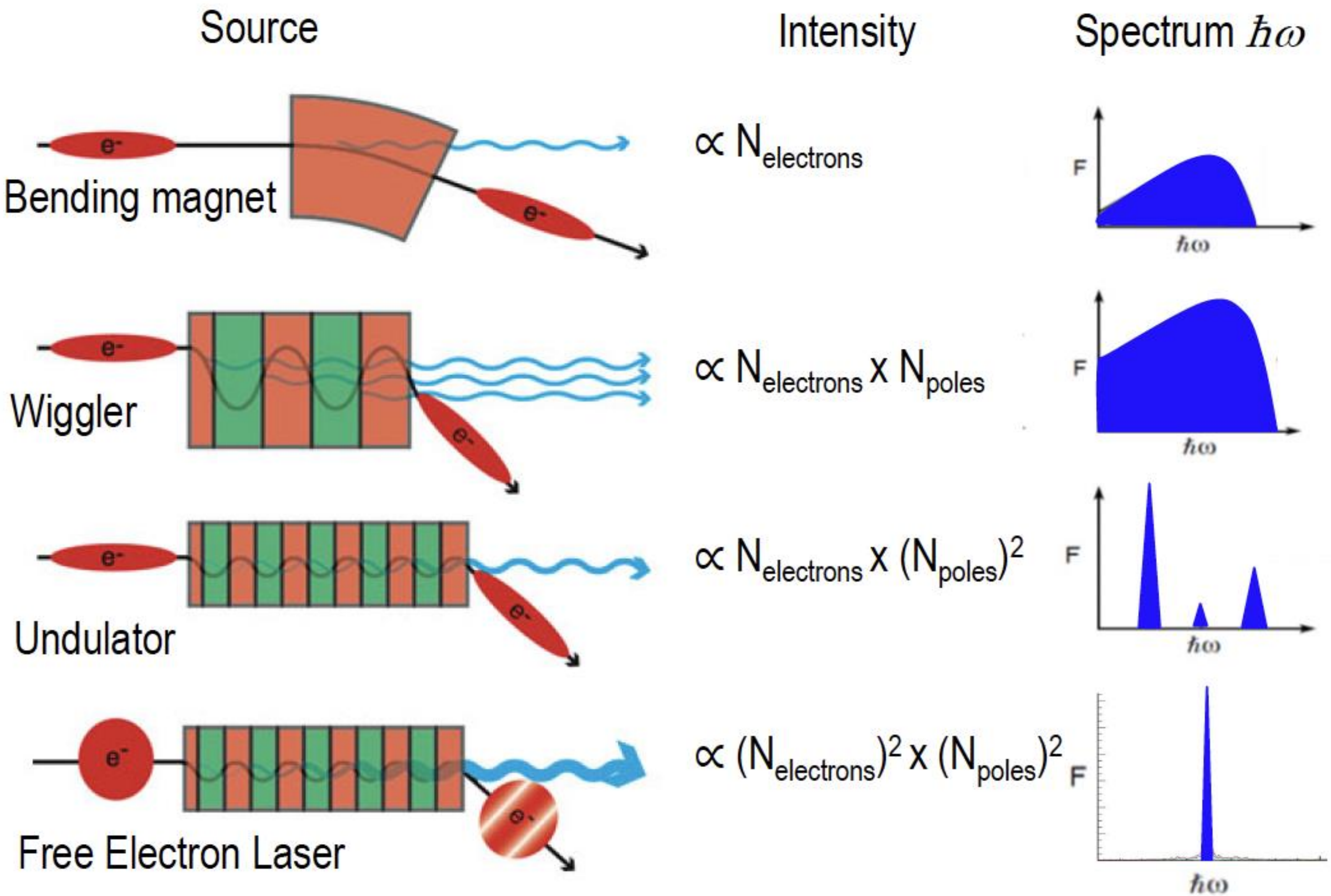


$$K = \frac{eB\lambda_u}{2\pi m_e c}$$

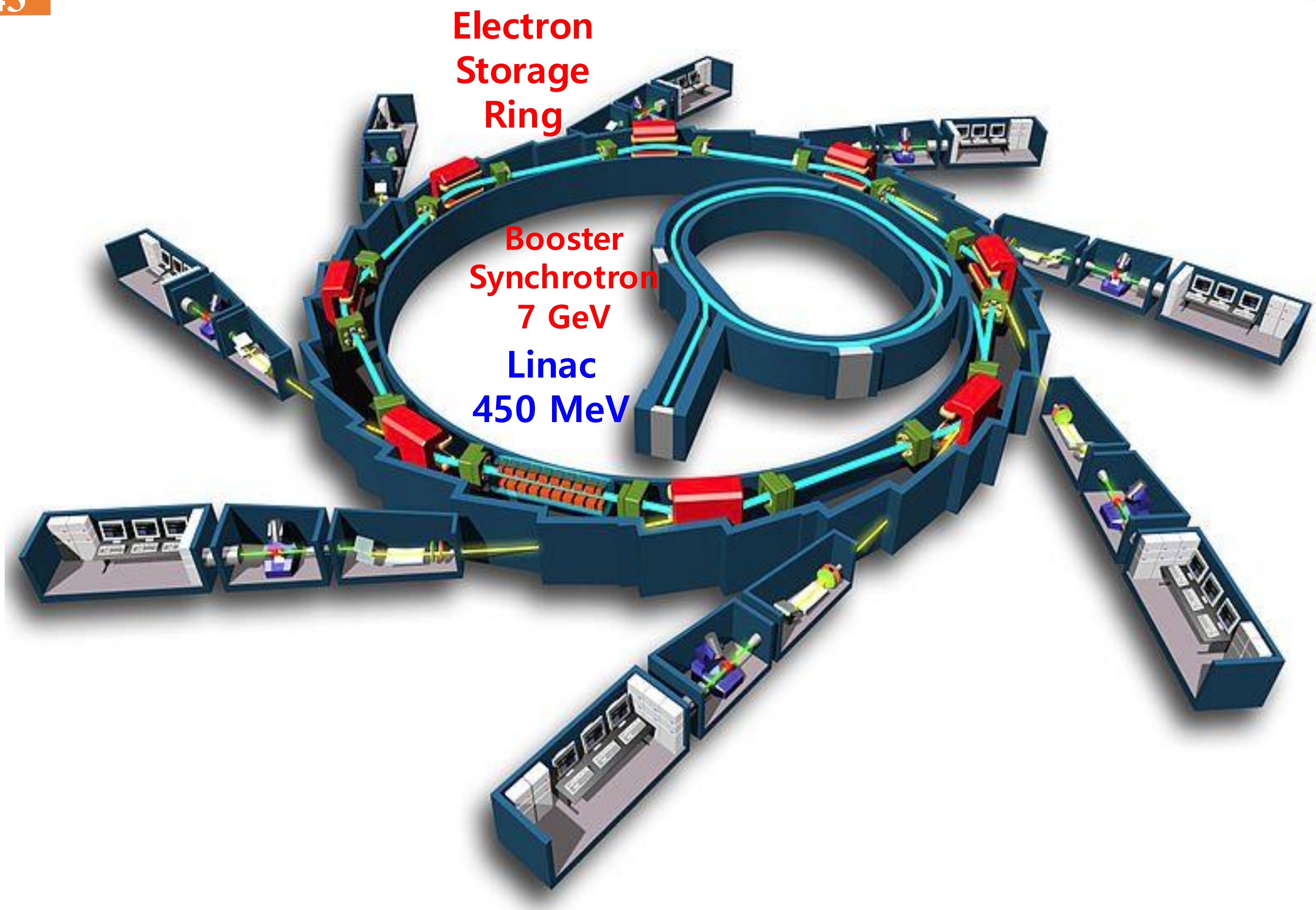
- B: 자기장 세기
- λ_u: 자석 주기
- K: 전자의 궤도 진동 크기

- **Wiggler: K >> 1**
- **Undulator: K ≤ 1**

Forms of Synchrotron Radiation



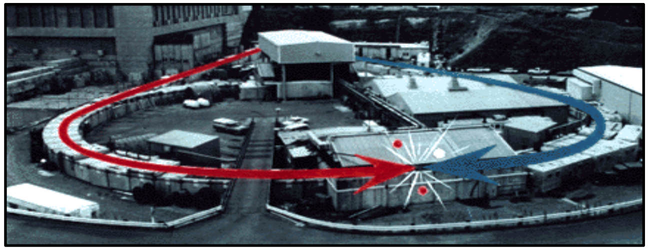
Major parts of Light Source (Synchrotron)



Electrons stay in the storage ring for 4 –12 hours.

Synchrotron Light Sources Evolution by Generation

- **First observation of manmade synchrotron radiation @ General Electric in 1947**



- **1st Generation:** parasitic synchrotron radiation source from the dipoles of an HEP collider storage ring (SPEAR, 1975)

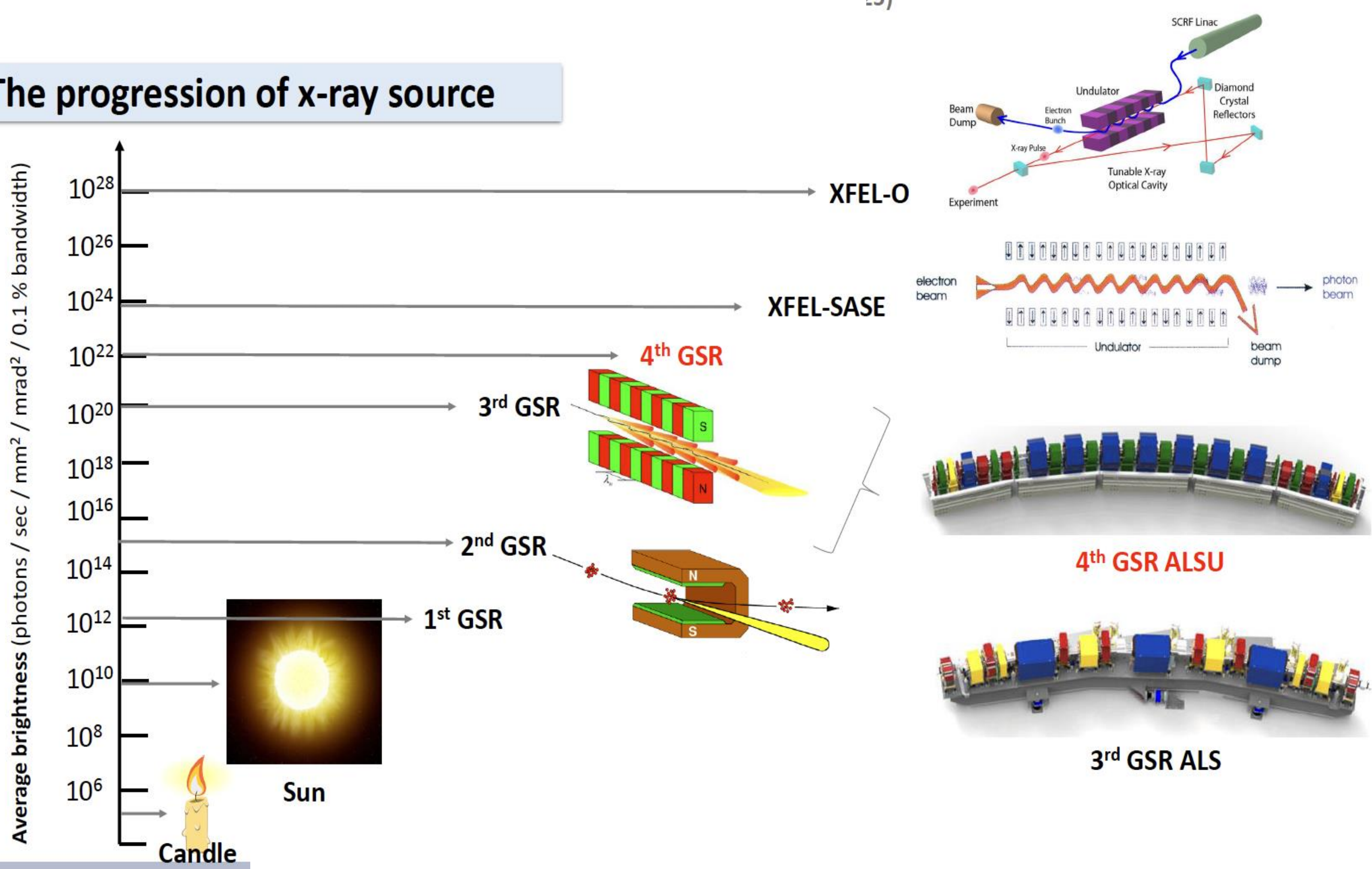
- **2nd Generation:** dedicated storage ring for synchrotron radiation, dipole radiation & some undulators (NSLS, 1982)

- **3rd Generation:** dedicated storage ring optimized for undulator radiation; very high brightness (ALS, 1993; APS, 1996; SSRL, 2004; NSLS-II, 2014)

- **4th Generation:** dedicated linac driven free electron laser (LCLS, 2009)

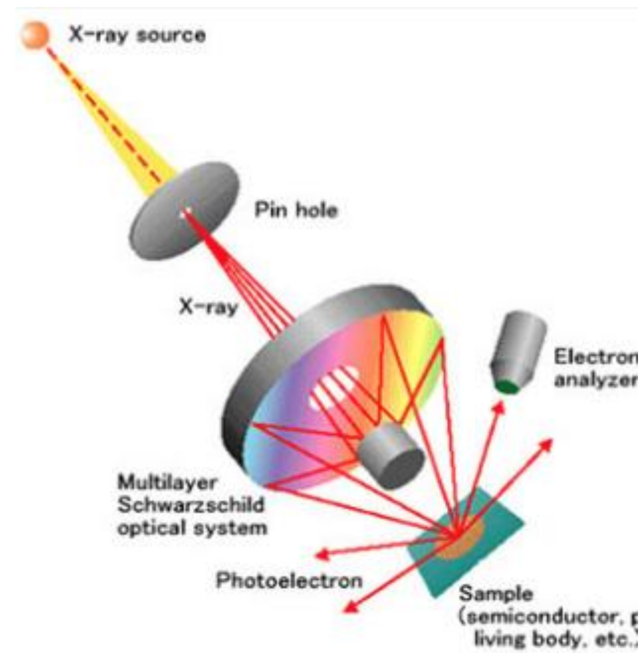
Brightness of source

The progression of x-ray source



Main Applications

- Life Science
  - Pharmaceuticals
  - Protein, biomaterial
  - Ultra dilute pollutants

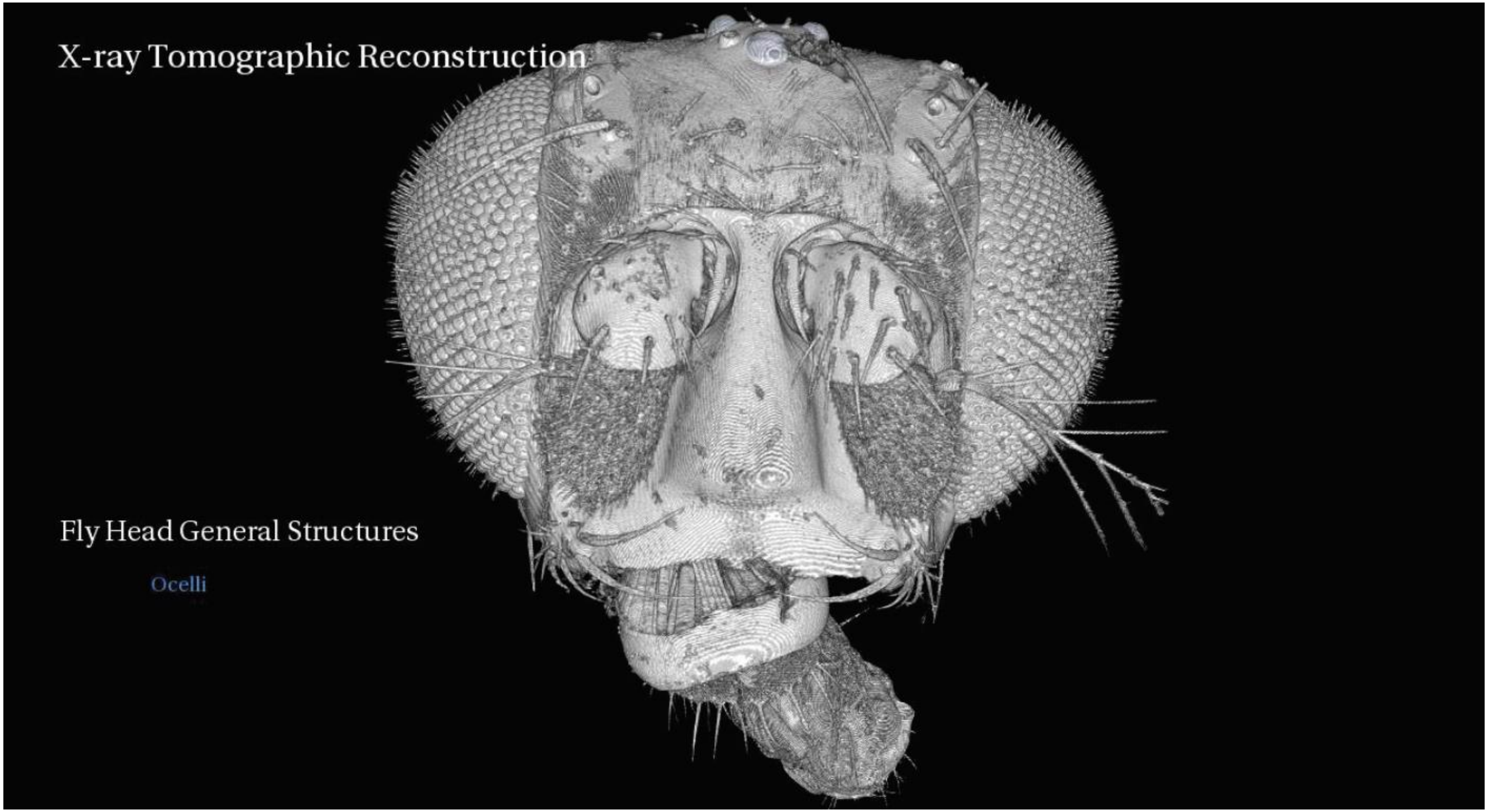


- High Energy Physics / Astrophysics
  - Simulate high energy radiation

- Engineering
  - Material stress (polarization)

- Even humanities… (Non-Destructive)
  Art history, Archaeology

CT-scans


X-ray Tomographic Reconstruction
Fly Head General Structures
Ocelli

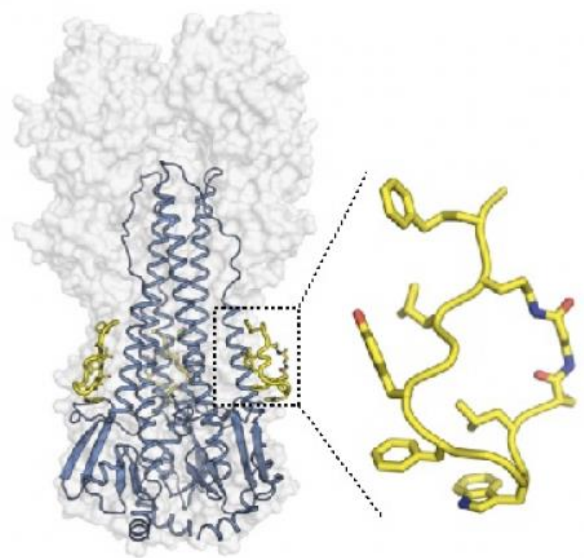
조류독감: Tamiflu(타미플루)

Structural Study of Potent Peptidic Fusion Inhibitors of Influenza Virus Hemagglutinin

March 2018

Influenza also called "Flu" is a disease of the human respiratory tract caused by influenza virus. Each year, seasonal influenza can cause severe and widespread disease in the human population and cost billions of dollars to the world economy. Such a problem occurred this year with the influenza A H3N2 virus. Currently available remedies to tackle influenza are the seasonal trivalent or tetravalent vaccines or FDA-approved antiviral drugs, such as Tamiflu and Relenza. Since influenza viruses are constantly mutating and circulating as new strains in the human population, influenza vaccines need to be updated each year. Furthermore, the efficacy of these currently available front-line drugs are declining due to the relentless evolution in the influenza virus strains (*1-3*). Therefore, there is an urgent need for universal influenza therapeutics with novel mechanisms of action and novel targets to tackle the threats posed by influenza viruses.

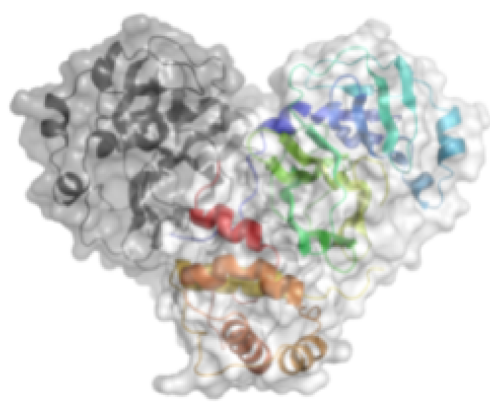
A collaboration between a team of researchers from Janssen Research & Development (Janssen, Netherlands) led by Dr. Maria van Dongen and The Scripps Research Institute led by Prof. Ian A. Wilson developed potent peptidic molecules based on broadly neutralizing antibodies (bnAbs) CR9114 and FI6v3 that target the highly conserved stem epitope on influenza virus hemagglutinin (HA). The designed peptides show high affinity and neutralization against a broad set of group 1 influenza A viruses (H1, H2, H5 and H6 subtypes), including the 2009 H1N1 pandemic and an avian H5N1 flu strain. The peptides are non-toxic, show stability to proteolysis, and have drug-like properties when evaluated in mice.



Synchrotrons on the coronavirus frontline

24 March 2020

Tessa Charles describes the impressive progress being made by synchrotron X-ray facilities to solve the structure of SARS-CoV-2.



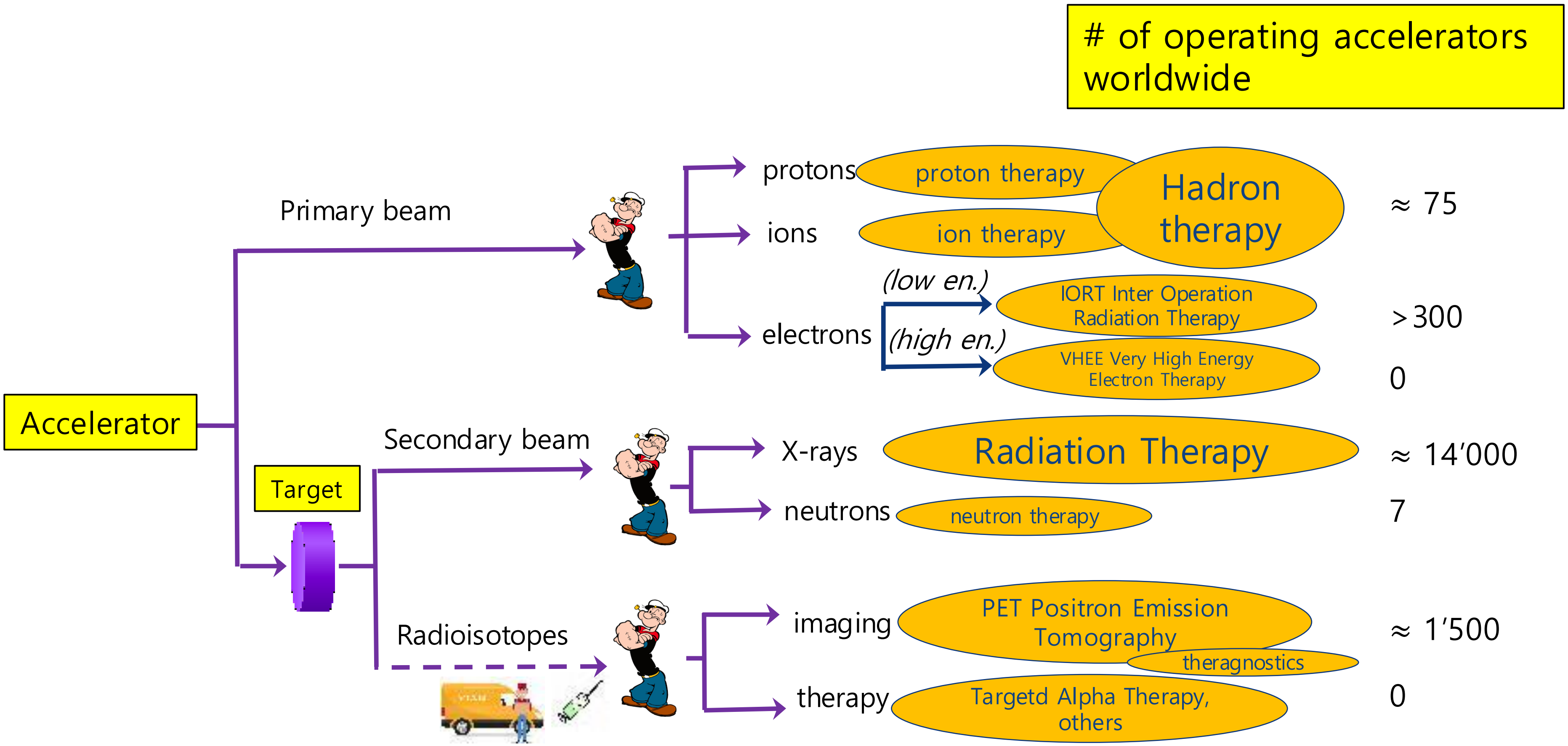
Representation of the 3D structure of the main SARS-CoV-2 protease, obtained using Diamond Light Source. The coils represent "alpha" helices and the flatter arrows are "beta sheets", with loops connecting them together. The organisation of alpha helices and beta sheets is often referred to as the secondary structure of the protein (with the primary sequence being the amino acid sequence and the tertiary structure being the overall 3D shape of the protein). Credit: D Owen/Diamond Light Source.

At a time when many countries are locking down borders, limiting public gatherings, and encouraging isolation, the Diamond Light Source in Oxfordshire, UK, has been ramping up its intensity, albeit in an organised and controlled manner. The reason: these scientists are working tirelessly on drug-discovery efforts to quell COVID-19.

It is a story that requires fast detectors, reliable robotics and powerful computing infrastructures, artificial intelligence, and one of the brightest X-ray sources in the world. And it is made possible by international collaboration, dedication, determination and perseverance.

Synchrotron light sources are particle accelerators capable of producing incredibly bright X-rays, by forcing relativistic

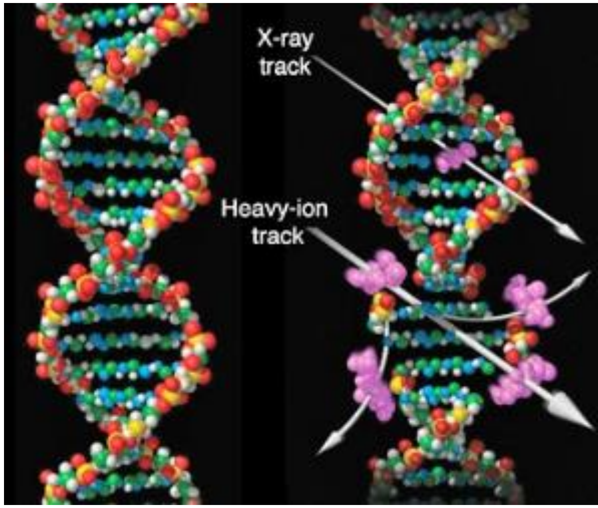
의료용 가속기



Total: ≈ 16,000 of accelerators operating for medicine.

방사선 암 치료

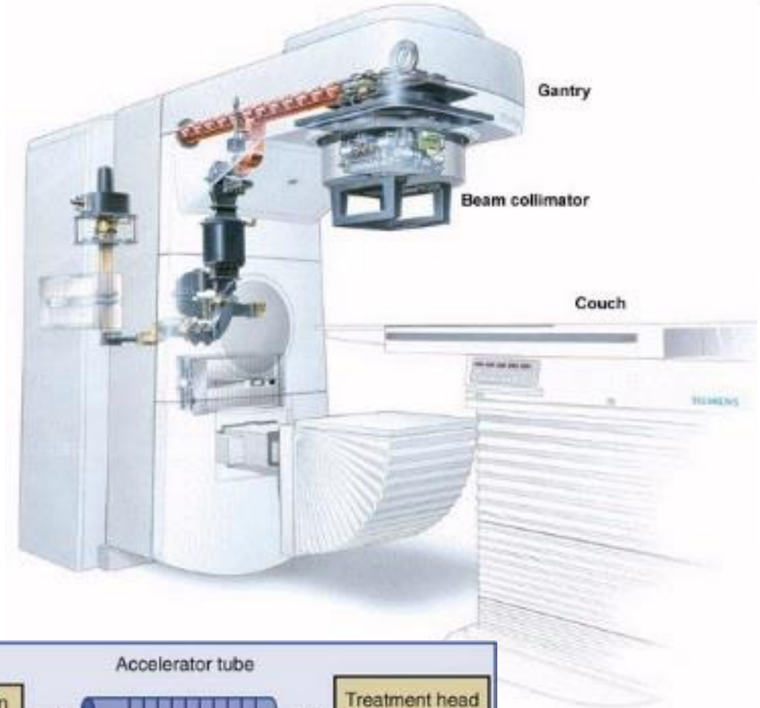
- 방사선을 사용하여 암세포의 DNA 손상을 유도함.
- 정상 세포를 최대한 보호하면서 암세포를 사멸하거나 증식을 억제함.

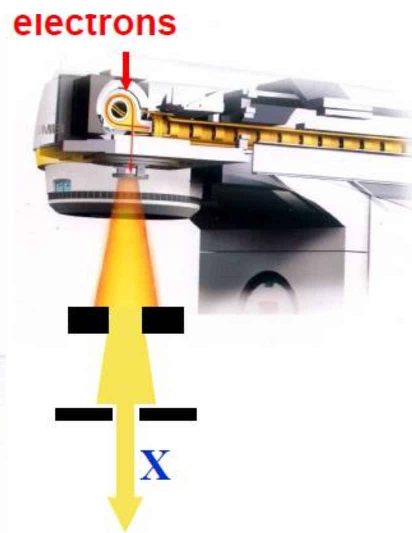


사용 입자	주요 특징
광자 (γ), 전자	가장 보편적이며 표준적인 치료 방식
양성자/중성자	높은 정밀도, 종양 부위 선량 집중도 우수
탄소 이온	생물학적 효과 극대화 및 정밀한 국소 제어

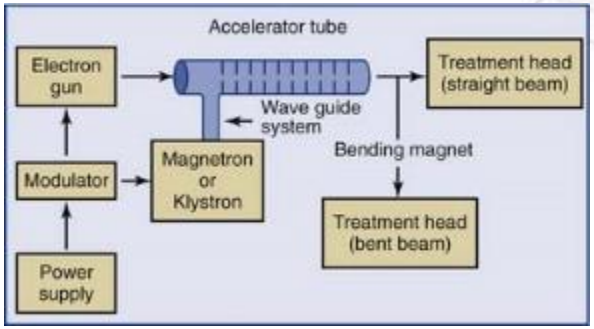
암치료: 전자선형가속기(X-ray)

Electron Linac (linear accelerator) for radiotherapy (X-ray treatment of cancer)





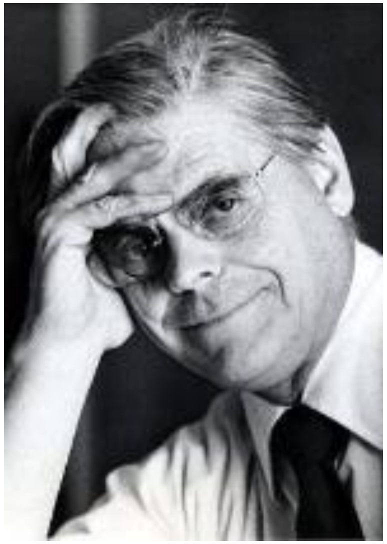
5 – 25 MeV e-beam
Tungsten target



14,000 in operation worldwide!

암치료: 양성자/탄소

- 1939년 11월 20일, 60인치 사이클로트론: 최초의 환자 방사선 치료 시행(중성자빔)



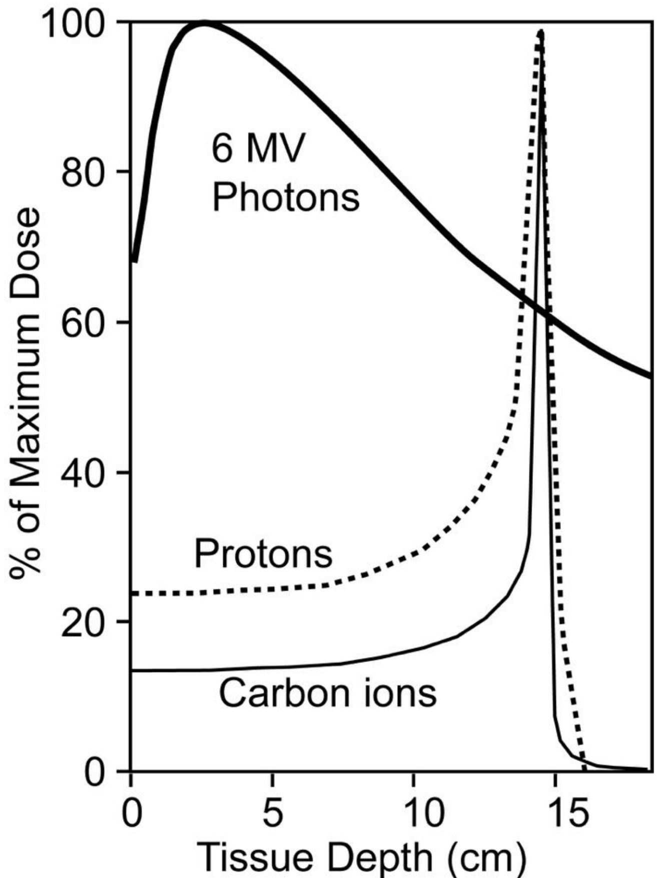
The 1st director of Fermilab

- 1946년 Robert R. Wilson이 브래그 피크를 이용한 양성자 암 치료 제안
- 1956년 Lawrence Berkeley National Laboratory에서 최초 암치료 시행
- 1990년 Loma Linda University Medical Center에서 최초 병원 기반 치료센터 구축

The Bragg peak

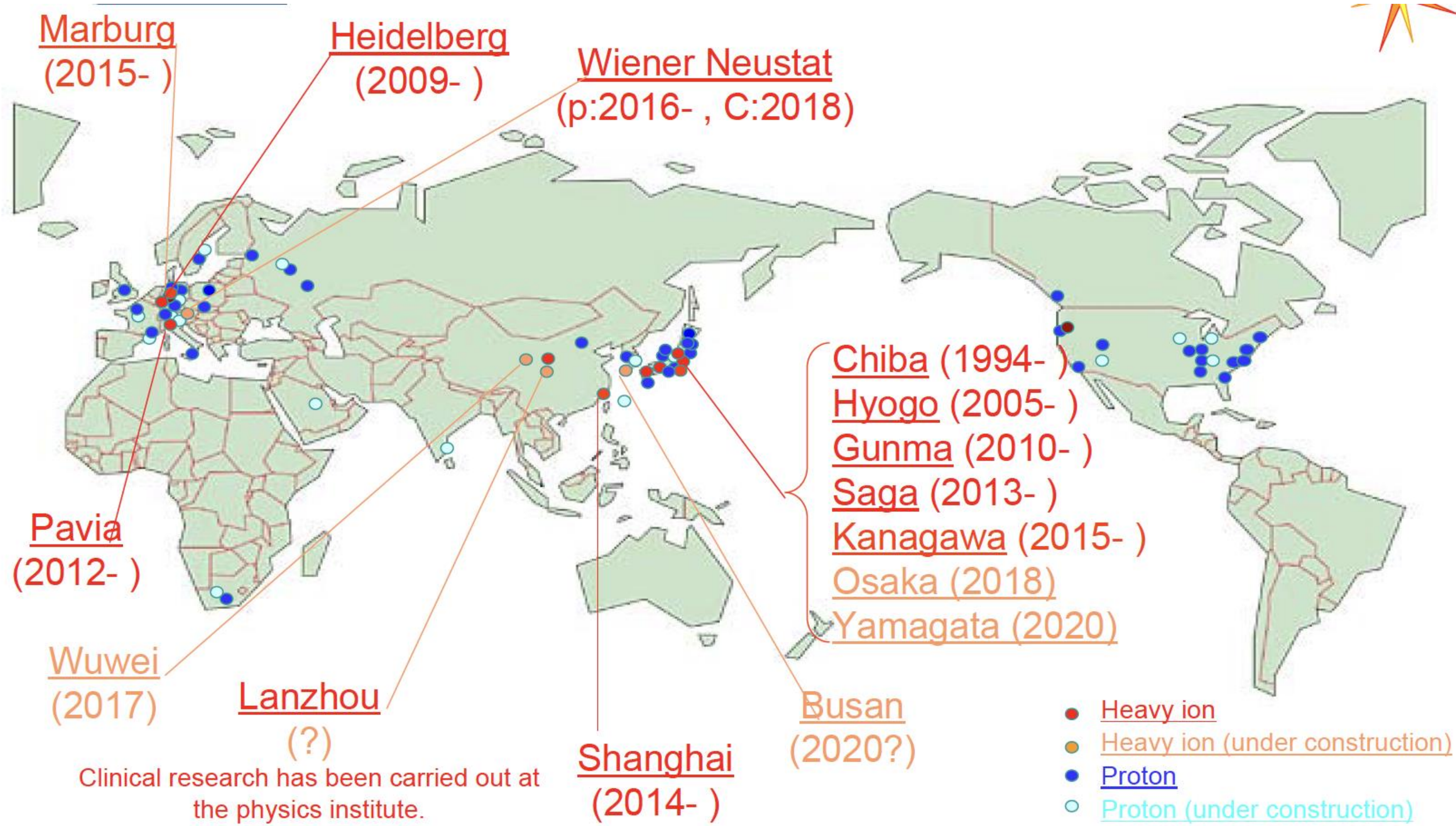
- **Bethe-Bloch equation:**
  ionization energy loss by charged particles

$$-\frac{dE}{dx}=\frac{4\pi}{m_e c^2}\cdot\frac{nz^2}{\beta^2}\cdot\left(\frac{e^2}{4\pi\varepsilon_0}\right)^2\cdot\left[\ln\left(\frac{2m_e c^2\beta^2}{I.(1-\beta^2)}\right)-\beta^2\right]$$



- **Bragg peak at 15 cm:**
  양성자 빔: ~ 150 MeV
  탄소 빔: ~ 285 MeV/u

Particle therapy centers worldwide

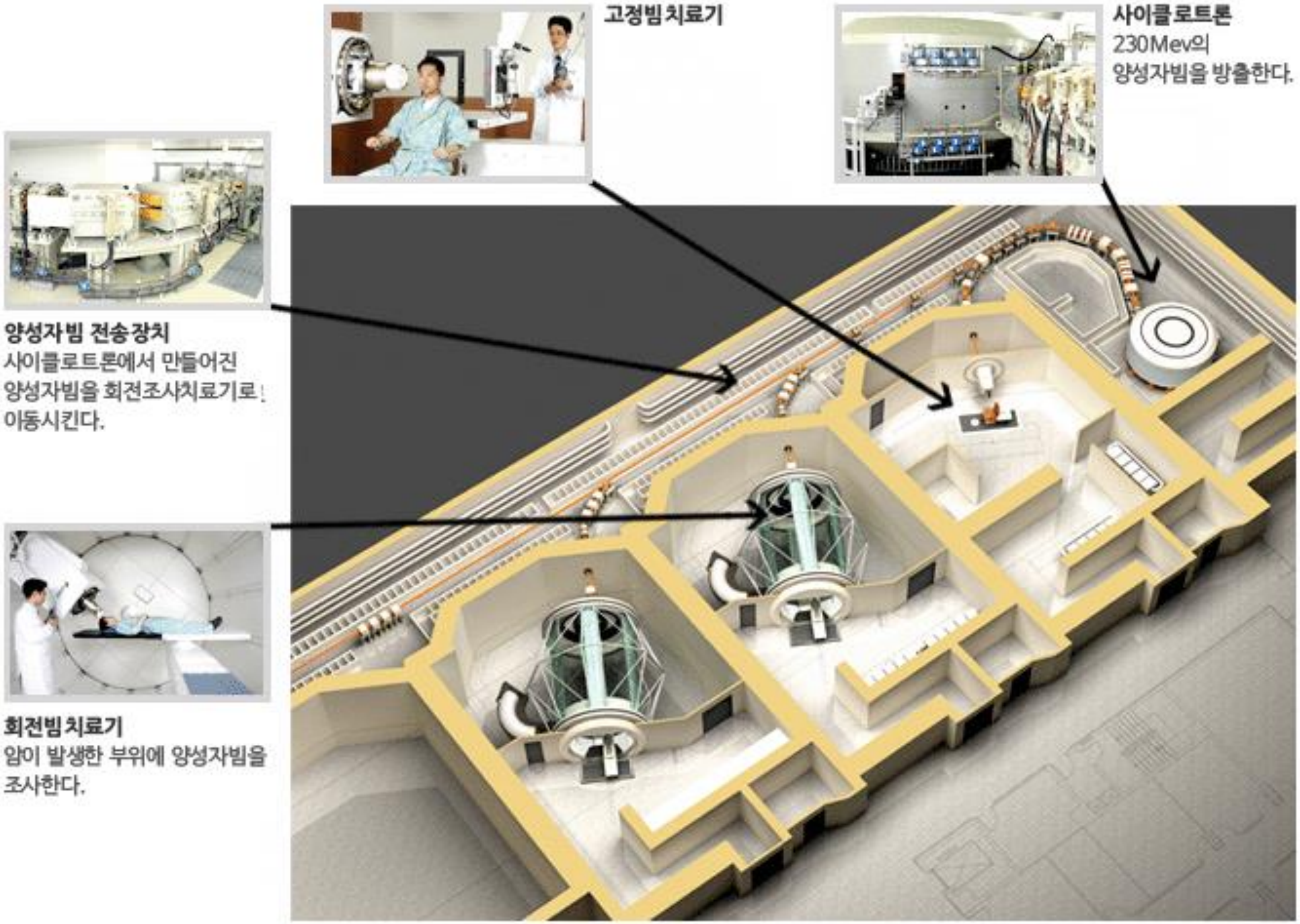


Particle therapy centers in Korea

- 양성자: Cyclotron, ~ 230 MeV
- 탄소: Synchrotron, 430 MeV/u,

빔	기관	장비명	치료시작(년)
양성자	국립암센터(일산)	IBA Proteus plus	2007
	삼성서울병원	Sumitomo Proton	2005
	계명대 동산병원	ProTom Radiance 330 (Synchrotron)	2029 ?
	칠곡경북대병원	?	2030 ?
탄소	세브란스병원(신촌)	Toshiba Carbon	2023
	서울대 기장병원	Toshiba Carbon	2027 ?
	아산 현대병원	Toshiba Carbon ?	2030 ?

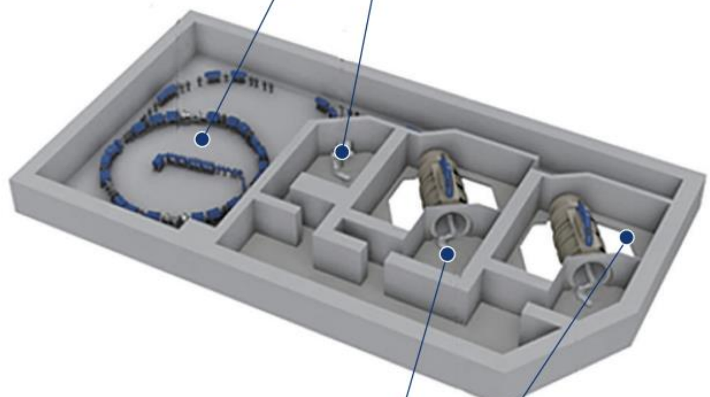
국립암센터(일산)


고정빔치료기
사이클로트론
230Mev의
양성자빔을 방출한다.
양성자빔 전송장치
사이클로트론에서 만들어진
양성자빔을 회전조사치료기로
이동시킨다.
회전빔치료기
암이 발생한 부위에 양성자빔을
조사한다.

세브란스병원
중입자 치료센터

가속기실

고정빔 치료실 내부



갠트리 치료실 내부

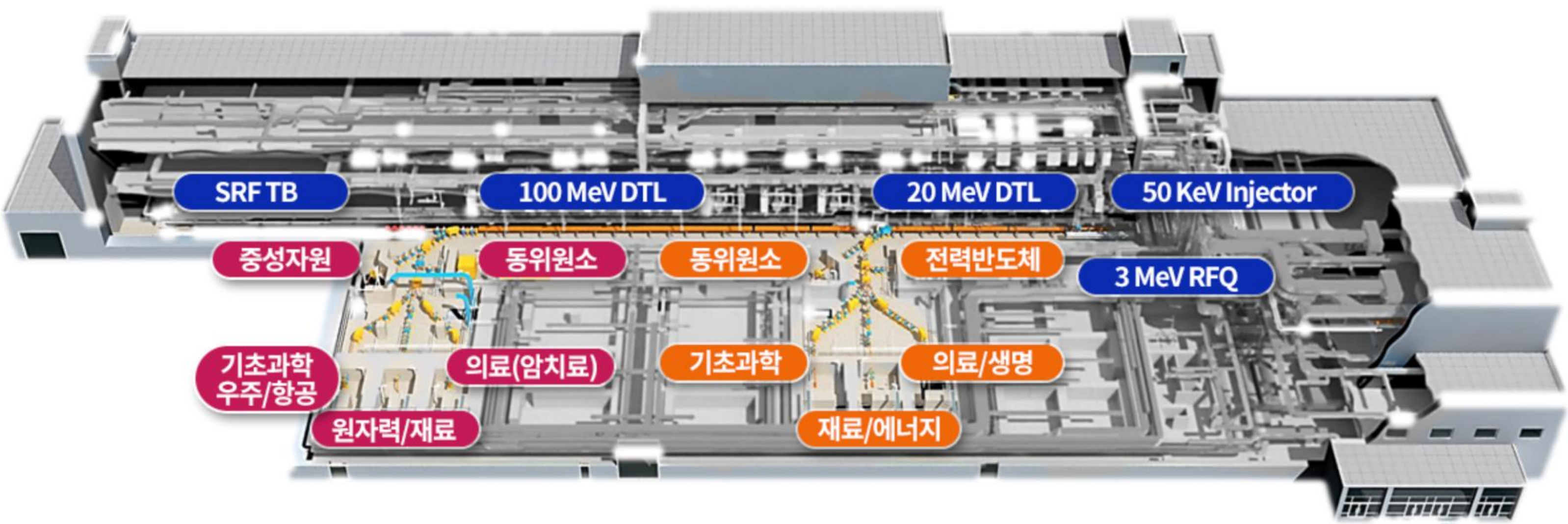
갠트리 치료실 외부

국내 연구용 가속기 현황: 방사광가속기

- **포항가속기 연구소**
  - **포항방사광 가속기(PLSI -> PLS-II): 2.5 GeV -> 3.0 GeV (1994.12. ~)**
  - **4세대 방사광가속기(PAL-XFEL): 10.0 GeV (2016.09 ~)**

국내 연구용 가속기 현황: 양성자가속기

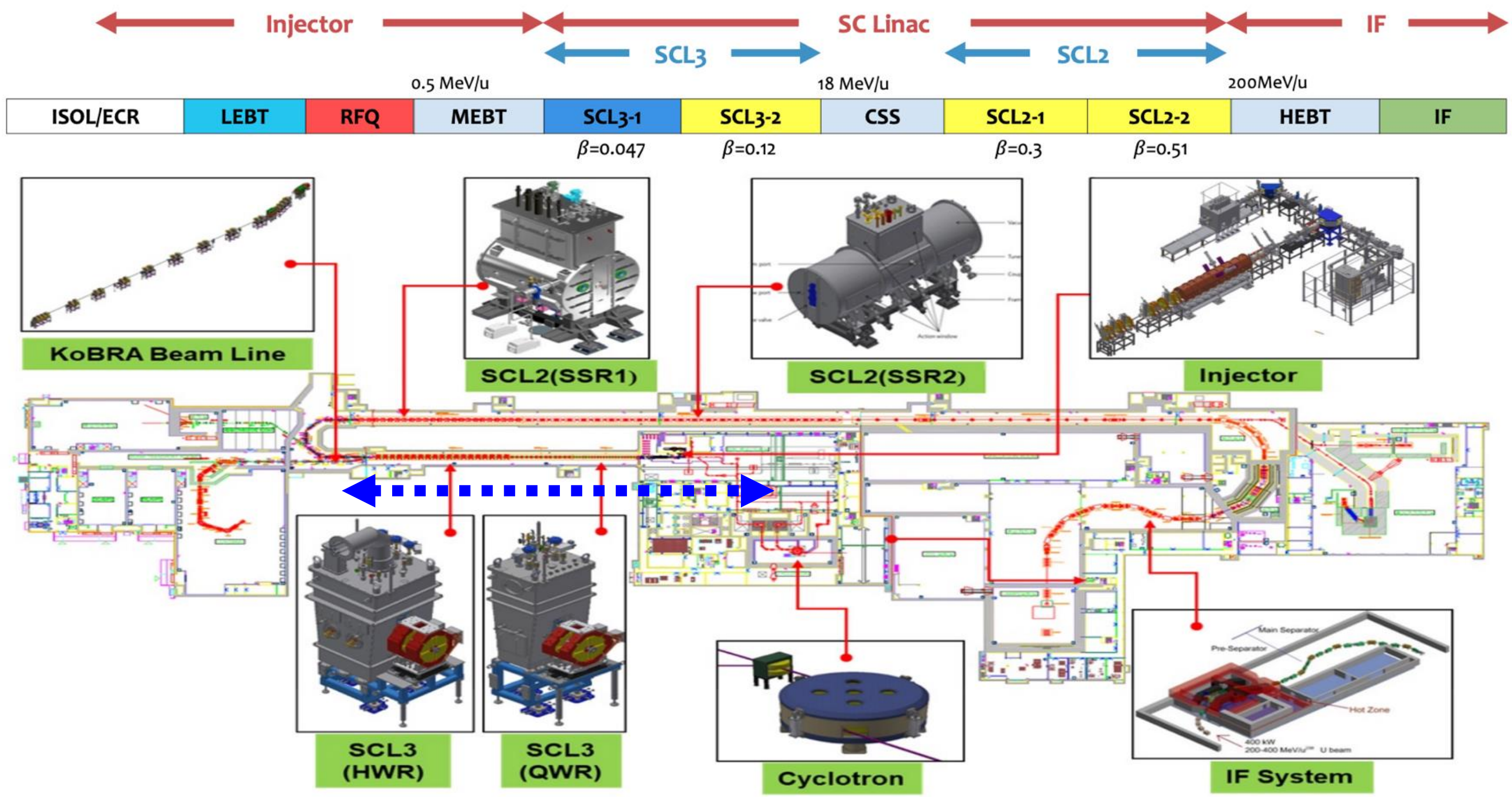
- 한국원자력연구원 양성자과학연구단
  - 100 MeV 양성자 (2013.07.~)



국내 연구용 가속기 현황: 중이온가속기

- 기초과학연구원(IBS) 중이온가속기연구소
  - ~20 MeV/u of Ar (2022.12.~)
  - 저에너지 가속기 완공

원자번호119
Korianium ?



국내 연구용 가속기 현황: 방사광가속기

- 기초과학지원연구원(KBSI) 방사광 가속기 구축중
  - 충북 청주
  - 4 GeV (2029 ?)

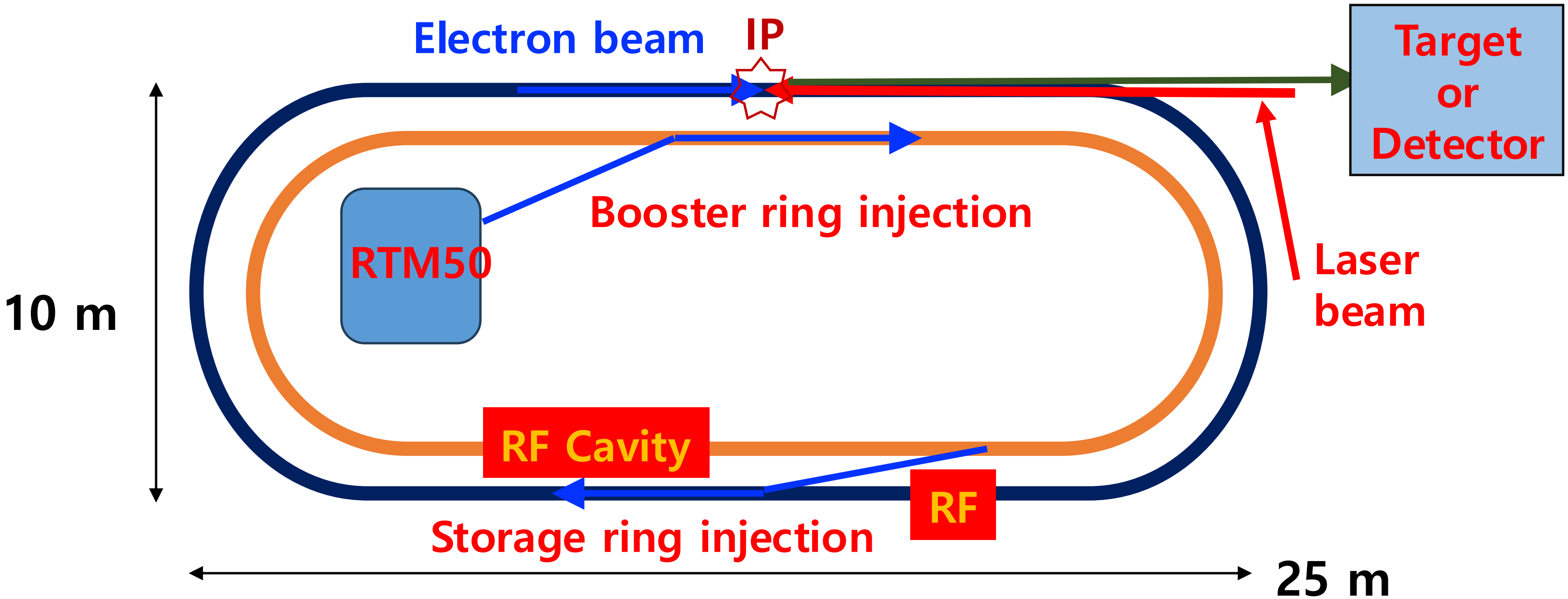
Electron accelerator at KU

- 독일 BESSY 방사광가속기 연구소 기증 RTM50 (Race Track Microtron)
  - 현재 설치 진행중(예산문제로 진행속도 다소지연)

Parameter	Specification
Electron Beam Energy	10.6 MeV ~ 53.0 MeV (에너지 5.3 MeV step으로 변화가능
Beam Pulse length	~ 50 ns
Pulse repetition frequency	10 Hz
Pulse current at 50 MeV	~27 mA (=1.35 nC/pulse)
RF frequency	2,999 MHz

My Dream: e^- →← Laser

- Injector: RTM50 electron microtron
- Build Booster ring and Storage ring
- Major parameters
  - Ar+ laser: CW, 1 Watt
  - Injector: 50 MeV, 10 Hz of 1.3 nC/bunch
  - Booster ring: 50 MeV to 620 MeV electron beam acceleration
  - Storage ring: 620 MeV electron beam storage
    No. of bunches in the ring: 60 (0.1 nC/bunch, beam current: ~36 mA)
- ~ 20 MeV of Gamma-ray flux: 2.5×10^5 – 5×10^6 photons/sec



My Dream: $e^- \rightarrow\leftarrow$ Laser

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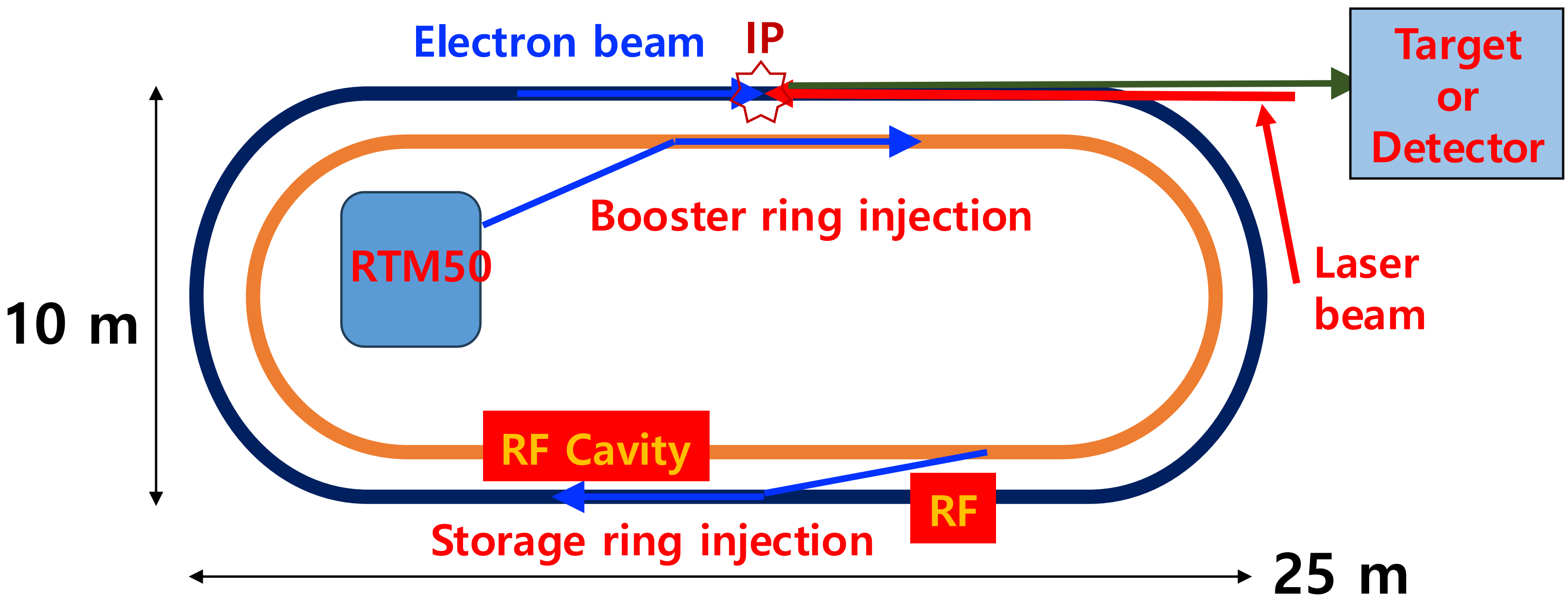
- Major parameters
  - Ar+ laser: CW, 1 Watt
  - Injector: 50 MeV, 10 Hz of 1.3 nC/bunch
  - Booster ring: 50 MeV to 620 MeV electron beam acceleration
  - Storage ring: 620 MeV electron beam storage

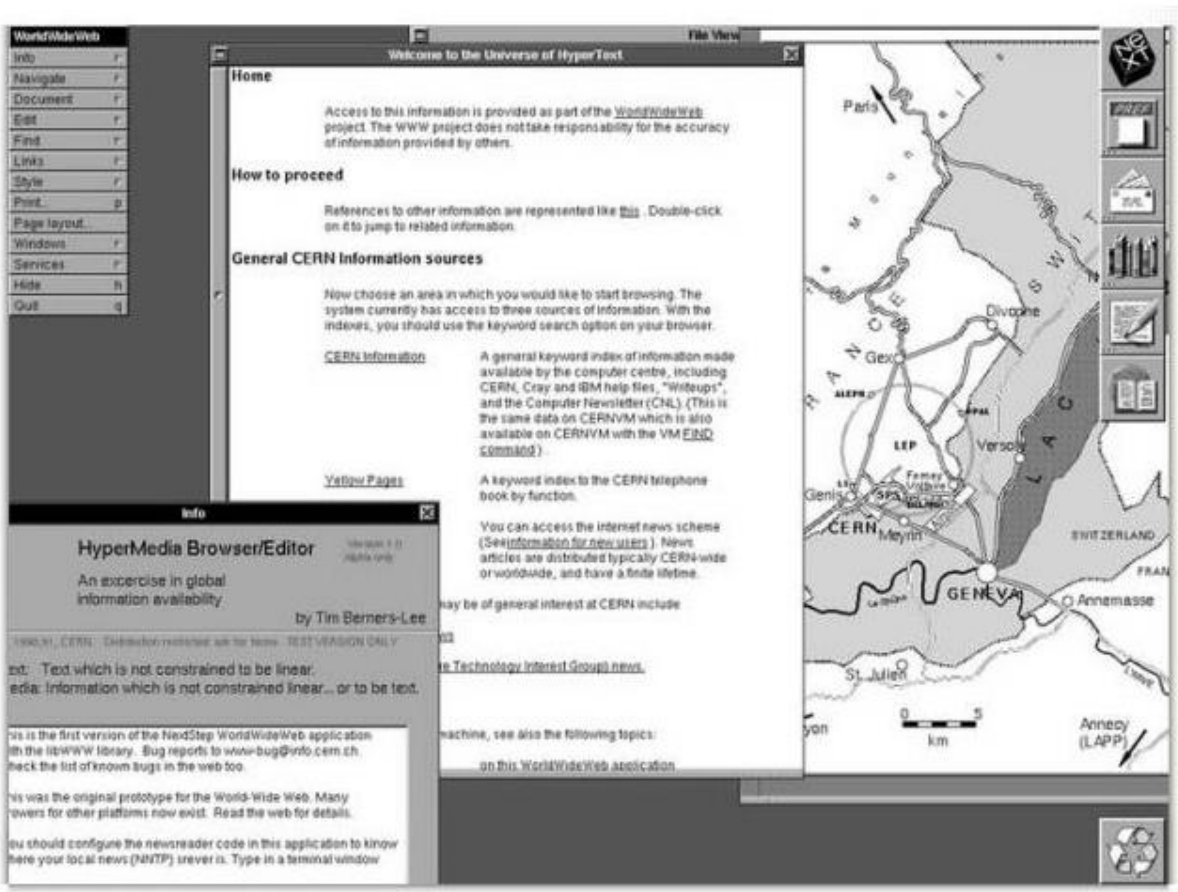
This will be the first collider in Korea !



입자물리 연구의 파생 성과: AI 데이터 생성기반

DECEMBER 1990

The world's first browser/editor, website and server go live at CERN



The 1st WWW server: NeXT machine

입자가속기의 활용분야

(Particle Accelerator Applications: Research, Medicine, Industry, and Next-Generation Energy)


OBRIGADO
TUSEN TAKK
TACK
HVALA
RAHMAT
SAWADDEE KRUP/KAA
TACK
KIITOS
DZIĘKUJE
DANKE 谢谢
THANK YOU
GRACIAS MERCI
RAHMAT
TERIMA KASIH
DANK JE
MATUR NUWUN
감사합니다
MÃLÕ
SHUKRAN
SALA AMAT
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ありがとうございます