Introduction to Particle Accelerators

ACS601: Accelerator Physics I, 2026 Spring

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Course Information I

- **Course Objectives**:
  - This course is to provide a comprehensive introduction to Accelerator Physics with an emphasis on beam dynamics and accelerator design.

- After taking this course, students will be able to:
  - Develop their knowledge of general particle accelerators,
  - Run various accelerator simulation codes including mad-x,
  - And design a simple particle accelerator lattice.

Course Information II

- **Textbook and Lecture Notes**
  - Particle Accelerator Physics by Prof. H. Widemann
    - Free online version is available from Springer website
  - Supplement: Accelerator Physics by Prof. S.Y. Lee
    - Free Kindle Version is available from Amazon

- Lecture Slides or Notes will be provided
  - Check LMS or Indico websites

- **(Recommended) Pre-requisites**
  - Classical Mechanics(ACS501/502), E&M(ACS503/504),
  - Beam Dynamics(ACS603/604)
  - Special Relativity Theory(ACS551), Advanced Mathematics(ACS607)

Course Information III

- **Class Hour**
  - 02:00 PM to 04:50 PM on Tuesday
- **Office Hour**
  - 05:00 PM to 06:00 PM on Tuesday
  - Or by appointment
- **Contact**
  - kuphy@korea.ac.kr
- **Grades:**
  - Homework(30 %), Midterm(25 %), Final(25%), and Group Project(20 %)

Course Schedule

Week	Lectures
1	가속기 개론 및 역사
2	상대론적 역학과 좌표계
3	단입자 횡방향 동역학 I
4	단입자 횡방향 동역학 II
5	종방향 동역학
6	선형가속기 물리
7	원형가속기와 저장링
8	중간고사

Week	Lectures
9	RF cavity와 가속
10	공간전하효과
11	임피던스와 불안정성
12	빔 상호작용
13	특수 가속기 (FEL, Plasma 가속)
14	가속기 진단 및 제어
15	종합 설계 프로젝트 발표
16	기말고사

가속기란

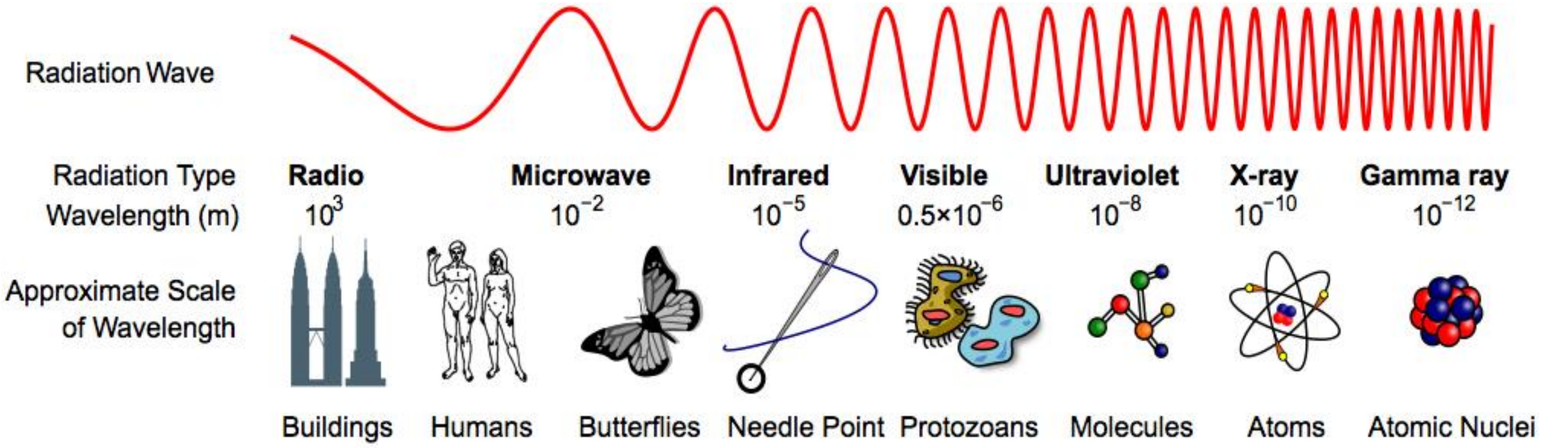
- **입자 가속기란**
  - 입자 빔(Particle)을 만들어 내고 가속하는 일련의 장치
    - 주요 입자 – 하전 입자 : 전자, 양전자, 양성자, 산소이온, 탄소이온 등
    - 이차 입자 – 중성 입자 : 광자, 중성자 등
- **전세계적으로 40,000 개 이상의 가속기가 운영 중**
  - 국내에는 대략 300 개 이상
  - 산업용 가속기 : > 200
  - 의료용 가속기 : > 100
- **응용 분야**
  - 기초과학 : 물리, 화학, 생물 등
  - 재료과학 : 반도체 등
  - 환경 : 수질 개선
  - 동위원소 생산 : 산업/의료 진단용 동위원소 생산
  - 암치료용 가속기

Applications of Particle Accelerators

- **Fundamental Physics**
  - **Nuclear Physics:** Ion accelerators, isotope separation.
  - **High-Energy Physics:** Fixed target experiments.
  - **Colliders:** Electron-positron & hadron storage rings.
  - **Linear Colliders:** Next-gen precision frontiers.
- **Power & Energy**
  - **Inertial Fusion:** Heavy ion drivers for fusion.
  - **Reactor Fuel Breeding:** Accelerator-driven systems.
  - **Waste Transmutation:** Reducing radioactive lifetime.
- **Industry & Tech**
  - **Ion Implantation:** Semiconductor manufacturing.
  - **Material Modification:** Surface hardening, sterilization.
  - **Radiography:** X-ray inspection of materials.
  - **Isotope Production:** Industrial tracers.
- **Photon Science**
  - **Synchrotron Radiation:** Biology, chemistry, materials.
  - **Coherent Radiation:** Free Electron Lasers (X-FEL).
  - **Microscopy:** X-ray holography, microprobes.
  - **Lithography:** X-ray lithography for chips.
- **Medicine & Health**
  - **Radiotherapy**
    - Linear accelerators (linacs) are the workhorses of cancer treatment, delivering precise X-ray or electron beams to destroy tumor cells while sparing healthy tissue.
  - **Isotope Production**
    - Cyclotrons produce short-lived radioisotopes (e.g., Technetium-99m, Fluorine-18) essential for PET scans and other diagnostic imaging.
  - **Advanced Therapies**
    - Hadron therapy (Protons/Carbon ions) and microsurgery using tunable Free Electron Lasers (FEL) offer new frontiers in non-invasive treatment.

가속기의 용도 I – 가속기는 현미경

- **가속기는 작은 물체를 연구(탐색)하기 위한 도구**
- 물체(object)를 연구하려면 물체보다 작은 파장이 필요
- 양자역학: $\lambda=h/p$
  - λ: 드브로이 파장
  - h: 플랑크 상수(~4.1e15 eV-s)
  - p: 입자의 운동량
- 더 나은 물체 분해능을 실현하려면 입자의 운동량이 높아야 하고 즉, 에너지가 증가해야 함

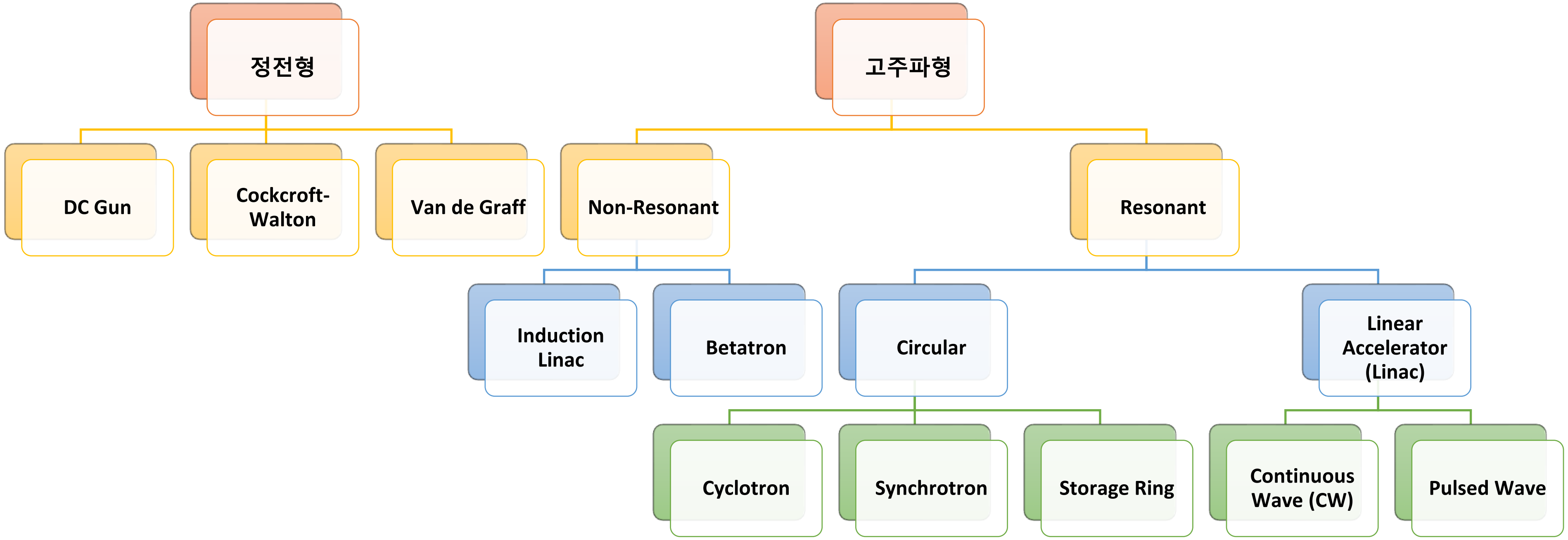


가속기의 용도 II – 입자 빔의 높은 에너지 이용

- 산업용 가속기
  - 전자빔 용접
  - 반도체 이온주입
  - 질량 분석기 (탄소 연대 측정)

- 의료용 가속기
  - 진단용 동위원소 생산
  - x선 발생 장치
  - 양성자/중입자를 이용한 암치료

가속기의 종류



정전형
고주파형
DC Gun
Cockcroft-Walton
Van de Graff
Non-Resonant
Resonant
Induction Linac
Betatron
Circular
Linear Accelerator (Linac)
Cyclotron
Synchrotron
Storage Ring
Continuous Wave (CW)
Pulsed Wave

Historical Overview of Accelerators

- 1895: Roentgen discovers x-rays
- **1897: J.J. Thomson discovers the electron**
- 1905: Einstein theory of relativity, Einstein's theory of light quanta
- 1907: Schott develops first theory of synchrotron radiation
- 1911: Rutherford discovers atomic nucleus using alpha particles
- 1920: Greinacher builds first cascade generator of about 100 kV
- **1924: Ising proposes first concept for acceleration by repeated application of voltage kicks**
- **1927: Wideroe makes first linear accelerator; accelerates Na and K ions**
- 1931: Van de Graaff builds first high-voltage generator
- 1932: Cockroft Cockroft and Walton construct first and Walton construct first "high-energy" accelerator, produce first artificially generated nuclear reaction: p + Li -> 2 He
- 1932: Lawrence and Livingston construct first cyclotron, accelerating 1.2 MeV protons
- **1939: Hansen and Varian brothers invent the klystron**
- 1941: Kerst and Serber build first build first betatron
- **1941: Touschek and Wideroe invent concept of a particle storage ring**
- **1943: Oliphant invents concept of synchrotron**
- **1947: First direct observation of synchrotron radiation at General Electric**
- **1947: Alvarez builds first proton linear accelerator**
- **1947: Ginzton builds first electron linear accelerator builds first electron linear accelerator**
- **1950-1952: Concept of strong-focusing is invented**
- **1954: R.R. Wilson et. al. builds first strong-focusing synchrotron at Cornell University**
- **1956: Hartmann uses synchrotron radiation for first spectroscopy experiments**
- 1960: First electron-positron collider: ADA at Frascati
- 1972: First proton-proton collider ISR at CERN proton collider: ISR at CERN
- 1981: First proton-antiproton collider: SPS at CERN

가속기의 필수 개념

- **입자 가속기**
  - 전기장과 자기장을 이용하여 입자 빔을 가속하는 장치

- **빔 세기**
  - 빔 안의 입자의 수
  - 입자 빔의 전류로 측정

- **빔 에너지**
  - 1 Coulomb의 전하를 띈 입자가 1 V의 전압차에 의해 에너지를 얻을 때 1eV라 함, E=qV

- **입자 가속기의 주요 장치**
  - 자석 과 고주파 가속관으로 구성
  - (전)자석은 입자의 운동 방향을 바꾸기 위해 쓰임
  - 고주파 가속관은 입자의 에너지를 높여 가속하기 위해 쓰임

가속기의 기본 원리

- Newton's Second Law: $\vec{F} = m\vec{a}$
  - Therefore, internal/external forces are needed to accelerate particles/beams

- Lorentz Force Law: $\vec{F} = q\left(\vec{E} + v \times \vec{B}\right)$
  - Forces are acting on **charged particles.**

- 전기장은 하전 입자가 운동하는 방향과 같은 방향으로 가속할 수 있는 힘에 영향
  - 입자의 에너지를 증가/감소 시킴

- 자기장은 하전 입자가 운동하는 방향에 수직 방향으로 가속할 수 있는 힘에 영향
  - 입자의 운동 방향을 변화

특수 상대론 기초

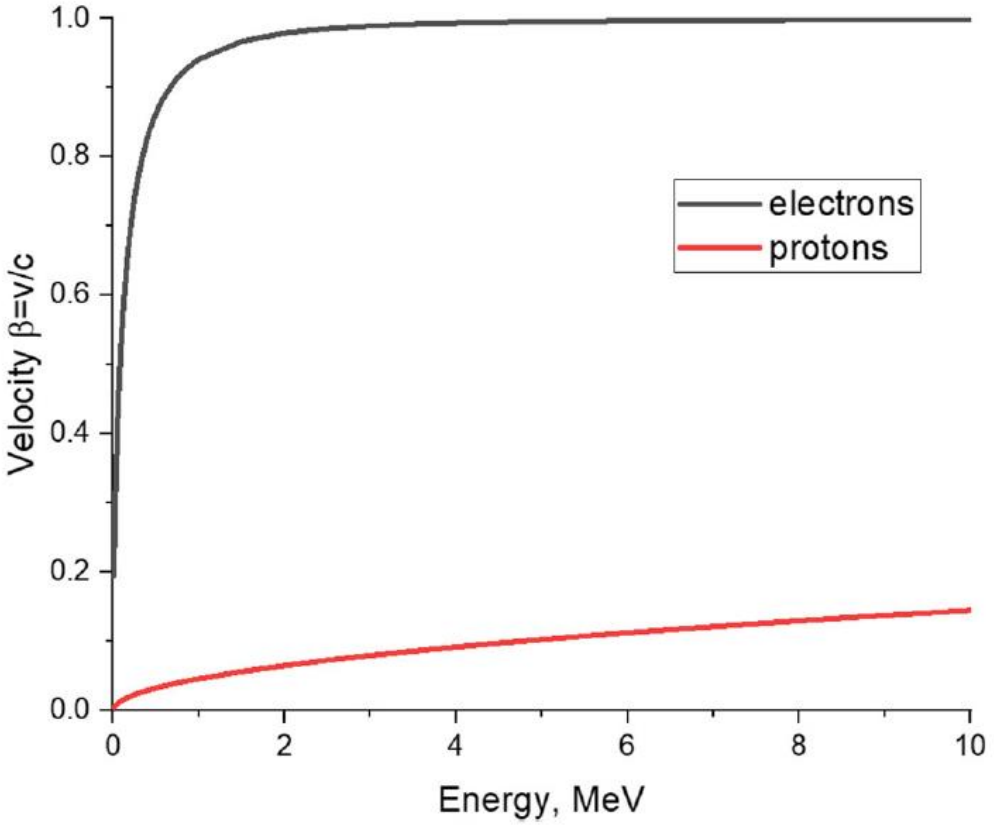
- **고전역학에서의 입자의 운동량 : $\boldsymbol{p = mv}$**
- **상대론적 역학에서의 입자의 운동량: $\boldsymbol{p = \gamma m v}$**
- $E = mc^2$: Einstein's the famous equation!
  - Mass-energy equivalence
- $E = mc^2 = \gamma m_0 c^2 = T + m_0 c^2 = (pc)^2 + (m_0 c^2)^2$
  - γ: Lorentz relativistic factor
  - m_0: particle's rest mass energy
  - T: particle's kinetic energy

- $\gamma = 1 + \frac{T}{m_0 c^2} = \frac{1}{\sqrt{1-(v/c)^2}} = \frac{1}{\sqrt{1-\beta^2}}$
  - $\beta = v/c$
- 기초단위:
  - **Energy (eV) : Energy is expressed in units of "electron volts"**
  - **Momentum (eV/c)**
  - **Mass (eV/c^2) : for masses at rest**

Electrons vs Protons

- Particle's rest mass
  - Electron: 0.511 MeV/c^2 (0.510 998 950 00(15))
  - Proton: 938.272 MeV/c^2 (938272 088 16(29))
  - $\gamma = 1 + \frac{T}{m_0 c^2} = \frac{1}{\sqrt{1-(v/c)^2}} = \frac{1}{\sqrt{1-\beta^2}}$
- Electron vs Proton

Kinetic Energy	Electron		Proton	
	β	γ	β	γ
10 keV	0.19498541	1.01956947	0.00461686	1.00001066
100 keV	0.54822043	1.19569472	0.01459875	1.00010658
1 MeV	0.94107906	2.95694716	0.04613212	1.00106579
10 MeV	0.99881756	20.5694716	0.14484393	1.01065788
100 MeV	0.99998708	196.694716	0.42819531	1.10657879
1 GeV	0.99999987	1957.94716	0.87502551	2.06578789
10 GeV	0.99999999	19570.4716	0.9963142	11.6578789



Basic Components of Accelerator Systems

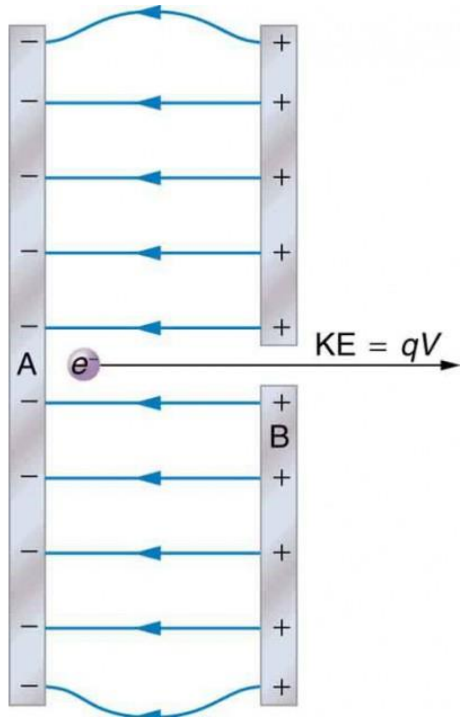
- **Source**
  - Electron Gun / Ion Source

- **Accelerating Structures**
  - High Voltage Electrodes/Acceleration Columns
  - RF Cavities
  - RF Quadrupoles(RFQ)
  - Steering/Focusing magnets: dipoles, solenoids, quadrupoles

- **Auxiliary System**
  - Beam pipes
  - Vacuum pumps
  - Cooling systems
  - Power Sources (RF amplifiers, Power supplies, etc.)
  - Diagnostics systems (Beam Profile Monitors, Beam Position Monitors, Wire Scanner, Allison Scanner, etc.)

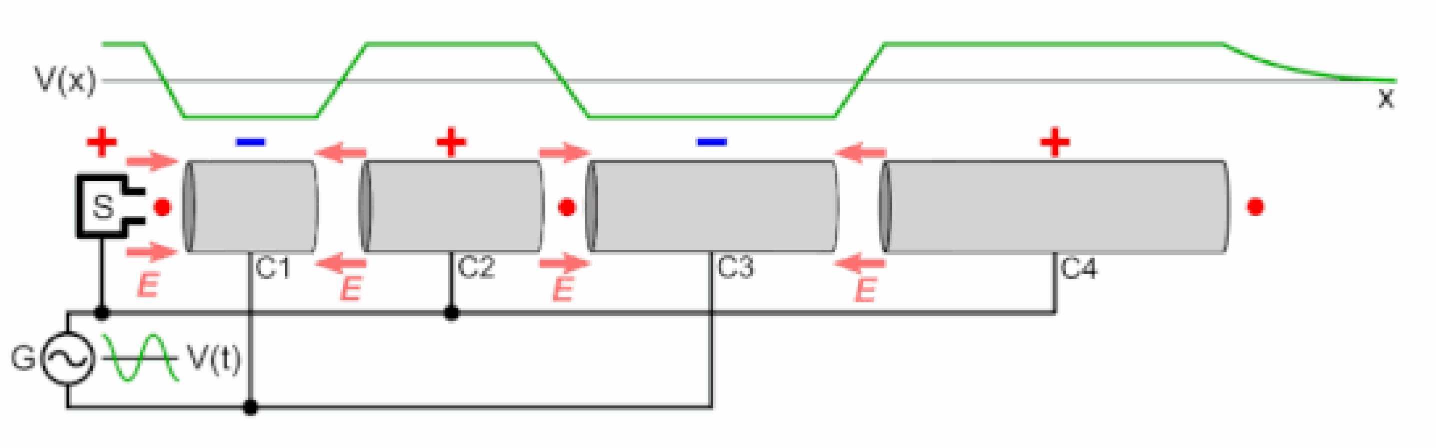
가속기의 가속 원리

- 한 개의 전자가 1 V의 전압차의 사이에서 얻는 에너지는 1 eV
- $1\ eV = (1.60 \times 10^{-19} C)(1V) = (1.60 \times 10^{-19} C)(1\ J/C) = 1.60 \times 10^{-19}\ J$
- 참고: 1 kg의 물체가 1 m의 높이에서 갖는 위치 에너지는 6e18 eV
- 1.5 V 건전지로 비슷한 크기의 전압차이를 만들 수 있음
- 양성자 또는 전자를 1 TeV (terra electron volt)의 에너지까지 가속하기 위해서는 약 6670억 개의 1.5 V 건전지가 필요
    - ~ 40,000,000 km
    - 달까지의 거리: ~384,400 km
    - 따라서 달까지의 거리의 100 배 이상



고주파 가속기의 가속 원리

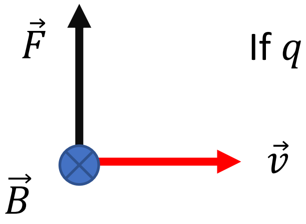
- 1928년 Widroe에 의해 고안된 선형 가속기
- 고주파 전기장 (RF Fields)에 의해 반복적으로 가속



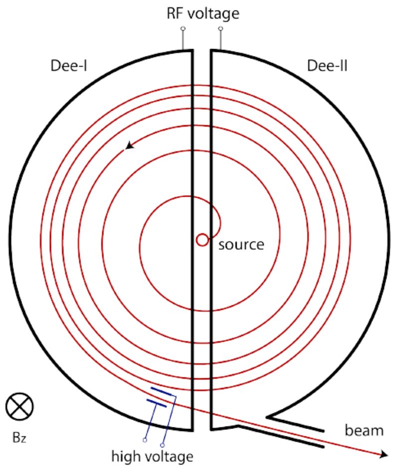
- 1929년에 Lawrence에 의해 사이클로트론의 기본 원리로 변형
  - Widroe의 선형가속기를 더 작게 만들기 위해 자석을 이용해 궤도를 감아보는 아이디어 제안

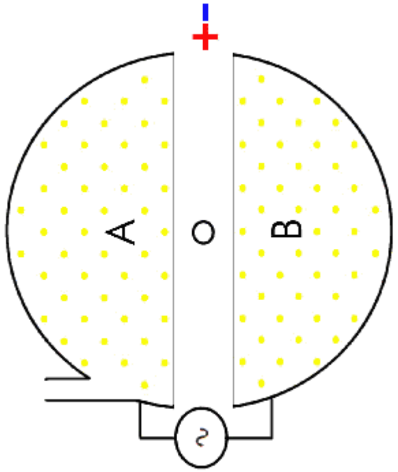
사이클로트론의 가속 원리

- 로렌츠의 힘의 법칙: $\vec{F} = q(\vec{E} + \vec{v} \times \vec{B})$
- 고주파(RF) 전기장에 의해 여기된 전극에 의해 입자의 에너지가 증가
- Dee 안에서의 전기장은 0!
- 자기장에 의한 원운동: $v = r\omega$
  - $F_c = \frac{mv^2}{r} = mr\omega^2$: 구심력
  - $F_B = qvB = qr\omega B$: 자기장에 의한 힘
- $F_C = F_B \rightarrow \omega = \frac{qB}{m}$: 사이클로트론 주파수
  - 입자는 에너지가 증가(가속)함에 따라 같은 주파수로 원운동
- 이때 원운동 반경은 속도(운동량)에 비례
- $r = \frac{mv}{qB} = \frac{p}{qB} \rightarrow Br = \frac{p}{q}$: Magnetic Rigidity (자기강성)



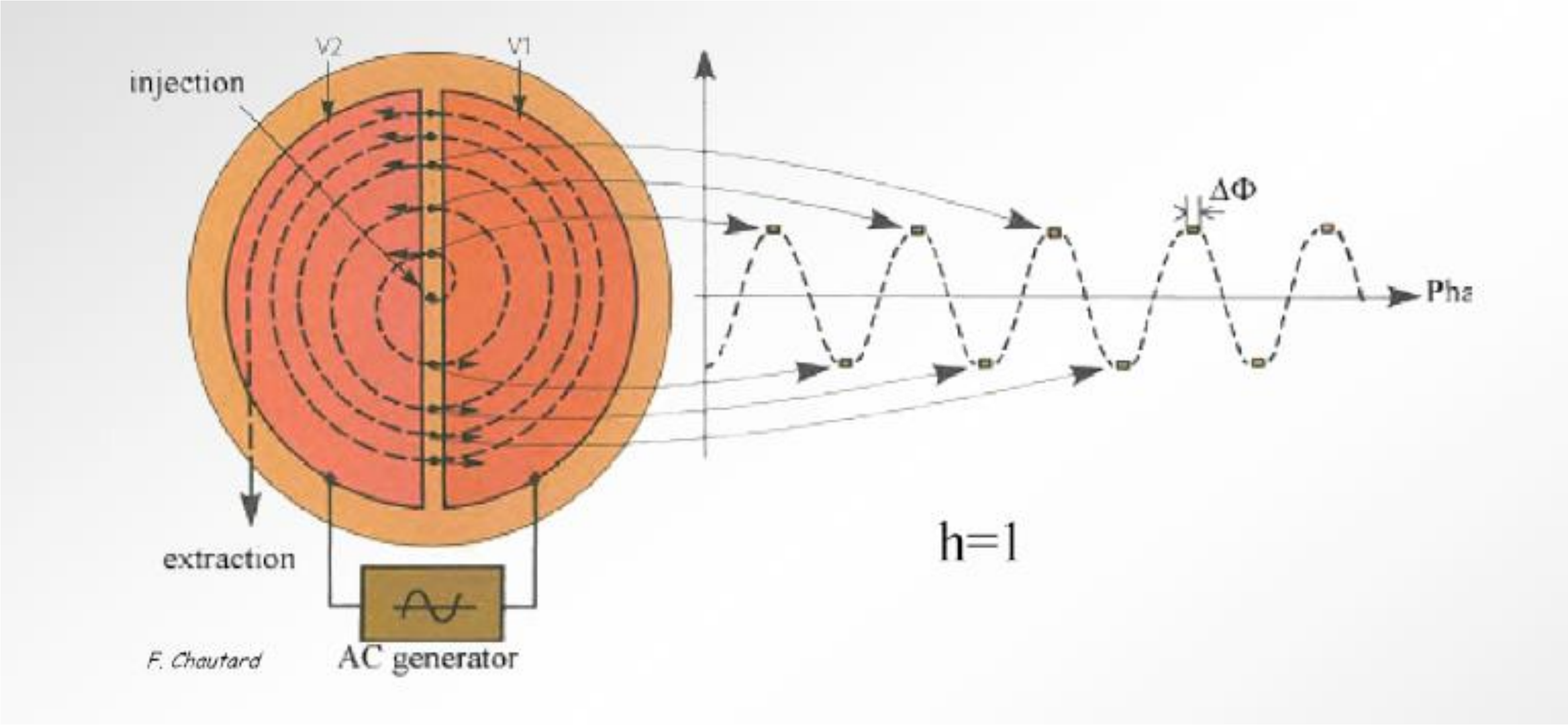
If $q > 0$



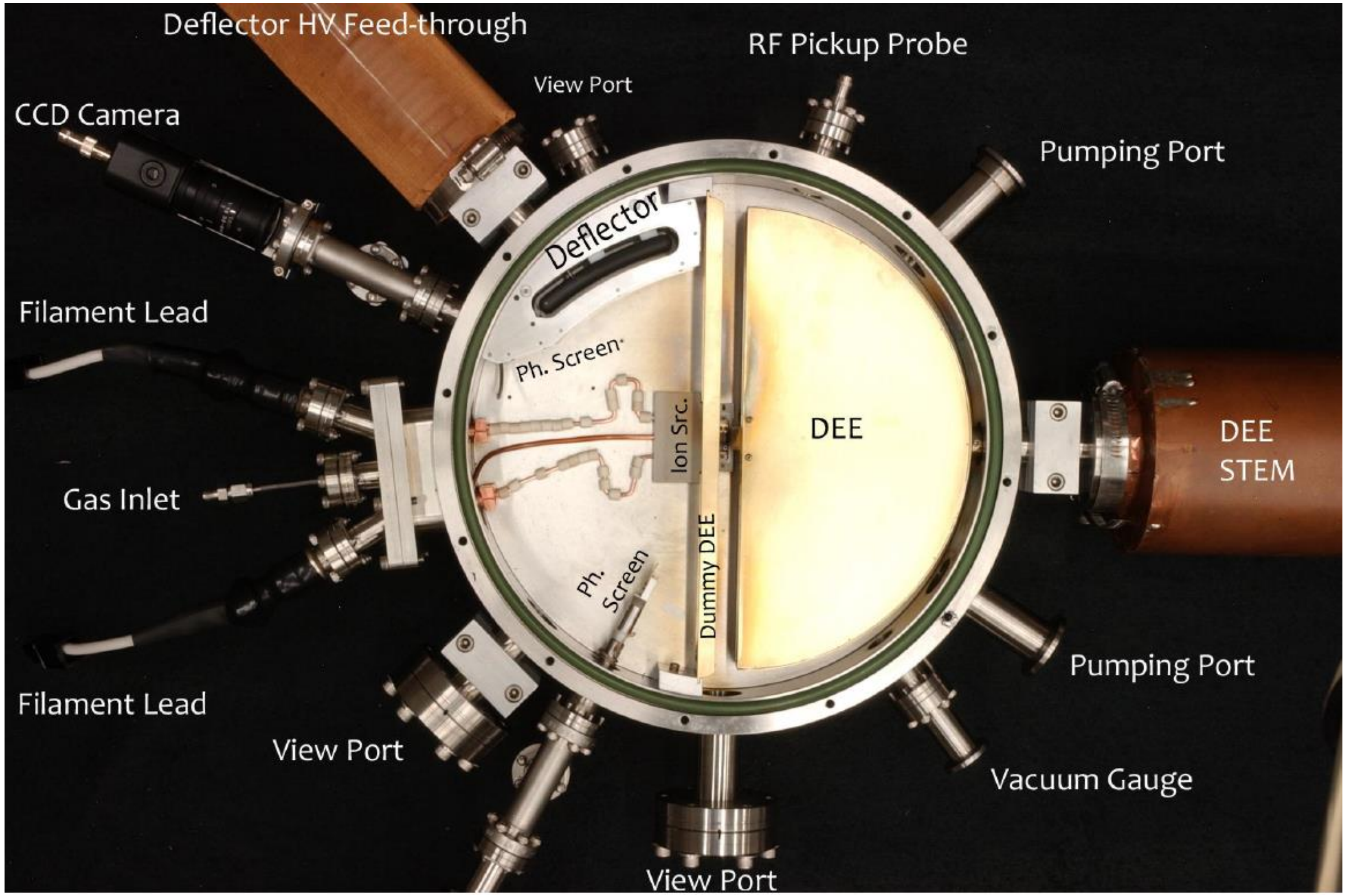


사이클로트론의 가속 원리

- $\omega_{RF} = h\omega_{rev}$ (h는 정수)이면 isochronous 입자는 일정한 시간마다 같은 속도로 회전



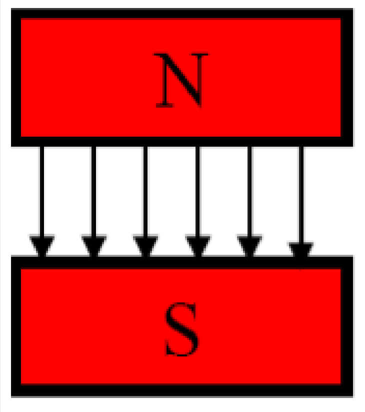
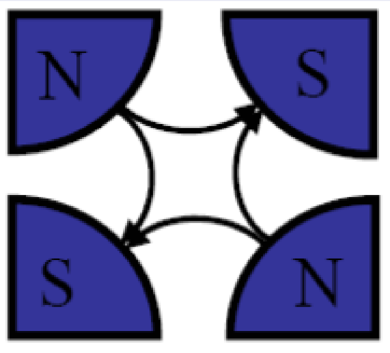
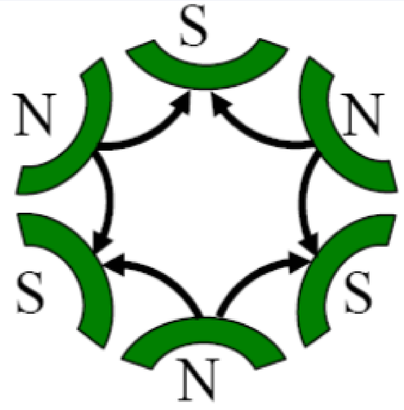
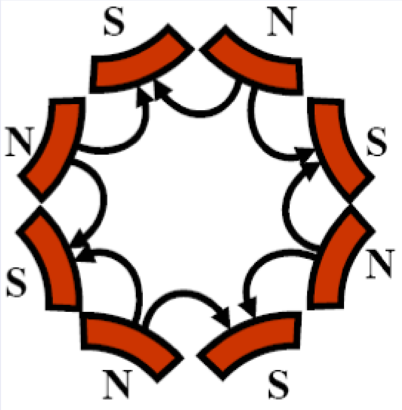
Rutgers 12-inch 사이클로트론



Magnets

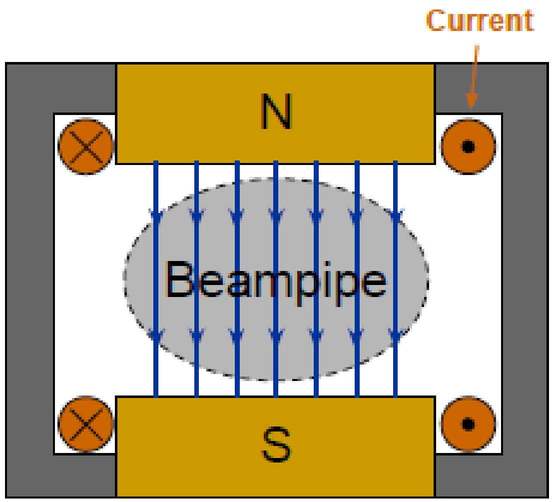
- Magnets steer the trajectory of the beam in particle accelerators.
  - Magnetic fields cannot be used to change the kinetic energy of a particle
  - Magnetic fields are used to bend particles for guidance and focusing
- From Lorentz Force Law, $\vec{F} = q(\vec{E} + \vec{v} \times \vec{B})$
  - The magnetic force will always be perpendicular to the beam velocity.
- Magnetic Rigidity
  - $B\rho = \frac{p}{q}$ [T-m]
  - To keep beam inside the machine, we increase the magnetic field strength B to maintain a constant radius

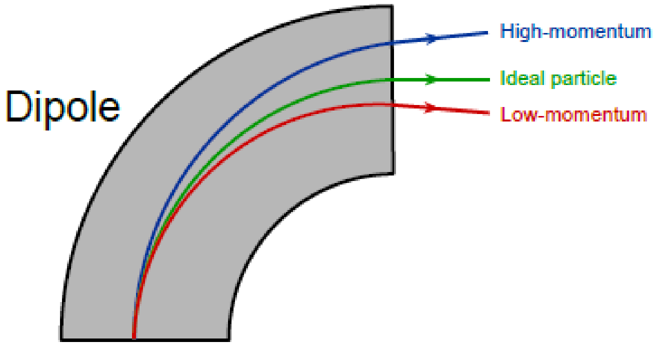
Multipole Magnets

n = 0	n = 1	n = 2	n = 3	n = 4
Drift	Dipole	Quadrupole	Sextupole	Octupole
Beam pipe, etc.				
$B_x = 0$	$B_x = 0$	$B_x = B'y$	$B_x = B''xy$	$B_x = \frac{1}{6}B'(3x^2y - y^3)$
$B_y = 0$	$B_y = B_0$	$B_y = B'x$	$B_y = \frac{1}{2}B''(x^2 - y^2)$	$B_y = \frac{1}{6}B'''(x^3 - 3xy^2)$

Dipole Magnets

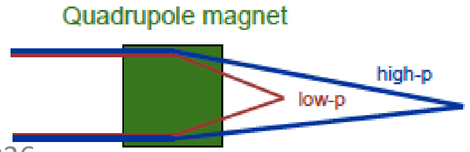
- Provide the horizontal or vertical “bending” that steers the beam and keeps its path circular in a synchrotron.
- In the case of the dipole, the magnetic field lines point uniformly in one direction inside the beam pipe. This provides a bending force that does not depend on where the beam is in the magnet aperture.
- Since the force exerted on the particle due to the magnetic field is velocity-dependent, particles of different momentum will bend in slightly different arcs.
- This effect is known as dispersion, and it transversely separates the trajectories of particles with different momenta.

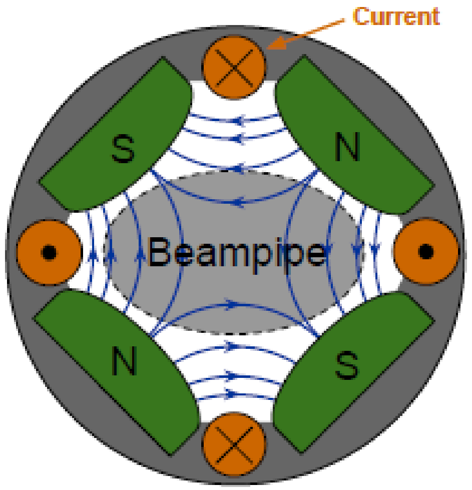


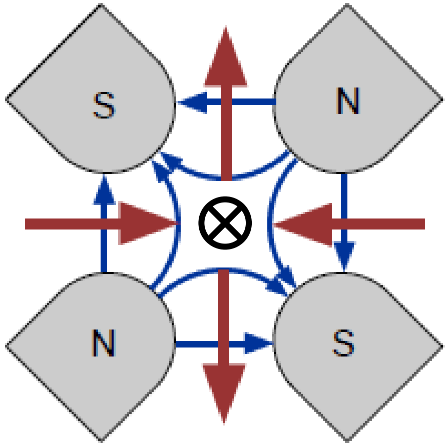


Quadrupoles

- Provide transverse focusing of the beam, keeping it constrained within the beam pipe; they effectively operate like lenses.
- Inside a quad the field strength is zero at the center of the magnet aperture and increases linearly with transverse displacement.
- This means that the quadrupole exerts a linear restoring force very similar to that of a spring F = -kx, encouraging particles to move toward the center of the beam pipe.
- Just like a spring causing a mass to oscillate, the quadrupole's restoring force causes the beam to oscillate transversely.
- The number of transverse oscillations per revolution is called the “tune,” controlled by the quadrupole field strength.
- A quadrupole magnet loses focusing ability for higher-momentum particles. This effect is known as chromatic aberration, which means that the focal length of a quadrupole magnet depends on the momentum of the beam particles.

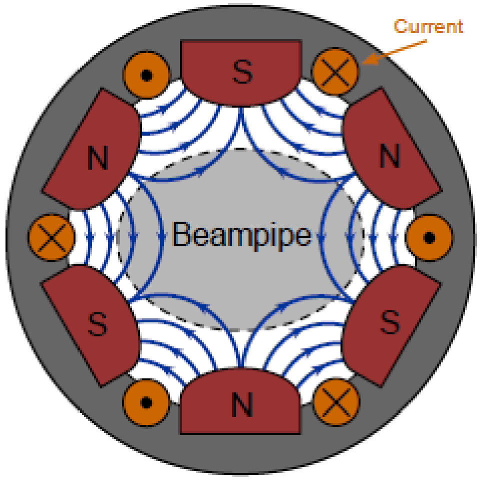


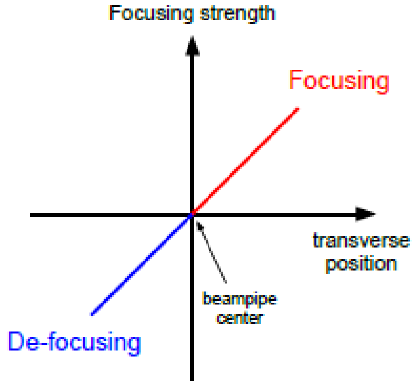




Sextupoles

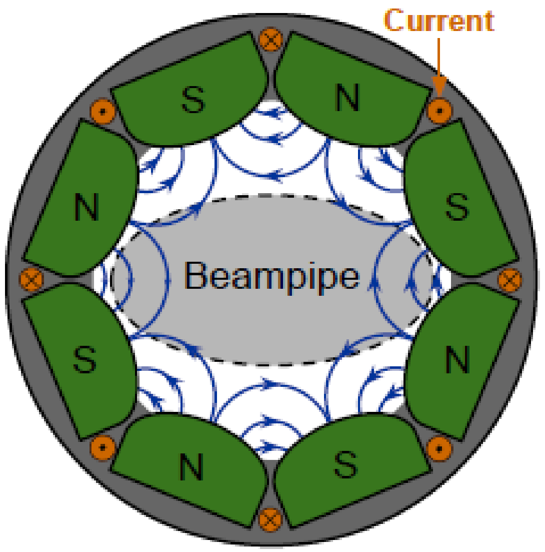
- Provide a field whose strength varies with the square of the displacement from the center of the beam pipe.
- This field dependence allows us to control the chromaticity effect by compensating for the loss of quadrupole focusing strength at higher beam momentum.
- The focusing strength of a sextupole magnet depends linearly on the transverse displacement from its center.
- Because of the dispersion of the dipole magnets, higher-energy particles will end up outside the center of the beam pipe, and lower energy particles will be on the inside. The sextupole thus focuses the higher-momentum particles more, which compensates for the loss of quadrupole focusing strength.



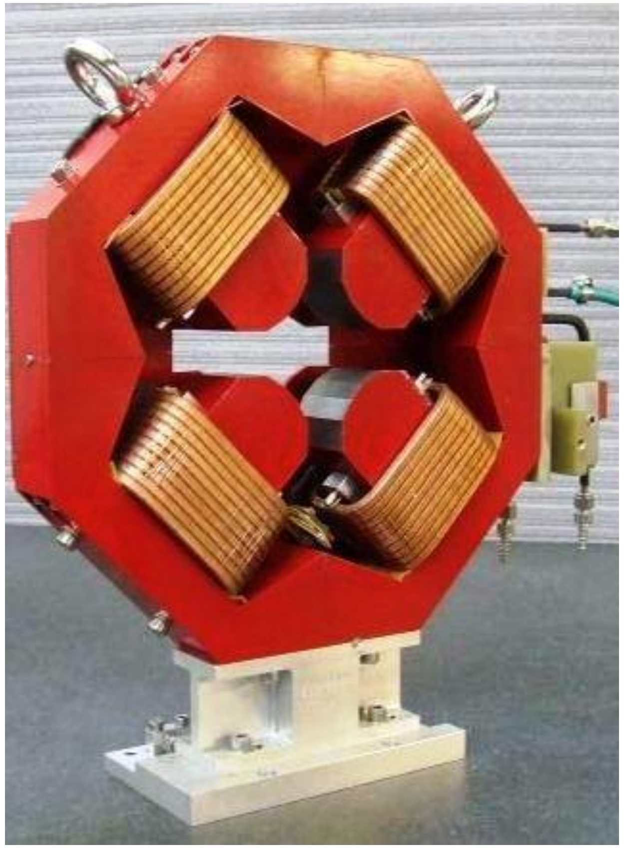


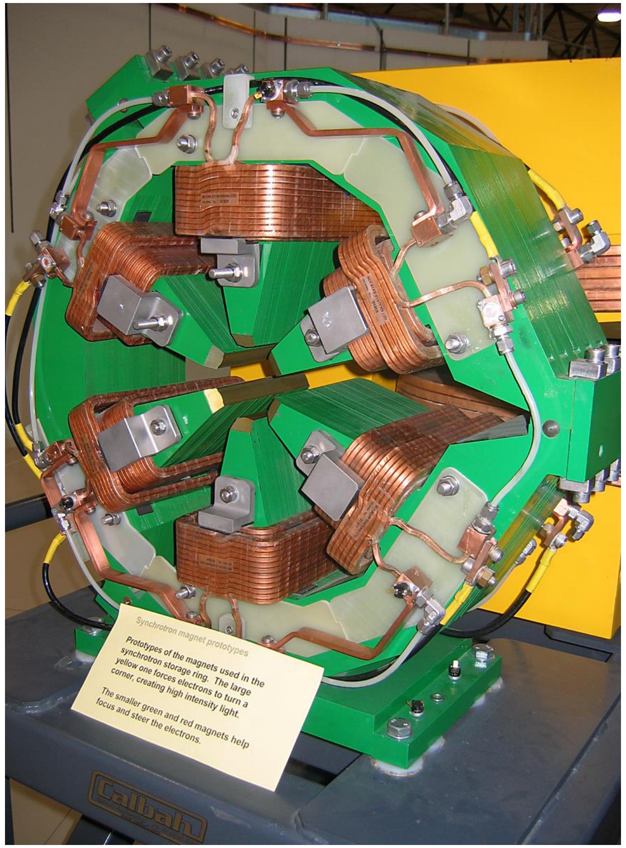
Octupoles

- The field strength of an octupole depends on the cube of the distance from the beam pipe center.
- Octupoles allow for control of how the tune spread depends on the amplitude of the betatron oscillations.



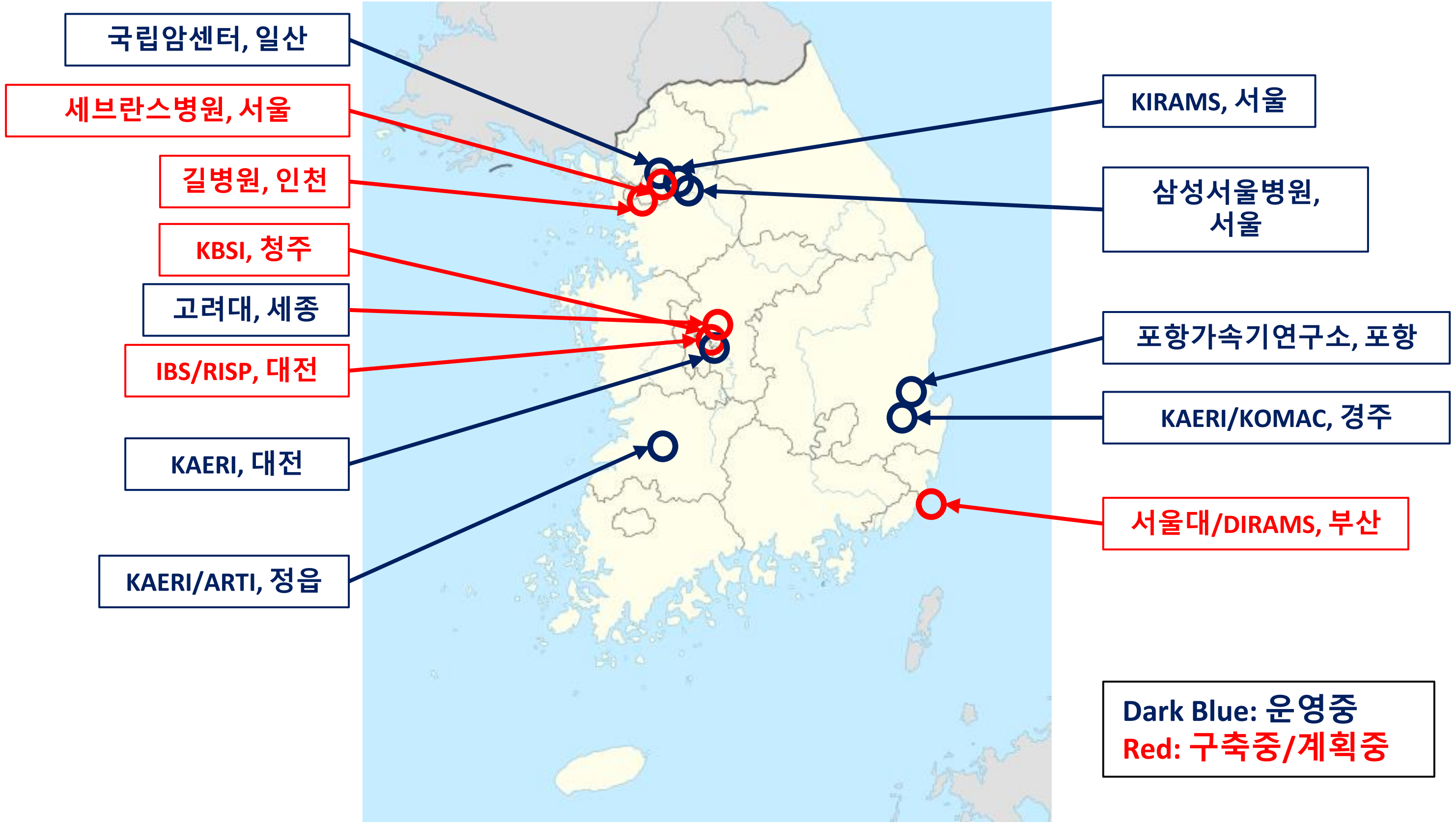
Images of Electromagnets





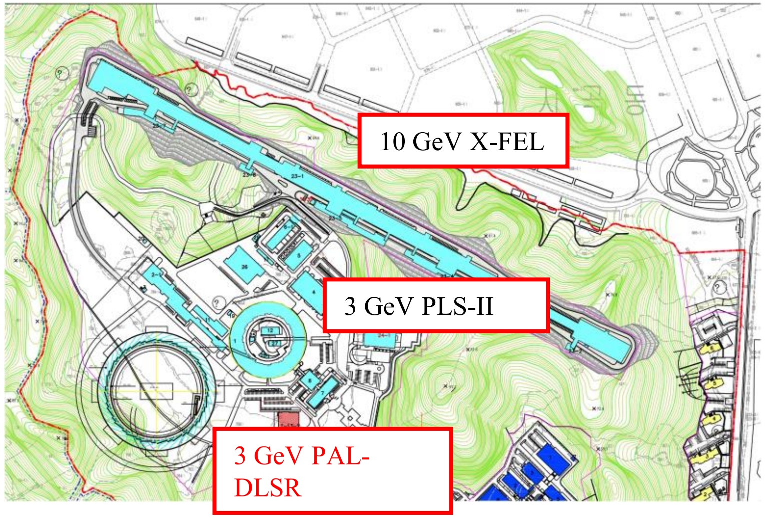
국내의 대형 가속기

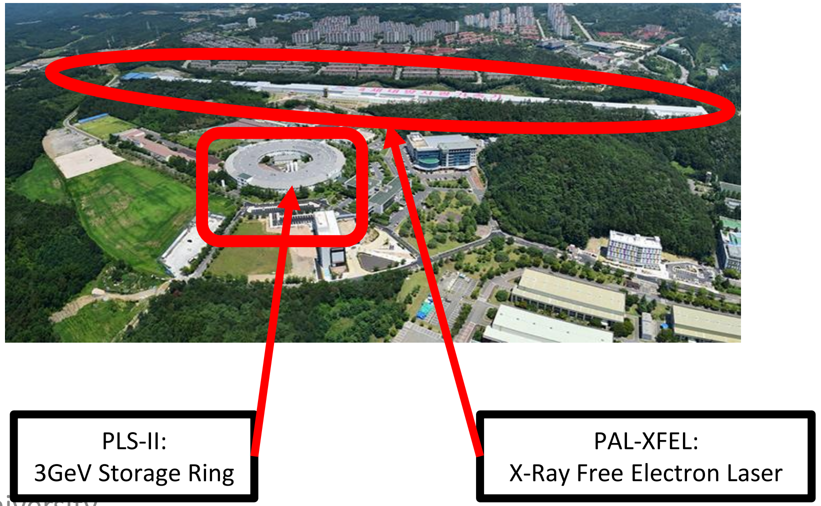
- There are more than 300 accelerators in Korea
- 43 cyclotrons in medical centers for RI production
- More than 60 linac-based radiosurgery units are working
- ~200 accelerators are used in industry
- Applications:
  - Basic Science (Physics, Chemistry, Biology, etc.)
  - Environment
  - Material Science
  - RI Production
  - Therapy



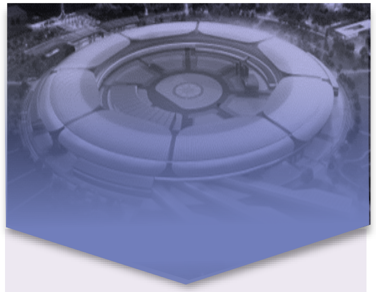
Pohang Accelerator Laboratory (PAL)

- PLS-II
  - has been provided stable photon beam
  - More than 1,600 experiments were conducted annually
- PAL-XFEL
  - A distinguishing performance (world best) was achieved
- Localization and commercialization
  - Most machine components can be delivered in Korea
  - PAL efforts with RISP and KOMAC will generate great synergy for localization and commercialization in Korea





KBSI Korea-4GSR (오창 다목적방사광가속기)



Location of Ochang

Period & Budget

Period	2021~2029
Budget	1.1643 Trillion KRW = USD 834 M

Land & Building

Land	540,000 m^2
Building	69,959 m^2

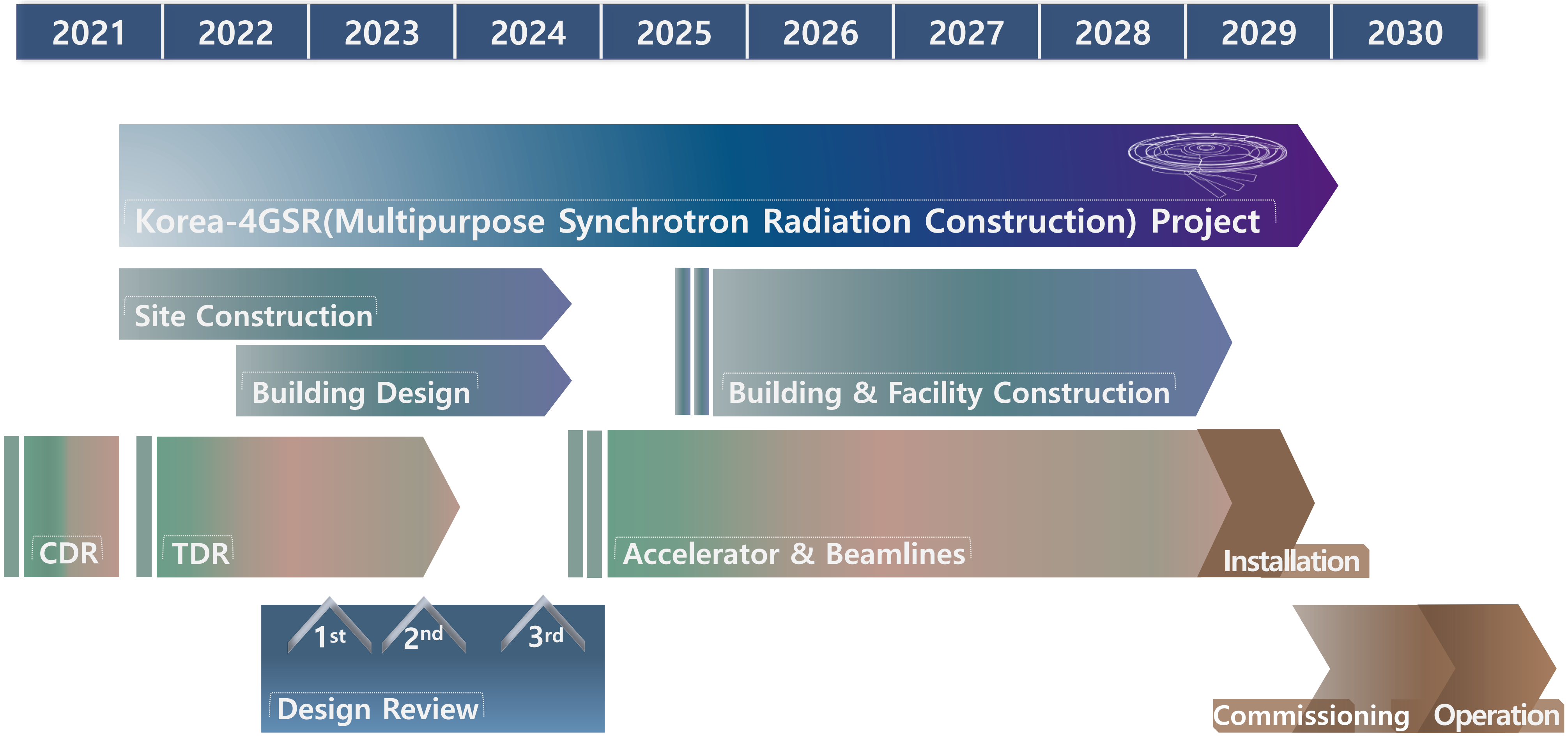
Location

Location	Ochang, Cheongju-si, Chungcheongbuk-do

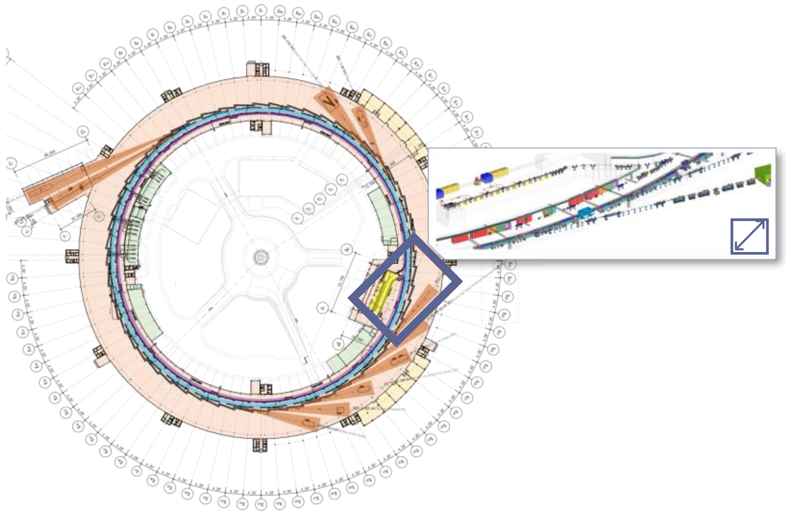
Characteristics

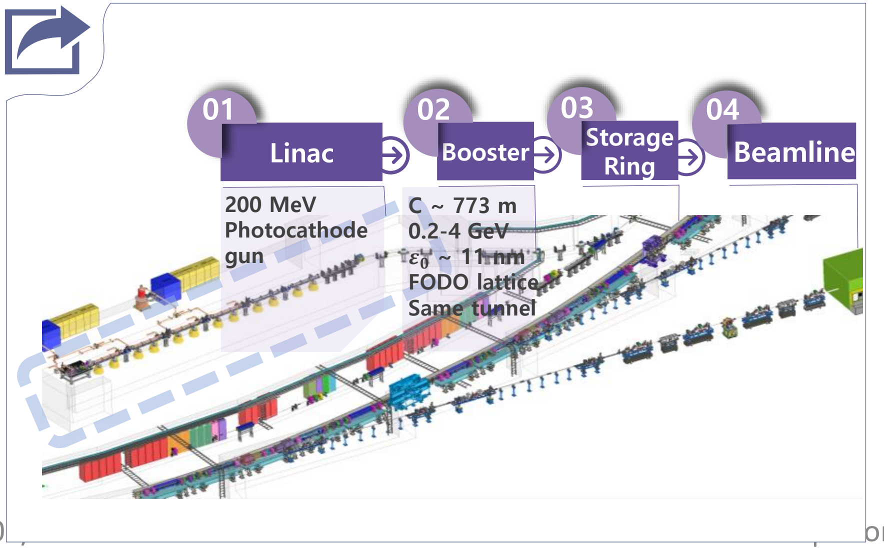
Beam Energy	4 GeV
Beam Emittance	less than 100 pm·rad (Design: 62 pm·rad)
Circumference	800 m
Beamlines	10 in the first phase (more than 40 in final phase)
Accelerator	Gun, Injector LINAC, 4 GeV Booster and Storage Ring
Lattice	Hybrid 7 Bend Achromat (H7BA)
-	Normal conducting RF cavity and 500 MHz

Korea-4GSR Project Timeline



Korea-4GSR Machine Parameters





SR Ring

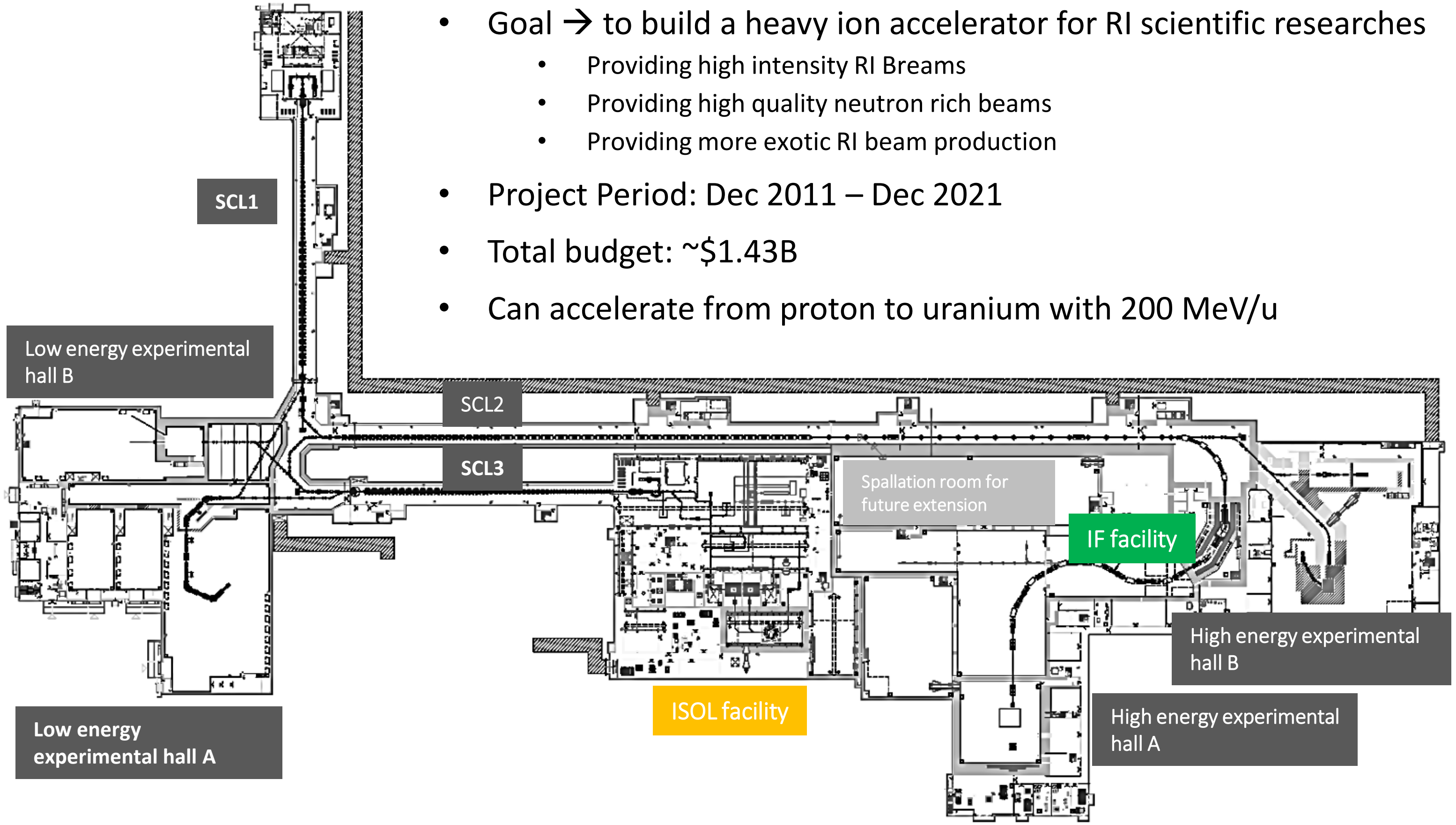
SR Ring Parameter	Vaule
Energy [GeV]	4.0
Beam current [mA]	400
Nat. Emittance [pm·rad]	61.57 (WO Ids), 52.55 (W 9 IDs)
Emittance coupling [%]	10
Energy spread	1.26E-3
Bunch Length(rms) [mm]	3.6 (without HC) / 14.4 (with HC)
Lattice	Hybrid 7 Bend Achromat
Ring Circumference [m]	799.297
Length of Straight Sections [m]	6.06
Tune (H/V)	68.18 / 23.26
(corrected) Chromaticity (H/V)	5.8 / 3.5
Momentum compaction factor	7.8 x 10^{-5}
Number of buckets	1332
Injection scheme	4 Kicker bumps, off-axis, 2Hz

SR RF

SR RF Parameter	Vaule
RF frequency [MHz]	499.5935
RF Voltage [MV]	3.5
Energy loss per turn [KeV]	1098 (with 9 IDs: 1449)

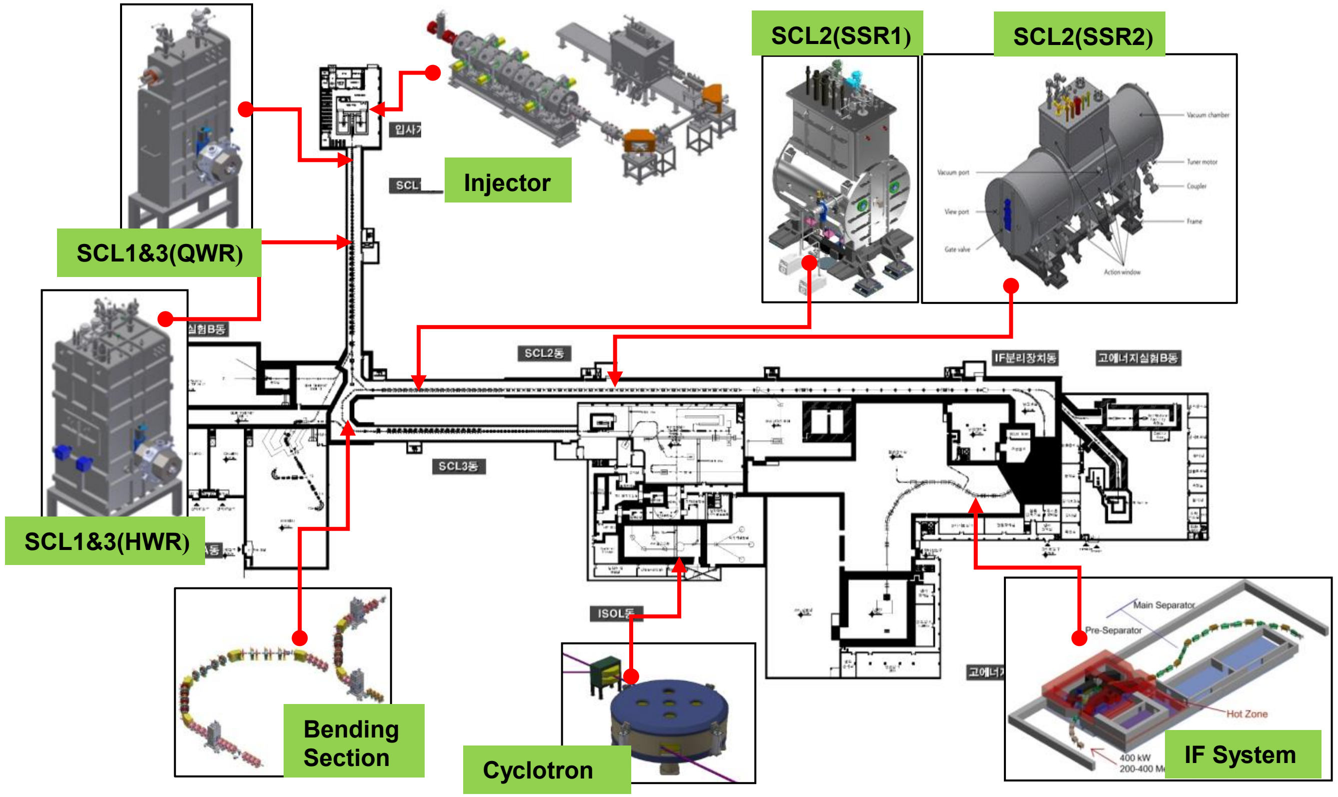
기초과학연구원/중이온가속기연구소 – RAON

- Goal → to build a heavy ion accelerator for RI scientific researches
  - Providing high intensity RI Breams
  - Providing high quality neutron rich beams
  - Providing more exotic RI beam production
- Project Period: Dec 2011 – Dec 2021
- Total budget: ~$1.43B
- Can accelerate from proton to uranium with 200 MeV/u

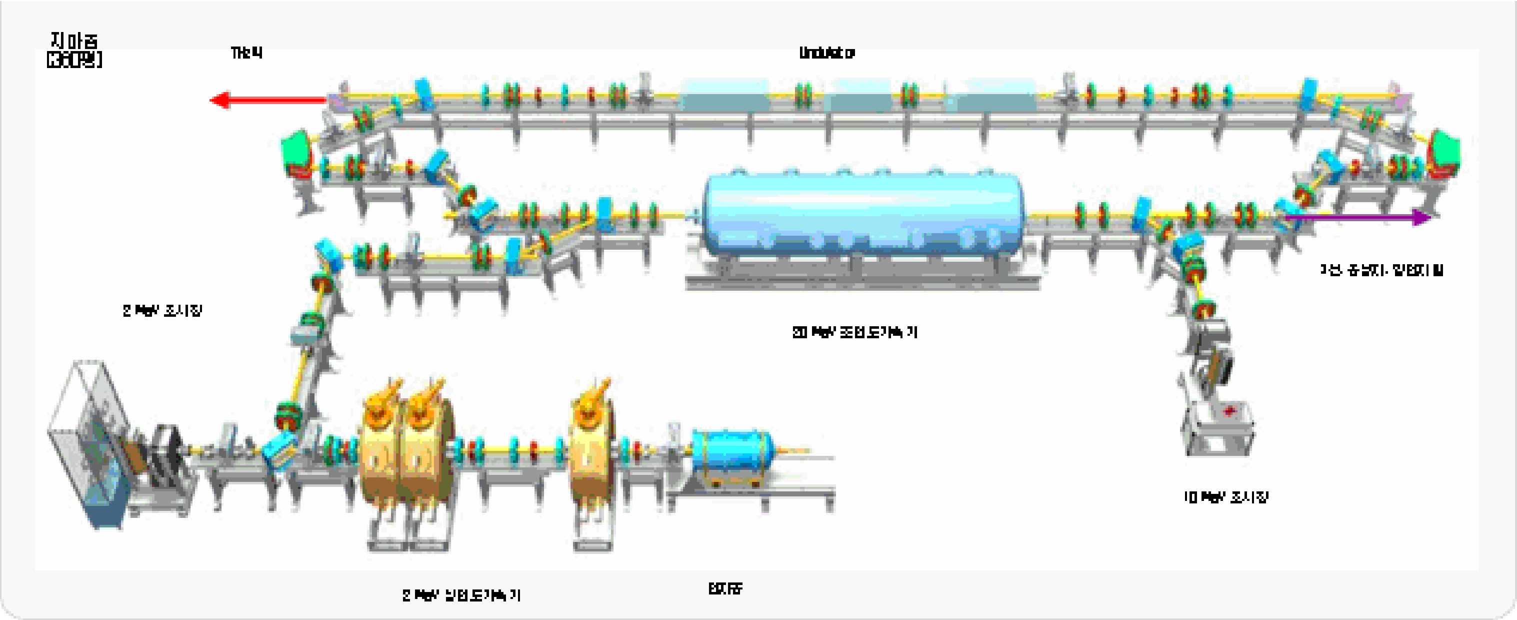


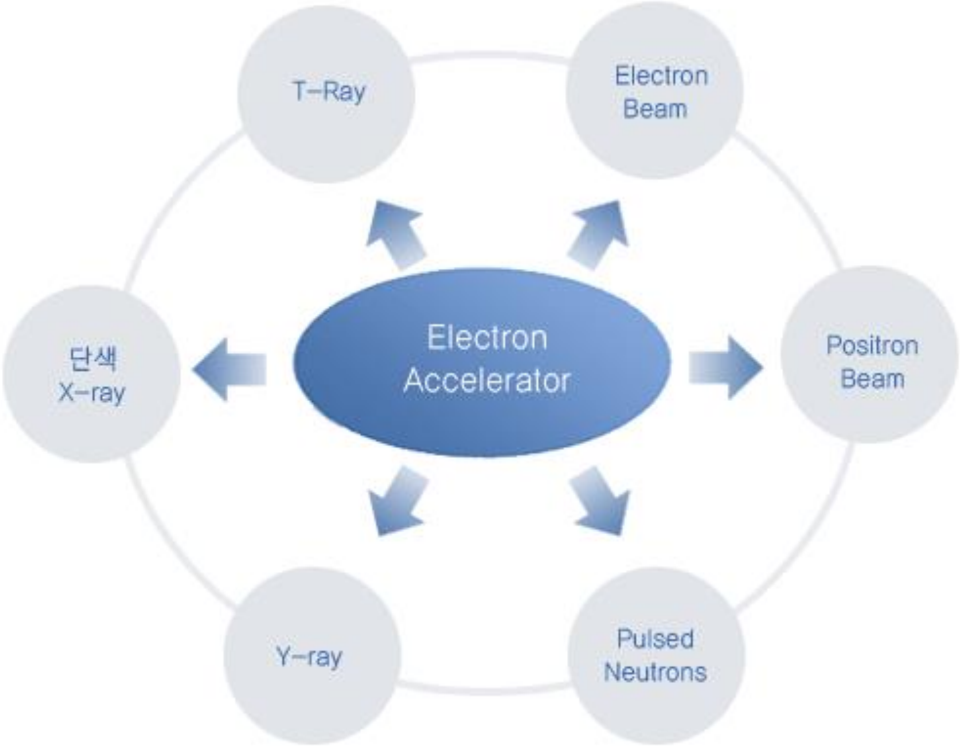
기초과학연구원/중이온가속기연구소 – RAON

- Accelerator
  - Mass production for SCL3 is under way
  - SCL2 is under pre-production phase
  - From April 2019, installation for SCL will start from SCL3
- By the end of 2021
  - Stable / RI beams will be delivered to low-E experimental hall
  - Beam commissioning starts for SCL2
- Post RISP (after 2021)
  - Beam acceleration for ISOL → SCL3 → SCL2 → IF (ISOL+IF)
  - Beam commissioning and experiments for IF, LAMPS, Neutron, bio-medical and muSR
  - Ramping-up to get the 400kW beams (more 5 yrs)
  - Energy upgrade to 400MeV/u (require budget)



한국원자력연구원/대전

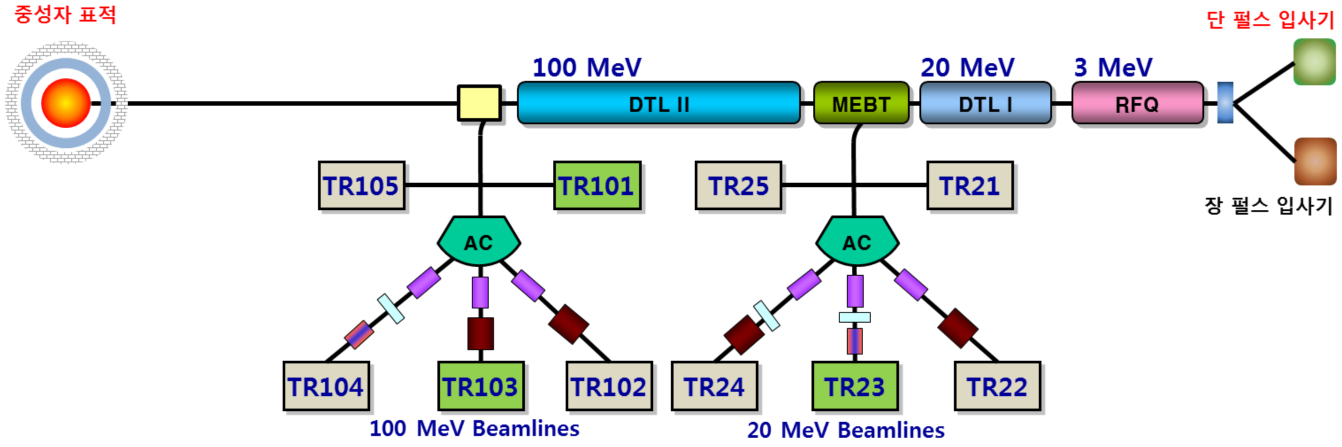

Undulator


T-Ray
Electron
Beam
단색
X-ray
Electron
Accelerator
Positron
Beam
Y-ray
Pulsed
Neutrons

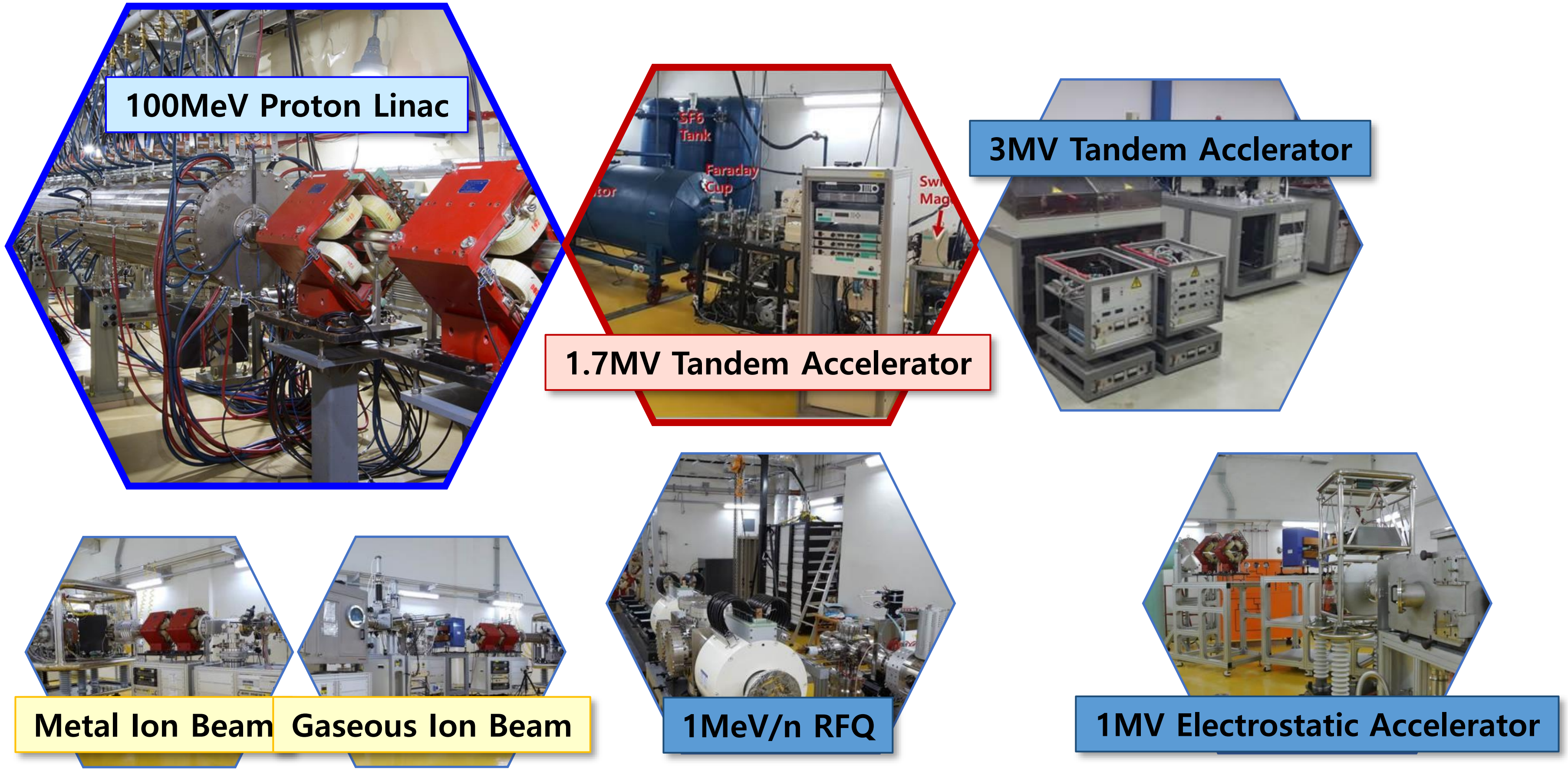
KAERI/양성자과학연구단

- 100 MeV proton linac
  - Machine availability : ~95%
  - Steady beam service
  - Multi-purpose beamlines for 20 MeV and 100 MeV
  - RI production beamline : 2016~
  - Low-flux beamline : 2017~
  - Pulsed-neutron beamline & short pulse injector : in development
  - Li-8 beamline: in development
- Plan for Upgrade
  - 1 GeV, 2 MW Proton Linac
  - Short/Long Pulse Neutron Source
  - Muon Source (HEP)
  - Neutrino Source (HEP)

- Ion Beams Facilities
  - Gas / Metallic ion beam implanters : normal user service
  - 1.7 MV tandem : PIXE, RBS, irradiation, Std. neutron, e-PIXE
  - 3.0 MV tandem, 1 MV accelerator, 1 MeV/n RFQ : in development



KAERI/양성자과학연구단



KAERI/첨단방사선연구소

- 동위원소 생산용 사이클로트론

- 한국원자력의학원 개발
- 방사성 동위원소 생산
- 양성자, 30 MeV, 250 μA
- Producible SPECT radionuclides:
  - ^{57}Co, ^{67}Ga, ^{123}I, ^{201}Tl, ^{111}In, ^{77}Br, ^{91}Br
- Producible PET radionuclides:
  - ^{124}I, ^{94}Tc, ^{76}Br, ^{69}Ge, ^{45}Ti, ^{19}F, ^{11}C, ^{15}O, ^{13}N
- Producible Therapeutic radionuclides:
  - ^{103}Pd, ^{196}Re

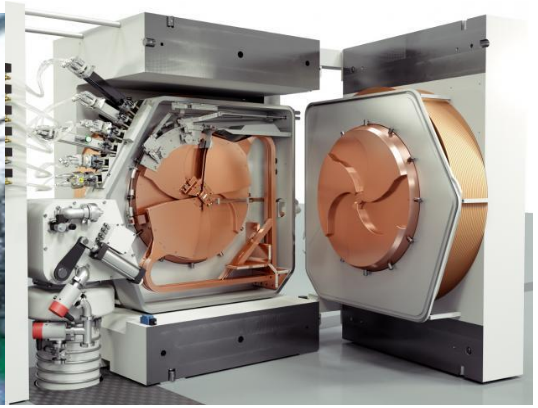
한국원자력의학원

- 암진단용 동위원소 생산을 위한 사이클로트론

MC-50
(Scanditronix)

KIAMS-13
(KIRAMS)

Cyclone-30
(IBA)



PETtrace 880
(GE)

국립암센터

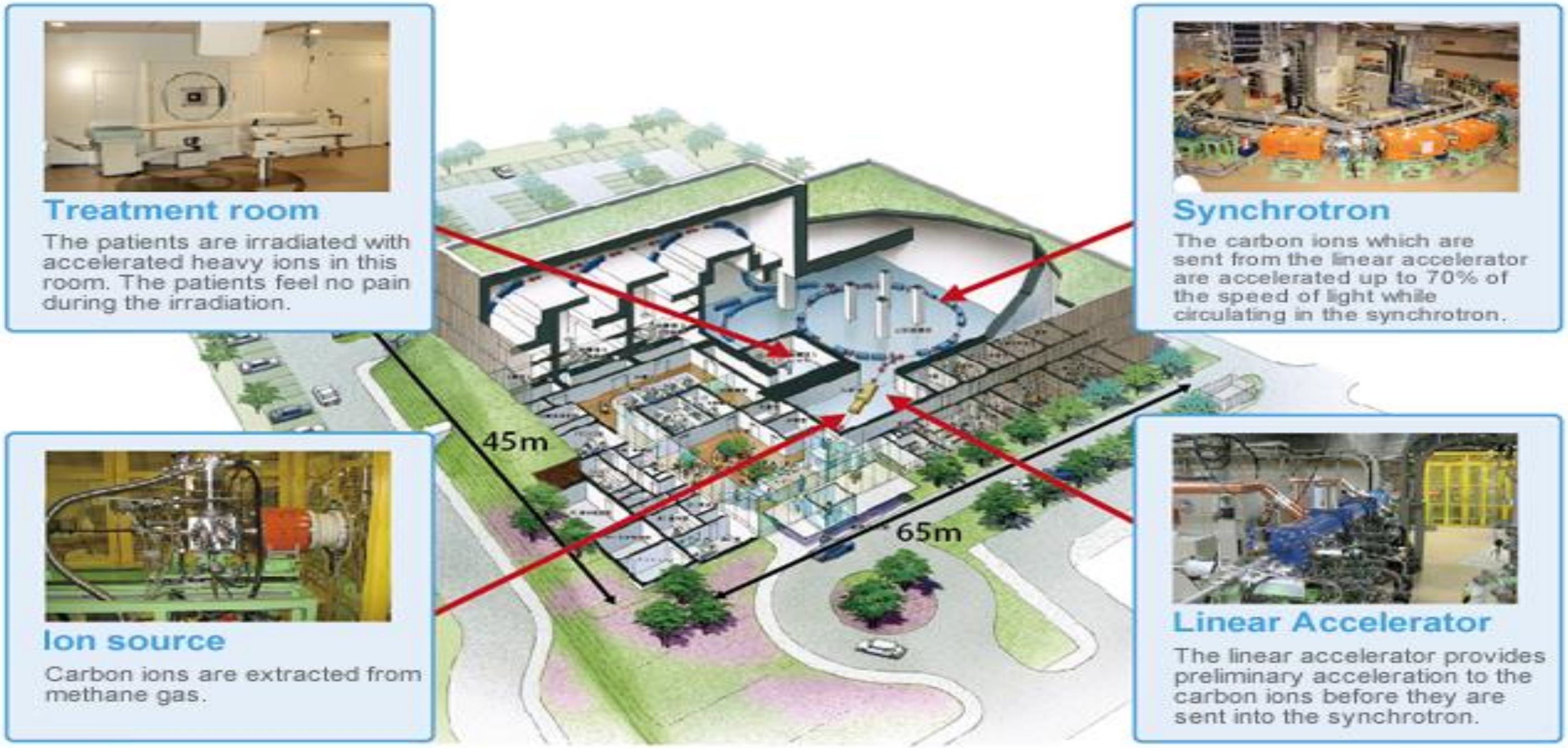
- 암치료용 양성자 사이클로트론

삼성서울병원

- 암치료용 양성자 사이클로트론

연세 세브란스병원

- 암치료용 중입자 가속기



가천대 길병원

• BNCT – 붕소 중성자 포획 치료