특론: 가속기 실험실습 I

(NUCE719P-01/PHYS715P-01, 정모세)

1. 입자가속기 개요 및 방사선 환경

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첨단원자력공학부

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1

입자가속기란?

입자가속기란?

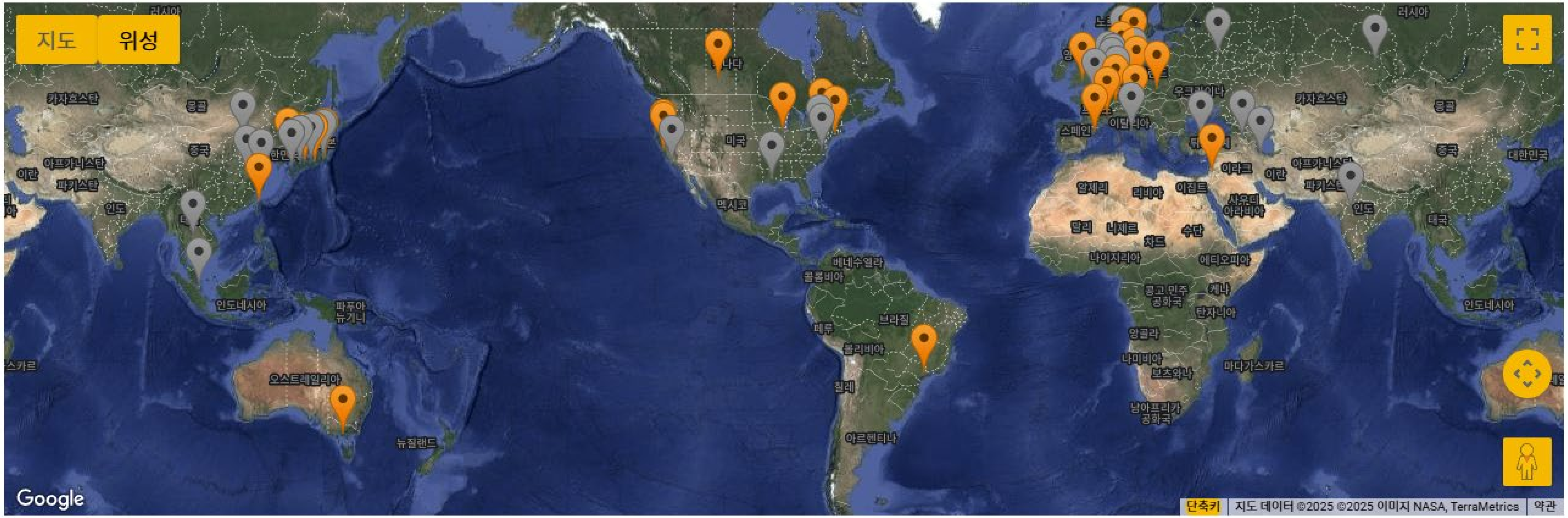
- **가속기의 사용 목적 :**
  1. 입자의 발견 : 핵물리/입자물리연구, 우주의 근원
     - LHC, ILC, RAON, ….
     * 부가적인 활용 : 방사선 안전연구
  2. 입자의 활용 :
     - 분석도구 등 : p (ion), e, n, photon
       방사광가속기 (Synchrotron Radiation), 정전압가속기,
       파쇄중성자원 (Spallation Neutron Source), ….
     - 치료 : e, photon, p, carbon,…
     - 기타

- **가속입자의 종류, 가속입자의 에너지**
  1. 하전입자
  2. ~ 수백 TeV …… 높은 에너지 입자가 만들어 내는 또 다른 문제

- **일차 가속입자와 이차 방사선의 방출**

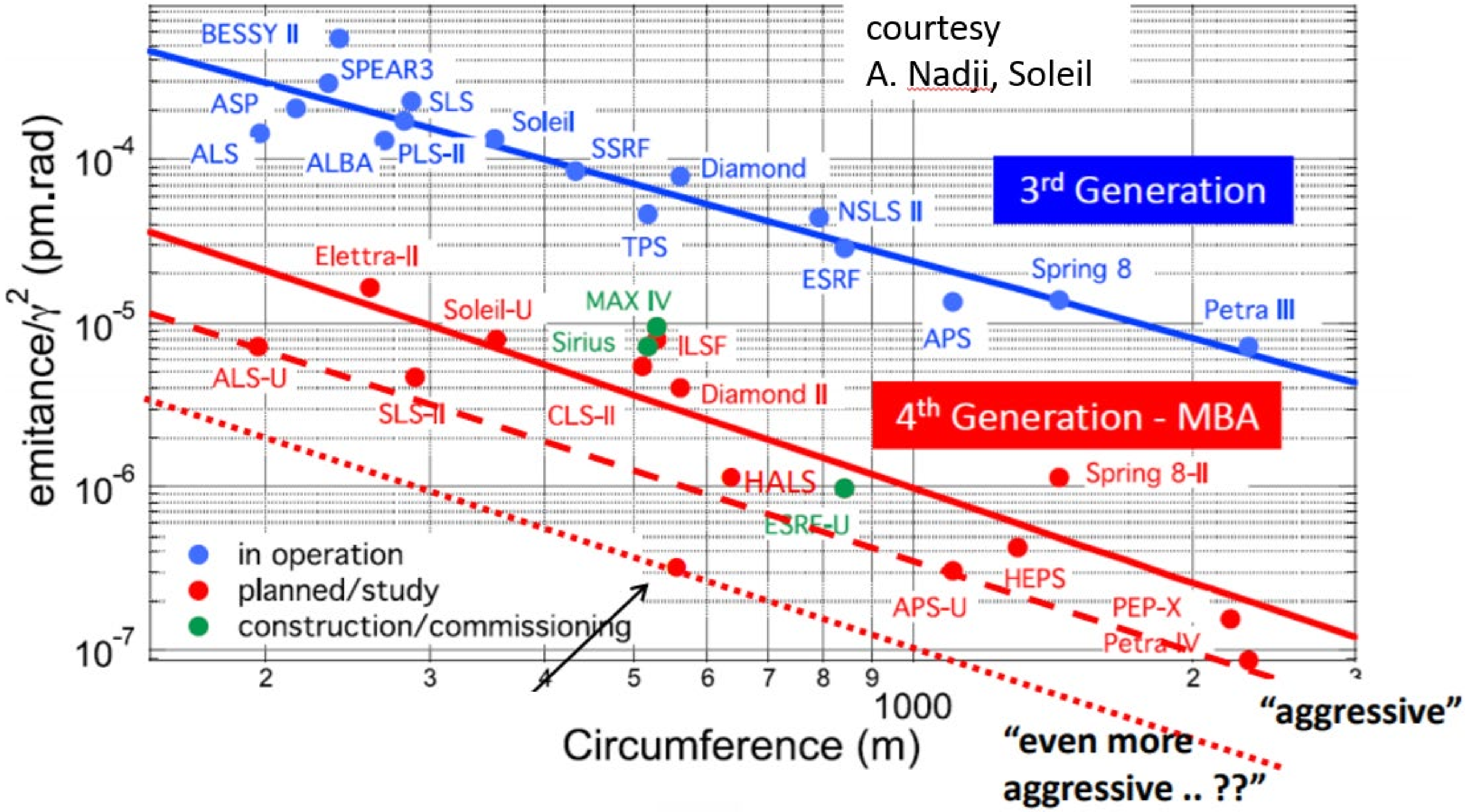
Synchrotron Radiation World!

There are more than 50 light sources in the world (operational, or under construction). This page lists all the members of the lightsources.org collaboration.


지도
위성
러시아
카자흐스탄
몽골
중국
아프가니스탄
이란
파키스탄
인도
대한민국
태국
인도네시아
파푸아 뉴기니
오스트레일리아
뉴질랜드
캐나다
미국
멕시코
베네수엘라
콜롬비아
브라질
페루
볼리비아
칠레
아르헨티나
스페인
이탈리아
우크라이나
알제리
리비아
이집트
이라크
사우디 아라비아
말리
니제르
차드
수단
나이지리아
에티오피아
콩고 민주 공화국
케냐
탄자니아
앙골라
나미비아
보츠와나
남아프리카 공화국
마다가스카르
Google
단축키
지도 데이터 ©2025 ©2025 이미지 NASA, TerraMetrics
약관

Orange pins on the map represent members of the lightsources.org collaboration.

Synchrotron Radiation World!


courtesy
A. Nadji, Soleil

입자가속기의 유형

직류형/정전형

교류형/펄스형

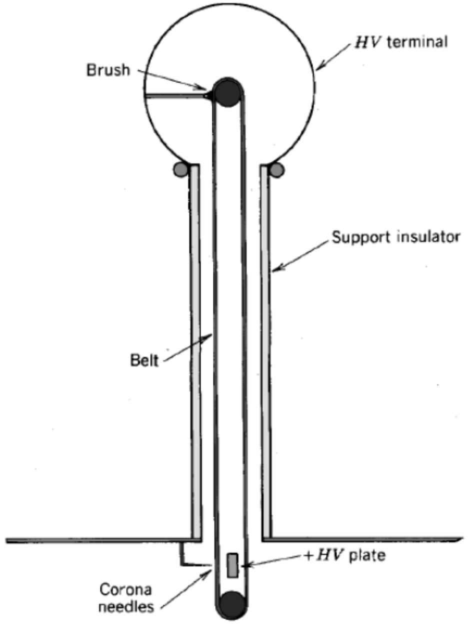
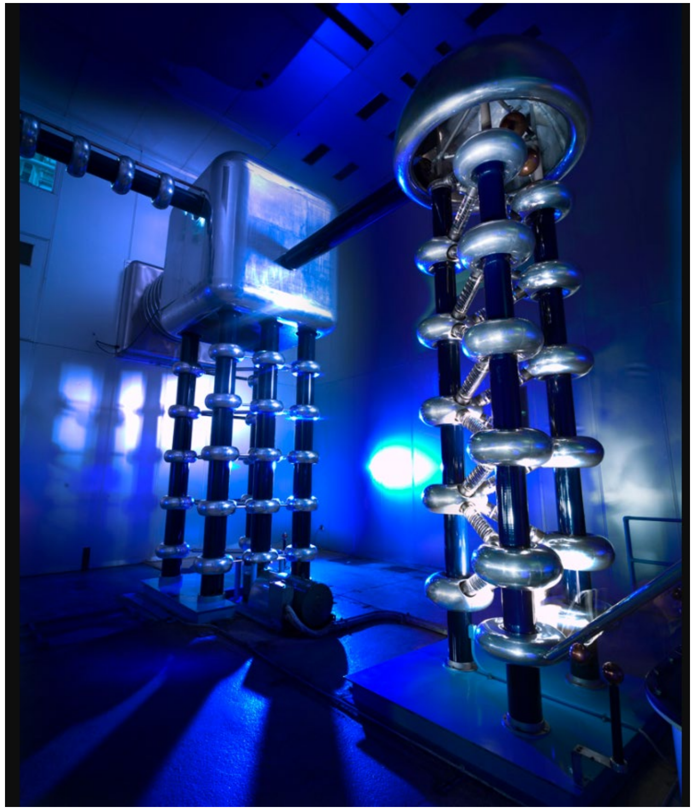
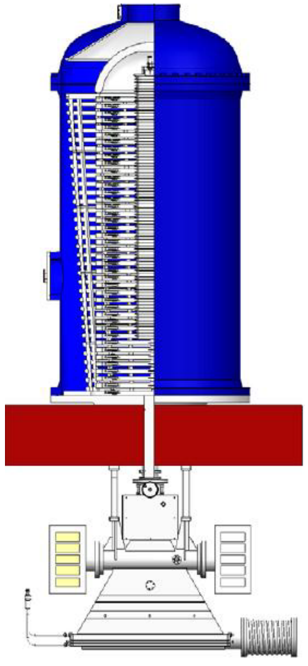

Brush
HV terminal
Support insulator
Belt
+HV plate
Corona
needles

Figure 2: Principle of the original Van de Graaff generator.



**Cockcroft
Walton Acc.
-Fermi lab**



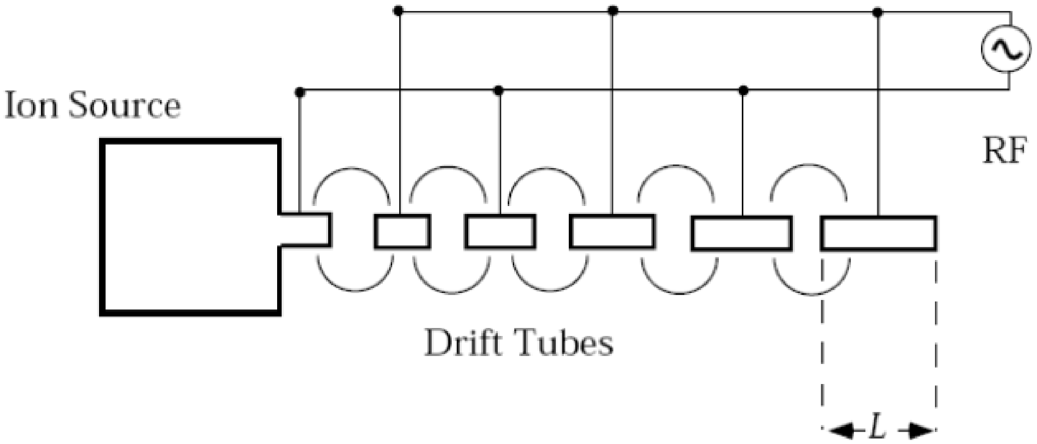
전자조사기
- 이비텍

**Tandem VandeGraff
Acc. - Kyushu Univ.**

**Tandem VandeGraff
Acc.
- KIST**

입자가속기의 유형

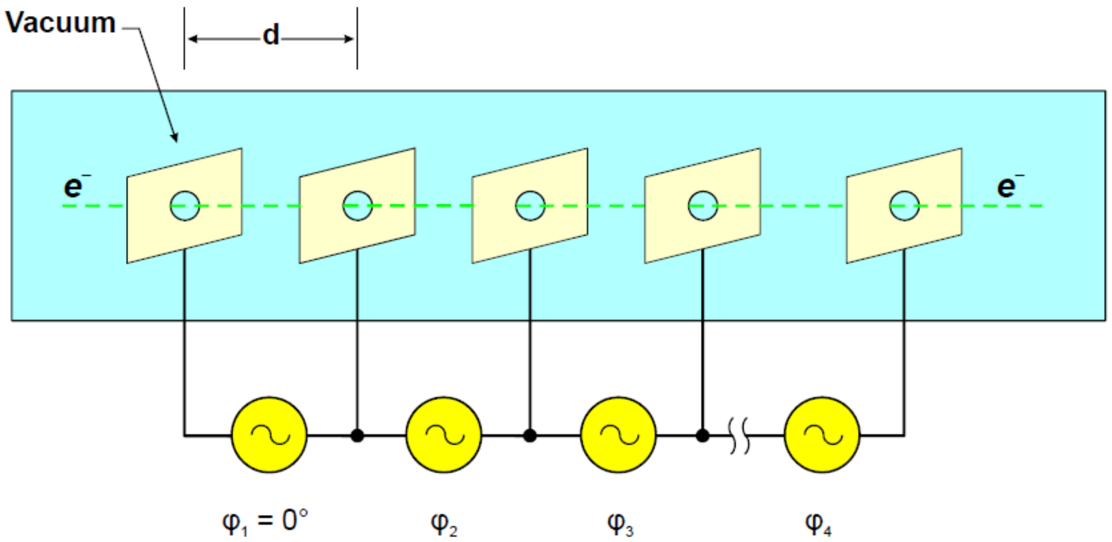
- 직류형/정전형
- 교류형/펄스형
  - 선형가속기

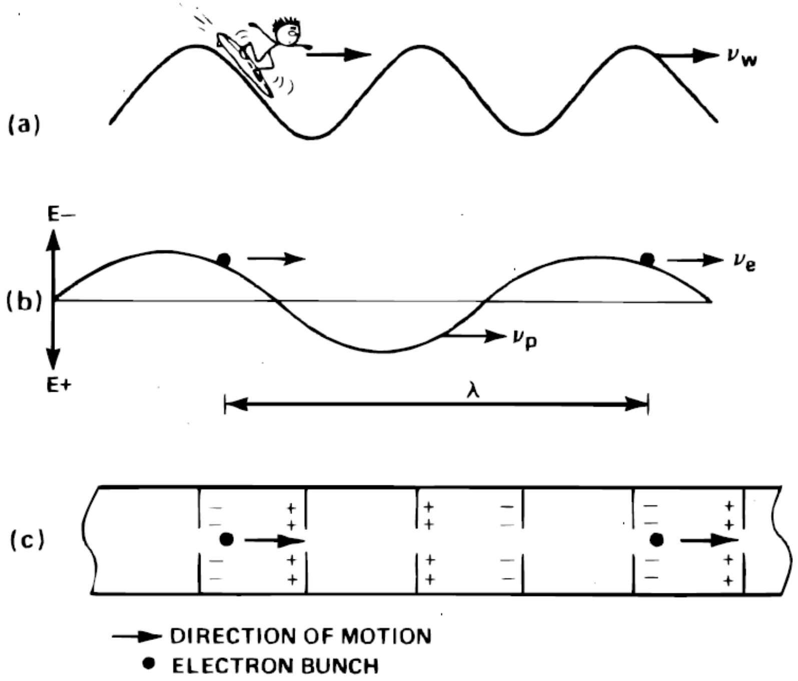

Ion Source
RF
Drift Tubes
L

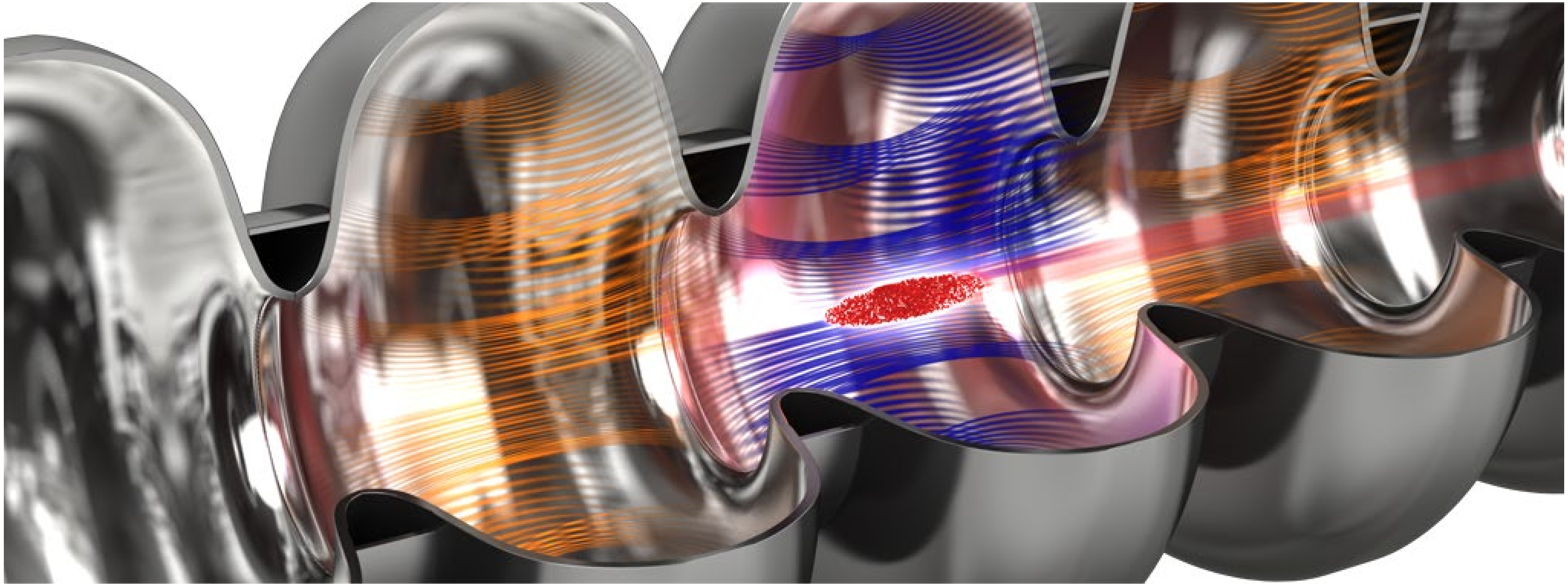
Proton/Heavy Ion Linear Accelerator

Figure 3: Basic operation of Rolf Wideröe's linac for heavy ion acceleration

Electron Linear Accelerator


Vacuum
d
e⁻
e⁻
φ₁ = 0°
φ₂
φ₃
φ₄


(a)
v_w
(b)
E−
E+
v_e
v_p
λ
(c)
DIRECTION OF MOTION
ELECTRON BUNCH

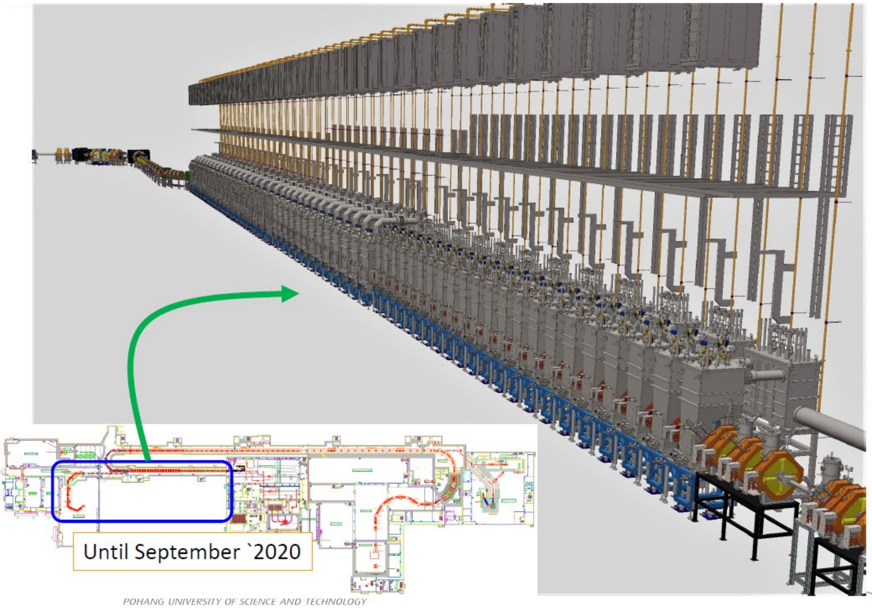


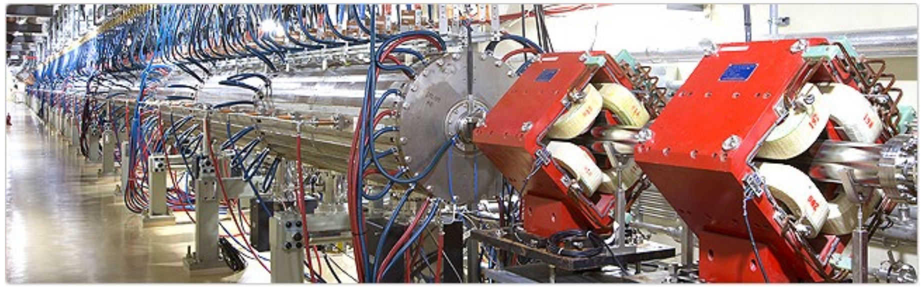
입자가속기의 유형

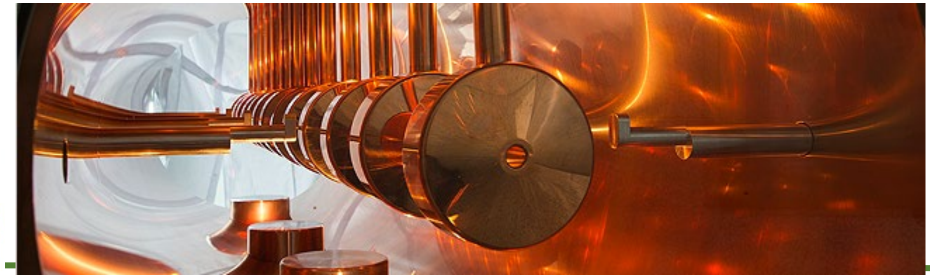
- 직류형/정전형
- 교류형/펄스형
  - 선형가속기

Electron Linear Accelerator

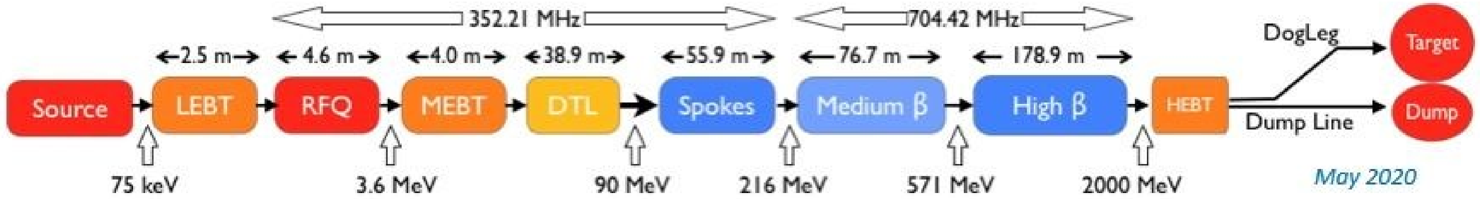
Proton/Heavy Ion Linear Accelerator (초전도 / 상전도)

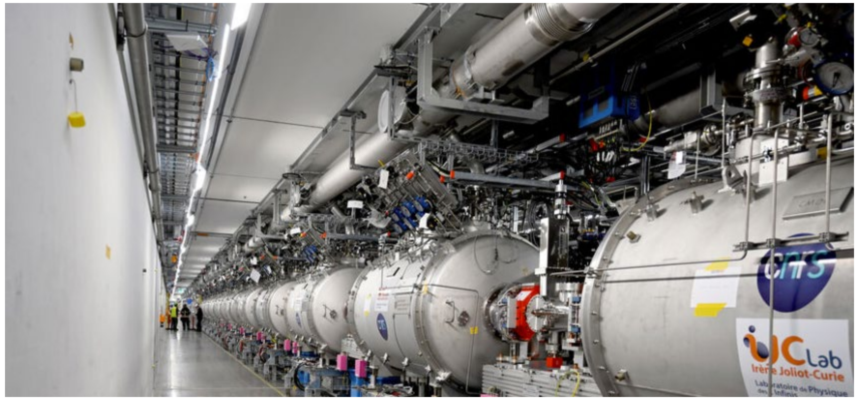

Until September `2020
POHANG UNIVERSITY OF SCIENCE AND TECHNOLOGY



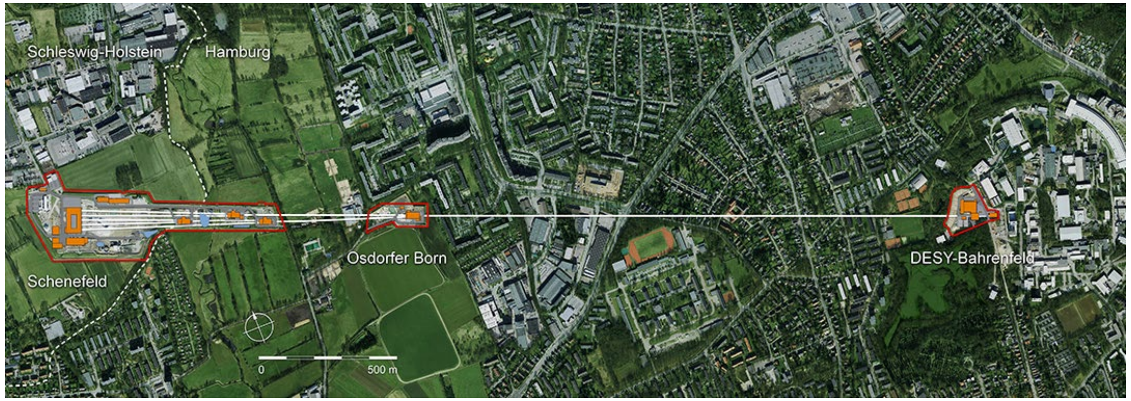


European Spallation Source (Proton)


352.21 MHz
704.42 MHz
2.5 m
4.6 m
4.0 m
38.9 m
55.9 m
76.7 m
178.9 m
Source
LEBT
RFQ
MEBT
DTL
Spokes
Medium β
High β
HEBT
DogLeg
Target
Dump Line
Dump
75 keV
3.6 MeV
90 MeV
216 MeV
571 MeV
2000 MeV
May 2020


CNRS
IJCLab
Irène Joliot-Curie

European XFEL (Electron)


Schleswig-Holstein
Hamburg
Osdorfer Born
DESY-Bahrenfeld
Schenefeld
0
500 m

입자가속기의 유형

직류형/정전형

교류형/펄스형

원형가속기

- **Cyclotron**
- **Synchrotron**
- **Betatron**
- **Microtron**
- **FFAG**

Cyclotron 원리

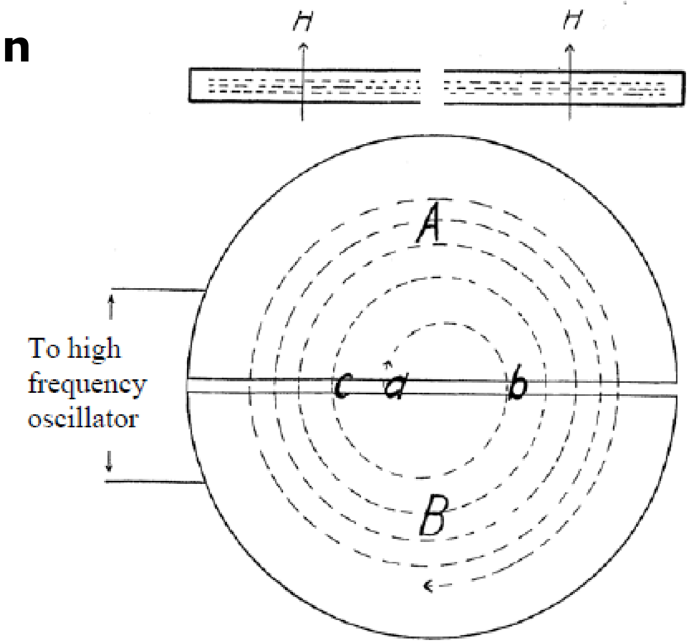

H
H
A
To high
frequency
oscillator
c
a
b
B

Figure 5: Schematic of Lawrence's cyclotron (Lawrence and Livingston, 23).

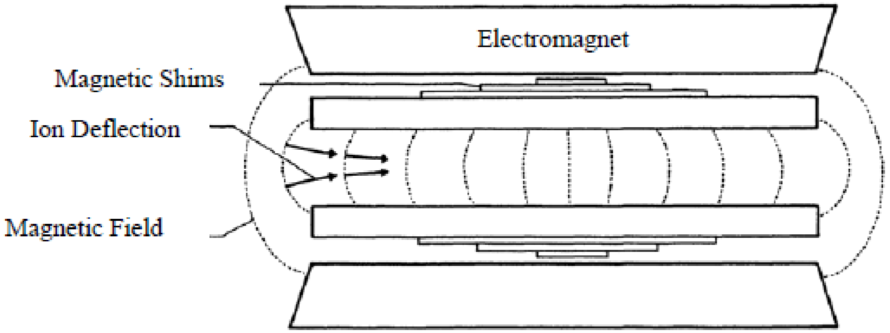
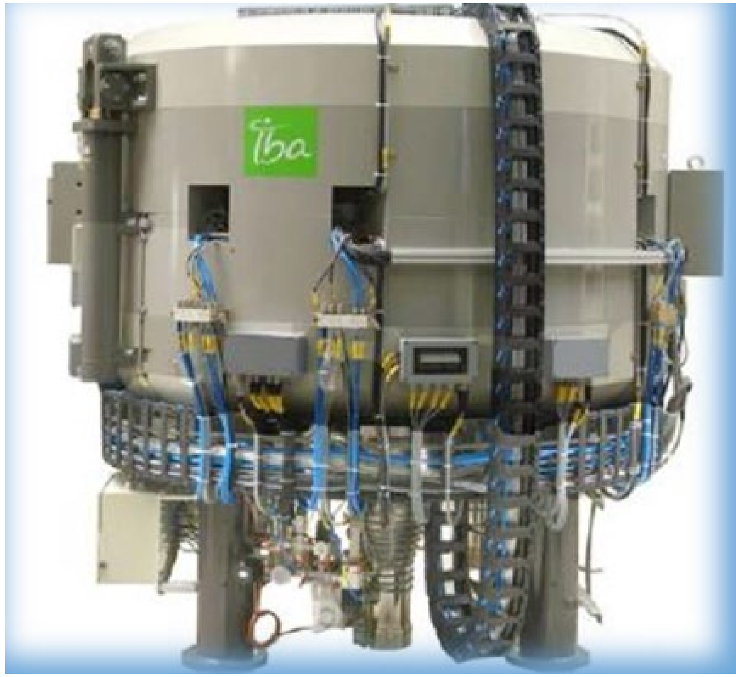

Electromagnet
Magnetic Shims
Ion Deflection
Magnetic Field

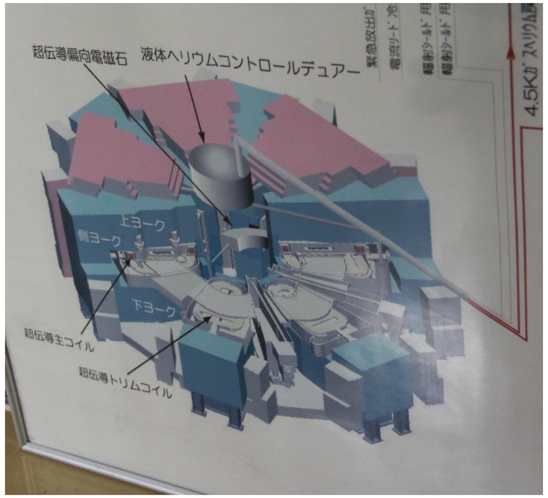
Figure 6: Effect of shims on the magnetic field (Lawrence and Livingston, 29).

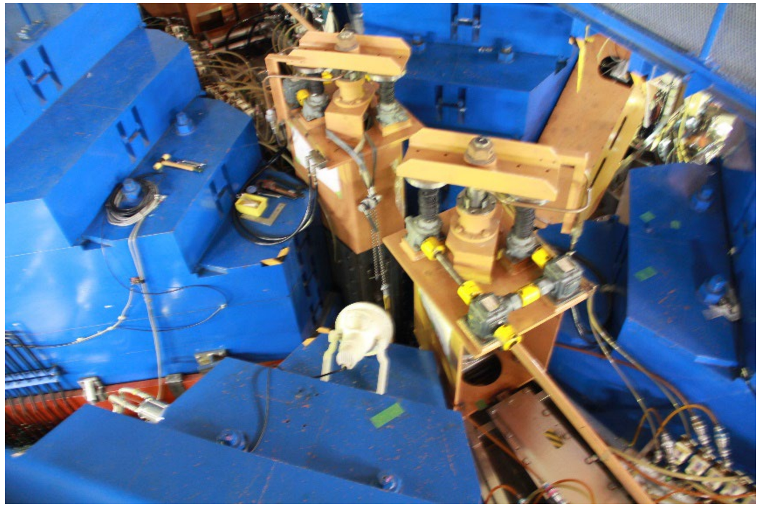


입자가속기의 유형

- 직류형/정전형
- 교류형/펄스형
  - 원형가속기
    - Cyclotron
    - Synchrotron
    - Betatron
    - Microtron
    - FFAG

Cyclotron


超伝導偏向電磁石
液体ヘリウムコントロールデュアー
上ヨーク
側ヨーク
下ヨーク
超伝導主コイル
超伝導トリムコイル



일본 RIKEN

입자가속기의 유형

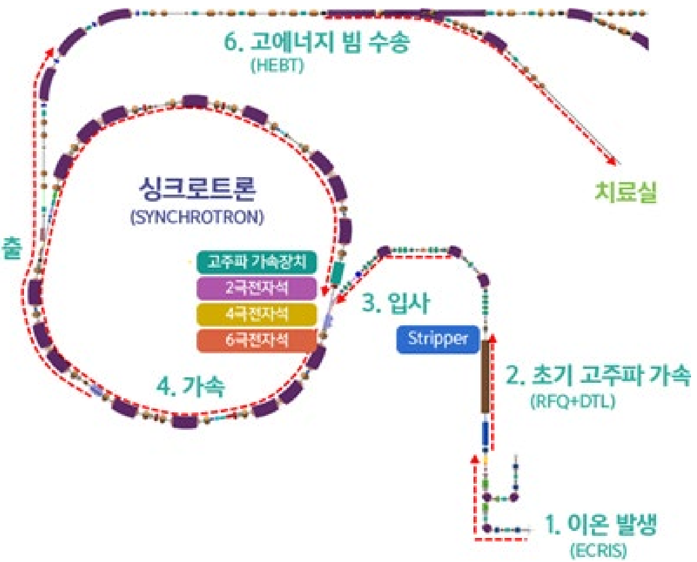
직류형/정전형

교류형/펄스형

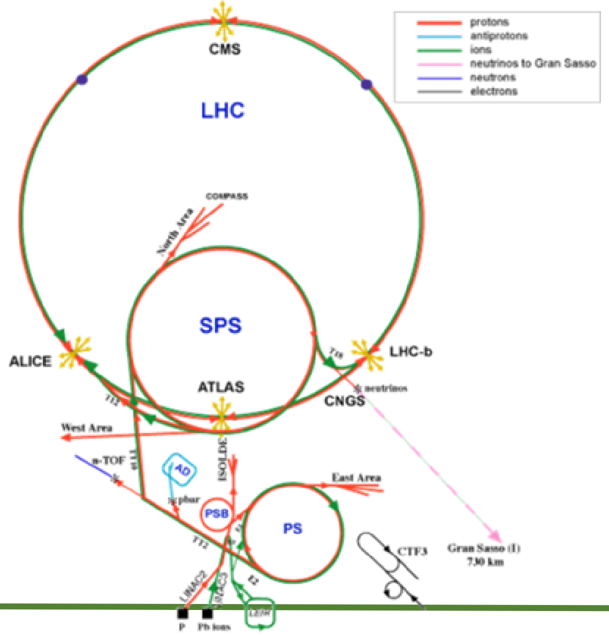
원형가속기

- **Cyclotron**
- **Synchrotron**
- **Betatron**
- **Microtron**
- **FFAG**

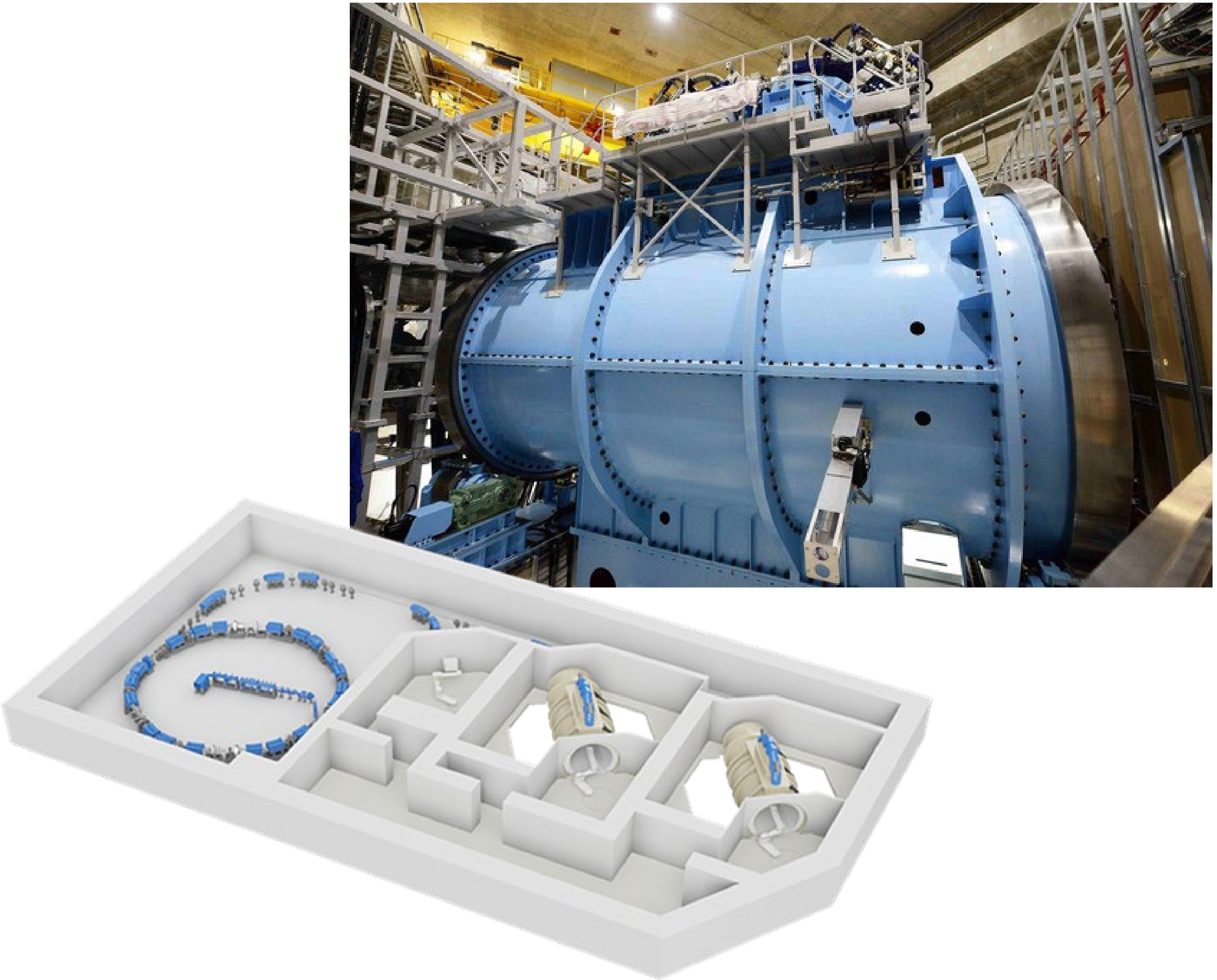
Synchrotron


6. 고에너지 빔 수송
(HEBT)
치료실
싱크로트론
(SYNCHROTRON)
5. 인출
고주파 가속장치
2극전자석
4극전자석
6극전자석
3. 입사
Stripper
4. 가속
2. 초기 고주파 가속
(RFQ+DTL)
1. 이온 발생
(ECRIS)

세브란스 -Toshiba


protons
antiprotons
ions
neutrinos to Gran Sasso
neutrons
electrons
CMS
LHC
COMPASS
North Area
SPS
ALICE
LHC-b
T18
ATLAS
CNGS
neutrinos
T12
West Area
n-TOF
TT10
AD
ISOLDE
pbar
East Area
PSB
PS
TT2
CTF3
Gran Sasso (I)
730 km
LINAC2
LINAC3
E2
LEIR
P
Pb ions

입자가속기의 유형

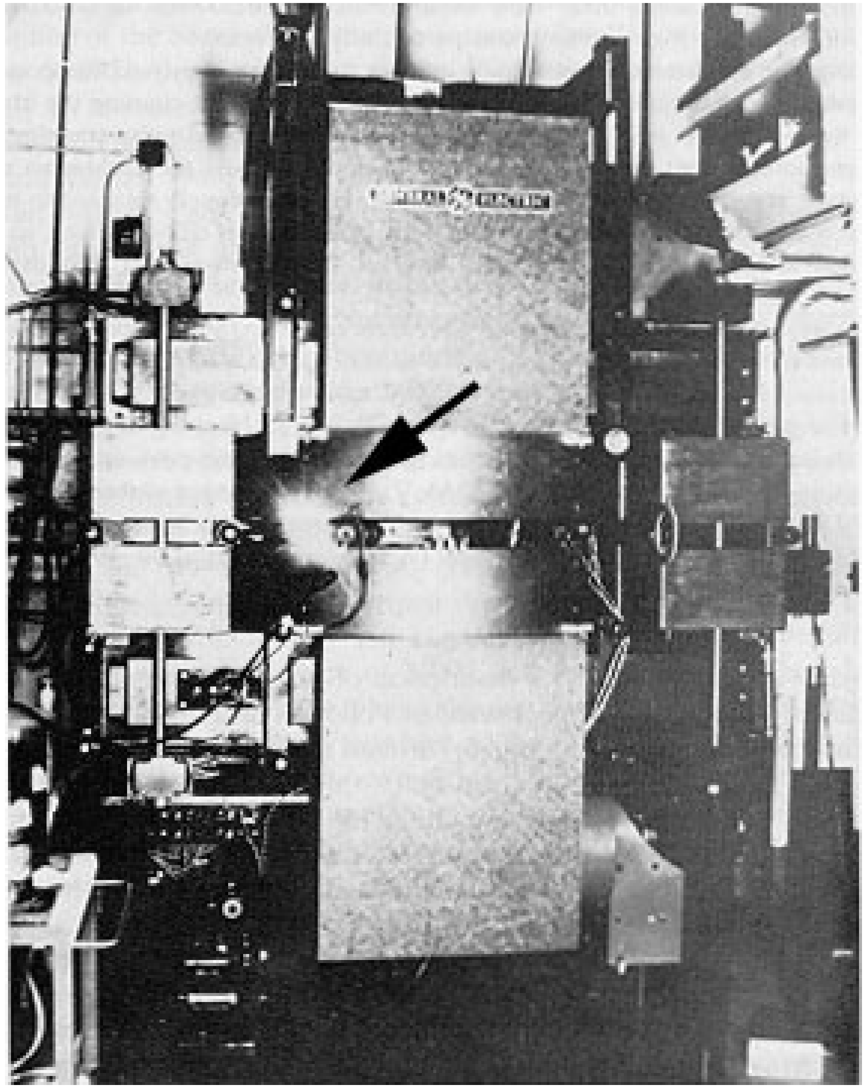


연세암병원 | 중입자치료센터
TOSHIBA
TOSHIBA

방사광가속기 (Synchrotron Radiation / Light Source)!

In May 1947, Elder, Gurewitsch, Langmuir, and Pollock published a letter entitled "Radiation from Electrons in a Synchrotron," in which they reported their visual observation of synchrotron radiation from the 70-MeV electron synchrotron (shown above) at General Electric Research Laboratory, Schenectady, NY.

"If the accelerator tube of the 100-MeV betatron at Schenectady had not been opaque, the visual observation would probably have been made three years earlier by Westendorp or Blewett soon after the publication of your letter to the Physical Review (Phys. Rev. 5:343, 1944).



방사광가속기의 구성

입사기

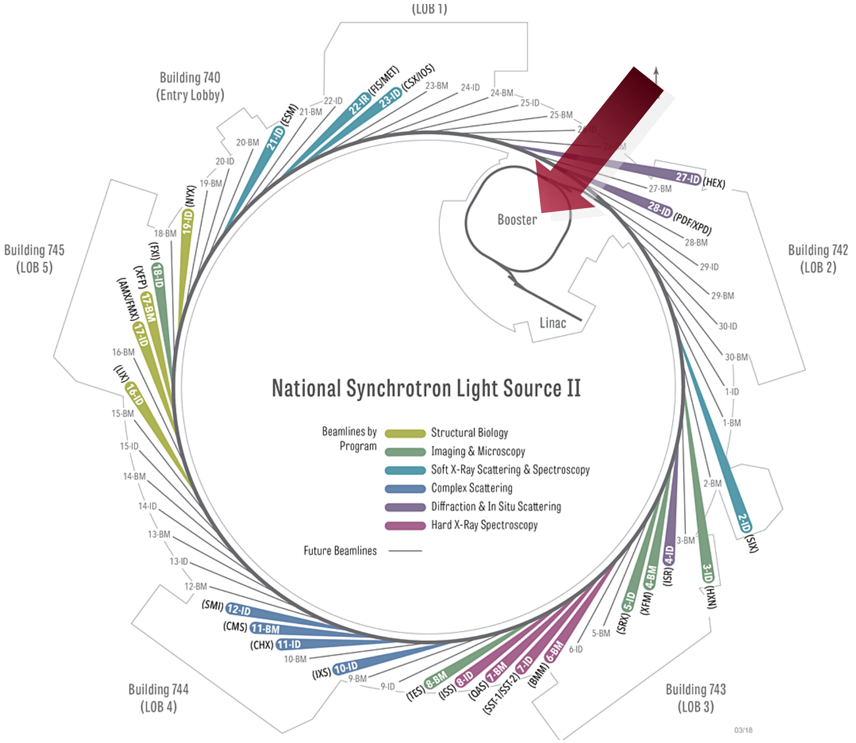
- Long Linear Accelerator
- Small Linear Accelerator + Booster Synchrotron

저장링

- Storage Ring – Synchrotron Accelerator
- Small Ring / Large Ring (원형궤도 길이)

방사광빔라인

- X-ray Beamline (Hard / Soft)
- VUV Beamline (Vacuum Ultra-Violet 진공자외선)


(LOB 1)
Building 740
(Entry Lobby)
Building 745
(LOB 5)
Building 742
(LOB 2)
Building 744
(LOB 4)
Building 743
(LOB 3)
Booster
Linac
National Synchrotron Light Source II
Beamlines by Program
Structural Biology
Imaging & Microscopy
Soft X-Ray Scattering & Spectroscopy
Complex Scattering
Diffraction & In Situ Scattering
Hard X-Ray Spectroscopy
Future Beamlines
21-ID (ESM)
22-ID
21-BM
22-IR (FIS/MET)
23-ID (CSX/IOS)
23-BM
24-ID
24-BM
25-ID
25-BM
27-ID (HEX)
27-BM
28-ID (PDF/XPD)
28-BM
29-ID
29-BM
30-ID
30-BM
1-ID
1-BM
2-BM
2-ID (SIX)
3-BM
3-ID (HXN)
4-ID (ISR)
4-BM (XFM)
5-ID (SRX)
5-BM
6-ID
6-BM (BMM)
7-ID (SST-1/SST-2)
7-BM (QAS)
8-ID (ISS)
8-BM (TES)
9-ID
9-BM
10-ID (IXS)
10-BM
11-ID (CHX)
11-BM (CMS)
12-ID (SMI)
12-BM
13-ID
13-BM
14-ID
14-BM
15-ID
15-BM
16-ID (LIX)
16-BM
17-ID (AMX/FMX)
17-BM (XFP)
18-ID (FXI)
18-BM
19-ID (NYX)
19-BM
20-ID
20-BM
03/18

방사광가속기의 구성

입사기

- Long Linear Accelerator
- Small Linear Accelerator + Booster Synchrotron

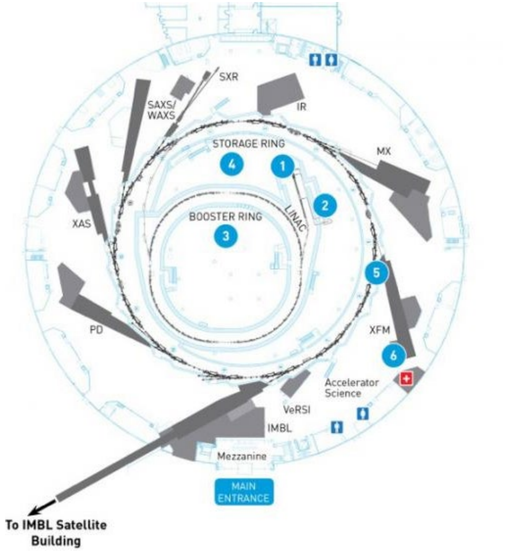
저장링

- **Storage Ring – Modified Synchrotron**
- **Small Ring / Large Ring (원형궤도 길이)**

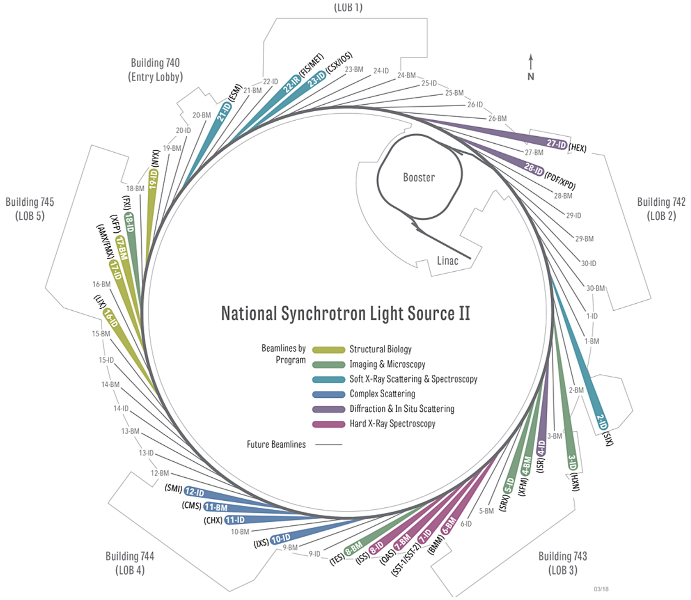
방사광빔라인

- X-ray Beamline (Hard / Soft)
- VUV Beamline (Vacuum Ultra-Violet 진공자외선)

~ 300 m (AS)


SXR
SAXS/WAXS
IR
STORAGE RING
MX
BOOSTER RING
LINAC
XAS
PD
XFM
Accelerator Science
VeRSI
IMBL
Mezzanine
MAIN ENTRANCE
To IMBL Satellite Building
1
2
3
4
5
6

~ 500 m (NSLS II)


National Synchrotron Light Source II
(LOB 1)
Building 740 (Entry Lobby)
Building 742 (LOB 2)
Building 743 (LOB 3)
Building 744 (LOB 4)
Building 745 (LOB 5)
N
Booster
Linac
Beamlines by Program
Structural Biology
Imaging & Microscopy
Soft X-Ray Scattering & Spectroscopy
Complex Scattering
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27-ID (HEX)
28-ID (PDF/XPD)
2-ID (SIX)
3-ID (HXN)
4-ID (ISR)
4-BM (XFM)
5-ID (SRX)
6-BM (BMM)
7-ID (SST-1/SST-2)
7-BM (QAS)
8-ID (ISS)
8-BM (TES)
10-ID (IXS)
11-ID (CHX)
11-BM (CMS)
12-ID (SMI)
16-ID (LIX)
17-ID (AMX/FMX)
17-BM (XFP)
18-ID (FXI)
19-ID (NYX)
03/18

~ 1 km (Spring-8)

방사광가속기의 구성

입사기

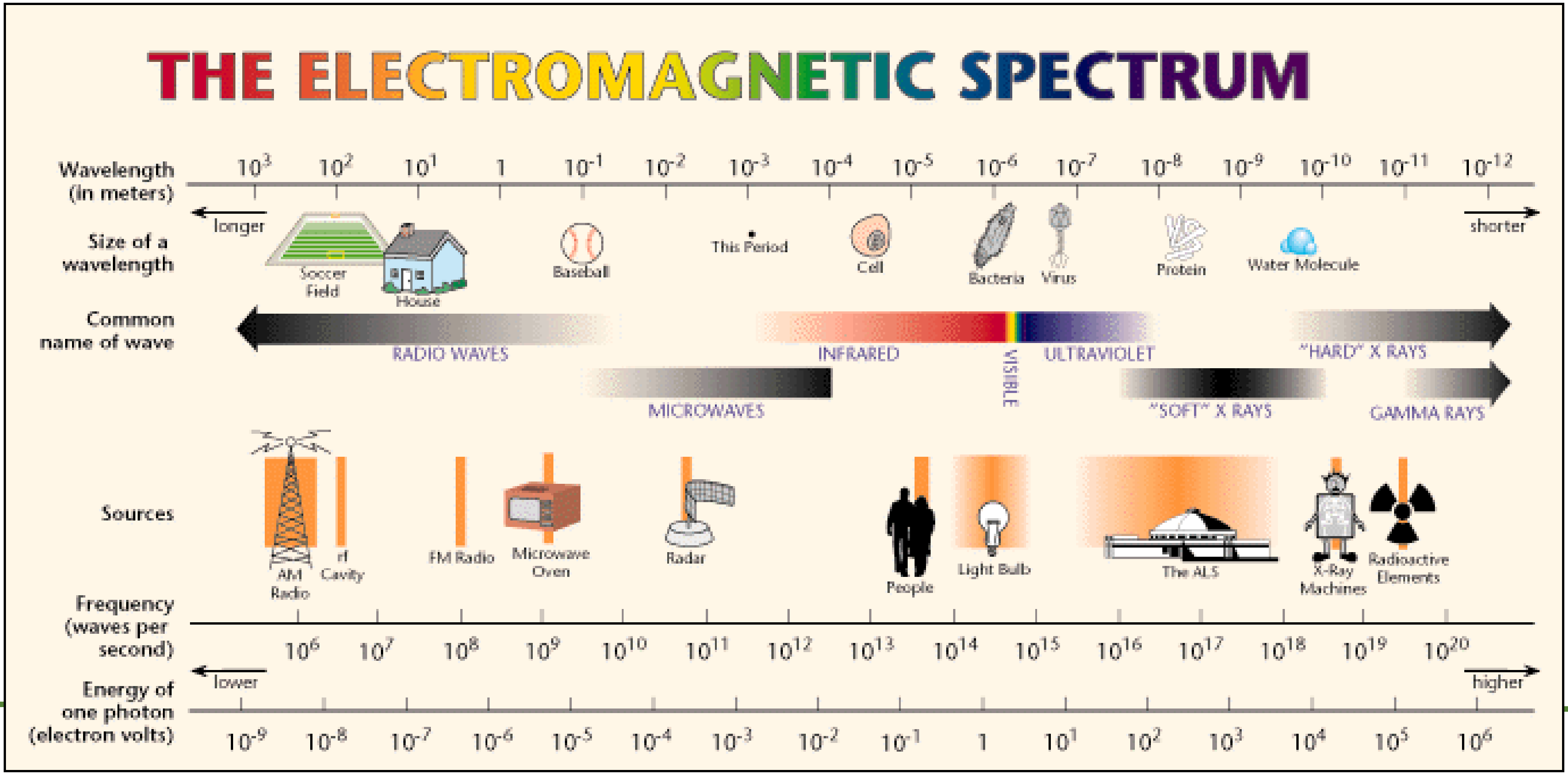
- Long Linear Accelerator
- Small Linear Accelerator + Booster Synchrotron

저장링

- Storage Ring – Modified Synchrotron
- Small Ring / Large Ring (원형궤도 길이)

방사광빔라인

- **X-ray Beamline (Hard / Soft)**
- **VUV Beamline (Vacuum Ultra-Violet 진공자외선)**


THE ELECTROMAGNETIC SPECTRUM
Wavelength (in meters)
10^3 10^2 10^1 1 10^{-1} 10^{-2} 10^{-3} 10^{-4} 10^{-5} 10^{-6} 10^{-7} 10^{-8} 10^{-9} 10^{-10} 10^{-11} 10^{-12}
longer
shorter
Size of a wavelength
Soccer Field
House
Baseball
This Period
Cell
Bacteria
Virus
Protein
Water Molecule
Common name of wave
RADIO WAVES
INFRARED
VISIBLE
ULTRAVIOLET
"HARD" X RAYS
MICROWAVES
"SOFT" X RAYS
GAMMA RAYS
Sources
AM Radio
rf Cavity
FM Radio
Microwave Oven
Radar
People
Light Bulb
The ALS
X-Ray Machines
Radioactive Elements
Frequency (waves per second)
10^6 10^7 10^8 10^9 10^{10} 10^{11} 10^{12} 10^{13} 10^{14} 10^{15} 10^{16} 10^{17} 10^{18} 10^{19} 10^{20}
lower
higher
Energy of one photon (electron volts)
10^{-9} 10^{-8} 10^{-7} 10^{-6} 10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 1 10^1 10^2 10^3 10^4 10^5 10^6

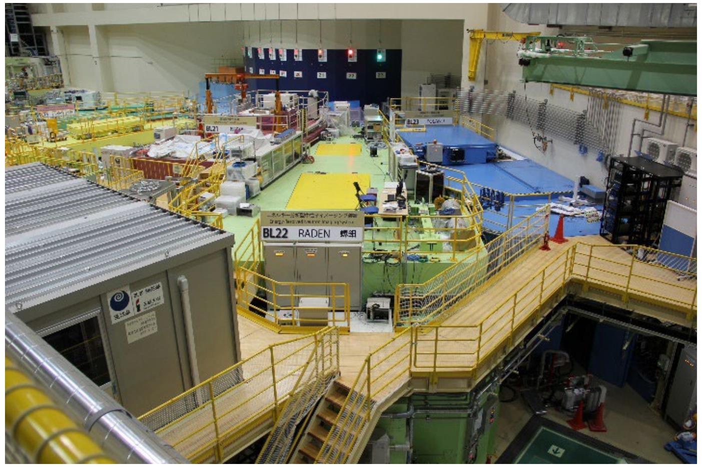
2

입자가속기의 활용

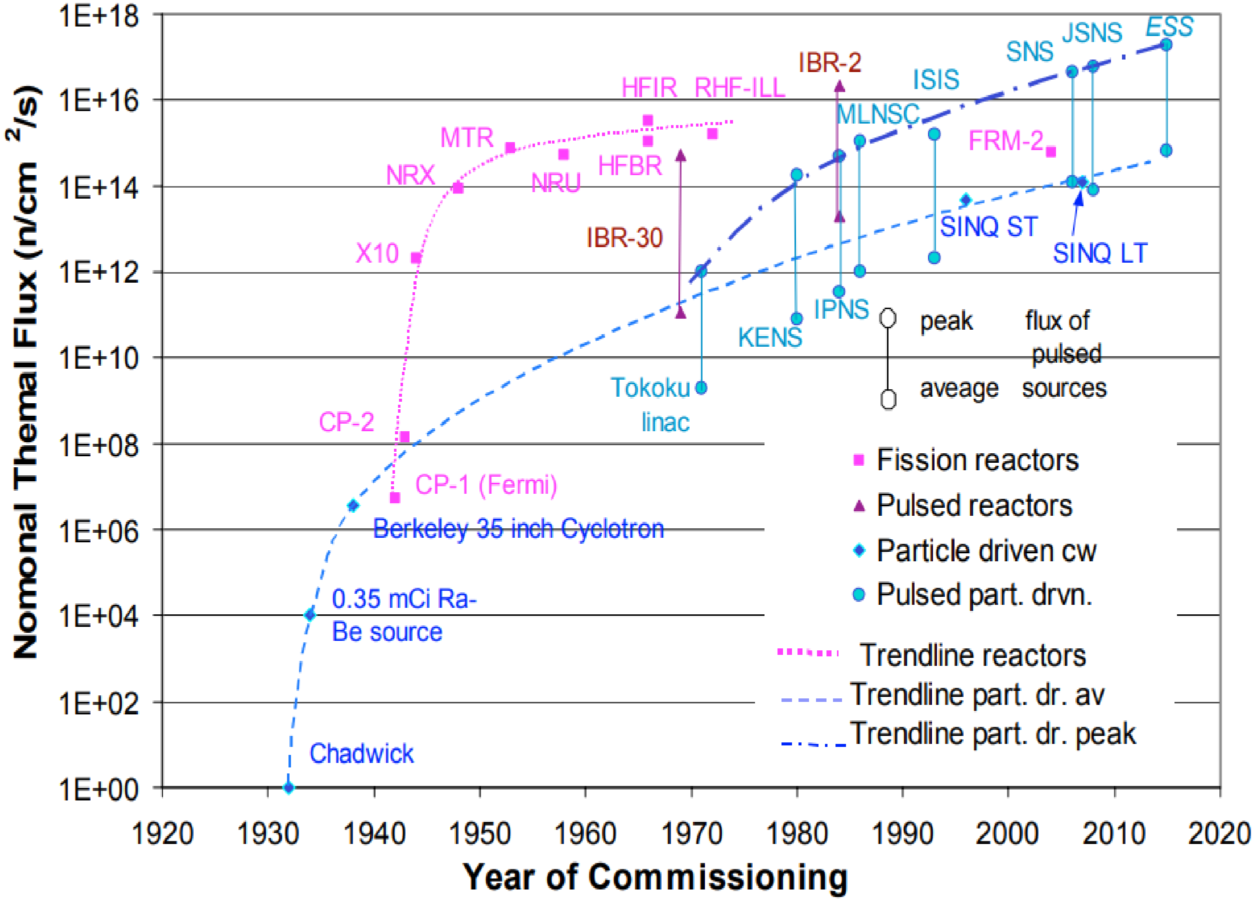
(강력한 물질분석도구)

중선자 선원 – Spallation Neutron Source

- **SNS (Oak Ridge Nat. Lab)**
- **JPARC (JAEA)**
- **ESS (ESS at Lund)**
- **CSNS**



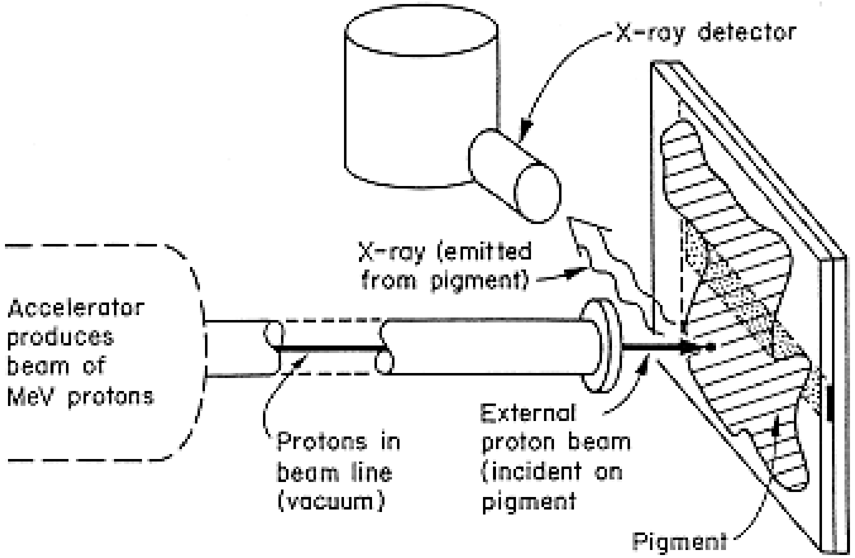
중성자 선원의 발전



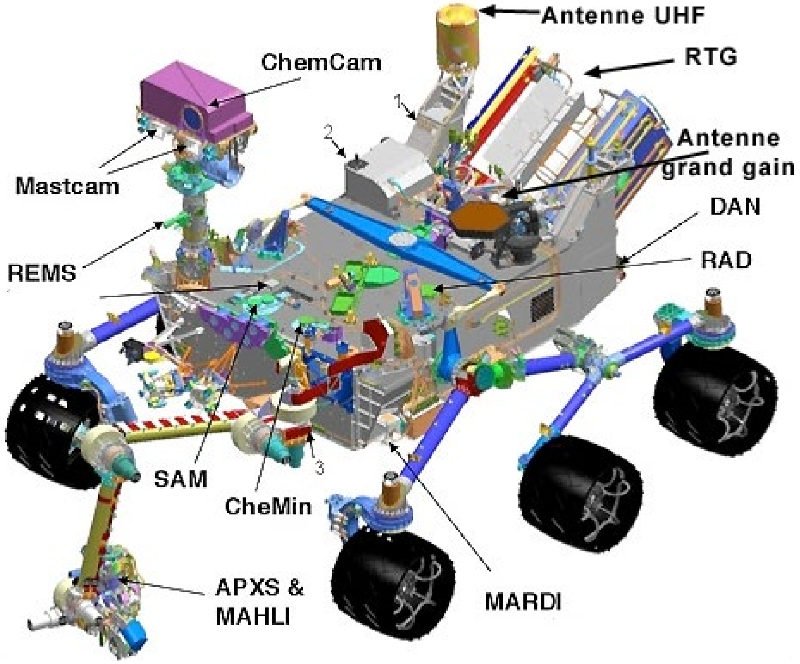
양성자, 이온빔 – PIXE, RBS, AMS etc

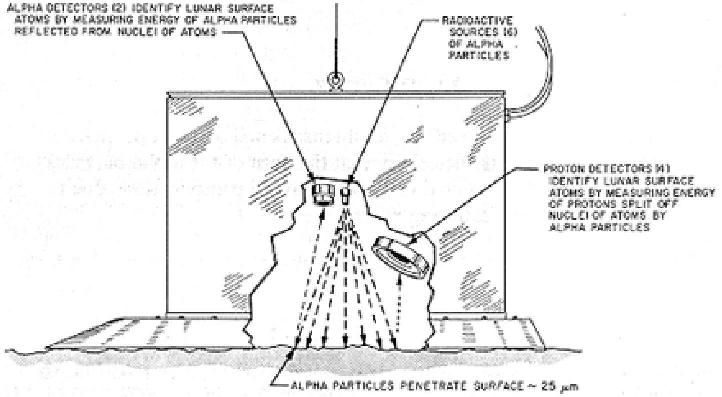
PIXE 원리와 활용 사례

- **Particle-induced X-ray Emission**


X-ray detector
X-ray (emitted from pigment)
Accelerator produces beam of MeV protons
Protons in beam line (vacuum)
External proton beam (incident on pigment
Pigment

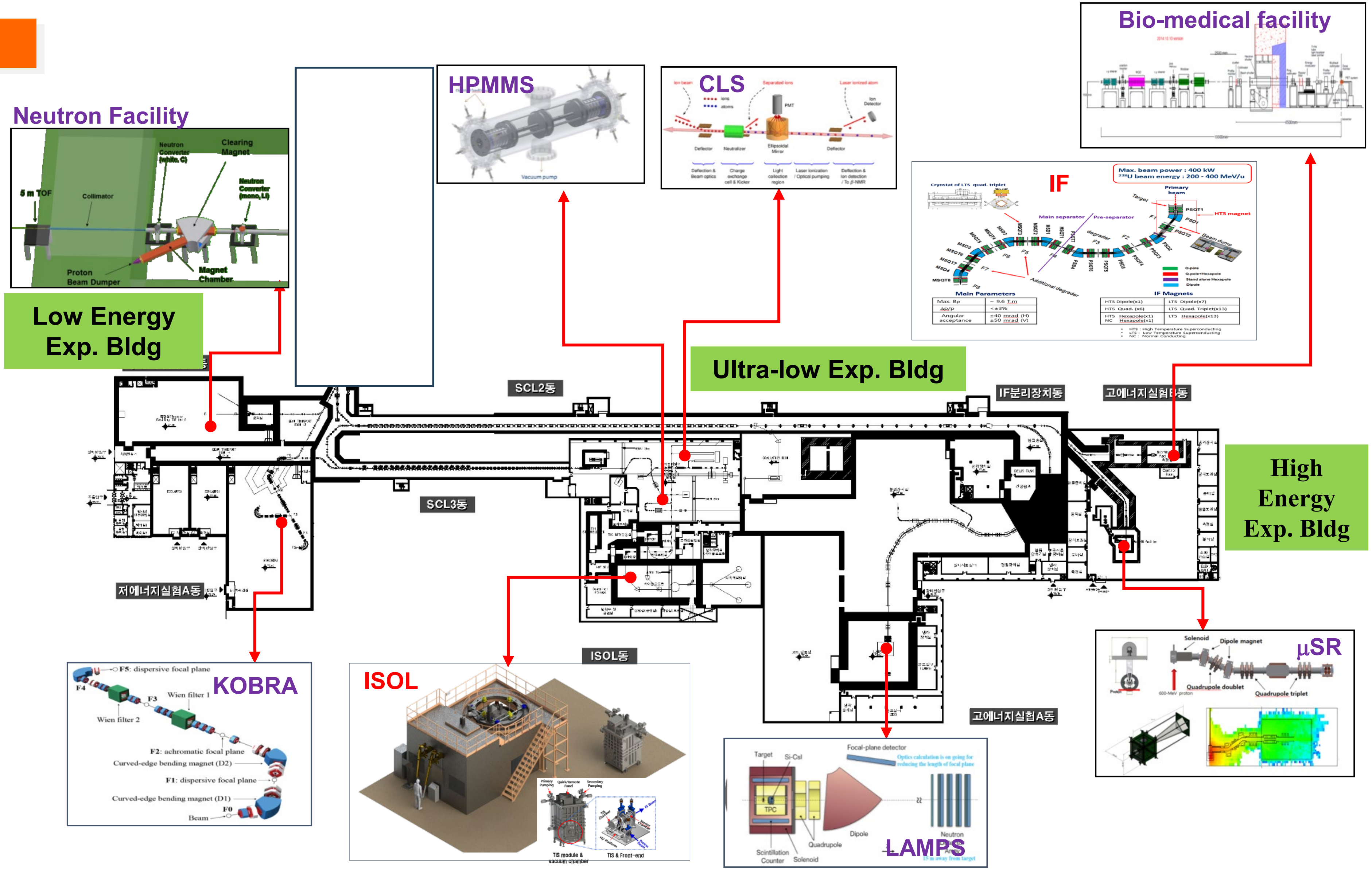
- **Mars Rover (NASA)**


Antenne UHF
ChemCam
RTG
1
2
Antenne grand gain
Mastcam
DAN
REMS
RAD
SAM
3
CheMin
APXS & MAHLI
MARDI


ALPHA DETECTORS (2) IDENTIFY LUNAR SURFACE ATOMS BY MEASURING ENERGY OF ALPHA PARTICLES REFLECTED FROM NUCLEI OF ATOMS
RADIOACTIVE SOURCES (6) OF ALPHA PARTICLES
PROTON DETECTORS (4) IDENTIFY LUNAR SURFACE ATOMS BY MEASURING ENERGY OF PROTONS SPLIT OFF NUCLEI OF ATOMS BY ALPHA PARTICLES
ALPHA PARTICLES PENETRATE SURFACE ~ 25 μm

IBS/RISP 중이온 가속기 실험장치들

실험 장치


Neutron Facility
5 m TOF
Collimator
Neutron Converter (white, C)
Clearing Magnet
Neutron Converter (mono, Li)
Proton Beam Dumper
Magnet Chamber
Low Energy Exp. Bldg
HPMMS
Vacuum pump
CLS
Deflector
Neutralizer
PMT
Ellipsoidal Mirror
Ion Detector
Bio-medical facility
IF
Max. beam power : 400 kW
238U beam energy : 200 - 400 MeV/u
Primary beam
Target
Main separator
Pre-separator
HTS magnet
Beam dump
Main Parameters
IF Magnets
Ultra-low Exp. Bldg
SCL2동
SCL3동
IF분리장치동
고에너지실험B동
High Energy Exp. Bldg
저에너지실험A동
ISOL동
고에너지실험A동
KOBRA
F5: dispersive focal plane
F4
F3
Wien filter 1
Wien filter 2
F2: achromatic focal plane
Curved-edge bending magnet (D2)
F1: dispersive focal plane
Curved-edge bending magnet (D1)
F0
Beam
ISOL
TIS module & vacuum chamber
TIS & Front-end
LAMPS
Target
Si-CsI
Focal-plane detector
TPC
Dipole
Quadrupole
Scintillation Counter
Solenoid
Neutron
μSR
Solenoid
Dipole magnet
Quadrupole doublet
Quadrupole triplet
600-MeV proton

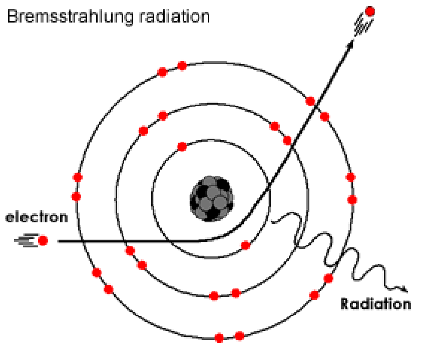
방사광 (High Brightness Photon Source)

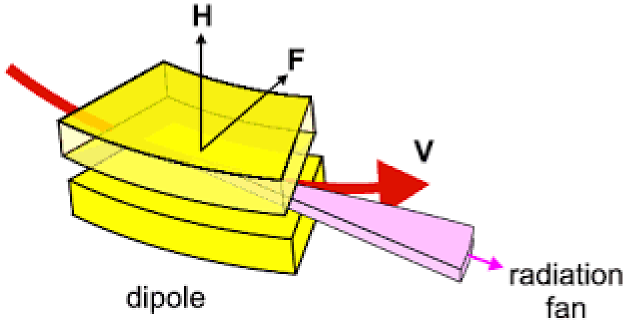
Bending Magnet (이극자석)

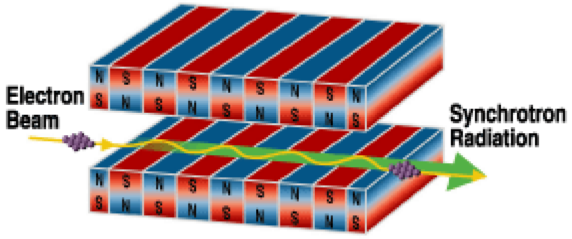
Wiggler (삽입장치)

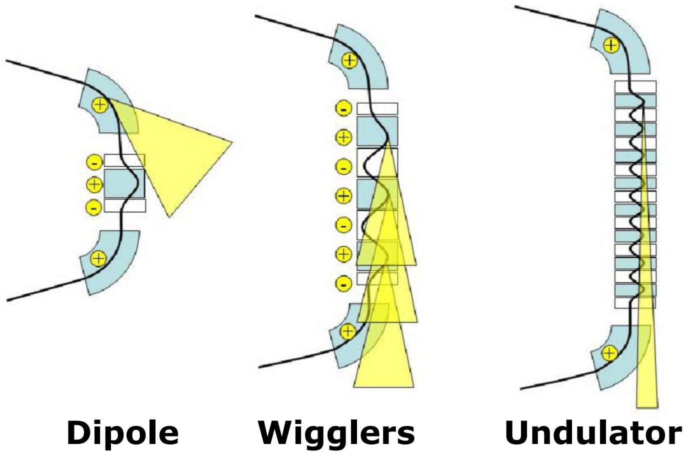
Undulator (삽입장치)

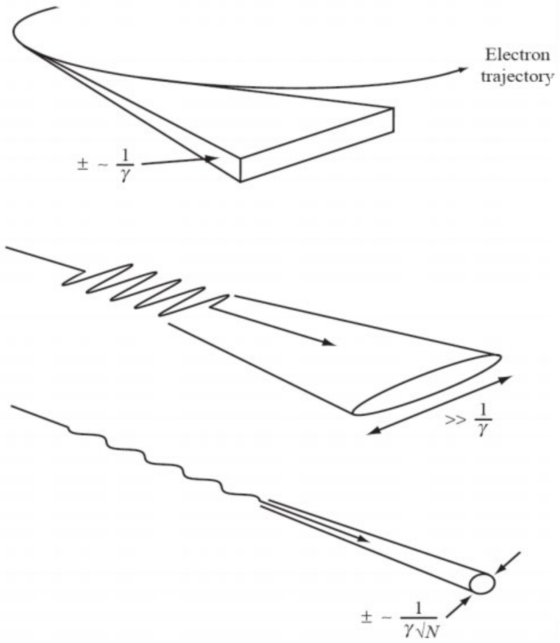
- **Bremsstrahlung X-ray & Synchrotron Radiation**

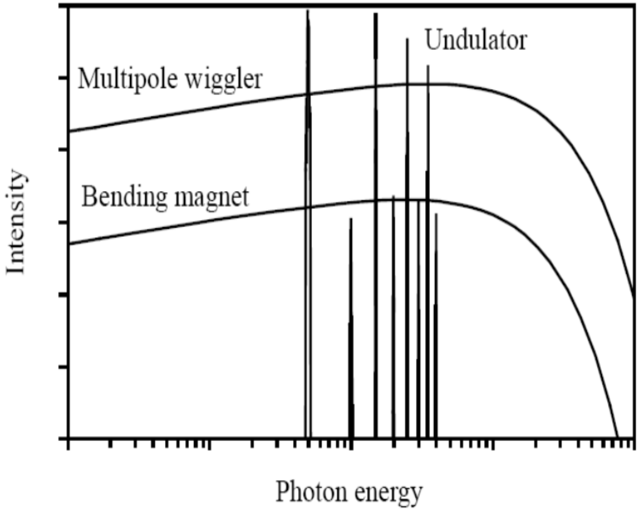

Bremsstrahlung radiation
electron
Radiation


H
F
V
dipole
radiation
fan


Electron
Beam
Synchrotron
Radiation
N
S


Dipole
Wigglers
Undulator

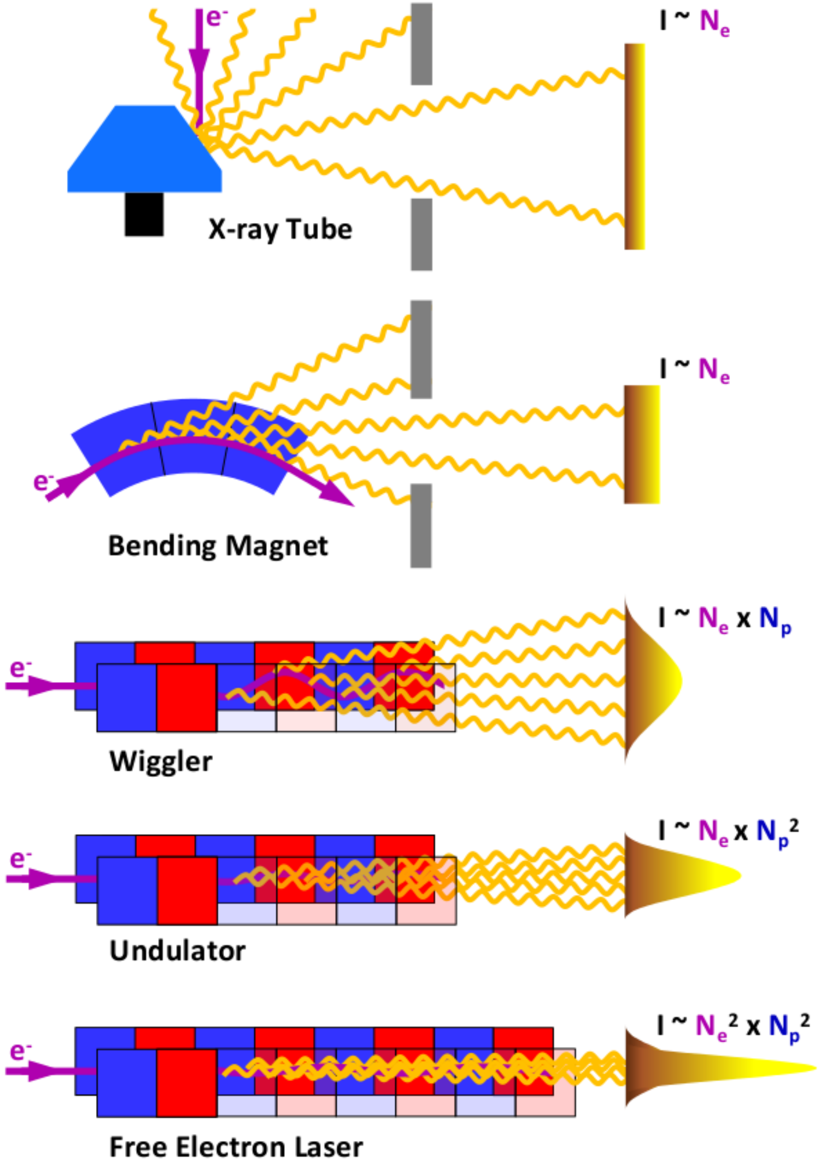

Electron
trajectory
$\pm \sim \frac{1}{\gamma}$
$>> \frac{1}{\gamma}$
$\pm \sim \frac{1}{\gamma\sqrt{N}}$

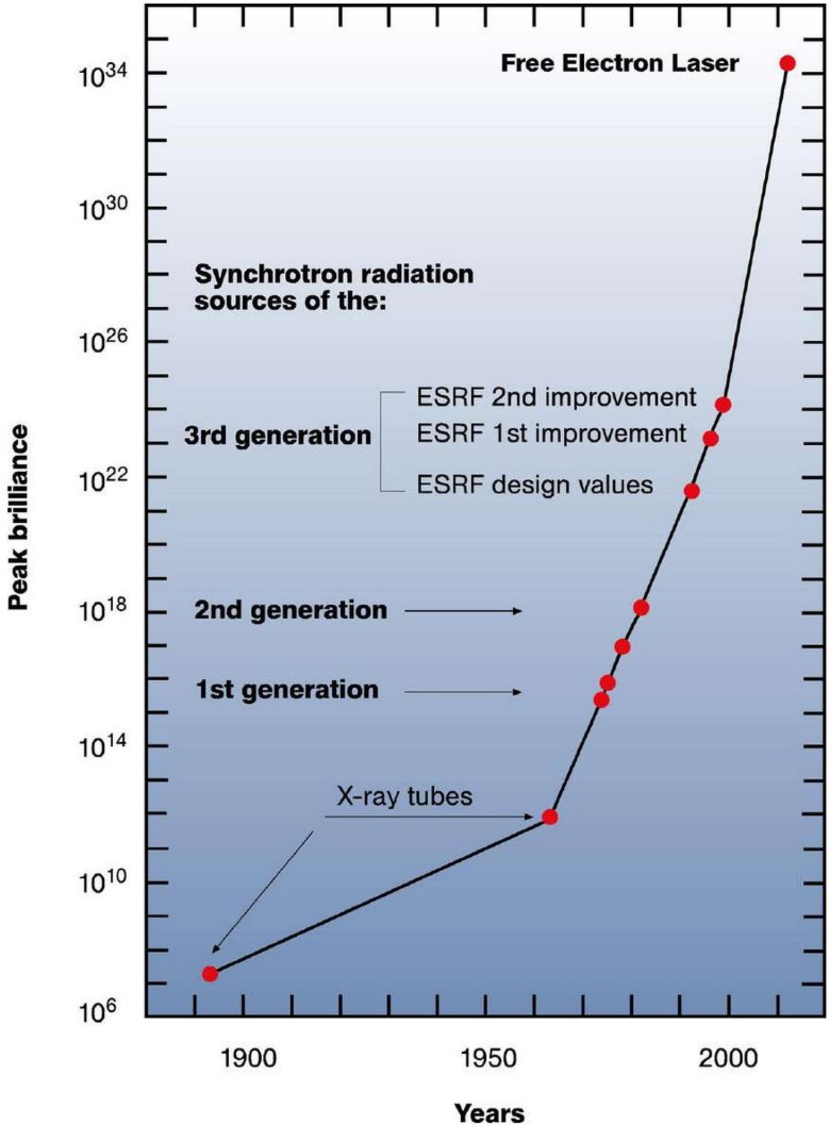


3

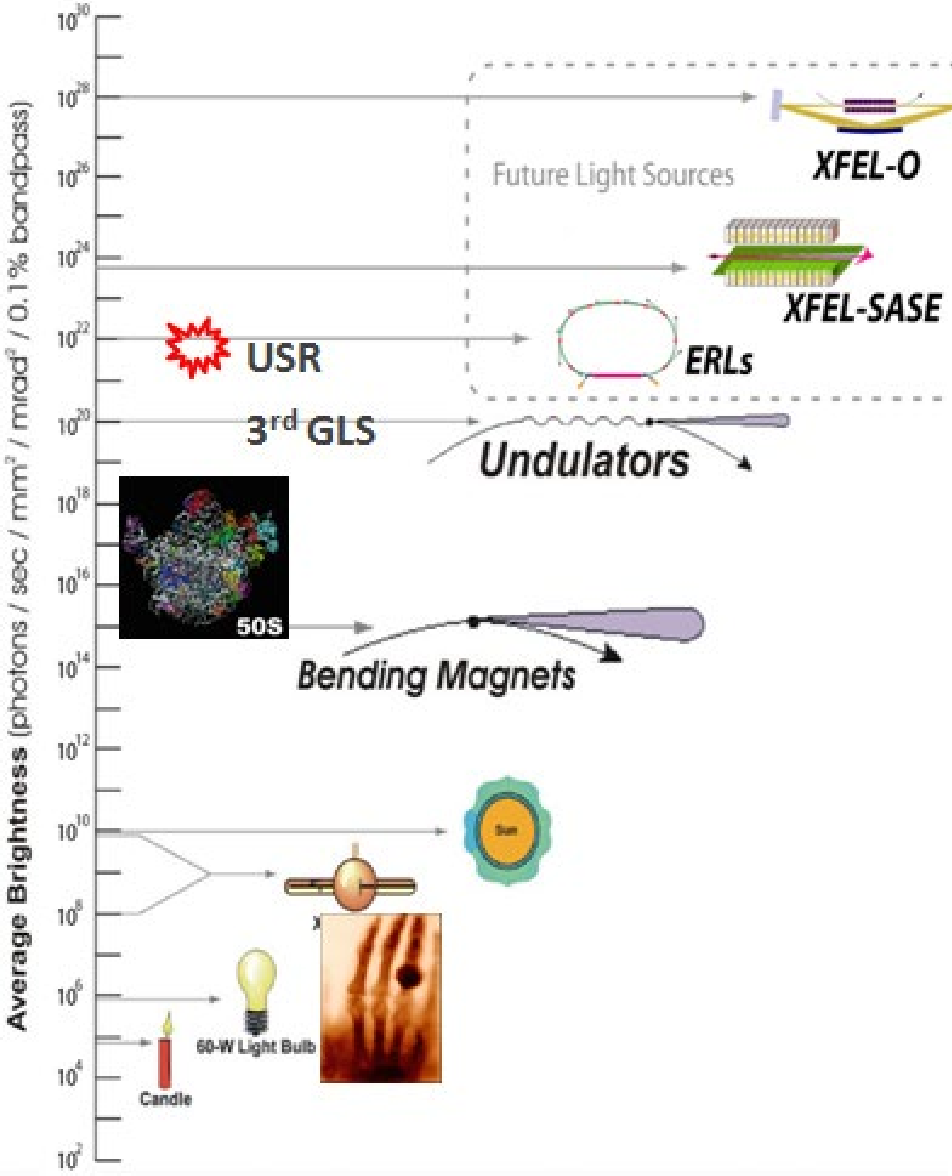
방사광가속기의 단계적 발전과 포항방사광가속기

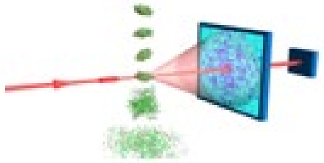
빛 (Photon)의 생성

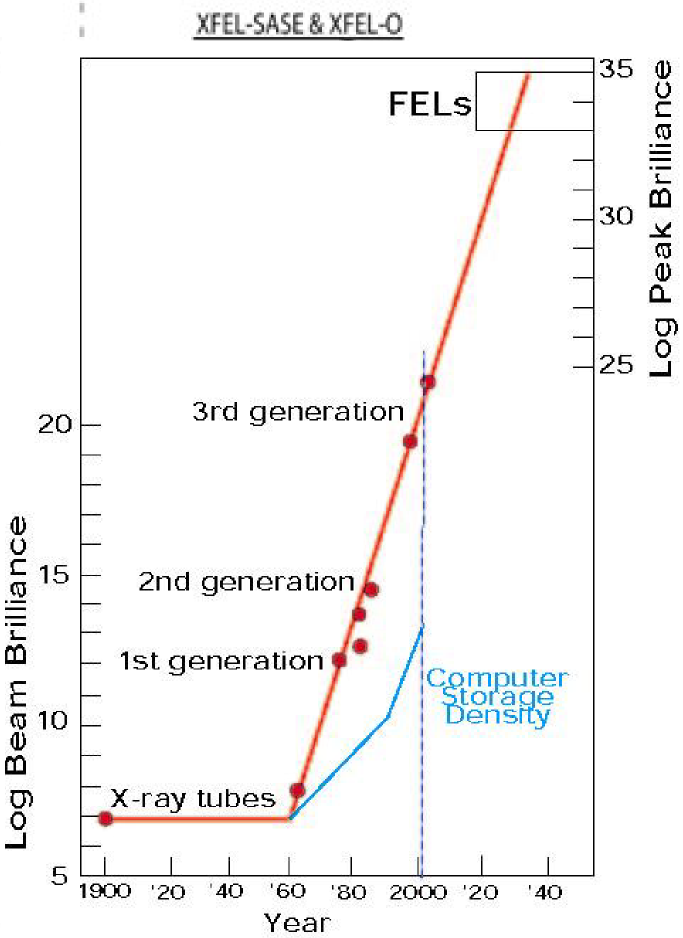

e^-
$I \sim N_e$
X-ray Tube
e^-
$I \sim N_e$
Bending Magnet
e^-
$I \sim N_e \times N_p$
Wiggler
e^-
$I \sim N_e \times N_p^2$
Undulator
e^-
$I \sim N_e^2 \times N_p^2$
Free Electron Laser


Free Electron Laser
Synchrotron radiation
sources of the:
ESRF 2nd improvement
3rd generation
ESRF 1st improvement
ESRF design values
2nd generation
1st generation
X-ray tubes
Peak brilliance
10^{34}
10^{30}
10^{26}
10^{22}
10^{18}
10^{14}
10^{10}
10^{6}
1900
1950
2000
Years

방사광가속기의 발전 – 더 밝은 빛



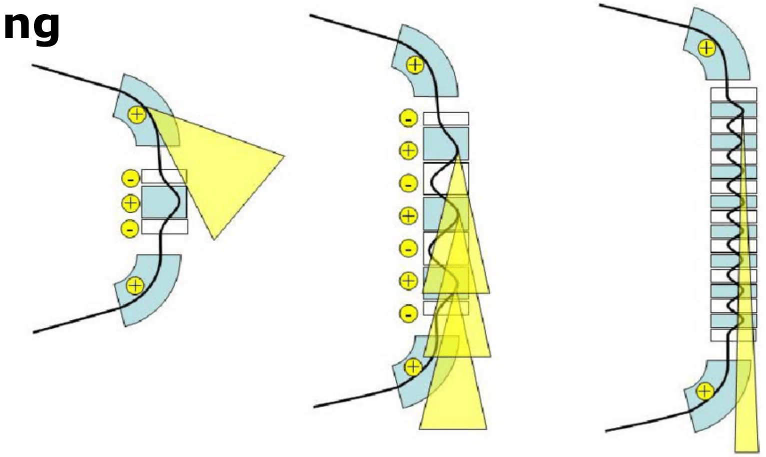




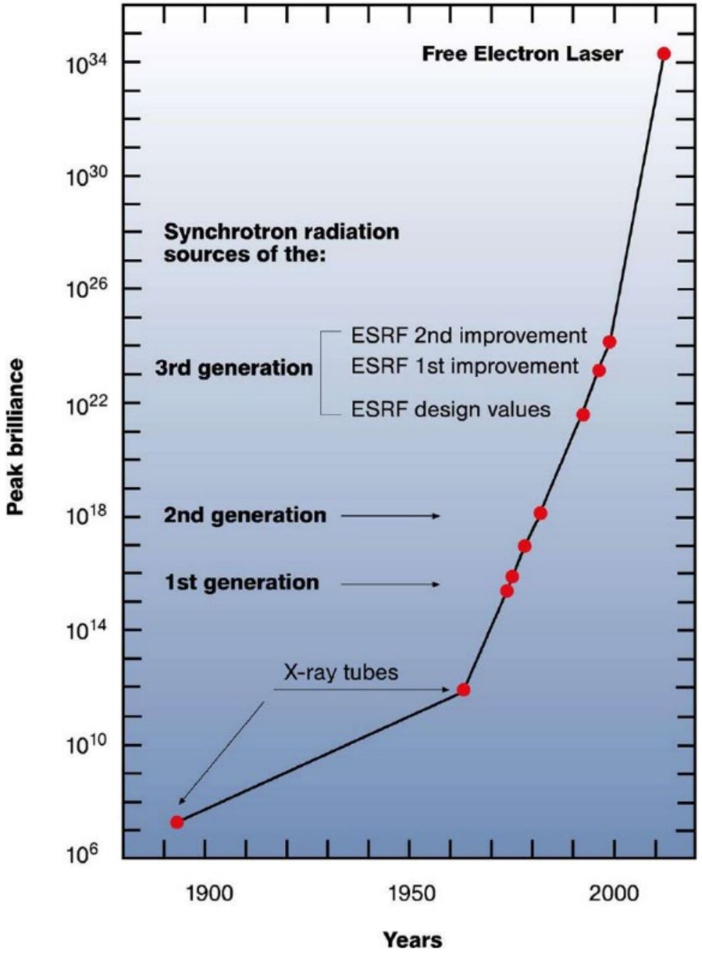
방사광가속기의 발전단계

Generation	Time period	Radiation use from	Energy range (GeV)	Emittance nm-rad	Average Brilliance
1	60s and early 70s	Parasitic	0.18-6	500	10^{13}
2	Mid 70s to 80s	Dipoles	0.7-2.5	100	10^{16}
3	90s to 2015	Wigglers and Undulators	0.7-8 many in 2-3 GeV	1-20	10^{19}
NGSR	**2015-2035**	**Undulators**	**2 – 8 for the moment**	**0.02-0.5**	10^{22}

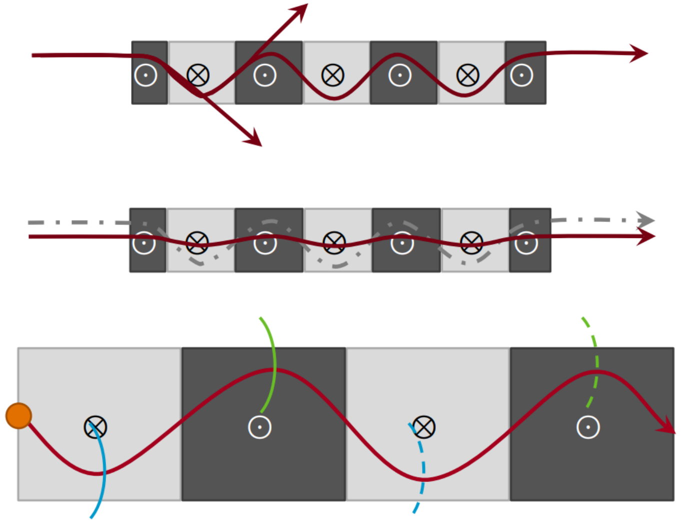
*** Next Generation SR ,**
4th Generation Storage Ring



Dipole **Wigglers** **Undulator**

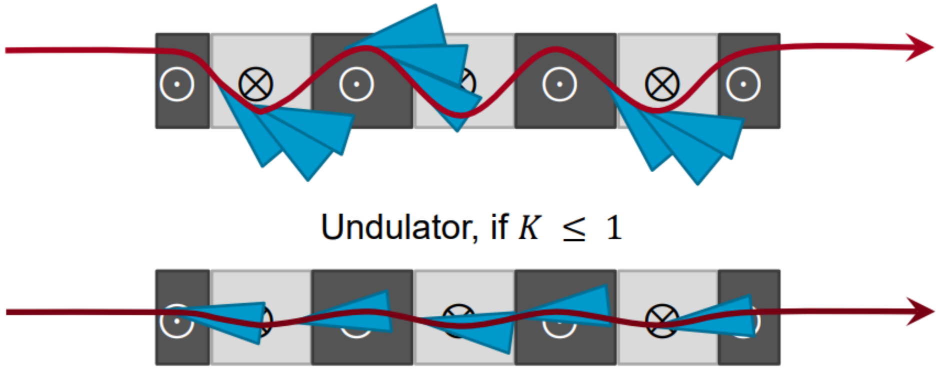


삽입장치 (Wiggler & Undulator)



$$\theta_w = \frac{K}{\gamma}$$

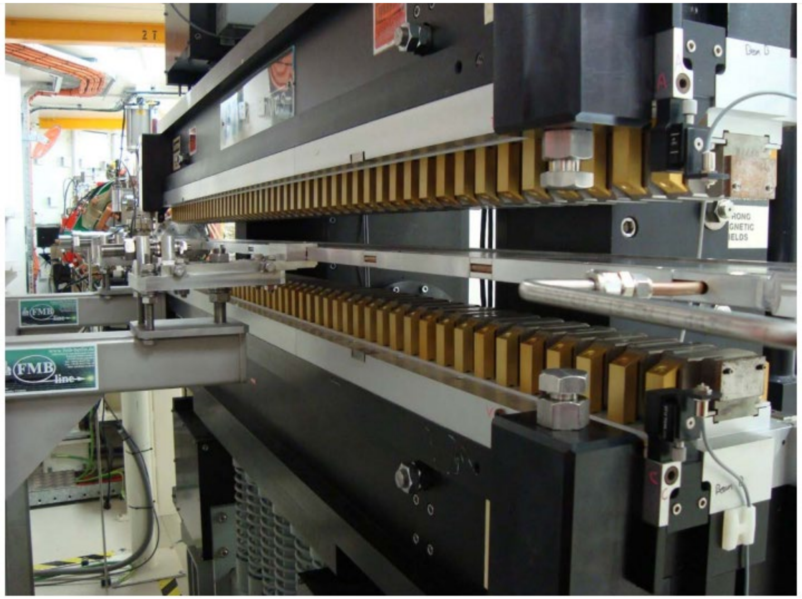
Wiggler, if $K \gg 1$



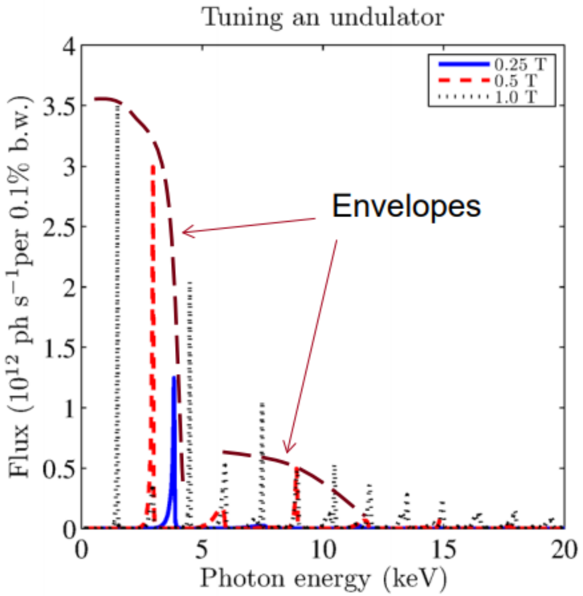
Undulator, if $K \leq 1$

근본적으로 차이 없지만 Wiggler는 Incoherent superposition 발생, Undulator의 방사광은 Coherent Harmonics가 존재

K: a dimensionless value that describes the curvature of an electron's trajectory



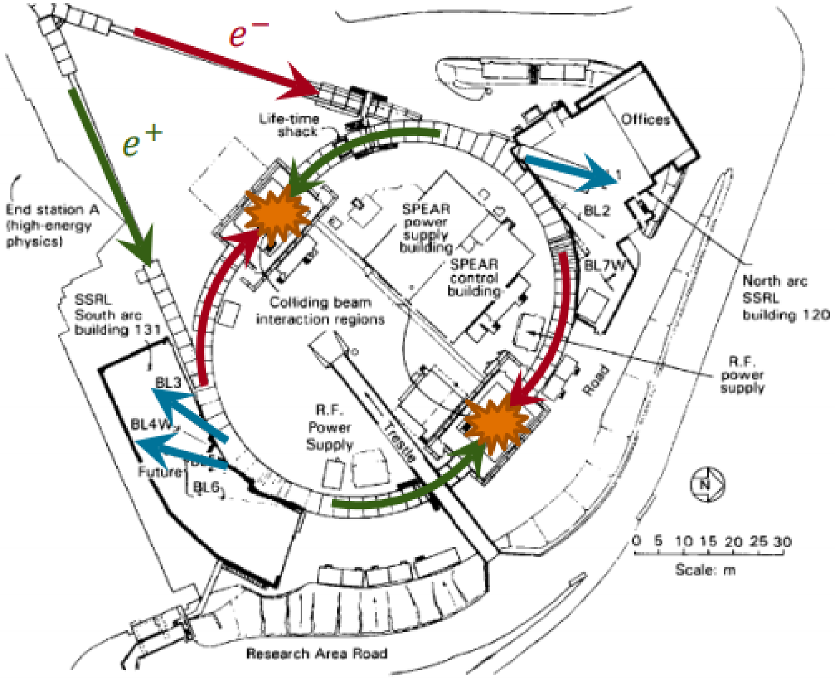
Undulator 사진과 방사광 에너지분포



방사광가속기의 발전단계

1세대 방사광가속기: SPEAR-1

- Parasitic use of synchrotrons, storage ring colliders
- Bending magnet radiation (incoherent, broadband)

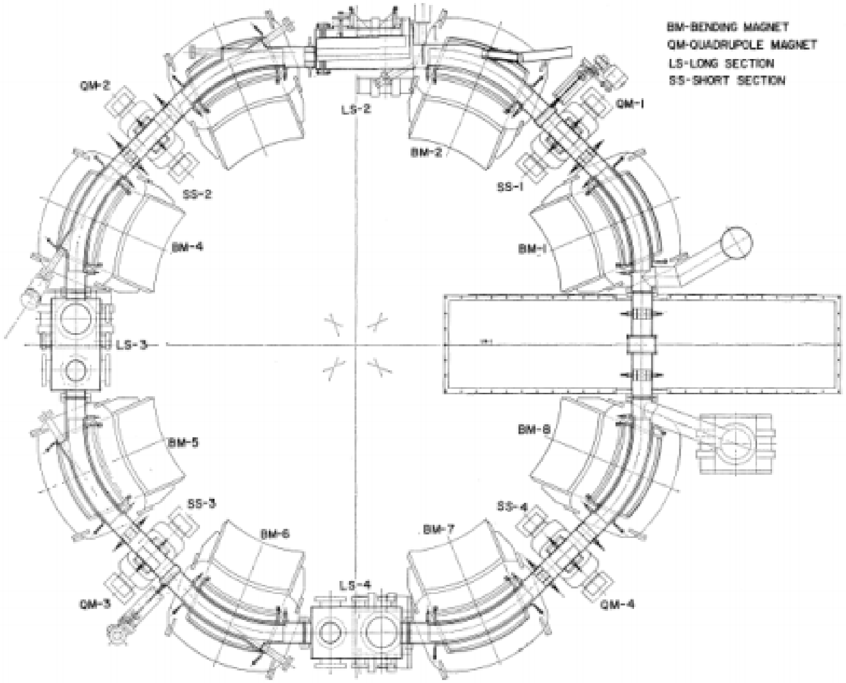

e^-
e^+
Life-time shack
Offices
End station A (high-energy physics)
SPEAR power supply building
SPEAR control building
BL1
BL2
BL7W
North arc SSRL building 120
SSRL South arc building 131
Colliding beam interaction regions
R.F. power supply
Road
BL3
BL4W
R.F. Power Supply
Trestle
Future
BL6
N
0 5 10 15 20 25 30
Scale: m
Research Area Road

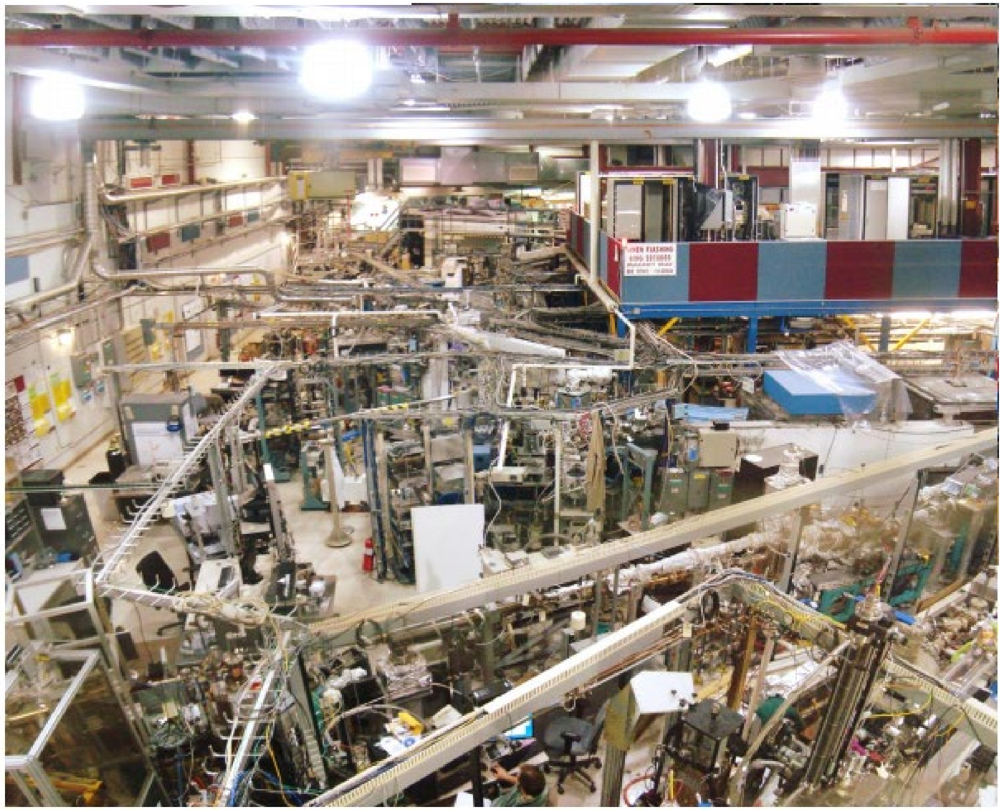
S. Doniach, et al., J. Synchrotron Radiat., 4, 380-395 (1997).

방사광가속기의 발전단계

2세대 방사광가속기: National Synchrotron Light Source (BNL)

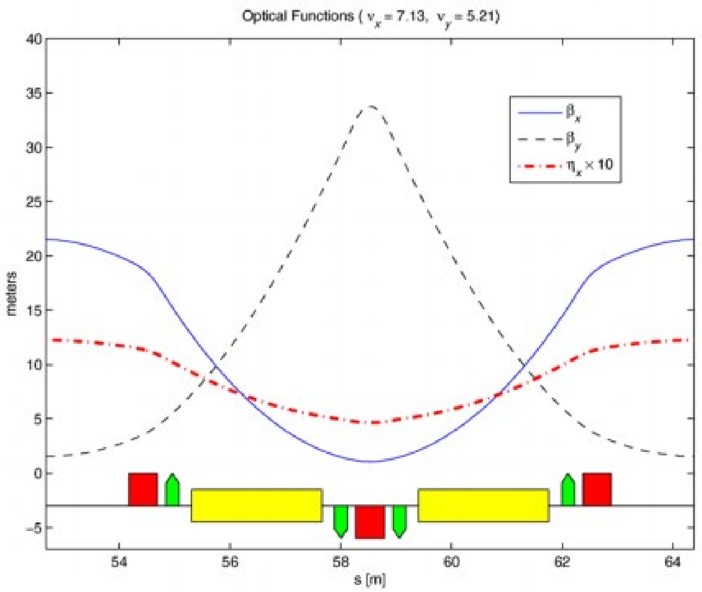
- 전용 전자 저장링 사용
- 주로 VUV, soft X-ray, 일부 hard X-ray


BM-BENDING MAGNET
QM-QUADRUPOLE MAGNET
LS-LONG SECTION
SS-SHORT SECTION
QM-2
QM-1
LS-2
BM-2
SS-1
SS-2
BM-4
BM-1
LS-3
BM-5
BM-8
SS-3
SS-4
BM-6
BM-7
LS-4
QM-3
QM-4

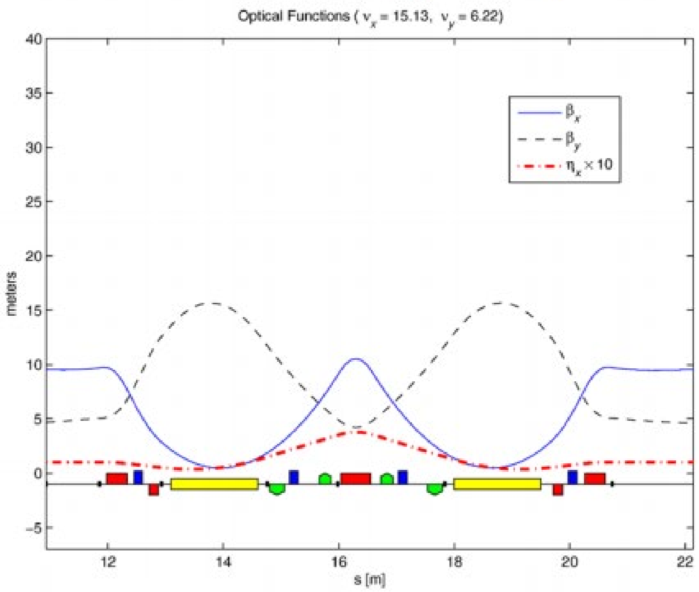


방사광가속기의 발전단계 (2 → 3세대)

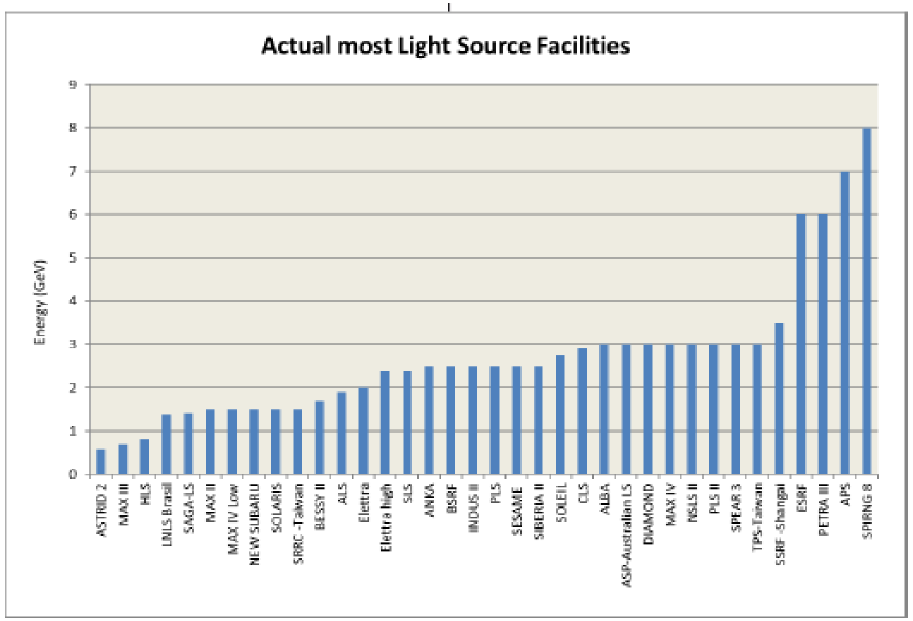
SPEAR-2 (FODO)

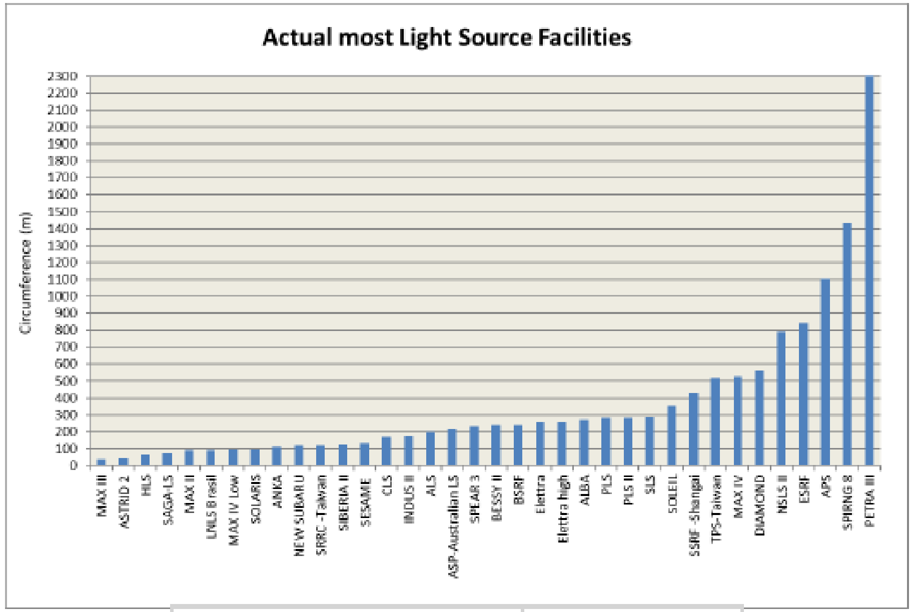


SPEAR-3 (DBA)



가동중인 방사광가속기의 에너지와 크기





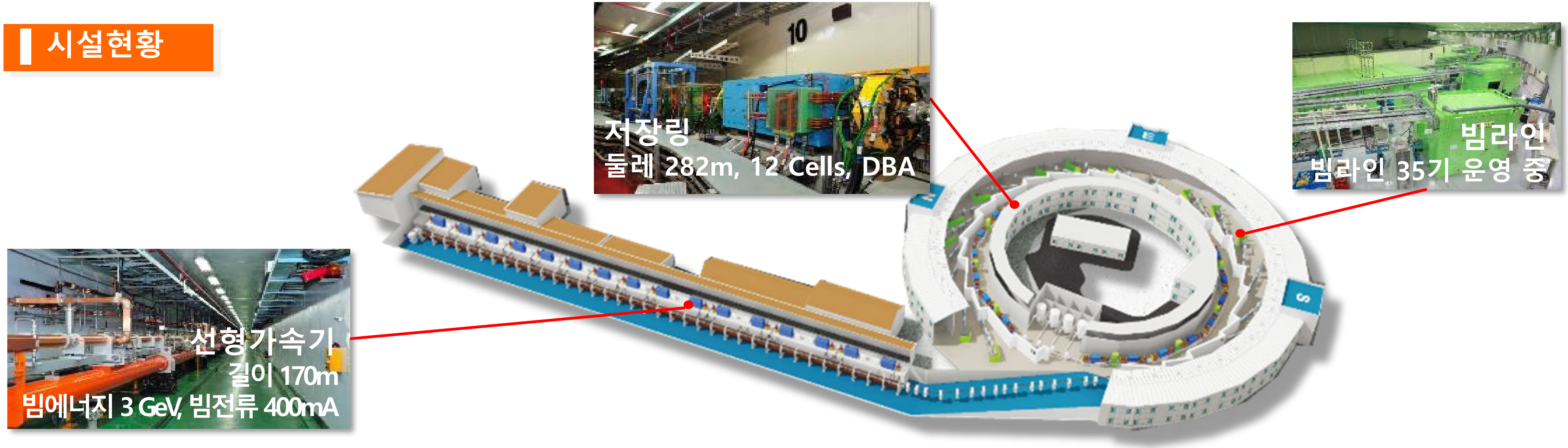
GeV	# of facilities
< 1	3
1 ≤ < 2	9
2≤ < 3	11
3≤ < 4	9
6≤ ≤ 8	4
tot	36

Circumference (m)	# of facilities
<100	8
100 ≤ < 200	8
200 ≤ < 300	10
300 ≤ < 400	1
400 ≤ < 500	1
500 ≤ < 600	3
600 ≤ < 700	0
700 ≤ < 800	1
800 ≤ < 900	1
above 1000	3
sum	36

Courtesy of E. Karantzoulis

PLS-II(3세대 방사광가속기)

시설현황

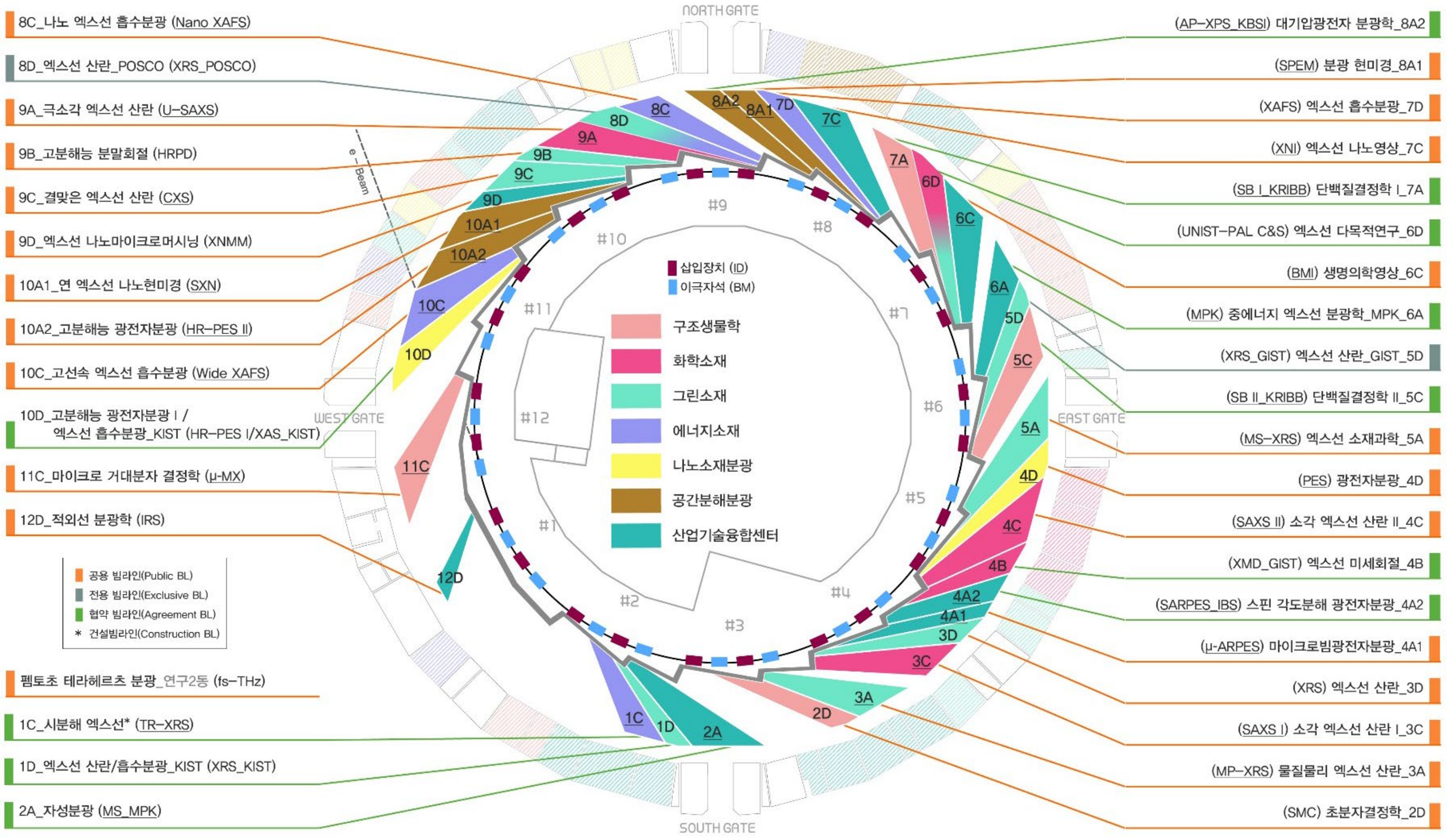

저장링
둘레 282m, 12 Cells, DBA
빔라인
빔라인 35기 운영 중
선형가속기
길이 170m
빔에너지 3 GeV, 빔전류 400mA

연도	주요 연혁
‘88.05	포항가속기연구소 설립(포스텍 부설)
‘94.12	PLS(3세대 방사광가속기) 준공
‘95.09	PLS(3세대 방사광가속기) 이용 개시
‘09~’11	PLS-II 성능향상 사업(3개년)
‘17.09	포항 방사광가속기 국유화(3·4세대)
‘19.10	빔라인 35기 운영, 1기 건설 중

구 분	3세대 방사광가속기 (PLS-Ⅱ)
대지/건물	126,800 m^2 / 18개동 연면적 45,358.17 m^2
주요장치	▪ **선형가속기** : 길이 170m, 빔에너지 3GeV, 빔전류 300 ~ 400mA ▪ **저장링 :** 둘레 281.8m, 12 Cells, DBA ▪ **빔라인 :** 빔라인 35기 운영, 1기 증설 중
구축기간 (운영기간)	▪ **PLS :** 1988년 ~ 1994년 (1995년~2010년) ▪ **PLS-Ⅱ :** 2009년~2011년 (2012년 ~)
형 태	선형+원형 (다수 빔라인 동시 운영)
특 징	태양빛의 100억배 밝기, 1나노(10^{-9})초 분해능
실험수준	정적 분석 (이미지) ⇒ 기초과학 전분야 및 산업체 활용 중

PLS-II(3세대 방사광가속기)

PLS-II 빔라인 현황


NORTH GATE
SOUTH GATE
WEST GATE
EAST GATE
e⁻ Beam
8C
8D
9A
9B
9C
9D
10A1
10A2
10C
10D
11C
12D
1C
1D
2A
2D
3A
3C
3D
4A1
4A2
4B
4C
4D
5A
5C
5D
6A
6C
6D
7A
7C
7D
8A1
8A2
#1
#2
#3
#4
#5
#6
#7
#8
#9
#10
#11
#12
삽입장치 (ID)
이극자석 (BM)
구조생물학
화학소재
그린소재
에너지소재
나노소재분광
공간분해분광
산업기술융합센터

- 8C_나노 엑스선 흡수분광 (Nano XAFS)
- 8D_엑스선 산란_POSCO (XRS_POSCO)
- 9A_극소각 엑스선 산란 (U-SAXS)
- 9B_고분해능 분말회절 (HRPD)
- 9C_결맞은 엑스선 산란 (CXS)
- 9D_엑스선 나노마이크로머시닝 (XNMM)
- 10A1_연 엑스선 나노현미경 (SXN)
- 10A2_고분해능 광전자분광 (HR-PES II)
- 10C_고선속 엑스선 흡수분광 (Wide XAFS)
- 10D_고분해능 광전자분광 I / 엑스선 흡수분광_KIST (HR-PES I/XAS_KIST)
- 11C_마이크로 거대분자 결정학 (μ-MX)
- 12D_적외선 분광학 (IRS)

🟧 공용 빔라인(Public BL)
⬛ 전용 빔라인(Exclusive BL)
🟩 협약 빔라인(Agreement BL)
* 건설빔라인(Construction BL)

- 펨토초 테라헤르츠 분광_연구2동 (fs-THz)
- 1C_시분해 엑스선* (TR-XRS)
- 1D_엑스선 산란/흡수분광_KIST (XRS_KIST)
- 2A_자성분광 (MS_MPK)

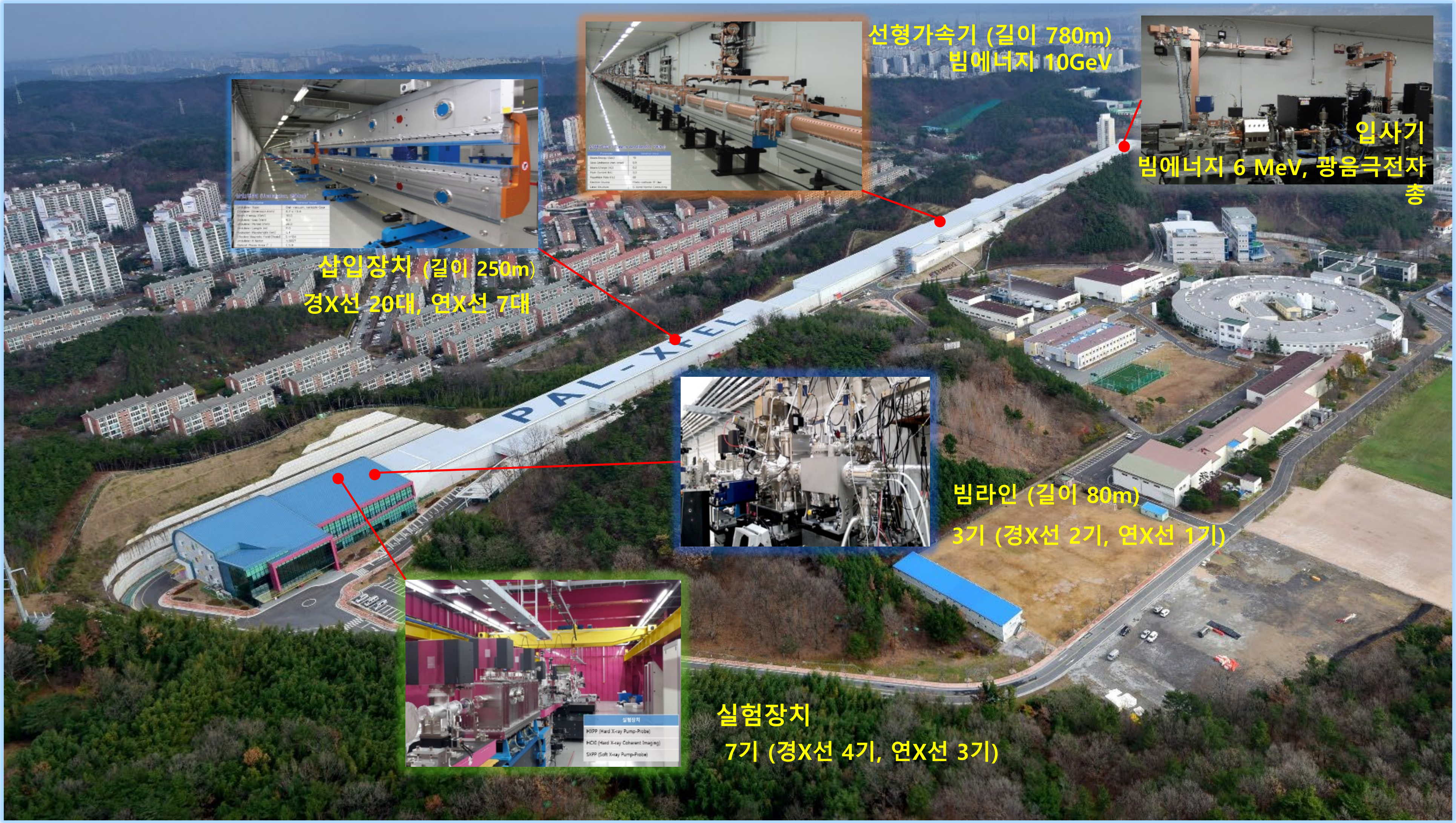
- (AP-XPS_KBSI) 대기압광전자 분광학_8A2
- (SPEM) 분광 현미경_8A1
- (XAFS) 엑스선 흡수분광_7D
- (XNI) 엑스선 나노영상_7C
- (SB I_KRIBB) 단백질결정학 I_7A
- (UNIST-PAL C&S) 엑스선 다목적연구_6D
- (BMI) 생명의학영상_6C
- (MPK) 중에너지 엑스선 분광학_MPK_6A
- (XRS_GIST) 엑스선 산란_GIST_5D
- (SB II_KRIBB) 단백질결정학 II_5C
- (MS-XRS) 엑스선 소재과학_5A
- (PES) 광전자분광_4D
- (SAXS II) 소각 엑스선 산란 II_4C
- (XMD_GIST) 엑스선 미세회절_4B
- (SARPES_IBS) 스핀 각도분해 광전자분광_4A2
- (μ-ARPES) 마이크로빔광전자분광_4A1
- (XRS) 엑스선 산란_3D
- (SAXS I) 소각 엑스선 산란 I_3C
- (MP-XRS) 물질물리 엑스선 산란_3A
- (SMC) 초분자결정학_2D

포항가속기연구소 과학기술정보통신부

PAL-XFEL(4세대 방사광가속기)

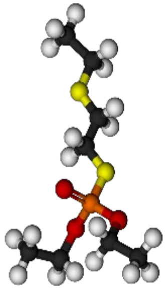
시설현황

- 3세대(PLS-II)의 1억배 밝기와 펨토(10^{-15})초 분해능

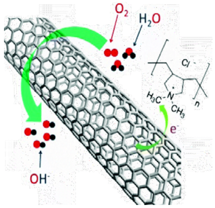

선형가속기 (길이 780m)
빔에너지 10GeV
입사기
빔에너지 6 MeV, 광음극전자총
삽입장치 (길이 250m)
경X선 20대, 연X선 7대
PAL-XFEL
빔라인 (길이 80m)
3기 (경X선 2기, 연X선 1기)
실험장치
7기 (경X선 4기, 연X선 3기)

방사광가속기의 발전단계

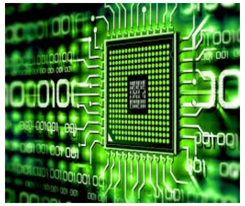
신소재, 에너지, 반도체, 물질 구조변화 연구



Molecule



Energy Catalyst



Semiconductor

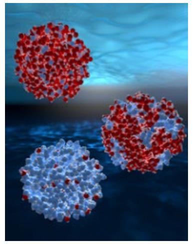
물질의 초고속 구조 변화 규명

신소재 물질개발

신성장 동력 산업

연구성과

('17.12.) '물' 분자구조 변화에 관한 연구
- 스톡홀롬대 앤더스닐슨+김경환 연구팀 -

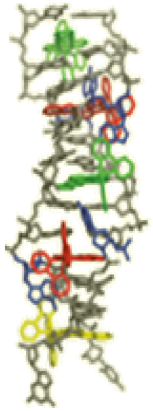


과냉각 상태에서의 **무거운 구조(고밀도, 빨강)**과 **가벼운 구조(저밀도, 파랑)**가 존재하면서 요동치는 현상이 **-44 °C에서 최대치**를 갖게 됨을 **실험으로 입증**하여 **물의 특이한 성질을 설명**

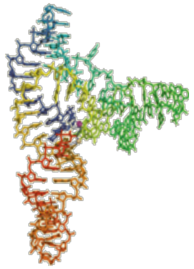
과냉각 상태 물의 열역학 반응 및 상관함수에서의 최고한계
Science 2017.12

생명, 신약 연구

Protein



DNA



RNA

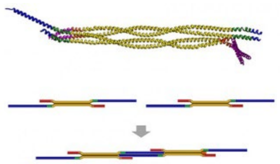
생명현상 규명

신약 개발

산업 응용

연구성과

('19.8.) 세포 노화 관여물질 '라민' 단백질 구조분석
- 서울대 하남출 연구팀 -



인간 세포 구조를 유지하는 단백질인 **라민의 3차원 구조를 고해상도로 규명**해 라민 단백질이 세포핵의 구조를 어떻게 지탱하고 유지하고 있는지 밝힘

라민 단백질 구조 규명
Nature Communications 2019.8

4

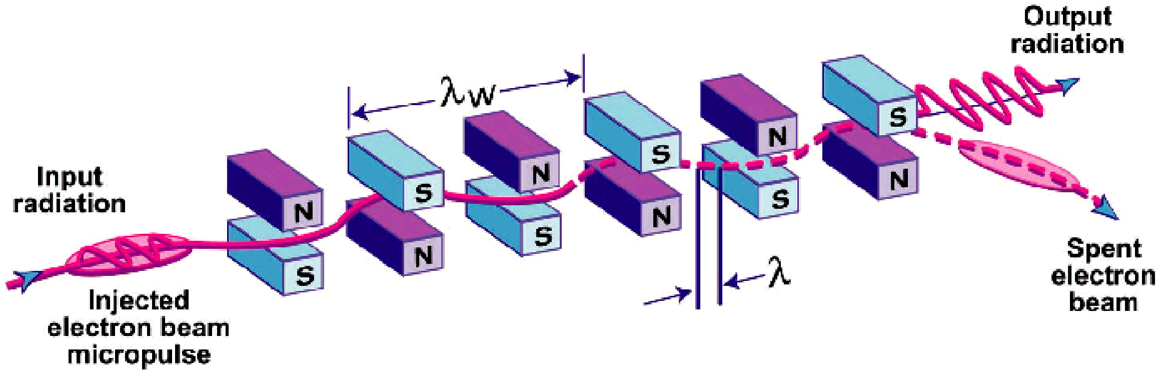
4세대 방사광가속기

4세대 방사광가속기 (X-ray Free Electron Laser)

미래기반 가속기
전문인력양성 사업단

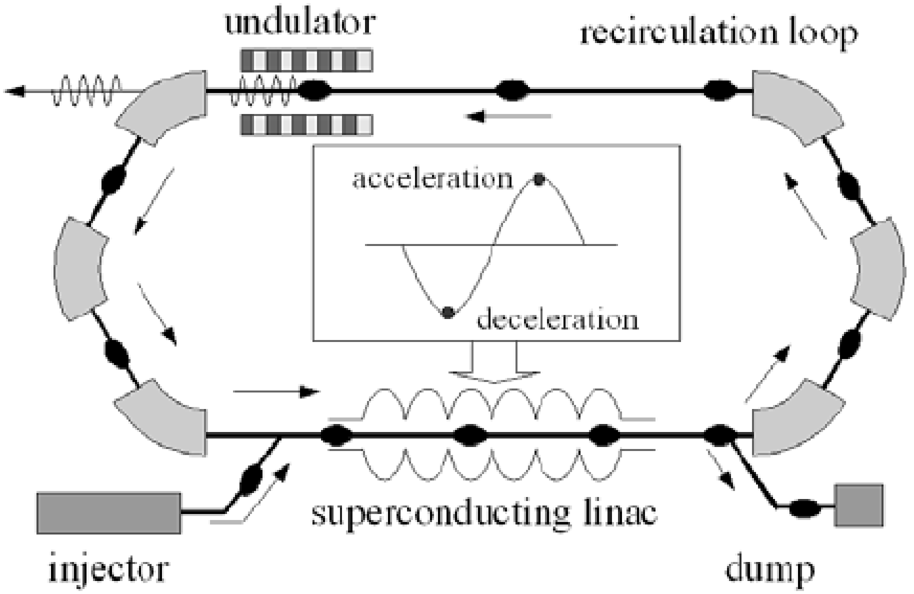
X-ray Free Electron Laser

성공적으로 완공되어 연구결과를 생성
LCLS, SCULA, PALXFEL, European XFEL, Swiss FEL

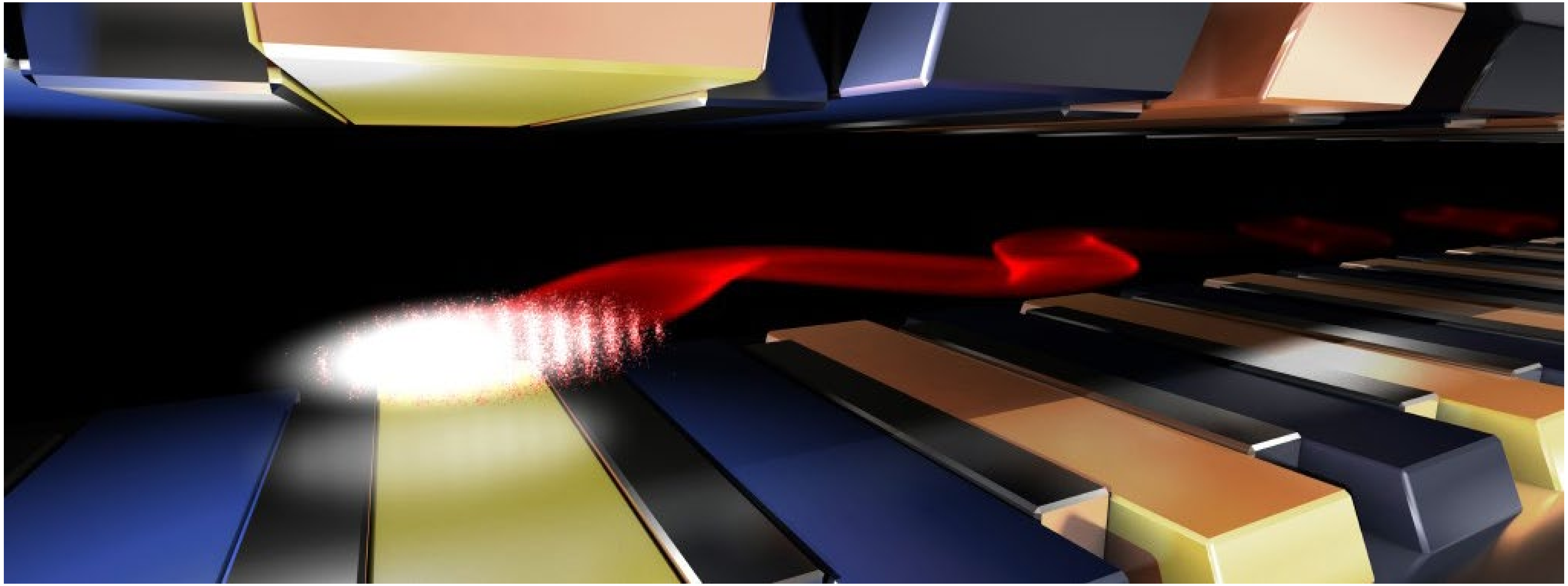

Output radiation
λw
N
S
S
N
N
S
S
N
N
S
S
N
Input radiation
Injected electron beam micropulse
λ
Spent electron beam

Energy Recovery Linac

현재까지 성공적인 방사광을 생성한 시설이 없음

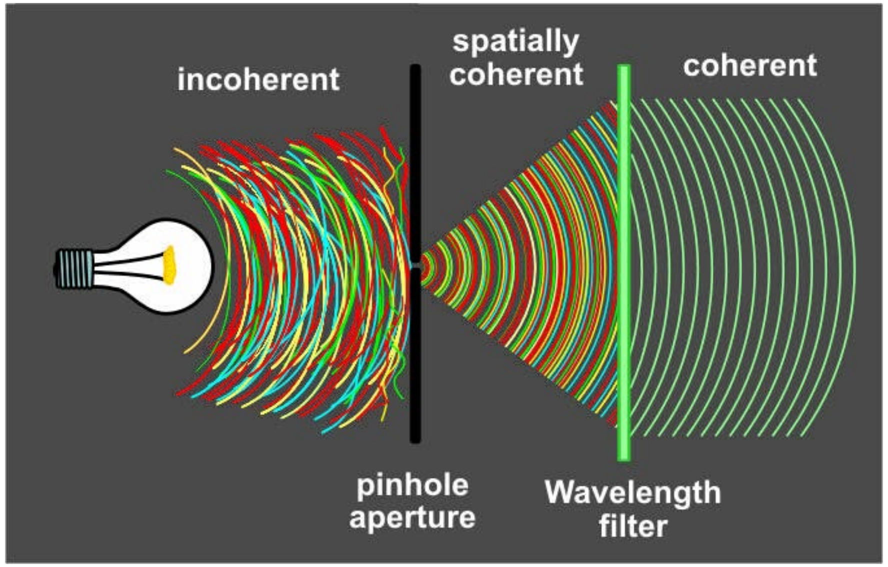

undulator
recirculation loop
acceleration
deceleration
superconducting linac
injector
dump

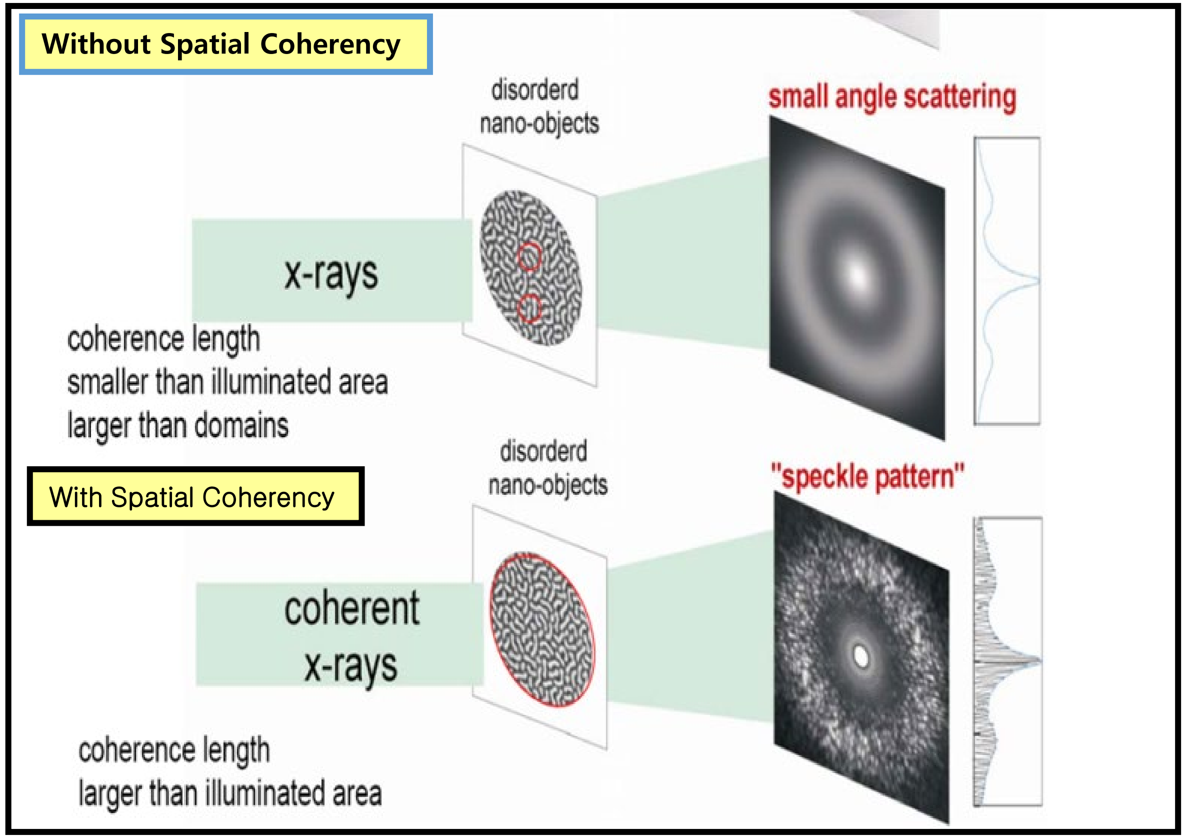
4세대 방사광가속기 (X-ray Free Electron Laser)

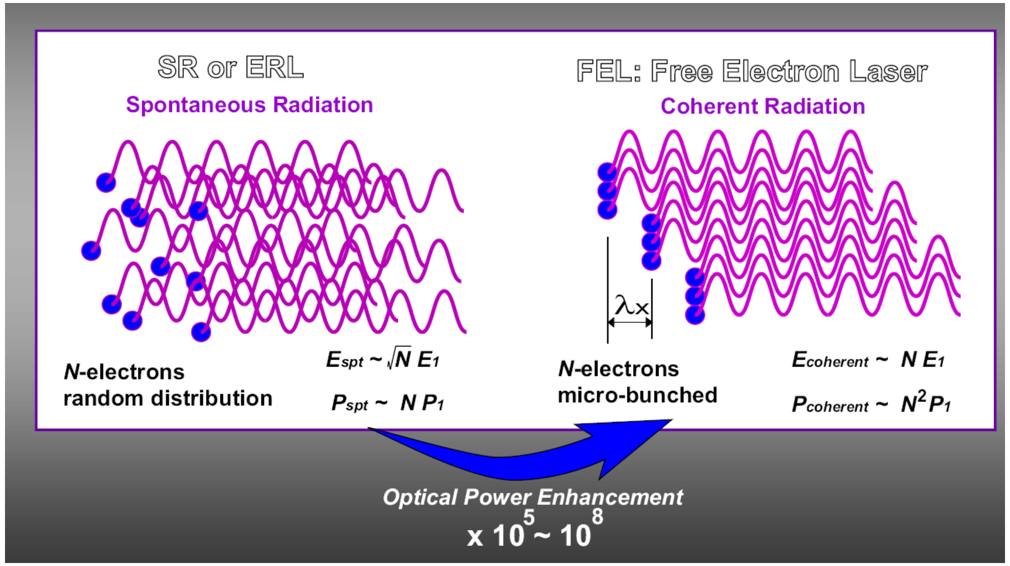


4세대 방사광가속기의 특징 (Ultra-fast, Ultra-small)

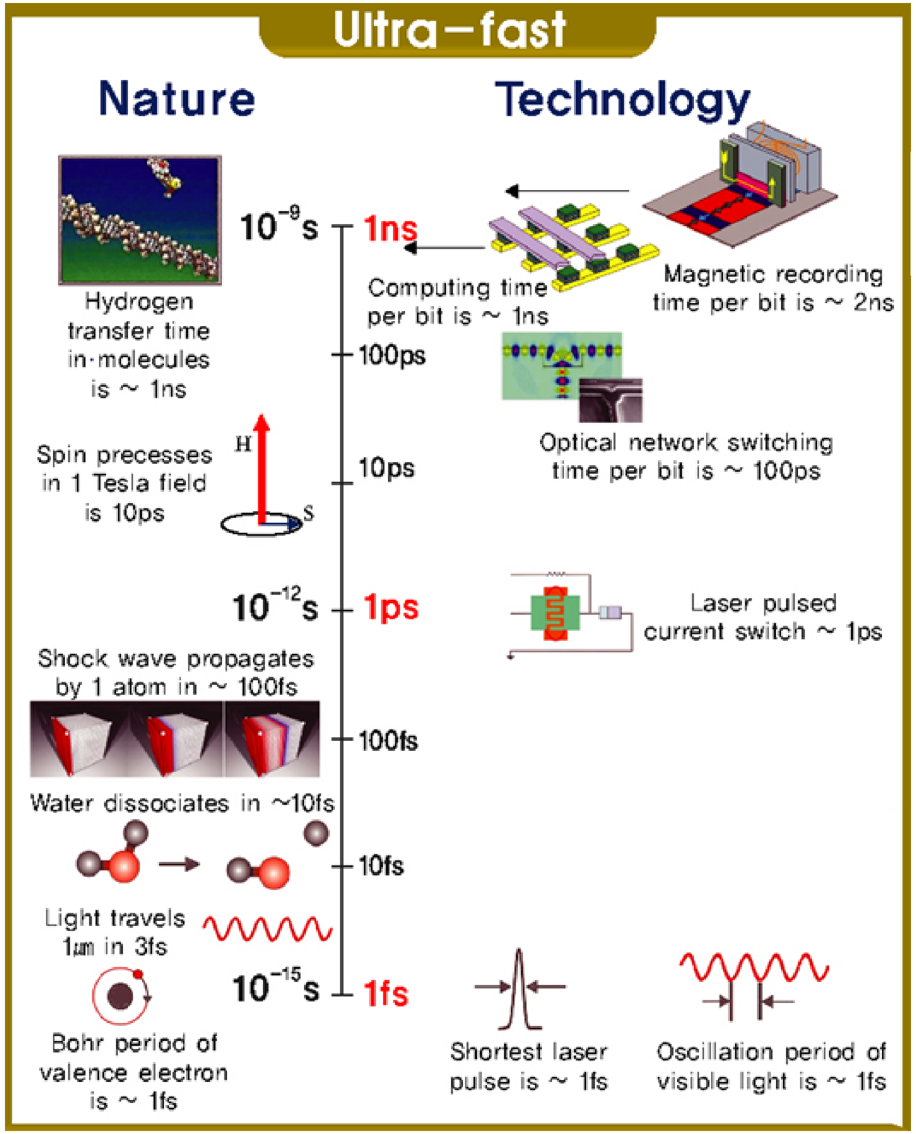
- 높은 공간 결맞음성
- 매우 짧은 길이 – 시간분해능 우수
- 매우 높은 밝기가 요구됨

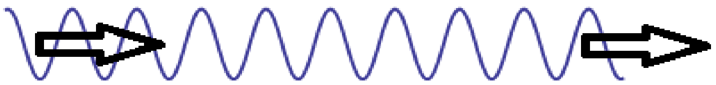

incoherent
spatially coherent
coherent
pinhole aperture
Wavelength filter


Without Spatial Coherency
disorderd nano-objects
small angle scattering
x-rays
coherence length
smaller than illuminated area
larger than domains
With Spatial Coherency
disorderd nano-objects
"speckle pattern"
coherent x-rays
coherence length
larger than illuminated area


SR or ERL
Spontaneous Radiation
FEL: Free Electron Laser
Coherent Radiation
λx
N-electrons random distribution
$E_{spt} \sim \sqrt{N}\, E_1$
$P_{spt} \sim N P_1$
N-electrons micro-bunched
$E_{coherent} \sim N E_1$
$P_{coherent} \sim N^2 P_1$
Optical Power Enhancement
$\times 10^5 \sim 10^8$

4세대 방사광가속기의 특징 (Ultra-fast, Ultra-small)


Ultra−fast
Nature
Technology
10^{-9}s
1ns
Hydrogen transfer time in·molecules is ~ 1ns
Computing time per bit is ~ 1ns
Magnetic recording time per bit is ~ 2ns
100ps
Optical network switching time per bit is ~ 100ps
Spin precesses in 1 Tesla field is 10ps
H
S
10ps
10^{-12}s
1ps
Laser pulsed current switch ~ 1ps
Shock wave propagates by 1 atom in ~ 100fs
100fs
Water dissociates in ~10fs
10fs
Light travels 1㎛ in 3fs
10^{-15}s
1fs
Bohr period of valence electron is ~ 1fs
Shortest laser pulse is ~ 1fs
Oscillation period of visible light is ~ 1fs

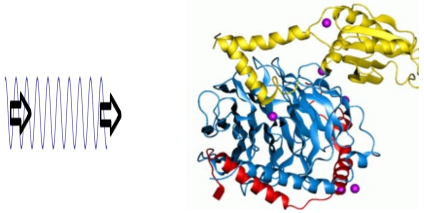


Photon Wave Train이 매우 짧은 빛을 이용하면 결과가 어떻게 달라질까요?

rayonix
MX325

평균영상이 아닌 단독영상을 갖겠지만 적은 광량의 인해 흐린 영상이 나타나겠지요

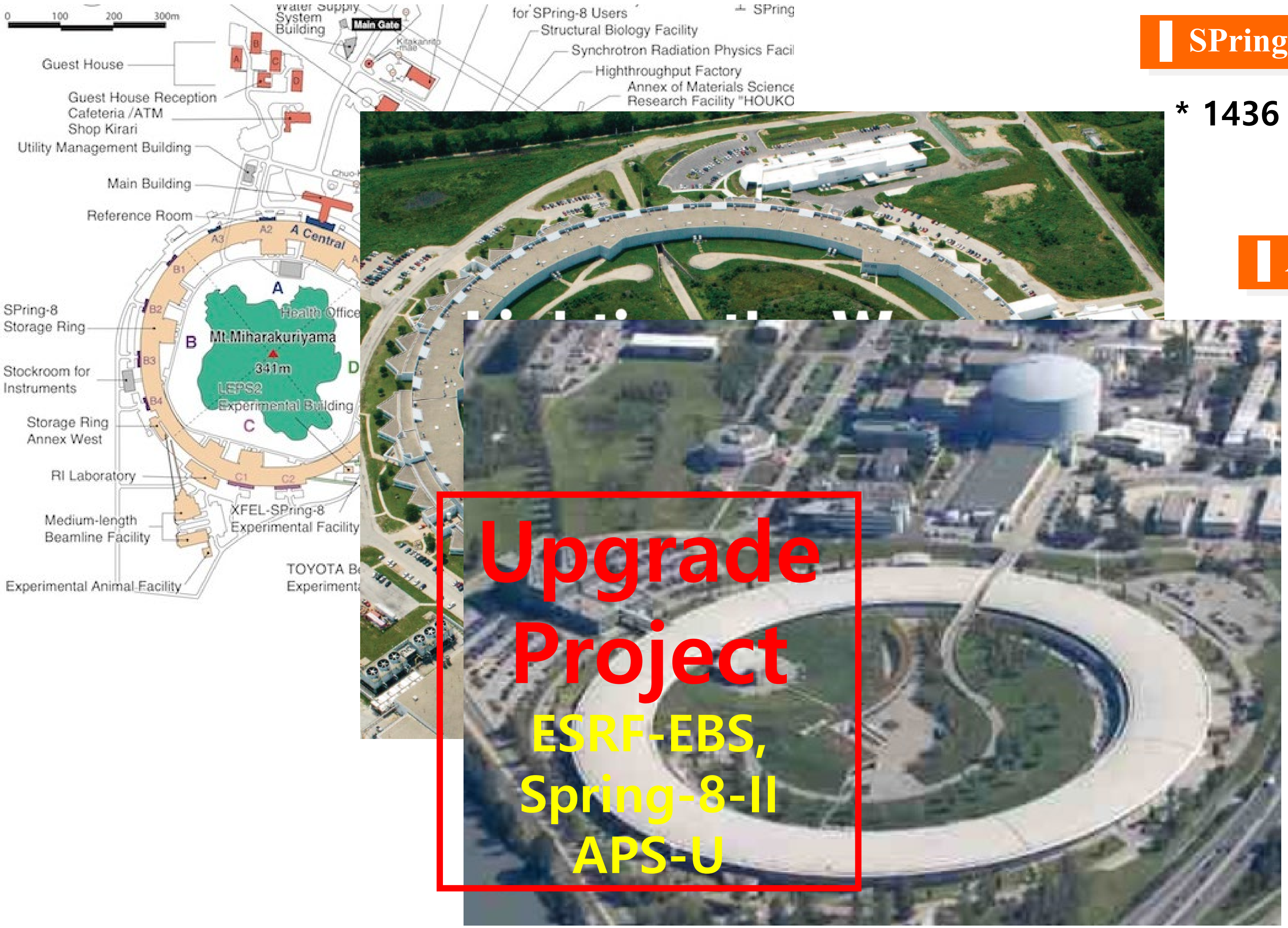
그럼 매우 짧고, 매우 강한 빛을 사용하면 어떻게 될까요?



5

4GSR
(4th Generation Storage Ring)

3 Brothers, 7 Sisters의 변신


0
100
200
300m
Water Supply
System
Building
Main Gate
for SPring-8 Users
SPring
Structural Biology Facility
Synchrotron Radiation Physics Facil
Highthroughput Factory
Annex of Materials Science
Research Facility "HOUKO
Guest House
Guest House Reception
Cafeteria /ATM
Shop Kirari
Utility Management Building
Main Building
Reference Room
A Central
SPring-8
Storage Ring
Stockroom for
Instruments
Storage Ring
Annex West
RI Laboratory
Medium-length
Beamline Facility
Experimental Animal Facility
XFEL-SPring-8
Experimental Facility
TOYOTA B
Experiment
Health Office
Mt.Miharakuriyama
341m
LEPS2
Experimental Building
A
B
C
D
A2
A3
B1
B2
B3
B4
C1
C2

Upgrade Project

ESRF-EBS,
Spring-8-II
APS-U

SPring-8 (8 GeV)

* 1436 m (1997년)

Advanced Photon Source (7 GeV)

* 1104 m (1996년)

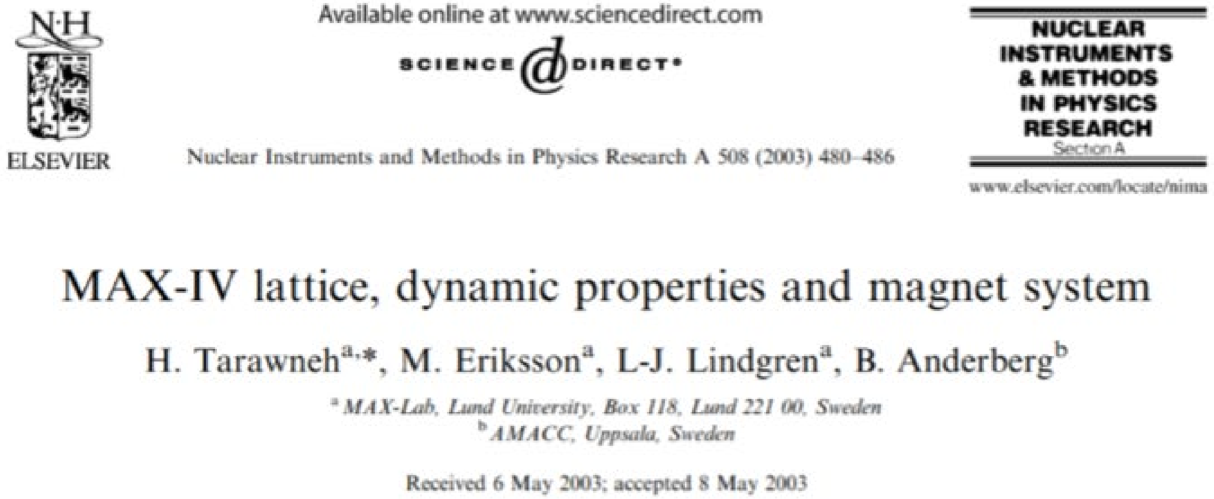
ESRF (6 GeV)

* 844 m (1994년)

저장링(SR)을 이용한 방사광의 새로운 가능성

- 첫번째 개념 논문은 1993년에 발간되었고, 2003년 MAX-IV가 설계되고 2016년 6월 실현됨

MAX-IV - Sweden



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Nuclear Instruments and Methods in Physics Research A 508 (2003) 480–486

NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH

Section A

www.elsevier.com/locate/nima

MAX-IV lattice, dynamic properties and magnet system

H. Tarawneh[a],*, M. Eriksson[a], L-J. Lindgren[a], B. Anderberg[b]

[a] MAX-Lab, Lund University, Box 118, Lund 221 00, Sweden

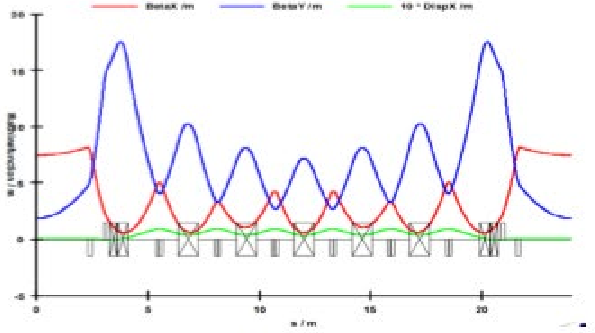
[b] AMACC, Uppsala, Sweden

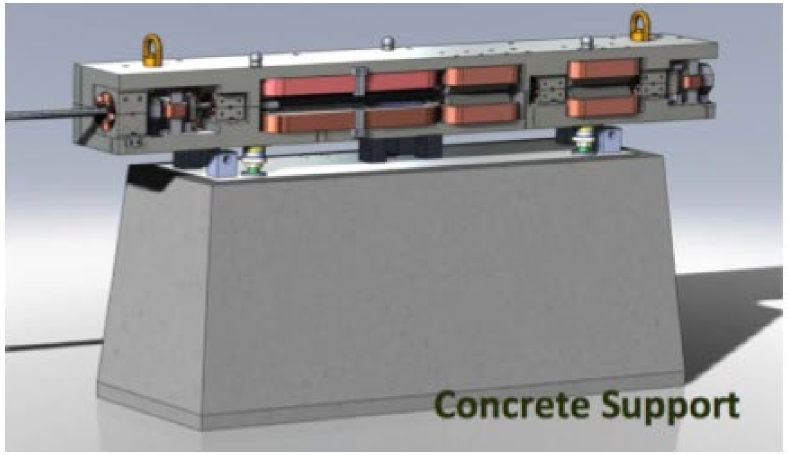
Received 6 May 2003; accepted 8 May 2003

2003: 3 GeV, 528 m

330 pm

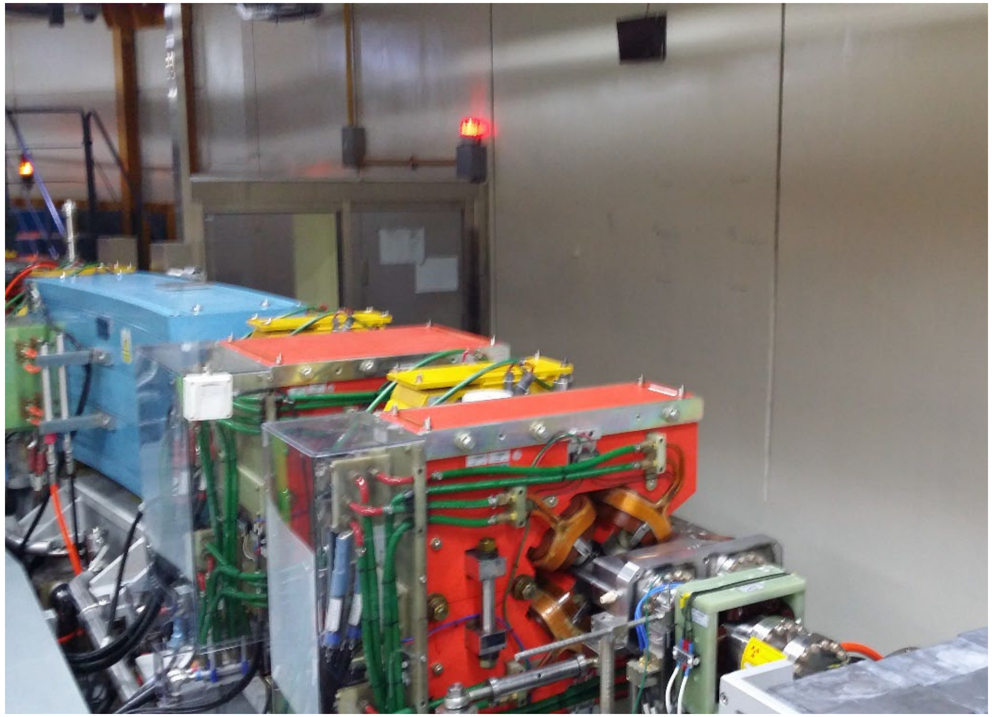
7BA





방사광가속기(4GSR)의 Lattice 변경

- DBA/TBA (Double/Tripple) Lattice에서 MBA (Multi-Bend Achromatic) 로
- Off-axis injection에서 on-axis injection



차세대 방사광가속기의 정의 (4세대 SR?)

USR

- The term “ultimate storage ring” was first use in 2000:

  A. Ropert, J.M. Filhol, P. Elleaume, L. Farvacque, L. Hardy, J. Jacob, U. Weinrich, **"Towards the Ultimate Storage Ring-Based Light Source"**, Proc. EPAC 2000, Vienna.
- “Ultimate” may have many meanings, including providing everything for every user

Robert Hettel
APSU Project director

DLSR

- Diffraction limited storage ring
- All storage rings are diffraction limited for some λ

$$\varepsilon_r(\lambda) = \frac{\lambda}{4\pi}$$

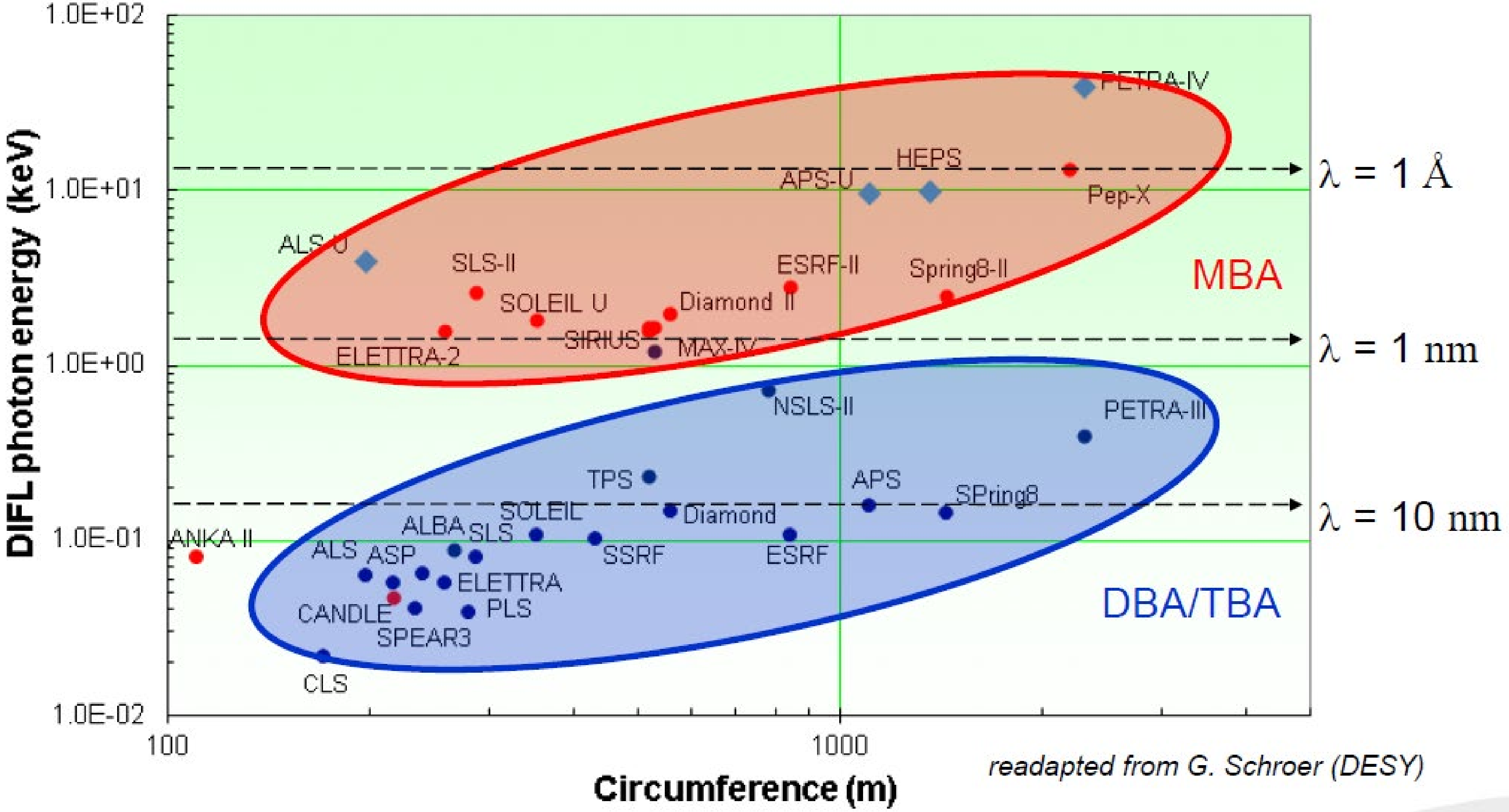
4GSR

- 4th generation storage ring

● **XFEL을 4세대 방사광가속기라고 명명한 것은 부적절했던 것이고 1세대 XFEL이 적합하다.**

Diffraction Limited Light Source

- **Single Photon Diffraction – 이용할 수 있는 X선 회절 현상의 한계가 있음**



readapted from G. Schroer (DESY)

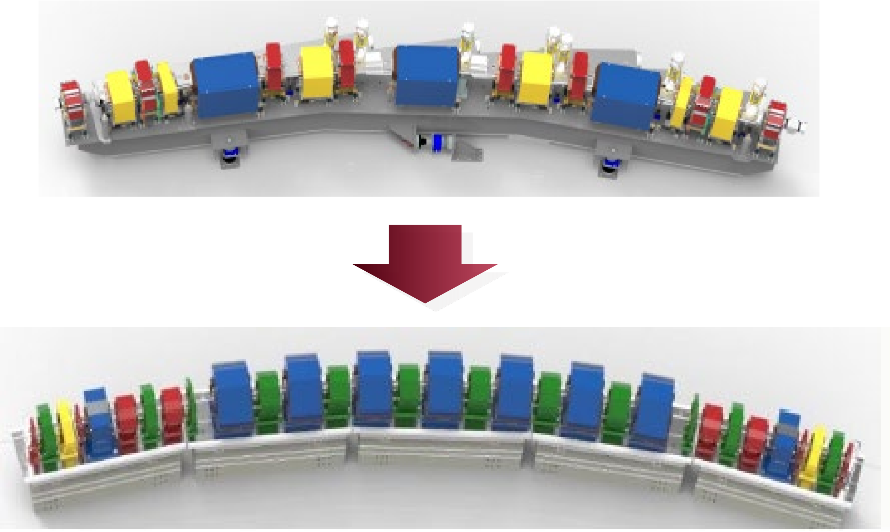
Courtesy R. Bartolini

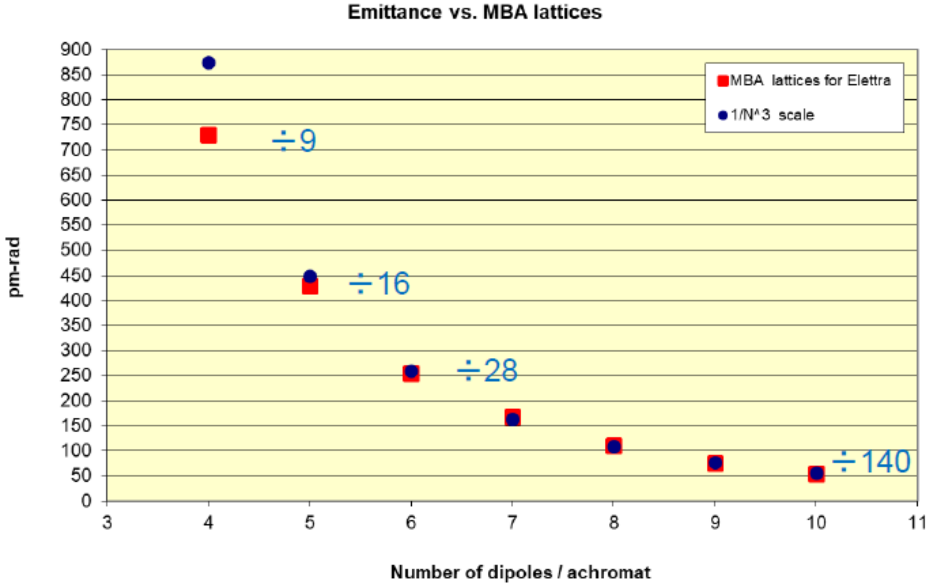
차세대 방사광가속기(4GSR)의 특징

- Higher Brilliance → Smaller emittance
- Higher transverse coherence
- Smaller photon beam size
- Smaller photon beam divergence
- Cleaner spectral flux
- Additionally, Shorter electron pulses (Time resolved) & Round Beam

XFEL정도는 안되지만 예리한 탐침(분석도구)를 만들자

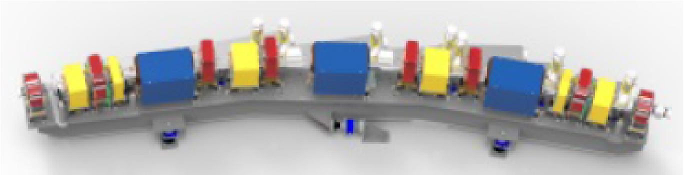
XFEL의 활용 한계 (제한된 빔라인수)의 보완 책으로!

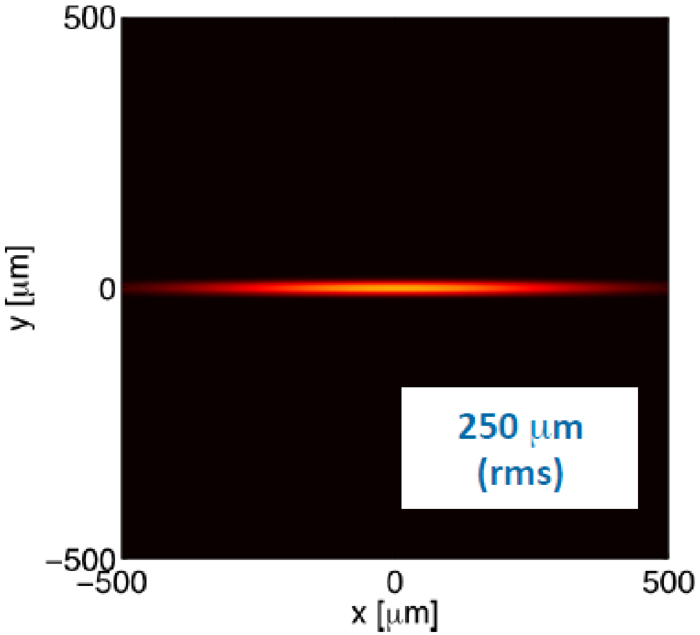




차세대 방사광가속기(4GSR)의 특징

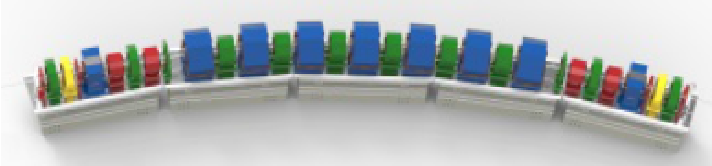
Advanced Light Source
(Triple Bend Achromat)

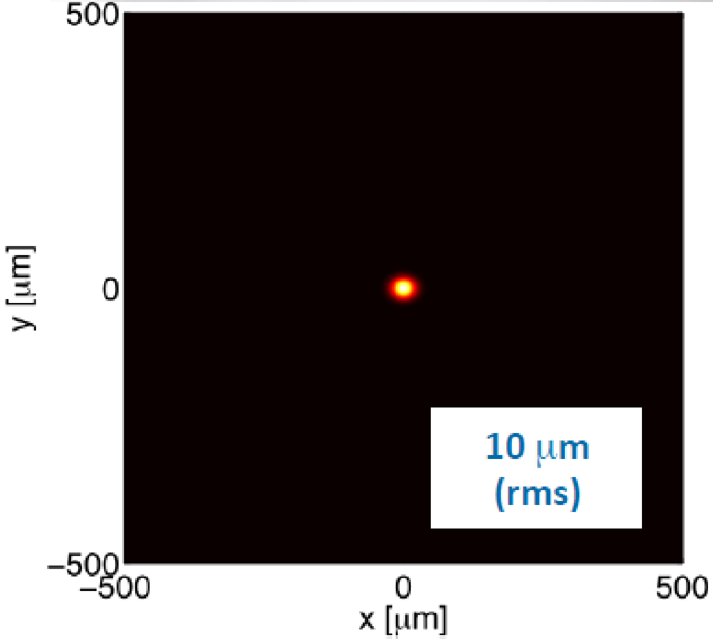




Study mostly *simply organized*, *homogenous*, and *static* materials

Advanced Light Source Upgrade
(Multi-Bend Achromat)

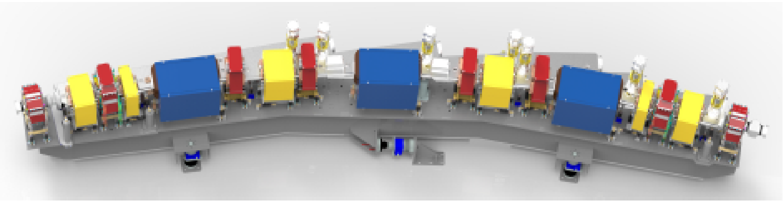


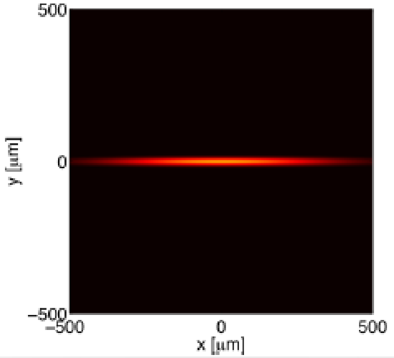


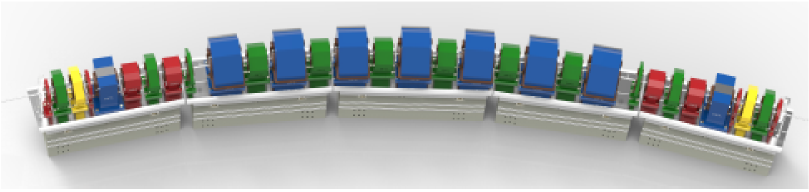
Study more *complex* materials under *dynamic* conditions

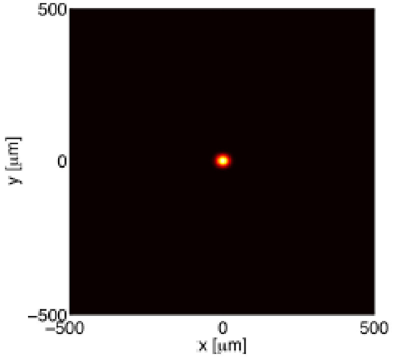
Courtesy of D. Robin

차세대 방사광가속기(4GSR)의 특징 (향상된 변수들)





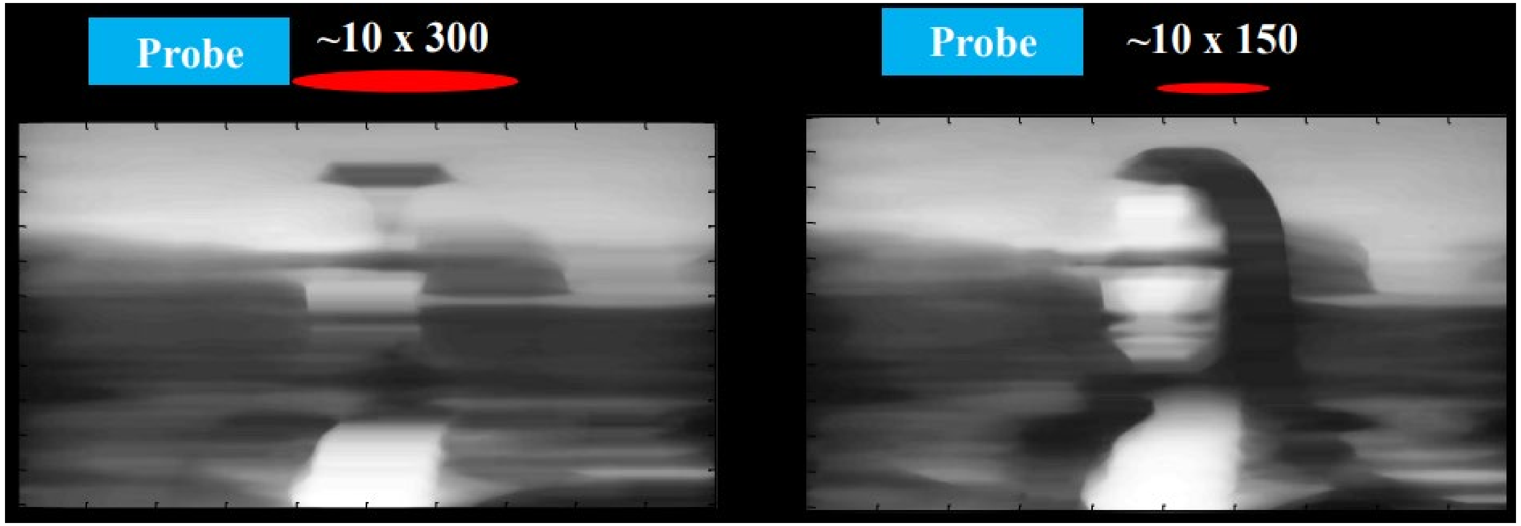


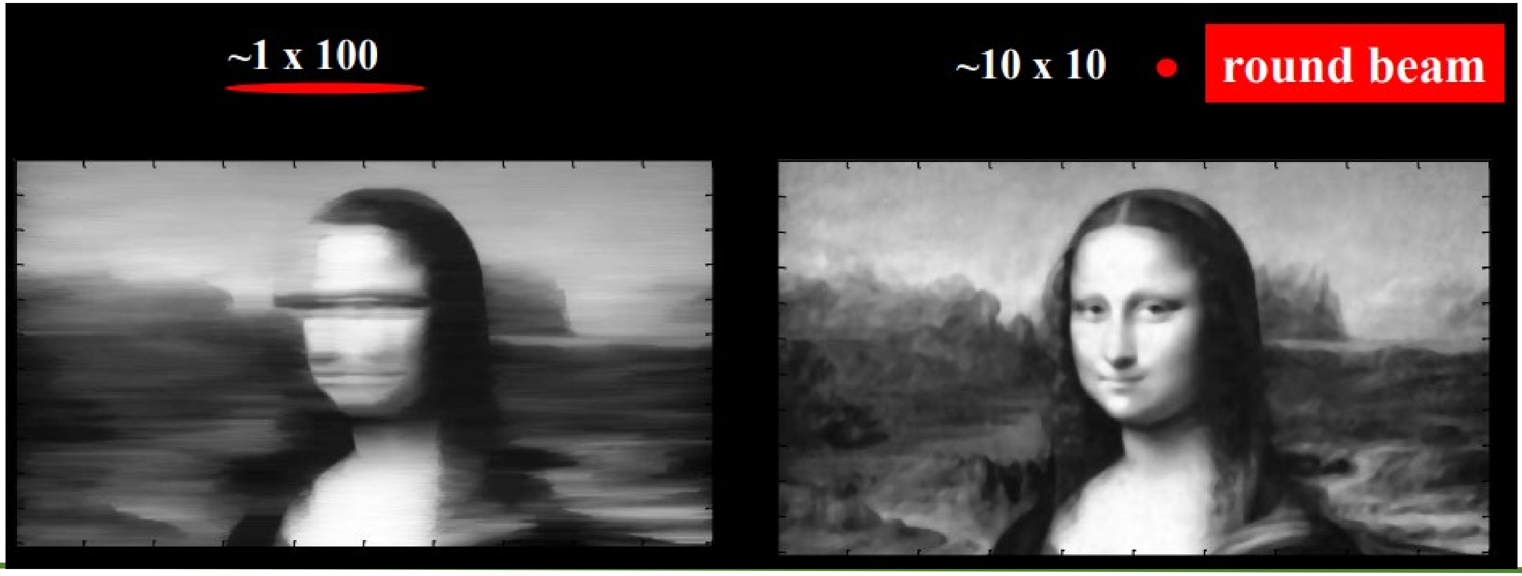


Parameter	Units	ALS	ALS-U
Electron energy	GeV	1.9	2.0
Horiz. emittance	pm	2000	<70
Vert. emittance	pm	30	<70
Beamsize @ ID center (σ_x/σ_y)	mm	251 / 9	<10 / <10
Beamsize @ bend (σ_x/σ_y)	mm	40 / 7	<5 / <7
bunch length (FWHM)	ps	60-70 (harmonic cavity)	120-200 (harmonic cavity)
RF frequency	MHz	500	500
Circumference	m	196.8	~196.5

Courtesy of D. Robin

Round beam의 효과 (Total Flux가 동일하면)


Probe
~10 x 300
Probe
~10 x 150


~1 x 100
~10 x 10
round beam

- 3세대 방사광 가속기도 collimator를 이용해서 round beam을 만듬.
- 따라서 선량이 낮음

Courtesy of A. Somogyi

차세대 방사광가속기(4GSR)의 주요기술

- 이극자석이 매우 높은 자기장기울기를 갖도록 궤도구조를 최대한 작게 만들어야 하고 동시에 매우 센 4극자석도 필요
- 이극자석의 수가(N_d) 증가하면 6극자석의 자력도 증가해야 함
- 에미턴스(Emittance)를 줄이기 위해 조정하면 Dispersion은 작아지고 Chromaticity는 증가해서 더 강력한 6극자석이 요구됨
- 궤도구조(Lattice)가 오차에 매우 민감하게 됨 (자기장이나 정렬문제)
- 각 자석간의 공간이 너무 협소해짐
- 효과적인 자석구조를 위해서 진공용기의 반경이 매우 작아져야만 함
- 이극자석의 수가 증가하면서 이극자석에서 발생되는 불필요하지만 매우 강력한 방사광이 문제를 일으킬 수 있음

◆ 궤도 설계는 상대적으로 작은 부분이고, 이 시설을 현실화 시키는 공학적 노력이 많이 요구됨

생활속의 비전리 방사선

개요

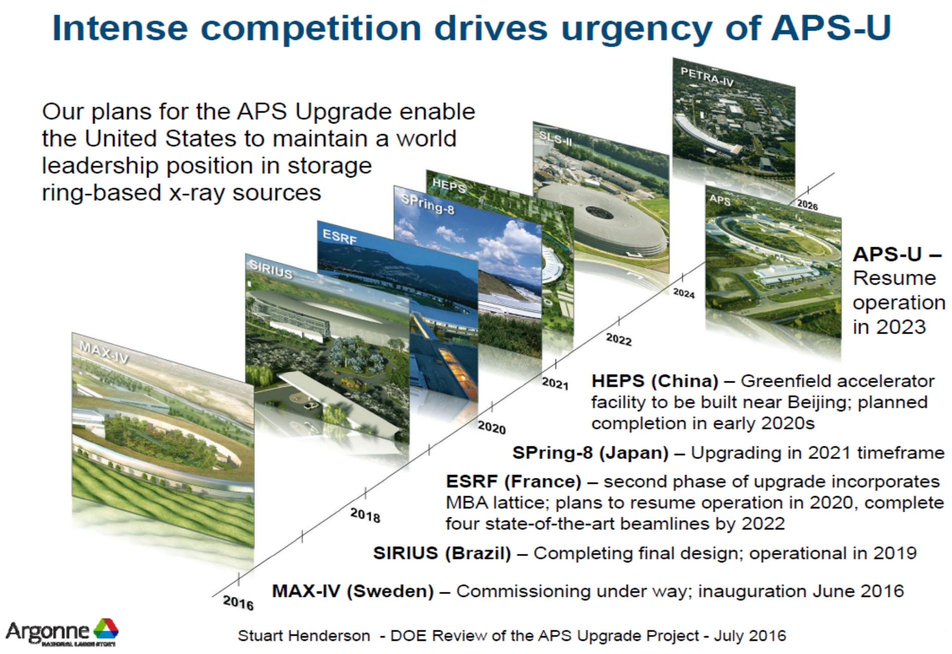
■ **차세대 4GSR : 4세대 원형 방사광가속기(4th Generation Storage Ring)**

- 기존 3세대 방사광가속기 대비 밝기를 약 100배 개선한 차세대 방사광가속기 (Multi Bend Achromat Lattice)

주요특징

- 저장링 내부 전자석 증가, 빔 집중도를 기존 대비 약 100배 향상
- 우수한 성질(결맞음)의 방사광 생성, 3세대 방사광가속기보다 미시세계 관찰 가능

연구동향



Intense competition drives urgency of APS-U

Our plans for the APS Upgrade enable the United States to maintain a world leadership position in storage ring-based x-ray sources

APS-U – Resume operation in 2023

HEPS (China) – Greenfield accelerator facility to be built near Beijing; planned completion in early 2020s

SPring-8 (Japan) – Upgrading in 2021 timeframe

ESRF (France) – second phase of upgrade incorporates MBA lattice; plans to resume operation in 2020, complete four state-of-the-art beamlines by 2022

SIRIUS (Brazil) – Completing final design; operational in 2019

MAX-IV (Sweden) – Commissioning under way; inauguration June 2016

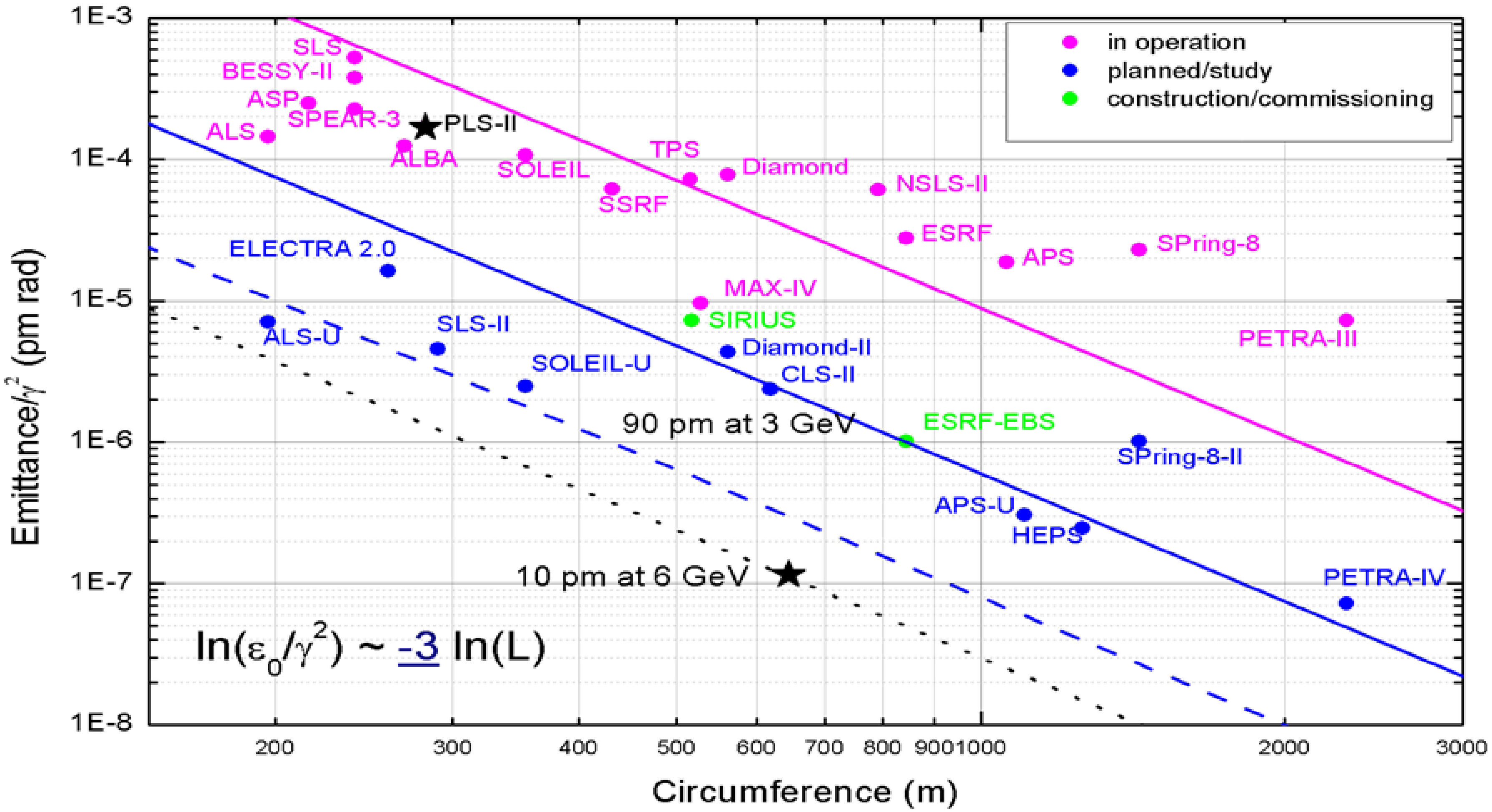
Stuart Henderson - DOE Review of the APS Upgrade Project - July 2016

가속기명	현황('24 기준)	비고
MAX-IV(스웨덴)	가동 중('16)	신축
SIRIUS(브라질)	가동중	신축
ESRF-EBS(유럽연합)	가동중	개선
SPring-8 II(일본)	추진 중	개선
HEPS(중국)	시운전중 (~'25)	신축
APS-U(미국)	가동중	개선
ALS-U(미국)	승인	개선
SLS-II(스위스)	승인	개선
PETRA-IV(독일)	추진 중	개선
Diamond-II(영국)	추진 중	개선
SOLEIL II(프랑스)	추진 중	개선
ELETTRA 2.0	추진 중	개선

출처 : Argonne(美, 2016)

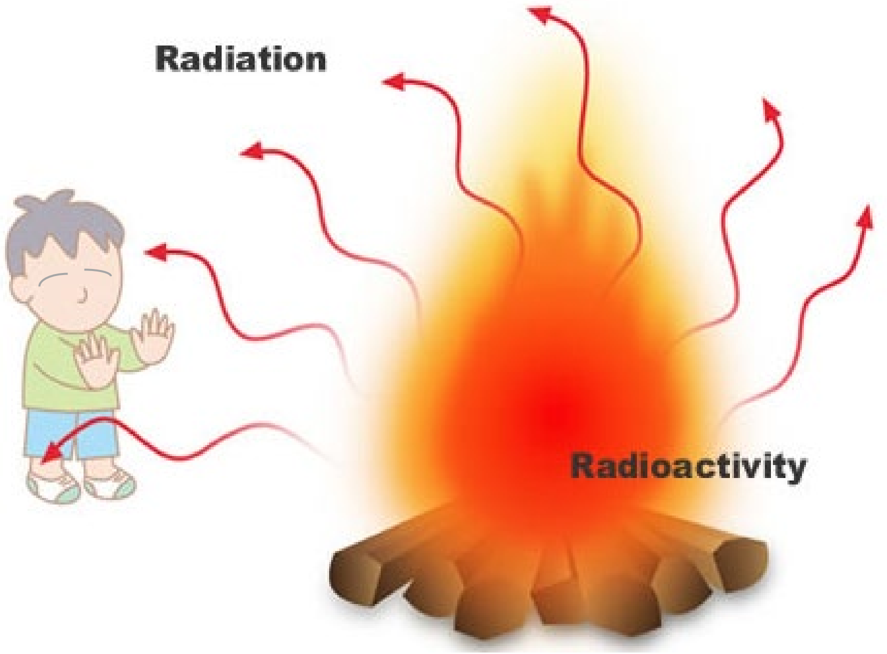
차세대 방사광가속기(4GSR)의 개념 정리

세계 3세대 및 4세대 방사광가속기(4GSR) 성능비교



6

방사선


Radiation
Radioactivity

방사선이란?

- **방사선(Radiation)은 에너지의 흐름이다**
  - ✓ 물질을 전리시키는 입자선(n, p, d, β, α,..) 또는 전자파(X선, 감마선)
  - ✓ 일반적으로 **전리방사선**을 말함

- **원자력안전법 시행령 제6조**

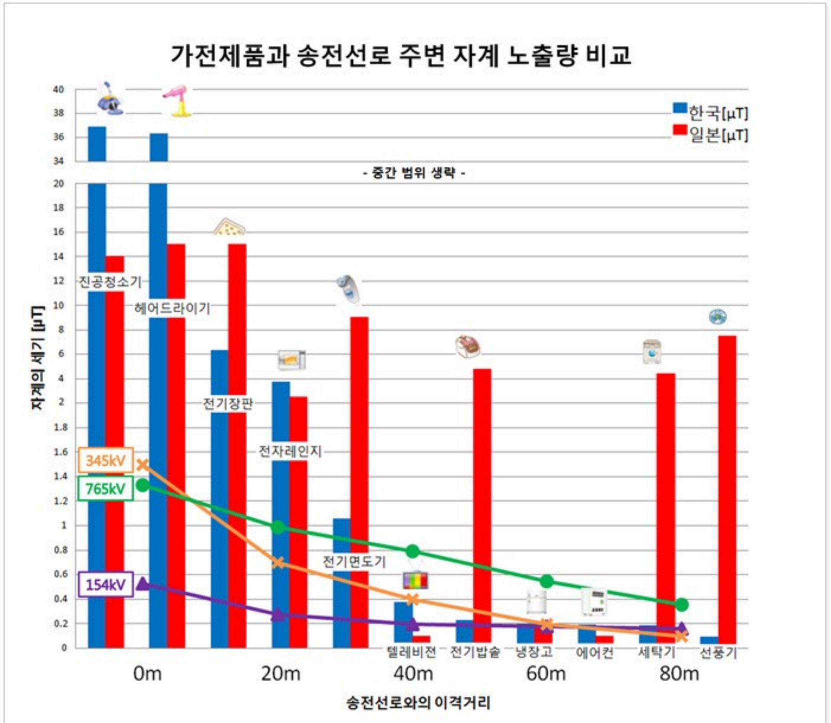
"알파선·중양자선·양자선·베타선 기타 중하전입자선, 중성자선, 감마선 및 엑스선, 5만 전자볼트 이상의 에너지를 가진 전자선"

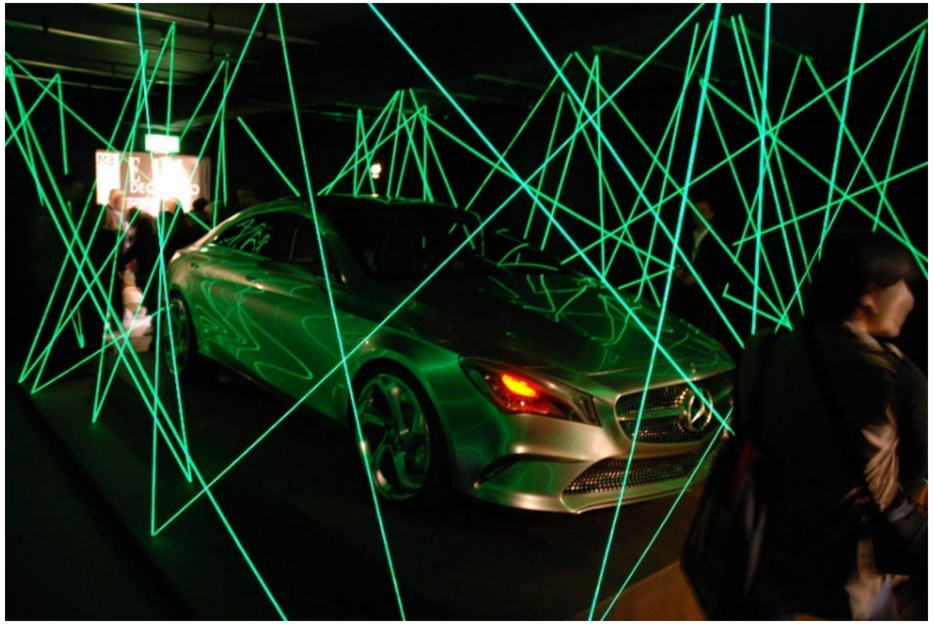
- 미국 NRC **10CFR20 (Standards for Protection against Radiation)**

"Radiation means alpha particles, beta particles, gamma rays, X-rays, neutrons, high-speed electrons, high-speed protons, other atomic particles capable of producing ion. Radiation, as used in this regulation, does not include non-ionizing radiation, such as radio- or microwaves, or visible, infrared, or ultraviolet light."

차세대 방사광가속기(4GSR)의 개념 정리

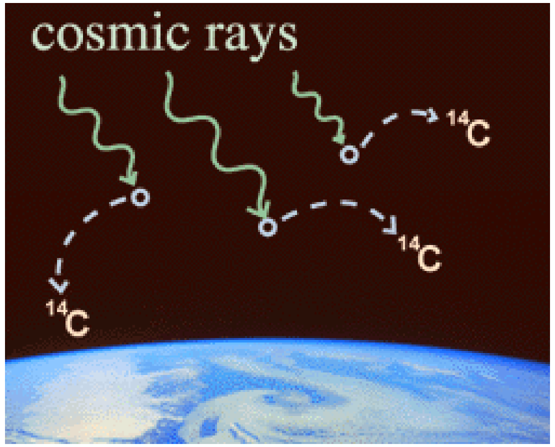
12:00
SAMSUNG



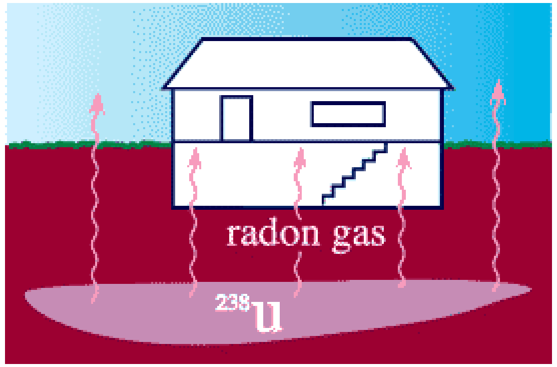


자연방사선의 이해

- 우주방사선 (Cosmic rays)
  (양성자,중성자, 전자, 알파선, 뮤온..)
- 우주선에 의해 생성되는 이차방사선 (^{14}C, ^{7}Be, ^{3}H)


cosmic rays
^{14}C
^{14}C
^{14}C

- 지구상의 방사선
  (U, Th, Ra, Rn ...)
- 인체내의 방사선: ^{40}K


radon gas
^{238}U

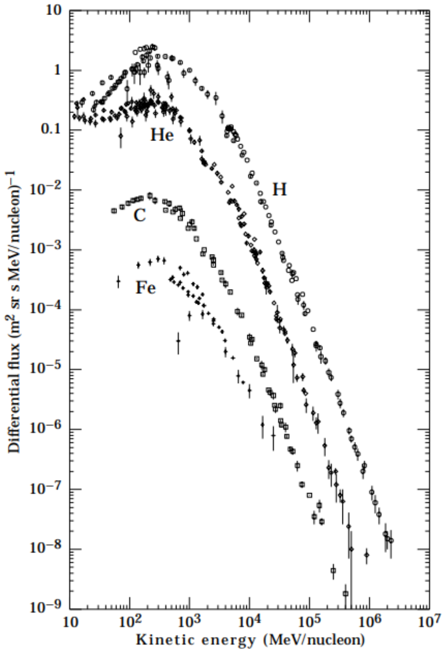
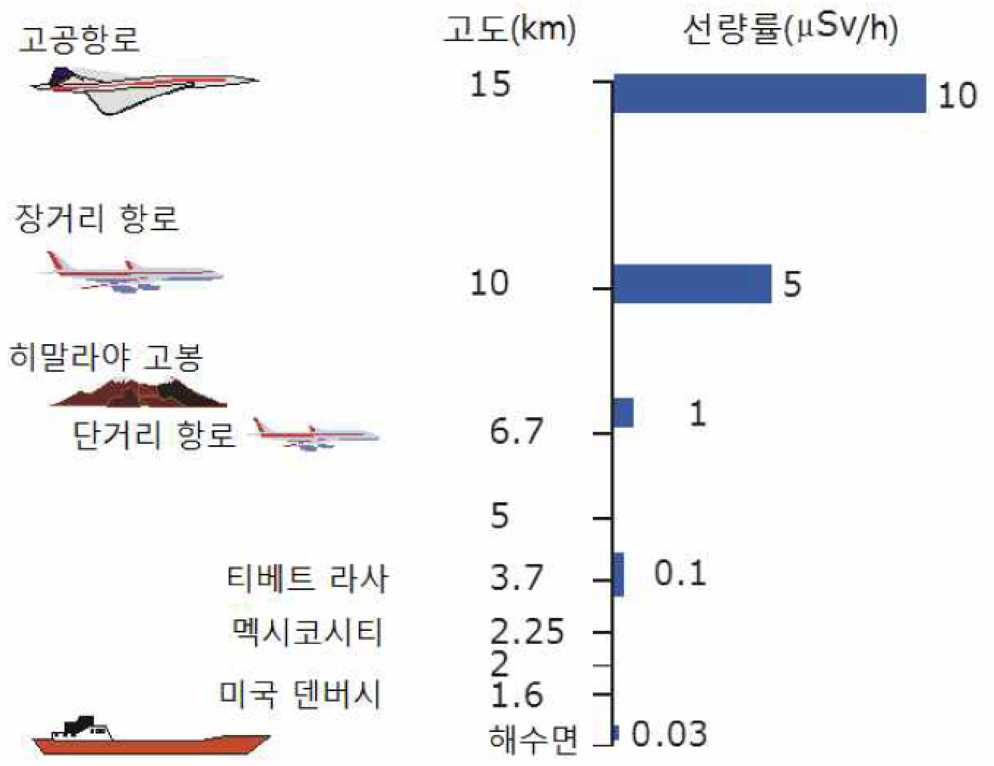


Figure 1: Major components of the primary cosmic rays (from Simpson).

우주방사선

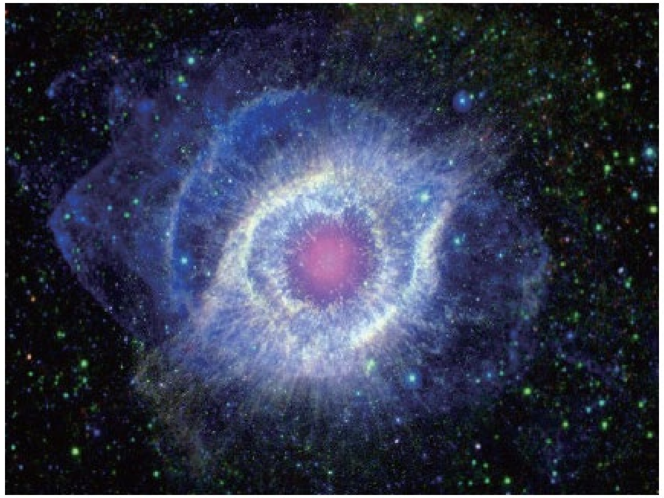
고도에 따른 전형적 우주방사선량률



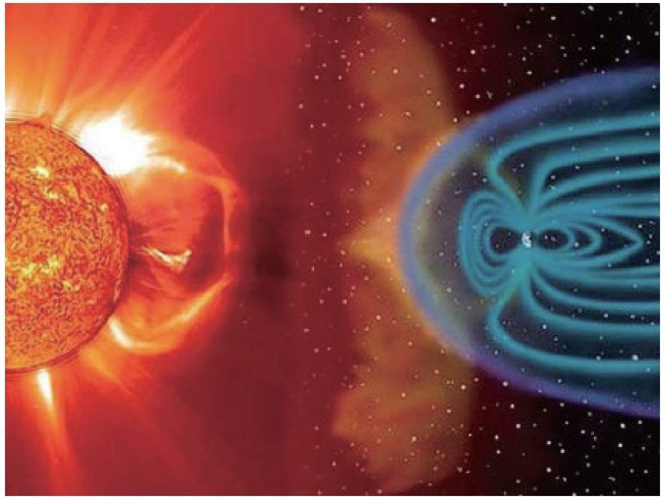
<역주> 고도에 따른 우주방사선 선량률 변화(중위도, 전형적 태양활동 기준). 보편적 장거리 항로인 지상 10~12 km에서는 시간 당 5 μSv 정도를 피폭한다. 고도가 낮은(7 km 내외) 단거리 비행은 선량률도 현저히 낮고 비행시간도 짧아 우주방사선 피폭이 관심사가 아니다.

From ICRP 132

[Galactic Cosmic Ray]



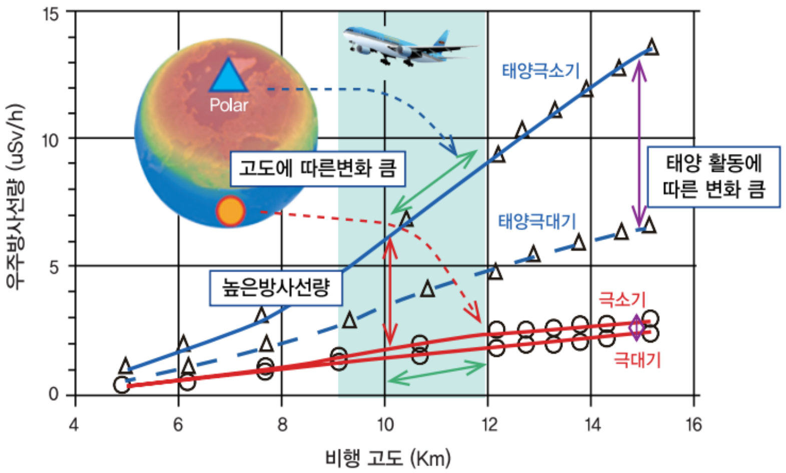
[Solar Energetic Particle]

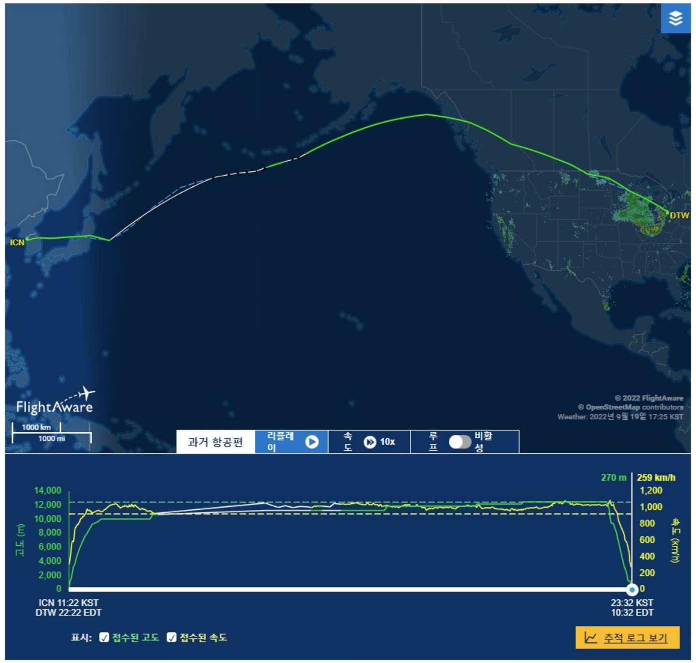


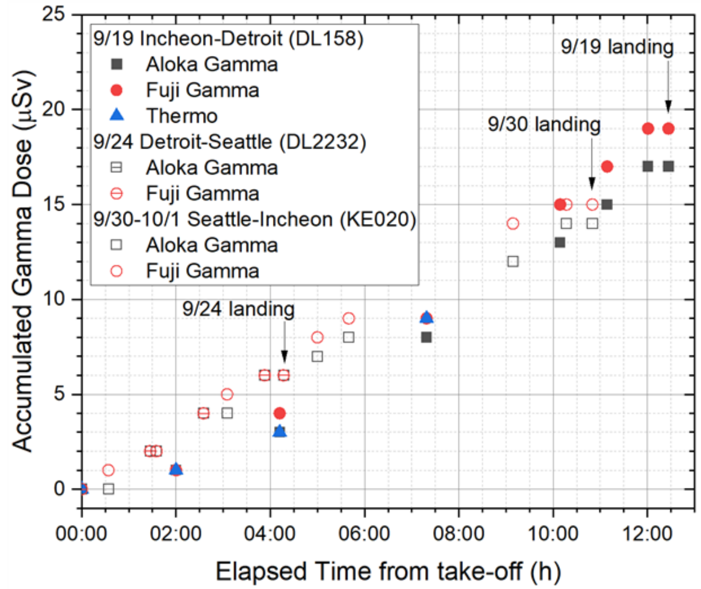
지구를 향해 날라오는 태양풍의 정체는?

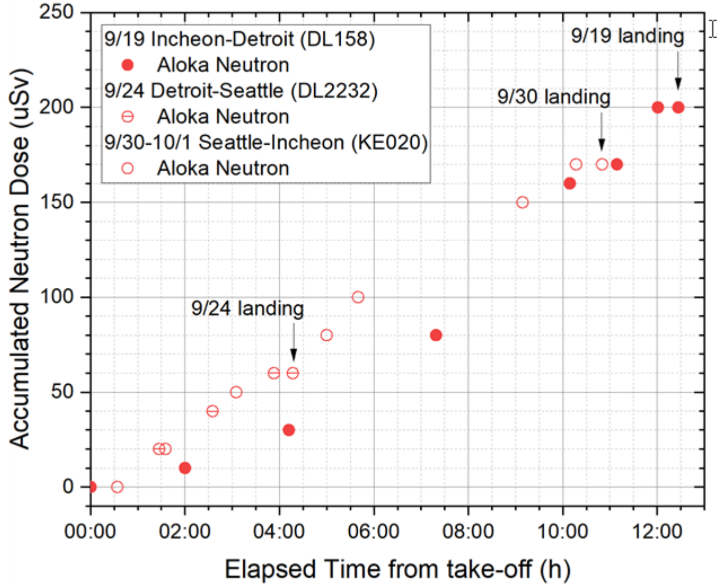
우주방사선

[우주방사선 특징]

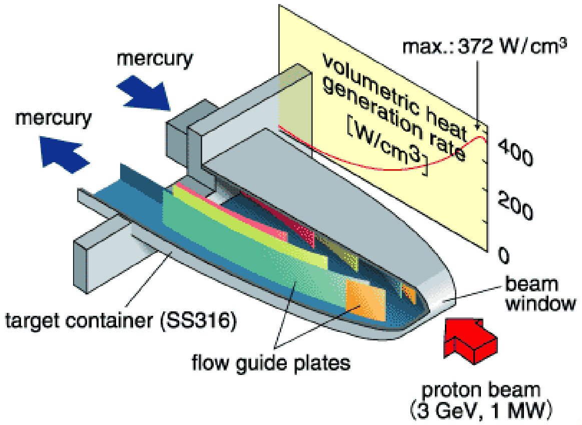



ICN
DTW
FlightAware
1000 km
1000 mi
© 2022 FlightAware
© OpenStreetMap contributors
Weather: 2022년 9월 19일 17:25 KST
과거 항공편
리플레이
속도
10x
루프
비활성
270 m
259 km/h
14,000
12,000
10,000
8,000
6,000
4,000
2,000
0
고도 (m)
1,200
1,000
800
600
400
200
0
속도 (km/h)
ICN 11:22 KST
DTW 22:22 EDT
23:32 KST
10:32 EDT
표시:
☑ 접수된 고도
☑ 접수된 속도
추적 로그 보기





입자가속기를 이용한 중성자원

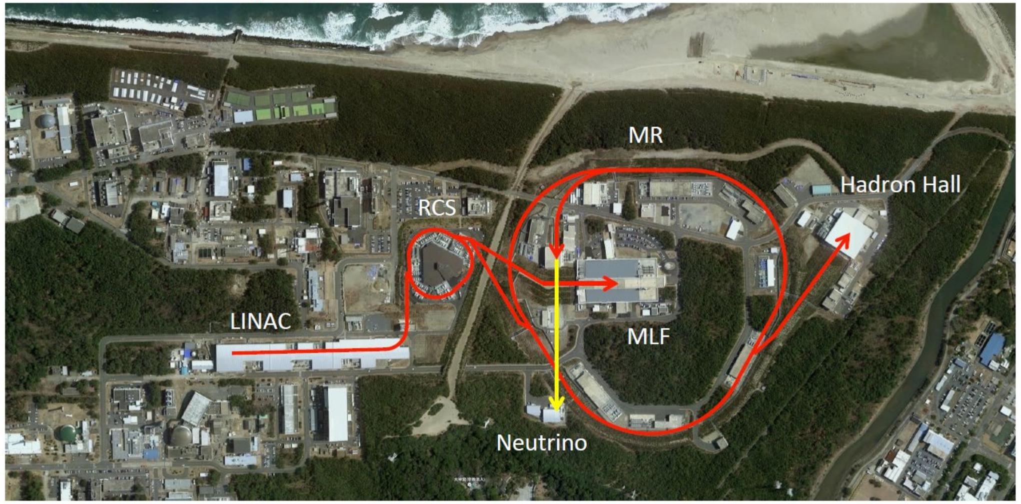

mercury
mercury
max.: 372 W/cm³
volumetric heat generation rate [W/cm3]
400
200
0
beam window
target container (SS316)
flow guide plates
proton beam (3 GeV, 1 MW)

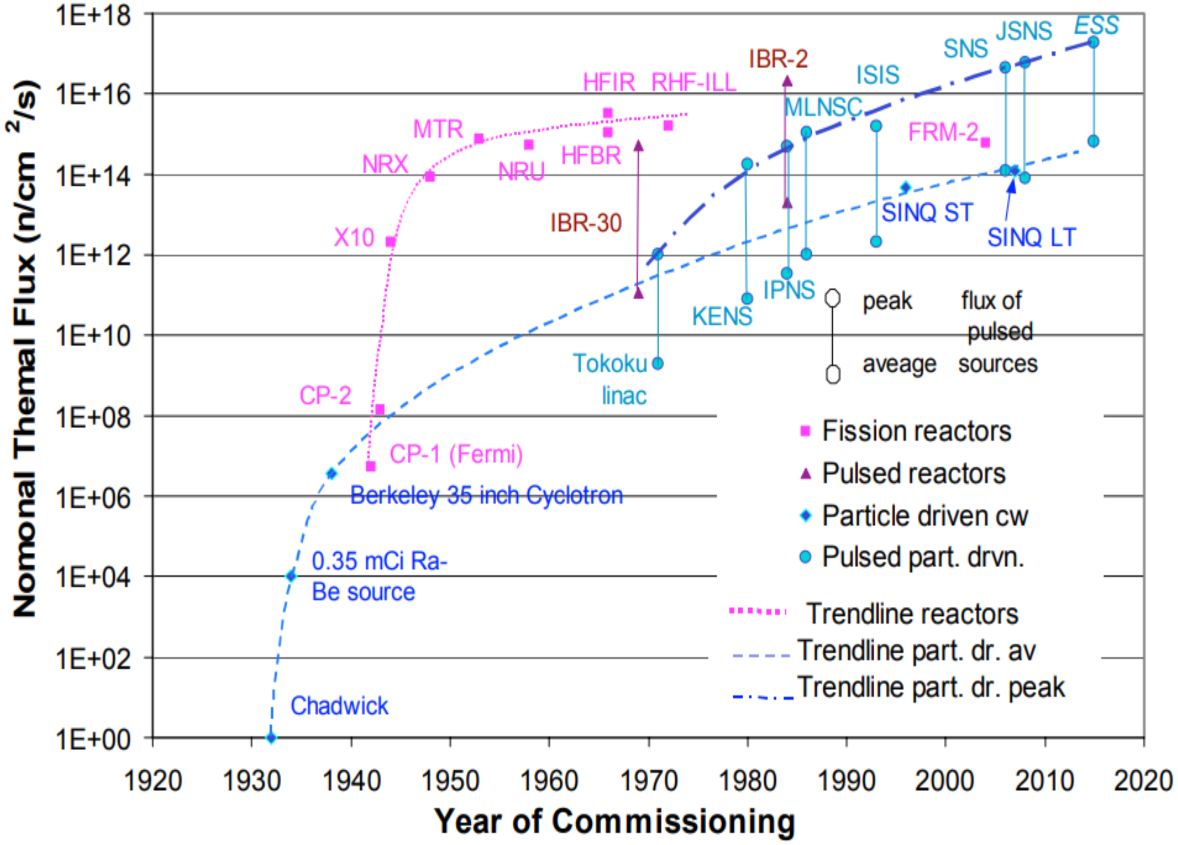
Japan Proton Accelerator Research Complex (J-PARC)

- High Intensity Proton Accelerators
- Facilities to use the secondary beams
- Operated by Japan Atomic Energy Agency (JAEA) and High Energy Accelerator Research Organization (KEK)

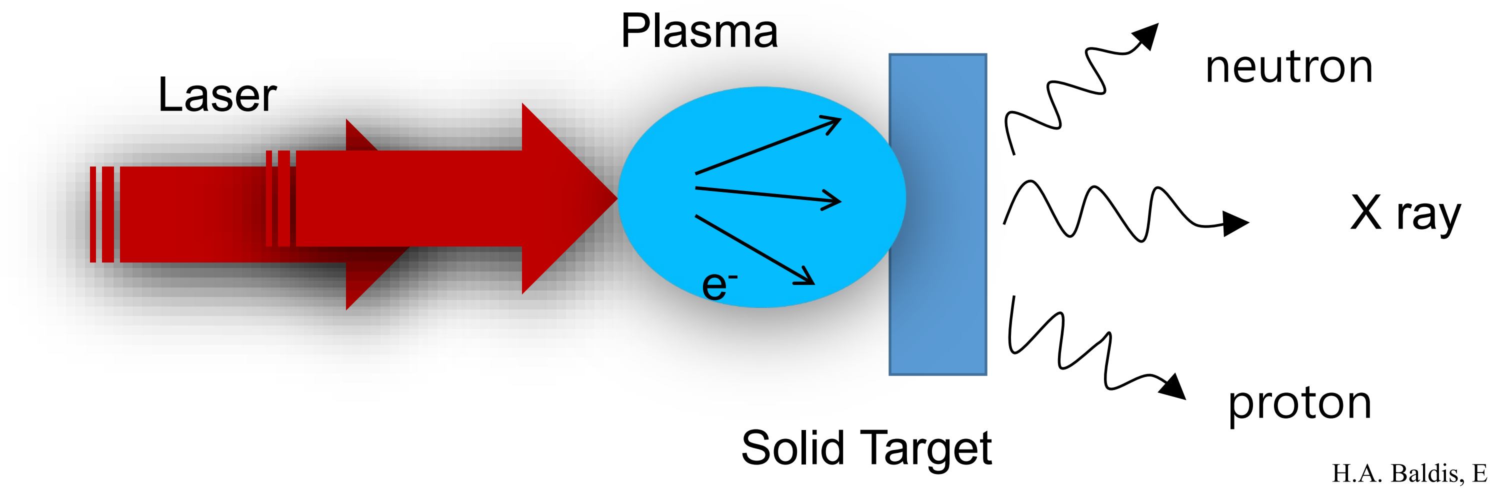
- LINAC (400 MeV)
- Rapid Cycling Synchrotron (RCS) (3 GeV)
  - Material and Life science Facility (MLF)

- Main Ring (MR) (30 GeV)
  - Neutrino Facility
  - Hadron Hall


MR
Hadron Hall
RCS
LINAC
MLF
Neutrino



고출력레이저와 표적 충돌에 의한 방사선생성



H.A. Baldis, E.M. Campbell, W.L. Kruer. "Hand book of Plasma Physics", Chapter 9, Elsevier Science Publishers, (1991).

When a high power laser pulse strikes a solid target

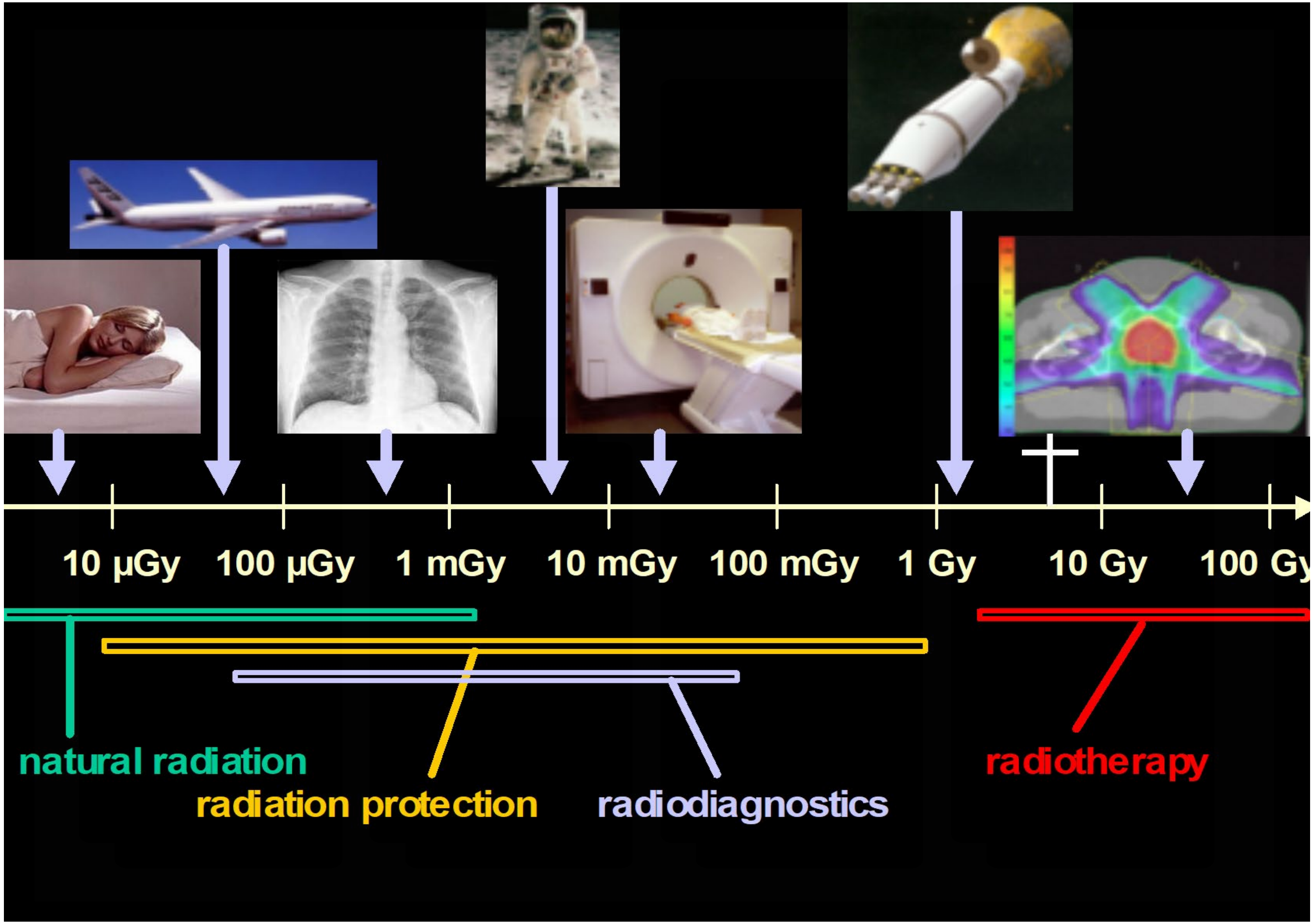
- A hot, dense plasma is produced
- Hot electrons are produced and accelerated as a result of the resonant interaction between the laser and the plasma
- Hot electrons produce bremsstrahlung radiation when they interact with the target
- X rays produce high energy neutron by photonuclear interactions
- Energetic protons can also be produced by electrostatic field generated inside the target

방사선원의 정확한 정의

- 방사성동위원소 (Radioactive Isotope)
  1. 방사선을 방출하는 동위원소
  2. 일정 수량 및 농도를 초과하는 것

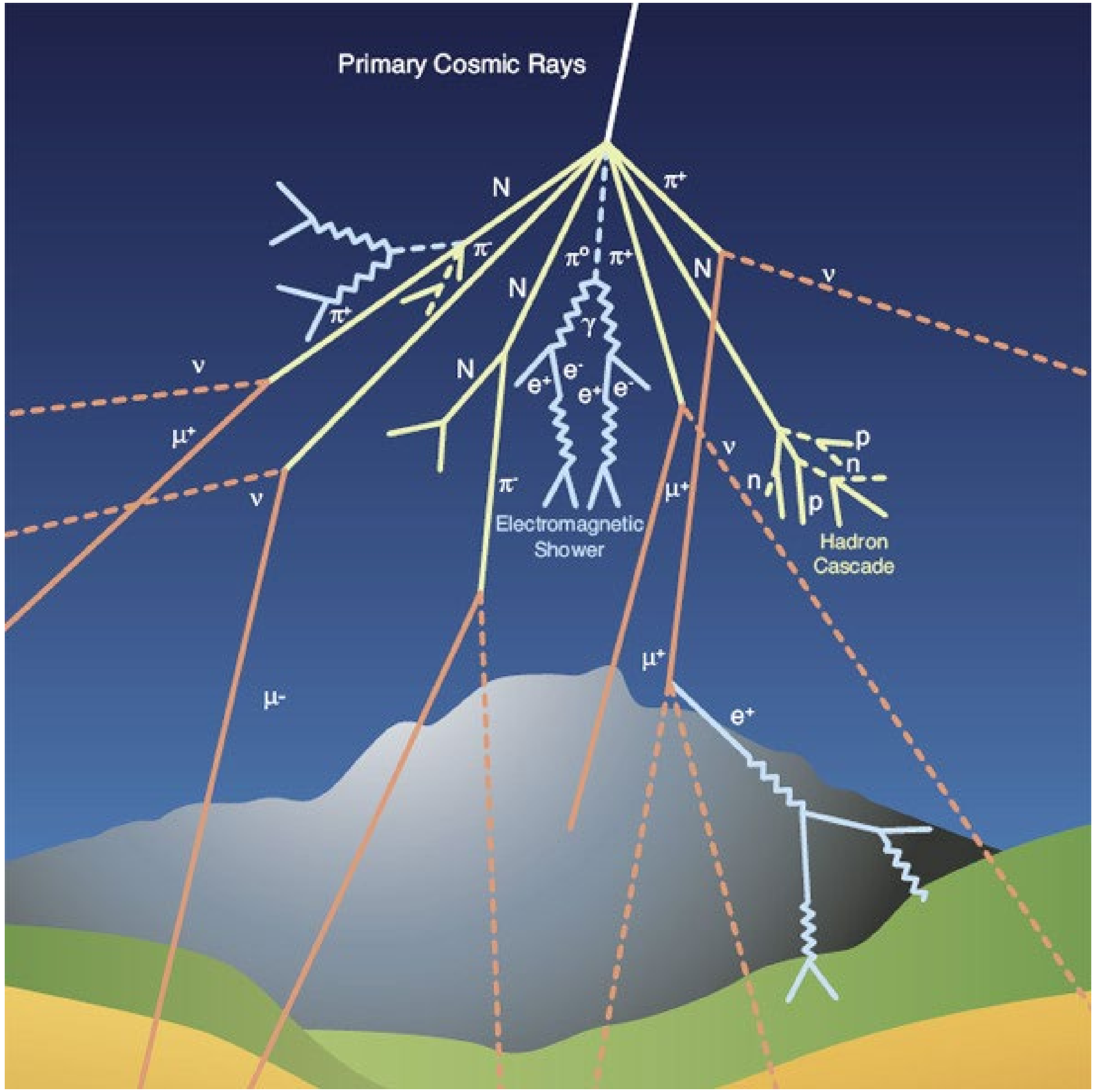
- 방사선발생장치 (Radiation Generator)
  1. 하전입자를 가속시켜 방사선을 발생시키는 장치
  2. (다양한 종류의 입자 가속기들 / 핵융합기기)
  3. 일정조건 만족해야 함
     - 방사선의 최대 에너지가 5 keV이하인 것
     - 의료진단용으로 사용하는 것 (원자력안전법)
     - 완전방호형중 가속관 최대전압이 50 keV이하 이고 모든 접촉부위의 표면방사선량이 시간당 1 μSv 이하인 것

방사선 방호관점에서 방사선량의 크기는?

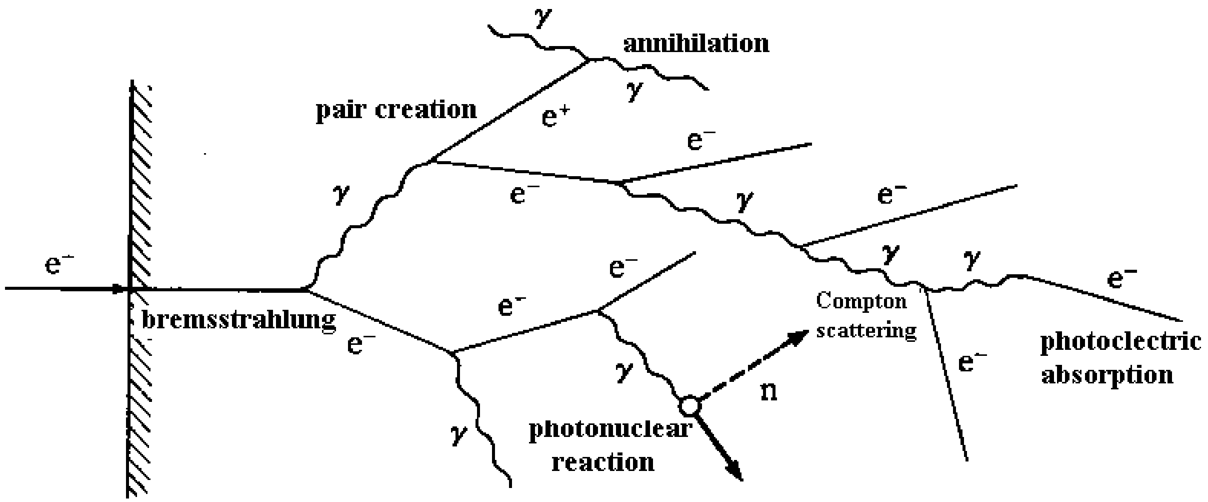

10 µGy
100 µGy
1 mGy
10 mGy
100 mGy
1 Gy
10 Gy
100 Gy
natural radiation
radiation protection
radiodiagnostics
radiotherapy

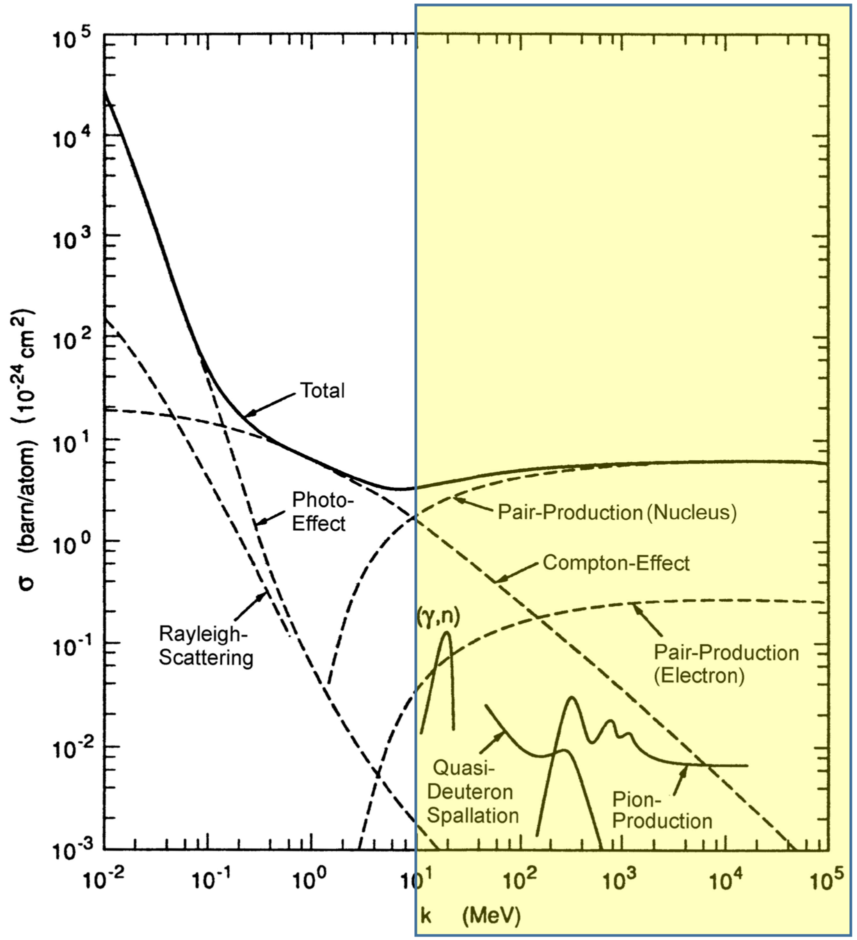
7

가속기 방사선


Primary Cosmic Rays
N
π^+
π
π^+
π^0
π^+
N
N
N
ν
γ
e^-
e^+
e^+
e^-
μ^+
ν
ν
π^-
Electromagnetic Shower
μ^+
ν
p
n
n
p
Hadron Cascade
μ^+
μ^-
e^+

Reactions at Electron Accelerator


γ
annihilation
γ
pair creation
e+
e−
γ
e−
γ
e−
e−
γ
γ
e−
e−
bremsstrahlung
e−
e−
e−
Compton
scattering
photoclectric
absorption
γ
n
e−
photonuclear
reaction
γ



Major Reactions and Particles

- Electromagnetic Shower + Photonuclear reation
- Low Energy
- High Energy
  * Neutron, Meson

Reactions at Proton Accelerator, etc

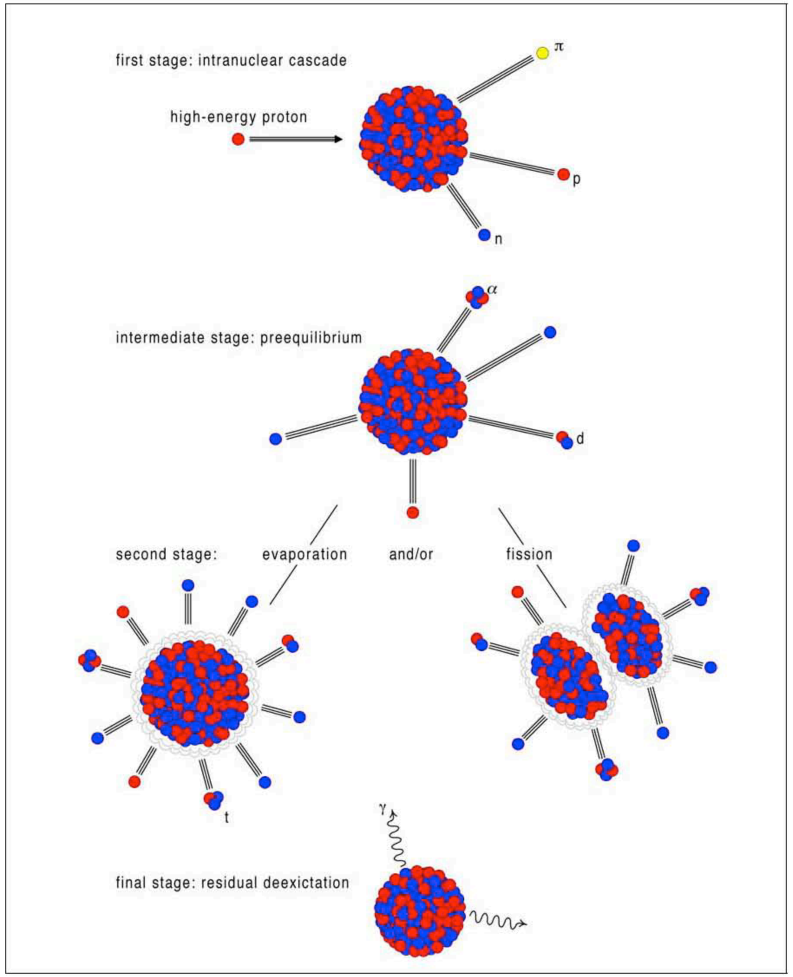
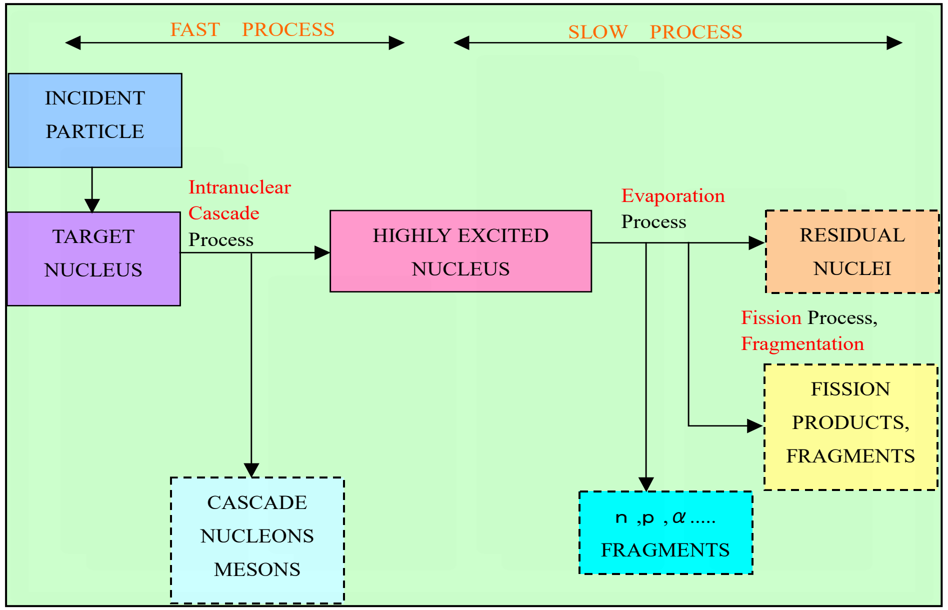

first stage: intranuclear cascade
high-energy proton
π
p
n
intermediate stage: preequilibrium
α
d
second stage:
evaporation
and/or
fission
t
final stage: residual deexictation
γ

Figure 4-1. Interaction processes.



FAST PROCESS

SLOW PROCESS

INCIDENT
PARTICLE

TARGET
NUCLEUS

Intranuclear
Cascade
Process

HIGHLY EXCITED
NUCLEUS

Evaporation
Process

RESIDUAL
NUCLEI

Fission Process,
Fragmentation

FISSION
PRODUCTS,
FRAGMENTS

CASCADE
NUCLEONS
MESONS

n ,p ,α .....
FRAGMENTS

Major Reactions

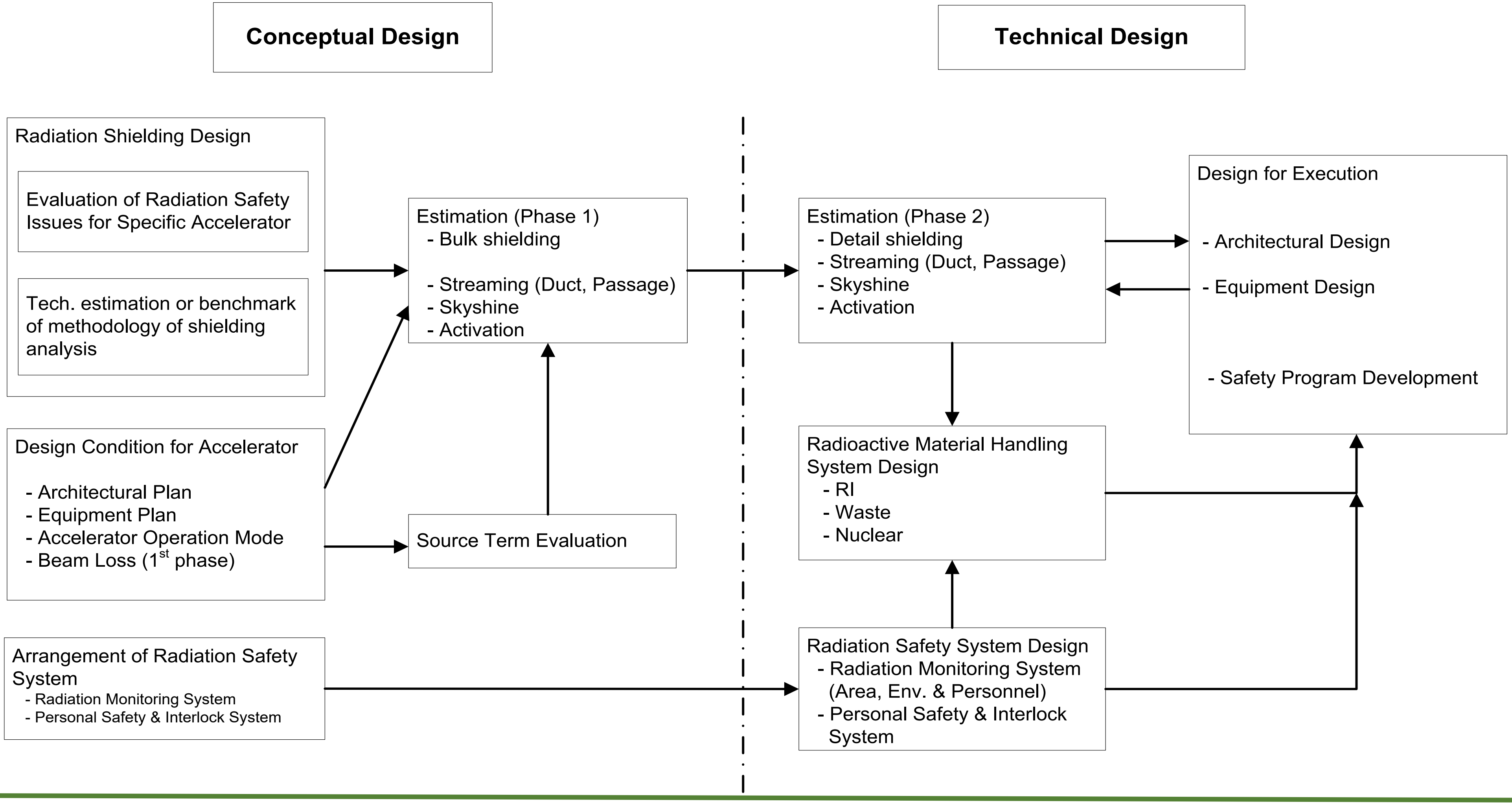
- Intranuclear Cascade (Bertini, JQMD, ….)
- Pre-equilibrium Transition (Exciton, …)
- Evaporation, etc (GEM, Dresden,…)

방사선 방호에서 고려해야할 사항

1. 일차 방사선원의 특성 (입자빔)
2. 이차 방사선의 발생
3. 방사선원의 형태
4. 이차방사선의 유형 (방사화 유도 O/X) – 중성자 생성 !!
5. 방사선 차폐 해석 및 안전시스템 구축
6. Groundshine & Skyshine
7. 잔류방사능에 의한 피폭
8. 방사성폐기물
9. 방사선에 의한 기기손상 (위험?)
10. 환경영향 (+ 동식물)
11. 방사선사용 인허가
12. 핵물질 사용여부 (예, 우라늄)
13. 새로운 형태의 방사선원, 가속기(Plasma-wakefield, High Power Laser)

설계단계에서의 방사선안전해석 (예)

General flow of shielding analysis and safety system design for high energy accelerator



Conceptual Design

Technical Design

Radiation Shielding Design

Evaluation of Radiation Safety Issues for Specific Accelerator

Tech. estimation or benchmark of methodology of shielding analysis

Design Condition for Accelerator
- Architectural Plan
- Equipment Plan
- Accelerator Operation Mode
- Beam Loss (1st phase)

Arrangement of Radiation Safety System
- Radiation Monitoring System
- Personal Safety & Interlock System

Estimation (Phase 1)
- Bulk shielding
- Streaming (Duct, Passage)
- Skyshine
- Activation

Source Term Evaluation

Estimation (Phase 2)
- Detail shielding
- Streaming (Duct, Passage)
- Skyshine
- Activation

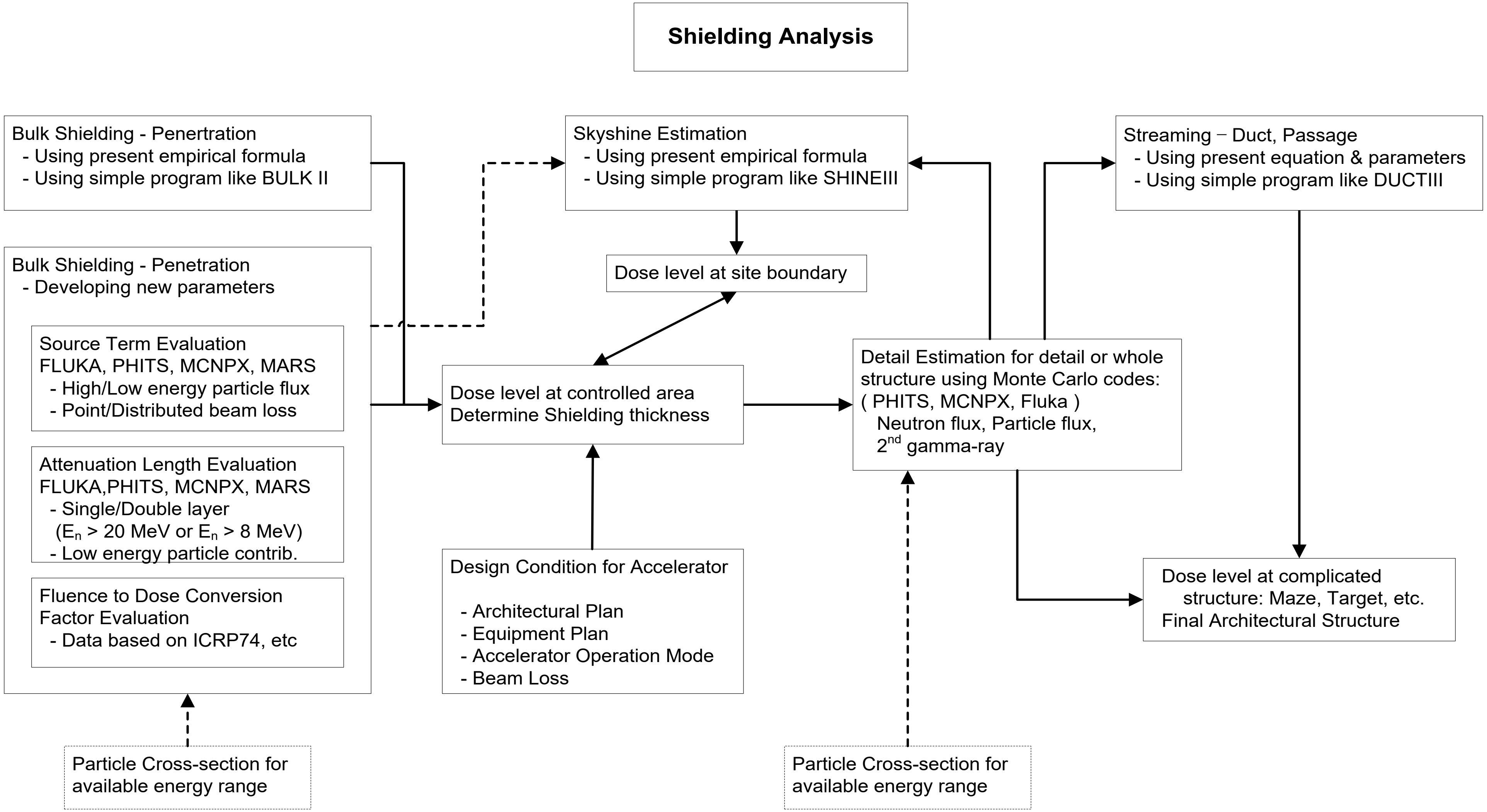
Radioactive Material Handling System Design
- RI
- Waste
- Nuclear

Radiation Safety System Design
- Radiation Monitoring System (Area, Env. & Personnel)
- Personal Safety & Interlock System

Design for Execution
- Architectural Design
- Equipment Design
- Safety Program Development

설계단계에서의 방사선안전해석 (예)

General flow of shielding analysis



Shielding Analysis

Bulk Shielding - Penertration
- Using present empirical formula
- Using simple program like BULK II

Bulk Shielding - Penetration
- Developing new parameters

Source Term Evaluation
FLUKA, PHITS, MCNPX, MARS
- High/Low energy particle flux
- Point/Distributed beam loss

Attenuation Length Evaluation
FLUKA,PHITS, MCNPX, MARS
- Single/Double layer
  ($E_n > 20$ MeV or $E_n > 8$ MeV)
- Low energy particle contrib.

Fluence to Dose Conversion
Factor Evaluation
- Data based on ICRP74, etc

Particle Cross-section for
available energy range

Skyshine Estimation
- Using present empirical formula
- Using simple program like SHINEIII

Dose level at site boundary

Dose level at controlled area
Determine Shielding thickness

Design Condition for Accelerator
- Architectural Plan
- Equipment Plan
- Accelerator Operation Mode
- Beam Loss

Streaming – Duct, Passage
- Using present equation & parameters
- Using simple program like DUCTIII

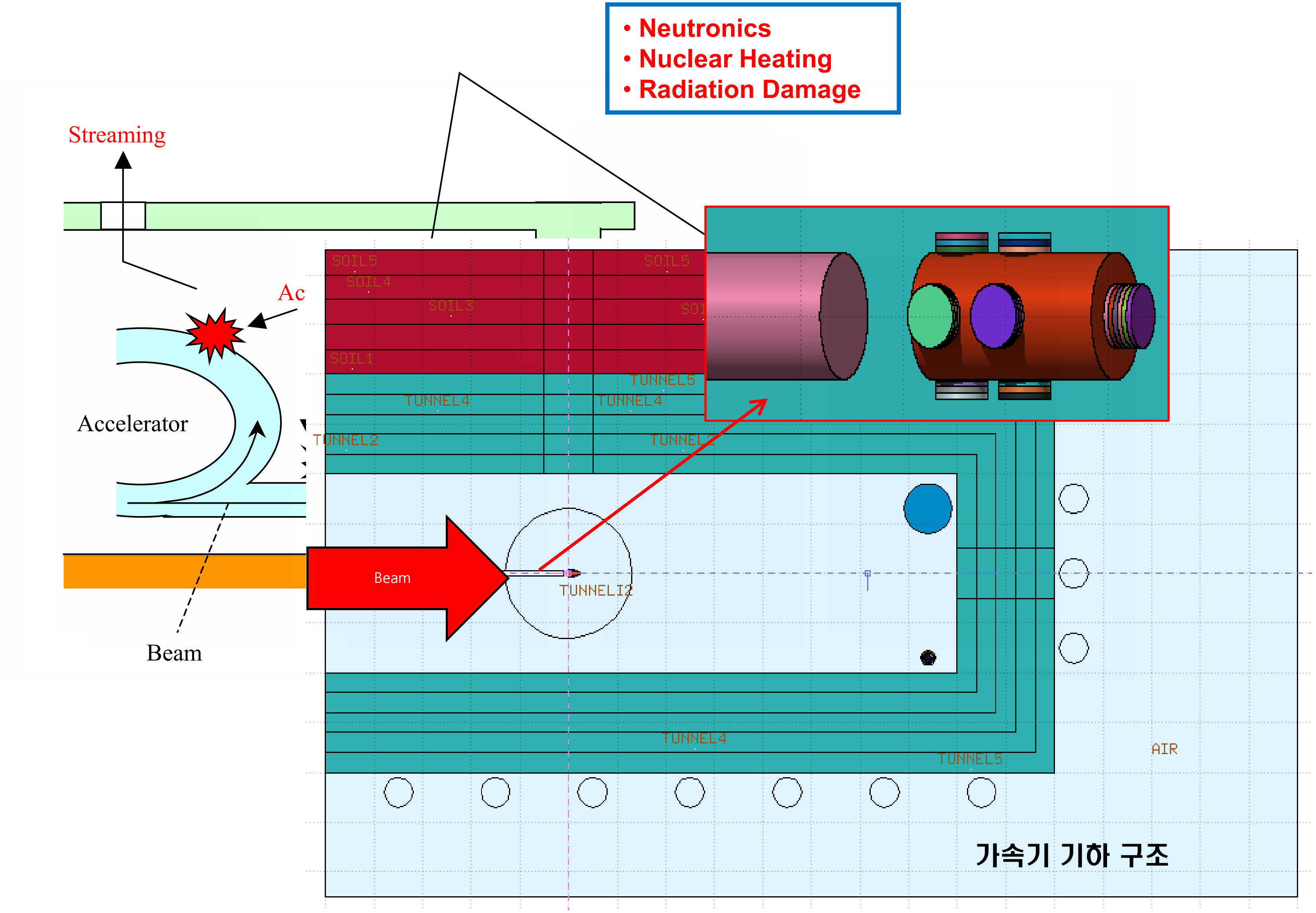
Detail Estimation for detail or whole structure using Monte Carlo codes:
(PHITS, MCNPX, Fluka)
Neutron flux, Particle flux,
2^{nd} gamma-ray

Dose level at complicated
structure: Maze, Target, etc.
Final Architectural Structure

Particle Cross-section for
available energy range

이차방사선의 발생 특성 (입자가속기)

- 입자가속기의 가속입자를 일차방사선으로 정의하면 입자빔의 충돌에 의해 다양한 이차방사선이 방출되며, 이때 중성자 발생량과 특성은 상대적으로 중요함.
- 주요입자인 양성자, 전자, 탄소이온, 우라늄이온에 대해서 표준구조를 가정하여 이차방사선의 발생 특성과 전파 특성을 평가함.

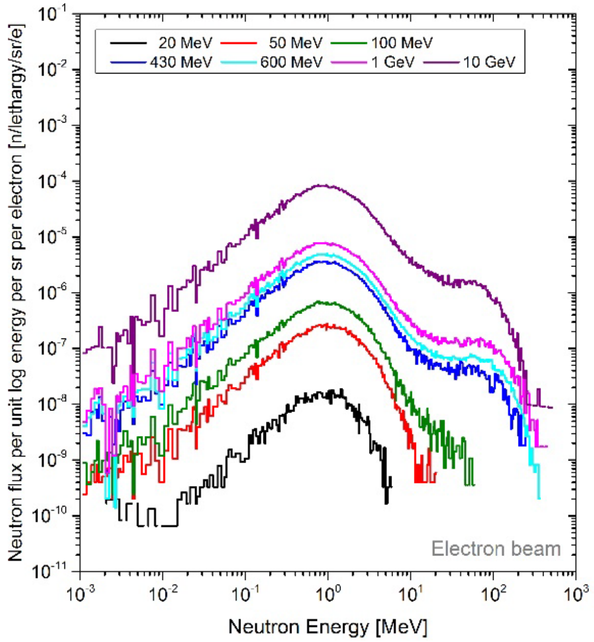


- Neutronics
- Nuclear Heating
- Radiation Damage

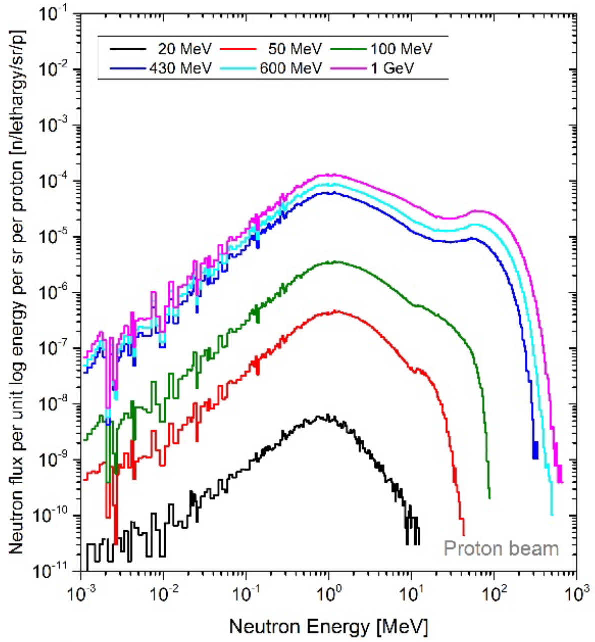
Streaming
Ac
Accelerator
Beam
SOIL5
SOIL4
SOIL3
SOIL1
SOIL5
TUNNEL5
TUNNEL4
TUNNEL4
TUNNEL2
Beam
TUNNEL12
TUNNEL4
TUNNEL5
AIR

가속기 기하 구조

Radiation Yields : Neutrons at 90°

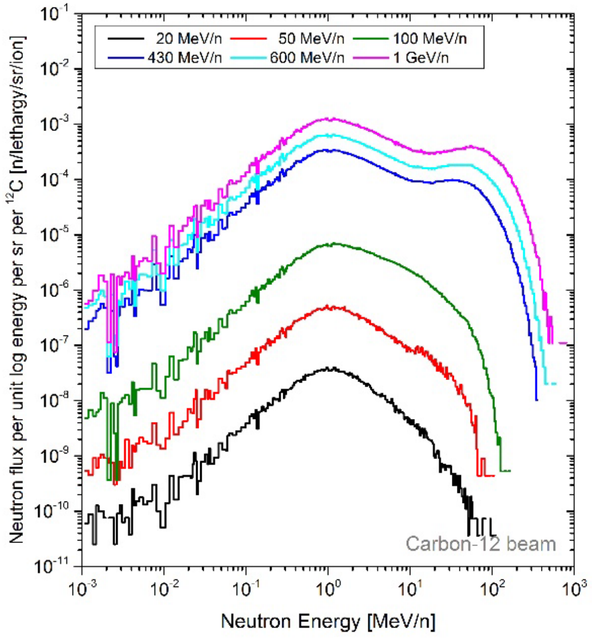


Electron

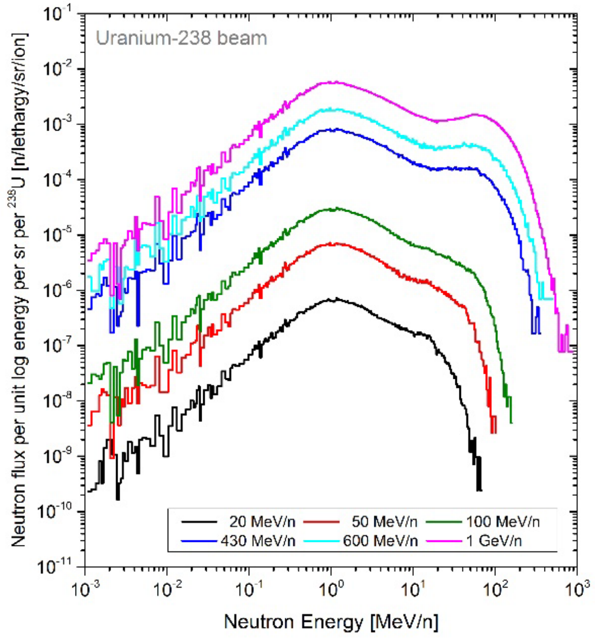


Proton

Yields per number of incident particles



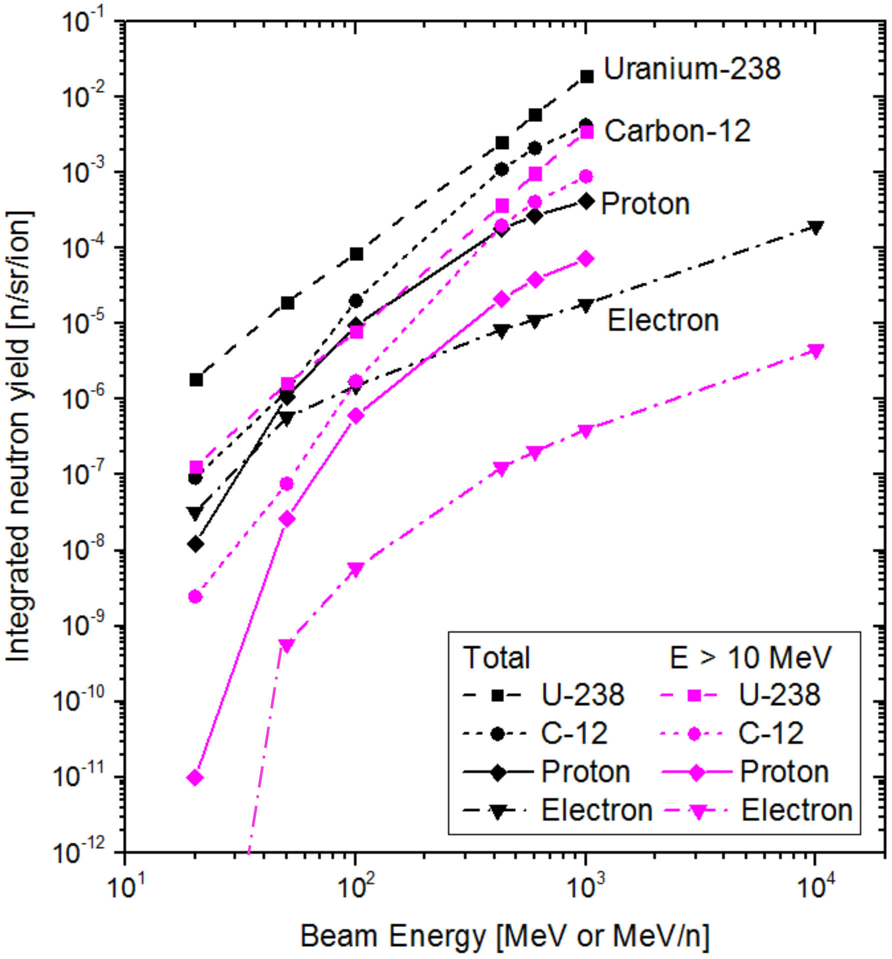
C-12

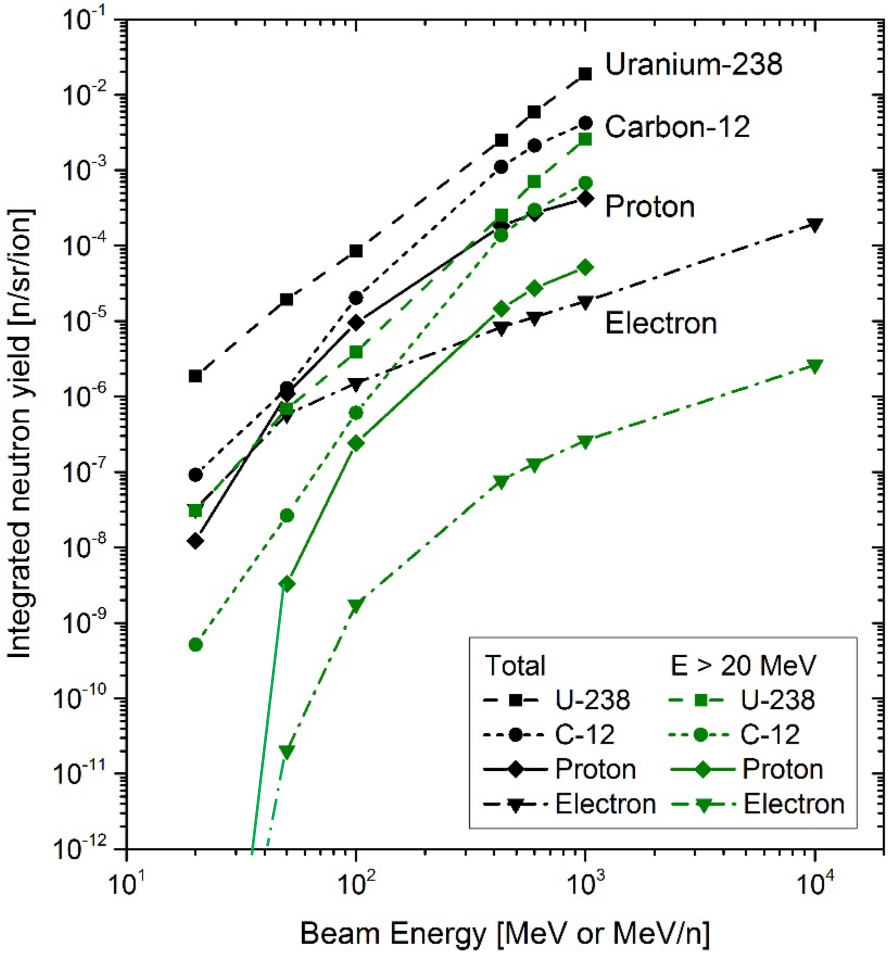


U-238

Radiation Yields : Neutrons at 90°

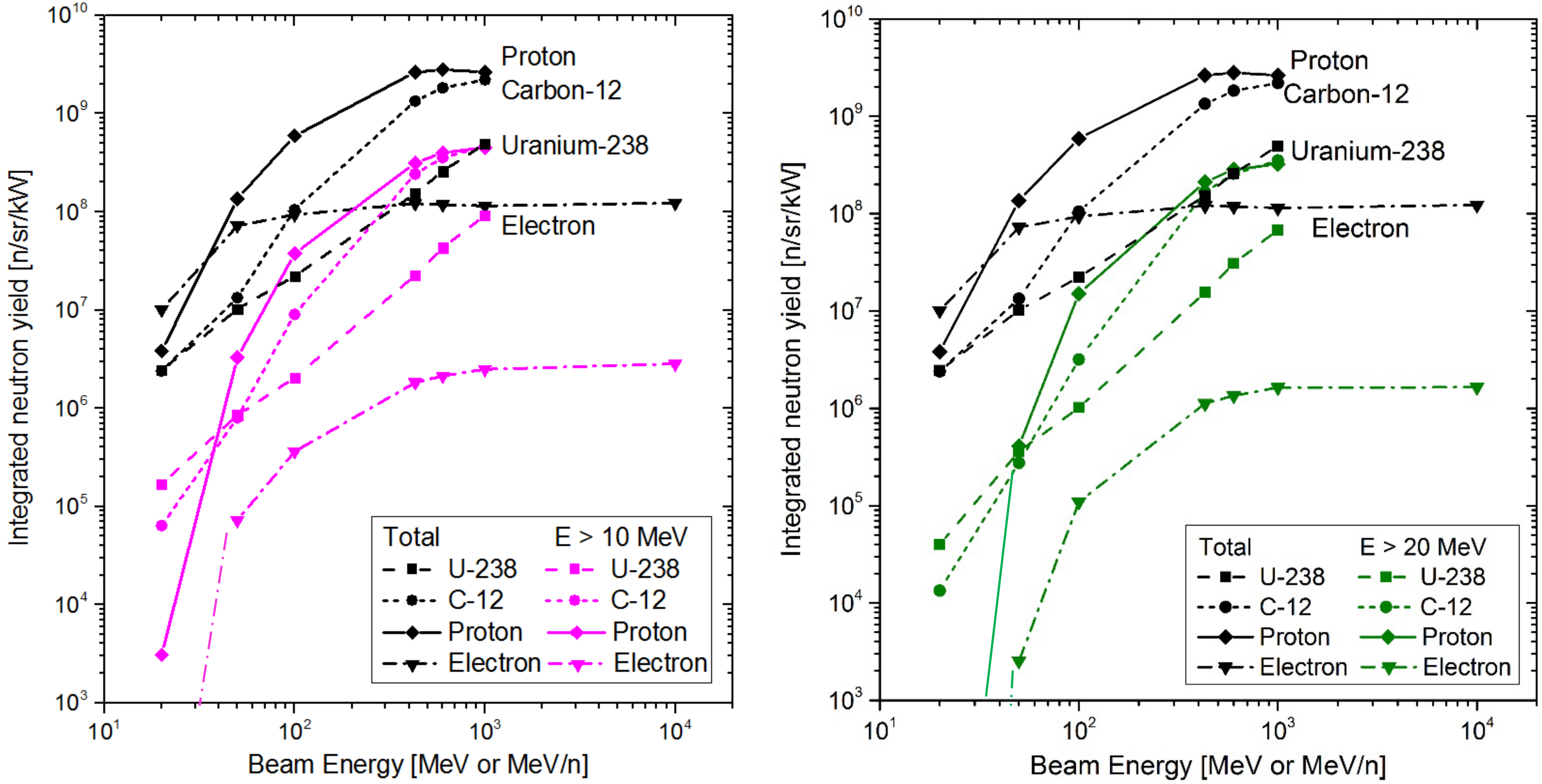
Comparison of Integrated Neutron Yields (per particles)
for different type of incident particles and different energies



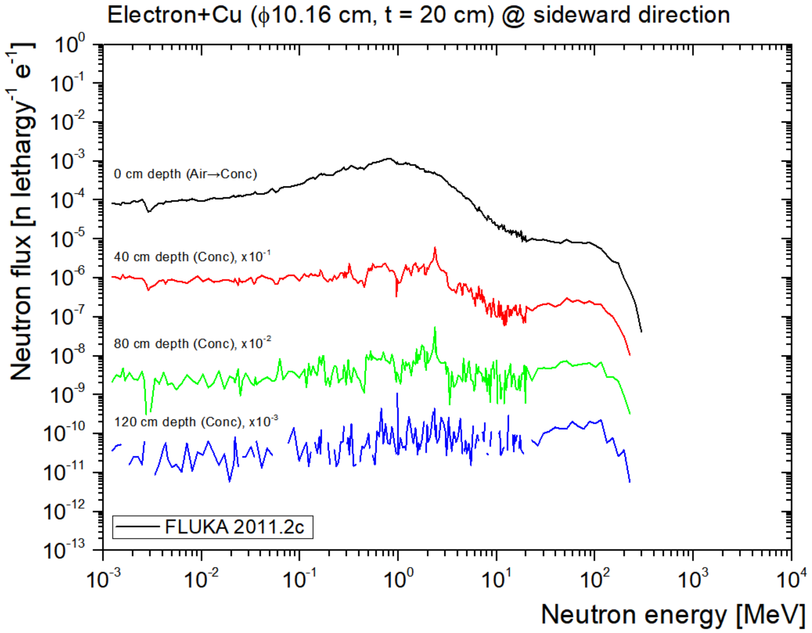


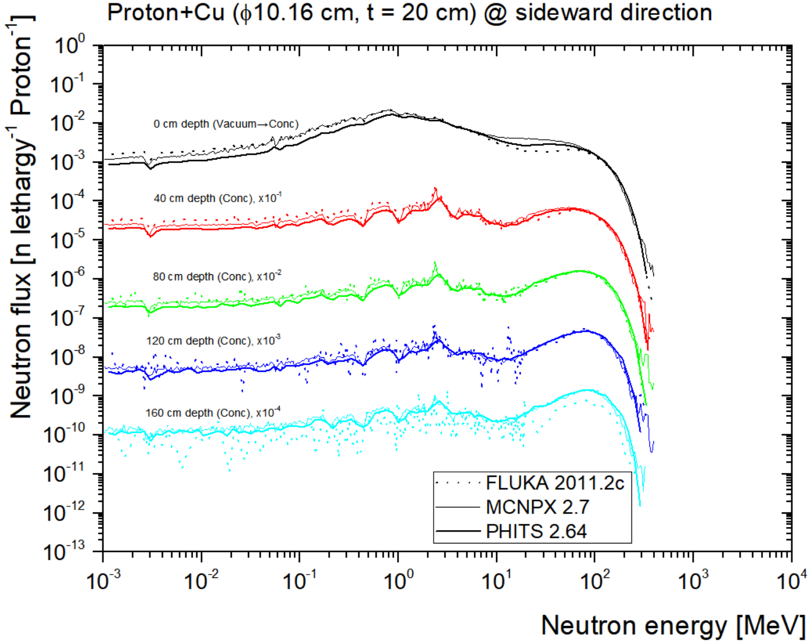
Radiation Yields : Neutrons at 90°

Comparison of Integrated Neutron Yields (per kW)
for different type of incident particles and different energies

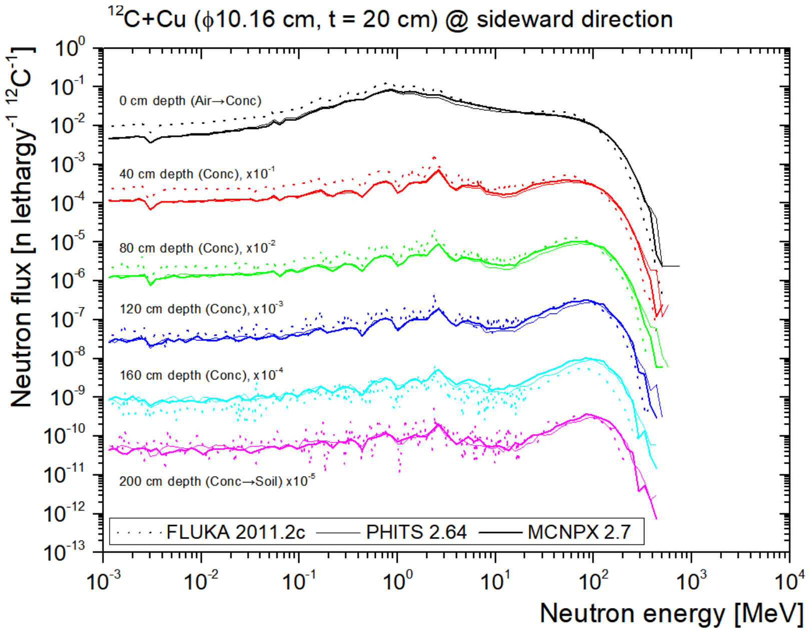


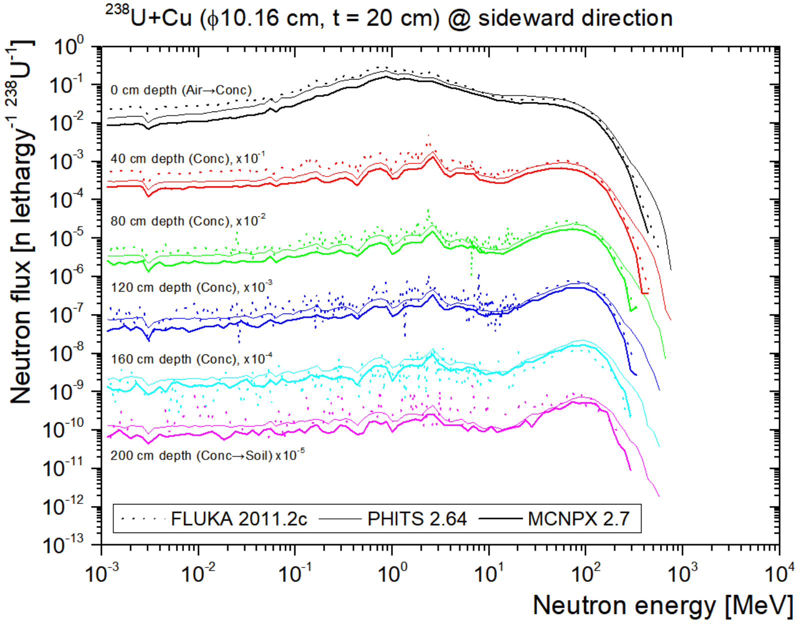
Secondary Particle Transport, Shielding





Transport itself is not changed seriously depending on type of incident particles.
We evaluated each attenuation length and compare those.



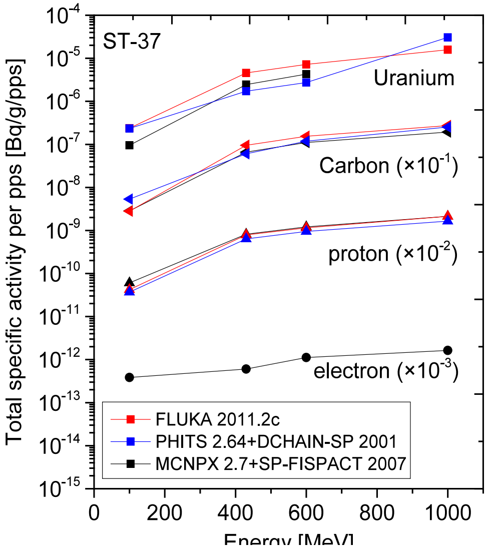


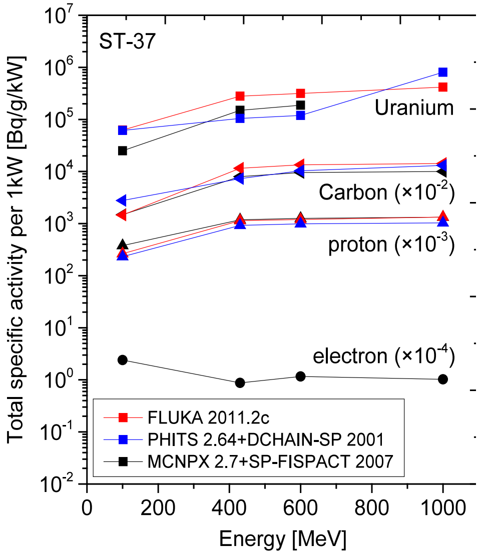
가속입자별, 에너지별 방사화 정도 비교

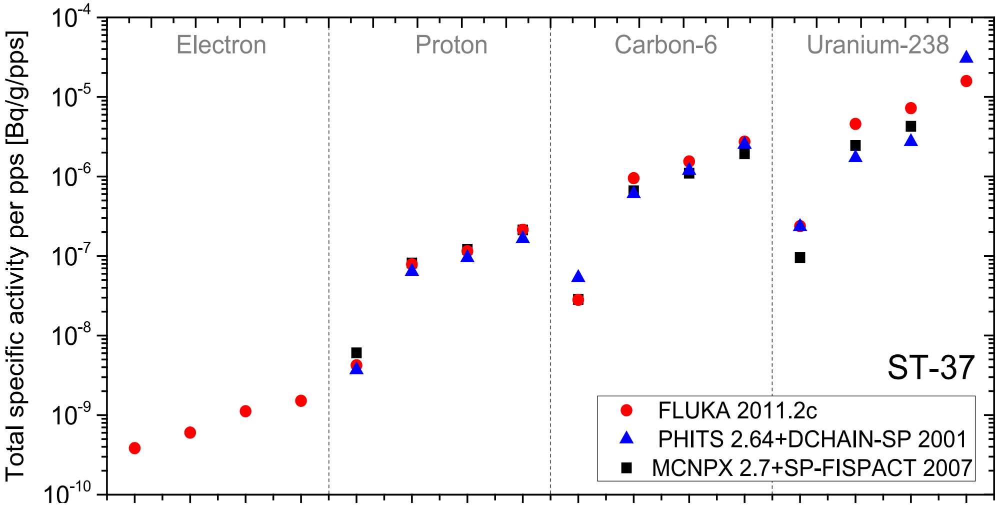
미래기반 가속기
전문인력양성 사업단

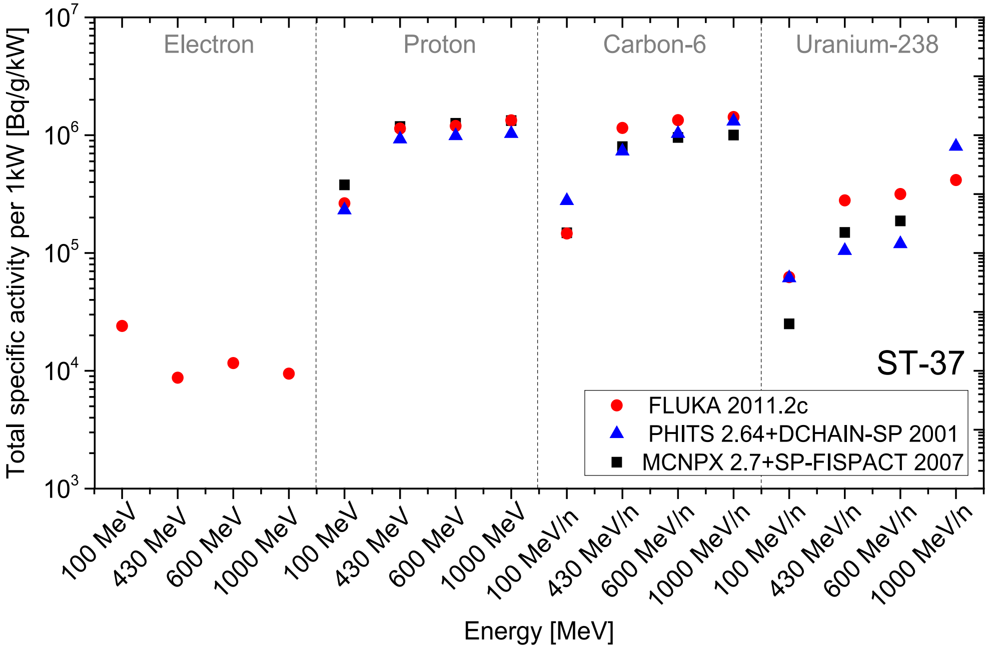
입사빔 출력당 방사화 정도는 입자에너지의 변화에 무관, 입자의 종류에 따라 변함

여기서 몬테카를로 코드 계산의 정확도는 별도로 고려하지 않음

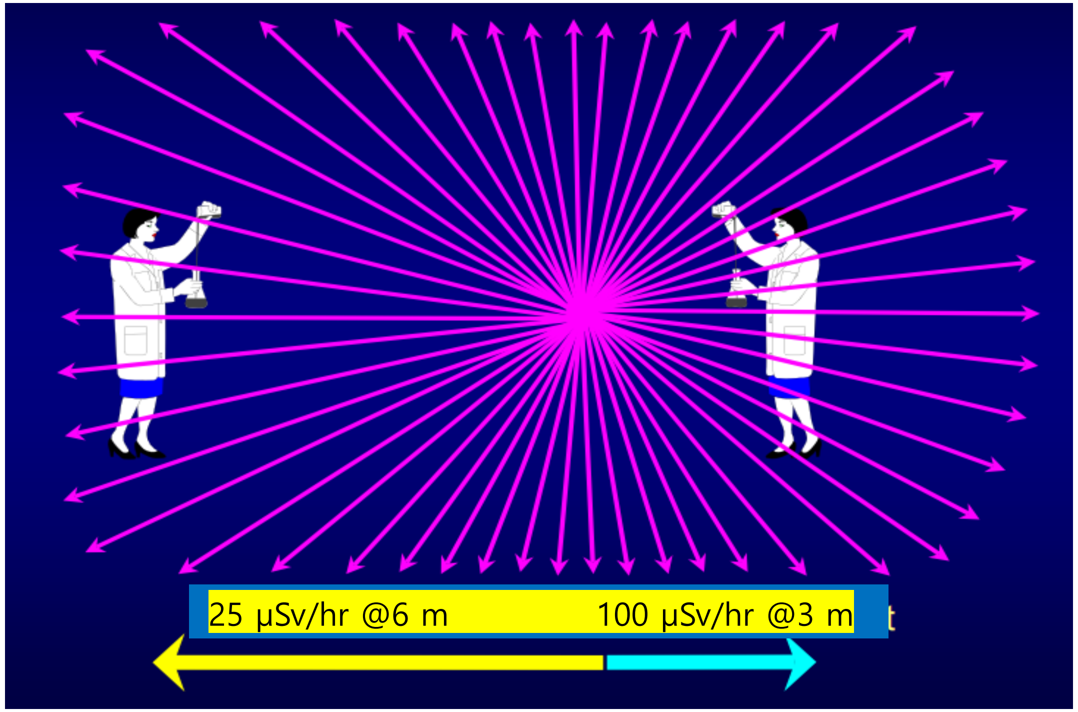








차세대



- **역좌승의 법칙: 1/R²**

- **실제는 복잡한 역좌승의 법칙이 요구됨**

- 중성자 등가선량률

$$\dot{H} = \frac{BSqe^{-\Sigma_r t}}{4\pi R^2}$$

B: Build-up factor,   S: Source strength (n/sec),

q: fluence-to-dose conversion factor

dose-equivalent rate per unit neutron fluence rate

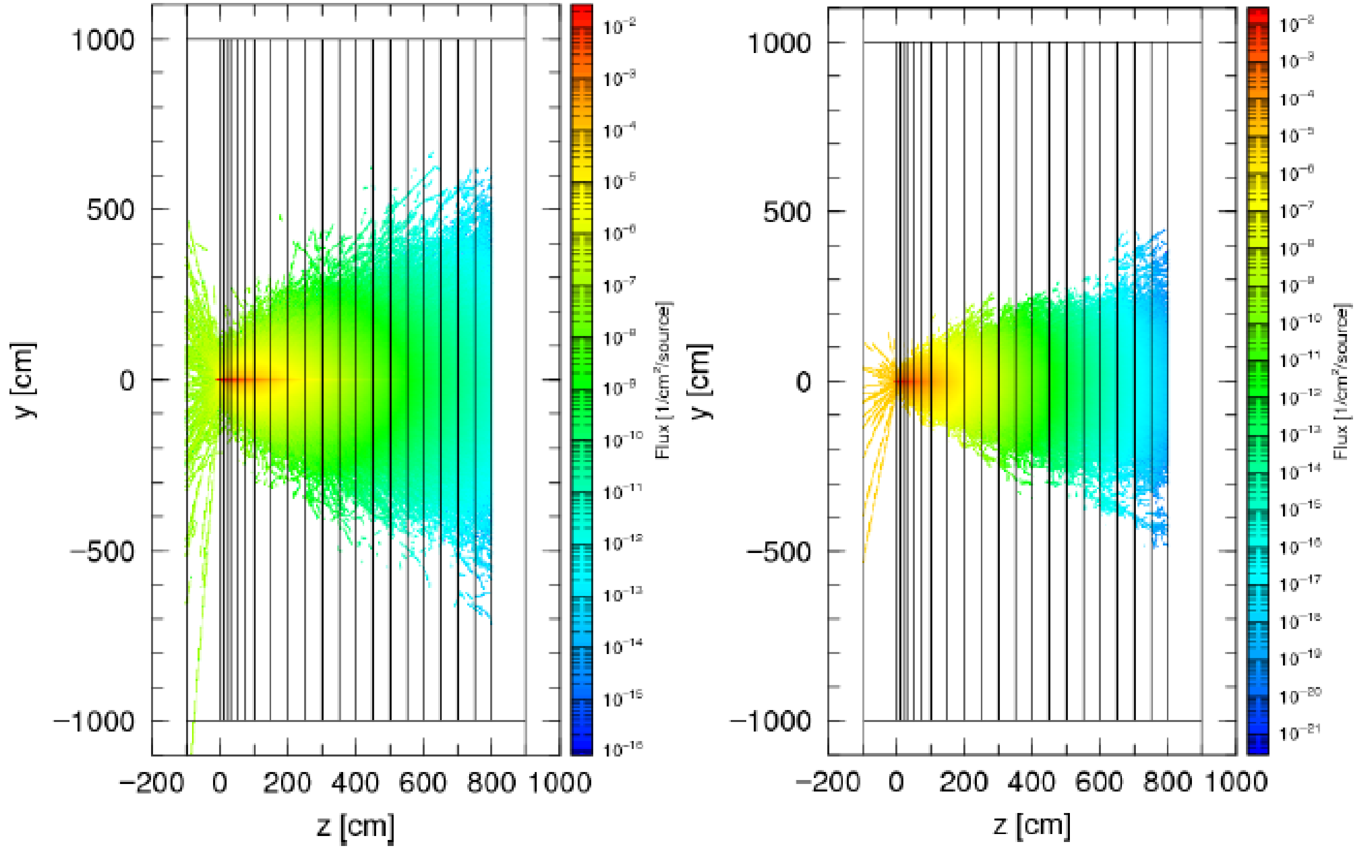
(Sv/h per n/cm^2/sec)

Σ_r: removal cross-section   t : shielding thickness

직접 차폐계산식을 만들어 보자 - Bulk Shielding Analysis

입자빔이 표적에 충돌한 후에 방출된 중성자가 차폐체내에서 전파되는 것을 모사

-➔ 선형감쇄계수를 작성

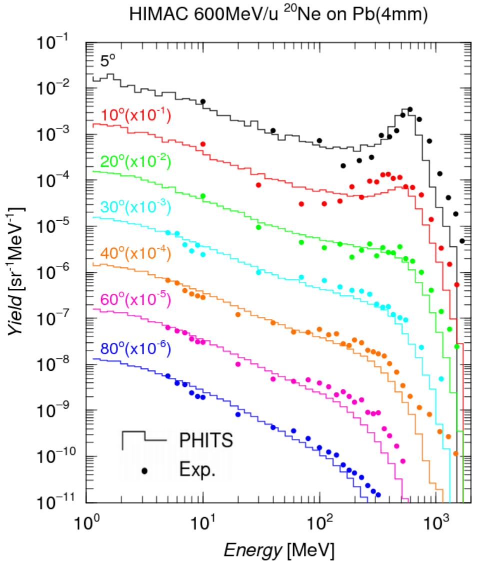


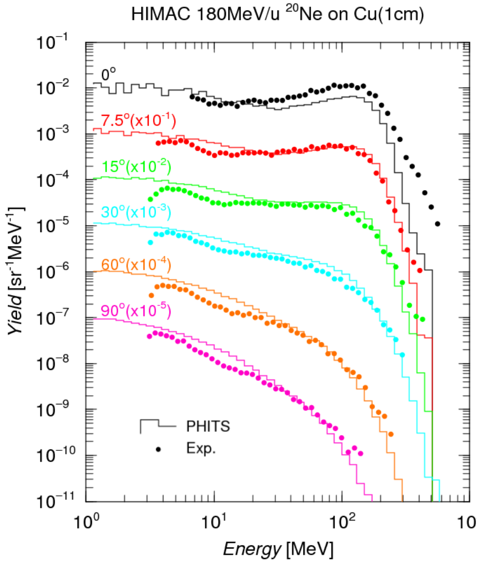
(a) Concrete shield (b) Iron shield

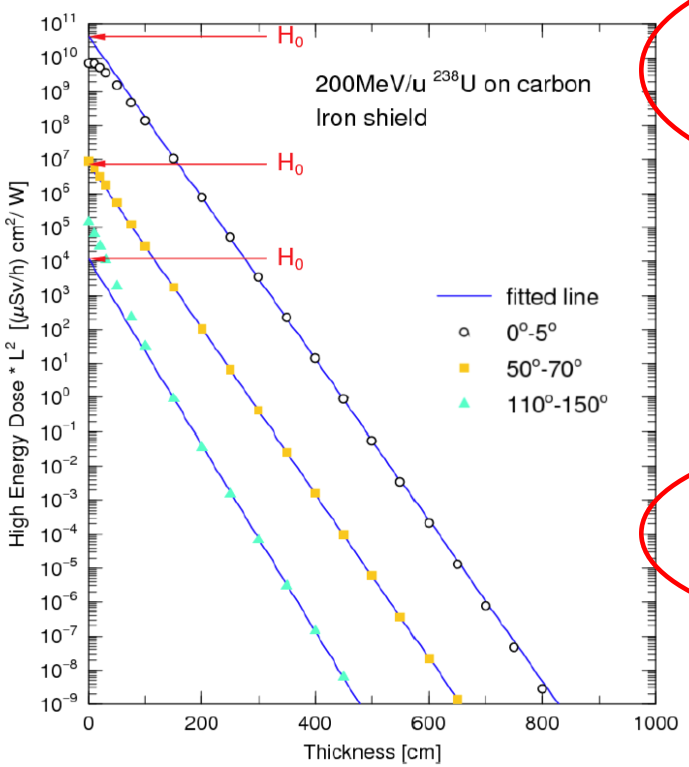
Fig.7: Two-dimensional neutron track plots on the shielding transmission simulations using the neutron source from the graphite target at 0 degree by 200 MeV/u ^{238}U beam.

직접 차폐계산식을 만들어 보자 - Bulk Shielding Analysis

입자가 충돌할 때 표적에서 방출되는 중성자의 생성률 평가:
각도별로 다름







$$H = JH_0\frac{1}{r^2}\ exp\left(-\frac{d\rho}{\lambda}\right)$$

Fitting region
Concrete : 250-700 cm
Iron : 100-600 cm
→ can be limitations for thickness d of the empirical formulae

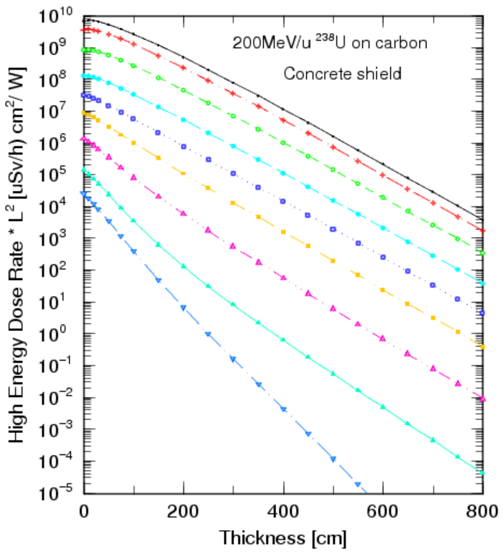
Shielding parameters
H_0 : source term [(μSv/h) cm^2 /W]
λ : attenuation length [g/cm^2]

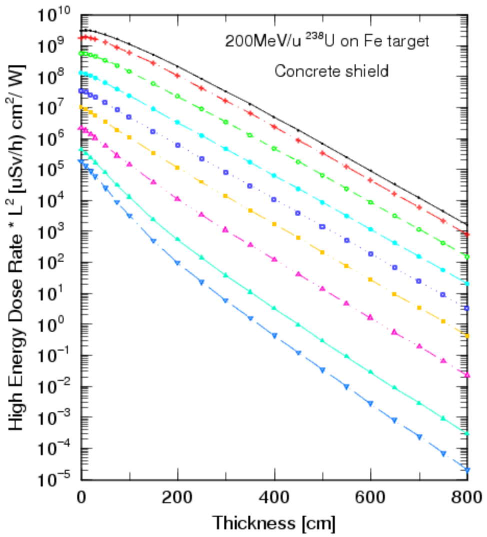
Prompt Dose Rate after Concrete
D_total ≦ D_high-n × 2.0
→ H_0 is multiplied by 2.0

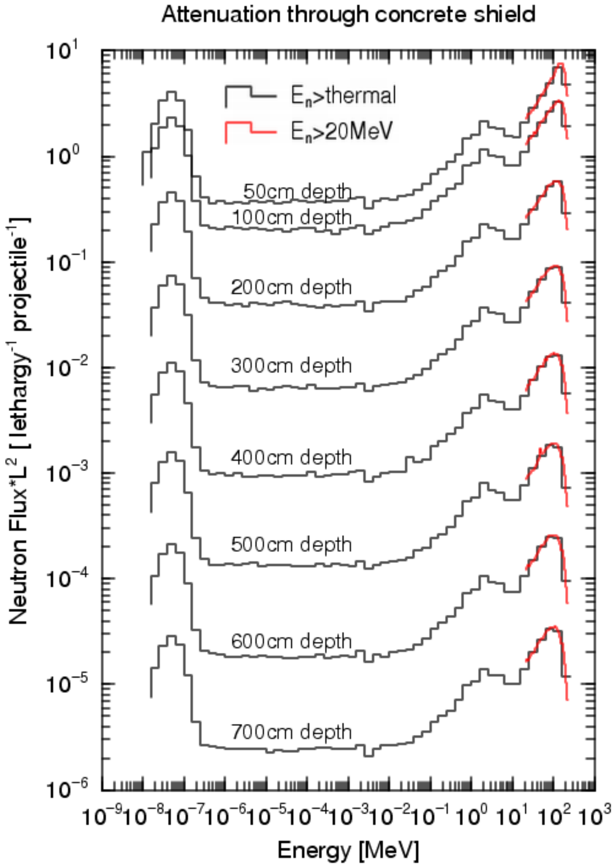
직접 차폐계산식을 만들어 보자 - Bulk Shielding Analysis

미래기반 가속기 전문인력양성 사업단

차폐체내에서 중성자의 감쇄특성 비교 – 차폐물질과 조합에 따른 차이







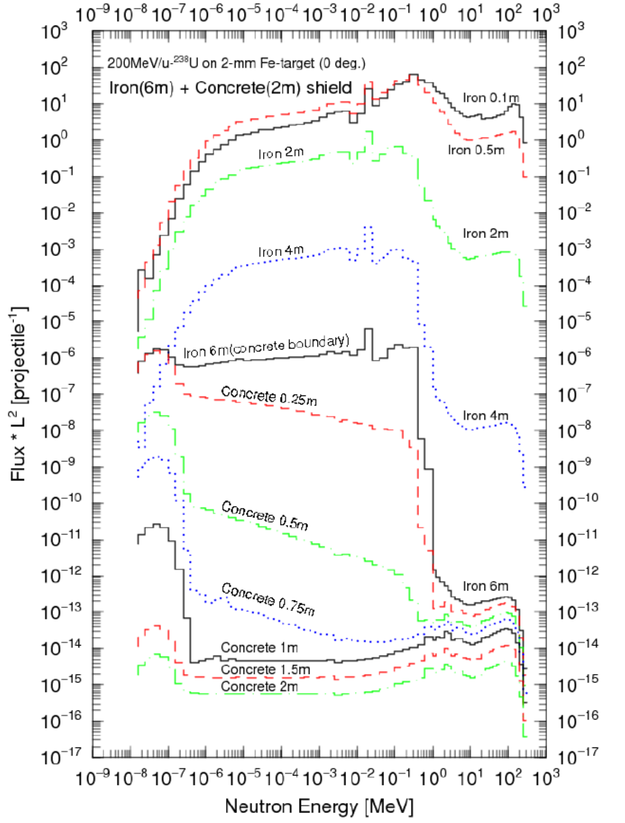
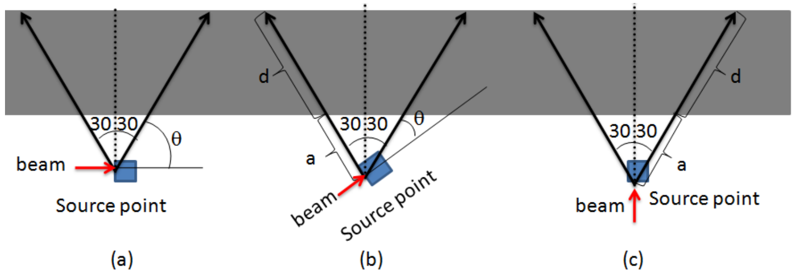


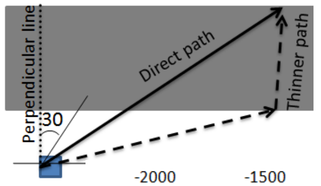
Fig. 16: Neutron energy spectra down to thermal energy inside the 6m-iron followed by 2m-concrete shield for 200 MeV/u ^{238}U on Fe target (0 degree).

직접 차폐계산식을 만들어 보자 - Bulk Shielding Analysis

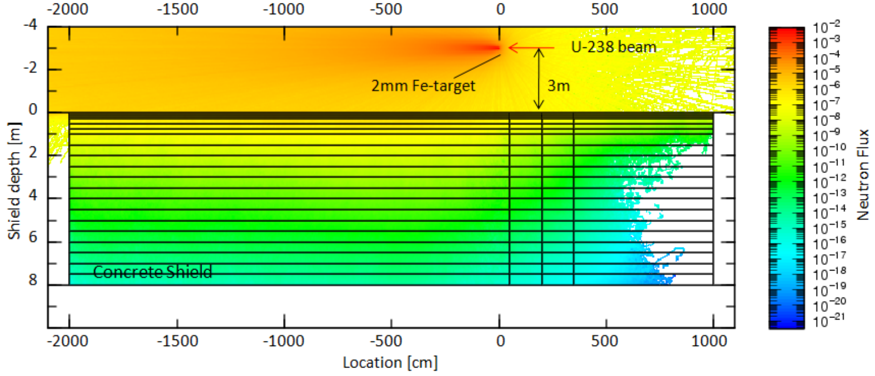
이러한 단순한 계산식은 적용의 한계가 있음을 기억해야 함.

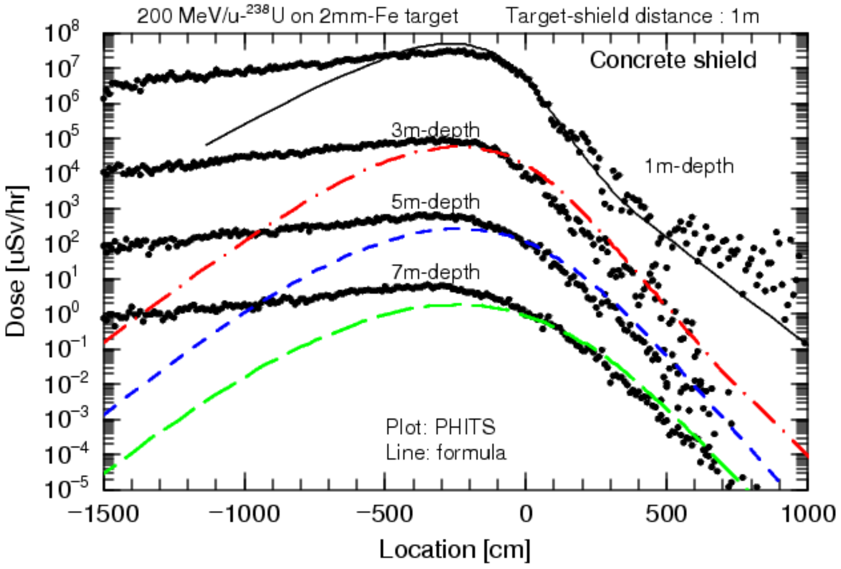
- 이 경우는 90도 전후의 차폐구조에서만 적합함.

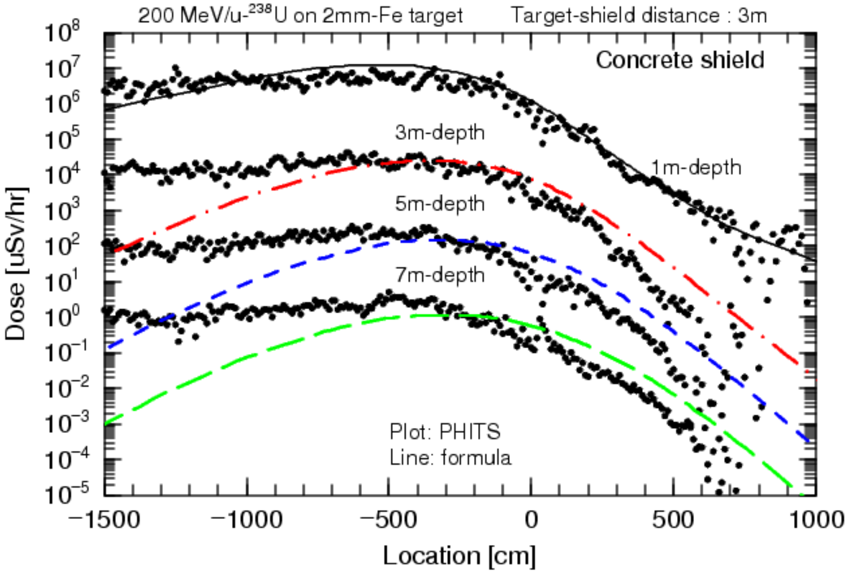

30 30
θ
beam
Source point
(a)
d
30 30
θ
a
beam
Source point
(b)
30 30
d
a
beam
Source point
(c)


Perpendicular line
30
Direct path
Thinner path
(d

$$H = JH_0 \frac{1}{r^2} \; exp\left(-\frac{d\rho}{\lambda}\right)$$







Skyshine & Groundshine

- 시설에서 외부로 방출되는 방사선 (감마선, 중성자)은 공기중 분자 또는 바닥면 아래의 물질과 충돌하여 역으로 먼거리 (시설 부지경계) 위치의 방사선량을 높게 한다.
- Skyshine – 공기분자와 충돌
- Groundshine – 바닥면 아래의 콘크리트 등 물질과 충돌

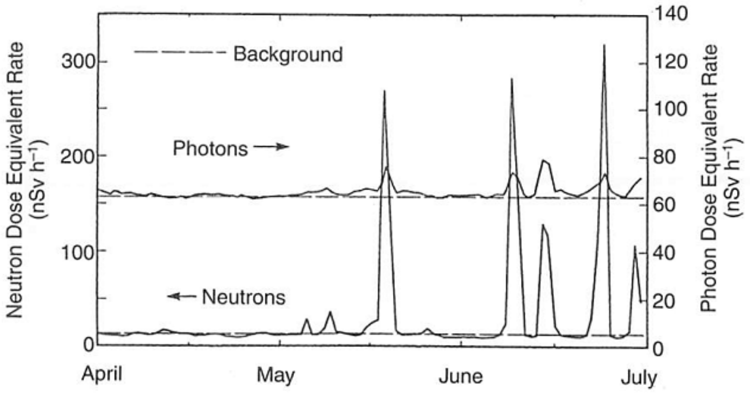
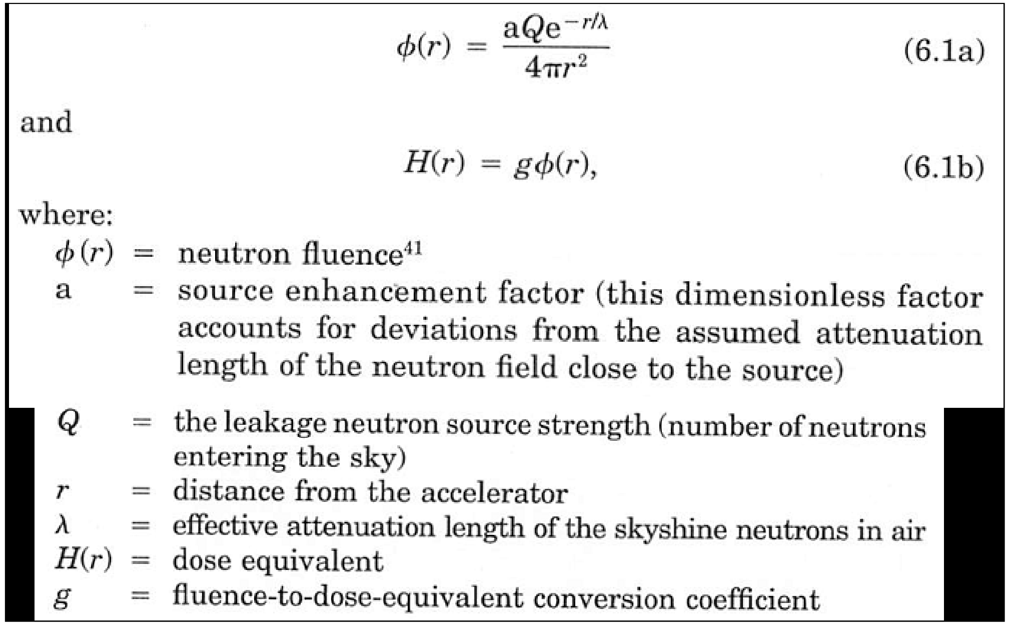


Fig. 6.1. The variation in dose-equivalent rates with time as observed at the boundary of SLAC. The dose-equivalent rates due to both photons and neutrons are indicated by solid lines; natural background due to each component by dashed lines. Periods of intense accelerator operation are evident from the fluctuations in neutron dose-equivalent rate (Jenkins, 1974).

Skyshine & Groundshine

- **Skyshine 계산식**
  - ➢ **습도 등 공기상태 중요**



$$\phi(r) = \frac{aQe^{-r/\lambda}}{4\pi r^2} \qquad (6.1a)$$

and

$$H(r) = g\phi(r), \qquad (6.1b)$$

where:

$\phi(r)$ = neutron fluence[41]
a = source enhancement factor (this dimensionless factor accounts for deviations from the assumed attenuation length of the neutron field close to the source)
Q = the leakage neutron source strength (number of neutrons entering the sky)
r = distance from the accelerator
λ = effective attenuation length of the skyshine neutrons in air
$H(r)$ = dose equivalent
g = fluence-to-dose-equivalent conversion coefficient

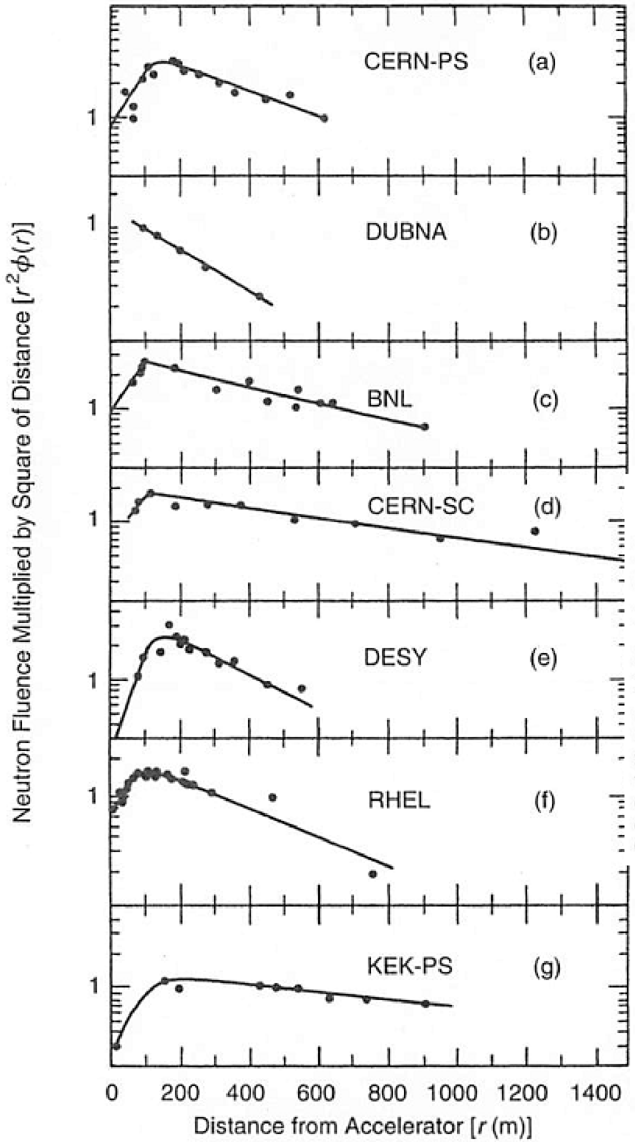
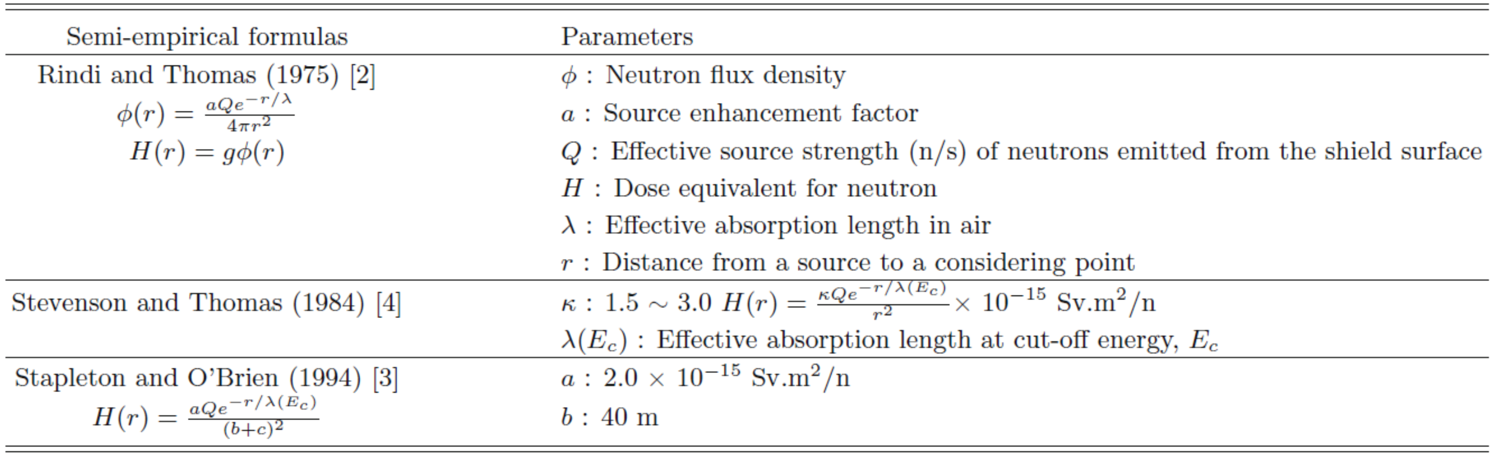


Fig. 6.3. Measurements performed around various accelerators. On the abscissa is the distance from the accelerator in meters; on the ordinate is the product of the measured neutron fluence and the square of the distance. In these conditions, an r^{-2} variation is represented by a horizontal line. (a) Measurements of fast-neutron fluence density performed at the CERN 28 GeV Proton Synchrotron (Ollendorf, 1964). (b) Measurements of fast-neutron fluence density performed at the Dubna 10 GeV Proton Synchrophasotron (Komochkov, 1970; Lebedev *et al.*, 1965). (c) Measurements of dose-equivalent rate performed at the Brookhaven 30 GeV Proton AGS (Distenfeld and Colvett, 1966). (d) Measurements of the fast-neutron fluence density performed at the CERN 600-MeV Proton Synchrocyclotron (Rindi and Baarli, 1963). (e) Fast-neutron fluence density measurements performed at the Deutsches Electronen Synchrotron 7.5 GeV Electron Synchrotron (Bathow *et al.*, 1966). (f) Fast-neutron fluence density measurements performed at the Rutherford Laboratory Proton Linear Accelerator for a proton beam of 50 MeV (Simpson and Laws, 1962; Thomas *et al.*, 1962). (g) Measurements made at the 12 GeV Proton Synchrotron at KEK (IAEA, 1988).

Skyshine을 직접 평가해보자

Table 2. List of semi-empirical formulae and parameters



Semi-empirical formulas	Parameters
Rindi and Thomas (1975) [2] $\phi(r) = \frac{aQe^{-r/\lambda}}{4\pi r^2}$ $H(r) = g\phi(r)$	ϕ : Neutron flux density a : Source enhancement factor Q : Effective source strength (n/s) of neutrons emitted from the shield surface H : Dose equivalent for neutron λ : Effective absorption length in air r : Distance from a source to a considering point
Stevenson and Thomas (1984) [4]	κ : $1.5 \sim 3.0$ $H(r) = \frac{\kappa Qe^{-r/\lambda(E_c)}}{r^2} \times 10^{-15}$ Sv.m^2/n $\lambda(E_c)$: Effective absorption length at cut-off energy, E_c
Stapleton and O'Brien (1994) [3] $H(r) = \frac{aQe^{-r/\lambda(E_c)}}{(b+c)^2}$	a : 2.0×10^{-15} Sv.m^2/n b : 40 m

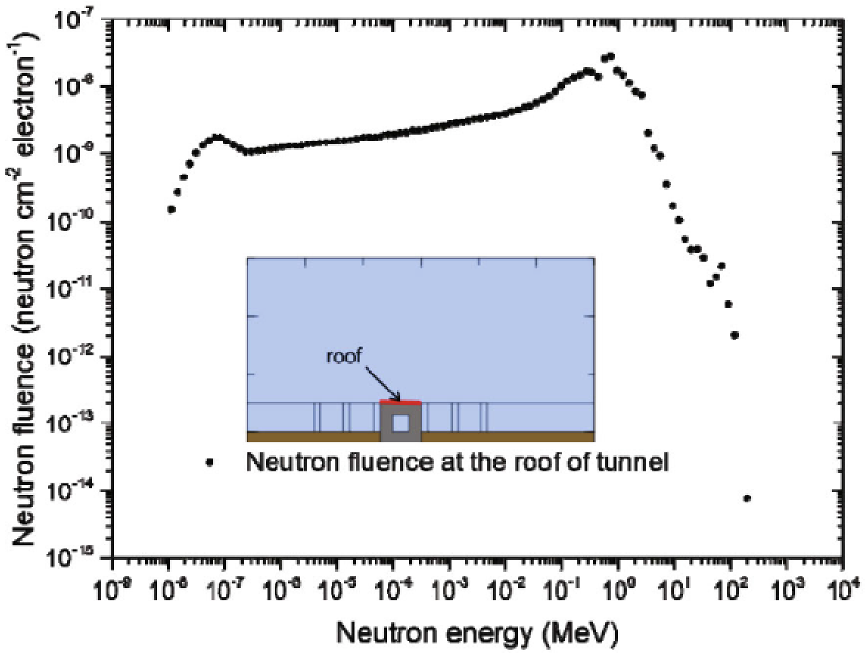


Fig. 6. (Color online) Neutron fluence at the roof surface of accelerator tunnel with 2 m-thick concrete shielding (calculated using the PHITS code).

Skyshine을 직접 평가해보자

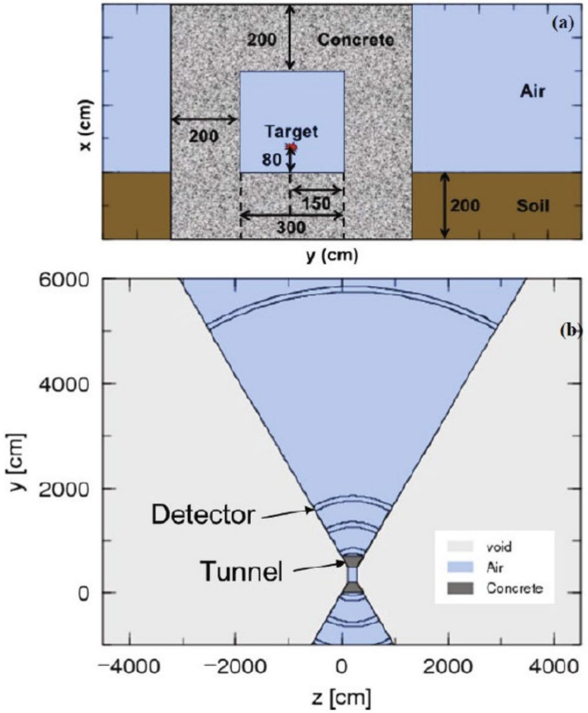

(a)
200
Concrete
Air
x (cm)
200
Target
80
150
300
200
Soil
y (cm)
(b)
6000
4000
2000
0
y [cm]
Detector
Tunnel
void
Air
Concrete
−4000
−2000
0
2000
4000
z [cm]

Fig. 5. (Color online) Input geometry of accelerator tunnel and off-site area in the PHITS code for calculating secondary neutron fluence from outer surface of accelerator building to a distance of 1 km: (a) cross-sectional view and (b) top view.

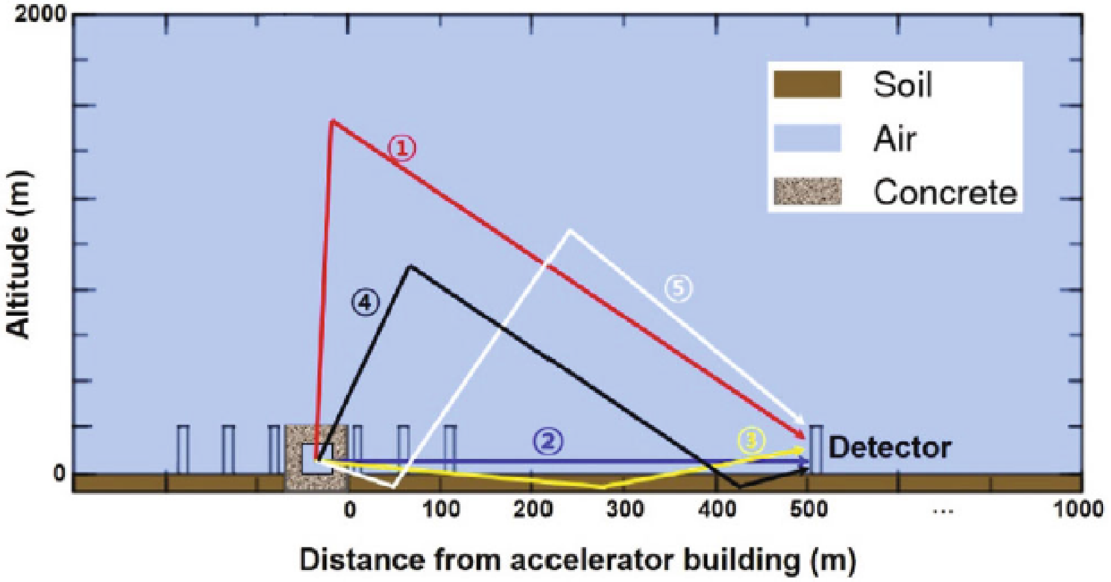

2000
0
Altitude (m)
Soil
Air
Concrete
①
②
③
④
⑤
Detector
0
100
200
300
400
500
...
1000
Distance from accelerator building (m)

Fig. 2. (Color online) Classification of transport paths of secondary neutrons from the accelerator building: (1) skyshine, (2) direct, (3) groundshine, (4)&(5) multiple-shine.

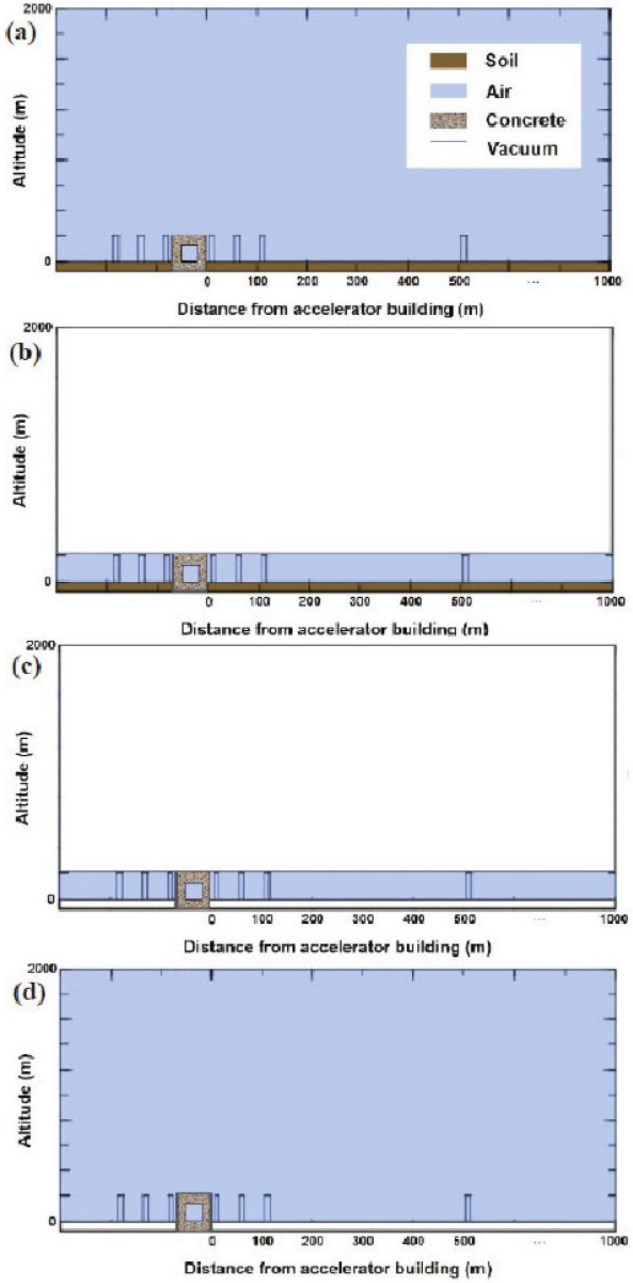

(a)
2000
0
Altitude (m)
Soil
Air
Concrete
Vacuum
0
100
200
300
400
500
...
1000
Distance from accelerator building (m)
(b)
(c)
(d)

Fig. 3. (Color online) Calculation methods for the separation of transport paths of secondary neutrons from the accelerator building: the transport paths for (a) total (b) direct and groundshine (c) direct, and (d) skyshine and direct.

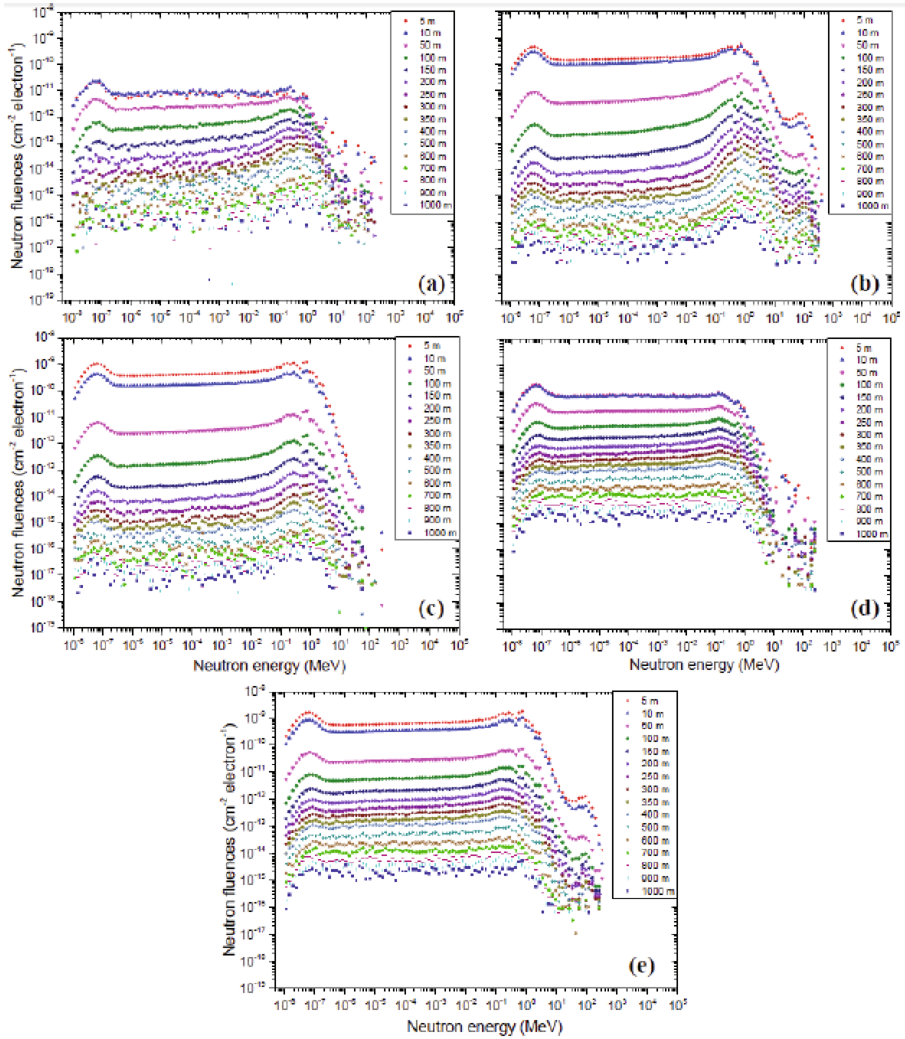


Fig. 8. (Color online) Distributions of differential neutron fluences at different distances from the accelerator tunnel for each transport path: (a) skyshine, (b) direct, (c) groundshine, (d) multiple-shine, and (e) all paths (calculated using the PHITS code).

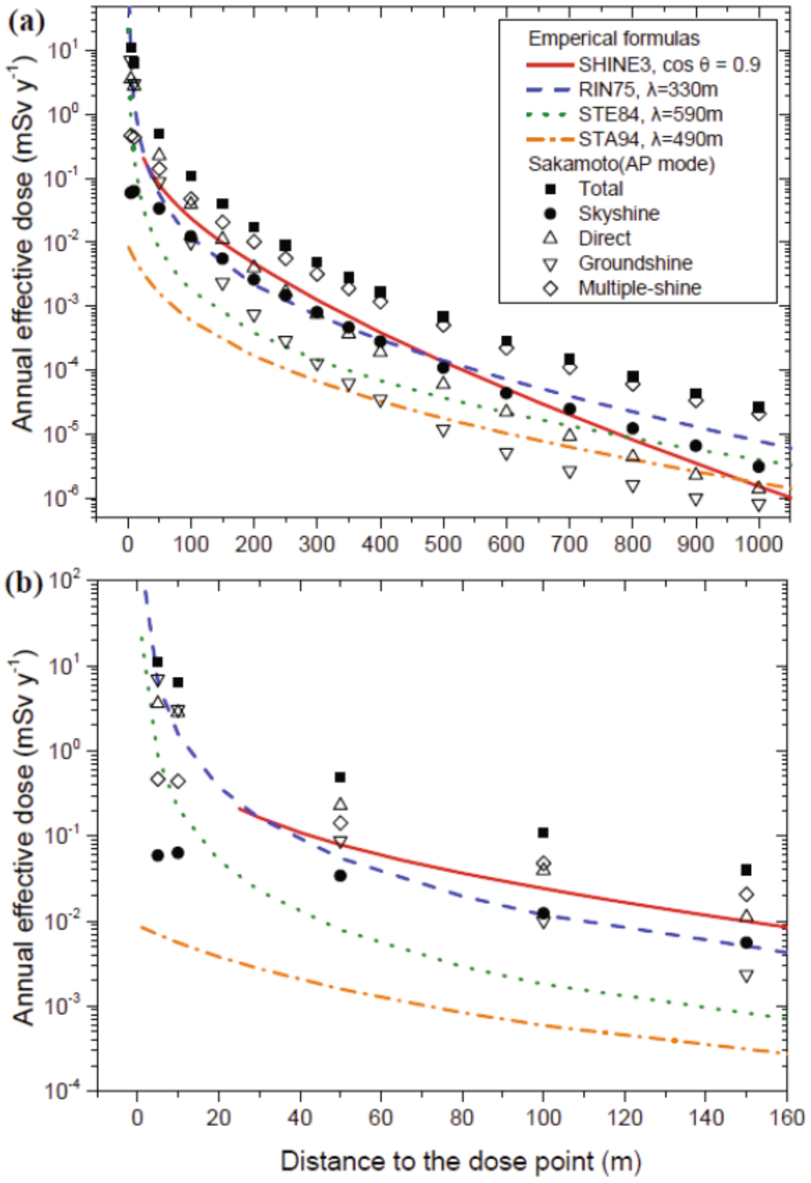
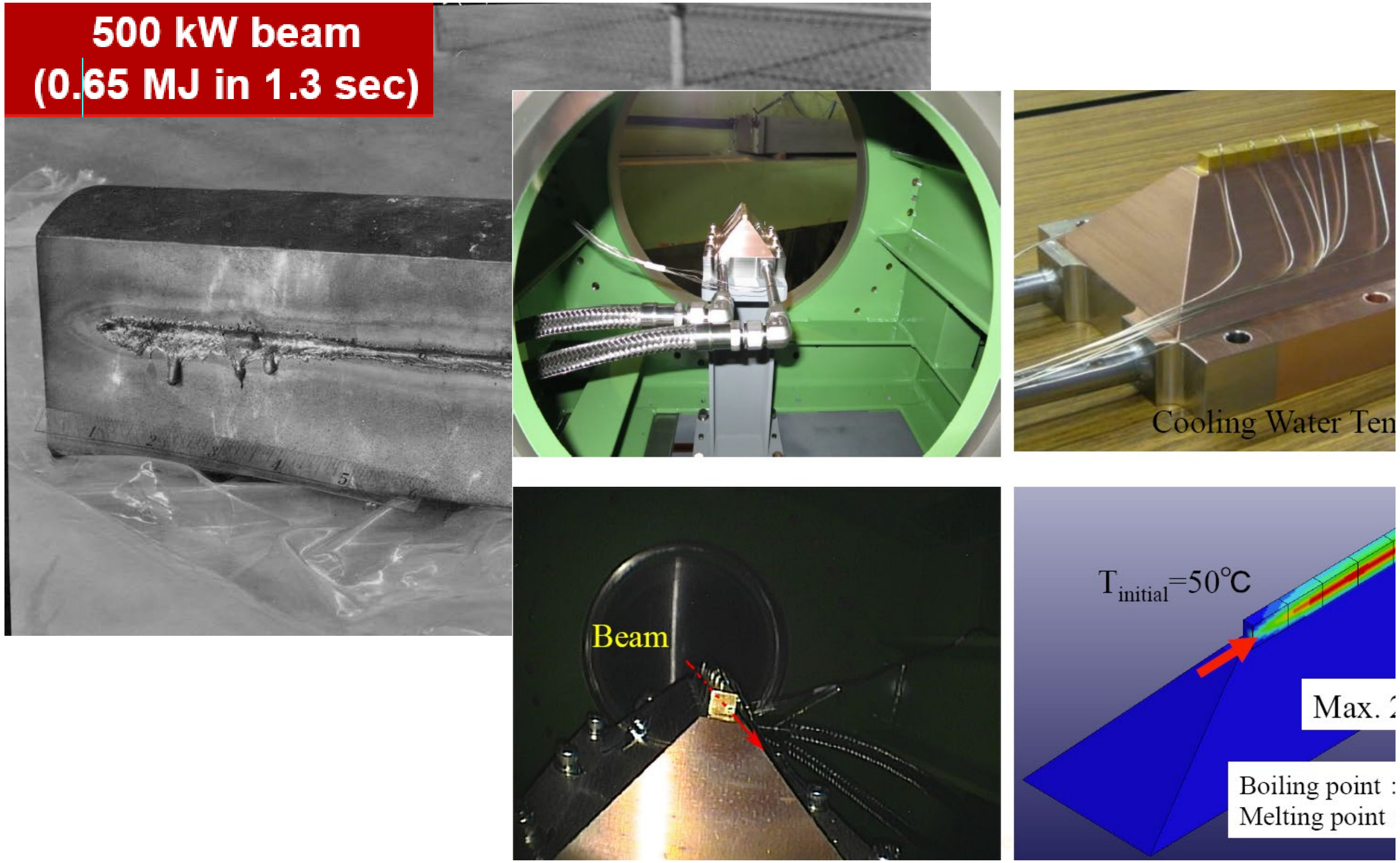


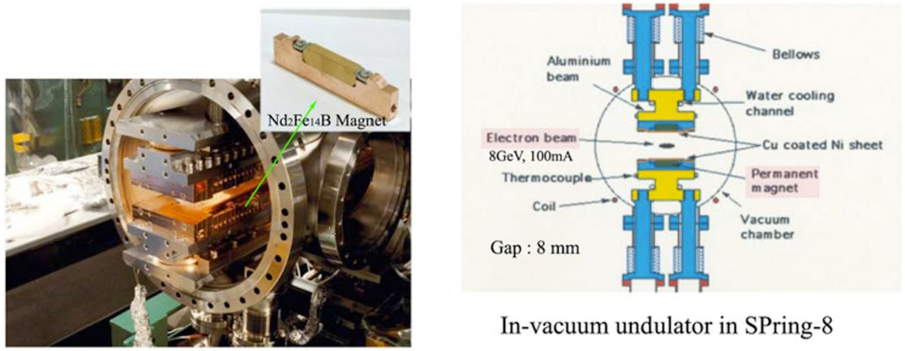
Fig. 9. (Color online) Comparison of the annual neutron effective dose as a function of the distance from tunnel by using Sakamoto's dose conversion factors [15] with the dose calculated by using various semi-empirical formulas: (a) up to 1 km distance and (b) up to the PAL-XFEL boundary from the accelerator tunnel. Rin75, STE84 and STA94 were used with the semi-empirical formulas of Rindi and Thomas [2], Stevenson and Thomas [4], and Stapleton and O'Brien [3].

방사선 손상

- 방사선 안전 관점에서 위험한가?

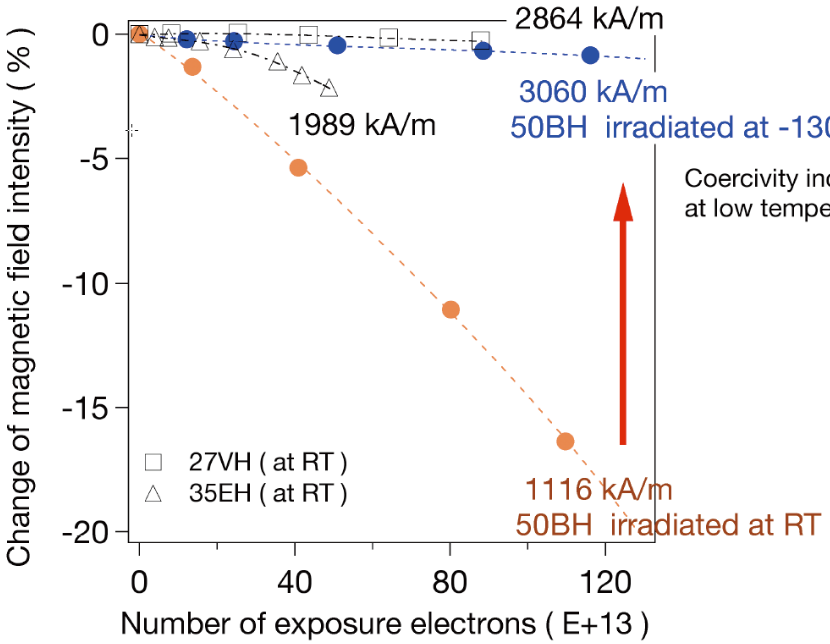

500 kW beam
(0.65 MJ in 1.3 sec)
Cooling Water Ten
Beam
T_initial=50°C
Max. 2
Boiling point :
Melting point

삽입장치-Undulator


Nd2Fe14B Magnet
Aluminium beam
Bellows
Water cooling channel
Electron beam
8GeV, 100mA
Cu coated Ni sheet
Thermocouple
Permanent magnet
Coil
Vacuum chamber
Gap : 8 mm

In-vacuum undulator in SPring-8

Resistance to radiation increases at low temperature

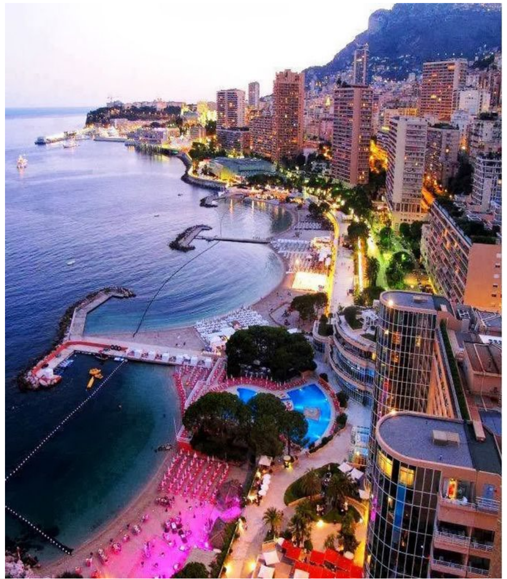


8

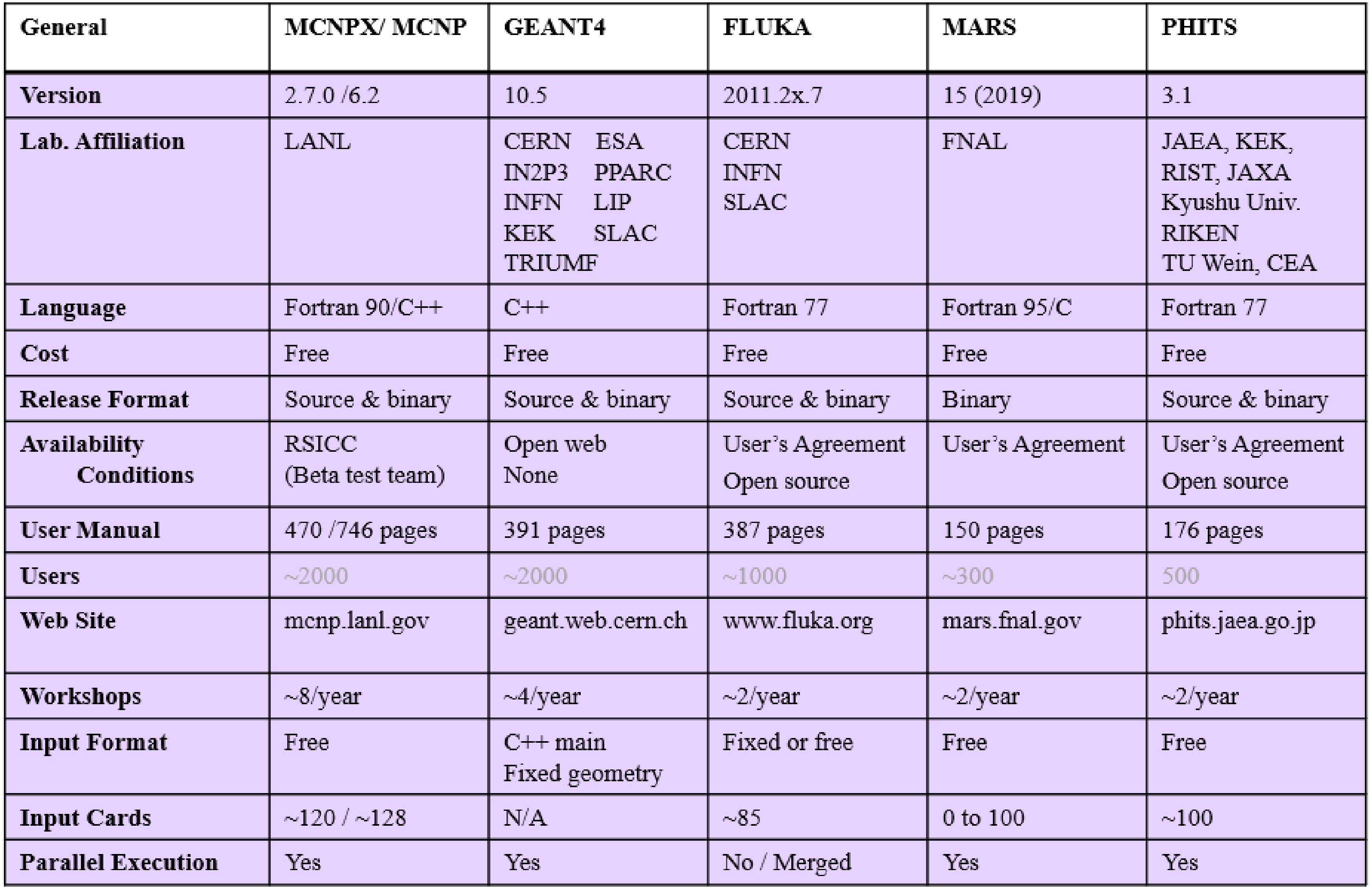
Monte Carlo 코드의 발전 동향

(사실적 모사 / 기초데이터의 정확성)

Monte Carlo in Monaco



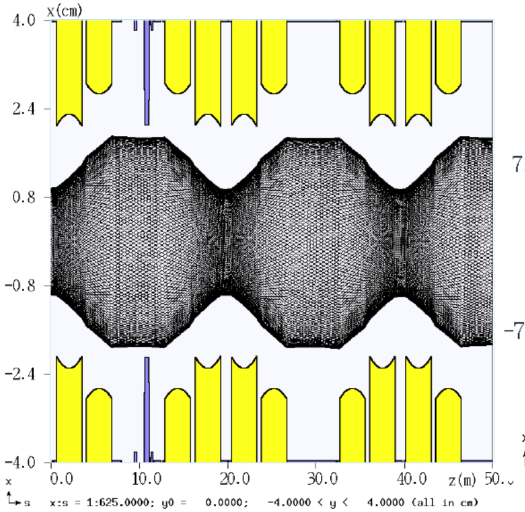
Multiparticle Monte Carlo codes



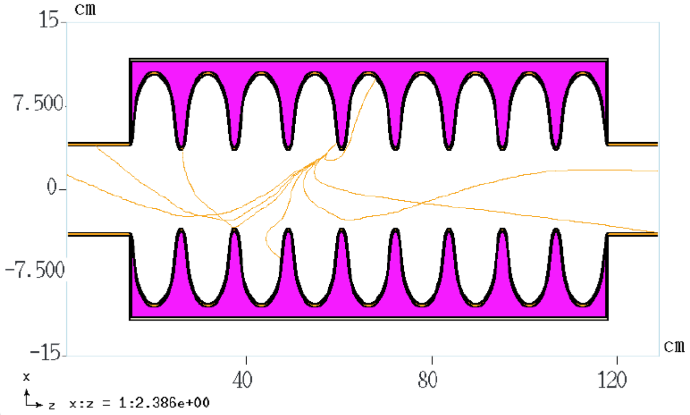
General	MCNPX/ MCNP	GEANT4	FLUKA	MARS	PHITS
Version	2.7.0 /6.2	10.5	2011.2x.7	15 (2019)	3.1
Lab. Affiliation	LANL	CERN ESA IN2P3 PPARC INFN LIP KEK SLAC TRIUMF	CERN INFN SLAC	FNAL	JAEA, KEK, RIST, JAXA Kyushu Univ. RIKEN TU Wein, CEA
Language	Fortran 90/C++	C++	Fortran 77	Fortran 95/C	Fortran 77
Cost	Free	Free	Free	Free	Free
Release Format	Source & binary	Source & binary	Source & binary	Binary	Source & binary
Availability Conditions	RSICC (Beta test team)	Open web None	User's Agreement Open source	User's Agreement	User's Agreement Open source
User Manual	470 /746 pages	391 pages	387 pages	150 pages	176 pages
Users	~2000	~2000	~1000	~300	500
Web Site	mcnp.lanl.gov	geant.web.cern.ch	www.fluka.org	mars.fnal.gov	phits.jaea.go.jp
Workshops	~8/year	~4/year	~2/year	~2/year	~2/year
Input Format	Free	C++ main Fixed geometry	Fixed or free	Free	Free
Input Cards	~120 / ~128	N/A	~85	0 to 100	~100
Parallel Execution	Yes	Yes	No / Merged	Yes	Yes

Current Trends : Beam Line Builder

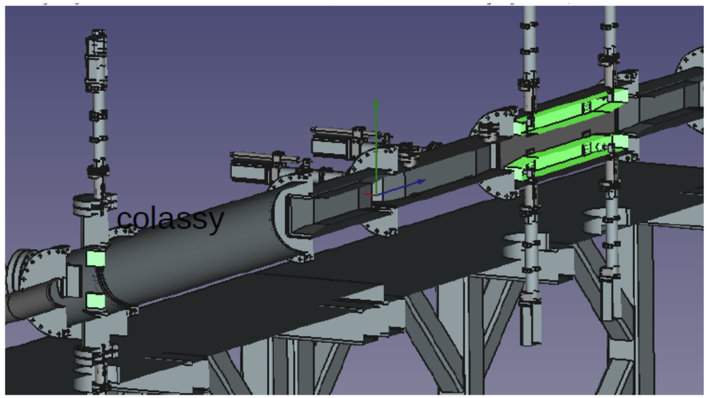
Extended Cross-over with beam transport simulation program MARS15 + MAX-D (Imagine again HUGE facility!)

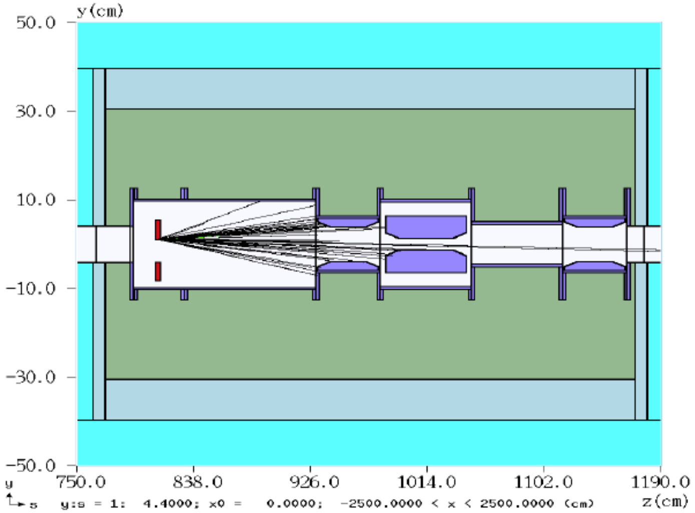


3-sigma proton beam envelope in the Fermilab booster, E=400MeV - MAD-X PTC module.



Trajectories of a field emitted electronts, E ~ 5 eV in ILC (LCLS) cavities for several time moments – CavityStepper

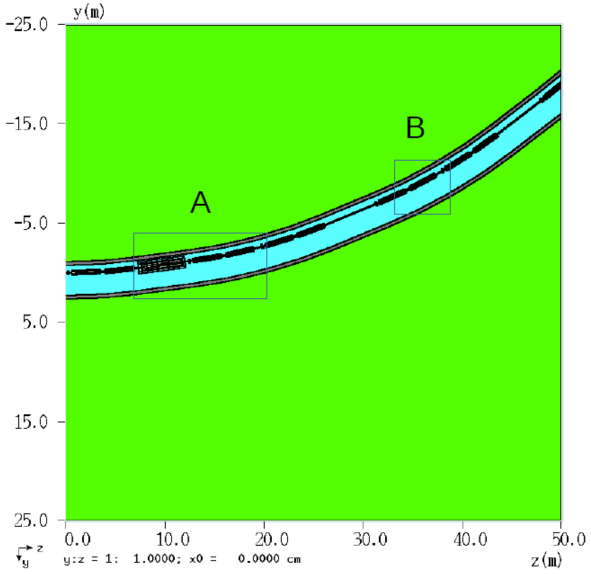




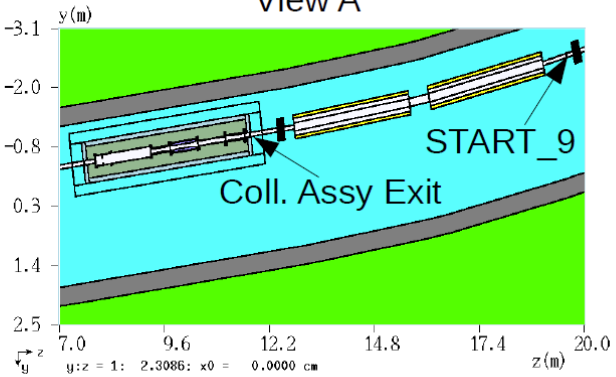
Courtesy Tropin

Current Trends : Beam Line Builder

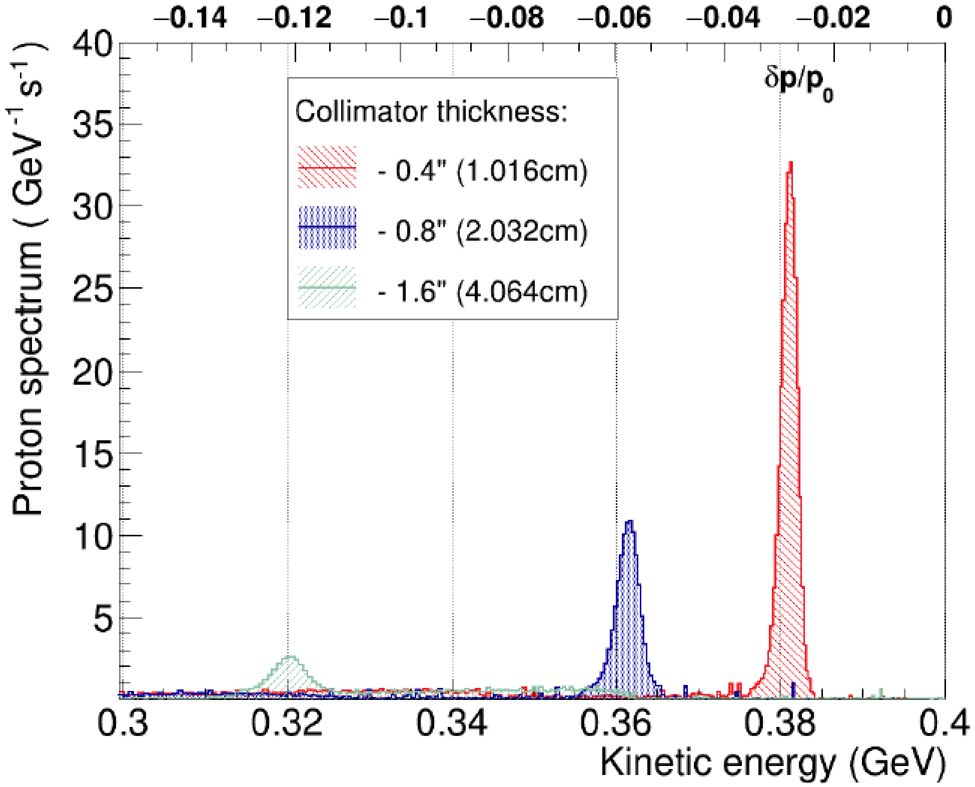
Easy to get particle information at marked (scoring) points


y(m)
-25.0
-15.0
-5.0
5.0
15.0
25.0
A
B
0.0
10.0
20.0
30.0
40.0
50.0
z(m)
y:z = 1: 1.0000; x0 = 0.0000 cm

View A


y(m)
-3.1
-2.0
-0.8
0.3
1.4
2.5
START_9
Coll. Assy Exit
7.0
9.6
12.2
14.8
17.4
20.0
z(m)
y:z = 1: 2.3086; x0 = 0.0000 cm

Courtesy Tropin



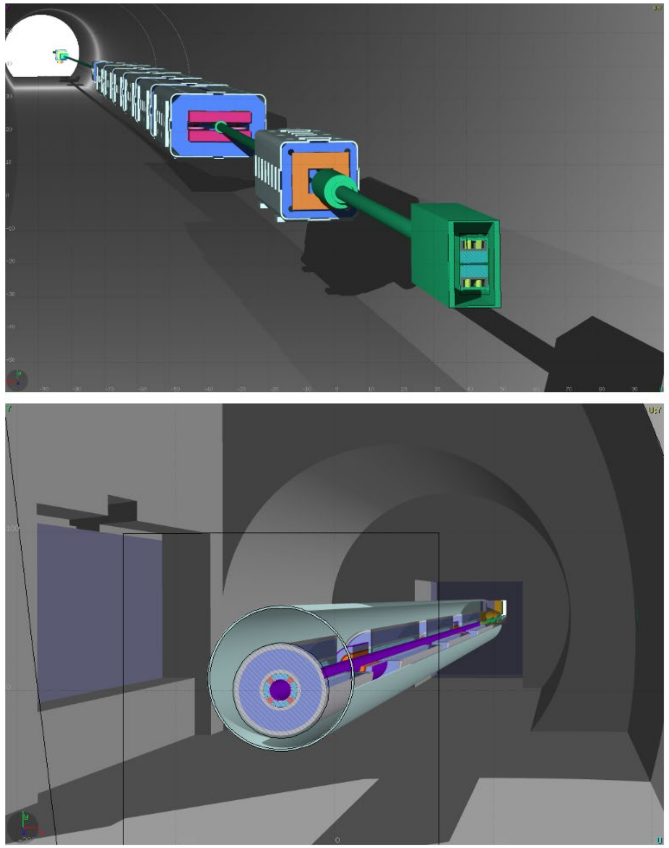
Proton Spectra Inside Aperture at Exit of Collimator Unit: Horizontal Collimator

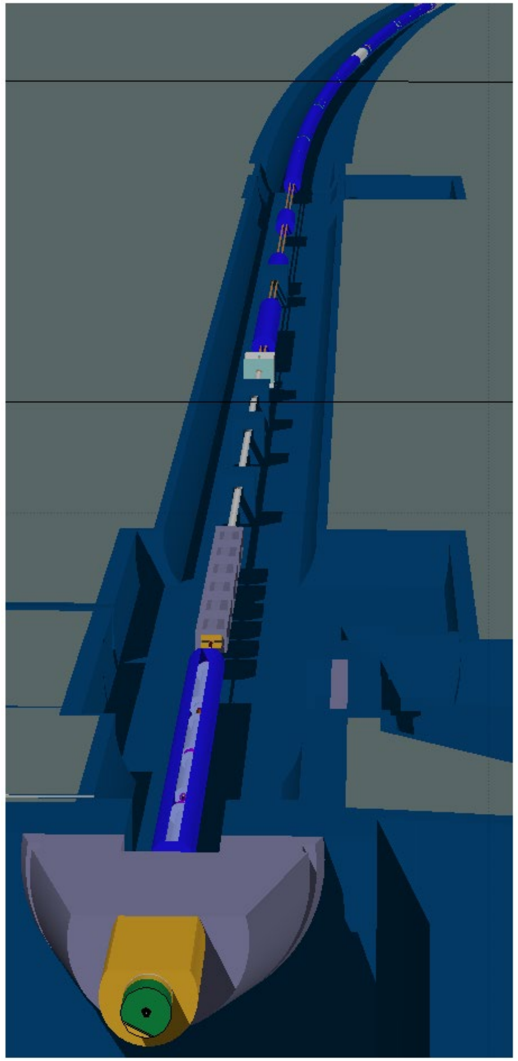
Current Trends : Beam Line Builder

Extended Cross-over with beam transport simulation program - FLUKA Line Builder

- Super fast at stitching elements (Element database)
- Easy to use once configured, one command
- Easy to use accelerator planning files as construction plan
- Requires a Twiss file (output from transport code), which is prone to maths errors
- Accuracy with FLUKA ~ 1 um
- Easy to handle the complicated element and strutures

Courtesy Cowley

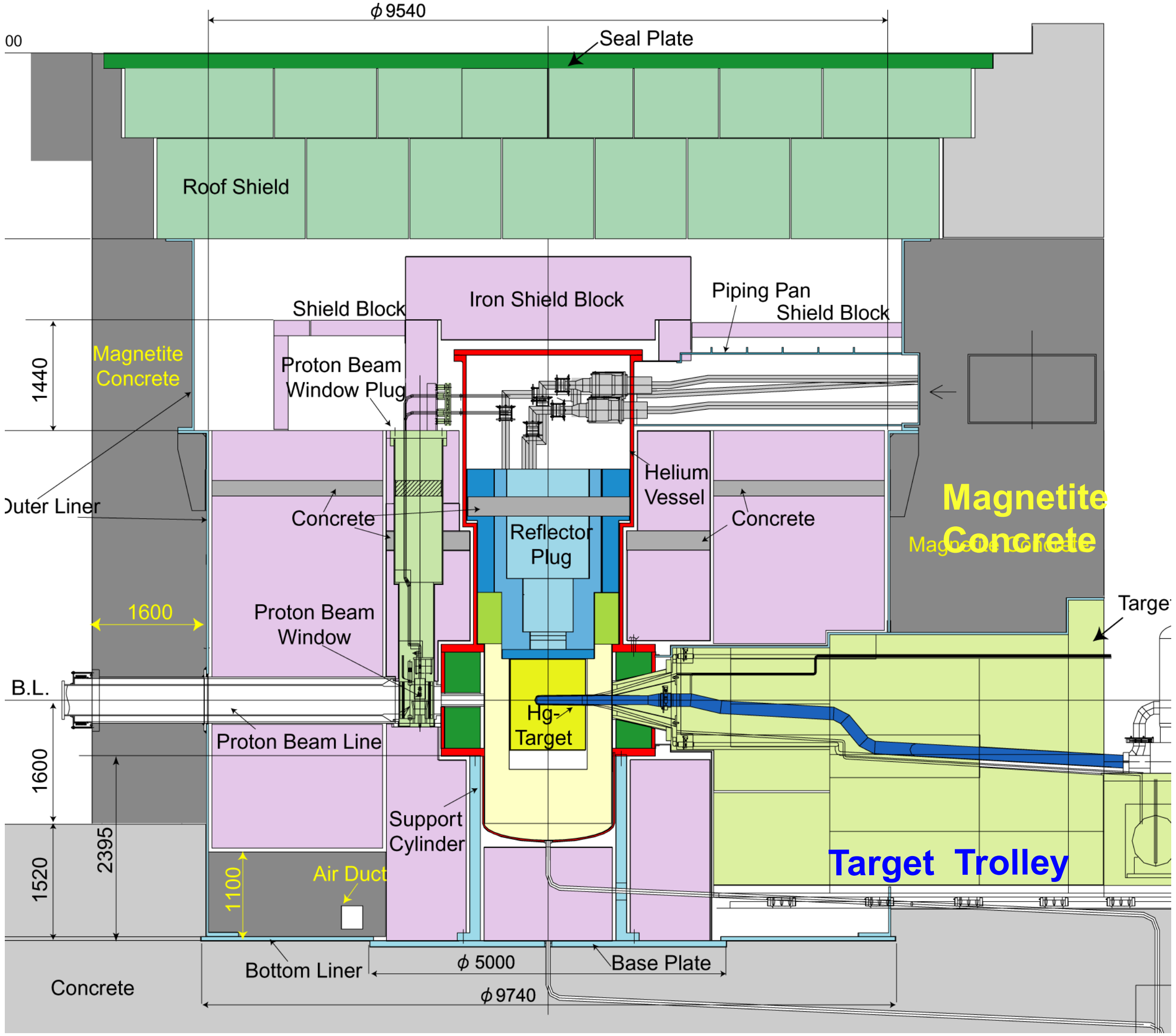




Simulation Capabilities (JPARC/MLF)

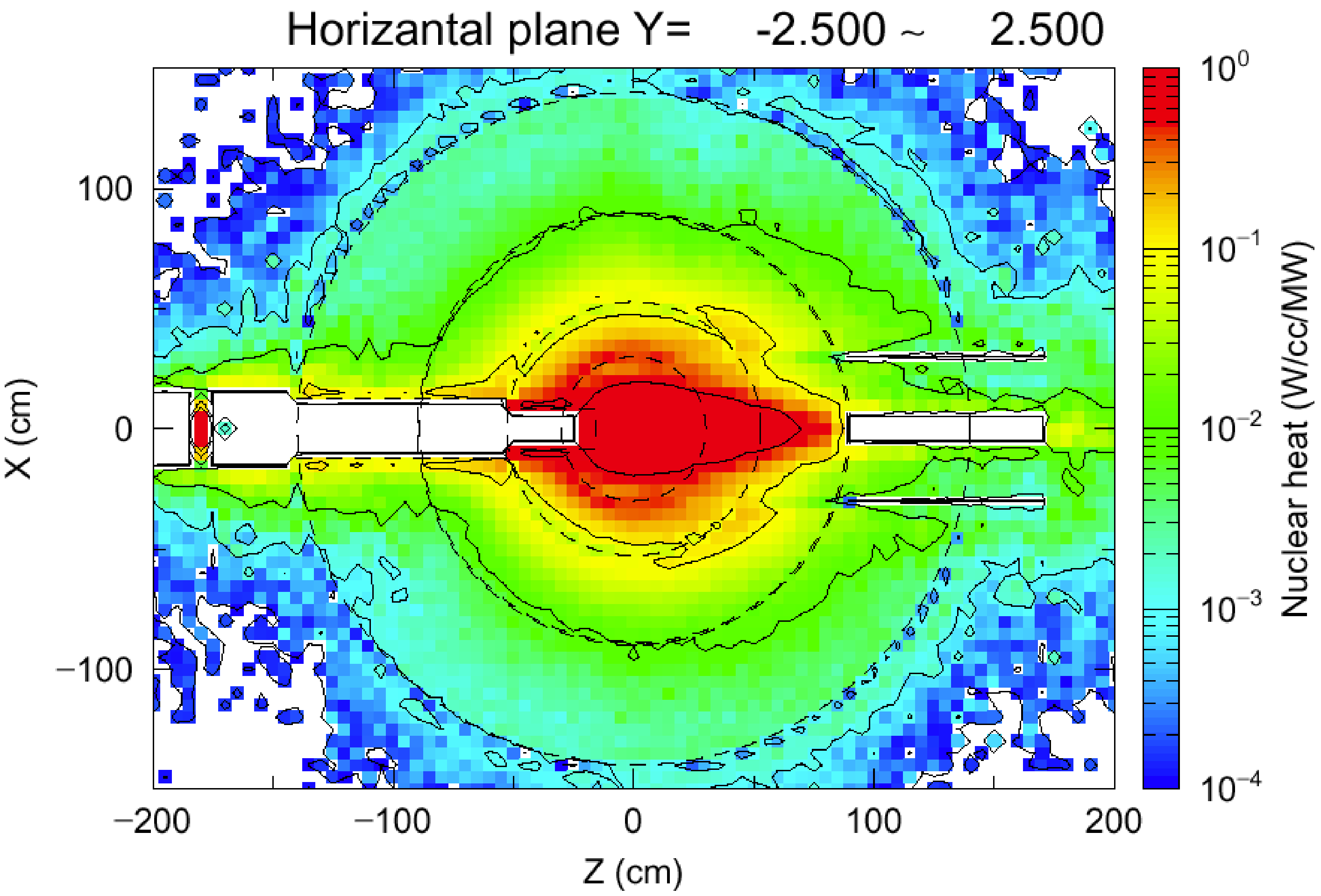
Specification

- 3GeV, 1MW, 25Hz Proton beam
- Mercury target of 1.4m^3
- Three moderators with liquid hydrogen of 260L
- Shield of about 10,000t
- Movable target structure


ϕ9540
Seal Plate
00
Roof Shield
Shield Block
Iron Shield Block
Piping Pan
Shield Block
Magnetite
Concrete
1440
Proton Beam
Window Plug
Helium
Vessel
Outer Liner
Concrete
Concrete
Reflector
Plug
Magnetite
Concrete
Magnetite Concrete
1600
Proton Beam
Window
Targe
B.L.
Hg
Target
Proton Beam Line
1600
Support
Cylinder
2395
1520
1100
Air Duct
Target Trolley
Bottom Liner
ϕ 5000
Base Plate
Concrete
ϕ9740

Simulation Capabilities (JPARC/MLF)

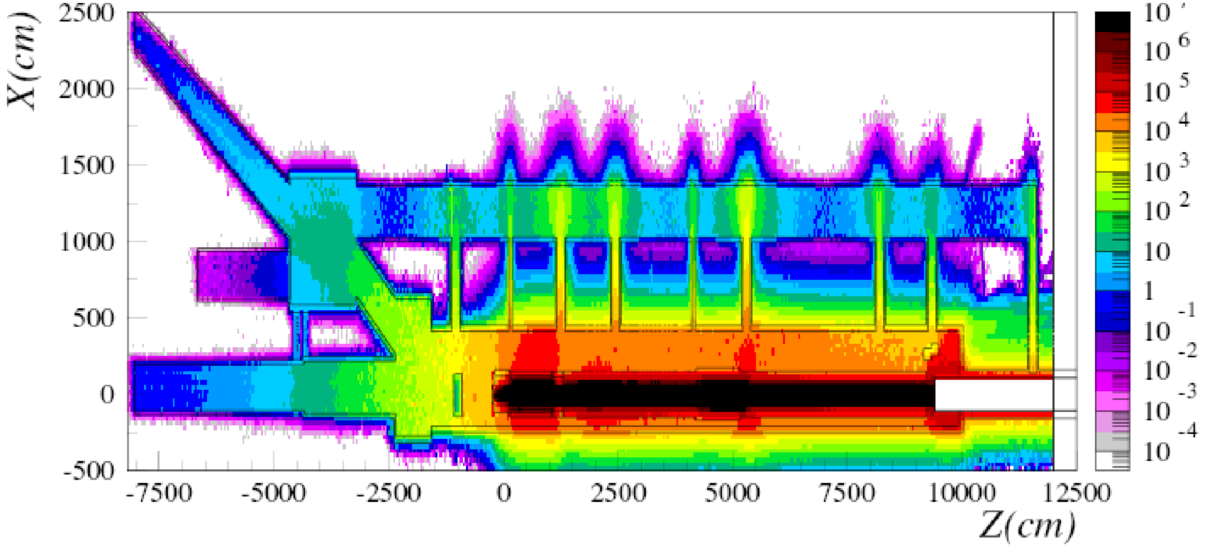
Distribution of nuclear heat on horizontal plane around mercury target



Simulation Capabilities (JPARC/MLF)

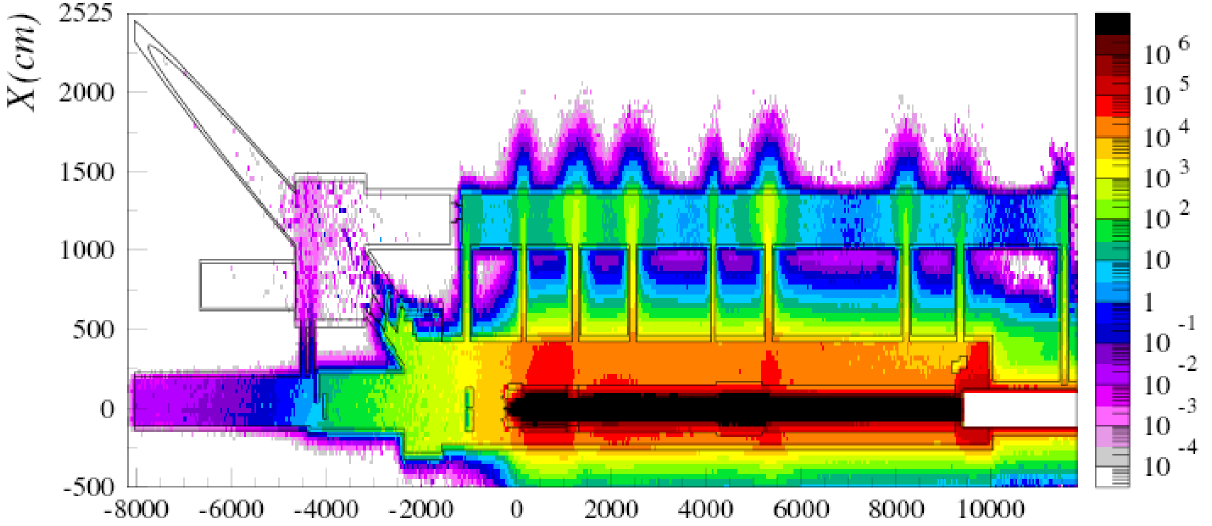
Annual Dose in Shielding Cal.(FLUKA)

Without Shielding



4.5 x 10^{19} protons / year

With New Shielding



Simulation Capabilities (JPARC/MLF)

미래기반 가속기
전문인력양성 사업단

Estimation of Aircrew Dose & Impact of Solar Flare (PHITS)

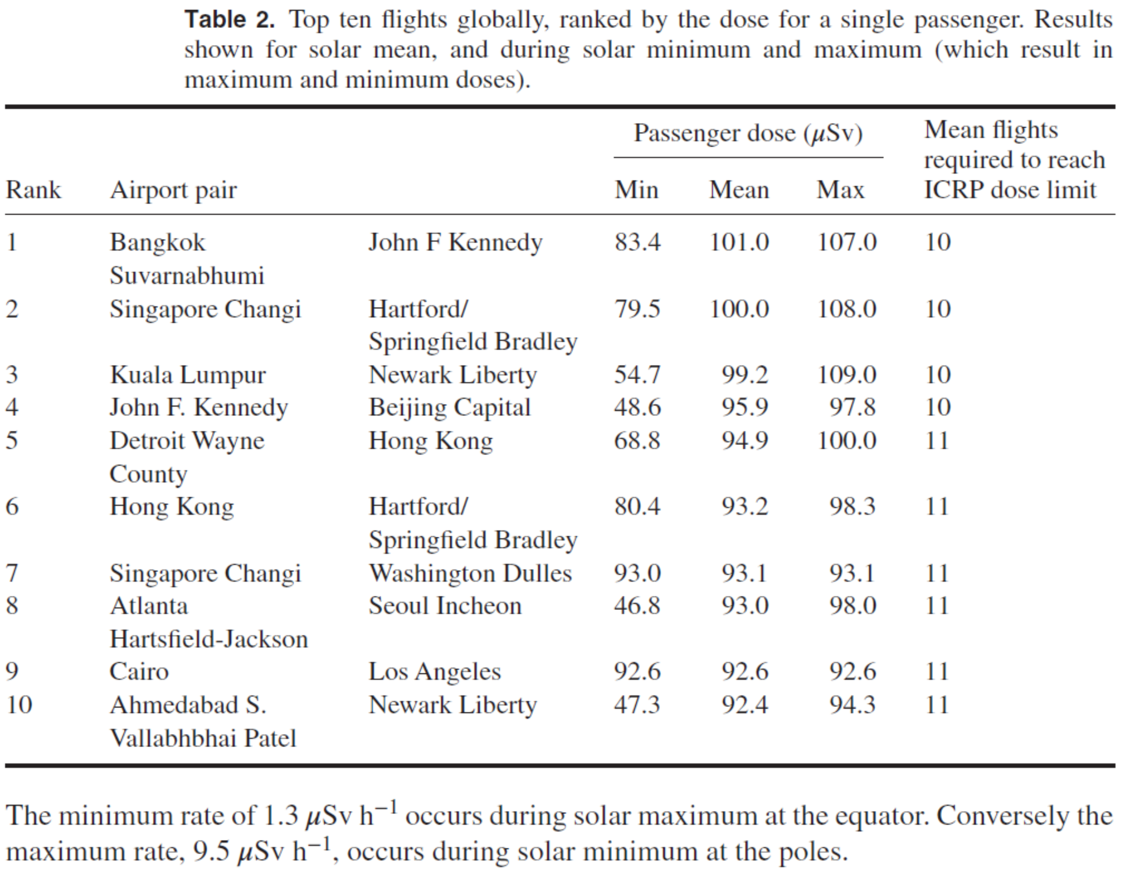


Table 2. Top ten flights globally, ranked by the dose for a single passenger. Results shown for solar mean, and during solar minimum and maximum (which result in maximum and minimum doses).

Rank	Airport pair		Passenger dose (μSv)			Mean flights required to reach ICRP dose limit
			Min	Mean	Max	
1	Bangkok Suvarnabhumi	John F Kennedy	83.4	101.0	107.0	10
2	Singapore Changi	Hartford/ Springfield Bradley	79.5	100.0	108.0	10
3	Kuala Lumpur	Newark Liberty	54.7	99.2	109.0	10
4	John F. Kennedy	Beijing Capital	48.6	95.9	97.8	10
5	Detroit Wayne County	Hong Kong	68.8	94.9	100.0	11
6	Hong Kong	Hartford/ Springfield Bradley	80.4	93.2	98.3	11
7	Singapore Changi	Washington Dulles	93.0	93.1	93.1	11
8	Atlanta Hartsfield-Jackson	Seoul Incheon	46.8	93.0	98.0	11
9	Cairo	Los Angeles	92.6	92.6	92.6	11
10	Ahmedabad S. Vallabhbhai Patel	Newark Liberty	47.3	92.4	94.3	11

The minimum rate of 1.3 μSv h^{-1} occurs during solar maximum at the equator. Conversely the maximum rate, 9.5 μSv h^{-1}, occurs during solar minimum at the poles.

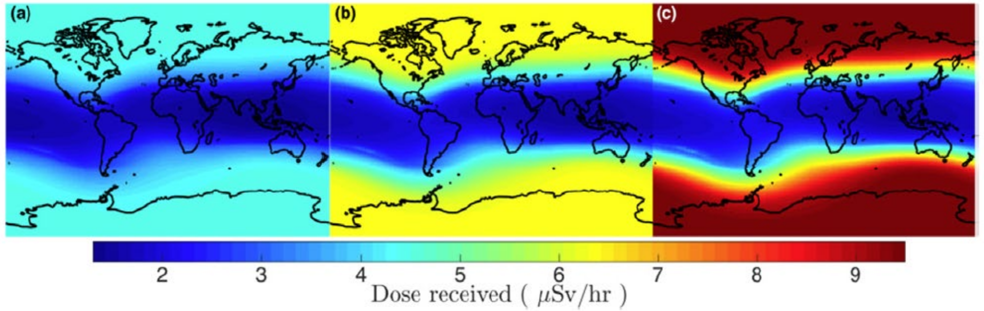
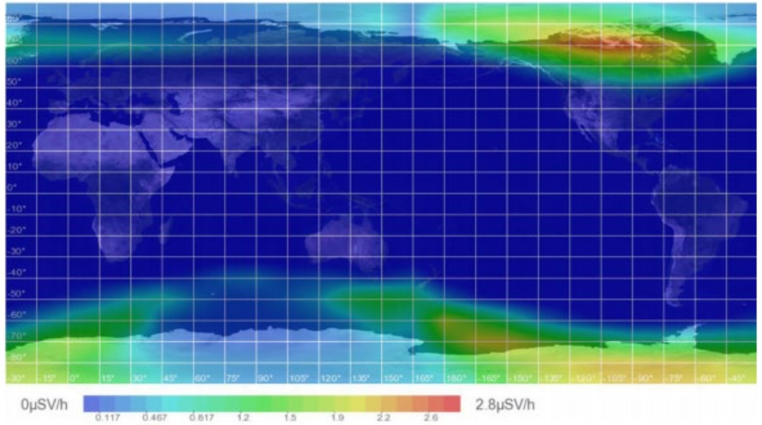


Figure 2. Global dose rate maps at 35 000 ft for (a) maximum, (b) mean, and (c) minimum solar modulation potential.

J. Radiol. Prot. **36** (2016) 93–103



Radiation dose rate map at flight altitude during solar flare on Sep. 2017

Courtesy T. Sato

가속기 방사선안전의 동향

1. 각종 계산 코드의 진화 : *FLUKA, PHITS, MARS, MCNP(X), GEANT4.*

2. 새로운 방사선원에 대한 연구: Wake-field Accelerator, High power laser.

3. 새로운 운전변수에 대한 준비: FCC, High Power Beam
   High-energy, High-power particle induced damage issue.

4. 규제기준의 변화 및 개발

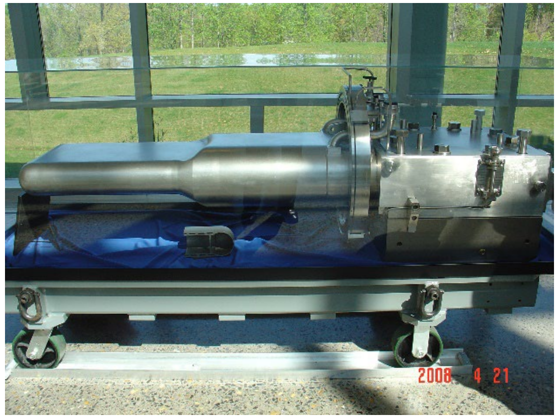
5. 방사성폐기물, 해체에 대한 연구 (Upgrade Project가 진행중)

6. 가속기시설 폐기후 환경복원에 대한 예비검토도 추진됨

Spallation Neutron Source, ORNL

방사선 관리 구역의 요건 : 원자력시설 (중성자생성표적) ➔ 가속기 시설

Pulsed Spallation Neutron Source
180 kW
2008 4 23



JPARC, JAEA

관리구역의 변경 (오염관리 구역설정) : 2012 ➔ 2016년