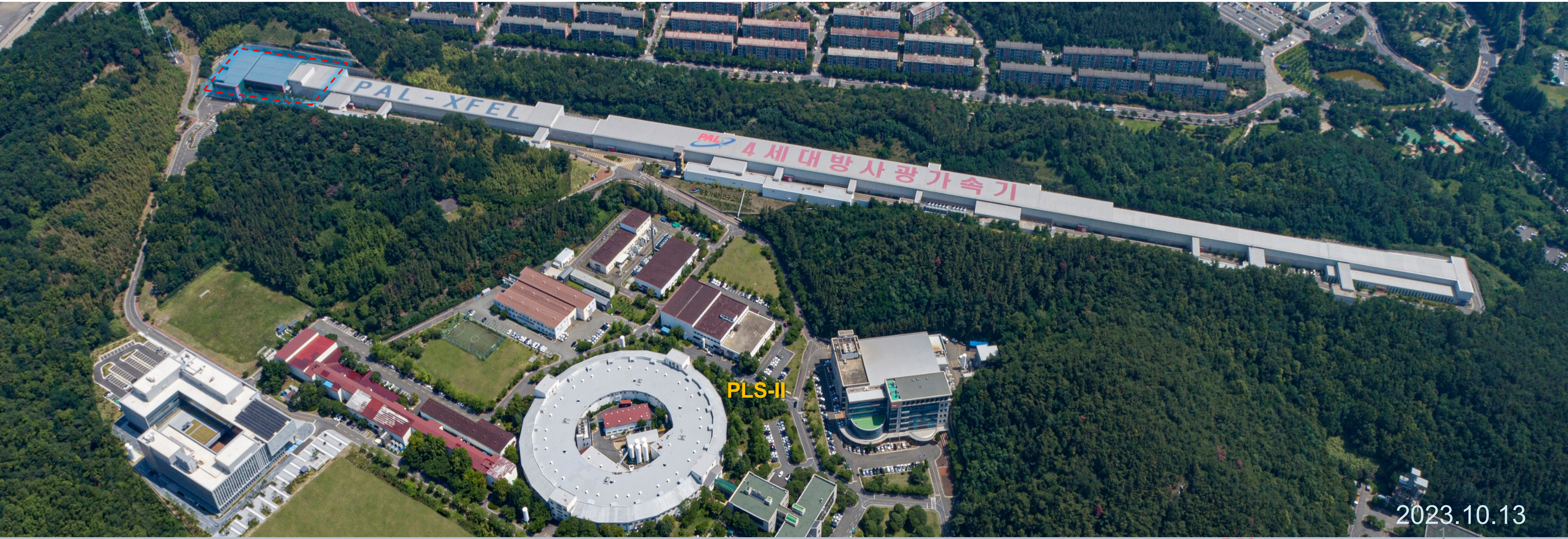
Wolfram Language Conference 2023, Seoul, Nov. 10, 2023

방사광 가속기 핵심 부품인 삽입장치 설계에서의 Mathematica 응용

포항가속기연구소 김동언



2023.10.13

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Meeting of two legends

- Taejoon Park from POSCO (the founder chairman)
- Hogil Kim from POSTECH (the first president)

The light brightening the Korea's Science

A Science Powerhouse for Korea's science and industry
- 6,000 researchers annually conducting about 1,600 experiments
- publishing 600 papers for the SCI journals

- 1986 Launch the Pohang Light Source(PLS) project by Dr. Hogil Kim (the first president of POSTECH)
- 1988 Foundation of PAL (Entire support by Mr. Taejoon Park) Construction of PLS initiated
- 1994 Completion of PLS construction (the 5th synchrotron light source in the world)
- 1995 User service opened (with 2 Beamlines)
- 2023 PLS-II 36 Beamlines, PAL-XFEL 3 Beamlines in operation

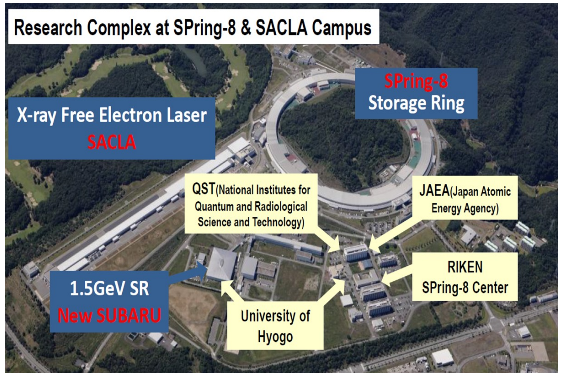
Global 5 Institutes

- 3rd Generation Synchrotron Light Source
- PAL-XFEL is also in operation

Competing for the world technological supremacy

Pohang Accelerator Laboratory

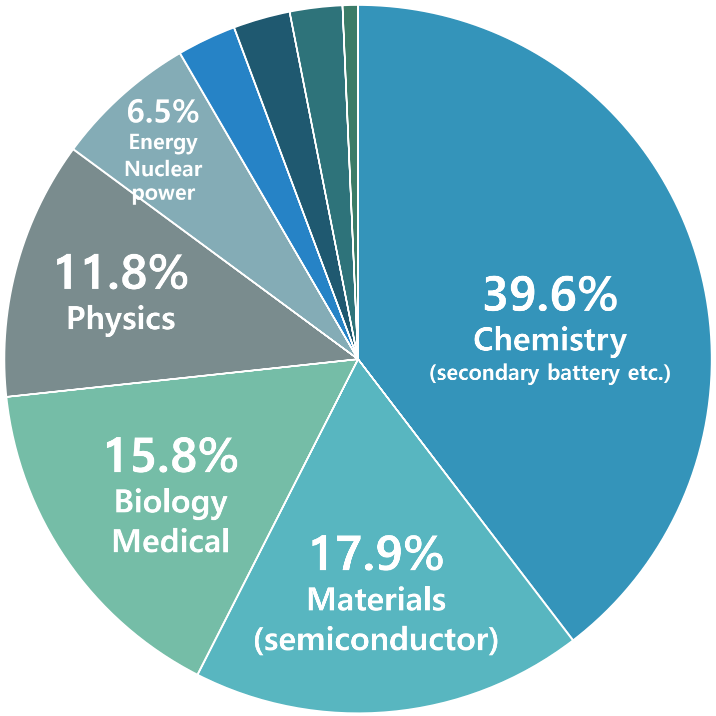
Institute	Country	3rd Generation Light Source	XFEL	Employees
PAL	KOREA	PLS-II	PAL-XFEL	223
SLAC	USA	SPEAR-III	LCLS	600
RIKEN	JAPAN	SPring-8	SACLA	450
DESY	GERMANY	PETRA-III	European XFEL	950
PSI	SWITZERLAND	SLS	SwissFEL	

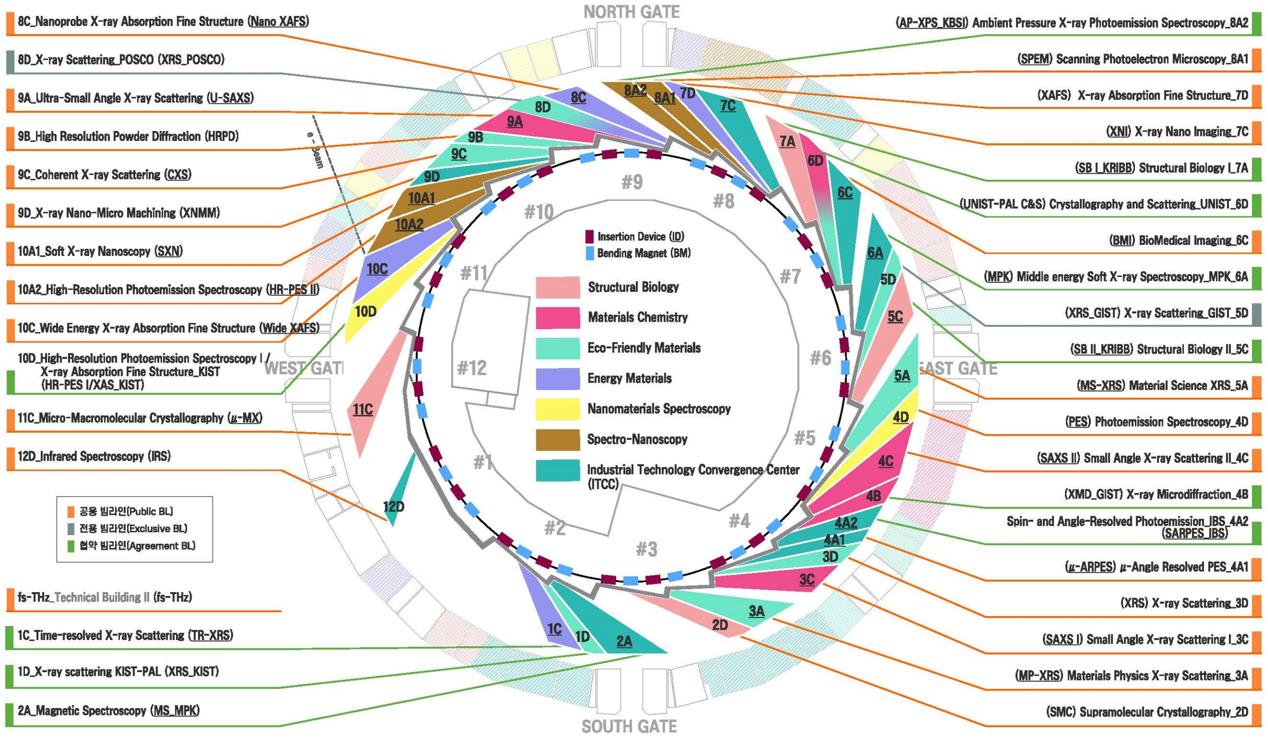


PLS-II Beamline Map and Research Area

Supporting the growth of new industries in Korea

Year	University	estic		International	Total
		Laboratory	Industry		
‘21	1,539 (82.3%)	234 (12.5%)	52 (2.8%)	46 (2.4%)	1,871
‘22	1,691 (84.2%)	220 (11.0%)	73 (3.6%)	25 (1.2%)	2,009

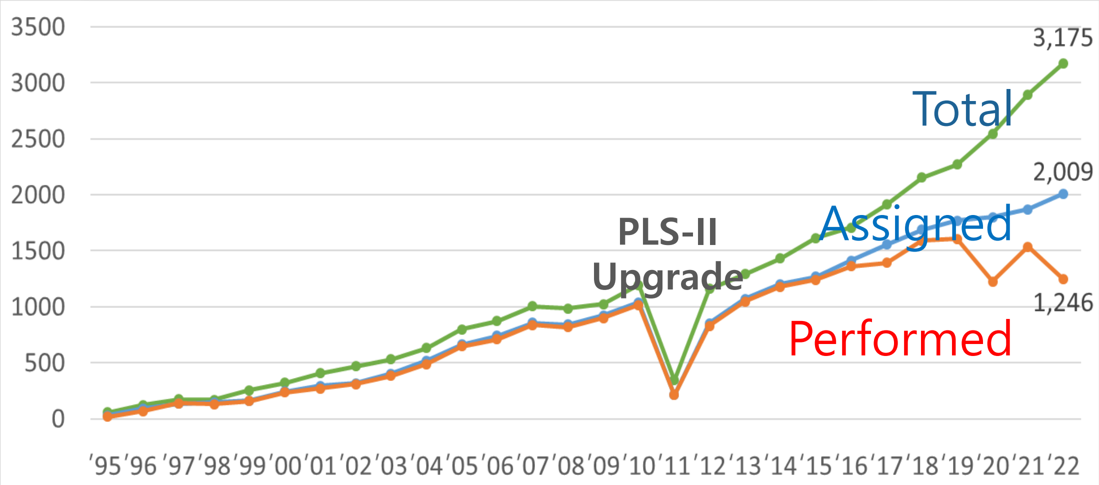


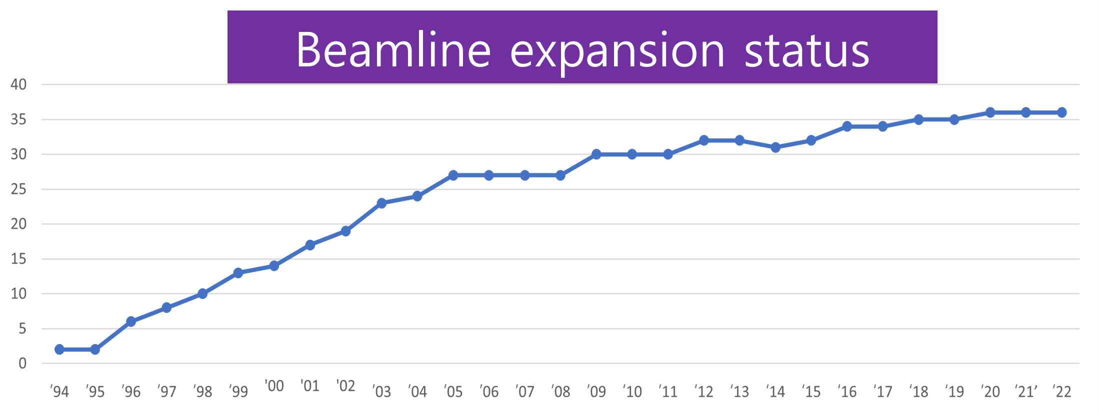


PLS-II Statistics of beamtime proposals & SCIE papers

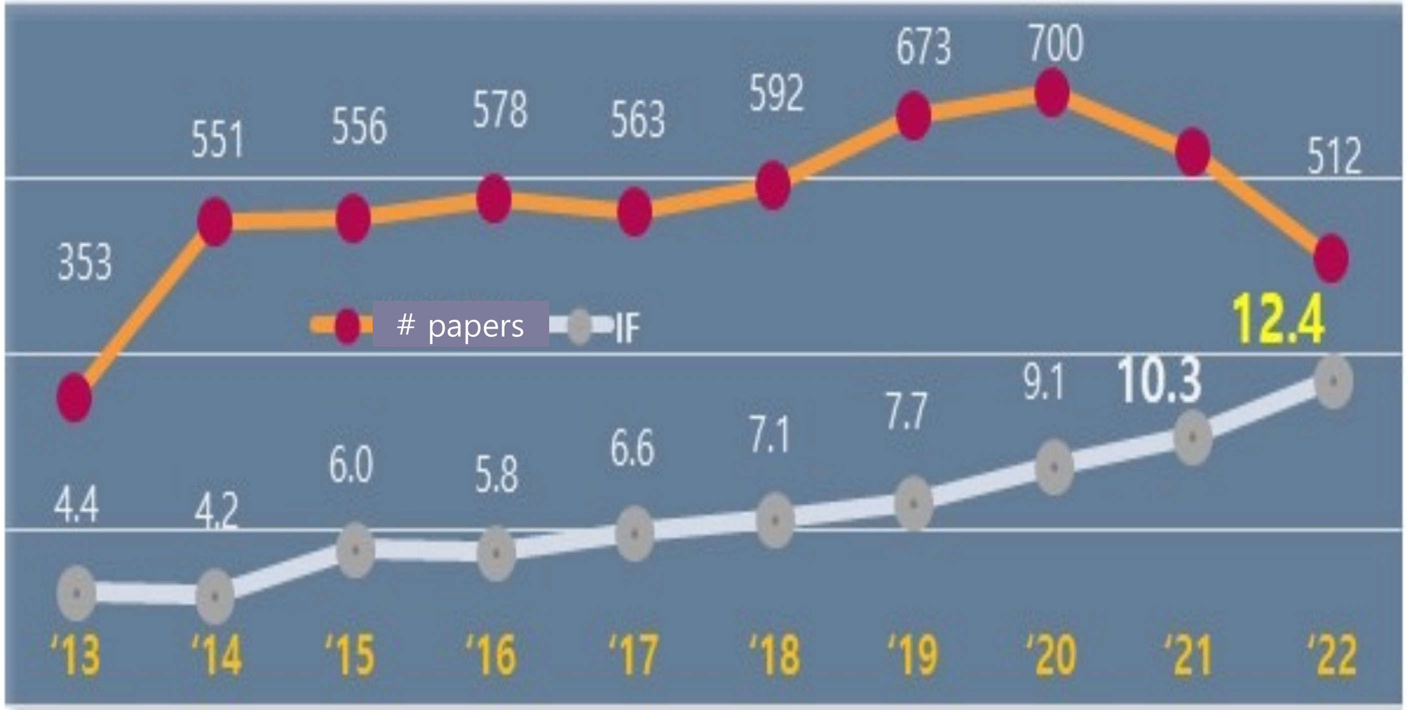
No. of Beamtime Proposals

Statistics of PLS-II Experiments and Proposals('22)





SCIE Papers (PLS-II+PAL XFEL)



4GSR Outline

- Project - Period: 2021 July to 2027 June (6yrs)
- Budget: 1.0454 Trillion KRW (≈ USD 750M)
- Land: 540,000 ㎡ / Building: 69,400 ㎡
- Location: Ochang, Chungcheongbuk-do

<4GSR Project Budget Plan> (Million USD)

Years	2021	2022	2023	2024	2025	2026	2027	Sum
Machine	8	44	77	172	180	97	28	606
Site	72	72	-	-	-	-	-	144
Sum	80	116	77	172	180	97	28	750

4GSR Specifications

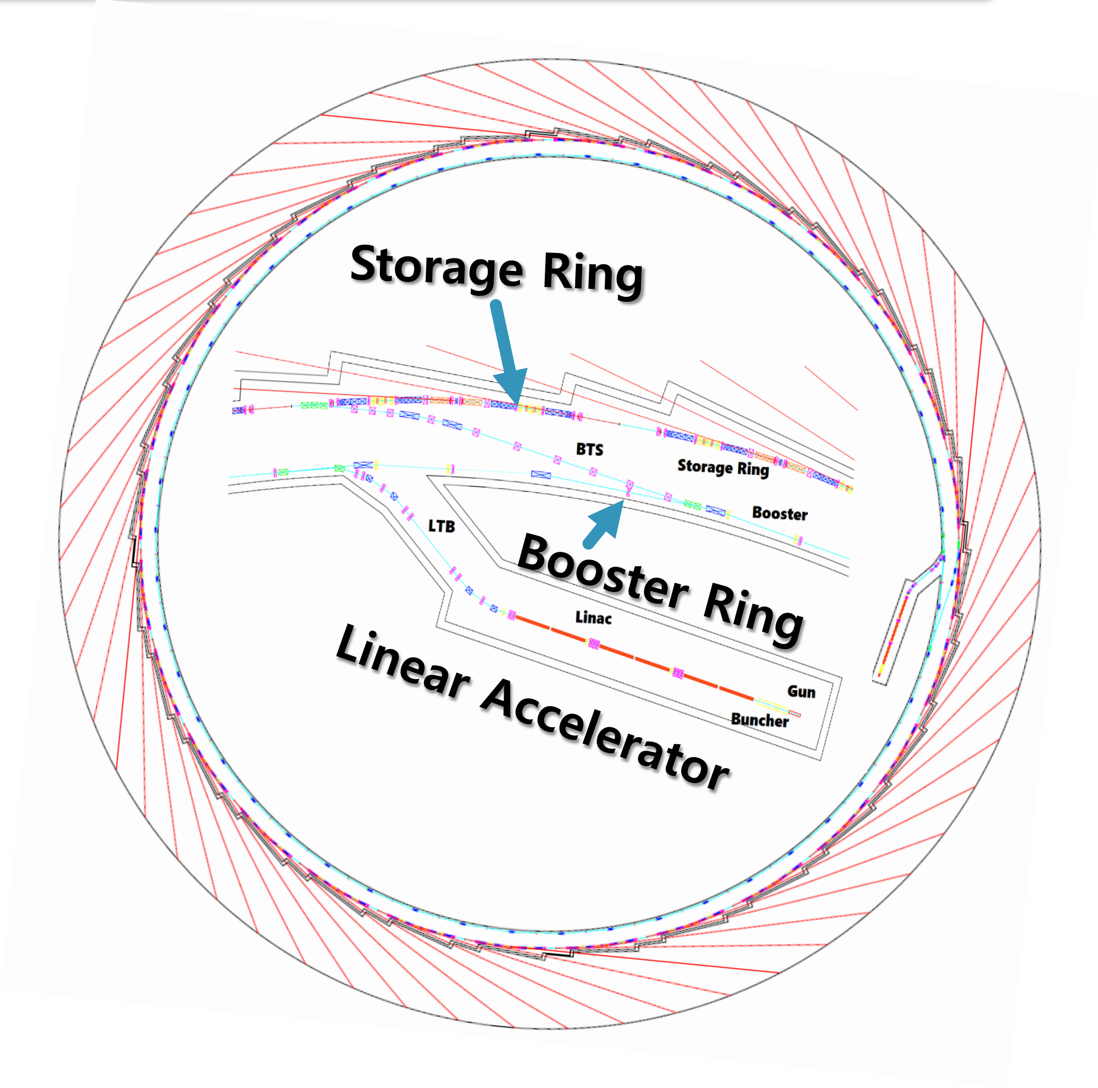
- Beam Energy: 4 GeV
- Beam Emittance: less than 100 pm·rad
- Circumference: 800m
- Beamlines : more than 40
- Accelerator: Gun, Injector LINAC, 4 GeV Booster
- Lattice: MBA-7 Bend Achromat

✓ Brighter
✓ More coherent
✓ Low emittance

한국기초과학지원연구원
KOREA BASIC SCIENCE INSTITUTE
다목적방사광가속기구축사업단

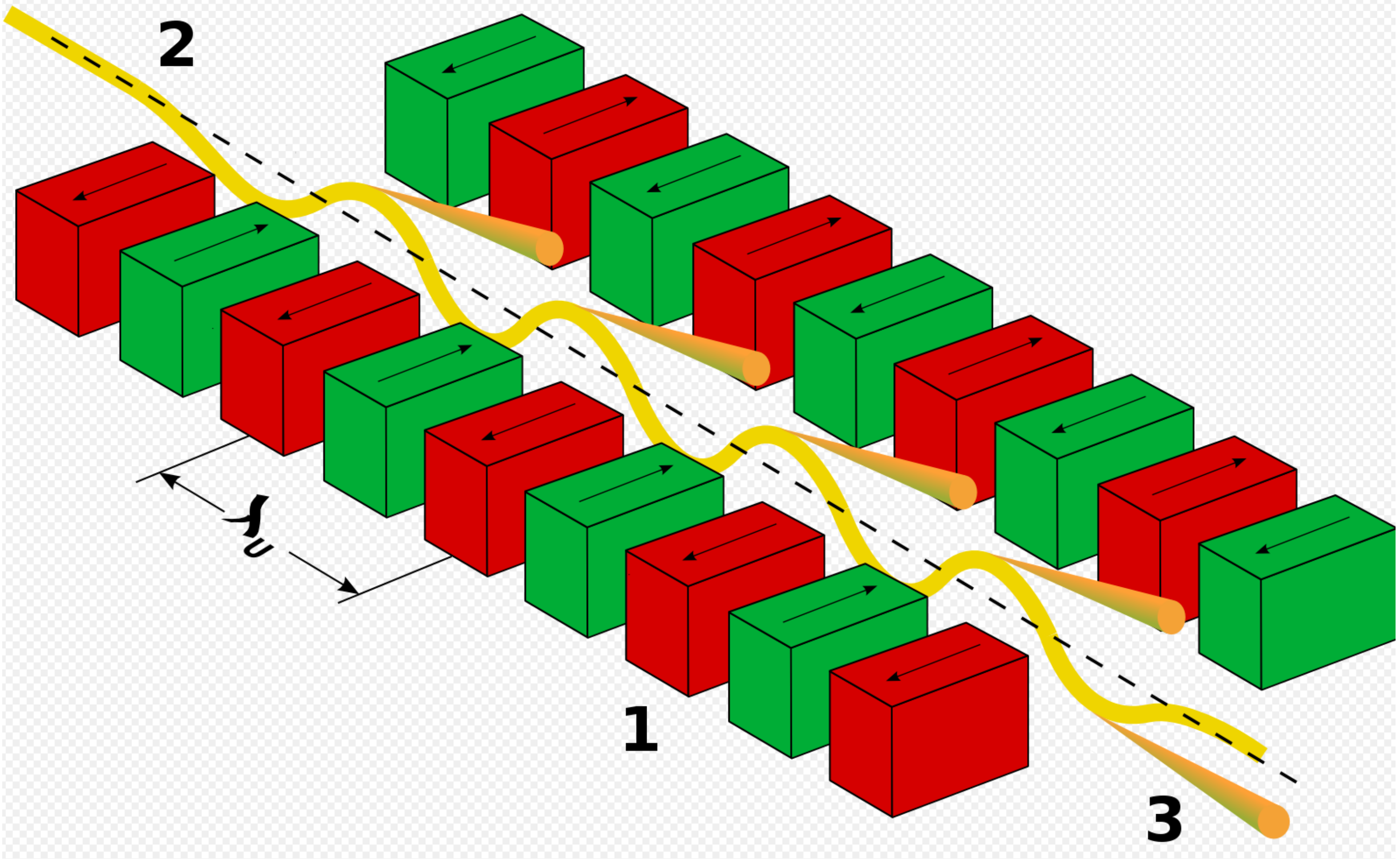
POHANG ACCELERATOR LABORATORY
4GSR 구축지원단

Storage Ring for 4GSR



Parameter	4GSR	PLS-II
Beam energy[GeV]	4	3
Beam current[mA]	400 Top-up mode	250(Max. 400), Top-up mode
Circumference[m]	798.8	281.82
Lattice structure	Multi-Bend	Double-Bend
Super-period	28	12
Emittance	62 pmrad	5800 pmrad
RF frequency	499.877 MHz	499.96 MHz
Bunch length[ps]	10.68 (without HC)	20
	53.43 (with HC)	
Number of Bunches	1065	300
Energy spread	0.126%	0.1 %

삽입장치 (Undulator, Wiggler)의 작동 개념



Schematics of Undulator: 1=자석, 2=전자빔, 3=방사광.

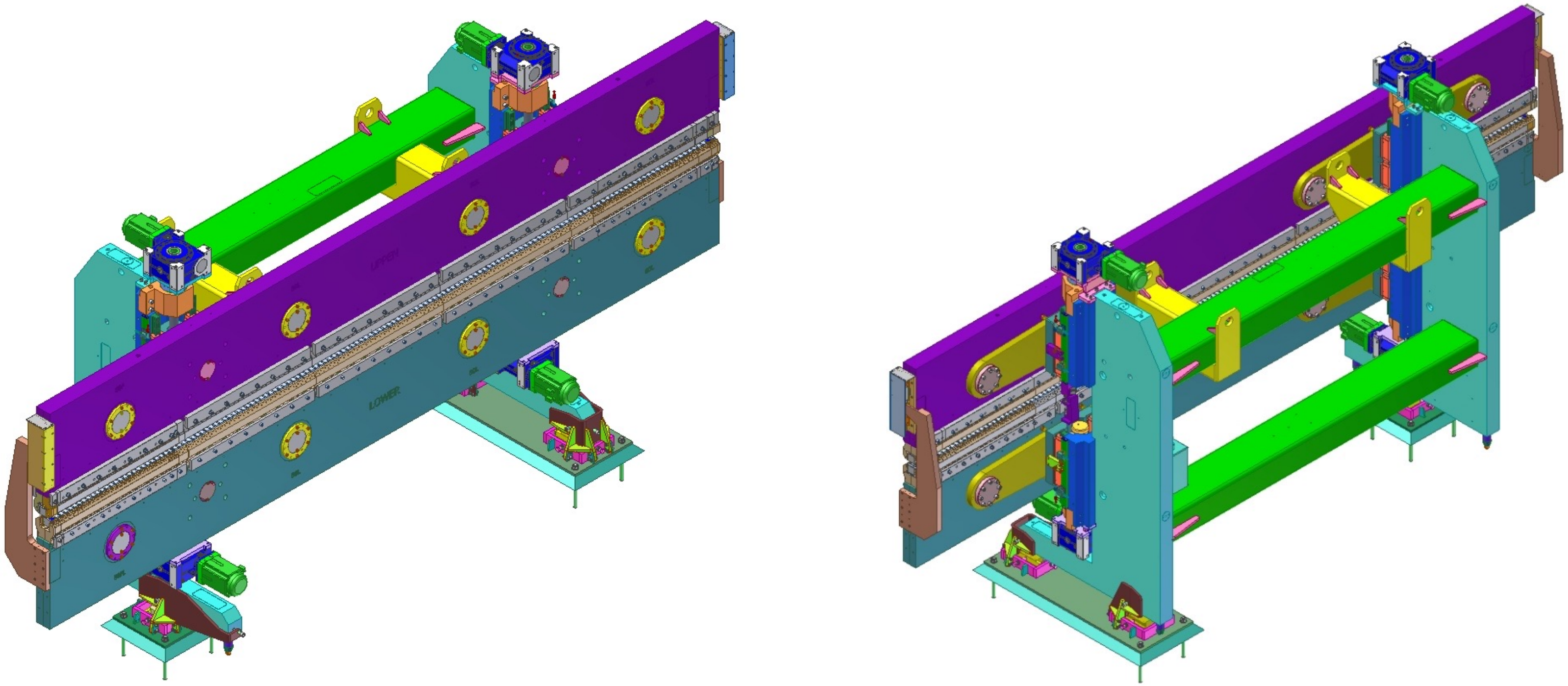
Source : D .A. Attwood “Soft X-rays and Extreme Ultraviolet Radiation” Lectures.

Insertion Devices at PLS-II

ID (20)	Model, Supplier	Key Features, Remark
IVU(13)	IVU20A(ADC USA) IVU20B(SSRF China) Revolver(Spring8 Japan) IVU20C(In house, Korea)x10	- Period=20 mm, min gap= 6.0 mm, B_{eff}=0.826 T, - Magnet Material NdFeB or Sm_2Co_{17}, - Pole=Low carbon steel, - Flange to Flange length=1.8~2.2 m, - Revolver Undulator (period=24,20,15,10), → Leased from SPring8, Riken (Thanks!)
EPU(3)	EPU72 (Kyma, Italy) EPU58 (Kyma, Italy) EPU114 (Kyma, Italy)	
Hybrid Undulator	U68(Kelin, China)	
Wiggler(3)	MPW10 (In House) MPW14 x 2	- Minimum gap=12.0 mm, B_{max}=1.8 T - 2.0 T - Magnetic Length: 1.2 m-1.6 m

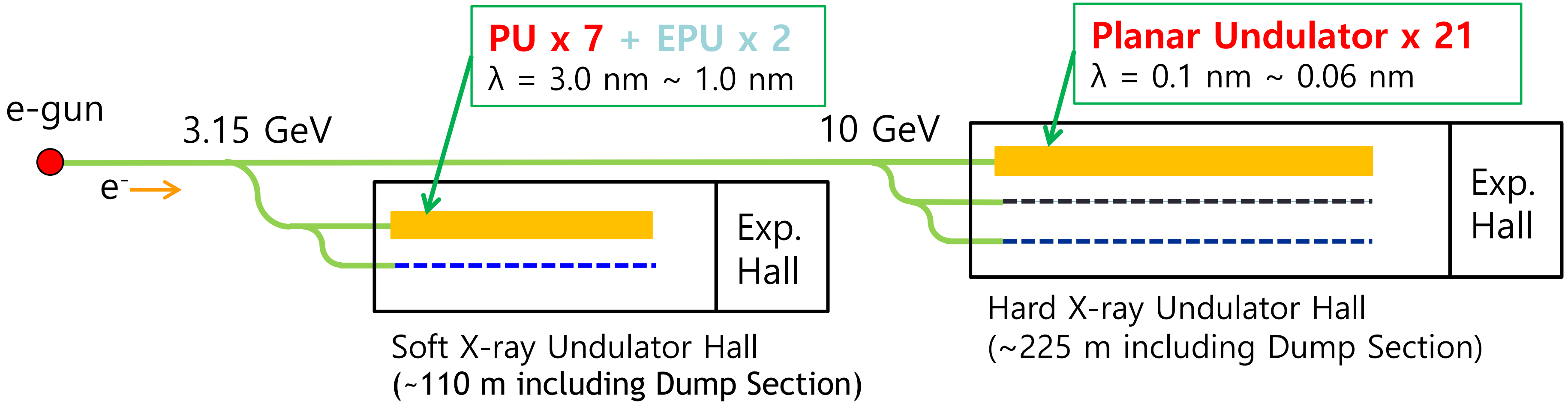
- 10 IVU20s, 3 MPWs are domestic version
- PLS-II has very high number of IDs (20) compared to it's circumference (282m)

• PAL-XFEL undulator layout



- To reduce the development efforts and period, EU-XFEL undulator design is benchmarked. A MOU to use the EU-XFEL design is agreed on 2011 June between PAL and EU-XFEL.
- The design is cost effective and adapted for mass serial production.
- PAL modification includes, new magnetic design reflecting different period/gap, EPICS IOC, update of the control system to move the undulator midplane.
- Application of tilt-meter for extra safety, “local” touch screen for easy maintenance.

• PAL-XFEL undulator layout



- Two FEL beamlines in the first phase: one soft X-ray (SXFEL1) and one hard X-ray (HXFEL1)
- **Planar Undulator + EPUs** in soft x-ray FEL provides the capability of **full polarization control**

XFEL	HXFEL1	SXFEL1
Beam Energy [GeV]	**10.0**	**3.15**
Wavelength [nm]	**0.7 ~ 0.06**	**3.0 ~ 1 .0**
Wavelength tuning	**Beam energy: 0.7 ~ 0.1** **Gap change : 0.1 ~ 0.06**	**Undulator gap**
Undulator type	**Planar**	**Planar+EPUs**
Undulator period [mm]	**26.0**	**35.0**
Undulator gap [mm]	**8.3**	**8.3**

☞ EPU after burner is being planned (not installed yet)
Total : 21+7=28 Eu-XFEL type undulators are built domestically and installed

3원 전자기장 계산 FEM vs BIM

- 전자기장 의 계산으로는 구성 미분 방정식을 풀기 위하여 FEM (Finite Element Method) 등이 주로 사용됨.
- FEM 이 유용한 Tool이고 주로 사용되지만 특수 목적으로는 BIM (Boundary Integral Method)* 도 있음.
- 1997년에 France의 ESRS (European Synchrotron Radiation Source) 라는 가속기에서 Mathematica AddOn Application 으로 "RADIA" 발표. (영구자석과, DC 전자석의 특수목적 계산)
- https://www.esrf.fr/Accelerators/Groups/InsertionDevices/Software/Radia/
- 그 두 방법의 장단점은

FEM 의 장단점	BIM의 장단점
장점: (1) General Purpose로 사용가능, AC, DC 등 단점: (1) S/W 비용이 비싸고, (2) H/W 요구 수준이 높으며 (3) 정확한 분석을 위하여 많은 교육/훈련이 필요하며 (4) Air 부분까지 모델링해야 해서 element수가 많이 필요하고 (5) Modelling 바깥부분은 계산불가라서 Far Boundary 계산은 부정확함	장점: (1) S/W 비용이 싸고 (무료+Mathematica) (2) Active Material 만 모델링 (3) Far field 계산도 FEM 보다 정확 (4) FEM 과 비교하여 약 1/10의 element수로 동등 accuracy. 단점: (1) 영구자석, 전류, Ferromagnetic steel 등 단순한 DC application만 가능. (2) Element 수에 따라서 필요 Memory, CPU가 급격히 증가.

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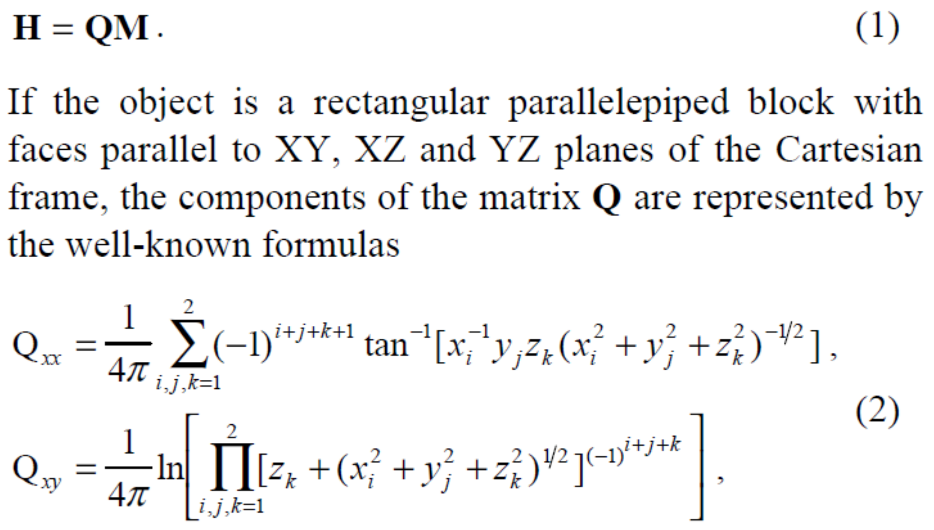
*P. Elleaume, O. Chubar, J. Chavanne, "Computing 3D Magnetic Field from Insertion Devices", Proc. of the PAC'97 Conference May 1997, p.3509-3511.

RADIA (BIM: Boundary Integral Method)

1. 균일하게 자화된 Magnet volume에 의한 자장의 해석적 표현을 사용.
2. 자장을 발생할 수 있는 자석, 코일, 자화가능 물질 (Ferro) 들의 “Object” 를 생성
3. 각 Object를 독립적인 magnetization 을 가지는 sub volume으로 나눔.
4. 각 미소 volume으로 부터 해석적으로 각 sub volume center에서의 자장 계산
5. 비선형 투자율로 부터 새로운 magnetization 계산
6. 다시 step 4로 가서 변화량이 규정값 이하일때 까지 반복

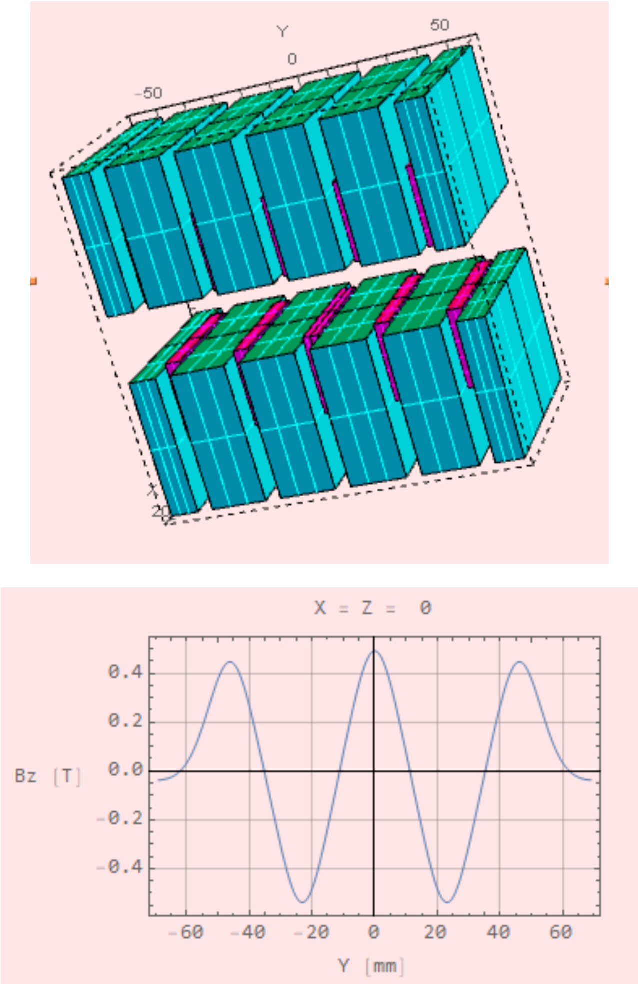


$$\mathbf{H} = \mathbf{QM}\,. \tag{1}$$

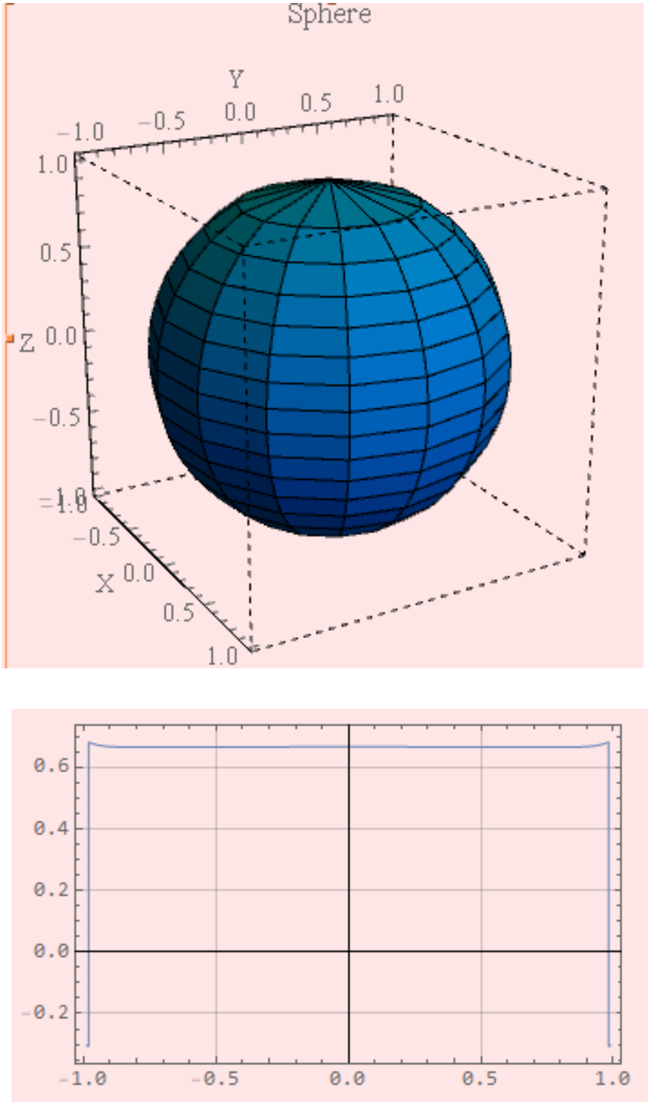
If the object is a rectangular parallelepiped block with faces parallel to XY, XZ and YZ planes of the Cartesian frame, the components of the matrix **Q** are represented by the well-known formulas

$$\begin{aligned} Q_{xx} &= \frac{1}{4\pi}\sum_{i,j,k=1}^{2}(-1)^{i+j+k+1}\tan^{-1}\left[x_i^{-1}y_j z_k\left(x_i^2+y_j^2+z_k^2\right)^{-1/2}\right], \\ Q_{xy} &= \frac{1}{4\pi}\ln\left[\prod_{i,j,k=1}^{2}\left[z_k+\left(x_i^2+y_j^2+z_k^2\right)^{1/2}\right]^{(-1)^{i+j+k}}\right], \end{aligned} \tag{2}$$

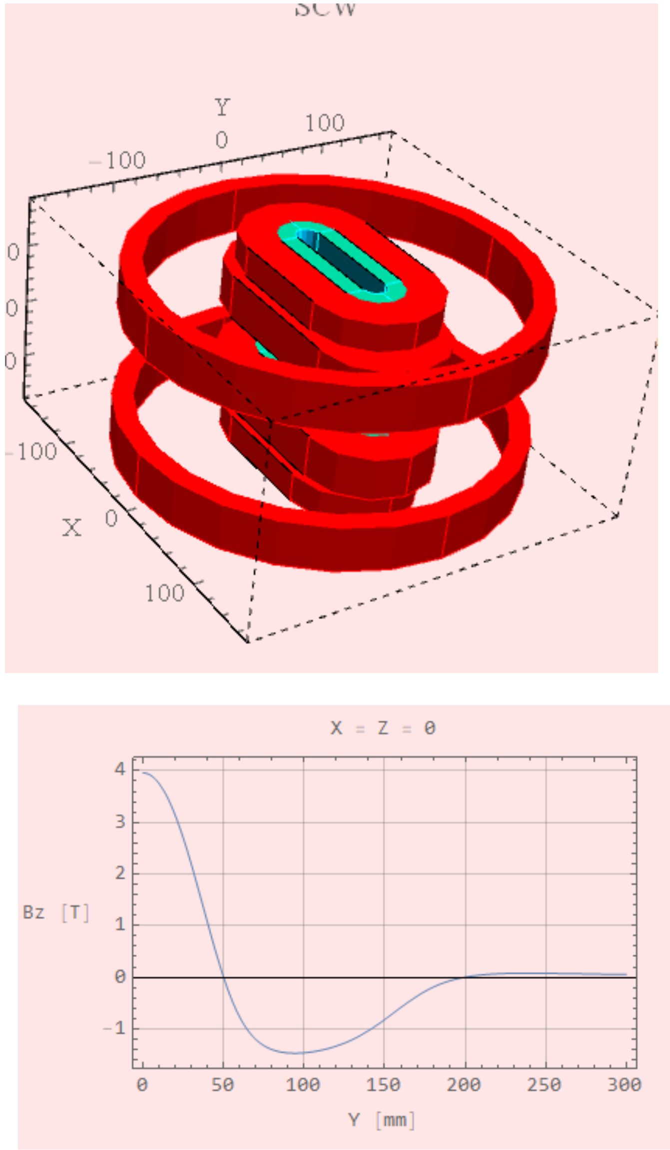
RADIA (A Few Example)



Hybrid Undulator
(Pole+NdFeB 영구자석)

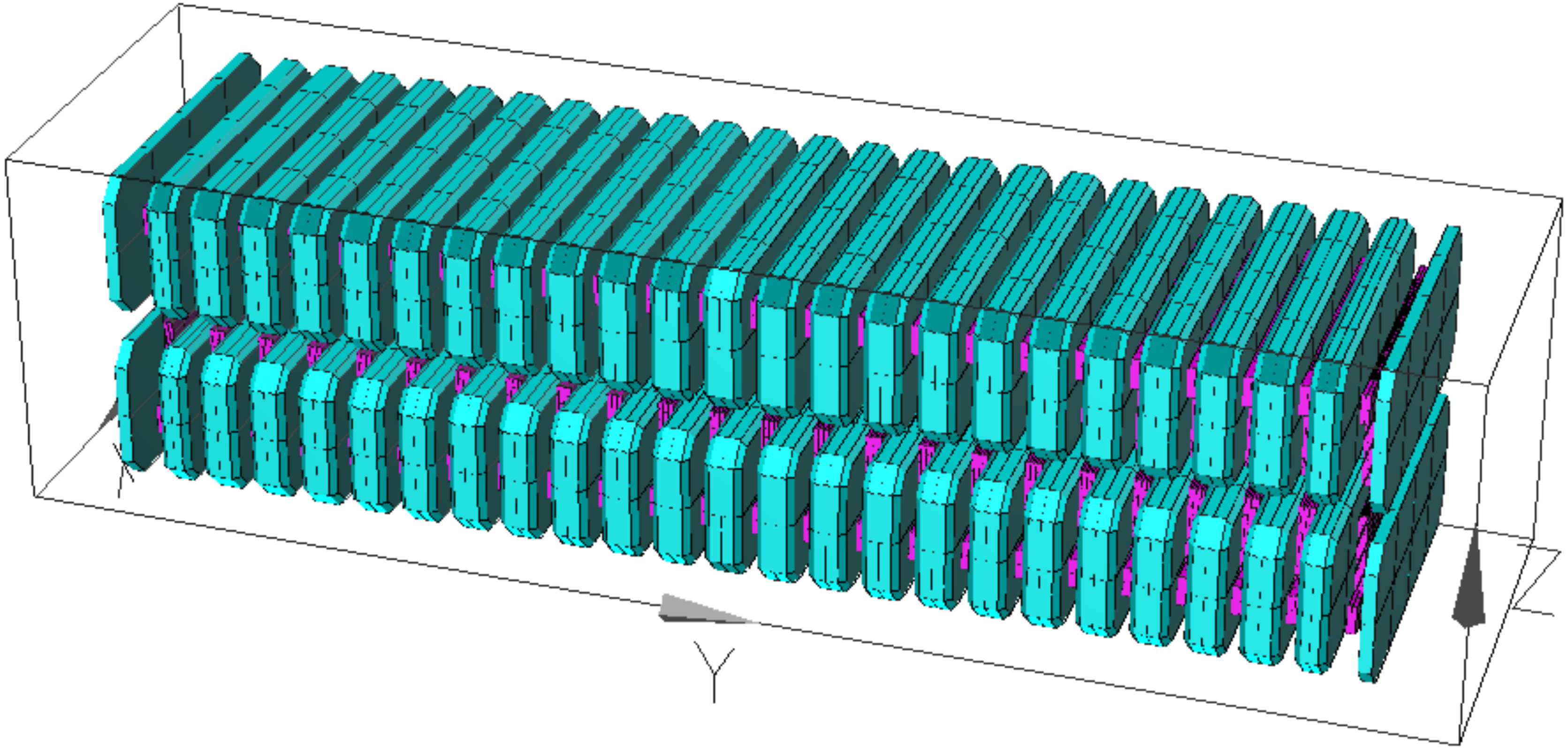


균일하게 자화된 Sphere



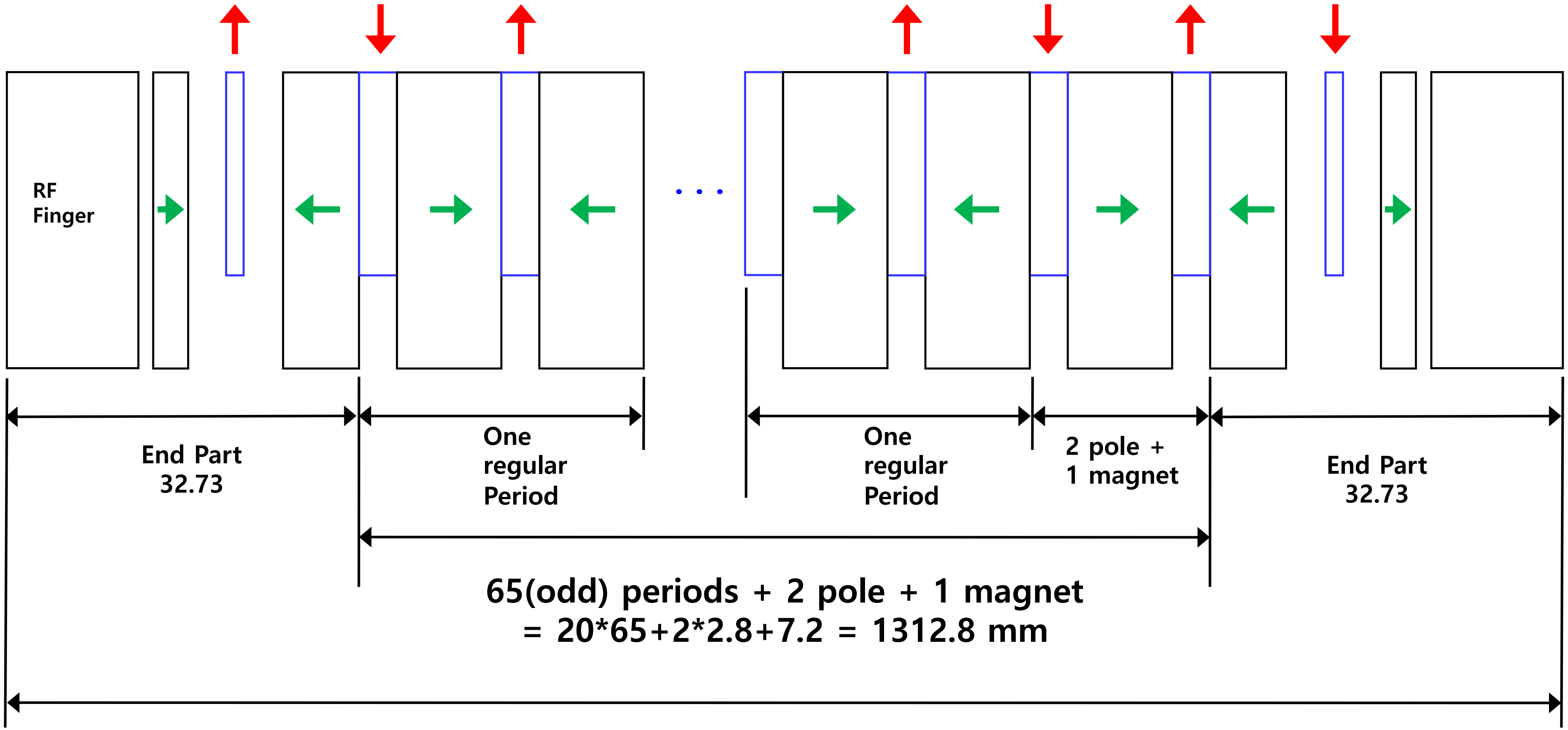
초전도 Coil에 의한 자장

Radia 3D model, 22 full field pole version



Blue : NdFeB Magnet, Purple: ferromagnetic pole

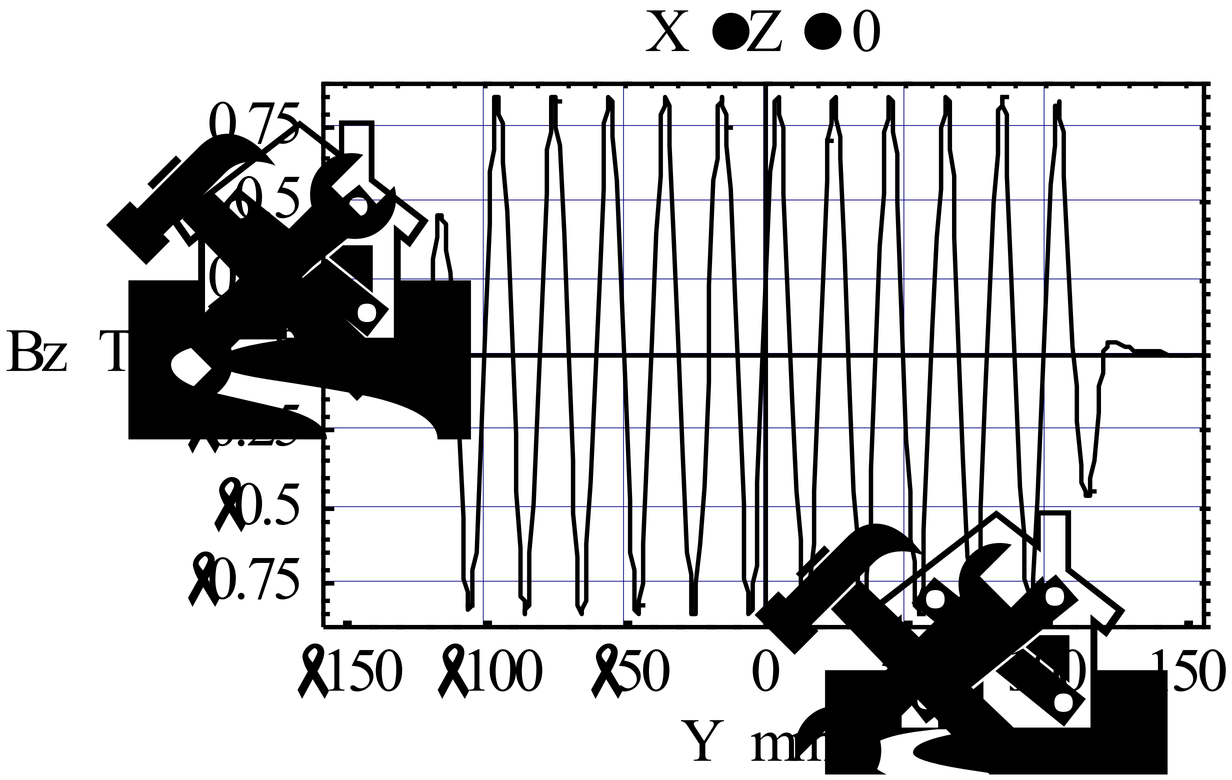
Magnet Structure



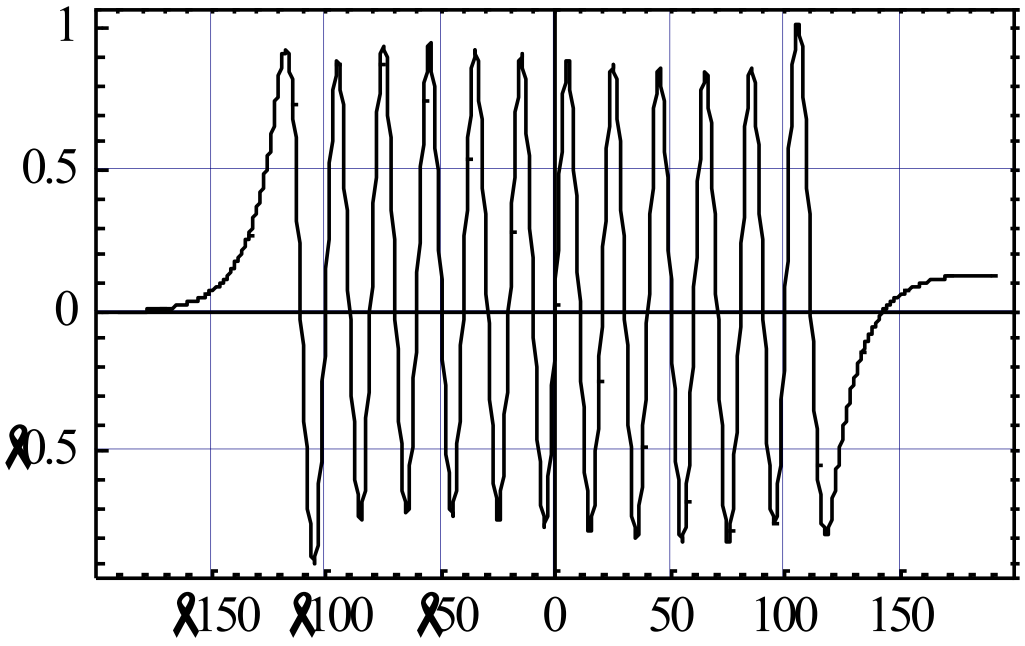
65(odd) periods + 2 pole + 1 magnet
= 20*65+2*2.8+7.2 = 1312.8 mm

Total Length
(1312.8+2*32.73= 1378.26 mm)

B_z (y), and orbit profile



Bz (y) profile



Orbit profile along z (μm)

요약

- 방사광 가속기에서는 주요 방사광원 (Synchrotron Radiation Source)로서 삽입장치라는 핵심 자기 구조물을 개발하여 사용중.

- 가속기에 필요한 자기 구조물을 설계하기 위해서는
  ① 3차원 FEM code
  ② Mathematica 기반 BIM Code 등이 각각의 영역을 서로 보완하며 사용되고 있음.

- 포항가속기 연구소에서는 방사광원의 핵심인 삽입장치 (Undulator, Wiggler) 자기 구조물을 설계하는데 Mathematica 를 pre/post processor로 사용하는 RADIA를 성공적으로 적용해 왔음.

- 희토류 영구자석이나 전자석은 많은 일반인, 학생들의 호기심의 대상이지만 학생, 일반인들이 자기장에 대해서 정량적인 계산을 하기는 어려움.

- Mathematica 상의 RADIA를 활용하면 적은 비용으로 학생, 일반인들의 창의 적인 계산에 Motivation 을 줄 수 있을 것으로 생각함. (예를 들면 특정 geometry에서 자석이 받는 힘, 영재교육단에서의 영구자석에 의한 자장의 계산 및 측정과 비교)

끝!

Thank you for your attention!

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한국방사광이용자협회