다목적방사광가속기구축사업

2022. 7. 11.

고려대학교 세종캠퍼스

고인수
다목적방사광가속기구축사업단

Acceleration

- Lorentz force

$$F = q(E + v \times B)$$

- Electric field inside Maxwell's equation

$$\nabla \cdot E = 4\pi\rho$$

$$\nabla \times E = -\frac{1}{c}\frac{\partial B}{\partial t}$$

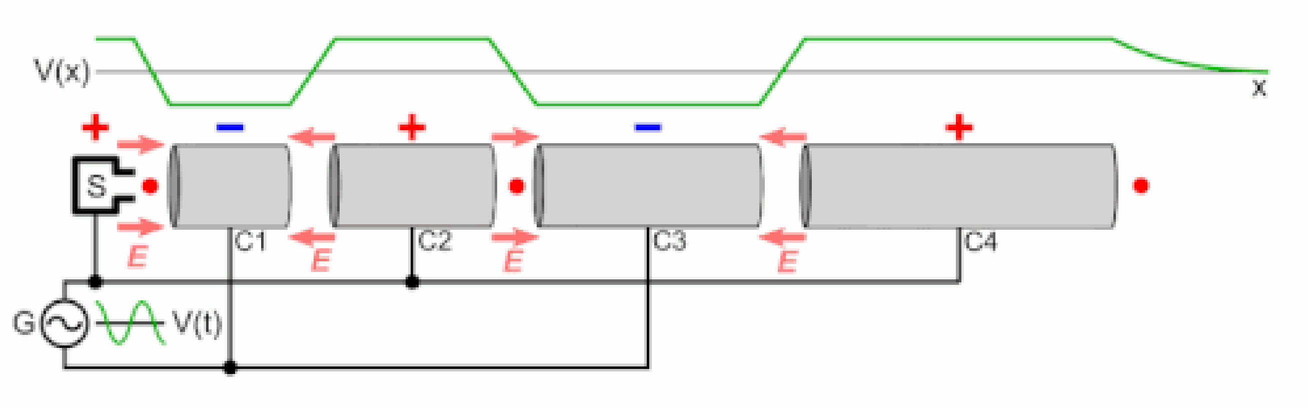
- Electric field inside Electromagnetic wave

$$\frac{1}{c^2}\frac{\partial^2 E}{\partial t^2} - \nabla^2 E = 0$$

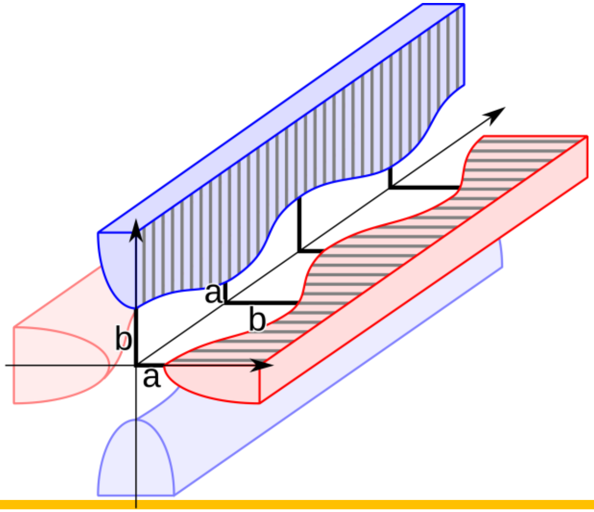
Types of Accelerator (by charged particle)

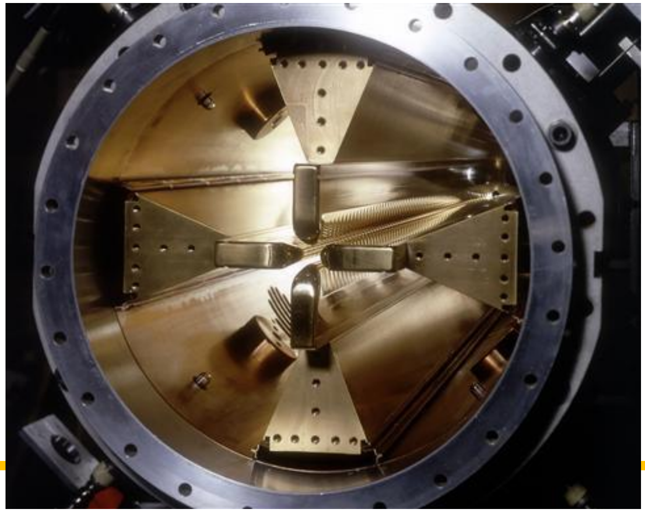
종 류	원 리	가속입자/이용입자	활 용
방사광가속기 Light Source	전자를 가속한 후, 직진하는 전자의 방향을 바꿀 때 발생하는 방사광을 이용	전자 방사광(X선-가시광선)	**물질의 구조 분석 및 미세가공** (생명, 재료, 화학, 물리, 기계, 반도체, 응용과학분야)
양성자가속기 Proton Accelerator	가속한 양성자(수소원자에서 전자를 제거한 이온)를 물질에 조사함으로써 물질 변화시키거나, 중성자 생산	양성자 양성자, 중성자	**물질을 변화시키거나(연금술), 중성자 생산** (의료용, 산업용 동위원소 생산, 전력반도체 제조, 파쇄 중성자원, 양성자 암치료)
중이온가속기 Rare Isotope Accelerator	양성자 가속기와 원리는 유사하나 양성자보다 무거운 다양한 원소(헬륨이온, 탄소이온, 우라늄 이온 등)를 가속하여 물질에 조사	양성자~우라늄핵 중성자,양성자~우라늄	**핵물리 등 기초연구 활용** (중이온 암치료, 신물질, 신품종 개발, 핵물리연구)
중입자가속기 Heavy Ion Accelerator	탄소 등 무거운 원소의 원자를 가속시켜 암세포에 쏘이는 장치, 암세포만을 파괴	탄소핵 탄소핵, 중성자	**의학분야 활용** (중입자 암치료, 의학연구)

Types of Accelerator: RF linac 1/2

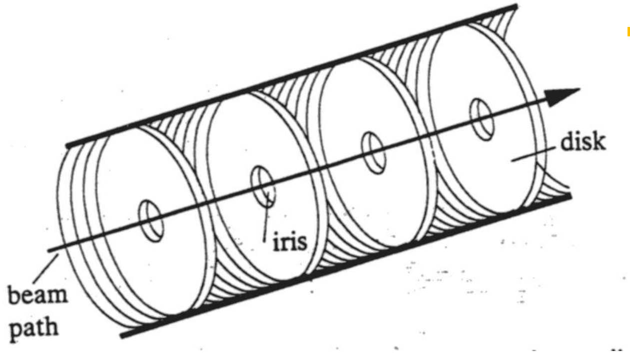


- Gustav Ising (1924) published the first concept of the linac using a series of accelerating gap.
- Rolf Wideroe (1927) built an 88-inch long, two gap version.
- Luis Alvarez (1947) achieving 31.5 MeV proton with Alvarez-type resonant chamber.
- Strong focusing is introduced inside the drift tube.
- I. M. Kapchinsky and Vladimir Teplyakov (1971) proposed the radio-frequency quadrupole (RFQ) type of accelerating structure.

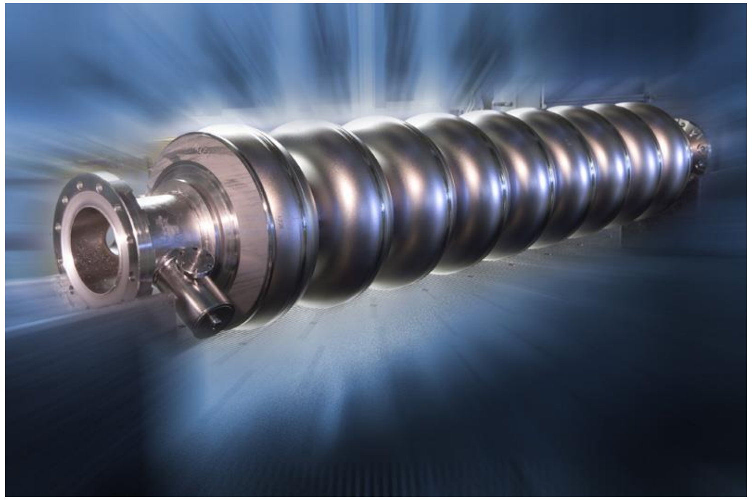




Types of Accelerator: RF linac 2/2

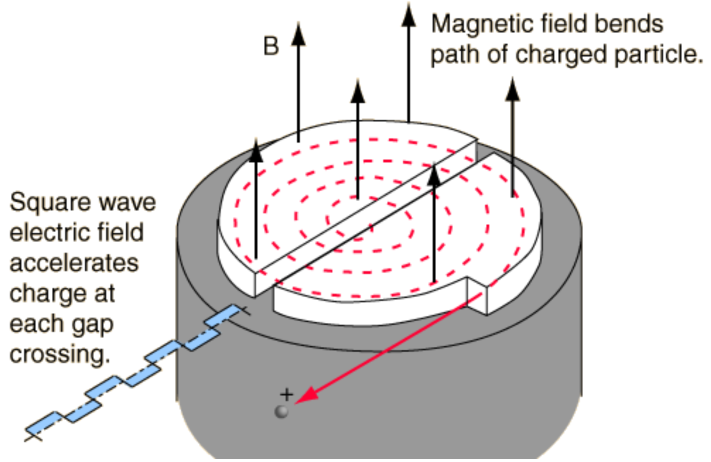


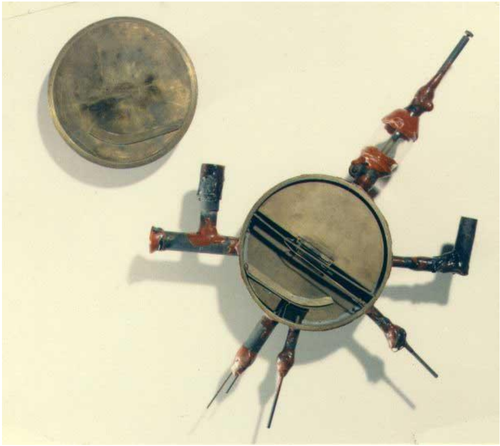
- William Hansen (1947) constructed the first travelling-wave electron accelerator at Stanford University, and accelerated the electron beam to 6 MeV.
- This research expanded to a size of 2 miles (3.2 km) and to 50 GeV (SLAC).
- SLAC produced three Nobel prizes in Physics.
- Now, the linac was converted to XFEL called LCLS.

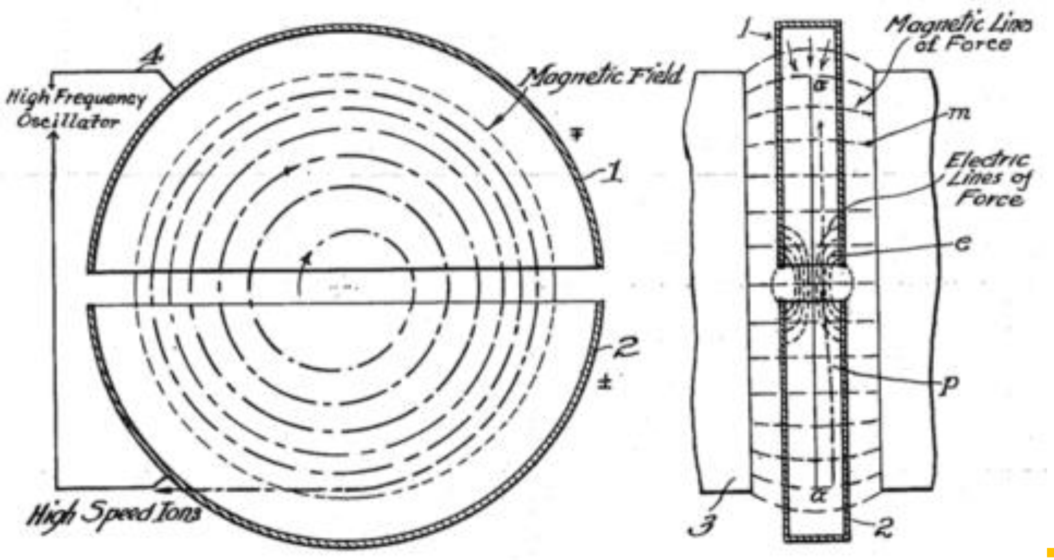


Type of Accelerator: Cyclotron

- Ernest O. Lawrence (1932)

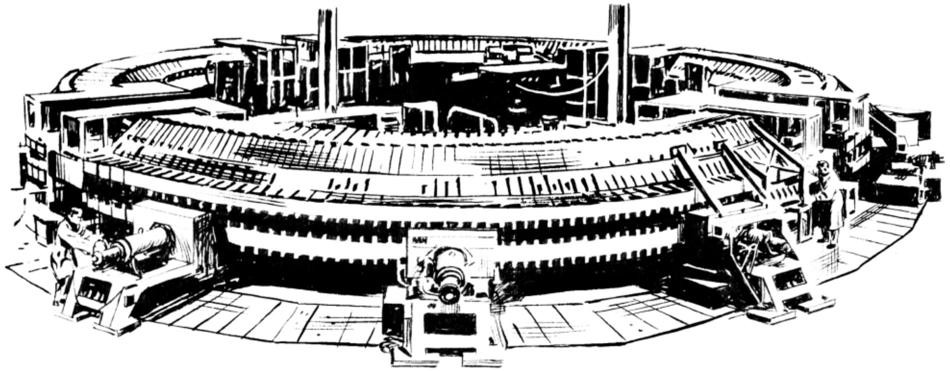






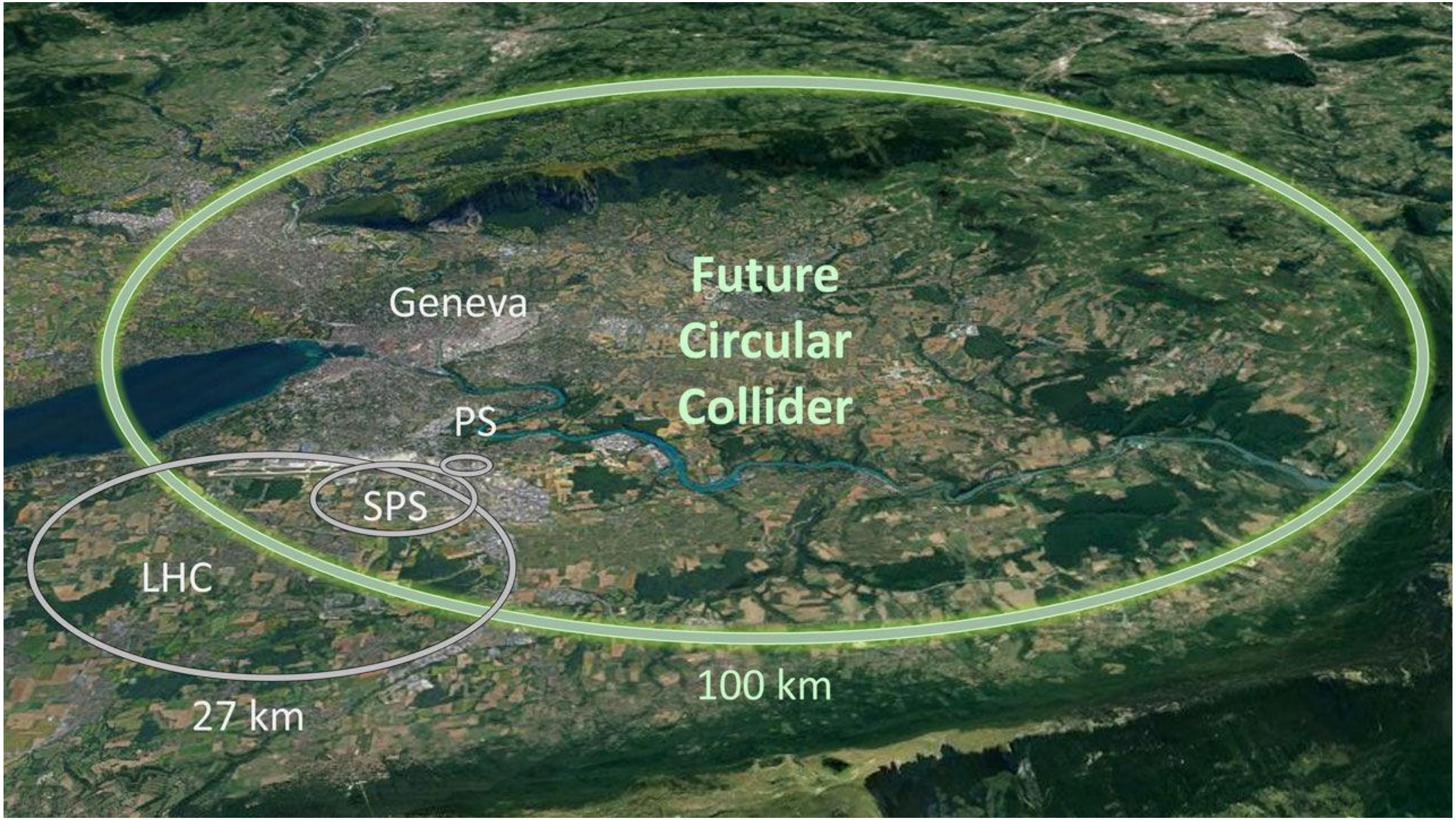
Type of Accelerator: Synchrotron/Collider

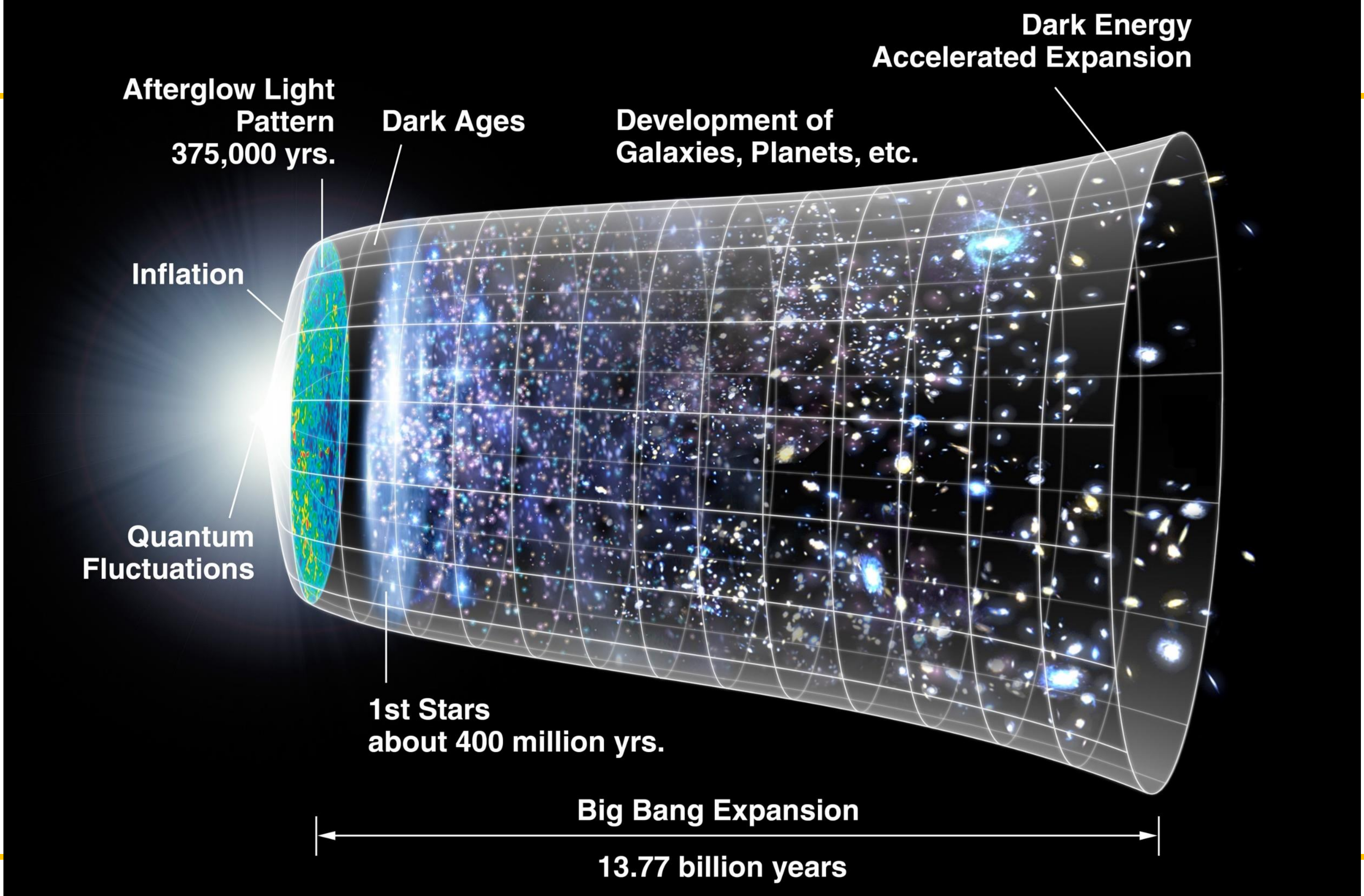
- Cosmotron (1948~1966) at BNL
  - Proton up to 3.3 GeV
- Tevatron (1983~2011) at Fermilab
  - 980-GeV p and anti-p
- LEP (1985~2000) LHC (2008~) at CERN
  - 209 GeV e+e- (LEP)
  - 14 TeV pp (LHC)



CERN (EU) @ Geneva, Switzerland

Future Circular Collider (FCC): 21BEuro by 2040



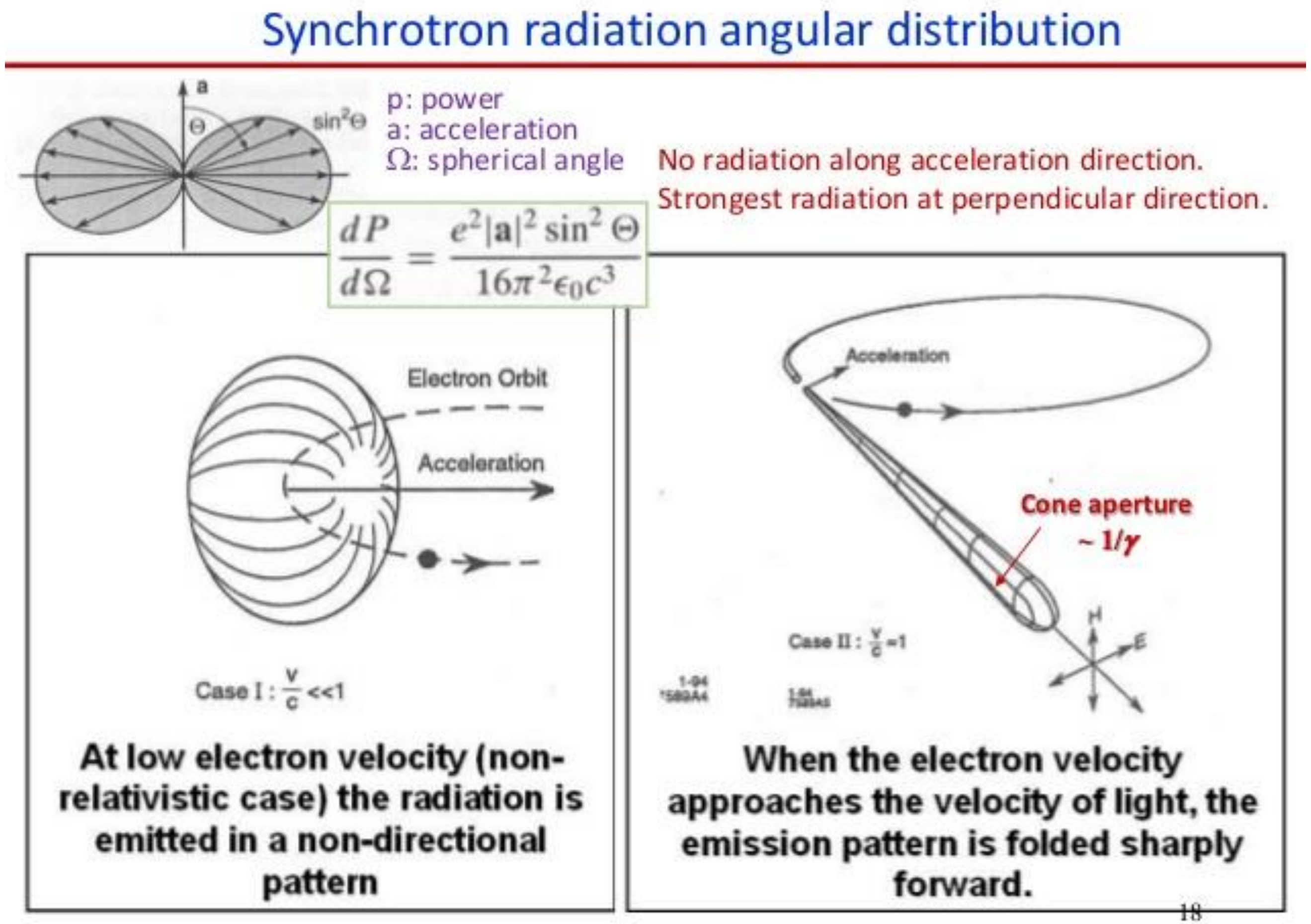

Dark Energy
Accelerated Expansion
Afterglow Light
Pattern
375,000 yrs.
Dark Ages
Development of
Galaxies, Planets, etc.
Inflation
Quantum
Fluctuations
1st Stars
about 400 million yrs.
Big Bang Expansion
13.77 billion years

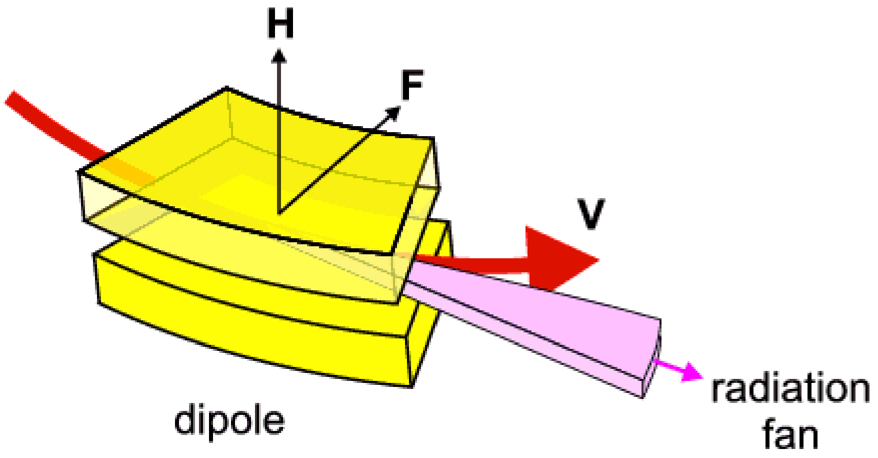
Robert R. Wilson (1914~2000)

- First Director of Fermilab (1967~1978)
- Congressional Joint Committee on Atomic Energy (April 19, 1969)

- Wilson was among a number of scientists who testified in Washington, DC before the Joint Committee on Atomic Energy concerning a proposed multimillion-dollar particle accelerator to be built in Batavia, Illinois. Despite the key role physicists played in ending World War II, some members of Congress were skeptical of paying a hefty price tag for a machine that did not seem to directly benefit the U.S. national interest.
- During Wilson's testimony, then-senator John Pastore bluntly asked, "Is there anything connected with the hopes of this accelerator that in any way involves the security of the country?"
- "No, sir, I don't believe so," Wilson replied.
- "It has no value in that respect?"
- "It has only to do with the respect with which we regard one another, the dignity of man, our love of culture. It has to do with: Are we good painters, good sculptors, great poets? I mean all the things we really venerate in our country and are patriotic about. It has nothing to do directly with defending our country except to make it worth defending."

Synchrotron Radiation



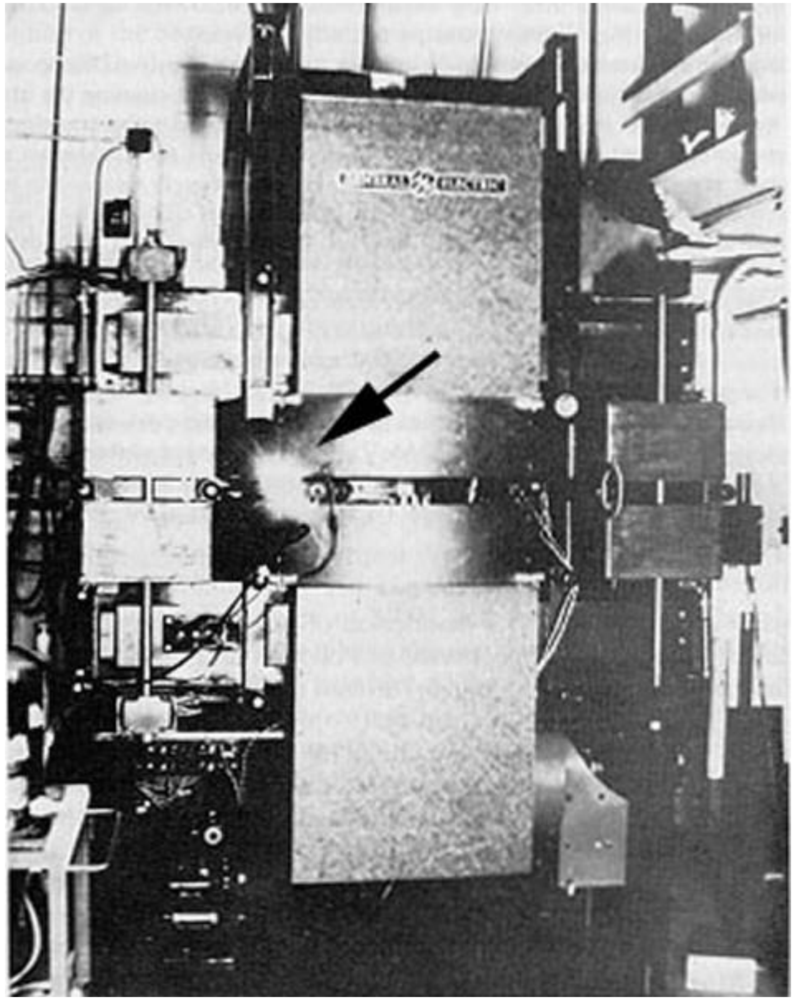


$$\Delta E = \frac{e^2}{3\varepsilon_0 (m_0 c^2)^4} \frac{E^4}{R}$$

$$\Delta E\,[\mathrm{keV}] = 88.5 \frac{E^4\,[\mathrm{GeV}^4]}{R\,[\mathrm{m}]}$$

$$\frac{P_\mathrm{p}}{P_\mathrm{e}} = \left(\frac{m_\mathrm{e}}{m_\mathrm{p}}\right)^4 = 8.80 \times 10^{-14}$$

First man-made synchrotron radiation (1947)

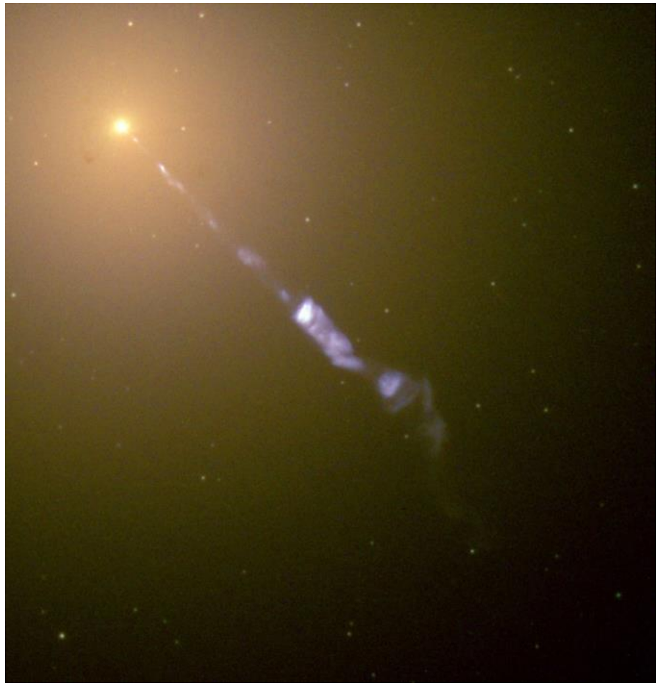


General Electric betatron built in 1946, the origin of the discovery of Synchrotron radiation.

The radiation was named after its discovery in a General Electric synchrotron accelerator built in 1946 and announced in May 1947 by Frank Elder, Anatole Gurewitsch, Robert Langmuir, and Herb Pollock in a letter entitled "Radiation from Electrons in a Synchrotron." Pollock recounts:

> "On April 24, Langmuir and I were running the machine and as usual were trying to push the electron gun and its associated pulse transformer to the limit. Some intermittent sparking had occurred and we asked the technician to observe with a mirror around the protective concrete wall. He immediately signaled to turn off the synchrotron as "he saw an arc in the tube." The vacuum was still excellent, so Langmuir and I came to the end of the wall and observed. At first we thought it might be due to Cherenkov radiation, but it soon became clearer that we were seeing Ivanenko and Pomeranchuk radiation

First observation of SR from galaxy

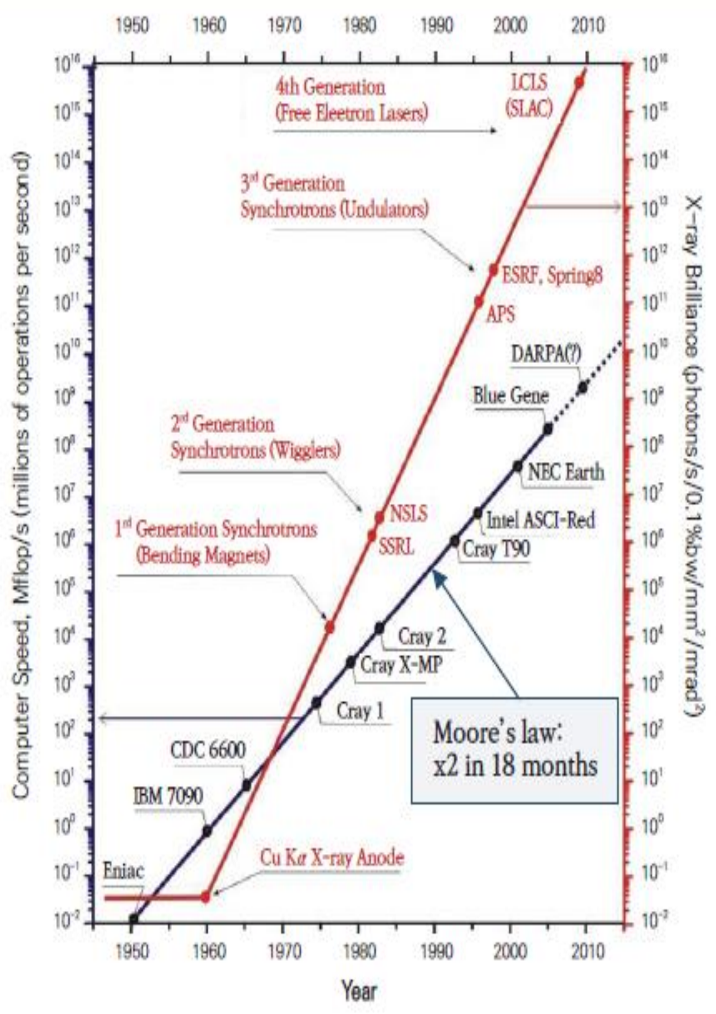


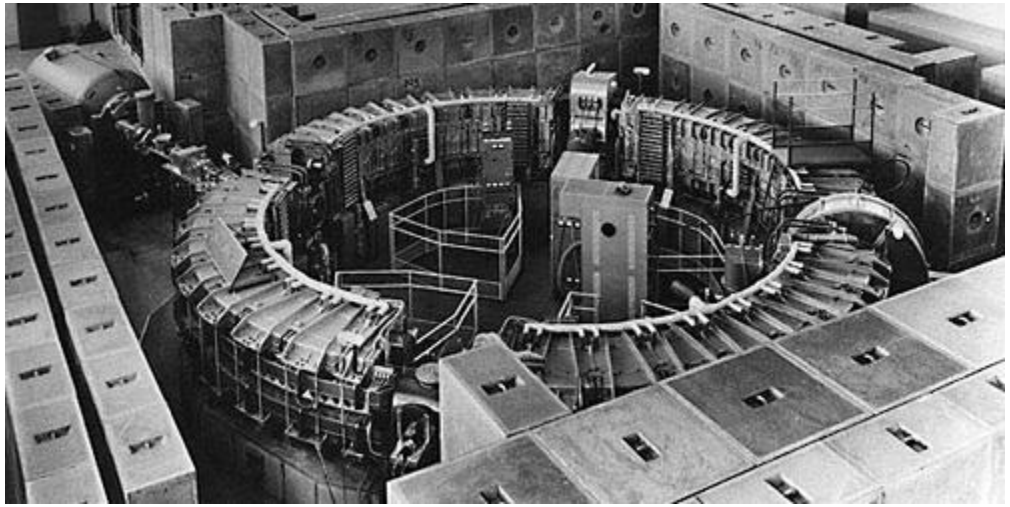
M87's Energetic Jet. The glow is caused by synchrotron radiation, high-energy electrons spiraling along magnetic field lines, and was first detected in 1956 by Geoffrey R. Burbidge in M87 confirming a prediction by Hannes Alfvén and Nicolai Herlofson in 1950, and Iosif S. Shklovskii in 1953.

The supernova SN1054 was observed by Chinese/Japanese/Islamic astronomers in the year 1054. The pulsar (the bright compact emission) produces highly relativistic electrons which themselves produce synchrotron radiation in the magnetic field of the nebula.

Generations of Synchrotron Radiation

구분	시기	주요 특징	주요 장치
1세대	1970년대 이전	입자물리학용 전자가속기의 부산물로 방사광 이용	BEPC (중국)
2세대	1980년대	방사광 이용을 주목적으로 설계된 전용 설비	Photon Factory (일본) NSLS (미국)
3세대 원형	1990년대 ~ 현재	영구자석을 이용한 삽입장치가 다수 사용되어 2세대 대비 수천 배 밝음	PLS-II (한국), SSRL (중국) TPS (대만), AS (호주) Elettra (이태리)
4세대 원형	2016년 ~ 미래	3세대 대비 100배 밝음	MAX-IV (스웨덴) Sirius (브라질) HEPS (중국) ESRF-EBS (EU @ Grenoble) 다목적방사광가속기 (한국)
4세대 선형	2009년 ~ 미래	3세대 대비 1억배 이상 밝고 펨토(10^{-15})초의 시간 분해능을 가진 X-선 레이저광원 (방사광이 아님)	LCLS/LCLS-II (미국) SACLA (일본) PAL-XFEL (한국) Euro-XFEL (EU @ Hamburg) SwissFEL (스위스)

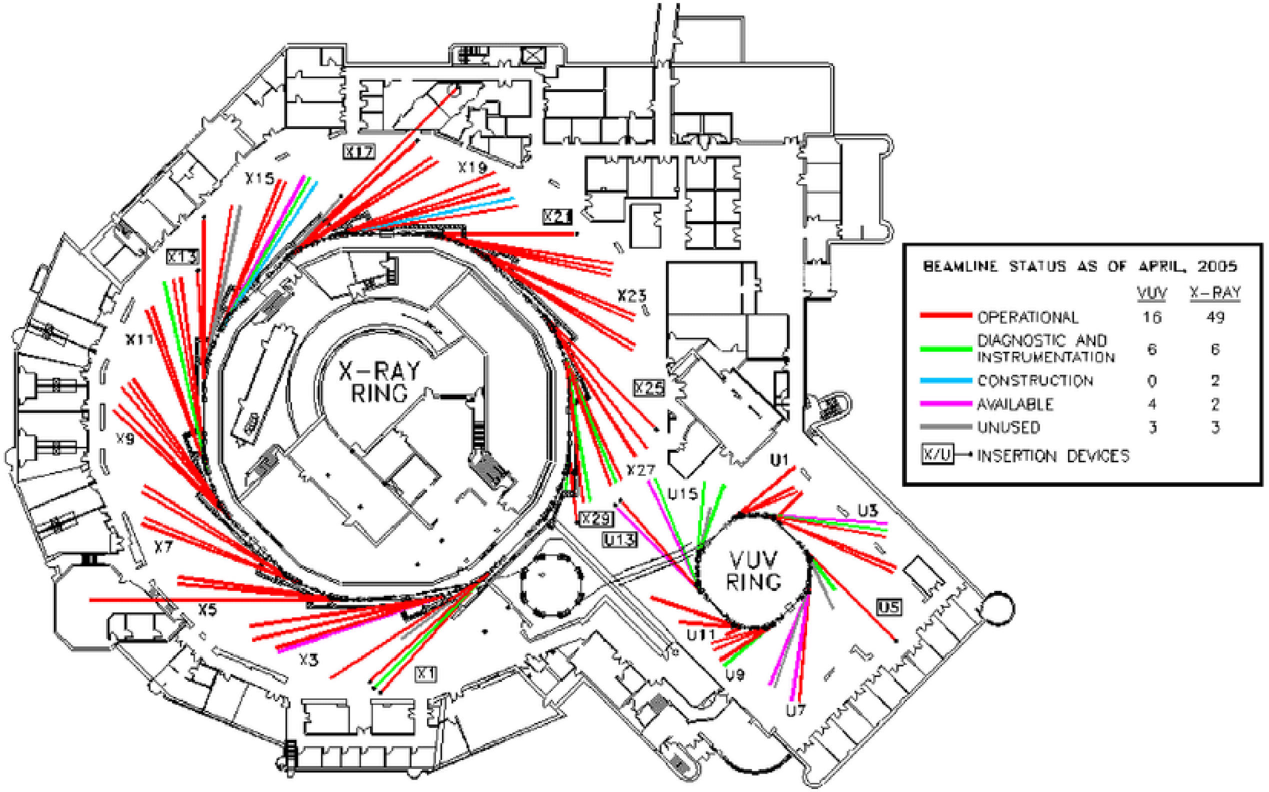




1세대 가속기 (Frascati 1.1 GeV 이탈리아 1959)

1세대: 방사광 때문에 가속기의 크기가 커지기 힘들다.

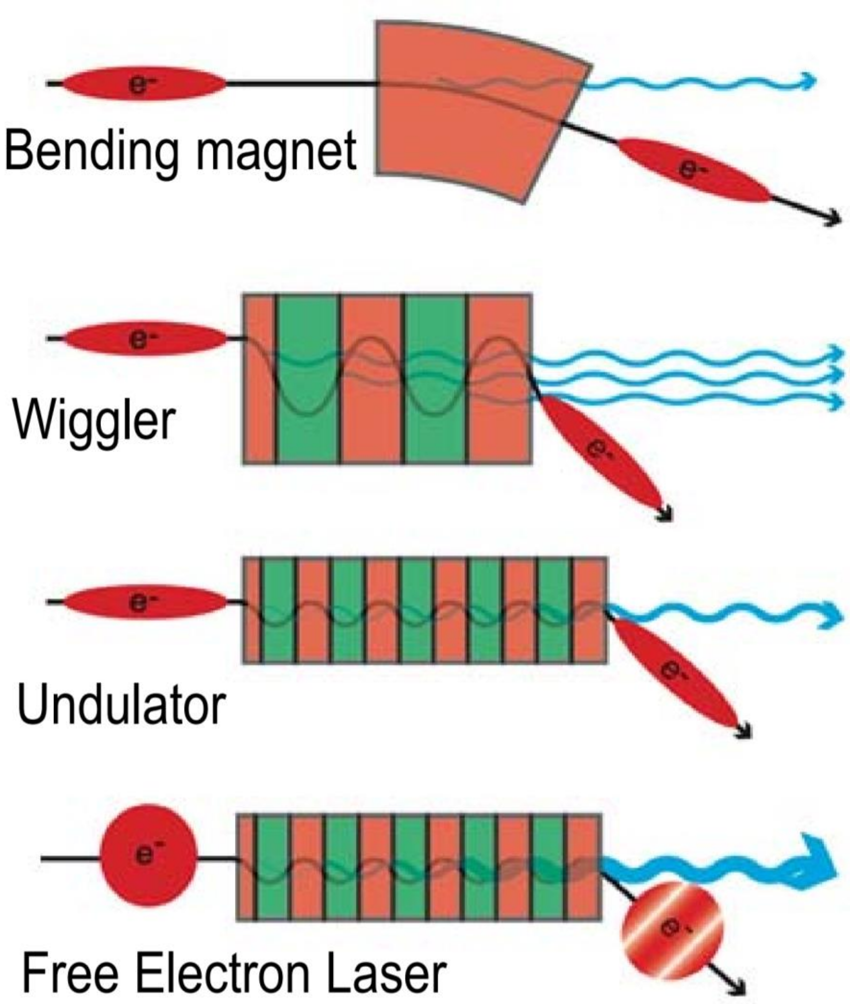
2세대: 방사광 전용 가속기

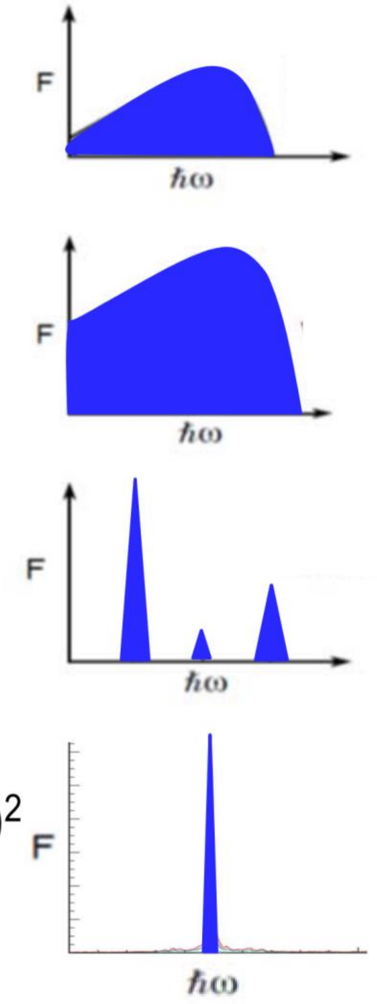


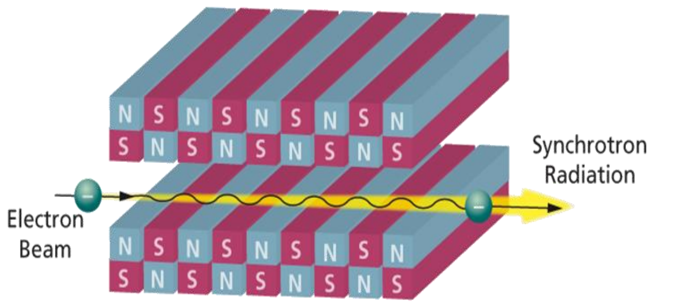
2세대 (NSLS 2.5-GeV, Brookhaven National Laboratory, 미국 1980년대)

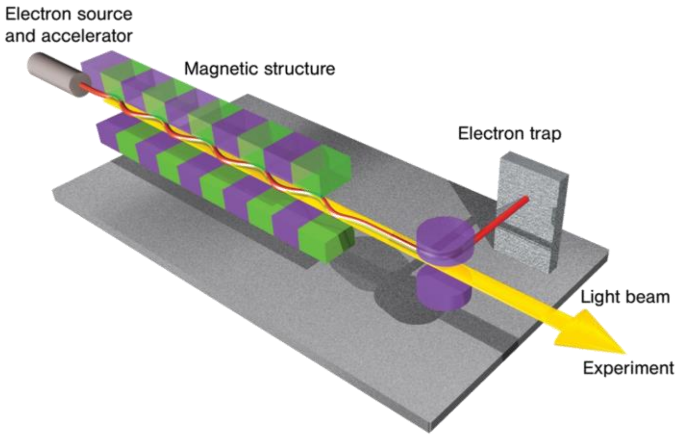
Insertion Devices

Source	Intensity	Spectrum $\hbar\omega$
Bending magnet	$\propto N_{electrons}$	
Wiggler	$\propto N_{electrons} \times N_{poles}$	
Undulator	$\propto N_{electrons} \times (N_{poles})^2$	
Free Electron Laser	$\propto (N_{electrons})^2 \times (N_{poles})^2$	

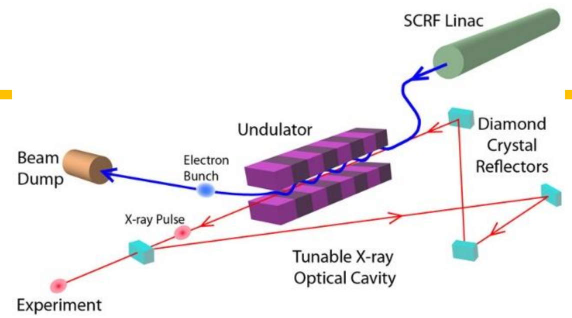


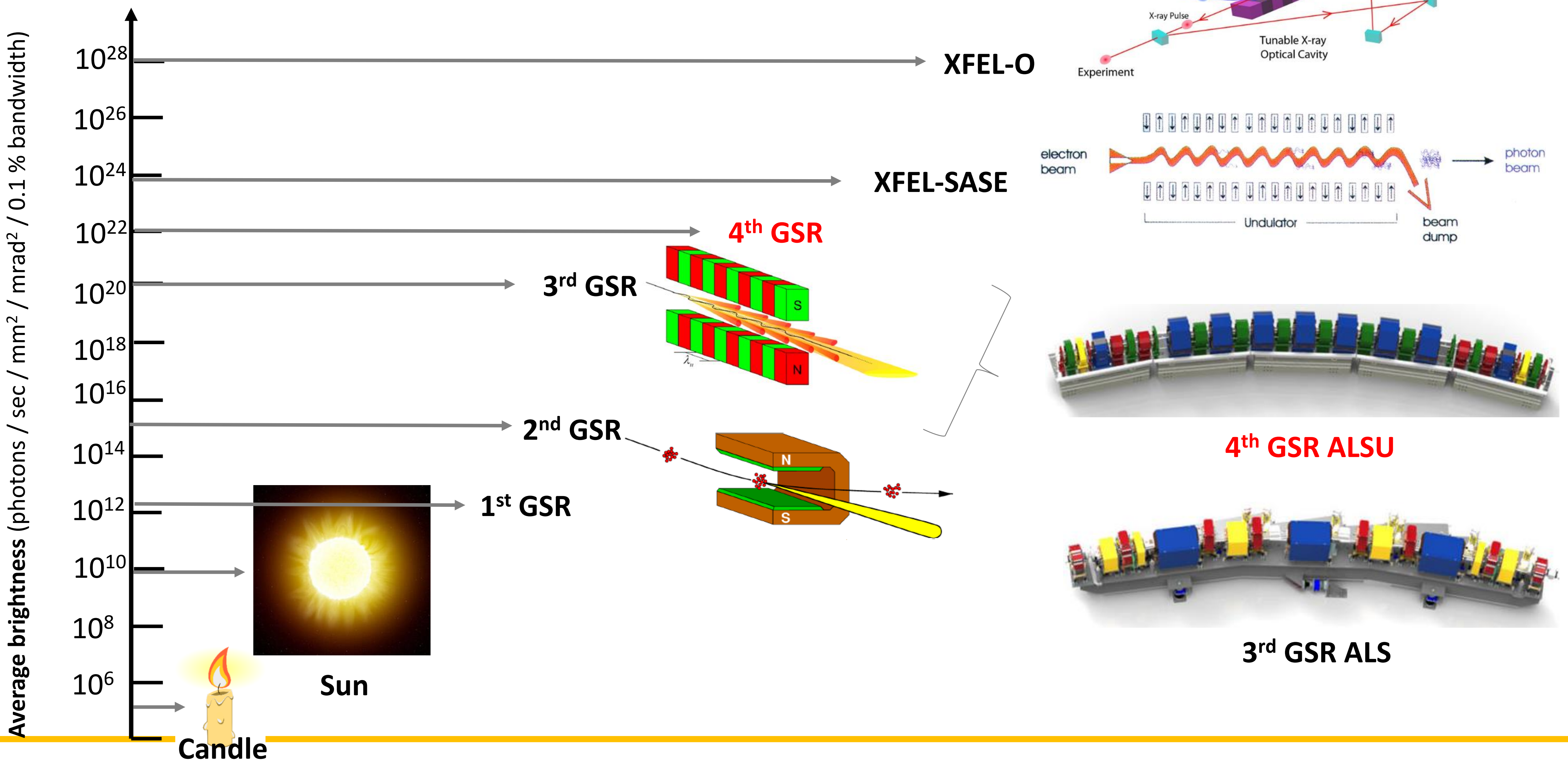




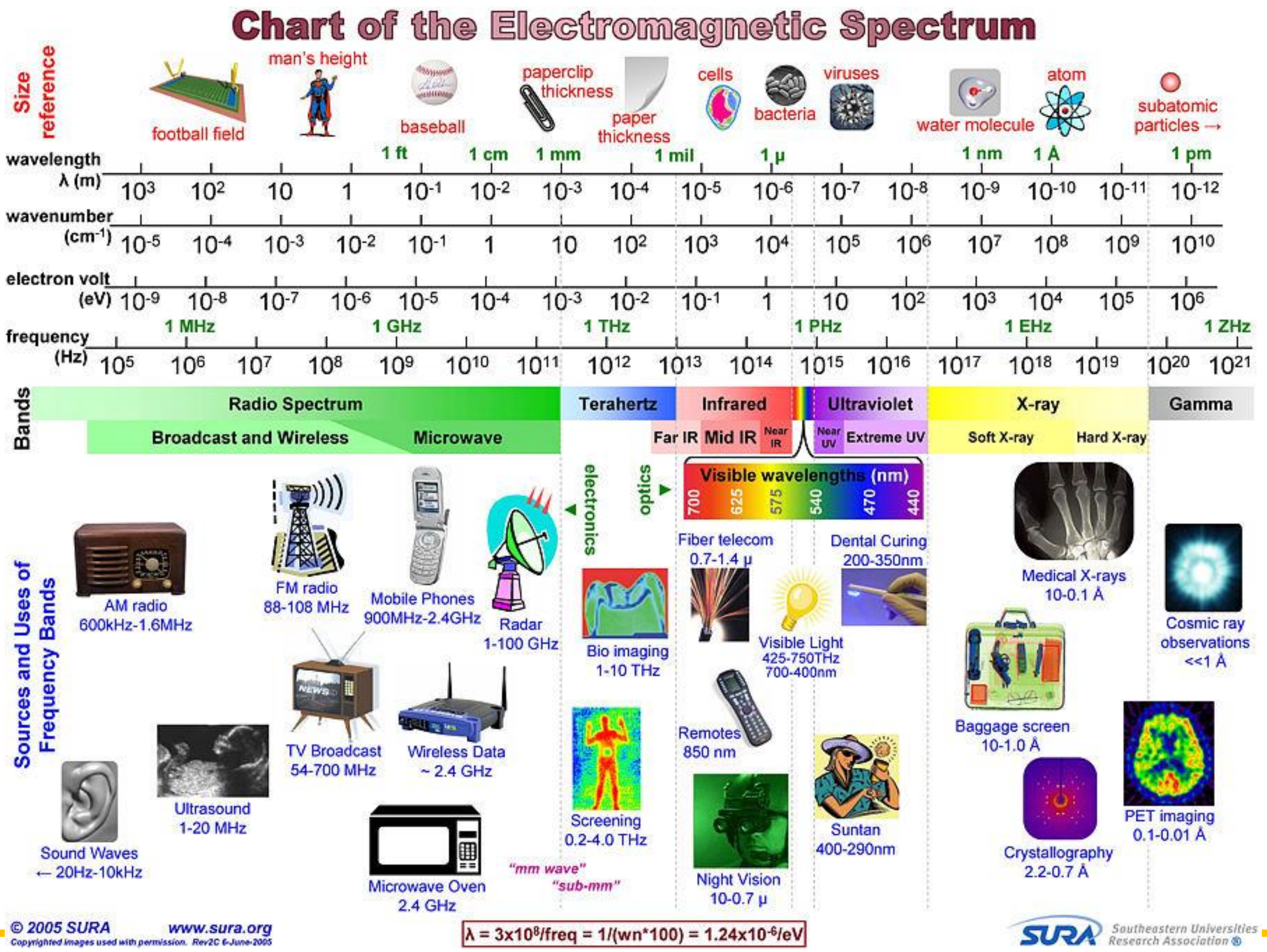


Progression of X-ray source

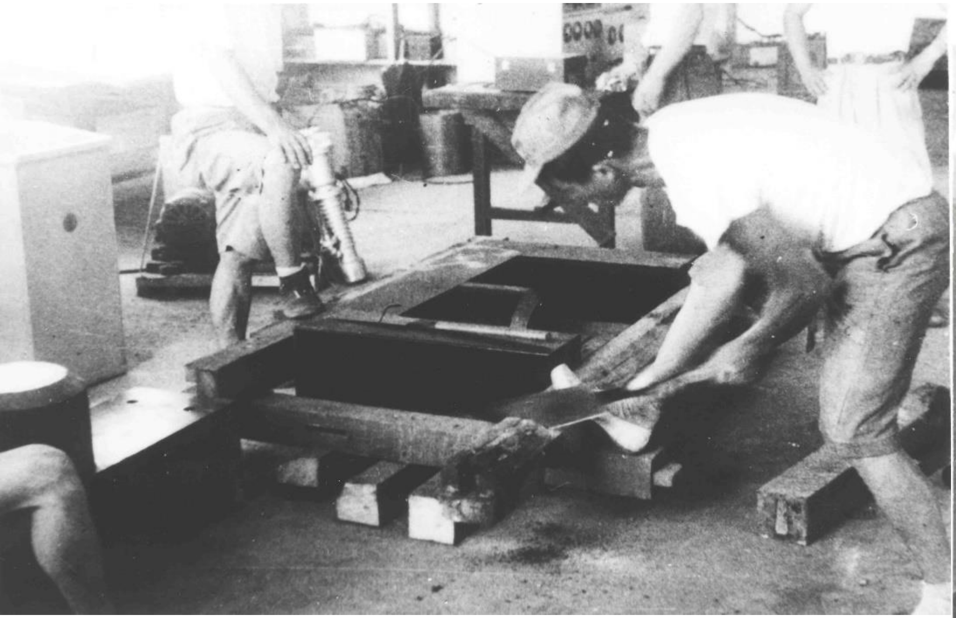




Spectrum of Radiation Source



대한민국 최초의 가속기 (1958~1959)

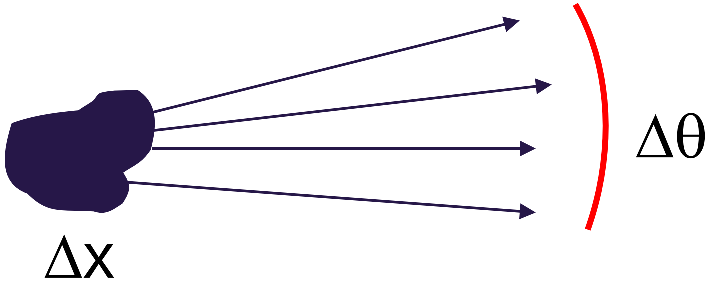


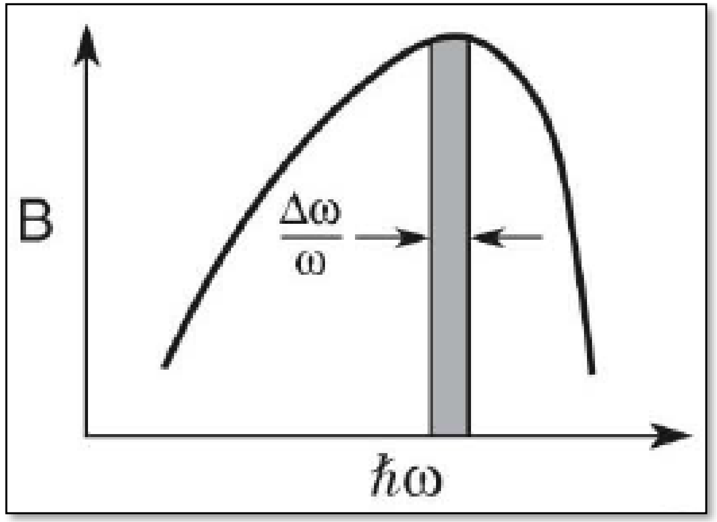
서울대학교 문리대 대학원생들이 1MeV급 사이클로트론을 제작

이문종 대학원생의 시운전 모습
(나중에 미국 매릴랜드대학교 교수가 됨)

Aerial View of PAL (July 27, 2016)

Brightness



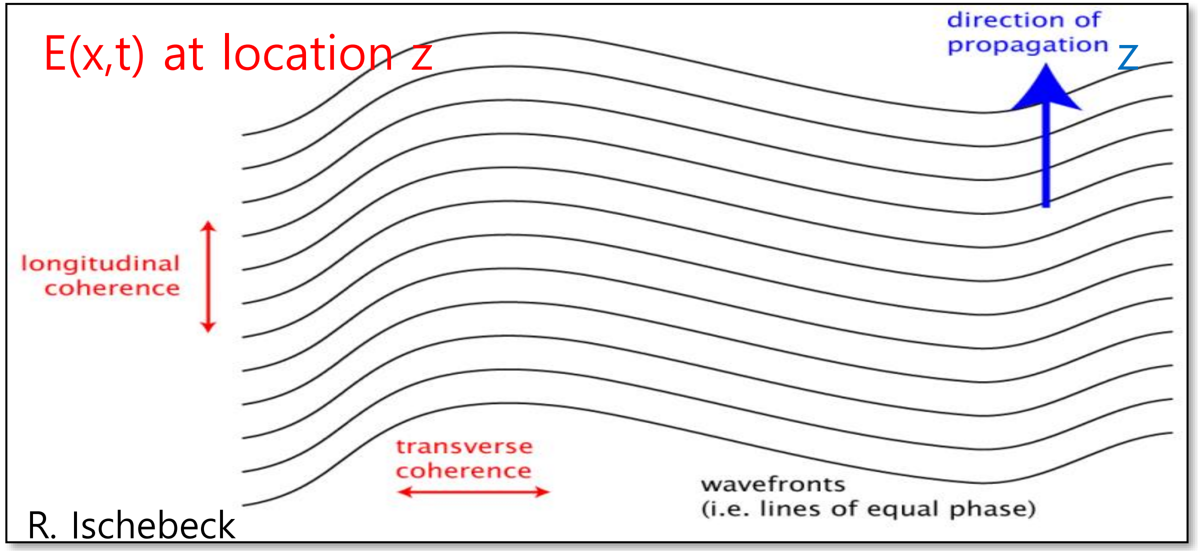


Emittance ~ (source size x divergence)

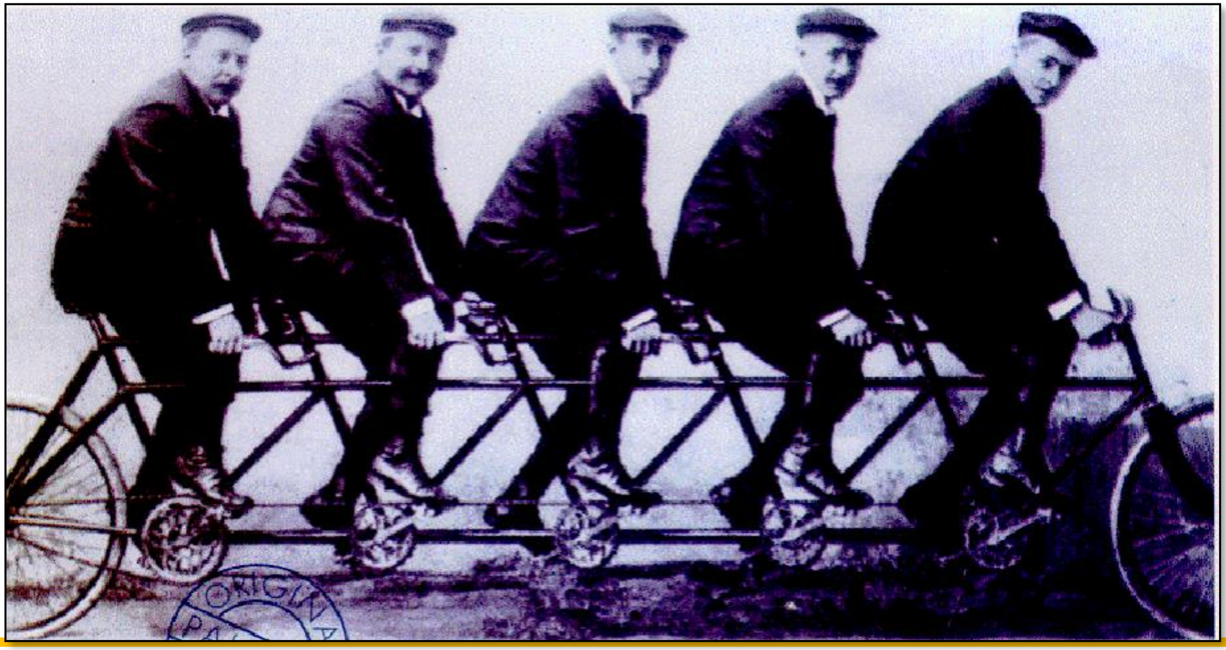
$$B = \frac{\text{Photons in unit spectral range in unit time}}{(\text{source size} \times \text{divergence})^2}$$

Units: photons/s/mm²/mrad²/0.1%BW

Coherence

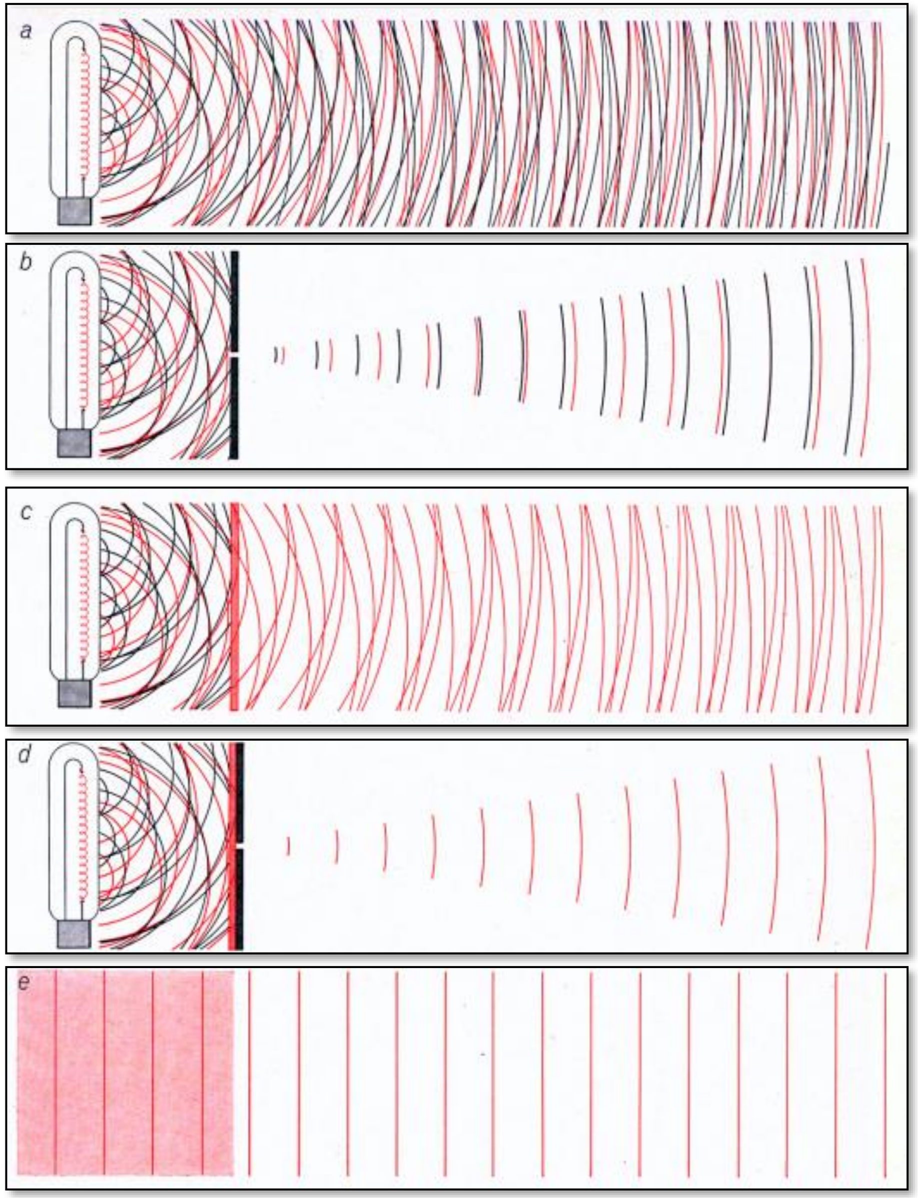


E(x,t) at location z
direction of propagation
z
longitudinal coherence
transverse coherence
wavefronts
(i.e. lines of equal phase)
R. Ischebeck



ORIGINA

Ideal Source of Light



Radiation emitted from light bulb is chaotic.

Pinhole can be used to obtain spatial coherence.

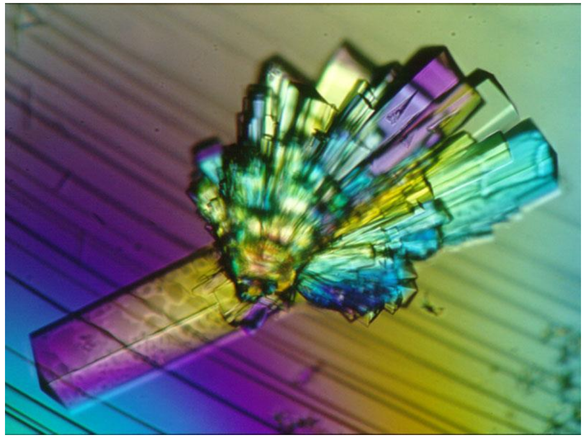
Monochromator can be used to obtain temporal coherence.

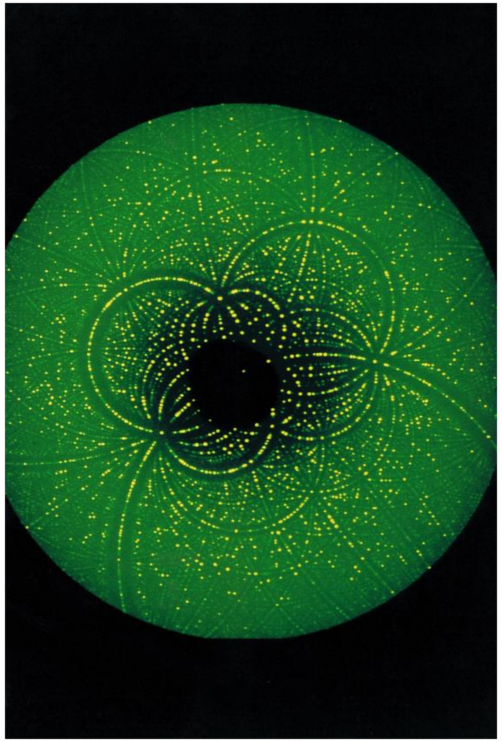
Pinhole and Monochromator can be combined for coherence.

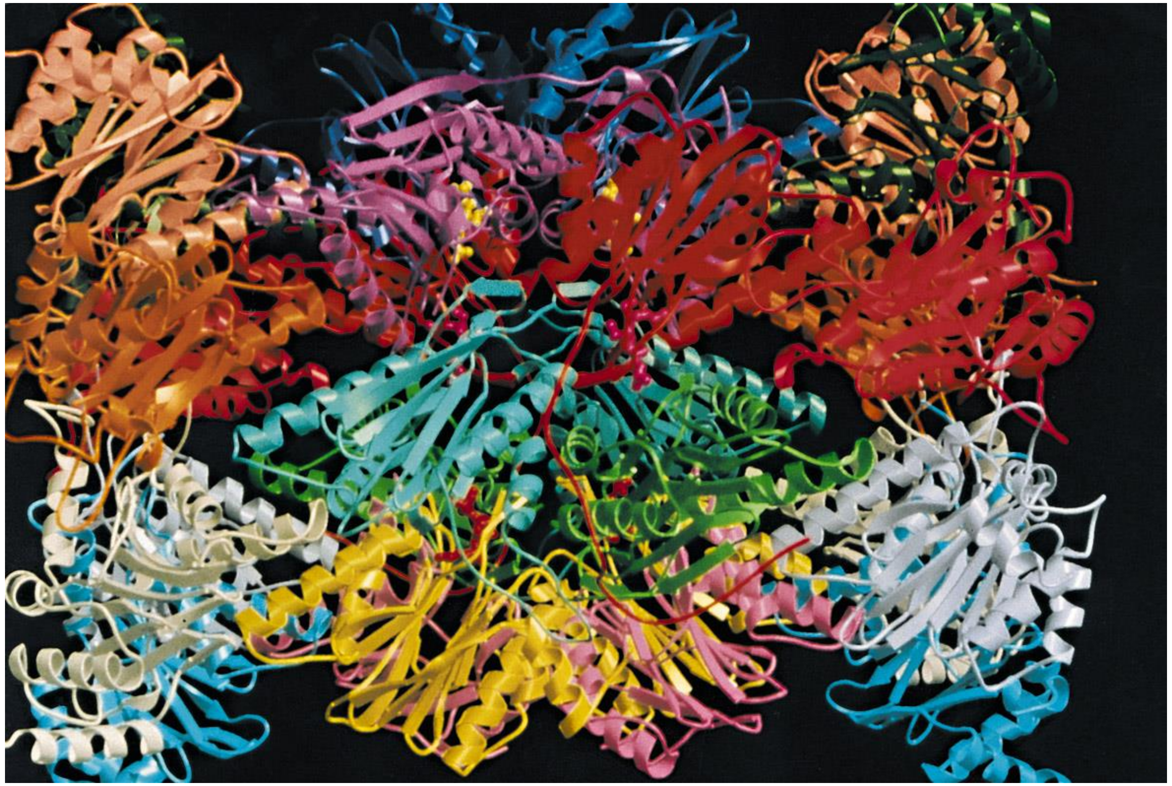
Laser light is spatially and temporally coherent.

A. Schawlow (co-inventor of laser concept), Scientific Americans, 1968

Structure of Large Bio-molecules

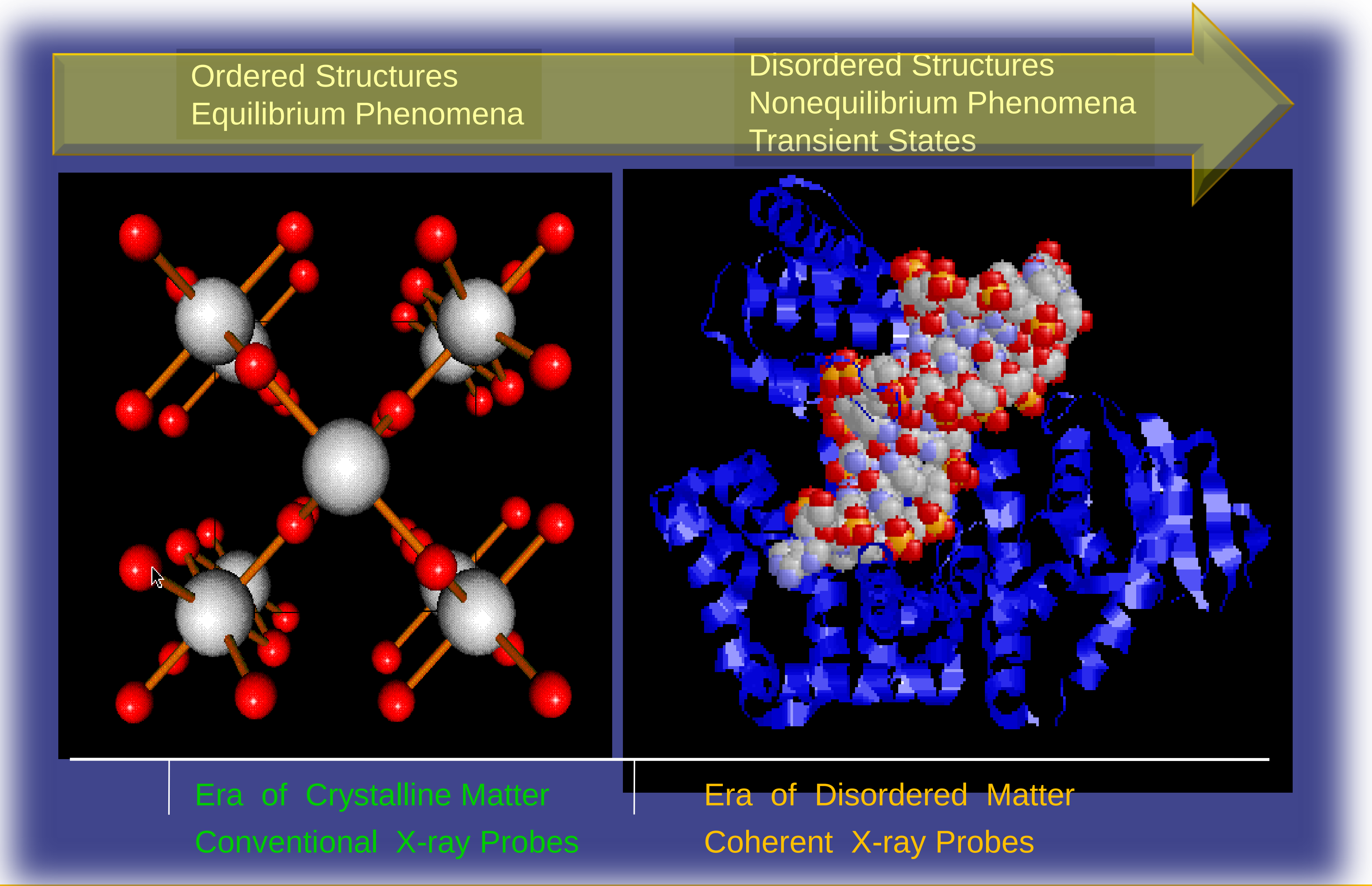






Proteasome

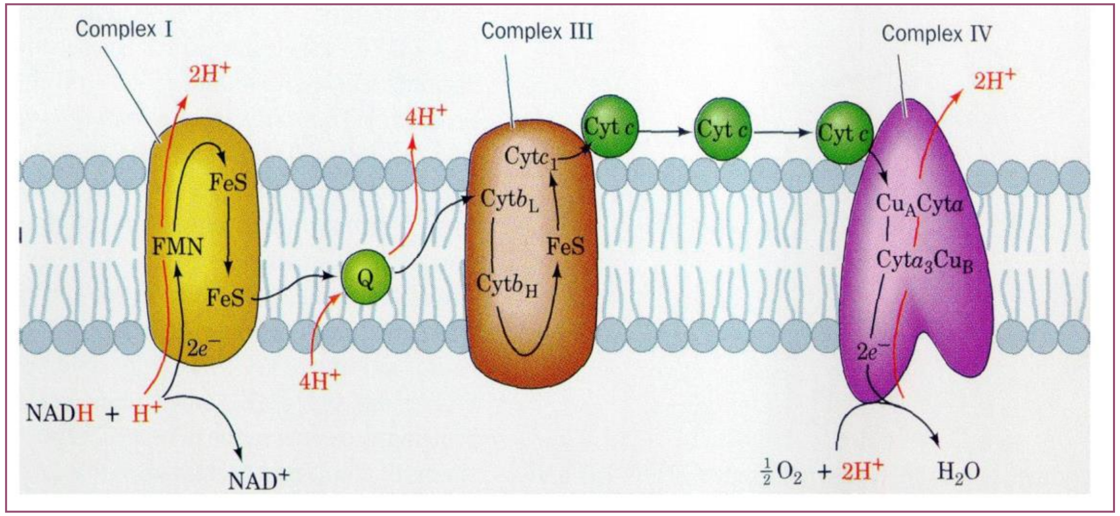
Single molecule imaging

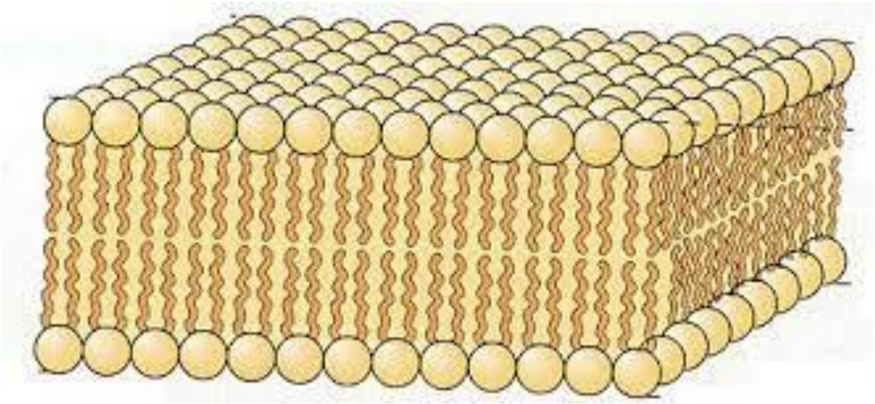


1900 2000 future H. Dosch (DESY)

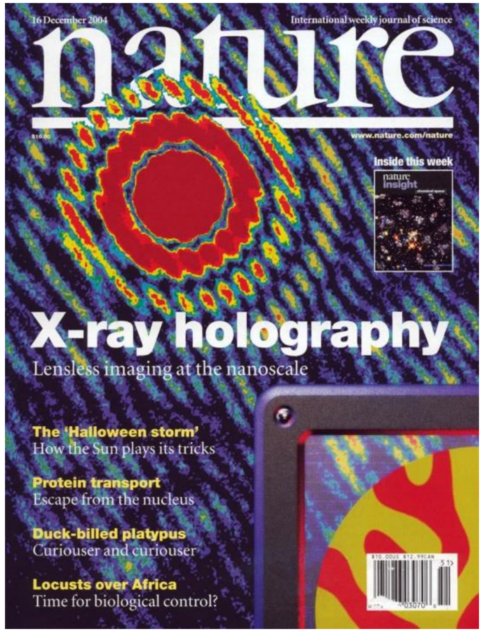
Limits of conventional light source

- Difficult to use X-ray crystallography to samples which are difficult or impossible to crystallize.
  - protein molecules with membrane proteins
  - some of whole cells
  - some viruses, polymers, or nanostructures

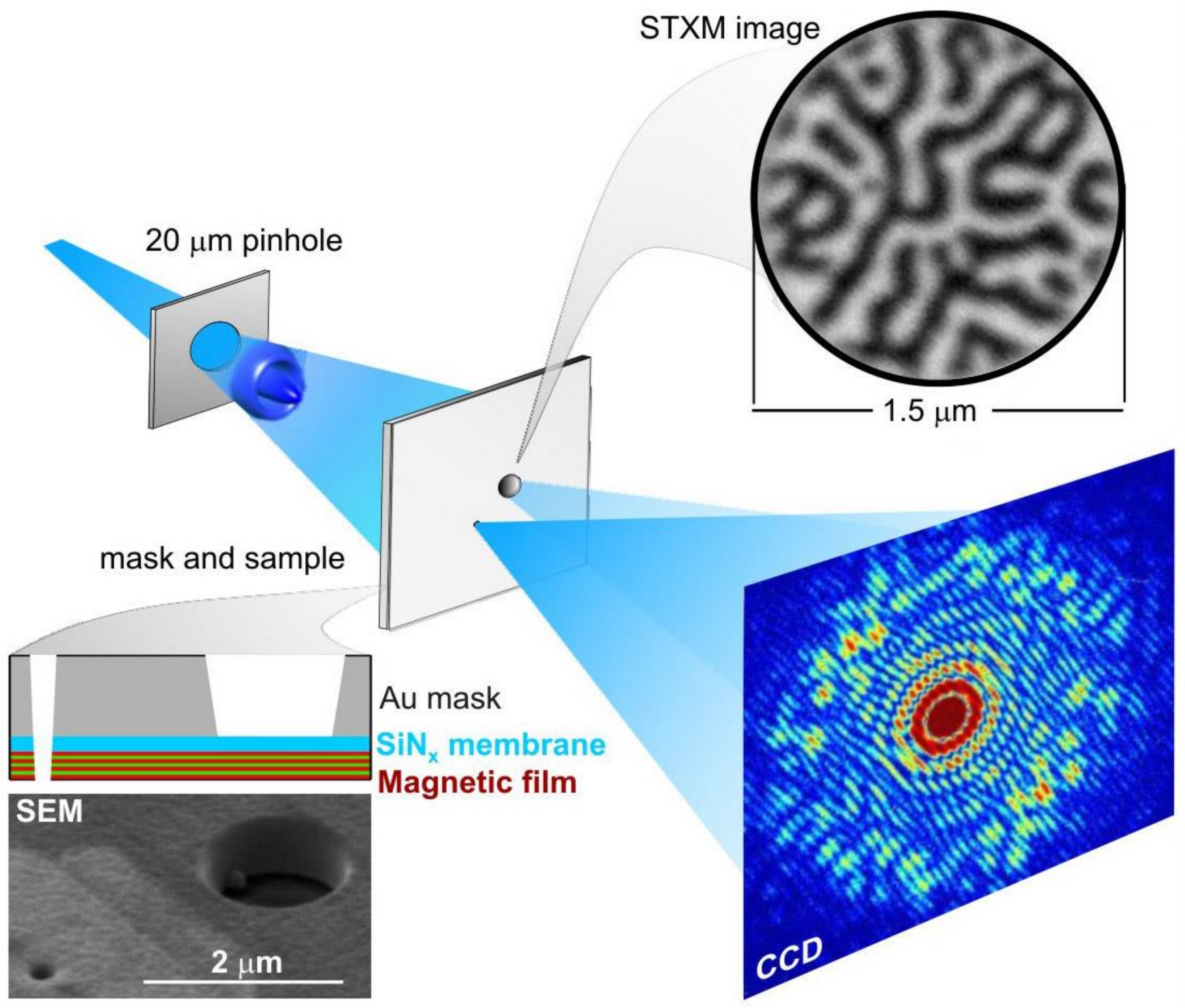




Coherence Wanted



Lensless imaging of magnetic nanostructures by X-ray holography

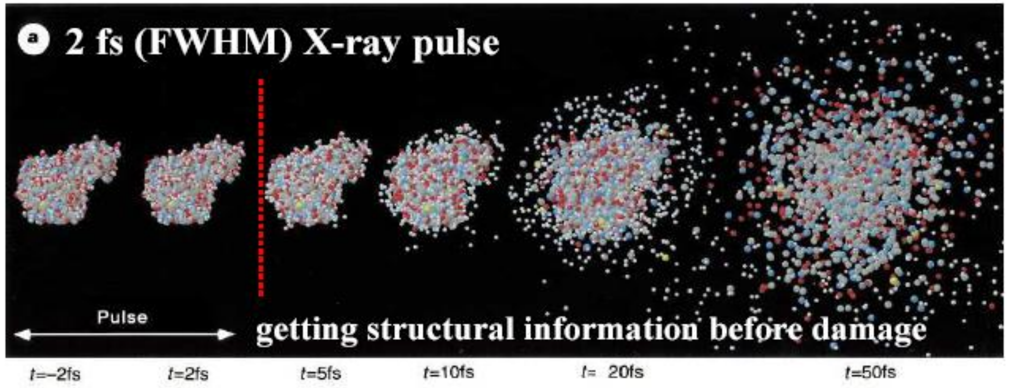


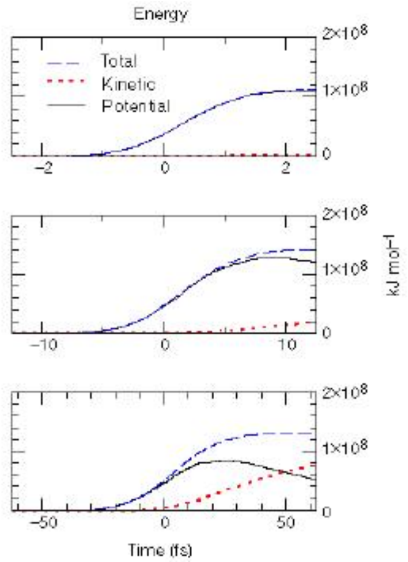
S. Eisebitt, J. Lüning, W.F. Schlotter, M. Lörgen, O. Hellwig, W. Eberhardt & J. Stöhr / *Nature*, 16 Dec 2004

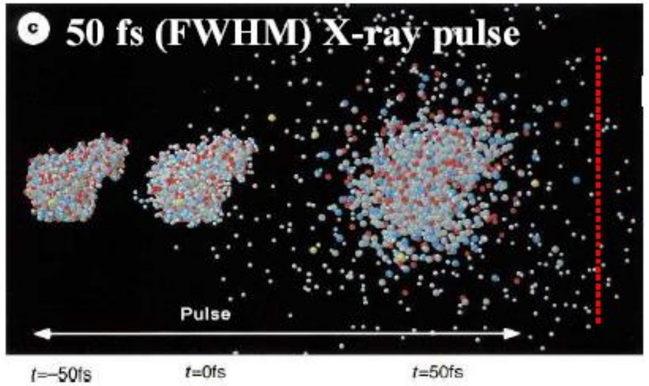
LenslessImagingF1.ai

Needs for Shorter Pulses

- Intense X-ray with long pulse damages biological samples due to photoelectric effects.
  - Note that the minimum pulse duration length of 3rd generation light source ~ 10 ps due to quantum nature of ISR and CSR.





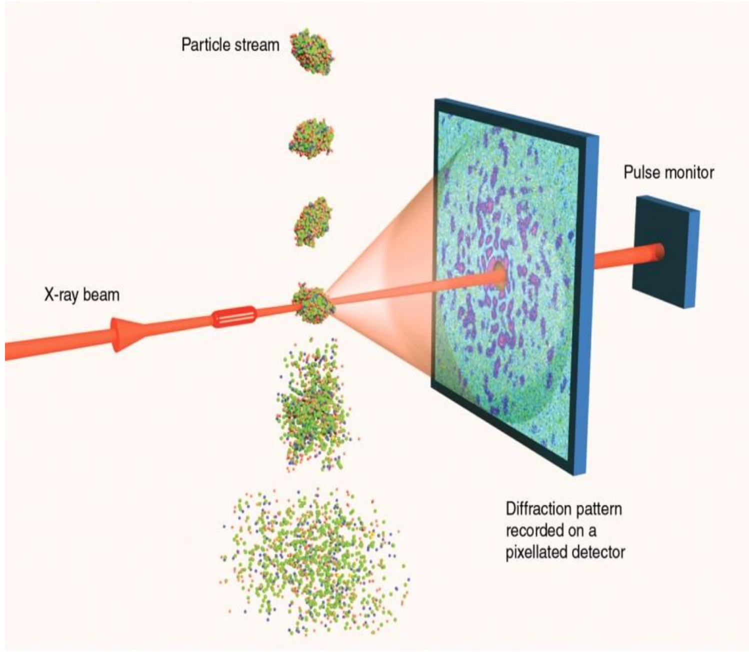


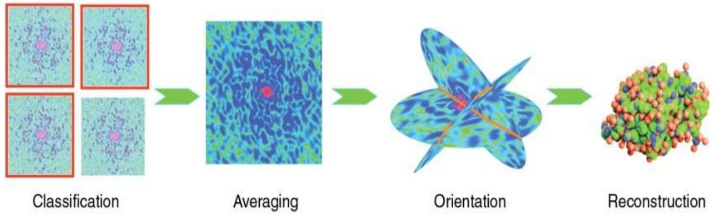
~ 3.8×10^{6} photons per $Å^2$ with 12 keV photon energy.

Explosion of a single protein molecule (T4 lysozyme)
white, grey, blue, red, and yellow mean H, C, N, O, and S, respectively.

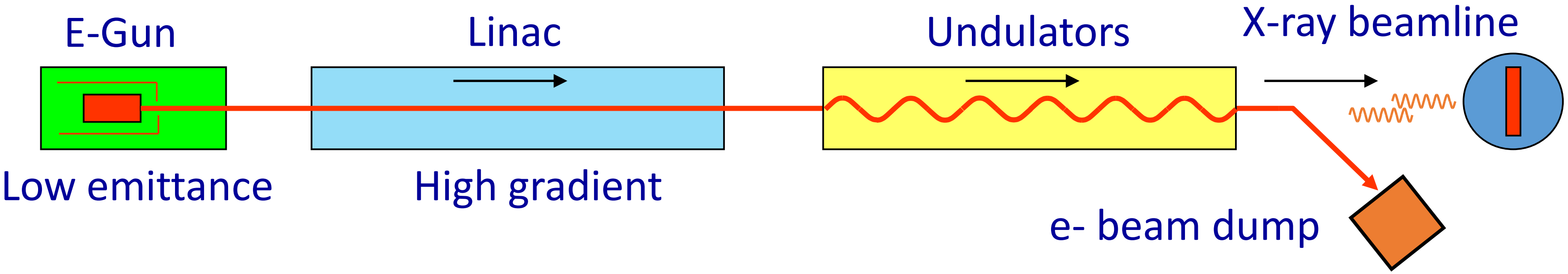
Nature Vol 406, p. 752 by R. Neutze

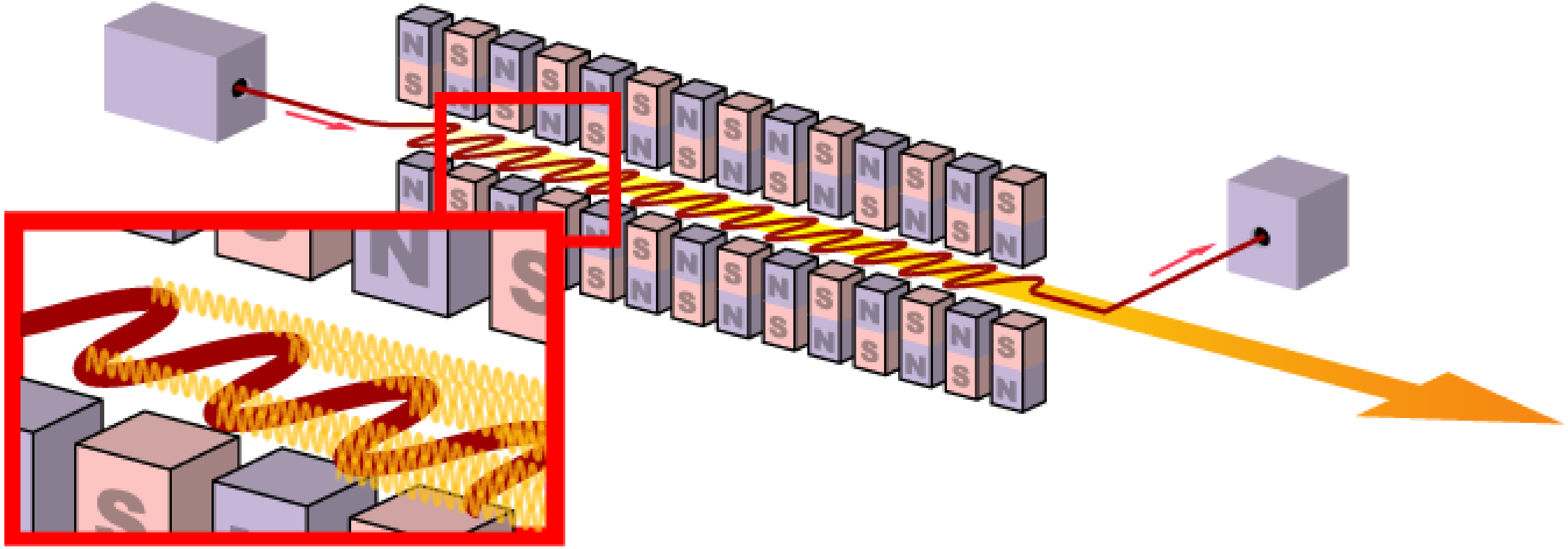
Single-molecule coherent diffraction imaging





Free Electron Laser (FEL)



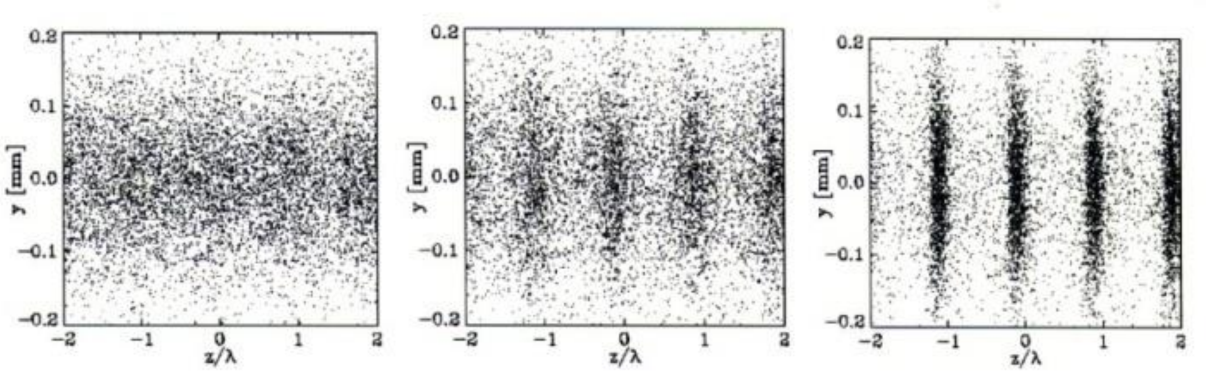


Mechanism of FEL: SASE

Self-Amplified Spontaneous Emission (SASE)

A wonderful instability !

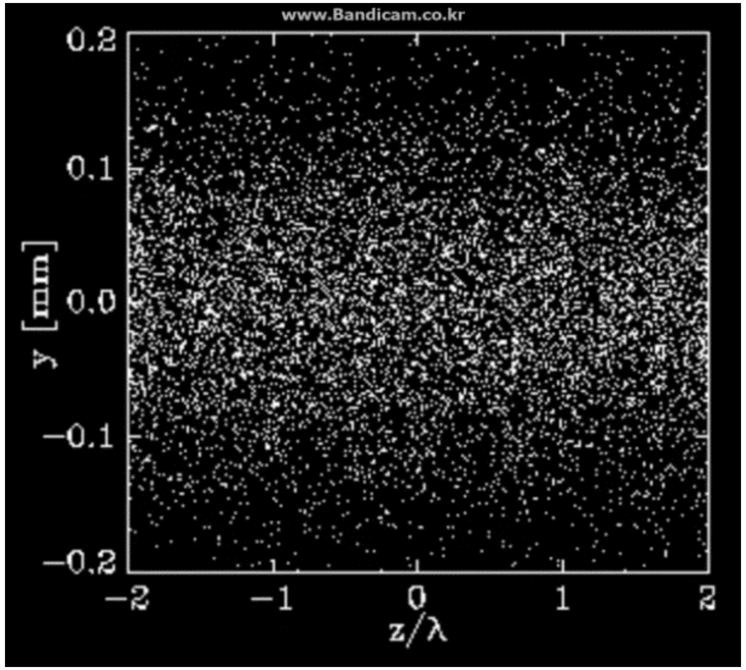
The initial random field of spontaneous radiation in an undulator is amplified in the medium of a relativistic electron beam traveling through a long undulator to intense, coherent radiation by strong interaction between radiation and electron beam.



At entrance to the undulator

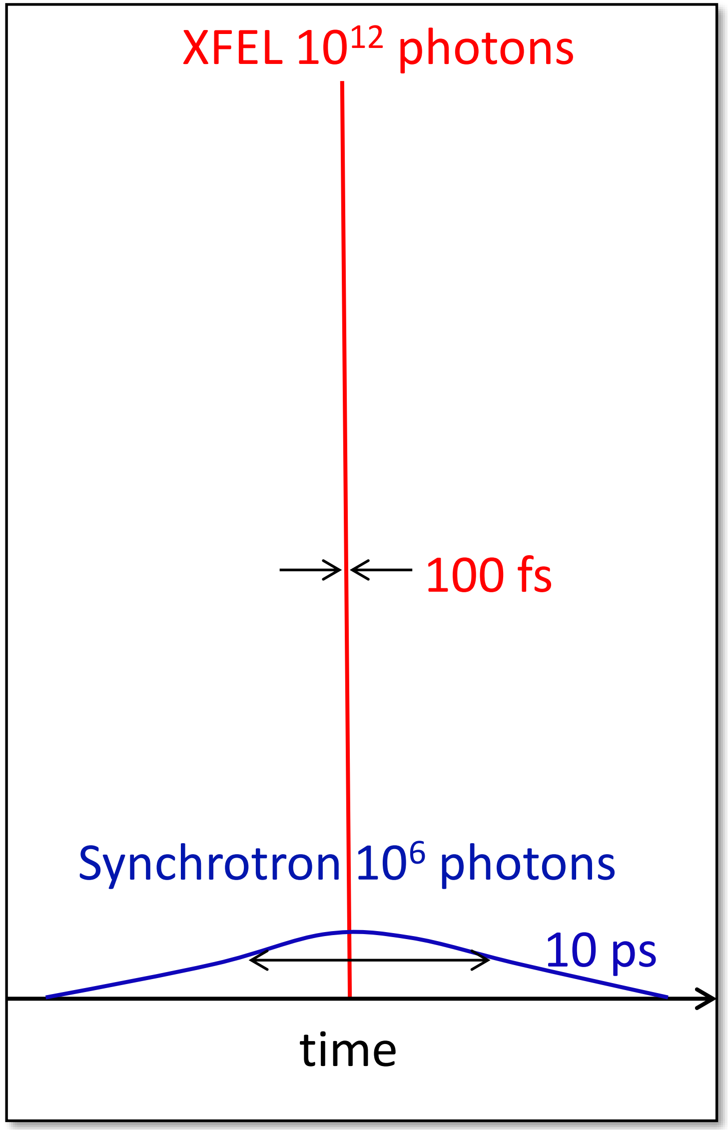
Exponential gain regime

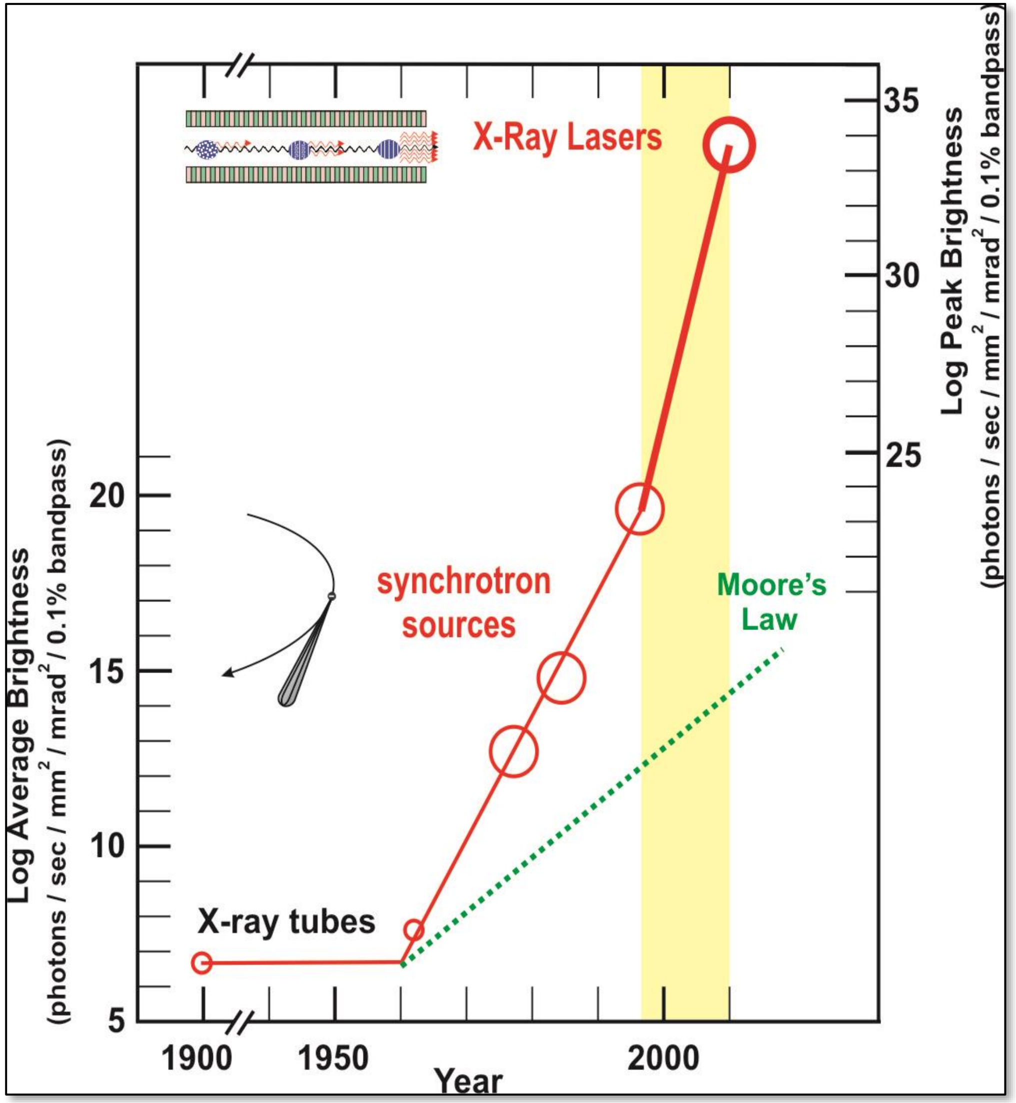
Saturation (maximum bunching)



(J. Madey, H. A. Schwettman, W. M. Fairbank, IEEE Transactions on Nuclear Science, 20, 980 (1973))

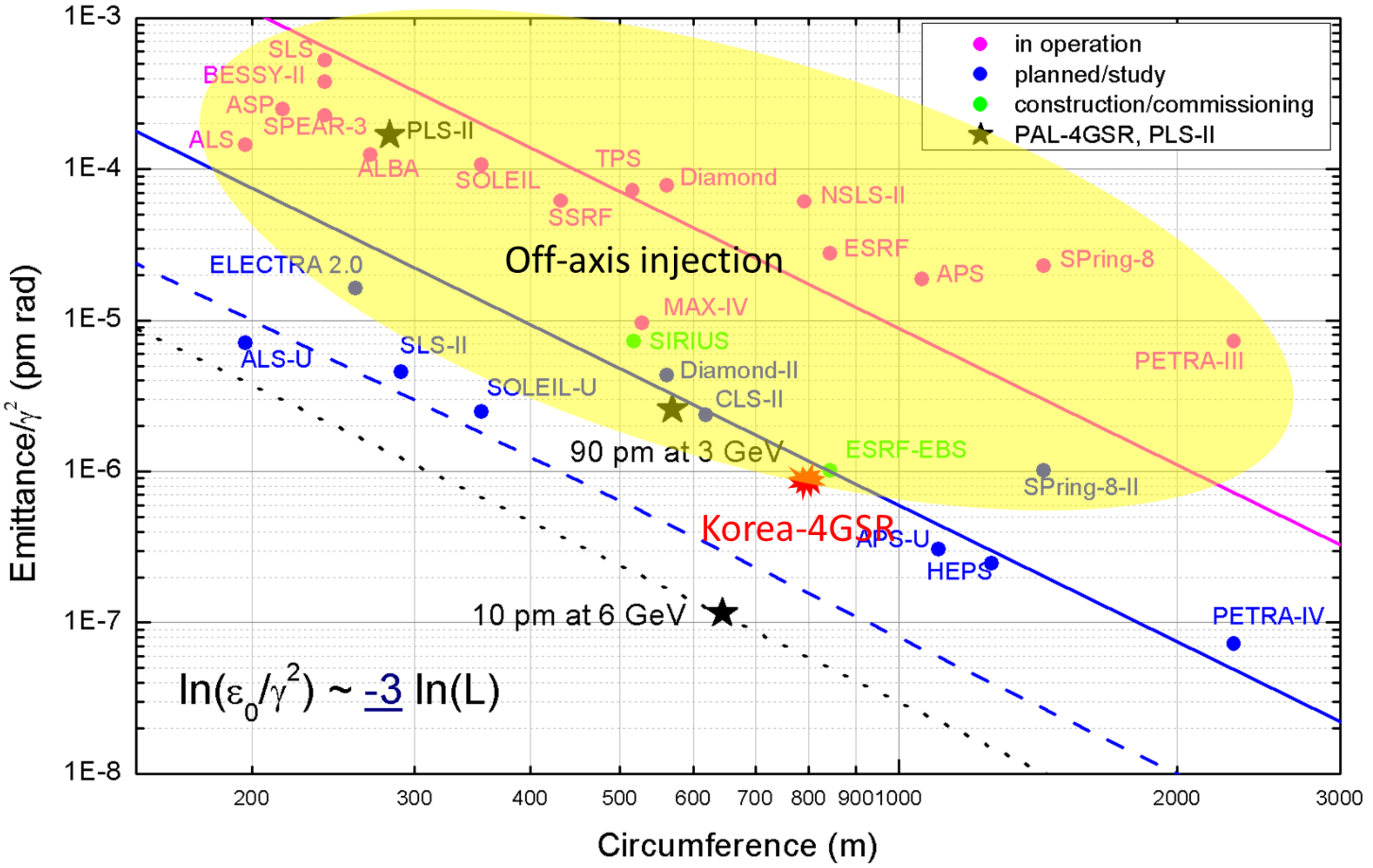
XFELs are extremely brighter and ultrafast!





Note: Synchrotron sources are much higher rep. rate than XFELs

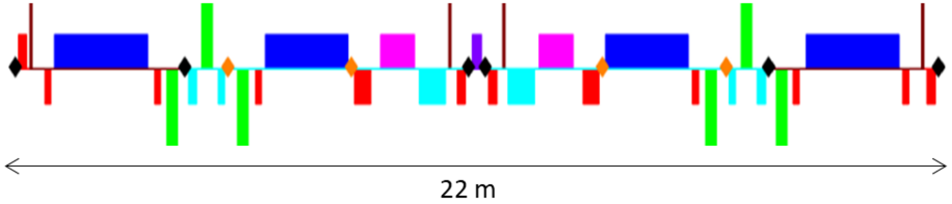
Worldwide light sources

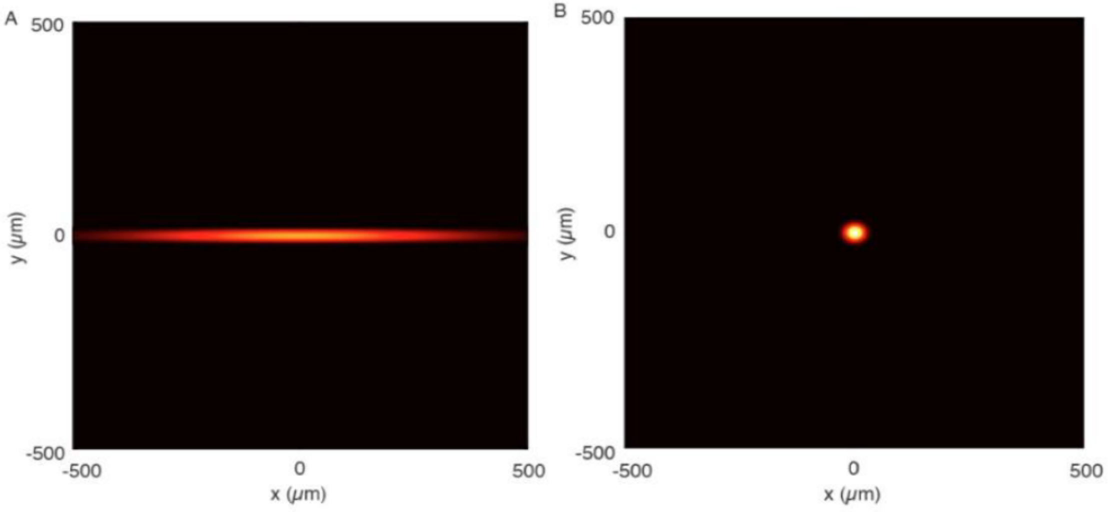


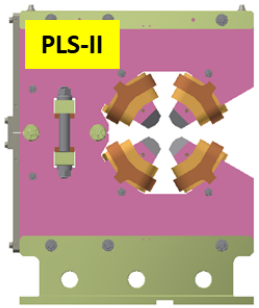
3GSR vs. 4GSR (with challenging technology)

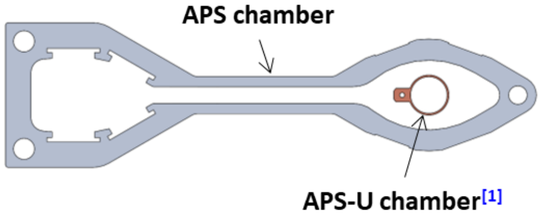
- **The 3rd Generation Storage Ring Lattice:**

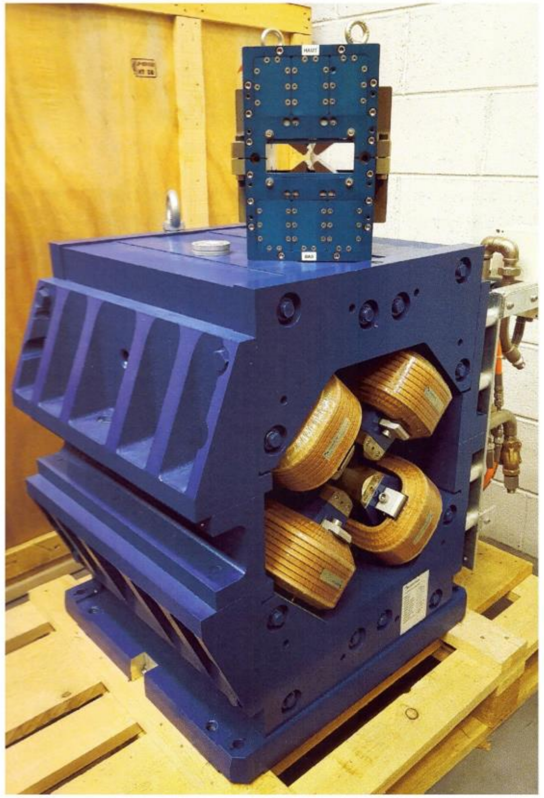
- **The 4th Generation Storage Ring Lattice:**





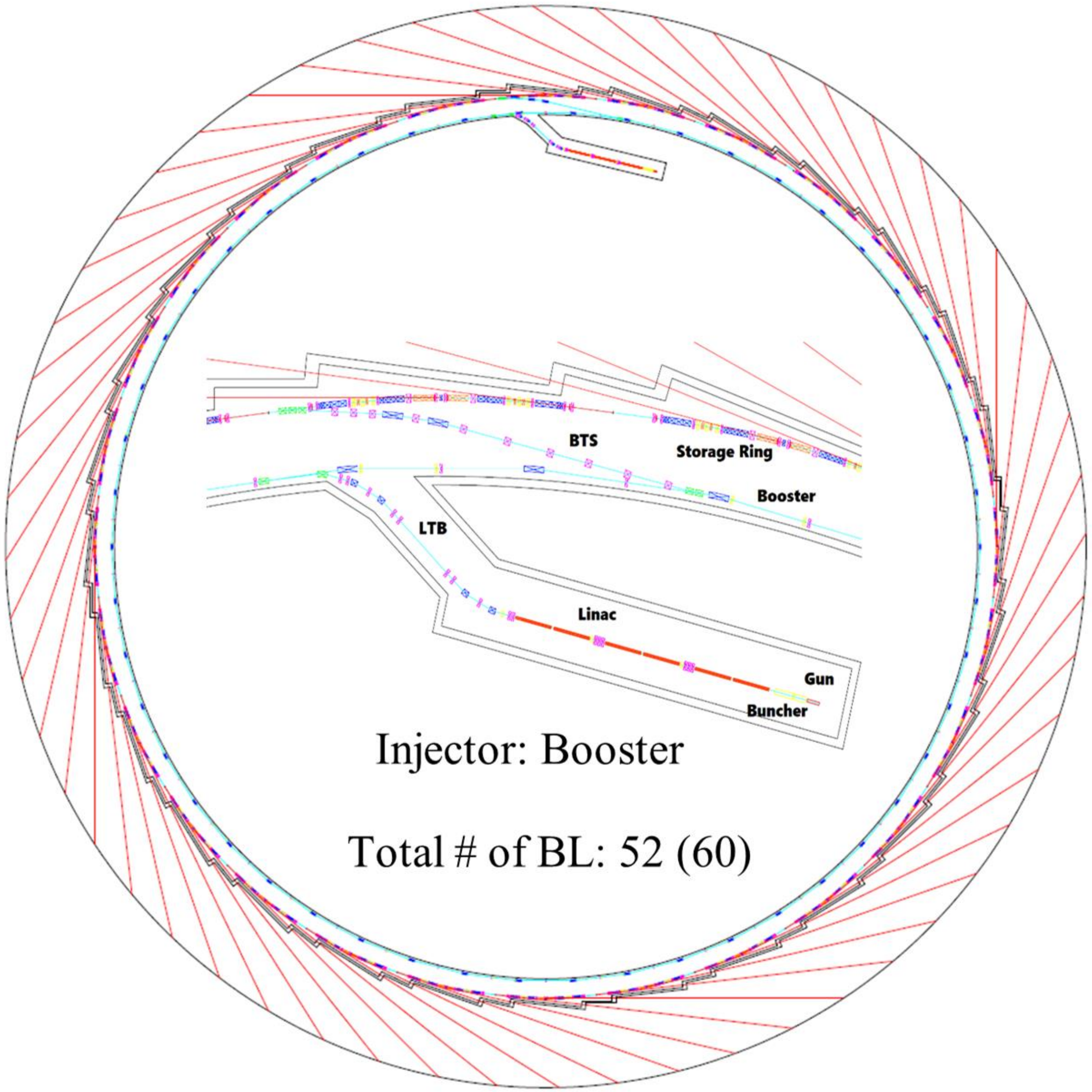




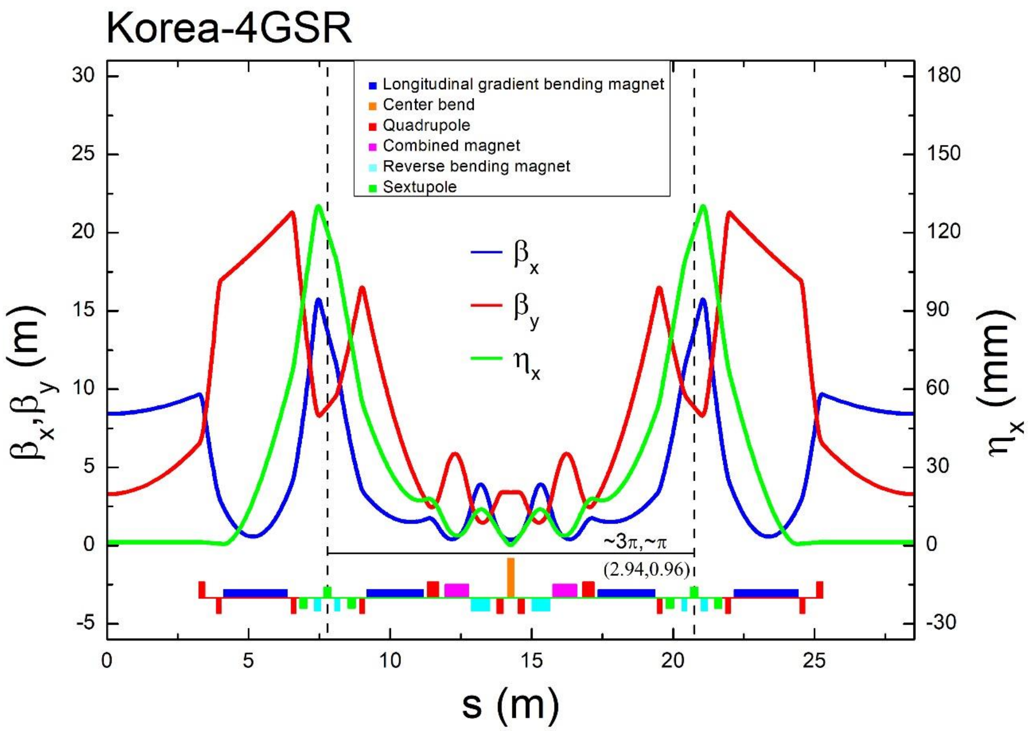


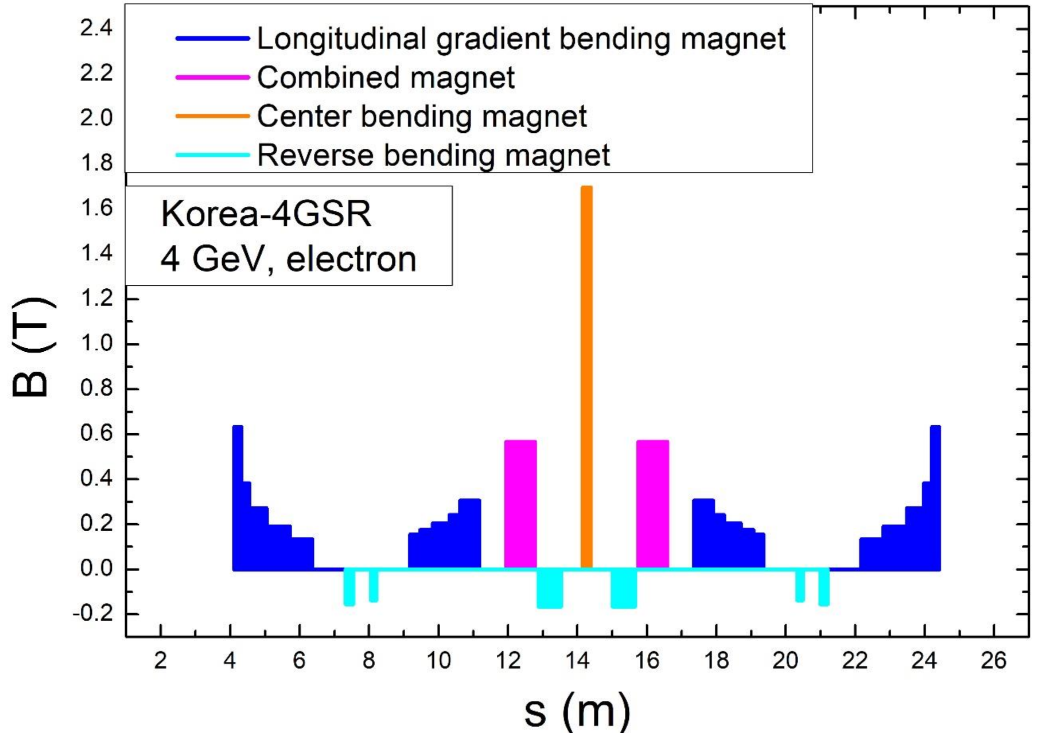
Major Parameters for Korean 4GSR

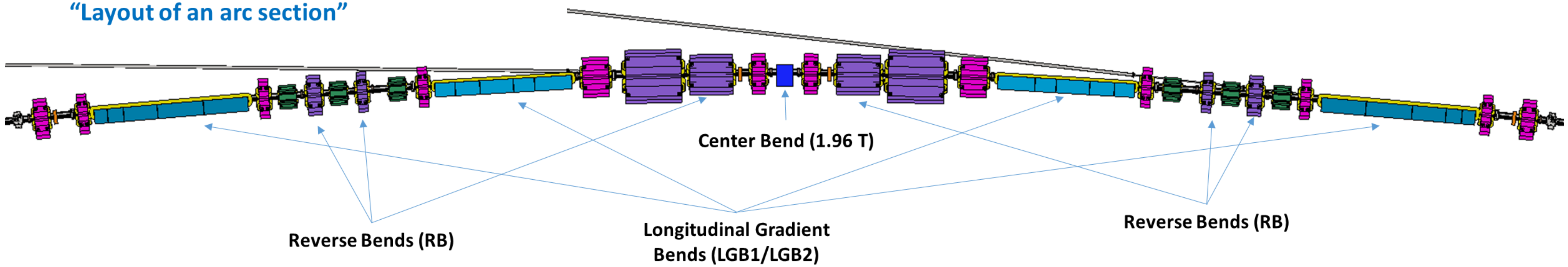
4GSR Ring		Value	Unit
Design Parameters	Cell Number	28	-
	Circumference	**798.84**	**[m]**
	Electron Energy	**4**	**[GeV]**
	Natural Emittance	**58**	**[pm rad]**
Tune and Chromaticiy	Horizontal Tune	67.395	-
	Vertical Tune	24.275	-
	Natural Horizontal Chromaticity	-115.344	-
	Natural Vertical Chromaticity	-84.693	-
	Horizontal Chromaticity	3.5	(target)
	Vertical Chromaticity	3.5	(target)
Radiation related quantities	**Energy Loss per Turn**	**1009**	**[keV]**
	Energy Spread	0.1197	[%]
	Horizontal Damping Time	11.075	[ms]
	Vertical Damping Time	21.127	[ms]
	Longitudinal Damping Time	19.342	[ms]
Twiss functions at the ID	Horizontal beta function at the ID center	8.564	[m]
	Vertical beta function at the ID center	2.459	[m]
	Dispersion function at the ID center	1.3	[mm]



Hybrid 7-bend archromat

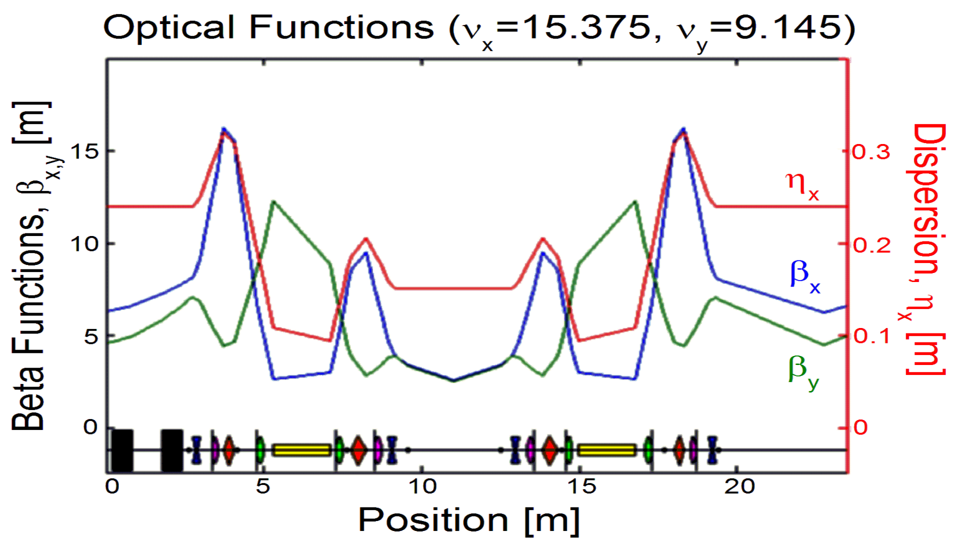


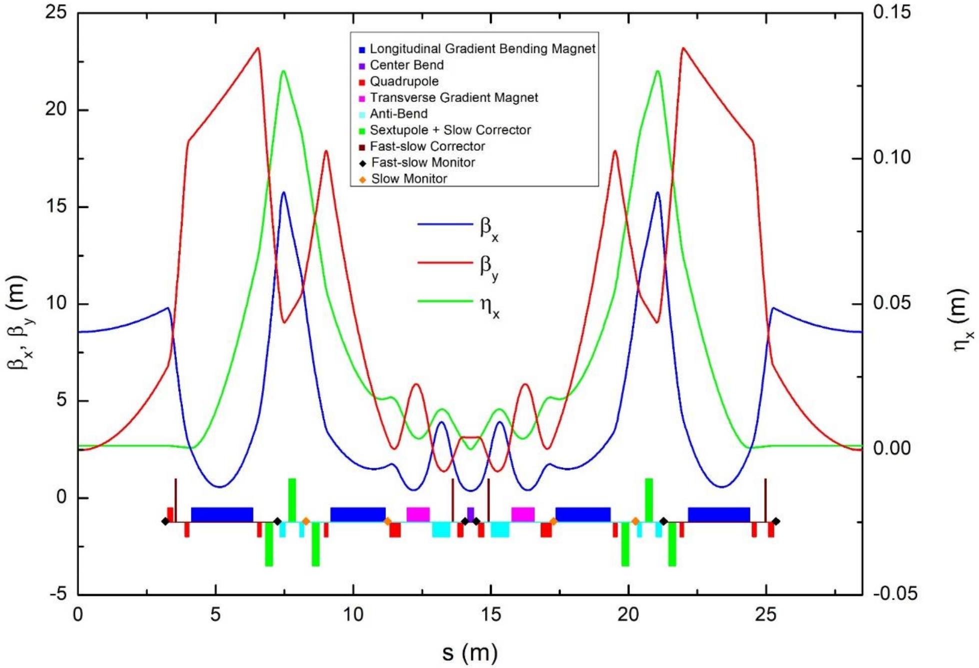




Comparison between PLS-II and 4GSR

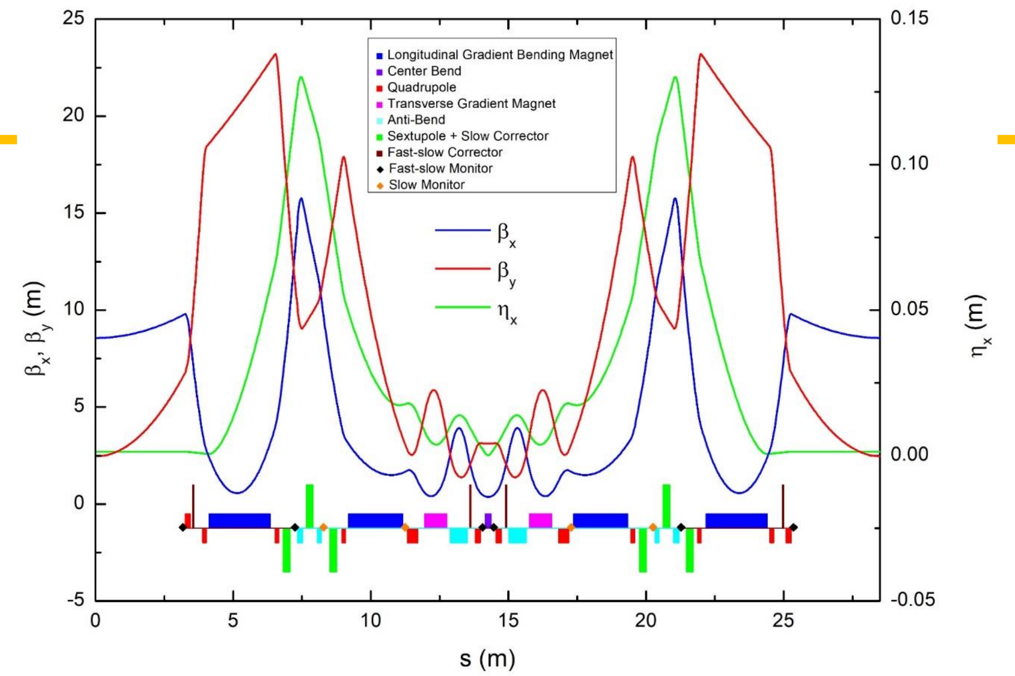
Parameter	Units	PLS-II	KOREA-4GSR
Electron energy	GeV	3	4
Horizontal emittance	pm	5800	58 (RB: 39)
Vertical emittance	pm	~ 58	~ 5.8 (RB: 39)
Bunch length (rms)	ps	16	13 (50 with HC)
Circumference	m	281.82	798.84
Superperiod		12	28
Tunes (H/V)		15.36/9.15	67.395/24.275
Harmonic number		470	1332
RF frequency	MHz	500	500
Energy loss per turn	keV	1040	1009
Beam stability @ ID (x/y)	μm	< 4 / 2	< 2.5 / 0.45
Injection mode		Top-up	Top-up



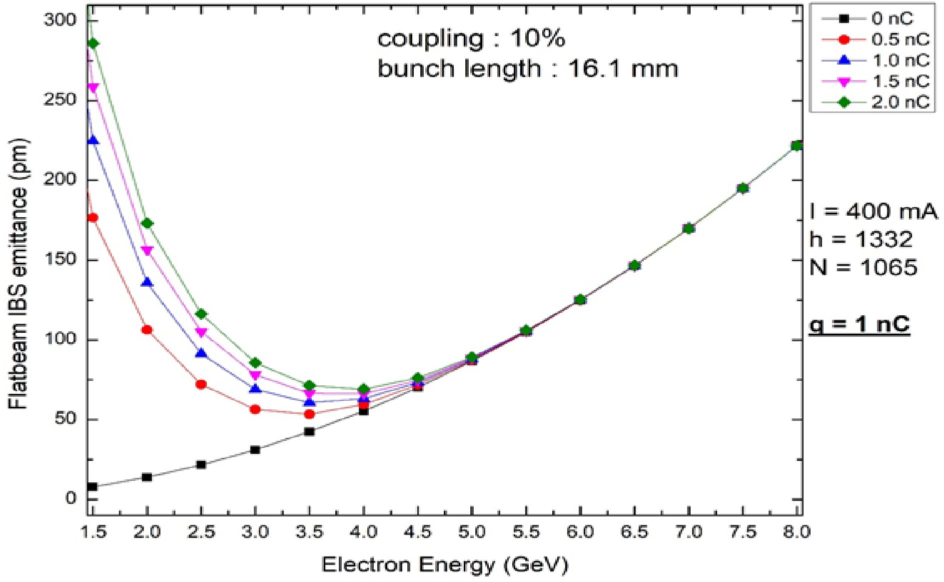


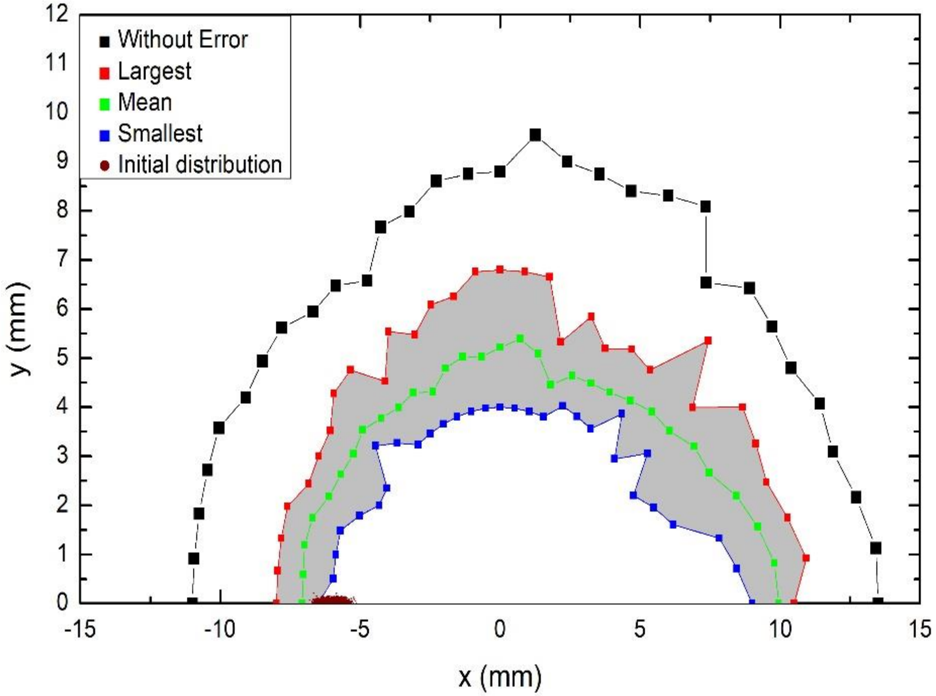
SR Lattice Structure (linear)

1. Natural evolution of ESRF-EBS and APS-U
2. ESRF-EBS type
   - Dispersion bump w/sextupoles.
   - Longitudinal gradient dipoles.
   - Phase advance of $\Delta\phi_x \sim 3\pi$ and $\Delta\phi_y \sim \pi$ between corresponding sextupole
3. APS-U type: Reverse bends in Q4, Q5, and Q8.
4. Massive use of combined function magnets
5. 6.5 m straight section and 2 T center-bend (E_c=21 keV)



Minimum emittance @ 4 GeV

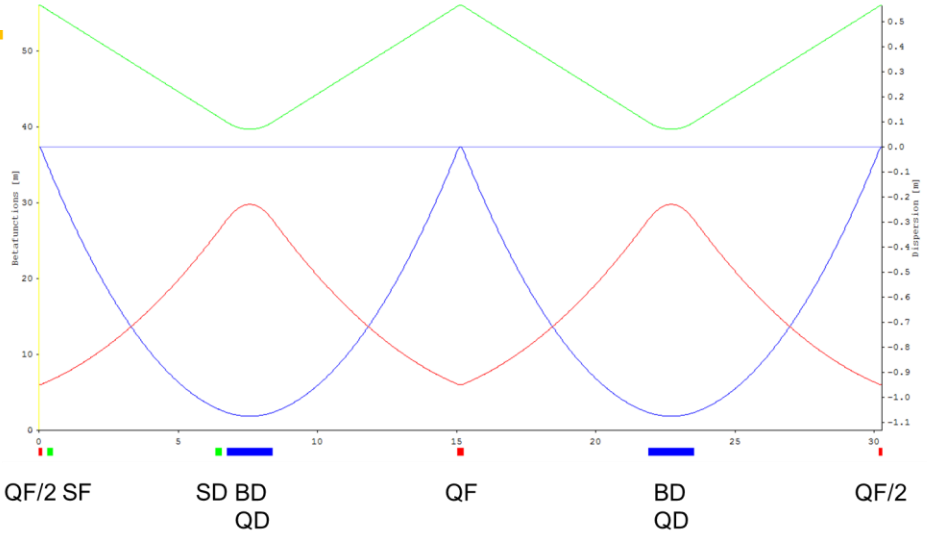




Injector System

Booster

1. Same tunnel with SR
2. Enough dynamic aperture: (Ax: -27 ~ 27 mm, Ay: ~ 14 mm).
3. Two normal cavities in one straight section.



Linac

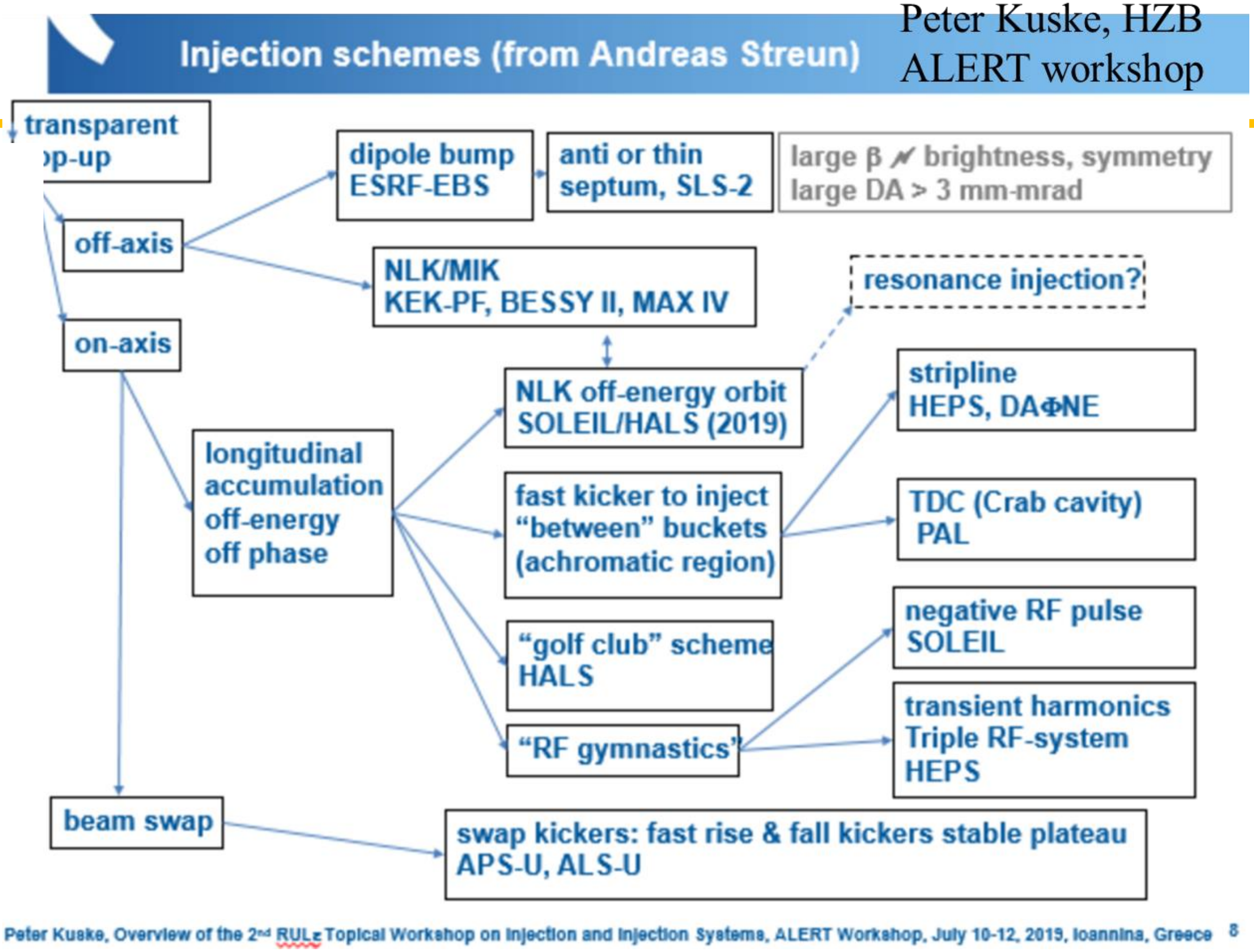
1. 2.997 GHz RF system for better injection
2. Photocathode gun and 6 accelerating sections under design

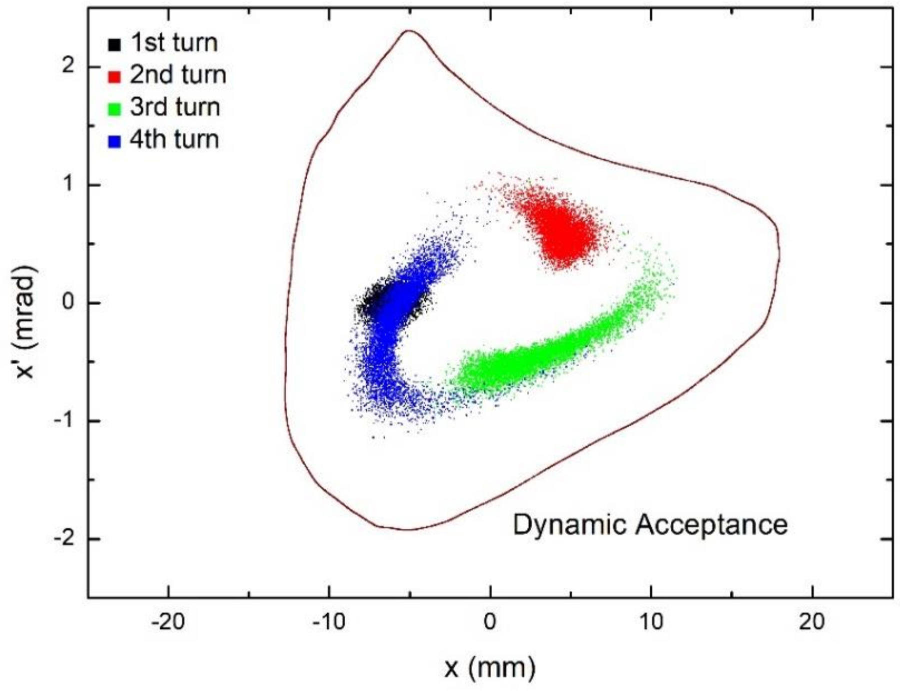
4GSR Linac	Multi-bunch	Single-bunch	Unit
Energy	200	200	MeV
Frequency (e-gun and SHB)	499.546	499.546	MHz
Frequency (Accelerator)	2997.28	2997.28	MHz
Emittance (at 200 MeV)	≤ 200	≤ 200	nm
Relative energy spread (rms)	≤ 1	≤ 0.5	%
Pulse to pulse energy variation	≤ 0.25	≤ 0.25	%
Pulse to pulse beam position	≤ 0.20	≤ 0.20	mm
Pulse to pulse jitter	≤ 100	≤ 100	ps
Pulse charge	3 to 10	0.01 to 2.5	nC
Pulse duration	100 to 400	≤ 1	ns
Repetition rate	2	2	Hz

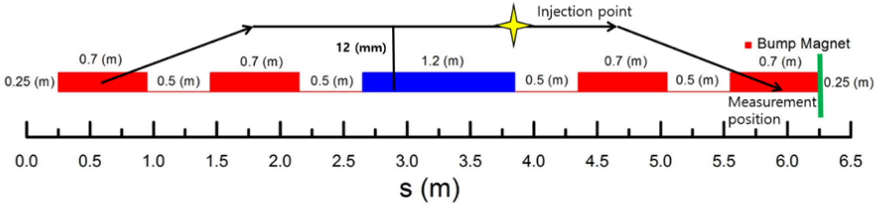
4GSR Booster		Value	Unit
Design Parameters	Cell Number	50	-
	Circumference	756.86	[m]
	Electron Energy	0.2 - 4	[GeV]
	Natural Emittance	6906	[pm rad]
Tune and Chromaticity	Horizontal Tune	19.208	-
	Vertical Tune	9.268	-
	Natural Horizontal Chromaticity	-35.146	-
	Natural Vertical Chromaticity	-14.617	-
	Horizontal Chromaticity	-2	(target)
	Vertical Chromaticity	-2	(target)

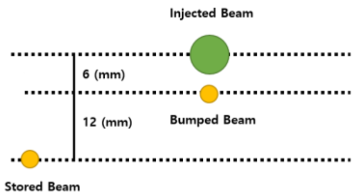
SR Injection Schemes

Peter Kuske, HZB
ALERT workshop

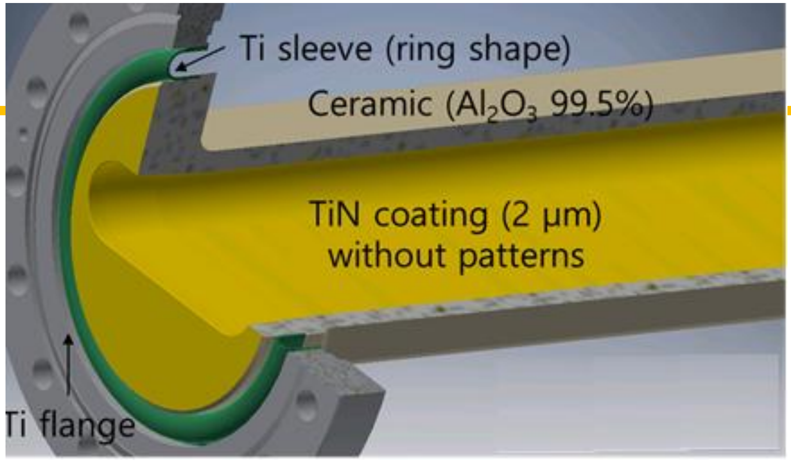




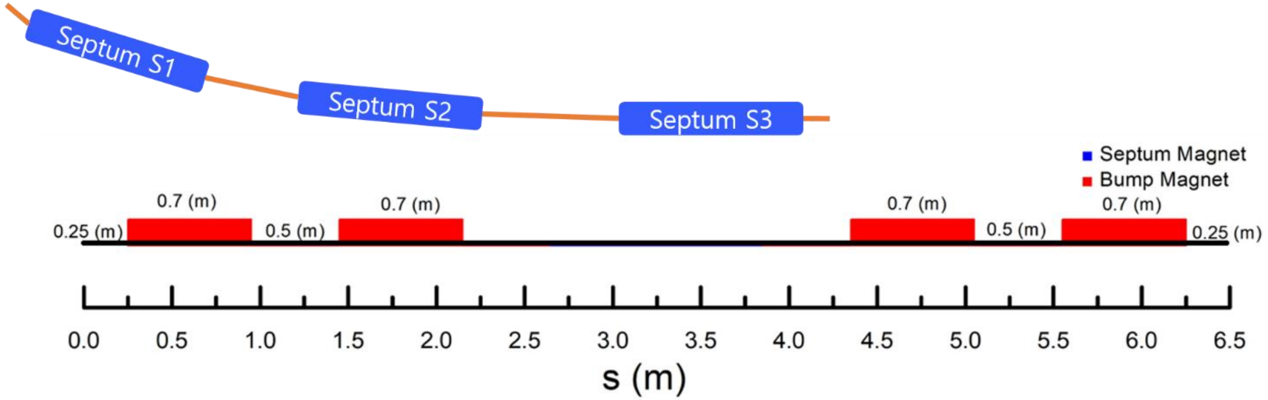


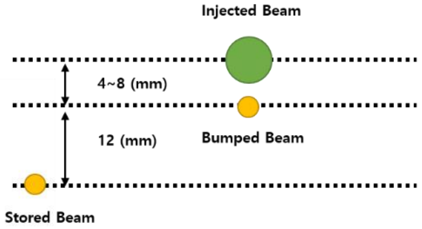


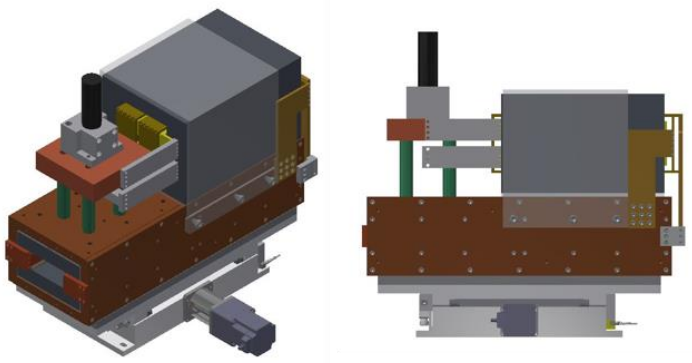
SR Beam Injection



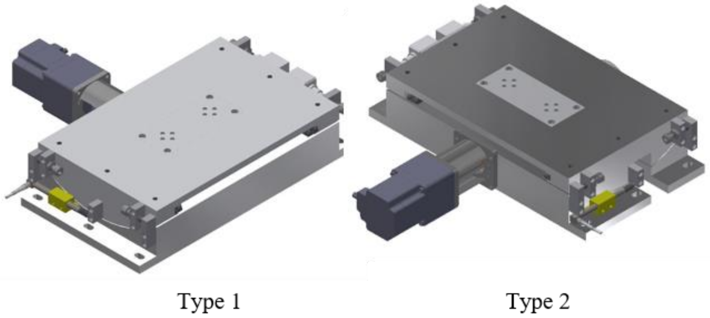
1. Well demonstrated scheme will be used.
2. Baseline: conventional four kickers injection.
   - Dynamic aperture: (Ax: -10 ~ 10 mm).
3. Including advanced scheme: NLK.



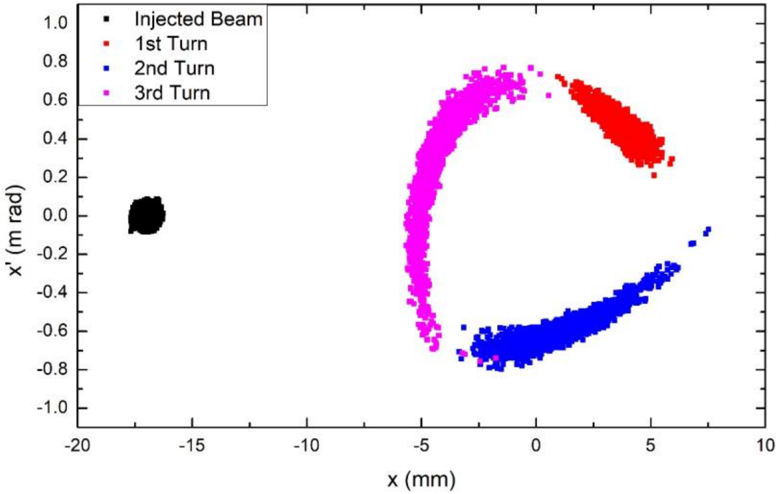




3D Modeling with Kicker magnet



3D Modeling of Tilting Stage



No beam loss in injection simulation with RF

Magnet System for SR

1. Korea-4GSR needs 980 demanding magnets.
2. Center bend features 2T field, and Permendur is adopted for the pole.
3. Longitudinal Dipole used staggered independent coils, and reluctance gap in the return yoke to follow the design field.
4. Quadrupole, Dipole Quad magnet achieved 60 T/m gradient using tapered pole, without using expensive Permendur.
5. Sextupole is not so demanding but requires non-interfering H/V/SQ windings.

Magnet	No.	Remarks
Central BM	28	1*28 (Permanent magnet)
LGBM	112	4*28
Reverse Bend	168	2*3*28 (should have B, B’)
Quad Bend	56	2*28 (should have B, B’)
Quadrupoles	336	6*2*28
Sextupoles	168	6*28 (should have B”, H/V Corr, Skew Quad)
Fast corrector	112	4*28 (H/V combined corrector)
Magnets/Sec	35	31+4 (fast corr.)
Total	980	

SR magnets

Magnets for Booster and transport lines

- In addition to SR magnets, we need 341+ magnets for the booster and LTB (Linac to Booster), BTS (Booster to SR) line.
- Parameters of the magnets are being optimized for BD, and manufacturing aspects. (For example, the field strength, and length of the dipole magnets in the booster).
- Physical parameters (eg, minimum pole gap, required uniformity) are being summarized to start the actual design.
- No technical difficulties are expected for these magnets since the magnets are more easily realizable compared to SR magnets.

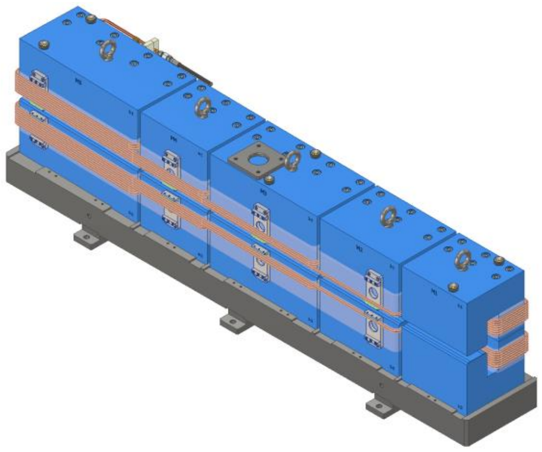
Magnet	Required Number	Remark
Gradient Bend	100	2*50
Quadrupoles	100	2*50
Sextupoles	100	H/V Correctors Combined
Fast Corr.	?	
Total	300+	Total number of magnets

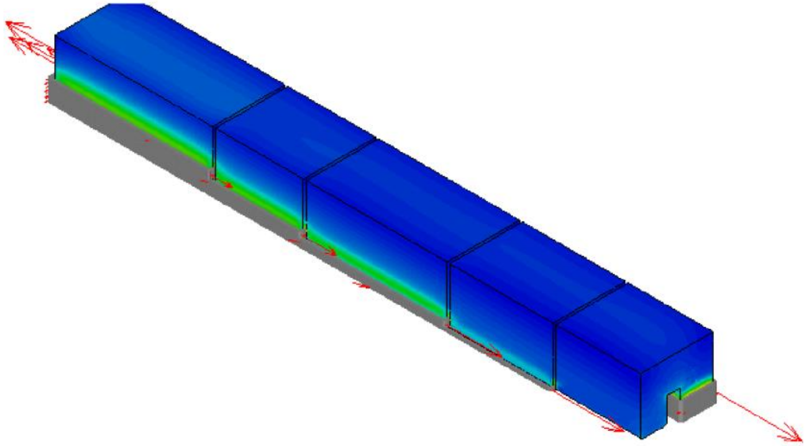
Booster magnets

	Magnet	Required Number	Remark
LTB Magnets	BM	4	0.5m, 0.35 T
	Septum	1	0.8 m, 0.30 T
	Kicker	1	0.8m, 0.0125 T
	Quad	10	0.2 m, 5.7 T/m
	Correctors (H/V)	4	0.1 m, 0.01 T
BTS Magnets	BM	2	1.6 m, 0.73 T
	Septum	5	0.6 m, -1.17 T
	Quad	10	0.5 m, 21 T/m
	Correctors (H/V)	4	0.3 m, 0.08 T

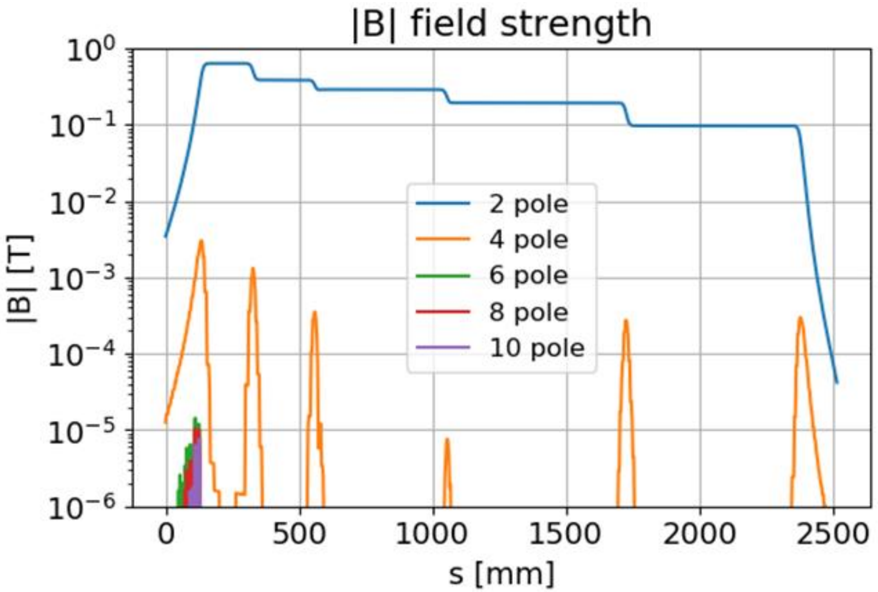
LTB, BTS Magnets (41+ Magnets)

Longitudinal Gradient Bending Magnet (LGBM)



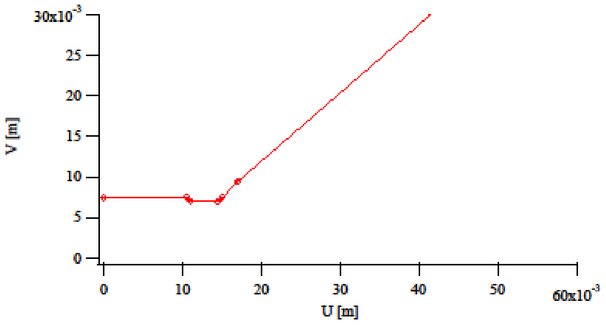


Dipole and higher order multipole along the orbit.



- EM version is selected for construction costs and total cost of operation during the lifetime.
- 3D field map with 1mm step size is calculated, and the multipole along the orbit is calculated.
- Except the quadrupole component which comes from the edge focusing, higher order was negligible.
- To match the design field, reluctance gap at the return yoke is implemented for each magnet section

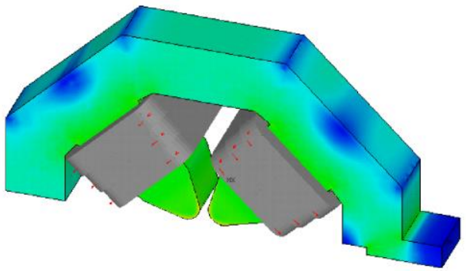
DQ and Quadrupoles



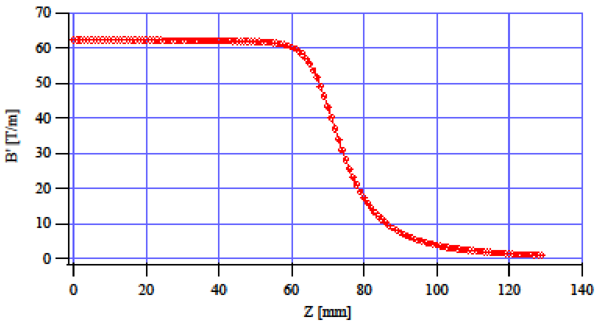
U plane

Conformal map

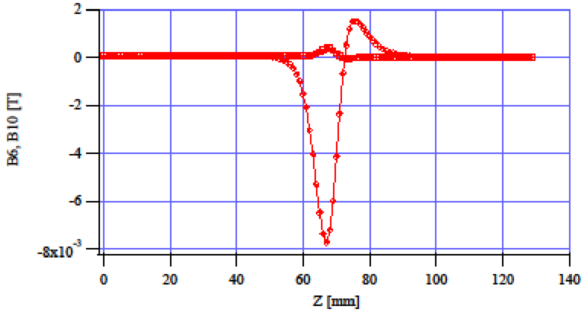
$$w = u + iv = \frac{z^2}{2r_c} = \frac{(x+iy)^2}{2r_c}$$



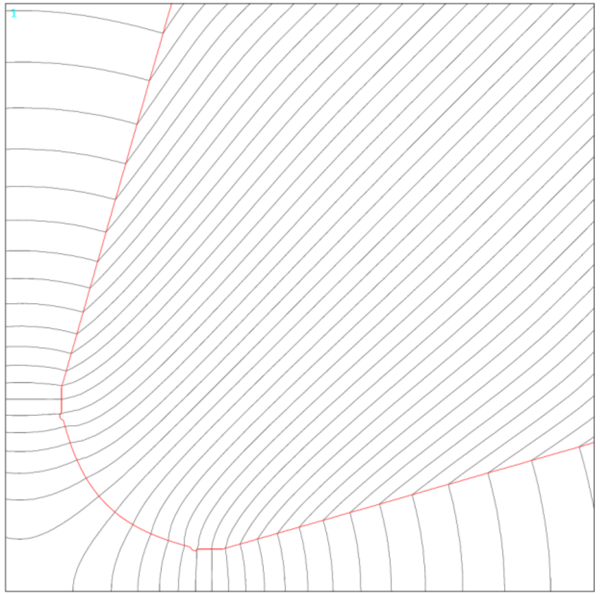
3D FEM Model



B’ along the magnet



b6, b10 along the magnet



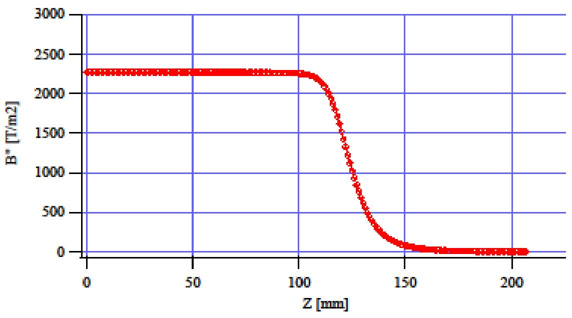
z plane

- Quad, and DQ magnets are similar design. Two DQ types have longer effective length and decided to be arc shape. Other quad, DQs have straight shape.
- Apertures are all 15 mm for quad, and 15, 20, 30 mm for DQ magnets.
- Shims are introduced in w plane, and transformed to z plane and the geometry is analyzed in 2D, and 3D with real permeability.
- The fundamental component, and two first allowed harmonics b6, b10 along the magnet is calculated for each 1mm slices which were well within requirements.
- Each quadrupole and DQ types have different photon exit slot size.

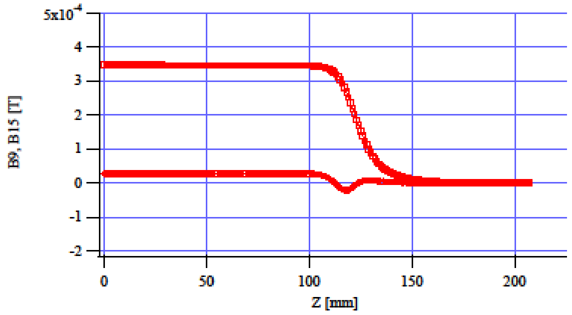
Sextupoles

Conformal map

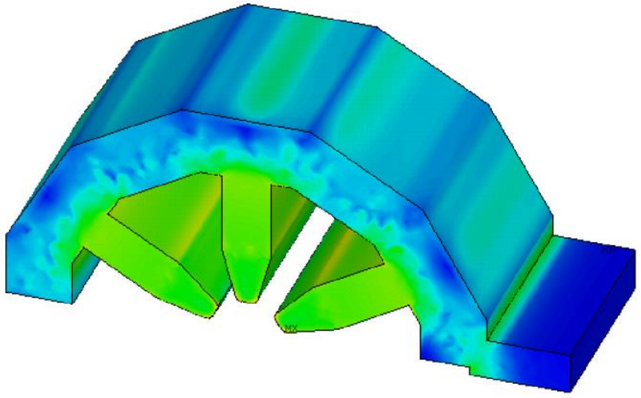
$$w = u + iv = \frac{z^3}{3r_c^2} = \frac{(x+iy)^3}{3r_c^2}$$



B" along the magnet

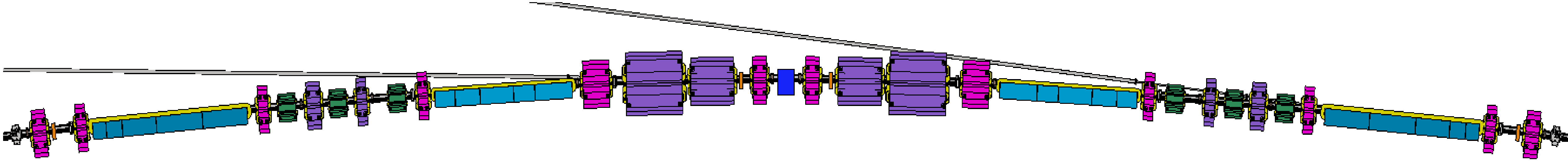


b9, b15 along the magnet

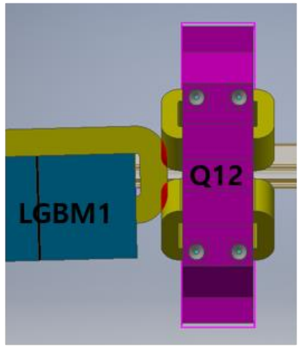


- Like quadrupole, shims are introduced in w plane, and transformed to z plane and the geometry is analyzed in 2D, and 3D with real permeability.
- Max B"=2212 T/m2, with effective length 250 mm.
- Apertures are all 22 mm to meet the minimum vertical photon slot size requirements.
- The fundamental component, and two first allowed harmonics b9, b15 along the magnet is calculated for each 1mm slices which were well within requirements.
- All sextupoles should have H-corr/V-corr/Skew Quad windings.
- To minimize the interference between the coils, the magnetic efficiency should be kept high (about 98%) which is achievable due to low pole tip field.

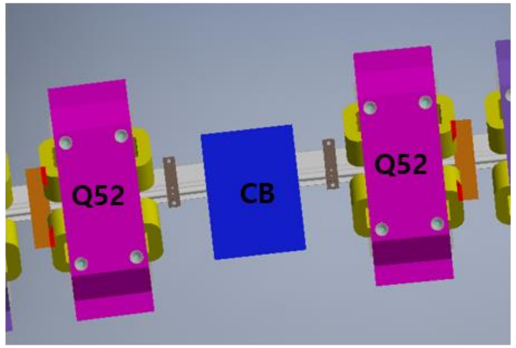
Cross check for overlapping components



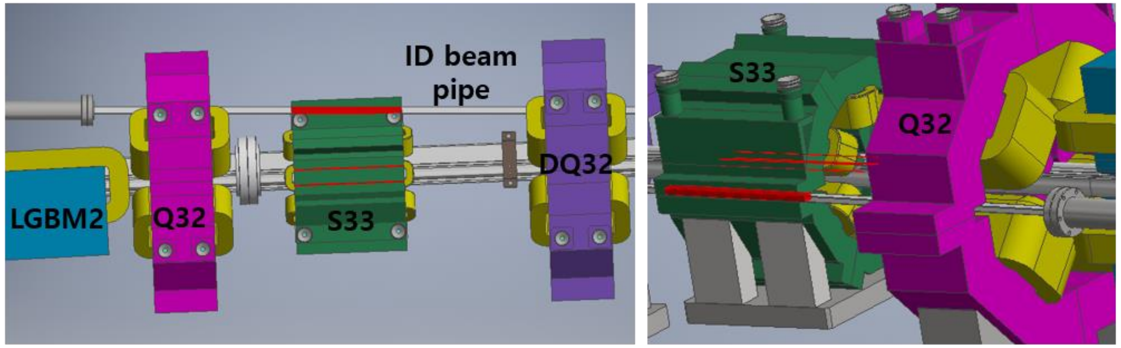
LGBM1 - Q12



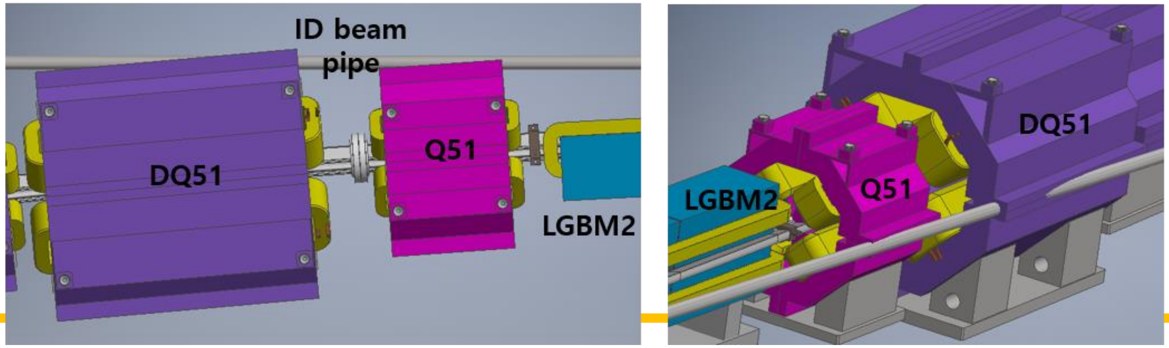
Corrector2 – Q52



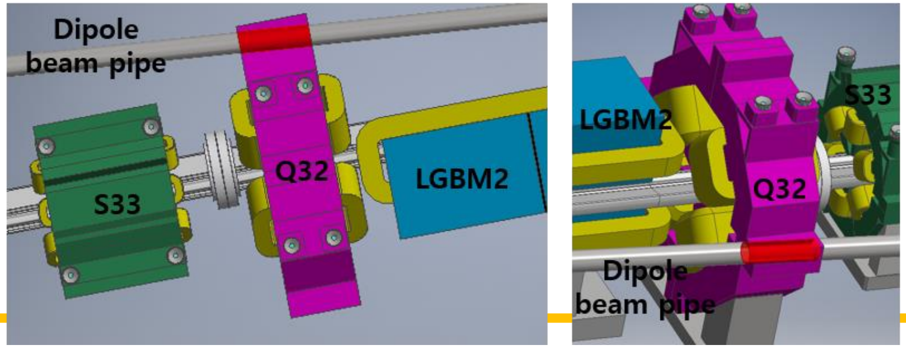
S33 – ID beam pipe



DQ51 – ID beam pipe



Q32 – Dipole beam pipe



Magnet Power Supply (MPS)

1. PS configuration with modular structure for easy and fast recovery from fault.
2. PS connection option: Individual or grouping (series) for high power unipolar PS.

Quantity	**1,228**
MPS Type	Unipolar
Input Voltage	380VAC 3phase
Max. Current	120 A
Max. Voltage	40 V
Max. Power	4.8 kW
Accuracy	TBD
Repeatability	10 ppm
Reproducibility	100 ppm
Ripple and Noise	10 ppm
Long-term Stability (8h)	10 ppm
Temperature Stability	5ppm / K
Line Regulation	±10 ppm
Load Regulation	±10 ppm
Setting Resolution	>18 bit
Readback Resolution	>18 bit
Parallel Operation up to	4

Specification of Power Module
for High Power MPS

Quantity	**840**
MPS Type	Bipolar
Input Voltage	220VAC 1phase
Max. Current	15 A
Max. Voltage	5 V
Max. Power	75 W
Accuracy	TBD
Repeatability	10 ppm
Reproducibility	100 ppm
Ripple and Noise	50 ppm
Long-term Stability (8h)	100 ppm
Temperature Stability	5ppm / K
Line Regulation	±10 ppm
Load Regulation	±10 ppm
Setting Resolution	18 bit
Readback Resolution	18 bit

Specification of Slow MPS

Quantity	**112**
MPS Type	Bipolar
Input Voltage	220VAC 1phase
Max. Current	5 A
Max. Voltage	20 V
Max. Power	100 W
Accuracy	TBD
Repeatability	10 ppm
Reproducibility	100 ppm
Ripple and Noise	50 ppm
Short-term Stability (30min)	10 ppm
Temperature Stability	5ppm / K
Line Regulation	±10 ppm
Load Regulation	±10 ppm
Setting Resolution	20 bit
Readback Resolution	24 bit
Small Signal Bandwidth	10 kHz

Specification of Fast MPS

SR Vacuum System

❖ Main features of recent vacuum systems for 4GSR:

Small aperture

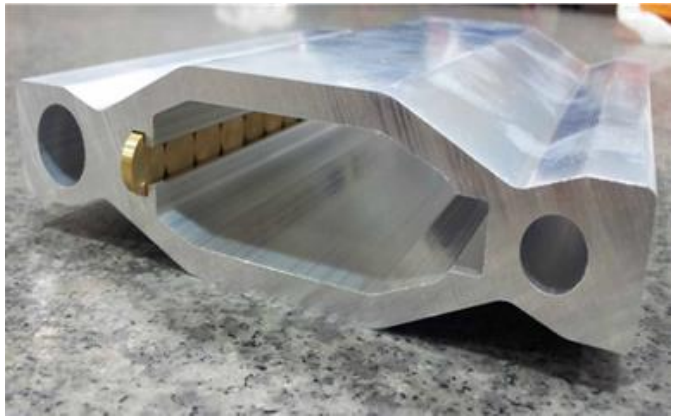
Tight space

→

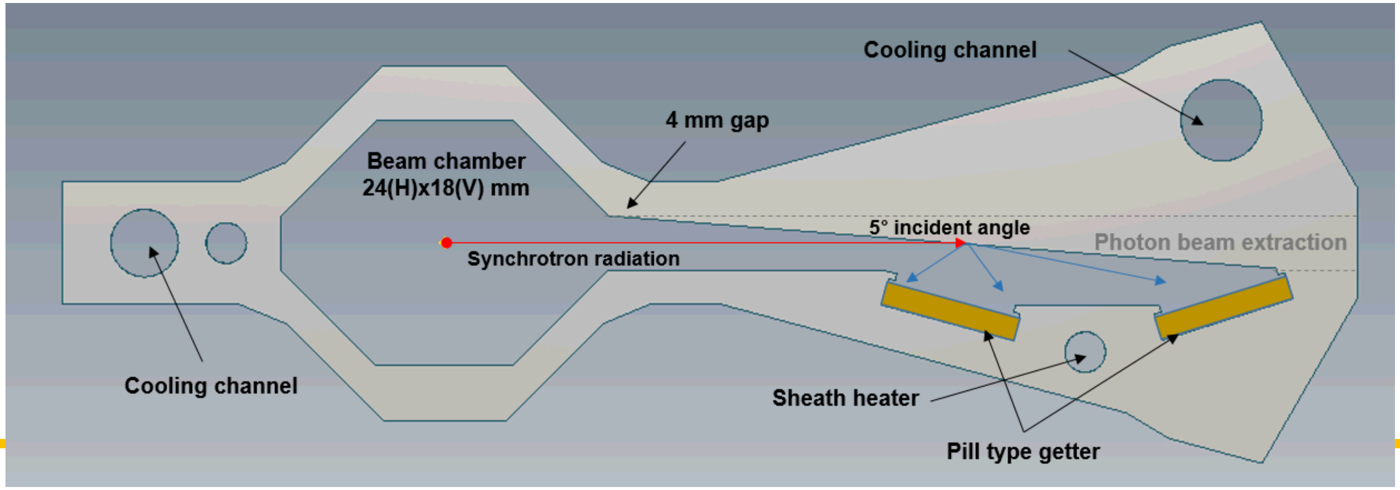
- Low gas conductance
- Hard to install discrete vacuum components

→

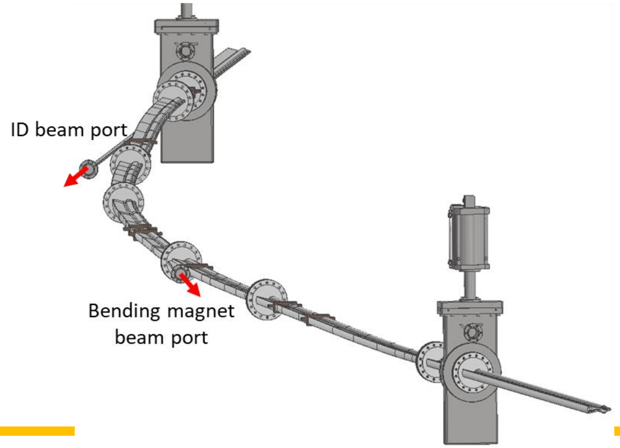
"Distributed" pumping and "distributed" photon absorption



1. Required average vacuum pressure is low 10^{-9} mbar (CO equivalent).
2. PSD gas is pumped by distributed pill-type NEGs and lumped sputter ion pumps.
3. 5 ° Inclined side chamber wall absorbs SR photon beams.
4. Thermo-mechanical analysis results show that both aluminum and copper alloy are suitable for the SR vacuum chamber material.
5. Booster ring vacuum chambers are made of 1 mm-thick stainless steel and pumped with lumped Sputter ion pumps.



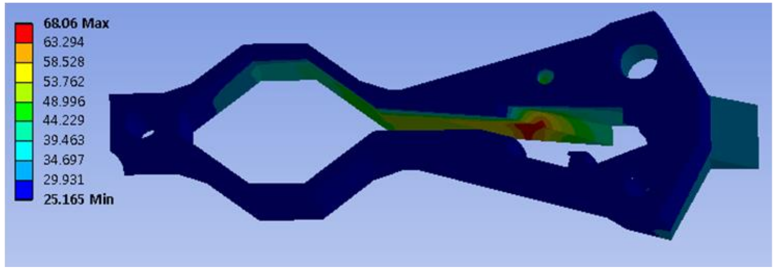
✓ **Vacuum chambers of an arc-section**



Thermo-mechanical analysis

❖ **Handling of SR heat load and chamber material**

- Most intense thermal load is 0.77 W/mm^2 from the center bend.
- Thermal analysis results show that both aluminum and Cu alloy can be used for the vacuum chamber material.
  - Aluminum chamber can be fabricated by extrusion, bending and welding.
  - Cu alloy chamber can be fabricated by machining of two pieces (top and bottom) and welding.
- Temperature of the sharp edge at a beam exit branch is 68℃ (endurable).

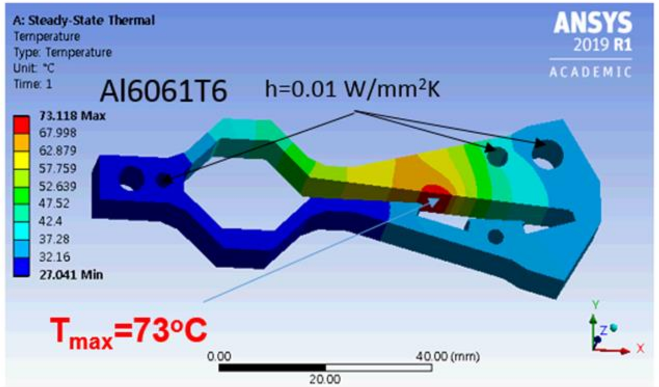


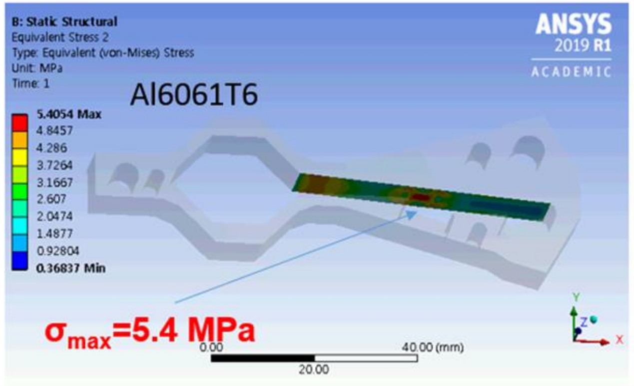
❖ **Heat load from Center Bends**

	B	Bend angle	Total power	Source distance	Inc_angle (H)	Inc_angle (V)	Foot print V-height	Thermal load
Center bend	1.96 T	1.6°	6 kW	2.25 m	2.35°	5°	0.44 mm	**0.77 W/mm^2**

❖ **Results**

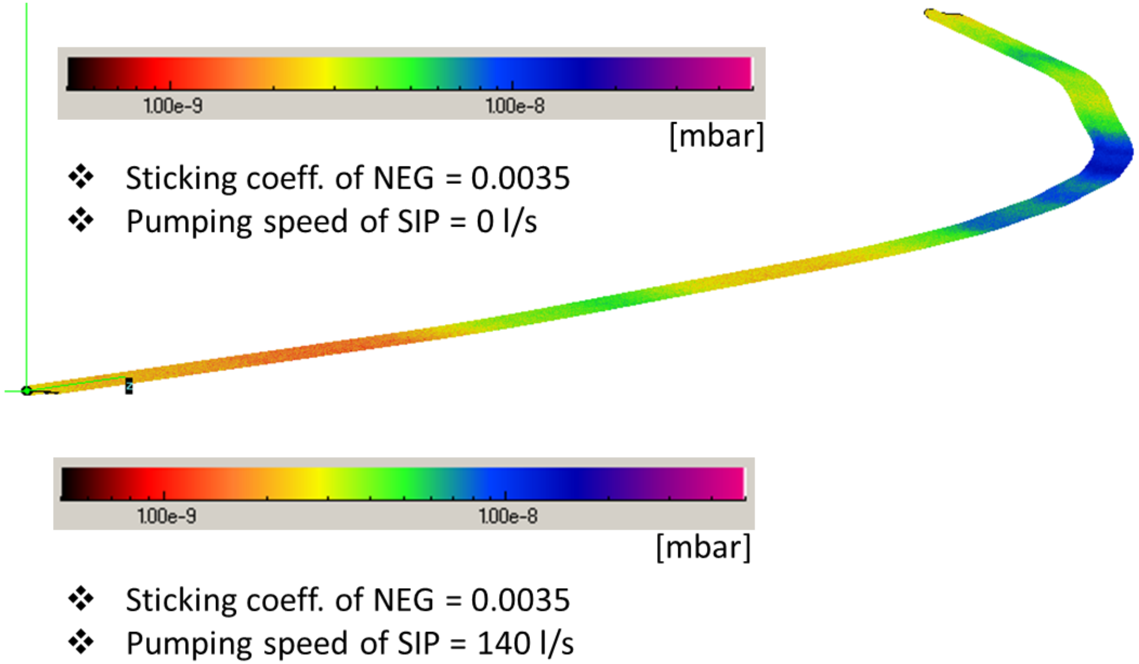
Material	T_{max} (chamber)	T_{max} (Water channel)	σ_{max}	σ_{yield} (Cold worked)
Al6061T6	**73°C**	**46°C**	**5.4 MPa**	214 MPa
OFC Cu (C10100)	**58°C**	**40°C**	**9 MPa**	120 MPa
CuCrZr (C18150)	**60°C**	**41°C**	**11 MPa**	210 MPa

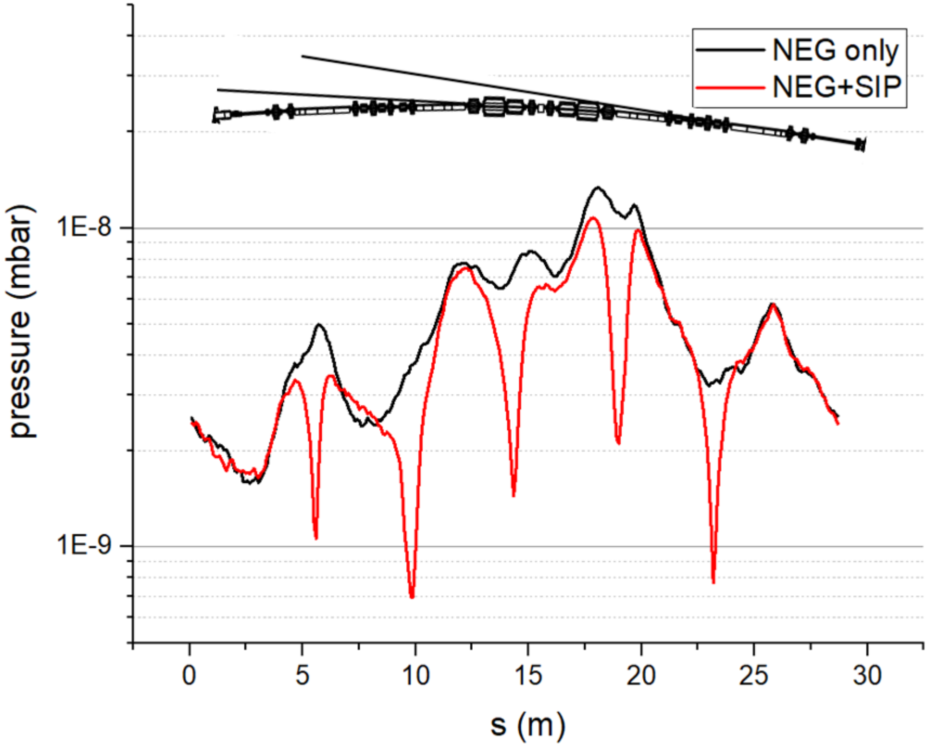




Dynamic pressure calculation

- **H_2 pressure distribution (Molflow+)**
  - 0.0035 is used for the sticking coefficient of pill-type NEG.
  - Average pressure with only pill getter pumps is 5E-9 mbar and 4E-9 mbar with additional 7 sputter ion pumps.
  - Wire heater is inserted into the side channel of the vacuum chamber for 180℃ bake-out.

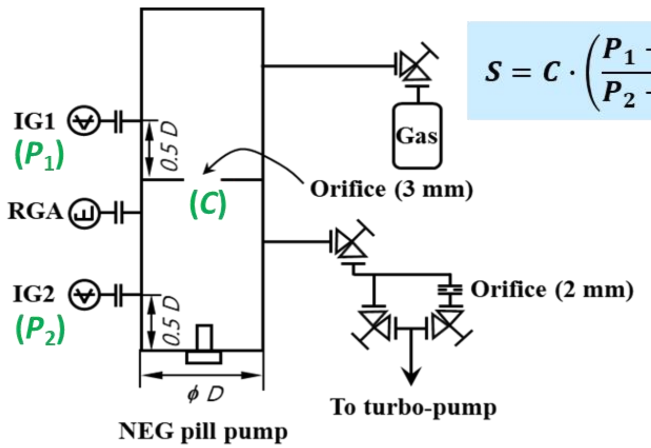




Prototype of a 3D printed getter

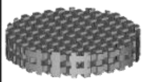
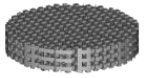
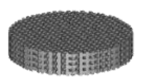
- Mesh structure design for maximum specific surface area
- Fabrication of Ti getter using 3D printer with titanium powder in vacuum environment (Electron Beam Melting in vacuum → high purity Ti)
- Pumping speed of one 3D printed Ti getter is measured to be 0.6 l/s, which is as much as 60% that of the conventional NEG
- <u>Alloy (Ti, Zr, V, Al,…) powders are necessary to increase the pumping speed and to lower the activation temperature</u>

"Pumping speed (*S*) measurement"

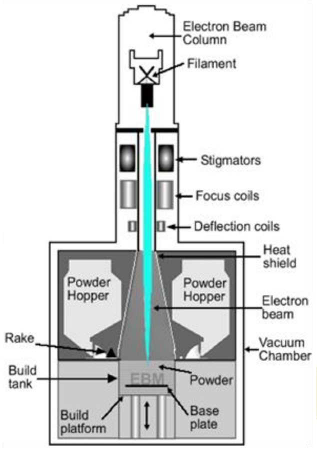


$$S = C \cdot \left(\frac{P_1 - P_{01}}{P_2 - P_{02}} - 1 \right)$$

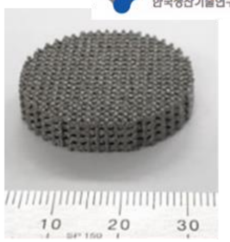
"Design of 3D printed getters"

Sample	3D CAD design	Diameter (mm)	Height (mm)	Area (mm²)	Relative Area (%)
Bulk		30	6	1978	100
C2		30	6	4859	246
C3		30	6	6974	353
C4		30	6	9094	460

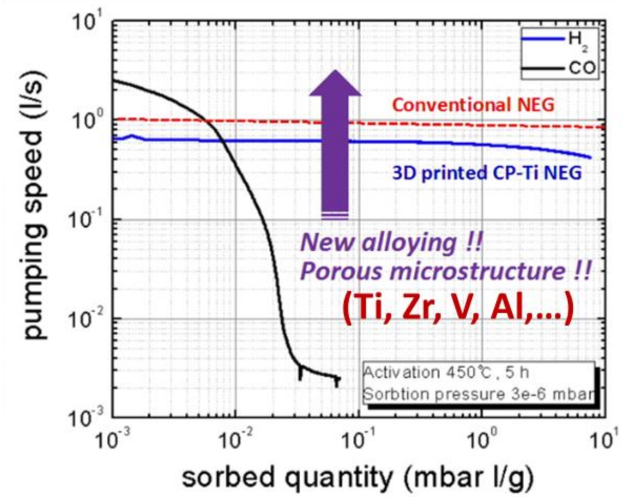
"3D printing *via* EBM"



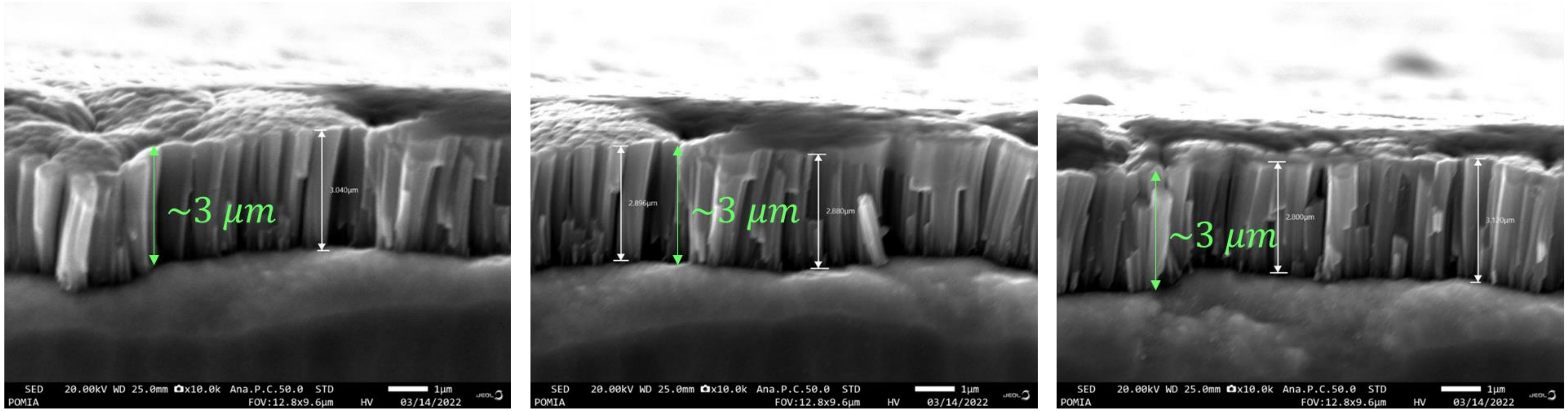
Electron Beam Melting

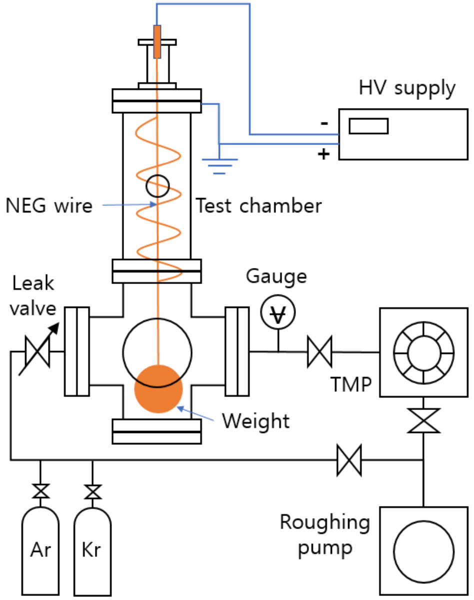


3D printed Ti NEG

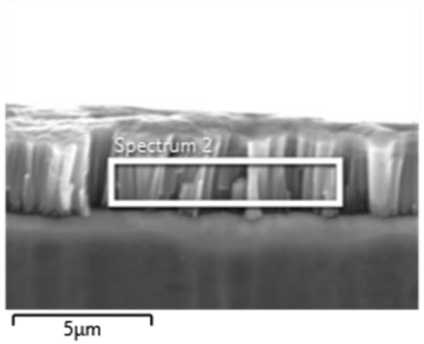


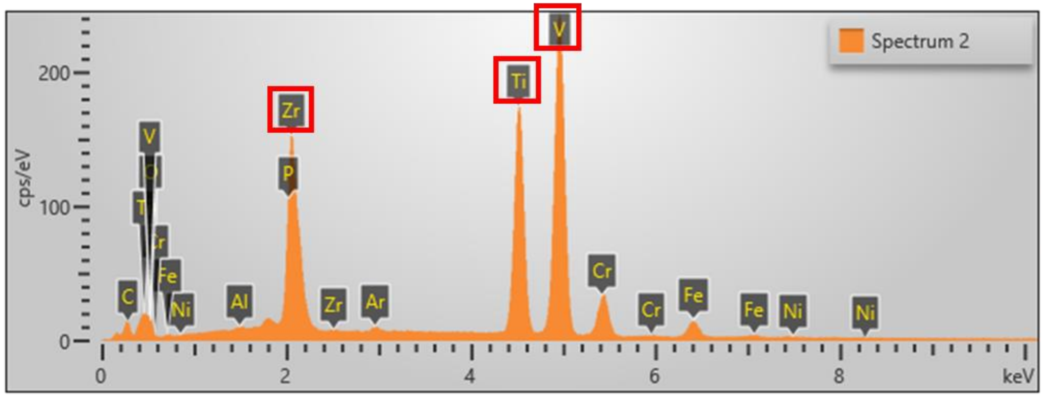
NEG coating (test)





Electron Image 2



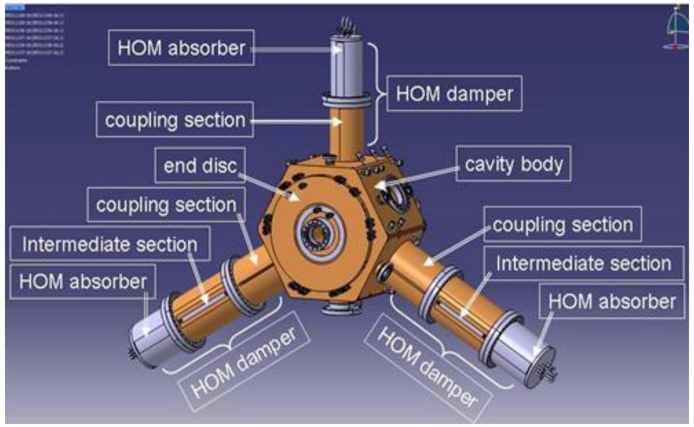


Spectrum 2		
Element	Wt%	Wt% Sigma
C	13.25	0.72
O	5.35	0.81
Al	0.18	0.04
P	0.58	0.11
Ar	0.32	0.03
Ti	23.04	0.33
V	33.93	0.48
Cr	0.74	0.08
Fe	3.17	0.09
Ni	0.24	0.07
Zr	19.21	0.61
Total:	100.00	

SR RF System: HOM-damped Cavity

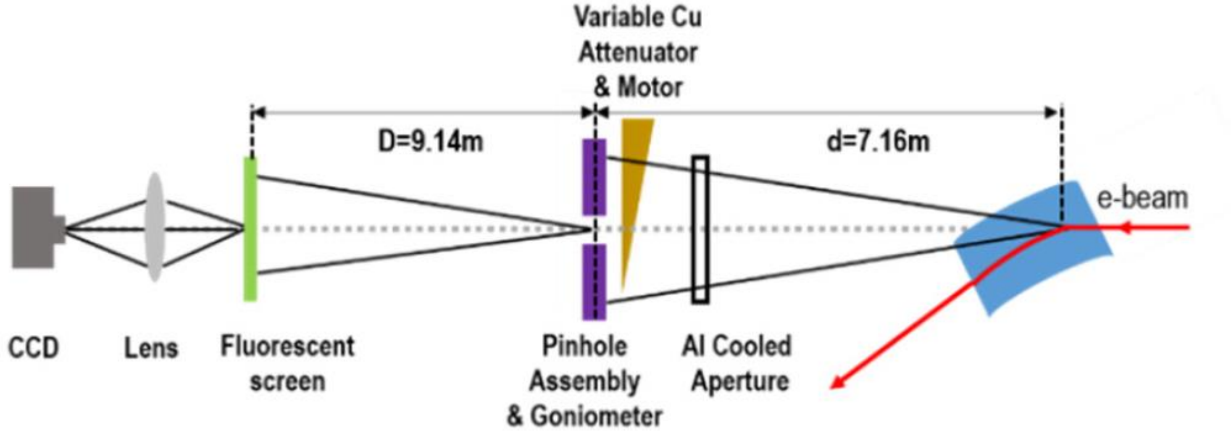
- EU HOM damped cavity
- HOM: Higher Order Modes
- BESSY developed 500 MHz copper cavity with HOM dampers in radial direction.
- Many light sources adopted this system such as BESSY II, ALBA, ESRF-EBS, and PAL-EUV
- Diamond (UK, 500 MHz), Soleil (France, 352 MHz) have changed their RF system from SRF to NRF for their upgrade facility to avoid long shutdown in case of the system failure.
- NRF: Normal conducting RF
- SRF: Superconducting RF

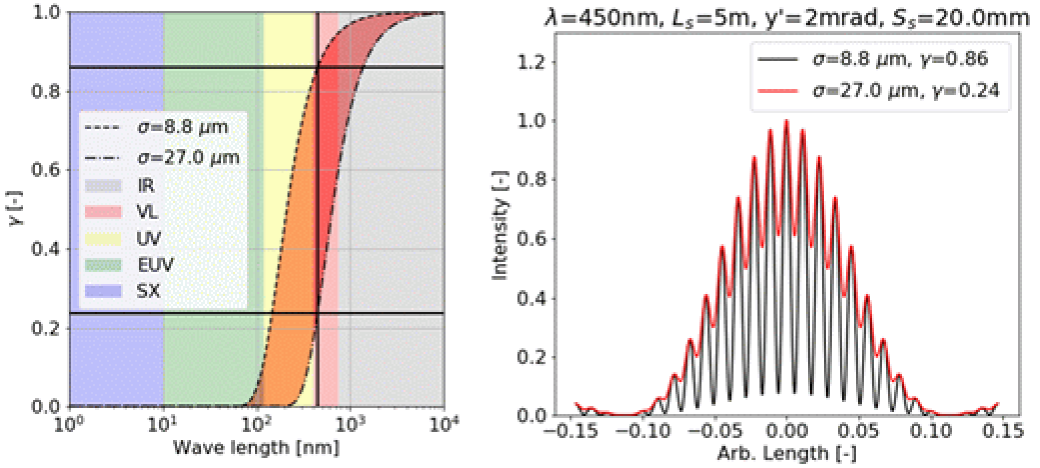
Parameter	Unit	Value
Resonant frequency	MHz	499.82
Shunt Impedance[1]	MOhm	3.4
Quality factor Q_0	-	>29 000
Coupling beta (variable)	-	1-8
Max. power coupler	kW	120
Eff. gap voltage at 70kW	kV	700
Operating temperature	°C	30
Cooling air overpressure	mbar	>10
Cooling air flow	m^3/hour	23
Water pressure	bar	10
Total water flow	l/min	143
Leak Rate	mbar l/s	<2e-10



Diagnostics

1. Most diagnostics will be available from 3GLS with minor improvement excepting PBPM and beam size measurement.
2. Compact visible interferometer and soft x-ray pinhole will measure beam size up to 5~7 μm limit @ large beta.

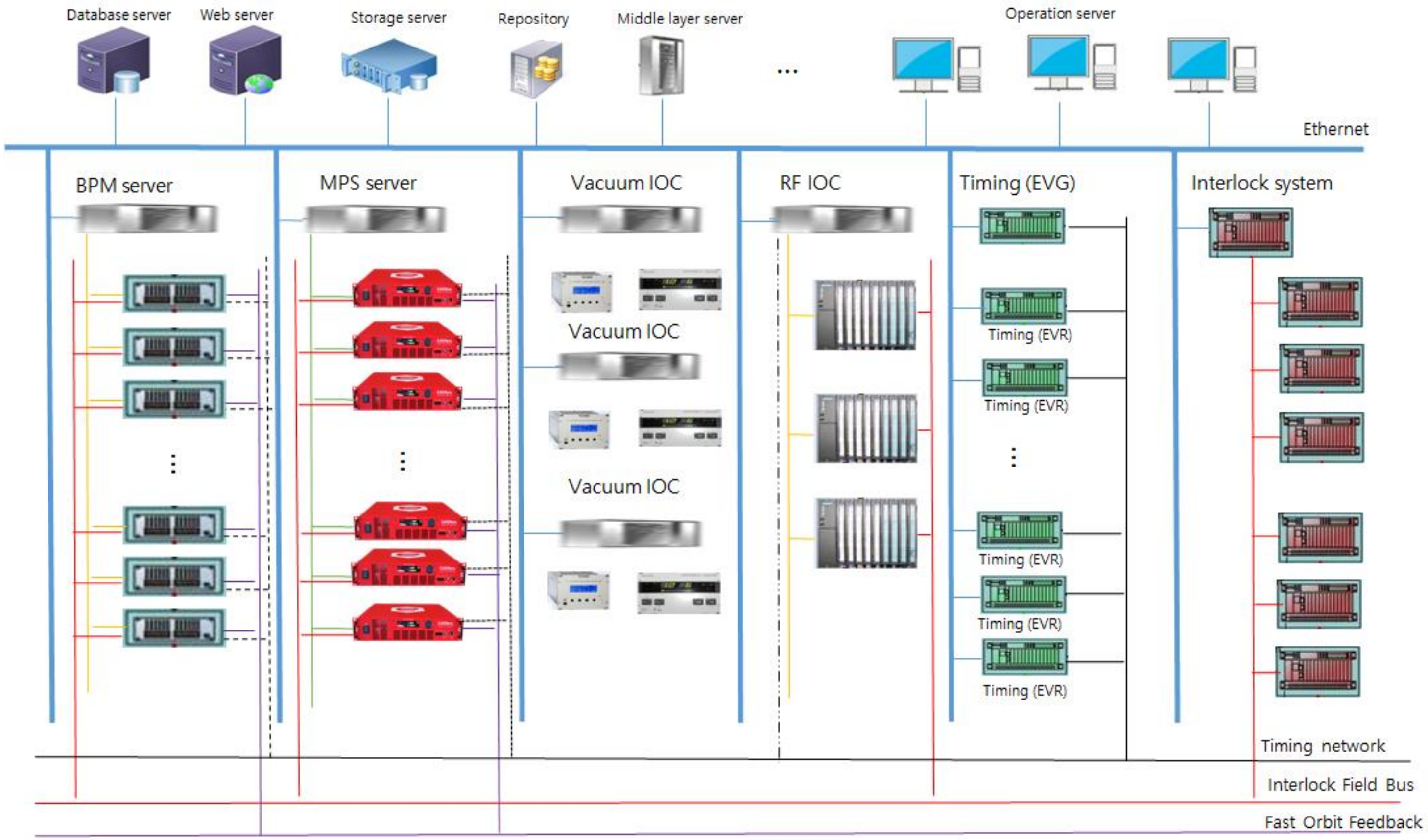


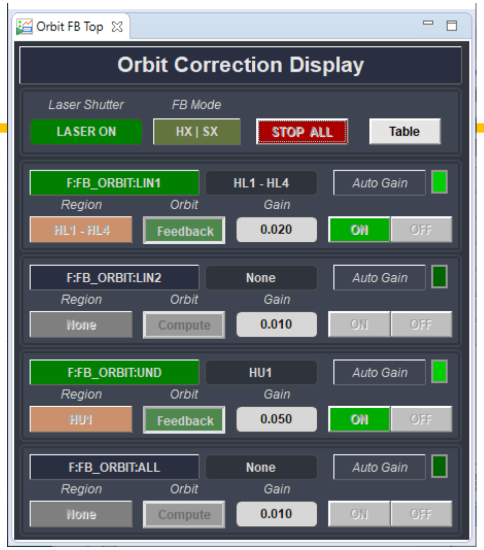


Compact visible Interferometer system

Control

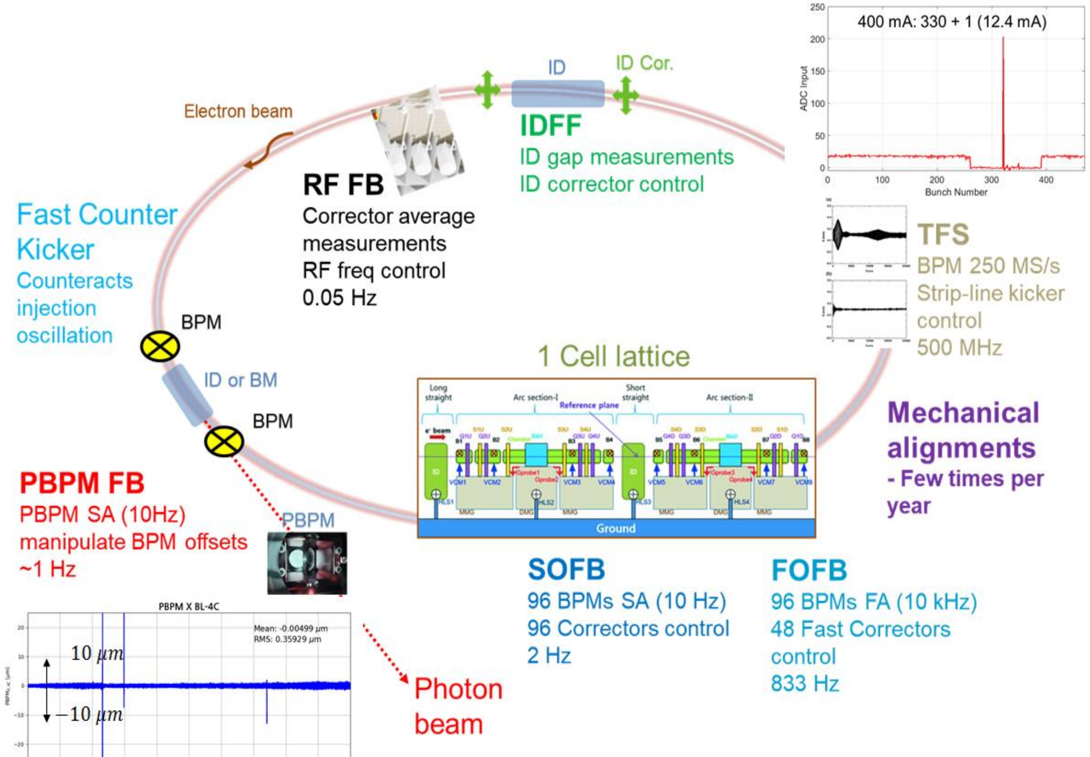
1. EPICS based control system (epics.anl.gov)
2. Reliable control system with PLS-II and PAL-XFEL experiences will be prepared with DB capability for AI.

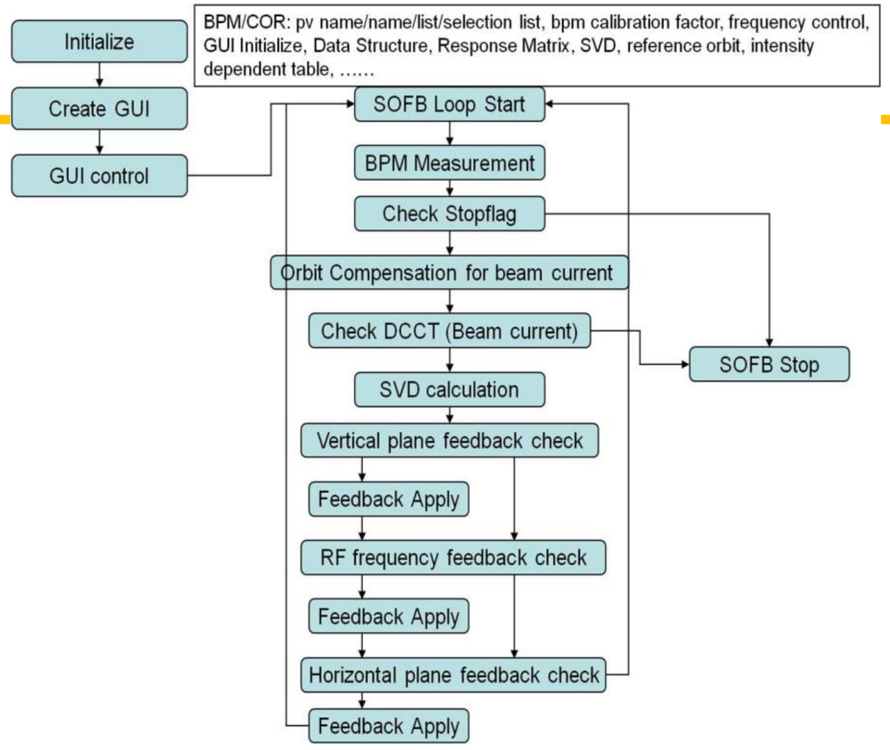


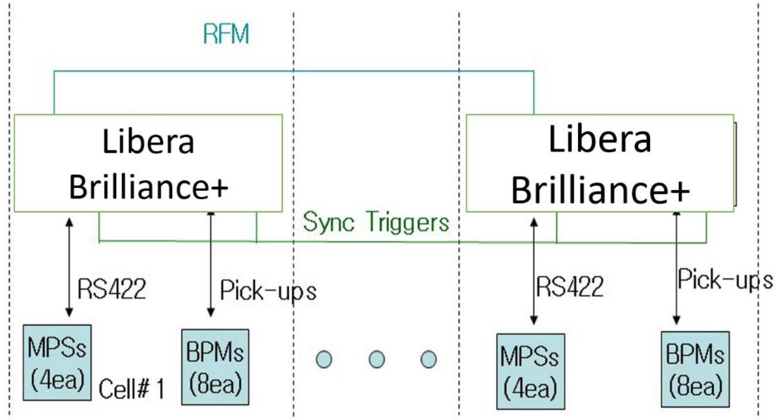


Beam Stability

1. Beam stability goal @ 10 % coupling
   - RMS position stability: < 2.5 um (H) and < 0.45 um (V)
   - RMS angle stability: < 600 nrad (H) and < 110 nrad (V)
2. Beam oscillation without FB: < 1 µm for H and V (Vibration suppression)
3. All FB: SOFB+FOFB, RF FB, PBPM FB, IDFF, Fast Counter Kicker, etc.
4. PBPM: Diamond blade and calibration table
5. On discussion for including BPM drift effect into FB system.



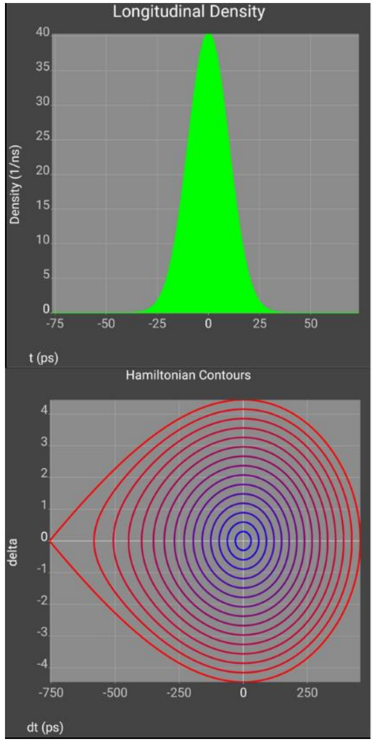


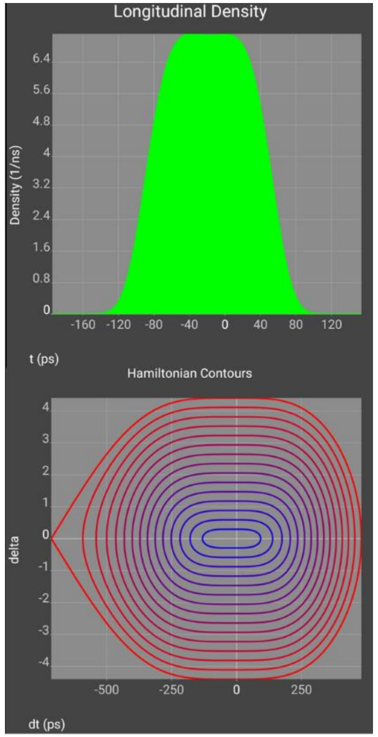


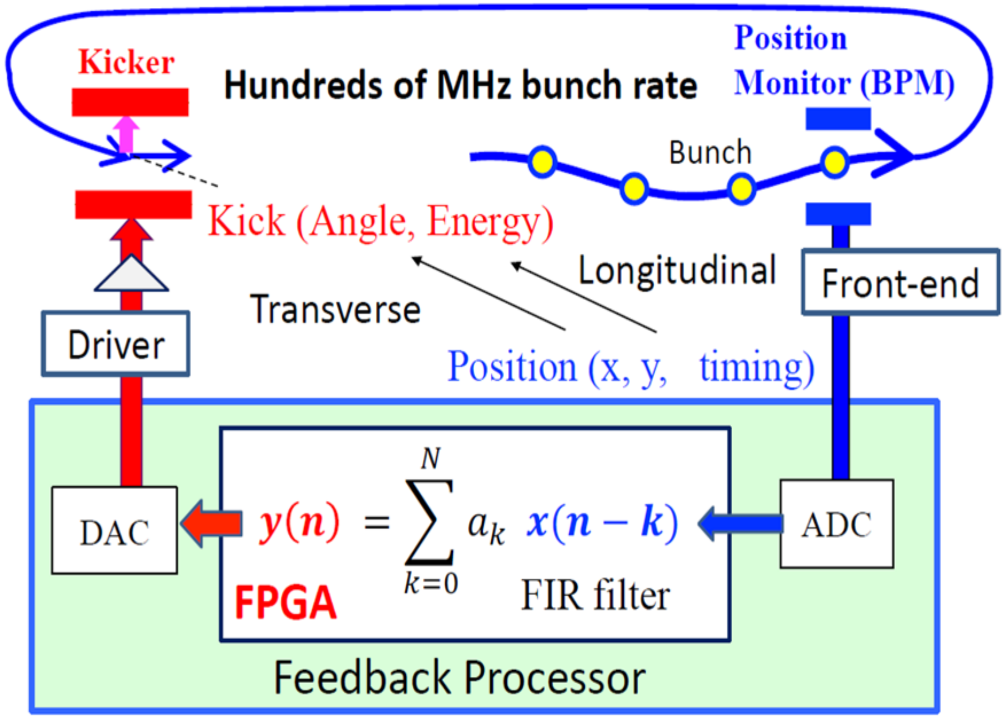
SOFB algorithm and FOFB system configuration

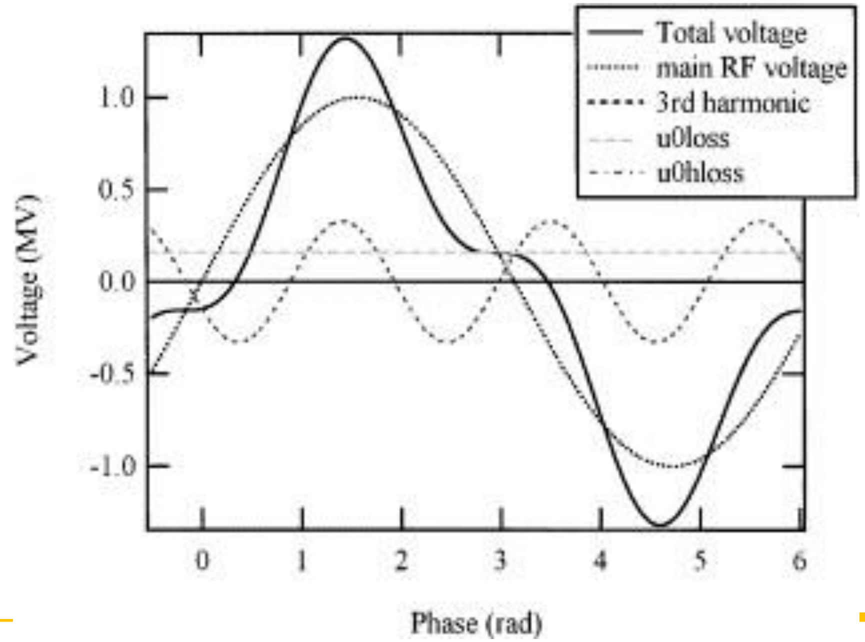
Beam Instability

1. Impedance budget will be managed during TDR.
2. Impedance database will be taken for particle tracking.
3. Active and passive harmonic cavity (3HC) were used in particle tracking and bunch length increase to 16 mm.
4. Transverse ByB feedback system will be prepared.









Beamlines (10 initially)

빔라인	빔에너지	분해능	광원	실험기법	활용
① 바이오신약-바이오소각산란 (BioPharma-BioSAXS)	5~20 keV	SAXS: 1 Å 이하 ΔE/E < 10^{-4}	IVU	① Bio-SAXS	바이오
② 소재 구조 분석 빔라인 (Material Structure Analysis)	5~40 keV	ΔE/E < 10^{-4}	Undulator	① XRD ② XAFS	소재, 에너지
③ 연엑스선 나노프로브 빔라인 (Soft X-ray Nano-probe)	0.1~5.0 keV	sub-micro beam ΔE/E>1.5×10^{-4}@1keV	EPU	① XAS ② XPS	반도체, 소재
④ 나노스케일 각분해 광전자 분광 빔라인 (Nanoscale Angle-resolved Photoemission)	0.1~2 keV	100 nm 이하 ΔE/E < 10^{-4}	Undulator	① Nano-ARPES	반도체, 소재
⑤ 결맞음 X-선 회절 빔라인 (Coherent X-ray Diffraction)	3~30 keV	sub-micro beam	Undulator	① XRD ② CDI	반도체, 지질, 소재, 화학
⑥ 결맞음 소각산란 빔라인 (Coherent Small-angle X-ray Scattering)	4~40 keV	수 nm ~ 수 μm ΔE/E < 2×10^{-4}	IVU	① SAXS/WAXS ② XPCS	소재, 화학
⑦ 실시간 엑스선 흡수 분광학 빔라인 (Real-time X-ray Absorption Fine Structure)	5~40 keV	수 μm	Undulator	① XAFS	에너지, 환경, 소재, 지질
⑧ 생체분자 나노 결정학 빔라인 (Bio Nano crystallography)	5~20 keV	1 Å 이하	IVU	① MX	바이오
⑨ 고에너지 현미경 빔라인 (High Energy Microscopy)	5 ~ 100 keV	공간분해능 0.1μm	Superbend	① Projection imaging	소재, 에너지, 바이오
⑩ 나노 프로브 빔라인 (Nano-probe)	5~25 keV	50nm 이하 1~10 μm	IVU	① Ptychography/XRF ② XRS	반도체, 소재, 에너지, 환경, 화학
1~3: 산업우선지원 빔라인					

Brilliance (PLS II vs 4GSR)

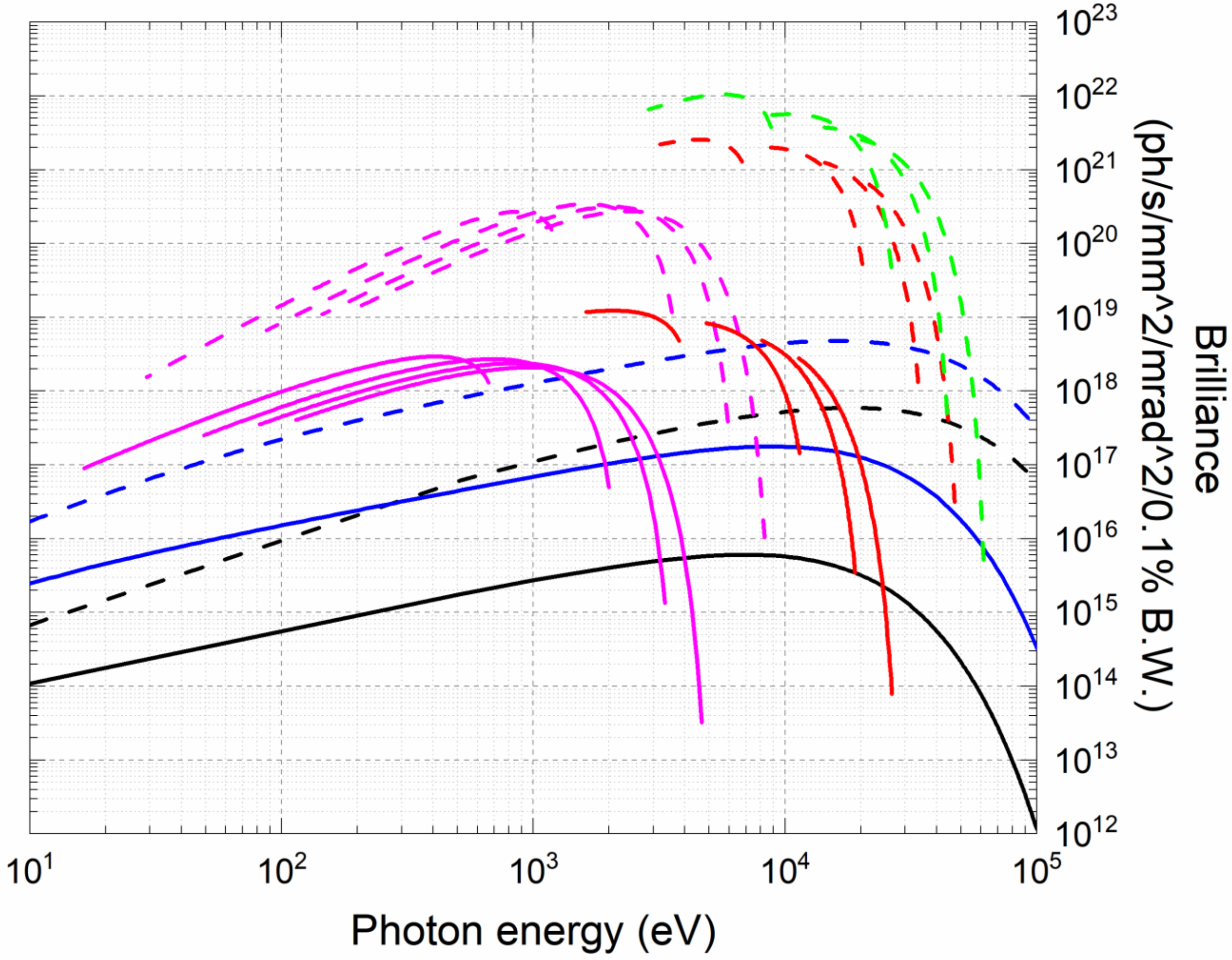
BM: Line(PLS-II), Dot(4GSR)

Wiggler: Line(PLS-II), Dot(4GSR)

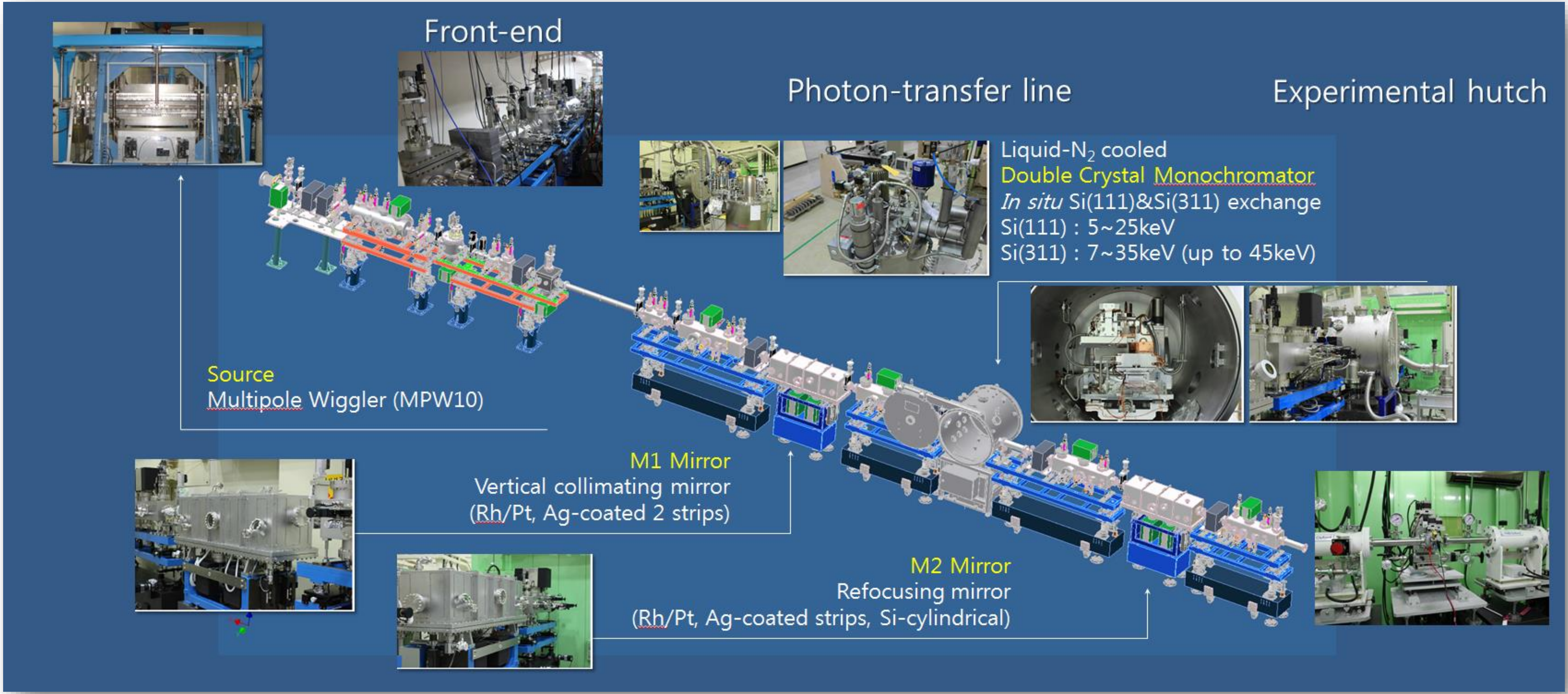
Out vacuum undulator: Line(PLS-II), Dot(4GSR)

In vacuum undulator: Line(PLS-II), Dot(4GSR)

Cryogenic undulator: Line(4GSR)



Typical X-ray Beamline



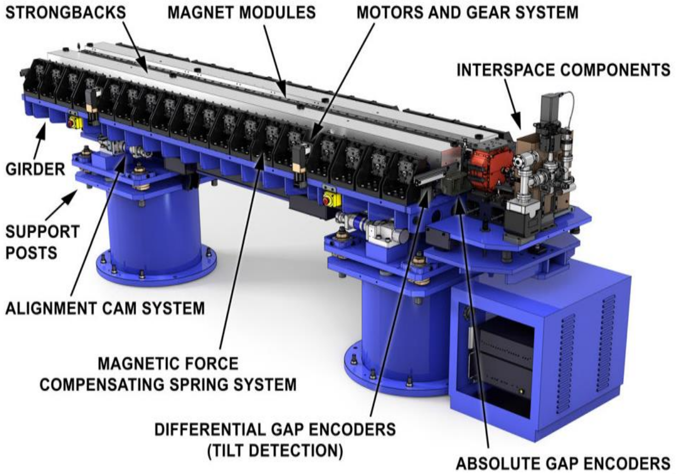
Difficulties for 4GSR beamlines

- High Thermal Load
- Vibration
- Beam Stability
- Mechanical Stability
- Fine Control
- Data Server
- Infrastructures
- ⋮

PLS-II (in-use)
DCM Cooling Power ~ **500** W
Max. Power Density ~ **35** W/mm^2

APS-U (required)
DCM Cooling Power > **700** W
Max. Power Density > **80** W/mm^2
Mirror Colling Power > **500** W

Horizontal Gap Vertical Polarization Undulator (HGVPU) (example)



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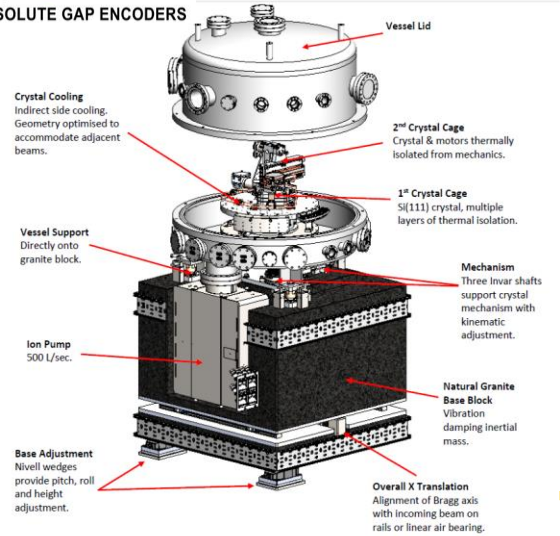
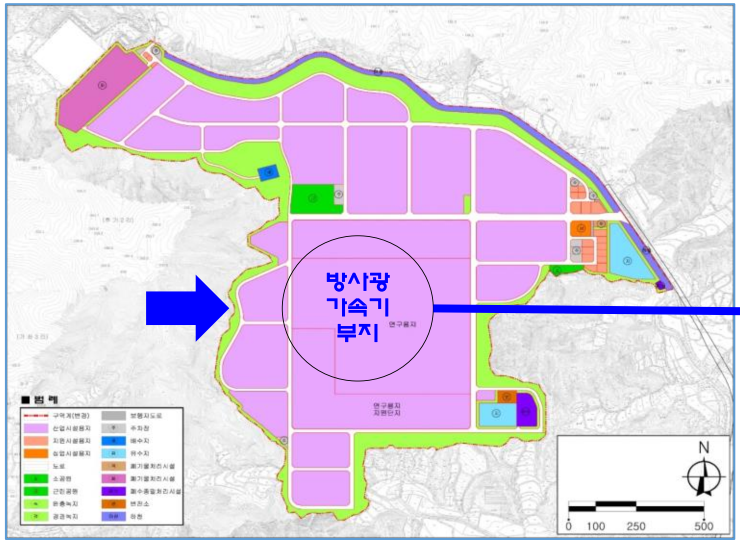
Horizontal Double Crystal monochromator (example)

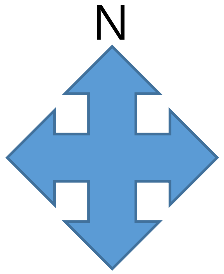
Advanced Photon Source Upgrade Project (APS-U) : Considerations for the APS Upgrade

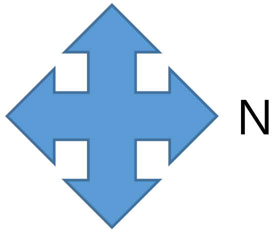


Site Preparation



방사광가속기 부지⇒ 전체 흙깎기 600만㎥ 중 400만㎥ 완료 (공정율 약 65%)


N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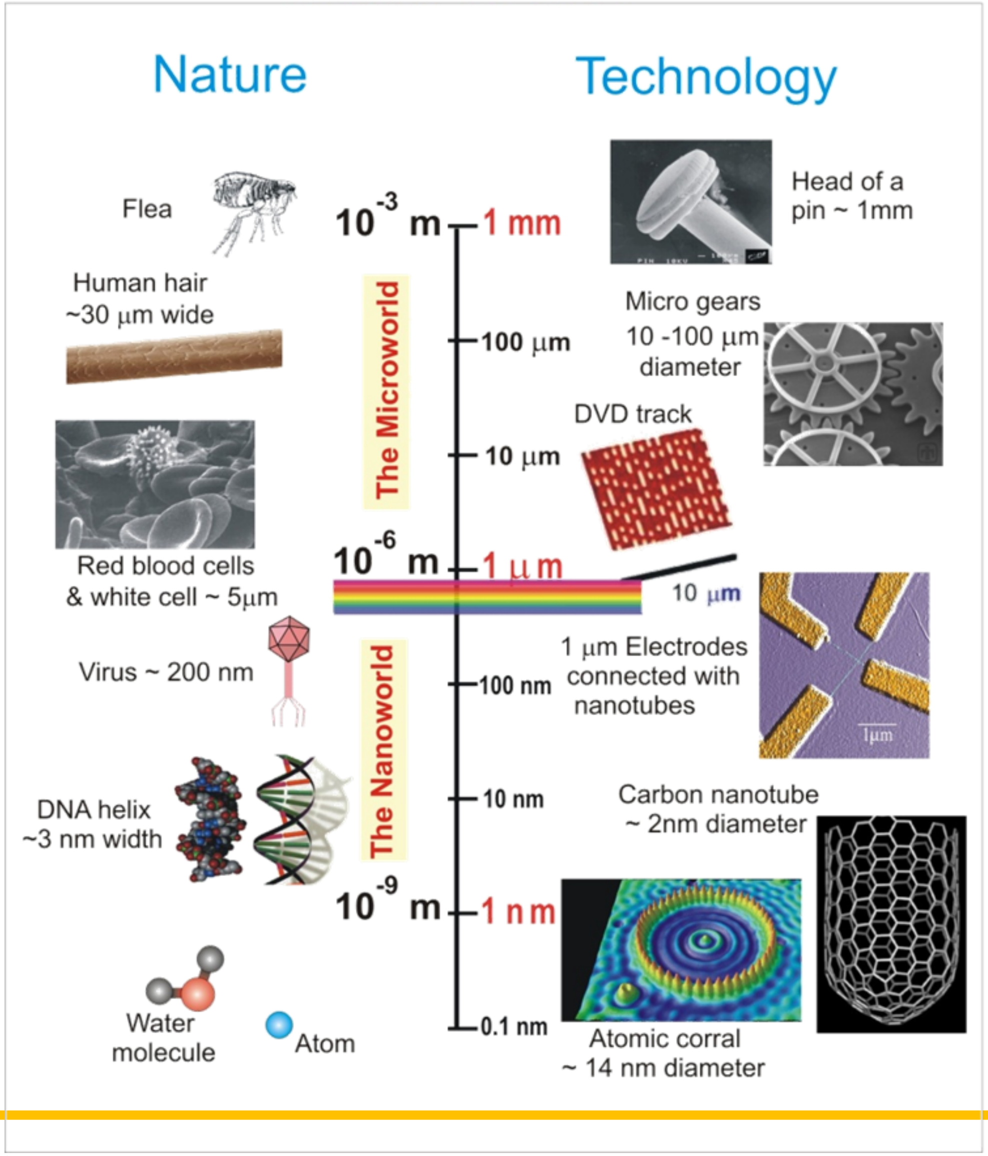
NSLS-II (C=790m) USA

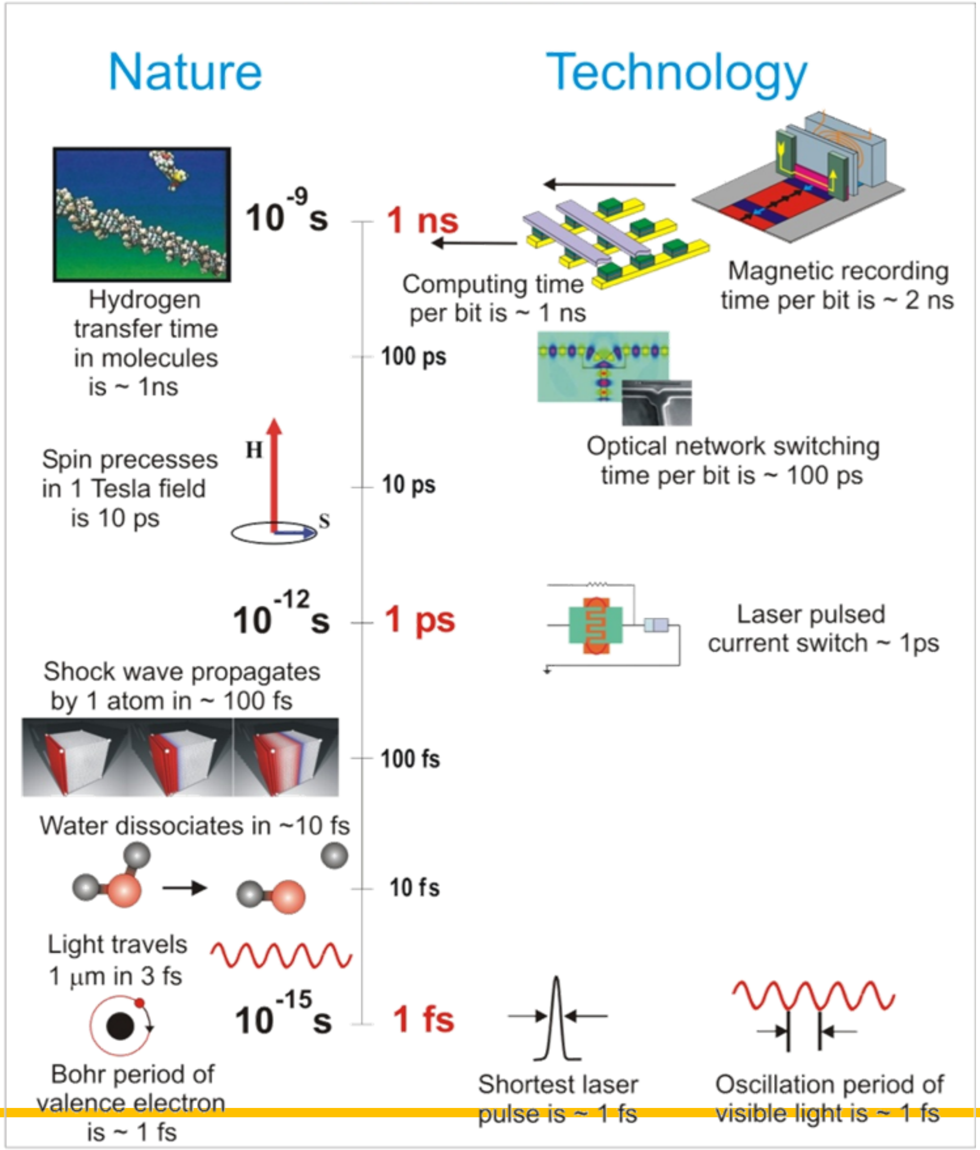
Sirius, Brazil (2020)

X-Rays have opened the Ultra-Small World
X-FELs open the Ultra-Small and Ultra-Fast Worlds

Ultra-Small



Ultra-Fast

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