國家同步輻射研究中心
National Synchrotron Radiation Research Center

IPAC16

Challenge of in-vacuum and cryogenic undulator technologies

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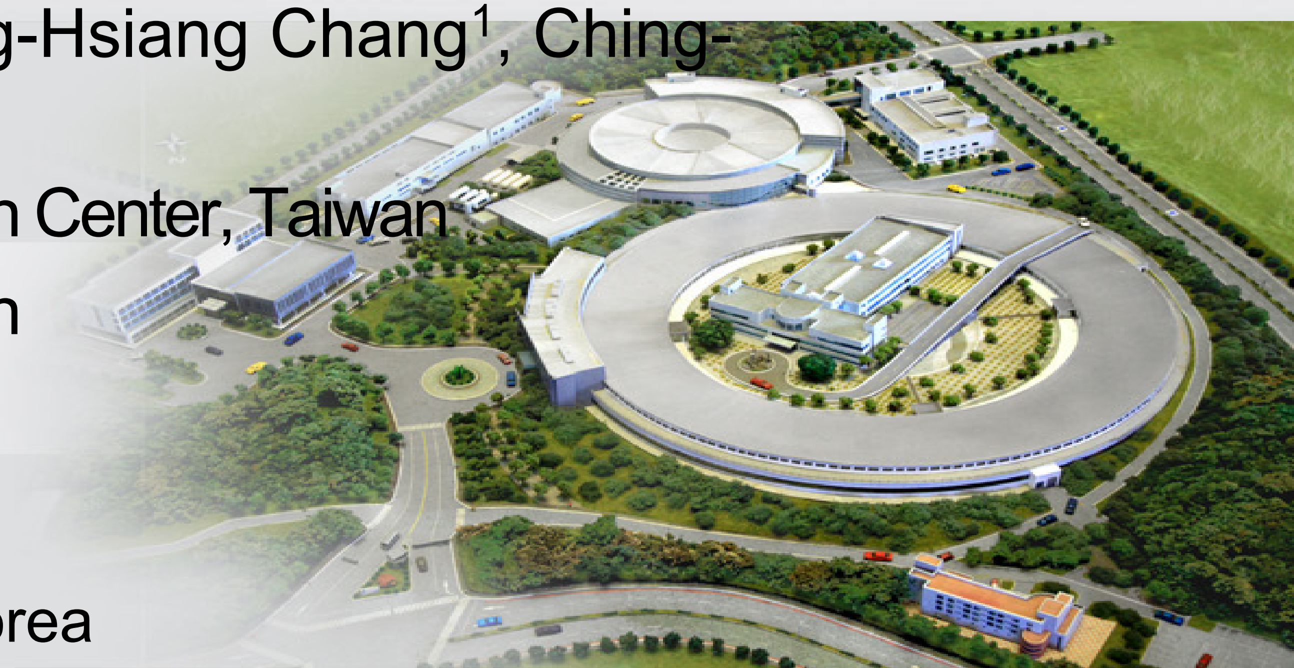

IPAC 2016, Busan, Korea

Why In-Vacuum Undulator?

To obtain short wavelength of undulator radiation --> Using a short period undulator is more cost-effective than increasing beam energy.

$$\lambda = \frac{\lambda_u}{2n\gamma^2}\left(1 + \frac{K^2}{2}\right), \qquad K = 93.4B(\mathrm{Tesla})\lambda_u(\mathrm{m})$$

Advantages by using a short period undulator :

1. shorter wavelength radiation.
2. more periods for a given length and more photon flux is obtained.

Most important issue in development of a short period undulator is to use a very small undulator gap (in order to provide sufficient magnetic field).

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Ad

1.

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Mo to use a very small undulator gap (in order to provide sufficient magnetic field).

In-vacuum undulator(IVU) is suitable for a short period undulator development.
IVU opens the utilization of high-brilliance X-rays in the medium energy storage rings.

History of IVU development

Early Phase <1990

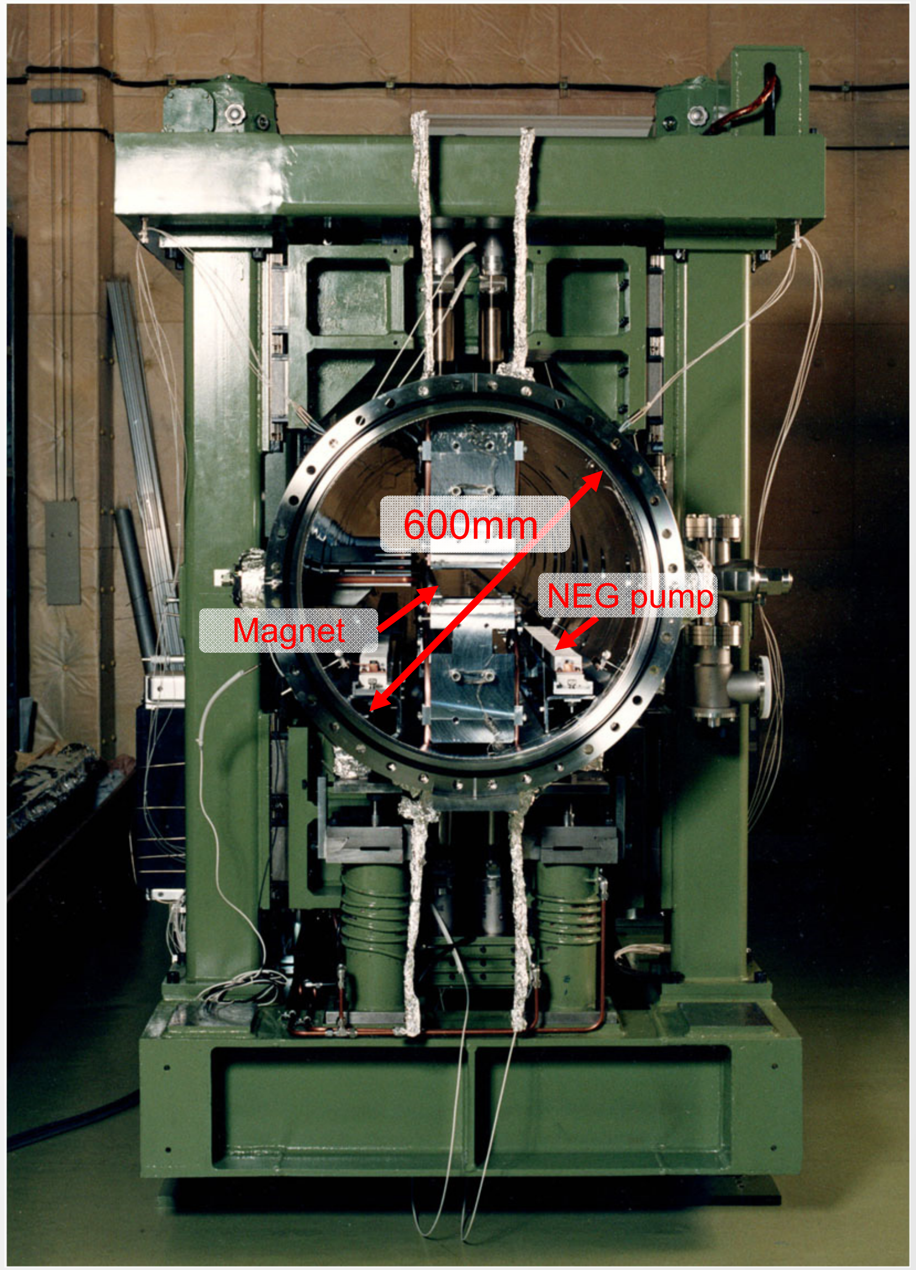
1983 Undulator with Permanent Magnet(PM) arrays located in vacuum at NSLS-BNL.

Removed from the ring due to the vacuum problem. .

1986 R&D on in-vacuum undulators was started at KEK.

1987 Undulator with PM arrays encapsulated in thick metal plates at BESSY operated for SR users.

1990 First true in-vacuum undulator at KEK.



H. Kitamura EFST2009

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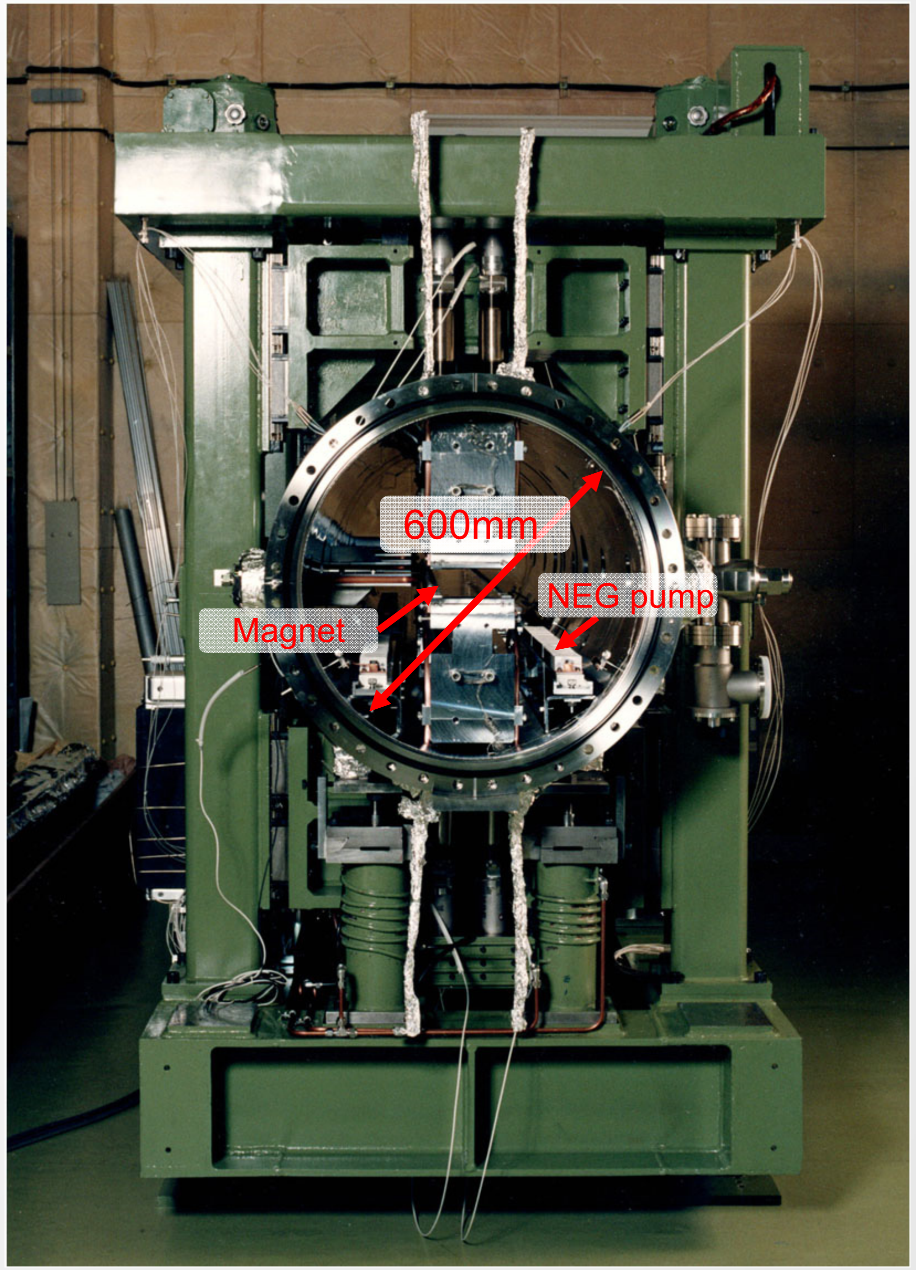

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IVU development at KEK (1986~)

All the IVUs in the world are based on KEK IVU design.

A. Development for UHV compatible magnets

Magnet material : NdFeB or Sm_2Co_{17}

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Plan A, Baking: High-temperature baking of PMs.

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C. Choice / Thermal treatment for PMs for Plan A

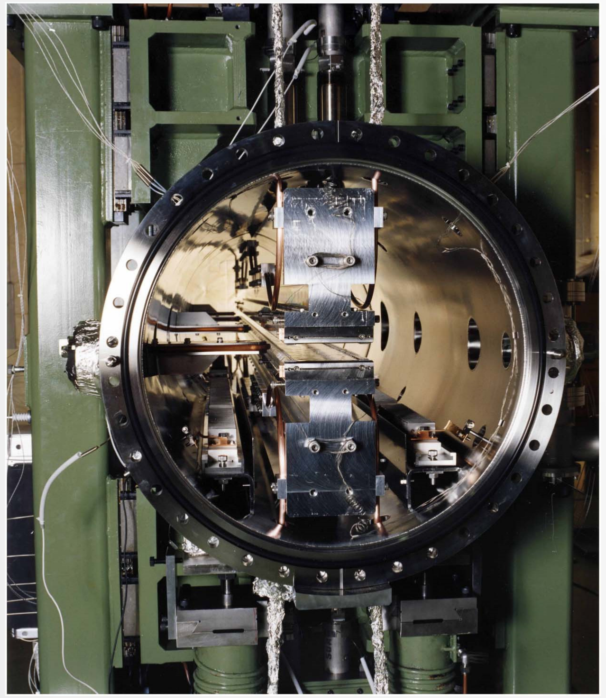
Avoid demagnetization at baking process (flux loss <0.1%)

Against radiation damage

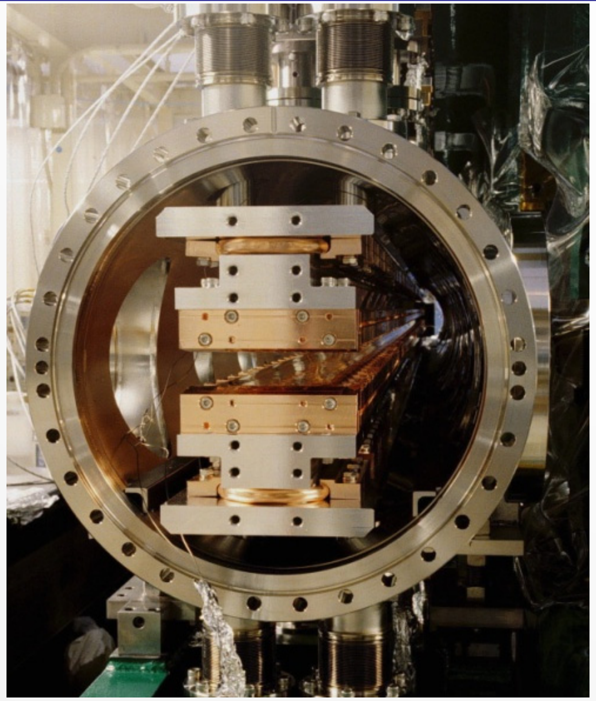
D. Impedance issue

Magnet Cover and RF transition

IVU photos

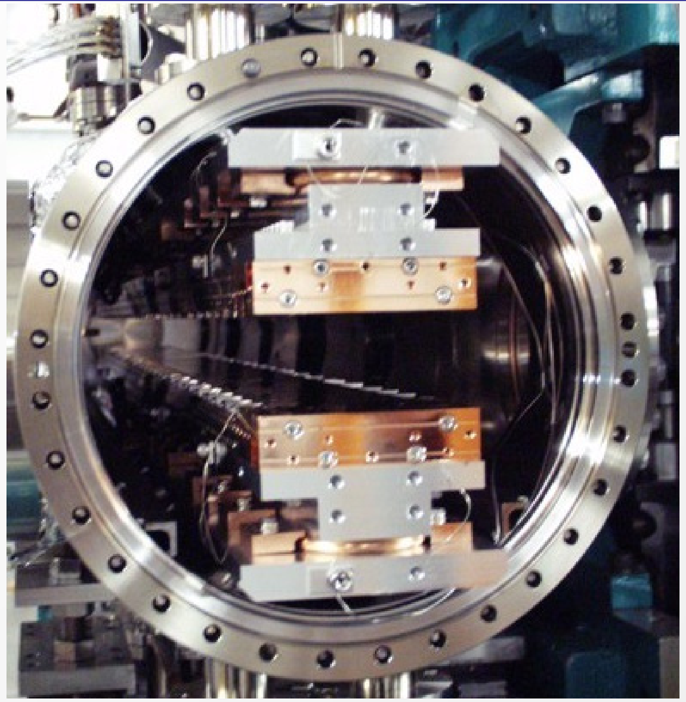


1990, KEK

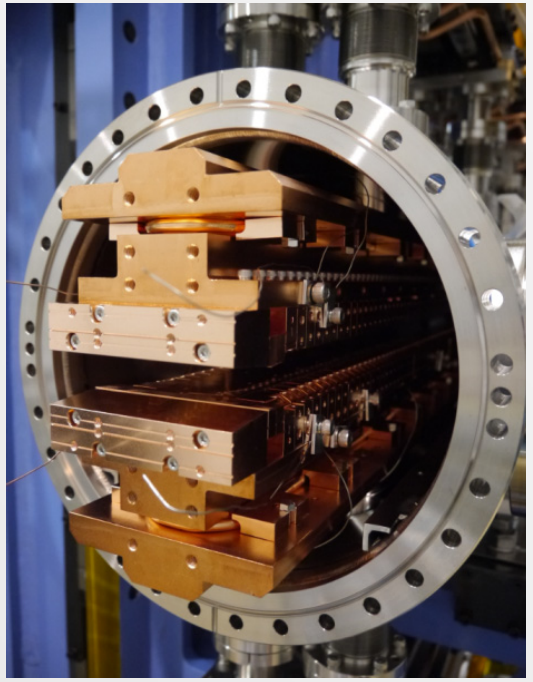


1997, SPring-8

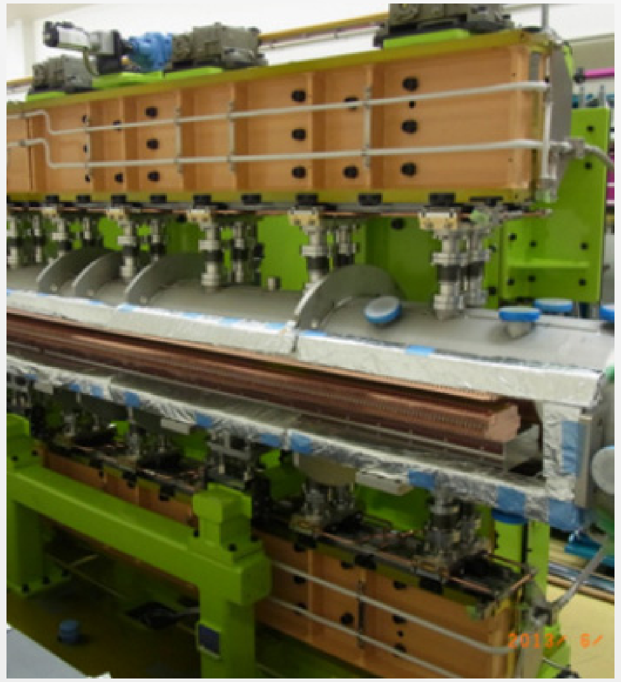
1999, ESRF



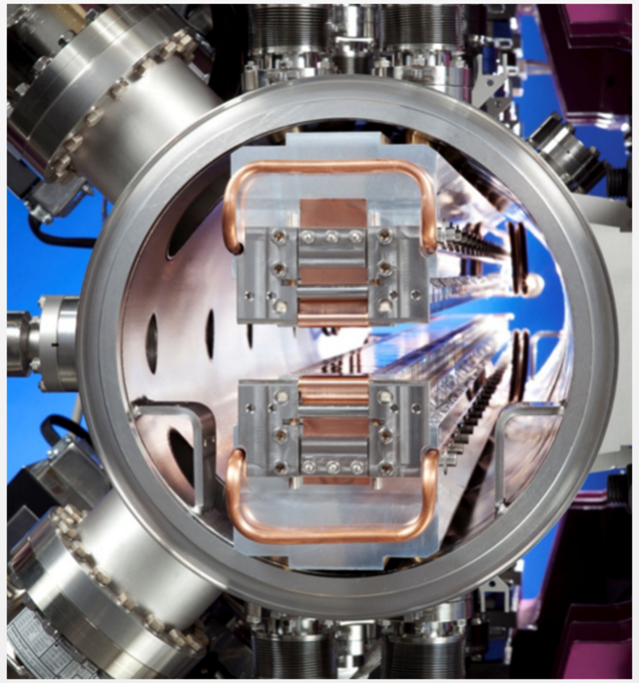
2001, SLS



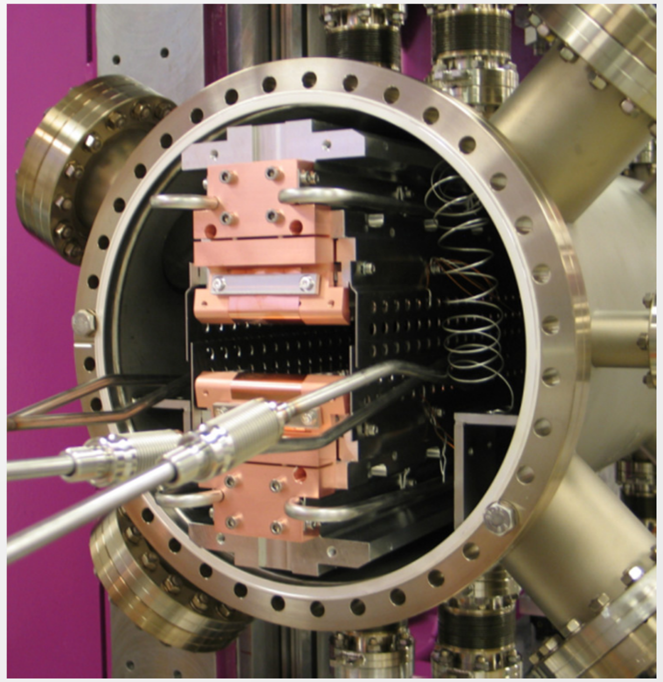
2015, TPS-NSRRC



2014, NSLS II



2010, ALBA-CELLS



2007,DLS

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- Avoid demagnetization at baking process (flux loss <0.1%)
- Against radiation damage

D. Impedance issue

- Magnet Cover and RF transition

UHV compatible magnets

Magnet material to be resistant against UHV baking

NdFeB (with high coercivity*) or Sm_2Co_{17}

1. NdFeB is very hard compared to Sm_2Co_{17}. Sm_2Co_{17} is easily broken to powder, which may cause a contamination problem in UHV systems.
2. NdFeB has high remanent field up to 1.4 T. (higher than Sm_2Co_{17} 1.05T)

*High coercivity NdFeB magnet means

Hcj >2000 kA/m :against demagnetization during baking & radiation damage.

(Deposition Dy-Diffusion/ Grain-Boundary diffusion Hcj increase ~400kA/m)

To reduce the outgassing from magnet surface

TiN ion-plating or Ni electroplating-coating

1. Coating thickness TiN ~ 5 μm; Ni ~ 30 to 100 microns.
2. TiN coating is hard compared to Ni/Al coating.
3. Magnet with TiN coating has good vacuum property compared to Ni-coating.

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C. Choice

Avoi

Agai

D. Imped

Magnet Cover and RF transition

By adopting 'aging process', Plan A was found to be applicable, therefore, Plan B was withheld for future development. Because, low cost and few manpower is needed for plan A.

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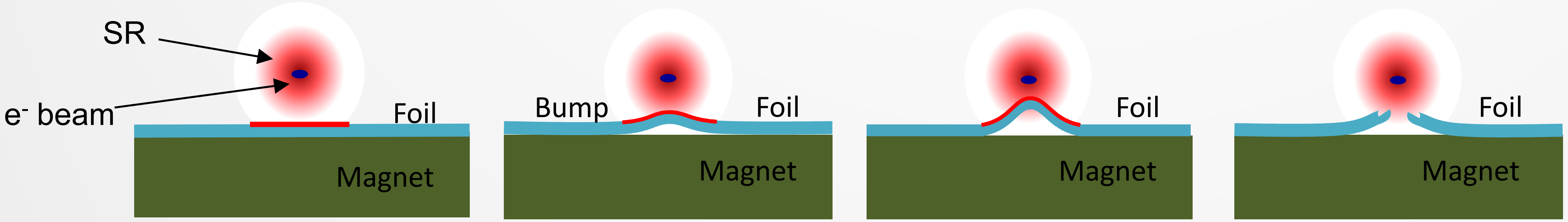
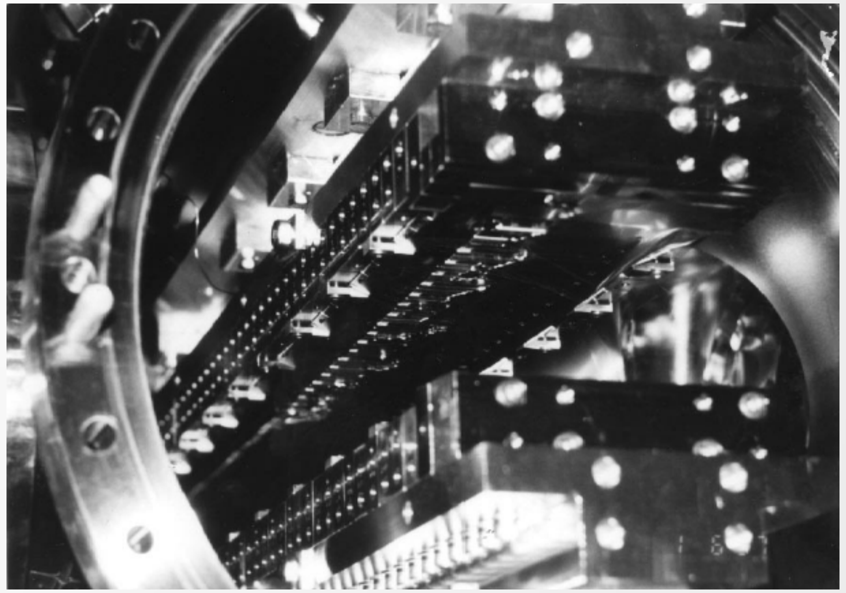
Magnet Cover and RF transition

Magnet cover

In an early development, a SUS foil was melted by the combination effect of image current and SR heating, a Copper Ni-plating foil becomes a standard solution.

Avalanche meltdown of a magnet cover





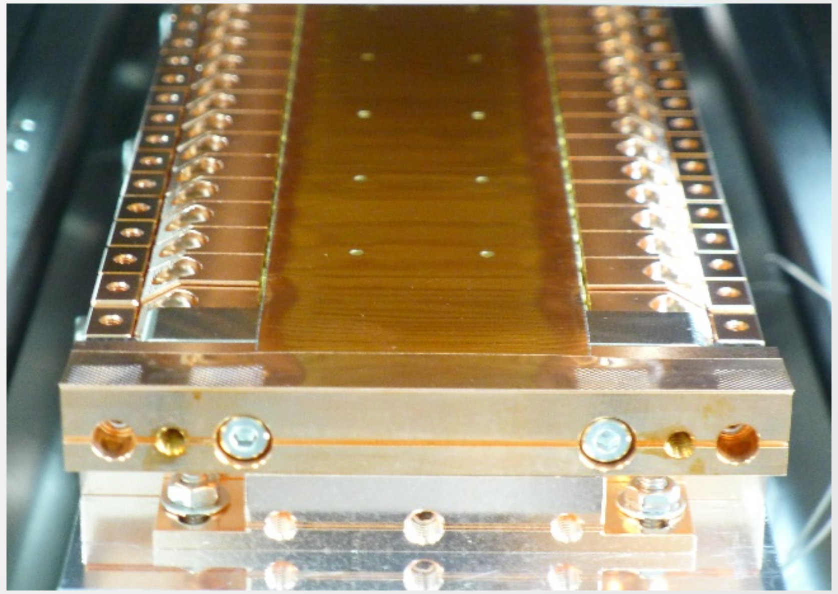
T. Hara, J. Synchrotron Rad. 1998 ,5, 406

The linear power density absorbed on a foil <10 W/m.

Ni-plating thickness of Cu-Ni foil .

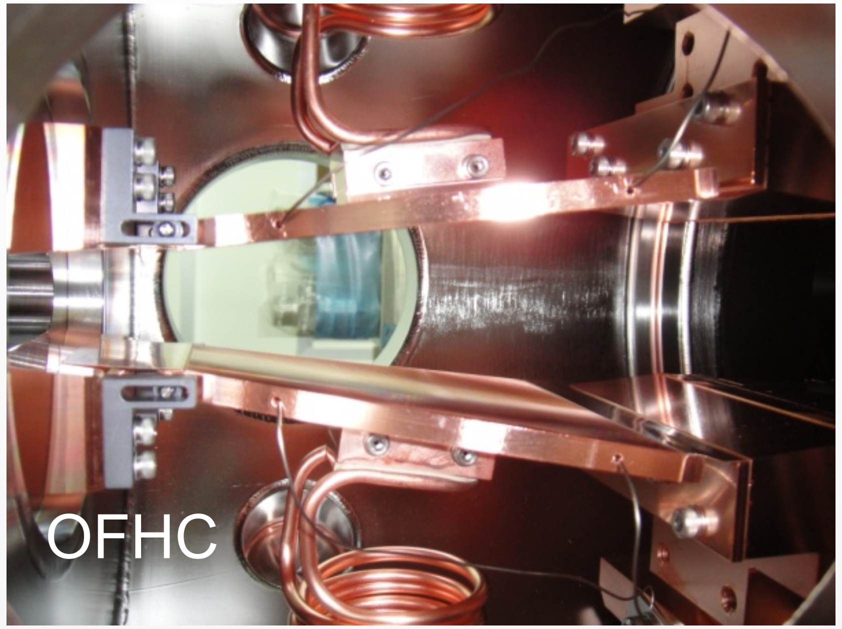
Thin Ni layer : Contact force becomes small and high thermal resistance exists between PMs and foil.

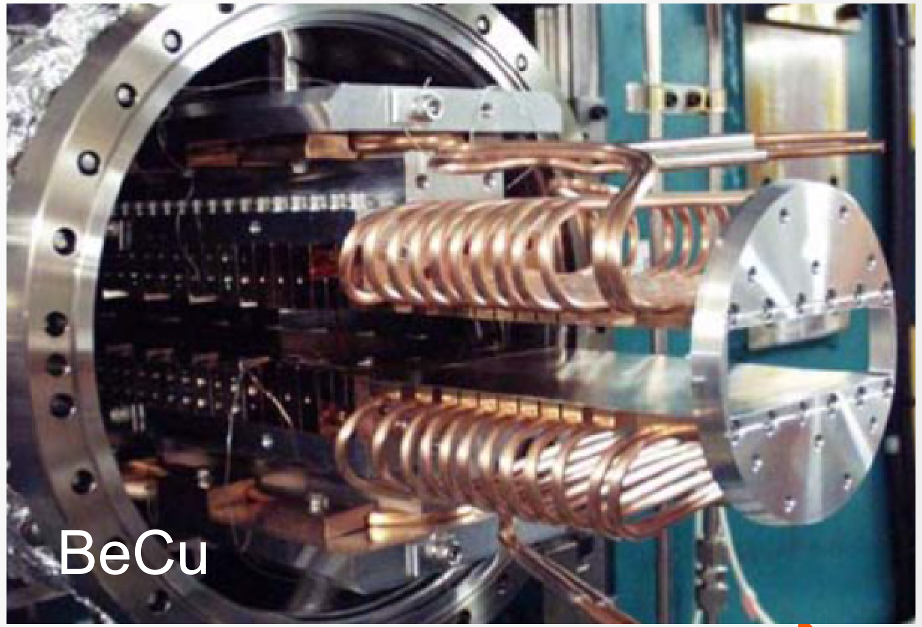
Thick Ni layer: loss the valuable undulator gap .



Cu-Ni magnet cover
TPS in-vacuum undulator

Flexible transition





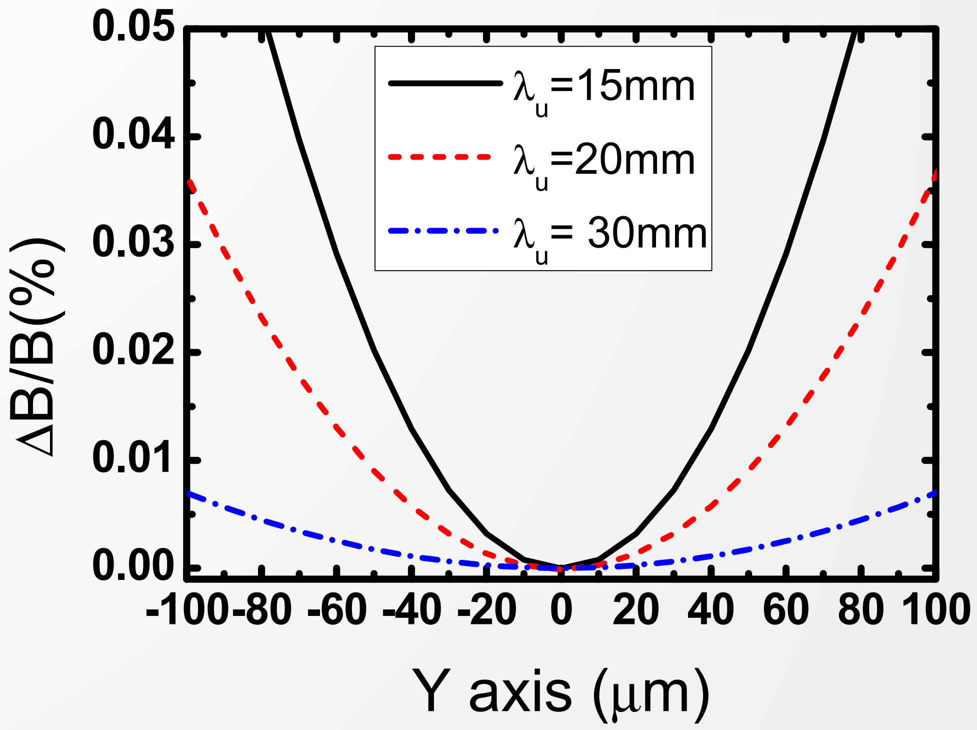
~a few W ~10W ~100W Cooling capacity

SPring-8 (H. Kitamura, EPAC 2004) TPS (Designed by H. Kitamura) SLS (G. Ingold / H. Kitamura)

- Flexible transitions are necessary between the entrance/exit of undulator vacuum chamber and IVU magnet arrays to avoid wake-field instability.
- Allow displacements from gap change and thermal expansion from baking.
- Water-cooling channels are necessary to remove the heat derived from SR coming from upstream bending magnet or image-current heating.

Challenge of short period undulators

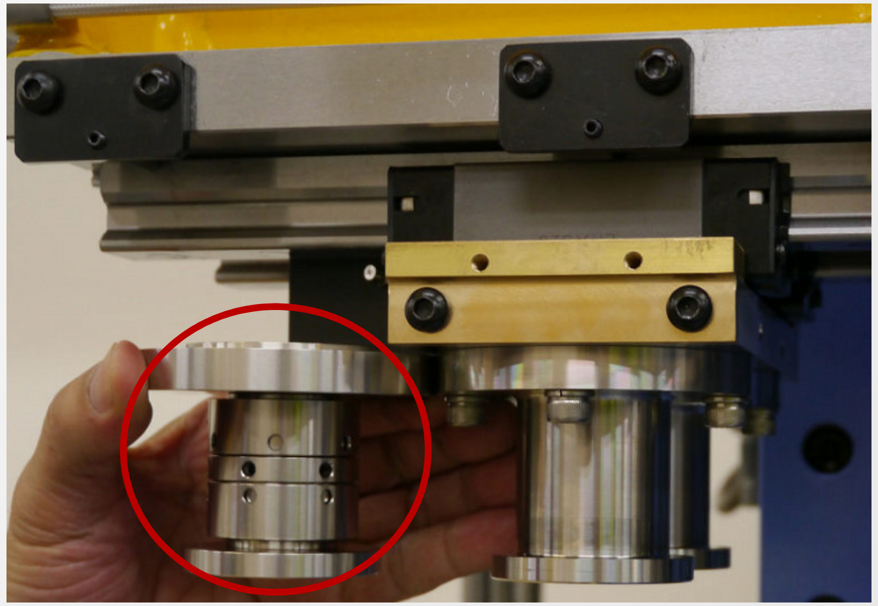
Field correction is performed without vacuum chambers, and gap reproducibility is typically around 10~20μm after re-assembly.



The above is effective only for long-period IVUs, but

•Magnetic field is more sensitive to the gap value for short period. To verify the field performance of a short period IVU after assembly, an in-situ measurement system is necessary.

•Field errors due to gap differences can be corrected by differential adjusters developed at SPring-8.



A Differential adjuster
(1μm per revolution)

Phase Error issue

For a short period / small gap undulator, the performance of phase error can be degraded by:

- **Poor reproducibility of IVU gap after re-assembly.**

  Assembly errors (mentioned in previous slide).
- **Deformation of in-vacuum girder at a small gap.**

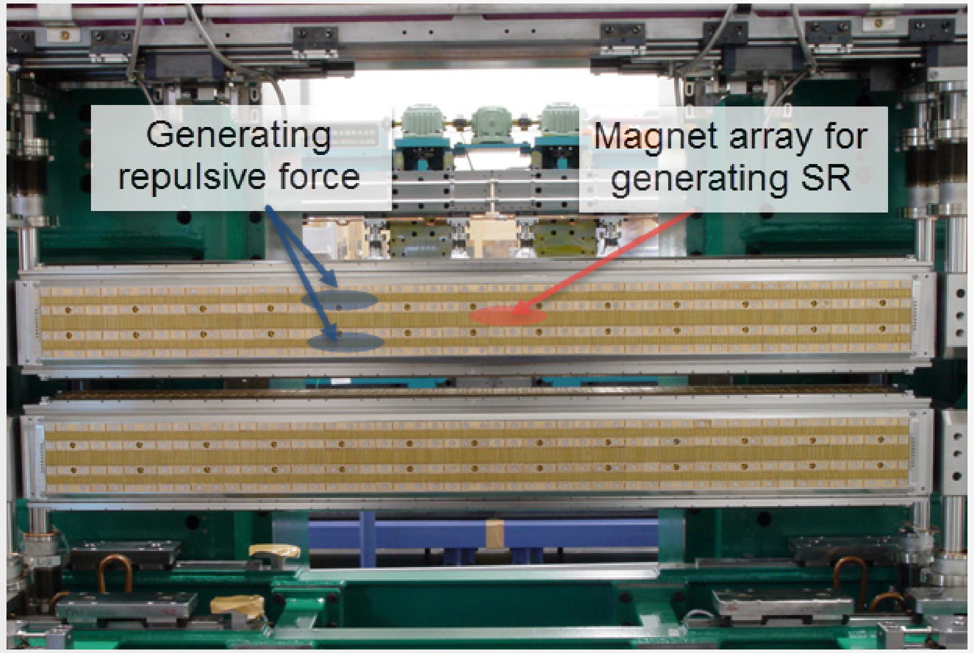
  Gap error induced by large magnetic force.
- **Pole saturation at a small gap.**

  Earth field behavior changes when a pole is saturated.
- **Manufacturing errors of PMs and poles.**

  Machining errors of PM keepers, at best, ~10 μm. Undulator magnetic field errors increase as gap-error to period ratio increases.

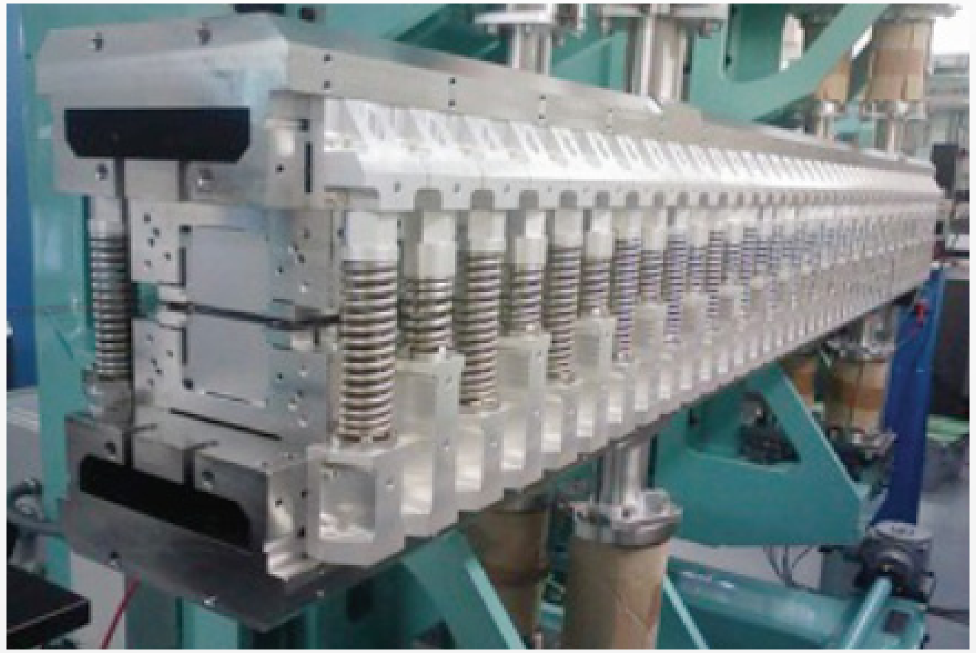
Counterforce system

Repulsive Force- Magnet
(Revolver IVU, SPring-8)



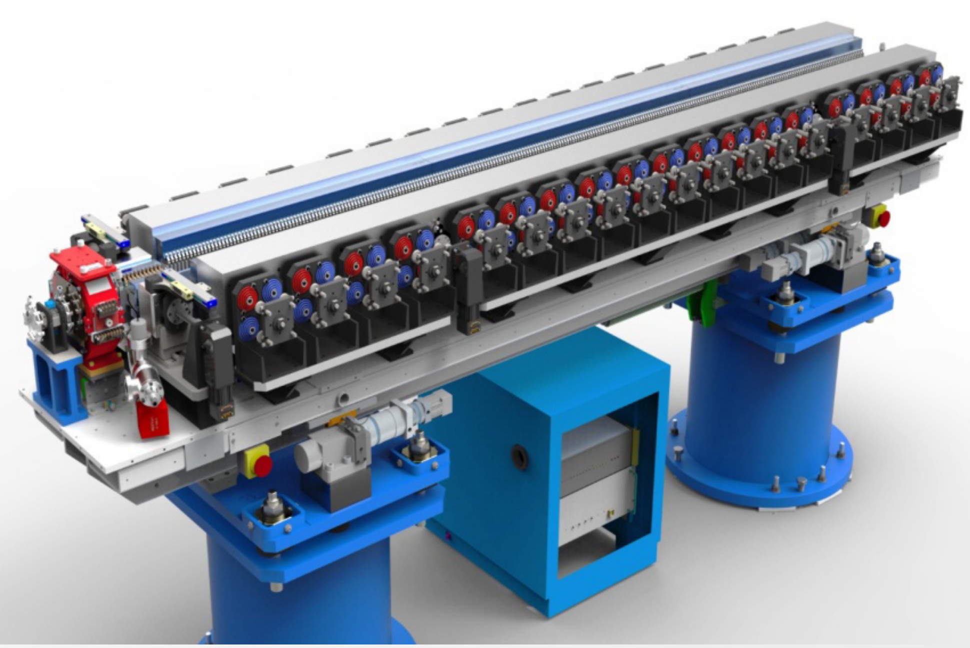
(H. Kitamura, EPAC 2014)

Spring system in vacuum
(In-vacuum wiggler, SOLEIL)



(M.E. Couprie, IPAC 2013)

Spring system in air
(Vertical Pol. Undulator, APS)



(Courtesy of J. Xu, APS)

- No effect on the magnetic field of the beam center line.
- No damage from upstream BM synchrotron radiation.
- Simple structure to be adopted in vacuum to avoid risk of fatal failure.
- Good accessibility for a magnetic field measurement system.

Heat load issue

Beam-induced heat load limits a small gap IVU operation.

- **Synchrotron radiation from upstream bending magnet (and its upstream part ← rare case)**

  Heat load on magnet cover increases dramatically when the gap is small.

  Take precautions about scattering SR.

- **Image current heating**

  Power on the magnet cover is inversely proportional to undulator gap.

- **Slope of magnet cover (PMs manufacturing errors)**

  Slope angle on a cover increases due to magnet/keeper manufacturing errors.

  ➔ Local heat load derived from SR increases a factor of 2~5 from zero slope case.

Cryogenic Permanent Magnet Undulator

A. Development of a CPMU

1. Development, motivated by KEK plan B for IVUs, has been advanced at SPring-8 .
2. PM outgassing is suppressed at cryogenic temperature(CT).
3. CPMU technologies can be extended from IVU.
4. CPMU operates at CT and PM fabrication is at RT, therefore, the aging process is unnecessary.

B. Performance of Nd/Pr based magnets is improved at lower temperatures.

PMs remanence / coercivity increases in accordance with cooling.

But, the remanence of Nd-PMs reaches the maximum around 150 K.

Development of CPMUs around world

	Period Length [mm]	Status	Magnet type	Br [T]		Hcj [KA/m]		Magnet type	L [m]	Baking	Operating Temp. [K]
				300K	150K(Nd) 77K(Pr)	300K	150K(Nd) 77K(Pr)				
NSLS	18	Laboratory	Nd	1.37	1.45	1910	4217	NEOMAX42AH	0.1	YES	150
ESRF	18	3rd GSR	Nd	1.16	1.31	2600	4616	NEOREM-595t	2.0	YES	150
DLS/Dyanfysik	17.7	3rd GSR	Nd	1.31		1670		Vacodymn 776	2.0	NO	150
SOLEIL	18	3rd GSR	Pr	1.35	1.57	1355	6090	NEOMAX53CR	2.0	NO	77
SLS	14	3rd GSR	Nd	1.33	1.50	1670	3980	NEOMAX45SH	2.0	NO	135
SPring-8	15	3rd GSR	Nd	1.36	1.48	1273	3025	NEOMAX49CH	1.4	NO	150
DLS	17.6	Construction	$Pr_{0.8}Nd_{0.2}$	1.38	1.62	1640	5340	VAC	2.0	NO	77
HZB	15	Construction	$Pr_{0.8}Nd_{0.2}$	1.41	1.70	1273	5809	VAC	1.6	NO	77
TPS	15	Construction	Pr	1.40	1.67	1680	6200	NEOMAX68CU	2.0	NO	77

Magnet Choice

Remanent (Br) : NdFeB : improved by 11 % around 150 K.
PrFeB : improved by 20 % around 77 K.

Coercive force(Hcj):improved by a factor of 2～3 at CT.

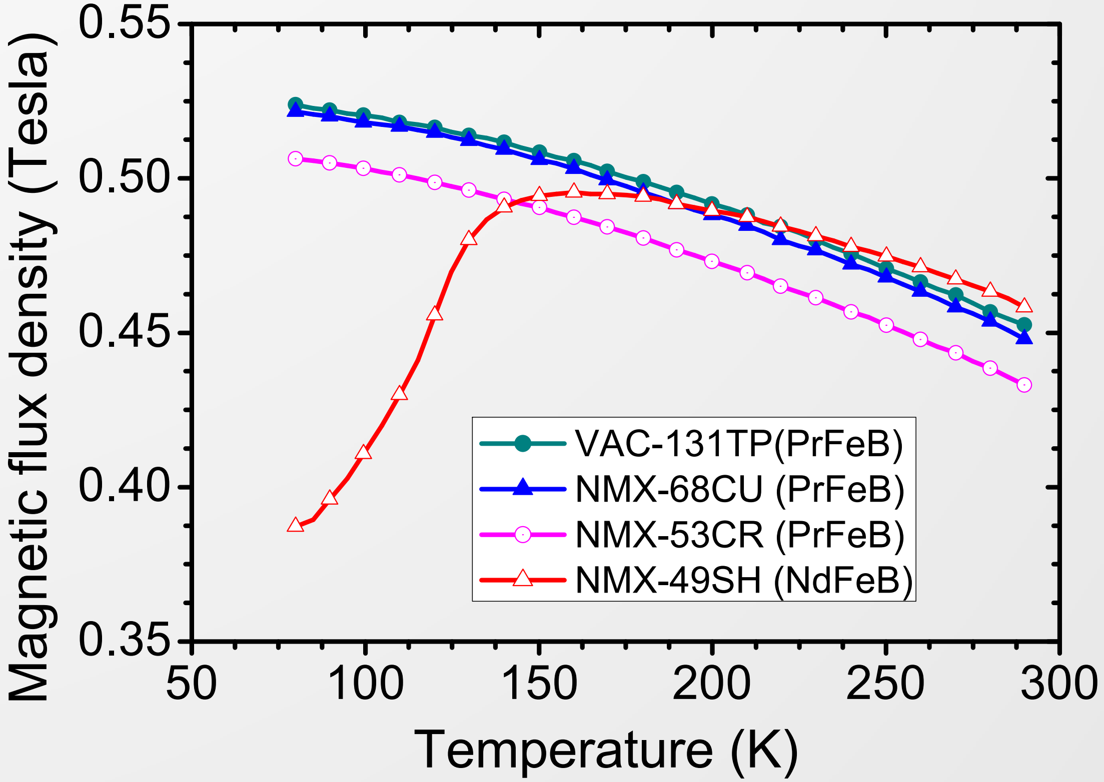
Hcj increases at CT, so another magnet grade with higher Br can be adopted.

Hcj at RT >1000 kA/m :avoid demagnetization during assembly at Room Temp.

Magnetic materials can be selected for a CPMU.

Magnet Model	Type	Br [Tesla]	Hcj [kA/m]
		300K /77K	300K / 77K
VAC-131TP	$Pr_{0.8}Nd_{0.2}$	1.40/1.62	1640/5340
NMX-68CU	PrFeB	1.40/1.67	1680/6200
NMX-53CR	PrFeB	1.35/1.57	1355/3980
NMX-49CH	NdFeB	1.36/1.48	1273/3025

Permanence coefficient ~1.



Cooling method

LN_2 cooling (ESRF, SOLEIL, DLS, HZB)

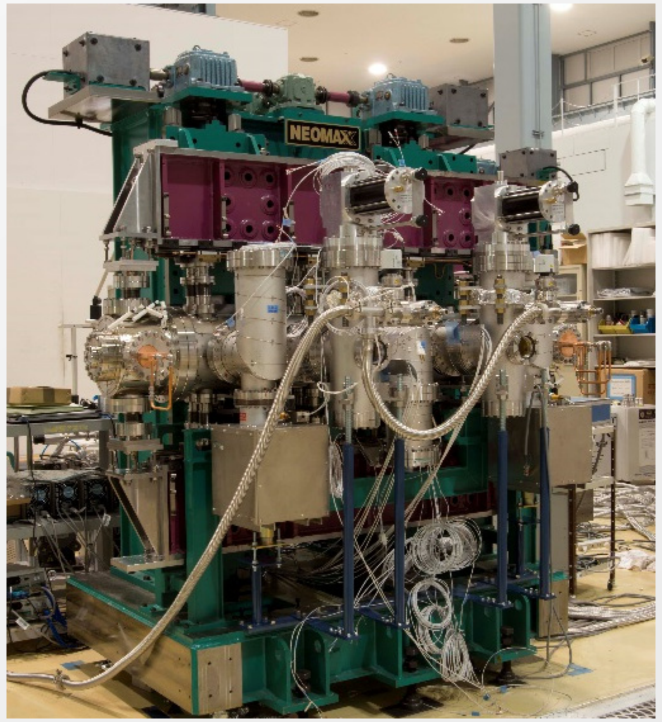
Stable closed-loop LN_2 cooling is operating. (cooling system is used for Monochromator/ Thermosiphon cooling system)

SOLEIL (M. E. Couprie, IPAC 2013)

ESRF (J. Chavanne, SRI2012)

Cryo-coolers cooling (SPring-8 ,HZB/LUM, TPS)

Cryo-cooler cooling can provide wide range of PM temperature below 77K and obtain good magnetic performance for a PrFeB / (NdPr)FeB CPMU.



SPring-8 (R. Kinjo ,SRN 2105,28(3) 46)

Temperature variation in magnet arrays

Temperature variation increases phase error

–gap errors due to material contraction.

–magnet properties (remanent field) variation.

Practical experiences from ESRF and SOLEIL

ESRF [J. Chavanne(PAC 2009) : NdFeB CPMU(~150K) LN_2 cooling with Al-alloy girder]

PM temperature variation is 26K and gradient around 1K/m at small gap.

SOLEIL [M. Couprie(IPAC2013) : PrFeB CPMU(~85K) LN_2 cooling with Al-alloy girder]

PM temperature variation is 2.5K (500mA) and gradient is around1.2K/m.

Improvement of temperature variation in magnet arrays (Target <0.1K/m)

Adopt OFHC girders.

Increase the cooling capacity (Thermosiphon cooling system).

Distribute several heaters with precise temperature controls.

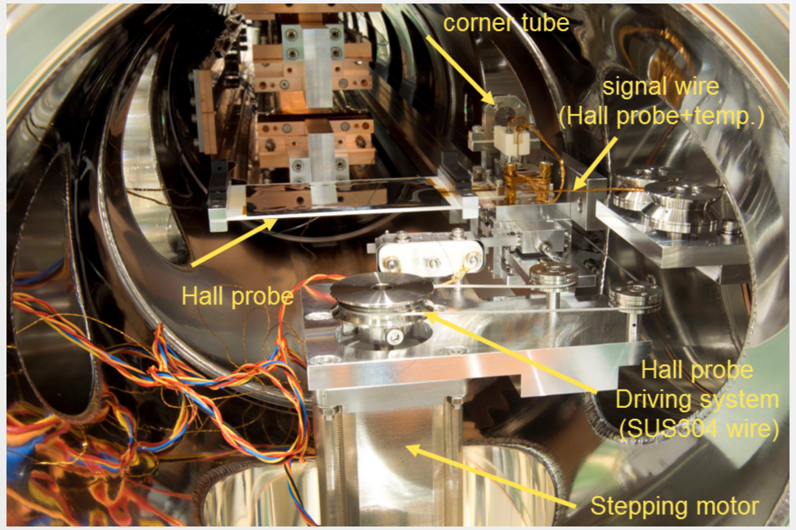
Optimize cooling points in cryo-cooler cooling method.

In-situ field measurement in a CPMU

To measure magnetic performance in low temperature and correct gap errors due to temperature variations.

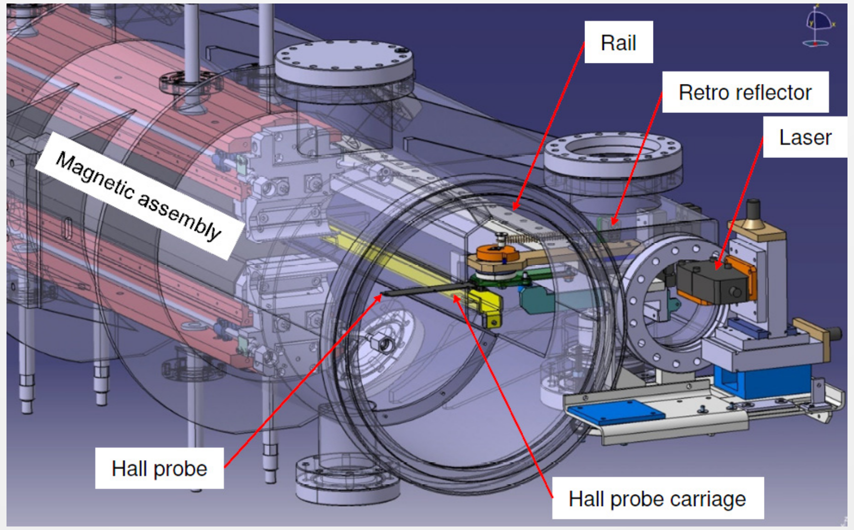
- A compact *in-situ* measurement system shall be located in insulation vacuum.
- Need temperature-dependent calibration of the Hall probes. Hall sensors is cooled by vicinity of cold magnets.
- All the components of the system shall be vacuum compatible to avoid contamination.

Customized Rail (Adjust rail position to field center)



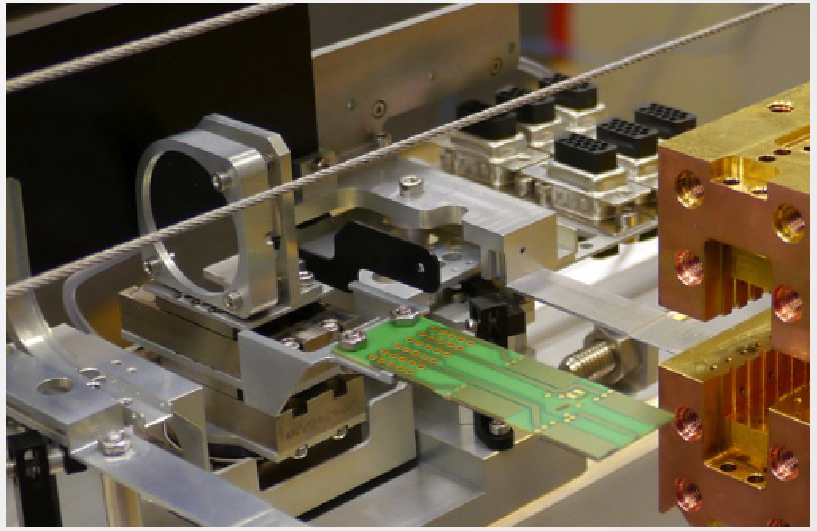
SP8 (T. Tanaka / H. Kitamura)

Linear guide rail (corrected field with rail errors)



ESRF (C. Kitegi / J. Chavanne)

Stainless strings(angle correction on HP)

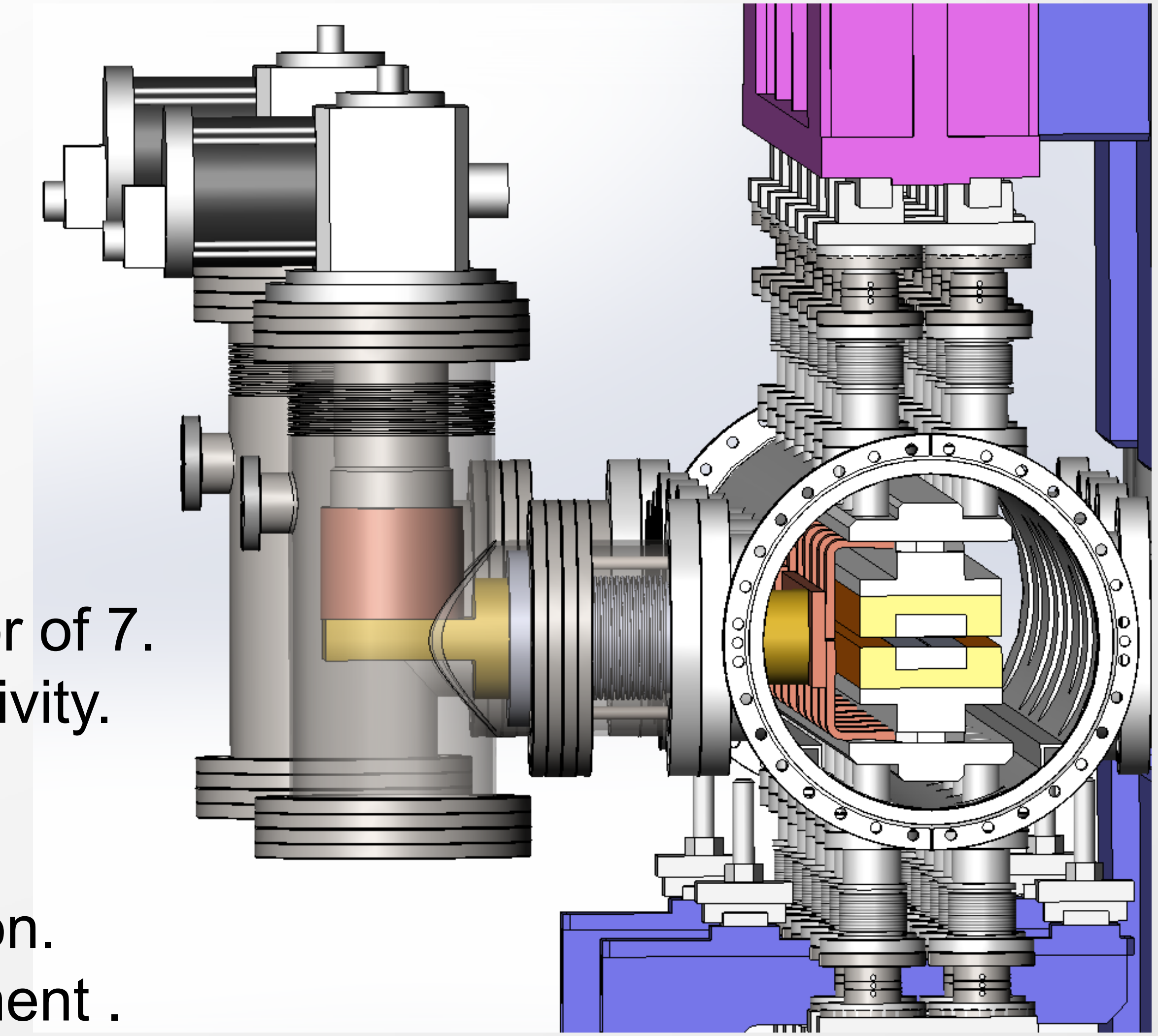


HZB (C. Kuhn / J. Bahrdt)

Design of TPS CPMU

Cooling system based on SPring-8 CPMU design

1. Cryo-coolers (200W @80K x2) .
2. Separate vacuum for cryo-cooler maintenance.



Mechanical frame

Spring systems are adopted in the mechanical frame to compensate magnetic attractive force.

Thermal budget

1. 400W(50Wx8) heaters to balance on beam-induced heat load.
2. Hollow bellows shafts reduces conduction heat transfer by a factor of 7.
3. In-vacuum girder is made of OFHC and has high thermal conductivity.

Thermal contraction and temperature variation

1. In-vacuum girder is made of OFHC to have low thermal contraction.
2. Flexible thermal strapes adopted to absorb longitudinal displacement .
3. Optimal cooling points to minimize temperature variation to be less than 0.1K/m.
4. Optical system adopted to measure the actual undulator gap at low temperature.

Lattice Functions for IVU/CPMUs

‘Low emittance, low emittance coupling and low energy spread’ is essential, but the most important matter is to obtain ‘high brilliance of SR’, not ‘low emittance’

- **Betatron functions, β_x / β_y, at IVU/CPMUs**

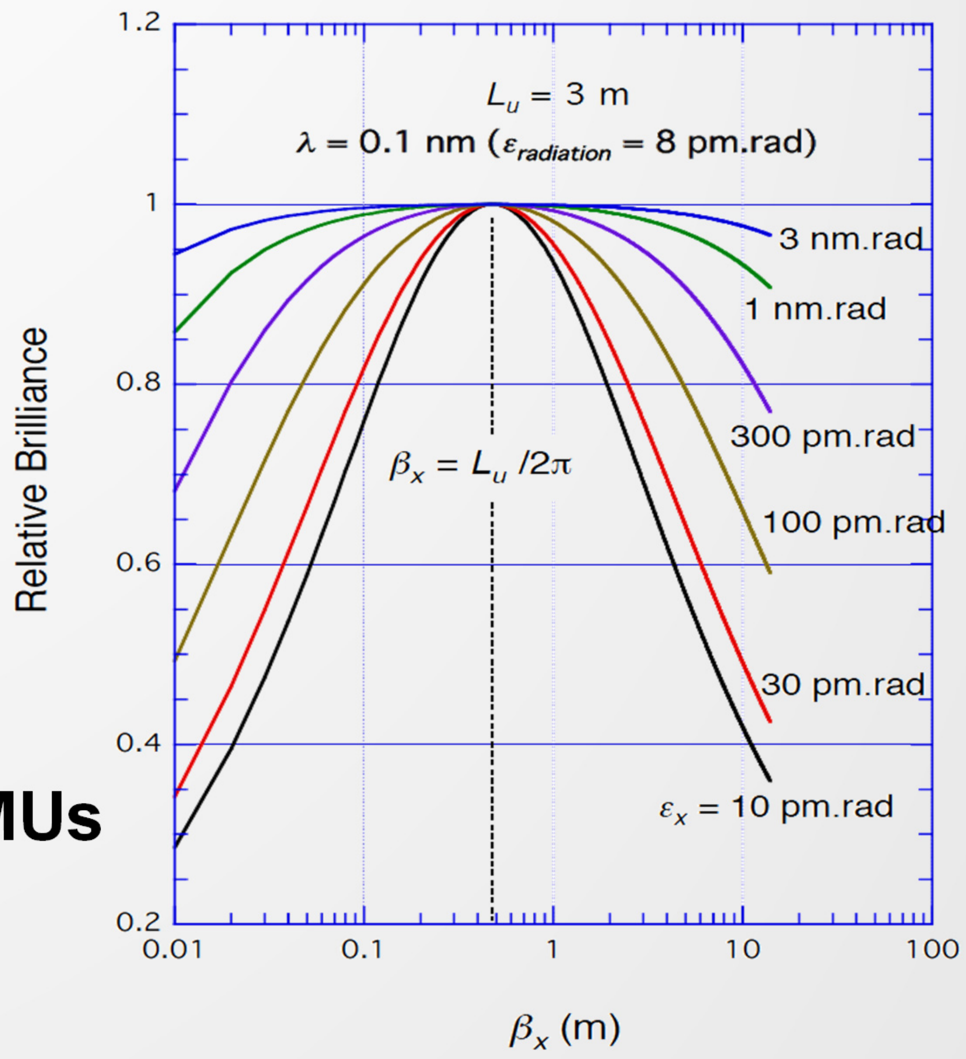
  $\beta_{x,y} = L_u / 2\pi$ (typical value≦1 m) for maximum brilliance

  - very important for USRs where $\varepsilon_x / \varepsilon_y$ is comparable to $\varepsilon_{radiation}$
  - saving pole width of magnets
    → low attractive force, compact and low cost IVU/CPMUs
  - Injection at SS, β_x shall be high for high injection efficiency

  $\beta_y = L_u / 2$ (typical value≦2 m) for longest beam lifetime

  - important for small gap operation of IVU/CPMUs

  – **as a result, $\beta_x = L_u / 2\pi$, $\beta_y = L_u / 2$ recommended for IVU/CPMUs**



- **Dispersion function, η_x, at IVU/CPMUs**

  η_x at SSs for IVU/ CPMUs shall be zero

  - to avoid reduction of brilliance due to increase of source size by energy spread
  - to avoid emittance growth and to expect emittance reduction derived from damping effect

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  $\beta_{x,y} = L_u / 2\pi$ (typical value≦1 m) for maximum brilliance

  - very im
  - saving
    → low

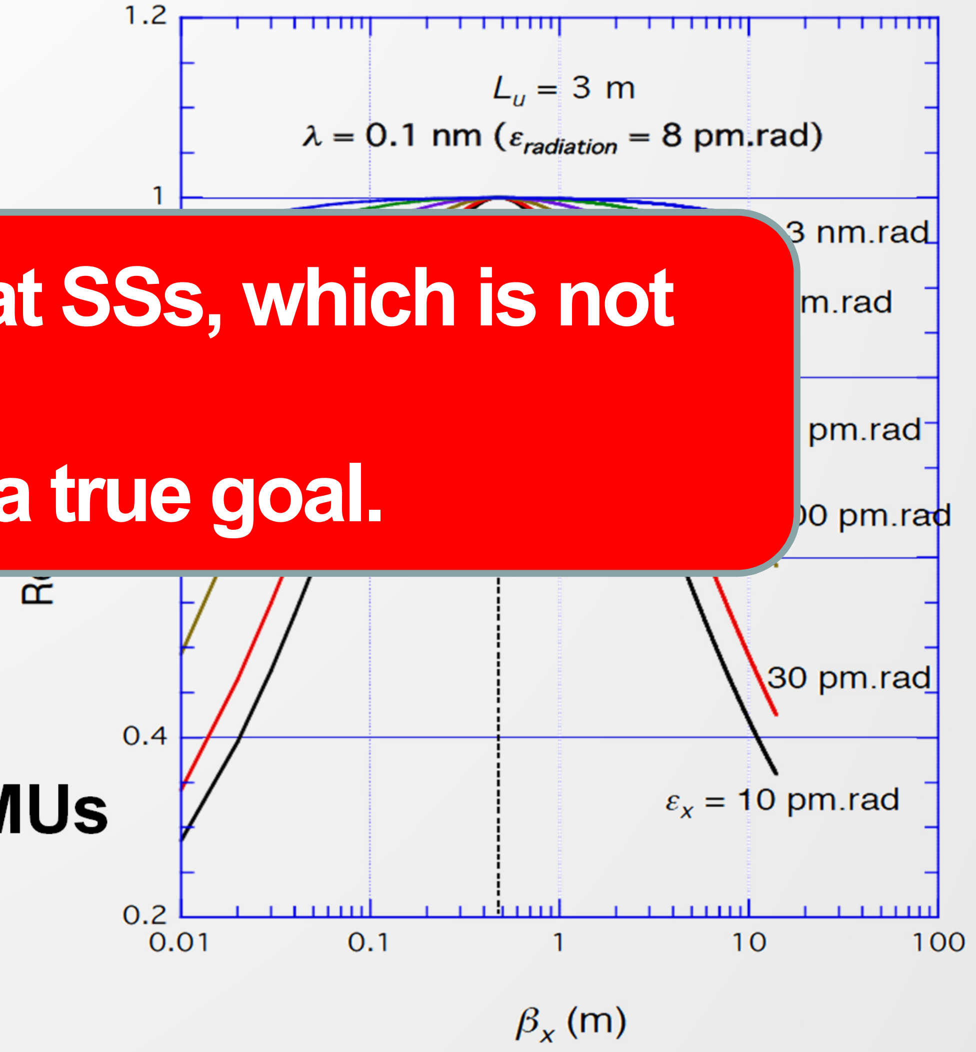
Emittance can be lowered by finite dispersion at SSs, which is not always effective for high brilliance.
'low emittance' is not a goal, 'high brilliance' is a true goal.

  - Injectio

  $\beta_y = L_u / 2$ (typical va **gest beam lifetime**

  - important for small gap op VU/CPMUs

  – **as a result, $\beta_x = L_u / 2\pi$, $\beta_y =$ 2 recommended for IVU/CPMUs**



- **Dispersion function, η_x, at IVU/CPMUs**

  η_x at SSs for IVU/ CPMUs shall be zero

  - to avoid reduction of brilliance due to increase of source size by energy spread
  - to avoid emittance growth and to expect emittance reduction derived from damping effect

In-Vacuum undulators for XFEL

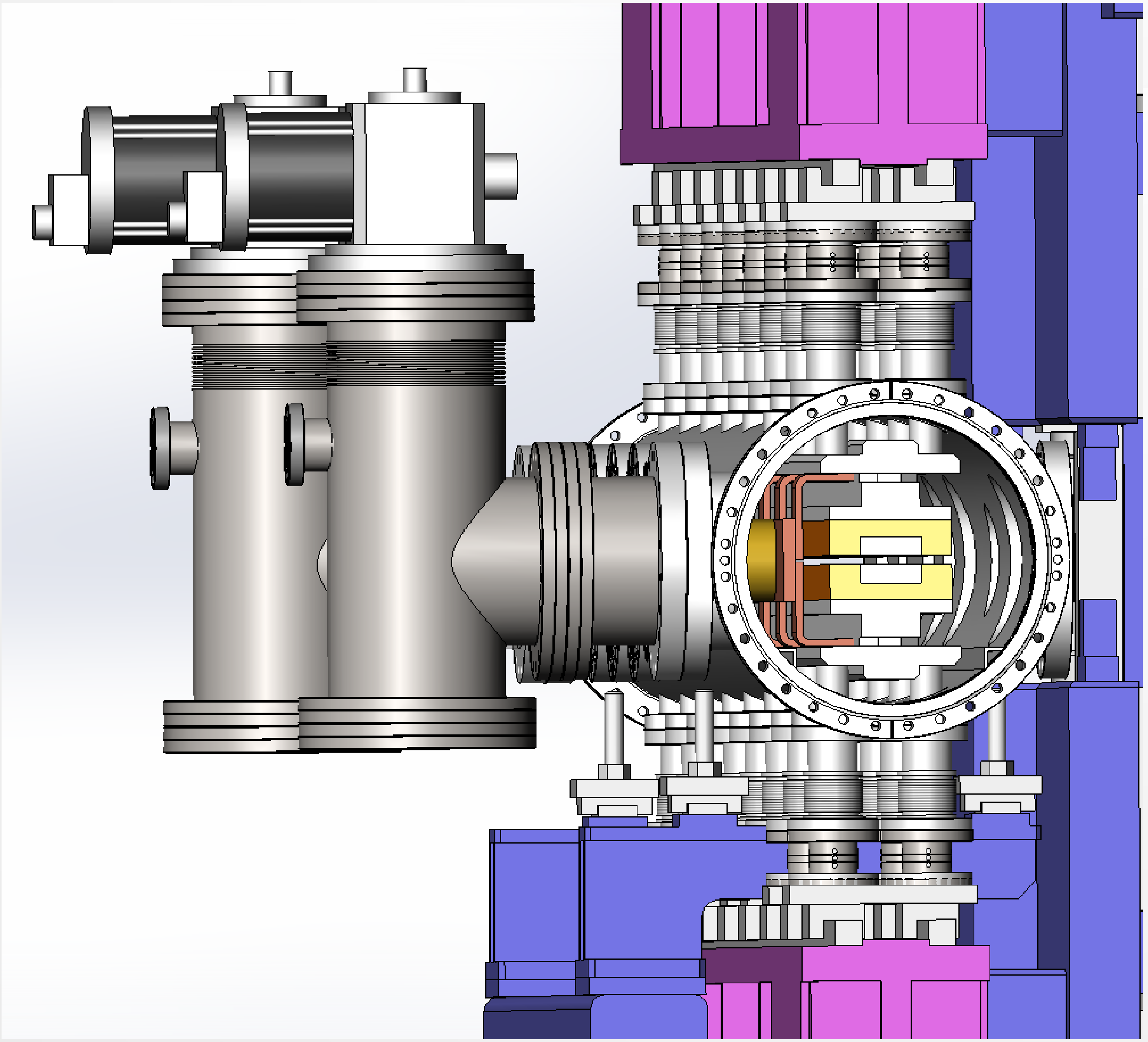
On adopting IVUs having a short period ,the beam energy can be decreased and the facility becomes compact (SACLA, Swiss FEL)

Design criteria	LINAC based XFEL	Storage Ring
Vacuum requirement	P<1E-6 Pa (No-baking) Components are not always UHV compatible.	P<1E-8 Pa (Baking) Components shall be UHV compatible.
Phase Error	Critical.	Very critical for utilization of higher harmonics.
Averaged beam current/ Heat load issue	~µA/ not critical.	>100mA / very critical at small undulator gap operation.
Minimum Gap	G_{min}~2mm and limited by electron beam loss.	G_{min}~4mm and limited by beam lifetime and beam heating.
Magnet design	Narrow pole allowed.	In high β_x case, wide pole necessary to keep high injection efficiency.

Summary

Development of short period IVU/CPMUs is a recent trend for X-ray sources.

- **In-vacuum undulators**
  - The technologies of an IVU are mature.
  - Phase error and heat load issues are challenges for USR IVU.
- **Cryogenic permanent magnet undulators**
  - Performance is proven and related technologies are developing.
  - CPMU has high resistance against thermal budget compared to SCU (Superconductive U) and a very narrow gap may be allowed.
  - Low temperature gradient to ensure low phase error performance.



TPS CPMU under development

Thank you very much for your attention.