DESIGN CRITERIA
AND
TECHNOLOGY CHALLENGES
FOR THE UNDULATOR OF THE FUTURE

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Undulator

Quasi-monochromatic radiation
Highly collimated radiation
High brightness !!

\[
\lambda = \frac{\lambda_u}{2n\gamma^2} \left( 1 + \frac{K^2}{2} \right)
\]

Magnetic period

\[ K = 93.4 B_0 \lambda_u \text{ (SI unit)} \]
X-ray SR Facilities

Beam Energy
GeV

Large Scale Facilities

SPring-8
APS
ESRF

Medium Scale Facilities operating

PFNSLS
SRS
ALS
PLS
SLS

Medium Scale Facilities under construction

CLS
SOLEIL
DIAMOND
ASSRF

Year

Short-period undulators as X-ray sources

EPAC2004
Ordinary Undulators (Out-of-Vacuum)

Vacuum Duct

Magnet

$G_{MAG}$

Magnet

$G_{VAC}$

Shorter period  Narrower $G_{MAG}$
Short-period Undulators
(Out-of-Vacuum)

$G_{MAG} \gg G_{VAC}$
Short-period Undulators

In-Vacuum Undulators

\[ G_{MAG} = G_{VAC} \]
Three Different Types for In-Vacuum Undulators

In-vacuum undulators (IVUs)
   based on permanent magnet technology.
   Since 1990.

Superconducting undulators (SCUs) of in-vacuum type
   Since 1999.

Cryoundulators (CryoUs)
   Cryogenic permanent magnet undulators
   just proposed at SPring-8 in May, 2004
In-vacuum undulator (SPring-8)

Electron beam
Brief History of In-vacuum Undulator Development

1990 First IVU was operated at KEK
1997 Four IVUs were operated at SPring-8
1997 IVU of mini-gap type was operated at NSLS

\[ \lambda_u = 11\text{mm}, N = 27, G_{\text{min}} = 3.2\text{mm} \] (collaboration with SPring-8)
Brief History of In-vacuum Undulator Development

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1999 IVU was operated at ESRF
2001 IVU was operated at SLS
2004 34 IVUs are operated in the world.
   SPring-8:20, ESRF:4, SLS:3, KEK:2, UVSOR:2, NSLS:2, PLS:1
Important Technological Points in IVU Developments

1. Ultrahigh vacuum → Baking
   - Permanent magnet (PM) with high coercivity
   - Thermal treatment for PMs
   - Coating on PMs

2. Flexible transition
   - Smooth and flexible transition necessary between PM array and vacuum chamber

3. Image current heating

4. Radiation damage in permanent magnets
\[
P = M I_b^2 \frac{L_u}{\pi G} \frac{\Gamma(3/4)}{\omega_0 \sigma_t^{3/2}} \sqrt{\frac{\mu_0 \rho}{2}}
\]

K. Bane

**SPring-8 case**

\[I_b = 6 \text{ mA}, \quad M = 16, \quad \sigma_t = 30 \text{ psec},\]
\[\omega_0 = 1.3 \text{ MHz}, \quad \rho = 8 \times 10^{-7} \text{ ohm.m (SS)}\]

\[P = 50 \text{ W/m} \text{ !!}\]

\[\rho = 2 \times 10^{-8} \text{ ohm.m (copper)}\]

\[P = 8 \text{ W/m} \text{ !!}\]
Metal cover for magnet arrays

- Ni-plated Cu foil
- Water cooling channel
Radiation Damage in NdFeB PMs

Neutrons produced by electron beam irradiation

Observed in out-of-vacuum undulators at ESRF/APS

However,

Not observed in IVUs at SPring-8
Radiation Damage Test for NEOMAX-XX
2-GeV LINAC at PLS

500 times as many as the number of electrons at 100 mA (SPRing-8)

EPAC2004
Summary of Radiation Damage Test

Radiation resistance higher for NdFeB PMs with higher coercivity

Resistance improved drastically by thermal treatment for NdFeB PMs

Choice/treatment of PMs against radiation damage is the same for IVUs as UHV systems
SCU of In-Vacuum Type

Proposed by Forschung Karlsruhe Anka & ACCEL


Prototype, $\lambda_u = 14$ mm

$B = 1.3$ T at $G_{\text{MAG}} = 5$ mm

In-vacuum PM undulator

$B = 0.7$ T
Proposed Scheme for In-Vacuum SCUs

How to realize $G_{\text{MAG}} = G_{\text{VAC}}$

Rossmanith et al. Forschung Karlsruhe Anka
Possibility of Reduction of Image Current Heating

If $RRR = 60$ (copper),
Heating power can be reduced to 1/8 compared to that at room temp.

$$RRR = \frac{\rho (T = 300K)}{\rho (T = 4K)}$$

Cooling capacity at 4K: several watts!
3.5-T SC wiggler
Cold-bore type (not in-vacuum)

E. Wallén and G. LeBlanc, MAX Lab.

Operating !!
3.5-T SC wiggler
Cold-bore type (not in-vacuum)

E. Wallén and G. LeBlanc, MAX Lab.

Operating !!

\[ \lambda_u = 61 \text{ mm}, \quad N = 23, \quad L = 1.47 \text{ m} \]
\[ G_{VAC} = 10.2 \text{ mm}, \quad B = 3.5 \text{ T} \]

\[ I = 200 \text{ mA}, \quad \sigma = 25 \text{ psec}, \]
\[ P_{image} = 1.37 \text{ W} \]
\[ P_{SR} = 0.26 \text{ W} \]

Scaling to SPring-8 case
100 mA, 16-bunch operation

\[ P_{image} = 40 \text{ W} ! \]
Cryoundulators
(Cryogenic PM Undulators)

Motivation:

NdFeB PMs

Remanent field : - 0.1 %/K
Coercivity : - 0.6%/K
Magnetic Performance of Various PMs at 300K

- 50BH
- 48H
- 39SH
- Sm$_2$Co$_{17}$
- 35E
- 32EH
- 27VH

Available for IVUs

Cooling down
Temperature Dependence of Remanent Field
NEOMAX-XX (NdFeB, PrFeB)
Temperature Dependence of Coercivity
NEOMAX-XX (NdFeB, PrFeB)
Characteristics of CryoU

1. Extension from ordinary IVU design

2. Compact cryocooler with 200 W at 80 K available

3. High resistance against large thermal budget

4. High resistance against radiation damage

5. 30 - 50 % higher field compared to ordinary IVU
Evaluation of Magnetic Performance of Cryoundulator ($\lambda_u = 14$ mm)

Pure (Halbach) type

Hybrid type

Pole: Perpendicular
Calculated Magnetic Field in CryoU

\[ \lambda_u = 14 \text{ mm} \]

RADIA (Chubar, Elleaume and Chavanne)
Comparison of IVU, SCU & CryoU at $G_{MAG}=5$ mm

![Graph showing comparison of field vs period for different undulator configurations at G_{MAG}=5 mm. The graph includes data points for CryoU-pure, 3mm, CryoU-hybrid, 3mm, SCU, 5 mm, CryoU-hybrid, 5mm, and CryoU-pure, 5mm.](image)
Summary

1. In-vacuum undulators
   - Performance proven.
   - Standard device as an X-ray source in a medium-scale facility.
   - NdFeB with high coercivity or Sm$_2$Co$_{17}$ should be adopted.

2. Superconducting undulators of in-vacuum type
   - Generating highest field at the same magnetic gap.
   - First operation in an electron storage ring is expected.
   - Successful operation depends on the measure against thermal budget problem.

3. Cryoundulators
   - Magnetic performance is much higher than that of IVU but somewhat lower than that of SCU.
   - Extension from IVU design. An old IVU can be remodeled to CryoU.
   - High resistance against thermal budget.
     Very narrow gap may be allowed.
     Practical performance may be higher than that of SCU.
   - Principle should be verified as soon as possible.

4. Outlook
   Future undulator design?
   One of the candidates: Combination of CryoU and HTSC
Thank you for your attention!