Undulators and magnetic elements of LUNEX5

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free electron Laser Using a New accelerator for the Exploitation of X-ray radiation of 5th generation

0.4-1 GeV, emittance 1 π nmrad, 1 ps - 10 fs

- Low energy FEL beam → Short period high field undulators
- High diverging LWFA beam → Compact high gradient quadrupôles

Undulator Implementation scheme

LUNEX5 baseline - V3

Section ID
(insertion devices)

Section BL
beam line)
400 MeV slice energy spread CLA : 0.02 %, LWFA : 0.1 %
1.5 π mm.mrad emittance : CLA : 1.5, LWFA 1
peak current : CLA : 400 A, LWFA : 10 kA, 50 pC
electron bunch length : CLA : 1 ps, LWFA : 2 fs

$$\lambda = \frac{\lambda_0}{2\gamma^2} \left(1 + \frac{K^2}{2}\right)$$

For low energy FEL beam 400 MeV
To reach short wavelength energy we need to use short period high field undulators

In-vacuum and cryogenic undulators

M. Labat talk FROBI01
C. Evain poster WEPD14
T. Tanikawa poster TUPD05

Cryogenic undulators

- CPMU (Proposed by SPring-8) takes benefit from improved magnetic properties of RE$_2$Fe$_{14}$B at cryogenic temperatures.

- Cooling down permanent magnet increases the remnant magnetisation and the intrinsic coercivity
  
  - The increase of Nd$_2$Fe$_{14}$B remnant magnetisation is limited by the appearance of Spin Reorientation Transition phenomenon. CPMU working temperature is around 140 K.
  - The increase of Pr$_2$Fe$_{14}$B remnant magnetisation is not limited because of the absence of SRT phenomenon. CPMU working temperature is at liquid nitrogen one 77 K.

C. Benabderrahmane et al., Nd$_2$Fe$_{14}$B and Pr$_2$Fe$_{14}$B magnets characterisation and modelling for Cryogenic Permanent Magnet Undulator applications. *Nucl. Instr. And Meth. (2012) A 669, 1-6*

- CPMU is an adaptation of an in vacuum undulator with a cooling system and a dedicated low temperature magnetic bench
### Cryogenic undulator state of the art

<table>
<thead>
<tr>
<th>ESRF* (1)</th>
<th>18</th>
<th>FS</th>
<th>Nd$<em>2$Fe$</em>{14}$B</th>
<th>1.18</th>
<th>2400</th>
<th>2</th>
<th>Yes</th>
<th>150</th>
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</thead>
<tbody>
<tr>
<td>ESRF* (2)</td>
<td>18</td>
<td>FS</td>
<td>Nd$<em>2$Fe$</em>{14}$B</td>
<td>1.37</td>
<td>1355</td>
<td>2</td>
<td>No</td>
<td>150</td>
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<tr>
<td>Danfysik*/Diamond</td>
<td>17.7</td>
<td>FS</td>
<td>Nd$<em>2$Fe$</em>{14}$B</td>
<td>1.31</td>
<td>1670</td>
<td>2</td>
<td>No</td>
<td>150</td>
</tr>
<tr>
<td>SPring-8*/SLS</td>
<td>14</td>
<td>FS</td>
<td>Nd$<em>2$Fe$</em>{14}$B</td>
<td>1.33</td>
<td>1670</td>
<td>2</td>
<td>No</td>
<td>135</td>
</tr>
<tr>
<td>SOLEIL*</td>
<td>18</td>
<td>FS</td>
<td>Pr$<em>2$Fe$</em>{14}$B</td>
<td>1.35</td>
<td>1355</td>
<td>2</td>
<td>No</td>
<td>77</td>
</tr>
<tr>
<td>SPring-8***</td>
<td>15</td>
<td>P</td>
<td>Nd$<em>2$Fe$</em>{14}$B</td>
<td>1.41</td>
<td>1114</td>
<td>0.6</td>
<td>No</td>
<td>135</td>
</tr>
<tr>
<td>SOLEIL***</td>
<td>20</td>
<td>P</td>
<td>Nd$<em>2$Fe$</em>{14}$B</td>
<td>1.41</td>
<td>1114</td>
<td>0.1</td>
<td>No</td>
<td>145</td>
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<tr>
<td>SOLEIL***</td>
<td>18</td>
<td>P</td>
<td>Pr$<em>2$Fe$</em>{14}$B</td>
<td>1.35</td>
<td>1355</td>
<td>0.1</td>
<td>No</td>
<td>77</td>
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<tr>
<td>NSLS II***</td>
<td></td>
<td>P</td>
<td>Pr$<em>2$Fe$</em>{14}$B</td>
<td></td>
<td></td>
<td></td>
<td>No</td>
<td></td>
</tr>
<tr>
<td>UCLA/BESSY***</td>
<td>9</td>
<td>P</td>
<td>(Pr$<em>{0.8}$Nd$</em>{0.2}$)Fe$_{14}$B</td>
<td>1.41</td>
<td>1040</td>
<td>0.18</td>
<td>No</td>
<td>30</td>
</tr>
</tbody>
</table>

* * constructed in house ** Laboratory prototypes
2 m $\text{Pr}_2\text{Fe}_{14}\text{B}$ Cryogenic undulator

<table>
<thead>
<tr>
<th>PM</th>
<th>$\text{Pr}<em>2\text{Fe}</em>{14}\text{B}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pole</td>
<td>Vanadium P</td>
</tr>
<tr>
<td>Period:</td>
<td>18 mm</td>
</tr>
<tr>
<td>$N^\circ$ periods:</td>
<td>107</td>
</tr>
<tr>
<td>$Bz_0$:</td>
<td>1.15 T à 77 K</td>
</tr>
<tr>
<td>$K$:</td>
<td>1.9</td>
</tr>
<tr>
<td>Gap min:</td>
<td>5.5 mm</td>
</tr>
</tbody>
</table>
Gain of 10% on the magnetic peak field between 293 K and 77 K

Phase error at 77 K is 3° RMS

Correction of the electron trajectory angle (9 µm) at 77 K
2 m Pr$_2$Fe$_{14}$B Cryogenic undulator

Test RP : 13 december 2011

U20 Nd$_2$Fe$_{14}$B à 293 K

U18 Pr$_2$Fe$_{14}$B à 77 K
No baked CPMU with low vacuum pressure due to the cryo pumping

Gap closed for the first time with in 40 min (Beam 400 mA)

Vacuum pressure grows when the temperature increases
Thermal gradient on the magnetic system $< 1.5 \text{ K/m}$
Total temperature variation due to electron beam (400 mA) and gap variation $< 2.5 \text{ K}$
### Radiator Undulators

<table>
<thead>
<tr>
<th>Type</th>
<th>In- vacuum</th>
</tr>
</thead>
<tbody>
<tr>
<td>PM</td>
<td>Nd$<em>2$Fe$</em>{14}$B</td>
</tr>
<tr>
<td>Pole</td>
<td>Vanadium P</td>
</tr>
<tr>
<td>Period:</td>
<td>15 mm</td>
</tr>
<tr>
<td>N° periods:</td>
<td>200</td>
</tr>
<tr>
<td>Bz$_0$:</td>
<td>1.5 T</td>
</tr>
<tr>
<td>K:</td>
<td>2.10</td>
</tr>
<tr>
<td>Gap min:</td>
<td>3 mm</td>
</tr>
<tr>
<td>Magnetic length:</td>
<td>3000 mm</td>
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<tr>
<td>Number:</td>
<td>4</td>
</tr>
</tbody>
</table>

### Type CPMU at 77 K
- PM: Pr$_2$Fe$_{14}$B
- Pole: Vanadium P
**Modulator Undulators**

**Type**: In- vacuum

**PM**: Nd$_2$Fe$_{14}$B

**Pole**: Vanadium P

**Period**: 30 mm

**N° periods**: 9

**Bz$_0$**: 2.2 T

**K**: 6.25

**Gap min**: 3 mm

**Magnetic length**: 270 mm

**Number**: 2
Laser Wake Field Acceleration beam

- Very short
- Strongly diverging
- Large relative E-spread

Compact variable high gradient permanent magnet quadrupôle

### CLA/LWFA

<table>
<thead>
<tr>
<th></th>
<th>Source</th>
<th>Normal quad layout</th>
<th>Compact quad layout</th>
</tr>
</thead>
<tbody>
<tr>
<td>Norm. H emittance</td>
<td>1</td>
<td>23</td>
<td>6.7</td>
</tr>
<tr>
<td>Norm. V emittance</td>
<td>1</td>
<td>35</td>
<td>11</td>
</tr>
<tr>
<td>Length</td>
<td>2 fs</td>
<td>12 fs</td>
<td>4.2</td>
</tr>
<tr>
<td>Peak current</td>
<td>4 kA</td>
<td>1 kA</td>
<td>2.2 kA</td>
</tr>
<tr>
<td>Max gradient</td>
<td>-</td>
<td>20 T/m</td>
<td>120 T/m</td>
</tr>
</tbody>
</table>
**Permanent magnet quadrupôle**

Magnet

Bore diameter: 20 mm  
Gradient: 115 T/m – 17 T/m

Y. Iwashita et al, Super strong adjustable permanent magnet quadrupole for the final focus in the linear Collider. *Proceeding of EPAC 2006, Edinburgh, Scotland*

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Magnet

pole

Bore diameter: 13.6 mm  
Gradient: 60.4 T/m – 15 T/m

**B.J.A. Shepherd** et al, Construction and measurement of novel adjustable permanent magnet quadrupoles for CLIC. *Proceeding of IPAC 2012, New Orleans, USA*
Permanent magnet quadrupôle
Based on HALBACH configuration
Inner diameter: 10 mm
Thickness: 100 mm
Height: 100 mm
Gradient 150 T/m

Founded from RTRA “Triangle de la physique” to develop a compact, strong and variable gradient permanent magnet magnet quadrupole
Conventional magnetic elements

Chicane dipole

Air cooled dipole
Density = 1.5 A/mm²
$B_{Z0} = 0.35$ T

Quadrupoles
Tosca model
Gradient : 5 T/m

Beam dump dipole

Water cooled dipole
Density = 5 A/mm²
$B_{Z0} = 1.6$ T
Development of a 3 m Cryo-Ready in-vacuum undulator, design of magnetic system, carriage and adaptation of the vacuum chamber

Characterisation of $(\text{Nd}_{1-x}\text{Pr}_x)_2\text{Fe}_{14}\text{B}$ permanent magnet

Study of short period undulator between 15 mm and 12 mm

Development of a variable gradient permanent magnet quadrupole

Detailed design of dipoles, quadrupoles, chicanes and correctors
Thank you for your attention