Superconducting wigglers and undulators

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Superconducting shifters and multipole wigglers at the BINP

Types of superconducting magnet systems used as generators of synchrotron radiation:

Superconducting 3 (5) pole shifters with 7-10 Tesla field:
manufactured 5, 3 of them are working for about 20 years.

Superconducting high field 7-7.5 Tesla multipole wigglers:
fabricated- 4, 3 of them are working and 1 is ready to put in operation this year.

Superconducting multipole wiggler with a medium period of 48 to 60 mm and field of 3-4.3 Tesla:
fabricated- 10, 8 of them are working and 2 are ready to put in operation this year.

Superconducting multipole wiggler with a short period of 30-34 mm and field of 2-2.2 Tesla:
fabricated 2, both are working.

Superconducting undulator with period 15.6 mm and field 1.2 Tesla is under fabrication now. Should be ready this year.
International collaboration on SR generators

Germany:

- 17 poles 7 Tesla, $\lambda=148$ mm superconducting wiggler for BESSY-2 light source (Berlin) 2002
- 44-pole 2.5 Tesla, $\lambda=48$ mm superconducting wiggler for ANKA light source (Karlsruhe) 2014
- 72-pole 3 Ttsla, $\lambda=51$ mm superconducting wiggler for ANKA-CLIC (Karlsruhe) 2016
- Indirect cooling system. 2016
- 22-pole 7 Tttsla, $\lambda=125$ mm superconducting wiggler for DELTA (Dortmund) 2019

USA

- 15-pole 7.5 Tesla, $\lambda=198$ mm superconducting wiggler for LSU CAMD light source (Baton Rouge) 2013
- 7 Tesla superconducting shifter for LSU CAMD light source (Baton Rouge) 1997

Italy

- 49-pole 3.5 Tesla, $\lambda=60$ mm superconducting wiggler for ELETTRA light source (Trieste) 2002

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England

49-pole 3.5 Tesla, $\lambda=60$ mm superconducting wiggler for Diamond Light source. 2006

49-pole 4.2 Tesla, $\lambda=48$ mm superconducting wiggler for Diamond Light source. 2009

Canada

27-pole 4.2 Tesla, $\lambda=48$ mm superconducting wiggler for Canadian Light source. 2007

63-pole 2.2 Tesla, $\lambda=32$ mm superconducting wiggler for Canadian Light source. 2005

Brasil

35-pole 4.2 Tesla, $\lambda=60$ mm superconducting wiggler for LNLS light source. 2009

Australia

49-pole 4.2 Tesla, $\lambda=52$ mm superconducting wiggler for AS light source. 2012

Spain

119-pole 2.1 Tesla, $\lambda=30$ mm superconducting wiggler for ALBA light source. 2010

Japan

10 Tesla superconducting shifter for SPring-8. 2000

Republic Korea

7.5 Tesla superconducting shifter for PLS light source. 1996.
History of superconducting magnet activity for 40 years

1979 – first in the world 3.5 Tesla superconducting 20 pole wiggler (SCW) for VEPP-3
1984 – 5 pole 8 Tesla superconducting wiggler for VEPP-2
1985 – 4.5 Tesla Superconducting Wave Length Shifter (WLS) for Siberia-1, Moscow
1992 – 6 Tesla superbend (SB) prototype for compact storage rings
1996 - 7.5 Tesla superconducting WLS for PLS, South Korea
1997 - 7.5 T superconducting WLS with fixed point of radiation for CAMD-LSU (USA)
2000 – 10 Tesla WLS for Spring-8, Japan
2000 – 7 Tesla WLS with fixed radiation point for BESSY-2, Germany
2001 – 7 Tesla WLS with fixed radiation point for BESSY-2, Germany
2002 – 3.5 Tesla 49 pole SCW for ELETTRA, Italy
2002 – 7 Tesla 17 pole SCW for BESSY-2, Germany
2004 – 9 Tesla Superbend for BESSY-2, Germany

Red- in operation, black- not in operation
History of superconducting magnet activity for 40 years

2005 – 2 Tesla 63 pole SCW for CLS, Canada  
2006 – 3.5 Tesla 49 pole for DLS, England  
2006 – 7.5 Tesla 21 pole SCW for Siberia-2, Moscow  
2007 – 4.2 Tesla 27 pole SCW for CLS, Canada  
2009 – 4.2 Tesla 49 pole SCW for DLS, England  
2009 – 4.1 Tesla 35 pole SCW for LNLS, Brasil  
2010 - 2.1 Tesla 119 pole SCW for ALBA, Spain  
2012 - 4.2 Tesla 63 pole SCW for AS (Australia)  
2013 - 7.5 Tesla 15 pole wiggler for LSU CAMD, USA  
2014 - 2.5 Tesla 44 pole wiggler for ANKA-CATACT, Germany  
2016 - 3 Tesla 72 pole wiggler for ANKA/CLIC, Germany/CERN  
2018 – 7 Tesla 22 pole wiggler for DELTA, Dortmund, Germany  
2018 – 3 Tesla 54 pole 2 wigglers for Siberia -2, Moscow, Russia

Red- in operation, green- ready to install
3 groups of SC wiggler

High field SC multipole wigglers
(B=7-7.5 Tesla, $\lambda$~125-200 mm)

Medium field SC wigglers
(B=3.5-4.2 Tesla, $\lambda$~48-60 mm)

Short period SC wigglers
(B=2-2.2 Tesla, $\lambda$~30-34 mm)
High field long period superconducting multipole wigglers are used for production of hard X-rays on storage rings with low electron energy (BESSY 1.7 GeV, CAMD LSU 1.35 GeV, Siberia-2 2.5 GeV, Dortmund university 1.5 GeV)

7.5 Tesla 15 pole superconducting wiggler (CAMD LSU, USA)

Magnetic field distribution at different field levels

The installation of an insertion device with so high field at an accelerator working energy of 1.35 GeV is quite a complex accelerating challenge, as considerable effort was required for compensation of the influence of the magnetic field on the magnetic structure of the storage ring. All problems connected with the influence of the wiggler field on the beam dynamics were successfully solved during the wiggler commissioning with electron beam.
Superconducting multipole wigglers with medium period

Angular-spectral photon distribution from the wiggler (63 poles):

\[ B_0 = 4.2 \text{T}, E = 3 \text{ GeV}, I = 0.2 \text{ A}, \]

\[ 140 \text{ m long Imaging and medical beamline} \]
Short period superconducting multipole wigglers

Longitudinal magnetic field distribution

119-pole 2.1 Tesla SC wiggler for ALBA CELLS

½ of the wiggler magnet

119

Magnet pole – main element of the magnet

**Cryogenic system of SC insertion devices progress (Budker INP)**

**1979**

Liquid helium consumption ~ **4 l/hr**

**2002**

Liquid helium consumption ~ **0.6 l/hr**

**2007**

Liquid helium consumption < **0.03 l/hr**

**2015**

Indirect cooling system. Liquid helium used as cooling agent.

For initial cooling of the magnet thermal tubes on the basis of nitrogen and helium are developed, fabricated and tested.
SCUs at the APS (on behalf Efim Gluskin)

- **SCU0:**
  - 16-mm period length
  - 0.33-m long magnet
  - Operation: Jan2013-Sep2016

- **SCU1(SCU18-1):**
  - 18-mm period length
  - 1.1-m long magnet
  - Operation: since May2015

- **SCU18-2:**
  - 18-mm period length
  - 1.1-m long magnet
  - Operation: since Sep2016.

- **LCLS R&D SCU:**
  - 21-mm period length
  - 1.5-m long magnet
  - Project completed in 2016.

- **Helical SCU:**
  - 31.5-mm period length
  - 1.2-m long magnet
  - Installed in Dec2017.
  - Operation: since Jan2018
### APS SCUs operational performance

- SCUs have been essentially transparent to the APS SR beam
- Most quenches occur during unplanned beam dumps
- SCU0,18-2 quenches decreased dramatically after beam abort system added in January 2016

#### Table: SCU and HSCU Quench Performance

<table>
<thead>
<tr>
<th>Year</th>
<th>APS delivered</th>
<th>SCU0 and SCU18-2</th>
<th>SCU18-1</th>
<th>HSCU</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Oper.</td>
<td>Down</td>
<td>quench</td>
<td>avail. %</td>
</tr>
<tr>
<td>2013</td>
<td>4871 h</td>
<td>4189 h</td>
<td>20 h</td>
<td>34 + 3</td>
</tr>
<tr>
<td>2014</td>
<td>4926 h</td>
<td>4391 h</td>
<td>174 h [1]</td>
<td>32 + 2</td>
</tr>
<tr>
<td>2015</td>
<td>4940 h</td>
<td>4834 h</td>
<td>0 h</td>
<td>26 + 1</td>
</tr>
<tr>
<td>2016</td>
<td>4941 h</td>
<td>4647 h [3]</td>
<td>0 h</td>
<td>9 + 0</td>
</tr>
<tr>
<td>2017</td>
<td>4840 h</td>
<td>4756 h</td>
<td>0 h</td>
<td>8 + 1</td>
</tr>
<tr>
<td>2018 [4]</td>
<td>3327 h</td>
<td>3236 h</td>
<td>5 h</td>
<td>11 + 1</td>
</tr>
<tr>
<td>Total</td>
<td>27845 h</td>
<td>26053 h</td>
<td>199 h</td>
<td>120 + 8</td>
</tr>
</tbody>
</table>

- *e-beam has never been lost due to self-quenches*
- **Red** = beam dump-induced quench
- **Blue** = non-beam dump, possible self-induced quench

[1] November: Partial loss of one cryocooler capacity
[2] Installed in May; operated May – Dec. 2015
SCU0 3310 h, SCU18-2 1337 h
APS SCU cryostat

- Vacuum vessel
- Cryogenic circuits
- Undulator magnet
- Mechanical supports & alignment systems
Thermoshield with cryocoolers

Planar SCU – “cold mass”: LHe tank and undulator magnet

Planar SCU – magnet and vacuum chamber
Planar SCU: magnets/cores

Existing magnet/beam vacuum chamber assembly.

A two-magnet/core structure.

Beam chamber is thermally isolated from both, top and bottom magnets, and cooled independently.

NbTi coils are cooled indirectly with LHe helium passing through channels in the magnet cores.
Phase errors control

- The SCU field quality depends on:
  - Precise machining of a magnet core
  - Quality of conductor winding
  - Uniformity of the magnetic gap

- A dedicated R&D program was targeted at achieving a very uniform gap.
  - A gap correction scheme was developed and implemented using a set of mechanical clamps

<table>
<thead>
<tr>
<th>Undulator</th>
<th>Measured phase errors (° rms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SCU18-1</td>
<td>5*</td>
</tr>
<tr>
<td>SCU18-2</td>
<td>2</td>
</tr>
<tr>
<td>LCLS R&amp;D SCU</td>
<td>3.8</td>
</tr>
</tbody>
</table>

* without gap correction

Measured phase errors in SCU18-1 and SCU18-2.
SCAPE magnet and vacuum chamber design

- Two orthogonal magnet pairs
- \(\frac{1}{4}\)-period longitudinal offset
- Beam vacuum chamber operates at elevated temperature, screens magnet from beam heating
SCAPE: 0.5m prototype tests

- 30 mm period
- 10 mm pole gap
- Four 0.5 m long magnets
- Planar, circular, and elliptical modes were measured in a vertical LHe bath cryostat
B-OST suggested the HT profile modified by FNAL

- 0.6 mm diameter conductor with filament diameter of 35 microns
- No thick epoxy build-ups
- HT cycle optimized
In-line double Nb$_3$Sn undulator for APS

Schedule

- Short Magnets R&D: 12/18
- 0.5 m Magnets R&D: 8/19*
- 1.3 m Full Scale SR grade Magnets: 11/20
- Cryostat fabrication & Assembly: 4/21

*Go, no go decision

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APS-U SCU Developments

- The APS Upgrade includes four full-ID-length SCUs, each with two 1.8-m planar SCU magnets in series separated by either a phase shifter or a canting magnet.
- The APS Upgrade also includes one SCAPE SCU and re-uses one existing SCU.
- New long SCU cryostats will be modeled on the HSCU 2nd-generation design.
Thanks for attention