Fixed gap undulators: design and performance

• A brief history of Adjustable Phase Undulators

• The Cornell Compact Undulators

• An APU for a linac-based machine: the FERMI afterburner prototype

• An APU for a storage-ring: the new undulator for the ALOISA beamline

• Plans for a prototype fixed-gap EPU for FERMI
The Adjustable Phase Undulator

Conventional PPM device, closed gap

Conventional PPM device, open gap (AGU mode)

Conventional PPM device, shifted arrays (APU mode)

Field, deflection parameter and photon energy vs array shift

$\frac{Z_S}{S} = \frac{\lambda_0}{2}$

$B = B_{\text{MAX}}$

$B = 0$

$\lambda_0 = 2.0 \text{ GeV}$

$e_1 (\text{eV})$
Adjusted phase insertion devices as X-ray sources

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First Test Results for an Adjustable Phase Undulator

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What happened to APUs after 1992?

- A helical/elliptical version was built at SSRL and successfully tested on SPEAR (R. Carr, 1993). More on this later in this talk.

- A hybrid version short prototype was built at SRRC (Taiwan).

- No further work on APUs until recently...
The Cornell Compact Undulator

In the context of the R&D program on Energy Recovery Linacs, starting from 2008 several APU prototypes were built and tested at Cornell. These include the DELTA undulator and several versions of a fixed polarization APU of the type considered here.

- A first prototype was an in-vacuum device (5 mm gap, 24 mm period, L=1 m).
A second prototype was built out-of-vacuum (29 mm period, L=30 cm) and incorporates a thin-wall vacuum chamber which allows a magnetic gap of 6.5 mm.

This prototype was installed on CESR in 2013 and successfully beam tested (5 GEV, 200 mA).
Based on the success of these tests, CHESS decided to replace two existing wiggler sources with CCUs. Two 1.5 m undulators (period = 28.4mm, K max = 2.5) were built by KYMA, working in strict collaboration with Cornell. They were installed at the end of 2014.

“We have very position experience of operating two CCUs built by KYMA in CESR for more than a year. We see that this type of undulators is very reliable and efficient”.
A. Temnykh
A prototype APU for FERMI

- More or less in the same period, we were also working on an APU prototype for FERMI. The objective was to build a low-cost device to be used for a test of the so-called “afterburner” configuration, a method to enhance harmonics in a FEL.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Period length</td>
<td>20 mm</td>
</tr>
<tr>
<td>Number of periods</td>
<td>60</td>
</tr>
<tr>
<td>Total length</td>
<td>1.2 m</td>
</tr>
<tr>
<td>Magnetic gap</td>
<td>8.2 mm</td>
</tr>
<tr>
<td>Maximum field</td>
<td>0.574 T</td>
</tr>
<tr>
<td>Maximum K</td>
<td>1.07</td>
</tr>
</tbody>
</table>

Main project goals:

- Simplify construction, without sacrificing quality
  - Reduce as much as possible the number of mechanical parts
  - Use only one motor and one encoder
  - Use simple rectangular cross section magnets
A prototype APU for FERMI: support structure

- Designed for easy access to the magnet arrays (important for assembly, shimming and measurement)

- NB the key aspects of the mechanical design illustrated in these slides are patent pending.
A prototype APU for FERMI: magnet arrays

- Multi-block, comb-like holders
- Solid magnet positioning is very important, due to the variable forces (vertical & horizontal, attractive & repulsive) acting on the APU. Staggering the magnets achieves this with a simple construction.

Magnet assembly tool
A prototype APU for FERMI: measurements

- Magnetic field mapping performed with a Hall sensor is an essential part of the performance optimization process.
- Typical of the APU and other similar “boxed” structures is the lack of lateral access for the Hall probe. Measurements on the complete device are therefore usually restricted to small side openings. This only provides a partial information on the field quality.

- Our structure can be opened, allowing easy measurements of the upper and lower arrays separately, which is normally the first step in the optimization process.
A prototype APU for FERMI: measurements

- Moreover, there is one phase (shift $Z_s$) for which the net vertical force balances the weight:

- This allows to perform a full scan ($-\infty < Z < + \infty$) at this equilibrium phase by removing the side supports.
• Having observed that most of the field errors (i.e. trajectory and multipoles) are to a large extent shift-independent, optimizing only at this specific set point is not a particularly limiting factor.

• Field error compensation is performed using a combination of two complementary techniques: iron shims (placed on the magnet faces) and side-screws (tuning studs):
A prototype APU for FERMI: final results

- Measured peak field agrees well with model prediction.

- Multipoles were corrected with small effort in the (narrow) good field region required by this device.

Notice that these are 11 measurements superimposed, with $Z_s$ spanning the full tuning range ($\pm10$ mm). In agreement with model calculations, the field integrals change very little with phase.
A prototype APU for FERMI: installation

- The undulator was installed in 2014 on a small gap, circular cross-section vacuum chamber.

- In operation, the undulator behaved as well as expected.

- Calibration based on magnetic measurements (peak field vs phase) allowed to set the wavelength to the required values with good accuracy.
A prototype APU for Elettra: parameters

- Following the realization of the 20 mm period device for FERMI, a second APU, this time suitable for the use on the storage ring, was designed and built.

- Its parameters were chosen in agreement with the ALOISA beamline scientists so that the device could replace the present AGU, in use since 1995:

\[
\begin{align*}
\lambda_0 &= 7.0 \text{ cm} \\
gap &= 32 \text{ mm} \\
N_{\text{per}} &= 21 \ (L=1.5 \text{ m}) \\
K_{\text{max}} &= 2.95
\end{align*}
\]

Period = 70.0 mm, \( N_p = 21 \), \( K_{\text{max}} = 2.95 \), \( E = 2.0 \text{ GeV} \)

U8 (ALOISA)
Magnets purchased in 1994
Material: Neorem 450i
Uncoated
A prototype APU for Elettra: mechanics

- Despite the longer period and wider magnets, also in this case the support structure turned out substantially smaller and lighter than for a conventional AGU with the same parameters.
A prototype APU for Elettra: magnetic field

• Multiple-magnet modules were used also in this case for simplicity (very cost effective solution)

• Good quality magnets (θ_M < 0.4°, ΔM/M < 0.4%) & sorting allowed us to obtain a very good field quality already after the initial assembly:
A prototype APU for Elettra: shimming

- Variation of the field integrals with phase was in good agreement with model prediction:

- The integrals are reduced applying small iron screws on the side of the magnets:
A prototype APU for Elettra: field quality

- As usual, “magic fingers” were used to bring multipole errors within the tight storage ring tolerances. At constant gap this procedure turned out to be greatly simplified.
A prototype APU for Elettra: installation

- So, everything’s fine in the lab. What about performance in real life?

- Device installed last June
- Tested with beam in July
- User’s beam time in September
APU prototype in real life: injection/lifetime

- First injection was performed with the phase set to $\lambda_0/2$ (on-axis field switched off) and proceeded with the usual injection rate (0.2-0.3 mA/s).

- Changing the phase didn’t produce any measurable effect.

- No impact was observed on the lifetime while scanning the phase across the whole interval $0 \div \lambda_0/2 = 35$ mm.
Dynamic aperture calculation

Method:
Elegant + RADIA kick maps

As in the old undulator

AGU mode, $K=3.0$
Pole width = 100 mm

APU mode, $K=3.0$
Pole width = 100 mm

APU mode, $K=3.0$
Pole width = 50 mm

Calculations performed by S. Di Mitri
The predicted invariance of the vertical focusing strength could not be explicitly verified, because the tune shift is below the resolution/reproducibility of the tune measurement system (0.5-1%).

\[ \Delta Q = \frac{KL\beta}{4\pi} \]

\[ K = \left( \frac{e}{\gamma mc} \right)^2 \frac{B_0^2}{2} = \frac{1}{2\rho^2} \]

**Measurement**

**RADIA model calculation**

--> 0 for wider magnets
A closed orbit distortion was observed in the horizontal plane, reaching up to a negligible 3 μm rms for Zs=±35 mm. The perturbation is well correlated with the magnetic field integrals as calculated and measured in the laboratory (|y_max| ~ 0.3 Gm).

NB this without any correction coil, which is a further significant advantage over the existing AGUs.
Commissioning of the undulator and its integration in the control and interlock systems were completed in a few days. Emission spectra were measured soon afterwards at the ALOISA end-station, equipped with a scanning grating monochromator. Well defined high-order harmonics were observed, in reasonable agreement with the magnetic measurements.
A prototype fixed-gap EPU for FERMI

- The idea of testing a compact, fixed gap \textit{variably polarized device} naturally followed from the positive results of the APU project outlined above. Realization of a prototype of this kind of undulator for FERMI was recently approved.

- The main \textit{presumed} advantages of the fixed gap solution are:
  - reduced cost
  - simplified control system (higher reliability)
  - reduced variation of the focusing strength compared to an AGU (to be confirmed)

- Goal of this project is to validate the above points and address possible construction or operational issues.

- Space is available on FEL-2 for two additional undulator segments. We have therefore the opportunity to field-test the new device.
• The first fixed gap EPU for a third generation light source was built at PSI and operated since 2006:

• Studies on fixed gap EPUs were also performed at the Photon Factory, Bessy-II and at Diamond Light Source.

• Some undesirable effects on the radiation spectra were noticed at the SLS, which are not present on conventional adjustable gap EPUs. These effects are understood to be related to transverse field gradients showing up when $Z_s \neq 0$. However, this is not an issue for operation on lower emittance machines, like linac-based FELs and next generation storage rings.
A circular cross-section vacuum chamber (8 mm external, 6 mm internal diameter) is already installed in the last undulator slot since 2014.

An identical chamber will be installed also in the second-to-last slot.

This allows implementation of the APPLE-III geometry:

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**Magnetic design**

**APPLE-II**
\[ \lambda_0 = 30 \text{ mm} \]
\[ \text{gap} = 4/8 \text{ mm} \]
\[ N_{\text{per}} = 40 \ (L=1.2 \text{ m}) \]

\[ B_R=1.26 \text{ T}, \ H_{CJ}=2000 \text{ kA/m} \]

**APPLE-III**

<table>
<thead>
<tr>
<th>( \theta (^\circ) )</th>
<th>( K_{\text{CIR}} )</th>
<th>( K_{\text{HOR}} )</th>
<th>( K_{\text{VER}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1.7</td>
<td>2.3</td>
<td>2.5</td>
</tr>
<tr>
<td>15</td>
<td>1.9</td>
<td>2.6</td>
<td>2.6</td>
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<tr>
<td>30</td>
<td>1.9</td>
<td>2.9</td>
<td>2.6</td>
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<tr>
<td>45</td>
<td>1.9</td>
<td>3.0</td>
<td>2.5</td>
</tr>
<tr>
<td>60</td>
<td>1.8</td>
<td>3.0</td>
<td>2.3</td>
</tr>
</tbody>
</table>

+ 12% in circular polarization

**NB** \( K_{\text{CIR}} = 2.3 \) from an 8 mm gap DELTA

**Circular Polarization Mode**

<table>
<thead>
<tr>
<th>period (mm)</th>
<th>Nper (L = 2.4 m)</th>
<th>chamfer (mm)</th>
<th>gap (mm)</th>
<th>Krms_max</th>
<th>lambda_max @ 1.8 GeV (nm)</th>
<th>Krms @ 2.5 nm 1.8 GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>34.8</td>
<td>66</td>
<td>-</td>
<td>10</td>
<td>1.63</td>
<td>4.1</td>
<td>0.89</td>
</tr>
<tr>
<td><strong>30</strong></td>
<td><strong>80</strong></td>
<td><strong>3.5 x 3.5</strong></td>
<td><strong>4.0</strong></td>
<td><strong>1.74</strong></td>
<td><strong>4.9</strong></td>
<td><strong>1.05</strong></td>
</tr>
</tbody>
</table>
Mechanical Design

- Mechanical design is based on the experience gained with the construction of the previous fixed-gap devices
- Multi-block, comb-like holders
- Different size H and V magnets
• 3 movable arrays (Q1, Q2, Q3) allow generating arbitrary polarization states.

• Wavelength tuning at fixed polarization is achieved shifting Q1&Q2 vs Q3&Q4
Status of the project

• Most of the components have been ordered or are in the tender evaluation process. Assembly will start in January. Installation is planned for the 2017 summer shutdown.

Still to do:

• Focusing properties in various array-shifting modes have to be studied. Modeling this aspect is important for integration in the existing high-level software responsible for proper matching the e-beam into the undulator.

• New shimming techniques will be probably required because:

  - the method used on the fixed-polarization APU (iron shims and iron screws) may not be applicable or may prove insufficient

  - virtual shimming (individual blocks adjustment, often used in APPLE-type devices) is not allowed in our modular construction.
Conclusion

• We’re carrying out R&D on alternative undulator schemes, aiming to help future decisions on FEL and storage-ring upgrades.

• Two fixed gap, linearly polarized undulators were built and successfully tested on FERMI and on Elettra. They show several advantages over equivalent adjustable gap devices.

• A fixed gap, variably-polarized undulator is under construction, and will be tested on FERMI in 2017.

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