Elettra 2.0 – The upgrade of Elettra

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Outline:
• Elettra - points of view
• Trends and requirements
• Lattice analysis
• Best lattices
• Current Elettra 2.0
• Short pulses
• Brilliance and IDs
• Schedule and dark time
• Conclusions
Different views but we MUST consider the whole picture in order to reach good and productive results -> scope of the workshop
## SR generations and trends

<table>
<thead>
<tr>
<th>Generation</th>
<th>Time period</th>
<th>Radiation use from</th>
<th>Energy range (GeV)</th>
<th>Emittance nm-rad</th>
<th>Average Brilliance</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>60s and early 70s</td>
<td>Parasitic</td>
<td>0.18-6</td>
<td>500</td>
<td>(10^{13})</td>
</tr>
<tr>
<td>2</td>
<td>Mid 70s to 80s</td>
<td>Dipoles</td>
<td>0.7-2.5</td>
<td>100</td>
<td>(10^{16})</td>
</tr>
<tr>
<td>3</td>
<td>90s to 2015</td>
<td>Wiggles and undulators</td>
<td>0.7-8 many in 2-3 GeV</td>
<td>1-20</td>
<td>(10^{19})</td>
</tr>
<tr>
<td>NGSR</td>
<td>2015-2035</td>
<td>Undulators</td>
<td>2 – 6 for the moment</td>
<td>0.02-0.5</td>
<td>(10^{22})</td>
</tr>
</tbody>
</table>
Next generation: Ingredients

Those are partially based on the trends in this field:

- Higher brilliance
  \[ B_n = \frac{F_n}{4\pi^2(\varepsilon_x + \lambda_n/4\pi)(\varepsilon_y + \lambda_n/4\pi)} \]
  \[ \varepsilon_{x0}[\text{mrad}] = F_x(q_x, \text{lattice}) \frac{E^2(\text{GeV})}{N_x^3} \]

- High level of coherence in both planes (3rd generation sources have only high vertical coherence),
- Smaller spot size and divergence
- Higher flux and a variety of undulators

However not all users ask for higher brilliance and coherence. Others instead are interested in:

- Short pulses
- High field dipoles (2 T and above)
The requirements for the new machine were based on the interaction with the beam lines and users’ community.

A dedicated workshop on the future of Elettra was held in April 2014 to examine the various requirements. At that time the requirements were defined as follows:

### Design boundary conditions

- **Beam energy:** 2 GeV
- **Beam intensity:** 400 mA
- **Emittance:** to be reduced by more than 1 order of magnitude
- **Horizontal electron beam size:** less than 60 µm
- **Conserve filling patterns:** multibunch, hybrid, single bunch, few bunches
- Keep the same building and the same ring circumference (259-260 m)
- **Existing ID beam lines and their position should be maintained**
- **Conserve space available for IDs:** not less than that of Elettra
- **Conserve the existing beam lines from dipoles**
- **Use the existing injectors, that means off-axis injection**

**Easier part**

**Tougher part**
All Elettra-like multi-bend lattices have been created up to 10BA

**Emittance vs. MBA lattices**

<table>
<thead>
<tr>
<th>Number of dipoles / achromat</th>
<th>Emittance (nm-rad) @ 2 GeV</th>
<th>$\sigma_x$ (µm) @ LS</th>
<th>$\sigma_y$ (µm) @1% coupling @ LS</th>
<th>Brilliance increase factor at 1keV</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>7</td>
<td>240</td>
<td>14</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>0.74</td>
<td>80</td>
<td>4.5</td>
<td>8</td>
</tr>
<tr>
<td>5</td>
<td>0.43</td>
<td>70</td>
<td>3</td>
<td>12</td>
</tr>
<tr>
<td>6</td>
<td>0.25</td>
<td>55</td>
<td>2.2</td>
<td>17</td>
</tr>
<tr>
<td>7</td>
<td>0.17</td>
<td>40</td>
<td>1.9</td>
<td>21</td>
</tr>
<tr>
<td>8</td>
<td>0.11</td>
<td>26</td>
<td>1.7</td>
<td>26</td>
</tr>
<tr>
<td>9</td>
<td>0.075</td>
<td>22</td>
<td>1.5</td>
<td>29</td>
</tr>
<tr>
<td>10</td>
<td>0.054</td>
<td>20</td>
<td>1.3</td>
<td>32</td>
</tr>
</tbody>
</table>

**Brilliance increase factor for a well matched undulator as compared with its brilliance in the actual Elettra.**
Free space is important. Also coherence for some users

Red: free space available for IDs in the long straight section (dispersion free)
Green: free space available for IDs in the arc (dispersive)
Lattices fulfilling the free space criteria

For optics + graphics used “OPA version 3.81”, PSI, 2015 by A. Streun
Current version:
Emittance 0.25 nm-rad (0.15 if round beam) 169 keV/turn
Dipoles are electromagnets at 0.8 T
No Longitudinal Gradient in the dipoles

Free space for IDs (4.5 + 1.6 m) – fixed at 2 GeV

How to save the dipole beam lines?
Taking care of the Dipole beam lines in S6BA

Our MBAs use dipoles with fields of about 0.8 T while at the actual Elettra the fields are 1.2 T at 2 GeV and 1.44 T at 2.4 GeV

Solutions:

- Use LG dipoles with central field of ~2 T (for ~3.3 deg in S6BA) and anti-bends, no emittance increase
- Use short wigglers, emittance increases depending on the field. For each 2 T is 2.7% but with the SCW at 3.5 T the increase is reduced to 1.0%
- Use separate super-bends for 5.7 deg - > Larger emittance increase
S6BA Lattices; fulfill all criteria

LG + anti-bend version:
Emittance 0.19 nm-rad (0.1 if round beam)

The 2 and 5 dipoles in LG with central field at ~2 T. 245 keV/turn

The 3 and 4 dipoles in LG with central field at ~2.2 T. 225 keV/turn

Free space for IDs (4.5 +1.55 m) – fixed at 2 GeV
Some beam-lines cannot use 2T short wigglers e.g. SYRMEP (Mammography) and/or they need high critical energy (> 8.0 keV). Below is shown half of Elettra 2.0 with 2 super-bend sections. The emittance increases from 0.25 to 0.37 nm rad at 3.5 T (Ec=9.3 keV). The emission angle is 5.7 deg.

But also Elettra can accommodate super-bends.
Large free space for IDs or other (4.5 + 3 m), lower quadrupole strengths, less magnets, larger dynamic aperture. Higher energy possible (but at a higher emittance).

Emittance 0.75 nm-rad (0.43 if round beam) 207 keV/turn
Dipoles electromagnets at 0.8 T
No LG.

LG+anti-bend version:
Emittance 0.68 nm-rad (0.37 if round beam) 251 keV/turn
The 2 and 3 dipoles in LG with central field at 2.2 T.
Best configuration up to now, satisfying all requirements, including the free space for IDs is based on a special **six-bend** achromat (S6BA). Versions that minimize interferences and induce minimal position shift of the dipole beam lines were examined.
## Magnet List for S6BA

### Dipoles

<table>
<thead>
<tr>
<th>name</th>
<th>( L_{mag} ) (m)</th>
<th>( k )</th>
<th>( B_0 ) (T)</th>
<th>( B_1 ) (T/m)</th>
<th>Angle (°)</th>
<th>( \rho ) (mm)</th>
<th>( N )</th>
<th>( N_{sum} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>BF1</td>
<td>0.75</td>
<td>1.91</td>
<td>0.5585</td>
<td>12.7</td>
<td>3.6</td>
<td>11937</td>
<td>24</td>
<td>72</td>
</tr>
<tr>
<td>BF2</td>
<td>0.84</td>
<td>2.03</td>
<td>0.7896</td>
<td>13.5</td>
<td>5.7</td>
<td>8444</td>
<td>48</td>
<td></td>
</tr>
</tbody>
</table>

### Quadrupoles

| name   | \( L_{mag} \) (m) | \( k \)  | \( B_1 \) (T/m) | \( \Omega \) (mm) | \( |B_{pole}| \) (T) | \( N \) | \( N_{sum} \) |
|--------|-------------------|--------|-----------------|------------------|----------------|------|----------|
| Q1     | 0.13              | -2.840 | 18.93           | 26               | 0.246         | 24   | 192      |
| Q2     | 0.22              | 5.774  | 38.49           |                  | 0.500         | 24   |          |
| Q35a   | 0.13              | -0.450 | 3.00            |                  | 0.039         | 24   |          |
| Q35b   | 0.22              | 6.200  | 41.33           |                  | 0.537         | 24   |          |
| Q35a   | 0.22              | 6.780  | 45.20           |                  | 0.588         | 24   |          |
| Q533b  | 0.22              | 6.492  | 43.28           |                  | 0.563         | 24   |          |
| Q4_1   | 0.22              | 5.780  | 38.53           |                  | 0.501         | 24   |          |
| Q4     | 0.22              | 6.220  | 41.47           |                  | 0.539         | 24   |          |

### Sextupoles

| name   | \( L_{mag} \) (m) | \( m \)     | \( B_2 \) (T/m²) | \( \Omega \) (mm) | \( |B_{pole}| \) (T) | \( N \) | \( N_{sum} \) |
|--------|-------------------|-------------|------------------|------------------|----------------|------|----------|
| SF     | 0.15              | 253.3       | 253.3            | 32               | 0.105          | 24   | 240      |
| SD**   | 0.15              | -234.7      | 3735.2           |                  | 0.478          | 24   |          |
| SD2*   | 0.15              | -233.3      | 6200.0           |                  | 0.711          | 24   |          |
| SFIS   | 0.24              | 250.0       | 3666.7           |                  | 0.469          | 24   |          |
| SDL*   | 0.15              | -253.3      | 3715.5           |                  | 0.476          | 48   |          |
| SFMSL  | 0.18              | 265.6       | 3894.9           |                  | 0.499          | 24   |          |
| SDE*   | 0.12              | -183.3      | 2688.4           |                  | 0.544          | 24   |          |
| SD0    | 0.12              | -33.3       | 489.0            |                  | 0.063          | 24   |          |
| SEXP   | 0.12              | 45.0        | 660.0            |                  | 0.084          | 24   |          |

### Correctors

<table>
<thead>
<tr>
<th>name</th>
<th>( L_{mag} ) (m)</th>
<th>( \rho ) (mm)</th>
<th>( N )</th>
<th>( N_{sum} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Comb (*)</td>
<td>nan</td>
<td></td>
<td>120</td>
<td></td>
</tr>
<tr>
<td>Alone</td>
<td>0.12</td>
<td></td>
<td>72</td>
<td>192</td>
</tr>
</tbody>
</table>

In total
72 + 192 + 240 + (120) + 72 = 576 (696) magnets
(50 A - 20V )

Actual machine about half 24 + 108 + 72 + 88 = 292

Dipole power each
(422 - 700 W)

Quad power each range ( 60 - 178 W)

Sextupole power each range (73 - 222 W)

Magnets and PS’s air cooled
Magnets

The short intra-magnet available space led us to design magnets with $L_m \approx L_p$ (max 10 mm difference). Use of new materials such as Cobalt – Iron alloys will also be considered.

The bending integrated quadrupole component is done by only the pole profile geometry. In order to optimize space and performances, different coil and frame geometries are evaluated. Space between the pole terminations will be employed in order to obtain the requested frame stiff.

The quadrupole designs were developed with the vacuum chamber in order to resolve all the possible transversal interferences (beam lines). Asymmetric poles geometry has been opted.

The sextupole magnets have the higher design issue. The transversal interferences between coils and vacuum chamber are resolved.

Ref. D. Castronovo (Opera)
Other facts

✓ Use of some permanent magnet dipoles is also considered
✓ Including errors and the existing IDs the dynamic aperture is ±7 mm horizontally and ± 2.5 mm vertically. This aperture permits off axis injection with an efficiency of more than 95%
✓ Lifetime is 6 hours at 2 GeV and with the third harmonic cavity (3HC, bunch lengthening) will be 18 h
✓ Intra-beam scattering increases the emittance by 90% at 400 mA however using the 3HC the effect is reduced down to 40%
✓ Vacuum chamber best compromise (considering also the magnet power) seems to be a circular cross section with 25 mm external diameter. For the long straight sections the current vertical dimension of 9 mm is assumed. Material stainless steel and aluminium.
✓ The impedances of the low gap chambers and the rf transitions dominate. Estimated 230 kohm/m for both planes. Microwave threshold 0.6 mA for a bunch length of 5 ps.
There is a range of time resolved experiments that require high repetition rate without damaging the sample.
Controlling the electron pulse

\[ \sigma_{\tau} = \sqrt{\frac{\alpha E}{2\pi V_{RF} f_{RF} f_{\text{rev}} \cos(\varphi_s)} \left( \frac{\sigma_E}{E} \right)} \]

- Low alpha
- Increasing the rf power and/or frequency

Assuming 2.4 MV effective RF gap voltage for S6BA the bunch length is 5 ps. For 2.5 ps one needs 10 MV

But it is not all the story as we shall see…

- Employing double higher harmonic cavities
- Using crab cavities
- (Femto) bunch-slicing
Unfortunately the bunch length changes with the intensity. The smaller the emittance is the stronger the magnets should be resulting in smaller vacuum chamber cross sections which in its turn increases the electromagnetic impedance of the vacuum chamber which amongst other problems lengthens the electron bunch.

\[
\frac{Z_{//}}{n} \leq \frac{8 \ln 2}{2\pi} \frac{h V_{RF} \cos(\varphi_s)}{\sqrt{2\pi I_b}} \left(\frac{\sigma}{R}\right)^3
\]

<table>
<thead>
<tr>
<th>VRF</th>
<th>MV</th>
<th>Threshold current (mA) / bunch</th>
<th>BL (sigma) ps</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.4</td>
<td>0.57</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>0.5</td>
<td>4.4</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>0.43</td>
<td>3.8</td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>0.23</td>
<td>2</td>
<td></td>
</tr>
</tbody>
</table>

For higher than threshold

Thus increasing the main RF voltage or decreasing alpha does not always help since it cannot serve all users simultaneously.
Tricks to mitigate

Crabbing

Double detuned higher harmonic RF.

Dedicated straight section is needed

The variable bunch length scheme, proposed at HZB (BESSY) (G. Wüstefeld et al. “Simultaneous long and short electron bunches in the BESSY II storage ring”. In: Proceedings of IPAC2011THPC014 (2011), pp. 2936–2937), Claim to get 1.7 ps short bunch with some 0.8 mA per pulse

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\[
\sigma_\tau = \frac{E}{2\pi V_{c} f_{c-rf}} \sqrt{\sigma_{y,e}^2 + \sigma_{y,ph}^2}
\]

Assuming a 3rd harmonic crab cavity (1.5 GHz with 3 MV) and beam divergences of the order of 15 micro-rad the x-ray produced pulse is 1 ps and since the bunch revolves the impedance does not have time to interfere and lengthen the bunch.

Side Effects: Emittance growth, brilliance and transverse coherence loss
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>Elettra</th>
<th>Elettra 2.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Circumference</td>
<td>m</td>
<td>259.2</td>
<td>259.2</td>
</tr>
<tr>
<td>Energy</td>
<td>GeV</td>
<td>2 - 2.4</td>
<td>2</td>
</tr>
<tr>
<td>Horizontal bare emittance</td>
<td>pmrad</td>
<td>7000</td>
<td>190-250</td>
</tr>
<tr>
<td>Vertical emittance</td>
<td>pmrad</td>
<td>70 (1% coupl)</td>
<td>2.5</td>
</tr>
<tr>
<td>Beam size @ ID ($\sigma_x, \sigma_y$)</td>
<td>$\mu$m</td>
<td>245 , 14 (1% coupl)</td>
<td>43 , 3</td>
</tr>
<tr>
<td>Beam size at short ID</td>
<td>$\mu$m</td>
<td>350 , 22 (1% coupl)</td>
<td>45 , 3</td>
</tr>
<tr>
<td>Beam size @ Bend</td>
<td>$\mu$m</td>
<td>150, 28 (1% coupl)</td>
<td>17 , 7</td>
</tr>
<tr>
<td>Bunch length (zero current)</td>
<td>ps</td>
<td>17 (100 with 3HC )</td>
<td>5.6 (70-100 with 3HC )</td>
</tr>
<tr>
<td>Energy spread</td>
<td>DE/E %</td>
<td>0.08</td>
<td>0.07</td>
</tr>
<tr>
<td>Bending angle half achromat</td>
<td>degree</td>
<td>15</td>
<td>3.6 and 2x5.7</td>
</tr>
</tbody>
</table>
Brilliance with existing IDs
New IDs

Performance in case of new insertion devices (brilliance, flux and coherent flux of three hypothetical IDs well matched are shown) with the following characteristics:

**U100** period = 100 mm,  
$N_{\text{per}} = 45, \ K_{\text{max}} = 9,$

**U50** period = 50 mm,  
$N_{\text{per}} = 90, \ K_{\text{max}} = 4.5,$

**U25** period = 25 mm,  
$N_{\text{per}} = 180, \ K_{\text{max}} = 2.3$

(Ref. Bruno Diviacco)
Scheduling

At the moment 5 years and 9 months with 50 FTEs are considered sufficient for the completion of the project. This period includes final study and drawings, purchasing and construction, decommissioning of the old machine, installations and commissioning of Electra 2.0. Additionally the system leaders were asked to consider also the Electra 2.0 requirements when upgrades of the present machine are needed.
Dark period is estimated to 18 months. Can it be avoided? How?

Modular installations? Theoretically maybe yes, but practically it must be extremely complicated.
Summary

- For Elettra 2.0 our S6BA optics is chosen as the best compromise to the various requests (up to now).
- The optics is very flexible and can accommodate a number of super-bends.
- Installation of insertion devices also possible in the middle of the arc. For the moment the space available there, is 1.6 m.
- The 1.0 version of the Elettra 2.0 conceptual design report is available.
- Other types of MBAs are also studied.
The following people contributed to the technical CDR 1.0 document


Many thanks to Prof. W. A. Barletta for reading, proofing and commenting on the technical part of the CDR.
Thank you for your attention