Nonlinear Harmonic Generation in the STARS FEL

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STARS design group:
2004
- BESSY Soft X-Ray FEL Technical Design Report
  - design uses up to four HGHG stages

2005-2006
- review by German Science Council
  - recommendation to first show multistage HGHG operating
  - output wavelength range 1.24nm to 50nm
  - short (20fs), reproducible pulses

2006
- Conceptual Design Report for STARS, the Superconducting Test Accelerator for Radiation by Seeding
  - two HGHG stages

2009
- Proposal for the Construction

Frontiers in FEL Physics and Related Topics, Elba, September 8-14, 2007
- normal conducting PITZ-type gun
- three sc TESLA-type acceleration modules
- 3rd harmonic cavity
- magnetic bunch compression
- collimator
- two HGHG stages with modulator, dispersion, radiator. Fresh bunch chicane.

-> conservative, robust design
-> concentrate on demonstration of HGHG cascading

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam energy</td>
<td>325</td>
<td>MeV</td>
</tr>
<tr>
<td>Bunch charge</td>
<td>1</td>
<td>nC</td>
</tr>
<tr>
<td>Peak current</td>
<td>500</td>
<td>A</td>
</tr>
<tr>
<td>Bunch rep. rate</td>
<td>100</td>
<td>Hz</td>
</tr>
<tr>
<td>Slice emittance</td>
<td>1.5</td>
<td>mm mrad</td>
</tr>
<tr>
<td>Slice energy spread</td>
<td>&lt;32</td>
<td>keV</td>
</tr>
<tr>
<td>Accelerating gradient</td>
<td>17.2</td>
<td>MV/m</td>
</tr>
<tr>
<td>HGHG stages</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Wavelength range</td>
<td>40-70</td>
<td>nm</td>
</tr>
<tr>
<td>Output power</td>
<td>100-1000</td>
<td>MW</td>
</tr>
</tbody>
</table>
STARS planned on-site next to BESSY II storage ring in Berlin

Step 1: STARS demonstrates HGHG cascade

Step 2: User facility to complement the BESSY FEL
STARS can remain operational when/after BESSY Soft X-Ray FEL is built
Demonstration of cascaded HGHG
- stable FEL operation
- wavelength range below 100nm
- variable polarization output
- reproducible, short pulses

Test of BESSY FEL technology
- superconducting RF
- high rep rate operation of gun and linacs (1kHz)
- seeding and timing

Design leaves space for upgrade options
- HHG seeding

Provide short-wavelength radiation for experiments
- coherent output
- harmonic radiation to reach shorter wavelengths
Electrons 325 MeV

Seed

- Ti:Sa laser 700-900nm
- 4th / 5th harmonic 160-200nm
- 3rd / 4th harmonic 40-70nm

Modulator 1, Radiator 1
(and Modulator 2)

- planar undulators
- undulator period length 50 mm
- minimal gap 10-20 mm

Radiator 2 configured as APPLE III undulator

- high field
- variable field polarization
- wide resonance tuning range
- minimal gap 7 mm
Output varies between ~100MWs and GWs (superradiance)
- three undulator modules
- 150 periods
- period length 2.2cm
- radiation source point variable along radiator

Simulations show that cascaded HGHG can be demonstrated at 70nm without 3rd harmonic cavity.

Requirements met.
Everything else is optional - but very interesting:
Electrons
325 MeV

Output varies between ~100MWs and GWs (superradiance)
- three undulator modules
- 150 periods
- period length 2.2cm
- radiation source point variable along radiator

Output of STARS FEL

OPTION 1
Harmonic radiation in the range of 8-20nm

OPTION 2
HHG seeding of second radiator plus harmonic radiation

Shorter Wavelengths
Output at 66nm, planar ("power optimized")

- simulations with new version of Genesis 1.3
  (S. Reiche et al, PAC07)
- start-to-end bunch from tracking through gun, linac and undulator
- FEL simulation stopped after first undulator module of radiator 2

<table>
<thead>
<tr>
<th>Harmonic</th>
<th>Power (MW)</th>
<th>Energy (μJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>330</td>
<td>9.35</td>
</tr>
<tr>
<td>3</td>
<td>8</td>
<td>0.11</td>
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<tr>
<td>5</td>
<td>0.25</td>
<td>0.009</td>
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</table>
Harmonic Content at 50nm

Output at 50nm, planar ("power optimized")

- simulations with new version of Genesis 1.3
- start-to-end bunch from tracking through gun, linac and undulator
- FEL simulation stopped after first undulator module of radiator 2

<table>
<thead>
<tr>
<th>Harmonic</th>
<th>Power (MW)</th>
<th>Energy (µJ)</th>
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<tbody>
<tr>
<td>1</td>
<td>300</td>
<td>6.13</td>
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<td>3</td>
<td>4</td>
<td>0.05</td>
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<tr>
<td>5</td>
<td>0.18</td>
<td>0.004</td>
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Output at 40nm, planar ("power optimized")

- simulations with new version of Genesis 1.3
- start-to-end bunch from tracking through gun, linac and undulator
- FEL simulation stopped after second undulator module of radiator 2

<table>
<thead>
<tr>
<th>Harmonic</th>
<th>Power (MW)</th>
<th>Energy (μJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>125</td>
<td>2.85</td>
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<tr>
<td>3</td>
<td>0.7</td>
<td>0.01</td>
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<tr>
<td>5</td>
<td>0.015</td>
<td>0.0001</td>
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</table>
**HHG seeding, 32nm, planar**

- 23rd harmonic of 740nm laser
- HHG pulse simulated with new code RHYNO

(T. Leitner, Diploma Thesis 2007)

Simulation assumes:
- Gaussian shape laser
- 30fs FWHM duration
- waist size 17.6 µm

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<tr>
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<th>Energy (µJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1300</td>
<td>14.9</td>
</tr>
<tr>
<td>3</td>
<td>13</td>
<td>0.07</td>
</tr>
<tr>
<td>5</td>
<td>0.25</td>
<td>0.001</td>
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STARS: Proposal for a two-stage HGHG FEL

- demonstration of multistage HGHG
- and more:
  investigation of nonlinear harmonics, HHG seeding
  test and learn gun and linac operation, timing, seeding

Output and experiments

- short pulse (20fs) short wavelength radiation (40-70nm)
- output power in range of 100MW to 1GW
- STARS planned as user-facility after BESSY FEL is built:
  e.g. for experiments usually conducted with HHG,
  example: molecular photoionization

Harmonic content

- third harmonic radiation with several MWs available at 13 to 20nm with pulse energies in range of 0.01 to 0.1µJ. Very short pulse duration (10-15fs).
- HHG seeding and harmonics very promising to reach coherent short wavelength radiation.