Higher order harmonics coupling in different free electron laser codes

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• The possibility of simulating the dynamics of a FEL including the fields of the higher order harmonics in linear undulators, is available in several existing codes as Medusa [1] and Perseo [2], and has been recently implemented in Genesis 1.3 [3-4].

• Medusa and Genesis also include the dynamics of even harmonics induced by the coupling through the betatron motion. In addition Medusa, which is based on a non – wiggler averaged model, is capable of simulating the generation of even harmonics in the transversally cold beam regime, i.e. when the even harmonics coupling arises from the non-linear effects associated to longitudinal particles dynamics and not to a finite beam emittance.

Codes tested

• **Perseo**
  – 1D (pendulum equation+pulse prop.)
  – 1D + filling factor & inhomogeneous broadenings for emittances (1DPlus)
  – 3D Kirchhoff integral

• **Medusa**
  – 1D version (non wiggler averaged, pulse prop)
  – 3D version

• **Genesis 1.3**
  – New version including higher order harmonics
Medusa

• Fully 3-D & 1-D versions

• **E&M fields treated using the polychromatic SVEA approximation**
  – Time-dependent and/or polychromatic physics
  – Modal decomposition of the fields
  – Amplifier/Oscillator

• **Particle dynamics are treated from first principles (not KMR)**
  – Harmonics & sidebands implicitly included in orbit dynamics

• **Can easily add of new features for Engineering Design Evaluation**
  – New wiggler models
    • For example, an APPLE wiggler that can be configured for planar or helical symmetry
    • Input from a field map
  – New beam models
    • non-Gaussian distributions

• **Single CPU & parallel cpu versions available**
**Perseo**

*Perseo* is a library of functions devoted to the simulation of FEL dynamics in the *Mathcad* environment.

Functions for the generation of phase space variables, for the solution of the pendulum-like equation and for manipulating the phase space in a number of devices are available.

These functions can be combined in order to model more complicated situations as time dependent simulations, 3D simulations, oscillator FEL configurations, optical klystron, cascaded FELs …

Mathcad Worksheet for 1D – 1D plus correction for 3D filling factor & emittance induced inhomogeneous broadenings and 3D versions have been tested.
Genesis 1.3

Features

• Solves eikonal field equation (slow varying amplitude).
• Field discretized on fully Cartesian grid
• Fully 6 dimensional tracking of electron beam
• Equations of motion averaged over undulator period.
• Runs in steady-state, time-dependent and scan mode.
• External input of magnetic lattice, electron distribution and seeding radiation pulse
• Parallel & serial versions available
### Test Cases

- **1D Simulations**
  1. Perseo – Medusa – Steady state 10 kW seed on fundamental
  2. Perseo – Medusa – Time dependent seed on fundamental
  3. Perseo – Medusa – Time dependent seed on 3h

- **3D Simulations**
  4. Perseo (1DPlus,3D) / Medusa 3D / Genesis 1.3 – Steady state, Seed on fundamental
  5. Perseo (1DPlus,3D) / Medusa 3D / Genesis 1.3 – Steady state Seed on third harmonic 1-2-3 harmonic (Perseo only odd)
  6. Perseo (1DPlus) / Genesis 1.3 – Time dependent, seed on fundamental

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<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>$E_b$</td>
<td>200 MeV</td>
</tr>
<tr>
<td>$I_{pk}$</td>
<td>110 A</td>
</tr>
<tr>
<td>$R_b$</td>
<td>95.3 microns</td>
</tr>
<tr>
<td>$\Delta \gamma / \gamma$</td>
<td>0.0001</td>
</tr>
<tr>
<td>$B_w$</td>
<td>7.4588 kG</td>
</tr>
<tr>
<td>$K$</td>
<td>1.95</td>
</tr>
<tr>
<td>$\lambda_{und}$</td>
<td>2.8 cm</td>
</tr>
<tr>
<td>$\lambda_{rad}$</td>
<td>265.151 nm</td>
</tr>
</tbody>
</table>

*Only in 3D simulations*

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>$\varepsilon_x$</td>
<td>1 µm</td>
</tr>
<tr>
<td>$\varepsilon_y$</td>
<td>1 µm</td>
</tr>
</tbody>
</table>
Other details

- **Seed:**
  - Matched at the spontaneous emission central frequency (first, second, third harmonic ..)
  - Peak 10 kW
  - Duration 50 fs rms (in time dep simulations)

- **Time dependent simulations:**
  - 1 ps flat top current pulse
  - About 700 slices in z
  - 2 ps long z window
  - Shot noise off

- **1D Simulations**
  - without any inhomogeneous broadening due to emittances,
  - without any correction for diffraction (Filling factor, Xie scaling ...)

- **3D Simulations**
  - Seed Rayleigh range
  - Waist position
    - 40 cm
    - 70 cm

- **Output**
  - Energy vs Z
  - And @ z = 3.25m/4.06m/4.6 m
    - In time dep. simulations: Pulse & Spectrum
RUN 1 – 1D Steady state
Perseo 1D – Medusa 1D

Fundamental
265.151 nm

3rd Harmonic
88.384 nm

5th Harmonic
53.030 nm
RUN2 – 1D time dep.
Energy vs. z

![Graph showing energy vs. z for different runs.](image-url)
RUN2 – 1D time dep.
Medusa 1D – Perseo 1D, z = 3.25 m

1st harmonic

3rd harmonic

5th harmonic

Power (W)

z (um)

Power (W)

z (um)

Power (W)

z (um)

10^{-7}

10^{-5}

10^{-7}

10^{-5}

10^{-5}

10^{-3}

10^{-4}

10^{-5}

10^{-5}

10^{-5}

wavelength (nm)

Power Spectrum (norm.)

wavelength (nm)

Power Spectrum (norm.)

wavelength (nm)

Perseo

Medusa

Perseo

Medusa

Perseo

Medusa
RUN2 – 1D time dep.
Medusa 1D – Perseo 1D, $z = 4.06$ m

1st harmonic

<table>
<thead>
<tr>
<th>$z$ (um)</th>
<th>Power (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>$2 \times 10^7$</td>
</tr>
<tr>
<td>0</td>
<td>$1.5 \times 10^7$</td>
</tr>
<tr>
<td>200</td>
<td>$5 \times 10^6$</td>
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3rd harmonic

<table>
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<tr>
<th>$z$ (um)</th>
<th>Power (W)</th>
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<tbody>
<tr>
<td>0</td>
<td>$4 \times 10^6$</td>
</tr>
<tr>
<td>0</td>
<td>$3 \times 10^6$</td>
</tr>
<tr>
<td>200</td>
<td>$2 \times 10^5$</td>
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</table>

5th harmonic

<table>
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<th>$z$ (um)</th>
<th>Power (W)</th>
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<tbody>
<tr>
<td>0</td>
<td>$6 \times 10^5$</td>
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<tr>
<td>0</td>
<td>$4 \times 10^5$</td>
</tr>
<tr>
<td>200</td>
<td>$2 \times 10^5$</td>
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</table>

Power Spectrum (norm.)

<table>
<thead>
<tr>
<th>Wavelength (nm)</th>
<th>Perseo</th>
<th>Medusa</th>
</tr>
</thead>
<tbody>
<tr>
<td>262</td>
<td>88</td>
<td>88</td>
</tr>
<tr>
<td>264</td>
<td>88.2</td>
<td>88.2</td>
</tr>
<tr>
<td>266</td>
<td>88.4</td>
<td>88.4</td>
</tr>
<tr>
<td>268</td>
<td>88.6</td>
<td>88.6</td>
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</table>

<table>
<thead>
<tr>
<th>Wavelength (nm)</th>
<th>Perseo</th>
<th>Medusa</th>
</tr>
</thead>
<tbody>
<tr>
<td>88</td>
<td>52.8</td>
<td>52.8</td>
</tr>
<tr>
<td>88.2</td>
<td>53</td>
<td>53</td>
</tr>
<tr>
<td>88.4</td>
<td>53.2</td>
<td>53.2</td>
</tr>
<tr>
<td>88.6</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
RUN2 – 1D time dep.
Medusa 1D – Perseo 1D, $z = 4.60$ m
RUN3 – 1D time dep. Seed 3h
Medusa 1D – Perseo 1D, Energy vs. z
RUN3 1D time dep. Seed 3h
Medusa 1D – Perseo 1D

Z=3.25 m

Z=4.06 m

Z=4.6 m

Power Spectrum (norm.)

wavelength (nm)

Power (W)

z (um)

3rd harmonic

Perseo

Medusa

Power Spectrum (norm.)

wavelength (nm)

Power (W)

z (um)

3rd harmonic

Perseo

Medusa

Power Spectrum (norm.)

wavelength (nm)

Power (W)

z (um)

3rd harmonic

Perseo

Medusa
RUN4 - 3D steady state

3D Medusa – 3D Perseo – Genesis 1.3
RUN5 - 3D steady state, seed 3h
Perseo 3D/1D - Medusa 3D - Genesis

[Graphs showing power distribution along z (m) for different simulations.]
RUN6 – 3D time dep.
Perseo 1DPlus - Genesis

![Graph showing energy (mJ) vs. z (m) for different time periods and simulation settings.](image-url)
RUN6 – 3D time dep.
Perseo 1DPlus - Genesis
Pulse @ z=3.25m
RUN6 – 3D time dep.
Perseo 1DPlus - Genesis
Pulse @ z=4.06m

1st harmonic

3rd harmonic

1st harmonic

3rd harmonic

Power (normalized)

Power (W)

Perseo 1D
Genesi s

Perseo 1D
Genesi s
RUN6 – 3D time dep.
Perseo 1DPlus - Genesis
Pulse @ z=4.60m

![Graph of 1st harmonic power vs. z (um)]

- Power (normalized)
- Power (W)

1st harmonic

- Perseo 1D
- Genesis
**RUN6**

**Shift of 0.5 m in z**

**Z=2.7 m - Perseo**
**Z=3.25 m - Genesis**

**Z=3.51 m - Perseo**
**Z=4.06 m - Genesis**
Conclusions

• Despite the differences in the models on which the codes are based, a reasonably (sometime very) good agreement has been observed in almost all the tested cases.

• The even harmonics comparison between MEDUSA and GENESIS 1.3 has pointed out some of the physical differences associated to non averaged codes, as Medusa 1D & 3D.

• The comparison of higher order harmonics is leading to similar results and the relative implementation of the underlying model may be considered reliable.