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Compact

Work Package 6: Beam dynamics and Start-to-End (S2E) modelling

FEL computer codes for the facility design

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Overview

Introduction

- Semi-analytical methods
- FEL simulation codes

Study case: Generation of hard X-Rays from a cryogenic permanent magnet undulator (CPMU)

- Comparison between Ming Xie and Dattoli
- Comparison between GENESIS and PERSEO
  - Comparison of FEL figures of merits
  - Simulation codes and Start-to-End(S2E)

Concluding remarks

Introduction

FEL simulation and WP6

Different options

- 1D and 3D Theory of FELs.
- Semi-analytical approaches.
  1. Ming Xie [1]
  2. Dattoli et al.[2]
- 1D and 3D simulation codes.
  1. 1D Codes (Prometeo, `PERSEO` [4])
  2. 3D Codes (`GENESIS`[3], FAST, GINGER, MINERVA, PUFFIN)

Integration to a Start to End (S2E) environment

- Integration and interfacing to beam dynamics and optical codes (OCELOT, XFEL simulation toolkit, `ASTRA` ⇒ `GENESIS`, `SDDS-Toolkit`, `ELEGANT` ⇒ `GENESIS`)
- Integration to Optics propagation codes (OPC, SRW)
- Simulation time and scope of the study.

1D FEL theory and Ming-Xie

1D FEL theory

- Pierce parameter (FEL efficiency)

$$\rho = \frac{1}{2\gamma}\left(\frac{I_0}{I_A}\right)^{\frac{1}{3}}\left(\frac{\lambda_u K f_B}{2\pi\sigma_x}\right)^{\frac{2}{3}}$$

  - I_0(peak current), I_A (Alfvén current), $\gamma = E_{\text{beam}}/m_e c^2$, λ_u (undulator period), K (undulator parameter), σ_x (rms of electron beam size), f_B (coupling between electrons and the field).
- Gain length $L_{g,1D} = \frac{\lambda_u}{4\sqrt{3}\pi\rho}$
- Saturation length $\approx 20\ L_{g,1D}$
- Saturation power $P_{sat} = 1.6 \times \rho P_{noise}$
- $BW_{sat} \approx \rho$

Ming Xie

Correction to 1D theory

- $\Lambda(\eta_d, \eta_\varepsilon, \eta_\sigma)$ accounts for
  - Gain reduction due to diffraction, $\eta_d = \lambda/(4\pi\sigma_x^2)L_{g,1D}$.
  - Gain reduction due to finite emittance, $\eta_\varepsilon = (4\pi\varepsilon/\lambda)(L_{g,1D}/\beta)$.
  - Gain reduction to energy spread, $\eta_\gamma = (\sigma_\gamma/\gamma)(L_{g,1D}/\lambda_u)$
  - Frequency detuning optimised(shortest L_g).
- Gain length $\rightarrow L_g = L_{g,1D}\left[1+\Lambda\right]$
- Saturation Power $\rightarrow P_{sat} = \frac{1.6\rho P_{beam}}{\left(1+\Lambda\right)^2}$
- Saturation Length $\rightarrow L_{sat} = L_g \ln\left(\frac{P_{sat}}{\alpha P_0}\right)$

1D FEL theory and Dattoli et al.

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Ming Xie and Dattoli assume a transversely symmetric electron beam and a constant current profile.

Dattoli et al.

Correction to 1D theory

- Power as a function of z

$$P(z) = P_0 \frac{A(z)}{1 + \frac{P_0}{P_S}[A(z, L_{g,1D}) - 1]}$$

- Gain length L_g recalculated in terms of χ (correction function to include normalized emittance, RMS energy spread effects.)
- Gain Length $L_g = \chi\left(\rho, \frac{\sigma_\gamma}{\gamma}\right) L_{g,1D} \simeq \left(1 + \frac{0.185\sqrt{3}}{2}\mu_\varepsilon^2\right) L_{g,1D}, \quad \mu_\varepsilon = 2\frac{\sigma_\gamma/\gamma}{\rho}$
- Saturation Power

$$P_{sat,3D} = \sqrt{2}\Phi(\chi)\left(\frac{L_{g,1D}}{L_g}\right)^2 \rho_D P_{beam}$$

- Saturation Length

$$L_{sat,3D} = 1.066\, L_g\left(\rho_D, \frac{\sigma_\gamma}{\gamma}\right) \ln\left(\frac{9P_{sat}}{P_0}\right)$$

PERSEO

- 1D Library of functions within the Mathcad® framework (Luca Giannessi)[4].
- Solves the pendulum-like FEL equations coupled with the field equations.
- Correction needed for a FEL oscillator or seeding scheme or to include diffraction effects, a filling factor is added to the coupling between electrons and field.

GENESIS

- Widely used 3D simulation code implemented by Sven Reiche.
- Solution of Paraxial Equation (using SVEA and paraxial current approximations) on a Transverse Cartesian Grid.
- Integration of the field ⇒ Alternative Direction Implicit Method.
- Leapfrog method ⇒ avoid field and particle dynamics at the same grid position.
- Macro-particles per slice.

Code	PERSEO	GENESIS
Open Source	No	Yes
Start from shot noise	Yes	Yes (Hammersley sequence)
Time-Dependent	Yes	Yes
Parallelised	No	Yes
Radiation Field	1D	3D
Harmonics	Yes	Yes
Wiggler Errors	No	Yes
Wakefield Algorithm	No	Yes
Scripting	No	Yes

Bench-marking between codes

Comparison between GENESIS and PERSEO was done to simulate the performance of the SPARC facility [5] $\rightarrow$ agreement in saturation length and other figures of merit.

Study case: Generation of hard X-Rays from a cryogenic permanent magnet undulator (CPMU)

Study case: HXR generation

Setting up a CPMU (cryogenic permanent magnet undulator) with a length larger than the saturation length, tuned to generate radiation with photon energy of 16 keV.

- Estimations using Ming-Xie and Dattoli semi-analytical models.
- Time-dependent simulations using GENESIS (10 noise realisations) and PERSEO.

Beam Parameters

Beam parameter	Value
E_{beam}	5.5 GeV
I_0	5 kA
Shape	Flat-top
Bunch length	1.64 μm
Q_{bunch}	27 pC
Normalised $\varepsilon_{x,y}$	0.2 mm-mrad
RMS slice σ_γ	0.01%

Undulator parameters

Undulator parameter	Value
Type	Planar
Period	12.87 mm
a_{w_0}	0.628
Module length	2 m

Figure of merit	Ming-Xie	Dattoli
P_{sat} [GW]	17.97	22.02
L_{sat} [m]	20.81	19.47
L_{gain} [m]	1.12	0.974

FEL figures of merits

- Gain and saturation length agreed well, to within a relative difference $\Delta L_{\text{sat}}/L_{\text{Xie-sat}}$ of approximately 6%.
- Difference in saturation power between analytic models of a 22.53%.

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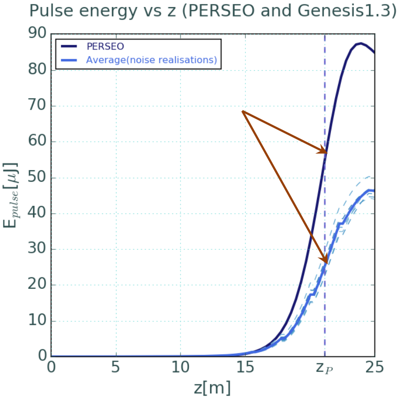
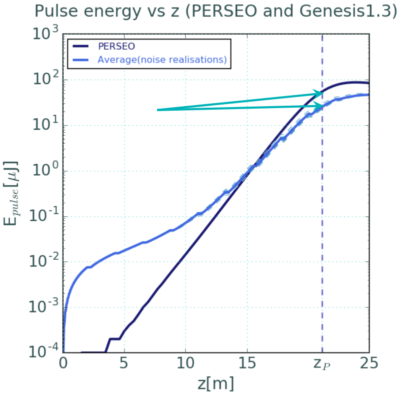
Comparison of FEL performance





- Similar saturation length.
- Difference in linear regime ⇒ growth rate, gain length

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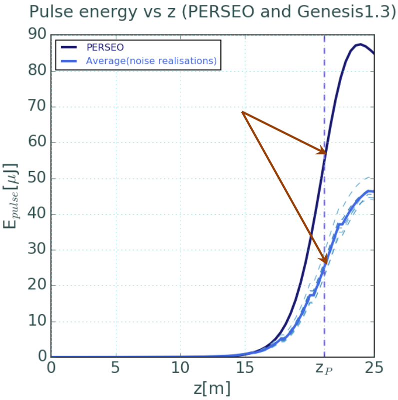

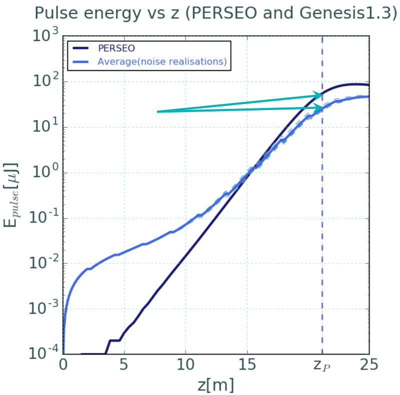

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Difference in pulse energy at saturation between the codes

Pulse energy obtained from GENESIS is around 50 % of the one obtained via PERSEO .

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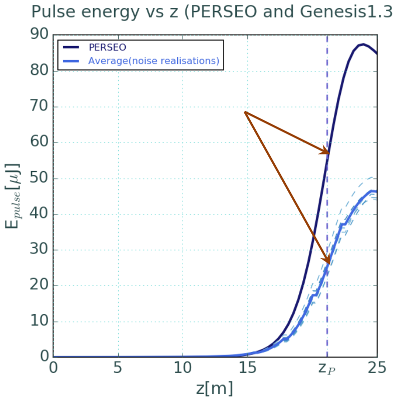

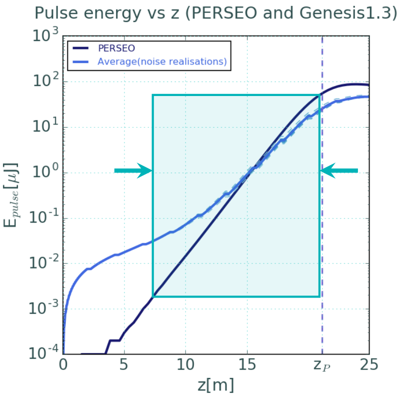

- Similar saturation length.
- Difference in linear regime $\Rightarrow$ growth rate,gain length

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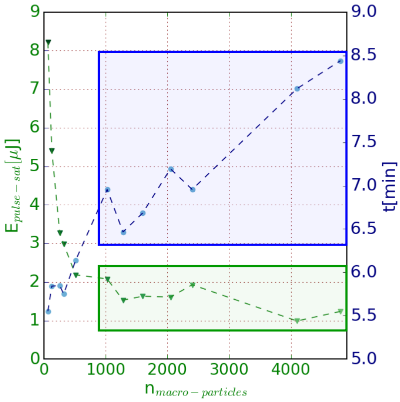
Figure of merit	PERSEO	GENESIS
P_{sat}[GW]	11.4	5.69
L_{sat}[m]	21.62	21.69
$E_{pulse}[\mu J]$	60	31.09
$N_{photons}$	2.3×10^{10}	1.28×10^{10}
Bandwidth[%]	0.055	0.064
B_{sat}	4.2×10^{32}	1.41×10^{32}
Running time	< 5 min[a]	90 min (25 processors)

[a] No compilation. Post-processing at running time.

Difference in figures of merits at saturation between the codes

- Ratio of Brightness calculated via the two codes of almost 3
- Difference $\Rightarrow$ Number of transverse higher modes between PERSEO and GENESIS [5]

Running time and S2E



Simulation time and S2E

- Faster simulation time for PERSEO .
- Ways to optimise the running time in GENESIS⇒ **number of macro-particles**, integration step, the dimension and resolution of the Cartesian Grid

- PERSEO ⇒ 1D beam dynamics codes (LiTrack) ⇒ Fast studies(longitudinal dynamics)
- GENESIS ⇒ 3D beam dynamics codes (ELEGANT, ASTRA) ⇒3D more comprehensive simulations

Concluding remarks

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- A brief description of the FEL codes and semi-analytical approximations available within the partners of the CompactLight collaboration is done.

FEL codes and S2E

- `PERSEO` provides a quick solution for scenarios in which longitudinal dynamics are relevant and can be interfaced to 1D beam dynamics codes (`LiTrack`) .
- `GENESIS` provides a more comprehensive solution for 3D and can be interfaced to 3D beam dynamics codes (`ELEGANT` and `ASTRA`).

Study case : Generation of HXR with a CPMU

- Bench-marking of semi-analytical models and FEL simulation codes (PERSEO and GENESIS) was done by setting up a CPMU, generating FEL radiation within the hard X-Ray domain ($E_{\text{photon}} = 16 keV$).
  - Ming Xie and Dattoli agree on the gain length (hence the saturation length). Difference between estimates of saturation power around 22%.
  - For the 3D simulations (PERSEO and GENESIS), the results agree with the benchmark study carried out by Giannessi et al. [5].
    - PERSEO shows a difference in the linear regime and pulse energy compared to GENESIS. This is due to a difference in the contributions of high order modes through the Cartesian Grid (for GENESIS). PERSEO only has a fundamental high order mode, corresponding to its 1D nature.

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Thank you!

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