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XLS Face-to-Face WP Leaders Meeting

FEL Simulations & Parameters for XLS-CompactLight

F. Nguyen, G. Dattoli, S. Di Mitri, L. Giannessi, A. Latina

March 5th 2019

CompactLight Specification

From J. Clarke – coordinator of the XLS WP on "FEL Science Requirements and Facility Design" – presented at the last XLS Collaboration Meeting @ ALBA

Disclaimer: Polarisation and Two-colour performance constraints not yet accounted for!

	Soft x-ray	Hard x-ray
Photon energy [keV] (min-max)	0.25 - ~2	~2 - 16
Wavelength [nm] (max-min)	5 - 0.6	
Repetition rate [Hz]	1000	100
Maximum pulse energy [mJ]	Competitive with other FELs	Competitive with other FELs
Number of photons		
Pulse duration [fs]	0.1 – 50	
Polarisation (at experiment)	Variable, selectable	Variable, selectable
Two-colour pulses: time separation [fs]	-20 -> +40	
Two-colour pulses: photon energy variation (max. of E2/E1)	2 (270-530eV), 1.2 for the rest of the range	1.1

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Goal: provide a table similar to the EuPRAXIA@SPARC CDR

	Units	Full RF case	Plasma case
Electron Energy	GeV	1	1
Bunch Charge	pC	200	30
Peak Current	kA	2	3
RMS Energy Spread	%	0.1	1
RMS Bunch Length	fs	40	4
RMS matched Bunch Spot	μm	34	34
RMS norm. Emittance	μm	1	1
Slice length	μm	0.5	0.45
Slice Energy Spread	%	0.01	0.1
Slice norm. Emittance	μm	0.5	0.5
Undulator Period	mm	15	15
Undulator Strength K		1.03	1.03
Undulator Length	m	12	14
Gain Length	m	0.46	0.5
Pierce Parameter ρ	x 10^{-3}	1.5	1.4
Radiation Wavelength	nm	3	3
Undulator matching β_u	m	4.5	4.5
Saturation Active Length	m	10	11
Saturation Power	GW	4	5.89
Energy per pulse	μJ	83.8	11.7
Photons per pulse	x 10^{11}	11	1.5

Also in XLS, two cases are foreseen: Hard & Soft X-rays

Following results are obtained considering longitudinal dynamics under discussion in WP3 and WP6, with significant INFN contributions

We analysed a couple of beams from S. Di Mitri and A. Latina accounting for considerations from M. Croia & A. Giribono

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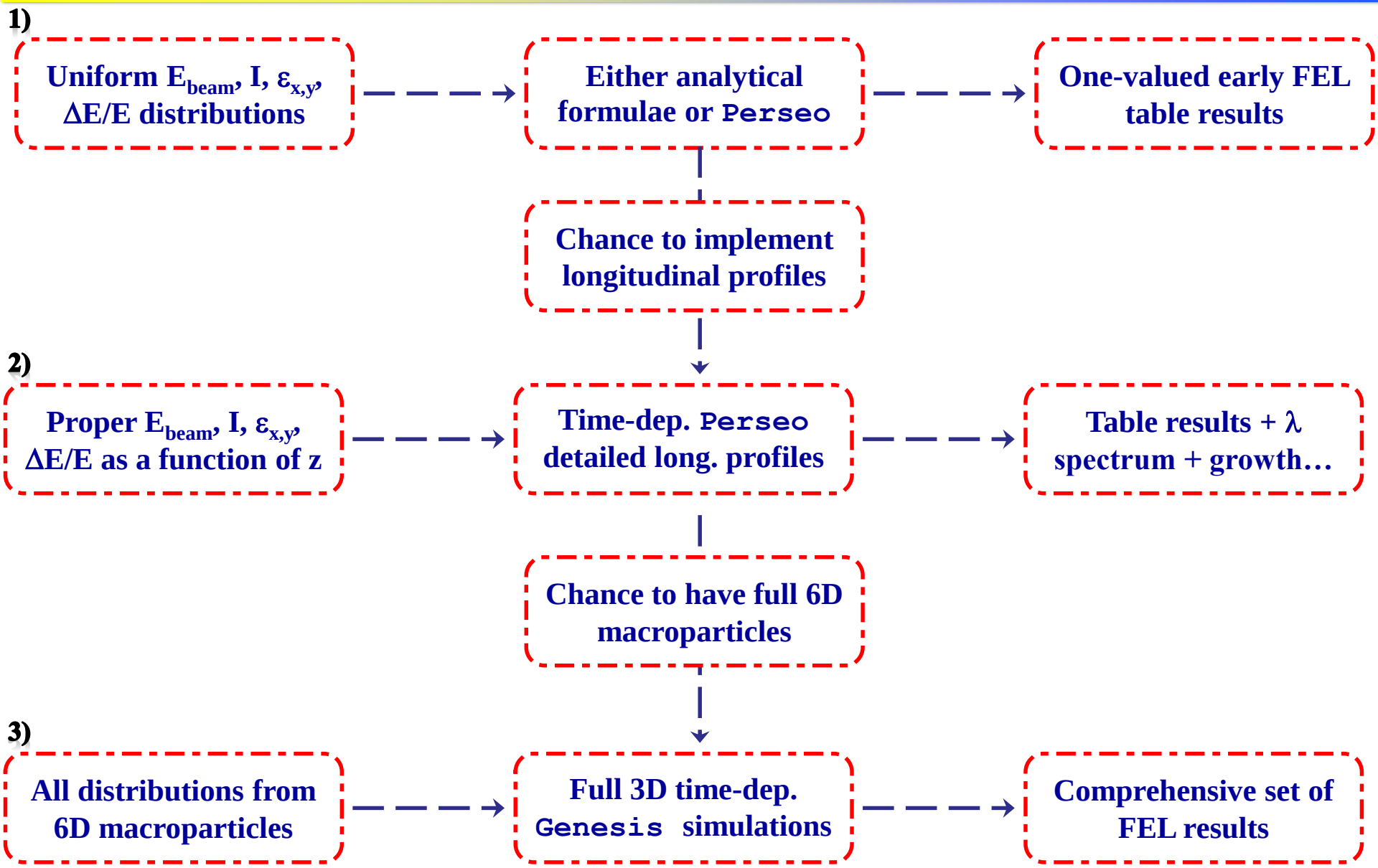
Workflow (after discussing with S. Di Mitri)



Hard X-ray beam from S. Di Mitri: uniform distributions

Beam parameters at the FEL undulator:

- Beam Energy $E := 7 \cdot GeV$ $\gamma := \frac{E}{m_0 \cdot c^2}$
- Peak current $I_{peak} := 7500 \cdot A$
- Relative Energy Spread (Slice) $\sigma_\varepsilon := 1.5 \cdot 10^{-4}$ Energy spread $E \cdot \sigma_\varepsilon = 1.05 \times 10^{3} \cdot keV$

- Normalized emittance $\varepsilon_{nx} := 0.2 \cdot mm \cdot mrad$
- Normalized emittance $\varepsilon_{ny} := \varepsilon_{nx}$

Geom. emitt. $\varepsilon_g := \frac{\varepsilon_{nx}}{\gamma}$, $\varepsilon_g = 0.015 \cdot \mu m \cdot mrad$

- Electron bunch length $\sigma_z := 1.5 \cdot \mu m$ $\sigma_z = 1.5 \times 10^{-3} \cdot mm$

Total bunch charge Q = 75 pC

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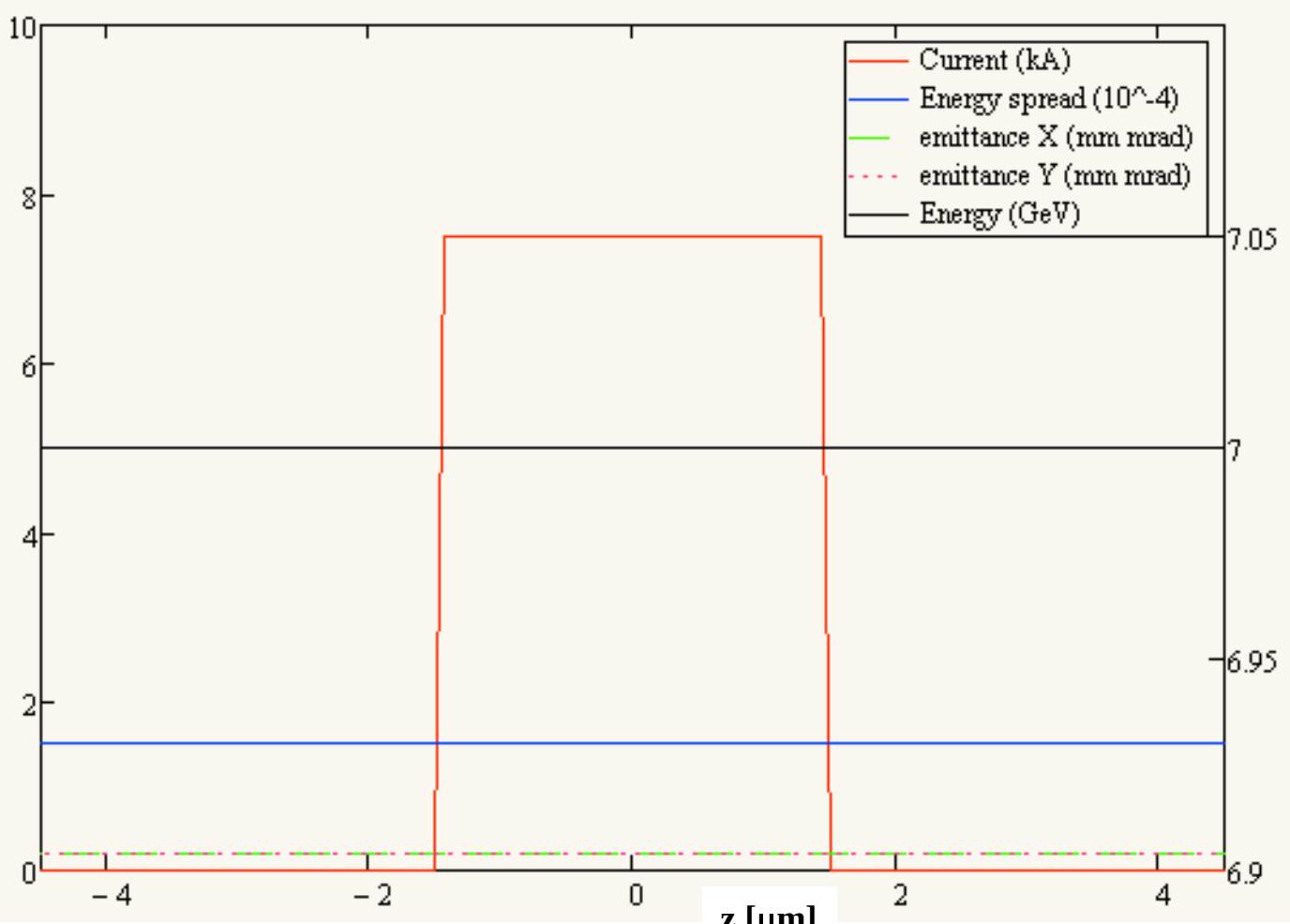
Hard X-ray beam from S. Di Mitri: uniform distributions



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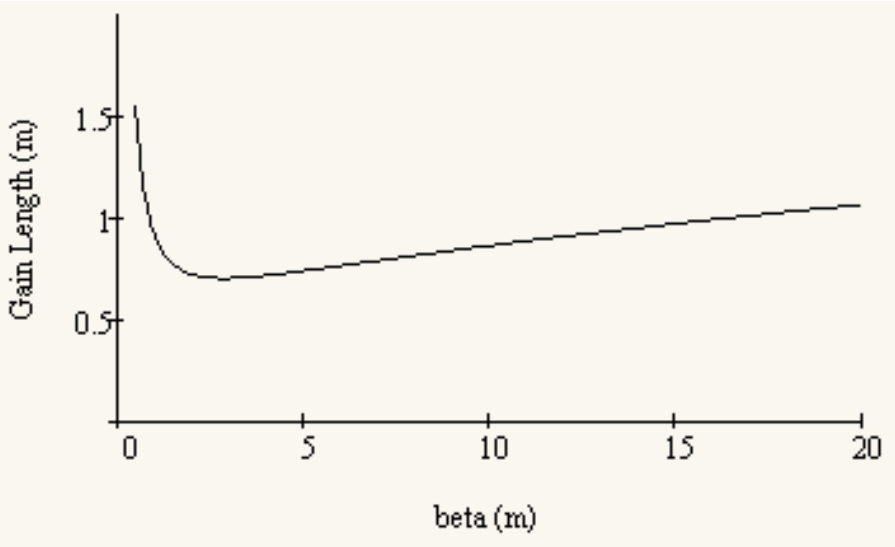
HX: undulator parameters

Undulator parameters	
undulator period	1.3 cm
undulator gap	3 mm
undulator strength K parameter	1.49

NdFeB In-vacuum undulator



Undulator_Table =	
"Period (cm)"	1.3
"K"	1.49
"Length (m)"	27.3
"Wavelength (nm)"	0.073
"Photon Energy (eV)"	$1.696 \cdot 10^{4}$
"Periods"	$2.1 \cdot 10^{3}$
"Twiss beta (m)"	8
"g0"	$2.859 \cdot 10^{3}$
"Sat. Power (W)"	$4.372 \cdot 10^{6}$
"Beam Size (rms-um)"	10.807
"Shot Noise Power (W)"	$1.452 \cdot 10^{4}$
"Pierce parameter"	$8.584 \cdot 10^{-4}$

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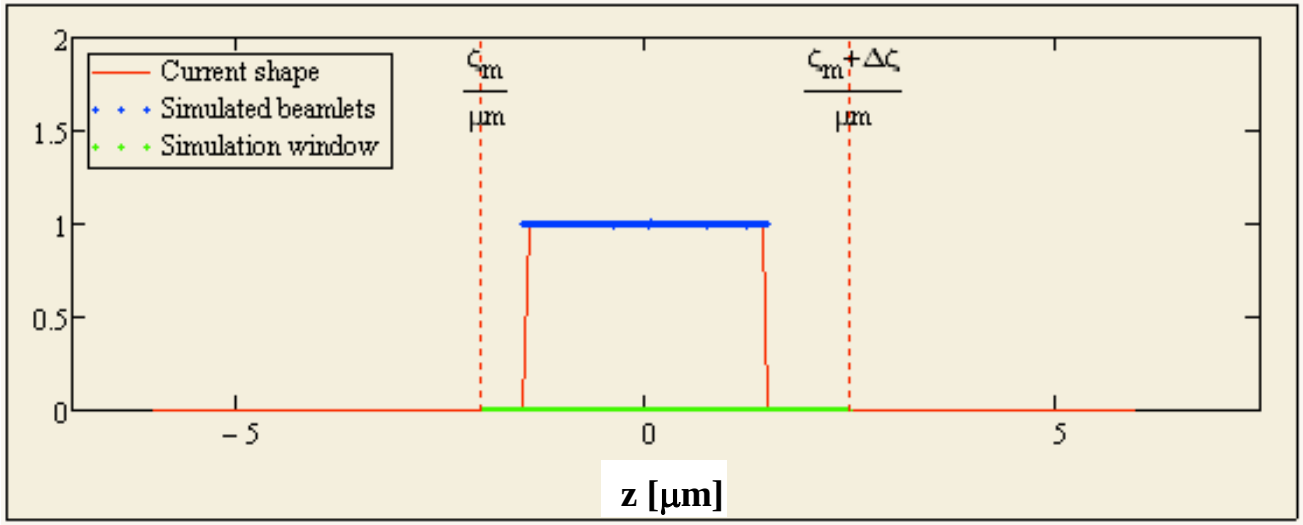
HX FEL results: tables

We have run the full time-dependent simulation to cover this current window



"Beam Energy (MeV):"	$7.000 \cdot 10^3$	"Position:"	"Saturation"
"I Peak (A)"	$7.500 \cdot 10^3$	"Wl. (nm)"	0.073
"En. Spread (%):"	0.015	"Ph_en (eV)"	$1.696 \cdot 10^4$
"Emittance (mm mrad)"	0.200	"z (m)"	14.959
"UM Section:"	1.000	"Energy (mJ)"	0.327
"Resonant wavelength(nm):"	0.073	"Duration (fs)"	2.916
"Gain Length (m)"	0.763	"Power (GW)"	44.684
"Saturation length (m):"	14.959	"Linewidth (%)"	0.086
0.000	0.000	"# phot"	$1.202 \cdot 10^{11}$
0.000	0.000	"Flux (ph./sec)"	$1.644 \cdot 10^{25}$
0.000	0.000	"Brtnss. (ph./sec/mmmrad^2/0.1%bw)"	$1.131 \cdot 10^{33}$

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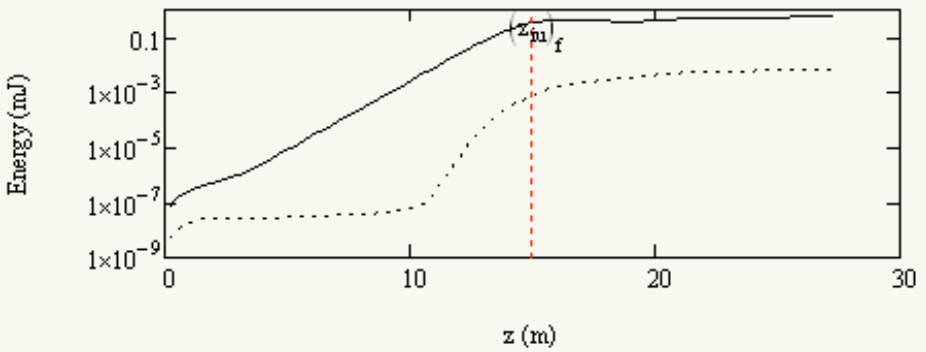
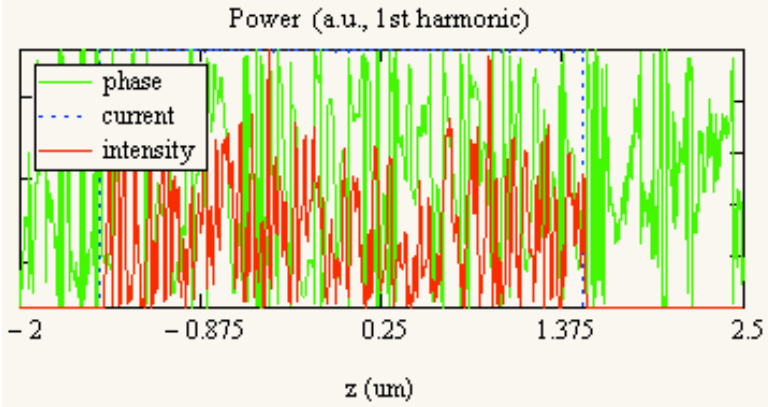
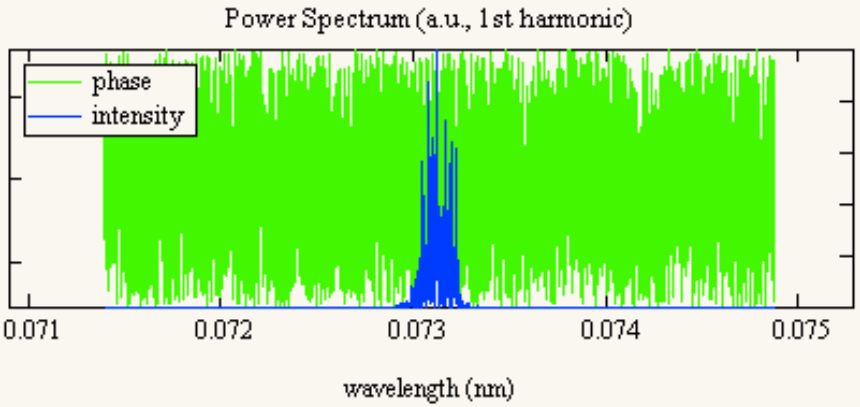
HX FEL results: profile, growth & spectrum

Parameters =

"Frame"	"55 of 100"	"Position (m)"	"15.015"
"Parameters@"	"1h"	"3h"	"5h"
"Energy (uJ)"	335.238	0.78	0.013
"length (rms, fs)"	2.914	2.933	2.961
"width (rms, %)"	0.087	0.26	0.433







Soft X-ray beam from S. Di Mitri: uniform distributions

Beam parameters at the FEL undulator:

- Beam Energy $E := 4 \cdot GeV$ $\gamma := \frac{E}{m_0 \cdot c^2}$
- Peak current $I_{peak} := 5400 \cdot A$
- Relative Energy Spread (Slice) $\sigma_\varepsilon := 2 \cdot 10^{-4}$ Energy spread $E \cdot \sigma_\varepsilon = 800 \cdot keV$

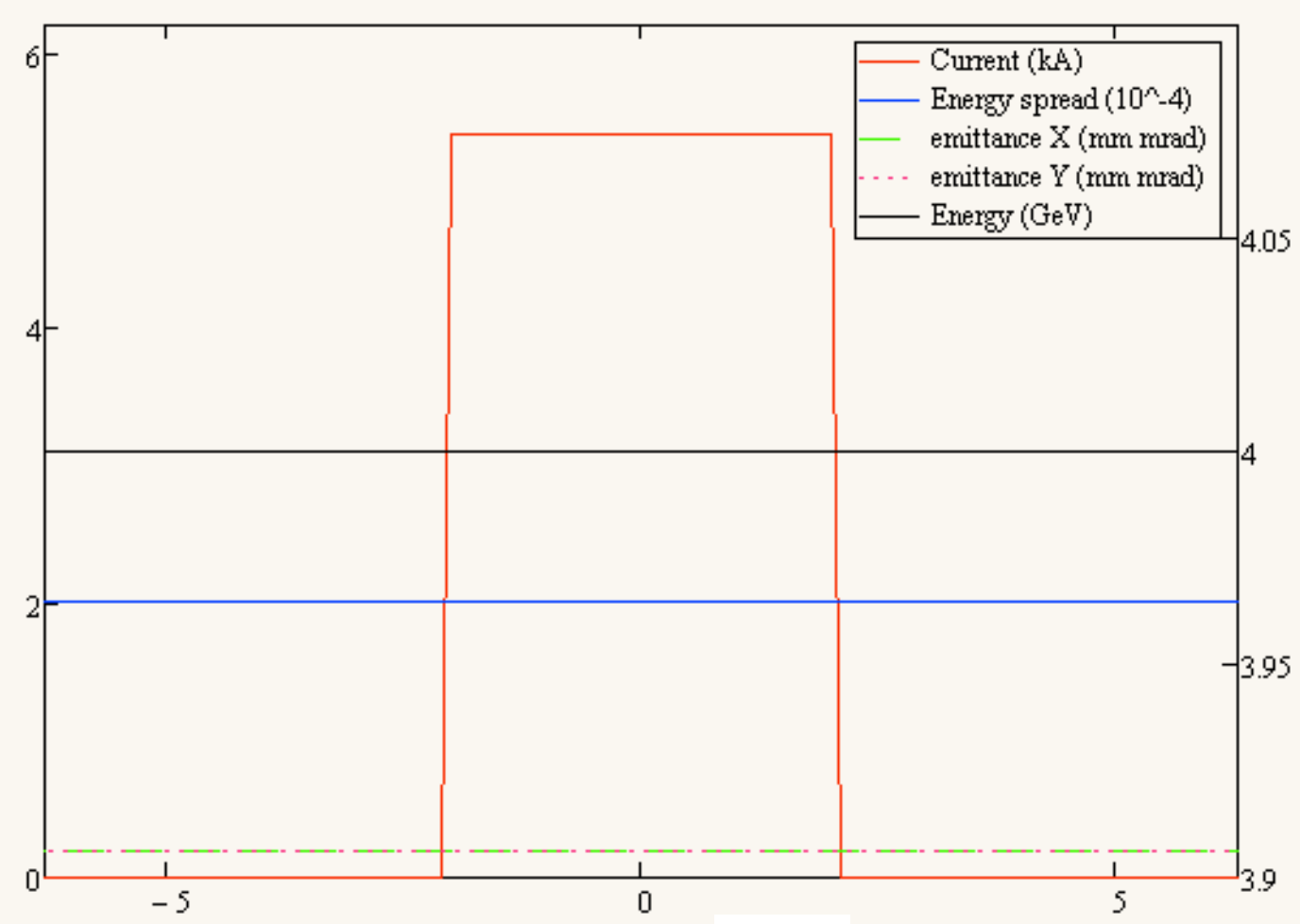
- Normalized emittance $\varepsilon_{nx} := 0.2 \cdot mm \cdot mrad$
- Normalized emittance $\varepsilon_{ny} := \varepsilon_{nx}$

Geom. emitt. $\varepsilon_g := \frac{\varepsilon_{nx}}{\gamma}$, $\varepsilon_g = 0.026 \cdot \mu m \cdot mrad$

- Electron bunch length $\sigma_z := 2.1 \cdot \mu m$ $\sigma_z = 2.1 \times 10^{-3} \cdot mm$

Total bunch charge Q = 75 pC

Soft X-ray beam from S. Di Mitri: uniform distributions



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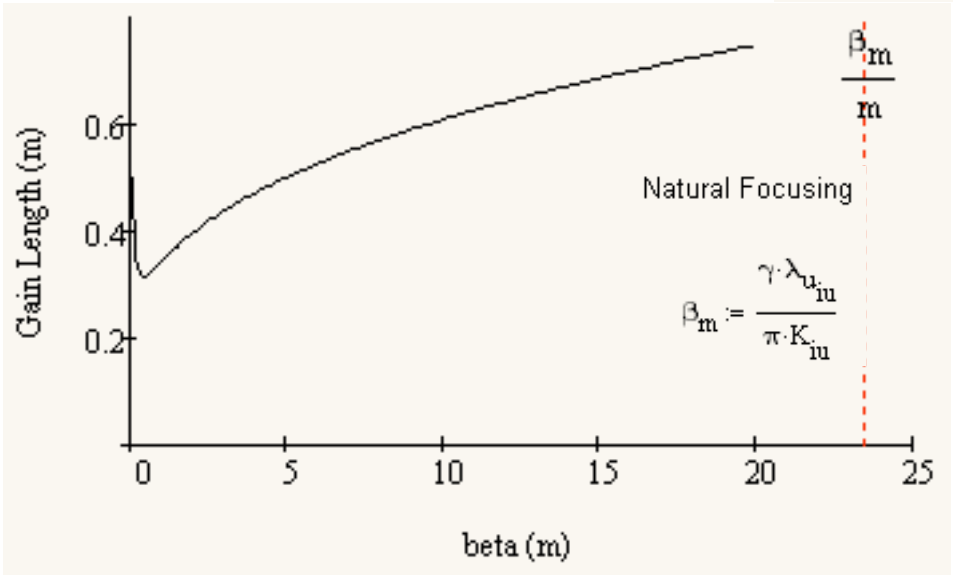
SX: undulator parameters

Undulator parameters	
undulator period	2.4 cm
undulator gap	6 mm
undulator strength K parameter	2.54

NdFeB In-vacuum undulator

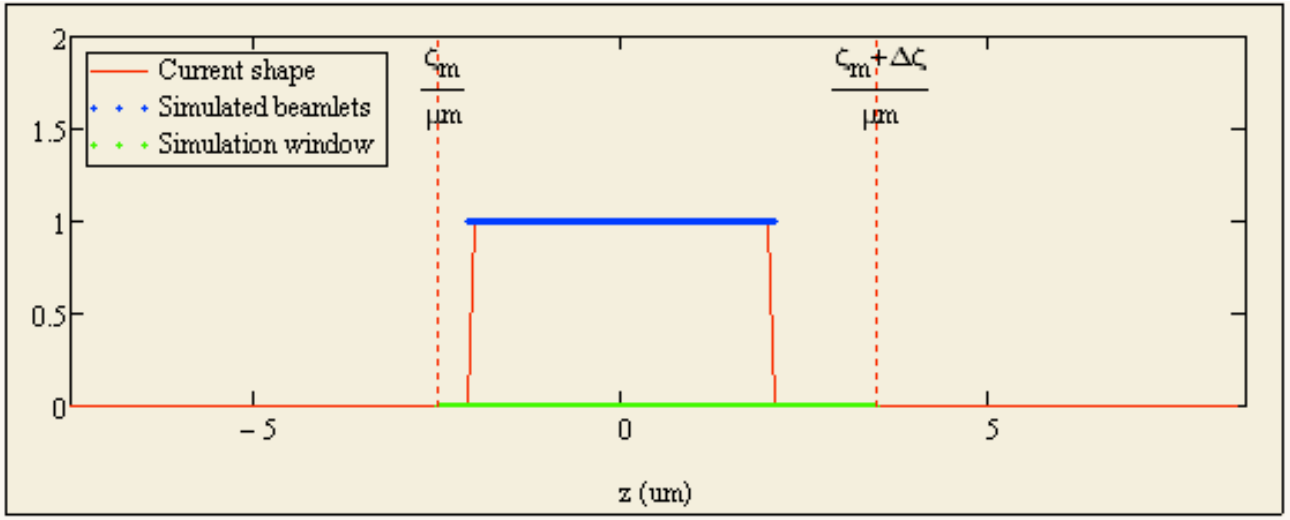
Undulator_Table =	
"Period (cm)"	2.4
"K"	2.54
"Length (m)"	50.4
"Wavelength (nm)"	0.828
"Photon Energy (eV)"	$1.498 \cdot 10^3$
"Periods"	$2.1 \cdot 10^3$
"Twiss beta (m)"	8
"g0"	$4.32 \cdot 10^4$
"Sat. Power (W)"	$1.191 \cdot 10^5$
"Beam Size (rms-um)"	14.297
"Shot Noise Power (W)"	$5.085 \cdot 10^3$
"Pierce parameter"	$2.255 \cdot 10^{-3}$

$\beta_m = 23.543\ m$



SX FEL results: tables

We have run the full time-dependent simulation to cover this current window



"Beam Energy (MeV):"	$4.000 \cdot 10^3$	"Position:"	"Saturation"
"I Peak (A)"	$5.400 \cdot 10^3$	"Wl. (nm)"	0.828
"En. Spread (%):"	0.020	"Ph_en (eV)"	$1.498 \cdot 10^3$
"Emittance (mm mrad)"	0.200	"z (m)"	11.494
"UM Section:"	1.000	"Energy (mJ)"	0.527
"Resonant wavelength(nm):"	0.828	"Duration (fs)"	4.085
"Gain Length (m)"	0.406	"Power (GW)"	51.483
"Saturation length (m):"	11.494	"Linewidth (%)"	0.201
0.000	0.000	"# phot"	$2.196 \cdot 10^{12}$
0.000	0.000	"Flux (ph./sec)"	$2.145 \cdot 10^{26}$
0.000	0.000	"Brtnss. (ph./sec/mmmrad^2/0.1%bw)"	$2.068 \cdot 10^{33}$

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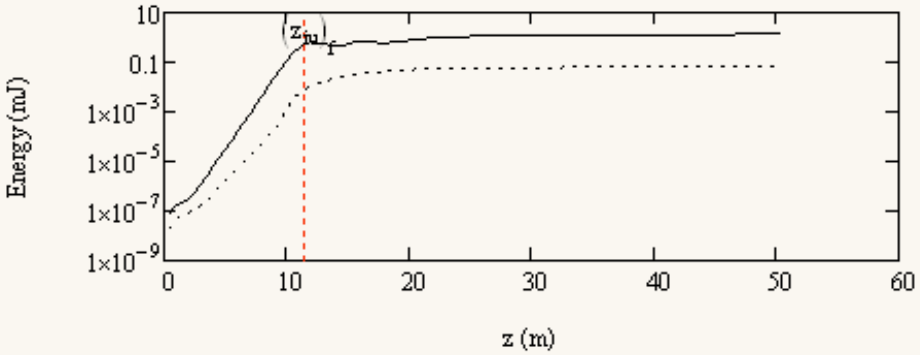
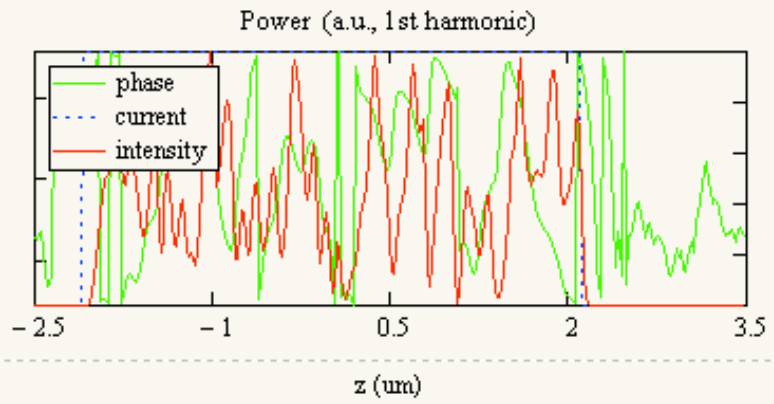
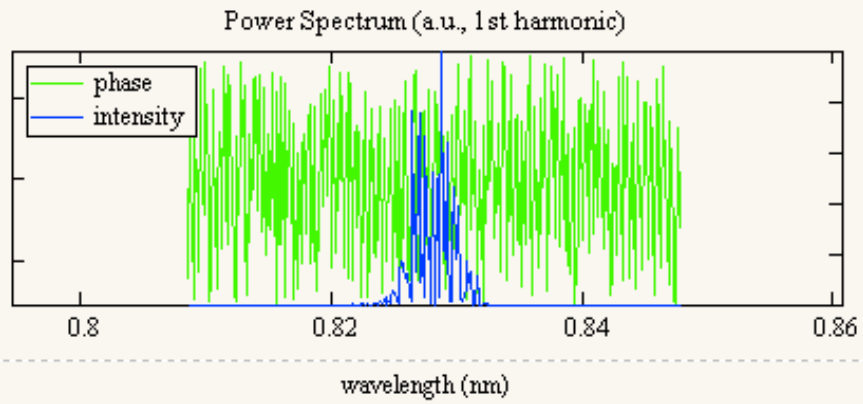
SX FEL results: profile, growth & spectrum

Parameters =

"Frame"	"23 of 100"	"Position (m)"	"11.592"
"Parameters@"	"1h"	"3h"	"5h"
"Energy (uJ)"	557.527	7.903	0.751
"length (rms, fs)"	4.091	3.933	3.993
"width (rms, %)"	0.202	0.606	1.01







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Tables to be circulated among XLS WP leaders

Input (i.e. beam and undulator) parameters similar to SwissFEL (see below), with improved performance

	Hard X-ray	Soft X-ray
Electron energy (GeV)	7	4
Bunch charge (pC)	75	75
Peak current (kA)	7.5	5.4
RMS bunch length (μm)	1.5	2.1
RMS matched beam spot (μm)	11	14
(Slice) energy spread (%)	0.015	0.02
(Slice) norm. emittance (μm)	0.2	0.2
Undulator period (mm)	13	24
Undulator K strength	1.49	2.54
Gain length (m)	0.76	0.41
Pierce ρ parameter (10^{-3})	0.86	2.26
Radiation wavelength (nm)	0.073	0.828
Photon energy (keV)	17	1.5
Undulator matching β_u (m)	8	8
Saturation active length (m)	15	11.5
Saturation power (GW)	45	51
Energy per pulse (μJ)	330	530
Photons per pulse (10^{10})	12	220

- Comprehensive one-value tables for both Hard and Soft X-ray FEL configurations are drawn at this 2nd iteration stage

- Parameter values are in the ballpark of the SwissFEL Concept Design Report tables, with improved light power and saturation length performance

- These 1D results describe uniform distributions: they target the "FEL slice definition" guiding the studies all the way back to the injector: "🡐"

- Then, at the "integrated CDR" stage, when also transverse dynamics and full 3D distributions are available, also full 3D FEL studies will be performed: "🡒" within a joint WP2+WP5+WP6 collaboration,

Soft X-Ray 🡐🡒 Uppsala Hard X-Ray 🡐🡒 ENEA+STFC

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Thank you!

CompactLight@elettra.eu

www.CompactLight.eu

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Comparison with SwissFEL

Number of FEL lines	2 (Aramis and Athos)
Undulator type, Aramis	In-vacuum permanent magnet with λ_U=15 mm
Wavelength range, Aramis FEL	1Å-7Å
Polarization, Aramis	Linear
Undulator type, Athos	Apple II permanent magnet with λ_U=40 mm
Wavelength range, Athos FEL	7Å-70Å
Polarization, Athos	Variable (circular, elliptical and linear)

Performance of Aramis for 5.8 GeV electron energy and 1Å lasing wavelength	
Maximum saturation length (m)	50
Saturation pulse energy (μJ)	60
Effective saturation power (GW)	2
Photon pulse length at 1 Å (fs, rms)	13
Number of photons at 1 Å ($\times 10^9$)	31

Performance of Athos (SASE) For example at 3.4 GeV electron energy and 2.8 nm lasing wavelength	
Maximum saturation length (m)	22 m
Saturation pulse energy (μJ)	360
Effective saturation power (GW)	11.2
Photon pulse length (fs, rms)	13
Number of photons ($\times 10^9$)	5000

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Hard X-ray beam from S. Di Mitri

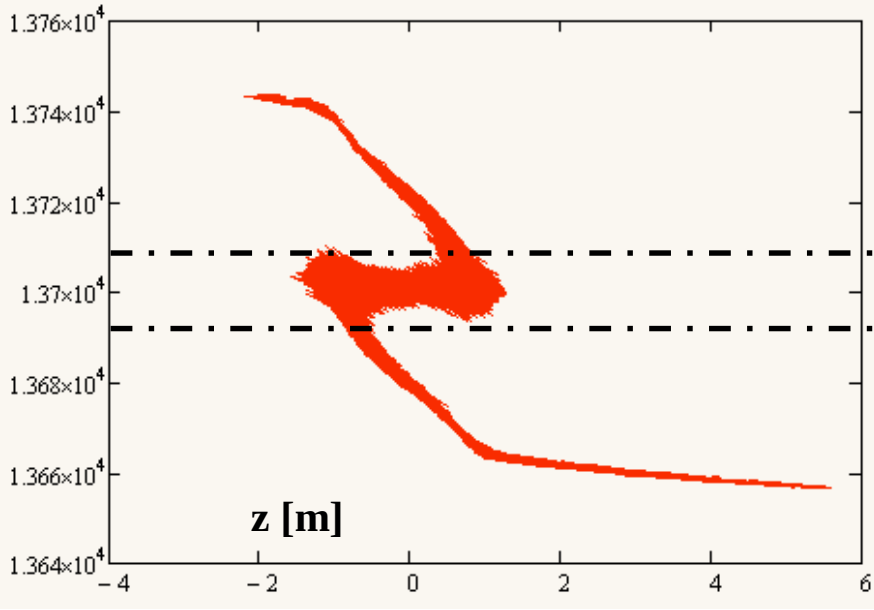
Beam parameters at the FEL undulator:

- Beam Energy $E := 7 \cdot GeV$ $\gamma := \frac{E}{m_0 \cdot c^2}$
- Peak current $I_{peak} := 15000 \cdot A$
- Relative Energy Spread (Slice) $\sigma_\varepsilon := 1.5 \cdot 10^{-4}$ Energy spread $E \cdot \sigma_\varepsilon = 1.05 \times 10^{3} \cdot keV$

- Normalized emittance $\varepsilon_{nx} := 0.2 \cdot mm \cdot mrad$
- Normalized emittance $\varepsilon_{ny} := \varepsilon_{nx}$ Geom. emitt. $\varepsilon_g := \frac{\varepsilon_{nx}}{\gamma}$, $\varepsilon_g = 0.015 \cdot \mu m \cdot mrad$
- Electron bunch length $\sigma_z := 0.9 \cdot \mu m$ $\sigma_z = 9 \times 10^{-4} \cdot mm$

Total bunch charge = 75 pC

100k macroparticles with given z, E



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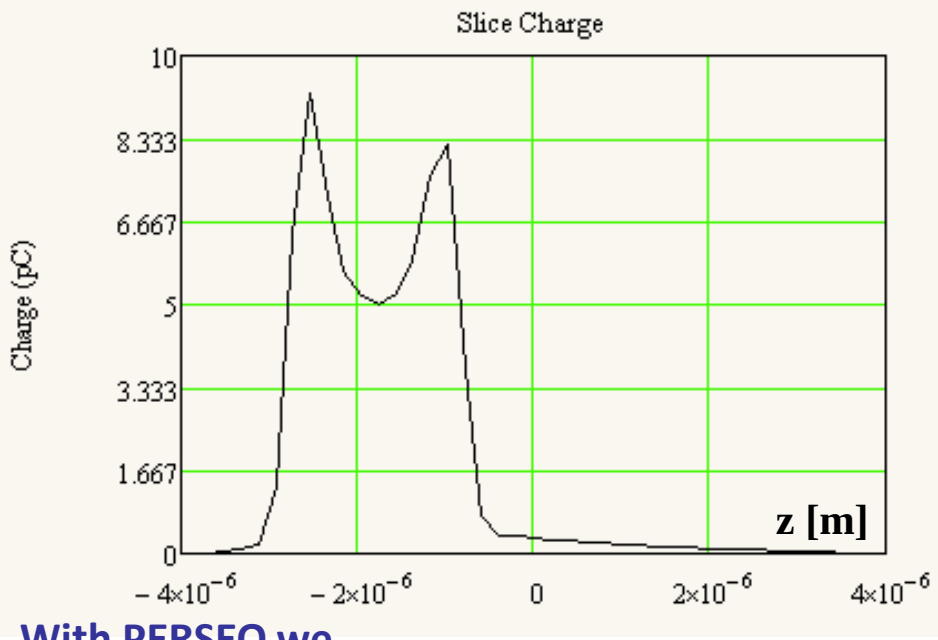
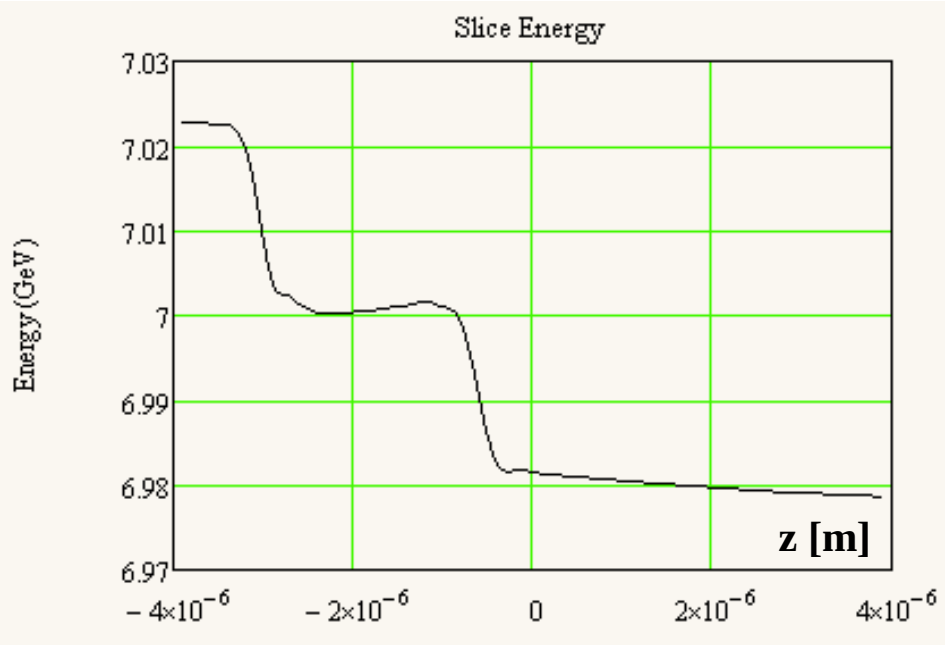
HX: slice energy and current parameterisations

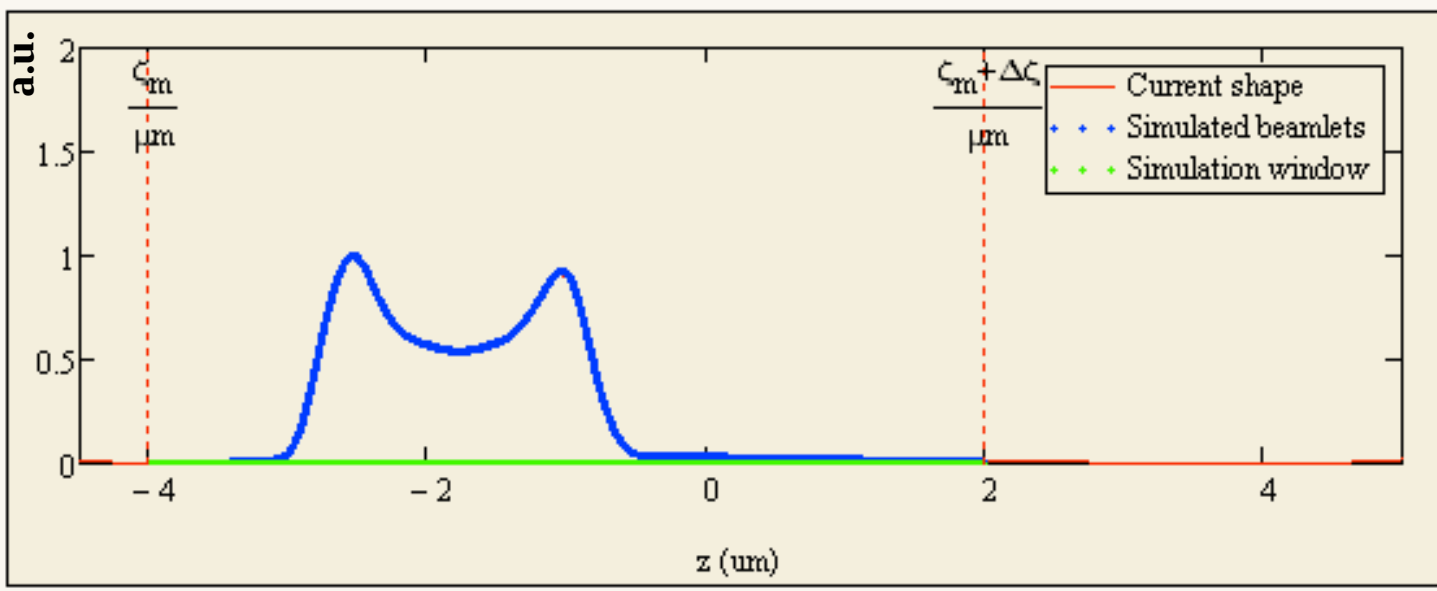
Compact





With PERSEO we analysed the slice energy spread parameterisation clipping the long off-energy tails

We run the full time-dependent simulation to cover the current window



Federico Nguyen
ENEA
Italian National Agency for New Technologies, Energy and Sustainable Economic Development

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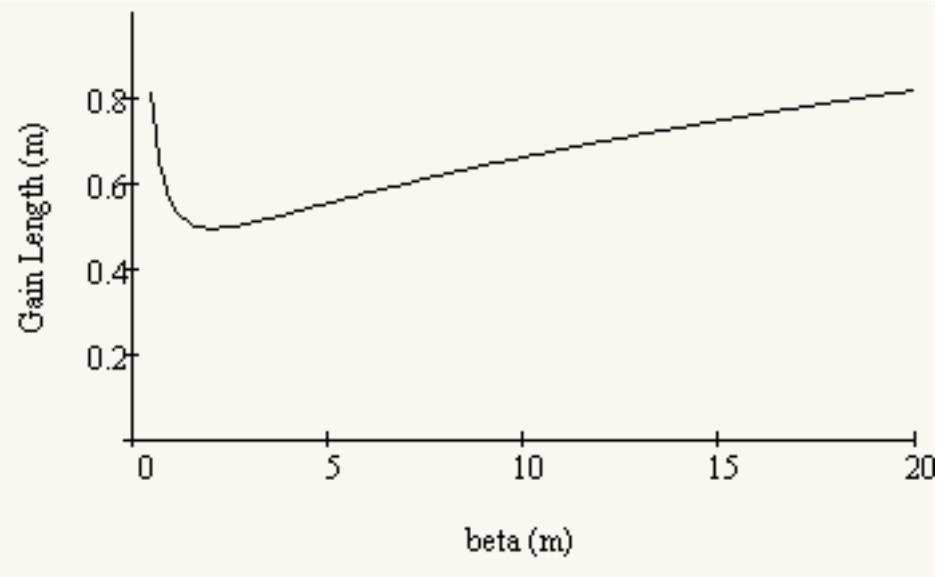
HX: undulator parameters

Undulator parameters	
undulator period	1.3 cm
undulator gap	3 mm
undulator strength K parameter	1.49

NdFeB In-vacuum undulator

"Period (cm)"	1.3
"K"	1.49
"Length (m)"	27.3
"Wavelength (nm)"	0.073
"Photon Energy (eV)"	$1.696 \cdot 10^{4}$
"Periods"	$2.1 \cdot 10^{3}$
"Twiss beta (m)"	8
"g0"	$6.027 \cdot 10^{3}$
"Sat. Power (W)"	$4.148 \cdot 10^{6}$
"Beam Size (rms-um)"	10.807
"Shot Noise Power (W)"	$2.404 \cdot 10^{4}$
"Pierce parameter"	$1.081 \cdot 10^{-3}$



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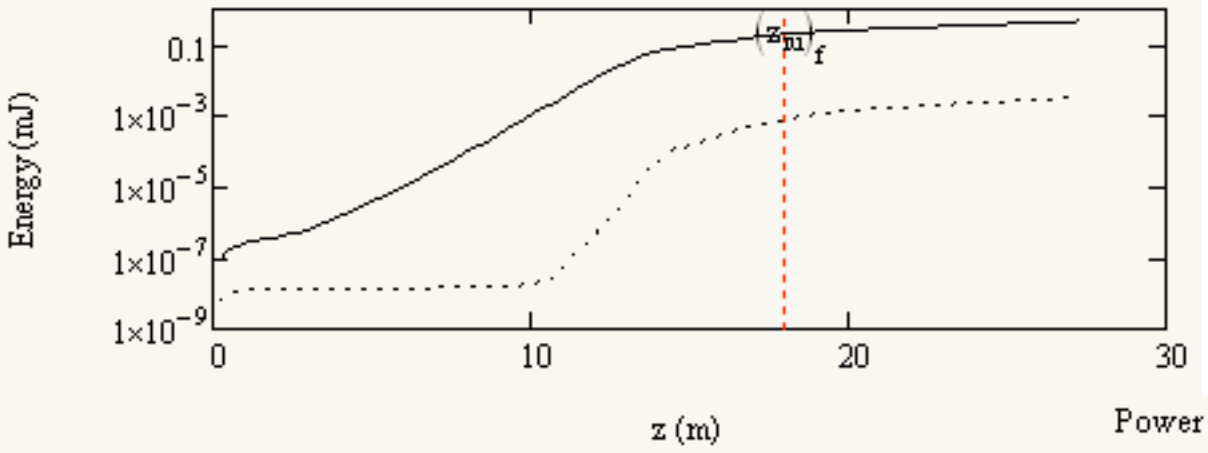
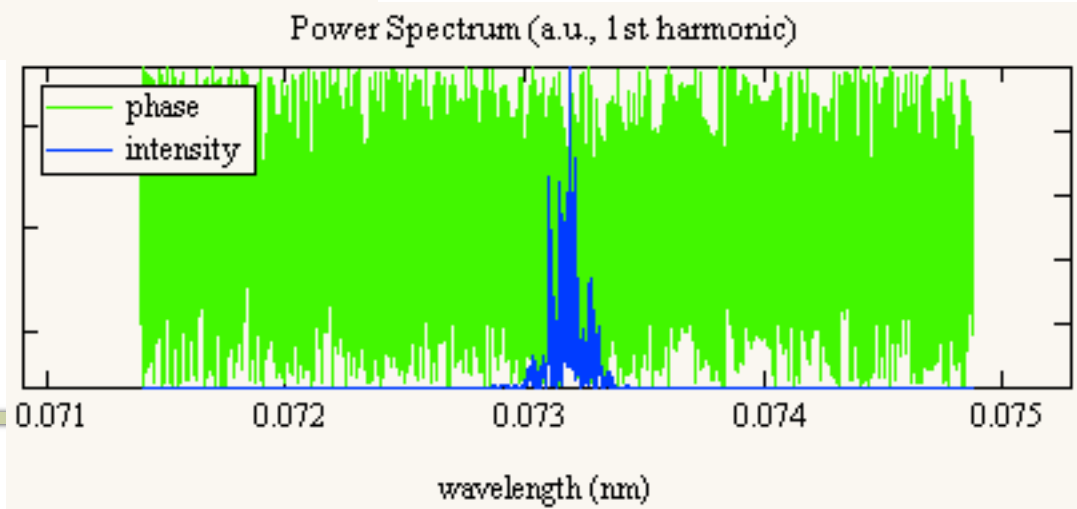
1D-FEL time dependent with slice E, σ_ε parameterisations

Compact

"Beam Energy (MeV):"	$7.000 \cdot 10^3$	"Position:"	"Saturation"
"I Peak (A)"	$1.500 \cdot 10^4$	"Wl. (nm)"	0.073
"En. Spread (%):"	0.010	"Ph_en (eV)"	$1.696 \cdot 10^4$
"Emittance (mm mrad)"	0.200	"z (m)"	18.015
"UM Section:"	1.000	"Energy (mJ)"	0.196
"Resonant wavelength(nm):"	0.073	"Duration (fs)"	2.317
"Gain Length (m)"	0.816	"Power (GW)"	33.707
"Saturation length (m):"	18.015	"Linewidth (%)"	0.107
0.000	0.000	"# phot"	$7.204 \cdot 10^{10}$





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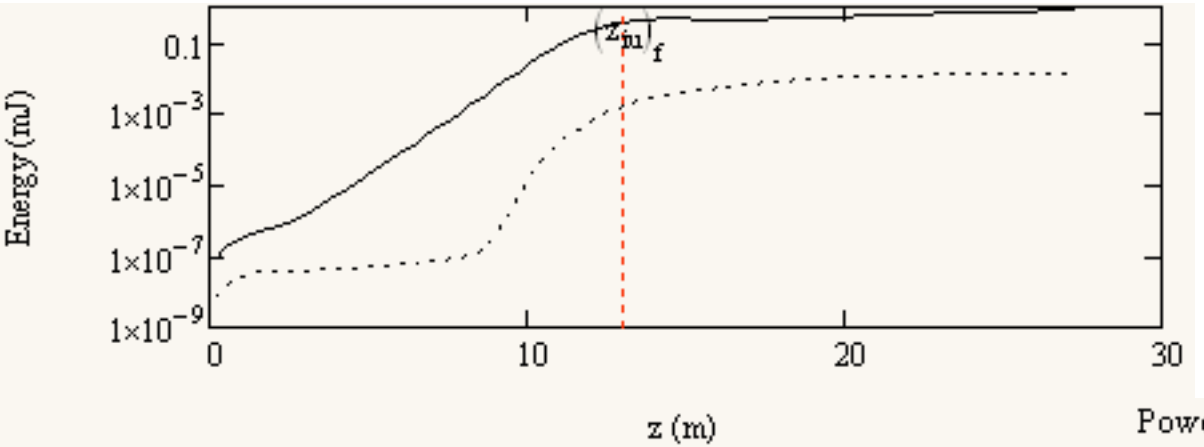
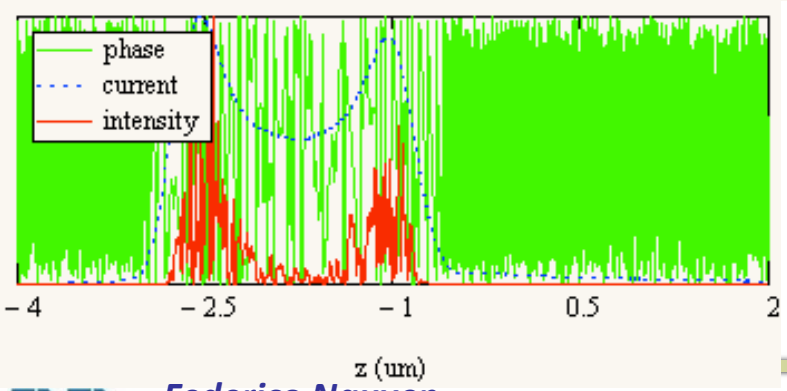
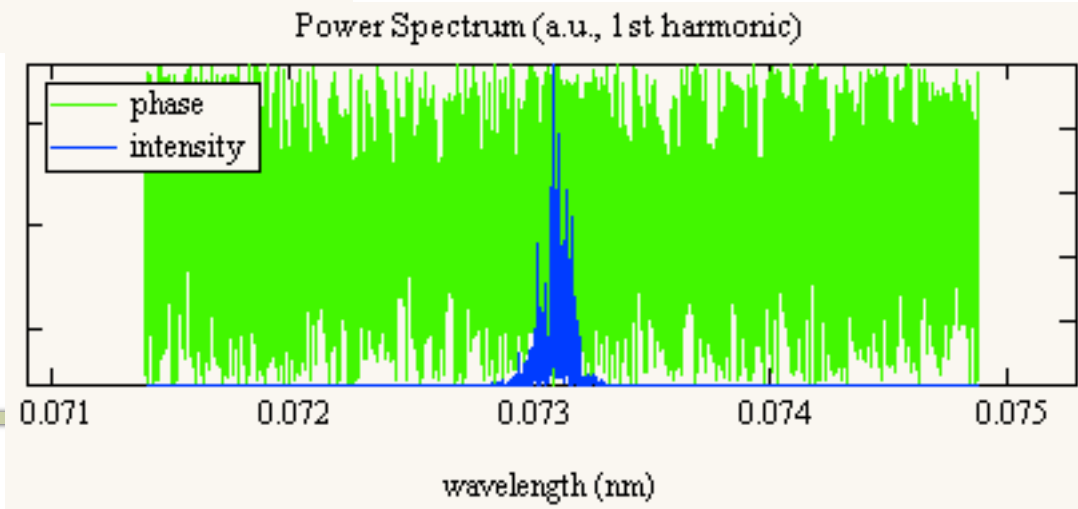
1D-FEL time dependent with $\sigma_\varepsilon = 1.5 \times 10^{-4}$

Compact

"Beam Energy (MeV):"	$7.000 \cdot 10^3$	"Position:"	"Saturation"
"I Peak (A)"	$1.500 \cdot 10^4$	"Wl. (nm)"	0.073
"En. Spread (%):"	0.010	"Ph_en (eV)"	$1.696 \cdot 10^4$
"Emittance (mm mrad)"	0.200	"z (m)"	13.169
"UM Section:"	1.000	"Energy (mJ)"	0.391
"Resonant wavelength(nm):"	0.073	"Duration (fs)"	2.155
"Gain Length (m)"	0.611	"Power (GW)"	72.373
"Saturation length (m):"	13.169	"Linewidth (%)"	0.096
0.000	0.000	"# phot"	$1.438 \cdot 10^{11}$







Federico Nguyen
ENEA
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Soft X-ray beam from S. Di Mitri

Beam parameters at the FEL undulator:

- Beam Energy $E := 4 \cdot GeV$ $\gamma := \frac{E}{m_0 \cdot c^2}$
- Peak current $I_{peak} := 5400 \cdot A$
- Relative Energy Spread (Slice) $\sigma_\varepsilon := 2 \cdot 10^{-4}$ Energy spread $E \cdot \sigma_\varepsilon = 800 \cdot keV$

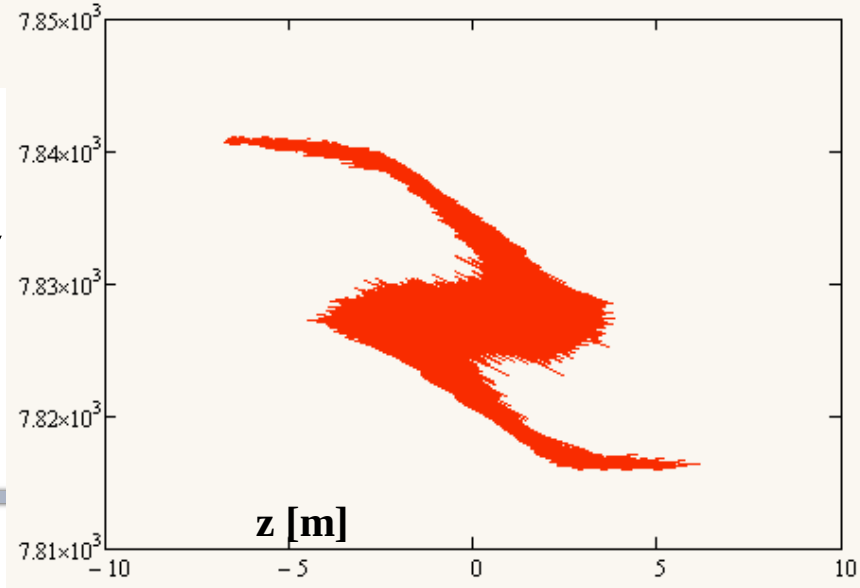
- Normalized emittance $\varepsilon_{nx} := 0.2 \cdot mm \cdot mrad$
- Normalized emittance $\varepsilon_{ny} := \varepsilon_{nx}$

Geom. emitt. $\varepsilon_g := \frac{\varepsilon_{nx}}{\gamma}$, $\varepsilon_g = 0.026 \cdot \mu m \cdot mrad$

- Electron bunch length $\sigma_z := 1.6 \cdot \mu m$ $\sigma_z = 1.6 \times 10^{-3} \cdot mm$

Total bunch charge = 75 pC

100k macroparticles with given z, E



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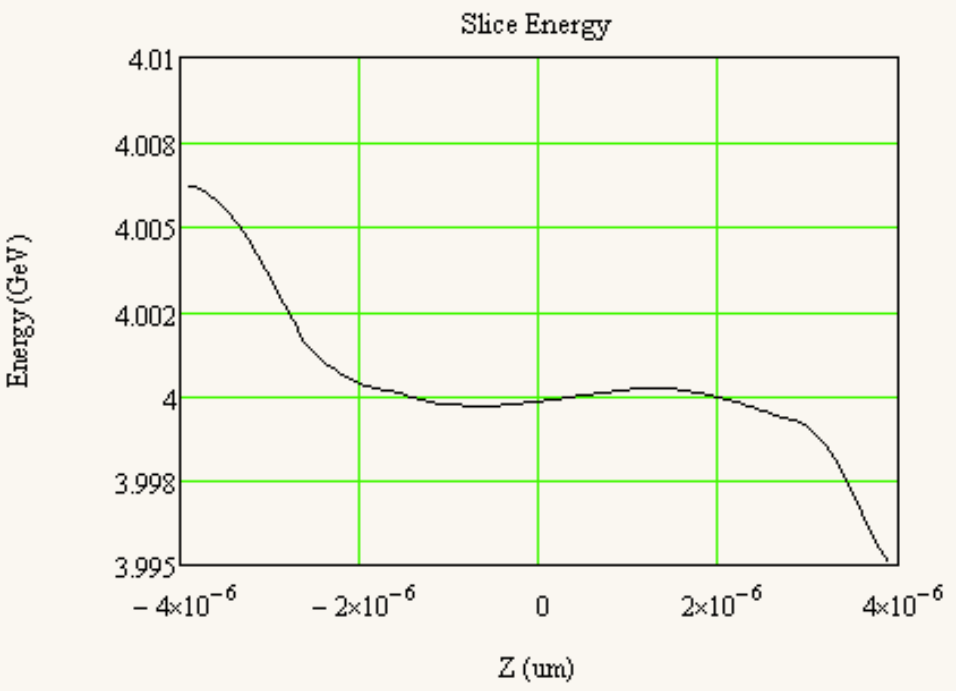
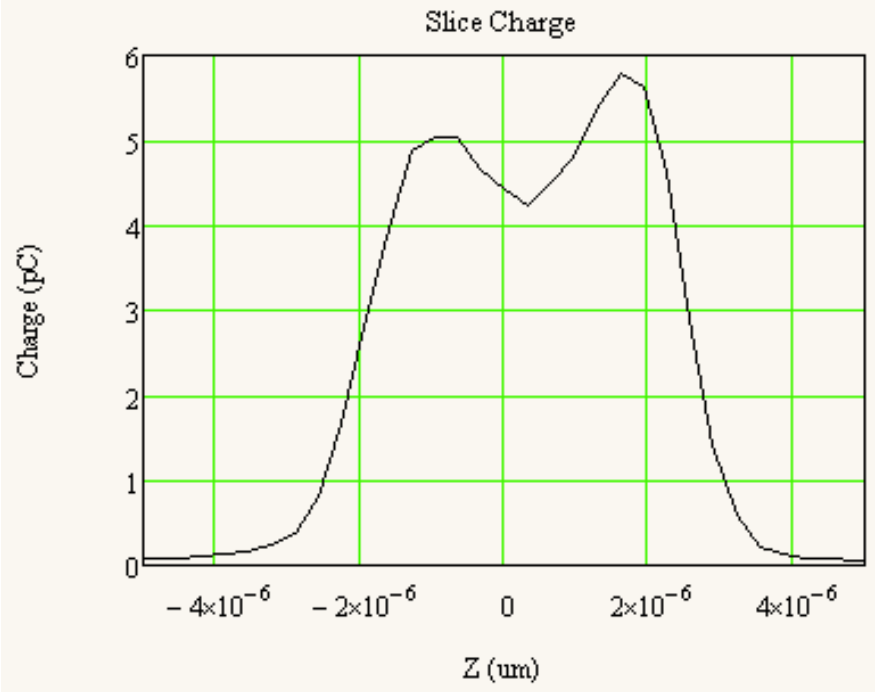
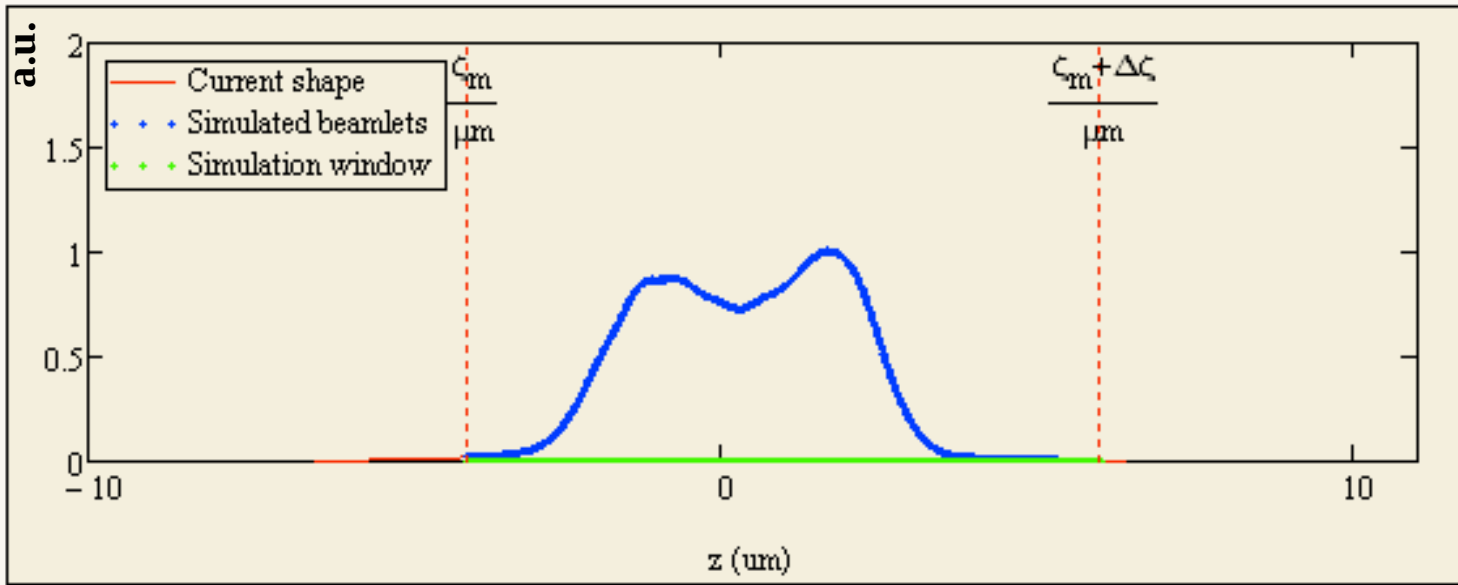
SX: slice energy and current parameterisations

Compact





We run the PERSEO simulation to cover the current window



Federico Nguyen
ENEA
Italian National Agency for New Technologies, Energy and Sustainable Economic Development

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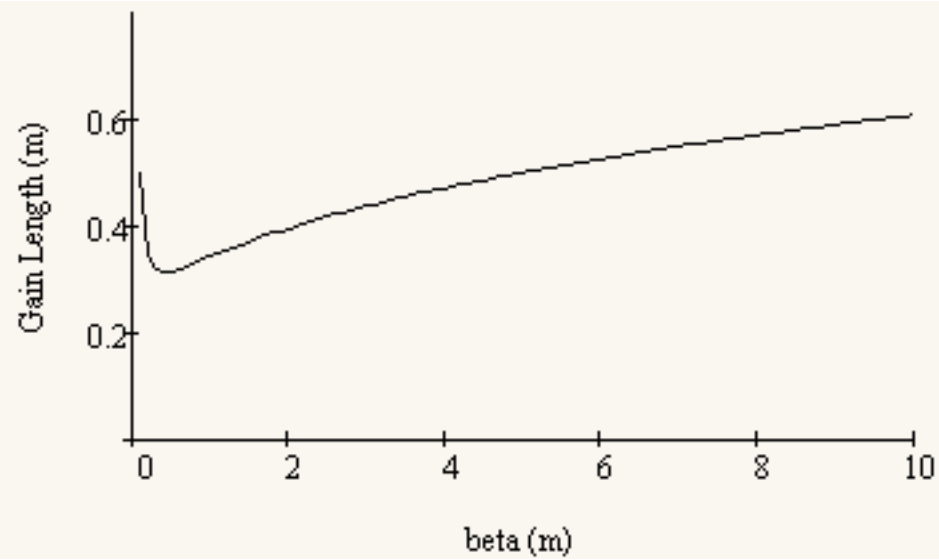
SX: undulator parameters

Undulator parameters	
undulator period	2.4 cm
undulator gap	6 mm
undulator strength K parameter	2.54



NdFeB In-vacuum undulator

"Period (cm)"	2.4
"K"	2.54
"Length (m)"	33.6
"Wavelength (nm)"	0.828
"Photon Energy (eV)"	$1.498 \cdot 10^{3}$
"Periods"	$1.4 \cdot 10^{3}$
"Twiss beta (m)"	8
"g0"	$1.28 \cdot 10^{4}$
"Sat. Power (W)"	$6.027 \cdot 10^{5}$
"Beam Size (rms-um)"	14.297
"Shot Noise Power (W)"	$5.085 \cdot 10^{3}$
"Pierce parameter"	$2.255 \cdot 10^{-3}$

Remark: not yet fully investigated whether this configuration could provide efficient Two-Colours operation

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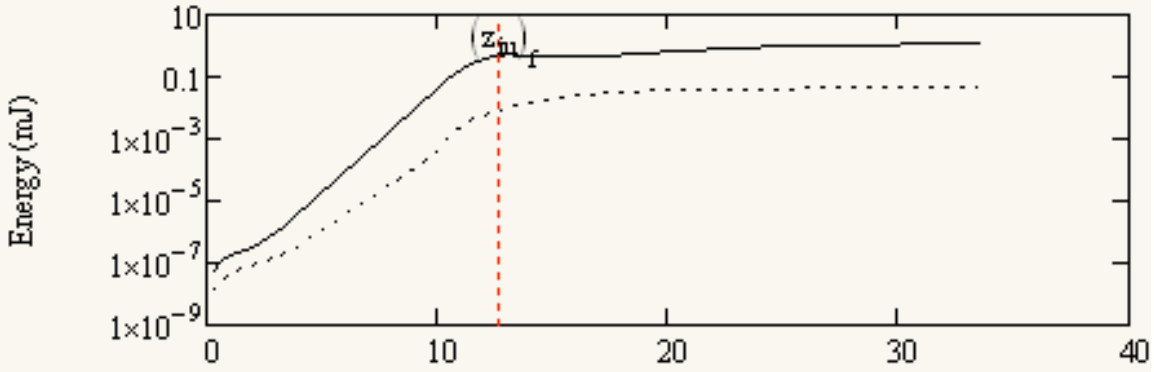
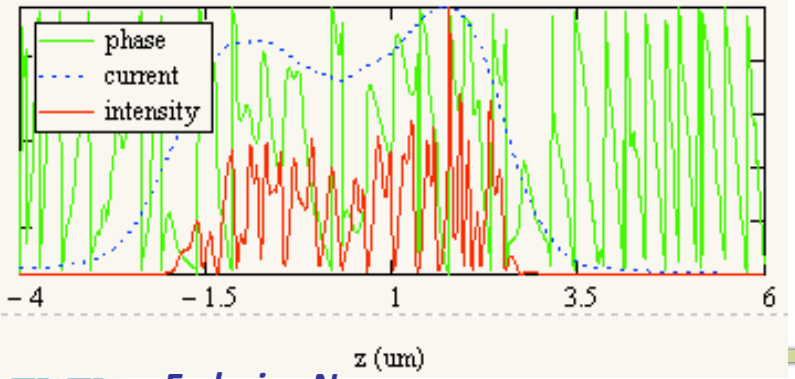
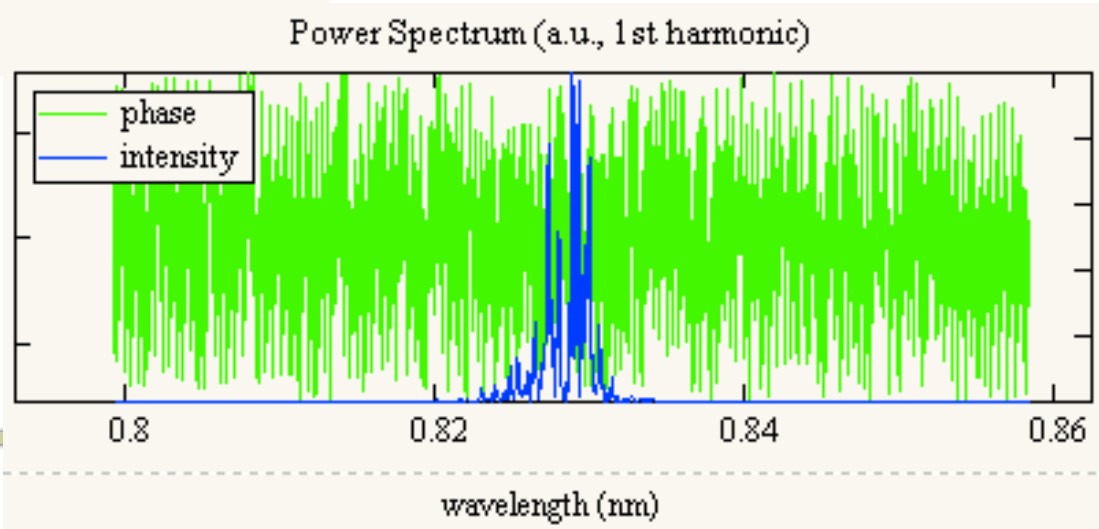
1D-FEL time dependent with $\sigma_\varepsilon = 2 \times 10^{-4}$

Compact

"Beam Energy (MeV):"	$4.000 \cdot 10^3$	"Position:"	"Saturation"
"I Peak (A)"	$5.400 \cdot 10^3$	"Wl. (nm)"	0.828
"En. Spread (%):"	0.020	"Ph_en (eV)"	$1.498 \cdot 10^3$
"Emittance (mm mrad)"	0.200	"z (m)"	12.616
"UM Section:"	1.000	"Energy (mJ)"	0.490
"Resonant wavelength(nm):"	0.828	"Duration (fs)"	4.022
"Gain Length (m)"	0.520	"Power (GW)"	48.613
"Saturation length (m):"	12.616	"Linewidth (%)"	0.213
0.000	0.000	"# phot"	$2.042 \cdot 10^{12}$







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ENEA
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Tables to be circulated among XLS WP leaders

Compact

Input (i.e. beam and undulator) parameters similar to SwissFEL (see below), with improved performance

	Hard X-ray	Soft X-ray
Electron energy (GeV)	7	4
Bunch charge (pC)	75	75
Peak current (kA)	15	5.4
RMS energy spread (%)	0.098	0.049
RMS bunch length (fs)	3	5
RMS matched beam spot (μm)	11	14
RMS norm. emittance (μm)	0.6	0.6
Slice length (μm)	0.2	0.4
Slice energy spread (%)	0.015	0.02
Slice norm. emittance (μm)	0.2	0.2
Undulator period (mm)	13	24
Undulator K strength	1.49	2.54
Gain length (m)	0.63	0.5
Pierce ρ parameter (10^{-3})	1.08	2.26
Radiation wavelength (nm)	0.073	0.828
Photon energy (keV)	17	1.5
Undulator matching β_u (m)	8	8
Saturation active length (m)	13.2	12.6
Saturation power (GW)	70	49
Energy per pulse (μJ)	380	490
Photons per pulse (10^{10})	14	200

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Conclusions

- Comprehensive one-value tables for both Hard and Soft X-ray FEL configurations are drawn at this 1st iteration stage

- Parameter values are in the ballpark of the SwissFEL Concept Design Report tables, with improved light power and saturation length performance

- These 1D FEL results describe the longitudinal dynamics details, guiding the studies all the way back to the injector: "←"

- Then, at a later stage, when also transverse dynamics and full 3D distributions are available, also full 3D FEL studies will be performed: "→" within a joint WP2+WP5+WP6 collaboration,

Soft X-Ray ←→ Uppsala

Hard X-Ray ←→ ENEA+STFC