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WP6: FEL Pilot Application – Update on FEL Results

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EuPRAXIA Retreat in the Bavarian Alps

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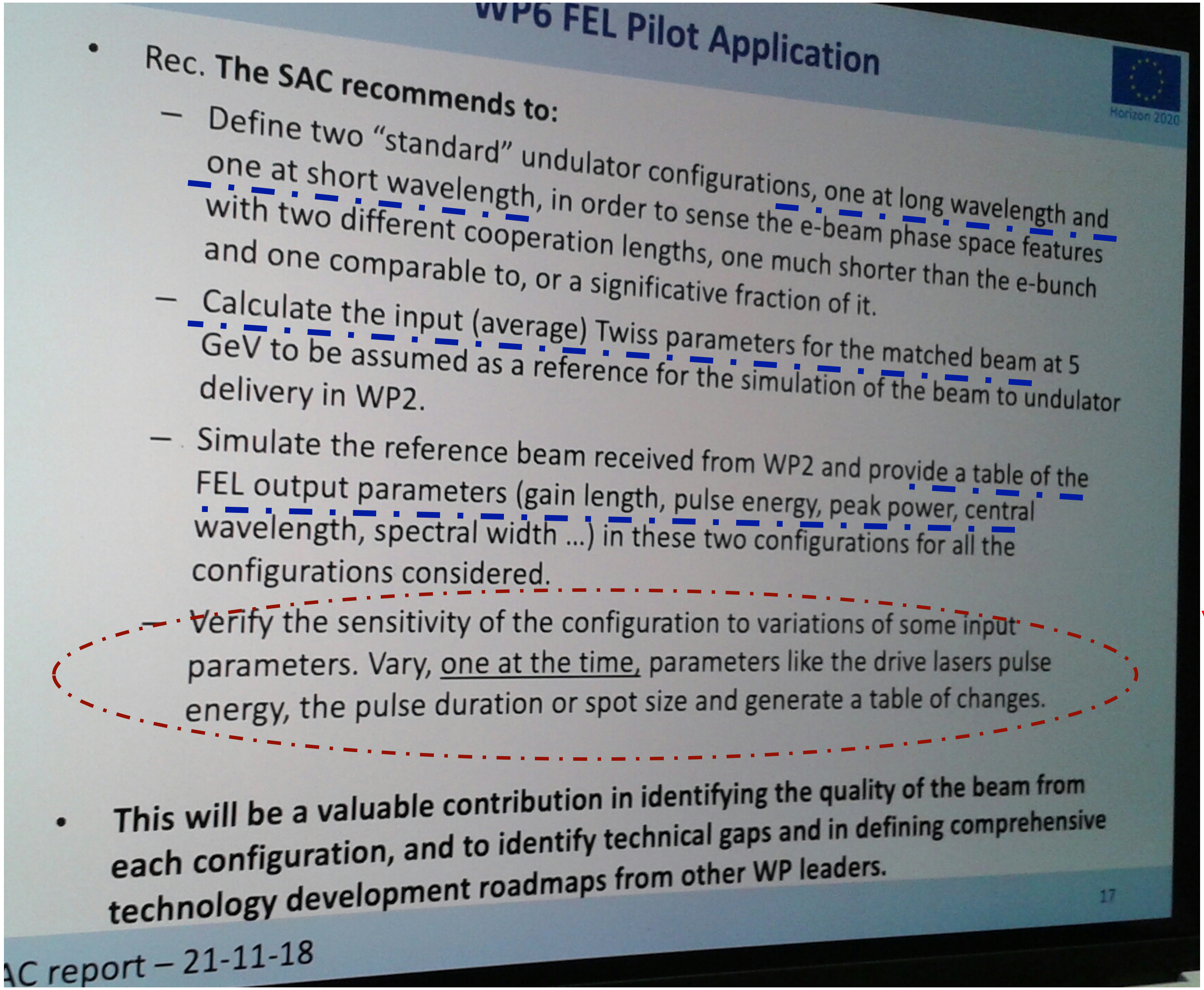
An outline

- Brief reminder of the SAC recommendations: how we addressed and implemented their suggestions
- Identification of a long FEL wavelength λ_R working point
- The periodic undulator lattice: the matching schemes for the beam distributions we analyzed
- FEL Results from analytical calculations and PERSEO simulations with longitudinal dynamics details: focus on the long wavelength working point
- Outlook and perspectives in view of the CDR

Reminder of the SAC recommendations to WP6



These variations refer to WP2 +WP4 parameters, in addition to plasma density, laser frequency, etc…
Not to any FEL WP6 parameter

Remark on the long λ_R choice

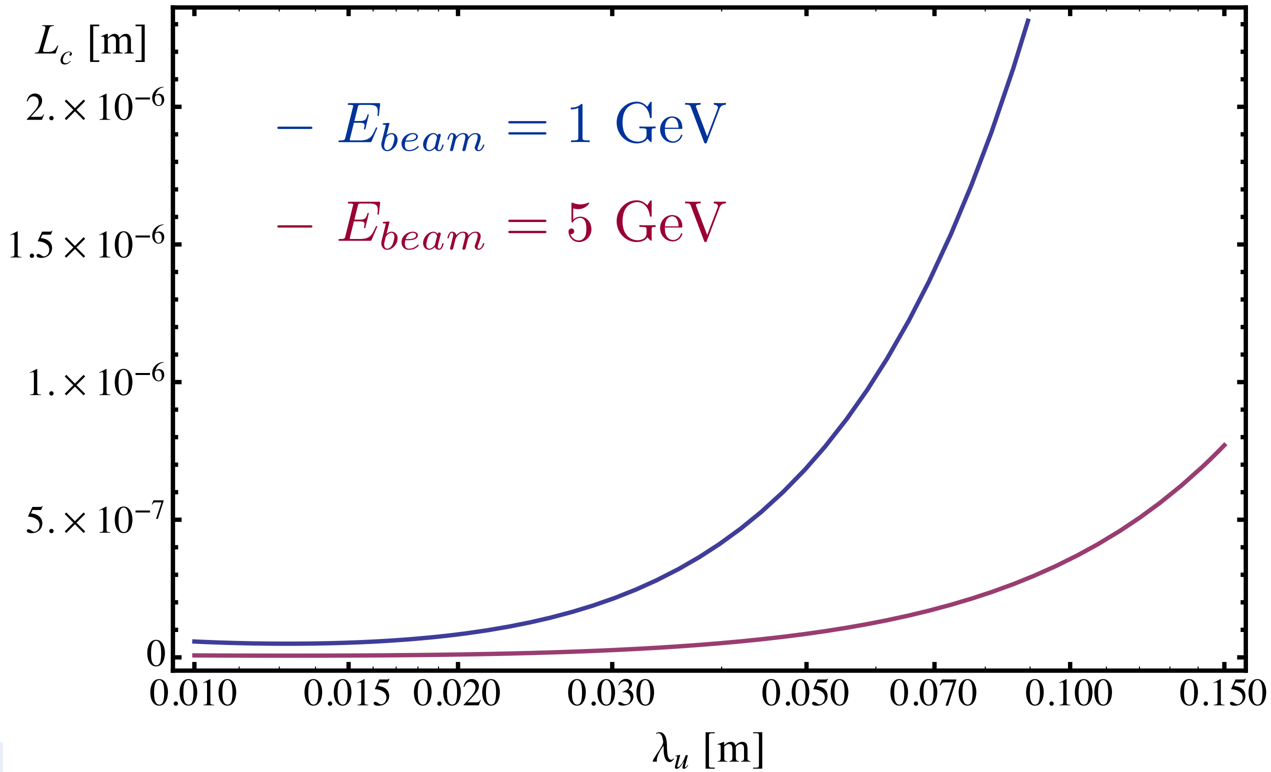
Horizon 2020

With the beam distributions under analysis, very hard for the cooperation length L_c to approach the bunch length, for sensible undulator period λ_u values:

$$L_c = \frac{\lambda_R(\lambda_u)}{4\pi\sqrt{3}\rho(\lambda_u)} \ll \sigma_z \sim \mathcal{O}(3\,\mu m)$$

where both resonant wavelength and Pierce parameter ρ depend on λ_u and on E_{beam}

For the cooperation length to reach for a relevant fraction of the bunch length, it takes extremely too long an undulator period!!!



Two working points per E_{beam} value

Horizon 2020

We decided parameters such that L_c ~ O(1%) @ 5 GeV and ~ O(0.1) @ 1 GeV of the bunch length, in the long λ_R configurations

These values are within reach with present technology, for both in-vacuum and cryogenic permanent magnet undulators, assuming gap = 6 mm or longer, to be less sensitive to wakefield deteriorating effects inside undulators

E_{beam} (GeV)	Wavelength (nm)	Und. period (mm)	K	B_{peak}
5	0.13	15	1.2	0.84
5	1.65	30	4.36	1.56
1	3.3	15	1.2	0.84
1	41	30	4.36	1.56

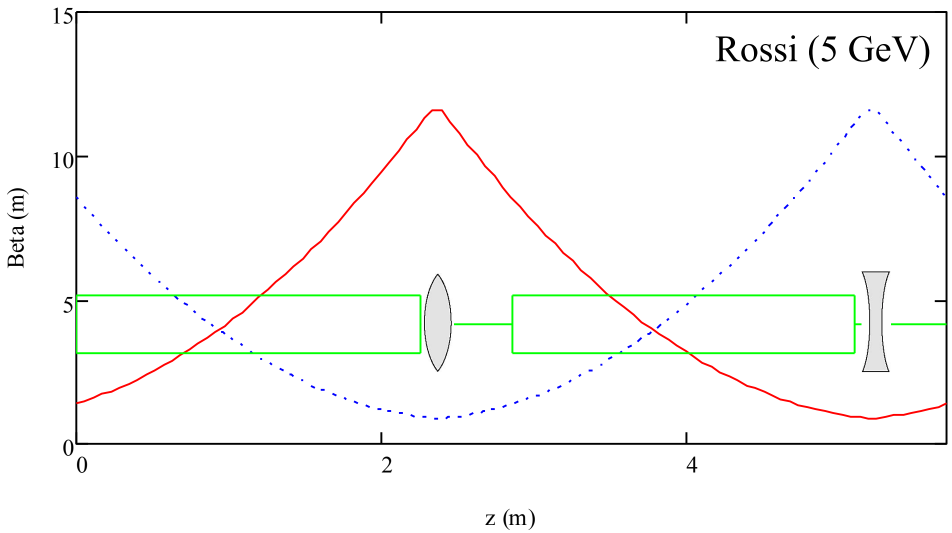
Also within the long undulator period/cooperation length configurations
→ we wish to probe short wavelengths

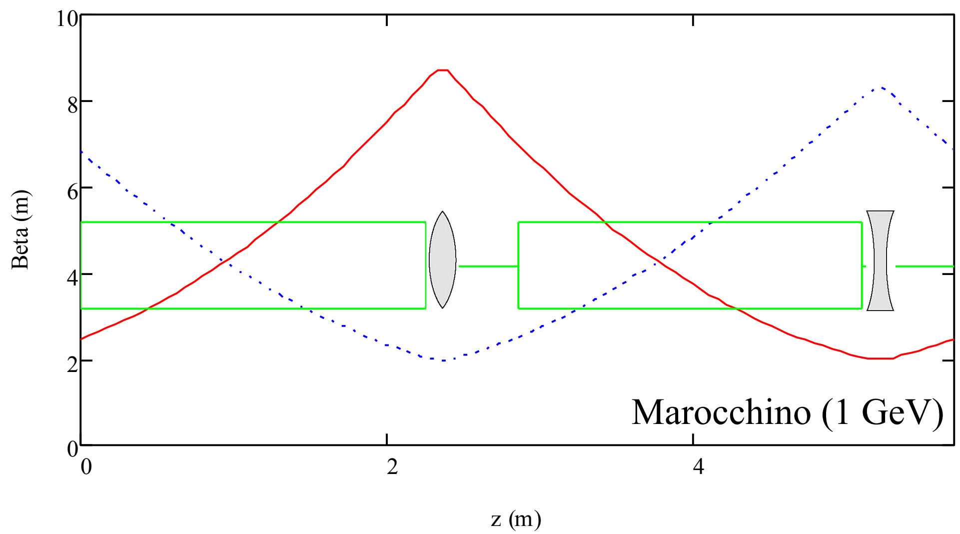
Matching scheme: short λ_R target

Matching implemented by A. Petralia

Short wavelength – Undulator: period $\lambda_u = 1.5$ cm, module length $L_u = 2.25$ m						
Beam distribution name (E_{beam})	average $\beta_{x,y}$ $\langle\beta_x\rangle = \langle\beta_y\rangle$ [m]	at undulator entrance β_x [m]	β_y [m]	α_x	α_y
Rossi (5 GeV)	4.5	1.394	8.582	-0.817	3.045
Tomassini (5 GeV)	4.5	2.201	7.357	-0.737	0.695
Rossi (1 GeV)	4.5	2.46	6.844	-0.675	1.54
Marocchino (1 GeV)	4.5	2.473	6.819	-0.672	1.518

We searched for the minimum reasonable average $\beta_{x,y}$ values, also featuring reasonable magnetic gradients → we would like the beams to be transported to these α, β values



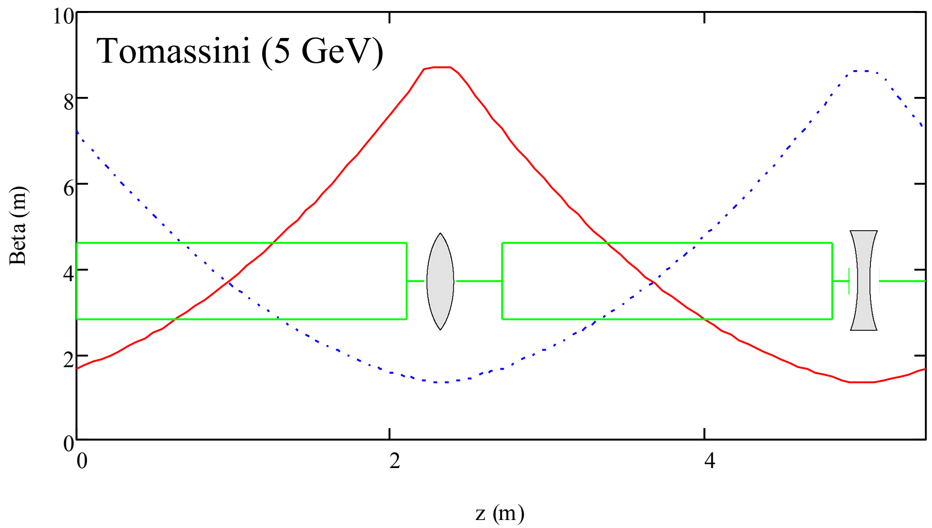


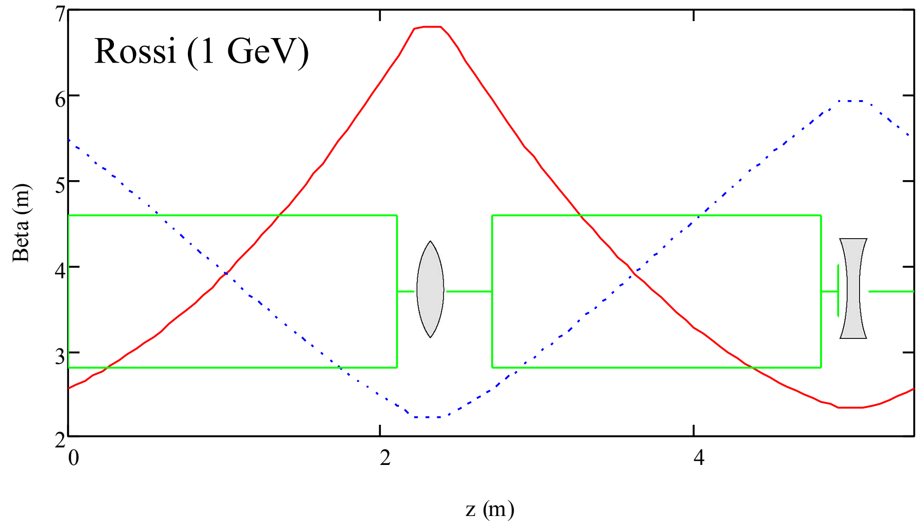
Matching scheme: long λ_R target

Long wavelength – Undulator: period $\lambda_u = 3$ cm, module length $L_u = 2.1$ m						
Beam distribution name (E_{beam})	average $\beta_{x,y}$ $\langle\beta_x\rangle = \langle\beta_y\rangle$ [m]	at undulator entrance β_x [m]	β_y [m]	α_x	α_y
Rossi (5 GeV)	5	8.672	0.74	2.463	-0.772
Tomassini (5 GeV)	4	1.666	7.225	-0.643	2.227
Rossi (1 GeV)	4	2.553	5.476	-0.438	0.717
Marocchino (1 GeV)	4	2.611	5.39	-0.419	0.65

Matching implemented by A. Petralia

We searched for the minimum reasonable average $\beta_{x,y}$ values, also featuring reasonable magnetic gradients → we would like the beams to be transported to these α, β values





Strategy: now and CDR

We are sending these tables to A. Chancé & WP5, for the beams at the plasma exit to be transported and reach these Twiss parameters at the undulator entrance

These values are obtained analyzing the best charge density slice out of the distributions at the plasma exit

Best charge density slice at plasma exit – slice parameter values							
Name	E_{beam} [GeV]	I_{peak} [A]	$\delta\gamma/\gamma$ [%]	$\epsilon_{n,x}$ [μm]	$\epsilon_{n,y}$ [μm]	σ_x^{RMS} [μm]	σ_y^{RMS} [μm]
Rossi–5	5.406	2853	0.046	0.376	0.32	1.06	0.98
Tomassini–5	4.922	1782	0.143	0.099	0.103	0.42	0.43
Rossi–1	1.091	1881	0.092	0.4	0.41	2.2	2.2
Marocchino–1	1.066	8747	0.098	0.67	0.59	0.83	0.98

Is the transport optics deployed to preserve the best slice parameters also effective to other slices cooperating to lase? Work in iterative progress for the CDR (see G. Dattoli)

While converging to optimally matched beams at undulator, we performed analytical and 1D (longitudinal dynamics only) estimates on the already transported beams

Transport criteria already available

We assumed <$\beta_{x,y}$> values along the undulator line and evaluated the best slice FEL performance with analytical scaling laws and `Perseo` *(FEL sim. toolkit from L. Giannessi)*

Transport implemented by A. Chancé

Input

- Total length: from 4 meters to 8 meters.
- Min: 30 mm between PMQs, 100 mm between EMQs, 50 mm after plasma.
- Length PMQ: 100 mm, length EMQ: 400 mm
- 2-8 PMQs and 4 EMQs.
- Maximum gradient of 700 T/m PMQs and 100 T/m in the EMQs.

Variables

- Gradient and positions of the quadrupoles.

Constraints

- Final Twiss parameters.
  $\beta_{x,1} = 5.04$ m, $\beta_{y,1} = 2.11$ m, $\alpha_{x,1} = 1.48$, $\alpha_{y,1} = -0.65$
- Minimisation of the emittance growth

Beam properties along the undulator

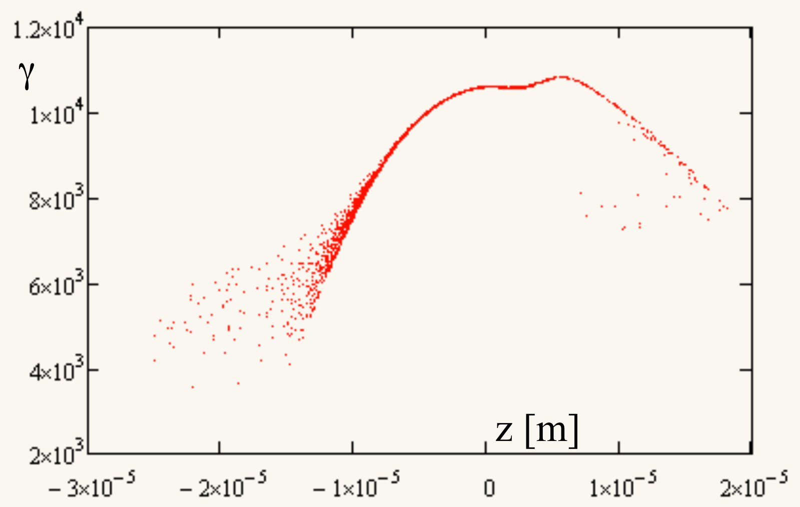
Before performing the full 3D simulation of the beam distributions at both long and short λ_R wavelengths, distributions need to get completely transferred and properly matched within both undulator+FODO configurations

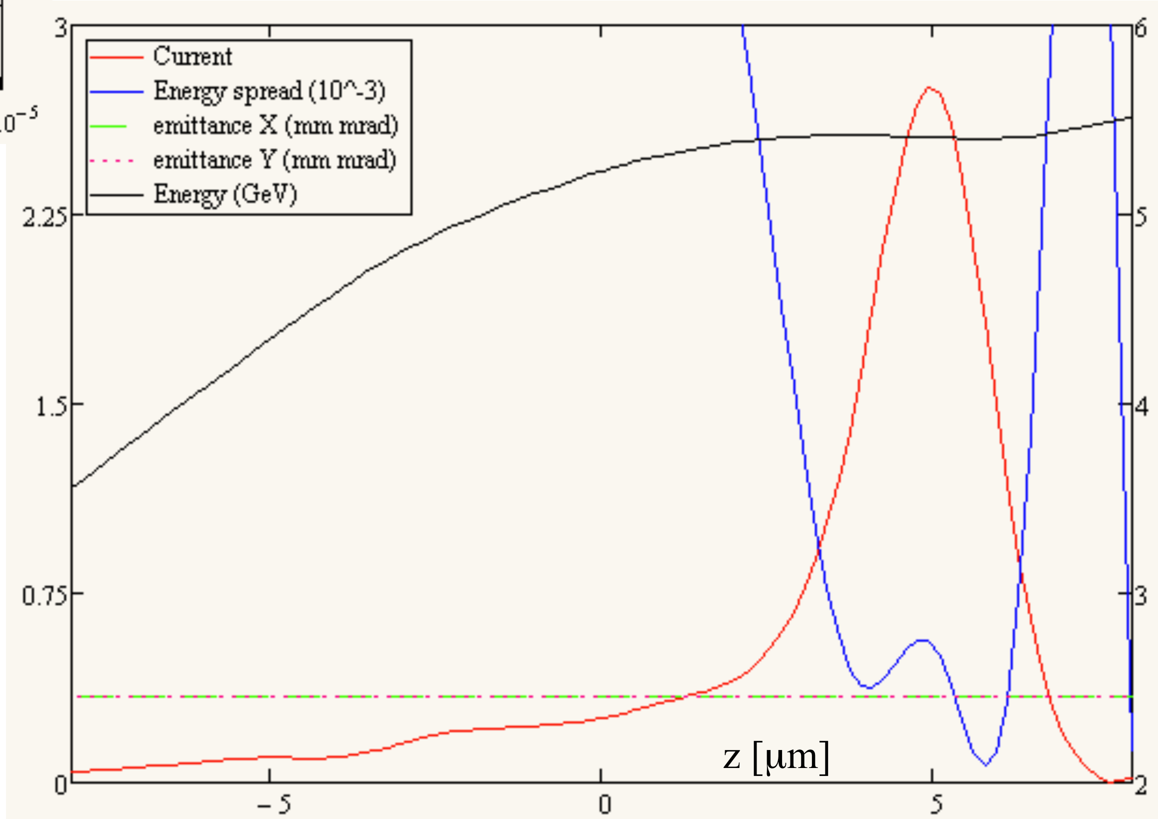
Best charge density slice along the undulator – slice parameter values						
Name	E_{beam} [GeV]	I_{peak} [A]	$\delta\gamma/\gamma$ [%]	$\langle\epsilon_n\rangle$ [μm]	$\langle\beta\rangle$ [m]	slice length [μm]
Rossi–5	5.407	2737	0.052	0.34	5	1.3
Tomassini–5	4.963	1563	0.138	0.08	5	0.15
Rossi–1	1.09	1212	0.106	0.44	4	2.4
Marocchino–1	1.062	6698	0.169	0.74	4	0.8

The following bunch of results is based on the slice norm. emittance and average <β> values, while accounting for the full longitudinal profile of current and energy spread

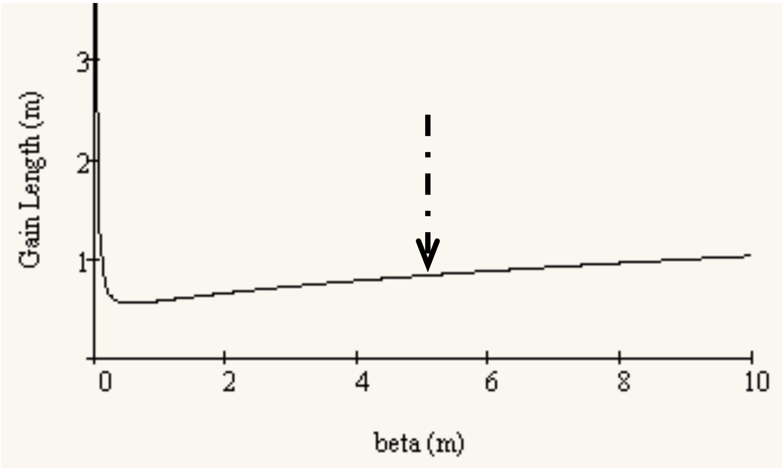
`Perseo` allows to take account of the beam longitudinal features only: current, energy and energy spread full profiles, while using average β and ε_n values – i.e. something half-way between the analytical scaling laws and the full 3D simulations: no need of the detailed transverse matching or norm. emittance profiles

Rossi-5: profiles at undulator entrance



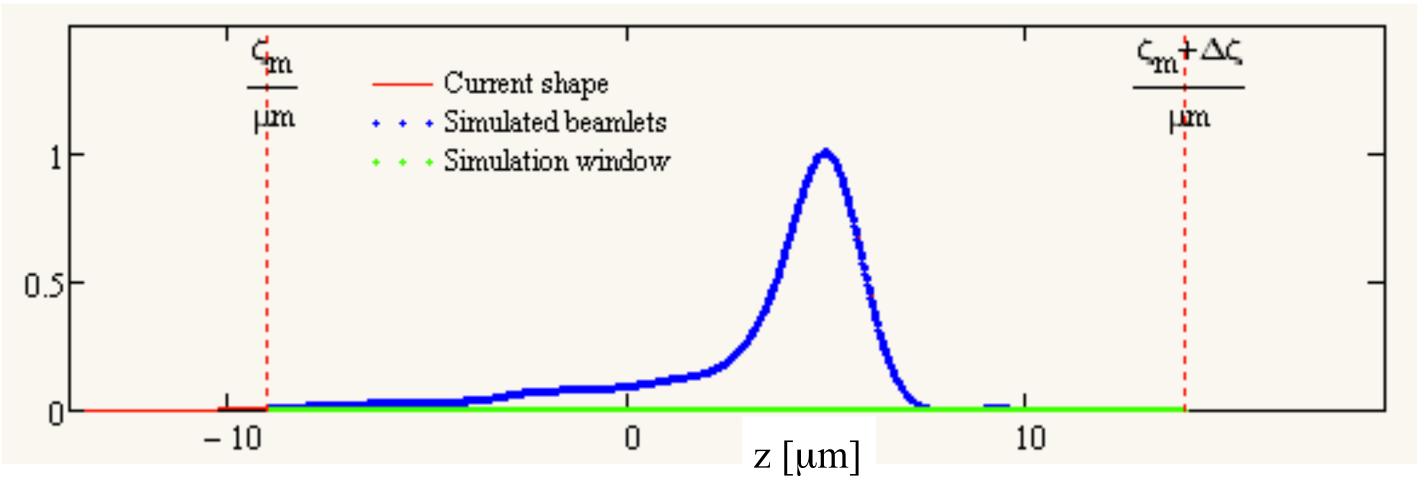


Rossi-5: matching at long λ_R



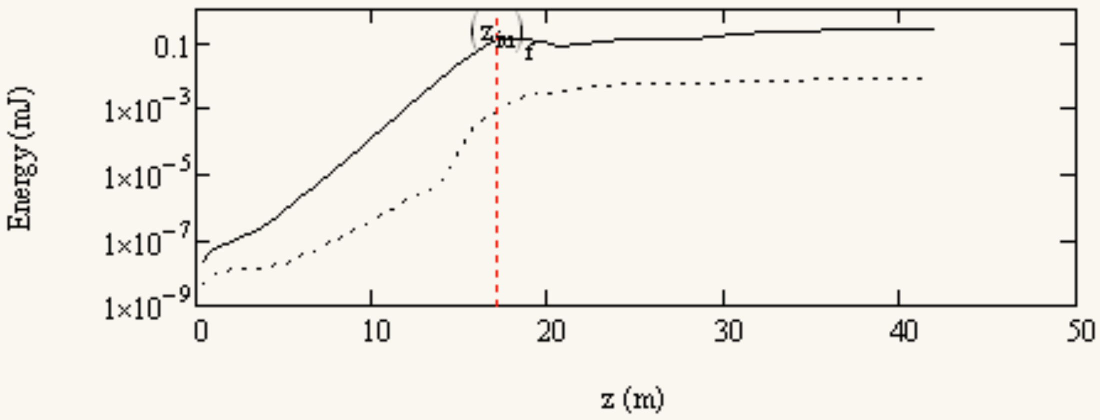
Undulator_Table =

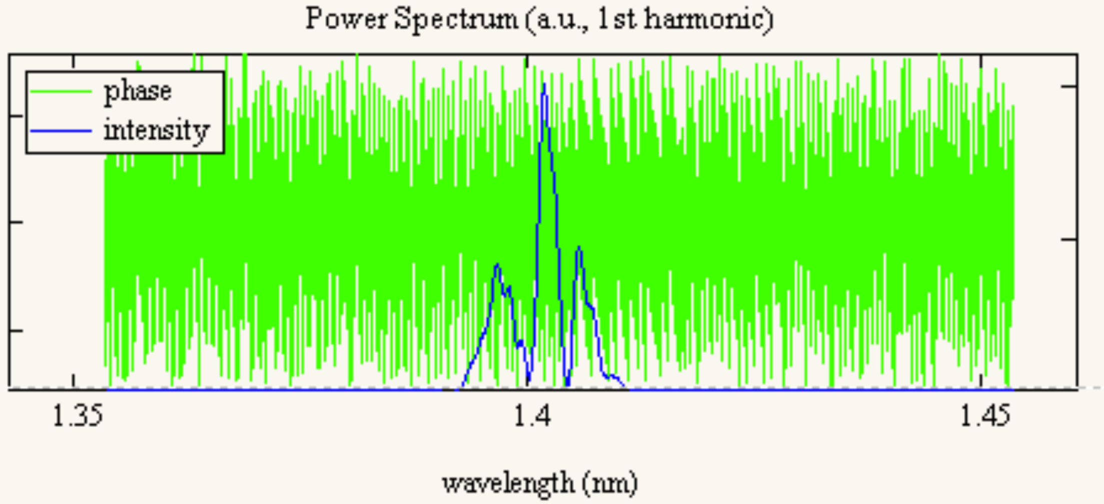
"Period (cm)"	3
"K"	4.35
"Length (m)"	42
"Wavelength (nm)"	1.402
"Photon Energy (eV)"	884.635
"Periods"	$1.4 \cdot 10^3$
"Twiss beta (m)"	5

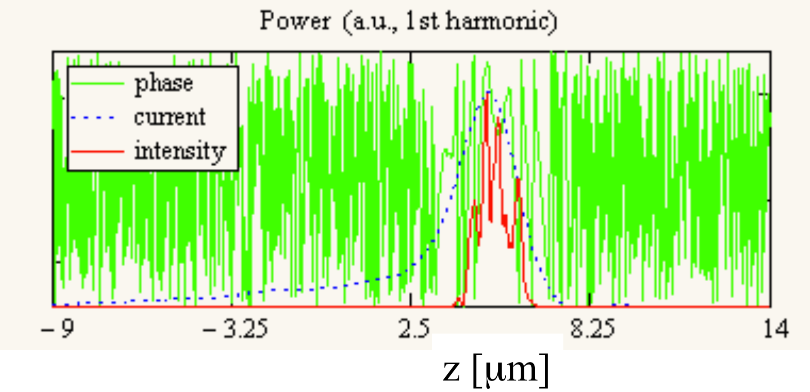


Rossi-5: results at long λ_R

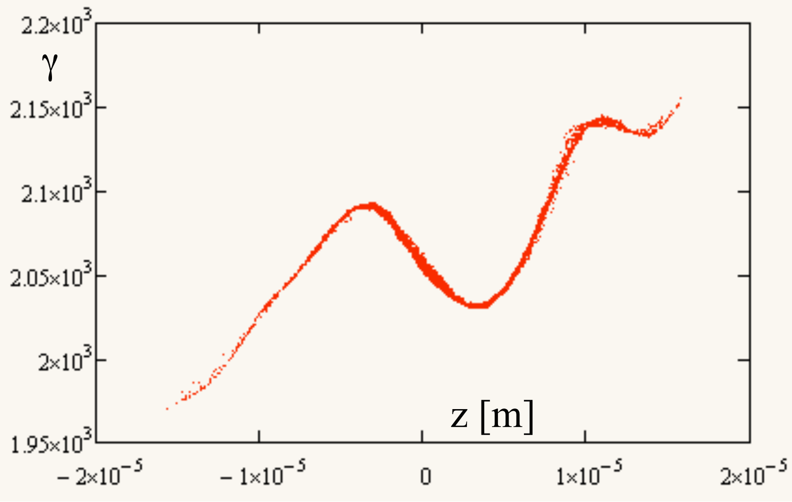
$\lambda_R = 1.4$ nm results	
Gain length	0.77 m
Saturation length	17.15 m
Saturation power	27 GW
Linewidth	0.273 %
Pulse duration	1.68 fs
Energy per pulse	116 μJ
Photons per pulse	8×10^{11}

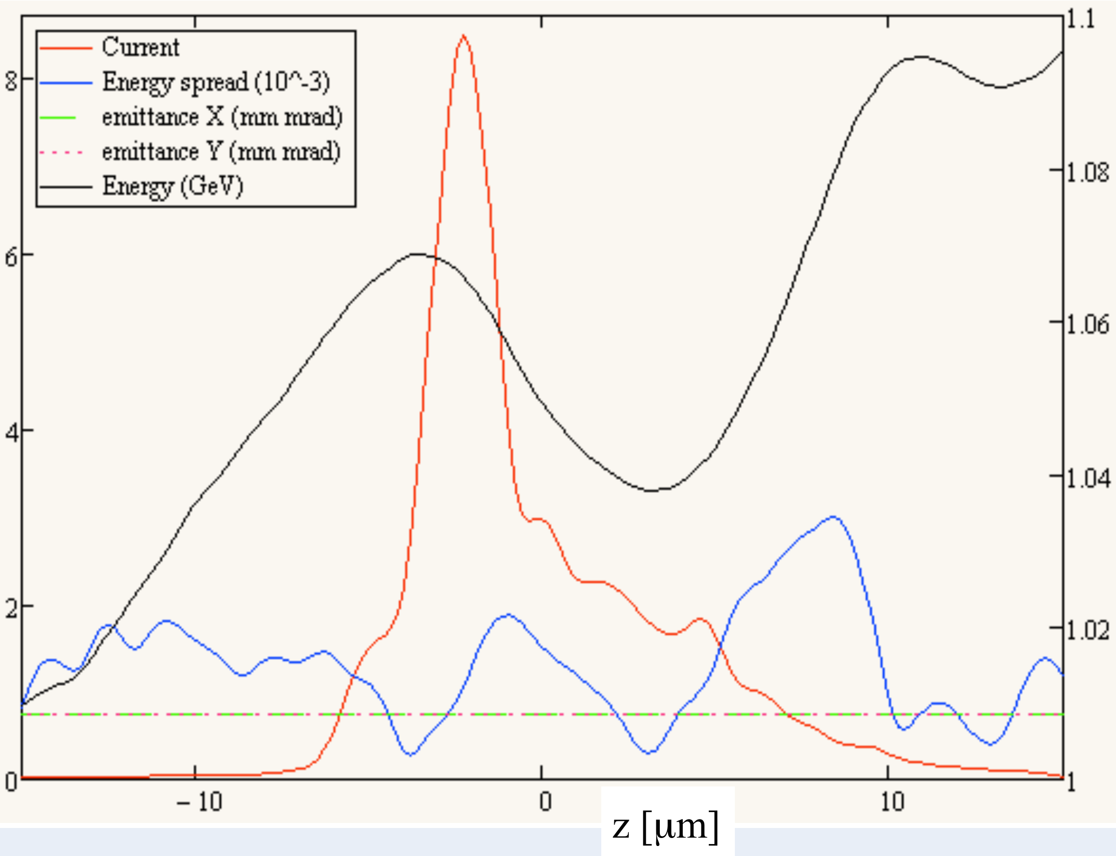






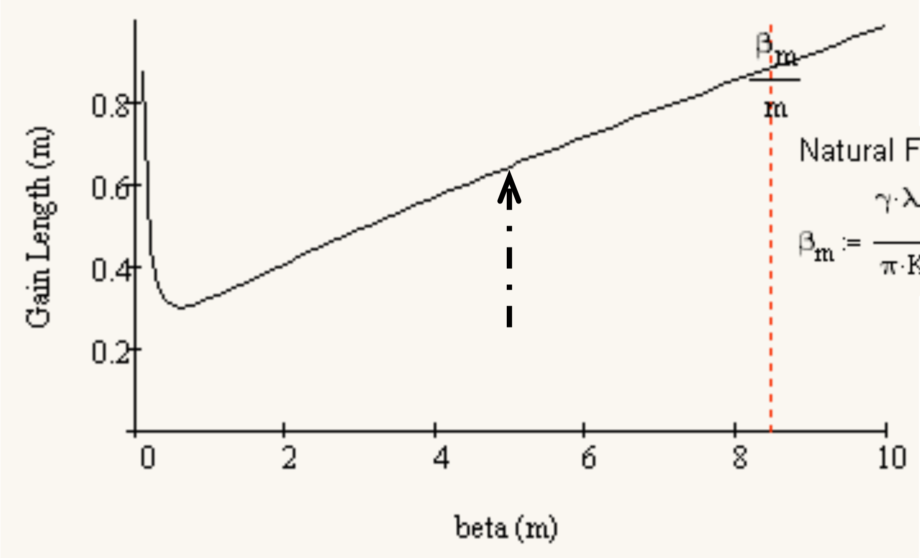
Marocchino-1: profiles at undulator entrance





Marocchino-1: matching at short λ_R

Horizon 2020

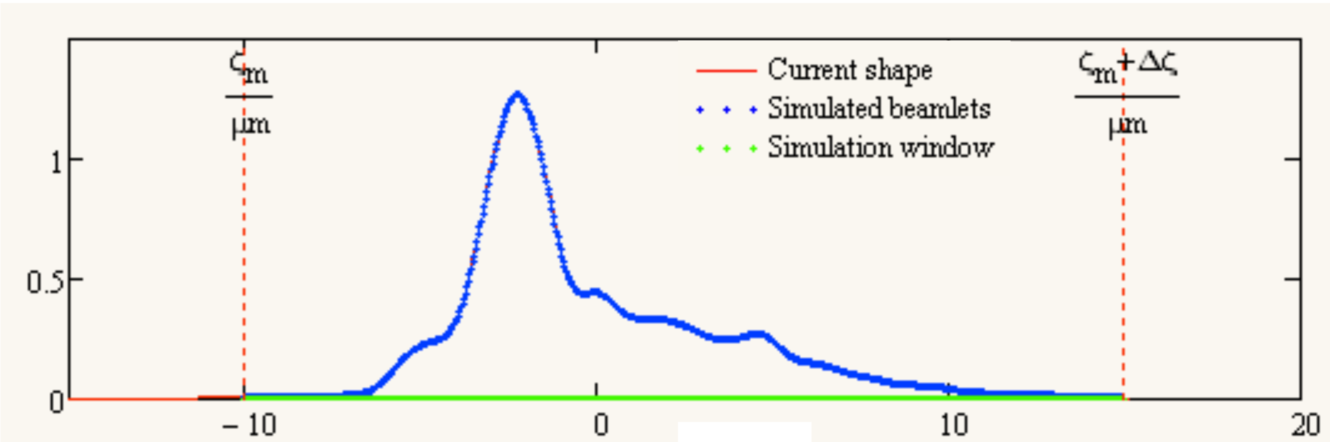


Natural Focusing

$$\beta_m := \frac{\gamma \cdot \lambda_{u_{iu}}}{\pi \cdot K_{iu}} \qquad \beta_m = 8.481\ m$$

Undulator_Table =

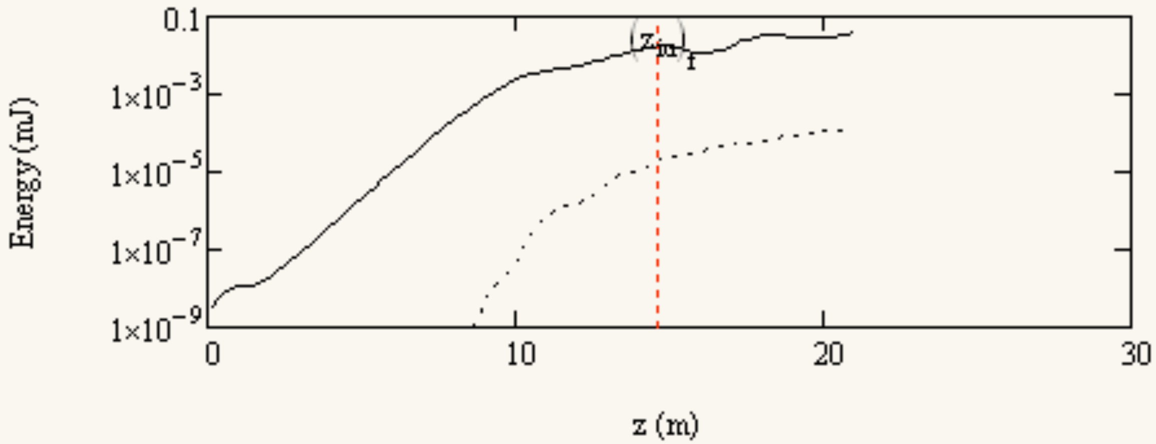
"Period (cm)"	1.5
"K"	1.17
"Length (m)"	21
"Wavelength (nm)"	2.925
"Photon Energy (eV)"	423.893
"Periods"	$1.4 \cdot 10^3$
"Twiss beta (m)"	4.8

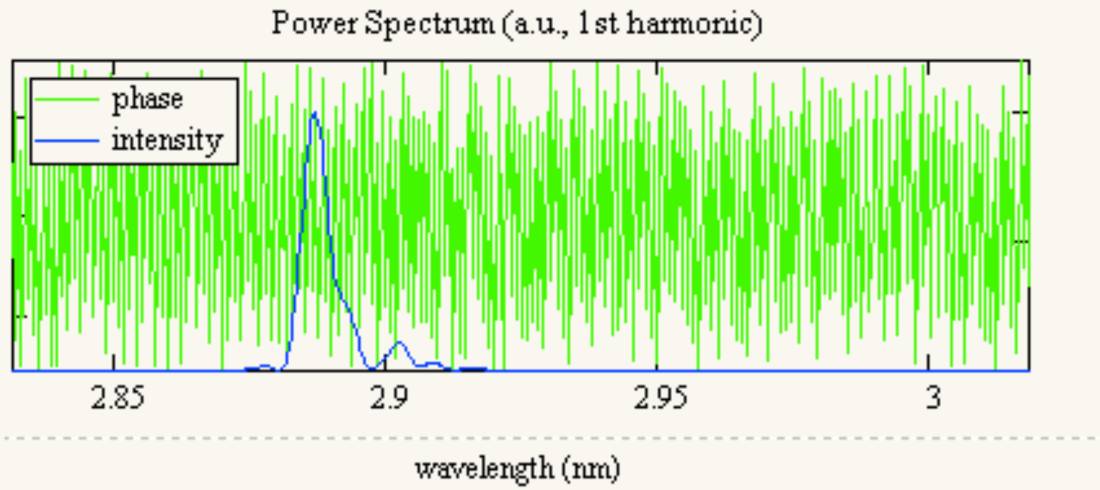


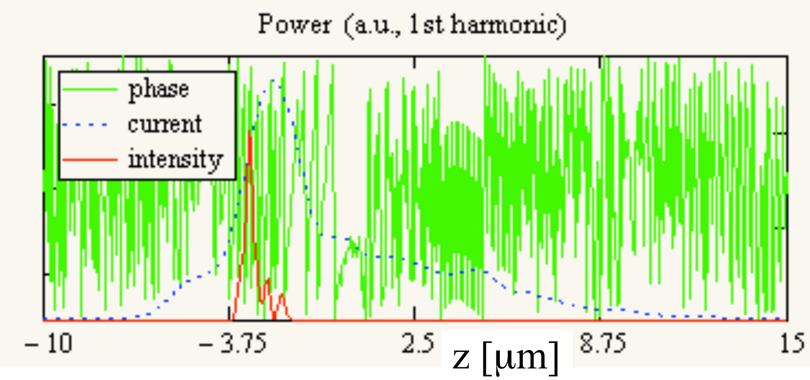
z [μm]

Marocchino-1: results at short λ_R

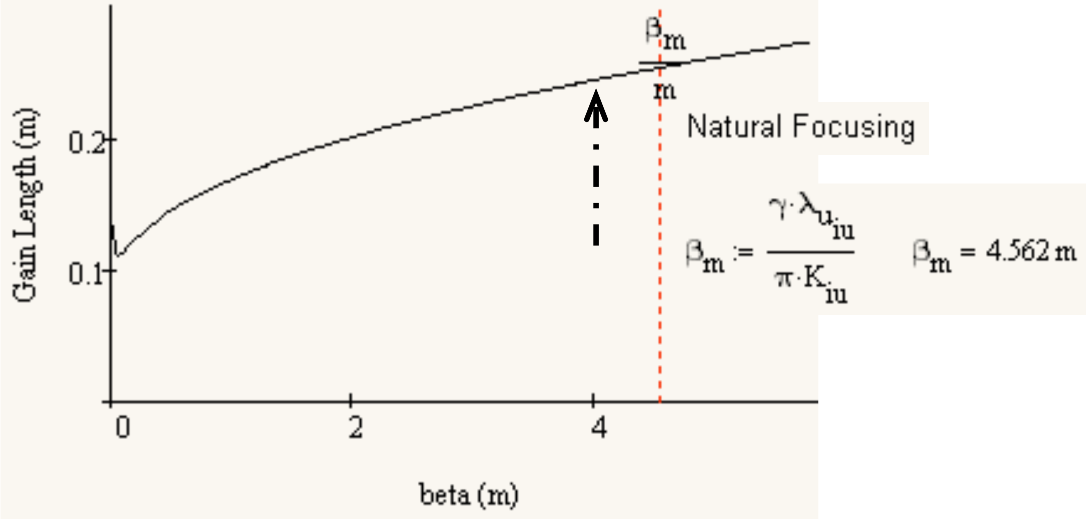
$\lambda_R = 2.9$ nm results	
Gain length	0.863 m
Saturation length	14.72 m
Saturation power	5.39 GW
Linewidth	0.208 %
Pulse duration	1.29 fs
Energy per pulse	17 μJ
Photons per pulse	2.56×10^{11}





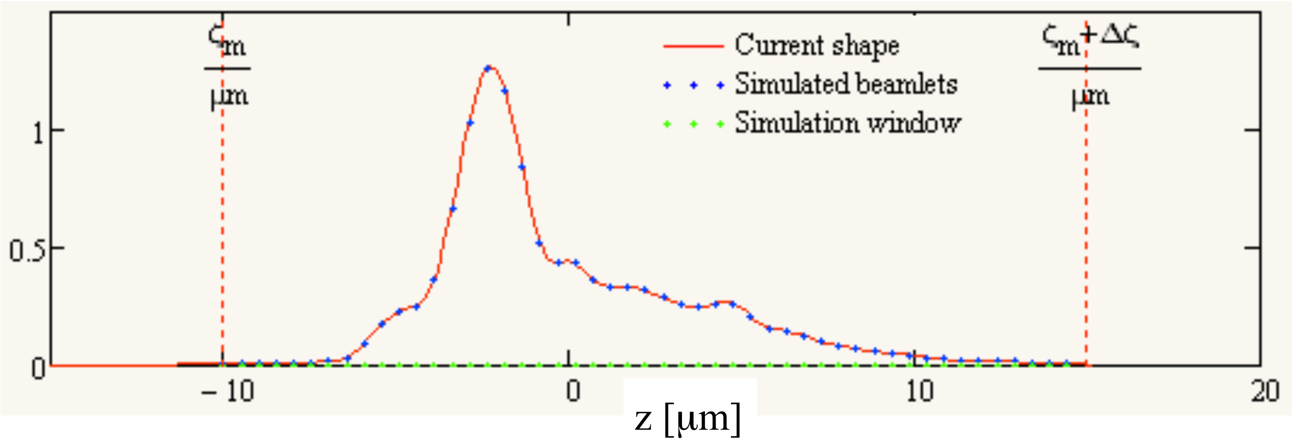


Marocchino-1: matching at long λ_R



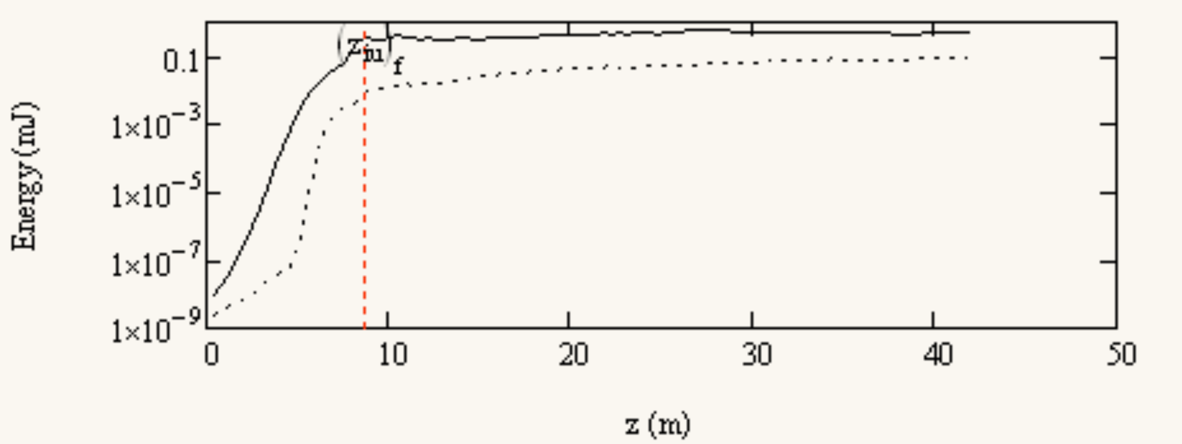
Undulator_Table =

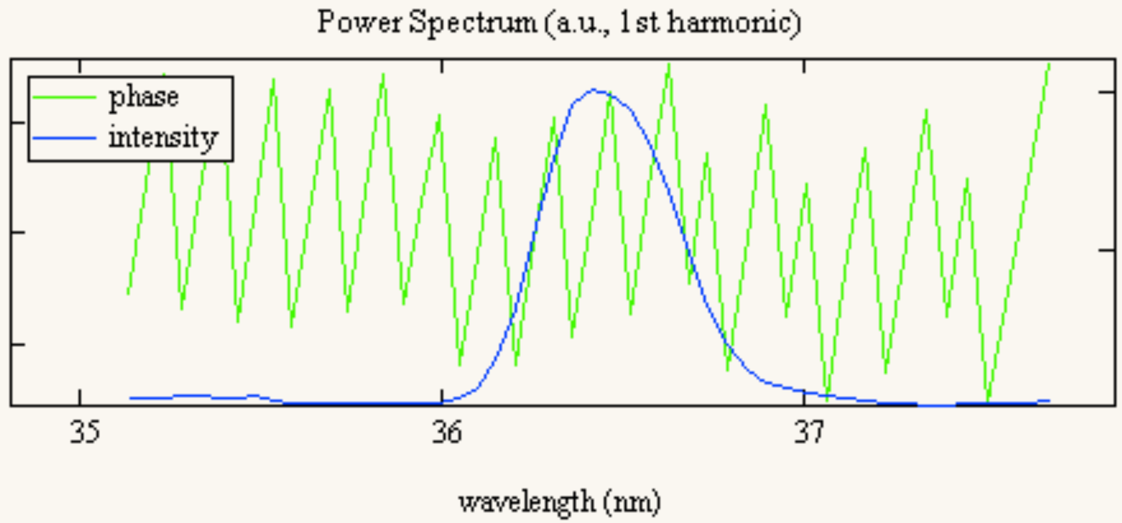
"Period (cm)"	3
"K"	4.35
"Length (m)"	42
"Wavelength (nm)"	36.33
"Photon Energy (eV)"	34.127
"Periods"	$1.4 \cdot 10^3$
"Twiss beta (m)"	4

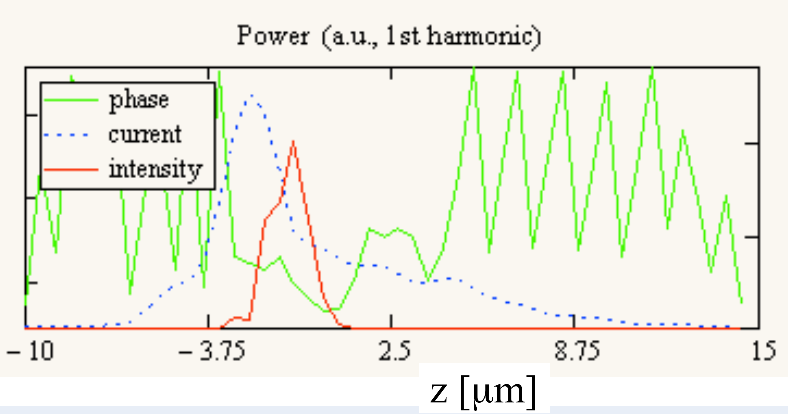


Marocchino-1: results at long λ_R

$\lambda_R = 36.3$ nm results	
Gain length	0.84 m
Saturation length	8.82 m
Saturation power	58 GW
Linewidth	0.77 %
Pulse duration	2.28 fs
Energy per pulse	331 μJ
Photons per pulse	6.05×10^{13}







To wrap up: analytical results at short λ_R

Results based on analytical formulae analyzing the "best slice" and reasonably optimum $\langle\beta_{x,y}\rangle$ values

From C. Lechner

Short wavelength – Undulator period $\lambda_u = 1.5$ cm				
Name	λ_R [nm]	Pierce ρ [%]	$L_{G,3d}$ [m]	P_{sat} [GW]
Tomassini (5 GeV)	0.137	0.0993	5.84	0.174
Rossi (5 GeV)	0.115	0.0698	2.6	2.38
Marocchino (1 GeV)	2.99	0.222	0.598	6.81
Rossi (1 GeV)	2.84	0.152	0.957	0.722

$$L_S = 1.066 L_g \ln\left(\frac{9P_S}{P_0}\right) \simeq 20\ L_{G,3d}$$

To wrap up: analytical results at long λ_R

Results based on analytical formulae analyzing the "best slice" and reasonably optimum $\langle\beta_{x,y}\rangle$ values

From C. Lechner

Long wavelength – Undulator period $\lambda_u = 3$ cm				
Name	λ_R [nm]	Pierce ρ [%]	$L_{G,3d}$ [m]	P_{sat} [GW]
Tomassini (5 GeV)	1.66	0.327	1.14	5.57
Rossi (5 GeV)	1.4	0.23	0.829	28.5
Marocchino (1 GeV)	36.3	0.73	0.253	46.3
Rossi (1 GeV)	34.5	0.5	0.428	4.38

$$L_S = 1.066 L_g \ln\left(\frac{9P_S}{P_0}\right) \simeq 20\ L_{G,3d}$$

Conclusions

- Each item issued to the WP6 by the SAC has been addressed!

- All FEL tools deployed in place: from analytical calculations through 1D evaluations with longitudinal profiles to full `Genesis` (discussed in Frascati-Nov.18 & Liverpool-July18) 3D simulations → these latter ones recently tuned to the optimum matching for the 2 undulator points

- Comparison 1 GeV vs. 5 GeV: if we wish to have similar FEL performance at a five higher energy → either stretch the ($\lambda_u \times$ K) product – but it raises the wavelength!  – or squeeze the energy spread by a similar factor!

$$L_{sat} \simeq 20 \left[1 + 0.16 \left(\frac{\delta\gamma/\gamma}{\rho}\right)^2\right] \frac{\lambda_u}{4\pi\sqrt{3}\rho} \qquad \frac{\delta\gamma}{\gamma} \ll \rho \propto \frac{1}{\gamma} \sqrt[3]{\frac{I_{peak}}{\epsilon_n} (\lambda_u K)^2}$$

$$\lambda = \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{K^2}{2}\right)$$

Please, stay FEL-tuned!

Thank you!