EuPRAXIA @ SPARC_LAB
Beam Dynamics studies for the X-band Linac

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On behalf of SPARC_LAB collaboration

Outline

- Introduction
- The Linac layout & parameter list
- WP's details
- BD studies for the nominal cases
- FEL simulation results from V. Petrillo
- Static and dynamic error studies: first results
- Conclusions

Introduction

In the framework of the Eupraxia Design Study an advanced accelerator facility EUPRAXIA at SPARC_LAB has been proposed to be realized at Frascati (Italy) Laboratories of INFN.

Two advanced acceleration schemes will be applied:

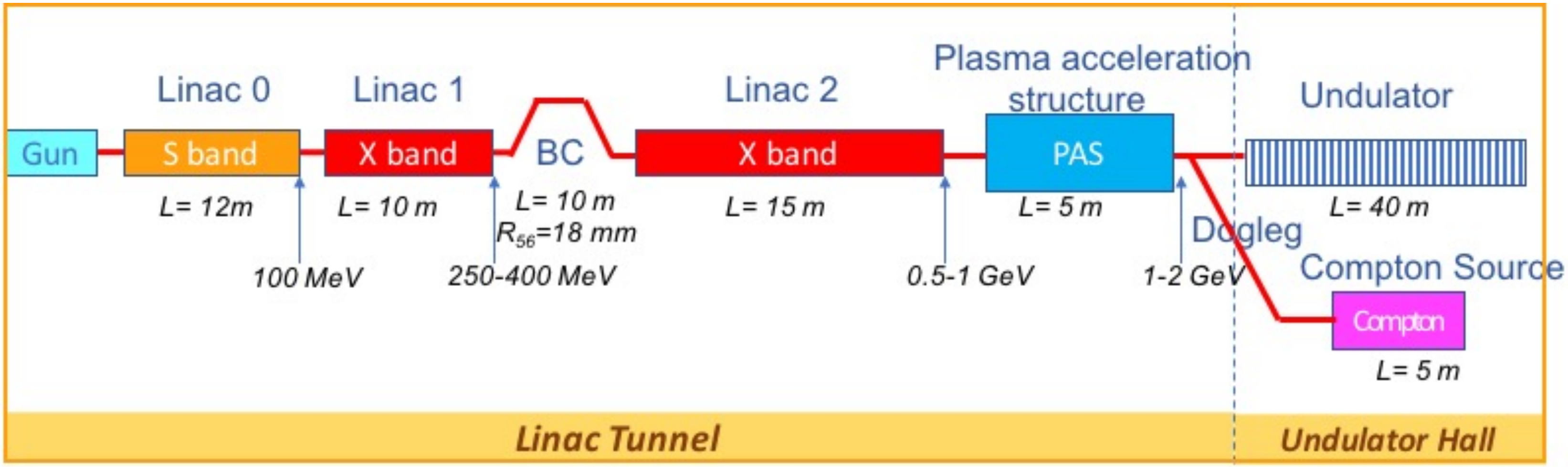
- an ultimate high gradient 1 GeV X-band linac and
- a plasma acceleration stage to provide accelerating gradients of the GeV/m order.

A FEL scheme is foreseen to produce X-ray beams within 3-10 nm range.

A 500-TW Laser system is also foreseen for electron and ion production/acceleration experiments and a Compton backscattering Interaction is planned together with extraction beamlines at intermediate electron beam energy for neutron beams and THz radiation production.

See M. ferrario talk today WP1-8 session at 18:00

The Linac Layout



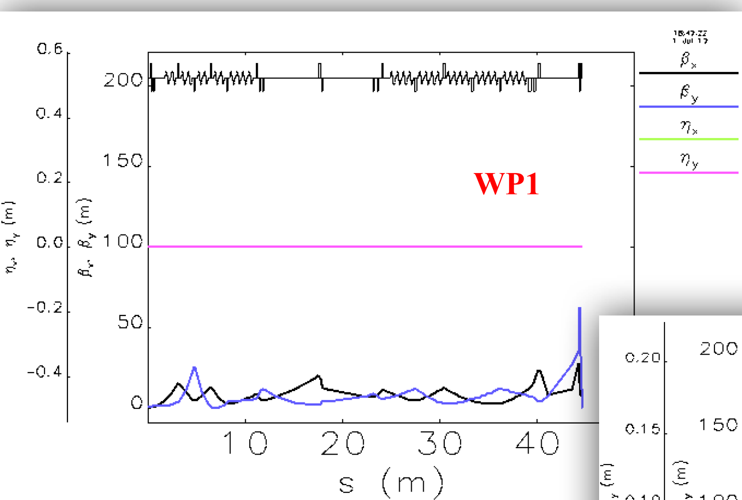
- S-band photoinjector: Gun+2÷3 acc. structures
- X-band Linac: 32 structures (50 cm)
- Plasma Acceleration Stage
- Magnetic chicane& Transfer Lines

Linac 1 & 2 parameter list for 3 WP's

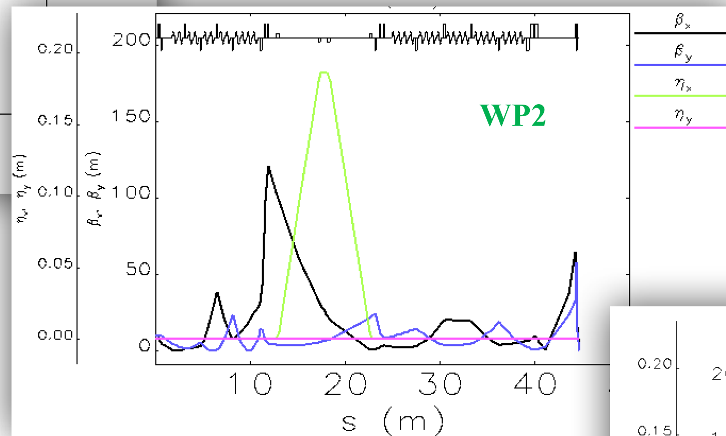
- **WP1:** Low Charge-High Current from the Photoinjector: 30 pC-3KA (FWHM) per bunch with only velocity bunching, suitable both for Beam Driven and Laser driven acceleration in Plasma
- **WP2:** Low Charge-Low Current from Photoinjector: 30 pC-100A per bunch, velocity bunching coupled with a magnetic longitudinal compression stage in the chicane to reach the desired current I = 3kA (Hybrid scheme), suitable both for Beam Driven and Laser driven acceleration in Plasma
- **WP3:** High charge-Low Currrent from Photoinjector: 200 pC-70 A, with and without the longitudinal bunch compression in the magnetic chicane to serve both the SASE-FEL, with peak current Ipk=2kA, and the Compton Source in the high flux operation scheme.

Beam Parameter	Unit	L1			L2		
		WP1	WP2	WP3	WP1	WP2	WP3
Initial energy	GeV	0.01	0.17	0.17	.21	.28	.51
Final energy	GeV	0.21	0.28	.55	.55	0.55	1.06
Active Linac length	m	6.0			10.0		
Accelerating Gradient	MV/m	20.0	20.0	57.0	36.0	26.8	57.0
RF phase (crest at 0)	deg	-20.0	-20.0	-12.0	-19.5	0	+15.0
Initial rms energy spread	%	0.30	0.22	0.67	0.15	0.22	0.47
Final rms energy spread	%	0.15	0.22	0.47	0.07	0.06	0.09
rms bunch length	μm	3	20	112	3	4	20

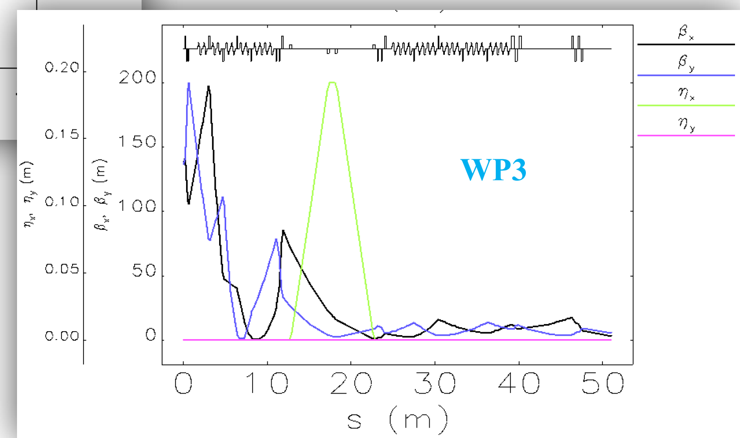
Twiss Parameters for the 3 WP's



R_{56}=9 mm



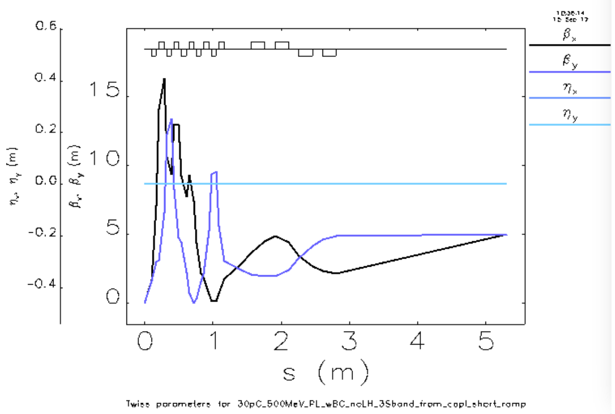
R_{56}=16 mm

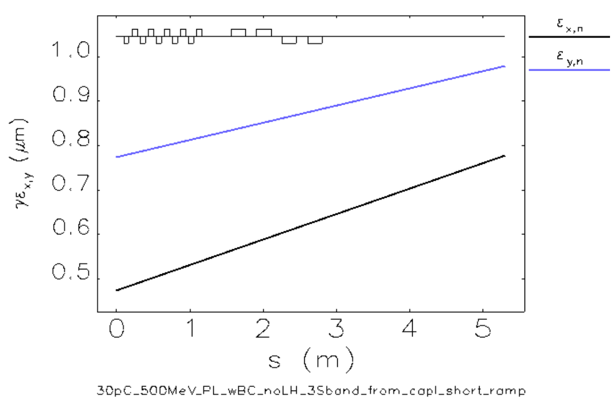


30 kp tracked with Elegant code

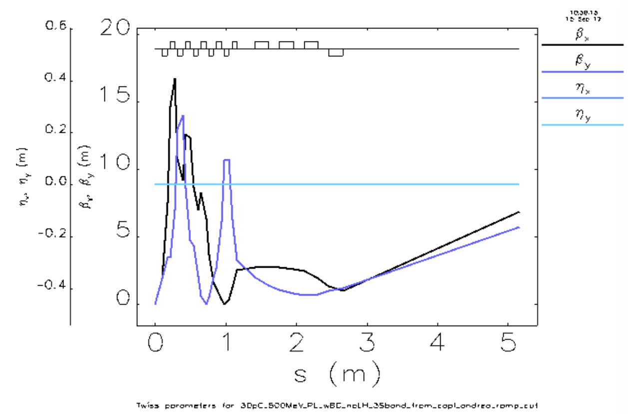
Twiss Parameters & emittance dilution in the Transfer line to undulator (WP1 case)

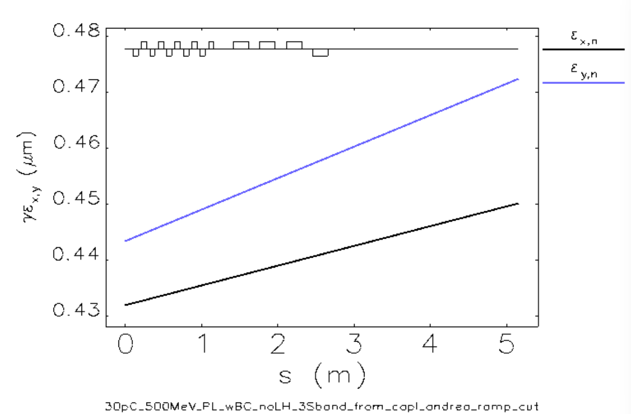
- Beam Driven





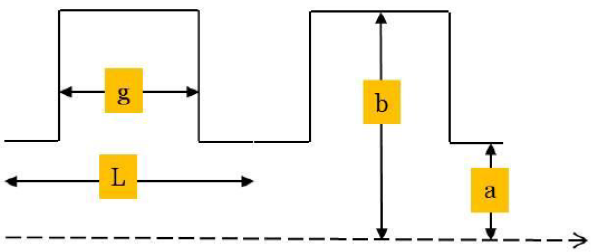
- Laser Driven



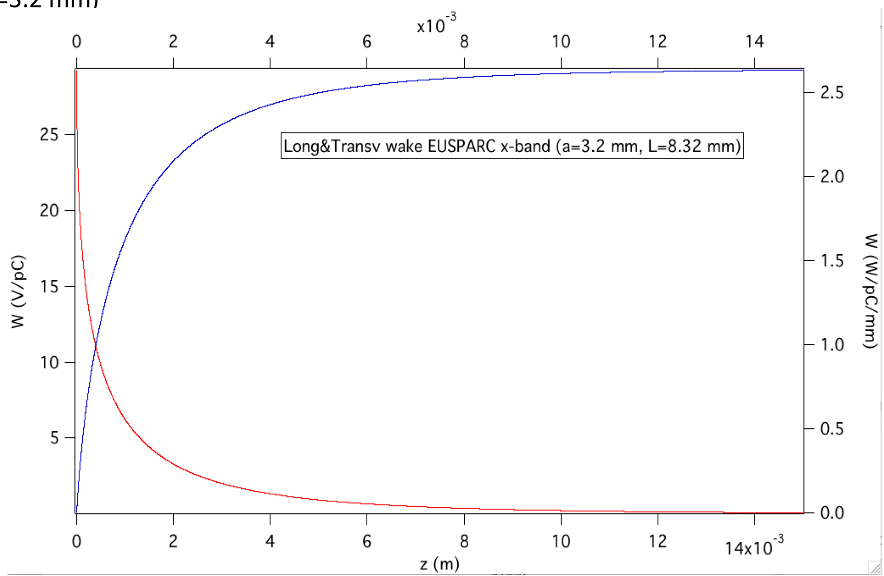


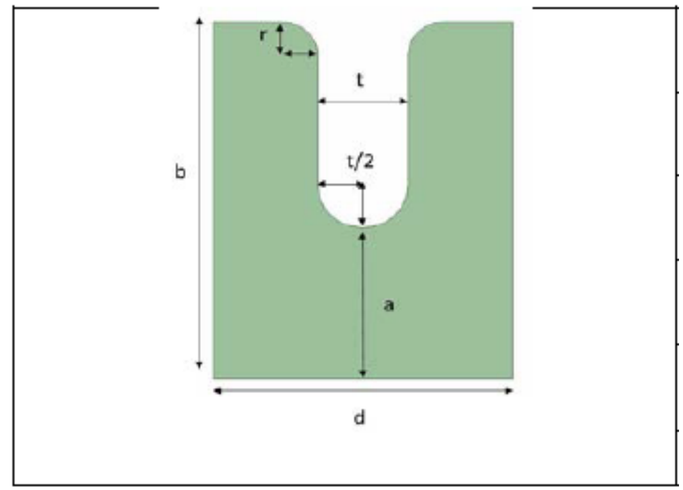
Long & Transv Wake field

See M.Diomede "Preliminary RF design of an X-Band LINAC for the EuSPARC/EuPRAXIA@SPARC_LAB proposals", this conference



Pill box cavity model considered for the wake feld calculations:
a is the iris radius, L is the cell length. The asymptotic values of the longitudinal and transverse wake functions have been calculated according to K. Bane SLAC{PUB{7862 (Revised) November 1998 with a=3.2 mm)

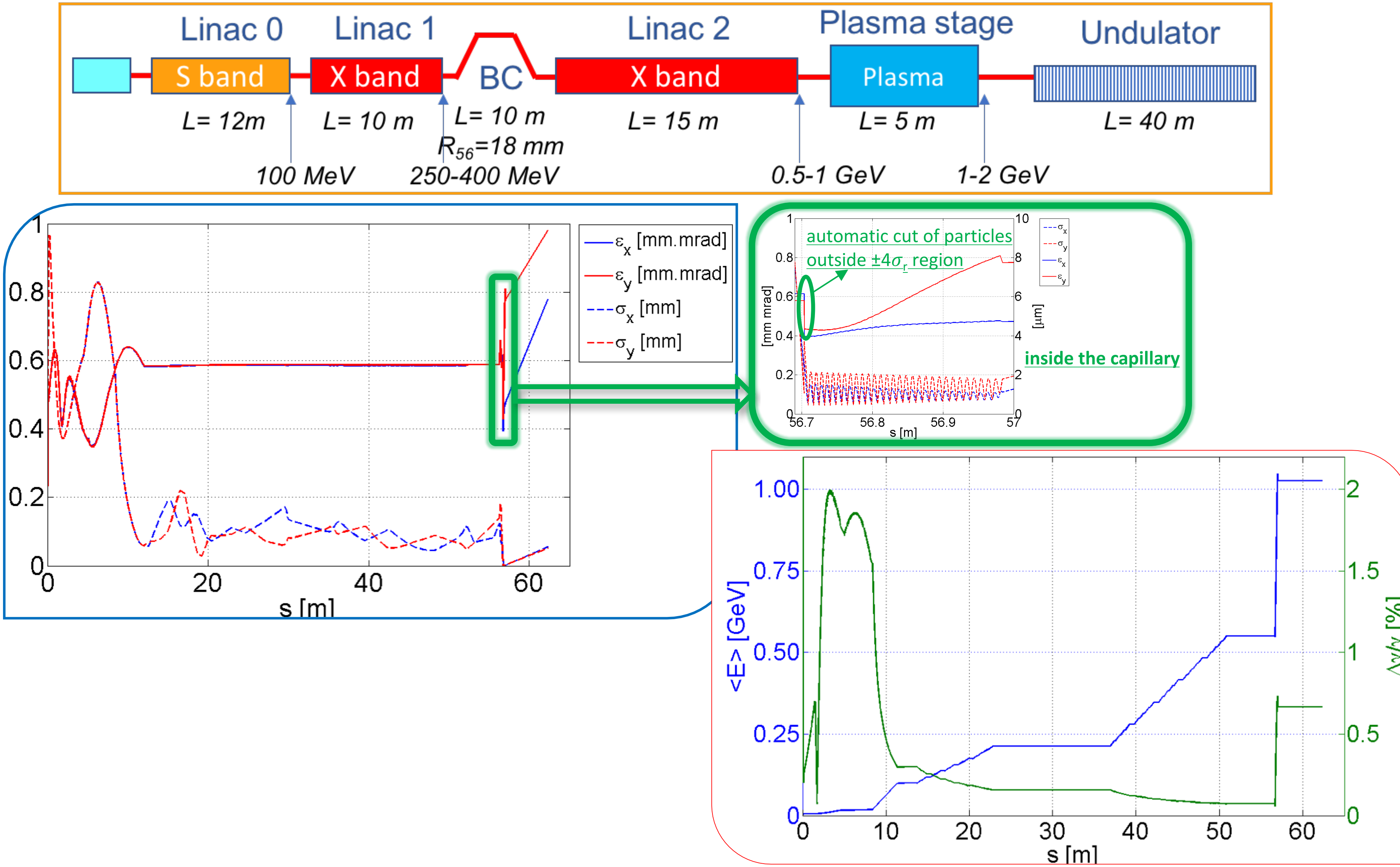




Geometrical parameters	
a[mm]	2 ÷ 5
b [mm]	9.828 ÷ 10.917
d [mm]	8,332 (2π/3 mode)
r [mm]	1
t [mm]	2.5

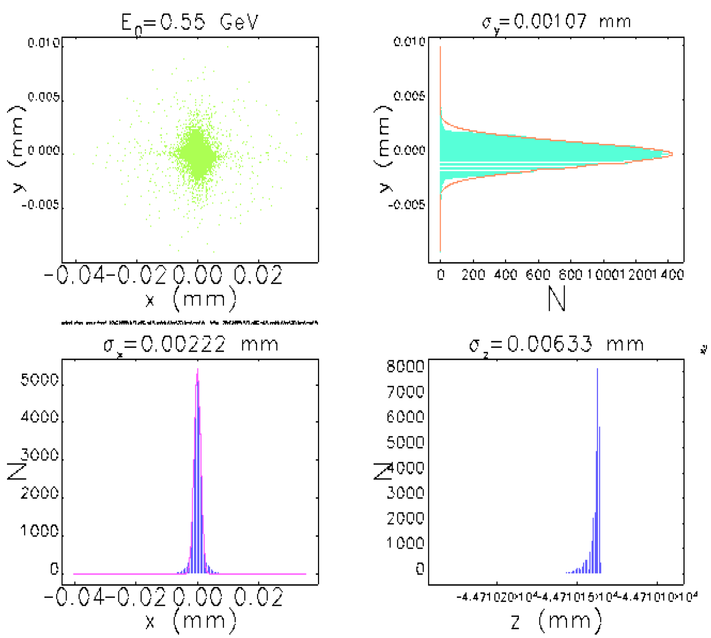
Longitudinal and transverse wakefield calculated for an iris radius of 3.2 mm and a cell length of 8.332 mm.

WP1 case: 30 pC beam evolution from Cathode to Undulator

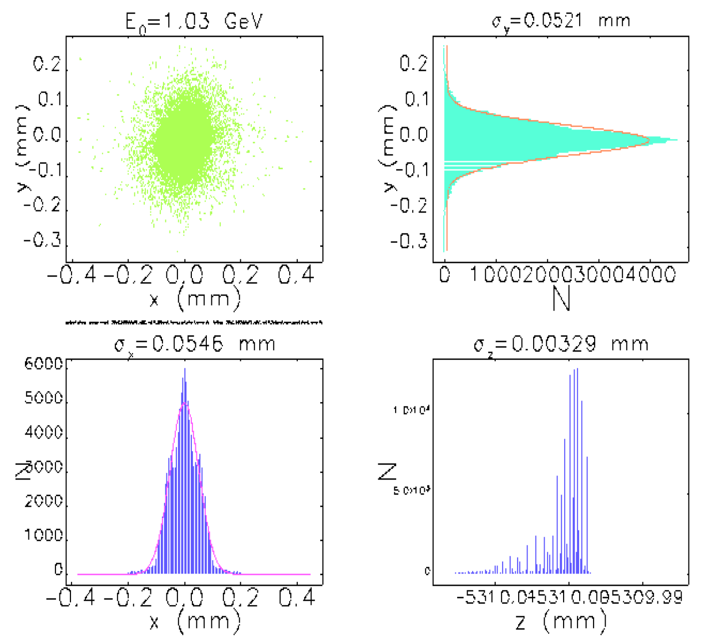


WP1 case: Transverse electron beam distribution (witness bunch)

- before the plasma acceleration (capillary entrance)

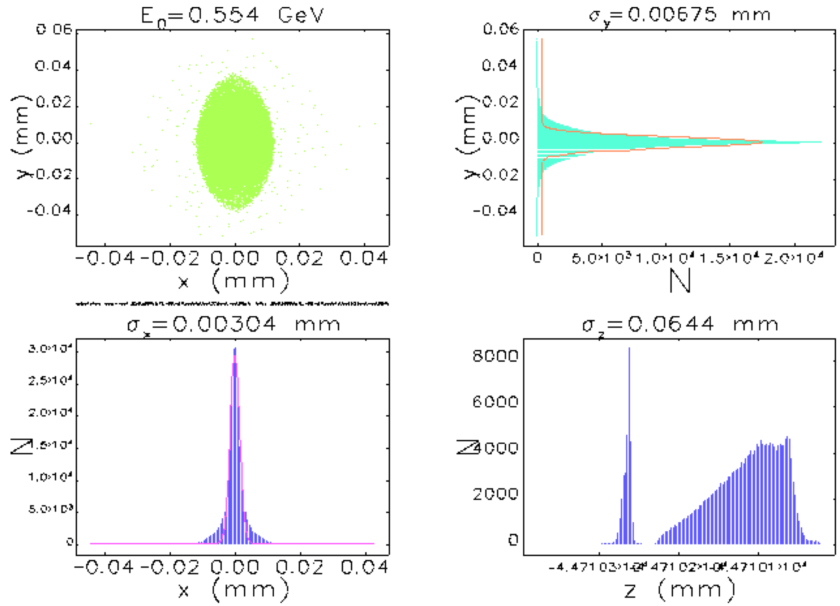


- undulator entrance

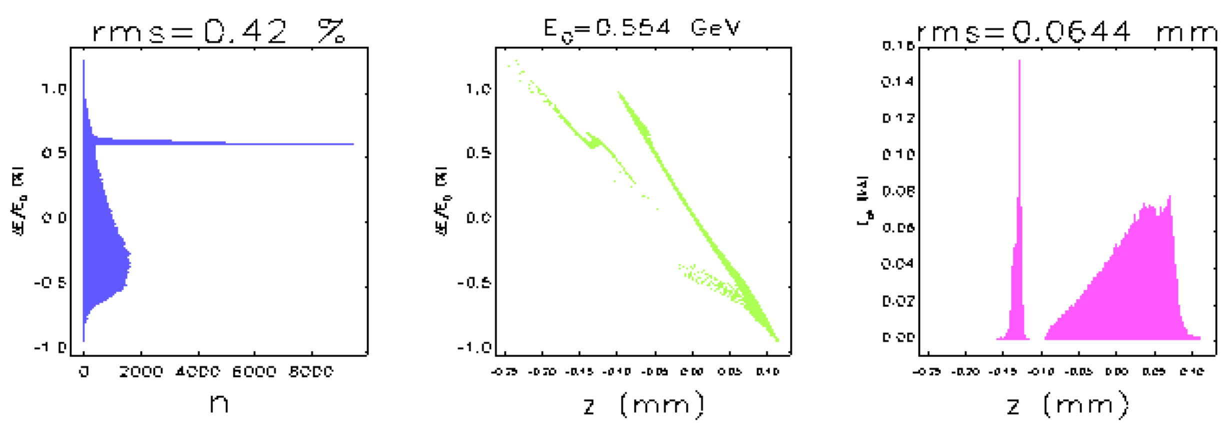


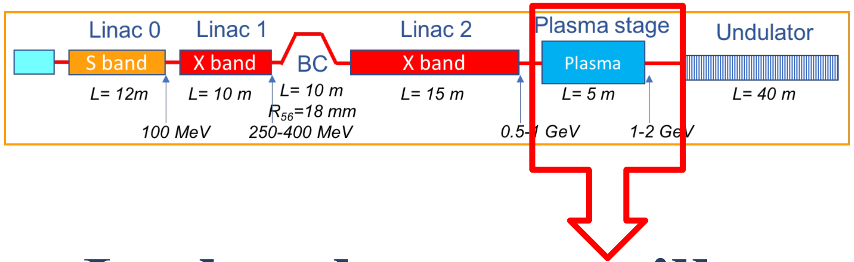
Linac BD results for Driver+Witness (WP1 extended)

Transverse distribution at the entrance of the plasma capillary.



Longitudinal phase at the entrance of the plasma capillary.

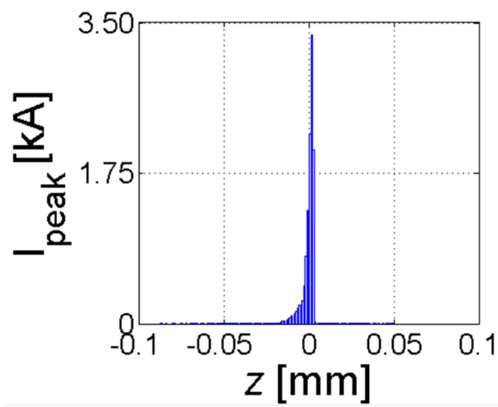




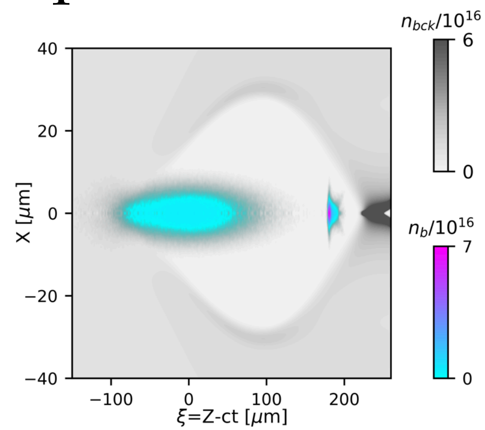
Architect simulations for particle driven plasma accelerated electron beams (WP1)

In the plasma capillary

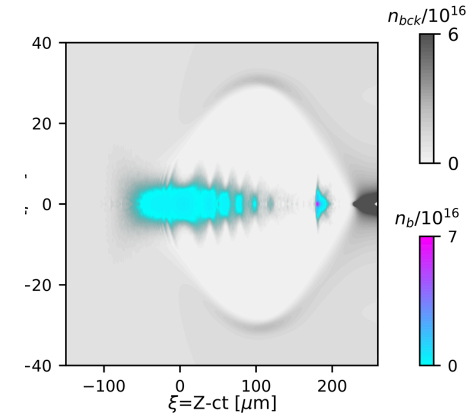
T-Step: hist (witness)



at plasma entrance



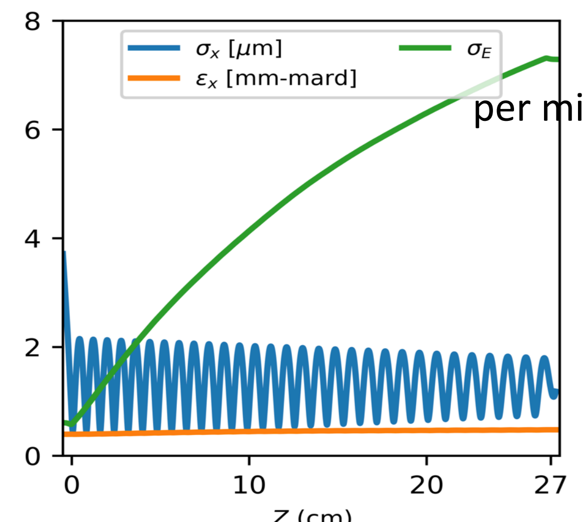
at exit



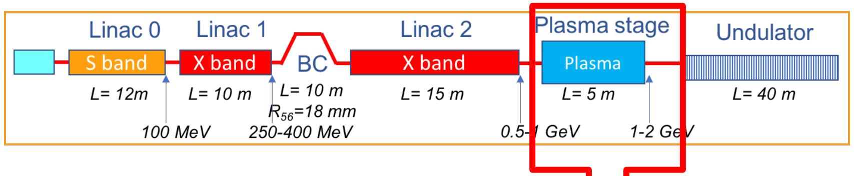
witness parameters

	Trailing Bunch	Trailing Bunch End-Capillary
Q (pc)	29	29
σx (μm)	0.73	1.2
σy (μm)	1.3	1.18
σz (μm)	3.5	3.3
εx (μm)	0.4	0.48
εy (μm)	0.4	0.81
σE (%)	0.06	0.73

witness evolution

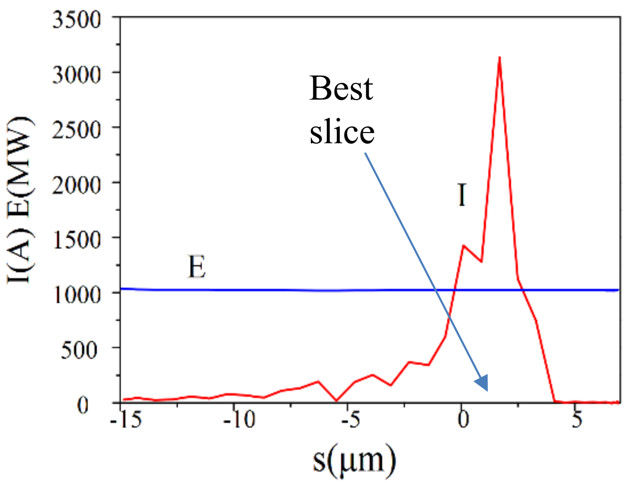


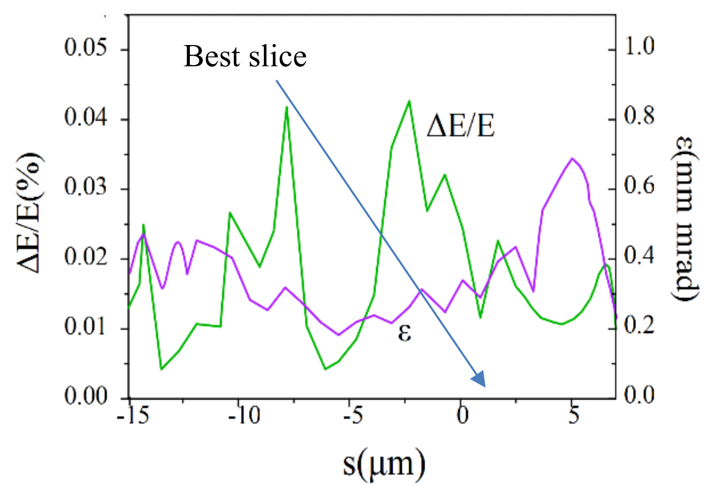
Courtesy of A. Marocchino & V. Petrillo



In the plasma stage

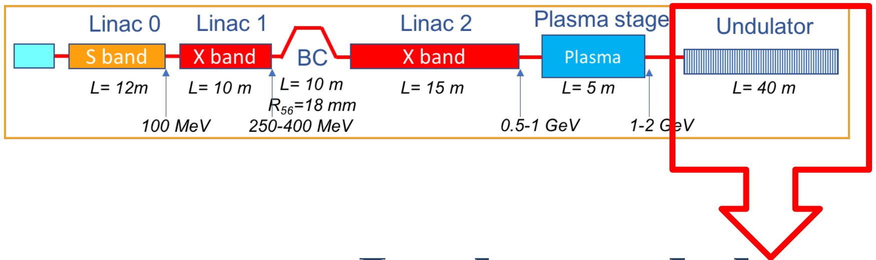
Characteristics of the electron beam **at the entrance of the undulator**





	(a1)
Q(pC)	30
ε_x (mmmrad)	0.39
ε_y (mmmrad)	0.309
$\Delta E/E$ (10^{-4})	2.49
I_{peak}(A)	3131

Courtesy of V. Petrillo



In the undulator

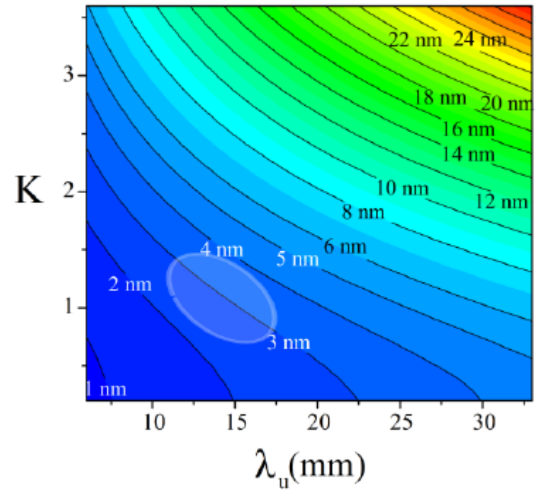
FEL Genesis simulation with **particle driven plasma accelerated electron beams**

Choice of the radiation scheme and undulator parameters

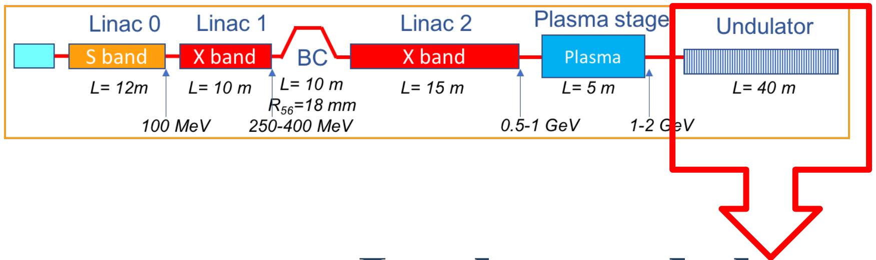
The comparison between the possible radiation schemes makes clear that seeding and cascaded techniques should require a linear space larger than the allocated one and could be considered for future upgrades. The stringent condition i) induced us to consider as primary option the use of a **conventional, not segmented undulator** and the operation in the **SASE mode**, with the possibility of exploiting the **single spike regime** for increasing the radiation coherence, combined potentially with the undulator tapering.

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

γ=2000

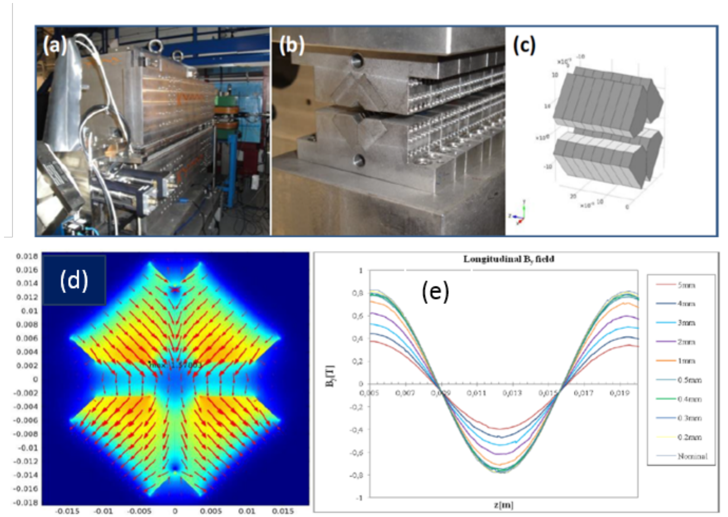


Courtesy of V. Petrillo



FEL Genesis simulation with **particle driven plasma accelerated electron beams**

In the undulator



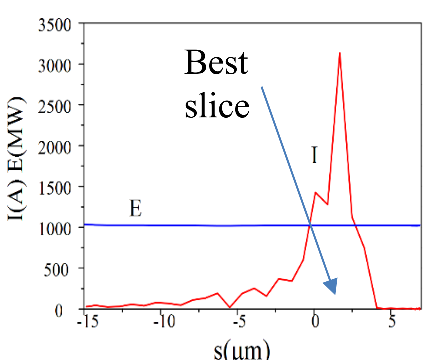
Undulator @SPARC_LAB
ENEA-Kyma
λ_u=1.5 cm,
a_w=0.7
K=1
$L_{und} \approx$ 30 m

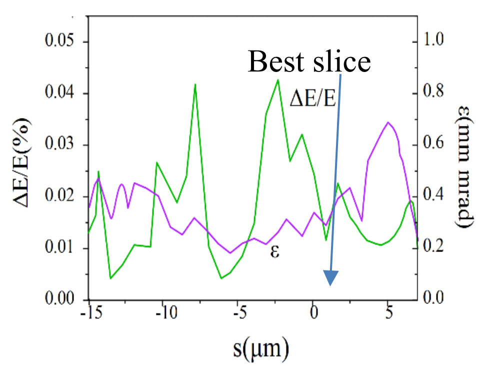
Radiation:

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

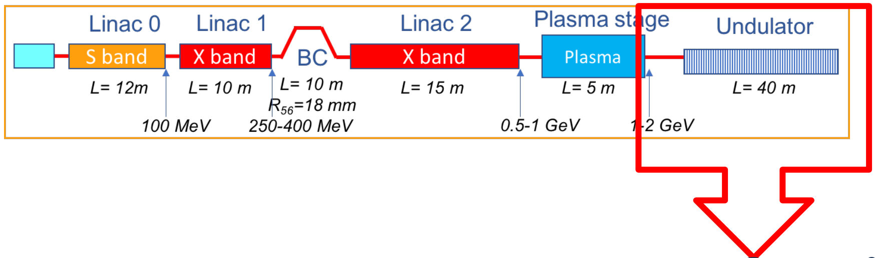
E=1 GeV
λ=2.78 nm
E_{phot}=0.44 keV

Characteristics of the electron beam

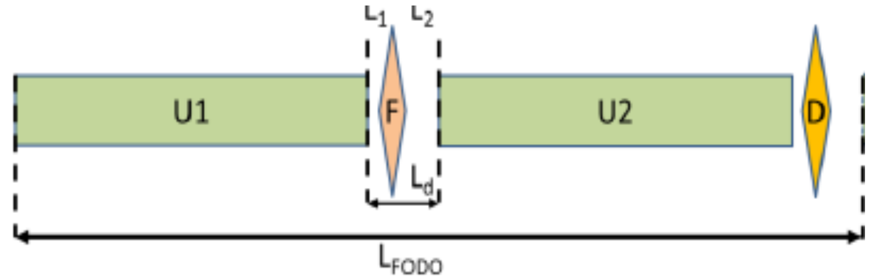


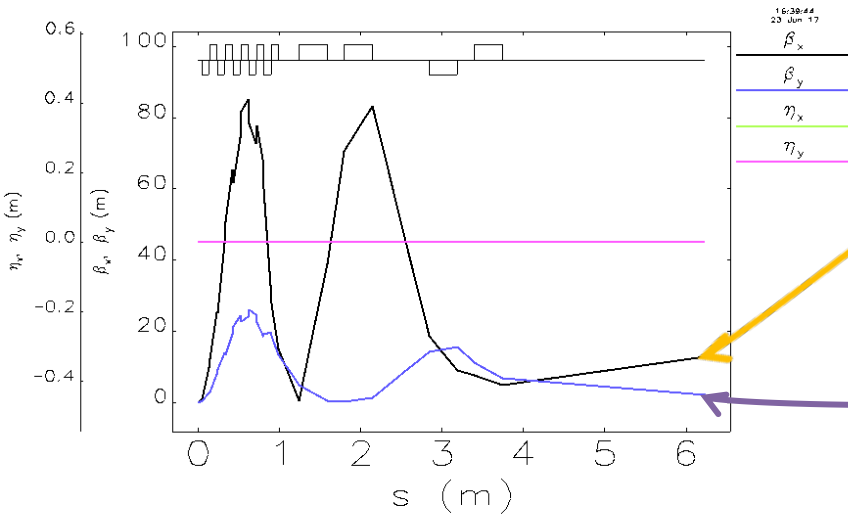


Courtesy of V. Petrillo



In the transfer line- undulator FODO





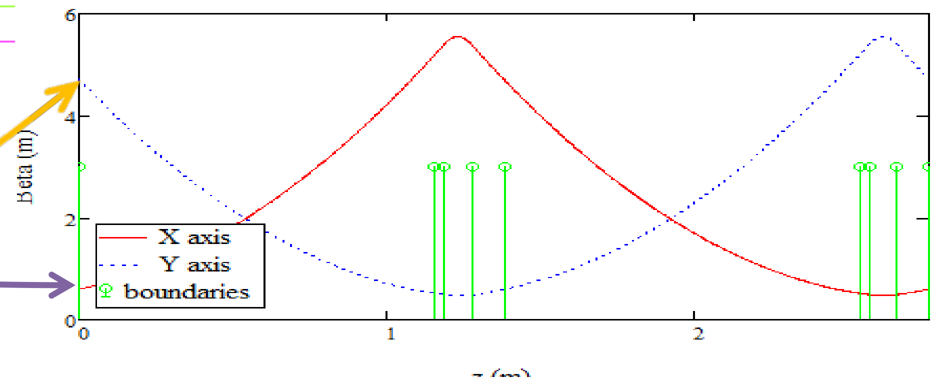
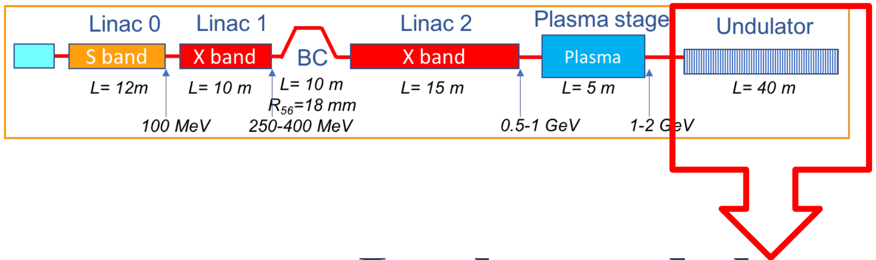


Table 3.3.2 – Twiss parameters and matching condition for transport in the undulator with N=77, λ_u=1.5 cm.

Case	Energy (GeV)	K	λ (nm)	$\overline{\beta_x},\overline{\beta_y}$ (m)	α_x (m)	β_x (m)	α_y (m)	β_y (m)	Q_{IG} (T)
A	0.8	1	4.59	4.274	-0.478	0.497	3.269	4.858	3.501
B		1.45	6.28	4.225	-0.475	0.5	3.167	4.775	3.453
C	1	1	2.94	4.289	-0.479	0.496	3.303	4.885	4.396
D		1.45	4.02	4.258	-0.477	0.498	3.237	4.832	4.358
E	1.2	1	2.04	4.298	-0.48	0.495	3.321	4.9	5.288
F		1.45	2.79	4.276	.0-478	0.497	3.275	4.863	5.256

Courtesy of V. Petrillo

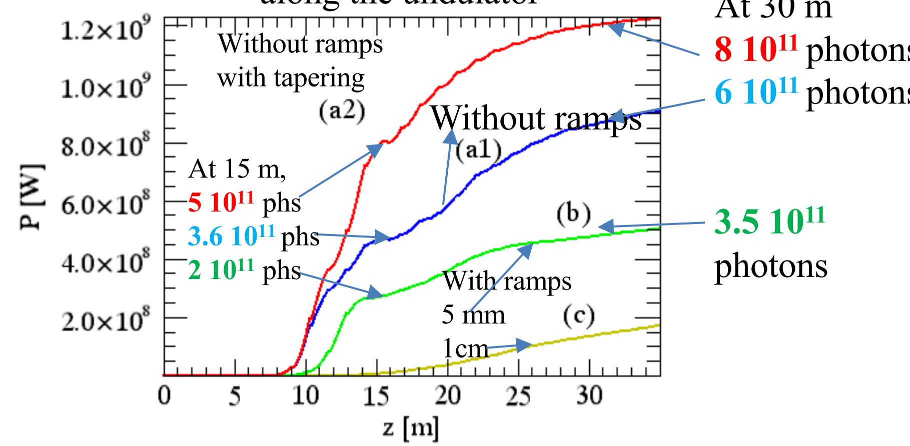


FEL Genesis simulation with particle driven plasma accelerated electron beams

In the undulator

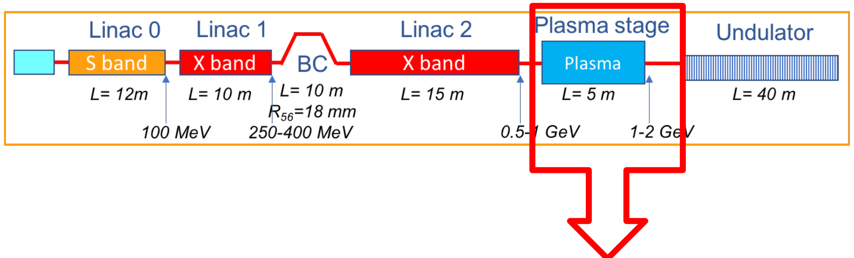
	Units	Particle external injection Without ramp(a1)	Particle external injection With ramp 0.5 cm(b)	Particle external injection With ramp 1 cm(c)	Optimized case with tapering(d)
Rms Energy Spread	%	0.52	0.64	0.79	0.52
Peak current	kA	3.1	3.1	2.3	3.1
Bunch charge	pC	30	30	30	30
Bunch length rms	μm (fs)	3.455 (11.5)	3.27(10.9)	3.83(12.7)	3.45 (11.5)
Rms norm. emittance	μm	0.41-0.46	0.47-0.77	0.78-1.5	0.41-0.46
Slice Length	μm	1.39	1.45	1.51	1.39
Slice Charge	pC	12	13	11.8	12
Slice Energy Spread	%	0.022	0.053	0.055	0.022
Slice norm. emittance	μm	0.39-0.309	0.48-0.53	0.7-0.64	0.39-0.309
Undulator period	cm	1.5	1.5	1.5	1.5
K		0.987	0.978	0.987	0.987-0.01z
ρ (1d/3d)	x 10^{-3}	2.-1.9	1.92-1.44	1.84-1.41	2-1.9
Radiation wavelength	nm (KeV)	2.79(0.45)	2.78 (0.45)	2.78 (0.45)	2.79 (0.45)
Saturation length	m	14-25	14-25	>35	15-35
Saturation power	MW	450-770	270-460	170	850-1200
Energy	μJ	23-49	14.6-24	13(at 30 m)	42-65
Photons/pulse	x 10^{10}	33-56.	20.3-33.5	18	58-91
Rel. Bandwidth	%	0.21-0.3	0.12-0.3	0.4	0.25-0.55
Rad. Size	μm	160-180	180-25	400	48-52
Divergence	μrad	45-41	54-52	62	170-240
Brilliance per pulse	(s mm^2 $mrad^2$bw(‰))$^{-1}$	1.06-1.2 10^{27}	6.6-2.3 10^{26}	2 10^{25}	1.2-3.7 10^{27}

Growth of the radiation along the undulator



Saturation length	m	15-35
Saturation power	MW	850-1200
Energy	μJ	42-65
Photons/pulse	x 10^{10}	58-91
Rel. Bandwidth	%	0.25-0.55
Rad. Size	μm	48-52
Divergence	μrad	170-240
Brilliance per pulse	(s mm^2 $mrad^2$bw(‰))$^{-1}$	1.2-3.7 10^{27}

Courtesy of V. Petrillo

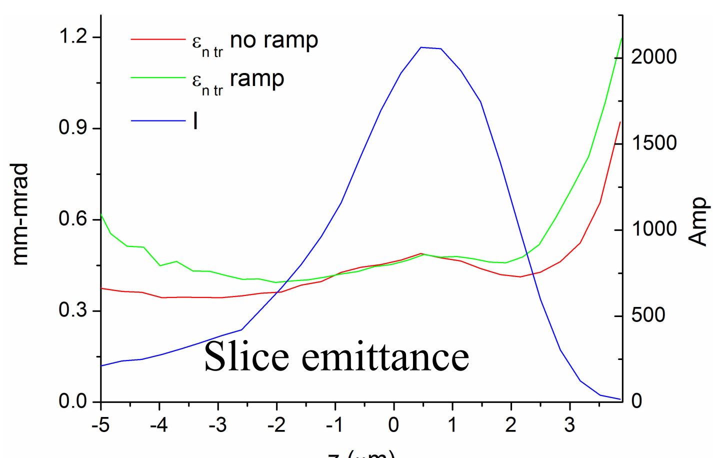


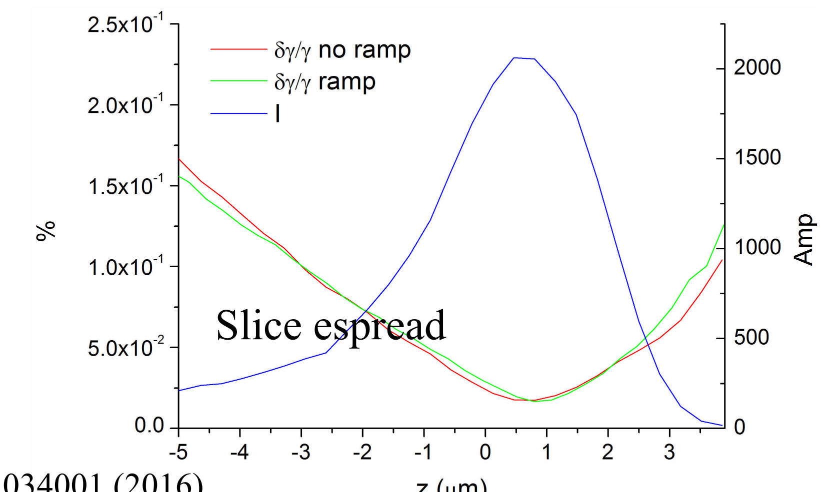
Q-Fluid simulations of LWFA external injection

In the plasma capillary

- Simulations with QFluid[1]
- Plasma density: 10^{17} cm^{-3}
- Plasma plateau length: 6 cm
- Exponential ramp with characteristic length λ_r = 2.5 mm
- Ramps span from 10^{14} to 10^{17} cm^{-3} for a total length L_r = 1.75 cm
- Effective accelerating gradient: 9 GV/m
- $\varepsilon_{n\,tr} = (\varepsilon_{n\,x}{}^2 + \varepsilon_{n\,y}{}^2)^{1/2}$

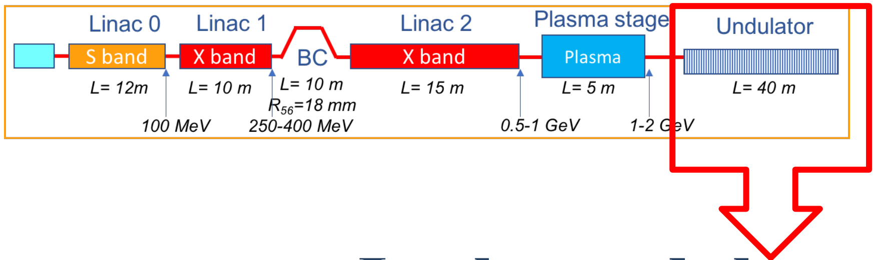
	Input	Output w/o ramp	Output with ramp
E [MeV]	536	1060	1035
ΔE/E	7 10^{-4}	1.2 10^{-2}	7 10^{-4}
$I_{peak\ FWHM}$ [kA]	1,8	1,8	1,8
Q [pC]	30	27	27
$\sigma_{z\ rms}$ [µm]	3,7	3,3	3,3
$\sigma_{z\ FWHM}$ [µm]	3,3	3,2	3,2
$\varepsilon_{n\ tr}$ [mm-mrad]	0,44	0,47	0,47
$I_{peak\ slice}$ [kA]	2,1	2,1	2,1





[1] P. Tomassini and A.R. Rossi, Plas. Phys. Cont. Fus. 58, 034001 (2016).

Courtesy of A. R. Rossi and V. Petrillo

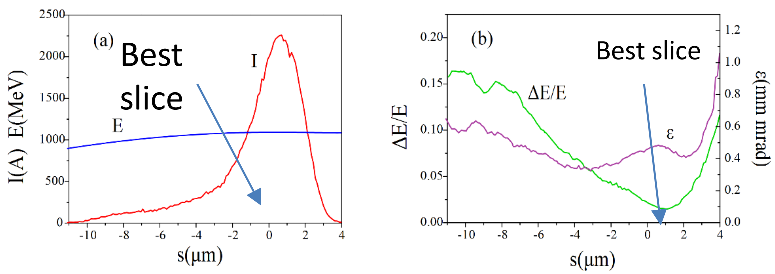


In the undulator

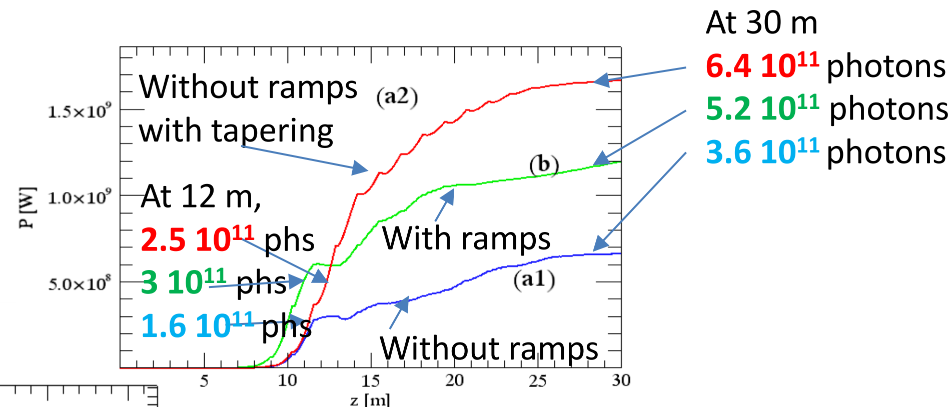
FEL Genesis simulation with **laser driven plasma accelerated electron beams**

Undulator λ_u=1.5 cm, a_w=0.8

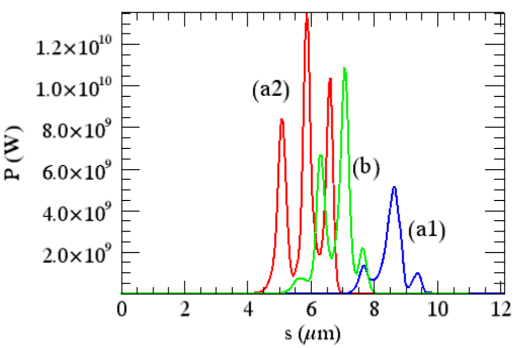
Radiation: λ=2.7 nm E_{phot}=0.45 keV



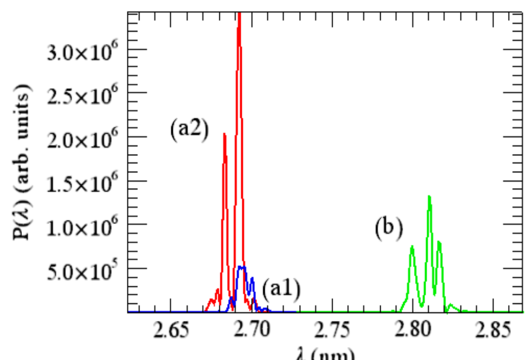
Characteristics of the electron beam, case a1



Growth of the radiation along the undulator



At 15 m, Power density
Quasi-single structure



At 15 m, Spectral density
Quasi-single spike structure

	(a)
Q(pC)	30
ε_x (mmmrad)	0.45
ε_y (mmmrad)	0.49
ΔE/E (10^{-4})	1.54
I_{peak}(A)	2258
z_1(m)	12
E(z_1) (μJ)	12
N_{phot}(z_1) (10^{11})	1.62
z_2(m)	30
E(z_2) (μJ)	27.
N_{phot}(z_1)(10^{11})	3.63
Bandwidth(%)	0.15
Divergence(μrad)	50
Rad. Size (μm)	155

Courtesy of V. Petrillo

FEL simulation with **linac accelerated electron beams, high flux case**

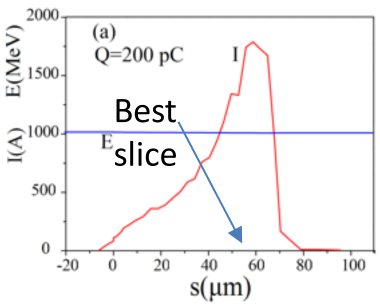
Case with 200 pC

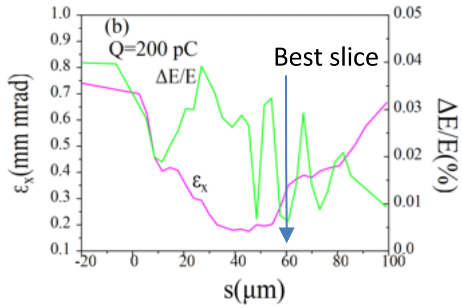
Undulator λ_u=1.5 cm, a_w=0.7

Radiation: λ=2.87 nm
E_{phot}=0.43 keV

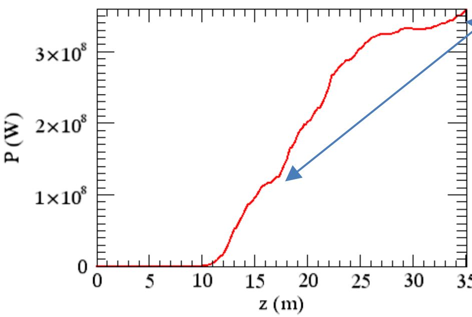
First saturation at 15 m with **9.1 10^{11}** photons

At 35 m, **2.7 10^{12}** photons

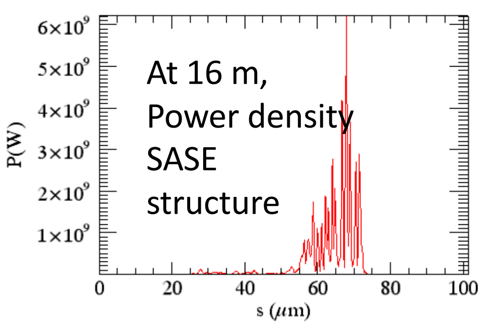


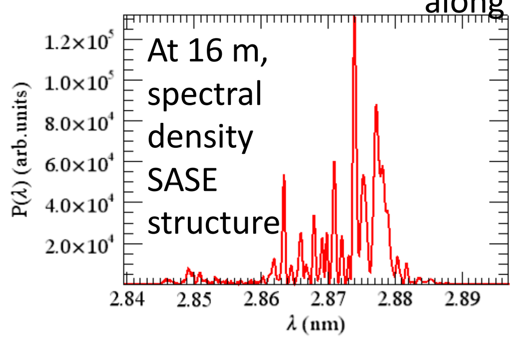


Characteristics of the electron beam



Growth of the radiation along the undulator

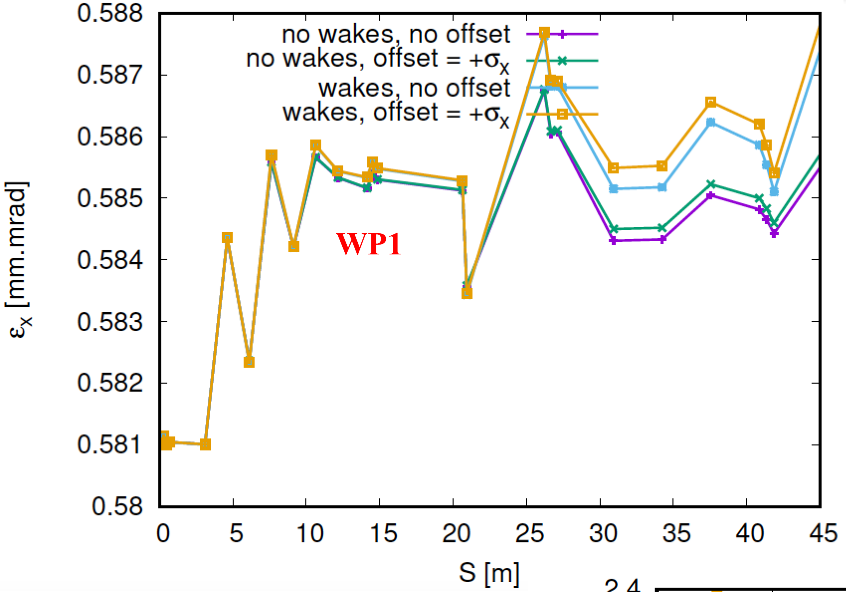


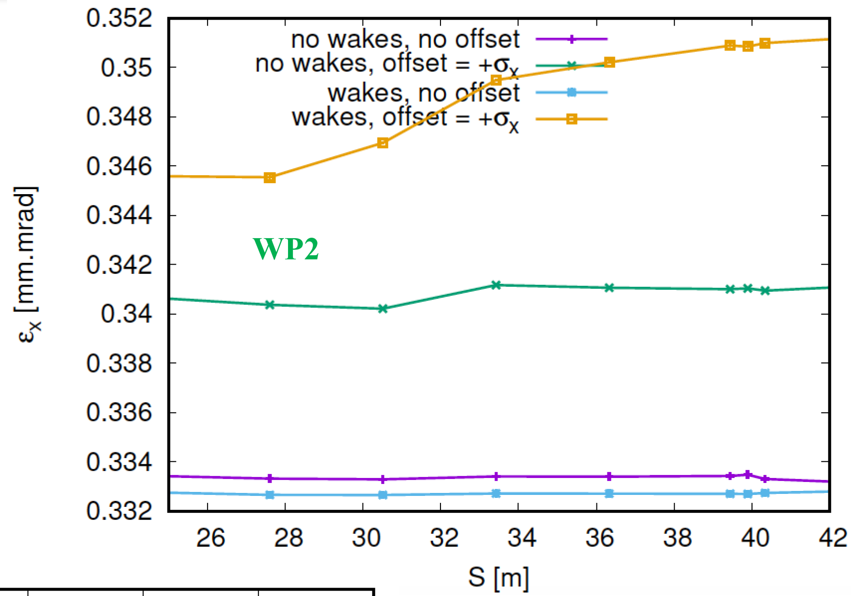


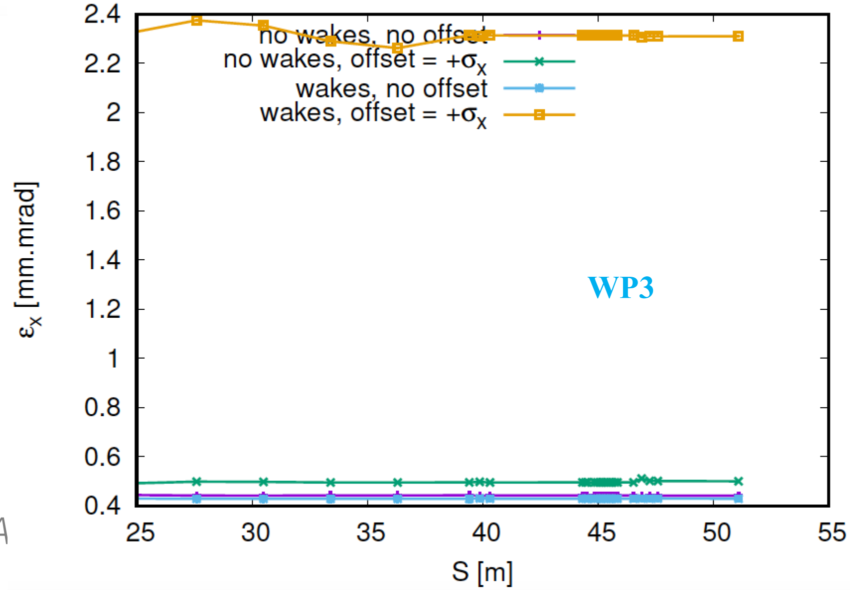
	(b)
Q(pC)	200
ε_x (mmmrad)	4.05
ε_y (mmmrad)	3.75
ΔE/E (10^{-4})	1.8
I_{peak}(A)	1788
z_1(m)	16
E(z_1) (μJ)	64
$N_{phot}(z_1)$ (10^{11})	9.1
z_2(m)	35
E(z_2) (μJ)	192
$N_{phot}(z_1)$(10^{11})	27.5
Bandwidth(%)	0.16
Divergence(μrad)	27
Rad. Size (μm)	220

Courtesy of V. Petrillo

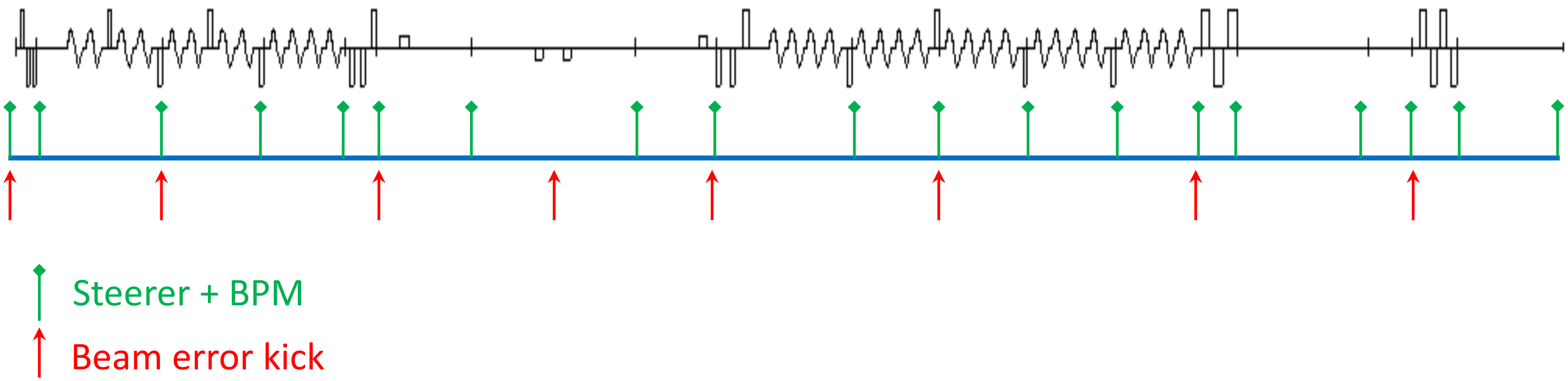
X band structures misalignement effect, Placet code (A. Latina CERN)







Static and dynamic errors simulation:

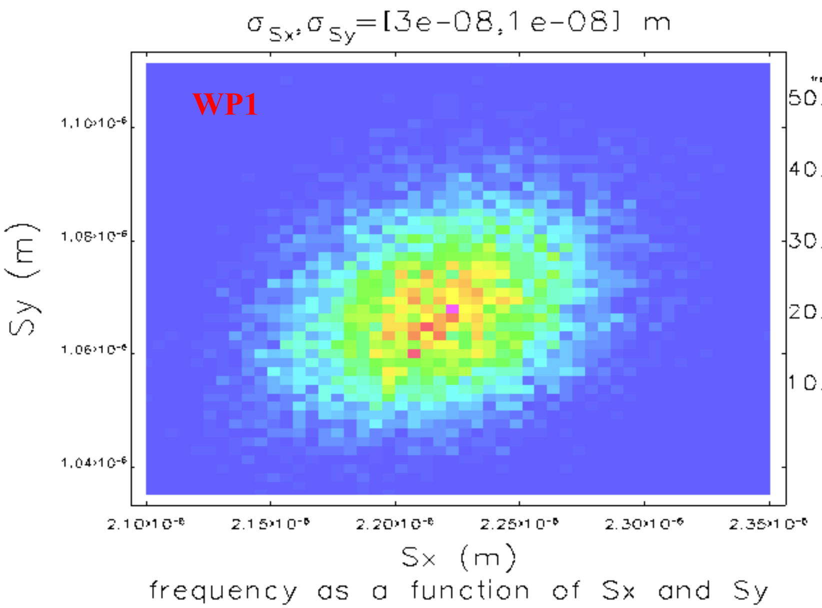


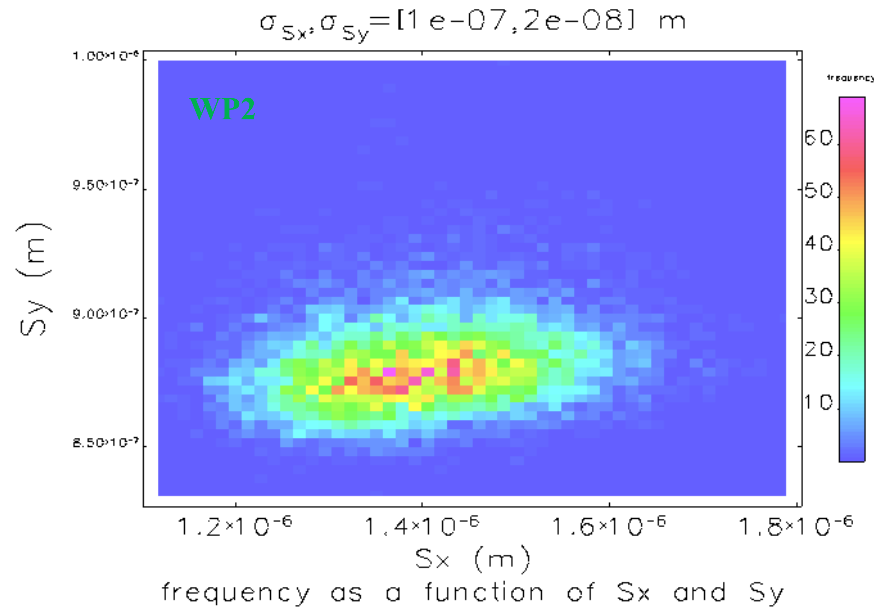
- ✓ Static errors:
  - 70 μm (x ,y) random misalignment on RF's structures and magnetic elements
  - 150 μm misalignment kick to the beam, ex. girder to girder
  - 100 random simulated machines
- ✓ Dynamic errors:
  - Quad strength errors 0.1% rms
  - Sterer kick errors 0.1% rms (1 μrad rms)
  - 100 random machine for each static arrangement

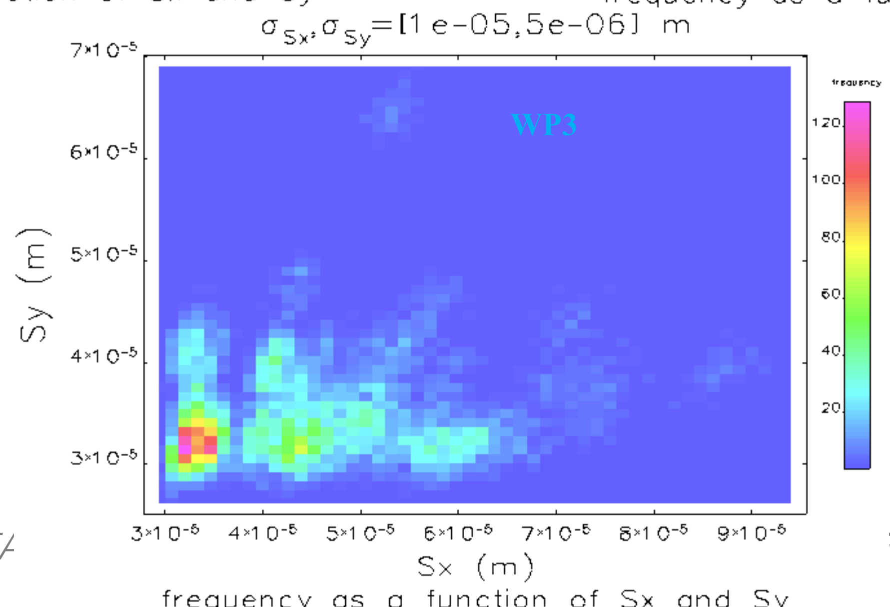
Beam quality parameters:

- End of line (capillary/undulator) entrance:
  - Centroid distribution
  - Beam spot size, emittance & energy spread distribution
- Along the linac:
  - Min,Max & Mean : trajectory, beam size, emittance & energy spread

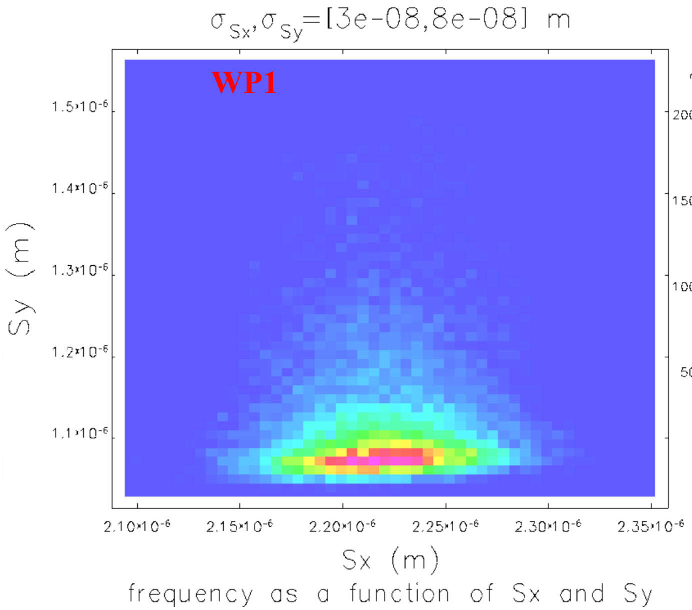
End of line beam size: WP1-2-3 results

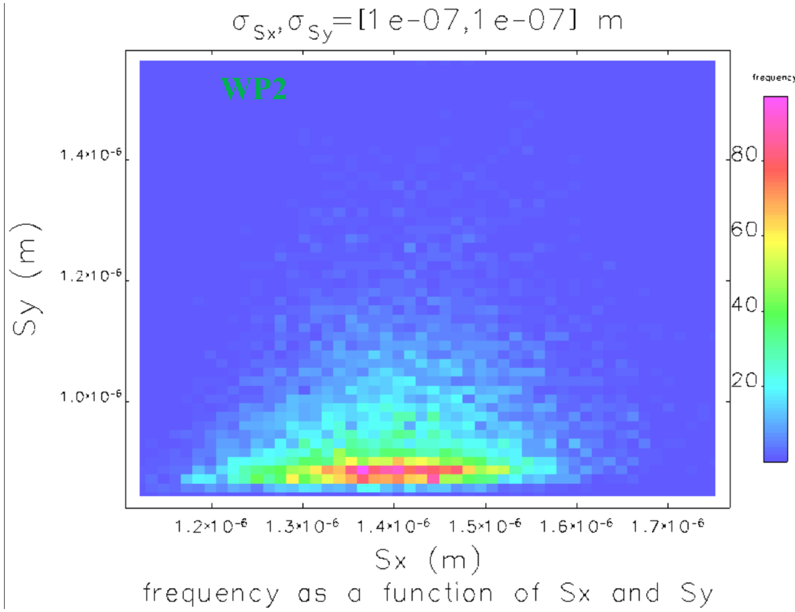


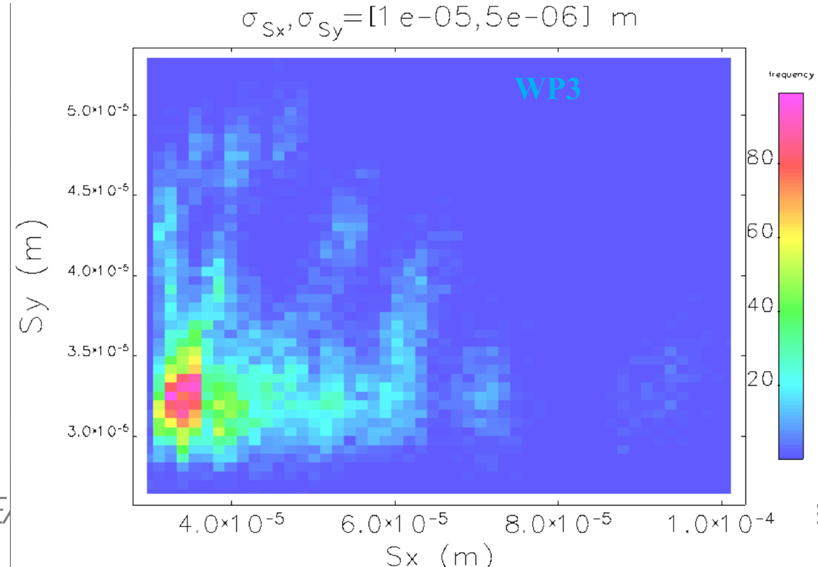




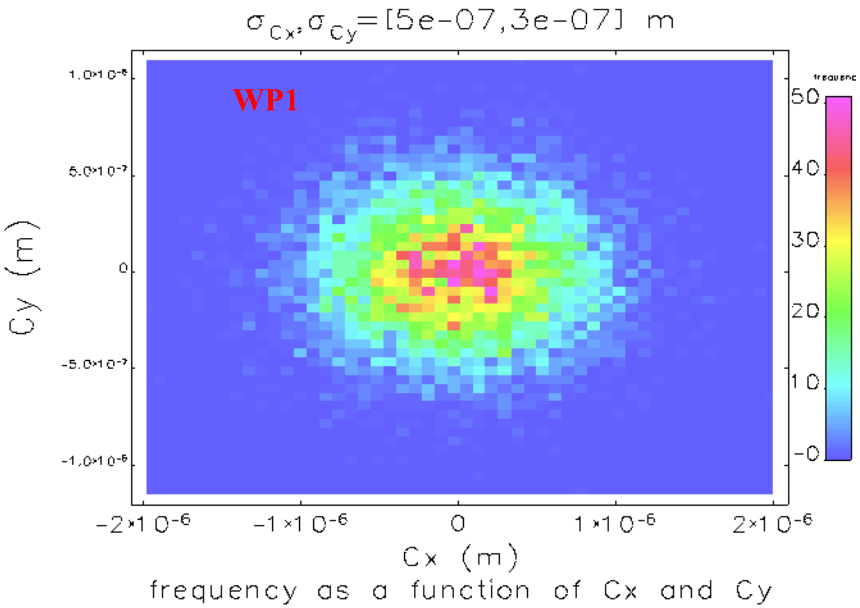
End of line beam size: WP1-2-3 results w BPM misalignment (± 3 μm)

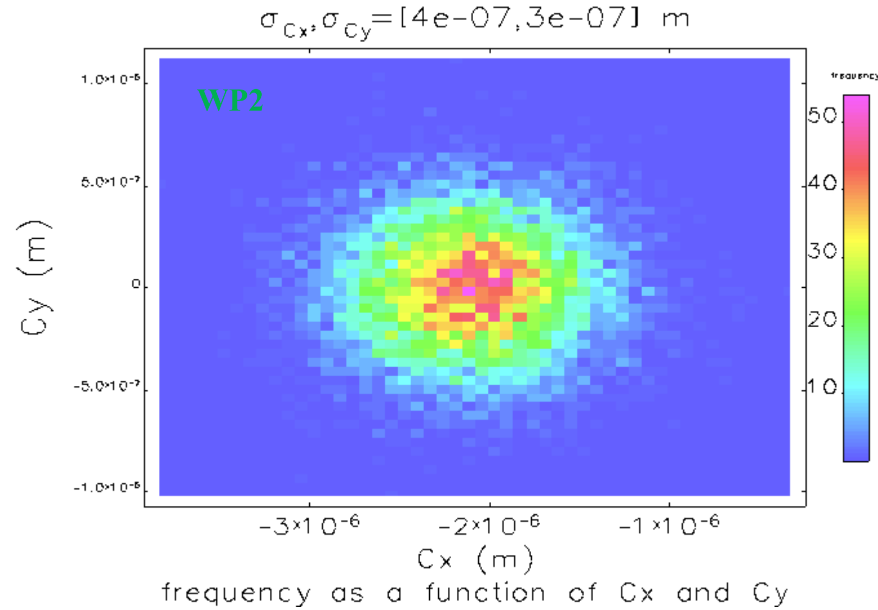


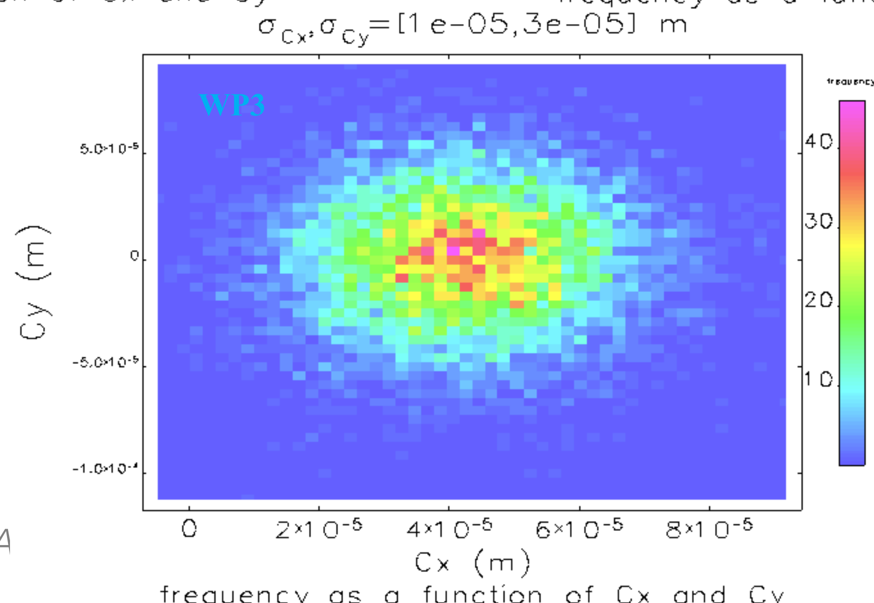




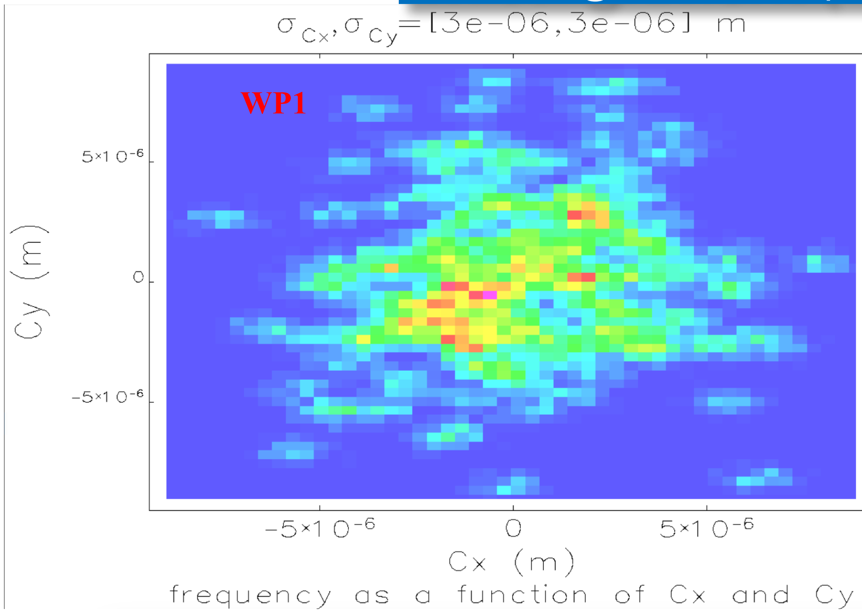
End of line centroid : WP1-2-3 results

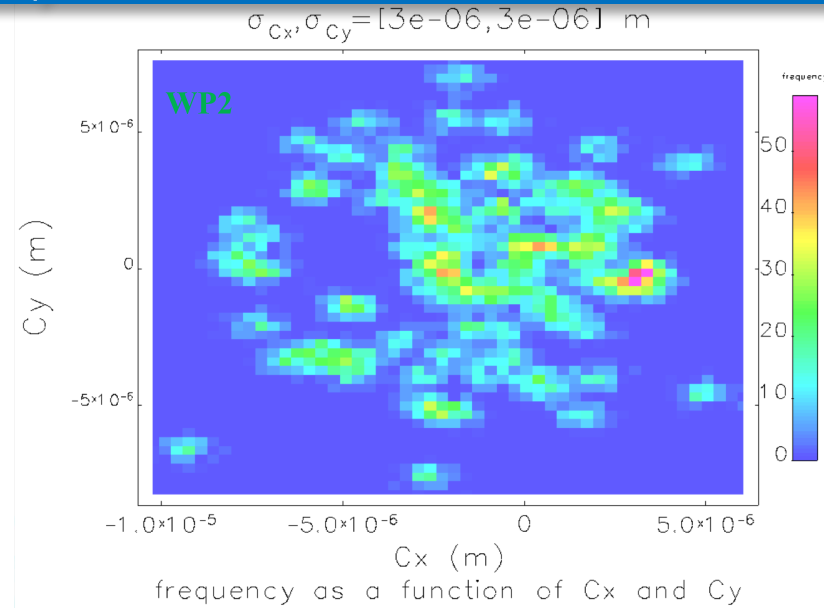


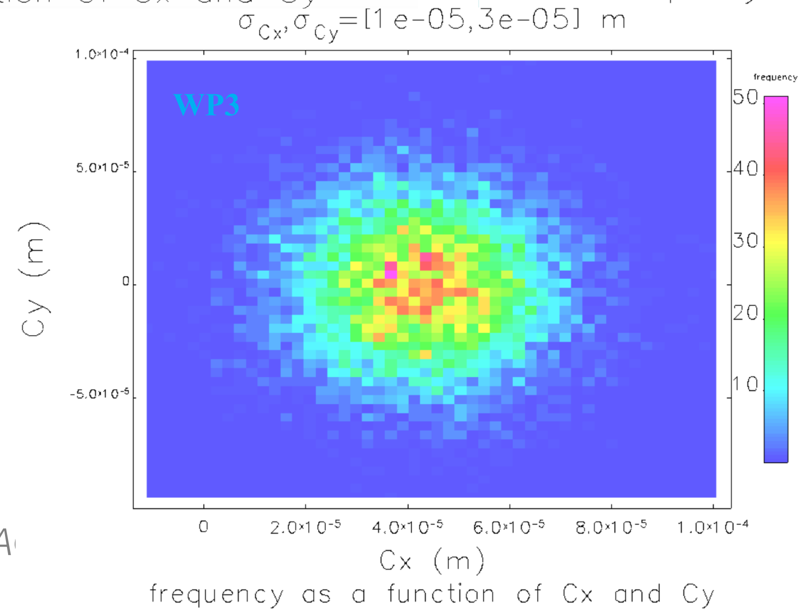




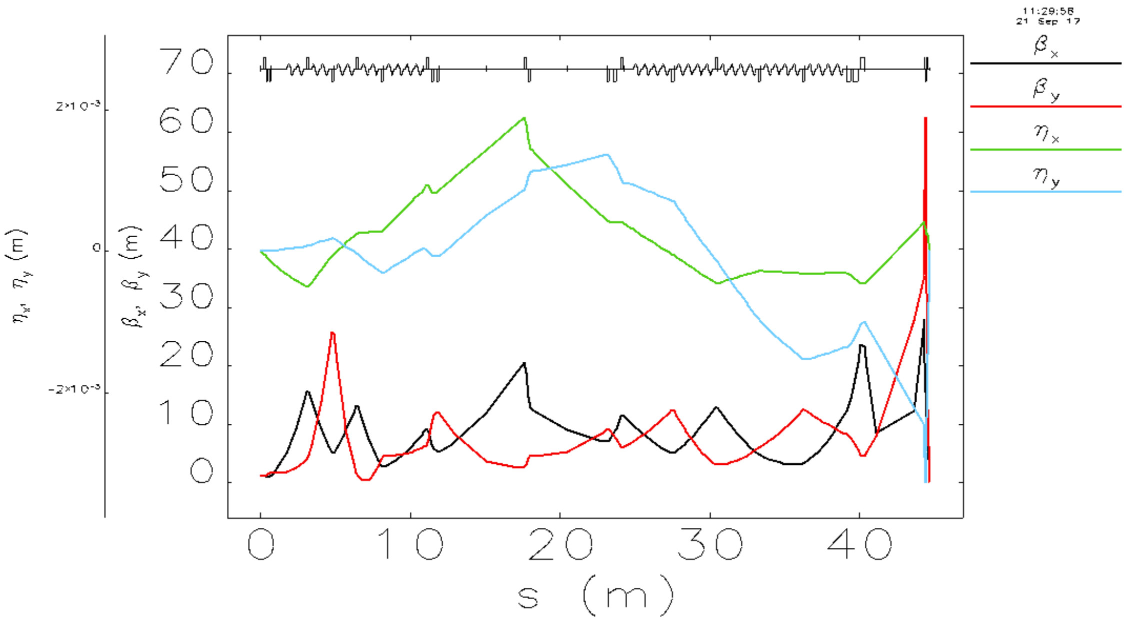
End of line centroid : WP1-2-3 results w BPM misalignment (± 3 μm)



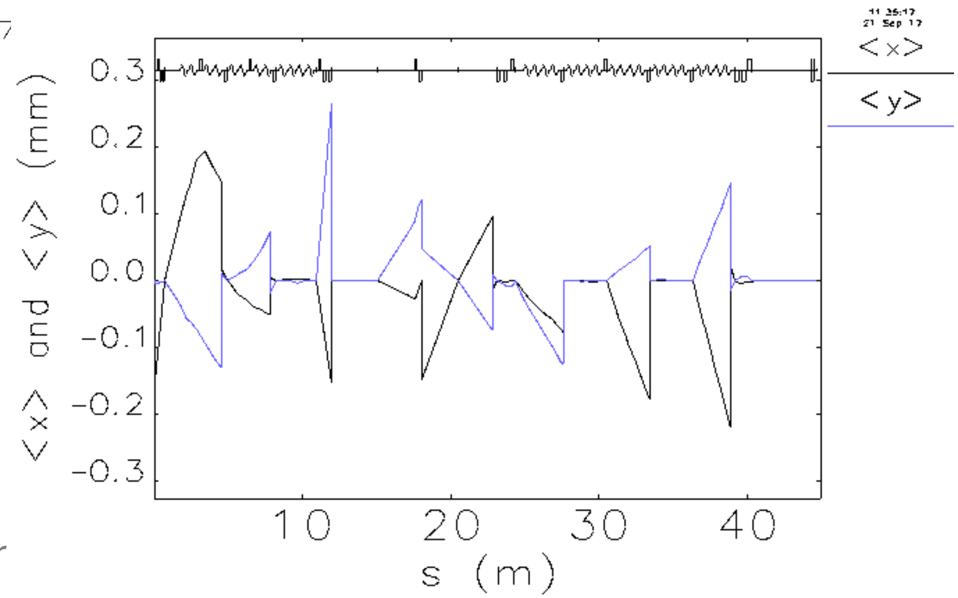




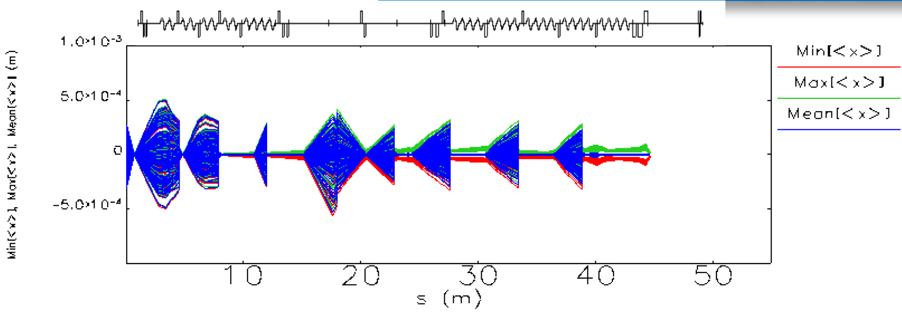
Trajectory steering example wo DSF

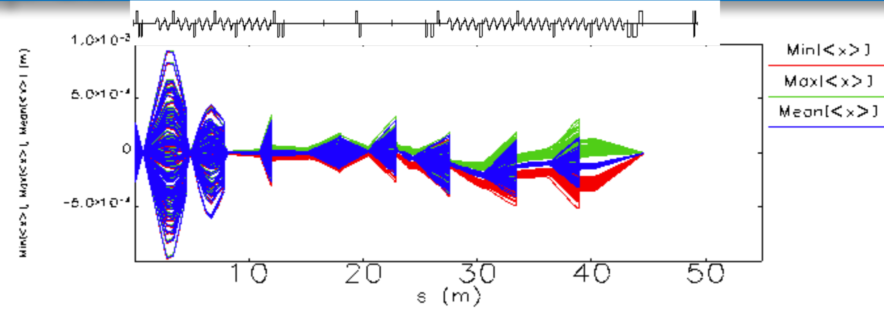


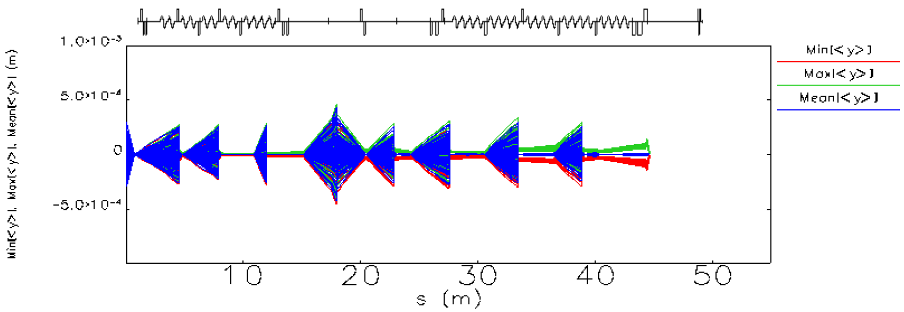
Twiss parameters for run1_WP1C-4425087

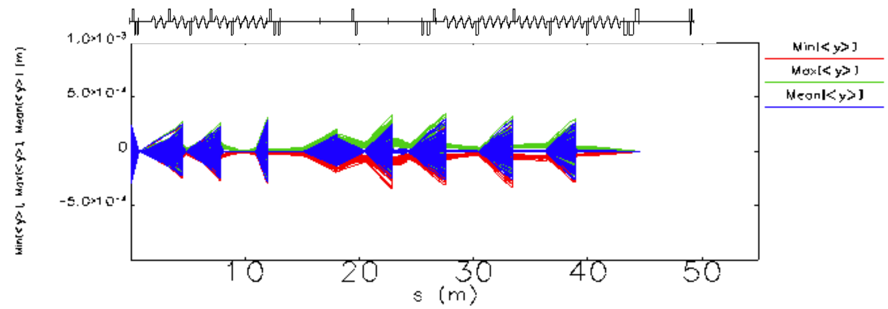


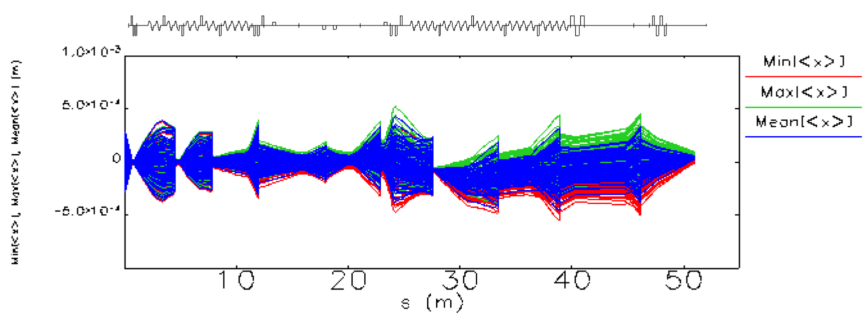
Trajectory envelope: WP1,2,3 results

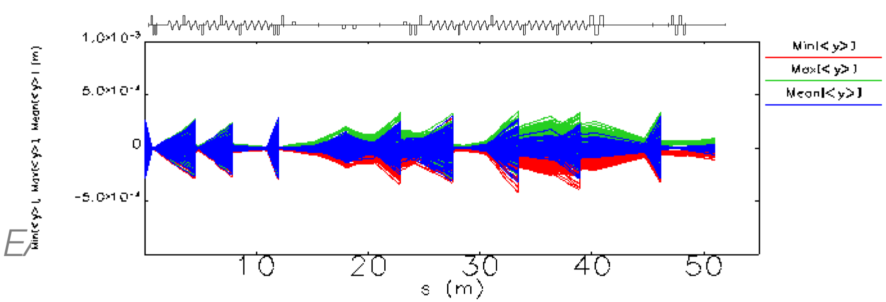




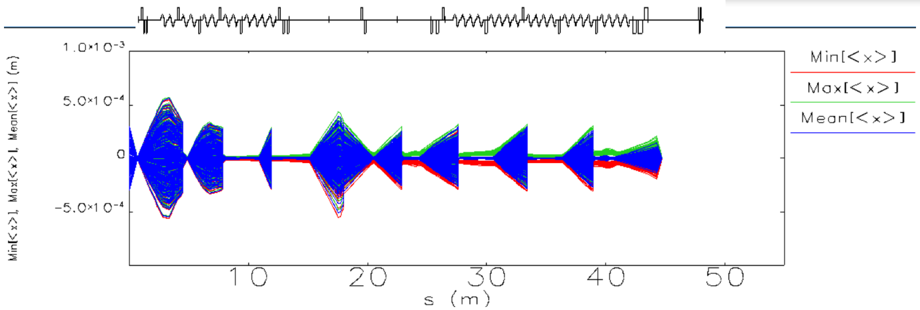


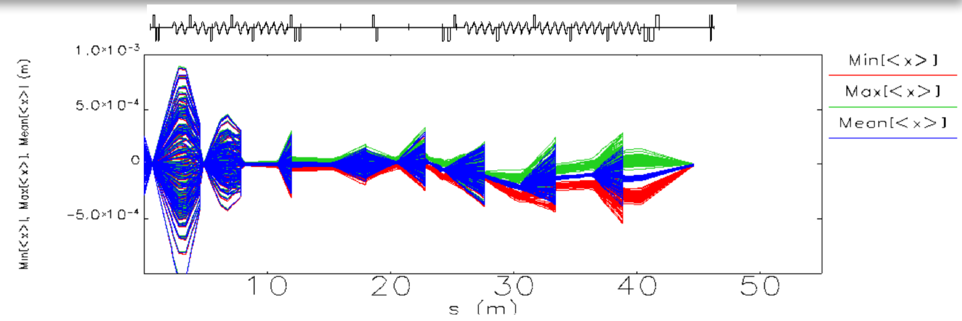


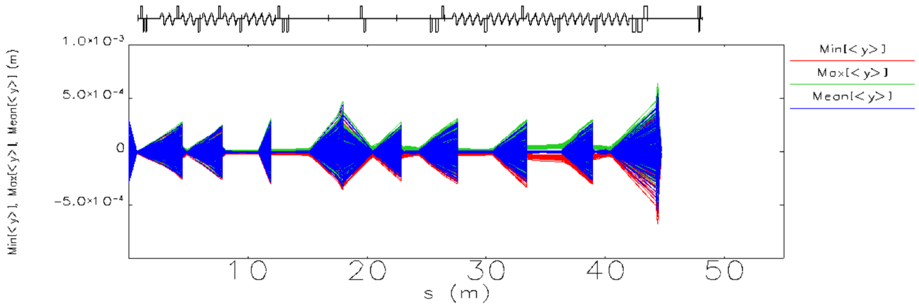


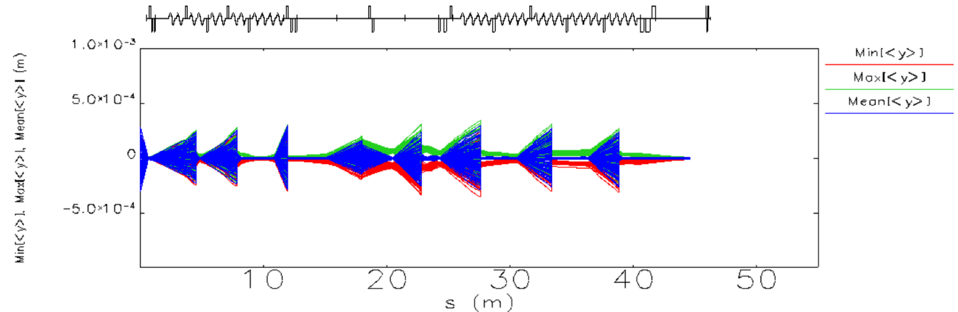


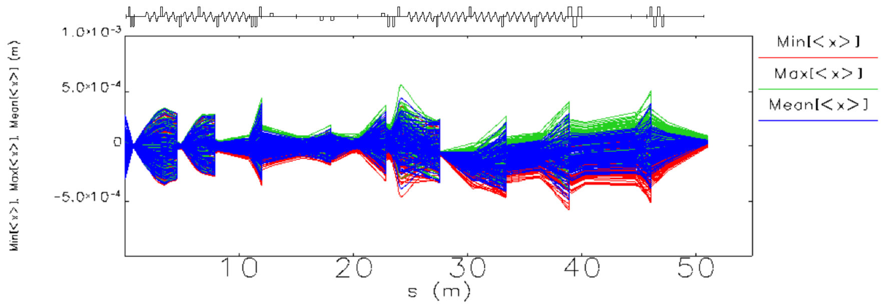
Trajectory envelope: WP1,2,3 results w BPM mis.

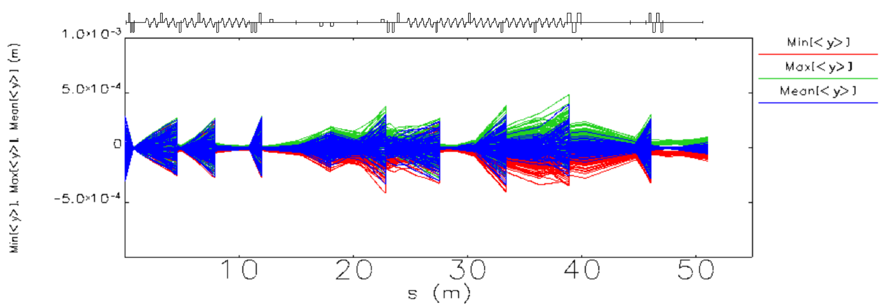




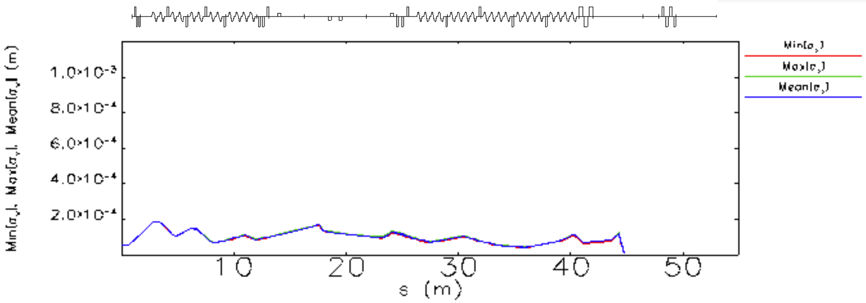


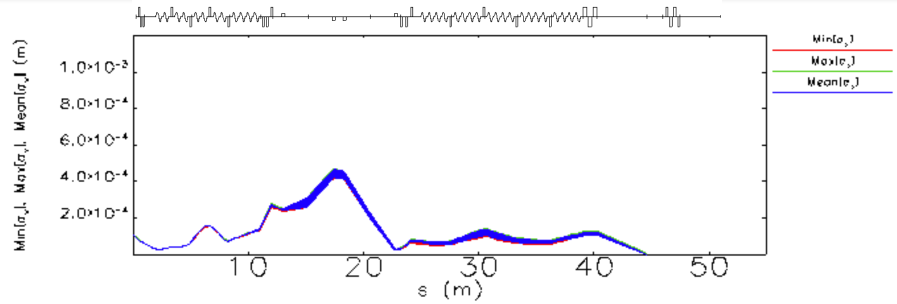


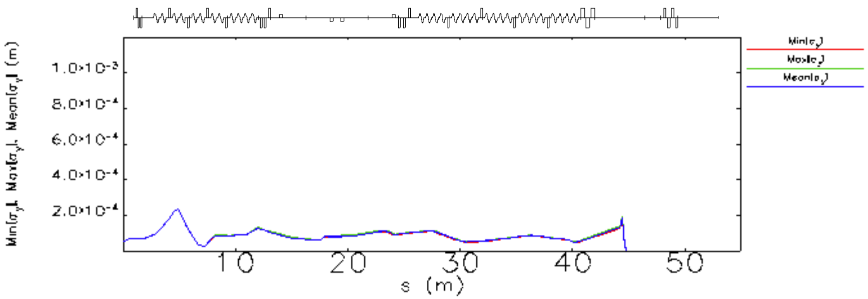


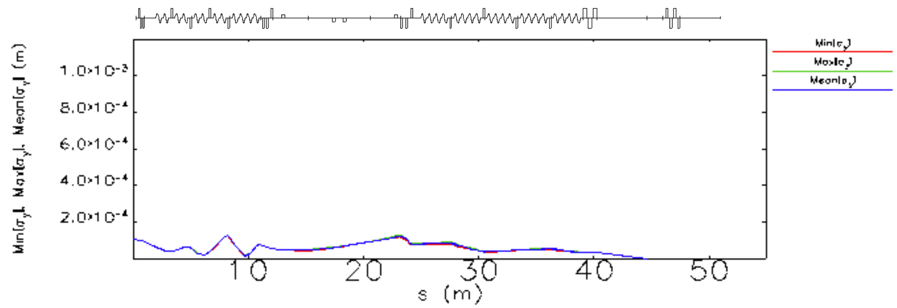


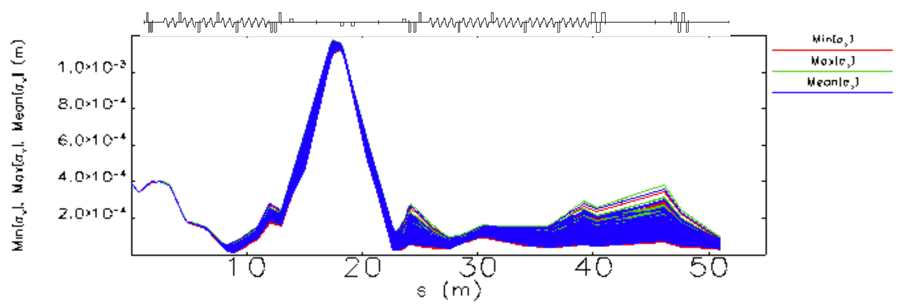
Beam envelope: WP1,2,3 results

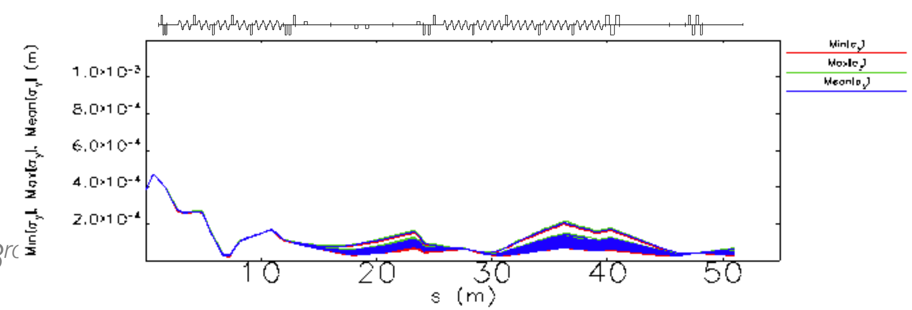




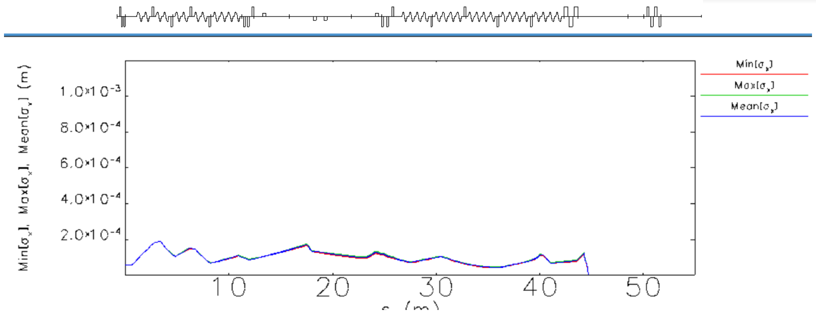


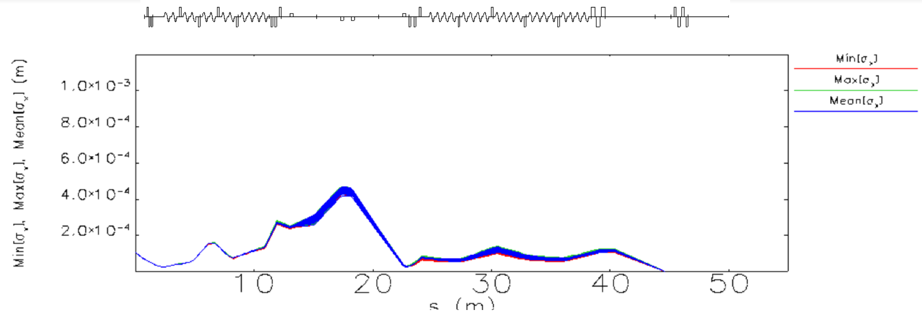


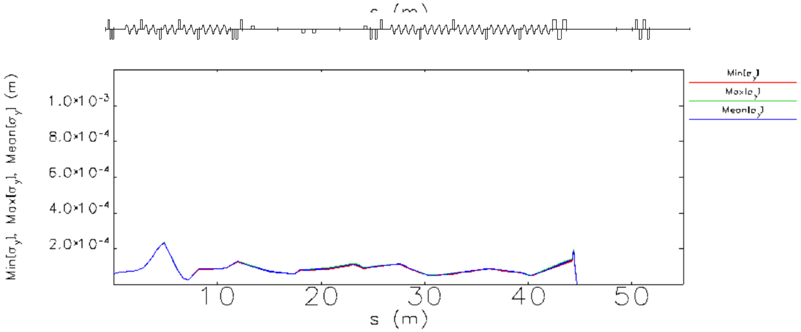


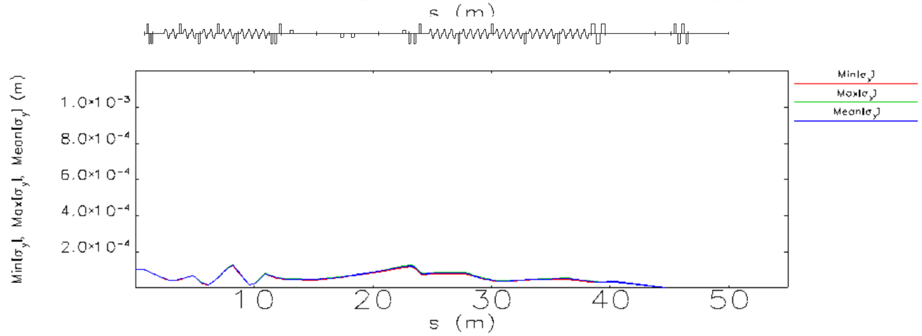


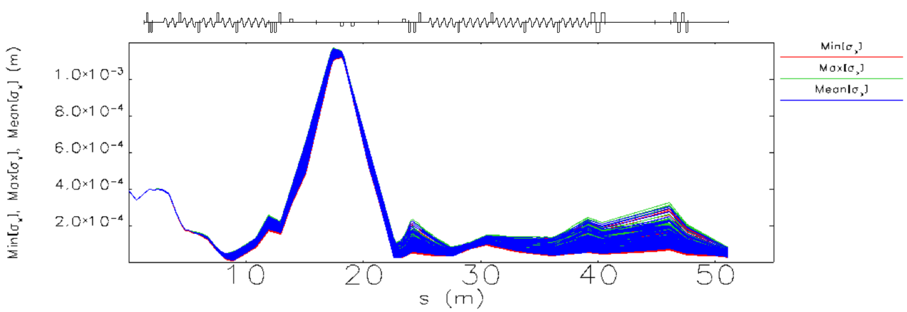
Beam envelope: WP1,2,3 results w BPM mis.

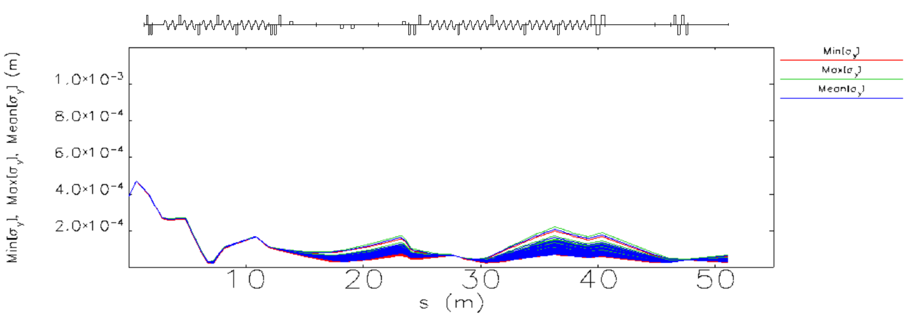




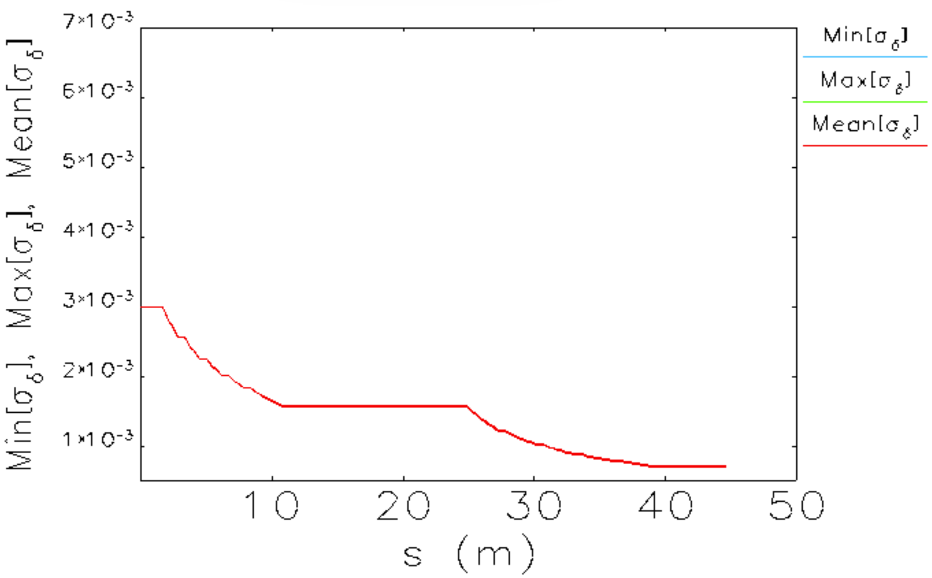


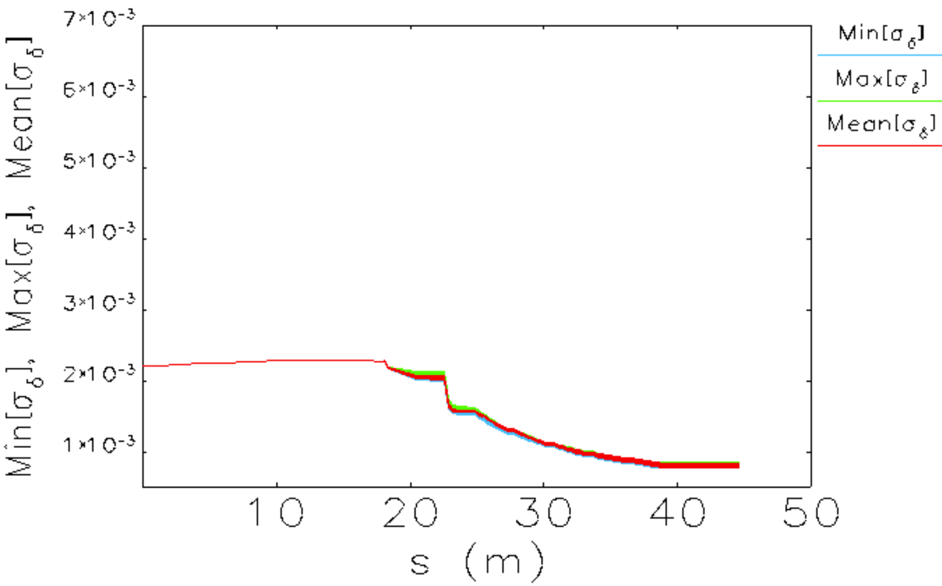


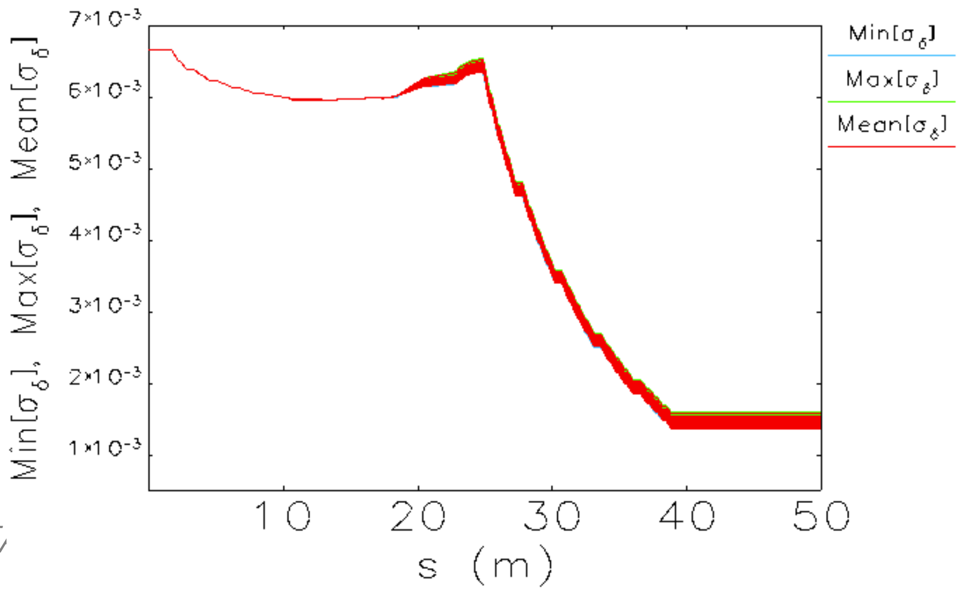




Energy spread along the linac: WP1,2,3 results







Static plus dynamic errors summary table

	WP1 (@capillary in)	WP2(@capillary in)	WP3(@undulator in)
Q (pC)	30	30	200
E (GeV)	0.5	0.5	1.0
σ_{Cx} (μm)	0.5	0.4	10
σ_{Cy} (μm)	0.3	0.3	30
σ_x (μm)	2	1	30
StDevσ_x (μm)	0.03	0.1	10
σ_y (μm)	1	1	40
StDevσ_y (μm)	0.01	0.02	5
σ_{δ} (%)	0.07	0.08	.14

Conclusions

- The X-band Linac for the EUPRAXIA@SPARC_LAB is under design
- This stage focuses on three different WP's nominal requirements and is meant to explore the line acceptance and robustness
- BD studies and FEL simulations have been presented for the nominal cases
- As first test bench the active elements (RF & magnetic) misalignments have been considered.
- These first results give an indication on the required tolerances and machine operation scenario (ex. active element and trajectory feedback) .
- Next steps will include RF phase and amplitude jitters, and Photocathode laser energy and pointing jitters.
- The space charge effects taken into account so far only on the nominal wps will be also considered.

Twiss parameters of the FODO cell for the L1 and L2 linac