EuPRAXIA@SPARC_LAB
Start to end Simulations

C. Vaccarezza
on behalf of WA1- Beam Physics & collaboration team

OUTLINE

- EuPRAXIA@SPARC_LAB parameter list & Linac operation scheme
- Recommendations from TDR-RC report Oct 2021
- WA1 - S2E simulations activity results
- Summary
- Next steps and Conclusions

EuPRAXIA@SPARC_LAB Parameter List

Nominal FEL parameters from CDR

Parameter	Unit	PWFA	Full X-band
Radiation Wavelength	nm	3	
Photons per Pulse	$\times 10^{12}$	0.1	1
Photon Bandwith	%	0.5	1
Undulator Area Length	m	30	
$\rho(1D/3D)$	$\times 10^{-3}$	1	2
Photon Brilliance per shot	$\left(\frac{s\ mm^2 mrad^2}{bw(0.1\%)}\right)$	1×10^{27}	

Electron Beam Parameters

Parameter	Unit	PWFA	Full X-band
Electron Energy	GeV	1	1
Bunch Charge	pC	30	200
Peak Current	kA	1-2	1-2
RMS Energy Spread	%	1.1	0.1
RMS Bunch Length	μm	6-4	24-20
RMS norm. Emittance	μm	1	1
Slice Energy Spread	%	0.03	0.02
Slice norm Emittance	mm-mrad	0.5	0.3

X-BAND LINAC OPERATION

PWFA Working point
The 500 MeV Witness+Driver scheme is adopted with a lattice able to drive the two bunches at the plasma entrance with the required characteristics

From TDR Rev Comm Oct 2021

1.6 Beam Dynamics and Plasma Simulations

Progress with beam dynamics work and simulation was hampered by loss/lack of personnel. However, acquisition and installation of a dedicated computer cluster and progress with the plasma code Architect will contribute to generating faster and better simulation results.

Achieving proper drive-witness timing, incoming energy (pre-)chirp of the witness bunch, small final energy spread and matching to the plasma remains challenging. The design of the beam line before the plasma, number of S- and X-band structures, compression schemes and general geometry are still not well defined. Reaching parameters to lase at 3 nm is still a challenge, possibly leading the decision to shift the lasing wavelength to 4 nm to be less demanding on bunch parameters. Tolerance studies will be key to determine possible parameters, and need to be performed soon.

The RC recommends that beam dynamics and plasma simulations remain a major effort for the project. Adequate resources and personal must be provided for this key activity. This is essential to make macroscopic decisions regarding beam line geometry and equipment.

WA1-S2E simulations activity up to now

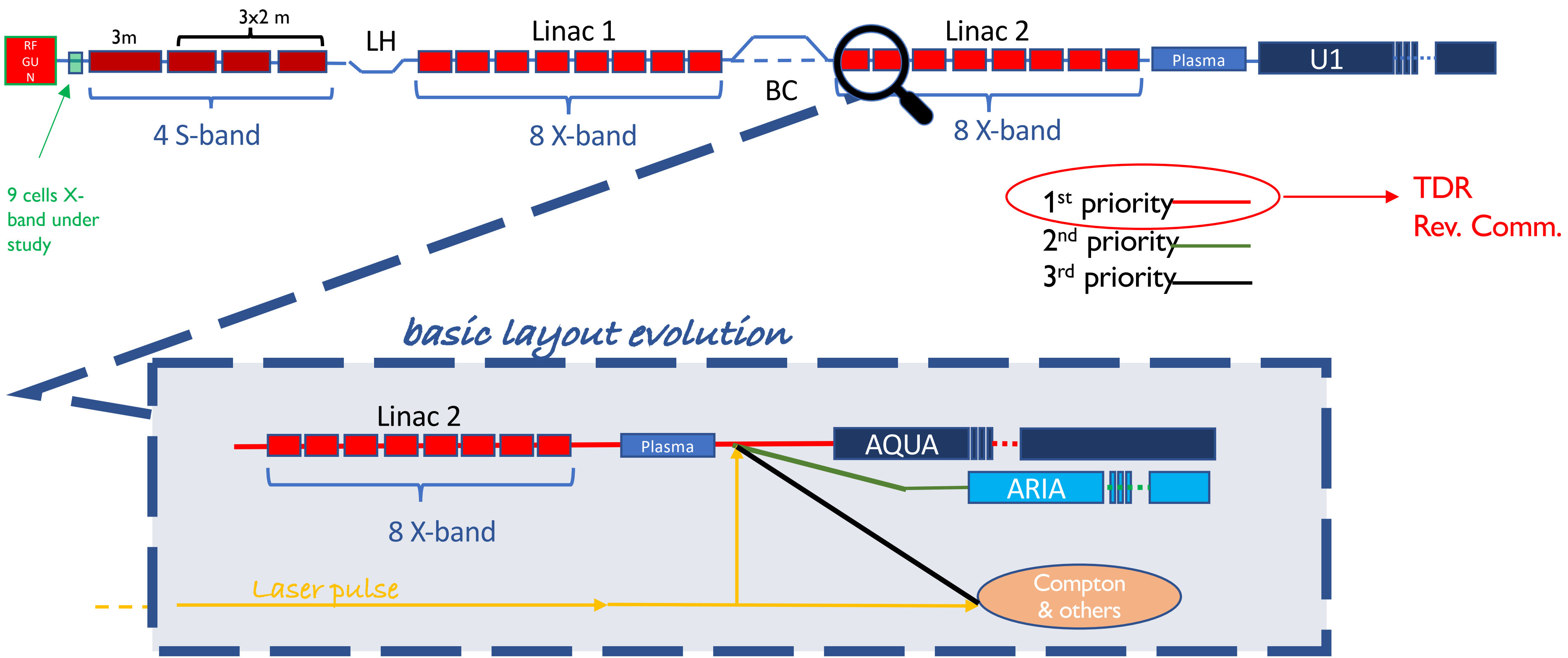
Within the following b.c.

- A total of 2.8 FTE available for the three WP1-2-3 averaging among the SPARC_LAB, INFN-MI, ELI_NP activities
- Computing Resources upgrade available from October 2021

The activity has been concentrated on the optimization of the electron beam for the acceleration in plasma in the Comb scheme and the main topics have been identified and addressed in parallel with iterative steering between the blocks:

- Photoinjector and Linac Optimization in terms of frequency, number of accelerating structures and RF distribution system
- X-band structure at the Gun exit for beam shaping and linearization
- Beam quality control at the plasma exit: energy spread, transverse emittance
- Space charge effects in the matching upstream and downstream the plasma module
- Architect code parallelization for simulations in plasma

THE BASIC LAYOUT-APRIL 2022



PHOTOINJECTOR OPTIMIZATION

In the CDR we got the 3x3m S-band scheme:

the goal was decreasing the L_{eff} to fit the building:

- 1st step = (2x3m S band+ 2x1m X band): good beam quality for the COMB beam non so much for the *"all RF"* solution, but mostly "odd" constraints on the RF distribution system

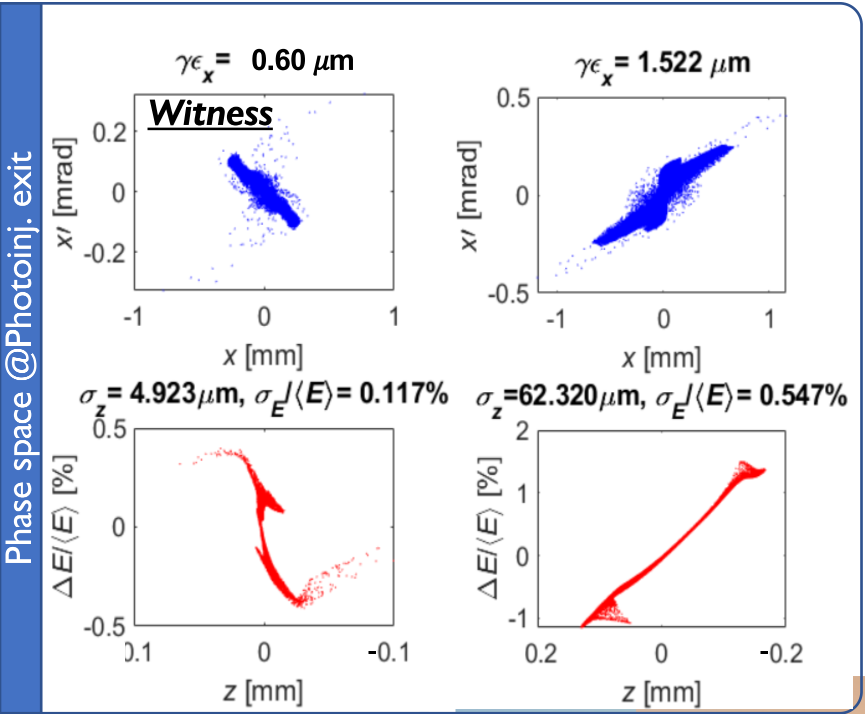
then thanks to <u>raised S-band accelerating gradient 25 to 35MV/m in a 2m section</u>:

- 2nd step = (4x2m) ***vs*** (3m+3x2 m) S-band

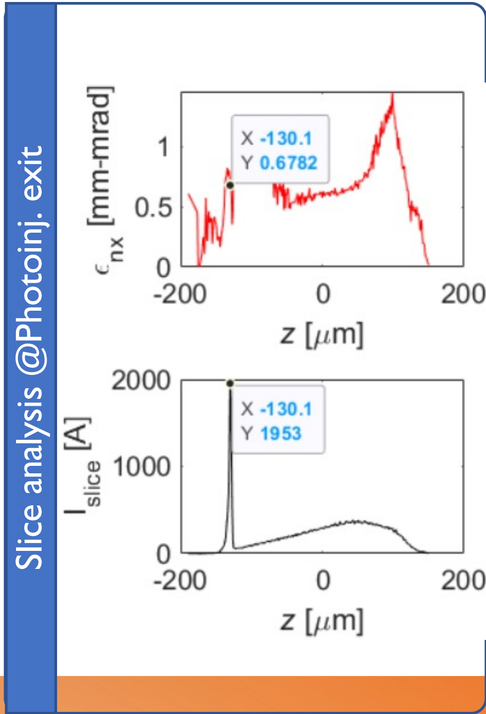
The latter is now the reference scheme even though some work is still in progress to complete the comparison work regarding the small X-band insertion at the Gun exit

UPDATED REFERENCE LAYOUT: 30+200PC AT PHOTOINJECTOR EXIT

A. Giribono



Beam parameters @Photoinj exit		
	Witness	**Driver**
E [MeV]	124.75	126.46
$\varepsilon_{x,y}$ [mm mrad]	0.60	1.52
$\sigma_{z\text{-rms}}$ [µm]	4.923	62.320
ΔE/E [%]	0.117	0.547
Δt [µm] (ps)	151.5 (0.505)	
$\sigma_{x\text{-rms}}$ [µm]	118	127
$\beta_{x,y}$ [mm]	6.127	2.609
$\alpha_{x,y}$	2.475	-1.534

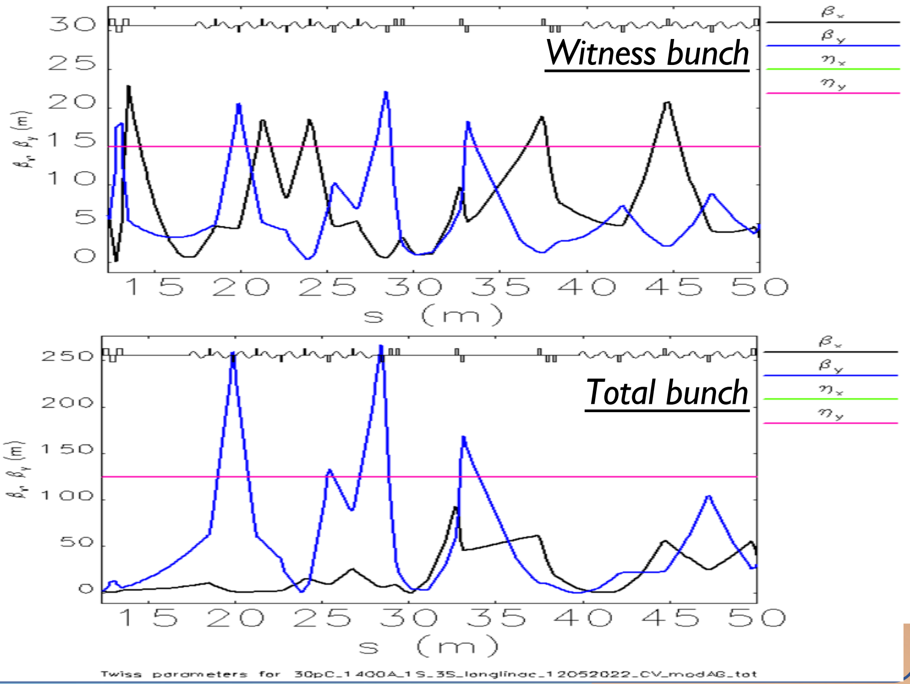


UPDATED REFERENCE LAYOUT: 30+200PC – ALONG THE XBAND LINAC

- The beams have been tracked along the X-band linac (Elegant code)

A. Giribono

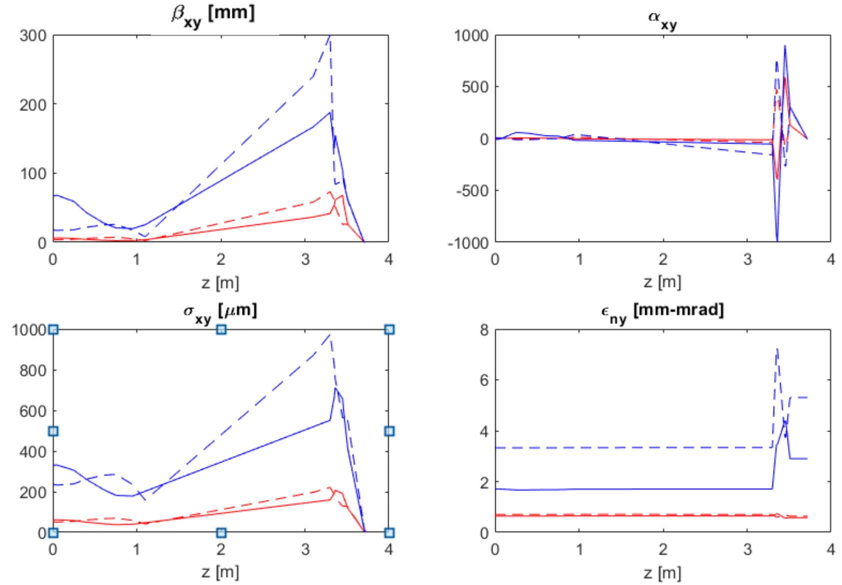
X-band linac with Elegant



Final focusing with TStep

Witness- Red lines

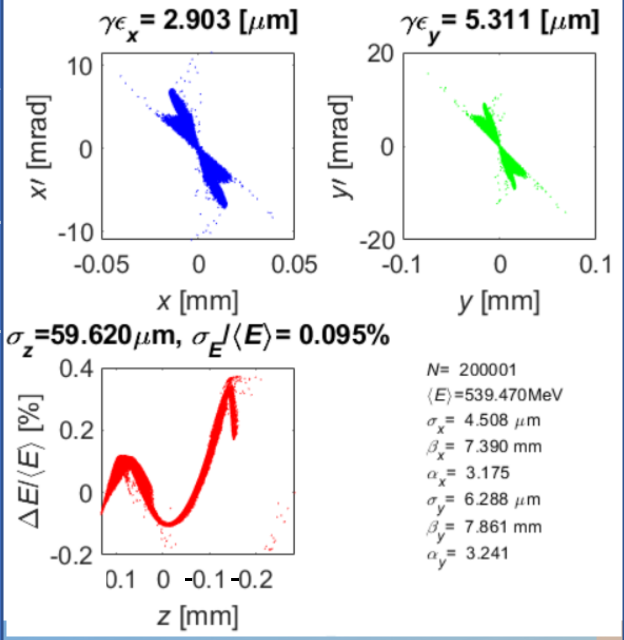
Driver – Blu Lines



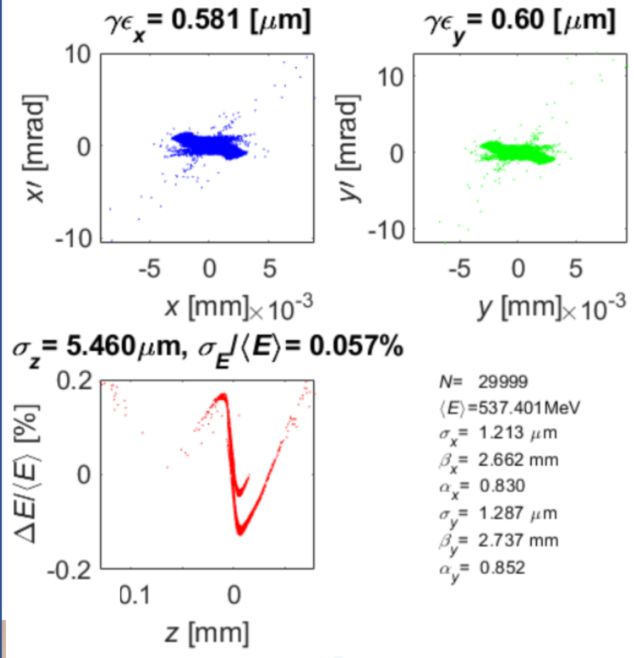
UPDATED REFERENCE LAYOUT: 30+200PC – AT PLASMA INJECTION

- The beams line matching has been performed with Mad8 and TRACE3d
- Then the beams have been tracked with Tstep (Commercial Parmela evolution)

Driver Phase space @plasma inj



Witness Phase space @plasma inj

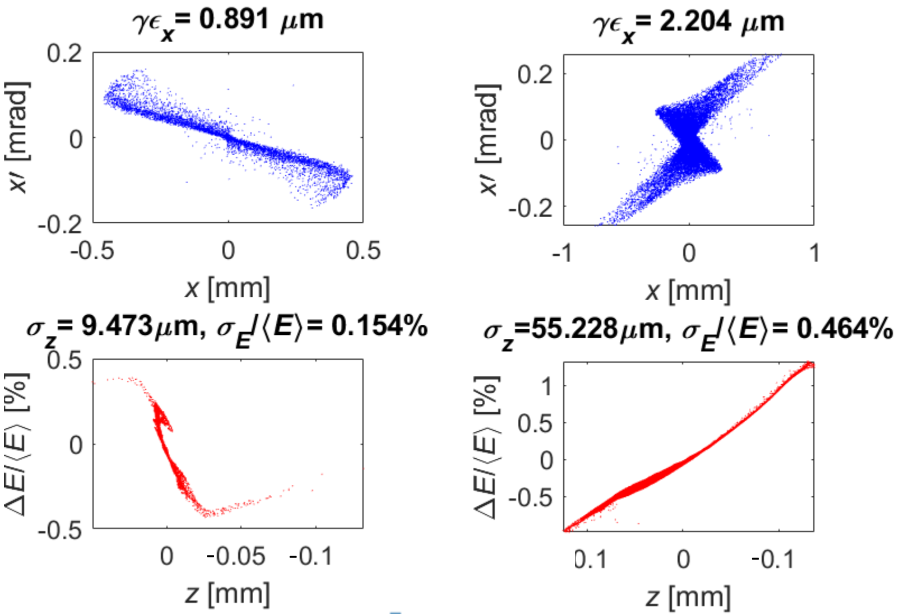


Beam parameters @Plasma inj.

	Witness	Driver
E [MeV]	537.6	539.5
$\varepsilon_{x,y}$ [mm mrad]	0.58-0.60	2.9-5.3
$\sigma_{z\text{-rms}}$ [μm]	5.460	59.620
ΔE/E [%]	0.057	0.095
Δt [μm] (ps)	151 (0.505)	
$\sigma_{x\text{-rms}}$ [μm]	1.2-1.3	4.5-6.3
$\beta_{x,y}$ [mm]	2.7-2.7	7.4-7.8
$\alpha_{x,y}$	0.83-0.85	3.2-3.2

Updated Reference Layout: Higher charge Q=50+200pc

- Op#3: One 3 meter-long plus 3x2meter long acc. sections
- Starting from nominal WoP1 (see CDR) with Δt=164 µm, a WoP1 has been generated with Δt between 148 and 164 µm.



Beam parameters @Photoinj exit		
	Witness	Driver
E [MeV]	124.306	125.834
$\varepsilon_{x,y}$ [mm mrad]	0.89	2.204
$\sigma_{z\text{-}rms}$ [µm]	9.473	55.228
ΔE/E [%]	0.154	0.464
Δt [µm]	150.08	
$\sigma_{x\text{-}rms}$ [µm]	245	139
$\beta_{x,y}$ [mm]	13.372	2.145
$\alpha_{x,y}$	**3.113**	**-0.567**

A. Giribono

X-band insertion: WPs comparison (Driver 200 pC – Witness 30 pC)

Astra code allows to use **m**acro-**p**articles (**mp**) with different weights
we used 10k mp for the Driver and 5k mp for the witness (in total 15k mp tracked).

A. Bacci, L. Faillace

A)	Injector layout: 2+2+2+2	No X- band		from scratch
B)	" " 2+2+2+2	TW X-band	x-iris from 6 → 4 mm	from scratch
C)	" " 2+2+2+2	SW X-band	x-iris rad from 6 → 4 mm	optimization from B
D)	" " **3**+2+2+2	SW X-band	x-iris rad from 6 → 4 mm	optimization from B

Case D still on going

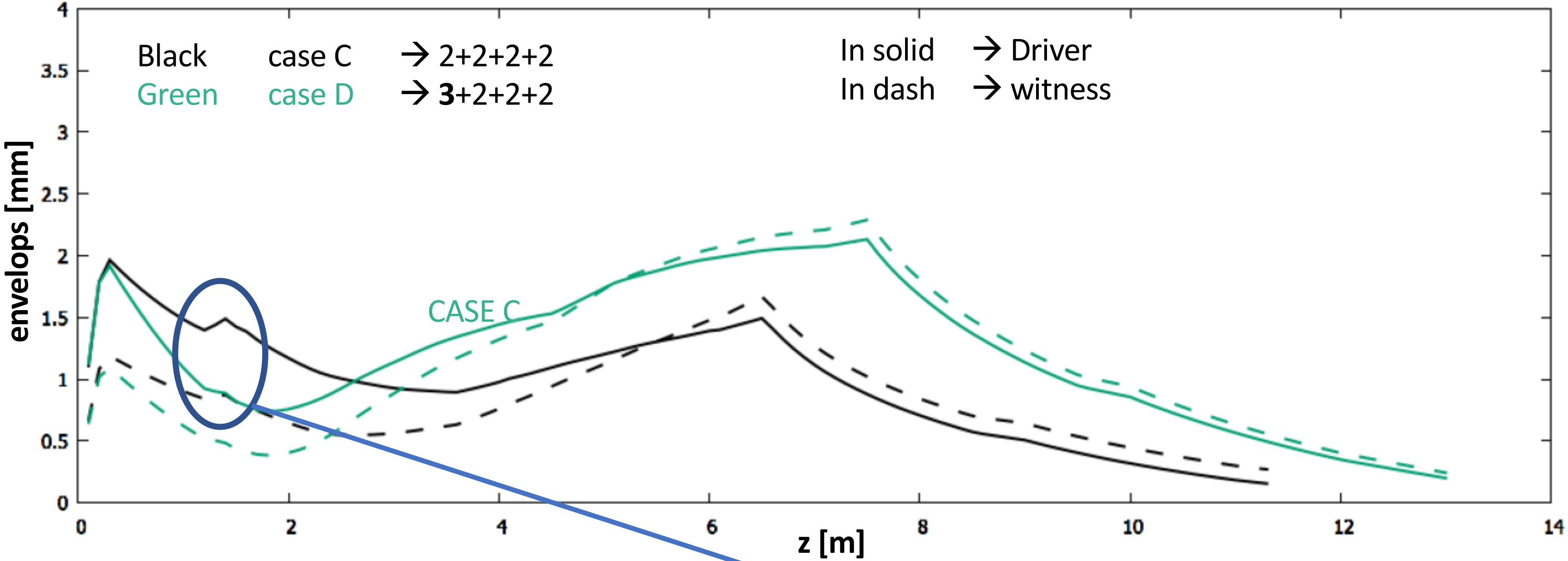
	Driver 200 pC			Witness 30 pC				Full Beam	
	σ_x	σ_z	$\varepsilon_{n,x\text{-}y}$	σ_x	<I>	σ_z	$\varepsilon_{n,x\text{-}y}$	<E>	Δ_z
	μm	μm	mm mrad	μm	kA	μm	mm mrad	MeV	μm
A) WP 4 – 2222	**218**	**55.0**	**1.54**	**522**	**1.00**	**2.6**	**0.43**	**102**	**150**
B) WP-X 3 TW – 2222	**112**	**55.0**	**2.68**	**229**	**0.80**	**3.2**	**0.32**	**166**	**150**
C) WP-X 4 SW – 2222	**106**	**55.0**	**2.78**	**220**	**0.77**	**3.3**	**0.34**	**167**	**149**
D) WP-X 5 SW – **3222**	**200**	**55.0**	**3.2**	**240**	**0.67**	**3.8**	**0.43**	**170**	**200**

Check Traffic light colors: green – Yellow – red

X-band help to:
reduce beam spot size @ injector end; find higher exit energy; control the witness emittance

@ moment the best case seems the SW X-band 2+2+2+2, but 3+2+2+2 is still ongoing. Let's see the differet interesting behaviour

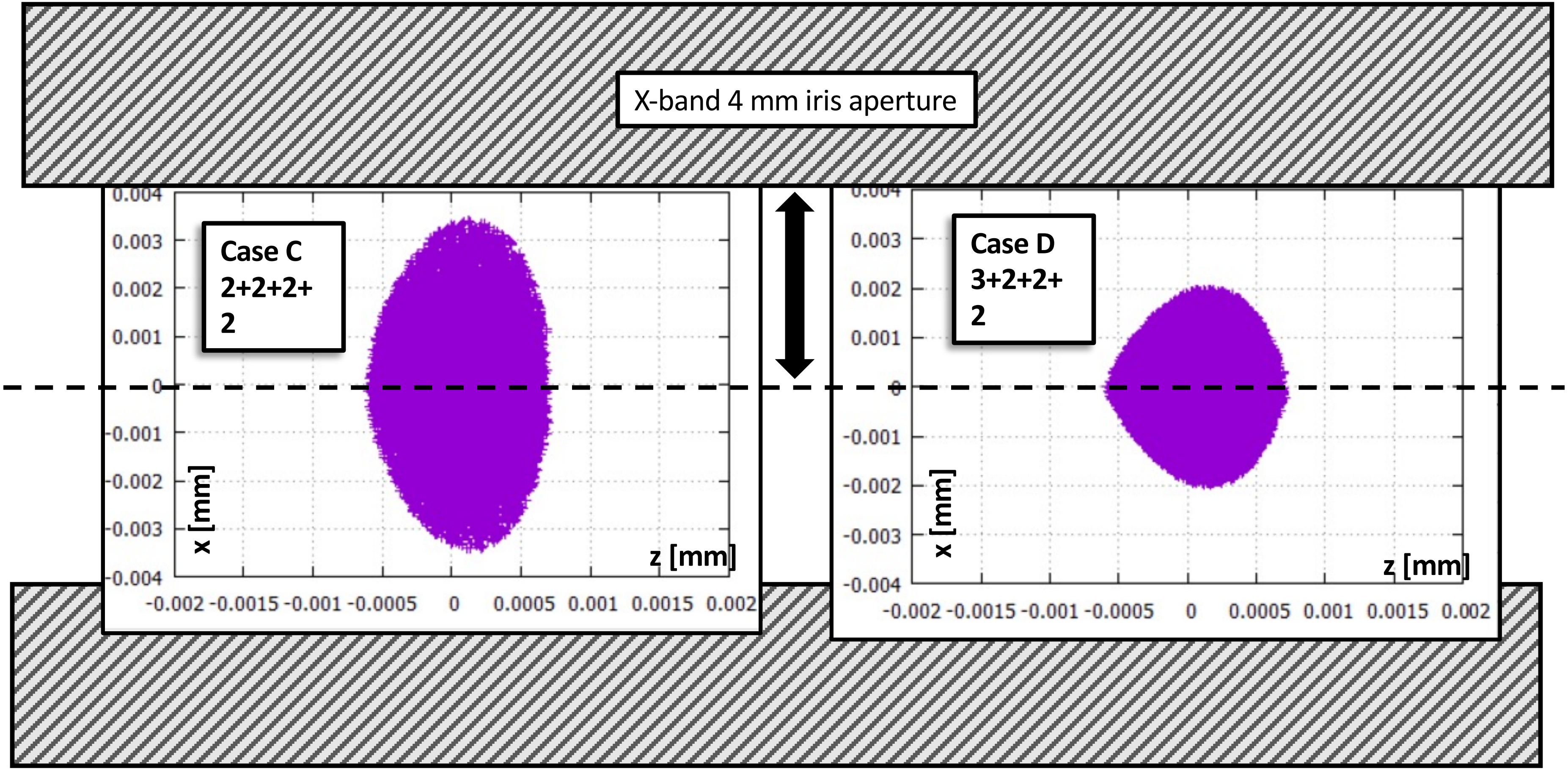
A. Bacci



It evident the defocusing effect of the X-band

CASE C – has a dynamic with larger envelops @ X-band – anyway the whole bunch passes the irises
CASE D – much better to host the X-band

A. Bacci



X-band 4 mm iris aperture
Case C
2+2+2+2
Case D
3+2+2+2
x [mm]
z [mm]
0.004
0.003
0.002
0.001
0
-0.001
-0.002
-0.003
-0.004
-0.002 -0.0015 -0.001 -0.0005 0 0.0005 0.001 0.0015 0.002

Some conclusions

Case A, The solution without X-band – 2+2+2+2 is critical for two main reason, a very large spot at the injector exit and an energy low: 100 MeV vs 160 MeV with x-band.

The X-band helps to:

- reduce beam spot size @ injector exit; find a higher exit energy; a lower witness emittance
- the SW and TW give very similar results.

Case D – 2+2+2+2:

at the moment meets all criteria it is a ready solution into the desk for 200pC driver and 30 pC Witness

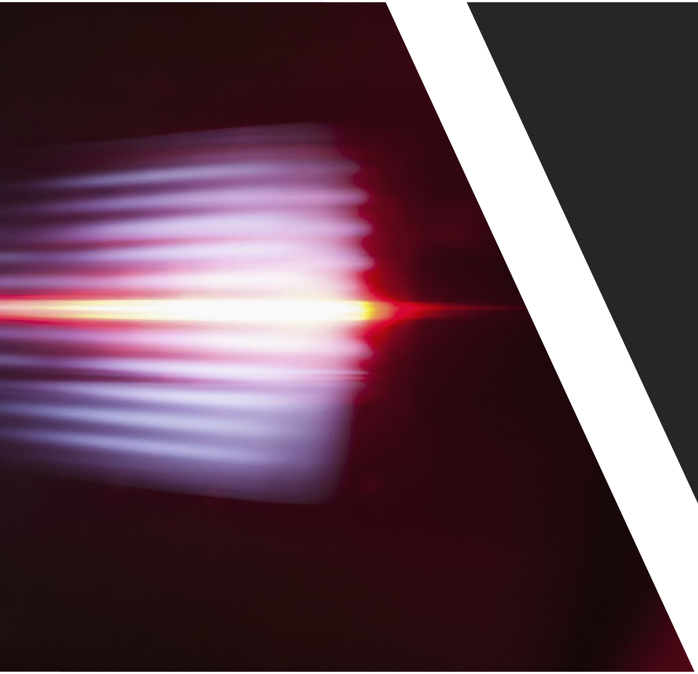
Could become problematic at high charge because the bunch has relatively large dimension in to the X-band

Case C – 3+2+2+2:

If, at the end of the study (still ongoing) will reach all goals, it is:

Better to host a X-band and so better for higher charges.

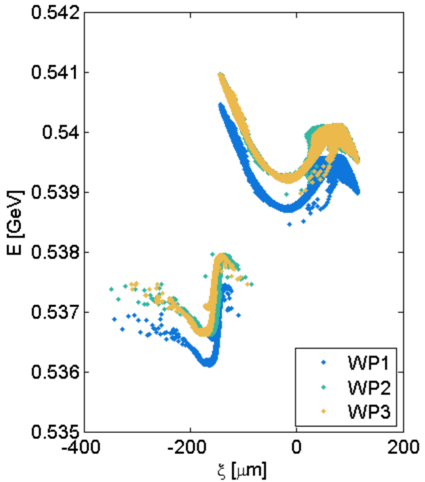
The space charge works in a different way and more analysis are needed



Plasma Simulations

Plasma Simulations

WP comparison



We performed a comparison between 3 working points. The first one did not include space charge at final focus, while the second and the third have slightly different compression phases.

NB.Simulations performed w e-beam particles generated with the old photoinjector scheme , i.e. (2x3m S band+ 2x1m X band)

Driver parameters

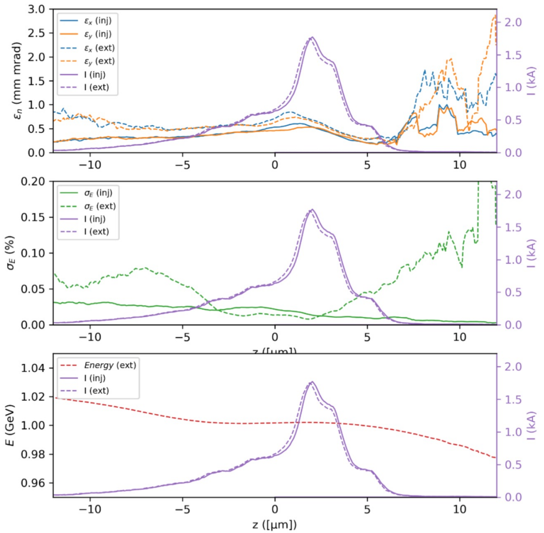
$$\sigma_x = 4.6\ \mu\text{m}$$
$$\sigma_y = 7.2\ \mu\text{m}$$
$$\sigma_z = 52.2\ \mu\text{m}$$
$$\varepsilon_{n(x,y)} = 1.8\ , 2.0\ \text{mm mrad}$$
$$\gamma = 1055$$
$$\sigma_E = 0.06\%$$

Witness parameters

$$\sigma_{x,y} \approx 1.2\ \mu\text{m}$$
$$\sigma_z = 6.3\ \mu\text{m}$$
$$\varepsilon_{n(x,y)} \approx 0.6\ \text{mm mrad}$$
$$\gamma = 1050$$
$$\sigma_E = 0.05\%$$
$$I \approx 1.9\ \text{kA}$$

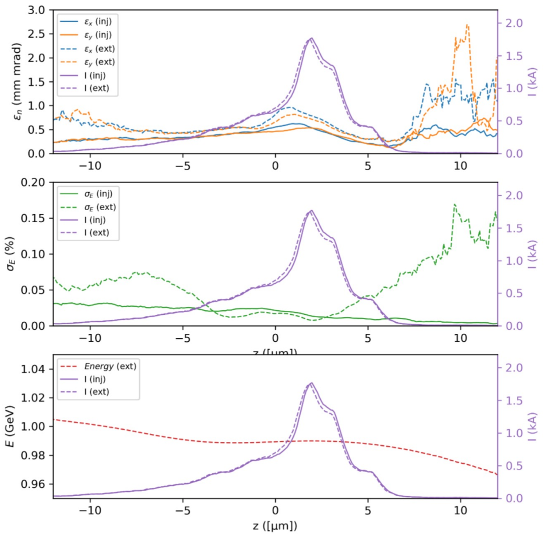
S . Romeo

Rolling slices WP1

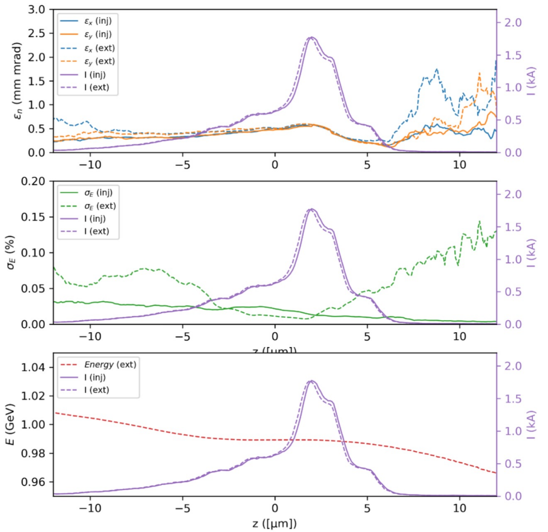


No SC in the focusing matching

Rolling slices WP2



Rolling slices WP3

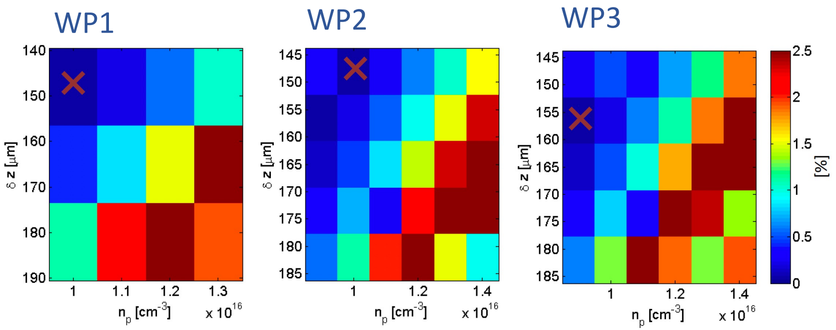


SC included, light difference in compression phase

Slice Analysis for the three cases

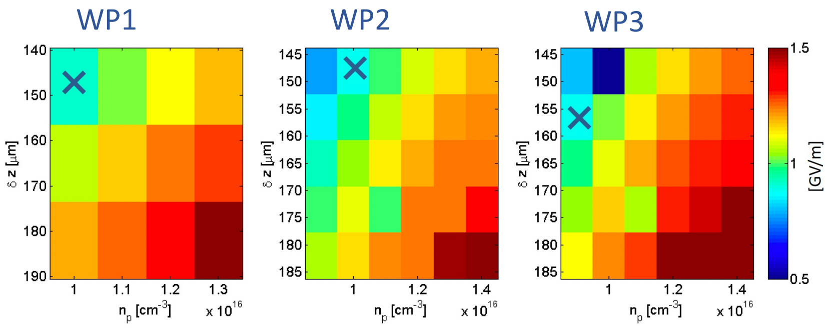
S . Romeo

Energy spread

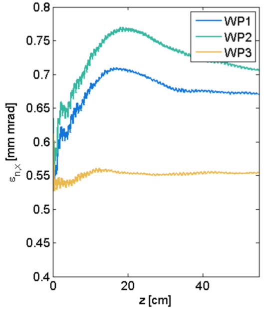


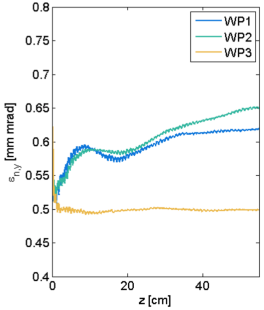
✕ 0.04-0.06%

Accelerating gradient *LOADED*



✕ 850-890 MV/m





S . Romeo

- Comparison of different working points highlighted the possibility that slightly different working points can have different phase matching
- No high difference in gradients and spread
- Improved emittance with the addition of space charge effect and better focusing
- The emittance reduction is due to some particles that are ejected from the bubble
- 99% of charge transported

Witness parameters (50-55 cm acceleration in plasma)

WP	ε_{in}-slice mm mrad	ε_{out}-slice mm mrad	$\sigma_{E_{in}}$-slice %	σ_{out}-slice %	I kA	E GeV
1	0.3-0.8	0.3-0.8	0.02-0.03	0.02-0.04	1.9	≈1.01
2	0.2-0.5	0.3-0.8	≤0.02	0.02-0.03	1.9	≈0.98
3	0.2-0.5	0.2-0.5	≤0.02	0.02-0.03	1.9	≈0.99

S . Romeo

WP-9 Architect code parallelization

Paolo Santangelo

- MPI

  given the length of the program, the use of MPI was considered prohibitive
- OpenMP
  - the parallelization is simpler since it is just a matter of adding directives in the code at the beginning of each loop
  - it is also a natural way to the possible use of GPUs since it does not require more than a few GB of RAM and is therefore compatible with the current GPU RAM

- Effectiveness of parallelization:
  - discrete scalability up to 8-16 processors
  - it is reasonable to perform up to 4 parallel runs for each machine

Last code version results (V3)

risultati in secondi per 100 time step e speedup

- locazioni di memoria con array contigui (SoA)

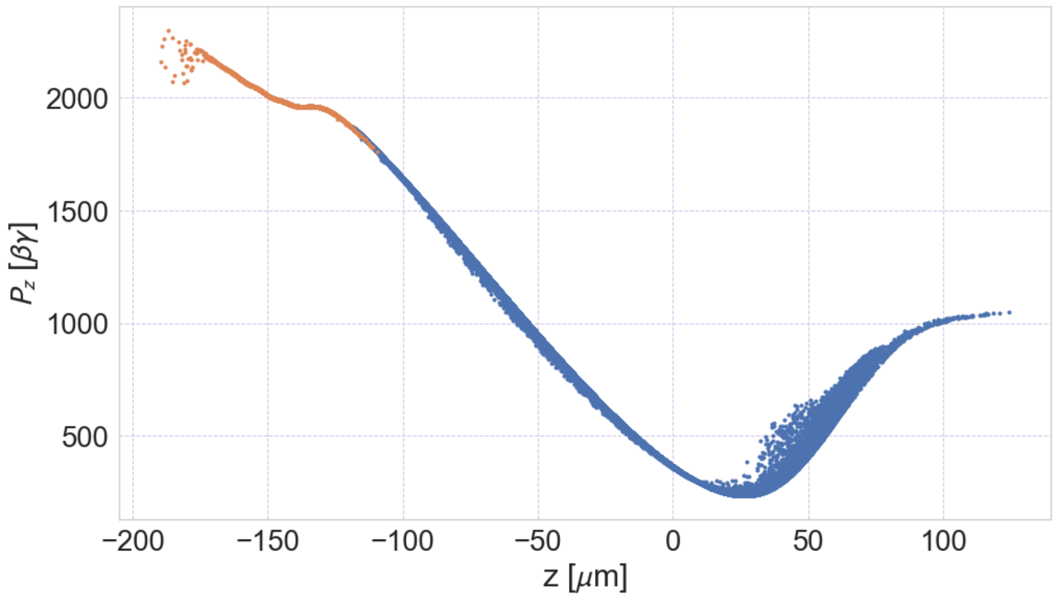
distribuzione	close		spread	
processori	seconds	speedup	seconds	speedup
1	**21,18**			
2	16,05	1,3	11,80	1,8
4	8,87	2,4	6,60	3,2
6	6,35	3,3	4,95	4,3
8	5,10	4,2	4,00	5,3
12	4,20	5,0	3,15	6,7
16	3,70	5,7	2,90	7,3

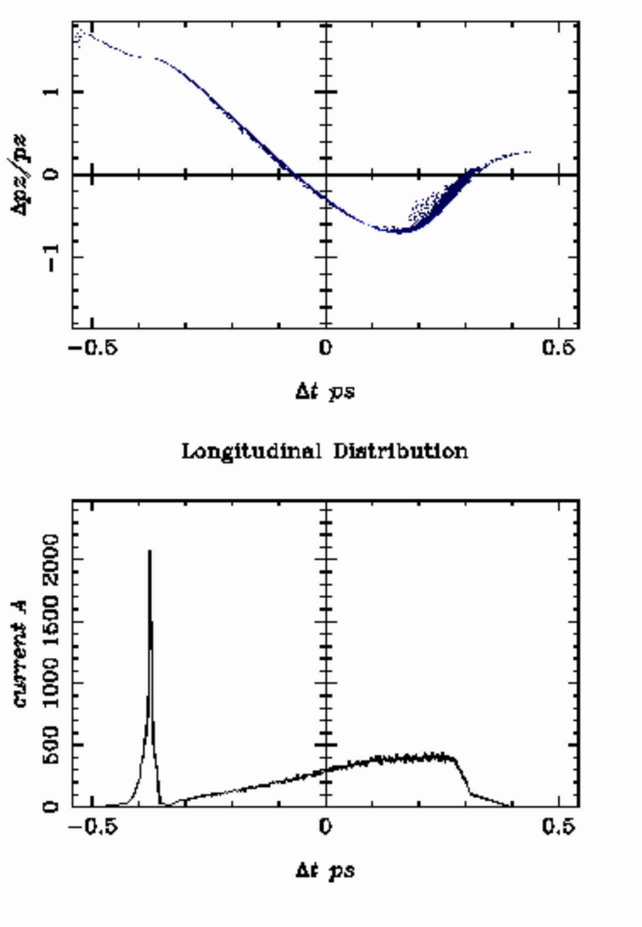
- originale con array non contigui (AoS)

distribuzione	close		spread	
processori	seconds	speedup	seconds	speedup
1	**44,40**			
2	28,58	1,6	23,80	1,9
4	15,21	2,9	12,25	3,6
6	10,65	4,2	8,65	5,1
8	8,55	5,2	7,50	5,9
12	6,75	6,6	5,10	8,7
16	6,08	7,3	4,50	9,9

Capture & Undulator matching

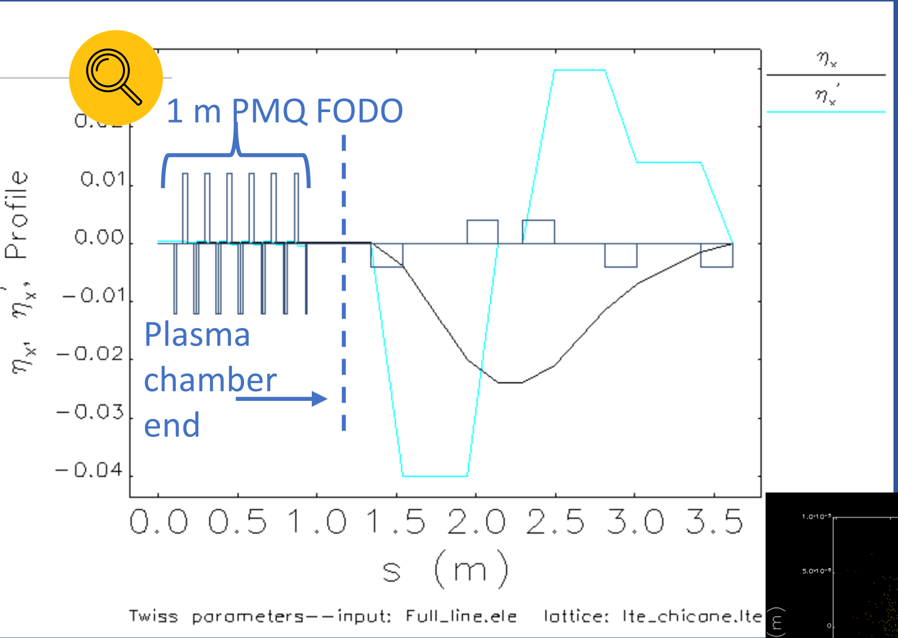
Witness and Driver

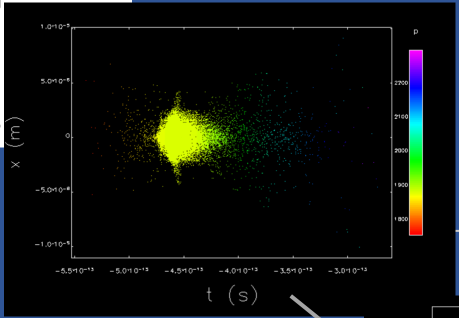


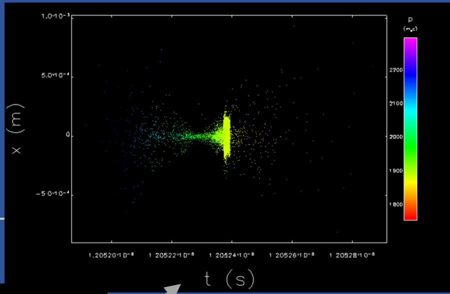


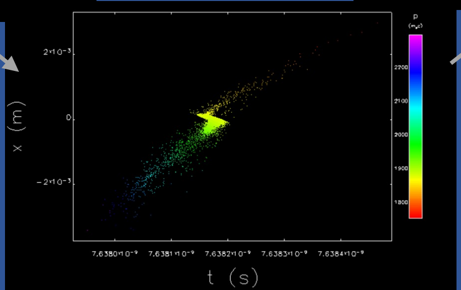
M. Rossetti Conti

Conventional Capture and Dri-Wit Separation Line









Witness transport
In the chicane

M. Rossetti Conti

Chromatic length evaluation

High energy spread and divergence combined lead to chromatic effects in drift space

$$\varepsilon_{n,x}^2 = \langle\gamma\rangle^2(\sigma_x^2\sigma_{x'}^2\sigma_E^2 + \varepsilon_x^2)$$

Chromatic Length, an analogue of the rayleigh range. $L_c = \frac{\sigma_x^0}{\sigma_{x'}^0\sigma_E}$ † Not shown in elegant.

Witness bunch

$\sigma_x^0 = 1.06 \cdot 10^{-6}\ m$

$\sigma_{x'}^0 = 3.23 \cdot 10^{-4}$

$\sigma_E = 1.05 \cdot 10^{-2}$

$L_c \sim$ 0.3 m

Witness core (78%)

$\sigma_x^0 = 1.01 \cdot 10^{-6}\ m$

$\sigma_{x'}^0 = 3.20 \cdot 10^{-4}$

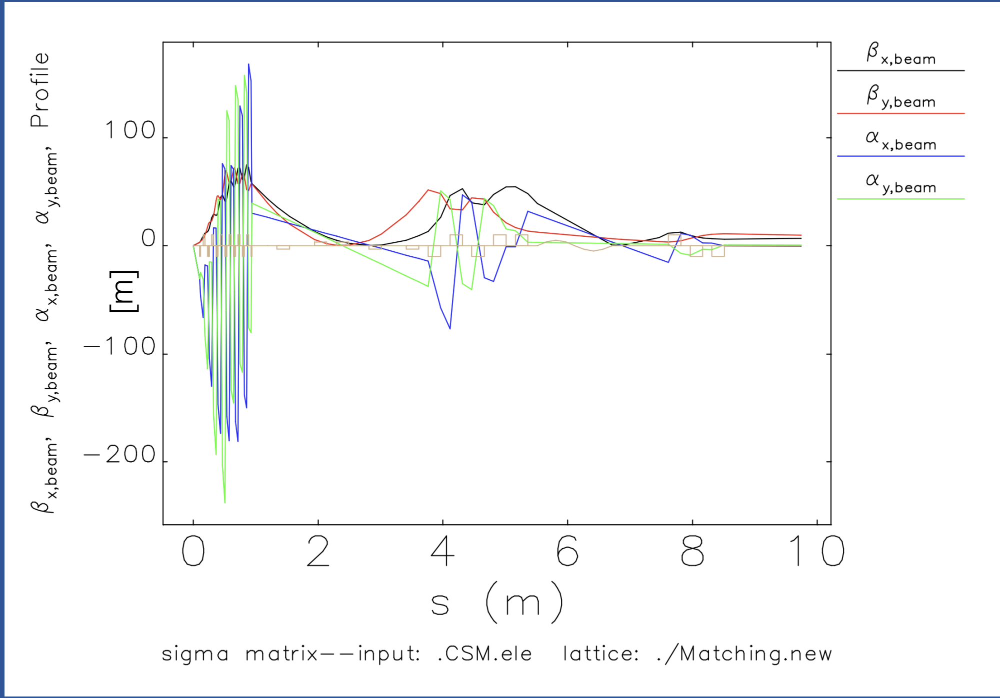
$\sigma_E = 6.73 \cdot 10^{-4}$

$L_c \sim$ 4.86 m

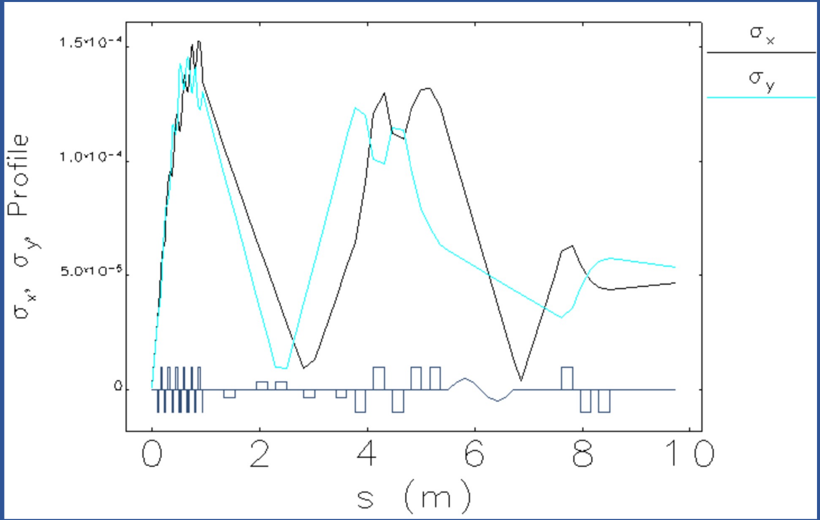
M. Rossetti Conti *et al, NIM-A* **909** (2018) †

Matching of the core

Full-line optimization is ongoing



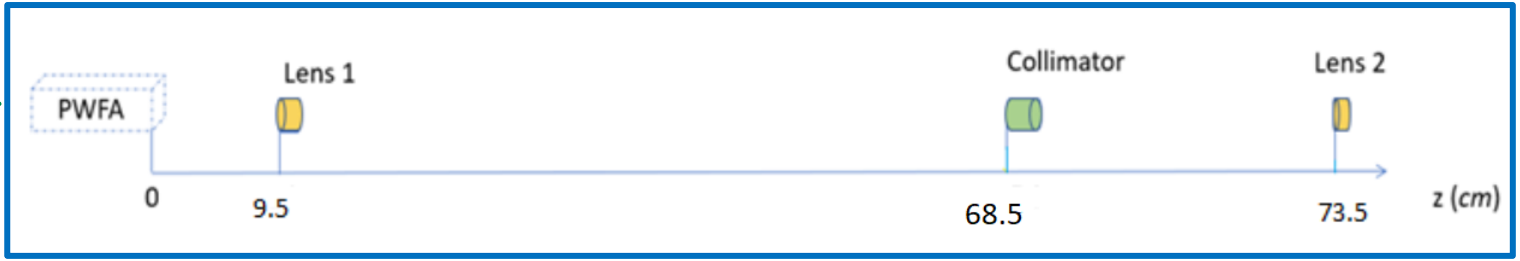
Transverse dimensions are under control



M. Rossetti Conti

Alternative solution with plasma lens channel (under study) P. Iovine

In place of the
1 m PMQ FODO ⟹



	l (cm)	d(cm)	I(kA)	r (μm)
lens1	4	9.5	0.85	500
lens2	1	73.5	0.8	500
coll	3	68.5	-	150

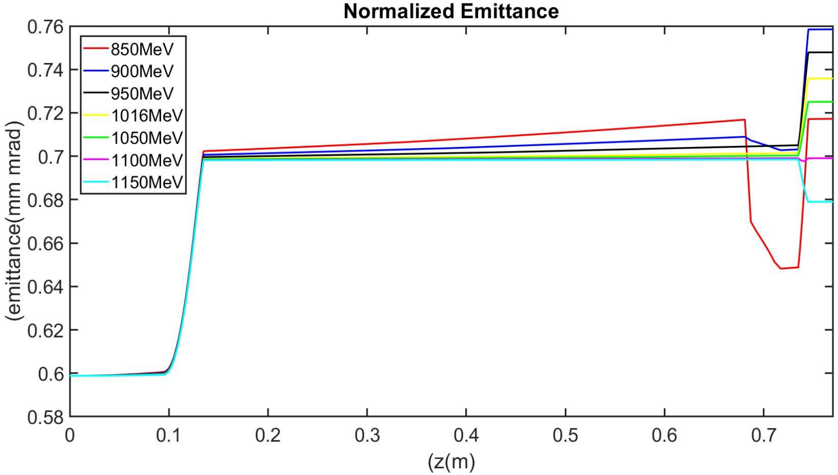
- ✓ transfer line of 74.5cm
- ✓ 20 % increase in rms emittance
- ✓ No change in bunch charge
- ✓ Energy spread remains about constant
- ✓ 1.3% driver charge at 74,5 cm
- ✓ 3 elements along transfer line

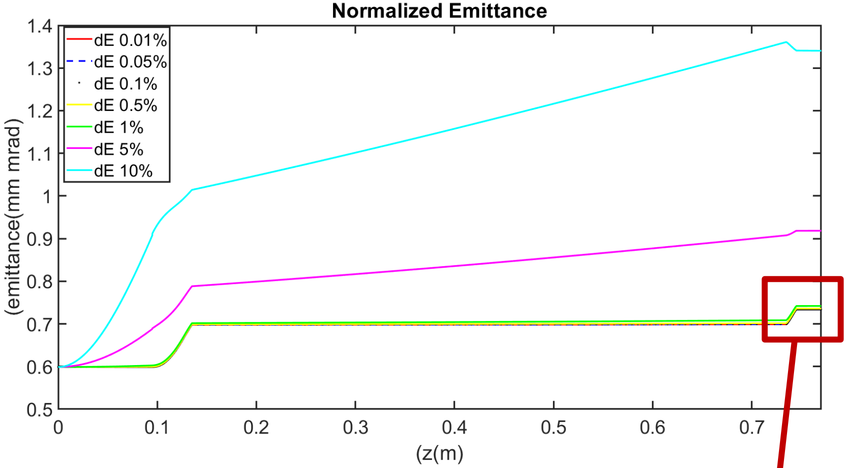
Simulated Witness beam in linear approximation

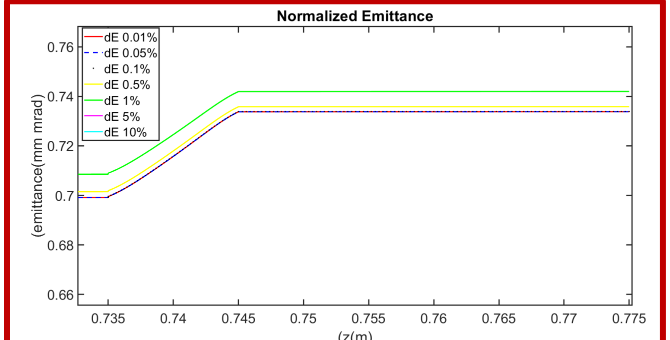
Witness	Z start (0 cm)	Z end (74.5 cm)
α_x	-1.02	-0.96
α_y	-0.4	-0.75
β_x(m)	0.006	1.76
β_y(m)	0.004	1.45

Energy acceptance & energy spread sensitivity in terms of transverse emittance dilution

P. Iovine







- 850MeV charge reduced of 5.7%
- 900MeV charge reduced of 0.4%

Summary

TD-RC Recommendations	Actions completed/non
Achieving proper drive-witness timing, incoming energy (pre-)chirp of the witness bunch, small final energy spread and matching to the plasma remains challenging.	Energy spread and transverse phase space now under control after plasma acceleration: 1.5 GeV/m -> 0.85 GeV/m loaded with beam loading matching for 1.9 kA e-beam
The design of the beam line before the plasma, number of S- and X-band structures, compression schemes and general geometry are still not well defined.	• Photoinjector actual layout: (3m + 3x2m) S-band • X-band structure (9 cells): e.m. design under optimization, allocated space after Gun • Linac 1-2 : total of 16 X-band modules (8+8)
Reaching parameters to lase at 3nm is still a challenge, possibly leading the decision to shift the lasing wavelength to 4nm to be less demanding on bunch parameters	The e-beam parameters are now nominally closer to the lasing requirements, see WA6 report for $\lambda_r = 3 \div 4nm$ discussion
Tolerance studies will be key to determine possible parameters, and need to be performed soon.	The robustness of the accelerator design is always roughly addressed during the optimization of the nominal working points, the detailed tolerance study on the updated layout must be performed

Next steps & Conclusions/MS

- ❑ Finalize SC effects in the beam line after the plasma (capture & undulator matching)
- ❑ <u>Check of the diagnostics & beam measurements before and after the plasma</u>
- ❑ Beam loading matching: from 0.85 GeV/m ⟹1 GeV/m loaded with beam current optimization
- ❑ Finalize plasma focusing w ramps
- ❑ Rise number of photons at undulator exit ⟹comparison with the "all_RF" beam of same charge
- ❑ Cluster evolution of Power9 setup ~ 57 k€ ⇒ 3D PIC (AlaDyn)
- ❑ Finalize spectrometers & dumpers
- ❑ Finalize 2nd transfer line to ARIA undulator
- ❑ Photoinjector actual layout: check for "*all_RF beam*" (100-200pC)

Reasonable milestones:

- **July 2022** end: S2E completion w new layout & beam quality control&virtual measurements feasibility (**30+200 pC nominal**)
- **December 2022**: optimization of the photon number-preliminary results
- **May 2023**: Stability&jitter sensitivity studies plus virtual measurements
- **June 2023**: Laser heater parameters w mbi studies for «*all RF*» beam

Thanks for your attention