EuPRAXIA@SPARC_LAB
Start to end Simulations

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

OUTLINE

- Recommendations from TDR-RC report Jun 2022
- WA1- S2E simulations activity results
  - Basic Layout Start to end Simulation Results
    - Parameter list update
- WA1- Main Topics-parallel studies:
  - X-band cavity at Gun exit
  - Jitter studies
  - 1.2 GeV operation
  - Non linear regime WPs
  - Plasma Tline
- Summary

From TDR Rev Comm Jun 2022

2.4 Start to End Simulations

Good progress has been made since last meeting, on converging towards a solution for the beam line options before the plasma in optimizing the electron beam parameters of the drive and witness bunches for acceleration in plasma in the comb scheme.

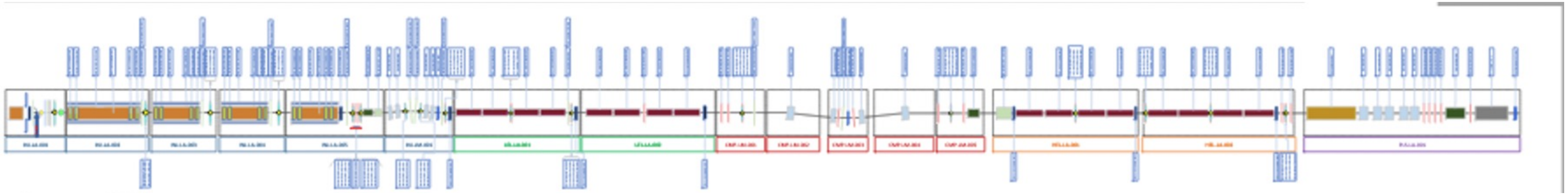
Two options are under consideration with different length/number of S-band structures in the injector: one using 4x2 m, and another using 3+3x2 m S-band structures have been studied for their suitability to insert an X-band linearizer after the gun. They were also compared with earlier injector layouts.

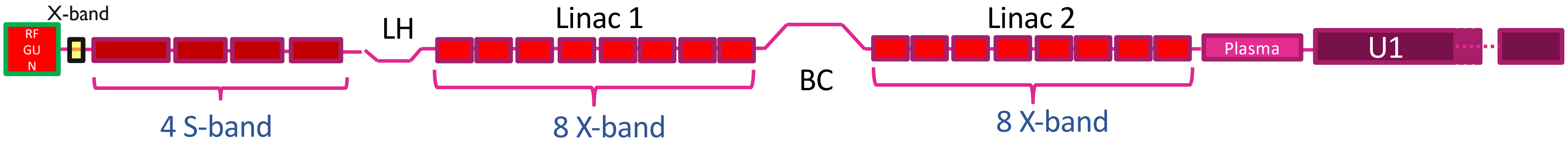
The first option offers a good solution for witness bunch charge up to 30 pC, whereas the second option looks better for higher charge of up to 50 pC. This latter solution does look promising and the RC endorses plans to study this option in more details. The planned tolerance and jitter studies will be important to make a final choice, as it may affect anticipated parameters of the driver/witness bunches at the entrance of the plasma.

The RC is pleased to see that more computing resources have been made available since the last meeting for optimization of injector with focus on controlling beam quality at the exit of the plasma and for parallelization of the Architect code for plasma simulations.

The RC recommends finalizing the injector layout and continuing to progress on tolerance and jitter studies.

The Basic Layout



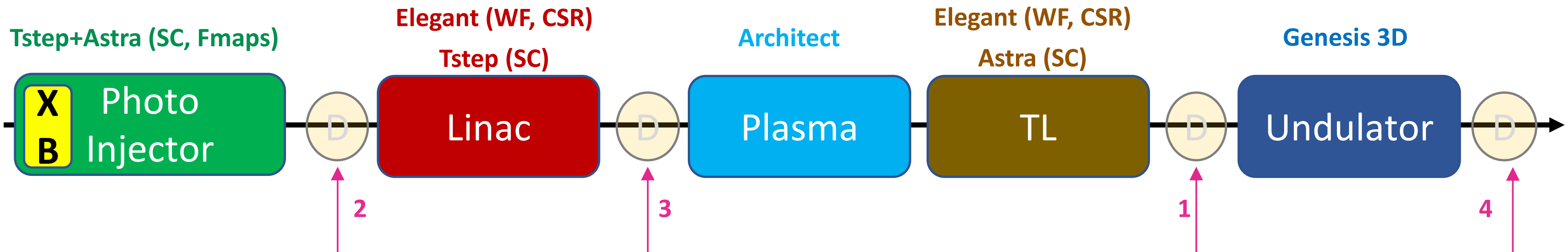


- **Focused on Plasma acceleration operation scheme = WoP1**
- **Checked at each iteration for the High Charge Single Bunch boosted by an *All-RF* Linac up to 1 GeV = WoP2**

Start2End for the basic layout

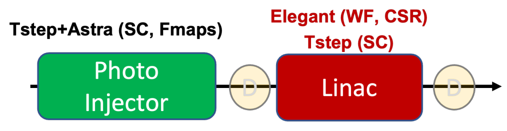
- **PhotoInjector Layout consolidation with 3m +3x2m S-band scheme:**
  - **Revision of nominal 30+200 pC WoP1 scheme for plasma acceleration: Photoinjector (no Xband)+ Linac + Plasma**
  - **Transfer Line with CSR & SC for Undulator optics matching**
  - **Undulator results**

done



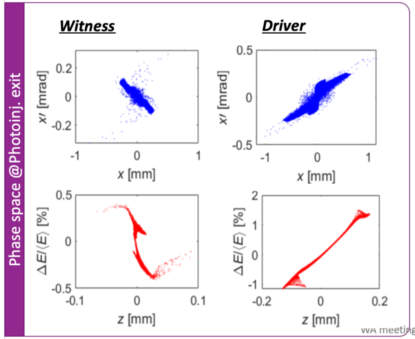
- **On going:**
  - **Diagnostics feasibility/efficiency check w virtual measurements (priority order) to finalize the basic layout**

S2E «basic» details:

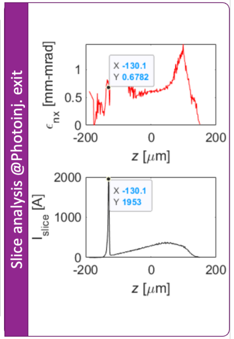


A. Giribono

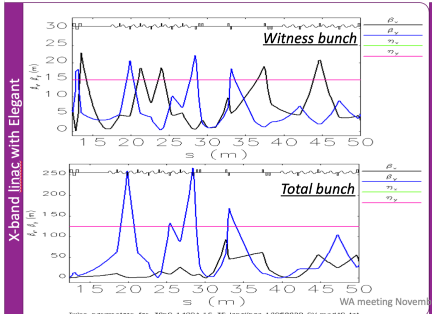
PhotoInjector

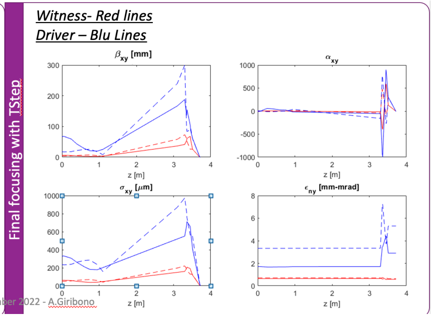


Beam parameters @Photoinj exit		
	Witness	Driver
E [MeV]	124.75	126.46
$\varepsilon_{x,y}$ [mm mrad]	0.70	1.52
$\sigma_{z\text{-rms}}$ [µm]	4.923	62.320
ΔE/E [%]	0.117	0.547
Δt [µm] (ps)	151.5 (0.505)	
$\sigma_{x\text{-rms}}$ [µm]	118	127
$\beta_{x,y}$ [mm]	6.127	2.609
$\alpha_{x,y}$	2.475	-1.534

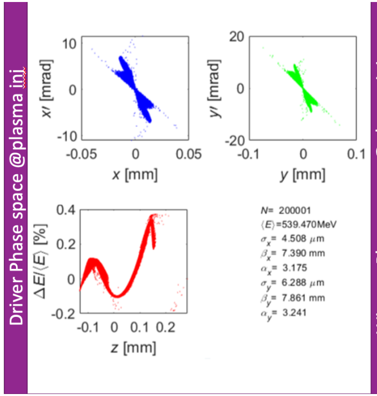


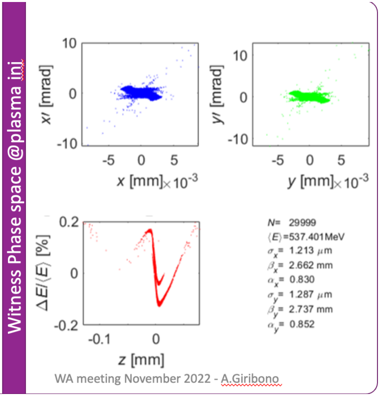
Linac





Capillary entrance





Beam parameters @Plasma inj.		
	Witness	Driver
E [MeV]	537.6	539.5
$\varepsilon_{x,y}$ [mm mrad]	0.68-0.70	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

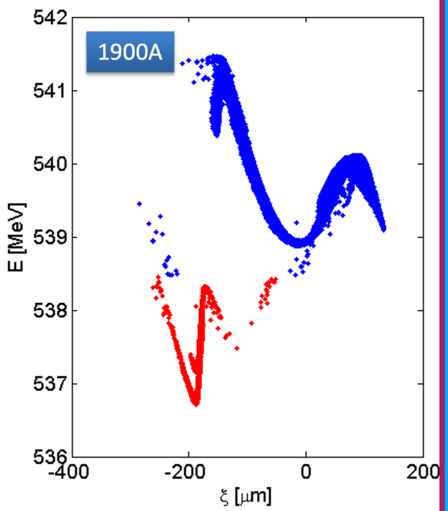
30 + 200 pC

S2E «basic» details:

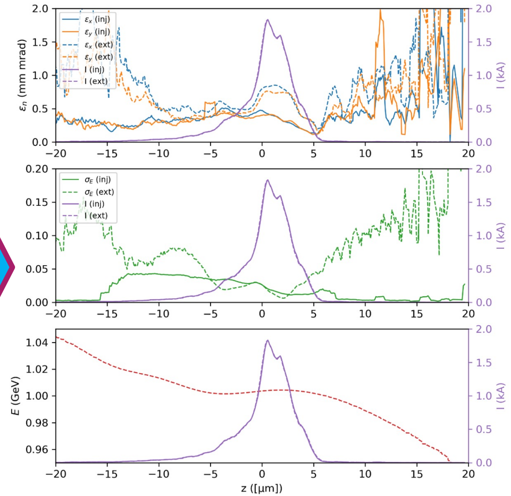
Architect

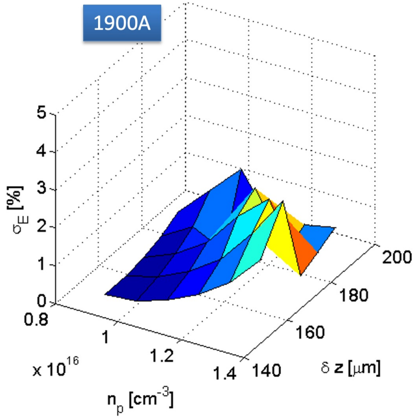
Plasma

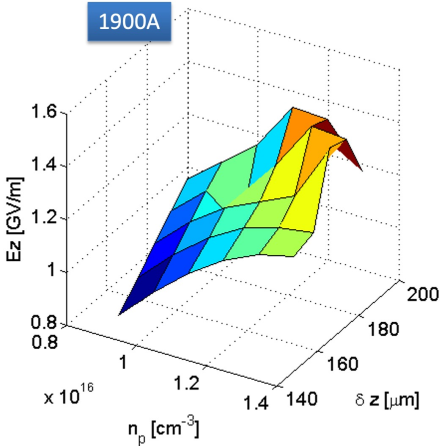
S. Romeo



- $\Delta z = 158\ \mu\text{m}$
- $n_p = 0.9 \cdot 10^{16}\ \text{cm}^{-3}$
- $\sigma_E = 0.06\%$
- $E_z = 0.9\ \text{GV/m}$ (including 1 cm injection ramp, so, actually, slightly higher)
- Slice energy spread, virtually untouched (or reduced)
- Slight emittance increase (to be improved with ramps)
- Accelerating length 0.56 m





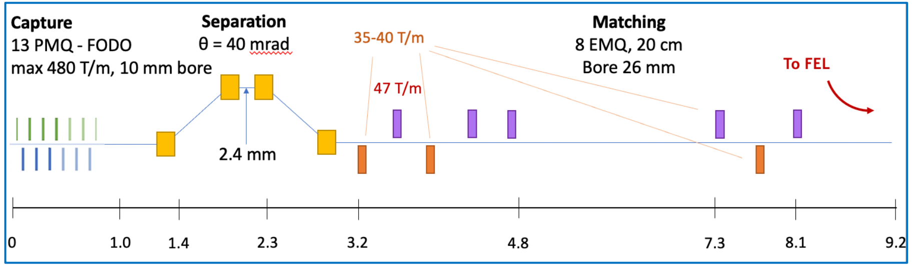


S2E «basic» details:

Elegant (WF, CSR)
Astra (SC)
TL

M. Rossetti Conti

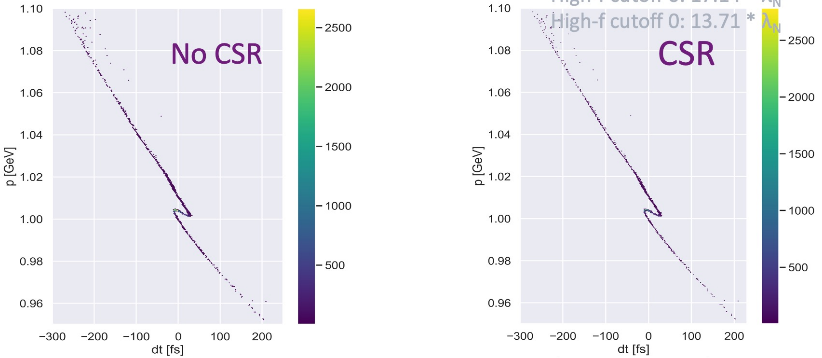
Layout



Evaluation of CSR (Elegant)

70 Bins

Nyquist wavelegth : 3.4 µm
High-f cutoff 0: 17.14 * λ_N
High-f cutoff 0: 13.71 * λ_N

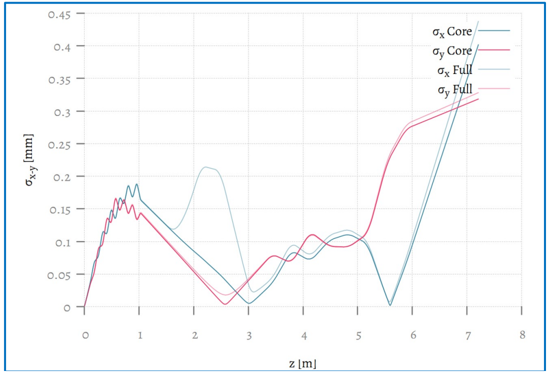


enx	Sdelta
3.759350e-06	8.322033e-03

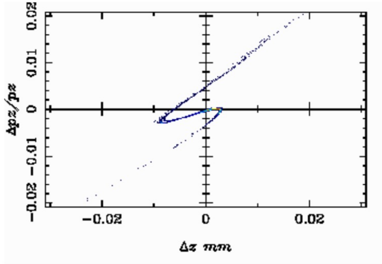
Variation of emittance and energy spread: < 2‰

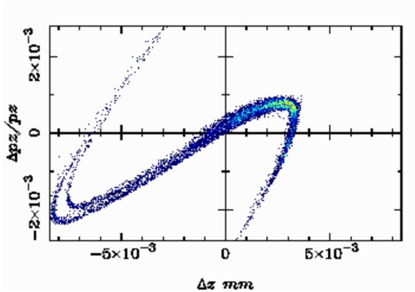
enx	Sdelta
3.766828e-06	8.333016e-03

Transverse beam size evolution w Space Charge (Astra)



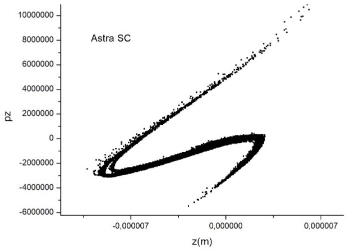
Aperture
0.250 mm diameter (11% cut)
8.35 MeV to 1.12 MeV



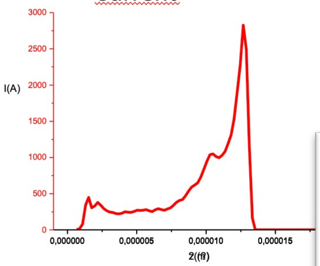


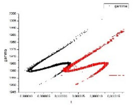
Beam from TL with space charge E=1GeV, Q= 30 pC.

Phase space

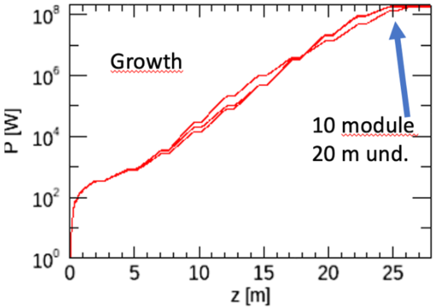


Current

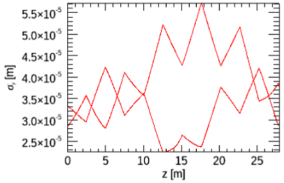


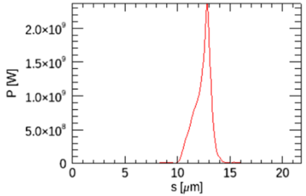


Comparison Astra(black)/Genesis 1.3 (red)

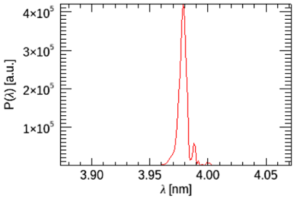


Matching





Clean single spike at 25 m



Energy	J	11.5 10^-6, 16. 10^-6
bw	%	0.1
size	m	1.4 10^-4
div	rad	1.7 10^-5
Photon number		**2.2 10^11, 2.85 10^11**
wavelength	nm	3.975

S2E «basic» details: $\lambda_r = 3.3\ nm$

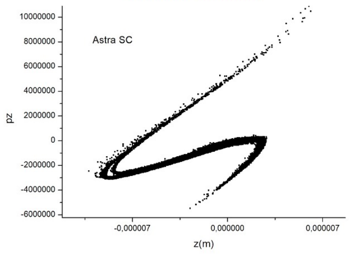
Genesis 3D

Undulator

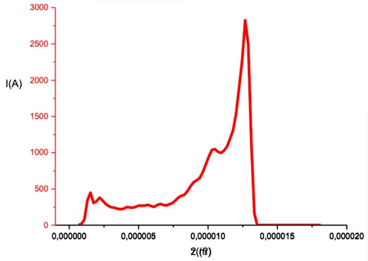
V. Petrillo

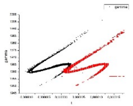
Beam from TL with space charge E=1GeV, Q= 30 pC.

Phase space



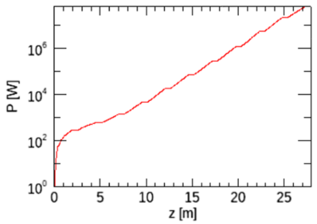
Current

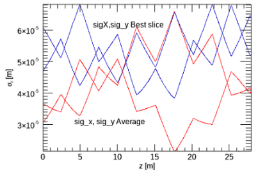


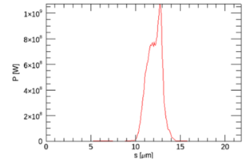


Comparison Astra(black)/Genesis 1.3 (red)

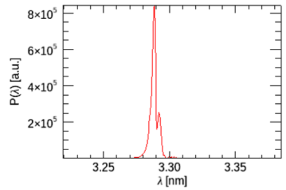
Same beam, undulator tuned at 3.3 nm







Energy	J	6,6 10^-6
bw	%	0.1
size	m	1.4 10^-4
div	rad	1.7 10^-5
Photon number		**1.09 10^11**
wavelength	nm	3.3



EuPRAXIA@SPARC_LAB Parameter List update 1

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	%	0.9	0.5
Undulator Area Length	m	30	
$\rho(1D/3D)$	$\times 10^{-3}$	1	2
Photon Brilliance per shot	$mm^2 mrad^2$ $bw(0.1\%)$	1×10^{27}	

FEL Parameters Nov 2022

Parameter	Unit	PWFA	Full X-band
Radiation Wavelength	nm	**3-4**	**4**
Photons per Pulse	$\times 10^{12}$	**0.1- 0.25**	1
Photon Bandwith	%	**0.1**	0.5
Undulator Area Length	m	30	
$\rho(1D/3D)$	$\times 10^{-3}$	**2**	2
Photon Brilliance per shot	$\left(\frac{s\, mm^2 mrad^2}{bw(0.1\%)}\right)$	$\mathbf{1{-}2 \times 10^{28}}$	1×10^{27}

EuPRAXIA@SPARC_LAB Parameter List update 2

Electron Beam parameters from CDR

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

Electron Beam Parameters Nov 22

Parameter	Unit	PWFA	Full X-band
Electron Energy	GeV	**1**-*1.2*	1
Bunch Charge	pC	**30**-*50*	**200**-*500*
Peak Current	kA	1-2	1-2
RMS Energy Spread	%	**0.1**	0.1
RMS Bunch Length	μm	6-3	24-20
RMS norm. Emittance	μm	1	1
Slice Energy Spread	%	≤0.05	≤0.05
Slice norm Emittance	mm-mrad	0.5	0.5

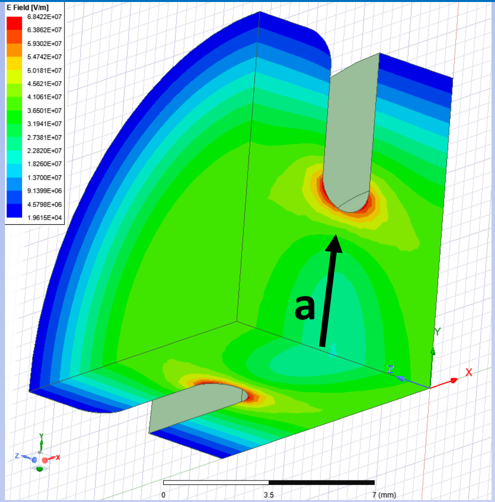
WA1-Main Topics parallel study

Xband cavity study

A. Bacci
L. Faillace

NEW Requirements from Beam dynamics:

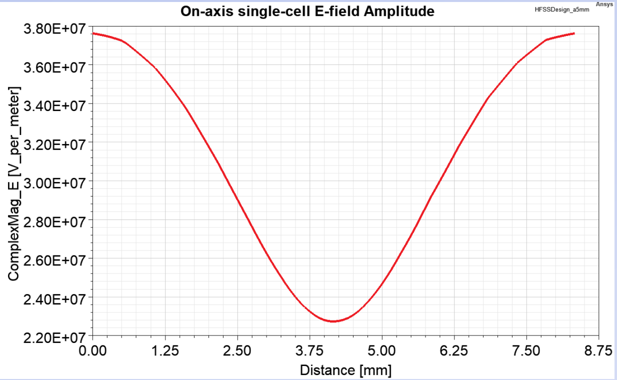
- E-beam Sigma_x=1.5-2 mm
  → cavity iris radius a=4mm
- Cavity Length = 10 cm
- 2pi/3 mode
- Accelerating Gradient
  TW option Eacc = 16.5 MV/m
  SW option Eacc = 16.3 MV/m



RF design – first step

Comparison
- TW structure, constant impedance
- SW structure

a = 4 mm	TW	SW
f	11.9942 GHz	11.9942 GHz
Q	6600	8,600
Vg	3.6 %	-
r	85.3 MΩ/m	80 MΩ/m
Eacc	16.5 MV/m	16.3 MV/m
alpha	0.63 1/m	-
Lt	10 cm	10 cm
Coupling β	-	2
Fill time Tf	9.3 ns	-
Build up τ	-	76 ns
Pin	3.2 MW	0.37 MW



NB: for higher gradients/powers no X-band recirculator for SW

Xband Insertion: Driver 200 pC – Witness 30 pC improvements

A. Bacci
L. Faillace

Older cases	Driver 200 pC σ_x	Driver 200 pC σ_z	Driver 200 pC $\varepsilon_{n,x-y}$	Witness 30 pC σ_x	Witness 30 pC <I>	Witness 30 pC σ_z	Witness 30 pC $\varepsilon_{n,x-y}$	Full Beam <E>	Full Beam 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

This case: X-band + 3.0 m S-band + 4 x (2.0 m S-band) has been optimized to reach the referece Δz of 150 um:
Further, we produced simulations also for Δz = 145 um and 140 um

D) Improv. – 3222	Driver 200 pC σ_x	Driver 200 pC σ_z	Driver 200 pC $\varepsilon_{n,x-y}$	Witness 30 pC σ_x	Witness 30 pC <I>	Witness 30 pC σ_z	Witness 30 pC $\varepsilon_{n,x-y}$	Full Beam <E>	Full Beam Δ_z
	124	55.0	4.2	187	835	3.1	0.6	162	150
	112	55.0	4.1	185	836	3.1	0.55	162	146
	115	55.0	4.1	180	831	3.2	0.55	162	141

To NOTE: the beam parameters are very close but with different distance between Driver and Witness

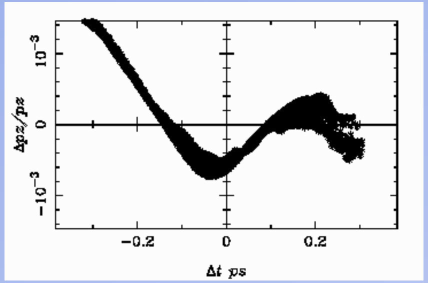
Xband Insertion: High Charge Single Bunch

A. Bacci
L. Faillace

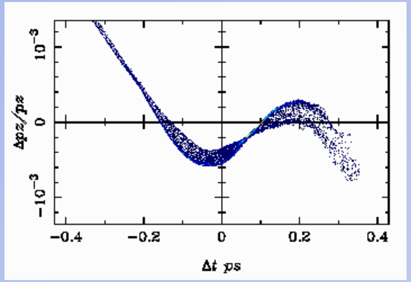
Example: Long Phase space analysis

Parameter	A	B	C	D	E
Charge *(pC)*	200	200	200	300	500
Current *(A)*	600	500	210	550	400
σ_z (μm)	46	50	100	65	150
$\varepsilon_{nx,y}$ *slice* $(\mu\, rad)$	0.5	0.5	0.5	0.5	0.8
$\Delta_E slice$ (keV)	20	20	8	10	20

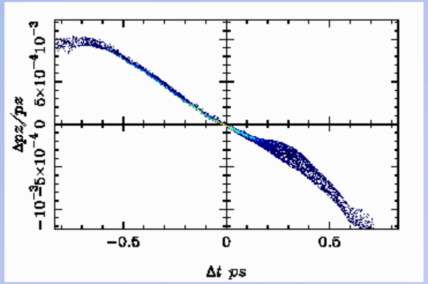
A



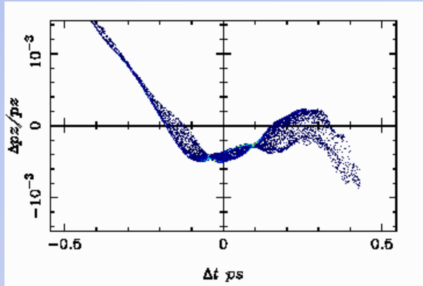
B



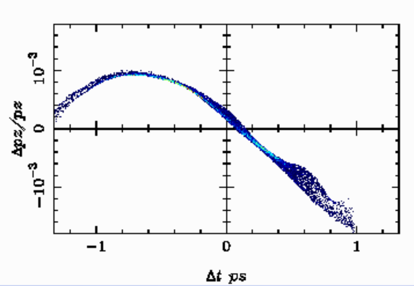
C



D

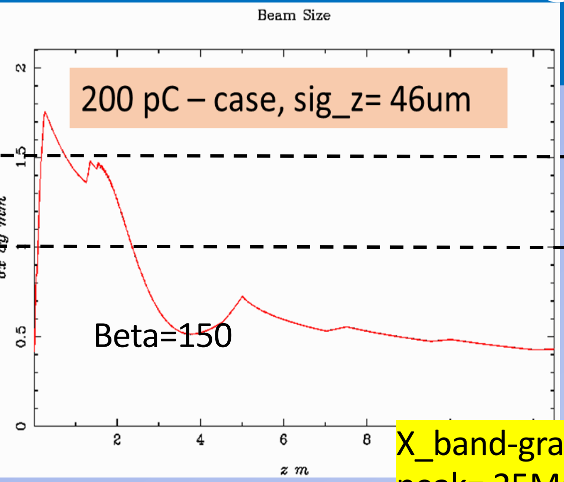


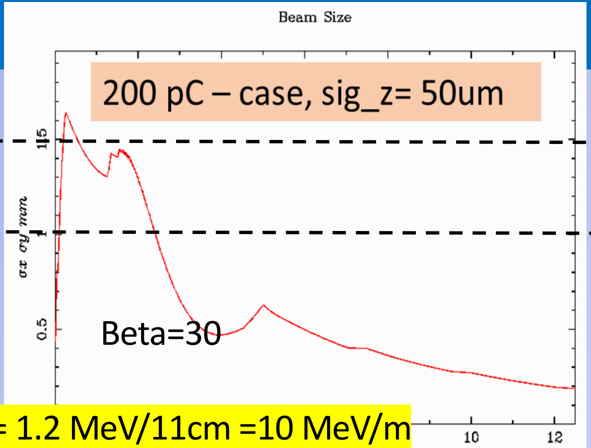
E

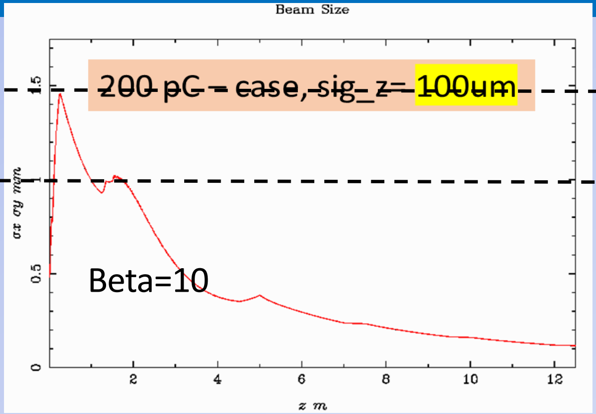


Xband Insertion: High Charge Single Bunch

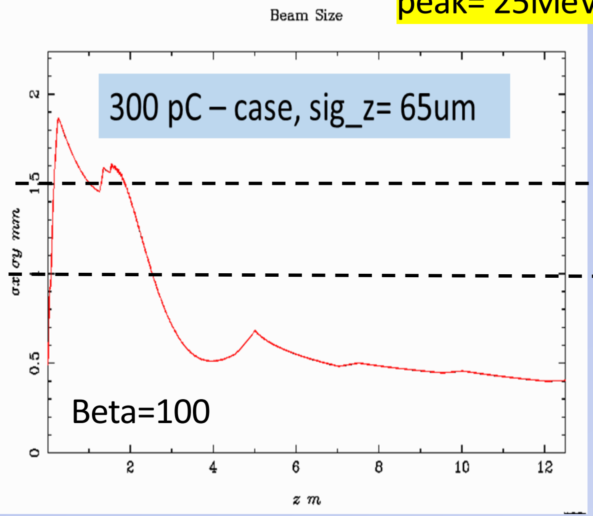
A. Bacci
L. Faillace

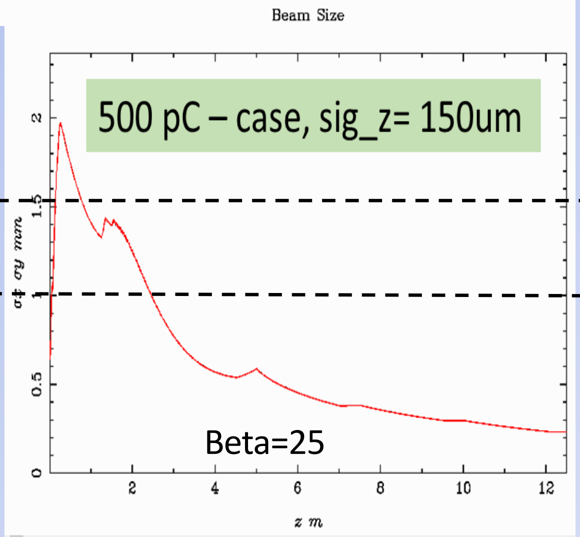






X_band-grad= 1.2 MeV/11cm =10 MeV/m
peak= 25MeV





No particle lossses from PIC simulations

Now the Comb & SB beams are ready to be tracked trhough the Linac and in the undulator to optimize the X-band correction

Jitter studies @SPARC_LAB A. Giribono

First step: benchmark w SPARC_LAB observation

- Photoinjector sensitivity studies are on going in order to test the robustness of the reference working point, especially with regards to the compression phase stability, as needed to ensure a μ-scale bunch length.
- At first, the study is being focused on the RF phase jitters, in the range ±0.1 degree for EuPRAXIA (worst case, ±0.03 degree seems nevertheless feasible), that are strictly connected with the RF compression scheme efficiency.
- In the meanwhile, experimental activities are ongoing at the SPARC_LAB test facility, even if considering higher RF phase jitter errors (±1 degree) due to the current accelerator technology, so to benchmark the beam dynamics simulations made for EUPRAXIA@SPARC_LAB with the experimental results.

- The experimental activity performed at SPARC_LAB has regarded three working point, f1-f2-f3 described in Table, relying on the velocity bunching scheme each with a different compression factor.
- Simulations have been performed with the TStep code

WP	RF phase (deg)	Energy (MeV)		Energy Spread (keV)		σ_z (rms - μm)	
		Exp	Sim	Exp	Sim	Exp	Sim
f1	-84.16	90.44	90.45	240	218.0	170.7	166
f2	-87.16	88.33	88.23	200	192.0	123.8	125.5
f3	-90.16	85.95	85.76	130	130.2	83	81.7

Jitter studies @SPARC_LAB A. Giribono

- **The results are in terms of coefficient of arrival time jitter (ATJ) defined as**

$$\Delta t_{\mathrm{linac}} \approx \sum_{i=1}^{4} c_i \Delta t_i$$

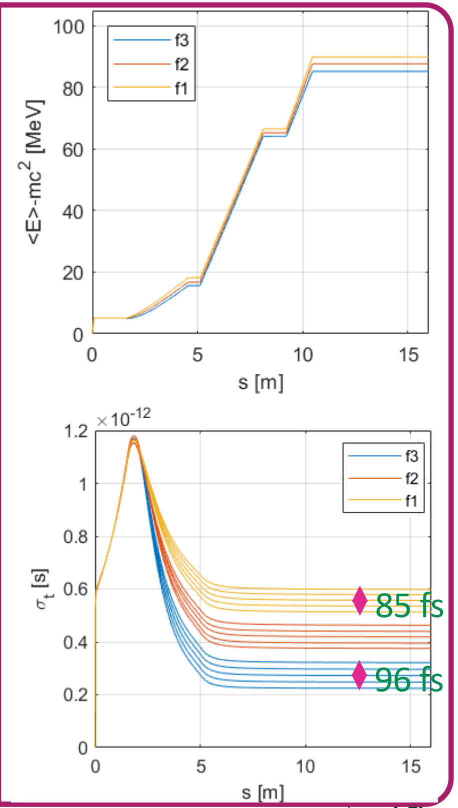
- **Experimental results show that, as expected by theory and simulations, at the maximum explored compression phase:**

– **the main contribution to the time arrival jitter comes from the phase jitter of the first accelerating structure, with ±1 degree phase error translating in ≈ ±1ps**
→ EUPRAXIA@SPARC_LAB worst case ΔΦ=0.1deg: driver and witness are expected to temporally jitter together of ±0.1 ps. The jitter between them, due to the fact that they enter the S1 with different compression phase that is linked to slightly different c_i, is under evaluation

– **±1 degree phase error on S1 results in ±17% error on the final beam length**
→ EUPRAXIA@SPARC_LAB worst case ΔΦ=0.1deg: expected witness length 6±0.1 μm, expected driver length 60±1 μm

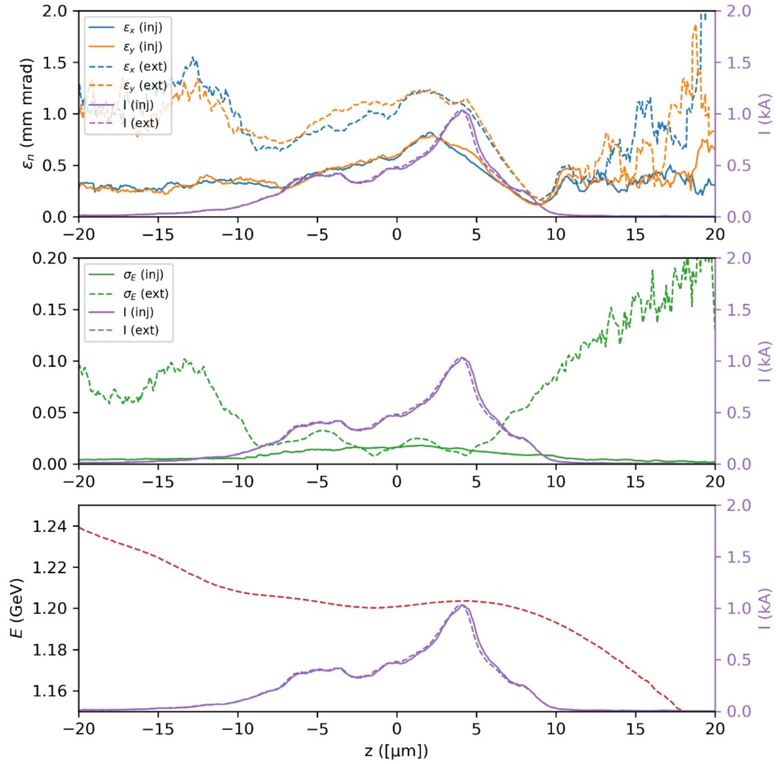
WP	RF phase (deg)	c_1 (laser)		c_2 (RF gun)		c_3 (S1-S2)		$\sum_{i=1}^{4} c_1$	
		Meas.	Sim.	Meas.	Sim.	Meas.	Sim.	Meas.	Sim.
f1	-84.16	0.12±0.05	0.13	0.02±0.04	-0.01	0.86±0.06	0.80	1.00±0.15	0.92
f2	-87.16	0.04±0.06	0.06	0.04±0.05	-0.03	1.00±0.07	0.97	1.08±0.18	0.99
f3	-90.16	-0.16±0.05	-0.12	-0.03±0.08	-0.05	1.14±0.06	1.08	0.95±0.19	0.91

Simulation Results by means of Tstep Simulation



Opt. 1 1300 A 500->1200 MeV

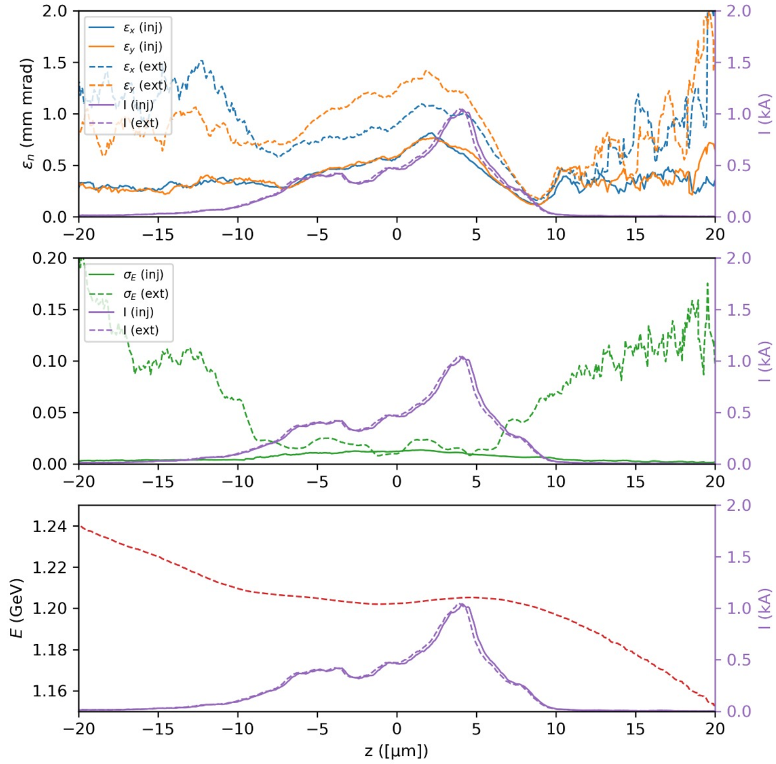
S. Romeo



- $\Delta z = 148\ \mu\text{m}$
- $n_p = 1.1 \cdot 10^{16}\ \text{cm}^{-3}$
- $\sigma_E = \mathbf{0.1}\%$
- $E_z = 0.95\ \text{GV/m}$ (including 1 cm injection ramp, so, actually, slightly higher)
- Slice energy spread, virtually untouched
- Slight emittance increase (to be improved with ramps)
- **Accelerating length 0.7 m**

Opt. 2 1900 A 700->1200 MeV

S. Romeo

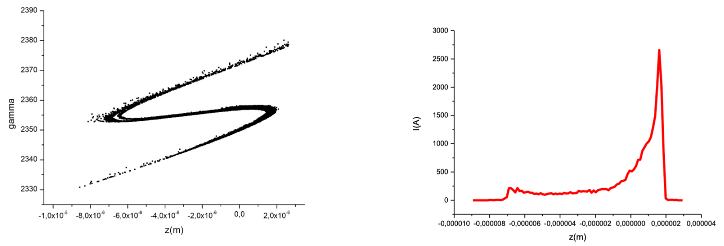


- $\Delta z = 174\ \mu\text{m}$
- $n_p = 0.9 \cdot 10^{16}\ \text{cm}^{-3}$
- $\sigma_E = 0.09\%$
- $E_z = 0.92\ \text{GV/m}$ (including 1 cm injection ramp, so, actually, slightly higher)
- Slice energy spread, virtually untouched (or reduced)
- Slight emittance increase (to be improved with ramps)
- Accelerating length 0.55 m

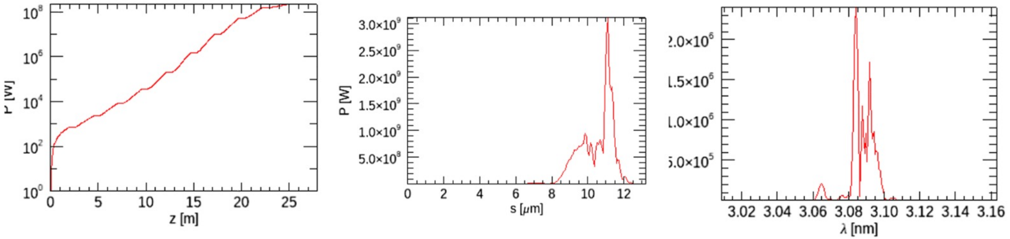
«*Exercise*» for the undulator: (from plasma exit only - no TL)

V. Petrillo

Beam from plasma exit (80 cm capillary) E=1.2 GeV



Undulator tuned at 3. nm

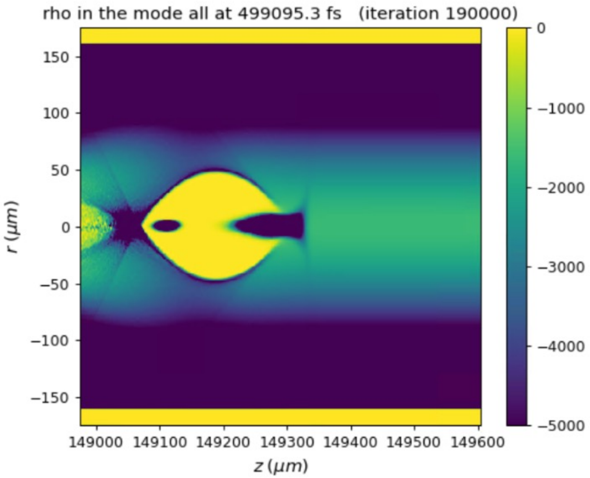


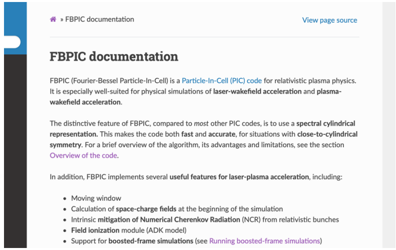
Energy	**J**	**10. 10^-6**
bw	%	0.25
size	m	8 10^-5
div	rad	1.3 10^-5
Photon number		**1.5 10^11**
wavelength	nm	**3.**

Undulator tuned at 2.5 nm

Energy	**J**	**3.6 10^-6**
bw	%	0.26
size	m	7.5 10^-5
div	rad	1.15 10^-5
Photon number		**0.45 10^11**
wavelength	nm	**2.52**

In order to correctly simulate Working Points where the $\tilde{Q}$ value exceeds 0.5, we are starting to employ the quasi-3D pic codes FBPIC [1] and Smilei [2]. With these codes, phenomena like hose instability can also be simulated.




» FBPIC documentation View page source

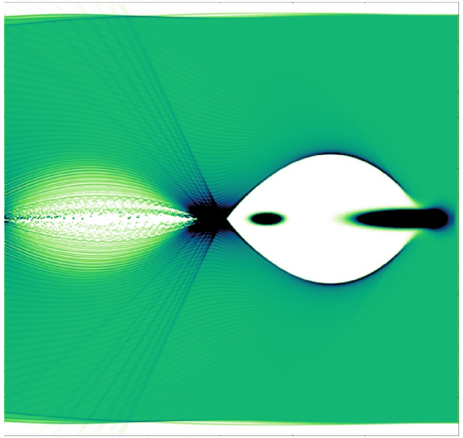
FBPIC documentation

FBPIC (Fourier-Bessel Particle-In-Cell) is a Particle-In-Cell (PIC) code for relativistic plasma physics. It is especially well-suited for physical simulations of **laser-wakefield acceleration** and **plasma-wakefield acceleration**.

The distinctive feature of FBPIC, compared to *most* other PIC codes, is to use a **spectral cylindrical representation.** This makes the code both **fast** and **accurate**, for situations with **close-to-cylindrical symmetry**. For a brief overview of the algorithm, its advantages and limitations, see the section Overview of the code.

In addition, FBPIC implements several **useful features for laser-plasma acceleration**, including:

- Moving window
- Calculation of **space-charge fields** at the beginning of the simulation
- Intrinsic **mitigation of Numerical Cherenkov Radiation** (NCR) from relativistic bunches
- **Field ionization** module (ADK model)
- Support for **boosted-frame simulations** (see Running boosted-frame simulations)



The WP under consideration has $q_W = 50$ pC, $q_D = 500$ pC and $\tilde{Q} > 2$ (depending on driver transverse size). The goal is to generate accelerating fields well in excess of 1 GV/m.

[1] https://fbpic.github.io

[2] https://smileipic.github.io/Smilei/index.html#

Low current configuration : lens-collimator-lens

A new beam line was designed to test the line at lower currents close to those currently reachable

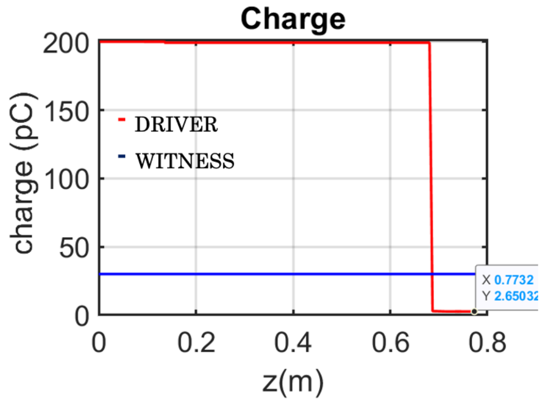
- Simulations have been perfomed by means of GPT for beam dynamics and a Matlab-based code for the plasma lens

GPT MATLAB

- Witness macro particles 29934
- Diver macro particles 293730

	l (cm)	d(cm)	I(kA)	r (μm)
lens1	4.0	9.5	0.85	500
lens2	1.0	73.5	0.80	500
coll	3.0	68.5	-	150

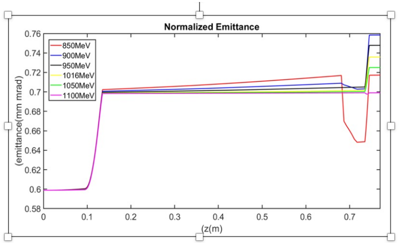
- ✓ transfer line of 74.5cm
- ✓ No change in bunch charge
- ✓ Energy spread remains about constant
- ✓ 1.3% driver charge at 74,5 cm



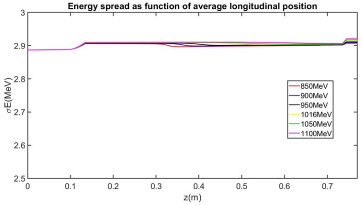
PLASMA Transfer Line

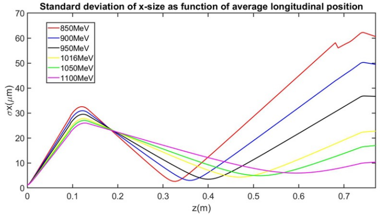
P. Iovine

Energy variation from 850 MeV to 1100MeV

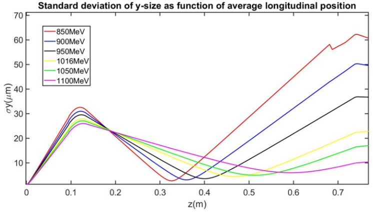


- 850MeV charge reduced of 5.7%
- 900MeV charge reduced of 0.4%

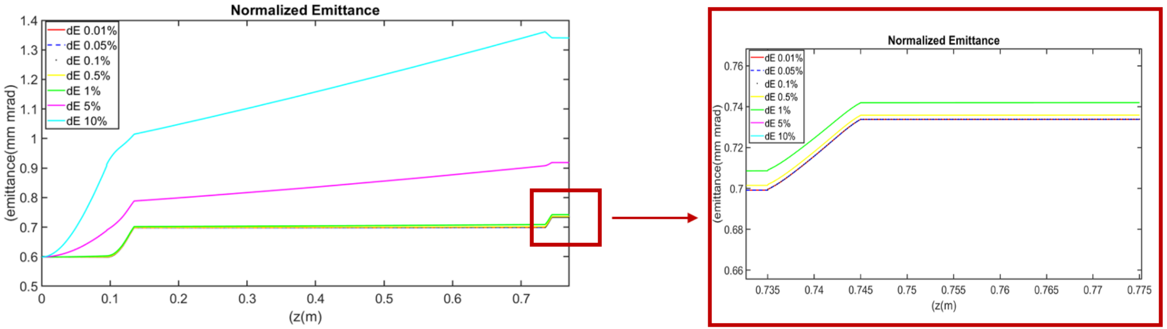




- ✓ Energy spread remains about constant for each run
- ✓ The trend of sigma x (y) is preserved



- **On going:** Architect code to verify the emittance growth inside active plasma lenses
- **Next:** - Geant 4 simulations to include electromagnetic processes (Production of gamma rays, Bremsstrahlung, Multiple scattering,…).
  - Parametric studies with different beam configurations.



- ✓ No change in bunch charge
- ✓ Energy spread remains about constant for each run
- ✓ The trend of sigma x (y) is preserved

Summary

TD-RC Recommendations	Actions completed/non
This latter solution (3m + 3x2m S-band) does look promising and the RC endorses plans to study this option in more details..	The PhotoInjector Layout has been consolidated with the 3m +3x2m S-band scheme
The planned tolerance and jitter studies will be important to make a final choice, as it may affect anticipated parameters of the driver/witness bunches at the entrance of the plasma..	The study has started with the benchmark of the simulation code/procedure with experimental results from SPARC_LAB, to provide the most realistic predictions for EuPRAXIA at SPARC_LAB. The work now has to be completed

In particular:

- **Now we have to address the capture& matching Tline after the plasma to not loose the beam quality and optimize the undulator performance,**
  - **The X-band at the gun exit could help reducing the twisting of the long phase space of the plasma accelerated beam after the HE separation chicane**
  - **A dogleg with R_{56}< 5E-4 will be studied**

Next steps & Conclusions/MS

- ❑ **Check of the diagnostics & beam measurements before and after the plasma**
- ❑ **Finalize plasma focusing w ramps**
- ❑ **Rise number of photons at undulator exit ⇒comparison with the "all_RF" beam of same charge (the 50+230 pC bem is ready to be simulated in plasma)**
- ❑ **Finalize spectrometers & dumpers**
- ❑ **Finalize 2nd transfer line to ARIA undulator**

Reasonable milestones:

- **May 2023**: Stability&jitter sensitivity studies plus virtual measurements
- **June 2023**: First results on laser heater parameters w MBI studies for «*all RF*» beam

Thanks for your attention