EUROPEAN
PLASMA RESEARCH
ACCELERATOR WITH
EXCELLENCE IN
APPLICATIONS

EuPRAXIA

RF Injector

E. Chiadroni / INFN-LNF - 1st Collaboration Week

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Injector Definition

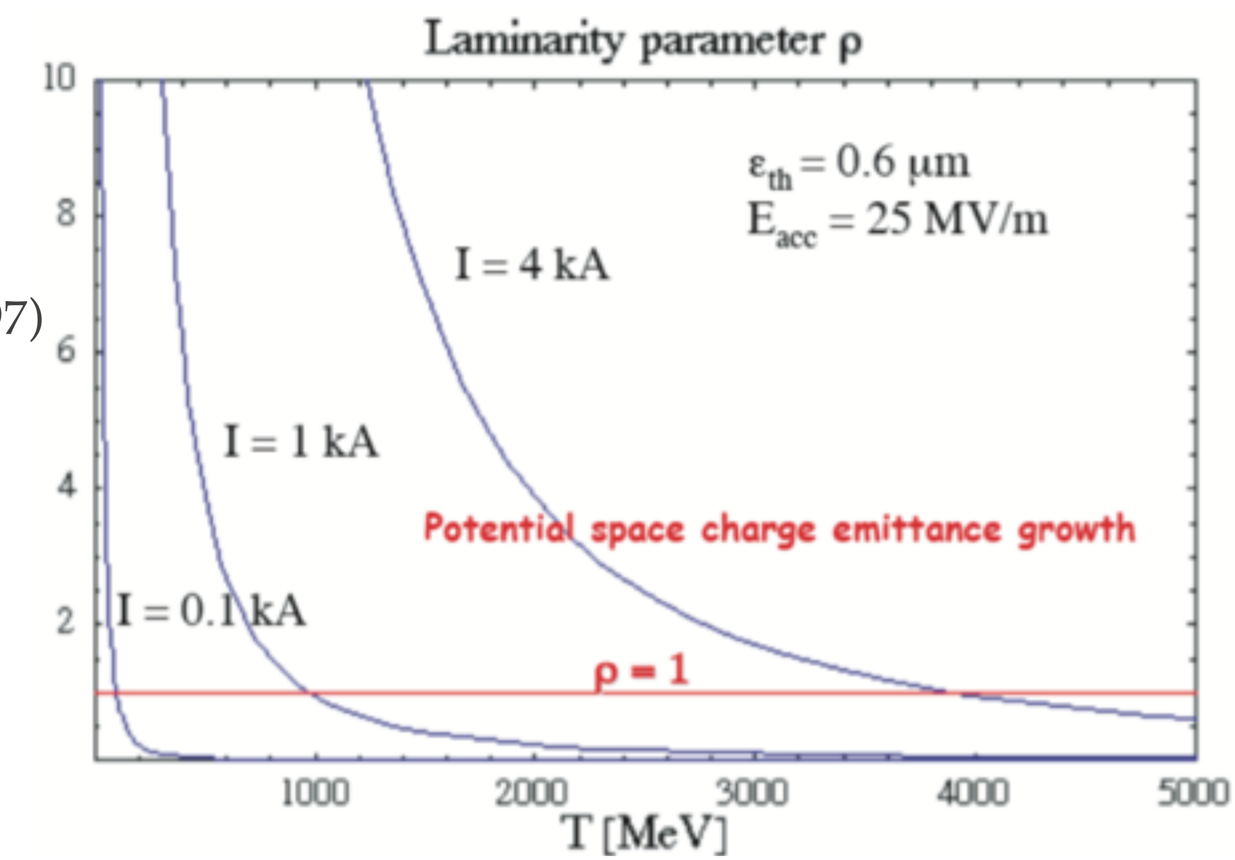
Horizon 2020

- An electron injector is the first part of the accelerating chain
  - The electron beam generated at rest energy is accelerated and guided up to energies where space charge force effects are negligible and under control
    - beam evolution is not space charge dominated anymore
- Space charge forces scale inversely with the square of the beam energy
- Space charge forces influence the beam dynamics and are one the main performance limitations in high brightness electron injectors

✤ L. Serafini and J. B. Rosenzweig, Phys. Rev. E, 55(6) - 7566-7590 (1997)

✤ L. Serafini and J. B. Rosenzweig, PAC97

✤ M. Ferrario et al. *New Journal of Physics* **8** (2006) 295



$$\gamma_t = \sqrt{\frac{2}{3}\frac{2k_s}{\varepsilon_{th}\gamma'}}$$

RF Photo-injector "users"

Horizon 2020

- **External injection schemes**
  - Laser driven (500 MeV)
    - witness generation
  - Particle driven (450 - 500 MeV)
    - both driver and witness generation

Two options can be studied

One **advantage** of PWFA with respect to LWFA is the availability of **high average power beams, ~100 W**

- **superconducting linac (*FLASH-like* to take profit of the *high rep rate*)**
  - WP9 (DESY people take care of simulations), WP5 *can coordinate* the work
- **high gradient normal conducting linac (e.g. *X-band* to take advantage of *compactness*)**
  - WP9 (INFN people take care of simulations), WP5 *coordinates* the work

The NRF Injector

- The RF injector is composed of
  - S-band photo-injector to generate multi-kA beam current (*TSTEP*)
  - X-band linac to boost the beam up to ~500 MeV (*Mad8 and Elegant*)
  - Focusing region to match the beam transversally at the plasma entrance (*Elegant,TSTEP)*

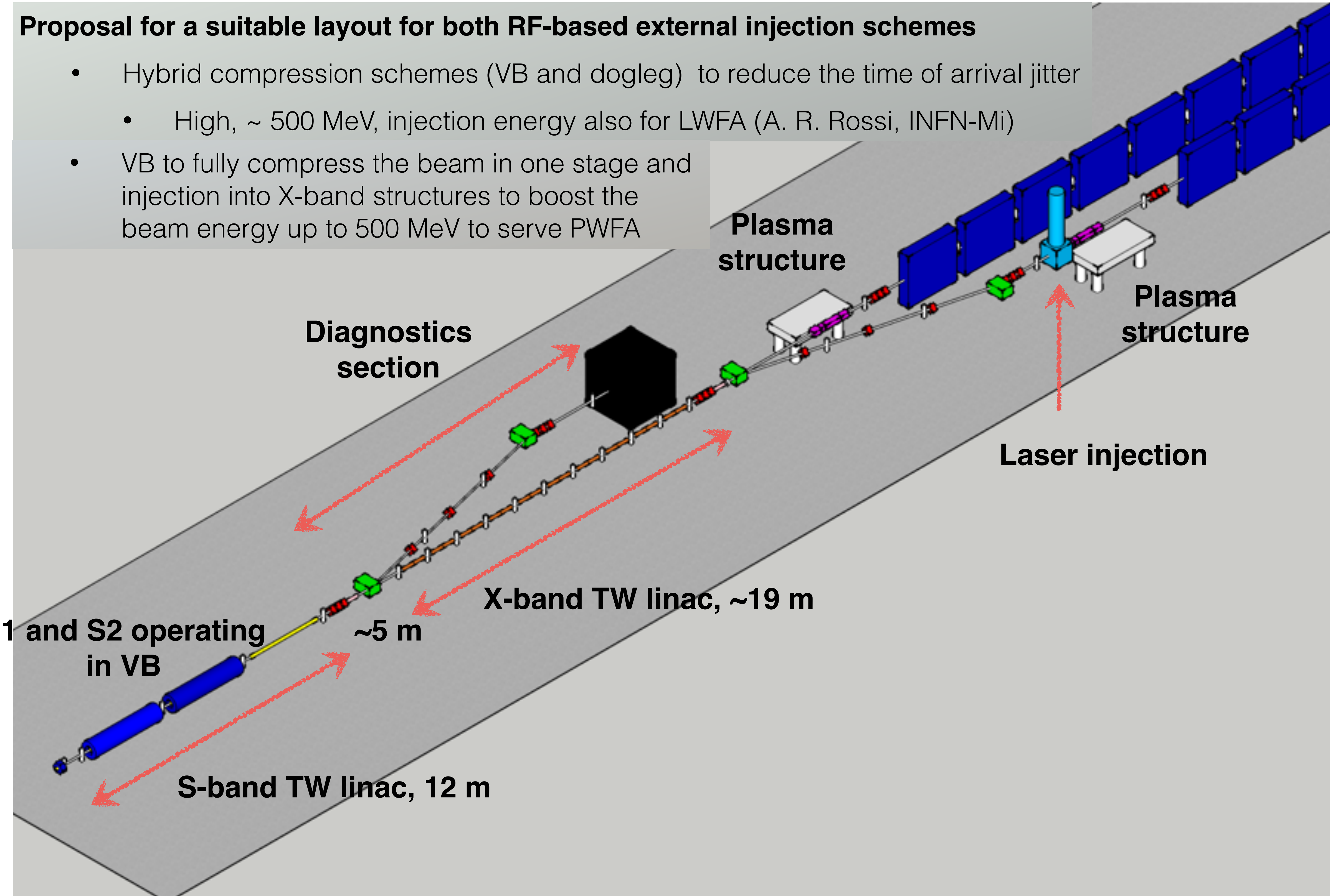
Beam dynamics simulations have been performed by means of **TSTEP** to take into account space charge degradation effects **in the photo-injector** and of **Elegant** code for the **high-energy linac**.

The beam dynamics in the **final focusing** system has been simulated with **both Elegant and TSTEP** to include the space charge degradation effects due to high density phase space in the strong focusing region.

Preliminary Layout

Proposal for a suitable layout for both RF-based external injection schemes

- Hybrid compression schemes (VB and dogleg) to reduce the time of arrival jitter
    - High, ~ 500 MeV, injection energy also for LWFA (A. R. Rossi, INFN-Mi)
- VB to fully compress the beam in one stage and injection into X-band structures to boost the beam energy up to 500 MeV to serve PWFA



Beam Parameters

	Units	EuPRAXIA FEL-CDR 1 GeV Witness bunch	
No.bunches		1	
Bunch separation	ps		
Rep. rate	Hz	10	
Injector energy	GeV	0.15	
Xband Acc. Gradient	MV/m	> 70	
Exit linac energy	GeV	0.5	
Rms Energy Spread	%	<1	<1
FWHM Peak current	kA	3	1.5
Bunch charge	pC	30	10
Bunch length ~~rms~~ FWHM	µm (fs)	3 (10)	2 (7)
Rms norm. emittance	µm	<1.5	<1
Slice Length	µm	0.75	0.75
Slice Charge	pC	7.5	3.7
Slice Energy Spread	%	0.1	0.1
Slice norm. emittance	µm	1	0.5
Undulator period	cm	1.5	1.5
K		1	1
ρ	x 10^{-3}	1.1	1.1
Radiation wavelength	nm (KeV)	3. (0.4)	3. (0.4)
Saturation length	m	26	27
Saturation power	MW	1210	492
Energy	µJ	12	3.3
Photons/pulse	x 10^{10}	17.	4.8

	Full VB and X-band linac	PWFA 2 FEL-SASE 1 GeV 1 Drive bunch	Full VB and X-band linac
No.bunches		1	
Bunch separation		1.	
Rep. rate		10	
Injector energy	~0.1	0.15	0.1
Xband Acc. Gradient	~60	> 70	~60
Exit linac energy	0.518	0.5	0.518
Rms Energy Spread	0.06	< 1	0.25
FWHM Peak current	~3 at the final focus	1.8	~3 at the final focus
Bunch charge	30	200	200
Bunch length	~3 (10)	34 (112)	~20 (67)
Rms norm. emittance	~0.46	< 2	~4

The slice length is 0.75 um

~4 slices with ~3 kA => more than half of the charge contributes to lasing

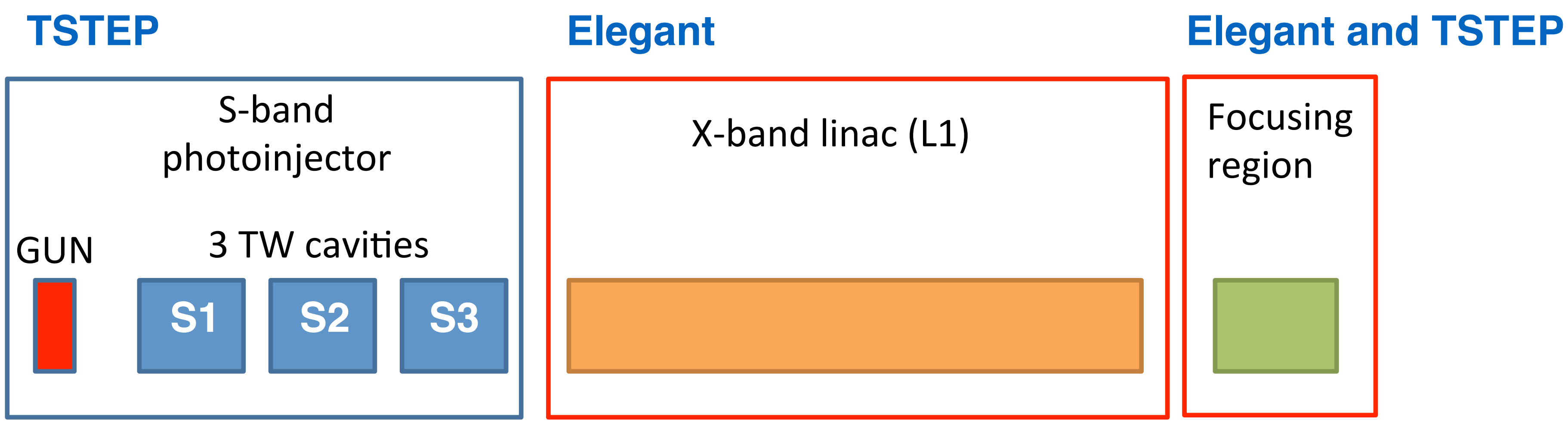
These parameters have been obtained as there were two injectors!!

Witness beam for LWFA

by Anna Giribono (INFN-RM1) and C. Vaccarezza (INFN-LNF)

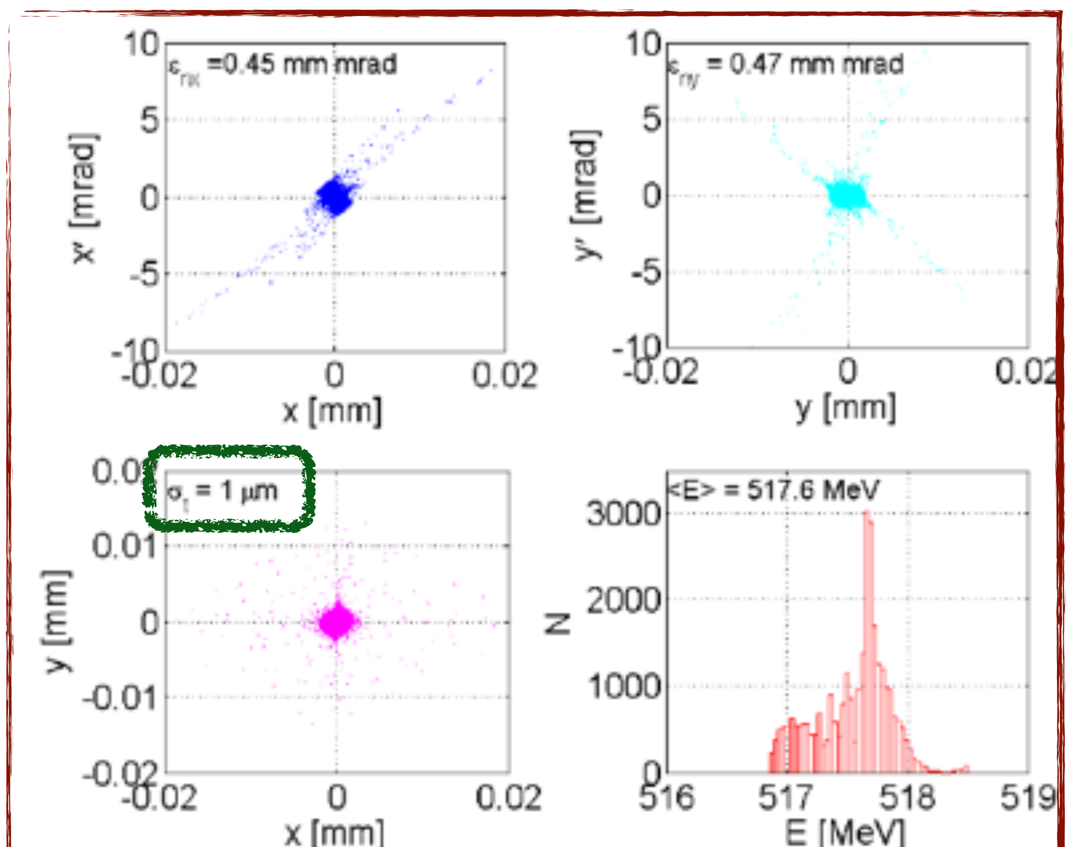
Horizon 2020

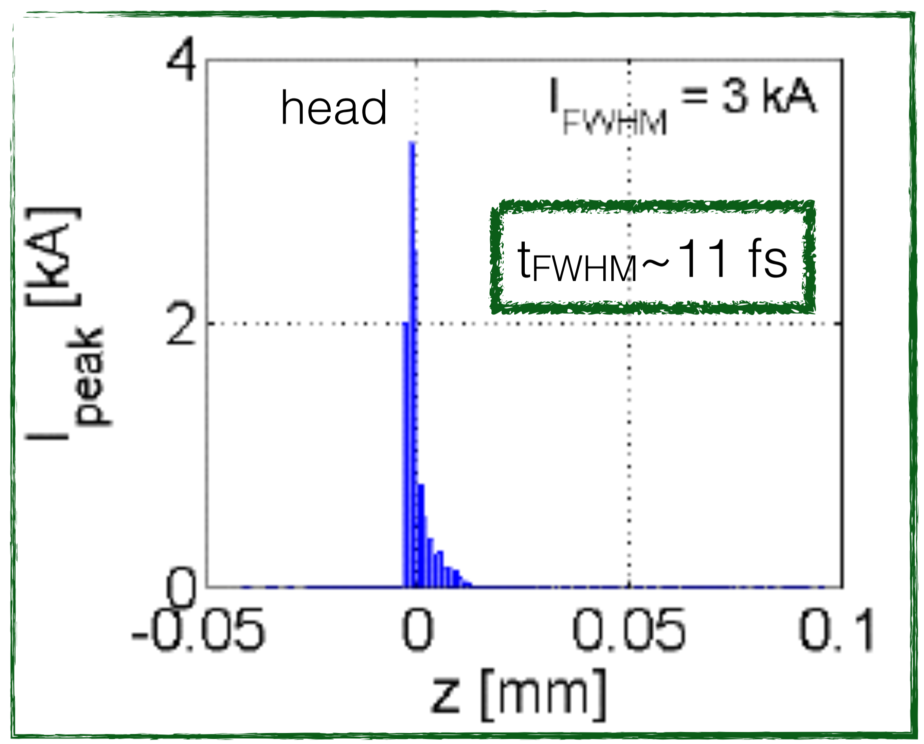
- Working point for the witness at the plasma entrance for both external injection schemes

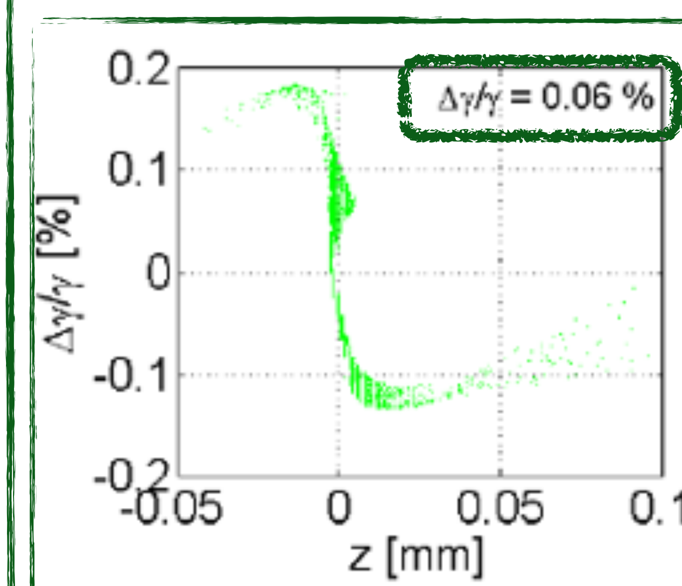


E [MeV]	**518**
ΔE/E [%]	**0.06**
$I_{peak-FWHM}$ [kA]	**3**
Q [pC]	30
$\sigma_{z\text{-}rms}$ [μm]	**6**
$\sigma_{z\text{-}FWHM}$ [μm]	**3**
$\varepsilon_{x,y}$ [mm mrad]	**0.46**
$I_{peak-Slice}$ [kA]	3.5

Velocity bunching in S1 and S2

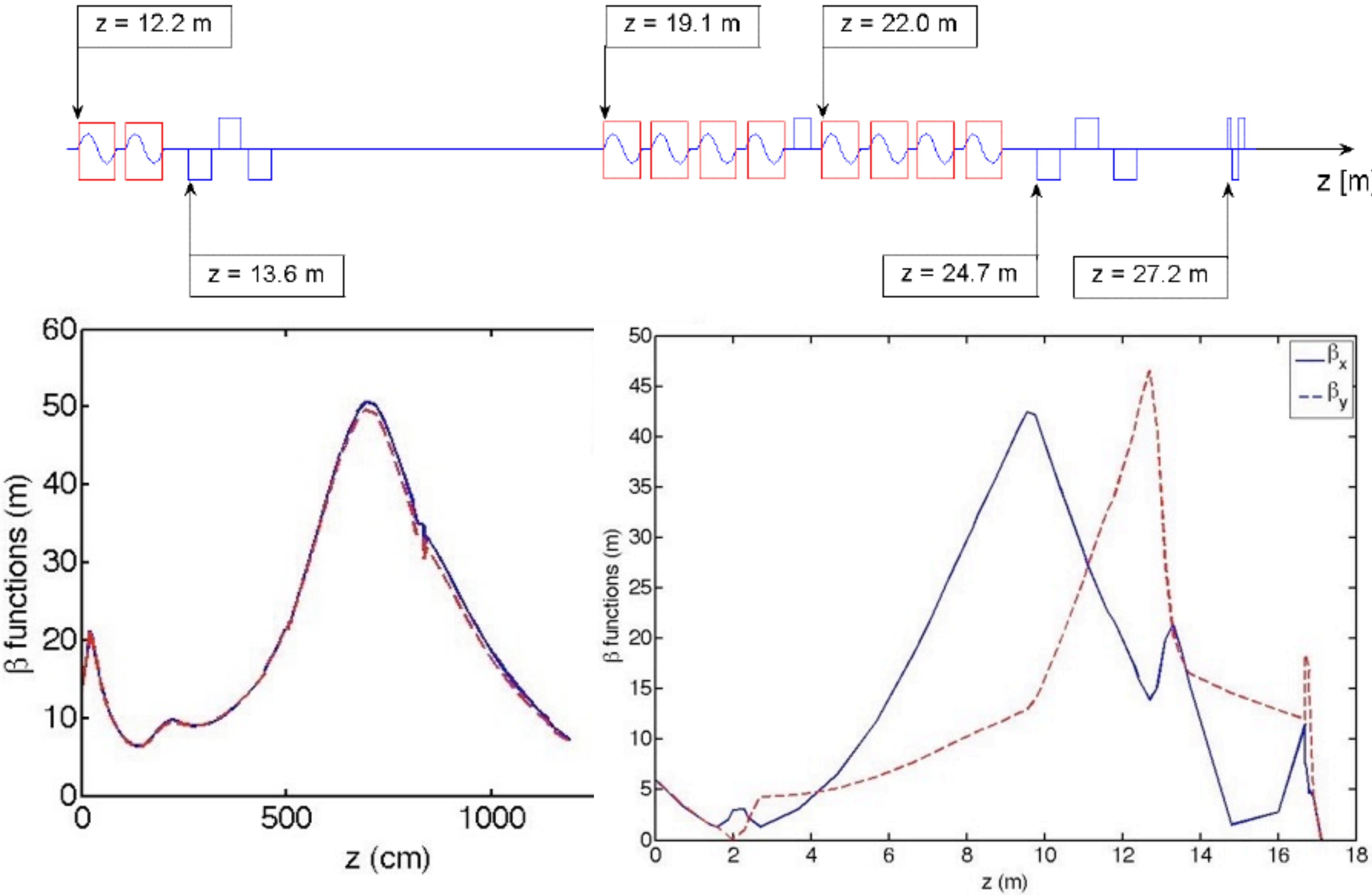






Witness beam for LWFA

by Anna Giribono (INFN-RM1)

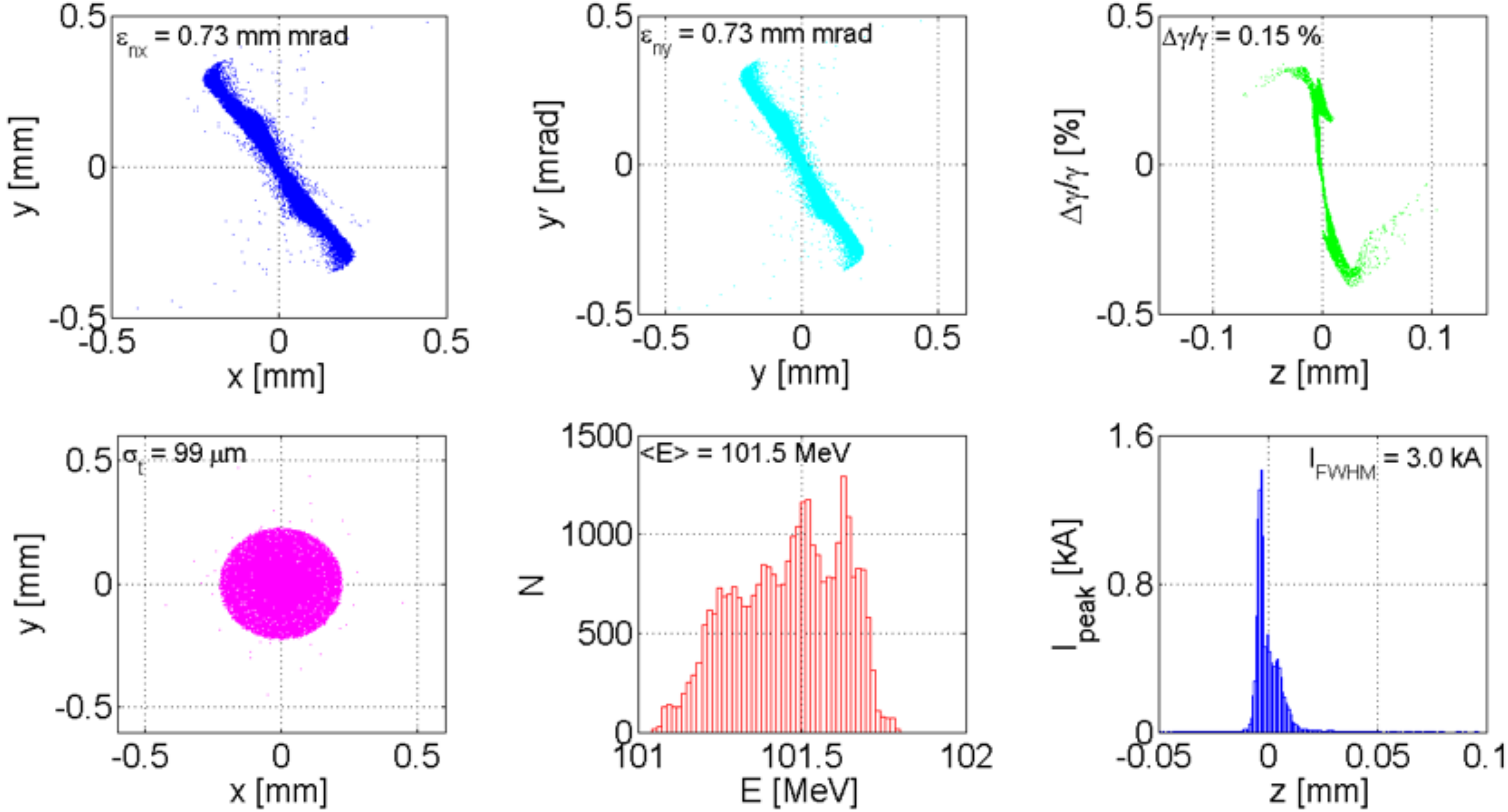


Comb-like beam for PWFA

by Anna Giribono (INFN-RM1)

Two bunches generated at the cathode, separated by 4 ps

Witness beam (30 pC) at the end of S-band linac: S1 and S2 in VB



Slice Parameters

In FELs, the resonance condition

$$\lambda_r = \frac{\lambda_u}{2\gamma^2}(1 + K_{rms}^2)$$

implies that the radiation slips forward, with respect to electrons, of λ_r each undulator period λ_u

- the amplification happens at the scale of the slippage length:

$$L_s = N_u \lambda_r$$

- **the beam quality has to be certified at scale of *L_s***
  - Beam parameters required at a given temporal range
    - **Slice parameters: slice emittance and slice energy spread** => **more relaxed request, but projected emittance plays a role in matching to the undulator!!**

LWFA external injection

by Andrea R. Rossi (INFN-Mi)

Original beam by A. Bacci

σ_{tr} = 13 μm σ_z = 12 fs E = 354 MeV

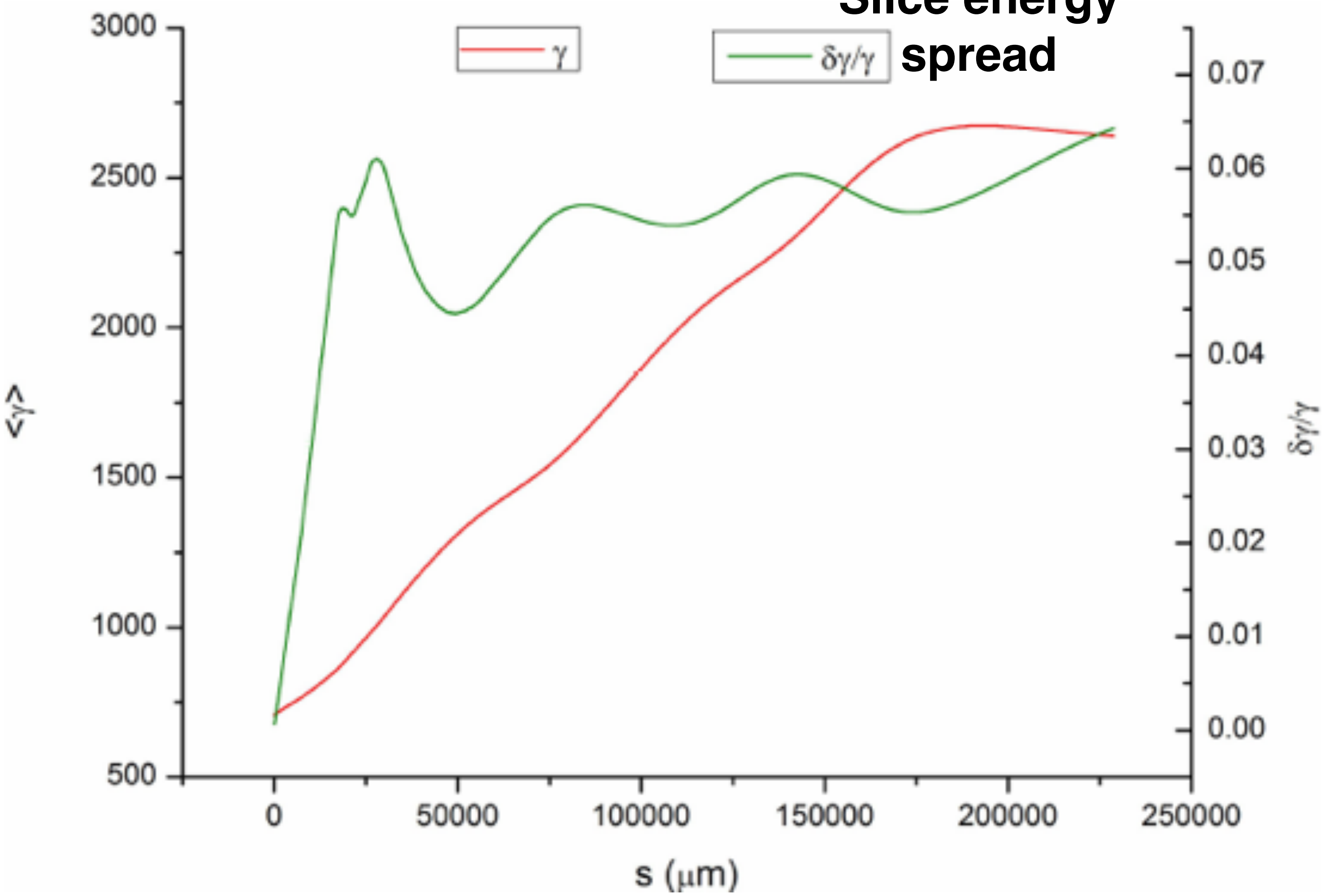
dE/E = 7.3 10^{-4} q = 40 pC

Laser param (matched in channel)

σ_{tr} = 75 μm τ_{FWHM} = 50 fs E = 12.5 J

a_0 = 1.14

Slice energy spread



plasma density = 10^{17} cm^{-3}

	EuPRAXIA@SPARC_LAB	
E	1 GeV	1400 MeV
Q	30 pC	40 pC
τ	10 fs	12 fs
I	3 kA	2.1 kA
f	10 Hz	
N	1	
σ_E/E	1%	2.7 %
$\sigma_{E,S}$/E	0.1 %	.1 % - 0.6 %
$\varepsilon_{N,x}$, $\varepsilon_{N,y}$	1 mm mrad	0.7 mm mrad
$\varepsilon_{N,x,S}$, $\varepsilon_{N,y,S}$	tbd	< 1 mm mrad
z_S	tbd	
α_x, α_y	0	-0.8
β_x, β_y	5 m	3.4 cm
σ_x , σ_y	50 μm	4 μm
$\sigma_{x'}$, $\sigma_{y'}$	10 μrad	270 μrad

Laminar Velocity Bunching

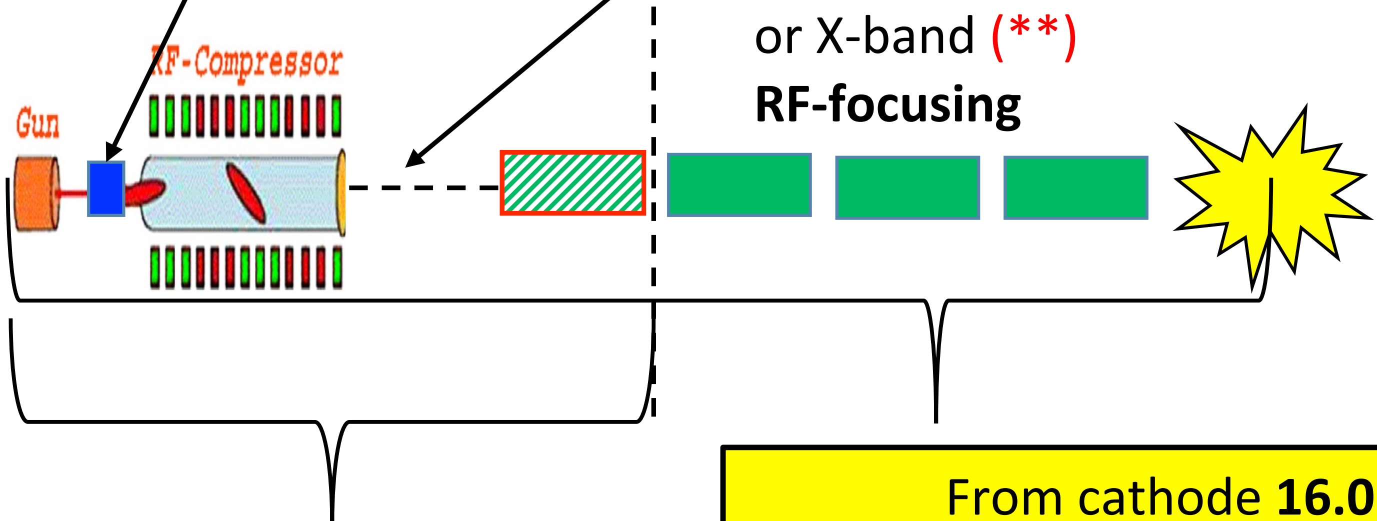
by Alberto Bacci (INFN-Mi)

Horizon 2020

High Harm. Cavity

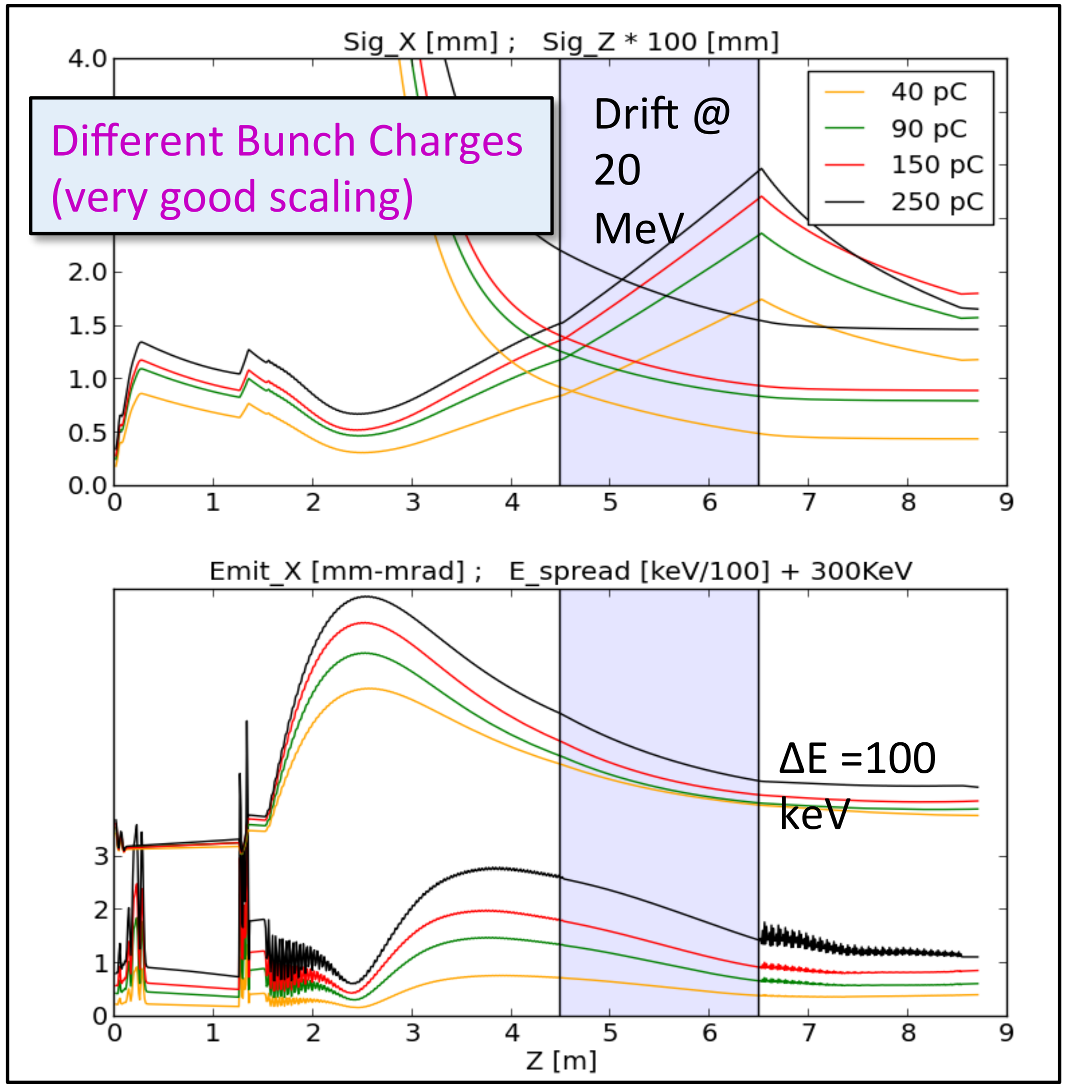
2.0 m DRIFT
Quads & diagnostic

C- band **booster**,
or X-band (**)
RF-focusing



8.7 m
Injector exit

From cathode **16.0 m**
Energy : 150 ÷ 400 MeV
Parameters ad-hoc for:
- Plasma external injection
- Comb test (PWFA)



σ_{tr} = 13 μm
dE/E = 7.3 10^{-4}

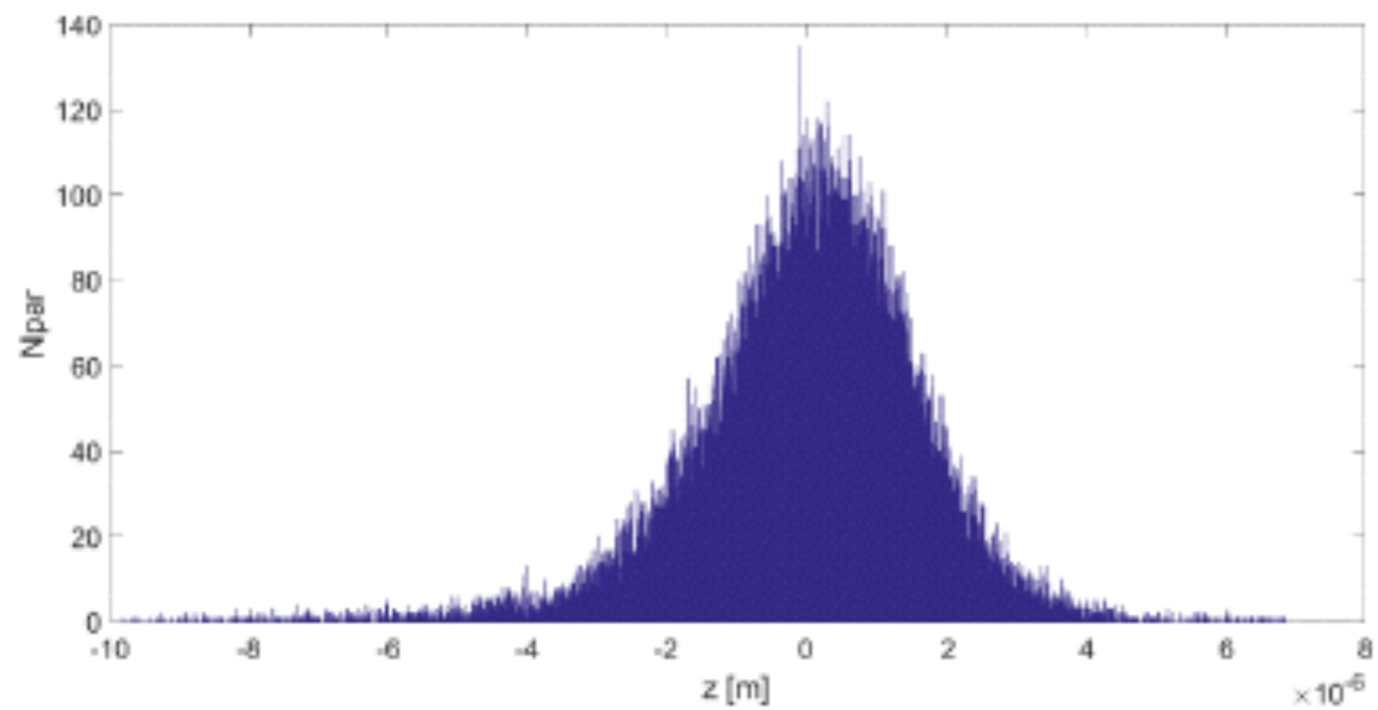
σ_z = 12 fs
q = 40 pC

E = 354 MeV

High Gradient RF Gun

by Michele Croia (INFN-LNF)

	Gun exit	Injector-end (VB+BB)
Q (pC)	30	30
E (MeV)	5,7	75
$\frac{\Delta E}{E}$	4×10^{-3}	1×10^{-3}
$\varepsilon_{n,rms}$	$1.9 \times 10^{-7}\ m * rad$	$3 \times 10^{-7}\ m * rad$
σ_x (m)	3.5×10^{-4}	1.5×10^{-3}
σ_z (m)	5.6×10^{-5}	2.1×10^{-6}
I (A)	160	4.28×10^{3}



- TO DO: Booster up to 500 MeV and final focus matching transfer line

Longitudinal Pulse Shaping

PHYSICAL REVIEW SPECIAL TOPICS—ACCELERATORS AND BEAMS **18**, 081301 (2015)

Tailored electron bunches with smooth current profiles for enhanced transformer ratios in beam-driven acceleration

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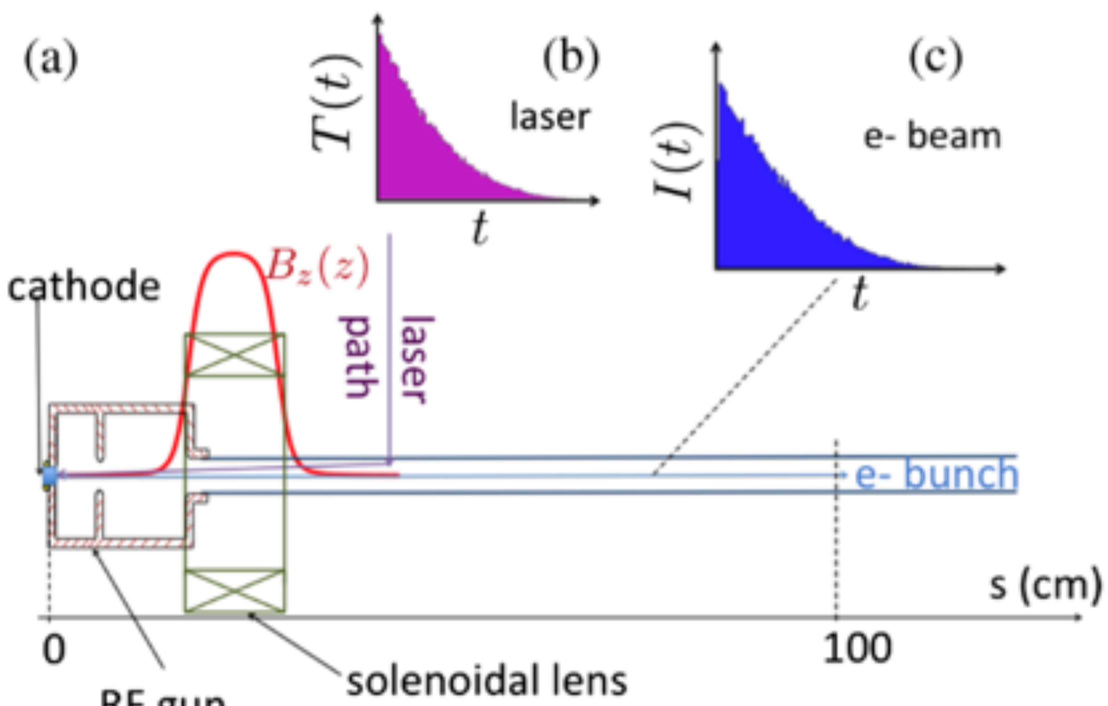
(Received 22 May 2015; published 3 August 2015)

$$T(t) = T_0 t^{\alpha} H(\tau - t),$$



1.6 cell S-band

- Charge density sufficiently low
  - the resulting distribution will be relativistically preserved through a drift
- larger charge densities,
  - the original longitudinal distribution will morph according to the integrated space charge forces inside the bunch
    - **A large (~140 MV/m) acceleration gradient in the gun helps preserving larger charge densities compared with, e.g., L-band guns (~40 MV/m)**

It is worth to investigate high gradient RF guns

Open Issues

- **Superconducting linac**
    - FLASH like
- **Normal conducting linac**
    - Compact design => x-band technology
- What beam **injection** energy
    - As high as needed to get out from space charge effects: ~ 500 MeV
- What beam quality
    - Consider the 6D brightness $B_{6D} \propto \frac{Ne}{\varepsilon_{nx}\varepsilon_{ny}\sigma_t\sigma_\gamma}$ ~ 10^{19} Am^{-2}
    - **N~10^8, en ~ 0.5 mm mad, sg ~ 0.1%, st ~ 10 fs**
- What peak current and which shapes
  - We need also the possibility to generate multi-bunch at the cathode
  - the choice is driven by most demanding user applications, e.g. FELs
  - Investigation of the effect of a higher harmonic cavity to linearize the longitudinal phase space
    - Is it really needed thinking to PWFA?
- What average current
  - the choice is driven by applications?
- Different plasma sources for different acceleration schemes
    - Different matching conditions

Agenda for WP5 meetings

Horizon 2020

Wednesday, 21st of June 2017

- **14:00 -15:30 => <u>RF injector working points</u>**
  - Layout introduction and Parameters table (including Twiss functions at peculiar positions) (E. Chiadroni, INFN)
  - RF compression for driver and witness up to the plasma (A. Giribono, INFN)
  - RF and magnetic compression (J. Zhu, DESY)
  - Electron diagnostics
    - Diagnostics conceptual design of EuPRAXIA-like machine (A. Cianchi, Roma2)
  - **Discussion**
    - **Bunch shapes, synchronization, …**

- **16:00 -18:00 => <u>Diagnostics</u>: Joint meeting WP3-WP5**
    - 6D characterization of witness beam before injection (B. Marchetti, DESY)
    - Beam Diagnostics for Plasma Accelerators (J. Wolfenden , CI)
    - Discussion on plasma-based devices for e-beam diagnostics
    - WP14: Challenges in diagnostics of ultrahigh 6d-brightness and laser insertion/removal (B. Hidding, U. Strathclyde)
  - Compatibility with plasma implementation
  - Plasma sources (for both LWFA and PWFA)
    - Plasma diagnostics
  - Radiation diagnostics

Agenda for WP5 meetings

Horizon 2020

Thursday, 22nd of June 2017

- **09:00 -10:30 => <u>Transfer lines</u>**
  - Optimization of the capture section (K. Wang, CNRS/LAL)
  - Matching and transfer lines in plasma injector (WP3)
  - Plasma lenses as novel transfer line devices (A. Marocchino, INFN)
  - Matching conditions to the undulator (WP6)
    - Discussion on witness beam longitudinal distribution
  - Matching conditions to HEP experiments (WP7)
  - **Discussion**
    - **Driver and laser beams after the plasma: how to remove them?**

- **11:00 -12:30 => <u>Joint meeting WP2-WP5-WP9</u>**
  - Code benchmarking discussion
  - Optimization of a comb-like beam down to the plasma for PWFA experiments (A. Giribono)
  - Discussion on driver and witness separation
  - Plasma source