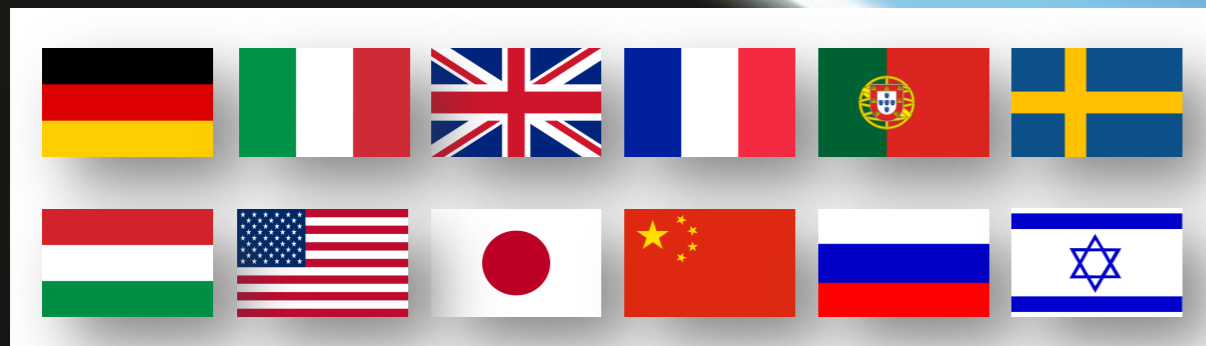


EUROPEAN  
PLASMA RESEARCH  
ACCELERATOR WITH  
EXCELLENCE IN  
APPLICATIONS



# Discussion on RF Injector choices

**E. Chiadroni (INFN-LNF) on behalf of RF injector team**  
**July 4-5, 2018 - 3rd Collaboration Week, Liverpool**



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## Target Values for the 1 GeV beam to drive a FEL SASE

## Target Values for OPA

	Units	1 GeV case	0.2 - 1-5 GeV
Bunch charge	pC	30	>100
Peak current	kA	3	
Rep. rate	Hz	10	
RMS norm. emittance	$\mu\text{m}$	1	1
RMS Energy Spread	%	1	any
RMS Bunch length	fs	10	fs
Slice norm. emittance	$\mu\text{m}$	<1	
Slice Energy Spread	%	0.1	
Slice Length	$\mu\text{m}$	0.75	
Radiation wavelength	nm	4	
Pierce parameter $\rho$	$10^{-3}$	>1	
Undulator period	cm	1.5	
Undulator strength K		0.872	

- These numbers, in particular kA current and 0.5 mm mrad emittance, are not consistent with the 150 MeV energy
  - Detailed study based on simulations to identify a consistent set of beam parameters for the photo-injector

Injector beams				
Quantity	Symbol	Baseline value	Range of exploration	
			Lower limit	Upper limit
<b>150 MeV - RF injector beam: at entrance of plasma 2 for LWFA with external injection</b>				
Energy	E	150 MeV	100 MeV	200 MeV
Charge	Q	50 pC	10 pC	50 pC
Bunch length (FWHM)	$\tau$	5 fs	3 fs	30 fs
Peak current per bunch	I	10 kA	1 - 10 kA	
Repetition rate	f	$\geq 10$ Hz	$\geq 10$ Hz	
Number of bunches	N	1	1	20
Shaped profile	-	tbd	tbd	
Total energy spread (RMS)	$\sigma_E/E$	0.1 %	0.1 %	
Transverse normalized emittance	$\epsilon_{N,x}, \epsilon_{N,y}$	0.5 mm mrad	0.5 mm mrad	
Alpha function	$\alpha_x, \alpha_y$	0	0	
Beta function	$\beta_x, \beta_y$	30 mm	30 mm	
Transverse beam size (RMS)	$\sigma_x, \sigma_y$	7.1 $\mu\text{m}$	6.1 - 8.6 $\mu\text{m}$	
Transverse divergence (RMS)	$\sigma_{x'}, \sigma_{y'}$	0.24 mrad	0.2 - 0.29 mrad	
Jitter, beam to global reference (RMS)	$\sigma_{\Delta t}$	10 fs	10 fs	

- The beam parameters at the plasma accelerating module must be those requested by the FEL
  - This requirement sets the minimum injection energy
- In principle, we could inject into the plasma even low energy beam, 10 MeV beam for instance, but not with kA current (and good quality)
- The minimum injection energy depends on the laminarity parameter rho

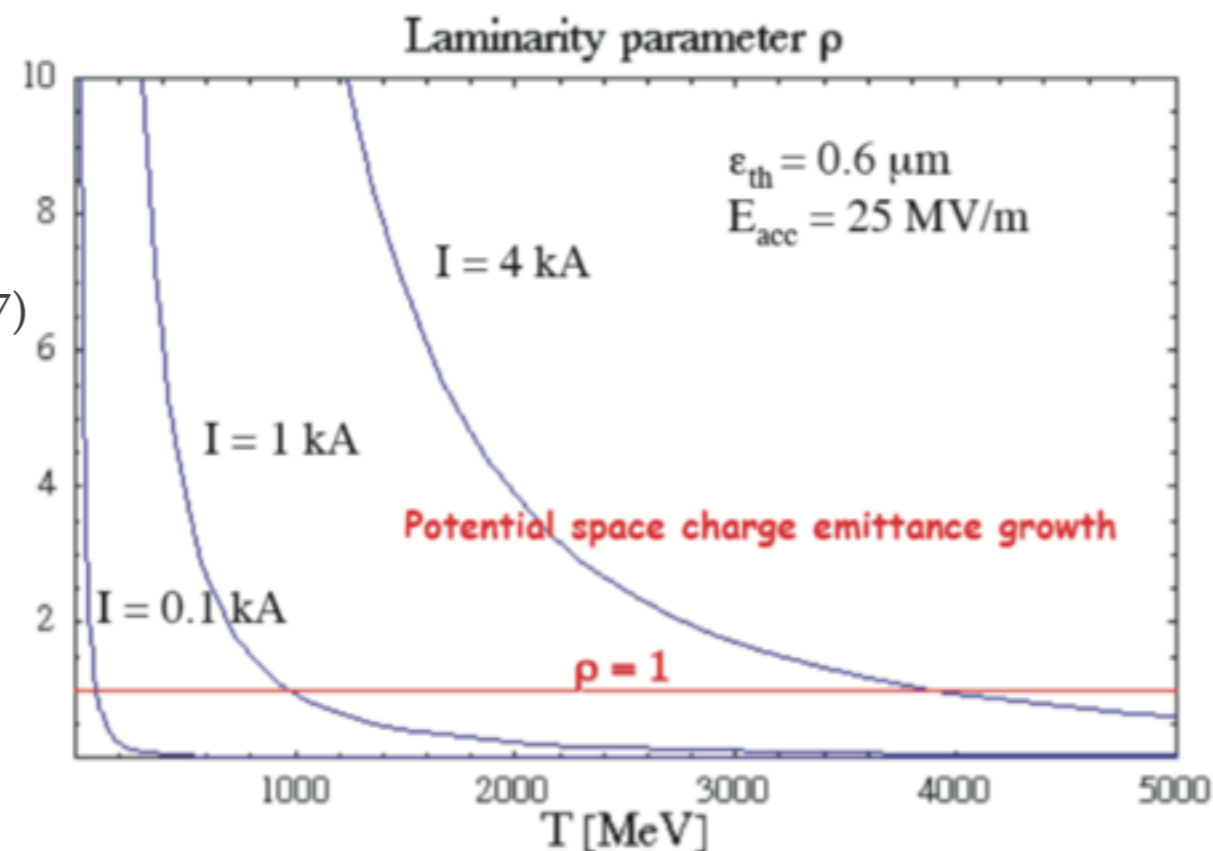
$$\rho = \frac{I}{2I_A \gamma} \frac{\sigma^2}{\varepsilon_n^2}$$

The laminarity parameter represents the ratio between the space charge term and the emittance term in equation

$$\sigma'' + \frac{\gamma'}{\gamma} \sigma' + K\sigma = \frac{k_s}{\gamma^3 \sigma} + \frac{\varepsilon_{th}^2}{\gamma^2 \sigma^3}$$

- For a typical electron linac driven by a photo-injector, the energy at which the transition occurs can be nevertheless quite high
- 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



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

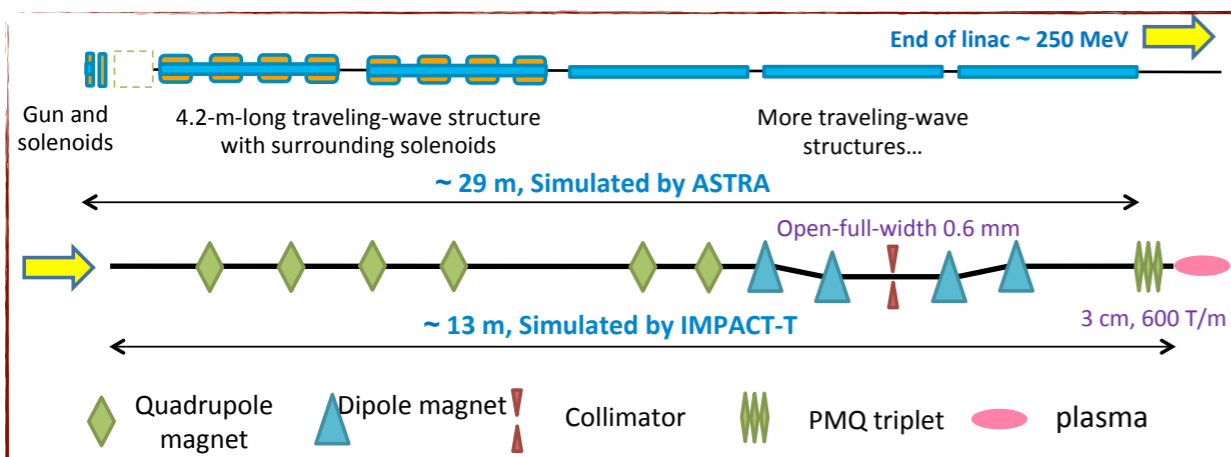
<https://bib-pubdb1.desy.de/record/401420/files/Thesis-Jun-final.pdf>

	WP1	WP2	WP3	WP4
Energy (MeV)	100.5	101.7	99.5	100.8
Bunch charge (pC)	0.75	5.5	28.5	16.5
Projected horizontal emittance ( $\mu\text{m}$ )	0.11	0.50	4.8	0.50
Projected vertical emittance ( $\mu\text{m}$ )	0.099	0.38	24.9	0.79
Slice horizontal emittance ( $\mu\text{m}$ )	0.10	0.32	4.2	0.42
Slice vertical emittance ( $\mu\text{m}$ )	0.077	0.37	12.1	0.82
$\beta_x$ (mm)	1.1	1.8	1.9	2.3
$\alpha_x$	-0.21	0.69	0.89	1.7
$\beta_y$ (mm)	1.0	1.8	3.5	1.2
$\alpha_y$	0.24	-0.58	0.14	-0.60
$\sigma_x$ ( $\mu\text{m}$ )	0.76	2.1	6.9	2.4
$\sigma_y$ ( $\mu\text{m}$ )	0.71	1.9	21.0	2.2
Bunch length [rms] (fs)	0.43	1.7	31.9	8.0
Peak current (kA)	0.62	1.1	0.54	1.5
Relative rms energy spread	0.0017	0.0043	0.0120	0.0027
Slice rms energy spread	0.0010	0.0028	0.0079	0.0021

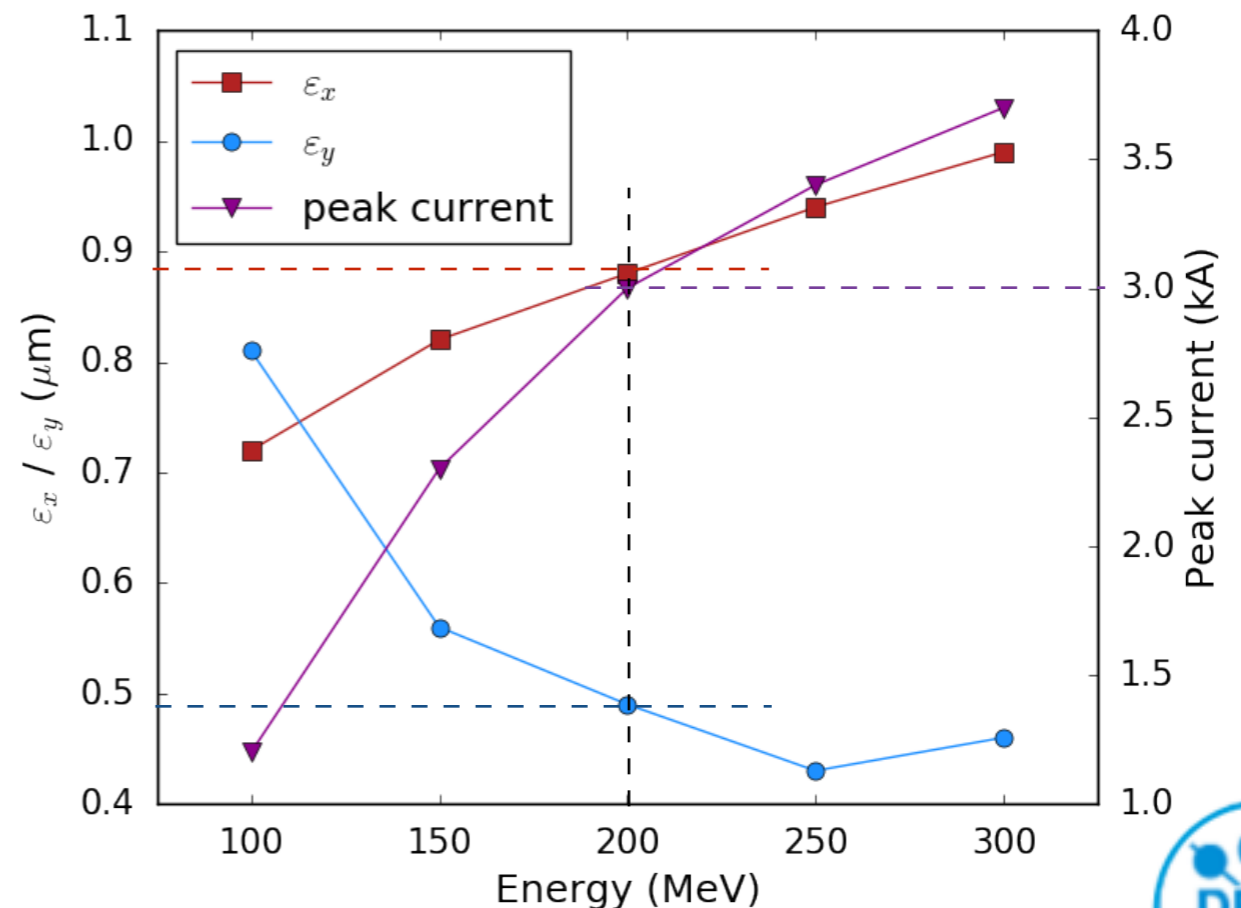


## Jun Zhu's study

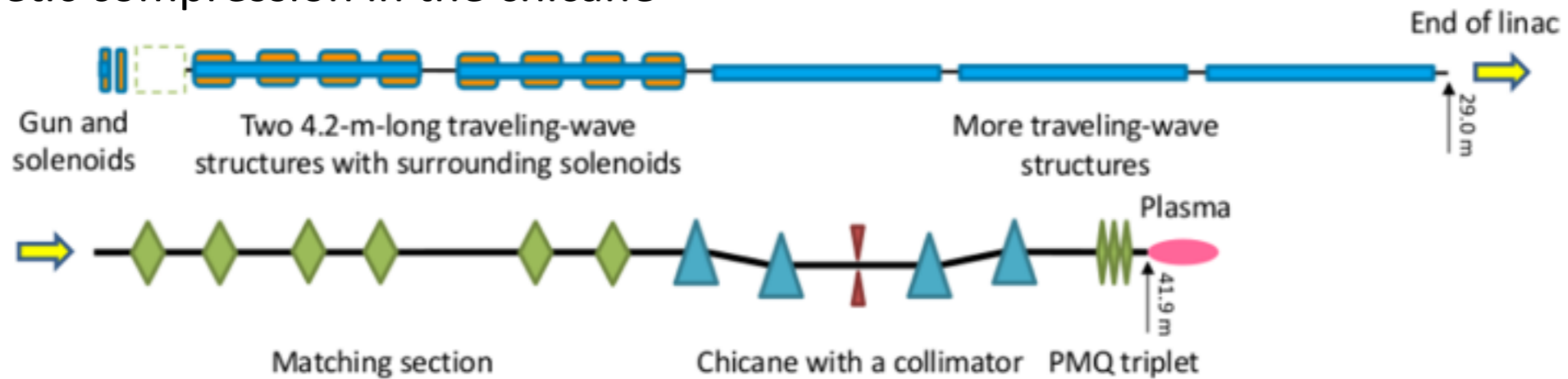
- Starting point: 100 MeV, 50 pC, 180 fs (rms)
  - ARES working point simulated by ASTRA using 1e6 particles: velocity bunching in the 1st S-band section for first compression stage down to 180 fs, then magnetic chicane with a slit collimator to reduce the charge from 50 pC to 30 pC and finally compress the beam down to the final bunch length



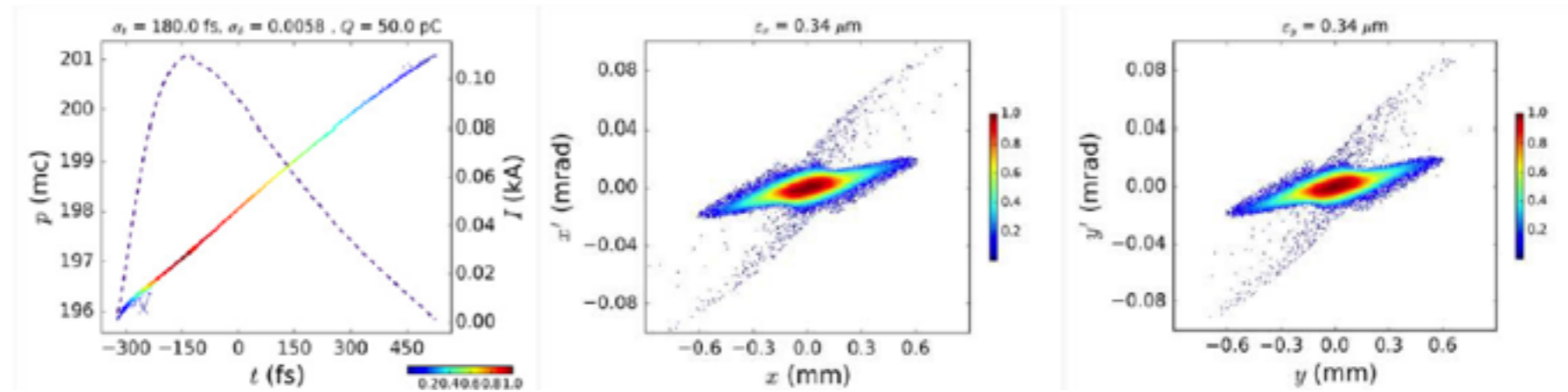
RF compression in the 1st S-band structure and magnetic compression in the dogleg



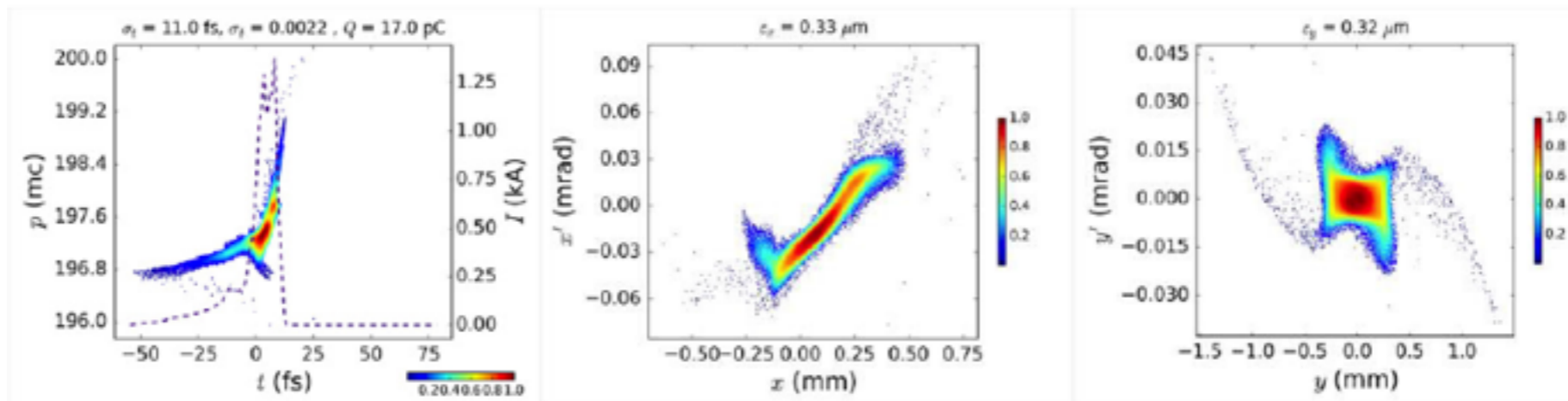
- **Two-stage hybrid compression:** Velocity Bunching in the first S-band section and magnetic compression in the chicane



Linac exit



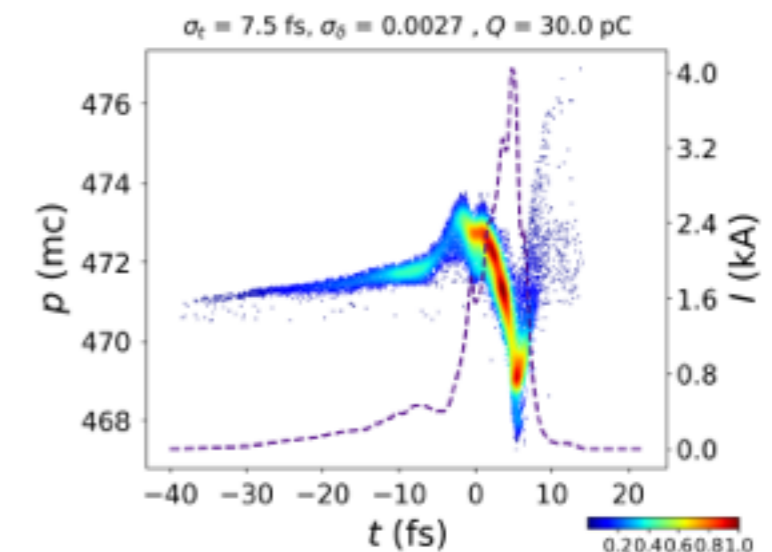
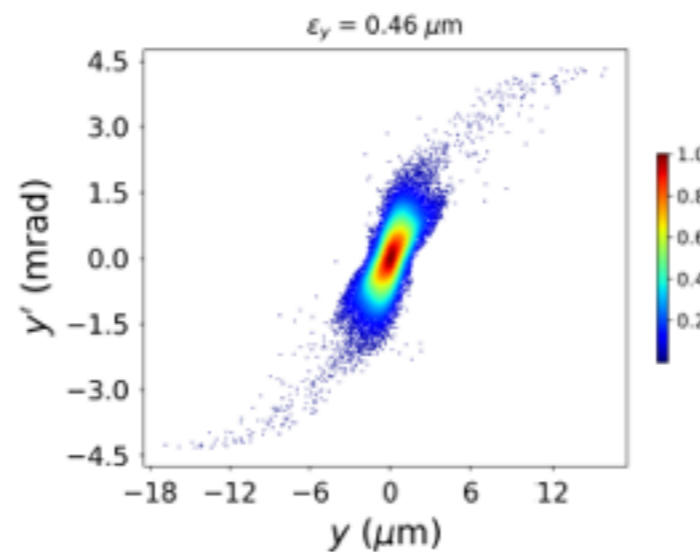
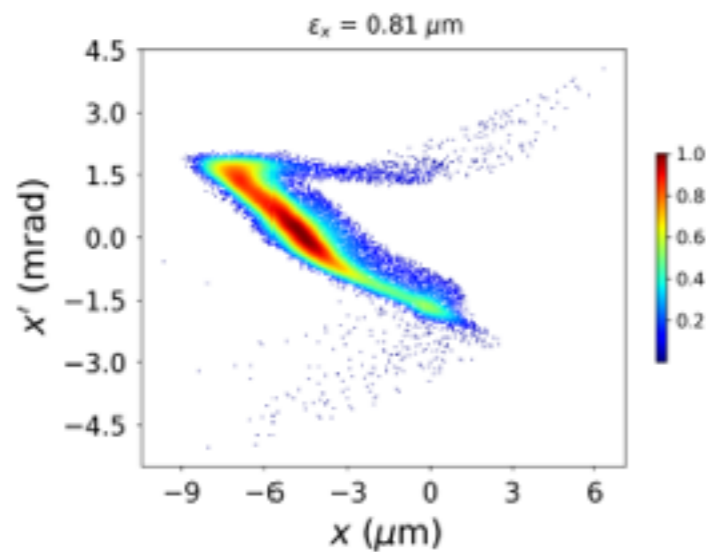
Chicane exit





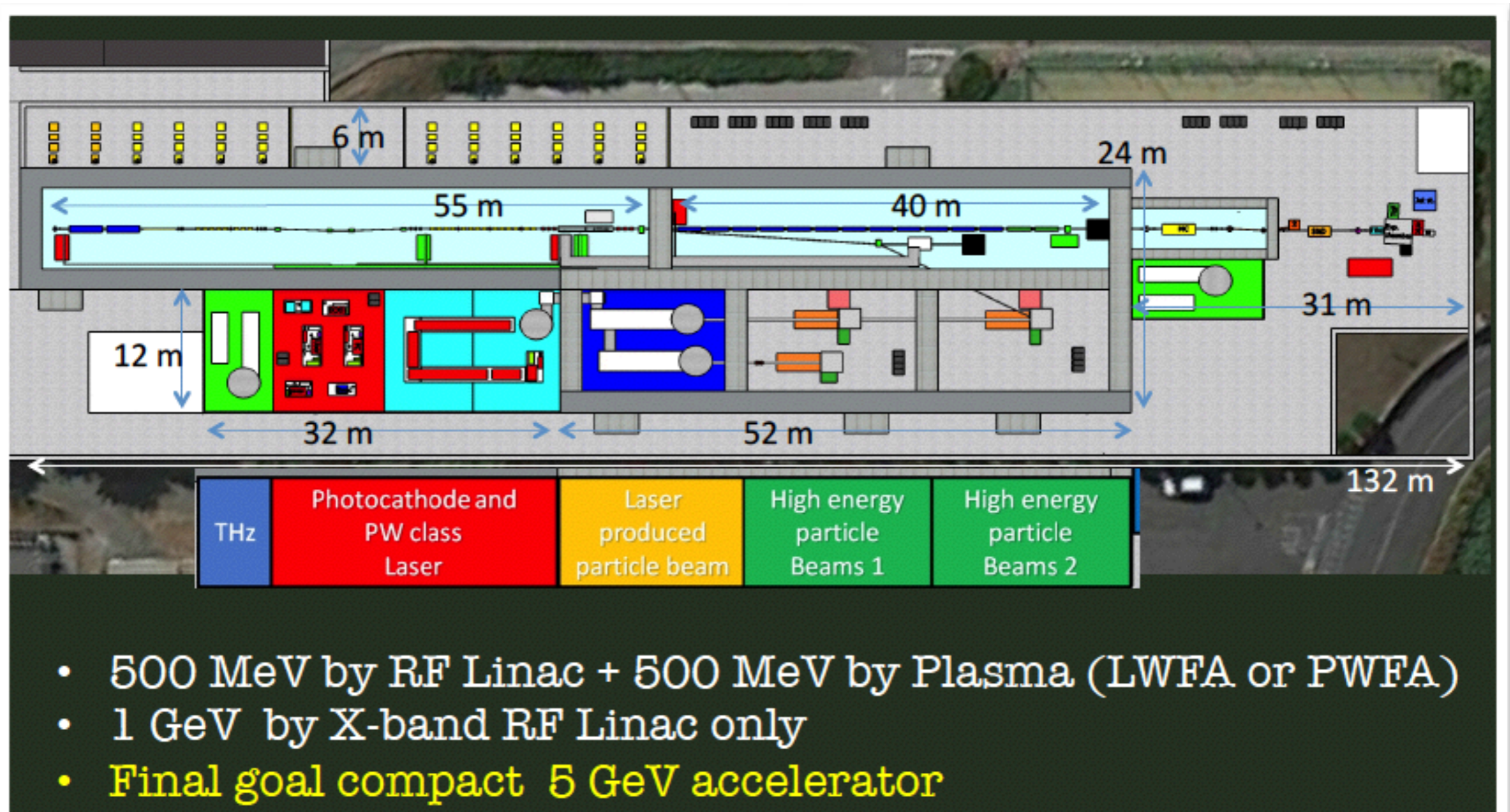
- **Two-stage hybrid compression:** Velocity Bunching in the first S-band section and magnetic compression in the chicane

Injection at the plasma



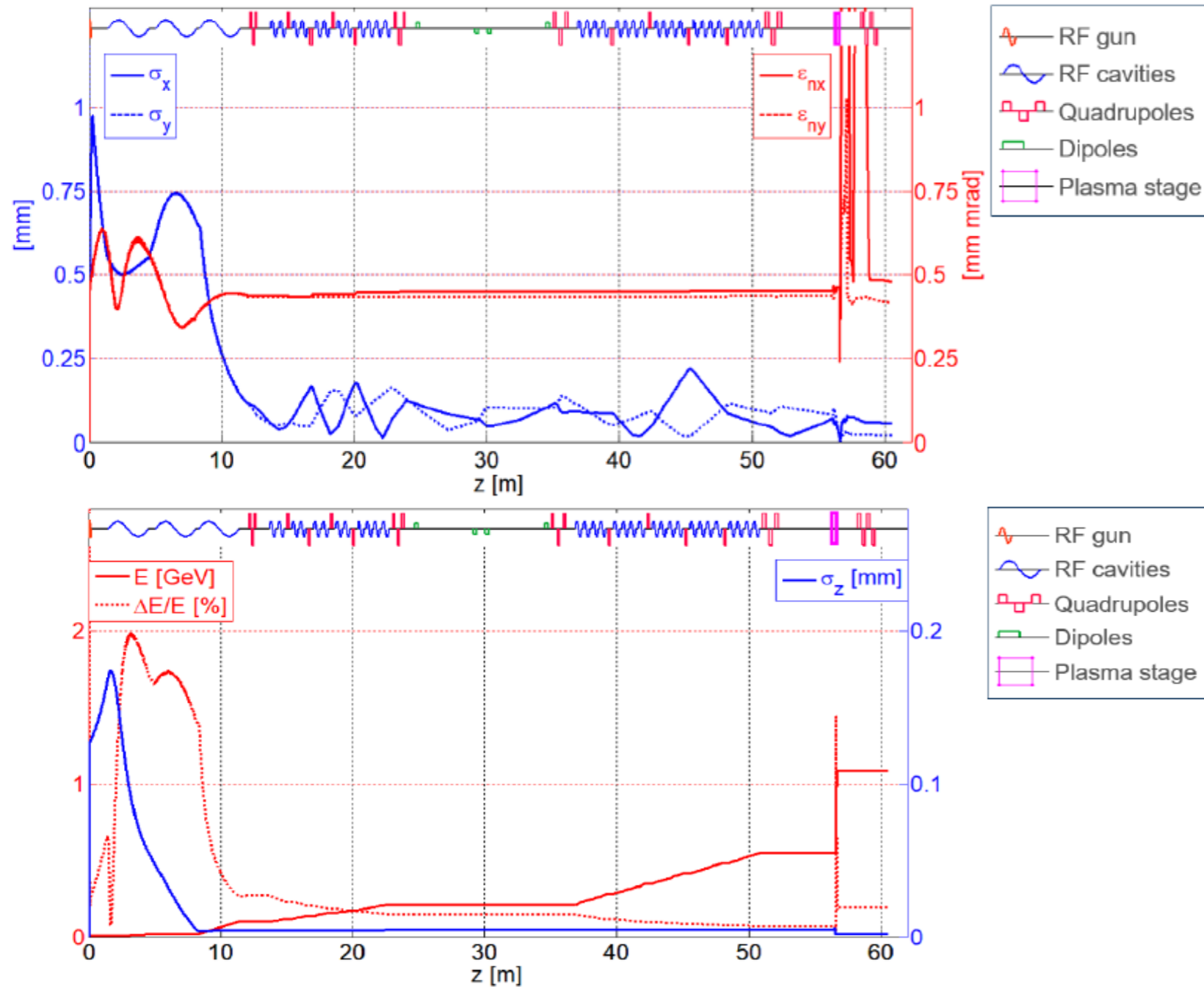
	Linac exit	Injection point
Energy (MeV)	242.0	240.8
Bunch charge (pC)	50.0	29.8
RMS bunch length (fs)	160.0	7.5
Peak current (kA)	0.13	4.0
Projected $\epsilon_x / \epsilon_y$ ( $\mu\text{m}$ )	0.30 / 0.30	0.81 / 0.46
Slice $\epsilon_x / \epsilon_y$ ( $\mu\text{m}$ )	0.28 / 0.28	0.59 / 0.34
$\beta_x / \beta_y$ (mm)	\	3.1 / 3.0
RMS energy spread (%)	0.50	0.27
Slice RMS energy spread (%)	0.05	0.23





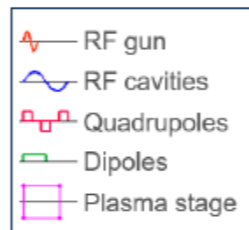
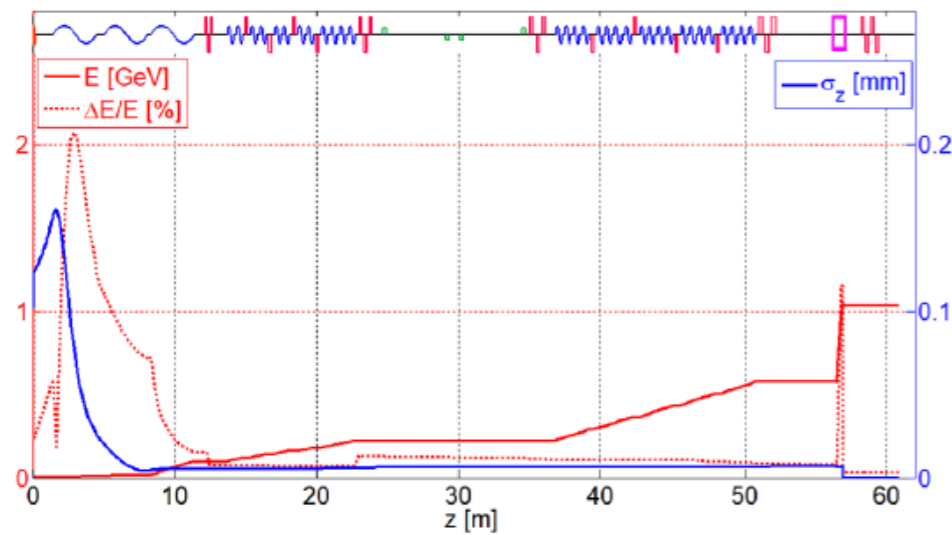
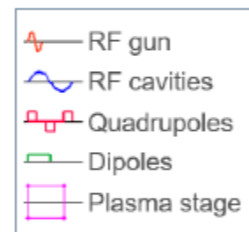
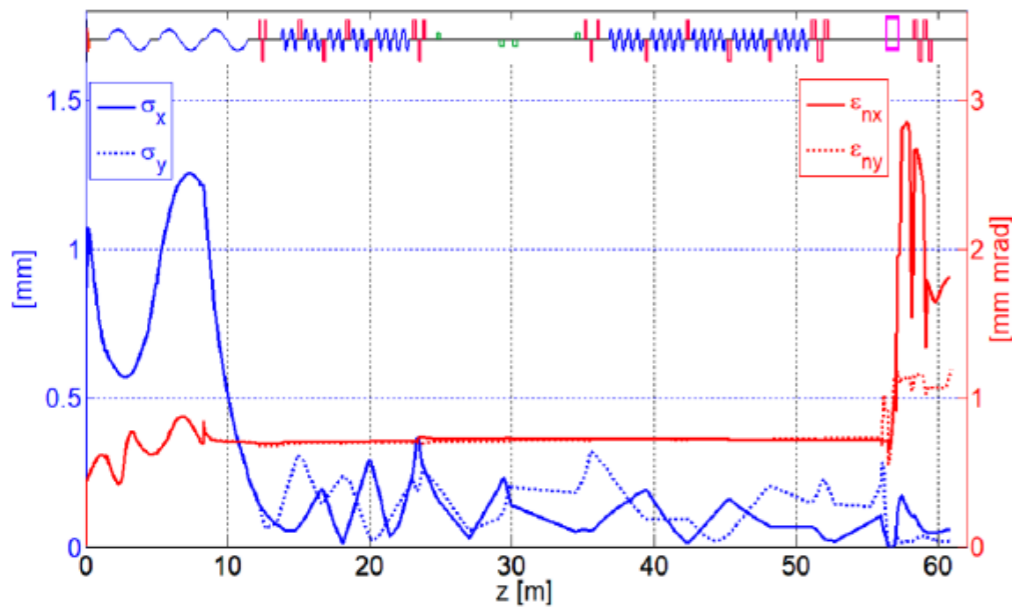
## EuPRAXIA@SPARC\_LAB case

- Full RF compression based on Velocity Bunching in the first 2 S-band sections

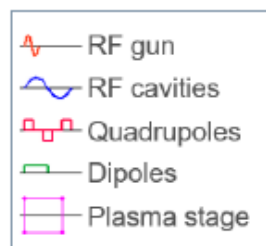
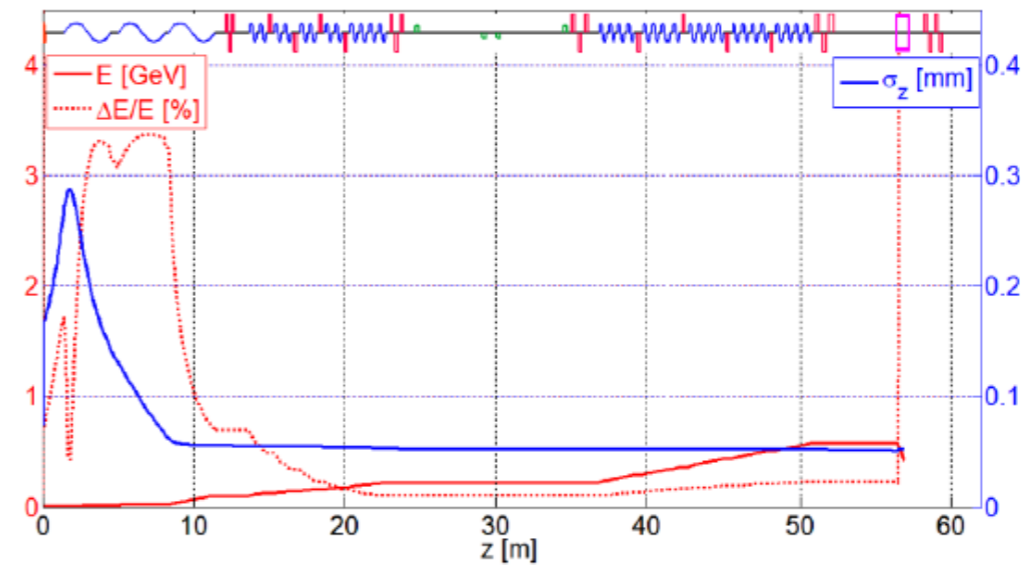
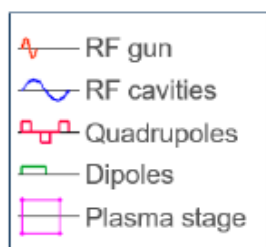
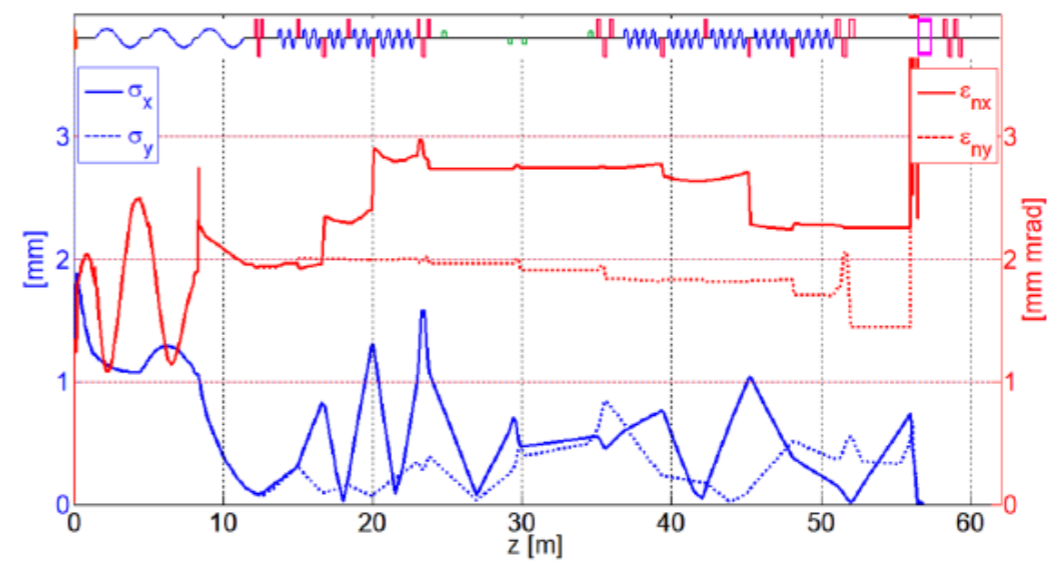


- Laser Comb Technique and full RF compression based on Velocity Bunching in the first 2 S-band sections

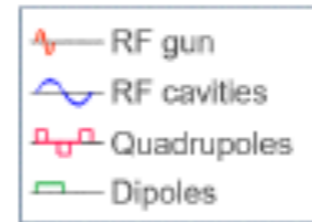
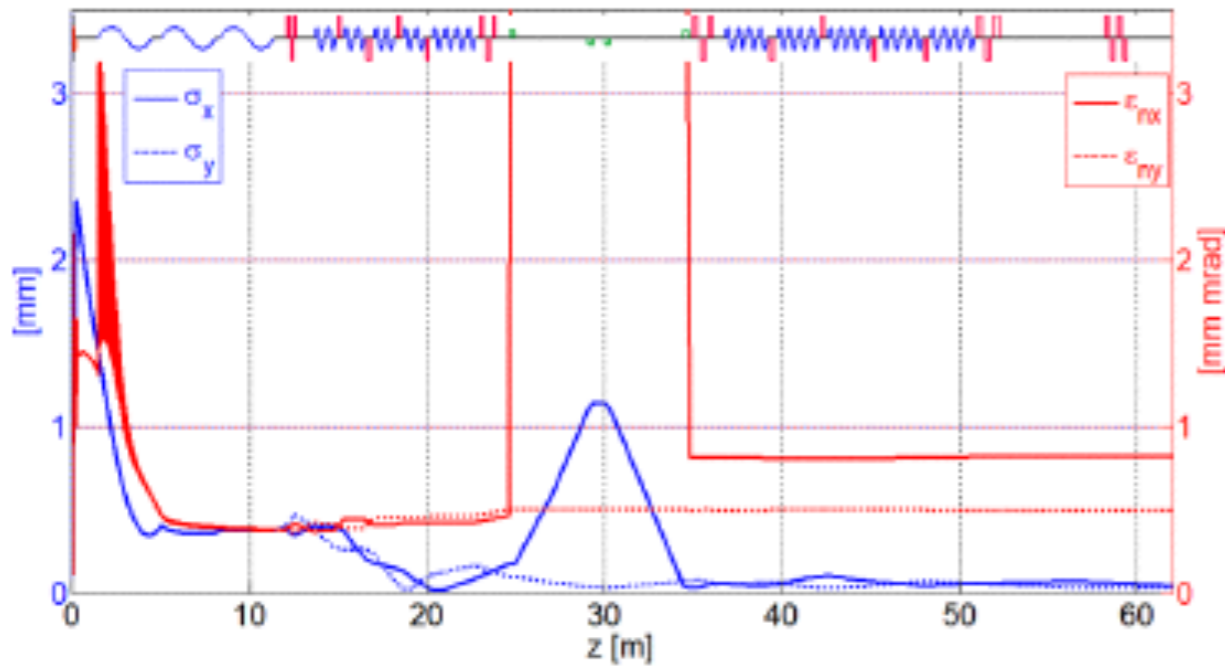
## Witness beam evolution



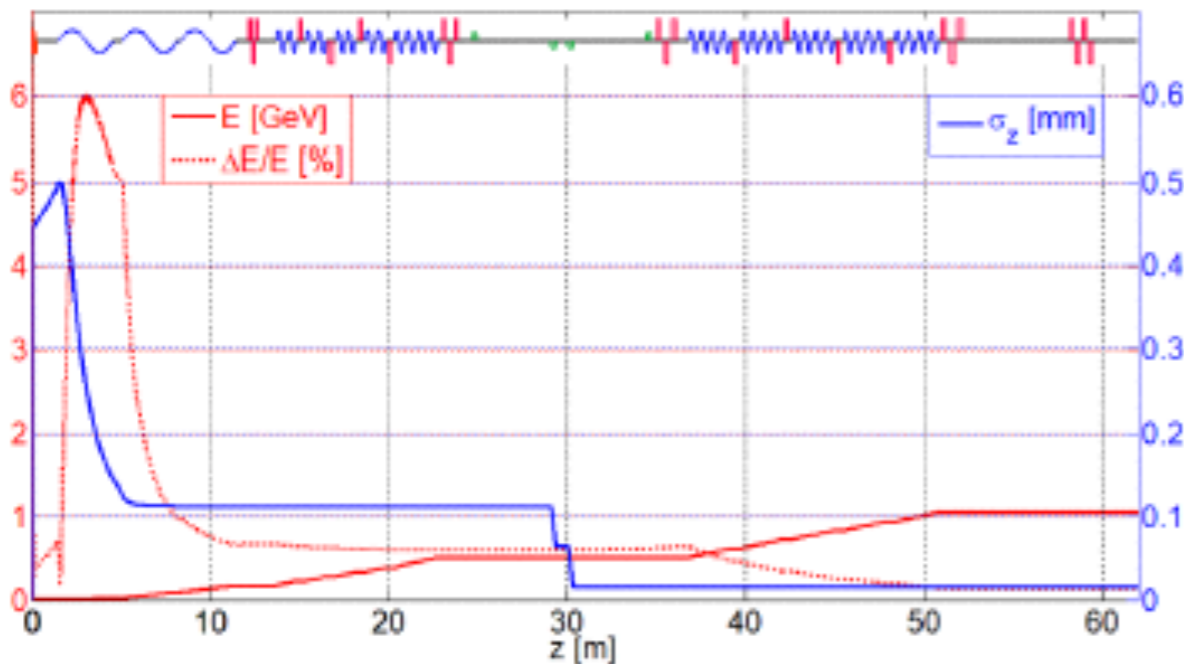
## Driver beam evolution



- Only RF linac to boost a **high charge beam up to 1 GeV energy**



RF Linac	Units	(a) 100 pC	(b) 200 pC
Rep. rate f	Hz	10	10
Exit linac energy	GeV	1.1	1
RMS Energy Spread	%	0.1	0.05
Peak Current	kA	2	1.79
Bunch Charge	pC	100	200
RMS bunch length	$\mu\text{m}$ (fs)	12.7(38.2)	16.7 (55.6)
RMS norm. emittance	mm mrad	0.5	0.5
Slice Length	$\mu\text{m}$	1.25	1.66
Slice Charge	pC	10	6.67
Slice Energy Spread	%	0.018	0.02
Slice norm. emittance (x,y)	mm mrad	0.35-0.24	0.4-0.37



If the request are

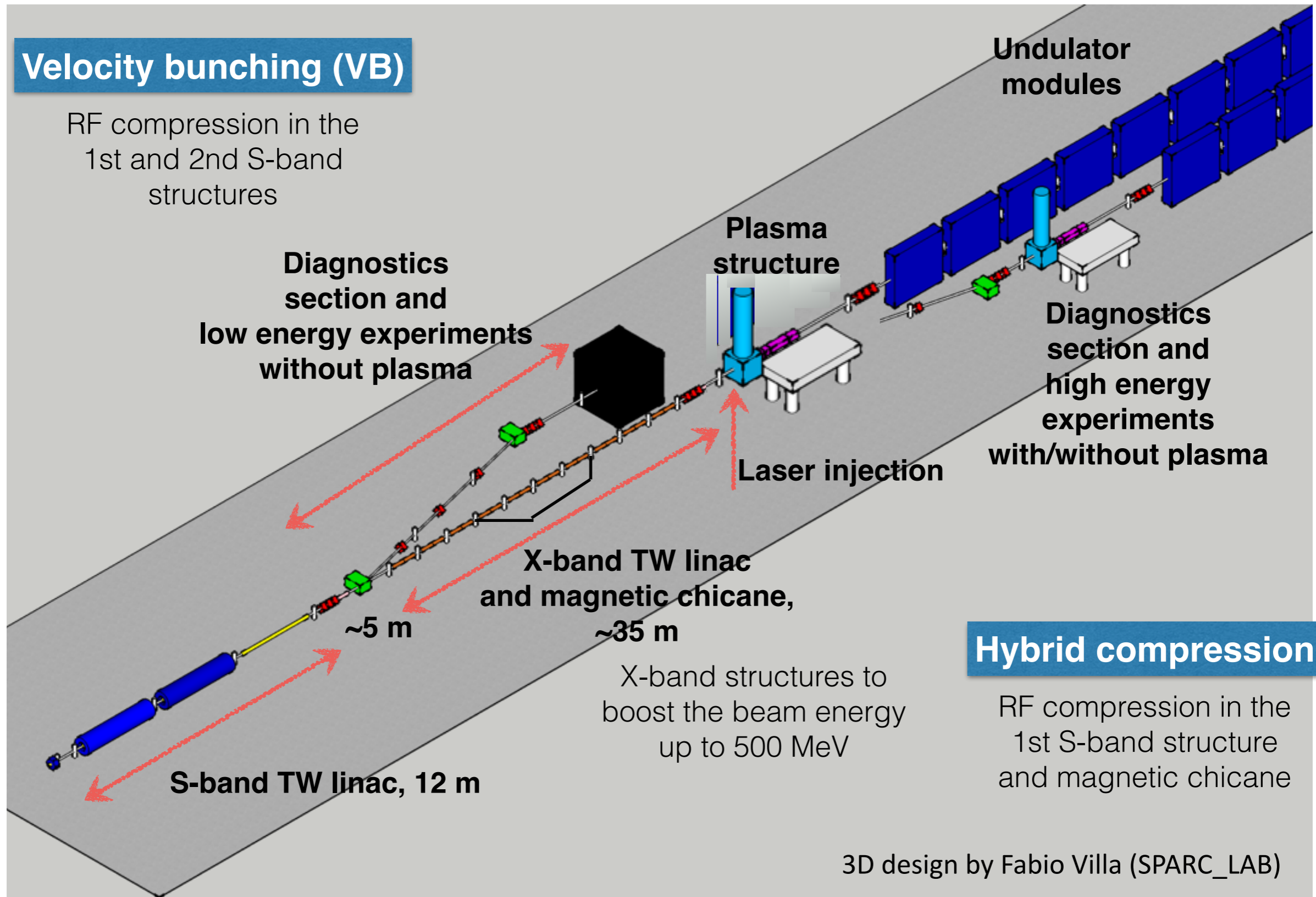
- 150 MeV
- 30 pC
- normalized emittance  $\sim 1$  mm mrad,
- alpha (Twiss)=1,
- beta (Twiss)=0.03 m,
- $\sigma_{z} = 2\mu\text{m}$  (15 fs)
- energy spread 5% and slice energy spread 3% (*actually I do not understand which experiment needs these values*)
- **Peak current  $\sim 800$  A**

then the RF injector is not the solution

If the 150 MeV wants to be considered, then the charge must be decreased down to 5 pC, but in any case the achievable peak current is only 1 kA!!!

## Velocity bunching (VB)

RF compression in the 1st and 2nd S-band structures



- INFN: E. Chiadroni, M. Ferrario, A. Giribono, C. Vaccarezza
- DESY: B. Marchetti, J. Zhu