SPARC_LAB: overview and recent results

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on behalf of EuPRAXIA@SPARC_LAB collaboration

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SPARC_LAB

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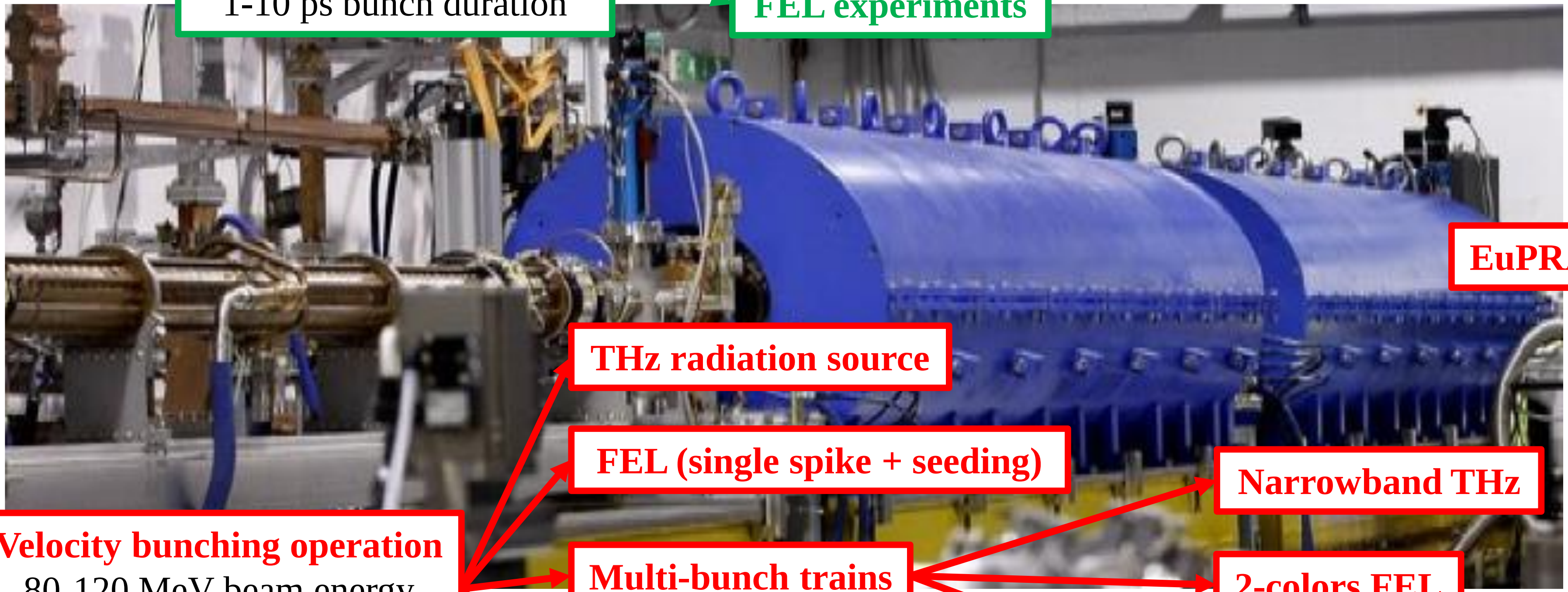
On-crest operation
30-170 MeV beam energy
1-10 ps bunch duration

→ **Thomson scattering**
→ **FEL experiments**



Velocity bunching operation
80-120 MeV beam energy
20 fs – 1 ps bunch duration

→ **THz radiation source**
→ **FEL (single spike + seeding)**
→ **Multi-bunch trains**
  → **Narrowband THz**
  → **2-colors FEL**
  → **PWFA (including resonant scheme)** → **EuPRAXIA@SPARC_LAB**
→ **LWFA (external injection)**

Serafini L., Ferrario M. *"Velocity bunching in photo-injectors." AIP conference proceedings. 2001.*
Anderson, S. G., et al. *"Velocity bunching of high-brightness electron beams." PRSTAB 8.1 (2005): 014401.*

EuPRAXIA@SPARC_LABS

	Units	Full RF case	LWFA case	PWFA case
Electron Energy	GeV	1	1	1
RMS Energy Spread	%	0.05	2.3	1.1
Peak Current	kA	1.79	2.26	2.0
Bunch Charge	pC	200	30	30
RMS Bunch Length	μm (fs)	16.7 (55.6)	2.14 (7.1)	3.82 (12.7)
RMS normalized Emittance	mm mrad	0.5	0.47	1.1
Slice Length	μm	1.66	0.5	1.2
Slice Charge	pC	6.67	18.7	8
Slice Energy Spread	%	0.02	0.03	0.034
Slice normalized Emittance (x/y)	mm mrad	0.35/0.24	0.45/0.465	0.57/0.615
Undulator Period	mm	15	15	15
Undulator Strength $K(a_w)$		0.978 (0.7)	1.13 (0.8)	1.13 (0.8)
Undulator Length	m	30	30	30
ρ **(1D/3D)**	$\times 10^{-3}$	1.55/1.38	2/1.68	2.5/1.8
Radiation Wavelength	nm (keV)	2.87 (0.43)	2.8 (0.44)	2.98 (0.42)
Photon Energy	μJ	177	40	6.5
Photon per pulse	$\times 10^{10}$	255	43	10
Photon Bandwidth	%	0.46	0.4	0.9
Photon RMS Transverse Size	μm	200	145	10
Photon Brilliance per shot	(s mm^2 mrad^2 bw(0.1%))$^{-1}$	1.4×10^{27}	1.7×10^{27}	0.8×10^{27}

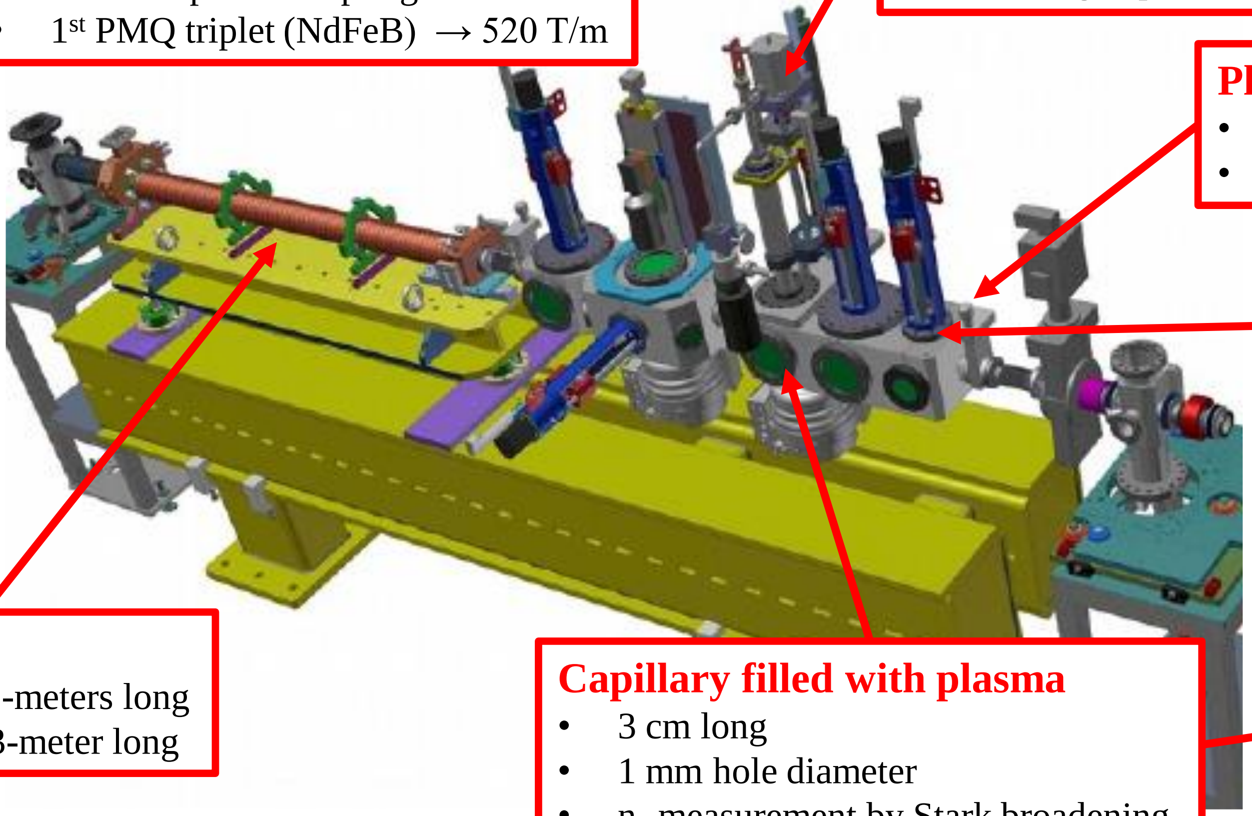
Plasma chamber

Beam injection
- Electro-optical sampling
- 1st PMQ triplet (NdFeB) → 520 T/m

Hydrogen injection
- Electrolytic hydrogen source
- 50-100 mbar
- Discharge up to 250 A

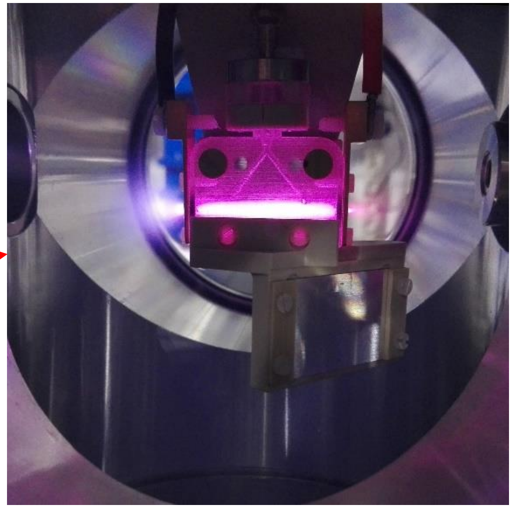
Plasma chamber
- 3D stage
- turbo pumps, 3x400 l/sec

Beam extraction
- 2nd PMQ triplet, 520 T/m
- THz station (CTR/CDR)

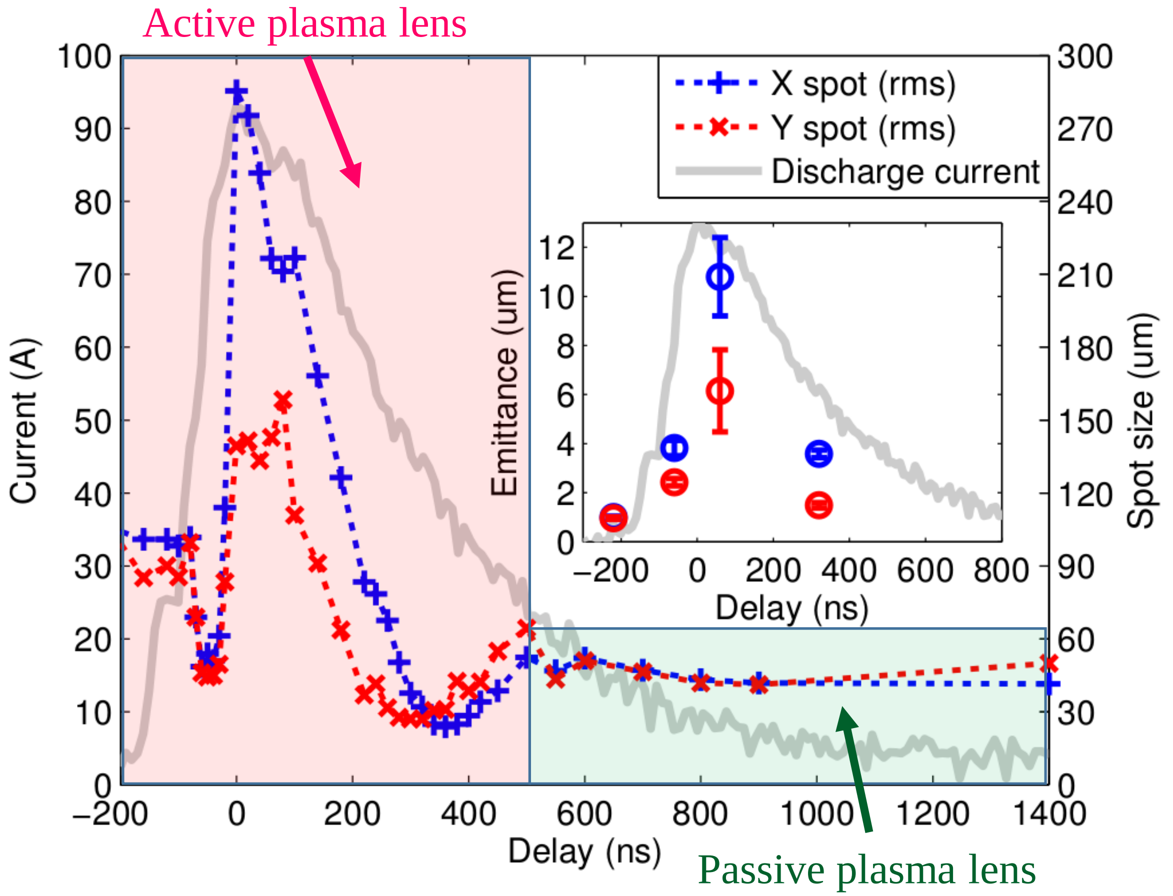


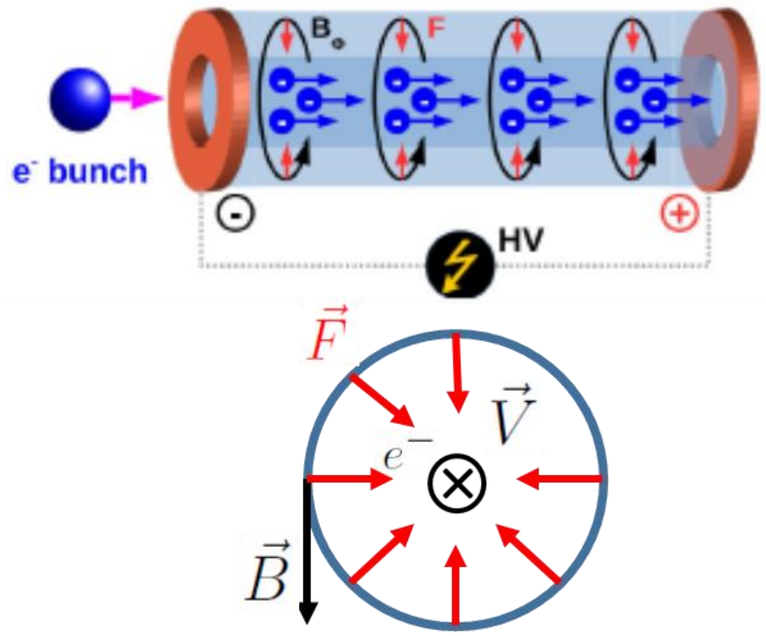
Sparc Linac
- 2 S-band, 3-meters long
- C-band, 1.3-meter long

Capillary filled with plasma
- 3 cm long
- 1 mm hole diameter
- n_b measurement by Stark broadening



Active plasma lens



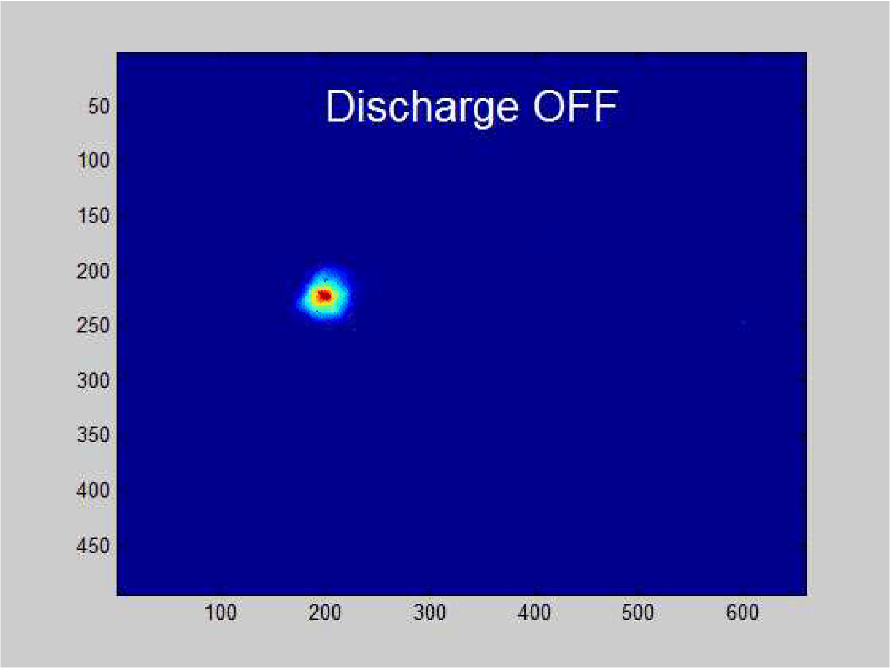


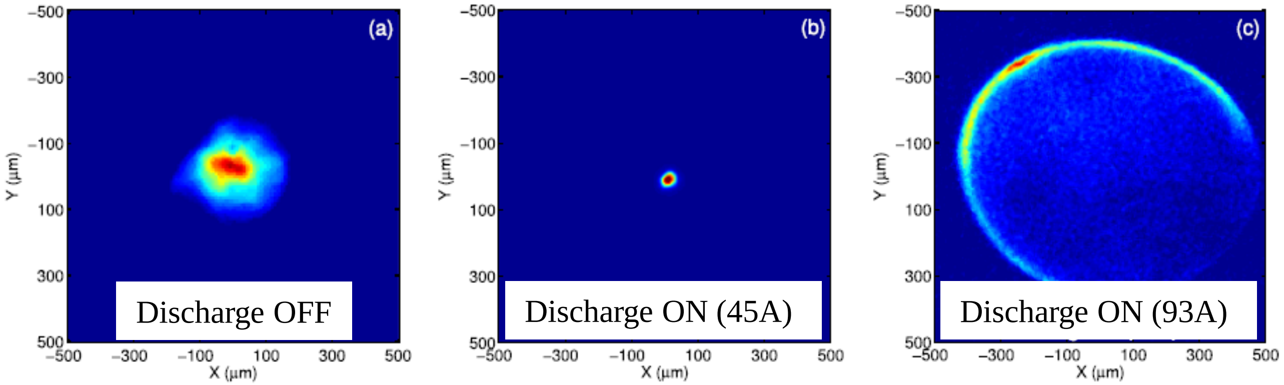
$$B_\phi(r) = \frac{\mu_0}{R}\int_o^R J(r) r dr$$

Pompili R., *et al. Applied Physics Letters 110.10 (2017): 104101.*
Marocchino A., *et al. Applied Physics Letters 111.18 (2017): 184101.*

Boborova N.A., et al., *Phys.Rev. E 65 (2001): 016407.*
Van Tilborg J., et al., *Phys.Rev. STAB 20 (2017): 032803.*

Active plasma lens





Non uniform distribution of the current leads to a non linear gradient of the magnetic field

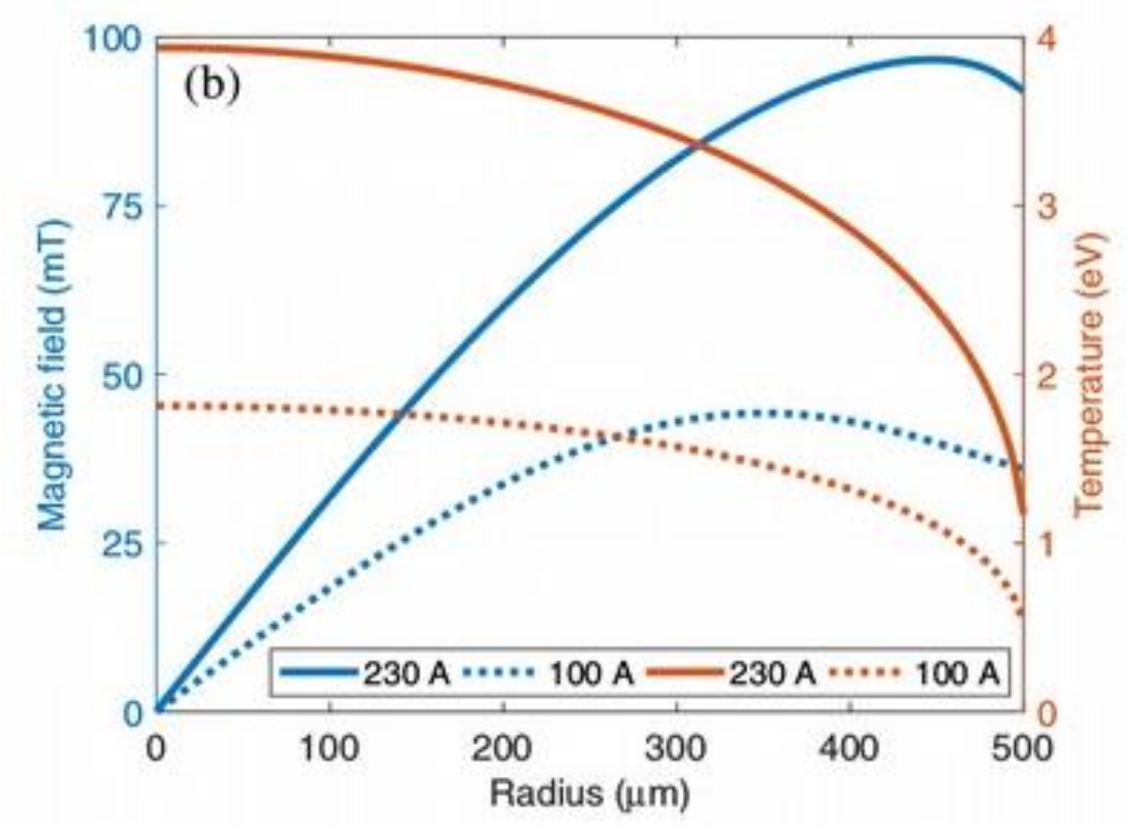
$$J(r) = \sigma E \propto T_e^{3/2}$$

$$B_\varphi(r) = \mu_0 r^{-1} \int_0^r J(r')r'dr'$$

- ✓ *Cylindrical symmetry in focusing (~ solenoids)*
- ✓ *Favorable focusing strength K~ 1/γ (~ quadrupoles)*
- ✓ *Large focusing gradient ~ kT/m*
- ✓ *Tunability by adjusting the current amplitude*

Boborova N.A., et al., *Phys.Rev. E 65 (2001): 016407.*
Van Tilborg J., et al., *Phys.Rev. STAB 20 (2017): 032803.*

Active plasma lens

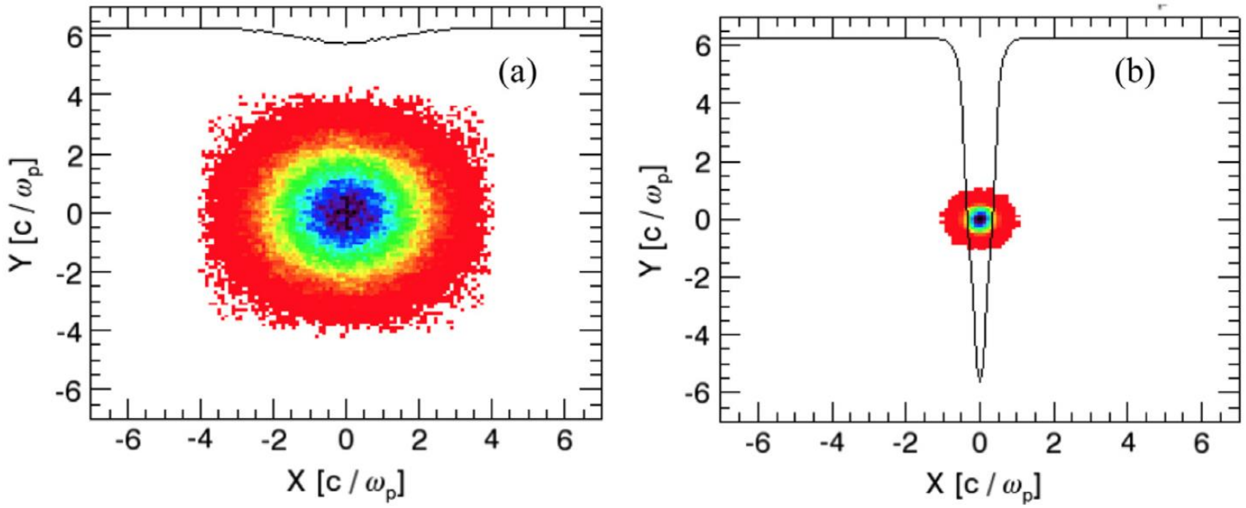


The peak current was increased from ~90 A to ~220 A, which extended a linear gradient area of the capillary

- ✓ *better ionization of the H2 led ot a better distribution of the current*
- ✓ *increased linear part of the magnetic field gradient*
- ✓ *the emittance was preserved (0.8 →0.9* mm•mrad*)*
- ✓ *improved minimum spot size (21 →17 µm)*

***Pompili R., et al.**, Focusing of High-brightness electron beams with active-plasma lenses, **PRL 121 (2018):** 174801.*
***Lindstorm C.A., et al.**, Emittance preservation in an aberration-free active plasma lens, **PRL 121 (2018):** 194801.*

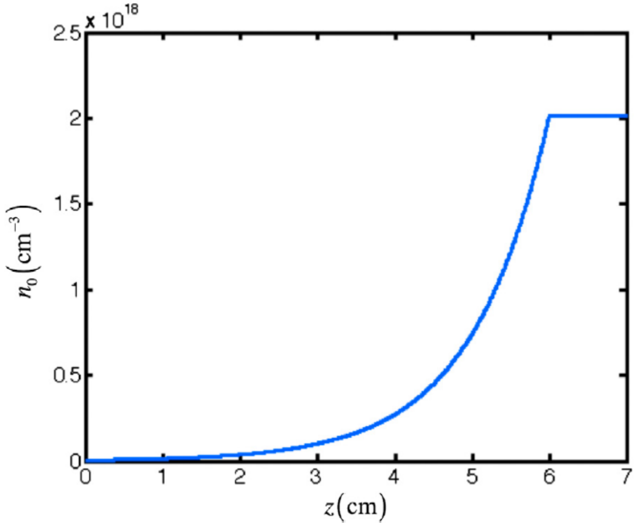
Passive plasma lens



Adiabatic plasma lens for LC:

- ✓ *Slow change of the plasma density (compare to the λ_β)*

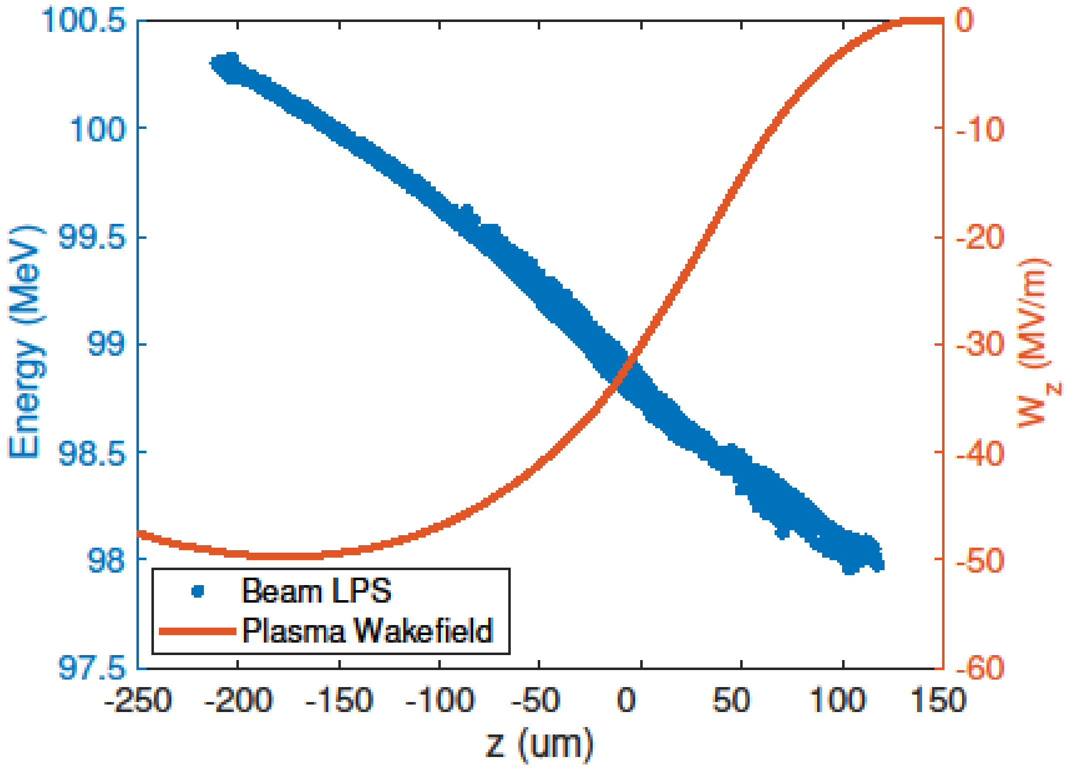
$$\beta_{q\text{-}eq}(z) \cong k_\beta^{-1}(z)$$
$$k_\beta^2(z) = 2\pi r_e n_0(z)/\gamma$$



- ✓ *for high plasma densities the gradient can be order of magnitude larger then for current PMQs. For $n_p \approx 10^{17}$ cm^{-3} the gradient is ~3 MT/m.*
- ✓ *Avoids the Oide effect in quadrupole focusing*
- ✓ *Allows to limit the final focus of the collider to a ~m scale*

J. Rosenzweig, et al., *Adiabatic plasma lens experiments at SPARC,* ***NIMA 909 (2018)*** *471-475.*

Self-wakefield created by the chirped beam



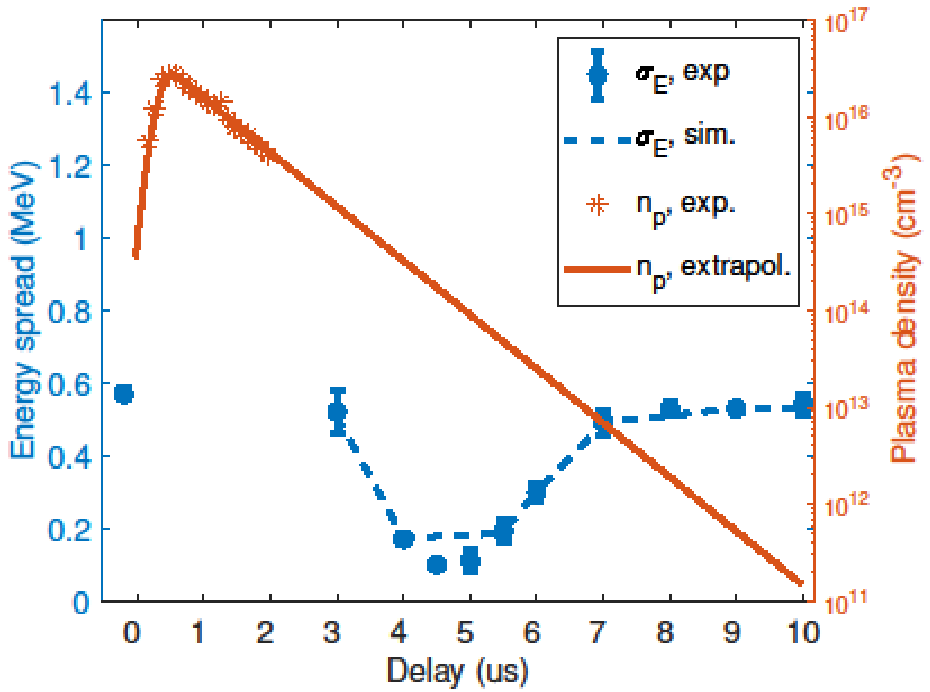
- **Longitudinal phase-space manipulation with the wakefield induced in plasma by the beam itself.**
  - ✓ *the large gradient that plasma can sustain (~ GV/m) allows to imprint or remove large energy correlation (chirp) from the beam by means of relatively short structures (~ cm).*
- **Large flexibility of the method, by varying parameters of the system:**
  - ✓ *plasma density (large density → large wake amplitude)*
  - ✓ *beam density (large density → large wake amplitude)*
  - ✓ *length of the plasma channel (cumulative effect)*

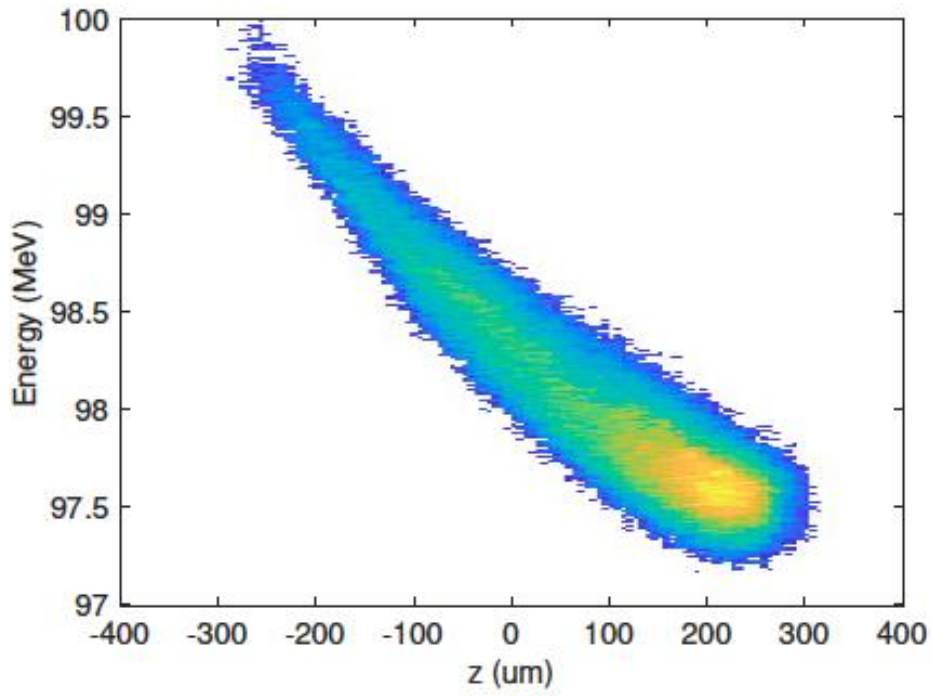
D'Arcy R., et al.,** Tunable plasma-based energy dechirper, **PRL 122 (2019): 034801.

Shpakov V., et al.,** Longitudinal phase-space manipulation with beam driven plasma wakefields, **PRL 122 (2019): 114801.

WU Y.P., et al.,** Phase space dynamics of plasma wakefield dechirper for energy spread reduction, **PRL 122 (2019): 034801.

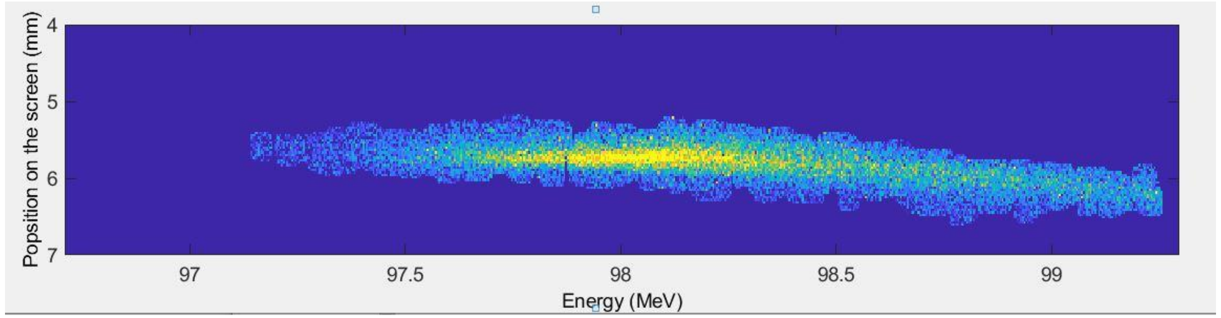
Plasma dechirper

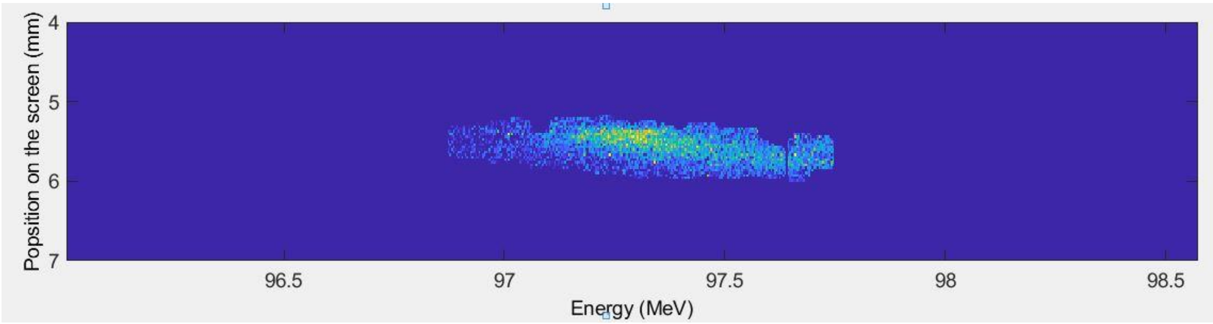




Beam parameters:

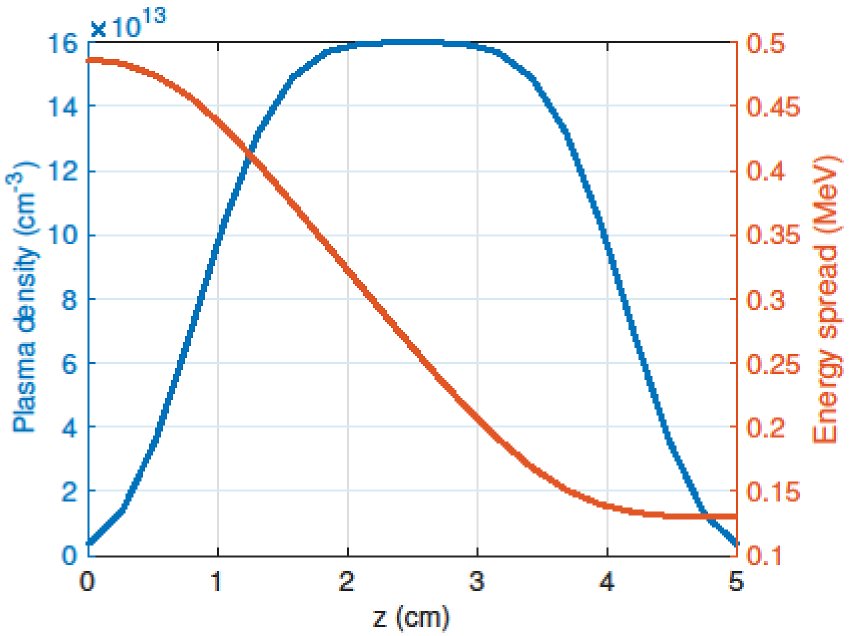
- ✓ *E=100 MeV*
- ✓ *Q=200 pC*
- ✓ $\sigma_{x,y} \approx 20(32)\ \mu m$
- ✓ $\sigma_z = 75\ \mu m\ (250\ fs)$
- ✓ $\varepsilon_{x,y} \approx 1.1(1.4)\ \mu m$





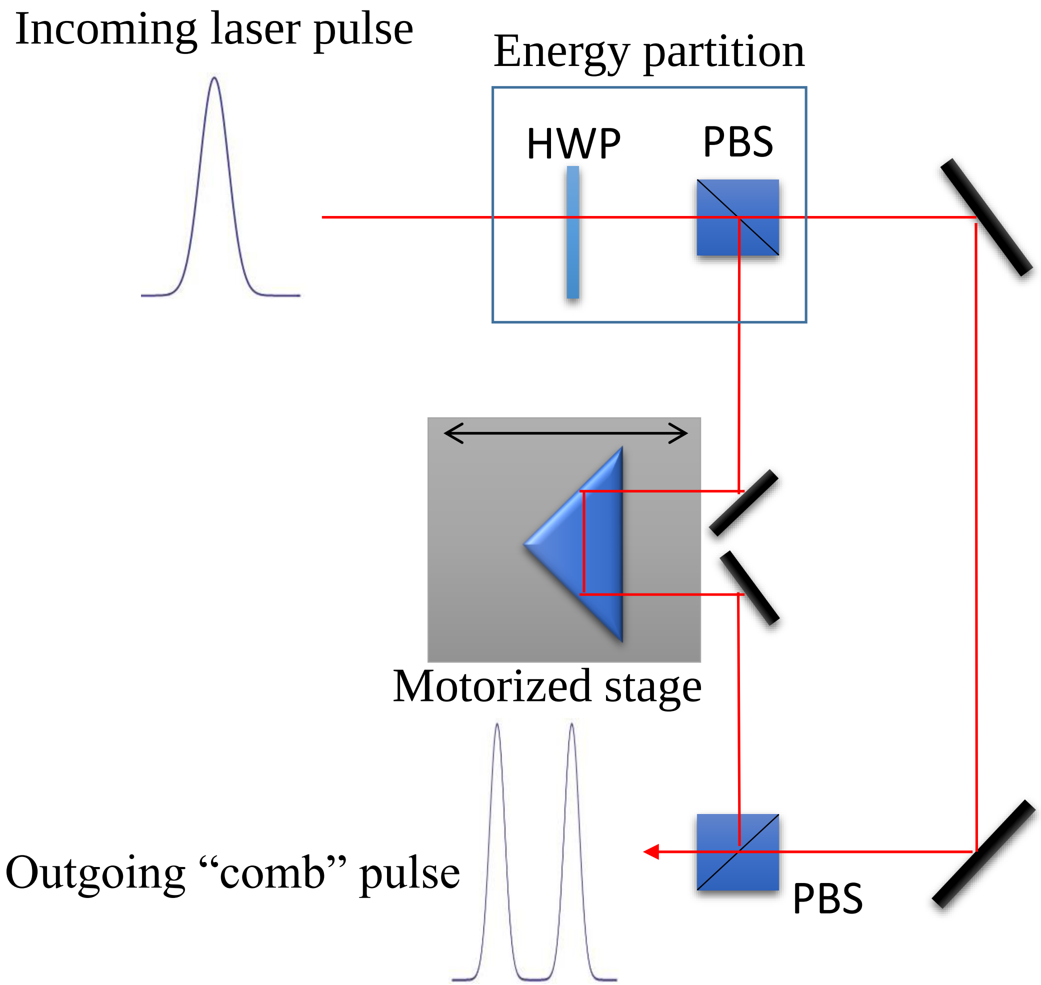
Plasma dechirper

Energy spread evolution inside the plasma



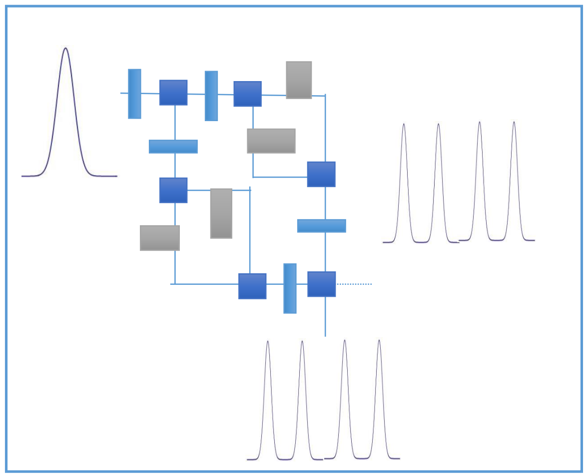
- **Plasma dechirper:**
  - ✓ *during the experiments we managed to decrease total energy spread from 0.6 to 0.1 %. The intrinsic energy spread at SPARC ~0.1 % → all correlated energy spread was removed*
- **Parameters of the plasma dechirper are not exactly "free":**
  - ✓ *bunch duration → max. plasma density*
  - ✓ *plasma density → plasma length / max. chirp to remove*
  - ✓ *electron bunch density ~ plasma density*
- **Works only in one direction:**
  - ✓ *can remove only negative chirp*
  - ✓ *perfect for PWFA and LWFA due to comparable gradient*

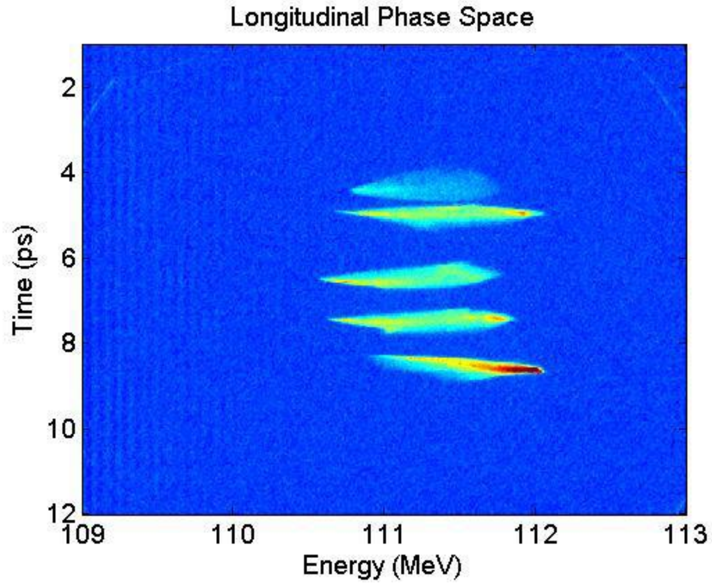
Shpakov V., *et al. Physical Review Letters 122 (2019), 114801*



Laser pulse shaping with splitting

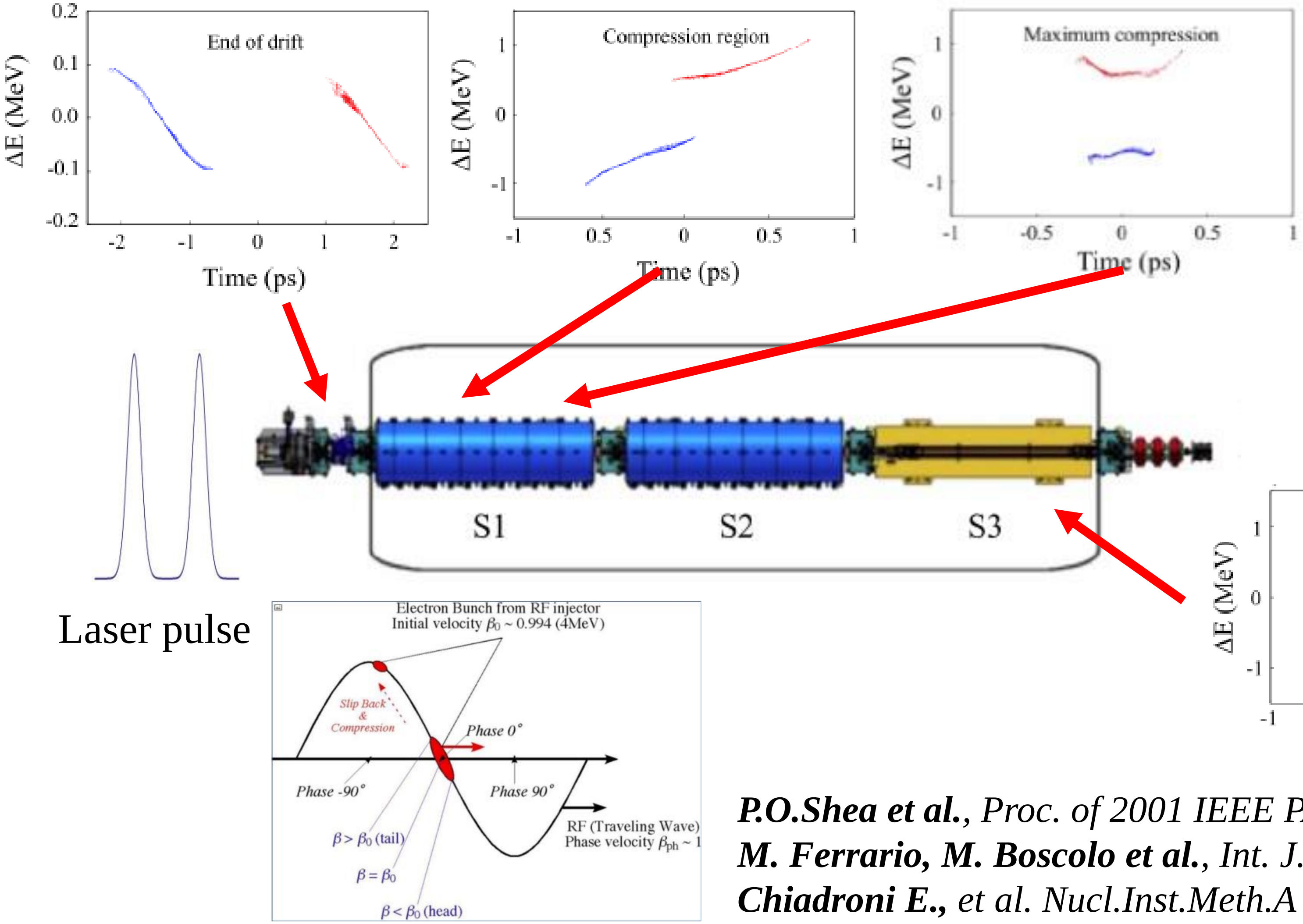
- ✓ *high level of flexibility*
- ✓ *online control of the parameters*
- ✓ *rather complicated setup for more than 2 laser pulses*





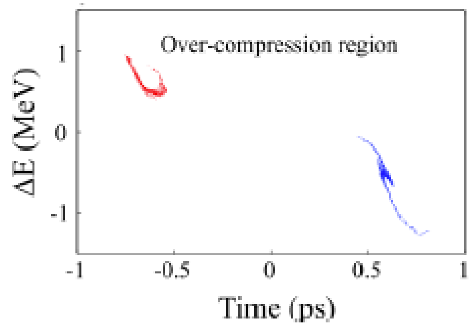
***Villa F.**, et al. Nucl.Inst.Meth.A 829 (2016): 446-451.*

Electron beam shaping



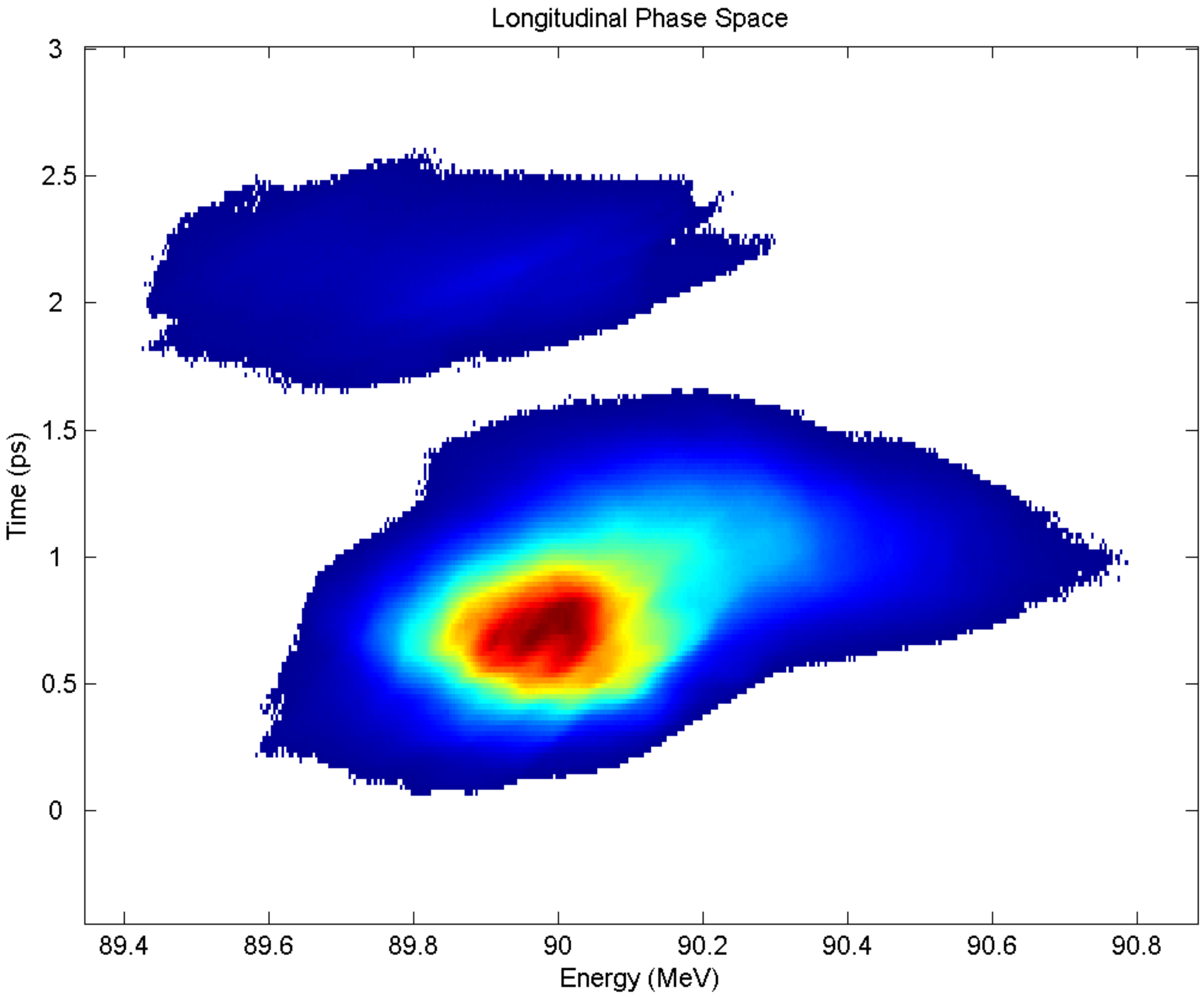
Velocity bunching

- ✓ *inside 1st section, while β<1*
- ✓ *the "witness" beam starts before the "driver", then they swap the positions*
- ✓ *VB gives certain level of control over the bunch, which is increased by laser manipulations*



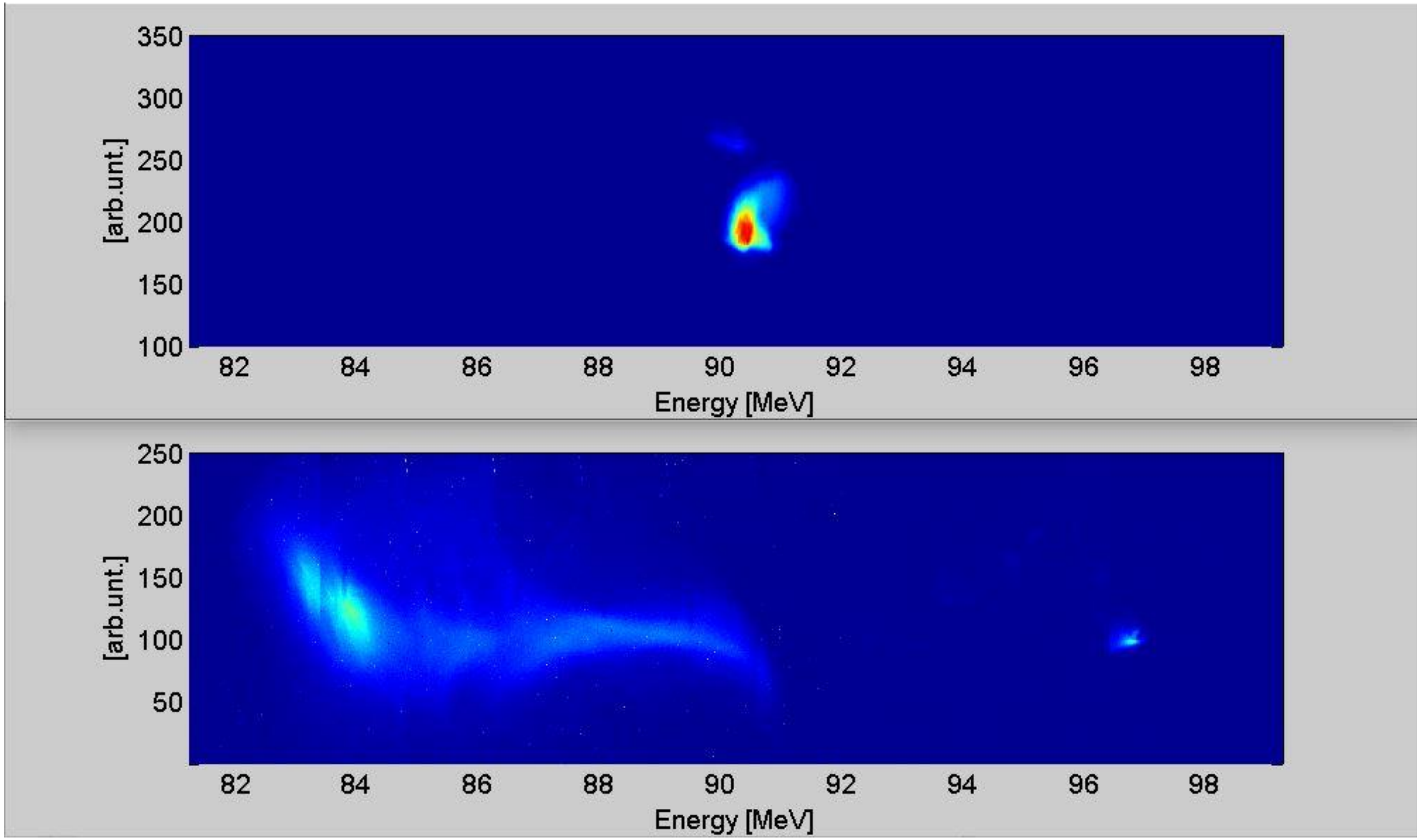
***P.O.Shea et al.**, Proc. of 2001 IEEE PAC, Chicago, USA (2001) p.704. (Low charge regime only)*
***M. Ferrario, M. Boscolo et al.**, Int. J. of Mod. Phys. B, 2006 (High charge, Beam Echo)*
***Chiadroni E.**, et al. Nucl.Inst.Meth.A 865 (2017), 139-143*

Bunch train parameters



Train parameters:

- ✓ *E=90.0 MeV*
- ✓ *Q1=200 pC*
- ✓ *Q2=20 pC*
- ✓ $\sigma_{z,\ driver}$ *=230 fs*
- ✓ $\sigma_{z,\ witness}$ *=40 fs*
- ✓ *Distance between bunches= 1.1 ps*
- ✓ *Initial emittance 1.0* μm
- ✓ *Spot size at the entrance to the capillary 20* μm
- ✓ *Plasma density* $n_p \approx 2.0\times10^{15}\ cm^{-3}$



After the acceleration:

- ✓ *Final witness energy ~ 96.5 MeV*
- ✓ *Accelerating gradient ~ 220 MeV/m*
- ✓ *The main goal was to demonstrate the viability of the Comb technique for creation of bunch trains for wake-field acceleration, which was done.*
- ✓ *Next step is the quality of the beam, which should be preserved after the acceleration.*

Summary SPARC_LAB plasma activities

- **Active plasma lens**
  - *ready for applications*
- **Passive plasma lens**
  - *adiabatic plasma lens for LC*
- **Plasma dechirper**
  - *proof-of-principle experiments*
- **Beam driven PWFA**
  - *the acceleration using the COMB technique was demonstrated*
- **Next step EuPRAXIA@SPARC_LAB**
  - *quality of the beam*
  - *increase of the gradient*
  - *resonant plasma acceleration*
  - *improved transformer ration*

Thank You for your attention

Thanks to SPARC_LAB team for their work

And many thanks to engineering and technical staff of LNF INFN for helping with SPARC operation and maintenance