CLICWEEK2019

Compact Linear Collider Workshop

January 21 - 25, 2019 @ CERN

Plasma activities at SPARC_LAB

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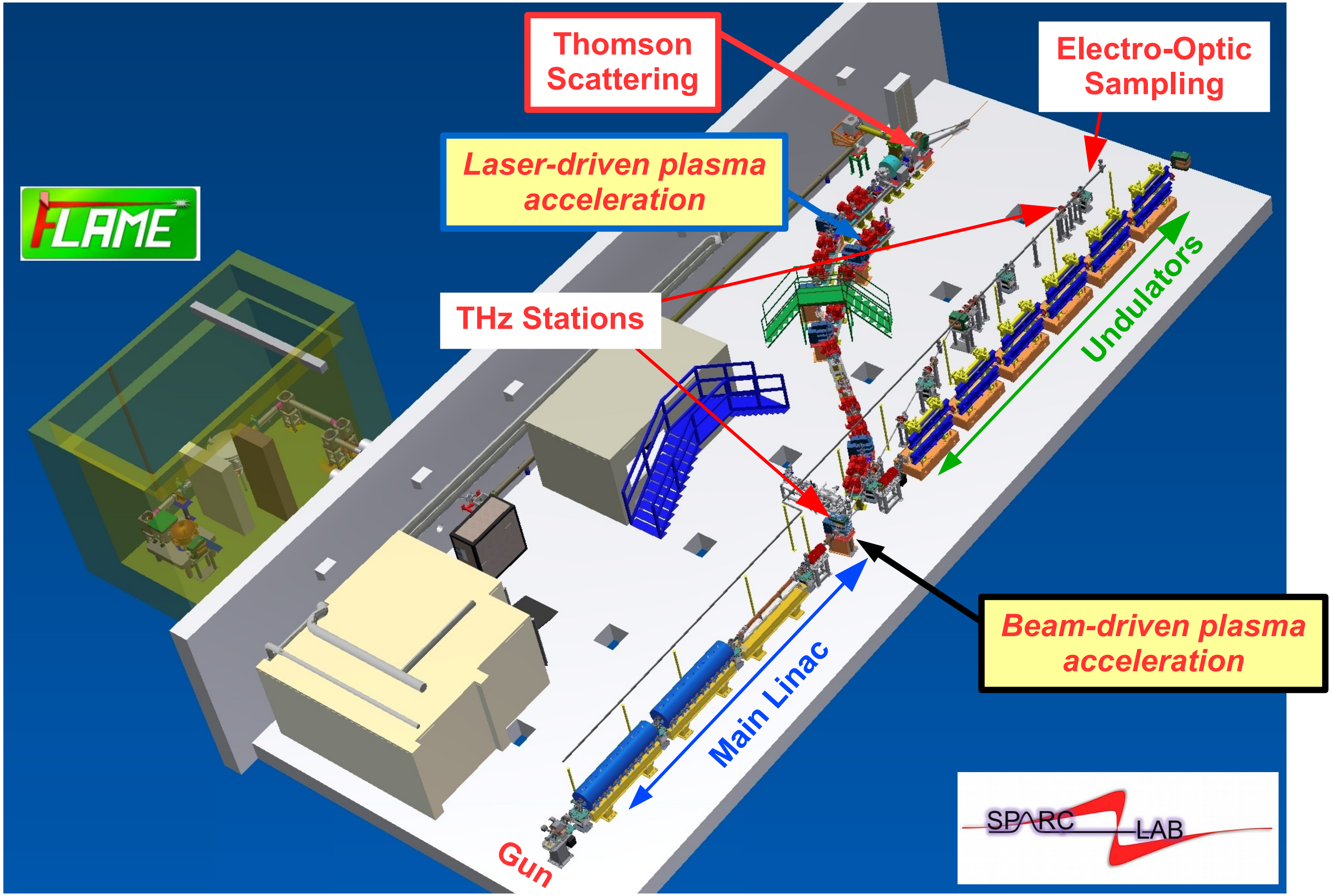
On behalf of the SPARC_LAB collaboration

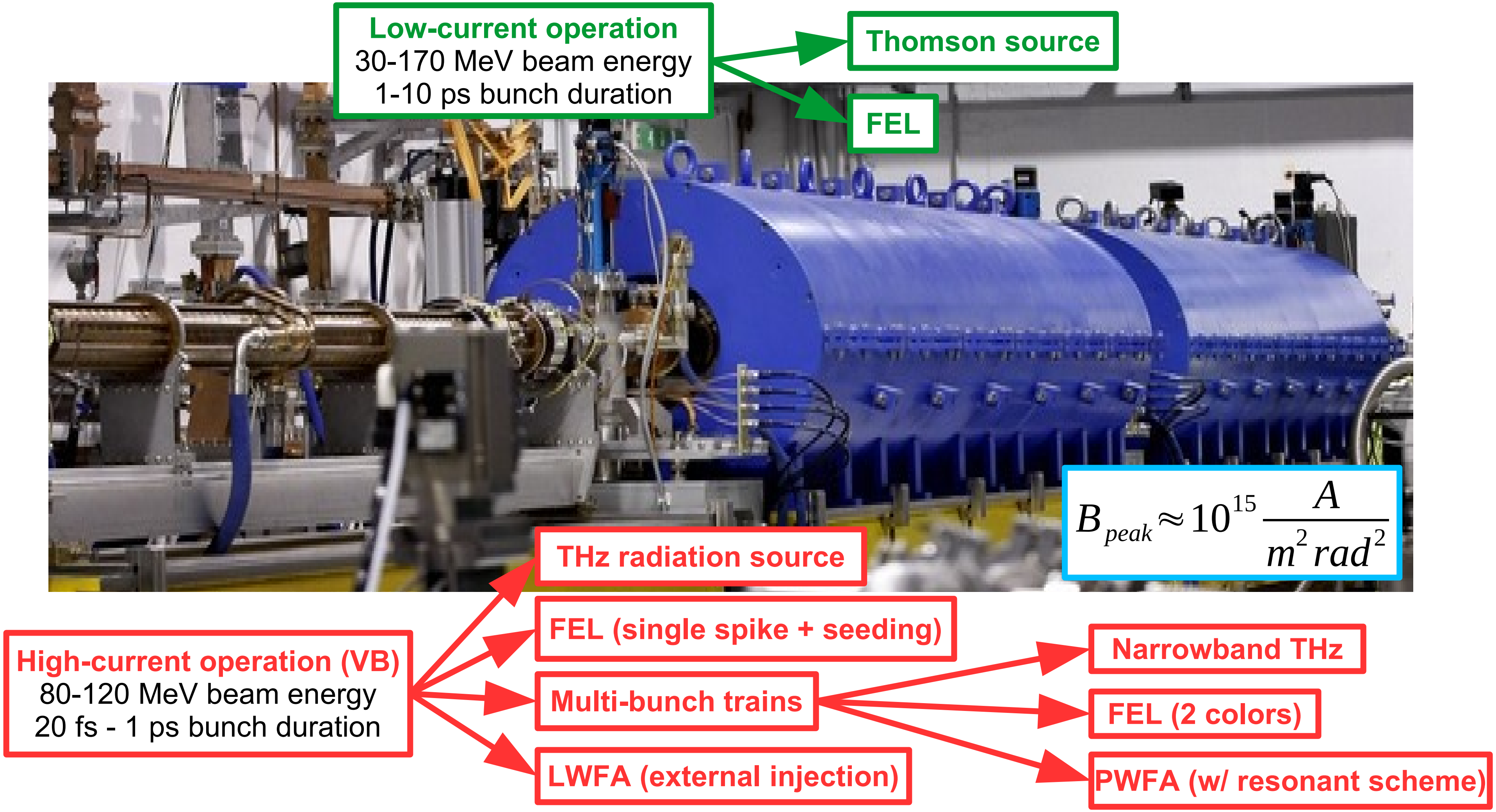
Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Frascati

The SPARC_LAB test-facility



Ferrario, M., et al. "SPARC_LAB present and future." NIMB 309 (2013): 183-188.

High-brightness photo-injector



Low-current operation
30-170 MeV beam energy
1-10 ps bunch duration

- **Thomson source**
- **FEL**

$$B_{peak} \approx 10^{15} \frac{A}{m^2 rad^2}$$

High-current operation (VB)
80-120 MeV beam energy
20 fs - 1 ps bunch duration

- **THz radiation source**
- **FEL (single spike + seeding)**
- **Multi-bunch trains**
  - **Narrowband THz**
  - **FEL (2 colors)**
  - **PWFA (w/ resonant scheme)**
- **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.

Plasma-based activities

Plasma lens

- Characterization of the focused beam (→ emittance) with active/passive lenses
- Tests with different geometries (short/long capillaries with small/large hole radii)

Plasma dechirper

- Tests with different beam configuration (energy-chirp, charge, duration)
- Complete characterization (→ emittance, energy spread)
- Tests with different geometries (short/long capillaries) and plasma densities

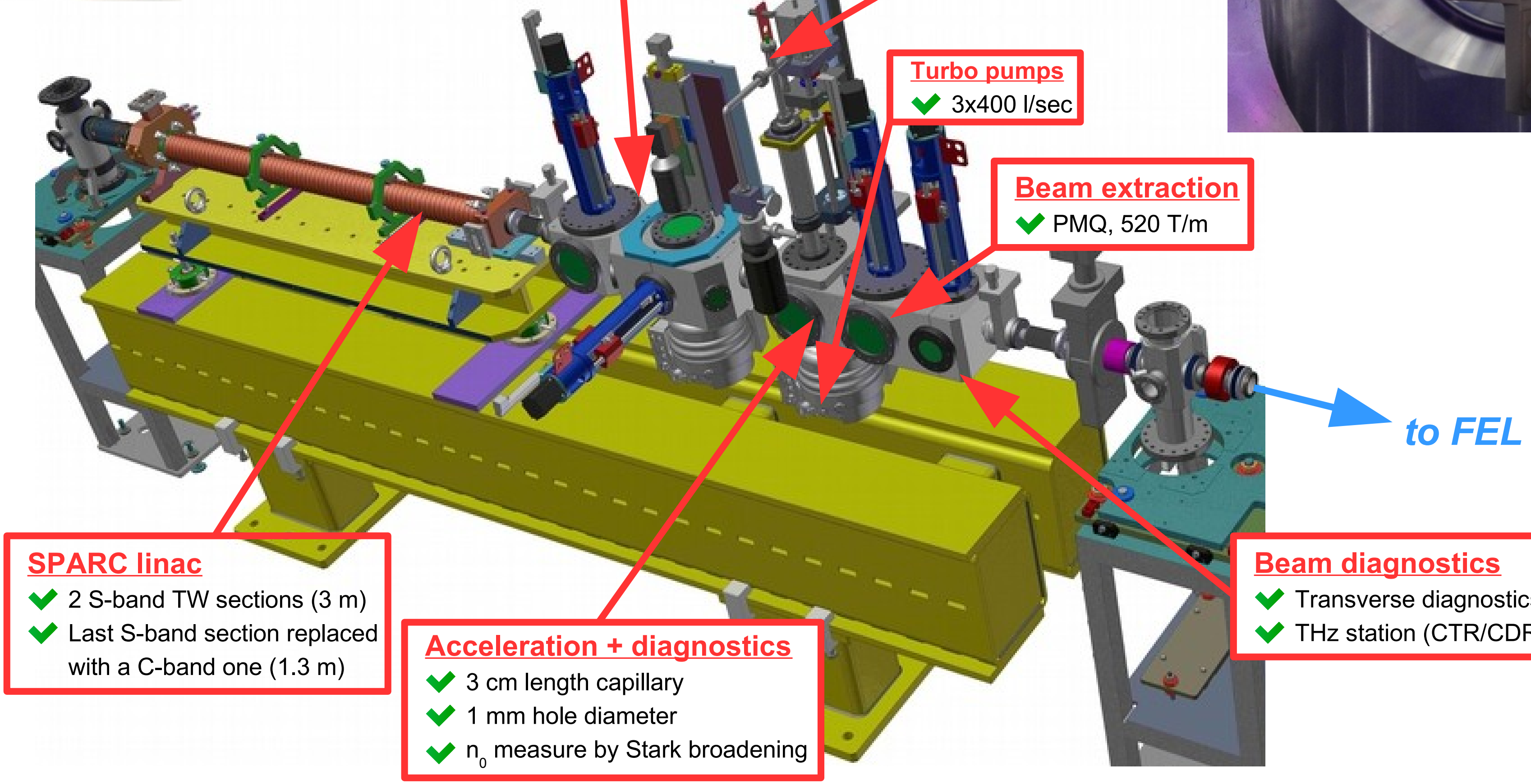
Plasma acceleration

- Deceleration studies (single bunch, different charge and duration)
- Acceleration and characterization of a small-charge witness bunch
- Studies with multi-drivers configuration

Plasma bending

- Characterization of curved capillary geometries with large discharge currents (few kA)
- Proof-of-principle experiment of particle bending

Experimental setup



Beam injection
- ✓ Longitudinal diagnostics (EOS)
- ✓ Transverse diagnostics (Ce:YAG screen)
- ✓ PMQ (NdFeB, $B_r > 1.3$ T) → 520 T/m

Hydrogen inlet
- ✓ 50-100 mbar from source
- ✓ 10 mbar in capillary

Turbo pumps
- ✓ 3x400 l/sec

Beam extraction
- ✓ PMQ, 520 T/m

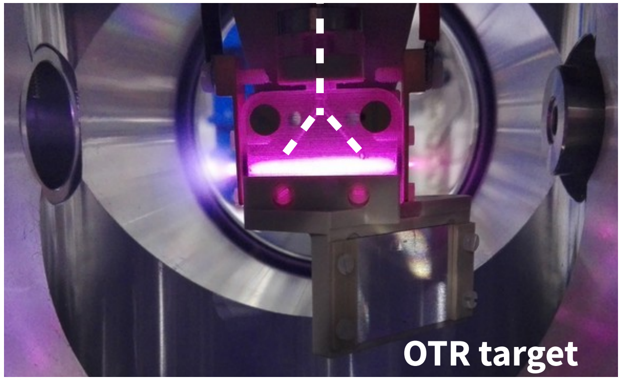
to FEL

SPARC linac
- ✓ 2 S-band TW sections (3 m)
- ✓ Last S-band section replaced with a C-band one (1.3 m)

Acceleration + diagnostics
- ✓ 3 cm length capillary
- ✓ 1 mm hole diameter
- ✓ n_0 measure by Stark broadening

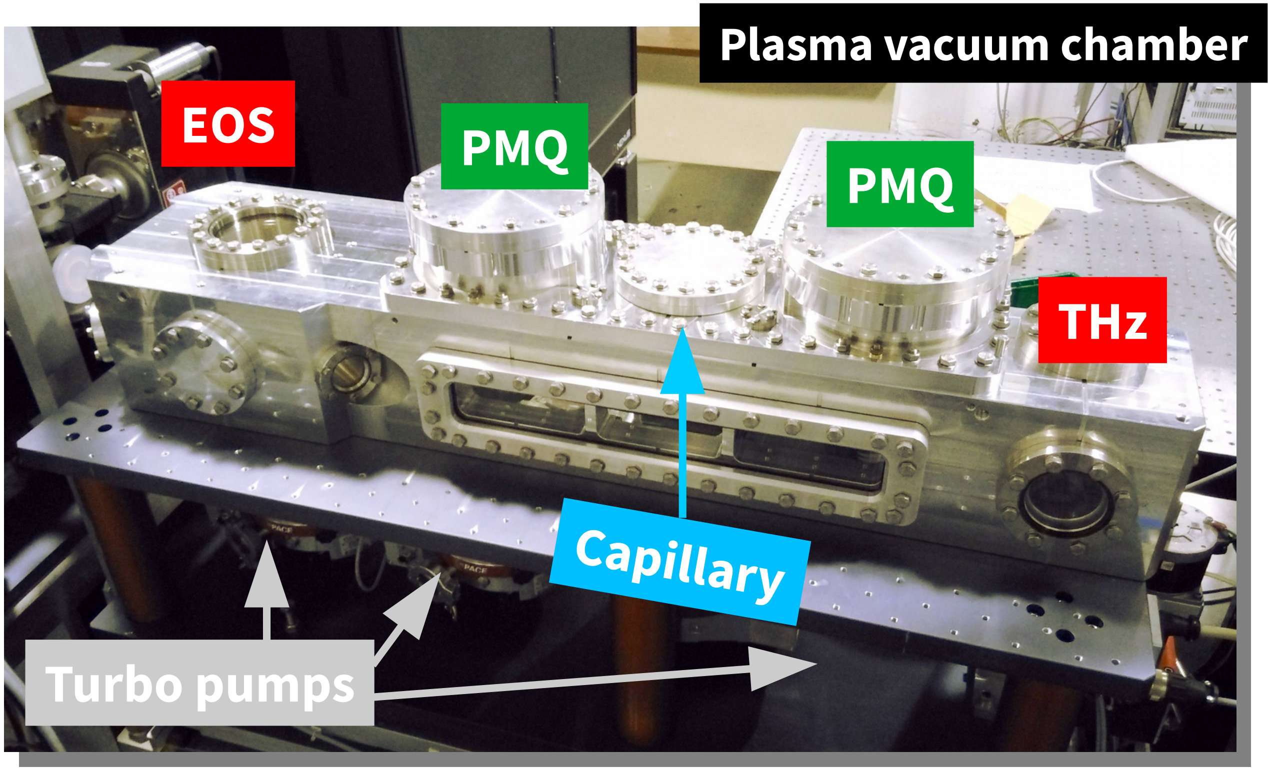
Beam diagnostics
- ✓ Transverse diagnostics (Ce:YAG screen)
- ✓ THz station (CTR/CDR)

Plasma generation in capillary

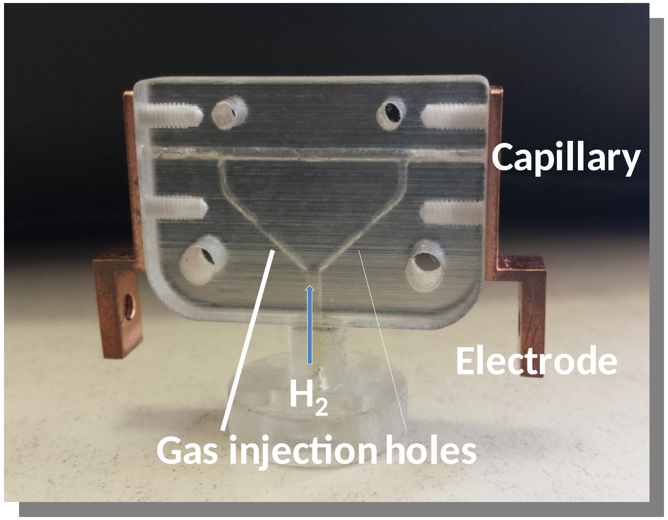


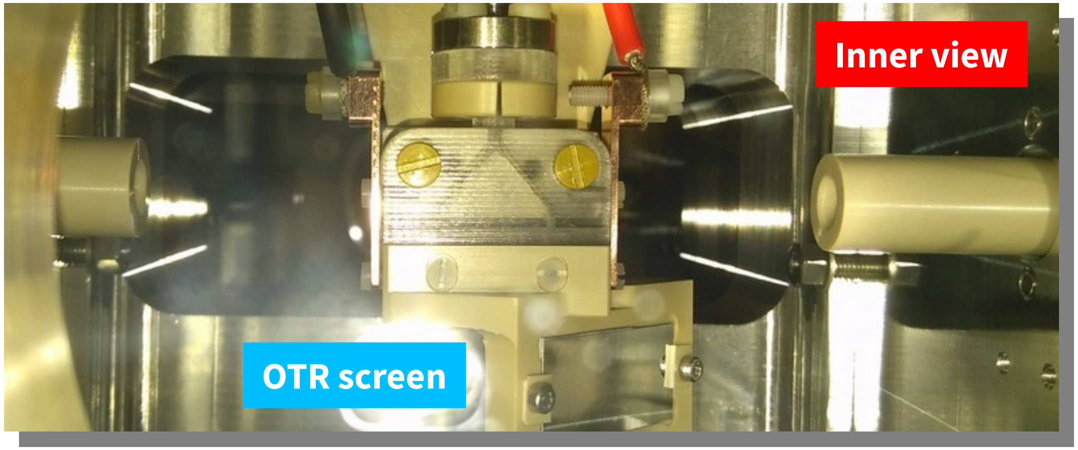
Plasma interaction chamber

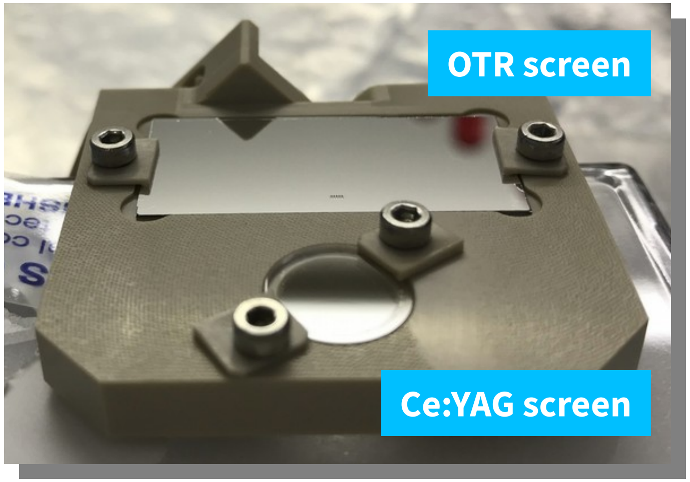
Plasma vacuum chamber



Capillary geometry







Compact and tunable PMQ triplets

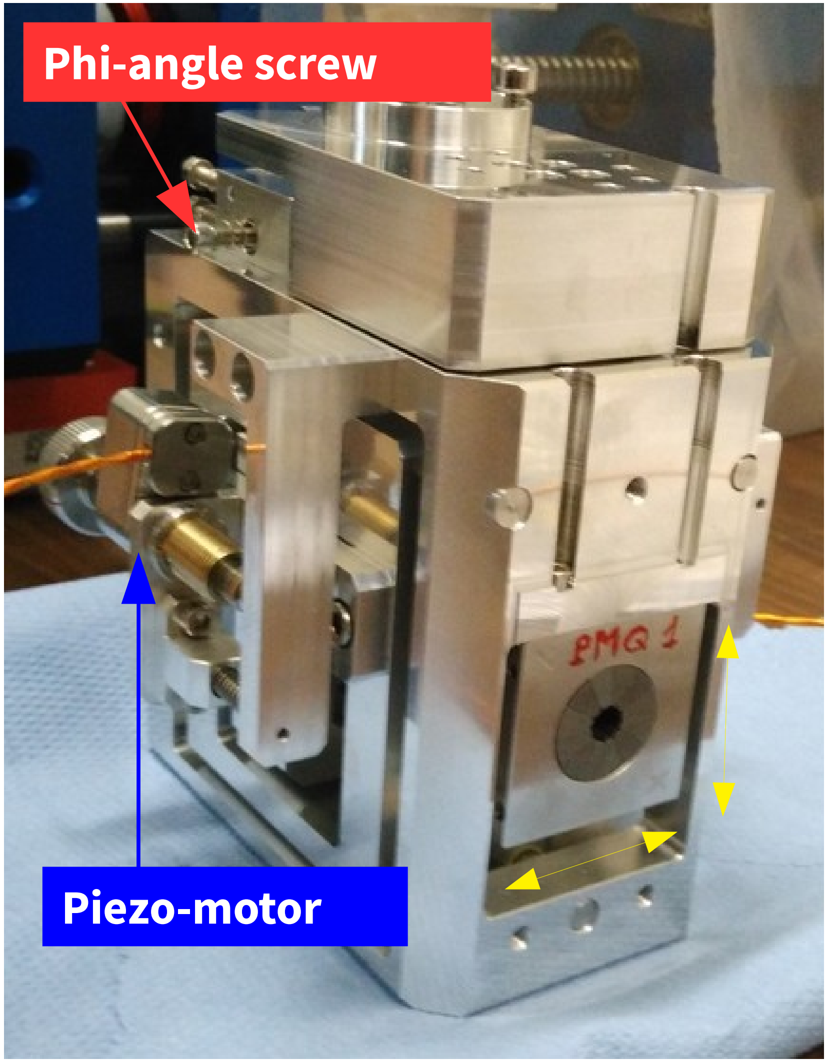
Three PMQs installed, z-position tunable

Two PMQs movable, 1 fixed

- Minimum distance ~ 2-3 mm
- Maximum distance ~ 8-10 mm

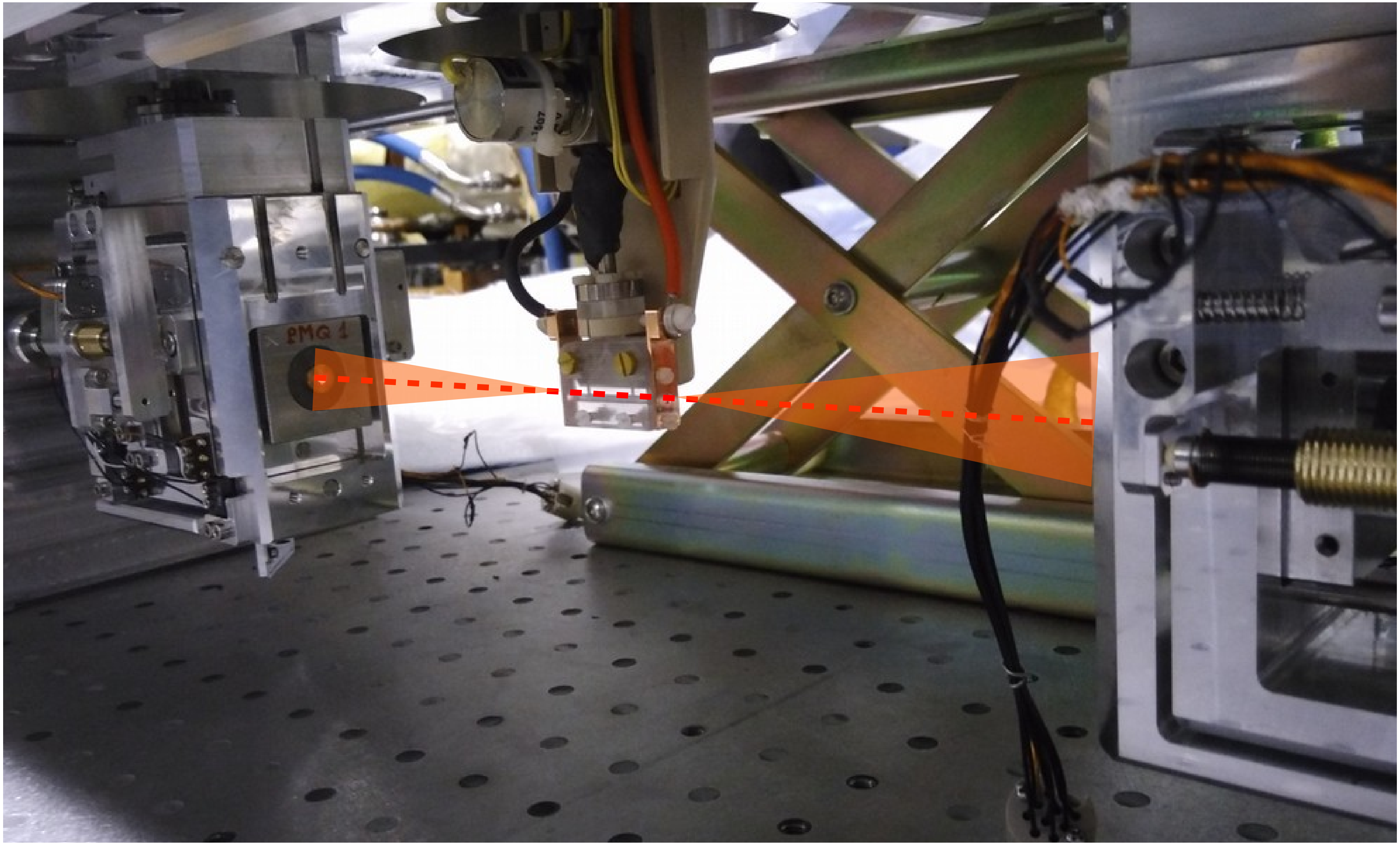
Piezo-actuators allow to z-move each PMQ

- 20 nm resolution
- Feed force > 40 N
- Holding force > 100 N
- UHV (10^{-9} mbar)
- Non-magnetic



Pompili, R., et al. "Compact and tunable focusing device for plasma wakefield acceleration." Review of Scientific Instruments 89.3 (2018): 033302.

Injection, acceleration and extraction



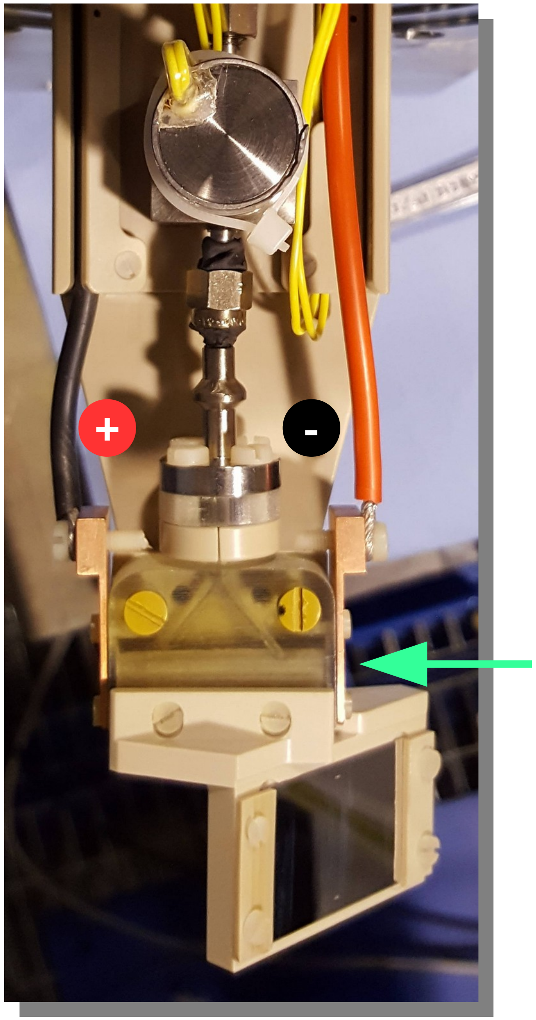
Shaping/study of the plasma structure

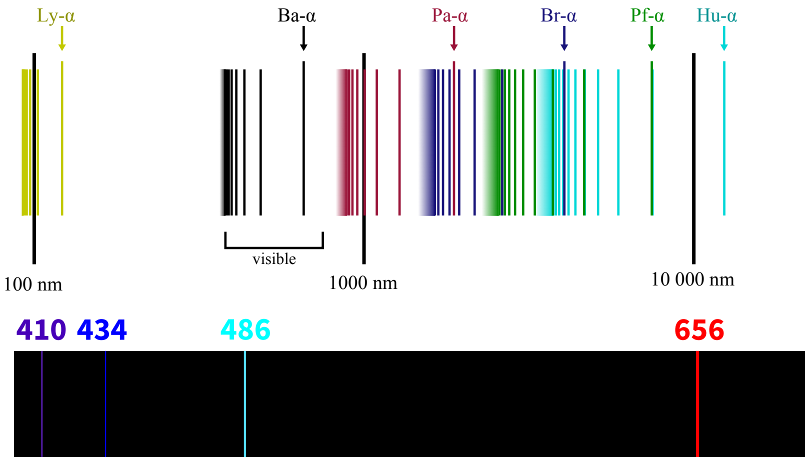
The goal of our activities is to apply plasma technology to new accelerator facilities

- Provide plasma acceleration (up to several GV/m) while preserving the high-brightness of the accelerated beam (emittance, energy spread)
- Demonstrate the possibility to use active plasma lenses as focusing device

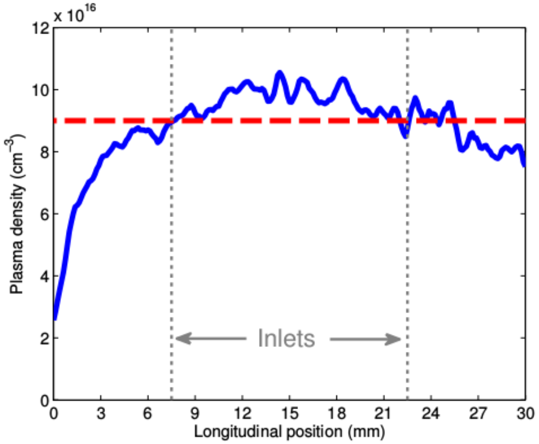
It requires a deep study of the plasma properties and capillary geometry

- Characterization of the plasma density profiles (longitudinal and transverse)
- Shaping of the capillary, use of different materials (sapphire, 3D-printed samples, ...)





Hydrogen emission spectrum lines in the Balmer series



$$\boxed{\Delta\lambda \propto \alpha(T)\, n_0^{2/3}}$$

Active-plasma lens

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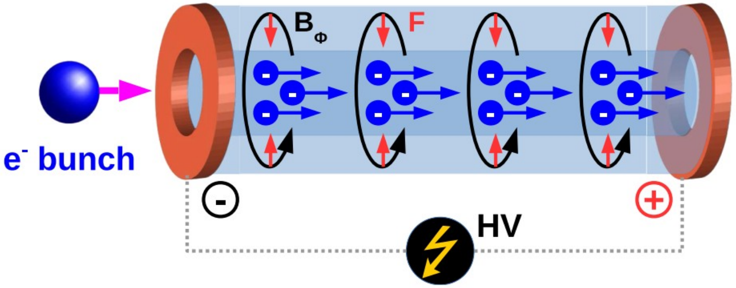
SPARC LAB

How it works

Discharge-current flowing in a gas-filled capillary

- The gas acts like a conductor between the two electrodes
- By the Ampere law, an azimuthal magnetic field is induced
  - It radially grows across the current and decreases outside of it
- The capillary radially confine the gas and, thus, the current



$$B_\phi(r)=\frac{\mu_0}{r}\int_0^r J(r')\,r'\,dr'$$

Benefits

- Cylindrical symmetry in focusing (like solenoids)
- Favorable focusing strength K~1/γ (like quadrupoles)
- Large focusing gradients (~ kT/m) → short focal length
- Tunability by adjusting the current amplitude

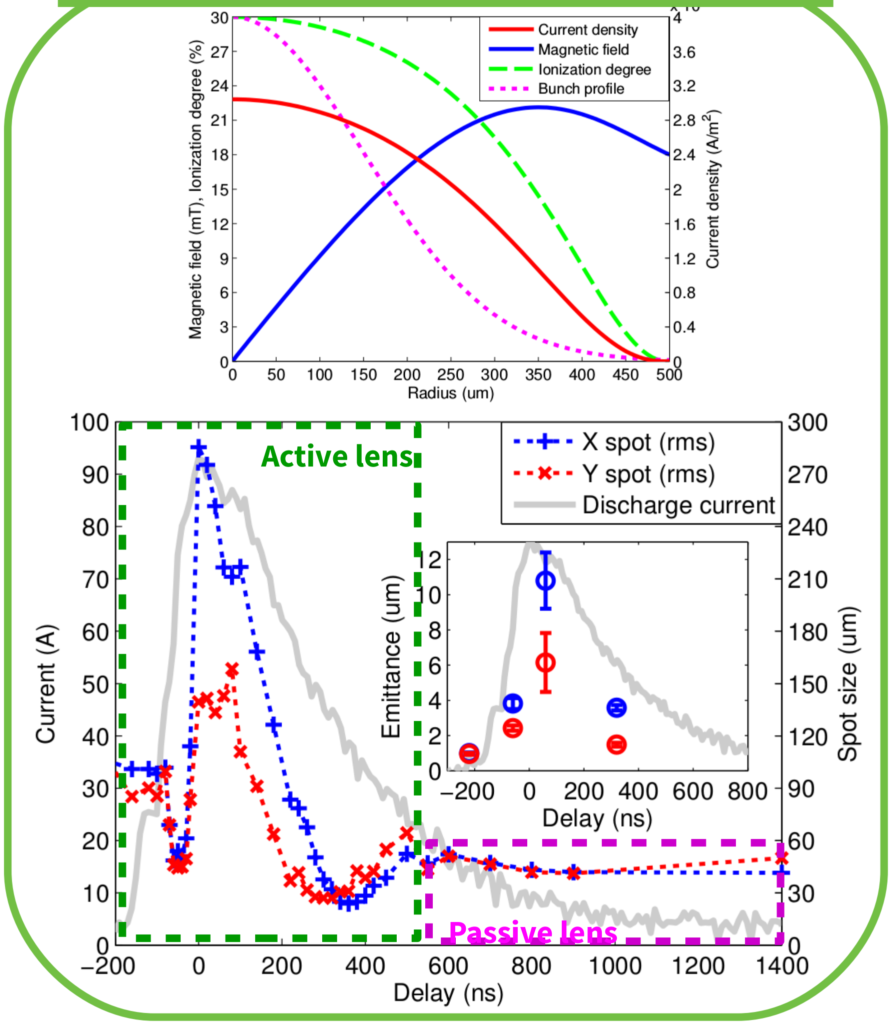
Similar to “passive” lenses

This is the real added value!

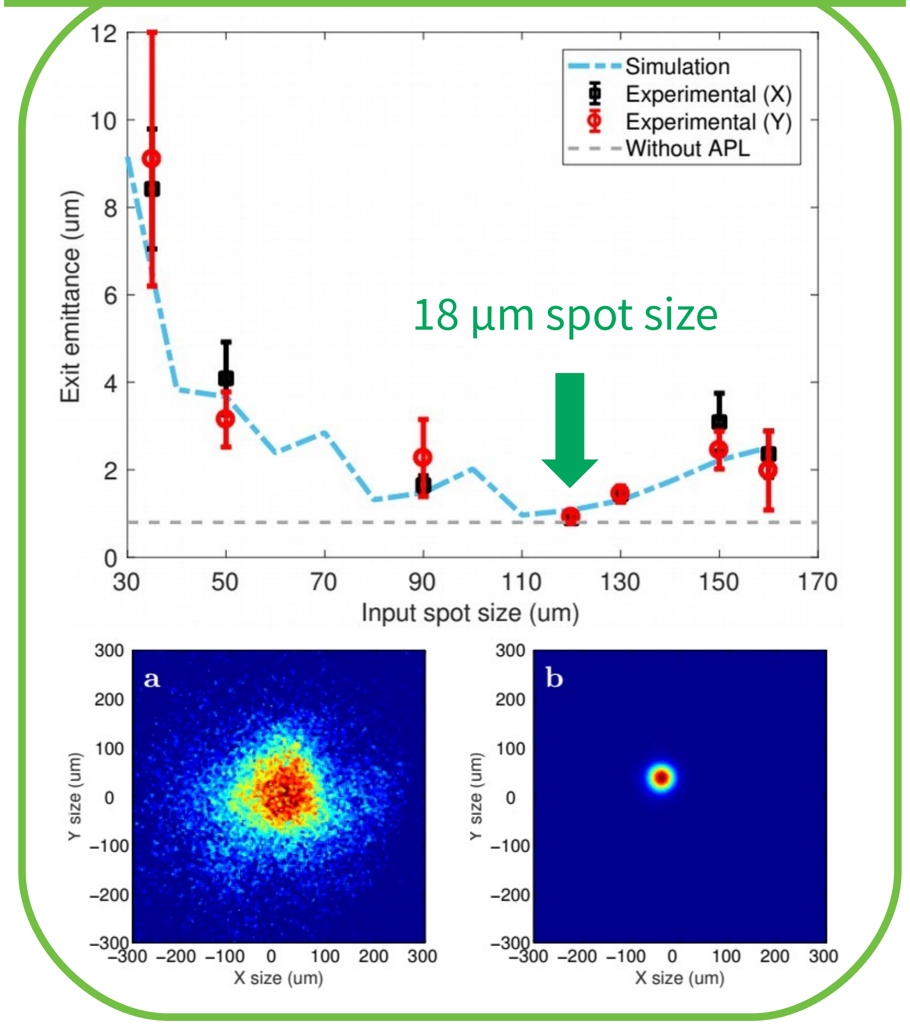
Panofsky, Wolfgang Kurt Hermann, and W. R. Baker. "A Focusing Device for the External 350-Mev Proton Beam of the 184-Inch Cyclotron at Berkeley." Review of Scientific Instruments 21.5 (1950): 445-447.

Summary of results @ SPARC_LAB

Demonstration of emittance growth



Demonstration of emittance preservation



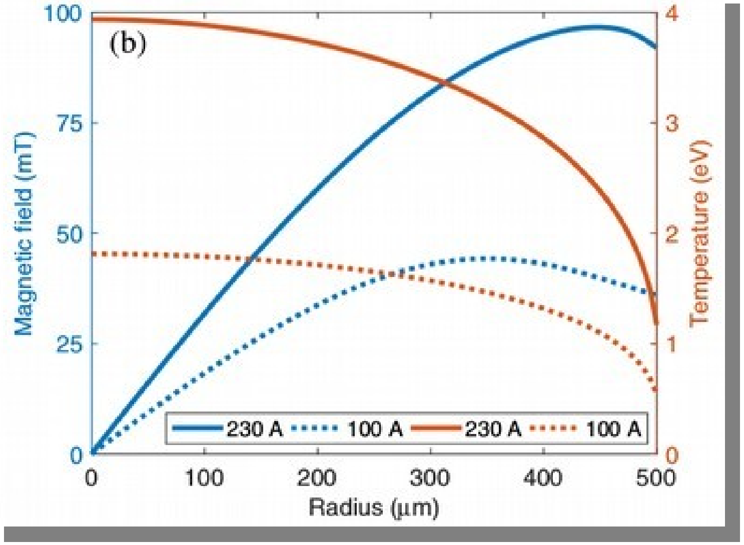
Pompili, R., et al. Applied Physics Letters 110.10 (2017): 104101.
Marocchino, A., et al. Applied Physics Letters 111.18 (2017): 184101.

Pompili, R., et al. Physical Review Letters 121.17 (2018): 174801.

Main findings

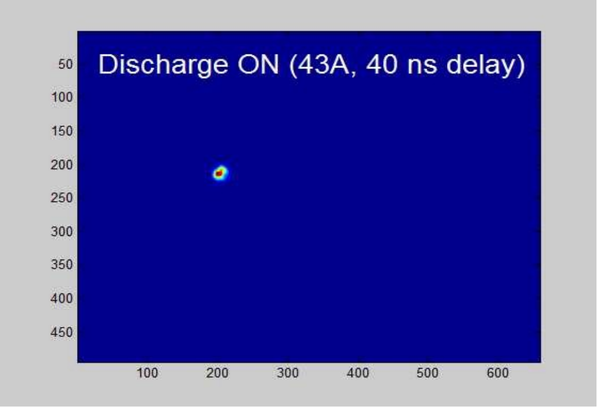
We have proved for the first time that the nonlinear focusing of an active plasma lens strongly affect the beam emittance

- Nonlinearities when using low discharge-currents in a partially ionized gas (**100 A** initially)
- Transverse plasma wakefields (passive lens effect) add more nonlinearities



Demonstration of emittance preservation

- Active lens: larger currents (**250 A**, now up to **600 A**) produce more linear fields and larger H_2 ionization
- Passive lens: low bunch densities are favorable



Next steps: test different capillary geometries

Plasma dechirper

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Working principle

Tuning of the bunch longitudinal phase-space (LPS) through the wakefields excited in a plasma

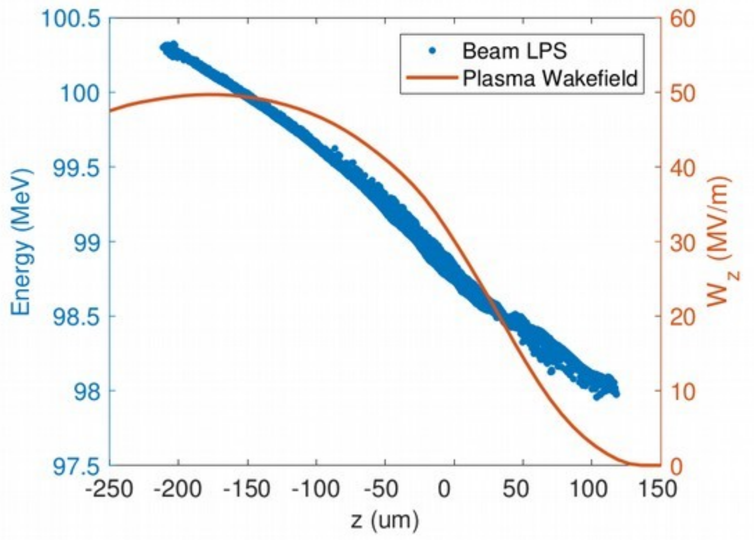
- Large wake (up to GV/m) allow to impress a time-energy correlation (→ chirp) on the bunch with small structures (cm-size)

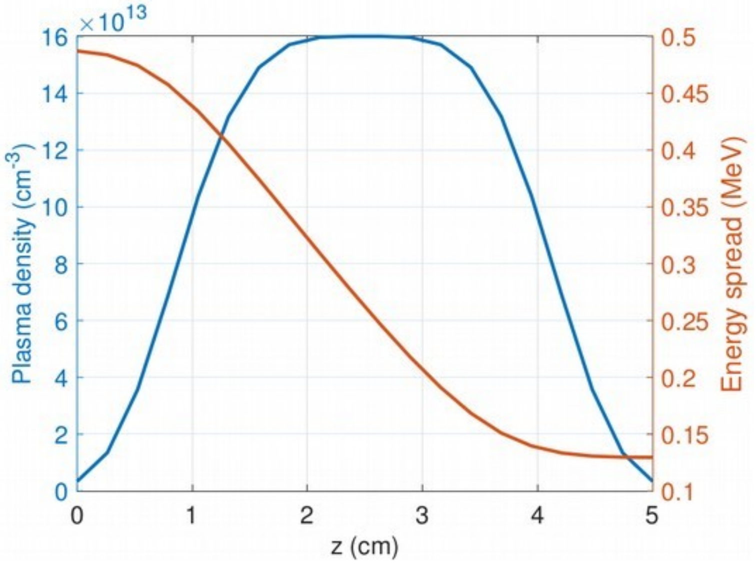
Several knobs can be used

- Plasma density (large densities → large wakes)
- Bunch density (large densities → large wakes)
- Length of the plasma channel (cumulative effect)

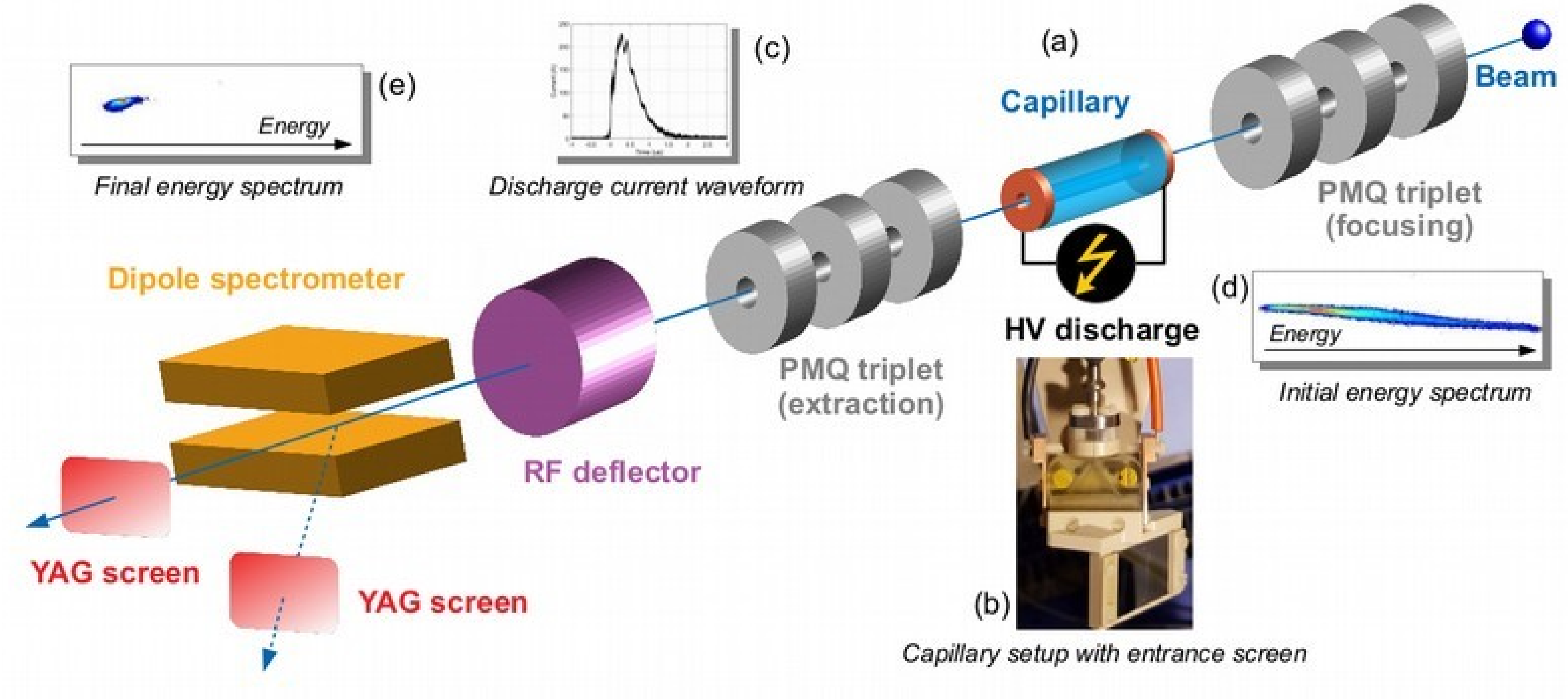
Applications

- Energy-chirp removal (aka “dechirper”)
- Bunch compressors (R_{56} in dogleg/chicane beamlines)

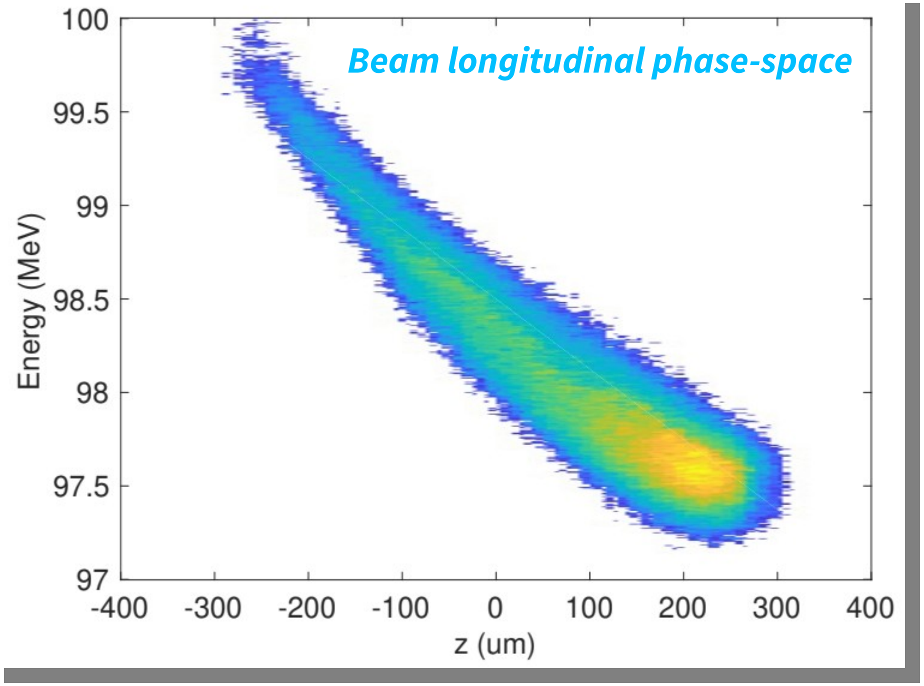




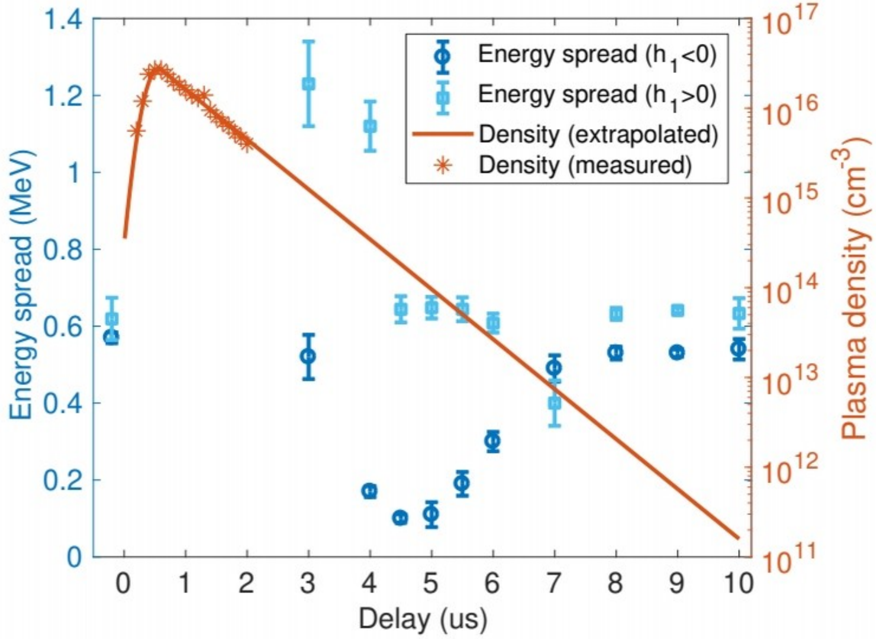
Experimental setup

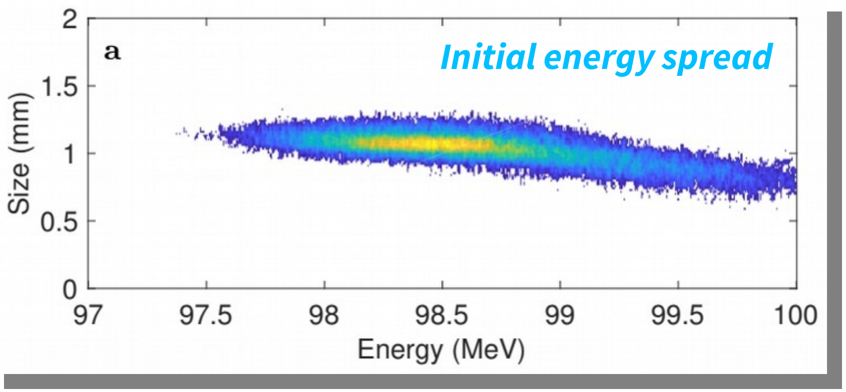


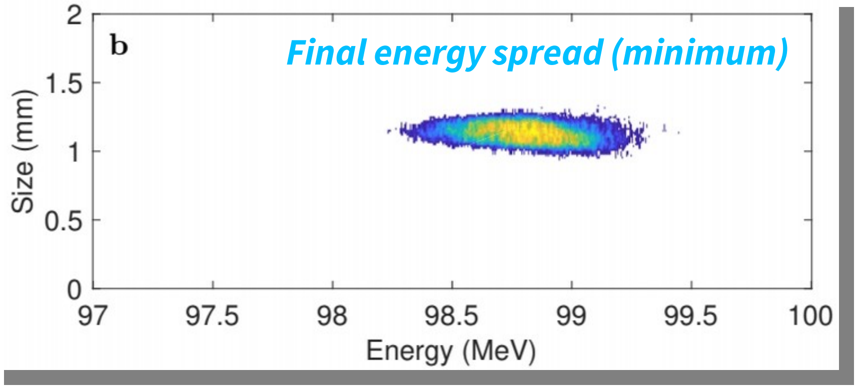
Experimental results


Beam longitudinal phase-space

Energy spread vs plasma density




Initial energy spread


Final energy spread (minimum)

Bending with plasma

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Particle bending in accelerator facilities

Bending magnets are widely employed in accelerator facilities

- Deflect particle beams to a different location, e.g. in experimental beamlines
- Manipulation of the beam longitudinal phase space (LPS), e.g. compression in chicane/dogleg beamlines
- Generation of synchrotron light

Different solutions can be implemented, depending on the beam energy, deflection angle and space constraints

- Electromagnetic dipoles (tunable, simple, cheap; small magnetic fields)
- Permanent magnets (simple, cheap, compact; no tunability, maximum field strength ~1.5 T)
- Super-conducting technology (large fields up to ~10 T, tunable; expensive, large size, needs cryogenic systems)
- Advanced concepts, e.g. channeling in crystals

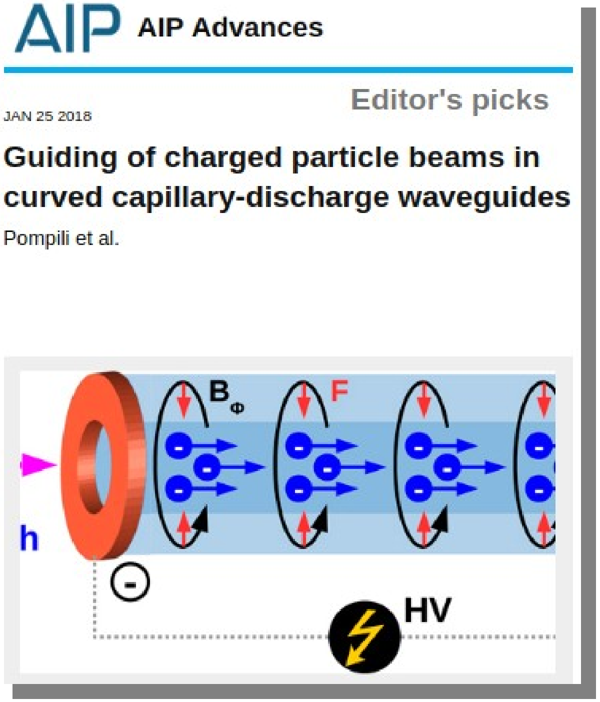
The Active Bending Plasma concept

Active Bending Plasma (ABP) is an extension of the APL mechanism

- The Lorentz force due to the current-induced magnetic field pushes the particles toward the capillary axis
- The same applies in a curved capillary: particles stay close to the bent path
- Plasma can sustain large currents (> 70 kA proved). As an example, **25 kA** current pulses (τ~200-300 ns) produce **~6 T** magnetic fields

What such a technology can offer

- Compactness. Large deflection angles, no need of cryogenic systems
- Tunability. The bending is tuned by adjusting the discharge-current
- Cheap solution (capillary+discharge pulser)
- ***Preservation of the beam Longitudinal Phase-Space (LPS) → not possible with devices providing constant magnetic fields***



AIP Advances

Editor's picks

JAN 25 2018

Guiding of charged particle beams in curved capillary-discharge waveguides

Pompili et al.

Pompili, R., et al. "Guiding of charged particle beams in curved capillary-discharge waveguides." AIP Advances 8.1 (2018): 015326.

Virtual experiment

The guiding efficiency of the ABP is tested with numerical simulations

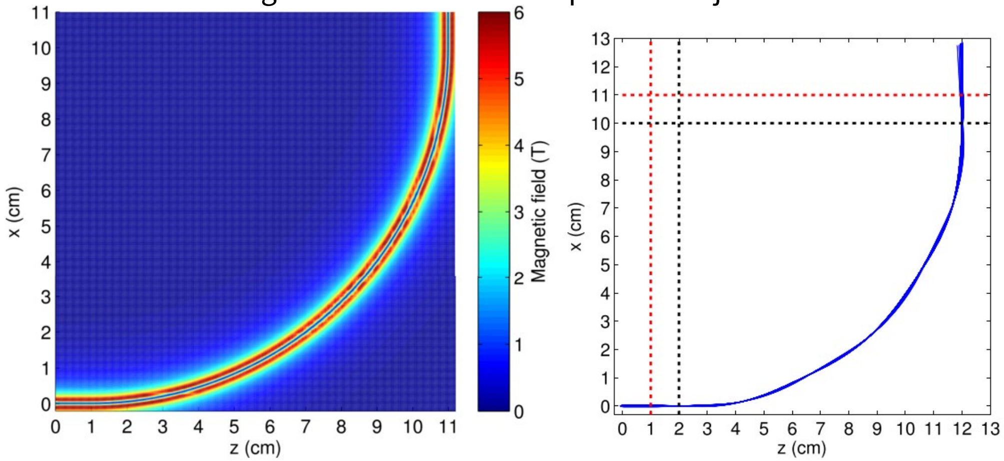
The device (simulated by **CST Studio**)

- **10 cm** curvature radius
- 1 mm capillary hole diameter
- Filled by H_2 gas (density 10^{19} cm^{-3})
- 25 kA current discharge

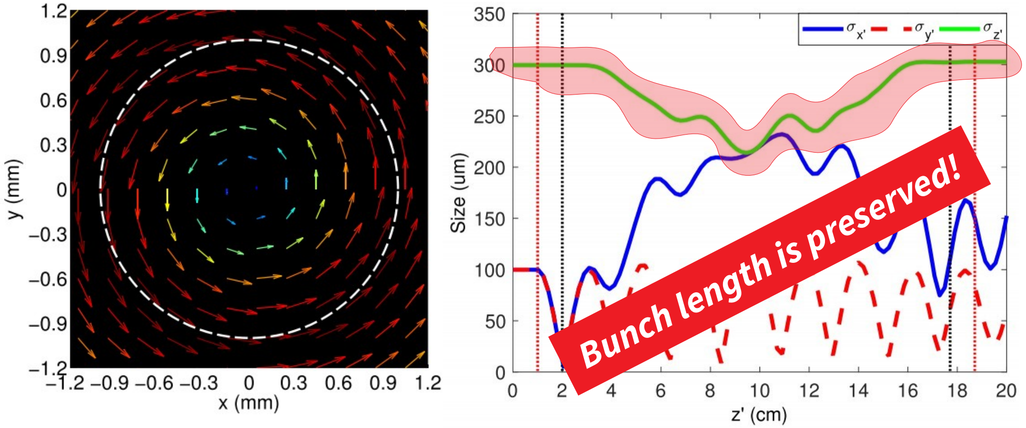
The beam (simulated by **GPT**)

- **100 MeV** (0,1% energy spread)
- $\sigma_{x,y} = 100$ µm, $\sigma_z = 300$ µm
- 1 µm normalized emittance

Bending field and its effect on particle trajectories



Field lines across the capillary and evolution of beam envelopes (x,y,z)



Bunch length is preserved!

NB: synchrotron emission not included in simulations!

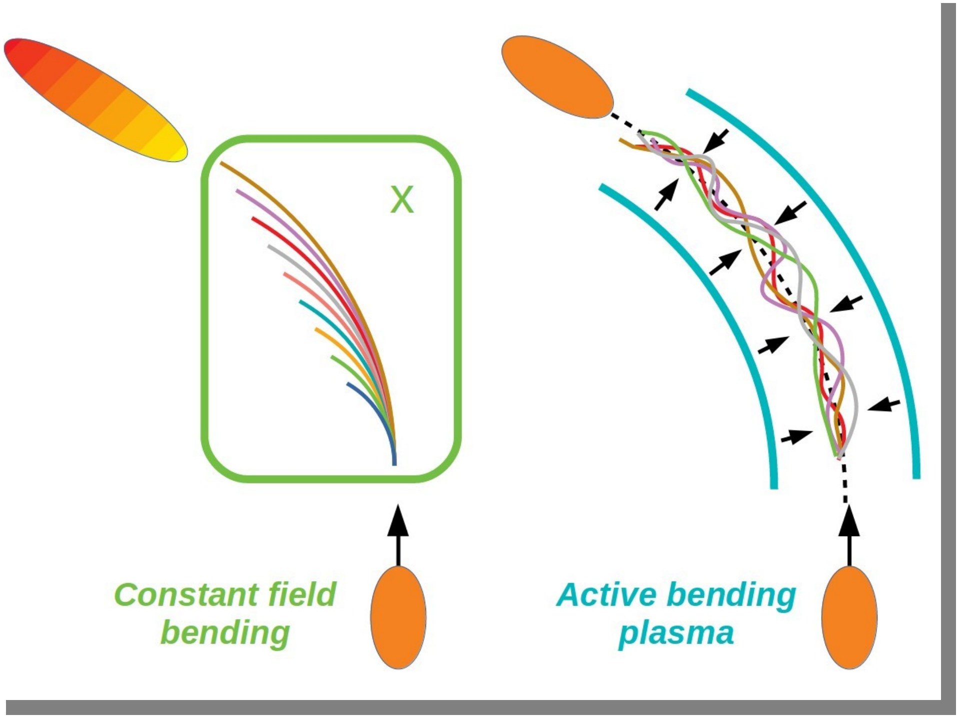
Longitudinal phase space preservation

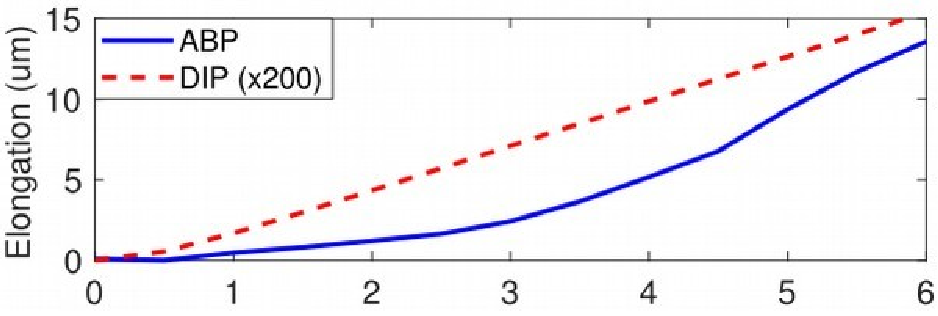
Conservation of bunch length is a direct consequence of ABP working mechanism

- Its magnetic field is radially increasing
- Large energy particles → large offset with respect to the capillary axis → stronger deflection (larger field)

Bunch elongation is negligible even with large energy spreads

- The ABP does not require any manipulation on the beam LPS as in the case of standard bending magnets!
    - No dispersion-matching optics (quads, sextupoles)!
- Simple and affordable solution in view of compact machines.





Thank you!

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