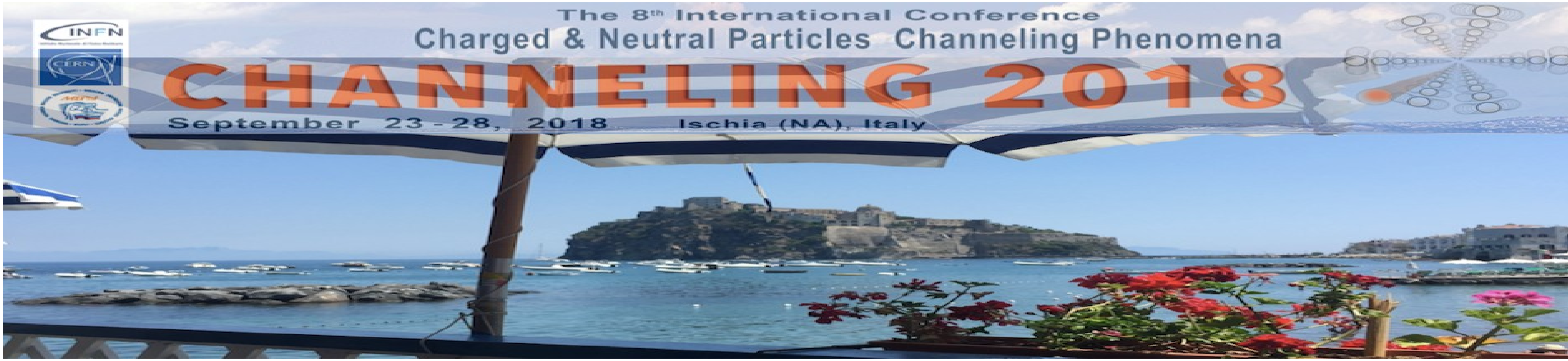

Guiding of charged particle beams in curved capillary-discharge waveguides

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On behalf of the SPARC_LAB collaboration

Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Frascati

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 (currently under study)

Plasma as a possible alternative

Use of plasmas confined in a small structure

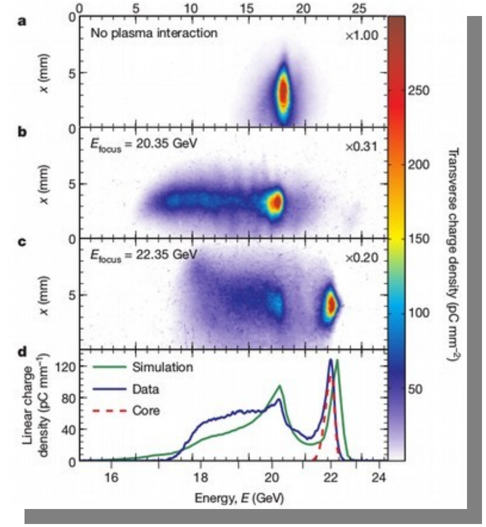
- Plasma sustains huge fields (~100's GV/m) and currents (~10's kA)
- Now many proofs demonstrated the possibility to develop compact plasma-based accelerators
- Possibility to be uses also as a focusing device

Active Plasma Lens (APL)

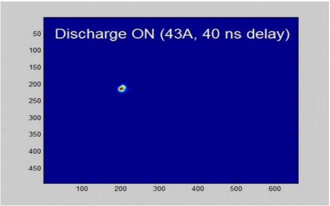
- Discharge-current driven through a plasma channel in capillary
- It induces a radially increasing (and symmetric) focusing field

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

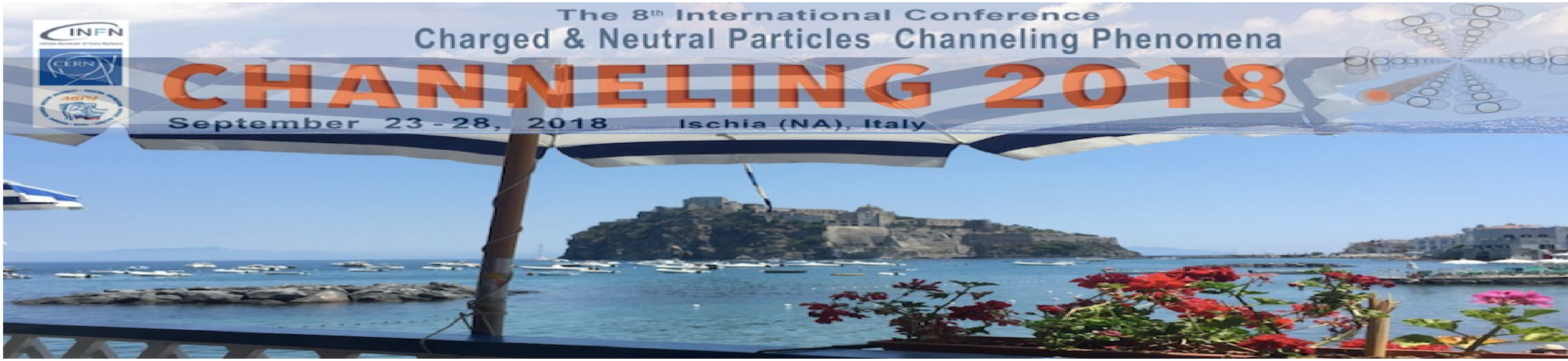
The idea: drive the current in curved capillaries for bending



Litos, M., et al. "High-efficiency acceleration of an electron beam in a plasma wakefield accelerator." Nature 515.7525 (2014): 92.



Pompili, R., et al. "Experimental characterization of active plasma lensing for electron beams." Applied Physics Letters 110.10 (2017): 104101.



Active Plasma lenses

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Toward new focusing devices

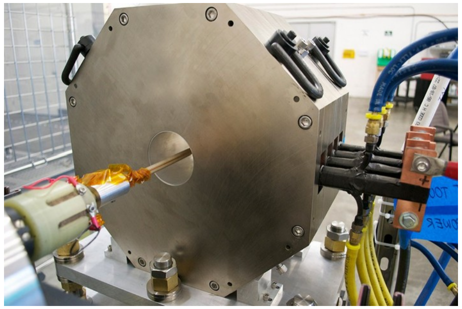
What we want

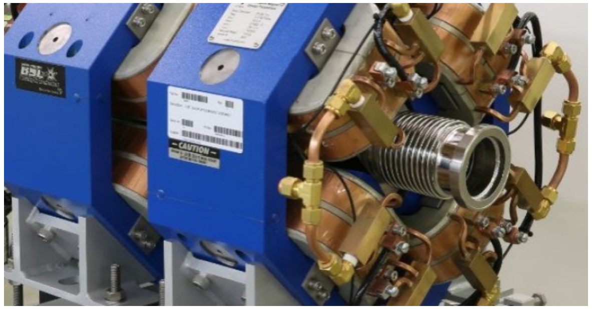
- Large focusing gradients (from kT/m up to MT/m)
  - State of the art is currently represented by Permanent Magnet Quadrupoles (PMQ): ~600 T/m
- Radially symmetric focusing
  - Avoid to use doublets or triplets that partly cancel with each other
- Low dependence of the focusing with the beam energy
  - Most favorable case is $K \sim 1/\gamma$
- Linear dependence with the radius
  - Avoid nonlinearities introducing geometric aberrations
  - Preservation of the beam emittance
- Focusing field independent on the beam distribution
- Tunability

Solenoid magnets

- ✔ Radial focusing
- ✖ Focusing strength (few T/m)

$$K_{sol} = \left(\frac{e B_z}{2 m_e c} \right)^2 \frac{1}{\gamma^2}$$





Electromagnetic quadrupoles

- ✔ Focusing strength (~250 T/m)
- ✔ Tunability
- ✖ Asymmetric focusing (we need 3 quads to make round bem)

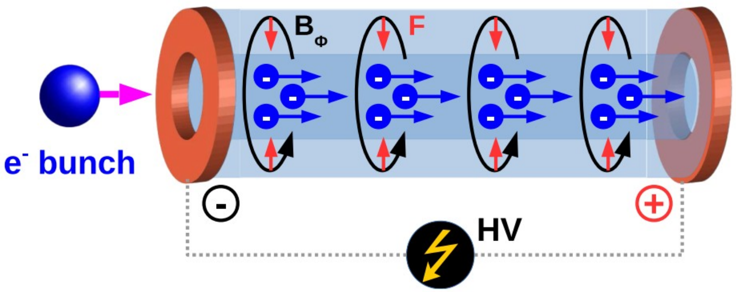
Permanent Magnet Quadrupoles (PMQs)

- ✔ Focusing strength (~600 T/m reached)
- ✖ No tunability and asymmetric focusing

$$K_{quad} = \left(\frac{e g}{\beta m_e c} \right)^2 \frac{1}{\gamma}$$

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

Similar to "passive" lenses

- Tunability by adjusting the current amplitude

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.

History and references

Early 1922: electrostatic focusing of a continuous low energy electron beam by beam-ionized gas within a cathode ray tube

- J.B. Johnson, J. Opt. Soc. Am. 6, 701 (1922) 6 J. Opt. Soc. Am. 6, 701 (1922)

Early 1930s: Passive plasma lens

- an electron stream can magnetically self-focus if it has sufficient current and its space charge is neutralized by positive ions, W.H. Bennett, Phys. Rev. 45, 890 (1934)

1950: Active plasma lens

- first idea of using externally driven plasma axial current to focus a proton beam by the azimuthal magnetic field, W.K.H. Panofsky and W.R. Baker, Rev. Sci. Instr. 21, 445 (1950)

Mid-1980s: Possible use of passive plasma lenses for the final focus in linear colliders

- P. Chen, Part. Accel. 20, 171 (1987)

Early 1990s: Further theoretical studies and final focus experiments at SLAC

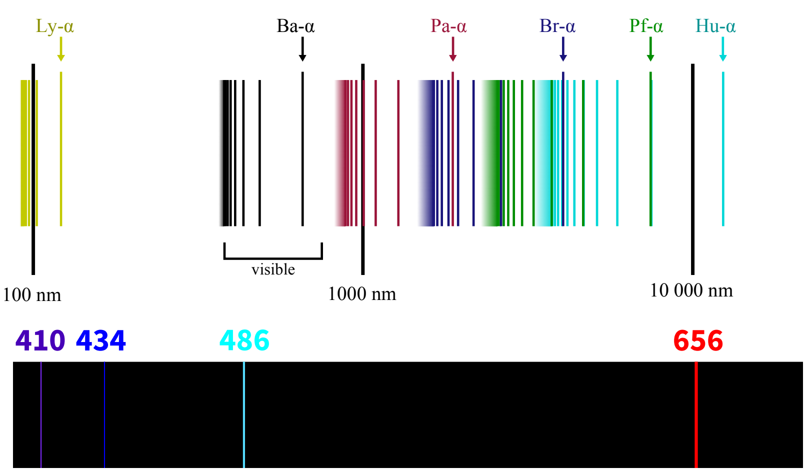
- Su, J. J., et al., Physical Review A 41.6 (1990): 3321.
- B. Barletta et al., Part. Accel. 20, 171 (1987)

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

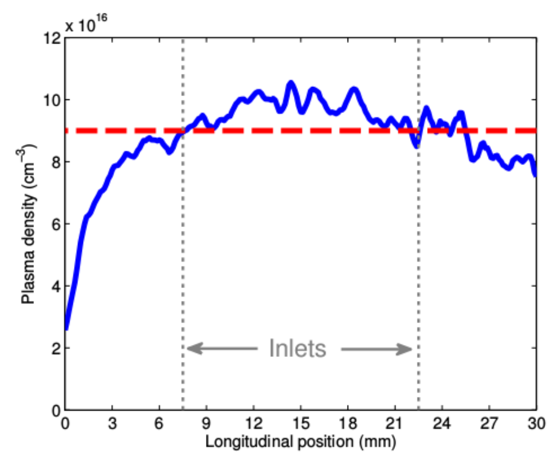
- Provide plasma acceleration (up to several GV/m) while preserving the high-brightness of the accelerated beam (emittance, energy spread)
- Demonstrate the possibility to use active plasma lenses as focusing device

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

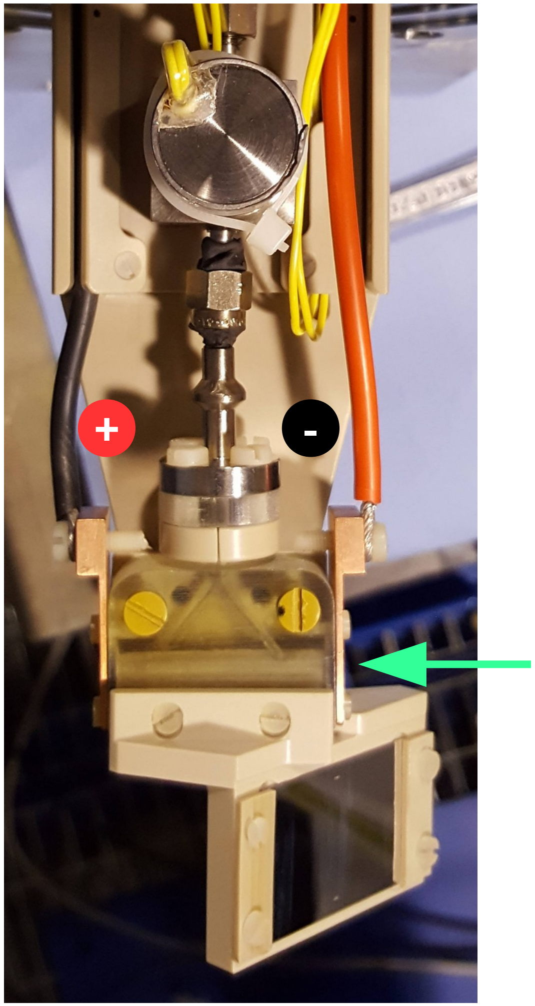
- Characterization of the plasma density profiles (longitudinal and transverse)
- Shaping of the capillary, use of different materials (sapphire, 3D-printed samples, ...)



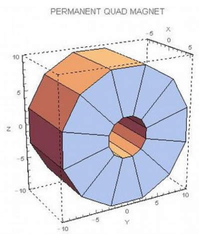
Hydrogen emission spectrum lines in the Balmer series



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



Experimental setup



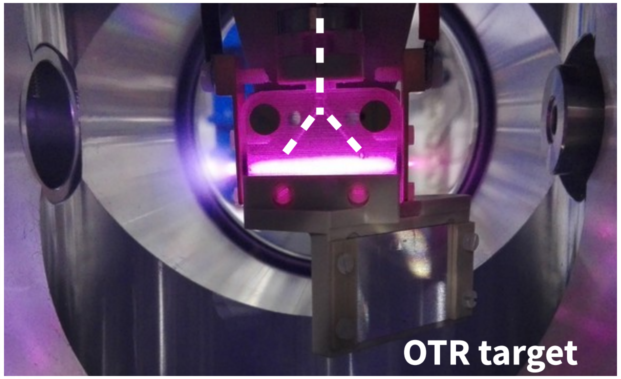
Beam injection

- ✓ 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

Plasma generation in capillary

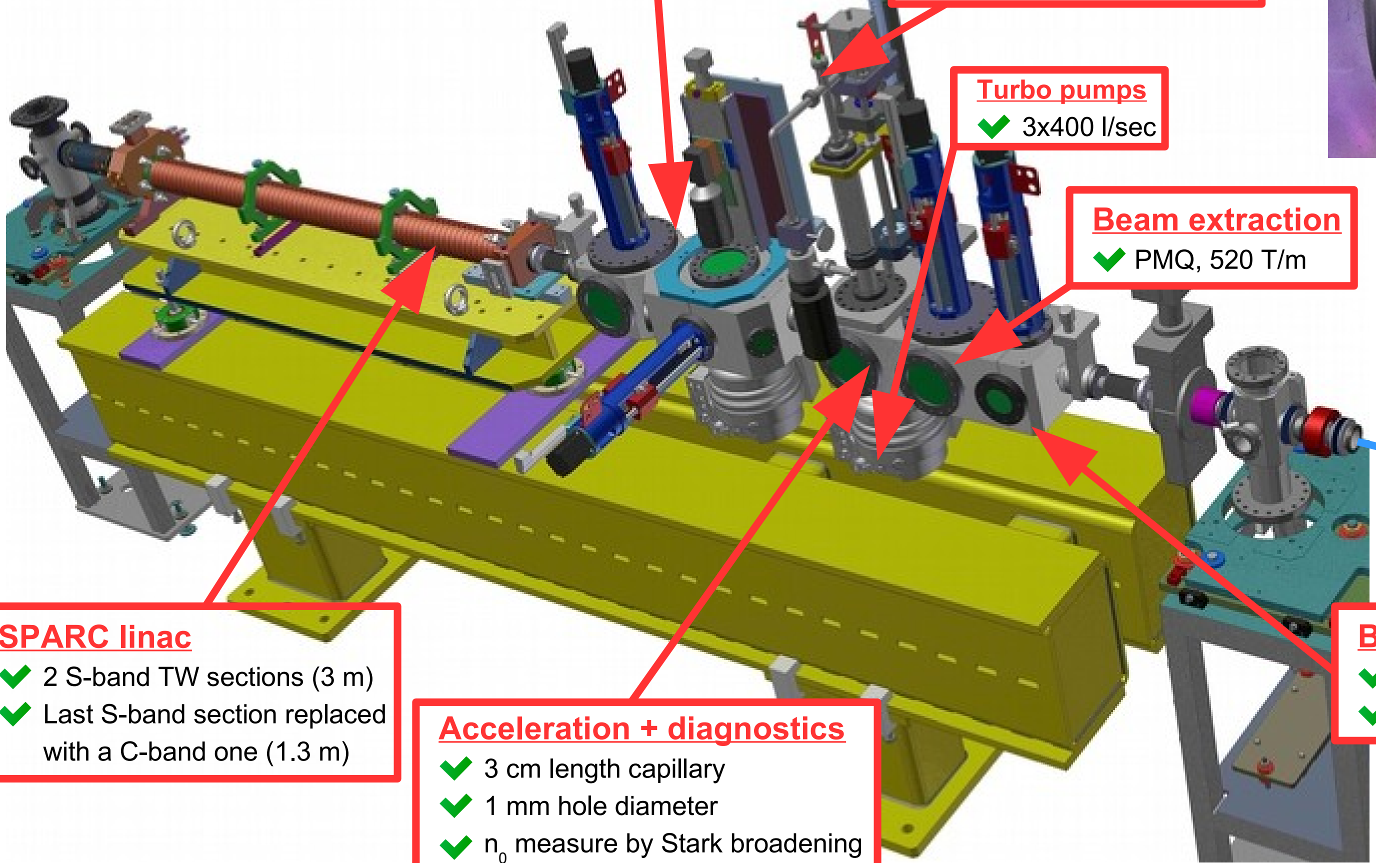


Turbo pumps

- ✓ 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)

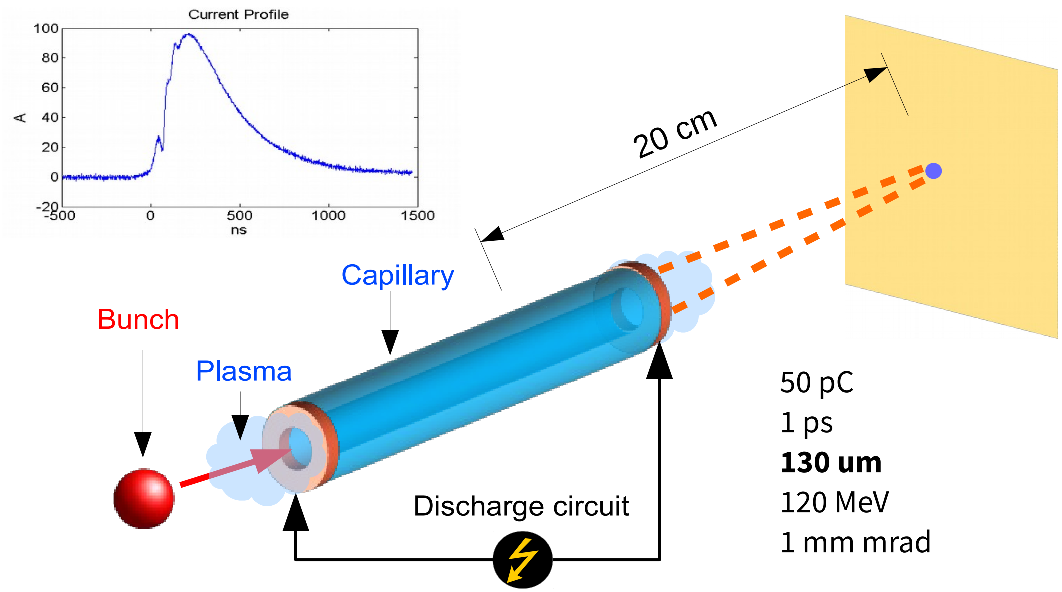
Acceleration + diagnostics

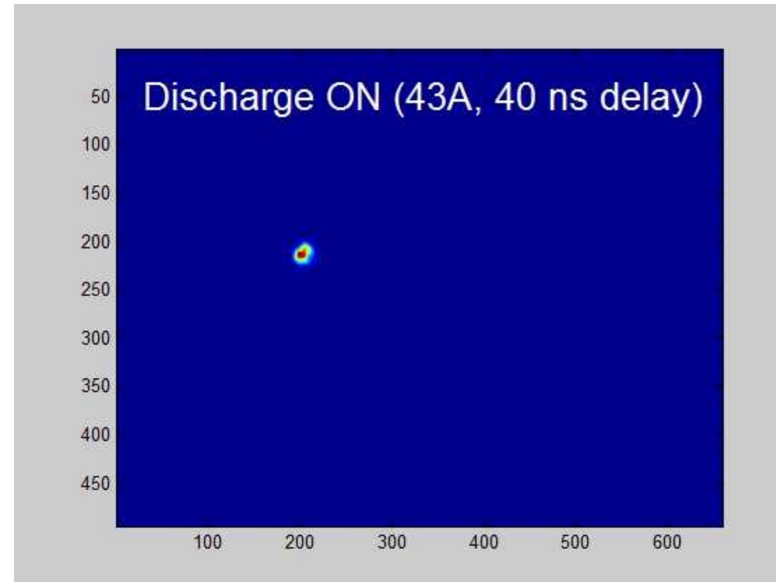
- ✓ 3 cm length capillary
- ✓ 1 mm hole diameter
- ✓ n_0 measure by Stark broadening

Beam diagnostics

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

Thanks to V. Lollo



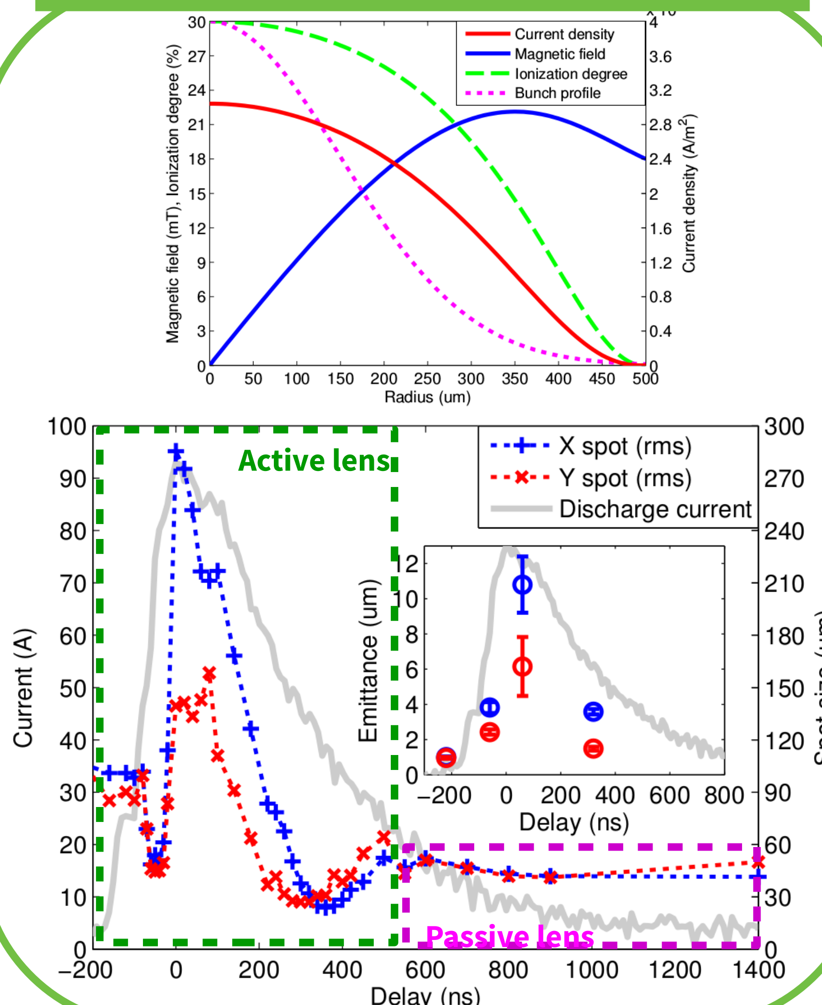


First demonstration of active plasma lensing with RF-accelerated beams

- We have demonstrated the effects of focusing on beam emittance, showing that strong spherical aberrations are induced on the beam
- We identified the problem in the non-uniform discharge current density across the capillary
- In last measurements we proved how to reduce these effects and preserve the beam emittance

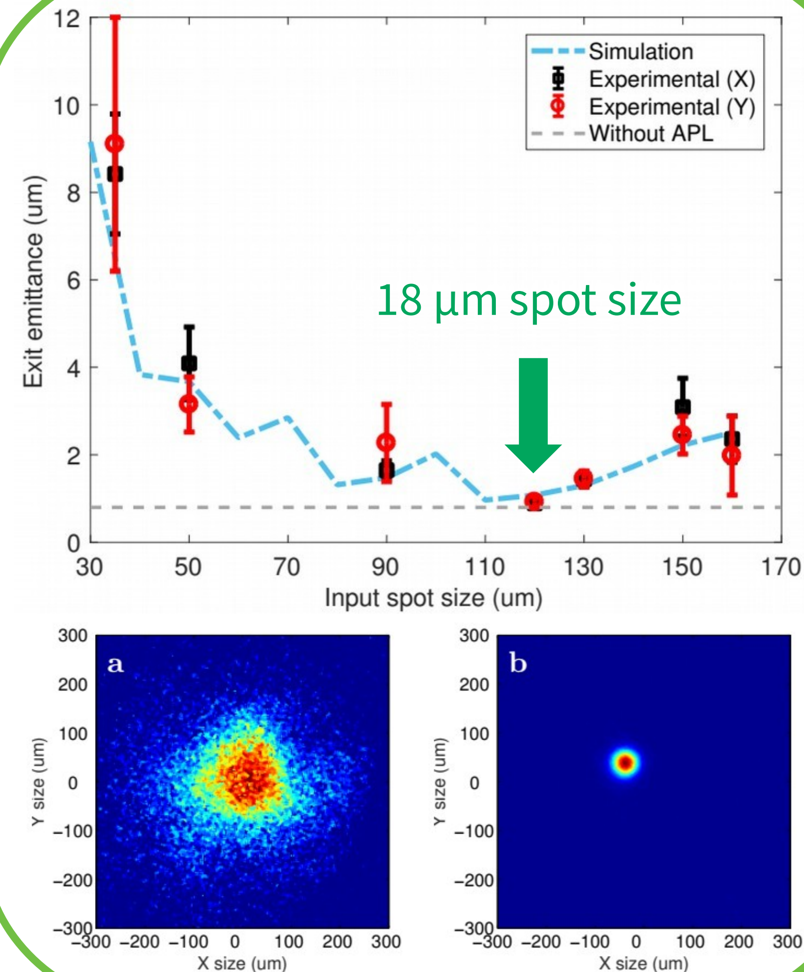
Results @ SPARC_LAB

Demonstration of emittance growth

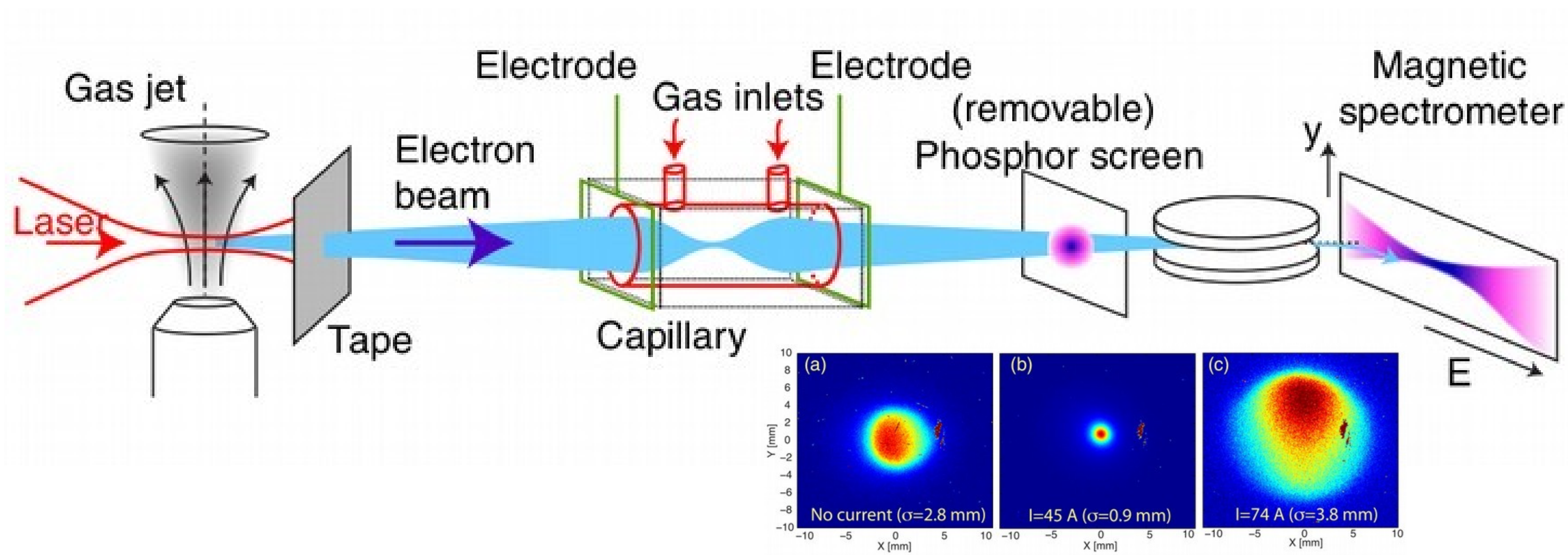


Pompili, R., et al. Applied Physics Letters 110.10 (2017): 104101.
Marocchino, A., et al. Applied Physics Letters 111.18 (2017): 184101.

Demonstration of emittance preservation



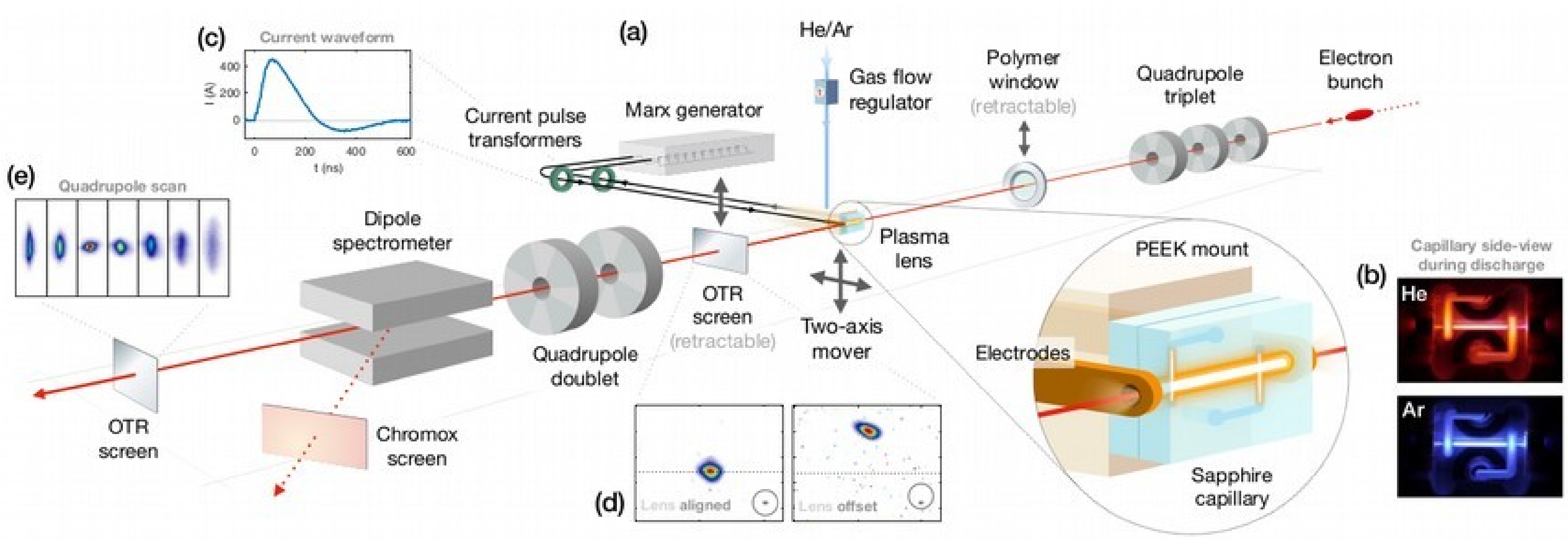
Pompili, R., submitted



Proof of APL usability to focus electron beams from laser-plasma accelerators

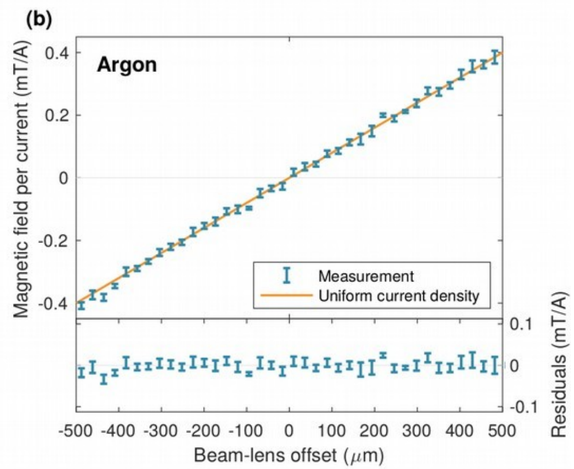
- 100 MeV beams with large divergence squeezed down to 0.9 mm
- Effective focusing gradient of ~kT/m
- APL used also in a further experiment to demonstrate staging of laser-plasma acceleration

Van Tilborg, J., et al. "Active plasma lensing for relativistic laser-plasma-accelerated electron beams." Physical review letters115.18 (2015): 184802.
Steinke, S., et al. "Multistage coupling of independent laser-plasma accelerators." Nature 530.7589 (2016): 190.

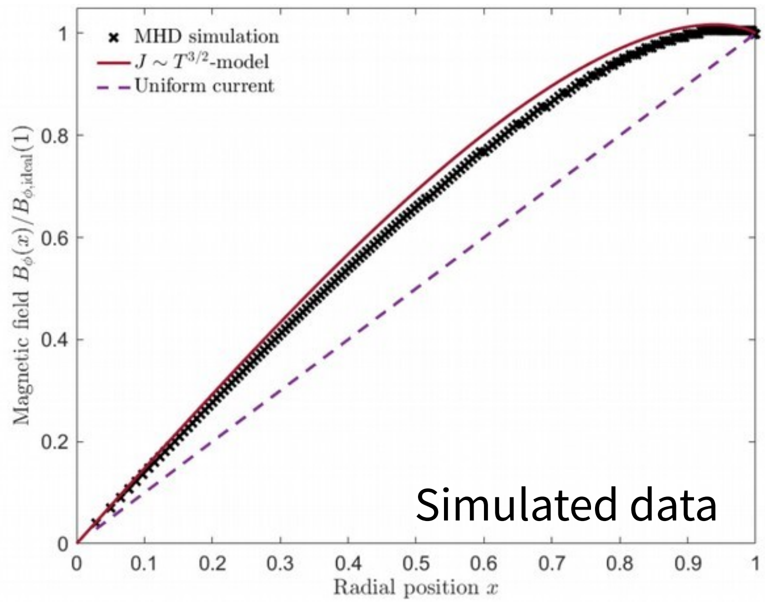


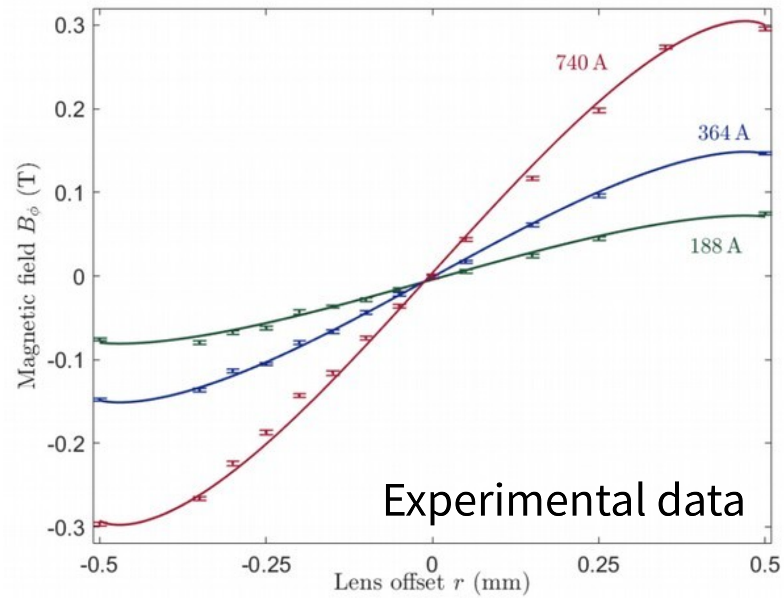
Test with APL using RF-accelerated electron bunches

- Theoretical/experimental study on both passive/active lensing
- Tests conducted with different gases (He and Ar). Best results (in terms of emittance) obtained with heavy gas (Ar)
- Direct measurement of the APL magnetic field



Lindstrøm, C. A., et al. "Emittance Preservation in an Aberration-Free Active Plasma Lens." arXiv preprint arXiv:1808.03691(2018).





Results obtained by testing the APL with a race-track Microtron (MaMi-B)

- MHD study of the field evolution across the capillary. Nonlinearities arising from non-uniform current density ($J \sim T^{3/2}$ model)
- Direct measurement of the APL magnetic field for several discharge-currents
- Measurement of the emittance growth

Röckemann, J-H., et al. "Direct Measurement of Focusing Fields in Active Plasma Lenses." arXiv preprint arXiv:1803.06663(2018).

Bending with plasma

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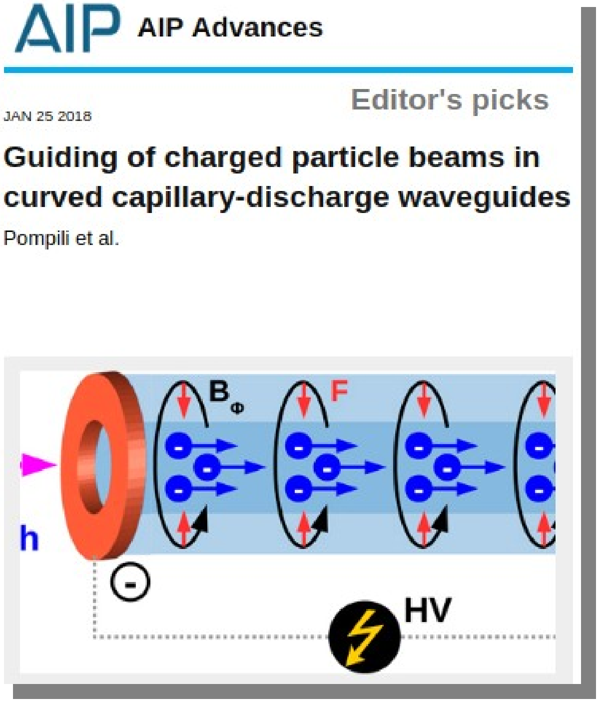
Active Bending Plasma (ABP) is an extension of the APL mechanism

- 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 have been proved). As an example, **25 kA** currents 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***



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

The PLADIP project

The **PLADIP** (compact PLAsma DIPole for particle bending) project has been recently approved by INFN

- 3 years duration
- Starting grant of 20 k€
- Goal: proof-of-principle experiment demonstrating particle bending

The project will provide the following tasks

- Realization of 10 cm-long curved capillaries for 10° bending
- Development of a 5 kA (20 kV) discharge-circuit with 100-300 ns pulse duration
- Offline tests in laboratory (plasma characterization)
- Online tests with electron beam @ SPARC_LAB test beamline
- Beam characterization (emittance, duration)

Virtual experiment

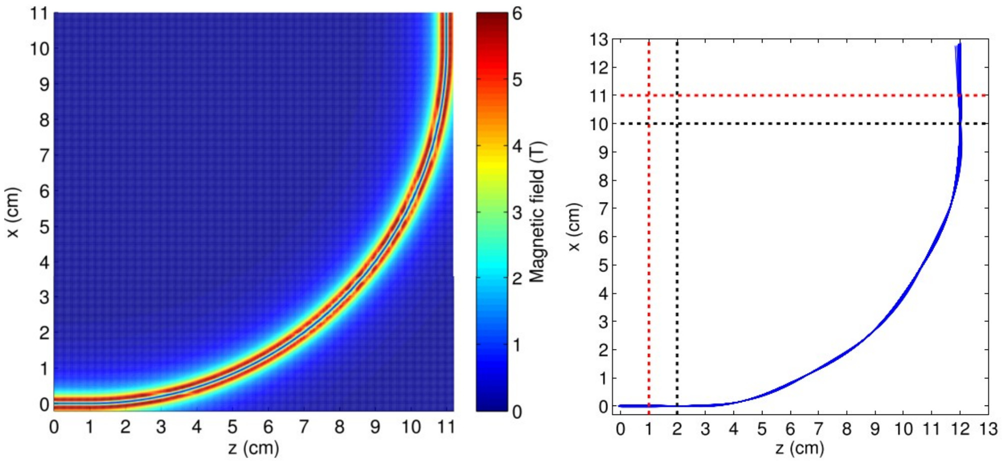
The guiding efficiency of the ABP is tested with numerical simulations

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

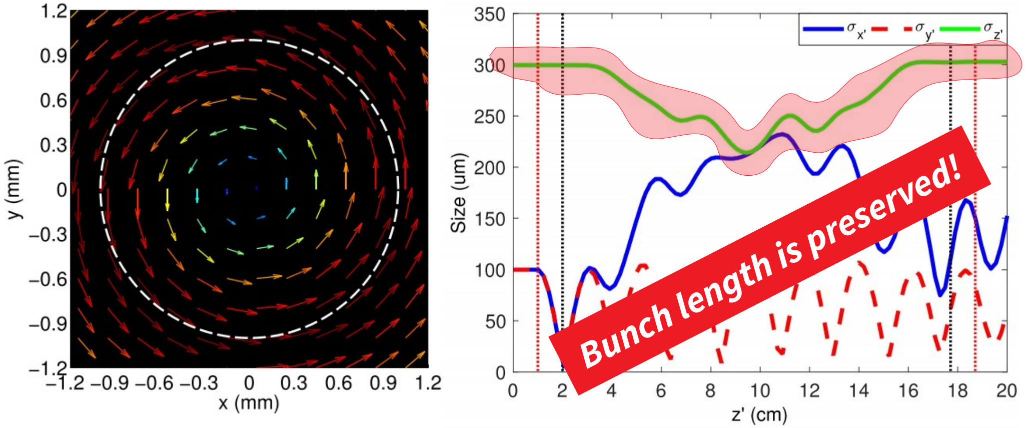
- 10 cm curvature radius
- 1 mm capillary hole diameter
- Filled by H2 gas (density 10^{19} cm^{-3})
- 25 kA current discharge

The beam (simulated by **GPT**)

- 100 MeV (0,1% energy spread)
- $\sigma_{x,y}$ = 100 µm, σ_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)

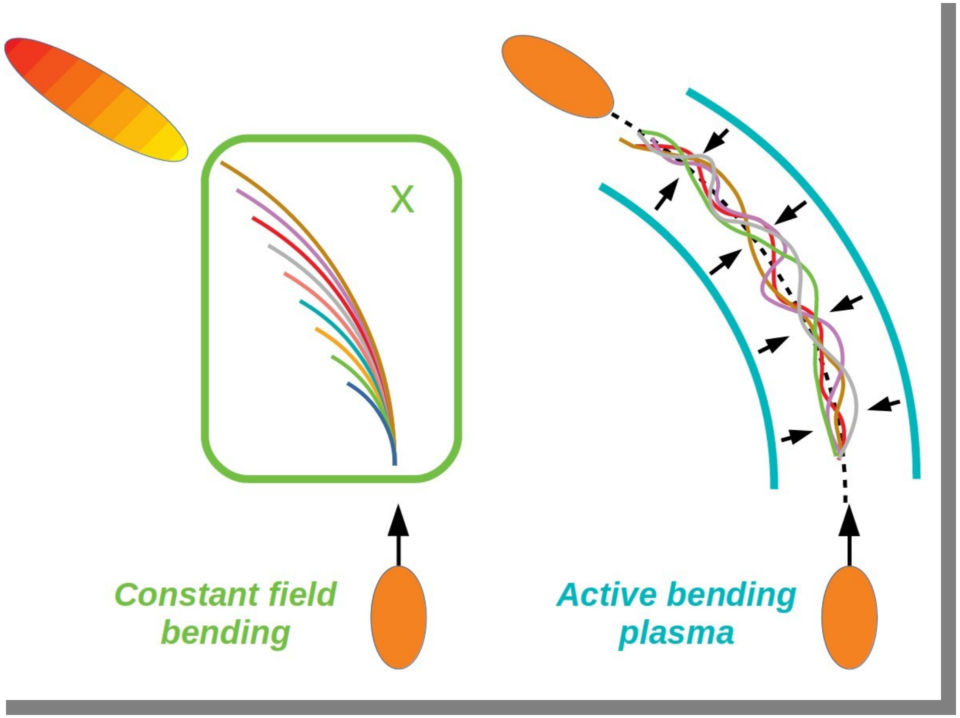
Longitudinal phase space preservation

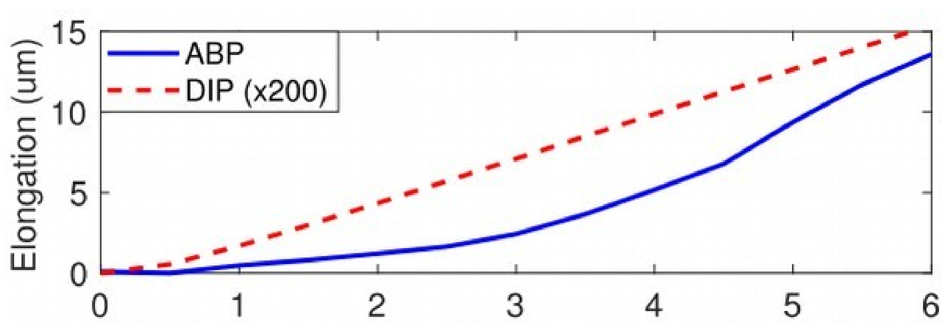
Conservation of bunch length is a direct consequence of ABP working mechanism

- 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.

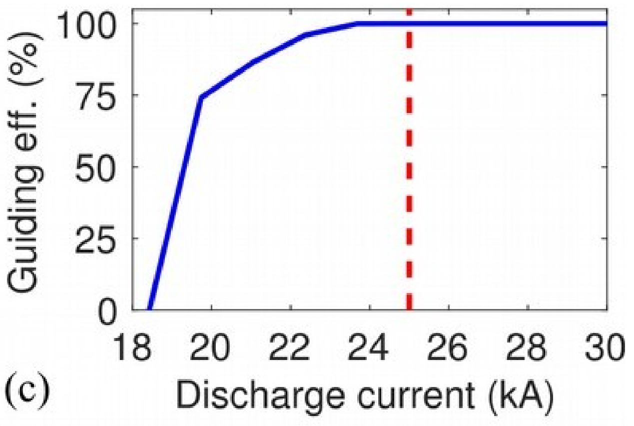




Operating range

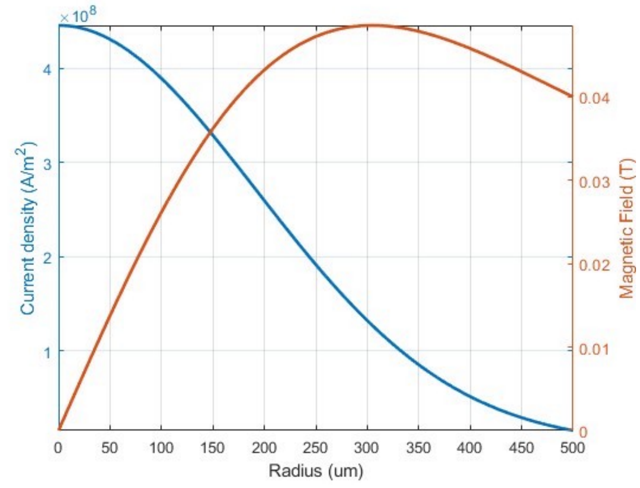
The ability to deflect particles and guide along the curved capillary axis is only determined by the discharge-current density

- Large densities needed to guide large energy beams
- The magnetic field across the capillary must be radially increasing



The last condition is satisfied only when operating in so-called *thermal (or Ohmic) regime*.

- Thermal pressure always larger than magnetic pressure to avoid plasma pinching
  - Need to achieve large temperatures → better to use light gases
  - It ensures no pinching instabilities along the transport channel



Conclusions

Plasma technology represents an affordable solution toward the development of new compact machines.

- Many laboratories are nowadays involved in plasma-based acceleration
- Several experiments are currently investigating active plasma lenses as focusing devices

So far there has not been any attempt to use it also like a particle bending

- Bending magnets can represents most of the size (and costs) of an accelerator facility.

Active Bending Plasma might be a promising alternative.

- Simple and affordable setup. Highly tunable.
- Need of a complete characterization and a proof-of-principle experiment!

We will start to study its implementation at SPARC_LAB from October 2018

- Expected proof-of-principle experiment within 3 years

Thank you!

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