Guiding of charged particle beams in curved capillary-discharge waveguides

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On behalf of the SPARC_LAB collaboration
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)
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 used 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

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

The idea: drive the current in curved capillaries for bending


Active Plasma lenses
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
Conventional focusing optics

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 beam)

Permanent Magnet Quadrupoles (PMQs)

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

\[ K_{quad} = \left( \frac{e g}{\beta m_e c} \right)^2 \frac{1}{\gamma} \]
Active plasma lenses

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

Benefits

- Cylindrical symmetry in focusing (like solenoids)
- Favorable focusing strength $K \sim 1/\gamma$ (like quadrupoles)
- Large focusing gradients ($\sim kT/m$) $\rightarrow$ short focal length
- Tunability by adjusting the current amplitude

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

Similar to “passive” lenses

This is the real added value!

History and references

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


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


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

- 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

\[ \Delta \lambda \propto \alpha(T) n_0^{2/3} \]
Guiding of charged particle beams in curved capillary-discharge waveguides

**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

**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 extraction**
- PMQ, 520 T/m

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

**Thanks to V. Lollo**

Plasma generation in capillary
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

Demonstration of emittance preservation


Pompili, R., submitted

18 μm spot size

Pompili, R., submitted
Results @ BELLA (LBNL)

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

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

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

Bending with plasma
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*
The **PLADIP** (compact PLAsma DIPose 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)
- $\sigma_{x,y} = 100$ $\mu$m, $\sigma_z = 300$ $\mu$m
- 1 $\mu$m 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!
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
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 represent 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!