Nonlinear plasma lens for achromatic staging

Follow-up on latest simulation and experiment

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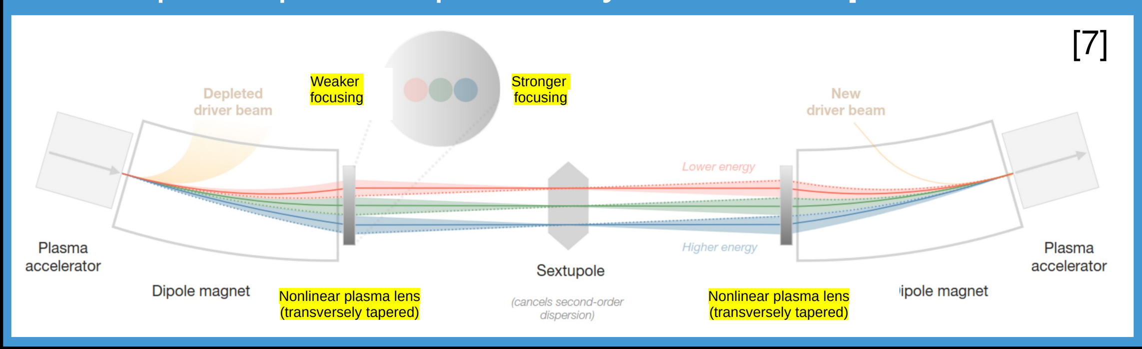
1. Introduction

Plasma accelerators [1] offer accelerating gradients that are typically **> GV/m** [2,3]… but ...

High **divergence** + large energy **spread** beams !

→ makes **staging complex** (e.g. Steinke *et al.* [4]).

Solution: specific transport lattice (SPARTA [5,6]) with quadrupoles replaced by **nonlinear plasma lens**



2. Nonlinear plasma lens concept

Active plasma lens:

- Gas filled capillary (~0.3-1mm diam, few mm length),
- Discharge ~ 1kA → creates current density $\vec{J} = J(x, y)\vec{e}_z$
- Focusing gradient ~ kT/m in **both planes** through $\nabla \times \vec{B} = \mu_0 \vec{J}$

Nonlinear asymmetric plasma lens:

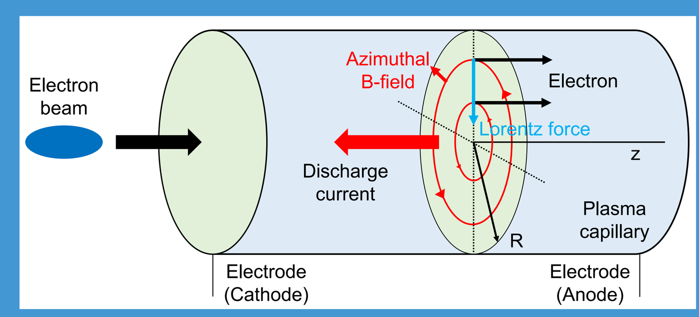
- Same but with add. ext. B-field to generate Hall-effect → current density $\vec{J}$ rearranges **asymmetrically**

$$J_z^{nonlinear} = \frac{2 g_0}{\mu_0}\left(1 + \frac{1}{D_x} x\right)$$

Transverse taper in x (nonlinear part for **B**)

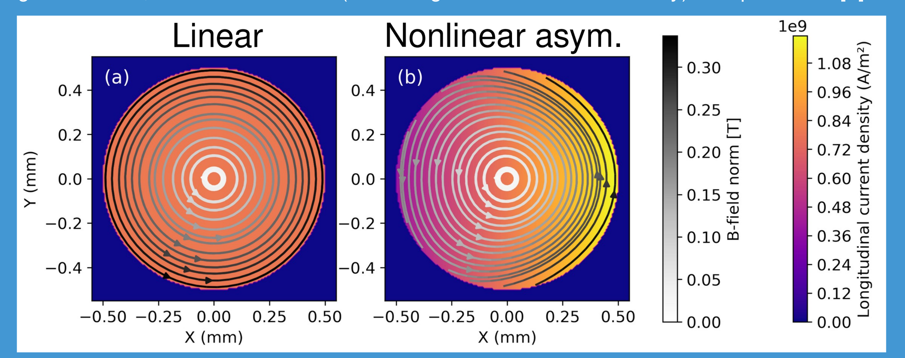
$$\begin{cases} B_x^{nonlinear} = -g_0\left(y + \frac{1}{D_x} xy\right) \\ B_y^{nonlinear} = g_0\left(x + \frac{1}{D_x}\frac{x^2 + y^2}{2}\right) \end{cases}$$

Mean focusing gradient — Dispersion



Schematic of an active plasma lens (image credit: Kyrre Sjobak)

Theoretical B-field: (a) linear case, (b) nonlinear case with asymmetry. Coefficients are: g_0 = 500 T/m, $1/D_x$ = 100% mm^{-1} ($1/D_x$ exagerated for better visibility). Adapted from [8].



3. Experimental setup

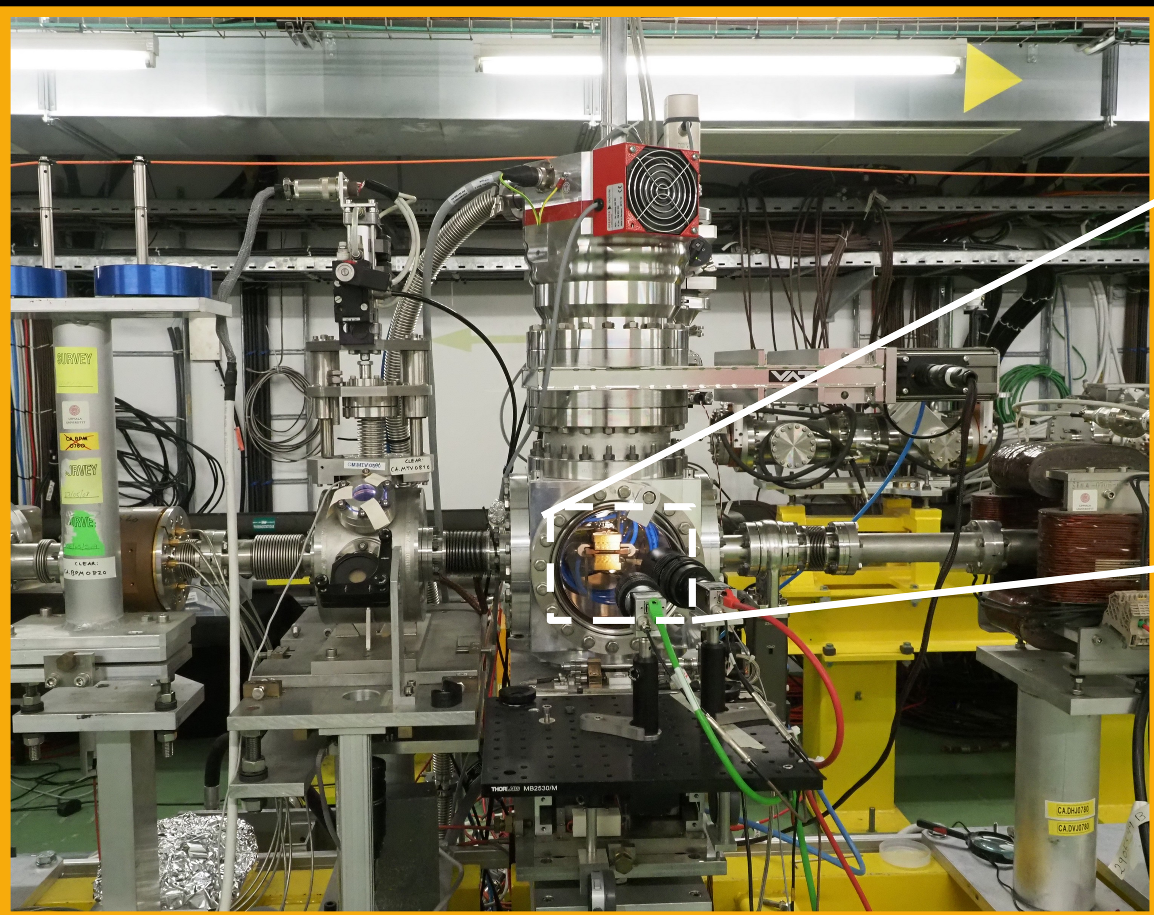
New plasma lens design:

- **Capillary** instead of solid block (easy replacement of spare parts, less used material, eased diagnostics),
- With an external **electromagnet (up to 150mT)** to induce Hall effect [9], and create nonlinear plasma redistribution,
- Argon around 10 mbar, 1kA discharge.

Experiments performed at CLEAR [10] in **2024 & 2025** (collaboration between CERN, Oxford and UiO).

Objectives:

- Test the new lens design (sparking OK, leaks OK),
- **Measure** the produced **B-field** using CLEAR e-beam as a probe [11] (beam observed on a screen 30 cm downstream)



Top: nonlinear plasma lens during June 2025 CLEAR exp. campaign.
Bottom: current with 6 Marx Banks.

Plasma Lens experimental area at CLEAR. Electron beam goes from right to left.

4. Preliminary experimental results

Objective: in an argon-plasma, map the lens B-field using beam displacements on a screen 30 cm downstream of the lens.

Expected displacements:

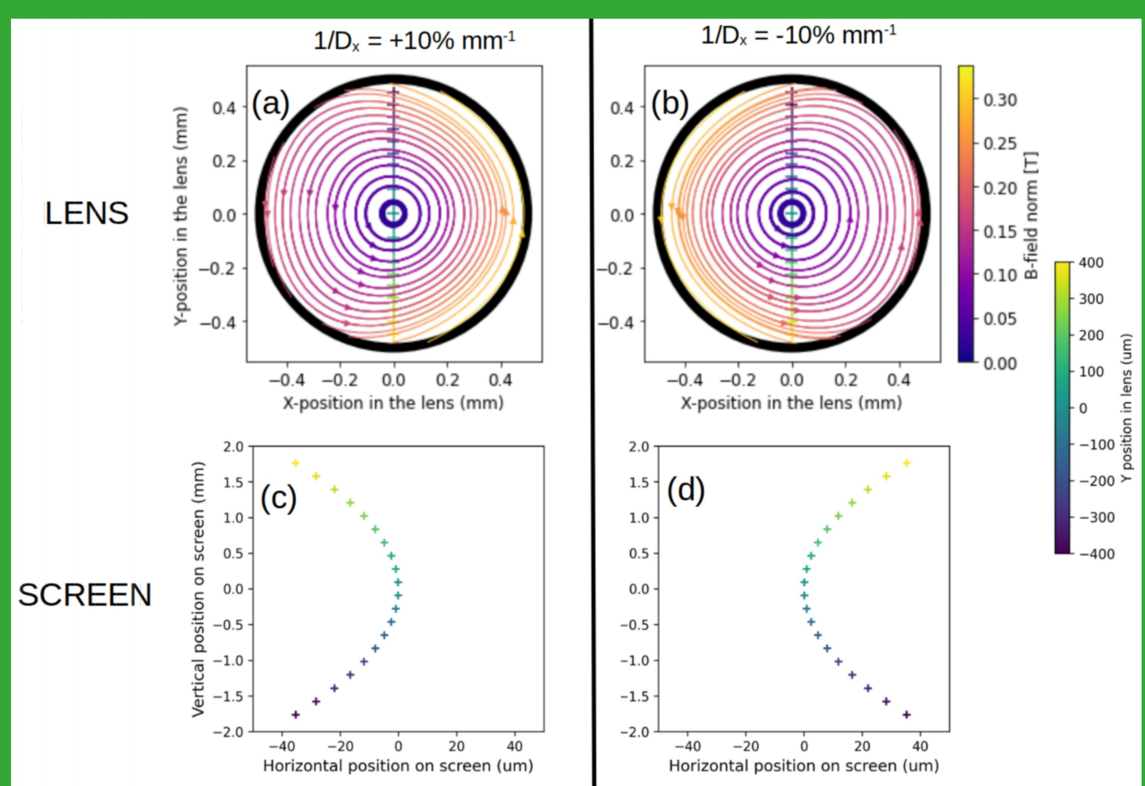
$$\begin{cases} \Delta x(x_L, y_L) = \frac{-ecL\Delta z}{E} g_0\left(-x_L + \frac{1}{D_x}\frac{x_L^2 + y_L^2}{2}\right) \\ \Delta y(x_L, y_L) = \frac{+ecL\Delta z}{E} g_0\left(y_L + \frac{1}{D_x} x_L y_L\right) \end{cases}$$

(x_L, y_L): lens position from beam axis, e: e⁻ charge, c: speed of light, L: lens length, Δz: screen distance, E: beam energy, g_0: average focusing strength, D_x: dispersion.

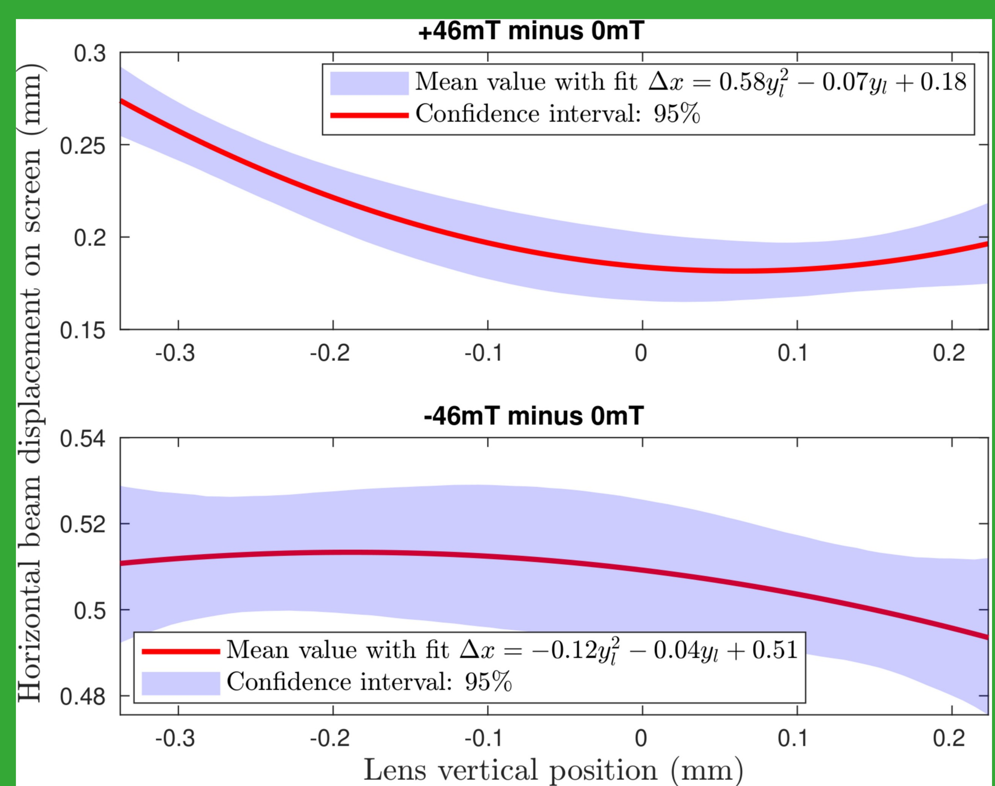
Preliminary results:

- During a centered vertical scan (i.e., with $x_L = 0$), apparition of a "banana"-like shape for Δx as predicted by $\Delta x(0,y) = -(ecL\Delta z/2E)(g_0/D_x)\, \mathbf{y}^2$, which flips when we flip D_x through the add. ext. B-field → there is a **nonlinearity and we can flip it**!
- Evaluated: g_0 ~ 800 T/m and $1/D_x$ ~ 9% mm^{-1} → OK for SPARTA lattice (we need a few %mm^{-1}).

Simulation: (a–b) theoretical B-field in the lens with g = 500 T/m, $1/D_x$ = ±10 % mm^{-1}, (c–d) predicted observation on the screen downstream of the lens (axis are <u>not orthonormal</u> !). The points scanned are displayed as crosses. The effect of the external B-field is neglected. Modified from [8].



Experiment: horizontal beam displacements observed on the screen from vertical scans with an external field of +46 mT (top) and −46 mT (bottom), relative to the displacements from a vertical scan without external field. The dipole contribution from the external field has been removed. The lens was centered horizontally. From [8].



5. Hydrodynamic simulation

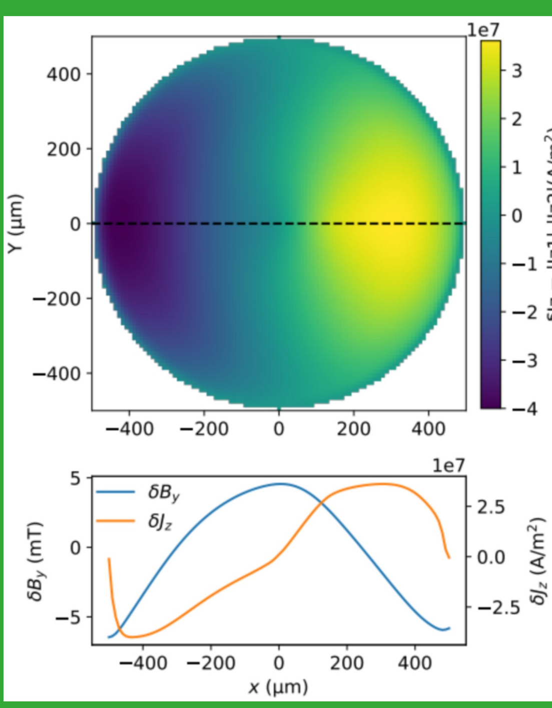
Model used: 2D hydrodynamic with H_2 (collaboration with DESY [12]).

Objective: study the influence of an external B-field on the plasma redistribution, and consequently, plasma-generated B-field.

Results: we manage to get (see right graph) g_0 = 1130 T/m and $1/D_x$ = 10% mm^{-1} which suits the SPARTA project.

<u>NOTE</u>: higher order terms present, likely from **light** gas thermal effects [13].

Top: difference in 2D absolute current density δJz between a simulation with 160 mT external field and no external field.
Bottom: 1D plots extracted at $(x_L, y_L) = (x, 0)$ for the difference in vertical *B*-field δBy (external *B*-field has been subtracted) and in current density.
Both graphs are with H_2 at 7 mbar, 185 ns.



6. Conclusion and outlook

Experiment:

- first results, a **nonlinear** effect is present.
- **full mapping** under analysis.

Simulations:

- theoretically possible to act on the plasma with an external B-field, and create **nonlinearity** on the overall B-field distribution.
- heavier gas model (Ar) under construction to get rid of light gas inherent parasitic high-order nonlinearities.

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Contribution n°: 463

7[th] European Advanced Accelerator Conference (EAAC), Elba, Italy, 21–27 September 2025

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