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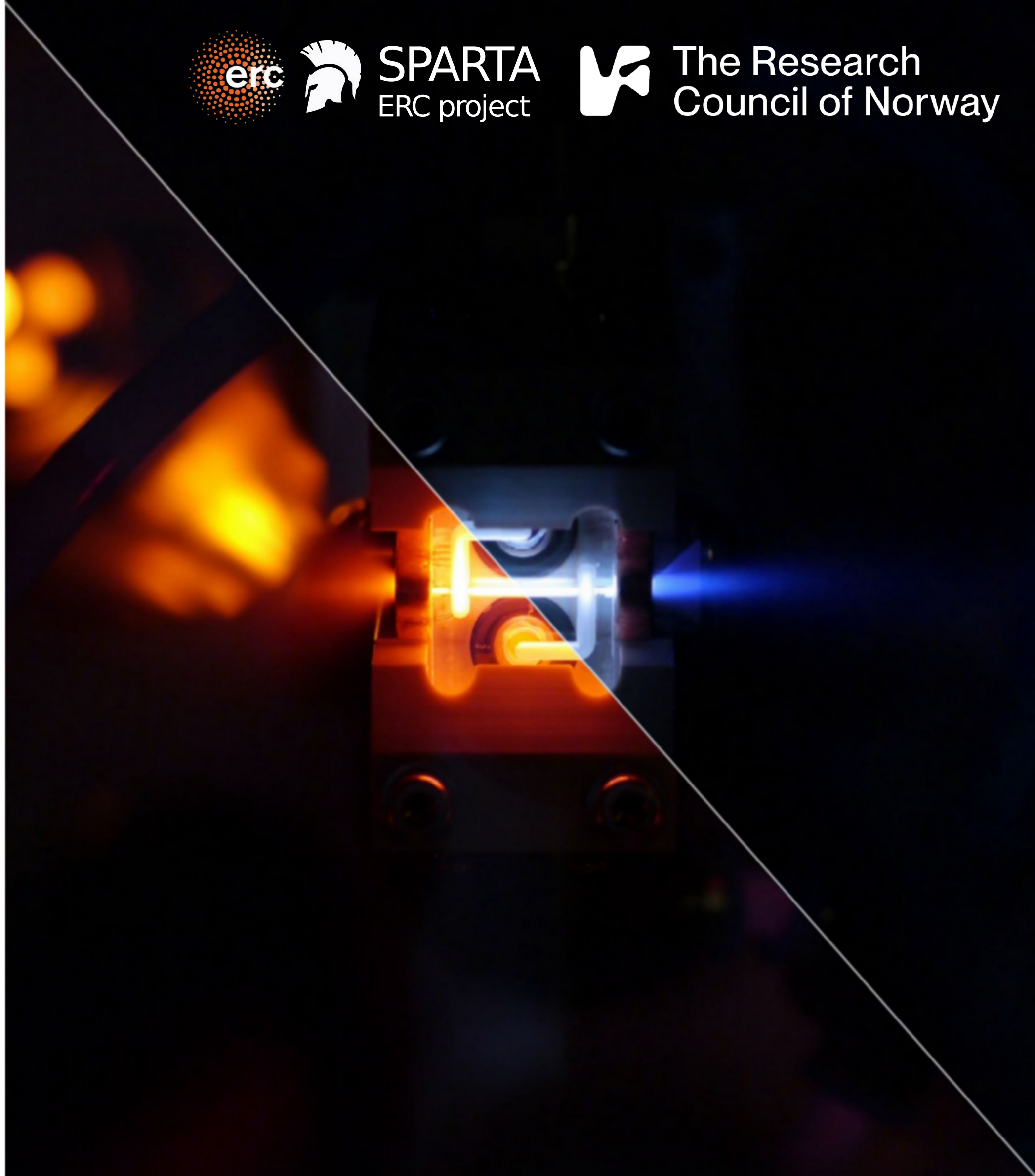
Development of a non-linear plasma lens for achromatic transport



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25^{th} July 2024 | NIU Naperville Conference Center | AAC24

Overview

1. SPARTA project
2. Achromatic staging
3. Non-linear plasma lens
4. Experimental campaign

1. SPARTA

Staging of **P**lasma **A**ccelerators for **R**ealizing **T**imely **A**pplications

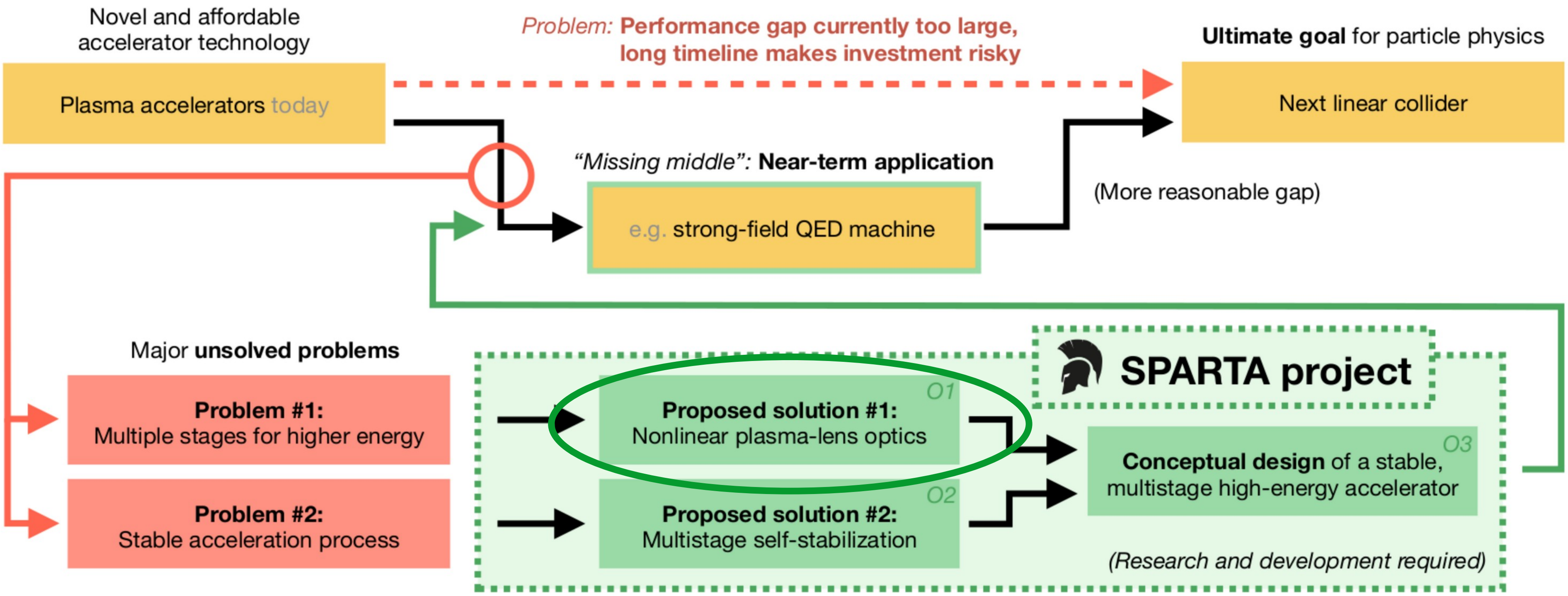
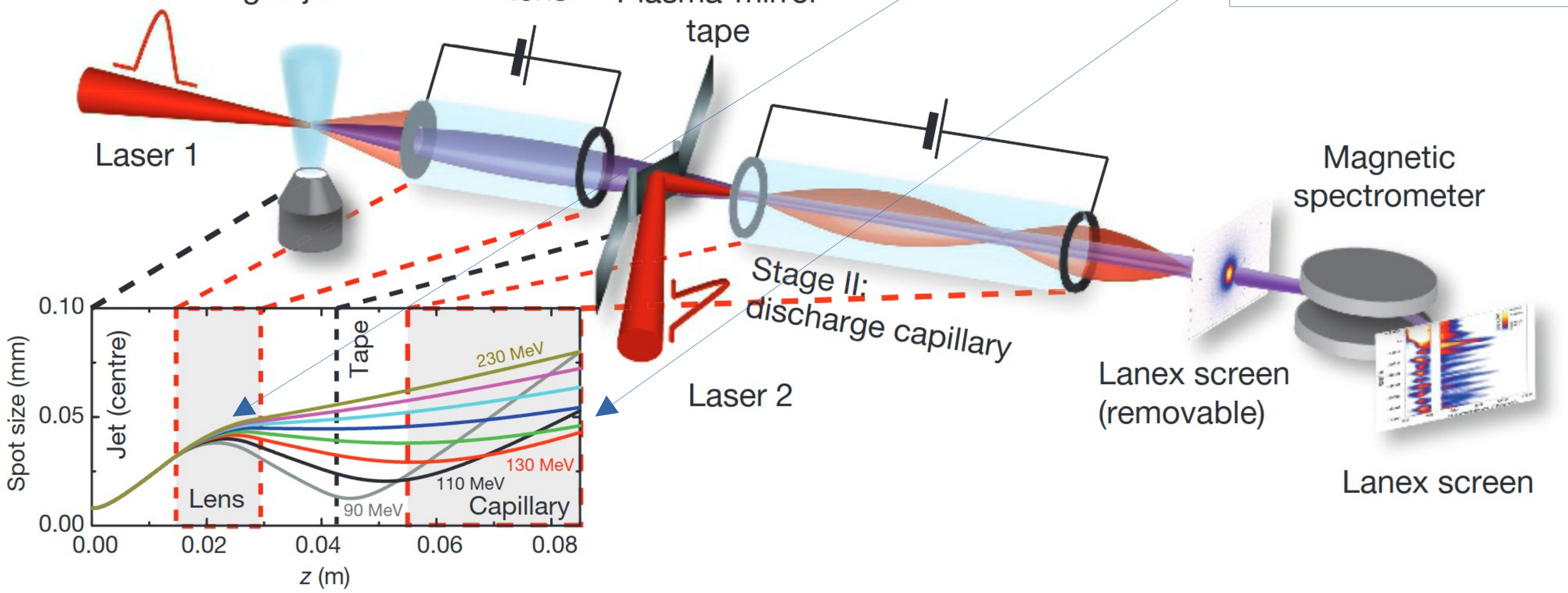


Image credits Carl. A. Lindstrøm

2. Achromatic staging

Motivation for achromatic solution



Chromatic lens

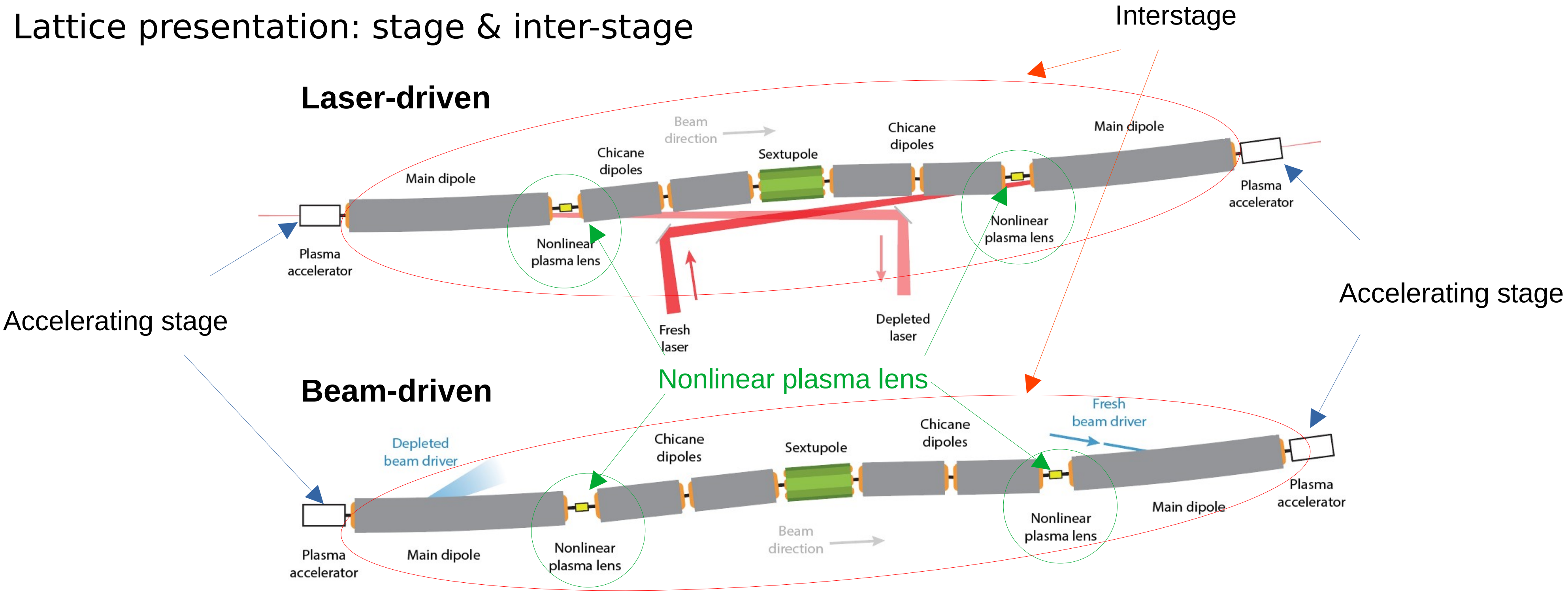
Chromatic staging
→ emittance increase
→ significant charge loss

Experimental setup from Steinke et al. (2016) [1]

[1] Steinke et al. (2016). Multistage coupling of independent laser-plasma accelerators. Nature, 530(7589), 190-193.

2. Achromatic staging

Lattice presentation: stage & inter-stage



Achromatic lattice for laser-driven / beam-driven schemes [2]

[2] Image adapted from a presentation given at the EuroNNAc Special Topics Workshop 2022: Lindstrøm, “Solutions and challenges for a multi-stage plasma accelerator”. Manuscript in preparation.

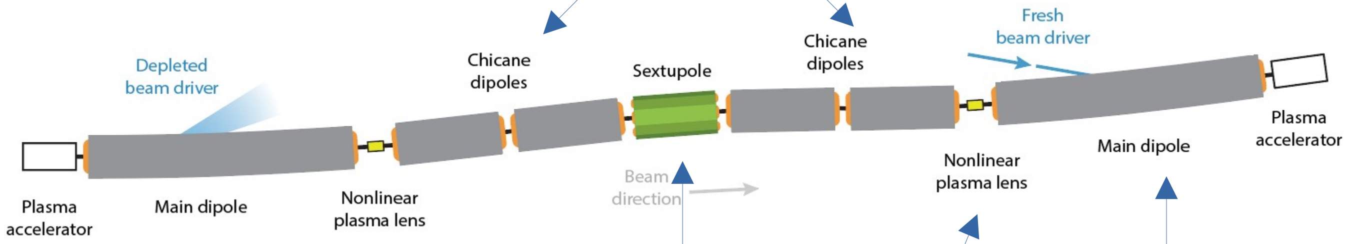
2. Achromatic staging

[2] Image adapted from a presentation given at the EuroNNAc Special Topics Workshop 2022: Lindstrøm, "Solutions and challenges for a multi-stage plasma accelerator". Manuscript in preparation.

Inter-stage: role of each element

Longitudinal phase-space control

Chicane → tunable longitudinal chirp (positive/negative R_{56})
Useful for **self-stabilisation** (2nd axis of SPARTA research)



[2]

Transverse phase-space control

1st dipole: dispersion (in horizontal plane)

1st **non-linear plasma lens:**
Achromatic focusing
+ non-linear kicks

Sextupole: second-order dispersion correction

2nd **non-linear plasma lens:**
Achromatic focusing
+ cancellation of non-linear kicks

2nd dipole: dispersion cancellation (to 2nd order)

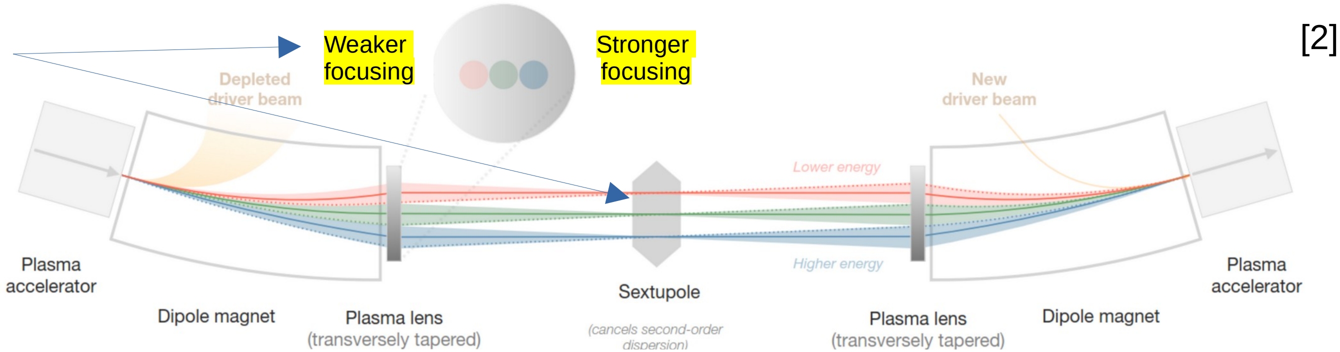
2. Achromatic staging

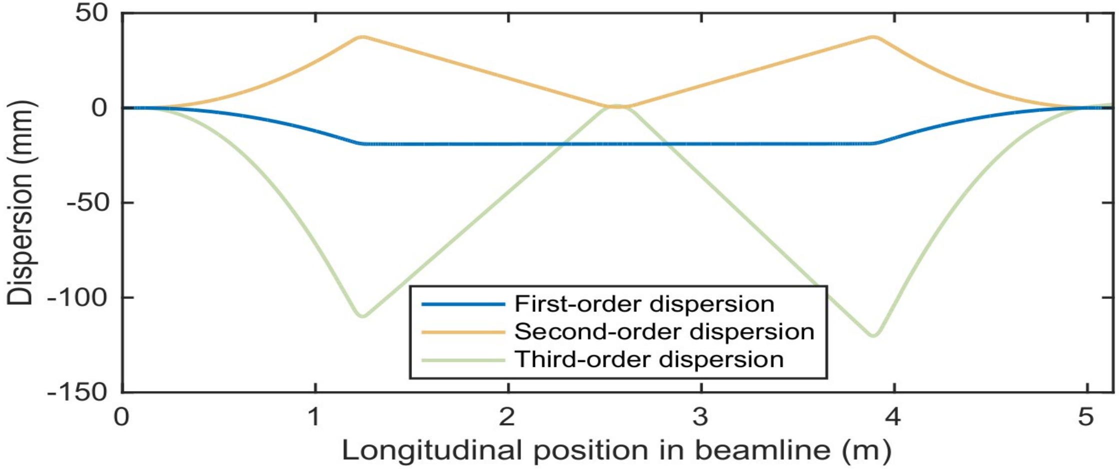
[2] Image adapted from a presentation given at the EuroNNAc Special Topics Workshop 2022: Lindstrøm, “Solutions and challenges for a multi-stage plasma accelerator”. Manuscript in preparation.

Look at the **transverse** phase-space only: **dispersion**

[2]

Achromatic focusing





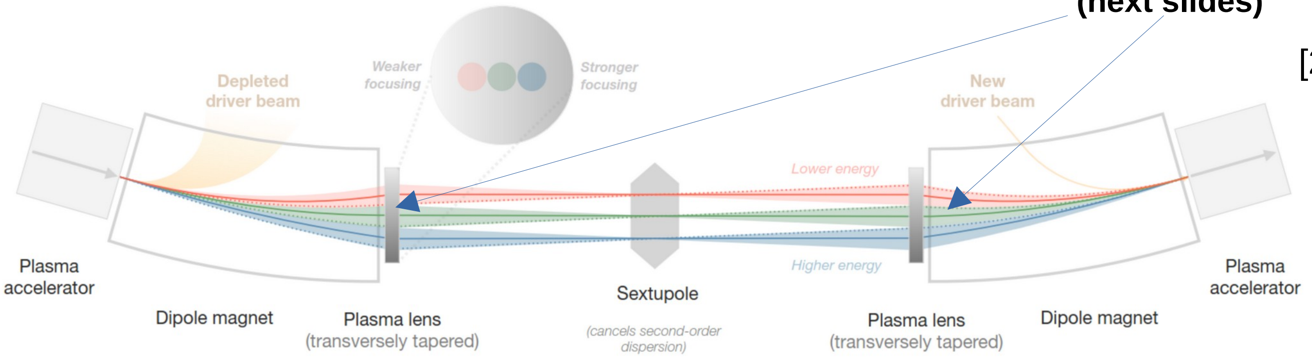
Dispersion:
- canceled up to 2nd order
- both in X and X’

2. Achromatic staging

Look at the **transverse** phase-space only: **emittance**

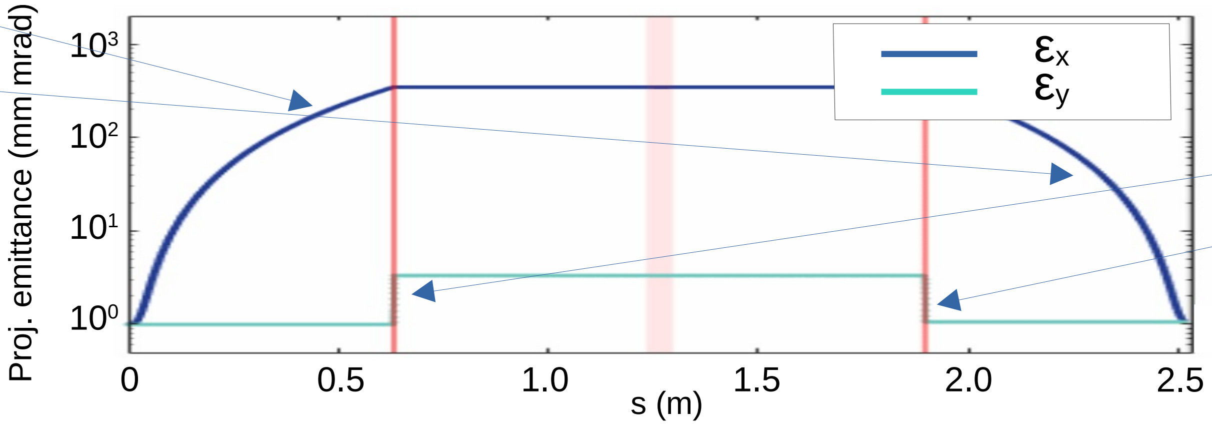
How to make these plasma lenses ? (next slides)

[2]



ε_x increase from dispersion in X

→ canceled there



ε_y increase from lens non-linear focusing (also in X, but not visible in the graph)

→ Canceled here

Emittances preserved

[2] Image adapted from a presentation given at the EuroNNAc Special Topics Workshop 2022: Lindstrøm, "Solutions and challenges for a multi-stage plasma accelerator". Manuscript in preparation.

3. Non-linear plasma lens

What is it ?

> B-field: generated by longitudinal current J_z along z, in capillary of radius R (see [4] for more information)

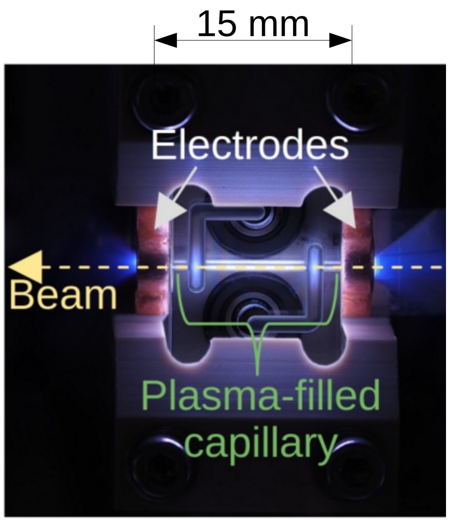
$$\frac{1}{r}\frac{\partial}{\partial r}(r B_\Phi)=\mu_0 J_z(r), \forall r<R$$

> If J_z is uniform: **linear** lens

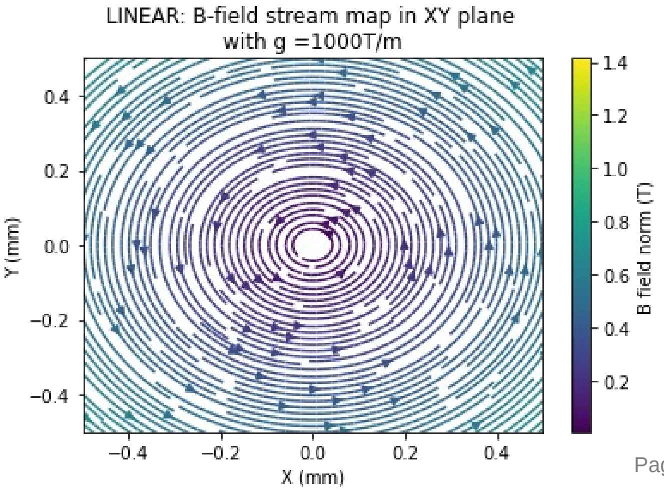
$$g_r=\frac{\partial B_\Phi}{\partial r}=\frac{\mu_0 I_0}{2\pi R^2}=cst$$

> If J_z is non-uniform: **non-linear** lens

$$g_r=f(x,y)$$



Existing plasma lens [3]



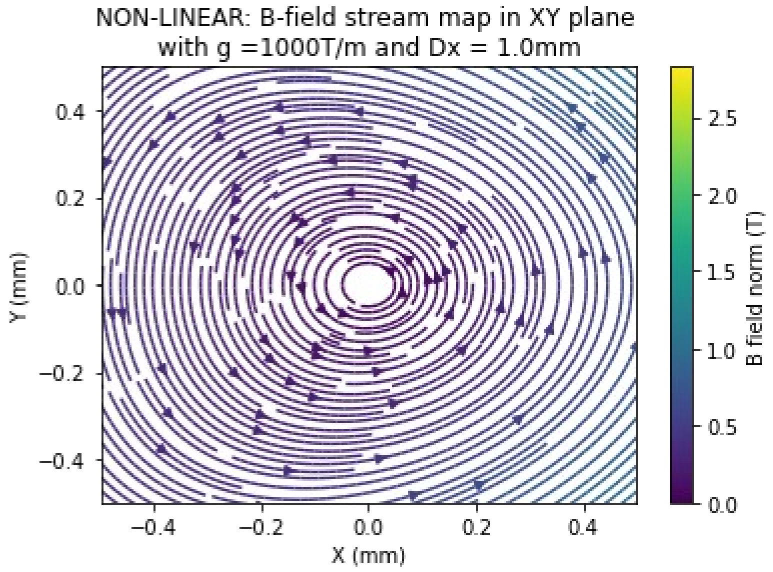
[3] Image adapted from: Sjobak et al. (2021). Strong focusing gradient in a linear active plasma lens. Physical Review Accelerators and Beams, 24(12), 121306.
[4] Lindstrøm, C. A. et al. (2018). Emittance preservation in an aberration-free active plasma lens. Physical review letters, 121(19), 194801.

3. Non-linear plasma lens

How to make the **non-radially-symmetric** B distribution?

[5] Kunkel, W. B. (1981). Hall effect in a plasma. American Journal of Physics, 49(8), 733-738.
[6] S. M. **Mewes** (DESY), G. J. **Boyle** (James Cook University) et al., Demonstration of tunability of HOFI waveguides via start-to-end simulations. Phy

- Motivation: article by Kunkel - **Hall effect in a plasma** - (1981) [5]
- Working principle:
  - External *B*-field (along Y for example)
  - Internal *E*-field (reaction of the plasma along X)
  - Non-radially symmetric n_e distribution
  - Non-radially symmetric J_z distribution (J depends on n_e)
  - **Non-radially symmetric (B_x, B_y) distribution**



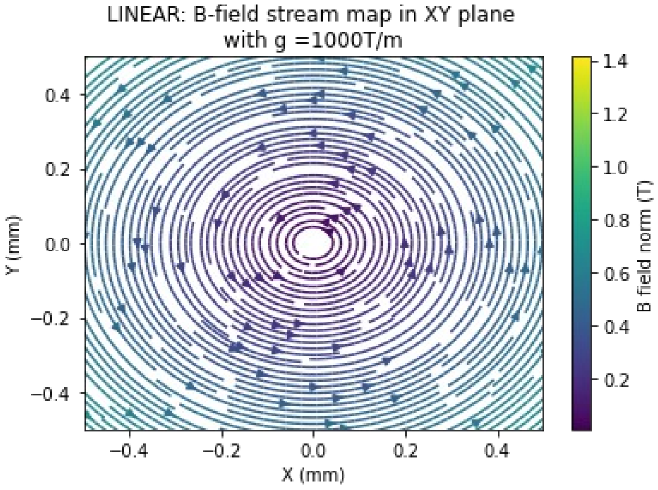
- Seems feasible according to Kunkel's article (with $B \propto 10\,mT$)
- Hydrodynamics simulations currently performed with the COMSOL module by **Mathis Mewes (DESY)** et al. based on [6]

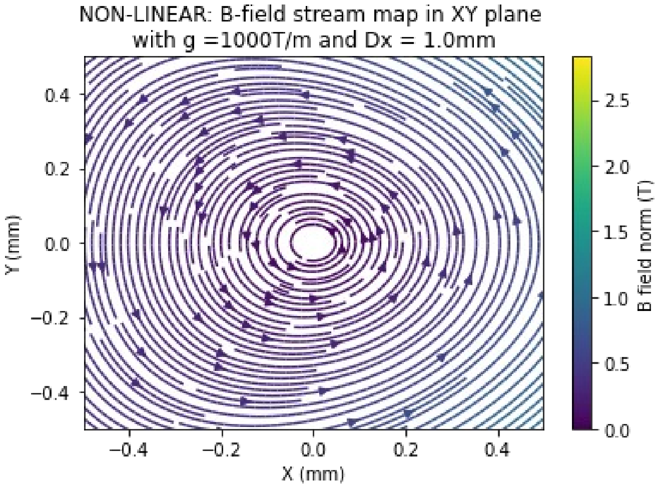
3. Non-linear plasma lens

Which B-field distribution in the lens ?

LINEAR
$$\begin{cases} B_x = -g\,y \\ B_y = g\,x \end{cases}$$

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





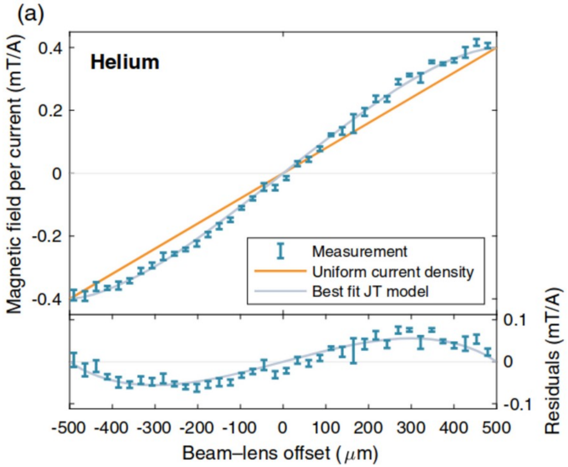
- Derived using:
  - D_x (given by the beam dispersion entering the lens)
  - *g:* desired focusing strength
- Ensuring that: *div(B̲) = 0*

Does not exist yet

3. Non-linear plasma lens

Is a non-linear B distribution feasible ?

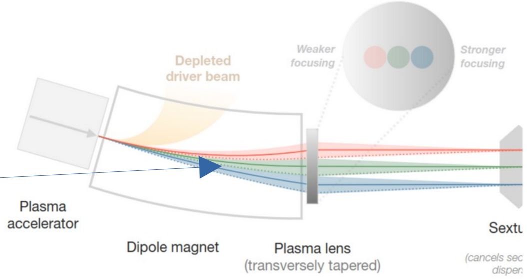
- Non-linear B-field distribution **already experimentally observed**
- Origins:
  - Non-uniform T distribution
  - Non-uniform conductivity
  - Non-uniform J_z distribution
  - **Non-linear** B-field distribution (= **dispersive**)



Experimental measurement of non-linear focusing strength (*r*-dependence) [4]

- **Comment**:
  - this observed non-linearity is **radially symmetric…**

    But we only want to disperse in X



[2]

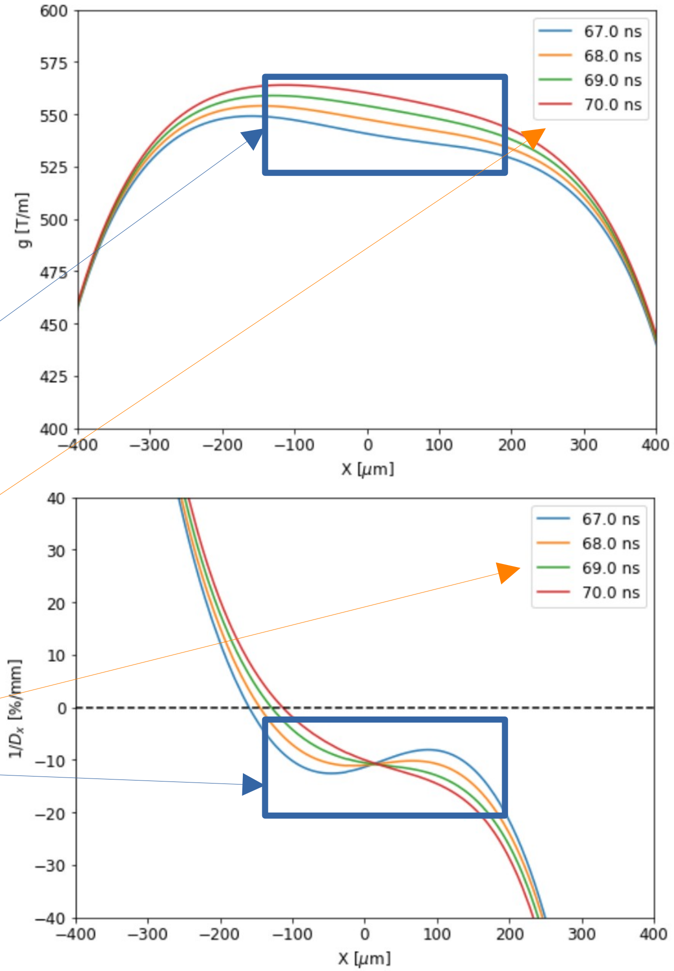
[2] Image adapted from a presentation given at the EuroNNAc Special Topics Workshop 2022: Lindstrøm, "Solutions and challenges for a multi-stage plasma accelerator". Manuscript in preparation.
[4] Lindstrøm, C. A. et al. (2018). Emittance preservation in an aberration-free active plasma lens. Physical review letters, 121(19), 194801.

3. Non-linear plasma lens

First MHD results

- Simulations:
  - in 1D (for the moment) only in X-direction (infinite in Y and Z), with 1 mm size
  - with *H_2* (for the moment; heavier-species model under construction)
- **Objective**: validate the **Hall effect** using an external B-field, resulting in
  - ***g*** ∈ [200 - 1000] T/m
  - ***D_x*** = 10 mm (***$1/D_x$*** = 10%/mm)
- **First results**
  - Good results for ***g*** and ***$1/D_x$***
  - Too short operating window (few ns)
  - Heavier species should make the dynamics slower (slower thermal exchanges)

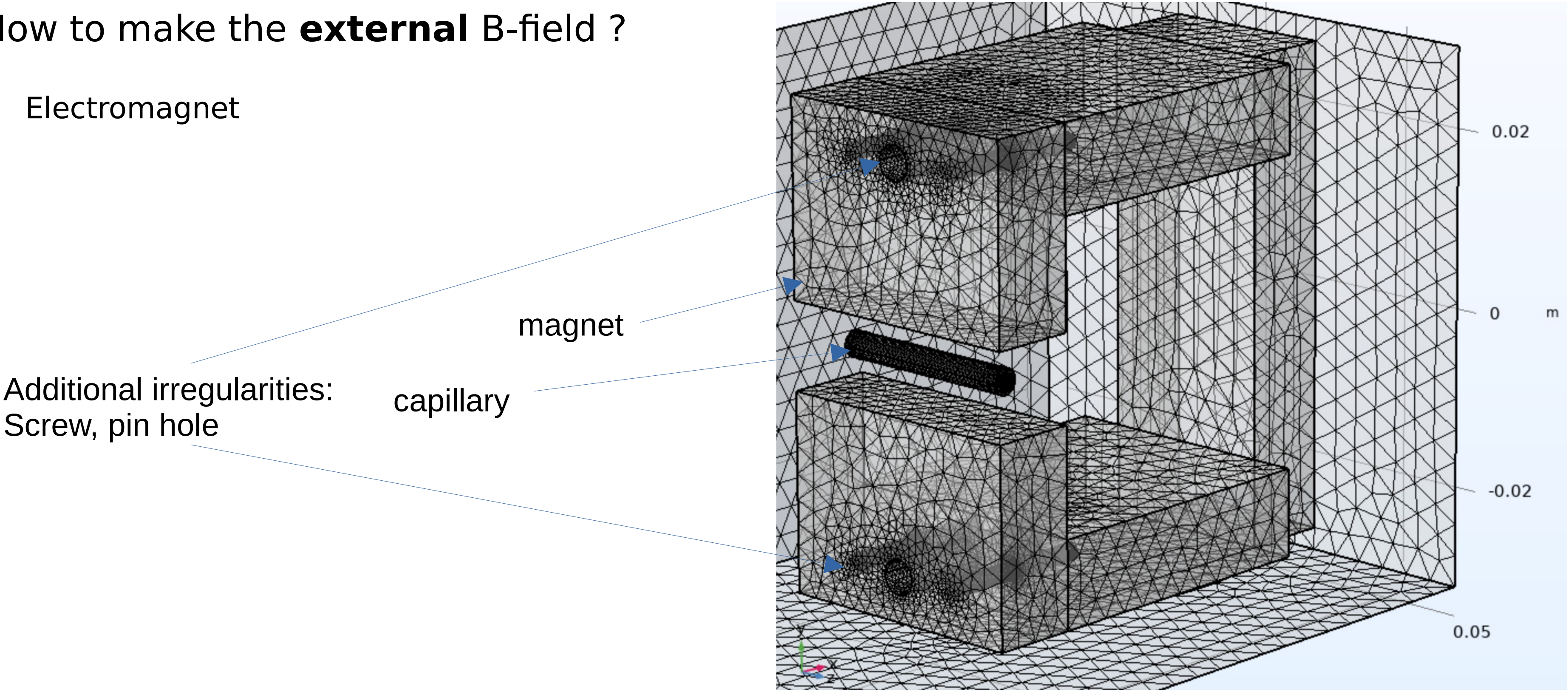
1D simulation of *g* and *D_x* across the capillary with *H_2* at *13* mbar, B_{ext} = *10* mT



3. Non-linear plasma lens

How to make the **external** B-field ?

- Electromagnet

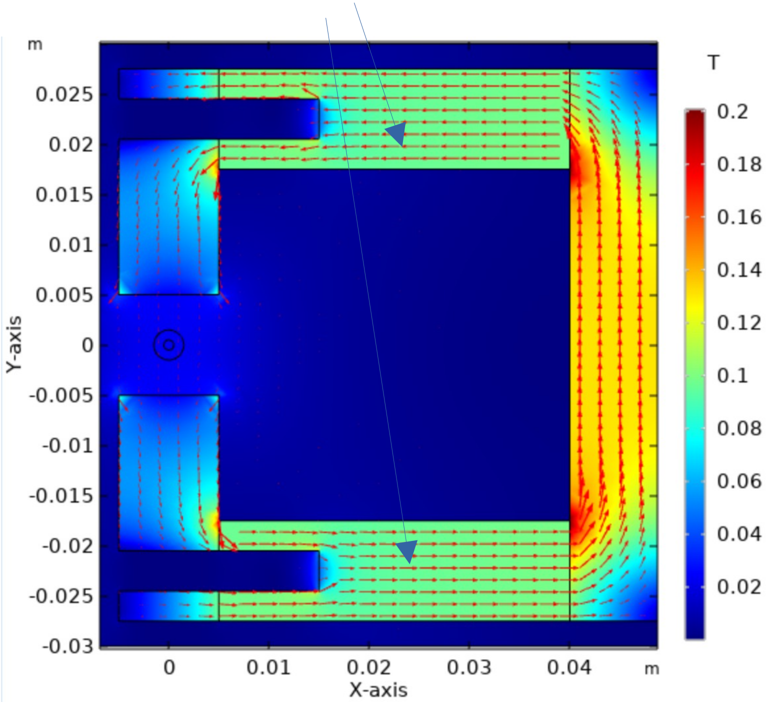


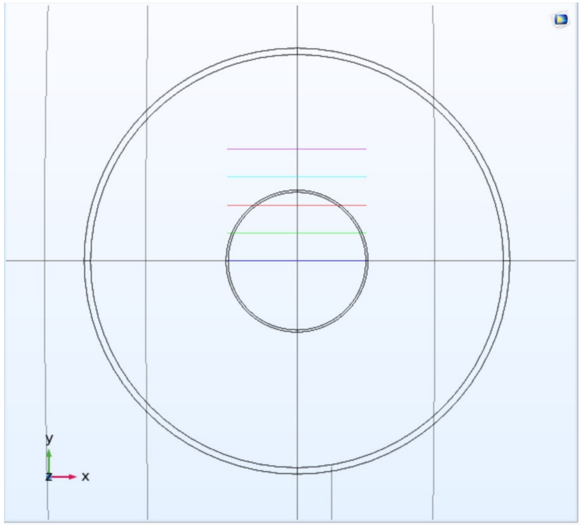
COMSOL model,
with magnet and 20 mm-long capillary

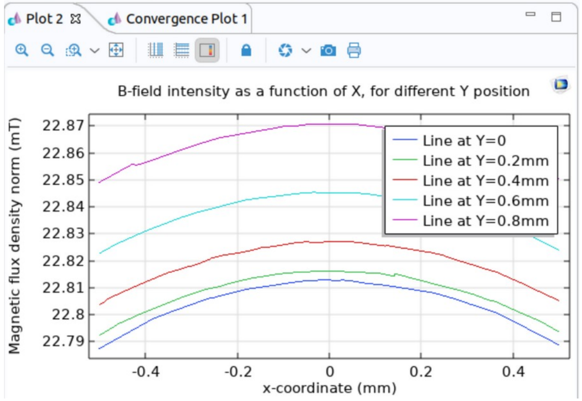
3. Non-linear plasma lens

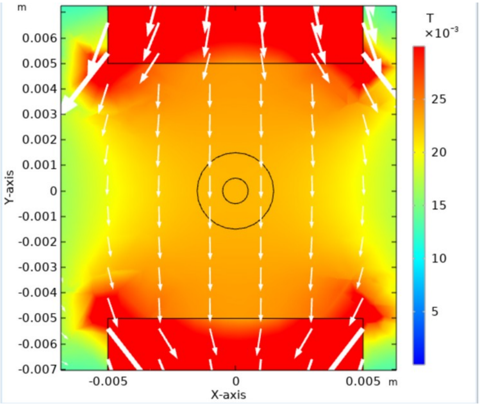
How to make the **external** B-field ?

Assuming 0.1T magnetisation





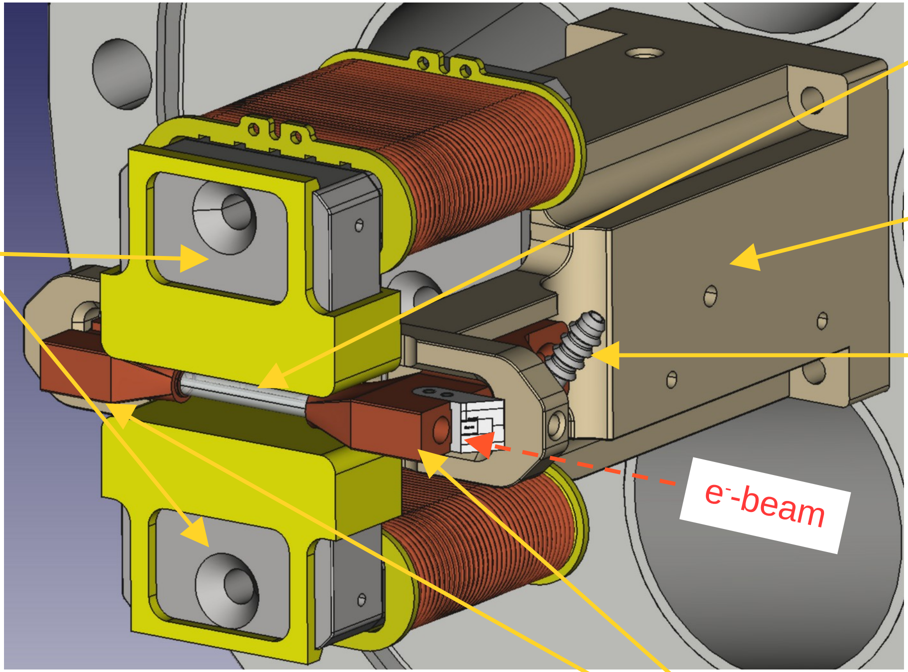




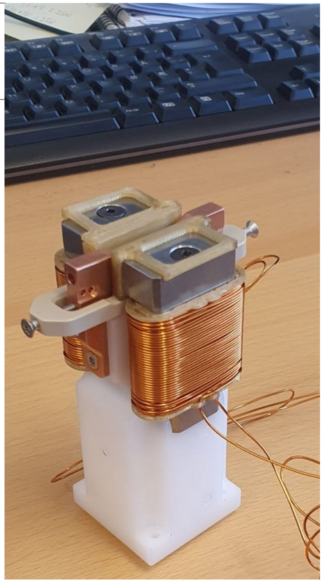
Uniform **<u>B</u>**
in the capillary

3. Non-linear plasma lens

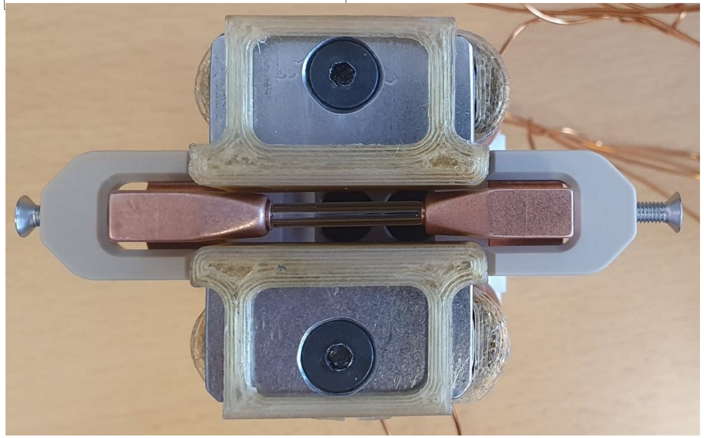
Design



Plasma lens design
15 Jul. 2024
(Credits: I-Lab)



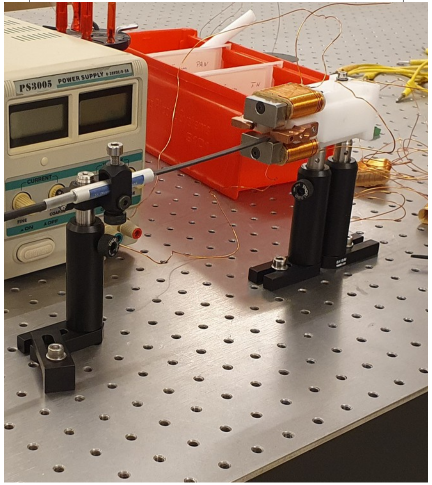
First built prototype,
5 Jul. 2024



First built prototype,
5 Jul. 2024
(XY-plane)

4. Experimental campaign

Current B-field measurements at UiO

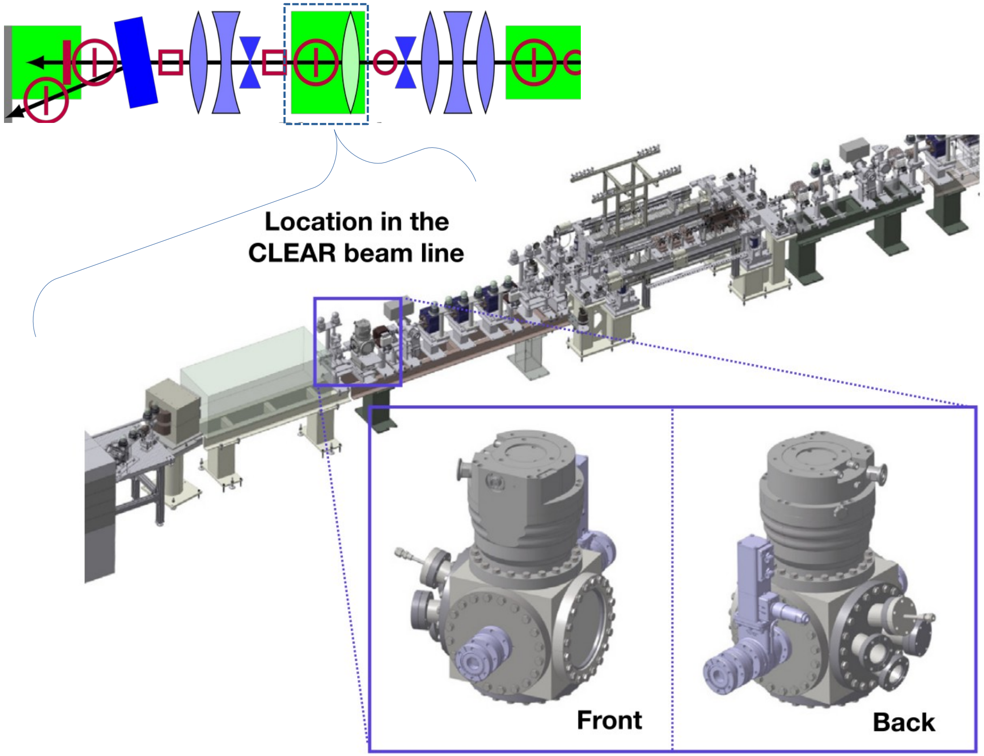


Objectives

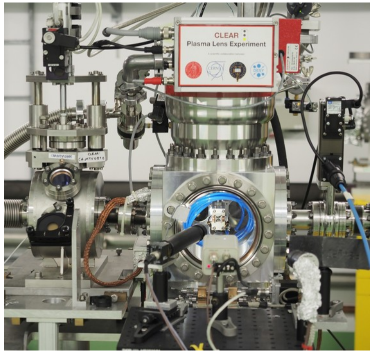
- **Design preliminary tests** at UiO (everything that does not require an accelerator):
  - Assembly (dimensions, materials, technical solutions selected)
  - Electromagnet (**external** B-field measurement)
- **Real operating condition** tests (accelerator facilities):
  - Short term: **characterise the lens** = map the **total** B-field in the XY-plane → **CLEAR (see next slides)**
  - Mid term: prove the non-linear lensing effect (1 lens only)
  - Long term: build an entire interstage (dipole+lens+sextupole+lens+dipole) to test **XY emittance preservation** & **charge preservation**.

4. Experimental campaign

Existing CLEAR facility and set-up



> **Beam parameters:**
- 60-200 MeV,
- 10 pC – 50 nC / pulse,
- 1 – 100 bunches / pulse,
- 1 – 10 pulses/s,
- pulse length 1 ps – 50 ns,
- Focus down to 50x50 µmxµm.



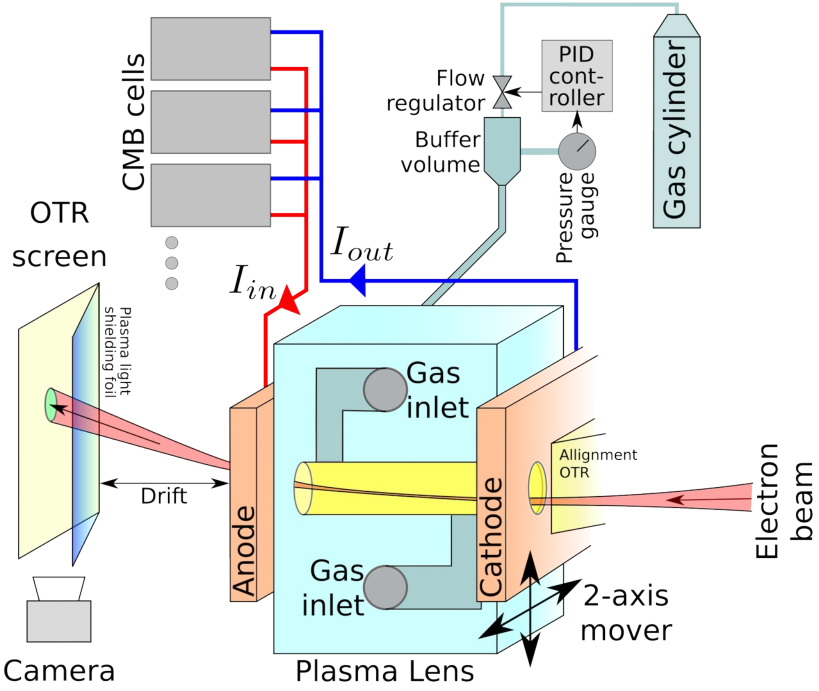
Existing **Plasma Lens Experiment** set-up at CLEAR [7]

[7] Credits to Kyrre Sjøbæk

4. Experimental campaign

2024 at CLEAR

- The CLEAR Plasma Lens Experiment (continuation)
- Collaboration with:
- **Objective: characterise the lens** = measure the **total** <u>B</u> by moving the lens relatively to the beam



Schematic of the CLEAR Plasma Lens Experiment [8]

[8] Sjobak et al. (2021). Strong focusing gradient in a linear active plasma lens. Physical Review Accelerators and Beams, 24(12), 121306.

Conclusion

- **SPARTA** project:
  - Several objectives, among which: **achromatic** staging
  - **Non-linear plasma lens** is a key element
- Achromatic staging:
  - Theoretically feasible
  - Should solve Steinke et al. (2016) issues of charge loss
- Non-linear plasma lens:
  - Development at UiO (design)
  - Collaboration with DESY for MHD simulations
- **Experimental campaign**:
  - UiO: experiments not requiring an accelerator facility (prototype development, electromagnet-generated B-Field measurement)
  - **CLEAR** (2024): first non-linear plasma lens characterisation
- Other developments:
  - Mid term objective: **prove achromatic lensing effect** (1 lens only)
  - Long term objective: **full achromatic staging** (2 lenses)

Acknowledgments

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