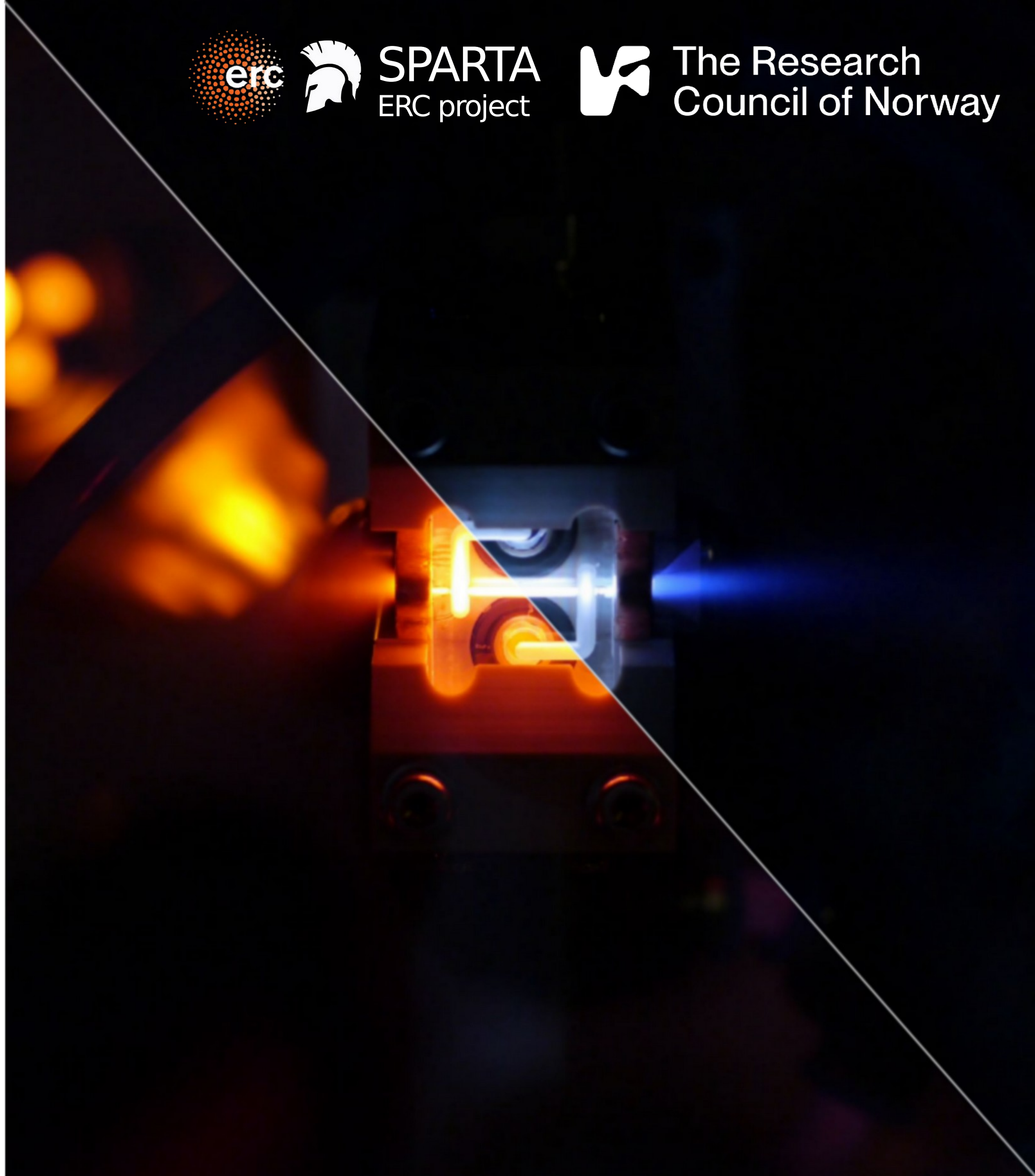
UNIVERSITY OF OSLO

Development of a non-linear plasma lens for achromatic transport

Pierre DROBNIAK
Department of Physics, University of Oslo

25th July 2024 | NIU Naperville Conference Center | AAC24



Overview

Overview

1. SPARTA project

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2. Achromatic staging

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2. Achromatic staging
3. Non-linear plasma lens

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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

1. SPARTA

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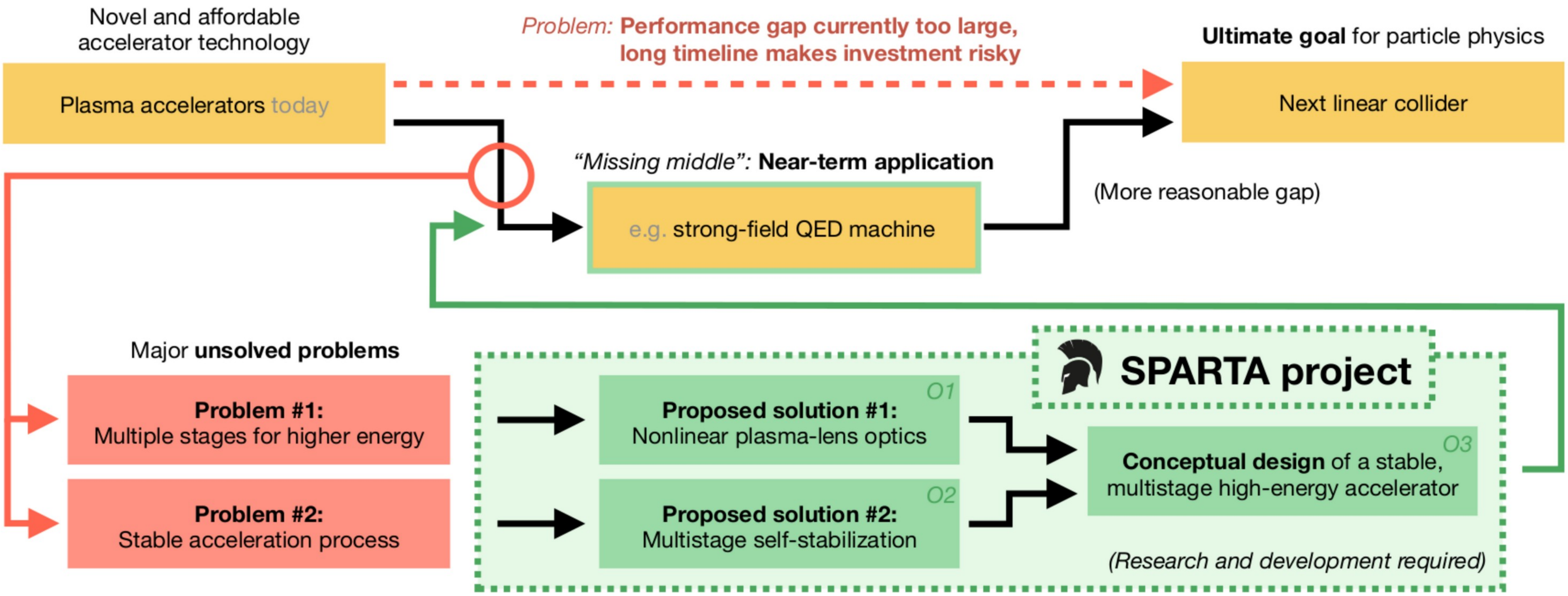

Image credits Carl. A. Lindstrøm

1. SPARTA

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

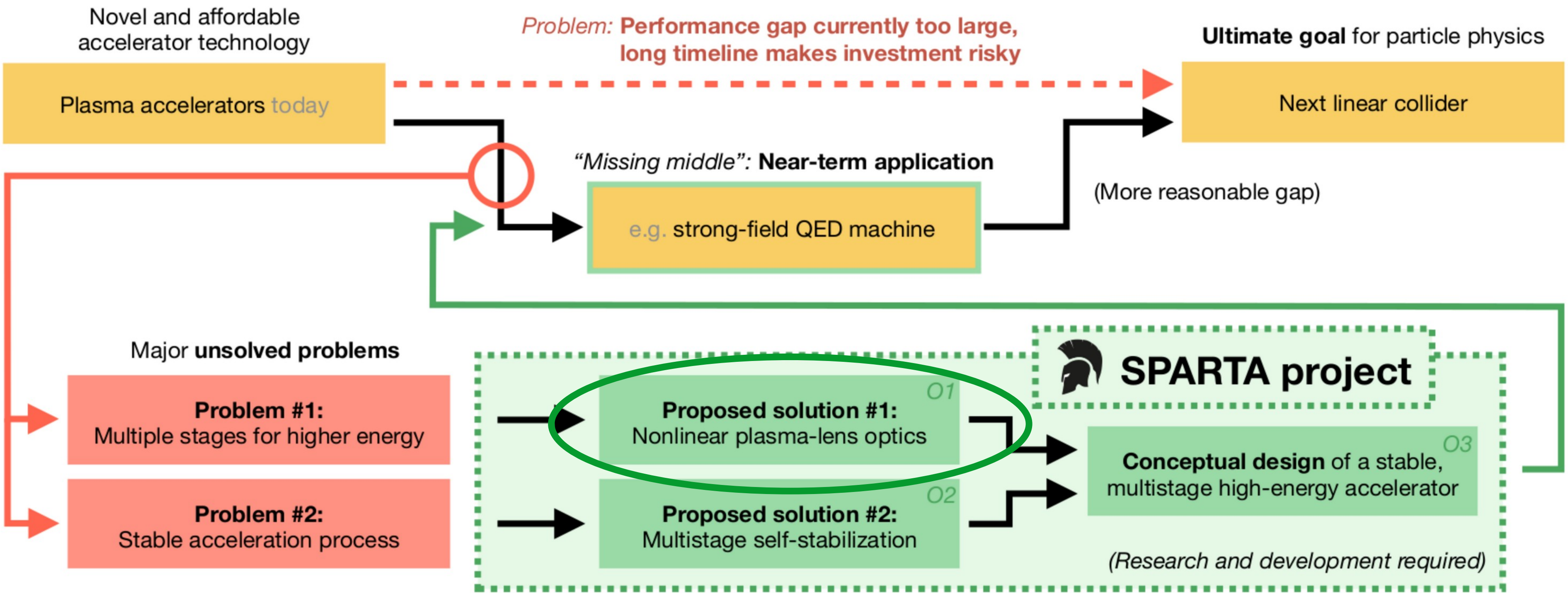

Image credits Carl. A. Lindstrøm

2. Achromatic staging

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Motivation for achromatic solution

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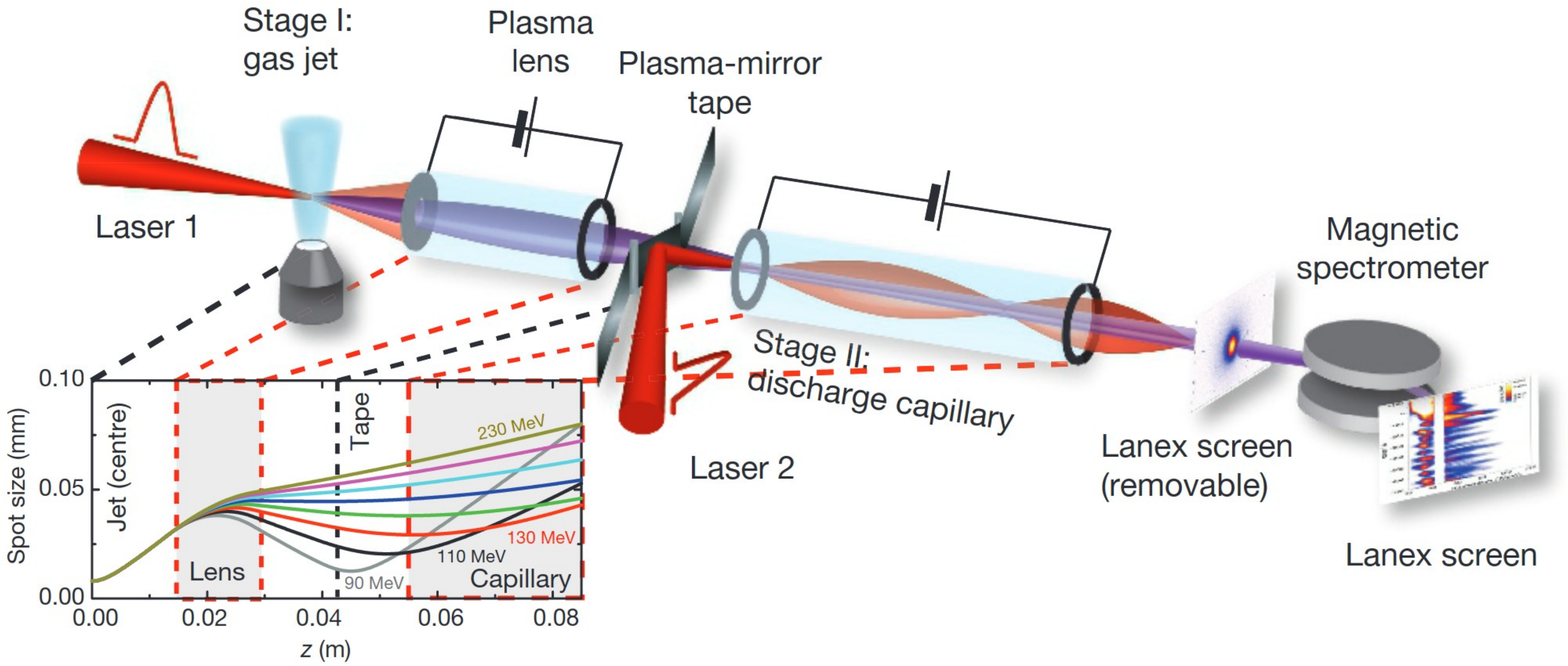

Experimental setup from Steinke et al. (2016) [1]

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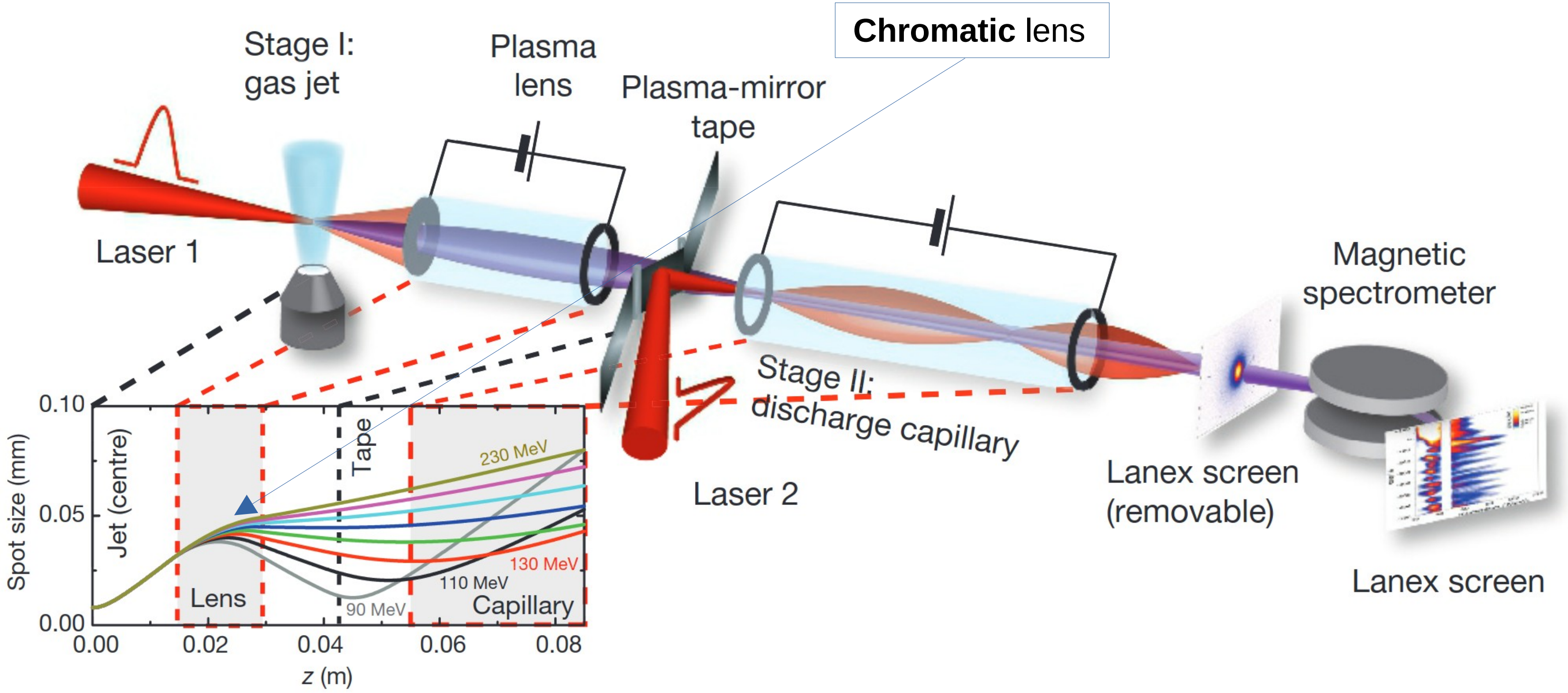
Motivation for achromatic solution



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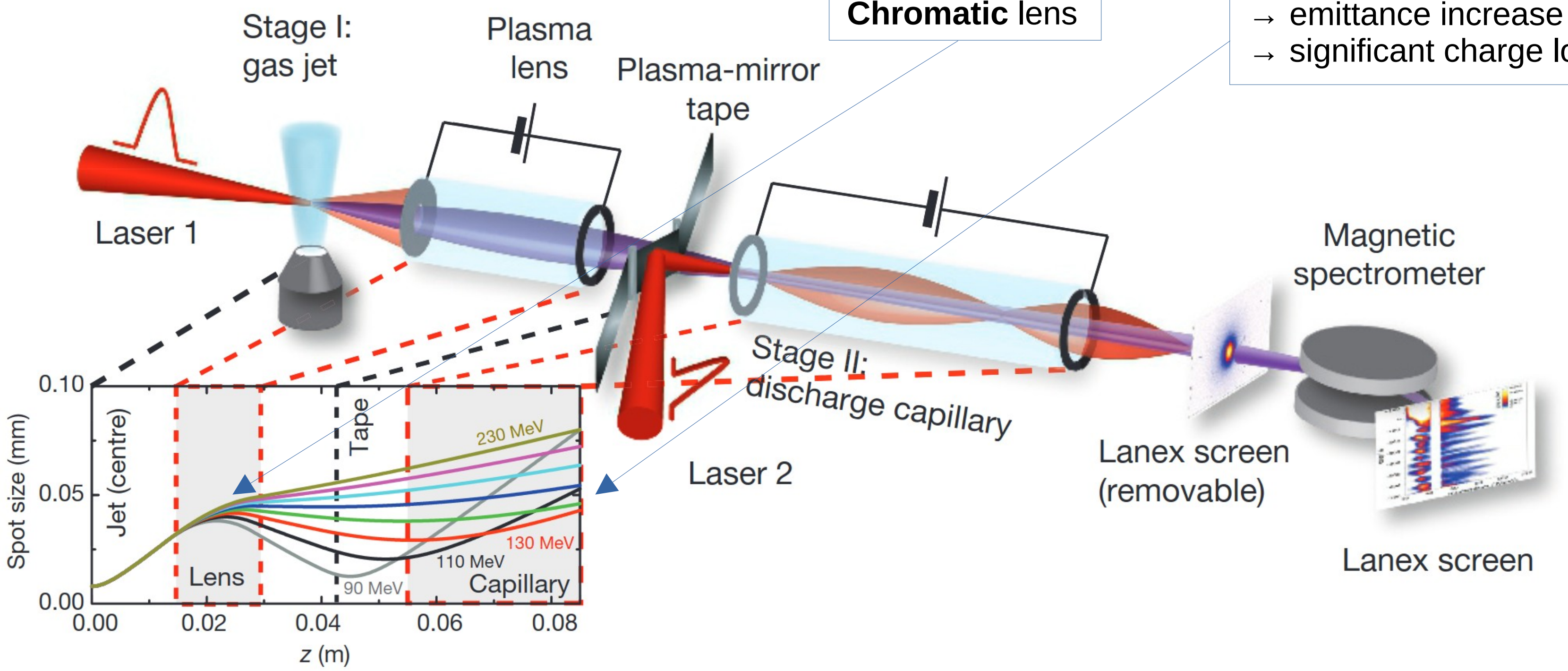
Motivation for achromatic solution

Chromatic staging
→ emittance increase
→ significant charge loss



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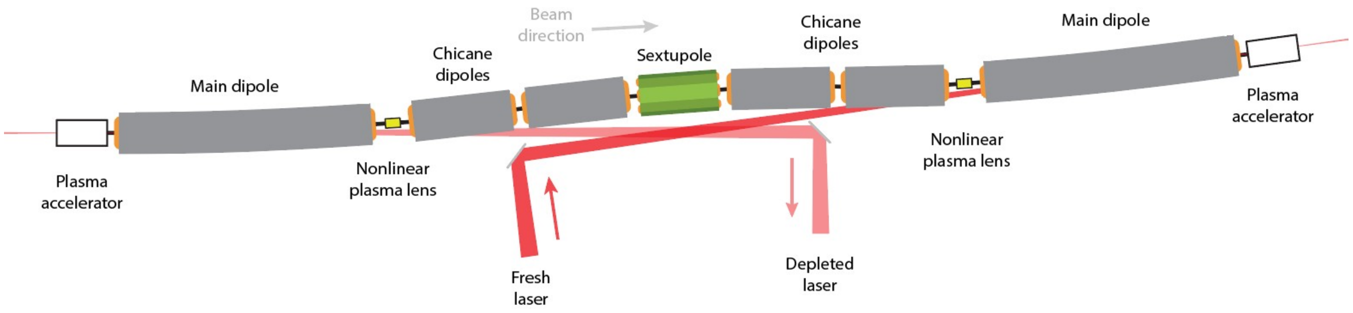
Lattice presentation: stage & inter-stage

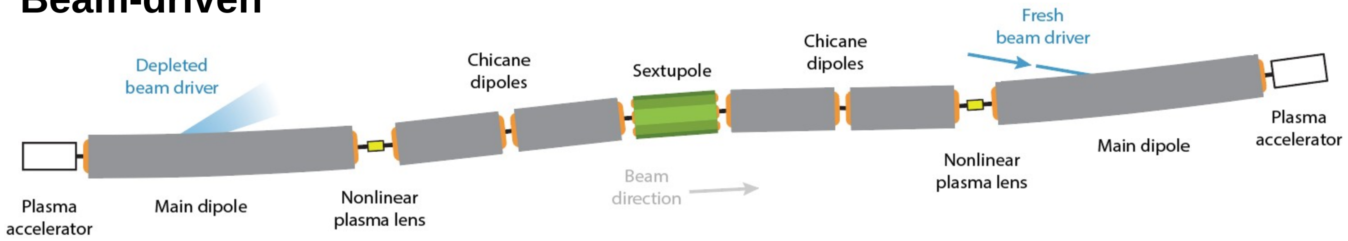
2. Achromatic staging

Lattice presentation: stage & inter-stage

Laser-driven



Beam-driven



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.

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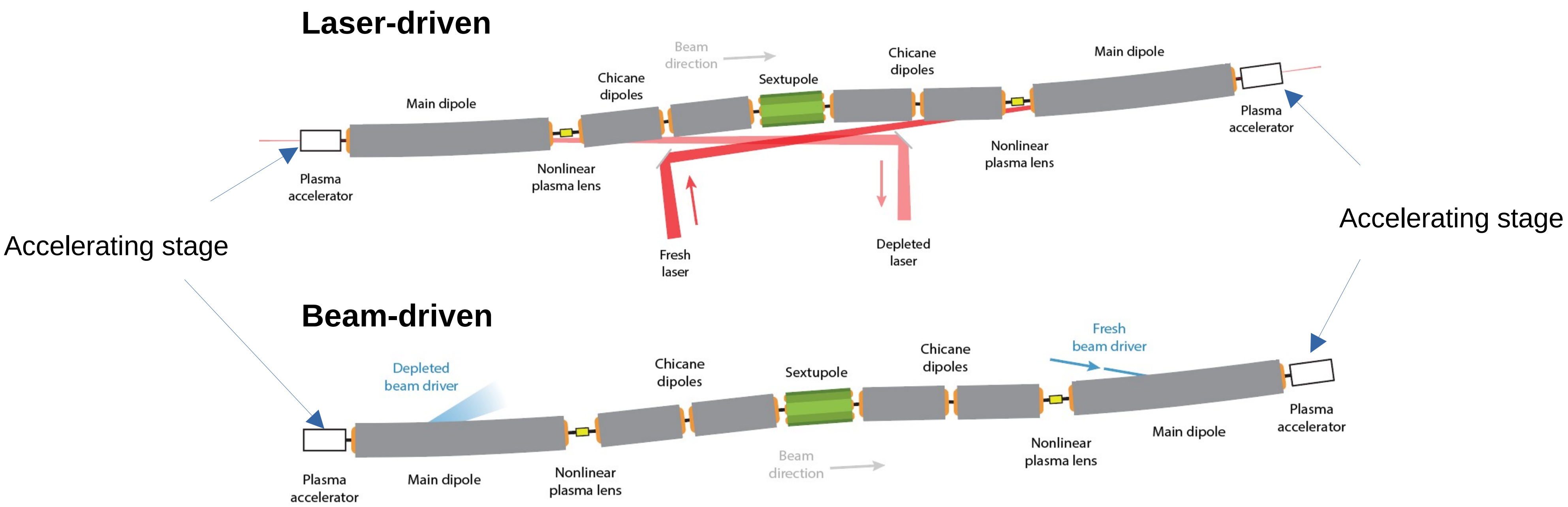
Lattice presentation: stage & inter-stage



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Lattice presentation: stage & inter-stage

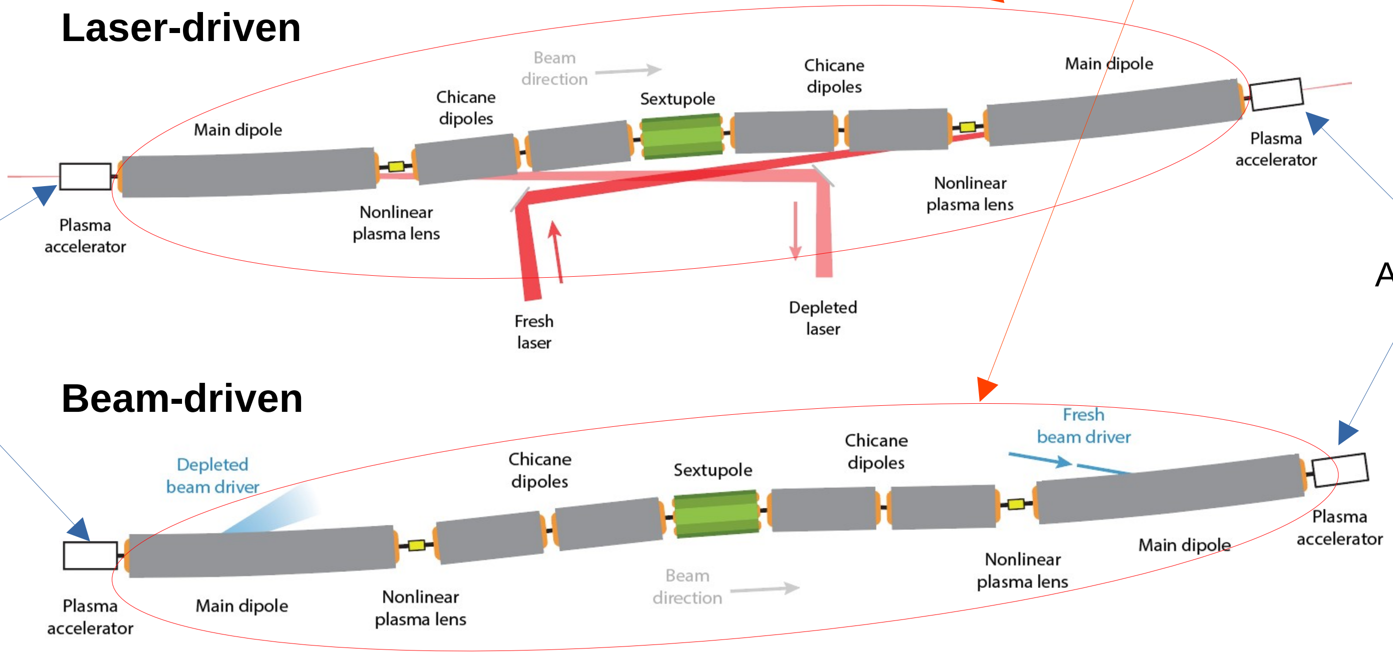
Interstage

Accelerating stage

Accelerating stage

Laser-driven

Beam-driven



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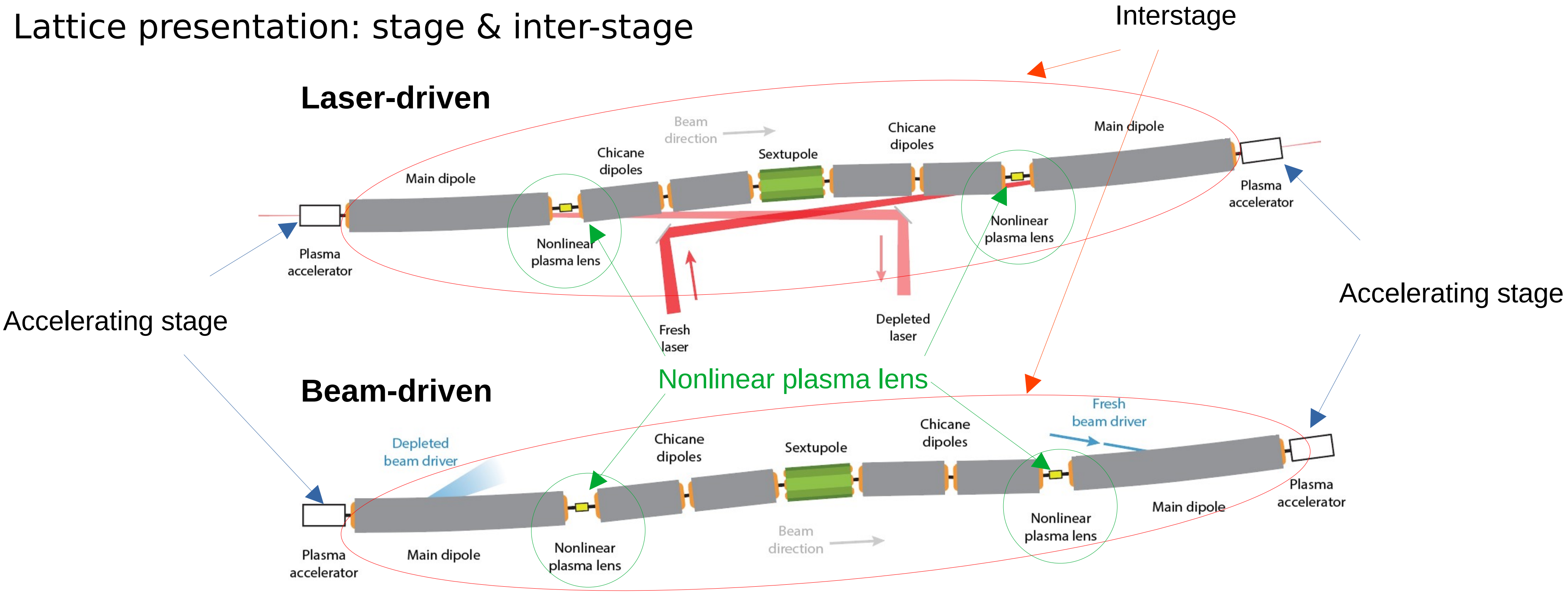

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Inter-stage: role of each element

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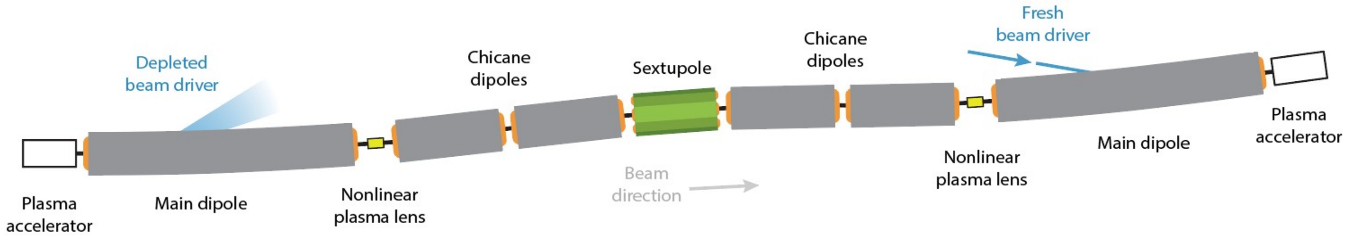

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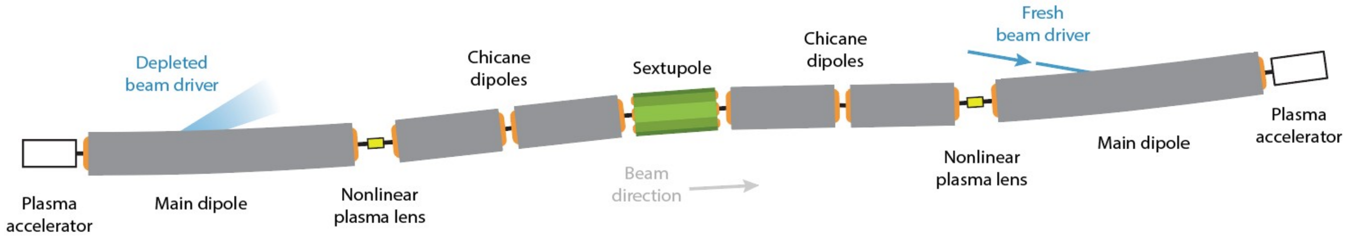
Inter-stage: role of each element

Longitudinal phase-space control



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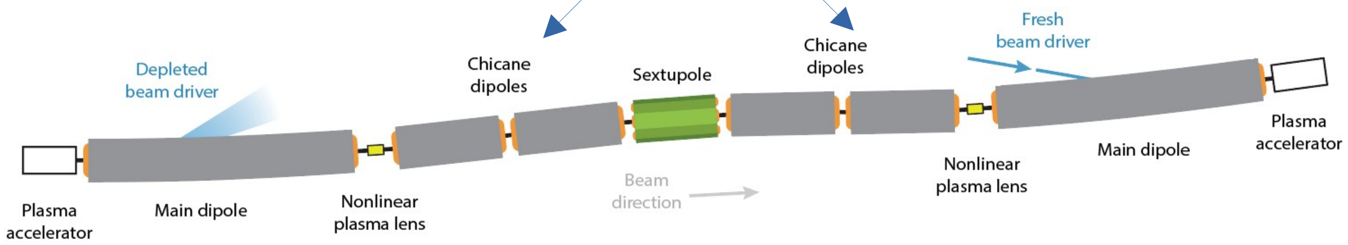
Inter-stage: role of each element

Longitudinal phase-space control

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



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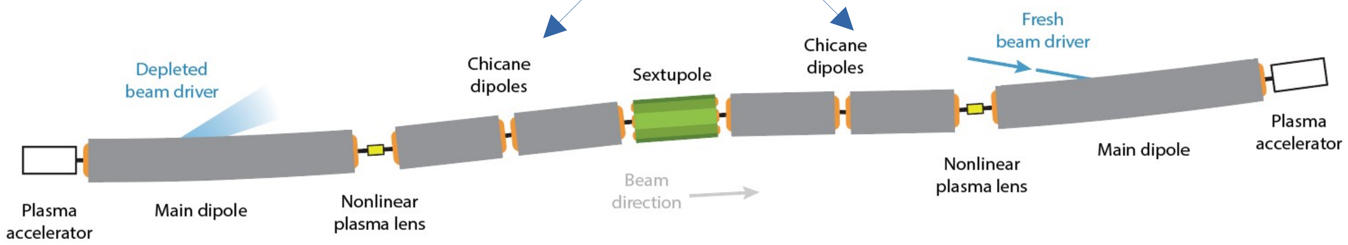

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Transverse phase-space control

2. Achromatic staging

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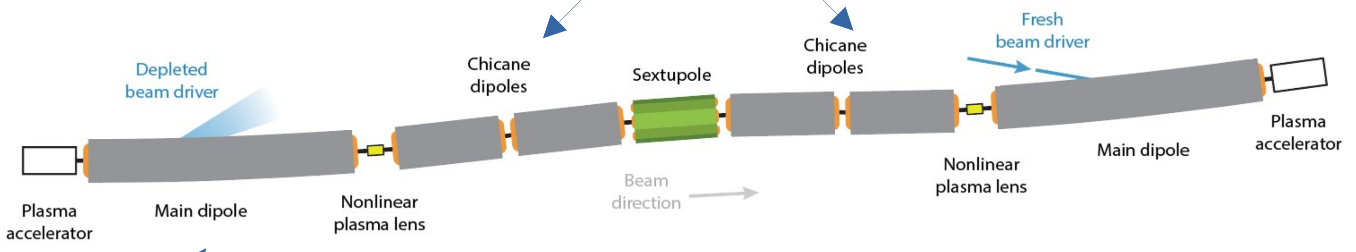

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Transverse phase-space control

1st dipole: dispersion
(in horizontal plane)

2. Achromatic staging

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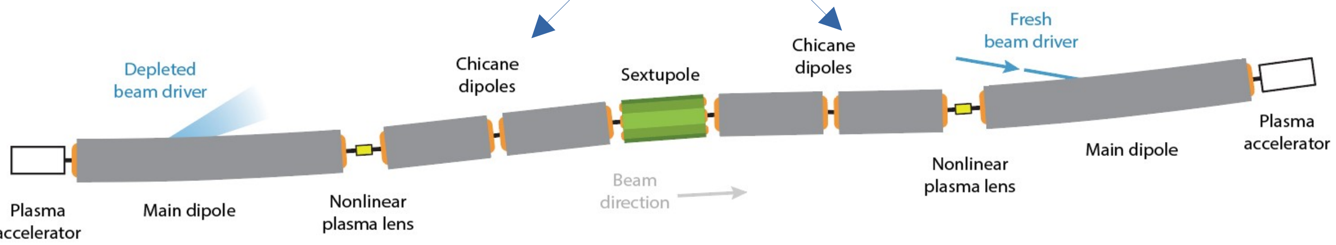

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1st **non-linear plasma lens:**
Achromatic focusing
+ non-linear kicks

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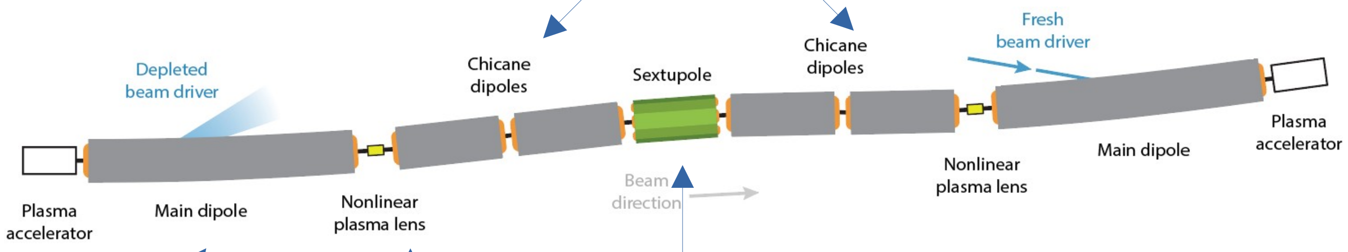

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Transverse phase-space control

1st dipole: dispersion (in horizontal plane)

Sextupole: second-order dispersion correction

1st **non-linear plasma lens:**
Achromatic focusing
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2. Achromatic staging

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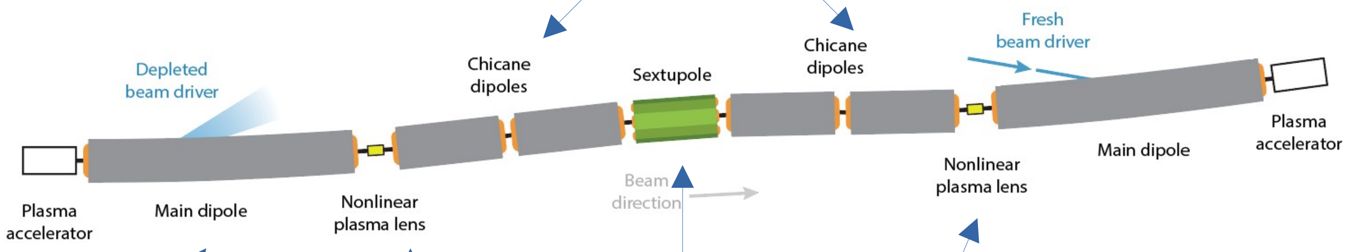

Transverse phase-space control

1st dipole: dispersion (in horizontal plane)

Sextupole: second-order dispersion correction

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

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

2. Achromatic staging

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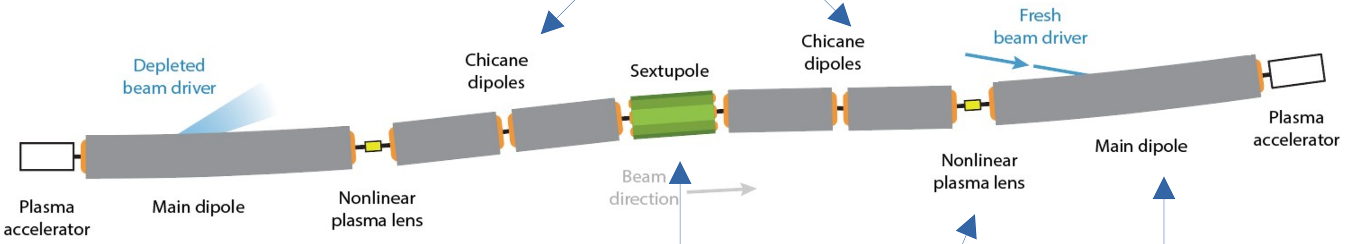

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1st dipole: dispersion (in horizontal plane)

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

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

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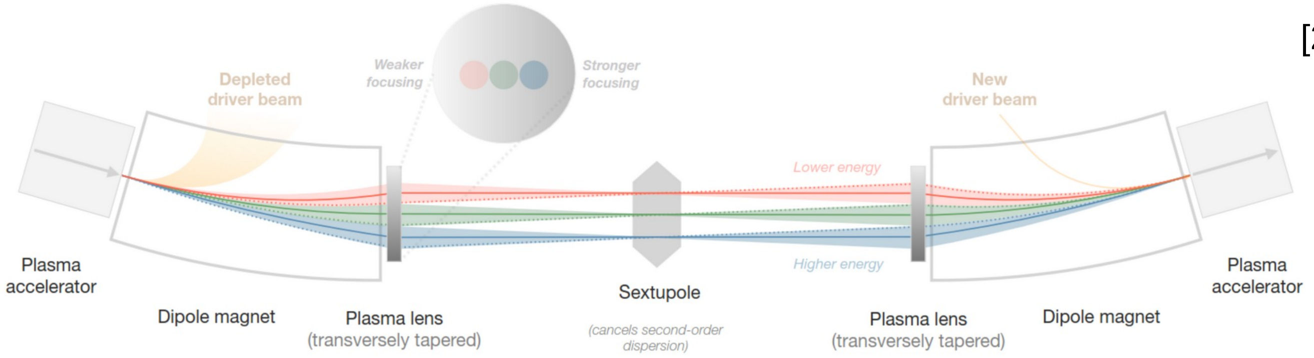

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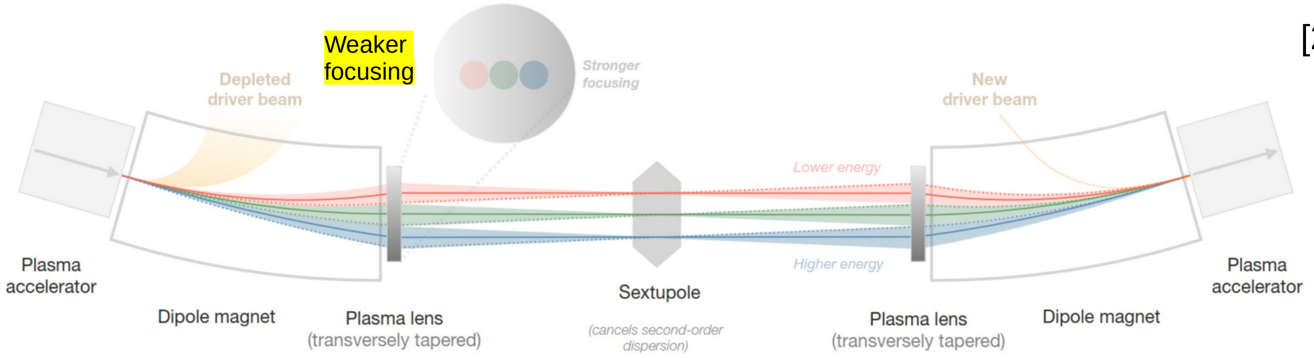

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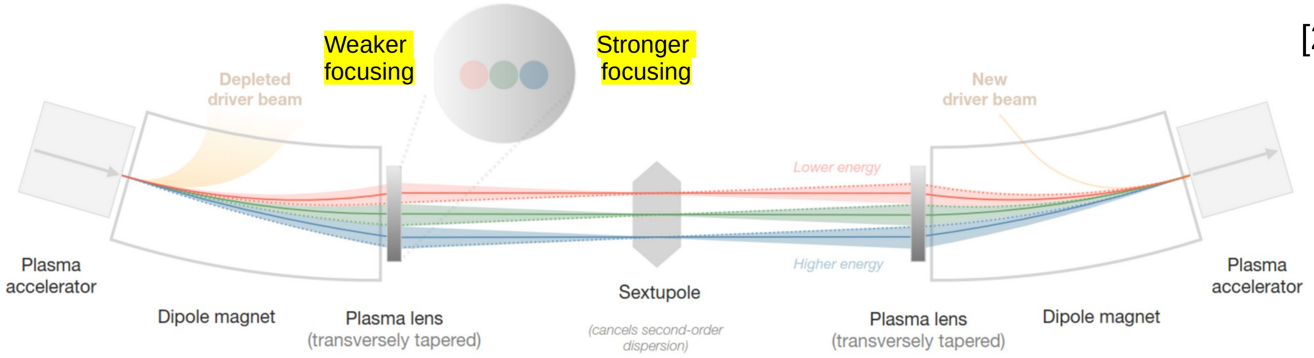

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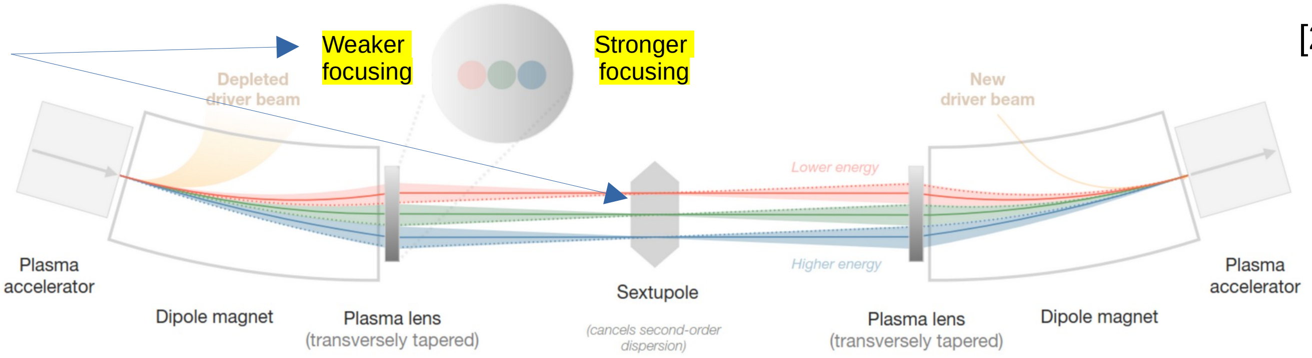
Achromatic focusing



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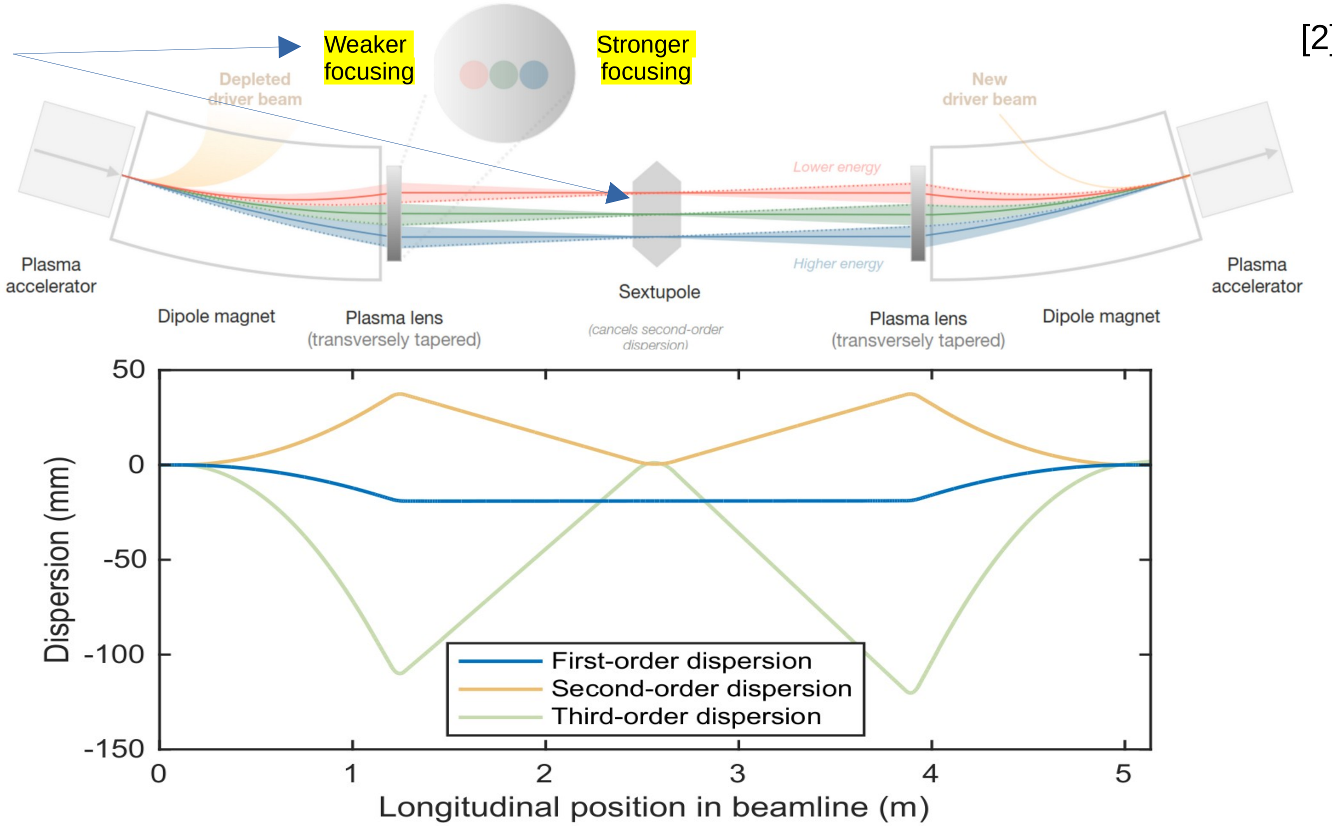

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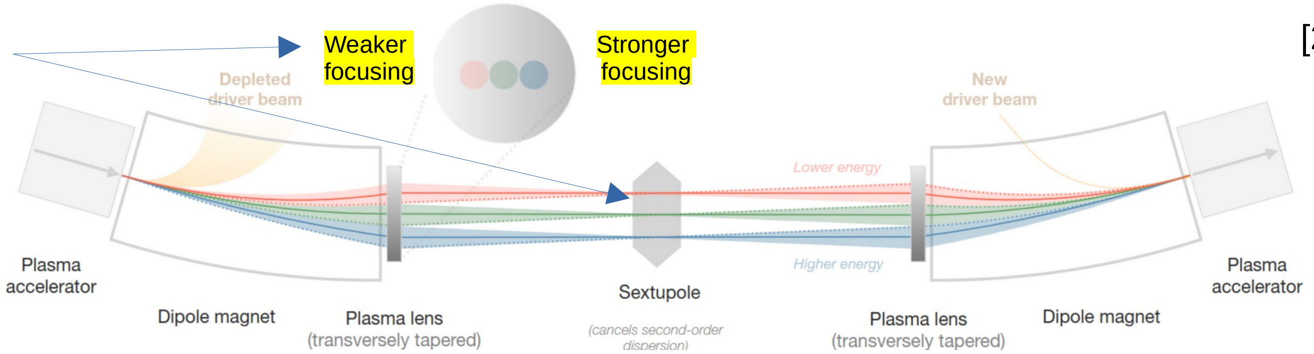

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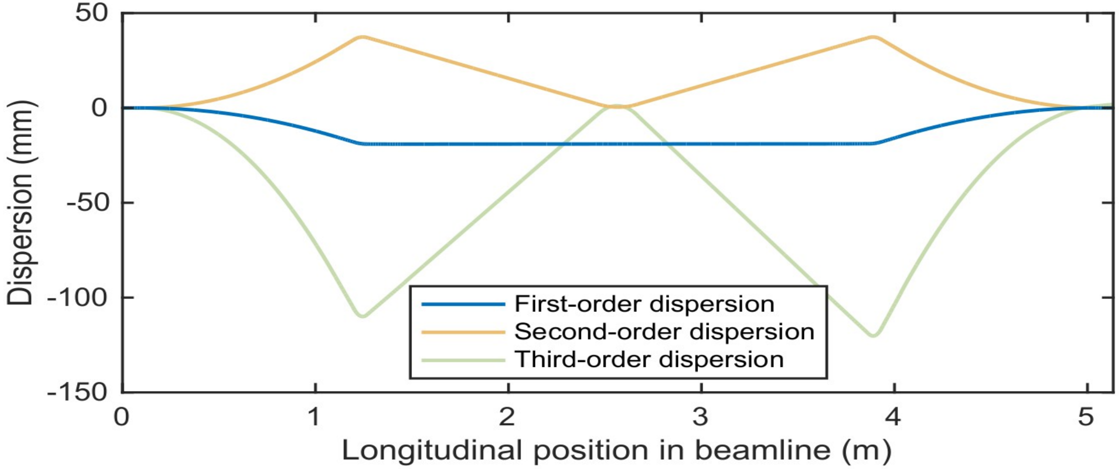

Dispersion:
- canceled up to 2nd order

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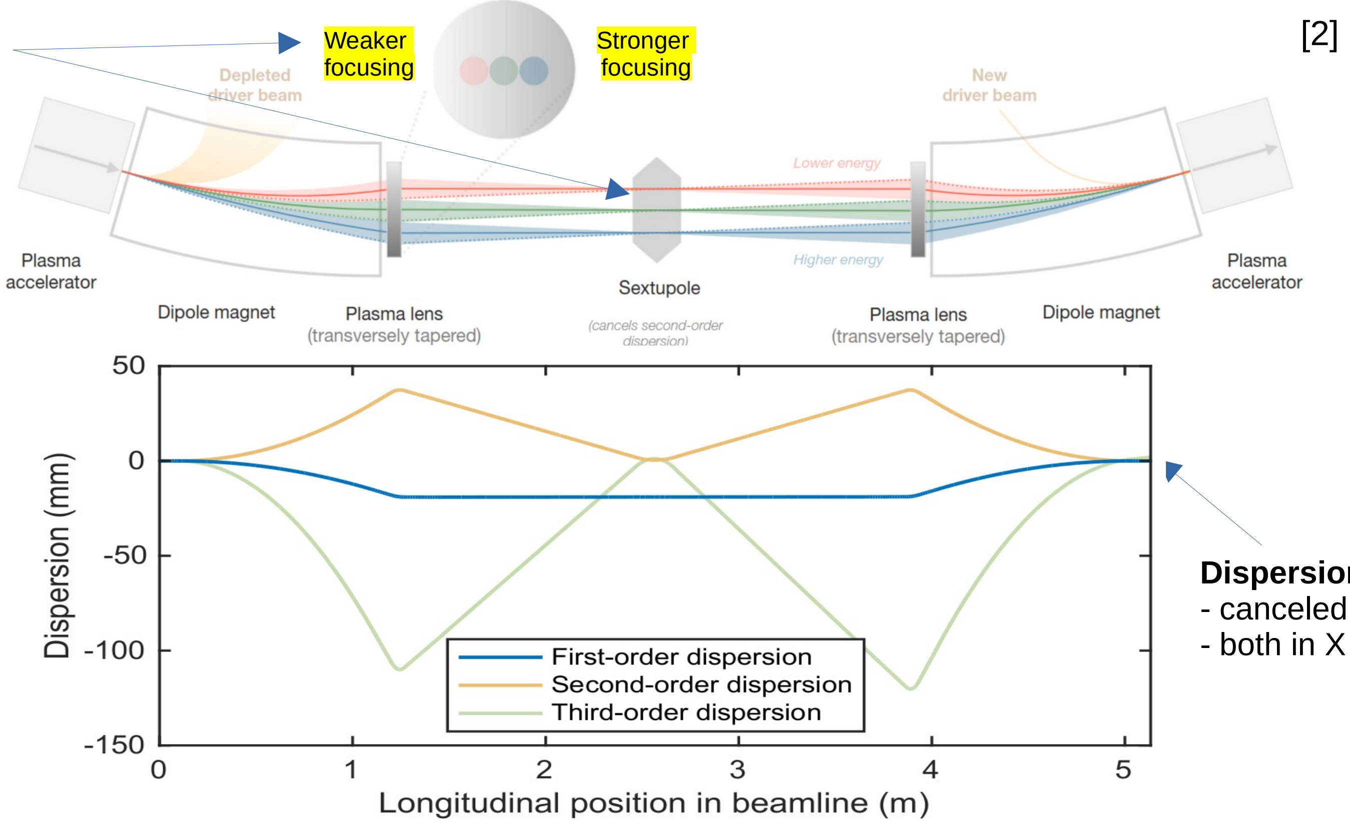
Look at the **transverse** phase-space only: **dispersion**

Achromatic focusing



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

2. Achromatic staging

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

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

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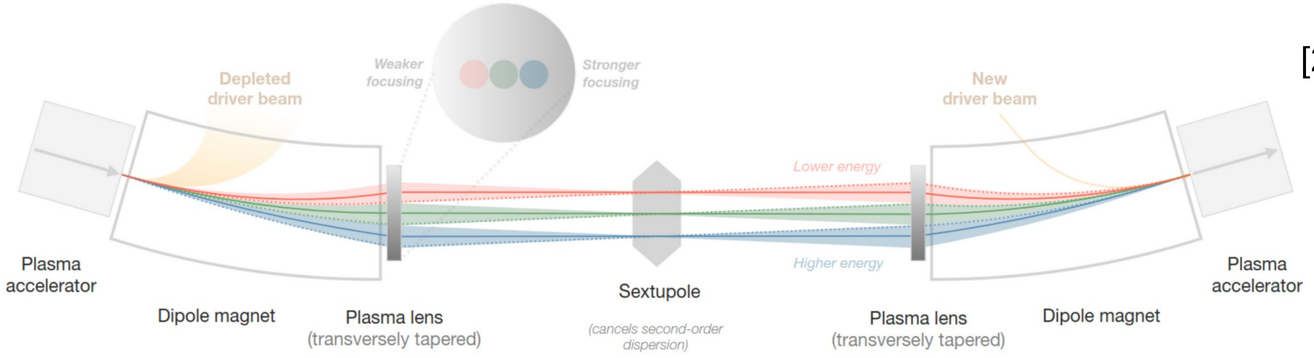

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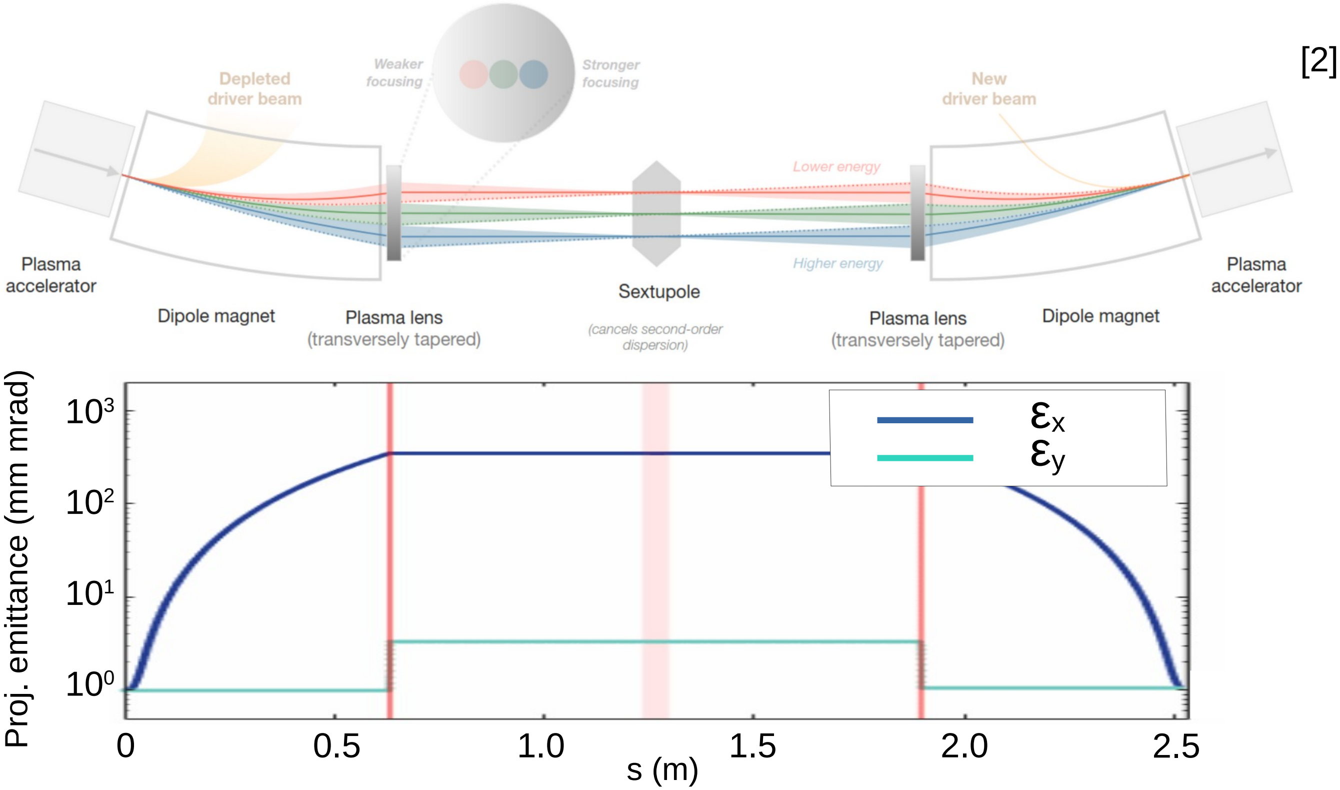

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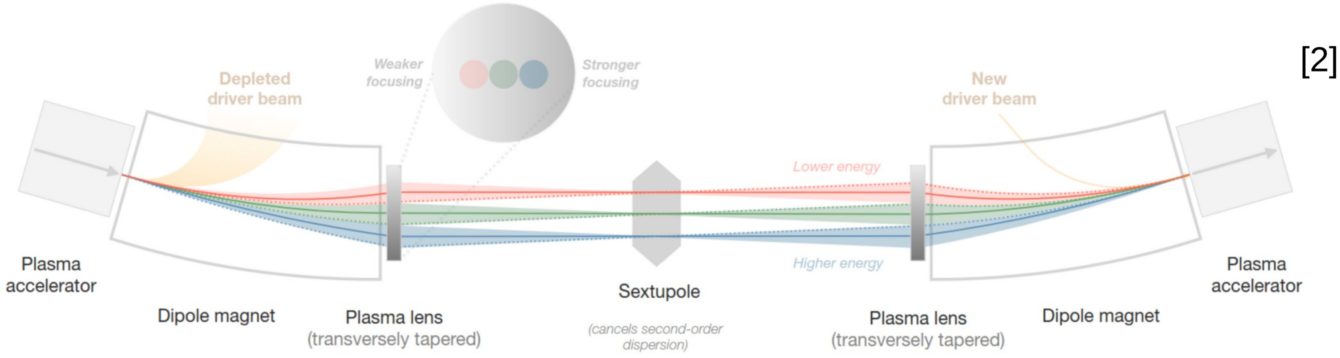
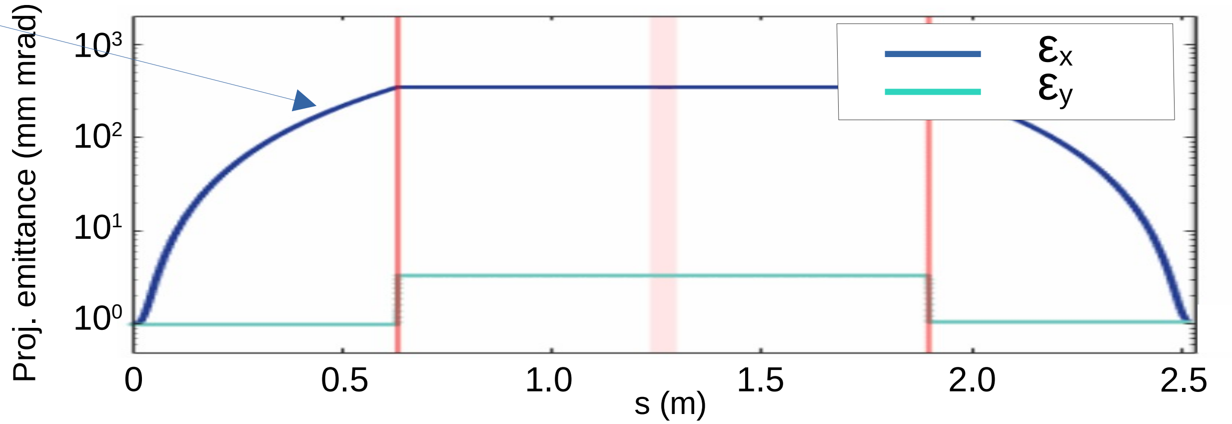


ε_x increase from dispersion in X



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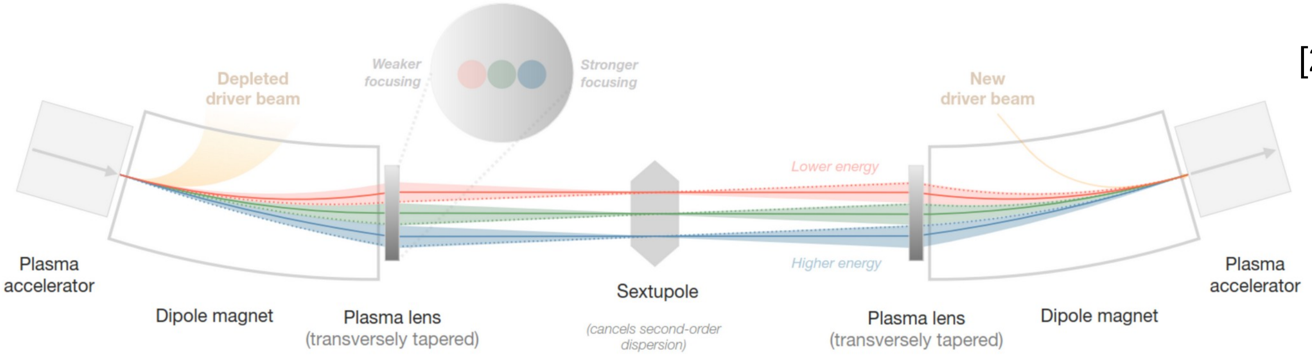

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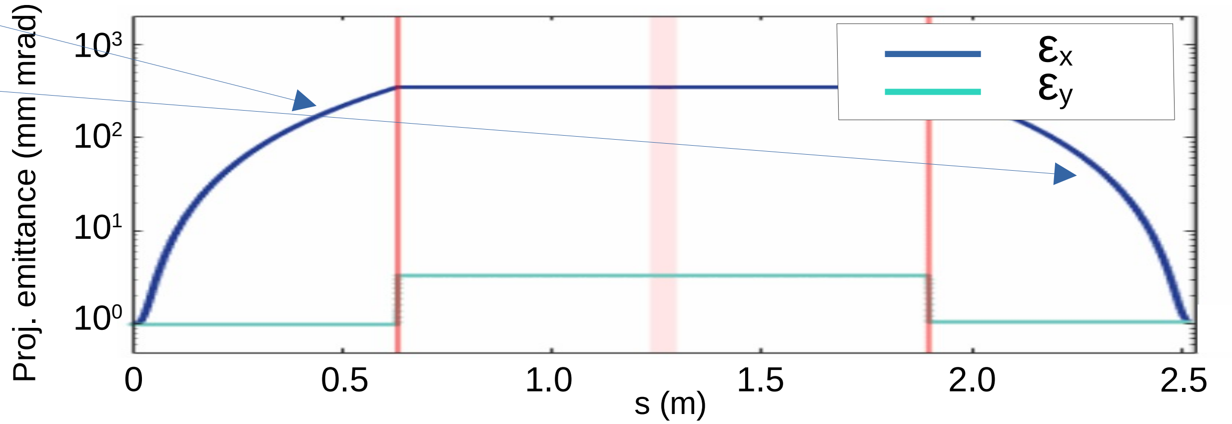
→ canceled there



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

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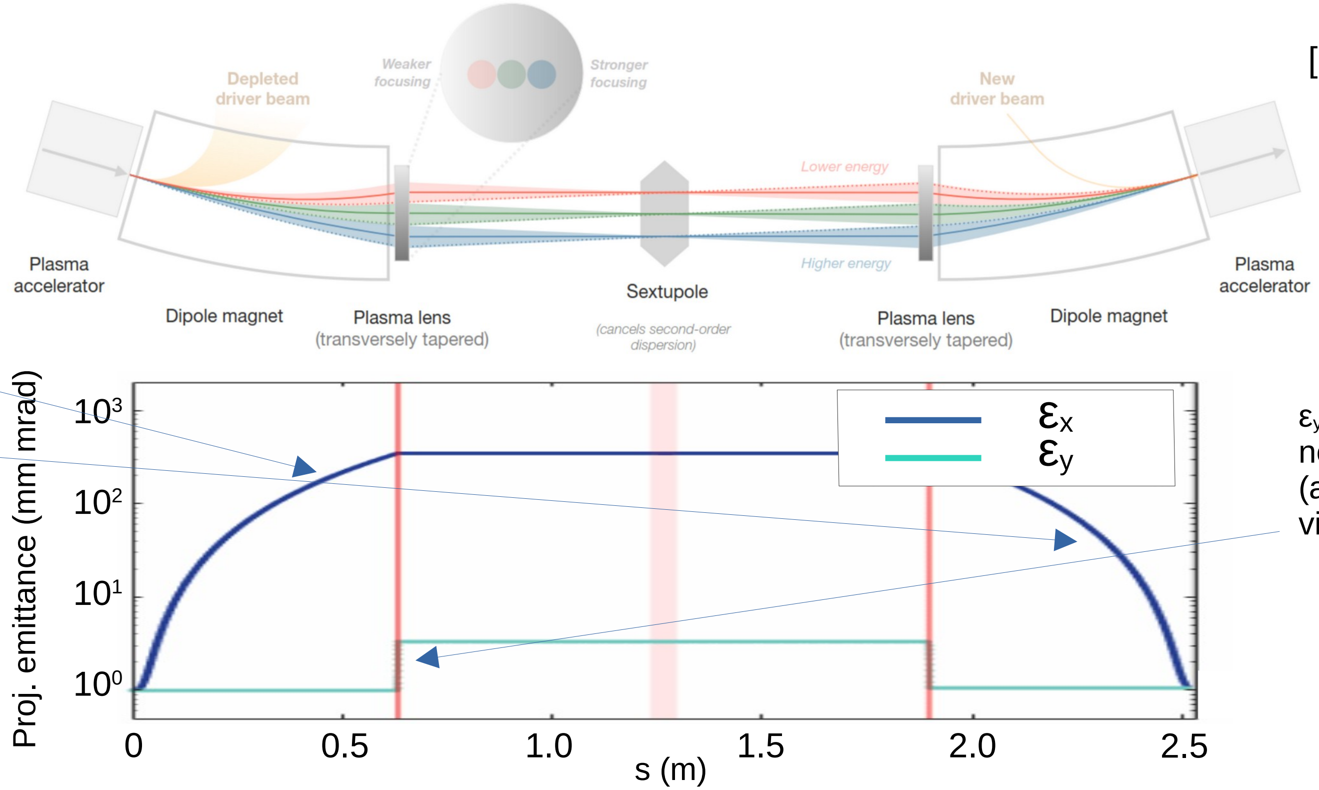

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ε_y increase from lens non-linear focusing (also in X, but not visible in the graph)

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

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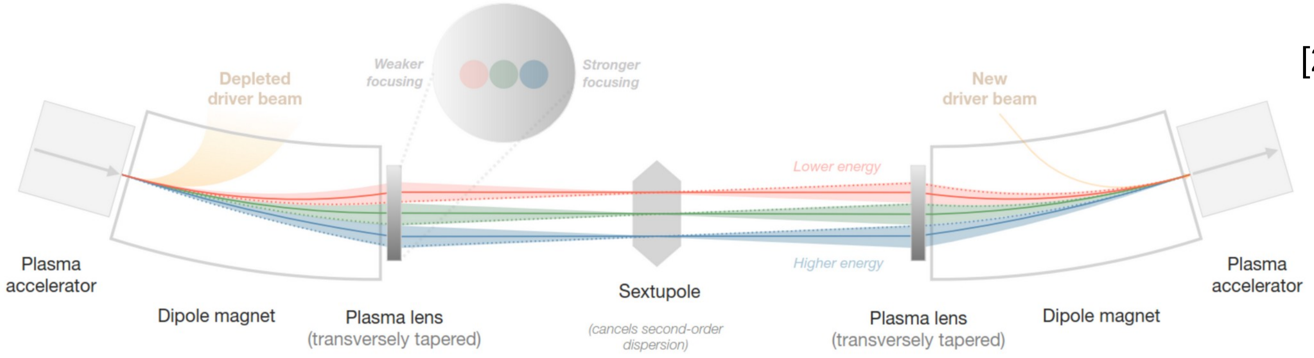

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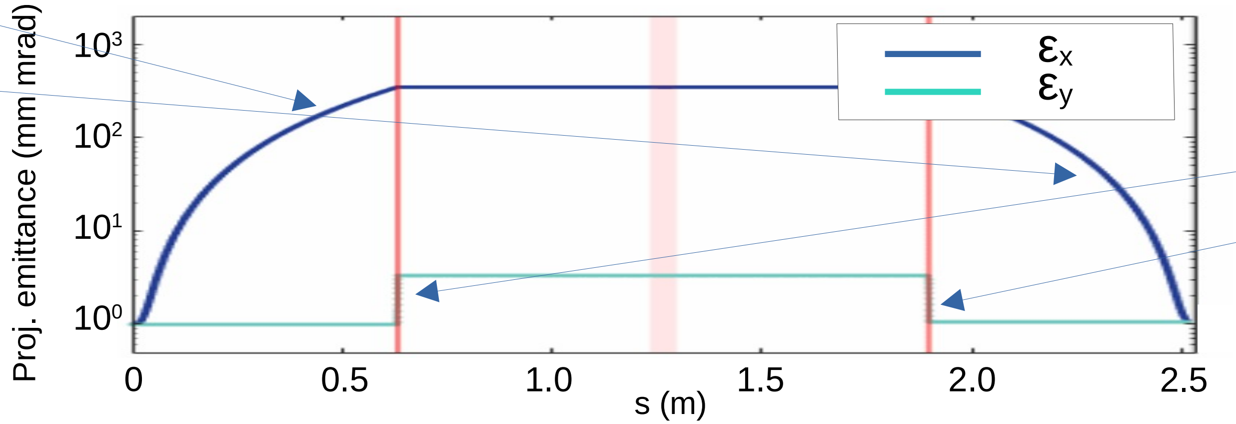

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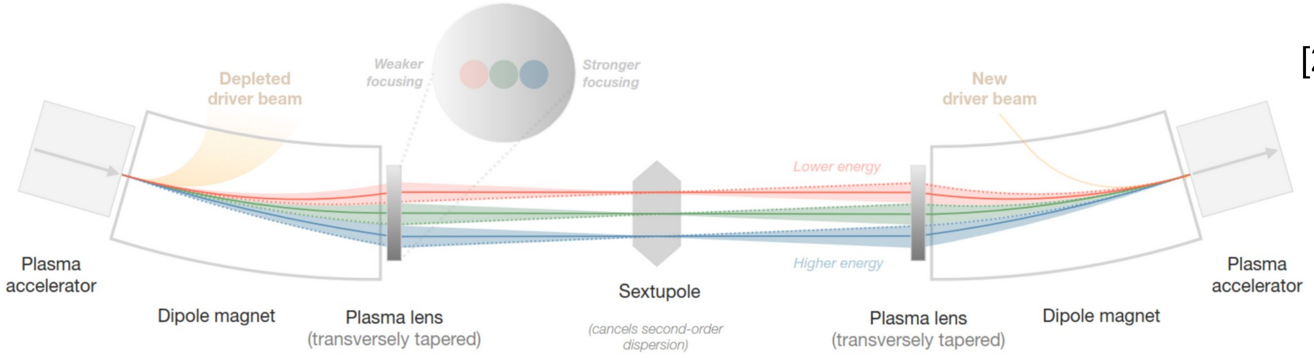

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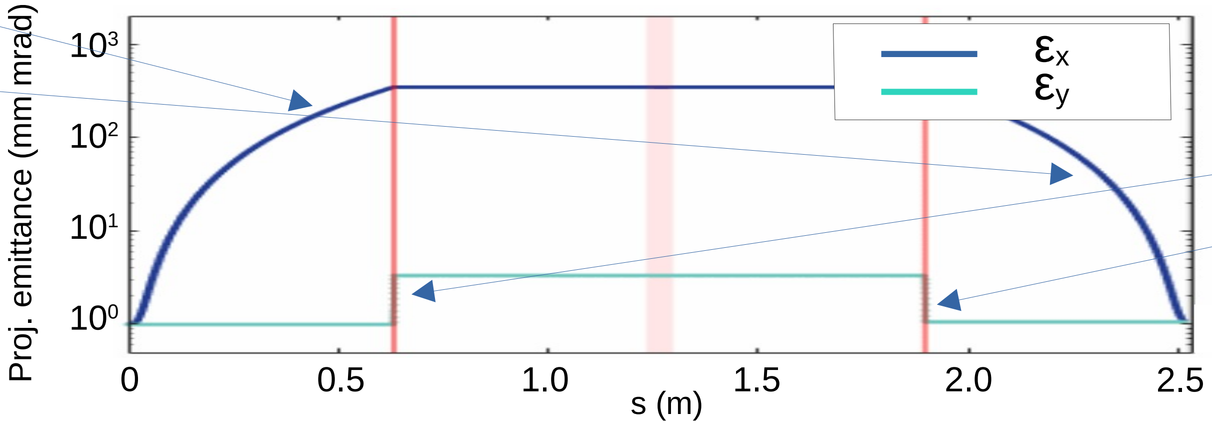

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Emittances preserved

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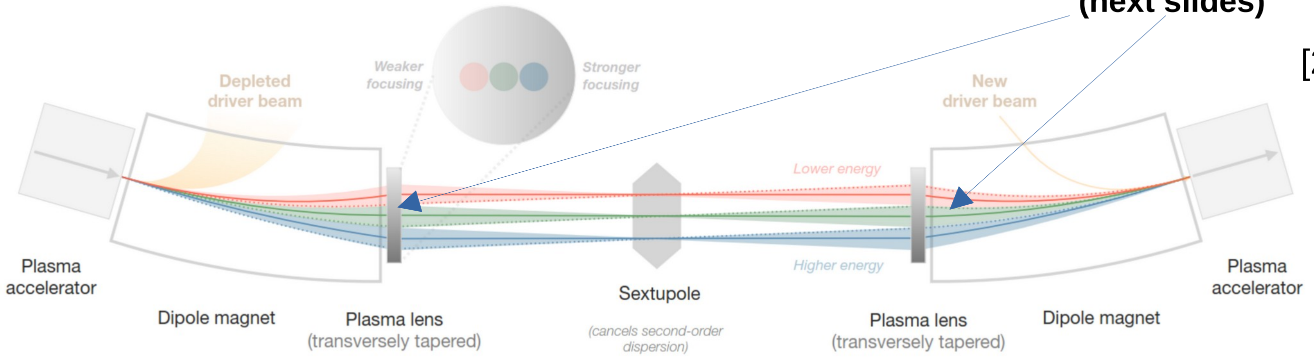
Look at the **transverse** phase-space only: **emittance**

How to make these plasma lenses ? (next slides)

[2]



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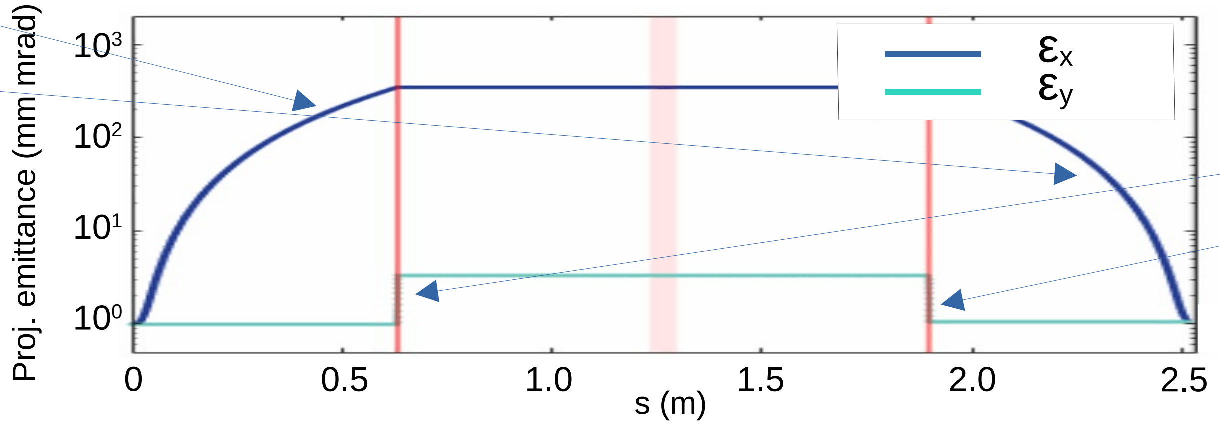

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3. Non-linear plasma lens

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What is it ?

3. Non-linear plasma lens

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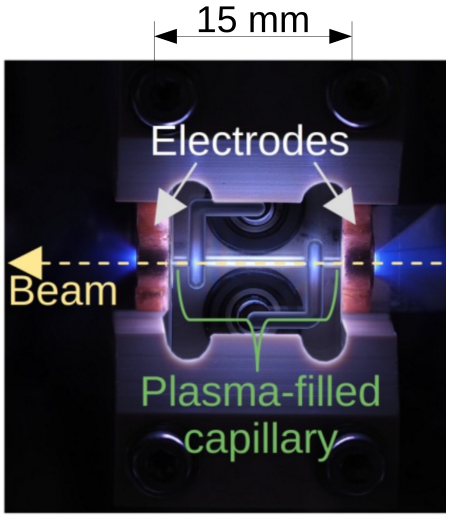
> B-field: generated by longitudinal current J_z along z, in capillary of radius R (see [4] for more information)



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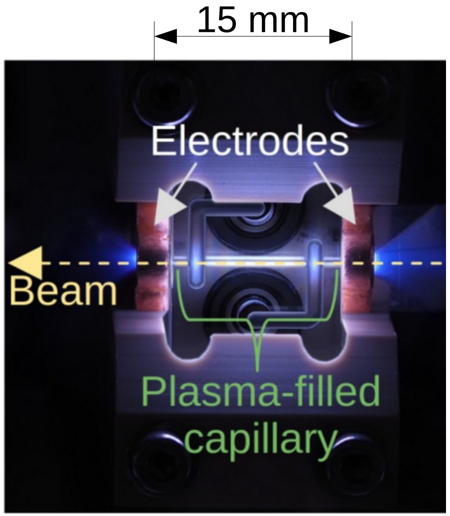

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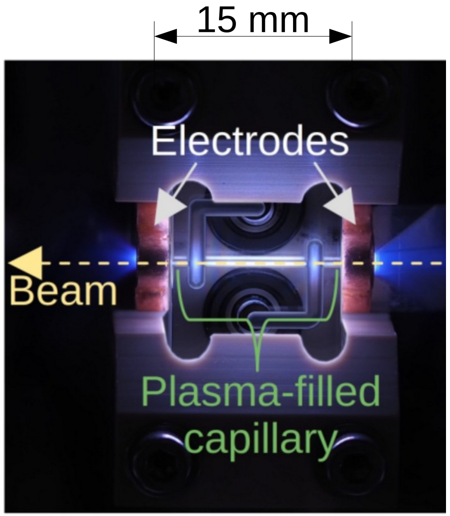

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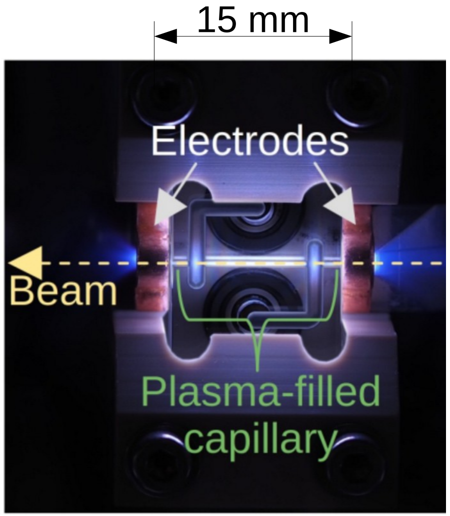

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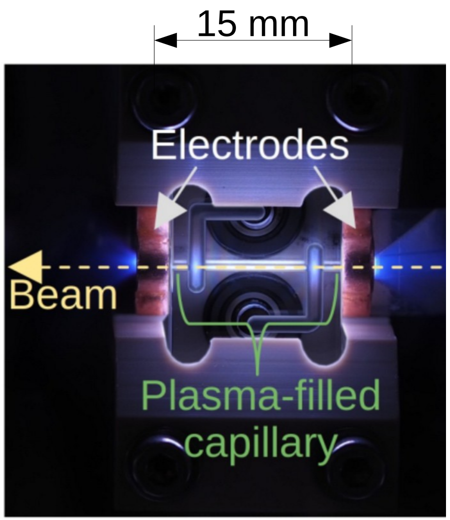

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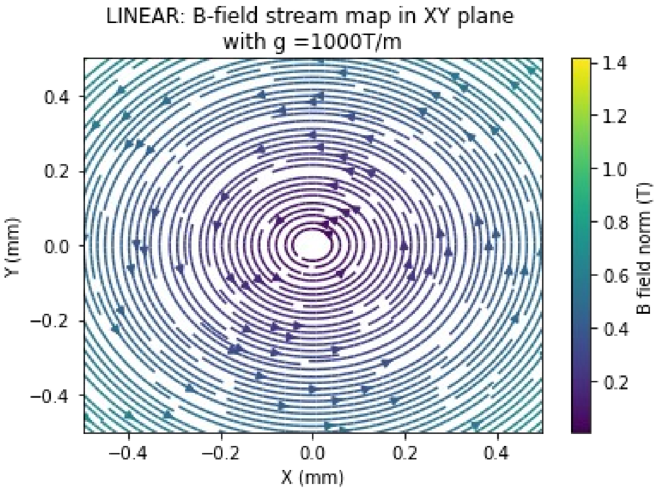

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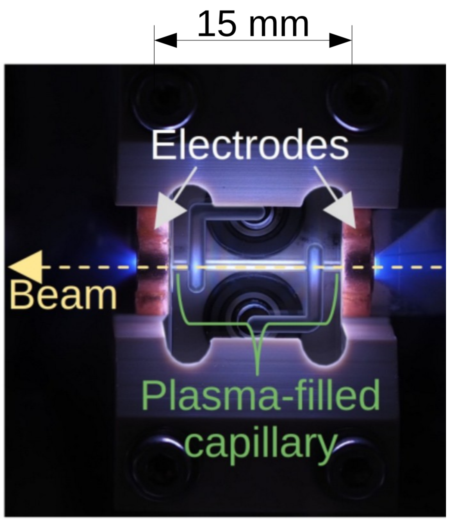

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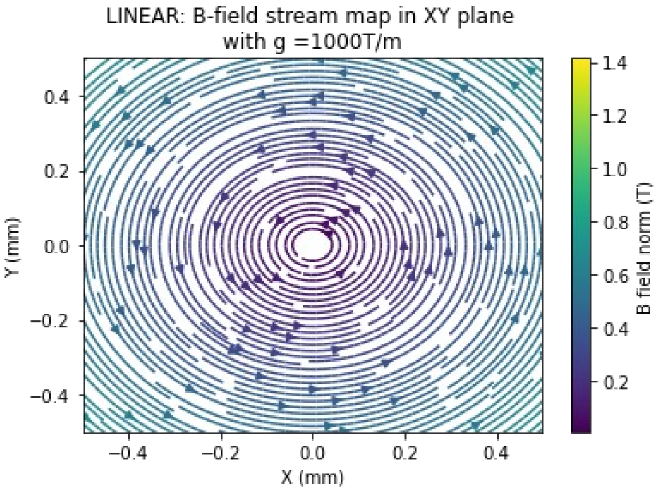

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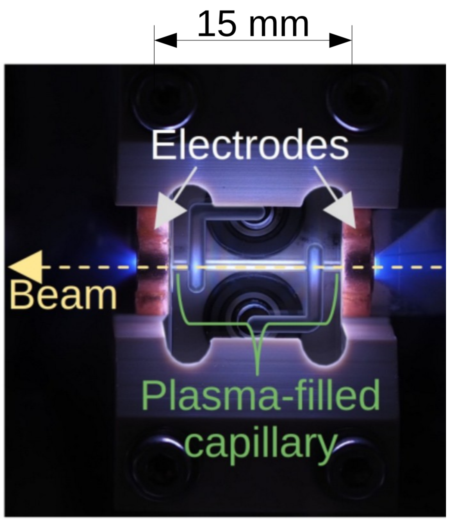

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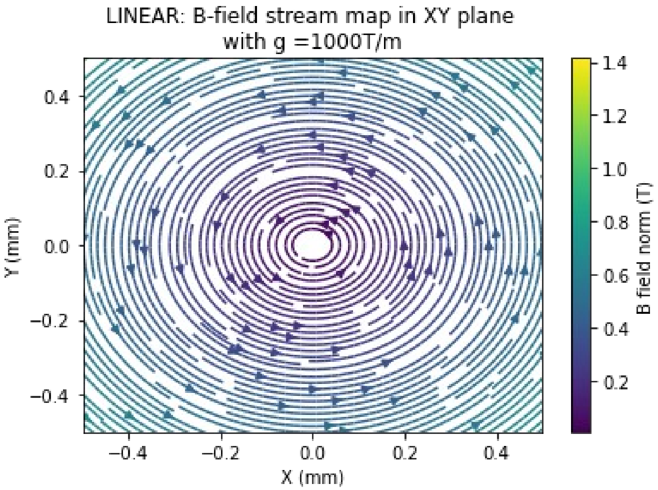

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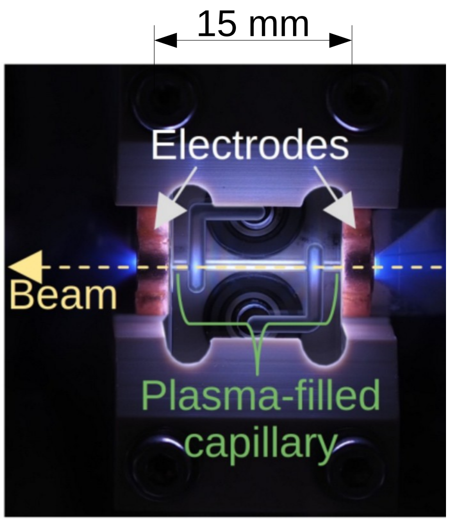

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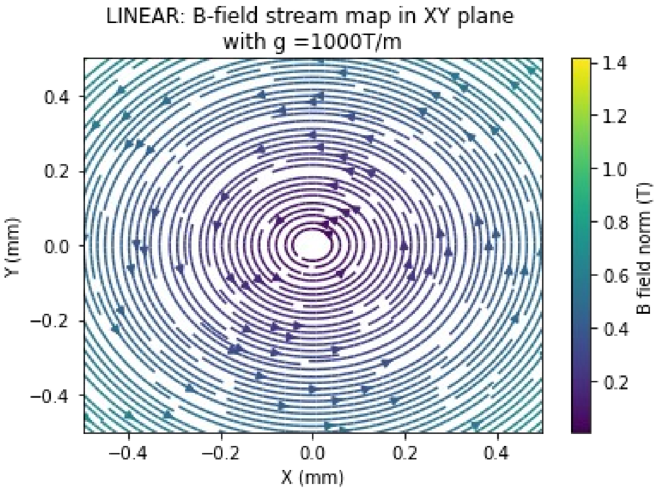

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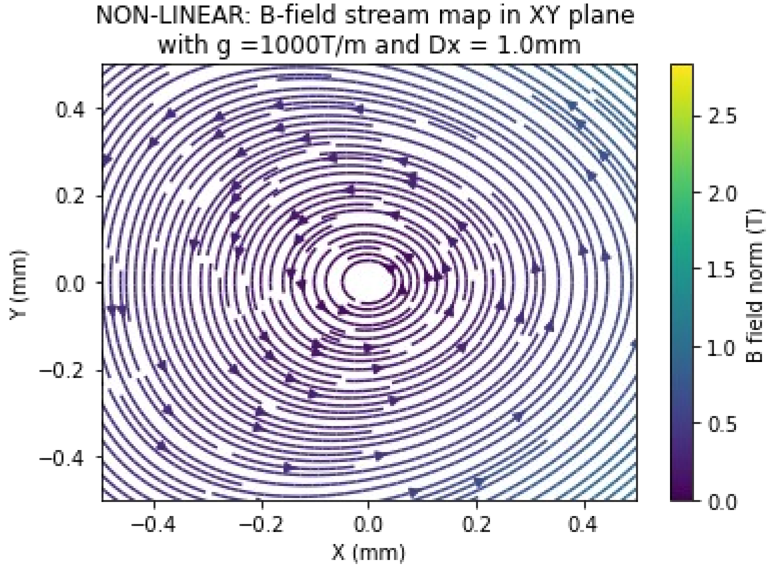
How to make the **non-radially-symmetric** B distribution?



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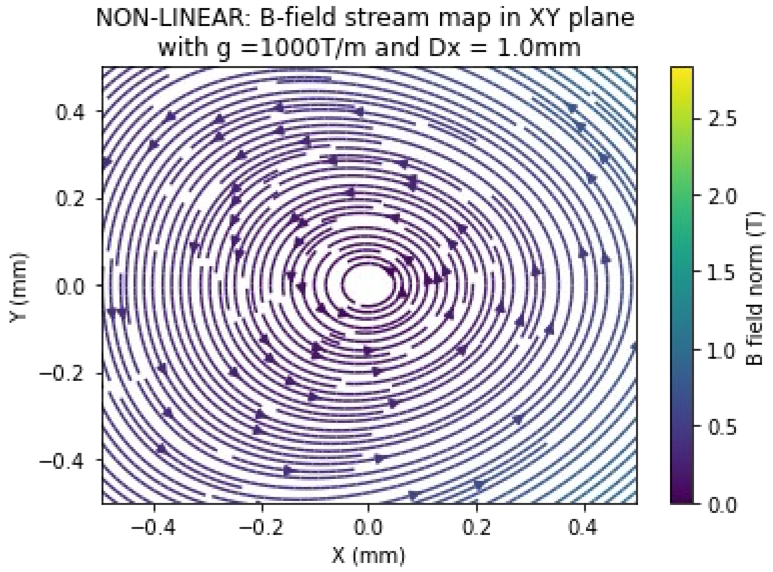

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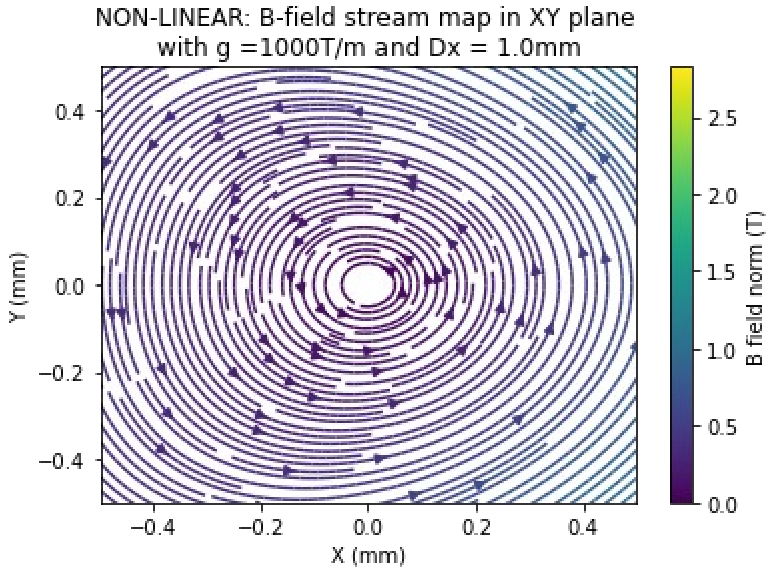

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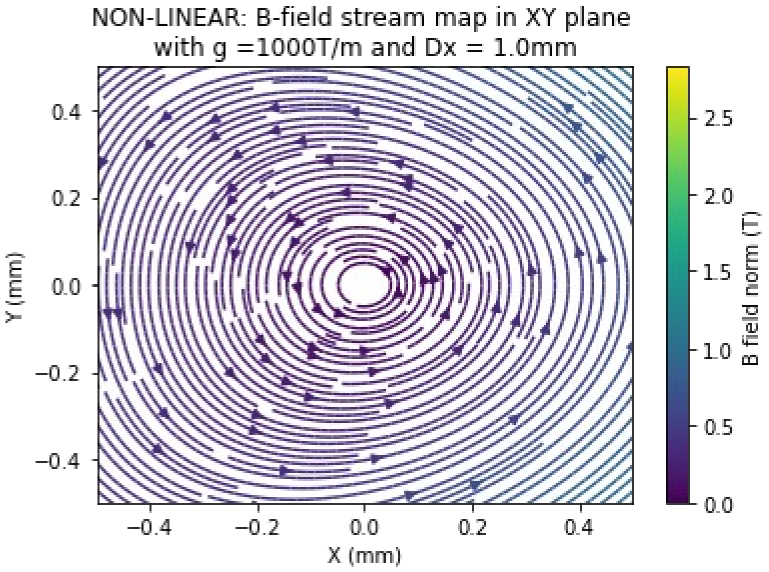

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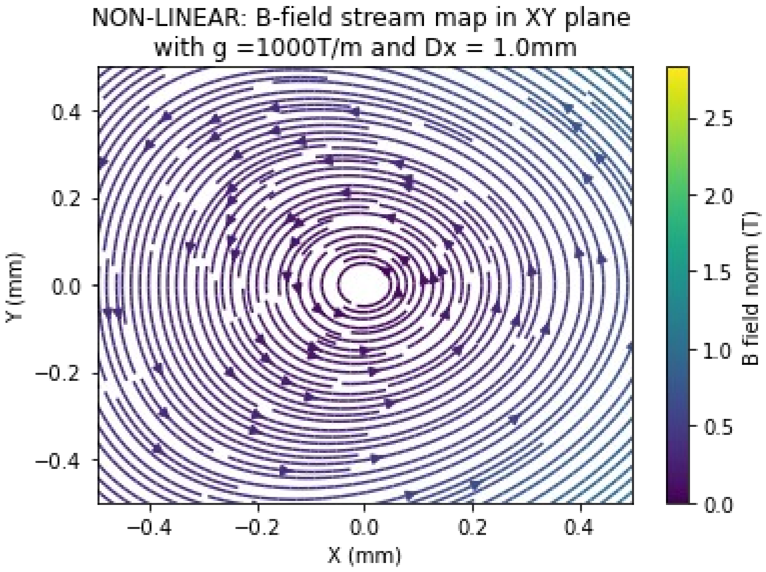

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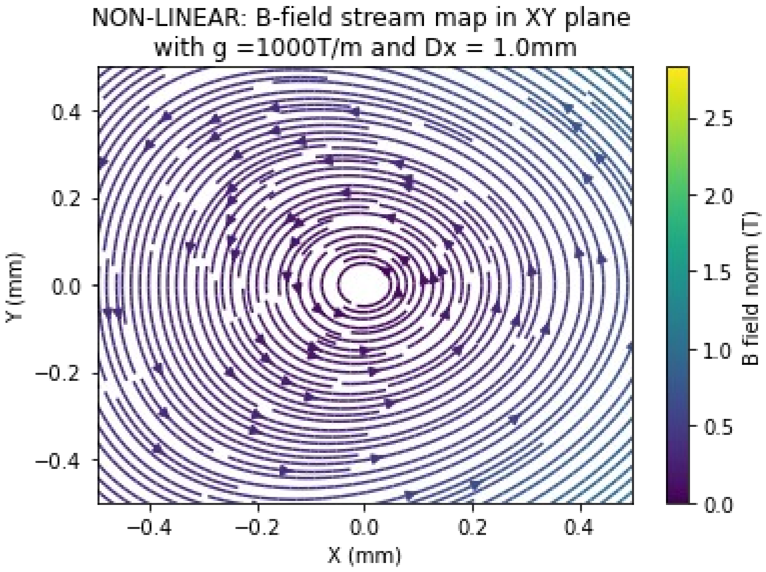

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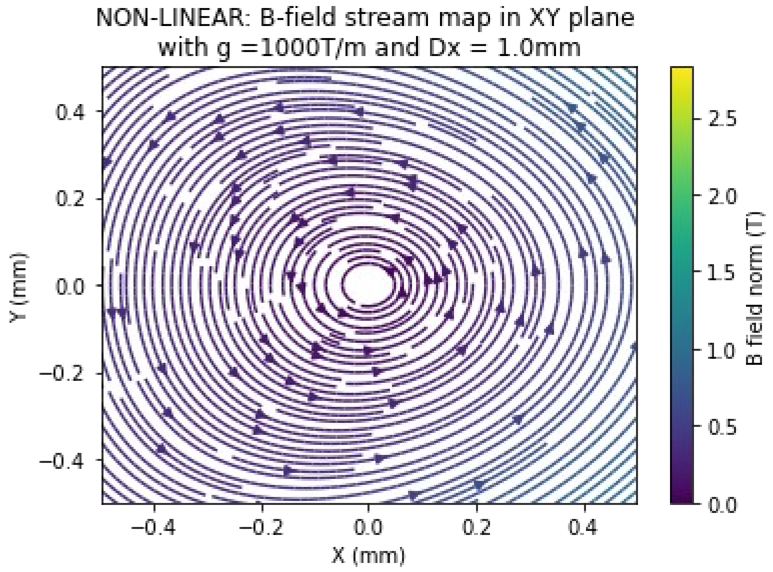

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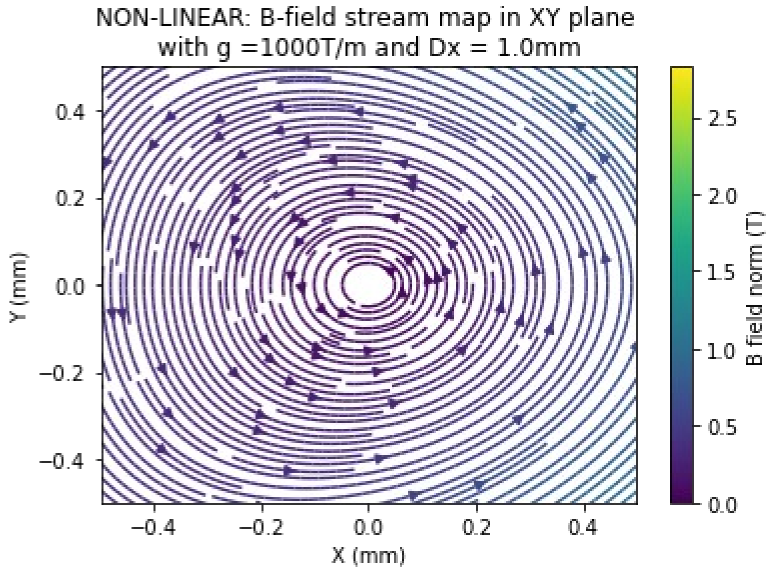

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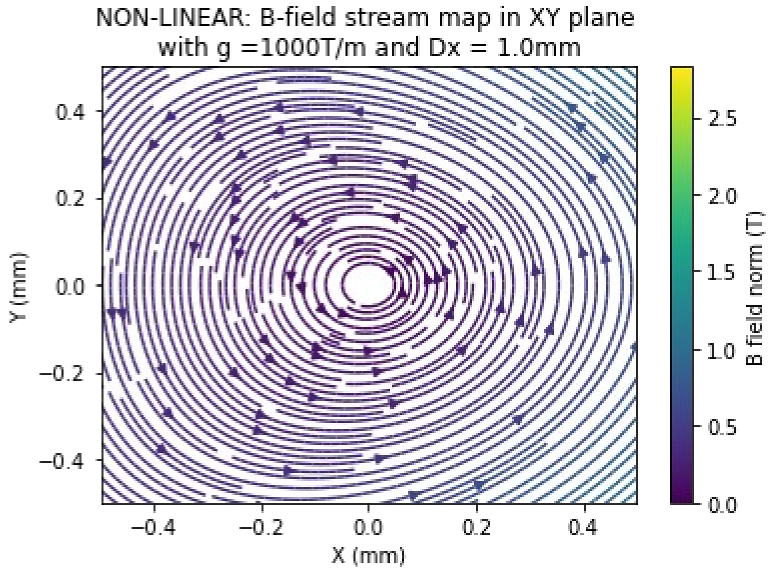

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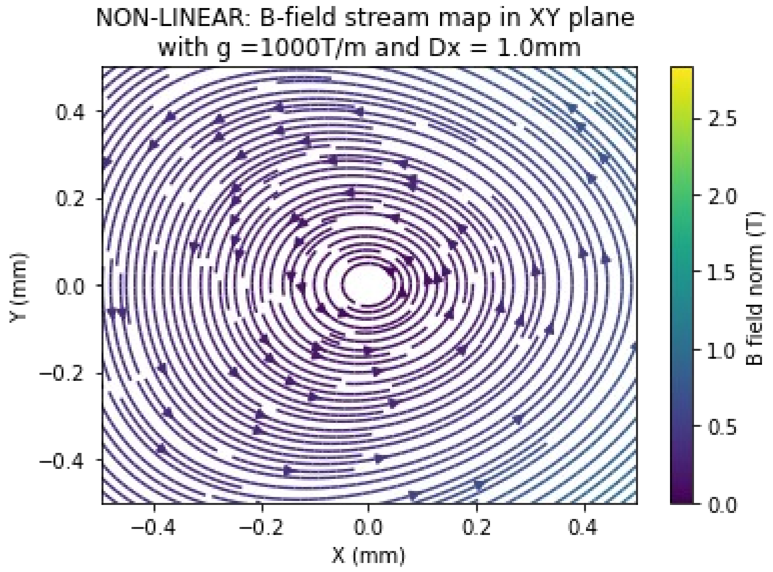

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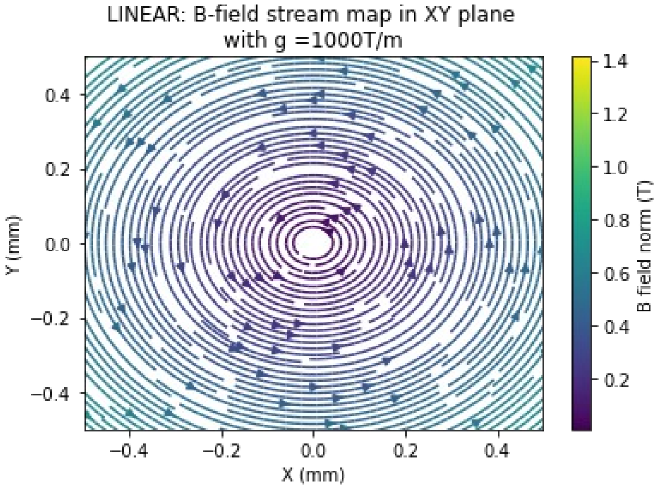

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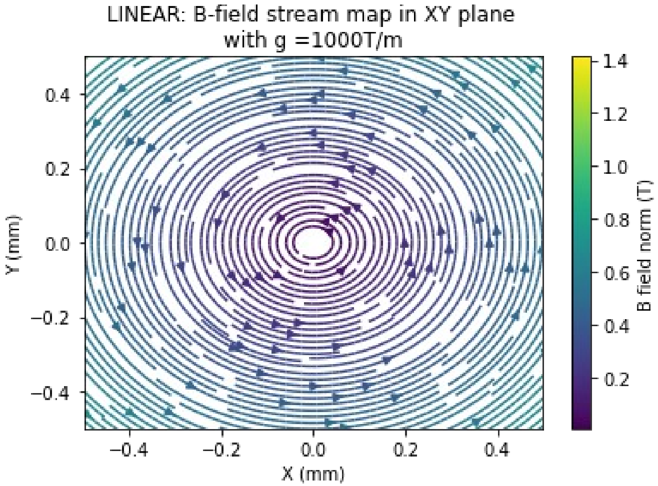

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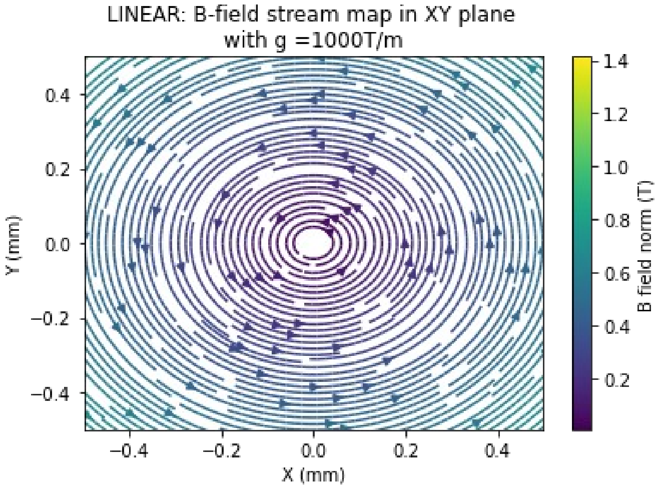

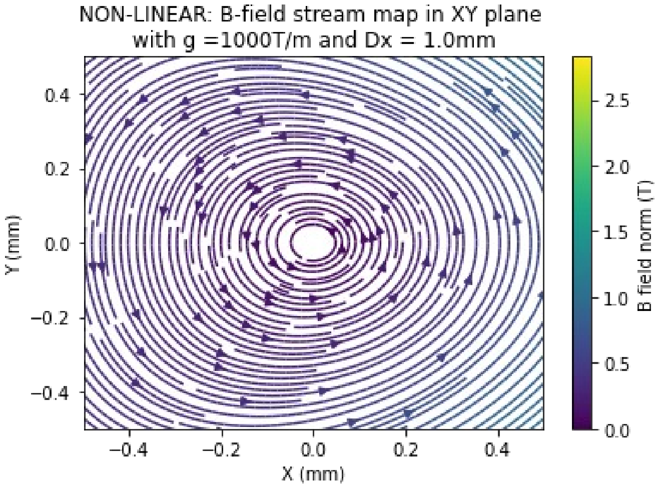

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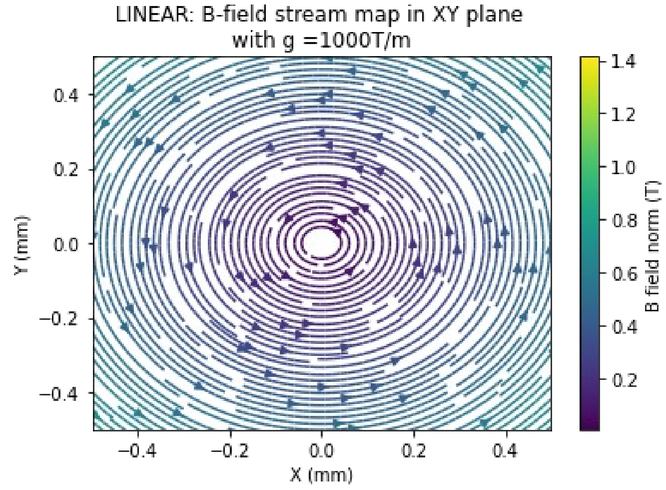

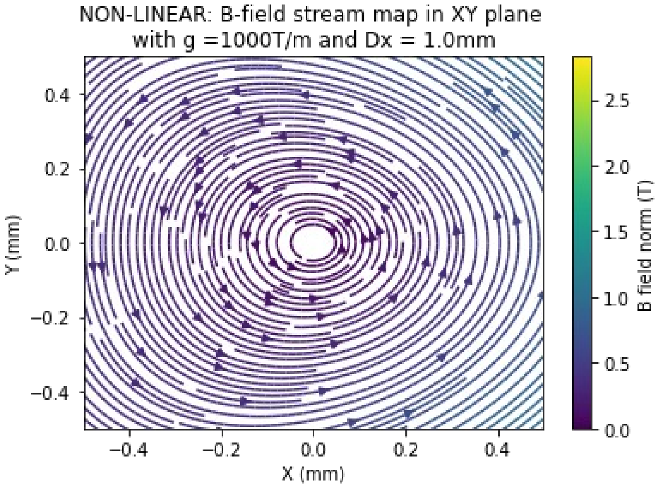

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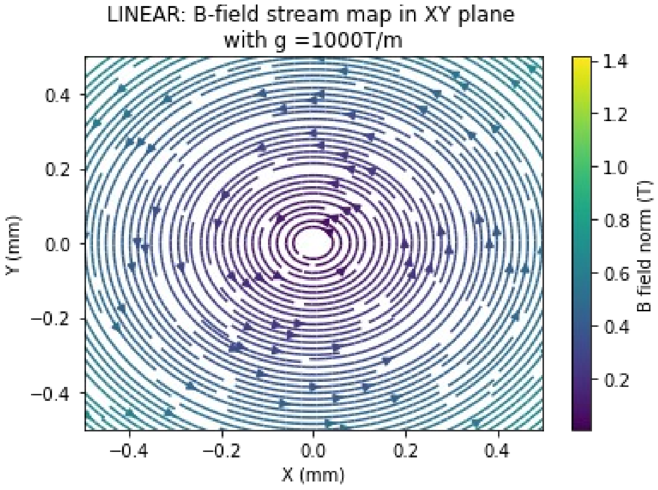

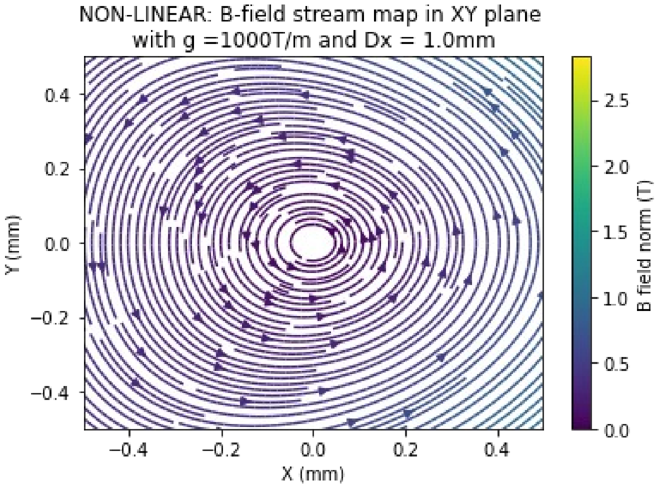

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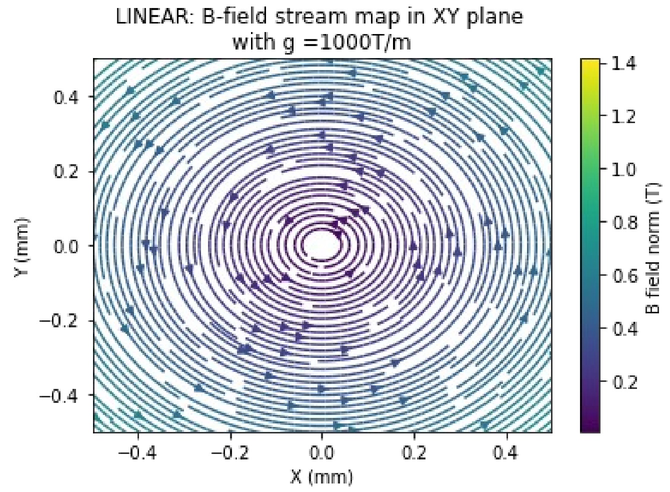

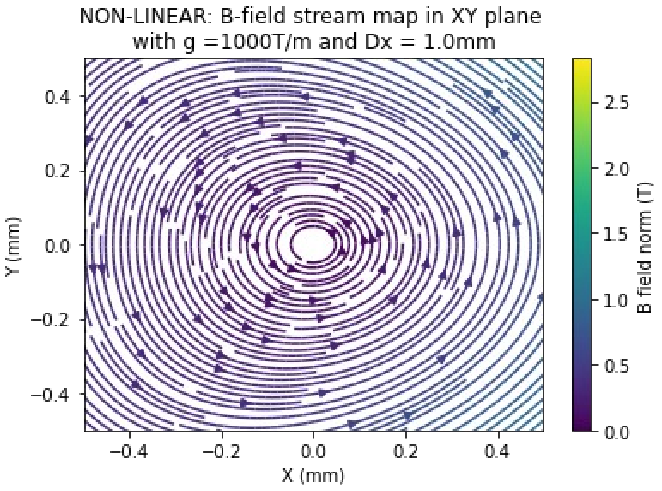

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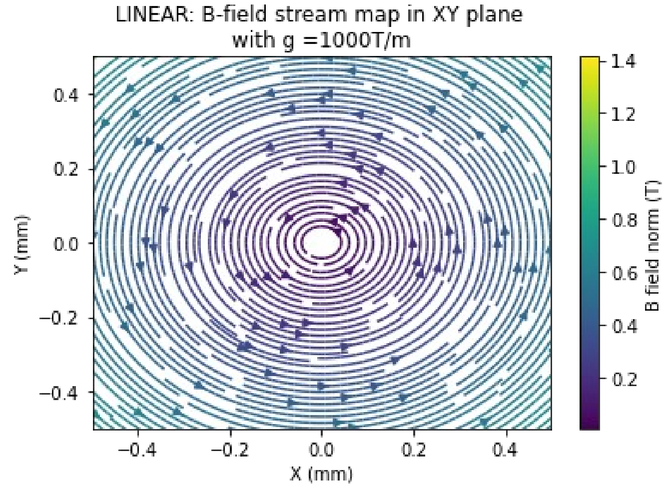

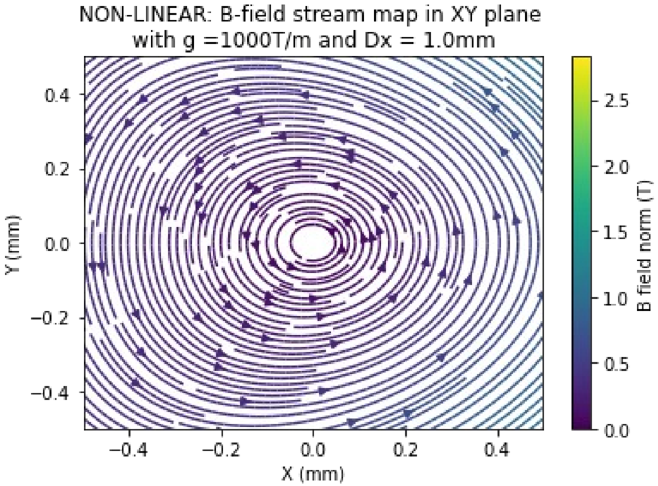

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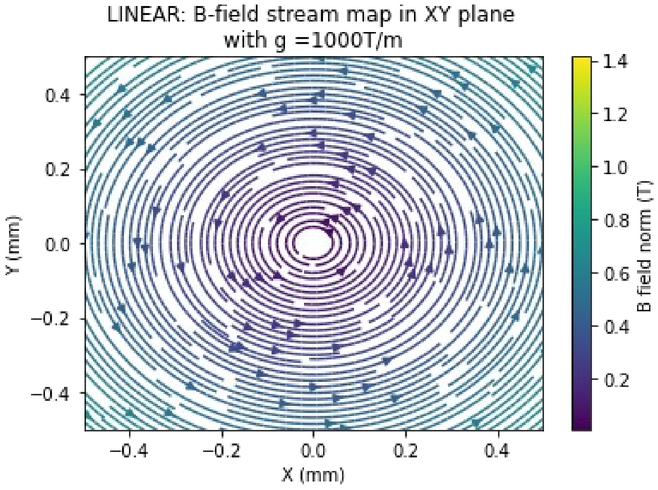

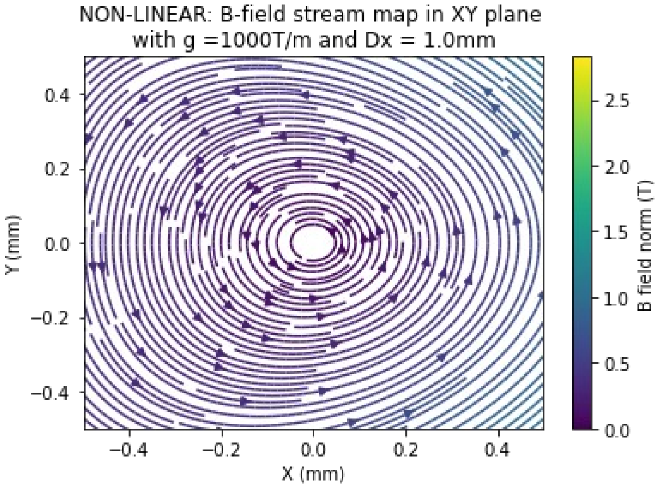

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Does not exist yet

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- Non-linear B-field distribution **already experimentally observed**

3. Non-linear plasma lens

Is a non-linear B distribution feasible ?

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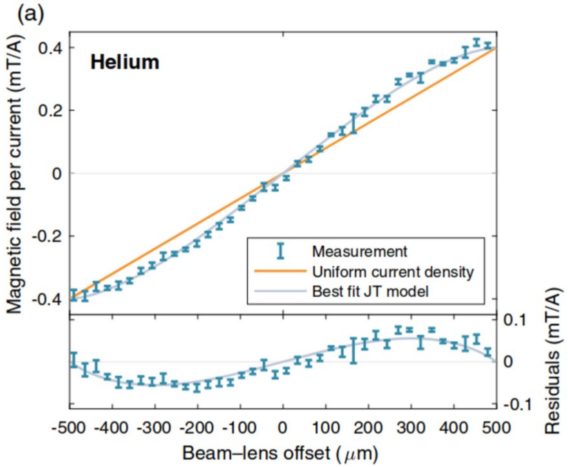

Experimental measurement of non-linear focusing strength (*r*-dependence) [4]

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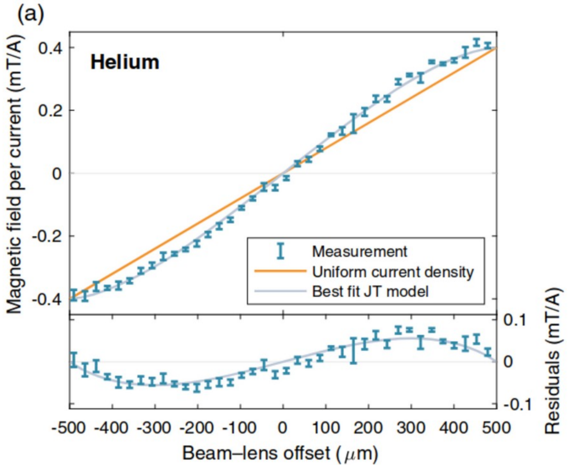

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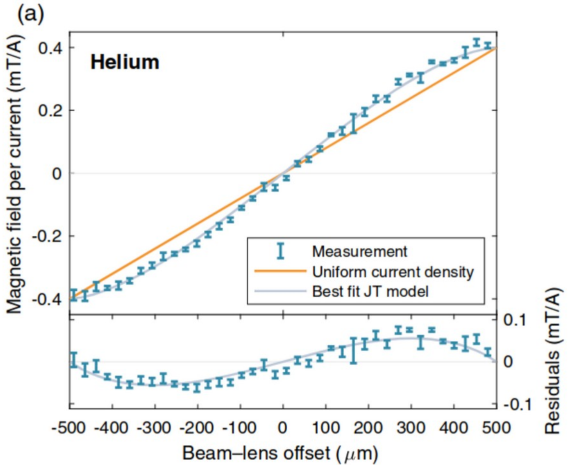
- Origins:
  - Non-uniform T distribution



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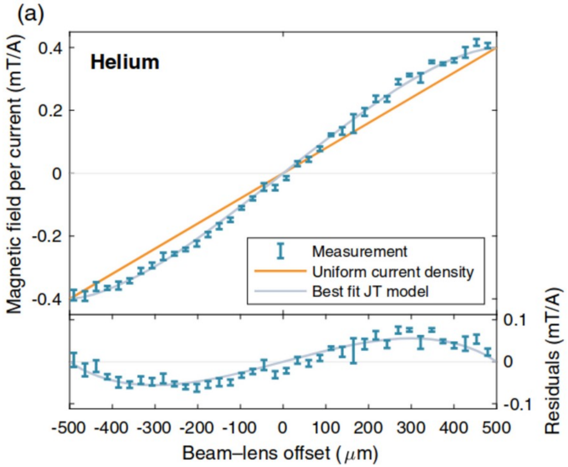
    ⬇
  - Non-uniform conductivity



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- Origins:
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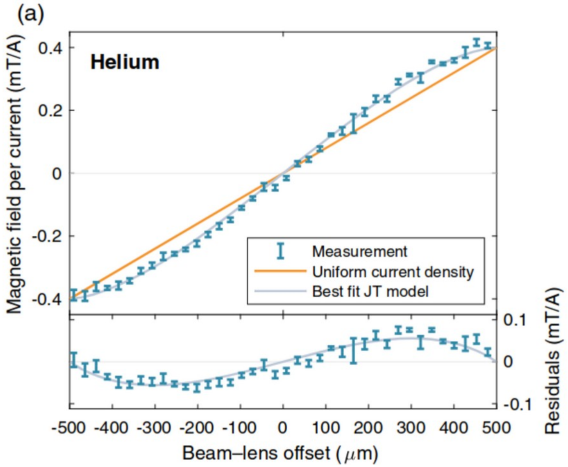
  - Non-uniform conductivity
  - Non-uniform J_z distribution



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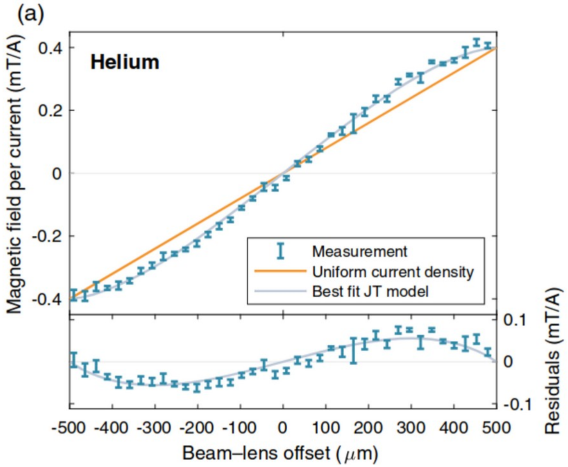

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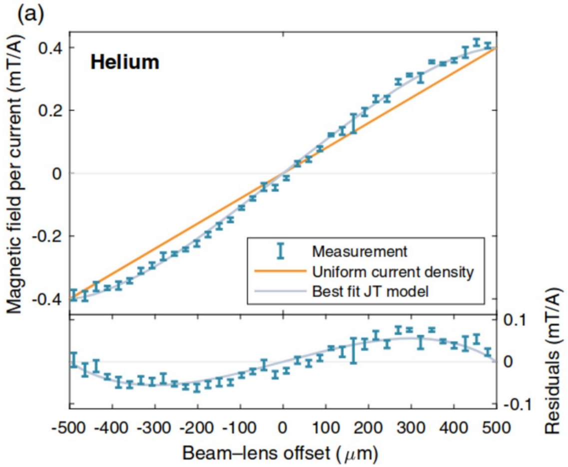

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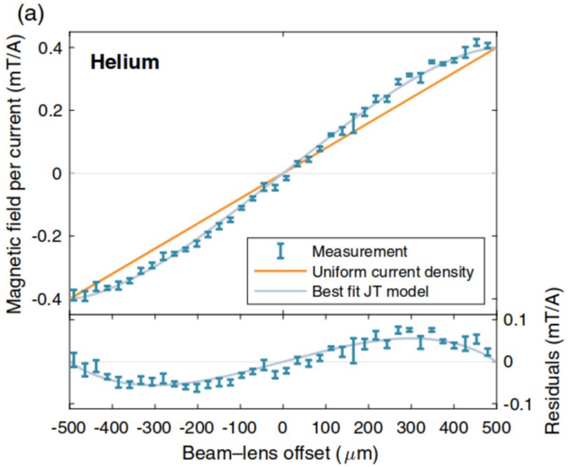
- **Comment**:
  - this observed non-linearity is **radially symmetric…**



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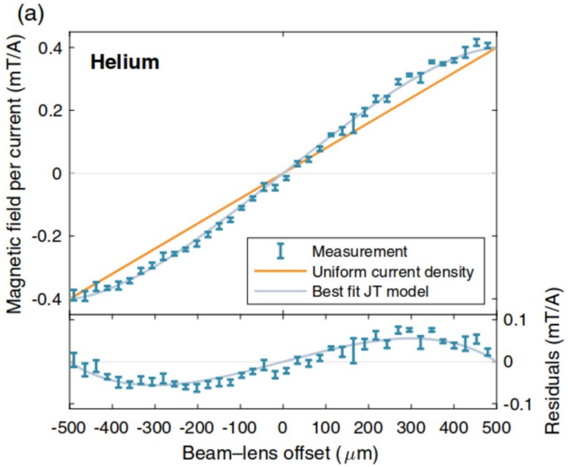

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- **Comment**:
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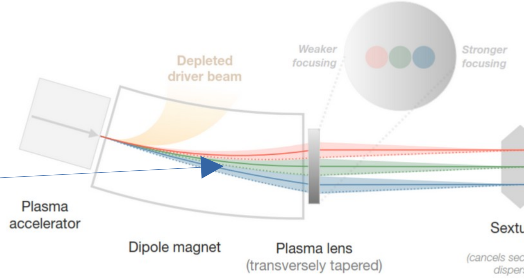
    But we only want to disperse in X



[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

3. Non-linear plasma lens

First MHD results

3. Non-linear plasma lens

First MHD results

- Simulations:

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

3. Non-linear plasma lens

First MHD results

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3. Non-linear plasma lens

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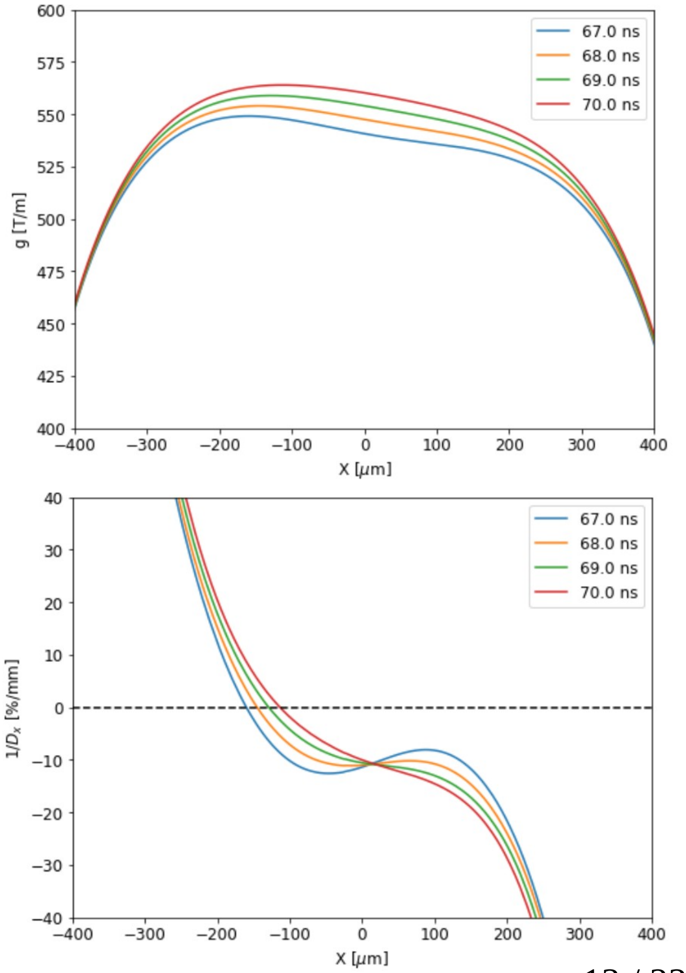
- **First results**

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



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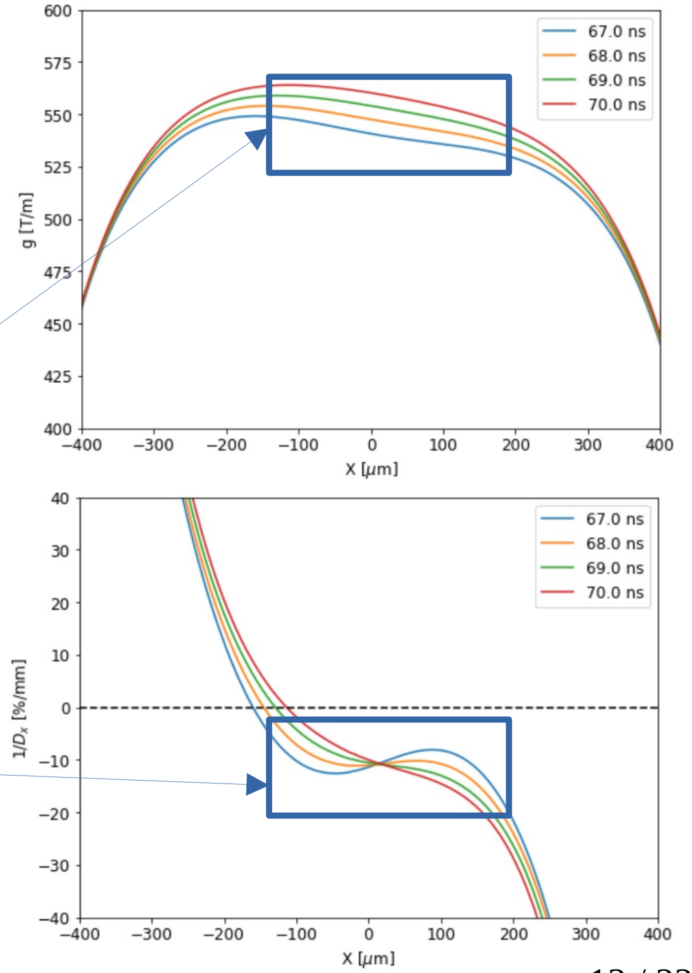

3. Non-linear plasma lens

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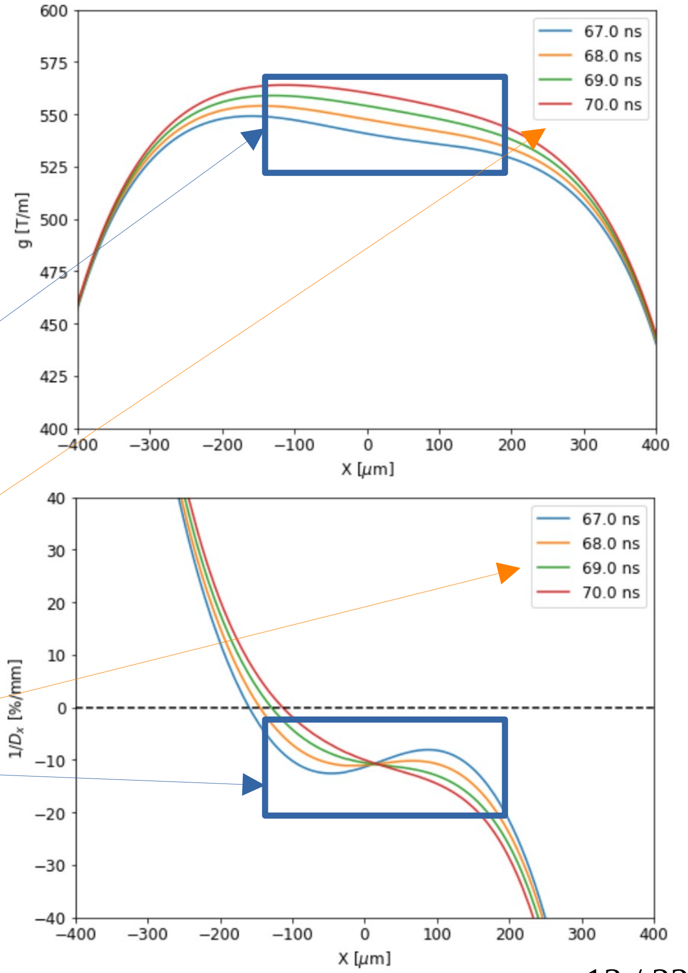
- **First results**
  - Good results for $\boldsymbol{g}$ and $\boldsymbol{1/D_x}$
  - Too short operating window (few ns)

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

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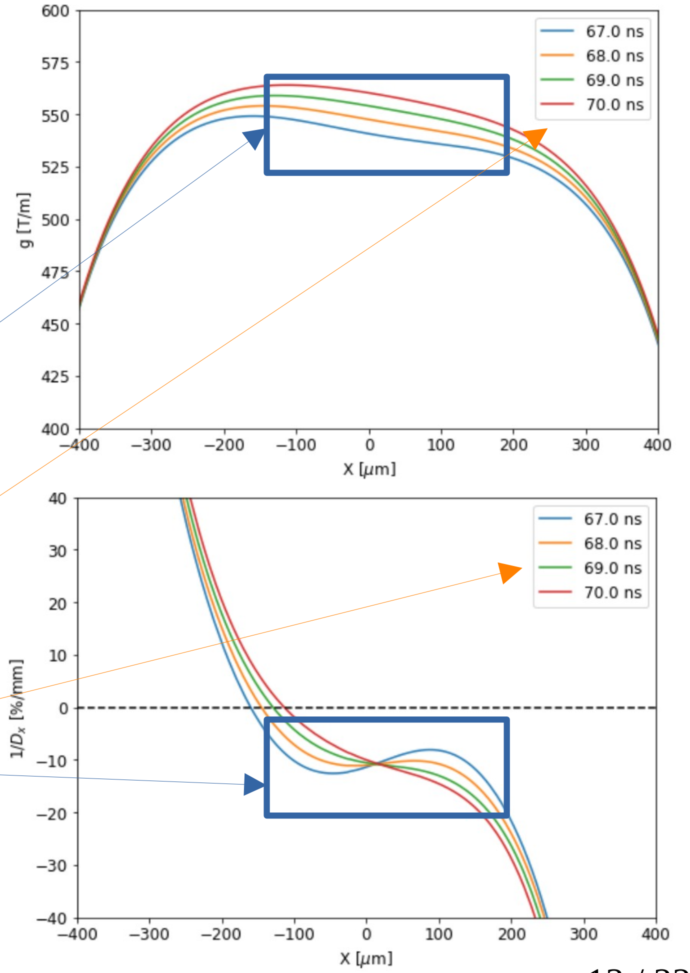
- **First results**
  - Good results for $\boldsymbol{g}$ and $\boldsymbol{1/D_x}$
  - Too short operating window (few ns)
  - Heavier species should make the dynamics slower (slower thermal exchanges)

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

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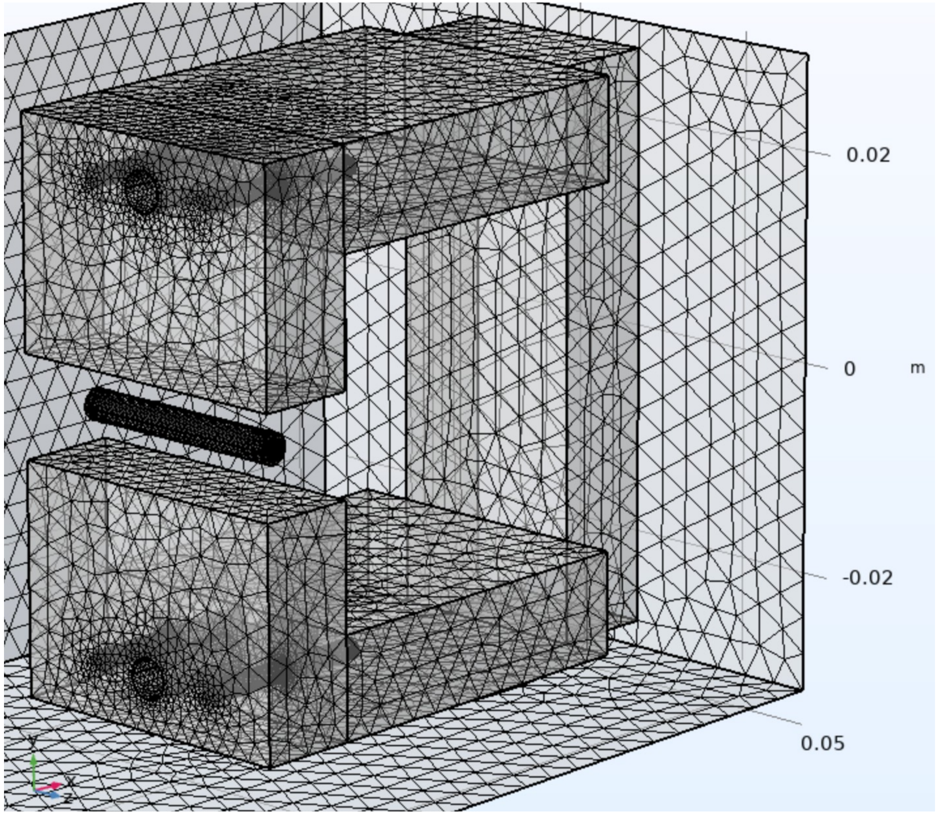
How to make the **external** B-field ?

3. Non-linear plasma lens

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

- Electromagnet



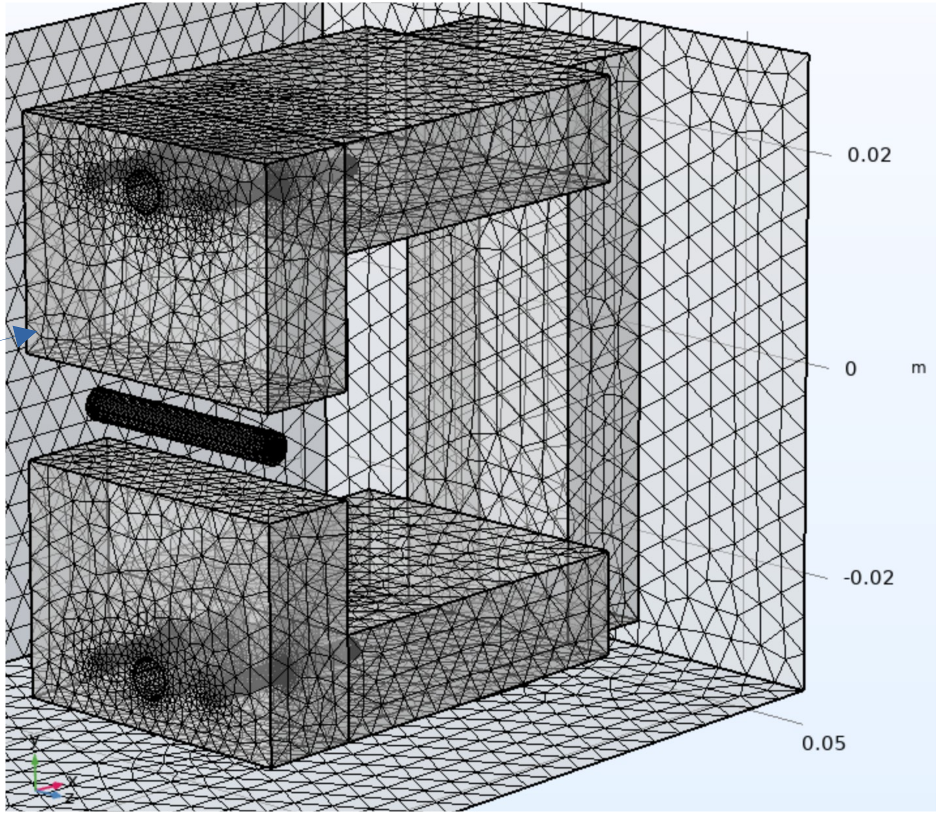
COMSOL model,
with magnet and 20 mm-long capillary

3. Non-linear plasma lens

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

> Electromagnet

magnet



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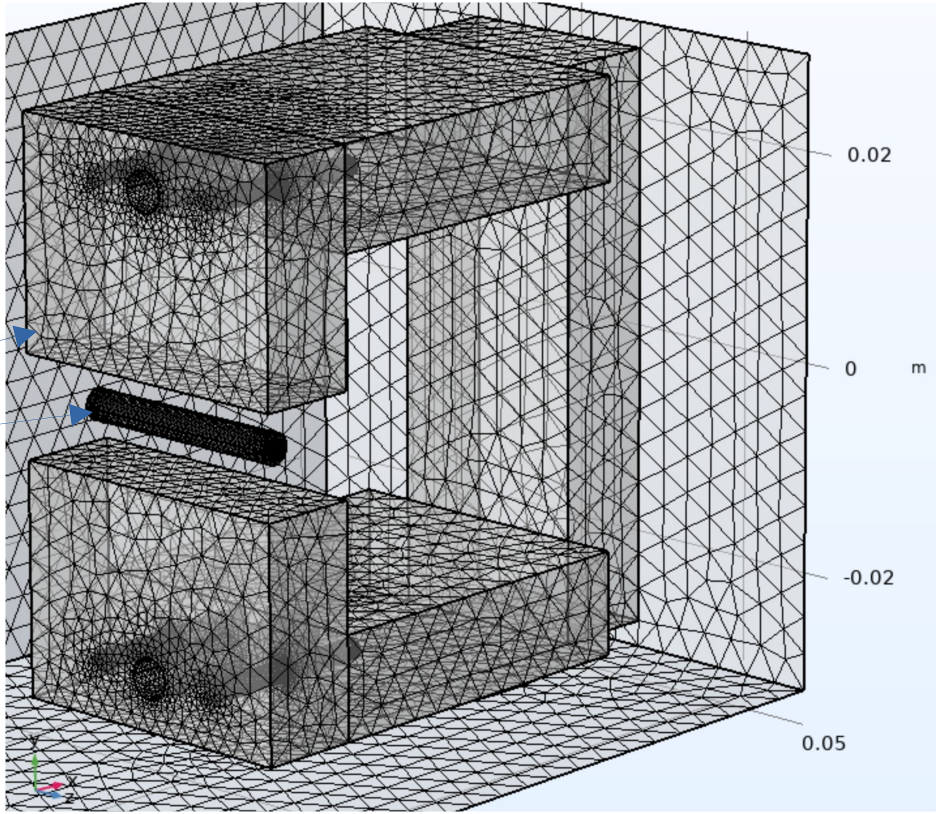

COMSOL model,
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3. Non-linear plasma lens

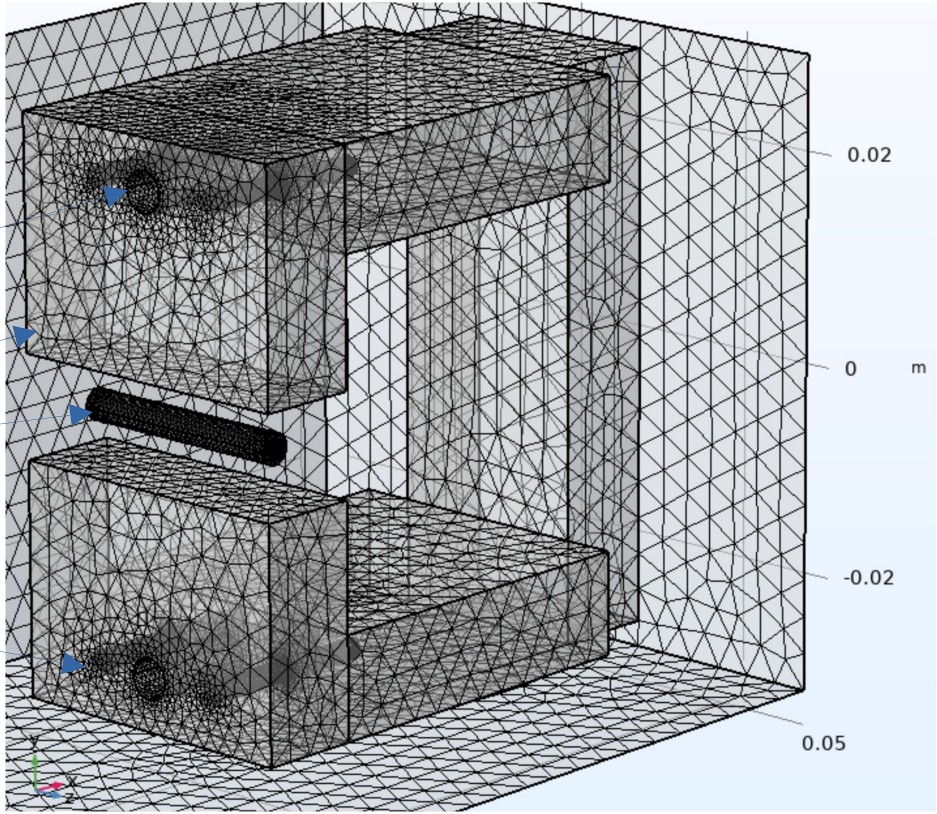
How to make the **external** B-field ?

- Electromagnet

magnet

capillary

Additional irregularities:
Screw, pin hole



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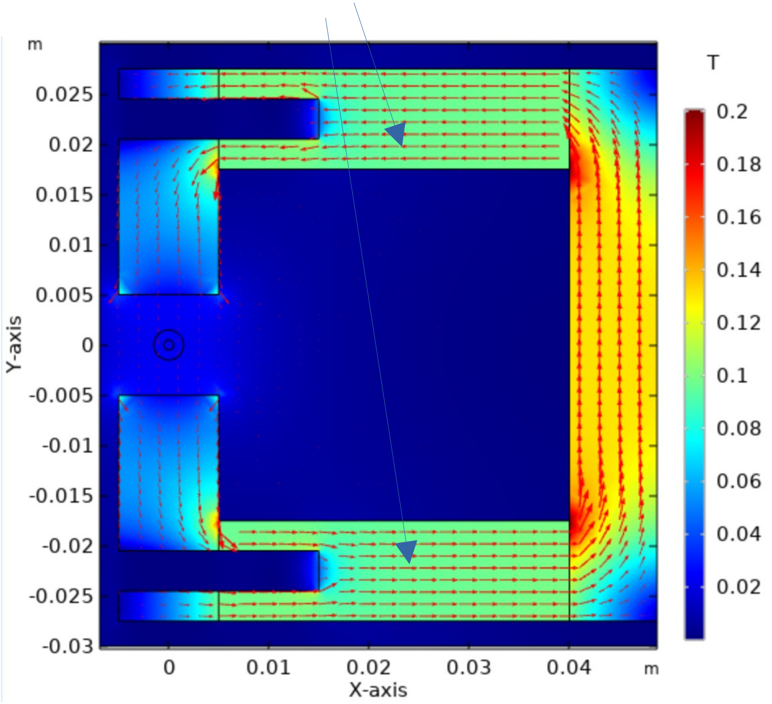
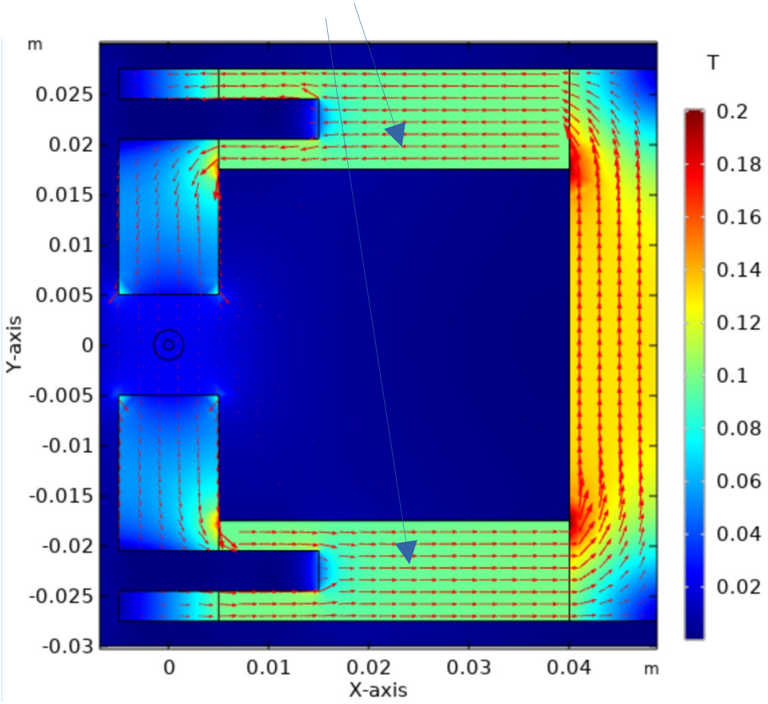
Assuming 0.1T magnetisation

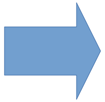


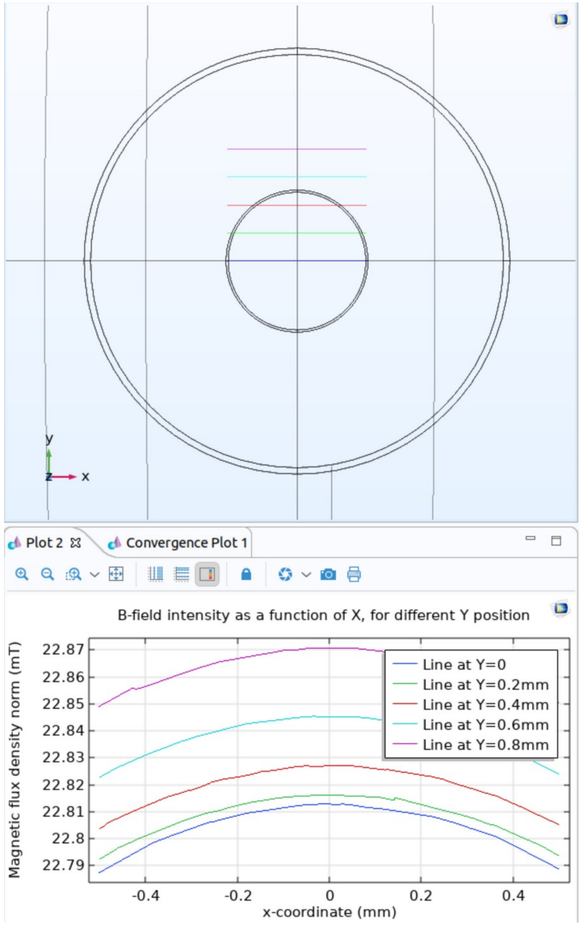
3. Non-linear plasma lens

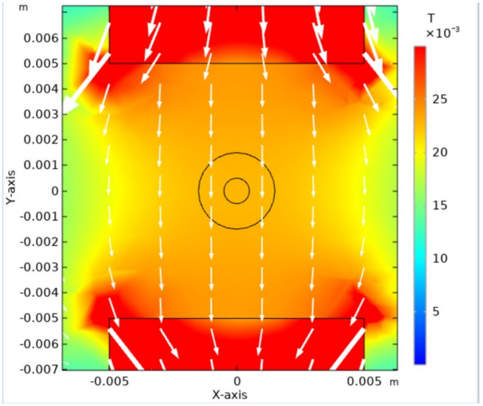
How to make the **external** B-field ?

Assuming 0.1T magnetisation









3. Non-linear plasma lens

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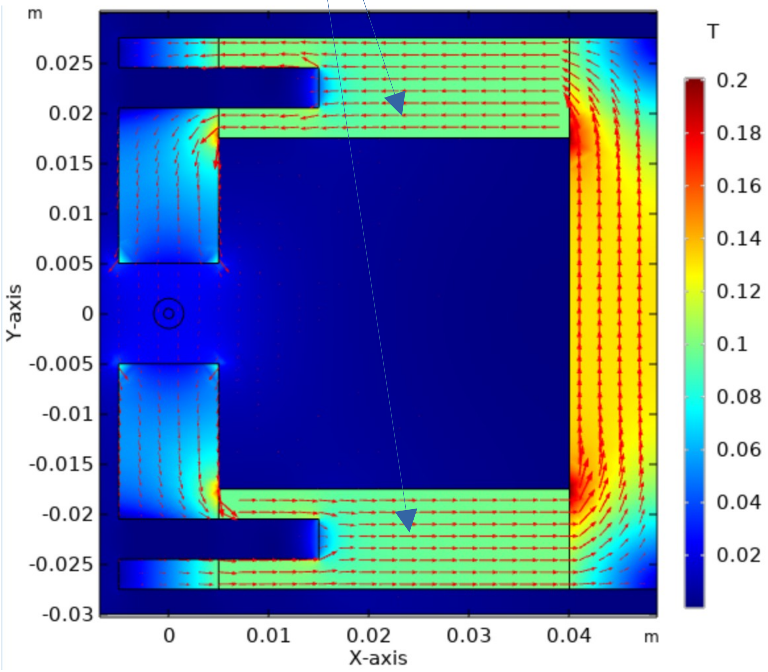

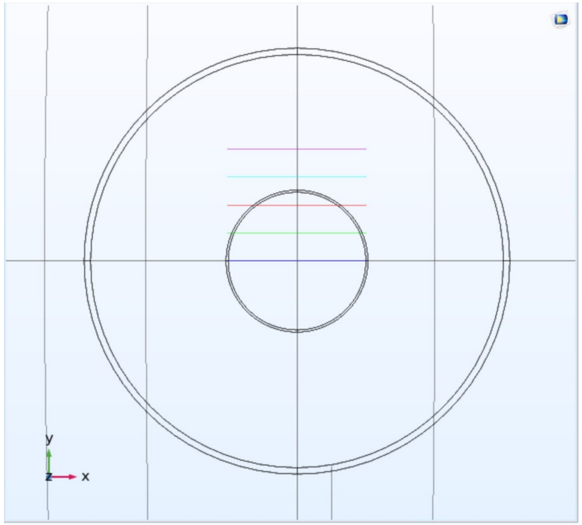

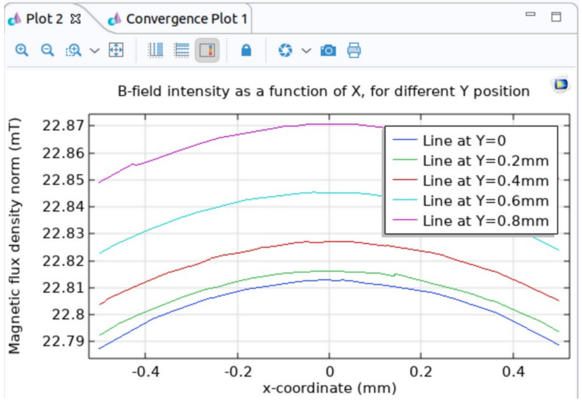

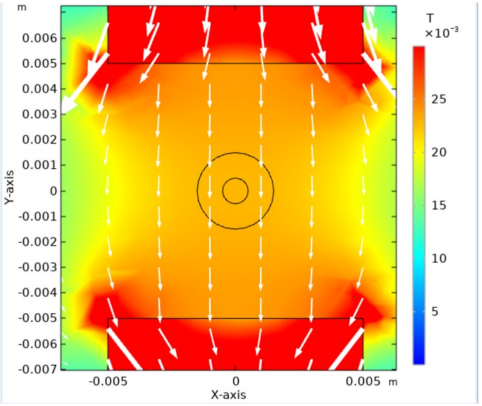

Uniform B
in the capillary

3. Non-linear plasma lens

3. Non-linear plasma lens

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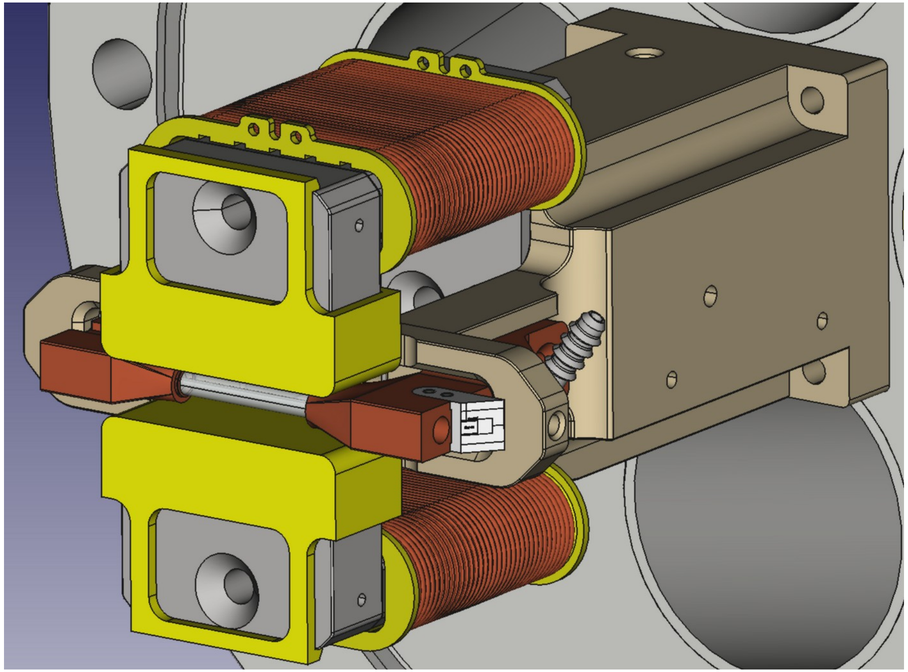
Design

3. Non-linear plasma lens

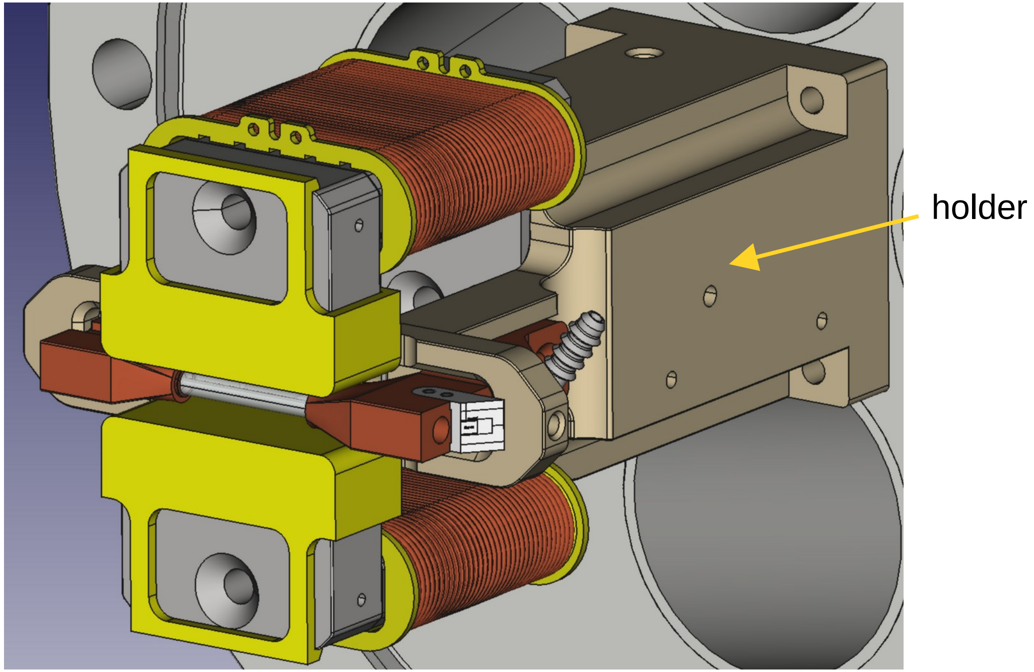
Design



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

3. Non-linear plasma lens

Design



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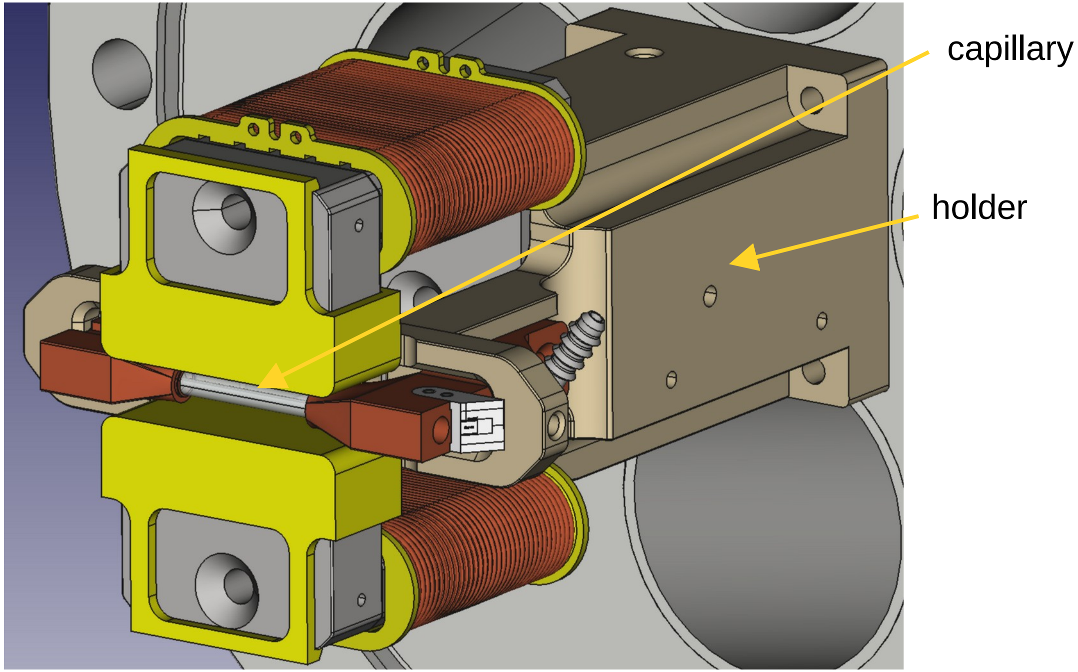

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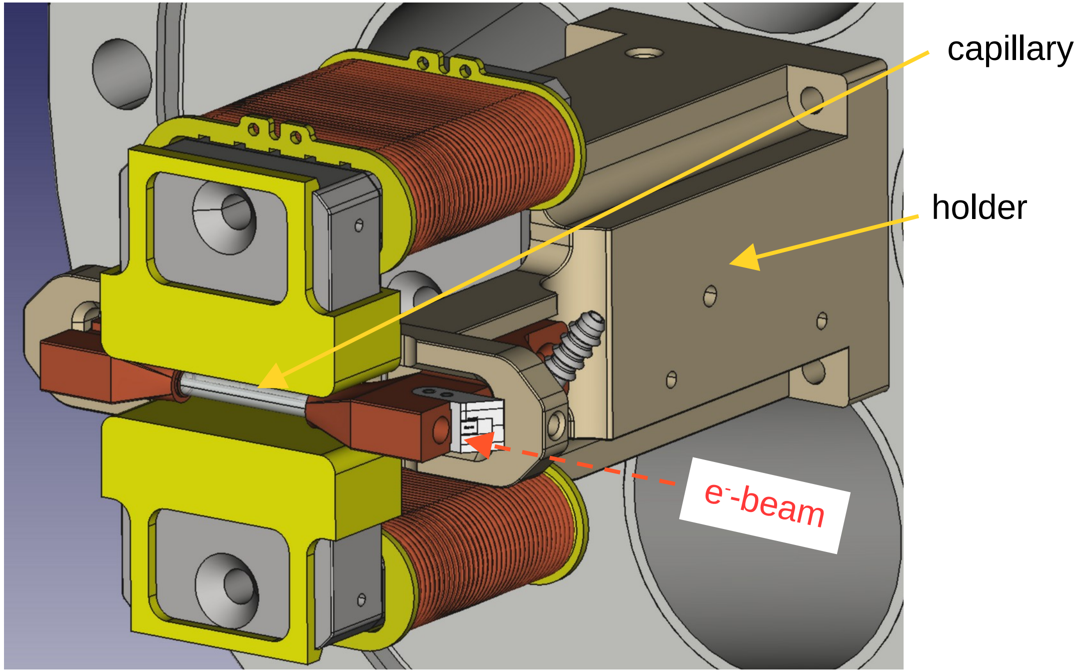

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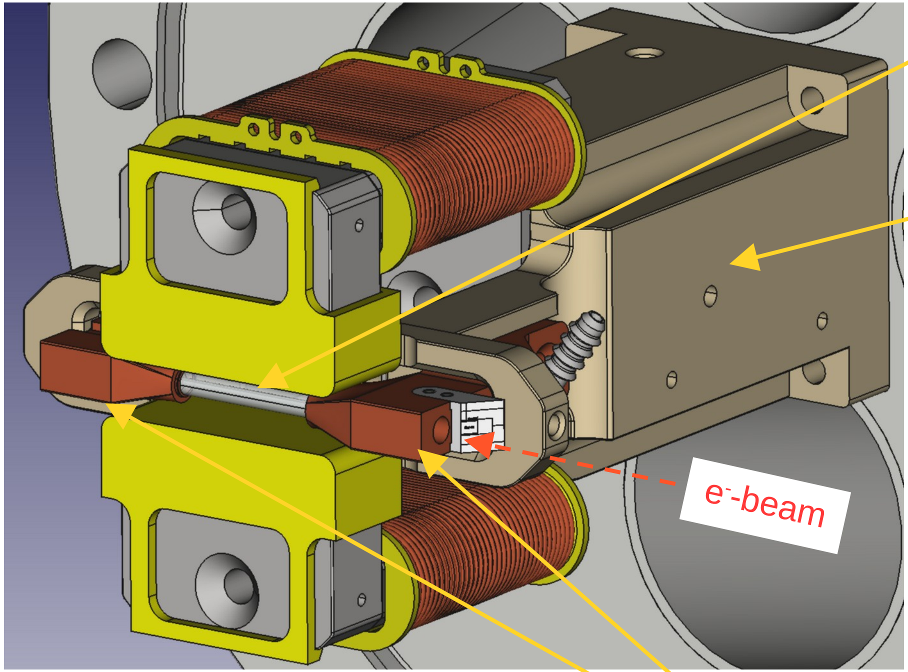

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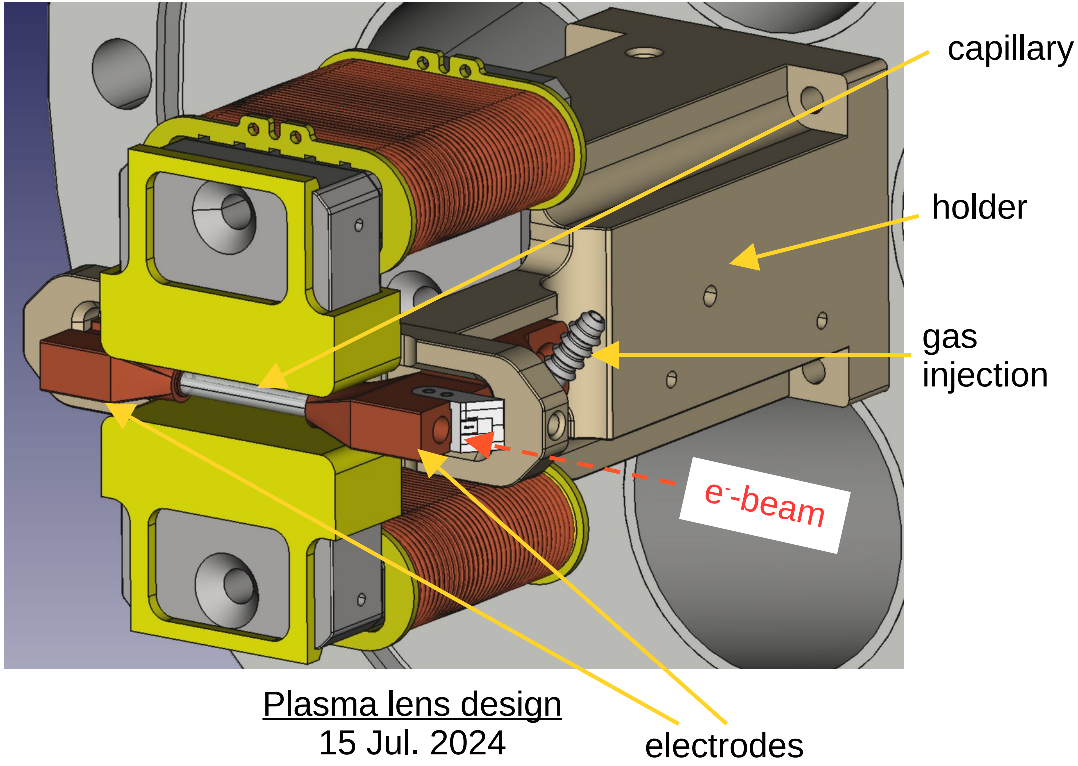

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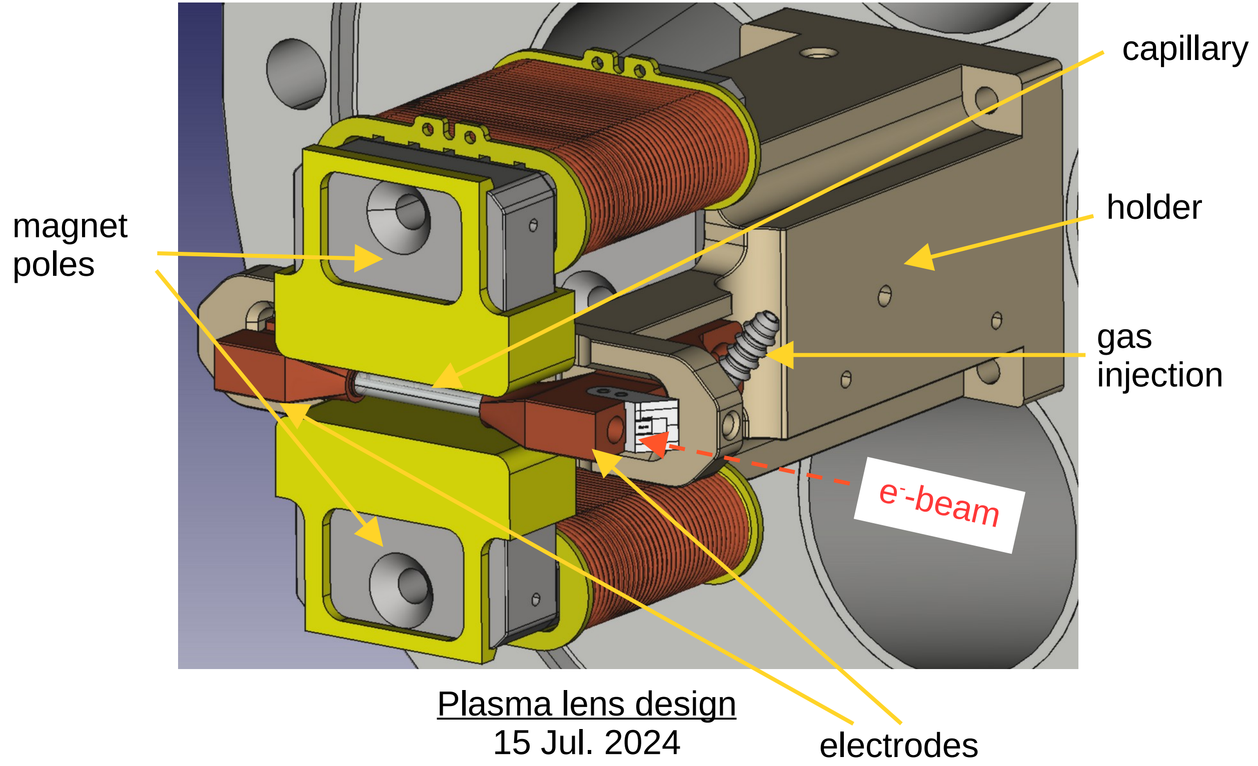

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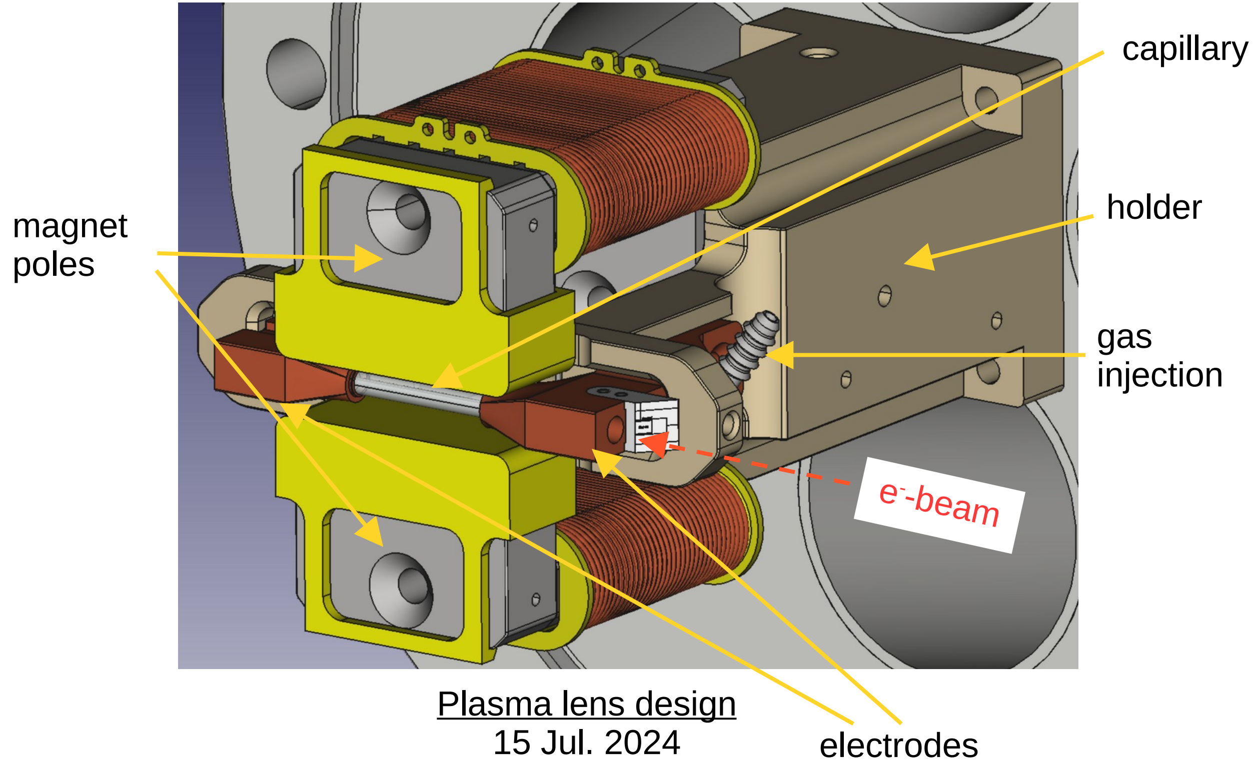
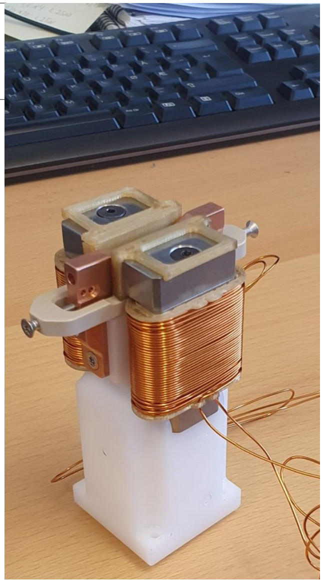


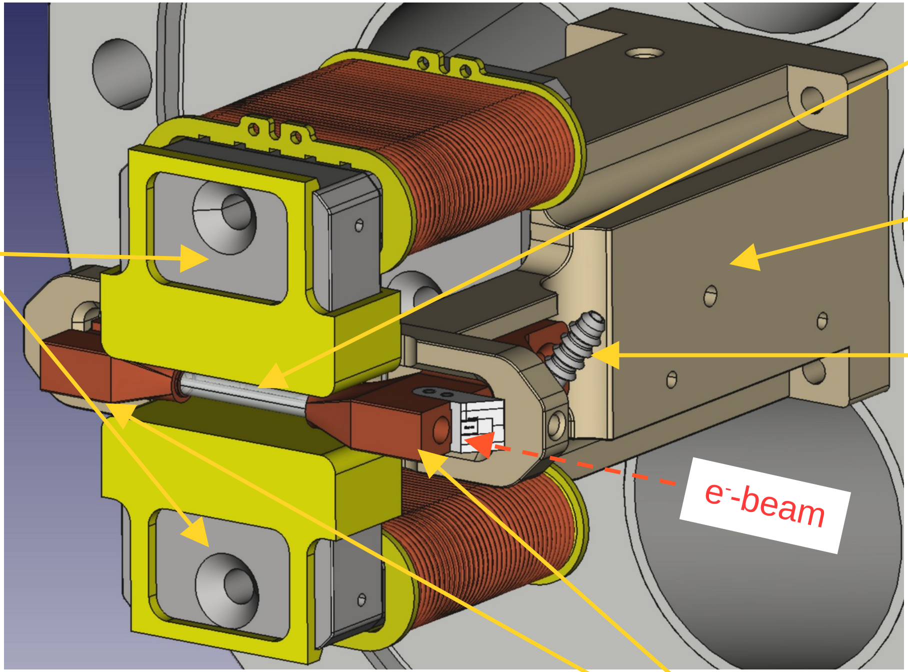
Plasma lens design
15 Jul. 2024
(Credits: I-Lab)

First built prototype,
5 Jul. 2024



3. Non-linear plasma lens

Design



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15 Jul. 2024
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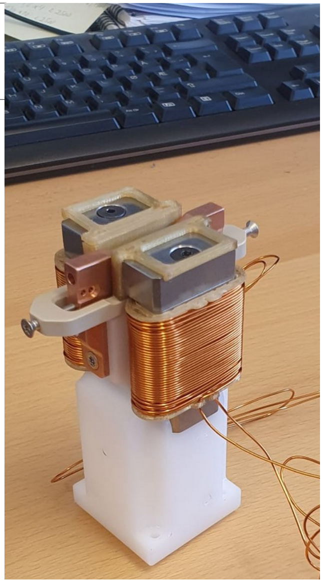
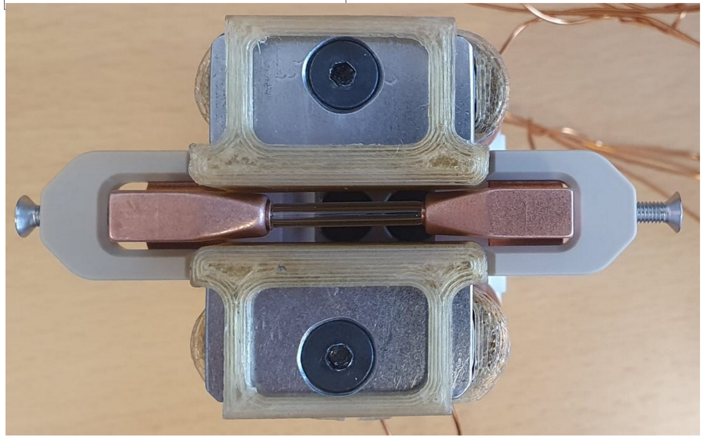


First built prototype,
5 Jul. 2024
(XY-plane)



4. Experimental campaign

Objectives

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- **Design preliminary tests** at UiO (everything that does not require an accelerator):

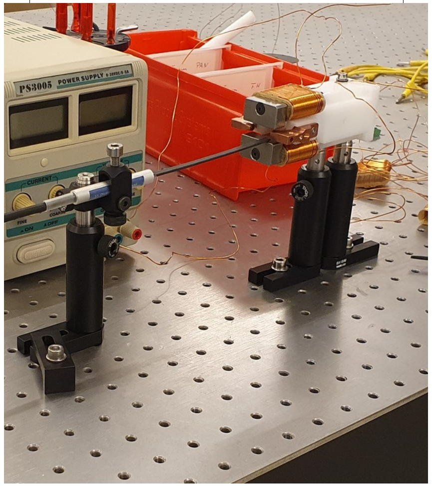
4. Experimental campaign

Objectives

- **Design preliminary tests** at UiO (everything that does not require an accelerator):
  - Assembly (dimensions, materials, technical solutions selected)

4. Experimental campaign

Current B-field measurements at UiO



Objectives

- **Design preliminary tests** at UiO (everything that does not require an accelerator):
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  - Electromagnet (**external** B-field measurement)

4. Experimental campaign

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>
> – Assembly (dimensions, materials, technical solutions selected)
>
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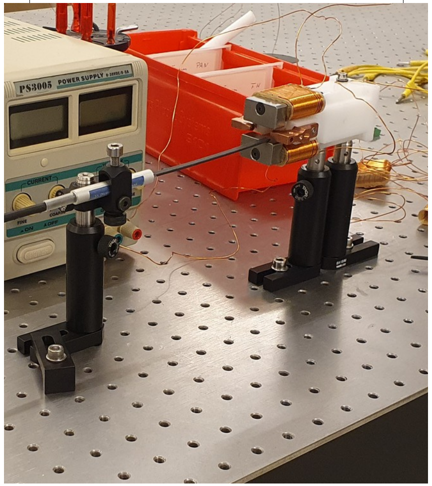
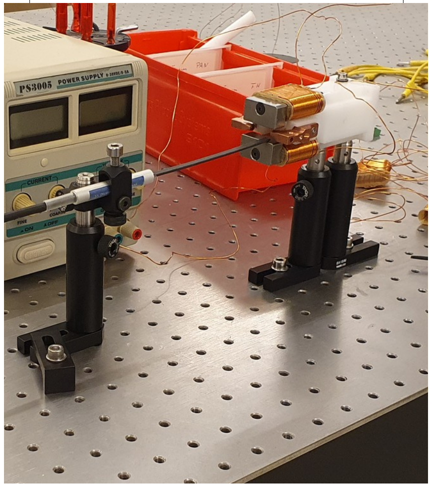
> **Real operating condition** tests (accelerator facilities):

Current B-field measurements at UiO



4. Experimental campaign

Current B-field measurements at UiO



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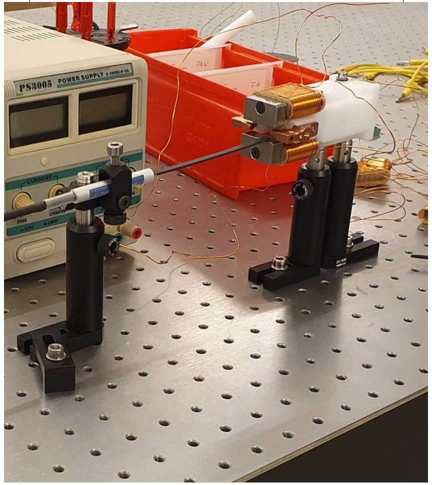
  - Assembly (dimensions, materials, technical solutions selected)
  - Electromagnet (**external** B-field measurement)
- **Real operating condition** tests (accelerator facilities):
  - Short term: **characterise the lens** = map the **total** B-field in the XY-plane → **CLEAR (see next slides)**

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)**
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CERN

4. Experimental campaign

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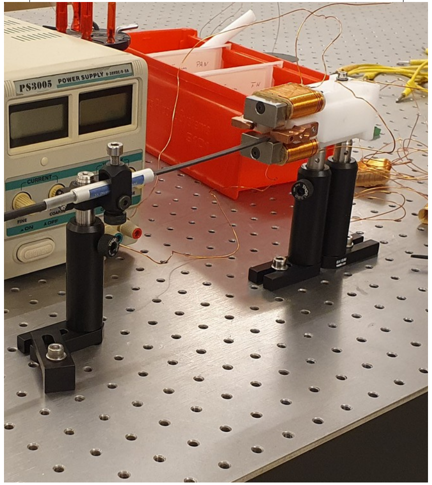

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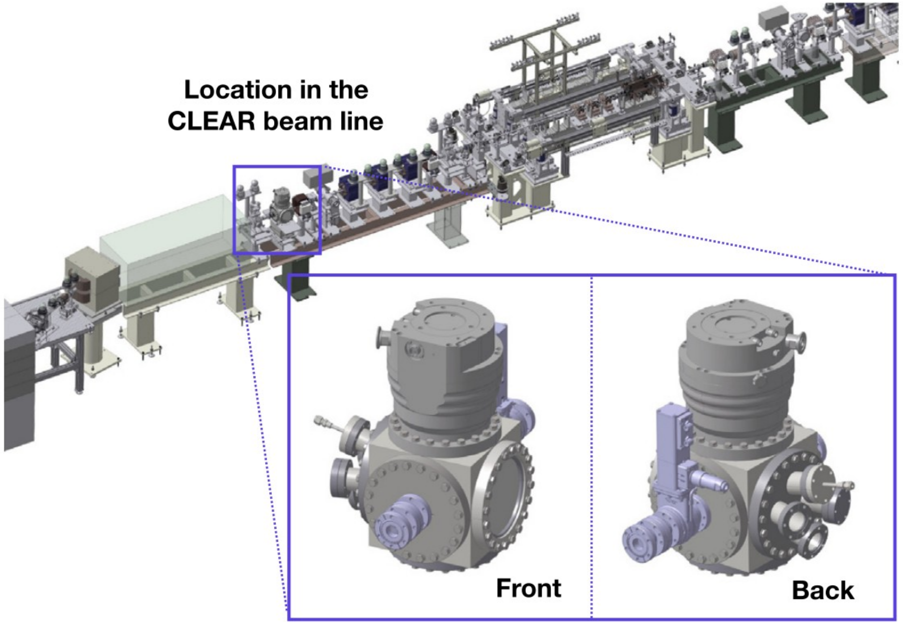
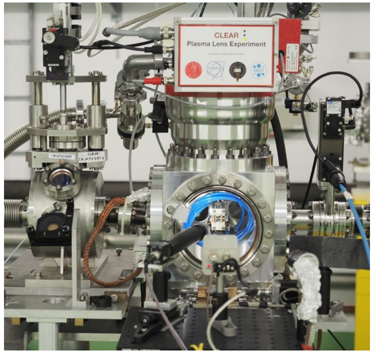
4. Experimental campaign

Existing CLEAR facility and set-up

4. Experimental campaign

Existing CLEAR facility and set-up



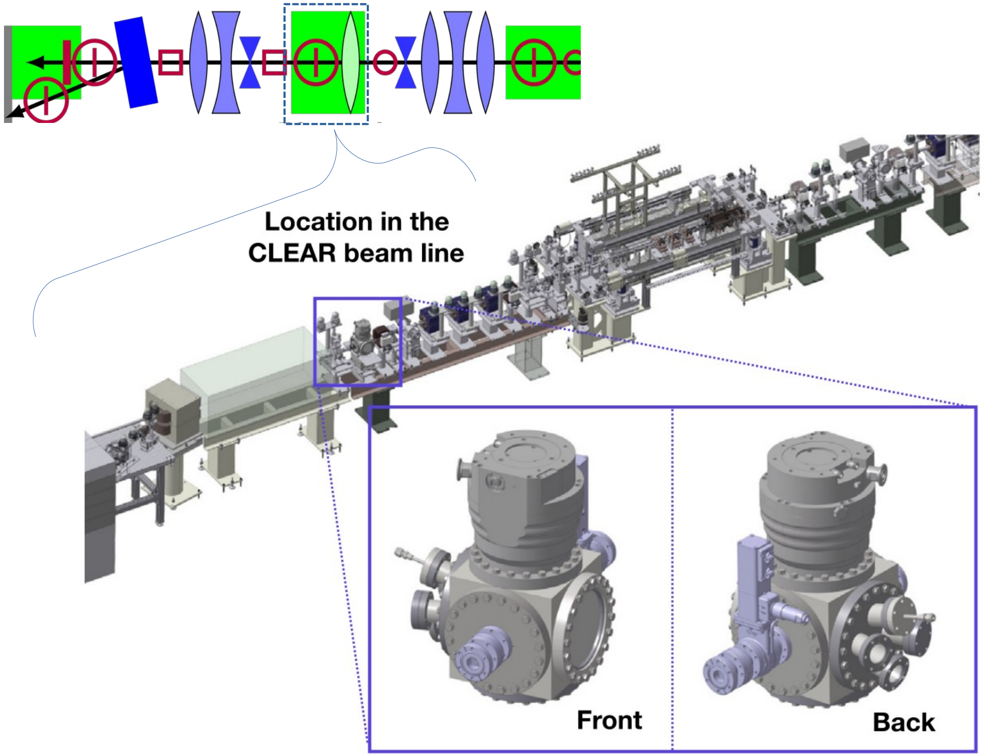


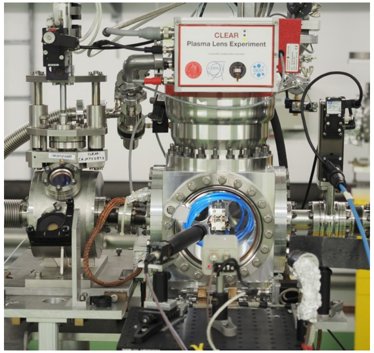
Existing **Plasma Lens Experiment** set-up at CLEAR [7]

[7] Credits to Kyrre Sjøbæk

4. Experimental campaign

Existing CLEAR facility and set-up





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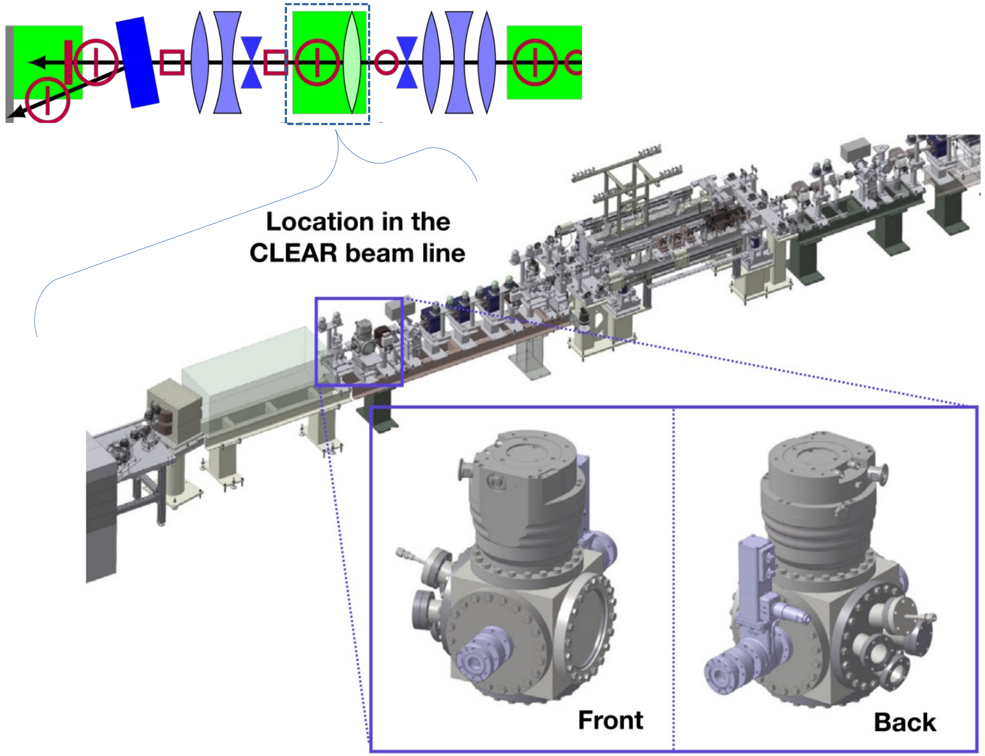

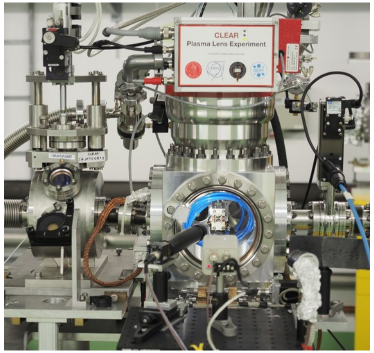

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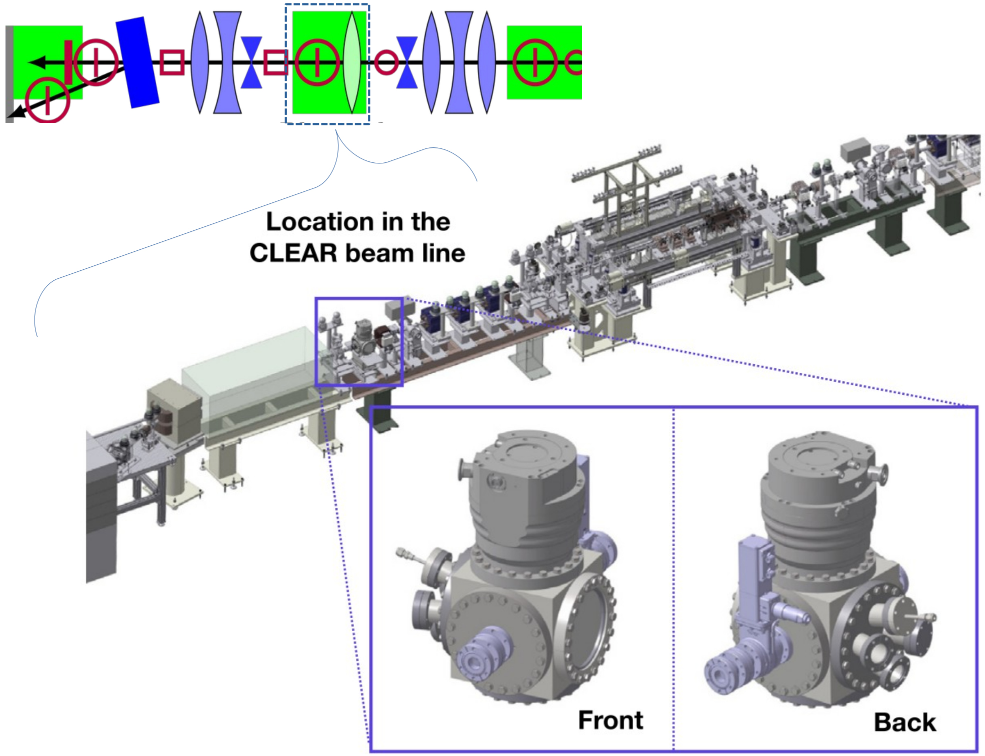

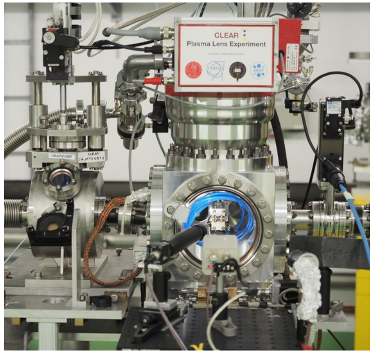

- **Beam parameters:**
  - 60-200 MeV,

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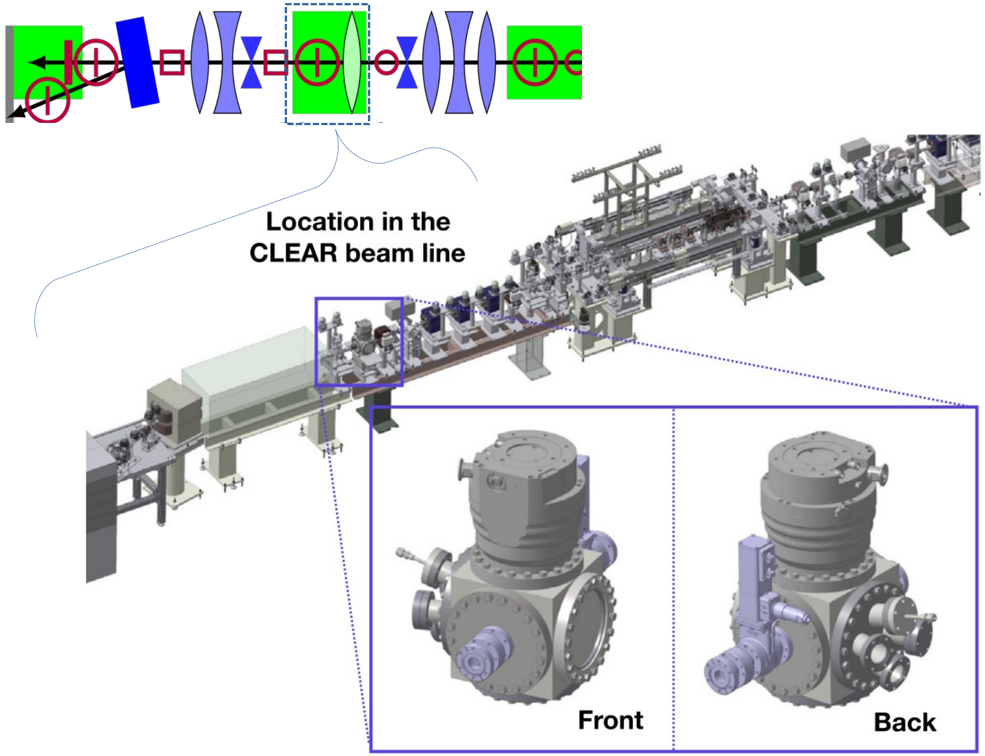

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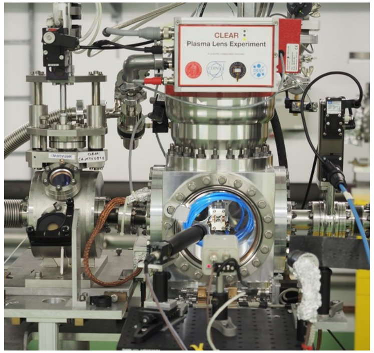

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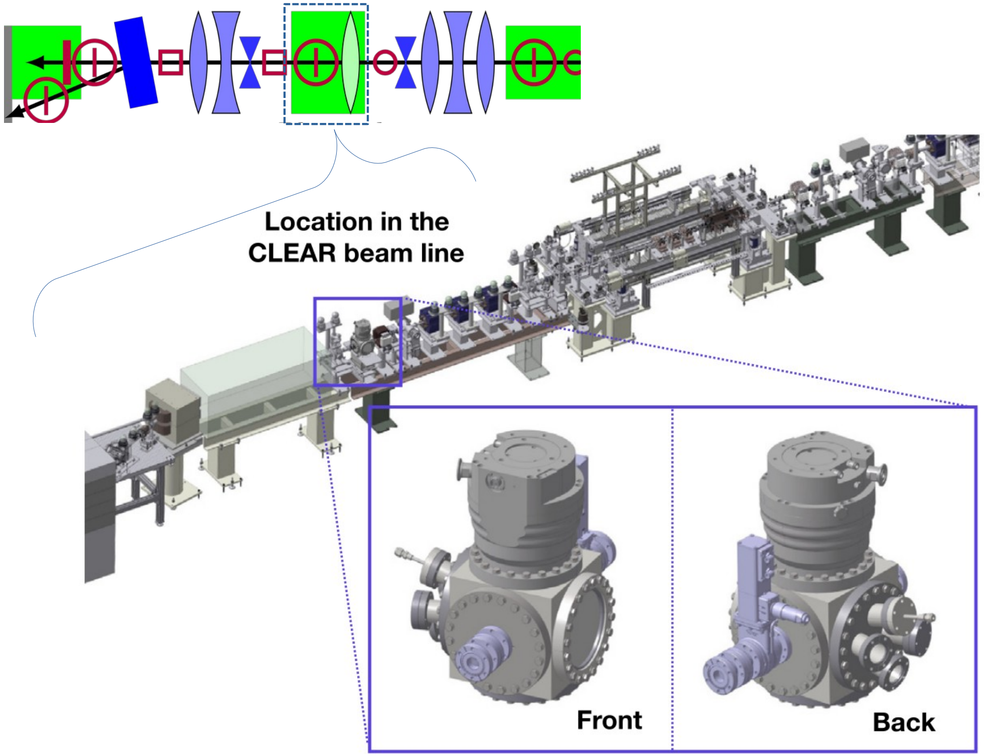

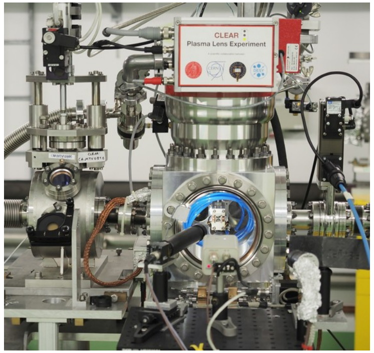

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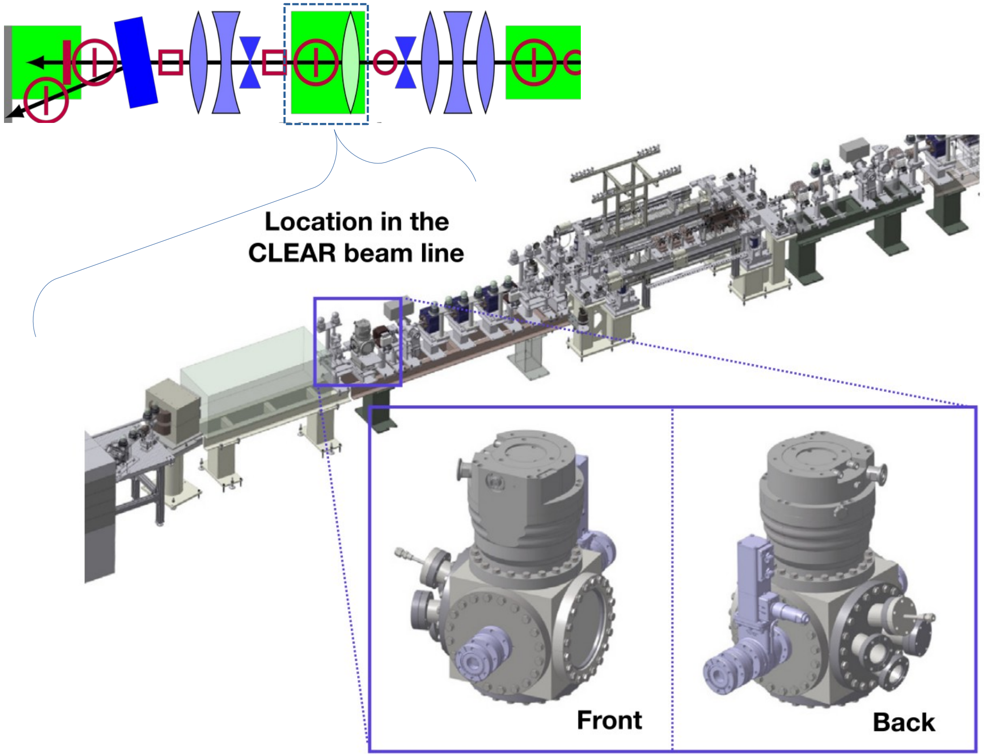

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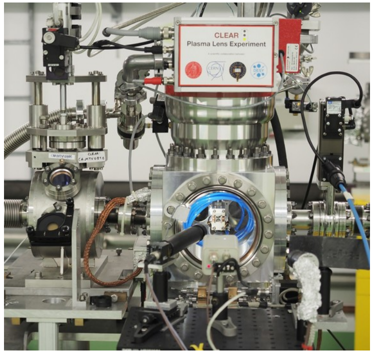

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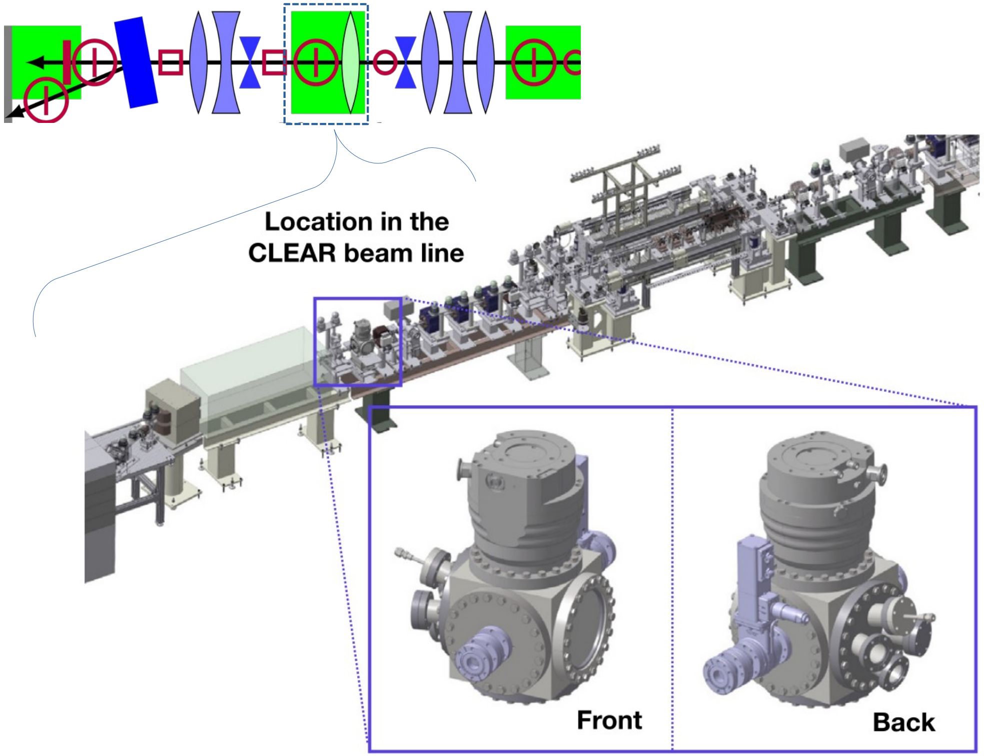

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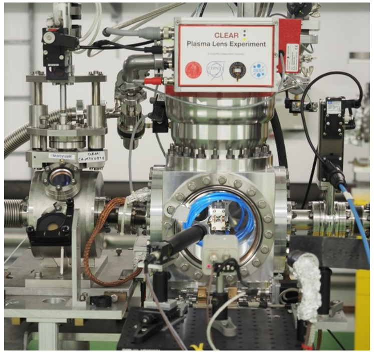

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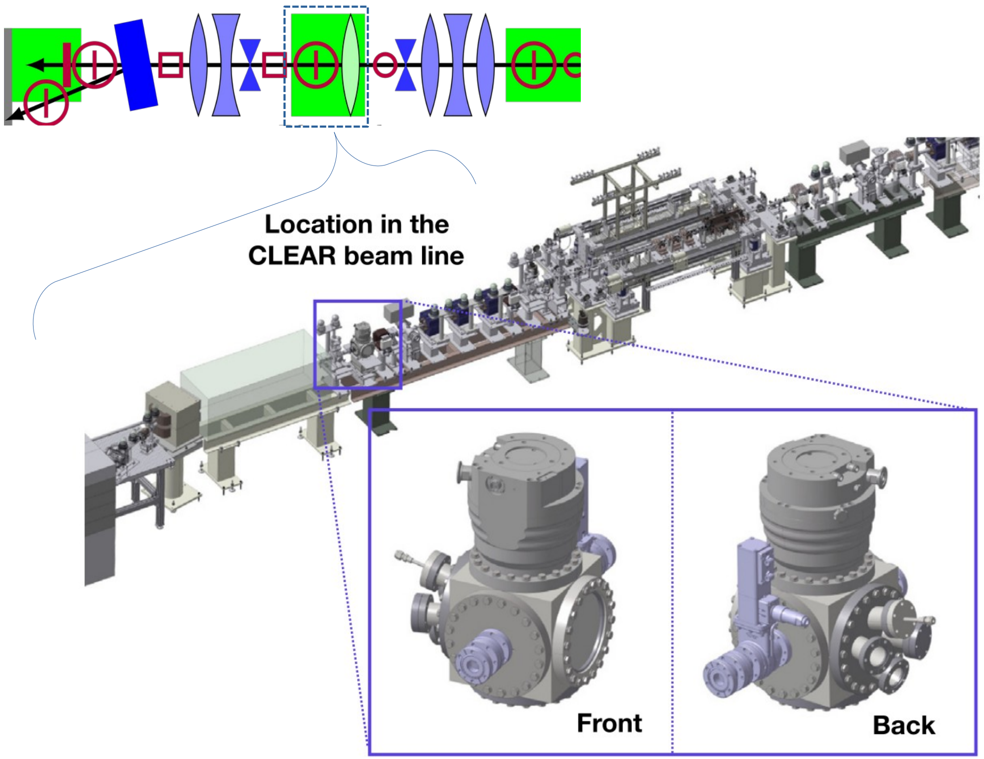

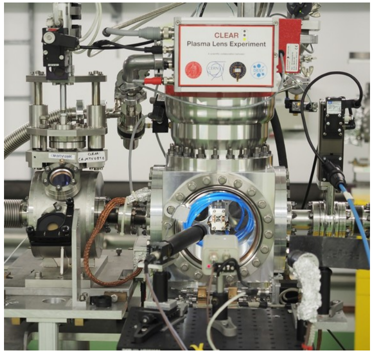

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4. Experimental campaign

2024 at CLEAR

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4. Experimental campaign

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4. Experimental campaign

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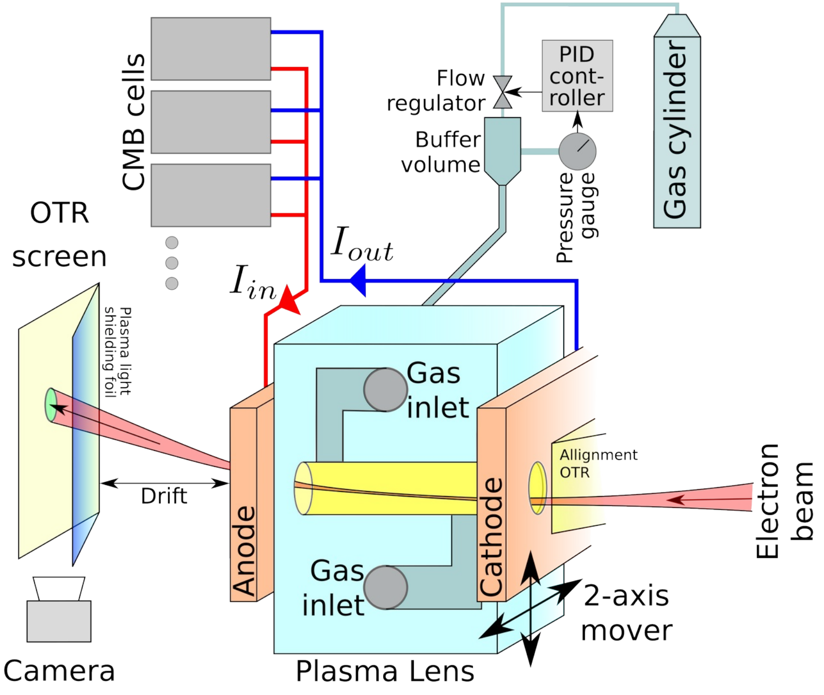

Schematic of the CLEAR Plasma Lens Experiment [8]

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

Conclusion

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- Other developments:
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  - Long term objective: **full achromatic staging** (2 lenses)

Acknowledgments

University of Oslo accelerator group:
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Maxence Thévenet, Mathis Mewes

SPARTA team:
Carl A. Lindstrøm (P.I.), Daniel Kalvik, Pierre Drobniak

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