SPARTA:
Staging of Plasma Accelerators for Realizing Timely Applications

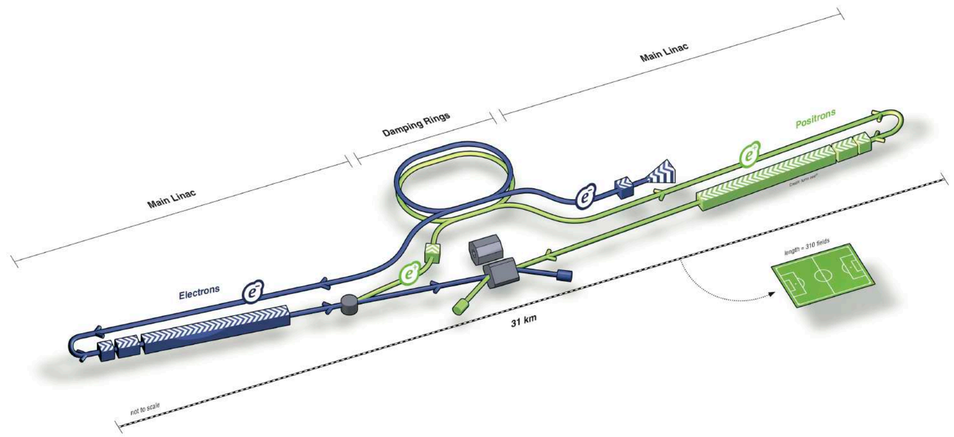
NorCC workshop
27 Sep 2023
Bergen, Norway

Carl A. Lindstrøm
Department of Physics, University of Oslo

Problem: Future high-energy physics = too expensive

- Consensus: build e^+–e^- collider
- *Linear colliders* (e.g., ILC) or *circular colliders* (e.g., FCC) → €10B scale

  ↳ cost driven by RF accelerating gradient (~100 MV/m)



International Linear Collider

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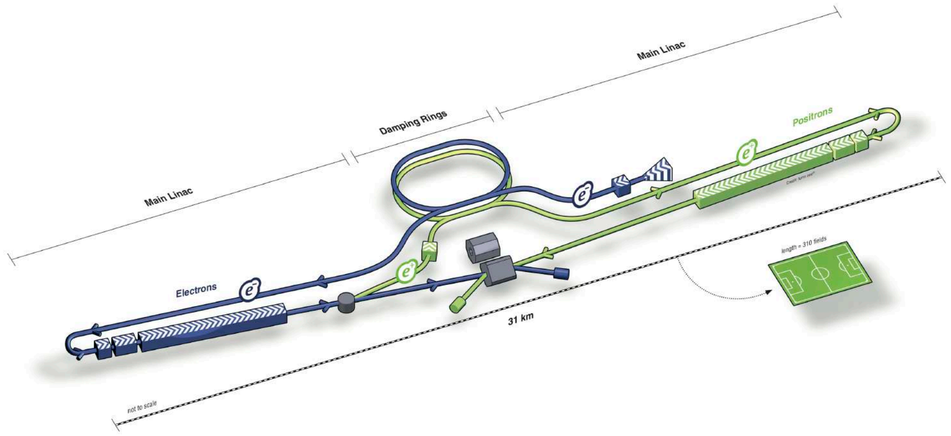
- EU Strategy for Particle Physics 2020[1]:
  - *"…**intensification of R&D** is required."*
  - e.g. *"Development and exploitation of **laser/plasma acceleration** techniques"*

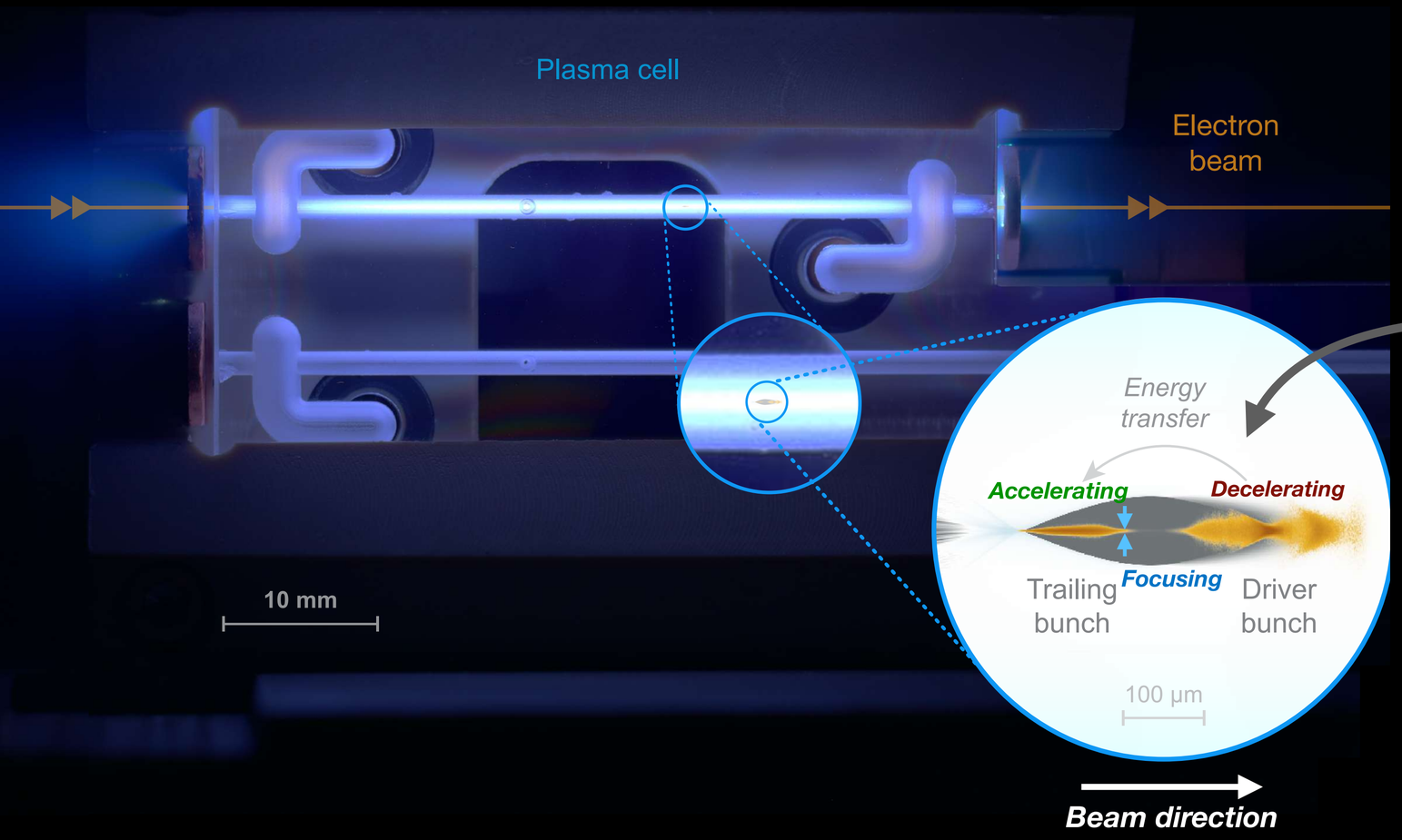


International Linear Collider

[1] European Strategy for Particle Physics - Accelerator R&D Roadmap (2022)

Solution: Plasma-based particle accelerators

Higher gradients (10–1000×, GV/m-scale) → shorter/cheaper accelerators



- *Plasma wakefields*:
  - Driven by **lasers** or **particle beams**
  - **Accelerating**, **focusing**
  - 10–100 μm-scale (tiny!)

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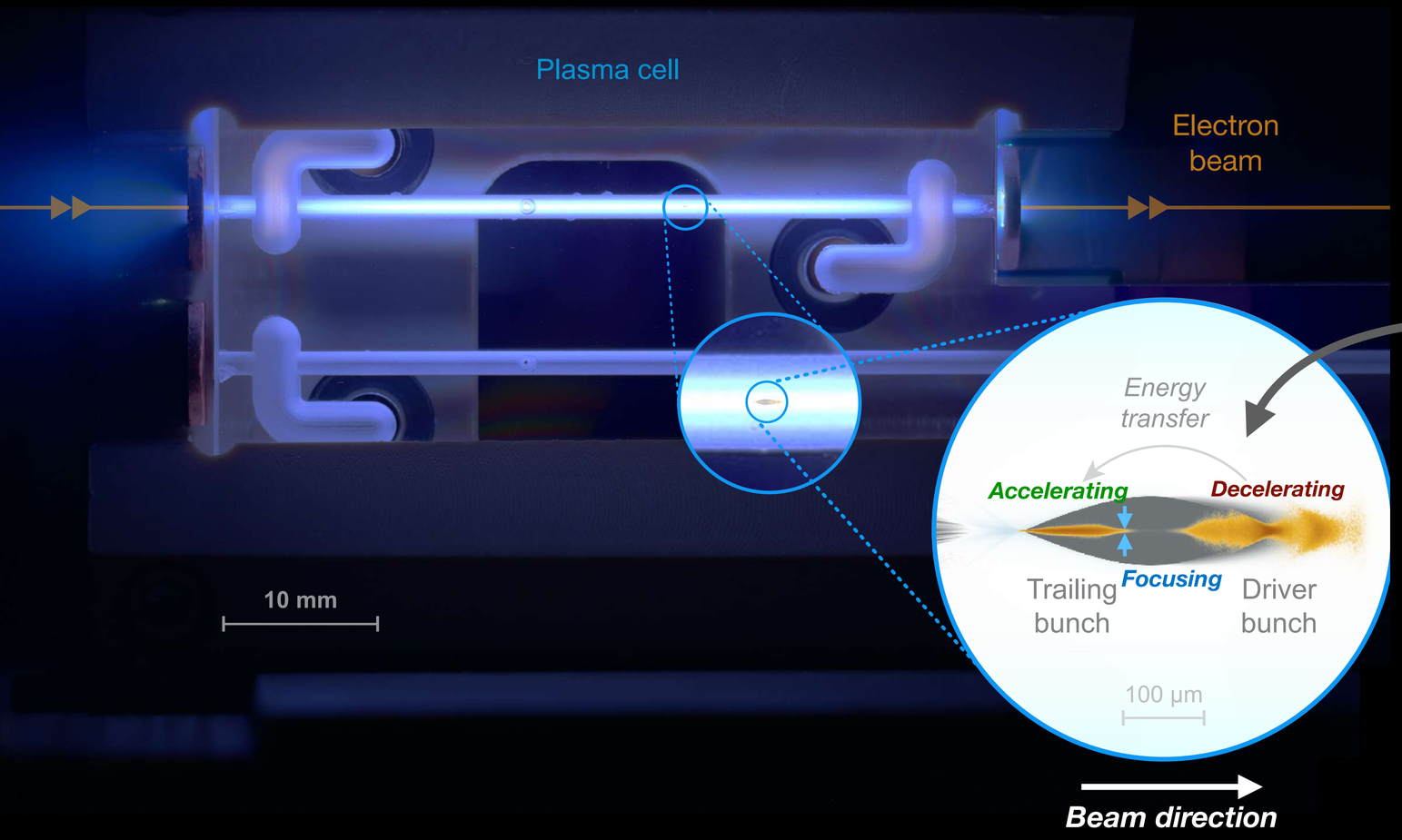

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  - Driven by **lasers** or **particle beams**
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- Recent application: FELs[2,3]
  - Why not HEP?

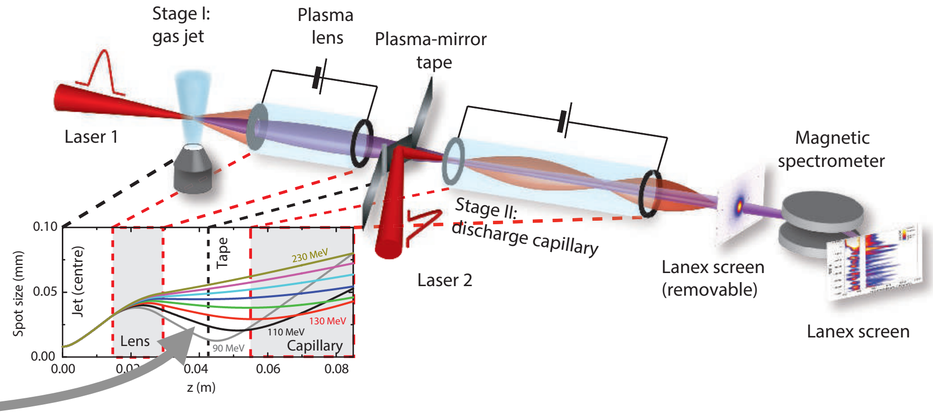
[2] Wang *et al.*, **Nature** 595, 516 (2021)
[3] Pompili *et al.*, **Nature** 605, 659 (2022)

Fundamental challenges: Prompting rethink of plasma accelerators

Staging (high energy unreachable in single stage) and ***stability***

1. **Staging problem**: *coupling beams between plasma accelerators (stages)*

   - In- and out-coupling of drivers
   - Refocusing beams → chromaticity



Steinke et al., Nature 530, 190 (2016)

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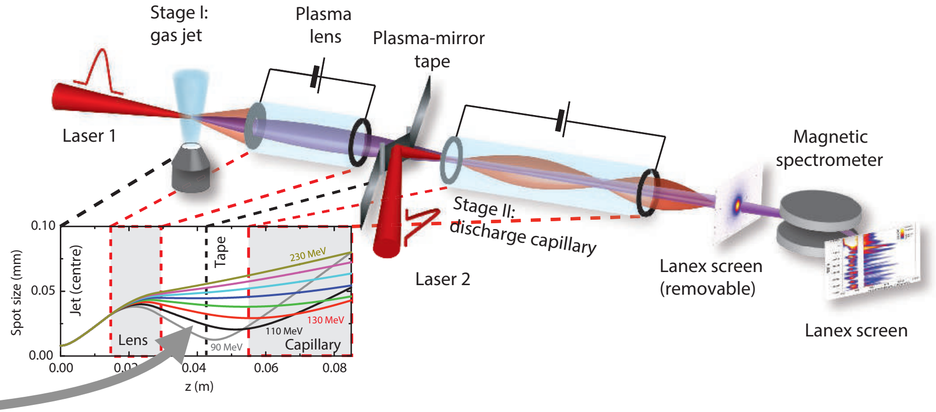

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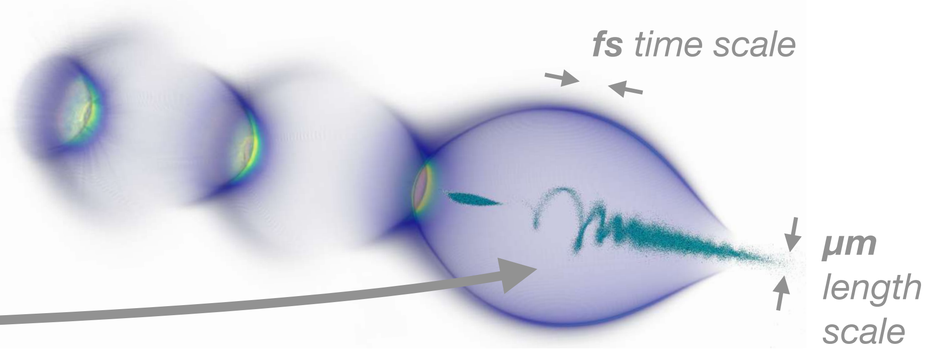
2. **Stability problem**: *extreme sensitivity*
   - µm/fs tolerances on alignment/timing
   - Instabilities

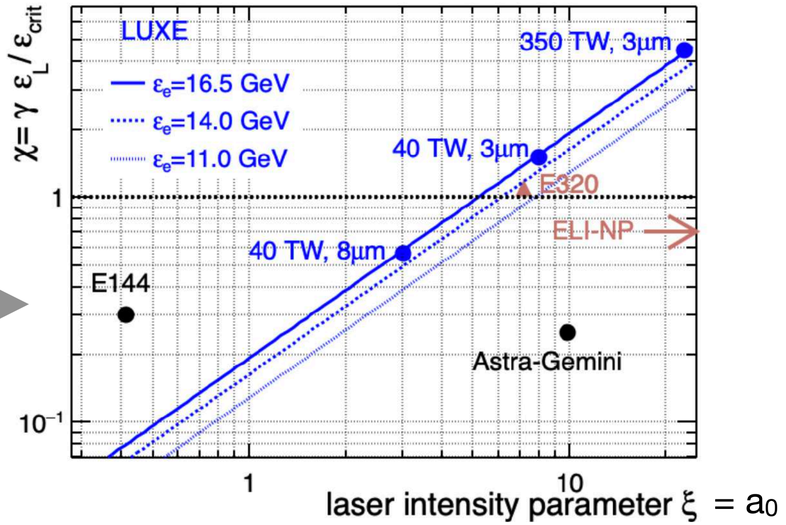


Particle-in-cell (PIC) simulation. Source: VisualPIC

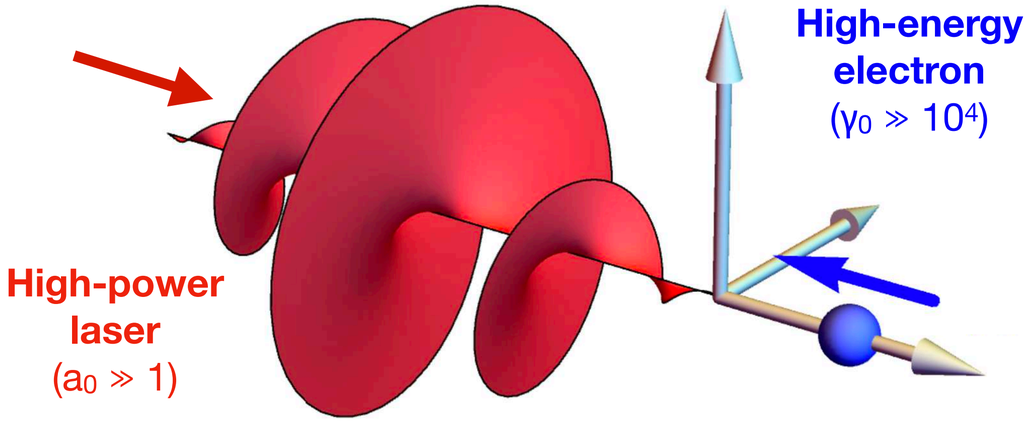
Near-term application: Strong-field QED

Tech demonstrator for *high energy* and *stability*

- Schwinger field: ~10^{18} V/m ⋙ high-power lasers
- Collide high-power laser with high-energy e^- → boost field
- Experiments reached $\chi \approx 0.3$ (fraction of Schwinger field)
  - $\chi \approx 10$–100 → lab astrophysics (e.g., surface of magnetars)
  - $\chi \gtrsim 1000$ → no theory! (new physics, emergent properties?)



LUXE Collaboration, EPJ-ST 230, 2445 (2021)



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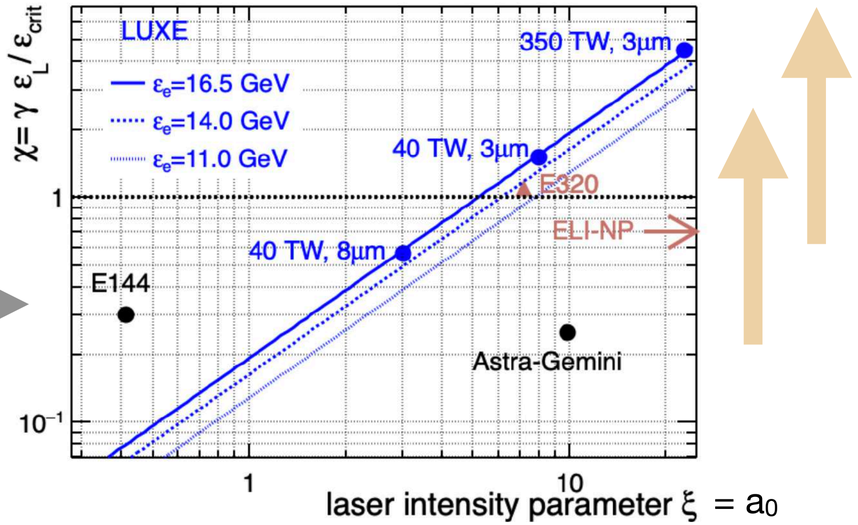

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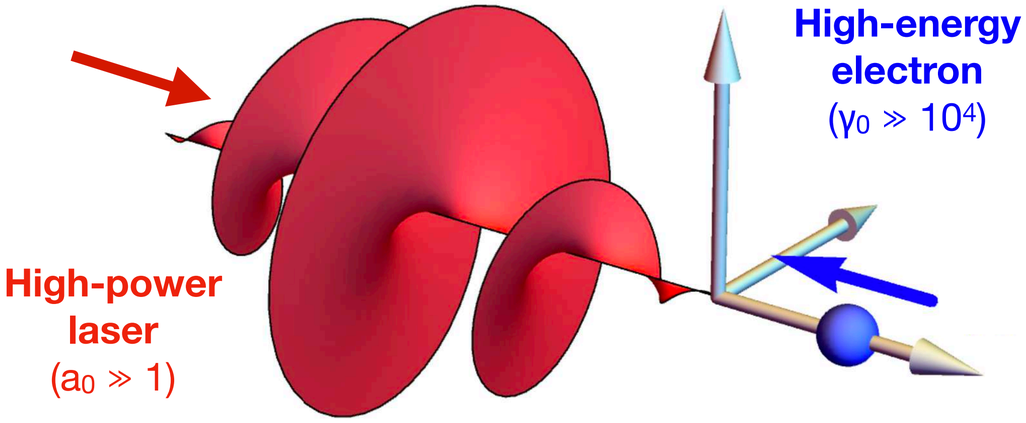

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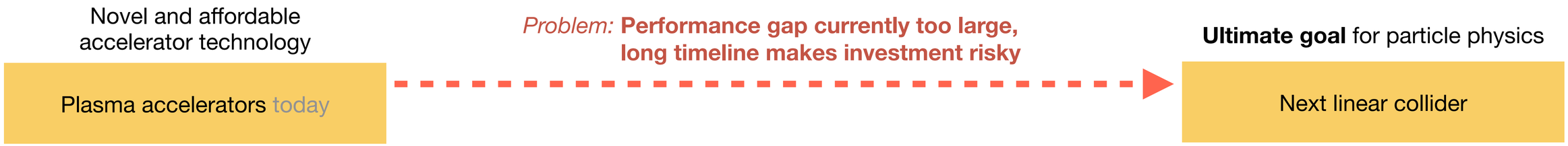
- Plasma-based SFQED machine → ***win-win***
  - 🥳 ***for SFQED research:***
    cheap, high-energy e^- → new experiments *($\chi \gg 1$)*
  - 💪 ***for plasma accelerators:***
    "minimal viable product" for HEP
    (high energy/stability—low quality/rep. rate)

The SPARTA project

A flow chart



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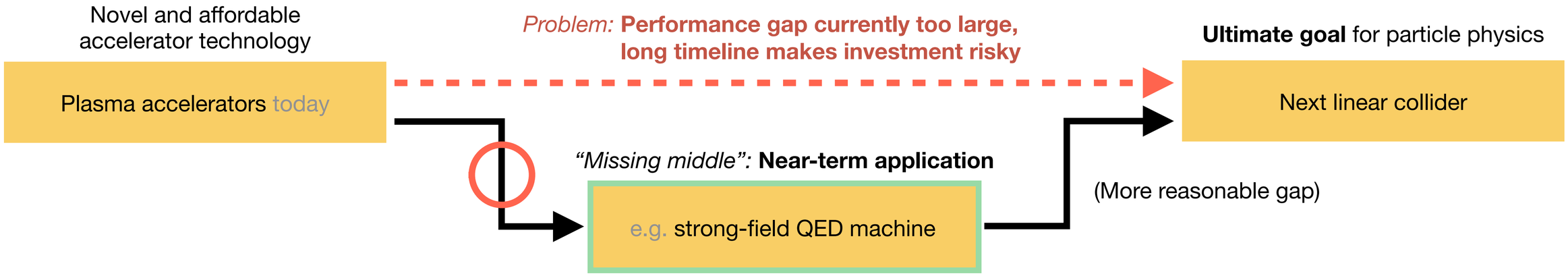

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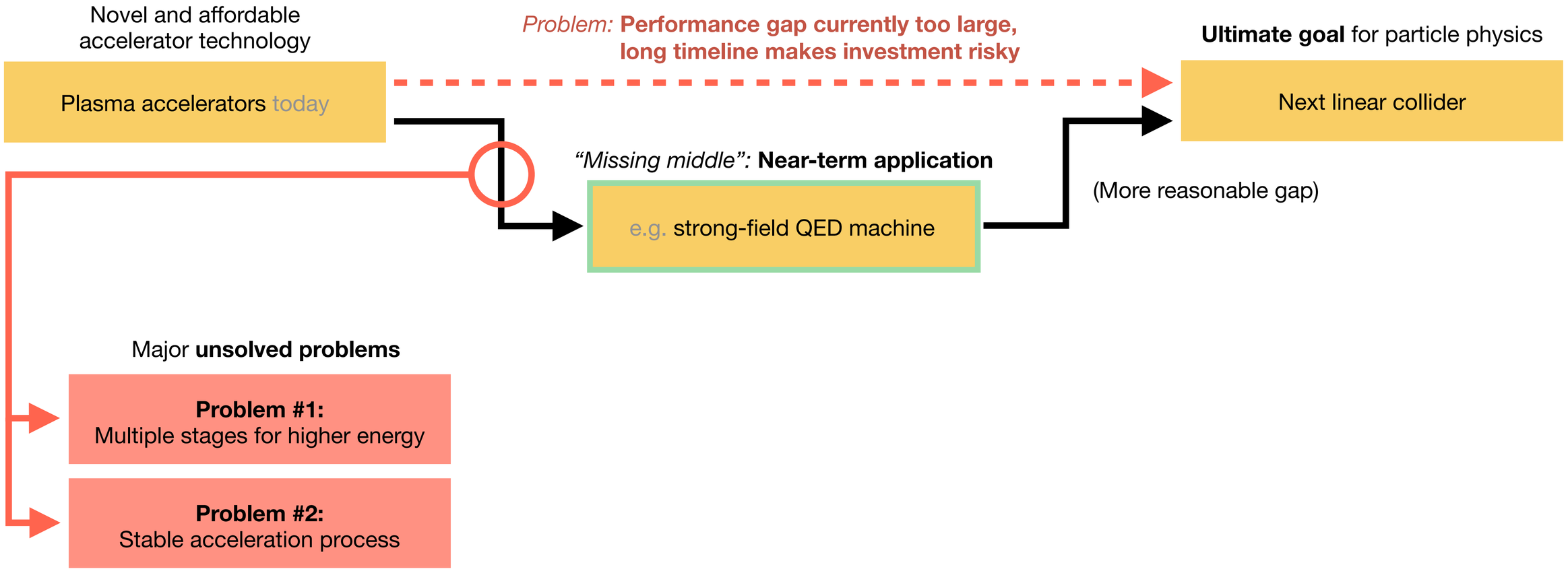

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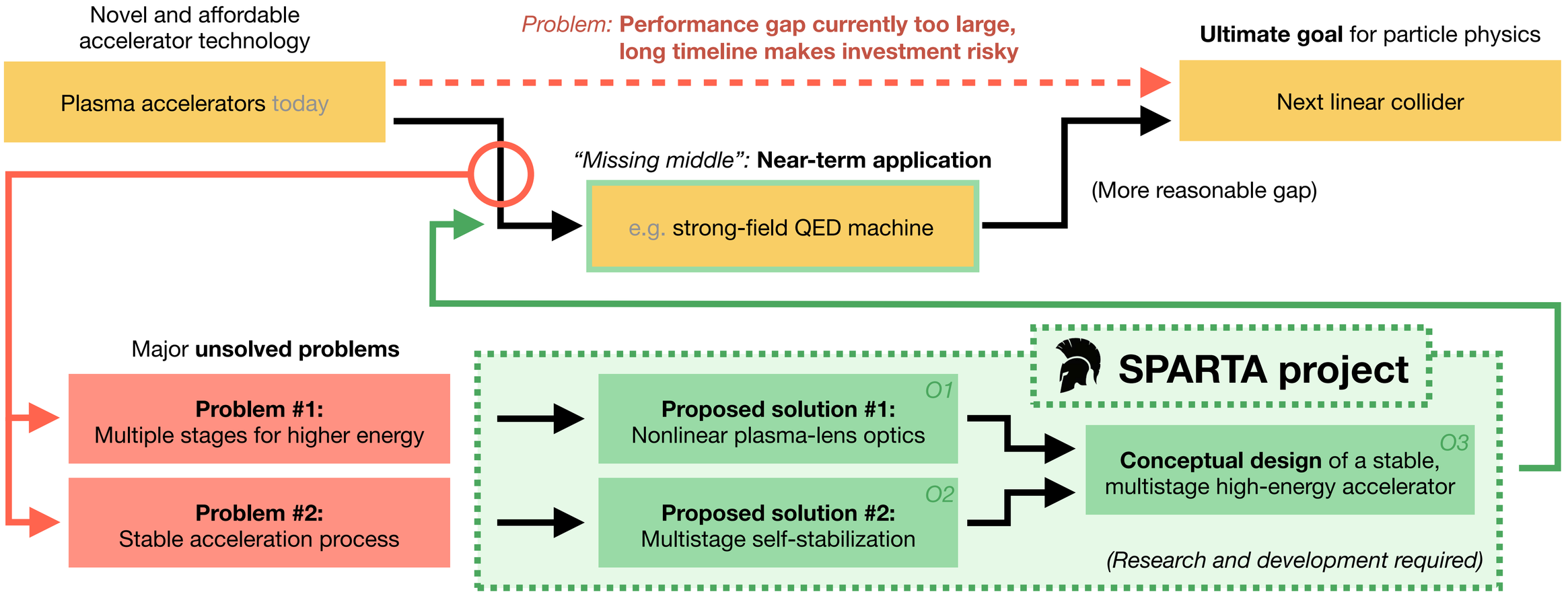

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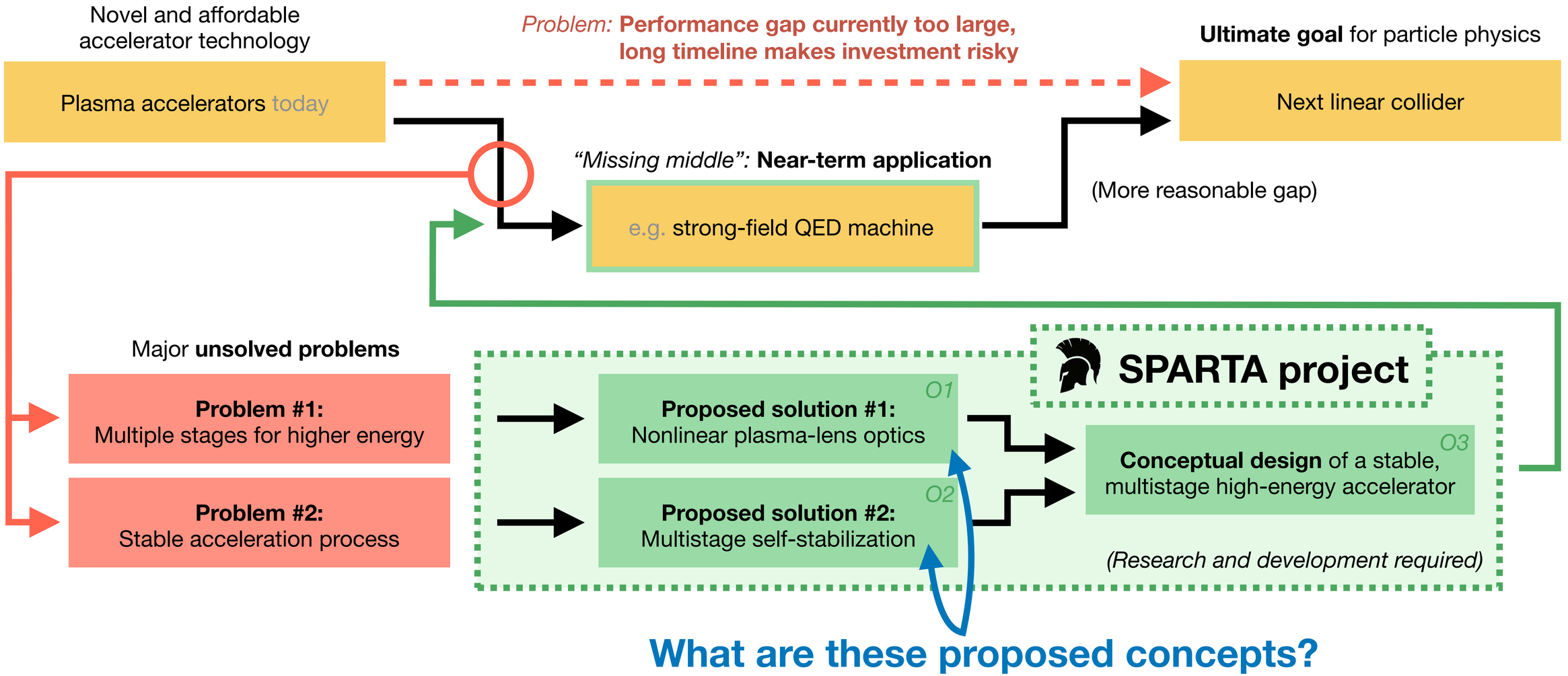
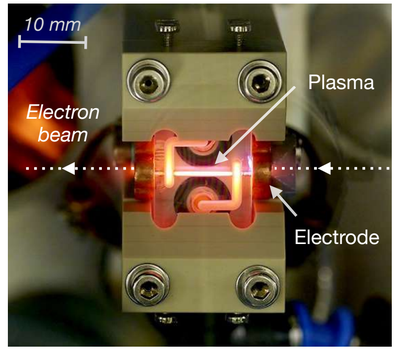


New concept #1: Nonlinear plasma lenses

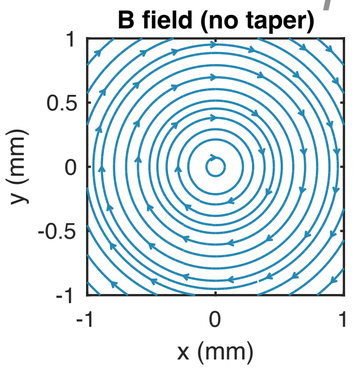
A new kind of plasma accelerator — ***solving staging***

- Plasma lens = strong, compact focusing device



"Active" plasma lens
= discharge current

Linear
(chromatic)



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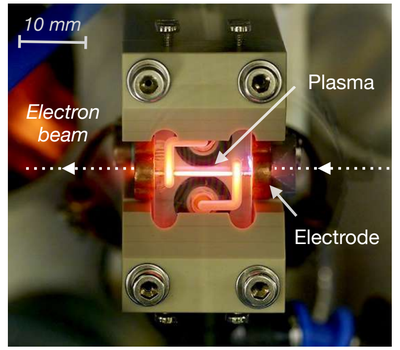

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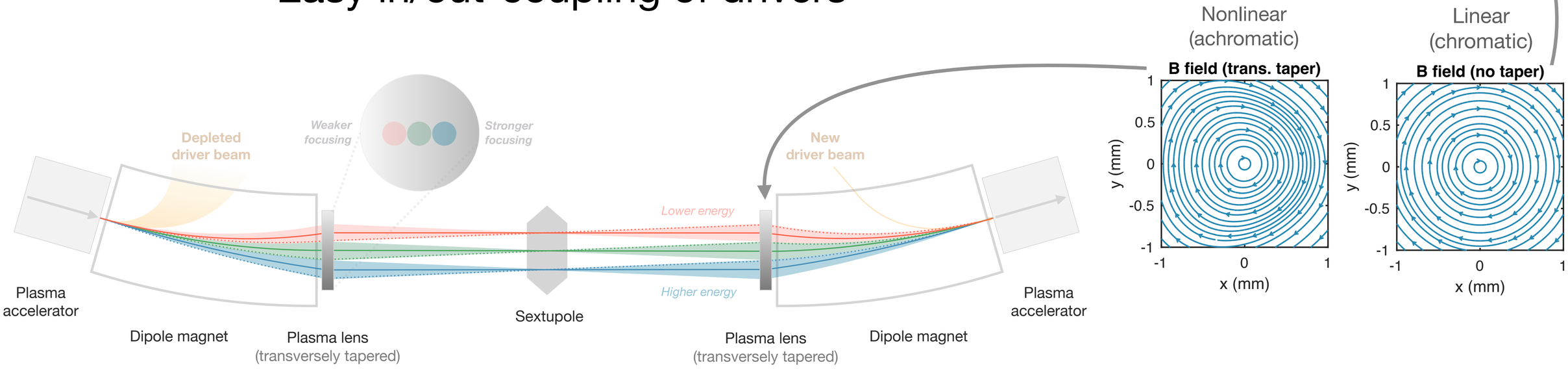

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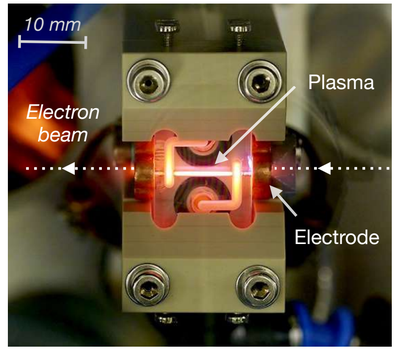

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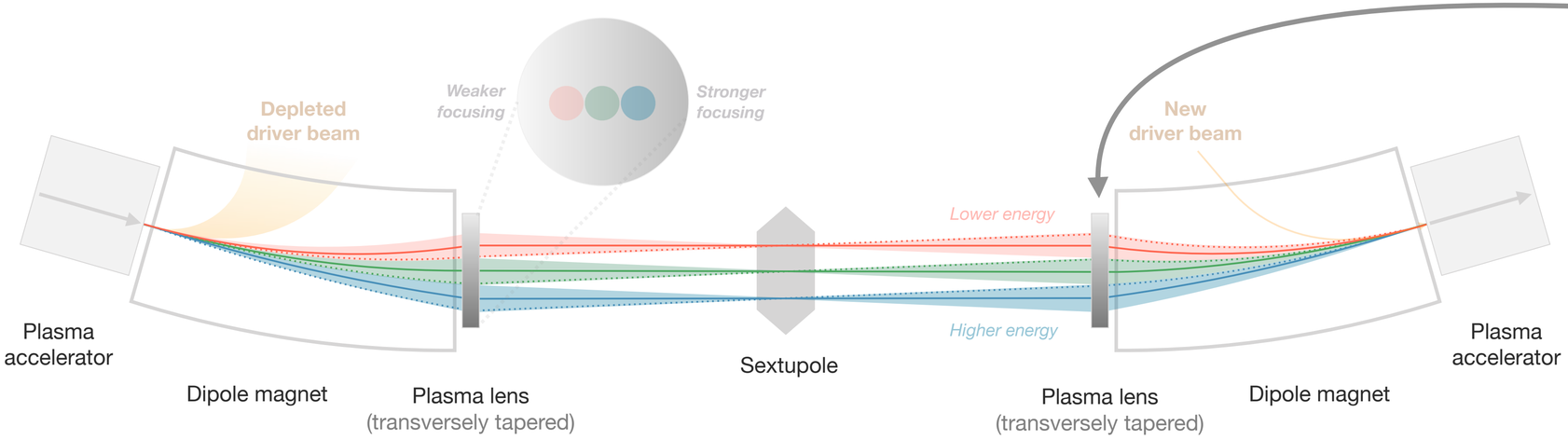
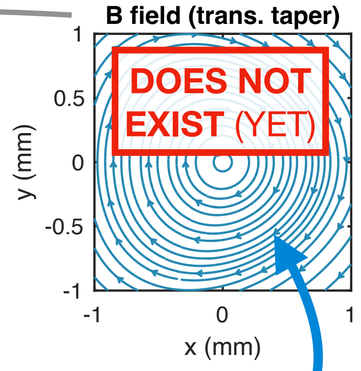
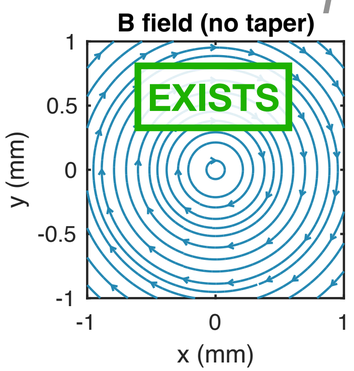


Nonlinear (achromatic)



Linear (chromatic)

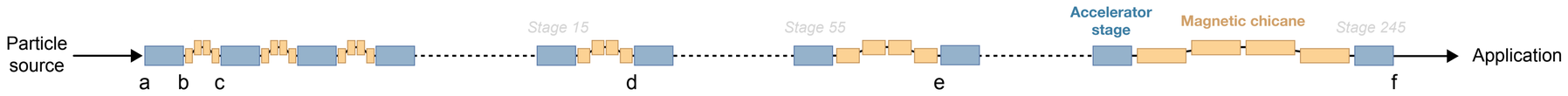


Research question:
Can we make this lens?

New concept #2: Self-correction mechanisms

A new kind of plasma accelerator — ***solving stability***

- Achromatic beamline between stages → longitudinal dispersion (R_{56})



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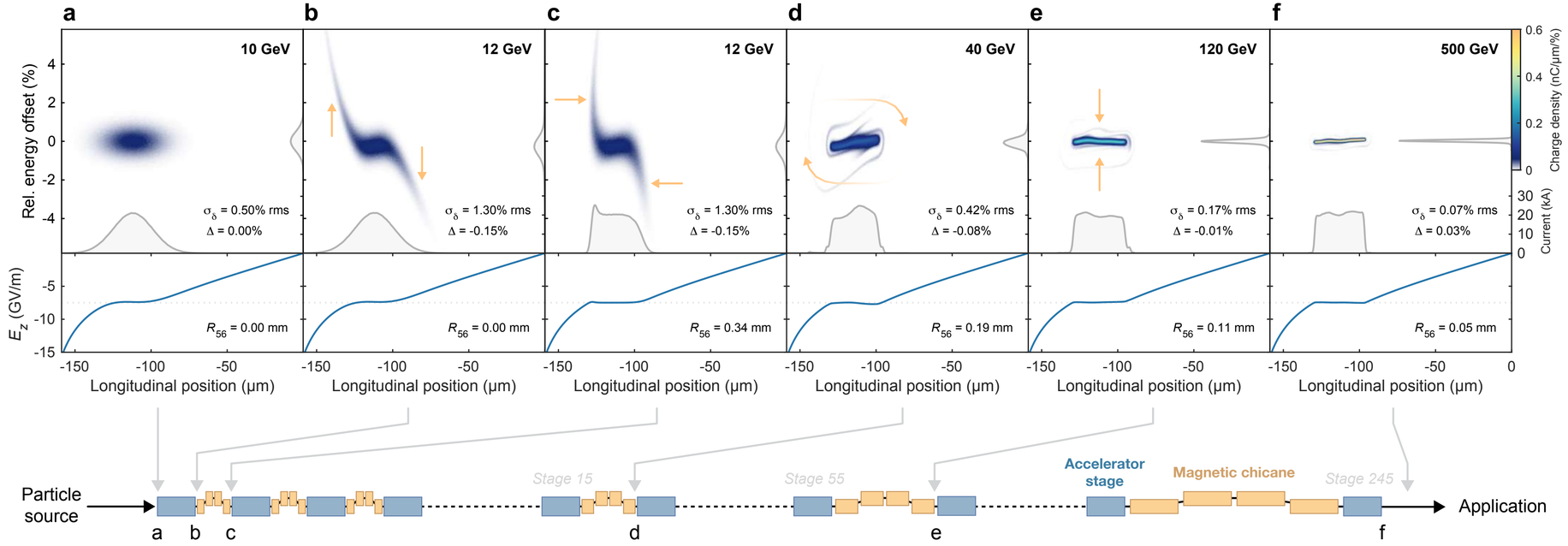

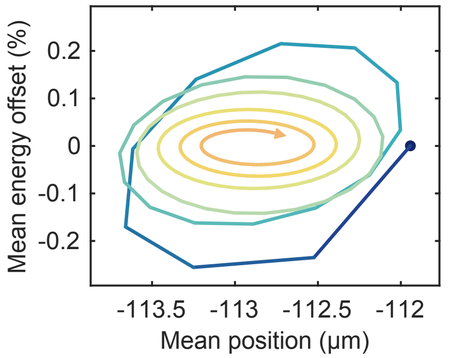

Lindstrøm, arXiv:2104.14460 (2021)

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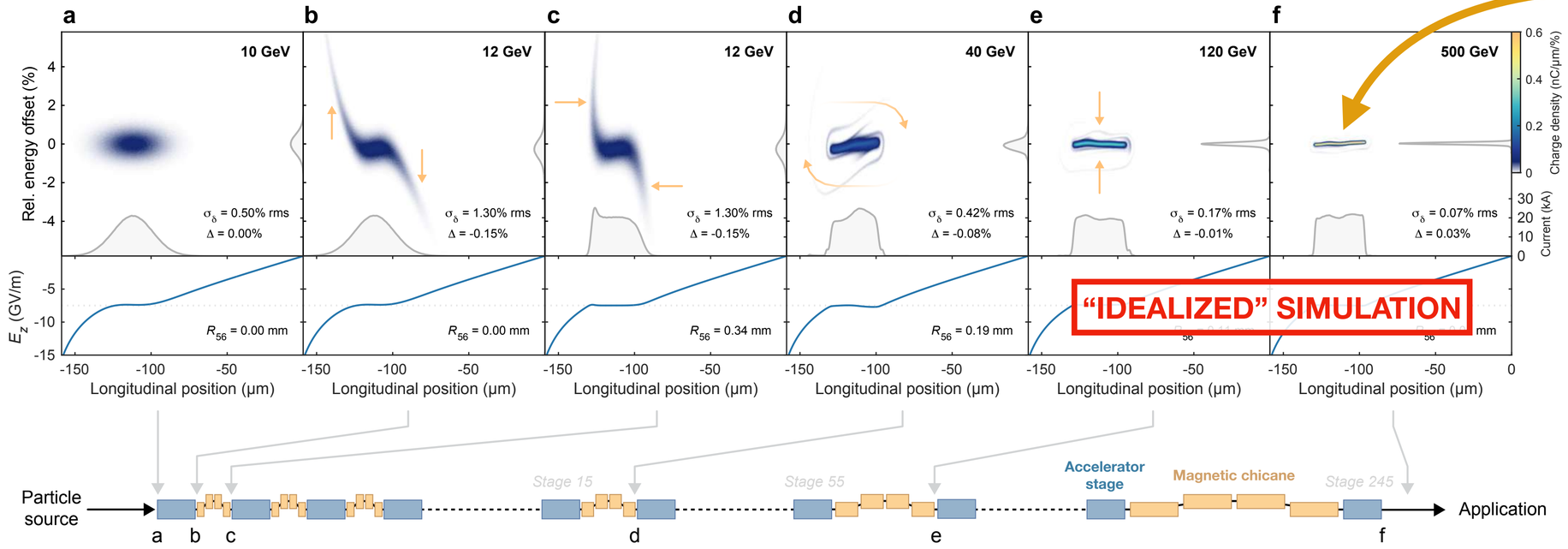
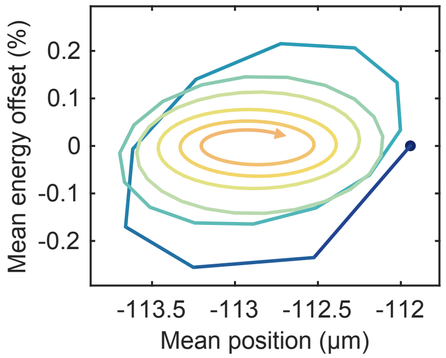
Research question:
Will this occur in a "real" machine?





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Final goal: Blueprints for a strong-field QED machine

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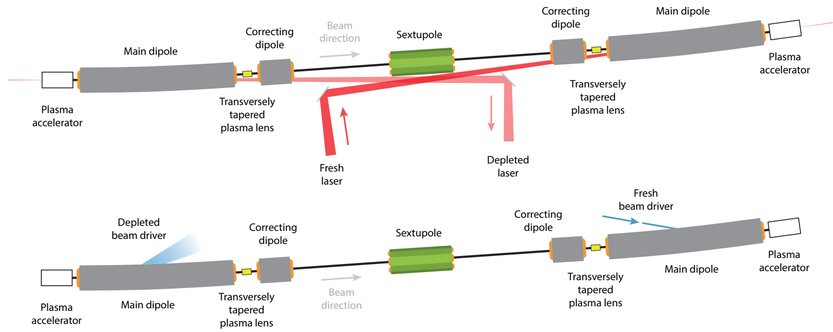

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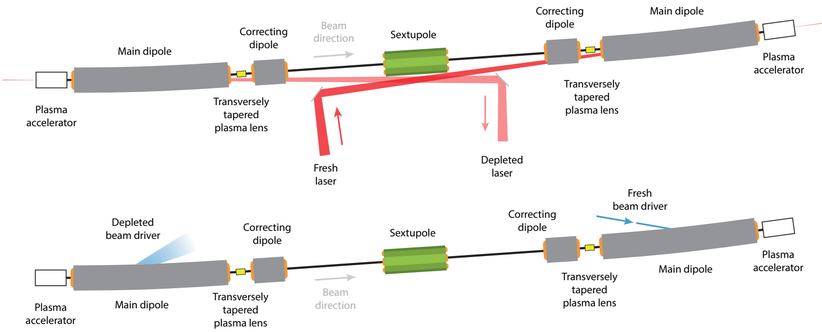

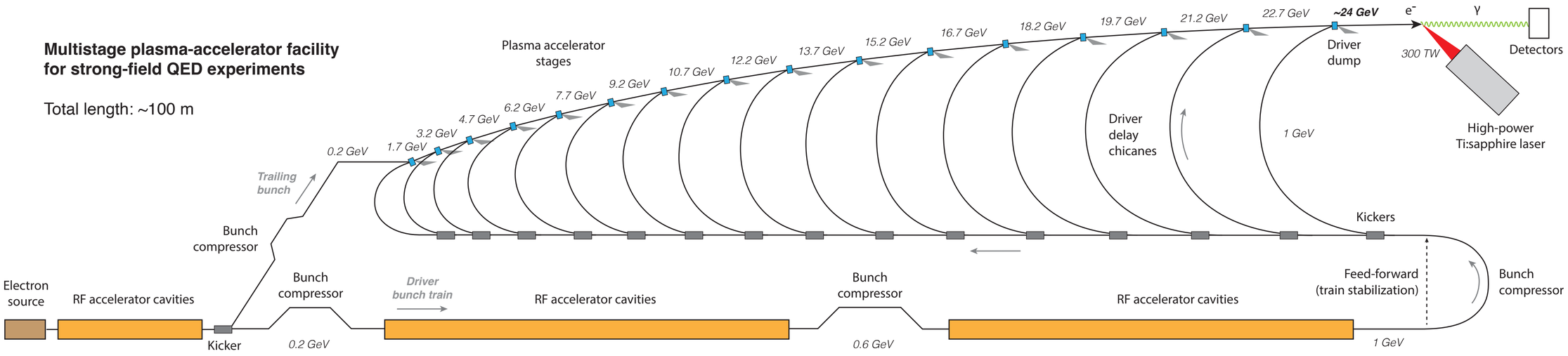

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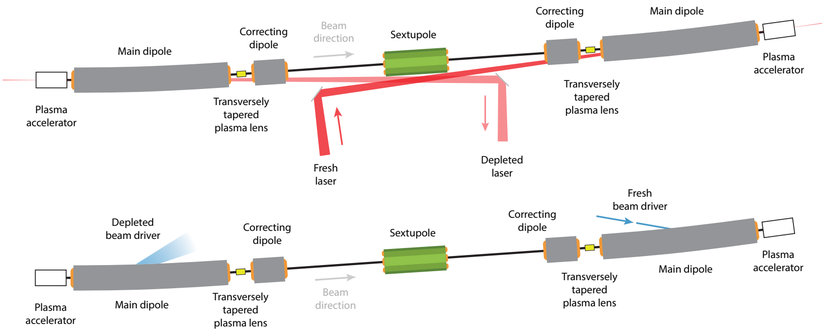
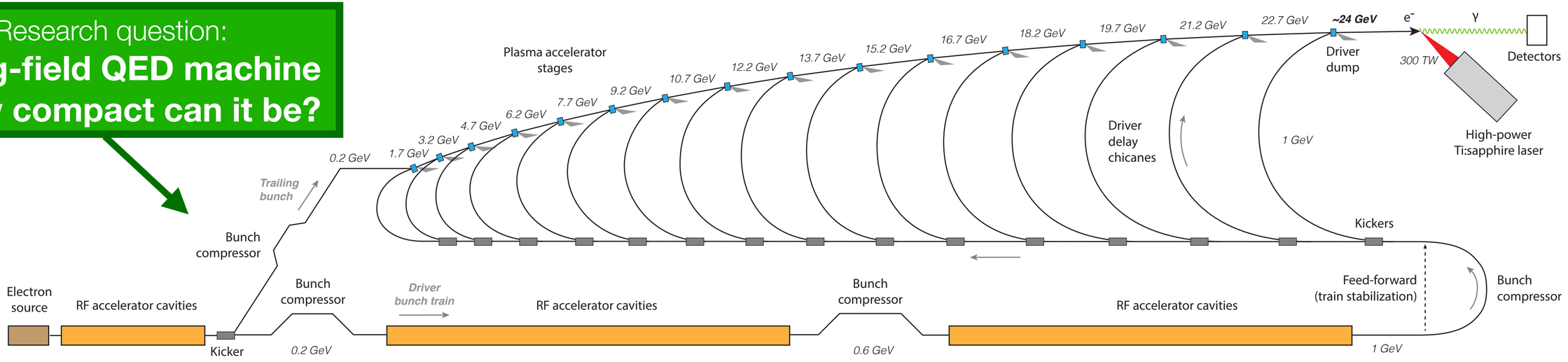


Research question:
Strong-field QED machine —how compact can it be?



The plan

Three main objectives

Objective #1: **Develop nonlinear plasma lenses**	**Year 1**	**Year 2**	**Year 3**	**Year 4**	**Year 5**
Objective #2: **Investigate self-stabilization in plasma accelerators**	**Year 1**	**Year 2**	**Year 3**	**Year 4**	**Year 5**
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- **Team:** PI (Carl A. Lindstrøm) + 2 postdocs + 2 PhDs
- **Collaborations:**

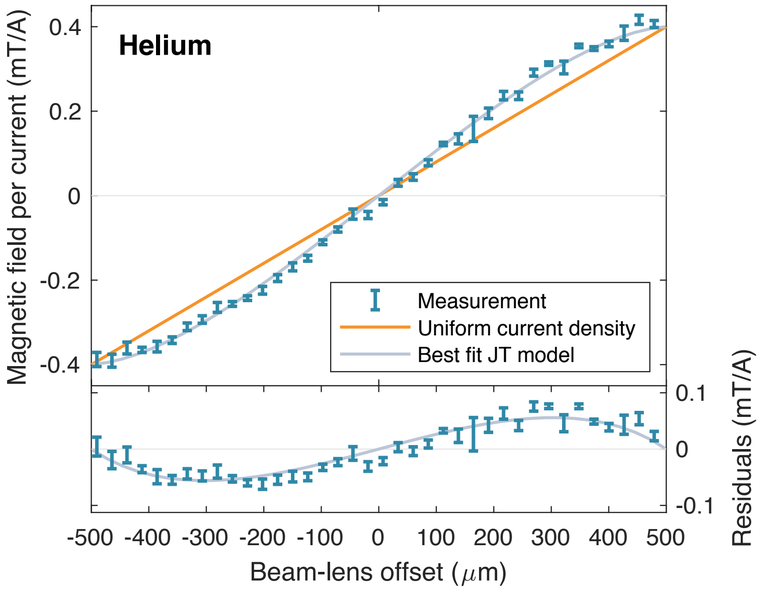
Accelerator laboratories

High-performance computing

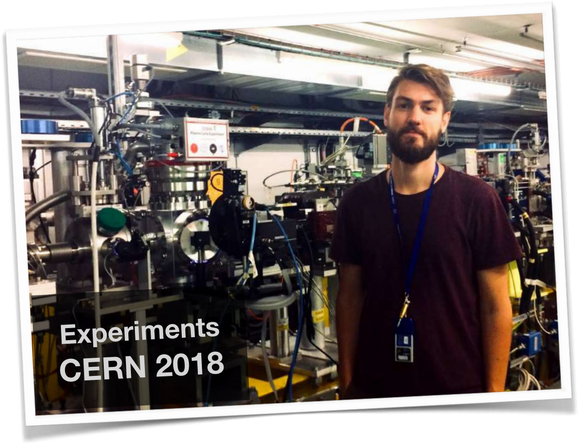
“But what will you actually do?”

Example of CERN-related experiments

- Plan for Objective #1:
  - Identify mechanism for making nonlinear plasma lens.
  - Construct the plasma lens
  - Measure the magnetic field profile.
- Beam-based B-field measurements at the CLEAR facility at CERN.
  - Collaboration with DESY and Oxford University
- Similarly, Objective #2 involves experiments at SLAC.



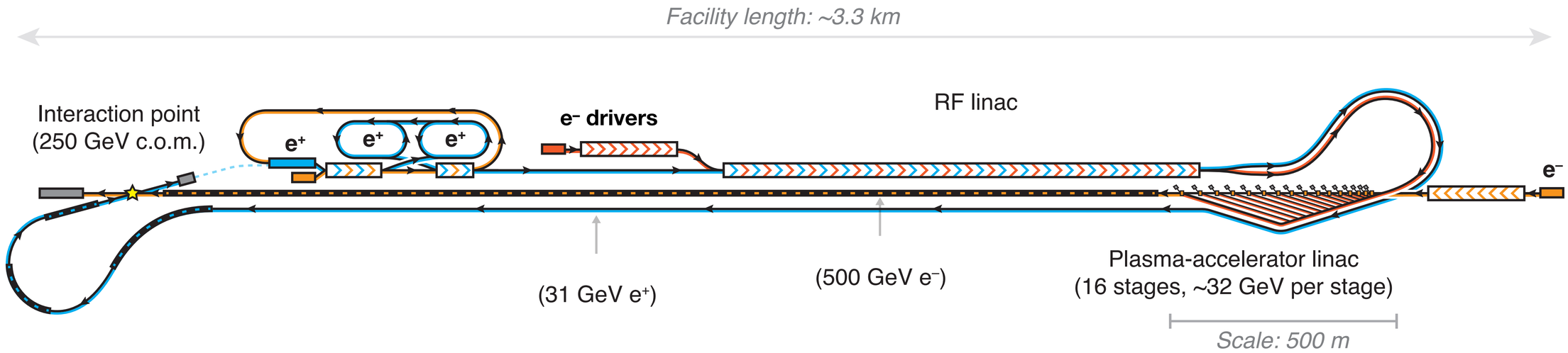
Lindstrøm et al., PRL 121, 194801 (2018)



Recent impact on HEP

New idea: plasma–RF hybrid Higgs factory — next step after SFQED machine?

- ***Asymmetric* collider concept** → avoids positron acceleration in plasma
- “National scale” (~3 km, ~€2.5B) → fits on the campus of ~any national lab



The HALHF collider concept — *Foster, D’Arcy & Lindstrøm, New Journal of Physics (accepted, 2023)*

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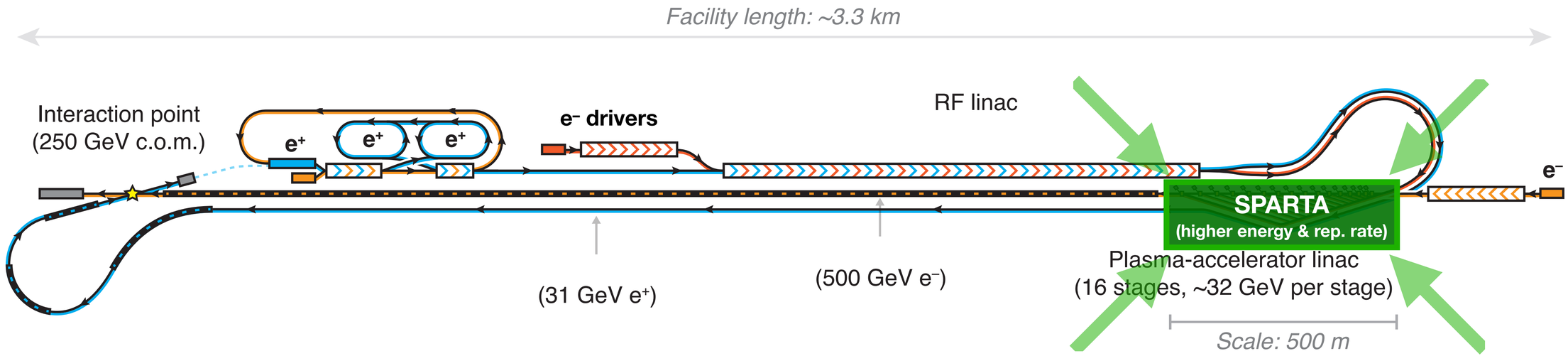

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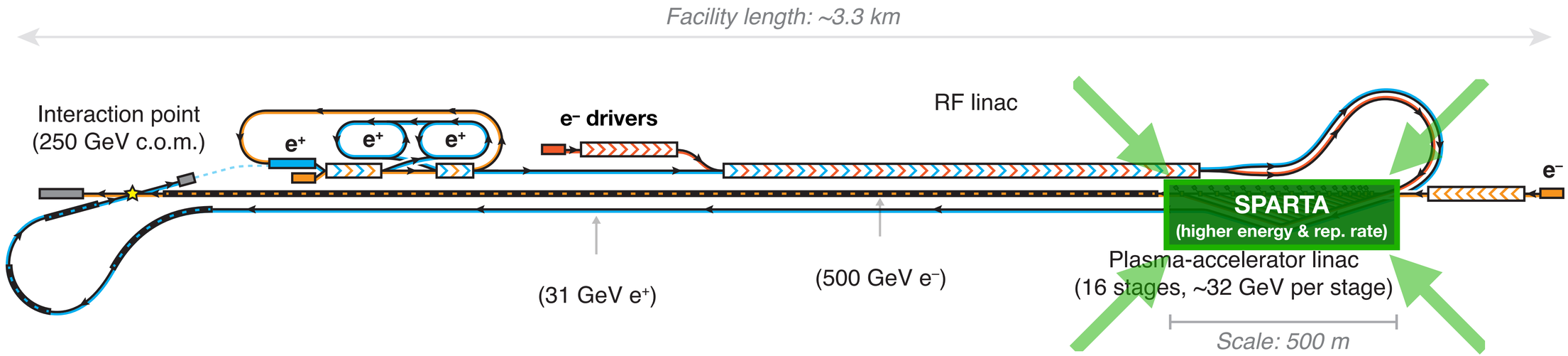

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- Massive interest from *plasma-accelerator* and *linear-collider* community

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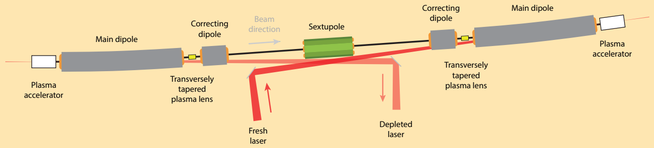
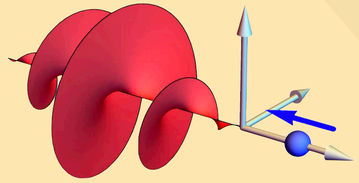
Objective #1:
Nonlinear plasma lens

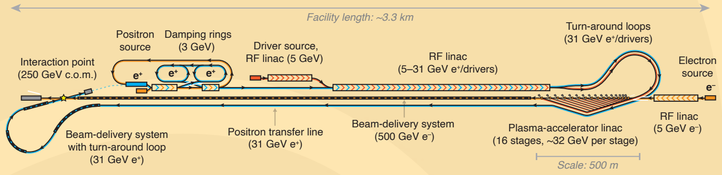
Objective #2:
Staging with self-stabilization



Objective #3:
SFQED machine



Long-term impact:
Next linear collider?

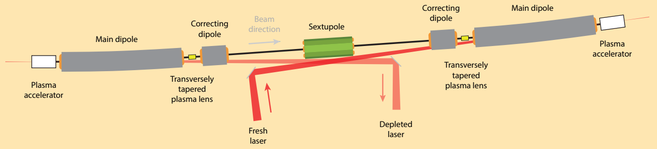


- Innovative solution to the cost problems in HEP

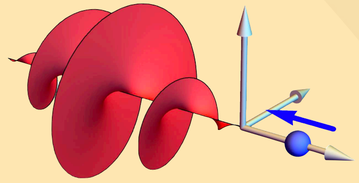
SPARTA: Staging of Plasma Accelerators for Realizing Timely Applications

Objective #1:
Nonlinear plasma lens

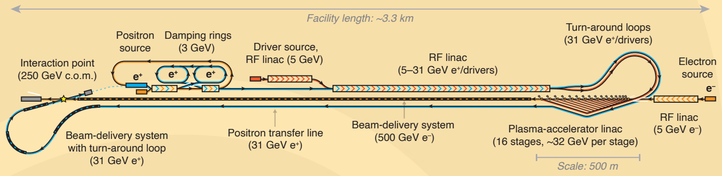
Objective #2:
Staging with self-stabilization



Objective #3:
SFQED machine



Long-term impact:
Next linear collider?



- Innovative solution to the cost problems in HEP
- Realizing two groundbreaking new concepts:

  (1) *Nonlinear plasma lenses: solving the staging problem*

  (2) *Self-correction mechanism: solving the stability problem*
- Goal: blueprints for a *strong-field QED machine* (a technology demonstrator)

"Plasma Spartans"
as generated
by MidJourney AI

The SPARTA project

Staging of Plasma Accelerators
for Realizing Timely Applications

Starts
1 Jan 2024
(5 years)

Thank you
for listening!