10 TeV Wakefield Collider Design Study
PWFA-Linac Working Group

Livio Verra

livio.verra@lnf.infn.it

European Advanced Accelerator Conference 2025

24.09.2025

Istituto Nazionale di Fisica Nucleare

Laboratori Nazionali di Frascati

What is the 10 TeV Wakefield Collider Design Study?

The Design Study aims to produce a unified, self-consistent concept for a 10 TeV parton-center-of-mass (pCM) collider based on wakefield accelerator (WFA) technology.

The Study is Initiated by the 2023 US P5 Report, but it is a **global** undertaking.

- We collaborate with on-going design efforts, including ALEGRO, HALHF, ALIVE, and XCC and contribute to the LC Vision program.

This is an HEP-wide **community** effort. The study requires input from:

- HEP Theorists
- Detector Physicists
- Accelerator Physicists
- Advanced Accelerator Research

We are an active community

The 10 TeV Wakefield Collider Design Study meets regularly as a collaboration and as individual working groups.

An in-person ALEGRO workshop was held at SLAC this past March with 100 attendees. The next ALEGRO workshop will be held at INFN-Frascati in March 2026.

The Design Study submitted input to ESPPU with over 200 endorsers!

We recently-launched a Design Study website:

https://10tev-wakefield-collider.github.io/

ALEGRO 2025 WORKSHOP | ADVANCED LINEAR COLLIDER STUDY GROUP

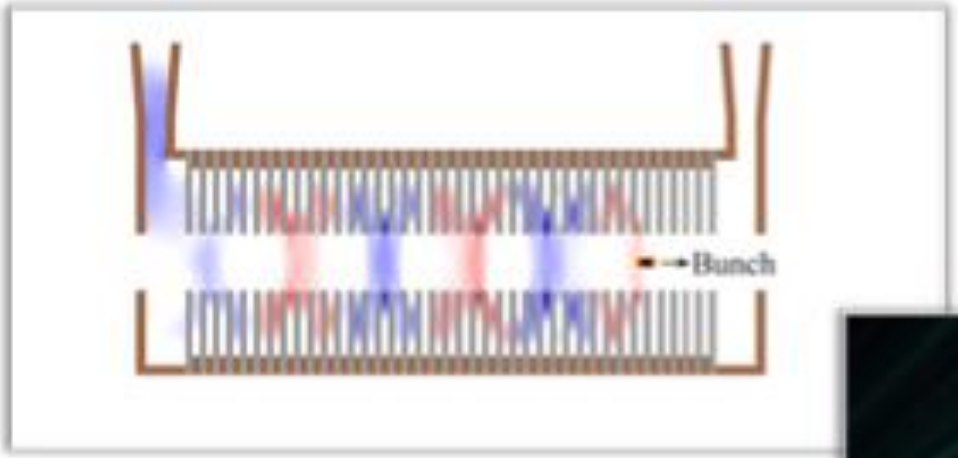
https://indico.slac.stanford.edu/event/9402/

https://www.nature.com/articles/d41586-025-01181-1

You can join the study here!

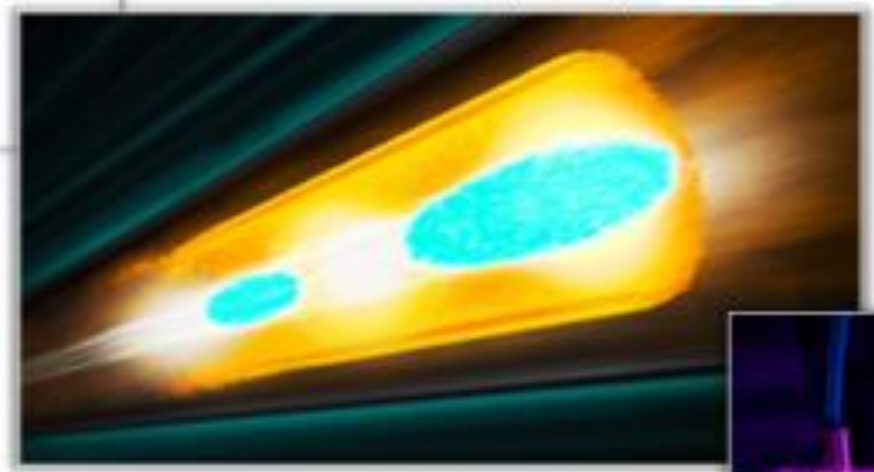
Technology options

Structure Wakefield Accelerators (SWFA)



The US Advanced Accelerator R&D program is led by 3 DOE laboratories supported by university research groups from within the US and abroad.

Beam-Driven Plasma (PWFA) SLAC

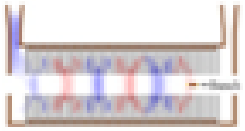
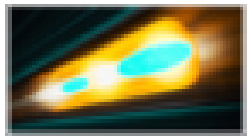
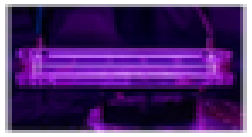


Laser-Driven Plasma (LWFA)

Each technology has advantages and challenges.

SLAC (S. Gessner)

Technology options

Technology	Advantages	Challenges
SWFA 	- Vacuum acceleration - High-efficiency - Mature driver technology	- Breakdown-limited - Strong external focusing req. - Stability
PWFA 	- Very high gradients - High-efficiency - Mature driver technology	- Positron acceleration in plasma - Driver in/out coupling - Stability
LWFA 	- Ultra-high gradients - Compact staging options - Near-term applications	- Positron acceleration in plasma - Laser-driver technology - Stability

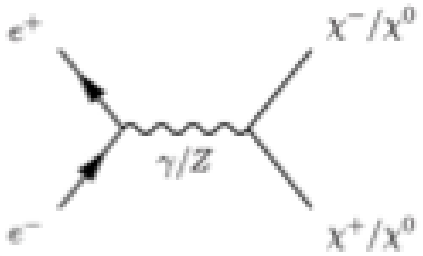
Technology advantages and challenges inform the physics program.

Physics options

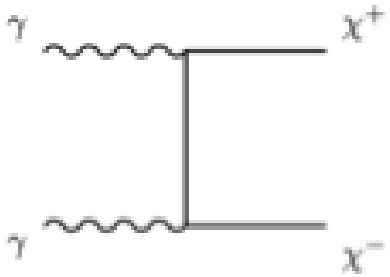
Positron acceleration in plasma is a challenge for PWFA and LWFA technology.

- Review article: G. Cao et al, PRAB 2024

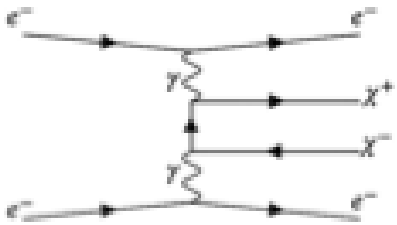
Linear Colliders assume e^+e^- collisions. We are motivated to explore e^-e^- and $\gamma\gamma$ collisions in addition to e^+e^- collisions.



Electron-Positron



Gamma-Gamma



Electron-Electron

PWFA Working Group

Conveners: Doug Storey, Alex Knetsch, Livio Verra

- Answer to the critical question:
  is beam-driven plasma wakefield acceleration a suitable technology for 10 TeV Collider?

- To answer, we are investigating (mostly with interaction with the community and help from HALHF):
  - Possible energy reach
  - Efficiency
  - Staging Considerations
  - Beam Flatness (driver and/or witness)
  - …

PWFA Working Group

Conveners: Doug Storey, Alex Knetsch, Livio Verra

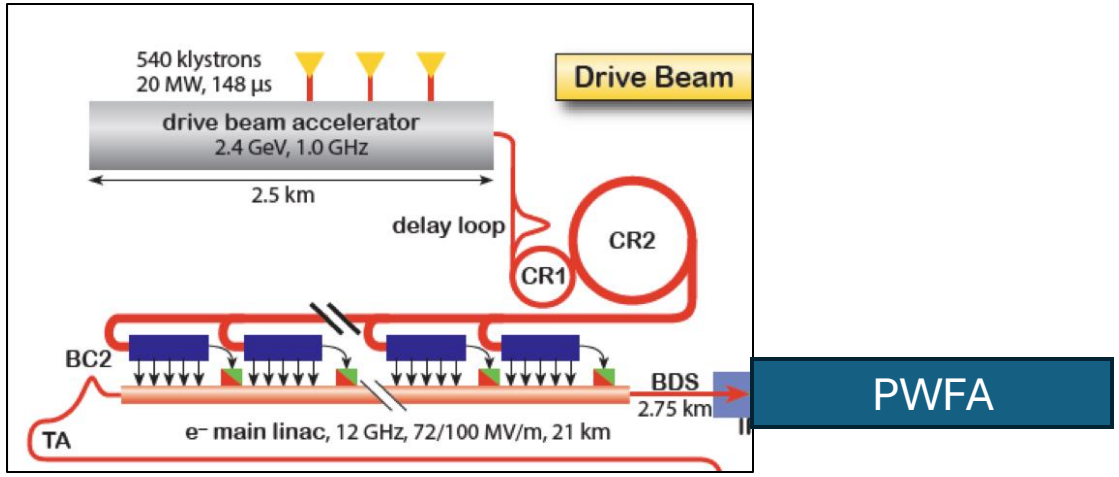
- Answer to the critical question:
  is beam-driven plasma wakefield acceleration a suitable technology for 10 TeV Collider?

- To answer, we are investigating (mostly with interaction with the community and help from HALHF):
  - Possible energy reach
  - Efficiency
  - **Staging Considerations**
  - Beam Flatness (driver and/or witness)
  - …

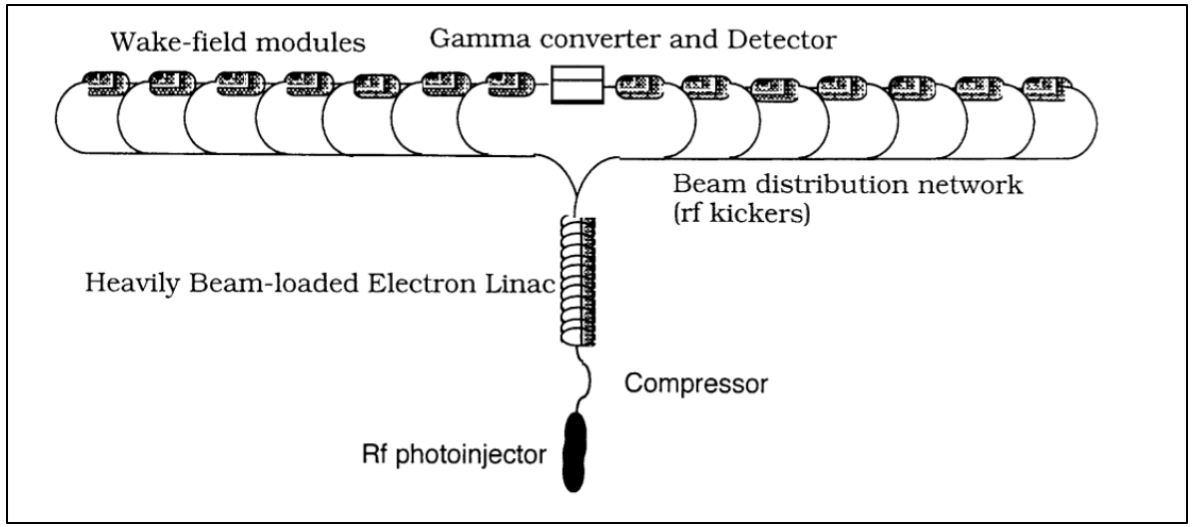
Why Staging?

- To reach 5 TeV:
  - **One highly energetic driver to accelerate witness in a single stage (afterburner):**

    Assuming transformer ratio R=2: energy tripling of witness bunch
    → need a 1.7 TeV driver and witness couple
    → CLIC-scale main linac



  - **Many low-energy (cheaper) drivers in multiple stages**
    Using e.g. 30 GeV drive bunch (requiring a > 300 m-long linac)
    → ΔE < 60 GeV (R<2 for single symmetric driver)
    → Need > 83 stages

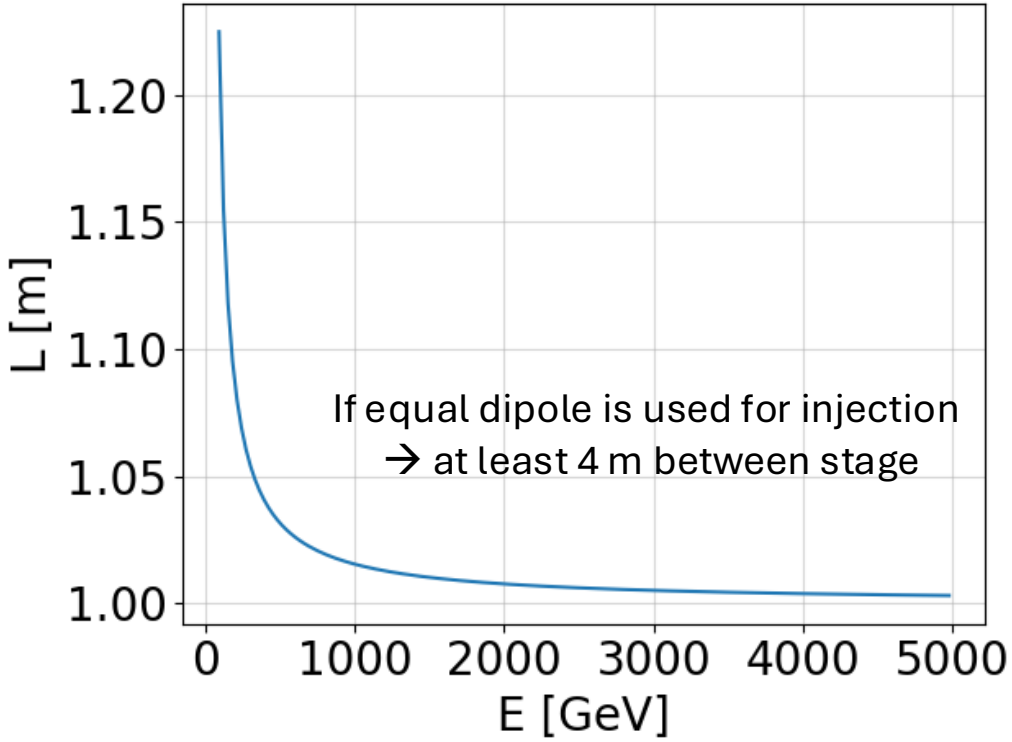


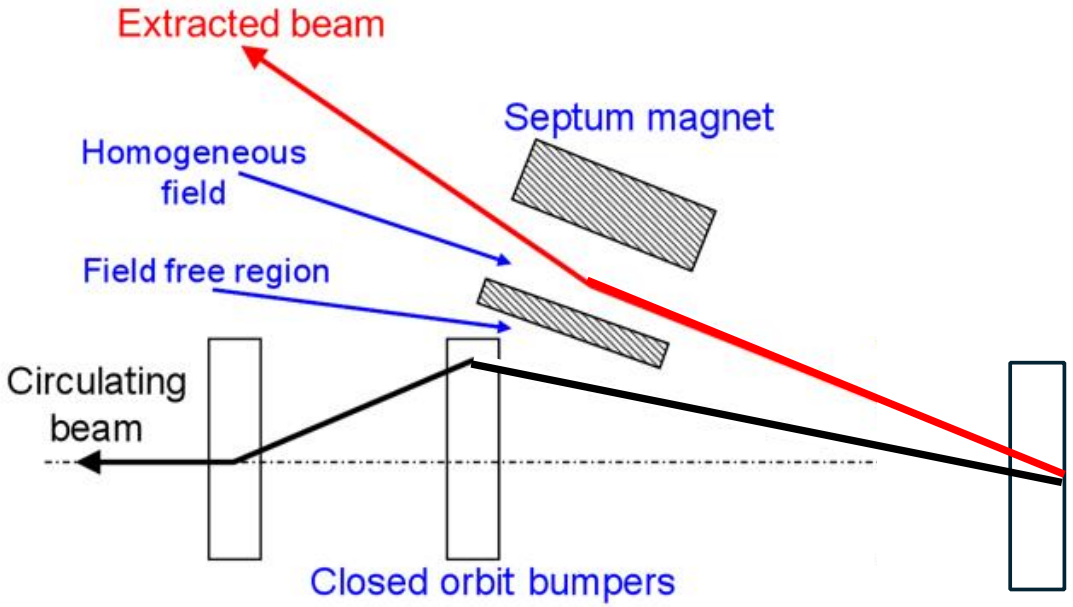
J. Rosenzweig et al., NIM A 410 (1998) 532—543

Driver Bunches in- and out-coupling

- → Separation with dipoles
- → $\Delta = BecL^2\left(\frac{1}{E_w} - \frac{1}{E_D}\right)$: separation and max B field gives the length of the magnet
- → Septum-like dipole to bend the spent driver even further (similar to extraction in rings)
  - → Minimize required transverse deflection

Length of 1-T dipole to obtain 1-cm offset between spent driver and witness

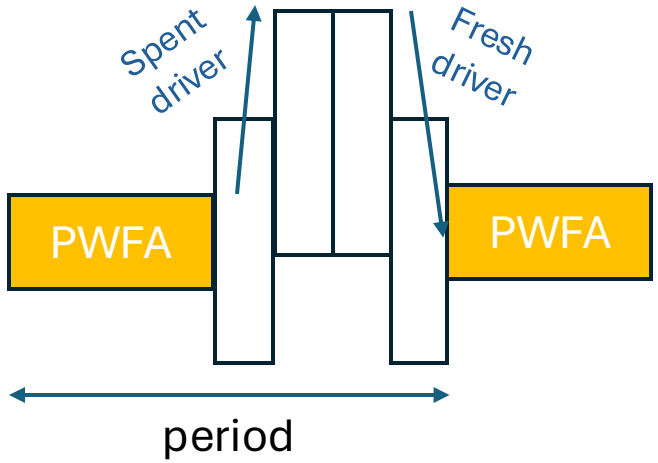




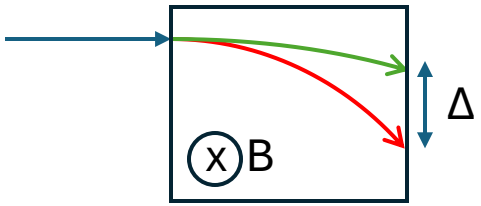
Adapted from : M.J. Barnes et al, arXiv:1103.1062

Back-of-the-envelope considerations on staging

Basic element of e-driven, staged PWFA linac:



→ $\Delta = BecL^2\left(\frac{1}{E_w} - \frac{1}{E_D}\right)$:
separation and max B field gives the length of the magnet



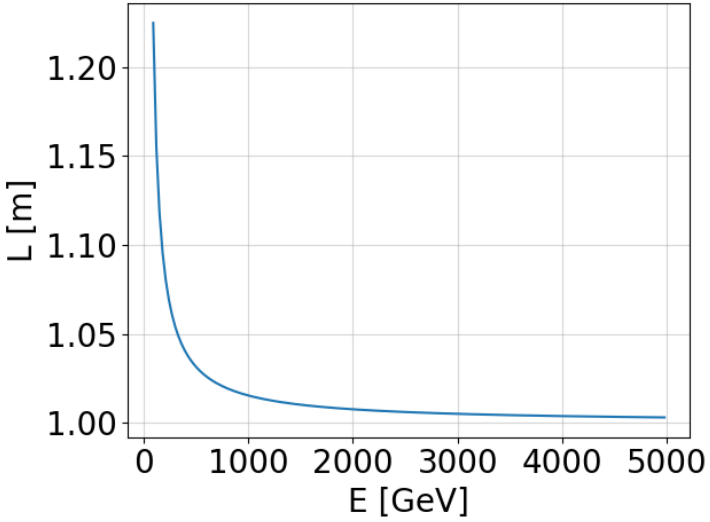
Length of 1-T dipole to obtain Δ=1 cm between spent driver and witness

→ Need dipole to separate witness from spent driver
→ Need dipole to inject fresh driver

→ Dipoles in between to complete chicane and remain on axis

→ Synchrotron Radiation

$$U_0 = \frac{q^2}{6\pi\varepsilon_0}\beta^3\gamma^4 L[m]\left(\frac{B[T]}{3.3pc[GeV]}\right)^2$$

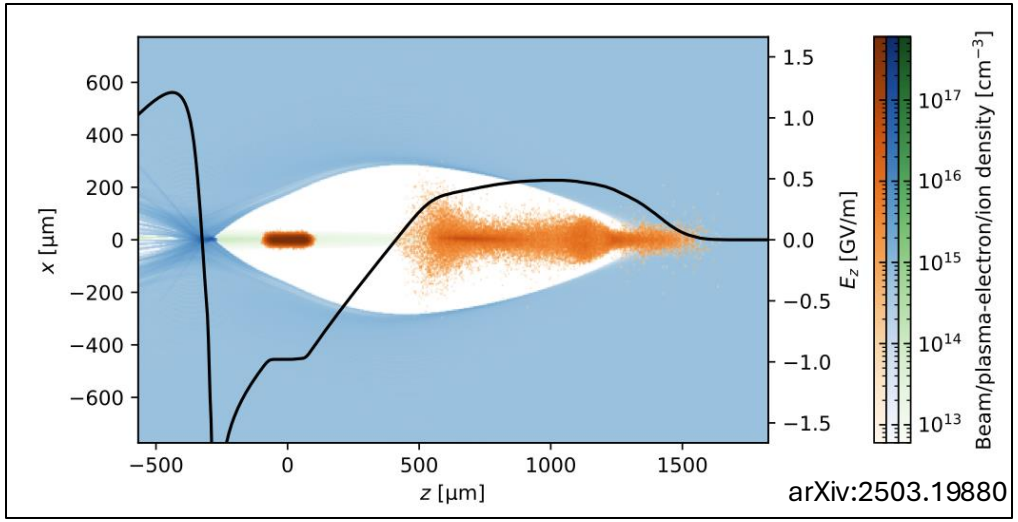


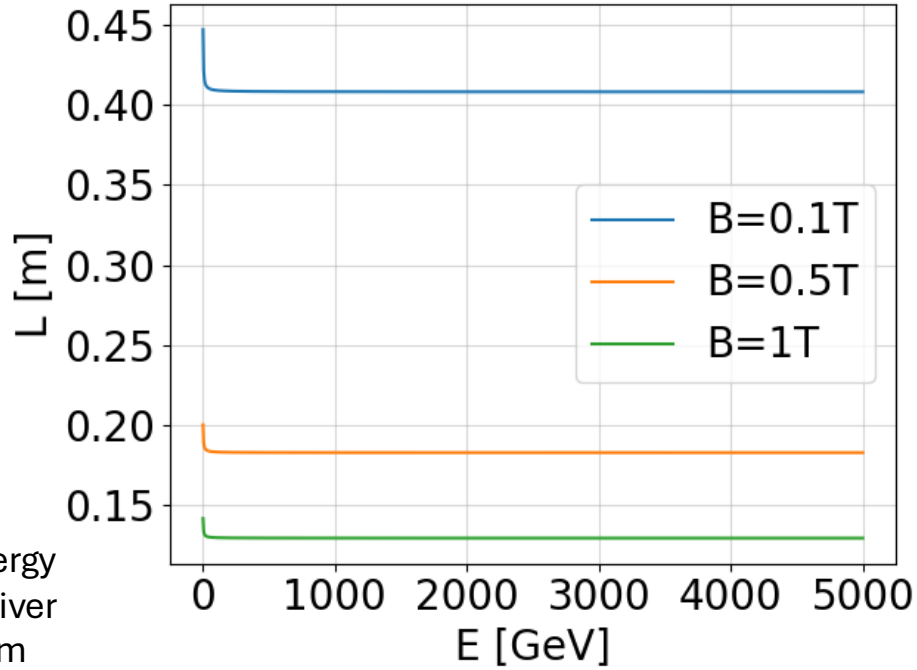
➔ Average energy loss due to SR in dipole with length L and magnetic field B

Simplest LINAC model

Let's assume:

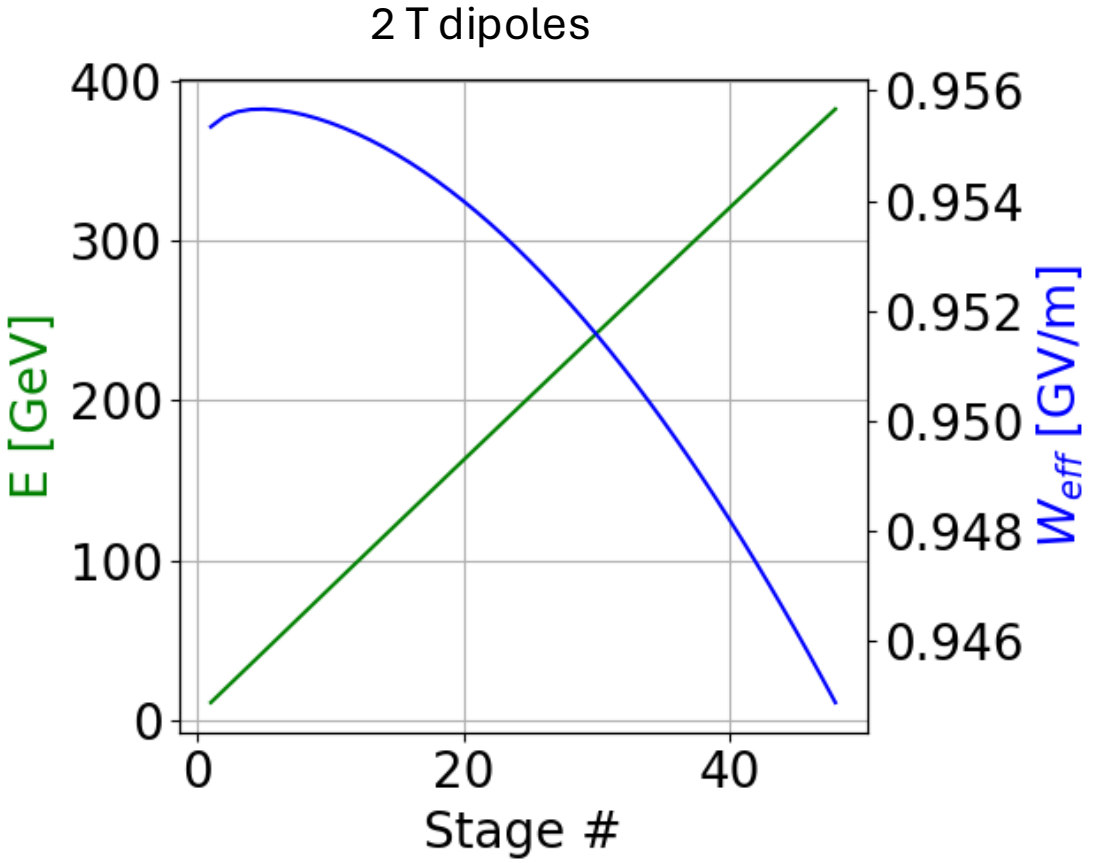
- $n_{pe} = 6 \cdot 10^{14}$ cm^{-3}
- $Q_D = 8$ nC
- Peak decelerating field W_{z-}=0.5GV/m
- R=2 → W_{z+}=1 GV/m
- E_D=8.6 GeV → Depleted in ~17.1m
- 17-m-long plasmas
- Dipole's length calculated to obtain Δ=1cm
- No drifts/optical elements
- Initial witness energy =3 GeV





Average energy depleted driver ~ 500MV/m

Simplest LINAC model



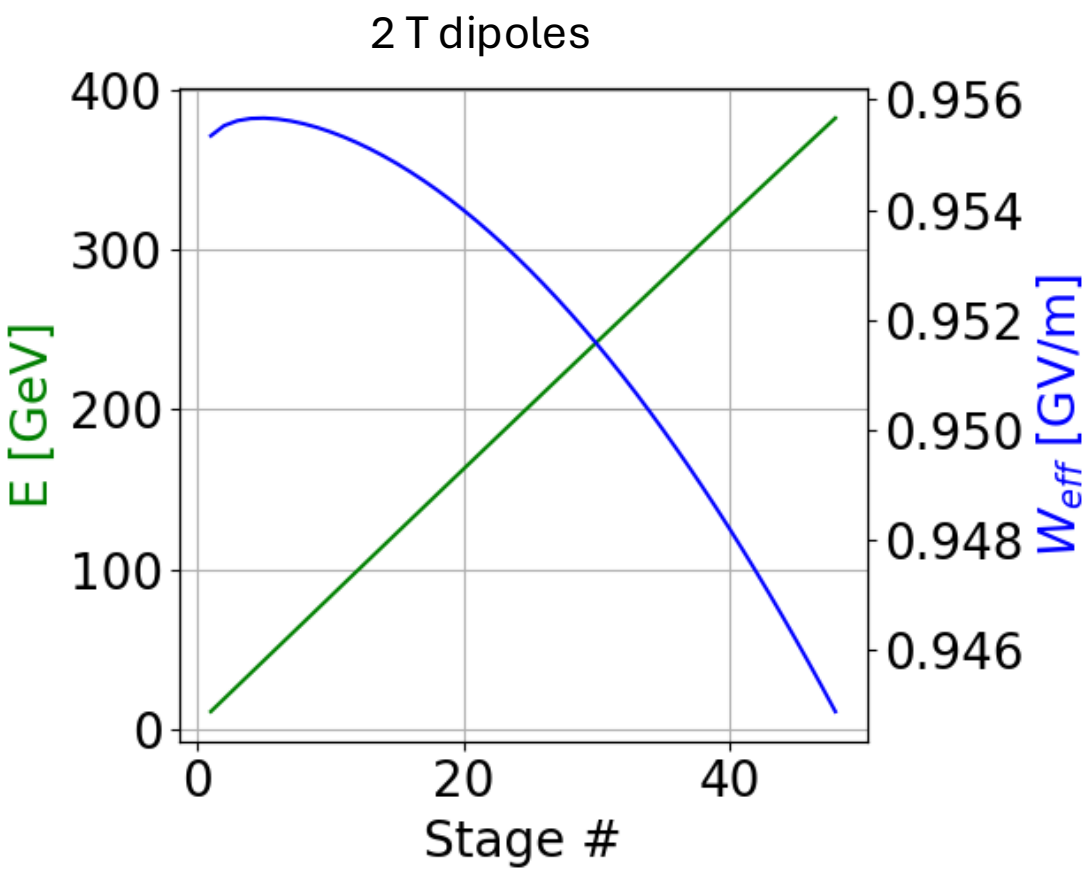
Running effective gradient:

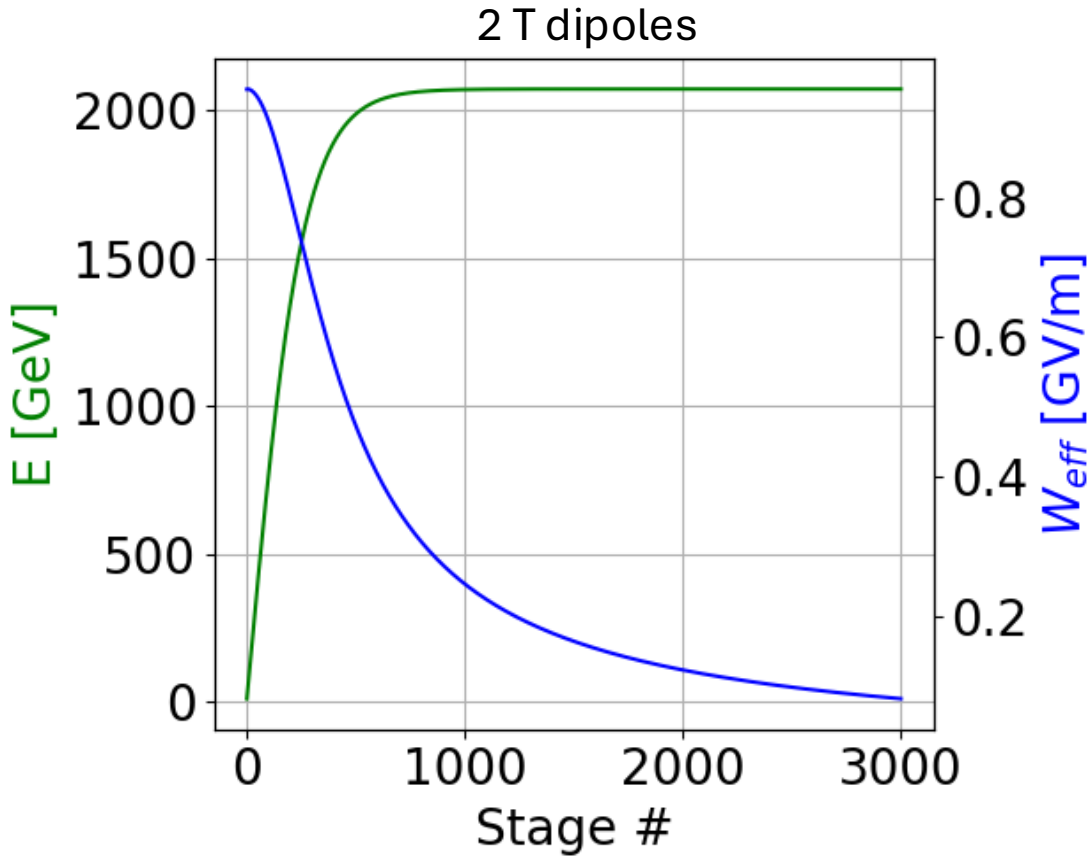
$$W_{eff}(z) = \frac{E(z)}{z}$$

Up to moderately high energies:

- Energy increases linearly stage after stage
- Strong B-field keeps interstage compact
- Effective gradient close to in-plasma gradient

Simplest LINAC model





Up to moderately high energies:

- Energy increases linearly stage after stage
- Strong B-field keeps interstage compact
- Effective gradient close to in-plasma gradient

At high energies

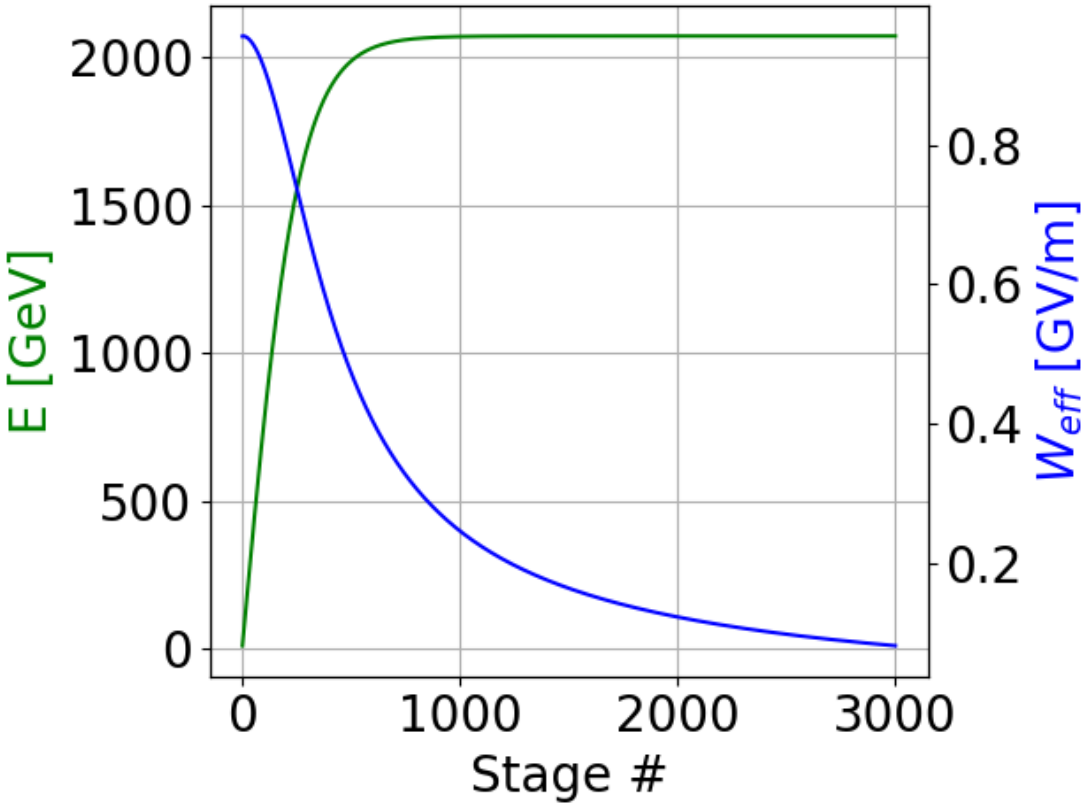
- Energy loss due to SR increases
- No further net energy gain
- Effective gradient decreases

Simplest LINAC model

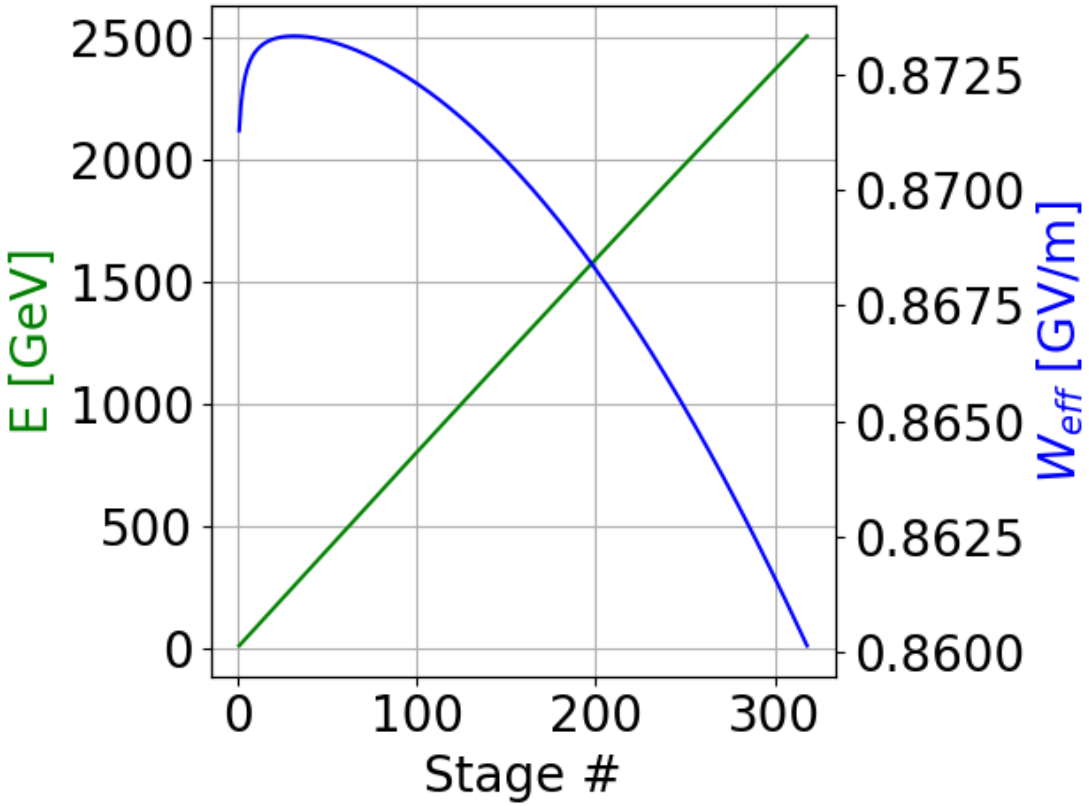
→ Decrease B-field to reduce SR emission:

- Longer dipoles

2 T dipoles

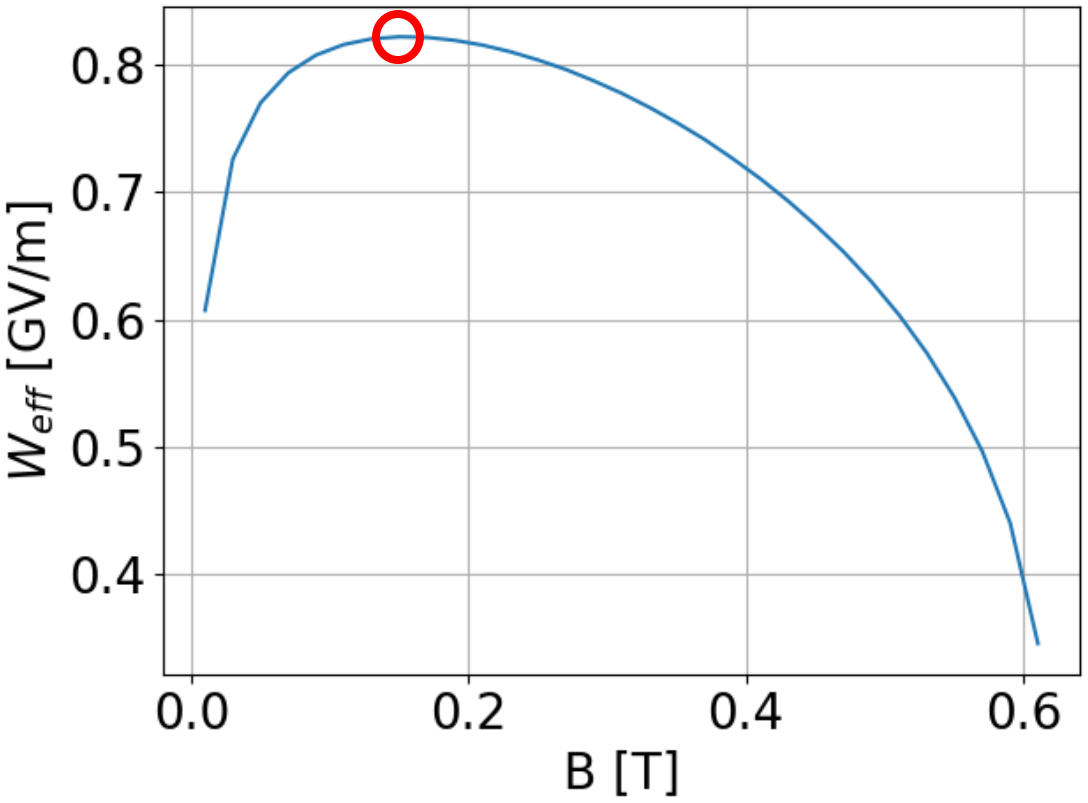


0.2 T dipoles



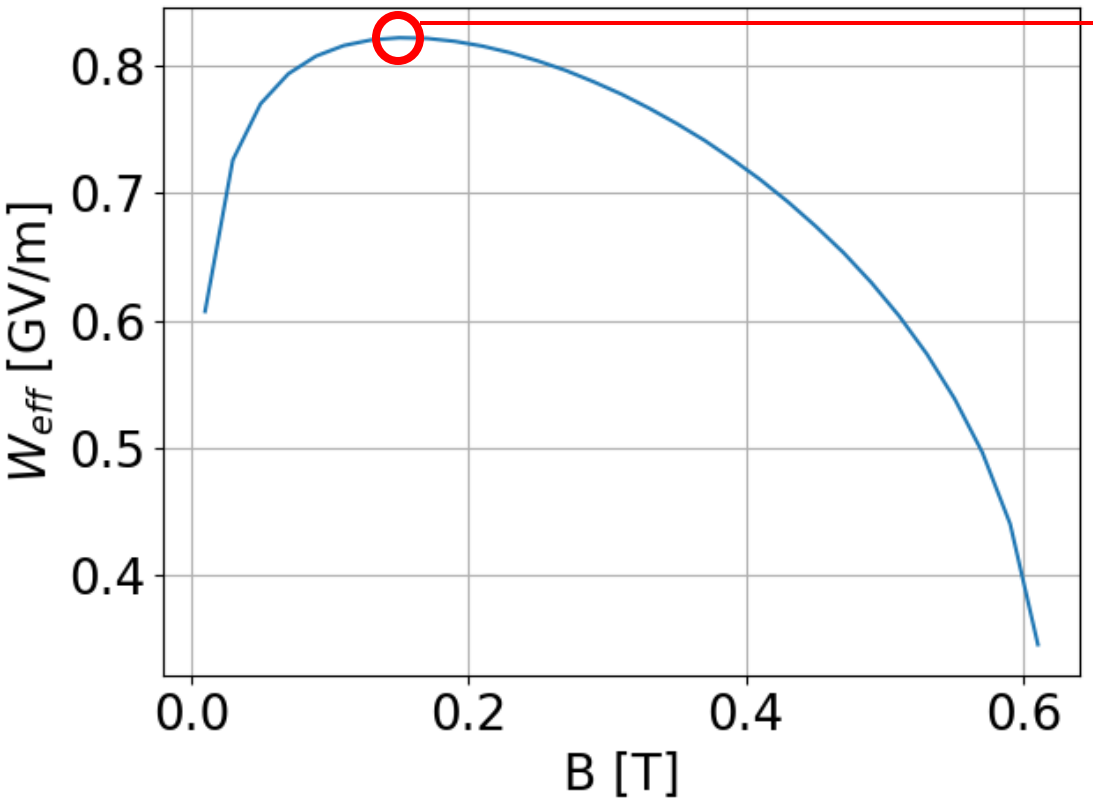
Simplest LINAC model

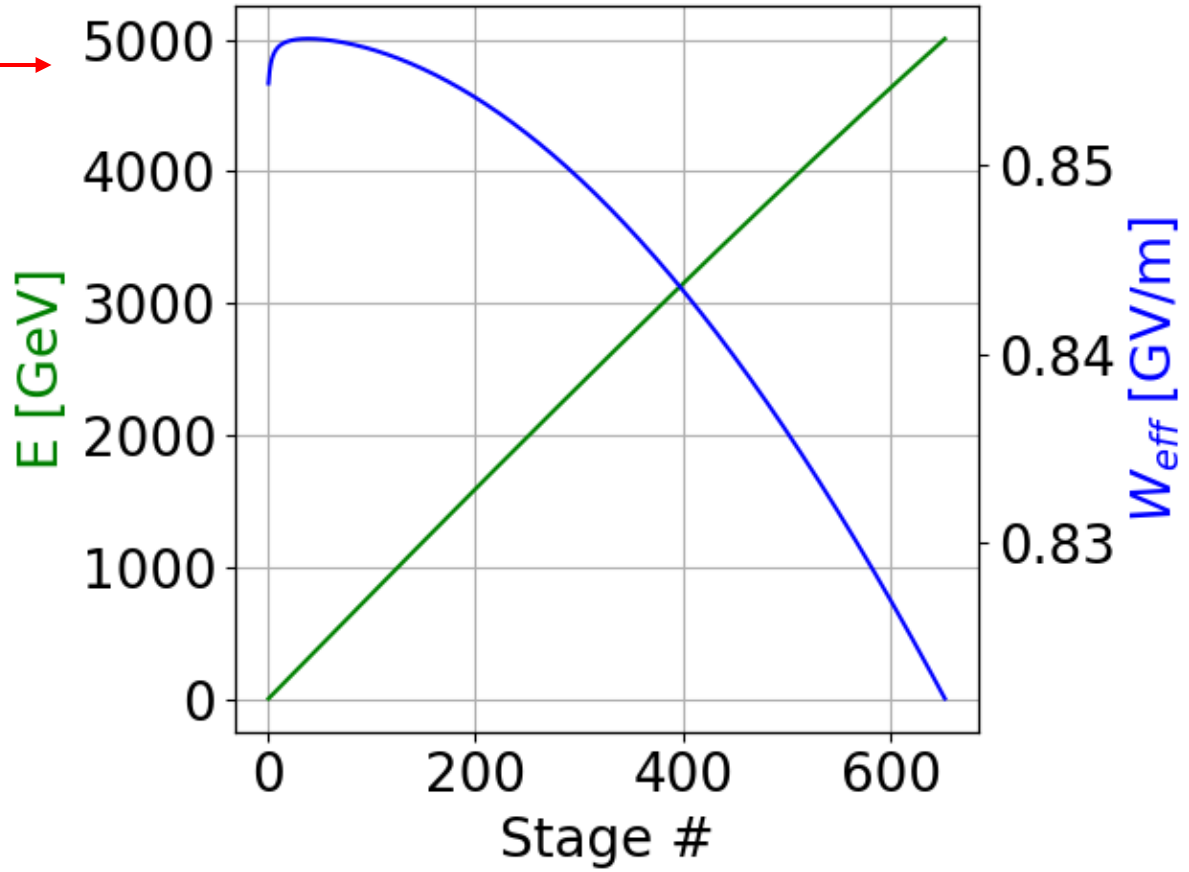
Target Energy = 5 TeV



Simplest LINAC model

Target Energy = 5 TeV

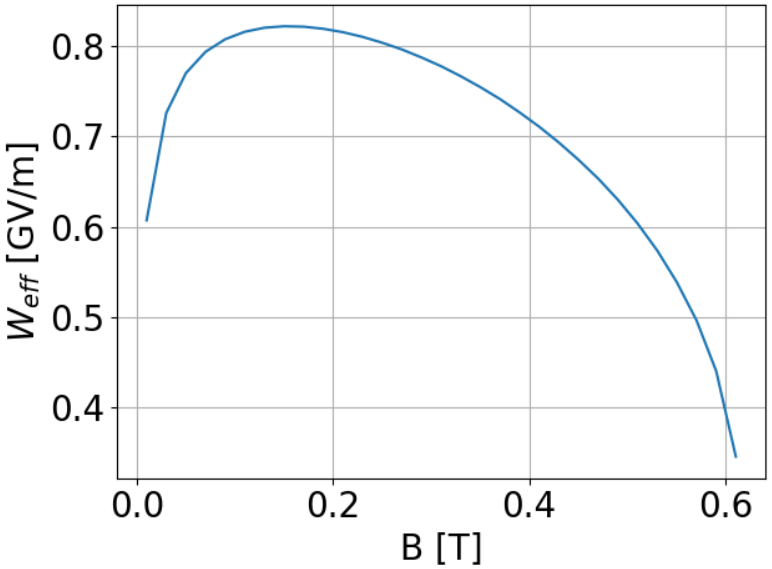




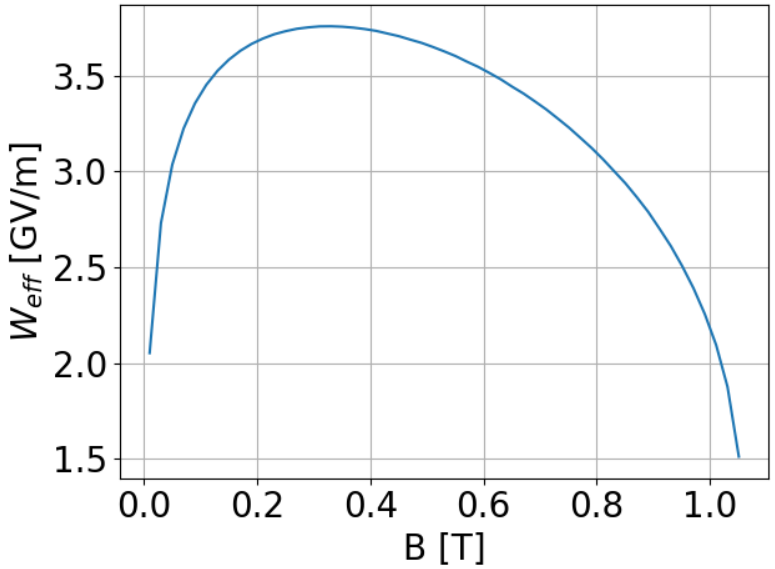
Total length to reach 5 TeV: 6.09 km

Simplest LINAC model

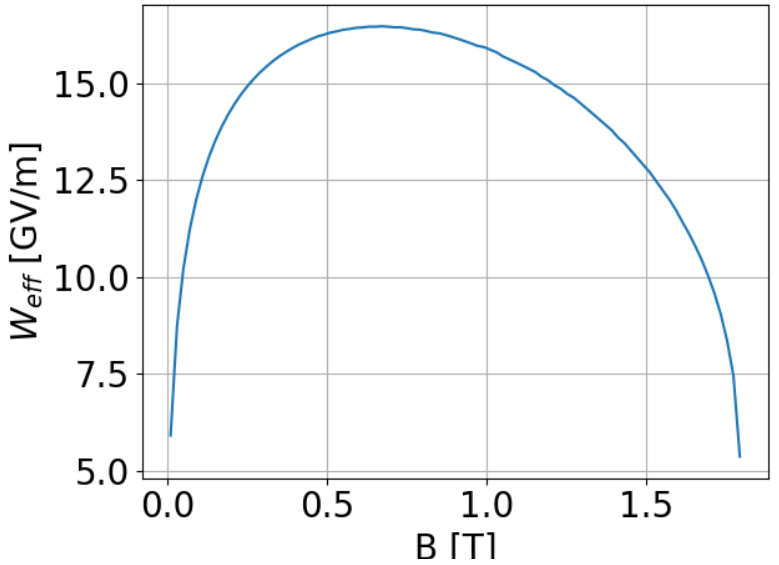
1GV/m in plasma, 4GeV driver



5GV/m in plasma, 9GeV driver



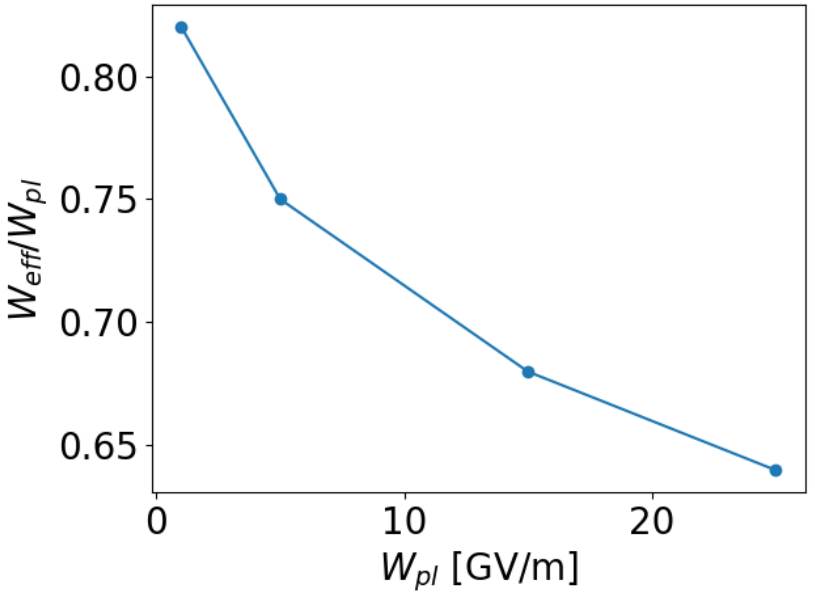
25GV/m in plasma, 20GeV driver



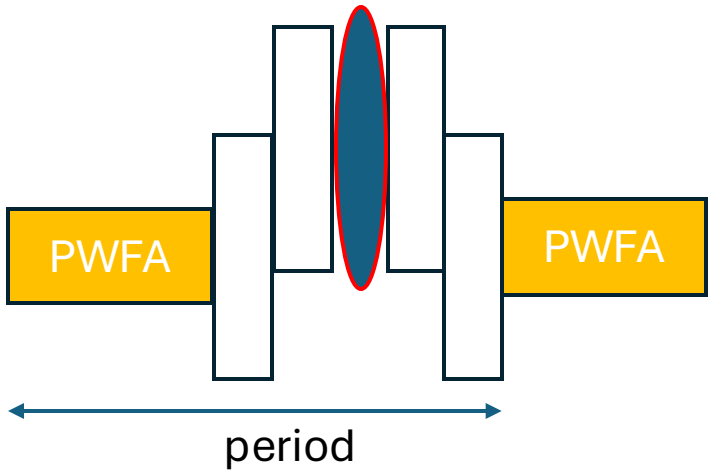
→ Longer period for higher-energy driver
→ Need for higher B field

→ Ratio max(W_{eff})/ W_{pl} decreases with W_{pl}

→ To keep in consideration when selecting charge and energy of driver beams

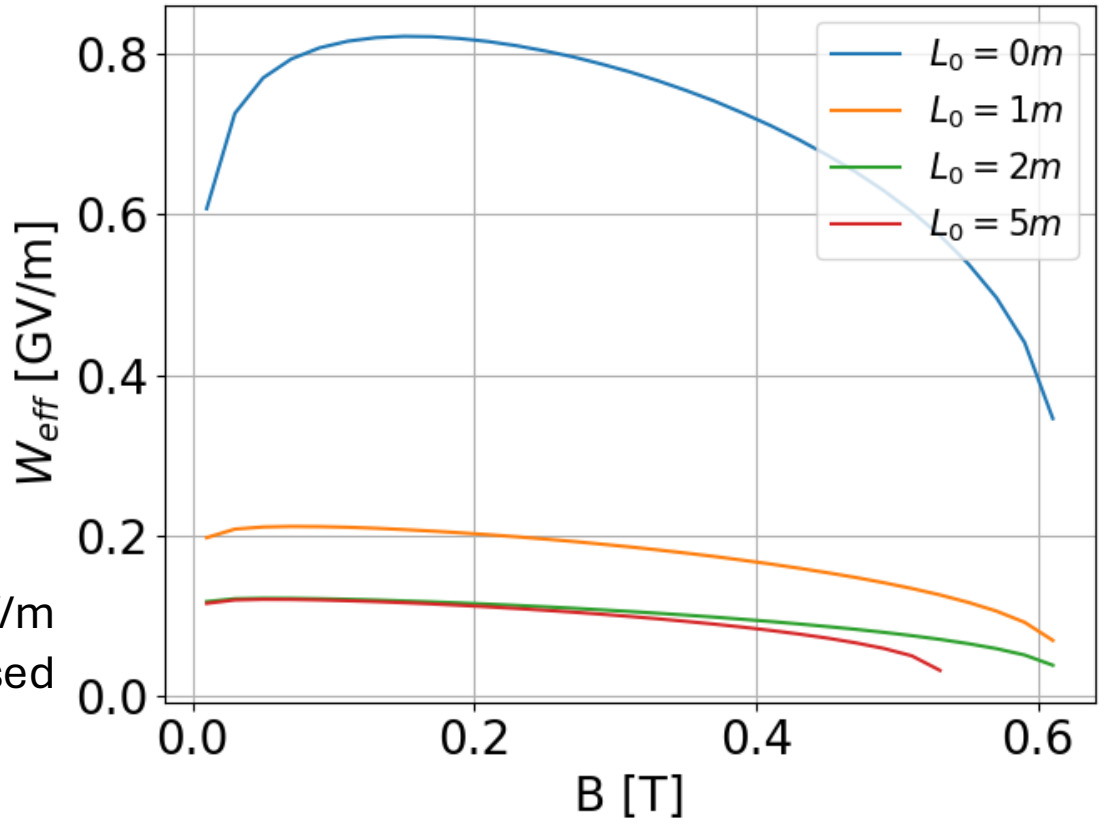


Simplest LINAC model



L_O: Length of optics (focusing elements + sextupoles+drifts)
→ Increases along the linac $\propto \sqrt{\gamma}$

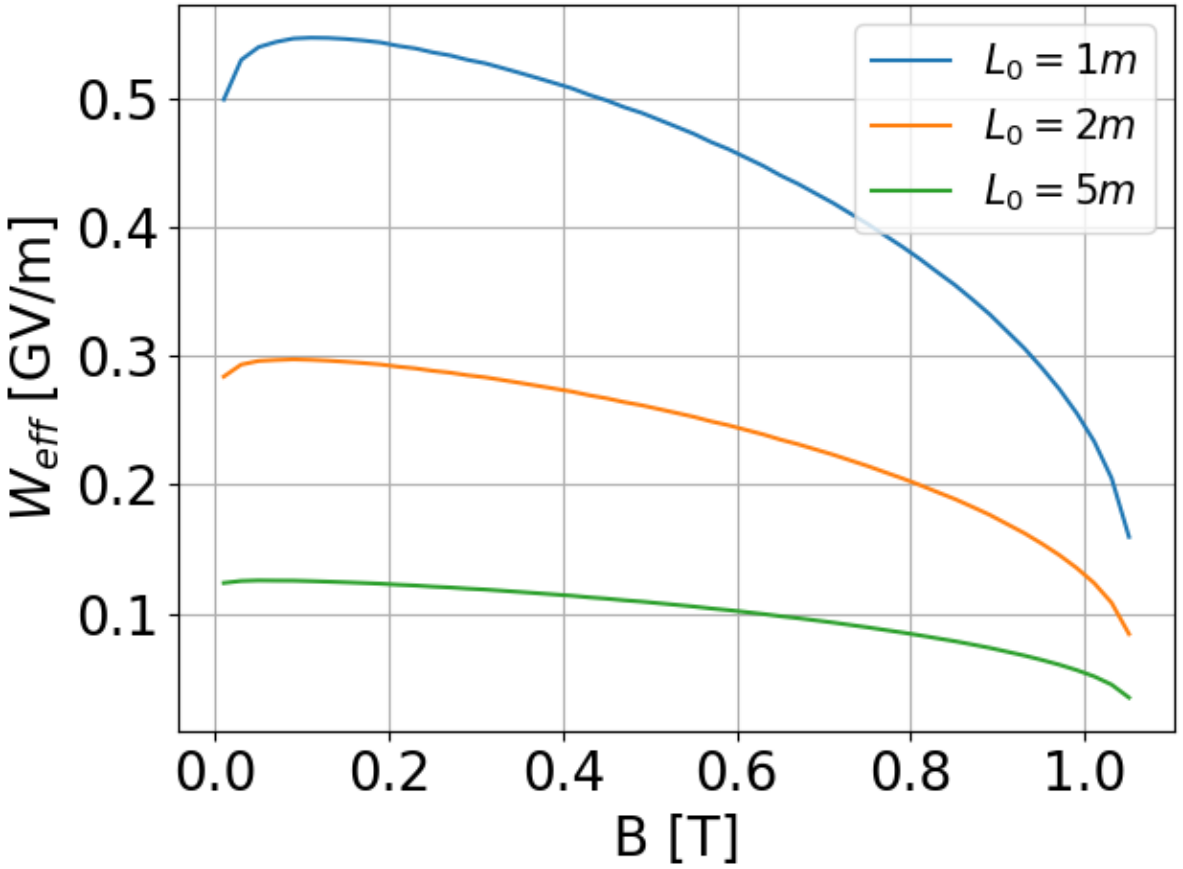
1GV/m in plasma, 4GeV driver



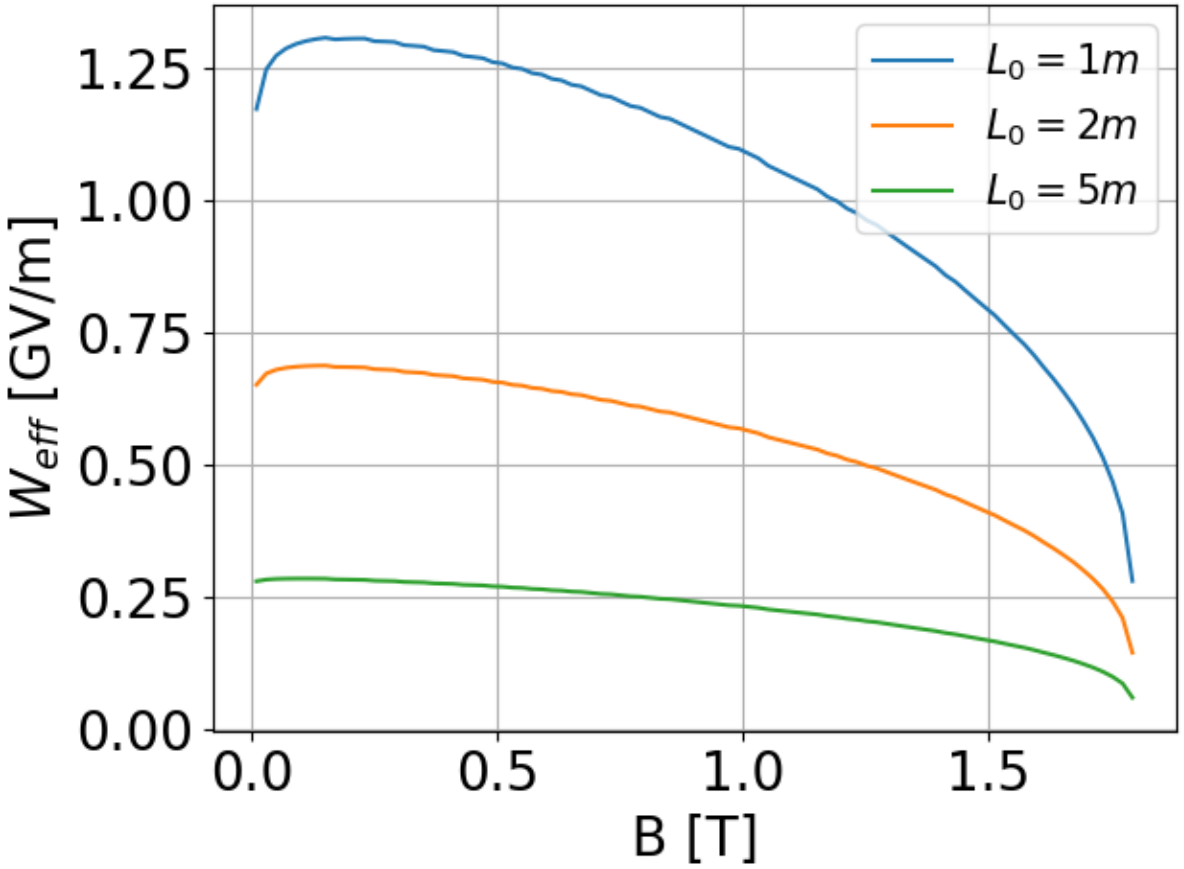
➔ W_{eff} quickly goes <0.5GV/m if length of optics is increased

Simplest LINAC model

5GV/m in plasma, 9GeV driver



25GV/m in plasma, 20GeV driver



➔ W_{Eff} quickly decreases with the length of optics

➔ Need very high in-plasma accelerating gradient to maintain W_{Eff} >0.5GV/m (or: extremely short optics for highly energetic beams) → Not necessarily the most cost-effective solution

Conclusions

- 10 TeV Wakefield Collider Design Study
  → Produce an end-to-end consistent design study for machine at energy frontier

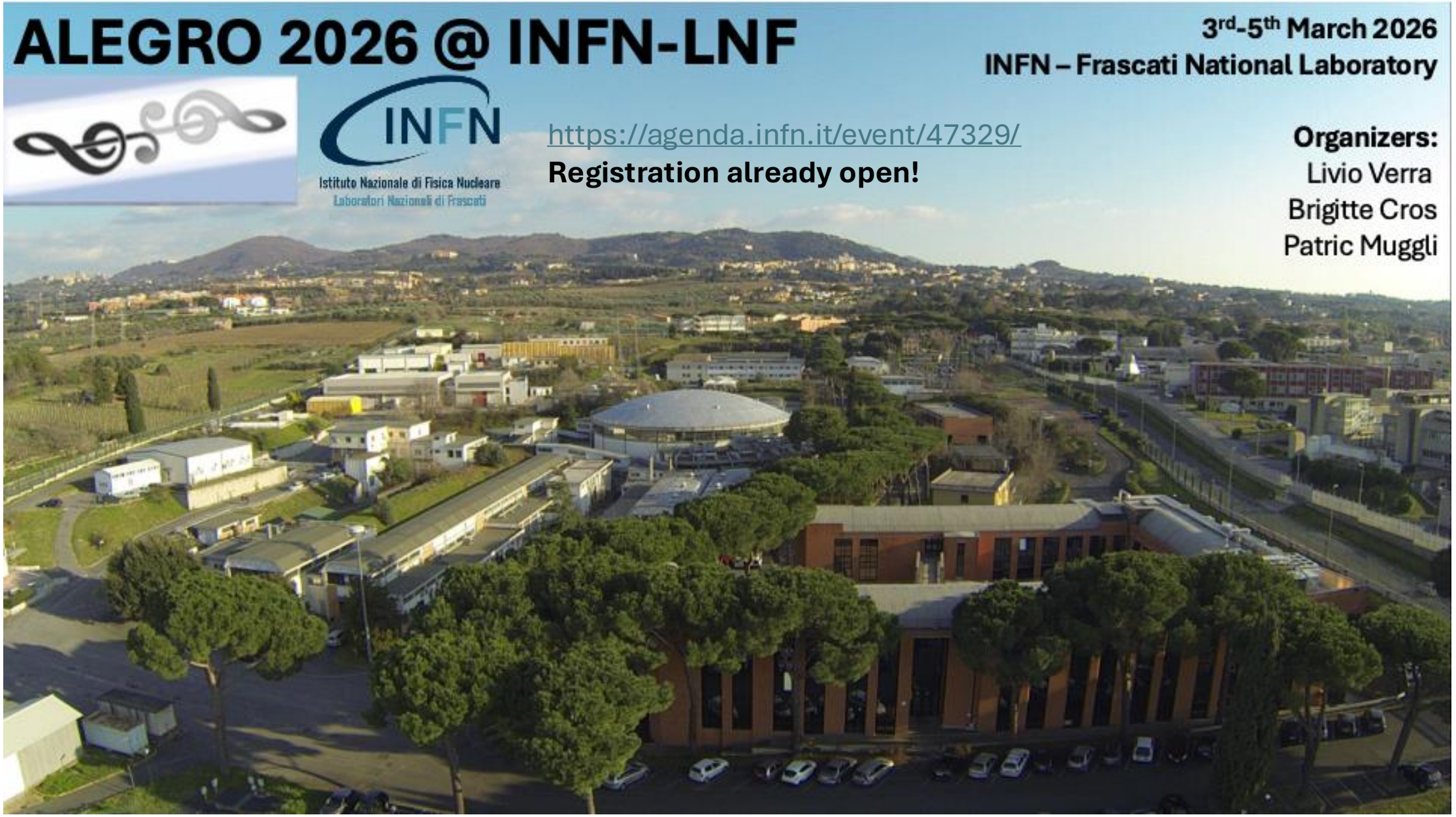
- Organization in Working Groups

- Input to European Strategy
  https://arxiv.org/abs/2503.20214

- Within PWFA Working Group:
  - Investigating critical questions such as staging
    → Effect of SR is not negligible at high energies
    → Challenging to reach >0.5GV/m

  - Still to understand: high-energy effects and management of emitted power.

ALEGRO 2026


ALEGRO 2026 @ INFN-LNF
3rd-5th March 2026
INFN – Frascati National Laboratory
INFN
Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Frascati
https://agenda.infn.it/event/47329/
Registration already open!
Organizers:
Livio Verra
Brigitte Cros
Patric Muggli

INFN
Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Frascati

Thank you!

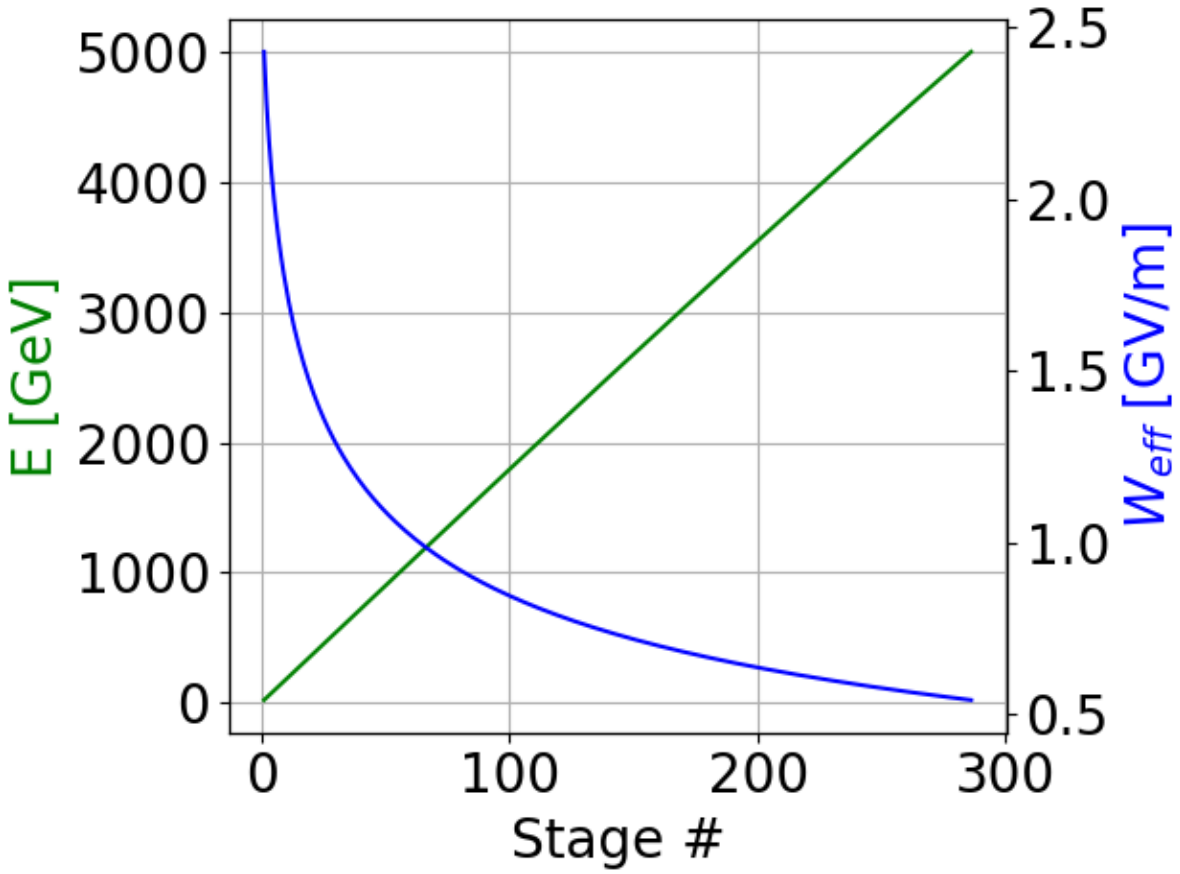
TOV

Simplest LINAC model – SR effect on emittance

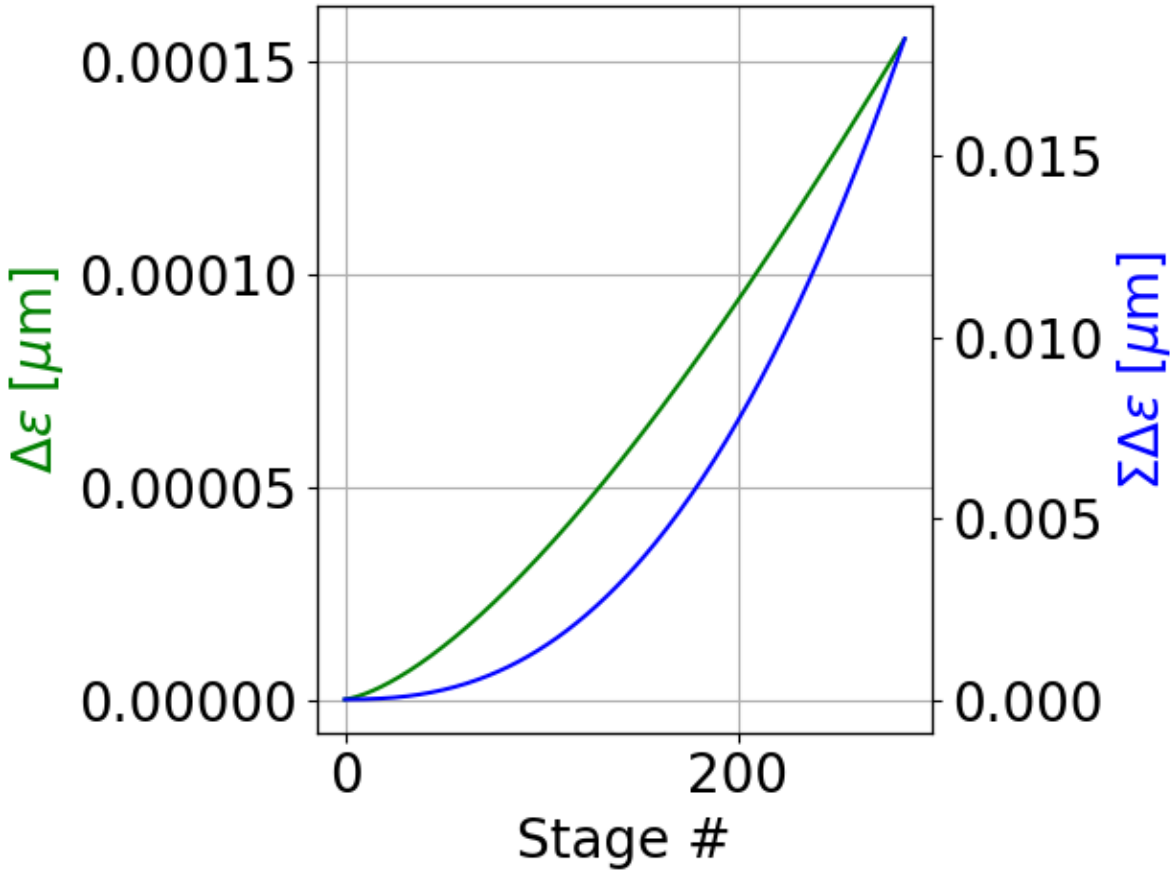
$\Delta\varepsilon = 10^{-62} \cdot E \cdot L_d^4 \cdot (Bc)^5 \cdot \left(L_d + L_0 \sqrt{\frac{E}{E_{in}}} \right)$, due to increased energy spread plus dispersion

T. Raubenheimer, P. Emma, S. Kheifets, proceedings of PAC93

5GV/m in plasma, 9GeV driver, L_0=1m



Emittance growth
~10's nm

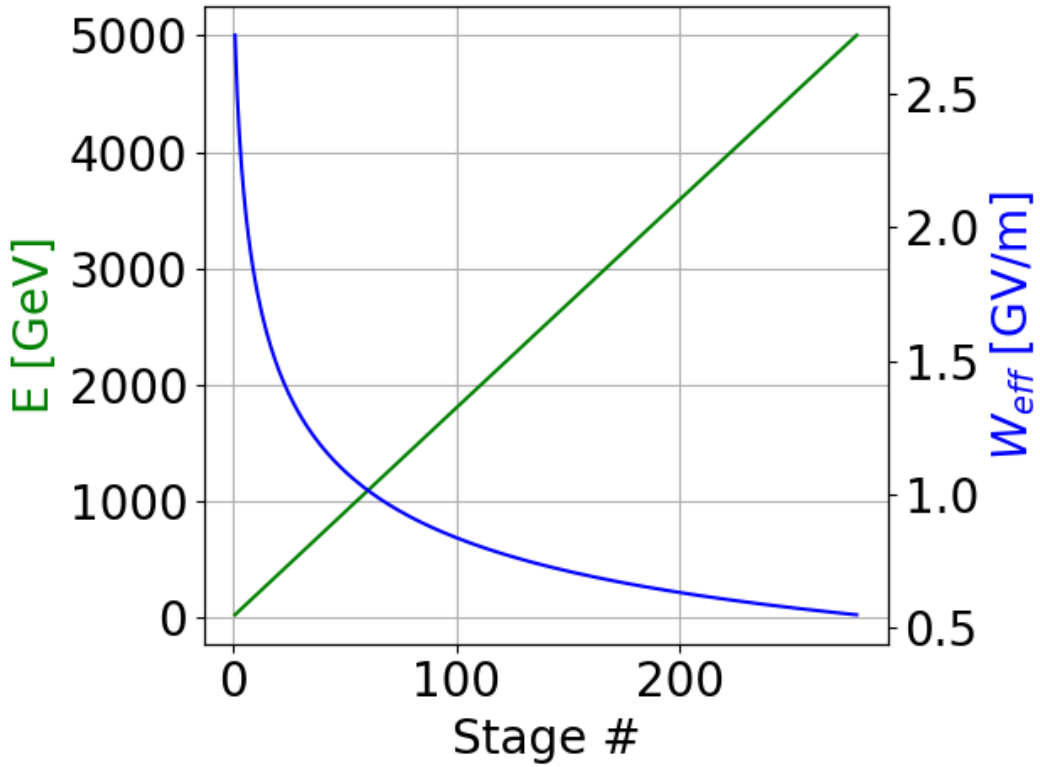
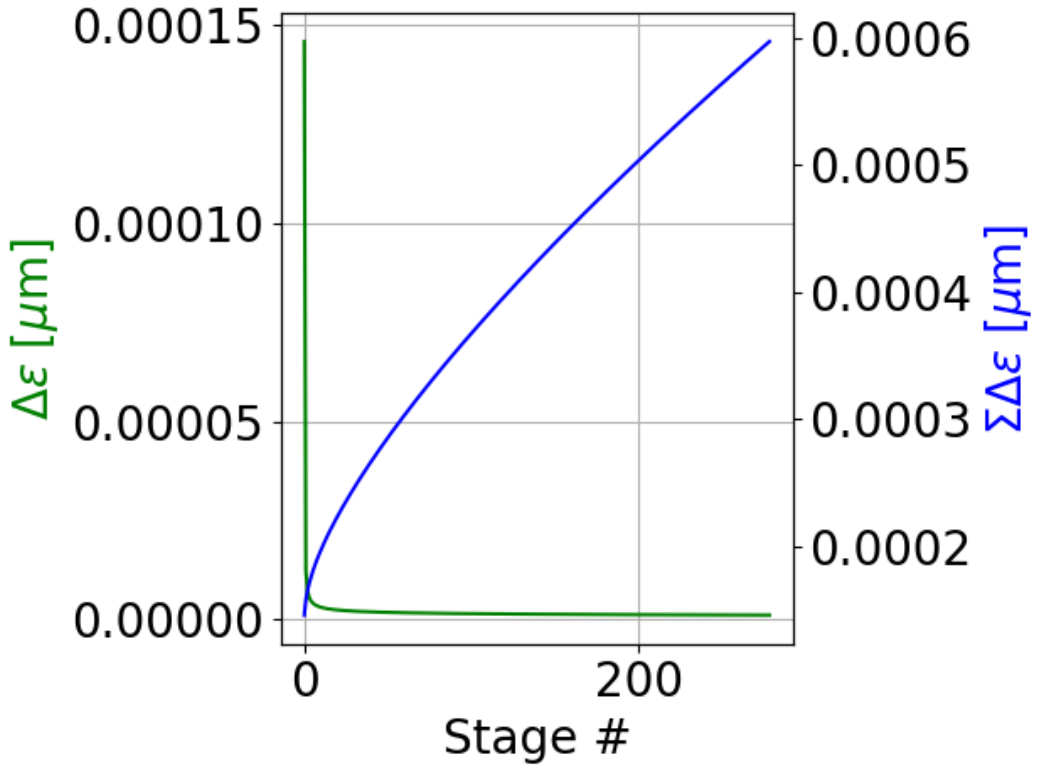


Simplest LINAC model – SR effect on emittance

$\Delta\varepsilon = 10^{-62} \cdot E \cdot L_d^4 \cdot (Bc)^5 \cdot \left(L_d + L_0 \sqrt{\frac{E}{E_{in}}} \right)$, due to increased energy spread plus dispersion

T. Raubenheimer, P. Emma, S. Kheifets, proceedings of PAC93

Possible mitigation: tapering of B-field:

$$B = B_0 \sqrt{\frac{E_{in}}{E}}$$

➔ Half emittance growth and almost no difference in effective gradient
(lower B field at higher energies → less SR emission)