150 MeV line status and updates

E. Belli, F. M.Velotti
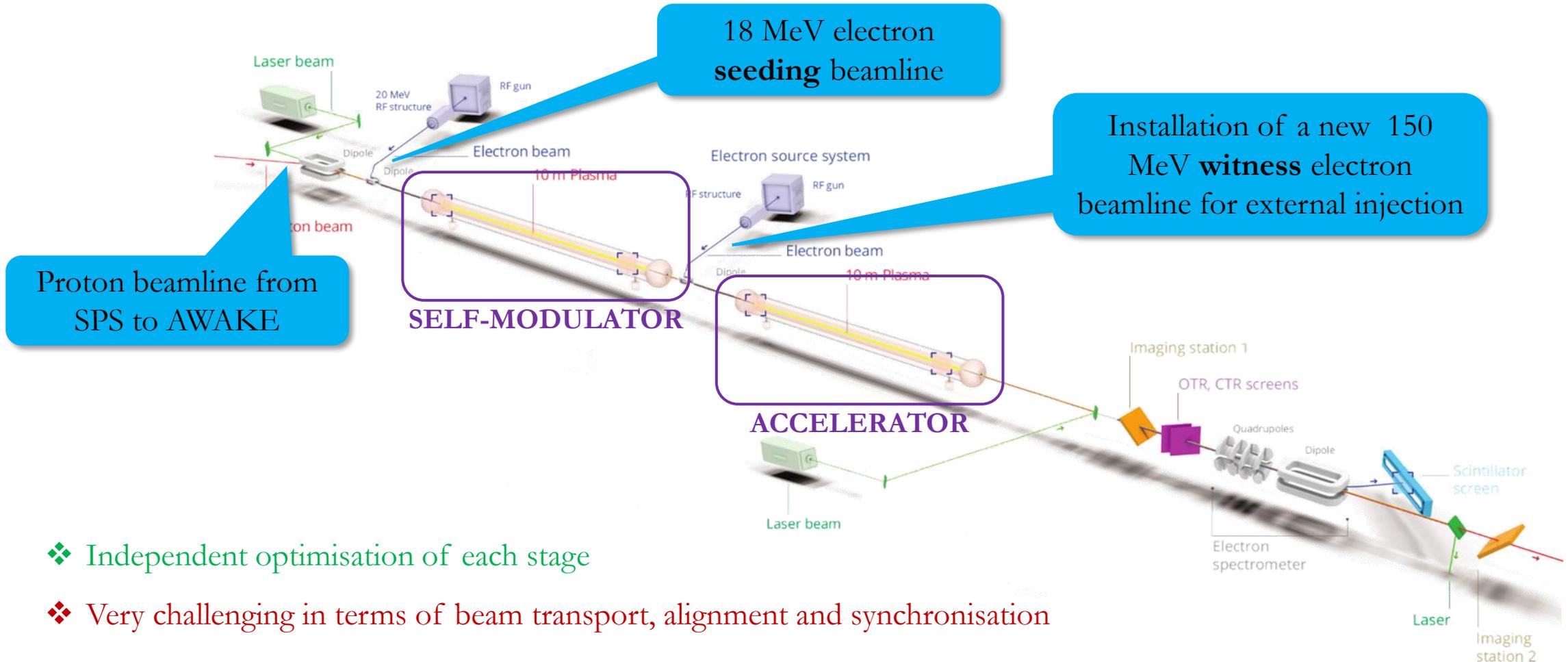
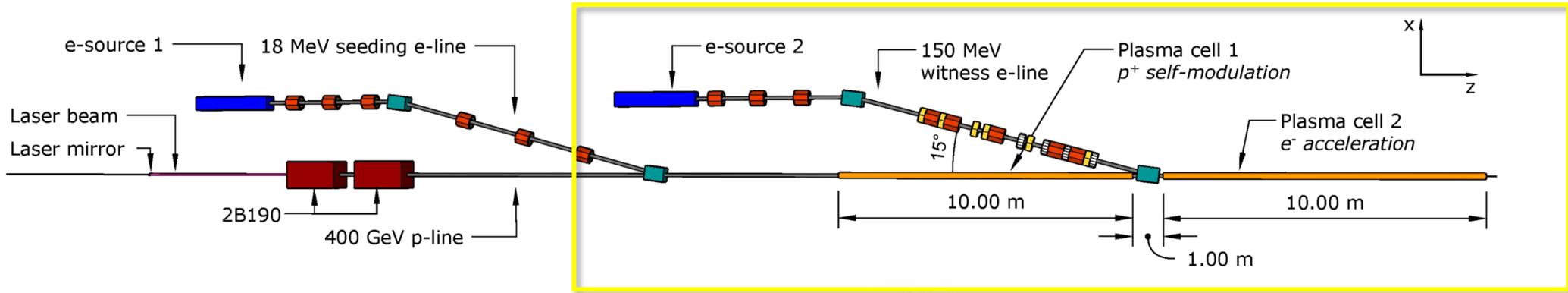AWAKE Collaboration Meeting

15-17 October 2025

- ➤ **Goal:** achieve electron energies up to 10 GeV while preserving the quality of the accelerated electron beam

- ➤ New modular two-stage configuration: p$^+$ self-modulation and e$^-$ acceleration will occur in two separate plasma cells

18 MeV electron **seeding** beamline

Installation of a new 150 MeV **witness** electron beamline for external injection

Proton beamline from SPS to AWAKE

SELF-MODULATOR

ACCELERATOR

- ❖ Independent optimisation of each stage

- ❖ Very challenging in terms of beam transport, alignment and synchronisation

E. Belli – `awake Run 2c program

1

150 MeV electron line

➢ New witness electron beamline to perform **external on-axis injection** into the 2nd plasma cell

➢ Electrons must be injected into the second plasma stage with micron-level precision in both position and beam size to ensure proper matching with the accelerating and focusing regions of the wakefields

Parameter	Value
Momentum (MeV/c)	150
Bunch length σ_z (μm)	60
Relative energy spread $\Delta p/p$ (%)	0.2
Normalised emittance $\varepsilon_{x,y}$ (mm mrad)	2
Beam size $\sigma_{x,y}$ at focal point (μm)	5.75
Dispersion $D_{x,y}$ at focal point (m)	0
α-function $\alpha_{x,y}$ at focal point	0
Relative e⁻- p⁺ offset (μm)	< 10

Bunch matched to the plasma wakefield bubble:

$$\sigma^* = \sqrt[4]{\frac{2\varepsilon_0 m_e c^2 \gamma}{n_{pe} e^2} \varepsilon^2}$$
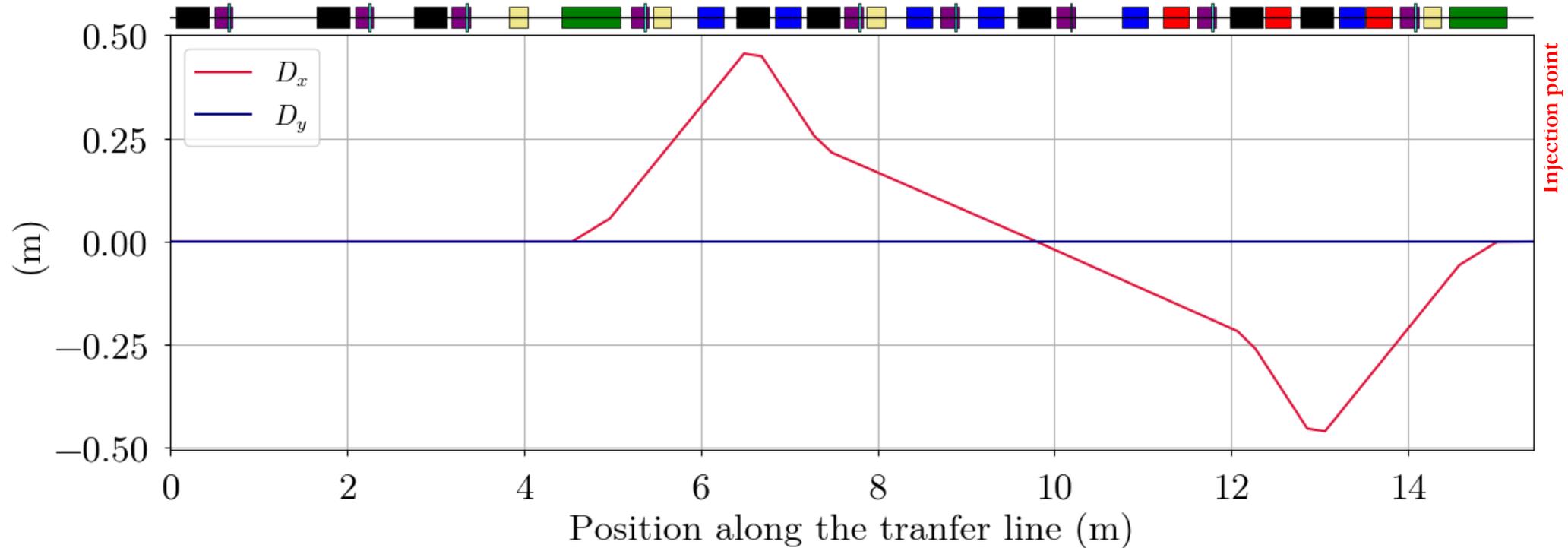
with n_{pe} = 7 x 10^{14} cm⁻³

❖ σ_{inj} < 1.5 σ^* (8.6 μm) to keep emittance growth within acceptable limits[1]

[1] Farmer, John P., et al. "Injection tolerances and self-matching in a quasilinear wakefield accelerator." *arXiv preprint arXiv:2203.11622* (2022).

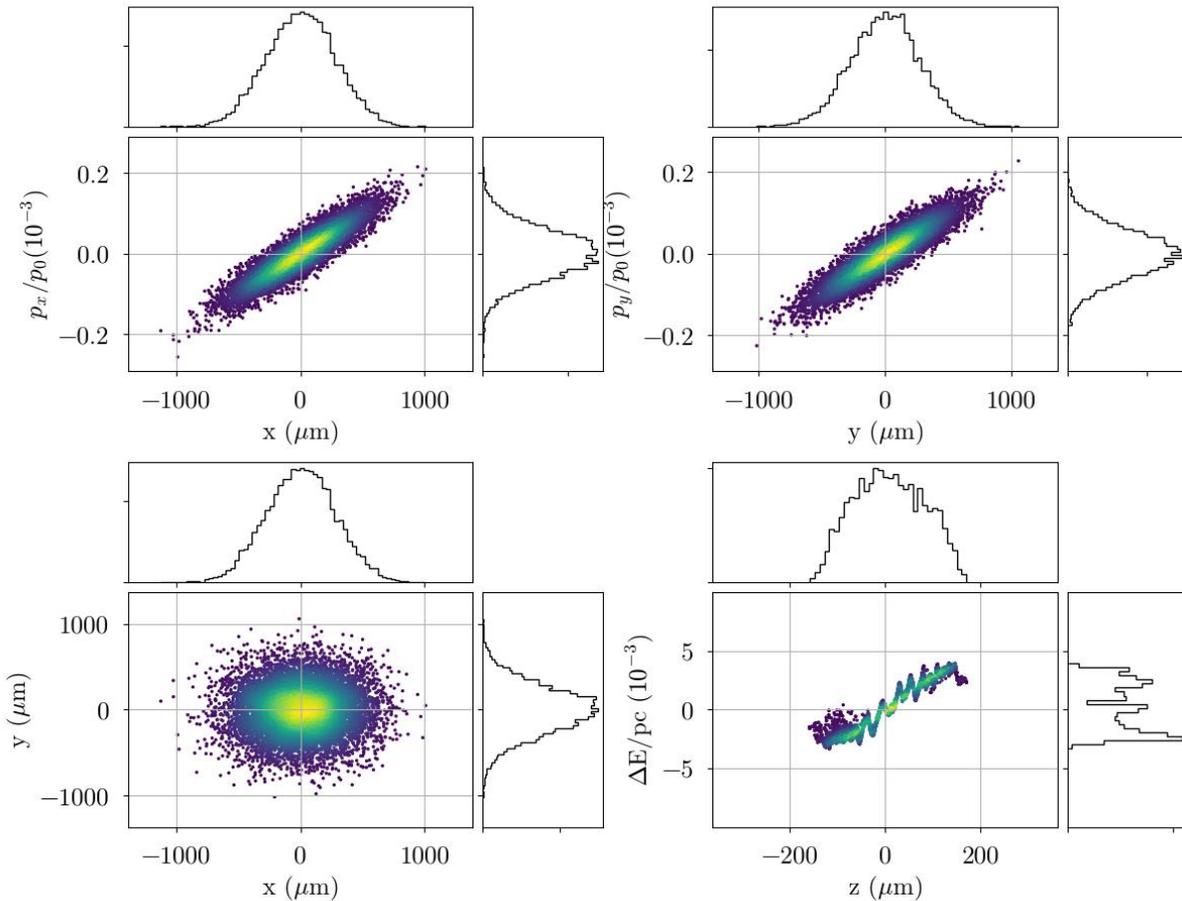➢ Spatial constraints given by the tunnel (**dog-leg with 15° bending dipoles**)

➢ **Quadrupoles** for matching, achromaticity and focusing

➢ **Sextupoles** to combat chromatic effects due to strong focusing

➢ **Octupoles** to mitigate remaining non-linear effects

[2] Ramjiawan, Rebecca, et al. "Design of the AWAKE Run 2c transfer lines using numerical optimizers." arXiv preprint arXiv:2203.01605 (2022).

E. Belli – 150 MeV electron line : design summary

3

Beam at injection point
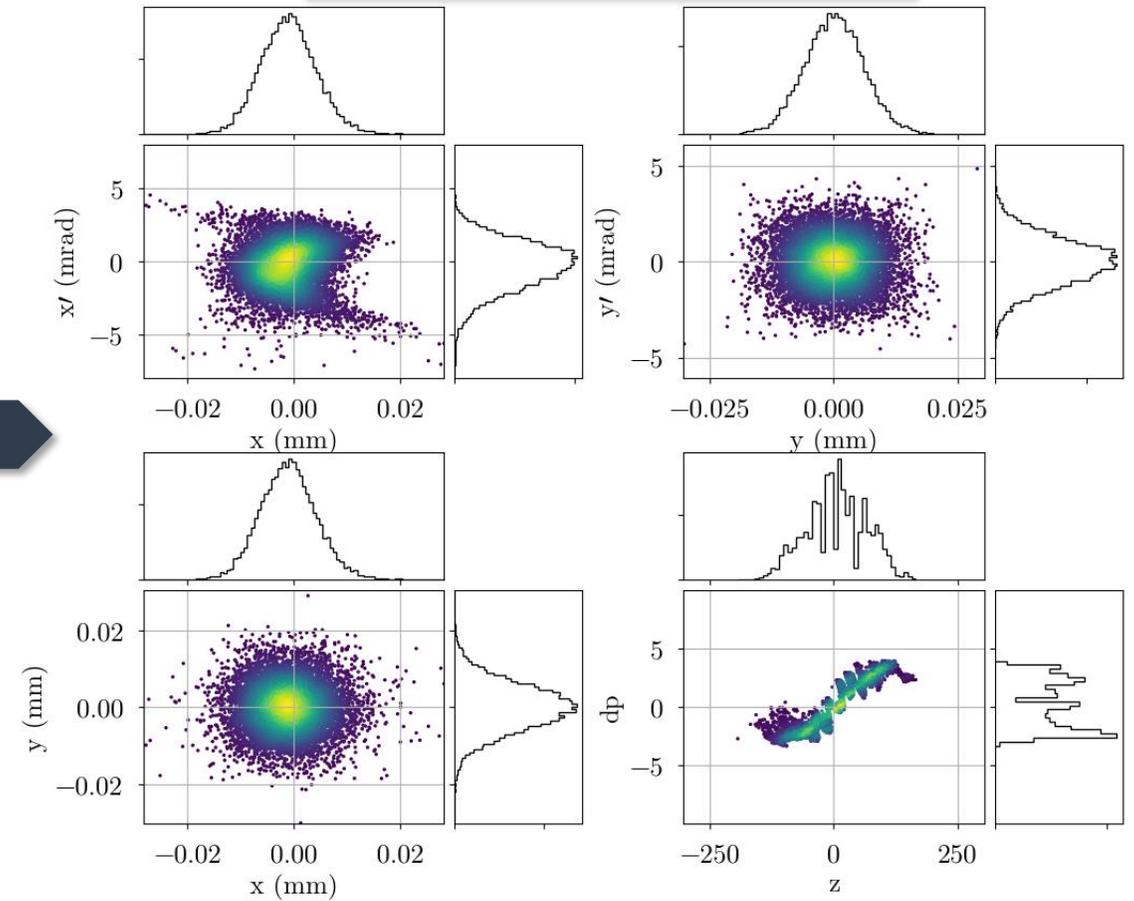
➢ Multi-particle tracking simulations using as input the beam distribution out of the electron injector

✓ **Beam size at injection meets experimental requirements**

$\sigma_x = 277.63\ \mu\text{m} - \sigma_y = 273.40\ \mu\text{m} - \sigma_z = 72.23\ \mu\text{m}$

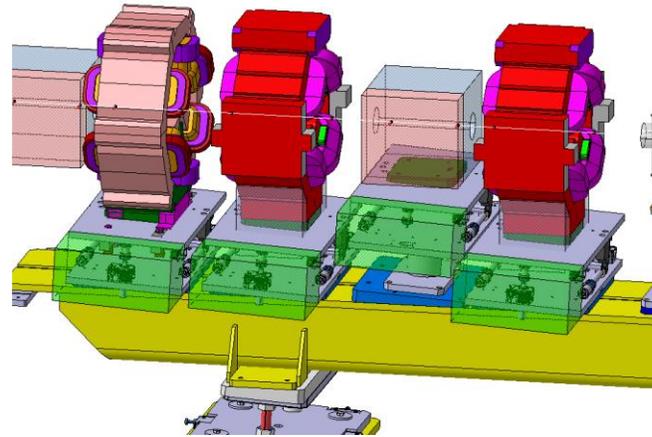$\sigma_{x,op} = 5.67 - \sigma_{y,op} = 6.07 - \sigma_{z,op} = 60.70$

E. Belli – 150 MeV electron line : design summary

4

➤ **The current solution is stable when introducing errors and after performing the alignment procedure**

  ❖ **To reach beam size and pointing specifications,** magnets need to be installed on
    movers (vertical and radial adjustment at um-level)

Parameter	Error
BTV resolution	1 μm
Magnet mover position	1 μm
Corrector kick	1 μrad
BPM resolution	10 μm
Magnets' misalignment	100 μm RMS
Power converters ripple	7 ppm
Momentum jitter	1e-3
Input beam position jitter	10 μm

  ❖ **Active alignment procedure**
    ❖ **Quadrupole shunt:** centre quadrupoles w.r.t. beam orbit
      ❑ Change quad strength Δk and measure Δx_{BPM}
      ❑ Compute quad-beam offset Δx_{QUAD}
      ❑ Move quadrupole of $- \Delta x_{QUAD}$
    ❖ **DFS:** minimize parasitic dispersion and orbit
      ❑ Change beam energy and measure Δx_{BPM}
      ❑ Use correctors to minimise beam offset
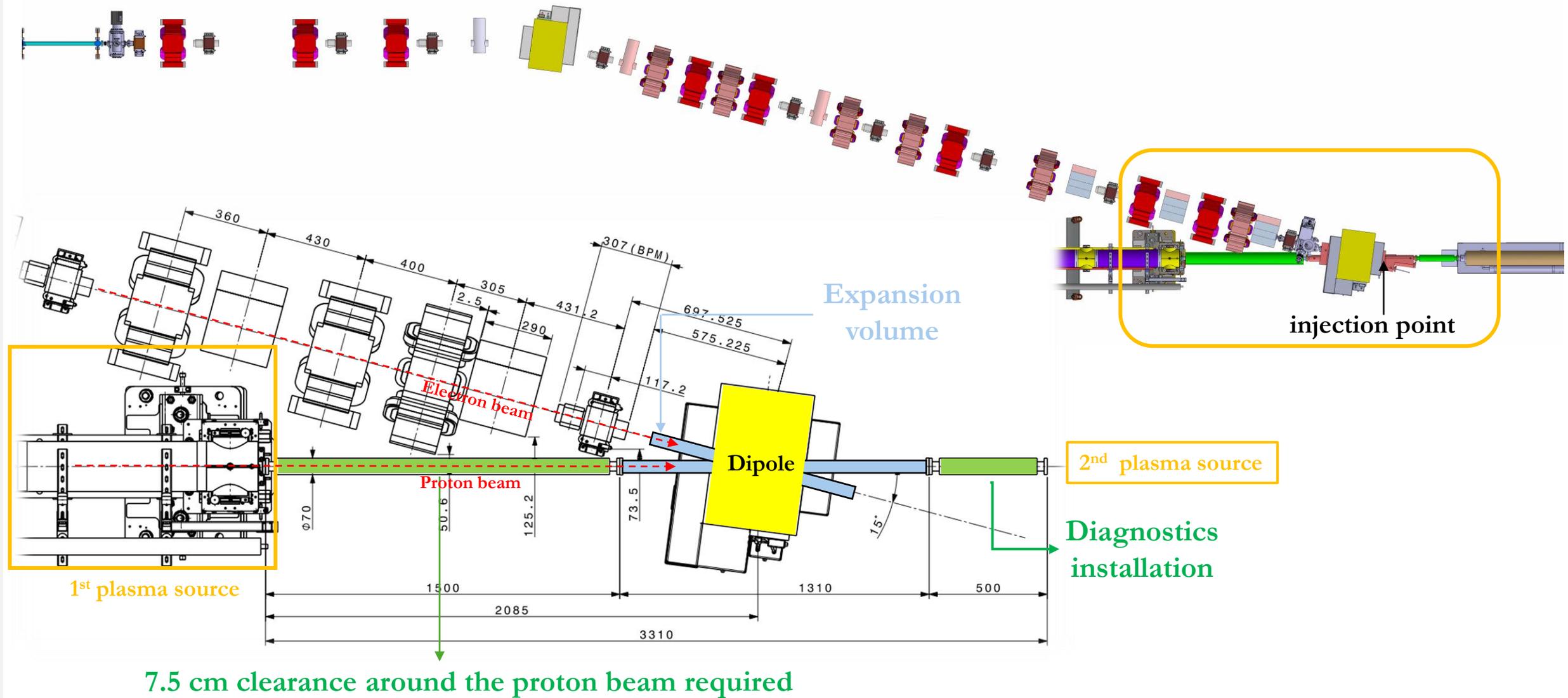   ❖ **Numerical optimisation**
      ❑ Align sextupoles and octupoles by minimizing σ_{inj} (BTV)

➤ Integration challenge due to experimental needs and limited space

7.5 cm clearance around the proton beam required

> Rb vapor from the entrance of the 1st plasma cell to the exit of the 2nd one → entire structure at 200°C

❖ Cooling system design

> IR dipole will bend e⁻ beam and p⁺ beam in two opposite directions

❖ Bending angle for a 400 GeV p+ beam ≈ 0.1 mrad → the two vapor sources will be angled

> 30 cm gap between plasma sections defined as the distance between the laser beam dump and the focal point

Gradient reduction of about 50% for 1 m gap[3]

New waist

Original waist

❖ **Waist has been moved 25 cm upstream the original one**

[3] Adli, Erik. "Towards AWAKE applications: Electron beam acceleration in a proton driven plasma wake." Proceedings of IPAC2016, Busan, Korea WEPMY008.

E. Belli – 150 MeV electron line : injection region

➢ Moving the focal point is equivalent to a full re-design of the beamline

❖ The beamline design is an **optimisation problem**: find a set of inputs which minimise an objective function

$$\sum_{i=1}^{n} w_i \left(y_i - y_i^{target} \right)^2$$

○ w_i: weights

○ y_i: simulated parameters

○ y_i^{target} : target parameters at injection $= \begin{cases} \sigma_{x,y} = \sigma_{req} \\ \sigma_{x} = \sigma_y \\ D = 0 \\ losses = 0 \\ \alpha_{x,y} = 0 \end{cases}$

○ inputs: magnets settings and positions ➔ **34 variables**

Optimisation procedure

At each iteration:

❑ Adjust variables ➔ track beam

❑ Evaluate tracked parameters vs targets

❑ Update best candidate

❑ Repeat until an optimum is reached

➢ Tracking simulations essential to model the line behaviour in presence of non-linear effects

➢ Computationally demanding simulations (memory + runtime)

E. Belli – 150 MeV electron line : next steps

Moving the focal point: implications

➤ Focal point shifted into dipole fringe fields (not fully decayed)

 ❖ for final estimation need to fully simulate dipole field map (first estimates possible using clever approximations)

➤ LS3 schedule: risk of delays in procurement and installation

 ❖ Functional specifications **not yet available → procurement blocked**

 ❖ **~2 years** lead time from specs to magnet installation

 ❖ PC specifications **dependent on magnet confirmation** (MEXICO compatibility)

 ❖ Potential **design changes → aperture/envelope impact** on diagnostics & vacuum

 ❖ **Stability tolerances** for alignment platforms cannot be validated before final design

 ❖ Resource availability cannot be guaranteed in case of schedule delays

➤ Plan & Next Steps

 ❖ Initial feasibility estimation: end of October.

 ❖ Full study: end of the year.

➤ **Documentation & Traceability**

 ❖ Track all design changes

 ❖ Update documentation accordingly

 ❖ Ensure visibility across all involved teams

Thank you for listening