A tale of three beams: towards stable and reproducible operation of the AWAKE facility

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Abstract

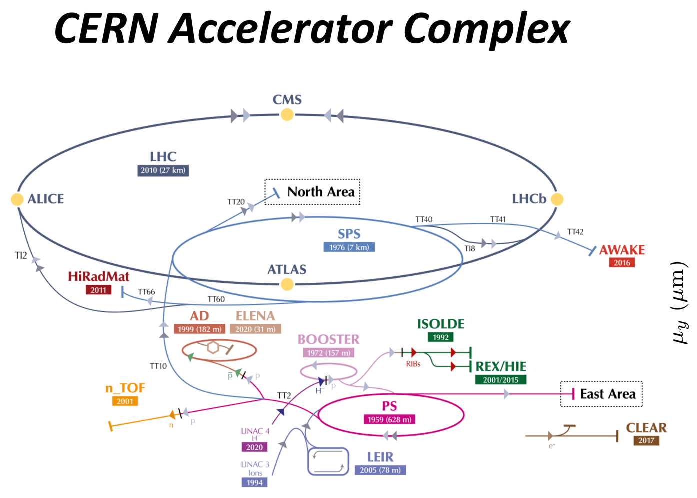
The Advanced Wakefield Experiment (AWAKE) relies on proton-driven wakefields created in a laser-ionized plasma to accelerate electrons. Accurate measurement and control of the optics, trajectory and timing of the three beams—proton, laser and electron—is a fundamental requirement for successful operation of the facility. Continuous advances in both instrumentation and methods are necessary to improve operational stability, reproducibility and efficiency. Since the three beams have drastically different characteristics, their performance is limited by different sources (such as thermal effects, magnetic hysteresis, current ripples, phase locking), requiring dedicated approaches. Recent improvements and measurement campaigns are described, highlighting the lessons learned. Finally, the challenges expected in future upgrades of the AWAKE facility are discussed.

PROTONS (400 GeV)

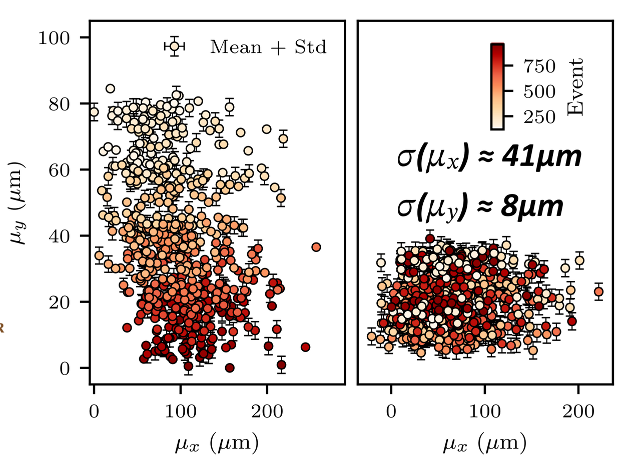
Trajectory

Measurements are essential to position the proton beam on the right trajectory. BTV screens are used instead of BPM due to their higher resolution

CERN Accelerator Complex



Trajectory Jitter



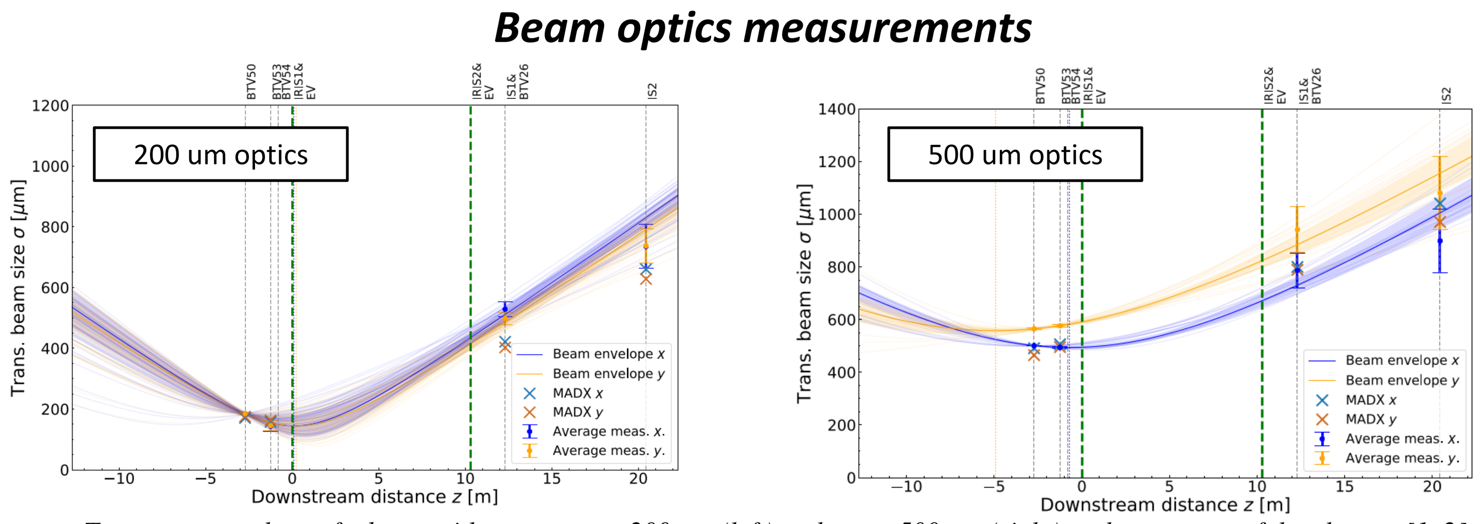
Positions of the bunch centroids at the waist. The left plot includes the drift of the bunch centroid with the time of the measurement. The right plot shows the same data with subtracted time drift [1]

- Proton beam jitter is generated by current fluctuations in the power converters of the transport line magnets
- A quantitative understanding of these source is essential to simulate and predict jitter at beam waist
- Work is ongoing to fill the gap between simulations and measurements

Optics

Dedicated proton bunch optics were developed using MAD-X and validated with envelope measurements. These optics were used for wide-beam studies [3] and current filamentation studies [4,5].

Beam optics measurements



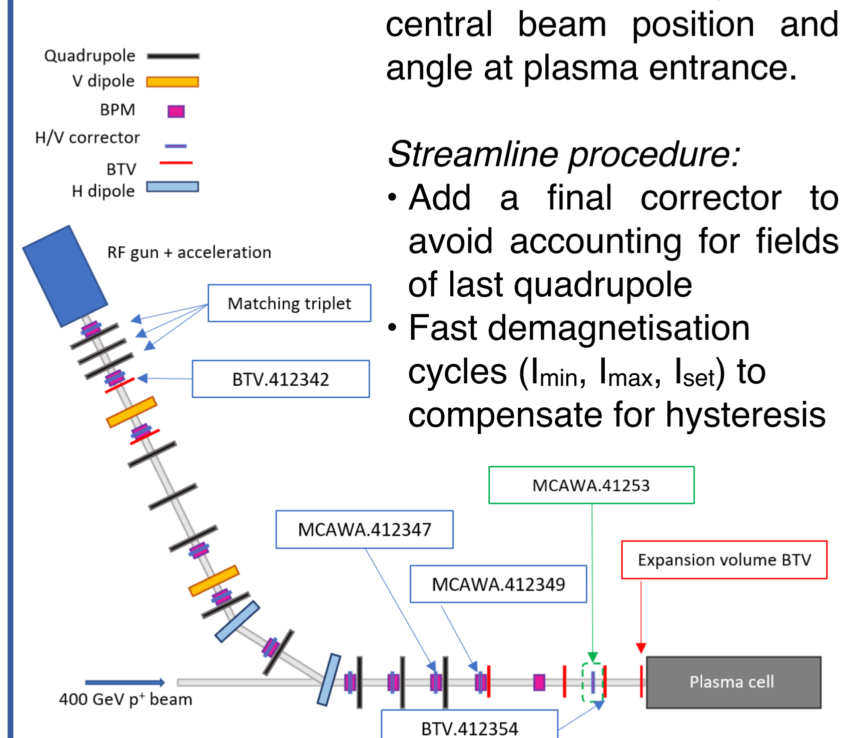
Transverse envelope of a beam with target $\sigma_{x,y}$ = 200 μm (left) and $\sigma_{x,y}$ = 500 μm (right) at the entrance of the plasma. [1, 2]

ELECTRONS (20 MeV)

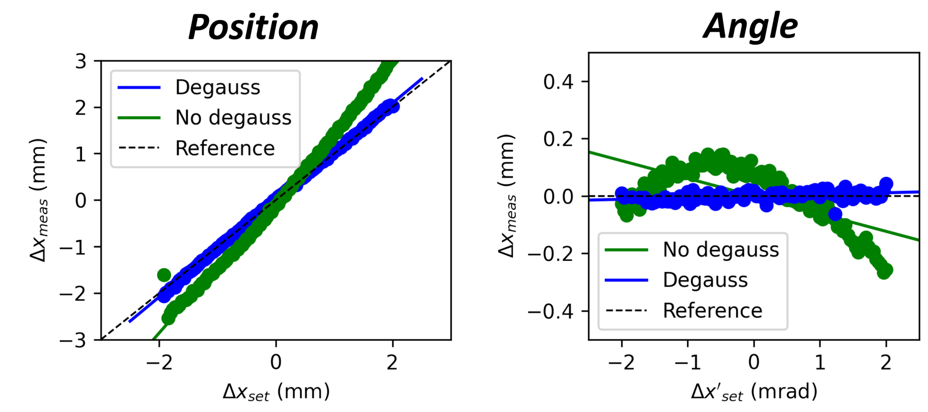
Trajectory

Orthogonal steering exploits two correctors to adjust the central beam position and angle at plasma entrance.

Streamline procedure:
- Add a final corrector to avoid accounting for fields of last quadrupole
- Fast demagnetisation cycles (I_{min}, I_{max}, I_{set}) to compensate for hysteresis



Fast steering without hysteresis



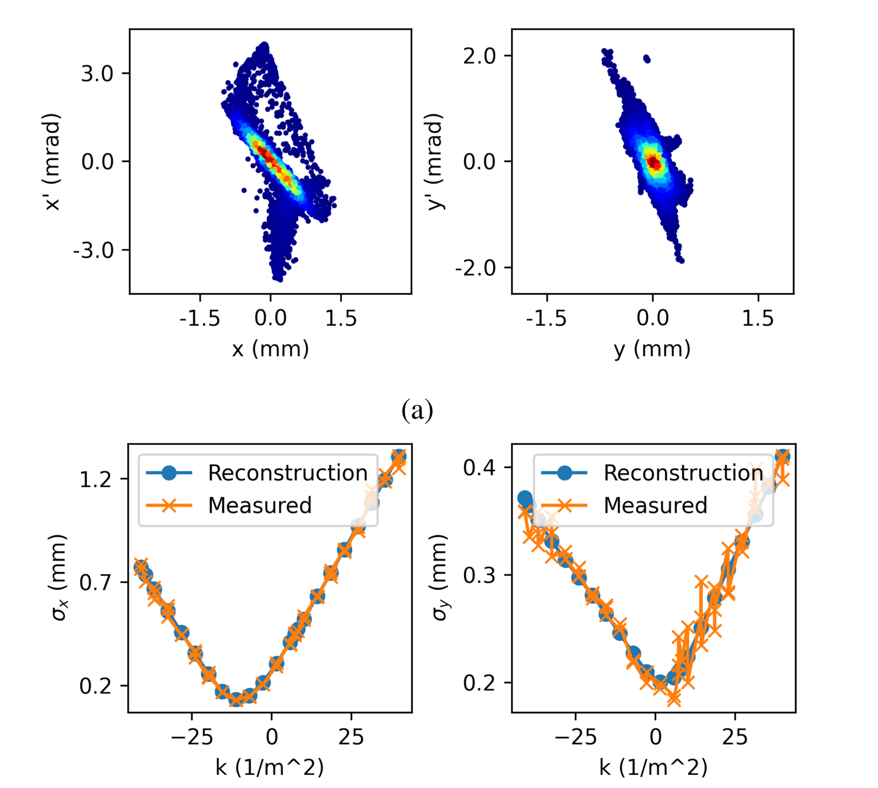
Measured response to orthogonal steering at BTV.412354, with and without fast demagnetisation (I_{min}, I_{max}, I_{set}) [7]

Optics

Emittance measurements are performed using a quadrupole scan in a dispersion-free region at the entrance of the beam line. A parabolic fit is effective for Gaussian distributions but loses accuracy for non-Gaussian beams.

New approach
- Quadrupole scan can be approached as a classical phase-space-tomography problem, equivalent to a rotation [8]
- Maximum Likelihood Maximum Expectation algorithm developed and commissioned using simulated beams and then validated with data [7]
- Non-Gaussian beams can be fully described and then used to develop beam line optics

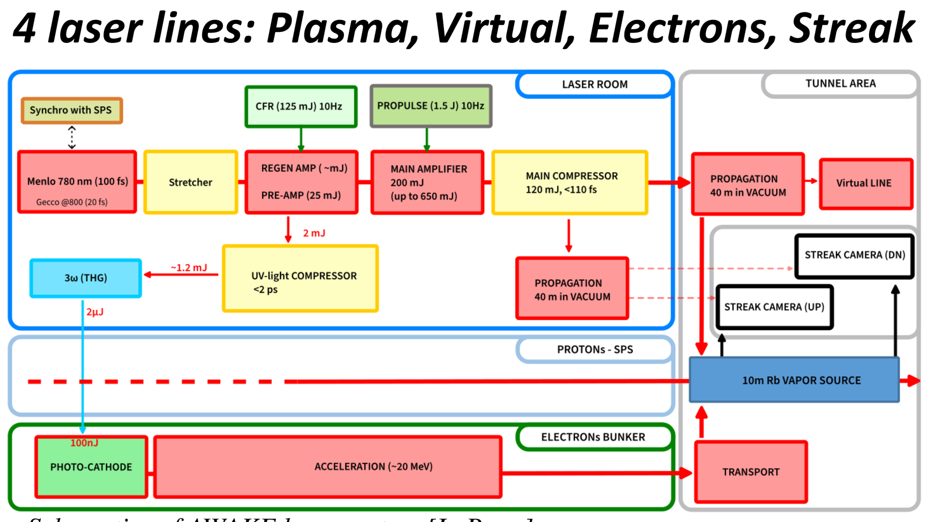
Reconstruction without gaussian assumptions



Top: Reconstructed distribution in x-x' and y-y'. Bottom: Comparison between reconstructed beam sizes and measurements [7]

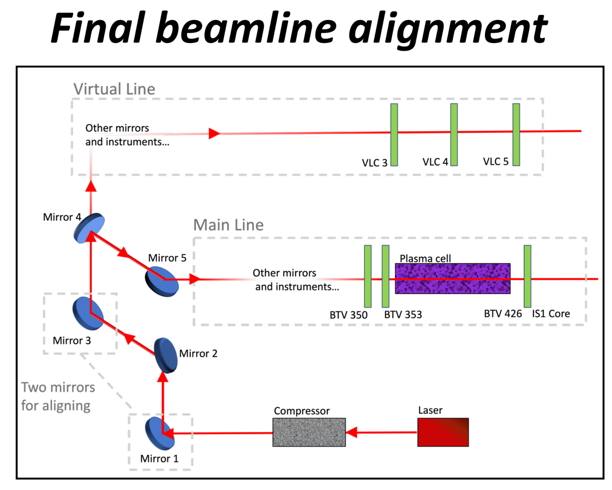
LASER (100 mJ, 100 fs)

4 laser lines: Plasma, Virtual, Electrons, Streak



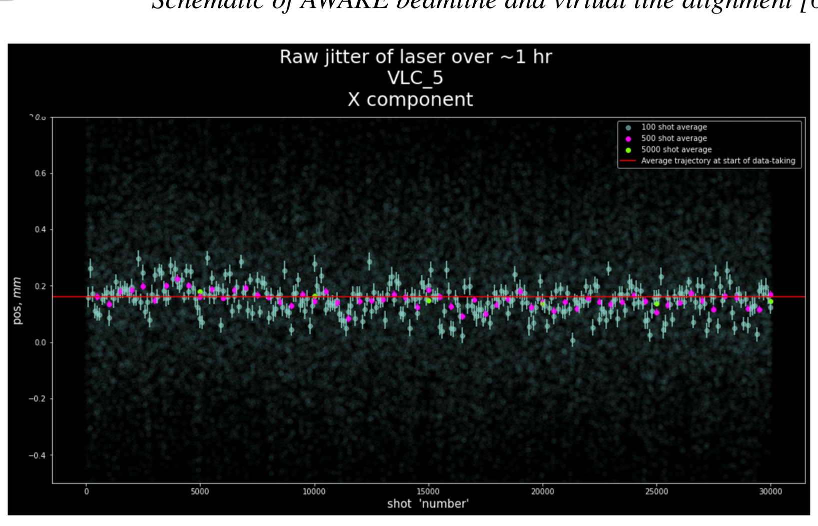
Schematics of AWAKE laser system [L. Ranc]

Final beamline alignment



Schematic of AWAKE beamline and virtual line alignment [6]

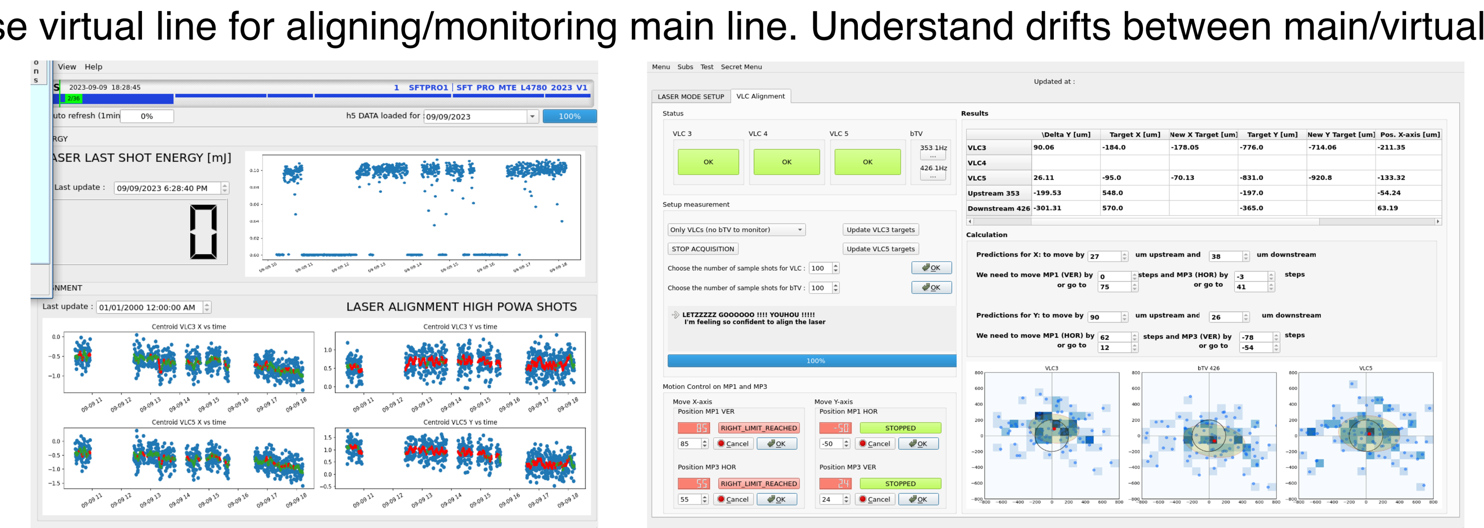
Challenging steering: jitter of laser trajectory is dominated by thermal fluctuations, preventing convergence at larger sample sizes. Accept this limitation, relax steering requirements, and rely on a wide beam to create a large plasma column.



VLC 5, mm	RMS all data	RMS for 100 shot average	RMS for 500 shot average	RMS for 5000 shot average
y actual	0.2741	0.1038	0.0832	0.0766
y random	0.2741	0.0274	0.0123	0.0039
x actual	0.2772	0.0553	0.0281	0.0155
x random	0.2772	0.0277	0.0124	0.0039

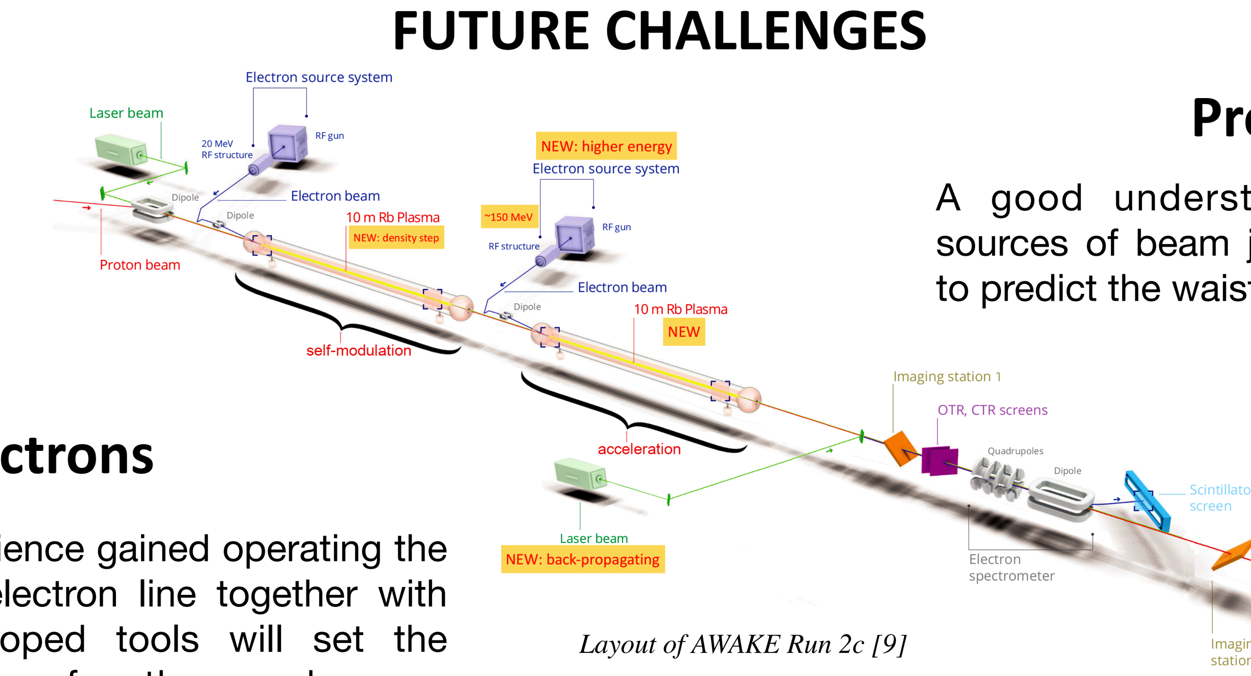
Standard deviation of all shots and 100-, 500-, 5000-shot averages on virtual line, compared to expected RMS from random fluctuations [6]

Use virtual line for aligning/monitoring main line. Understand drifts between main/virtual drifts.



Trajectory monitoring on virtual line (left). Laser alignment on virtual and main lines (right) [L. Ranc]

FUTURE CHALLENGES



Layout of AWAKE Run 2c [9]

Protons

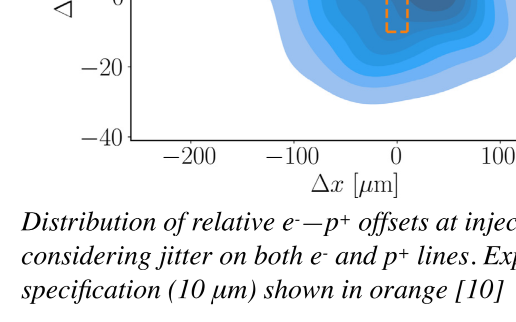
A good understanding of the sources of beam jitter is essential to predict the waist jitter in Run 2c.

Proton trajectory jitter

Correlate proton trajectory with power converter jitter, to reach required precision (10 μm)

Magnet class	Current r.m.s jitter (ppm)	Beam r.m.s jitter (μm)	
		x	y
B190	50	6.9	0.0
MBG	90	71.5	10.5
MBHC	100	22.0	0.0
Quadrupole	50–200	–	–
MSE.4	100	28.8	0.0

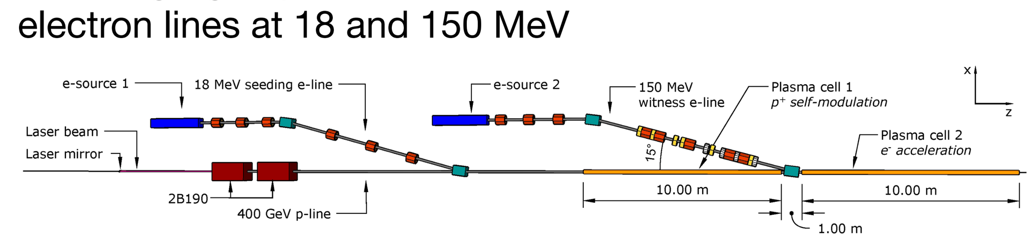
Measured magnet current jitter and corresponding beam position jitter propagated to the injection point [10]



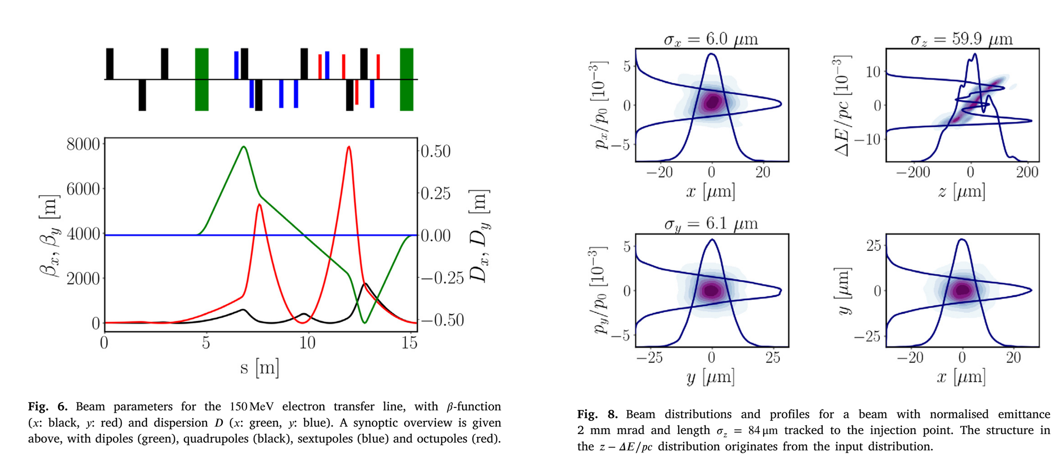
Distribution of relative e⁻—p⁺ offsets at injection, considering jitter on both e⁻ and p⁺ lines. Experiment specification (10 μm) shown in orange [10]

Electrons

The experience gained operating the 18 MeV electron line together with the developed tools will set the foundations for the much more challenging operation of Run2c electron lines at 18 and 150 MeV



150 MeV electron line



Left: Beam parameters and optics layout (dipoles to octupoles, in decreasing width) along the 150 MeV line. Right: Beam distributions at the injection point after transporting an initial beam with normalized emittance 2 mm mrad and σ_z = 84 μm [10]

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[4] See L. Verra, Talk, Wed W1
[5] P. Muggli, L. Verra, N. Lopes, and A. Sublet, *Self-modulation and current fila- mentation instabilities of long and wide proton bunches in plasma*, IPAC '23 (2023).
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6th European Advanced Accelerator Concepts workshop, 17–23 Sept 2023, Isola d'Elba, Italy