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Engineering Parameters

AWAKE RUN 2 ELECTRON LINE PARAMETERS

ABSTRACT: An overview of the current parameters and results towards the design of the AWAKE Run 2 electron line, including the electron source, transfer line, injection region and propagation of the beam in plasma.

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AWAKE collaboration

HISTORY OF CHANGES

REV. NO.	DATE	PAGES	DESCRIPTION OF THE CHANGES
1.1	2020-06-26	15	First draft for checking.

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1. LAYOUT

- The footprint of the beamline has a width less than 3 m (shown in Fig. 1.1), which fits within the tunnel (shown in Fig. 1.2).
- The length of the straight section before the dogleg is 5.3 m.
- The bending angles of the two dipoles in the dogleg are ±15°.
- The gap between plasma cells is currently assumed to be at most 1 m; this value will need to be updated when we have a better estimate of the size of the dipole and the BPM in the gap.
- Estimated to have approximately 17 cm between the end of the dipole and the injection point for the integration of e^- diagnostics.

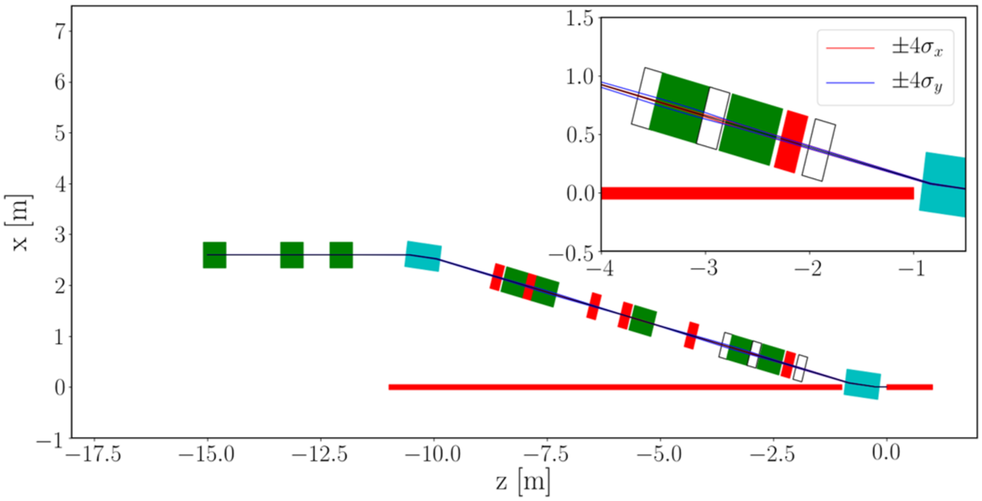


Figure 1.1: Footprint of electron transfer line showing estimated element sizes, with dipoles (cyan), quadrupoles (green), sextupoles (red), octupoles (black outline) and plasma cell (red); $4\sigma_{x,y}$ beam envelopes are also given.

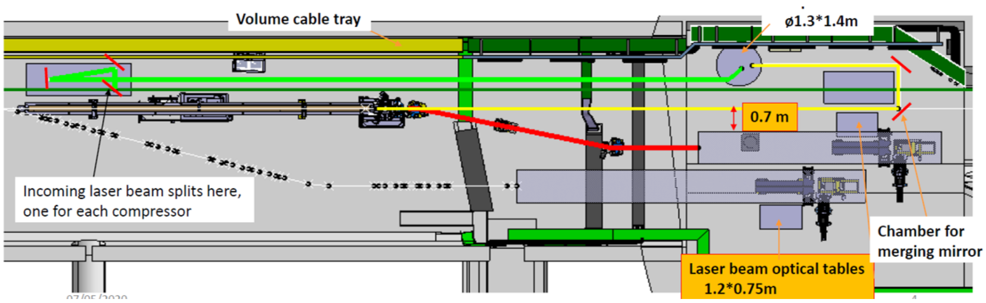


Figure 1.2: Possible placement of electron line within tunnel, as shown in P. Wiwattananon's talk at the 18th AWAKE Run 2 Meeting (07/05/2020). This would mean 0.5 m between electron source 2 and the tunnel wall.

2. ELECTRON SOURCE PARAMETERS

2.1 RUN 2 DESIGN PARAMETERS

The agreed nominal AWAKE Run 2 parameters from the electron source are

- $\epsilon_N = 2\,\mathrm{mm\,mrad}$,
- momentum spread $1\sigma = 0.2\%$,
- charge $= 100\,\mathrm{pC}$,
- energy $= 150\,\mathrm{MeV}$.

These numbers represent the worst-case scenario estimated to date.
The electron source is expected to be on the same horizontal plane as the proton beam, meaning it is expected to have the same vertical inclination as the proton line.

2.2 150 MEV BEAM-DISTRIBUTION PARAMETERS

150 MeV beam distribution from simulations of the electron source, provided by S. Doebert (25/03/2020). Beam distributions produced by simulating a uniform-distribution laser onto a cathode.

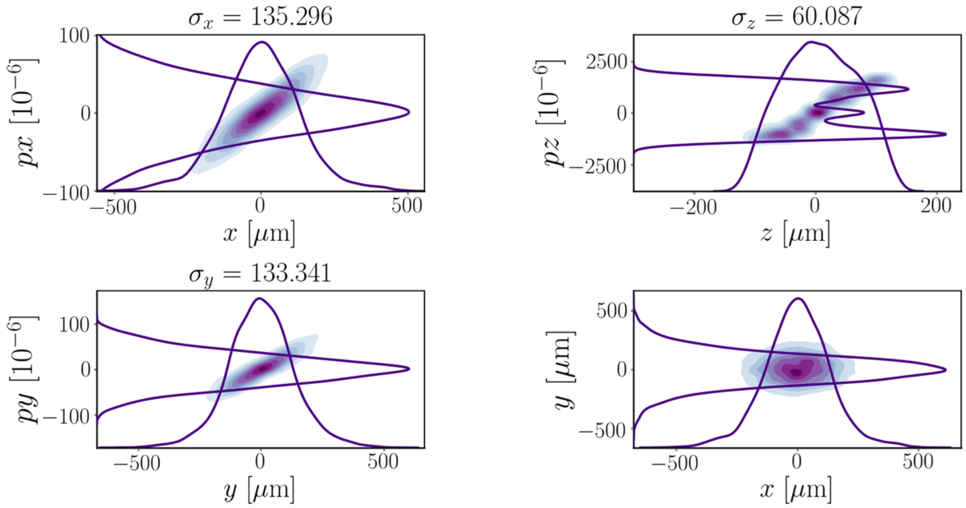


Figure 2.1: 150 MeV beam distributions.

Parameters of distribution:

- $\beta_{x,y} = 8.3\,\mathrm{m}$, $\alpha_{x,y} = -1.7$,
- $\sigma_x = 135.3\,\mu\mathrm{m}$, $\sigma_y = 133.3\,\mu\mathrm{m}$,
- $\epsilon_N = 0.7\,\mathrm{mm\,mrad}$,
- momentum spread $1\sigma = 0.095\%$.

During the 14th Run 2 meeting (12/03/2020) it was suggested that having a 150 MeV beam would mean it was possible to use a single klystron to power all of the components of the new electron source. In the 16th Run 2 meeting (09/04/2020), it was requested to have 150 MeV as the new 'nominal' energy.

2.3 160 MEV BEAM-DISTRIBUTION PARAMETERS

160 MeV beam distribution from simulations of the electron source, provided by S. Doebert (01/04/2020). Beam distributions produced by simulating a truncated-Gaussian laser onto a cathode.

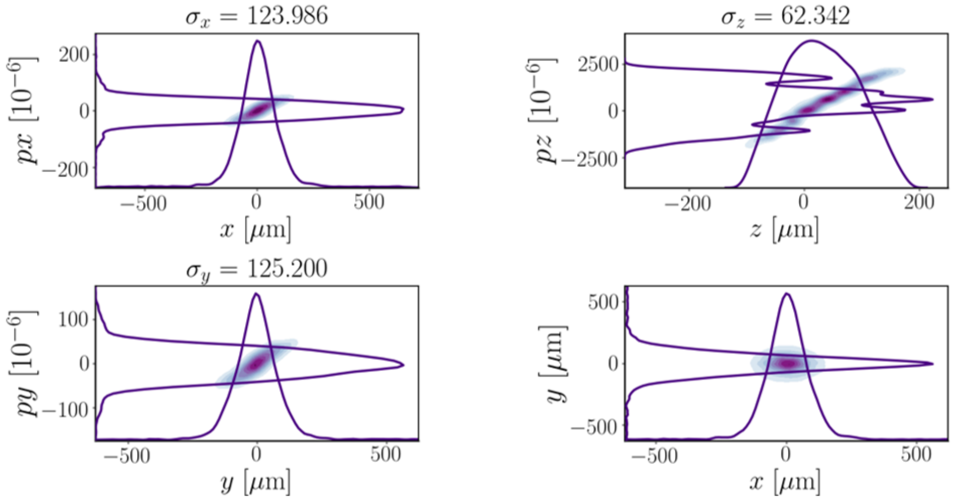


Figure 2.2: 160 MeV beam distributions.

Parameters of distribution:

- $\beta_{x,y} = 4.5\,\mathrm{m}$, $\alpha_{x,y} = -0.7$,
- $\sigma_x = 124.0\,\mu\mathrm{m}$, $\sigma_y = 125.2\,\mu\mathrm{m}$,
- $\epsilon_N = 1.0\,\mathrm{mm\,mrad}$,
- momentum spread = 0.103%.

2.4 165 MEV BEAM-DISTRIBUTION PARAMETERS

165 MeV beam distribution from simulations of the electron source, provided by S. Doebert (09/10/2019). Beam distributions produced by simulating a uniform-distribution laser onto a cathode.

Parameters of distribution:

- $\beta_{x,y} = 11\,\mathrm{m}$, $\alpha_{x,y} = -2.1$,
- $\sigma_x = 116.2\,\mu\mathrm{m}$, $\sigma_y = 117.5\,\mu\mathrm{m}$,
- $\epsilon_N = 0.4\,\mathrm{mm\,mrad}$,
- momentum spread = 0.110%.

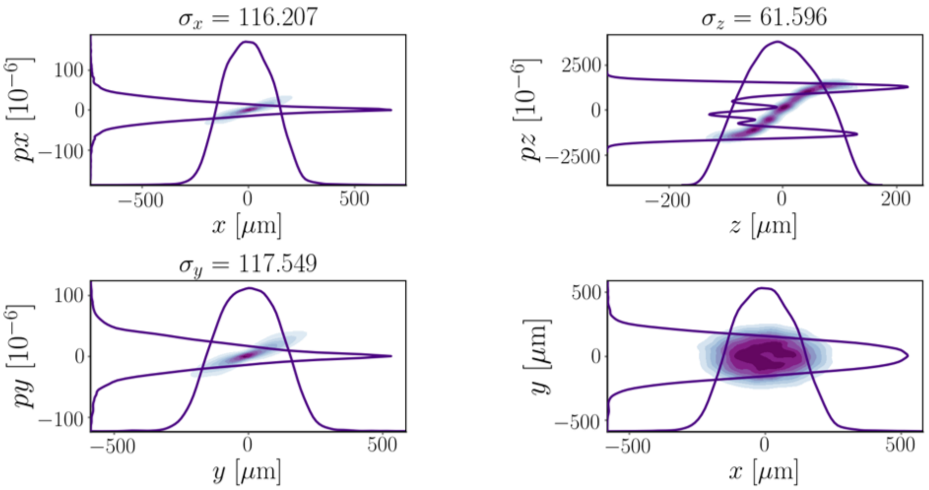


Figure 2.3: 165 MeV beam distributions.

3. REQUIREMENTS FOR BEAM AT INJECTION

3.1 BEAM-SIZE REQUIREMENTS

From [1], the beam size follows the envelope equation

$$\sigma''(z) + (\frac{n_{pe}e^2}{\epsilon_0 m_e c^2 2\gamma} - \frac{\epsilon^2}{\sigma^4(z)})\sigma(z) = 0, \tag{3.1}$$

where n_{pe} is the plasma density (baseline values: 2×10^{14} cm^{-3}, 7×10^{14} cm^{-3}). In order for the beam to be matched at injection we require

$$\sigma^4 = \frac{2\epsilon_0 m_e c^2 \gamma}{n_{pe}e^2}\epsilon^2, \tag{3.2}$$

which at 150 MeV ($\gamma = 293.5$), with $n_{pe} = 7 \times 10^{14}$ cm^{-3}, gives

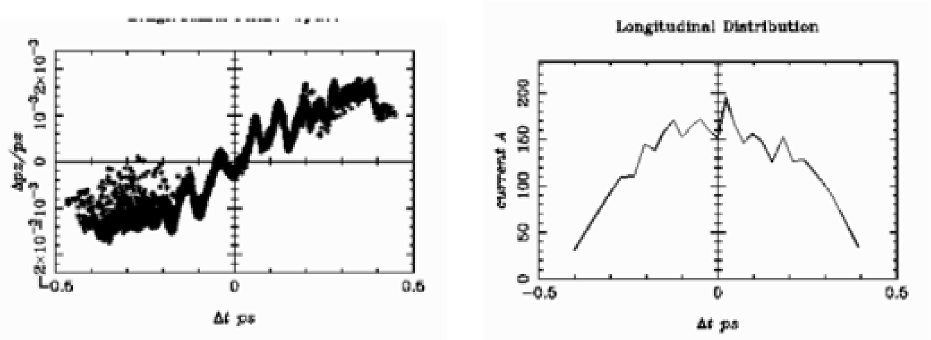
$$\sigma^2 = 4.87 \times \epsilon. \tag{3.3}$$

With a normalised emittance of 2 mm mrad, at 150 MeV this corresponds to an 'unnormalised' emittance of $\epsilon = 6.8 \times 10^{-9}$ m, so that to be matched we require a beam size of

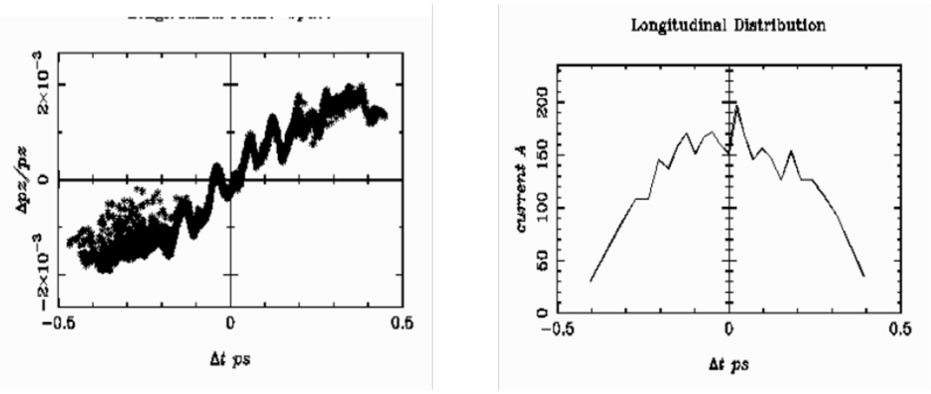
$$\sigma^* = 5.75\,\mu\text{m}. \tag{3.4}$$

3.2 DISTRIBUTION REQUIREMENTS

- Matching is only possible for a beam which is Gaussian in all six dimensions, as shown by J. Farmer in 17th Awake Run 2 meeting (23/04/2020).
- Simulated bunch from electron source shows longitudinal modulation, this is an effect which originates in the electron buncher, see Fig. 3.1.



(a) 150 MeV



(b) 160 MeV

Figure 3.1: Bunch distributions showing longitudinal bunching, plotted as $\frac{\Delta pz}{pz}$ vs. Δt (left) and current vs. Δt (right). Presented by S. Doebert at the 15th AWAKE Run 2 Meeting (26/03/2020).

4. TRANSFER LINE

4.1 OPTICS

Beam size and dispersion along the beamline are shown in Fig. 4.1. For the current design:

- Dispersion is closed.
- Magnets modelled with apertures of radius 2.5 cm.
- Currently, upstream beam waists in x and y not aligned - this alignment would be required for Option 2 of foil placement (Section 4.2).
- Design has six sextupoles and three octupoles, if possible this will be reduced.
- Preliminary estimations suggest we could expected a 10% increase of initial energy spread from the emission of coherent synchrotron radiation ($\frac{\Delta E}{E} = 0.22\frac{N r_0 L_d}{\gamma R^{2/3}\sigma_s^{4/3}}$), this needs confirming.
- **Future work**: consider diagnostics and correctors, simulate dispersion-free steering and design transverse tomography optics.

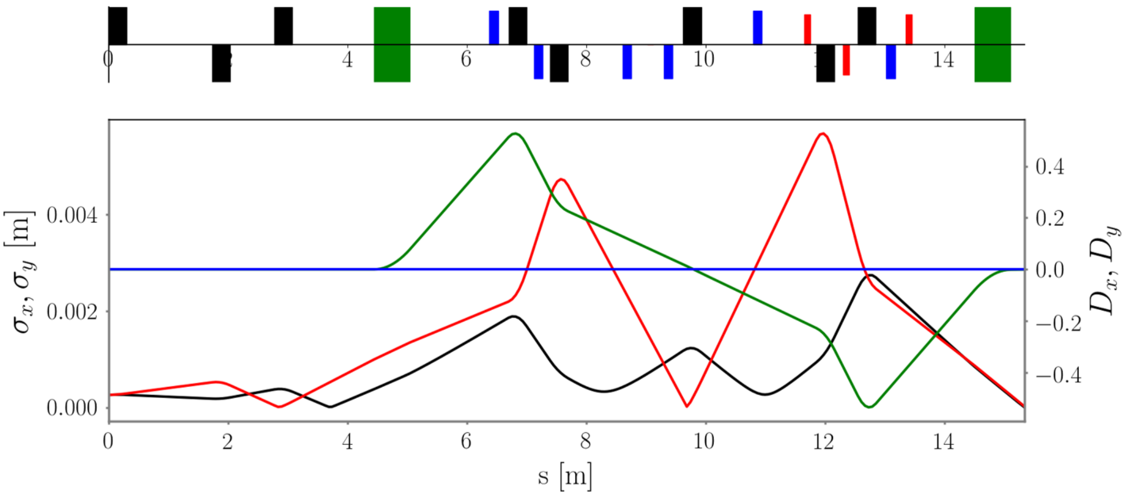


Figure 4.1: Beam size (σ_x: black, σ_y: red) and dispersion (D_x: green, D_y: blue) along the transfer line. Locations of elements are shown along the top, with dipoles (green), quadrupoles (black), sextupoles (blue) and octupoles (red).

4.2 FOIL/VACUUM WINDOW

Two options are under consideration for the positioning of the scattering foil which will be used as the vacuum window. For option 1, the foil is positioned upstream in the beamline at an imaging waist before the dogleg. For option 2, two scattering foils are positioned just before the injection-point, for the vacuum window and laser beam dump.

Multiple Coulomb Scattering of the electron beam by the foil increases the emittance as [1]

$$\epsilon_{out} = \sqrt{\epsilon_{in}^2 + \sigma^2\theta^2}; \tag{4.1}$$

therefore, to minimize emittance growth, the foil must be positioned where the beam size is small. For equal emittance growth in x and y, the beam size at the foil should be the same in both planes.

4.2.1 Option 1

The scattering foil is positioned upstream at an imaging waist, as shown in Fig. 4.2.

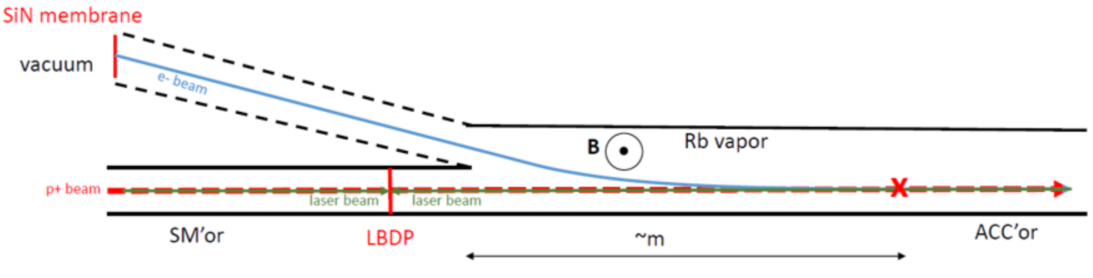


Figure 4.2: Schematic of the 'option 1' placement of a scattering foil and laser beam dump, presented by L. Verra at the 15th Awake Run 2 Meeting (26/03/2020).

4.2.2 Option 2

The vacuum window and laser dump are positioned just before injection. This requires two foils and so is more invasive for the beam optics and leads to more engineering difficulty.

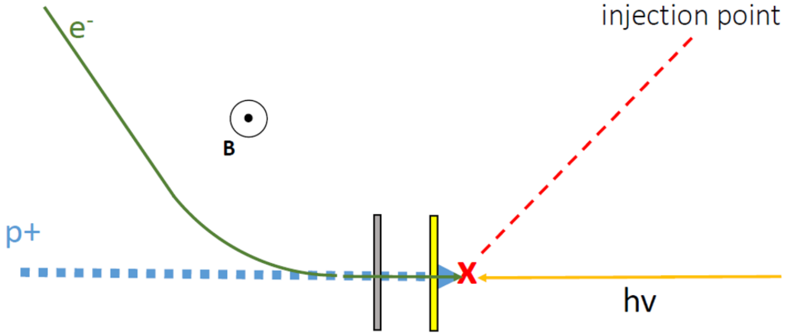
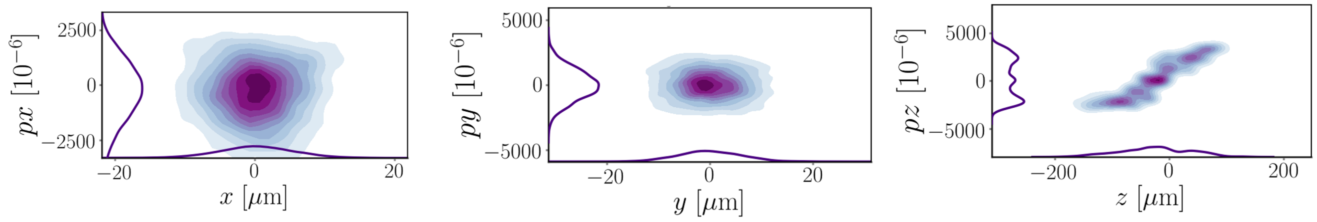


Figure 4.3: Schematic of the ‘option 2’ placement of a scattering foil and laser beam dump, presented by L. Verra at the 15th Awake Run 2 Meeting (26/03/2020).

4.3 BEAM AT INJECTION

- Tracking results of a 150 MeV Gaussian bunch with 2 mm mrad emittance and 96 µm bunch length (Fig. 4.4).



(a) $\sigma_x = 6.0\,\mu\text{m}$ (b) $\sigma_y = 6.26\,\mu\text{m}$ (c) $\sigma_z = 61\,\mu\text{m}$

Figure 4.4: Tracking results: beam distributions at injection-point.

- Comparison of the tracked beam distribution with a Gaussian distribution (Fig. 4.5).

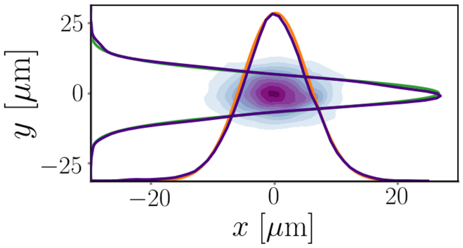
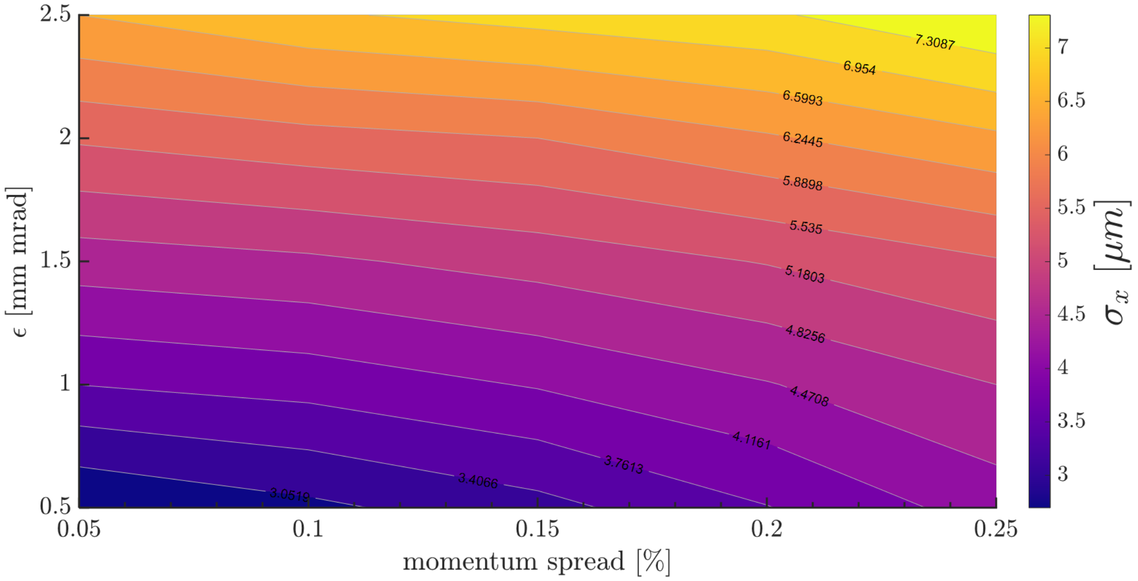
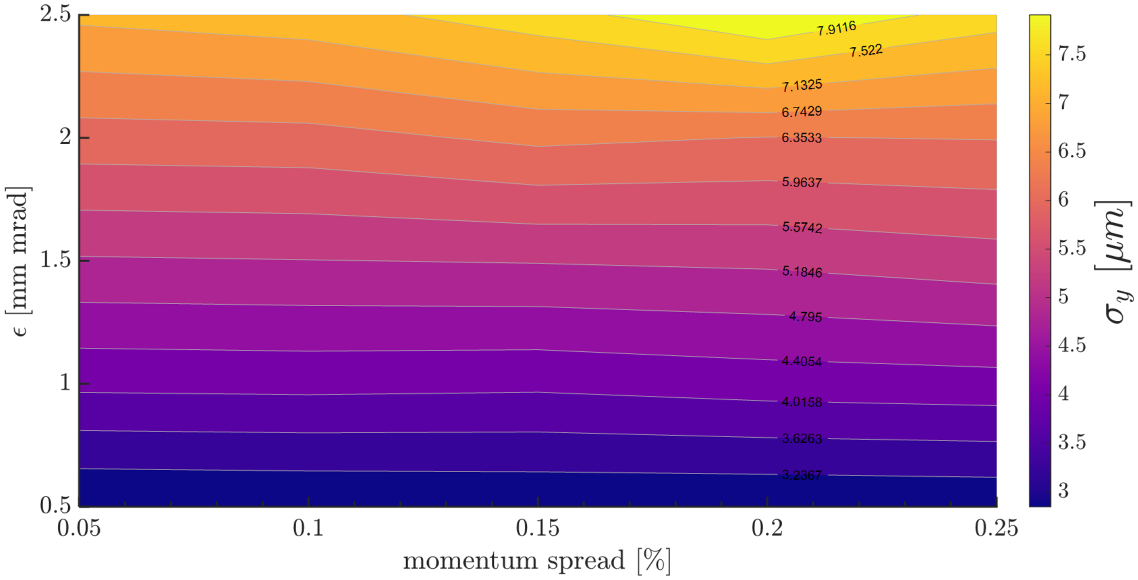


Figure 4.5: x-y beam distribution with 1D projections; $\sigma_x = 6.00\,\mu\text{m}$ and $\sigma_y = 6.26\,\mu\text{m}$. Gaussian distributions are shown in orange and green.

- The beam size at injection-point as a function of emittance and momentum spread is shown in Fig. 4.6.



(a) σ_x



(b) σ_y

Figure 4.6

- The beam size at injection-point normalised by ‘matched’ beam size is shown in Fig. 4.7 as a function of emittance and momentum spread.

4.4 BUNCH LENGTH

There is only a limited flexibility to control the change in bunch length throughout the line. For the current design iteration, a 200 fs input bunch would be shortened by almost a factor of two, this is a result of the strong focussing in the line. In order to produce a 200 fs bunch at the injection-point (as required by the experiment), the bunch length from the source would need to be:

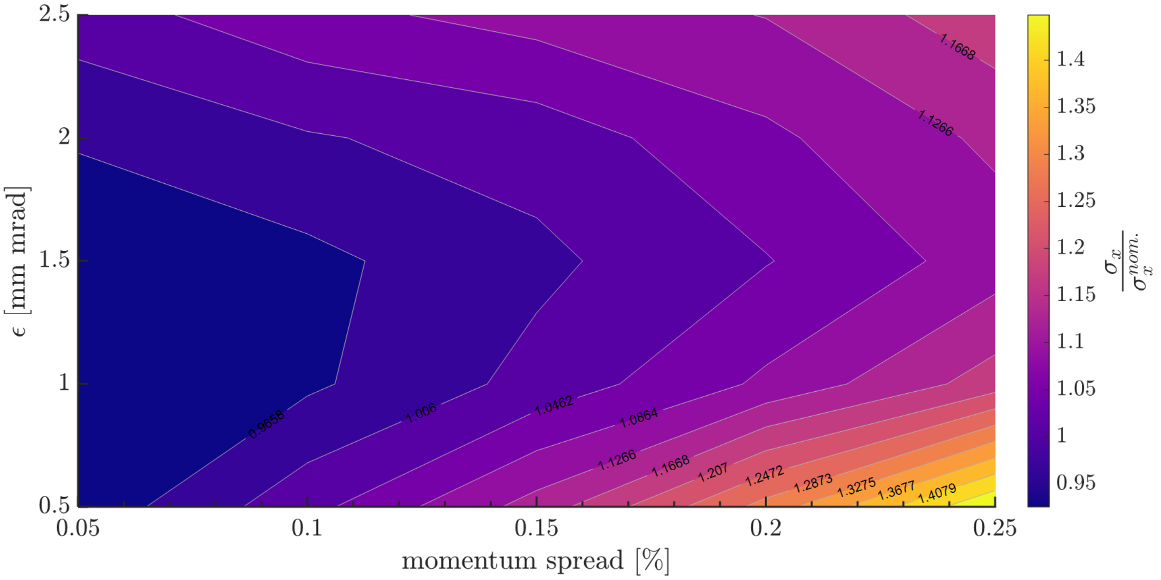
- Required initial bunch length: 320 fs.

S. Doebert anticipated that producing a bunch of this length should be possible.

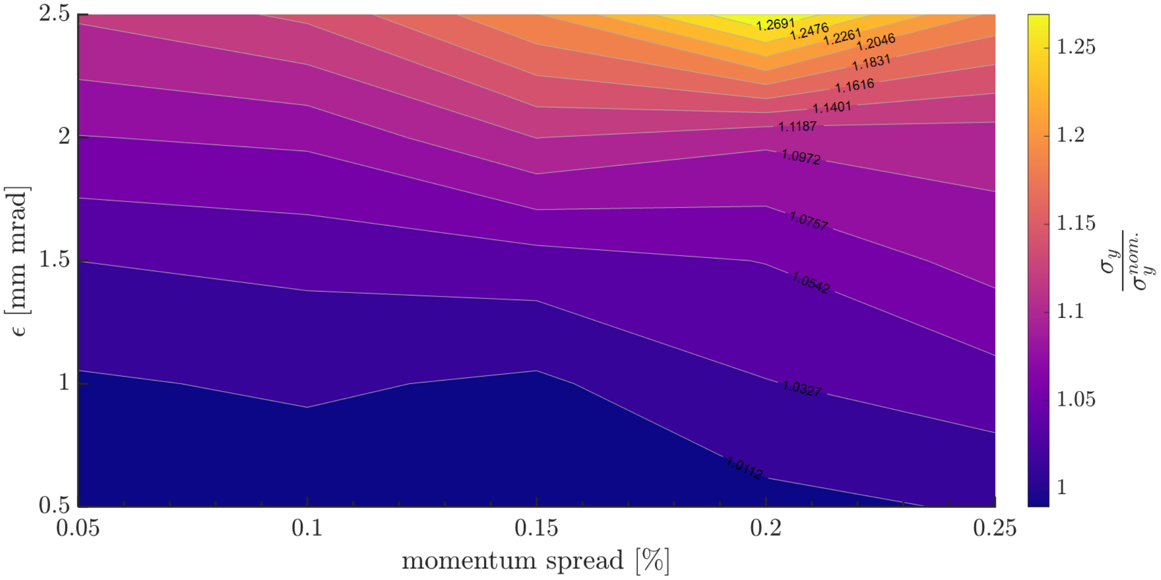
5. ERROR STUDIES

As a starting point, studies of each error modelled separately were performed to ascertain upper bounds on the error tolerances. E.g simulations including only the power converter ripples are shown in Fig. 5.1, showing that to achieve 2 µm r.m.s alignment we should have power converter ripples < 7 ppm. Following these studies, and after discussion with hardware experts, the following table shows working estimates for errors:

- Magnet mover error: 1 μm
- Corrector error: 1 μrad
- BPM resolution: 10 μm
- BTV resolution: 1 μm
- Initial magnet offsets: 100 μm r.m.s
- e-line power converter ripples = 7 ppm
- Momentum jitter = 1e-3
- e-line input position jitter = 10 μm
- p-line r.m.s jitter at injection point = 2 μm
- Power converter ripple = 10 ppm
- Angular jitter MSE = 10 ppm
- Dipole misalignments = 50 μm
- Magnet field error = 10 ppm
- Quad misalignments = 100 μm
- Sextupole misalignments = 100 μm
- Octupole misalignments = 100 μm
- BPM resolution = 10 μm
- Field homogeneity $< \pm 10 \times 10 - 4$ for the dipoles and $< \pm 4 \times 10 - 4$ for the quadrupoles, g.f.r ± 0.02m

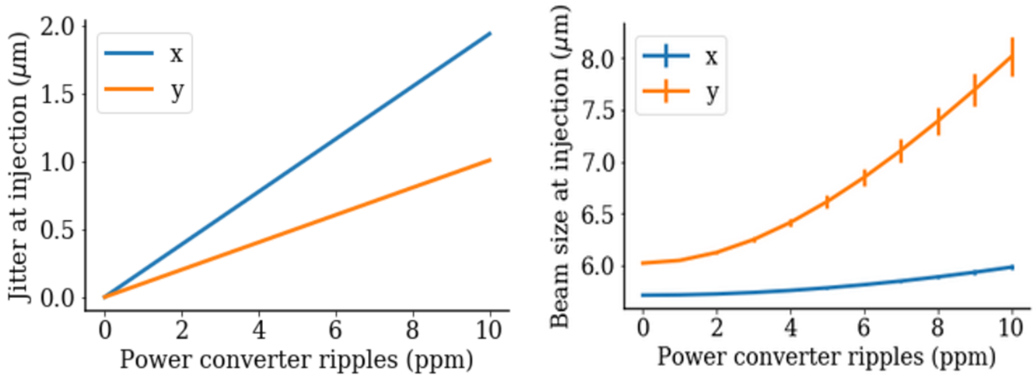


(a) σ_x



(b) σ_y

Figure 4.7



(a) (b)

Figure 5.1

To achieve the required levels of magnet beam alignment (10 µm) the magnets will need to be on movers with a step size of approximately 1 µm with a range of 100s of microns.

Multiple steering and alignmnent methods will need to be used. First it is proposed to use a quad shunting technique, varying the quad strength (between 80% and 100%) and measuring the deflection of the beam at a downstream BPM. This deflection can be used to estimate the offset of the quadrupole from the beam. Dispersion Free Steering (DFS) would then be used to minimise the parasitic dispersion by steering the beam through the centre of quadrupoles. With DFS, the beam offset is measured at all BPMs at different beam energies, the beam is then steered to both minimised the offset of the beam in the BPMs and minimise the difference in trajectory for different beam energies. DFS is first performed with higher order magnets switched off.

The deflections of the beam from offset sextupoles and octupoles are too small to be measured given the BPM resolution, although they do affect the beam size. Therefore, it is suggested to use the beam size at the injection-point BTV to quantify their alignment. By using an optimiser, the sextupole and octupole positions could be varied in order to minimise the beam size at the injection-point BTV.

- Quad shunt (with quad movers) – 2 loop, gain 0.7
- Quad shunt – 1 loop, gain 1 (15 minutes for all quad alignment)
- DFS – higher order magnets off – 3 loops gain 0.7, DFS weight 1 (15 minutes)
- Align sextupoles and octupoles using optimiser and movers – 100 cycles (6 minutes for optimisation)

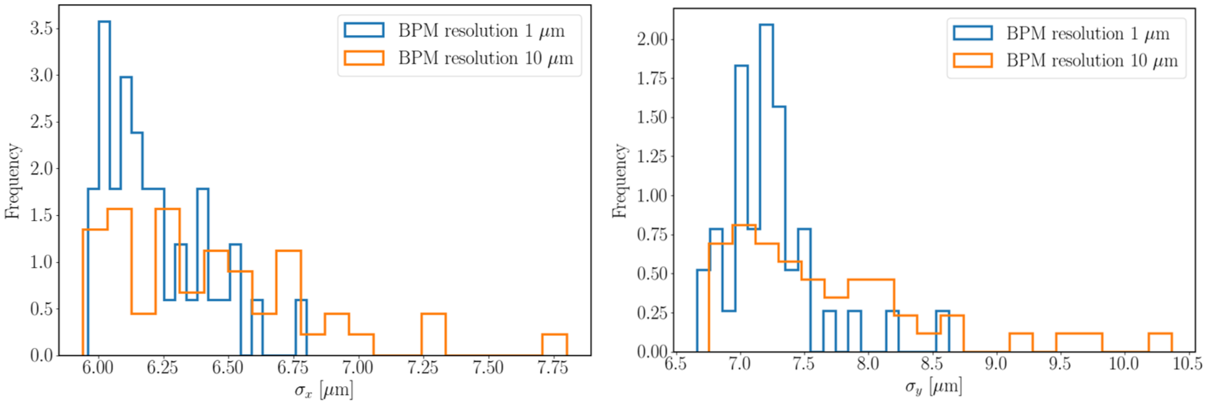
With this process, we would estimate that this full alignment process could be completed in under an hour.

Simulations of these alignment techniques were performed with errors and resolutions as given above (Fig. 5.2). For 10 µm BPM resolution: 6% of shots are within ±20% beam size of the nominal beam size and 100% were within a factor of two.

REFERENCES

[1] Verra, L., Gschwendtner, E. and Muggli, P., 2019. *Study of external electron beam injection into proton driven plasma wakefields for AWAKE Run2.* [arXiv:1912.00779.]

[2] V.K. Berglyd Olsen, E. Adli and P. Muggli, Phys. Rev. Accel. Beams **21** (2018) 011301.


Frequency
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
6.00
6.25
6.50
6.75
7.00
7.25
7.50
7.75
σ_x [μm]
BPM resolution 1 μm
BPM resolution 10 μm
Frequency
0.00
0.25
0.50
0.75
1.00
1.25
1.50
1.75
2.00
6.5
7.0
7.5
8.0
8.5
9.0
9.5
10.0
10.5
σ_y [μm]
BPM resolution 1 μm
BPM resolution 10 μm

(a)

(b)

Figure 5.2