Simulation tasks for Run 2c

March 2023

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Motivation

This talk gives an overview of the topics identified as most important for Run 2c, and who will be doing what.

Many other topics not covered in this list (instrumentation, alternative schemes)

Outline

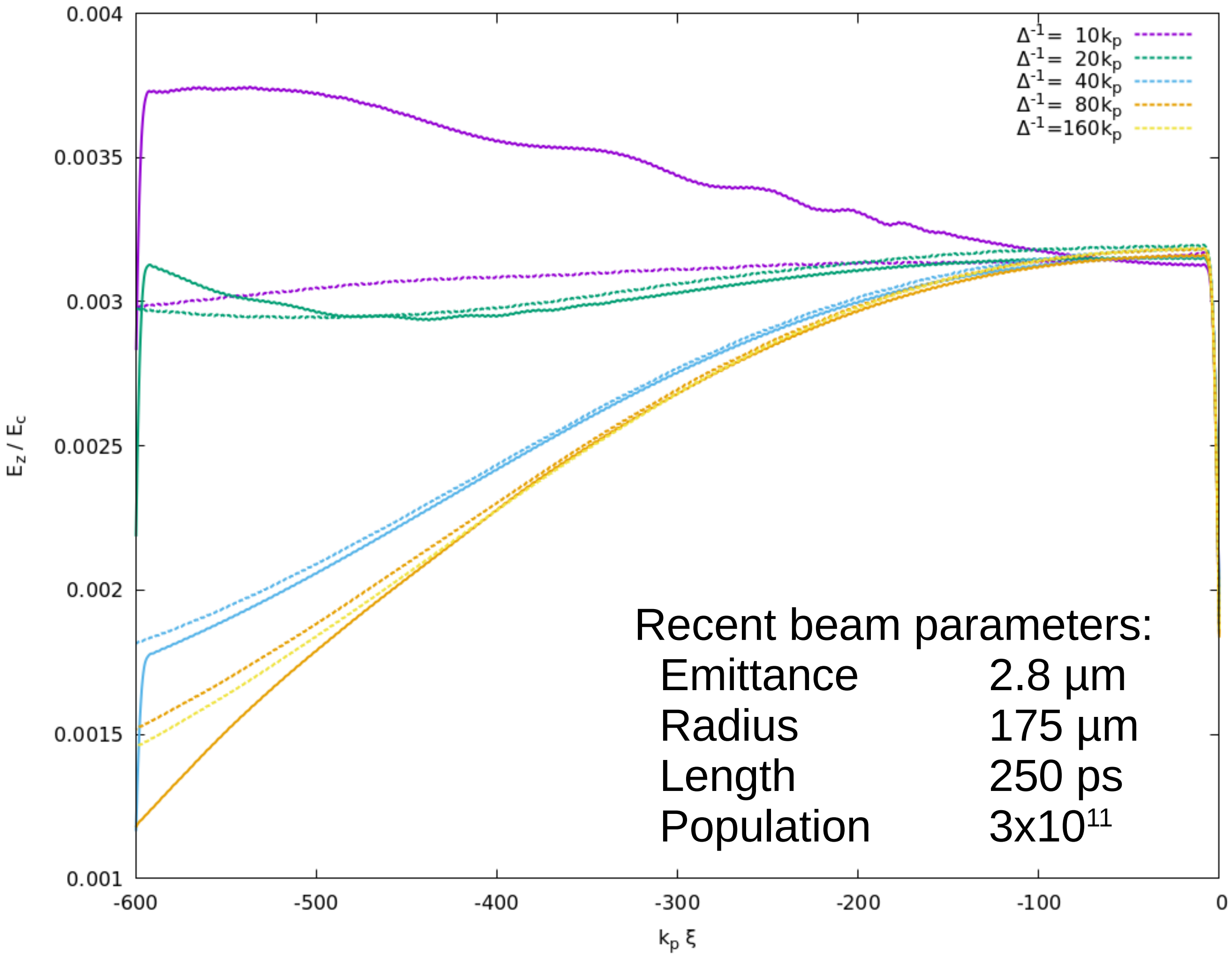
- Incomplete
  - Benchmarking / 2D vs 3D
  - Energy gain in Run 2a/b
  - Ramp at entrance
  - Ramp at exit
  - Step optimisation
  - Misalignment
  - Proton bunch train
  - End-to-end simulations
- Complete
  - Injection tolerances
  - Emittance at injection
  - Energy at injection

Benchmarking / 2D vs 3D

Convergence studies should be carried out often.

LCODE 2D is fast, so an obvious choice for studying convergence

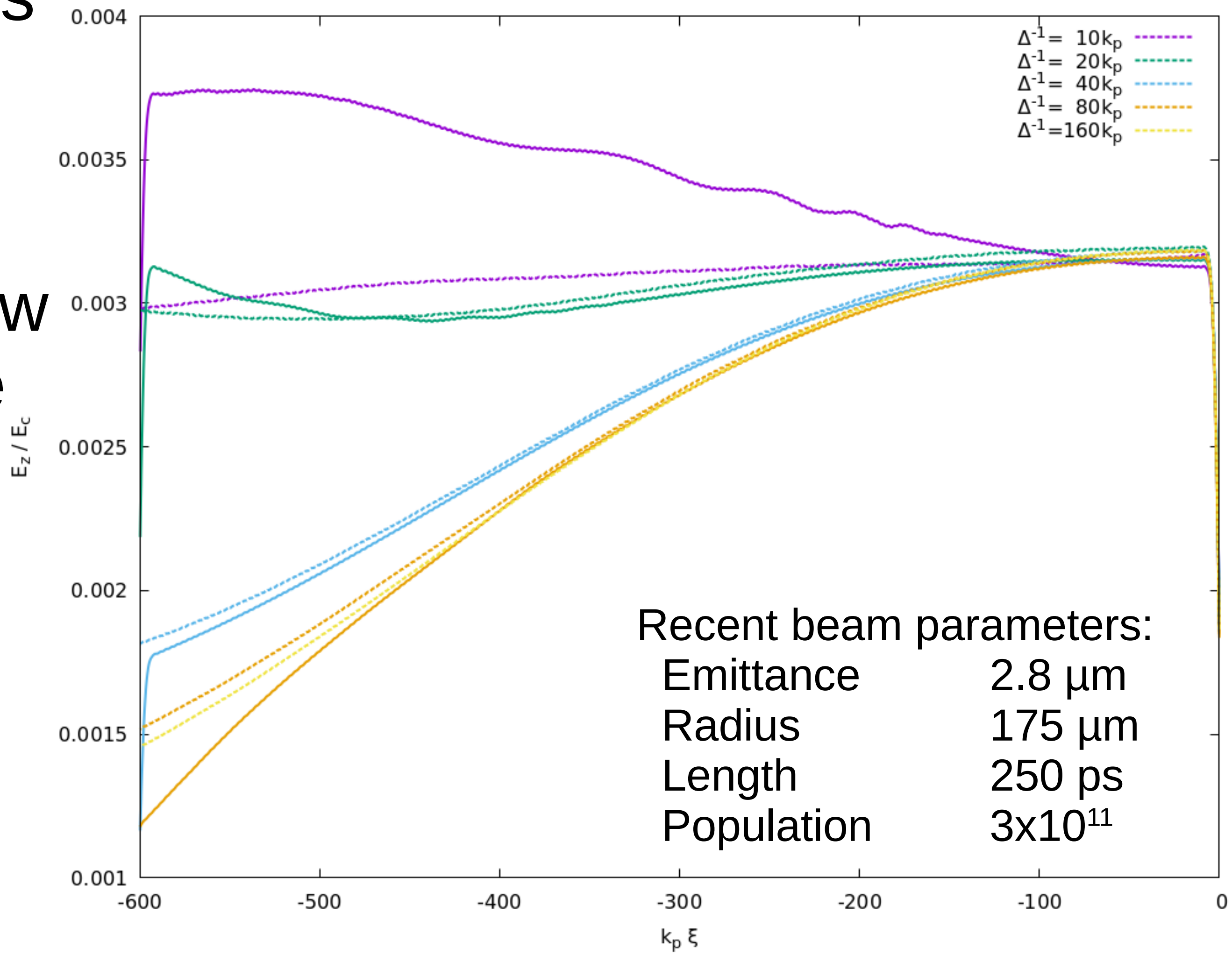
Example: long, cold, non-evolving proton beam
- Needs high resolution
- Good agreement with qv3d, although sensitive to numerical parameters



Benchmarking / 2D vs 3D

- Similar results to Konstantin's short drive bunch (Lotov, 2018)
- Higher resolution likely necessary as wakefields grow
- Is 2D sufficient? (Transverse wavebreaking - Gorn, 2020)
- EM-PIC simulations likely unfeasible in 3D

Full study to be completed by John



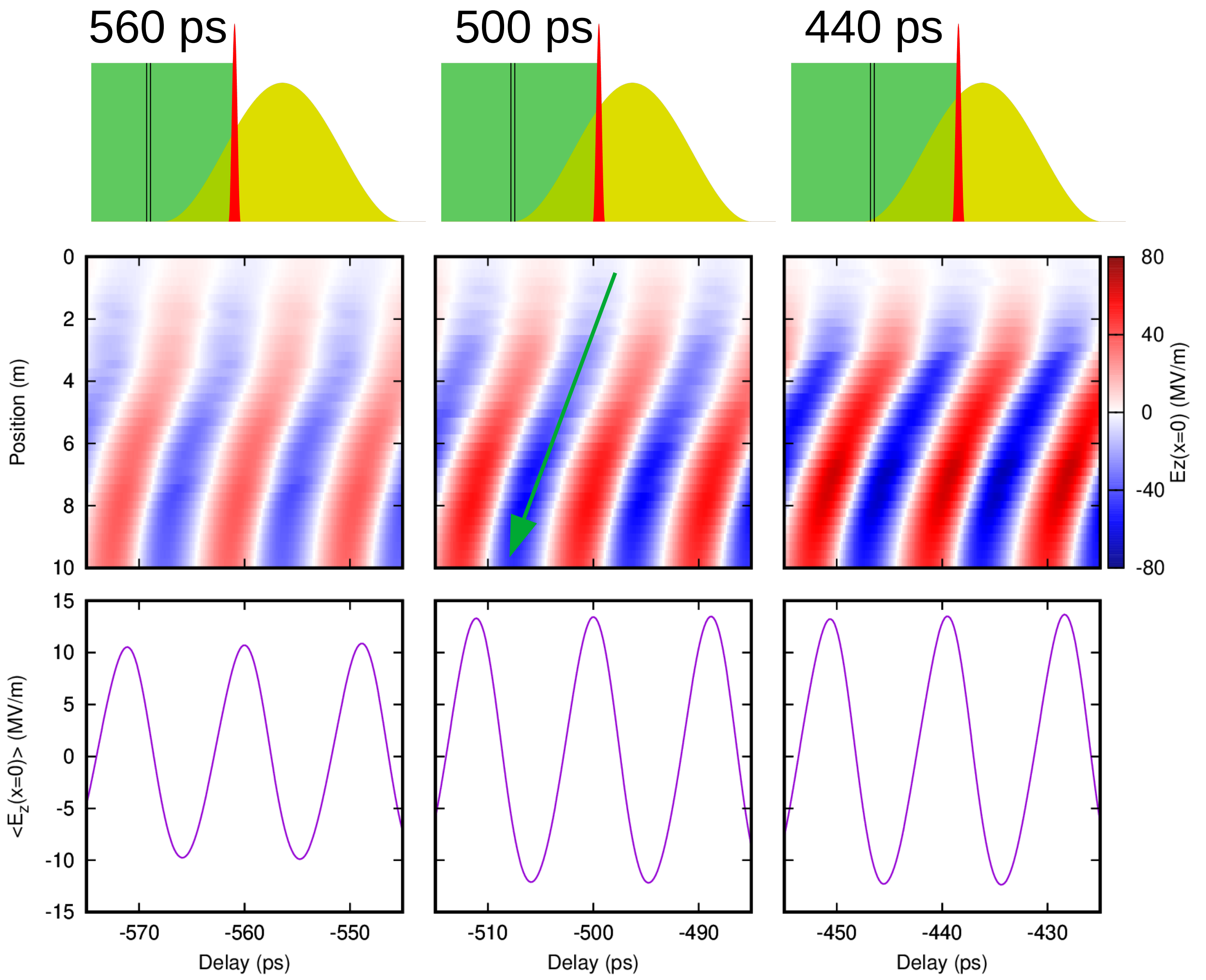
Energy gain in Run 2a/b

The plasma density step is a key part of AWAKE Run 2c.

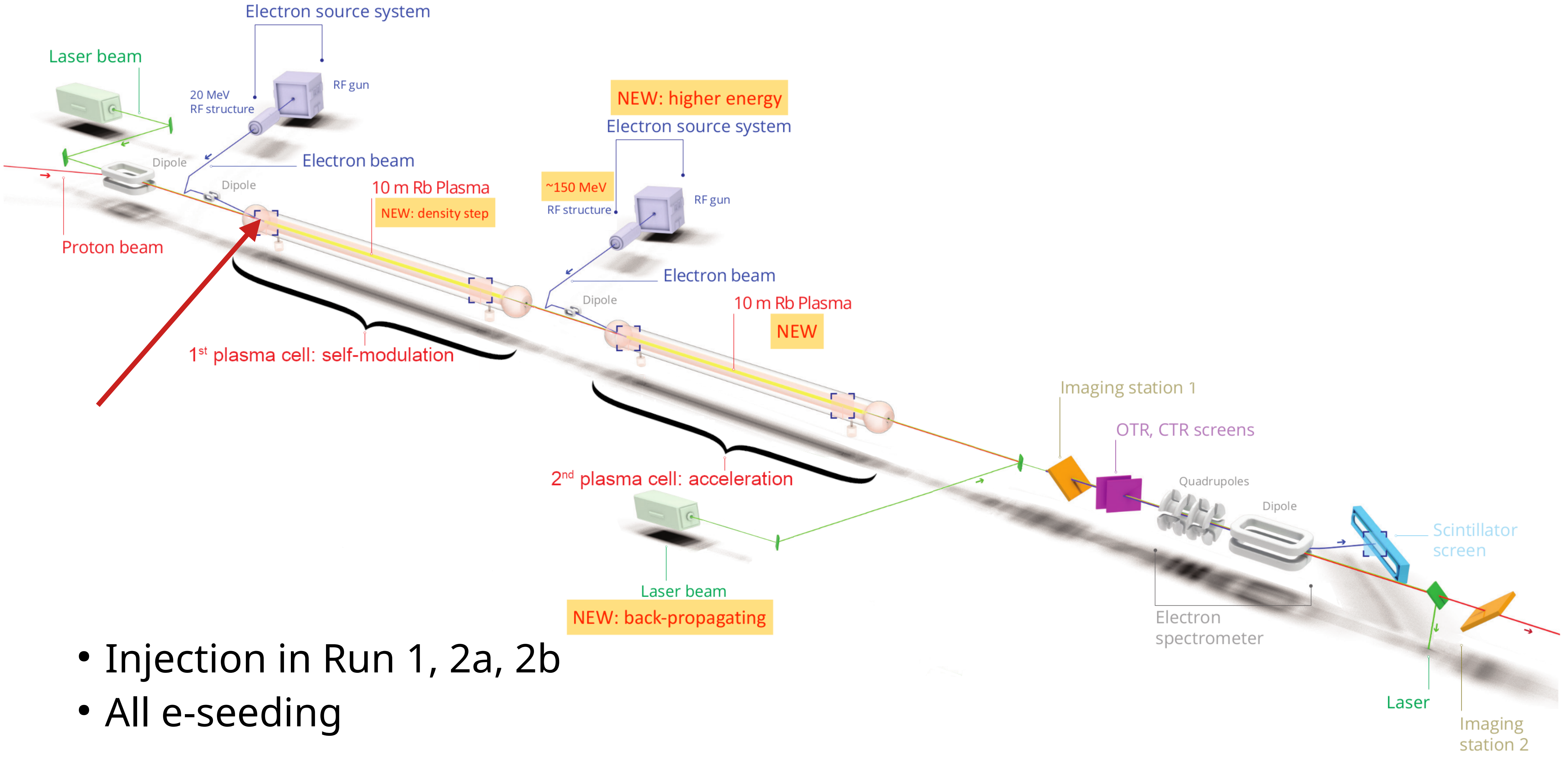
Simulations should be able to reproduce energy gain with/without the step.

Sensible to start now!

Full study to be completed by Johr

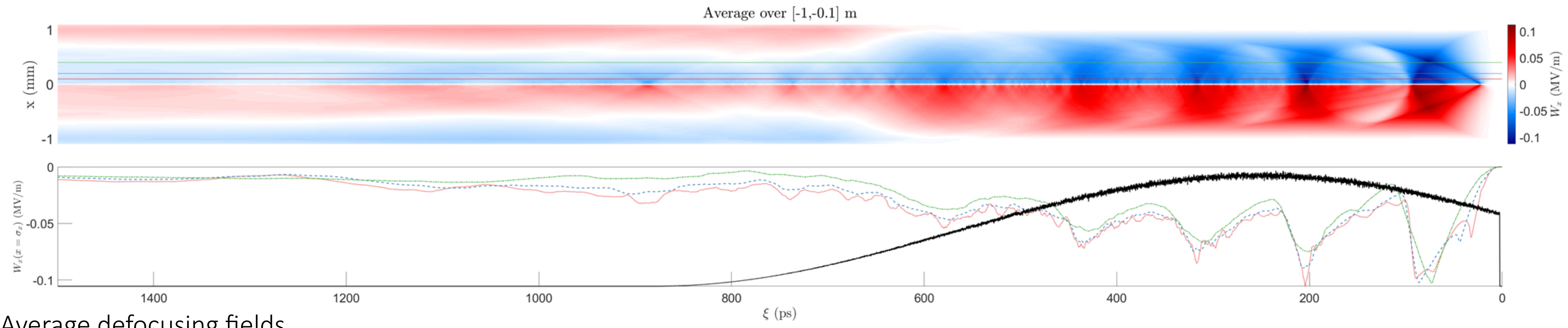


Ramp at exit

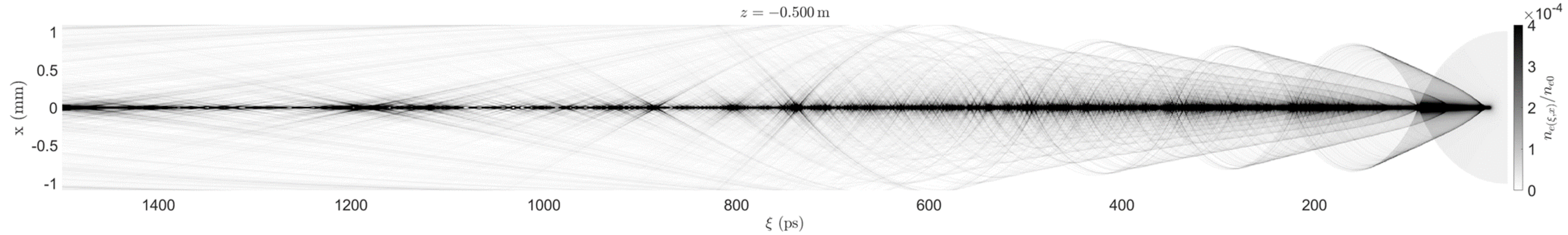


- Injection in Run 1, 2a, 2b
- All e-seeding

Ramp at entrance



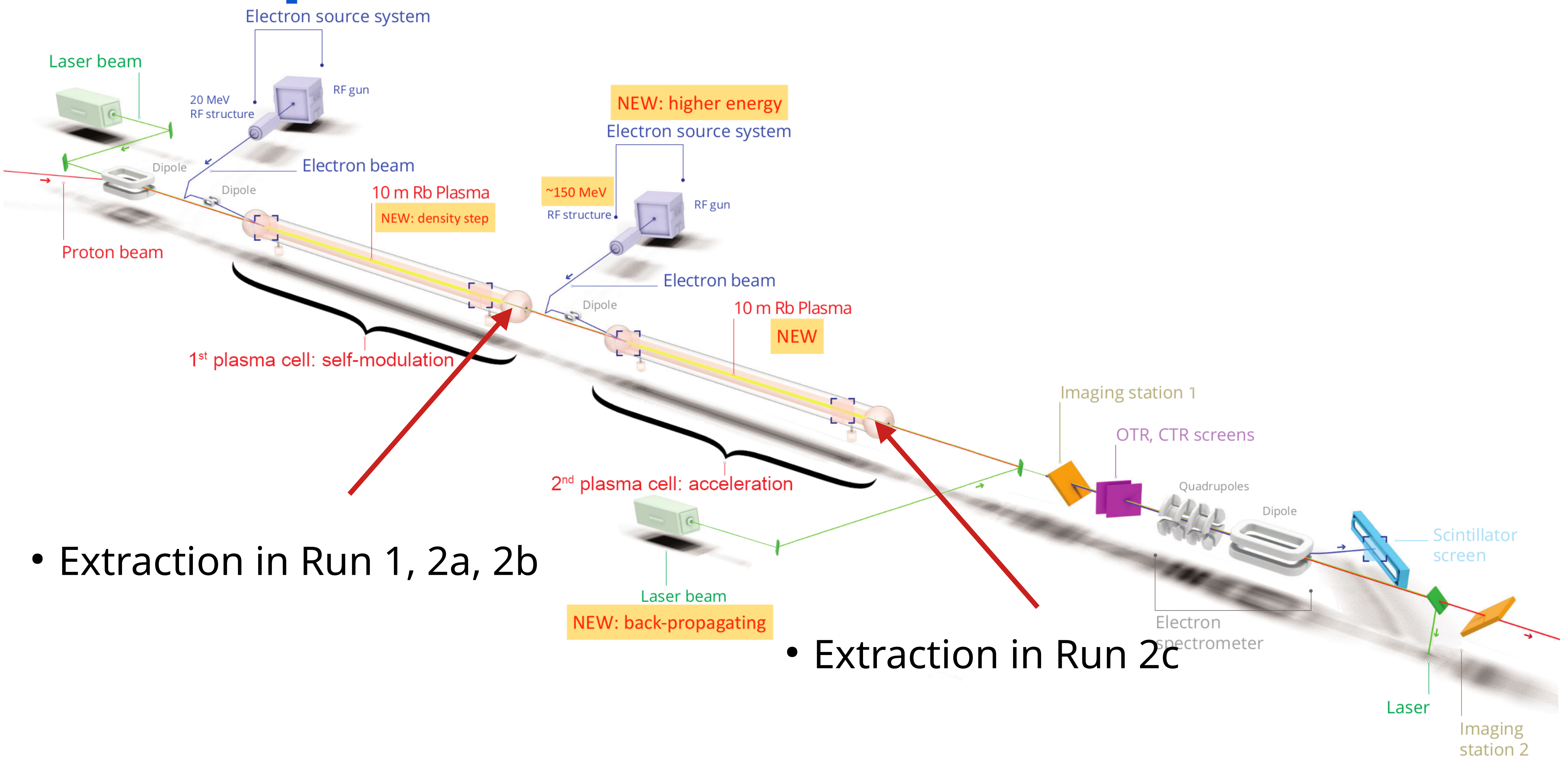
Average defocusing fields



(saturated plot)

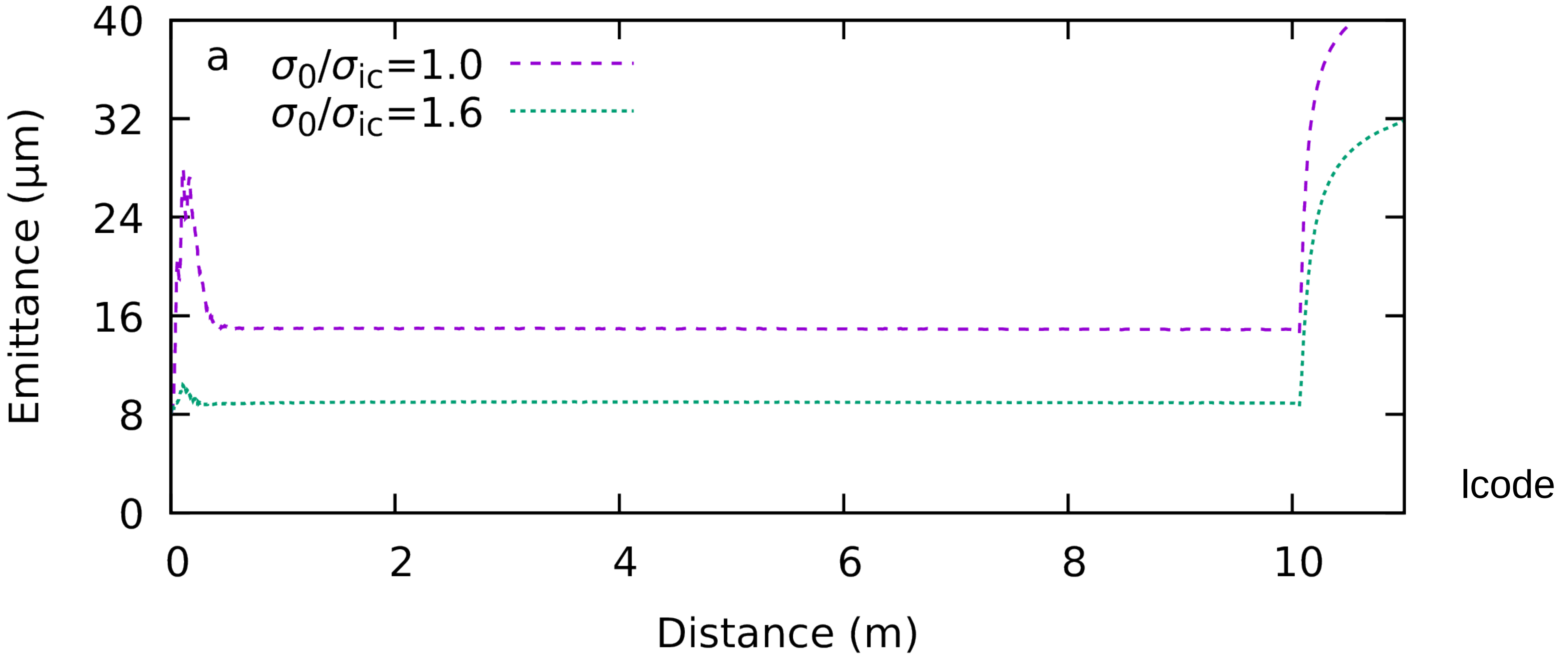
Protons “suck in” underdense plasma, create on-axis filament.
Makes injection difficult in Run 1, 2a/b

Ramp at exit



- Extraction in Run 1, 2a, 2b
- Extraction in Run 2c

Ramp at exit



- Plasma filament can defocus the accelerated (multi-GeV) bunch
- Spoils emittance
- Makes beam transport more difficult

Plasma ramps

Ramp at entrance: Initial simulations by Pablo

Ramp at exit: Initial simulations by John

Needs 3D simulations, full bunch train

Dr Pablo to take the lead on both tasks

Lots of physics here, should make for an interesting paper

Step optimisation

Builds on studies by Konstantin’s group.

Density step:

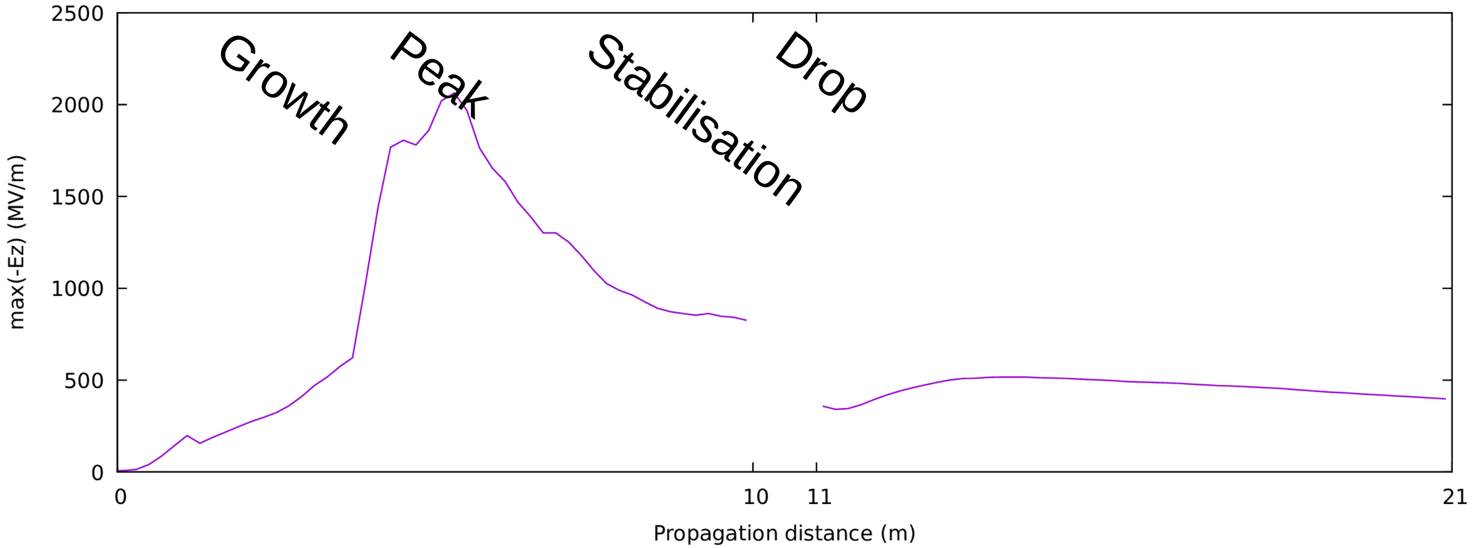
- Where?
- How high?
- What are the tolerances?
- What are the experimental observables?

Proposed by Alexander: How long should the SMI stage be?

Step optimisation

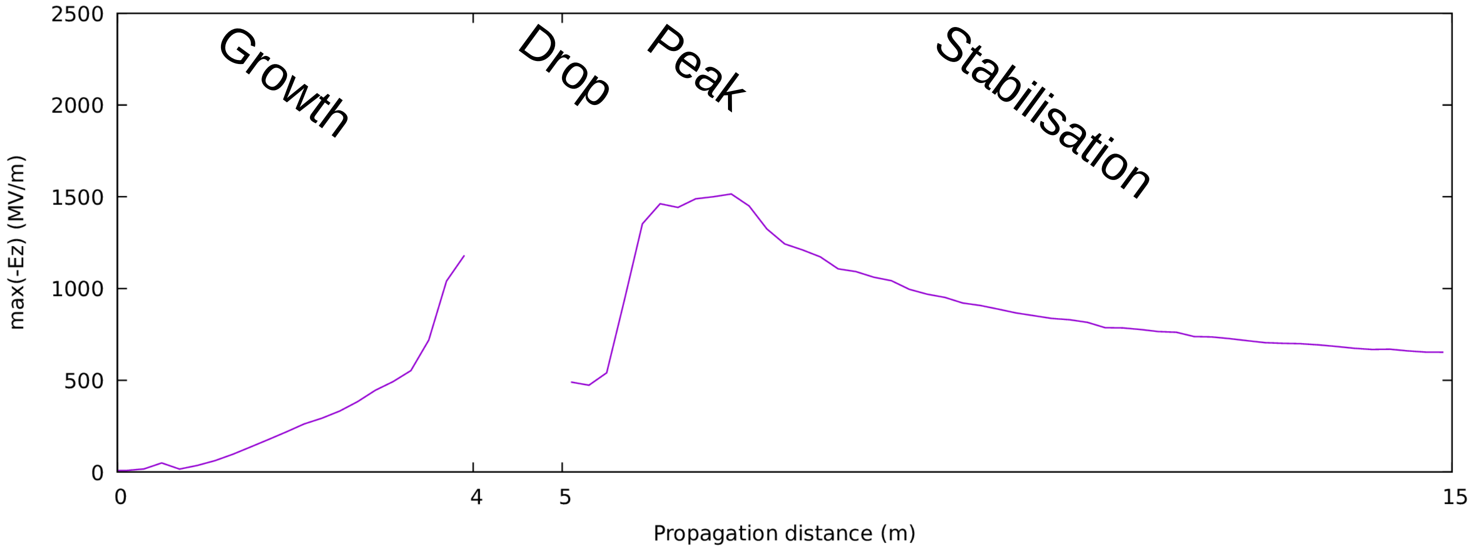
10 m first plasma, 1 m gap:

- $\langle E_z \rangle$ = 445 MV/m



4 m first plasma, 1 m gap:

- $\langle E_z \rangle$ = 680 MV/m



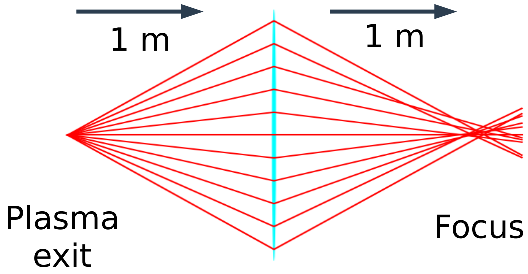
Step optimisation

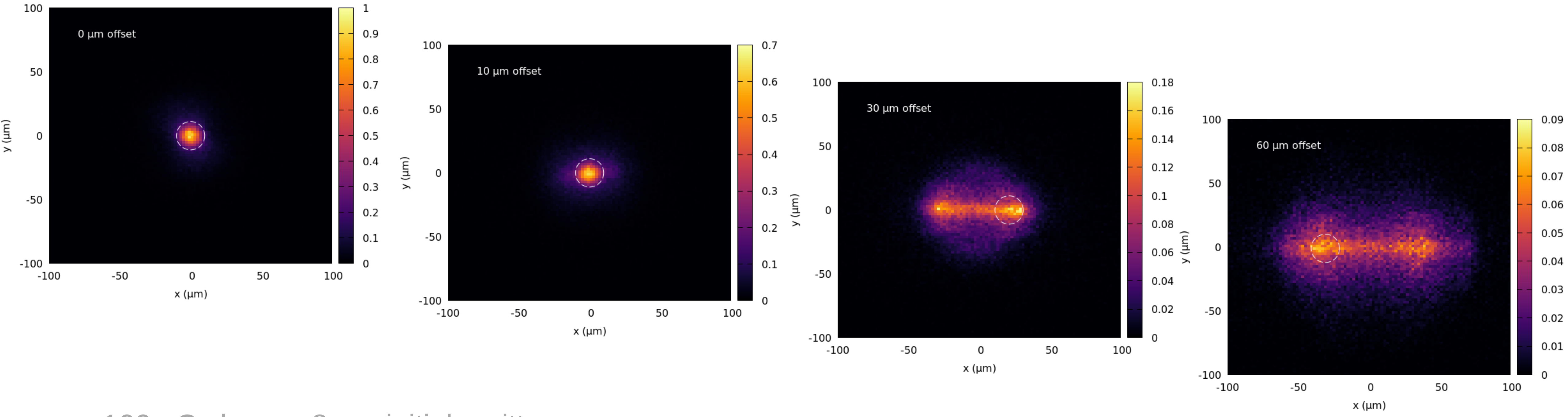
Initial studies by John,

Marlene to take over this work

Alignment

Simulations for different transverse offsets show smeared-out bunch at focus.

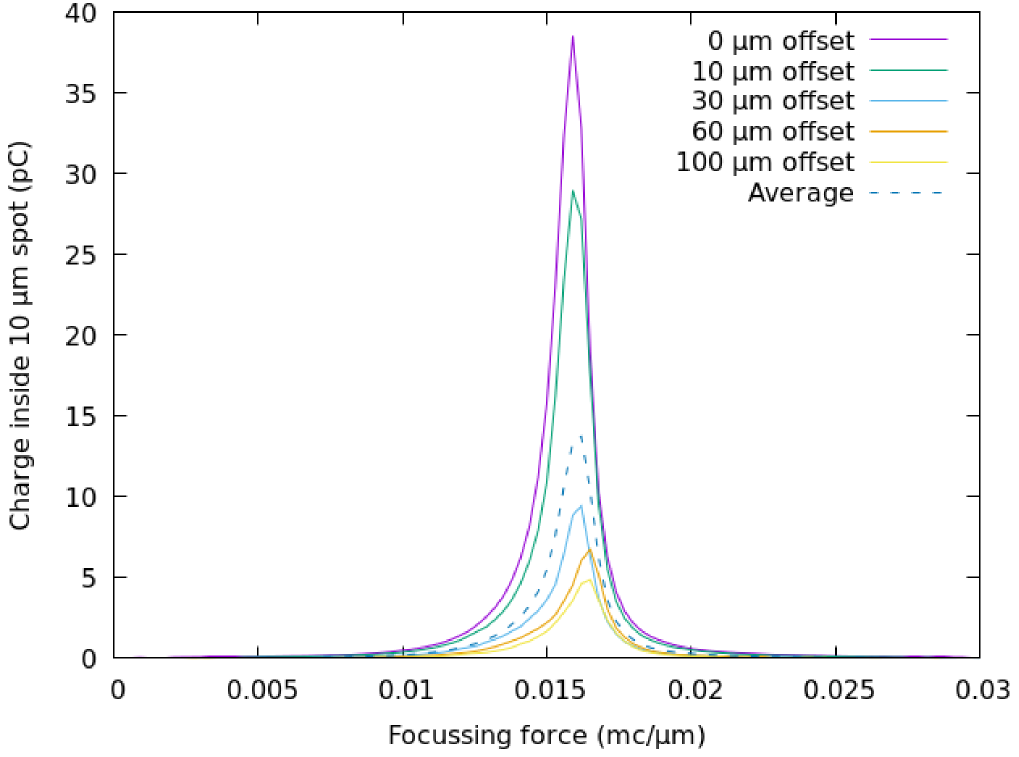


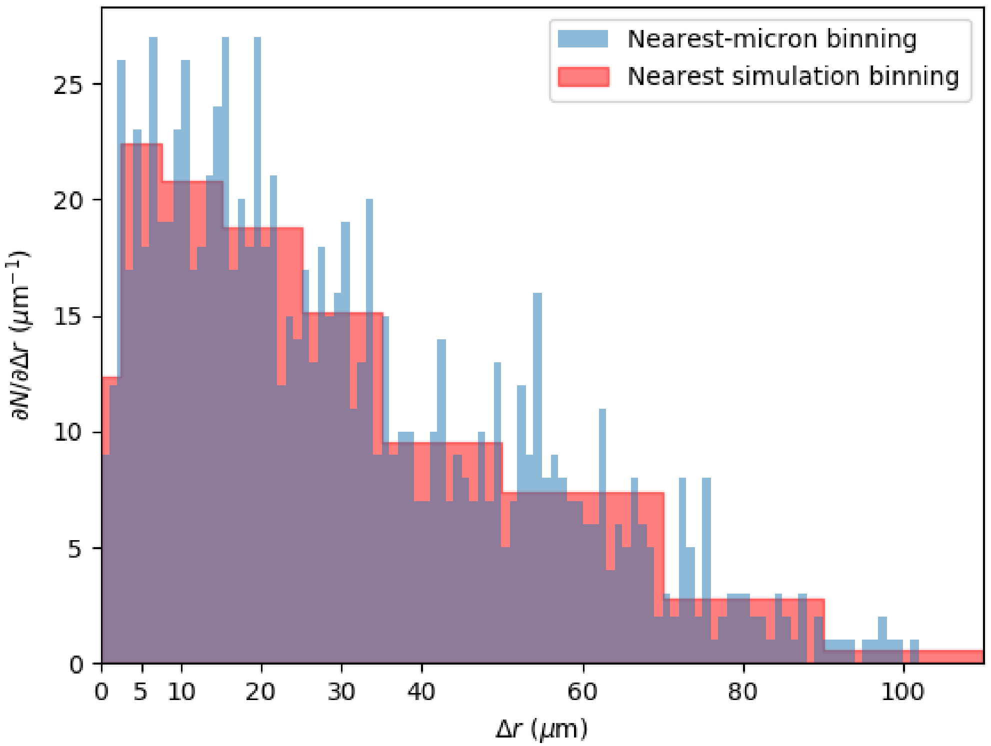


100 pC charge, 8 µm initial emittance

Alignment

Using simulated extractions from MAD-X,
the average values for beam quality can be extrapolated.





1000 simulated shots. Velotti *et al.*

Should be repeated for up-to-date values (emittance, energy, jitter).

Alignment

Initial studies carried out by John for the Cost-and-Schedule review

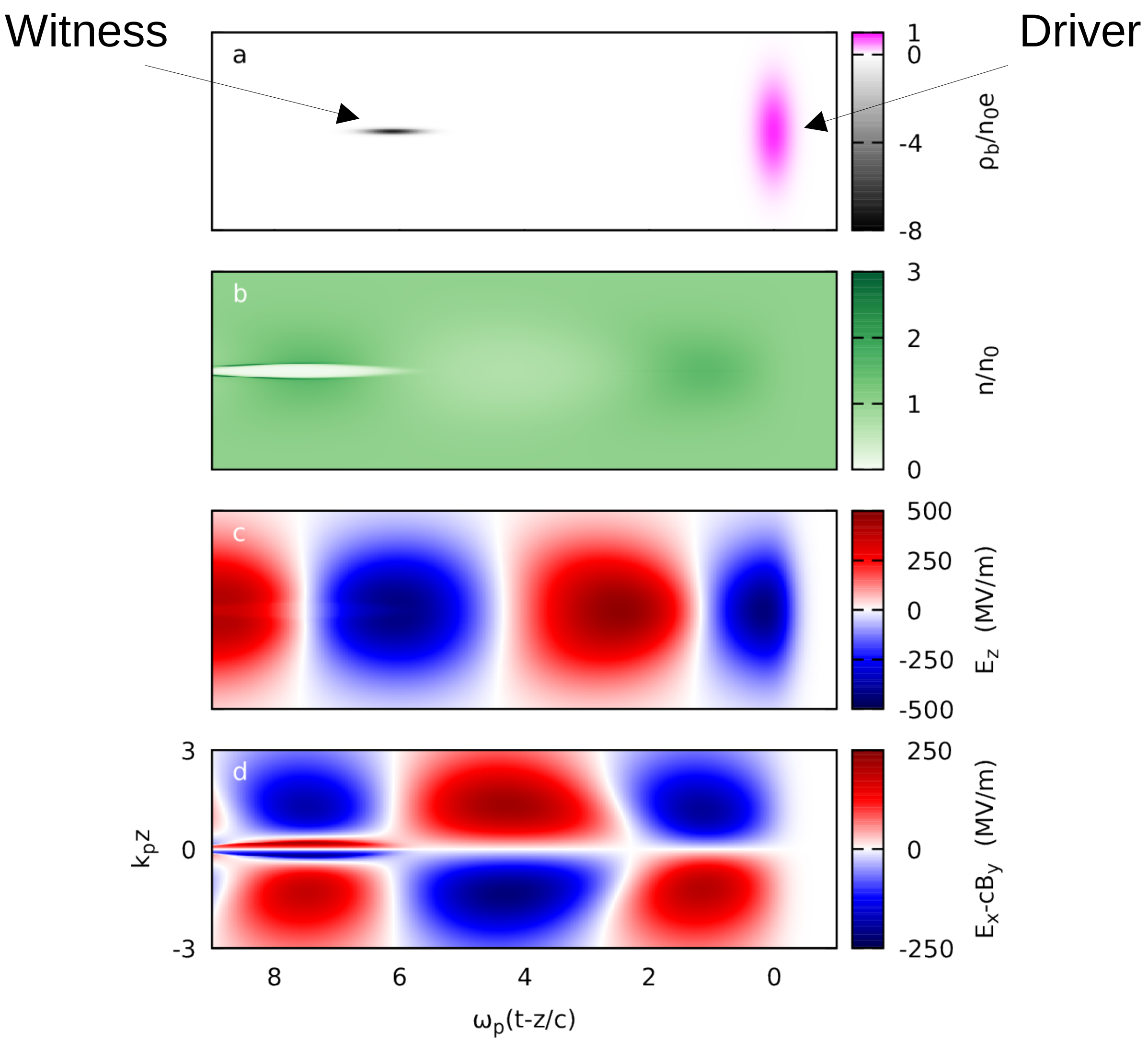
Martin (IPP) started developing an analytic model,
but left before it was finished

Ivan to take over this work as a test problem for LCODE 3D

Bunch train

Simulation studies for injection have used a "toy model" for the wakefields

Short driver
→ short window
→ low overhead



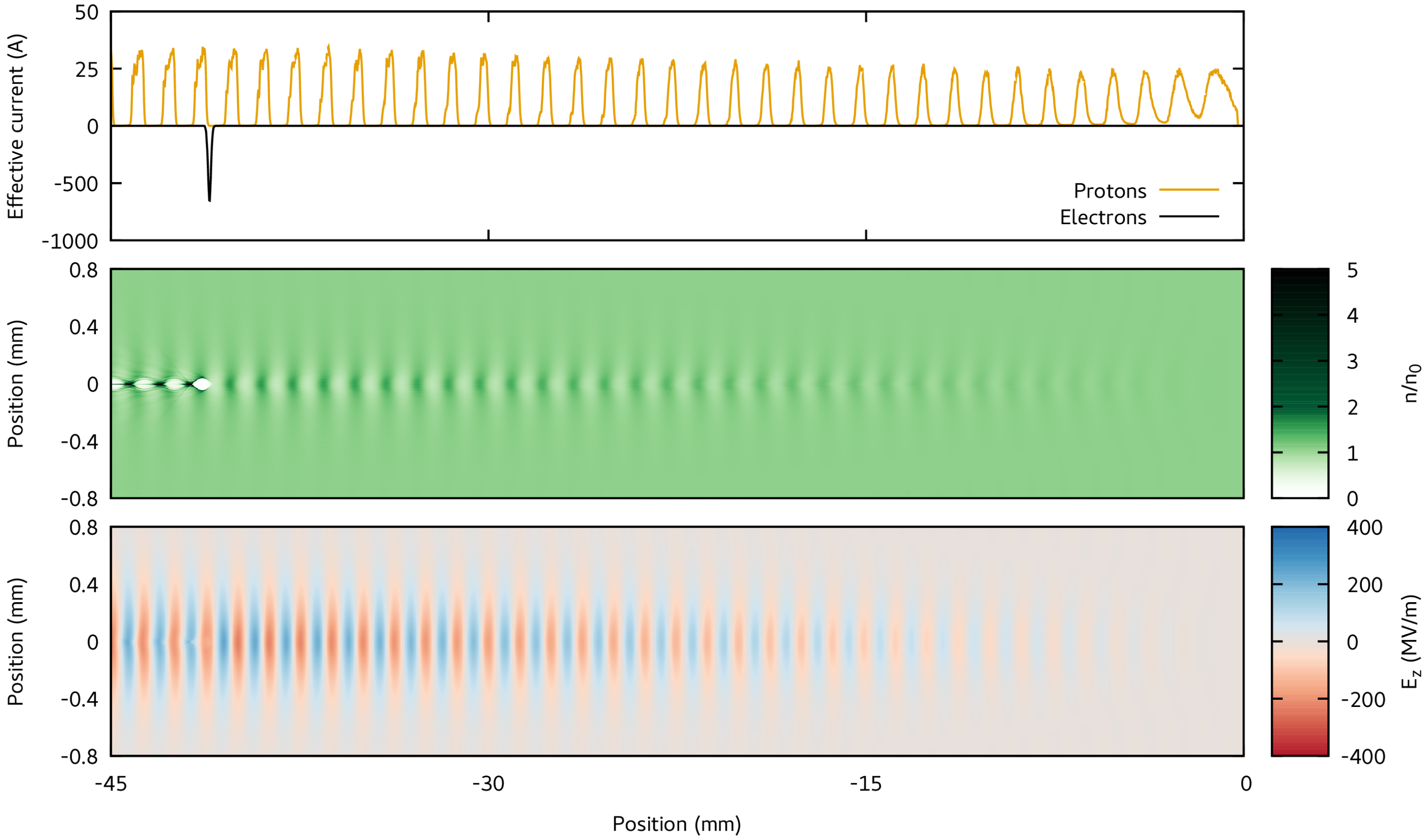
Olsen *et al.*, PRAB (2018)
Farmer *et al.*, arXiv:2203.11622 (2022)

Bunch train

In the full bunch train,
the witness partially overlap
with following proton
microbunch

Does this matter?
- Energy spread
- Beam−beam interaction

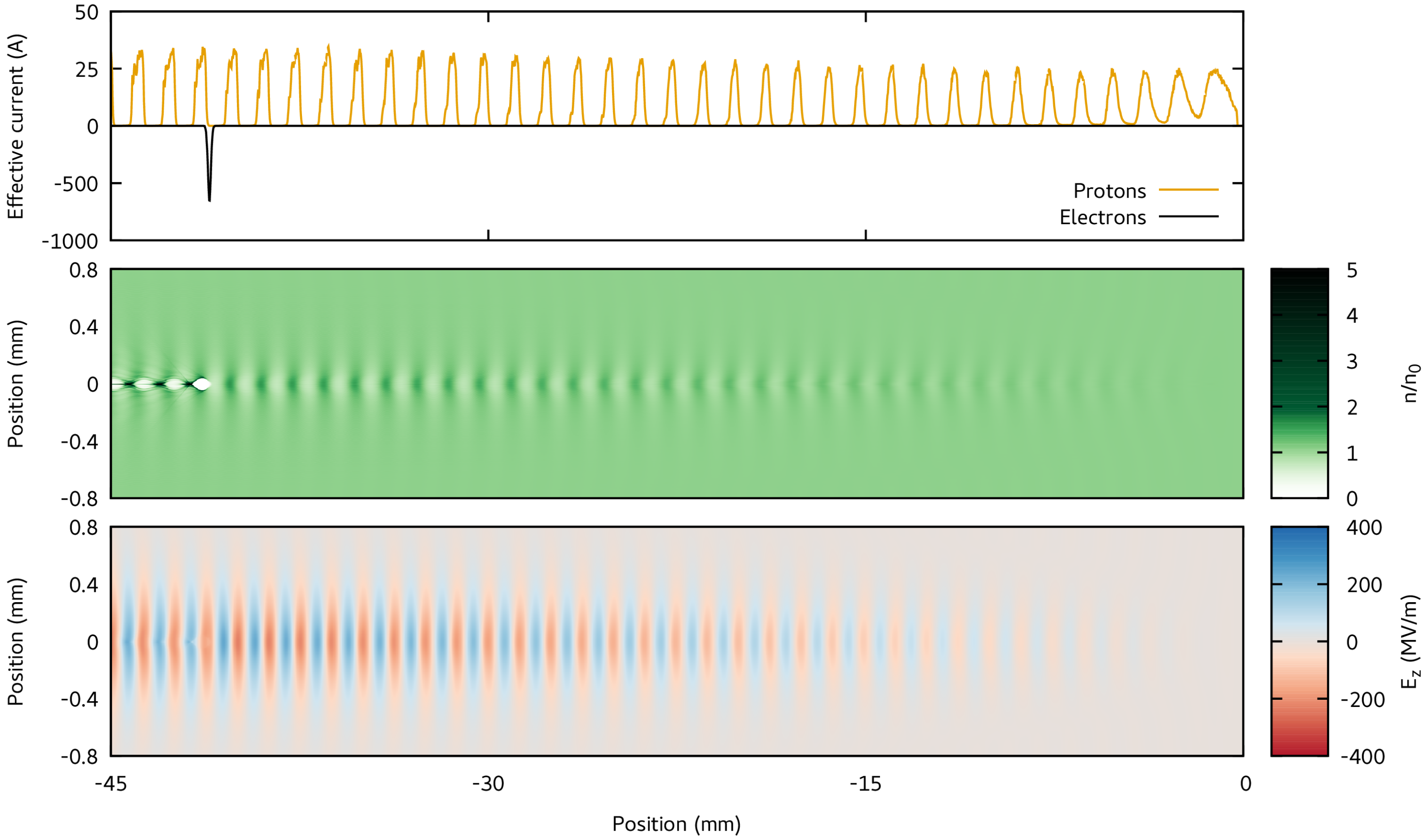
Mariana to take over
this study



End to end

The culmination of a lot of work (past and future)

- Full proton bunch train
- Witness from MAD-X
- Exit ramp
- Propagation to spectrometer



Many people will be involved
(John, Vittorio, Pablo, Dave),
Mariana to coordinate

Completed tasks

Many simulation tasks have been carried out,
but the main ones for Run 2c are:

- Injection tolerances
- Emittance at injection
- Energy at injection

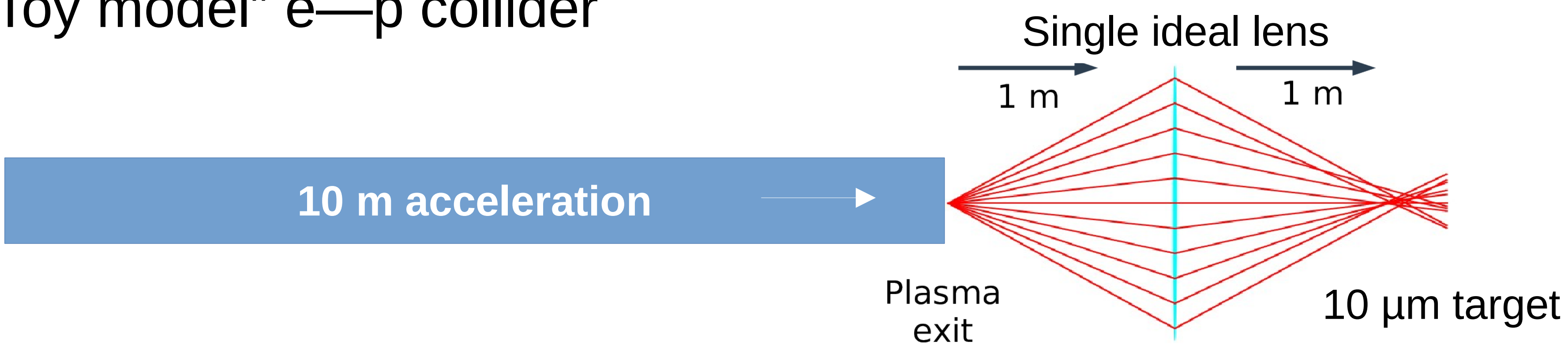
Injection tolerances

In many cases, emittance preservation can be improved at the expense of energy spread or charge capture

Best parameter set will depend on desired application

For an electron—proton collider, we want to maximize luminosity

"Toy model" e—p collider



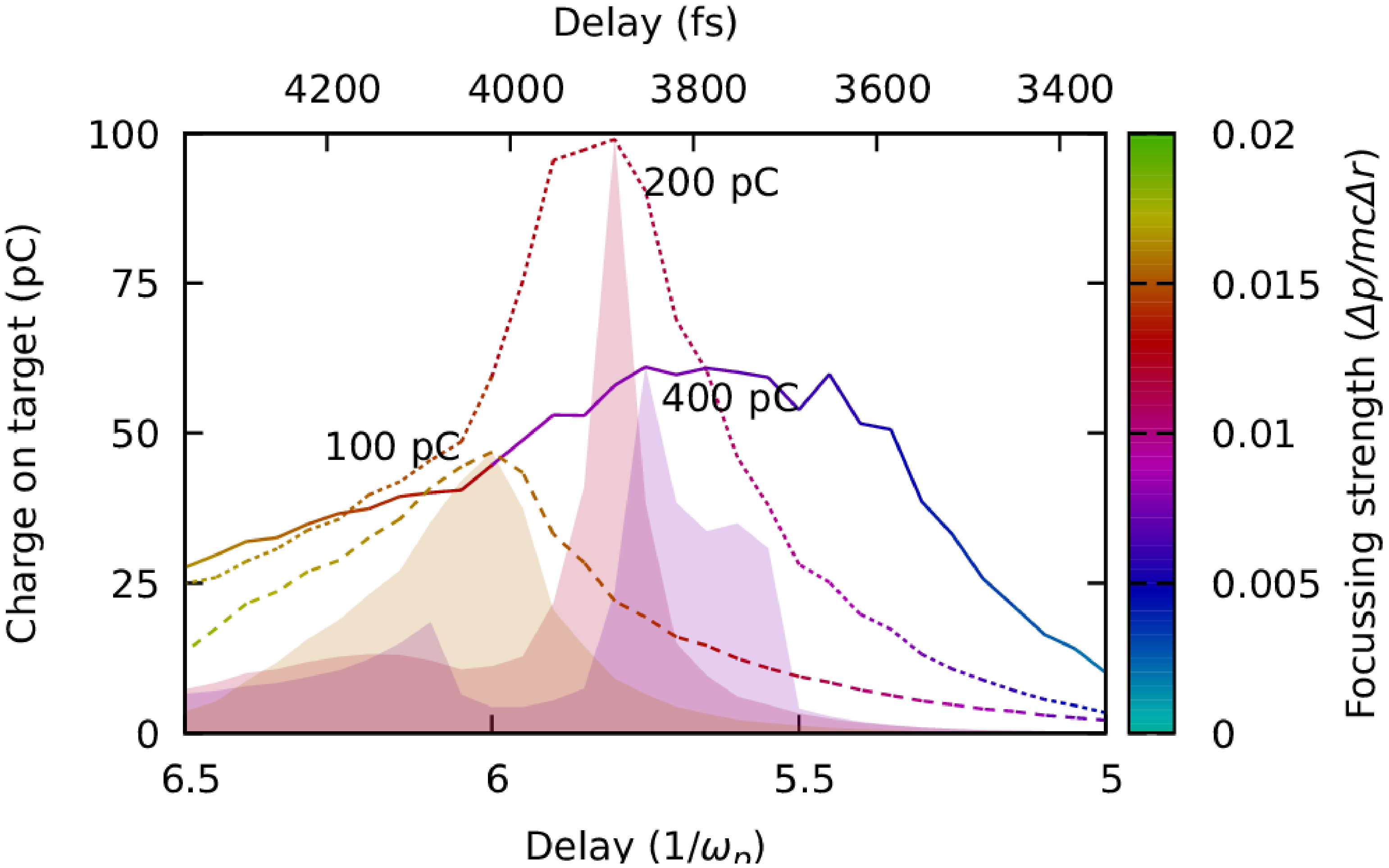
Farmer *et al.*, arXiv:2203.11622 (2022)

Injection tolerances

Can scan anything
e.g. witness delay

Lineout
– tuning tolerance

Filled area
– jitter tolerance



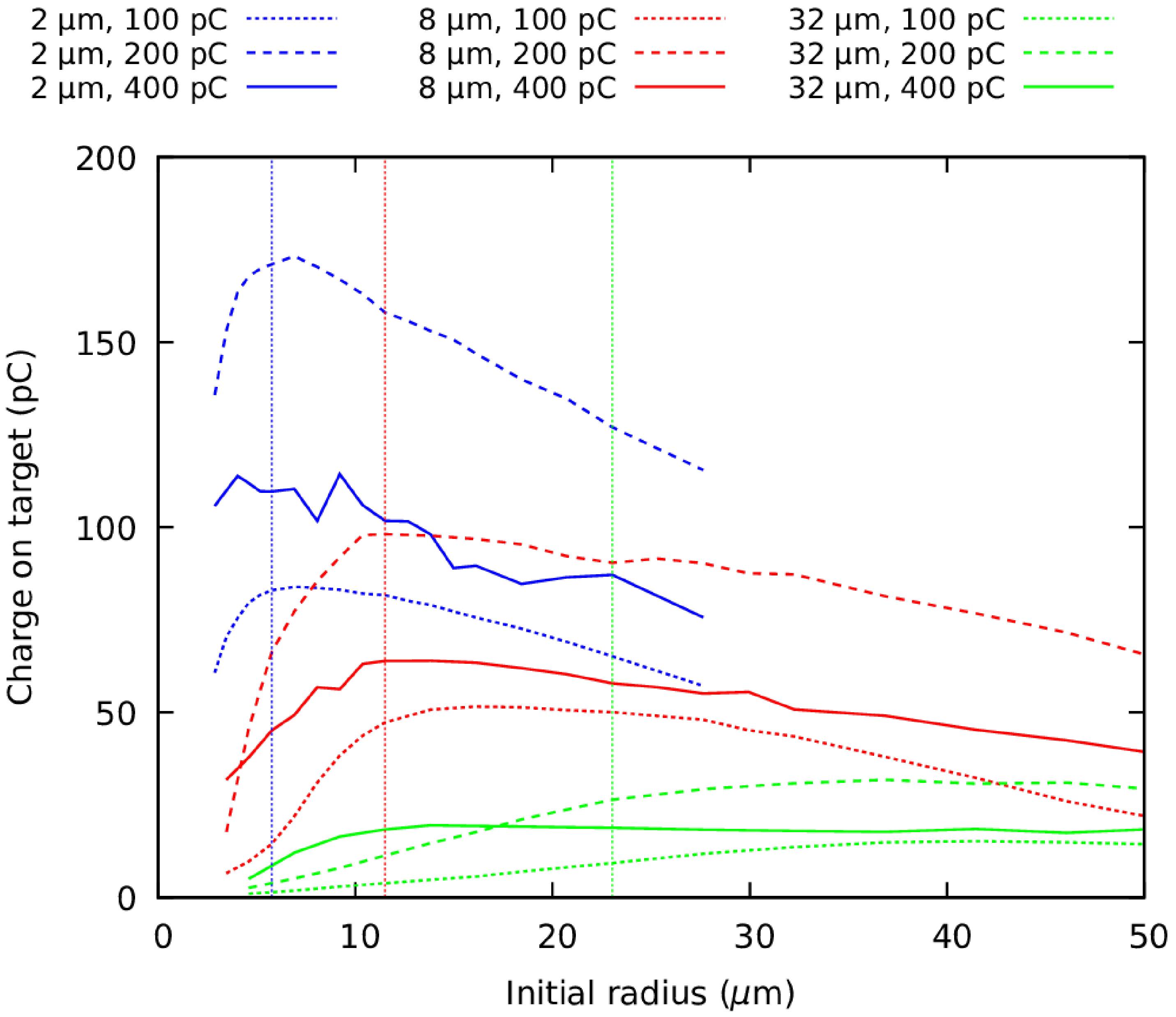
https://arxiv.org/abs/2203.11622v2

Injection tolerances

Can scan anything
e.g. witness radius

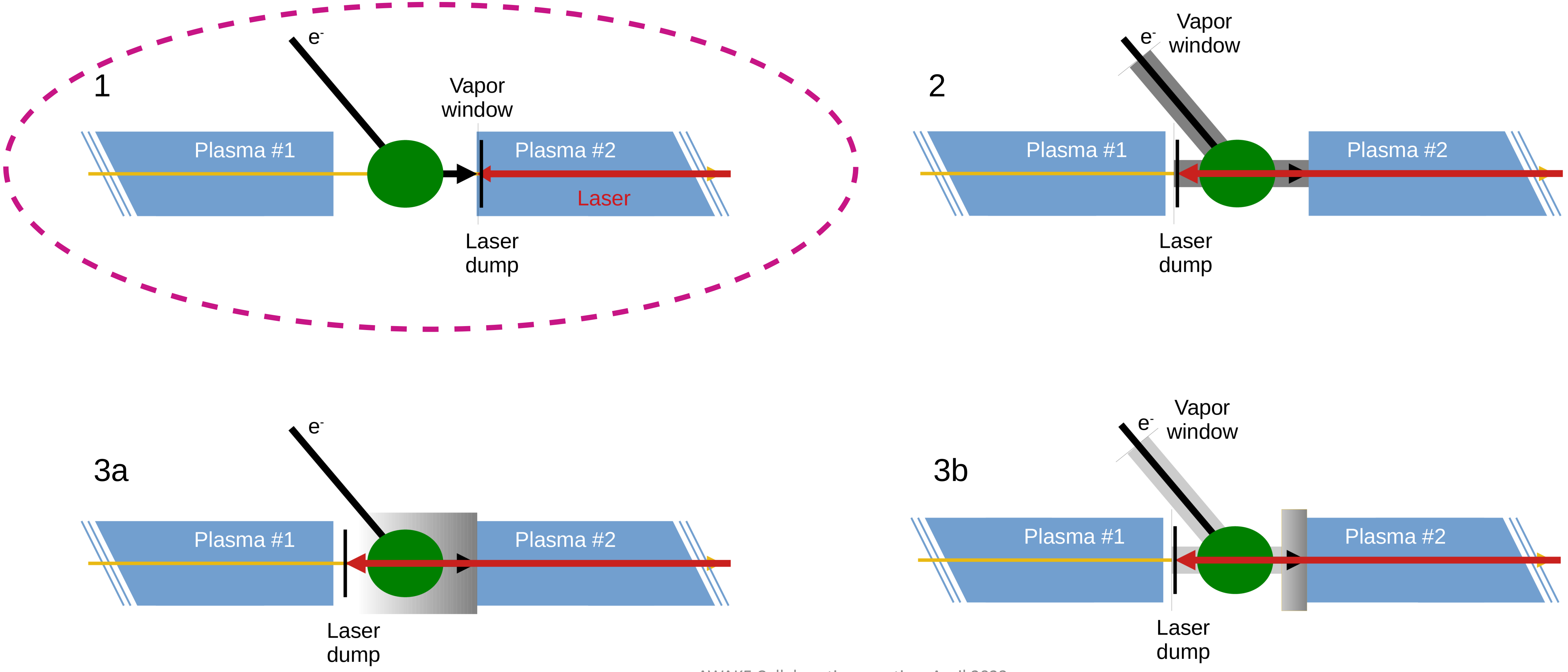
Charge on target for different witness:
- emittance
- Charge

https://arxiv.org/abs/2203.11622v2



Emittance at injection

Current baseline is option 1: injection through laser beam dump

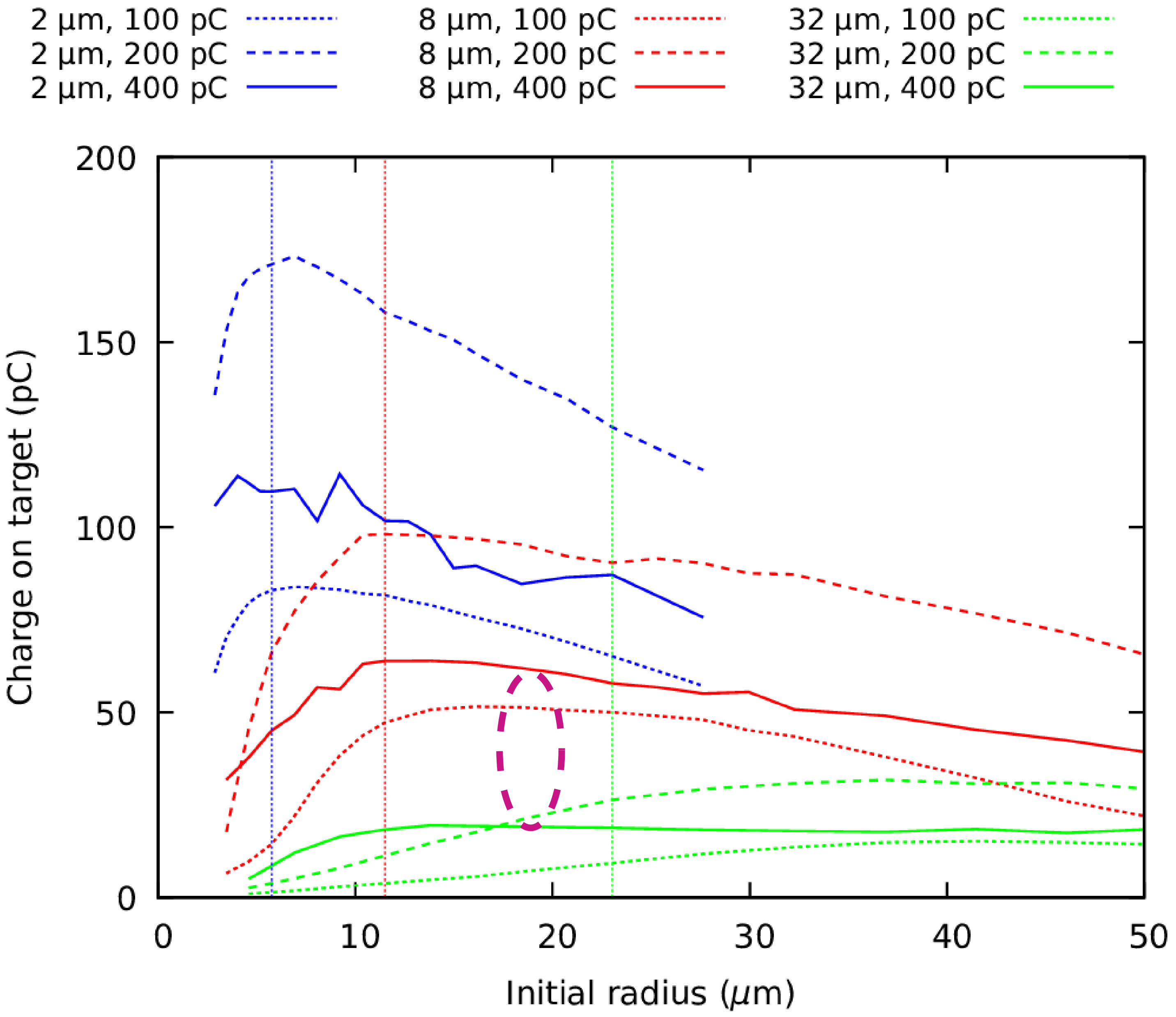


Emittance at injection

Rebecca calculated scattering by two 100 μm foils:

- radius of 17 μm
- emittance of 17 μm

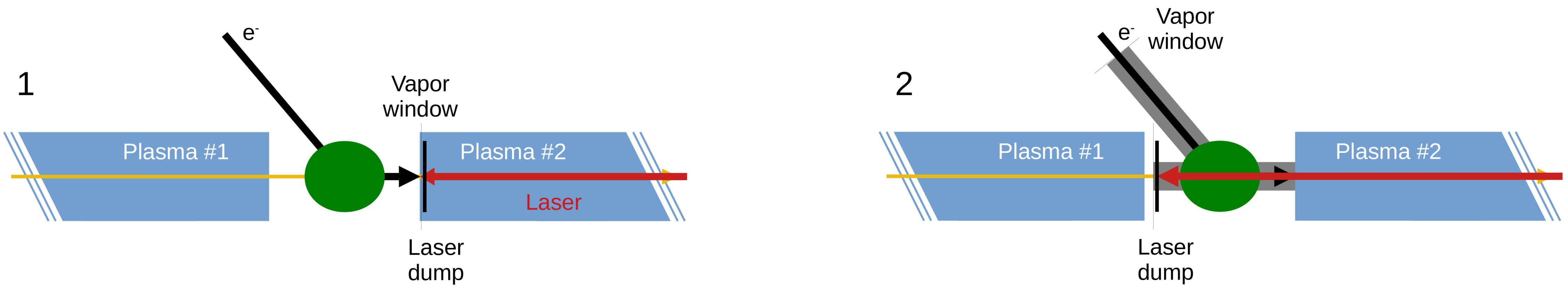
Ramjiawan *et al.*, PRAB (2022)



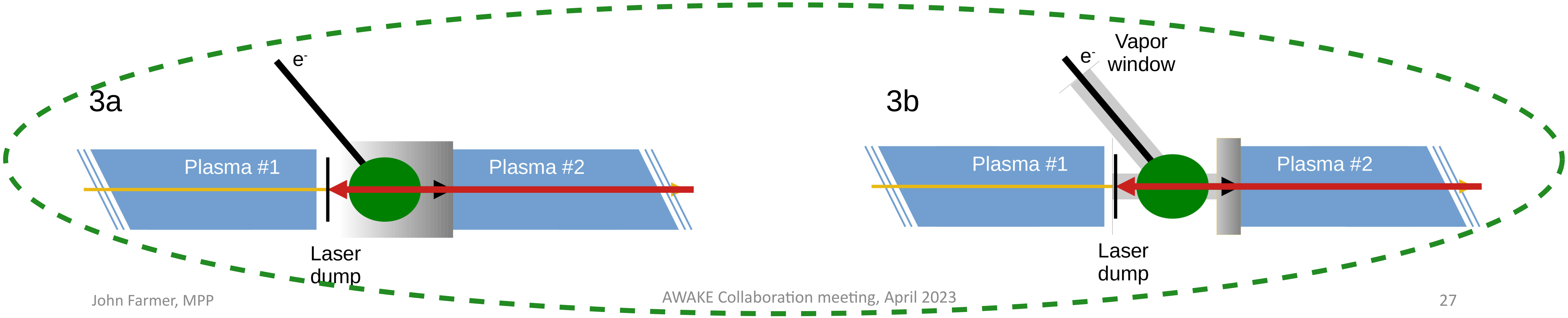
No flexibility to scan radius. Difficult to match at low density.

Emittance at injection

Current baseline is option 1: injection through laser beam dump

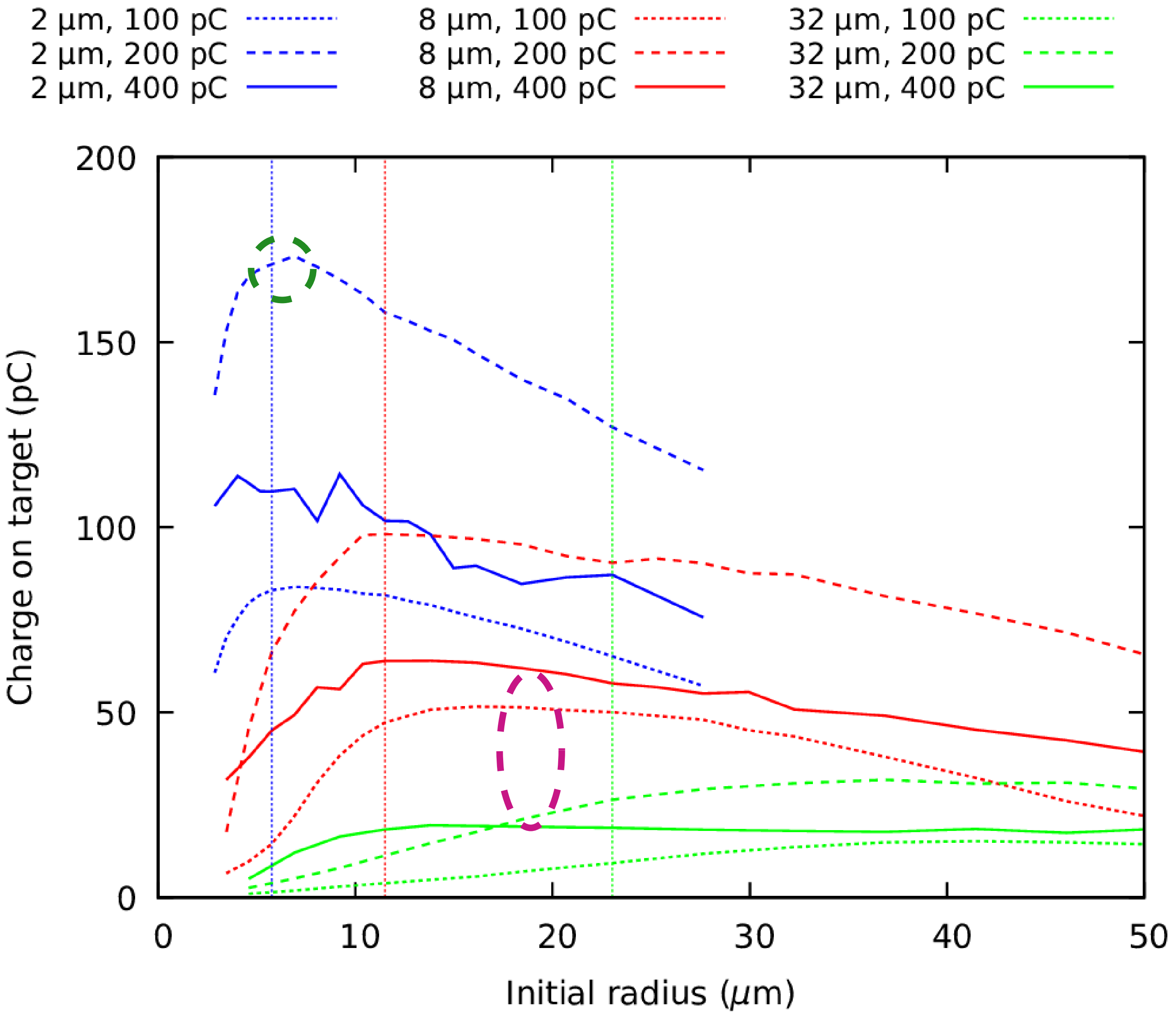


Alternative configurations will give better beam, more flexibility



Emittance at injection

- Better quality beam (>80% charge on target)
- Can change radius without impacting emittance
- Less sensitive to final focus (EARLI)



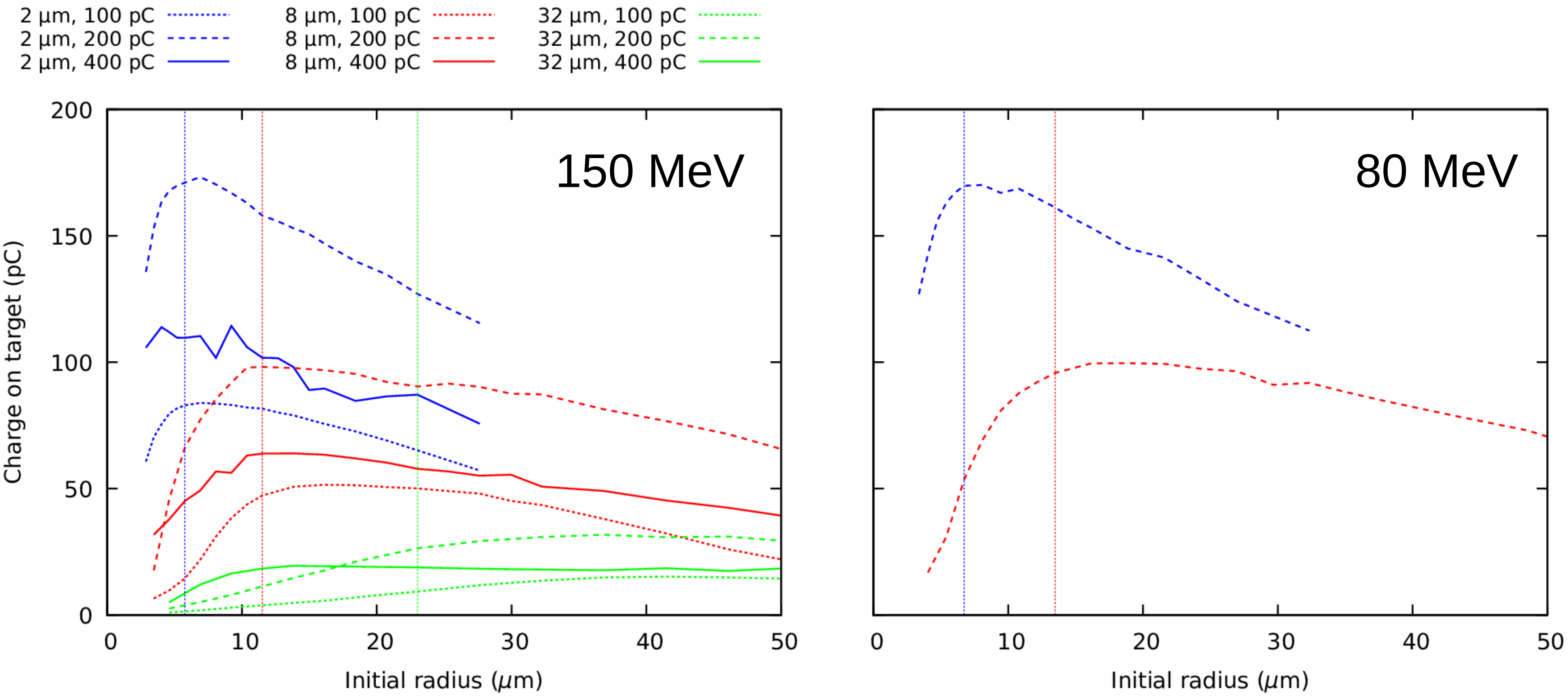
Energy at injection

No “plasma” reason not to inject at lower energy,
trapping condition is ~1 MeV (Khudiakov and Pukhov)

Blowout-matched radius: $$\sigma_x = \left(\frac{2c^2 {\epsilon'_x}^2}{\gamma \omega_p^2} \right)^{1/4}$$

- For 2 µm emittance at 150 MeV, $r_{matched}$ = 5.76 µm
- For 2 µm emittance at 80 MeV, $r_{matched}$ = 6.74 µm

Energy at injection



Conclusions

Prioritisation of tasks necessary for Run 2c should allow deadlines to be met

Lots has been done, lots more needs to be done.

AWAKE simulations remain extremely challenging.

AWAKE Simulation Coordination

If you're doing simulations for AWAKE, you should participate in the AWAKE simulation coordination meetings.

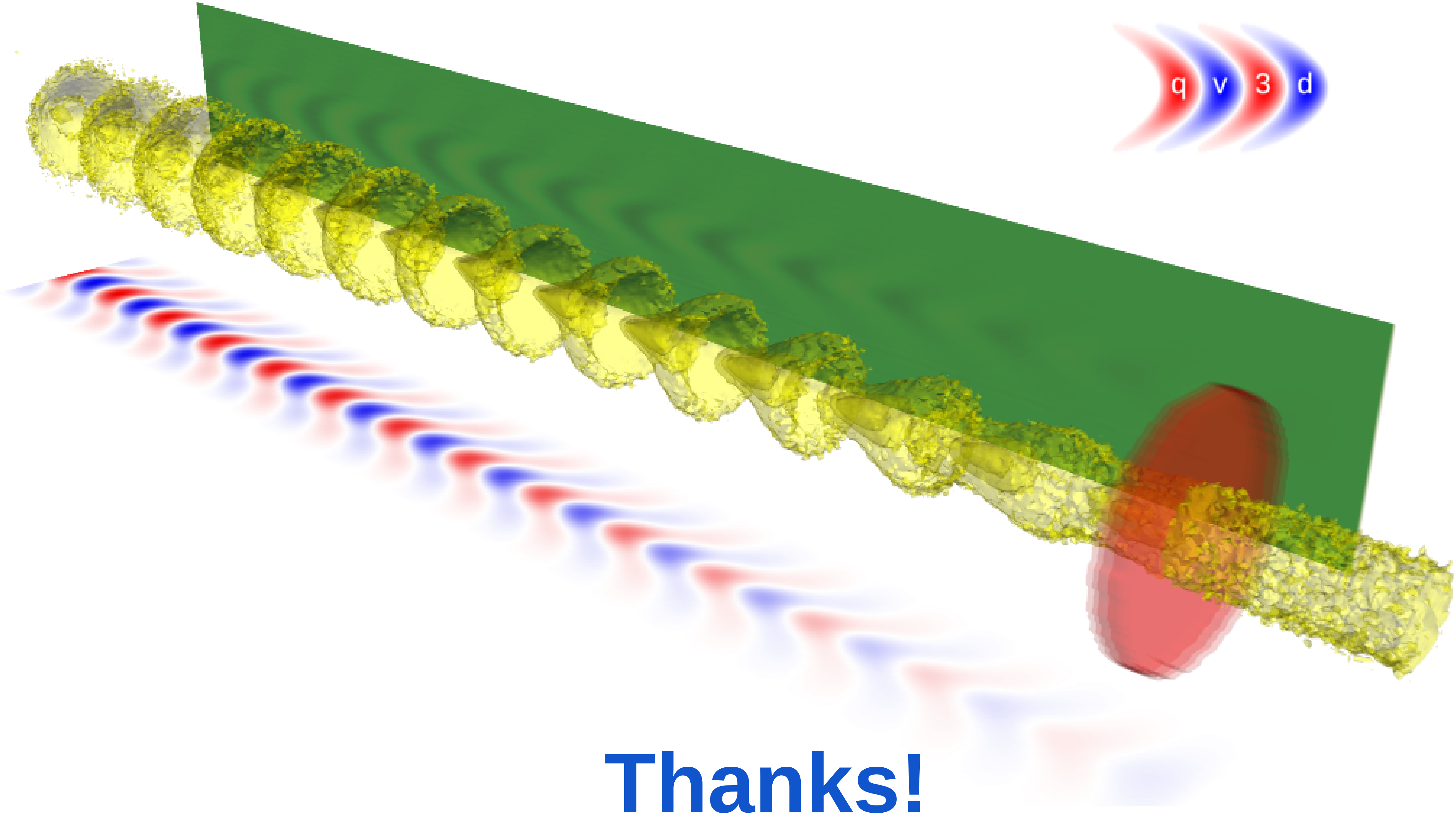
Weekly meeting, monthly review with supervisors.

1) Create a CERN lightweight account

https://account.cern.ch/account/Externals/

2) Subscribe to awake-simulations-students at

https://e-groups.cern.ch/

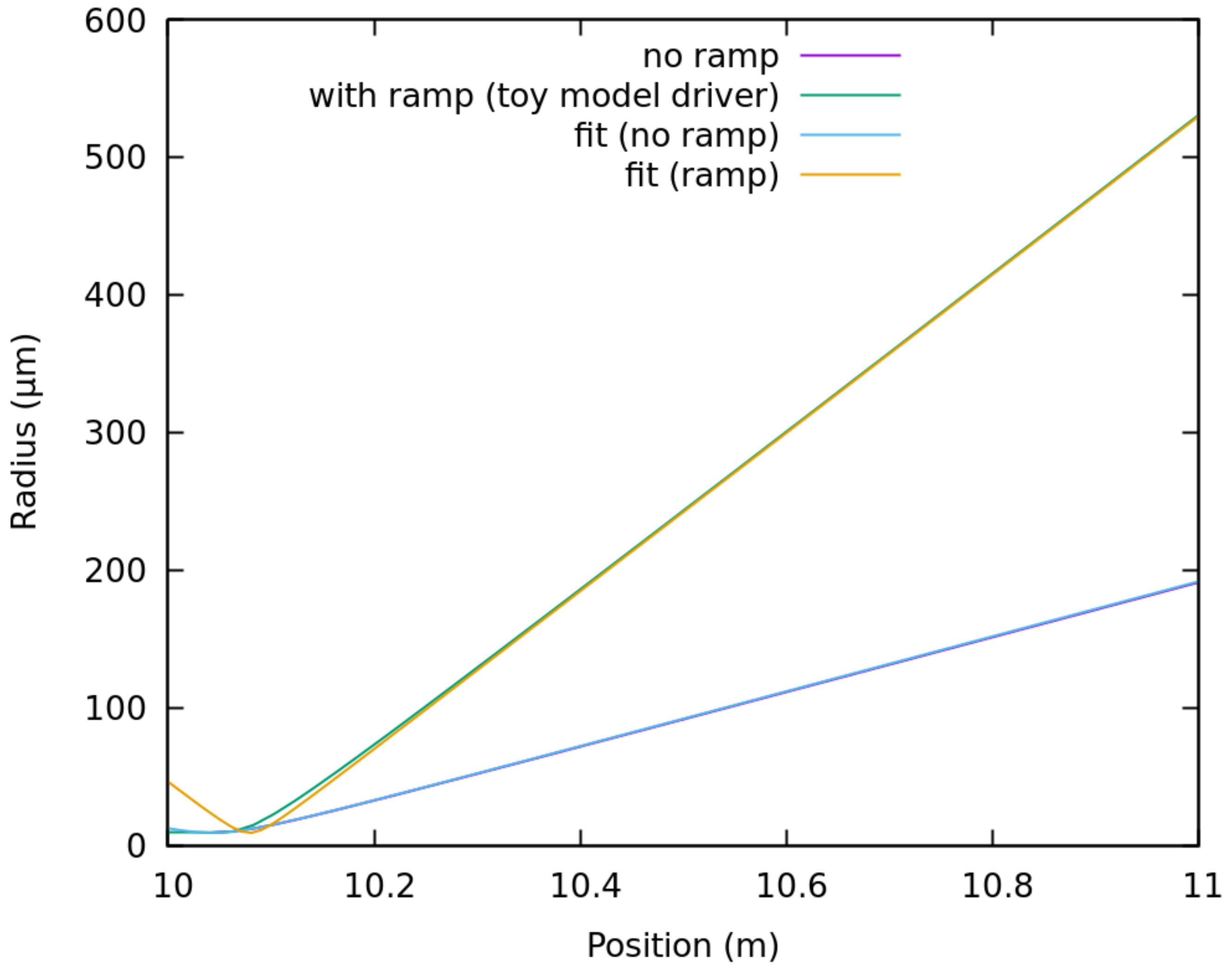


Thanks!

Extraction

Beam trajectory without ramp is well reproduced from Twiss parameters at 11 m

Beam trajectory with ramp is (initially) not ballistic – leads to characterization of a “virtual waist”



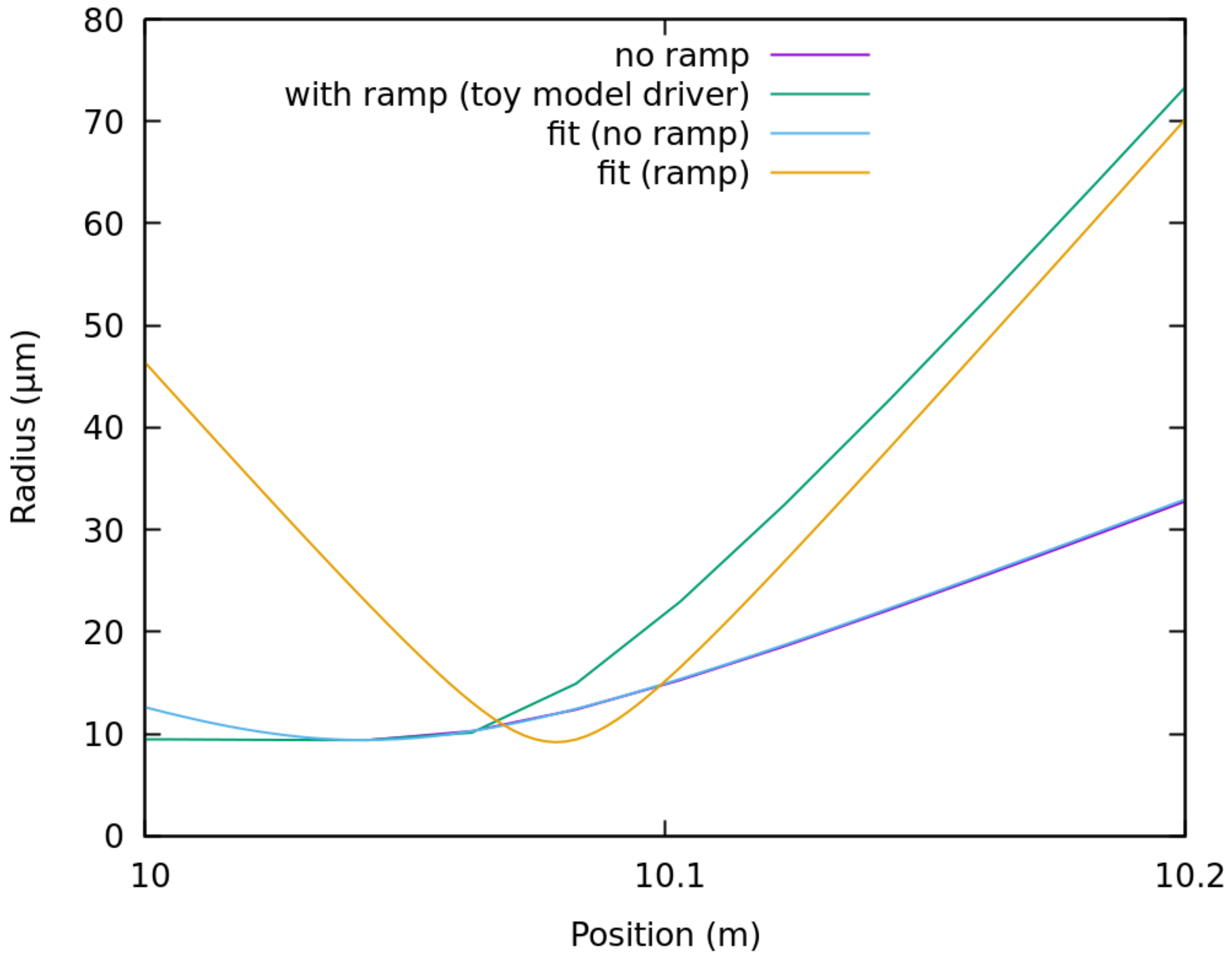
Extraction

Virtual waist has different position, size and divergence.

Effects beyond divergence is small for 4 GeV beam.

Effect for Run 2a/b should be simulated

- Larger beam
- Lower energy

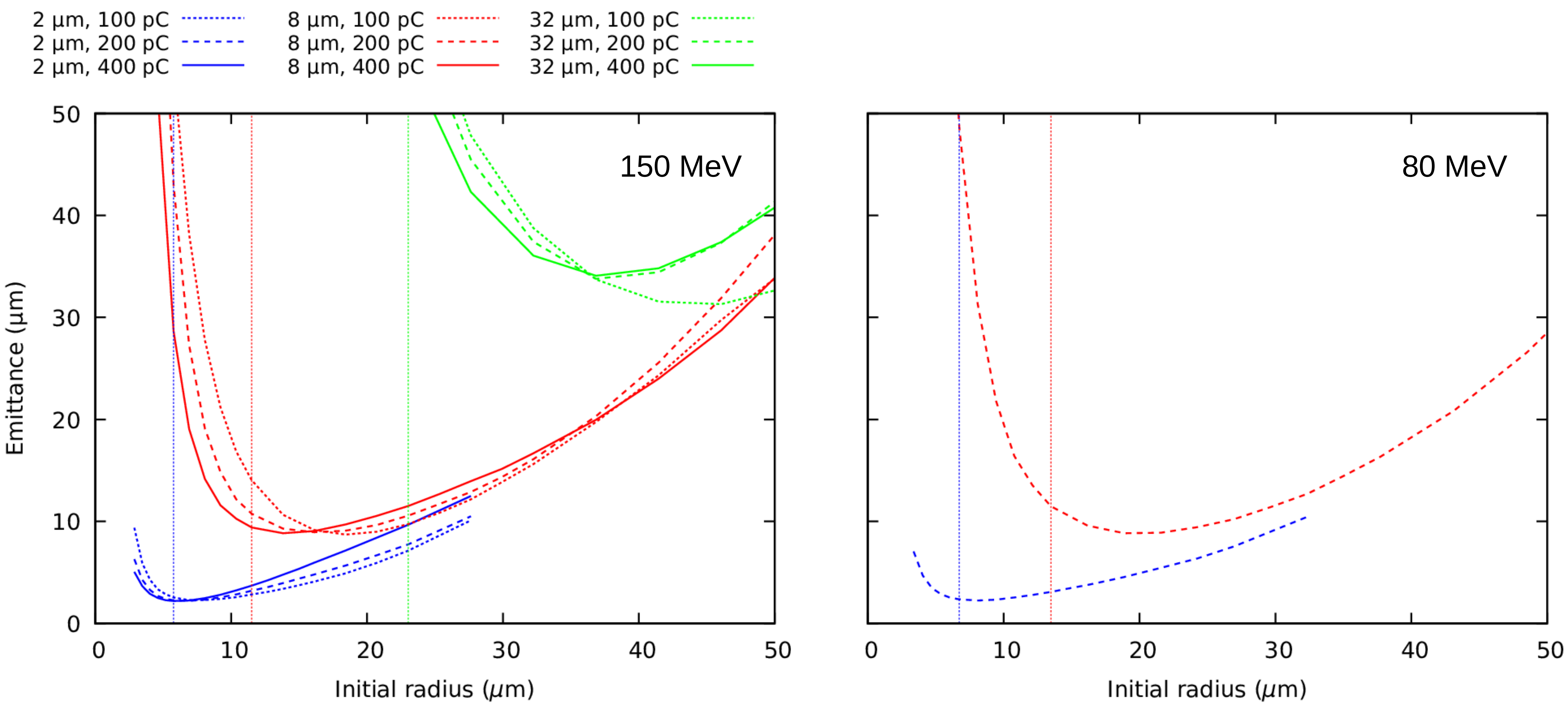


Influence of the gap

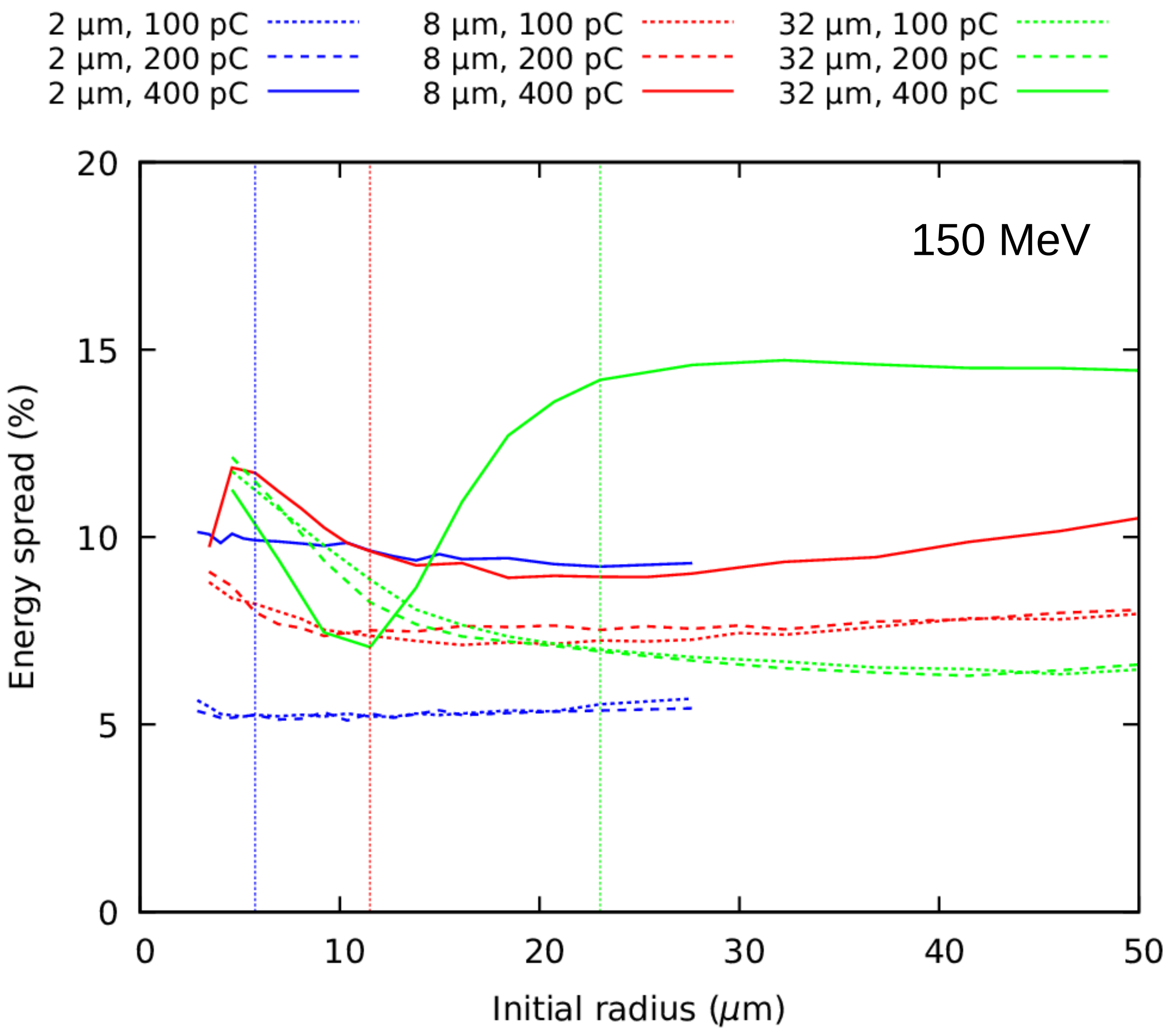
Average field over 10 m second plasma:

- No gap: ~750 MV/m
- 30 cm: ~670 MV/m
- 60 cm: ~550 MV/m
- 1 m: ~445 MV/m

Comparisons: 150 vs 80 MeV

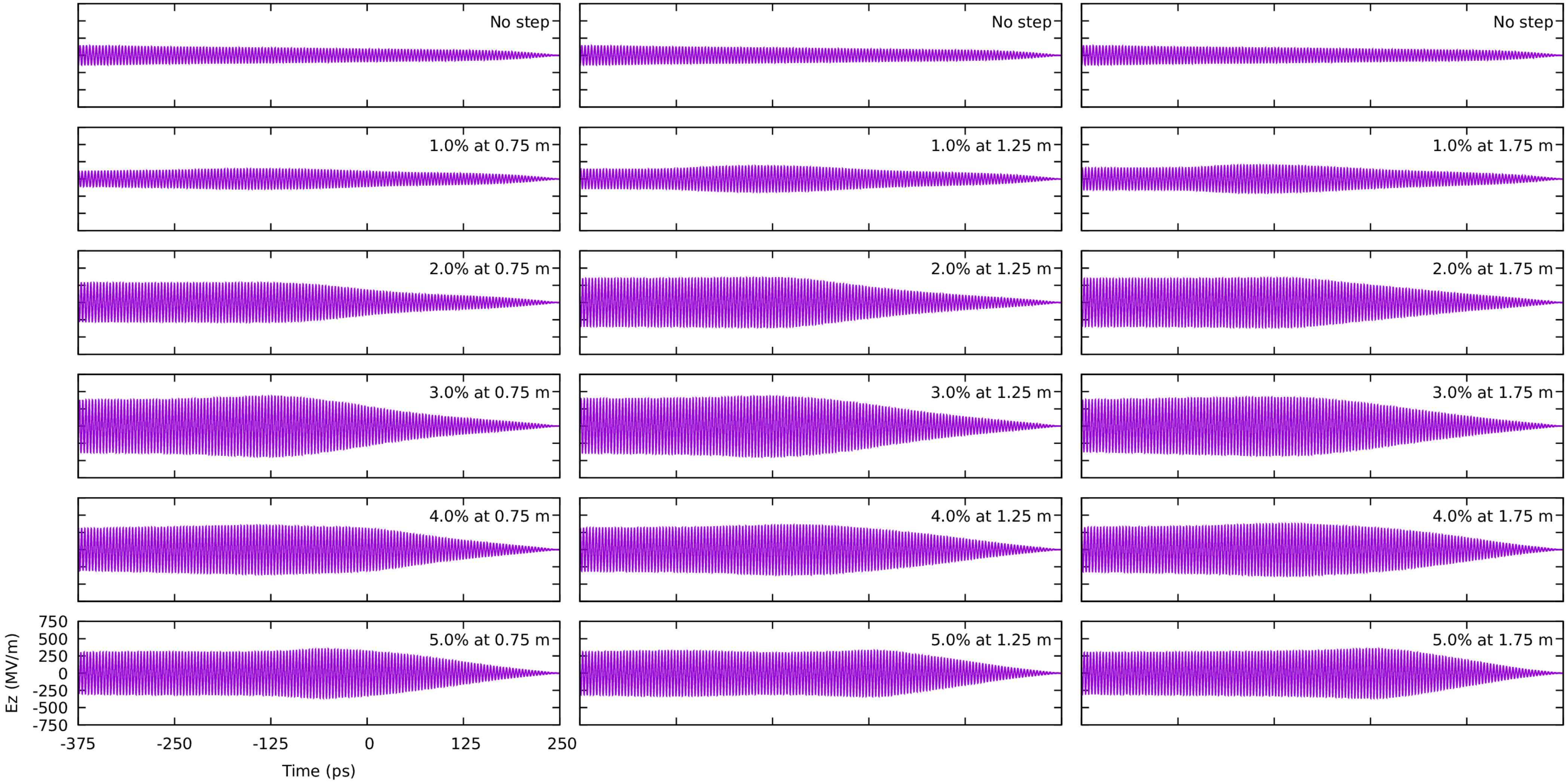


Energy spread



For 2, 8µm emittance cases, energy spread depends only weakly on initial radius.

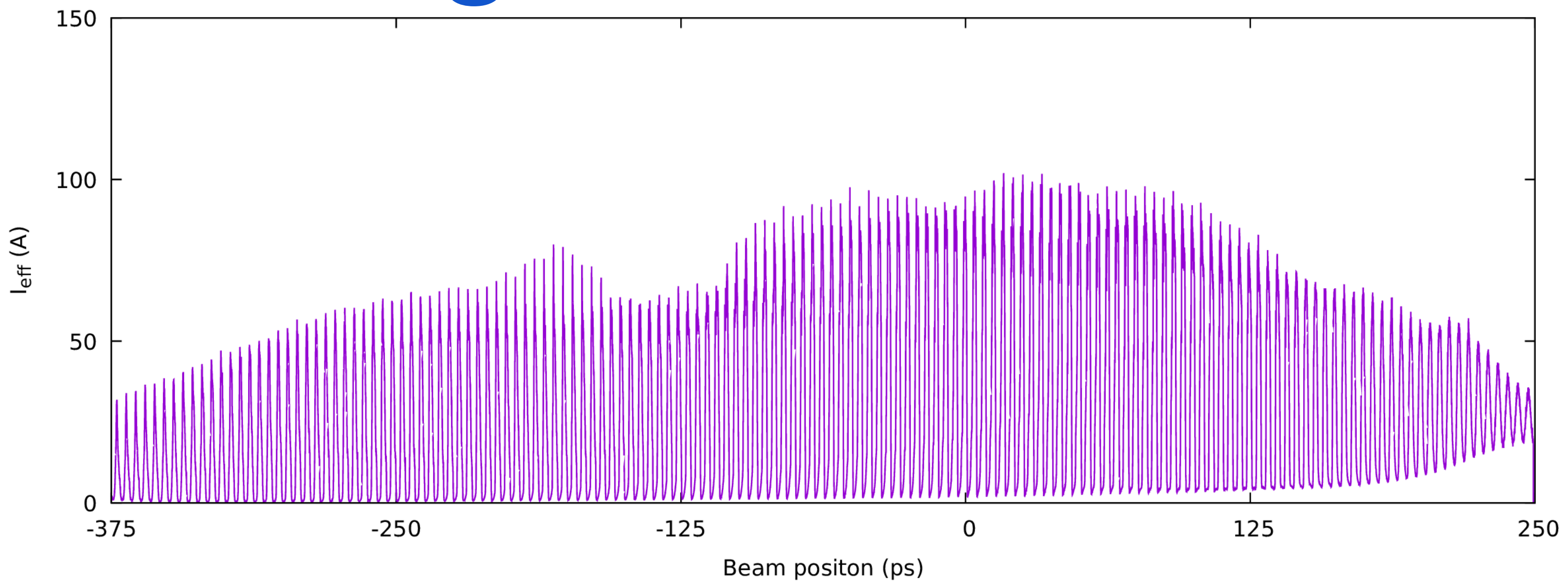
Step scan



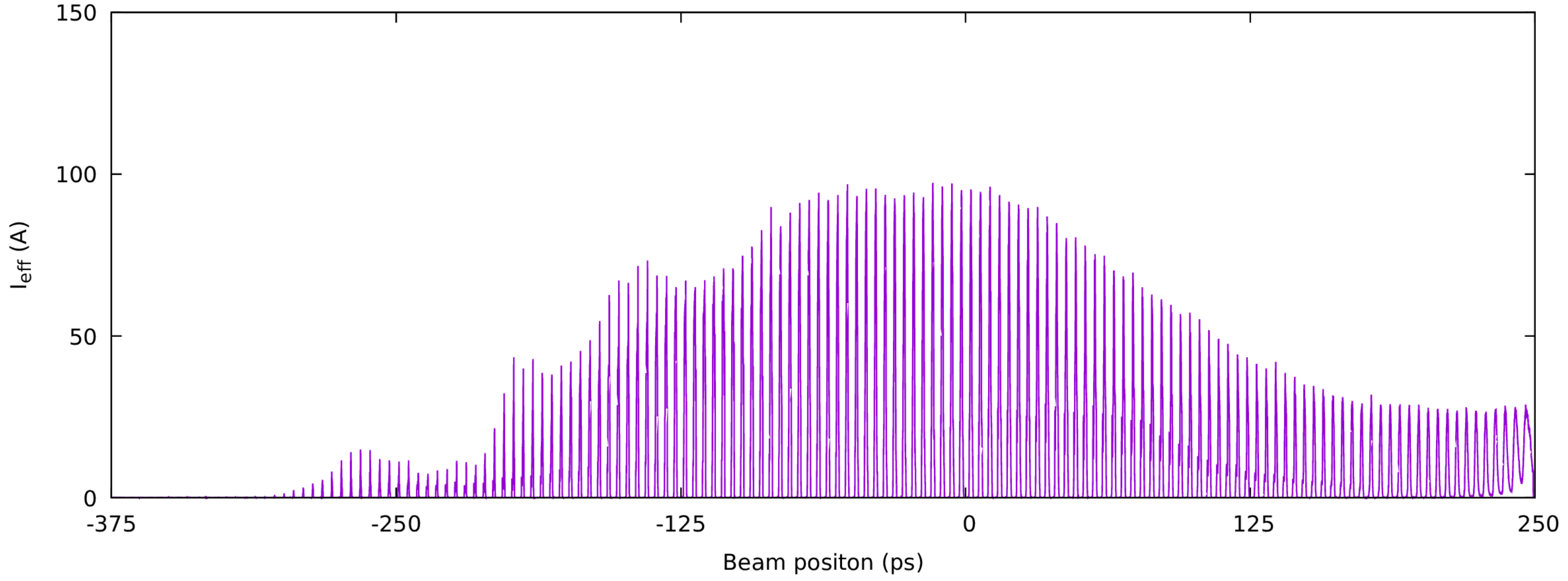
10-m first plasma, 1-m gap, average fields over 10-m second plasma

Self-modulation stage

Beam after 4m



Beam after 10m



Effective current can be calcualted from streak camera images. Charge within $1/k_p$ yields similar results

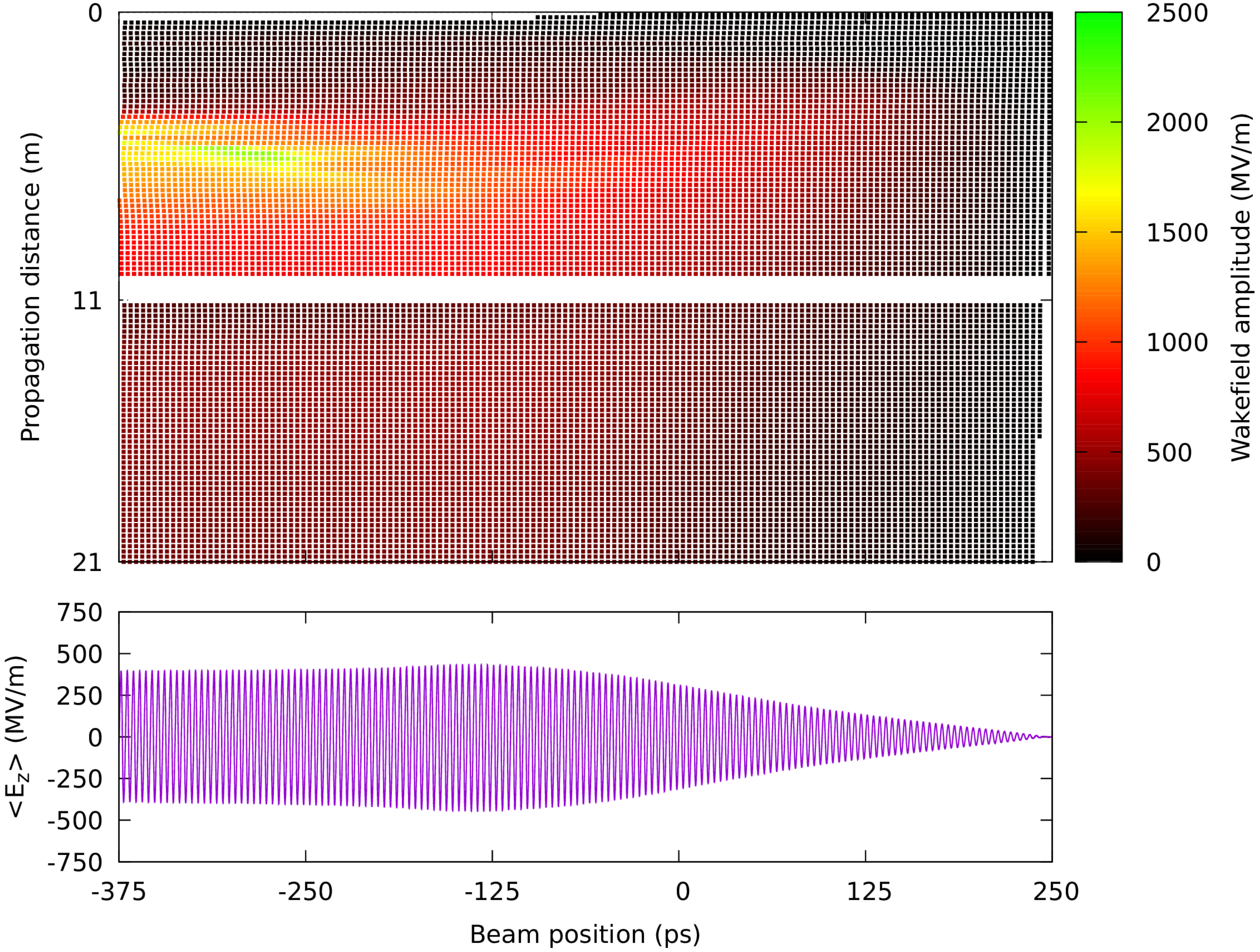
Baseline

Growth

Peak

Stabilisation

Drop over gap



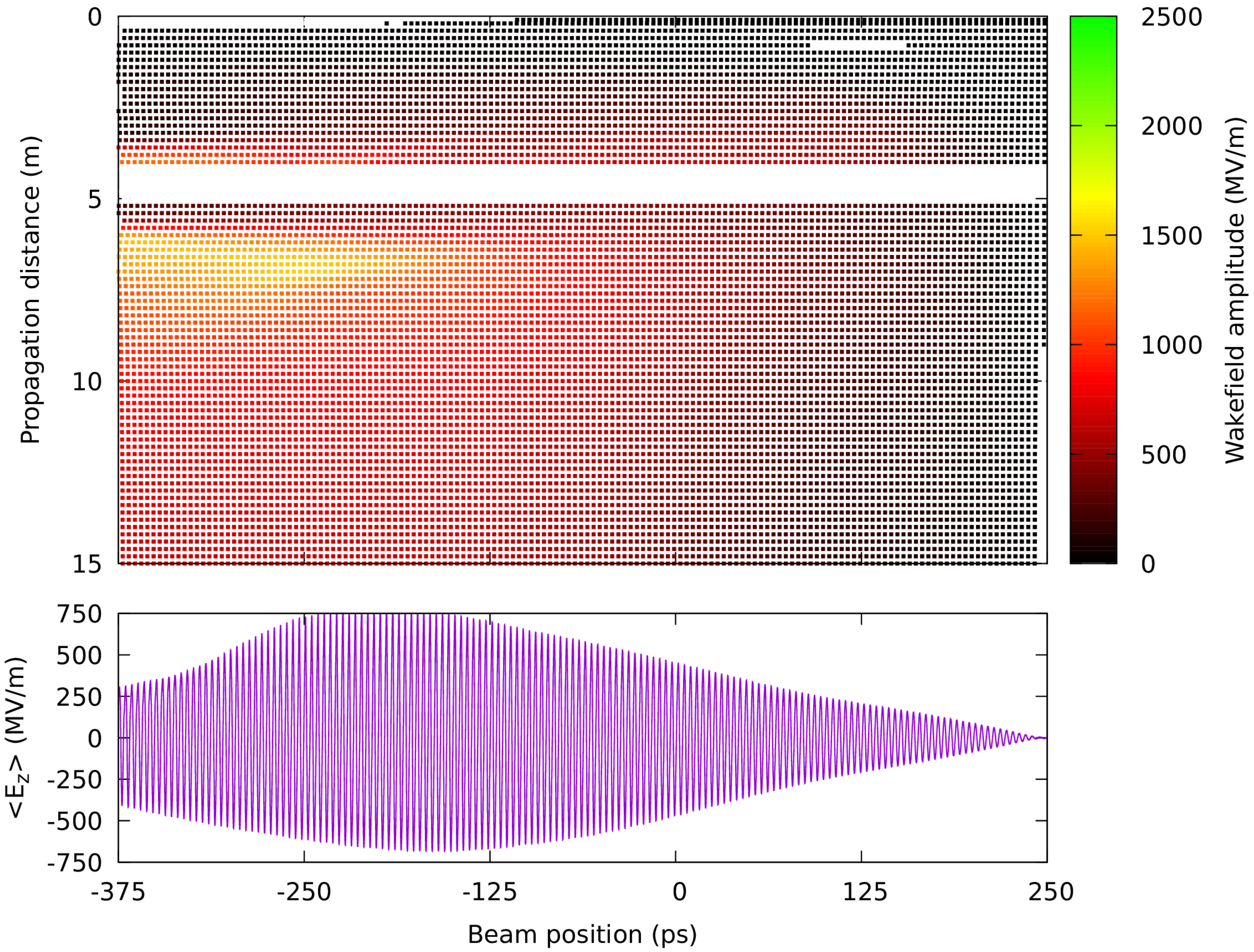
10 m first plasma, 1 m gap.

Shorter first plasma

Growth

Drop over gap
More growth
Peak

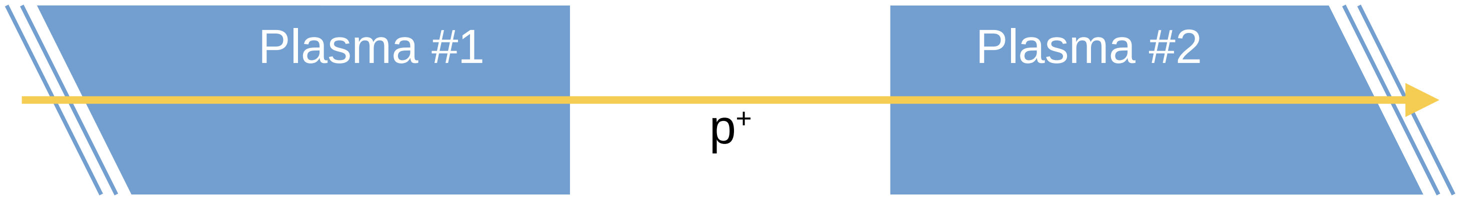
Stabilisation



4 m first plasma, 1 m gap.

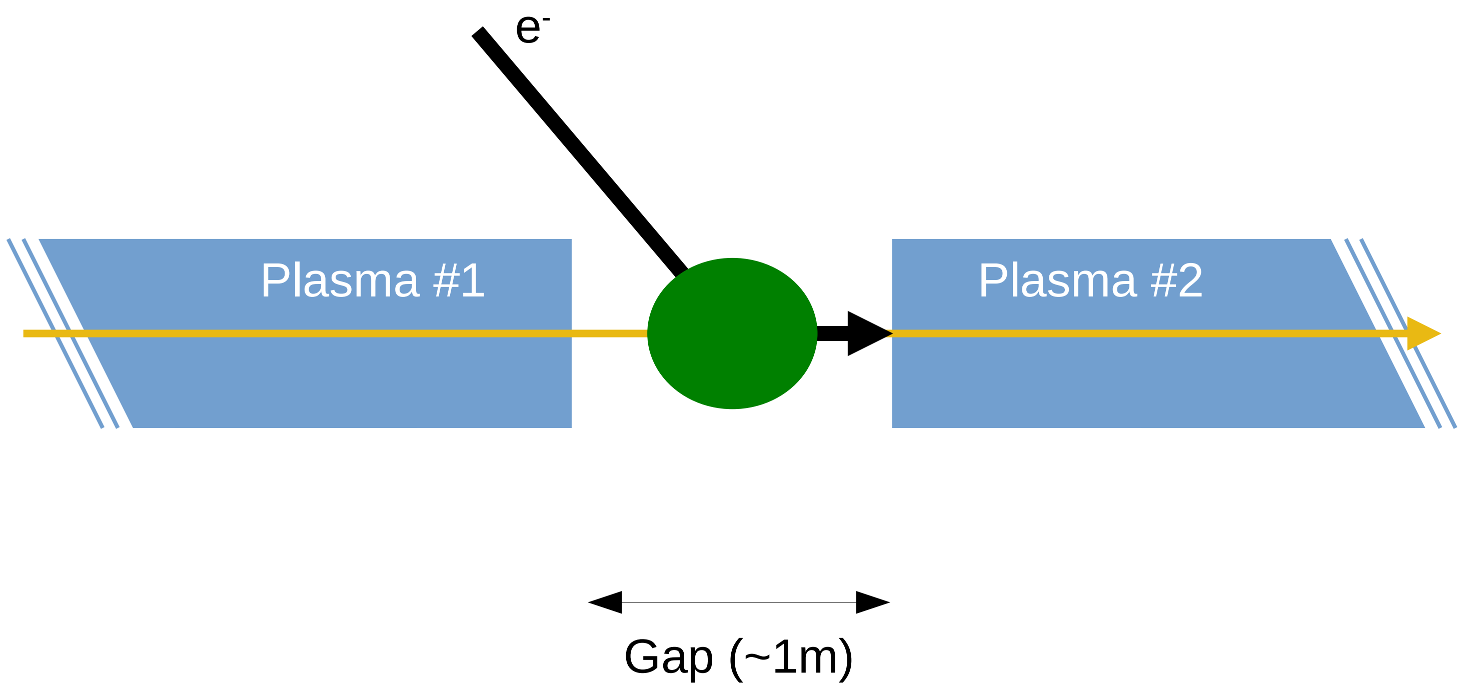
Run 2c configuration

- Protons self-modulate in the first plasma cell
- Acceleration takes place in the second plasma cell



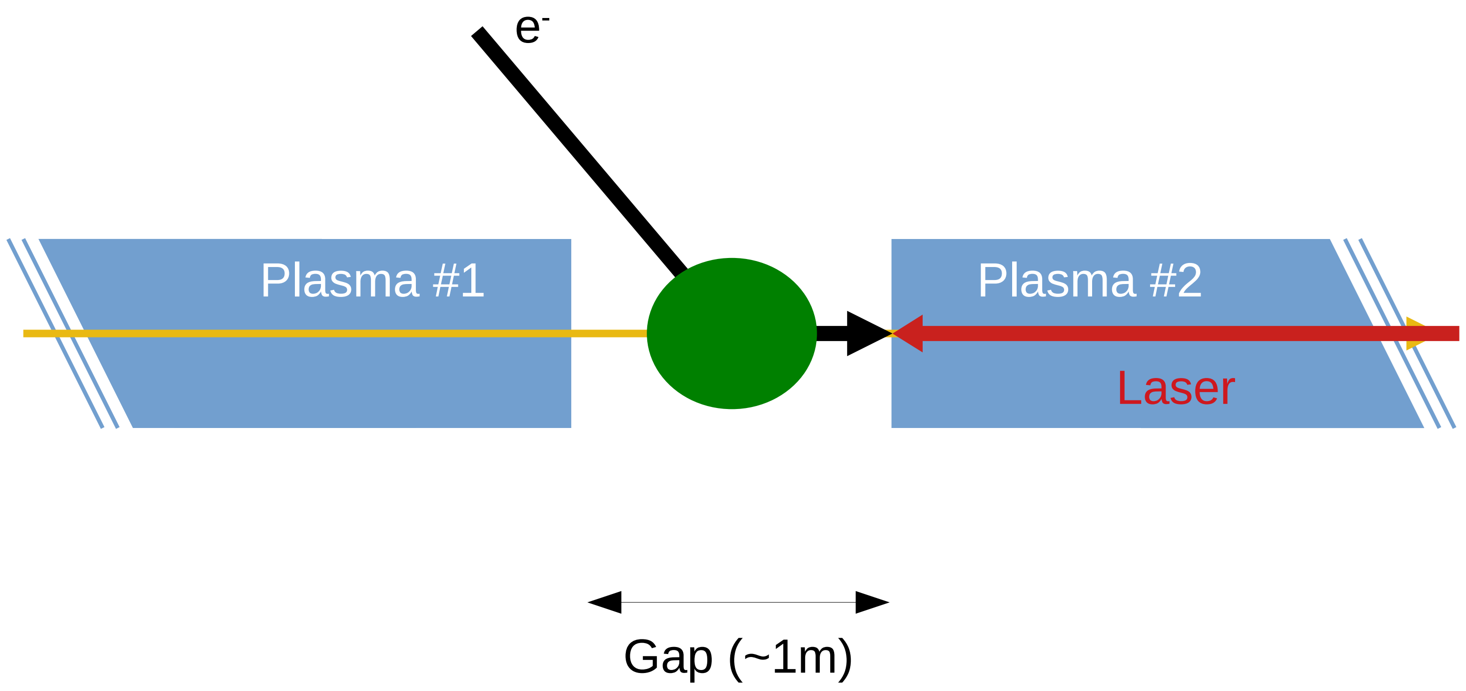
Run 2c configuration

- Need gap between plasma cells for electron injection



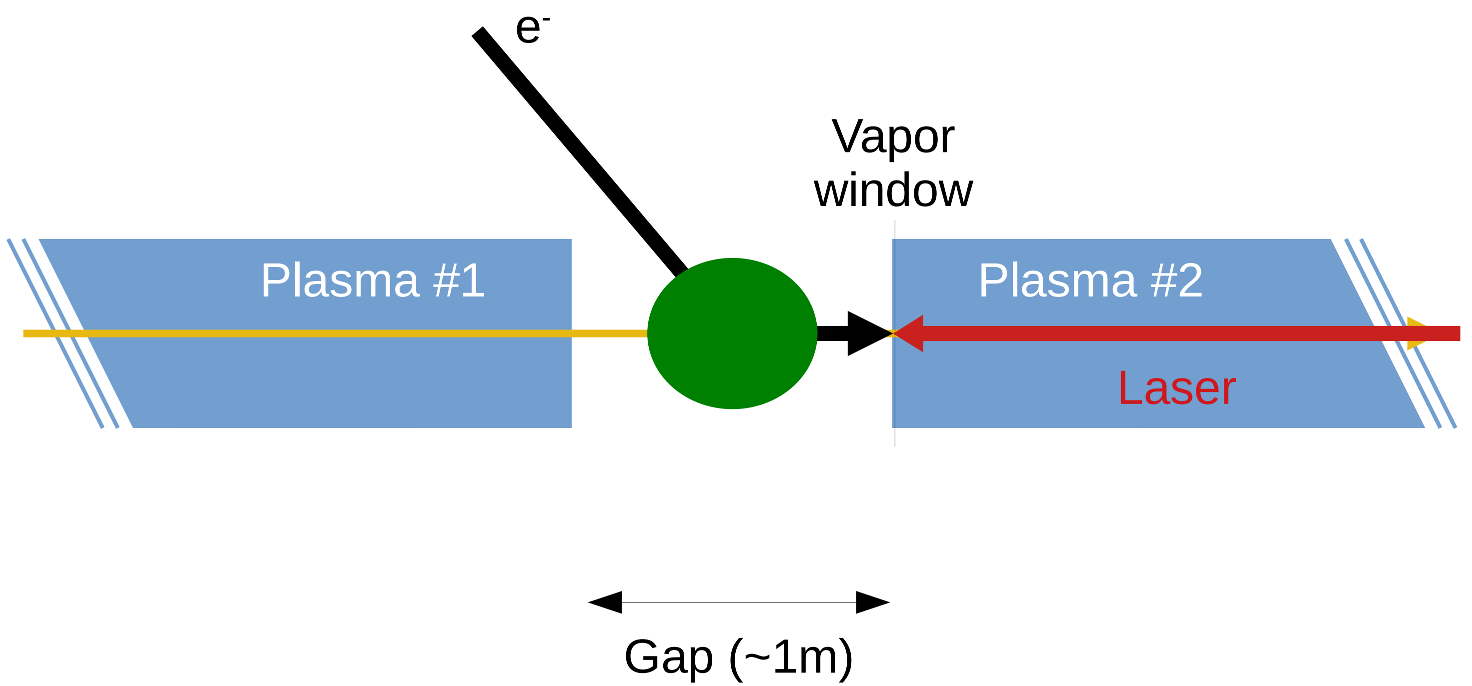
Run 2c configuration

- Need gap between plasma cells for electron injection
- Counter-propagating laser avoids plasma ramp



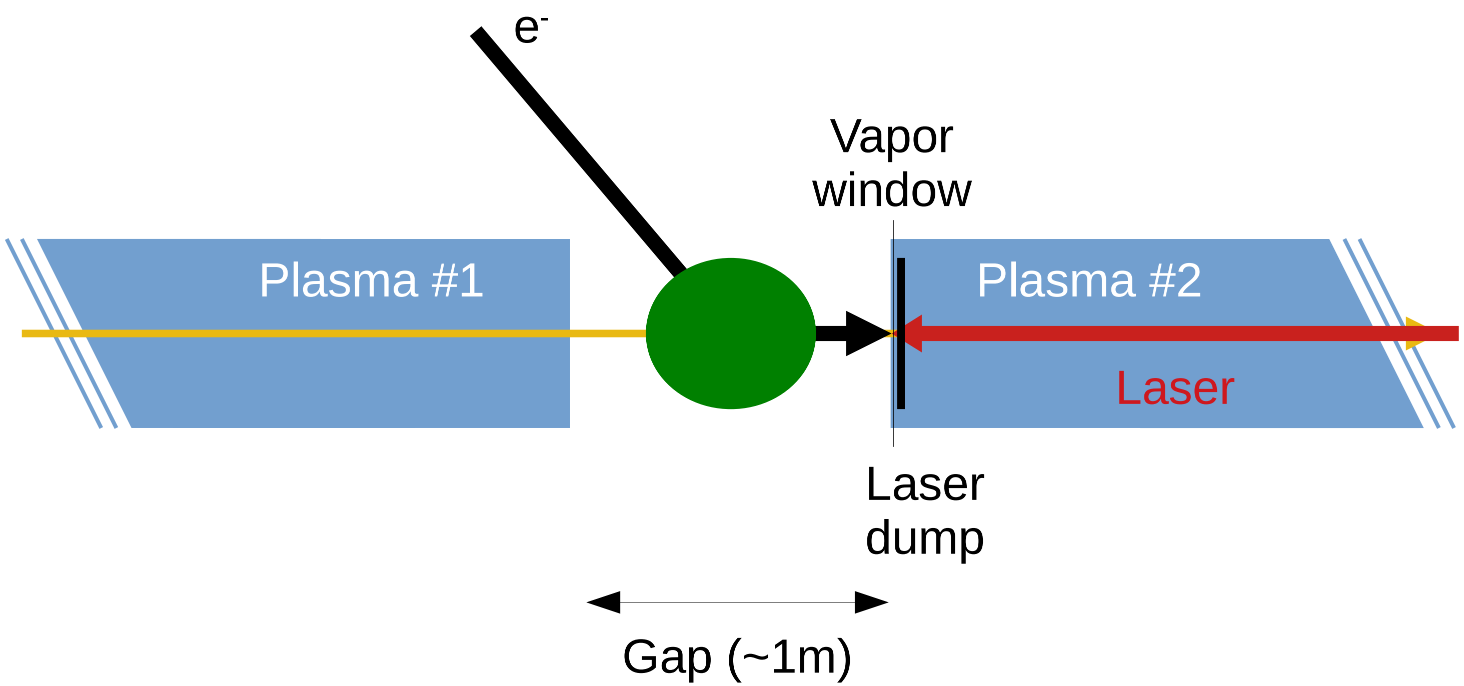
Option 1

- Use window at entrance to vapor source



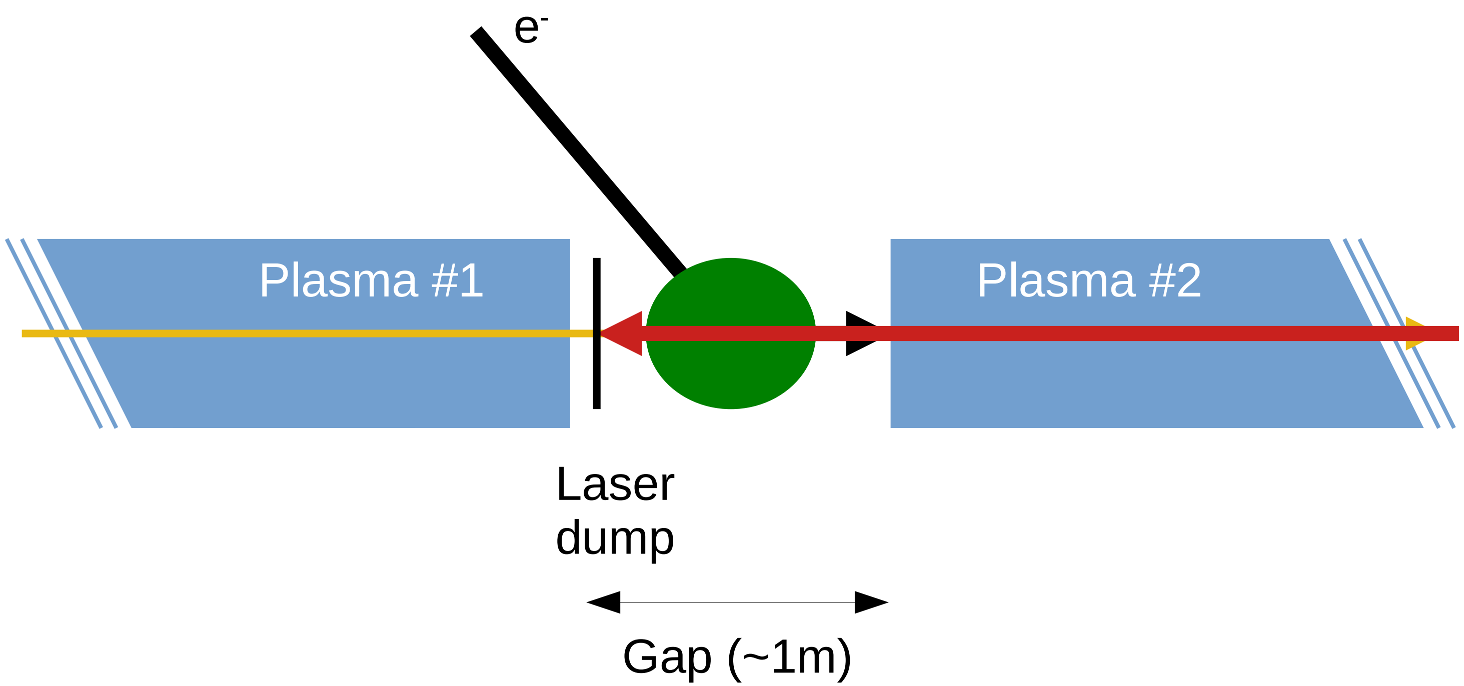
Option 1

- Use window at entrance to vapor source
- Needs laser beam dump
- Scattering increases witness emittance



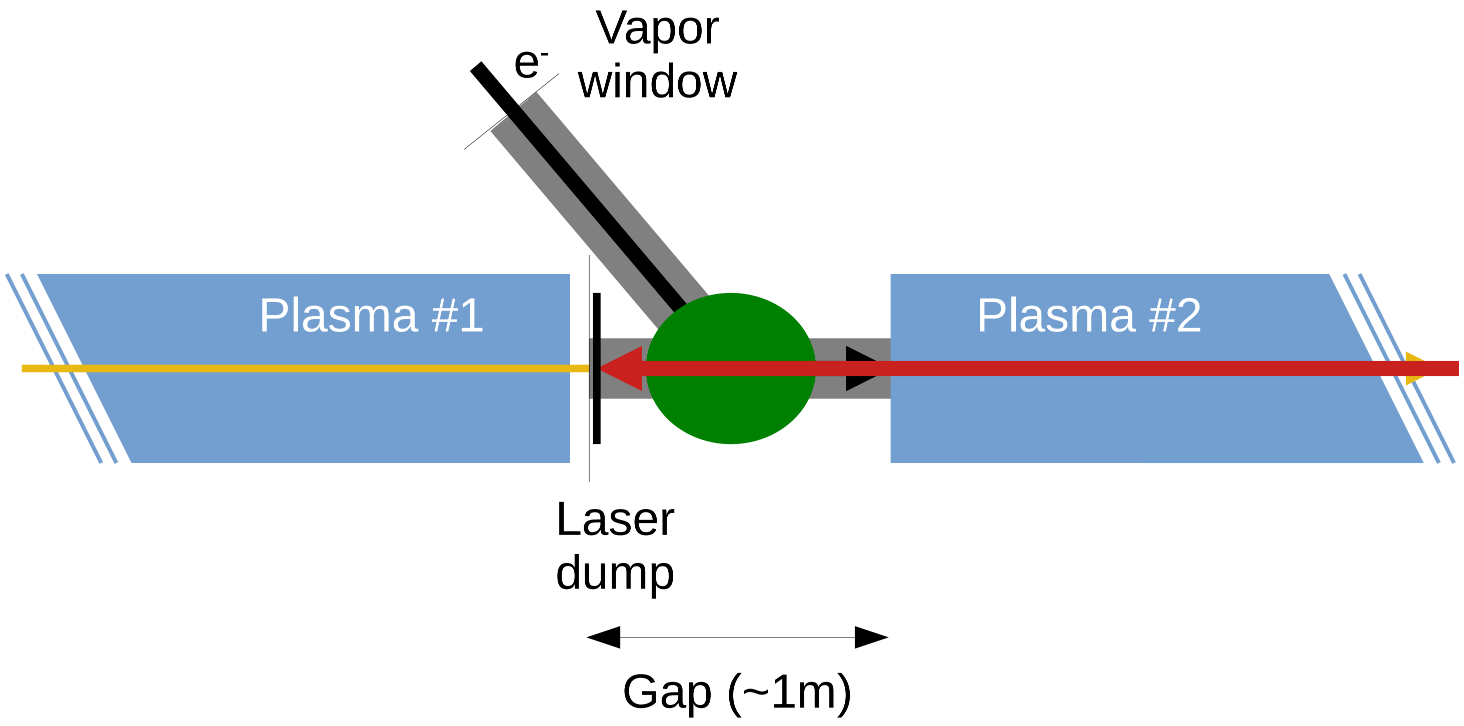
Option 2

- No window at vapor source entrance



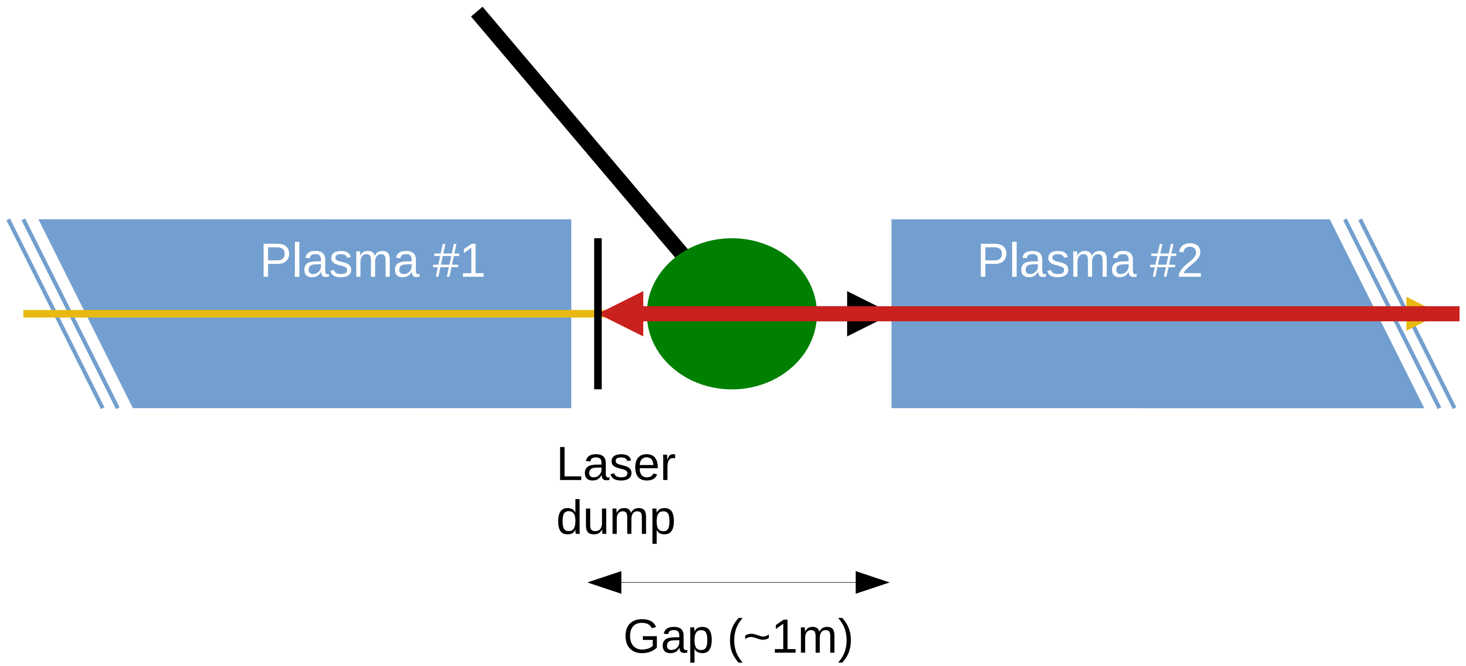
Option 2

- No window at vapor source entrance
- Beam pipe now full of Rb vapour.
  Scattering increases witness emittance



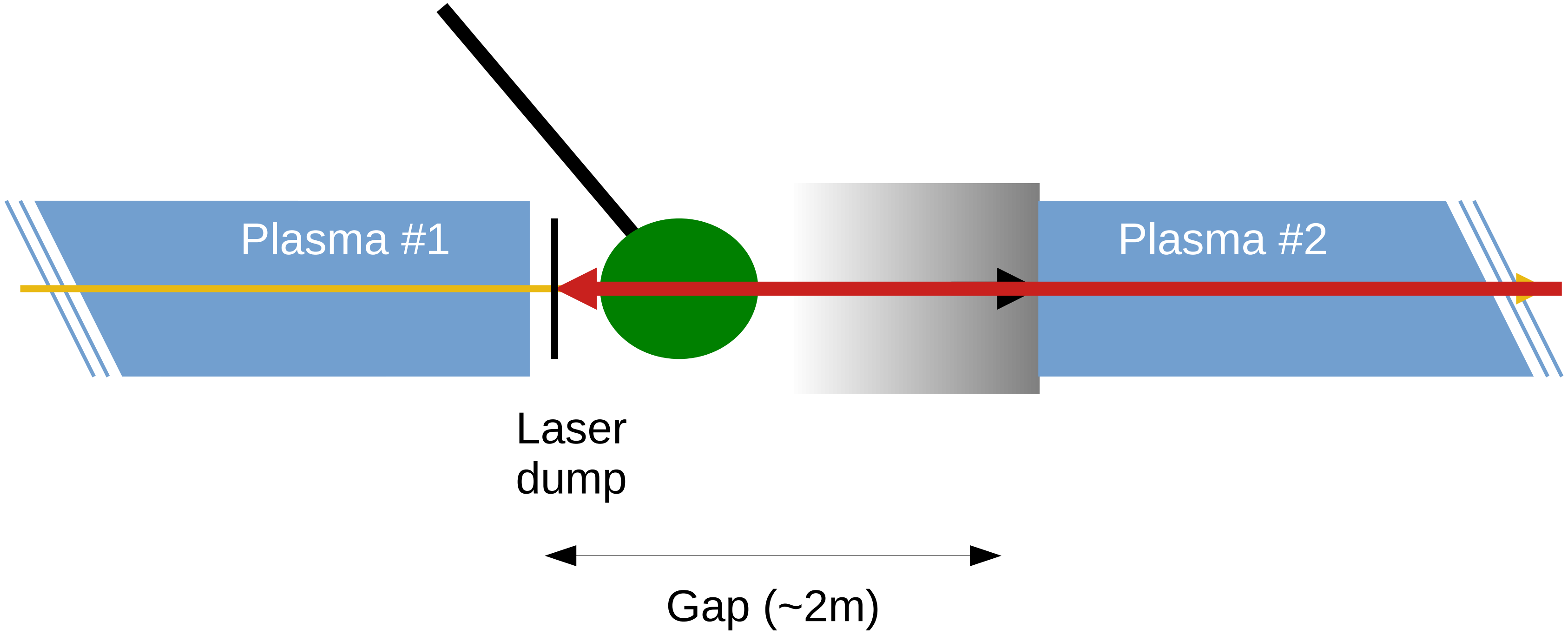
Option 3

- Use expansion volume at entrance to second plasma cell
- Similar to Run 1/2a/2b configuration



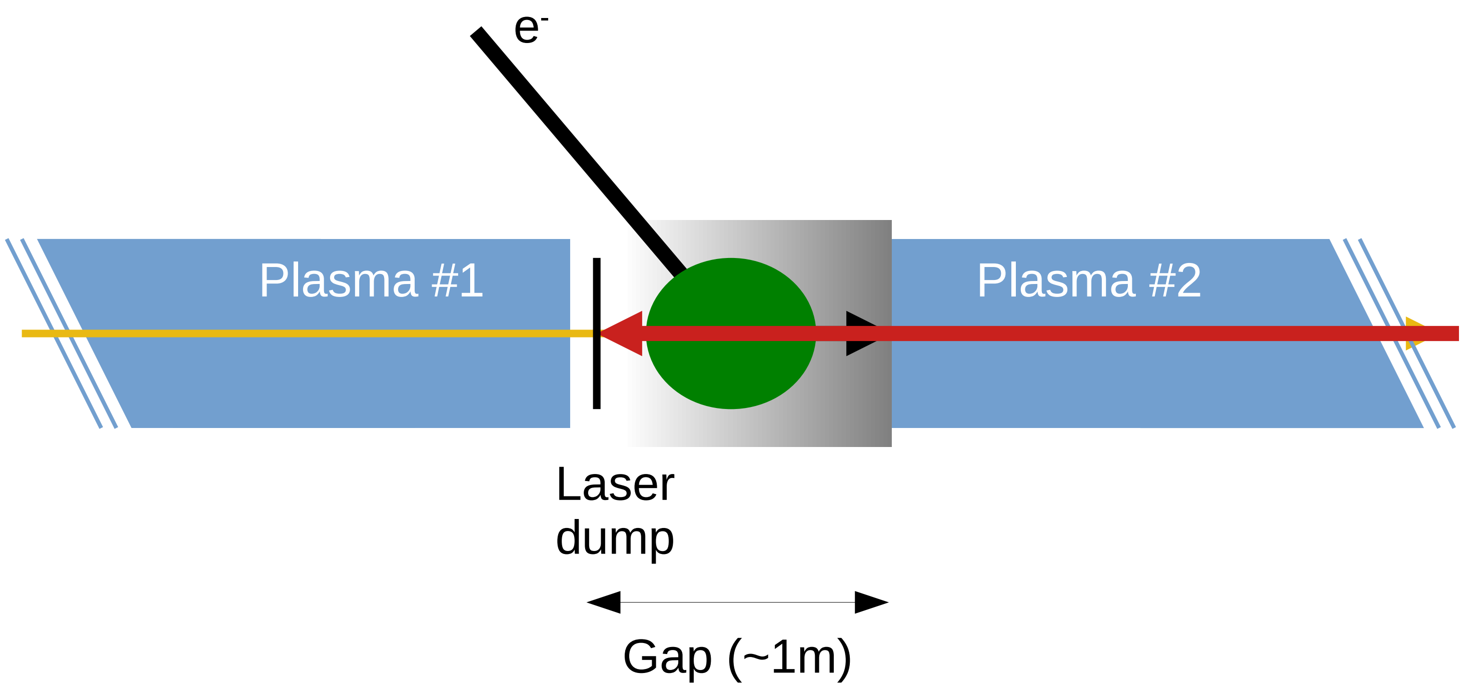
Option 3

- Use expansion volume at entrance to second plasma cell
- Similar to Run 1/2a/2b configuration
- Run 1 expansion volume is ~1m long - big gap!



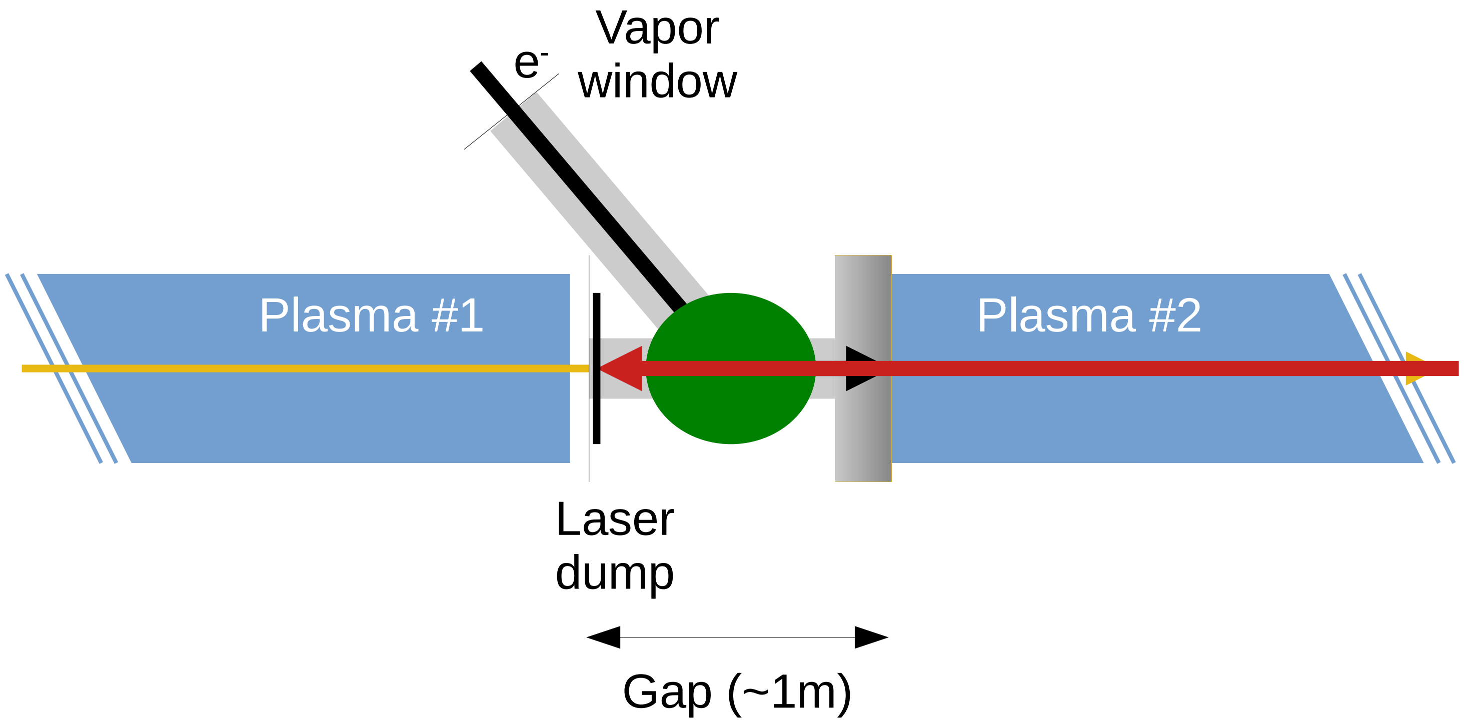
Option 3a

- Use expansion volume at entrance to second plasma cell
- Similar to Run 1/2a/2b configuration
- Save space by moving dipole inside expansion volume



Option 3b

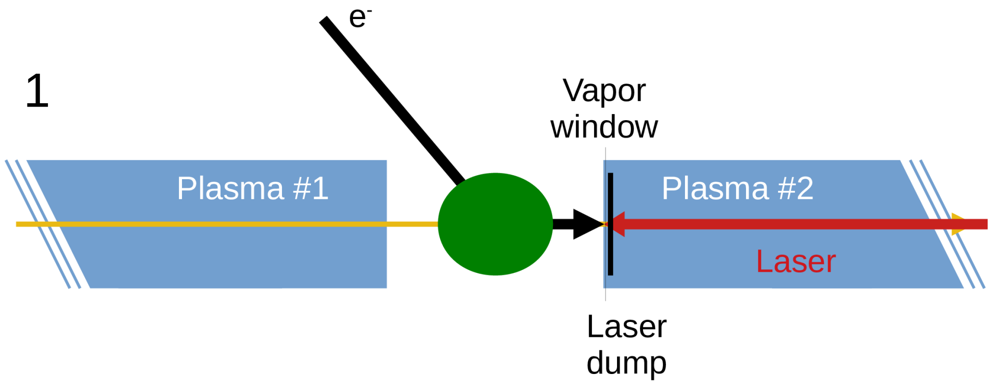
- Use *small* expansion volume at entrance to second plasma cell
- Smaller expansion volume low-density Rb vapour in beamline. Still requires vapor window.



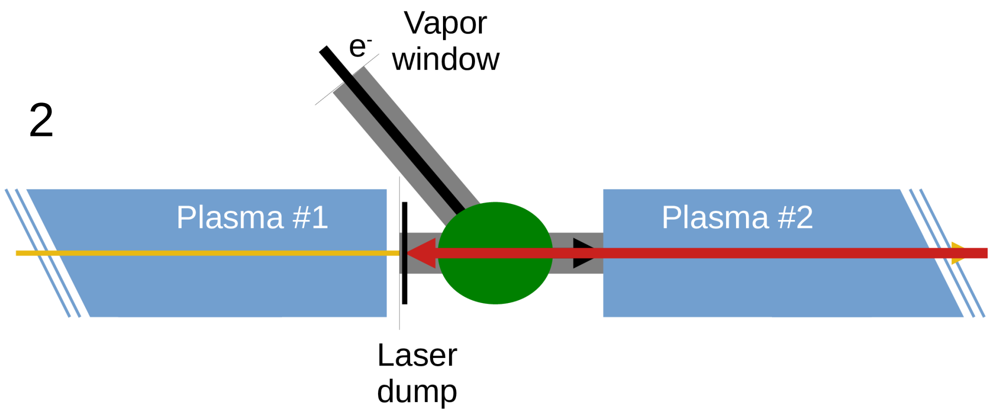
Run 2c configuration

Current baseline is option 1: injection through laser beam dump

1

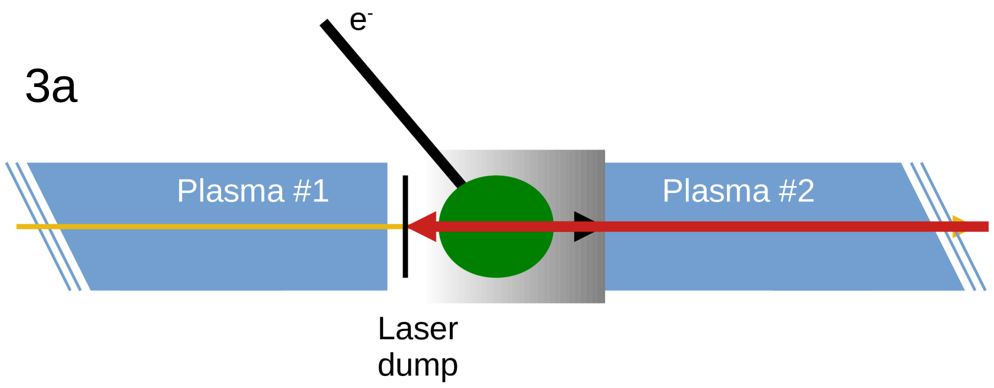


2



Alternative schemes are being evaluated.
May be more suitable for EARLI.

3a



3b