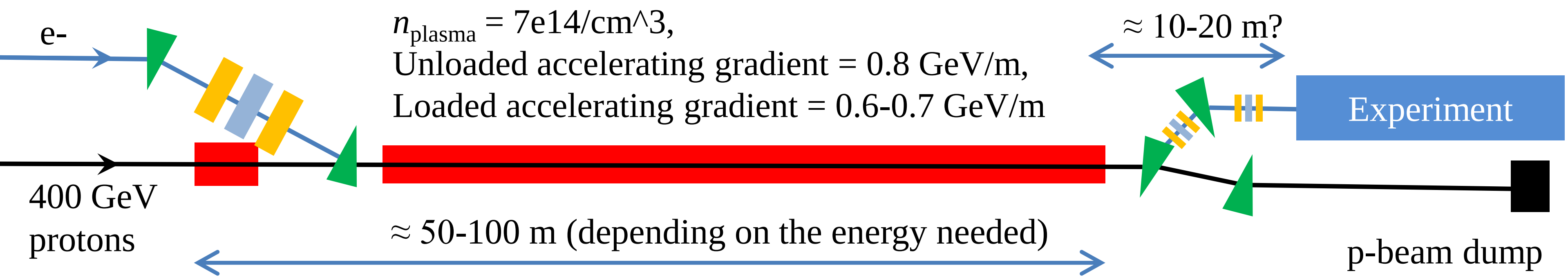
Max. e-energy with the SPS beam.
Dealing with defocused protons.
e-p separation.

A. Petrenko

4th AWAKE-PBC meeting, CERN, 24.05.2018

Summary of the previous presentation:



The length of the accelerator is limited by approximately 100 m due to the gradual e-p dephasing: electrons outrun the wake (travelling with the speed of protons).

50 m long accelerator:

Energy = 33 GeV, dE/E ≈ 2%
Charge = 107 pC (6.7e8 e^-)

100 m long accelerator:

Energy = 53 GeV, dE/E ≈ 2%
Charge = 134 pC (8.3e8 e^-)
(optimal parameters are slightly different)

Possible ways to reduce the accelerator length:

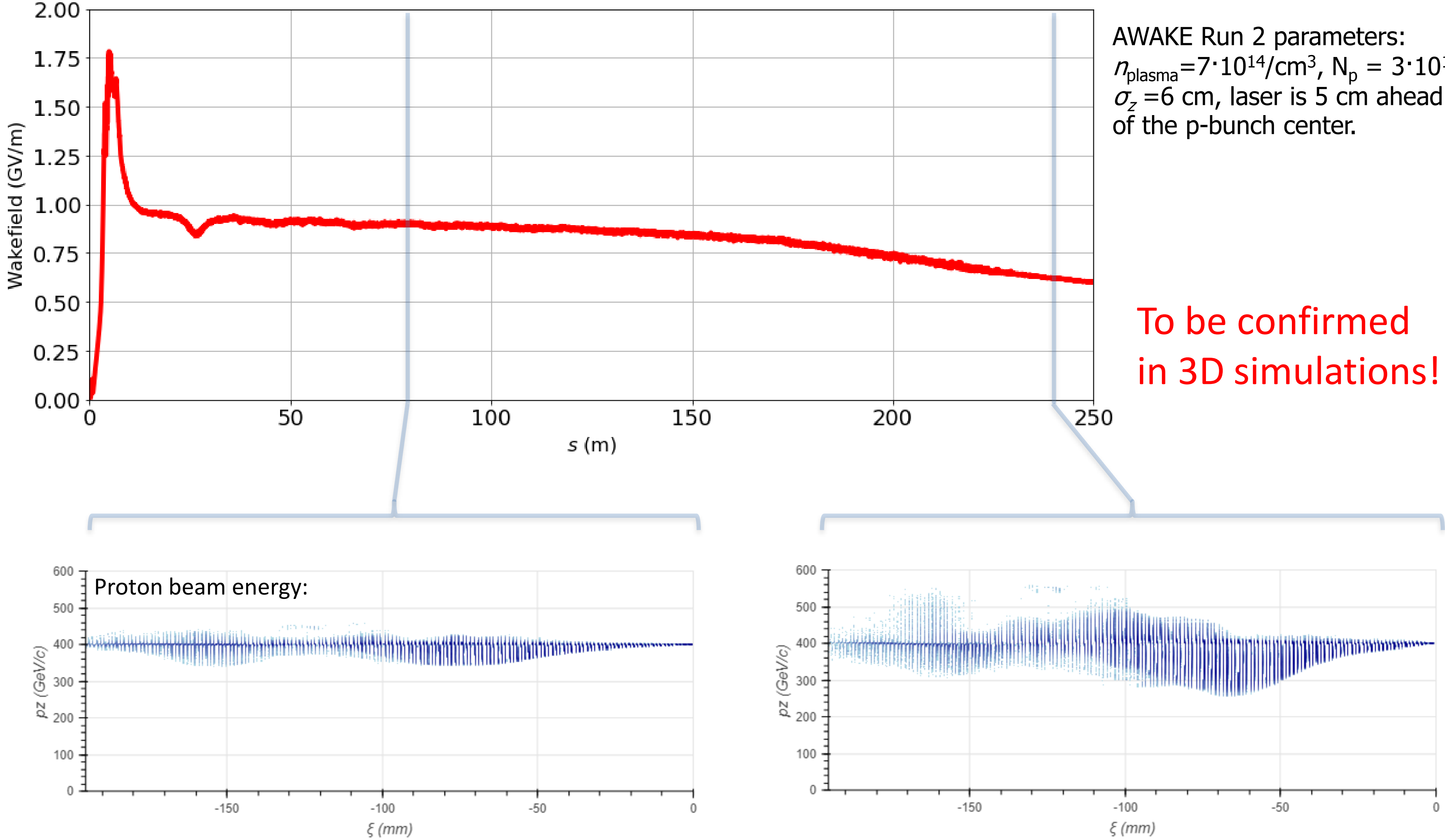
Try to use higher plasma density with existing proton beam (need more optimization studies).

Improve SPS beam transverse emittance (2x lower emittance will give 2x higher wakefield in 4x more dense plasma) – 2x lower p-beam emittance might be the result of planned upgrades.

Use more efficient micro-bunching technique with the same plasma density (2x gain might be possible). Also higher energy will be possible (120 GeV?).

List of questions:		Current status:
•What's the effect of higher plasma density?		✓ High n_{plasma} => small L_{plasma}
•What's the maximal plasma density?		✓ 2.8e15 looks reasonable…
•What's the upper limit we get with SSM?	In progress…	✓ ≈70 GeV so far (450 GeV p)
•Would it make sense to go to 450GeV/c protons?		✓ Yes: 70 GeV vs 53 GeV e-
•What can be done to improve the limits? • Delay line? • 2 plasmas?		In progress… (not clear if possible at all)
• Pre-modulation?		In progress… (looks promising)
•Proton beam divergence – is this an issue?		✓ In progress… (ext. quads)
•what's the effect of synchrotron radiation when we separate the electron from the proton beam?		In progress
•What's the beam size/emittance we can get for PEPIC?		Best case: few mm*mrad
•What are the halo parameters? • Give this as input to Christoph Hessler for PEPIC beam line design • Consider the halo in the FT Experiment.		In progress…

SSM-driven wakefield (LCODE 2D simulation):



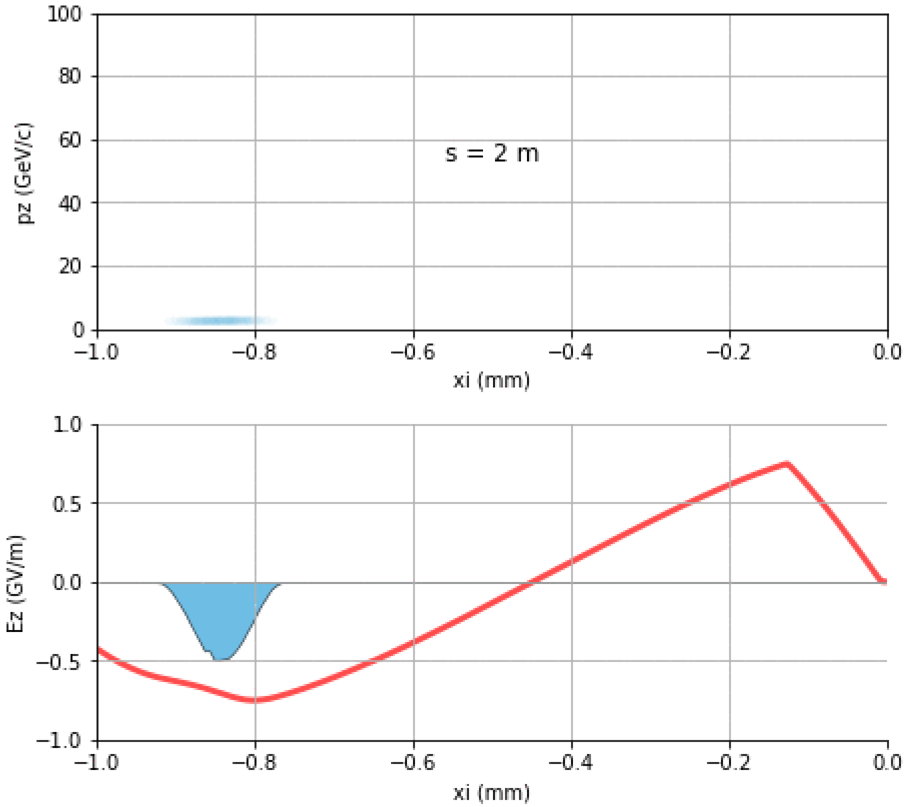
AWAKE Run 2 parameters: n_{plasma}=7·10^{14}/cm^{3}, N_p = 3·10^{11}, σ_z =6 cm, laser is 5 cm ahead of the p-bunch center.

To be confirmed in 3D simulations!

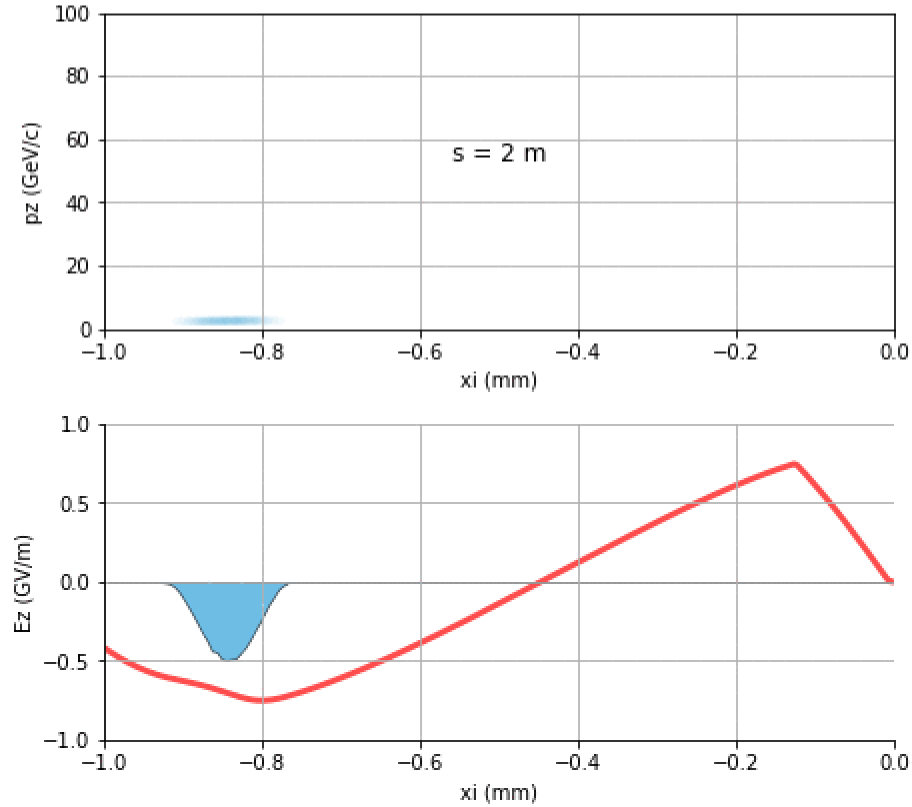
Does it makes sense to use 450 GeV instead of 400 GeV protons?

Yes, indeed, since the dephasing distance scales as $1/\gamma^2$ from this 12.5% gain in proton energy we can expect 25% accelerated energy gain. This is confirmed by simulations (LCODE 2D, one drive bunch):

400 GeV protons



450 GeV protons



e-bunch energy around **53 GeV after 100 m**.

e-bunch energy around **70 GeV after 130 m**.

Two accelerating stages with a chicane in between? – potentially 2x higher energy.

Interstage focusing should refocus p-beams with 10-20% energy spread and 50 GeV electrons. Could be possible, but should be studied in details. A long gap (~100 m) will be needed for sure. Apochromatic optics is an interesting option which should work for 10-20% energy spread:

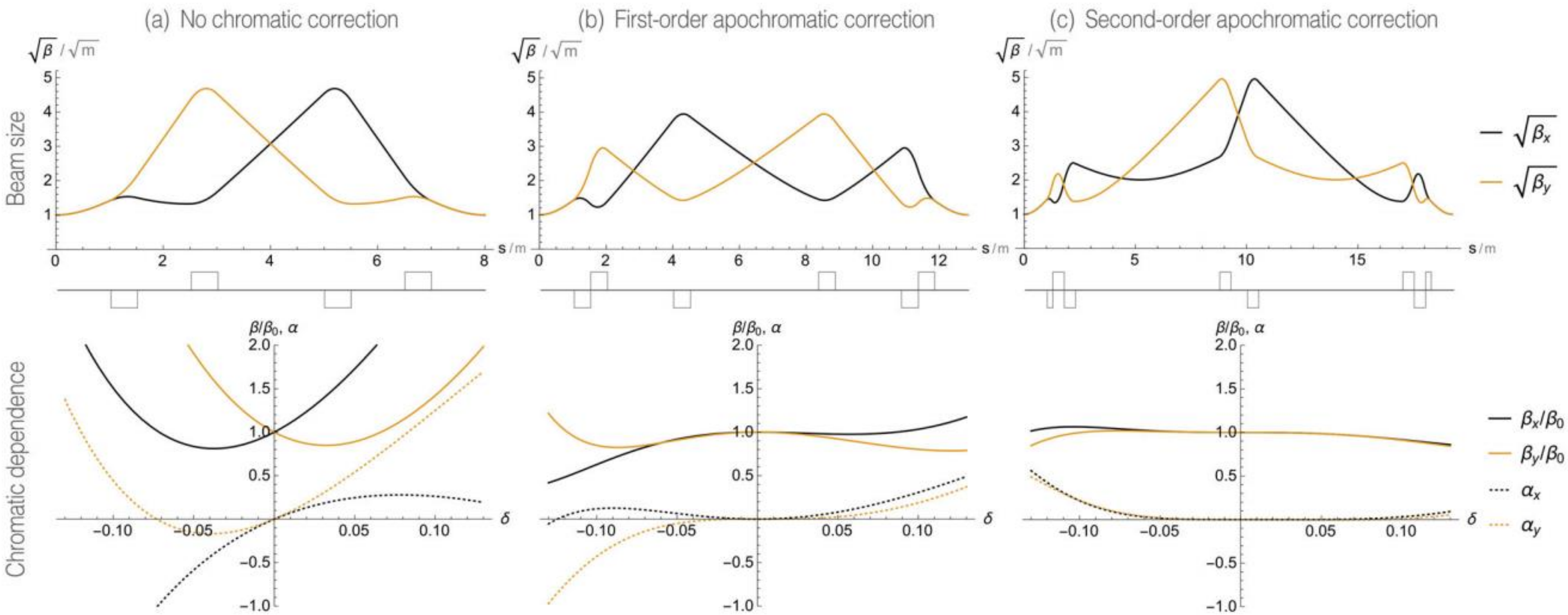
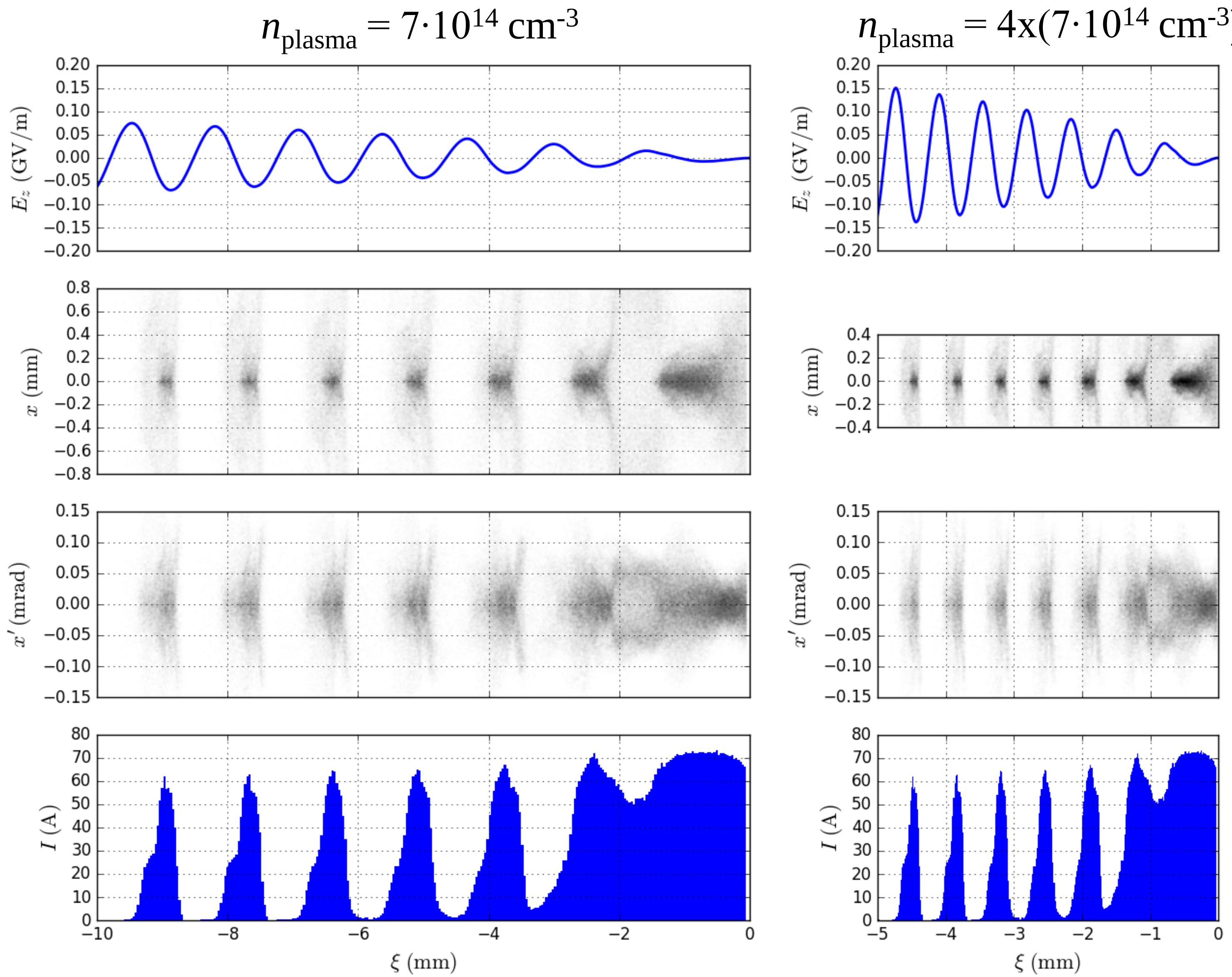


FIG. 2. Plots of $\sqrt{\beta}$ (proportional to rms beam size) vs beam line axis s, and chromatic dependence of $\beta(\delta)$ and $\alpha(\delta)$ vs δ, shown for different orders of apochromatic focusing. All solutions satisfy initial and final Twiss parameters $\beta = 1$ m and $\alpha = 0$ in both planes, with a 1 m drift before and after the first and last quadrupoles respectively. The chromatic dependence of the lattice flattens progressively with higher orders of apochromatic focusing; No chromatic correction (a) results in chromatic amplitude $W \neq 0$ (a slope) at nominal energy $\delta = 0$, whereas first order correction (b) removes this chromatic amplitude $W = 0$ (no slope), and second order correction (c) flattens it further by removing second order chromatic errors (curvature) around $\delta = 0$. Overall, the chromatic dependence can be decreased at the cost of longer lattices with more quadrupoles, where the appropriate order of the correction is determined by the energy spread of the beam.

https://journals.aps.org/prab/abstract/10.1103/PhysRevAccelBeams.19.071002

General scaling of beam parameters with plasma density



2x higher wakefield

2x smaller transv. size => 4x higher beam density.

The same angular spread => 2x lower beam emittance required.

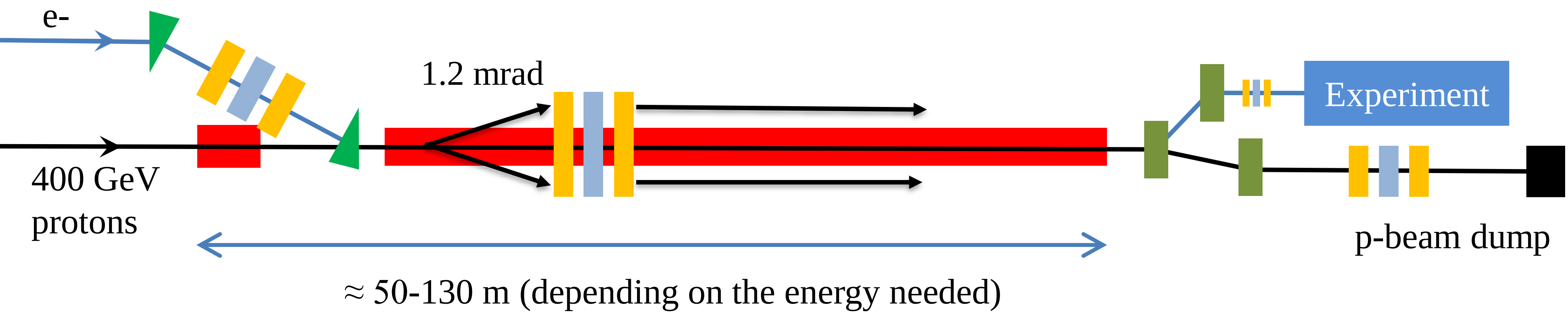
The same current => 2x less particles needed to drive 2x higher wake.
(Also 2x less accelerated particles).

If PS/SPS upgrade reduces the SPS beam emittance from 2 mm*mrad to **1 mm*mrad** then 4x increase in plasma density from 7e14 to **2.8e15** (Cs?) will be feasible => **2x reduction of L_{plasma}** => **2x reduction of N_e/bunch** (also less protons/bunch is needed, maybe higher rep. rate will be required).

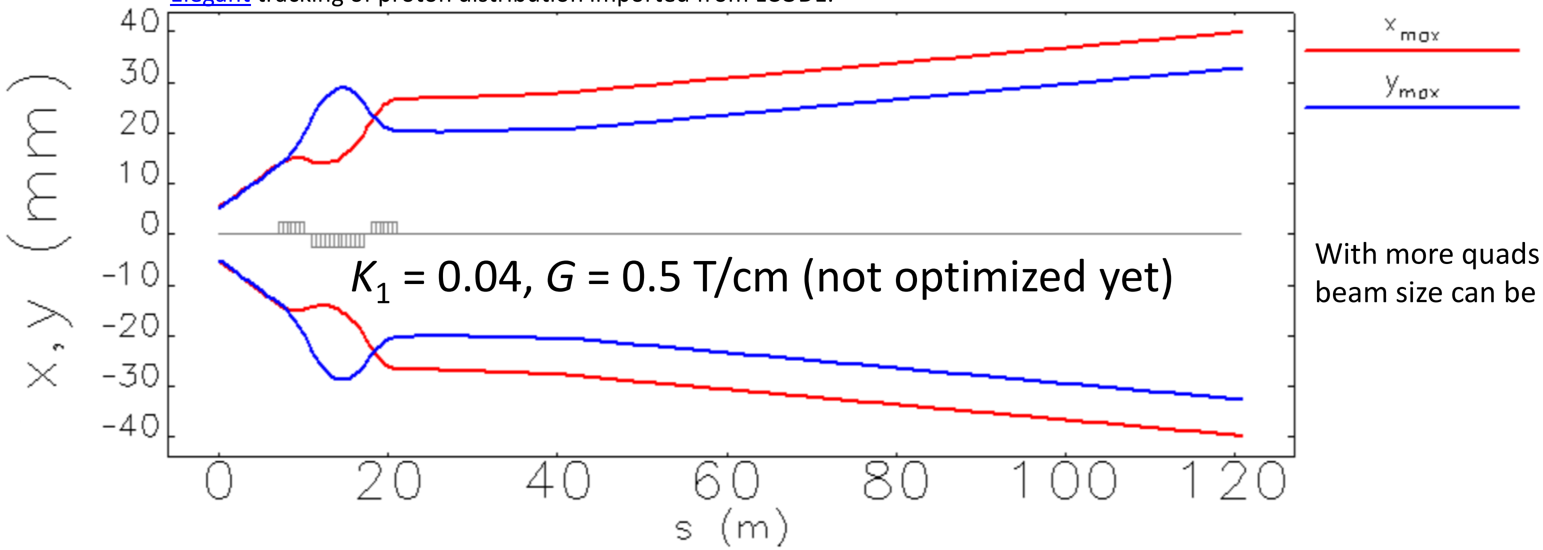
What to do with the defocused protons?

Large part of the proton beam is defocused. Can we transport all the protons to the beam dump?

Yes, external quads can solve the problem:



Elegant tracking of proton distribution imported from LCODE.



With more quads smaller beam size can be achieved.

Inside the wakefield such quadrupoles will create a very small field ~ 0.2 mm * 0.05 T/mm =
= 0.2 mm * 0.05 T/mm = 0.01 T = 100 Gs << E_r ~ 500 MV/m = 17000 statvolt/cm [equal to Gs].
The effect of such field on plasma wake is probably negligible, but we can check it with QV3D later.

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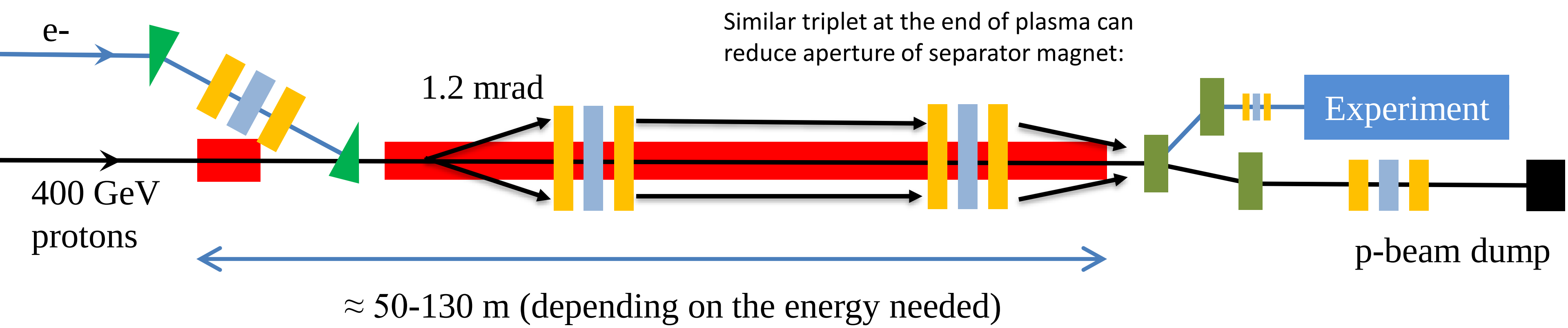

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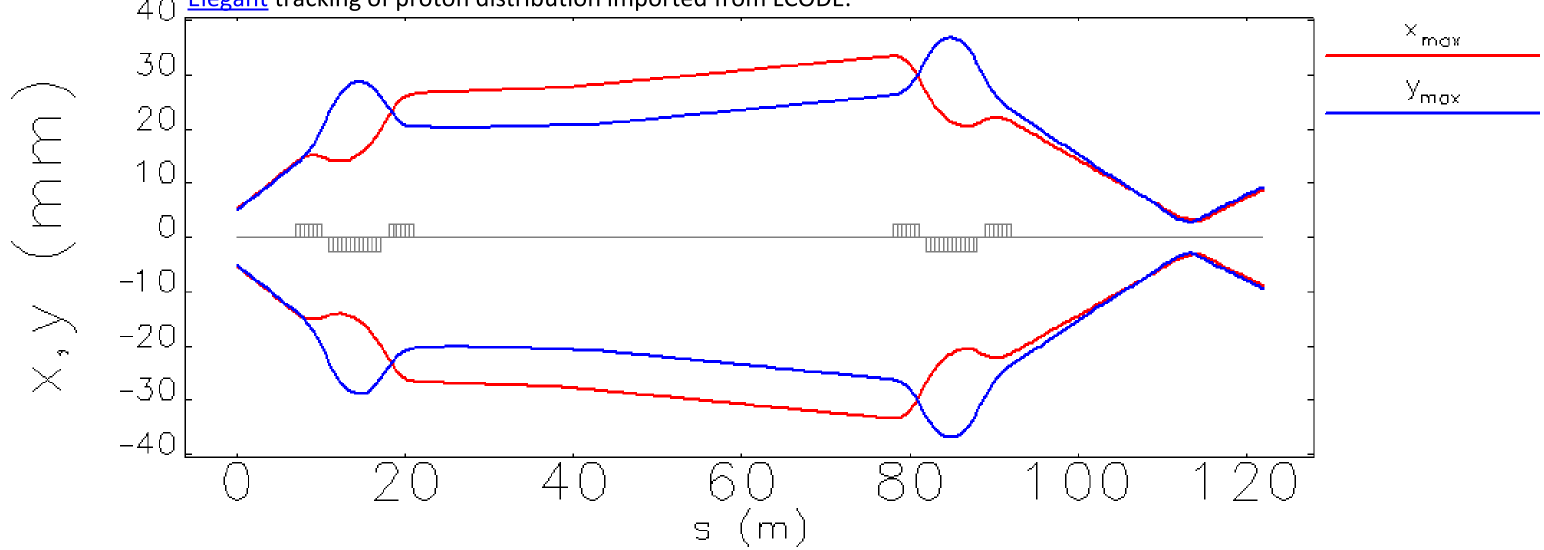
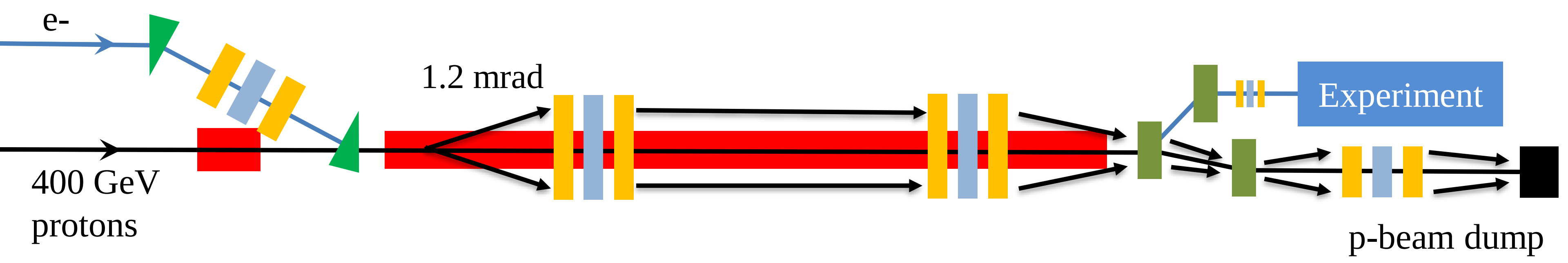


Proton beam loss before experiment can be avoided!

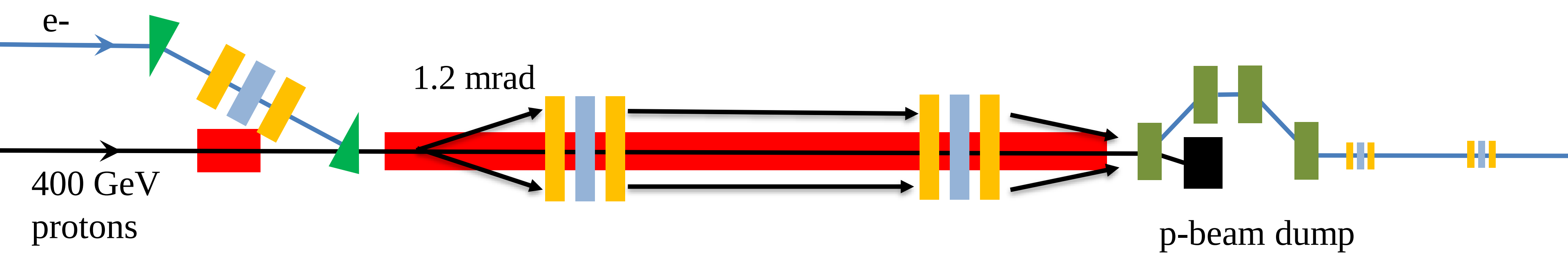
How should we separate electrons from protons?

It depends on the type of experiment

1) Fixed target experiment where we want to minimize proton-induced background, but the final e-beam emittance is not important.



2) Collider experiment where detector is far away (LHC) and we don't care about the proton-induced background but do care about electron beam emittance.



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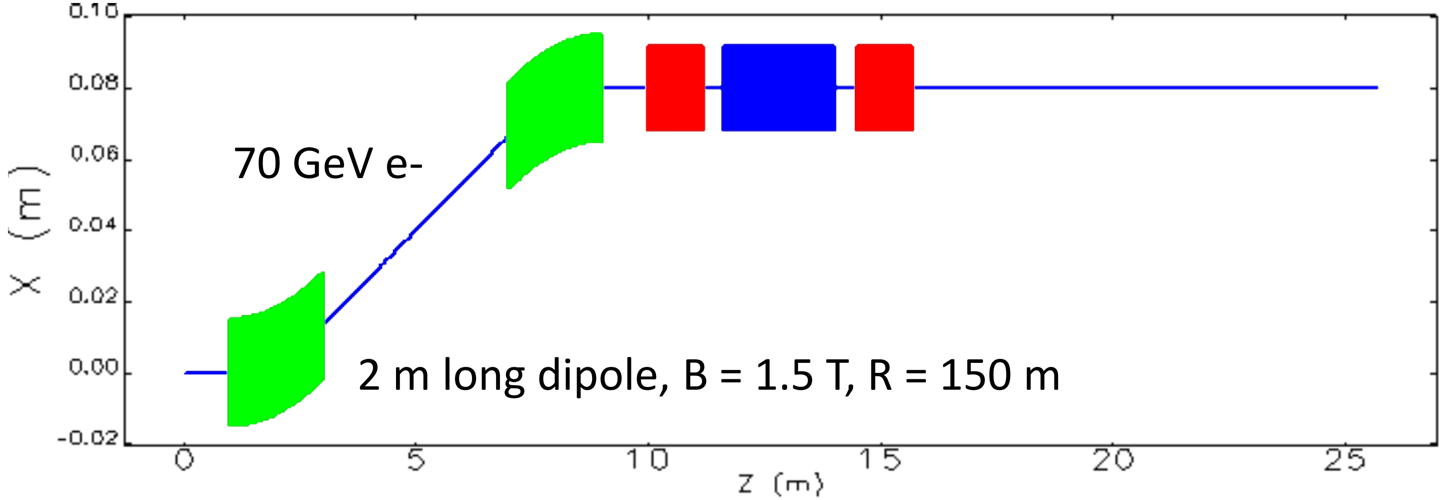
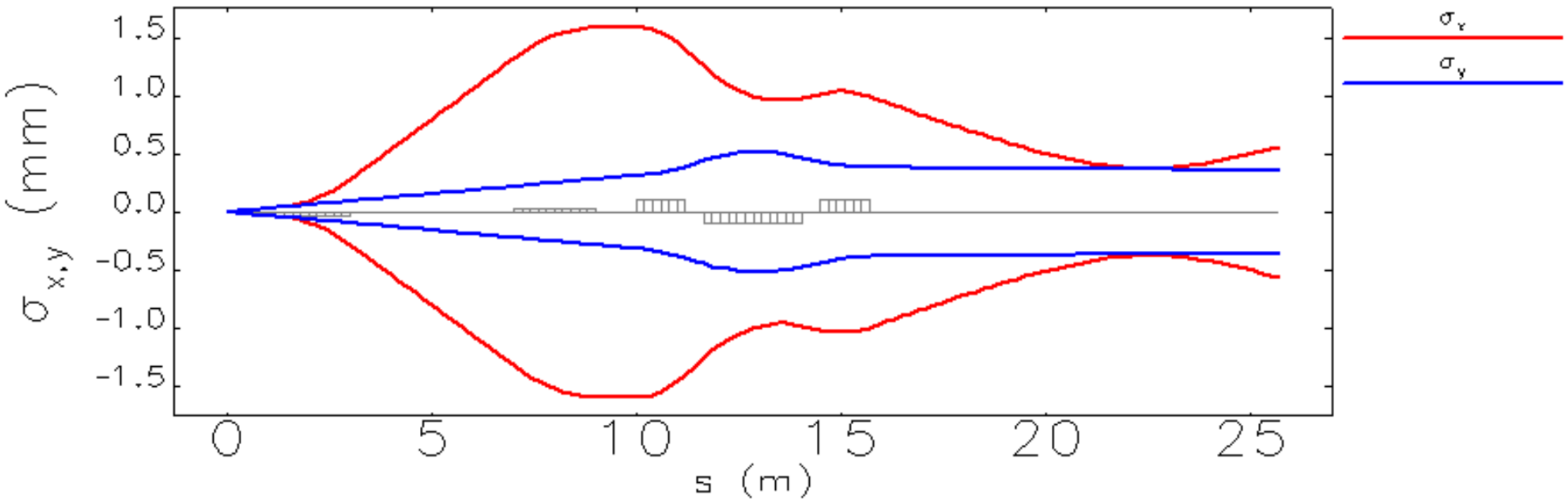
Example electron optics:





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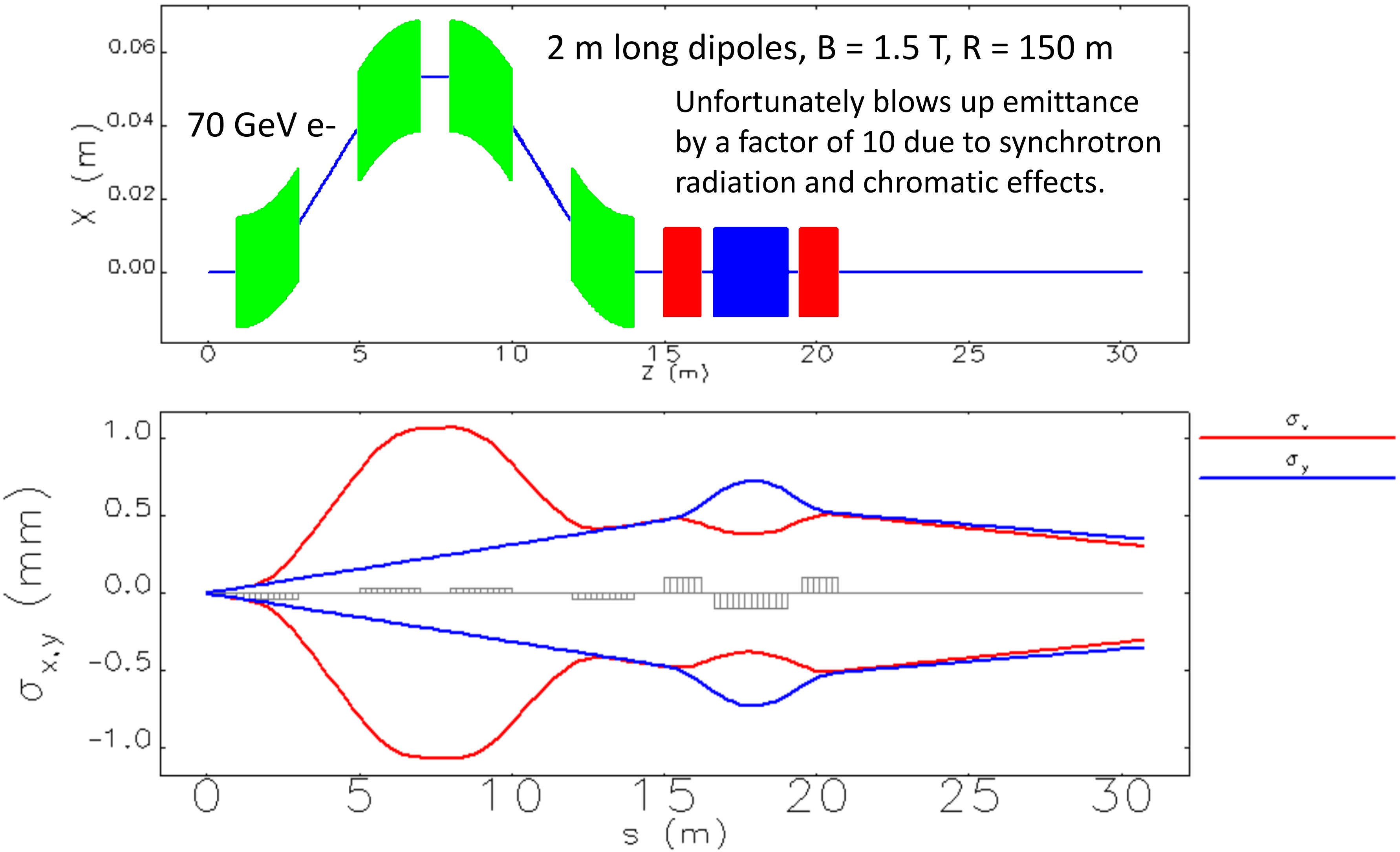
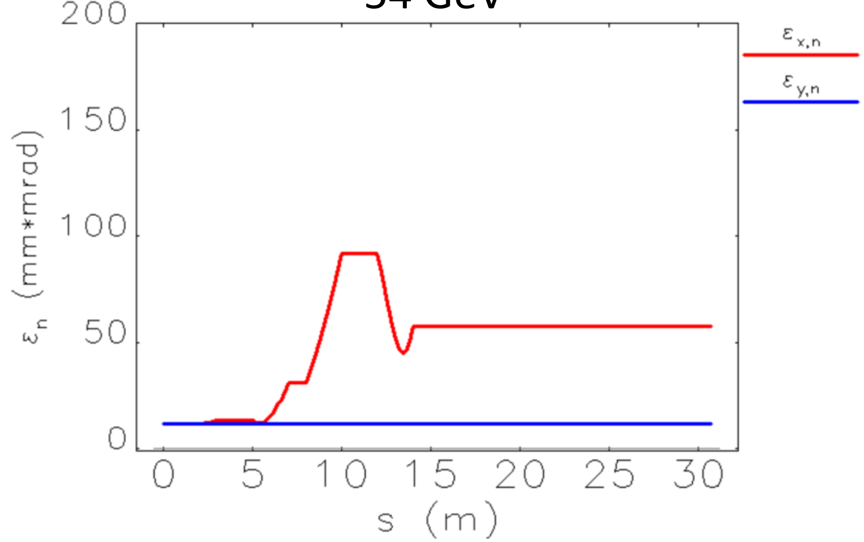


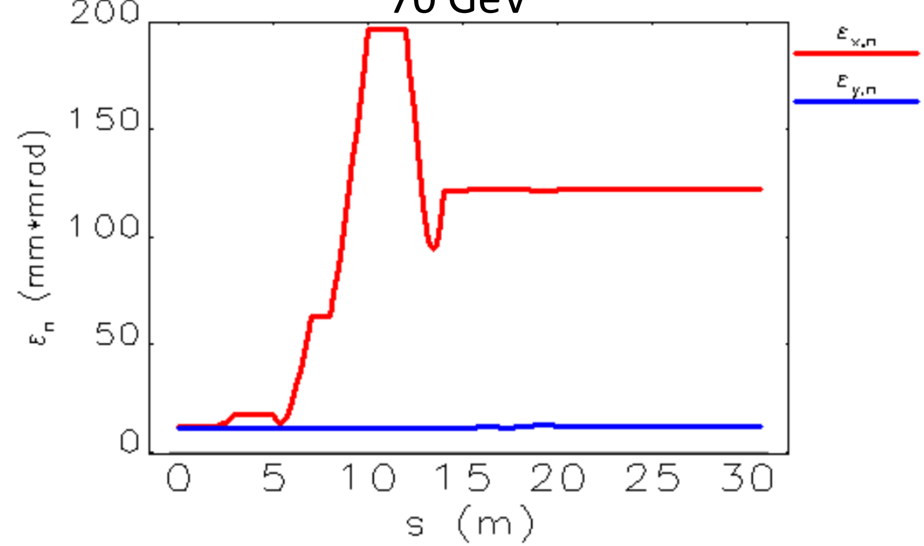
Elegant tracking with synchrotron radiation (using element CSBEND).

Zero energy spread:

54 GeV

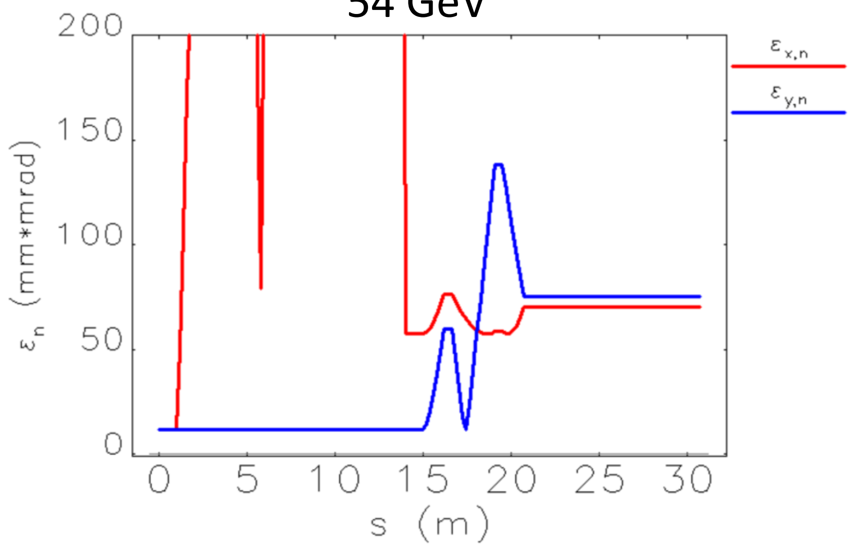


70 GeV

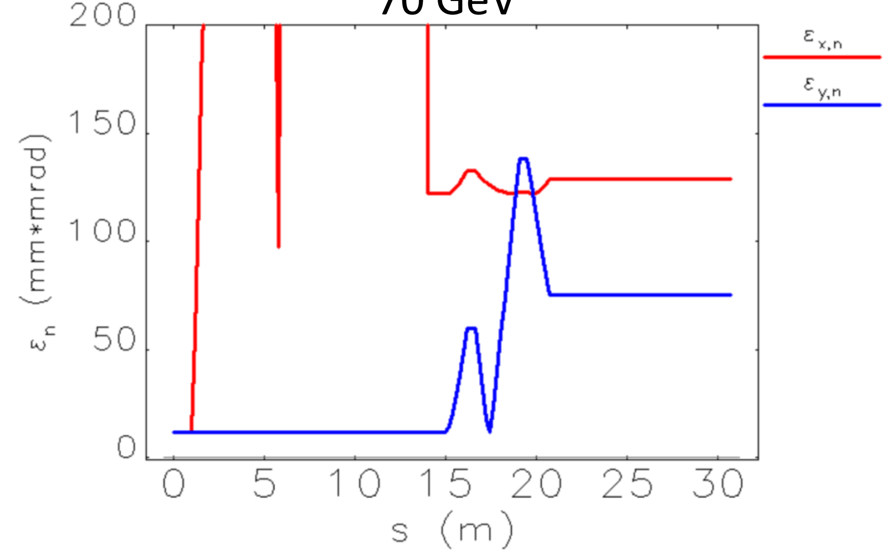


1% energy spread:

54 GeV



70 GeV



Conclusions

Using the 400 GeV SPS beam in plasma of 7e14/cm^3 a **50 m** long AWAKE-type accelerator can reach approximately **30 GeV** with 1-2% of total energy spread.

In order to reach **50 GeV** a **100 m** long plasma section will be required.

Using 450 GeV protons reduces dephasing and allows for a longer accelerator:
70 GeV in **130 m**.

Defocused protons can be kept inside a 5-10 cm wide pipe using external quadrupoles.

Synchrotron radiation is an important effect in the e-p separator after plasma (if we care about the e-beam emittance) – to be studied further.