Science and Technology Facilities Council

An FFAG Channel for the Transport of Laser Wakefield Accelerated Beams

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Introduction

- Laser wakefield acceleration
- Introduce channel of permanent magnet & constant gradient quadrupoles
- Look at changes of gradient of the quadrupoles
- Look at changes of lengths (quadrupoles & drifts in between)
- Look at the same line in GPT
- Try to explain the differences between MAD & GPT modelling
- Consider test line in GPT
- Look at the location of the start of the FFAG quadrupole channel w.r.t. the exit of the plasma – how close can we get it ?
- Look at geometrical considerations and the possibility of using the same line to go to higher energies

Laser wakefield acceleration

- Very high energy gain achieved in very short space but usually with a high energy spread as well
- Typical Twiss parameters at exit of plasma variable but have assumed:
  - $\beta_x = \beta_y = 5$ mm
  - $\alpha_x = \alpha_y = 0$
  - $\varepsilon_N (x,y) = 1\ \mu m$

  I will call these the "realistic" Twiss parameters
- Assume energy high enough, charge low enough and bunch length long enough that space charge can be neglected
- Given that

$$\gamma = \frac{1}{\beta}$$

- We need to find a way to capture the beam as quickly and as efficiently as possible as the divergence exiting the plasma is huge

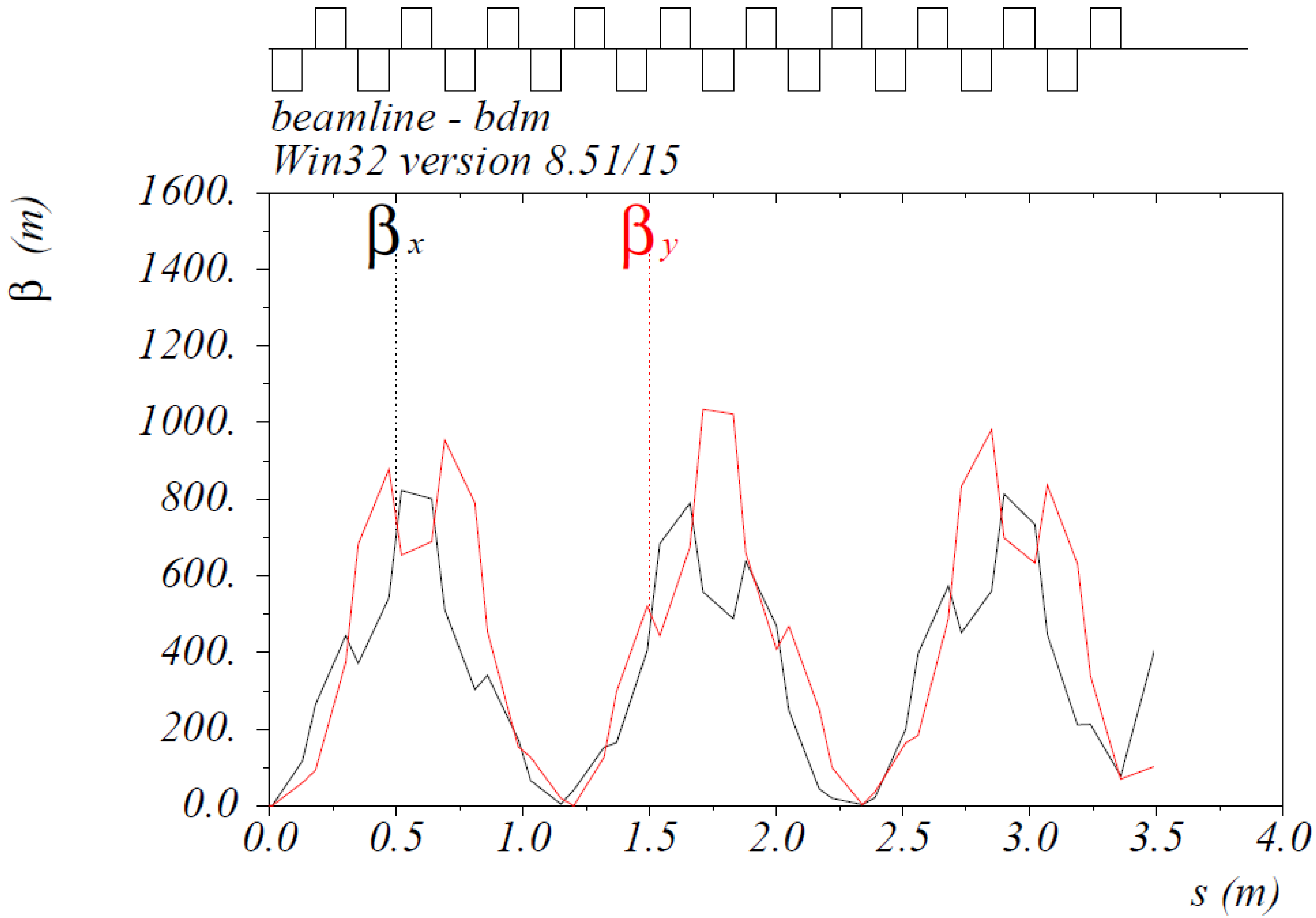
A channel of quadrupoles

- Constant permanent magnet quadrupoles of equal length
- Separated by equal drifts
- Consider worst case scenario and make the initial Twiss parameters even smaller to exaggerate the effect
  - $\beta_x = \beta_y = 0.2$ mm
  - $\alpha_x = \alpha_y = 0$
  - ε_N (x,y) = 1 μm

  I will call these the "extreme" Twiss parameters, for most of the talk I will use these !
- Observe what happens … ☺
- Vary all parameters and optimise the capture line (assuming the line captures)
  - Vary the drift lengths (currently all set at 5 cm between quadrupoles)
  - Vary the quadrupole strengths (currently set at 12 cm)
  - Vary the distance between the plasma exit and the channel (currently set at 1 cm)

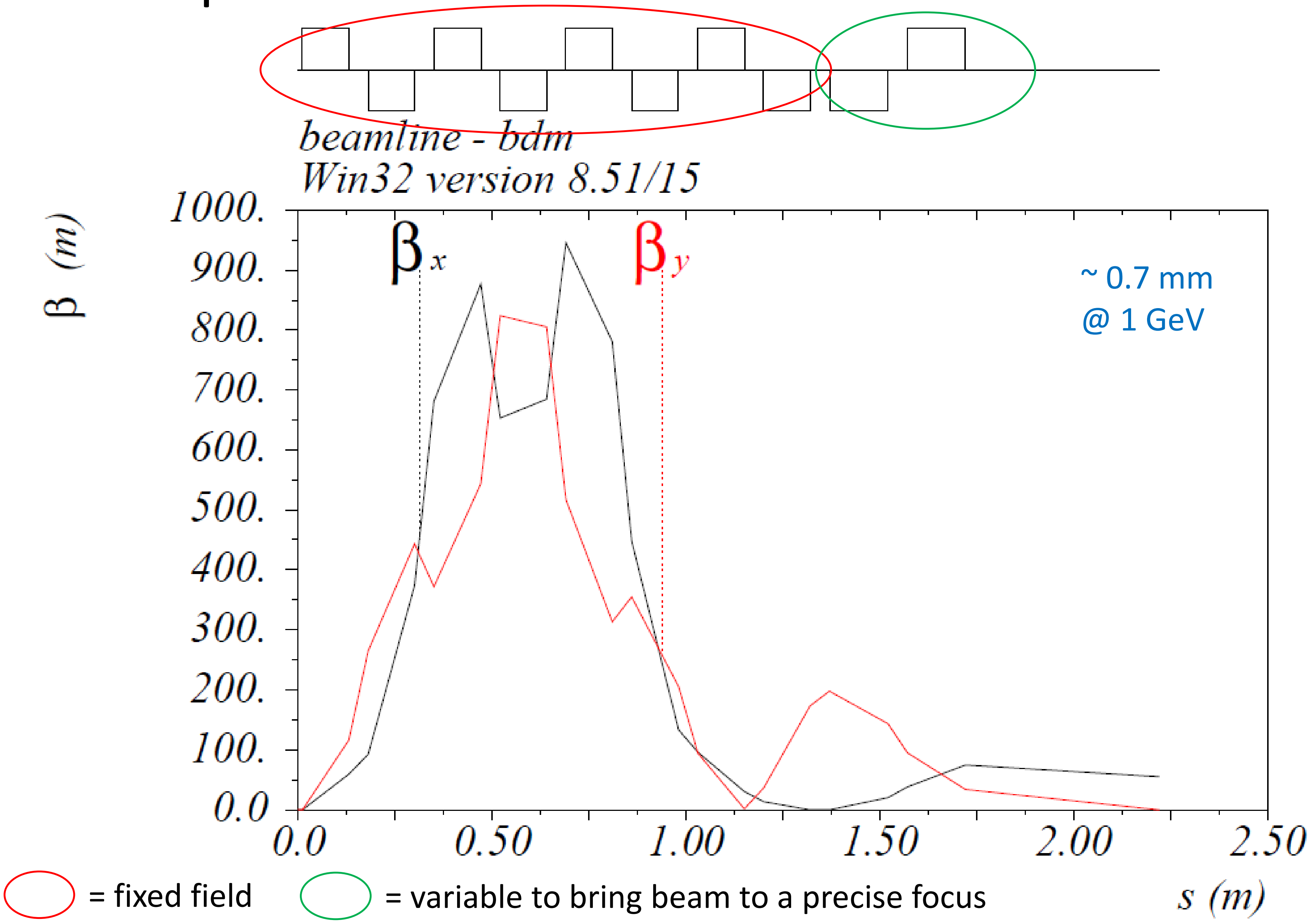
A channel of quadrupoles

- All quads fixed field at, for example, 200 T/m for 1 GeV
- Line can be extended and periods & super-periods are clearly seen
- For solution variable quads are needed – how many remains to be seen …



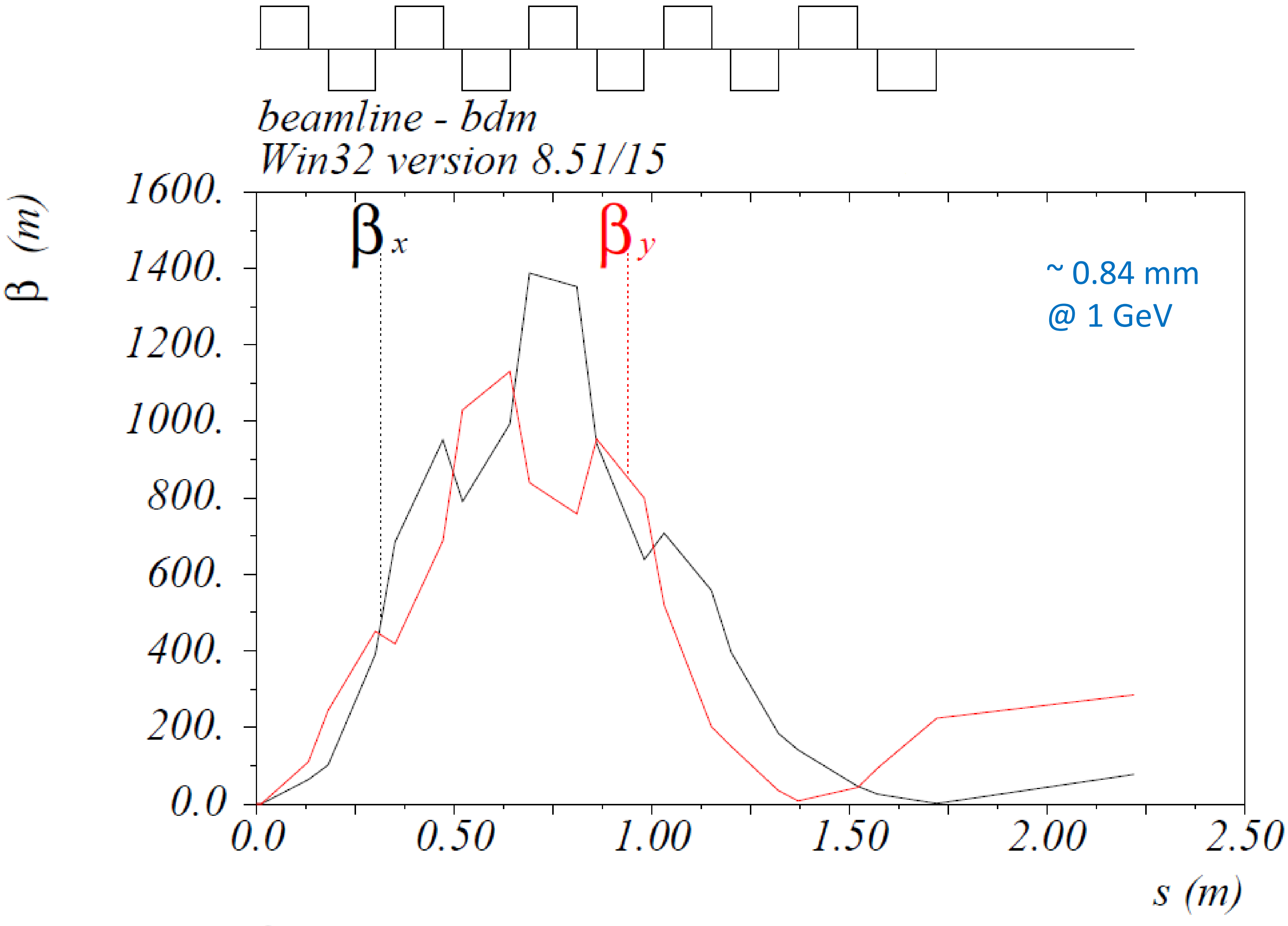
A channel of quadrupoles

- FFAG type transport (first 8 quads) optimised for drift & quad lengths from the point of view of beam size for a given energy & strength
- Only one type of drift & quad length
- First 8 quads are exactly 200 T/m each in +/- configuration as this turns out to be the best (1 GeV)



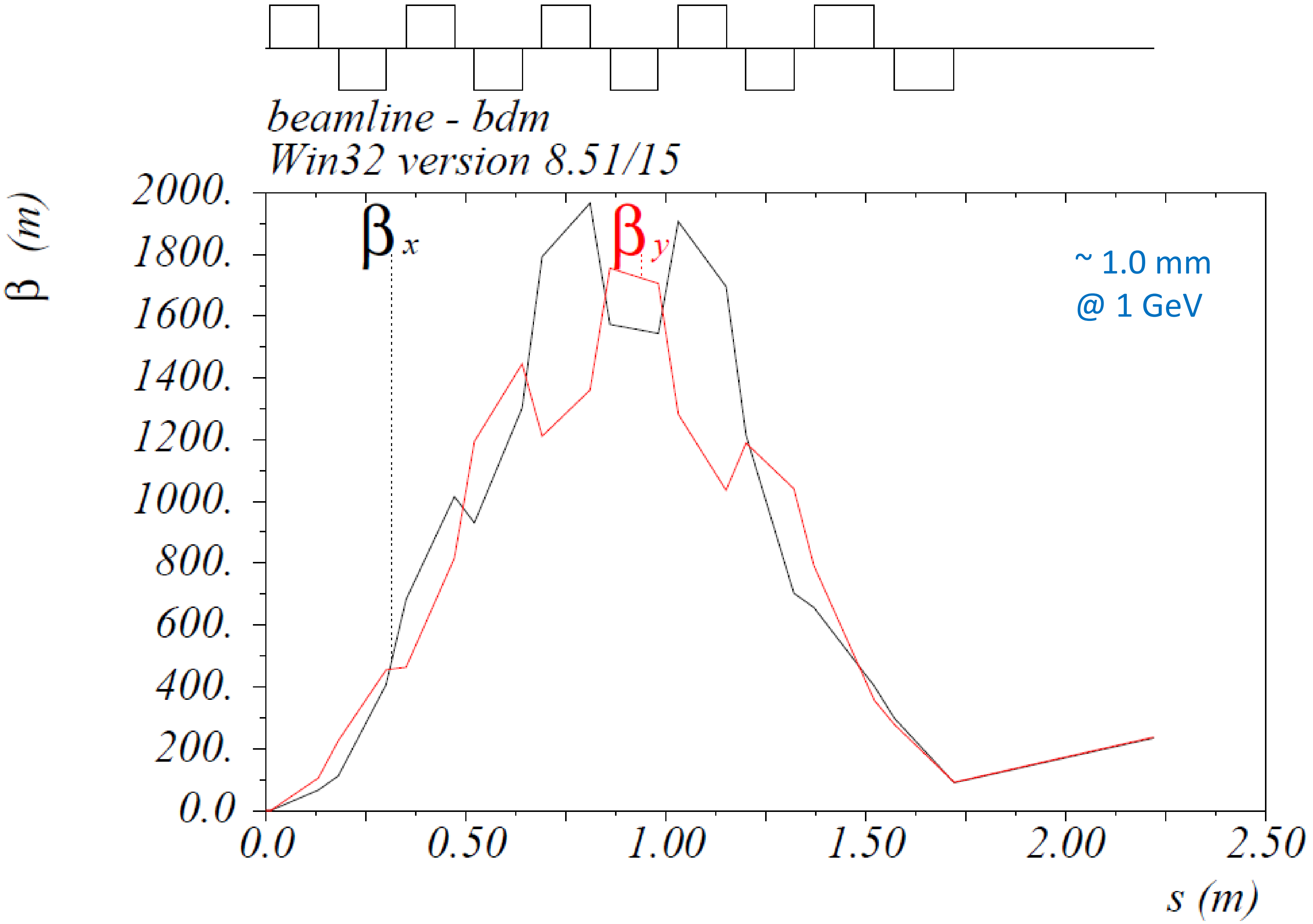
A channel of quadrupoles

- FFAG type transport (first 8 quads) optimised for drift & quad lengths from the point of view of beam size for a given energy & strength
- Only one type of drift & quad length
- First 8 quads are exactly 167 T/m each in +/- configuration as this turns out to be the best (1 GeV)



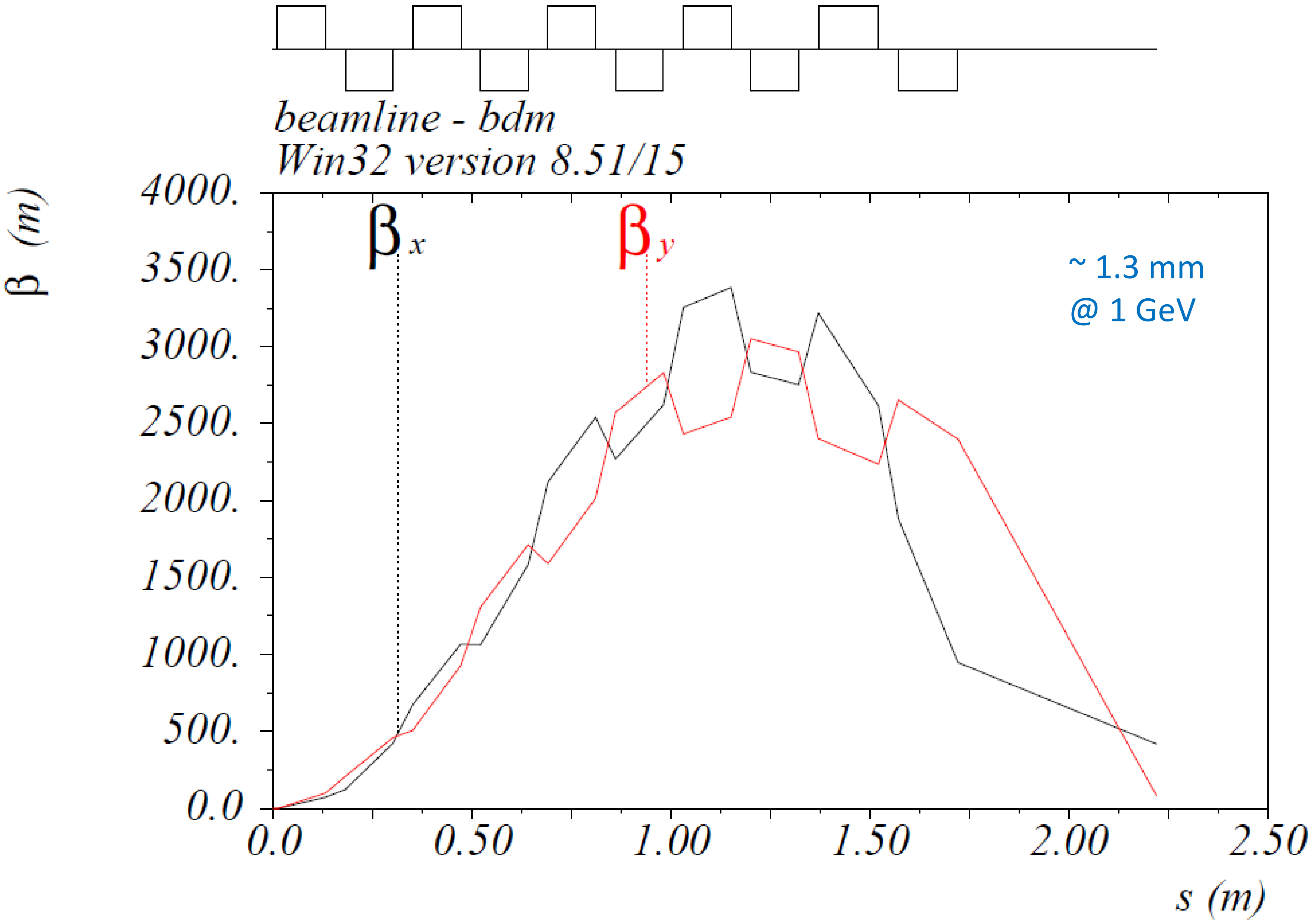
A channel of quadrupoles

- FFAG type transport (first 8 quads) optimised for drift & quad lengths from the point of view of beam size for a given energy & strength
- Only one type of drift & quad length
- First 8 quads are exactly 134 T/m each in +/- configuration as this turns out to be the best (1 GeV)



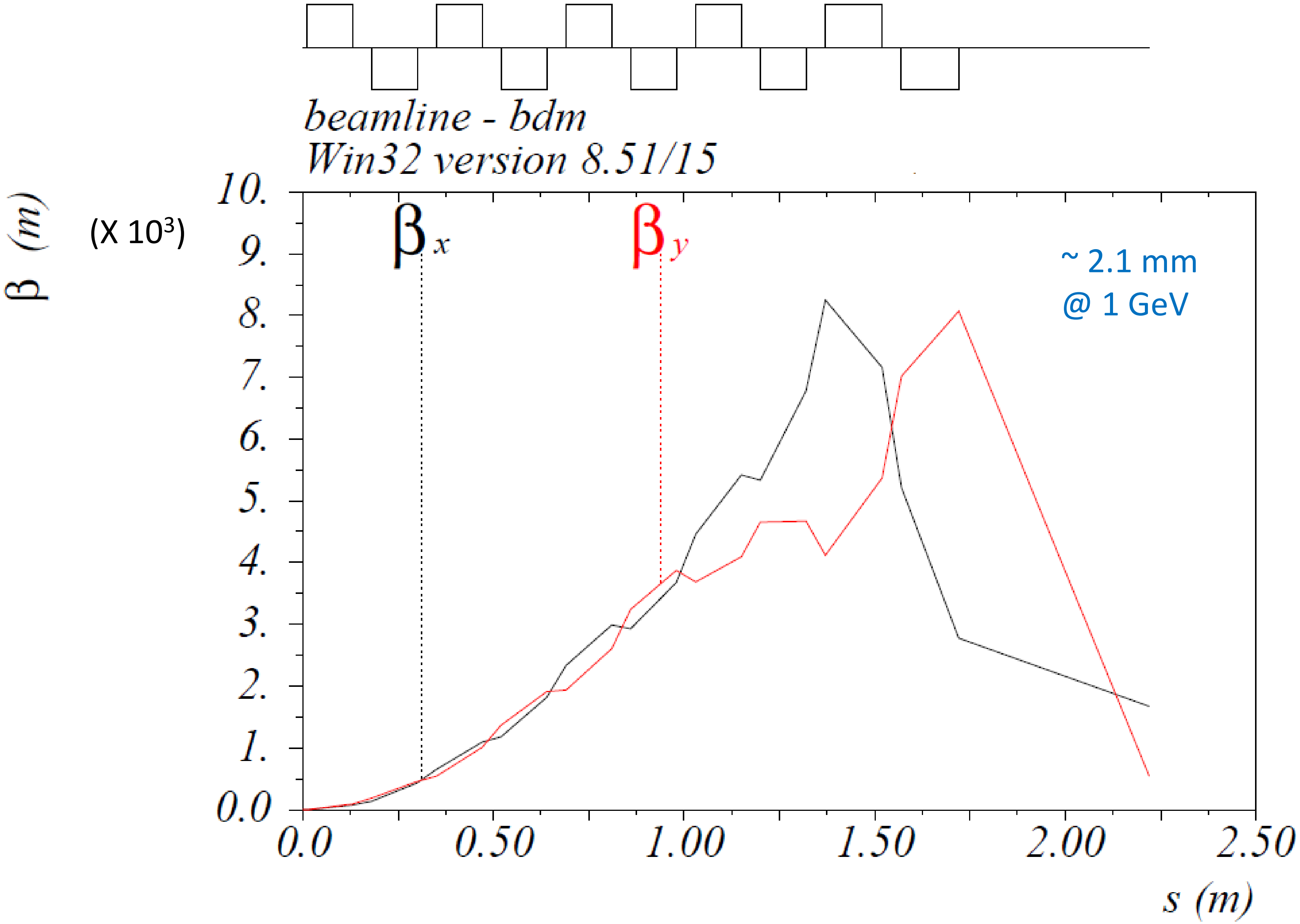
A channel of quadrupoles

- FFAG type transport (first 8 quads) optimised for drift & quad lengths from the point of view of beam size for a given energy & strength
- Only one type of drift & quad length
- First 8 quads are exactly 100 T/m each in +/- configuration as this turns out to be the best (1 GeV)



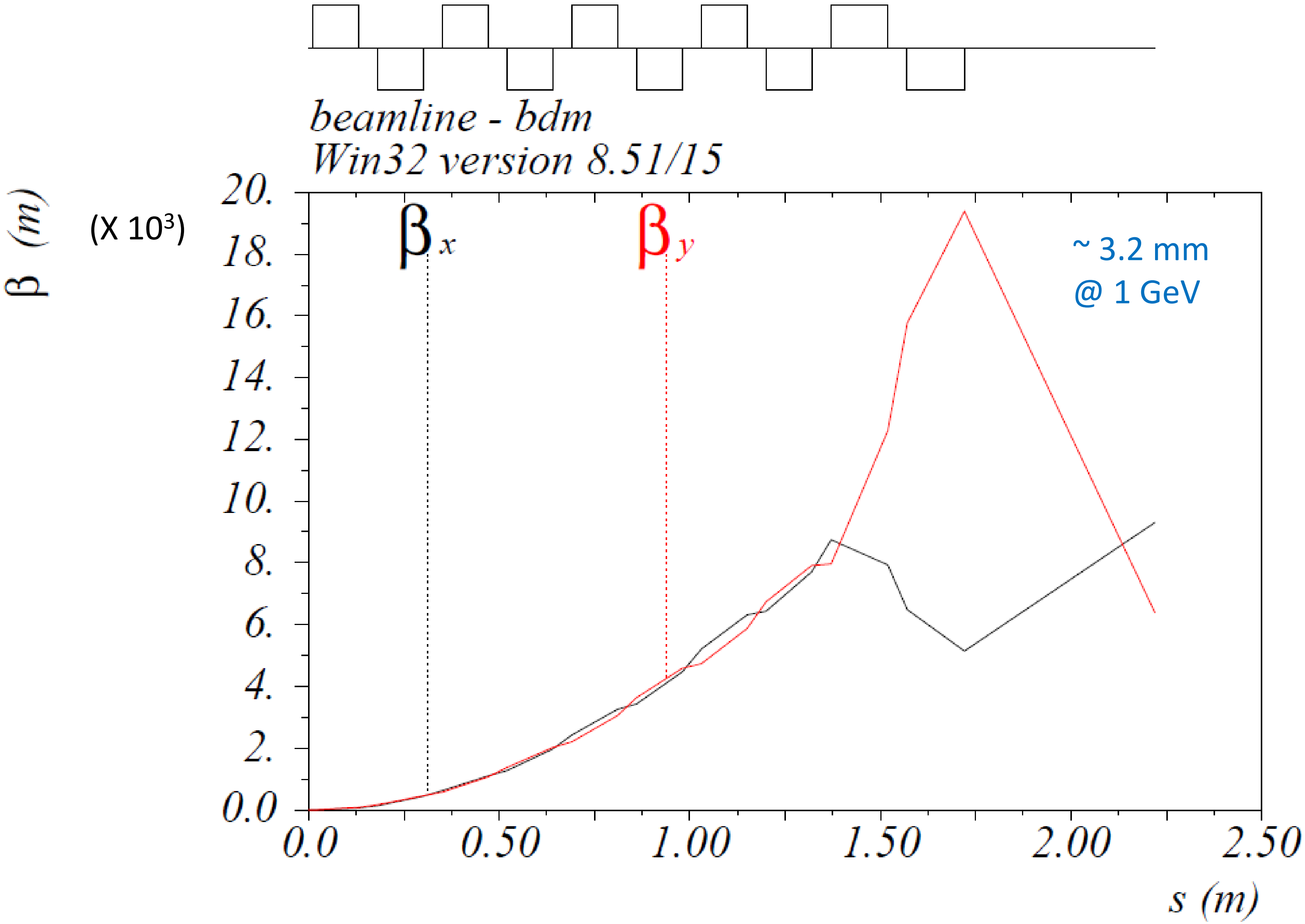
A channel of quadrupoles

- FFAG type transport (first 8 quads) optimised for drift & quad lengths from the point of view of beam size for a given energy & strength
- Only one type of drift & quad length
- First 8 quads are exactly 67 T/m each in +/- configuration as this turns out to be the best (1 GeV)



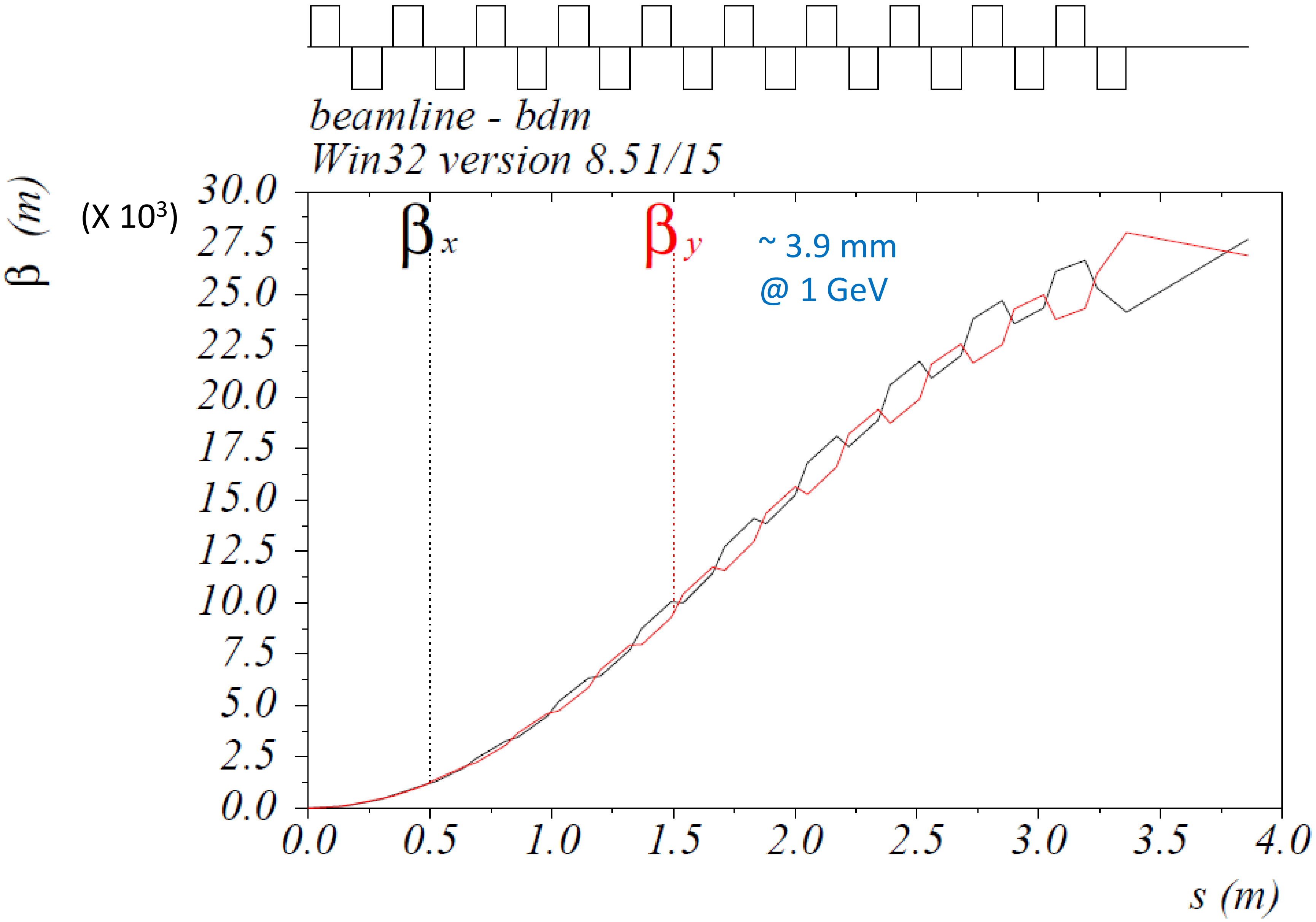
A channel of quadrupoles

- FFAG type transport (first 8 quads) optimised for drift & quad lengths from the point of view of beam size for a given energy & strength
- Only one type of drift & quad length
- First 8 quads are exactly 34 T/m each in +/- configuration as this turns out to be the best (1 GeV)



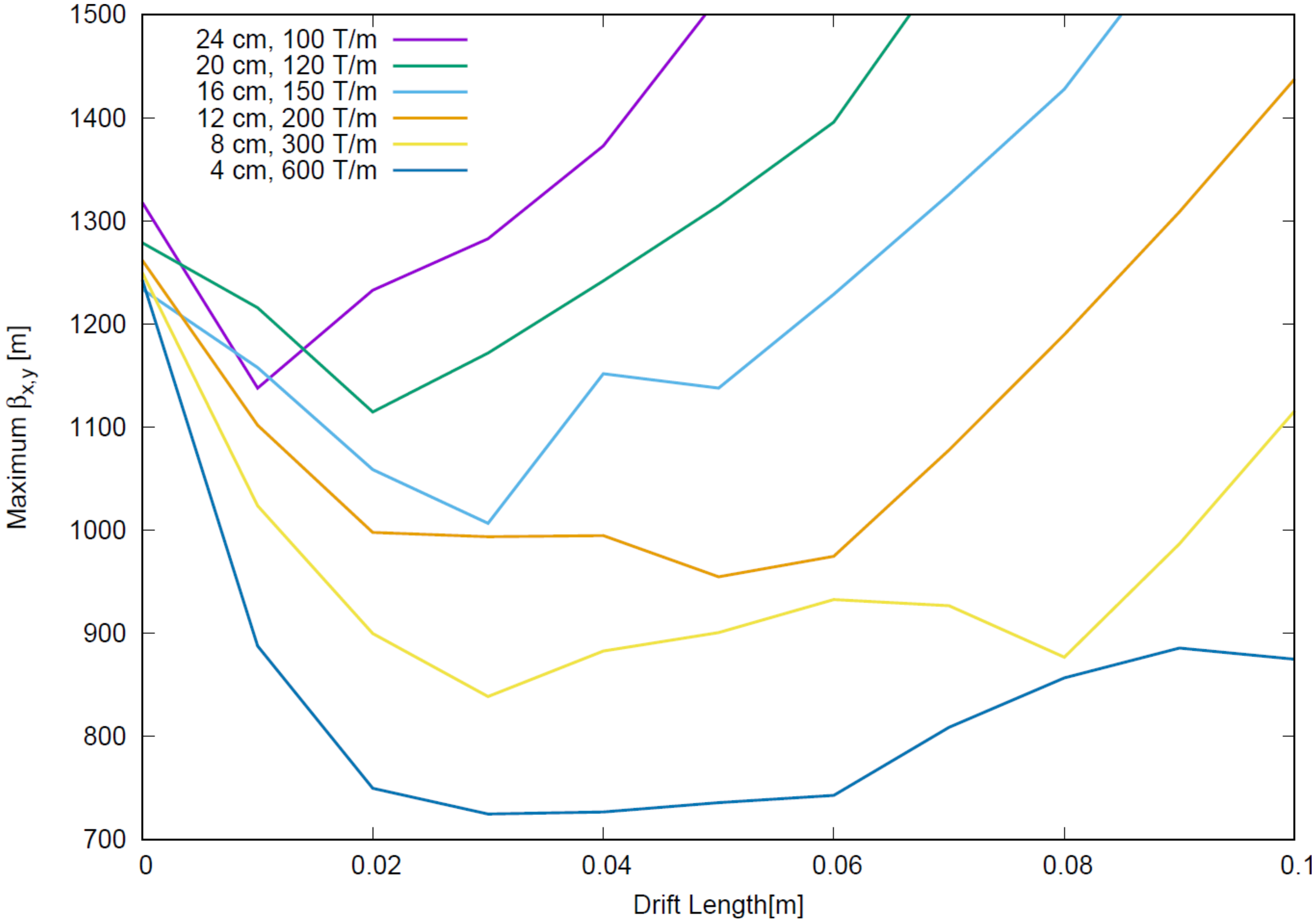
A channel of quadrupoles

- Length of super-period needs to be extended for low quadrupole gradients in order to bring the beam back to a waist
- This could make the line rather long but it can be done !
- All quads are exactly 34 T/m each in +/- configuration as this turns out to be the best (1 GeV)



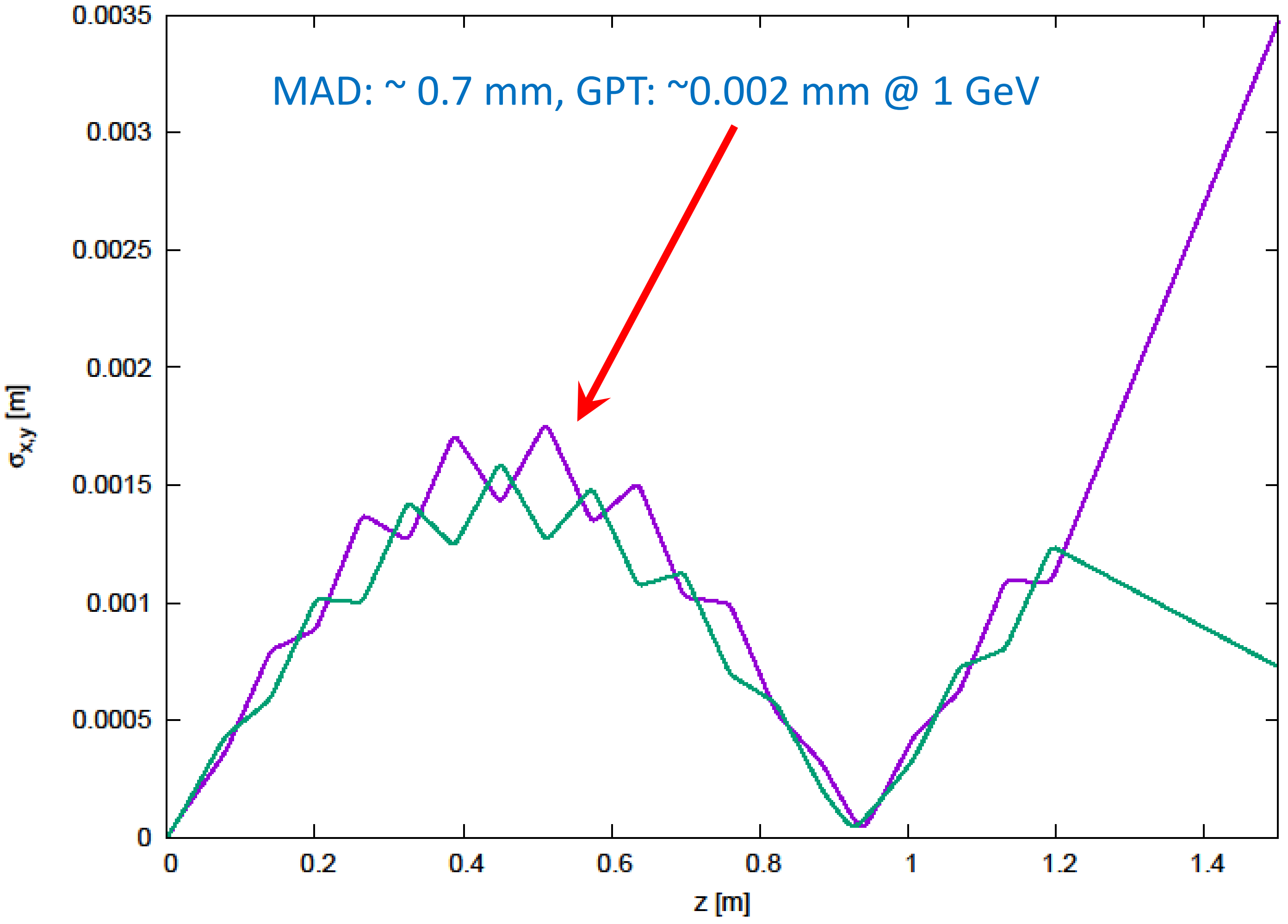
A channel of quadrupoles

- It is possible to optimise the channel according to quadrupoles strengths as well as the drifts between
- In this case they were optimised for maximum beam size because the biggest concern was aperture
- But you could also optimise on how far away down the channel the beam comes back to a focus



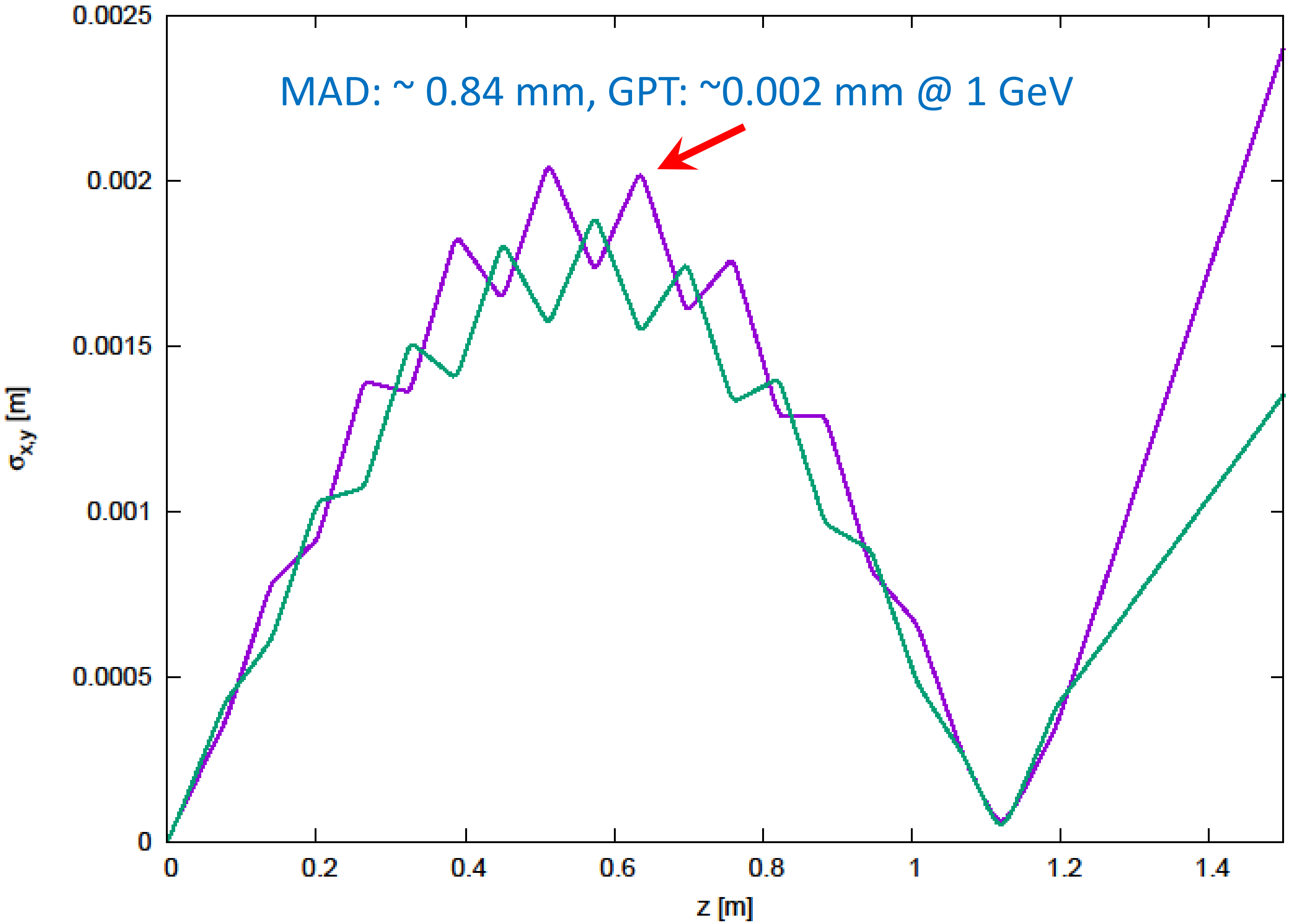
A channel of quadrupoles

- What happens when we track in GPT ?
- Quadrupoles at 200 T/m
- All drifts identical to MAD case done earlier
- Beam appears to be orders of magnitude smaller
- This is probably due to the paraxial approximation because the divergence is very high immediately after the exit of the plasma



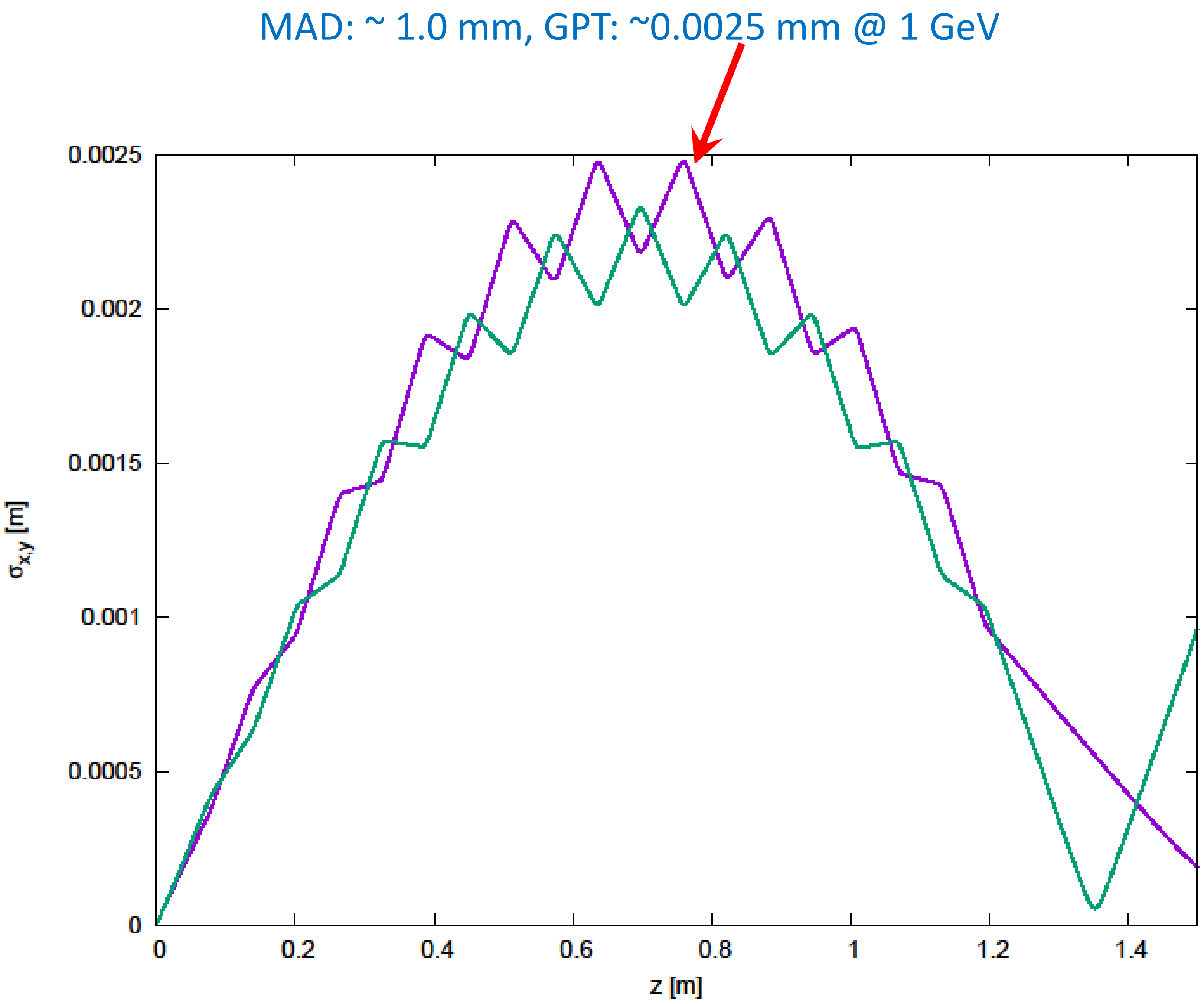
A channel of quadrupoles

- What happens when we track in GPT ?
- Quadrupoles at 167 T/m
- All drifts identical to MAD case done earlier
- Beam appears to be orders of magnitude smaller
- This is probably due to the paraxial approximation because the divergence is very high immediately after the exit of the plasma

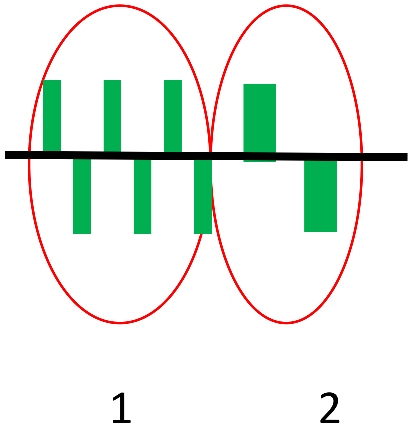


A channel of quadrupoles

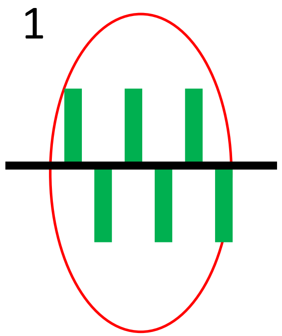
- What happens when we track in GPT ?
- Quadrupoles at 134 T/m
- All drifts identical to MAD case done earlier
- Beam appears to be orders of magnitude smaller
- This is probably due to the paraxial approximation because the divergence is very high immediately after the exit of the plasma



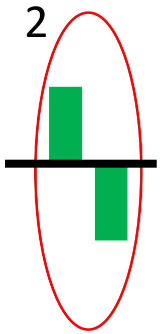
A channel of quadrupoles – sample beamline



- Once beam brought back down to a focus, can use extra quadrupoles to bring the beam to a precise focus
- Works at all energies & for low energies the beamline can be considerably shorter



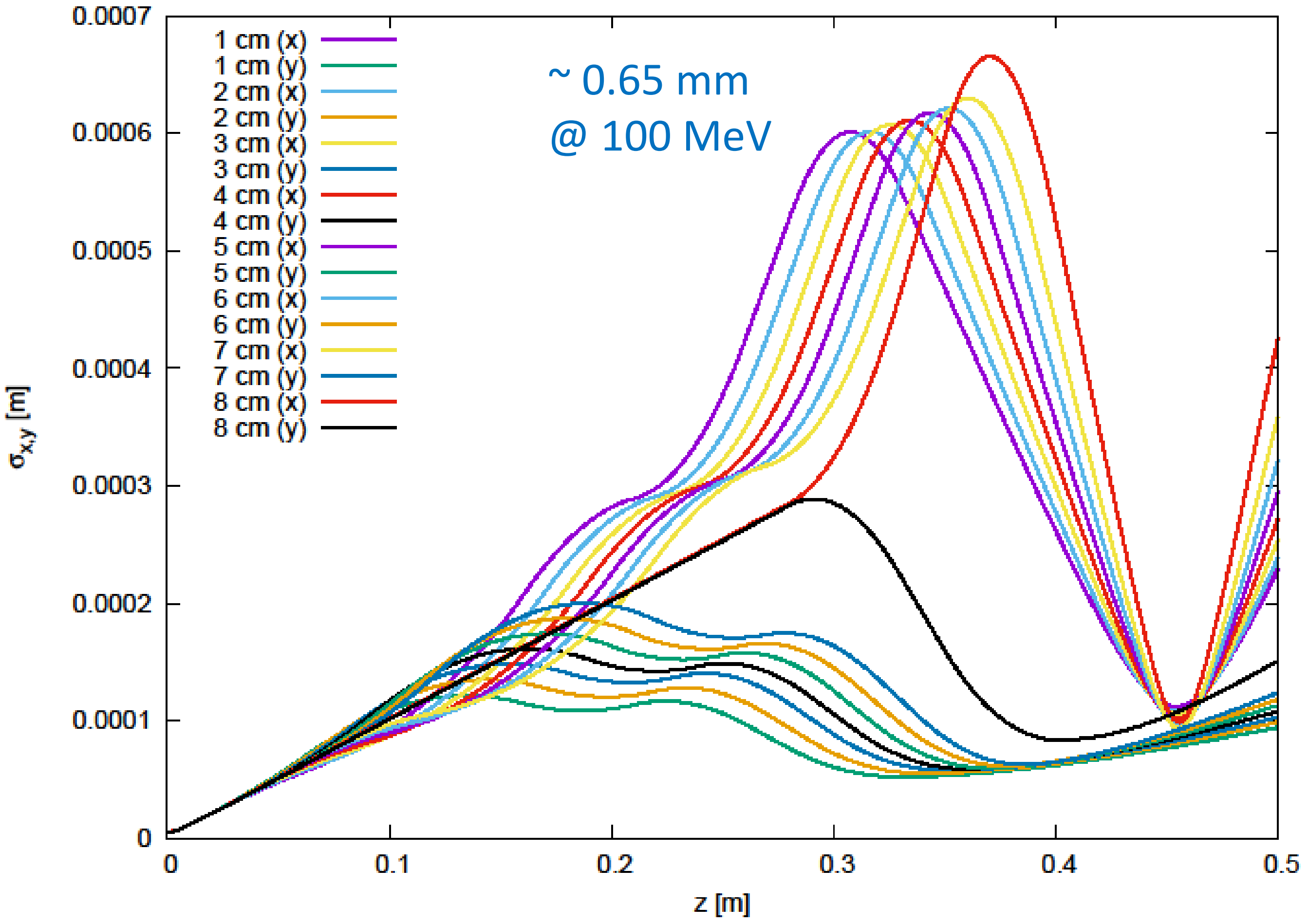
- Capture: 6 Halbach quadrupoles, 12 cm, 200 T/m with 5 cm between them. First quadrupole is 5 cm after plasma exit
- Energy is 100 MeV with the realistic Twiss parameters



- Transport: 2 EM quadrupoles, 15 cm, quadrupoles < 160 T/m with 5 cm between them

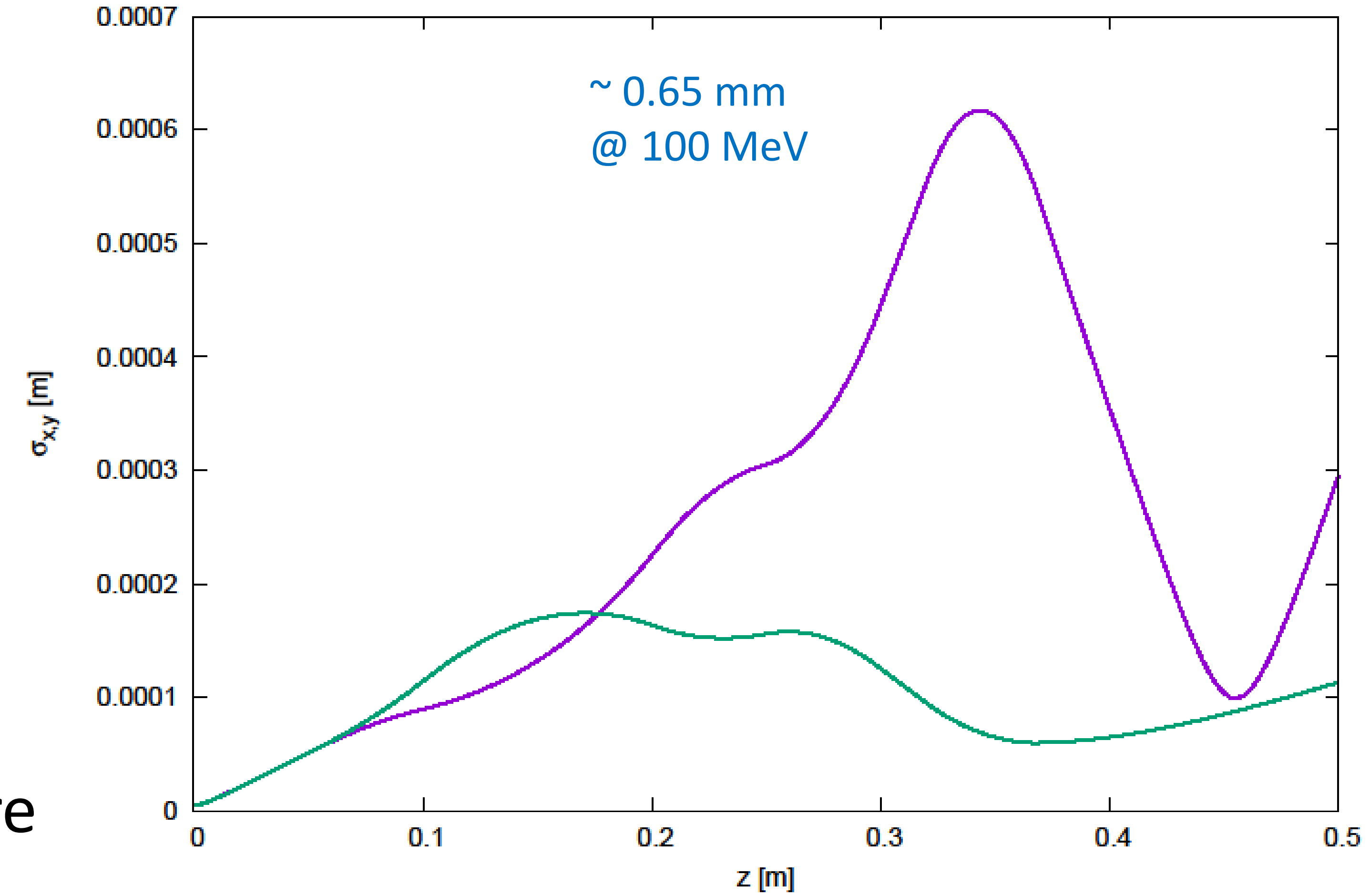
A channel of quadrupoles – sample beamline

- Where the channel starts after the exit of the plasma can & should also be optimised
- For a focus 4.5 m away it is possible to see that a distance between plasma exit & start of channel can be at most 7 cm
- Quadrupole strength considerations can further restrict this
- Eventually, when all choices are made, you are left with:



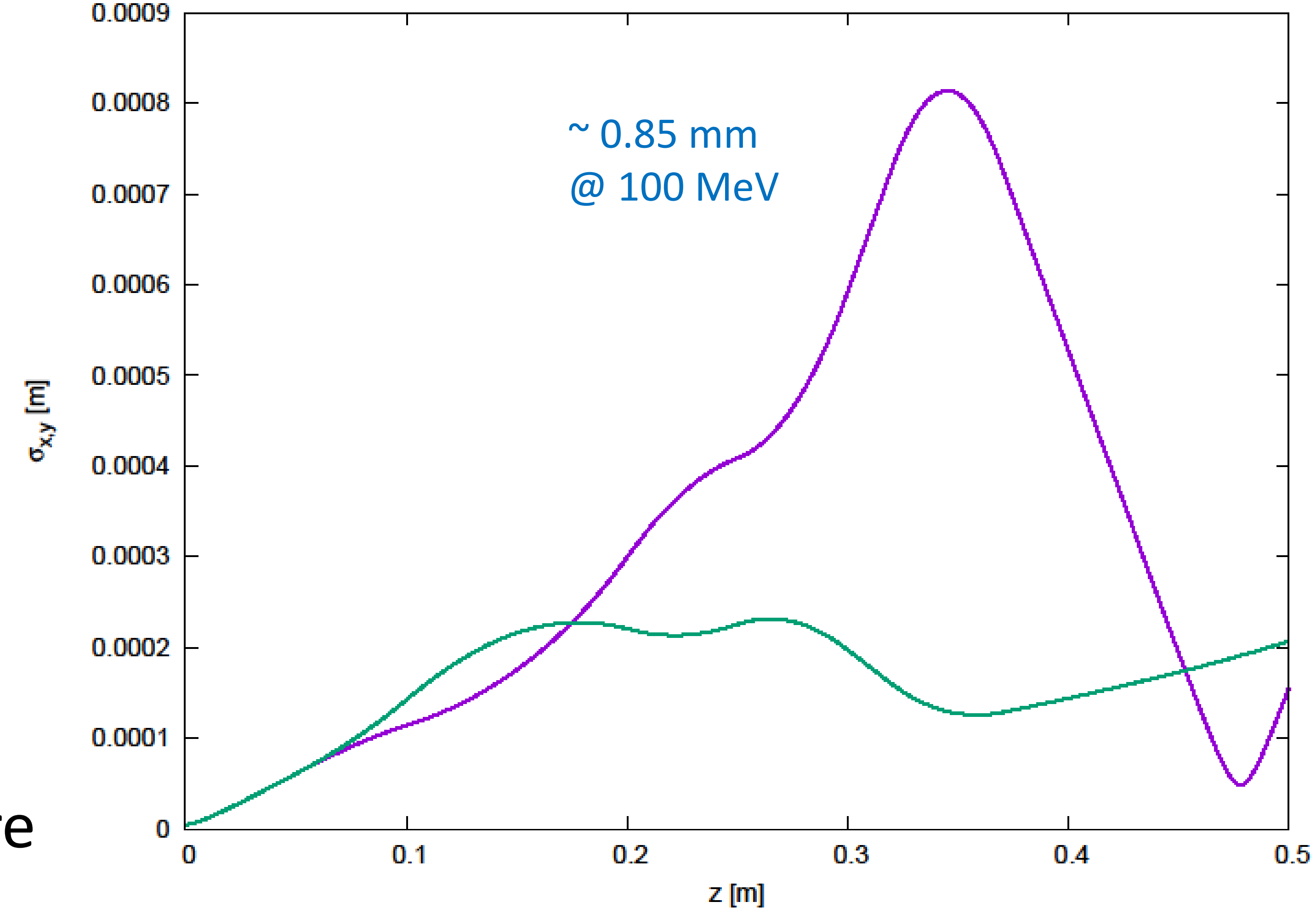
A channel of quadrupoles – sample beamline

- Eventually, when all choices are made, you are left with:
  - Nice waist at ~ 4.5 m
  - 650 µm beam size
- Modelling shown here is done without space charge
- Depending on the charge coming out of the plasma this may be necessary and may change the entire line
- Formally a triplet was used here but the principle is the same …



A channel of quadrupoles – sample beamline

- Eventually, when all choices are made, you are left with:
  - Nice waist at ~ 4.5 m
  - 850 µm beam size
- Shown here is with space charge but no re-matching…
- Depending on the charge coming out of the plasma this may be necessary and may change the entire line
- Formally a triplet was used here but the principle is the same …

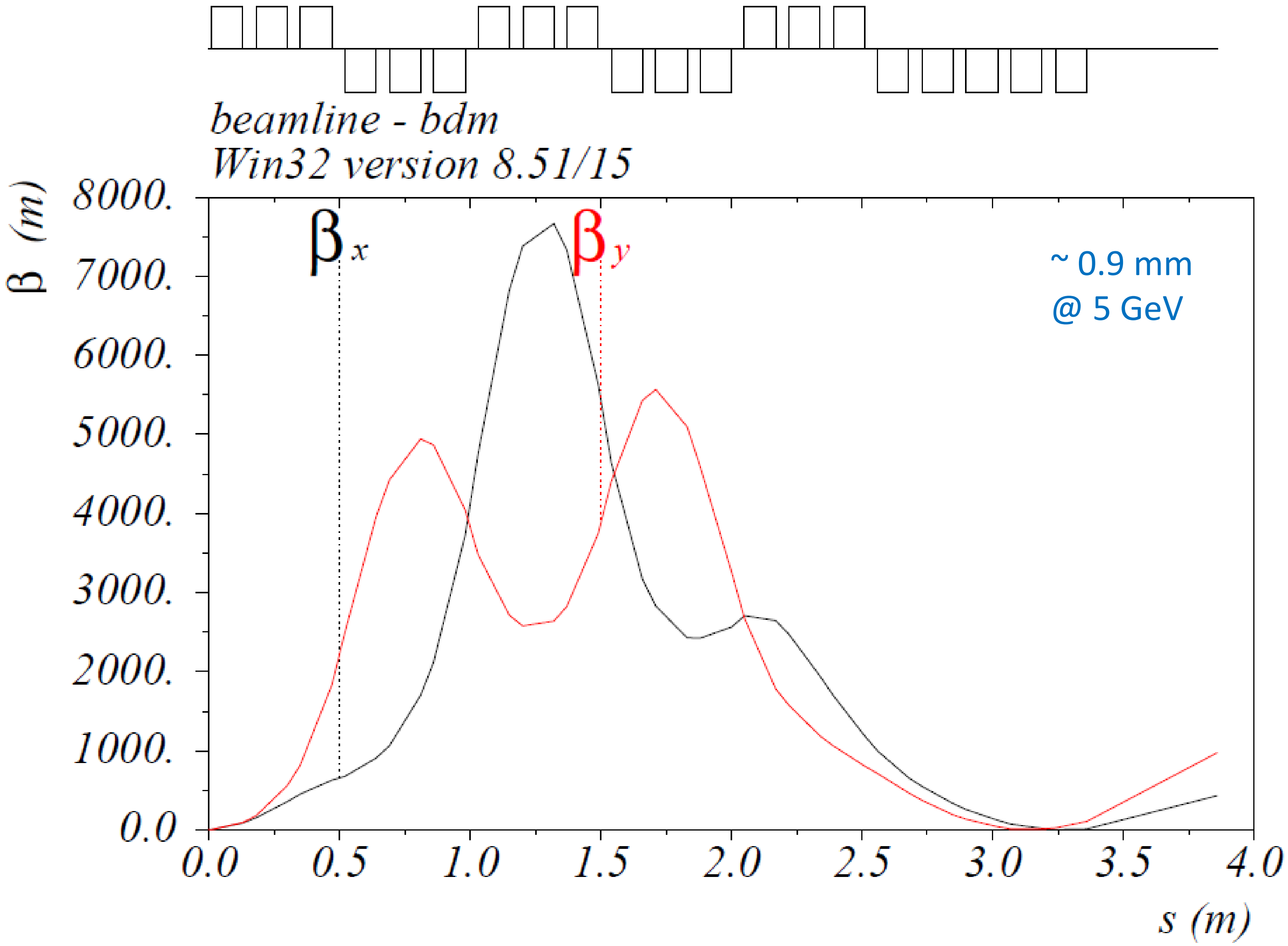


A channel of quadrupoles conclusions

- Beam “explodes” out of the plasma & the idea is to have an optimised channel for transport which brings it back to a focus which is almost a mirror image of what happens at the plasma exit
- It is possible to optimise this channel to some extent given space availability, possible quadrupole strengths, drifts
- MAD grossly overestimates the beam size due to the paraxial approximation present in all conventional matrix based codes
- However, the focus stays broadly in the same place and it is a useful tool in modelling the beamline quickly
- Two variable quadrupoles struggling to bring beam to a precise focus
- Full quadrupole fringe fields (fringe field paper: Phys. Rev. ST Accel. Beams **18,** 064001) essential because of off-axis behaviour / aperture implications

A channel of quadrupoles – last remark

- Rotate some Halbach magnets to change the focusing planes -> same line but higher energies
- So all quadrupoles still constant gradient apart from last two which could be e.g. Zepto quadrupoles
- Could even slide quadrupoles longitudinally & make them all into Zepto …



Thank you VERY much for listening / reading

If you have any questions please write them in the comments or send them to me anytime

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