EUROPEAN PLASMA RESEARCH ACCELERATOR WITH EXCELLENCE IN APPLICATIONS

Transfer lines status

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CEA/DRF/IRFU/DACM

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This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 653782.

Method to optimize transfer lines (1)

- A lot of different transfer lines are to be designed (plasma to FEL, inter-stage lines, PWFA, different initial beam distributions,...).
- Problem: optimization of the line is dependent on the initial conditions.
- If use of traditional methods (simplex, conjugate gradient), how to make sure that the solution is not a local minimum?
  - Better to use genetic algorithms (like GIOTTO), particle swarm optimization (PSO) or artificial bees to explore the domain.
  - Use of PSO to find an initial working point.
- Use of a conjugate gradient to speed up the convergence when near an optimum.
- Currently 10 minutes to find a transfer line on a serial computer (convergence criteria and method can still be improved).
- When a few lines are selected as the baseline, these transfer lines will be improved with additional criteria (like flexibility with different initial distributions).

Method to optimize transfer lines (2)

Input

- Total length and minimum distance between elements.
- # permanent Qpoles (PMQ) and electromagnetic Qpoles (EMQ).
- Minimum and maximum gradient.
- Initial distribution (Twiss parameters, momentum spread,...).

Variables

- Gradient and positions of the quadrupoles.

Constraints

- Final Twiss parameters (or matrix terms).
- Minimisation of the emittance growth (case $\alpha_{xy,0} = 0$):

$$\epsilon_{xy,1} \approx \epsilon_{xy,0} \left\{ 1 + \beta_{xy,1} \gamma_{xy,0} \sigma_\delta^2 \left[\left(\frac{T_{126}}{\beta_{xy,1}} \right)^2 + \left(T_{226} + \alpha_{xy,1} \frac{T_{126}}{\beta_{xy,1}} \right)^2 \right] \right\}^{1/2} \quad (1)$$

Case of the transfer line to FEL

Input

- Total length: from 4 meters to 8 meters.
- Min: 30 mm between PMQs, 100 mm between EMQs, 50 mm after plasma.
- Length PMQ: 100 mm, length EMQ: 400 mm
- 2-8 PMQs and 4 EMQs.
- Maximum gradient of 700 T/m PMQs and 100 T/m in the EMQs.

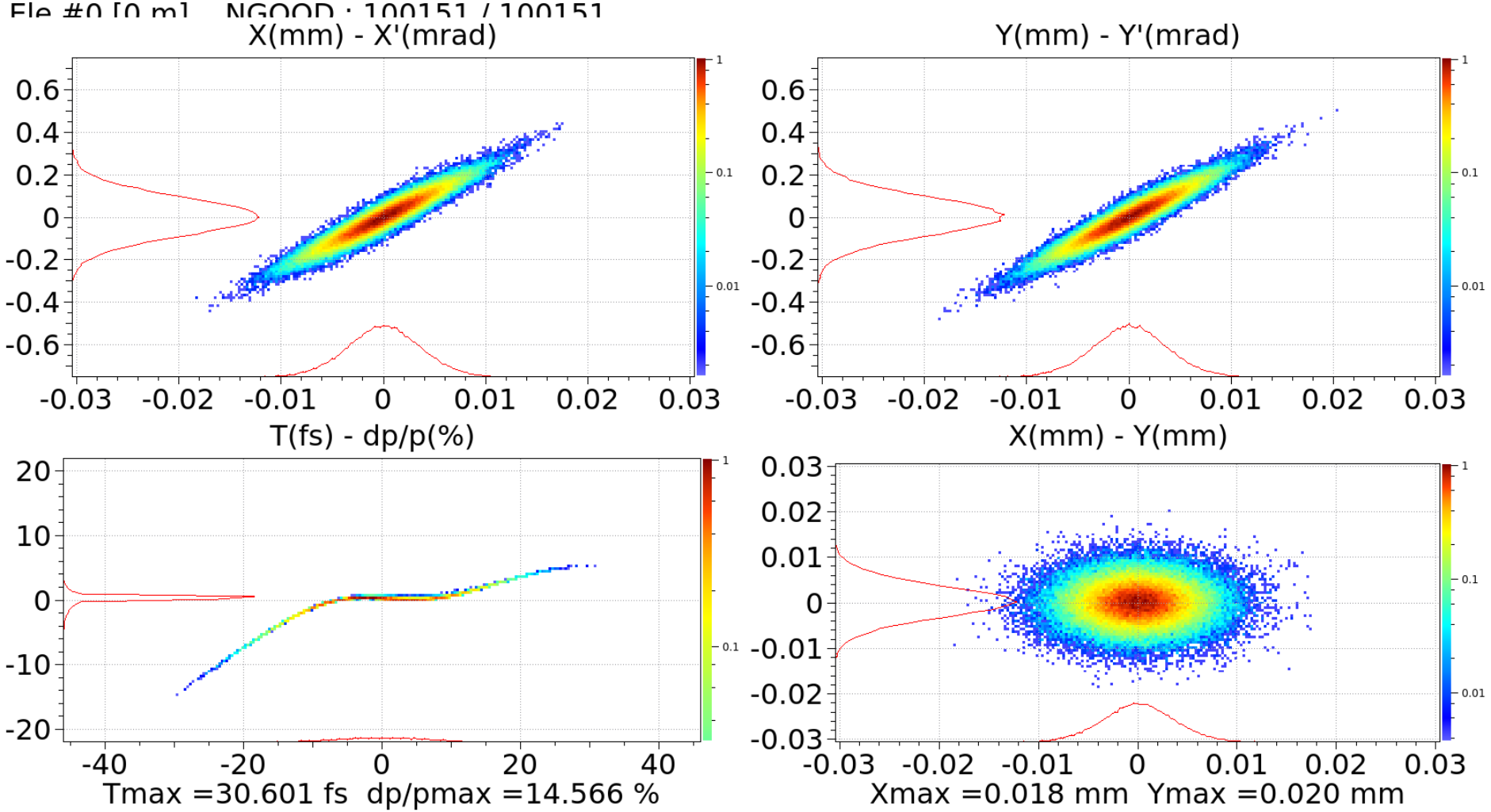
Variables

- Gradient and positions of the quadrupoles.

Constraints

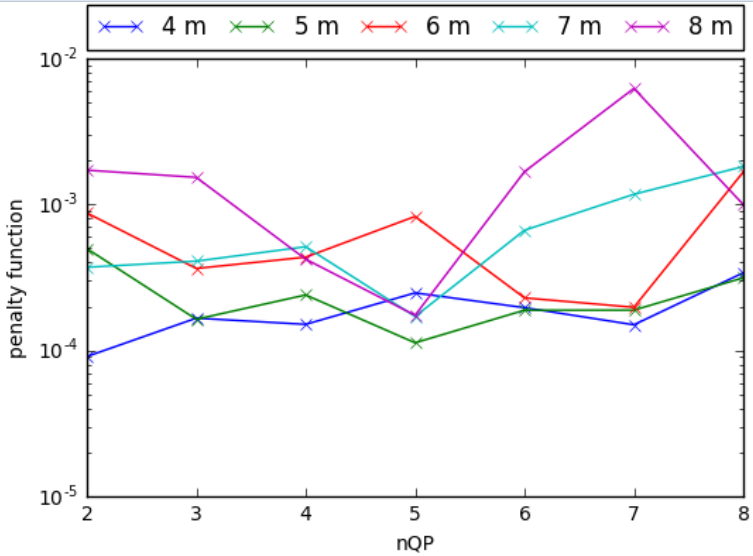
- Final Twiss parameters.
  $\beta_{x,1} = 5.04$ m, $\beta_{y,1} = 2.11$ m, $\alpha_{x,1} = 1.48$, $\alpha_{y,1} = -0.65$
- Minimisation of the emittance growth

Distribution Xiangkun Li (CEA)



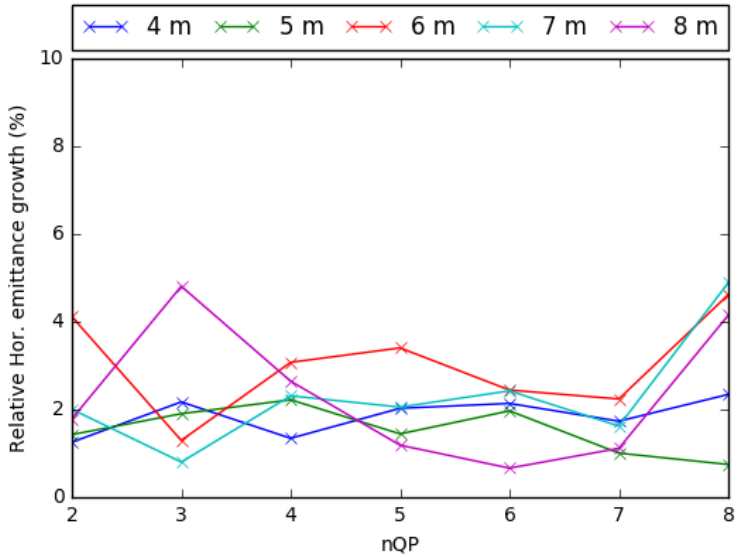
$\beta_{x,0} = 127$ mm, $\beta_{y,0} = 127$ mm, $\alpha_{x,0} = -3.0$, $\alpha_{y,0} = -3.0$, $\gamma_{x,0} = 79$ m^{-1}, $\gamma_{y,0} = 79$ m^{-1}

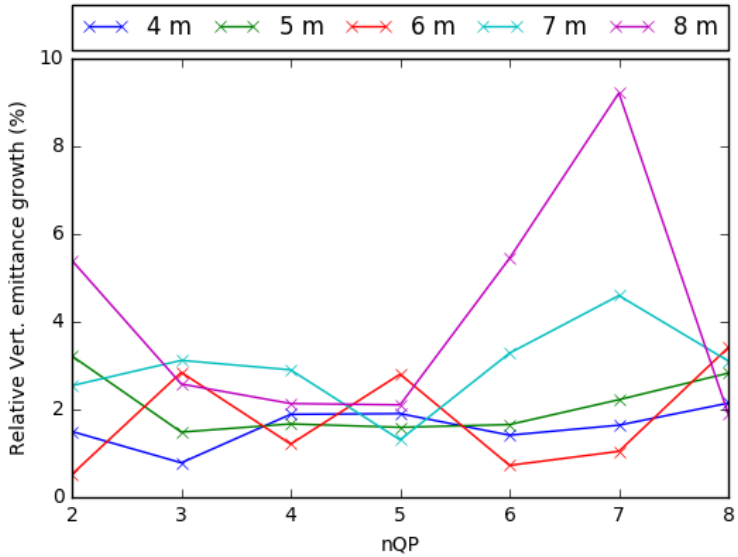
Transfer line (5 GeV Li)



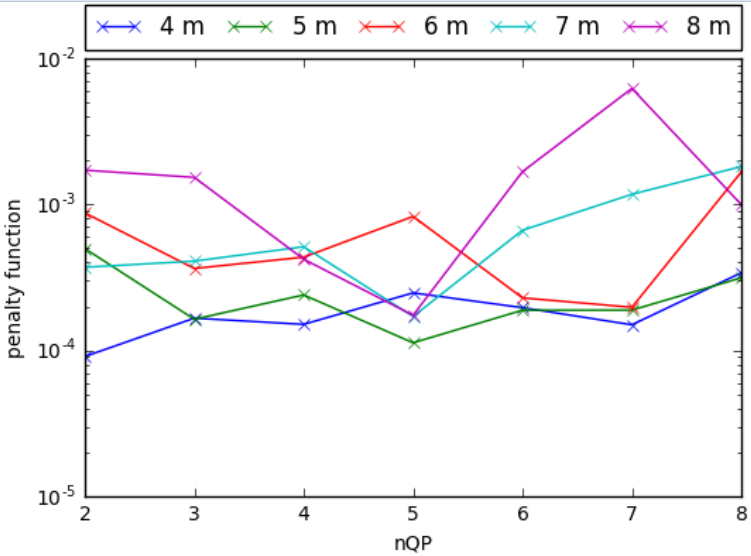
- Shorter transfer line is better.
- No gain in increasing the number of quadrupoles.
- Baseline: 2 PMQs followed by 4 EMQs for a total length of 4 m.
- Other solution if emittance growth balanced in both planes.

Cut in energy at ±0.2% (tracking with TraceWin)





Transfer line (5 GeV Li)



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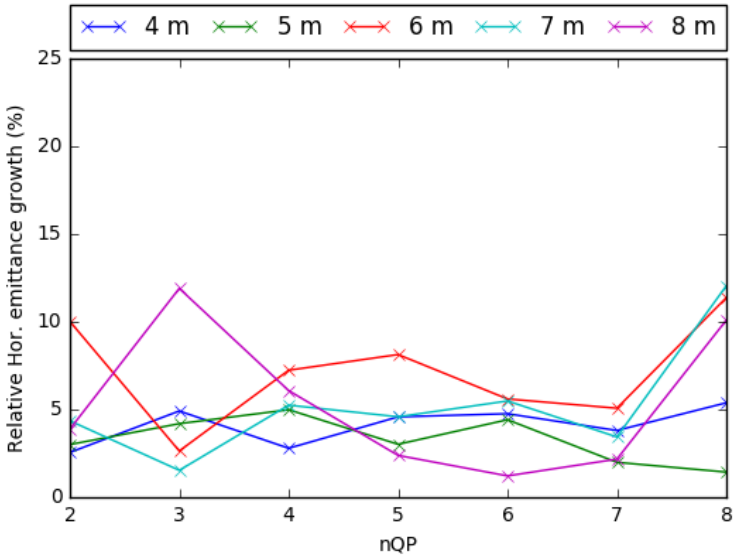
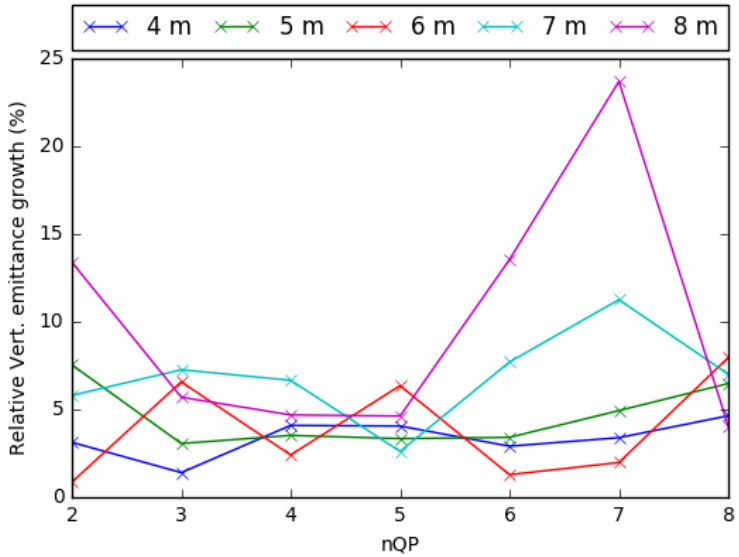
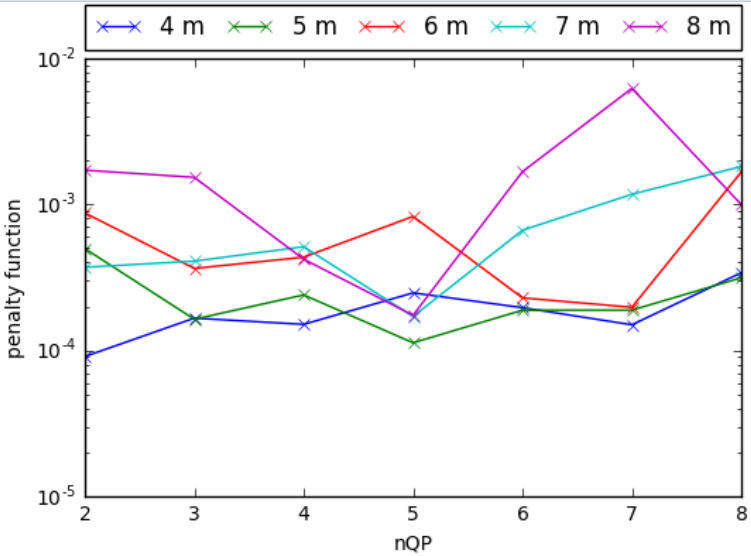
- Baseline: 2 PMQs followed by 4 EMQs for a total length of 4 m.
- Other solution if emittance growth balanced in both planes.

Cut in energy at ±0.4% (tracking with TraceWin)





Transfer line (5 GeV Li)



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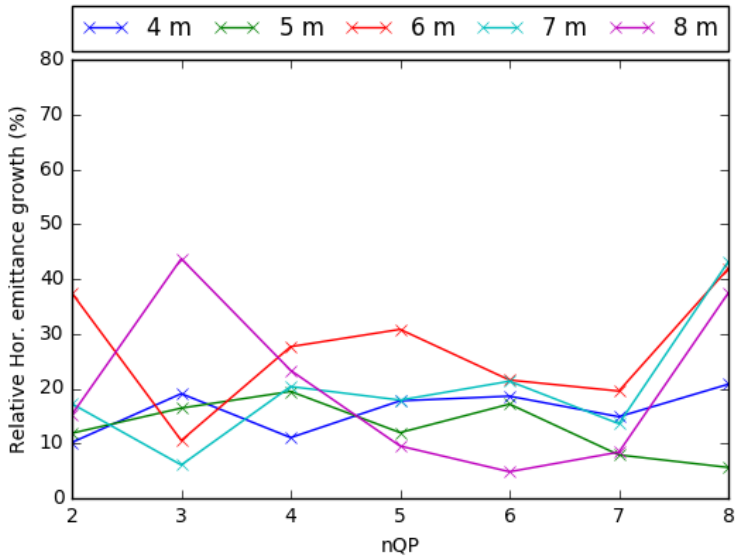
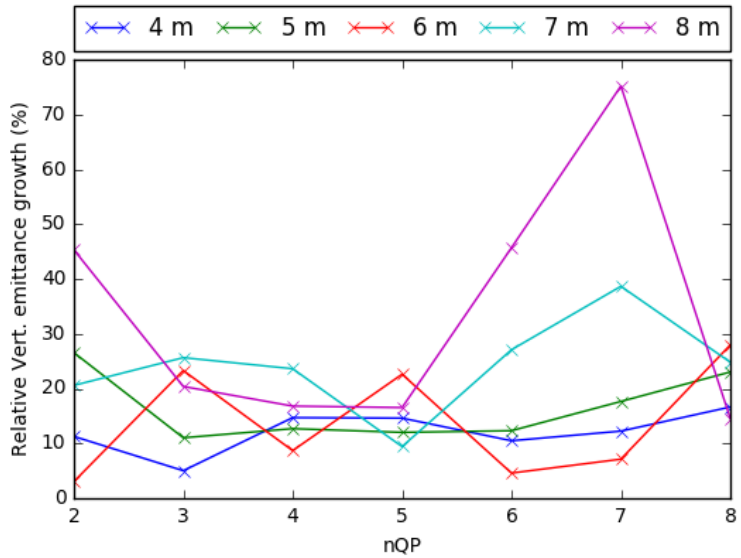
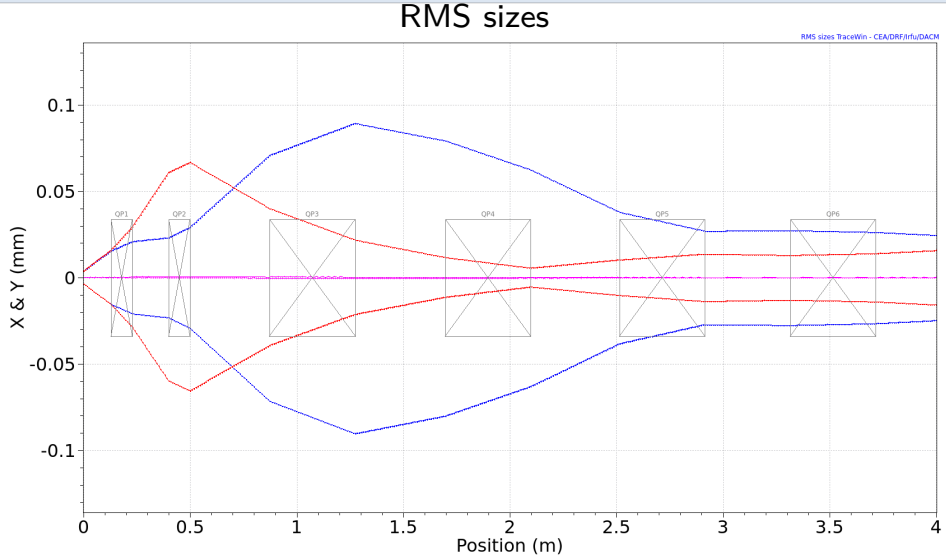
- No gain in increasing the number of quadrupoles.
- Baseline: 2 PMQs followed by 4 EMQs for a total length of 4 m.
- Other solution if emittance growth balanced in both planes.

Cut in energy at ±1.0% (tracking with TraceWin)





2 PMQs and 4 m (5 GeV Li)

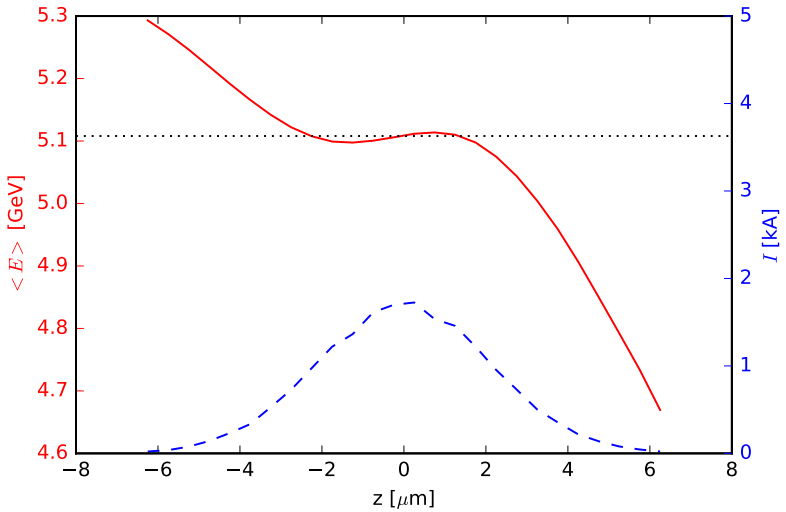


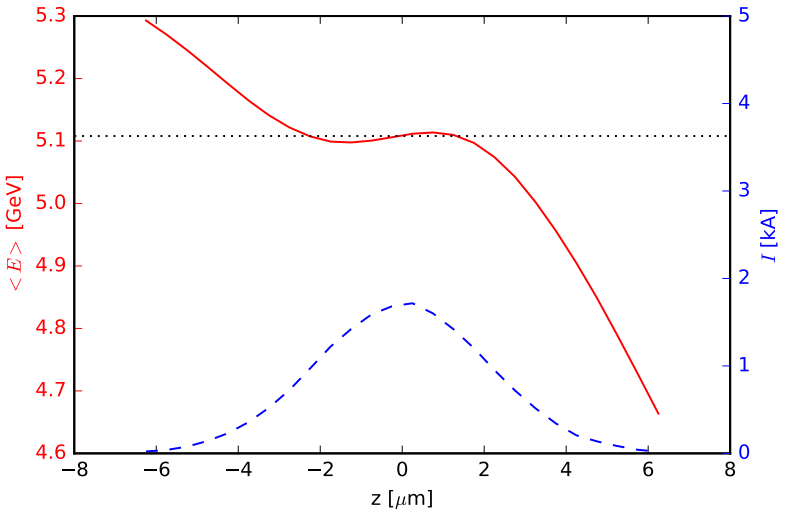
- Ref energy: 5.11 GeV.

⇒ Max. PMQ gradient: 713 T/m.

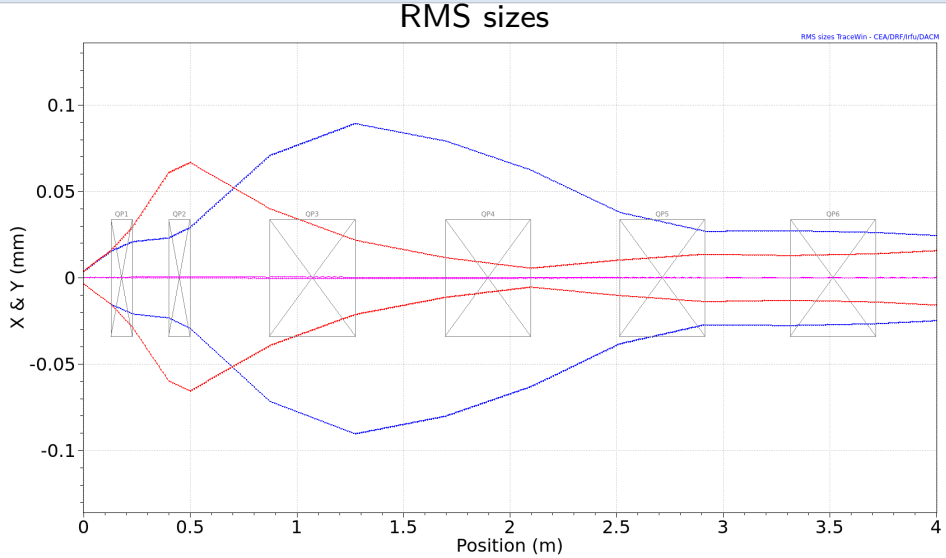
- Can be cured by lengthening a bit the PMQs or with a loop with WP2 to reduce final energy.
- Max. EMQ gradient: 83 T/m.

Initial/Final Current (bin: 0.5 μm) (from ASTRA).





2 PMQs and 4 m (5 GeV Li)



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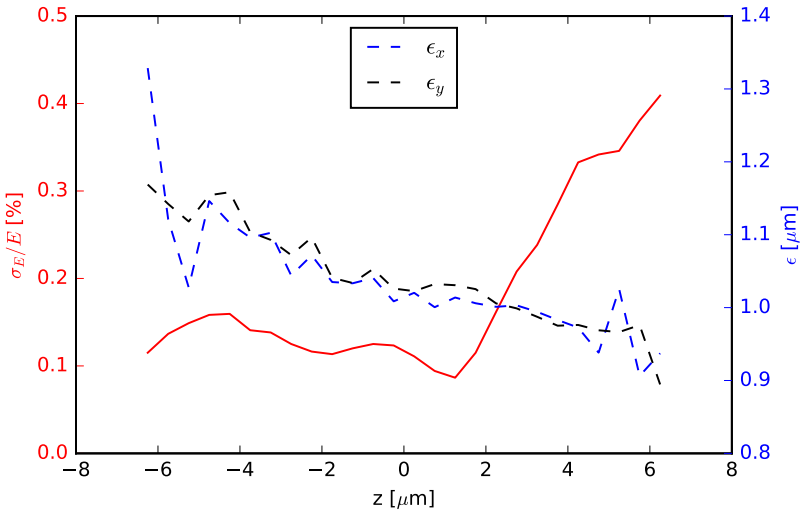
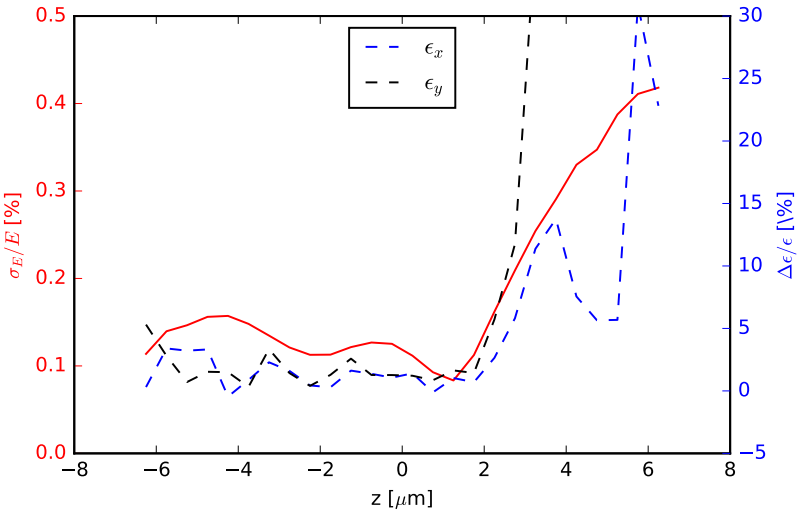
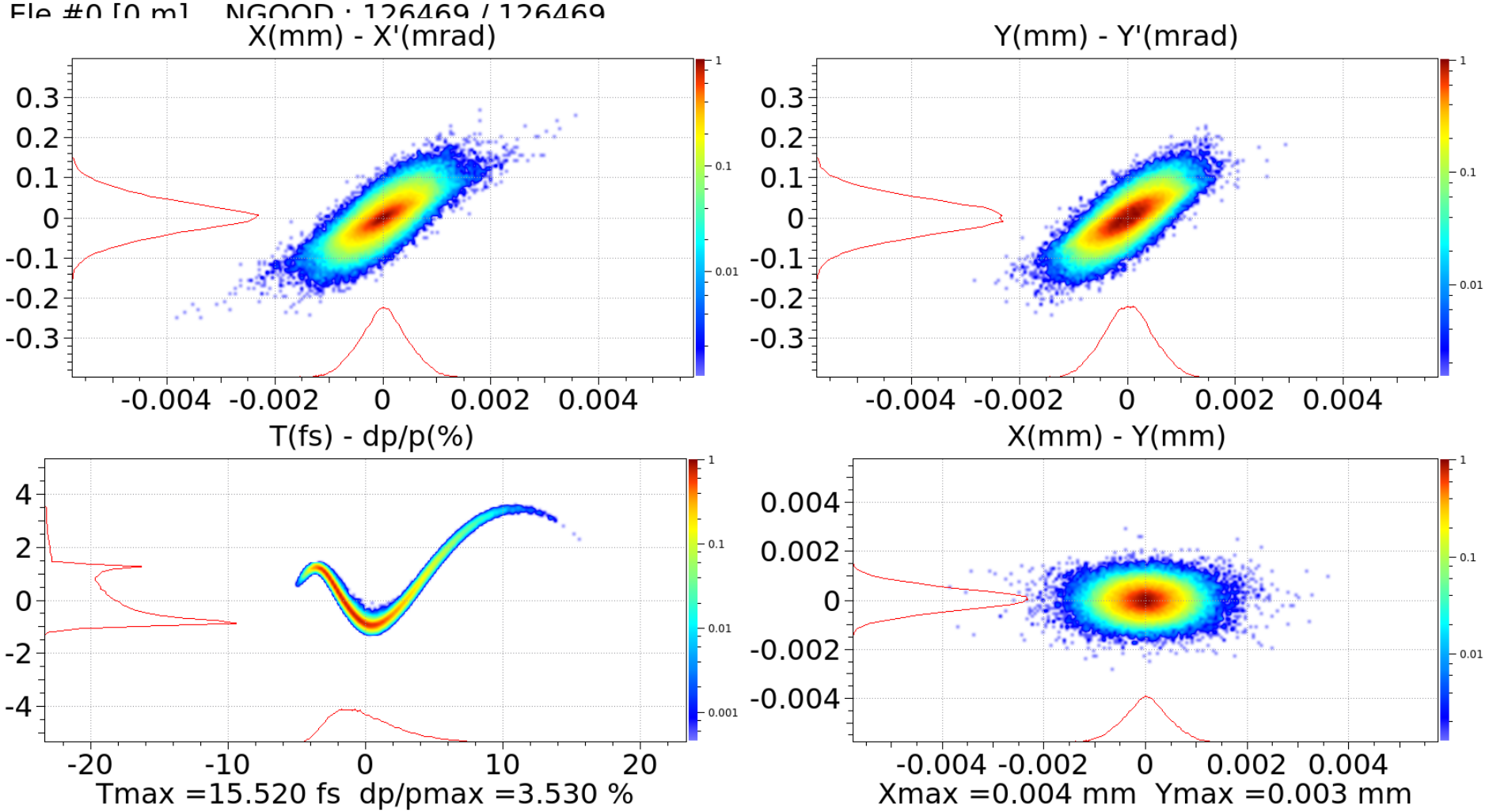


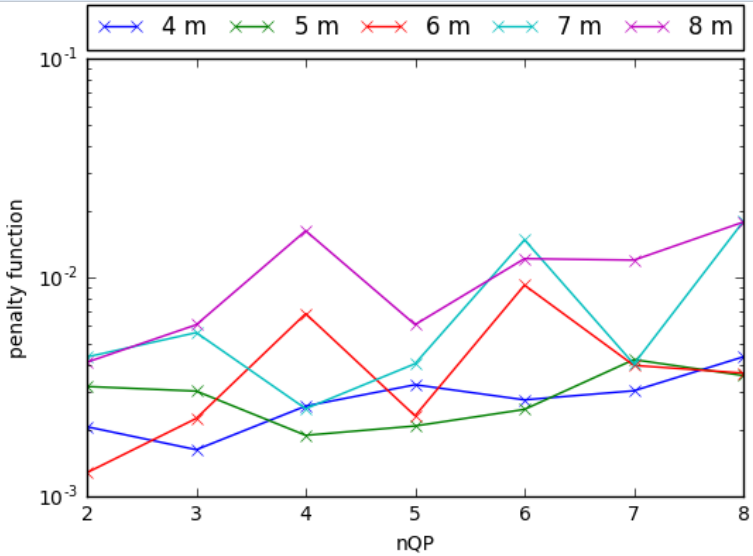


Distribution ReMPI Tomassini (INO)



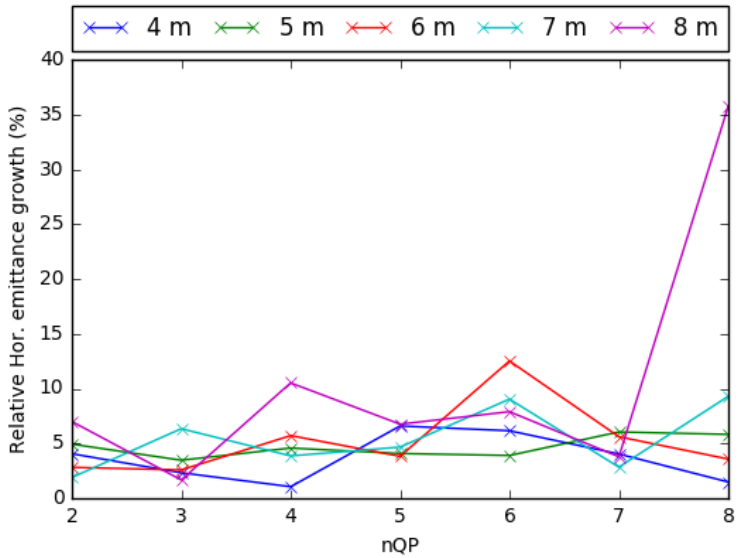
$\beta_{x,0} = 16$ mm, $\beta_{y,0} = 16$ mm, $\alpha_{x,0} = -1.3$, $\alpha_{y,0} = -1.3$, $\gamma_{x,0} = 162$ m^{-1}, $\gamma_{y,0} = 162$ m^{-1}

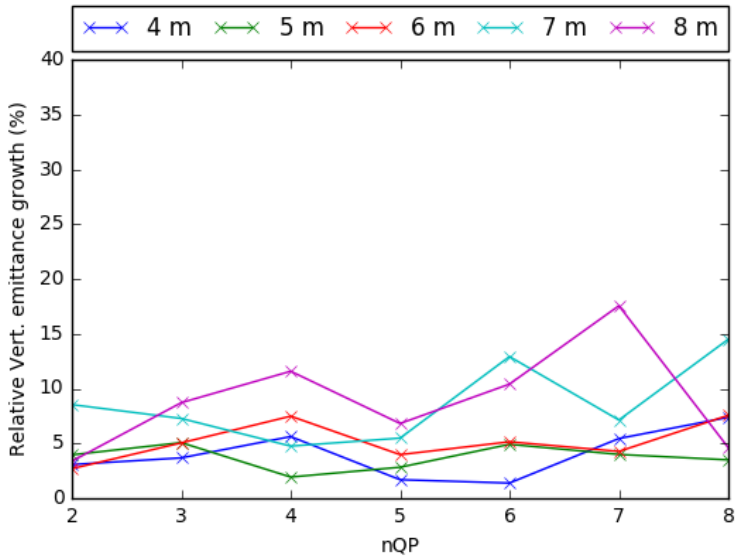
Transfer line (5 GeV Tomassini)



- Shorter transfer line is better.
- No gain in increasing the number of quadrupoles.
- Baseline: 2 PMQs followed by 4 EMQs for a total length of 4 m.
- Other solution if emittance growth balanced in both planes.

Cut in energy at ±0.2% (tracking with TraceWin)





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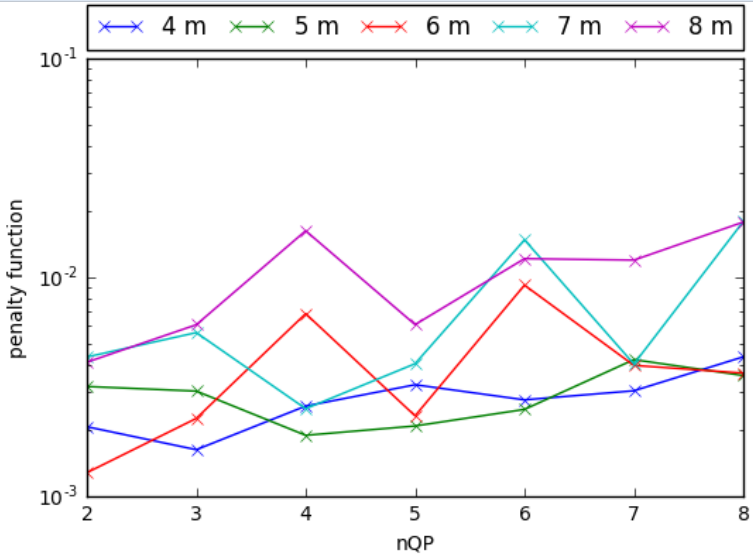

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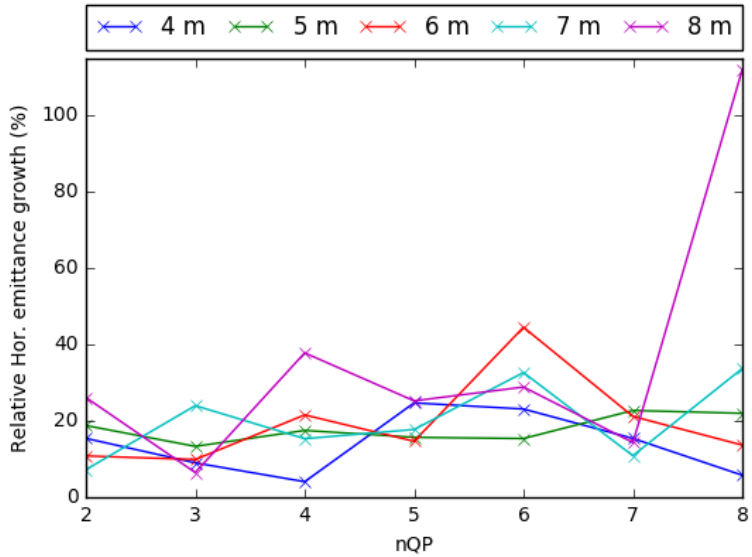
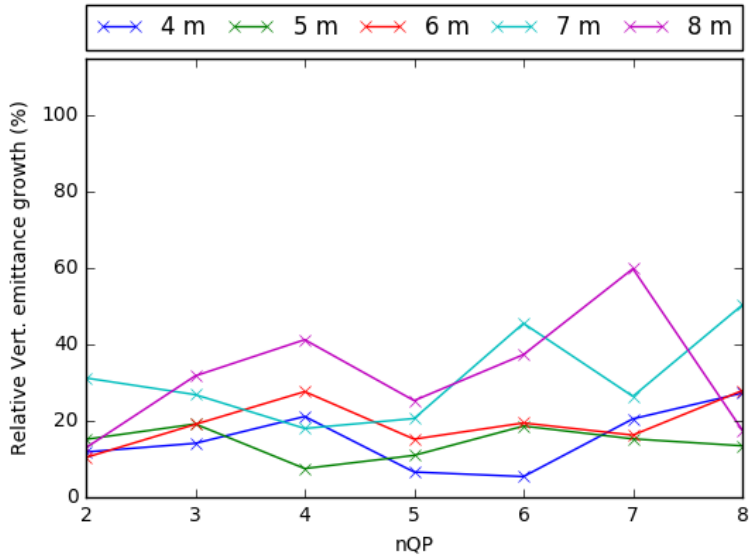
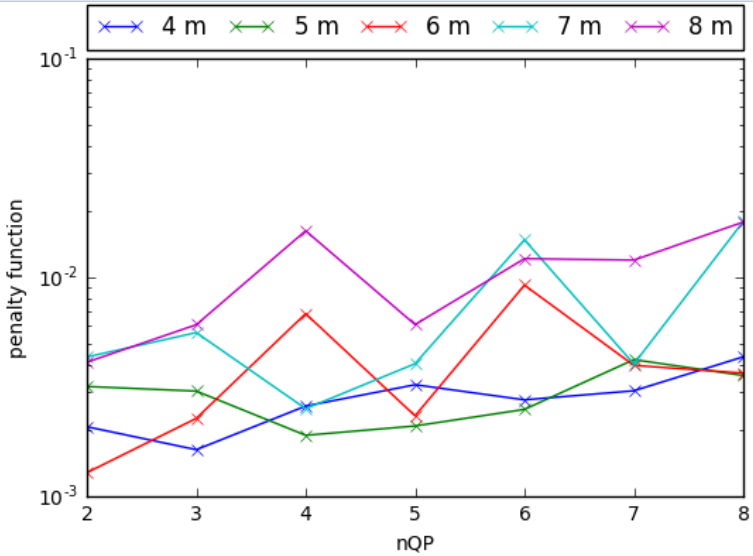
Cut in energy at ±0.4% (tracking with TraceWin)





Transfer line (5 GeV Tomassini)



- Shorter transfer line is better.
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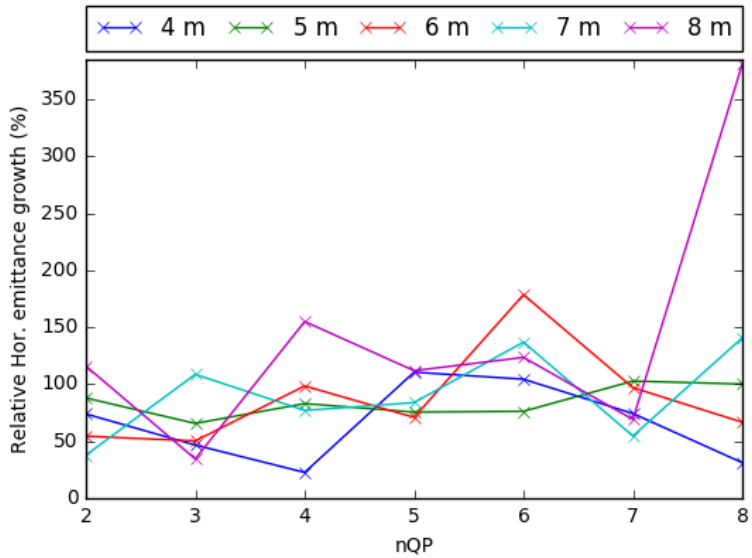
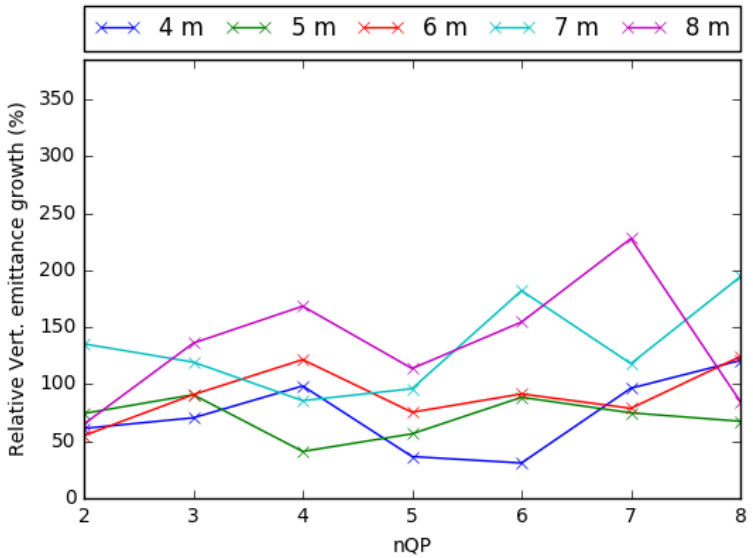
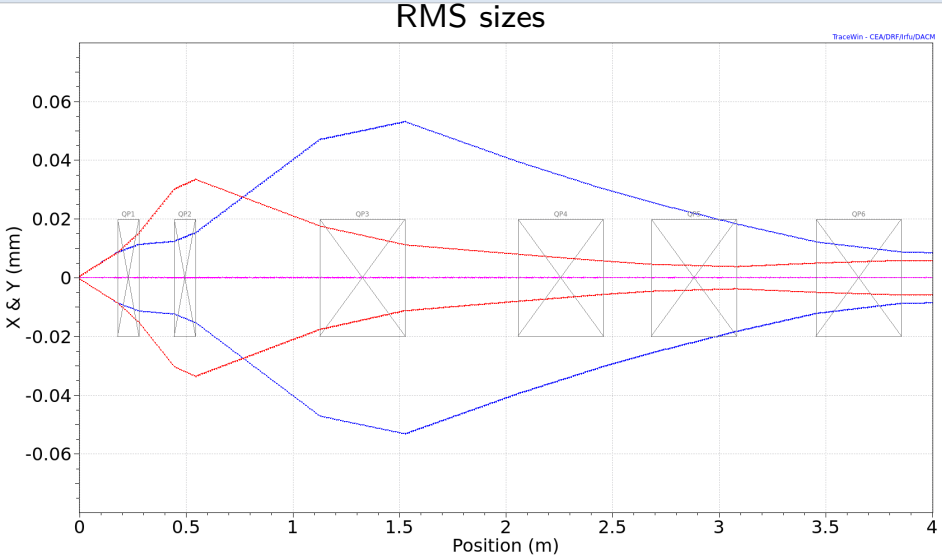
- Baseline: 2 PMQs followed by 4 EMQs for a total length of 4 m.
- Other solution if emittance growth balanced in both planes.

Cut in energy at ±1.0% (tracking with TraceWin)





2 PMQs and 4 m (5 GeV Tomassini)

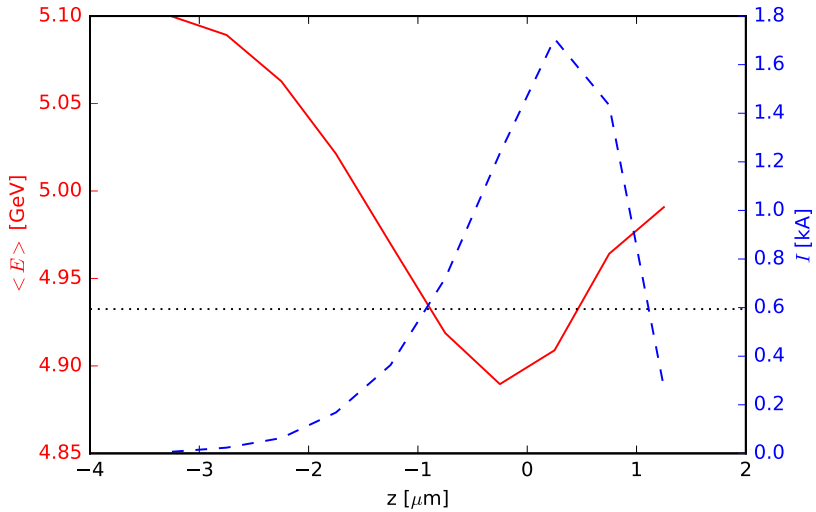


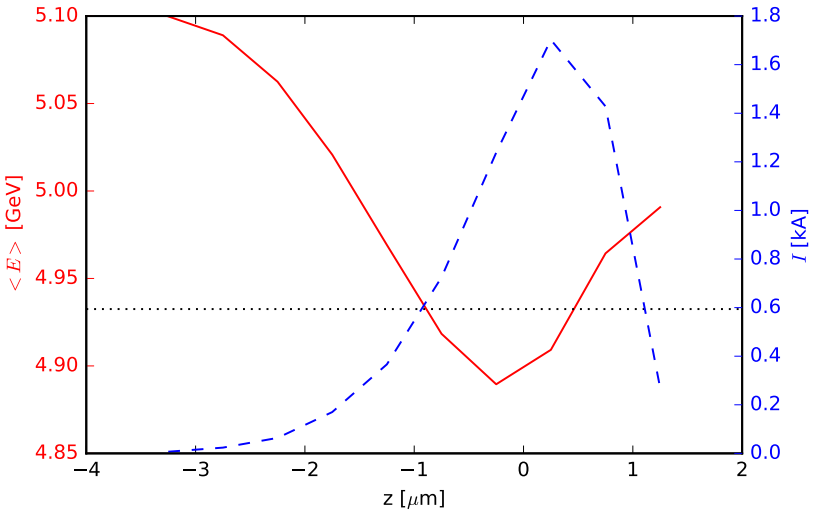
- Ref energy: 4.93 GeV.

$\Rightarrow$ Max. PMQ gradient: 637 T/m.

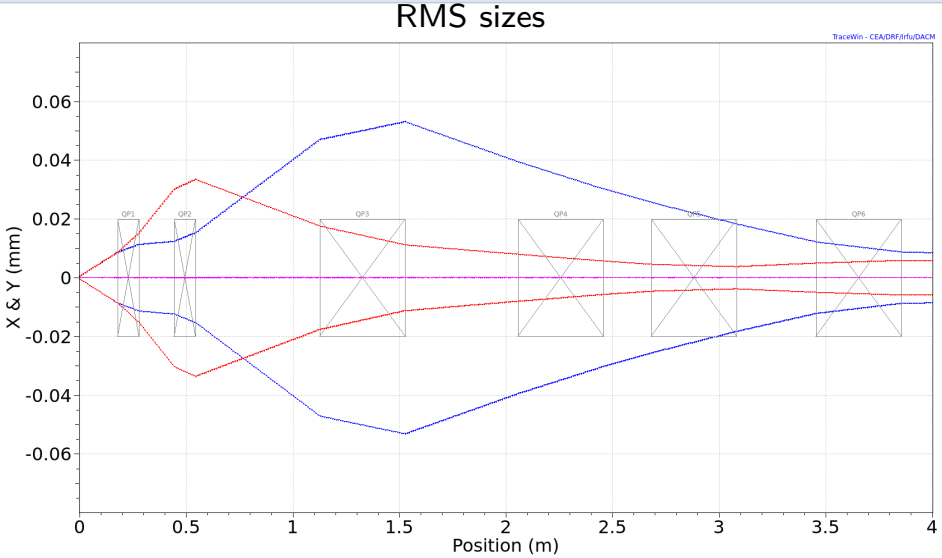
- Max. EMQ gradient: 63 T/m.
  Two weak EMQs (<10 T/m)

Initial/Final Current (bin: 0.5 μm) (from ASTRA).





2 PMQs and 4 m (5 GeV Tomassini)



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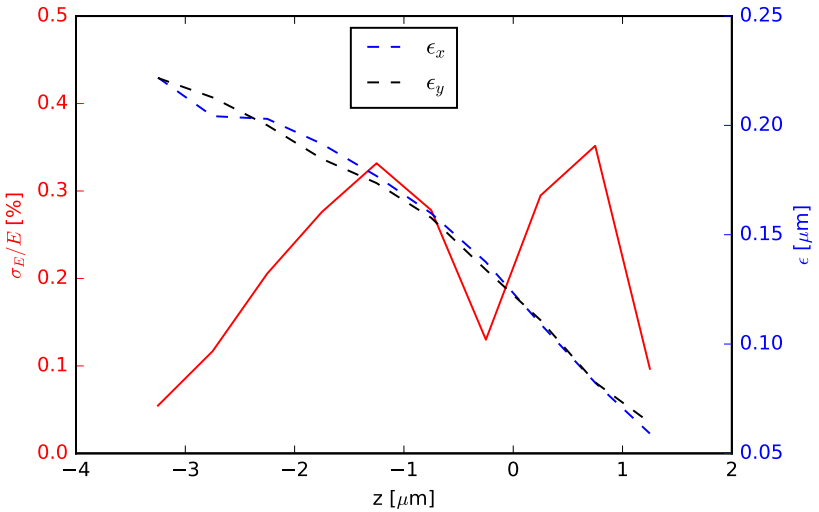
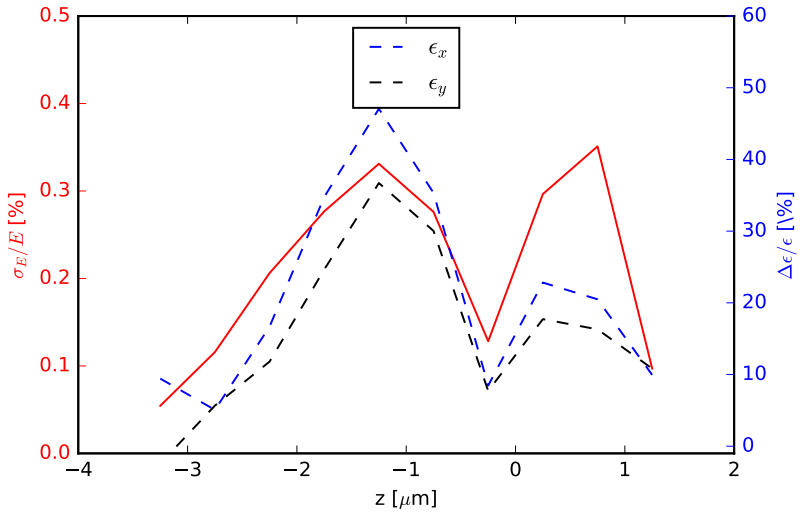
Initial/Final Norm emittance (bin: 0.5 μm) (from ASTRA).

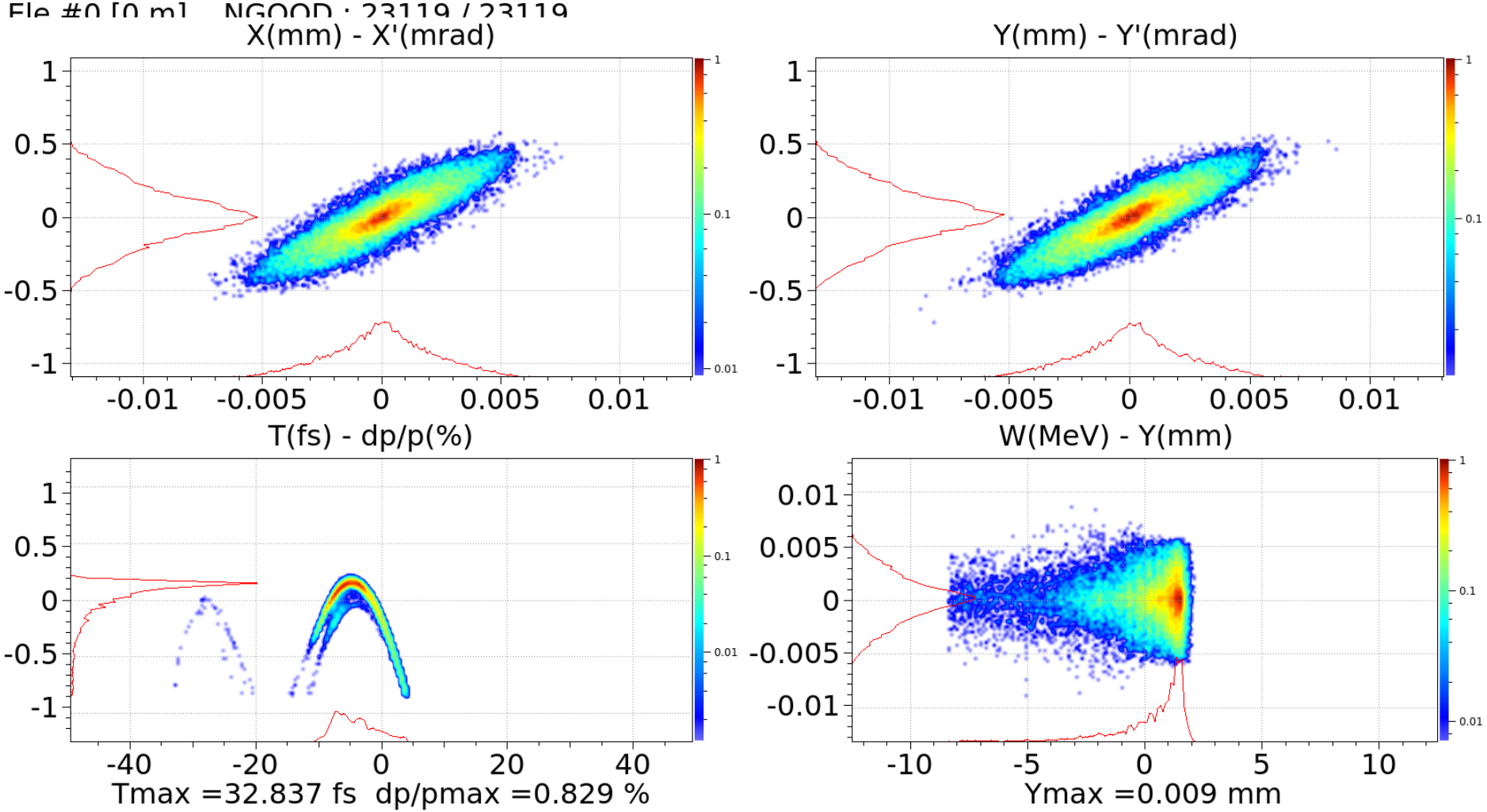




EuPRAXIA Distribution 1GeV LWFA Rossi (INFN)

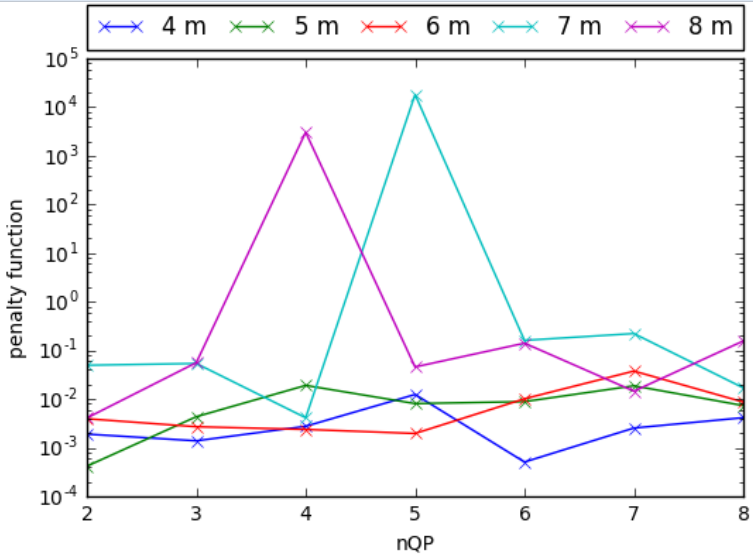
Horizon 2020

TraceWin - CEA/DRF/Irfu/DACM



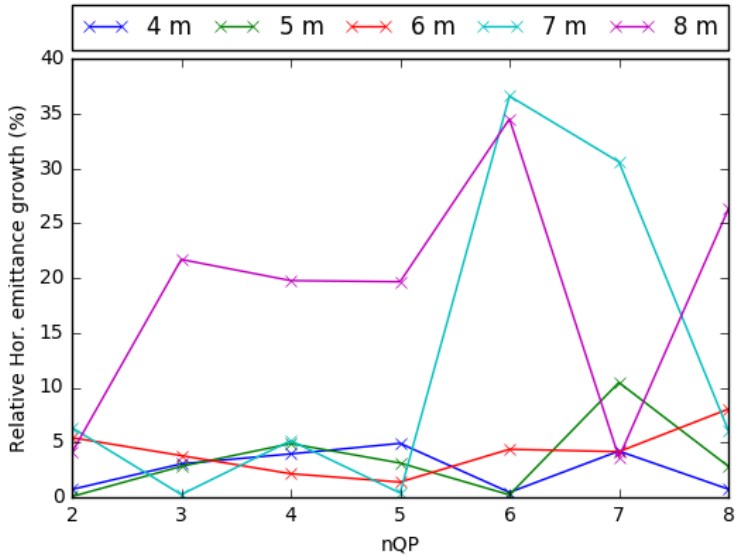
$\beta_{x,0} = 25$ mm, $\beta_{y,0} = 25$ mm, $\alpha_{x,0} = -1.8$, $\alpha_{y,0} = -1.8$, $\gamma_{x,0} = 175$ m^{-1}, $\gamma_{y,0} = 175$ m^{-1}

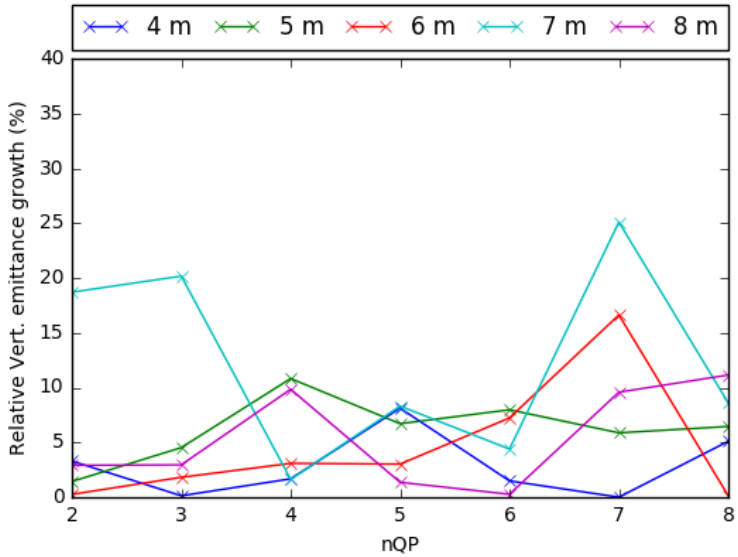
Transfer line (1 GeV Rossi)



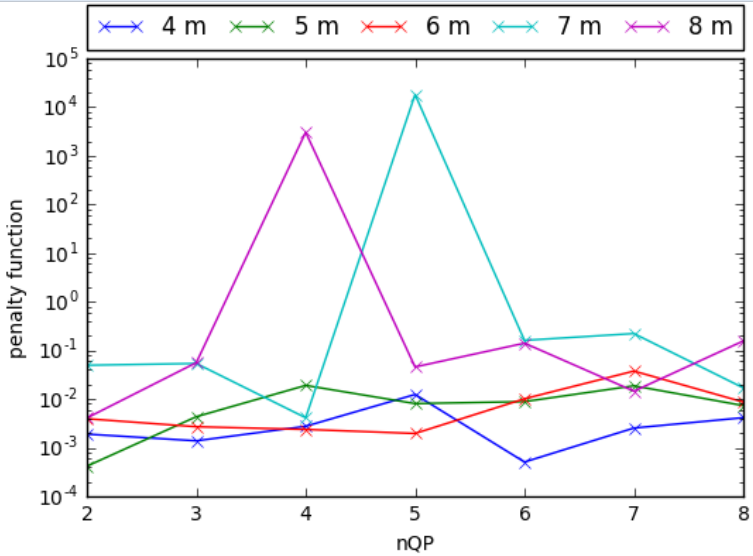
- Shorter transfer line is better.
- No gain in increasing the number of quadrupoles.
- Baseline: 2 PMQs followed by 4 EMQs for a total length of 4 m.
- Other solution if emittance growth balanced in both planes.

Cut in energy at ±0.2% (tracking with TraceWin)





Transfer line (1 GeV Rossi)



- Shorter transfer line is better.
- No gain in increasing the number of quadrupoles.
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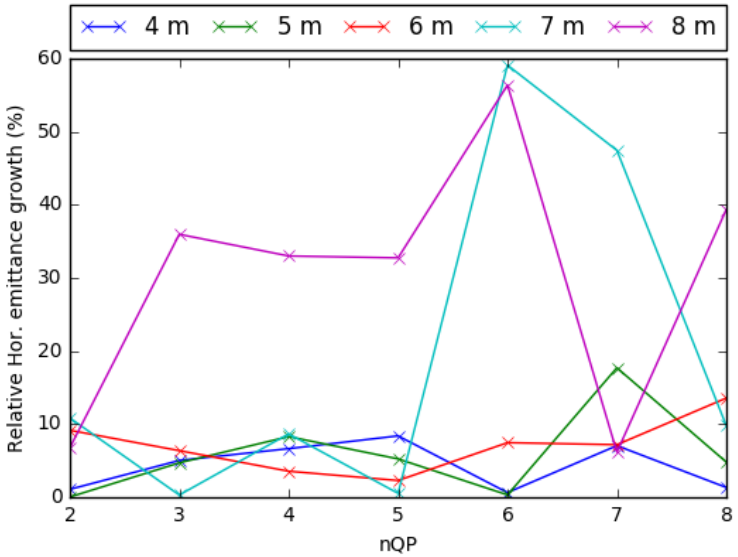
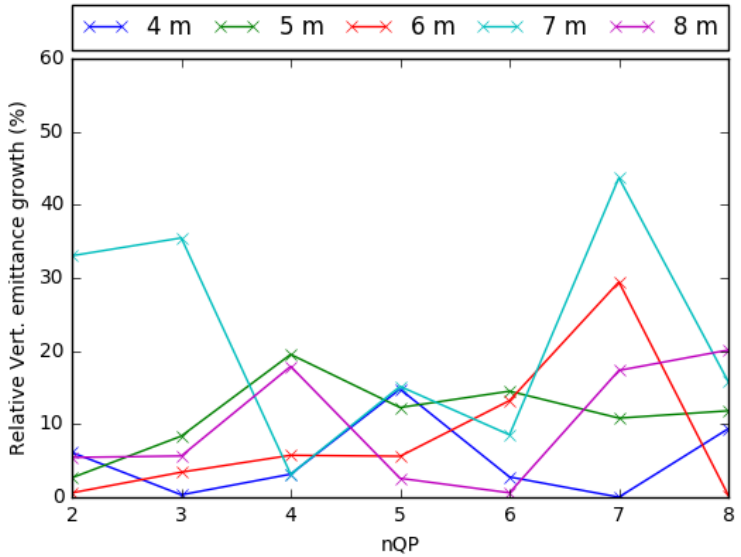
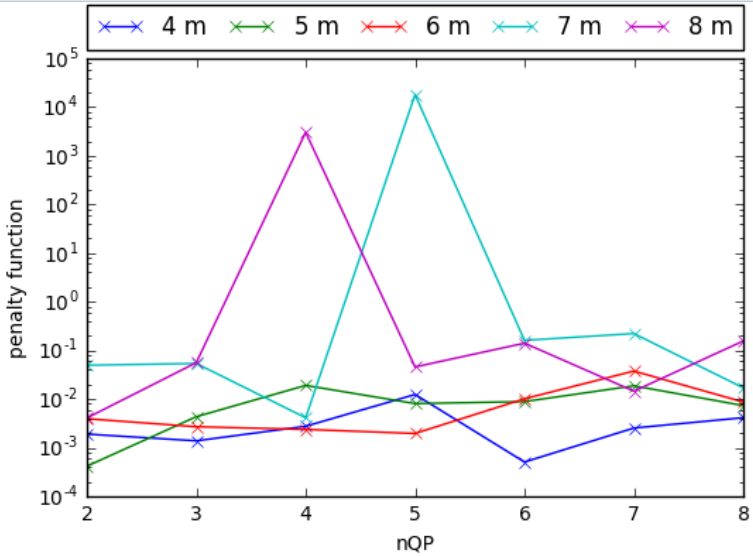
Cut in energy at ±0.4% (tracking with TraceWin)





Transfer line (1 GeV Rossi)



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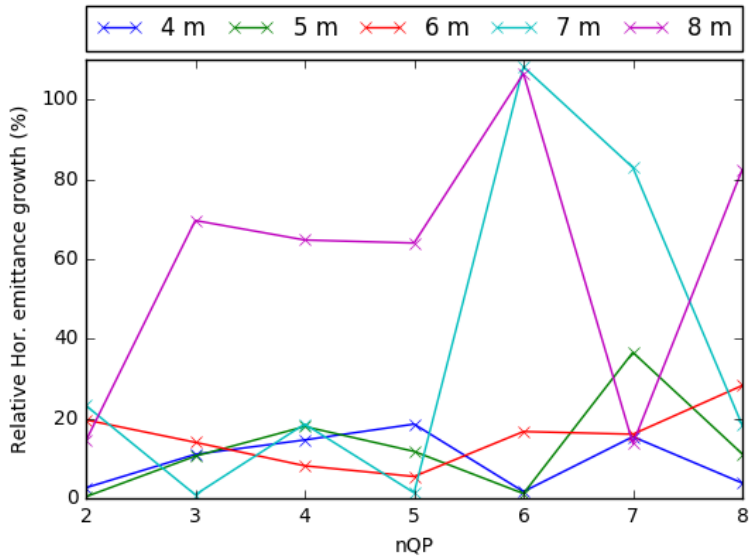
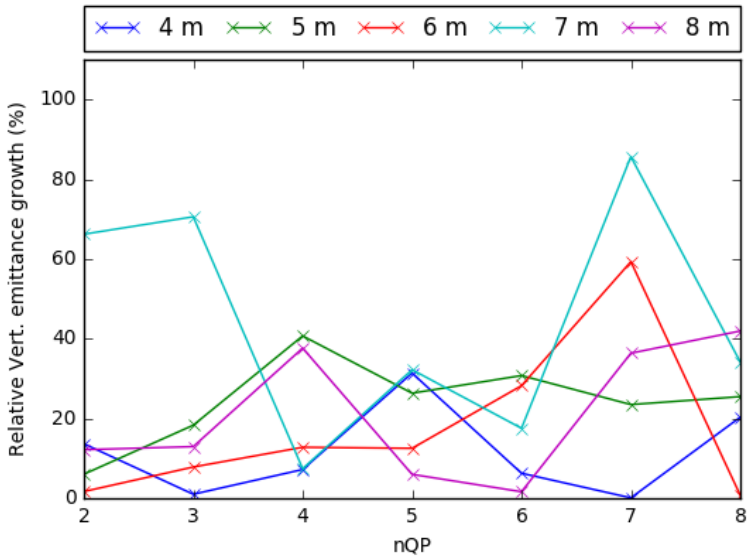
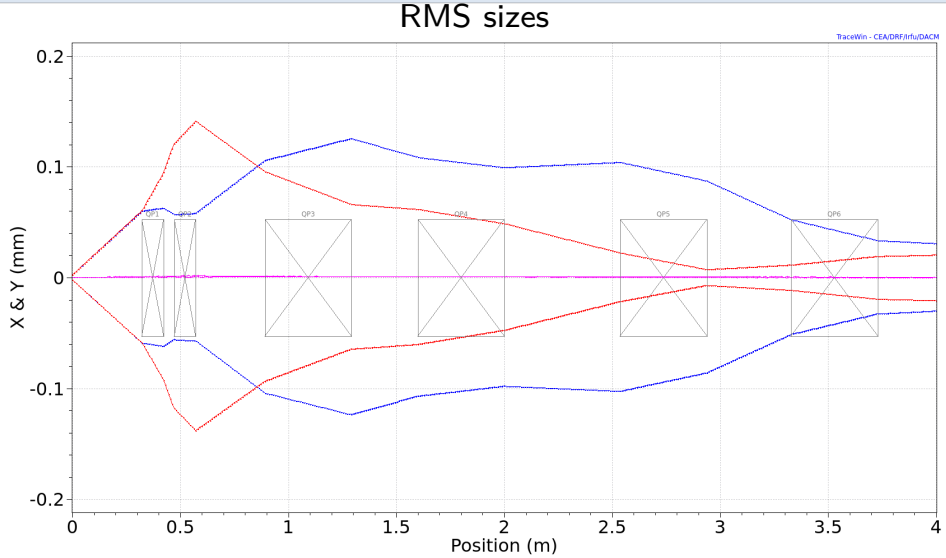
Cut in energy at ±1.0% (tracking with TraceWin)





2 PMQs and 4 m (1 GeV Rossi)

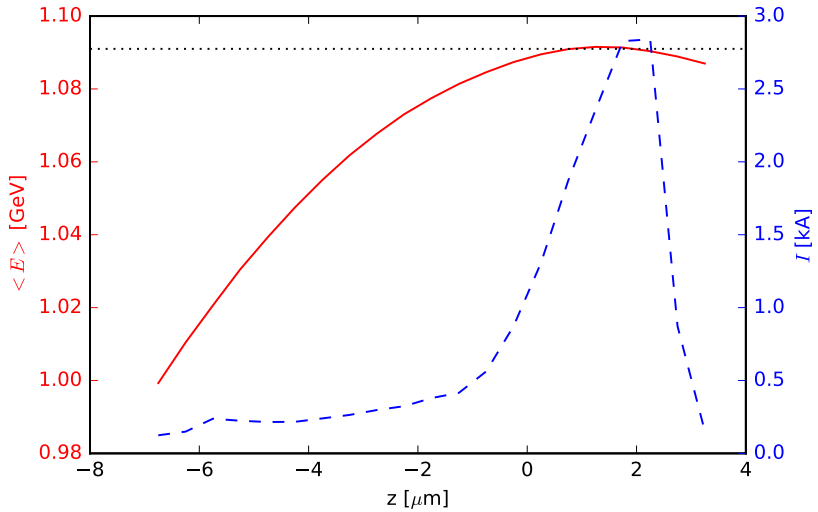


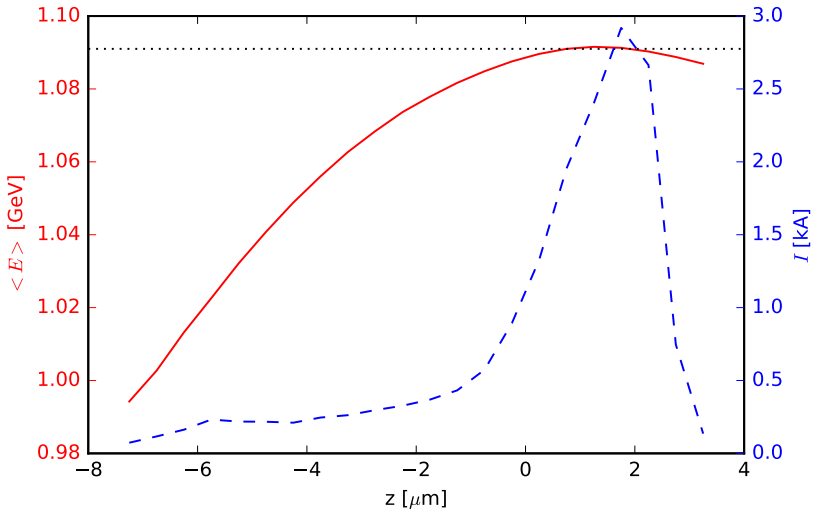
- Ref energy: 1.09 GeV.

⇒ Max. PMQ gradient: 181 T/m.

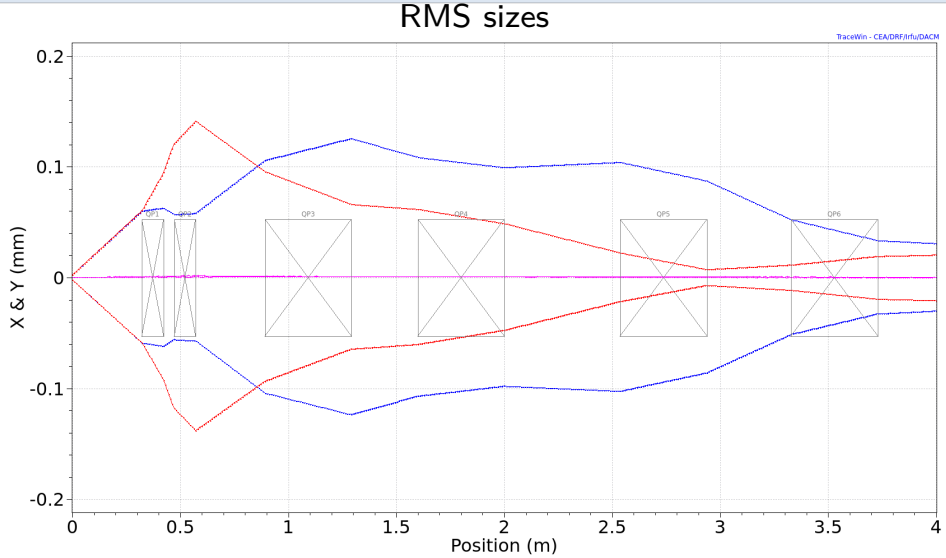
- Max. EMQ gradient: 18 T/m.
  Two weak EMQs (<10 T/m)

Initial/Final Current (bin: 0.5 μm) (from ASTRA).





2 PMQs and 4 m (1 GeV Rossi)

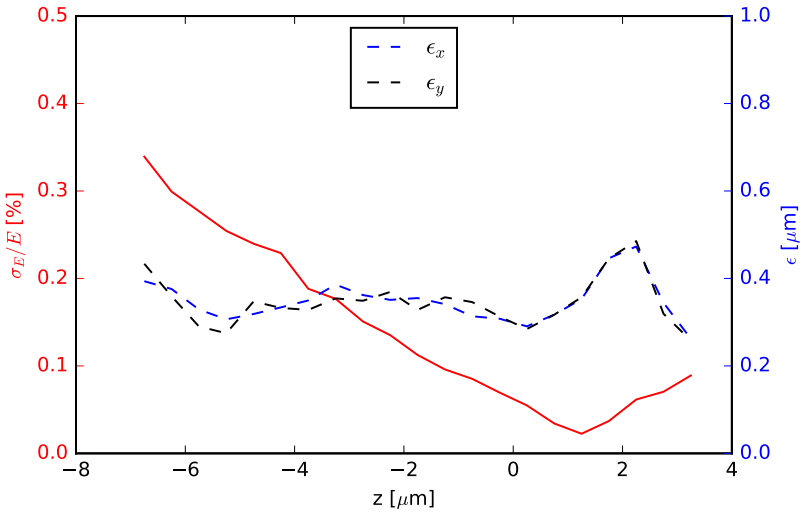


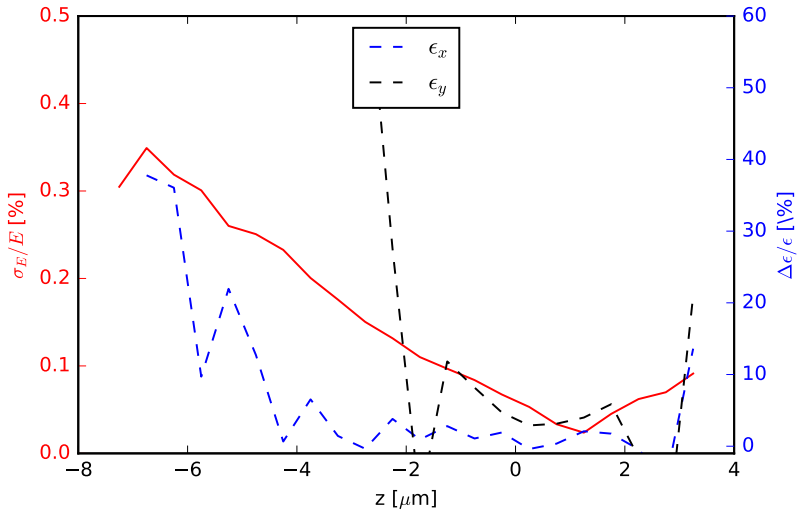
- Ref energy: 1.09 GeV.

⇒ Max. PMQ gradient: 181 T/m.

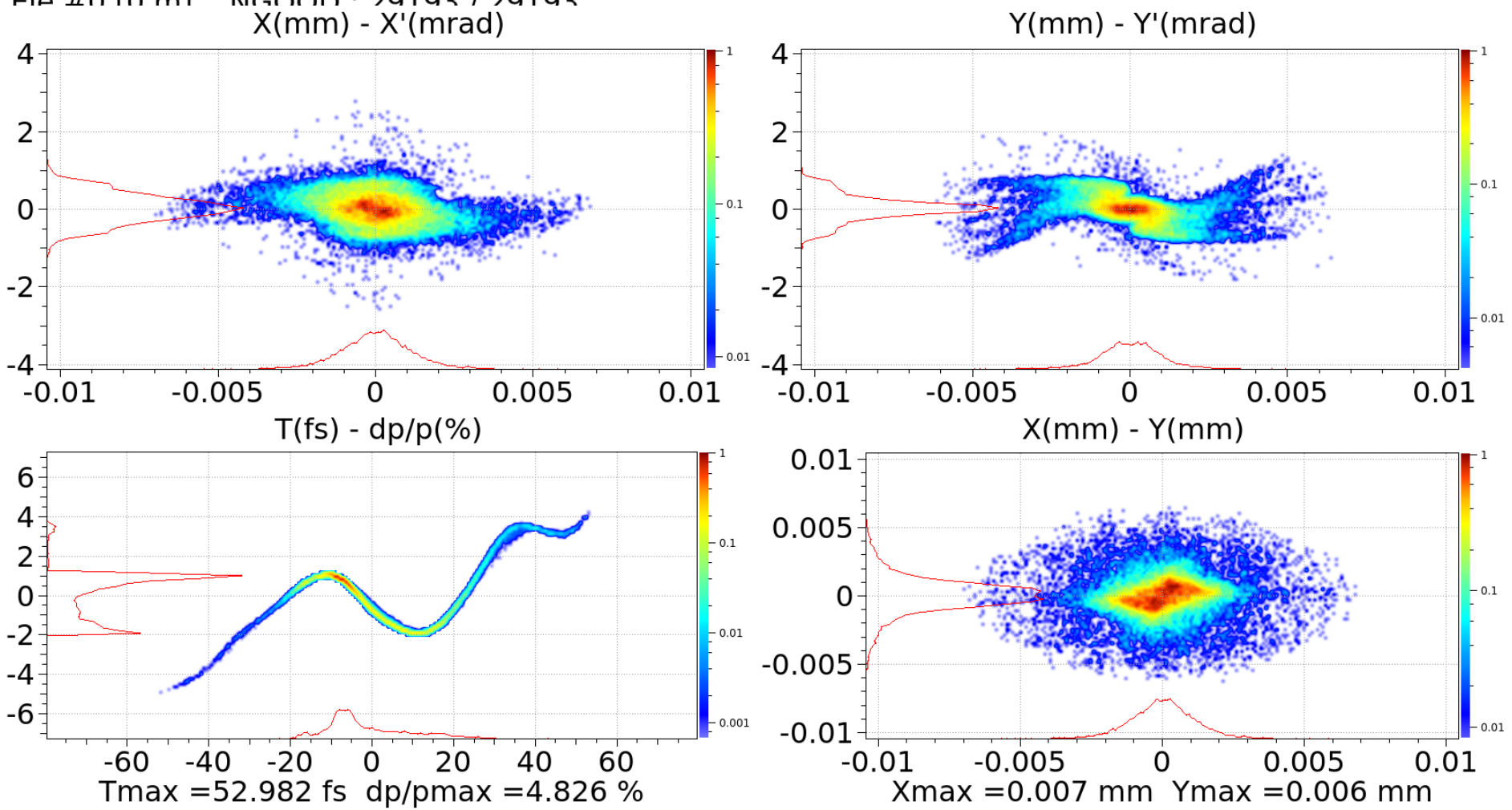
- Max. EMQ gradient: 18 T/m.
  Two weak EMQs (<10 T/m)

Initial/Final Norm emittance (bin: 0.5 μm) (from ASTRA).



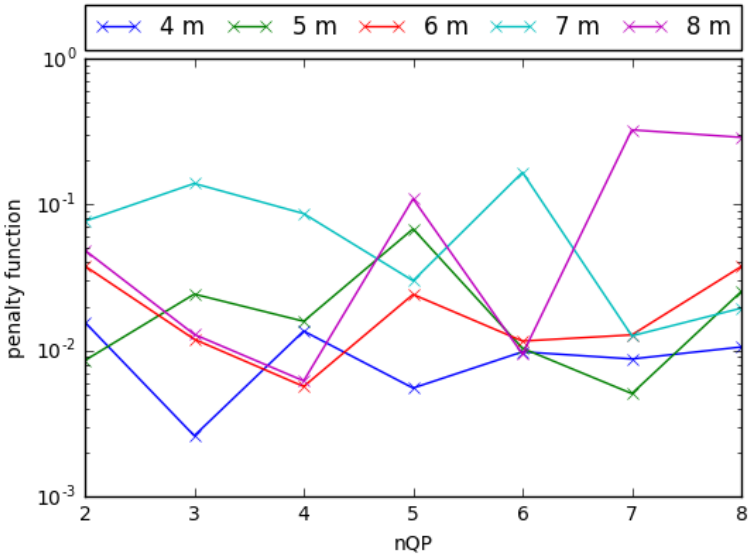


Distribution 1GeV Marocchino (INFN)



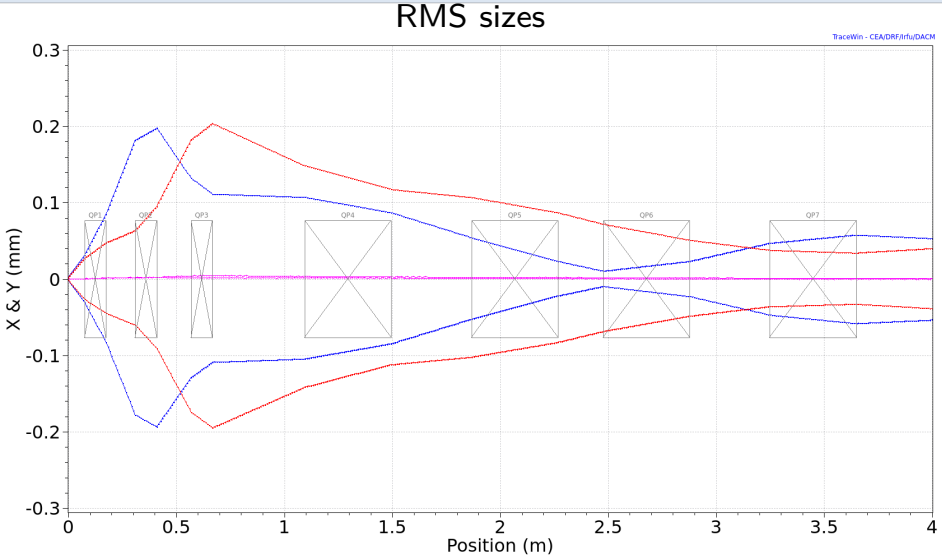
$\beta_{x,0} = 25$ mm, $\beta_{y,0} = 25$ mm, $\alpha_{x,0} = -1.8$, $\alpha_{y,0} = -1.8$, $\gamma_{x,0} = 175$ m^{-1}, $\gamma_{y,0} = 175$ m^{-1}

Transfer line (1 GeV Marocchino)



- Shorter transfer line is better.
- No gain in increasing the number of quadrupoles.
- Baseline: 3 PMQs followed by 4 EMQs for a total length of 4 m.
- Other solution if emittance growth balanced in both planes.

3 PMQs and 4 m (1 GeV Marocchino)

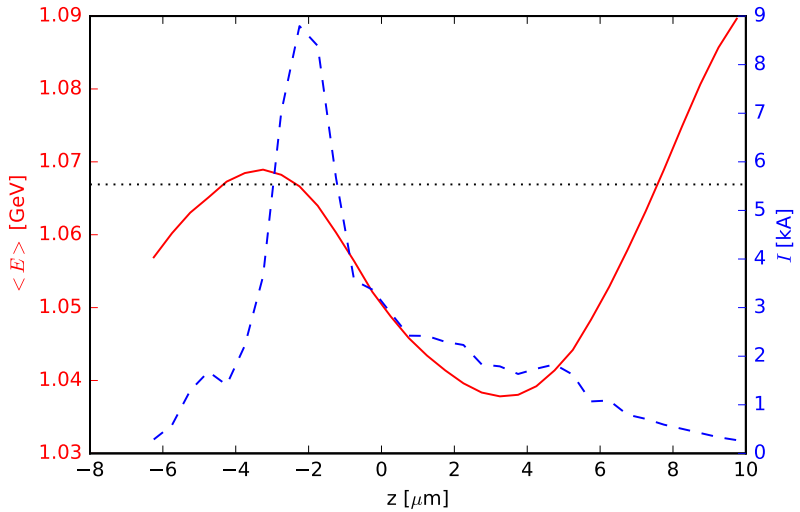


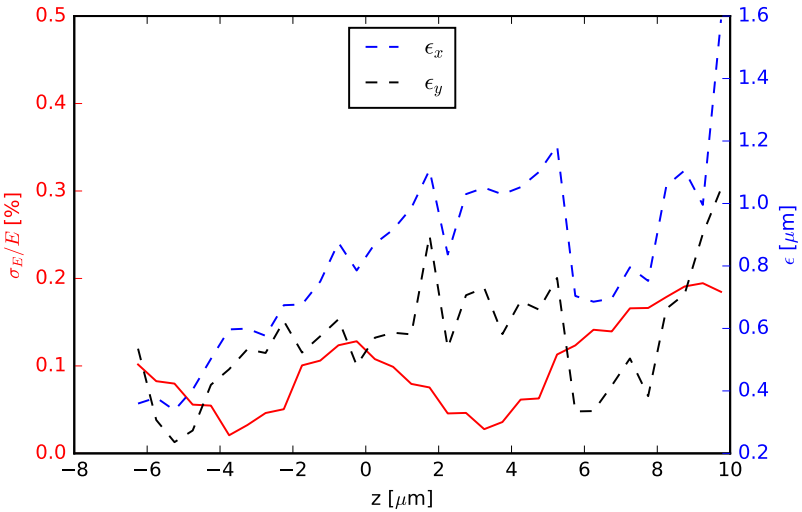
- Ref energy: 1.09 GeV.

⇒ Max. PMQ gradient: 198 T/m.

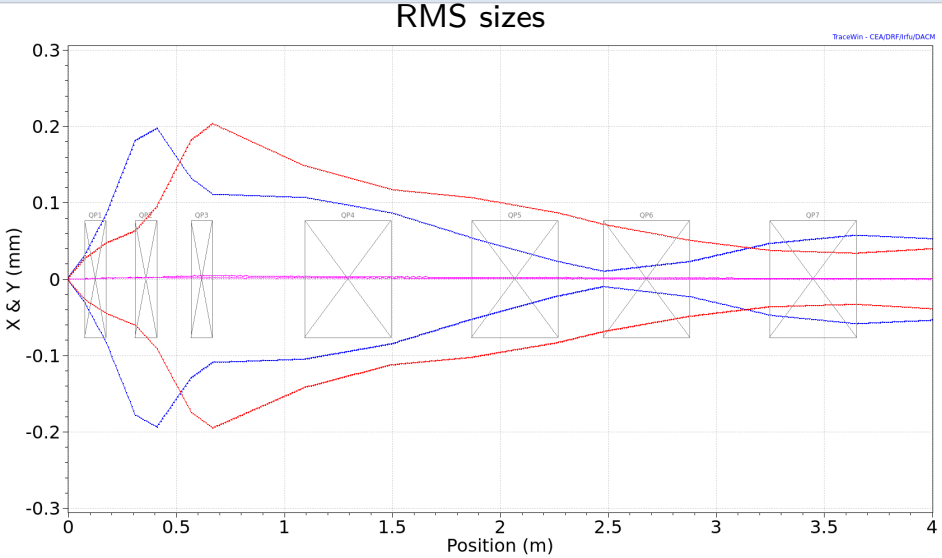
- Max. EMQ gradient: 18 T/m.
  Two weak EMQs (<10 T/m)

Slice emittance (bin: 0.5 μm) (from ASTRA). Initial conditions.





3 PMQs and 4 m (1 GeV Marocchino)

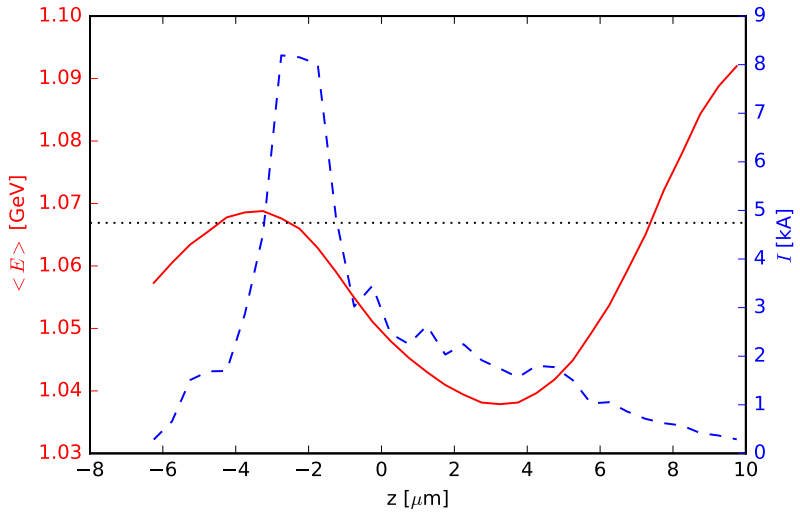


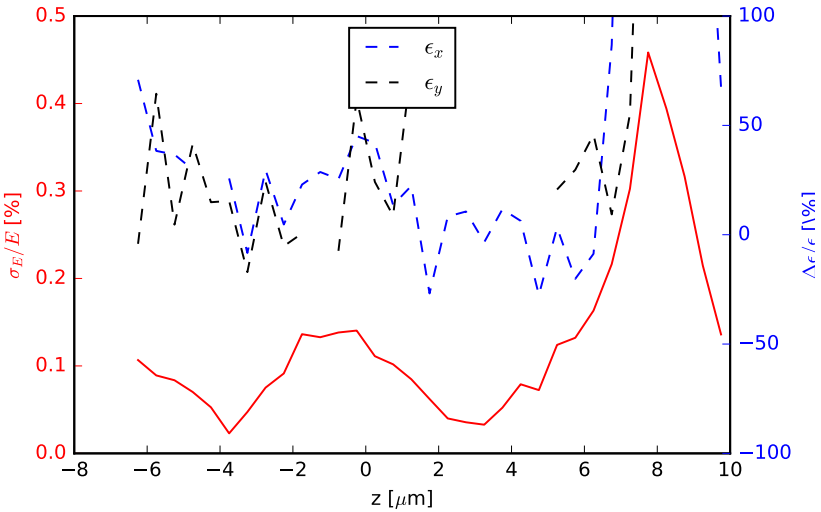
- Ref energy: 1.09 GeV.

⇒ Max. PMQ gradient: 198 T/m.

- Max. EMQ gradient: 18 T/m.
  Two weak EMQs (<10 T/m)

Slice emittance (bin: 0.5 μm) (from ASTRA). Final conditions.





Case of the 2-stage-transfer line

Input

- Total length: from 0.5 meters to 1.5 meters.
- Min: 30 mm between PMQs, 100 mm between EMQs, 50 mm after plasma.
- Length PMQ: 50 mm
- 4-10 PMQs.
- Maximum gradient of 600 T/m in PMQs.

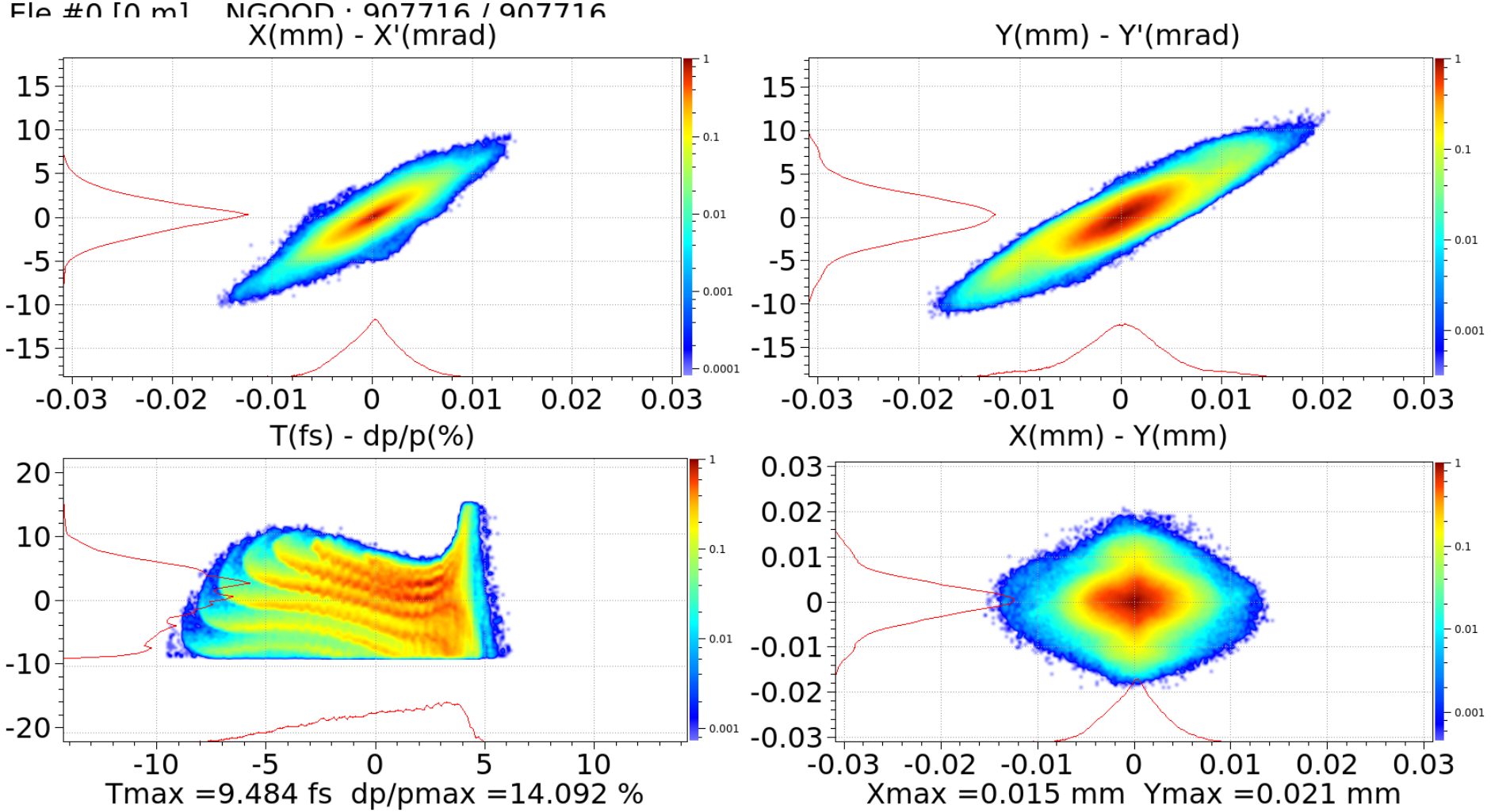
Variables

- Gradient and positions of the quadrupoles.

Constraints

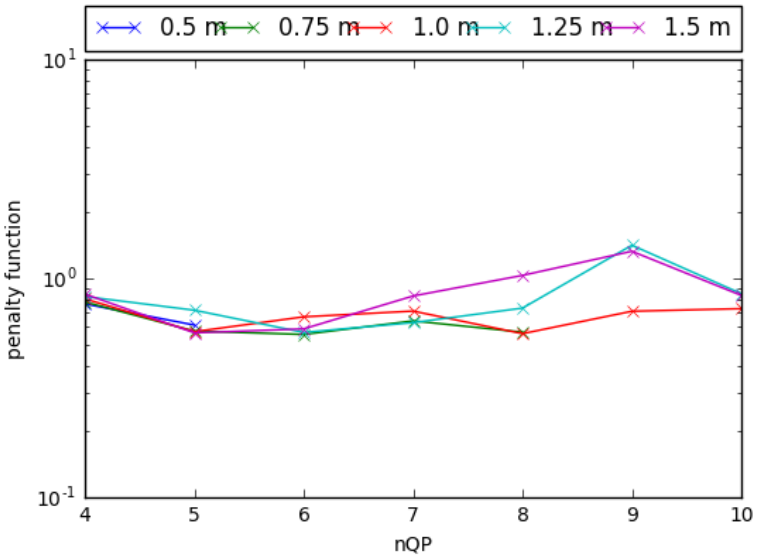
- Final Twiss parameters.
  $\beta_{x,1} = 30$ mm, $\beta_{y,1} = 30$ mm, $\alpha_{x,1} = 1.0$, $\alpha_{y,1} = 1.0$
- Minimisation of the emittance growth

Distribution Maynard (CNRS)



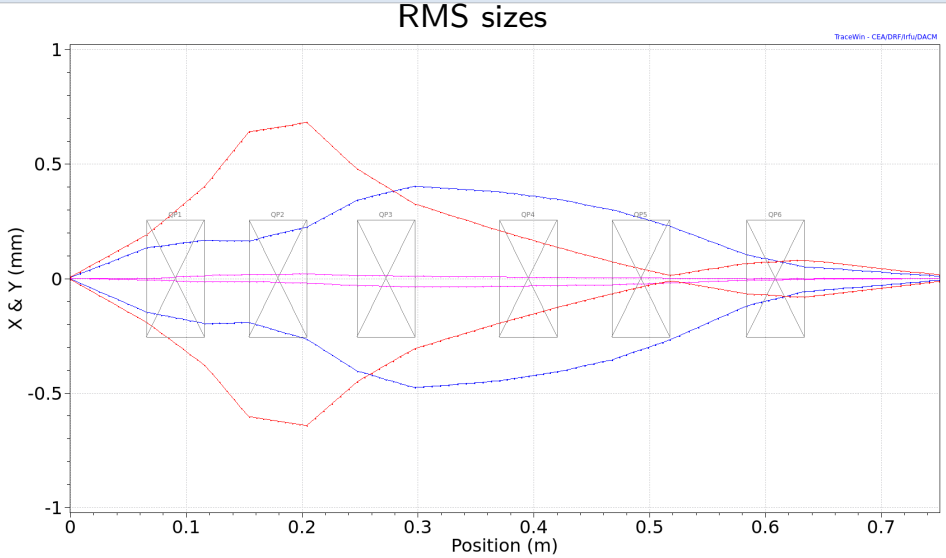
$\beta_{x,0} = 3$ mm, $\beta_{y,0} = 4$ mm, $\alpha_{x,0} = -2.0$, $\alpha_{y,0} = -2.1$, $\gamma_{x,0} = 1515$ m^{-1}, $\gamma_{y,0} = 1352$ m^{-1}

Transfer line (150 MeV Maynard)



- No gain in increasing the number of quadrupoles.
- Baseline: 6 PMQs for a total length of 0.75 m.
- Other solution if emittance growth balanced in both planes.

6 PMQs and 0.75 m (150 MeV)

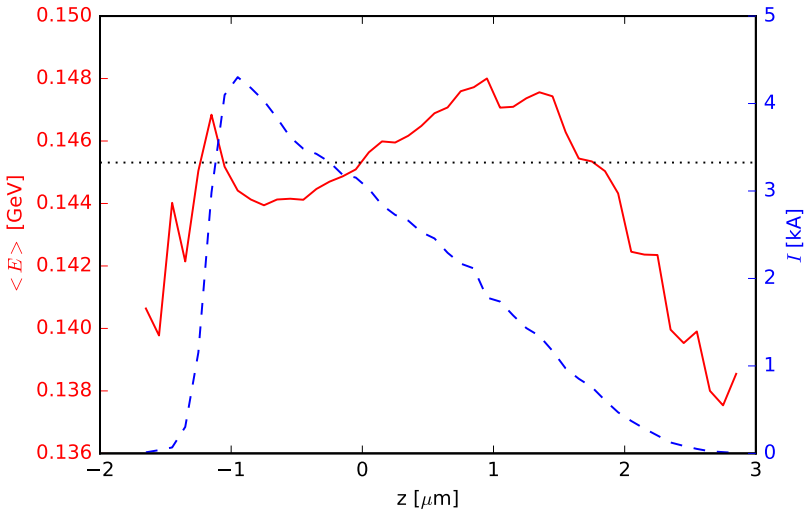


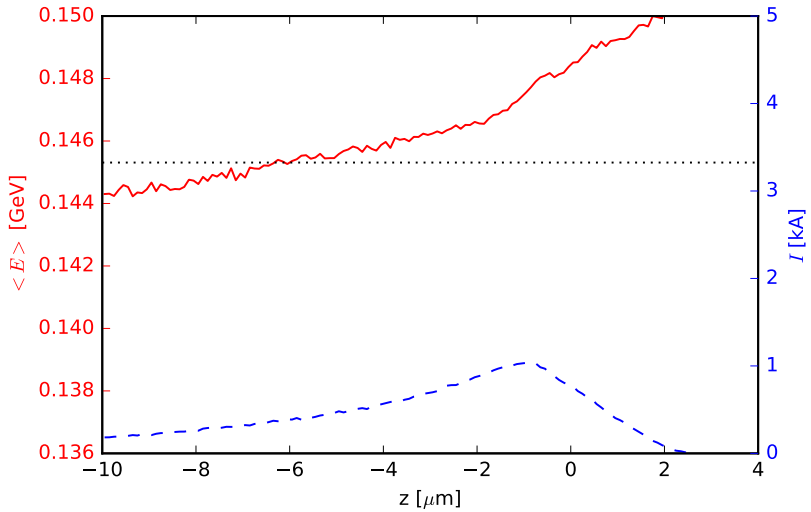
- Ref energy: 145 MeV.

$\Rightarrow$ Max. PMQ gradient: 220 T/m.

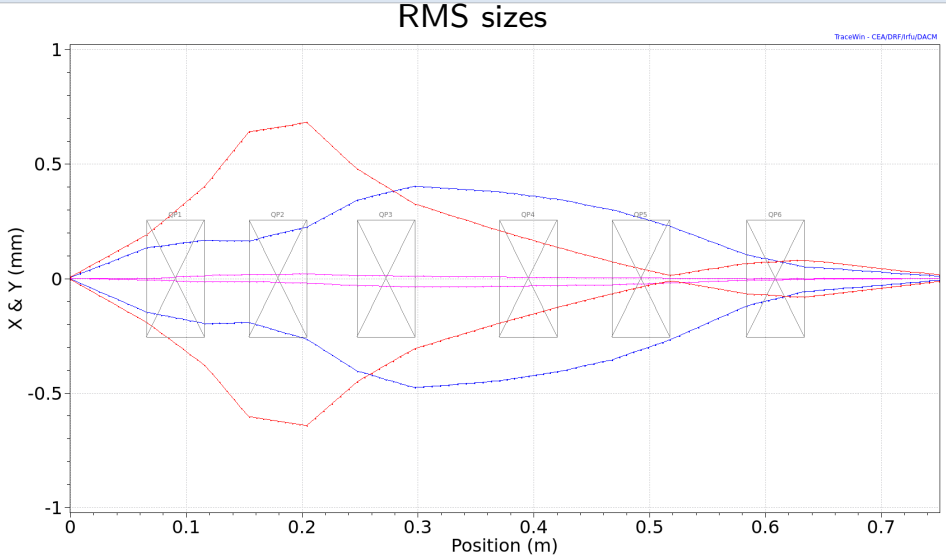
- The velocity spread is not negligible: correlation time-energy at the end of the transfer line.

Initial/Final Current (bin: 0.1 μm) (from ASTRA).





6 PMQs and 0.75 m (150 MeV)

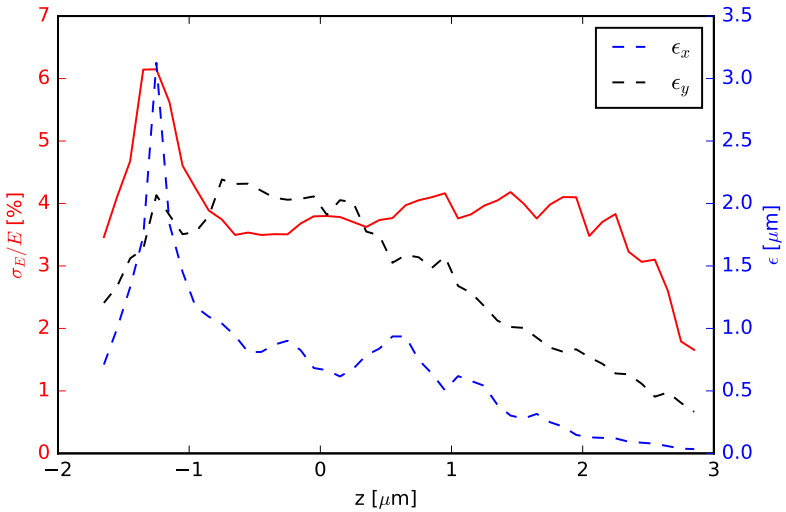


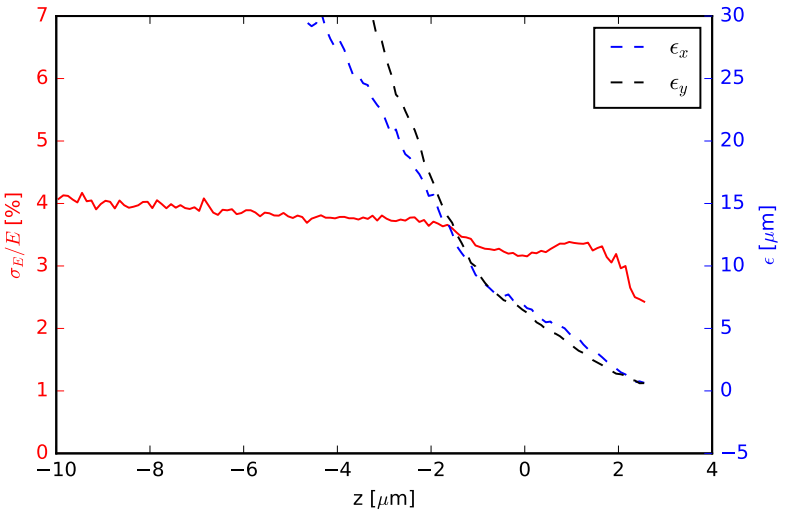
- Ref energy: 145 MeV.

$\Rightarrow$ Max. PMQ gradient: 220 T/m.

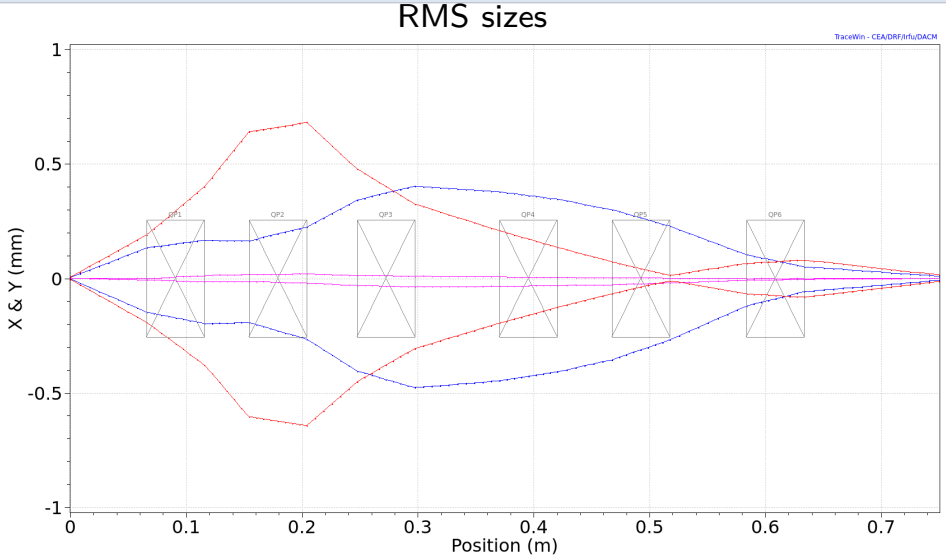
- The velocity spread is not negligible: correlation time-energy at the end of the transfer line.

Initial/Final Norm emittance (bin: 0.1 μm) (from ASTRA).





6 PMQs and 0.75 m (150 MeV)

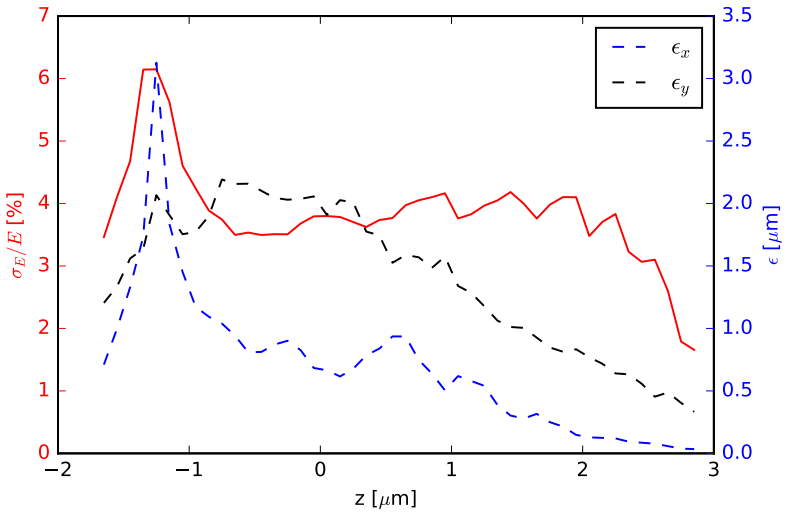


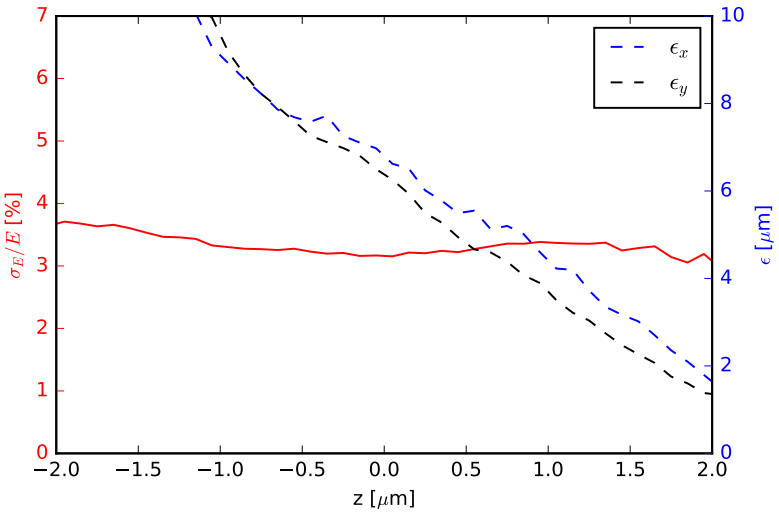
- Ref energy: 145 MeV.

⇒ Max. PMQ gradient: 220 T/m.

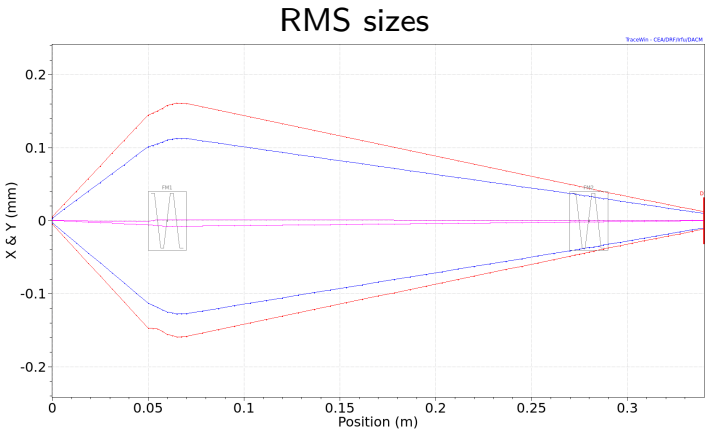
- The velocity spread is not negligible: correlation time-energy at the end of the transfer line.

Initial/Final Norm emittance (bin: 0.1 μm) (from ASTRA).





2 plasma cells (150 MeV)

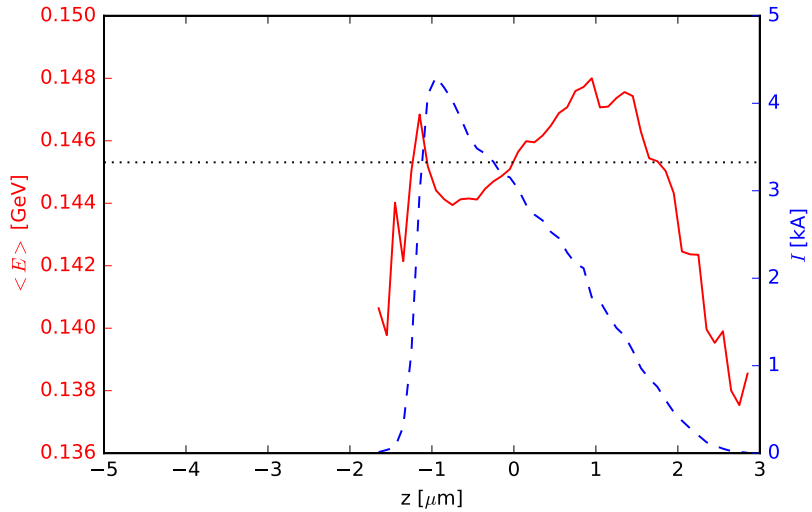


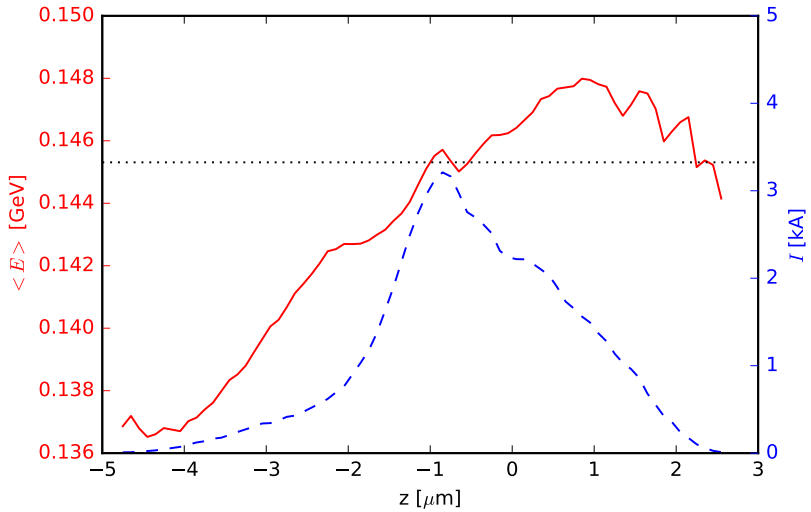
- Ref energy: 145 MeV.
- Length of the plasma cell: 20 mm.
- Minimum aperture: ≈ 1 mm.

⇒ Max. gradient: 425 T/m.

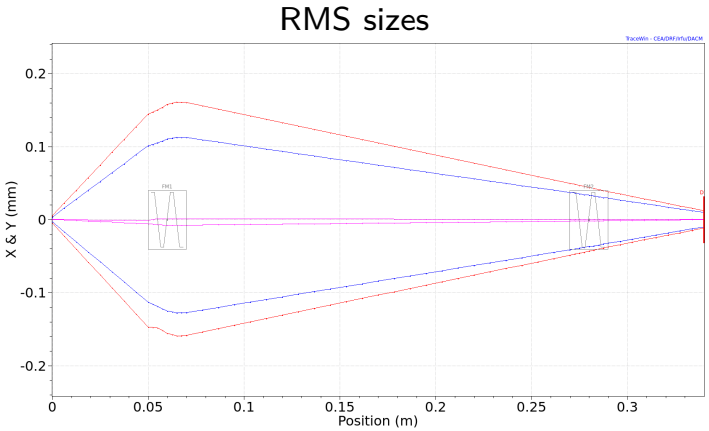
- Total length: 340 mm.

Initial/Final Current (bin: 0.1 μm) (from ASTRA).





2 plasma cells (150 MeV)

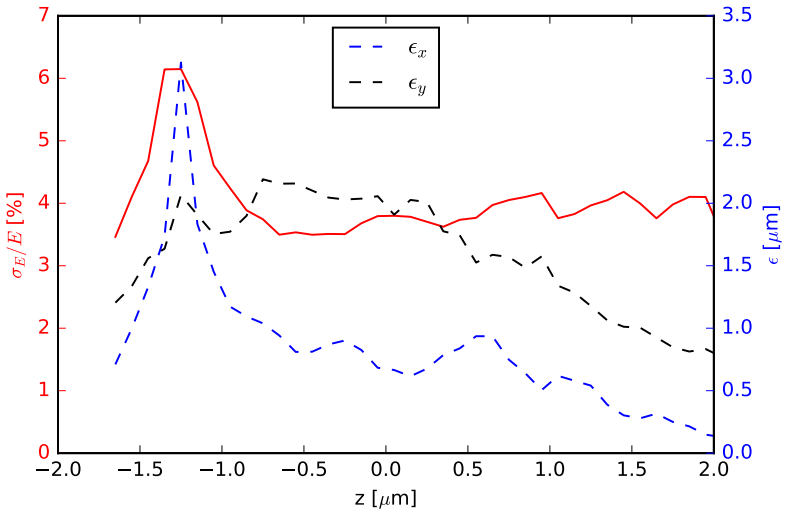


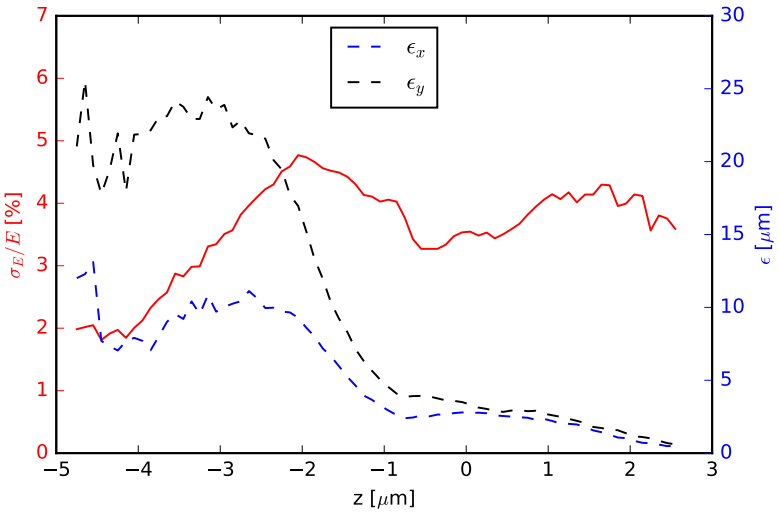
- Ref energy: 145 MeV.
- Length of the plasma cell: 20 mm.
- Minimum aperture: ≈ 1 mm.

⇒ Max. gradient: 425 T/m.

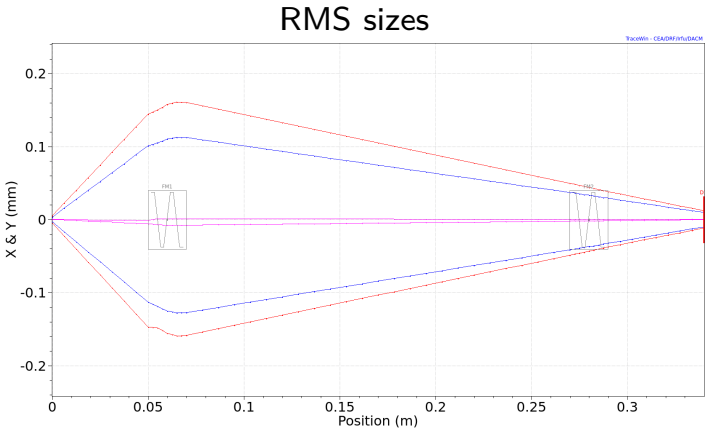
- Total length: 340 mm.

Initial/Final Norm emittance (bin: 0.1 μm) (from ASTRA).





2 plasma cells (150 MeV)

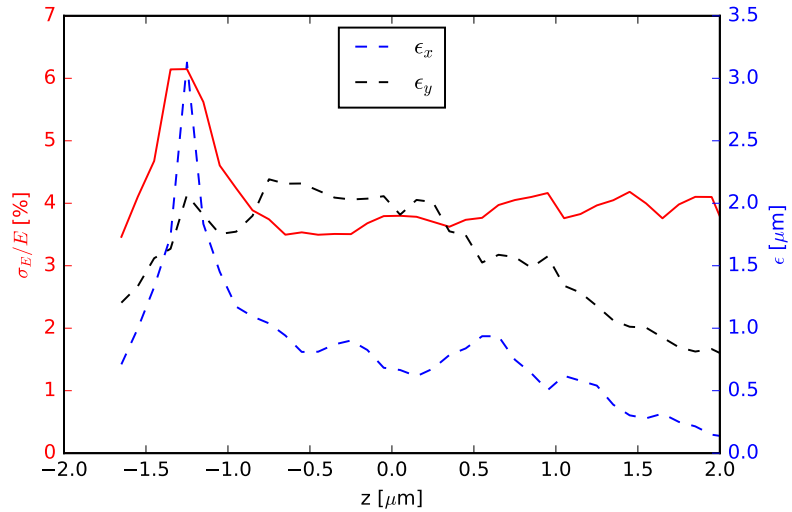


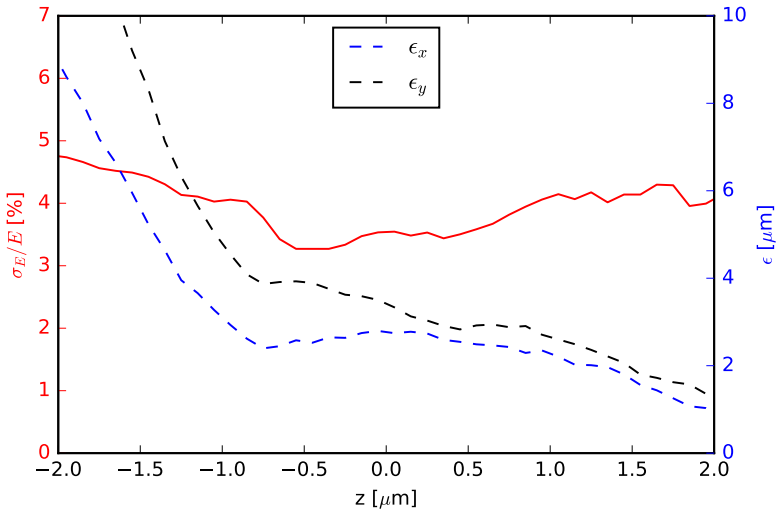
- Ref energy: 145 MeV.
- Length of the plasma cell: 20 mm.
- Minimum aperture: $\approx$ 1 mm.

$\Rightarrow$ Max. gradient: 425 T/m.

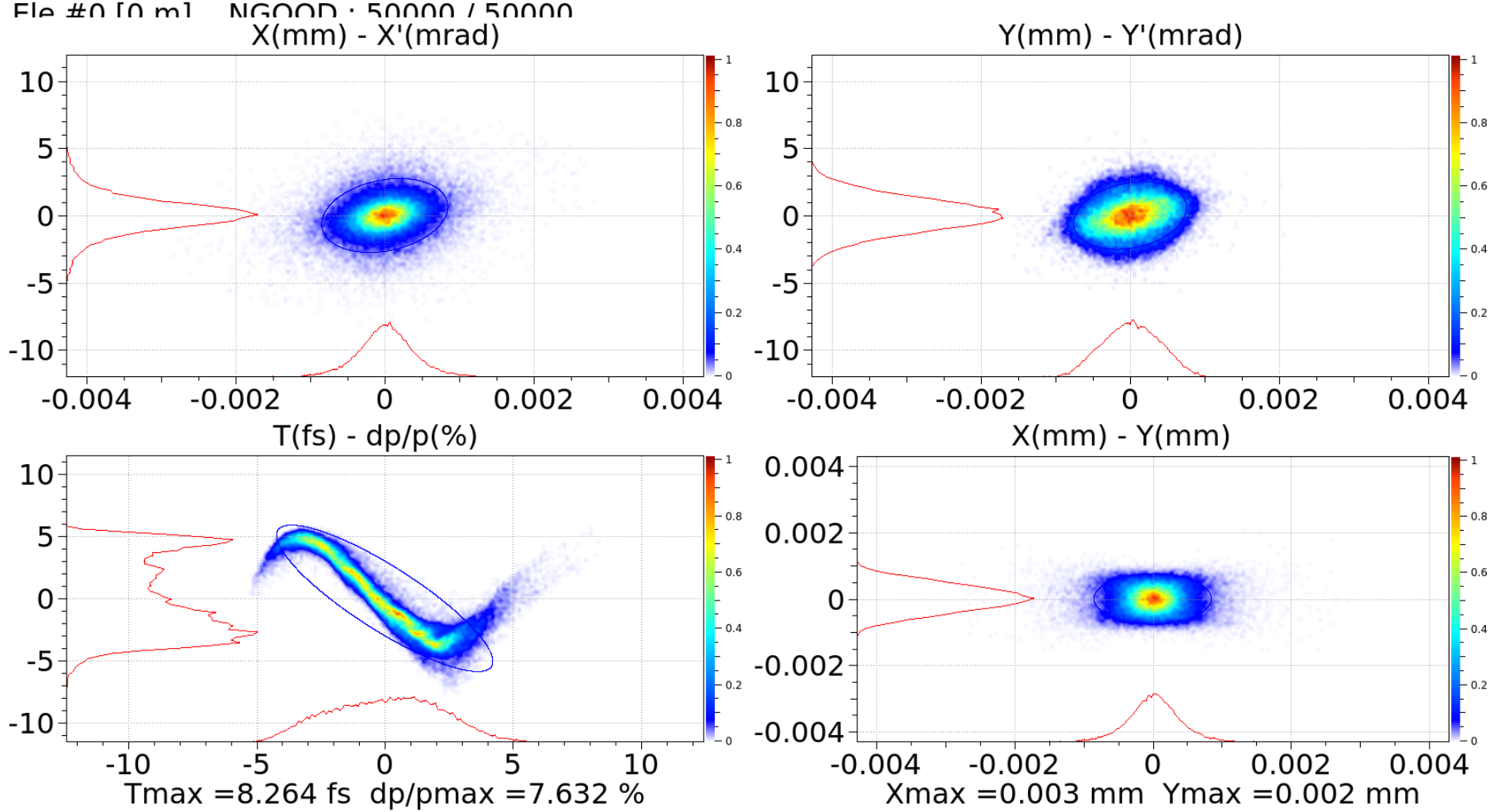
- Total length: 340 mm.

Initial/Final Norm emittance (bin: 0.1 μm) (from ASTRA).





Distribution ReMPI Tomassini (INO)



$\beta_{x,0} = 0.3$ mm, $\beta_{y,0} = 0.3$ mm, $\alpha_{x,0} = -0.2$, $\alpha_{y,0} = -0.2$, $\gamma_{x,0} = 3467$ m^{-1}, $\gamma_{y,0} = 3467$ m^{-1}

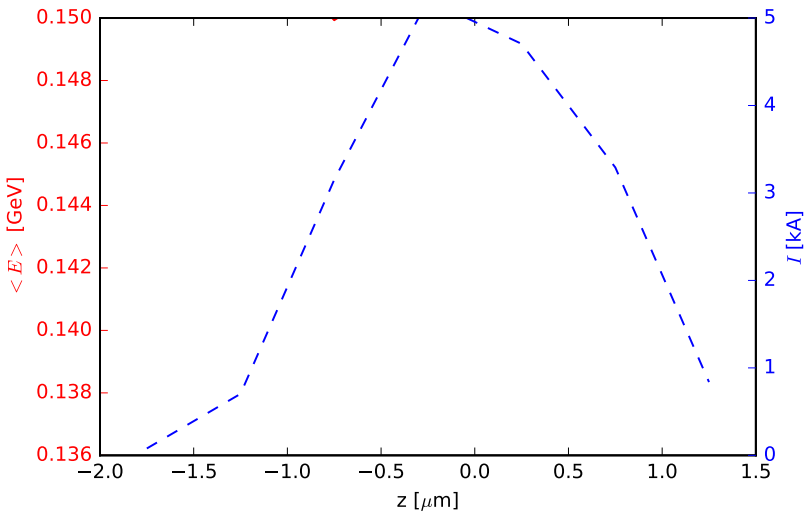
6 PMQs and 0.75 m (150 MeV)

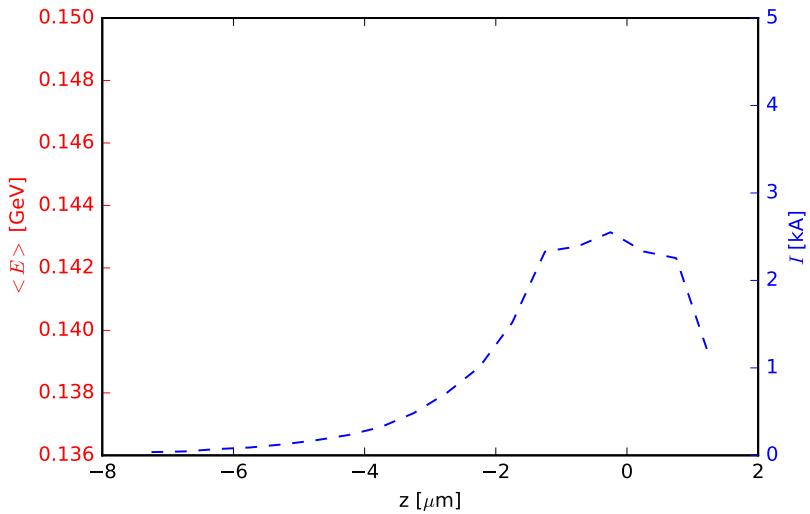
- Ref energy: 145 MeV.

⇒ Max. PMQ gradient: 169 T/m.

- The velocity spread is not negligible: correlation time-energy at the end of the transfer line.

Initial/Final Current (bin: 0.1 μm) (from ASTRA).





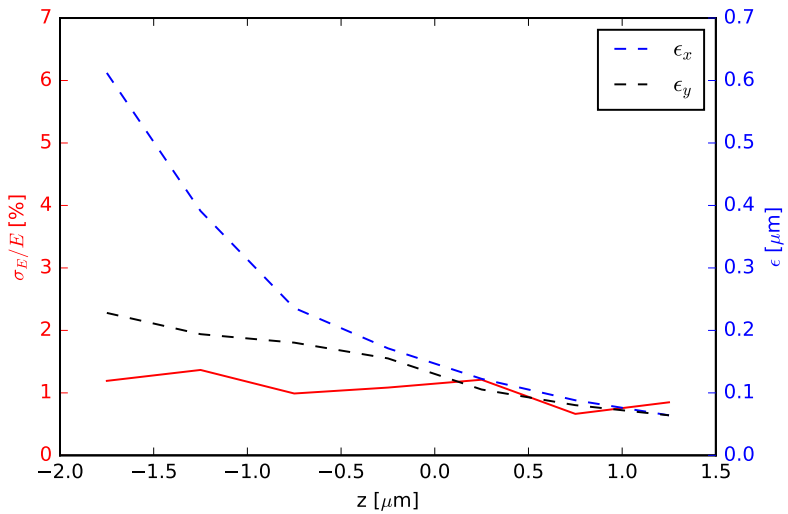
6 PMQs and 0.75 m (150 MeV)

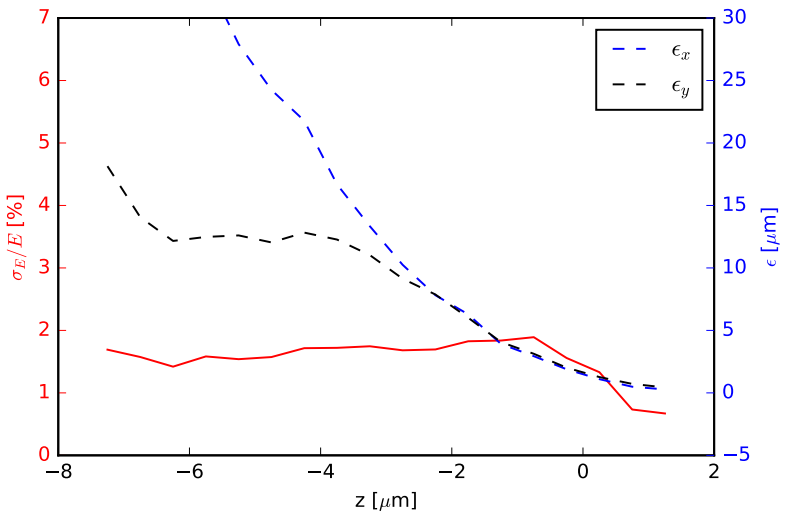
- Ref energy: 145 MeV.

⇒ Max. PMQ gradient: 169 T/m.

- The velocity spread is not negligible: correlation time-energy at the end of the transfer line.

Initial/Final Norm emittance (bin: 0.1 μm) (from ASTRA).





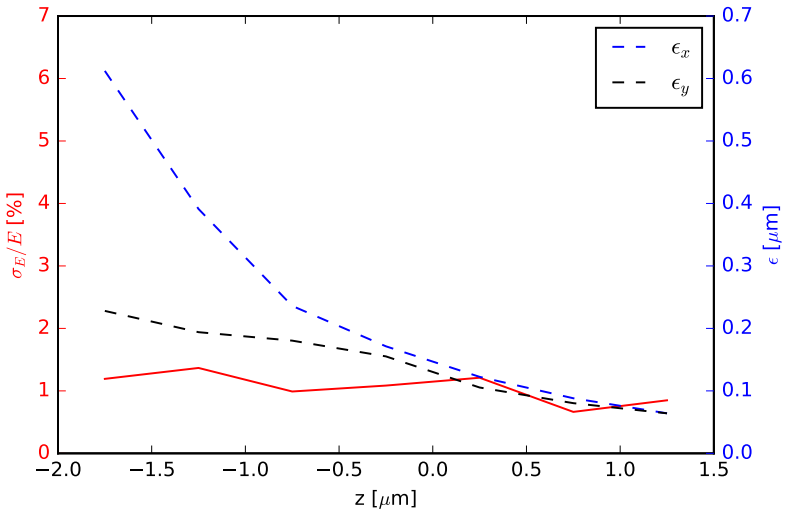
6 PMQs and 0.75 m (150 MeV)

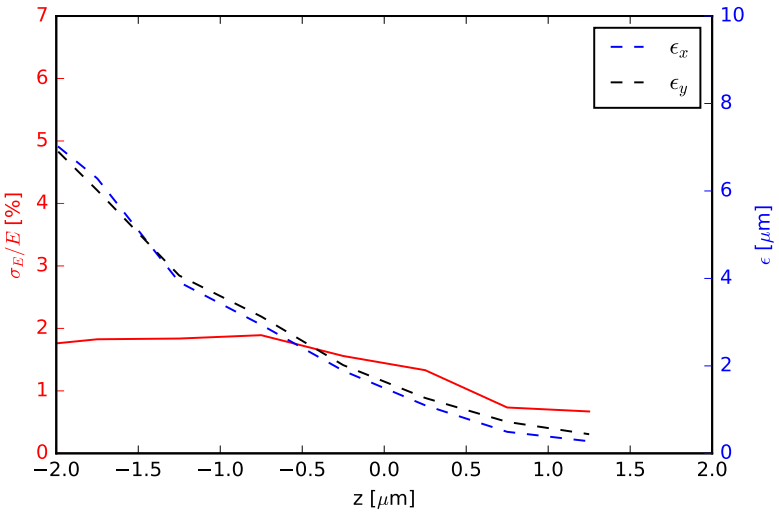
- Ref energy: 145 MeV.

⇒ Max. PMQ gradient: 169 T/m.

- The velocity spread is not negligible: correlation time-energy at the end of the transfer line.

Initial/Final Norm emittance (bin: 0.1 μm) (from ASTRA).





Conclusions

- Several transfer lines were realized to transport different initial distributions coming from different plasma schemes.
- Currently, the transfer line for a 5 GeV beam to a FEL, for a 1 GeV beam to FEL and 2-stage-scheme for a 150 MeV beam have been addressed.
- Results are encouraging for the 5 GeV beam. With a total of 6 QPs and a total length of 4-5 m, the beam can be transported up to the FEL with a growth of the slice emittance of only a few percent's. As expected, the smaller the initial divergence is, the less the emittance grows.
- At 1 GeV, the LWFA beam fits the specifications. A lerge amount of work was done by EuSPARC teams for PWFA (see CDR).
- For the 2-stage line, the emittance increase is not negligible (the emittance grows by a factor 4 to 5) because of the energy spread. An alternative with plasma lenses has been investigated.

Outlook

- To refine the transfer lines: to freeze some parameters to make the comparison easier between different distributions.
- To include space charge effects (relevant at 150 MeV). First studies have begun (strategy was first to see if we can find solutions with no charge effects).
- To improve the model and to check emittance calculation (use of macros developed as discussed in Lisbon on November 2017).
- To iterate with WP6 for FEL preformance and to check the magnet parameters is realistic (gradient and inter-distance).
- To realize doglegs to fit WP7 needs.