Beam Optics Studies - Emittance Growth

Paul Bogdan Jurj

Imperial College London

paul.jurj13@imperial.ac.uk

February 21, 2019

Non-linear emittance growth

- Excluding the beam-material interactions in the cooling channel, the 4-D transverse RMS emittance of the beam can be affected by non-linear effects
- The non-linear effects that contribute to optical heating come in multiple flavours:
  - High gradient/curvature field related effects
  - Kinematic, due to non-paraxial motion
  - Chromatic, due to non-zero spread in total momenta
- A map-based approach is currently explored, using the MaryLie/Impact code (Alex Dragt, Rob Ryne)

MaryLie/Impact code - Background

- Expands the Hamiltonian around the reference orbit:

$$H = H_0 + H_1 + H_2 + H_3 + H_4 + H_5 + H_6$$

  where the indices represent the order in the deviation variables.

- H_0 and H_1 have no contribution, while H_2 generates the linear dynamics.
- First non-linear term H_3 is purely chromatic
- H_4 predominantly contains geometric terms that are: independent of B_z, proportional to B_z and proportional $\partial^2 B_z/\partial z^2$. There are some terms that also have chromatic dependence.
- H_5 contains chromatic terms

Hamiltonian terms up to H_4 (K_4)

$$K_0 = 1/(\beta^2\gamma^2\ell),$$

$$K_1 = 0,$$

$$K_2 = \frac{P_x^2 + P_y^2}{2\ell} - \frac{B_o}{2\ell}(XP_y - YP_x) + \frac{B_o^2}{8\ell}(X^2 + Y^2) + \frac{P_\tau^2}{2\beta^2\gamma^2\ell},$$

$$K_3 = \frac{P_\tau(P_x^2 + P_y^2)}{2\beta\ell} - \frac{B_o P_\tau(XP_y - YP_x)}{2\beta\ell} + \frac{B_o^2 P_\tau(X^2 + Y^2)}{8\beta\ell} + \frac{P_\tau^3}{2\beta^3\gamma^2\ell},$$

$$K_4 = \frac{P_x^4 + 2P_x^2P_y^2 + P_y^4}{8\ell} - \frac{B_o(P_x^2 + P_y^2)(XP_y - YP_x)}{4\ell} + \frac{B_o^2(X^2P_x^2 + Y^2P_y^2)}{16\ell}$$

$$+ \frac{3B_o^2(X^2P_y^2 + Y^2P_x^2)}{16\ell} - \frac{B_o^2 XP_x YP_y}{4\ell} + \frac{(B_2 - B_o^3)(X^2 + Y^2)(XP_y - YP_x)}{16\ell} + \frac{(B_o^4 - 4B_oB_2)(X^4 + 2X^2Y^2 + Y^4)}{128\ell}$$

$$+ \frac{(3 - \beta^2)P_\tau^2(P_x^2 + P_y^2)}{4\beta^2\ell} - \frac{(3 - \beta^2)B_oP_\tau^2(XP_y - YP_x)}{4\beta^2\ell} + \frac{(3 - \beta^2)B_o^2P_\tau^2(X^2 + Y^2)}{16\beta^2\ell} + \frac{(5 - \beta^2)}{8\beta^4\gamma^2\ell}.$$

$$\begin{aligned} P_\tau &= -(1/\beta_0)\{[1 + (2\delta + \delta^2)\beta_0^2]^{1/2} - 1\} \\ &= -\beta_0\delta + (\delta^2/2)(\beta_0^3 - \beta_0) - (\delta^3/2)(\beta_0^5 - \beta_0^3) + \cdots \end{aligned}$$

MaryLie/Impact code - Implementation

- ML/I numerically computes the Lie algebraic transfer maps.
- Uses the longitudinal coordinate z as the independent variable.
- Magnetic field computed from the on-axis field and its derivatives up to 4th order.
- On-axis field modelled same as in MAUS, using cylindrical current sheets.
- Provided the coil parameters from the run MAUS geometry under study.
- Read in the particles extracted from the run under study.

Data

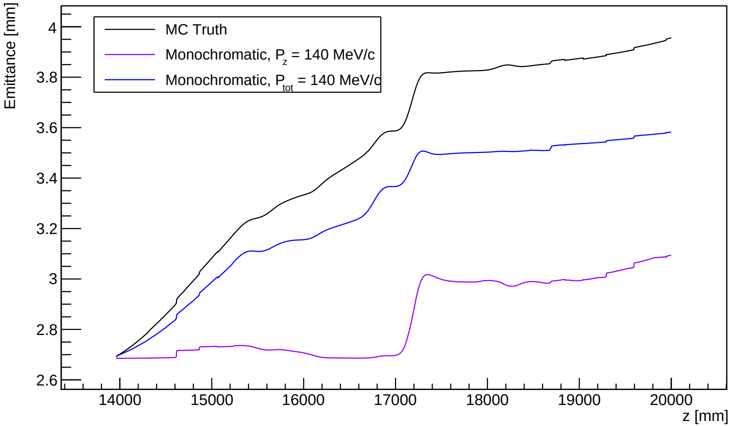
- Analysis H57a, Run 10448
- 2017-02-7 setting
- Flip mode, 3T in SSU (M1, M2 on), 2T in SSD (M1 off, **M2 on**)
- LiH Empty (None)
- 140 MeV/c, nominal emittance 3 mm, $\beta_\perp = 500$ mm

Cuts

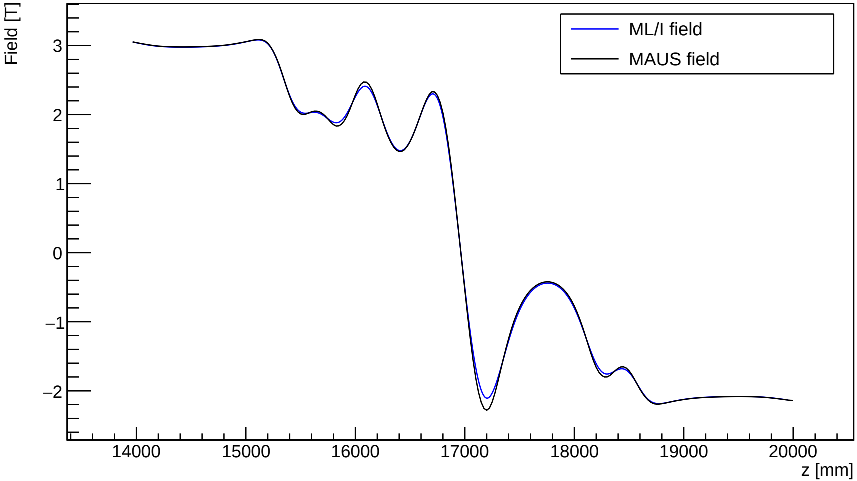
- 1 SP in both TOF0 and TOF1
- TOF01 consistent with muon peak : 29 - 31 ns
- Energy loss between TOF1 and TKD consistent with μ
- TKU: 135 MeV/c $<$ total momentum $<$ 145 MeV/c
- TKD: 110 MeV/c $<$ total momentum $<$ 170 MeV/c
- χ^2/ndf $<$ 4 (TKU & TKD)
- Transmission cut: analyse only events with 1 track in each tracker
- Fiducial radius cut: r $<$ 150 mm (TKU & TKD)
- Diffuser radius cut: r $<$ 90 mm

Preliminary data-driven MAUS simulations

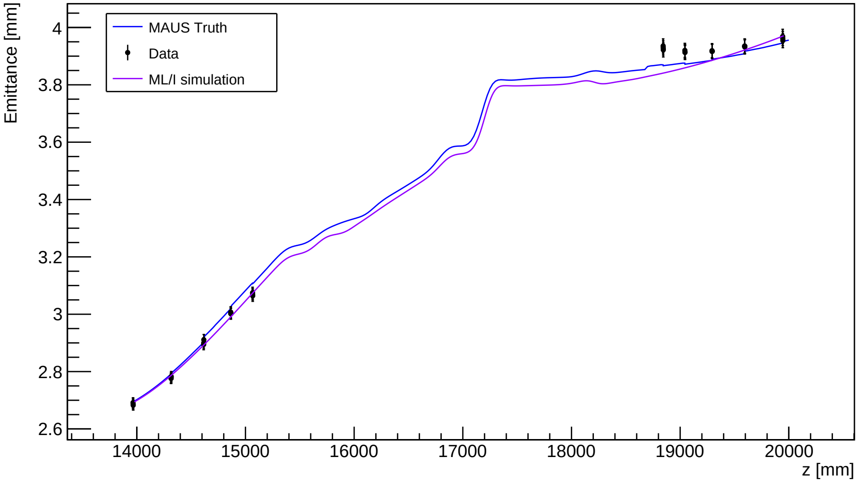
- Used particles extracted from data, run 10448.
- a) Changed initial P_z such that initial $P_{tot} = 140$ MeV/c.
- b) Changed their initial P_z to 140 MeV/c.



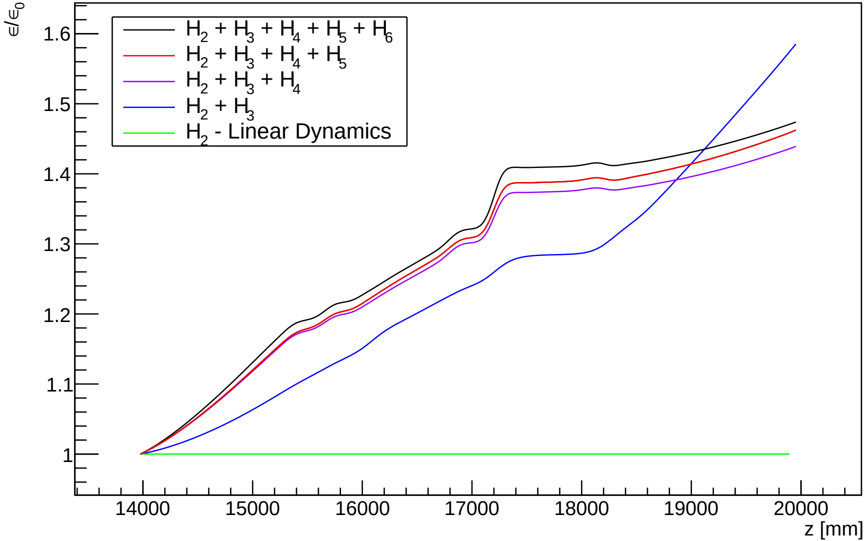
Magnetic field



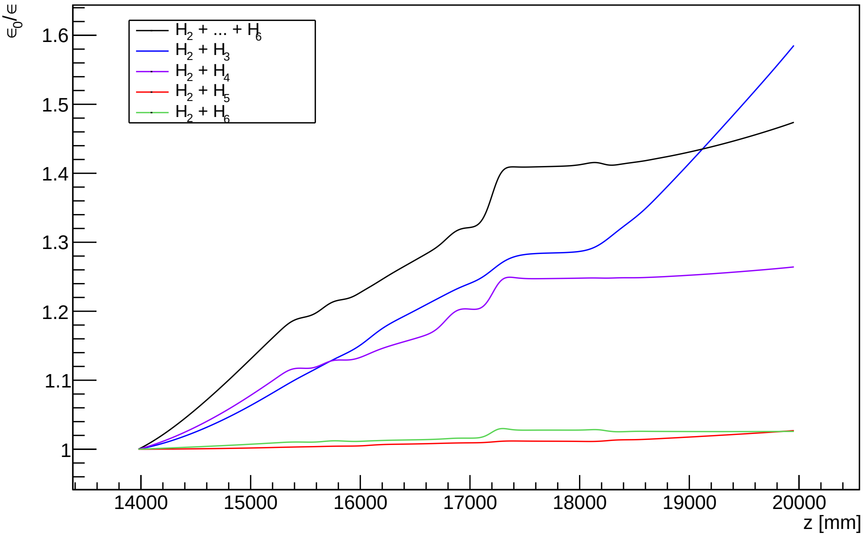
Emittance - ML/I vs MC Truth vs Data



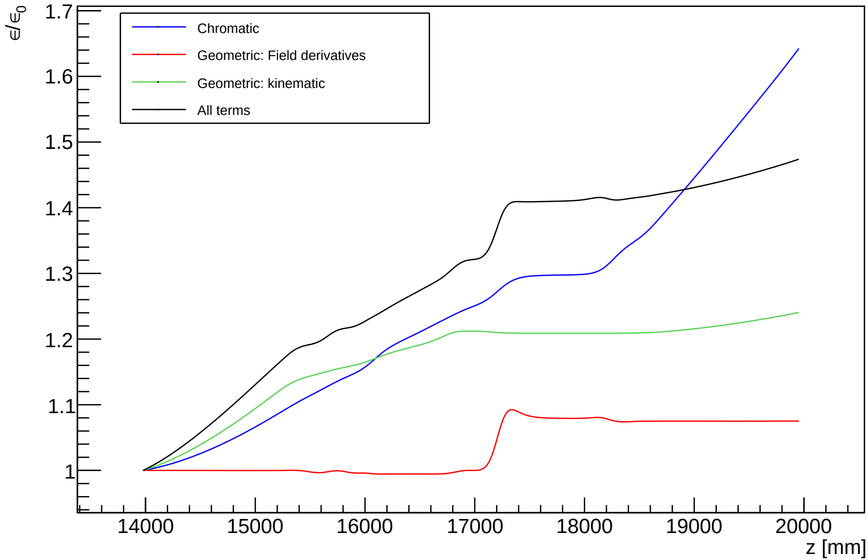
Emittance growth ML/I



Emittance growth - Individual expansion terms

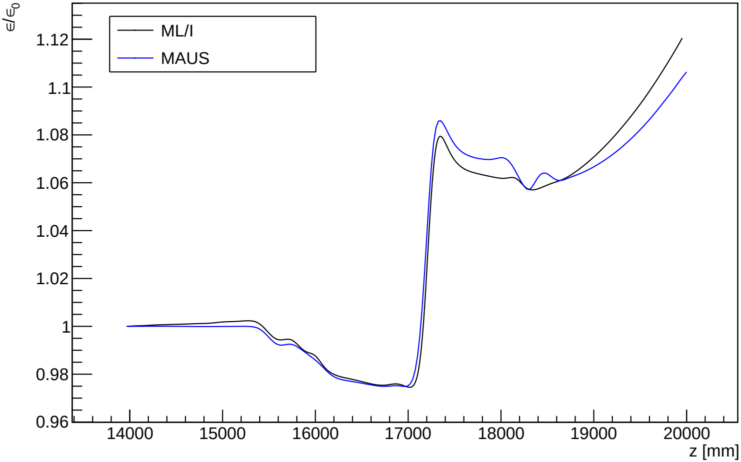


Emittance growth - Chromatic vs Geometric

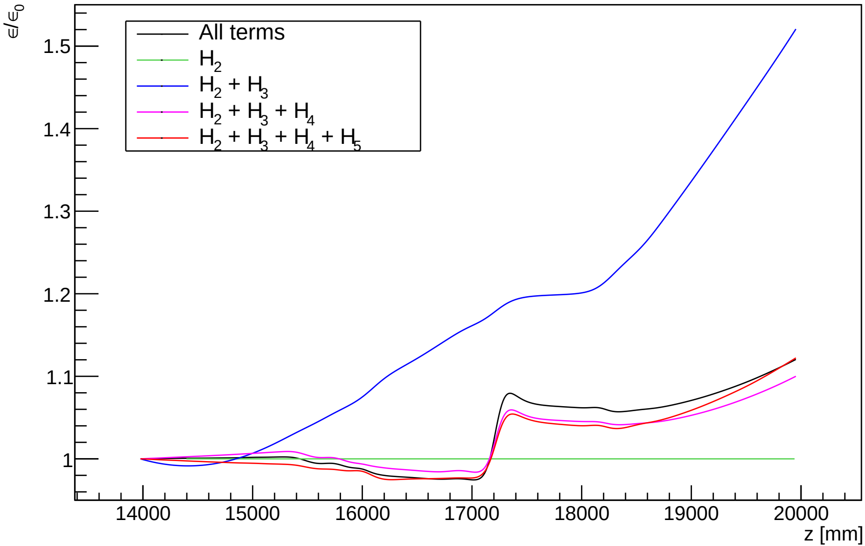


Monochromatic P_z beam

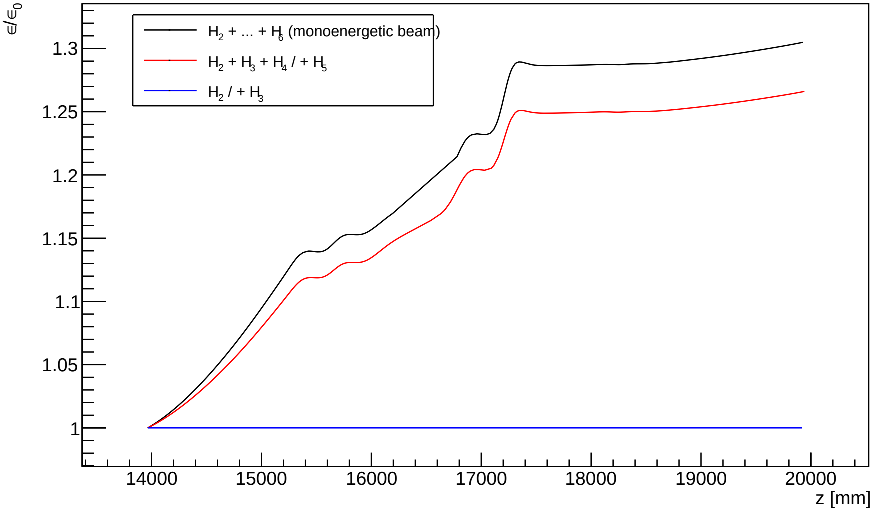
- Used particles extracted from data, run 10448. Changed their initial P_z to 140 MeV/c.



Monochromatic P_z beam - emittance growth ML/I



Monochromatic P_{tot} beam - emittance growth ML/I



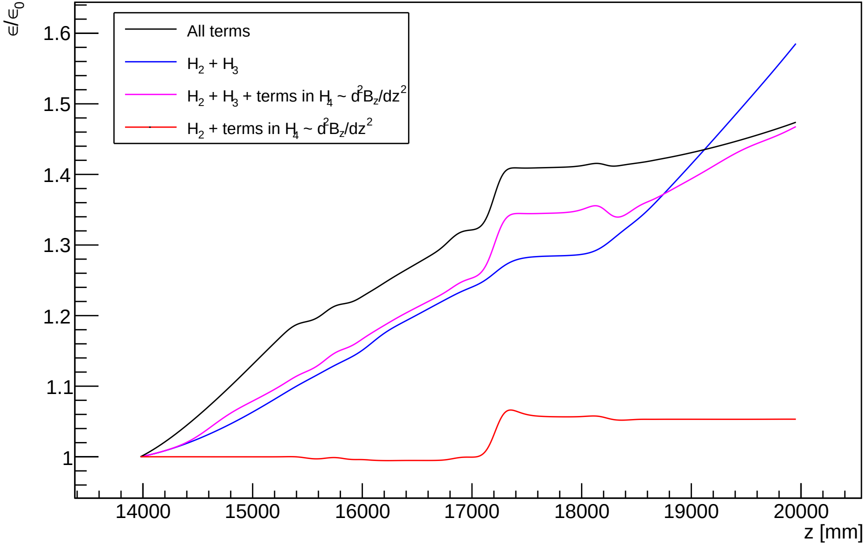
Summary

- Good agreement between Data, MAUS MC Truth and ML/I code
- Chromatic effects seem to dominate; the large curvature of the field (2nd derivative) just downstream of the absorber also has a significant contribution.
- Next steps
  - Apply this study to other beam and channel settings.
  - Study the decoupled x/y phase-space evolution in the channel.
  - Include the coil misalignments in ML/I code.

Thank you!

Backup

Emittance growth ML/I

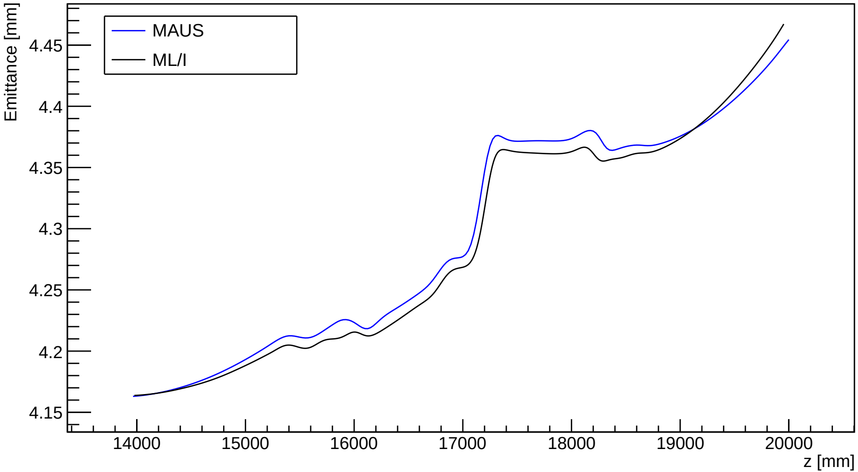


Analysis Procedure

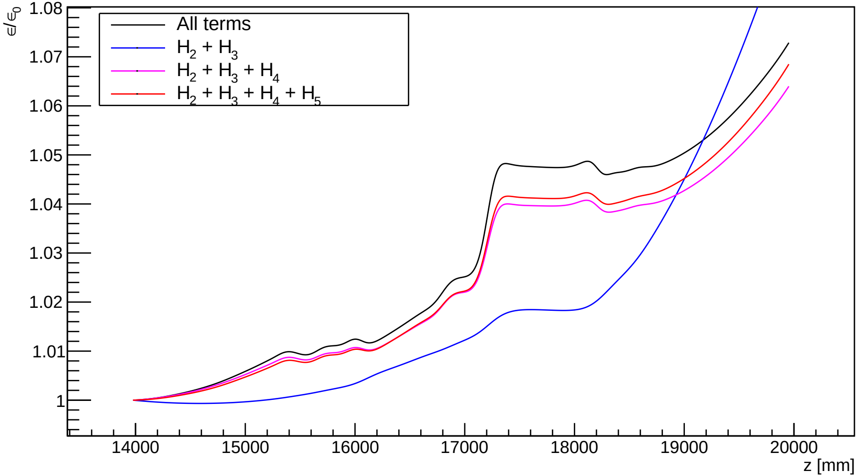
- All the particles that survive the cuts are extracted at the first SciFi plane in station 5 of TKU $\rightarrow$ fed them into the MC simulation

- Calculate beam optics of the MC simulated beam at a series of virtual planes along the cooling channel, between both stations 5 of TKU and TKD; also reconstruct the simulated data

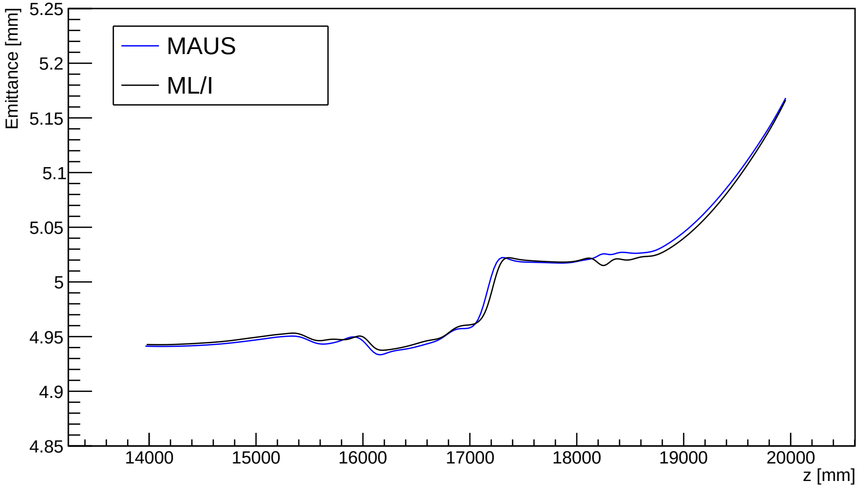
Run 10445, 4mm



Emittance growth ML/I



Run 10450, 6mm



Emittance growth ML/I