The Proscan Gantry 3 Proton Therapy Beamline

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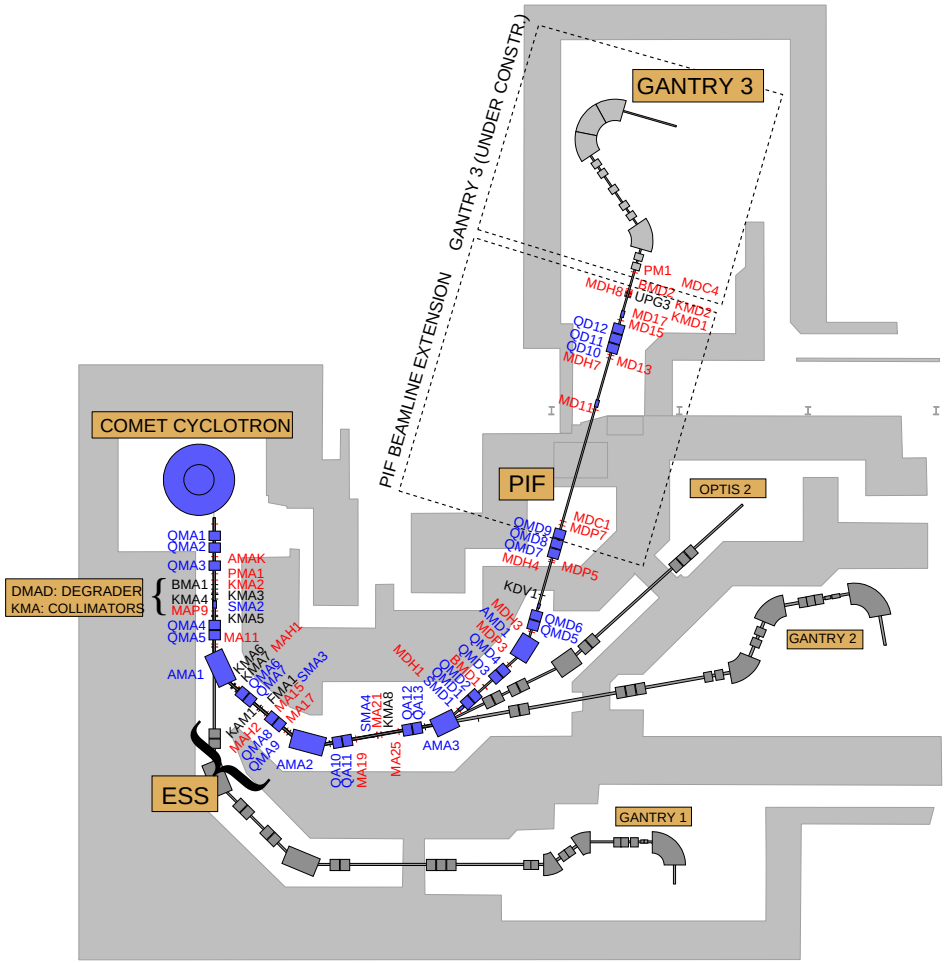
Outline

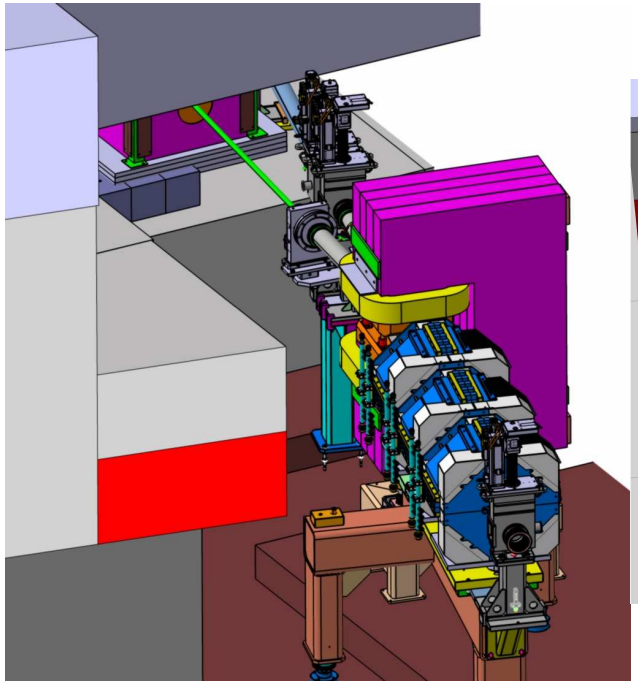
1. Proscan layout w/o new gantry 3 beamline
2. Beamline optics design goals
3. Intensity compensation
4. Beam optics computations
5. Model versus simulations.
6. Summary.

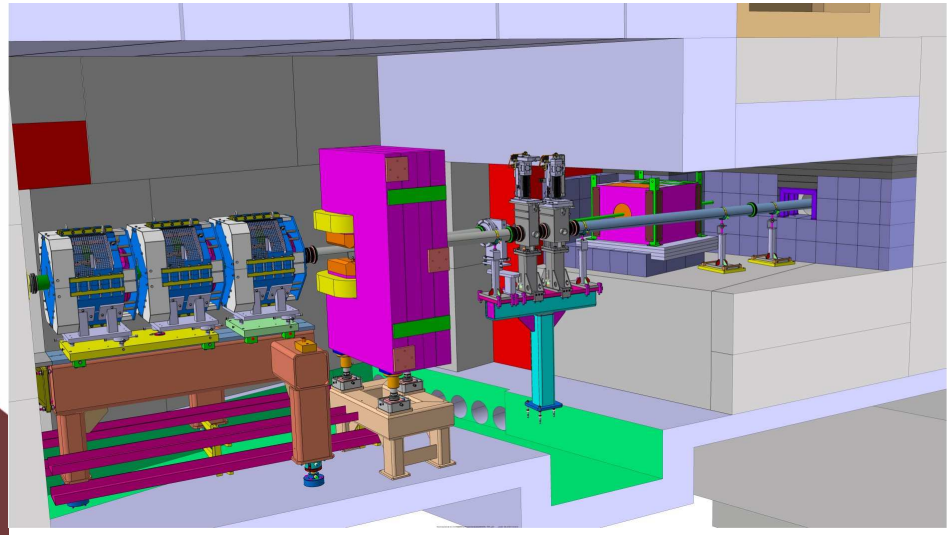
The Proscan Facility Layout



250 MeV superconducting cyclotron (COMET), carbon wedge degrader (DMAD) and moveable collimators (KMA), energy Selection System (ESS), proton irrad. facility (PIF).

Proton Irradiation Facility (PIF)





New Layout of the PIF vault: 10° bending magnet for PIF operation. Magnet off: Beam towards Gantry 3.

The Beam Optics Design Goals

The proton beam at transition point to Gantry 3 should

1. have a well-defined energy.
2. be achromatic (i.e. dispersion and derivative zero).
3. have limited and well-known momentum spread $\leq 0.7\,\%$.
4. be round: $\sigma_{11} = \sigma_{33}$
5. have double waist: $\sigma_{12} = \sigma_{34} = 0$.
6. The beam intensity $I(E)$ should follow a predefined energy dependence.

Reason for Intensity Compensation

Due to degrader, when going from 250 to 70 MeV

1. emittance increases from 2π to $> 115\pi\,\mathrm{mm\,mrad}$.
2. energy spread increases from ≈ 0.07 to $\approx 3.7\,\mathrm{MeV}$.
3. $\Rightarrow$ Emittance and energy spread $\gg$ acceptance: collimation and energy selection required.
4. $\Rightarrow$ Beam current varies by 10^3 (for $I_{cyc} = \mathrm{const}$).

Fast energy changes at PROSCAN: For reasons of patient safety and precision the beam intensity should vary with energy by factor ≤ 10.
The excess intensity variation has to be compensated (suppressed).

Method of Intensity Compensation

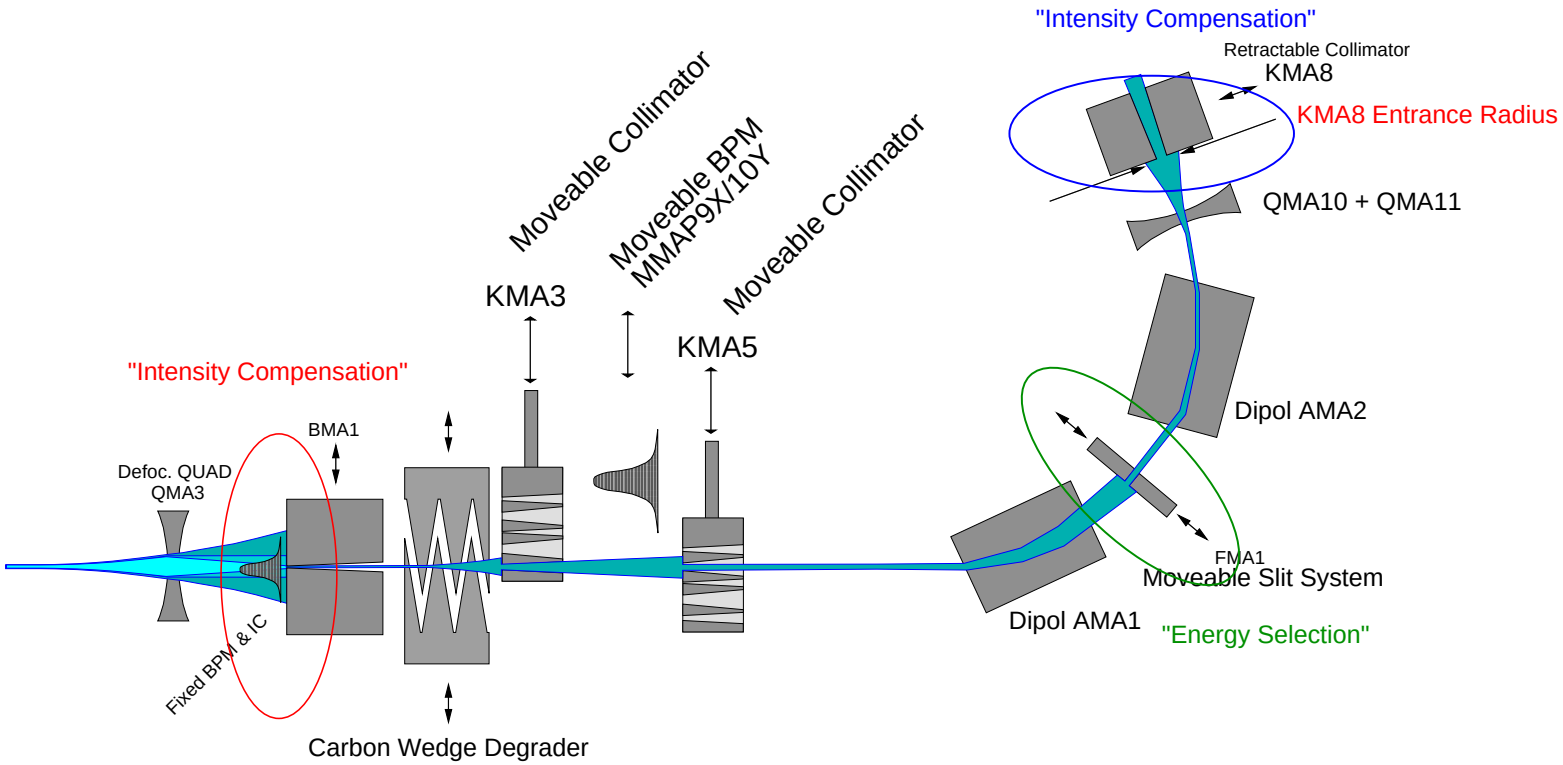
Objectives of intensity compensation for Gantry 3:

1. 1st: No intensity reduction $\leq 140\,\mathrm{MeV}$.
2. 2nd: Constant current $I(E \geq 140\,\mathrm{MeV}) = \mathrm{const}$.
3. 3rd: The transition should be smooth (for interpolation purposes).

Method: Defocuse beam at higher energies on collimator(s).

1. 1st: Defocuse beam before degrader with quadrupole QMA3 (dump into BMA1).
2. 2nd: Insert collimator KMA8 after ESS and defocuse with QMA10+QMA11.

Beam Formation and Intensity Compensation



Elements involved in beam formation and intensity compensation: Quadrupole QMA3, used to (de-)focuse beam through stopper BMA1 onto the carbon wedge degrader (DMAD). The moveable collimators KMA3 and KMA5 define the phase space. The energy selection system (ESS) consists of a sequence dipole-slits-dipole. A second collimator KMA8 is required for intensity compensation.

Challenges of Intensity Compensation

Problems / challenges:

1. Momentum scaling of beam tune not sufficient:
2. Defocusing at KMA8 requires energy specific tuning.

Fast energy change ⇒ for volumetric scanning/repainting.
Hence the tunes must fit together:

1. Smoothness: No overshoot when fine interpolation between 17 tunes is done.
2. Monotonic dependence: There is no time between energy changes for a hysteresis suppression cycle.
3. ⇒ Need monotonic dependence of quad fields vs. energy.

Beamline/Degrader Model with "QAD"

1. Traditional PSI tools: TRANSPORT and TURTLE. But:
2. TRANSPORT does beam envelope calculation only, no beam collimation.
3. TURTLE does not provide degrader model and includes no sample generator.
4. $\Rightarrow$ Write "QAD": Beam transport Monte Carlo with gaussian sample generator. (However: No fitting implemented yet.)
5. Create Gaussian ensemble with 10^7 trajectories [9].
6. $\Rightarrow$ modeling of collimators possible.
7. $\Rightarrow$ modeling of energy selection possible.
8. $\Rightarrow$ obtain results for envelopes, emittances, losses, energy spread, transmissions etcpp.

Beam representation in QAD.

Beam sample representation column-wise by matrix $\Psi_{6\times n}$:

$$\Psi_{6\times n} = \begin{pmatrix} x_1 & x_2 & \dots & x_n \\ x_1' & x_2' & \dots & x_n' \\ y_1 & y_2 & \dots & y_n \\ y_1' & y_2' & \dots & y_n' \\ z_1 & z_2 & \dots & z_n \\ \delta_1 & \delta_2 & \dots & \delta_n \end{pmatrix}$$

Obtain envelope matrix Σ by matrix multiplication:

$$\begin{array}{rcccc} \Sigma & = & \frac{1}{n} & \Psi & \Psi^T \\ 6\times 6 & = & & 6\times n & n\times 6\,. \end{array}$$

with $\Sigma_{11} = \langle x^2 \rangle$.

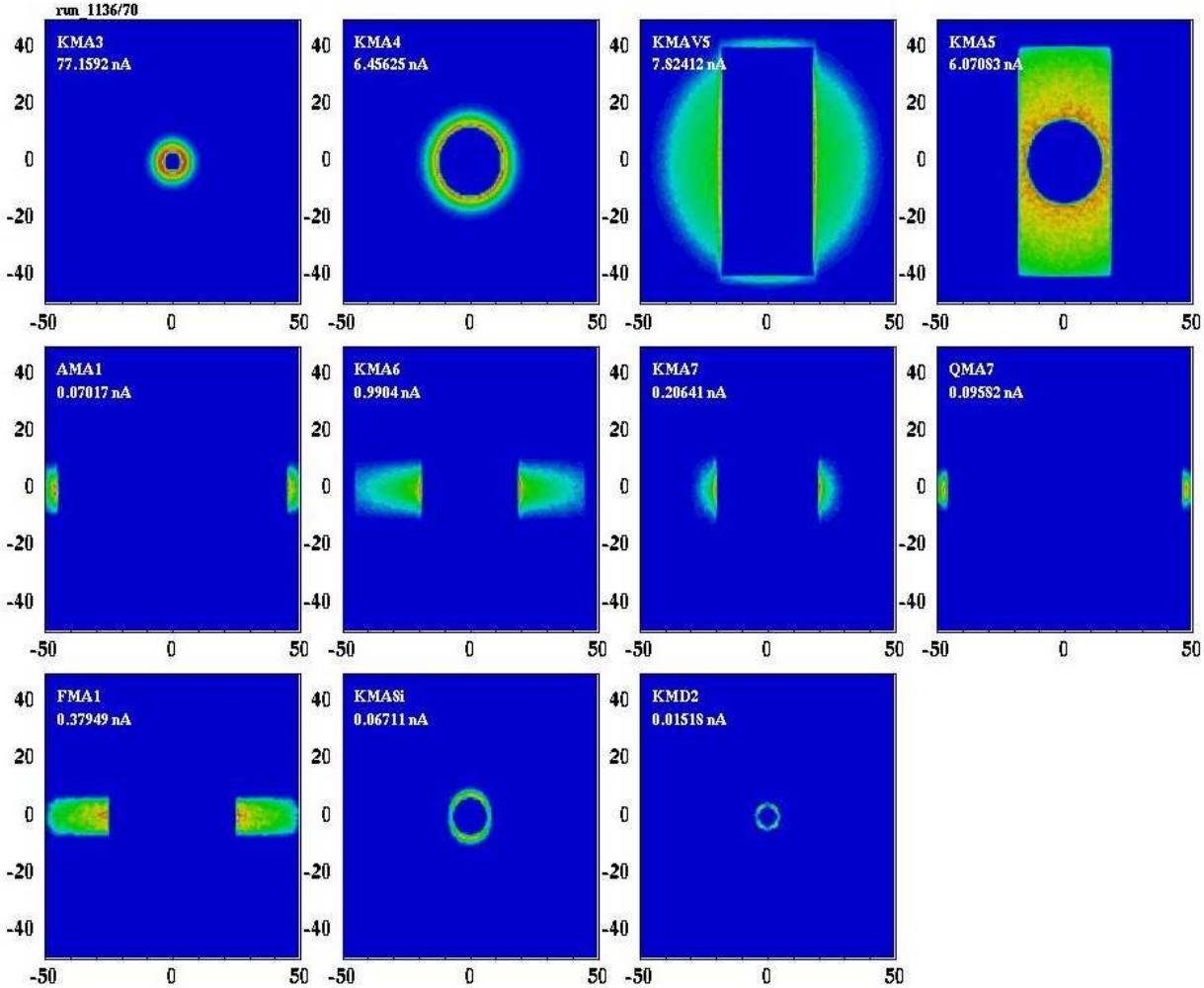
Beam transport in QAD

1. Linear beam transport by TRANSPORT matrix **M** as usual:

$$\begin{aligned} \Psi(s+\Delta s) &= \mathbf{M}(\Delta s)\,\Psi(s) \\ \Sigma(s+\Delta s) &= \mathbf{M}(\Delta s)\,\Sigma(s)\,\mathbf{M}^T(\Delta s)\,. \end{aligned}$$

2. At collimators: remove single trajectories (columns) that don't fit the aperture. Put losses in 2D-histograms.
3. Profile monitors: Make a horizontal or vertical histogram of the coordinates.

Example: Beam Loss Predicted for Collimators



Beam loss simulation with QAD. Start with 10^7 tracks so that for low transmission enough tracks remain.

QAD: Beam passage through matter

1. Generate a degrader matrix by combination of drift and scattering:

$$\dot{\Sigma} = \mathbf{F}_{drift}\,\Sigma + \Sigma\,\mathbf{F}_{drift}^{T} + \dot{\sigma}_{degrader}$$

   with $\dot{\sigma}_{22} = \dot{\sigma}_{44} = \frac{K_0}{p^2\,v^2}$ and $\dot{\sigma}_{66} = \frac{d}{ds}\,\frac{\Delta P}{P}$ [5, 6, 3].
2. Transport original sample by drift element.
3. Generate random sample for degrader matrix with size of beam sample.
4. Add degrader sample and beam sample (statistical independence).

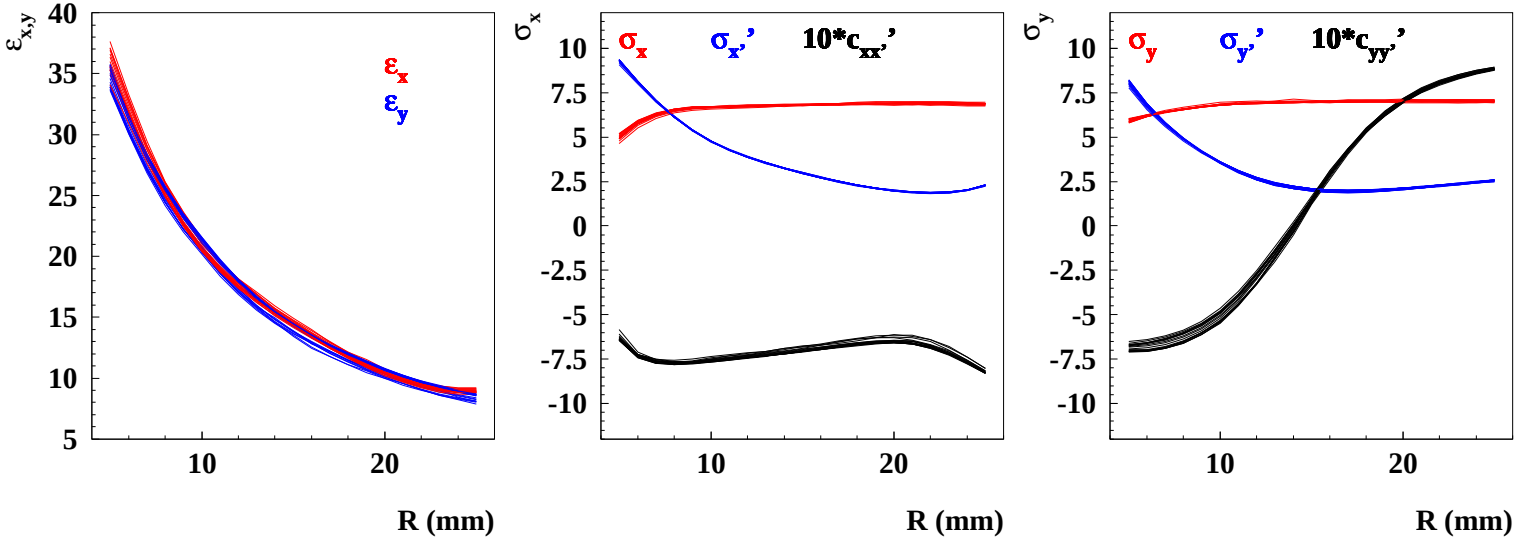
Gantry 3 Beamline Tunes

Task list:

1. Define 17 default energies $70 \ldots 230\,\mathrm{MeV}$ in steps of $\approx 10\,\mathrm{MeV}$.
2. Develop beam tunes for these 17 energies.
3. Interpolate quads and bends between the 17 energies.
4. Adjust QMA3 to obtain desired intensity as function of energy.
5. Verify (or optimize) beam tunes during commissioning measurements.

Use "QAD" to compute beam parameters

1. Use TRANSPORT to find QMA10 and QMA11 fields vs. beam radius at KMA8.
2. For all energies: Find beam parameters after KMA8 as function of beam radius.

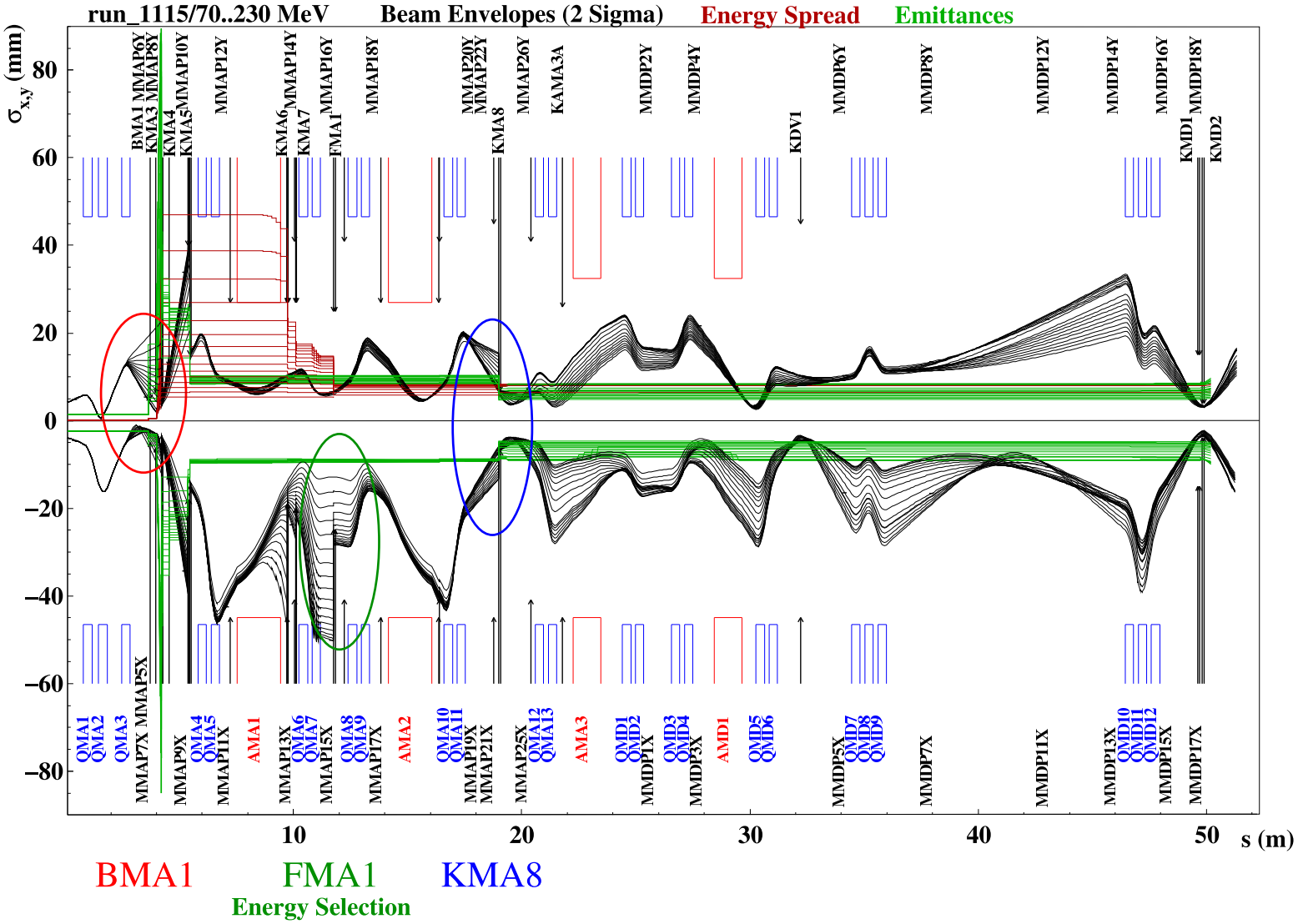


"QAD"-Results: Beam parameters at exit of KMA8 versus beam radius (adjusted with QMA10/QMA11) at entrance of KMA8 for 17 energies from 70 to 230 MeV: Almost no energy dependence, only radius dependence! Beam radius is good parameter for optics after KMA8.

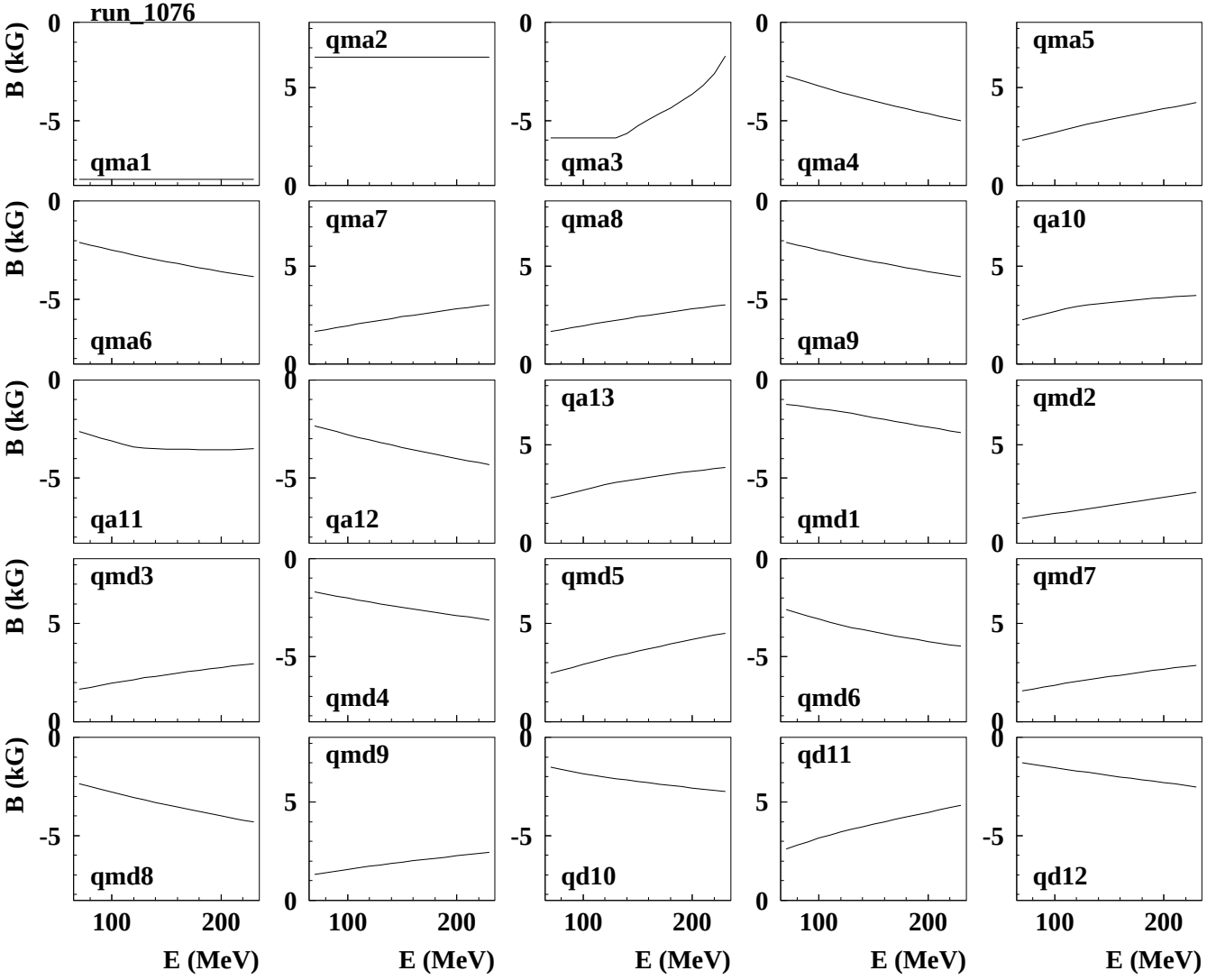
Steps Towards Beamline Tunes

1. Compute beam intensity suppression factors for QMA3/BMA1 and QMA10/QMA11/KMA8.
2. Create smooth intensity suppression function at KMA8.
3. $\Rightarrow$ beam radius at KMA8 as function of energy.
4. Use TRANSPORT to match beam at Gantry 3 transition point for these beams. (Problem underdetermined: Iteration and partial functional fixation of quads helpful.)
5. Use QMA3 for the remaining intensity reduction (no influence on optics).
6. Check that all quadrupole currents have monotonic energy dependence.

Results: Beamline Optical Tunes for all Energies



Results: Computed Quadrupole Fields



Commissioning Measurements

1. Gantry 3 vault with top open.
2. Install prelimenary beamdump (water tank).
3. Provide prelimenary shielding (concrete blocks).
4. **Agreed by authority: $\leq$ 6 sessions of $\leq$ 3 hours with** $\leq 0.2\,\mathrm{nA}$
5. First session: Make dosimetric mapping.
6. Next session: Finetuning of dipole and steerer settings for all 17 energies.
7. Then: Verify that we are done. (Well, check stability and reproducibility etcpp.)

Verification Measurements

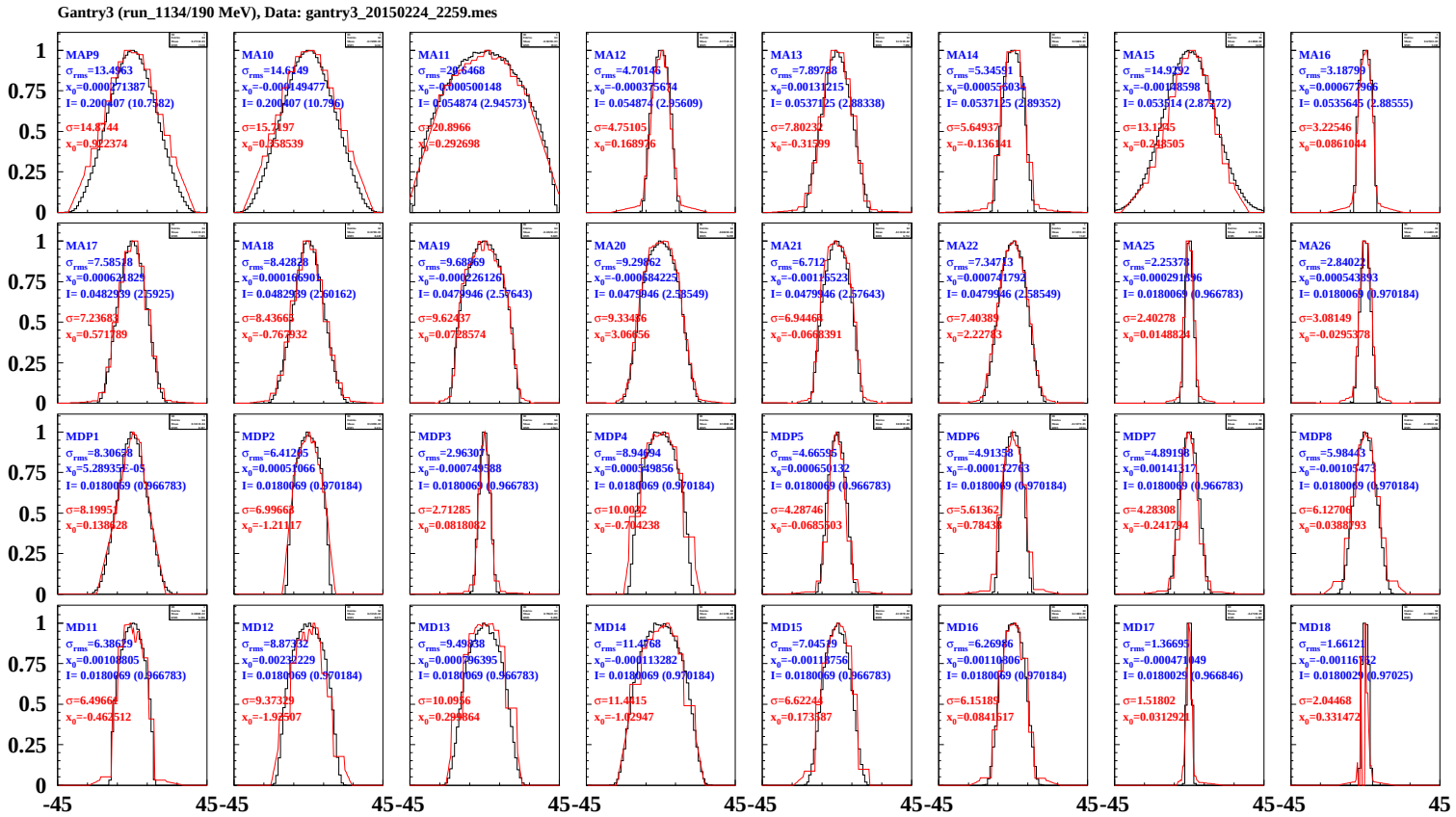
Data taken:

1. Beam energies, measured by water tank measurements.
2. Beam profiles with strip profile monitors (BPMs).
3. Integrated currents measured with BPMs and ionization chambers.
4. Emittance measurements by quaddrupole scanning method.

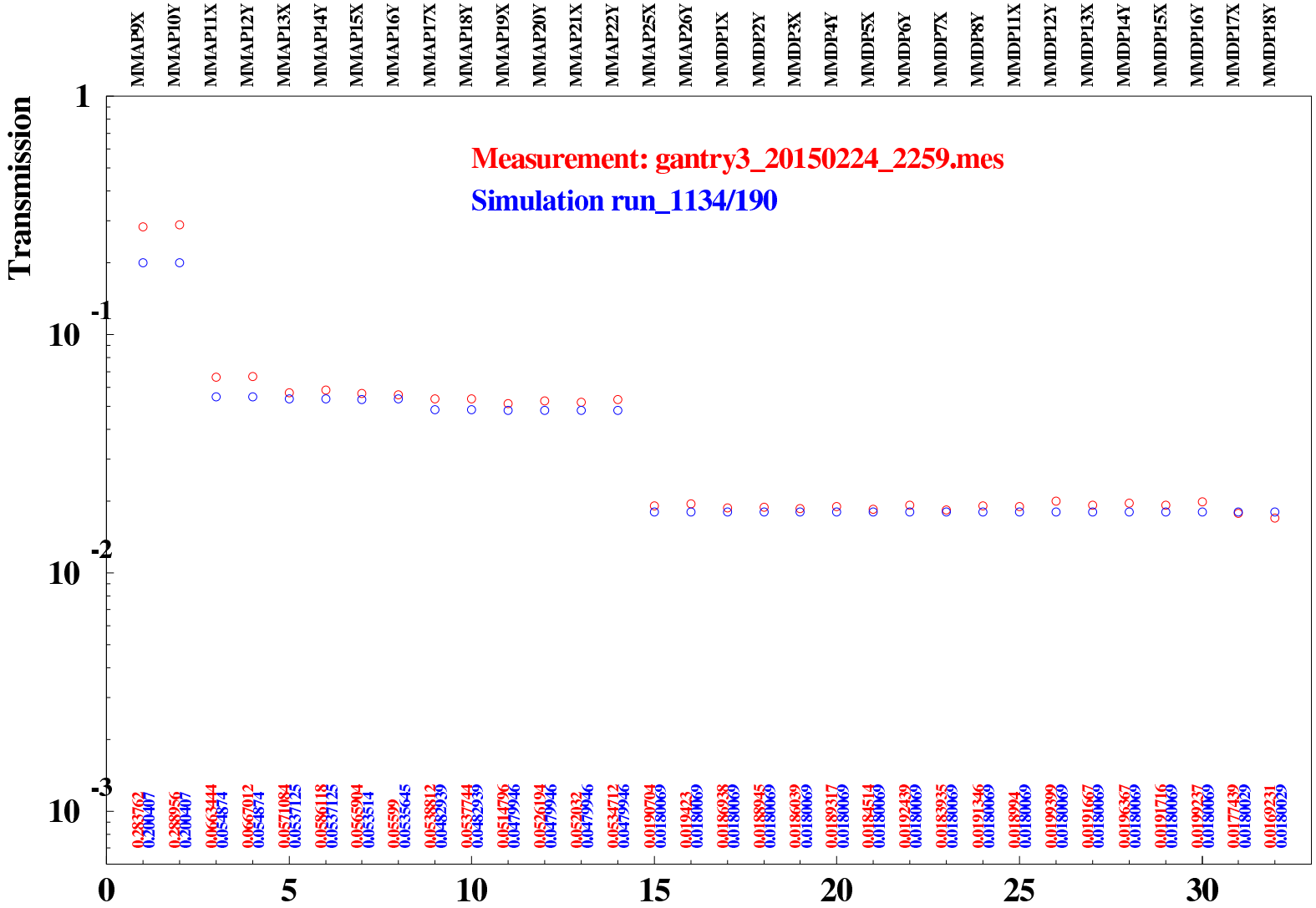
For patient treatment in Gantries only one setting of KMA3 and KMA5 is typically used. However we computed beam currents and profiles for other settings as well and compared with profile measurements.

Some Results: Profiles at 190 MeV

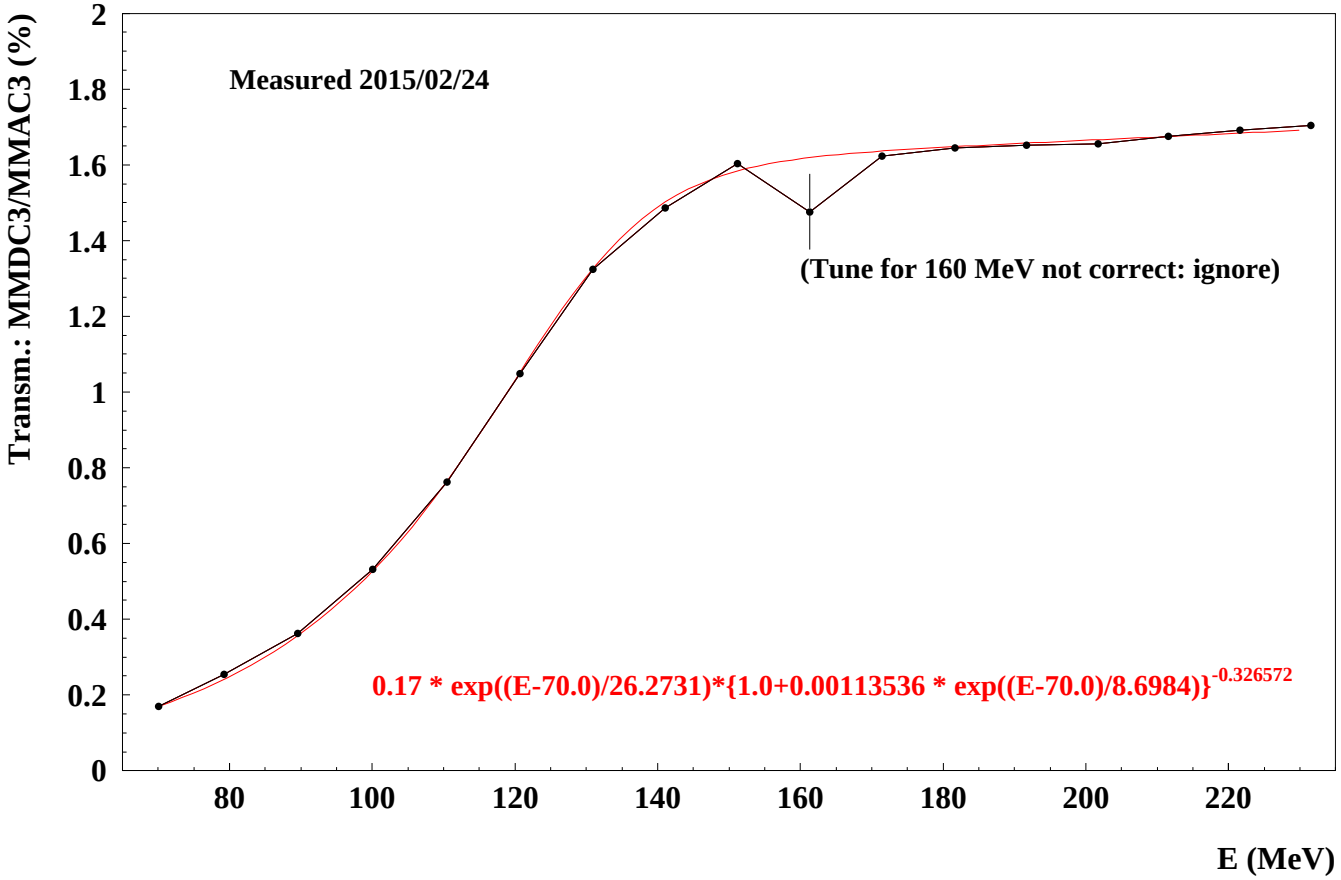
QAD predictions and Measurements:



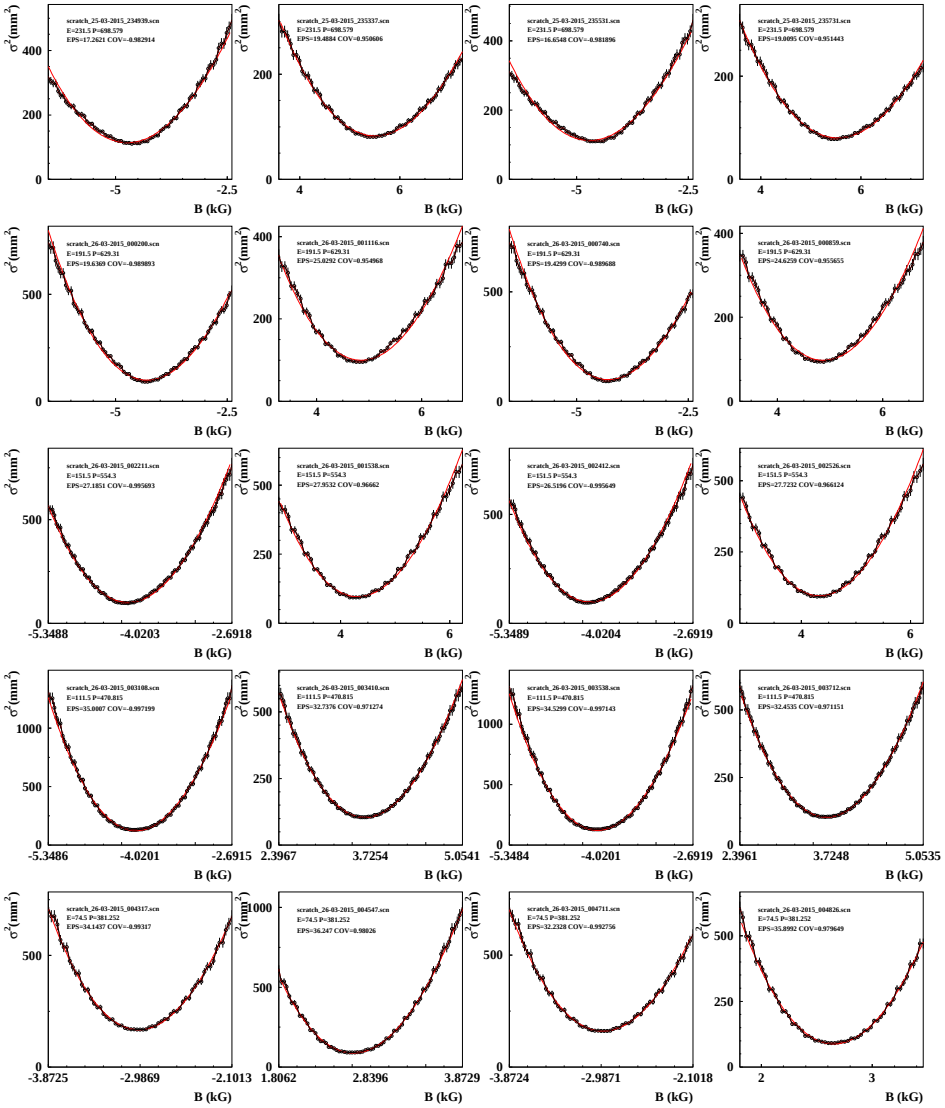
Some Results: Currents at 190 MeV



Results: Achieved Transmission Behavior I(E)



Quadscans: Emittance Measurements

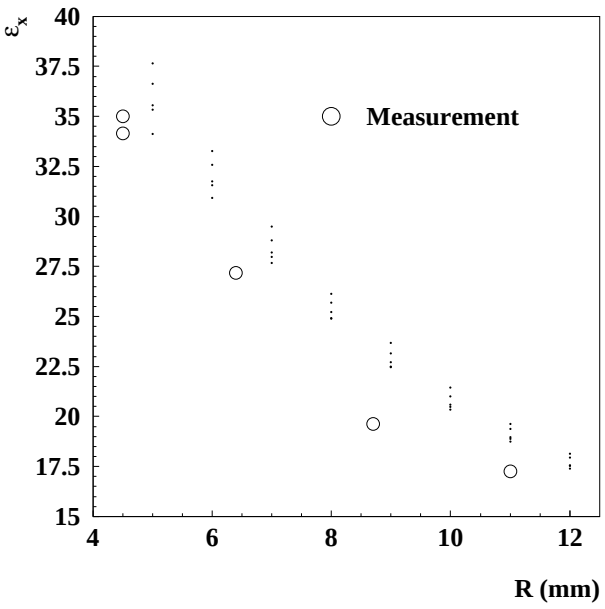


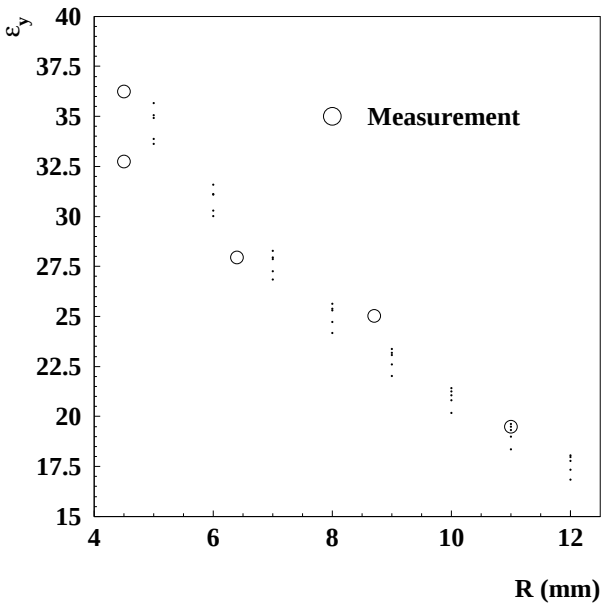
Use Quadscanning method to determine beam emittances for 70,110,150,190,230 MeV.

Emittances, measured vs computed.

Energie	Radius	X-Meas	X-Calc	Y-Meas	Y-Calc
70	4.5	34.14	33.20	36.25	33.88
110	4.5	35.00	35.70	32.74	32.64
150	6.4	27.19	28.26	27.95	27.71
190	8.7	19.64	22.54	25.03	23.89
230	11.0	17.26	18.95	19.49	19.28

Units: MeV, mm and $[\pi\,\mathrm{mmmrad}]$.





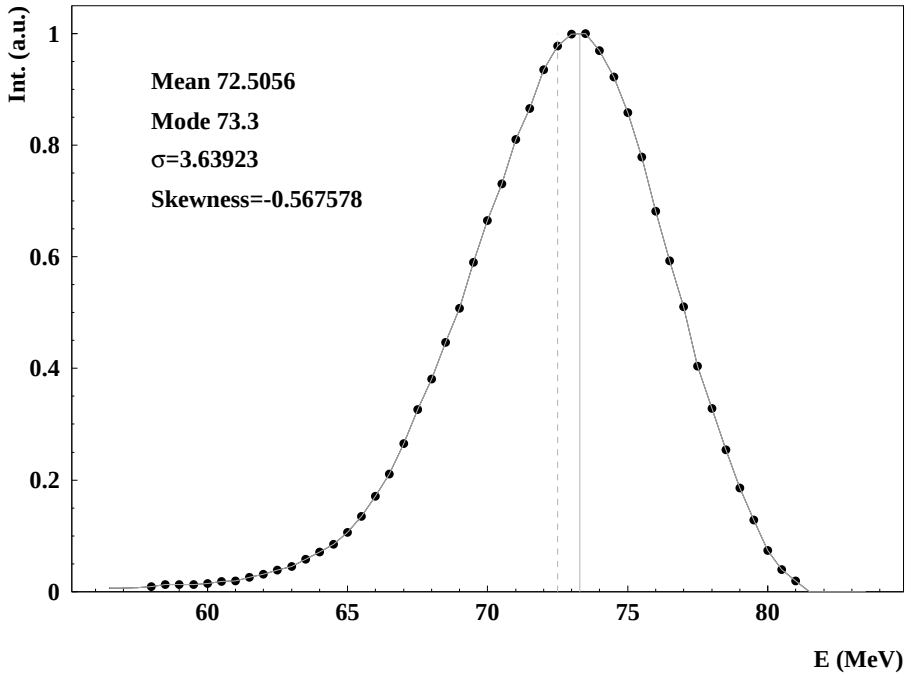
No Tricks?

1. However: Precalculated energies (Bethe-Bloch) energies are too low (meas. 73.5 MeV instead of 70 MeV). Why?
2. PSI degrader has been surveyed with high accuracy: Unlikely cause.
3. One reason for deviations: Bethe-Bloch-Theory gives average energy.
4. But we (have to) adjust to most probable energy in ESS.
5. Workaround: Adjust degrader parameter (density or wedge angle or mean ionization energy [7]) to match measured energy.

Furthermore: We veryfied "QAD" beforehand at Gantry 2 beamline.

Average energy vs. peak energy

We used AMA1 and ESS to measure energy distribution of beam.



The deviation between peak and mode ($0.8\,\mathrm{MeV}$) is too small to explain the complete energy deviation. OPAL and FLUKA Monte Carlos of Degrader with low-energy cut yielded better results. (For patient treatment, this is unimportant. Important only for precalculation of tunes and modeling of beamline.)

Summary

1. Beam tunes for all energies using a high accuracy beamline model.
2. Finetuning of dipoles and steerers done "by hand".
3. Beam energy was calibrated by watertank measurements.
4. Beam profiles agreed well between measurement and simulation.
5. Calculated beam intensities verified with BPMs and ionization chambers.
6. Objectives of intensity compensation reached.
7. Measured emittances with quadrupole scans. Agreement with QAD good.
8. Low-energy transmission could be increased by 8%.
9. $\Rightarrow$ We understand our beamline optics.

Thank you for your attention.

Watertank measurements done by D. Meer and S. Psoroulas.
Thanks to the Gantry 3 project team for the nice collaboration.

Thanks to the PSI control, magnet and radiation safety groups for their support.

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