Paul Scherrer Institut PSI

Wir schaffen Wissen – heute für morgen

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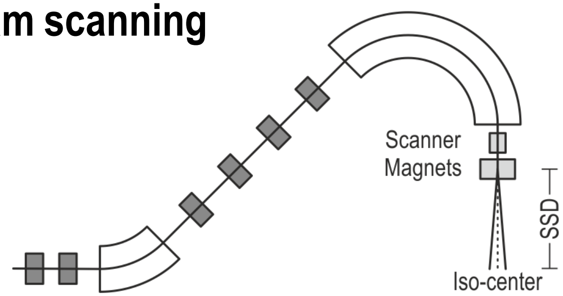
Oxana Actis

Parametrization of an upstream scanning system

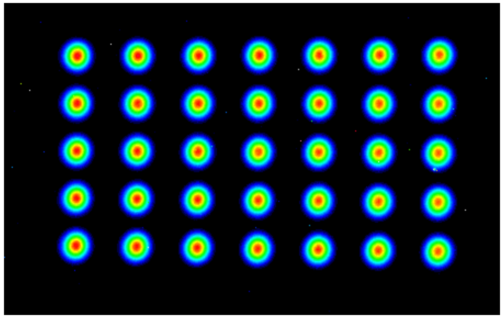
EuCARD^2 Superconductivity and other new Developments in Gantry Design for Particle Therapy

Gantry design for pencil beam scanning

Downstream scanning



- Sweeper magnets are last active beam elements
- In first order linear correlation between
  - Spot position at isocenter
  - Sweeper current
- Spot shape unaffected for different scan position
- Divergent scanned beam; calibration relies on exact longitudinal alignment at isocenter
- Situation similar to horizontal beam line

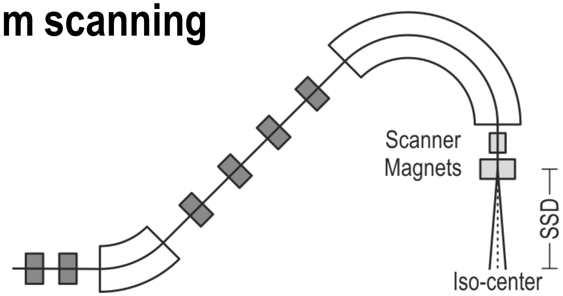


Example:
Horizontal beam line,
PSI test area,
170 MeV

Spot position with
linear current steps

Gantry design for pencil beam scanning

Downstream scanning



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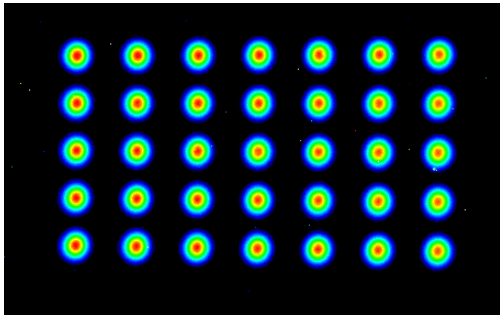
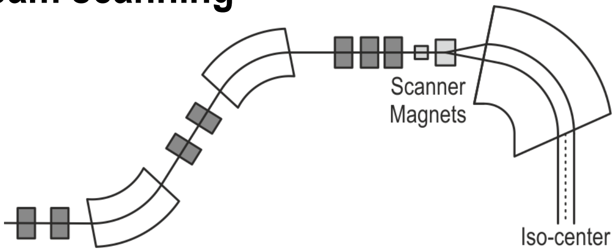


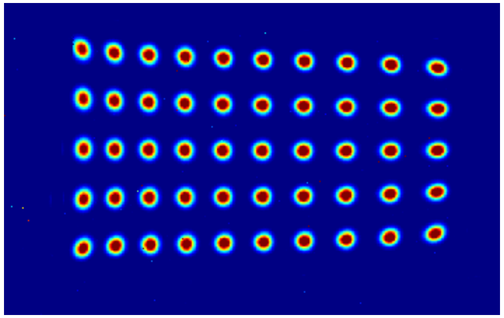
Example:
Horizontal beam line, PSI test area, 170 MeV

Spot position with linear current steps

Upstream scanning



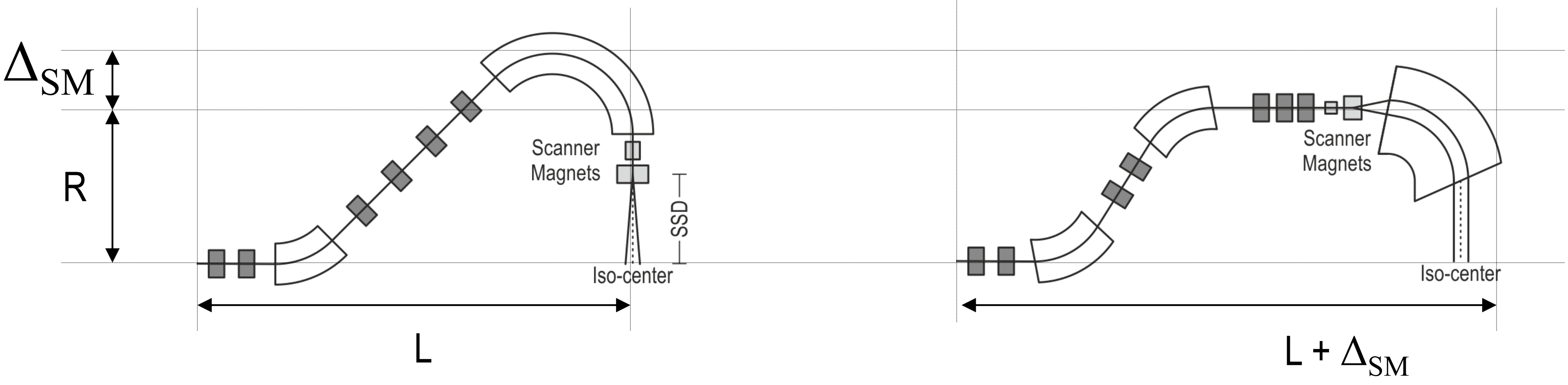
- Sweeper magnets placed in-front of last dipole
- Large gap of last dipole
- Field inhomogeneity can affect spot shape
- Beam focus depends on lateral position
- Beam with little / no divergence (= parallel beam)
- Higher order corrections for position-to-current conversion needed



Example:
Gantry 2, 100 MeV

Spot position with linear current steps

Gantry size and room volume



Downstream

Assuming square room cross-section

Upstream

$$V_{down} = 4*(R + \Delta_{SM})^2 * L$$

$$V_{up} = (L + \Delta_{SM}) * 4R^2$$

Using Gantry 2 as an example

$L \approx 3R \quad R \approx 3.5m \quad \Delta_{SM} \approx 1m$

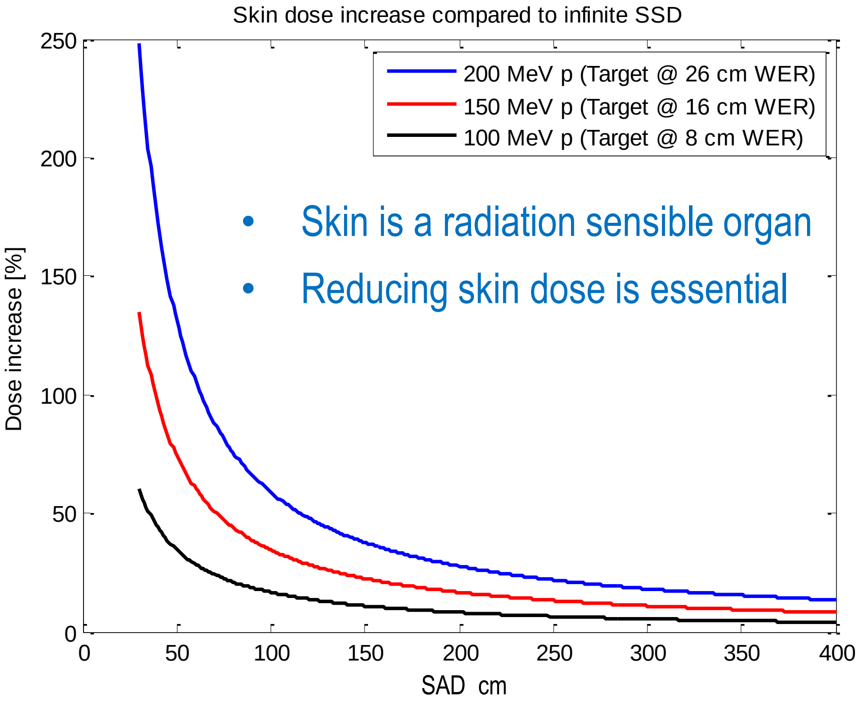
$$V_{down} = 4m*(4.5m)^2*10.5m = 850\ m^3$$

$$V_{up} = 11.5m*4m*(3.5m)^2 = 570\ m^3$$

$$\boxed{V_{down} - V_{up} > 250\ m^3}$$

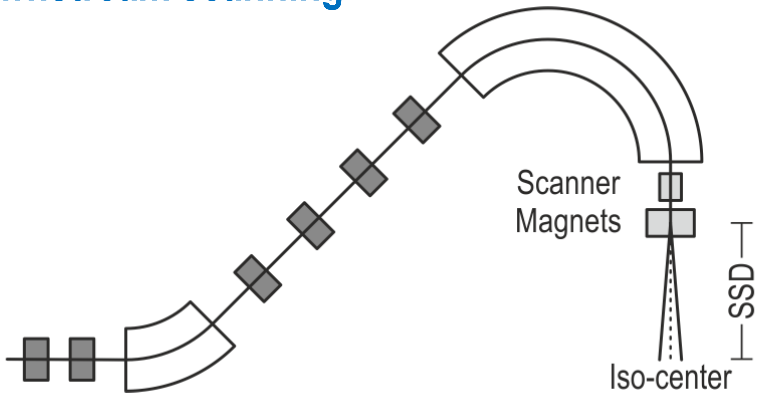
Advantages of parallel beam scanning

- No source to target ~$1/d^2$ dosimetry effects
- Simplified QA
- Easy field patching for large fields
- Almost infinite SAD possible



- Skin is a radiation sensible organ
- Reducing skin dose is essential

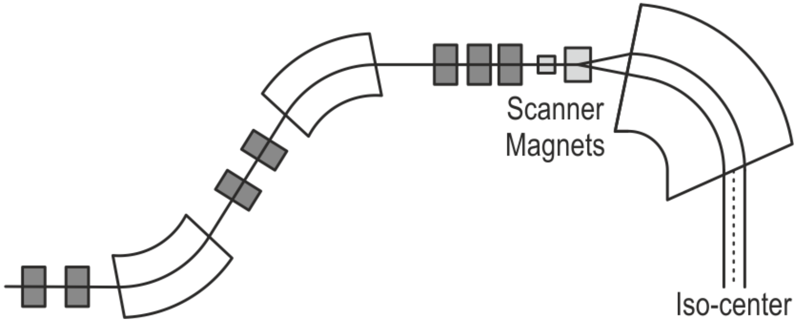
Downstream scanning



- Typical SAD ~ 2m

Upstream scanning

- PSI Gantry 2:
  SAD > 17 m



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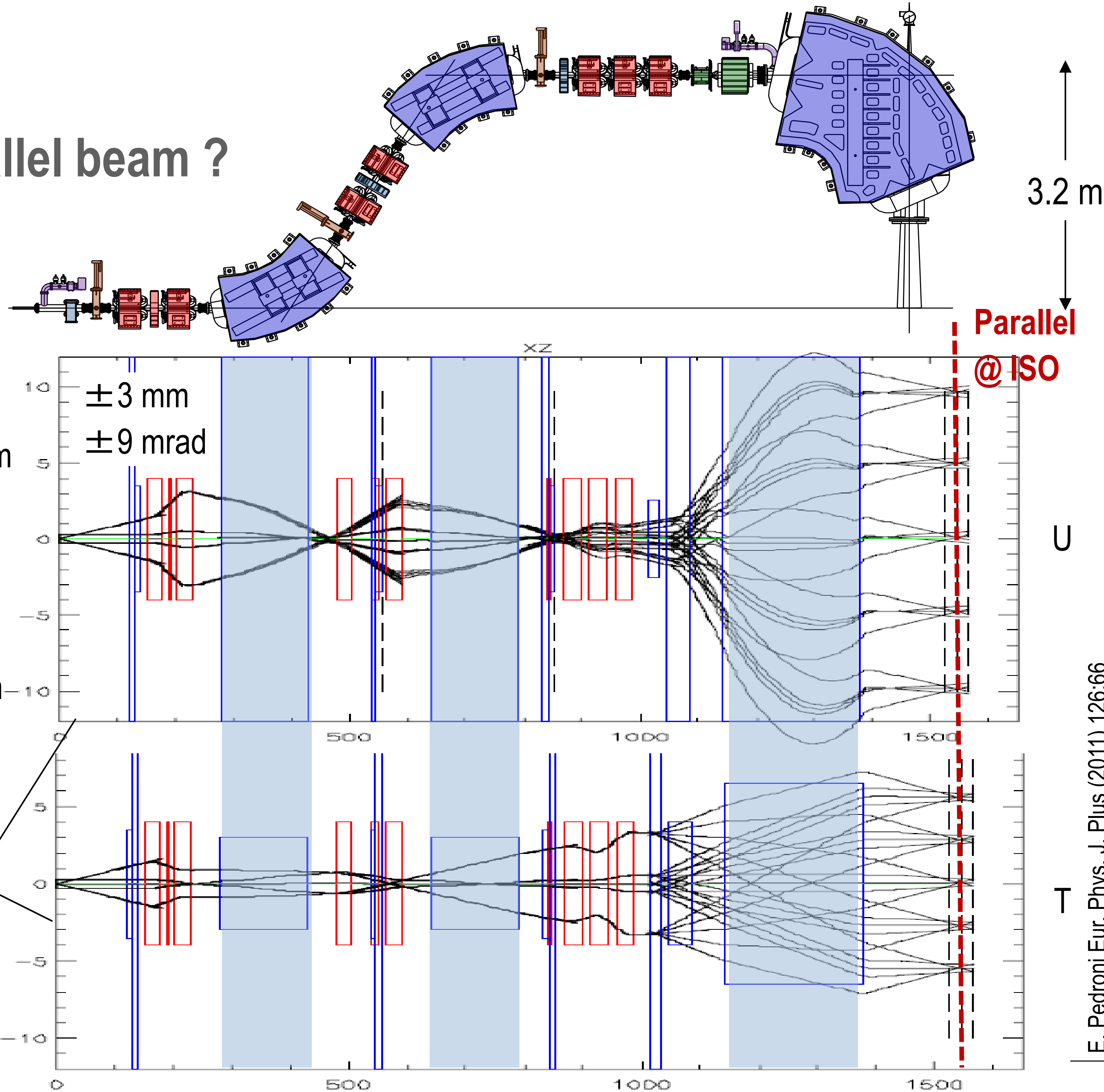
How to get parallel beam ?



RAYTRACE for beam calculations far away from the nominal trajectory (scanned beam)

3D analytical magnetic field maps for each beam line element

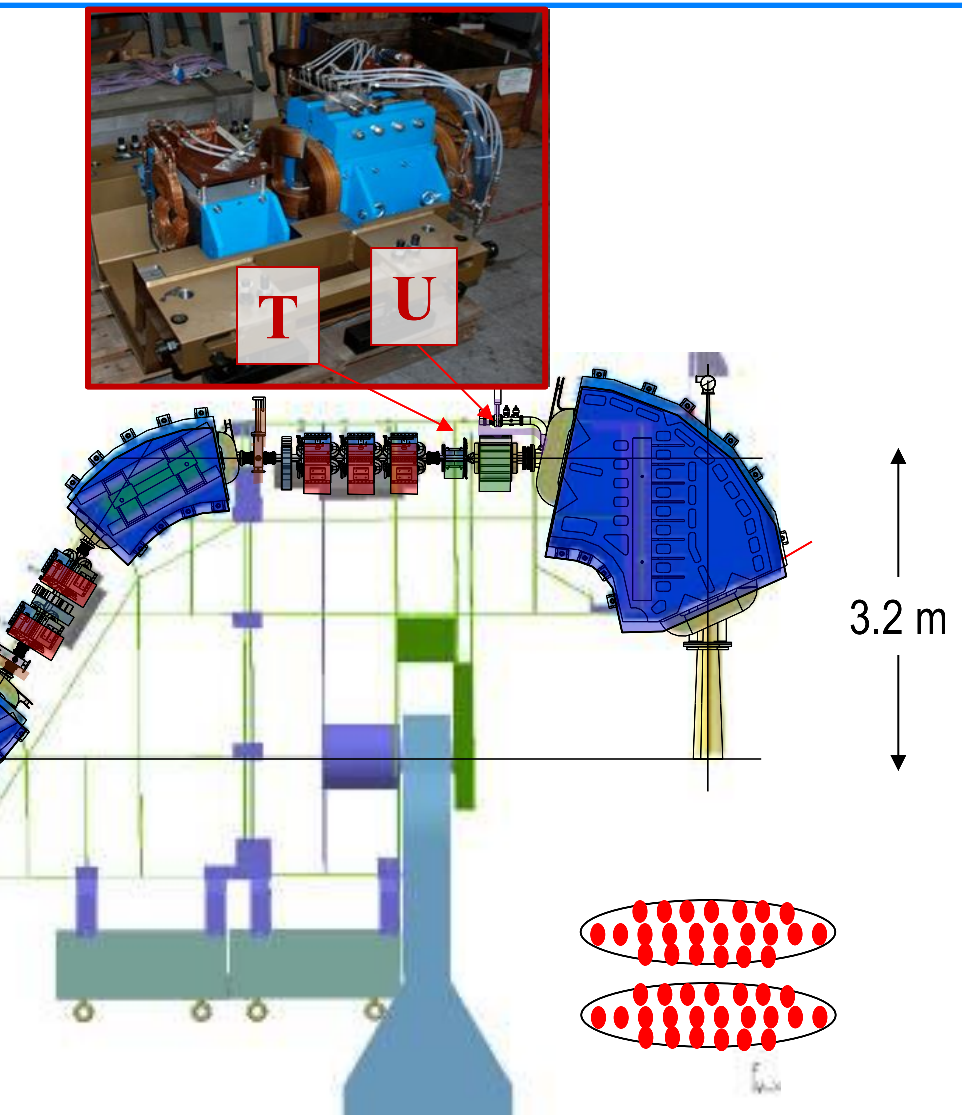
Sine- and Cosine-like projections in T and U planes

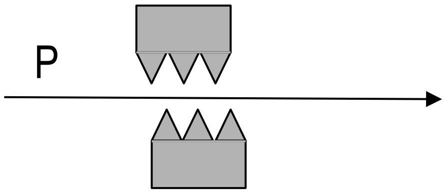
E. Pedroni Eur. Phys. J. Plus (2011) 126:66

Spot Scanning Technique @ Gantry 2

Parallel Lateral Scanning

- T sweeper magnet 2 cm/ms
- U sweeper magnet 0.5 cm/ms
- Scan area 20 x 12 cm
- Field patching for larger fields





Energy

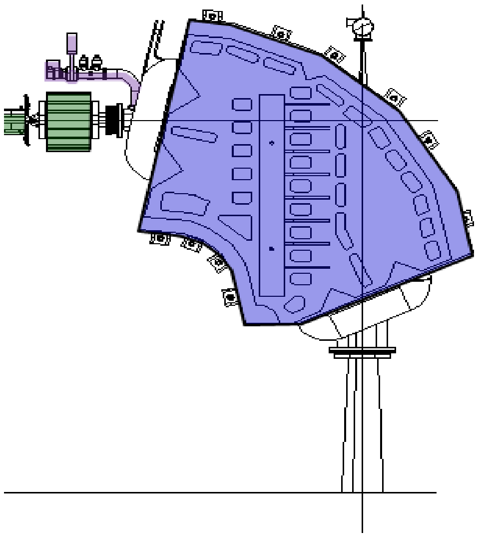
- Degrader based energy change within < 100 ms
  merit of optimized magnets and power supply
- Energies from 70 to 230 MeV
  (corresponding range 4.3 - 33 cm)
- Dose down to 5e05 protons per spot

Challenge: scanning though the last bending magnet

Last bending magnet: most challenging element

- Large aperture to accommodate deflected beam => large and heavy
- Special lamination to limit eddy currents effect for fast energy changes => works to a certain level

The GOAL: Parallel beam at isocenter with minimal beam shape and position distortions



- Sweeper current correction
- Magnet current correction
- SC magnet ?

Dose field homogeneity depends on:

Beam shape

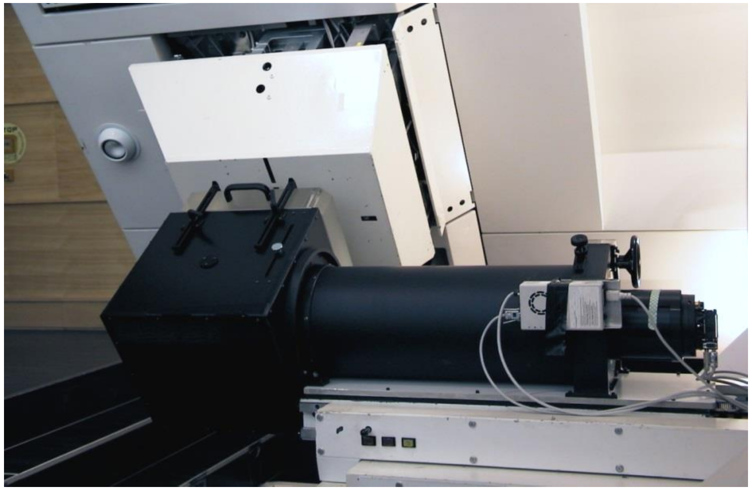
Position

Beam phase space measurement

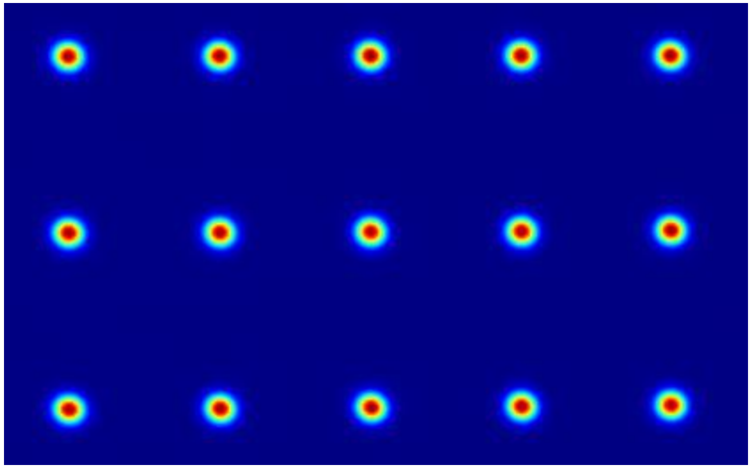
Beam phase space has to be verified @ ISO for

- Full scan area
- all Gantry angles
- beam energies

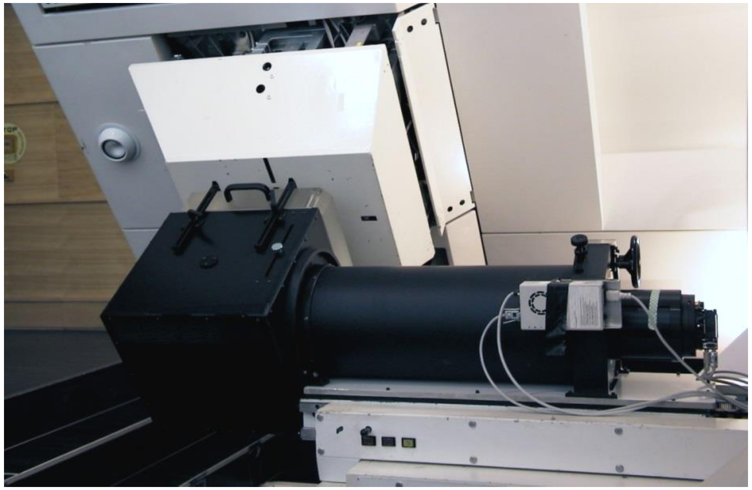
Beam phase space measurement

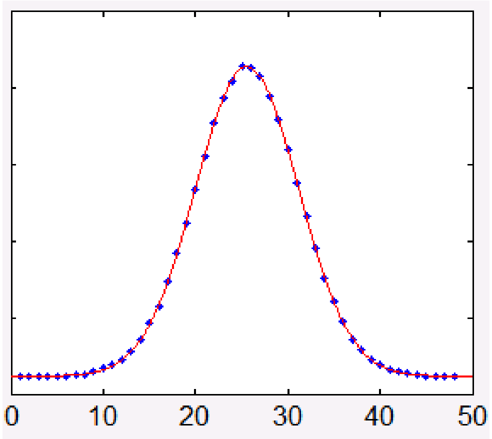


Full scan area @ iso-center



Beam phase space measurement





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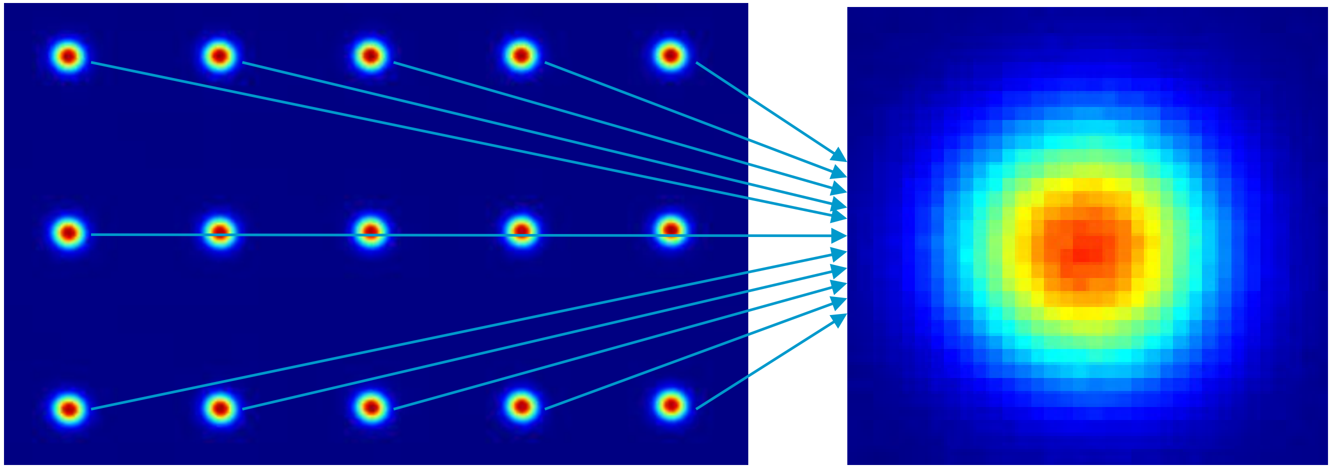
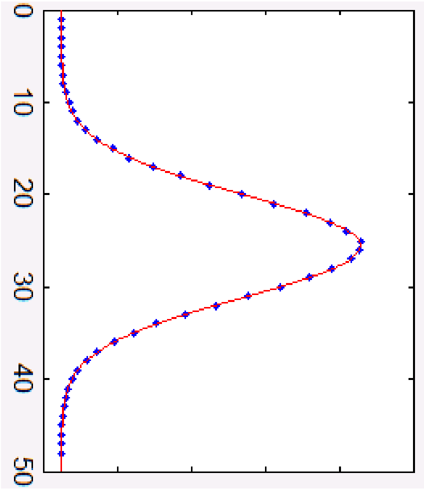
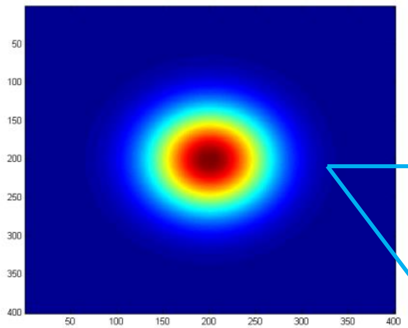
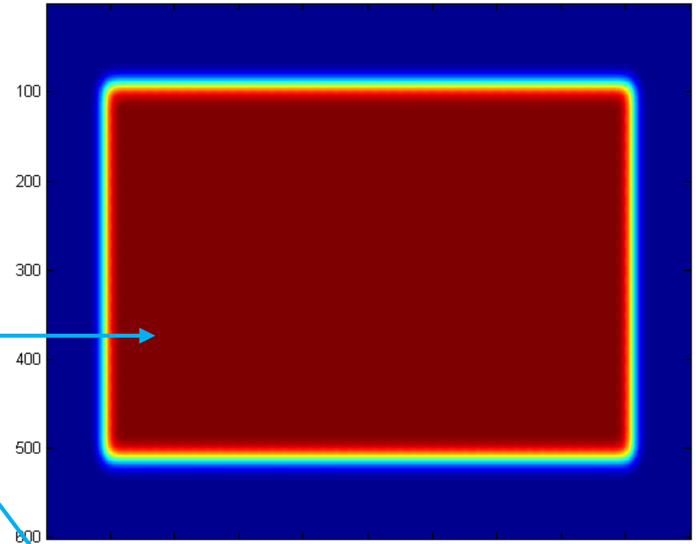




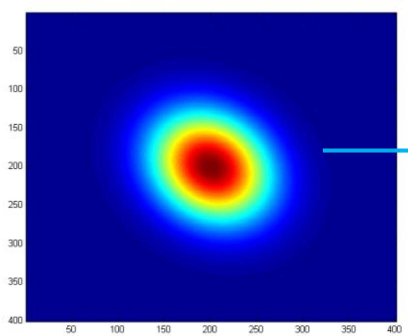
From beam shape to the dose homogeneity

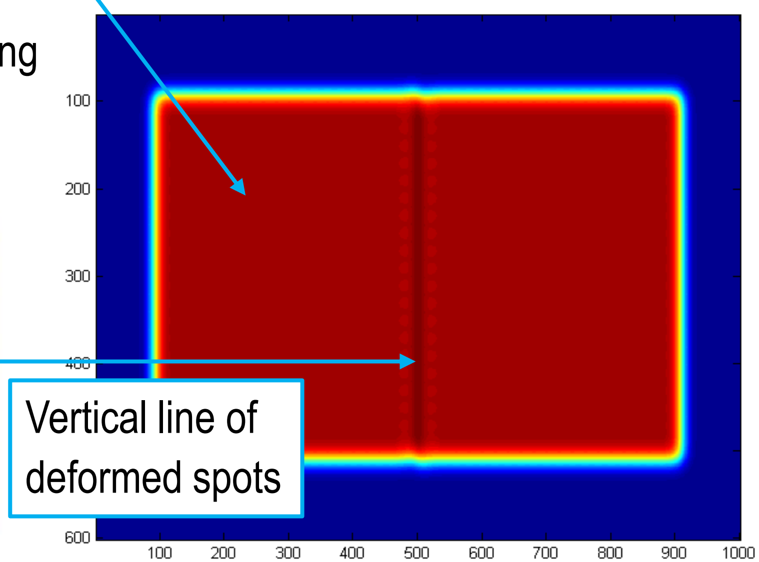
- Regular grid 4mm spacing
- Sigma ~ 5 mm





- Regular grid 4mm spacing
- Spot size 10% changed
- sigma + rotation





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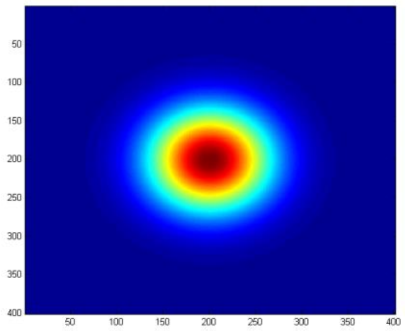

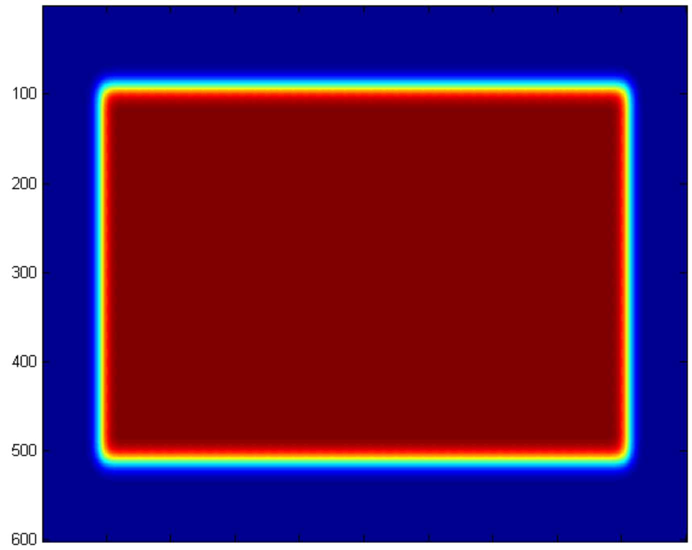

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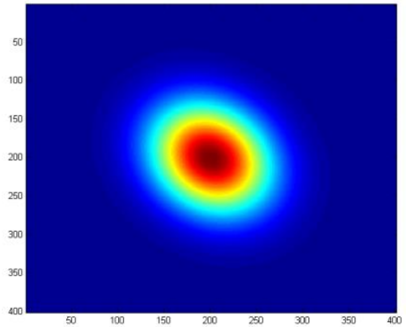
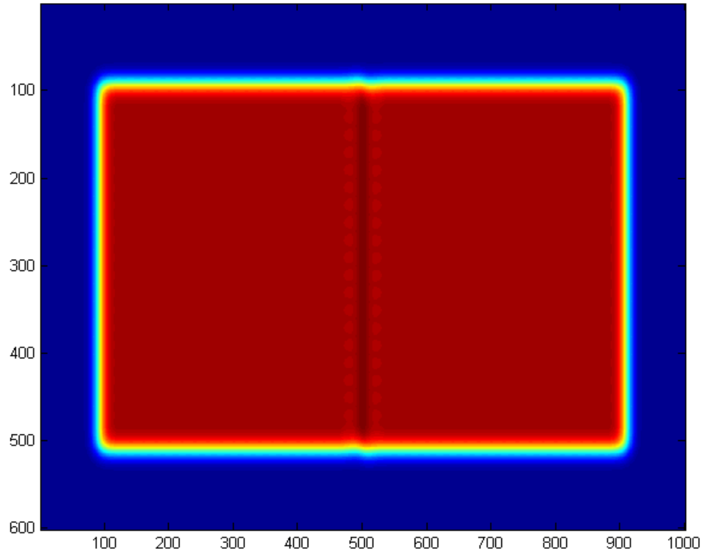
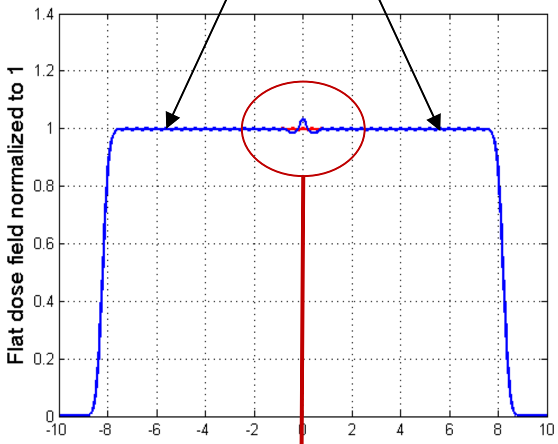
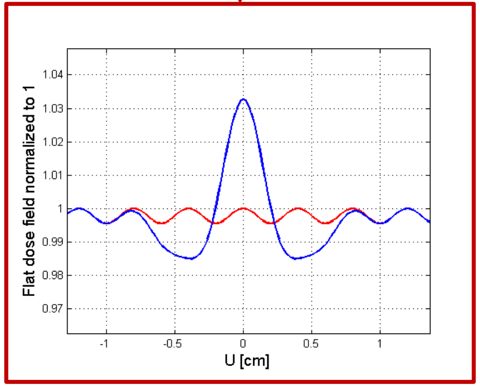




0.5% homogeneity



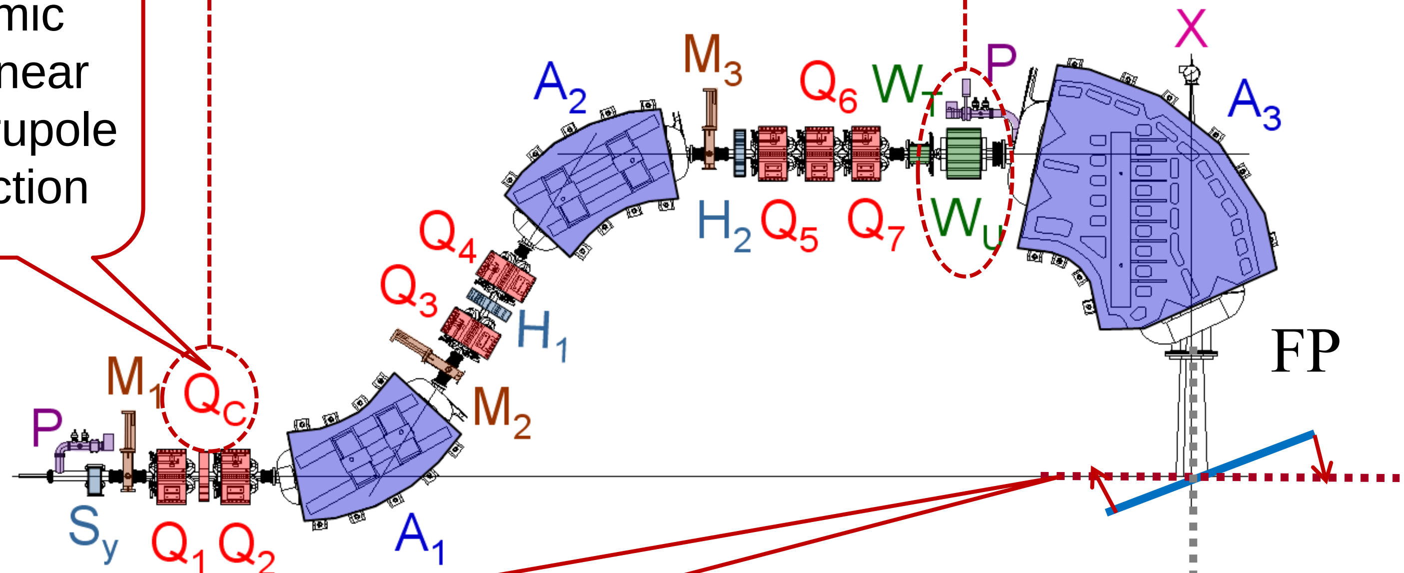


Moderate shape change
=> ~ 5 % inhomogeneity

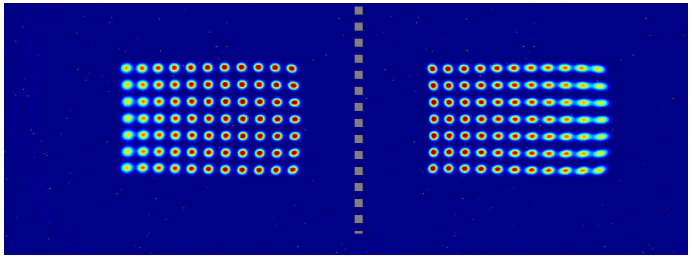
Dynamic beam focusing correction

Power Supply

Dynamic and linear quadrupole correction



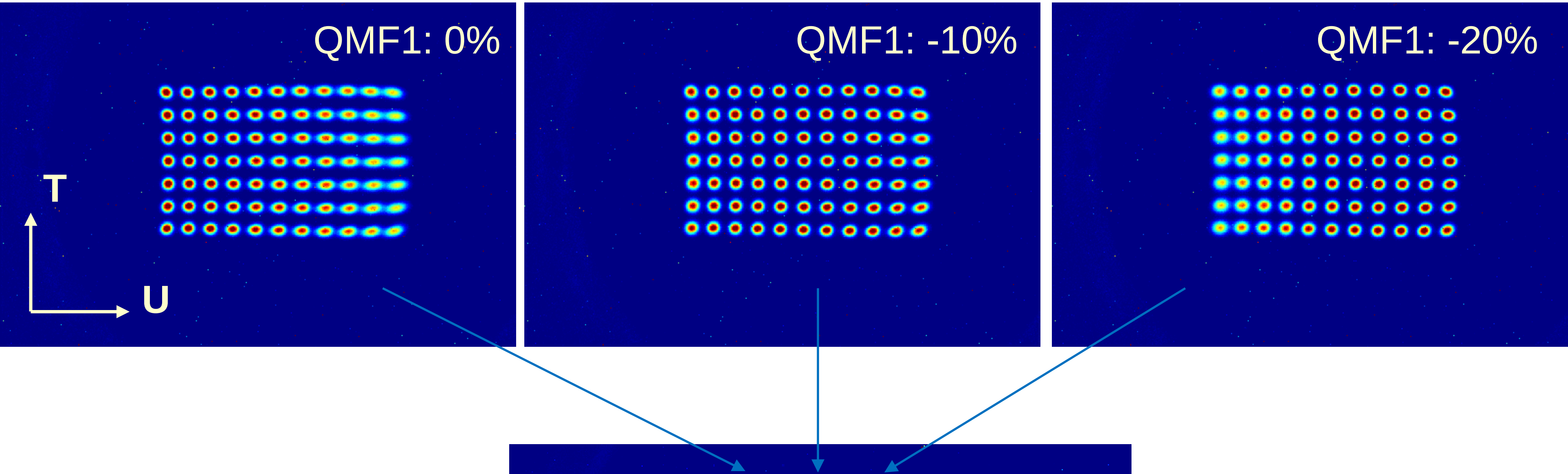
Focal plane FP not orthogonal to transversal direction at iso-center



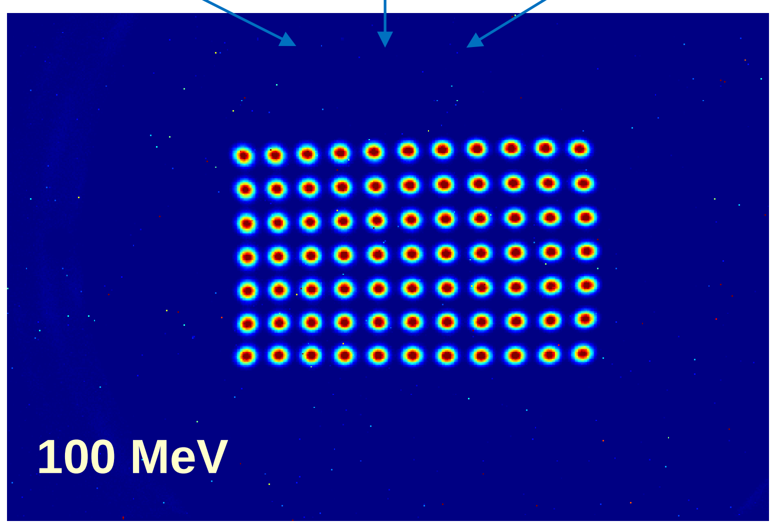
⇨ Spot shape is changing with position

Dynamic beam focusing correction

Static corrections



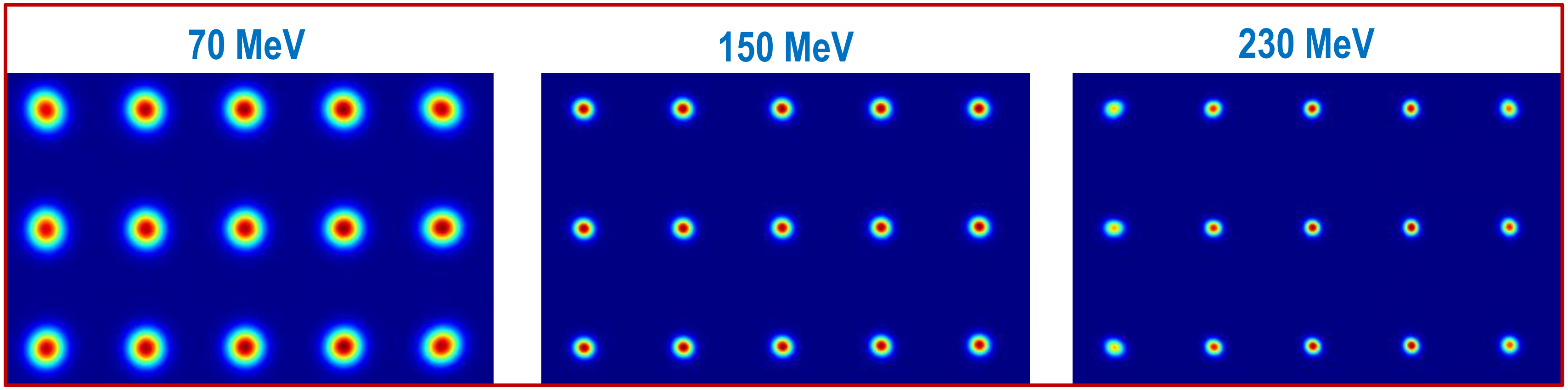
Dynamic correction:
$Q_c + W_U$



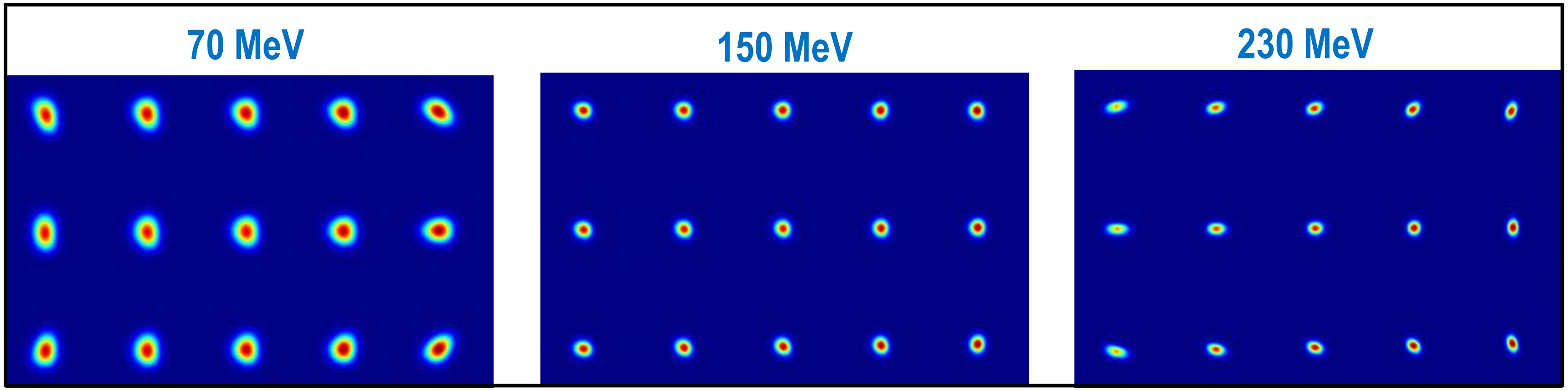
Quadrupole corrector in series with U-sweeper ⇨ **Invariant spot shape**

Delivered beam: off isocenter effect

20x12 cm @ iso-center: beam optics optimized for isocenter

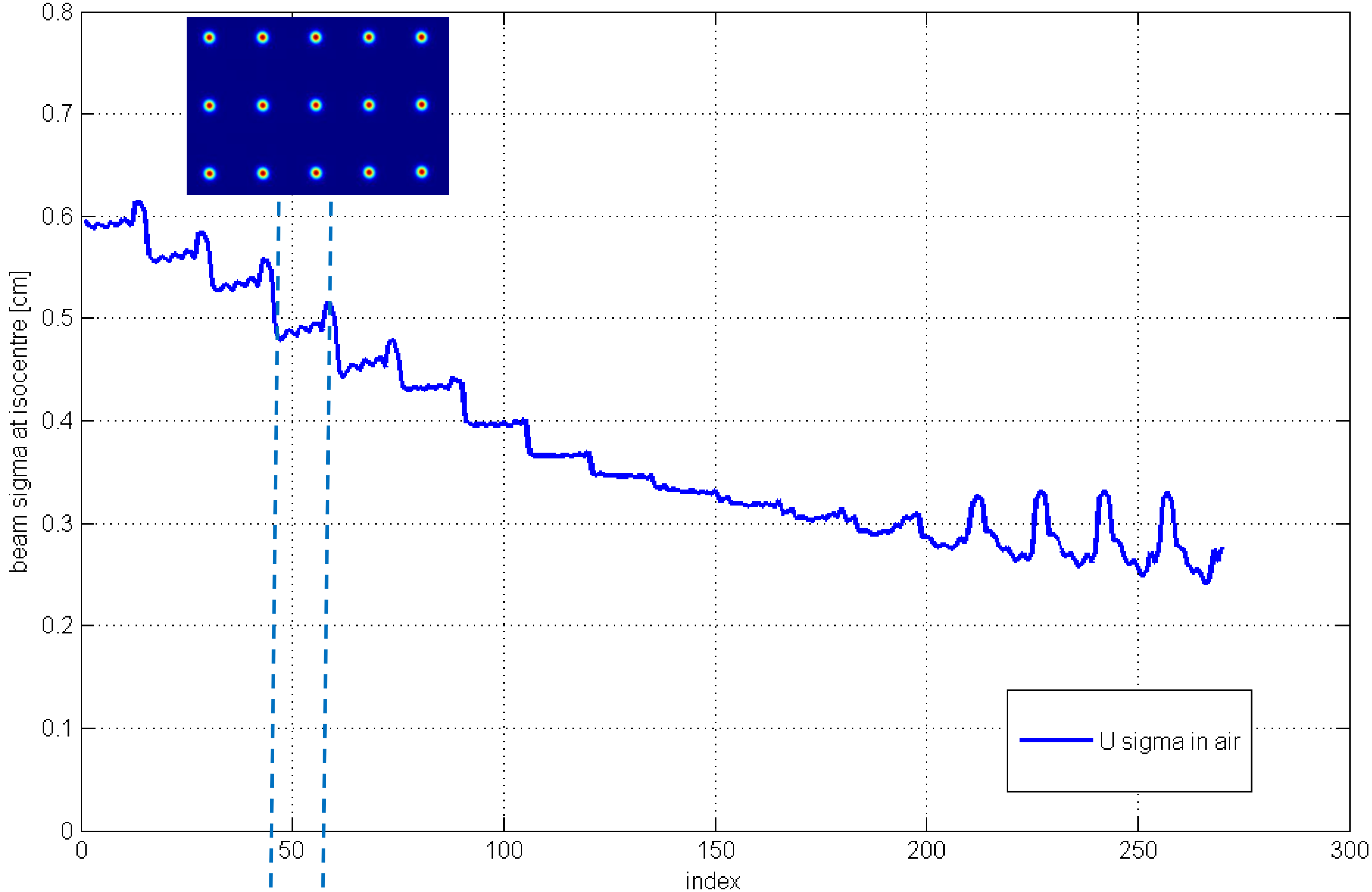


20x12 cm 40 cm above iso-center



Delivered beam in air @ Gantry 2

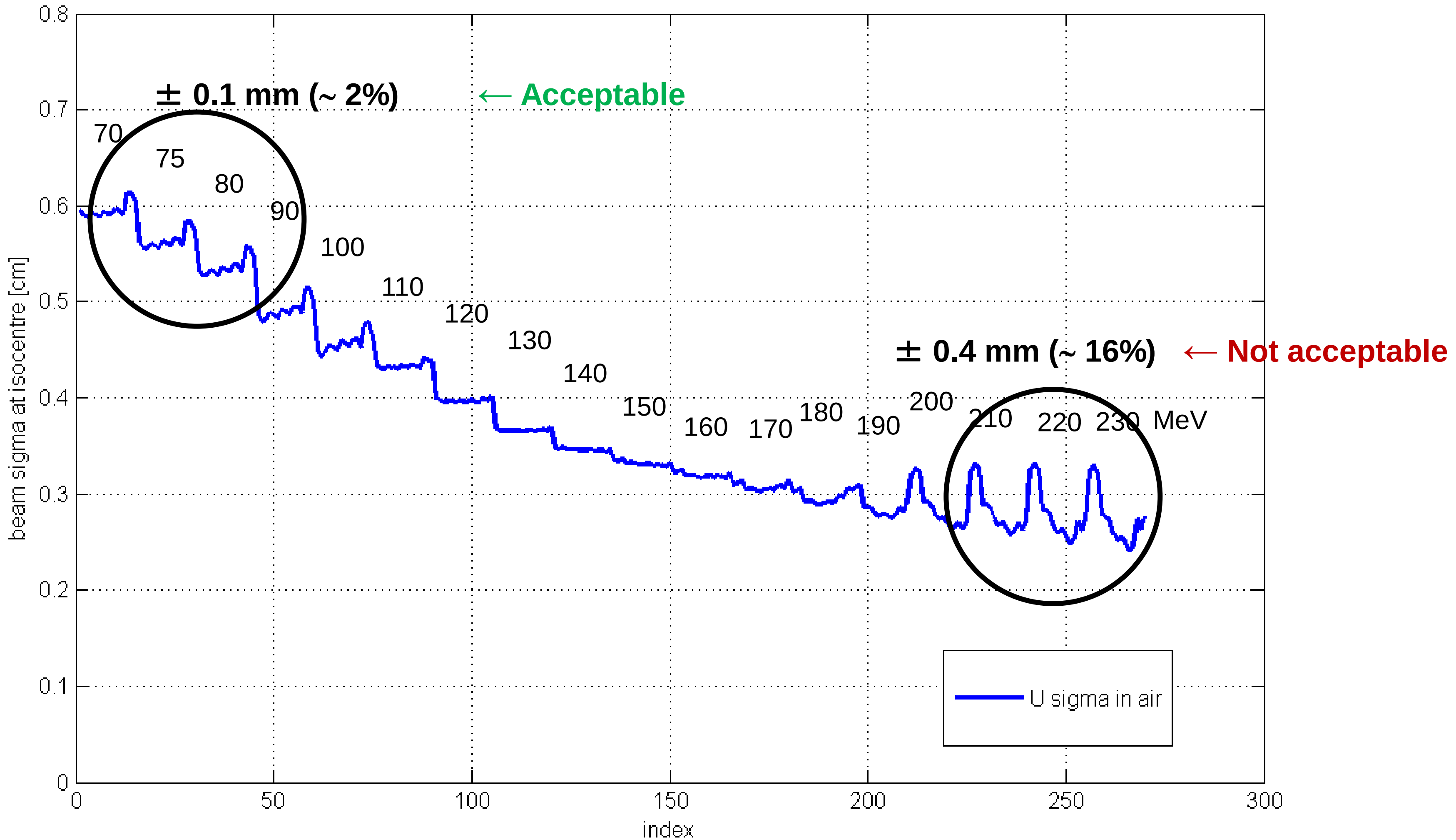
Beam sigma at isocenter in cm



Full scan area with 15 spots / 18 Energies

Delivered beam in air @ Gantry 2

Beam sigma at isocenter in cm



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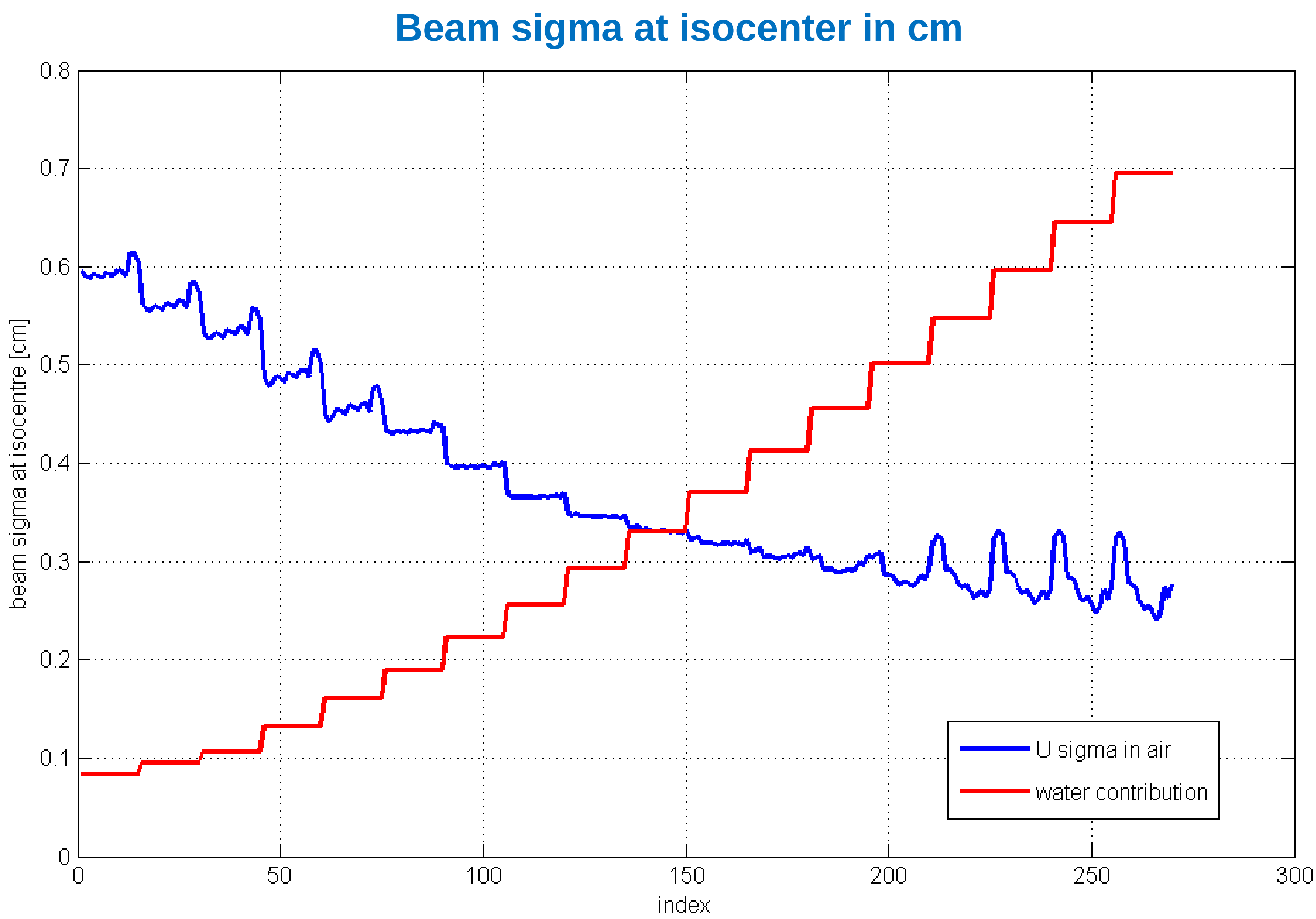

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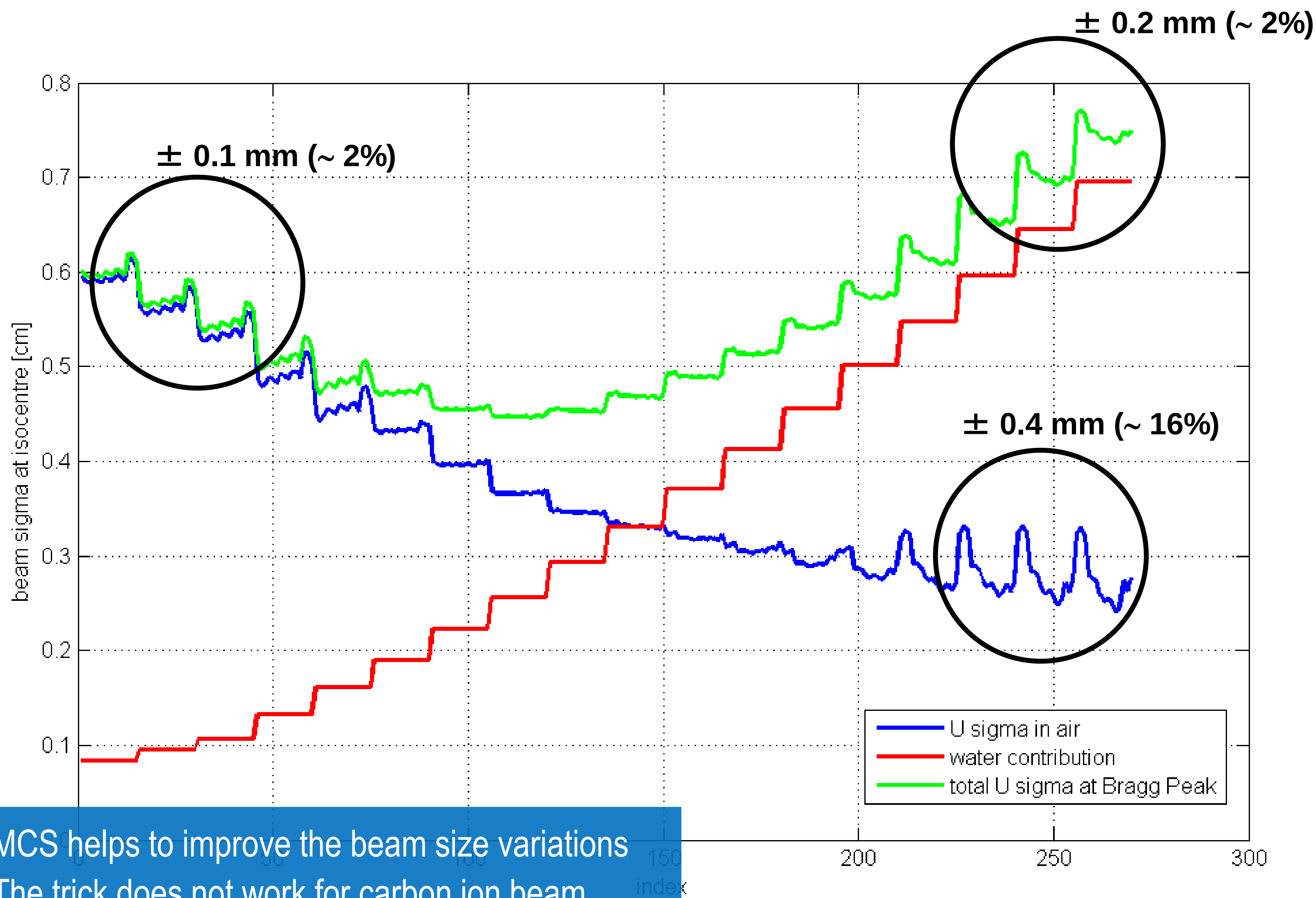


- MCS helps to improve the beam size variations
- The trick does not work for carbon ion beam

Challenge: scanning though the last bending magnet

Last bending magnet: most challenging element

- Large aperture to accommodate deflected beam
- Special lamination to limit eddy currents effect for fast energy changes

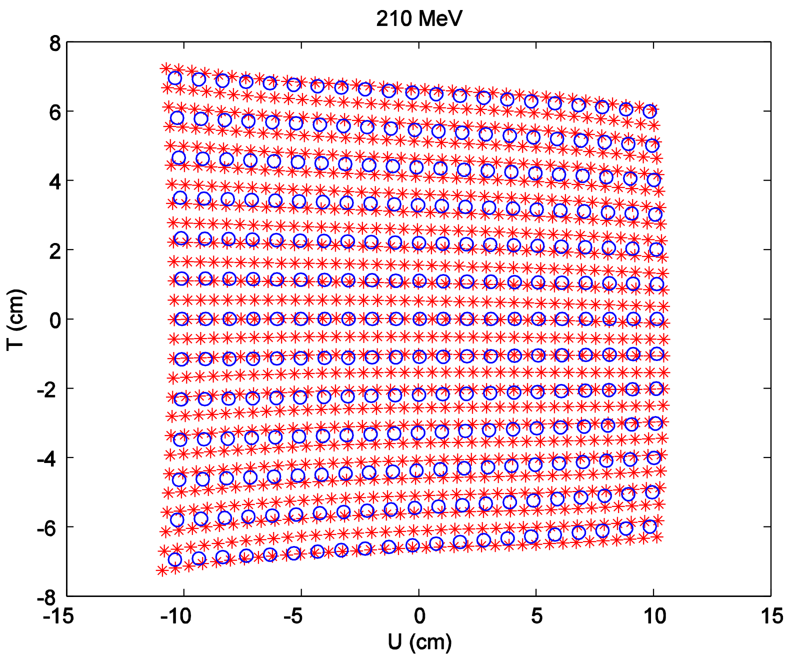
The GOAL: Parallel beam at isocenter with minimal beam shape and position distortions

Dose field homogeneity depends on:

Beam shape

Position

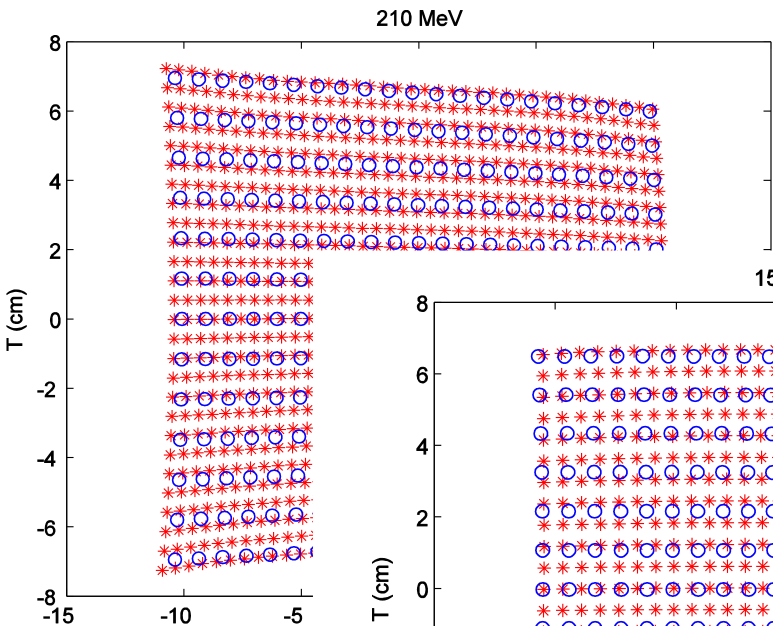
First measurements & beam transport calculation

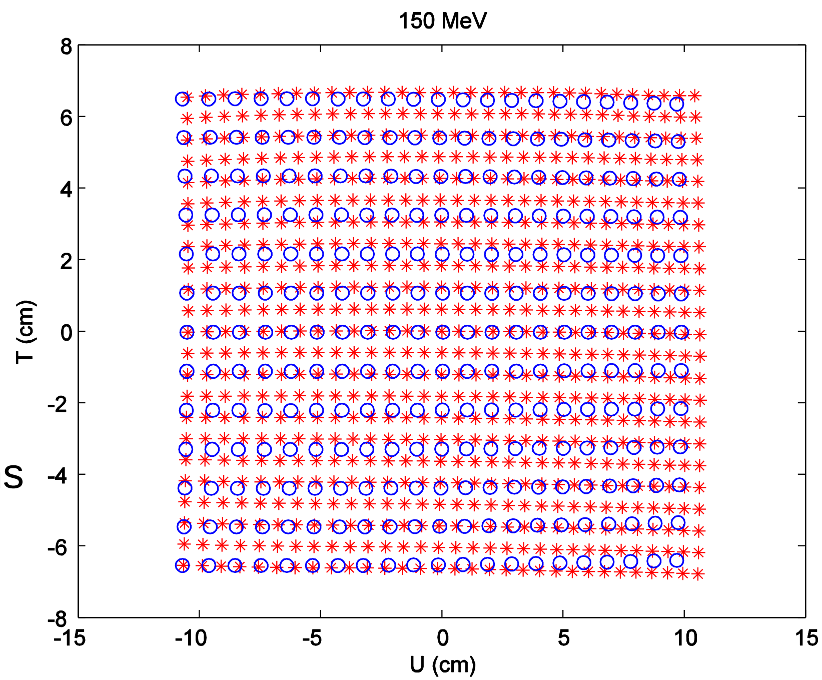


o Tracking predictions

* Measurements

First measurements & beam transport calculation

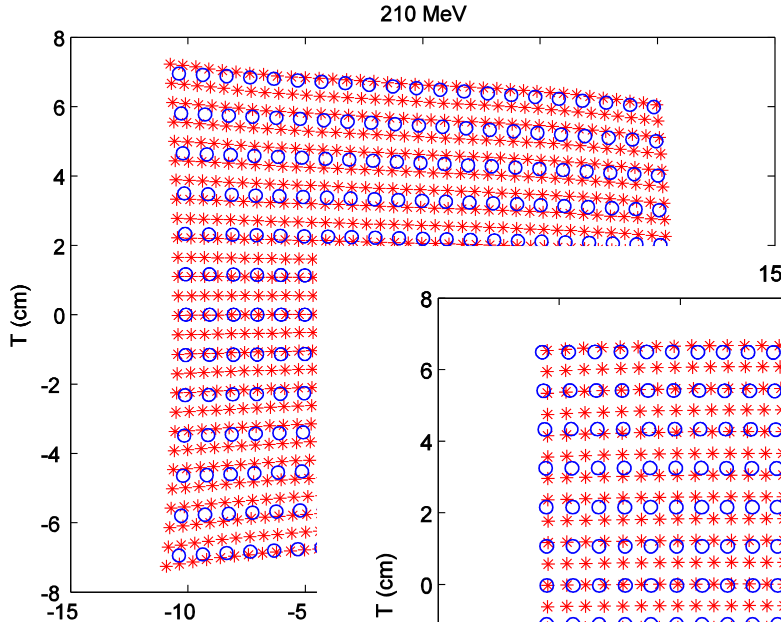


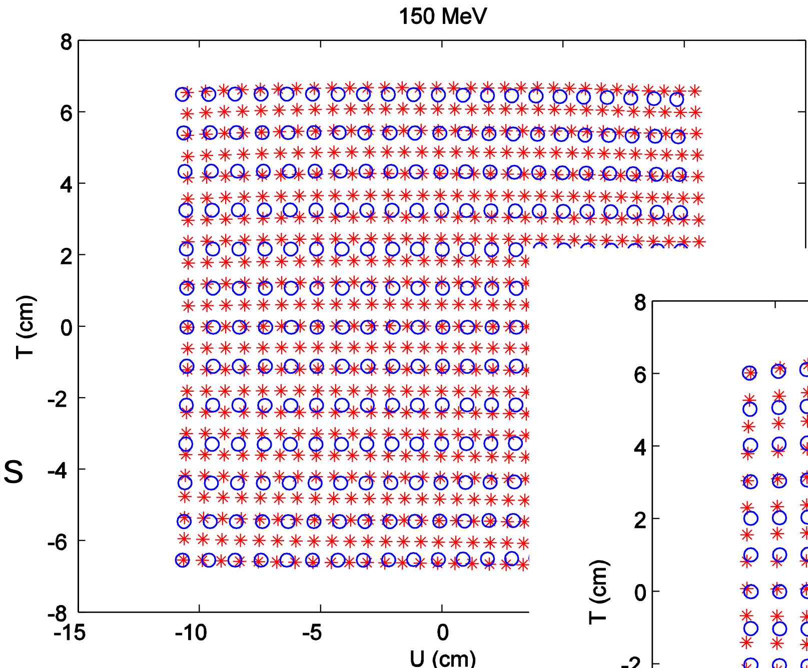


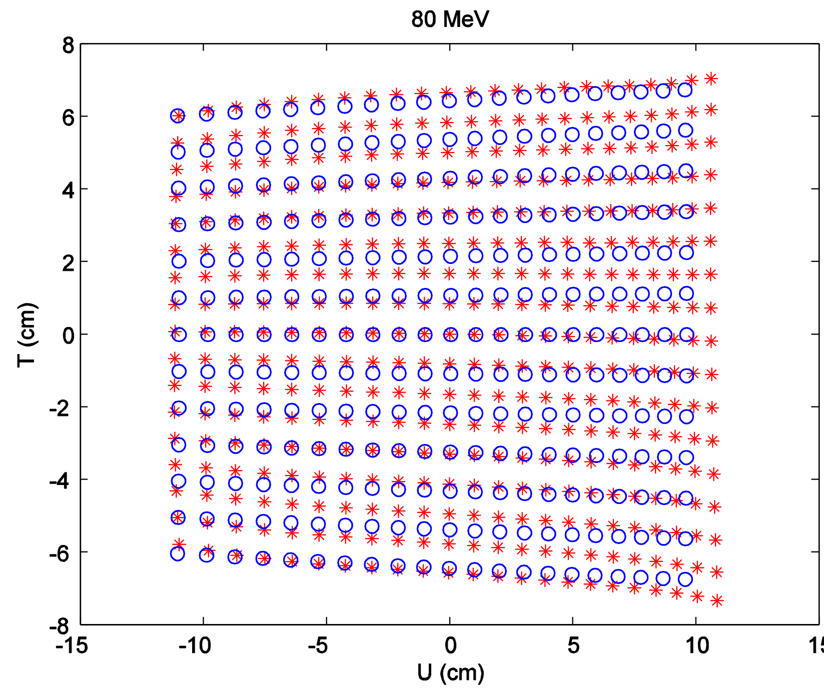
o Tracking predictions
* Measurements

Beam transport calculation vs measurements

The qualitative agreement indicates that the major distortions are due to the curvatures of the effective boundary of the magnetic field of the 90° bending magnet.







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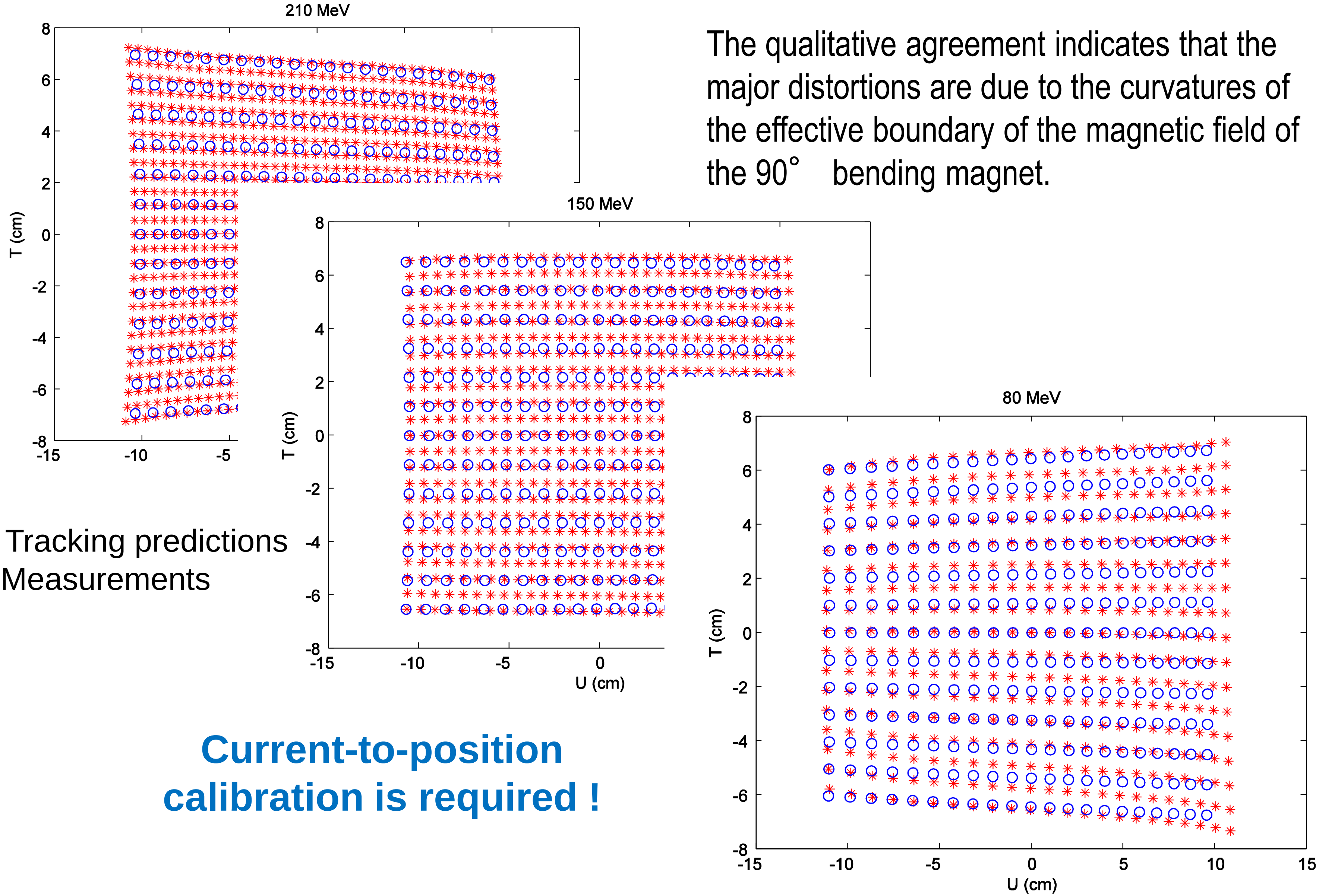


The qualitative agreement indicates that the major distortions are due to the curvatures of the effective boundary of the magnetic field of the 90° bending magnet.

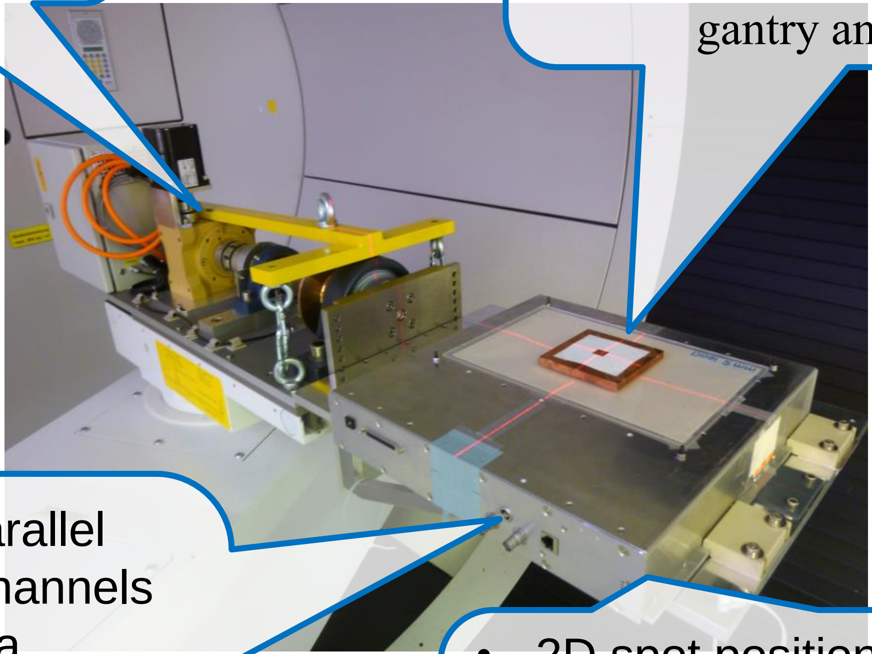
o Tracking predictions
* Measurements

Current-to-position calibration is required !

Detector for beam position measurements @ ISO

Rotation for all gantry angles controlled remotely

- Collimator for device calibration
- Alignment at isocenter < 0.2 mm
    - Room lasers @ $\alpha=0^{\circ}$
    - Nozzle lasers for different gantry angles



- Automatized parallel readout of all channels
- Data logged in a common log file
- Automatized on-line analysis procedure as for the nozzle chamber

- 2D spot position reconstruction
- Ionization strip chamber identical to nozzle:
    - 20x12 cm scan area
    - 2mm strip size

Sweeper calibration strategy

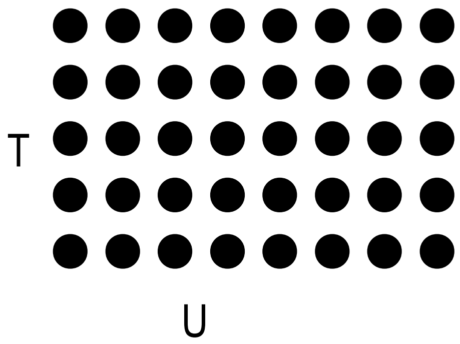
- Full sweeper area scan with a regular current grid
- Energies 70 MeV to 130 MeV, 10 MeV step
- All gantry angles 30 step

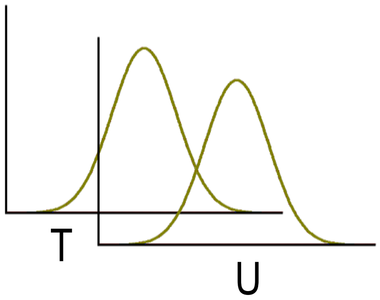
⇩

- Measure position @ isocenter
- Careful spot position reconstruction

⇩

- Parametrize in order to establish current-to-position dependence
- Smooth fit benefits from averaging mis-reconstruction uncertainties

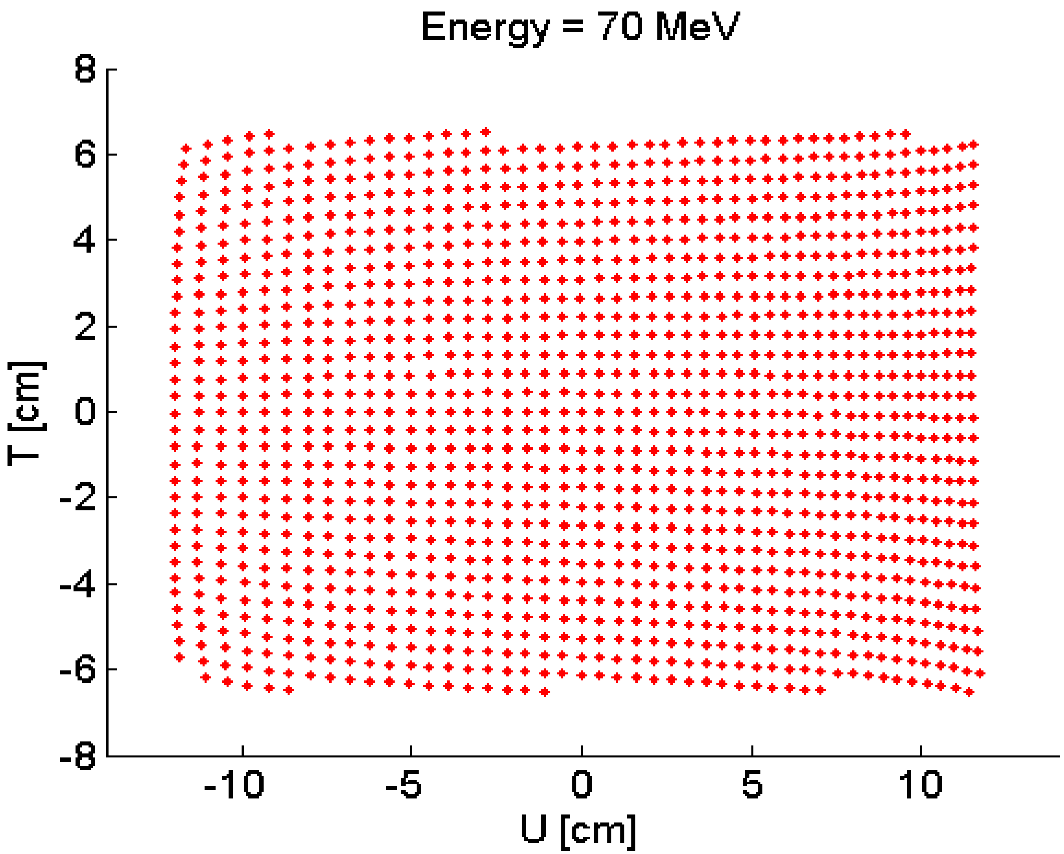




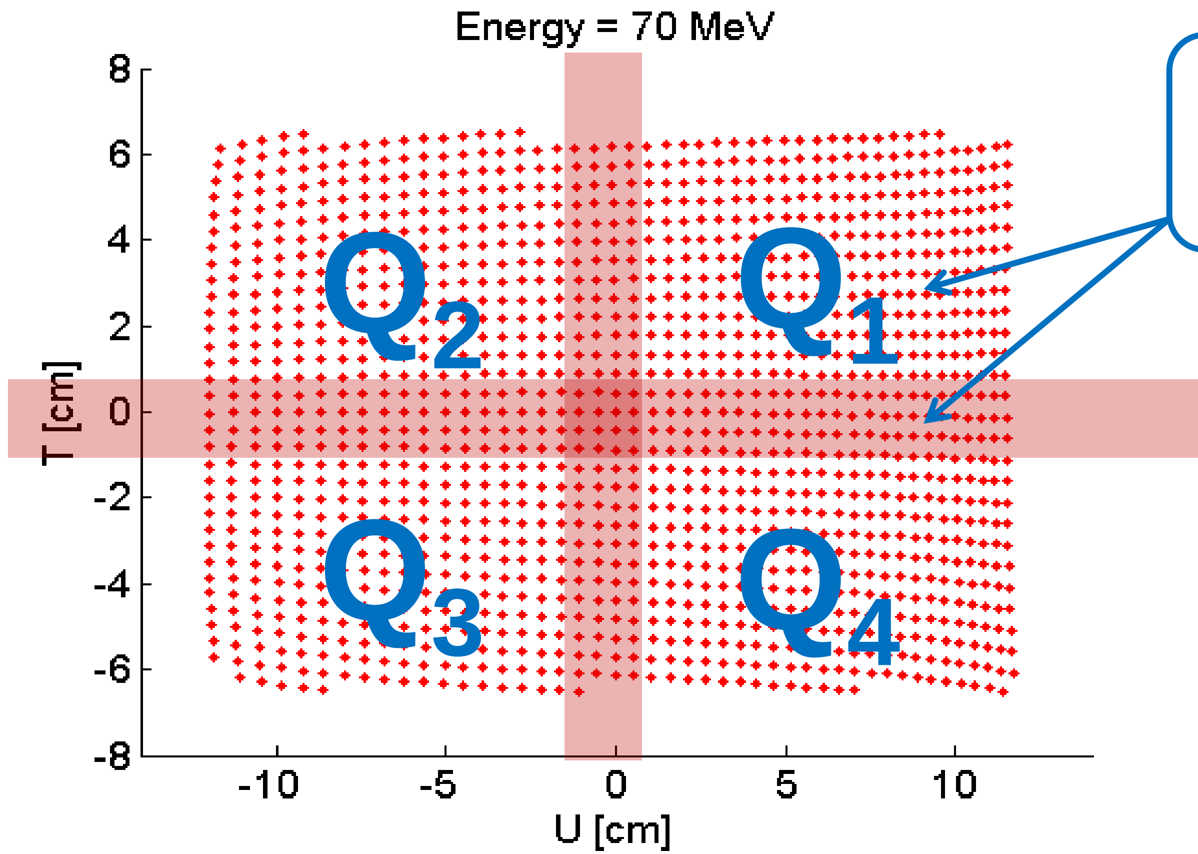
$$I_U = f(U,T,c)$$
$$I_T = f(U,T,c)$$

U and T are not independent !

Current to position parametrization



Current to position parametrization



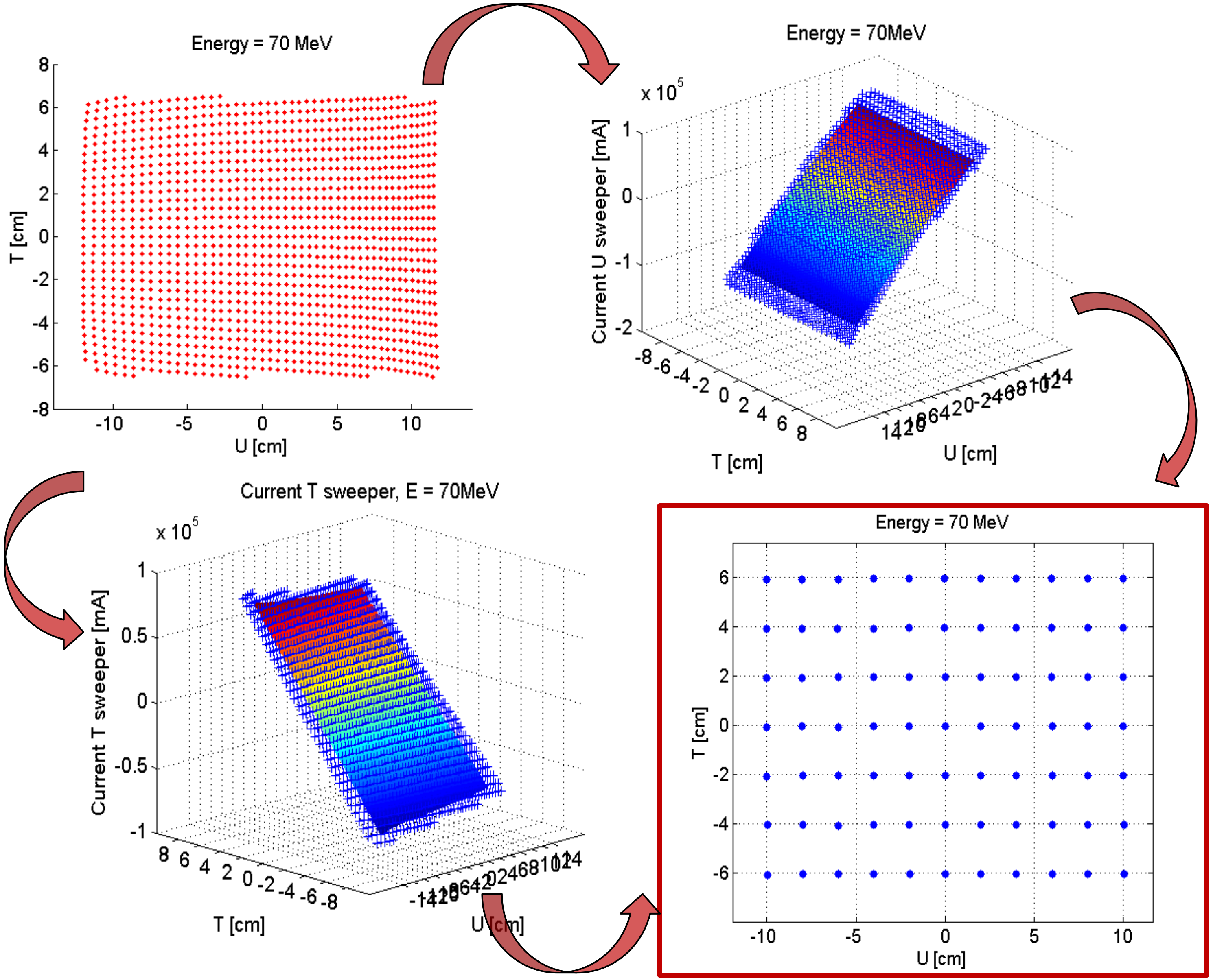
Global fit plus local fit for each quadrant

Smooth polynomial expression for sweeper current: $I_{\mathrm{T}}(T,U,)$ and $I_{\mathrm{U}}(U,T)$

$$I_{\mathrm{USweeper}}(U,T) = \overbrace{g_1U + g_2T + g_3U^2 + g_4T^2 + g_5U^3 + g_6U^4 + g_6U^5 + g_6U^6 + g_6U^7}^{\text{global function}} +$$

$$\sum_{q=1}^{4} \underbrace{l_1^qUT + l_2^qU^2T + l_3^qUT^2 + l_4^qU^3T + l_5^qU^2T^2 + l_6^qUT^3 + l_7^qU^4T + l_8^qU^3T^2 + l_9^qU^2T^3 + l_{10}^qUT^3}_{\text{local function for each quadrant}}$$

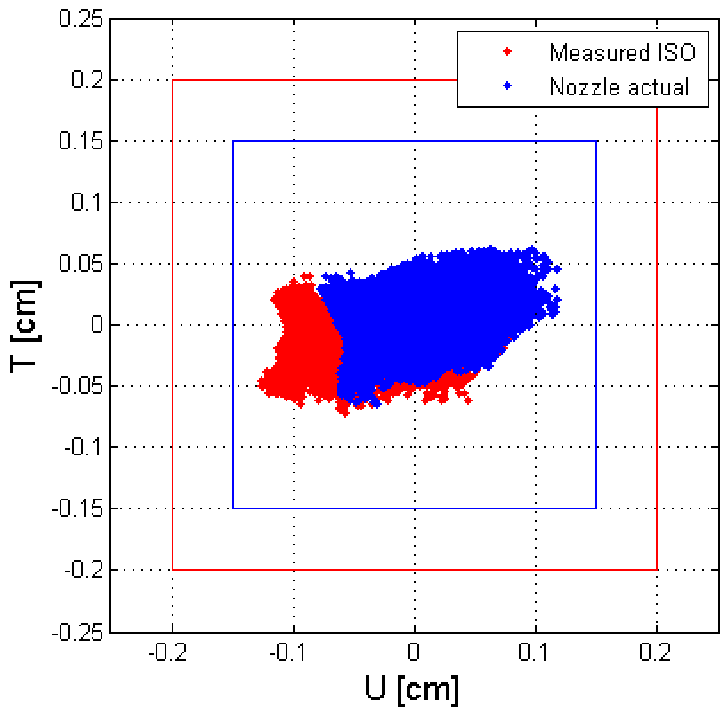
Current to position parametrization



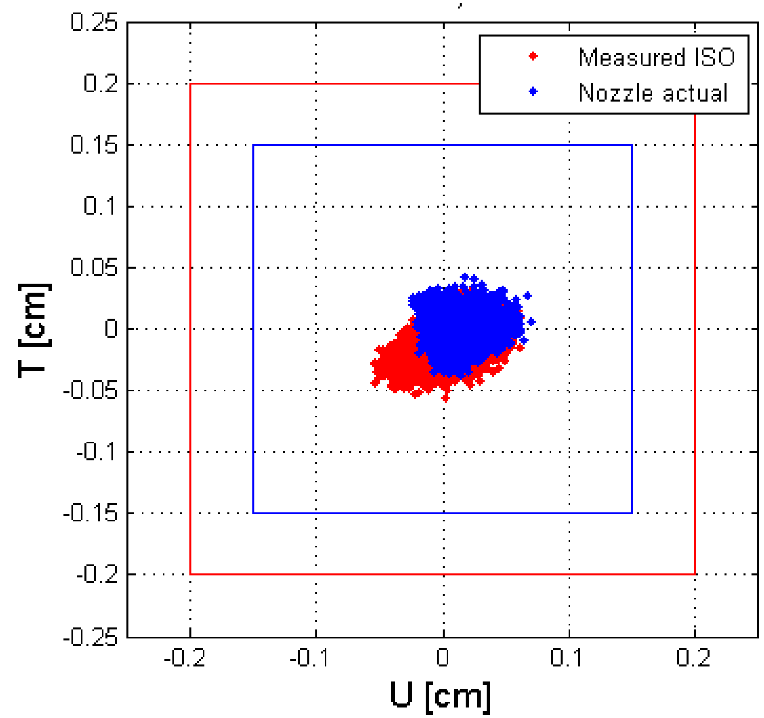
Angular dependent sweeper calibration

- Possible averaging over all gantry angles
- 2 years of operation using average sweeper magnet map in combination with patient specific correction for the lateral position deviations
- Angular dependent calibration performed using same calibration procedure with improved position reconstruction and detector alignment at the isocenter
- Angular dependent maps computed to 8 gantry angles

Averaged maps: Gantry @ 90



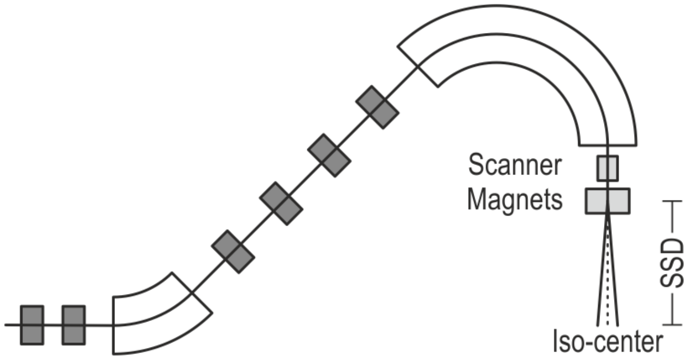
Angular dependent maps: Gantry @ 90

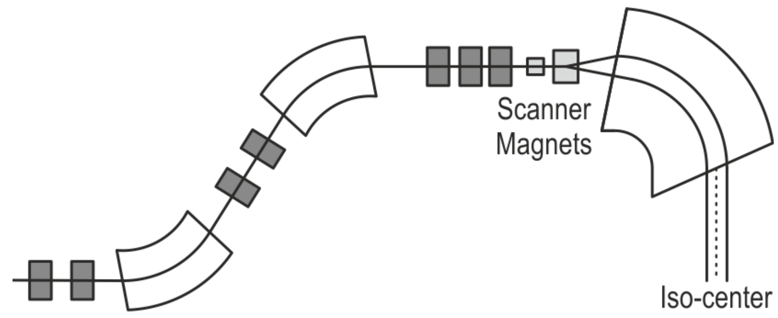


Nozzle back projection

Relevant for downstream scanning as well as upstream scanning

(deviation from perfect orthogonality)





First approximation:

- Distance from the source to the nozzle position monitor and to isocenter are known
- Nozzle position monitor would give information about the beam angle
- Linear projection from the source to isocenter

Ideally (no beam position distortion):

Beam in the nozzle @ any location is identical to isocenter

Reality

- The actual position of the nozzle monitor should be translated to isocenter
- Even minimal beam deviation from parallel is giving significant spot displacement at isocenter: beam angle over all scan area in both directions transverse to ISO should be calculated

Nozzle back projection @ Gantry 2

On-line position verification: spot position measurement and its propagation to the isocenter

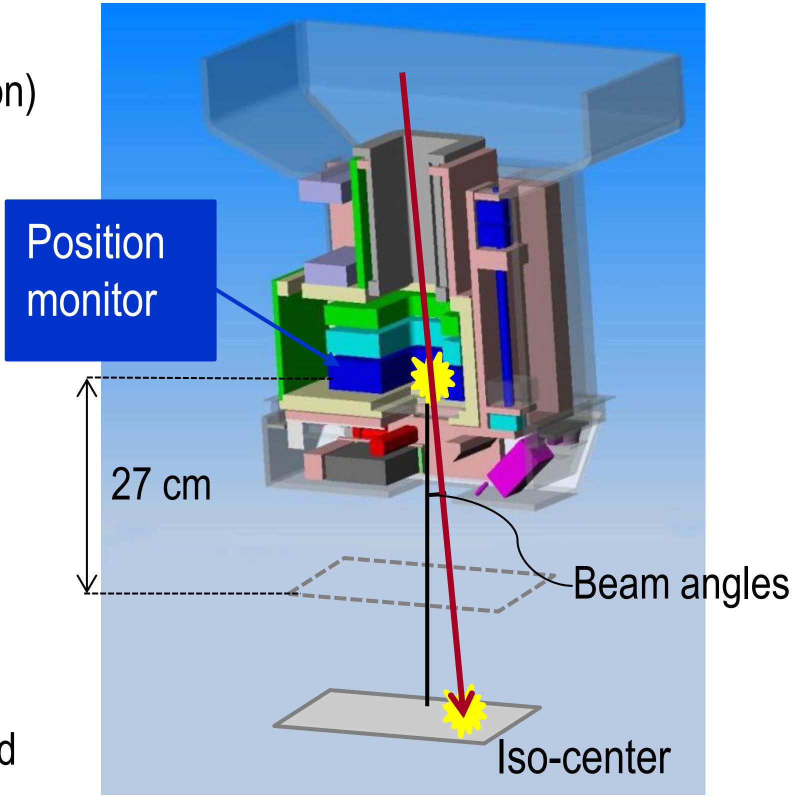
Position measurement of two orthogonal profiles

- Measurement with position monitor in nozzle
- Cross check position at iso-center (monitor position correction)

Position monitor → iso-center projection

– Beam angles for full scan range (per position and energy)
  - ○ Projection error should be < 0.2 mm
  - ○ Distance monitor - iso-center ~ 70 cm

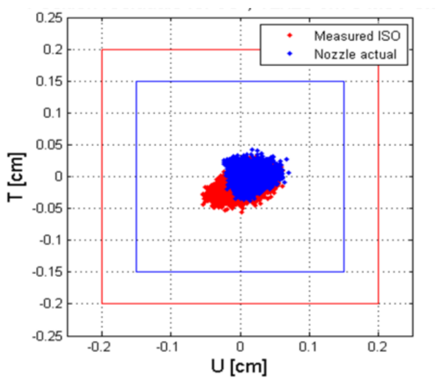
Measuring beam angel with precision < 0.5 mrad



- Projection calculation off-line: interpolation from LUT
- On-line correction calculation at ISO using position measured in the nozzle

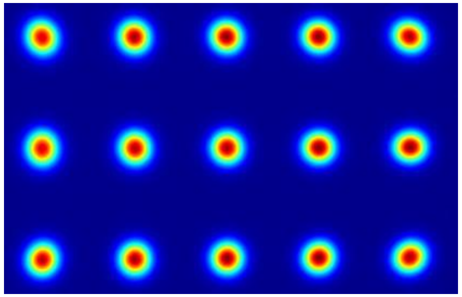
Achievable dose homogeneity for upstream system

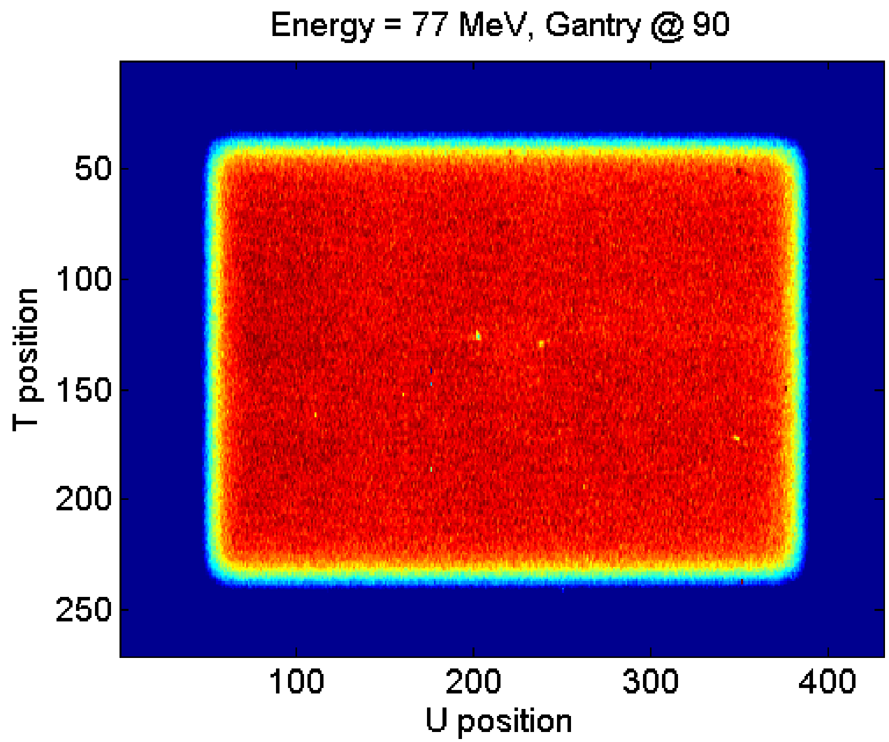
Lateral spot position precision is better than 1 mm



+

Spot shape deformation better than ±0.2 mm





Overall dose field homogeneity at the targetfor all energy and all gantry angles **< 2%**

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Conclusions

- **For conventional UP-stream scanning system it is feasible to achieve required spot position precision, beam shape translation to the isocenter and homogeneous dose field distribution**

- **Benefits of UP-stream system:**
  - Smaller room volume respect to down-stream systems
  - Parallel beam scanning
    - Low skin dose
    - Easily performed field patching and QA

- **Challenge:**
  - Maintenance of the symmetric spot shape
  - Current-to-position calibration
  - Back projection
  - Limited field size

- **What does it mean for superconducting gantry?**

Current to position parametrization