Proton dose calculation algorithms and configuration data

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Agenda

- Broad beam algorithms
- Concept of pencil beam dose calculation
- Beam configuration data for Eclipse Proton
- CT calibration

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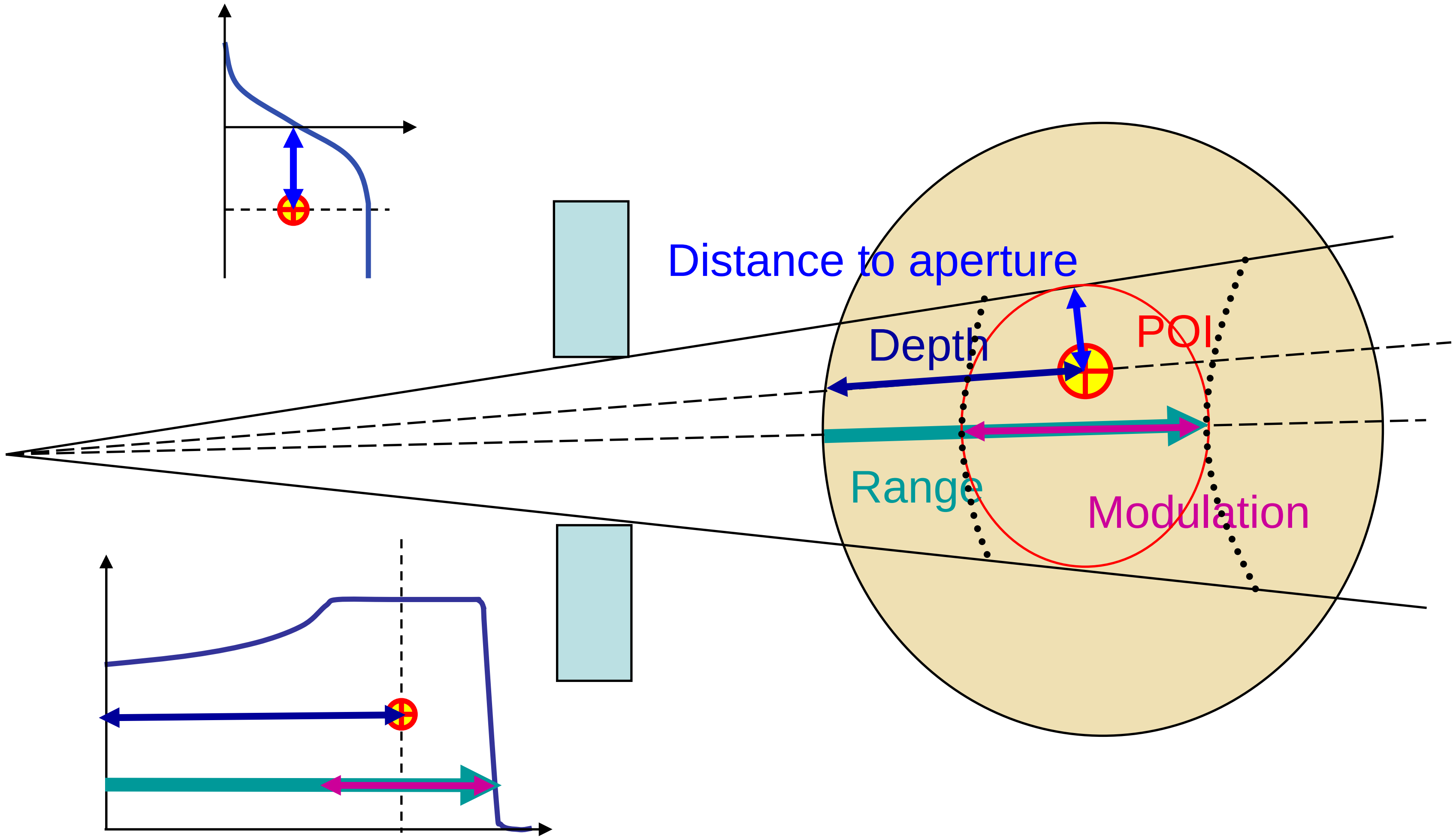
Broad beam algorithm - Concept

- Find the range and the modulation of the beam required to cover the target
- Find the depth and the distance to the aperture for each point of interest (POI)
- Use look-up tables for the dose in depth and apply a correction for the lateral penumbra

Broad beam algorithm - Concept



Broad beam algorithm - Applications

- First proton dose calculation algorithms
- Used today only for ocular applications
  - Very fast algorithm
  - Loss in accuracy is small due to homogeneous tissues

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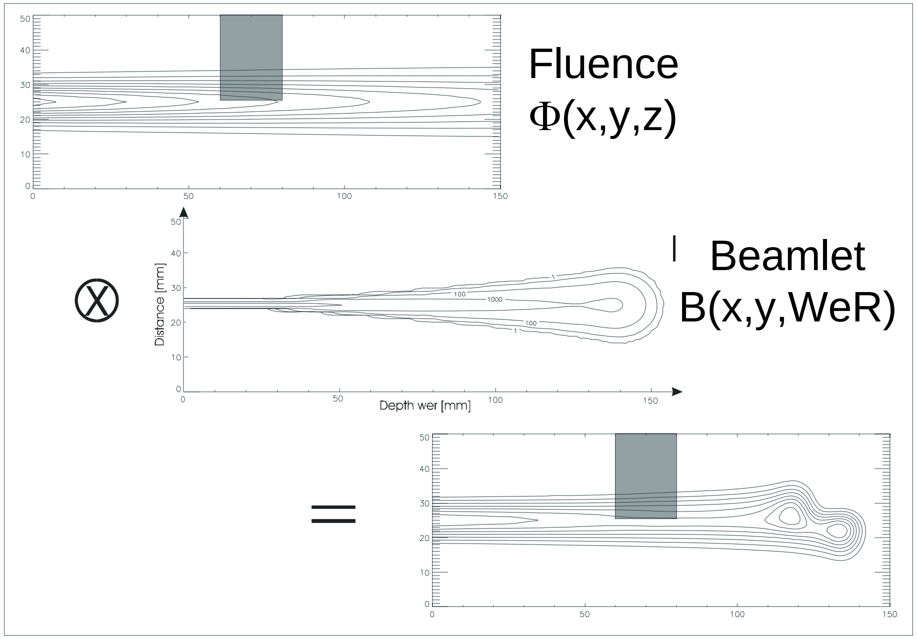
Eclipse pencil beam algorithm - Concept



- Principle
  - Convolution of 3D undisturbed proton fluence in air with a ‘beamlet’ in water.
- In practice
  - Superposition of inhomogeneity - corrected beamlets and multiplication with fluence at calculation position.

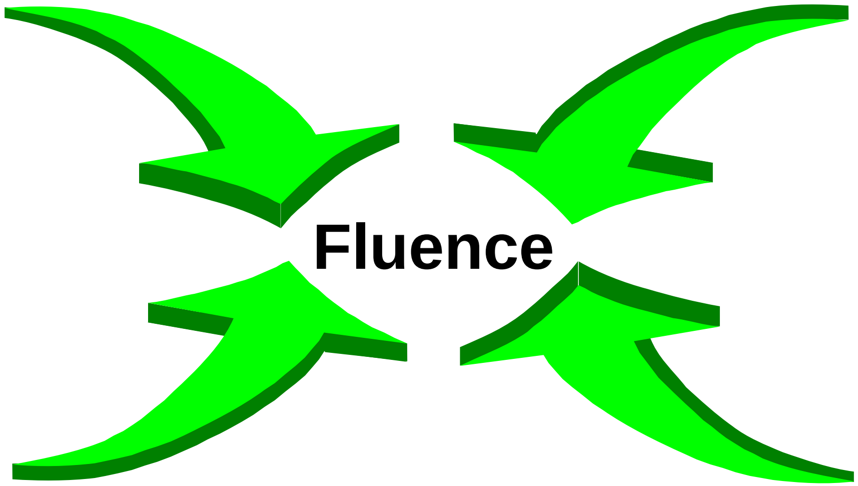
Fluence of a double scattering beam line

1st and 2nd scatterer

- Homogeneous fluence distribution
- Eff. Source size and position

Absorber, Modulator

Broadening of penumbra



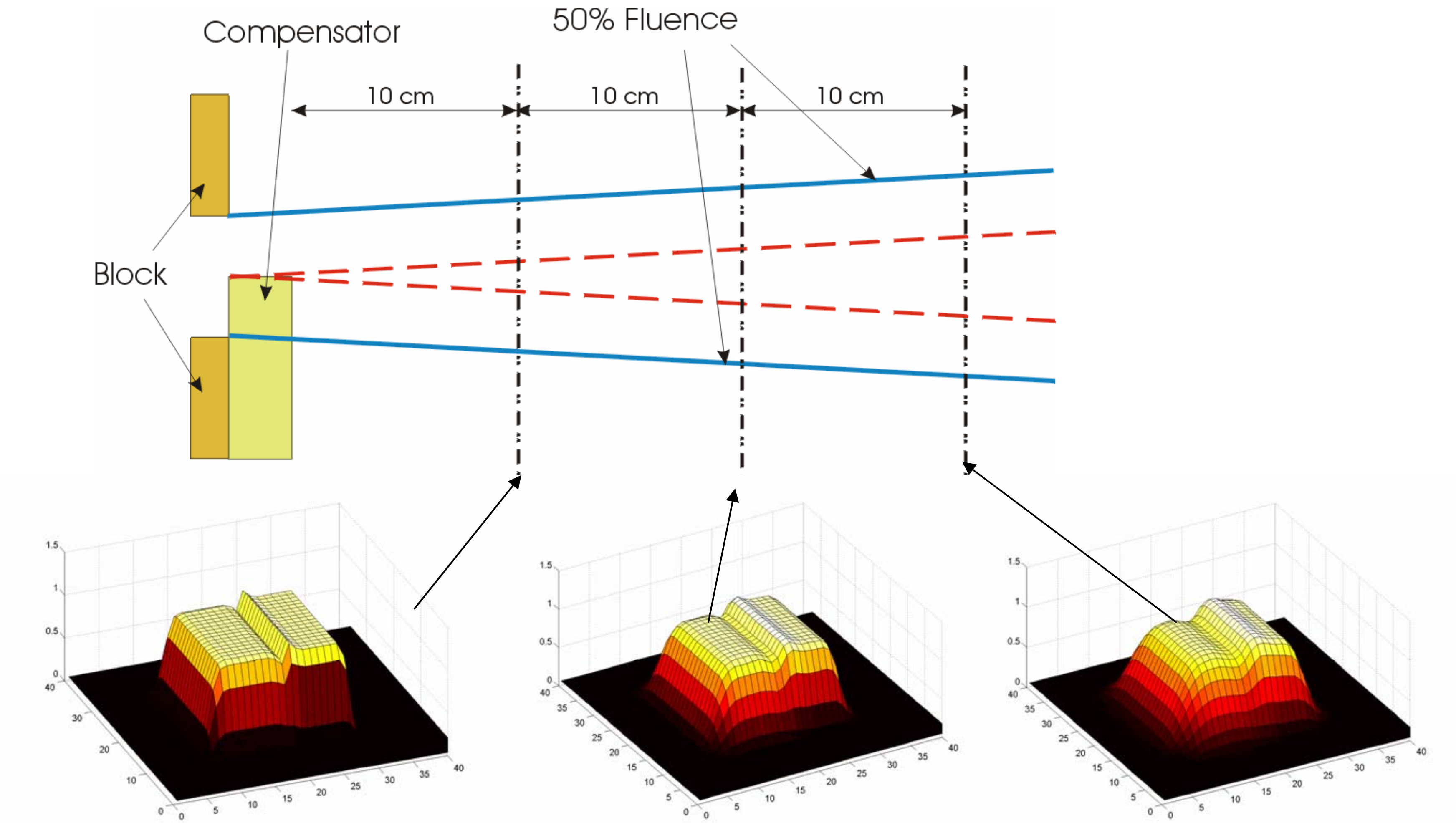
Compensator

- Broadening of penumbra
- Inhomogeneity of fluence

Block

- Transversal shape of beam
- (Block scattering component)

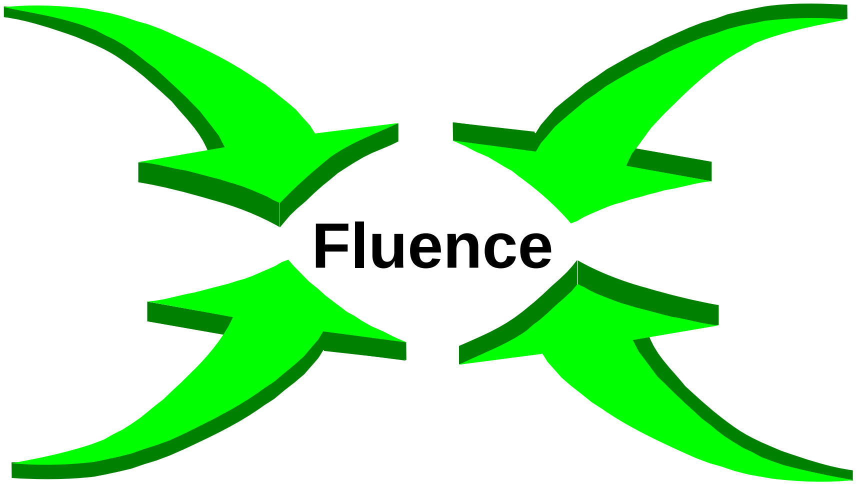
Example of fluence distribution



Fluence of a scanning beam line

Phase space of single beam spot

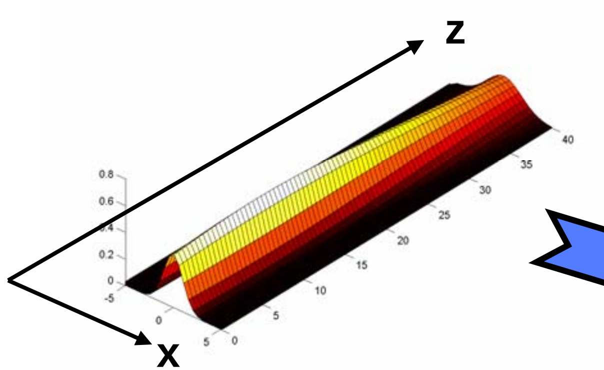
(Divergence, beam size at reference position)



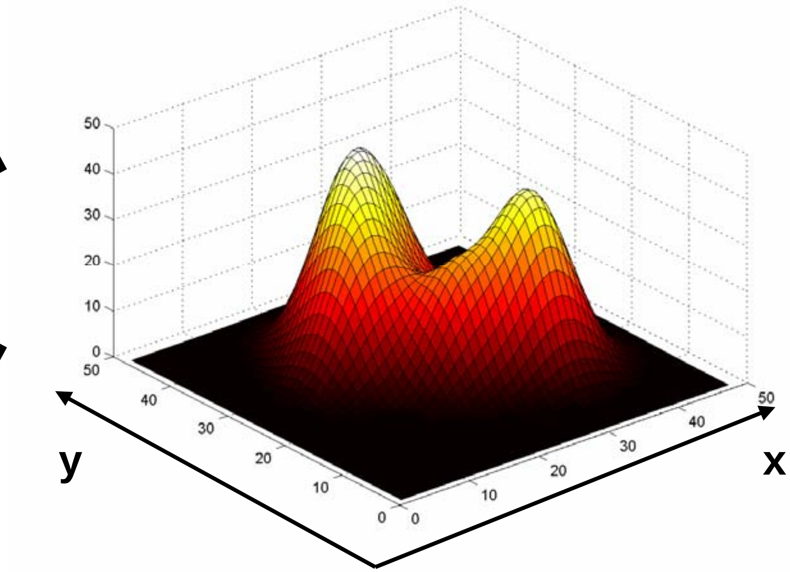
Scan pattern and weights of individual beam spots

Example of scanning fluence distribution

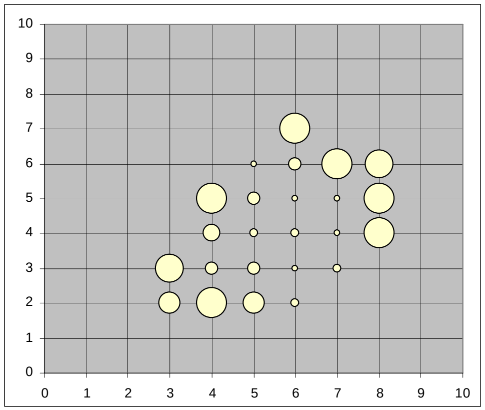
Fluence of single pencil beam



Total fluence



Scan pattern and weights



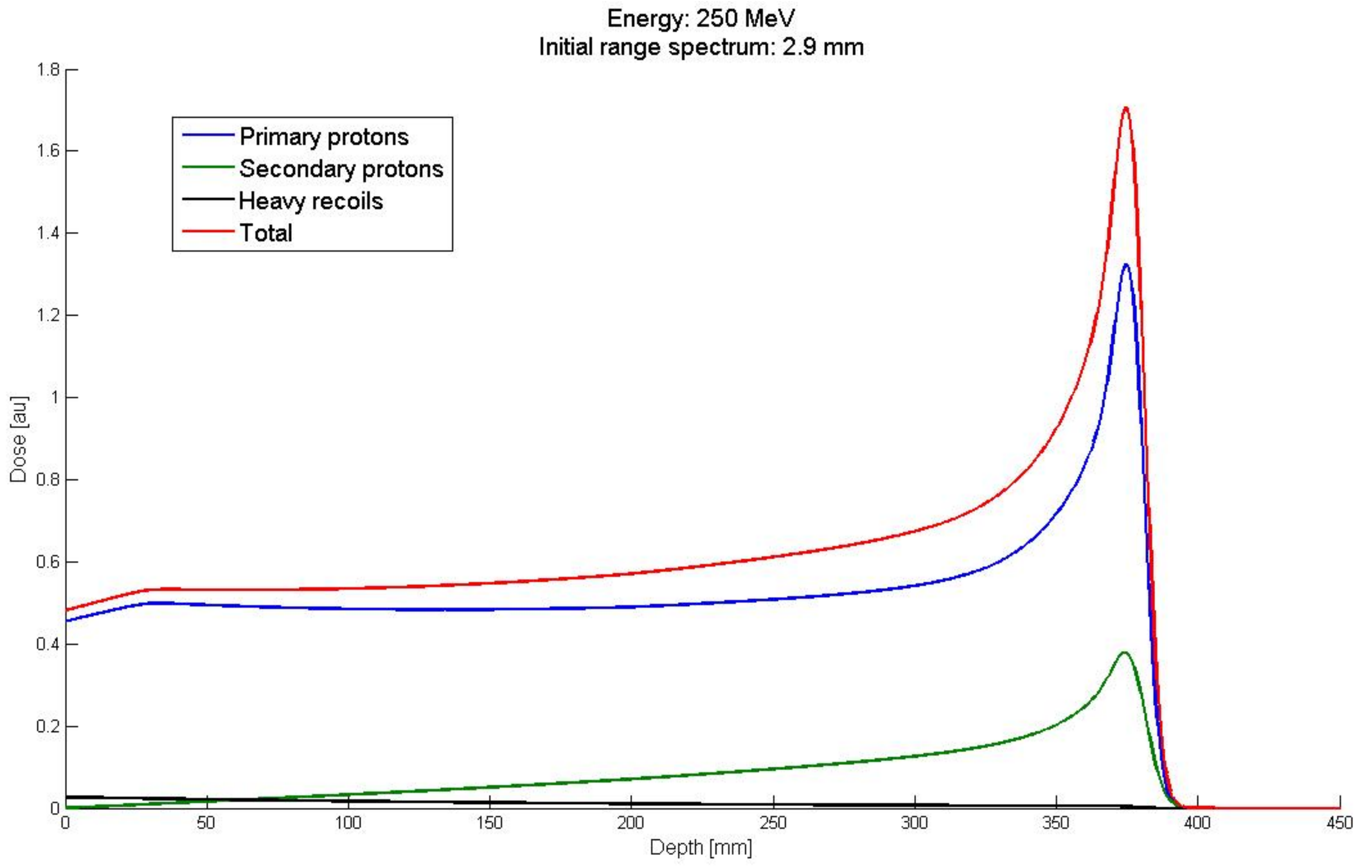
Beamlet in water

- Definition:
  - Dose deposited by a proton beam, which hits a water surface without lateral extension and without angular divergence or confusion.
- Characterization:
  - Depth dose distribution
  - Transversal distribution
  - Independant of technique!

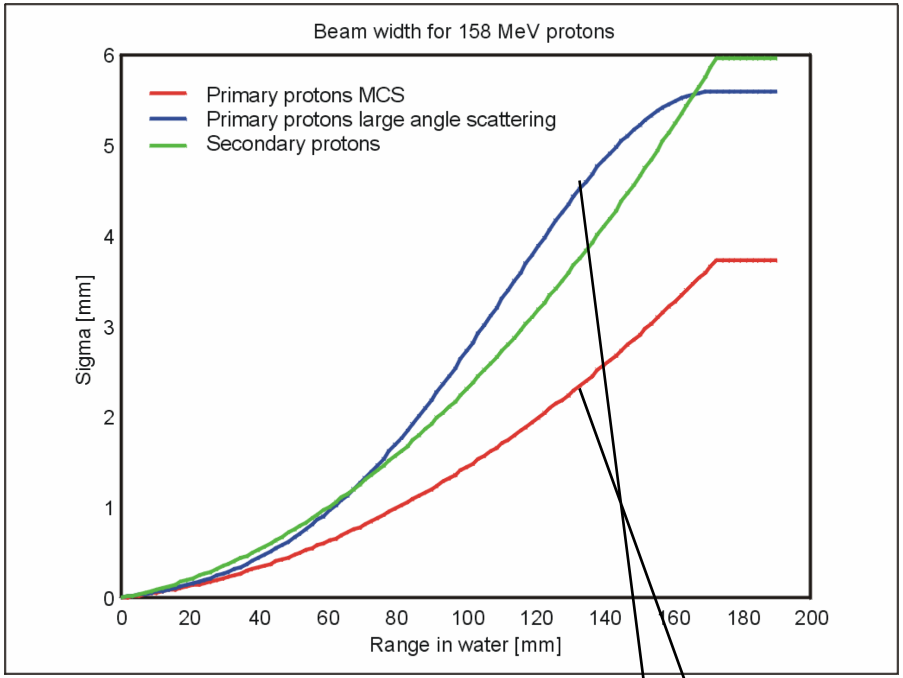
Model of beamlet in water

- Model is based on analytical functions fitted to Monte Carlo calculated depth dose distributions
- Depth dose and scattering distributions are modeled for primary and secondary protons separately
- Measured depth dose curves are used to extract beam-line specific parameters for the model

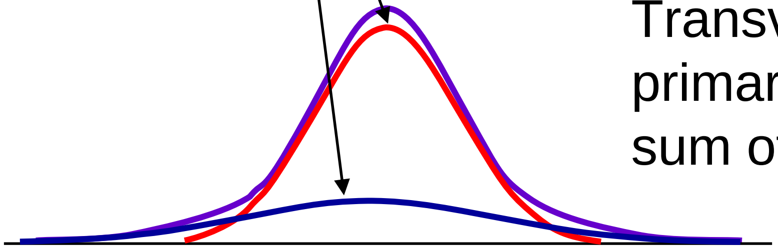
Example of calculated depth dose distribution



Transversal distribution

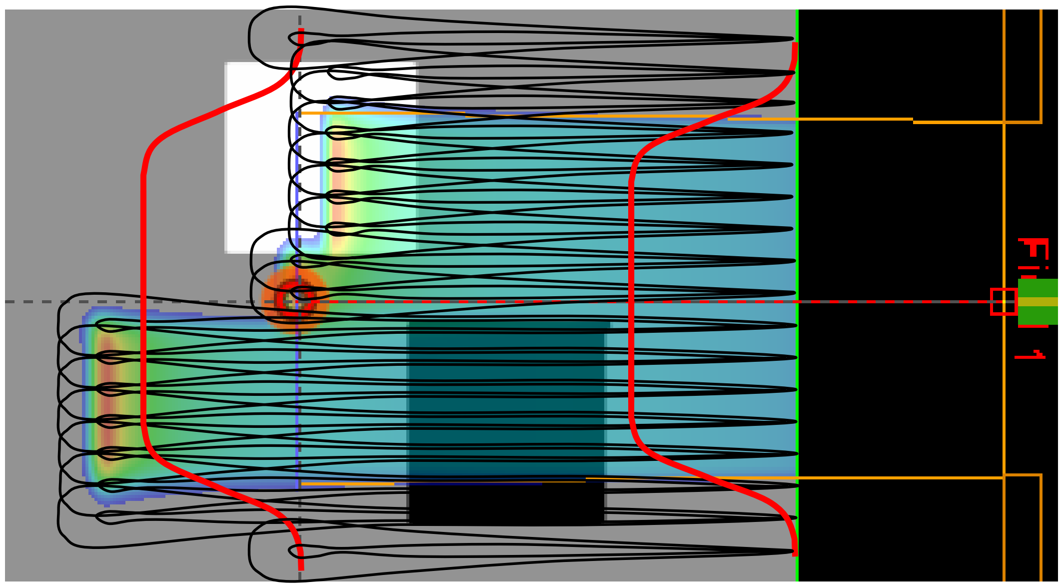


Beamlet transversal distribution at each position in depth is calculated from the sigma of one or several Gaussians.



Transversal distribution of primary protons = sum of two Gaussians

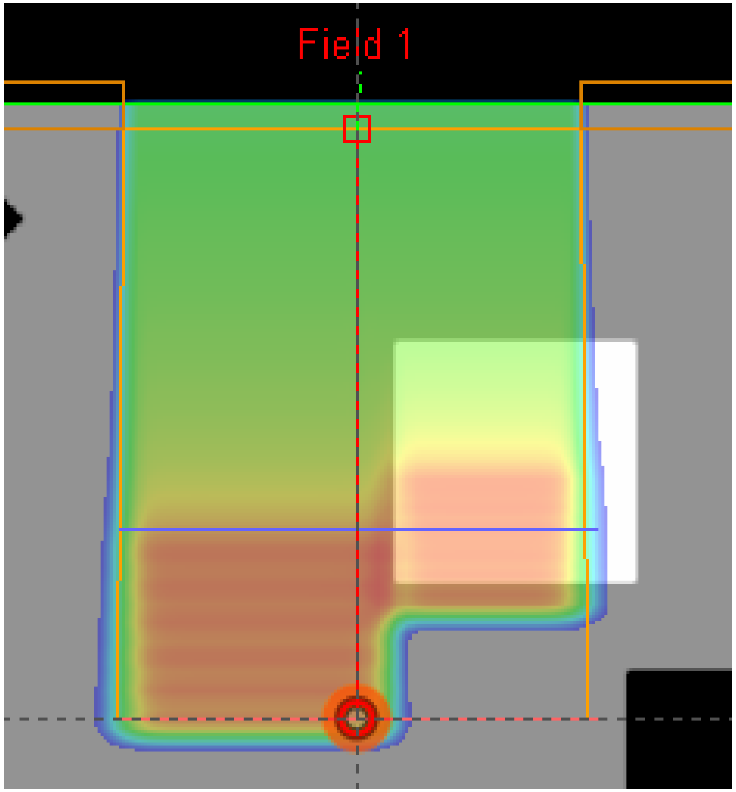
Inhomogeneity correction



- Each beamlet is corrected for density variations before it is multiplied with the proton fluence in air

Total SOBP dose

- Contributions of all layers are added in a final step.



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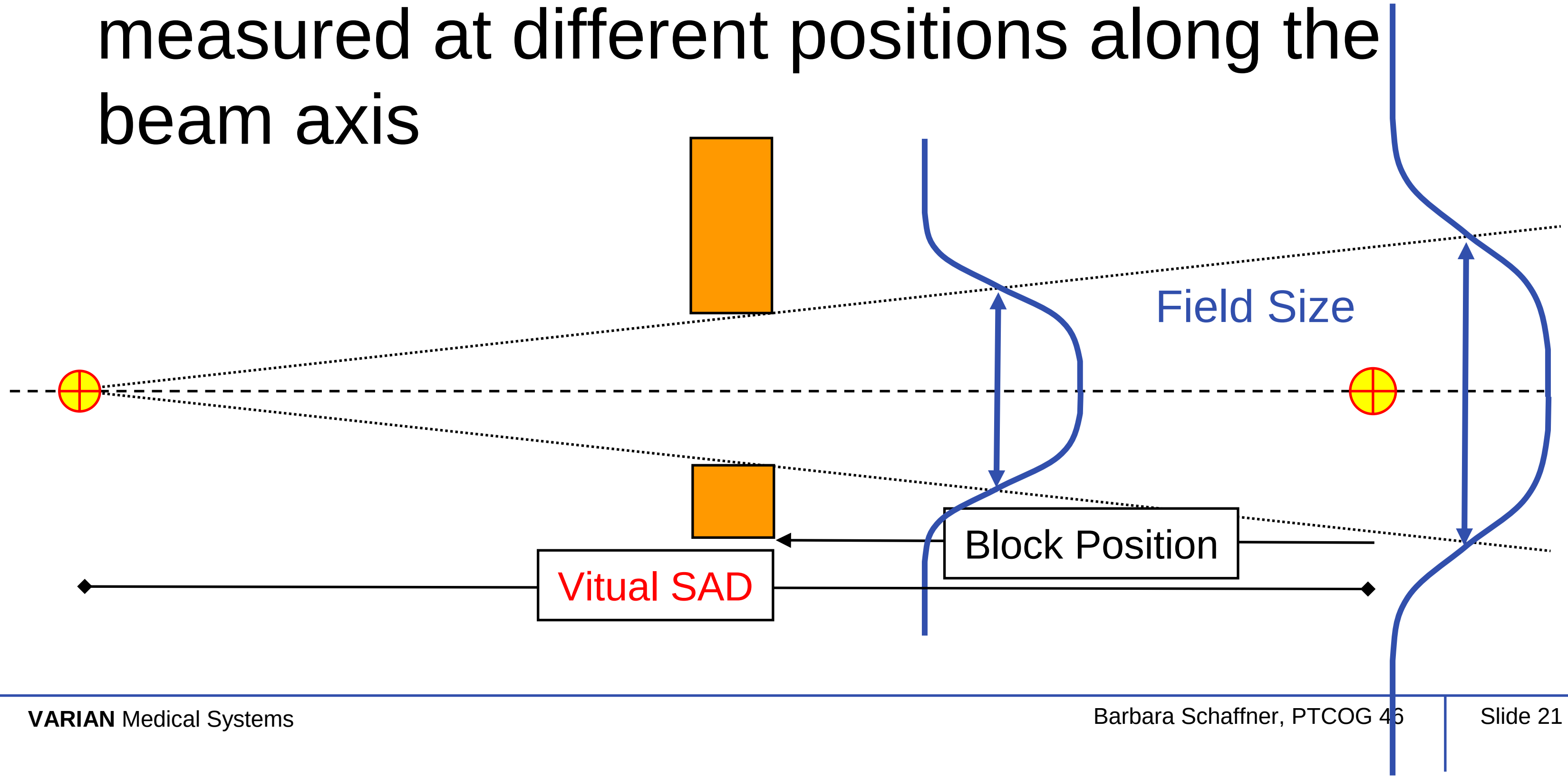
Measurements – the input for the dose model

- Fluence calculation
  - Open field cross profiles -> Virtual SAD
  - Fluence along Z axis -> Effective SAD
  - Half beam block -> Lateral penumbra of fluence
  - Cross profiles of spot fluence -> Phase space
- Beamlet calculation
  - Depth dose curve -> Depth dose parameters

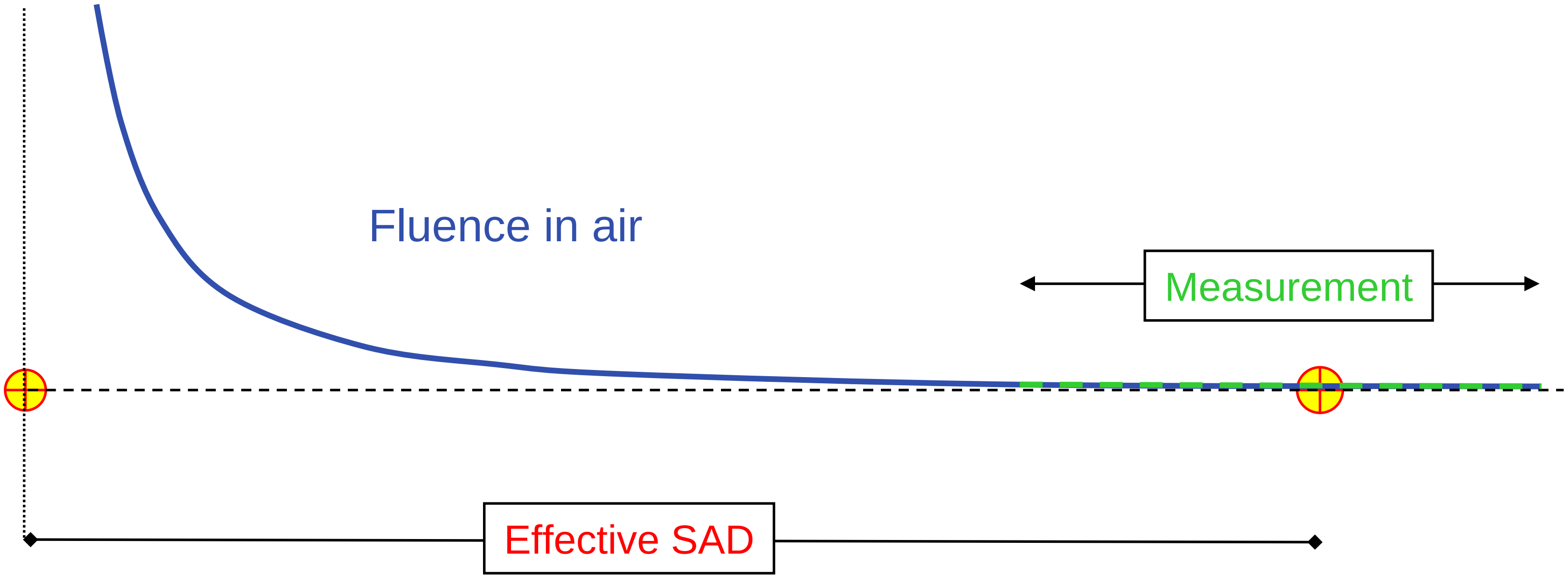
Virtual SAD Calculation

- The virtual SAD is the ‚geometric' SAD
- It is found by a linear fit to the field sizes measured at different positions along the beam axis



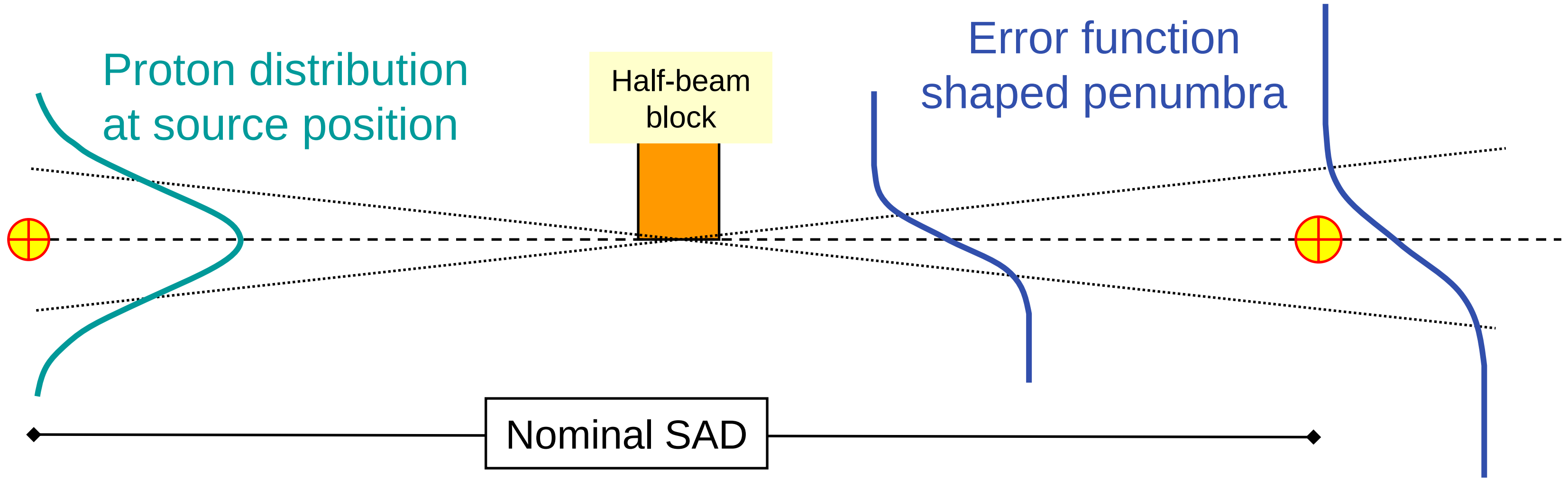
Effective SAD Calculation

- The effective SAD is the ‚dosimetric‘ SAD
- It is found by a $1/r^2$ fit to the measurements of the fluence along the beam direction



Effective Source Size Calculation

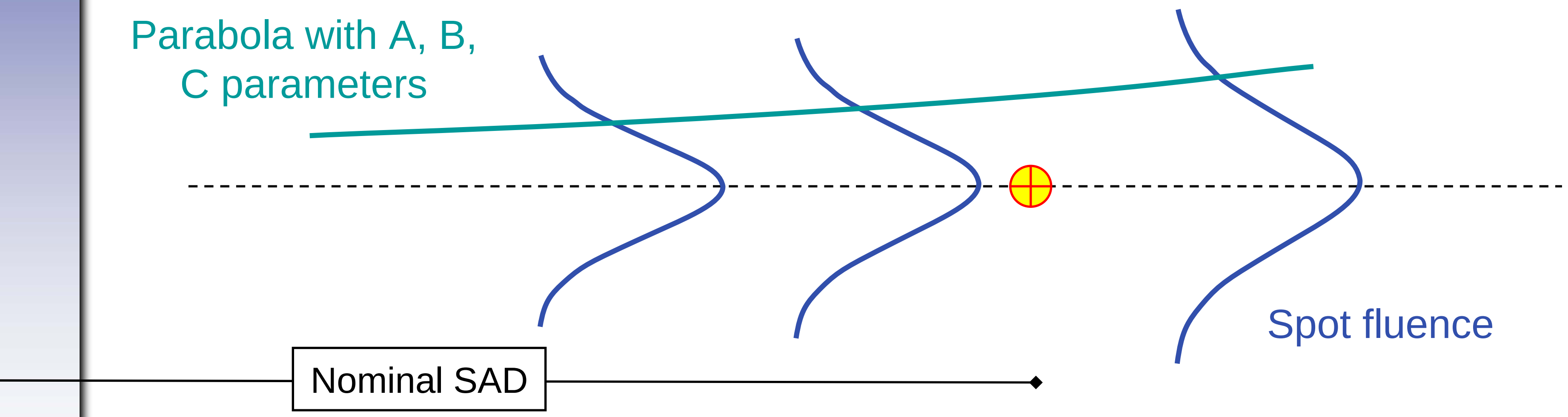
- It is assumed that the penumbra shape can be modelled by the effective source size concept introduced by Hong et al.
- The proton source is assumed to be located at the position of the nominal source and to have a Gaussian distribution.



Phase Space Parameters

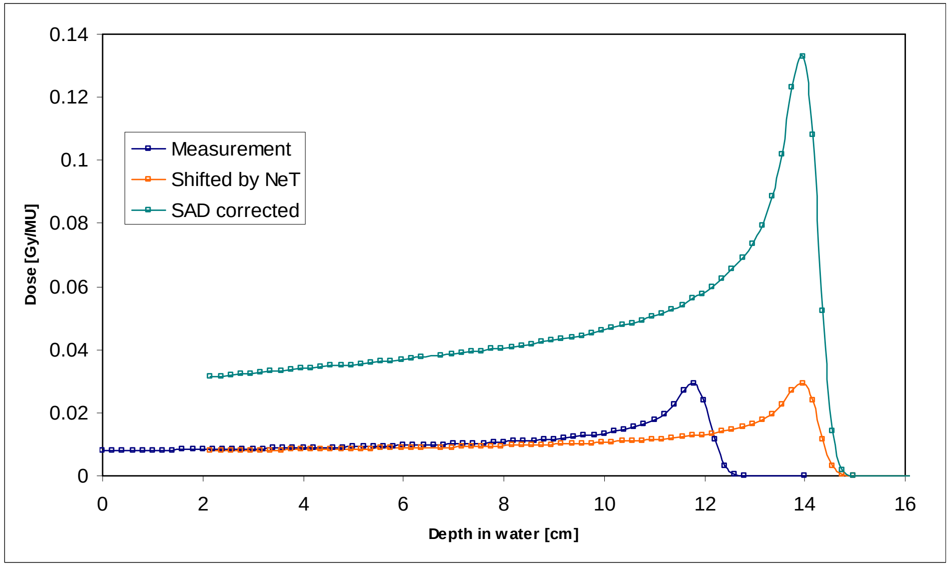
- Phase space parameters are extracted from cross profile measurements of the spot fluence in air.
- The following formula is fitted to the spot size plotted as a function of the distance from isocenter:

$$f(z) = \sqrt{\frac{A}{2} + B \cdot z + \frac{C}{2} \cdot z^2}$$



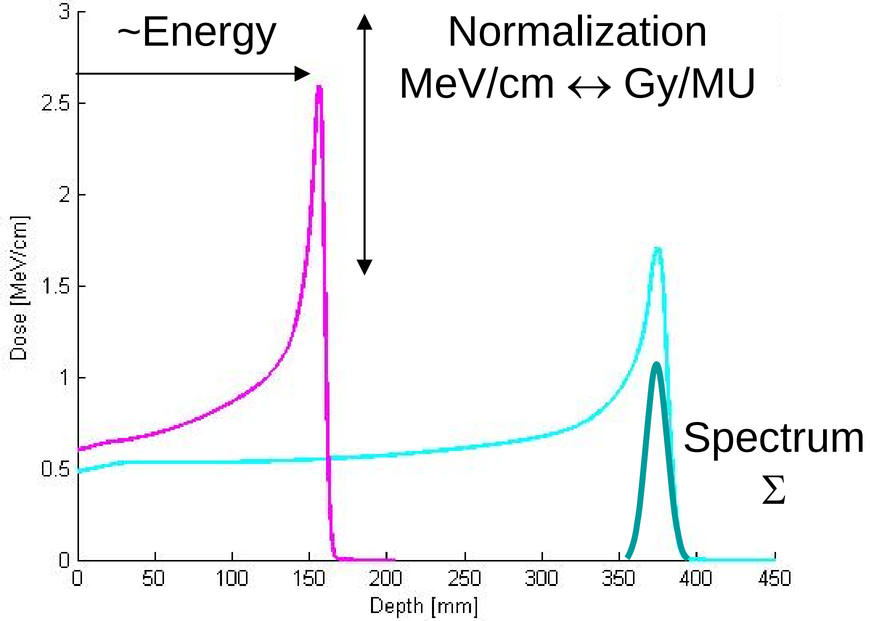
Preprocessing of measured depth dose

- Measured depth dose gets shifted in depth by water equivalent thickness of the beamline
- Measured depth dose is corrected for intensity loss due to $1/r^2$ effect



Calculation of Depth Dose Parameters

- Resulting depth dose is used for a least square fit of analytic depth dose formula with free parameters
  - Energy
  - Spectral distribution Σ
  - Normalization
  - Fraction of secondary protons (optional)

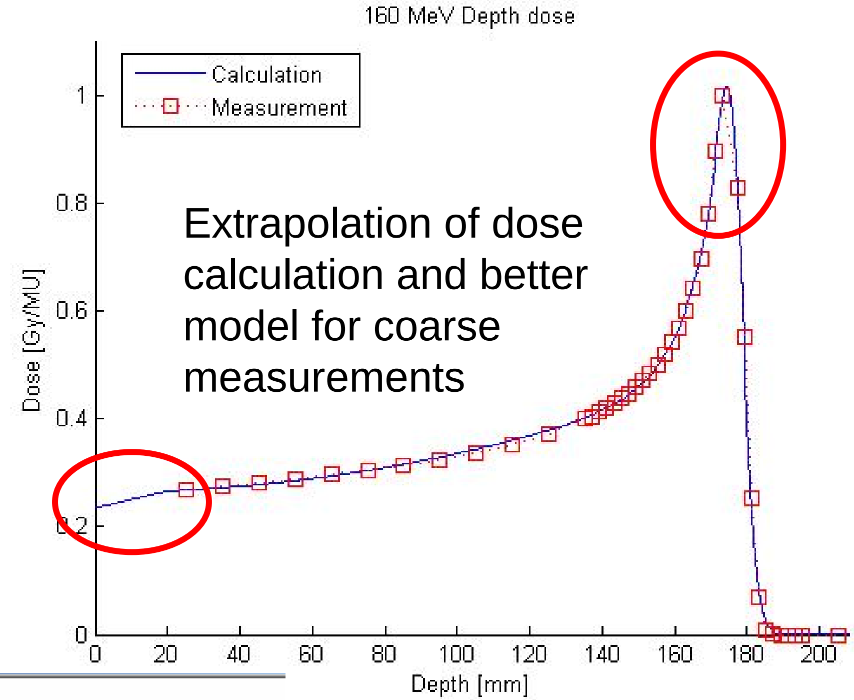


Parametrization vs. LUTs

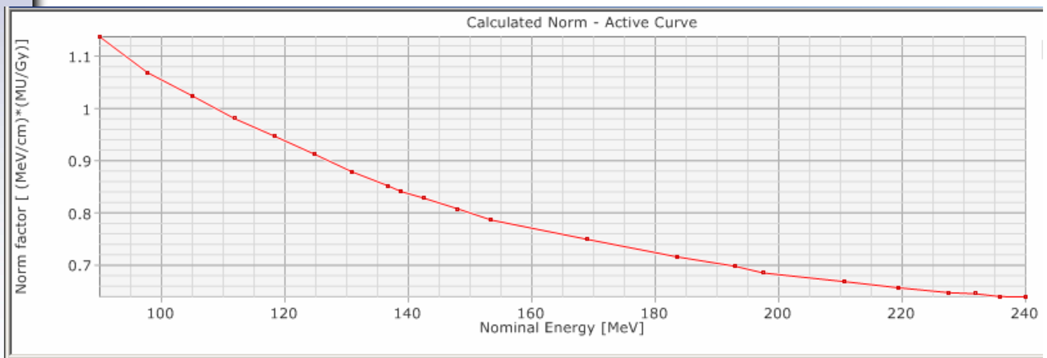
- Parametrization
  - Requires an analytical model for measured data. Failure of the model leads to bad dose calculation results
  - Allows interpolation (extrapolation) for situations other than the measured one (e.g. intermediate energy)
  - Smoothes or averages results from measurements
- LUT (Look up table)
  - Measured curve can have an arbitrary shape
  - Difficult to interpolate, almost impossible to extrapolate
  - Needs some processing of measurements to smooth uncertainties

Parametrization vs. LUTs – Example 1

- Depth dose

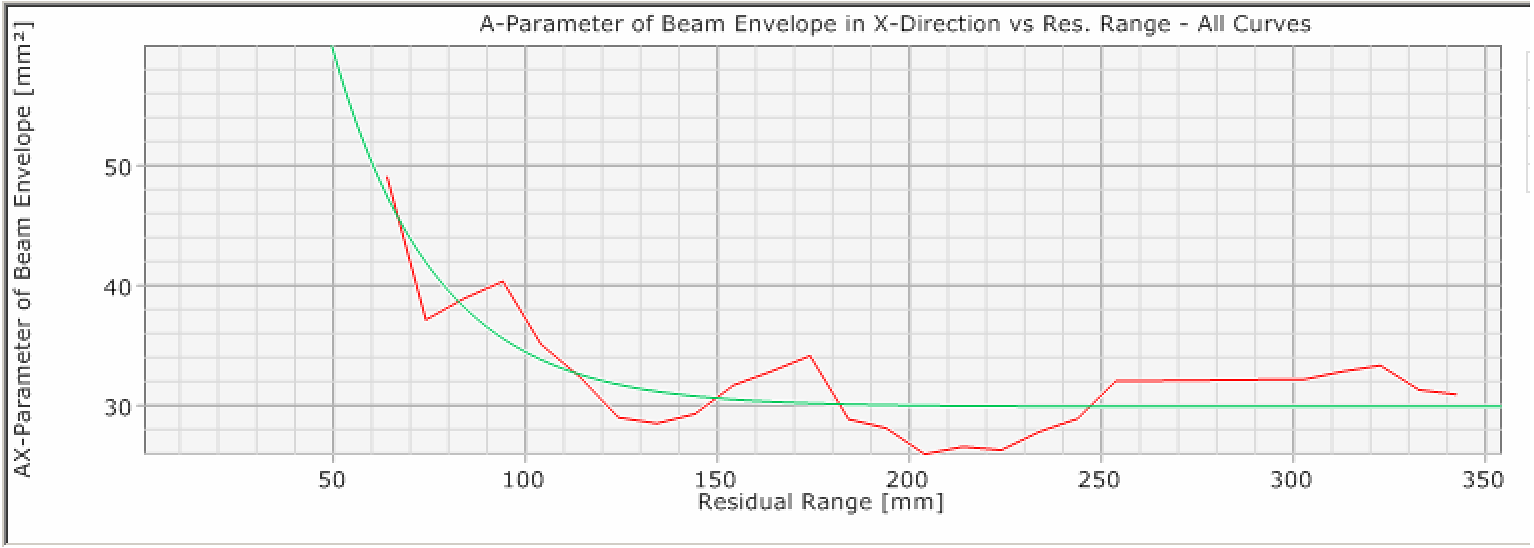


Interpolation of calibration factor for different energies



Parametrization vs. LUTs – Example 2

- A-Parameter (= 2*spot size at isocenter^2) for a scanning beam



- Note: User must know, whether observed behavior of spot size is due to measurement uncertainties or other effects.

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Why CT calibration?

- CT scanners measure Hounsfield units defined as

$$HU = 1000 \frac{\mu_{water} - \mu_{material}}{\mu_{water}}$$

- Hounsfield units are a measure for the attenuation of an X-ray beam
- Hounsfield units **cannot** be used directly to calculate the behavior of proton or even high energy photon beams

Definitions

- Scaled HU: $HU_{sc} = HU + 1000$
- Absolute stopping power (SP) : $-dE/dx$ [MeV/cm]
- Absolute mass SP : $-(1/\rho)dE/dx$ [MeV/(g/cm^2)]
- Relative SP : Ratio between abs. SP for material and water
- Relative mass SP : Ratio between abs. mass SP for material and water
- CT calibration: LUT for conversion between HU and relative SP

Importance of accurate CT calibration

- A few percent error in the CT calibration causes a few percent shift of the dose in depth
- Due to the high distal gradient of the dose, this may lead to 100% difference in dose!
- Note: The calibration curve is sensitive to the X-ray spectrum of the CT scanner. It is important, that each scanner is calibrated individually.

The stoichiometric CT calibration method

- Scan tissue equivalent samples of well known composition individually in the center of a water phantom
- Obtain parameters for HU_{sc} calculation by fitting results to HU-formula
- Calculate (HU_{sc},SP_{rel}) pairs for real tissue compositions
- Define calculation curve to follow calculated (HU_{sc},SP_{rel}) pairs for real tissue compositions

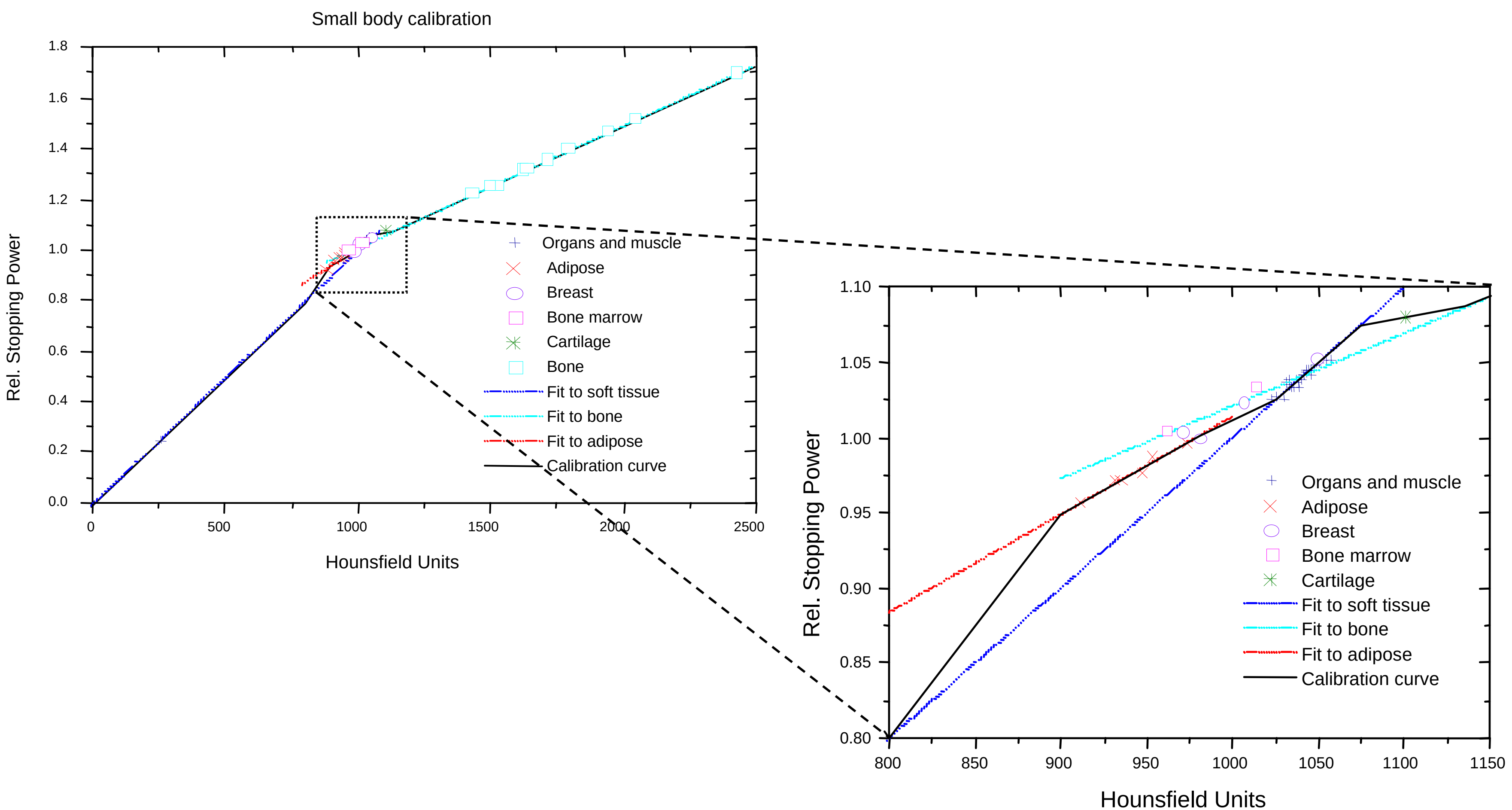
Properties of the stoichiometric CT calibration method

- Scanner specific due to the use of reference measurements
- Uses a simplified, empirical theory for the calculation of Hounsfield units
- Yields good results for commonly used scanner energies of approx. 80 keV and biological tissue

Calculation of (HU_{sc}, SP_{rel}) reference data pairs

- Calculation of HU_{sc} and SP_{rel} pair based on literature data for tissue composition
- $HU_{sc} = C_{mat}\left\{K^{ph}\tilde{Z}^{3.62} + K^{coh}\tilde{Z}^{1.86} + K^{KN}\right\}$ Don‘t use for MV CT!
  - K^{xy} parameterize the response of the scanner. They are determined by fitting the above formula to HU_{sc}-values measured on samples of well known chemical composition
- SP_{rel} calculated with Bethe-Bloch formula

Plot of calculated (HU_{sc},SP_{rel}) pairs and linear fits



Some references for further reading

- Schneider U, Pedroni E, Lomax A 1996 The calibration of CT Hounsfield units for radiotherapy treatment planning *Phys. Med. Biol*. **41** 111-124
- Schaffner B, Pedroni E 1998 The precision of proton range calculations in proton radiotherapy treatment planning: experimental verification of the relation between CT-HU and proton stopping power *Phys. Med. Biol.* **43** 1579-92
- Kanematsu N et al. 2003 A CT calibration method based on the polybinary tissue model for radiotherapy treatment planning *Phys. Med. Biol.* **48** 1053-64
- Schneider U et al. 2005 Patient specific optimization of the relation between CT-Hounsfield units and proton stopping power with proton radiography *Med. Phys.* **32(1)** 195-9

Thank you for your interest and attention