GERMAN CANCER RESEARCH CENTER IN THE HELMHOLTZ ASSOCIATION

Proton Dose Calculations

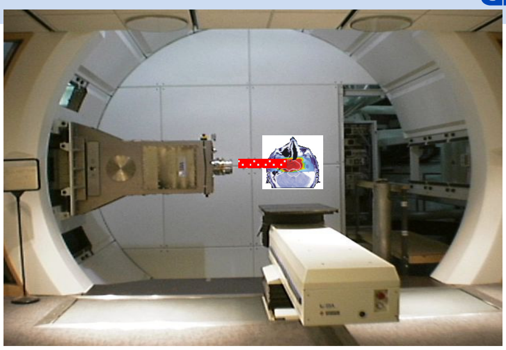
Semi-empirical models for scanning beams and IMPT

Uwe Oelfke

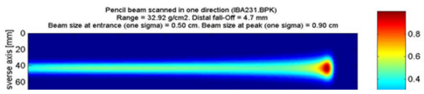
DKFZ Heidelberg
Department of Medical Physics (E040)
Im Neuenheimer Feld 280
69120 Heidelberg, Germany
u.oelfke@dkfz.de

Outline

- Phase Space, Physics and Dose
- Dose Kernels: Water
- Tissue Inhomogeneities
- Consequences



Phase space and dose of a beam spot



Dose = Phase Space ** Physics Pencil Beam (H_20)

Depth dose curve

A simple model

Stopping power, CSDA Range

Straggling, energy-spektrum

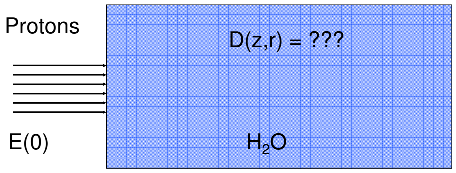
Inelastic nuclear interactions

Basic physics

- Dose factorizes in depth dose and lateral spread
- Laterally integrated depth dose curve
  - Energy loss due to collisons with e^-
  - Straggling
  - Energy spread of dose delivery system
  - Primary and nuclear interactions

Fluence and depth dose curve

dkfz.



Fluence: $\Phi = \frac{dN_p}{dA_\perp}$

Energy Fluence: $\vec{\Psi} = \frac{dN_p}{dA_\perp} E\,\vec{e}$

Dose and vectorial energy fluence

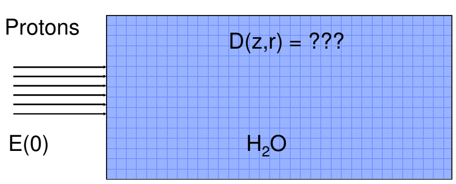
dkfz.

$$D(x) = \frac{dE_{ab}}{dm}(x) = -\frac{1}{\rho}\vec{\nabla}\vec{\Psi}(x)$$

Vectorial energy fluence

Depth dose curve: a simple model

dkfz.



$$D(z) = -\frac{1}{\rho}\frac{\partial}{\partial z}(\Phi(z)E(z)) = -\frac{1}{\rho}E(z)\frac{\partial\Phi(z)}{\partial z} - \frac{1}{\rho}\frac{\partial E(z)}{\partial z}\Phi(z)$$

Inelastic nuclear inter. Mass Stopping Power (collision)

Coulomb interaction with electrons
Stopping power - Range

Stopping Power

$$S(E) = -\frac{\partial E}{\partial z}(E)$$

Microscopic def. :

$$S(E) = \frac{\overline{E}_{tr}}{L}(E)$$

L = mean free pathlength

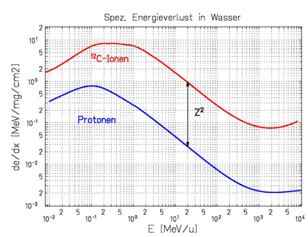
CSDA Range:

$$R_{CSDA} = \int_0^E dE' \frac{1}{S(E')}$$

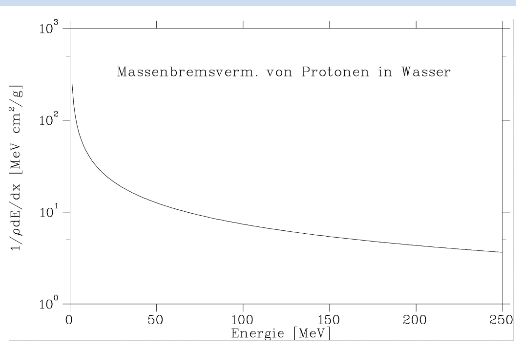
Bethe Bloch Formula

$$\left.\frac{dE}{dx}\right|_{el.} = -4\pi N \frac{Z_{eff}^2 e^4}{m_e c^2 \beta^2} Z_T \left[\ln \frac{2 m_e c^2 \beta^2}{I(1-\beta^2)} - \beta^2\right]$$

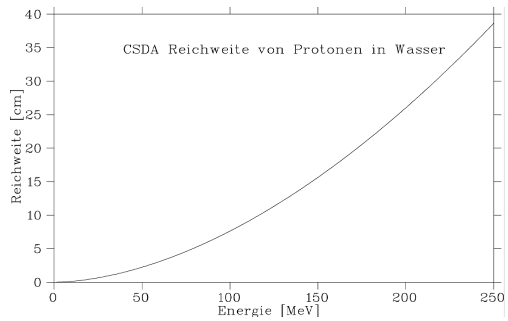
$$Z_{eff} = Z_p\left[1 - \exp\left(-125 \cdot \beta \cdot Z_p^{-2/3}\right)\right]$$ Barkas-Formel



Mass stopping power



CSDA Range



Coulomb interaction with electrons
Straggling and Bragg Peak

Statistical fluctuations: broadening of energy spectrum

Straggling width: $\Sigma(E) = \frac{\partial \sigma}{\partial z}(E)$

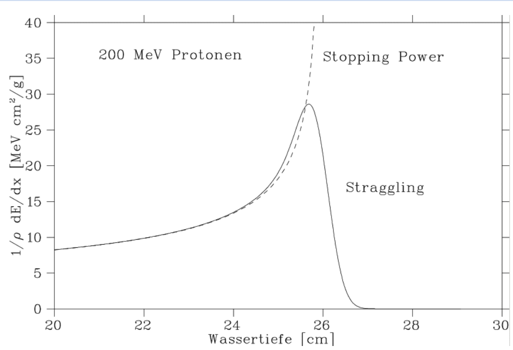
Microscopic def. : $\Sigma(E) = \frac{\overline{E}_{tr}\,\overline{E}_{tr}}{L}(E)$

$\sigma \propto R$

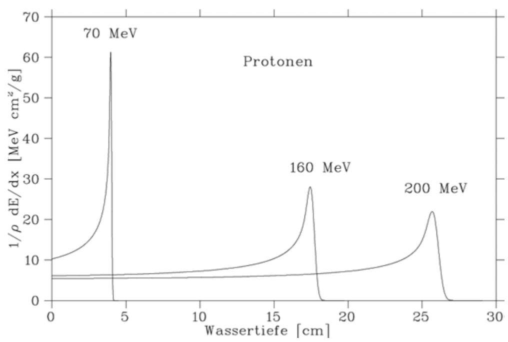
L = mean free pathlength

Bragg Peak: $BP = S ** G(\sigma)$

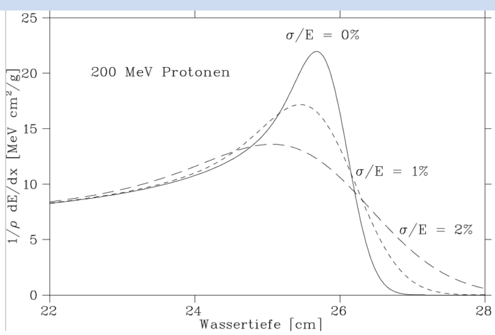
Depth dose: Straggling – Bragg Peak



Proton Bragg Peaks – Straggling



Energy spectrum of accelerator

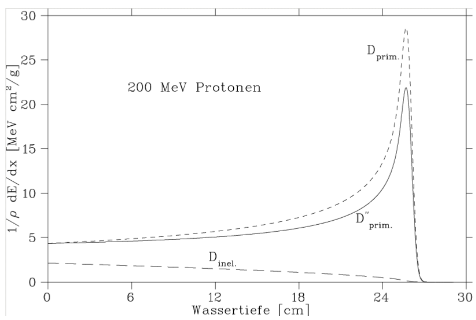


Inelastic Nuclear Interactions

Strong interaction with nuclei in the body

- creation of slower secondary protons, recoil heavier fragments
- creation of new background ‚Bragg peaks‘
- Lateral scattering at lower energies - halo

Inelastic nuclear interactions



Lateral Scattering

Coulomb interaction with nuclei shielded by electron cloud

- Moliere Theory: Gaussian width + Broader Background
- Drifting + Scattering = Transport Eq.
- 2 Gaussians for Modelling – Primary + Secondary

(Field Size Effect)

Distribution of scattering angles

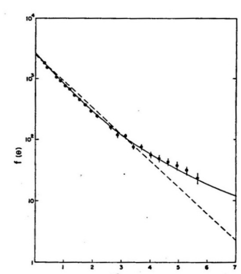
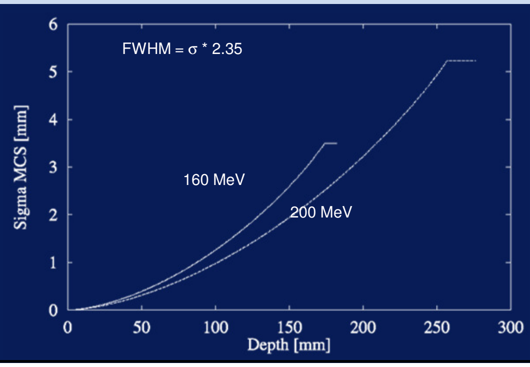
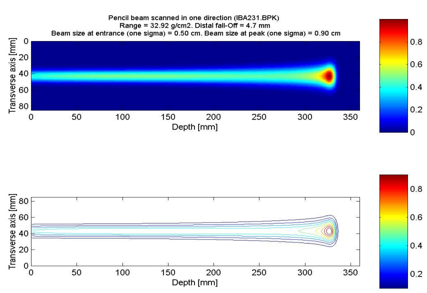


FIG. 5. Comparison of experimental data from Fig. 3 with theory. The solid line represents a normalized Molière function (adjusted with only one parameter: the absolute cross section). The dotted line represents a Gaussian curve, the zero-order term of the Molière function.

Lateral spread of beam (Highland)



Multiple Coulomb scattering



The Source(s): phase space of the accelator

Energy spectra	Source size, position
Lateral distributions	Collimator scattering
Angular distributions	Extrafocal radiation, ...

Calculation ?

$f_i\ (E, r, z, \theta_x, \theta_y)$ i = particle type

Calibration via a set of measurments
or
Monte Carlo Techniques !

Characterization of Phase Space

- ‚Physics‘ dose in water is defined by either semi-empirical source models or MC calculations
- Use a set of measurements to calibrate the parameters of a phase space model
- Aim: To determine a few parameters of your ‚machine‘ such that the dose for all beam spots in water is correct

Phys. Med. Biol. **52** (2007) 3151–3168 doi:10.1088/0031-9155/52/11/01

A beam source model for scanned proton beams

Peter Kimstrand[1], Erik Traneus[2], Anders Ahnesjö[1,2], Erik Grusell[1], Bengt Glimelius[1] and Nina Tilly[1,2]

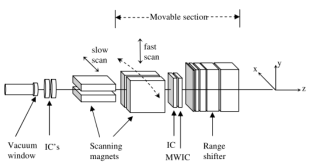


Figure 2. Schematic picture of the scanned proton beam at TSL, the rightmost part of the set-up is movable.

Assumptions:

- The radial shape of the elementary beam is assumed independent of scan spot lateral position.
- The direction of the elementary beam can be specified by applying two focal points describing the deflection by the scanning magnet in two orthogonal planes.

Parameters:

- two focal points for the lateral beam scanning;
- three parameters to describe the angular and radial distribution in the *x*- and *y*-direction, respectively;
- two parameters for the energy spectrum.

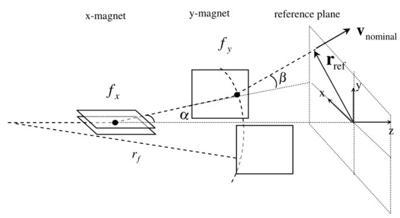


Figure 1. Geometry of the focal points and nominal direction of a general scanning system.

$$\Phi(\alpha, x) = \frac{\exp\left(-\frac{\sigma_\alpha^2 x^2 - 2\sigma_{x\alpha} x\alpha + \sigma_x^2 \alpha^2}{\sigma_\alpha^2 \sigma_x^2 - \sigma_{x\alpha}^2}\right)}{\pi\sqrt{\sigma_\alpha^2 \sigma_x^2 - \sigma_{x\alpha}^2}},$$

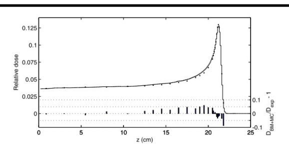


Figure 4. Result of the energy spectrum analysis. The filled circles show the measured depth dose and the solid line is the MC calculation using the beam model to provide the phase space including the derived effective energy spectrum. The lower bar plot shows the deviation of the calculated dose from the measured dose.

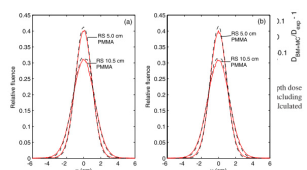


Figure 5. The beam profile in the (a) x- and (b) y-direction with 5.0 cm and 10.5 cm PMMA in the range shifter measured in air at $z = 0$ cm. The solid lines are the CCD-camera measurements and the dashed lines are the calculation, based on the phase space provided by the beam model.

Beyond Gaussians….

IOP Publishing — Physics in Medicine and Biology
Phys. Med. Biol. **57** (2012) 983–997 — doi:10.1088/0031-9155/57/4/983

Beyond Gaussians: a study of single-spot modeling for scanning proton dose calculation

Yupeng Li, Ronald X Zhu, Narayan Sahoo, Aman Anand and Xiaodong Zhang[1]

Department of Radiation Physics, The University of Texas MD Anderson Cancer Center, Houston, TX 77030, USA

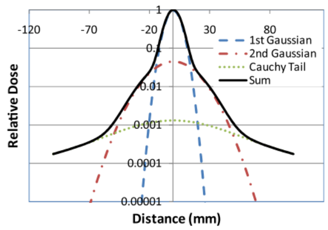


Figure 1. Lateral profile of a scanning spot in water modeled using the first and second Gaussian components and modified Cauchy–Lorentz function.

IOP PUBLISHING PHYSICS IN MEDICINE AND BIOLOGY

Phys. Med. Biol. **57** (2012) 1147–1158 doi:10.1088/0031-9155/57/5/1147

Golden beam data for proton pencil-beam scanning

Benjamin Clasie[1], **Nicolas Depauw**[1], **Maurice Fransen**[1,2], **Carles Gomà**[1], **Hamid Reza Panahandeh**[1], **Joao Seco**[1], **Jacob B Flanz**[1] **and Hanne M Kooy**[1]

[1] Department of Radiation Oncology, Massachusetts General Hospital & Harvard Medical School, Boston, MA, USA

[2] Department of Applied Physics, Eindhoven University of Technology, Eindhoven, The Netherlands

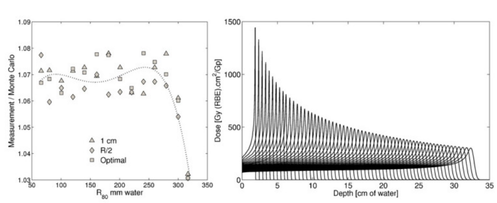


Figure 1. Left: normalization correction to the Monte Carlo generated pristine peaks. The normalization correction, defined as the ratio of measurement over Monte Carlo, is measured at three depths as indicated in the legend. The 'optimal' position is an intermediate depth between 1 cm and $R_{80}/2$. The correction factor as a function of R_{80} is parameterized by a fourth-order polynomial and applied to the Monte Carlo pristine peaks. Right: Monte Carlo generated pristine peaks normalized against measurement.

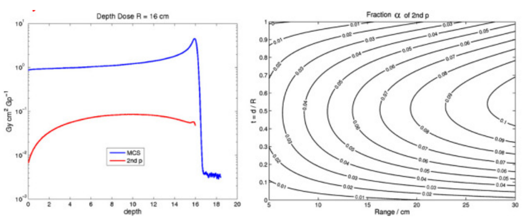
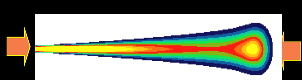


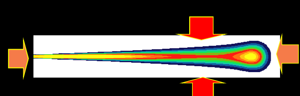
Figure 7. Left: example decomposition of the pristine peak depth dose into the primary and secondary components. Right: the fraction of the depth dose (equation (5)) that is delivered from secondary protons as a function of range R and range-scaled depth $t = d/R$. Note the general feature where most of the secondary energy is dissipated in the middle of the pristine peak and which rises to as much as 10% at the highest energy.

- Standard 1D scaling: pathlength scaling



Independent of inhomogeneity position and scattering properties

- New 2D scaling: pathlength AND radial scaling



Depends on inhomogeneity position and scattering properties

Pencil beam scaling methods

$$P(r,z,E_0)=\left(\frac{S}{\rho}\right)_w^m \frac{1}{(F_r)^2} P^w\left(\frac{r}{F_r},z_{eq},E_0\right)$$

- 1D scaling: $F_r=1$
- 2D scaling: $F_r = \frac{\sigma(z,E_0)}{\sigma_w(z_{eq},E_0)}$

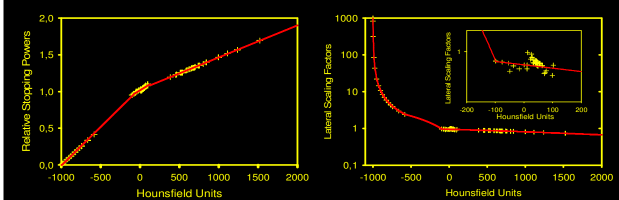
Use of Highland's formula for Multiple Coulomb Scattering

Implementation of the 2D scaling

We need:

- Depth dose curves in water
- CT calibration curve relating Hounsfield numbers to relative stopping powers
- Simple analytical formula for calculating the standard deviation of lateral spread (function of depth and energy)
- CT calibration curve relating Hounsfield numbers to material specific lateral scaling factors

CT Calibration curves



Example: Homogeneous Media

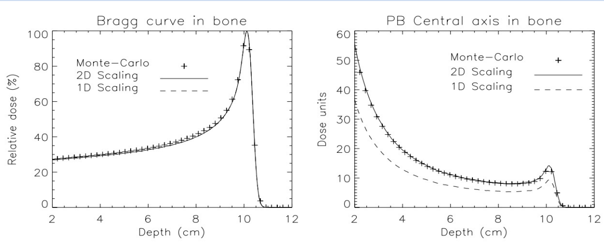
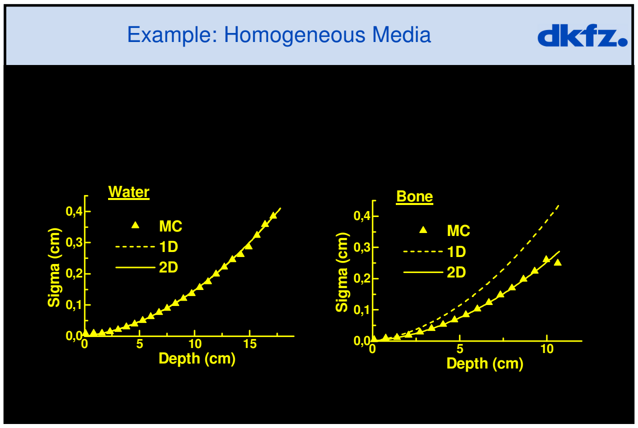
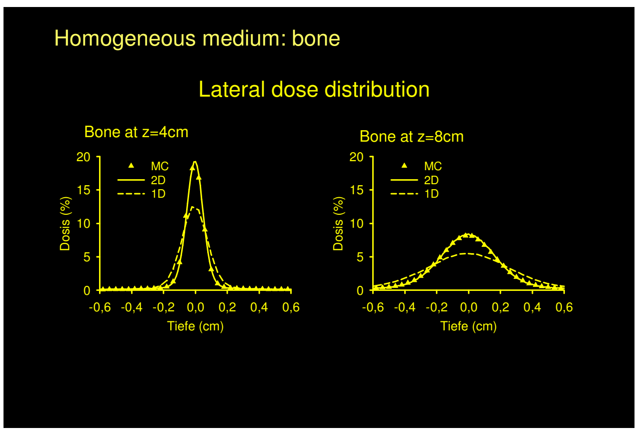


Figure 4. Right: central axis dose distributions in bone for a 160 MeV proton pencil beam. Left: Bragg curves, i.e. integration of the radial pencil beam dose distribution at each depth, in bone. The depth dose curves and the Bragg curves resulting from the 2D and the 1D scaling of the pencil beam simulated in water are compared to the Monte Carlo simulation in bone. The Bragg curves resulting from the 2D and 1D scalings superimpose.

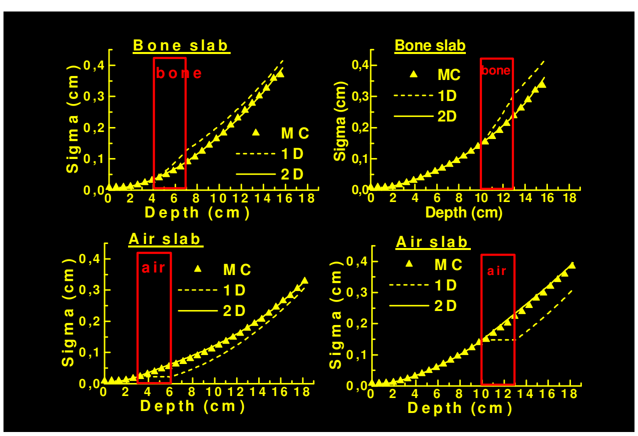
*Hanitra Szymanowski and Uwe Oelfke: Two-dimensional pencil beam scaling: an improved proton dose algorithm for heterogeneous media **2002** PMB 47.*



Example: Homogeneous Media
Water
Sigma (cm)
Depth (cm)
MC
1D
2D
Bone
Sigma (cm)
Depth (cm)
MC
1D
2D

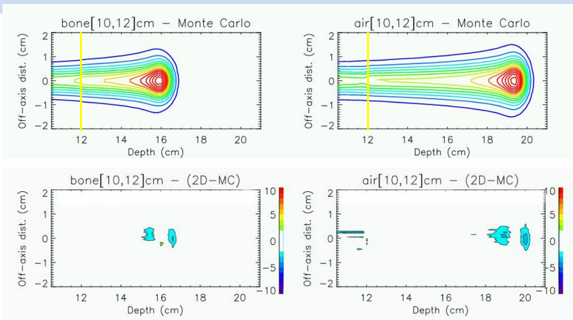


Homogeneous medium: bone
Lateral dose distribution
Bone at z=4cm
Bone at z=8cm
MC
2D
1D
Dosis (%)
Tiefe (cm)

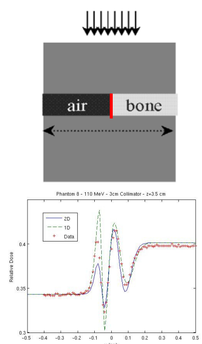


Bone slab
bone
Air slab
air
Sigma (cm)
Depth (cm)
MC
1D
2D

Comparison to GEANT4



Lateral inhomogeneities



Influence of dose algorithm on IMPT

Clinical example:

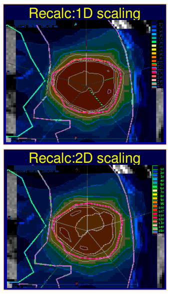
- Lung tumor
- 5 equally spaced proton beams, 3mm wide proton spots
- 3D spot scanning technique
- Distal-Edge-Tracking technique

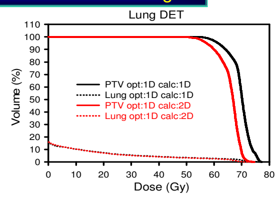
Treatment plans:

- Optimisation with 1D-scaling - Recalculation with 1D-scaling
- Optimisation with 1D-scaling - Recalculation with 2D-scaling
- Optimisation with 2D-scaling - Recalculation with 2D-scaling

Lung: Systematic error

Optimisation: 1D scaling

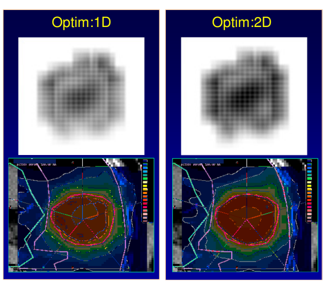


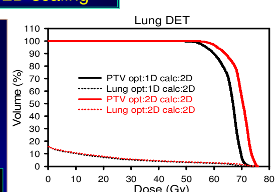


	PTV			Lung		
%	D_{min}	D_{max}	D_{mean}	D_{min}	D_{max}	D_{mean}
Δ_s(DET)	7.5	3.9	5.4	0.0	3.9	0.2
Δ_s(3D)	3.8	9.0	4.6	0.0	9.0	0.2

Lung: Convergence error

Recalculation: 2D scaling





	PTV			Lung		
%	D_{min}	D_{max}	D_{mean}	D_{min}	D_{max}	D_{mean}
Δ_c(DET)	-7.1	-1.9	-5.4	0.0	-1.9	-0.5
Δ_c(3D)	-4.9	-8.6	-5.8	0.0	-8.6	-0.6

Conclusions

- Calibration of dose for beam spots in water has to be done with outmost accuracy
- Integration of phase space and physics is done with phenomenological models
- There are clear limitations of this approach for tissue inhomogenieties