TOWARDS FLUENCE MODULATED PROTON COMPUTED TOMOGRAPHY

G. Landry[1], R.P. Johnson[2], M. Pankuch[3], S. Rit[4], C. Belka[5], R.W. Schulte[6], K. Parodi[1], G. Dedes[1]

[1]Department of Medical Physics, Faculty of Physics, Ludwig-Maximilians-Universität München (LMU Munich)

[2]Department of Physics, U.C. Santa Cruz

[3]Northwestern Medicine Chicago Proton Center, Warrenville

[4]Université de Lyon, CREATIS, CNRS UMR5220 Inserm U1044, INSA-Lyon, Université Lyon 1

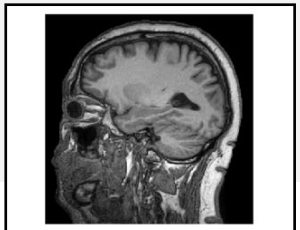
[5]Department of Radiation Oncology, University Hospital, LMU Munich and German Cancer Consortium (DKTK)

[6]Division of Radiation Research, Loma Linda University, Loma Linda

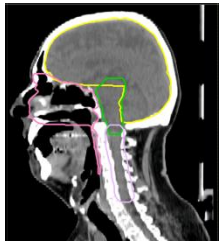
Friday June 15th 2018

Lyon Proton Imaging Workshop

THE CONVENTIONAL IMAGE GUIDED RADIOTHERAPY WORKFLOW

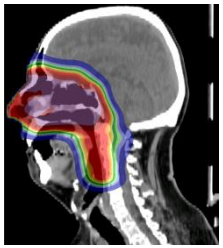


MRI

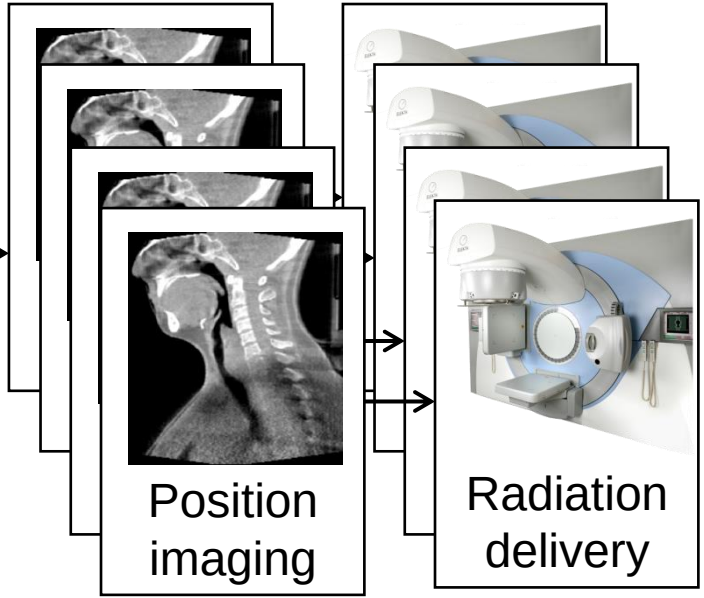


delineation

CT imaging



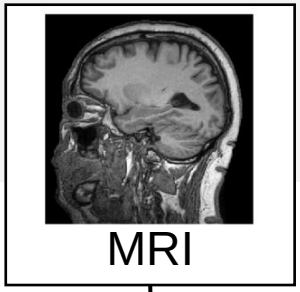
Treatment planning

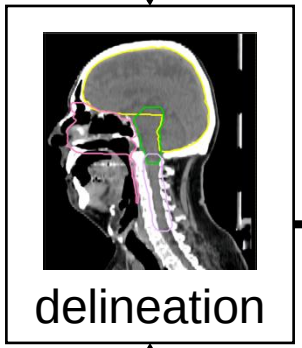


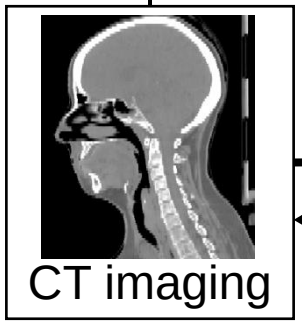
Position imaging

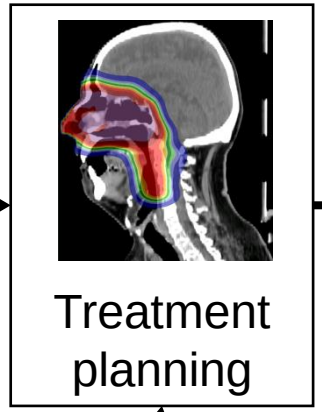
Radiation delivery

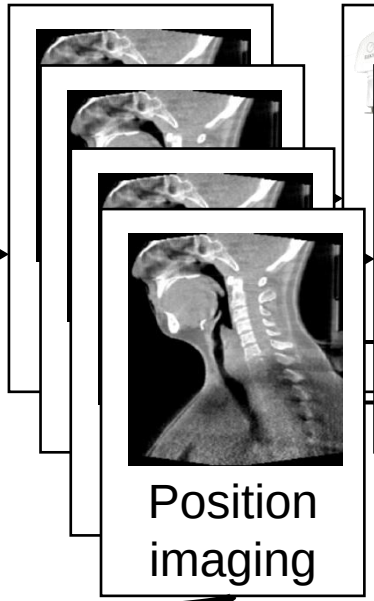
THE CONVENTIONAL IMAGE GUIDED RADIOTHERAPY WORKFLOW

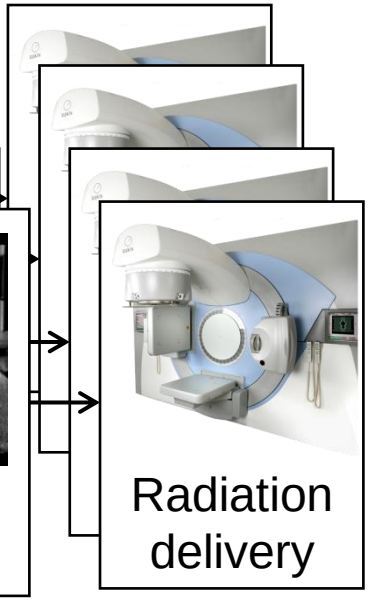










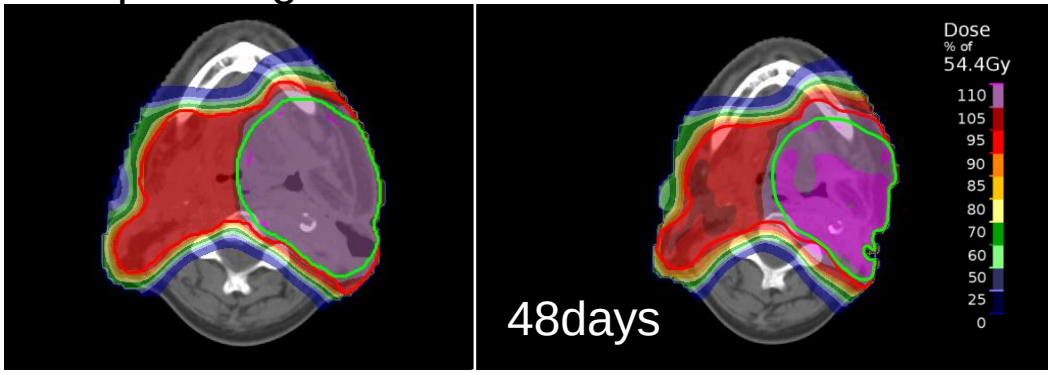


Plan adaptation

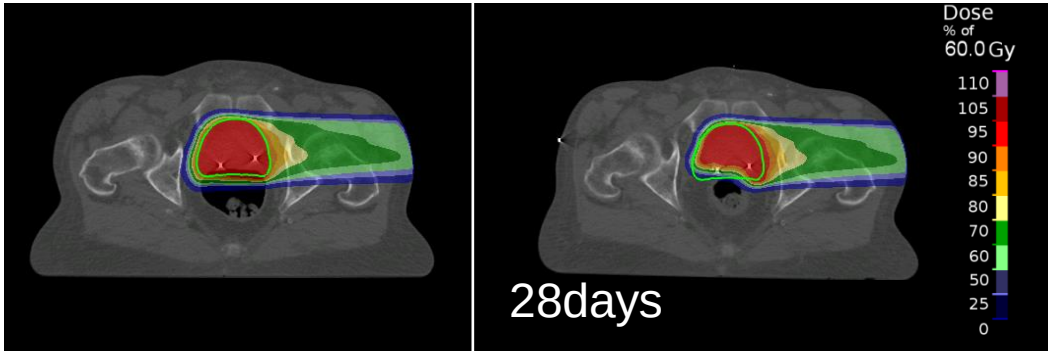
PROTON THERAPY AND ANATOMICAL CHANGES

planning CT

control CT



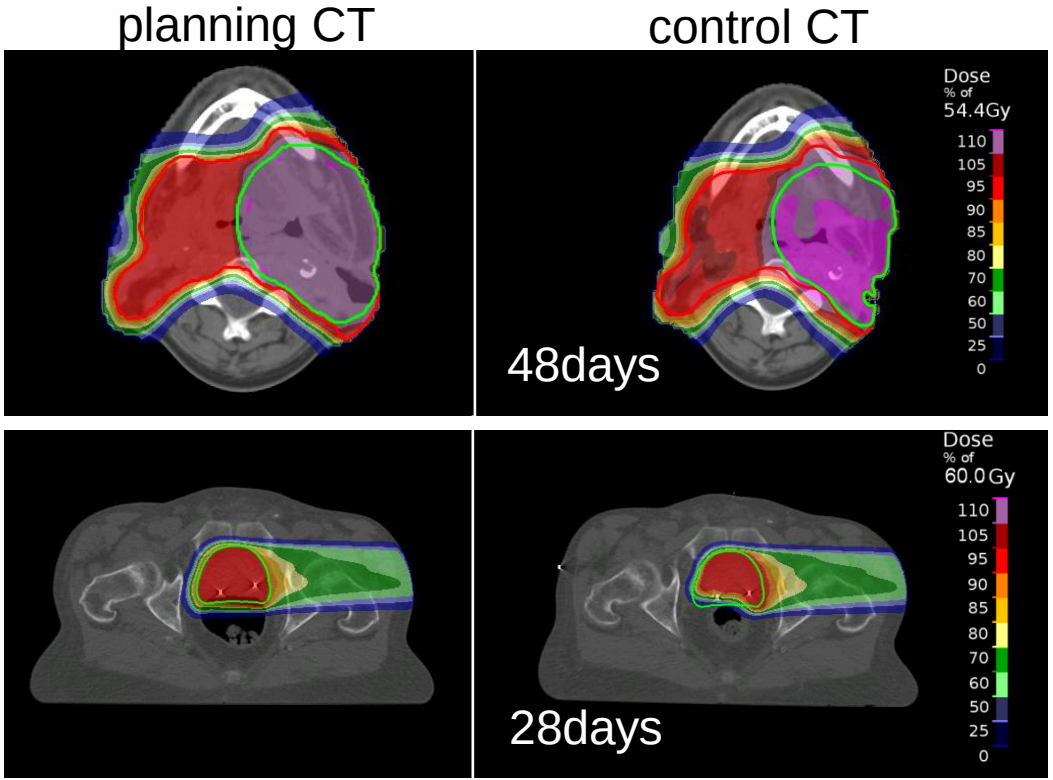
Head and neck:
Timescale:
days/weeks



Prostate:
Timescale:
minutes/hours/days

C. Kurz et al., ICTR-PHE 2016

PROTON THERAPY AND ANATOMICAL CHANGES



Head and neck:
Timescale:
days/weeks

Prostate:
Timescale:
minutes/hours/days

May be restored by **plan adaptation**

Requires **frequent** imaging and **accurate** up to date **3D dose calculation**

C. Kurz et al., ICTR-PHE 2016

DAILY IMAGING AND DOSE

Dose reduction in X-ray CT

- Bowtie filters
- Automatic exposure control

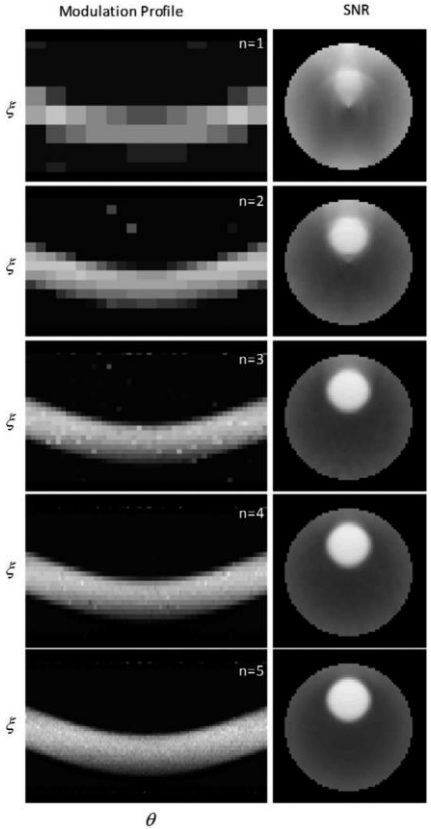
Bartolac et al. 2011 *Med Phys*

Fluence field modulated CT requirements

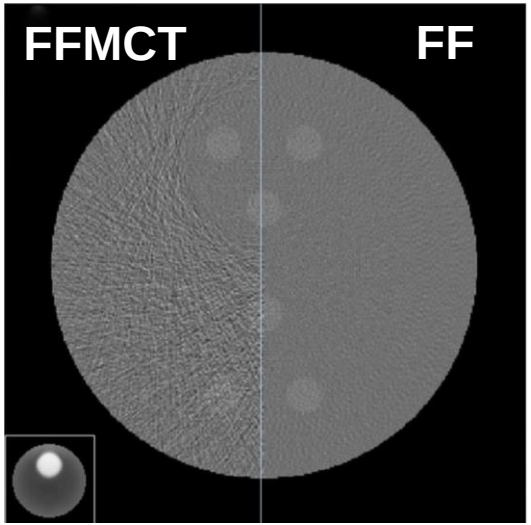
- Fluence modulation apparatus
  - digital beam attenuator[1]
  - binary collimator (Tomotherapy)[2]
  - multiple aperture devices[3]
  - piecewise-linear dynamic attenuators[4]

[1]Szczykutowicz and Mistretta 2014 *Phys Med Biol*
[2]Szczykutowicz et al. 2015 *Phys Med Biol*
[3]Stayman et al 2016 *SPIE Med Imaging*
[4]Shunhavanich et al. 2018 *SPIE Med Imaging*

DAILY IMAGING AND DOSE



Fluence field modulated CT requirements



Bartolac et al. 2011 *Med Phys*

PROJECT GOAL

Reduce pCT imaging dose as low as possible for frequent on-isocenter imaging

Extend FFMCT to proton CT → fluence modulated proton CT (FMpCT)

FLUENCE MODULATED PROTON CT

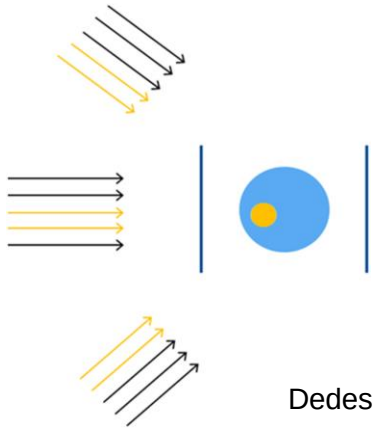
Imitate evolution of treatment technology

- From passively scattered **broad beams** to **pencil beam scanning** (PBS)
- **Most centers** are nowadays **equipped** with **PBS**
- PBS permits **fluence modulation** on a pencil beam **(PB) per PB basis**

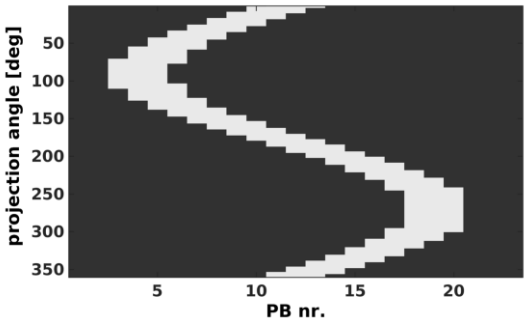
Proof of principle FMpCT

Simple binary scheme based on **PB-ROI intersection**

high fluence PB selection
— selected PB keep full fluence (FF)
— else reduction by fluence modulation factor (FMF)



binary sinogram



Dedes et al. 2017 *Phys Med Biol*

PROOF OF PRINCIPLE FMPCT

Monte Carlo (MC) simulation of idealized pCT collaboration scanner

- Geant4
- Two detection planes
- Ideal energy/position/direction scoring

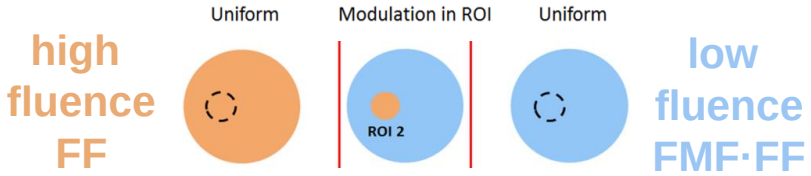
Reconstruction

FBP accounting for curved paths

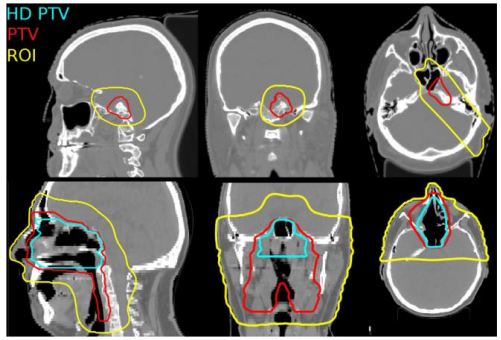
Rit et al. 2013 *Med Phys*

fluence modulation and phantoms

modulation cases studied



patient CT scans imported to Geant4



brain metastasis

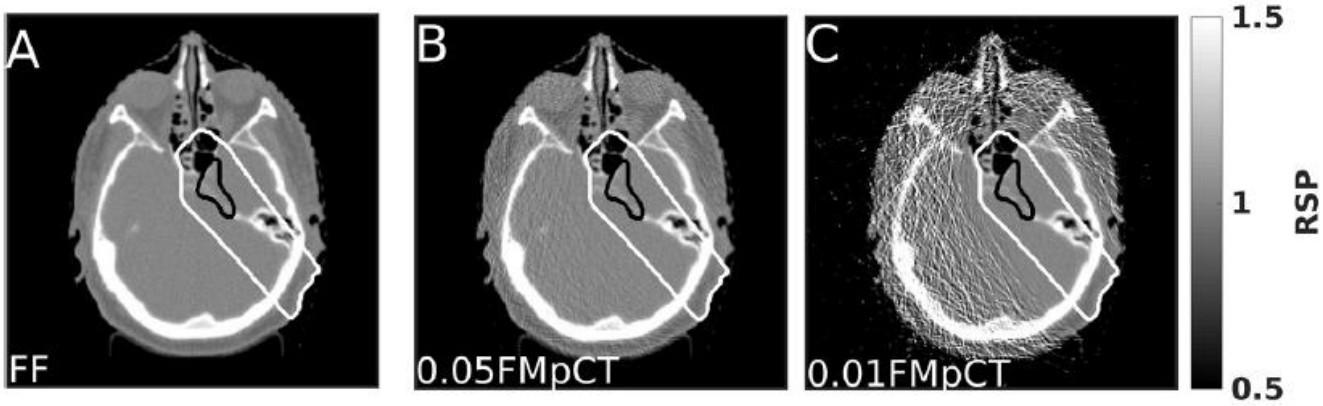
paranasal sinus tumor

FMpCT-ROI (in yellow) defined by the **10% isodose**

Dedes et al. 2017 *Phys Med Biol*

PROOF OF PRINCIPLE FMPCT

Fluence modulation on simulated pencil (PB) scans: **image quality**



Dedes et al. 2017 *Phys Med Biol*

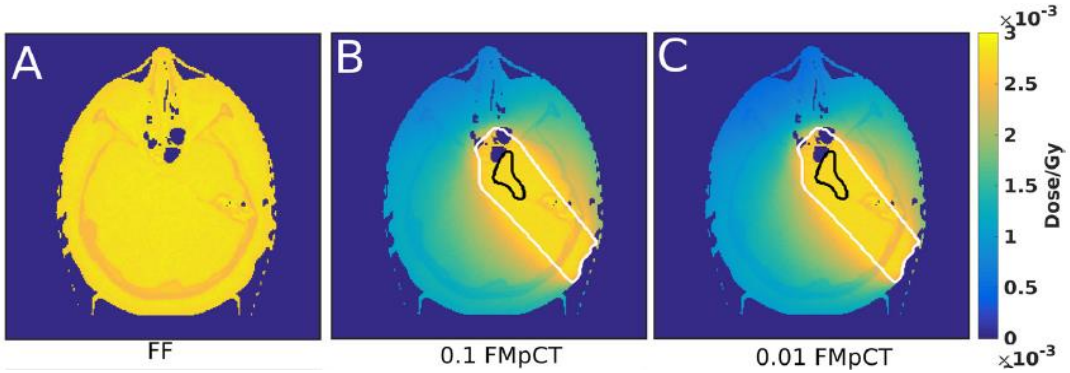
*noiseless reference RSP provided by Geant4 CT conversion

	(RSP − RSP$_{ref}$)/RSP$_{ref}$ (%)*		(RSP − RSP$_{ref}$)/RSP$_{ref}$ (%)*	
	Noise		Mean	
Pat1	Uniform	FMpCT	Uniform	FMpCT
FF	1.8	—	−0.1	—
0.1 · FF	5.5	1.8	−0.1	−0.2
0.05 · FF	8.3	1.8	−0.2	−0.2
0.01 · FF	30.1	1.9	0.6	−0.7

PROOF OF PRINCIPLE FMPCT

Fluence modulation on simulated pencil (PB) scans: **imaging dose**

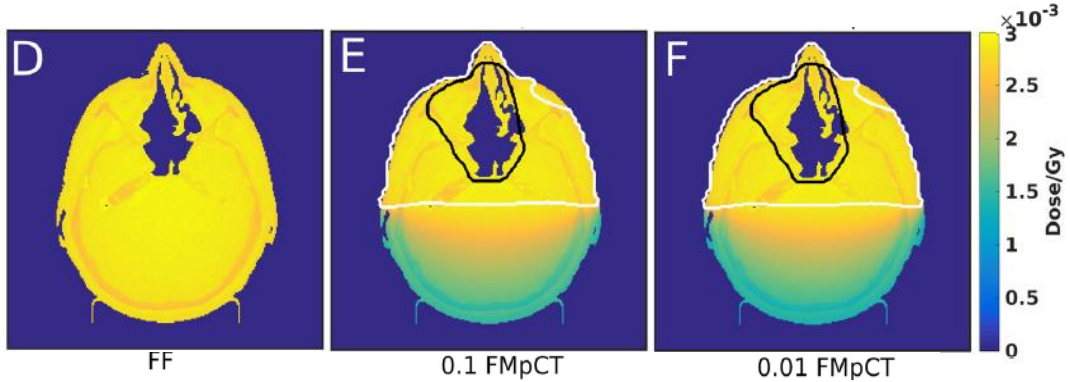
Patient 1



dose reduction

whole image	outside ROI
45-49%	51-56%

Patient 2



dose reduction

whole image	outside ROI
20-22%	34-37%

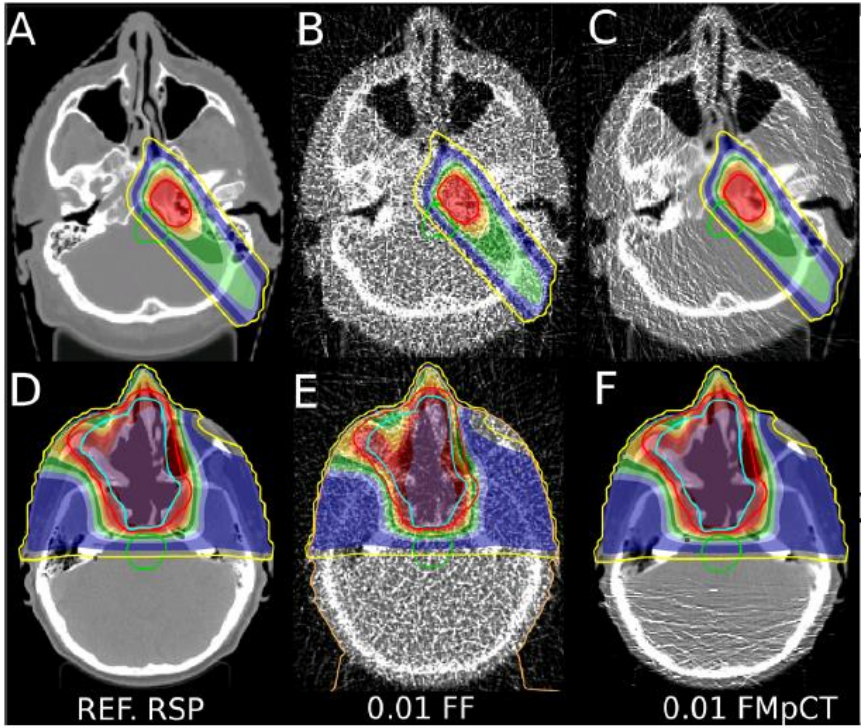
Dedes et al. 2017 *Phys Med Biol*

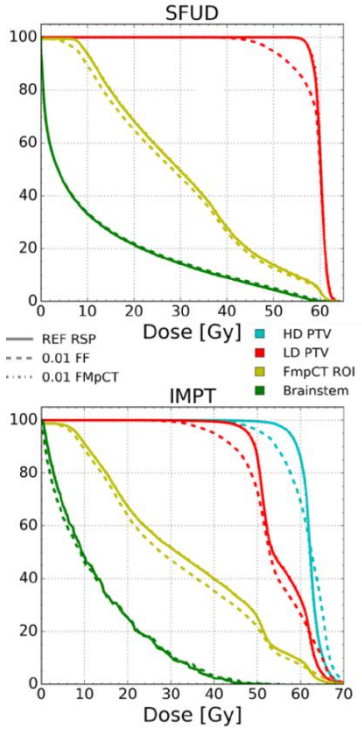
PROOF OF PRINCIPLE FMPCT

Fluence modulation on simulated pencil (PB) scans: **dose calculation**

Patient 1

Patient 2

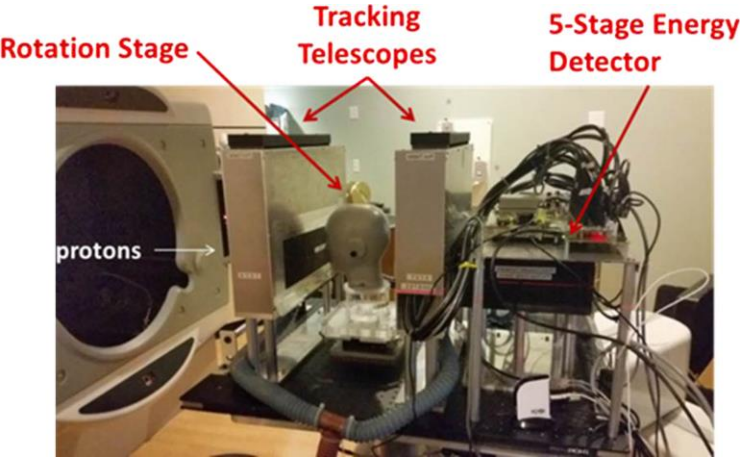




Dedes et al. 2017 *Phys Med Biol*

EXPERIMENTAL FMPCT

phase II preclinical prototype pCT scanner

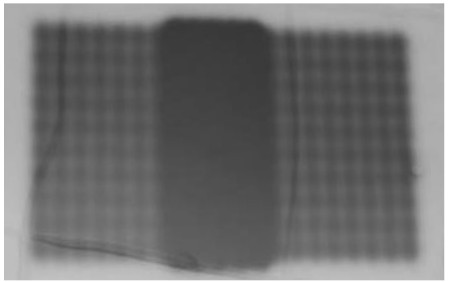


Operated at the PBS room of the Northwestern Medicine Chicago Proton Center

simple phantom

15 cm ⌀ PMMA container filled with water

central FMpCT-ROI



- PBS fluence pattern constant with rotation
- Fluence modulated by spot dwell time
- Beam current adjusted to yield 400 kHz
- 27 msec dwell time

EXPERIMENTAL FMPCT

step and shoot acquisition

45 projections

3 pCT scans acquired

FF (2.2 M protons/proj)

0.5 FMpCT

0.2 FMpCT

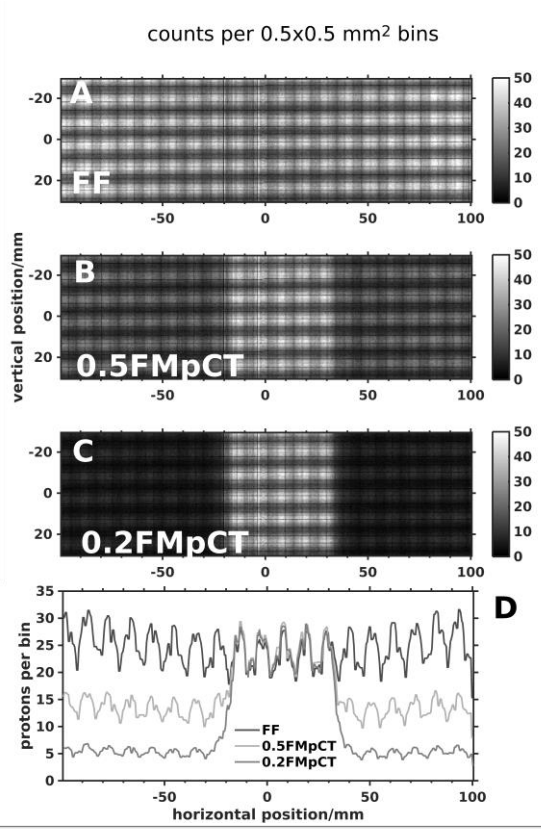
PB grid

10 × 20 PB

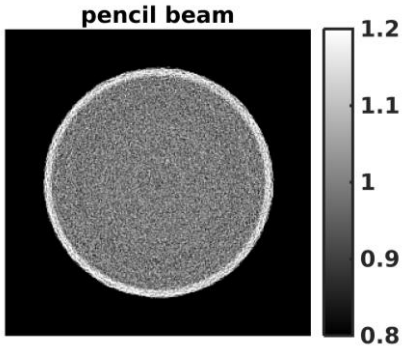
1 cm FWHM

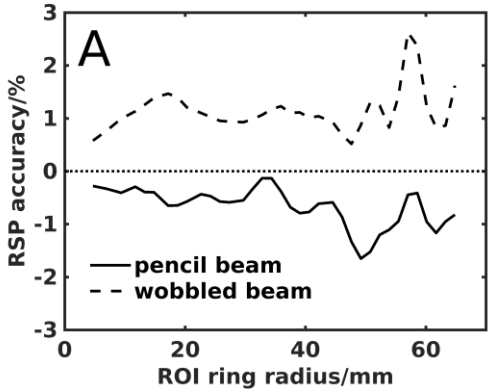
1 cm spacing

¼ PB shift



FF images

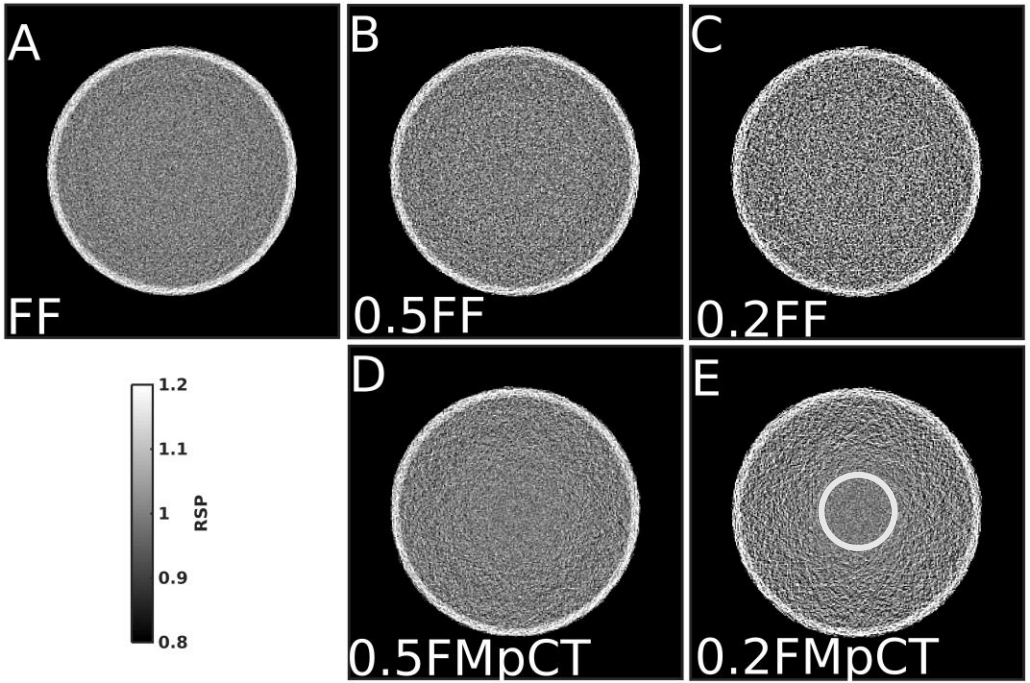


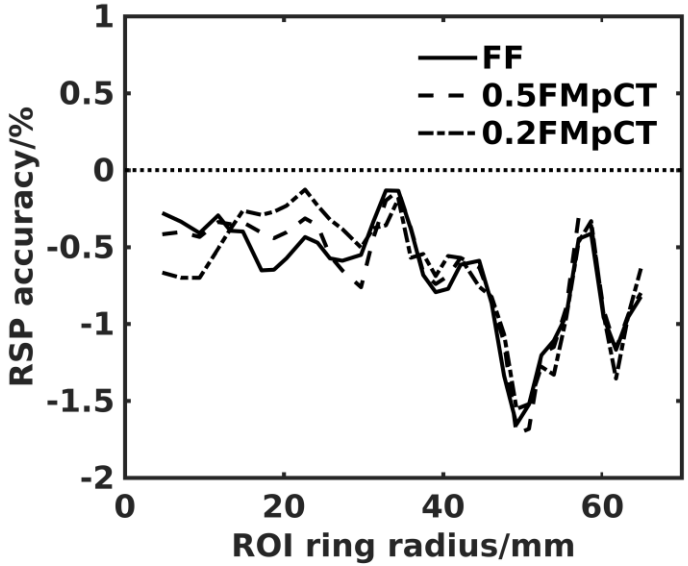


Dedes et al. 2018 *Med Phys*

EXPERIMENTAL FMPCT

Fluence modulation on experimental (PB) scans: **image quality**

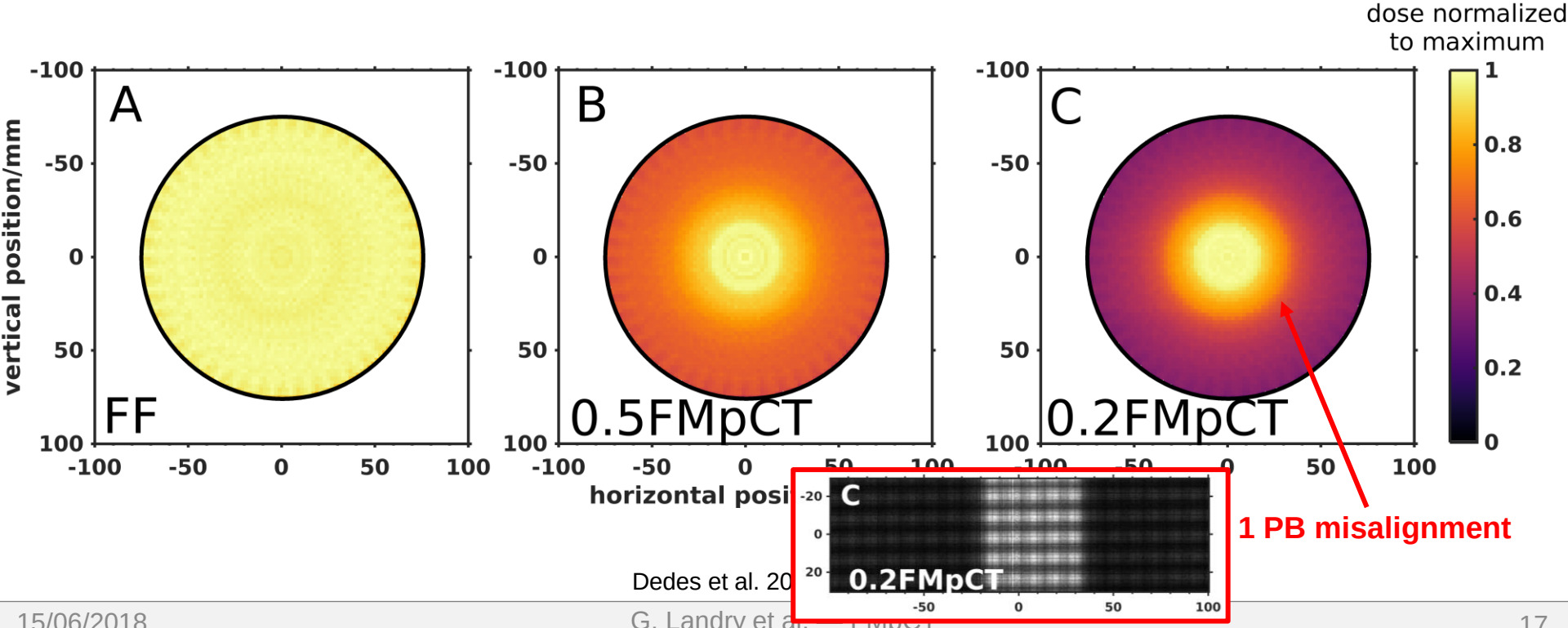




Dedes et al. 2018 *Med Phys*

EXPERIMENTAL FMPCT

Fluence modulation on experimental (PB) scans: **imaging dose**



Dedes et al. 20

IMAGE VARIANCE MODELLING

Relation between PB fluence and image quality

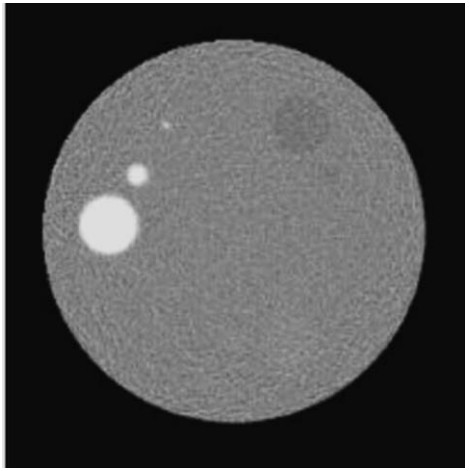
necessary to move beyond “forward planning” approach based on PB interception of ROI and binary fluence levels

Projection pixel variance

verified for the central pixel

$$\sigma^2_{\gamma_n}(j\Delta\xi) = \frac{\sigma^2_{E_{\mathrm{out}},\gamma_n}(j\Delta\xi)}{N_{\gamma_n}(j\Delta\xi)\cdot S^2_{\mathrm{W}}(\overline{E}_{\mathrm{out},\gamma_n}(j\Delta\xi))}$$

Schulte et al. 2005 *Med Phys*



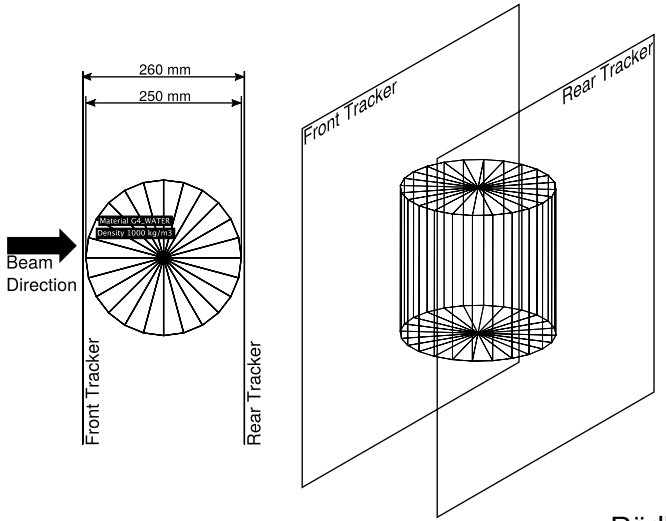
Schulte et al. 2005 *Med Phys*

Increasing noise towards object’s edge?

IMAGE VARIANCE MODELLING

Geant4 MC simulation

- parallel protons
- water cylinder
- ideal detectors



Rädler 2017 *MSc Thesis LMU Munich, pub. in prep.*

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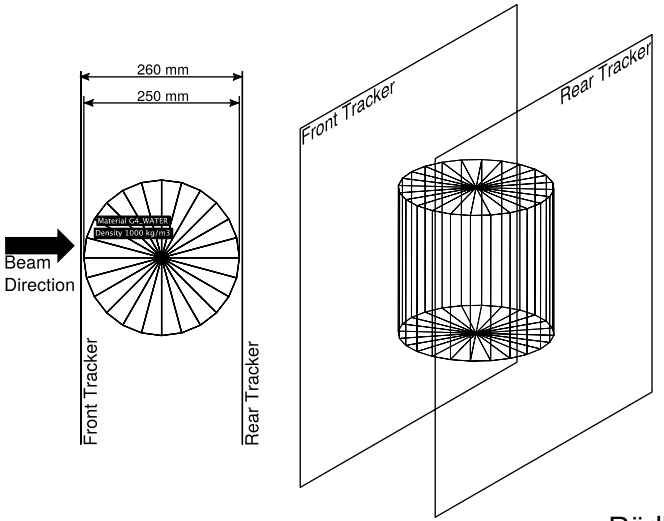

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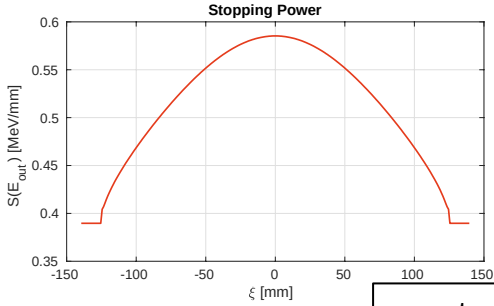
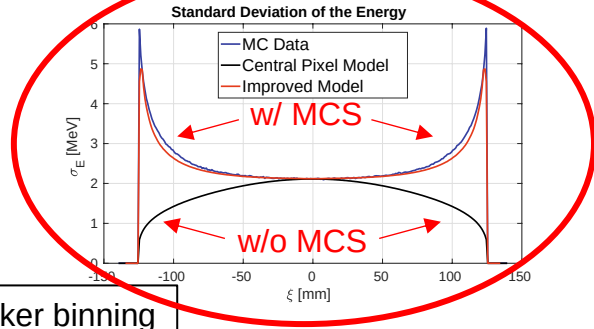
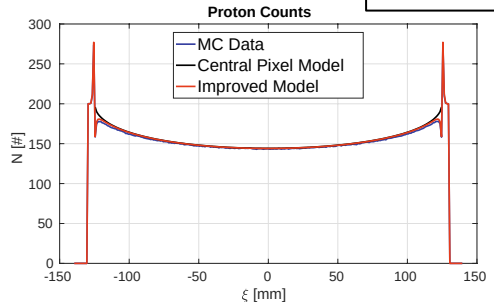
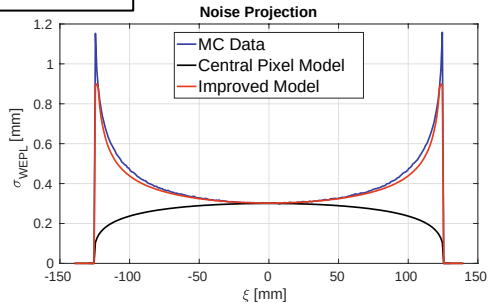




rear tracker binning





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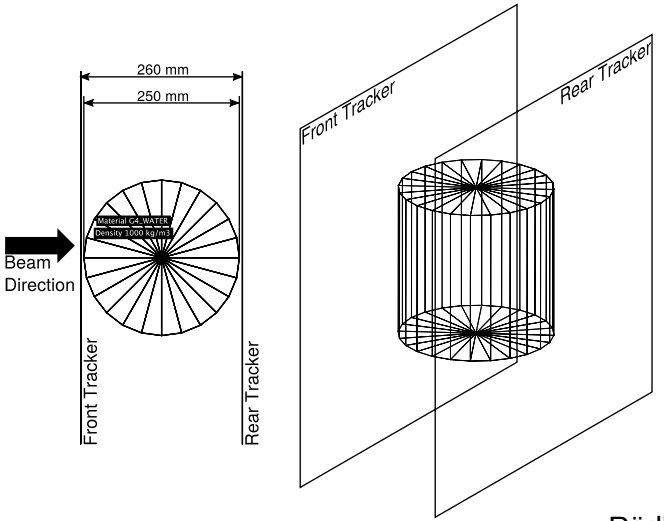

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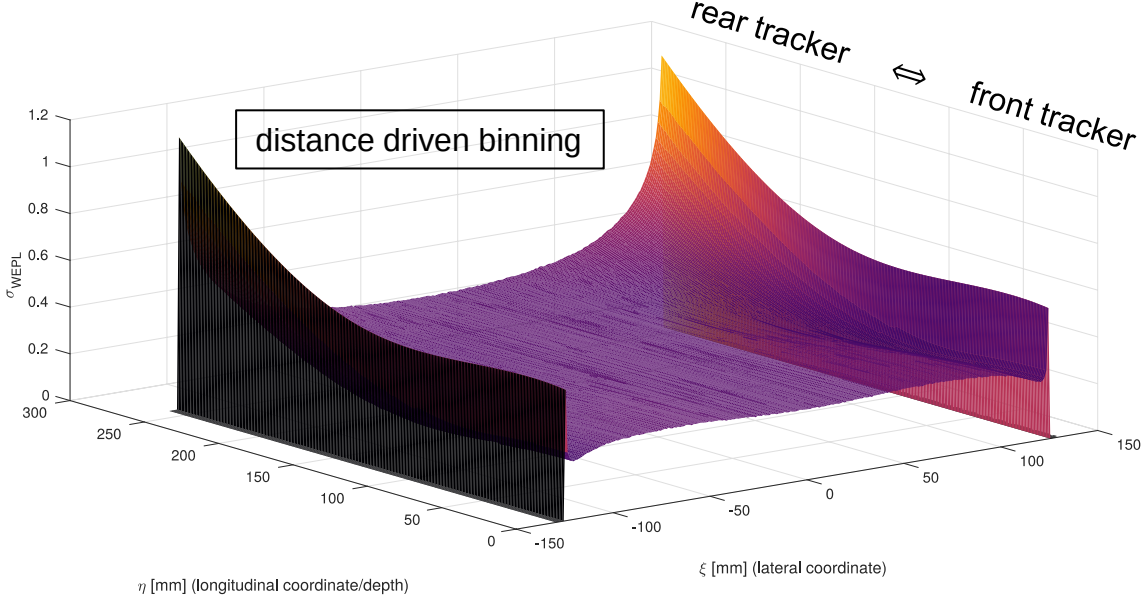

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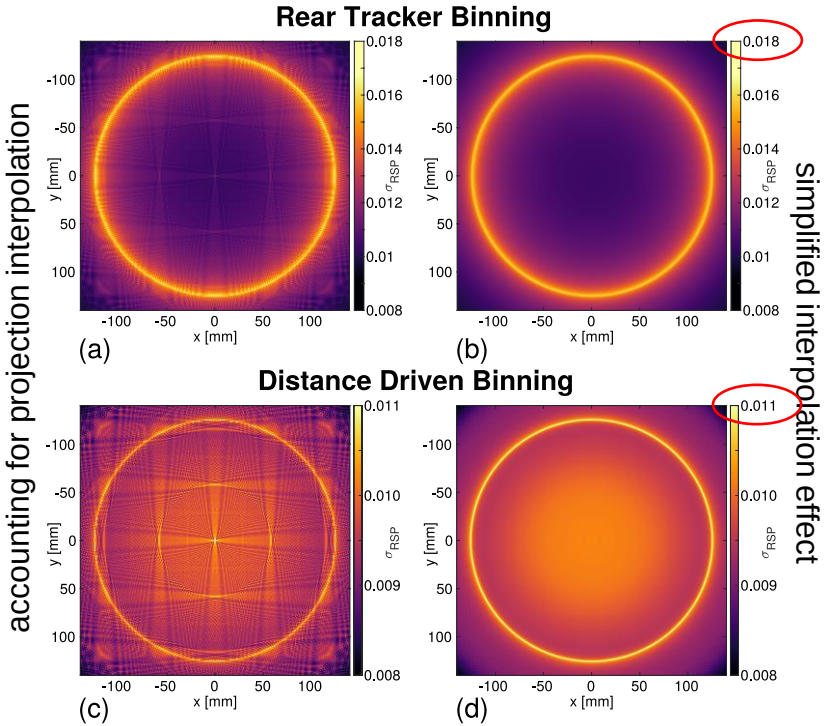
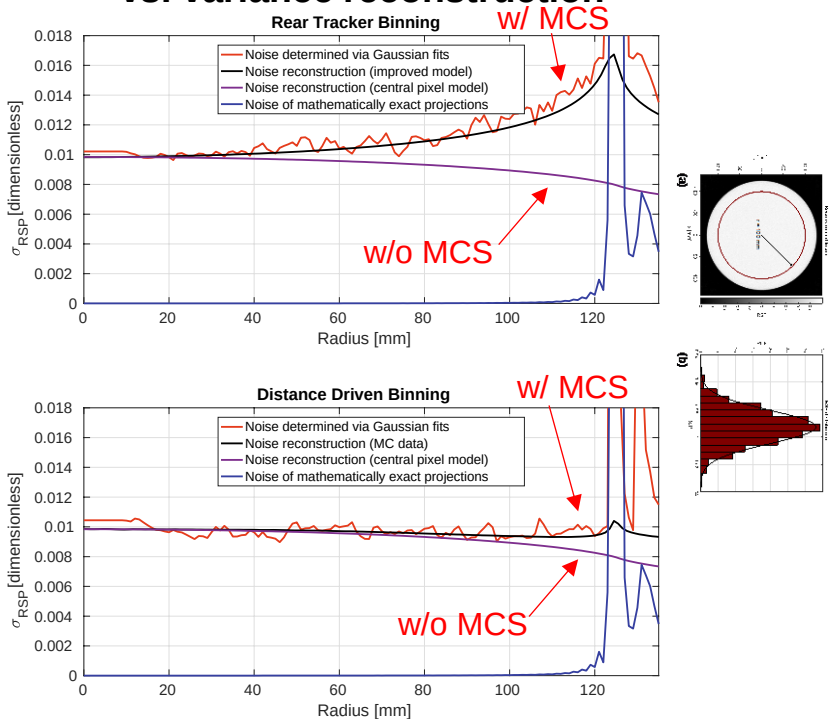
IMAGE VARIANCE MODELLING

Variance reconstructions



Standard deviation in annular ROIs vs. variance reconstruction

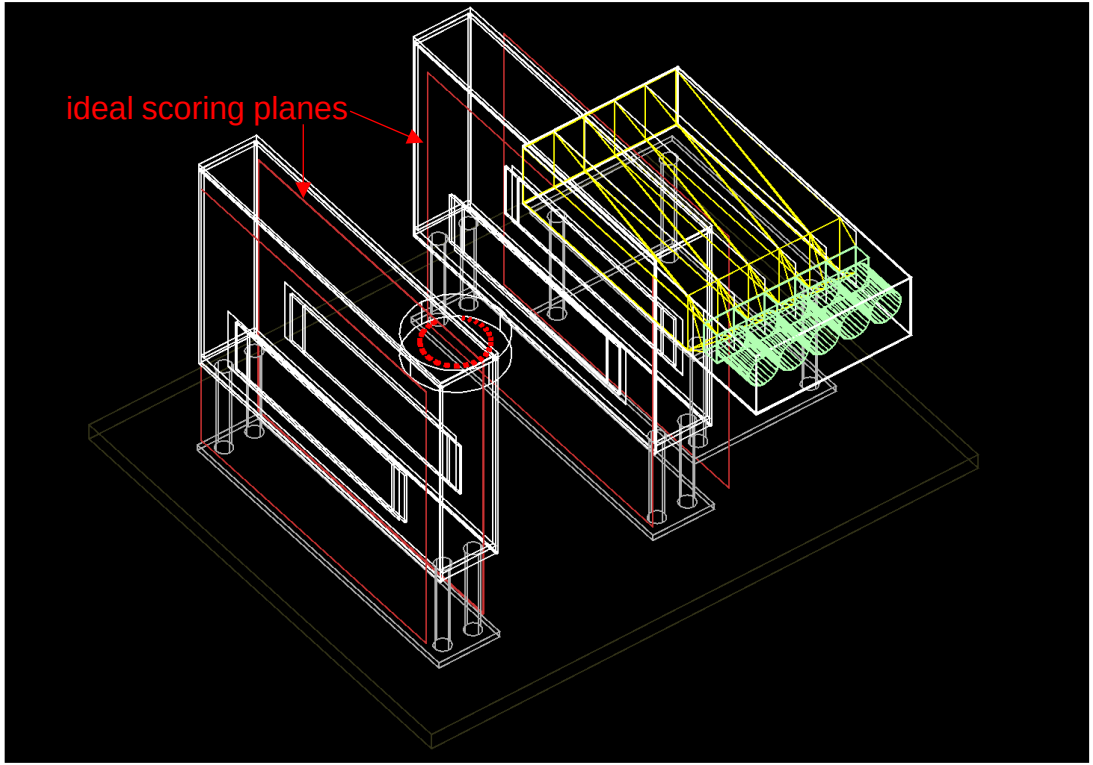


Rädler 2017 *MSc Thesis LMU Munich, pub. in prep.*

IMAGE VARIANCE MODELLING

“ideal” vs. realistic Geant4 MC simulation

- *N*=60 noise realizations
- image-pixel-wise standard deviation calculation
- distance driven binning reconstructions



software platform courtesy of the pCT collaboration, Giacometti et al. 2017 *Med Phys*

slide courtesy Jannis Dickmann, *LMU Munich*

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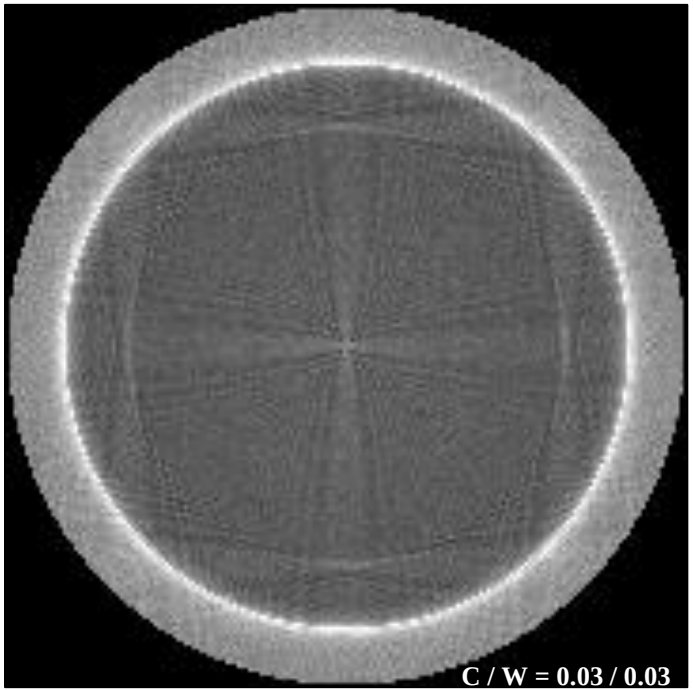
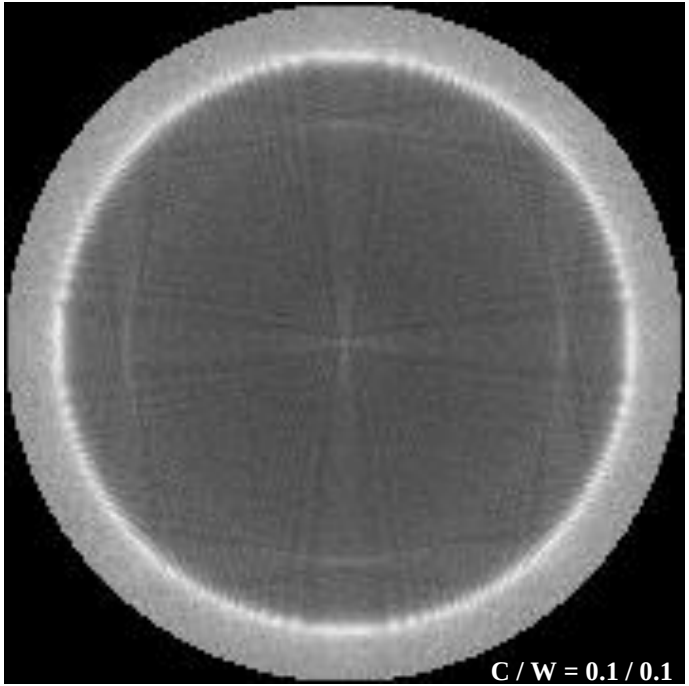
ideal simulation



realistic simulation



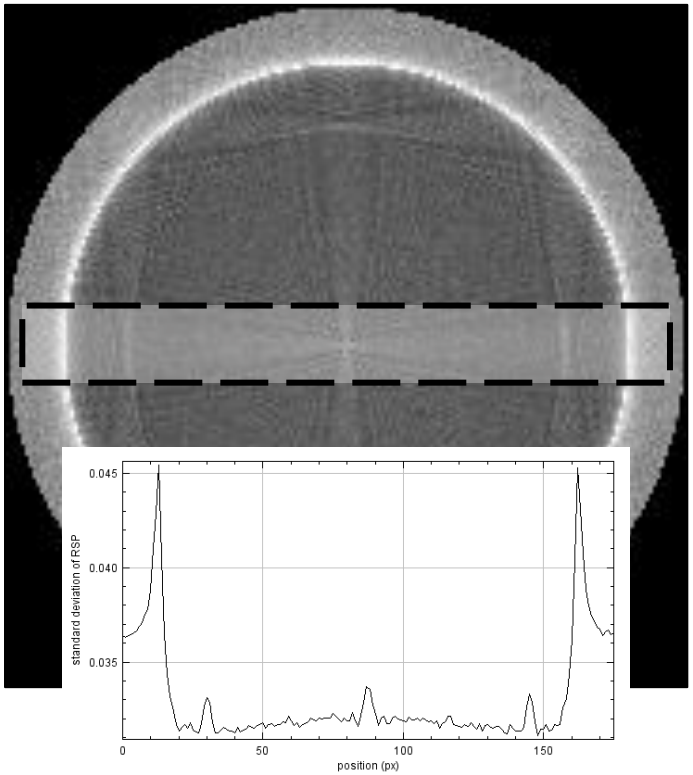
slide courtesy Jannis Dickmann, *LMU Munich*

IMAGE VARIANCE MODELLING

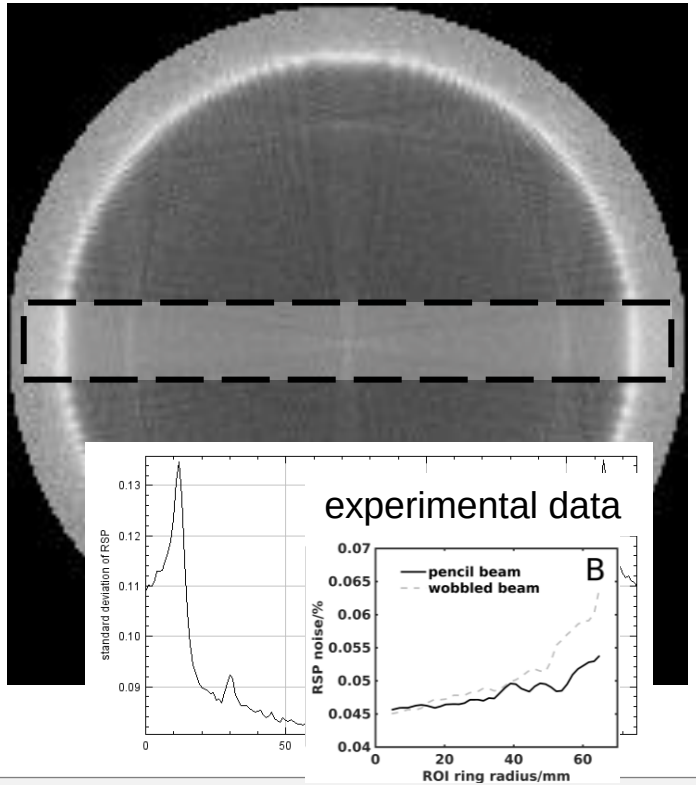
“ideal” vs. realistic Geant4 MC simulation

- *N*=60 noise realizations
- image-pixel-wise standard deviation calculation
- distance driven binning reconstructions

ideal simulation



realistic simulation



slide courtesy Jannis Dickmann, *LMU Munich*

OUTLOOK

Variance reconstruction

- Understand detector contribution using realistic simulations
- Compare to experimental data
- Impact of divergent beams?
- Heterogeneous/clinical geometries

Fluence modulation patterns

- Develop optimization based on variance reconstruction theory
- MC simulation based projection variance to account for MCS

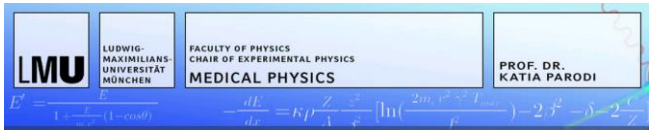
Experimental FMpCT

- Implement optimized fluence pattern
- Synchronize with scanner rotation
- Explore continuous rotation

Comparison to X-ray CT

- Fan beam and CBCT

ACKNOWLEDGEMENTS



Martin Rädler
Jannis Dickmann
Ludovica de Angelis
Willemijn M.A. Pols

LMU KLINIKUM DER UNIVERSITÄT MÜNCHEN

Dr. Florian Kamp

CHICAGO PROTON CENTER

Nick Detrich

RINECKER PROTON THERAPY CENTER

Martin Hillbrand

AARHUS UNIVERSITY

David Hansen

BAYLOR UNIVERSITY

Keith Schubert

LOMA LINDA UNIVERSITY

Valentina Giacometti
Vladimir Bashkirov

NORTHERN ILLINOIS UNIVERSITY 1895

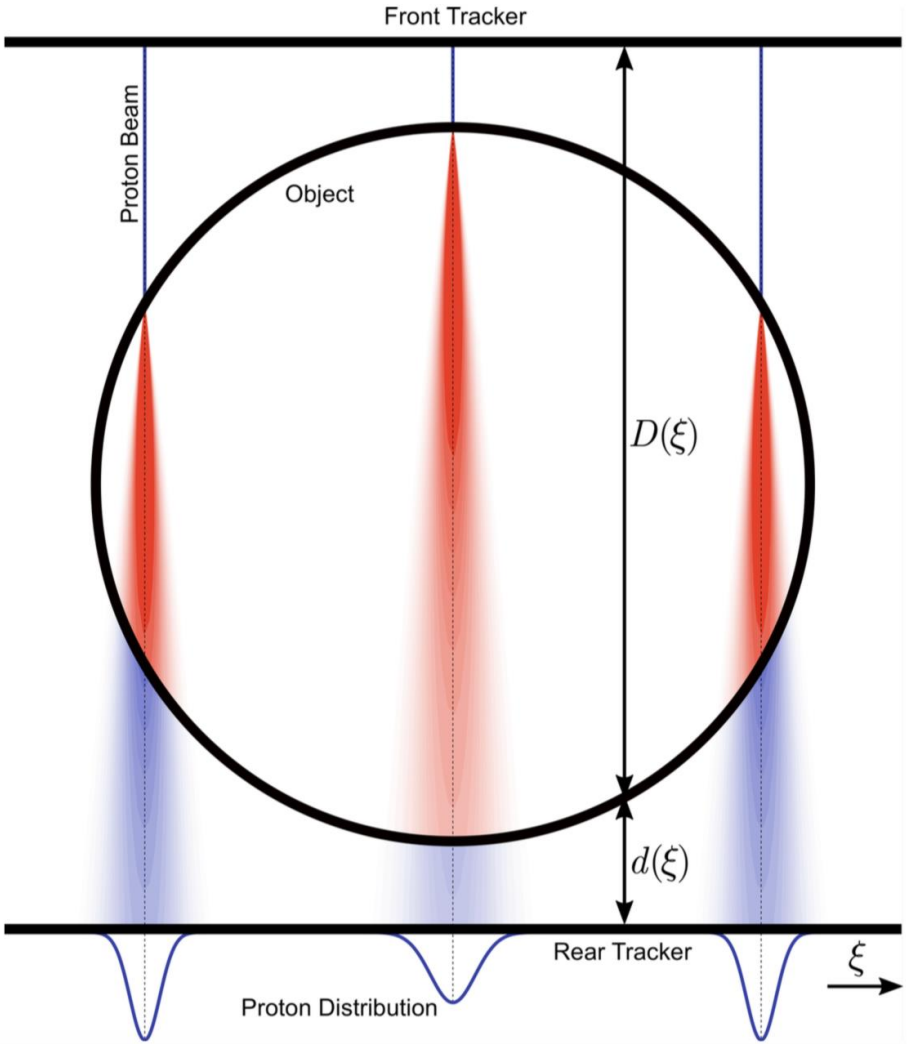
George Coutrakon

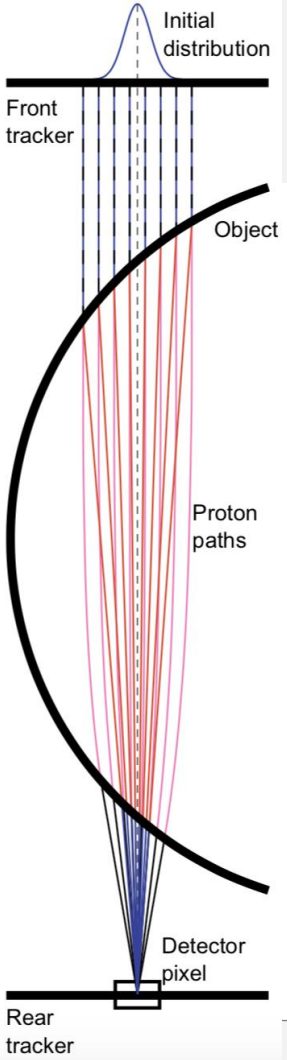
DFG Deutsche Forschungsgemeinschaft

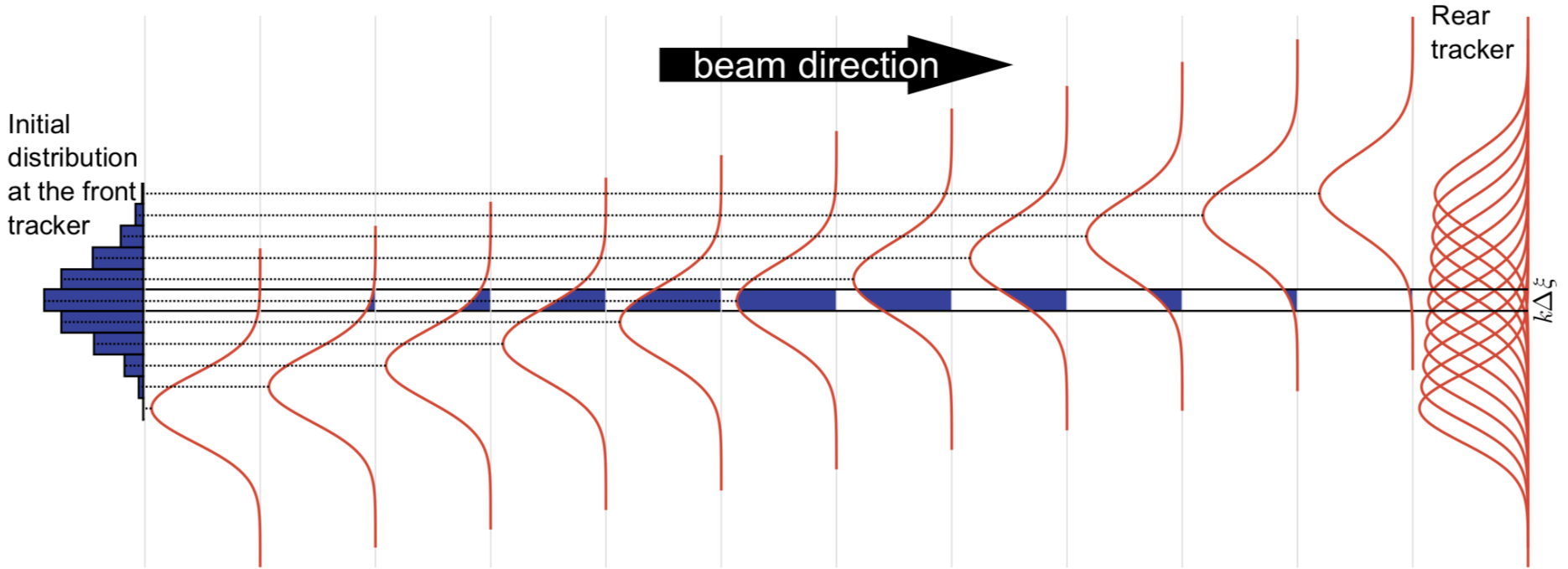
BaCaTeC

CENTRE DE COOPÉRATION UNIVERSITAIRE FRANCO-BAVAROIS

BAYERISCH-FRANZÖSISCHES HOCHSCHULZENTRUM


Front Tracker
Proton Beam
Object
$D(\xi)$
$d(\xi)$
Rear Tracker
ξ
Proton Distribution


Initial distribution
Front tracker
Object
Proton paths
Detector pixel
Rear tracker


beam direction
Initial distribution at the front tracker
Rear tracker
$k\Delta\xi$