# Fluence modulated proton computed tomography


George Dedes[a], Ludovica De Angelis[a], Simon Rit[b], David Hansen[c], Claus Belka[d] , Vladimir Bashkirov[e],Robert Johnson[f]
George Coutrakon[g], Keith Schubert[h], Reinhard Schulte[e], Katia Parodi[a], Guillaume Landry[a]

a Ludwig-Maximilians-Universität München, Department of Medical Physics
b Université de Lyon 1, CREATIS, CNRS, INSA Lyon
c Aarhus University Hospital, Department of Oncology
d LMU Munich, Department of Radiation Oncology, Munich,
e Loma Linda University, Division of Radiation Research
f U.C. Santa Cruz, Department of Physics
g Northern Illinois University, Department of Physics
h Baylor University, School of Engineering and Computer Science



**MCMA 2017, 17th of October, Naples, Italy**

LMU LUDWIG-MAXIMILIANS-UNIVERSITÄT MÜNCHEN

# Outline

- **Motivation**
- **Materials and Methods**
- **Results**
- **Conclusion**

# Motivation

- Proton imaging:
  - Proposed already in 1960s by Cormack
  - Registering proton position and direction before and after object and residual energy/range after object
  - Relative stopping power to water (RSP) determination at low imaging dose
  - Renewed interest with the spread of particle therapy facilities
  - Potential clinical use: treatment planning, positioning, plan adaptation/replanning

# Motivation

- Proton imaging:
  - Proposed already in 1960s by Cormack
  - Registering proton position and direction before and after object and residual energy/range after object
  - Relative stopping power to water (RSP) determination at low imaging dose
  - Renewed interest with the spread of particle therapy facilities
  - Potential clinical use: treatment planning, positioning, plan adaptation/replanning

- Dose reduction technique in X-ray CT:
  - Bow-tie filters
  - Automatic exposure control
  - Modulation of X-ray beam within a fan beam

  (Bartolac et al, 2011, Med. Phys. 38 S2), (Szczykutowicz et al, 2015, Phys. Med. Biol, 60 7245-57)

# Motivation

- Proton imaging:
  - Proposed already in 1960s by Cormack
  - Registering proton position and direction before and after object and residual energy/range after object
  - Relative stopping power to water (RSP) determination at low imaging dose
  - Renewed interest with the spread of particle therapy facilities
  - Potential clinical use: treatment planning, positioning, plan adaptation/replanning

- Dose reduction technique in X-ray CT:
  - Bow-tie filters
  - Automatic exposure control
  - Modulation of X-ray beam within a fan beam

  (Bartolac et al, 2011, Med. Phys. 38 S2), (Szczykutowicz et al, 2015, Phys. Med. Biol, 60 7245-57)

- Fluence modulated proton CT (FMpCT)
  - Extension of the main concept to proton CT acquired with pencil beams

  (Dedes et al, 2017, Phys. Med. Biol., 62 6026)

# Materials and Methods

- Simulation platform:
  - Geant4 v10.01.p02
  - Ideal pCT scanner
    (two detection planes registering energy, position and direction of individual protons)

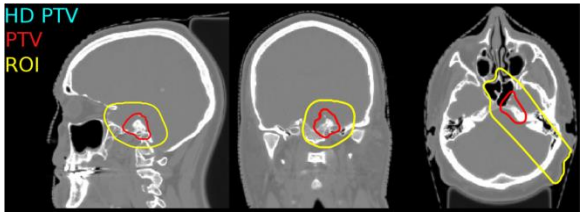
- Proton CT reconstruction:
  - Filtered backprojection along curved paths (Rit et al 2013 Med. Phys.**40** 031103)

# Materials and Methods

- Simulation platform:
  - Geant4 v10.01.p02
  - Ideal pCT scanner
    (two detection planes registering energy, position and direction of individual protons)

- Proton CT reconstruction:
  - Filtered backprojection along curved paths (Rit et al 2013 Med. Phys.**40** 031103)

- Virtual phantoms:
  - CT scan of a patient (Pat1) with a brain metastasis located near the base of the skull

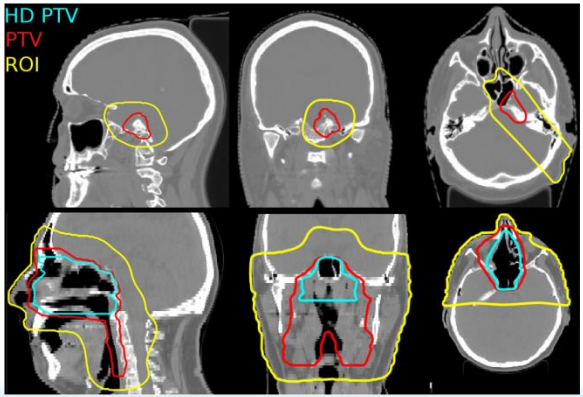


# Materials and Methods

- Simulation platform:
  - Geant4 v10.01.p02
  - Ideal pCT scanner
    (two detection planes registering energy, position and direction of individual protons)

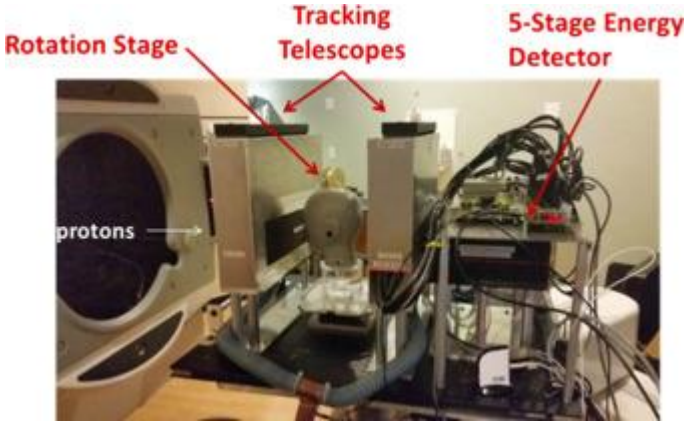
- Proton CT reconstruction:
  - Filtered backprojection along curved paths (Rit et al 2013 Med. Phys.**40** 031103)

- Virtual phantoms:
  - CT scan of a patient (Pat1) with a brain metastasis located near the base of the skull
  - CT scan of a paranasal sinus cancer (Pat2)



# Materials and Methods

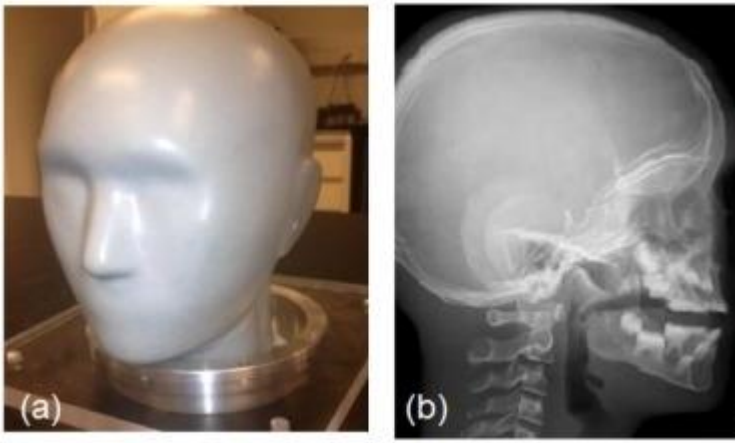
- Experimental data:
  - Phase II preclinical prototype pCT scanner
    (Sadrozinski et al 2016 Nucl. Instrum. Methods Phys. Res. A **831** 394–9)




Sadrozinski et al, Nucl Instrum Methods Phys Res A, 831 21 2016, 394–399

# Materials and Methods

- Experimental data:
  - Phase II preclinical prototype pCT scanner
    (Sadrozinski et al 2016 Nucl. Instrum. Methods Phys. Res. A **831** 394–9)
  - Pediatric head phantom (715-HN, CIRS)




Adapted from Giacometti et al Phys Med. 2017 Jan;33:182-188

# Materials and Methods

- Fluence modulation on simulated pencil (PB) scans:
  - Full fluence uniform images (FF) , uniform images with a fluence reduced by a fluence modulation factor (FMF·FF)
  - FMpCT with PBs intersecting ROI retaining FF and PBs outside reduced at FMF·FF

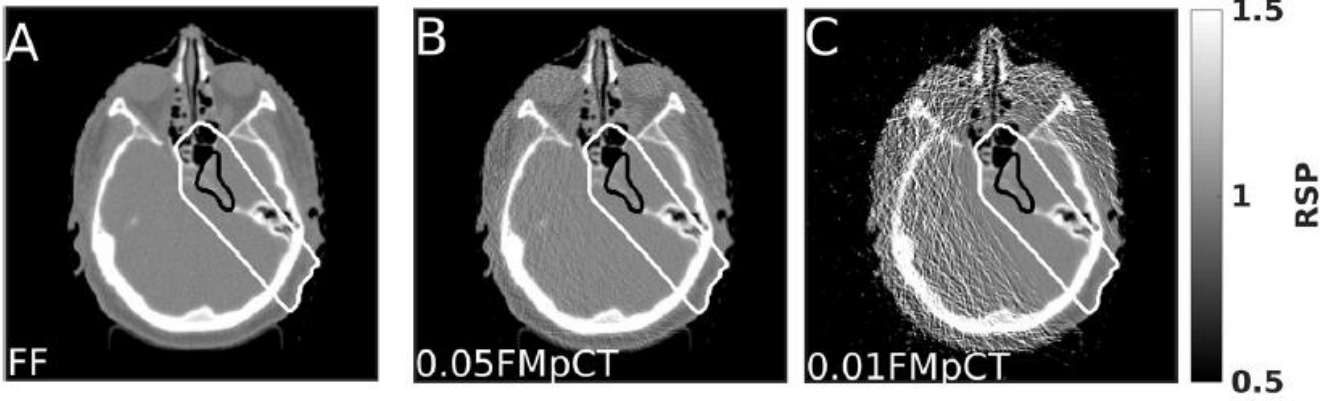
# Materials and Methods

- Fluence modulation on simulated pencil (PB) scans:
  - Full fluence uniform images (FF) , uniform images with a fluence reduced by a fluence modulation factor (FMF·FF)
  - FMpCT with PBs intersecting ROI retaining FF and PBs outside reduced at FMF·FF


- Fluence modulation on experimental cone beam scans:
  - Full fluence uniform images (FF), uniform images in which individual protons are discarded with a probability of 1-FMF
  - FMpCT with individual protons intersecting ROI retaining FF and protons outside discarded with a probability of 1-FMF

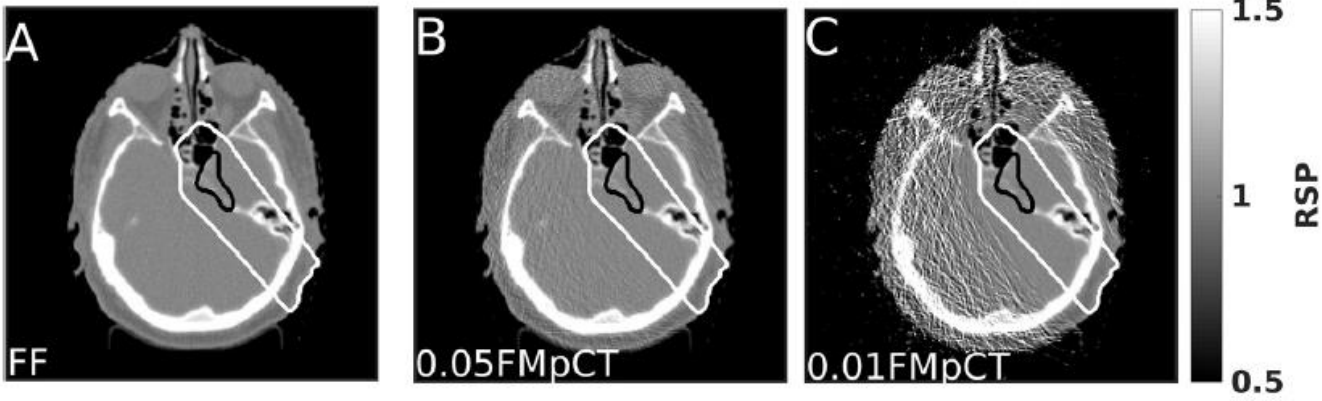
# Results: Pat1

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



# Results: Pat1

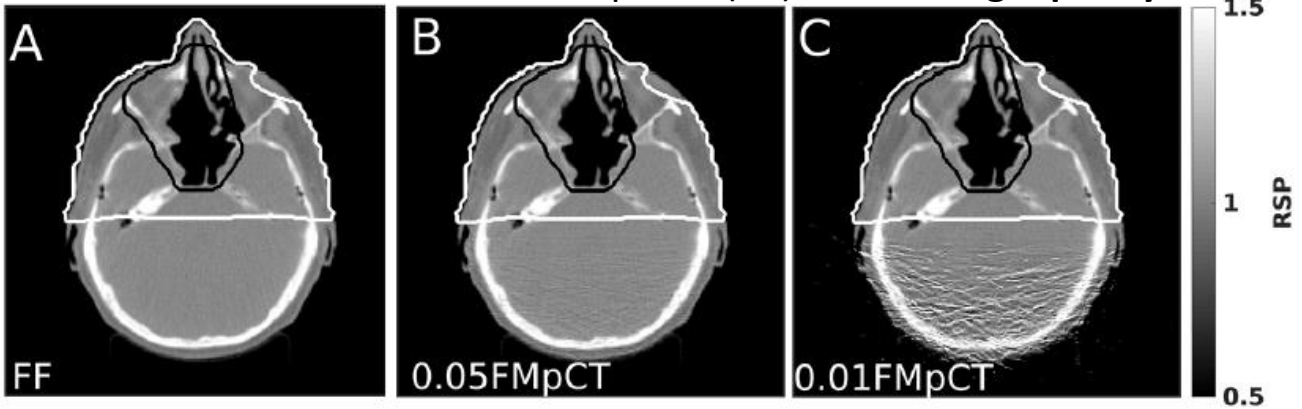
- Fluence modulation on simulated pencil (PB) scans: **Image quality**




| | $(RSP - RSP_{ref})/RSP_{ref}$ (%) | | $(RSP - RSP_{ref})/RSP_{ref}$ (%) | |
|---|---|---|---|---|
| | 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 |

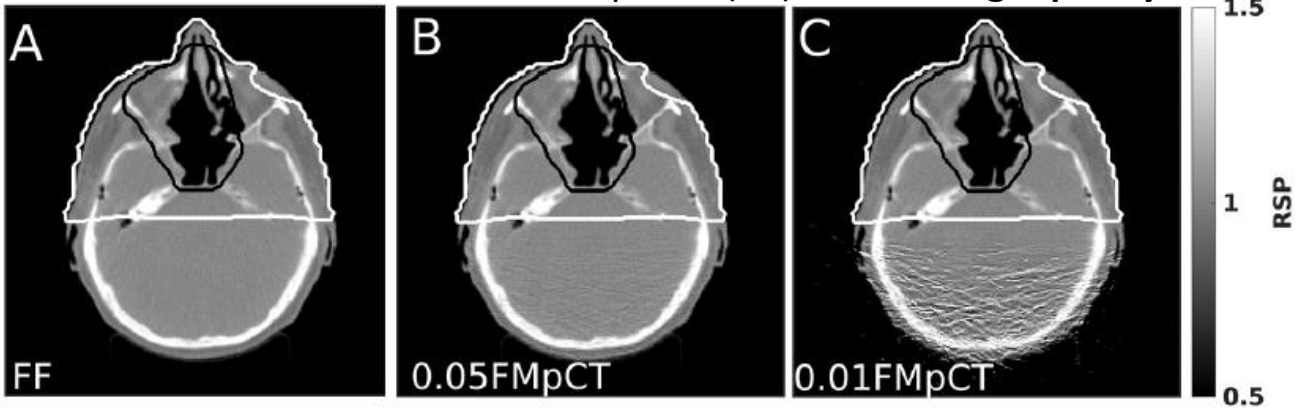
# Results: Pat2

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



# Results: Pat2

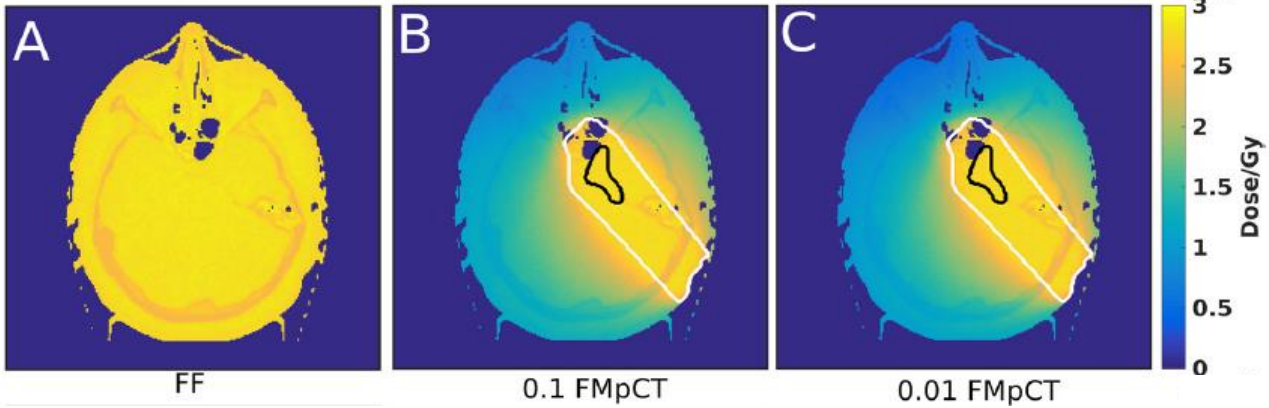
- Fluence modulation on simulated pencil (PB) scans: **Image quality**




| | $(RSP - RSP_{ref})/RSP_{ref}$ (%) | | $(RSP - RSP_{ref})/RSP_{ref}$ (%) | |
|---|---|---|---|---|
| | Noise | | Mean | |
| Pat2 | Uniform | FMpCT | Uniform | FMpCT |
| FF | 1.4 | — | −0.2 | — |
| 0.1 · FF | 4.2 | 1.5 | −0.2 | −0.2 |
| 0.05 · FF | 6.3 | 1.6 | −0.2 | −0.2 |
| 0.01 · FF | 32.5 | 1.6 | 0.5 | −0.4 |

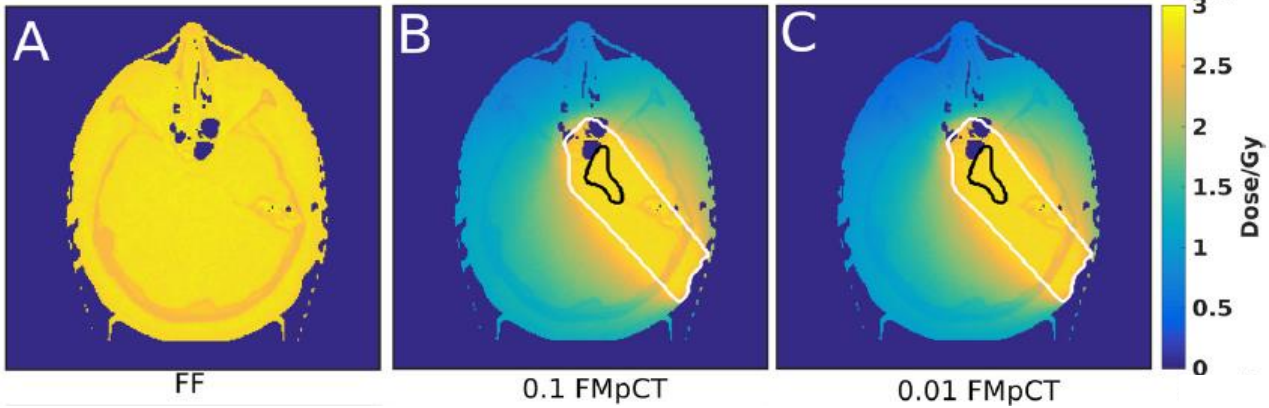
# Results: Pat1

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



# Results: Pat1

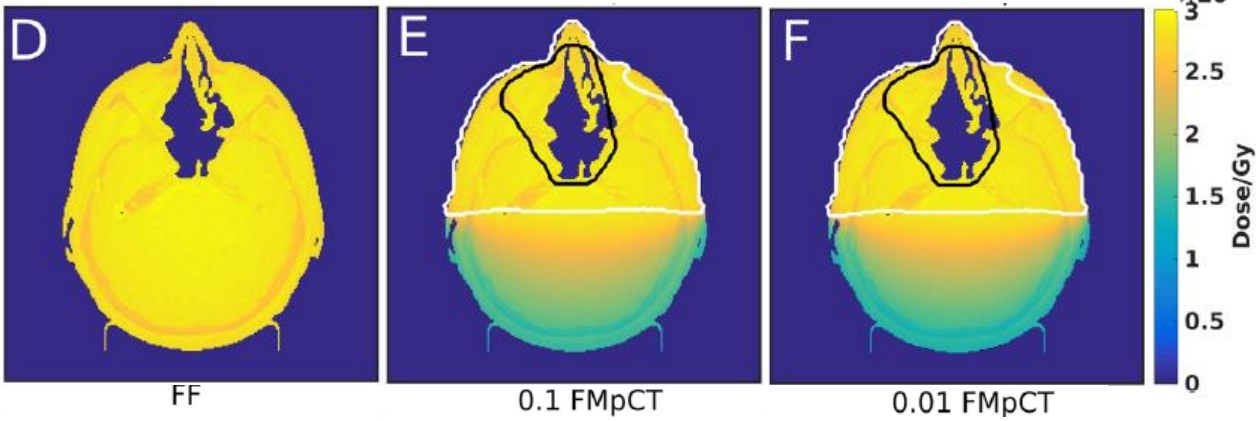
- Fluence modulation on simulated pencil (PB) scans: **Imaging dose**




| | Integral dose (mGy) | | Integral dose reduction 1 − FMF · FMpCT/FF | |
|---|---|---|---|---|
| Pat1 | Whole image | Outside ROI | Whole image | Outside ROI |
| FF | 2.57 | 2.56 | — | — |
| 0.1 · FMpCT | 1.42 | 1.25 | 0.45 | 0.51 |
| 0.05 · FMpCT | 1.35 | 1.18 | 0.47 | 0.54 |
| 0.01 · FMpCT | 1.30 | 1.12 | 0.49 | 0.56 |

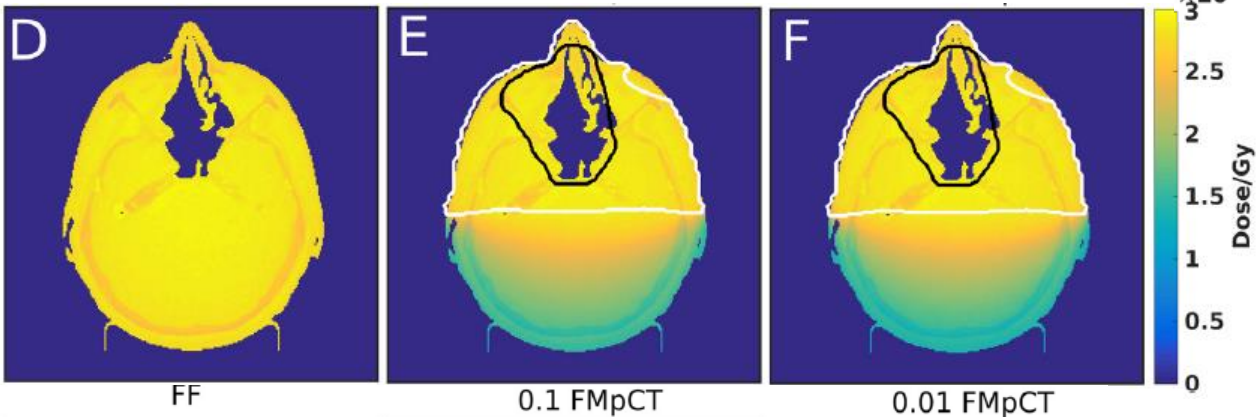
# Results: Pat2

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



# Results: Pat2

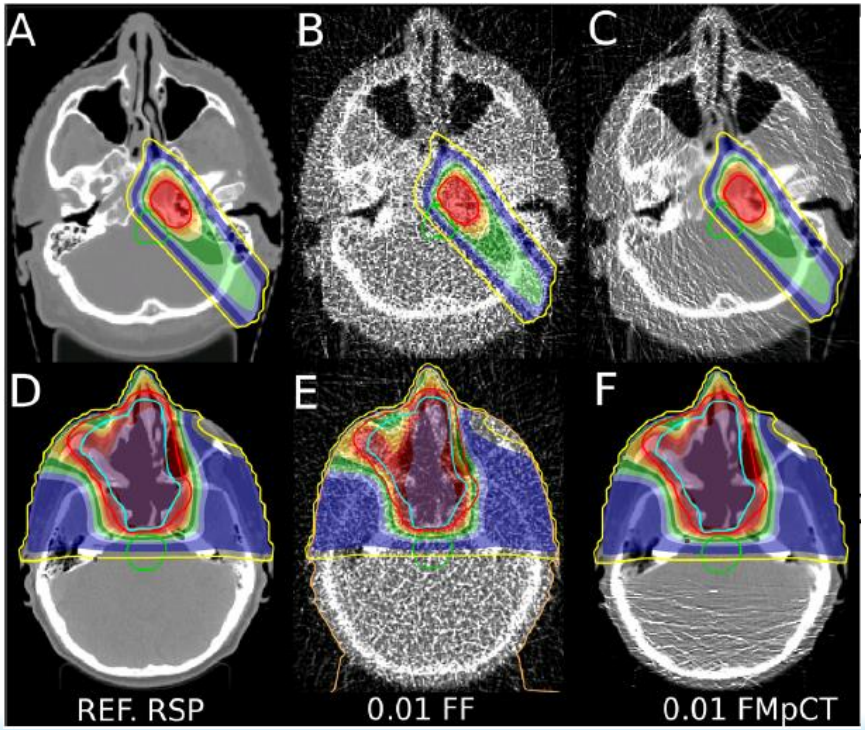
- Fluence modulation on simulated pencil (PB) scans: **Imaging dose**




| Pat2 | Integral dose (mGy) | | Integral dose reduction $1 - FMF \cdot FMpCT/FF$ | |
|---|---|---|---|---|
| | Whole image | Outside ROI | Whole image | Outside ROI |
| FF | 2.67 | 2.65 | — | — |
| 0.1 · FMpCT | 2.13 | 1.76 | 0.20 | 0.34 |
| 0.05 · FMpCT | 2.10 | 1.71 | 0.21 | 0.35 |
| 0.01 · FMpCT | 2.08 | 1.67 | 0.22 | 0.37 |

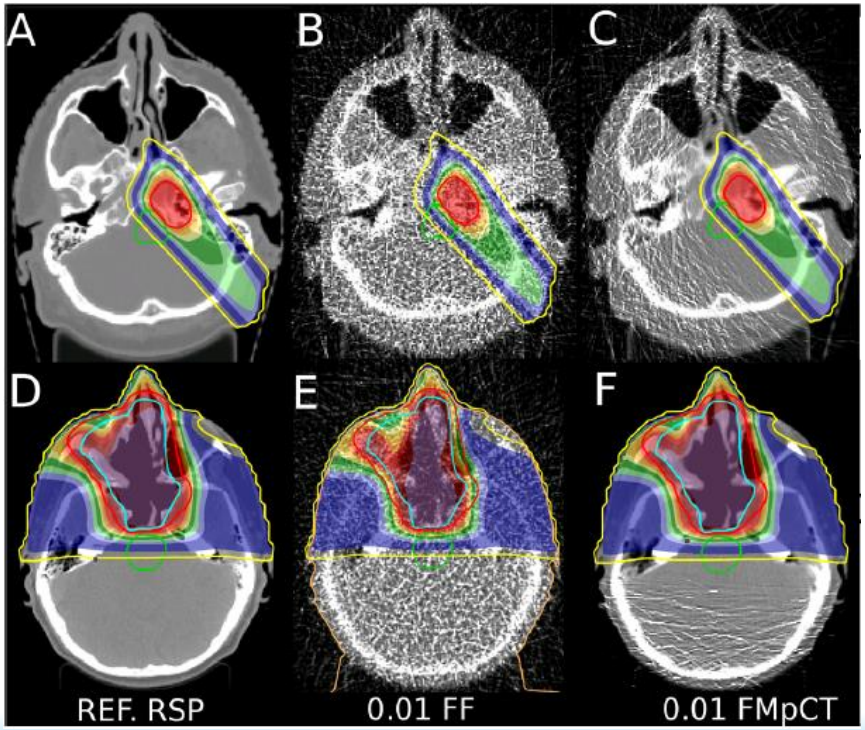
# Results:
# Pat1 & Pat2

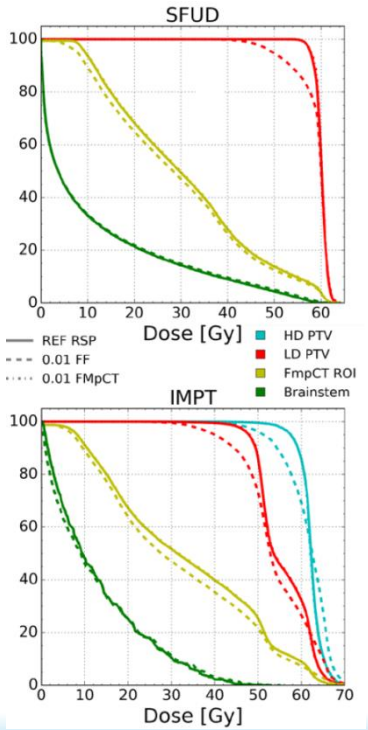
- Fluence modulation on simulated pencil (PB) scans: **Dose calculation**



# Results:
# Pat1 & Pat2

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



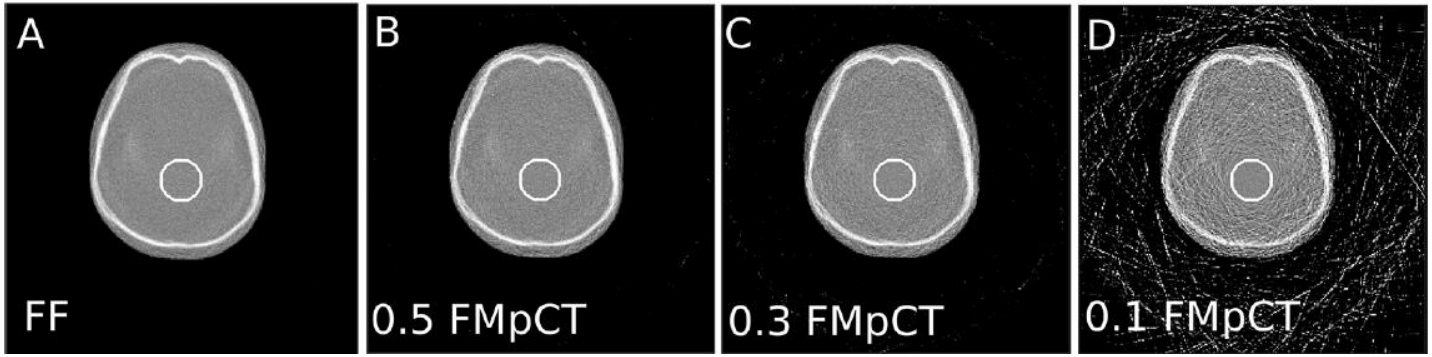
# Results: Pat1 & Pat2

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

| | RD < 1 mm (%) | | RD < 2 mm (%) | |
|---|---|---|---|---|
| Pat1 | Uniform | FMpCT | Uniform | FMpCT |
| $FF - RSP_{ref}$ | 93 | — | 99 | — |
| $0.05 \cdot FF - FF$ | 88 | 99 | 99 | 99 |
| $0.01 \cdot FF - FF$ | 0 | 97 | 0 | 99 |

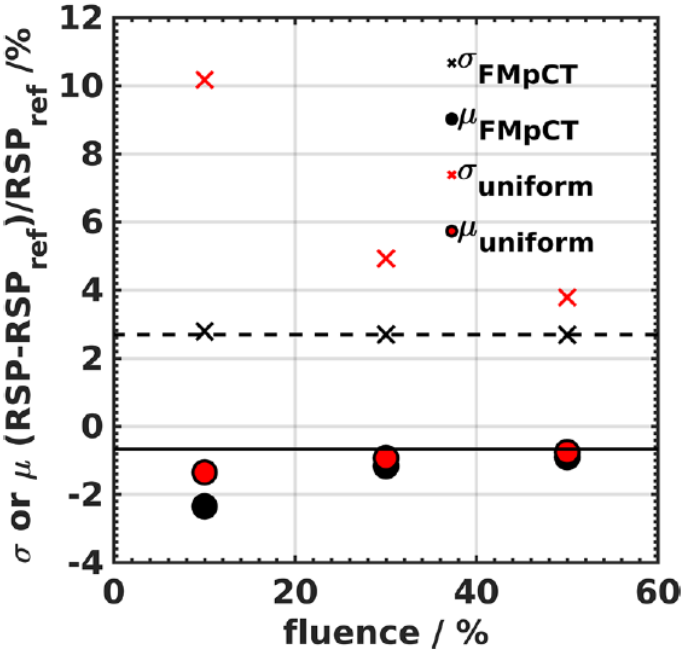
# Results:
# Pediatric head phantom

- Fluence modulation on experimental cone beam scans : **Image quality**



# Results: Pediatric head phantom

- Fluence modulation on experimental cone beam scans : **Image quality**



# Conclusions - Outlook

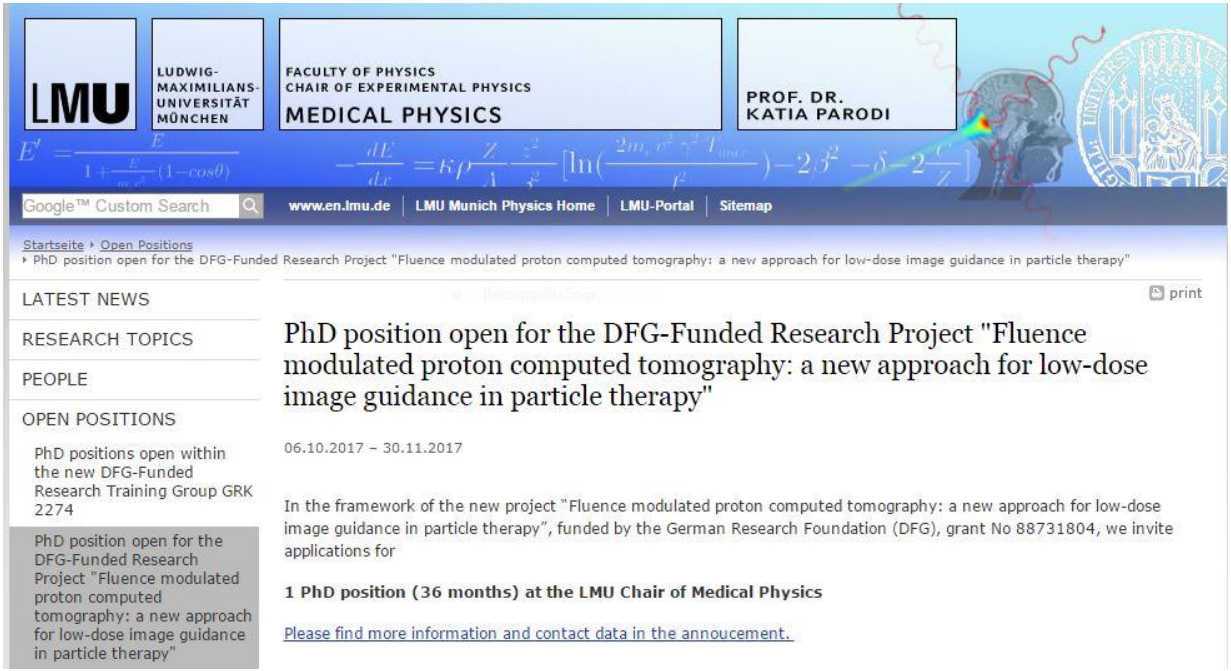
- Demonstration of the concept in homogeneous and anthropomorphic virtual phantoms
  - Dose reduction
  - Retaining of image quality
  - Accurate images for dose calculation

- Successful emulation of FMpCT from cone beam pCT experimental scans

# Conclusions - Outlook

- Demonstration of the concept in homogeneous and anthropomorphic virtual phantoms
  - Dose reduction
  - Retaining of image quality
  - Accurate images for dose calculation
- Successful emulation of FMpCT from cone beam pCT experimental scans
- Performing similar studies with a detailed modelling of the scanner
- Full experimental realization of the technique in a proton therapy facility
  - PB pCT scans (by the end of the year)
  - Testing of modulation patterns
  - Image quality prescription algorithms

- Available PhD position on fluence modulation pCT in LMU Munich:




https://www.med.physik.uni-muenchen.de/open_positions/dfg_fmpct/index.html