On the way to the Clinics: Tackle the Challenges in Prompt Gamma-Ray Timing

Theresa Werner

Partner von DRESDEN concept exzellenz-dresden.de

HZDR

HELMHOLTZ ZENTRUM DRESDEN ROSSENDORF

OncoRay - Dresden

Leader Medical Physics:

Wolfgang Enghardt

Group Leader:

Guntram Pausch

"In-vivo Dosimetry for new Types of Radiation"

Postdoctoral Fellow:

Toni Kögler

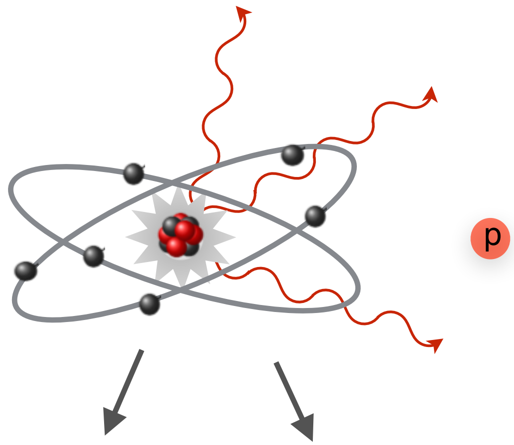
PhD student

Theresa Werner

Range Verification in Proton Therapy

Signatures for Range Verification

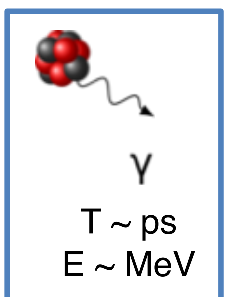
- Production of secondary particles
- Excited nucleus remains



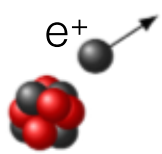
atom in the
patient body

Prompt Gamma
Emission

promptly emitted
gammas



ß+ emitter



T ~ sec/min
E ~ keV

Positron Emission
Tomography

Taiga Yamaya
"OpenPET for ion therapy imaging"

Concepts for Range Verification

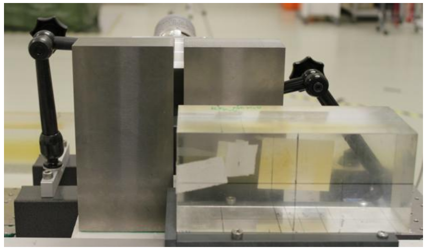
Concepts

- Energy measurements
  - Prompt Gamma Spectroscopy (PGS)
- Spatial measurements
  - Compton Camera / Slit Camera

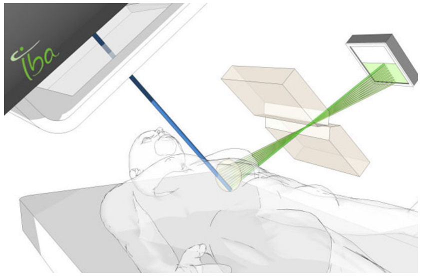
Gabriela Llosa
„MACACO II upgrade and first results"

- Timing measurements
  - Prompt Gamma Timing (PGT)

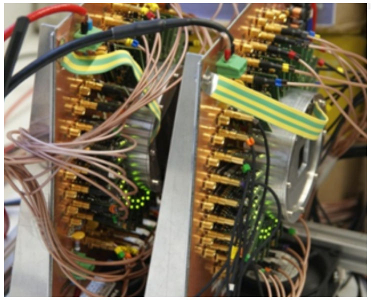
Theresa Werner
„Prompt Gamma-Ray Timing„



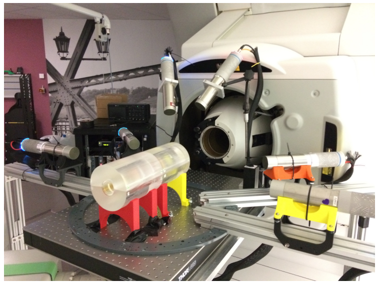
PG Spectroscopy



Slit Camera



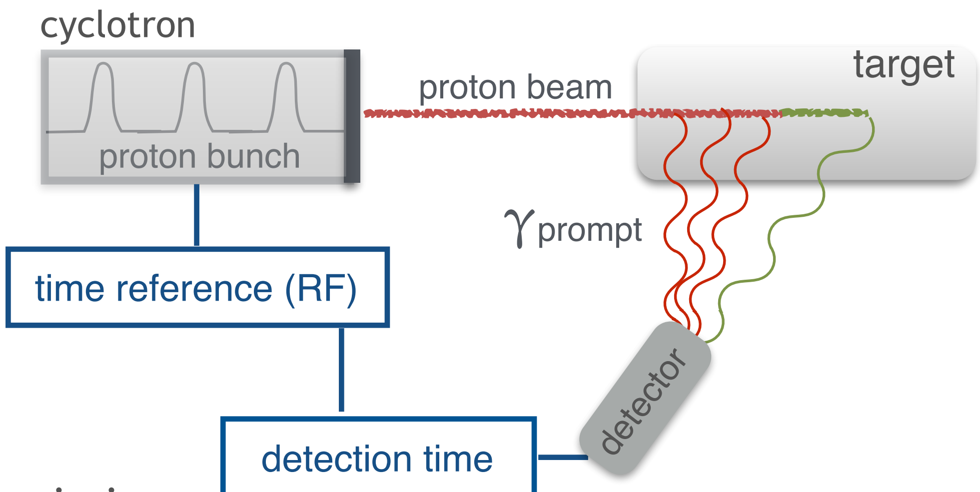
Compton Camera



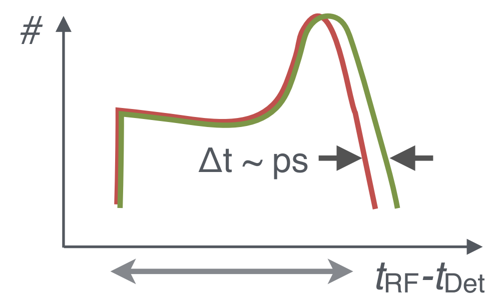
Prompt Gamma Timing

Principle of Prompt Gamma Timing

- Protons enter the tissue and excite nuclei
- Production of prompt gammas along particle track
- Record time resolved emission profile
- Longer range is reflected in a longer period of prompt gamma emission
- Time differences in ps scale



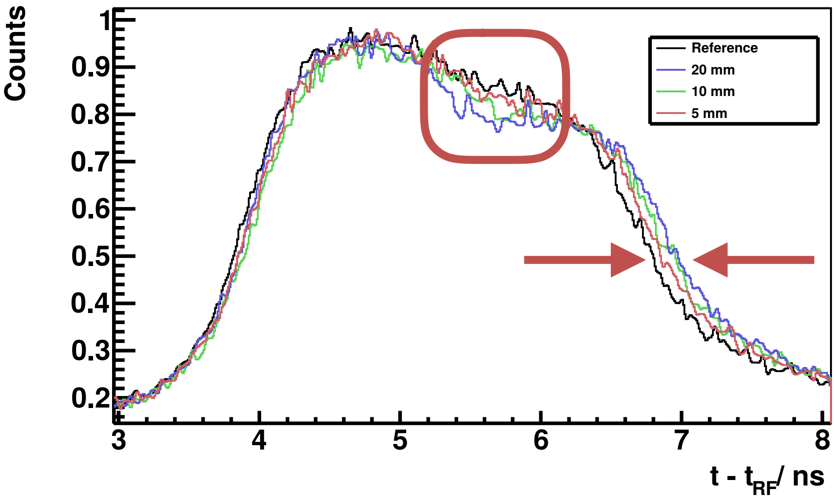
- Measure for range shifts
  - ➤ Δ width of PGT spectra (standard deviation Δσ)
  - ➤ Δ position of PGT spectra (mean Δμ)

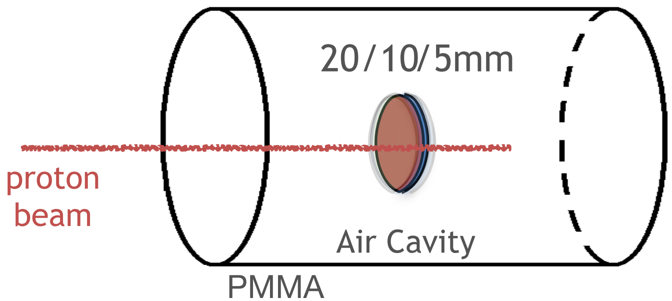


➤ particle range

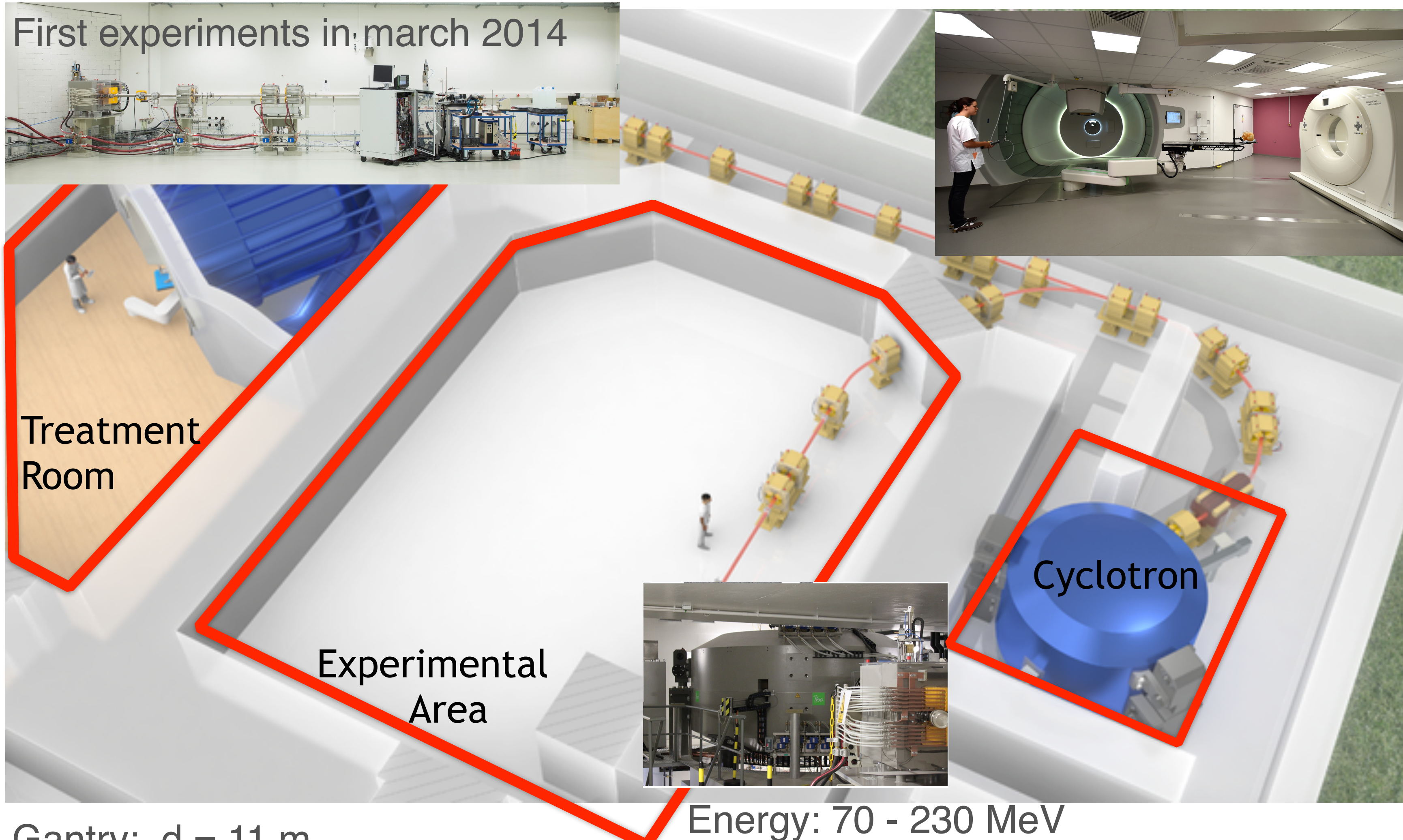
Proof of Prompt Gamma Timing

- PGT spectra measured in treatment Room (PBS Mode)
- Setup
  - ➤ 225 MeV Protons
  - ➤ One Layer 1000 MU
  - ➤ 1.43×10^{11} incoming protons
  - ➤ $CeBr_3$ (2"x2") detector
- Lack of prompt gamma production due to air cavity
- Overshoot caused by longer range





Experiments at OncoRay - Dresden



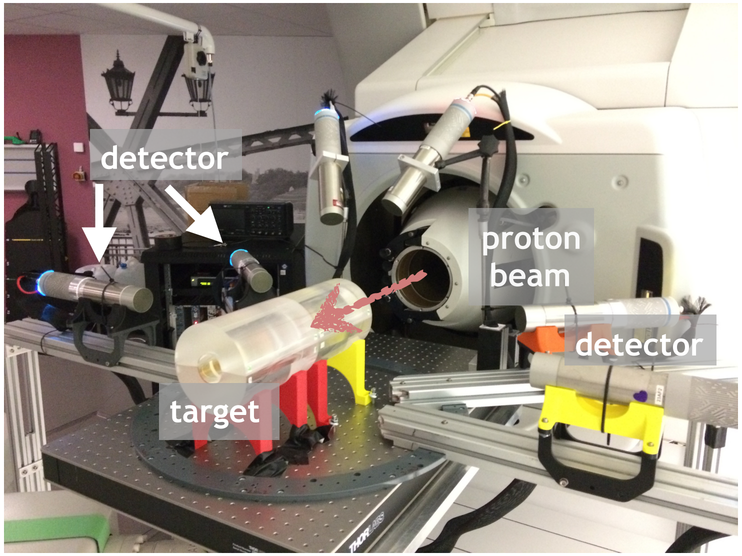
Energy: 70 - 230 MeV

Gantry: d = 11 m
m= 120 t

Experiments at Treatment Room

Pencil Beam Mode (PBS)

- Hollow PMMA target with inserts (e.g air, bone)
- Treatment conditions ➤ doses, dose rate, volume



Experimental setup in clinical treatment room

PGT detection unit

- ø 2“x1…2“ $CeBr_3$
- ΔT = 225 ps @ 4.5 MeV
- $\Delta E/E$ = 2.5 % @ 2.5 MeV
- 1 Mcps (asymptotic) throughput

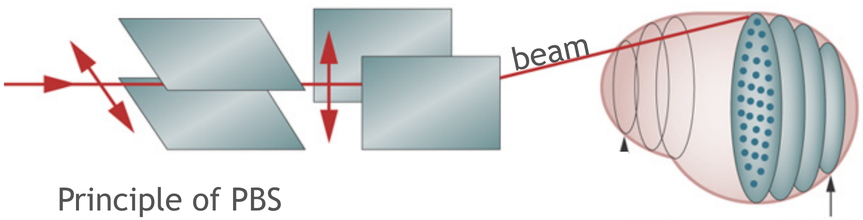
$CeBr_3$ PMT Digital spectrometer

PGT detection unit

Experiments at Treatment Room

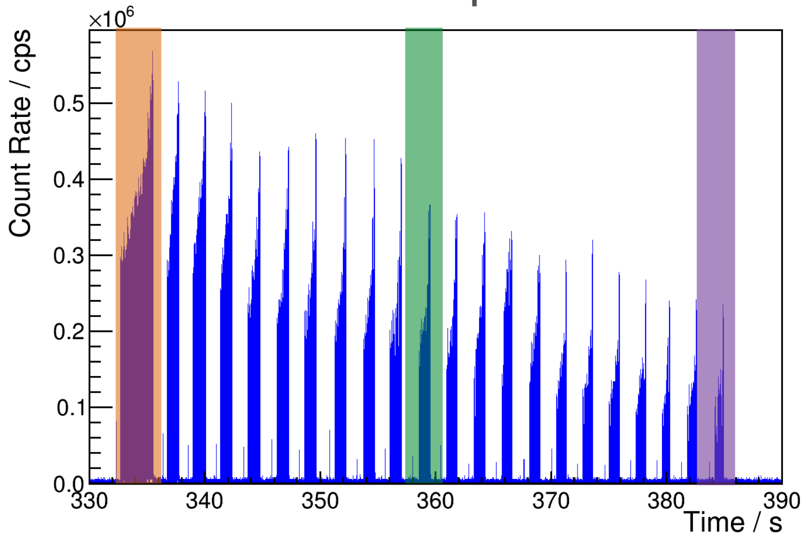
Pencil Beam Mode (PBS)

- Tumor-volume splitted in several iso-energy slices
- Spot-wise dose deposition in the target volume

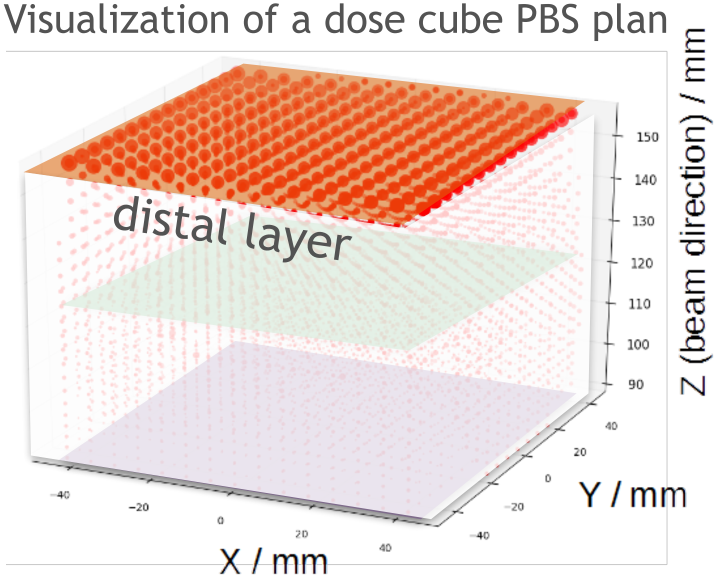


Principle of PBS

full PBS plan



Visualization of a dose cube PBS plan

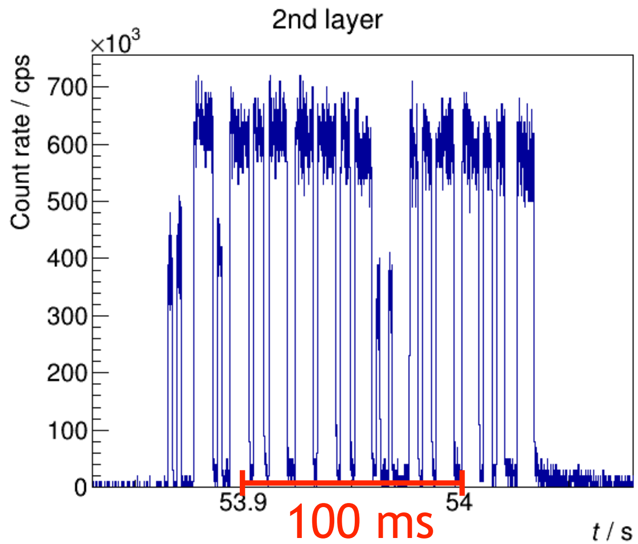


Challenges towards Clinical Translation

Dose delivery constraints

A) Strong detector load variations due to layer structure

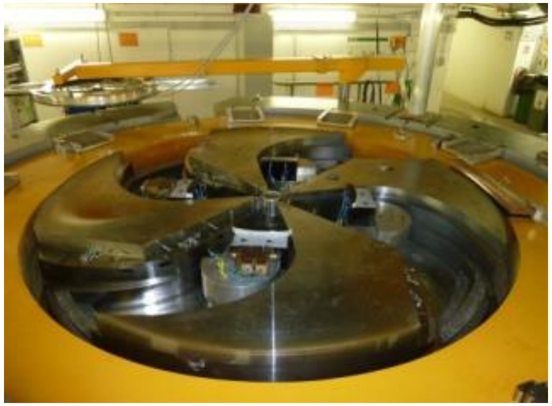
B) Ensure statistic in short irradiation time (Spot ~ ms)



Accelerator

C) Unstable time correlation between cyclotron RF and proton bunches

D) Oscillation of the phase between bunch and RF

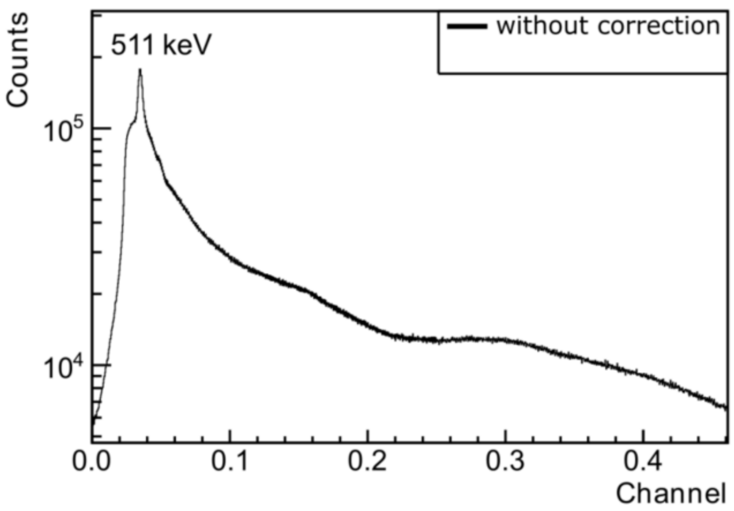


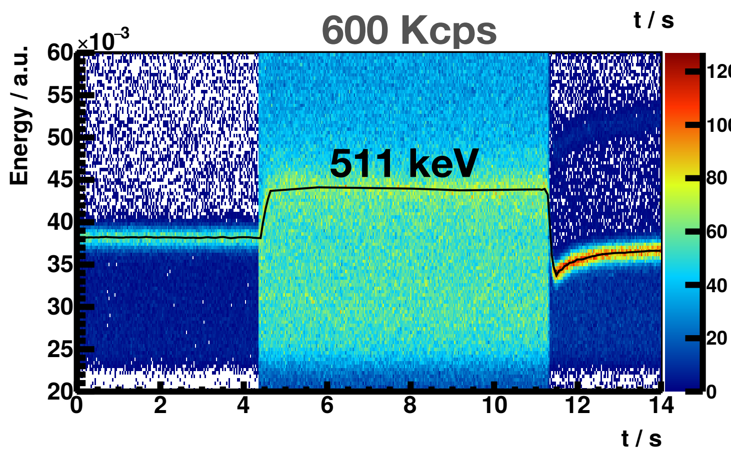
Dose Delivery Constraints

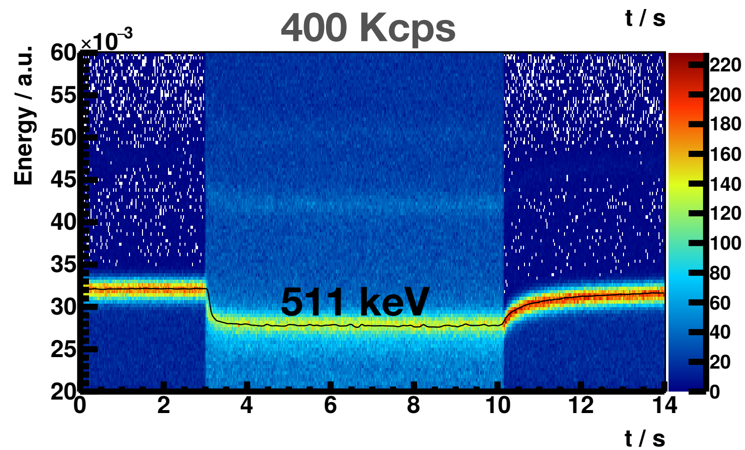
A) Load variations

- Gain depends on detector load
- Effects on gain and timing

➤ Corrections applied in the data analysis







Dose Delivery Constraints

B) Treatment time

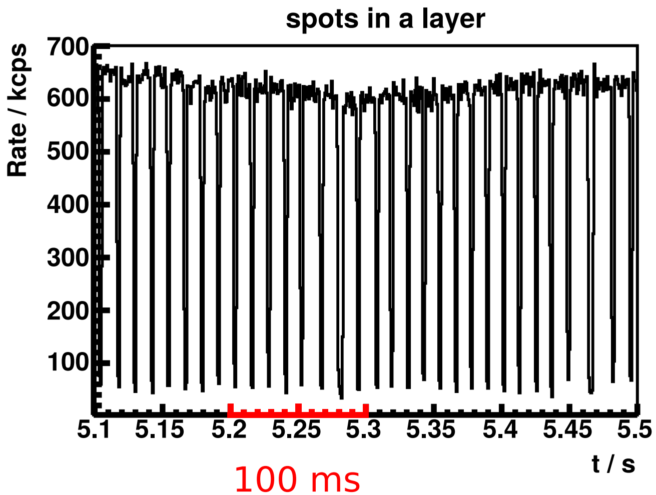
- Acquisition time few ms per spot
- Limiting factor is electronic / DACQ
- High detection rate > 10^6 cps

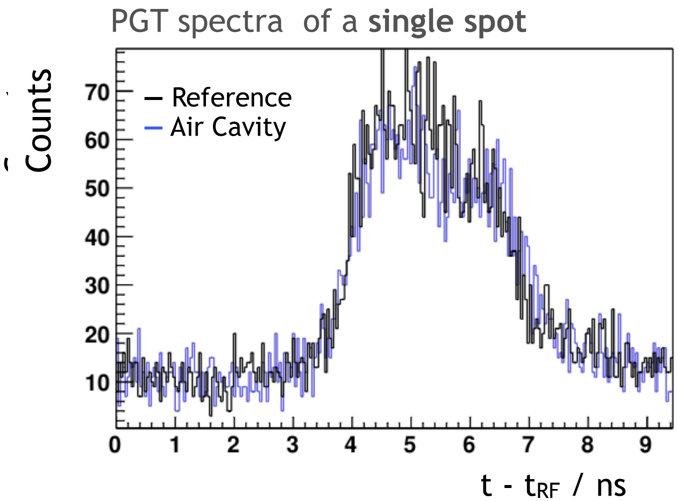
Global shifts:

Layer: ~ sec

Local shifts:

Spot: ~ ms

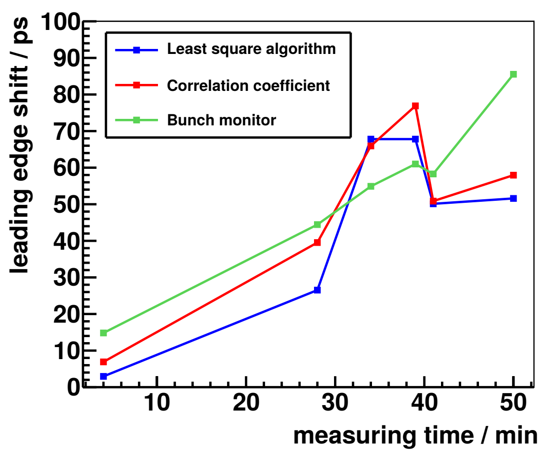


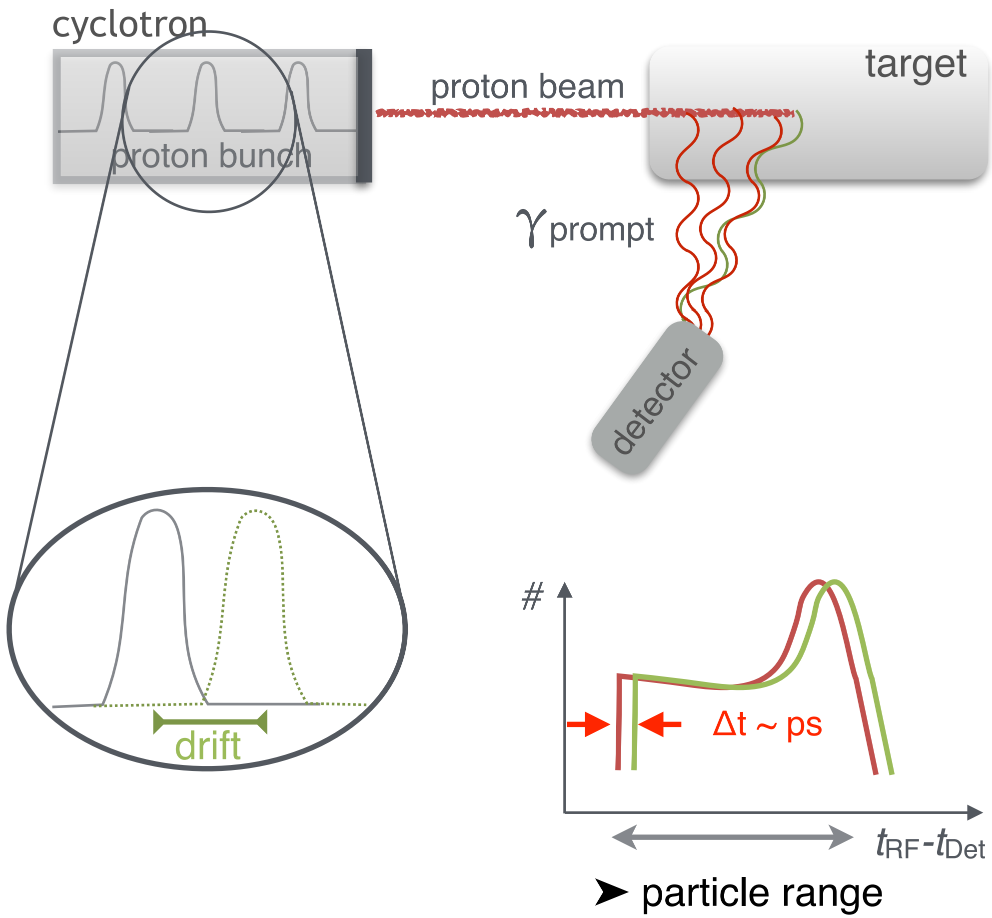


Accelerator

C) Bunch drifts

- Unstable time correlation between cyclotron RF and proton bunches
- Shift of leading edge of the PGT spectra



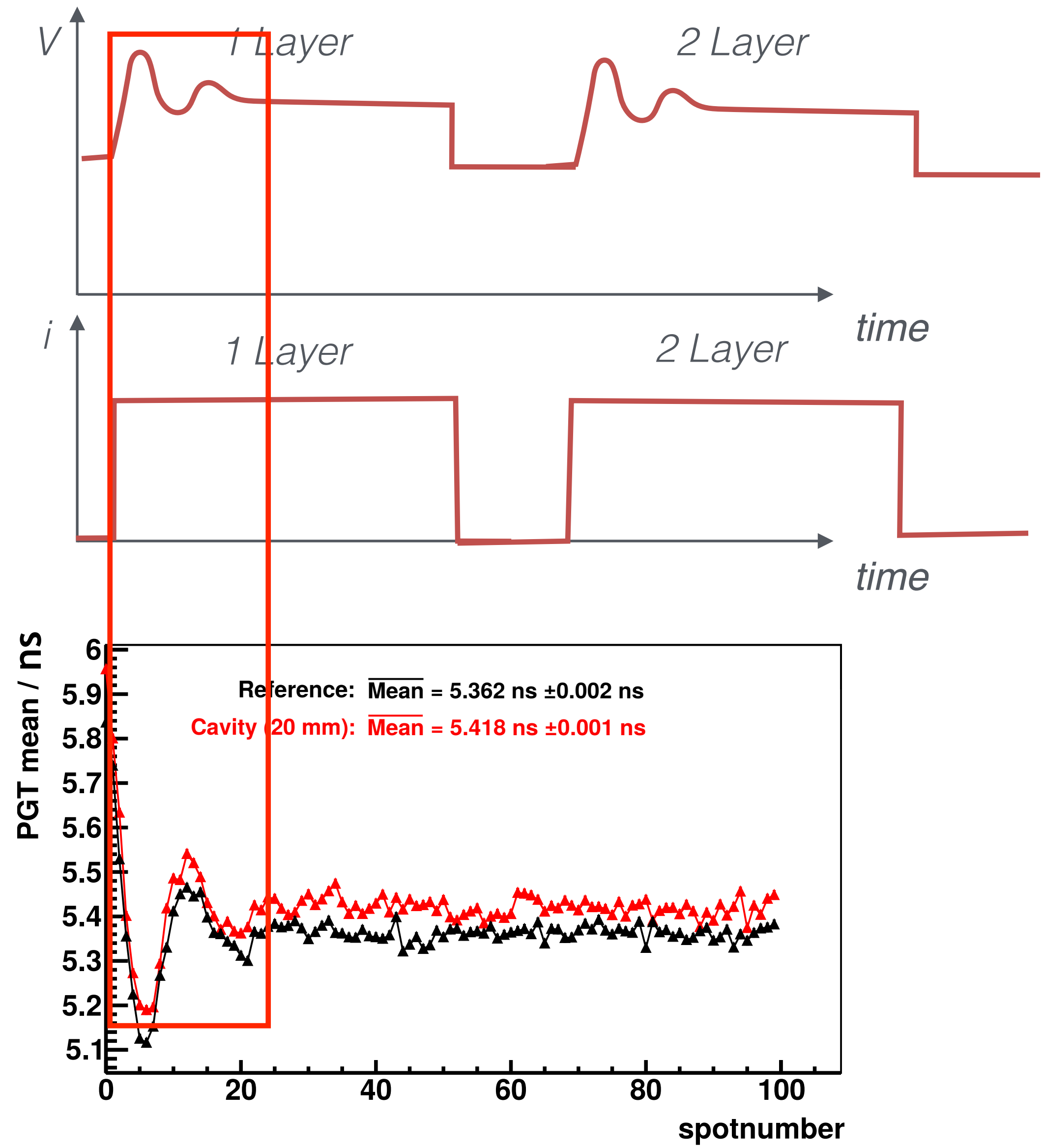


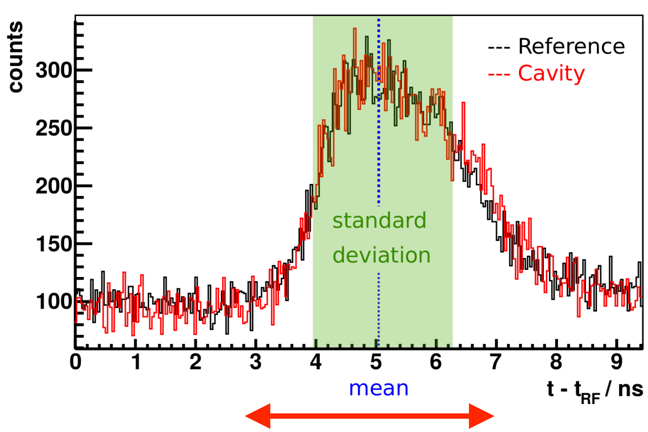
Accelerator

D) RF Oscillation

- Up/down regulation of high voltage between layers

➤ leads to oscillating bunch phase

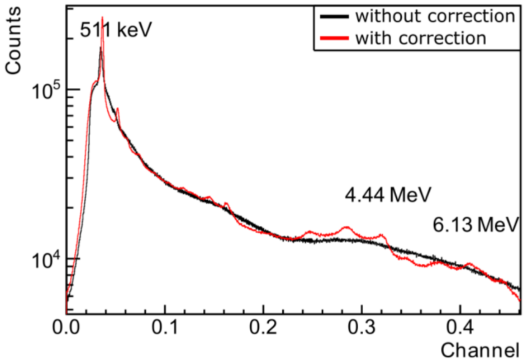




Solutions

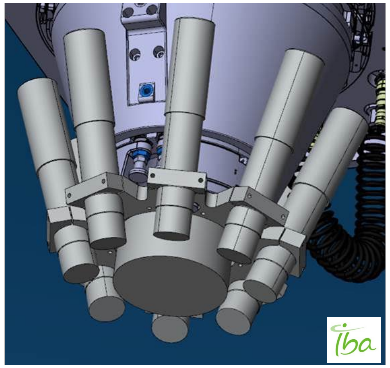
A) Load variations

- Track 511 keV line for event-wise correction function



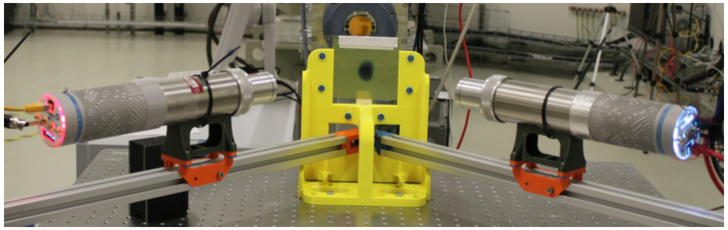
B) Statistics

- Use multiple detectors for treatment monitoring



C,D) Bunch drift and accelerator RF oscillation

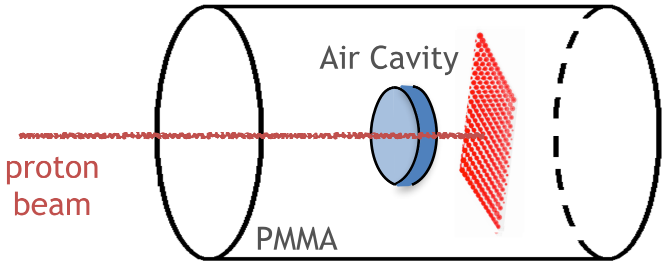
- Use proton bunch monitor to detect the bunch phase

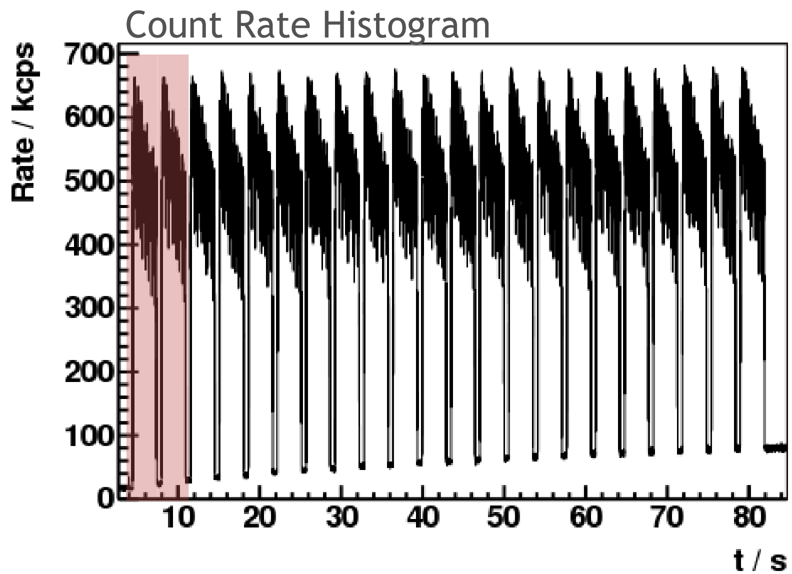


Experimental Results

Pencil Beam Scanning

- 22 x distal layer of so called "Dose Cube Plan"
- 1 Gy per Plan
- 500 kcps detector throughput





Local Range Shifts

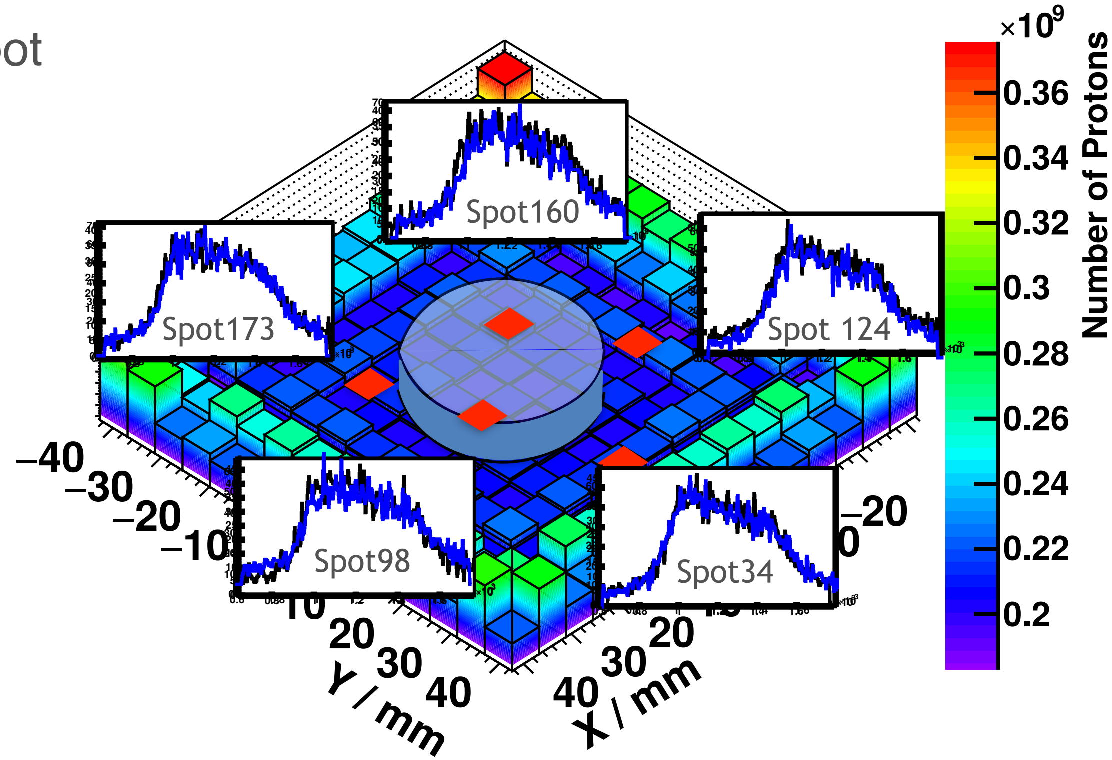
Spot-wise analysis of distal layer

- 1 Gy PBS plan
- about 2.2 x 10^8 protons per spot
- PGT spectra per Spot
  ➤ Mean μ and standard deviation σ

- Measure for range shift

$\Delta\mu_{Spot} = (\mu_{Ref} - \mu_{Cav})$

$\Delta\sigma_{Spot} = (\sigma_{Ref} - \sigma_{Cav})$



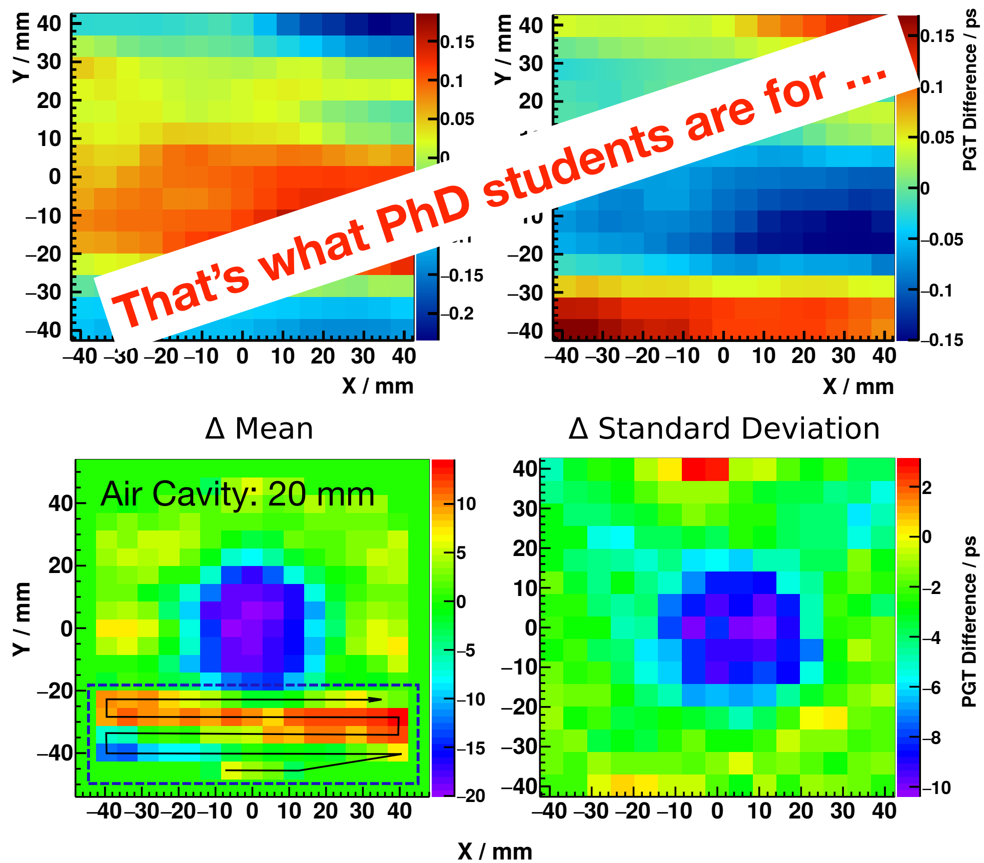
Imaging of Local Range Shifts

Data without corrections

- Raw data

Data with corrections

- Gain correction
- Energy cut (3-5MeV)
- PGT cut
- Statistic of 2 detectors (22 Layer)
- Without bunch monitor



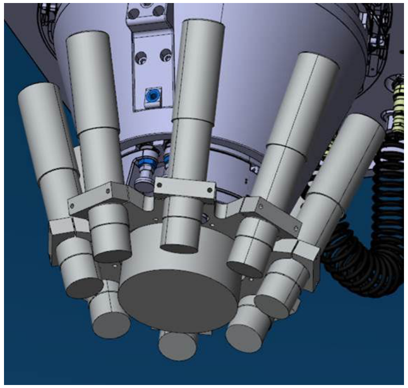
Conclusion

- PGT tested under treatment conditions
- PBS treatment plan structure retrievable
- Global and local range shifts detectable
- 20 mm to 5 mm shifts detectable for a 1 Gy plan with 6 detectors

Next Steps

- PGT snout for defined detector reproducibility
- Clinical trials of PGT

Sketch of PGT snout



L. Koffel

Thank you