IN VIVO IMAGING

PROTON BEAM RANGE VERIFICATION WITH PET/CT

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Siemens Medical Solutions Supports This Project

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HARVARD MEDICAL SCHOOL

UNIVERSITY OF HEIDELBERG

MOTIVATION

METHOD → GOAL

RESULTS → PHANTOM
~~PA~~TIENTS

OUTLOOK

CONCLUSION

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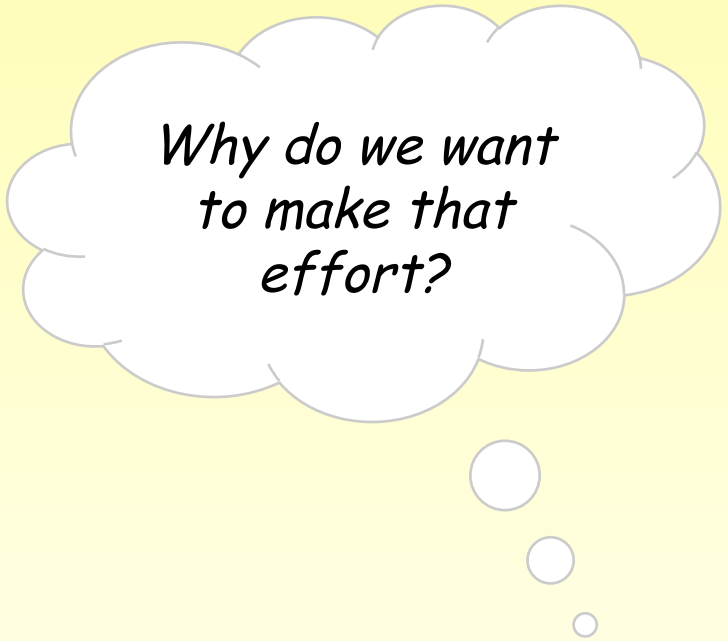
OUTLOOK

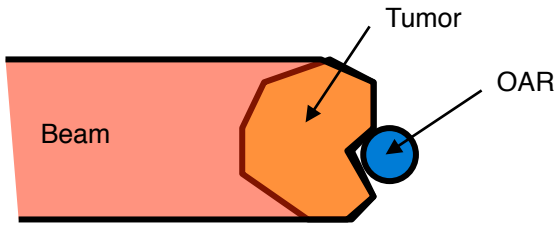
CONCLUSION

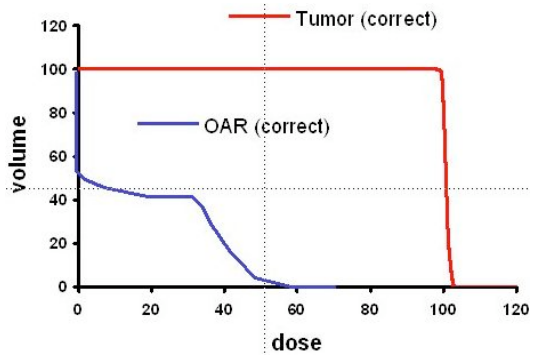


MOTIVATION

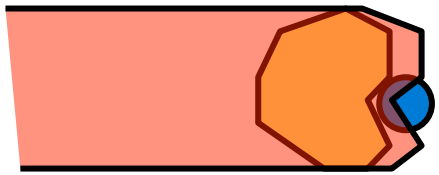
- **Optimal treatment**

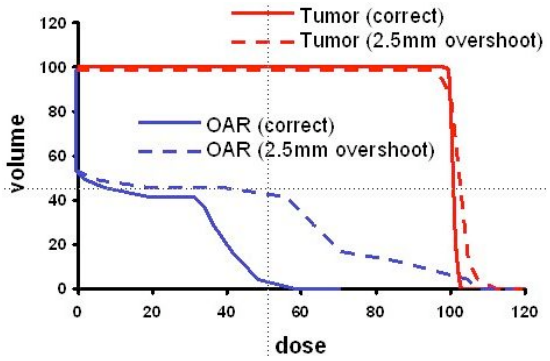
  Protons have the superior advantage of a finite range,





  but uncertainties compromise this advantage.

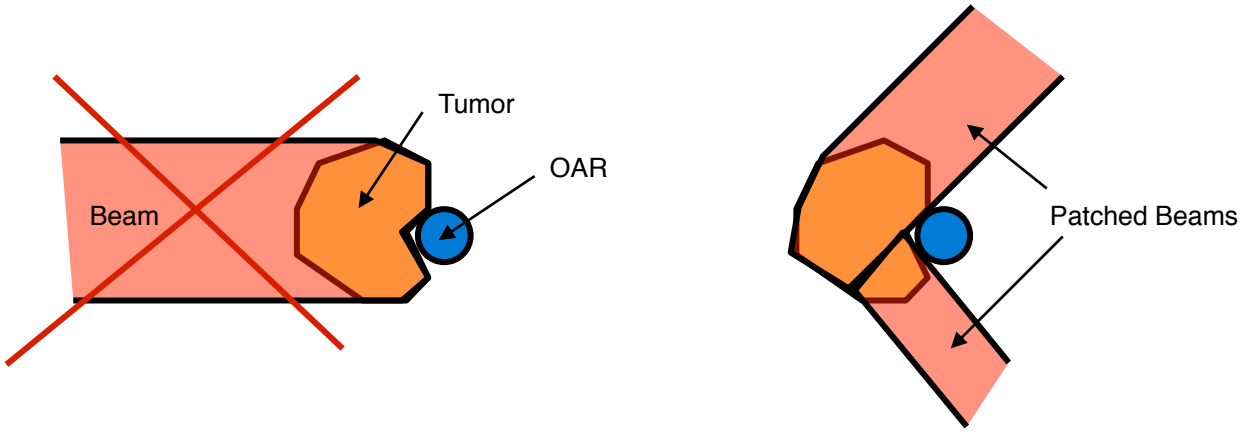




MOTIVATION

- **Optimal treatment**

  Since we often don't know the uncertainties we often don't apply the optimal treatment.



Uncertainties can be up to 10 mm. To take full advantage of the superior characteristics of proton beams mm-accurate tools to monitor and control these uncertainties are needed.

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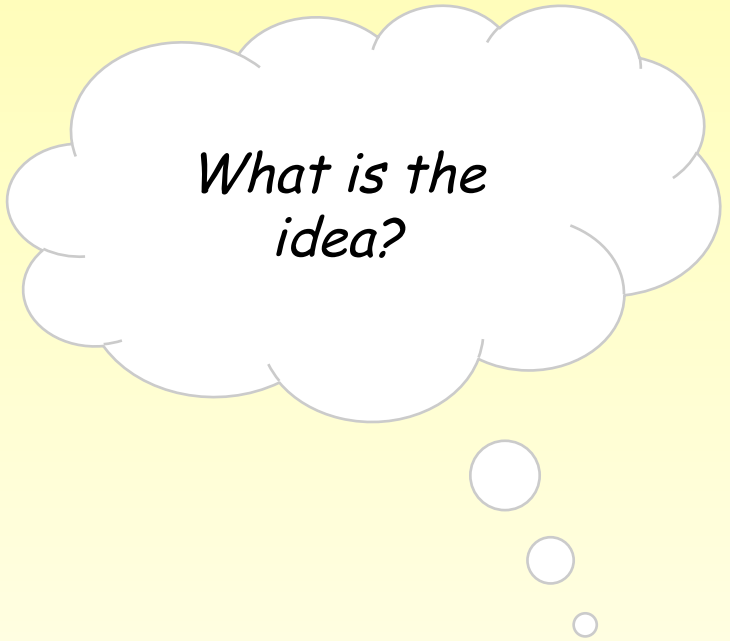
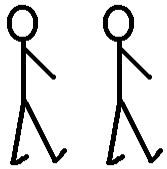


METHOD

- **Procedure**

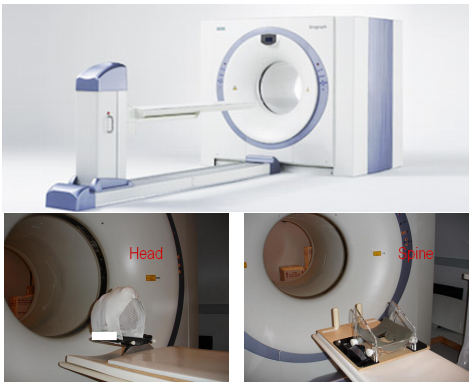
1.

Proton Treatment at the F. H. Burr Proton Therapy Center



2.

Walk the patient to the PET/CT scanner



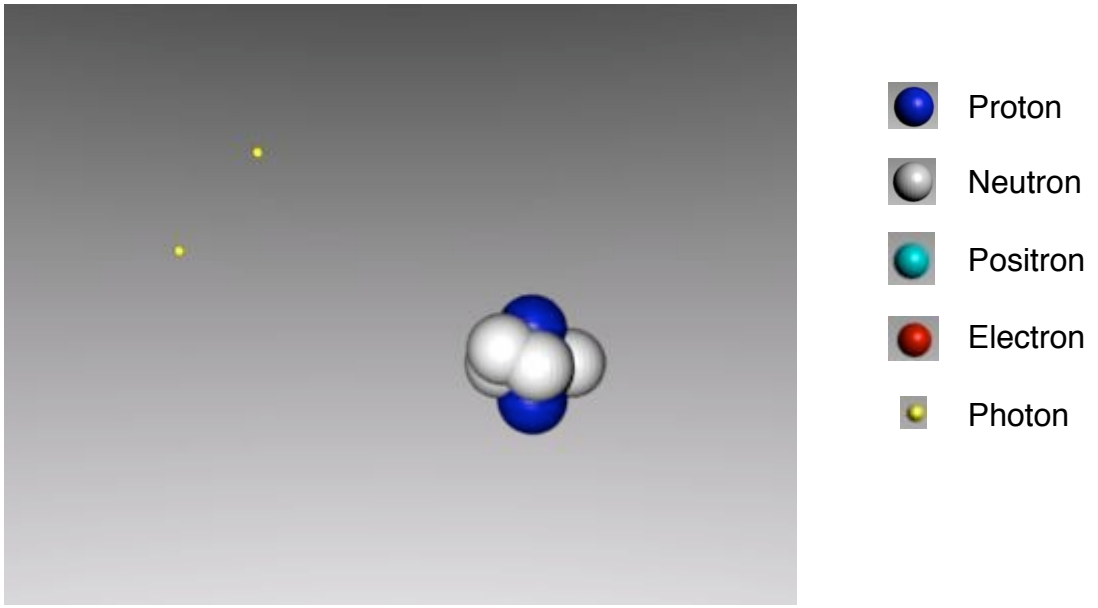
3.

PET/CT scan at a Siemens Biograph 64 PET/CT scanner

METHOD

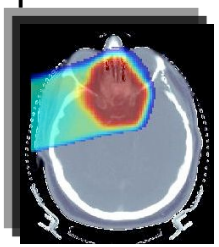
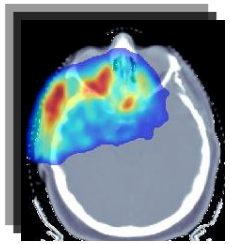
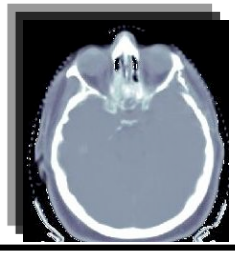
- **Nuclear reactions**

  In this approach we do not use any radioactive tracers but positron emitters, which are produced as a by-product of irradiation with protons.



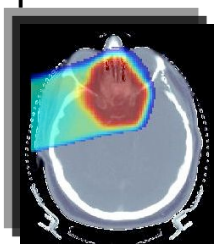
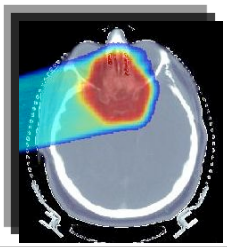
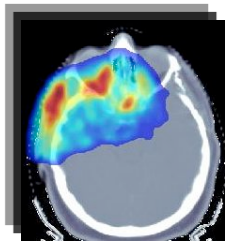
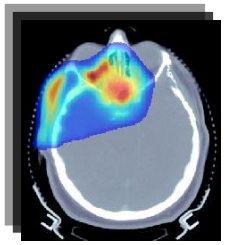
METHOD

- **Data**

DOSE	planned Dose 	
PET ACTIVITY	measured PET  - dyn. - FB - IT	
CT	planning CT 	PET CT 

METHOD

- **Data**

DOSE	planned Dose 	MC Dose 
PET ACTIVITY	measured PET  - dyn. - FB - IT	MC PET 
CT	planning CT 	PET CT 

The detailed simulations of the PET signal are based on Geant4 and FLUKA Monte Carlo (MC) code.

MOTIVATION

METHOD → GOAL

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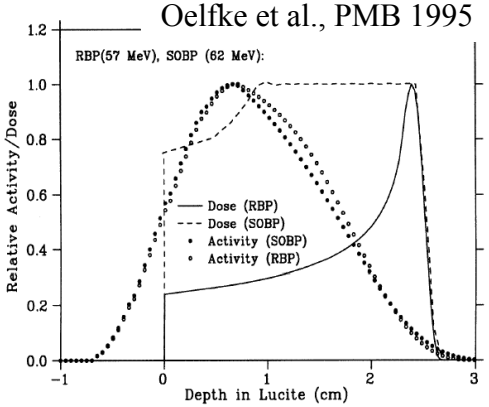
What do we want to achieve with this data?

GOAL

Dose verification

- difficult because:
  - no unique correlation between dose and activity distribution
  - patient and tissue specific activity wash-out

Oelfke et al., PMB 1995



GOAL

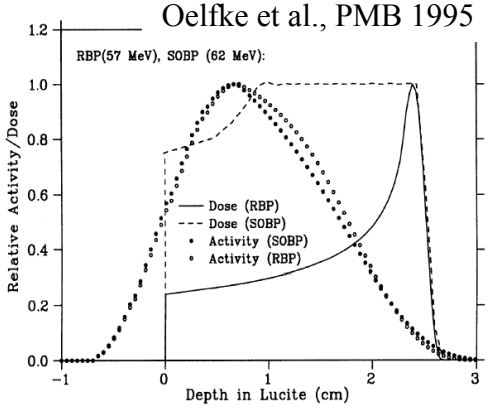
Dose verification

- difficult because:
  - no unique correlation between dose and activity distribution
  - patient and tissue specific activity wash-out

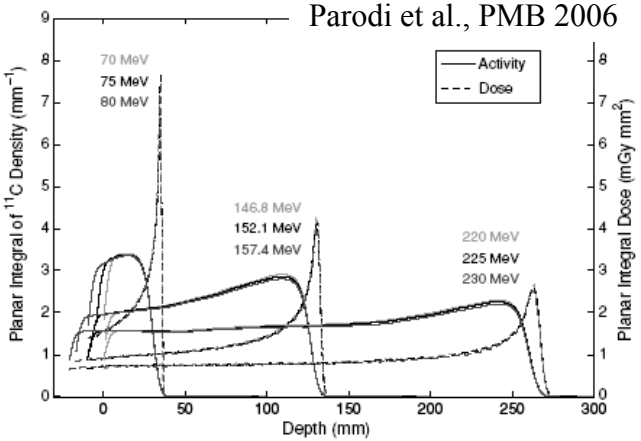
Range verification

- promising because:
  - unique correlation between dose and activity range
  - robust range determination through gradient analysis

Oelfke et al., PMB 1995

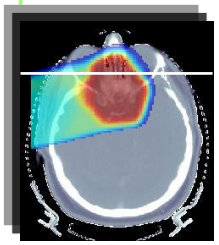
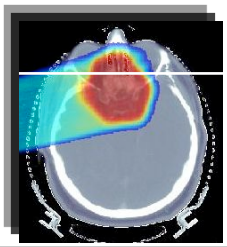
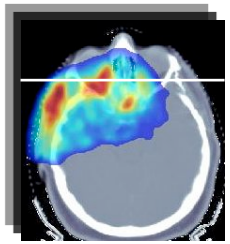
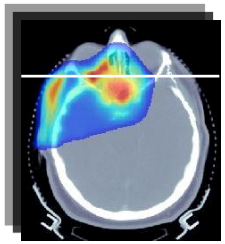
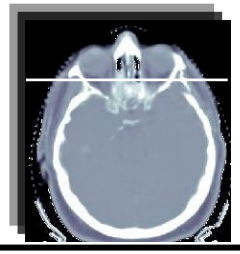


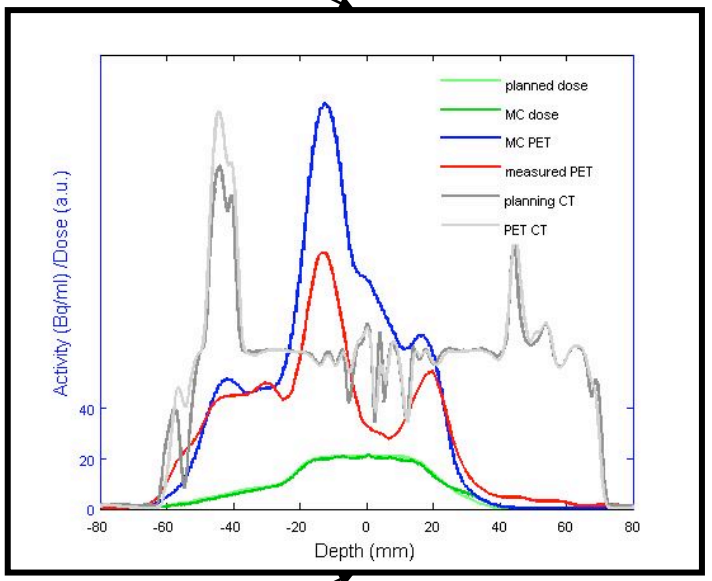
Parodi et al., PMB 2006



GOAL

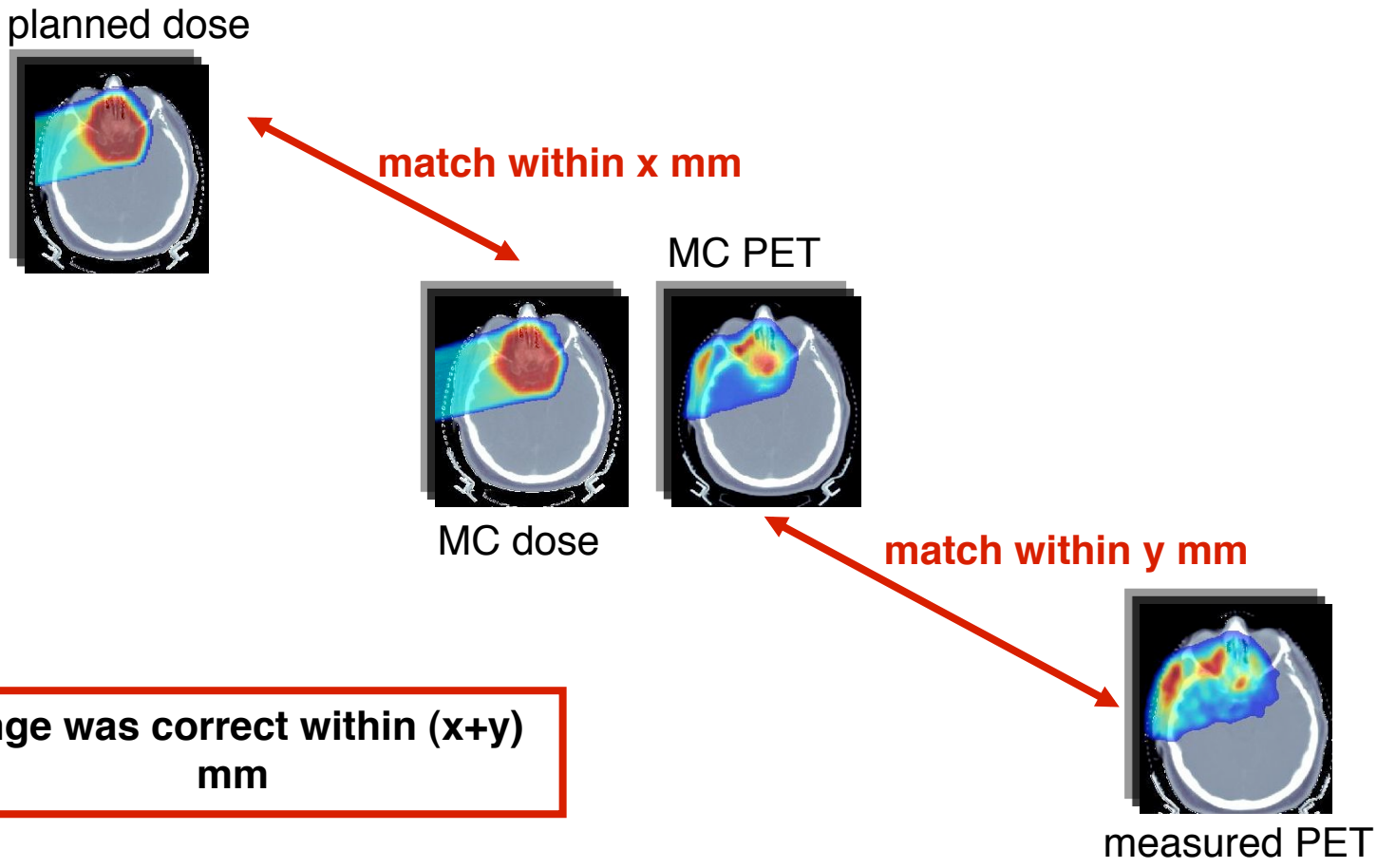
- **Range verification**

DOSE	planned Dose 	MC Dose 
PET ACTIVITY	measured PET  - dyn. - FB - IT	MC PET 
CT	planning CT 	PET CT 



GOAL

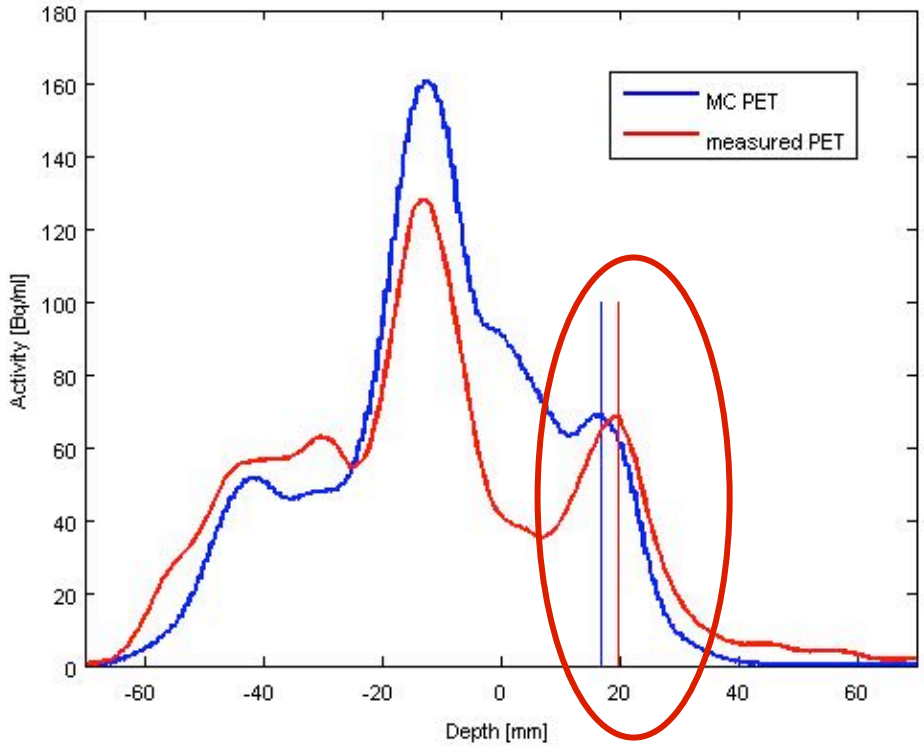
- **Range verification**



range was correct within (x+y) mm

GOAL

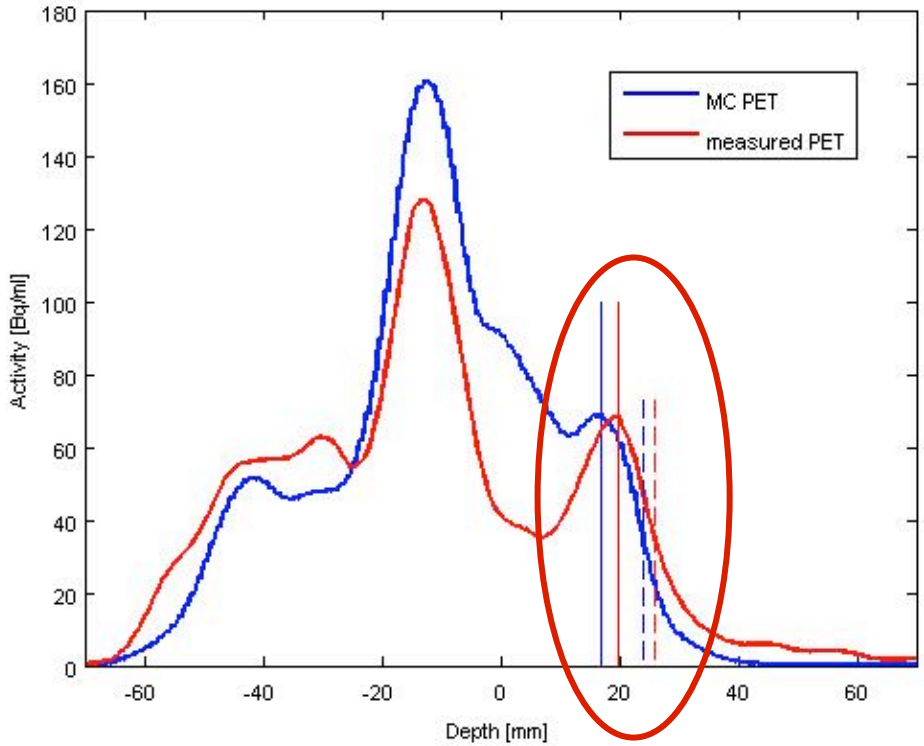
- **Range verification**



normalize

GOAL

- **Range verification**



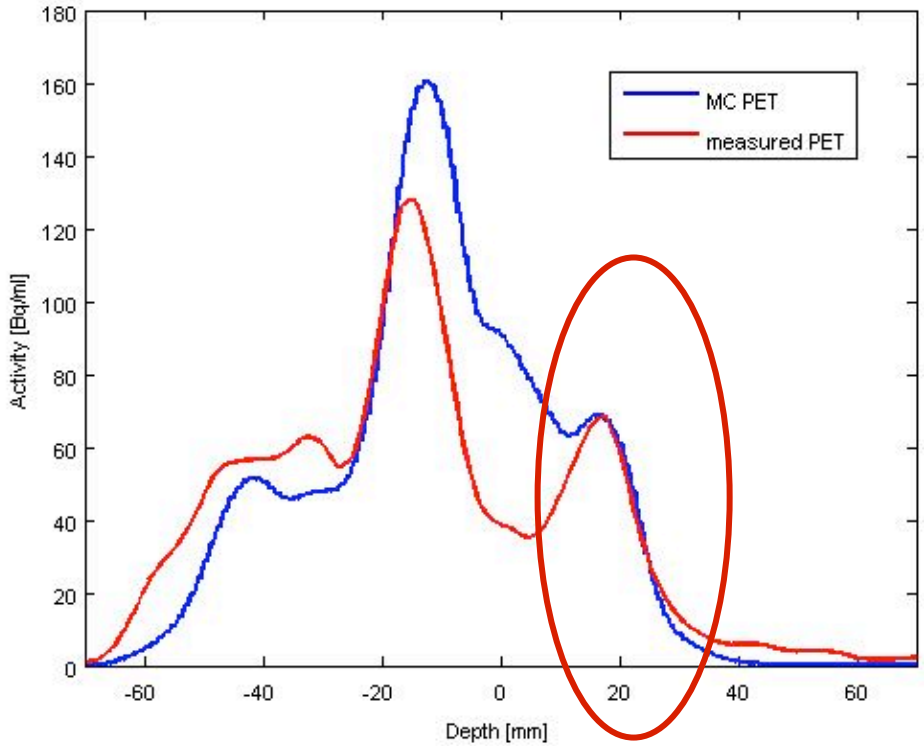
pointwise

20%: - sensitive to smoothing of MC profiles
- sensitive to back-ground noise

50%: - sensitive to noise in the data

GOAL

- **Range verification**



shift

more robust strategy for range verifications than a pointwise comparison

MOTIVATION

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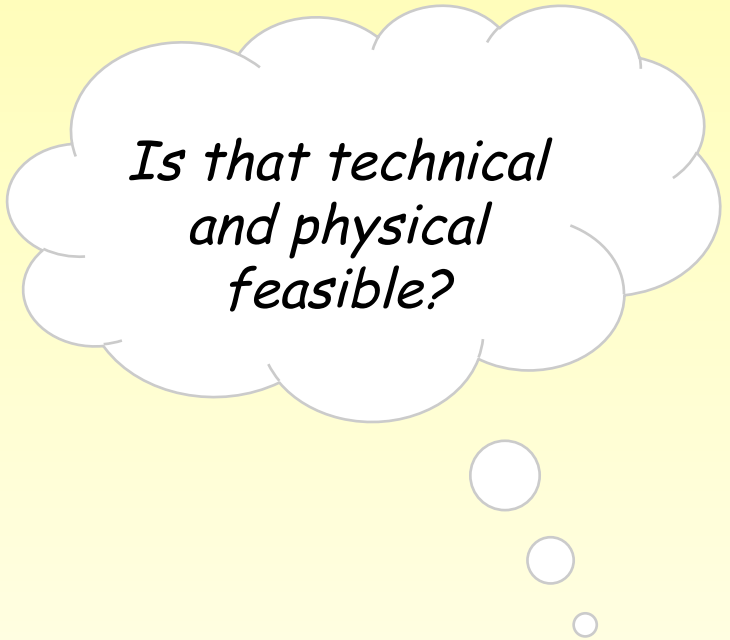
OUTLOOK

CONCLUSION



RESULTS

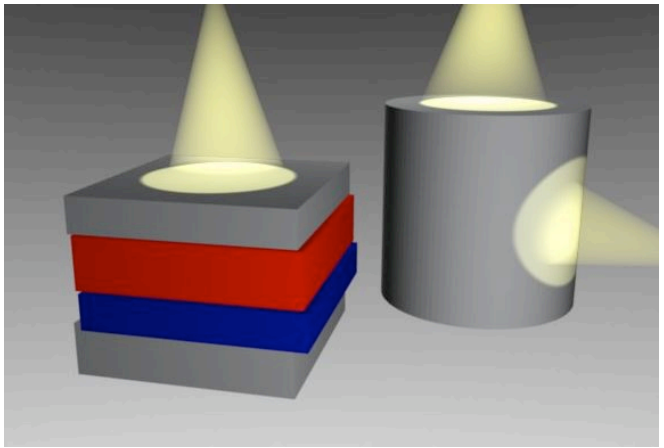
- **Phantom**

- **1.) Homogeneous phantom and simple slab phantom**

PMMA

bone equivalent

lung equivalent



Parodi et al "**PET/CT imaging for treatment verification after proton therapy- a study with plastic phantoms and metallic implants**", Medical Physics 2007: 34, 319-435

RESULTS

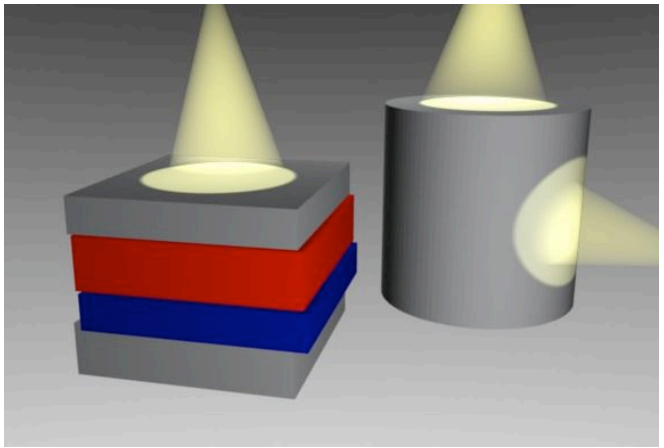
- **Phantom**

- **1.) Homogeneous phantom and simple slab phantom**

  Beam Parameter: Slab phantom: one field, 16cm range, 2Gy total dose
  Cylinder: two perpendicular fields, 15cm / 16cm range, 8Gy total dose

  To study: The composition and the total yield of activity that can be expected after a proton treatment

PMMA
bone equivalent
lung equivalent



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RESULTS

- **Phantom**

- **1.) Homogeneous phantom and simple slab phantom**

Results:

- Activity composition: Main fraction from ^{11}C, minor traces from ^{13}N and ^{15}O

- Imaging protocol: For a usual treatment fraction (1-3 Gy) and a delay of about 15 min between treatment and PET imaging 30 min of data acquisition should be sufficient for a mm accurate range monitoring.

Parodi et al "**PET/CT imaging for treatment verification after proton therapy- a study with plastic phantoms and metallic implants**", Medical Physics 2007: 34, 319-435

RESULTS

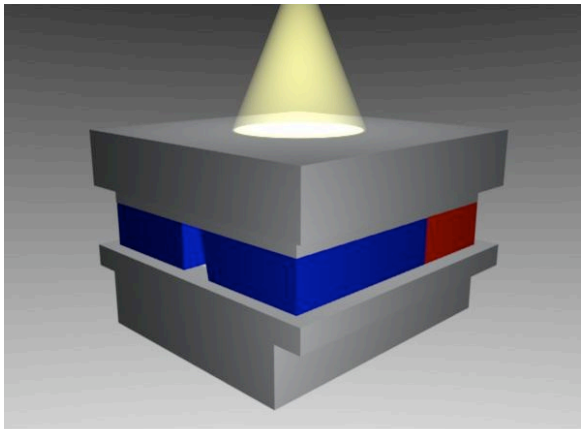
- **Phantom**

- **2.) Complex inhomogenous phantom with different angled tissue interfaces**

PMMA

bone equivalent

lung equivalent



Interfaces:

6° bone/air

0° bone/air

6° bone/lung

0° lung/air

6° lung/air

0° bone/lung

Knopf et al "**Quantitative assessment of the physical-potential of proton beam range verification with PET/CT**", submitted

RESULTS

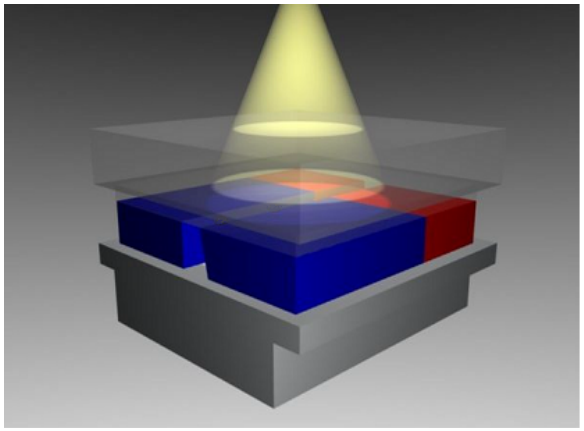
- **Phantom**

- **2.) Complex inhomogenous phantom with different angled tissue interfaces**

  Beam Parameters: One field, 15 cm range, 8 Gy total dose
  same routine as for patients was performed

  To study: The reproducibility of the method
  The consistency of the method
  The sensibility of the method

PMMA
bone equivalent
lung equivalent



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6° bone/air
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RESULTS

- **Phantom**

- **2.) Complex inhomogenous phantom with different angled tissue interfaces**

  Results:

  - Physical feasibilities: Reproducibility of range values within 1mm standard deviation

    Consistent range determination within 1 mm standard deviation

    PET measurements are sensitive enough to detect millimeter range changes induced by small tissue inhomogeneities.

Knopf et al "**Quantitative assessment of the physical-potential of proton beam range verification with PET/CT**", submitted

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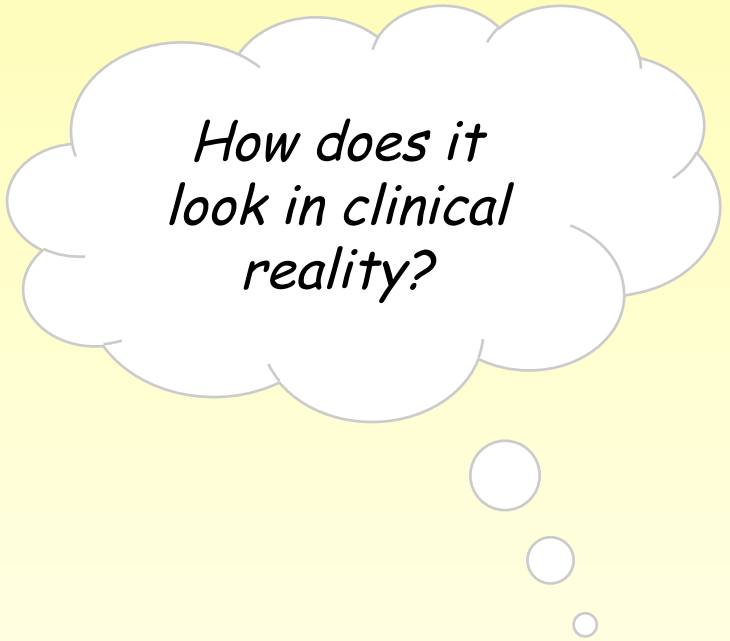
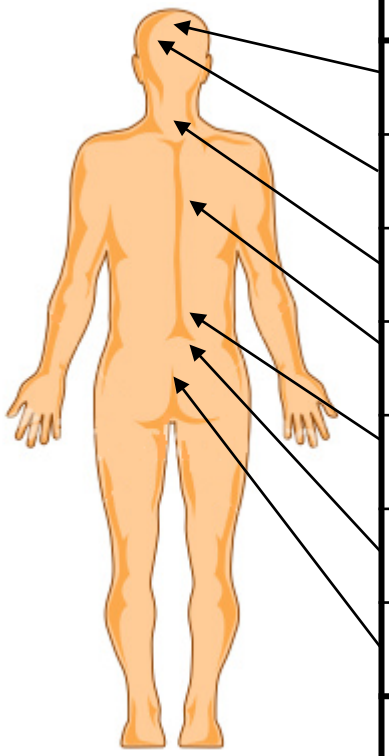


RESULTS

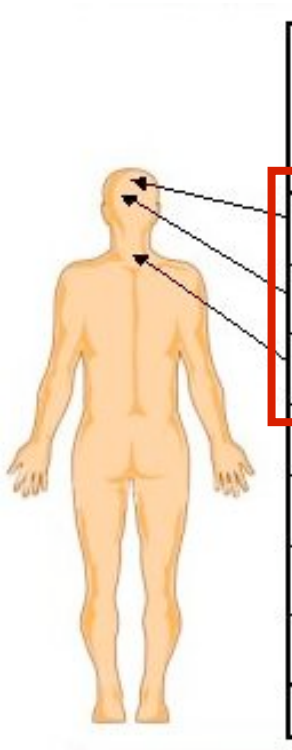
- **Patients**



	# of patients	# of patients that received 1 field	# of patients that received 2 fields	dose per field [GyE]
head	11	3	8	0.9-3
eye	1	1		10
C-spine	1		1	1
T-spine	2		2	0.6-1.8
L-spine	2	2		2
sacrum	2	1	1	1-2
prostate	2	2		2
TOTAL	**21**	**9**	**12**	**0.6-10**

RESULTS

- **Patients**
- **1.) Head and neck tumor sites**



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Parodi et al "**Patient study on in–vivo verification of beam delivery and range using PET/CT imaging after proton therapy**" Int. Journal of Radiation Oncology, Biology, Physics 2007

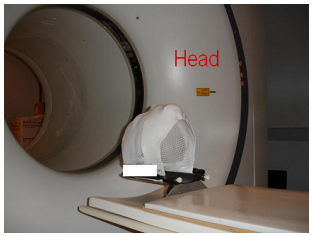
RESULTS

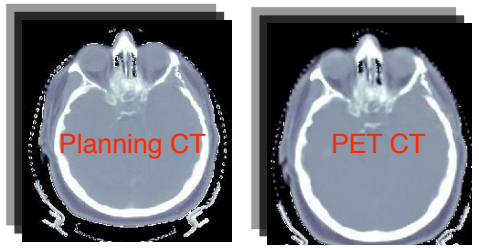
- **Patients**

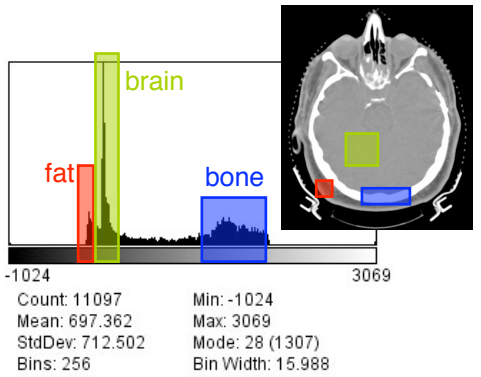
- **1.) Head and neck tumor sites**
  Advantages:
  - few patient motion
    -> the same immobilization as during the treatment is used

  - rigid target geometry
    -> small differences in the positioning are taken into account by coregisting planning and PET CT

  - few different tissues
    -> tissues can be resolved by means of CT numbers
    -> tissue specific elemental compositions and biol. washout parameters can be assigned in the simulation







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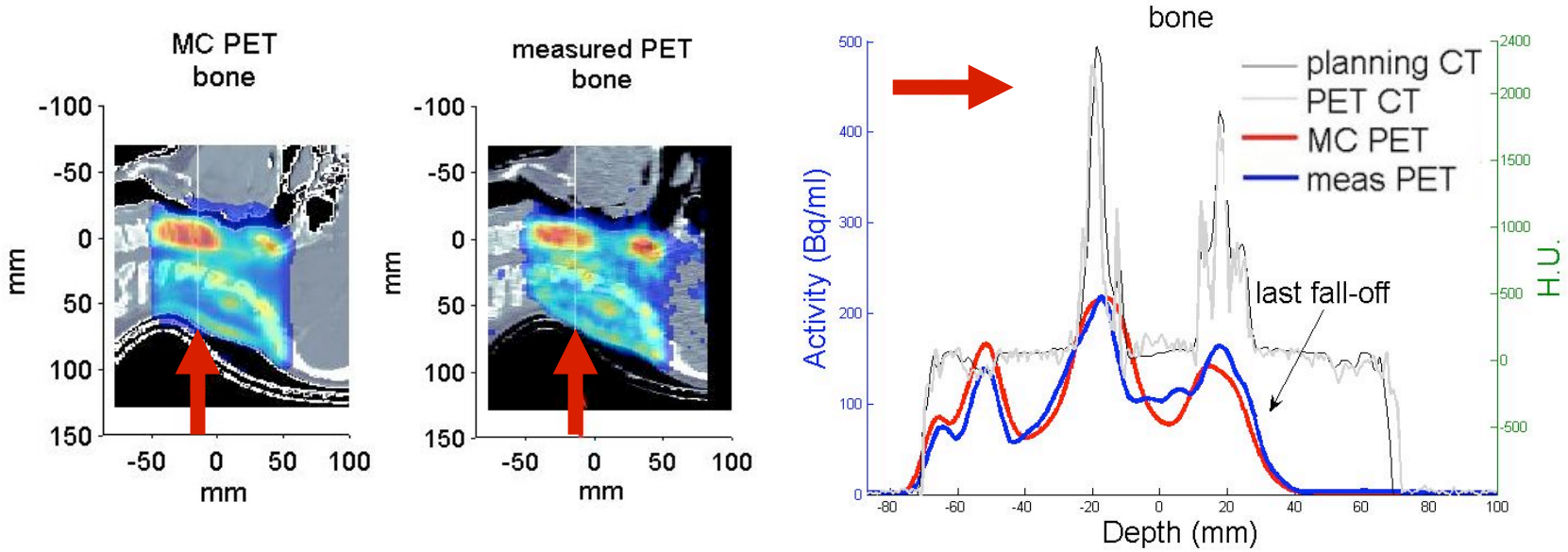
RESULTS

- **Patients**

- **1.) Head and neck tumor sites**
  Data analysis:
  - At positions where the beam stopped in bone

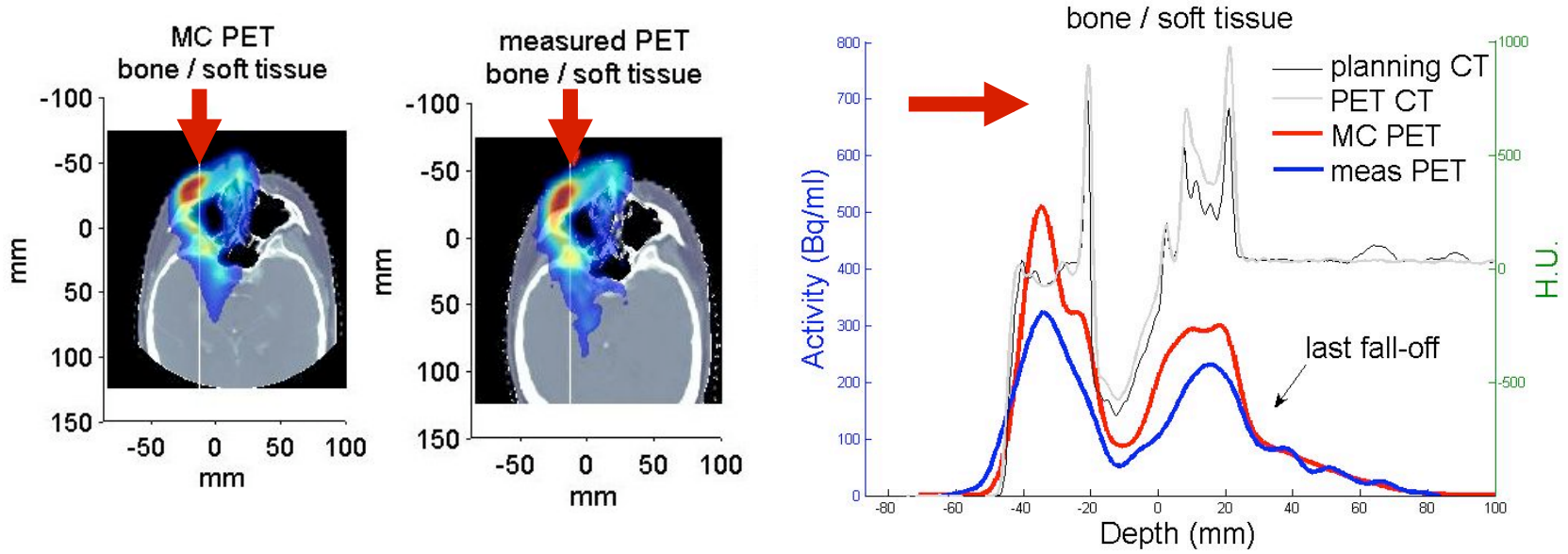


Parodi et al "**Patient study on in–vivo verification of beam delivery and range using PET/CT imaging after proton therapy**" Int. Journal of Radiation Oncology, Biology, Physics 2007

RESULTS

- **Patients**

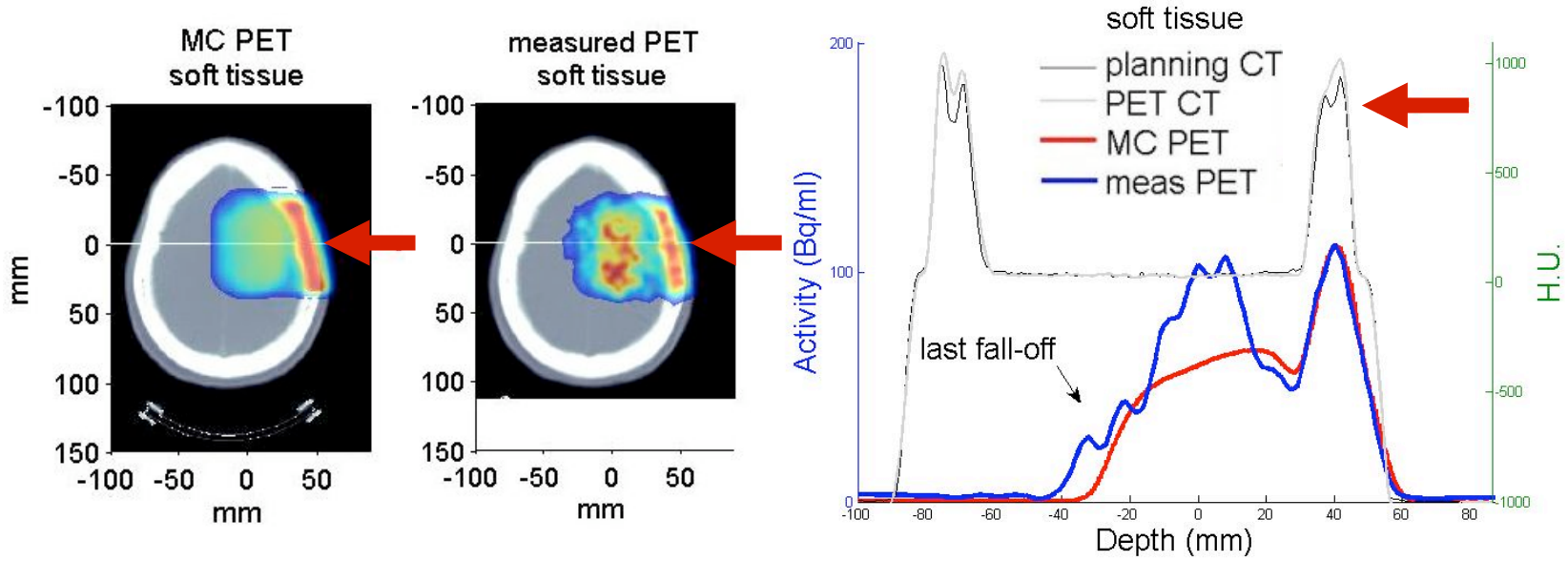
- **1.) Head and neck tumor sites**
  Data analysis:
  - At positions where the beam stopped shortly behind in bone



Parodi et al "**Patient study on in–vivo verification of beam delivery and range using PET/CT imaging after proton therapy**" Int. Journal of Radiation Oncology, Biology, Physics 2007

RESULTS

- **Patients**
- **1.) Head and neck tumor sites**
  Data analysis:
  - At positions where the beam stopped in soft tissue



Parodi et al "**Patient study on in–vivo verification of beam delivery and range using PET/CT imaging after proton therapy**" Int. Journal of Radiation Oncology, Biology, Physics 2007

RESULTS

- **Patients**

- **1.) Head and neck tumor sites**

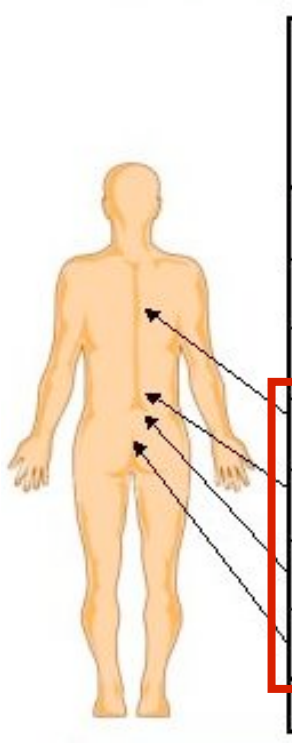
Results:

	Number of profiles	Mean agreement between measured and simulated range [mm]		
		pointwise verification		shift verification
		20 %	50%	
Bone	25	2.5	1.2	2.4
Bone/soft tissue	15	3.8	8.6	2.4
Soft tissue	30	6.8	3.9	4.3

- In soft tissue biological washout effects degrade the measured activity distribution and therefore prevent mm-accurate offline PET/CT range verification.
- **However offline PET/CT scans permit mm-accurate range verification in well-coregistered bony structures.**

RESULTS

- **Patients**
- **2.) Abdominopelvic tumor sites**

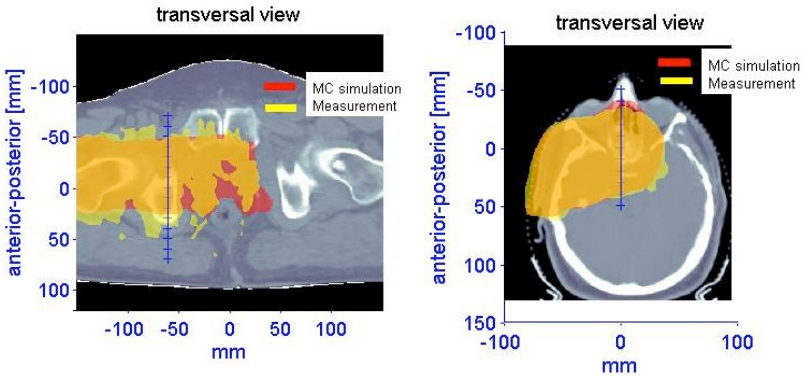


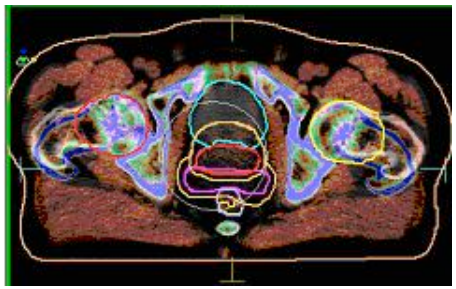
	# of patients	# of patients that received 1 field	# of patients that received 2 fields	dose per field [GyE]
head	11	3	8	0.9-3
eye	1	1		10
C-spine	1		1	1
T-spine	2		2	0.6-1.8
L-spine	2	2		2
sacrum	2	1	1	1-2
prostate	2	2		2
TOTAL	**21**	**9**	**12**	**0.6-10**

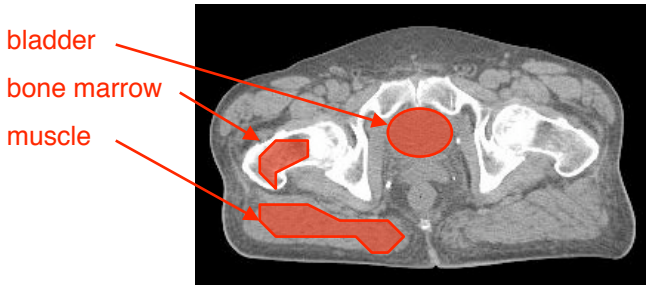
RESULTS

- **Patients**

- **2.) Abdominopelvic tumor sites**
  Challenges:
  - motion
    -> breathing and organ motion results in a blurring of the measured activity distribution
  - demanding positioning
  - complex tissue heterogeneities
    -> tissues like bladder, bone marrow and muscle with very different elemental compositions and washout characteristics can not be resolved by CT numbers



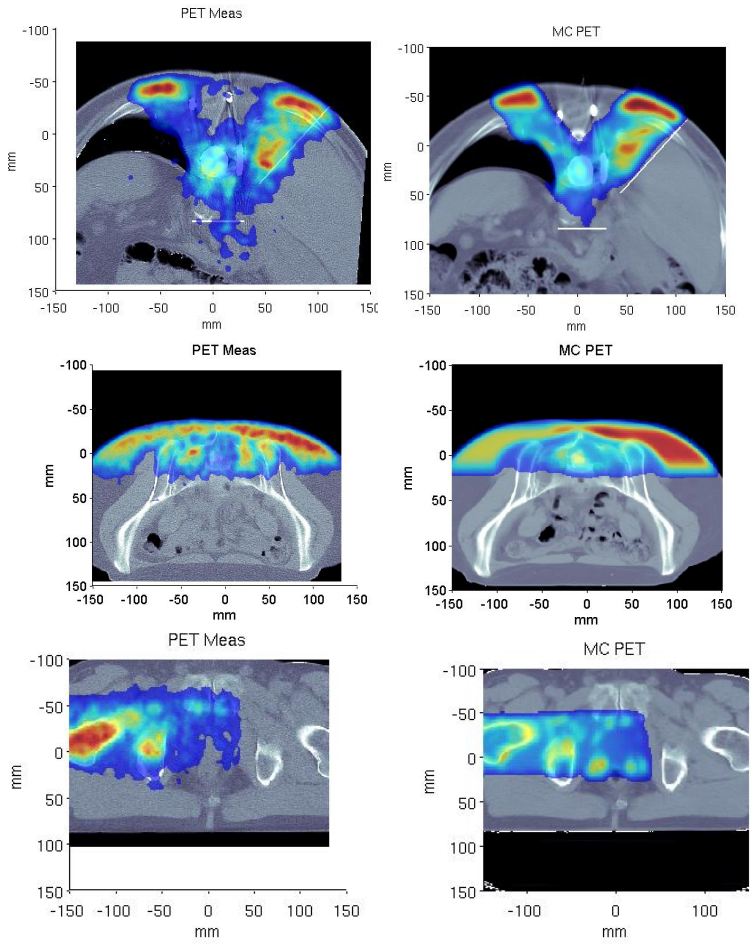




RESULTS

- **Patients**

- **2.) Abdominopelvic tumor sites**
  Challenges:
  - distal beam end in soft tissue
  - opposed beams
  - prostate patients need to void their bladder between treatment and imaging



RESULTS

- **Patients**

- **2.) Abdominopelvic tumor sites**

  Results:

  - for abdominal tumor sites, lateral blurring due to motion was fount to be up to 25mm where as the lateral conformity for head and neck tumor sides was within 5mm
  - For opposed treatment beams range verification was found to be not practicable.
  - **In abdominal tumor sites, mm-accurate offline PET/CT range verification is not feasible primarily due to patient motion and the position of the distal beam edge in soft tissue.**

MOTIVATION

METHOD → GOAL

RESULTS → PHANTOM
~~PA~~TIENTS

OUTLOOK

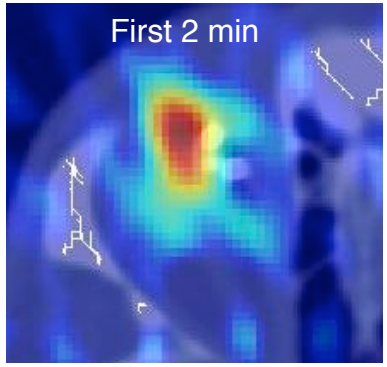
CONCLUSION

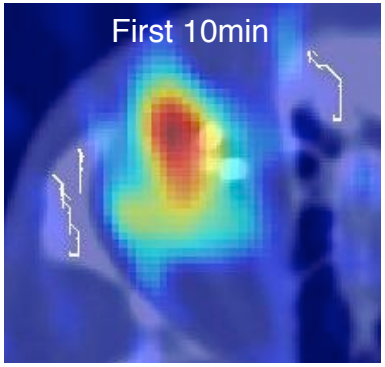
OUTLOOK

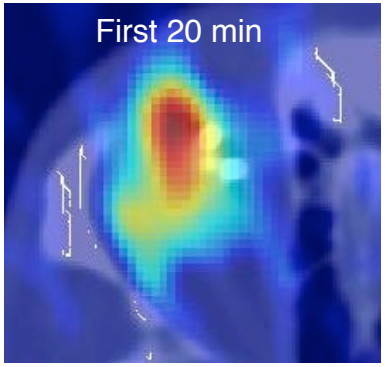
- **Better biological wash-out models**

  - scanning of high dose patients (>3Gy in a single session)
  - high dose translates into an enhanced positron emission
  - enables a time analysis of the PET distribution over the 30 min of data acquisition

Measured activity averaged over







➡ improved biological wash-out models

➡ estimate of the improvement of the image quality for an in room PET/CT scanner

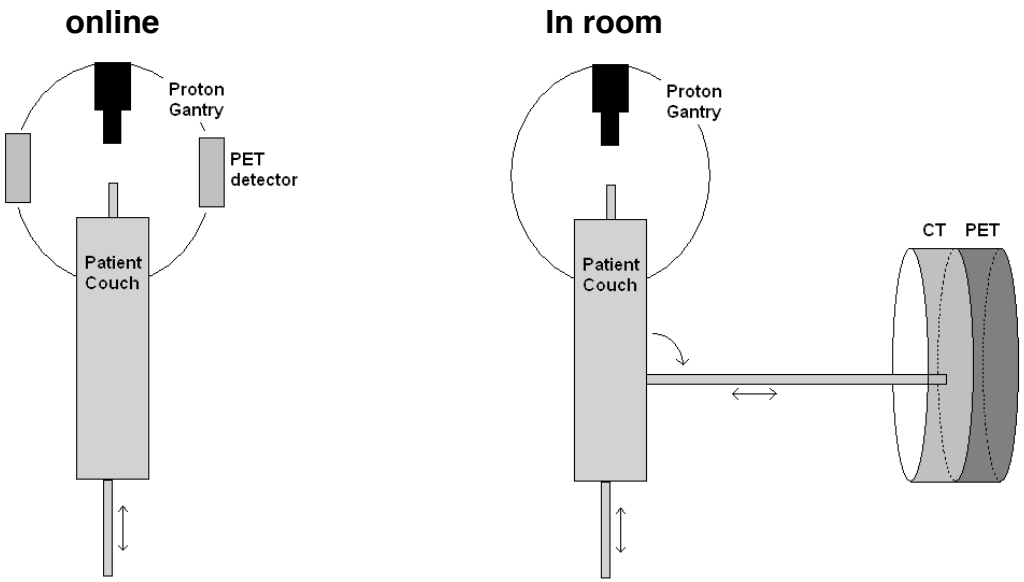
OUTLOOK

- **In room / online imaging**
  - Shorter / no delay between irradiation and PET imaging
  - Shorter data acquisition

⇒ less wash-out

⇒ better statistics

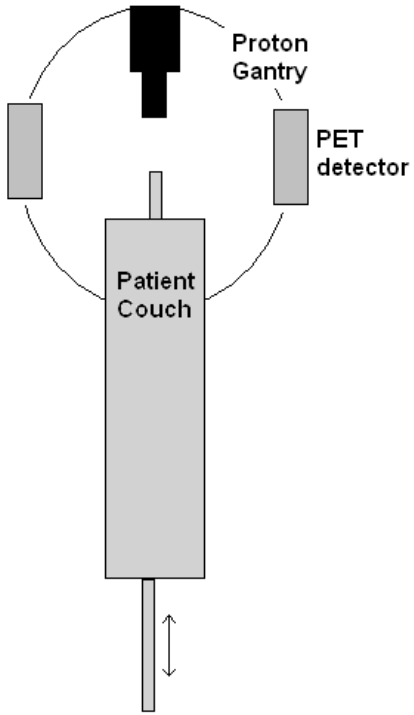
⇒ less motion



Parodi et al "**Comparison between in-beam and offline PET imaging of proton and carbon ion therapeutic irradiation at cyclotron and synchrotron-based facilities**, in press

OUTLOOK

- **In room / online imaging**
- **Online**



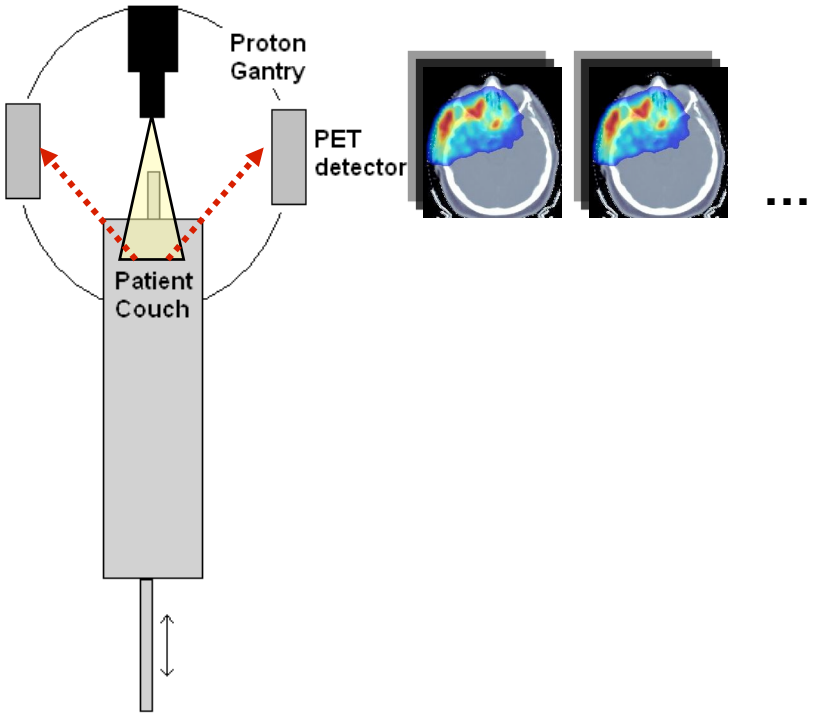
Parodi et al "**Comparison between in-beam and offline PET imaging of proton and carbon ion therapeutic irradiation at cyclotron and synchrotron-based facilities**, in press

OUTLOOK

- **In room / online imaging**
- **Online**

  - ⊕ **Minimal delay**

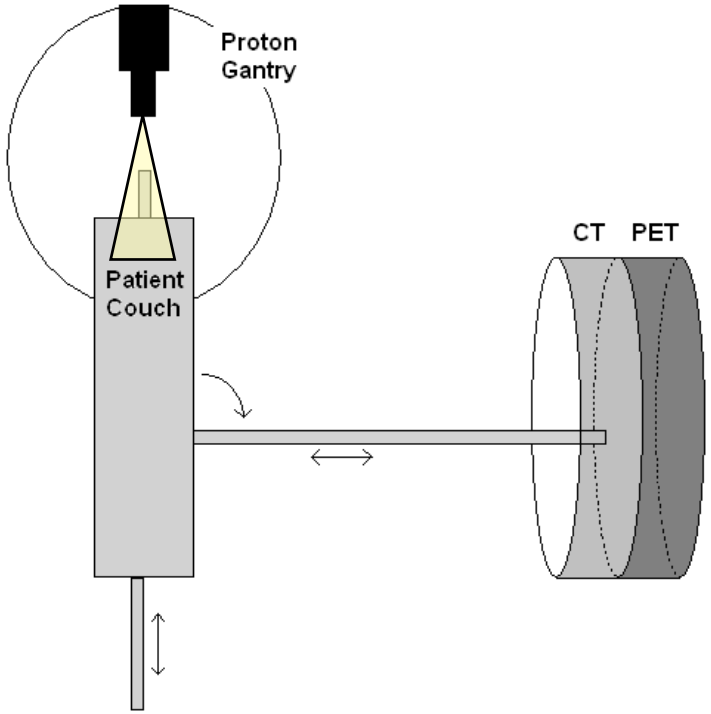
  - ⊖ Geometry compromises efficiency
  - ⊖ Detectors are exposed to scattered radiation
  - ⊖ Patient throughput is compromised



Parodi et al "**Comparison between in-beam and offline PET imaging of proton and carbon ion therapeutic irradiation at cyclotron and synchrotron-based facilities**, in press

OUTLOOK

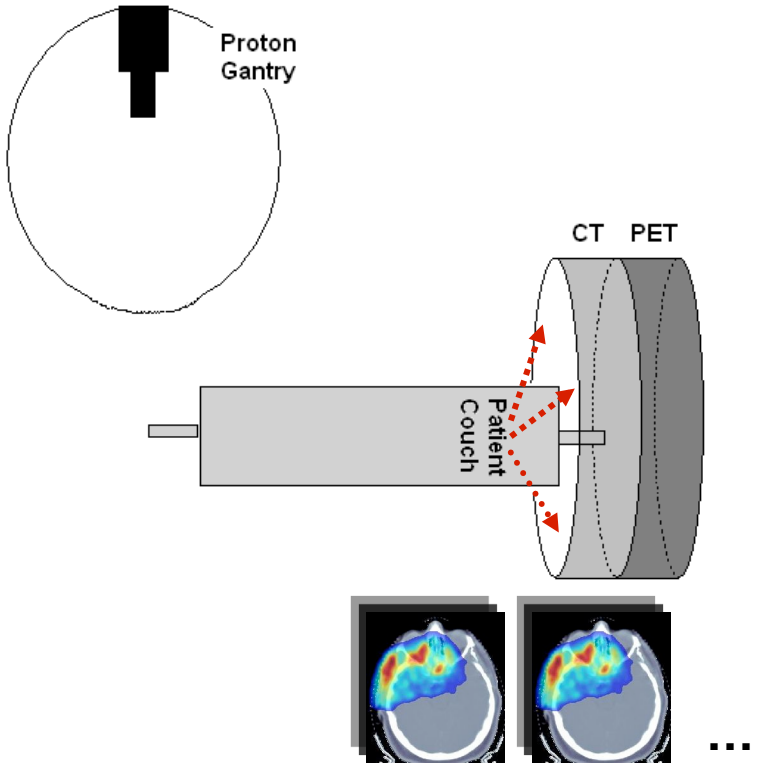
- **In room / online imaging**
- **In room**



Parodi et al "**Comparison between in-beam and offline PET imaging of proton and carbon ion therapeutic irradiation at cyclotron and synchrotron-based facilities**, in press

OUTLOOK

- **In room / online imaging**
- **In room**
  - ⊕ **Small delay**
  - ⊖ Patient throughput is compromised



Parodi et al "**Comparison between in-beam and offline PET imaging of proton and carbon ion therapeutic irradiation at cyclotron and synchrotron-based facilities**, in press

MOTIVATION

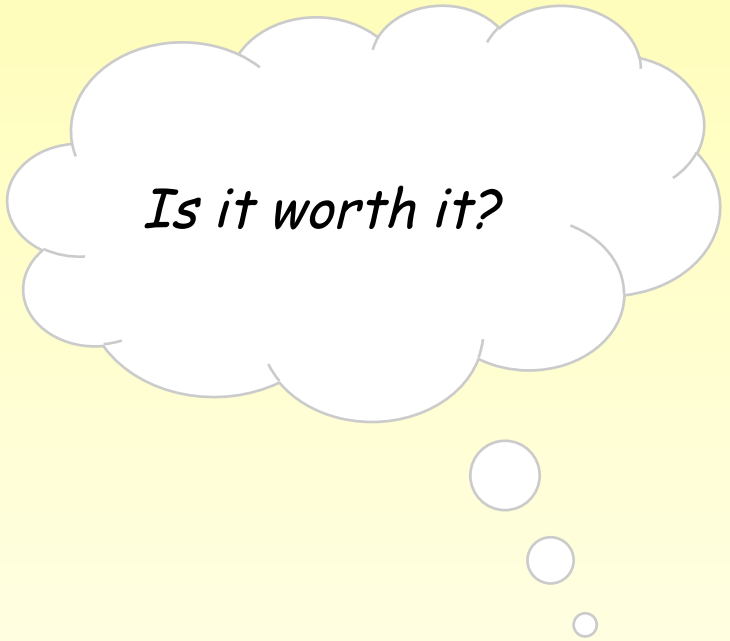
METHOD → GOAL

RESULTS → PHANTOM

~~PA~~TIENTS

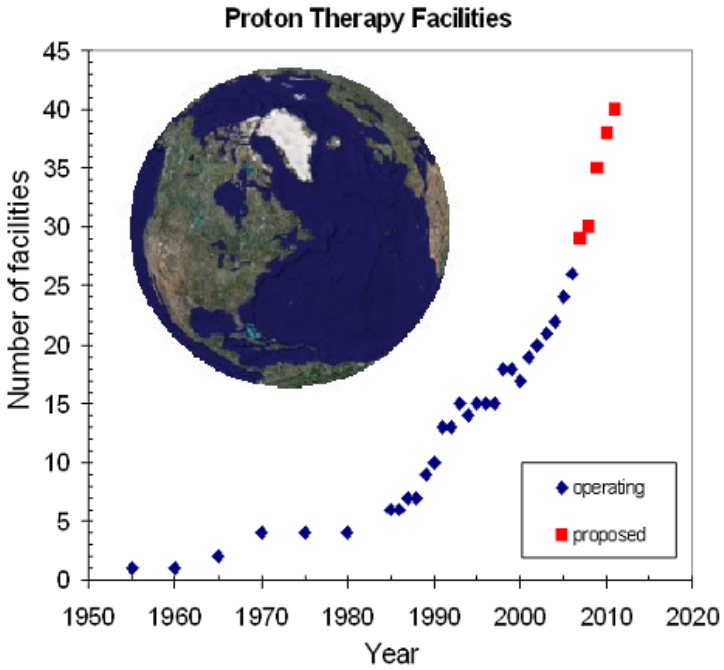
OUTLOOK

CONCLUSION



CONCLUSION

- **Proton Therapy seems to be the "standard" treatment of the future**



1993 **"Is it possible to verify directly a proton-treatment plan using positron emission tomography?"** UCL-Cliniques Universitaires St-Luc, Brussels, **Belgium**

1996 **"Proton dose monitoring with PET: quantitative studies in Lucite"** TRIUMF, Batho Biomedical Facility, Vancouver, **Canada**

2000 **"Potential application of PET in quality assurance of proton therapy"** Forschungszentrum Rossendorf, Dresden, **Germany**

2006 **"Dose-volume delivery guided proton therapy using beam on-line PET system"** National Cancer Center, Kashiwa, **Japan**

2007 **"Patient study of in vivo verification of beam delivery and range, using positron emission tomography and computed tomography imaging after proton therapy"** Department of Radiation Oncology, MGH, Boston, **USA**

2008 **"Experimental validation of the filtering approach for dose monitoring in proton therapy at low energy'** Department of Physics, University of Pisa, **Italy**

Thank you for your attention!