Medical Imaging
Experience from the Past 10 Years and State-of-the-Art

ENVISION General Meeting
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Institute of Radiation Physics

OncoRay
Radiation Research in Oncology

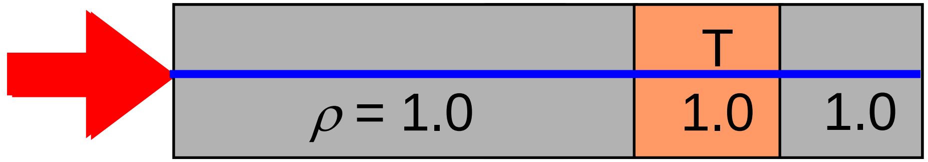
Outline

1. Imaging for hadron therapy quality assurance
2. Lessons learned from particle therapy PET
3. Towards a real-time in-vivo dosimetry

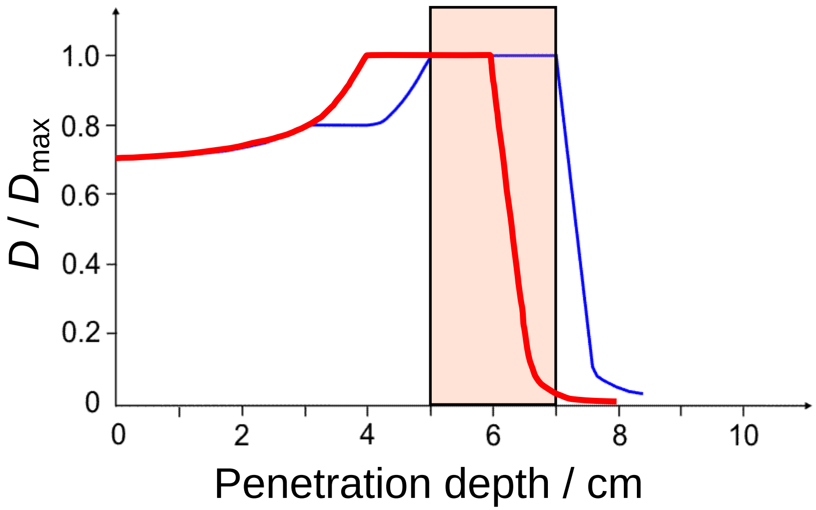
1. Imaging for hadron therapy quality assurance

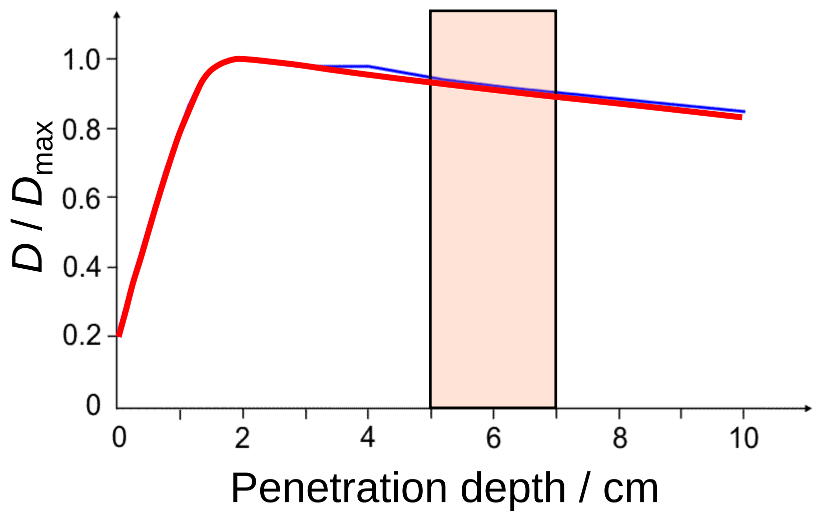
Dose delivery particularities in ion therapy (I)

Effect of density changes in the target volume



Ions





Photons

Similar effects for mispositioning or organ movement

1. Imaging for hadron therapy quality assurance

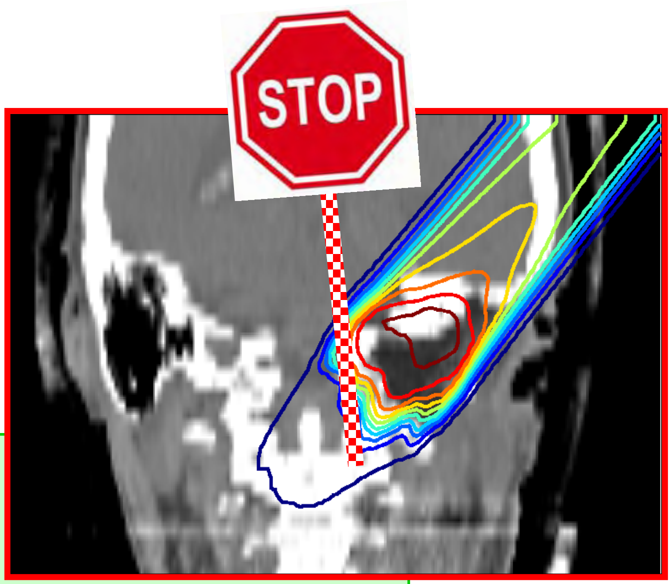
Dose delivery particularities in ion therapy (II)

The dose distribution deposited by ions is extremely sensitive to the ion range in vivo

The accuracy of the ion range is influenced by

(1) Systematic errors in the physical beam model used for treatment planning: $R = R(HU)$

(2) Random errors like
- mispositioning
- patient- or organ movement
- density changes within the irradiated volume
- treatment mistakes and accidents



Desirable: A procedure for the verification
- of the irradiation field position
- of the particle range
- simultaneous with the therapeutic irradiation

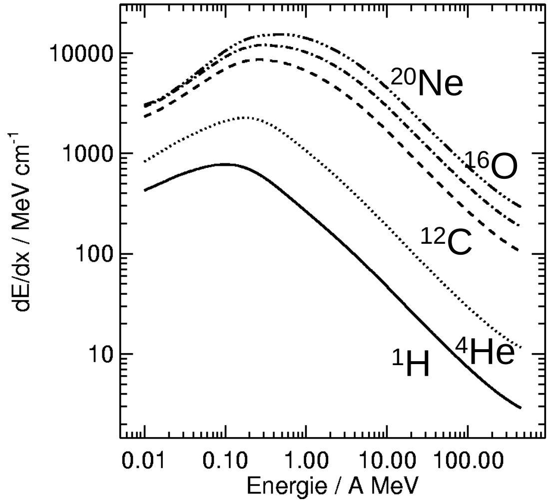
and, in particular a procedure for the quantification of the dose distribution
- in-situ
- in-vivo
- in real time.

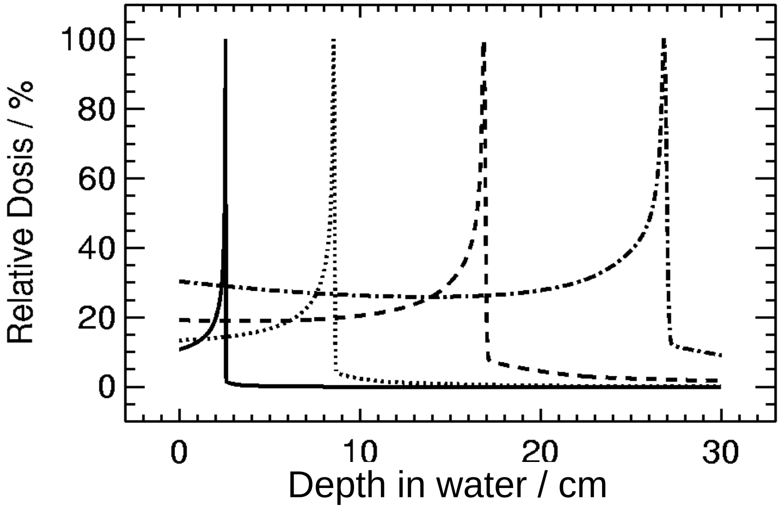
1. Imaging for hadron therapy quality assurance

The physical dilemma

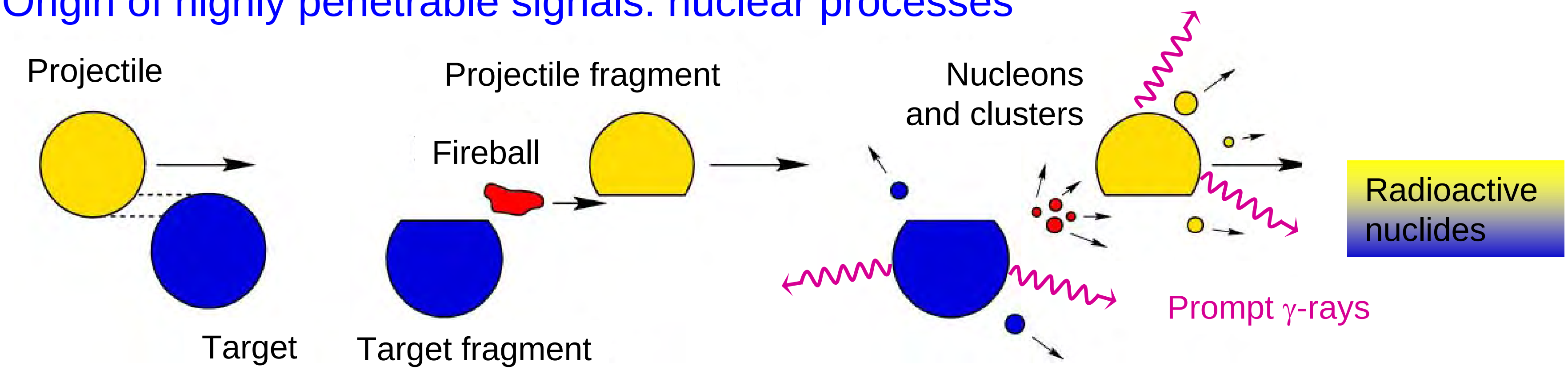
Dose deposition: electronic stopping of ions, i.e. atomic processes

$$-\left(\frac{dE_K}{dx}\right)_e = 2\pi\, N_A r_e^2 m_e c^2 \rho\, z^2 \frac{Z}{A}\frac{1}{\beta^2}\left[\ln\frac{2m_e c^2\beta^2\gamma^2 T_{\max}}{I^2} - 2\beta^2 - \delta - 2\frac{C}{Z}\right]$$





Origin of highly penetrable signals: nuclear processes

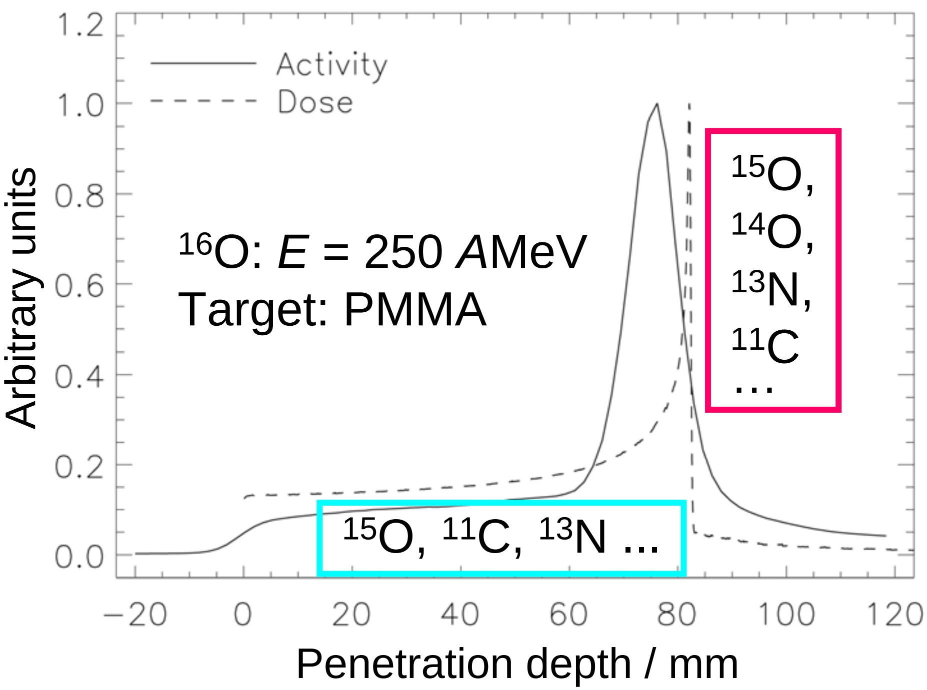


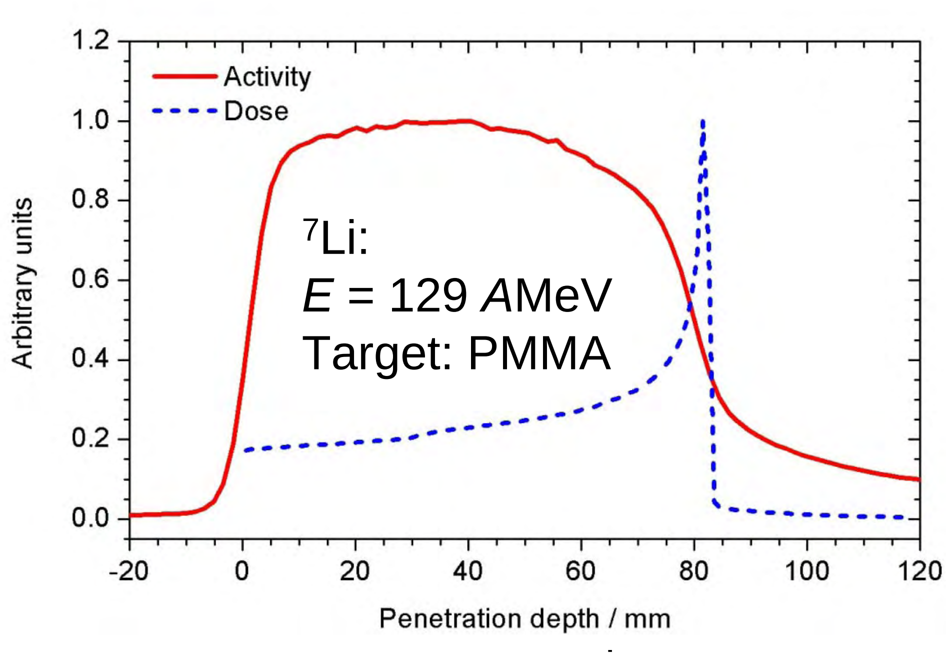
1. Imaging for hadron therapy quality assurance

The physical basis of PT-PET: Autoactivation

Peripheral nucleus-nucleus-collisions, nuclear reactions ($^{A}Z, xp, yn$), $\Delta \mathbf{p} \approx 0$

$Z \geq 6$ Projectile fragments | Target fragments $Z < 6$ Target fragments



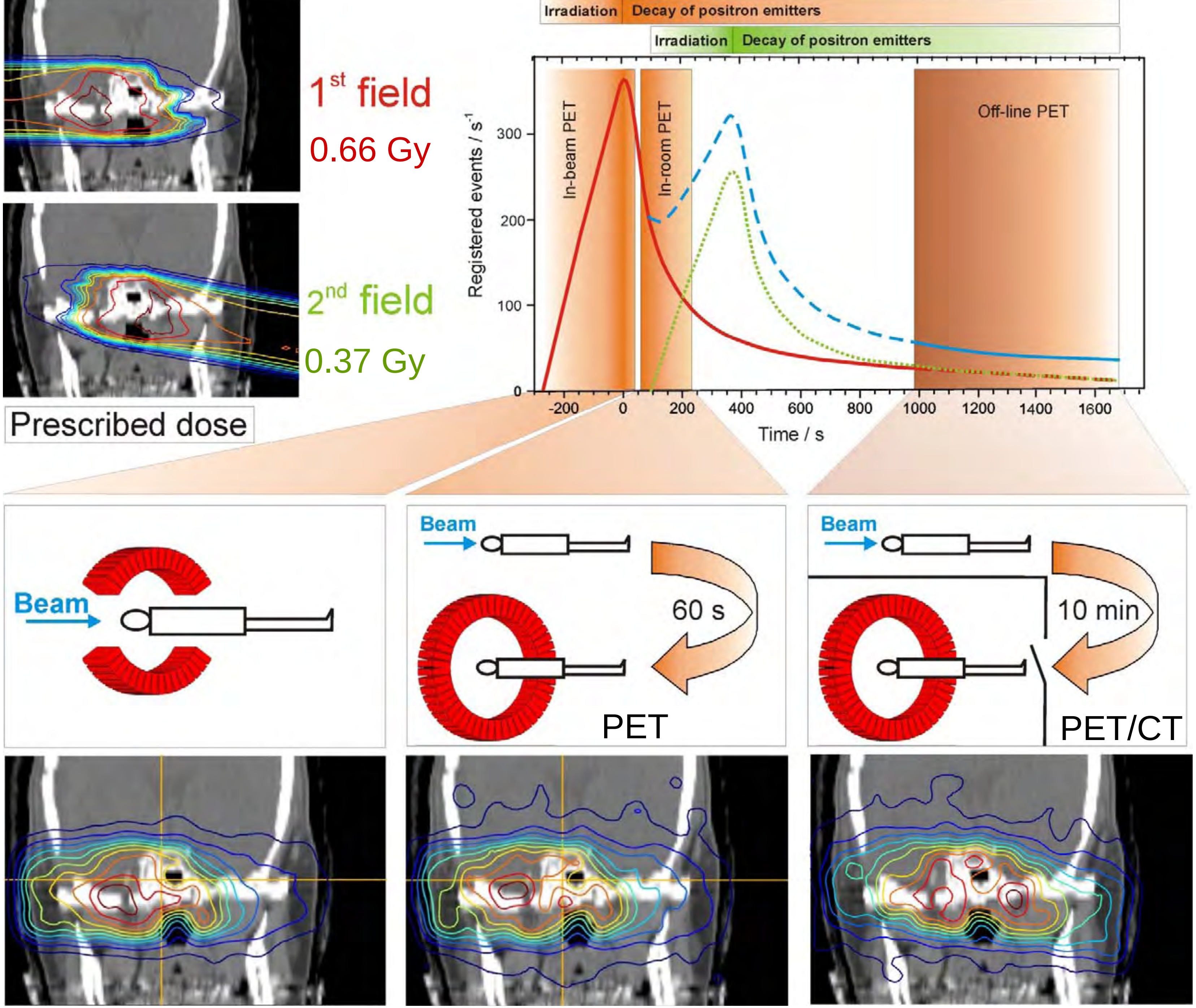


Therapy beam	^{1}H	^{3}He	^{7}Li	^{12}C	^{16}O	Nuclear medicine
Activity density / Bq cm^{-3} Gy^{-1}	6600	5300	3060	1600	1030	$10^{4} - 10^{5}$ Bq cm^{-3}

W. Enghardt et al.: Phys. Med. Biol. 37 (1992) 2127;
K. Parodi et al.: IEEE T. Nucl. Sci. 52 (2005) 778;
F. Sommerer et al.: Phys. Med. Biol. 54 (2009) 3979;
J. Pawelke et al.: IEEE T. Nucl. Sci. 44 (1997) 1492;
F. Fiedler et. al.: IEEE T. Nucl. Sci., 53 (2006) 2252;
M. Priegnitz et al.: Phys. Med. Biol. 53 (2008) 4443

1. Imaging for hadron therapy quality assurance

In-beam, in-room, off-line



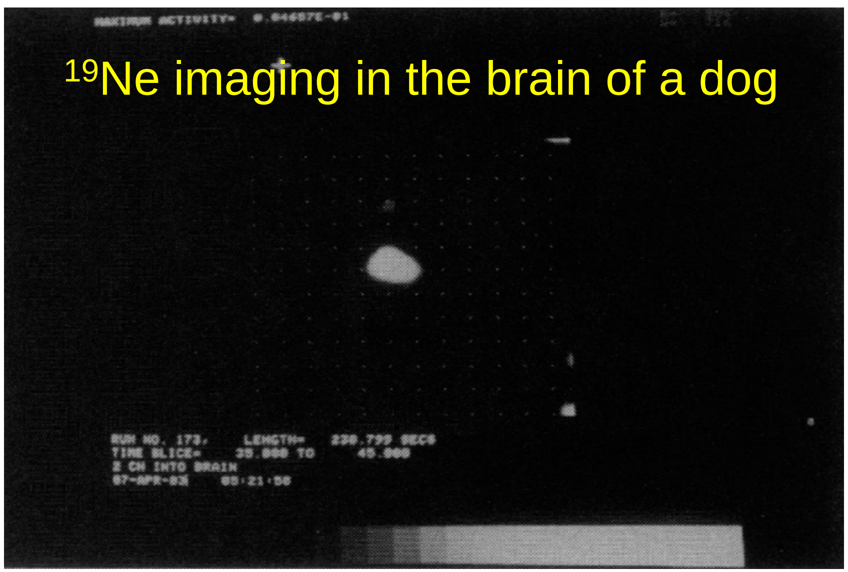
G. Shakirin: Thesis, TU Dresden, 2009, G. Shakirin et al.: IEEE NSS/MIC 2010, Conference Records

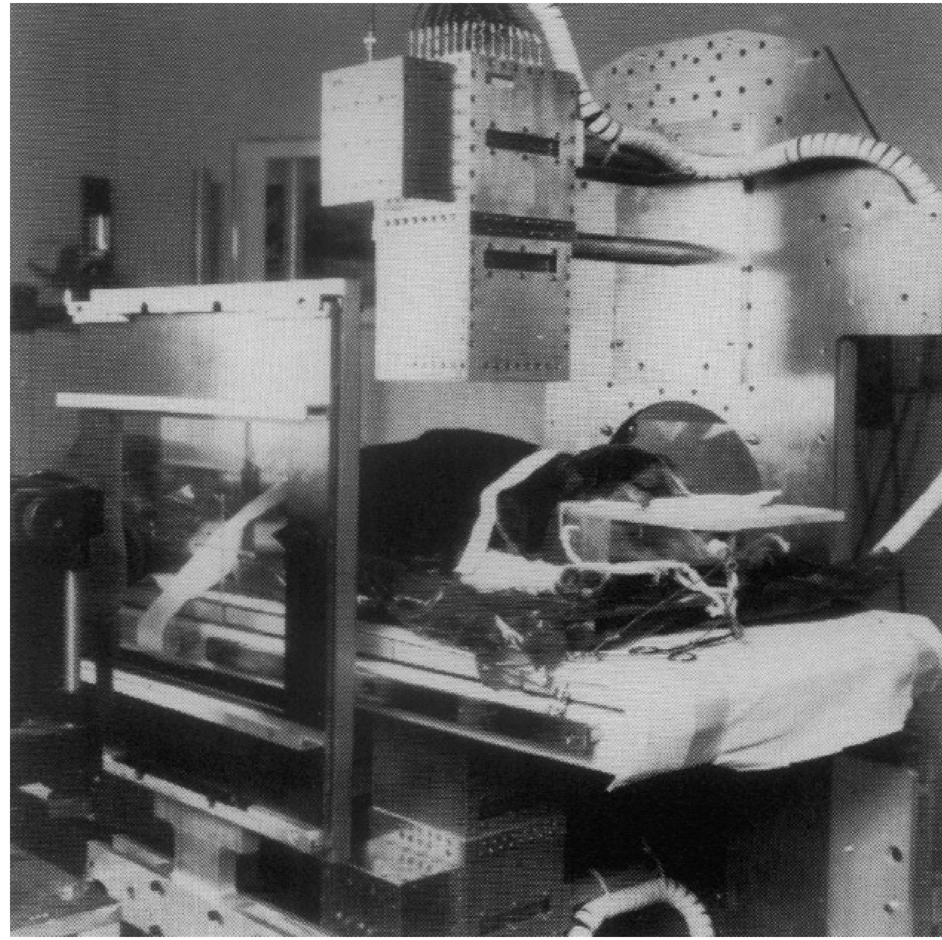
1. Imaging for hadron therapy quality assurance
Installations: LBL

In-beam PET

PEBA II

- Double head (10 × 10 cm^2) system
- 8 × 8 BGO crystals
- crystal size: 1.25 × 1.25 × 3 cm^3



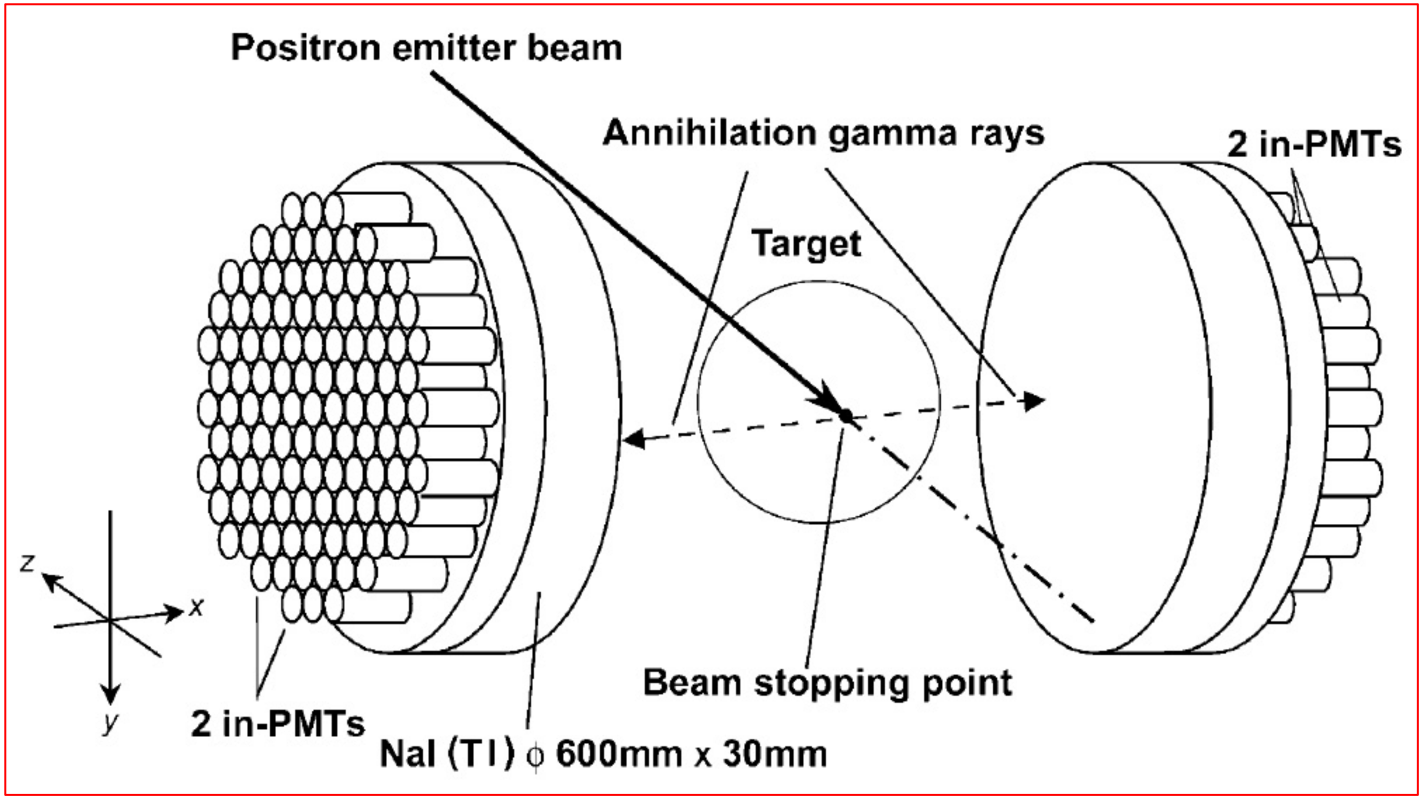


J. Llacer et al., IEEE TMI, 3 (1984) 80

1. Imaging for hadron therapy quality assurance

Installations: HIMAC

In-beam PET



Institute of Physics Publishing — Physics in Medicine and Biology

Phys. Med. Biol. 48 (2003) 2269–2281 — PII: S0031-9155(03)59468-4

Washout measurement of radioisotope implanted by radioactive beams in the rabbit

H Mizuno[1,2], T Tomitani[3], M Kanazawa[3], A Kitagawa[3], J Pawelke[4], Y Iseki[5], E Urakabe[3], M Suda[3], A Kawano[3], R Iritani[6], S Matsushita[6], T Inaniwa[7], T Nishio[8], S Furukawa[3], K Ando[3], Y K Nakamura[2], T Kanai[6] and K Ishii[1]

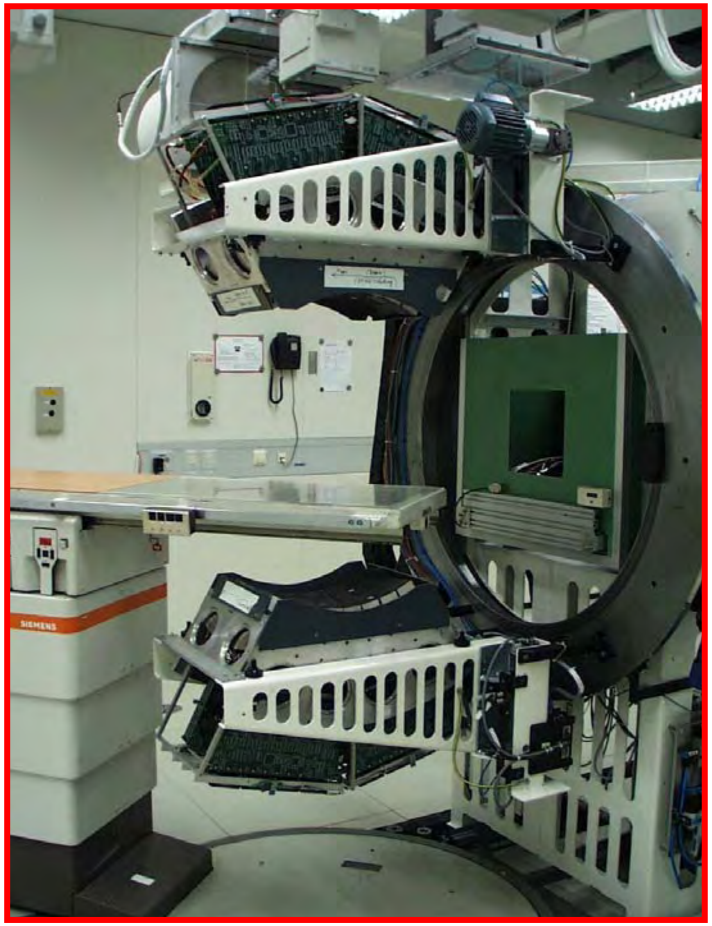
Y. Iseki et al NIM A 515 (2003) 840

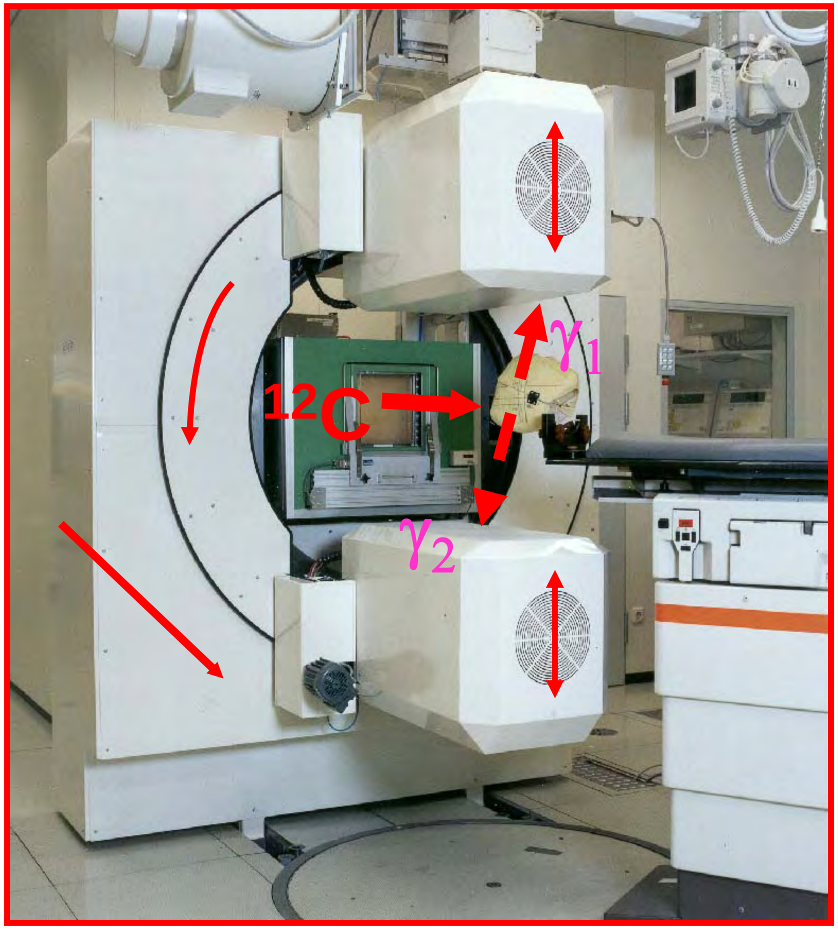
1. Imaging for hadron therapy quality assurance

Installations: GSI

In-beam PET

- Double head (42 × 21 cm^2) system
- 64 × 32 BGO crystals
- crystal size: 6,75 × 6,75 × 30 mm^3





J. Pawelke et al.: Phys. Med. Biol. 41 (1996) 279, W. Enghardt et al.: Nucl. Instr. Meth. A525 (2004) 284

1. Imaging for hadron therapy quality assurance

Installations: MGH

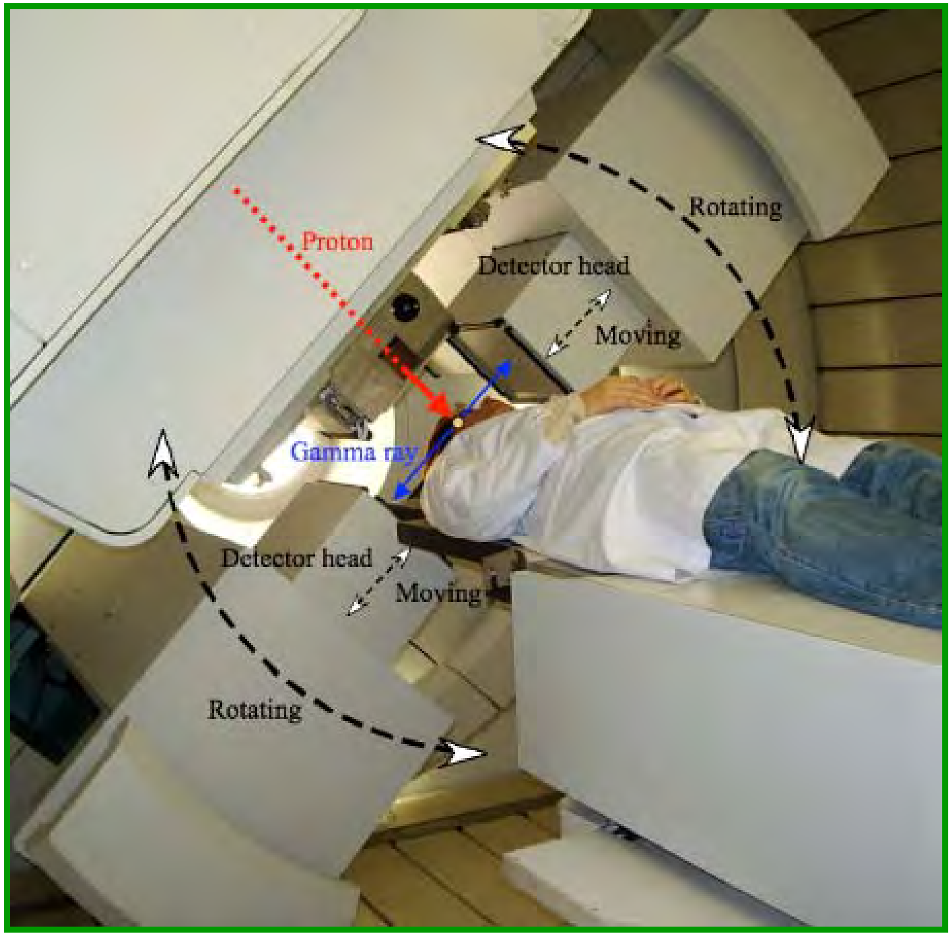
Off-beam PET

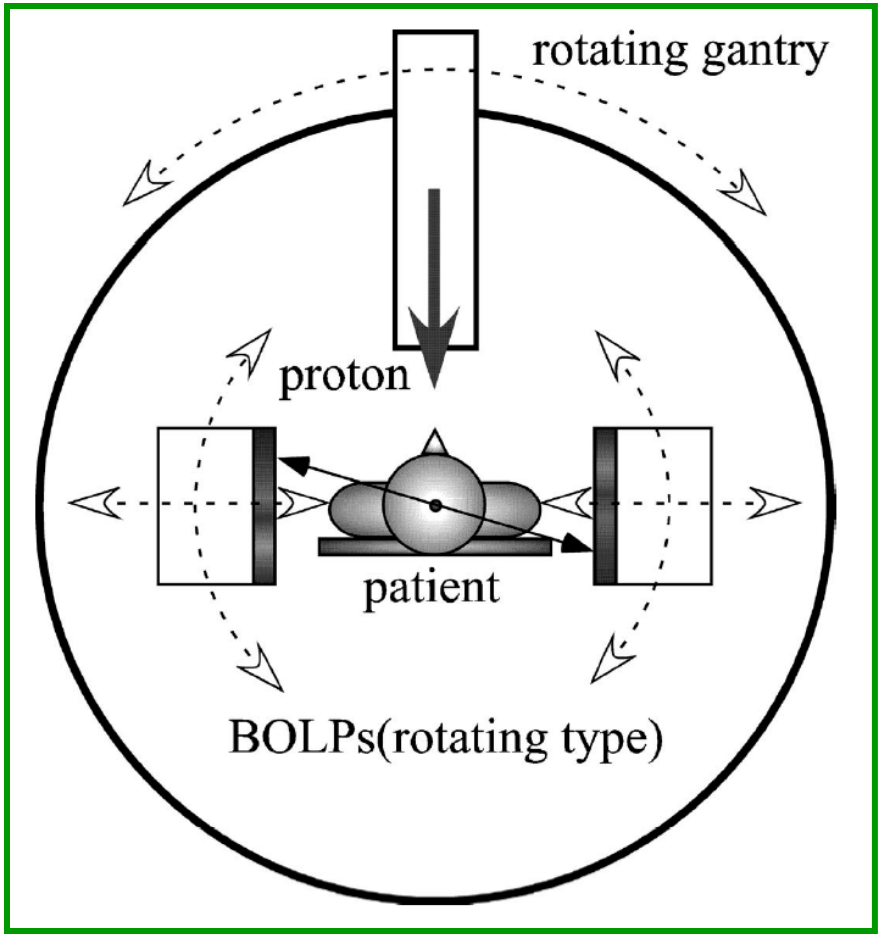
K. Parodi et al.: Int. J. Radiat. Oncol. Biol. Phys. 68 (2007) 920

1. Imaging for hadron therapy quality assurance

Installations: National Cancer Center, Kashiwa

In-room PET at a rotating beam delivery: Beam ON-LINE PET system





- Double head (12 × 19 cm^2) system
- 40 × 60 BGO crystals
- crystal size: 2 × 2 × 20 mm^3

- DAQ: 200 s after irradiation

T. Nishio et al.: Med. Phys. 33 (2006) 4190

1. Imaging for hadron therapy quality assurance

Further installations

Hyogo Ion Beam Medical Center, Hyogo, Japan: off-line

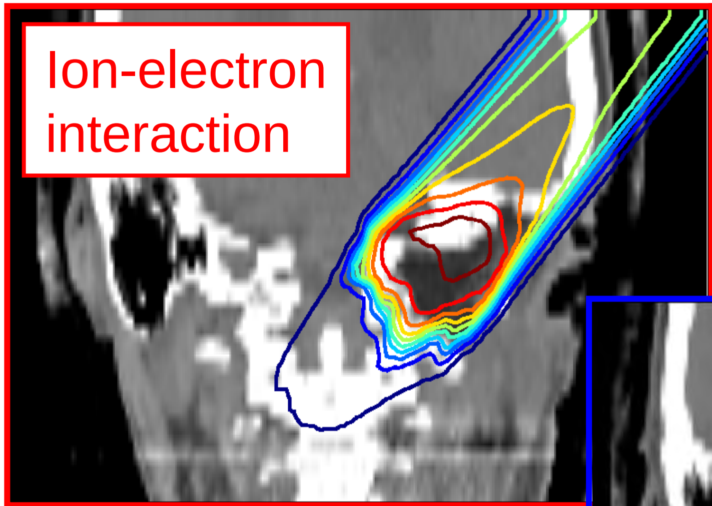
CATANA, Catania, ocular beamline, Catania, Italy: in-beam

University of Florida Proton Therapy Institute, Jacksonville, USA: off-line

2. Lessons learned from particle therapy PET

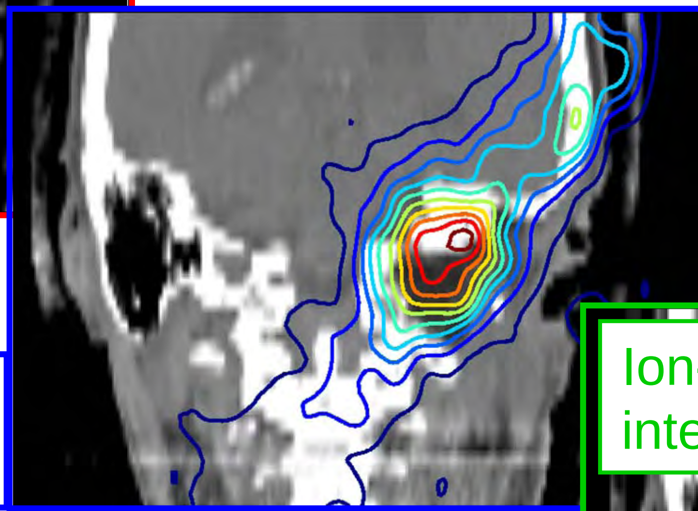
The clinical workflow

Chordoma, 0.5 Gy, 6 min



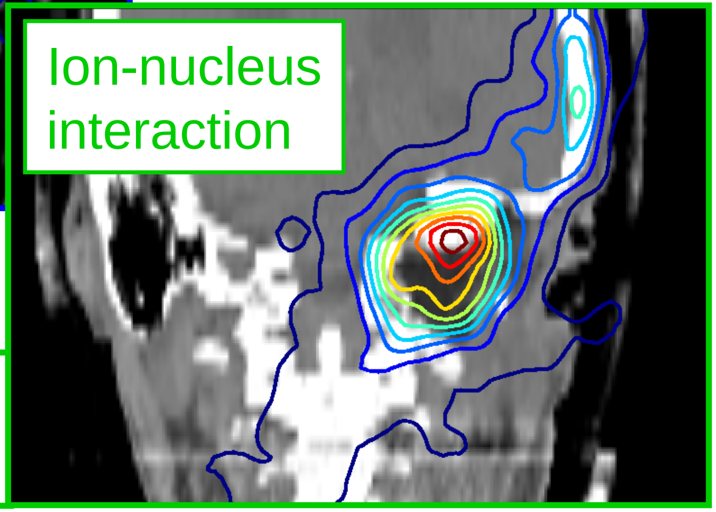
Ion-electron interaction

Treatment plan: dose-distribution



Monte Carlo: from the projectiles to the detection of annihilation γ-rays

β^+-activity: prediction



Ion-nucleus interaction

β^+-activity: measurement

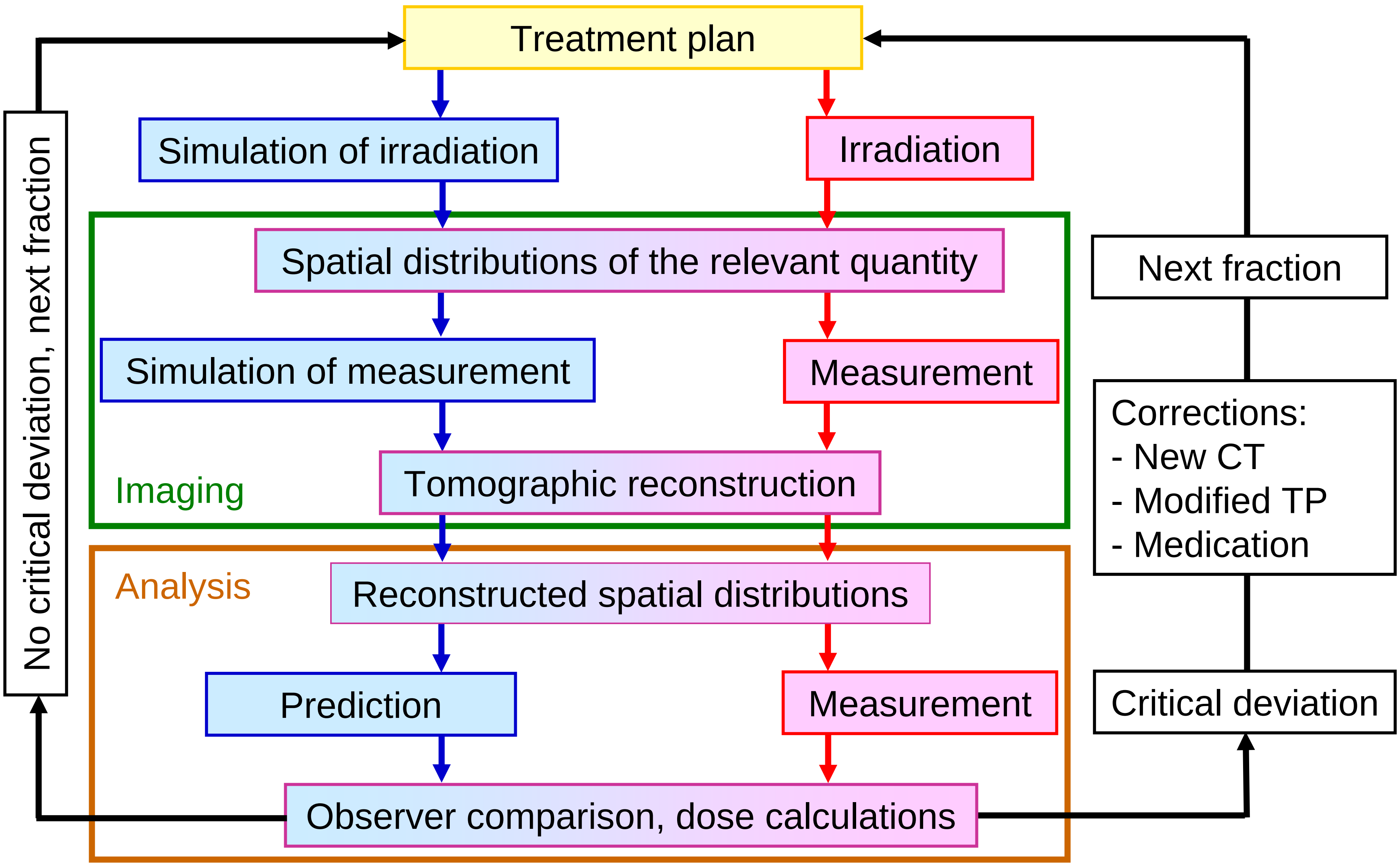
W. Enghardt et al.:
Strahlenther. Onkol. 175/II (1999) 33;

F. Pönisch et al.:
Phys. Med. Biol. 48 (2003) 2419,
Phys. Med. Biol. 49 (2004) 5217;

OncoRay

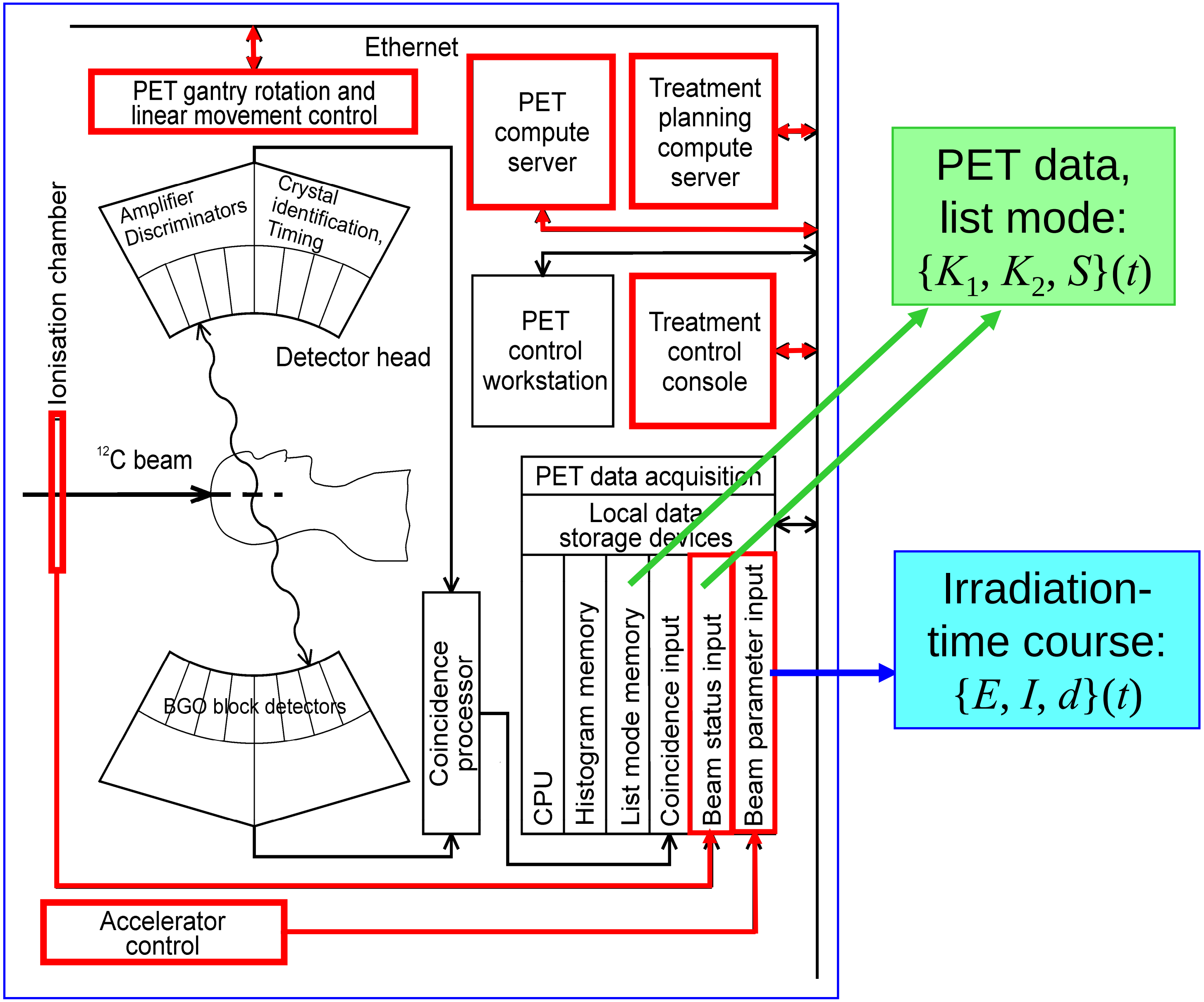
2. Lessons learned from particle therapy PET

The data processing



2. Lessons learned from particle therapy PET

The instrumentation (Example: in-beam PET)



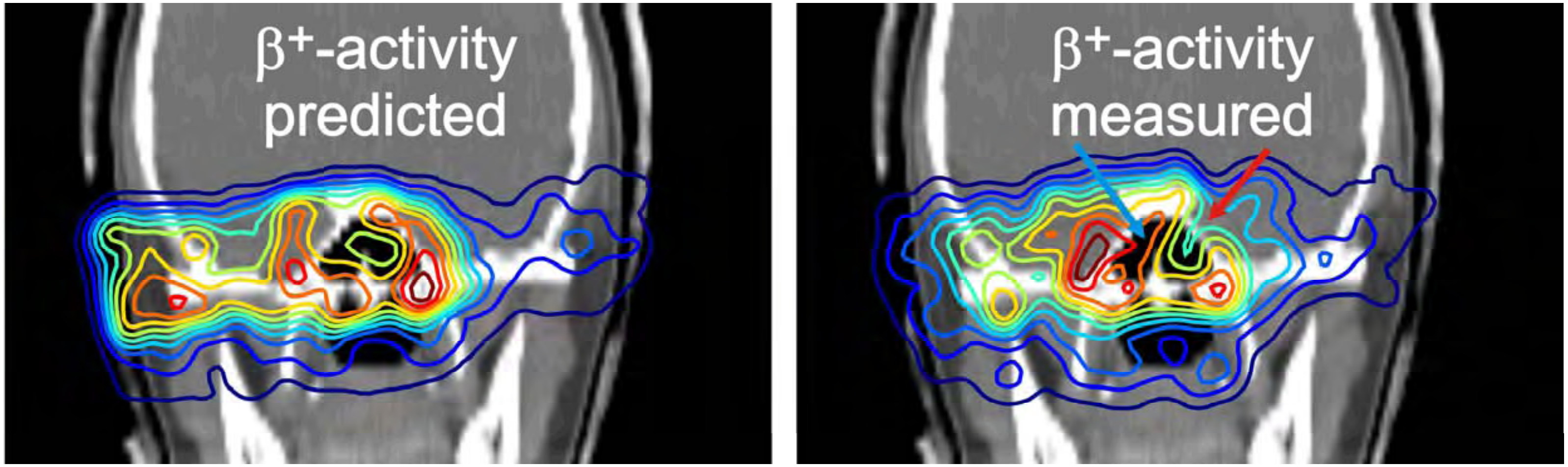
2. Lessons learned from particle therapy PET

Performance of PT-PET

- ☺ Particle range in vivo
- ☺ Lateral field position in vivo
- 😐 Patient positioning
- ☹ Semi-quantitative
- ☹ No direct dosimetry
- ☹ No real time capability
- ☹ Low signal-to-noise ratio

2. Lessons learned from particle therapy PET

Particle range in vivo



Range verification by visual inspection:

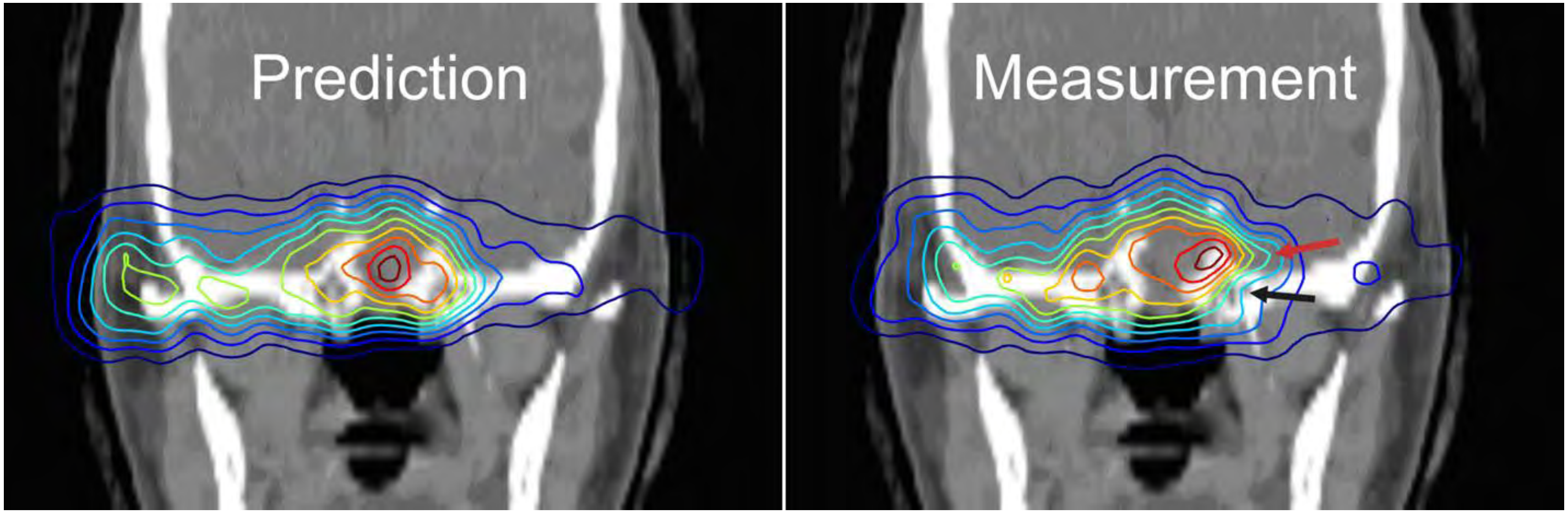
ΔR = 6 mm, *sensitivity* = (93 ± 4) %, *specifity* = (96 ± 3) %

Automatisation in progress (ENVISION, WP5)

F. Fiedler et al.: Phys. Med. Biol. 55 (2010) 1989, A. Santiago, Master Thesis, TU Dresden, 2009

2. Lessons learned from particle therapy PET

Patient positioning



2. Lessons learned from particle therapy PET

Semi-quantitative, no direct dosimetry

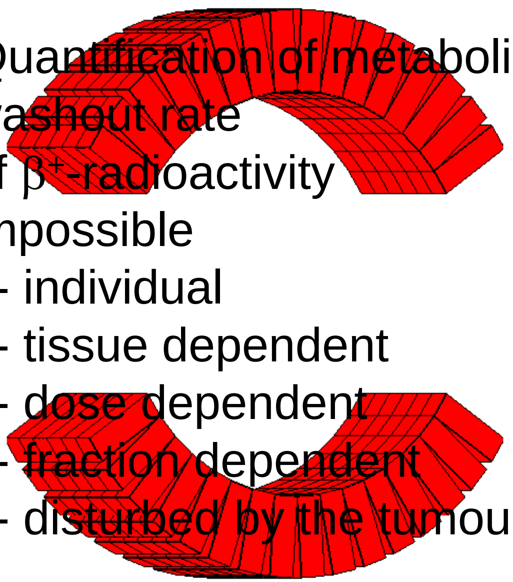
- Feasibility to solve the inverse problem:

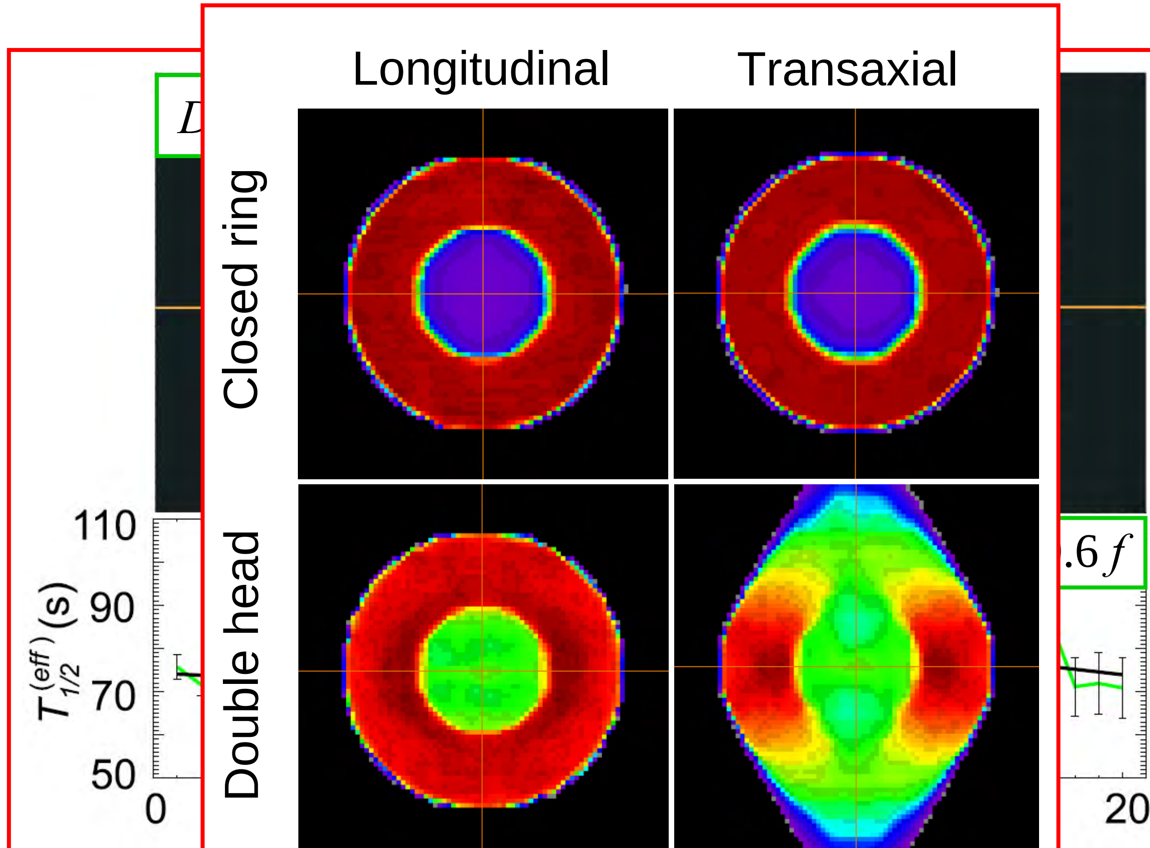
$$\mathbf{A}(\mathbf{r}) = \mathbf{T}\,\mathbf{D}(\mathbf{r})$$

$\mathbf{A}(\mathbf{r})$ – spatial distribution of activity
$\mathbf{D}(\mathbf{r})$ – spatial distribution of dose
$\mathbf{T}$ – transition matrix

- Limited angle artefacts (in-beam PET)

- Quantification of metabolic washout rate of β^+-radioactivity impossible
  - individual
  - tissue dependent
  - dose dependent
  - fraction dependent
  - disturbed by the tumour





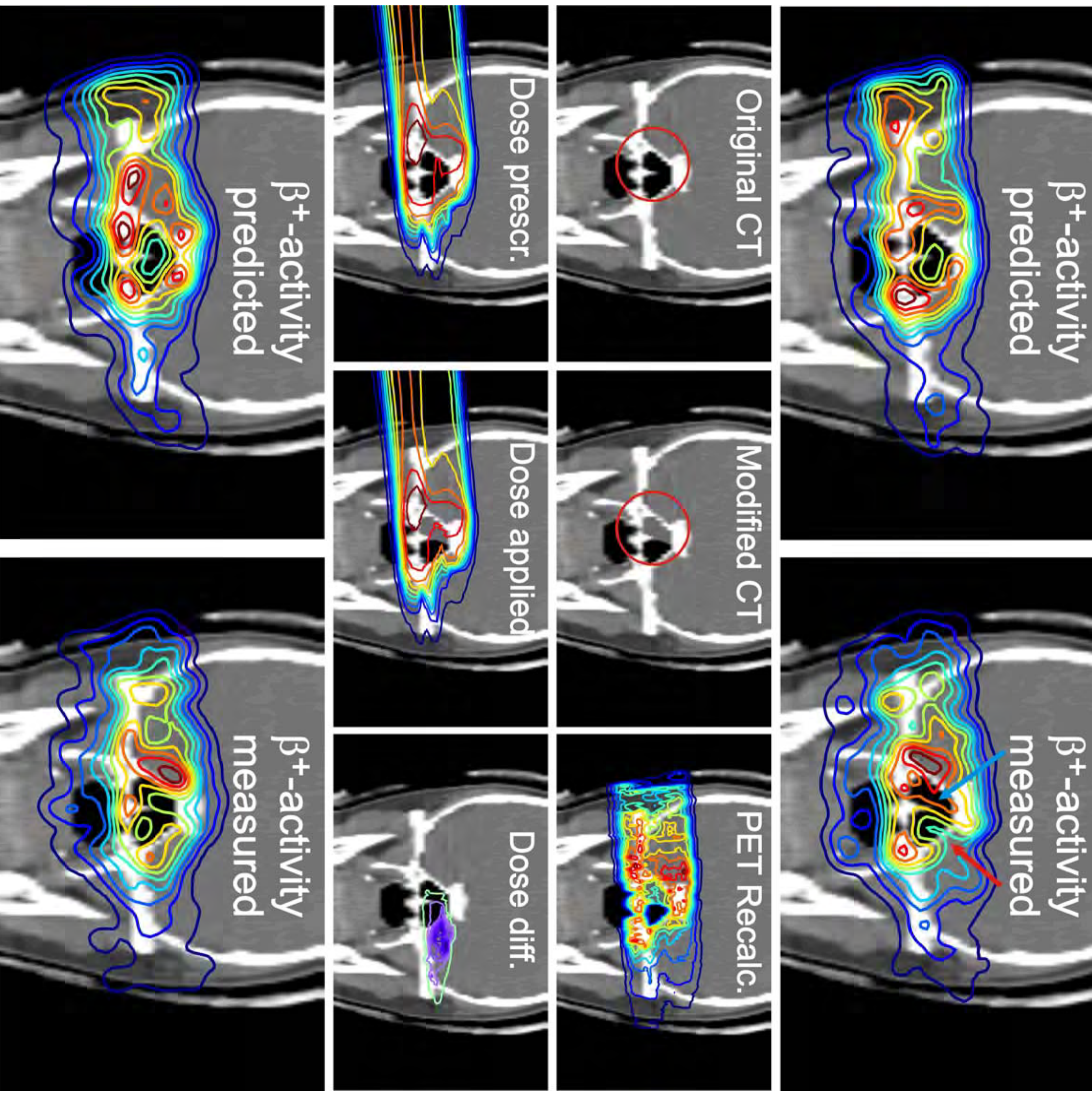
P. Crespo et al.:
Phys. Med. Biol. 51 (2006) 2143

2. Lessons learned from particle therapy PET

No direct dosimetry

Fraction $x + 3$

Fraction x



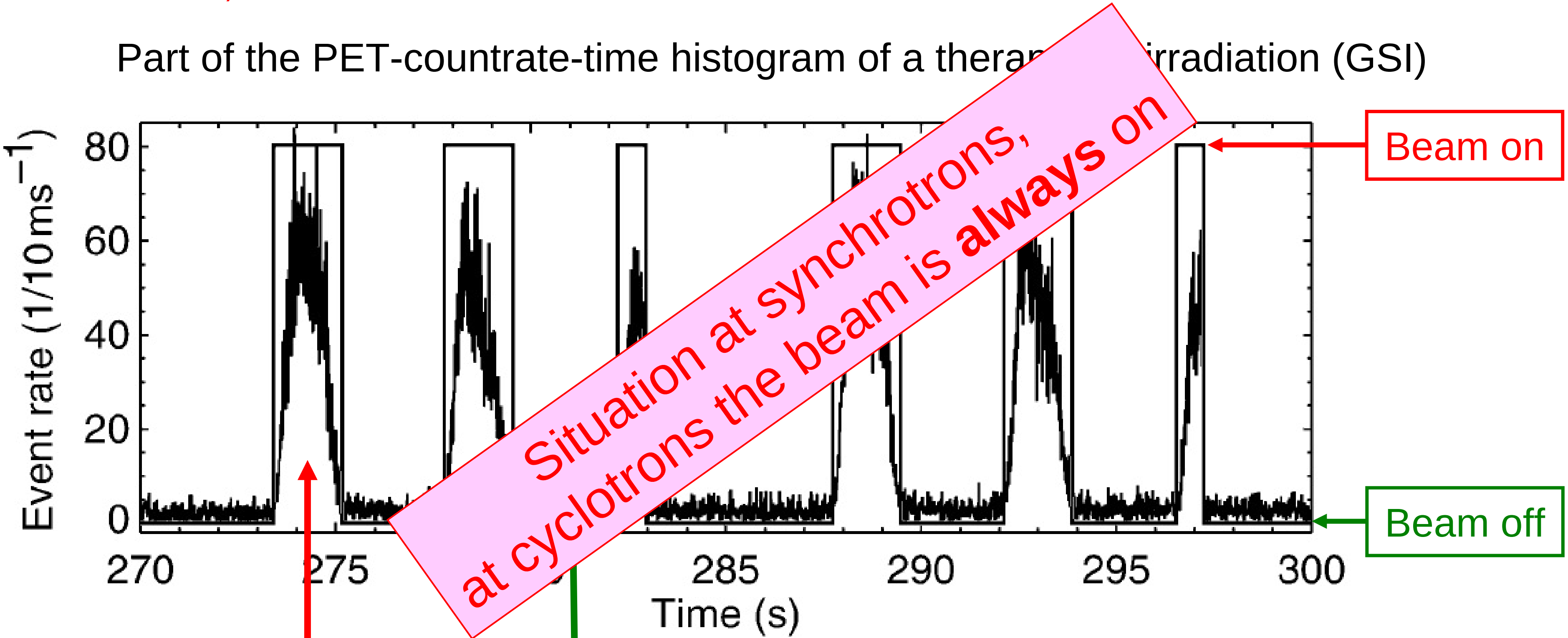
W. Enghardt et al.: Radiother. Oncol. 73 (2004) S96

2. Lessons learned from particle therapy PET

In-beam PET at cw-accelerators – cyclotrons (I)

Not realized, cf. BOLPs at Kashiwa: PET after irradiation

Part of the PET-countrate-time histogram of a therap... irradiation (GSI)



True coincidences from β^+-decay: used for reconstruction

Mainly random coincidences from γ-ray background during beam extraction: rejected from reconstruction

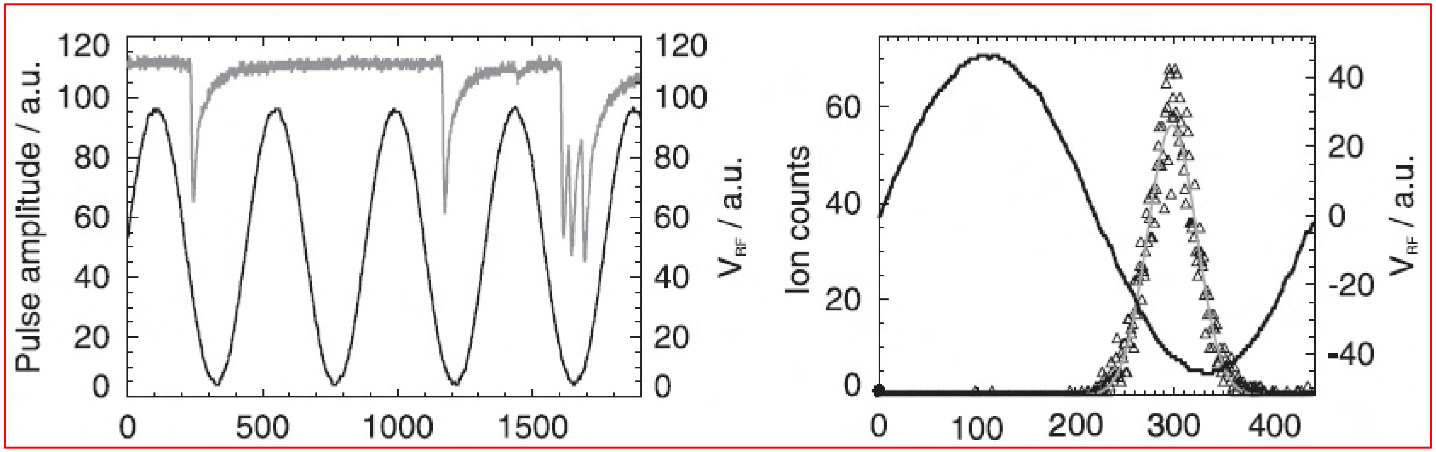
K. Parodi et al.: NIM A 545 (2005) 446, P. Crespo et al.: IEEE TNS 52 (2005) 980

2. Lessons learned from particle therapy PET

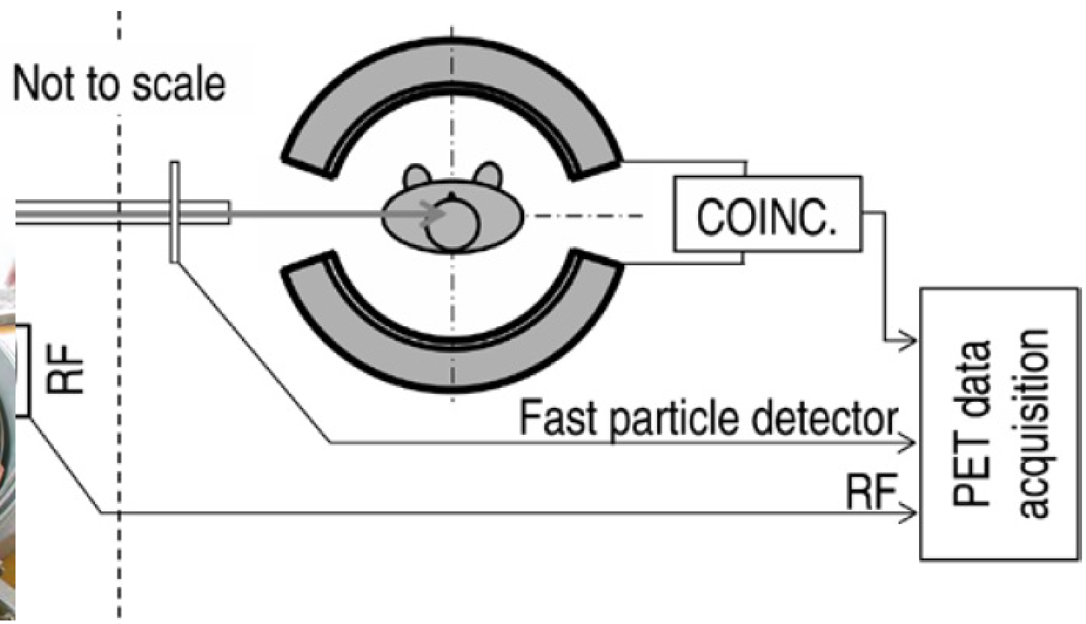
In-beam PET at cw-accelerators – cyclotrons (II)

The solution

Particle-RF
time measurement



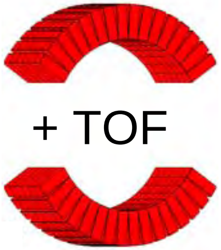
Veto during microbunch

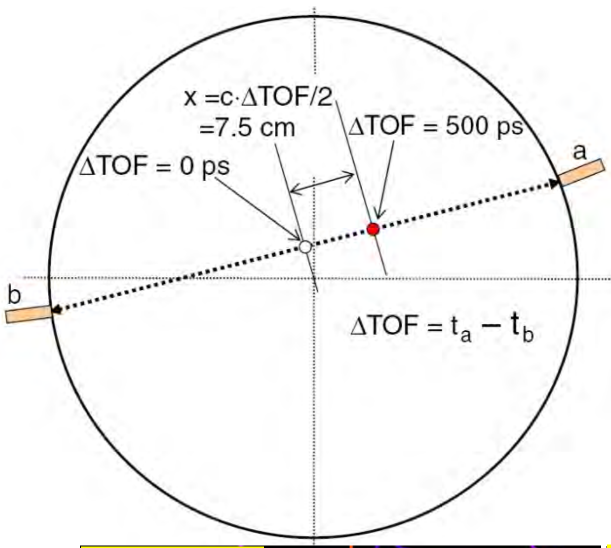


K. Parodi et al.: NIM A 545 (2005) 446, P. Crespo et al.: IEEE TNS 52 (2005) 980

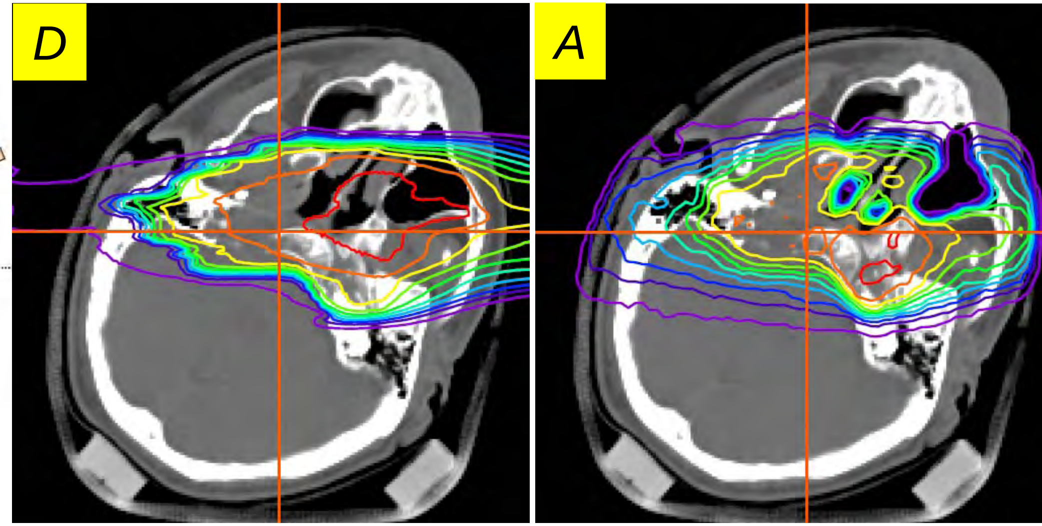
3. Towards a real-time in-vivo dosimetry

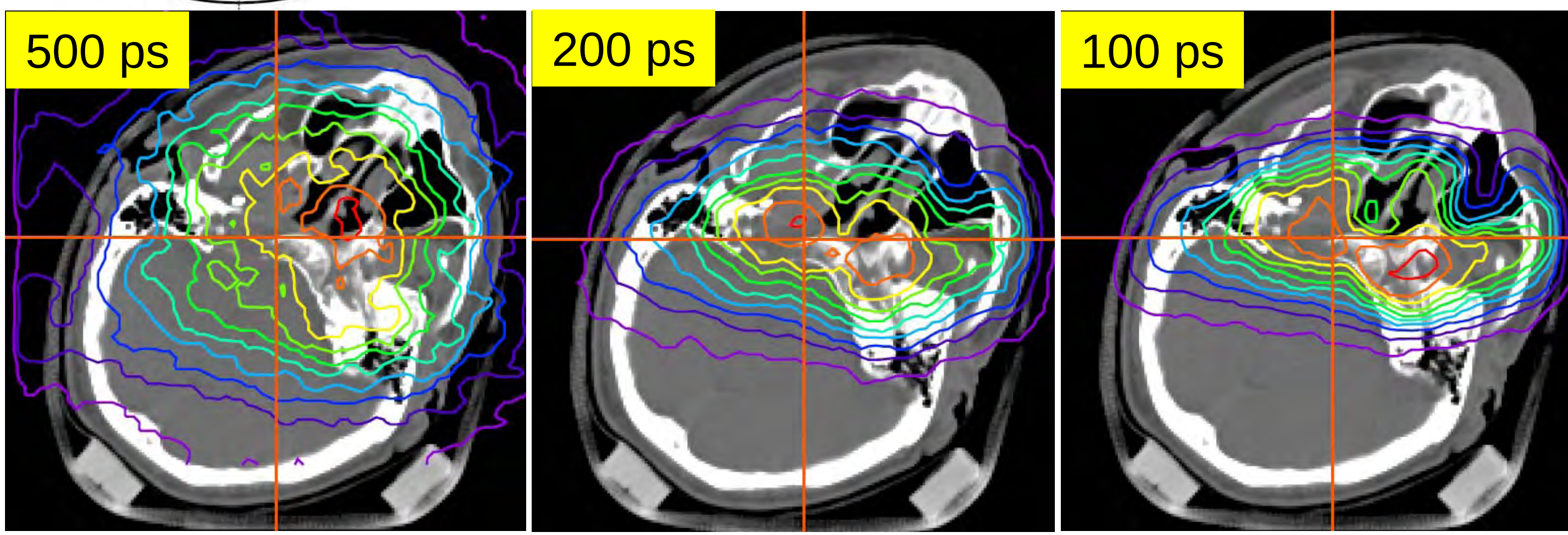
Direct TOF-PET (I)





dTOF-reconstruction, parameter τ (FWHM)





P. Crespo et al., Phys. Med. Biol. 52 (2007) 6795

3. Towards a real-time in-vivo dosimetry

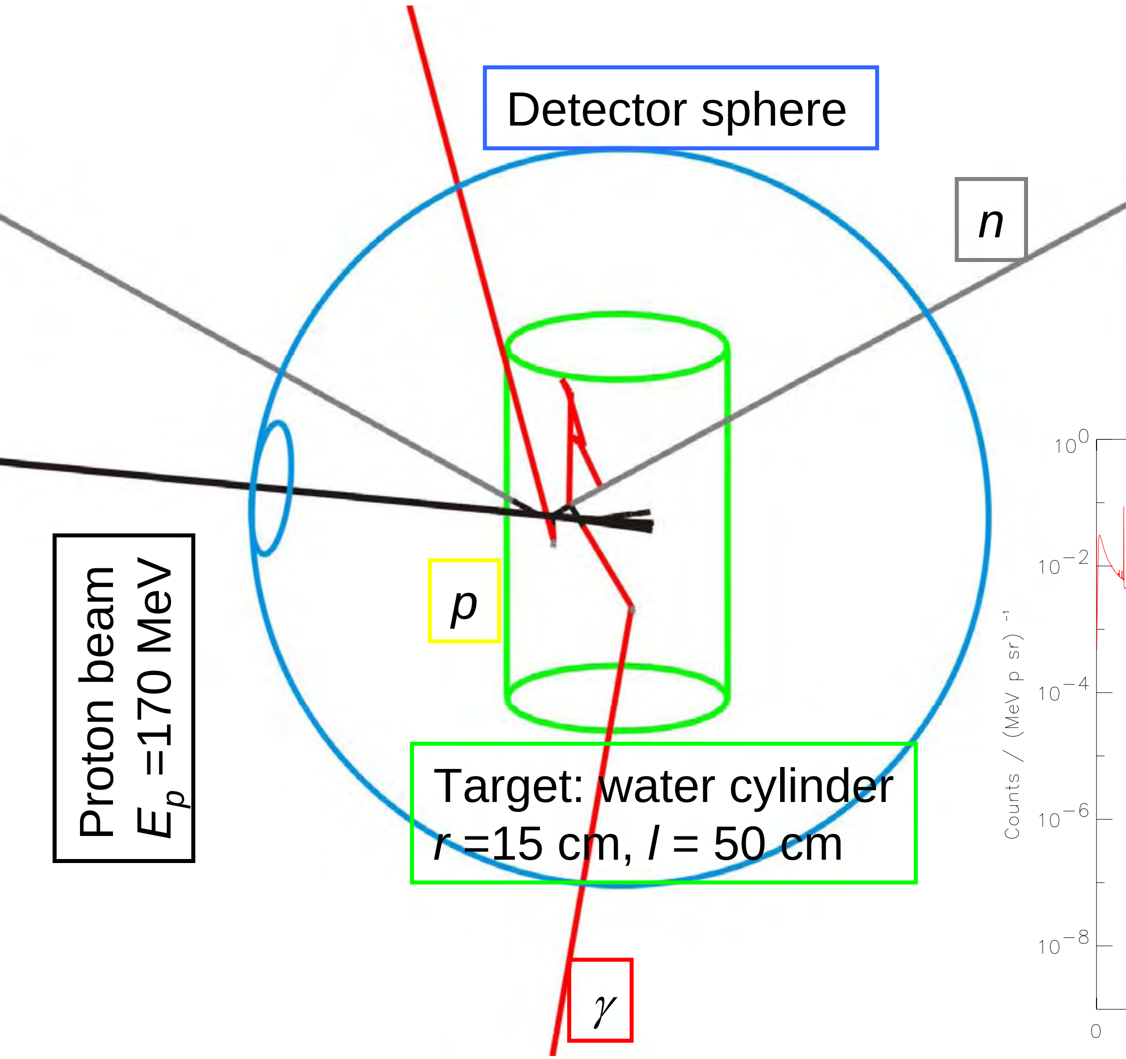
Direct in-beam TOF-PET (II)

- ☺ Particle range in vivo
- ☺ Lateral field position in vivo
- 😐 Patient positioning
- ☹ Semi-quantitative (metabolism)
- ☹ No direct dosimetry (metabolism)
- ☺ Real time capability
- ☹ Low signal-to-noise ratio (cross sections)

3. Towards a real-time in-vivo dosimetry

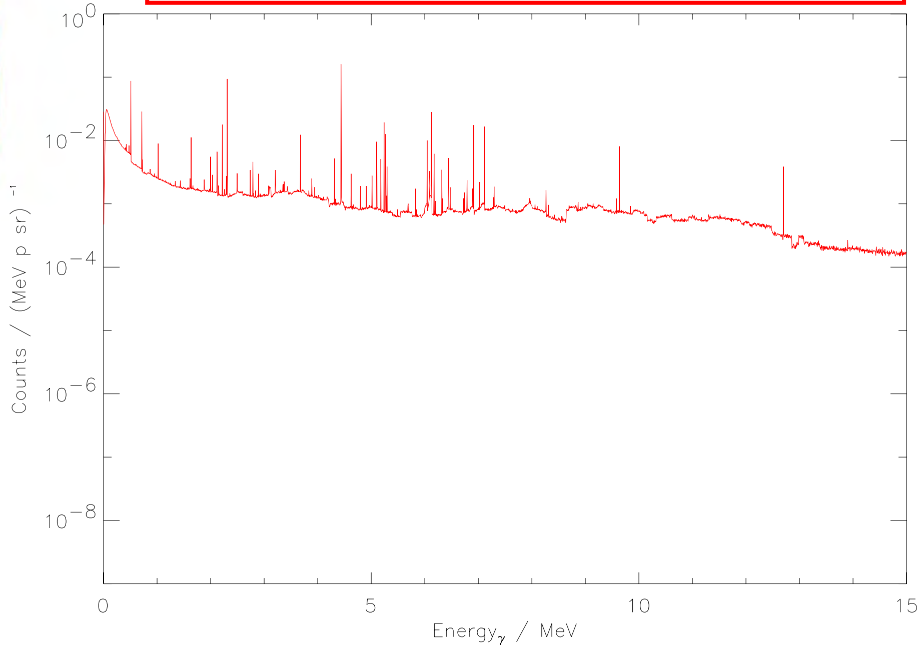
Prompt reaction products – in-beam SPECT

GEANT 4



Balance of promptly emitted particles outside the target:

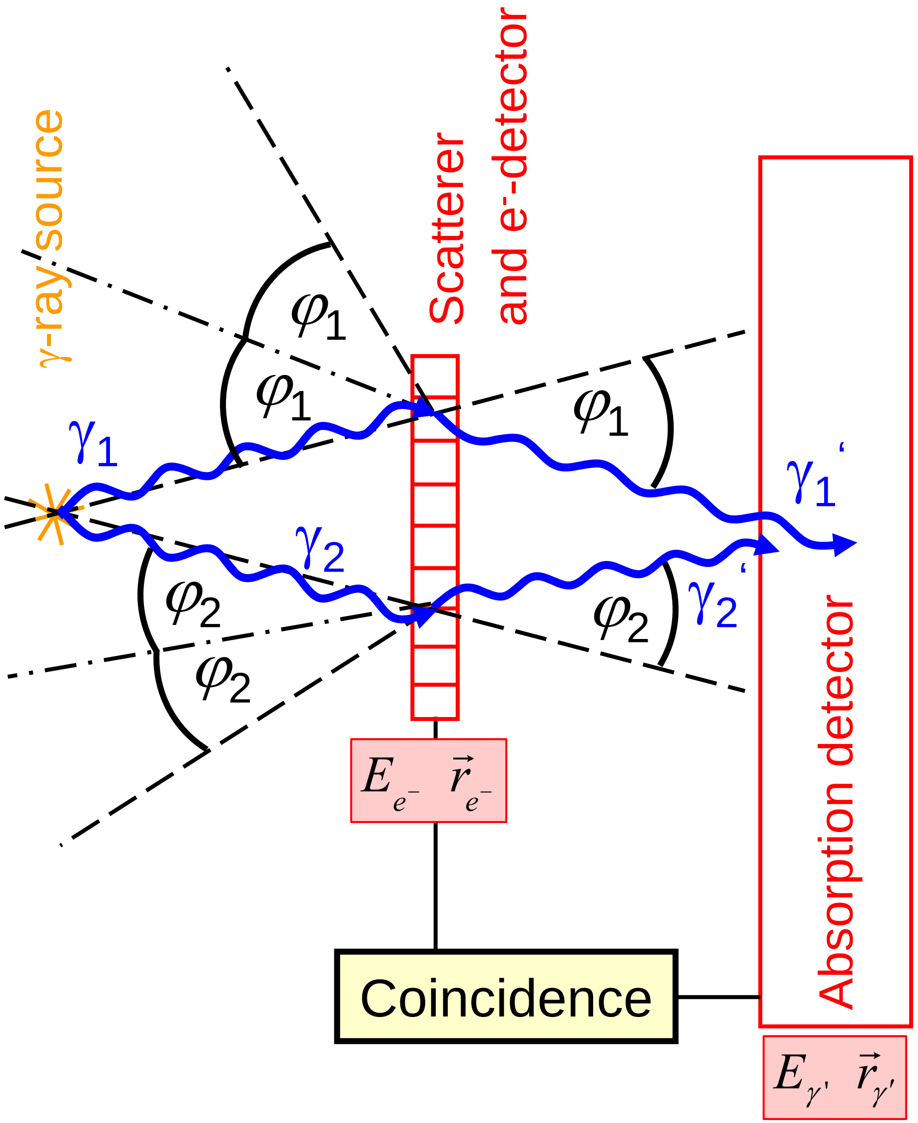
Incident protons:	1.0	(~10^{10})
γ-rays:	0.3	($3 \cdot 10^9$)
Neutrons:	0.09	($9 \cdot 10^8$)
Protons:	0.001	($1 \cdot 10^7$)
α-particles:	$2 \cdot 10^{-5}$	($2 \cdot 10^5$)



Requirement: Neutron blind, high spatial resolution γ-camera of wide energy acceptance

3. Towards a real-time in-vivo dosimetry

Detectors for in-beam SPECT: Compton cameras (I)



Kinematics of incoherent scattering:

$$\cos\varphi = 1 - m_0 c^2 \left(\frac{1}{E_{\gamma'}} - \frac{1}{E_{\gamma}} \right)$$

$$E_{\gamma} = E_{e^-} + E_{\gamma'}$$

Sensitivity:

$$\eta_{\mathrm{CC}} \approx 100\eta_{\mathrm{AC}}$$

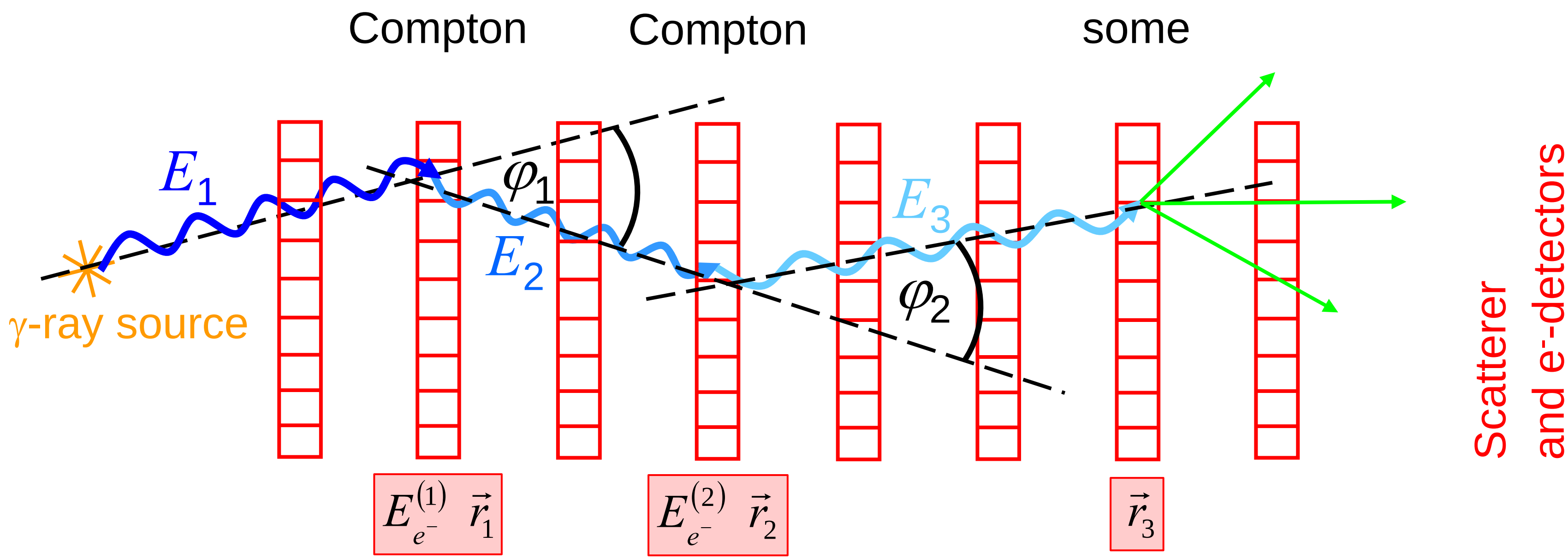
S. Chelikani et al.:
Phys. Med. Biol. 49 (2004) 1387

Problems:

- Continuous γ-ray spectra
- E_{γ} unknown
- γ' must be completely absorbed

3. Towards a real-time in-vivo dosimetry

Detectors for in-beam SPECT: Compton cameras (II)



$$\cos\varphi_1 = 1 - m_0c^2\left(\frac{1}{E_2} - \frac{1}{E_1}\right)$$

$$\cos\varphi_2 = 1 - m_0c^2\left(\frac{1}{E_3} - \frac{1}{E_2}\right)$$

$$E_{e^-}^{(1)} = E_1 - E_2$$

$$E_{e^-}^{(2)} = E_2 - E_3$$

Known : $\varphi_2, E_{e^-}^{(1)}, E_{e^-}^{(2)}$

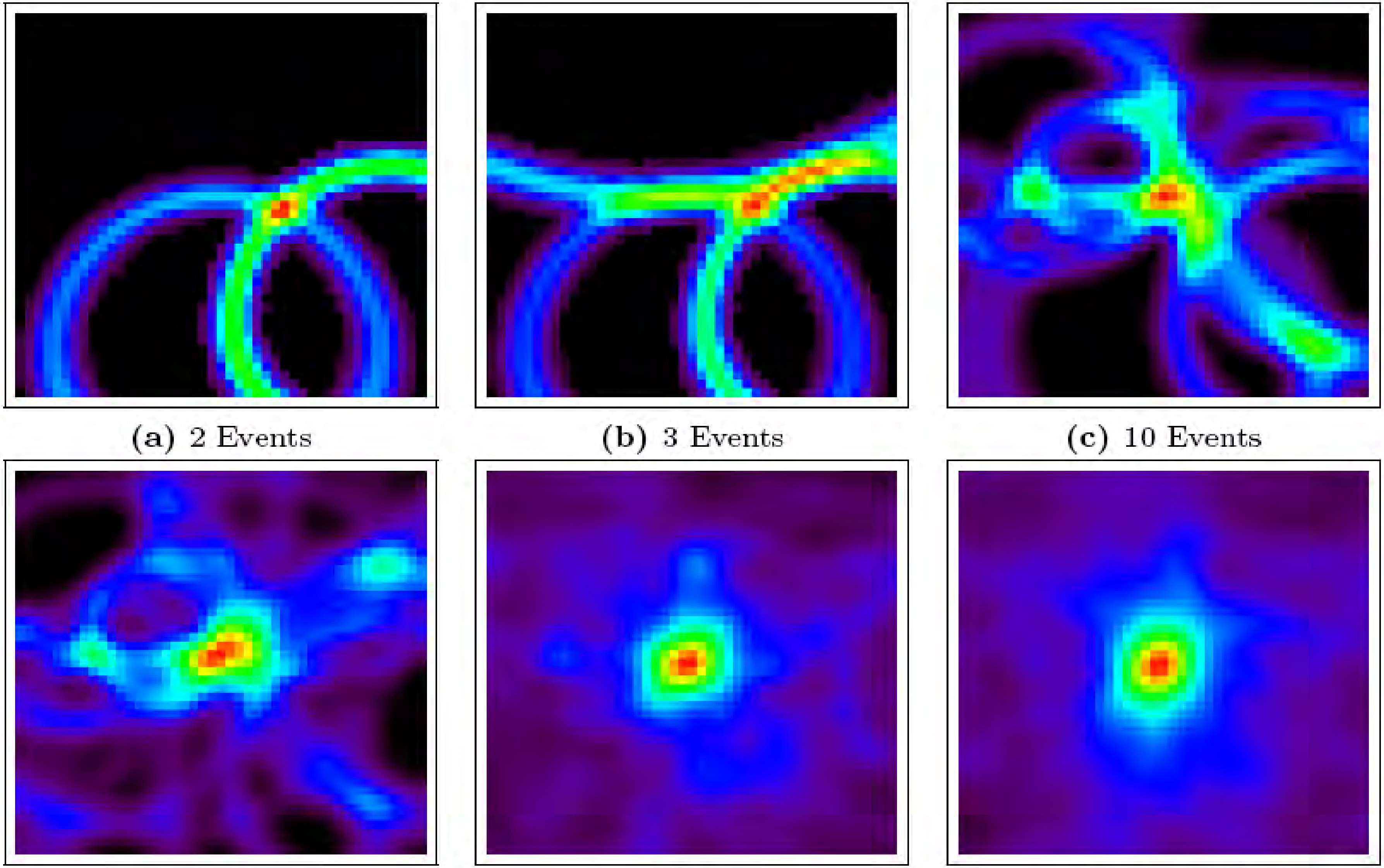
Unknown : φ_1, E_1, E_2, E_3

- Efficiency: 25 – 50 % for E_1 > 1 MeV
- No absorption necessary
- No high Z absorber required

J.D. Kurfess et al., 5th Compton Symposium,
Portsmouth, New Hampshire, AIP Conference Proceedings, 1999

3. Towards a real-time in-vivo dosimetry

Detectors for in-beam SPECT: Compton cameras (III)



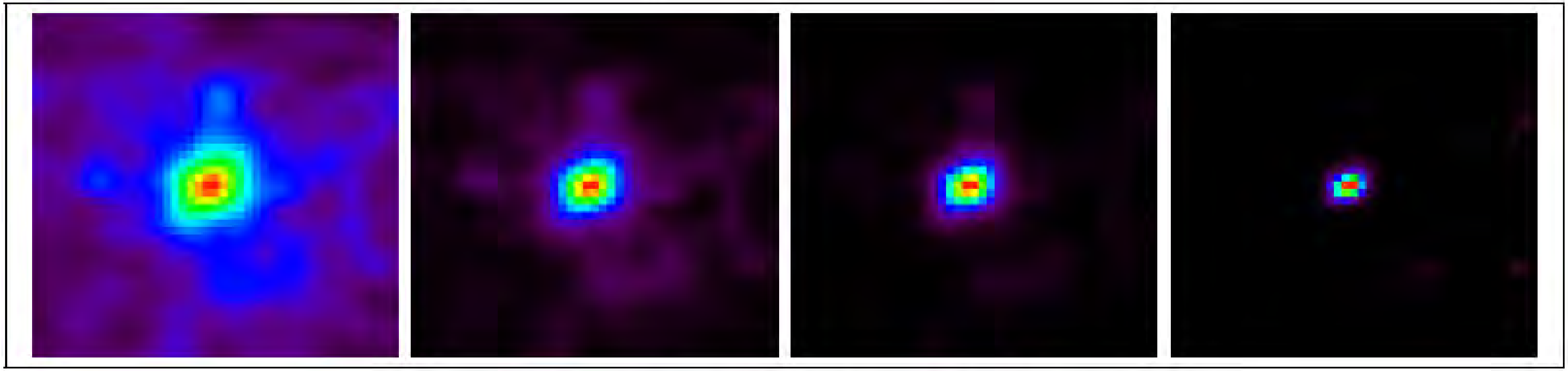
(a) 2 Events (b) 3 Events (c) 10 Events

(d) 20 Events (e) 100 Events (f) 300 Events

3. Towards a real-time in-vivo dosimetry

Detectors for in-beam SPECT: Compton cameras (IV)

Tomographic reconstruction



(c) 100 Events, nach Iteration 1, 2, 3 und 10