International Conference on Monte Carlo Techniques for Medical Applications (MCMA2017)

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Europe/Rome timezone

The dawn of PET Monte Carlo: a personal experience

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"Homemade" Neutron Transport Monte Carlo code

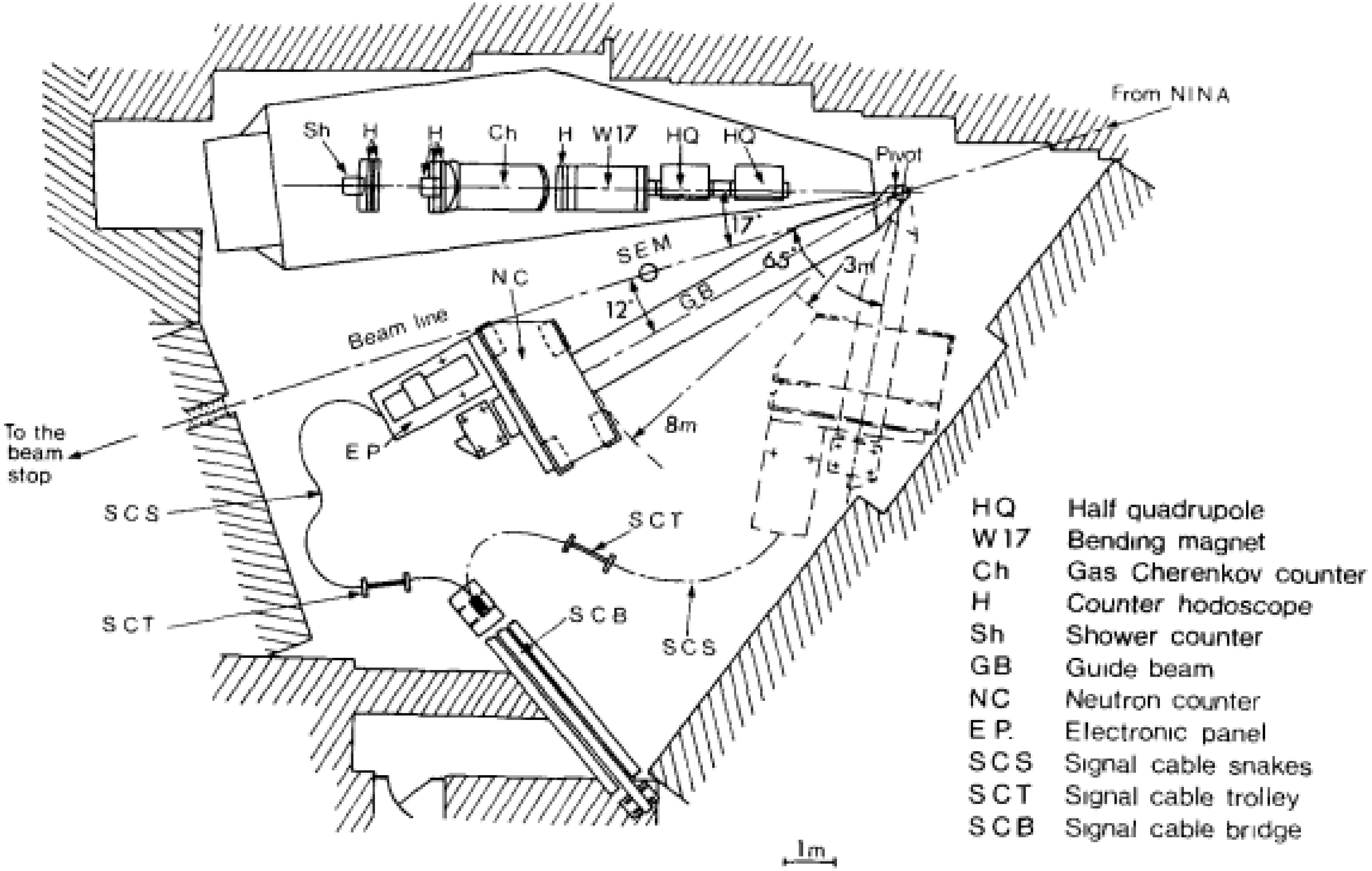


Fig. 1. Layout of the experiment.

HEP Experiment: Electroproduction of π^+ ($e+p \rightarrow e+n+\pi^+$) at threshold

(NINA 5 GeV electron accelerator at Daresbury Laboratory, UK)

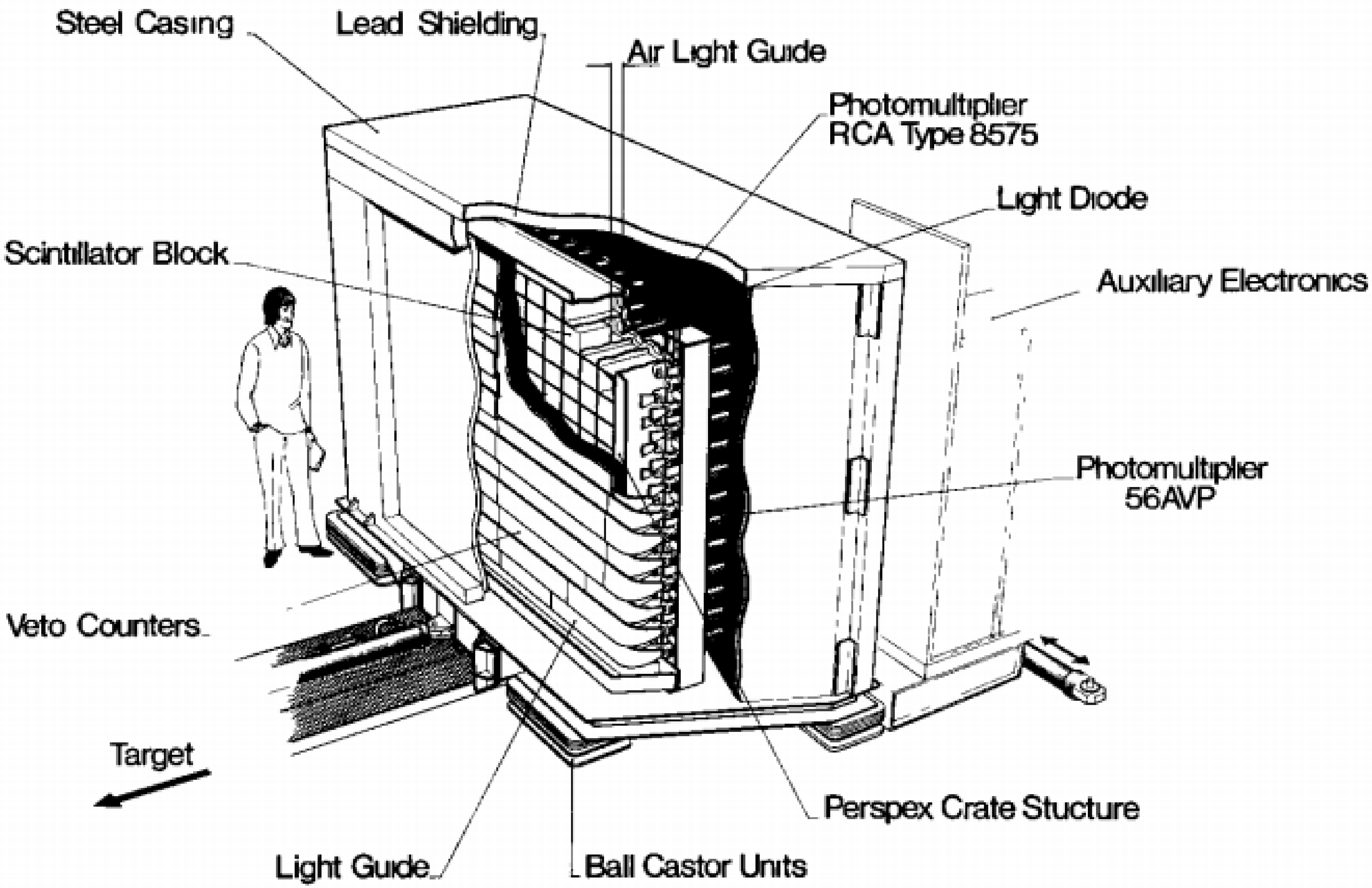


Fig. 3. Schematic diagram of the neutron counter

A. Del Guerra, et al. “*A large aperture neutron time-of-flight spectrometer* “Nuclear Instruments and Methods, Volume 135(2), 1976, 307-318

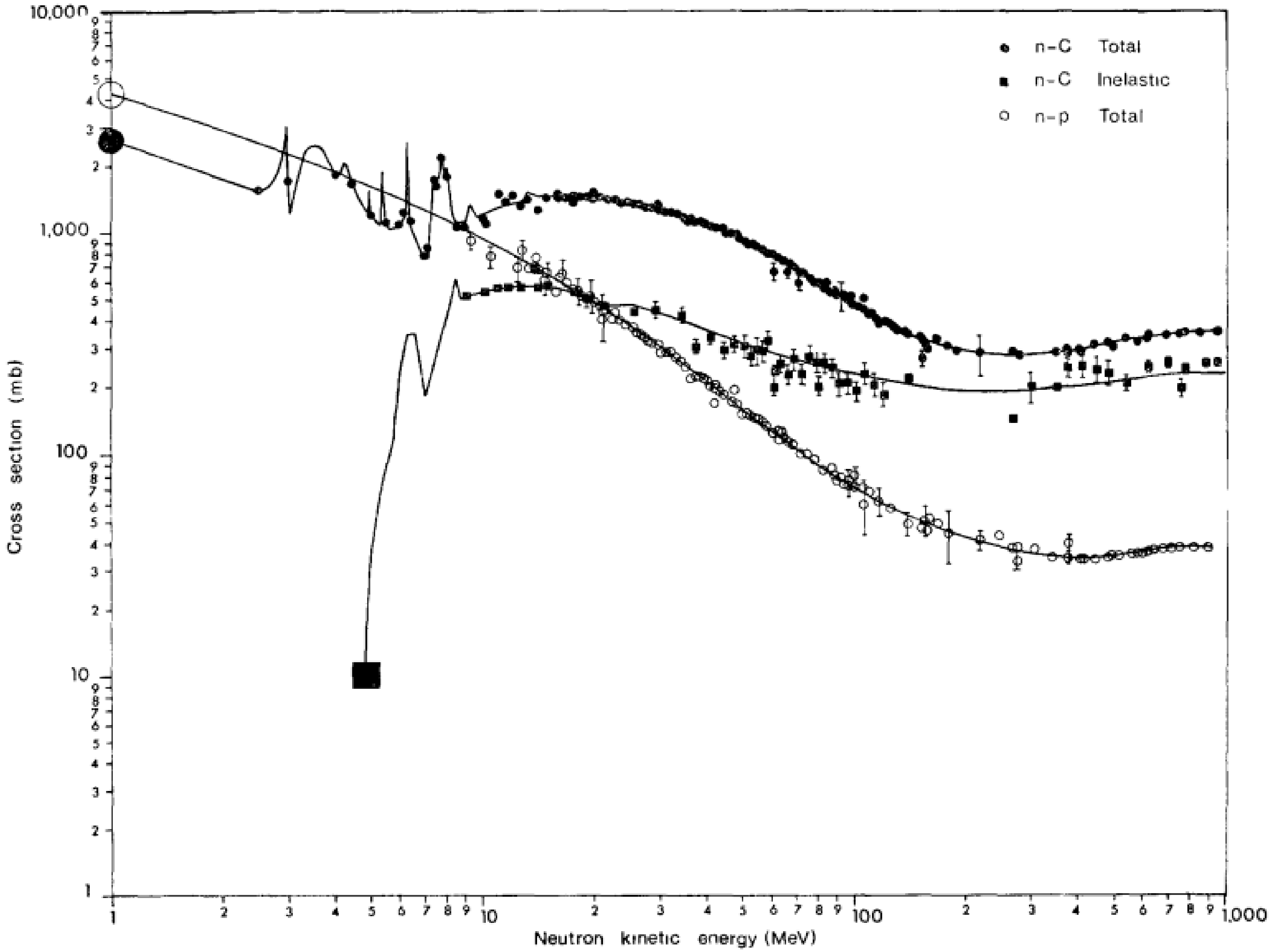


Fig. 1. n–C total, n–C inelastic and n–p total cross sections data. The full lines show the cross sections used in the Monte Carlo program.

A. Del Guerra, "*A compilation of n-p and n-C cross sections and their use in a Monte Carlo program to calculate the neutron detection efficiency in plastic scintillator in the energy range 1–300 MeV*", Nuclear Instruments and Methods, Volume 135(2), 1976, 337-352-

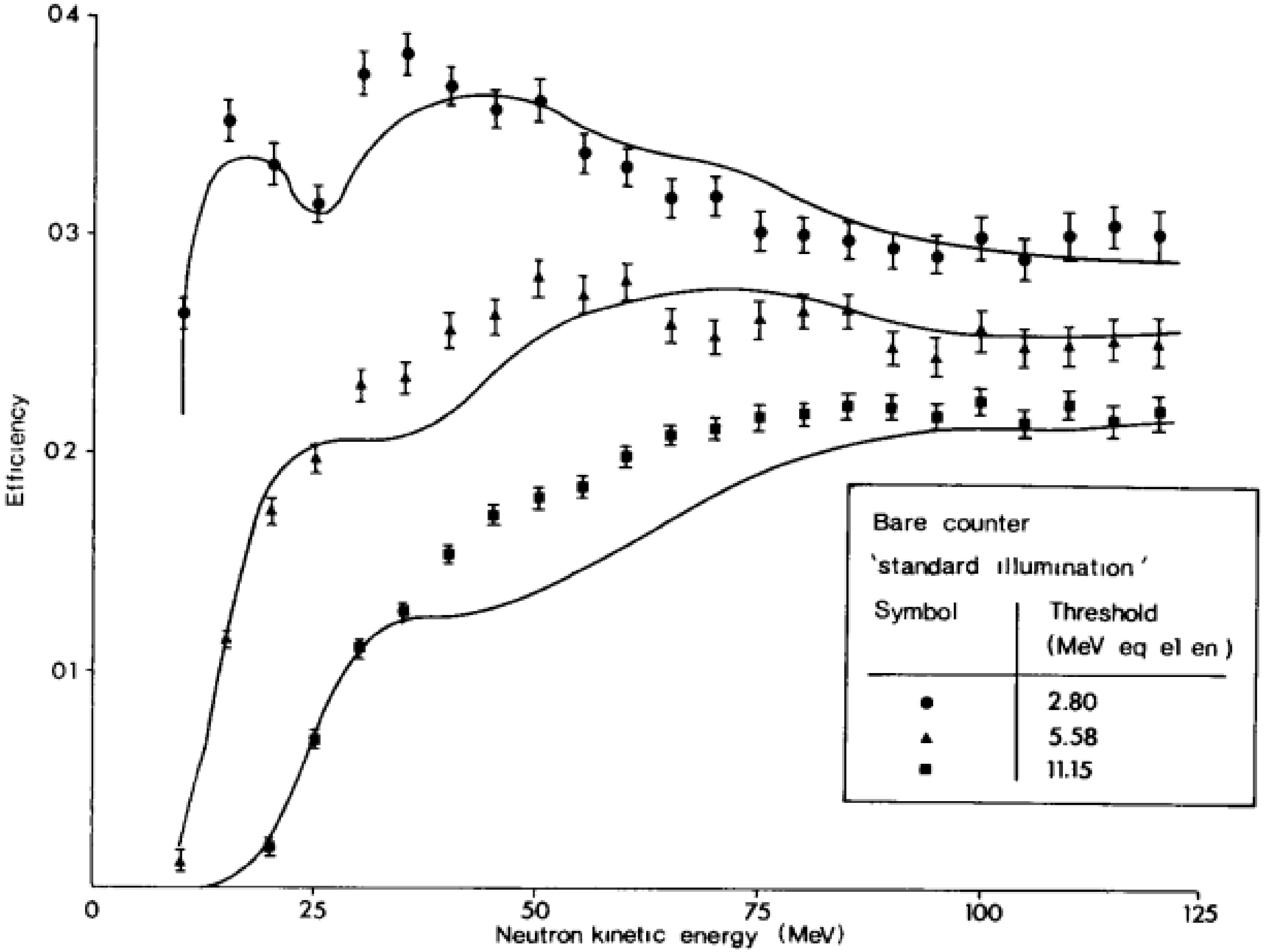


Fig. 3. Total efficiency of the bare counter for several threshold values. The solid curves are the Monte Carlo predictions.

G. Betti, A. Del Guerra, et al., "*Efficiency and spatial resolution measurements of a modular neutron detector in the kinetic energy range 15–120 MeV*", Nuclear Instruments and Methods, Volume 135(2), 1976, 319-330.

A bite of History

First Monte Carlo[1] applications using computers were done at Los Alamos (1943), by Metropolis, Ulam and Von Neumann with the ENIAC[2] for neutron diffusion problems ➔MCNP (Neutron Scattering and Absorption in U and Pu)

The problem of first interaction:

$$1-\exp(-\mu x) = R \quad [\text{ with } 0<R<1] \quad ; \exp(-\mu x) = 1-R \; ; \quad -\mu x = \ln(1-R)$$

$$-\mu x = \ln(R) \quad ; \quad x = -1/\mu x \; (\ln R)$$

Pseudo-random generator➔ R

The analog computer: the FERMIAC

____

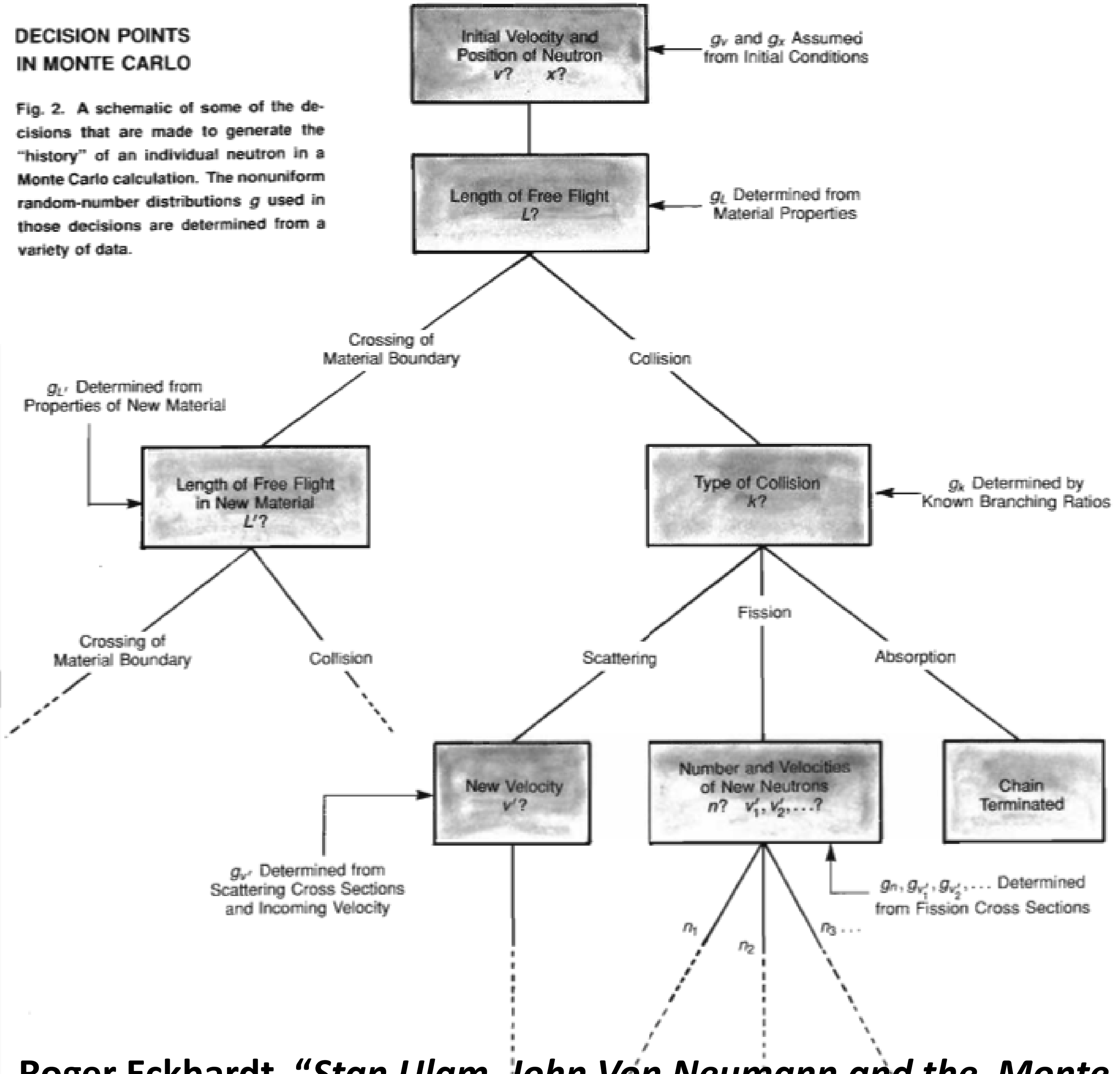
[1] Stan Ulam suggested the name after “Monte Carlo Casino”: he was a poker player.

[2] Electronic Numerical Integrator And Computer

[3] Invented by Fermi and built by Percy King in 1947. Used at LANL till 1949

DECISION POINTS IN MONTE CARLO

Fig. 2. A schematic of some of the decisions that are made to generate the "history" of an individual neutron in a Monte Carlo calculation. The nonuniform random-number distributions g used in those decisions are determined from a variety of data.



Roger Eckhardt, "*Stan Ulam, John Von Neumann and the Monte Carlo method*", Los Alamos Science, Special issue, 1987, 131-137

The FERMIAC

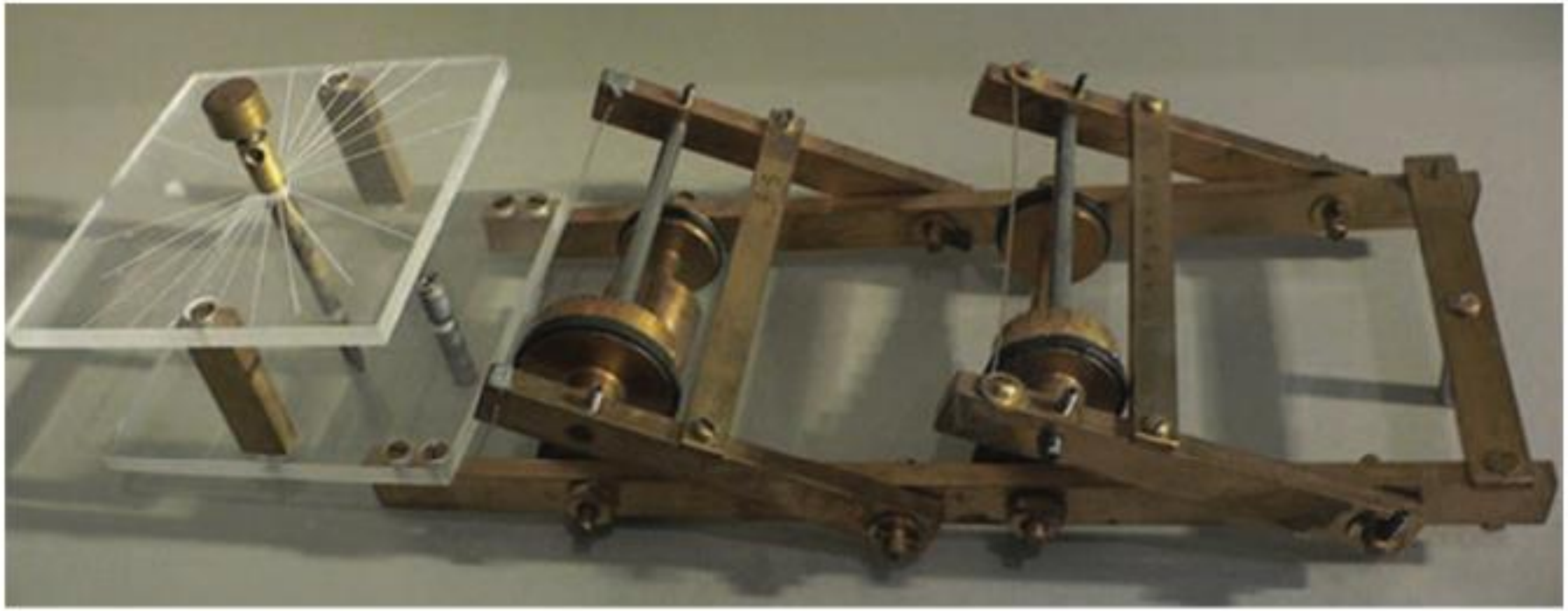


Fig. 1. – The *Fermiac* on display at the Bradbury Science Museum in Los Alamos. The *Fermiac* is a 30 cm long hand-operated computer conceived to study the change in time of the neutron population in a nuclear device, via the Monte Carlo method. The neutron population would either increase or decrease or remain constant in time, representing a supercritical, subcritical or critical system respectively.

F. Coccetti, "*The Fermiac or Fermi's Trolley*", Il Nuovo Cimento 39C, 2016 (296), DOI 10.1393/ncc/i2016-16296-7

How does it works? [(1)]

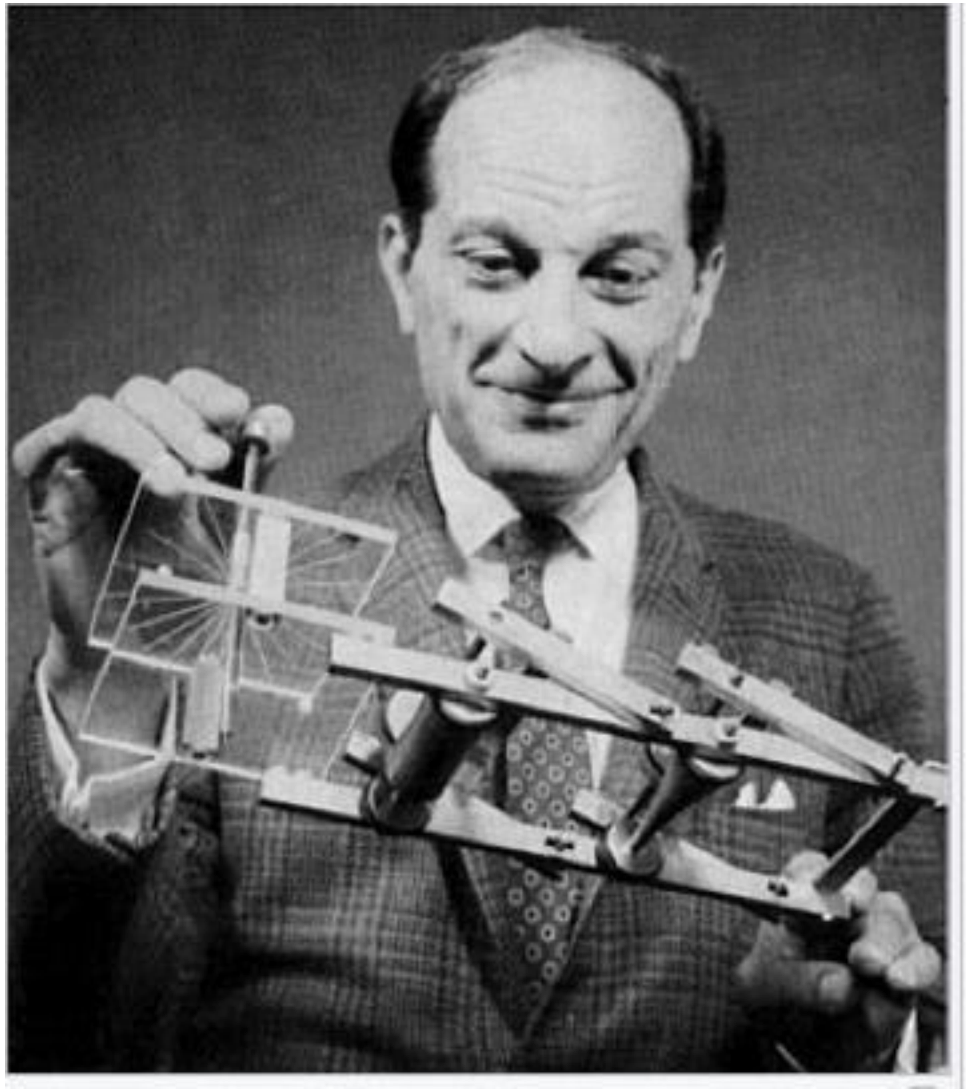
“The Fermiac mainly consists of three parts:

1. The *lucite platform*, that serves as a neutron direction selector

2. The *rear drum*, that measures the elapsed time based on the velocity of the particular neutron in question

3. The *front drum*, that measures the distance traveled by the neutron between subsequent collisions based on neutron velocity and the properties of the material being traversed”

[(1)] From: F.Coccetti, 2016



Stan Ulam with the FERMIAC in his hand, the analog computer invented by Fermi for neutron transport study (from: F. Coccetti, 2016)

The Encounter with Walter Ralph Nelson

From left to right: Walter Ralph Nelson, Alan Nahum, Alberto Del Guerra in front of Nelson's house at Palo Alto

- **The Ettore Majorana Center, ERICE (TP), Italy**

Director of the Center: Antonino Zichichi

- **The International School of Radiation Damage and Protection**

Director of the School: Alessandro Rindi (LBL, USA)

First Course in 1976

- **Advances in Radiation Dosimetry and Medicine**

Director of the Course: Ralph Thomas (LBL,USA)

*Speakers: J.V.Bailey, S.B:Curtis, E.Freytag, P.J.Gollon, M.Ladu, **W.R.Nelson**, M.Pelliccioni, **V.Perez-Mendez**, S.Pszona, H.H.Rossi, J.Routti, G.R. Stevenson*

Second Course in 1978

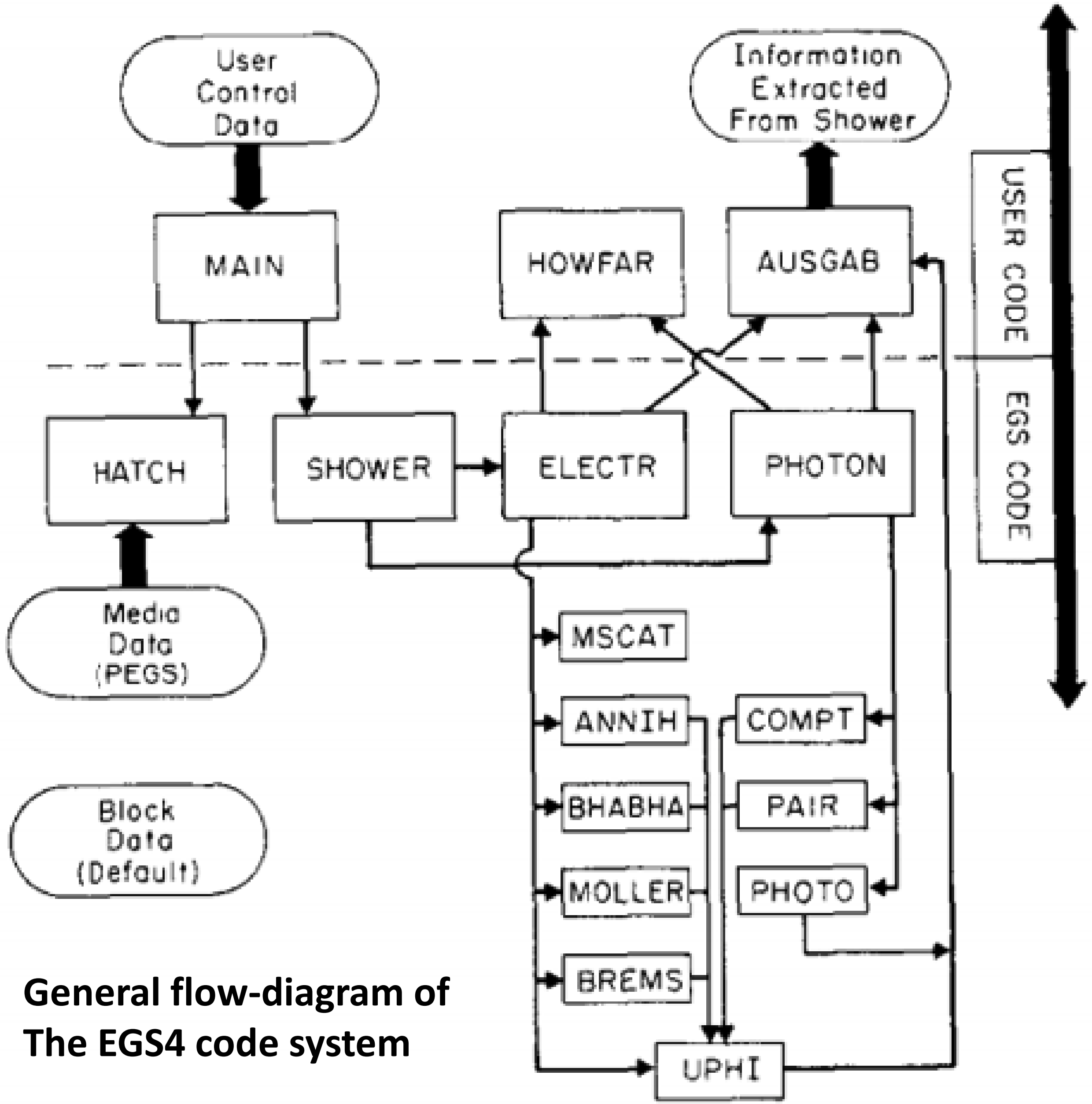
- **Computer Techniques in Radiation Transport and Dosimetry**

Directors of the Course: W.R.Nelson and T. Jenkins (STANFORD,USA)

*Speakers: G.R.Stevenson, **K,O'Brien**, W.W.Engle,**T.A.Gabriel**, C.Ponti, **W.R.Nelson, A.Van Ginneken, T.Amstrong, J.Ranft**, J.T.Routti, T. Nakamura*

*Monte Carlo programs discussed: (n-γ transport) ANISN,DOT, MORSE; (e-γ) EGS,ETRAN (with the **First Medical Applications**); (Hadronic cascade) AEGIS,CASIM, FLUKA, HETC*

Why did I fall in love with EGS?



General flow-diagram of The EGS4 code system

Our first application of EGS4: 90° Compton Scattering Tomography [1,2]

The principle of this technique is to irradiate a biological target with a narrow monoenergetic X- or γ-ray beam (100-2000 keV) and to detect the fluence of photons scattered into a well defined solid angle in order to obtain information on the mass density of the target.

Since the dominant process is Compton scattering, the fluence is proportional to the electron density, hence to the mass density. Original application was in densitometry as an alternative technique to trasmission densitometry.

The COSCAT experiment

Application to pulmonary studies at the CNR Institute of Physiology (Pisa, Italy): line source, 90° scattering, gamma camera.

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(1) R.L.Clark and G. Van Dick, Phys. Med. Biol. 1959(4),159-166

(2) J.J.Battista and M.J.Bronskill, Phys. Med. Biol. 1978(23), 81-99

90° Compton Tomography: the COSCAT experiment

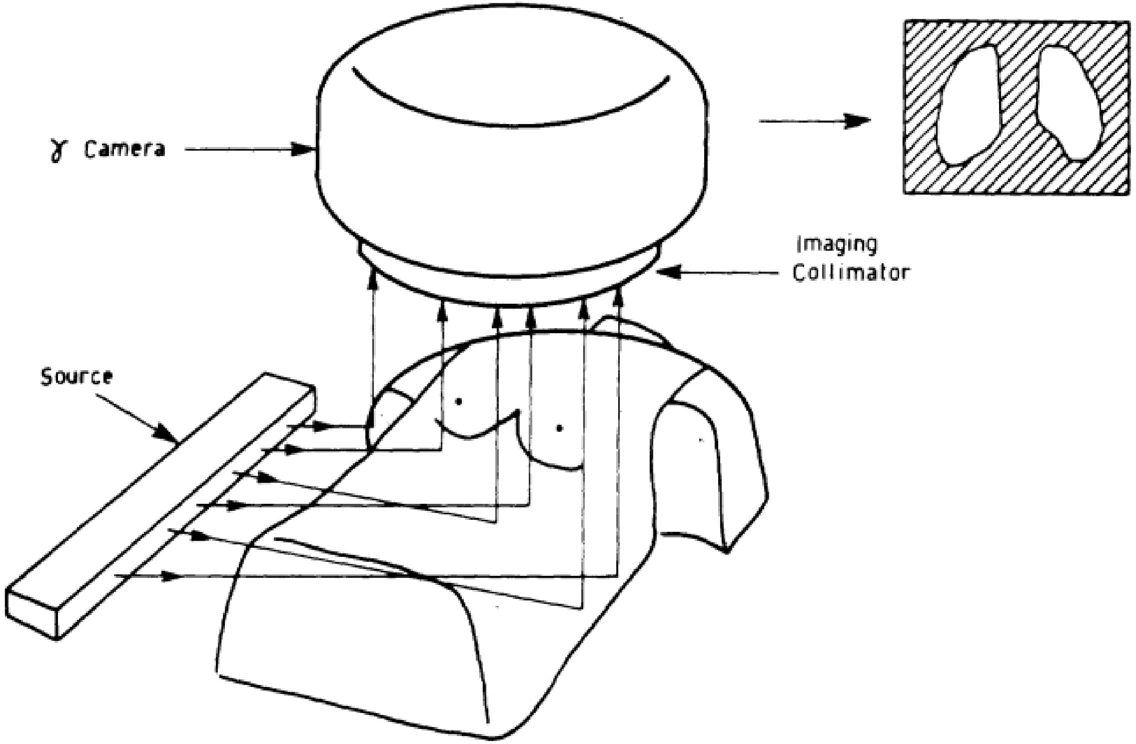
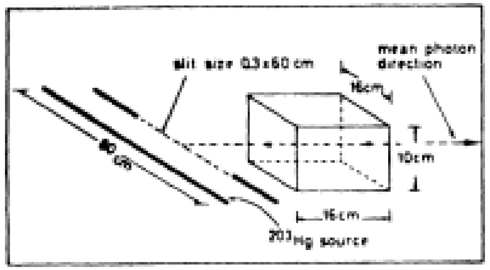


Fig. 1. Schematic drawing of the COSCAT apparatus: a ^{203}Hg line source collimated to a narrow planar beam irradiates a section of the human thorax; a large-field gamma camera detects the 90° Compton-scattered photons.

A. Del Guerra, et al., "*A Detailed Monte Carlo Study of Multiple Scattering Contamination in Compton Tomography at 90*", IEEE Transactions on Medical Imaging, vol. 1(2), 1982,147-152.



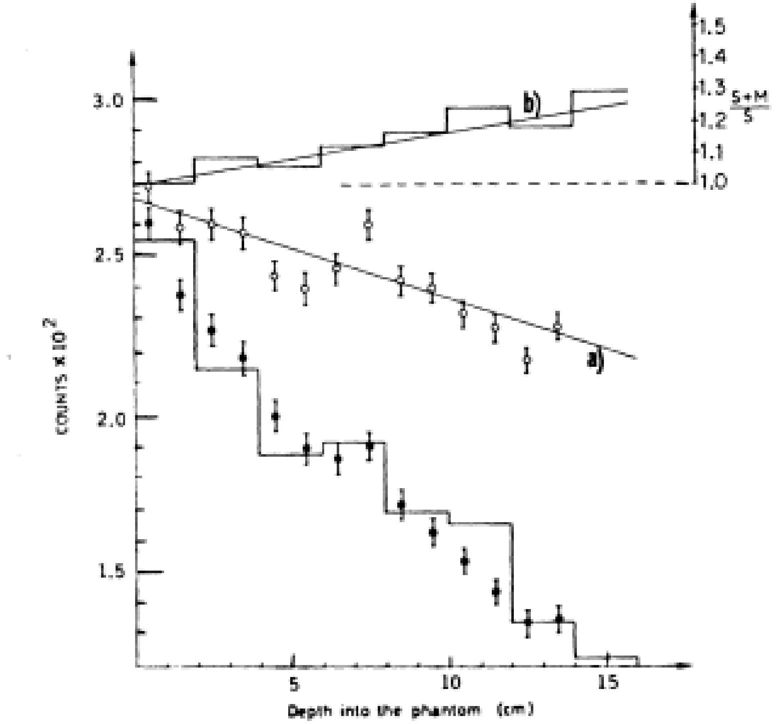


Fig. 8. Comparison of the Monte Carlo results with the experimental data taken with a sawdust phantom (density 0.3 g/cm^3) as described in the inset. The solid circles are the experimental raw data, and the superimposed histogram is the Monte Carlo simulation. The open circles are the experimental data after the attenuation correction has been applied and the solid line *a*) is a linear fit to these points. The solid line *b*) is the effect of applying a further geometric correction for the beam divergence. The total-to-single scattering ratio, as obtained by Monte Carlo calculation, is also superimposed as a histogram (right-hand scale).

The HIgh Spatial resolution Positron Emission Tomograph (HISPET)

A Hexagonal Positron Emission Tomography camera based on MWPC [1]

Expected figures of merit:

1-High Spatial Resolution: few mm (FWHM)

2- Long axial coverage: 45 cm

3- Low cost: gas chamber w/ lead-glass tube converter, instead of scintillator/PM

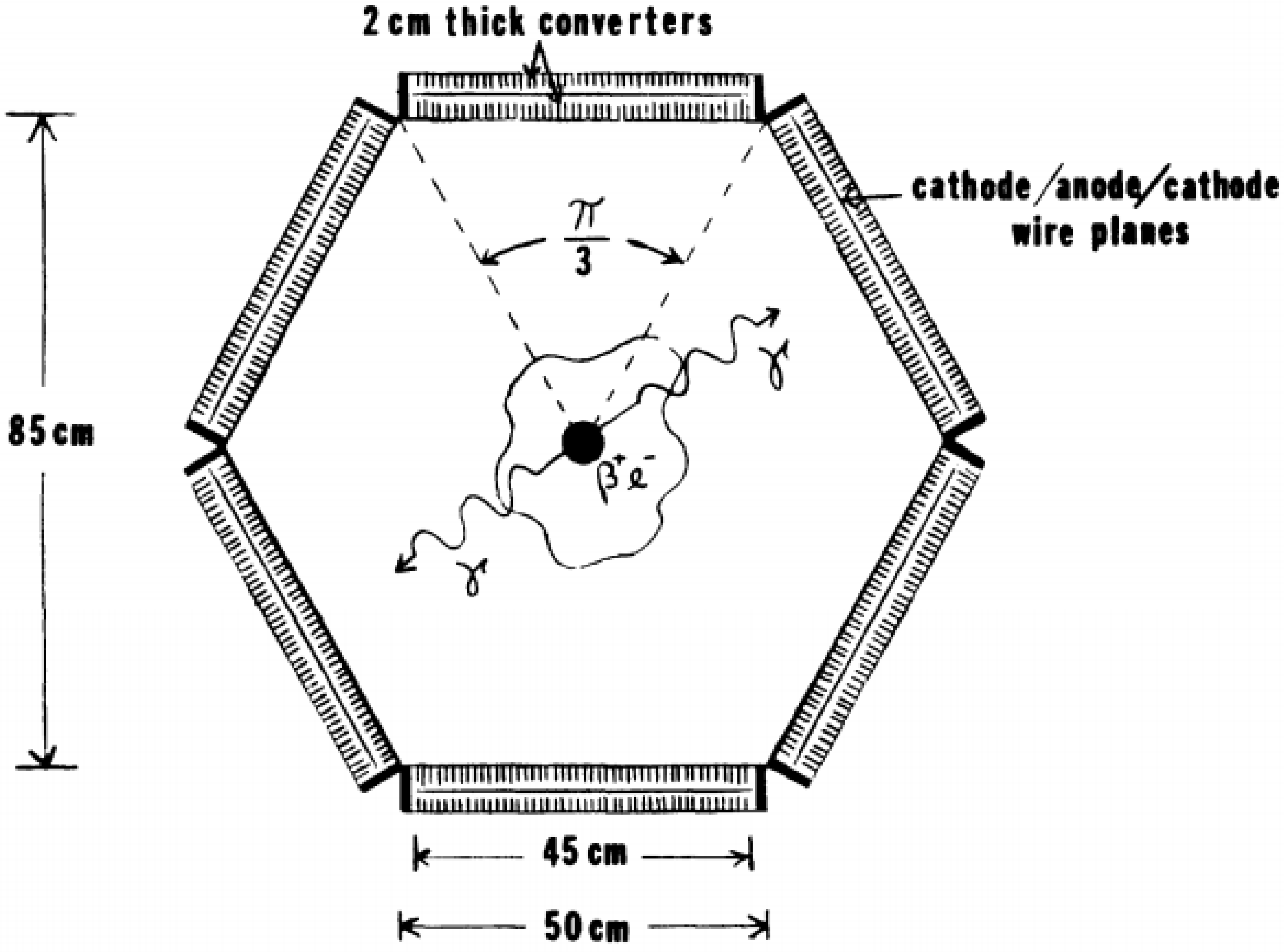


Fig. 7. Proposed Positron Camera made of six modules arranged to form a hexagonal prism. Each module has a 45 × 45 cm^2 active area and has two 2-cm thick lead glass tube converters.

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(1) A.Del Guerra et al., *" Medical Positron Imaging with a Dense Drift Space Multiwire Proportional Chamber",* IEEE TMI,1(1) 1982, 4-11

The nightmare of the simulation

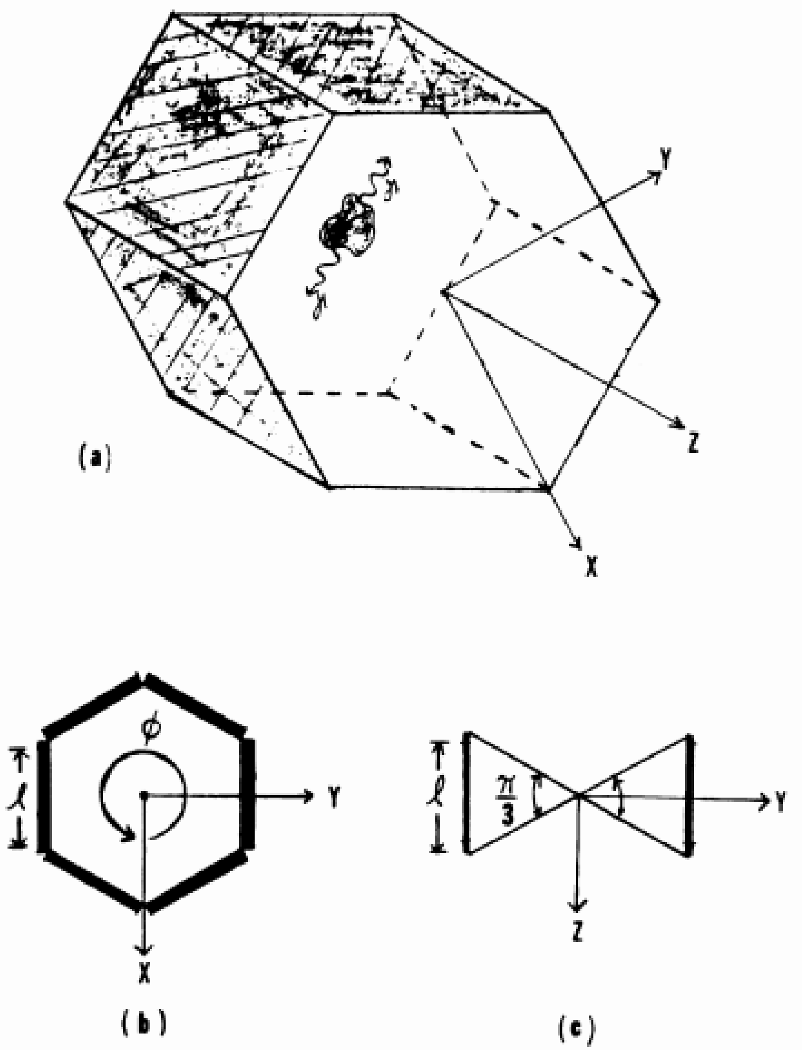
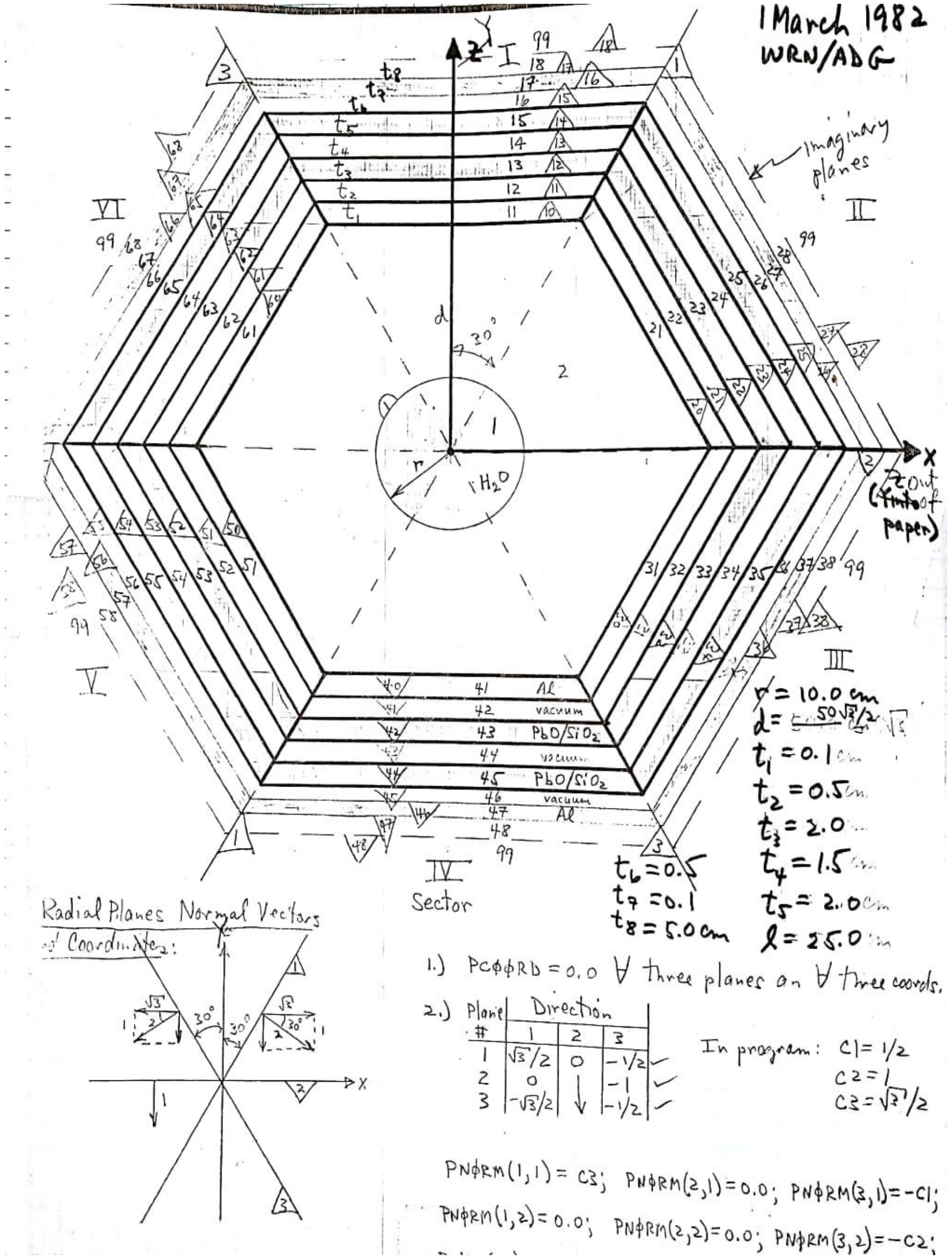


Fig. 1. A hexagonal-type multiplanar positron camera: a) perspective view, b) plan view, c) cross view.



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"*****************************************************************"
"**************************  STANFORD LINEAR ACCELERATOR CENTER  *"
"***    U C P E T 0 7    ***                                      *"
"**************************  EGS4 USER CODE -- 22 AUG 1983/2200  *"
"*****************************************************************"
"                                                                 "
"  PROGRAMMERS:  WALTER R. NELSON                                 "
"                RADIATION PHYSICS GROUP                          "
"                STANFORD LINEAR ACCELERATOR CENTER               "
"                STANFORD, CA 94305                               "
"                U.S.A.                                           "
"                                                                 "
"                AND                                              "
"                                                                 "
"                ALBERTO DEL GUERRA                               "
"                ISTITUTO DI FISICA                               "
"                UNIVERSITA DI PISA                               "
"                PIAZZA TORRICELLI 2                              "
"                I-56100 PISA                                     "
"                ITALY                                            "
"                                                                 "
"*****************************************************************"
"                                                                 "
"  PROGRAM:      UCPET07 (MORTRAN <FM>)  (ADAPTED FROM UCPET06)   "
"                                                                 "
"                EGS4 USER CODE TO SIMULATE POSITRON EMISSION     "
"                TOMOGRAPHY IN A HEXAGONAL DETECTOR ARRAY OF SIX  "
"                MODULES SURROUNDING A SPHERICAL LOW Z PHANTOM.   "
"                EACH MODULE HAS ELEVEN LAYERS CONSISTING OF:     "
"                  AL/VAC/CONV/VAC/CONV/VAC/CONV/VAC/CONV/VAC/AL  "
"                                                                 "
"                NOTE:  THIS USER CODE WAS ADAPTED FROM UCPET06   "
"                       IN ORDER TO ALLOW FOR A DETECTOR MODULE   "
"                       HAVING 'FOUR' CONVERTERS.                 "
"                                                                 "
"*****************************************************************"
"*****************************************************************"
"************* FEATURES IN THIS PARTICULAR VERSION ***************"
"*****************************************************************"

"                I.  P O S I T R O N   M O D E                   "

"        1.)  THE POSITRON ENERGY IS SAMPLED FROM A CDF TABLE"
"             (INITIALLY READ-IN) FOR ONE OF EIGHT ISOTOPES"
"             (C-11, N-13, O-15, F-18, NE-19, K-38, GA-68, AND RB-82)
."
"        2.)  THE POSITRON IS FOLLOWED IN THE PHANTOM UNTIL IT"
"             A) COMES TO REST (K.E. CUT=10 KEV) AND PRODUCES"
"             TWO 511 KEV ANNIHILATION PHOTONS, B) ANNIHILATES"
"             IN FLIGHT, OR C) LEAVES THE PHANTOM."
"        3.)  IN THE ABOVE 'POSITRON TRANSPORT' MODE, ALL"
"             SECONDARIES (GAMMA AND CHARGED) ARE DISCARDED."
"             NO PARTICLES ARE FOLLOWED OUTSIDE THE PHANTOM"
"             REGION IN THIS MODE.  ONCE ANNIHILATION HAS"
"             OCCURED, THE 'TWO-GAMMA' MODE TAKES OVER."
"        4.)  THE STATE FUNCTION FOR EACH OF THE PRODUCED"
"             GAMMAS IS SAVED FOR TWO SUBSEQUENT CALLS TO"
"             SUBROUTINE SHOWER IN THE 'TWO-GAMMA' MODE."
"             THE STARTING COORDINATES OF THE TWO GAMMAS CAN"
"
"             BE FORCED (IPOSRA=0) TO THE STARTING COORDINATES"
"             OF THE POSITRON IN ORDER TO STUDY ZERO RANGE EFFECTS."
"        5.)  THE BACK-TO-BACK NON-LINEARITY OF THE TWO GAMMAS"
"             THAT ARE PRODUCED WHEN ANNIHILATION OCCURS AT"
"             REST IS ACCOUNTED FOR (ITHETA > 0) BY SAMPLING A"
             FUNCTION USING A CDF TABLE (ALSO READ-IN INITIALLY)."

"                II.  T W O - G A M M A   M O D E                 "

"        1.)  IN THE 'TWO-GAMMA' MODE, THE PHOTONS ARE FOLLOWED"
"             AS THEY SCATTER AND/OR INTERACT IN EITHER THE"
"             PHANTOM (ICOMPT > 0) AND/OR THE DETECTOR PROPER."
"             THEY ARE DISCARDED WHEN THEY FALL BELOW A CUTOFF"
"             OF 100 KEV."
"        2.)  ALL CHARGED PARTICLES THAT ARE PRODUCED IN THE"
"             PHANTOM ARE IMMEDIATELY DISCARDED, BUT THOSE THAT"
"             ARE PRODUCED IN THE DETECTOR ARE TRANSPORTED UNTIL"
"             THEY FALL BELOW:   ECUT=TMAX(ISOTP)+1.022+0.001,"
"             WHERE TMAX IS THE MAXIMUM K.E. FOR THE PARTICULAR"
"             ISOTOPE CHOSEN."
"        3.)  A POSSIBLE CANDIDATE INTERACTION IS ONE THAT OCCURS"
"             IN ONE OF THE FOUR CONVERTERS WITH A CHARGED PARTICLE"
"             THAT HAS ENOUGH K.E. TO GET INTO A HOLE.  THIS IS"
"             DECIDED IN EITHER OF TWO WAYS:"
"               A) THE K.E. IS GREATER THAN A FIXED CUTOFF"
"                  ENERGY, CUTKE (ICUTKE=1), OR"
"               B) THE K.E. IS COMPARED AGAINST A PROBABILITY"
"                  TABLE BY SAMPLING METHODS (ICUTKE=0).  THE"
"                  USER CODE UCCELL4 WAS USED IN ORDER TO DETERMINE"
"                  THE DETECTION PROBABILITY TABLE FOR TWO HOLE"
"                  SIZES; I.E., 0.091/0.100 CM (IHOLE=1) AND"
"                  0.048/0.060 CM (IHOLE=2)."
"             IN EITHER CASE, WHEN MORE THAN ONE SUCH EVENT"
"             OCCURS IN ANY OF THE CONVERTERS, THE ONE CLOSEST"
"             TO THE 'WIRE PLANE' IS CHOSEN (I.E., CORRESPONDING TO"
"             THE SIGNAL THAT ARRIVES EARLIEST IN TIME)."
"        4.)  SUBSEQUENTLY, THE POINT OF INTERACTION IS TRANSLATED"
"             TO THE MIDDLE OF THE CONVERTER TO ACCOUNT FOR"
"             PARALLAX ERROR (IPARAL > 0) AND THE SPATIAL"
"             RESOLUTION OF THE DETECTOR IS SAMPLED AND"
"             INCLUDED (IDETEC > 0)."
"        5.)  AN ACCEPTABLE EVENT IS ONE IN WHICH COINCIDENCE"
"             INTERACTIONS OCCUR BETWEEN THE TWO GAMMAS IN"
"             DIRECTLY OPPOSITE HEXAGONAL SECTORS."
"        6.)  HISTOGRAMS ARE CREATED FOR:                          "
"               A) POSITRON K.E. DISTRIBUTION"
"               B) POSITRON RANGE (CROW FLIGHT)"
"               C) TWO-GAMMA ANGLE (BOTH AT REST AND IN FLIGHT)"
"               E) POINT SPREAD FUNCTION (NORMAL AND EXPANDED)"
"               F) LINE SPREAD FUNCTION (NORMAL AND EXPANDED)"
"             THE POINT AND LINE SPREAD FUNCTIONS ARE WEIGHTED"
"             IN ORDER TO ACCOUNT FOR PHASE SPACE (IDELTA > 0)."
"        7.)  A VERSATEC PLOT SHOWING THE TRANSPORT OF THE TWO"
"             GAMMAS IS PROVIDED ON REQUEST (IPLOT > 0)."

"*****************************************************************"
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RUNNING VERSION: 4 KS { UCPETCDF DATA
UCPET DATA

The simulation of the converter

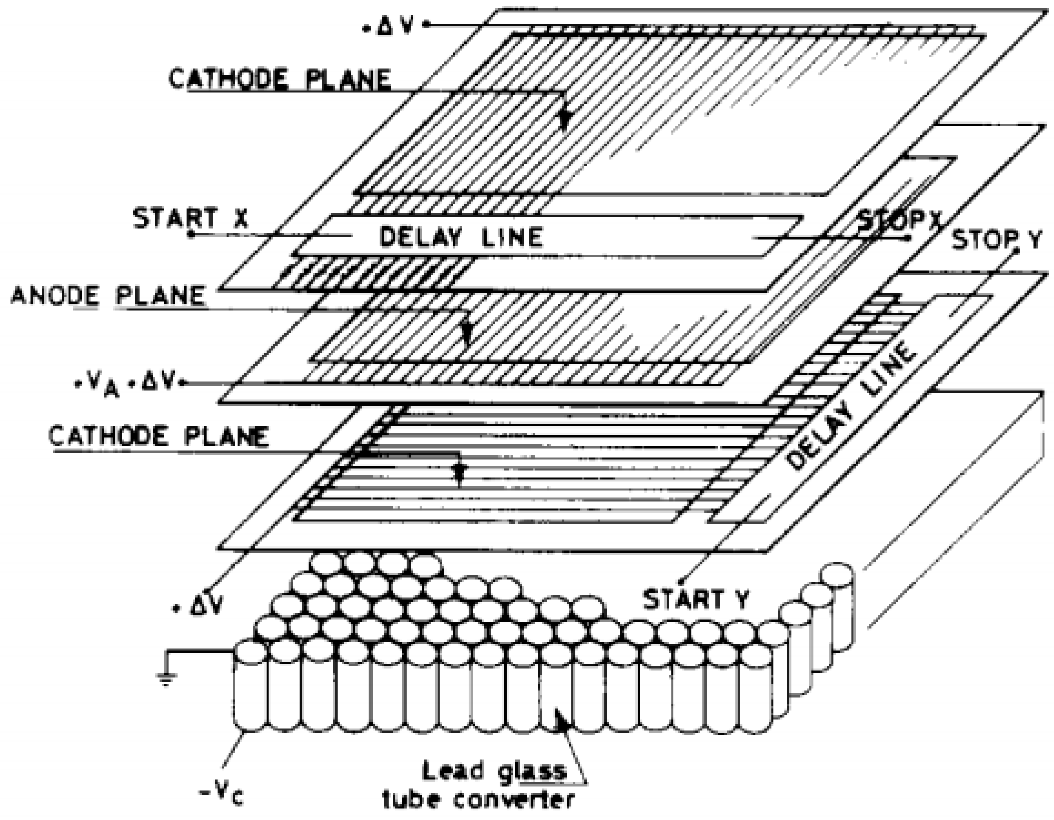


Fig. 1. Schematic drawing of a MWPC equipped with a lead glass tube converter plane for PET imaging.

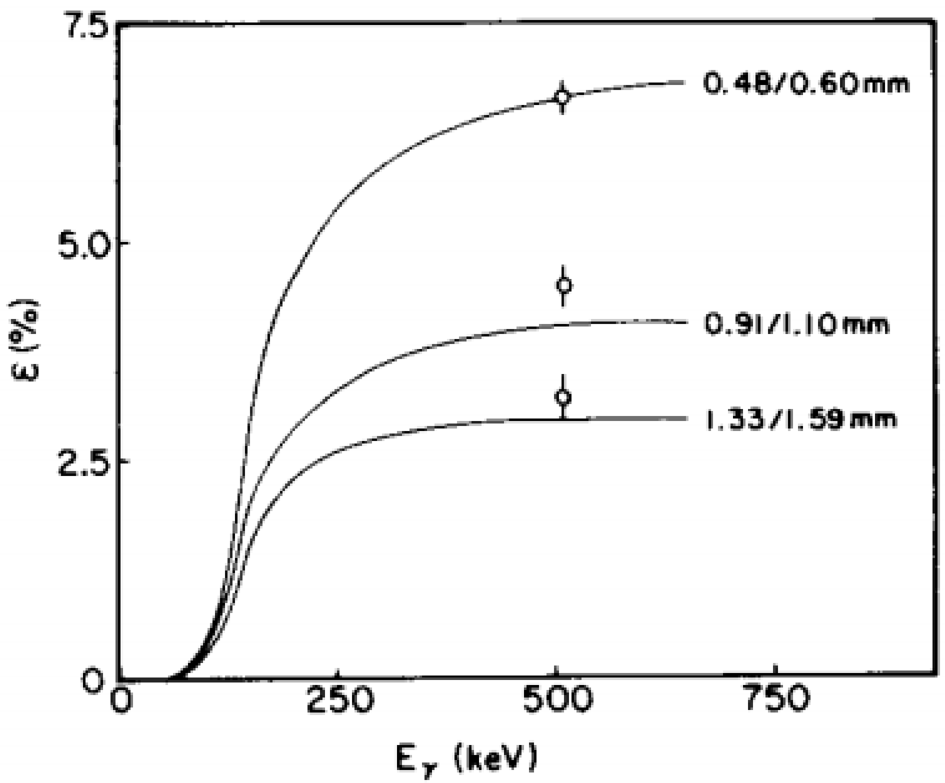


Fig. 2. Calculated efficiency of a 1 cm thick converter as a function of the photon energy (solid lines); ○ – experimental data.

A.Del Guerra et al., "*3-D PET with MWPCs: preliminary tests with the HISPET prototype*", Nuclear Instruments and Methods A269, 1988, 425-429.

HISPET Spatial resolution

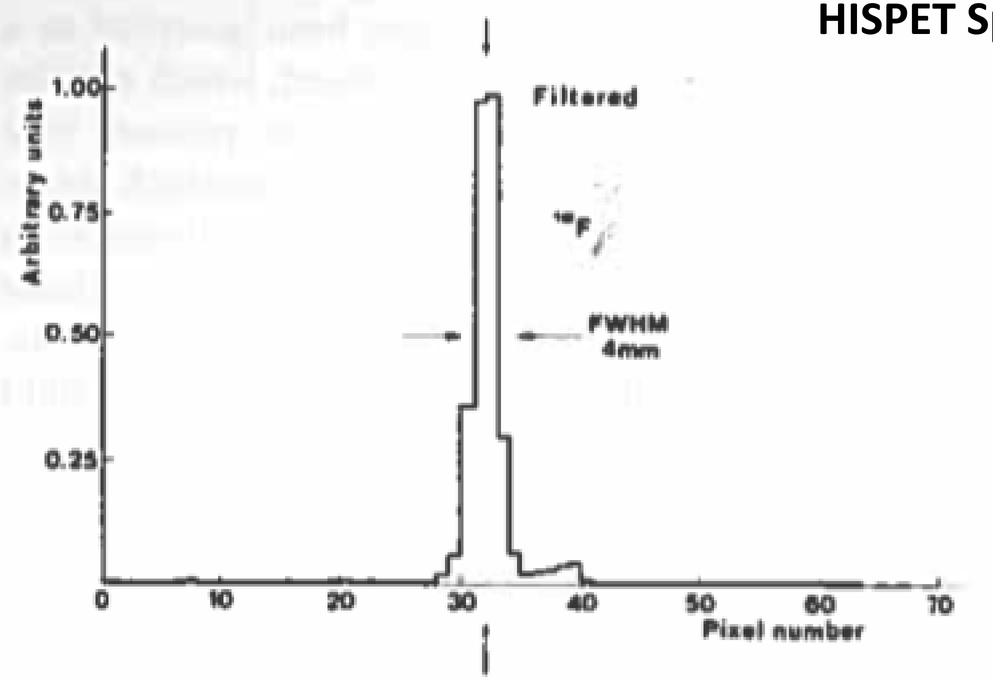
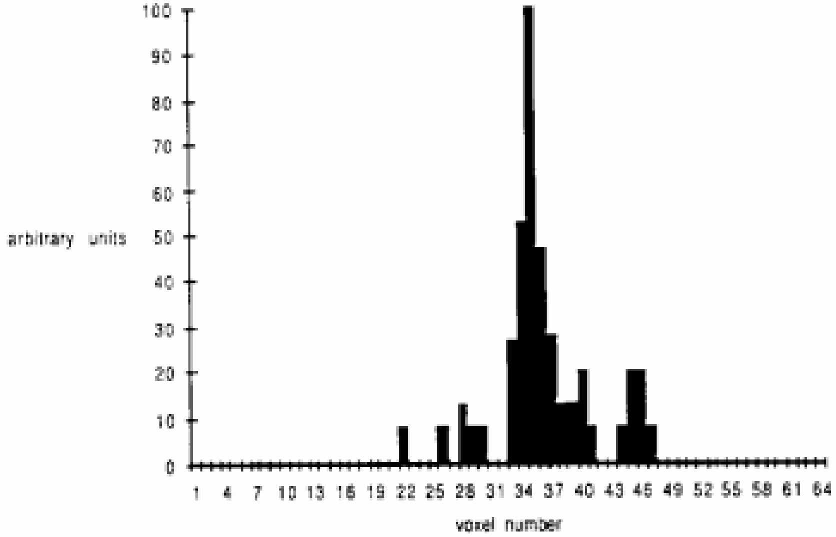


Fig. 6. Spatial resolution histogram of a pointlike ^{18}F source as obtained by the filtered back-projected algorithm.



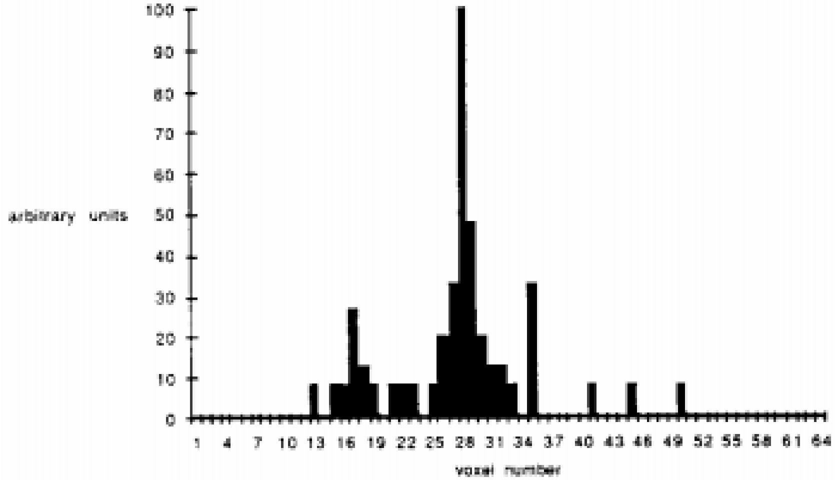
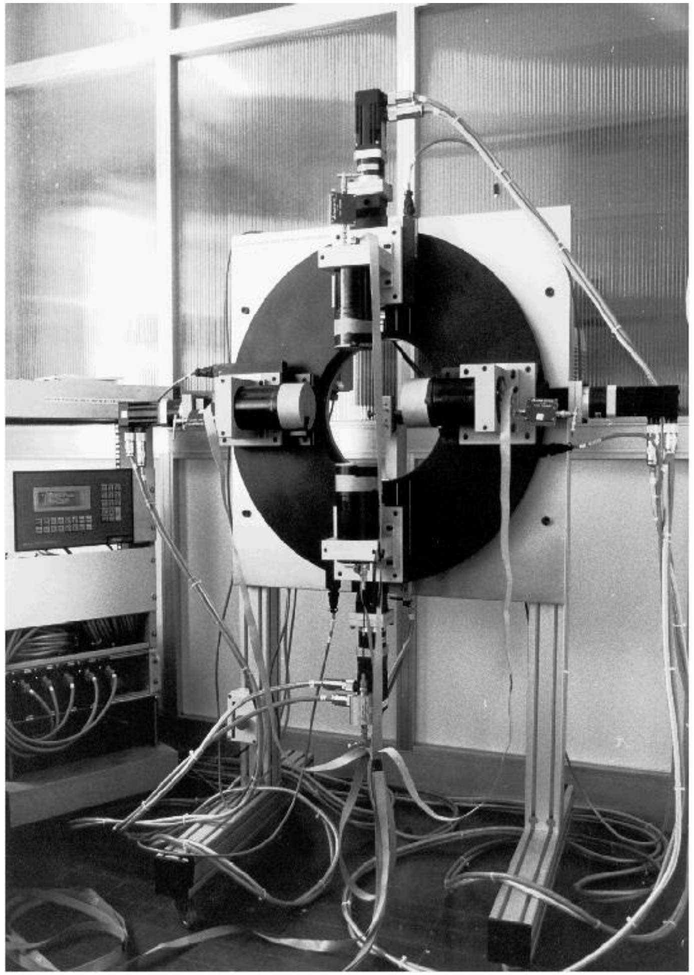


Fig. 7. Spatial resolution histograms along the y (top) and z direction (bottom) for a ^{22}Na pointlike source at the center of the HISPET prototype.

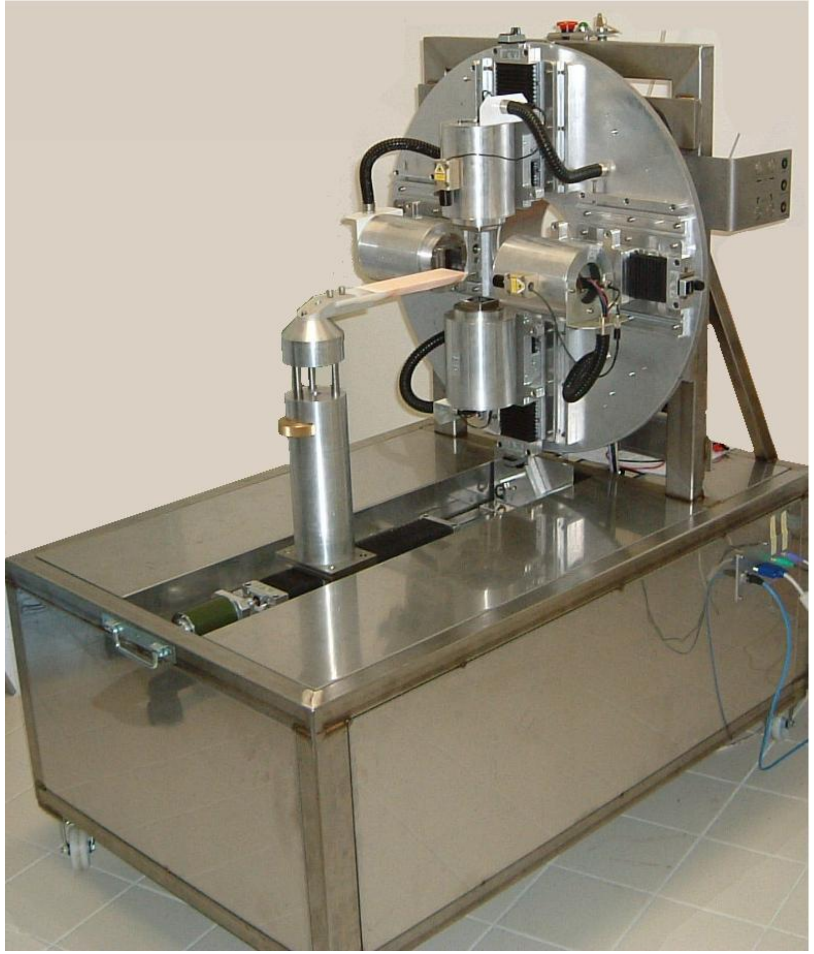
Left: Simulation results for a point-like source in the center of the complete HISPET tomograph: 4 mm (FWHM)

Right: Experimental results for the two planes only prototype: 8 mm FWHM (consistent with the simulation of the 2 plane prototype)

SMALL ANIMAL PET: YAPPET



The first research prototype
(University of Ferrara, 1998)



The first commercial prototype
(ISE, Pisa- University of Pisa, 2003)

Small scintillator matrix coincidence experiment vs simulation
(25 match-like 3x3x20mm^3 YAP cristals coupled to R2486-06 Hamamatsu PSPMT)

Pulse Height

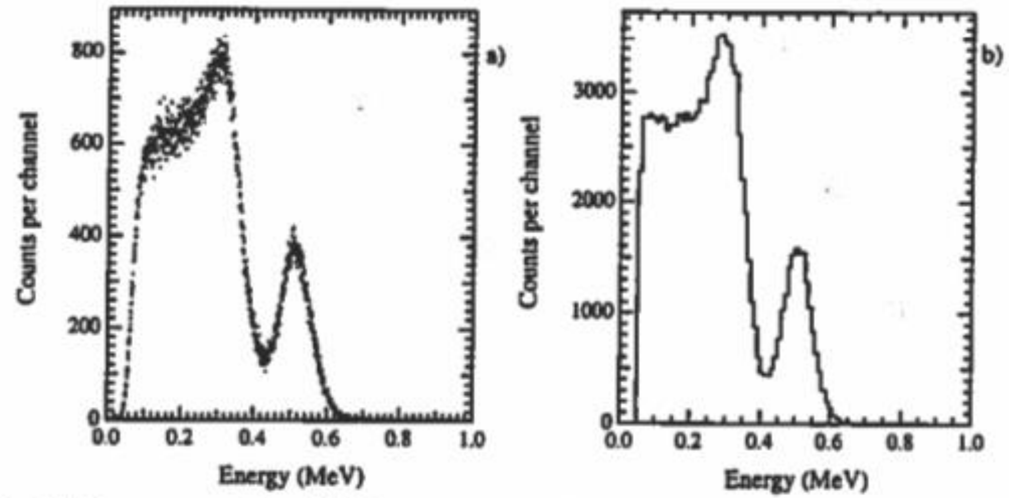


Fig. 1 Coincidence pulse height spectrum for a ^{22}Na source: experimental results (a) and Monte Carlo simulation (b).

Spatial Resolution

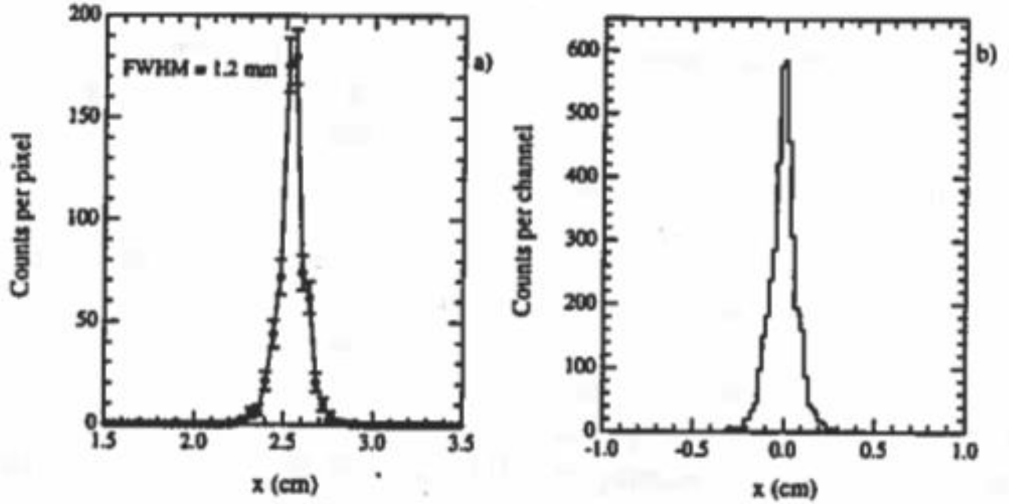


Fig. 2 Spatial resolution for a 0.8 mm diameter ^{22}Na source: experimental results (a) and Monte Carlo simulation (b).

D. Bollini, A. Del Guerra et al.,"*Sub-millimeter planar imaging with positron emitters: EGS4 code simulation and experimental results*," IEEE Transactions on Nuclear Science, 44(4),1997, 1499-1502.

The so-called first interaction method

Optimize the spatial resolution, by only using Compton interaction events and rejecting the photopeak events .

Make the pseudo-selection on the basis of the pulse-height.

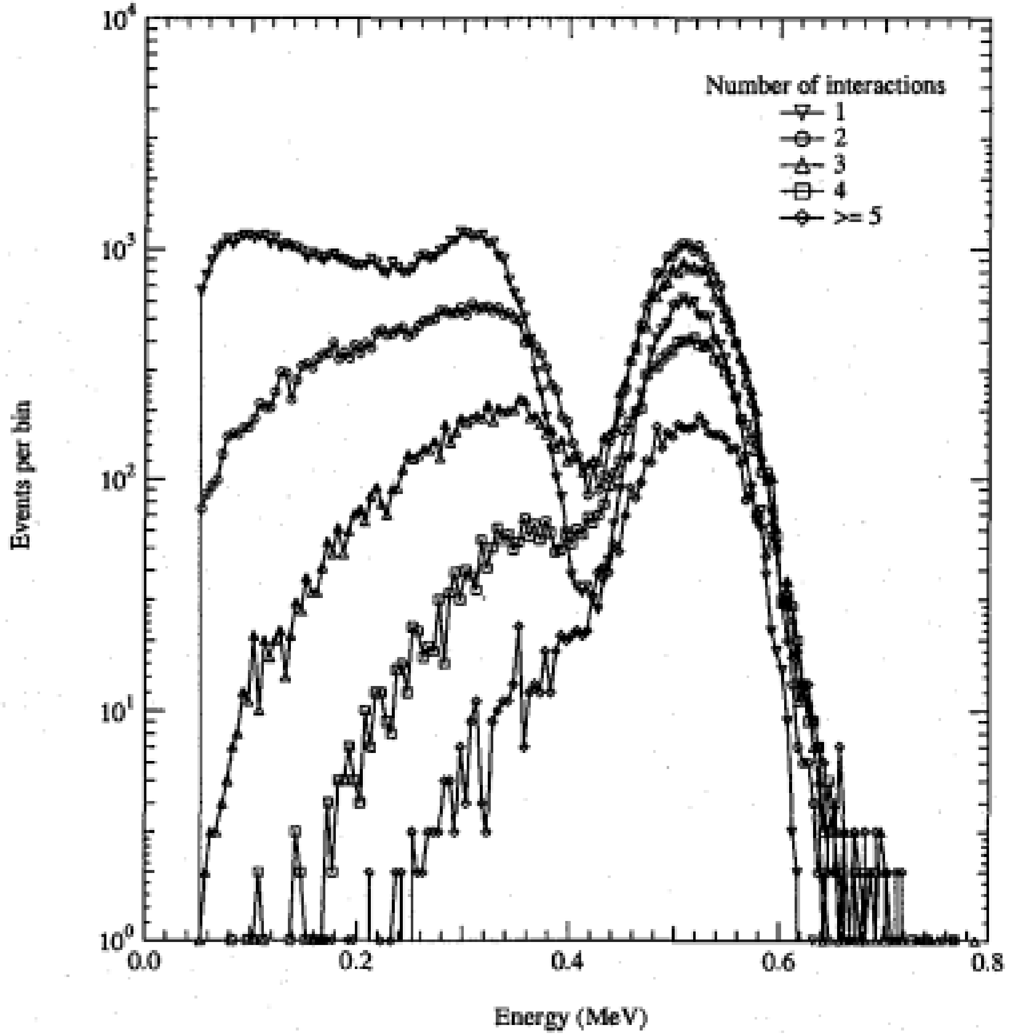


Fig. 2 Pulse height distributions as a function of number of interactions

A. Bevilacqua *et al.*, "*A 3-D Monte Carlo simulation of a small animal positron emission tomograph with millimeter spatial resolution*," IEEE Transactions on Nuclear Science, 46(3), 1999, 697-701.

Digital radiography with solid state detectors (Si/Ge/HgI_2/CdTe)

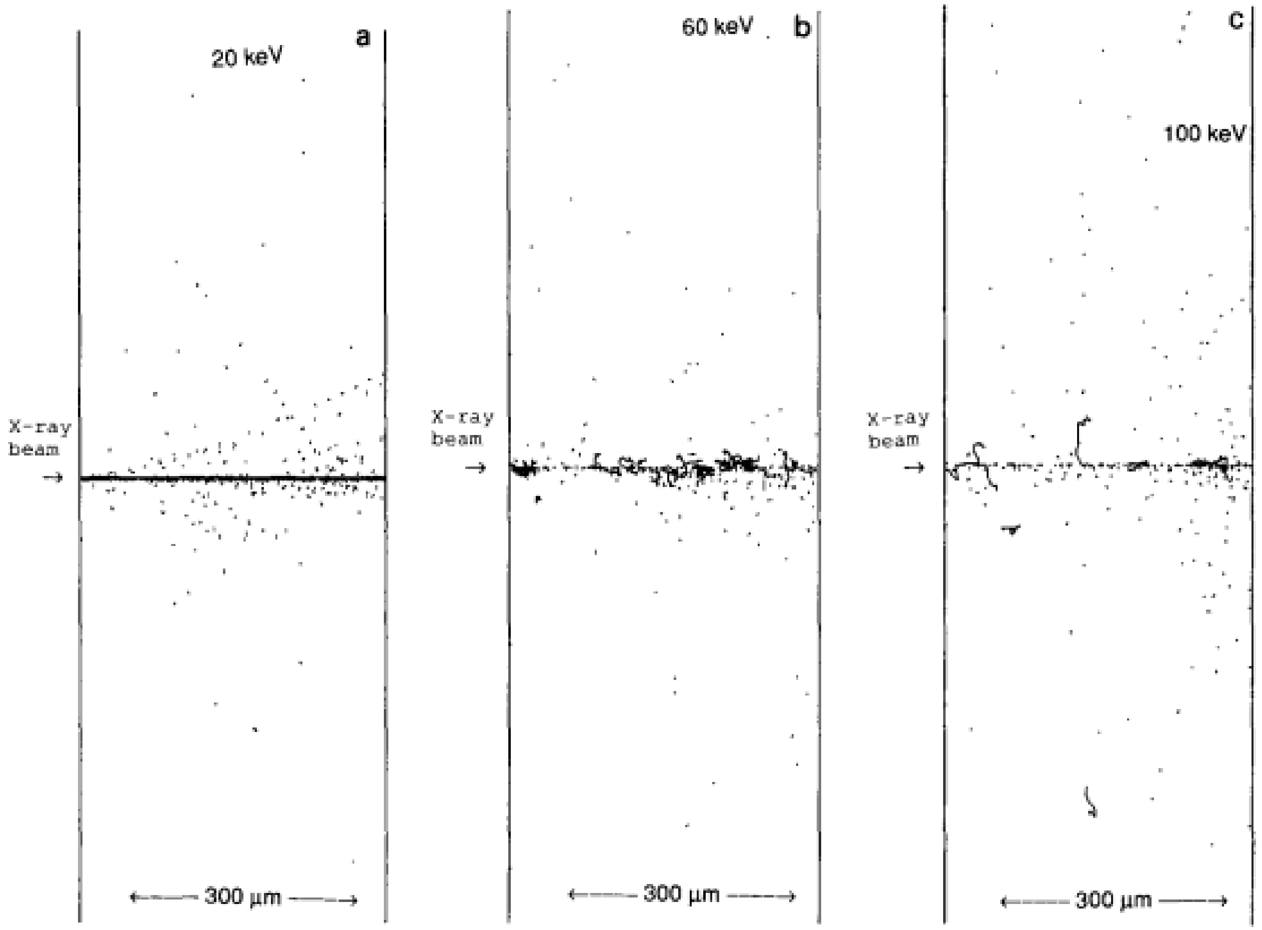
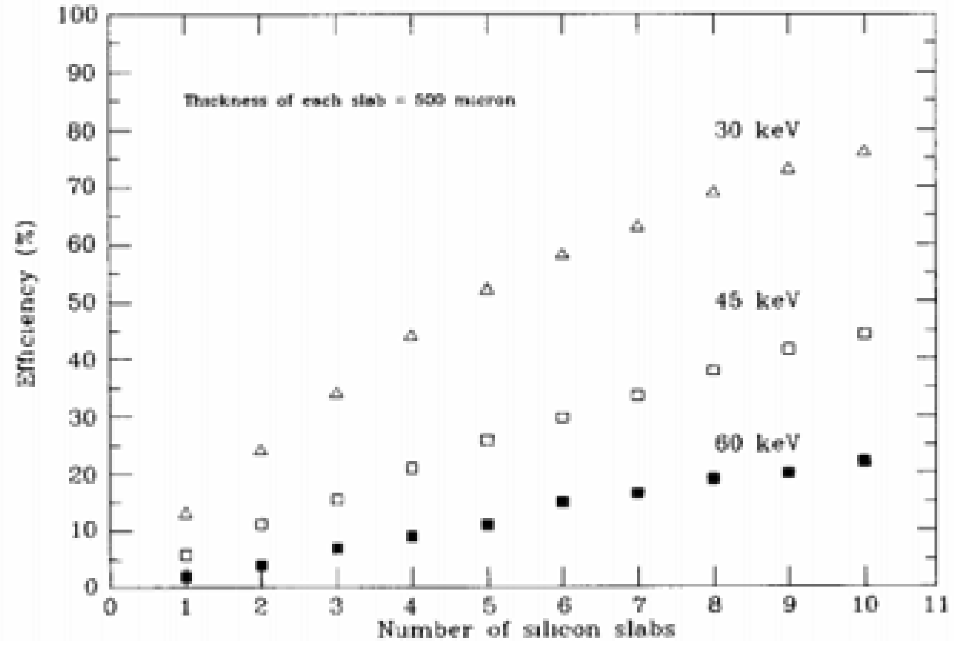
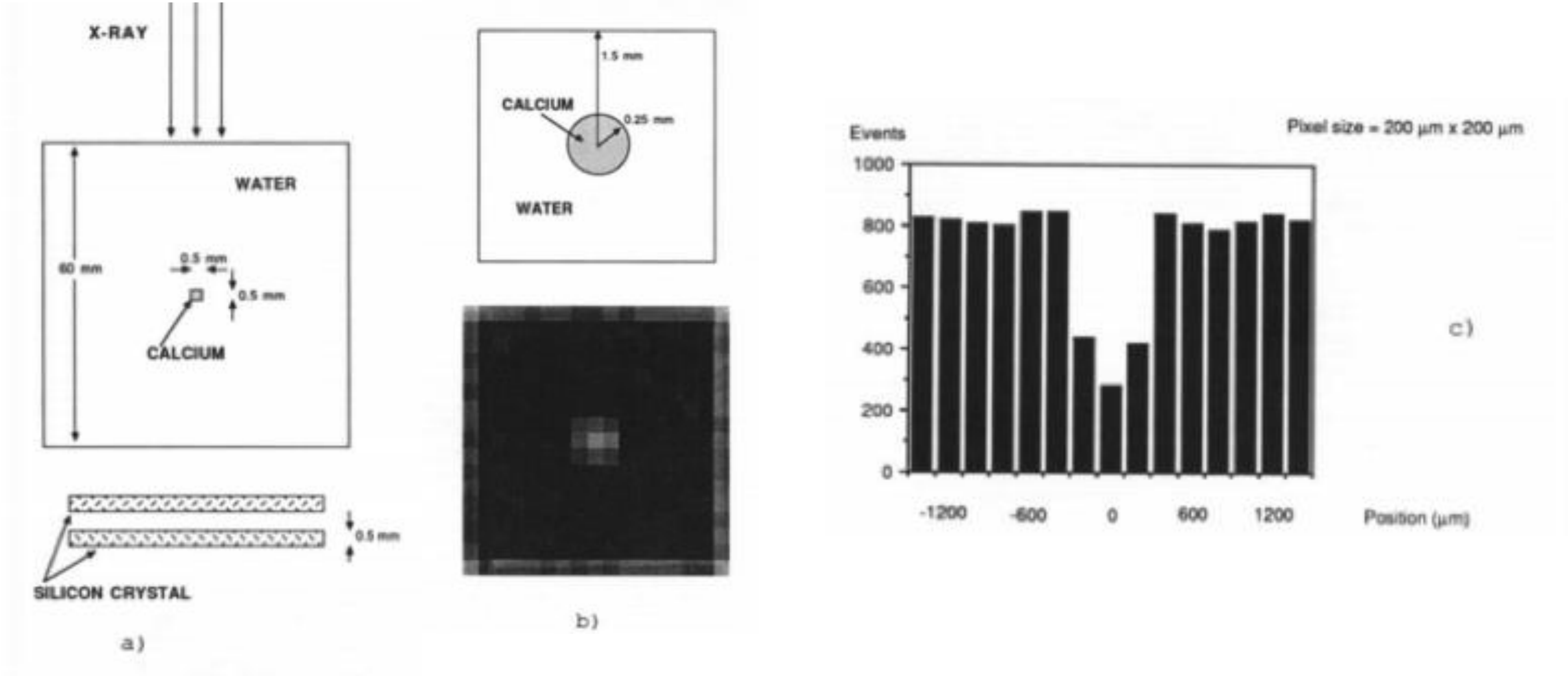


Fig. 2. Sample plots of photon (dots) and electron (solid) tracks as obtained with the SHOWGRAF package [5]. In the simulation a monochromatic pencil beam of 5000 photons impinges onto a 300 µm thick silicon crystal with infinite lateral dimensions: (a), (b) and (c) side view for an incident energy of 20, 60 and 100 keV, respectively. X- and Y-scale are the same.



Efficiency of a multilayers arrangement as a function of the number of slabs

W. Bencivelli, et al. , "*Use of EGS4 for the evaluation of the performance of a silicon detector for X-ray digital radiography*", Nuclear Instruments and Methods A, 305(3) 1991, 574-580.



Simulation of the imaging capability of a two-density phantom mimicking a breast calcification: (a) schematic drawing of the phantom and the two-slab detector; (b) 2D image of the phantom: cross view(top), grey-level representation as obtained from the simulation, pixel dimension 200x200 μm^2 (bottom); (c) profile cut through the calcification.

PET–based hadrontherapy treatment verification (PTRAN code)

Energy deposition (Ep=140.5 MeV) - Planar view **Energy deposition (Ep=140.5 MeV)- Lego plot**

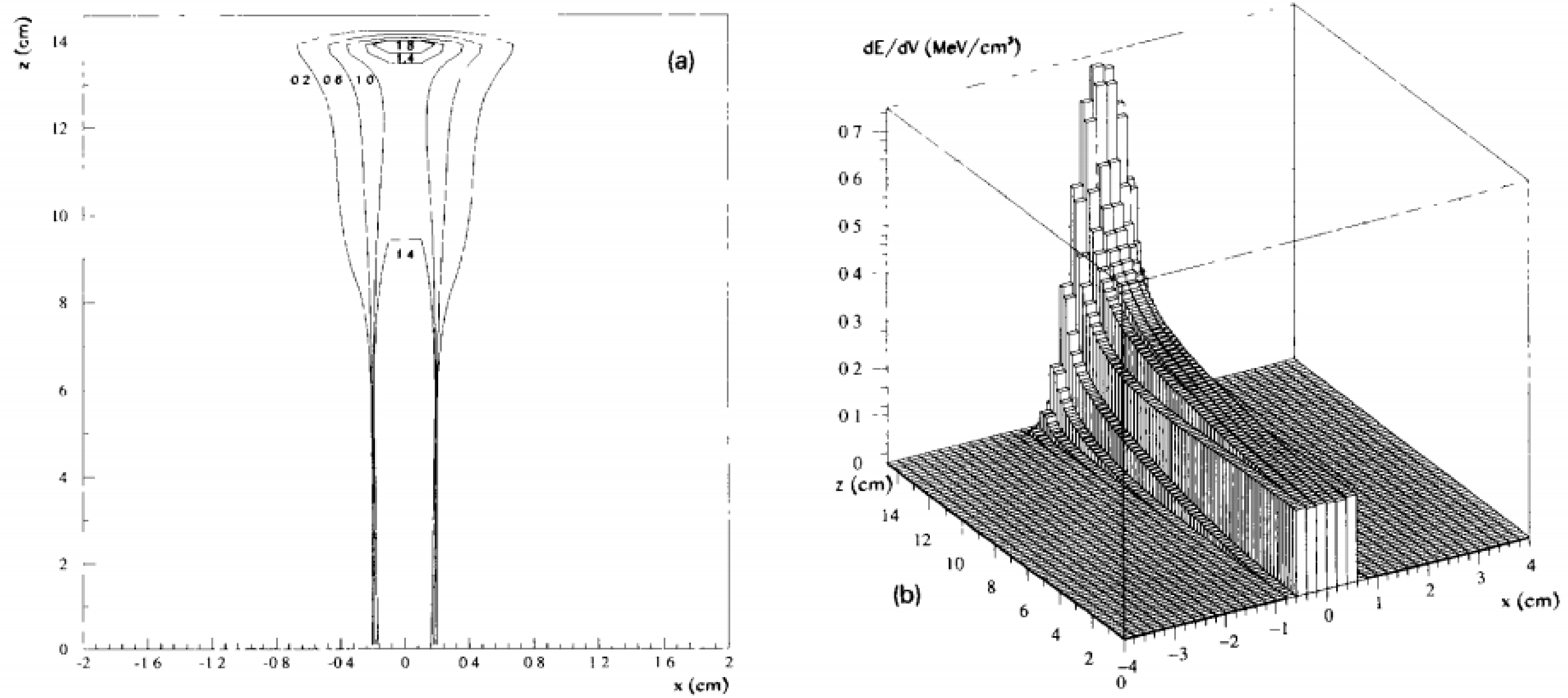


Fig. 3. Energy loss distribution in the zx plane (at $y = 0$), as obtained with a proton beam of 140.5 MeV in water: (a) isocontour plot for a 2 mm wide beam; (b) lego plot for a 12 mm wide beam.

A. Del Guerra, et al., "*A Monte Carlo simulation of the possible use of Positron Emission Tomography in proton radiotherapy*", Nuclear Instruments and Methods in Physics Research, A345(2), 1994, 379-384.

^{15}O activity distribution (Lego plot)

^{13}N activity distribution (Lego plot)

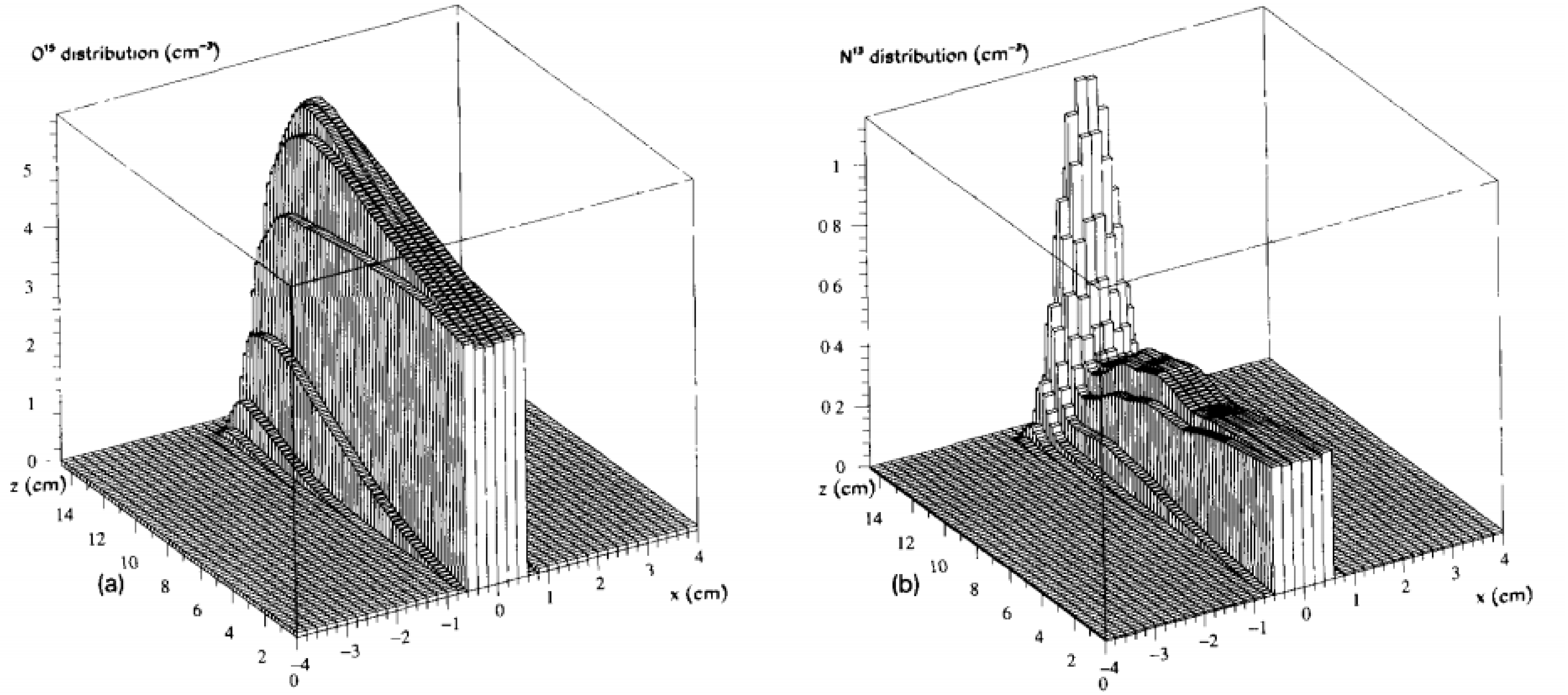
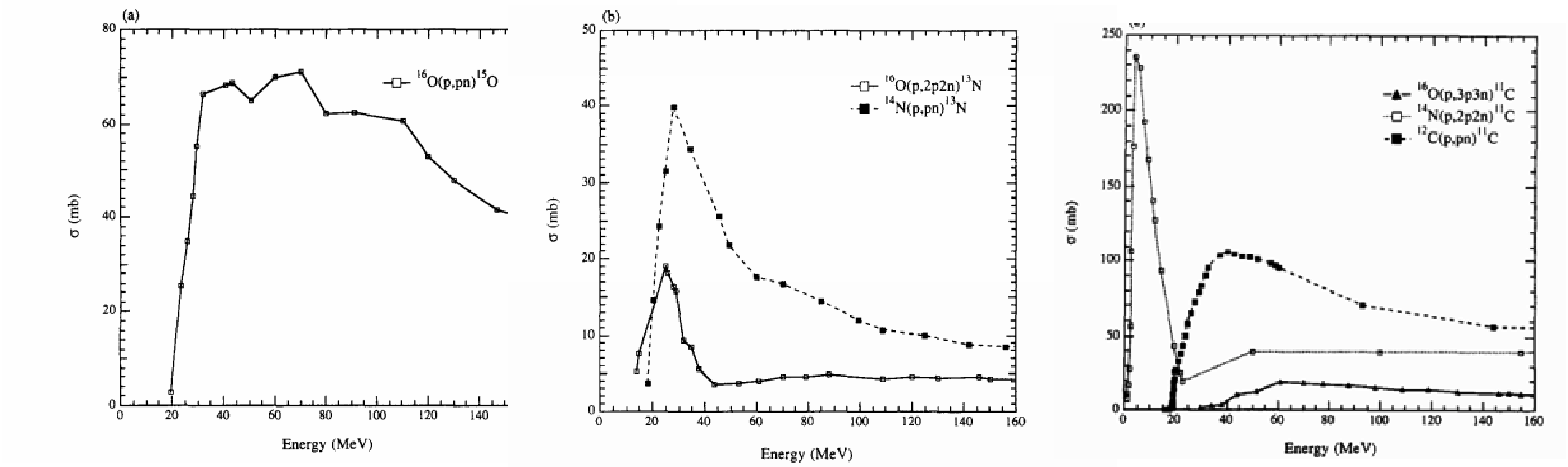


Fig. 6. (a) Distribution of ^{15}O nuclei as produced by 140.5 MeV protons in water along the *zx* plane at $y = 0$ for a 12 mm wide beam; (b) corresponding distribution of ^{13}N.

Rationale:
The p interactions within the human body produce β^+ emitters radioactive atoms. The activity distribution is somehow related to the dose distribution. In particular the activity fall-off can give an indication of the Bragg-peak



Positron Emitter nuclei production cross section vs proton energy for: (Left)^{15}O, (Center) ^{13}N, (Right) ^{11}C

A.Del Guerra, G. Di Domenico, D. Mukhopadhayay ,“*PET dosimetry in proton radiotherapy: a Monte Carlo study, In Applied Radiation and Isotopes*”, 48(10-12), 1997, 1617-1624.

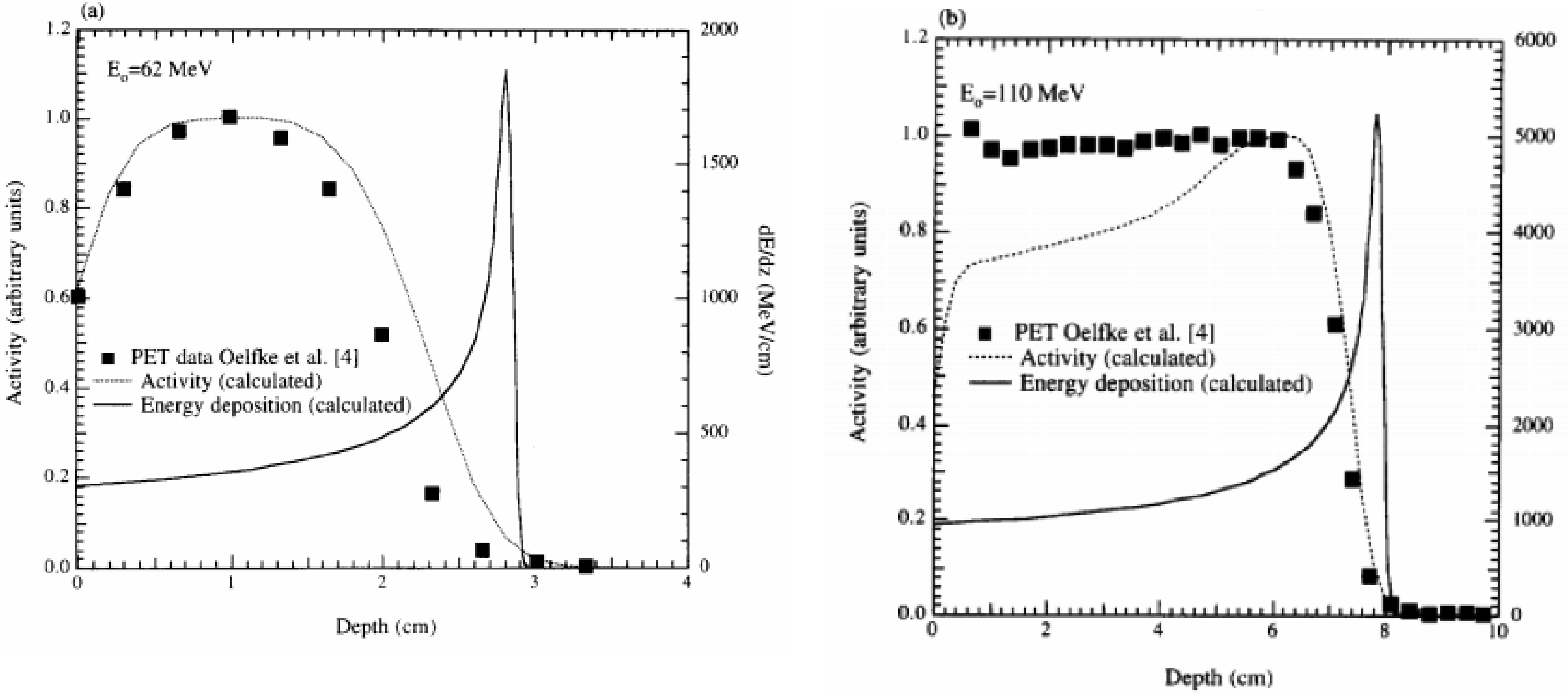
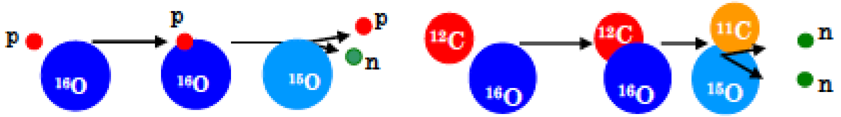


Fig. 5. Relative comparison between experimental data by Oelfke *et al*. (1996) and simulated activity curve. The calculated energy deposition vs *z* is also plotted. (a) After 23 min of irradiation with 62 MeV protons in Lucite; scan acquisition started 40 min after the end of irradiation. (b) After 26 min of irradiation with 110 MeV protons in Lucite; scan acquisition started 24 min after the end of irradiation.

PET–based hadrontherapy treatment verification (state of the art)



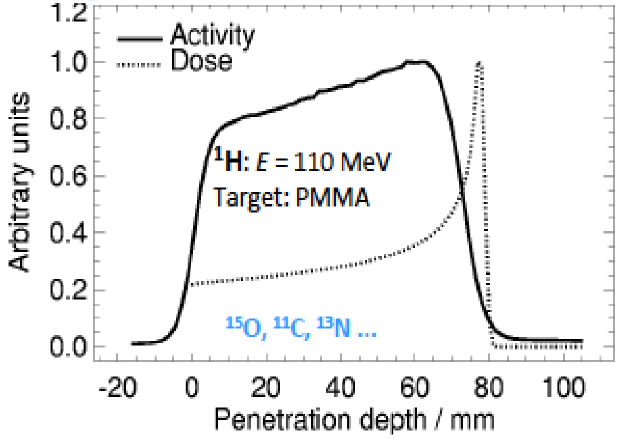
Main contribution:

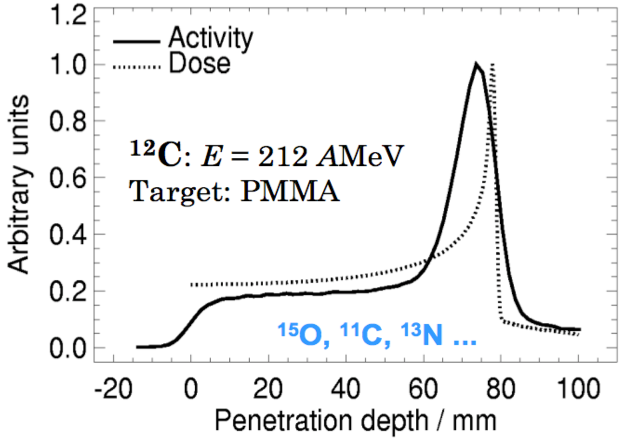
^{11}C ($T_{1/2} \approx$ 20.3 min)

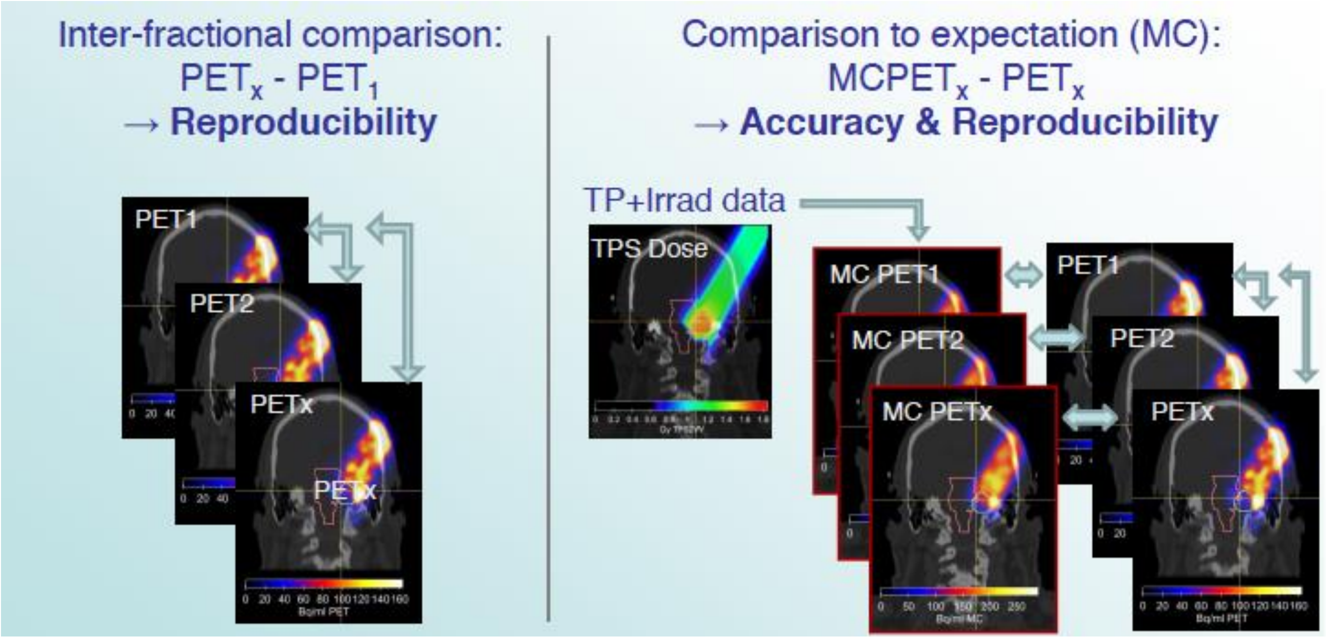
^{10}C ($T_{1/2} \approx$ 19.3 s)

^{15}O ($T_{1/2} \approx$ 2.0 min)

^{13}N ($T_{1/2} \approx$ 10.0 min)







J Pawelke et al., Proceeding: Ion Beams in Biology and Medicine (IBIBAM), 26.-29.09.2007, Heidelberg, Germany

Courtesy of J. Bauer, HIT

The InSide Project

(see talk by Elisa Fiorina – Tuesday 9.30 - Aula Magna)

DOSE PROFILER
Prompt secondary particles imaging

BI-MODAL IMAGING SYSTEM
for particle range monitoring and verification

IN-BEAM PET
induced β^+ activity imaging

BRAIN PET: the TRIMAGE project

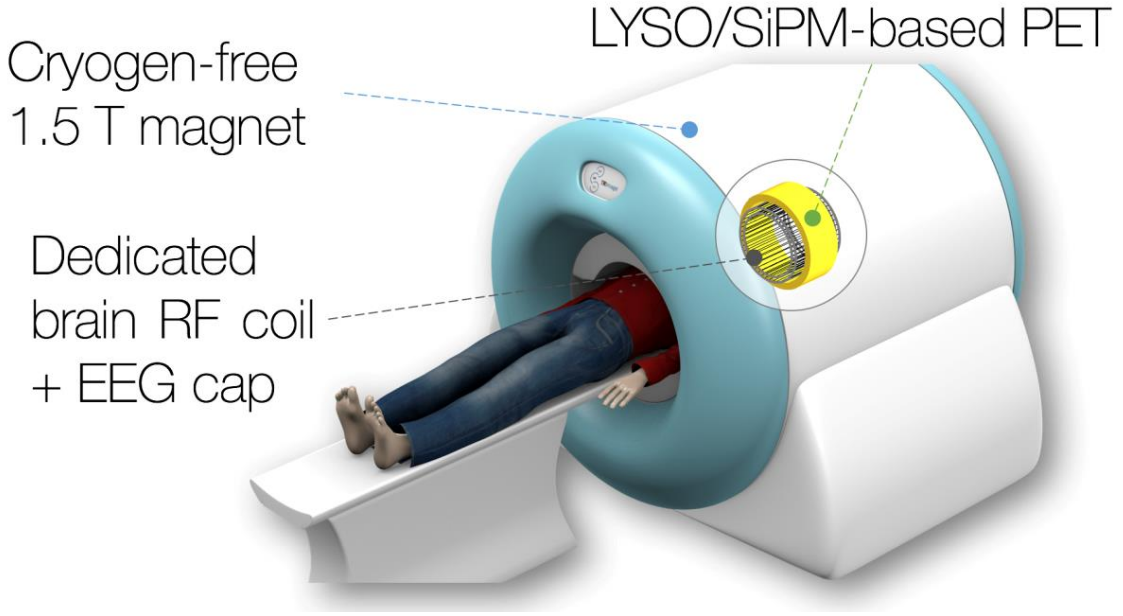
The MR system will be based on a very compact 1.5 T cryogen free superconducting magnet, with an integrated PET system:

- Reduction in cost for installation and maintenance.

- Reduction in claustrophobia effects.

- Better physiological measures since the patient’s arm will be accessible.

- High sensitivity of the PET detector



The PET System Monte Carlo Performance

- High Spatial resolution 2 mm (DOI)
(a factor 2 better than a clinical PET/MR)

- High Efficiency (6.8% at CFOV)
(at least a factor 3 better than a clinical PET/MR)

- Axial FOV = 150mm
(almost a factor 2 shorter than clinical PET/MR)

-Transaxial FOV =110 mm radius
(ok for the head)

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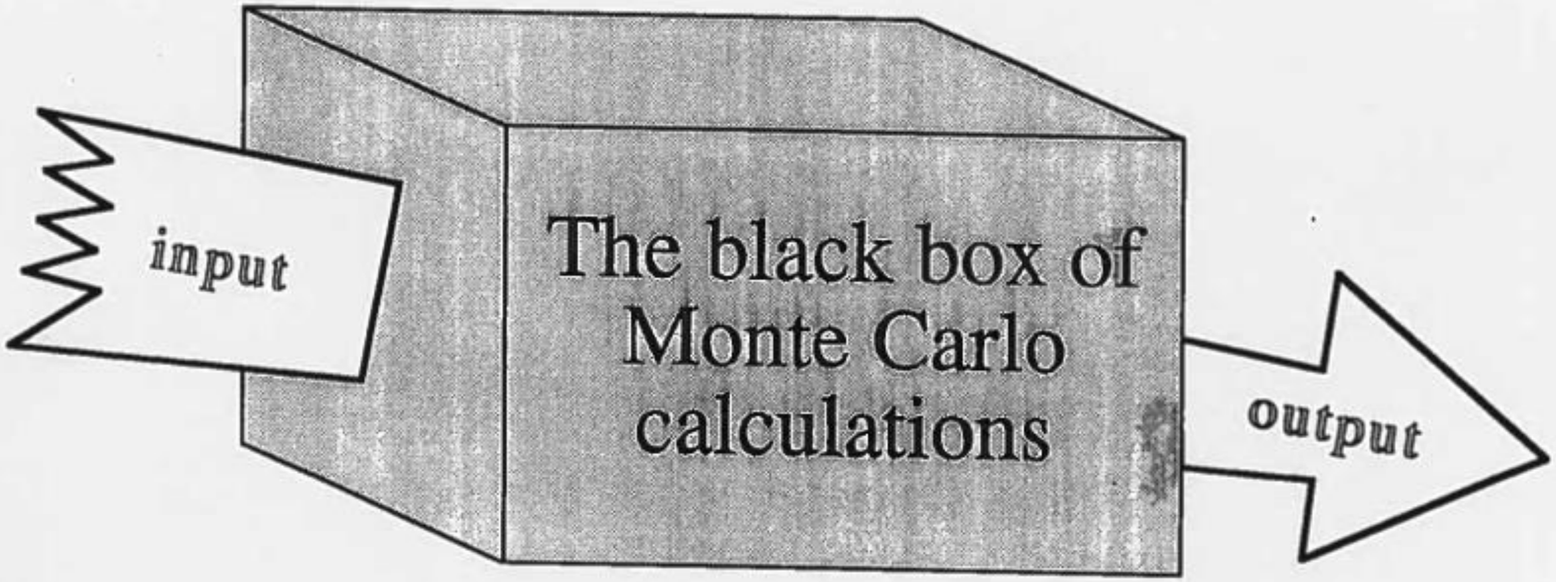
Giancarlo Sportelli
Stefano Ferretti
Maria Giuseppina Bisogni
Giuseppe Battistoni
Matteo Morrocchi
Esther Ciarrocchi
… and many more

TAKE HOME MESSAGE

Monte Carlo is not a magic black box



Be sceptical of the results of anybody else's
Monte Carlo computer code.
Be especially sceptical of your own code.
No matter how you word your disclaimer, you will
still "carry the can" filled with your own bugs (BLIF)

THANK YOU VERY MUCH FOR YOUR ATTENTION