Proton Computed Tomography

F. Cassol

Atelier proton CT, CPPM, 14 November 2012

Contents

The Proton Computed Tomography (pCT)

- Where?
- Why?
- How?
- Conclusion

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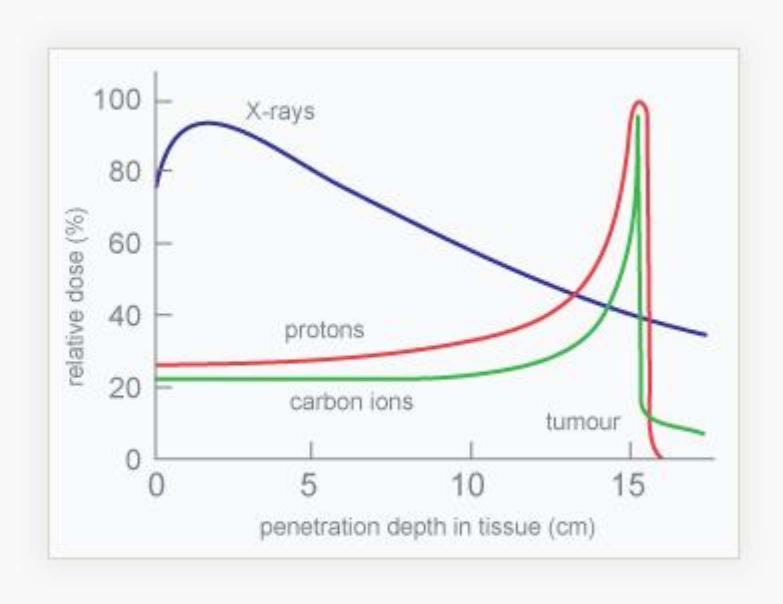
pCT useful in proton therapy

Advance form of radiotherapy based on the way protons lose energy in matter

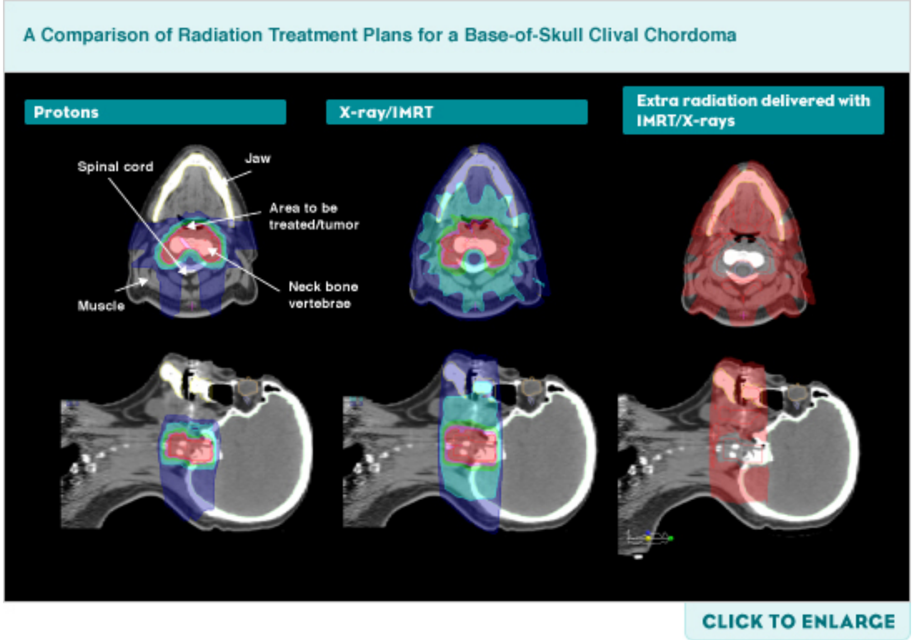


Thanks to the Bragg peak:

- Tumors can be precisely irradiated
- Close sensitive tissues can be avoided

In general:

Dose outside the target volume is reduced of a factor 2-5 compared to photons



Proton therapy

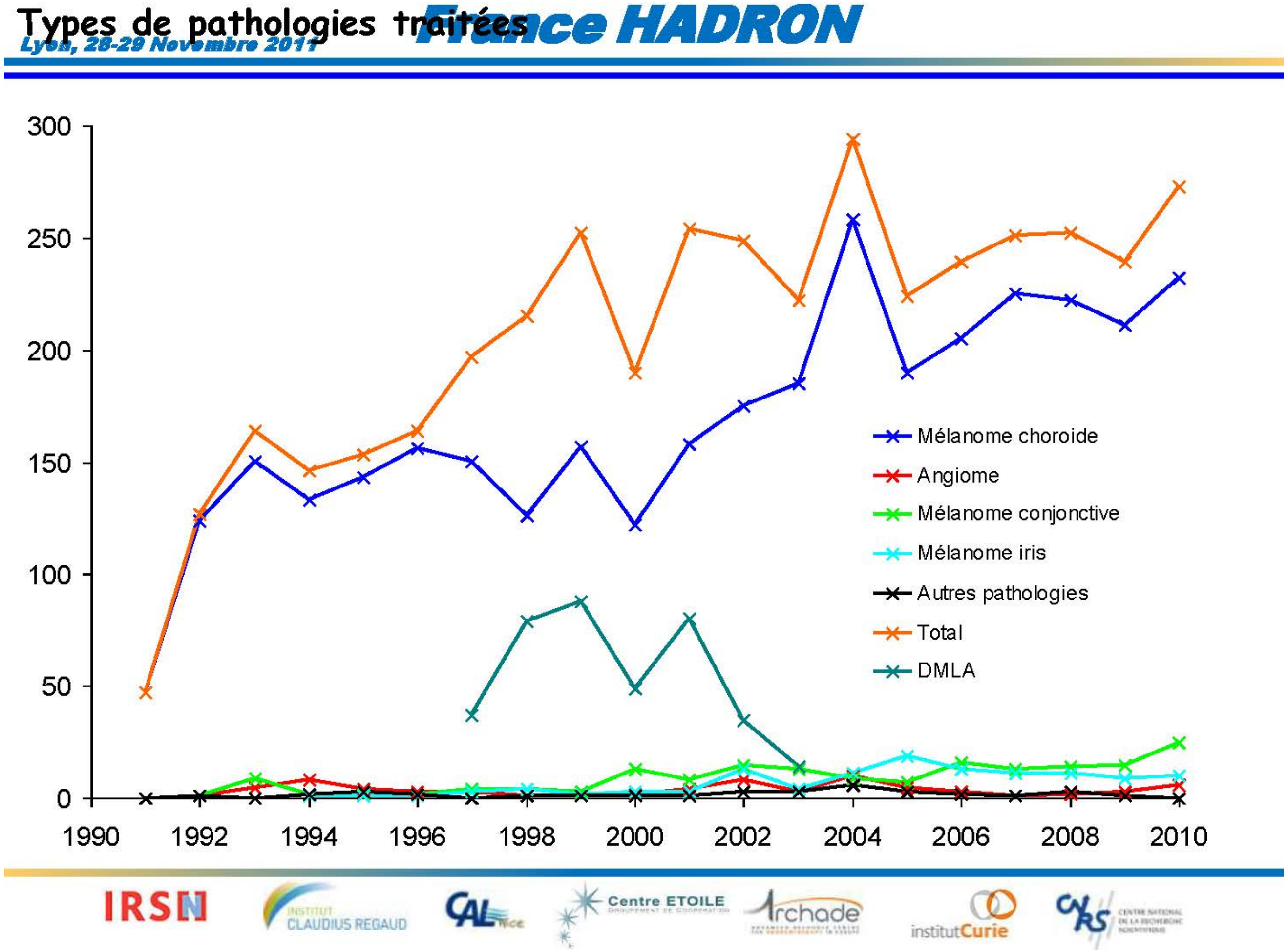
Good results overall for:

- Cancers that need high doses: eye, skull base, spinal tumor
- Cases where other tissues must be preserved: pediatric tumors
- For several cases the usefulness of PT is still a controversy

- Several centers from the '90-'00:

  Usa, Japan, Germany, France, Italy, Russia
- In France: Nice (1991) and Orsay (1991)

Centre Antoine Lacassagne Nice

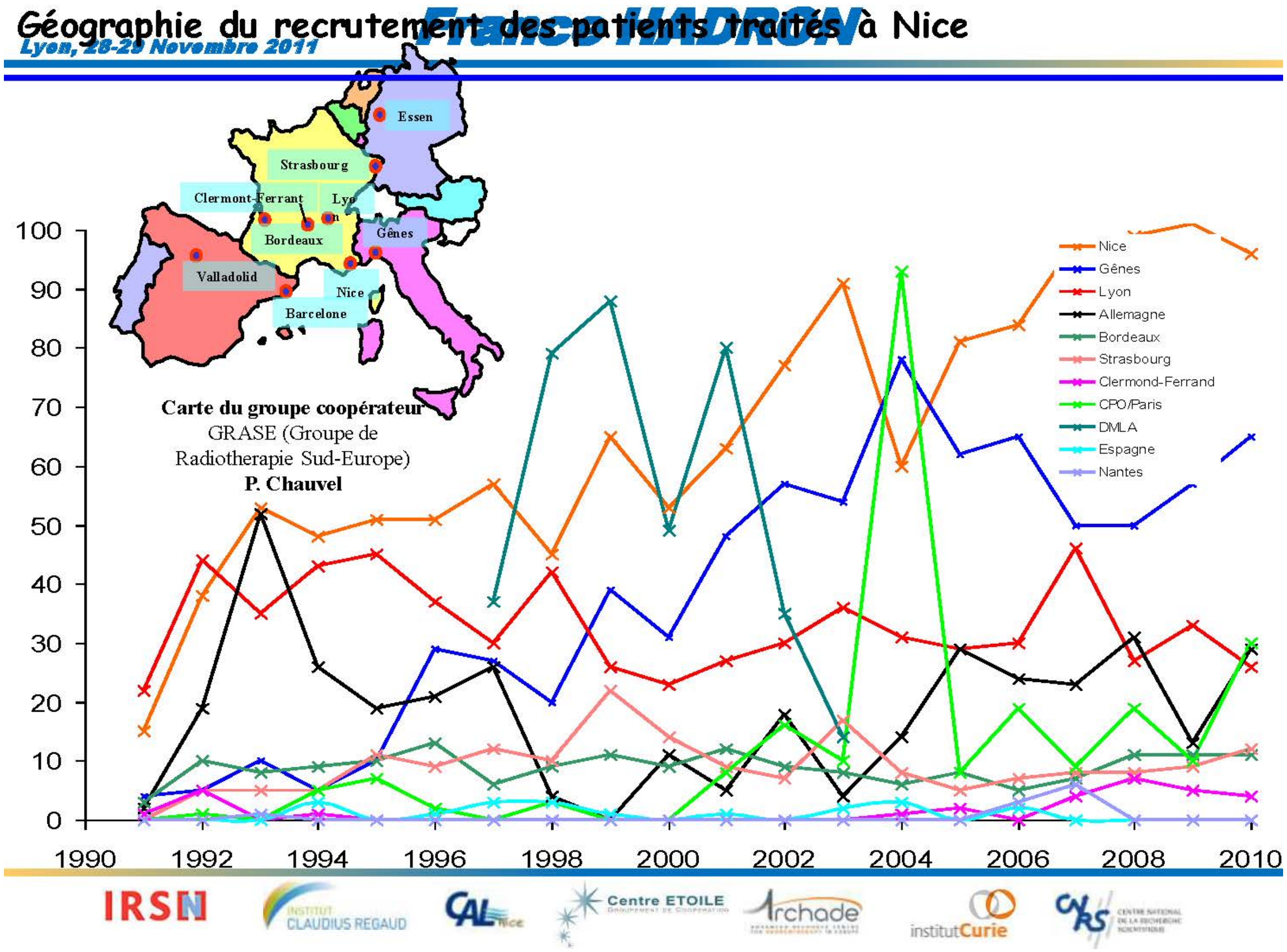


Types de pathologies traitées

France HADRON

Lyon, 28-29 Novembre 2011

Centre Antoine Lacassagne Nice

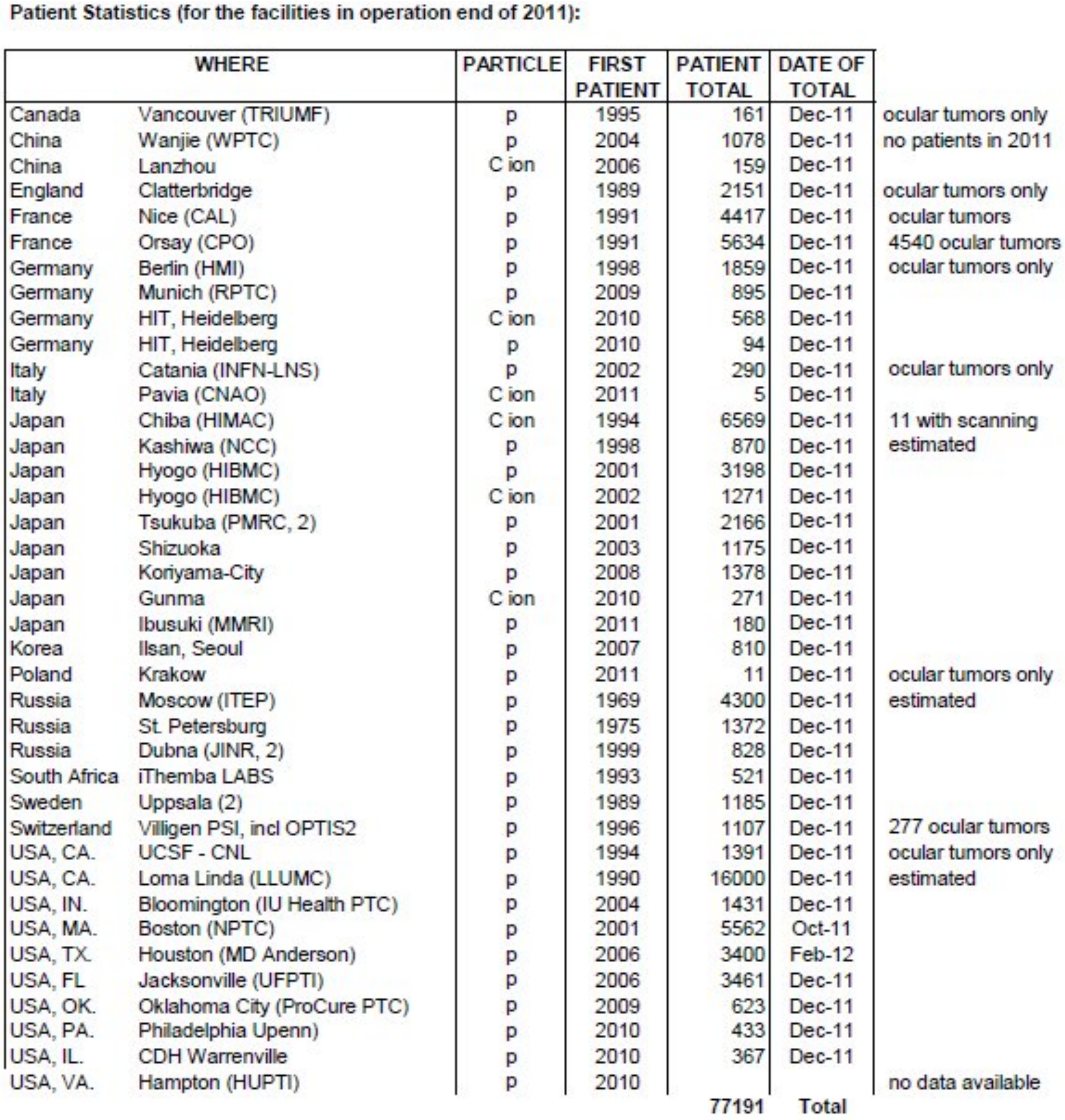


Géographie du recrutement des patients traités à Nice

France HADRON

Lyon, 28-29 Novembre 2011

Carte du groupe coopérateur
GRASE (Groupe de
Radiotherapie Sud-Europe)
P. Chauvel



Patient Statistics (for the facilities in operation end of 2011):

WHERE		PARTICLE	FIRST PATIENT	PATIENT TOTAL	DATE OF TOTAL	
Canada	Vancouver (TRIUMF)	p	1995	161	Dec-11	ocular tumors only
China	Wanjie (WPTC)	p	2004	1078	Dec-11	no patients in 2011
China	Lanzhou	C ion	2006	159	Dec-11	
England	Clatterbridge	p	1989	2151	Dec-11	ocular tumors only
France	Nice (CAL)	p	1991	4417	Dec-11	ocular tumors
France	Orsay (CPO)	p	1991	5634	Dec-11	4540 ocular tumors
Germany	Berlin (HMI)	p	1998	1859	Dec-11	ocular tumors only
Germany	Munich (RPTC)	p	2009	895	Dec-11	
Germany	HIT, Heidelberg	C ion	2010	568	Dec-11	
Germany	HIT, Heidelberg	p	2010	94	Dec-11	
Italy	Catania (INFN-LNS)	p	2002	290	Dec-11	ocular tumors only
Italy	Pavia (CNAO)	C ion	2011	5	Dec-11	
Japan	Chiba (HIMAC)	C ion	1994	6569	Dec-11	11 with scanning
Japan	Kashiwa (NCC)	p	1998	870	Dec-11	estimated
Japan	Hyogo (HIBMC)	p	2001	3198	Dec-11	
Japan	Hyogo (HIBMC)	C ion	2002	1271	Dec-11	
Japan	Tsukuba (PMRC, 2)	p	2001	2166	Dec-11	
Japan	Shizuoka	p	2003	1175	Dec-11	
Japan	Koriyama-City	p	2008	1378	Dec-11	
Japan	Gunma	C ion	2010	271	Dec-11	
Japan	Ibusuki (MMRI)	p	2011	180	Dec-11	
Korea	Ilsan, Seoul	p	2007	810	Dec-11	
Poland	Krakow	p	2011	11	Dec-11	ocular tumors only
Russia	Moscow (ITEP)	p	1969	4300	Dec-11	estimated
Russia	St. Petersburg	p	1975	1372	Dec-11	
Russia	Dubna (JINR, 2)	p	1999	828	Dec-11	
South Africa	iThemba LABS	p	1993	521	Dec-11	
Sweden	Uppsala (2)	p	1989	1185	Dec-11	
Switzerland	Villigen PSI, incl OPTIS2	p	1996	1107	Dec-11	277 ocular tumors
USA, CA.	UCSF - CNL	p	1994	1391	Dec-11	ocular tumors only
USA, CA.	Loma Linda (LLUMC)	p	1990	16000	Dec-11	estimated
USA, IN.	Bloomington (IU Health PTC)	p	2004	1431	Dec-11	
USA, MA.	Boston (NPTC)	p	2001	5562	Oct-11	
USA, TX.	Houston (MD Anderson)	p	2006	3400	Feb-12	
USA, FL.	Jacksonville (UFPTI)	p	2006	3461	Dec-11	
USA, OK.	Oklahoma City (ProCure PTC)	p	2009	623	Dec-11	
USA, PA.	Philadelphia Upenn)	p	2010	433	Dec-11	
USA, IL.	CDH Warrenville	p	2010	367	Dec-11	
USA, VA.	Hampton (HUPTI)	p	2010			no data available
				77191	**Total**	

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  - Positioning of the patient
  - Measurement of the proton energy loss
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Positioning of the patient

At present the positioning of the tumor is done in with X-radiographies compared with the XCT used for the treatment planning

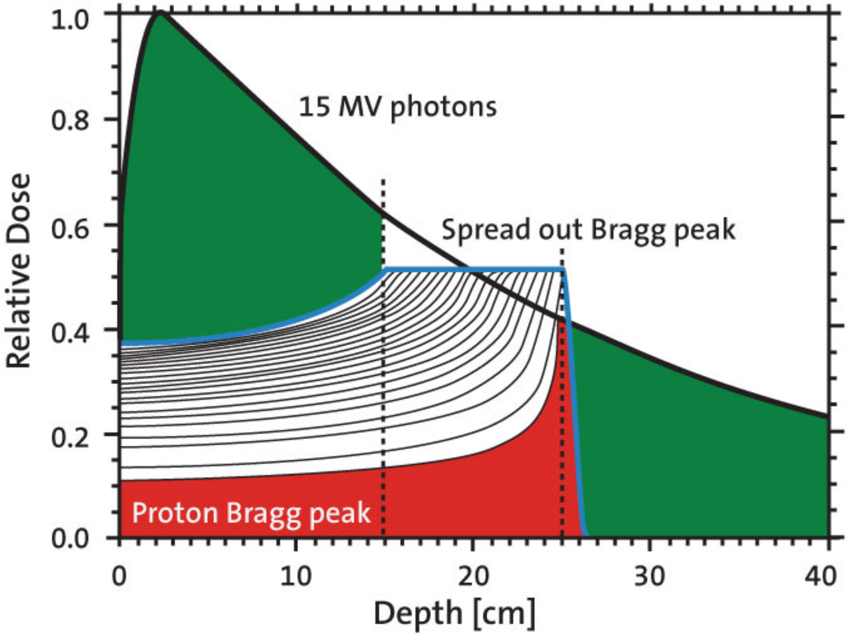
pCT would permit to directly 3D locate the tumor with the same beam that it would be used for the treatment

Which is the present uncertainty?
How much are we going to improve?

Measurement of the proton energy loss

Proton Therapy is successful only if

the p energy loss in the patient is precisely known



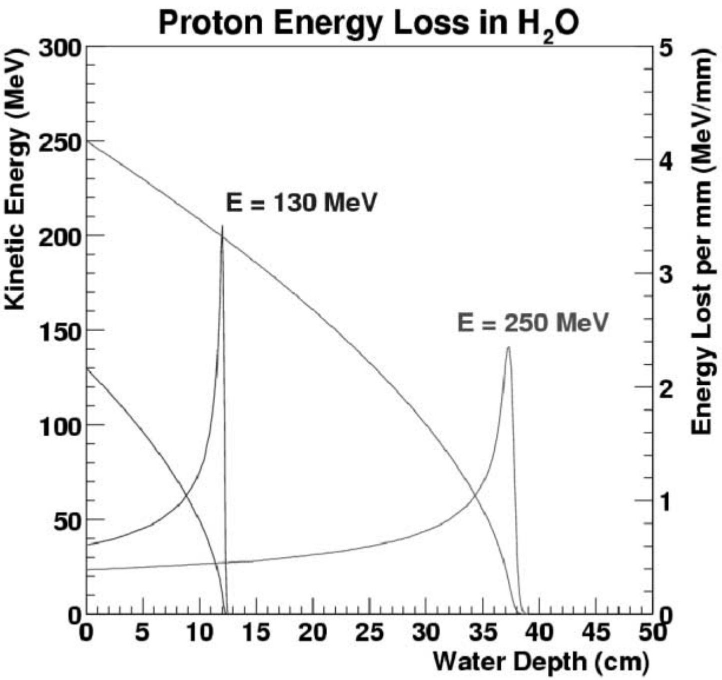
The beam energy is modulated
in order to :

1. cover the tumor
2. save the closed critical tissue

The proton energy loss (stopping power)

Protons lose most of their energy with the inelastic collisions with the outer atomic electrons (ionizations and excitations).

The Bethe-Bloch theory describes the proton stopping power:



$$-\frac{dE}{dx}(\bar{r}) = \eta_e(\bar{r}) S(I(\bar{r}), E(\bar{r}))$$

$$S(I,E) = K\frac{1}{\beta^2}\left[\ln\left(\frac{2m_e c^2}{I}\frac{\beta^2}{1-\beta^2}\right) - \beta^2\right]$$

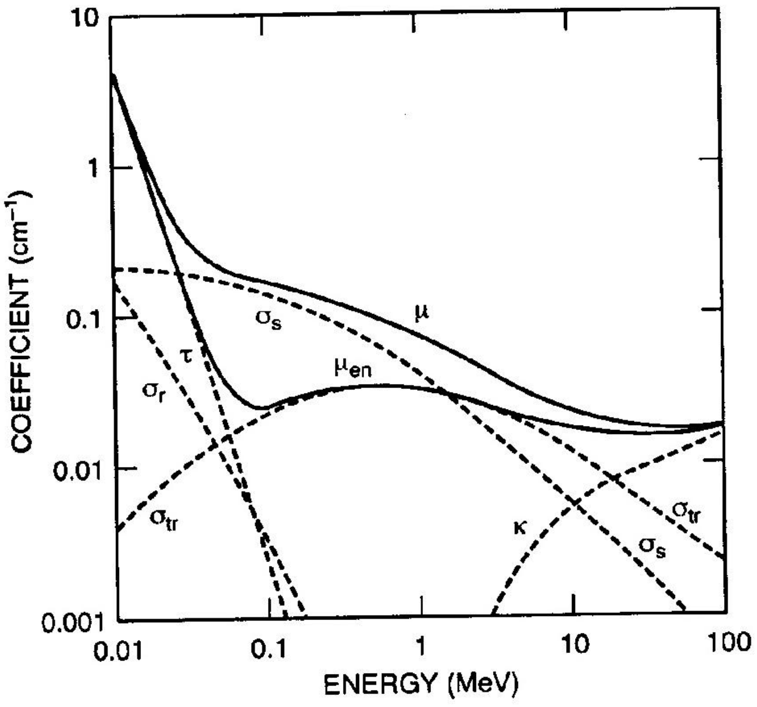
$\eta_e(r) = \rho_e/\rho_{e,\text{water}}$ = relative electron density

$I(\bar{r})$ = mean exitation potential (= 75 eV for water)

K = $4\pi r_e c^2 \rho_{e,\text{water}}$ = 0.170 MeV/cm

At present, electron density derived from XCT

XCT measures the attenuation coefficient of X-rays
which also depends from the electron density.



$$N(l) = N_0 e^{-\mu l}$$

$$\mu = \boxed{\rho_e^{\gamma}} \left(\sigma^{ph} + \sigma^{coh} + \sigma^{incoh} \right)$$

XCT gives HU

we need the calibration :

$$HU \Rightarrow \eta_e^{\gamma}$$

$$HU \Rightarrow \eta_e$$

Calibration for radiotherapy from XCT

Phantoms with known materials are used to the estimate η_e^γ

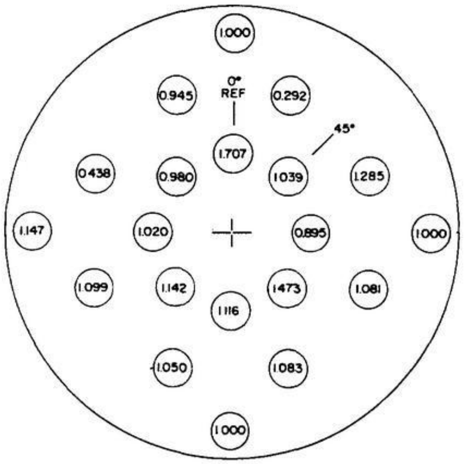
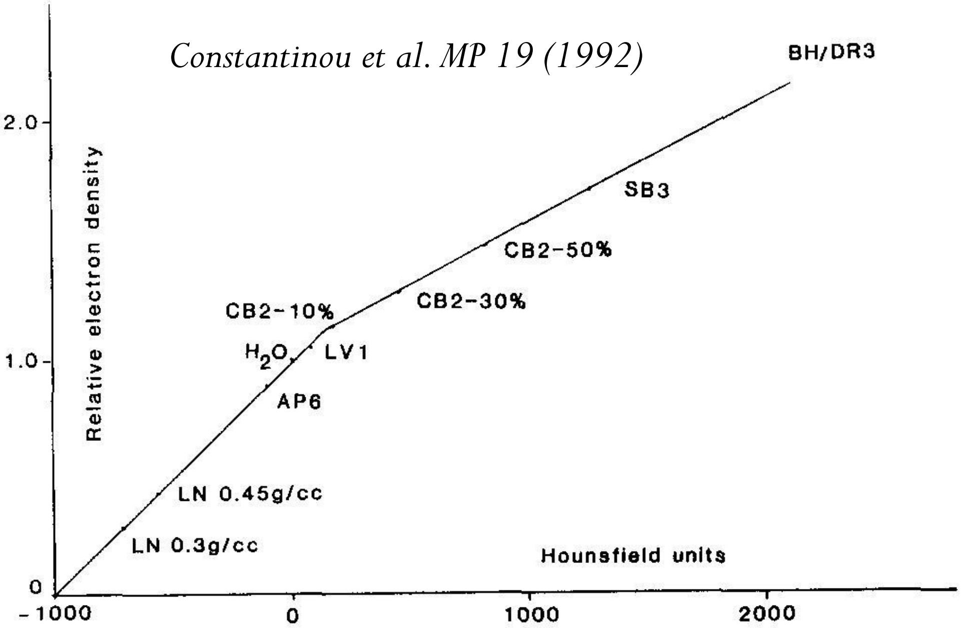


FIG. 1. The 33-cm-diam electron density calibration phantom. The numbers represent electron density relative to water for each rod. (Manufactured by RMI).



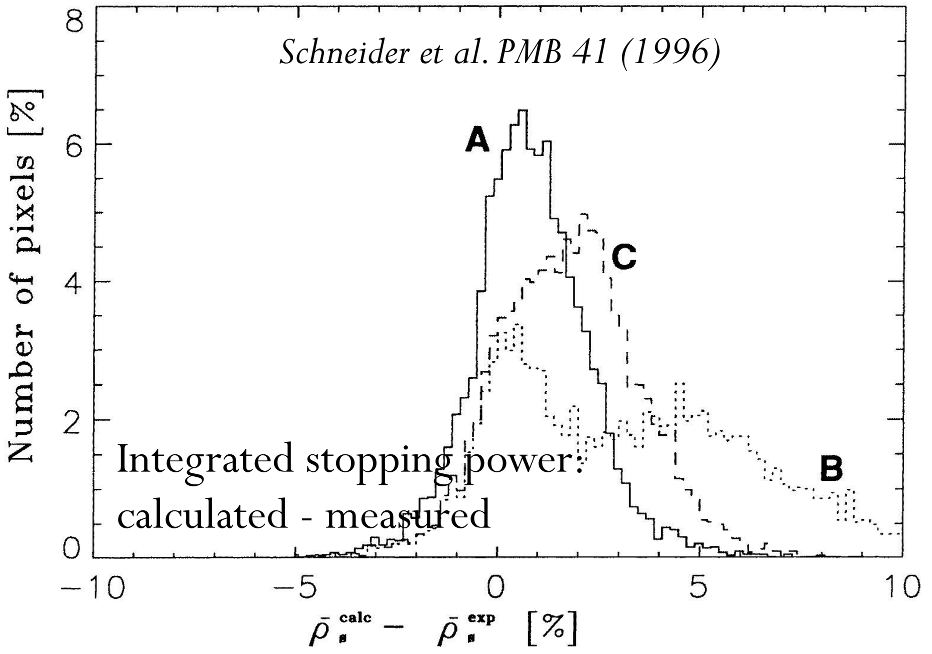
Constantinou et al. MP 19 (1992)

XCT has several sources of uncertainty : *(Schneider et al. PMB 41 1996)*

- HU variations of 1-2% in homogenous materials
- HU variations till 3% as function of the position
- HU variation of 10% as function of the scanner
- Errors due to the approximation real tissues/substitute tissues

Calibration of stopping power for pCT from HU

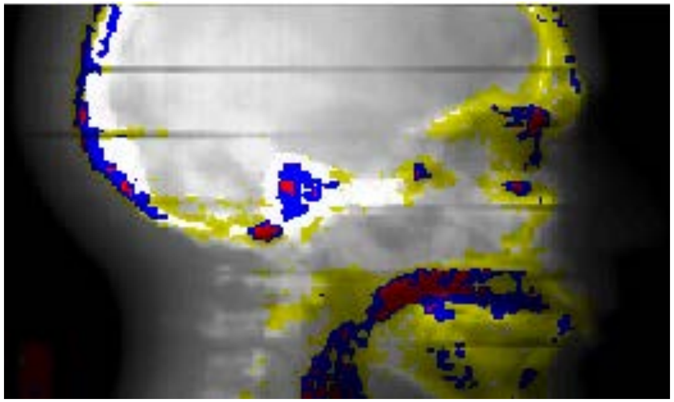
Different methods = different results



Schneider et al. PMB 41 (1996)

Integrated stopping power:
calculated - measured

Range uncertainty in inhomogeneous densities due to Coulomb scattering



🟨 > 5 mm
🟦 > 10 mm
🟥 > 15 mm

Schneider et al. MP 22 (1995)

The Bragg peak position is predicted to only 3-4% of the proton range in tissue or less in complicated tissue-air tissues-bone interfaces

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  - The method
  - Protons interactions, more precisely
  - Examples of pCT designs
- Conclusion

The method

Main goal of pCT : to determine the volume electron density by measuring the energy loss of protons after traversing the object

Proton stopping power

$$\boxed{-\frac{dE}{dx} = \eta_e \cdot S(I,E)}$$

Volume electron density

$$\boxed{\eta_e = -\frac{1}{S(I,E)}\frac{dE}{dx}}$$

Integral over the proton path

Radon transform of η

$$\boxed{\int_L \eta_e dx} = \int_L -\frac{1}{S(I,E)}\frac{dE}{dx}dx = \boxed{-\int_{E_{in}}^{E_{out}} \frac{1}{S(I,E)} dE}$$

First trails in the ’80

Assume a straight path L and only E_{out}, x_{in} and x_{out} measured

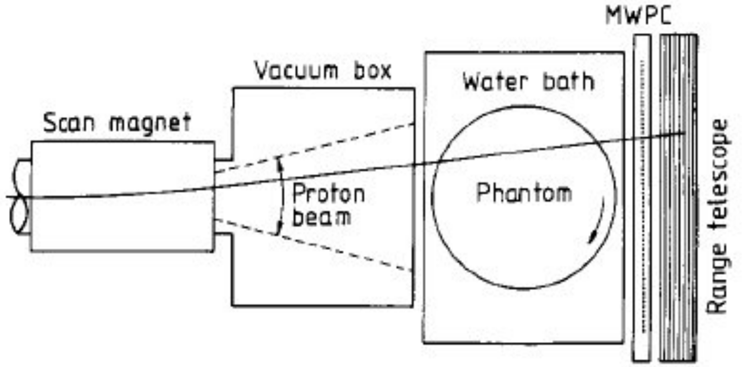
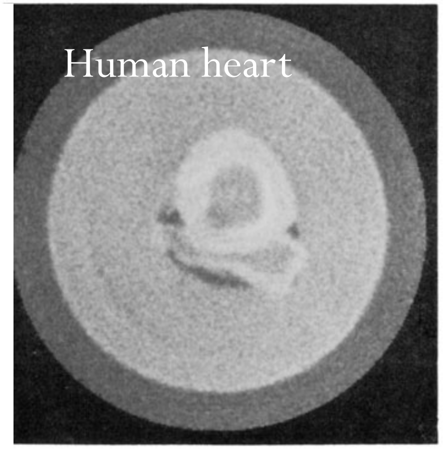
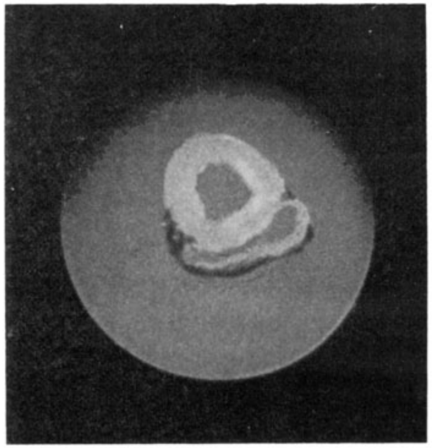


Figure 1. Schematic layout of apparatus.

Hanson et al. MPB 27 (1982)



pCT



XCT

Results are deceiving with respect to XCT, loss of interest for pCT

But more and more proton therapy centers,

in the 90’ people try to do better …

pCT, more precisely

In pCT, proton energy sufficient to traverse the body

- 200 MeV (R=25.8 cm) for adult skull (20 cm)
- 250 MeV (R=37.7 cm) for adult trunk (34 cm)

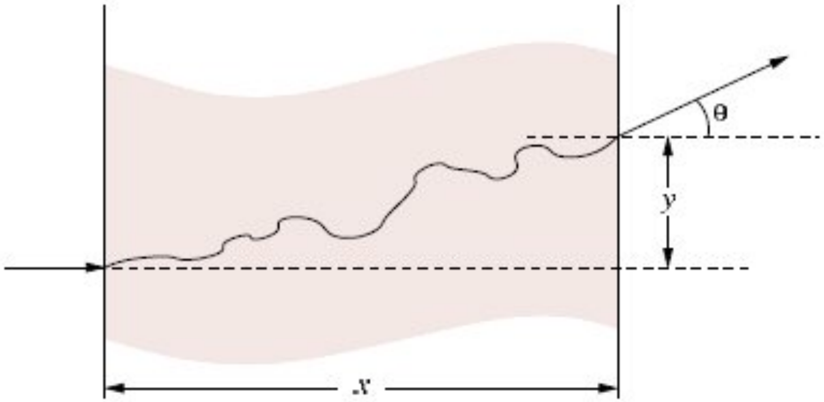
Reconstruction is made track by track (list mode)

Three phenomena define the intrinsic limitation of pCT:

1. Coulomb scattering → limiting spatial resolution
2. Energy loss straggling → limiting electron density resolution
3. Nuclear interactions → noise and additive dose

Multiple-Coulomb scattering

Protons undergo many individual elastic interactions that change their final direction and position



$$\sigma_\Theta \propto \frac{\sqrt{x/X_0}}{v^2} \propto \frac{Z}{v^2}\sqrt{x(cm)}$$

$$\sigma_y = \frac{1}{\sqrt{3}} x \sigma_\theta$$

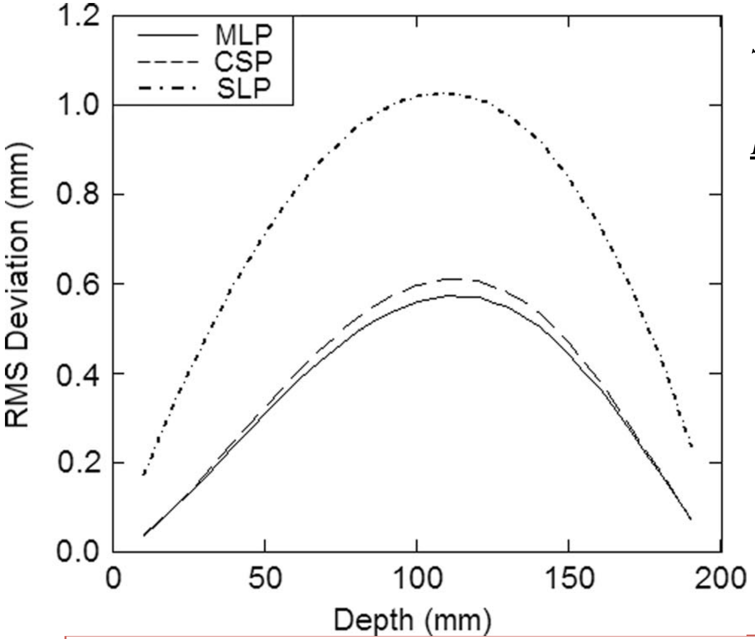
Protons don’t follow straight lines!

pCT reconstruction must include
a mathematical formalism to take into account MCS

Most Likely Path (MLP)

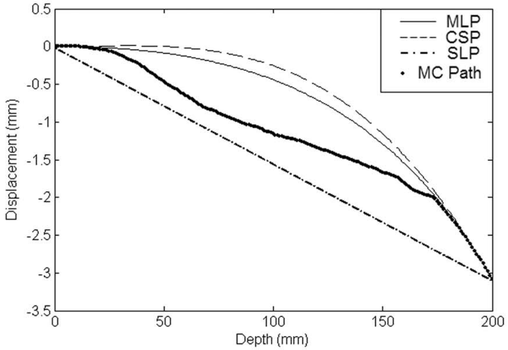
Algorithm based on :

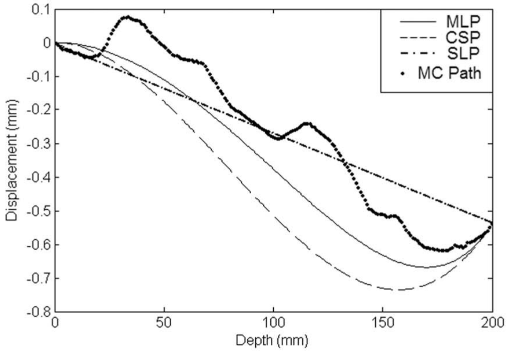
- proton position, energy and <u>direction</u>
- modeling of MCS

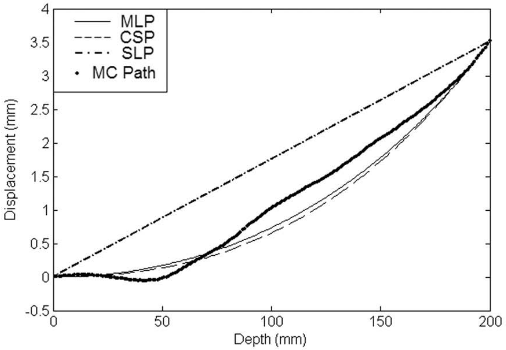


Shulte et al. MP 21 (1995)
Williams PMB 49 (2004)
<u>Li et al. MP 33 (2006)</u>

MLP = Most Likely Path
CSP = Cubic Spline Path
SLP = Straight Line Path







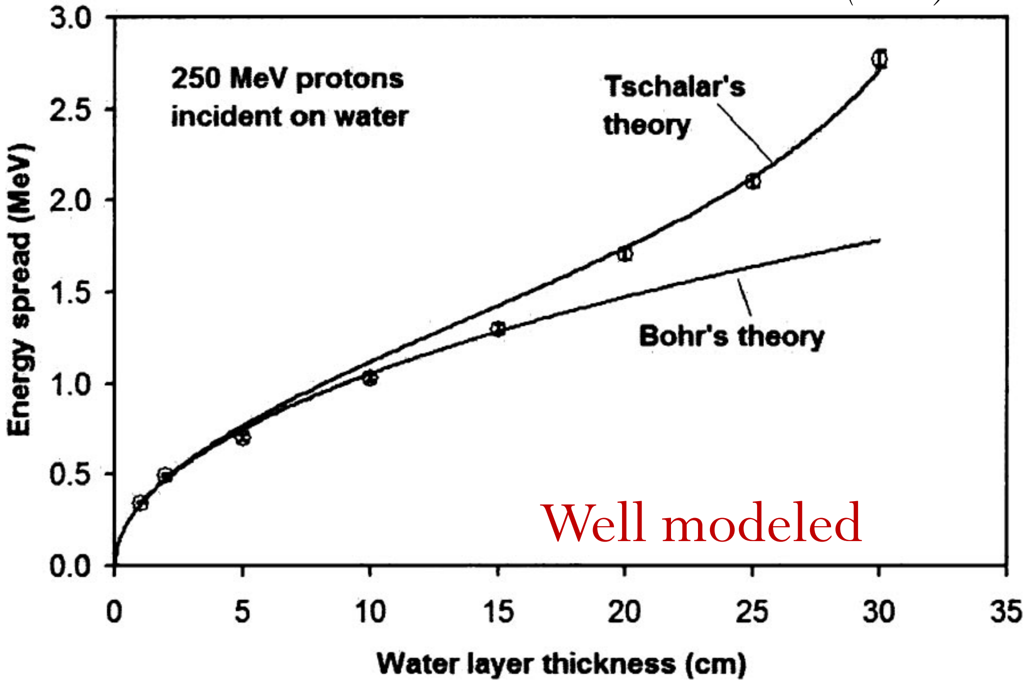
MCS limits intrinsically the pCT spatial resolution to ~ 1 mm

Energy loss straggling

Is due to :

- the varying number of collisions
- the energy transfer fluctuations

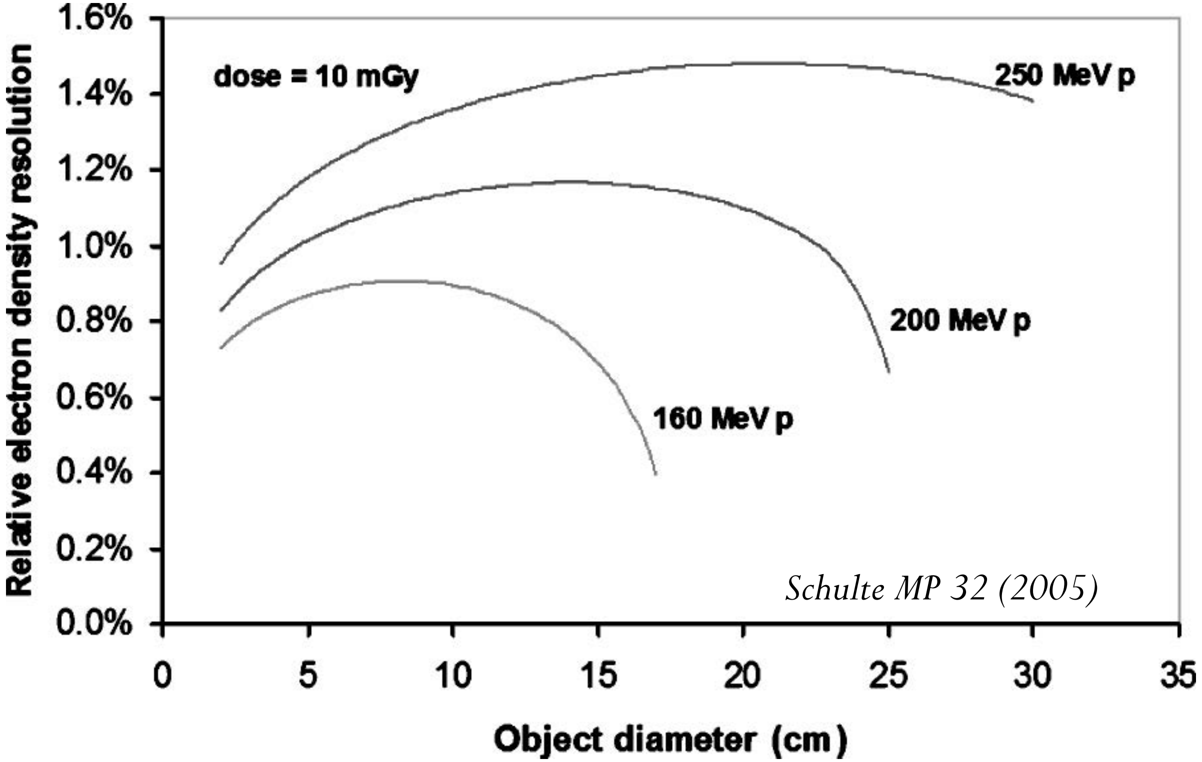
Schulte MP 32 (2005)



Well modeled

Energy loss straggling

$$\sigma_{\eta_e} = \frac{\pi \sigma_{E_{out}}}{\sqrt{D \cdot F(S(E_{out}), d, d_{voxel})}}$$

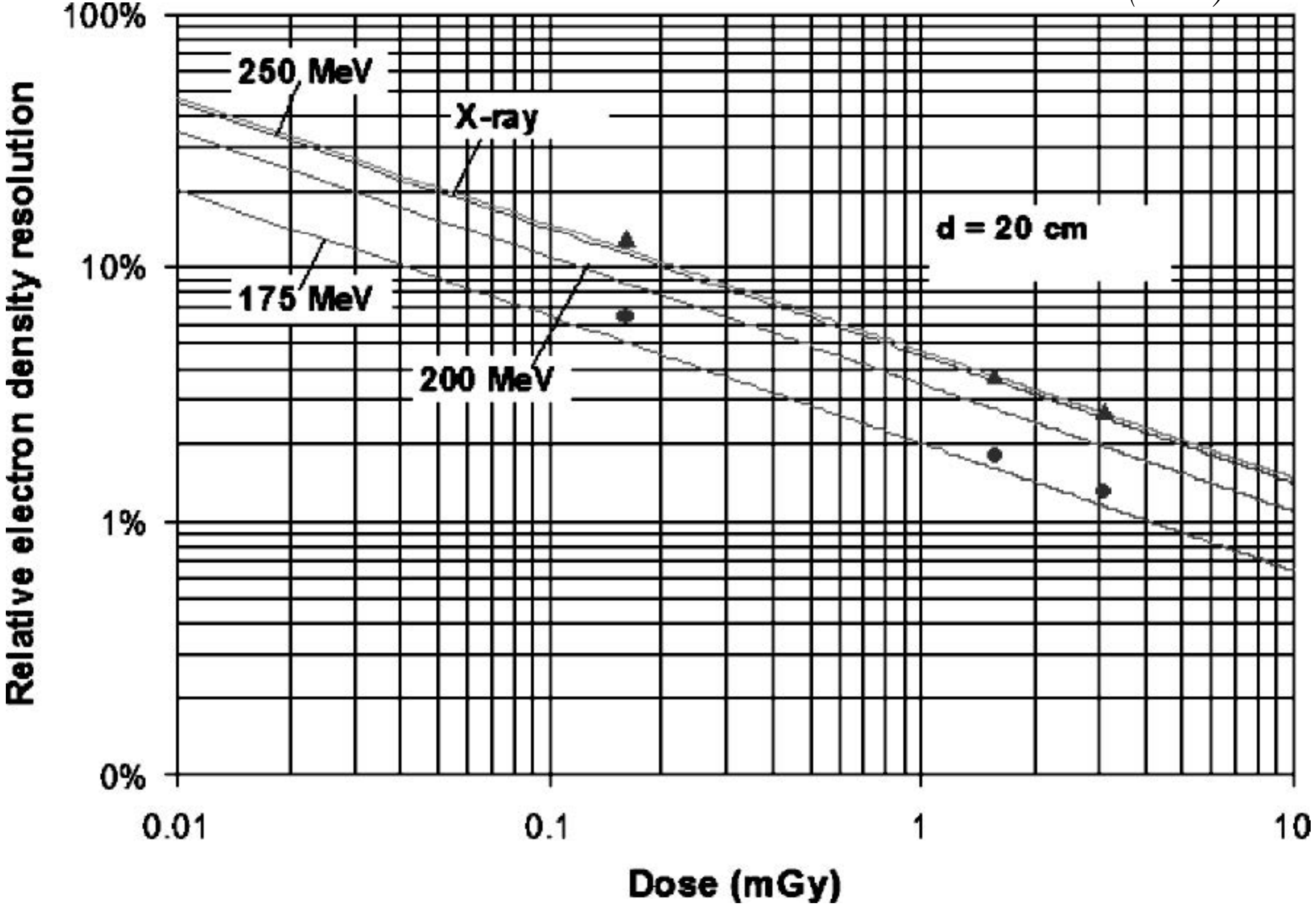


Schulte MP 32 (2005)

Energy straggling limits intrinsically the measure of η_e to ~ 1%

Energy loss straggling

Schulte MP 32 (2005)



pCT seems to be potentially better than XCT at E< 250 MeV

Non elastic-nuclear interactions

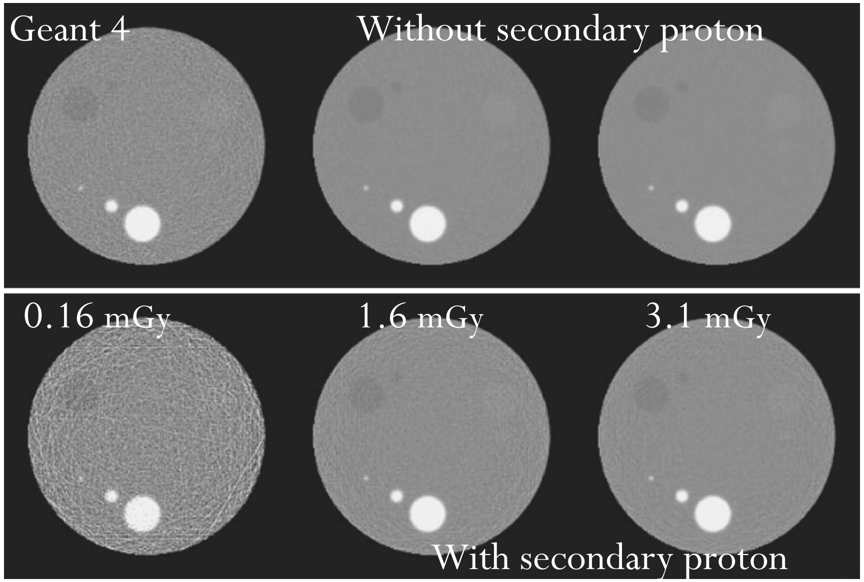
Loss of the primary proton and reduction of the p fluence

$$\Phi(x) = \Phi_0 \exp(-kx)$$

$k \sim 0.01\ \mathrm{cm}^{-1}$

$100\ \mathrm{MeV} < E < 300\ \mathrm{MeV}$

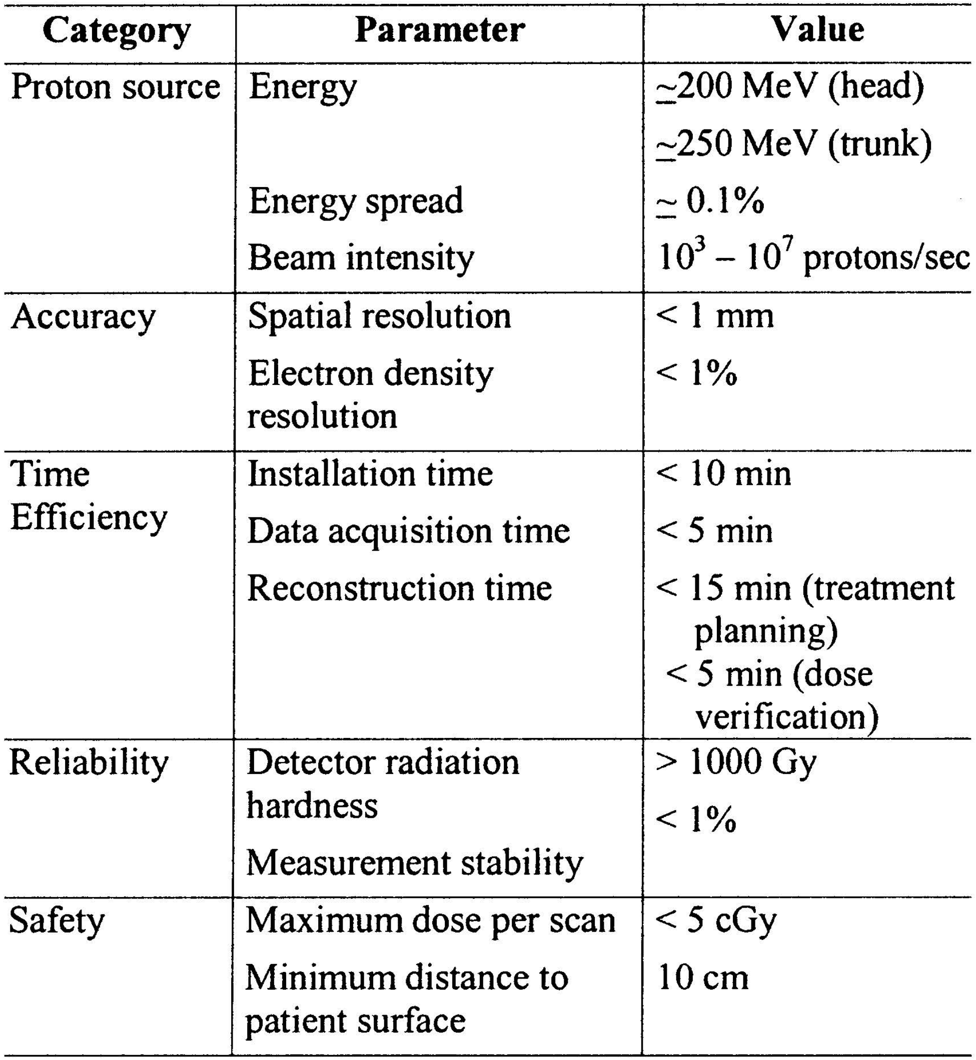
~10% (~20%) reduction after 10 (20) cm water



These protons induce noise in pCT,
They are eliminated with 3σ cut

Which error in the treatment plan?

pCT design: summary



Category	Parameter	Value
Proton source	Energy	≃200 MeV (head) ≃250 MeV (trunk)
	Energy spread	≃ 0.1%
	Beam intensity	$10^3 - 10^7$ protons/sec
Accuracy	Spatial resolution	< 1 mm
	Electron density resolution	< 1%
Time Efficiency	Installation time	< 10 min
	Data acquisition time	< 5 min
	Reconstruction time	< 15 min (treatment planning) < 5 min (dose verification)
Reliability	Detector radiation hardness	> 1000 Gy
	Measurement stability	< 1%
Safety	Maximum dose per scan	< 5 cGy
	Minimum distance to patient surface	10 cm

Schulte TNS 51 (2004)

Measure of x, p, E with $\sigma_x < 1\text{mm}$ $\sigma_E < 1\%$

MHz DAQ :

A head with 100 p, 1 mm voxel

$7\ 10^8$ p: 10 kHz = 20 hrs

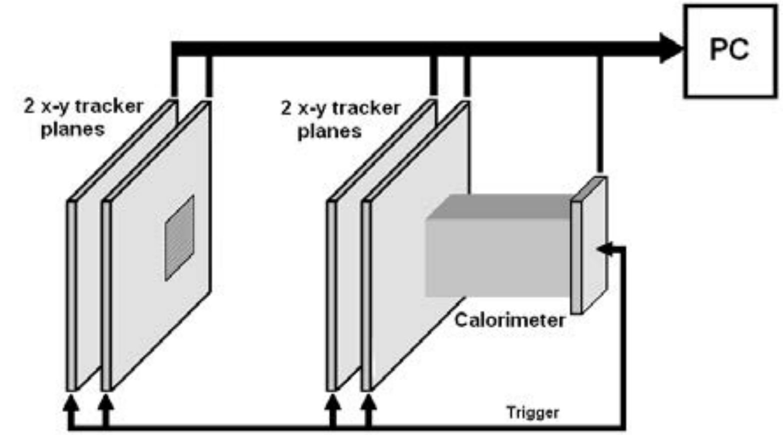
2 MHz = 6 min

GPU recontruction

Present designs

Group	Tracker	Energy detector
Firenze/LNS (Italy)	Silicon strip detector	YAG:Ce crystals
LLU-UCSC-NIU (USA)	Silicon strip detector	CsI crystals
NIU/FNAL (USA)	Scintillating Fibers+ SiPM	Range + WLSF+ SiPM
TERA/CERN (Italy)	Gas electrons multipliers	Range + WLSF+ SiPM
GSI/HIT (Germany): Ion radiography	Stack of Ionisation chambers	Stack of ionisation chambers

PROton IMAging (PRIMA) Firenze/LNS

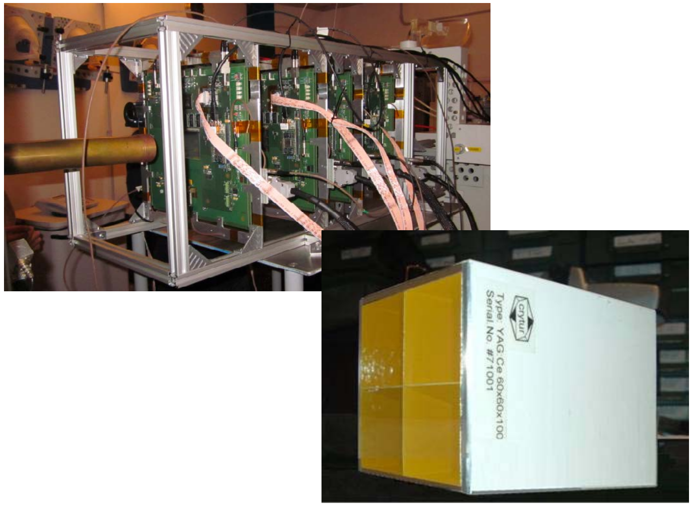


Tracker:

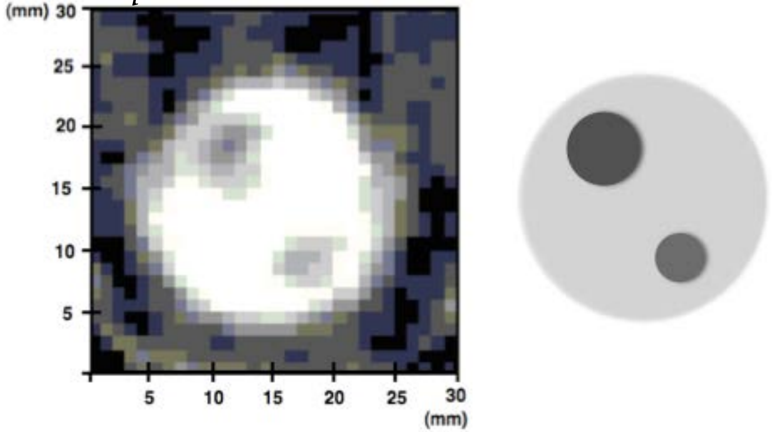
- Silicon strips, 200 µm pitch
- Active area 51 x 51 mm^2
- RAM for 10^6 events

Calorimeter:

- 4 scint. crystals 30 x 30 mm^2
- 4 PM Hamamatsu 1.8 x 1.8 mm^2
- 1 MHz

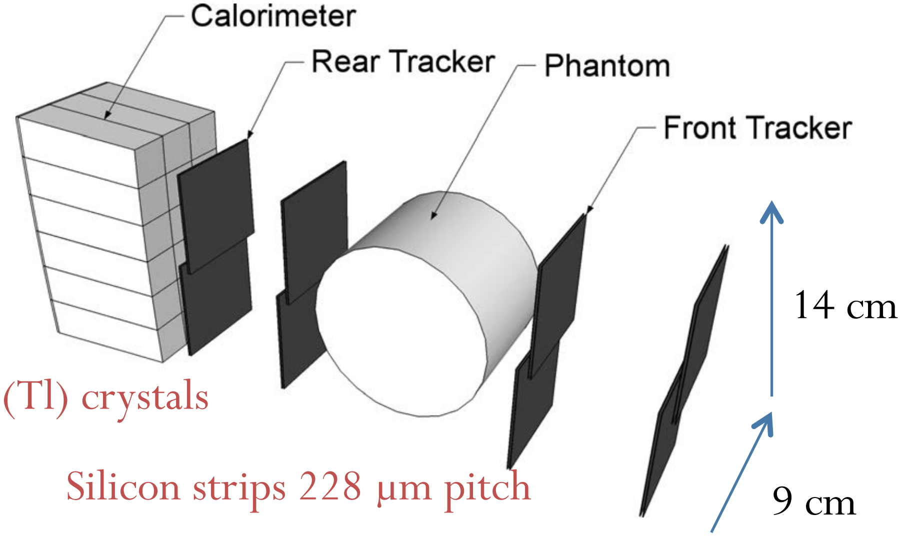


Sipala et al. IEEE 2011



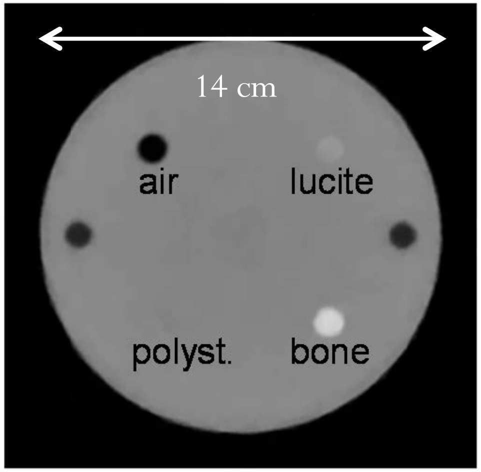
First tomographic image with 60 MeV p, 1 mm^2 voxel, (MLP +FDK)

LLU-UCSC-NIU collaboration



CsI(Tl) crystals

Silicon strips 228 μm pitch



Sadrozinsky et al. IEEE (2011)

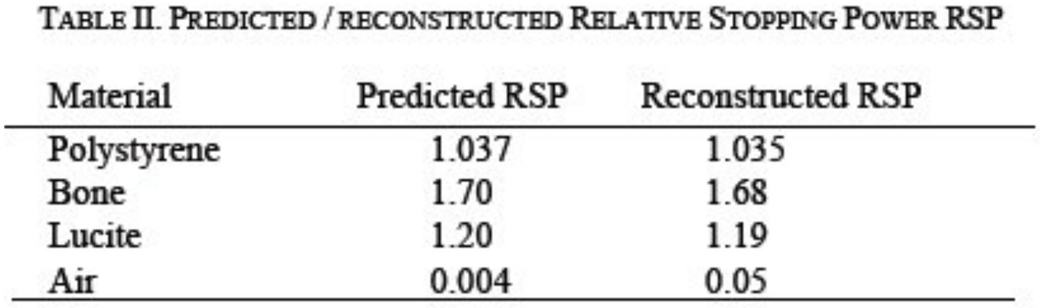


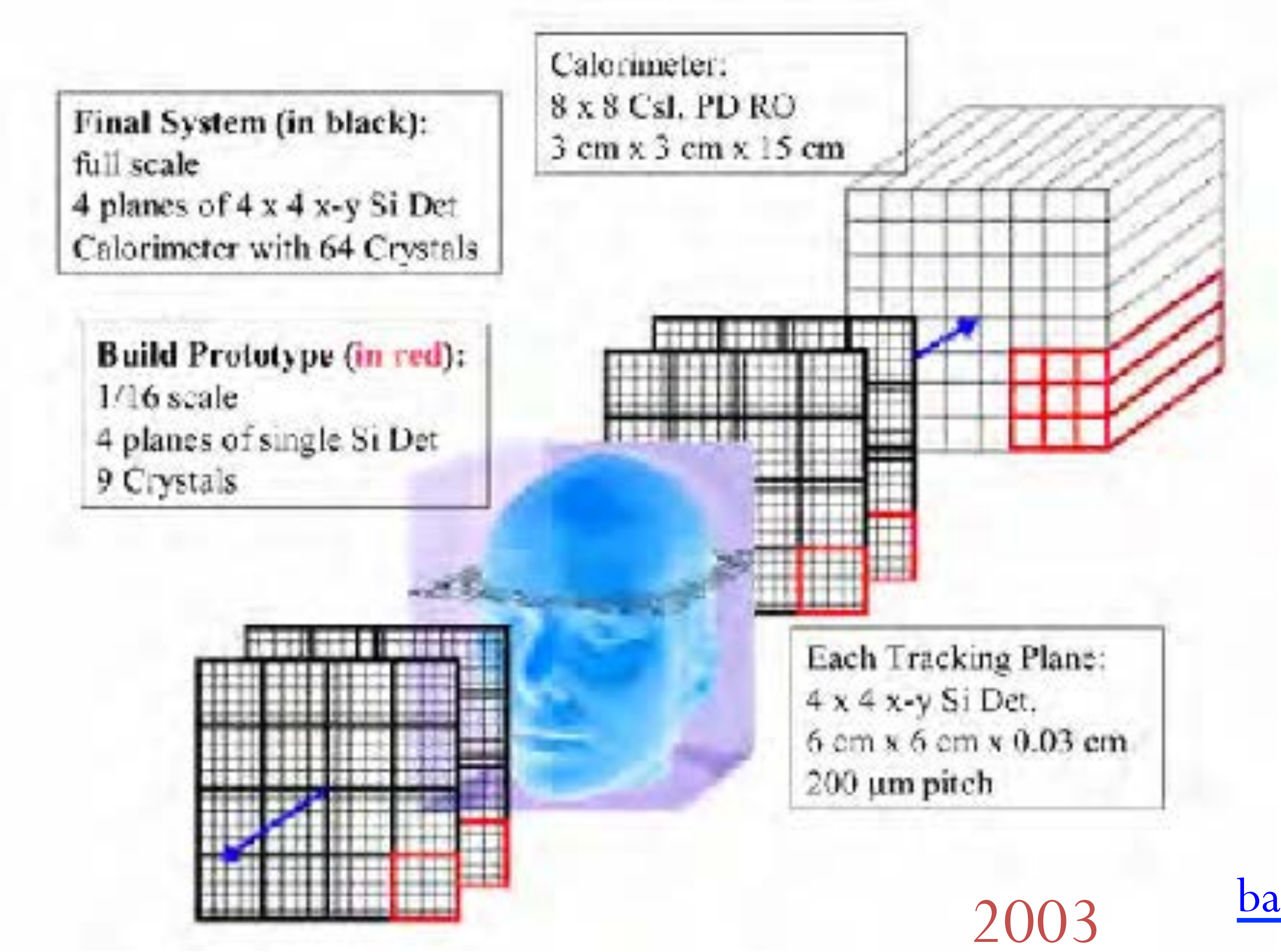
TABLE II. PREDICTED / RECONSTRUCTED RELATIVE STOPPING POWER RSP

Material	Predicted RSP	Reconstructed RSP
Polystyrene	1.037	1.035
Bone	1.70	1.68
Lucite	1.20	1.19
Air	0.004	0.05

Tomographic image 0.65 mm^2 voxel,

4 hrs at 20 kHz , reconstr. MLP+FDK+ART

LLU-UCSC-NIU collaboration



Final System (in black):
full scale
4 planes of 4 x 4 x-y Si Det
Calorimeter with 64 Crystals

Calorimeter:
8 x 8 CsI, PD RO
3 cm x 3 cm x 15 cm

Build Prototype (in red):
1/16 scale
4 planes of single Si Det
9 Crystals

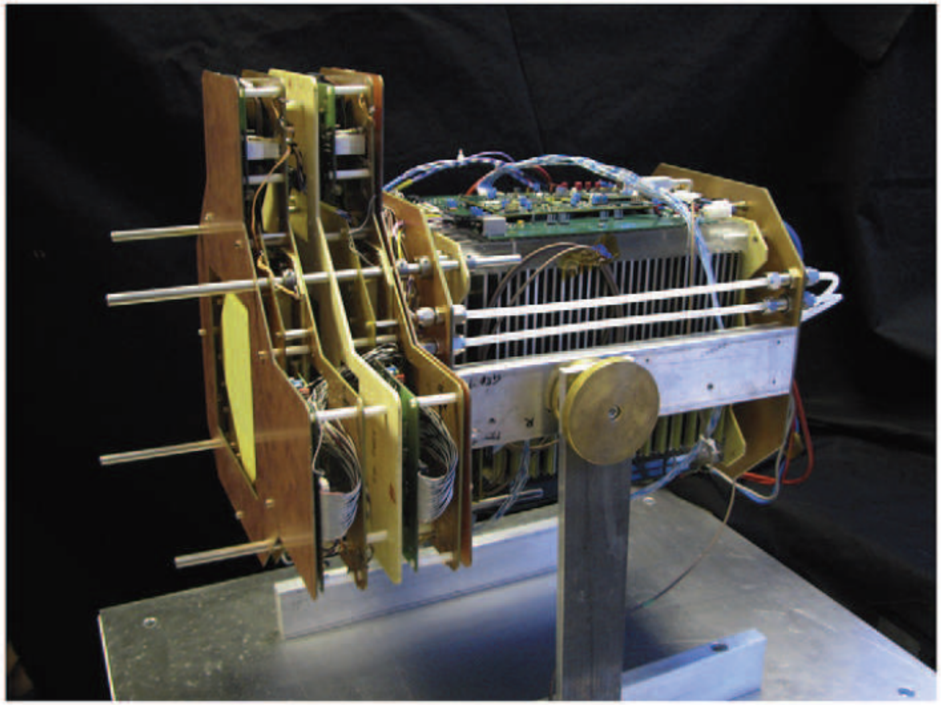
Each Tracking Plane:
4 x 4 x-y Si Det.
6 cm x 6 cm x 0.03 cm
200 µm pitch

2003

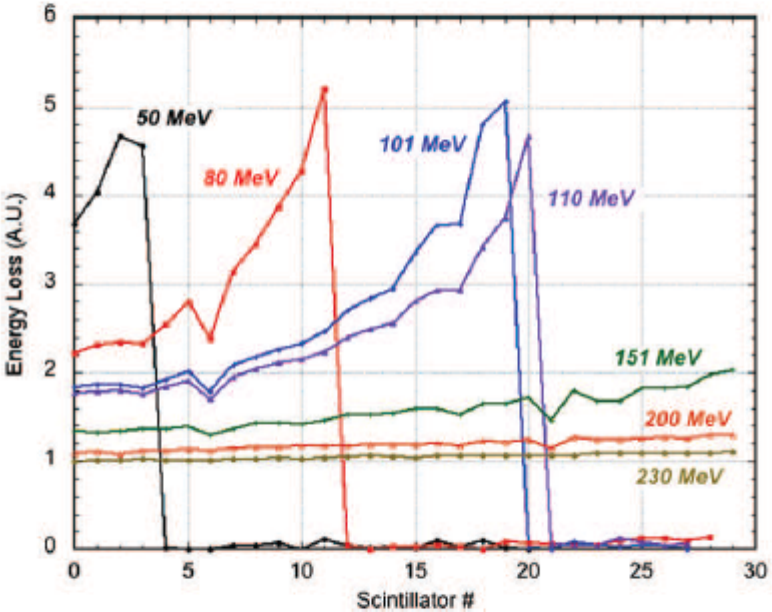
back

Proton Range Radiography (TERA)

F. Sauli et al. (NIMA629 (2011) 337)

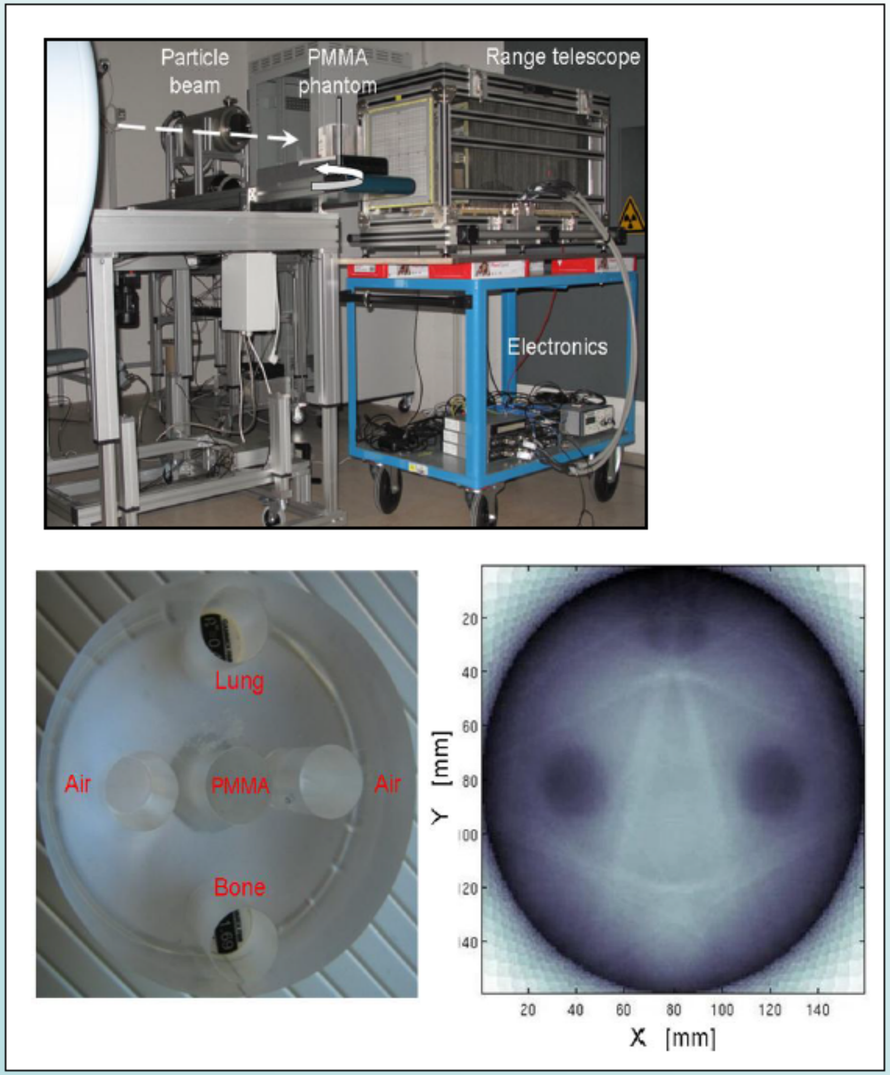


- Tracking: 2 GEM detectors
- Range telescope: stack of 30 plastic scint., 3mm thick, read by SiPMs



Range resolution : 1.7mm RMS
Expected count rate with suitable acquisition system : 10^6 Hz
30x30 cm^2 surface easily achievable

Towards ion radiography / tomography at HIT



Stack of ionization chambers (Voss et al, GSI) with new electronics

- Scanning 0°-180° in steps of 5°
  ^{12}C pencil-beam 400 MeV/u
  3.5 mm Gaussian FWHM
  5 x 10^6 pps
- PMMA phantom *D*=160 mm
  tissue equivalent rods *d*=28mm
- Multi-channel electrometer electronics highly integrated
- Simple 2D back-projected reconstruction

Proof-of-principle ^{12}C Heavy Ion Tomography

Rinaldi Ph.D. research at HIT/DKFZ (in collaboration with B. Voss, GSI); Voss et al GSI Report 2010, in press

K. Parodi, 2011

Conclusions

pCT must do better than 3-4% in proton range

but

can not be better than ~1% due to intrinsic limitations

Main challenges:

- Detector spatial resolution < 1 mm ☺
- Energy resolution < 1% ❓
- Fast DAQ > 1 MHz ☺
- Iterative reconstruction in GPU ☺

Thanks!