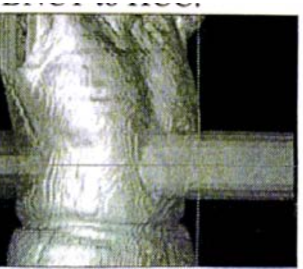
# Present-day neutron research : …much more than nucl physics !

*our projects at IPHC Strasbourg

- Detection: principles & systems
- Sources (old and modern)
- CMOS Recoil Proton Telescope*:

*still in Chadwick's steps…*

- UCN for fundamental physics
- Therapy: BNCT
- Dosimetry & the $\alpha$Rad chip*
- Secondary ***n*** in $\gamma$-therapy rooms*



# 1. Detection: principles & systems

With or without *slowing down*…

…***one*** single method:  produce & detect

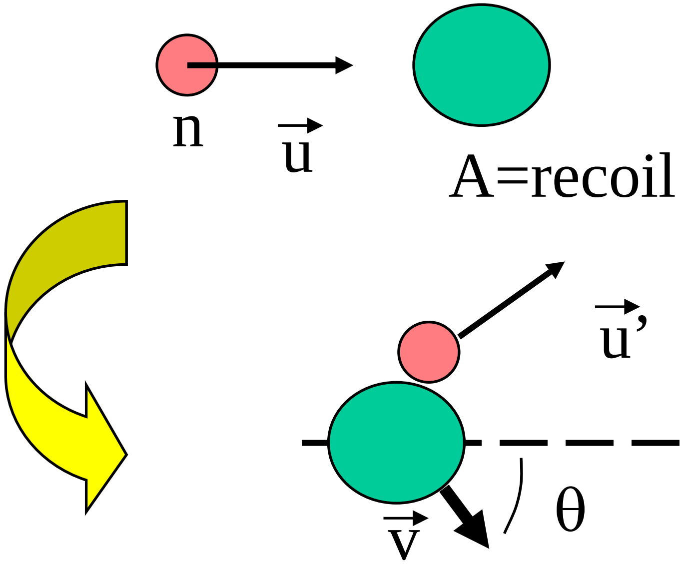
**secondaries**

a) Uncharged: γ photons
(capture reaction)

b) Charged: elastic (mostly **p**) / or inelastic:
(i)  Fission Fragments (FF) e.g. for UCN
(ii) Light particles: p, α, Li (+some others…)
followed by ***Prop.Chmb***, ***scintillation*** or ***tracking***

# Slowing down: why and how?

- Why ? Important cross sections go up if E goes down
- How ? Kinematics again…(mostly elastic)



$$\boxed{E_A=E_n\ .\ \cos^2(\theta).\eta}$$

$$\eta = \frac{4m_n m_A}{(m_n+m_A)^2}$$ $=1$ if $m_A=m_n$

$>> 1$ if $m_A >> m_n$

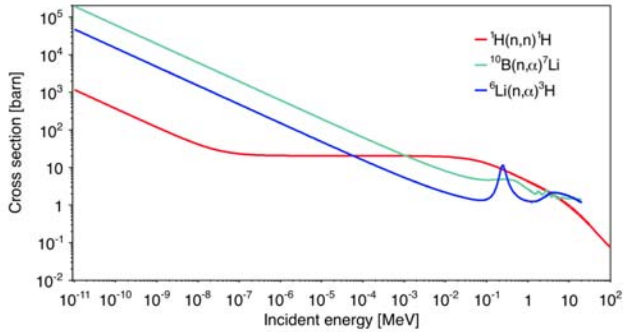
and $$\frac{(A-1)^2}{(A+1)^2} < (E'_{n)}\ )_{1\ \mathrm{coll}} / E_n < 1$$

***Lethargy*** change:

$u(\theta)=\mathrm{Ln}(E_n/E'_n)$ and $<u> = 1+\frac{(A-1)^2}{2A}\,\mathrm{Ln}\frac{(A-1)}{(A+1)} = \xi$ is a **constant** !

ex: $A={}^{12}C$ ($\xi=0.158$): $N_{coll}= u/\xi = 111$ if $E_n$ 1 MeV downto 1/40 eV

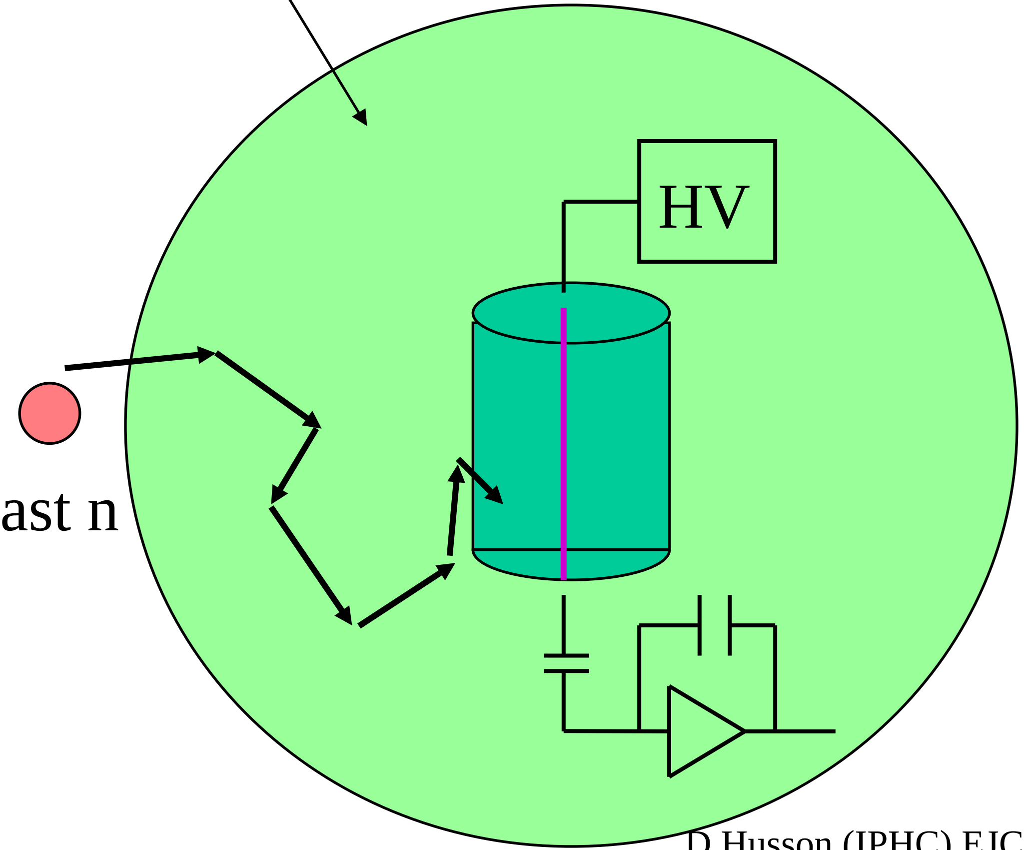
# Bonner spheres



1) Polyethylene sphere for moderation

2) Capture in gas chamber, filled with $BF_3$ (or $^3He \rightarrow {}^3H+p$)

3 ) High $\sigma$ process : $^{10}B(n,\alpha)Li$ +avalanche



*Complete system of standard spheres*

+ simu/deconvolution

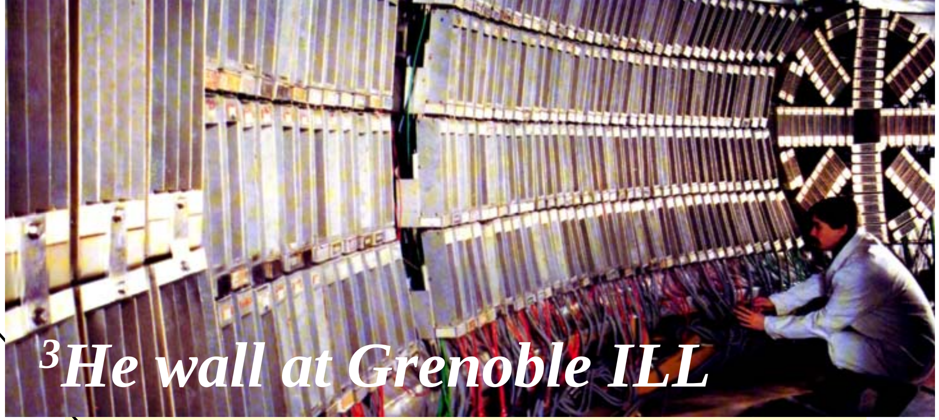
➔ spectrum

$^3$He: fast+easy
but ***rare*** element (on Earth..)
➡ costly

Solid track det.= SSD
(PN3, CR39): *cheap*
but only integrated response
(+post-process+saturation)

Scintillators:
Fast, efficient if long enough
+multisystems (DEMON)
(long-standing n/γ…)

Electronic systems


***$^3$He wall at Grenoble ILL***

Nuc.Phys: **σ(*n,2n*)…**,
prescission dynamics, …

Dosimetry
-passive
-active ***(our group)***

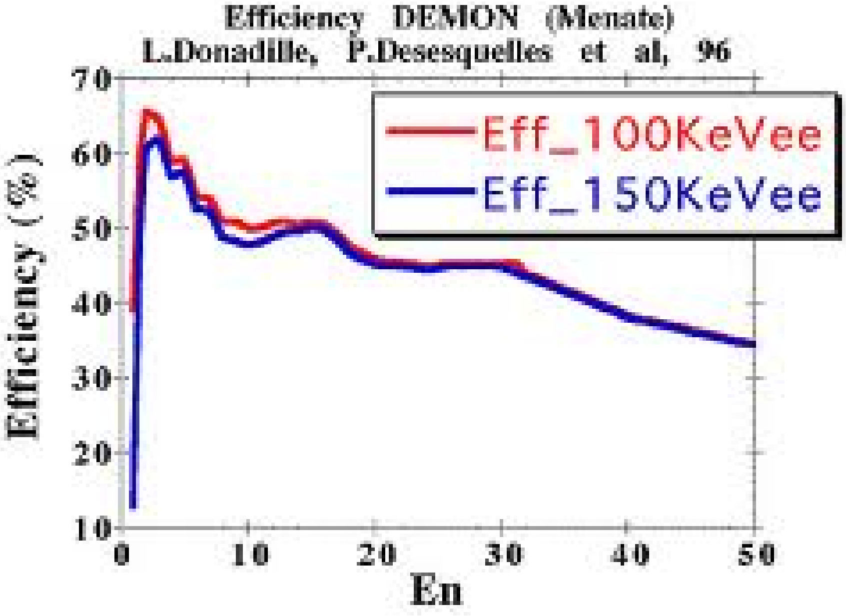
UCN detection,
material science

# DEMON

MOdular

4 π configuration

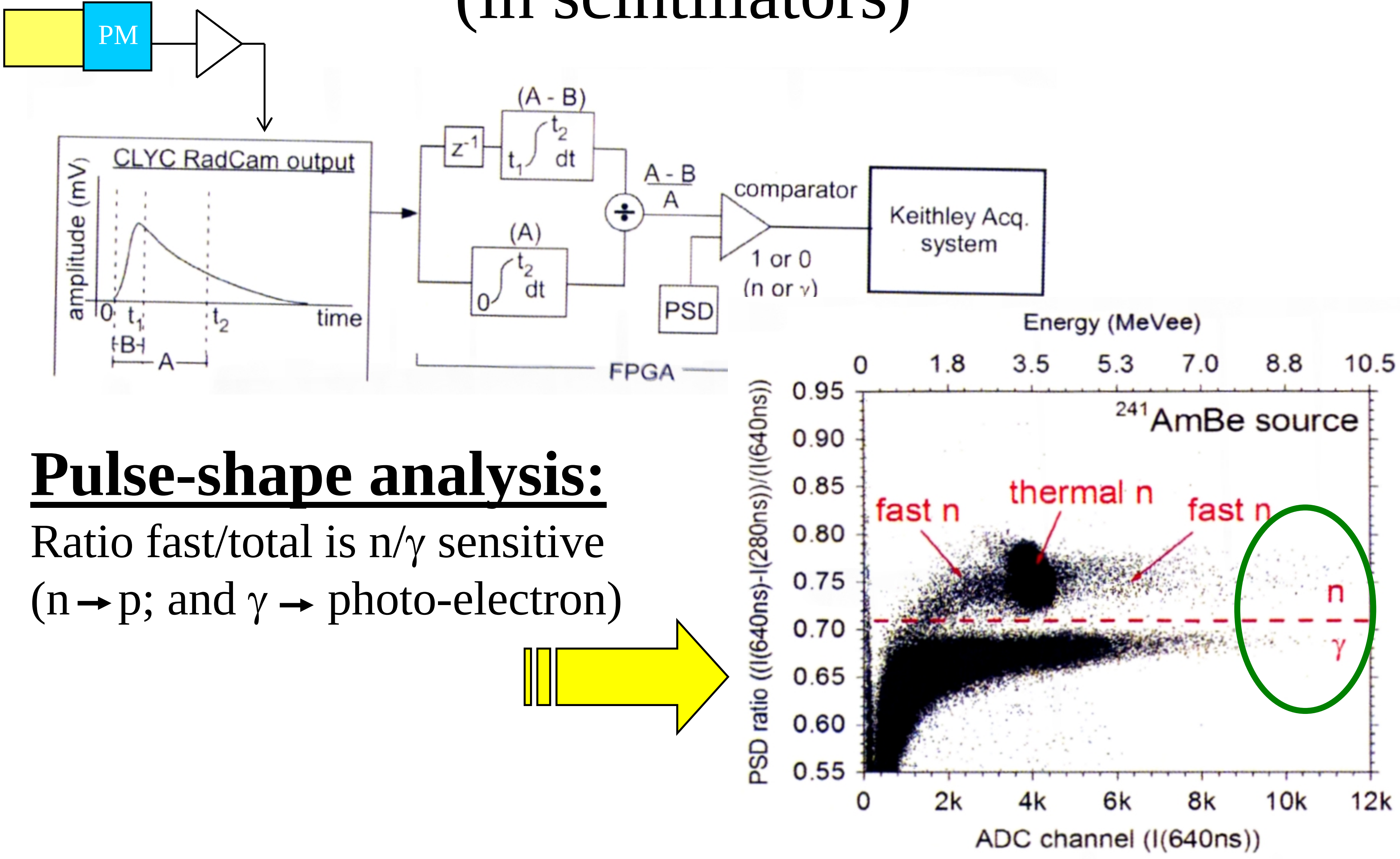
Single scintillating cell:



L=50 cm ➔ high effic @ 20 MeV

wall configuration

# A long-standing problem: n/γ discri (in scintillators)



## **Pulse-shape analysis:**

Ratio fast/total is n/γ sensitive

(n → p; and γ → photo-electron)

# 2. Sources

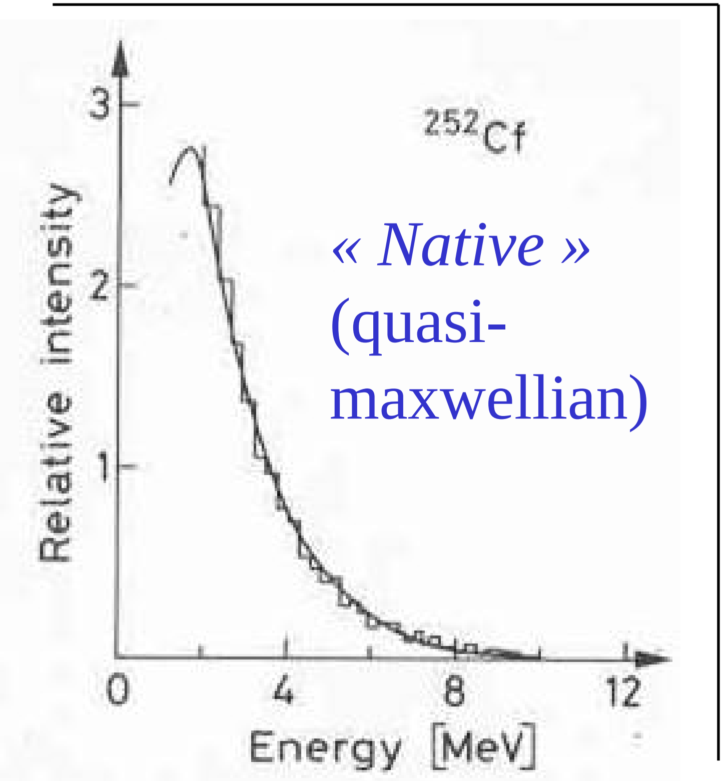
- Cf or AmBe : standard spectra $E_n$ ~ MeV
- Accelerators :
  - a) continous: mono-$E_n$ at selected angles
  - b) pulsed: {trigg.signal or γ-burst} ⇨ ***ToF*** measurement
- Reactors: very high fluences (meV-MeV)
- Spallation: very high energies (GeV) but broad spectrum

  or SUNS @ PSI $D_2O \rightarrow D_2(6K) \rightarrow$ ***UCN!***
- Unwanted: med.cyclotrons and LINACS

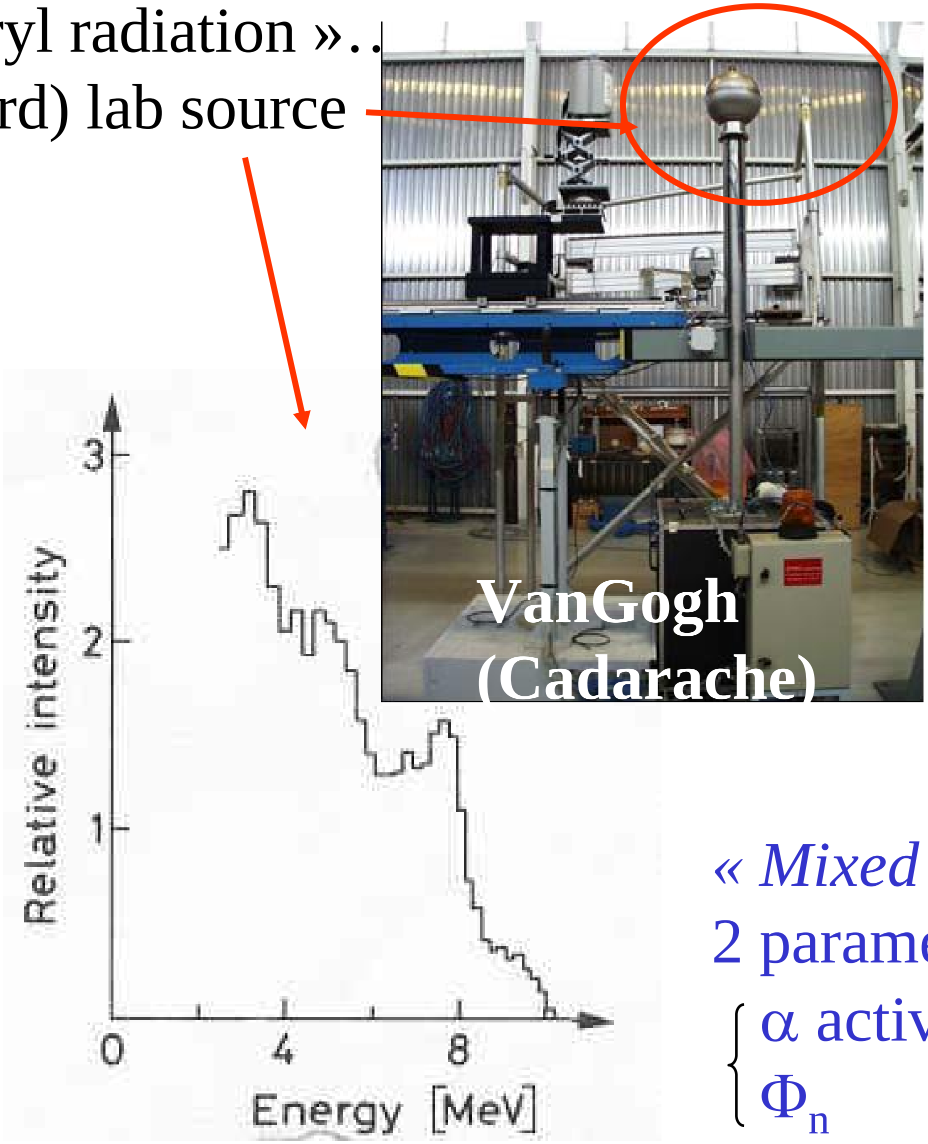
  (and tokamaks…)

1930: Bothe’s mysterious « **Be**ryl radiation »..

2015: Am**Be** is still a (standard) lab source



*« Native »*
(quasi-maxwellian)

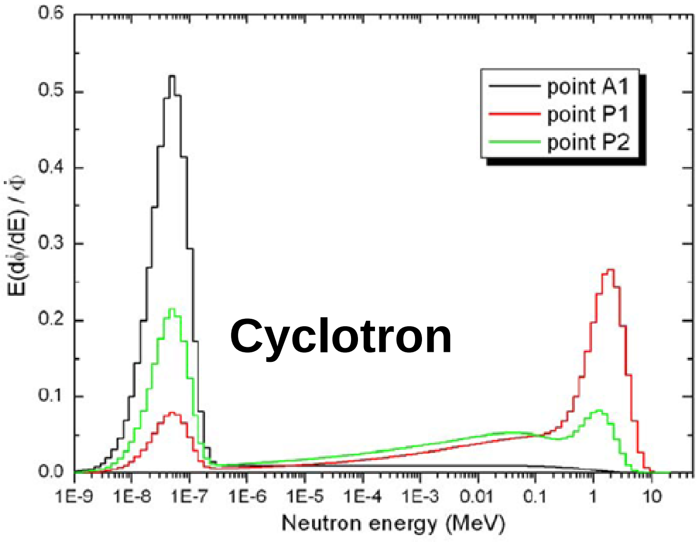


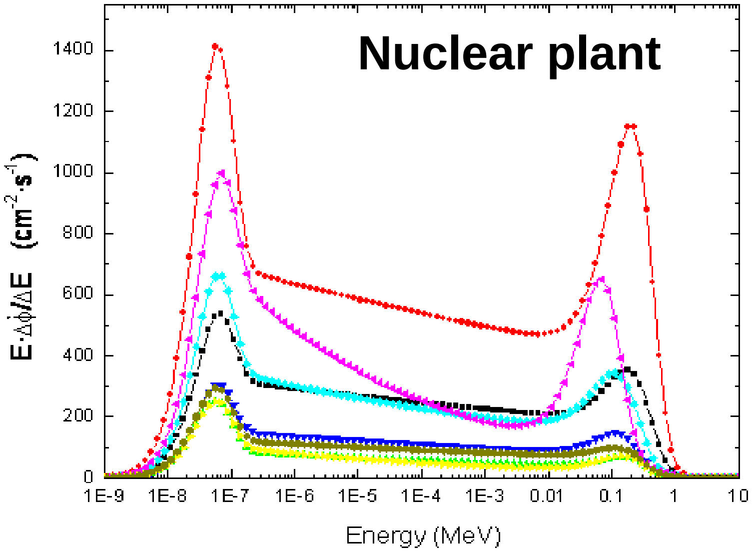
VanGogh
(Cadarache)

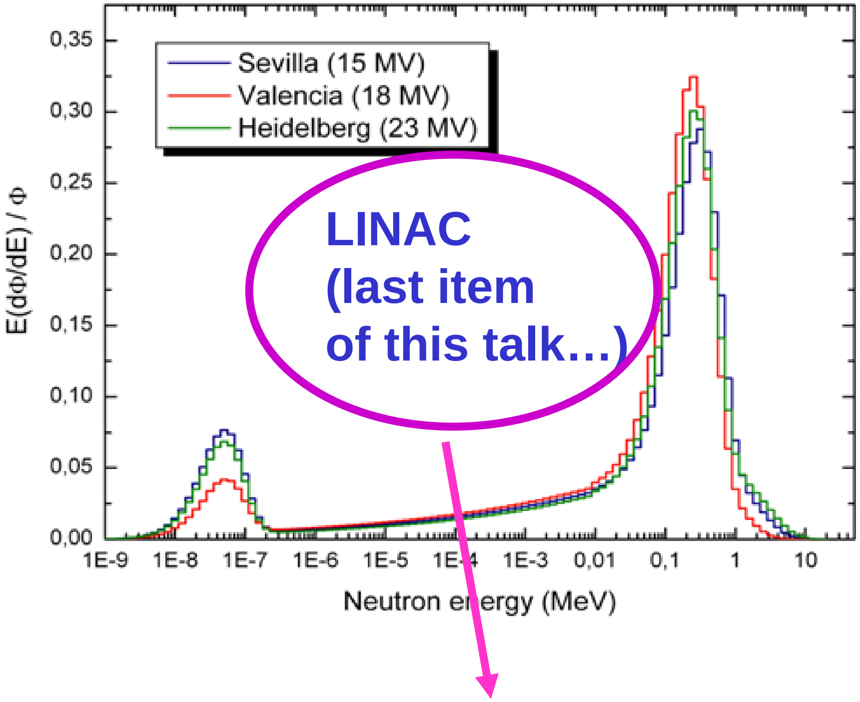
*« Mixed »*
2 parameters:
$\begin{cases} \alpha \text{ activity} \\ \Phi_n \end{cases}$

(~$2.10^6$ $s^{-1}$@ 37 GBq)

# Other broad band sources…


**Cyclotron**


**Nuclear plant**


**LINAC**
**(last item of this talk…)**

LINACs have replaced
~ all $^{60}$Co sources for medicine…

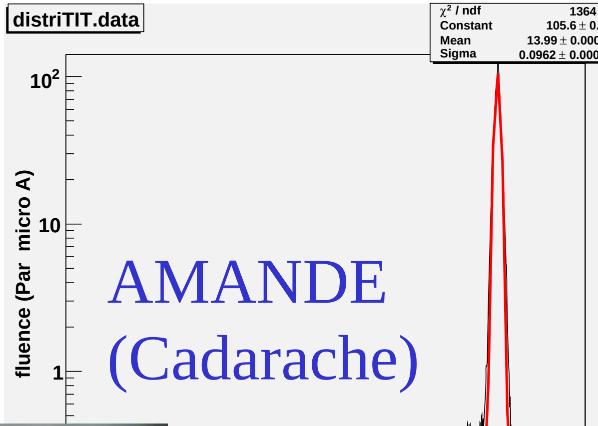
# Mono-energetic sources of *n*

Specific beams (p,d,..)

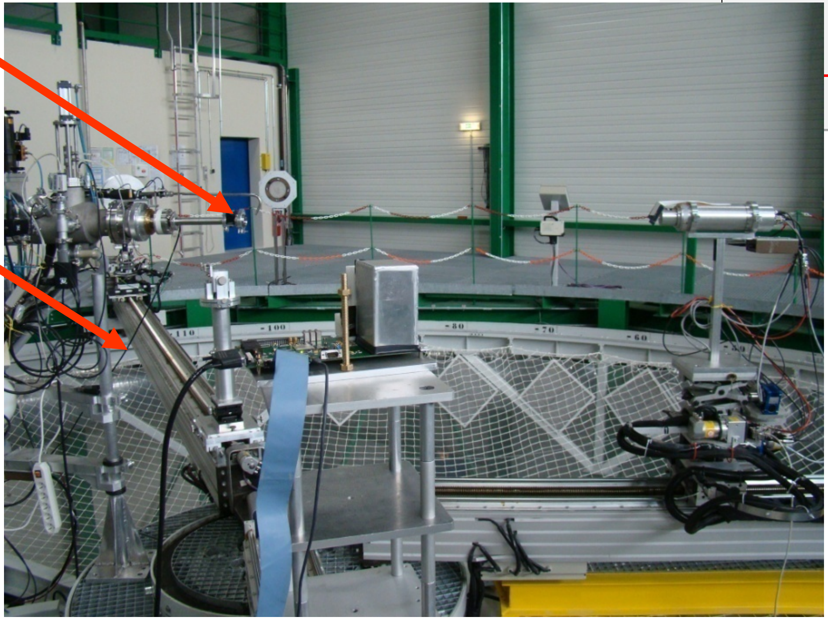
+ specific $E_p$,$E_d$

+ specific targets

+ selected angles



AMANDE (Cadarache)



mobile arms

Reactions:

$^{45}$Sc(p,n): 2 keV, 24 keV

$^{7}$Li(p,n) : 144, 250, 565 keV

$^{3}$H(p,n) : 1.2 , 2.5 MeV

$^{2}$H(d,n) : 2.8 ; 5 MeV

$^{3}$H(d,n) : **14.8*** ; 19 MeV

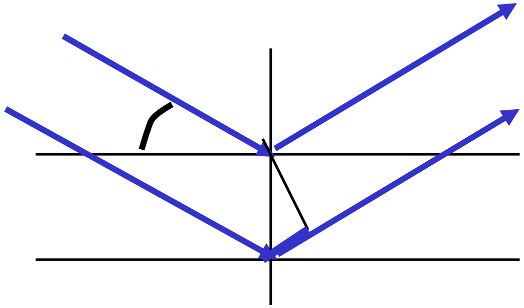
# Select/measure ***n*** energies: 4 methods

**source=reactor**

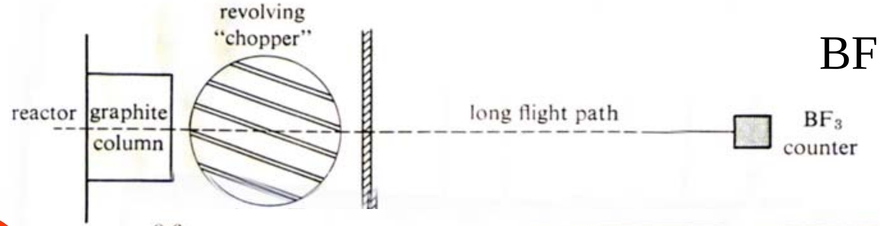
1) Low v: **Bragg** angle diffraction: $n.\lambda=2.d.\sin(\Theta)$, $\lambda=h/mv$

Cond.: $\lambda \sim d \sim 10^{-10}\text{-}10^{-9}$ m
or E~ **82 meV** – 0.82 meV

$$E=\frac{n^2h^2}{8md^2\sin^2\Theta}$$

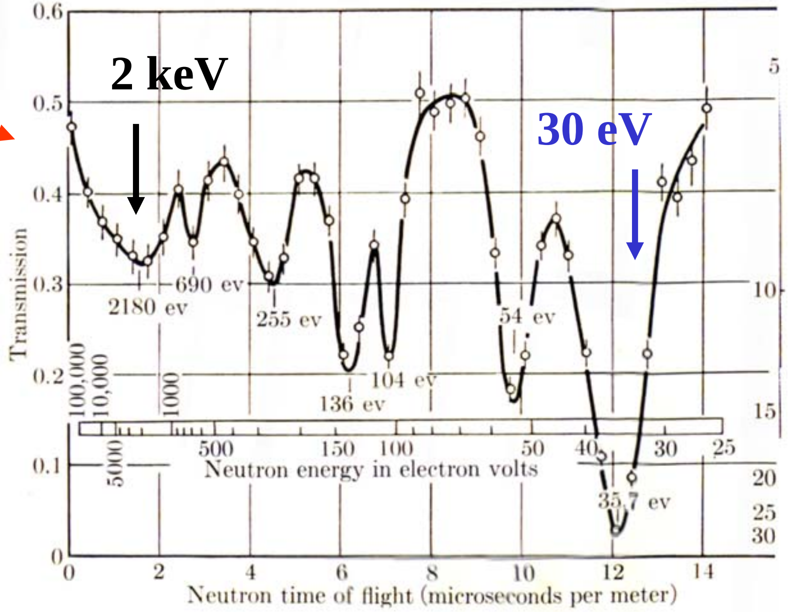


2) Moderate v (and E < **0.3 eV**):
mechanical choppers (Al/Cd)



BF3

3) Fast n (< **1 MeV**): pulsed bursts + ***ToF***
(1 MeV means ***70 ns/m***)

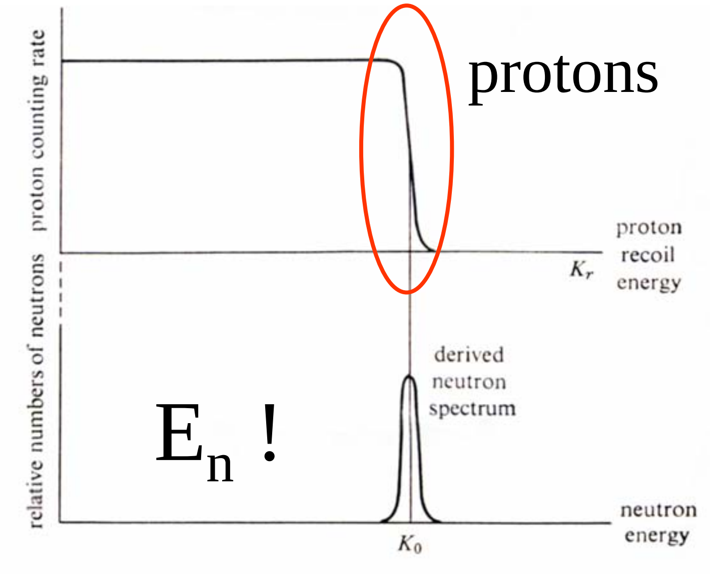


4) Above 1 MeV: **Recoil protons**
a) Mono-E « source »: edge of $E_p$ distri
b) broad sprectra: telescopes !

# Meth. nb 4: recoil protons

Two ***most*** important features:

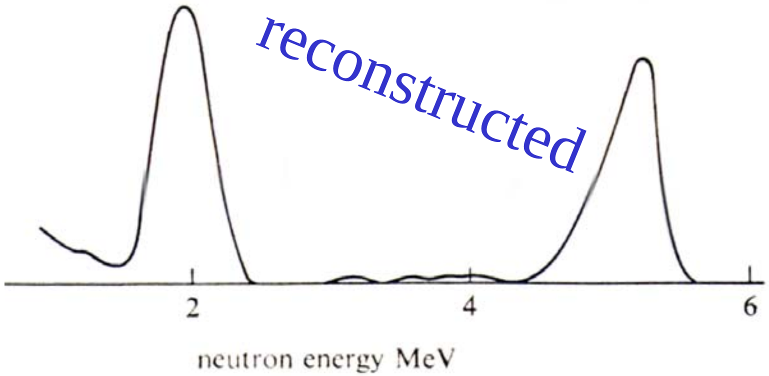
- $M_p = M_n \Rightarrow E_p = E_n . \cos^2 \theta_p$
- Fixed $E_n \Rightarrow$ $E_p$ distribution is flat



protons

$E_n$ !

<u>Example</u>: d ($E_d$=0.9 MeV) on N+$^2$D target, measured at 150° (***old time*** technology: photographic emulsion)



reconstructed

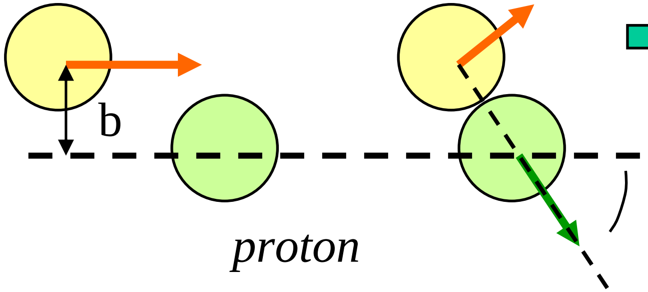
# The rules of billiard game (detail)

Elastic (n,p) behaves like ***hard spheres*** (square nuc.potential !)

$\sin \theta_p^{LAB} = b/2R$

***hello MC guys!***

<u>Distributions</u>: ***n***-beam uniform ➡ $f(b^2)db^2$ uniform

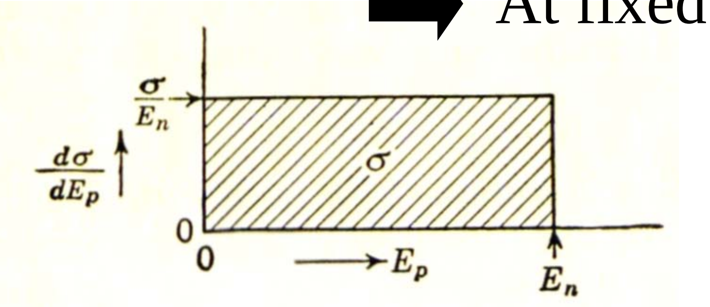


➡ $\sin^2\theta_p$ uniform (*not* $\theta_p$, and *not* $\sin \theta_p$ !)

➡ $\cos^2\theta_p$ uniform also

➡ At fixed $E_n$: $E_p = E_n.\cos^2\theta_p$ distribution is flat !

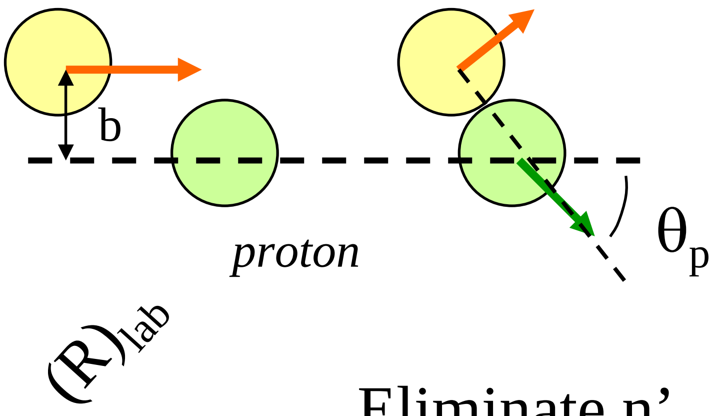
and $\langle E_p \rangle = E_n/2$ (LAB)



***(all this is ⇔ to isotropy in CM…)***

# The rules of billiard (detail of detail)

Demonstration of $E_p=E_n.\cos^2\theta_p$



From $\vec{p}$ and $E_n=E_{n'}+E_p$ : $\theta_n+\theta_p=\pi/2$ *

$$\vec{p}_n=\vec{p}_{n'}+\vec{p}_p \quad : \quad \begin{cases} p_n = p_{n'} \cos\theta_n + p_p \cos\theta_p \\ 0 = p_{n'} \sin\theta_n - p_p \sin\theta_p \end{cases}$$

Eliminate n' ⇨

$$\begin{aligned} p &= p_p \{ \sin\theta_p \operatorname{cotg}\theta + \cos\theta_p \} \\ &= p_p . \sin(\theta_p+\theta)^{*} / \sin(\theta) \\ &= p_p / \sin(\theta) \end{aligned}$$

⇨ $p_p=p_n.\sin\theta_n = p_n.\cos\theta_p$

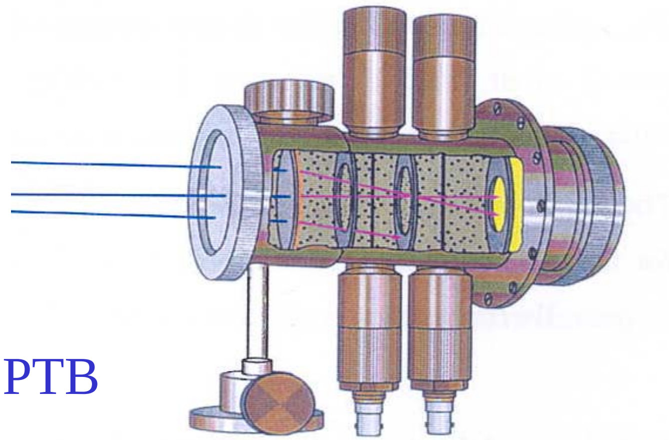
or $\boldsymbol{E_p=E_n.\cos^2\theta_p}$ (as $m_p=m_n$)

# 3. Recoil protons: modern times

1. Zero-angle « telescopes » :

⟺ select the edge of square distribution

( < 5% distrib. is useful: low stat !!)



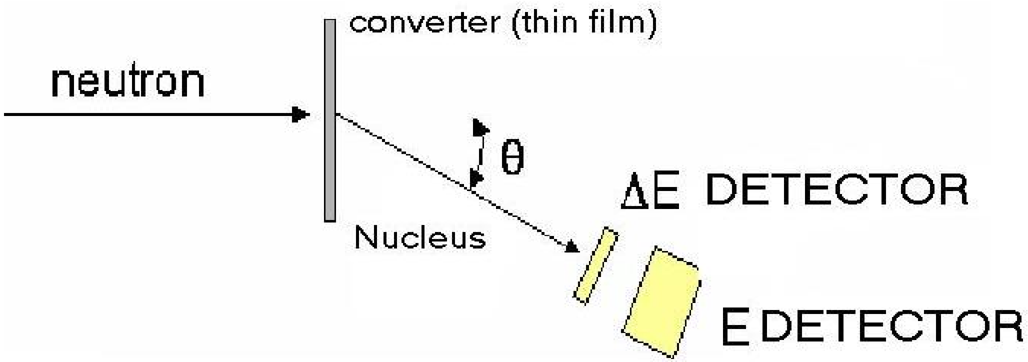
Ex: gaseous 0-angle tel. @ PTB
(Braunschweig, Germany)

2. True telescopes: tracking of « all » recoils ⇒ { meas. angle $\theta_p$, Stat x 10 !

$= \text{real use of } E_p=E_n.\cos^2\theta_p$

Various technologies @ HE (>20 MeV): scint, Si strips etc..
< 20 MeV: **CMOS pixels** thinned down to ***50 µm*** thickness

# Recoil Protons: mean *and* dispersion…



Any recoil:

$$E_n = \frac{(1+A)^2}{4A} E_r / \cos^2\theta$$

**Protons:**

$$E_n = \frac{E_p}{\cos^2\theta}$$

**Resolution:**

$$\left(\frac{\sigma_{\mathrm{E}_n}}{\mathrm{E}_n}\right)^2 = \left(\frac{\sigma_{\mathrm{E}_p}}{E_p}\right)^2 + 4.\tan^2\theta.(\sigma_\theta)^2$$

Performances of existing devices :

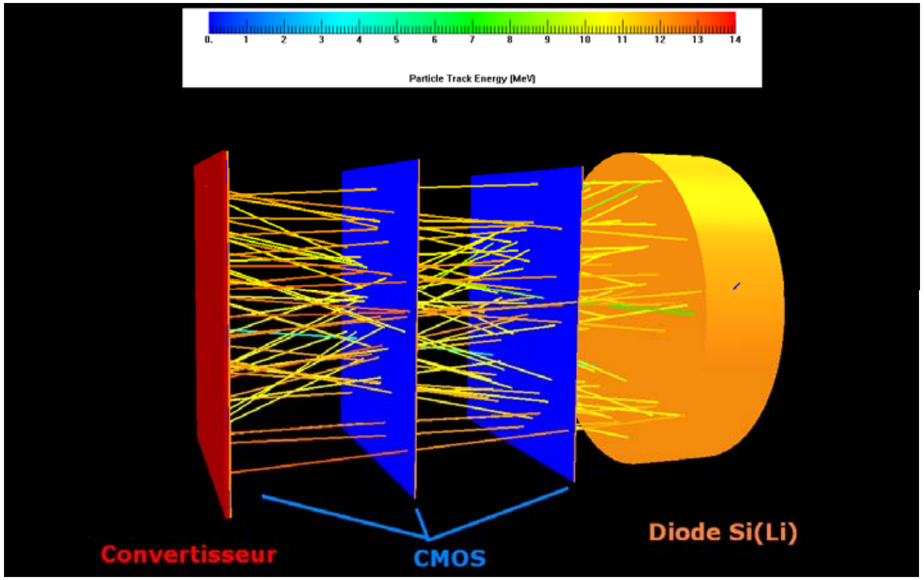
- fluence resolution : 2-3 %
- energy resolution : 5-8 %
- effic. n → p : ε ~$10^{-5}$

*Life is hard: even with σ ~ mrad, angles still limited to ~ 45°*

# The IPHC CMOS-RPT

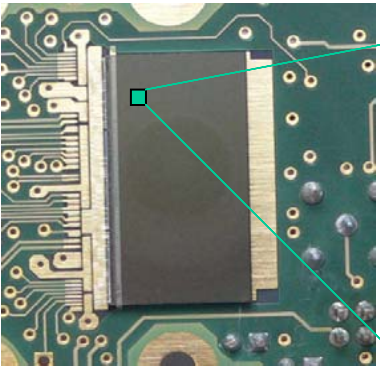
$E_{neutrons}$: 6 - 20 MeV

- ➢n/p converter : polyethylene $(CH_2)_n$
- ➢ 3 planes CMOS : (→40 ° emiss angle )
- ➢ Si(Li) diode: catching the proton energy

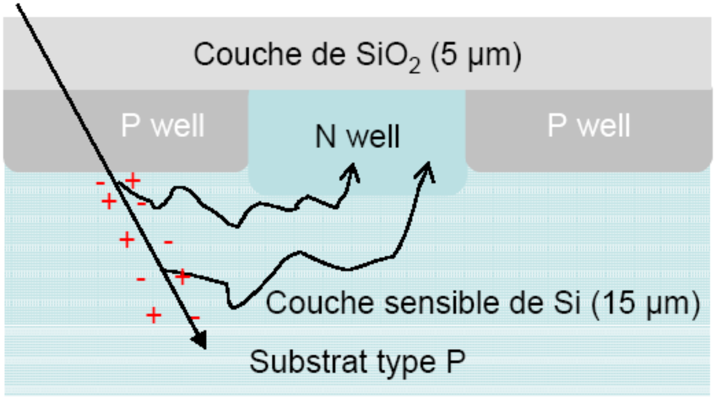


MCNPX Simulation (proton tracks)

**MIMOSA 20 (STAR Collab.)**
300 ->down to 50 µm!
640x320 pixels
Inter-pixel pitch =30 µm
Area : 2 cm²

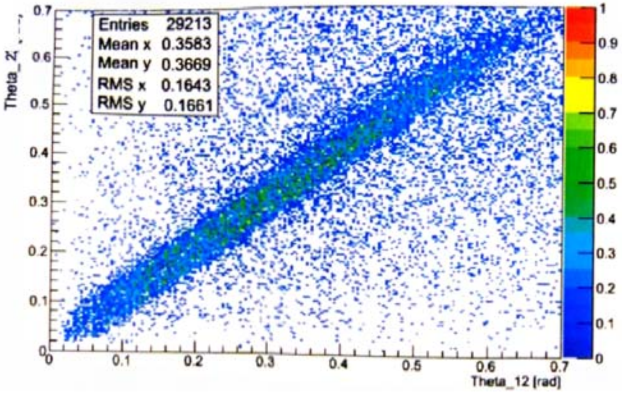


*MIMOSA20*

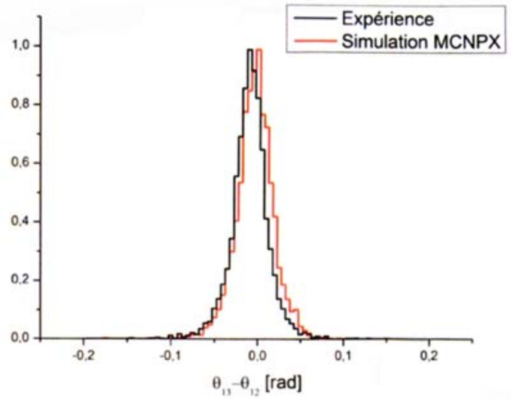


# Our CMOS-RPT in action….

$\varepsilon$ ~5 $10^{-4}$

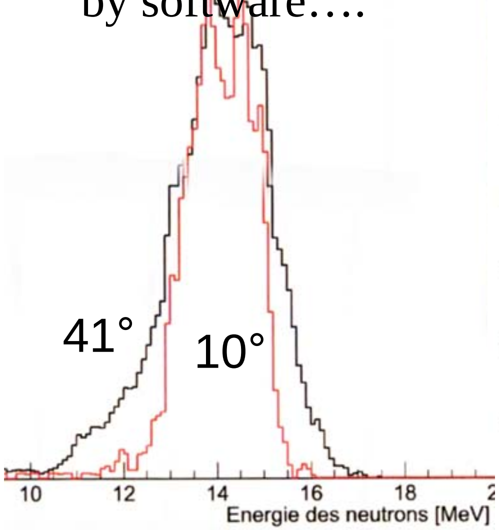


Correlation P1P2/P2P3

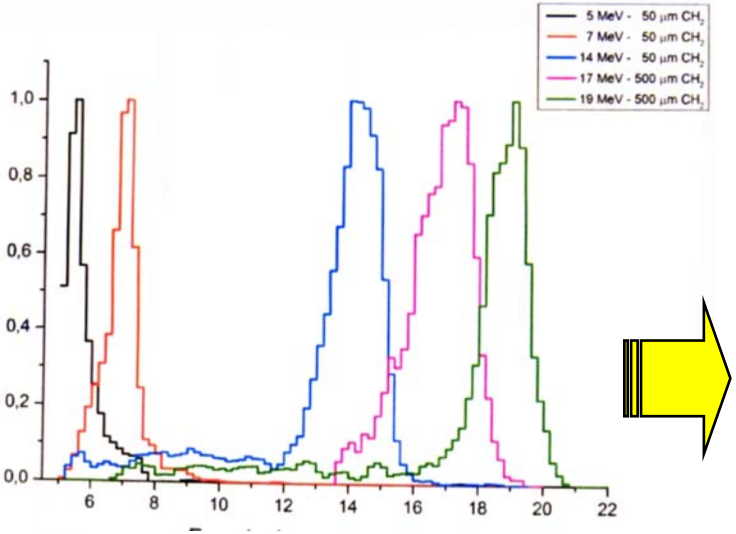


Multiple scattering: low

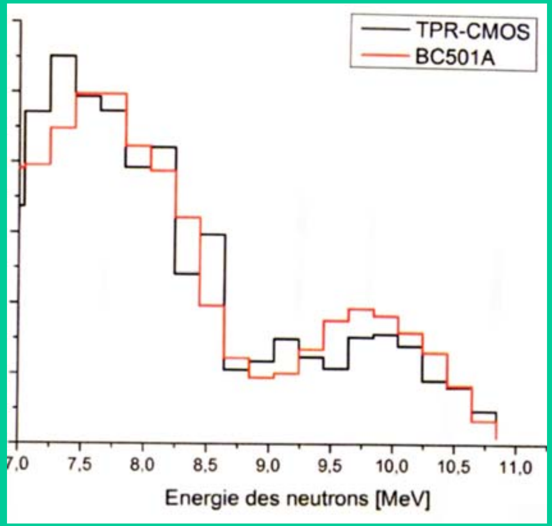
Select angles just by software….



$E_n$=14 MeV



mono-E peaks !



Broad source !

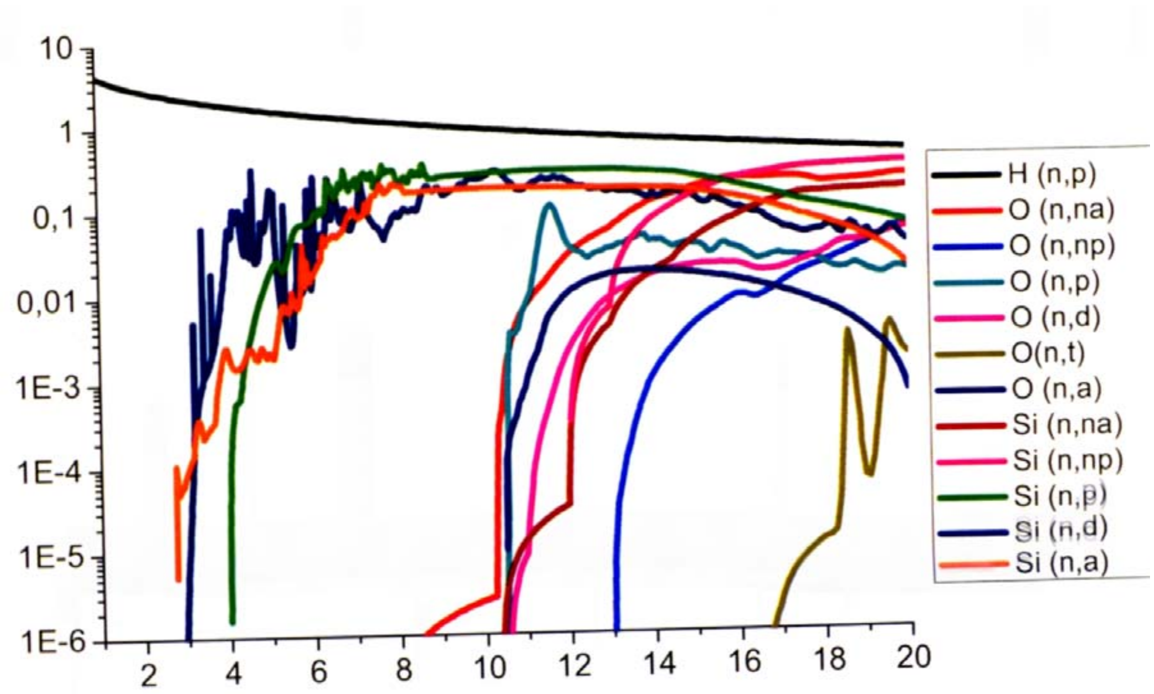
Main pb: background ! = direct ***n*** conversion in thick diode, in coïncidence with a true proton track ➡ wrong associations !

⬇

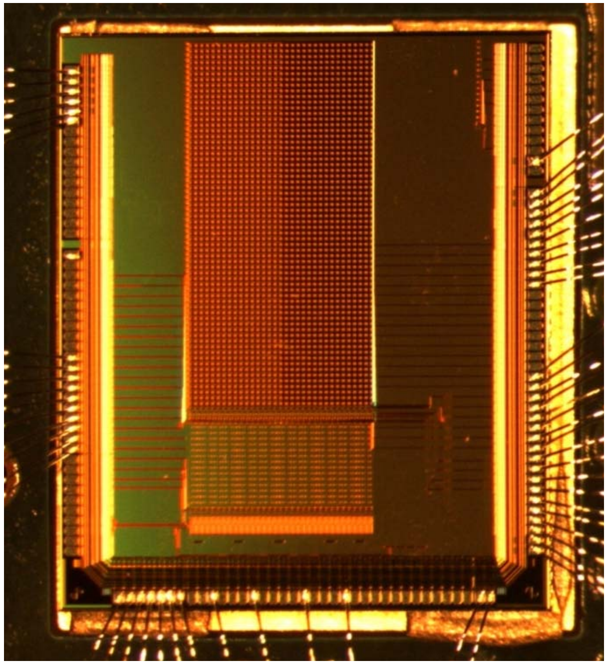
Solution: GO FAST !

Old chip: $t_{frame}$= 20 ms

New chip: $t_{frame}$= 12 µs



MeV



***FastPixN*** (XFAB 0.35 µm),
128 x 128 pixels, p = 50 µm

# 4. Ultra-Cold Neutrons

- How ? Take a reactor and select velocities !
- How much ? Very very *few*….

- What for ?

Very nice **fundamental** physics !

a) neutron life-time (⇨ CKM elt $V_{ud}$)
b) neutron electric dipole moment ( $\cancel{P}$ )
c) quantum physics amusement

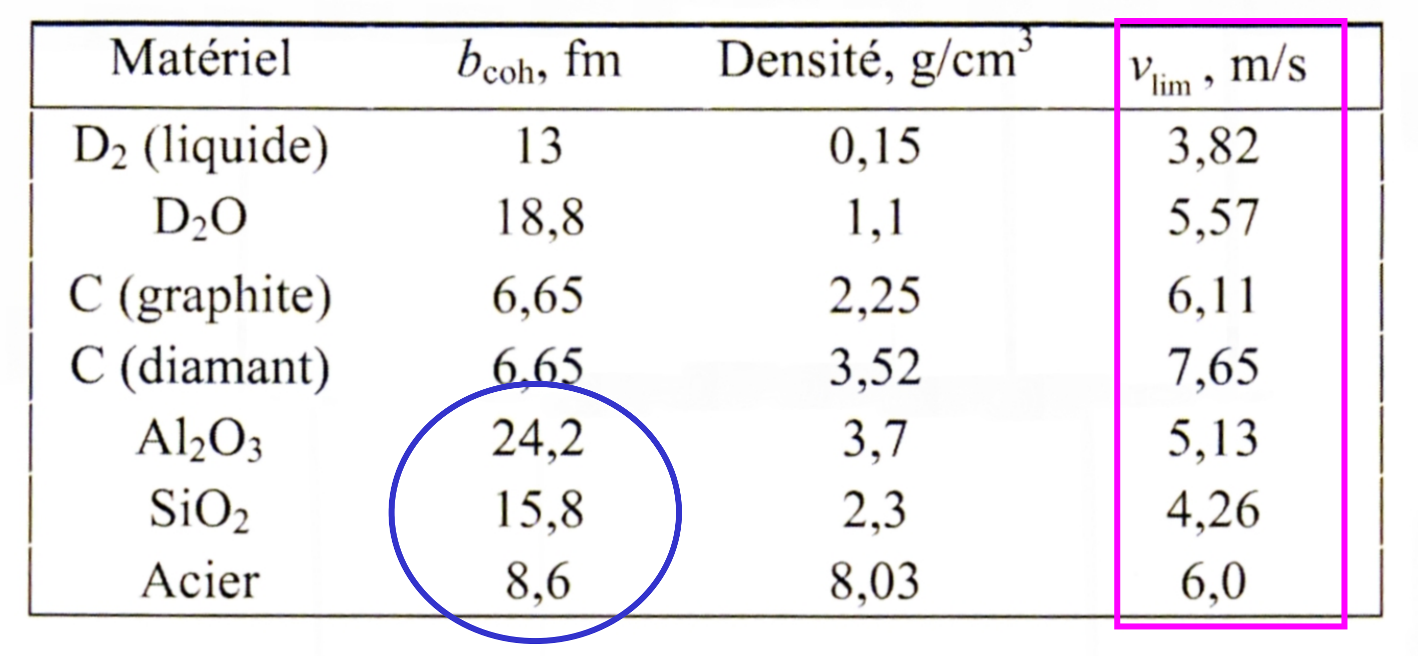
# The paradox…

- Rutherford (1920 !) : ***n*** can penetrate large thicknesses of materials…
- 1959: Y.Zeldovich JETP (1959) 36, 1952 points « mirror » effect ! ⇨ storage !!
- Explanation: @ v=10 m/s, **$\lambda$ = 100 nm:**

the ***n*** sees a many-body target, i.e. a ***Fermi potential*** $U=2\pi\hbar^2 b_{coh}N/m$. Solving the Schrödinger Eq. $\rightarrow$ $R=1-T$ with $R \sim 1$ !

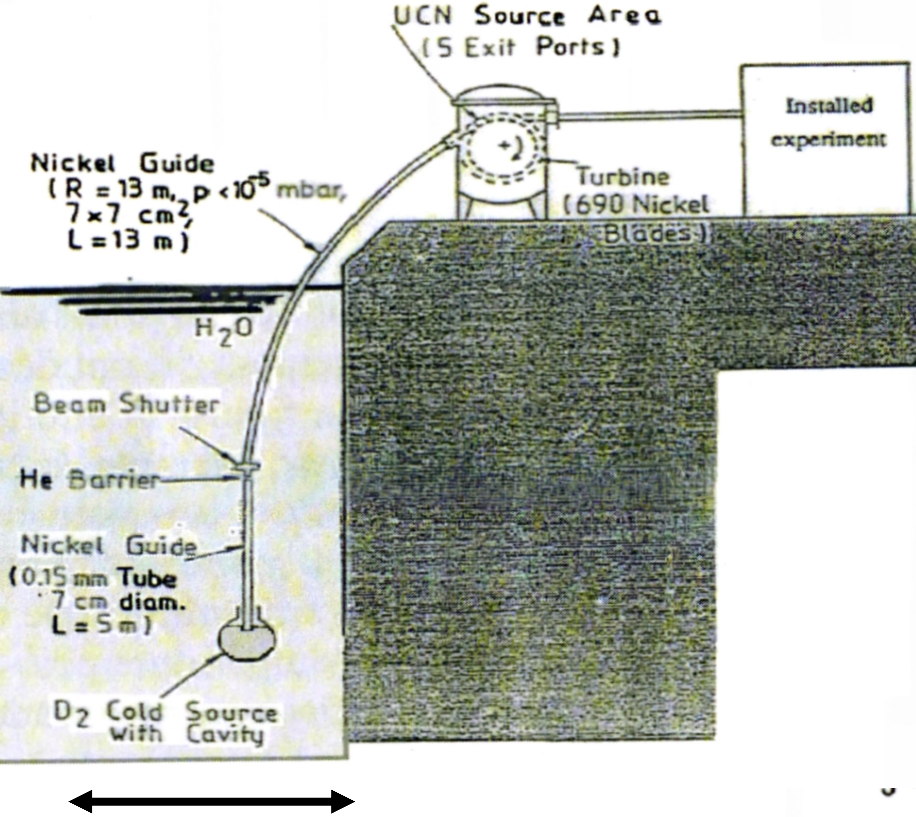
# Reflexion conditions

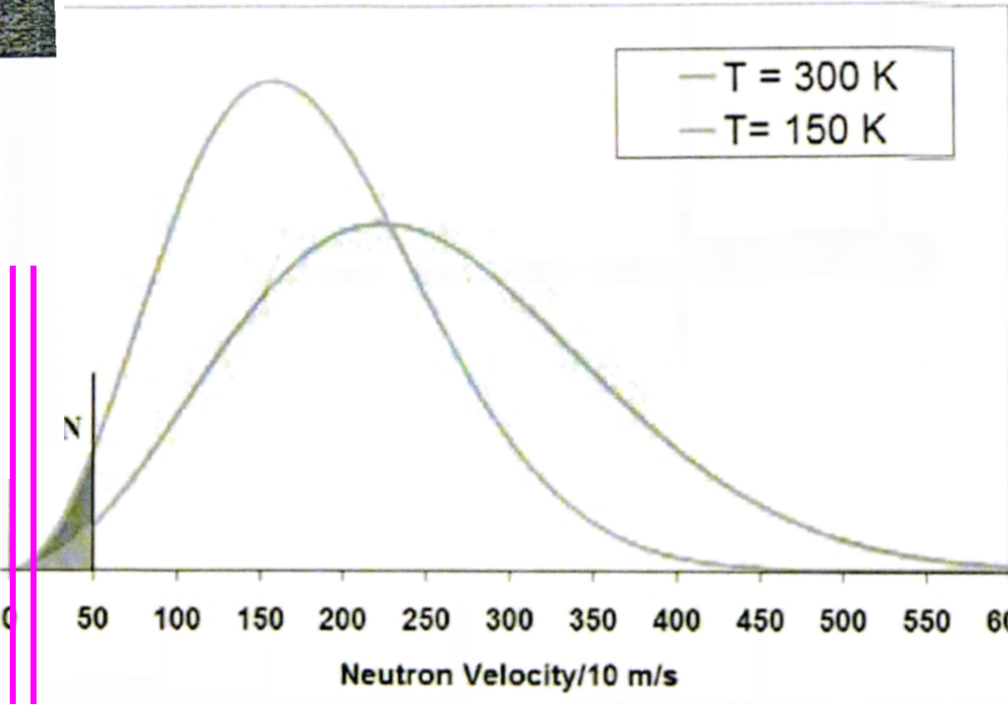
- If U>0: $v_{perp} < v_{lim}=(2mU)^{1/2}$ ➡ reflexion
- Purely elastic process : $T_{wall}$ may be >> $T_{UCN}$
- Numerical: $T_{UCN}$~ ***mK*** and $b_{coh}$ (« coherent diffusion length » inside wall) ~ some ***fm***



| Matériel | $b_{coh}$, fm | Densité, g/cm$^3$ | $v_{lim}$ , m/s |
|---|---|---|---|
| $D_2$ (liquide) | 13 | 0,15 | 3,82 |
| $D_2O$ | 18,8 | 1,1 | 5,57 |
| C (graphite) | 6,65 | 2,25 | 6,11 |
| C (diamant) | 6,65 | 3,52 | 7,65 |
| $Al_2O_3$ | 24,2 | 3,7 | 5,13 |
| $SiO_2$ | 15,8 | 2,3 | 4,26 |
| Acier | 8,6 | 8,03 | 6,0 |

# UCN: How ?





Inside (!) reactor:
Neutrons are scattered on cold $D_2$ target. Only the UCN are « guided » out
(passive meth: yield *poor*…)

$$\eta = \frac{\int_0^{v_{\lim}} n(v)dv}{\int_0^{\infty} n(v)dv} \simeq \frac{1}{8}\left(\frac{mv_{\lim}^2}{kT}\right)^2 \boxed{\sim 10^{-11}} \ @\ v_{\lim}(\mathrm{Cu})$$

# Physics purposes

- Life-time of free ***n***
- Parity violation
- Quantum levels in gravitational potential

# Life-time: why?

$n \rightarrow p + e^- + \overline{\nu}$ process is in fact $d \rightarrow u + e^- + \overline{\nu}$ at the parton level

Half-life: $\tau \sim 12$ min: what makes this number so interesting ?

1) CKM : $|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$ with $|V_{ud}|^2 = k/\tau(1+3\lambda^2)$

numerator k in known @ $4.10^{-4}$ (EW rad.corr)

and $\lambda = g_A/g_V$ (electroweak axial/vect-ax) can be measured with very high precision (asymetries)

⇨ The *limiting factor* is $\tau$ ! (present goal: reach $10^{-3}$)

2) Cosmology: Primordial nucleosynthesis (again !)

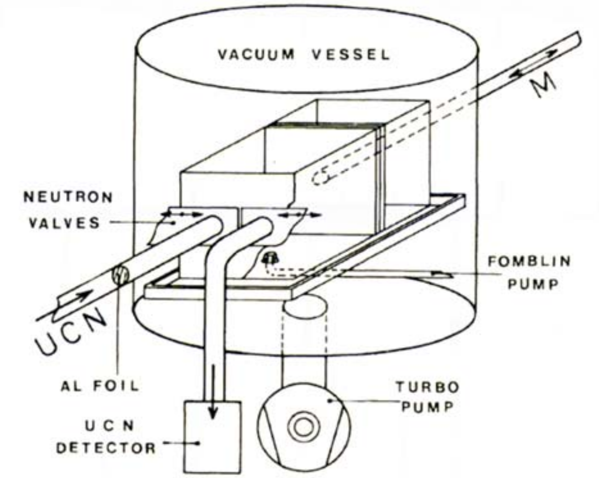
If ***n***-capture dominates the table for heavy A, detailed scenarii for *light* nuclei (i.e. D,$^3$He, $^4$He, $^7$Li) rely on ***n***'s life time; theoretical uncertainty on $^4$He abundance is dominated by $\sigma(\tau)$ !

*Lopez and Turner, Phys.Rev.D59(1999)*

# Life-time: how?

Two methods (both with UCN): 1) time of flight (v~ m/s)

or 2) desintegration rate of trapped ***n***

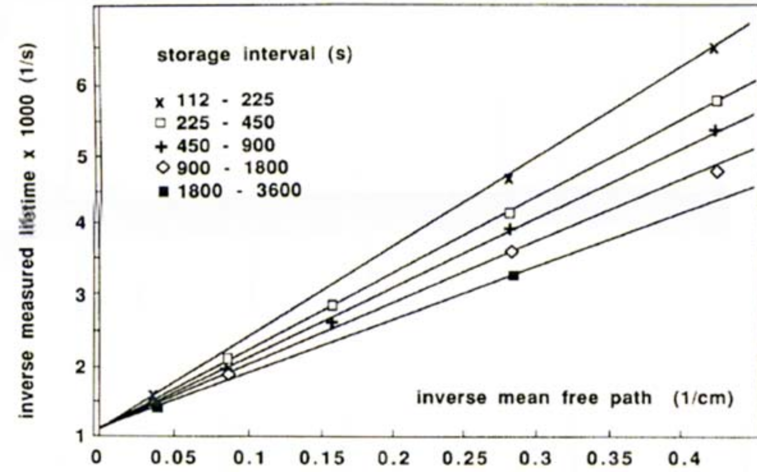


$N(t)=N_0\exp(-t/t_{eff})$

$t_{eff}$ = trapping time

$$1/t_{eff} = 1/\tau + \boxed{1/t_{losses}}$$

THE problem!



Solution: mobile walls
+measure mean free path

Result ( extrap at infinite m.f.p): $\tau$ = 887.6 +- 3.0 s ($3\ 10^{-3}$)

World aggregate results
all experiments (ToF & trapp.): $\tau$ = 885.7 +- 0.8 s

# Parity violation

- Remember: the ***n*** has a magnetic moment $\mu_n = -1.91\ \mu_N$
- <u>Open question</u>: does it have an ***electric*** moment ??

if $\vec{d} = e.\vec{r} \neq 0$, there is only ONE specif axis = $\vec{s}$: ⇒ $\vec{d}_n = d_n.\vec{s}$

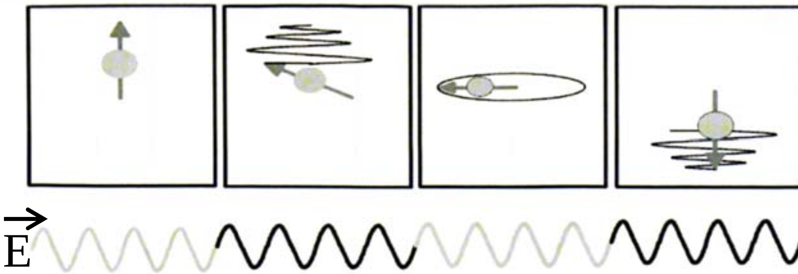
Under Parity : $P(\vec{r}) = -\vec{r}$ but $P(\vec{s}) = \vec{s}$ ⇒ $d_n$ = pseudoscalar

new source of $\cancel{CP}$ !! (after $K^0$ and $B^0$ mesons)

Standard Model says: $10^{-32}$-$10^{-34}$ e.cm : room for ***new physics*** !

Present limit: $d_n < 2.9\ 10^{-26}$ (with UCN…)

# How? Ramsey's method



- Single ***n*** in external fields B and E: $H = -\vec{\mu}_n.\vec{B} - \vec{d}_n.\vec{E}$
- QM : two states with $\Delta E = 2\mu_n.B \pm 2d_n.E$
- Ramsey's method: 1) static fields parallel 2) RF pulse for $\vec{s}$ perp. , then free precession
  3) new RF pulse to set $\vec{s}$ anti-parallel 4) measure the spin-flip ratio

If $d_n$ exists, inverting $\vec{E}$ => $\Delta\nu_{Larmor} = 4\,\mathbf{d_n}.E/h$

<u>Conditions</u>:

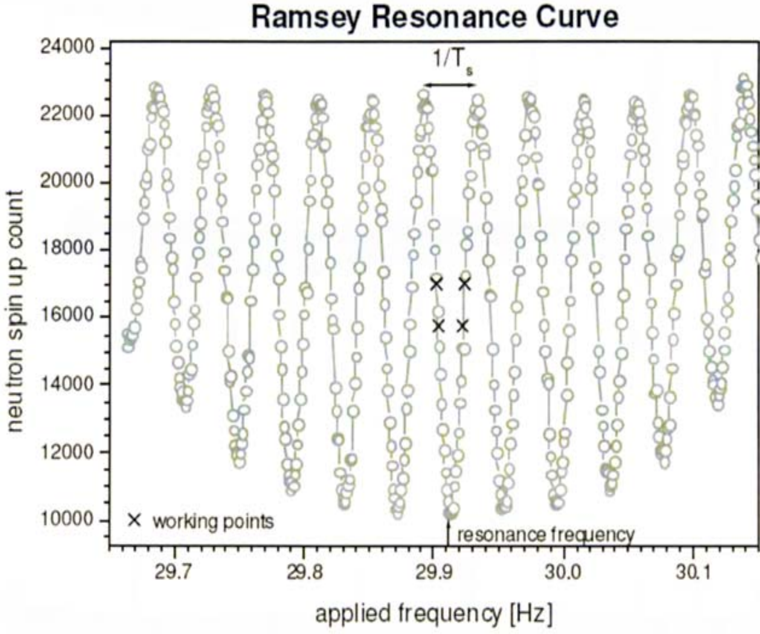
* B small (μT) but E large (15 kV/cm)

* error on $d_n$ is ~ $1/N^{1/2}$

* high contrast ($\vec{s}$ up/down) ***only*** for UCN

Just one thing to do: enhance $N_{UCN}$

New sources under development



# 5. Human biology

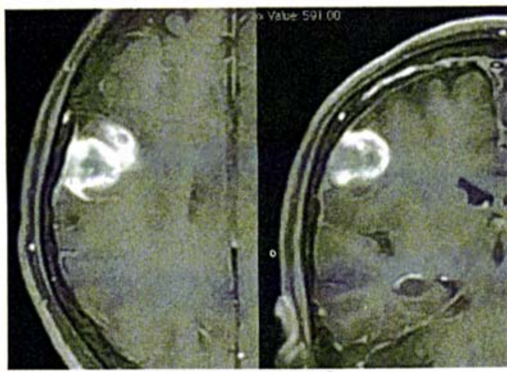
Dark side of the neutrons: they ***hurt*** !

→ Two things to do: measure (dosimetry)
\+ protect (radioprotection)

Luminous side: neutrons can ***heal*** cancer (BNCT)

More ambiguous: ***n*** can ***hurt*** inside radiotherapy
or protontherapy rooms…

# Neutrons against cancer: BNCT



Motivation: numerous head/neck melanomia are both chimio- and radio-resistant (even with p-therapy)

Idea: $^{10}$B+n ➔ $^{7}$Li+$^{4}$He: @ 1.5 MeV, R ~ **5-9 µm** !

(selective high dose directly in tumor cells)

Challenges (human bodies exposed to reactor ***n*** !!) :

- keep **N**ormal tissue **dose** << **T**umor dose : usually: T/N ~2.5

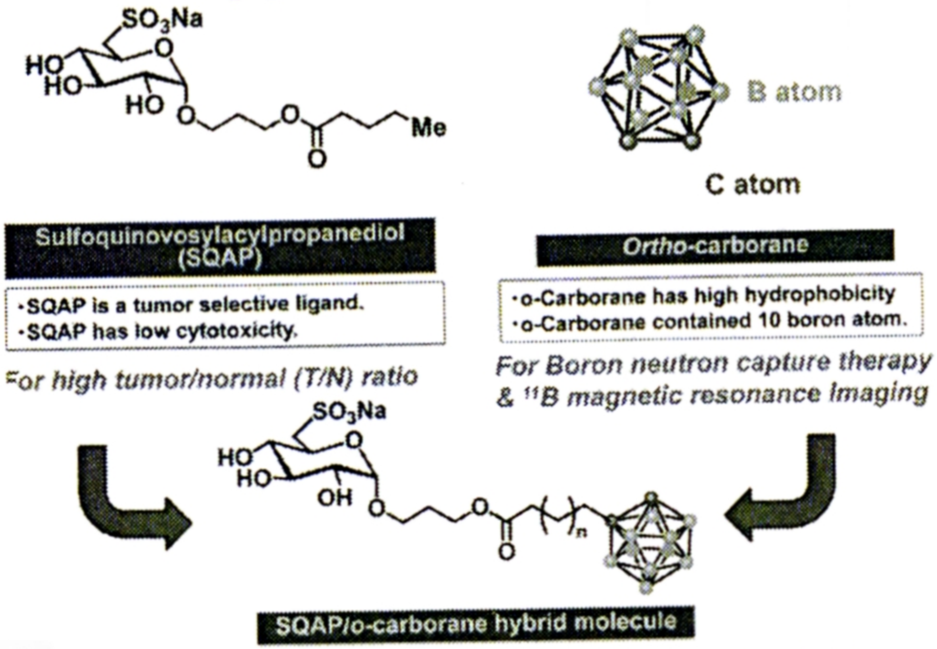
➔ epithermal 25 meV

- develop non-toxic B **molecules**:

tumor selective ligand
+ fullerene box ($^{10}$B or $^{11}$B (IRM))

- Japan at the forefront:

**Y.Mishima, Pigment Cell Res.,1(1973)215**
**T.Aihara, Int.J.Clin.Oncol (2013)**



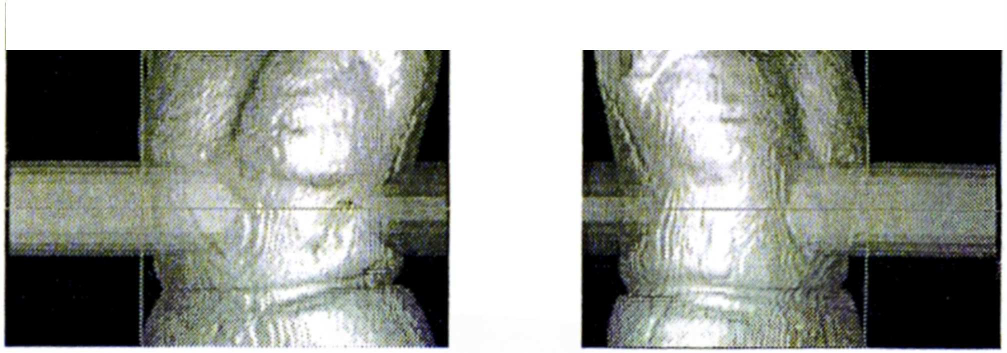
·SQAP is a tumor selective ligand.
·SQAP has low cytotoxicity.

·o-Carborane has high hydrophobicity
·o-Carborane contained 10 boron atom.

For high tumor/normal (T/N) ratio

For Boron neutron capture therapy & $^{11}$B magnetic resonance imaging

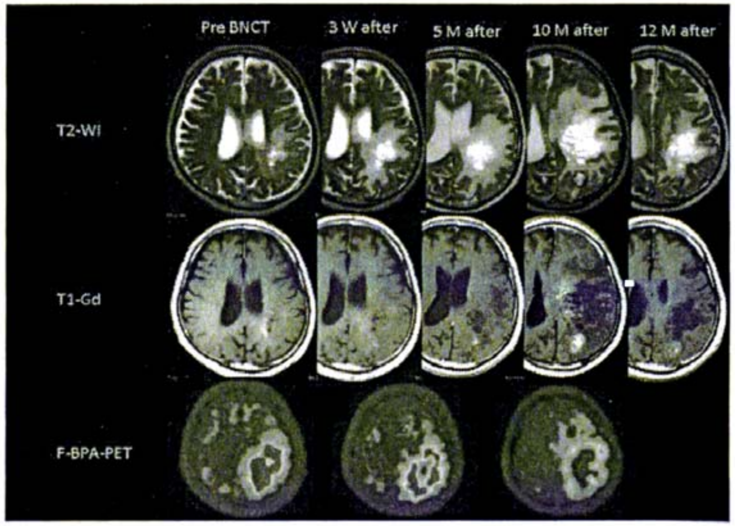
# Boron Neutron Capture Therapy



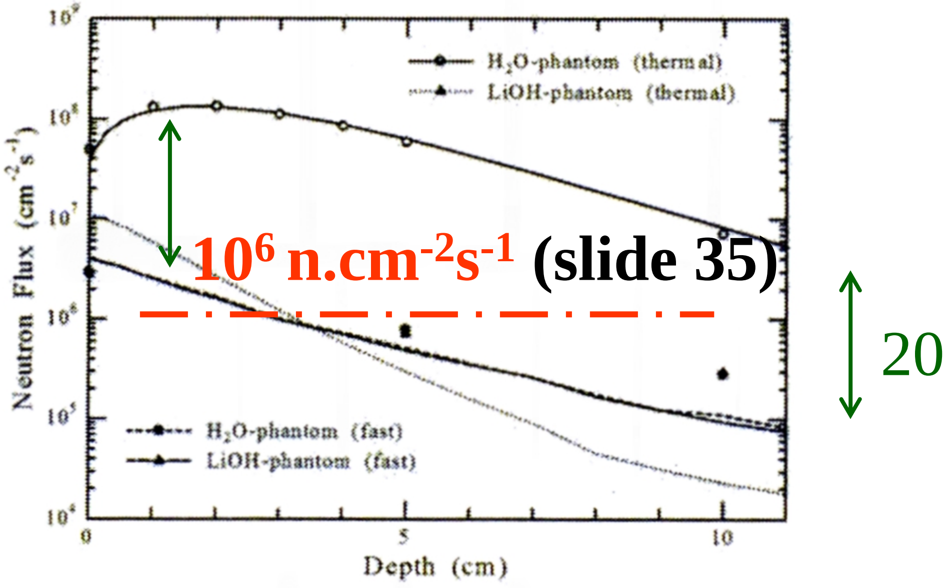
**Frontal view**

1: **Beam irradate from right 60° angle**

2 : **Beam irradate from left 40° angle**



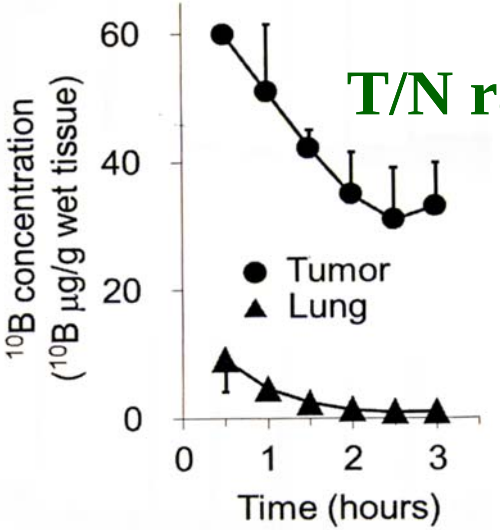
Evolution of a brain recurrent malignant glioma



**$10^6$ n.cm$^{-2}$s$^{-1}$ (slide 35)**

20

Delivered dose in normal tissue (phantom)



**T/N ratio**

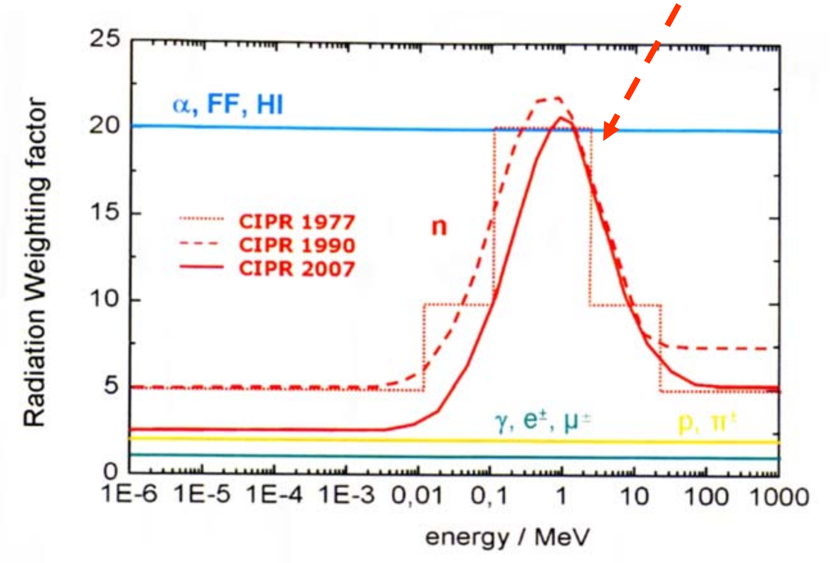
# Neutron dosimetry: juste one number

Equivalent dose for man (sievert):

**$H = D.\, w_R$**

D = abs.dose (Gy)

and for ***n***: weighting factor $w_R$ = 20

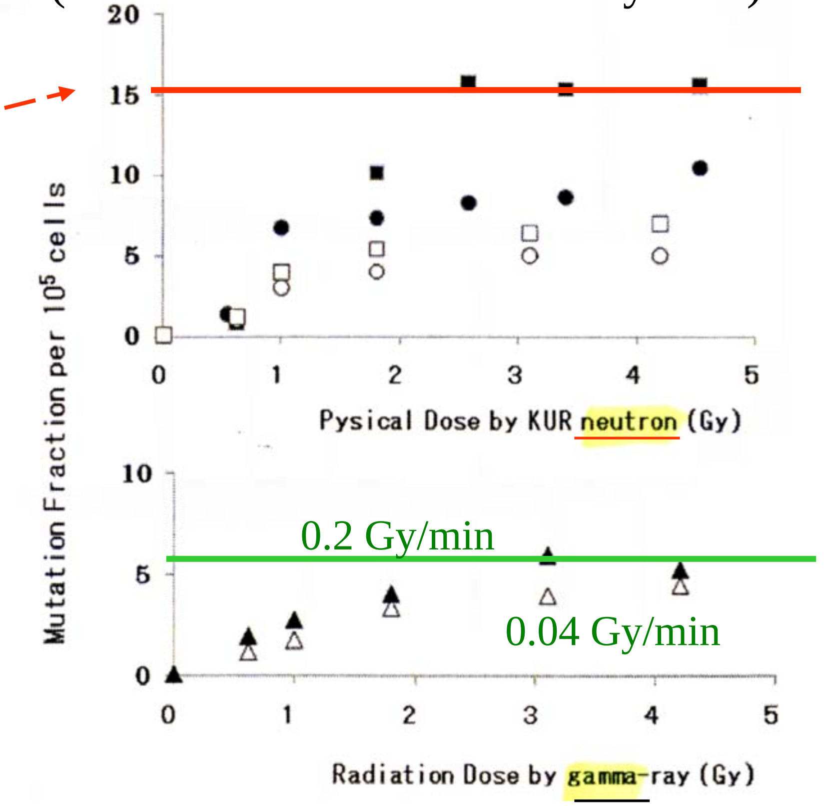


Legal « definition », periodically updated

by competent **authorities** (**ICRP.org**)

Basis: measured cell ***mutation*** rate

(CHO = chinese hamster ovary cells)



# Neutron dosimetry: juste ONE curve

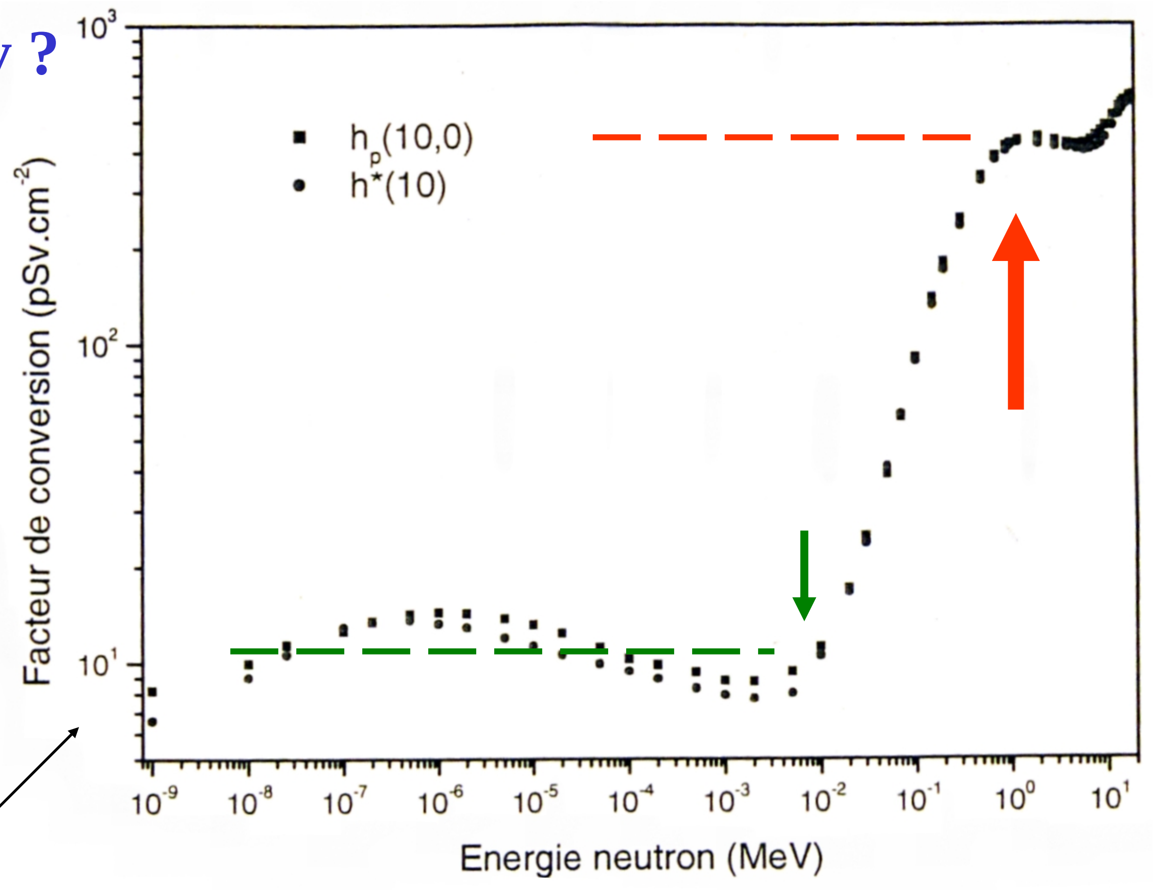
**How do $\Phi_n$ convert into Sv ?**

$\Phi = \mathbf{10^6\ n.cm^{-2}}$

= 10 µSv (slow < **10 keV**)

= **0.5 mSv** (fast > 1 MeV)
[mind: max=5 mSv/**Year** !]

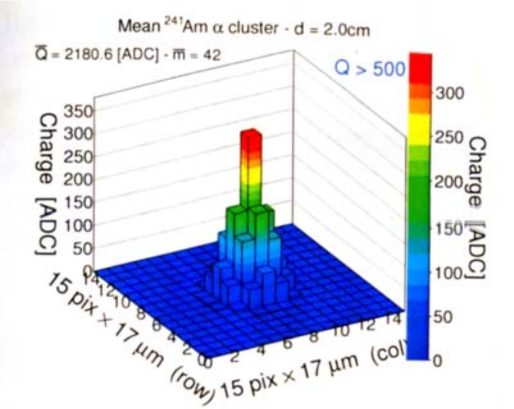
A « perfect » dosimeter should have exactly this response = f($E_n$)…



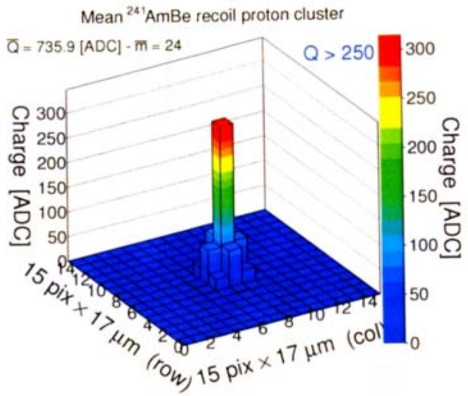
# Dosimetry with CMOS devices (I)

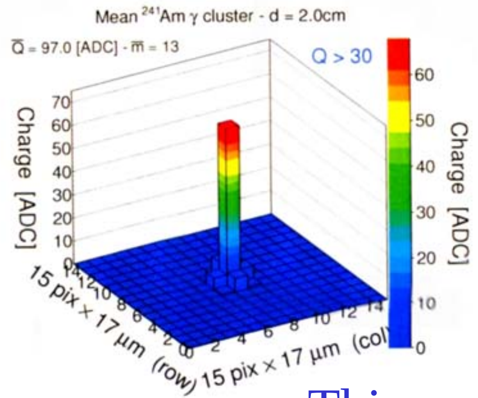
## a) True pixels: MIMOSA chip

(M.Vanstalle, UdS Thesis 2012)



p

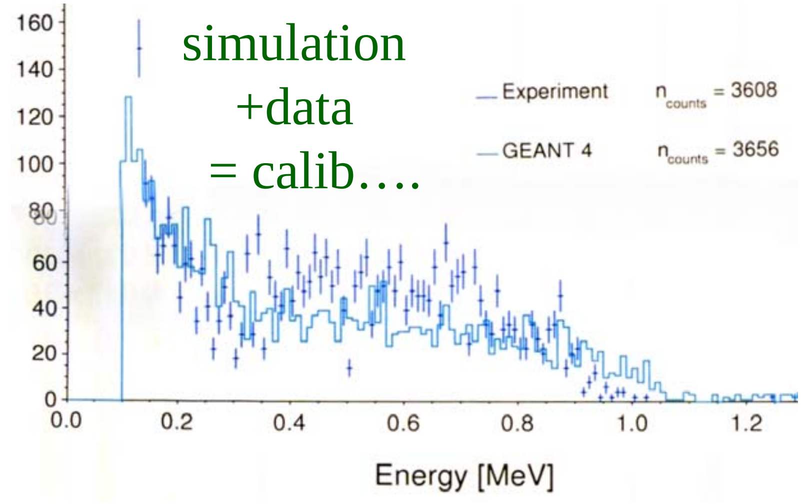




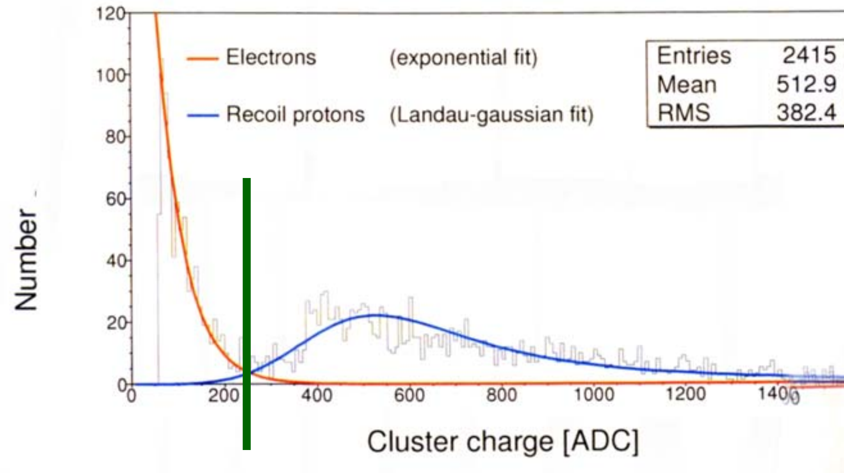
γ

Nice off-line clustering

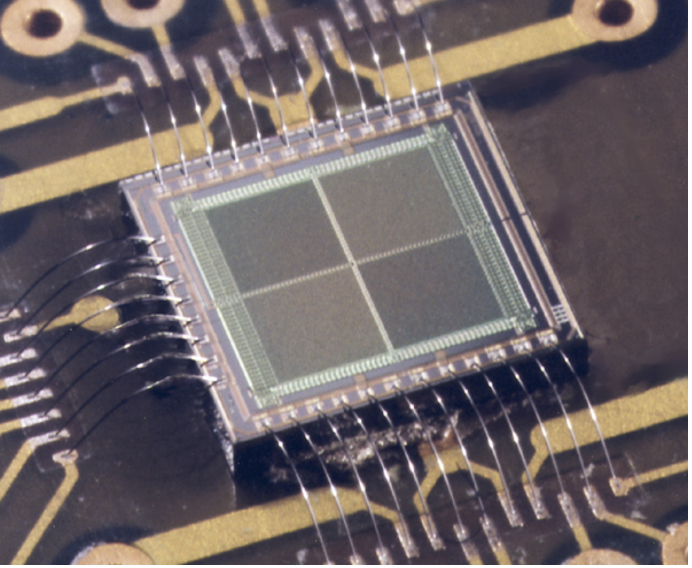
This was juste for the principle…

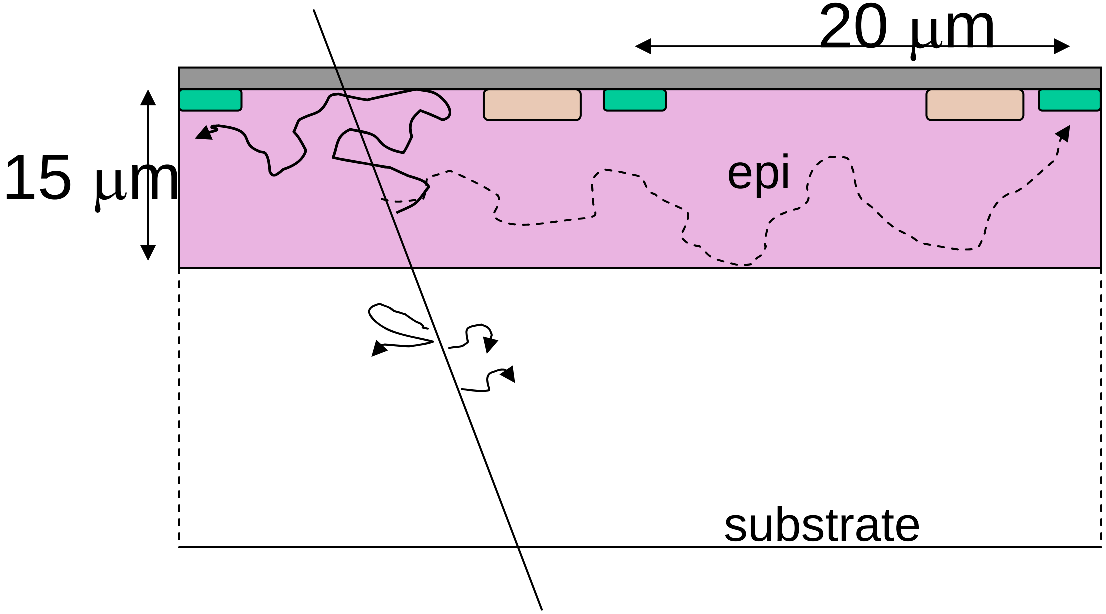


simulation
+data
= calib….



# MIMOSA I (1999)

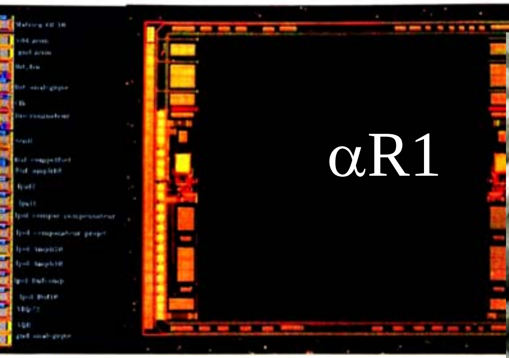


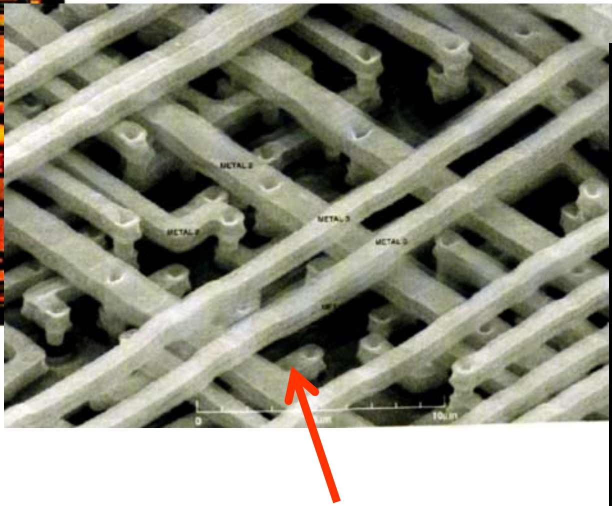


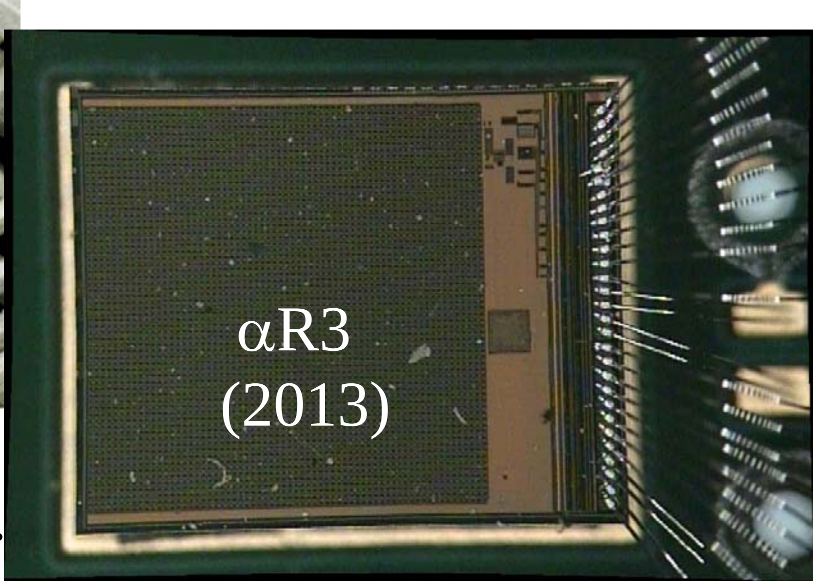
* Industry Si (low cost)
* 5V ($\vec{E}$~0, *chge collection by therm. diffusion*)
* $Q_{MIP}$ = 80*15 = *1200 e-*
* 64x64 ***active pixels (3T)***, sensitive area=1.2 x 1.2 mm
* $f_{RST}$=1 MHz (0.3 ms/frame)
* In CERN beam: $\sigma_{xy}$~1 μm (developed for tracking)

# Dosimetry with CMOS devices (II)

## the AlphaRad chip



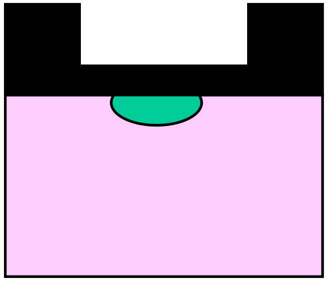


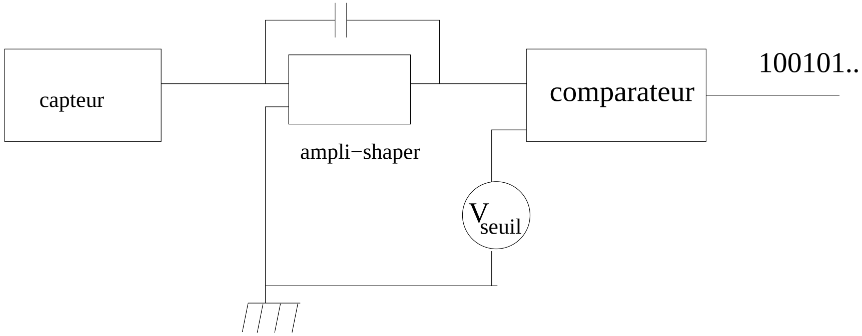


The problem: 8 μm $SiO_2$ + metal lines…

(1.4 MeV α particles are stopped !! )

➡ Solution: trenches in oxide





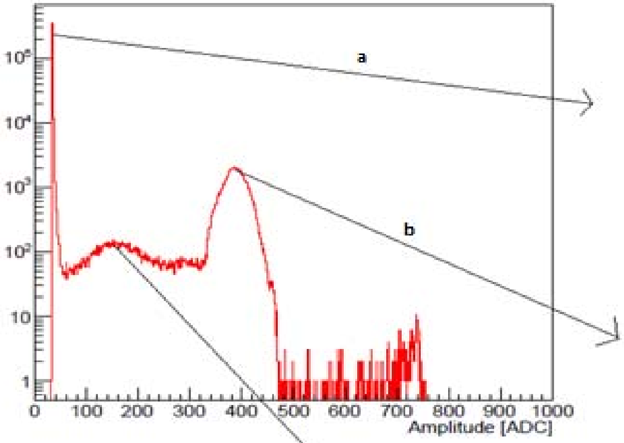
<u>Results</u>: poor efficiency in these trenches

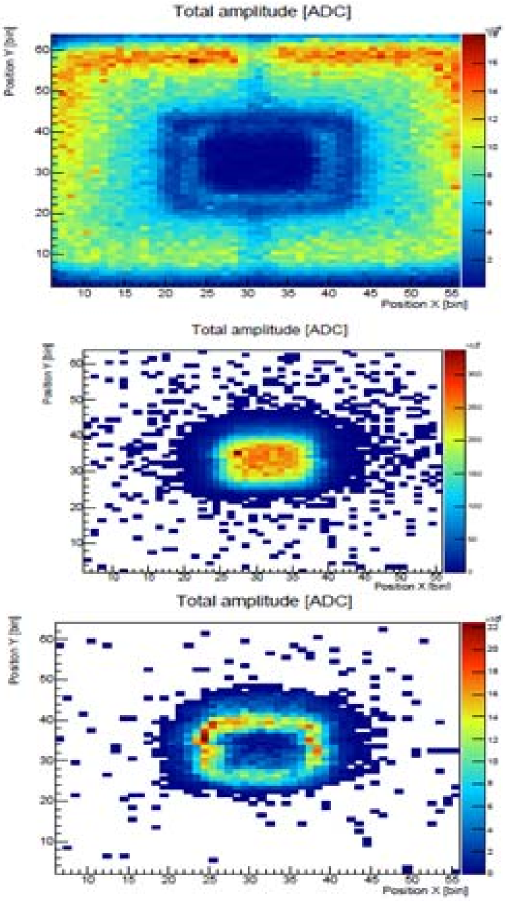
(XFAB 0.35 = new technol)

Extensive testing in AIFIRA microbeams (α and p,  0.7 – 3 MeV)

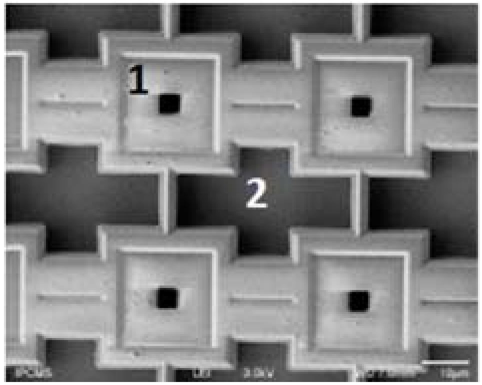
(more in spares..)

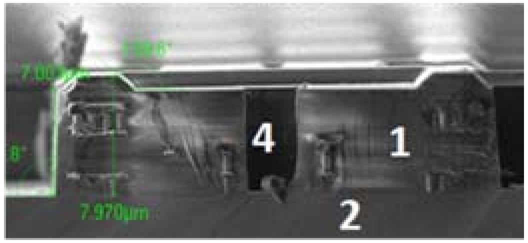
Chip alphaRad4
already underway….





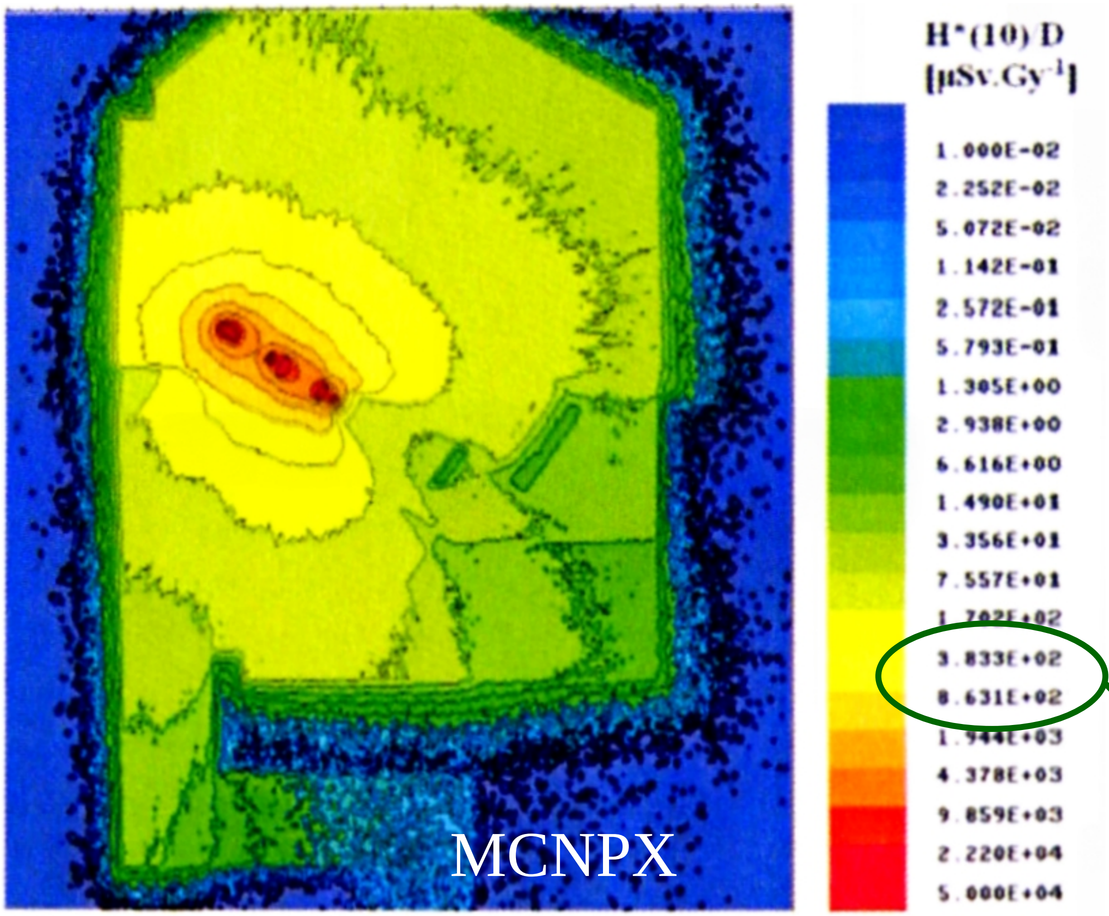
15 µm

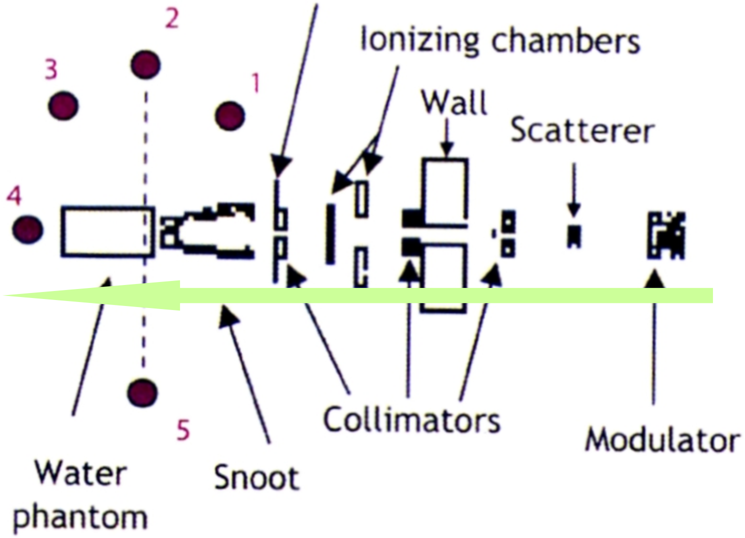




# **Global project**: secondary neutrons in radiotherapy rooms

*Special IDEX grant (thesis, 2015-2017)*





***Last elements of the accelerator system (collimators etc…) generate neutrons***

On table: 0.4-0.8 mSv/Gy!
(Full treatment ~50 Gy..)

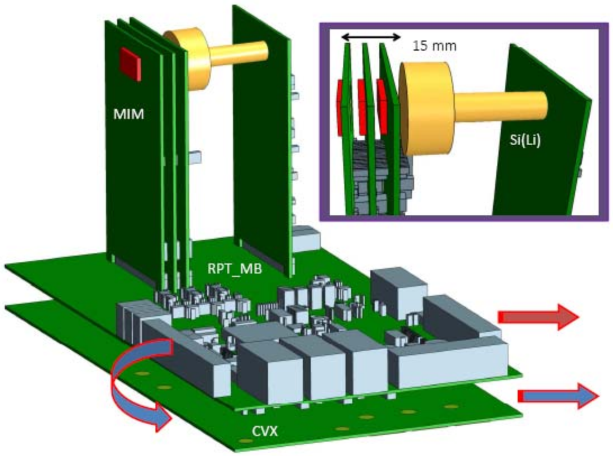
Farah &al. Phys.Med.Biol (2014)59

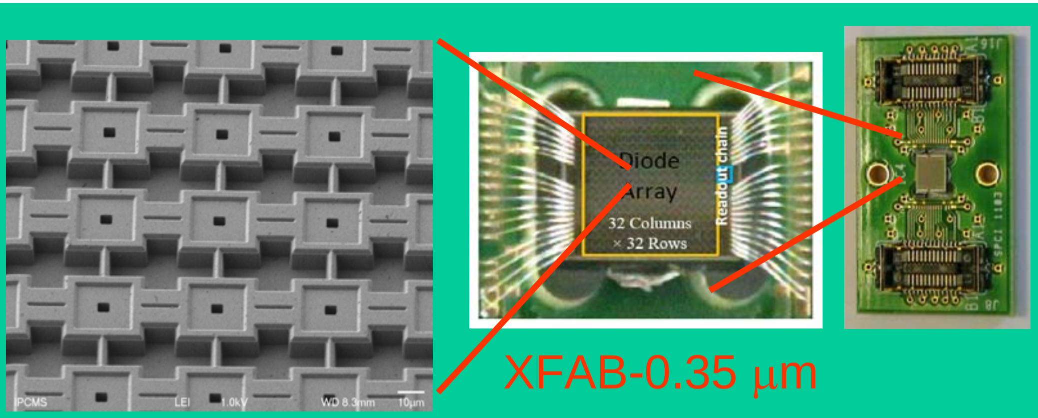
# Our 2 systems together for on-line *n*-dosimetry

RAMSES
Radioprotection et Mesures Environnementales

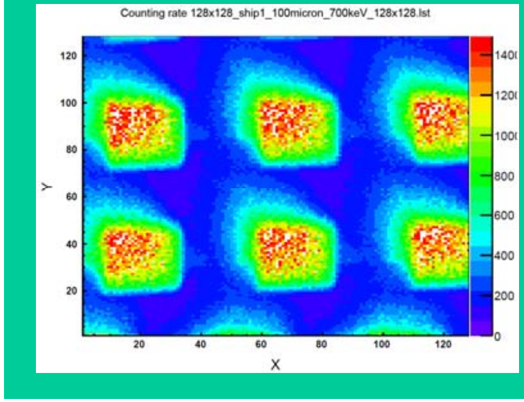
a) RPT ($E_n$=5-20MeV): flux $\Phi_n$ & $E_n$ with 5% precision

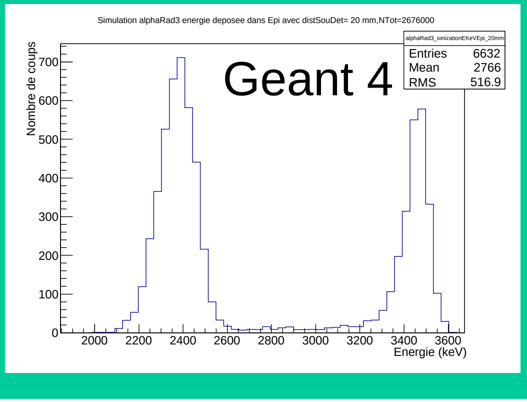
b) Sensor-on-chip **AlphaRad**: $E_n$= meV-MeV

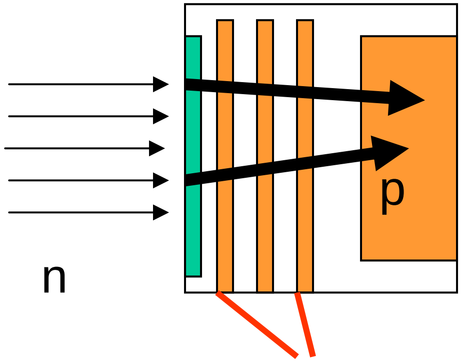




XFAB-0.35 μm



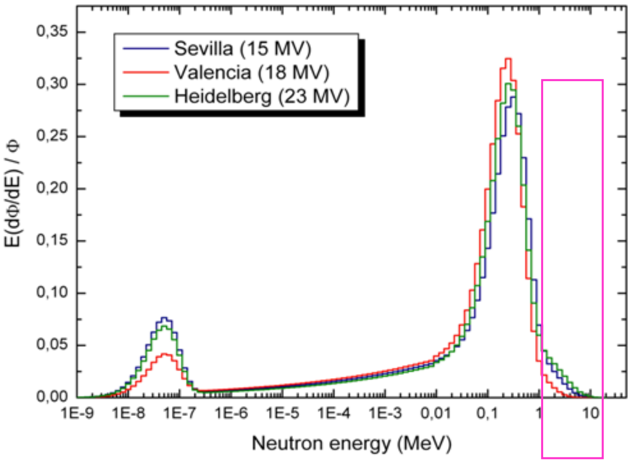




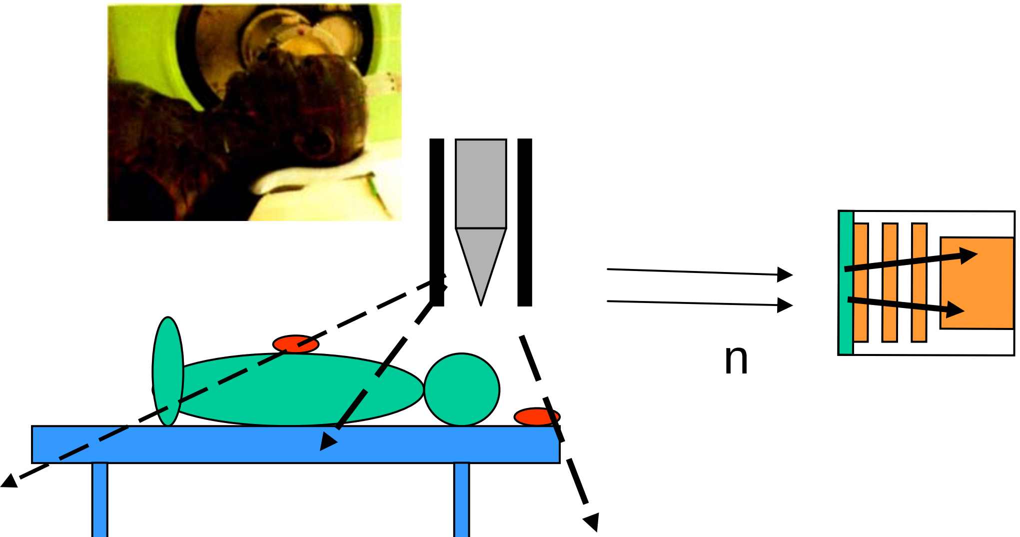
$E_n=E_p/\cos^2(\theta)$

CMOS pixels (FastPixN chip)

# Three steps method:



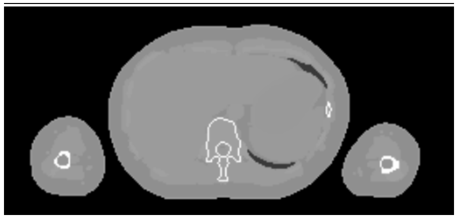
**1. Mesurement of the 5-20 MeV part of the spectrum with the RPT**



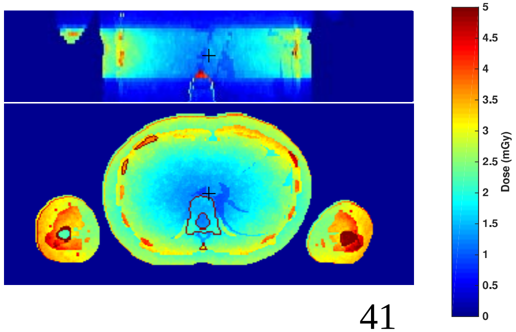
Bonner sph = fine but heavy +déconvolution !

**3. Calculation of the organ neutron dose**

Geant4/GATE (+ calibration with data)



Voxel phantom (ICRP 110)



**2. Real-time flux**

● AlphaRad sensors ($\Phi_{therm}+\Phi_{fast}$)

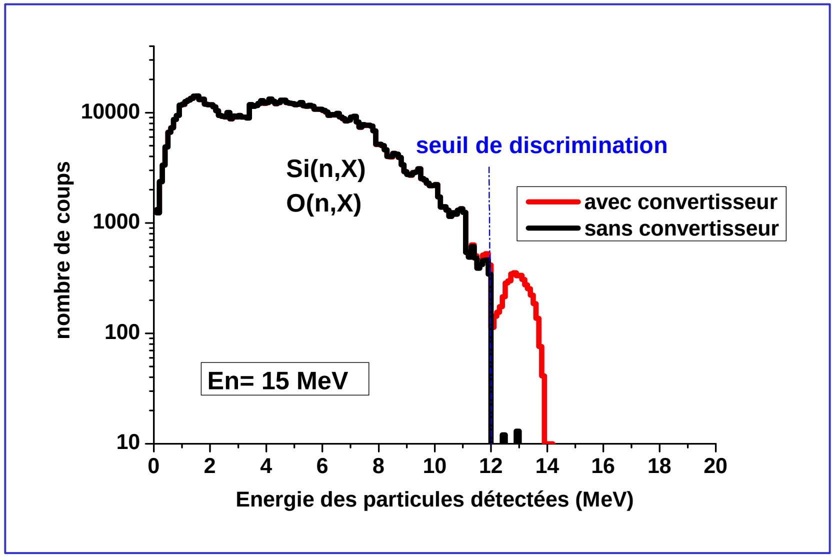
Thanks for attention !

# THE problem: inelastic events

- Proton signal : $\sigma_{\text{elastic}}$ H(n,p) ~1 bn at 14 MeV
- Several inelast. channels in Si(Li): Si(n,$\alpha$) + Si(n,d) + … ~ 1 bn too…

…but $e_{\text{diod}}$=3 mm = 30 x $e_{\text{conv}}$ !

➡ Fake coincidences: physical N/S ~ 30-50 !



Solution 1: low charge cut
(OK for mono-E neutrons)

Solution 2: high readout
frequency to lower fakes
(large spectra sources, Cf, Am)

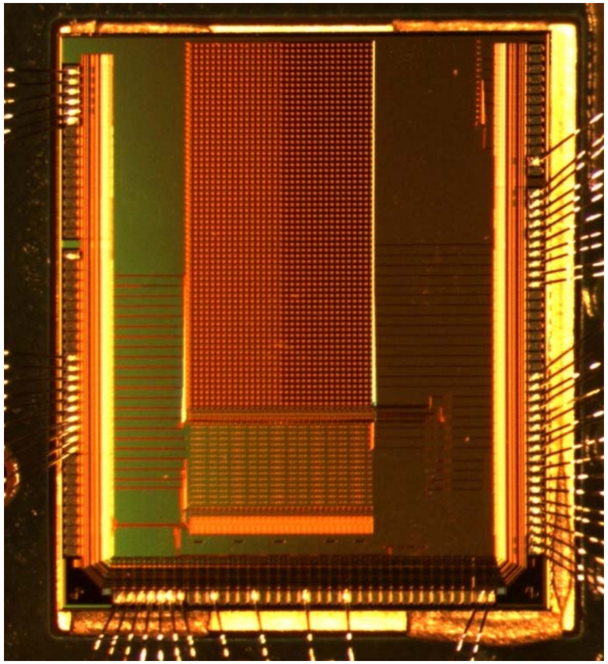
⬇

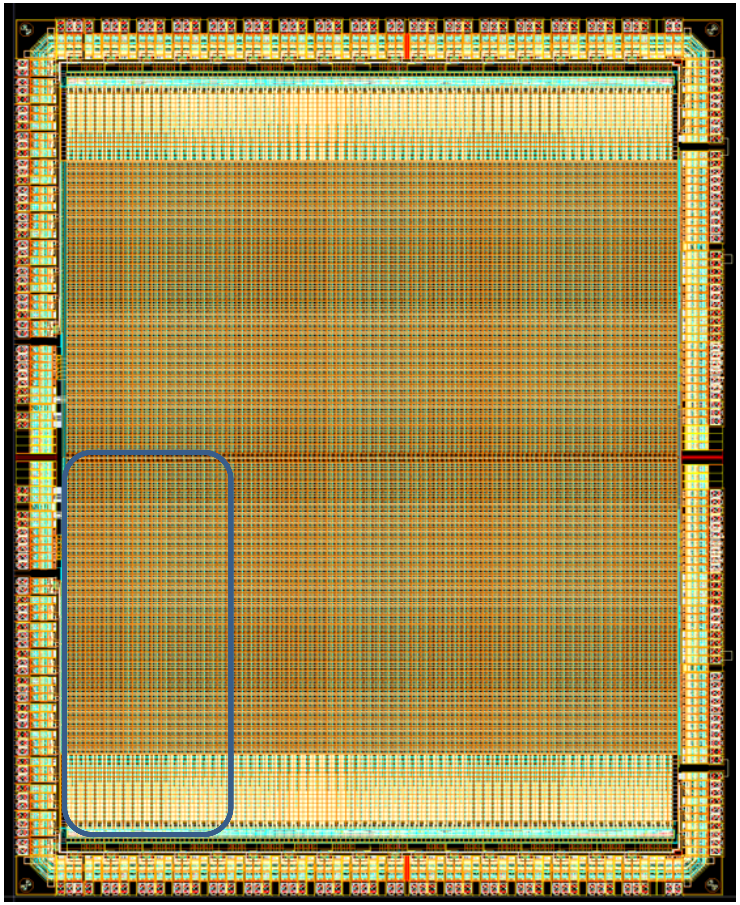
Fast ADC readout, 1/128 pix
128 x 50 $\mu$m: 6.5 x 6.5 mm

# FastPixN

## The final version

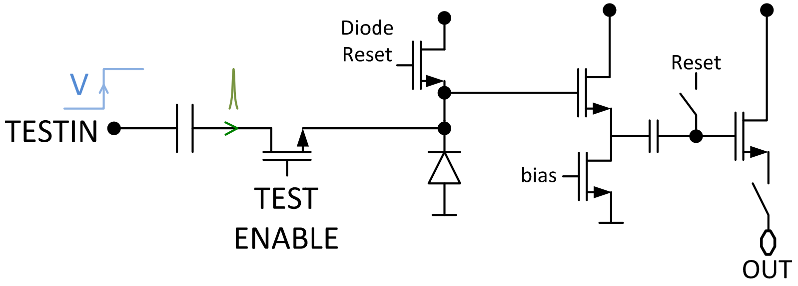
Test chip: 32 half-columns
4-bits flash ADC's

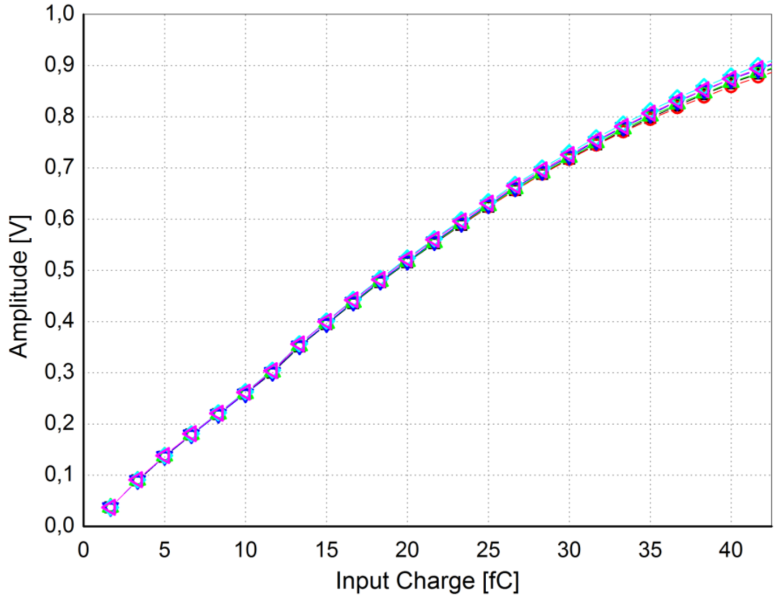




# *Electric tests : analog part*

## Response to the injected current pulses





- **Gain** = 2 µV/e$^-$ (12mV/fC)
- **Noise (ENC)** = 600e$^-$ (0.096fC)

**30<SNR<300**

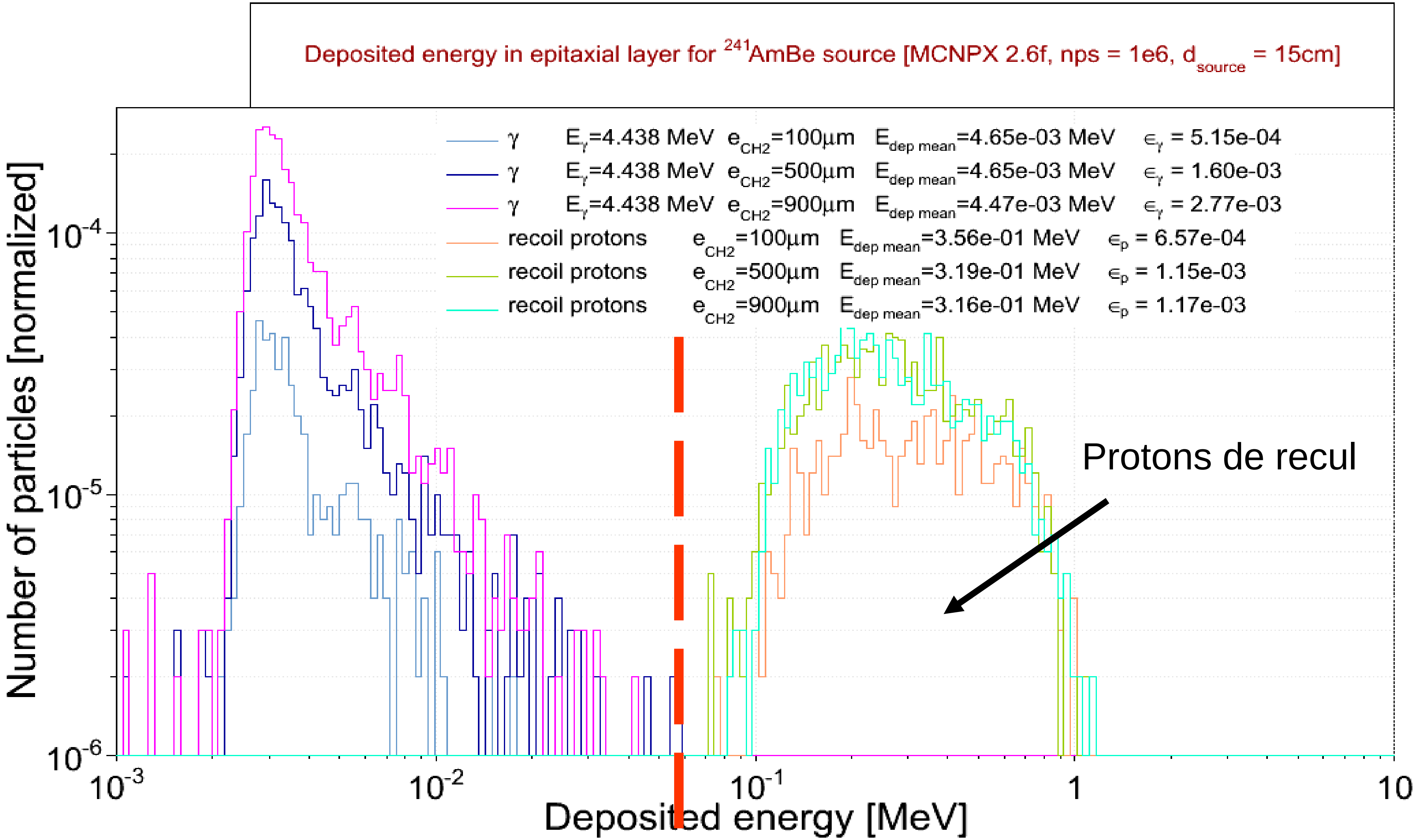
$Q_{min}$ = 18000e$^-$
(20 MeV protons)

$Q_{max}$ = 180000e$^-$
(2 MeV protons)

- Low dispersion of gain (50 nV / e$^-$ at 25 fC)
- Good linearity -> Evaluation of proton energy in each layer

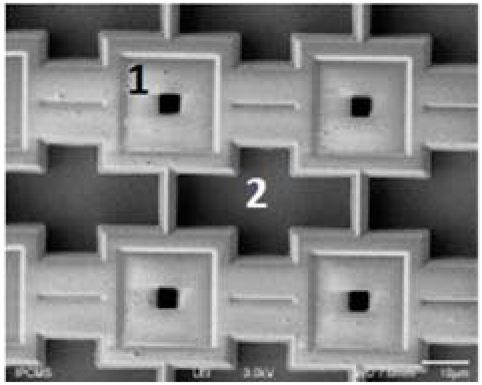
⇒ **AIFIRA beam test in Nov 2015**.

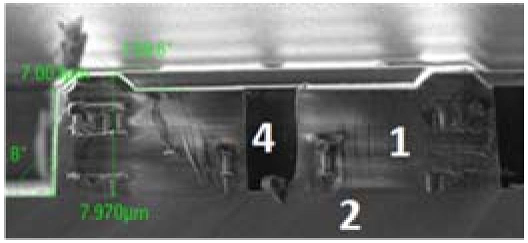
# **Discri n/γ** (simulation: Marie Vanstalle)

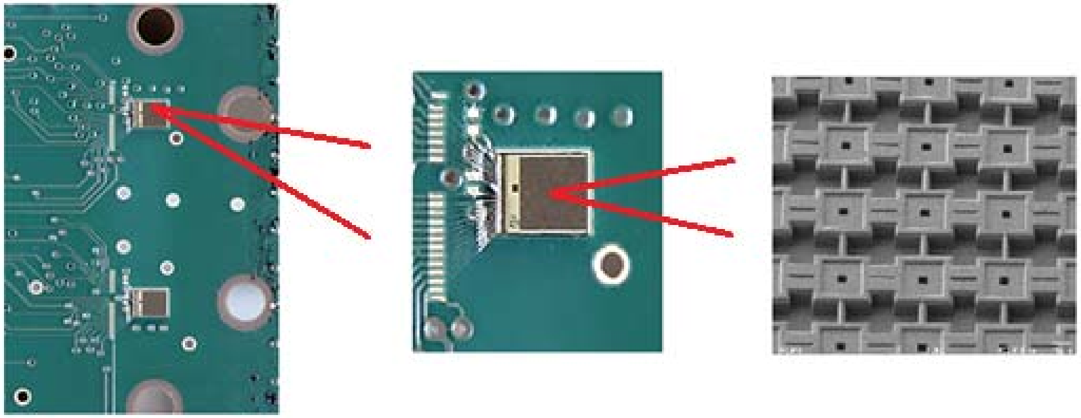


Protons de recul

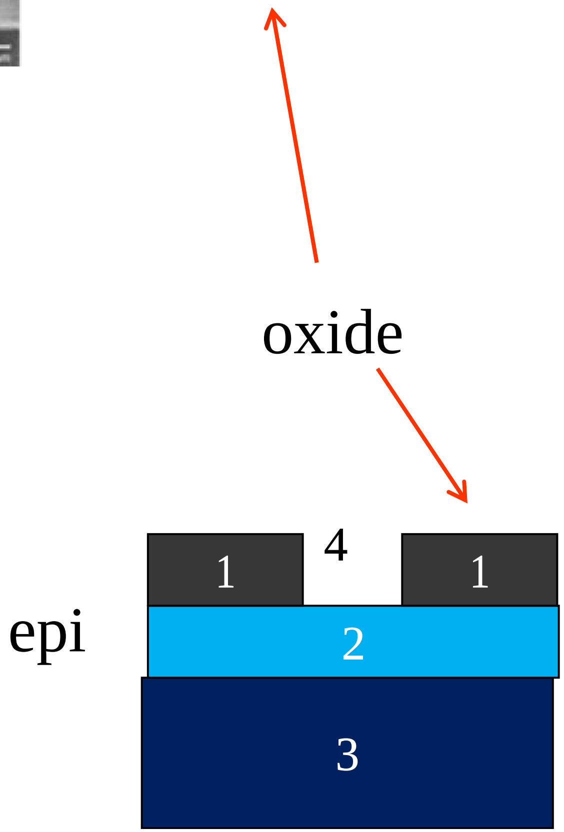
# AlphaRad 3







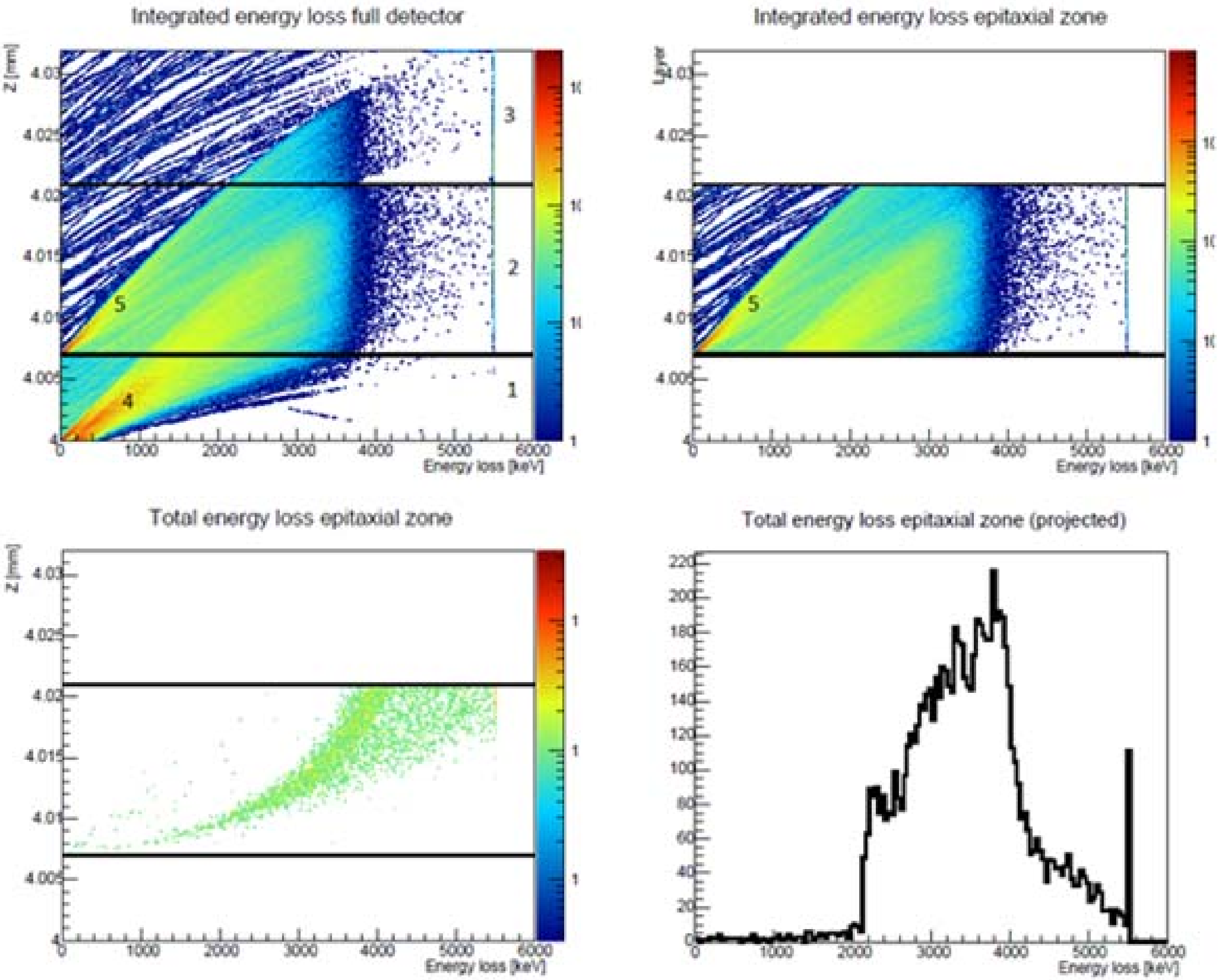
2-chips PCB
(slow+fast ***n***)



oxide

epi

- Geant4 simulations : here 5.5 MeV  alpha particles (Am source)

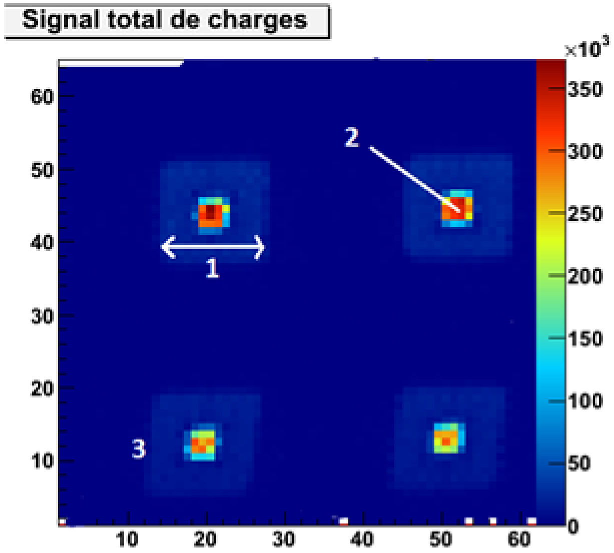

Integrated energy loss full detector

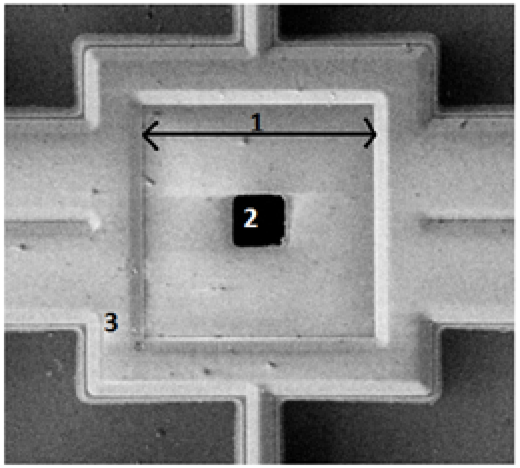
Integrated energy loss epitaxial zone

Total energy loss epitaxial zone

Total energy loss epitaxial zone (projected)

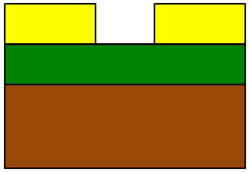
- 2.2 MeV **alphas (AIFIRA)**

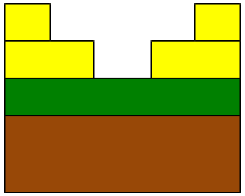


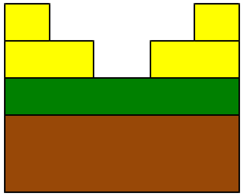


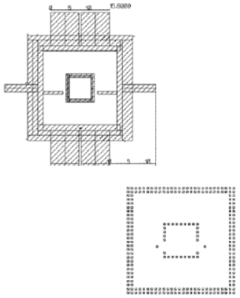
- Signal important au niveau des diodes (2)
- Signal plus faible au niveau des 7µm d'oxyde (1)
- Peu de signal ailleurs (3)
- Technologie XFAB relativement nouvelle!!
- Impact des 8 µm

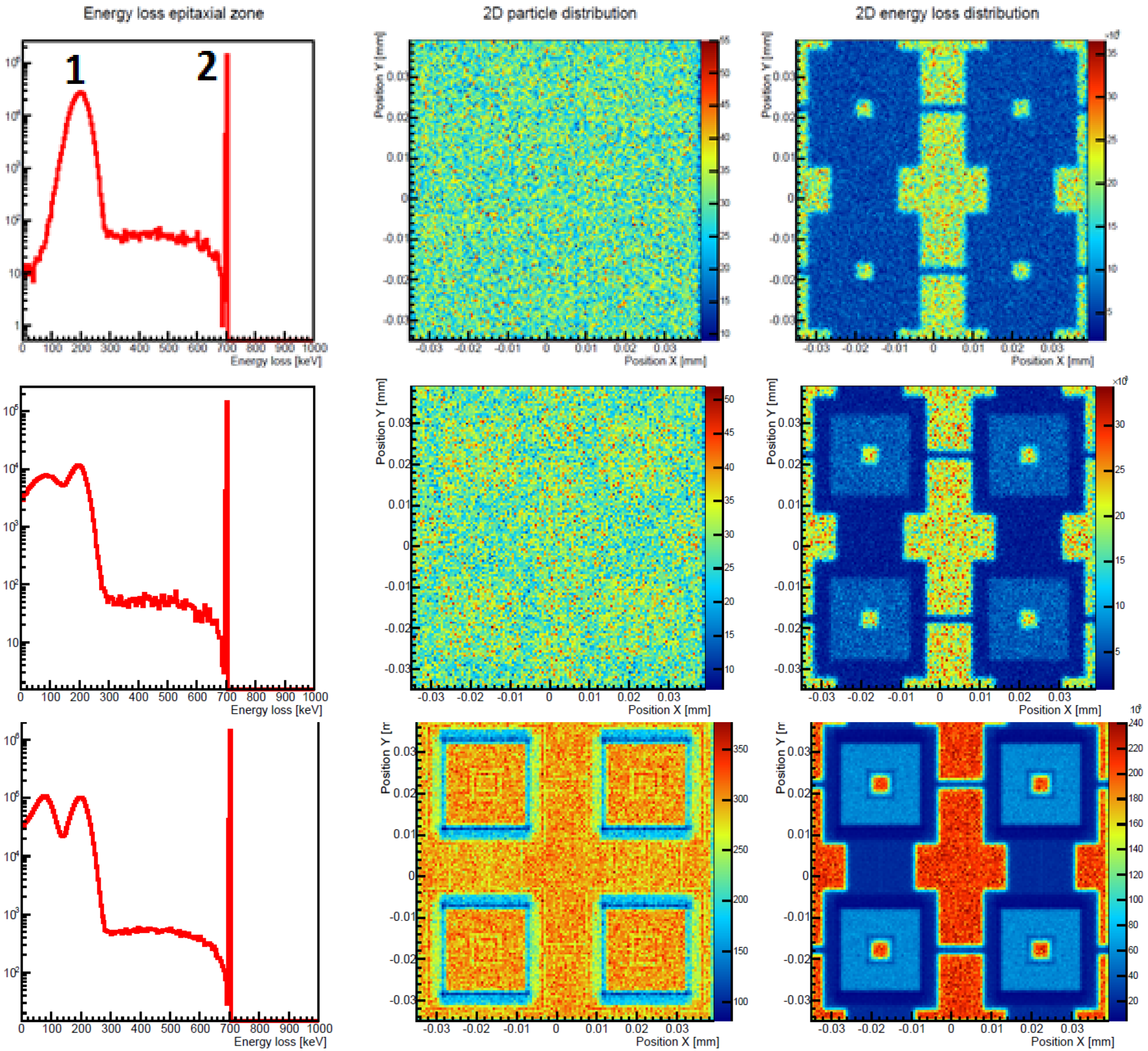
# 0.7 MeV protons





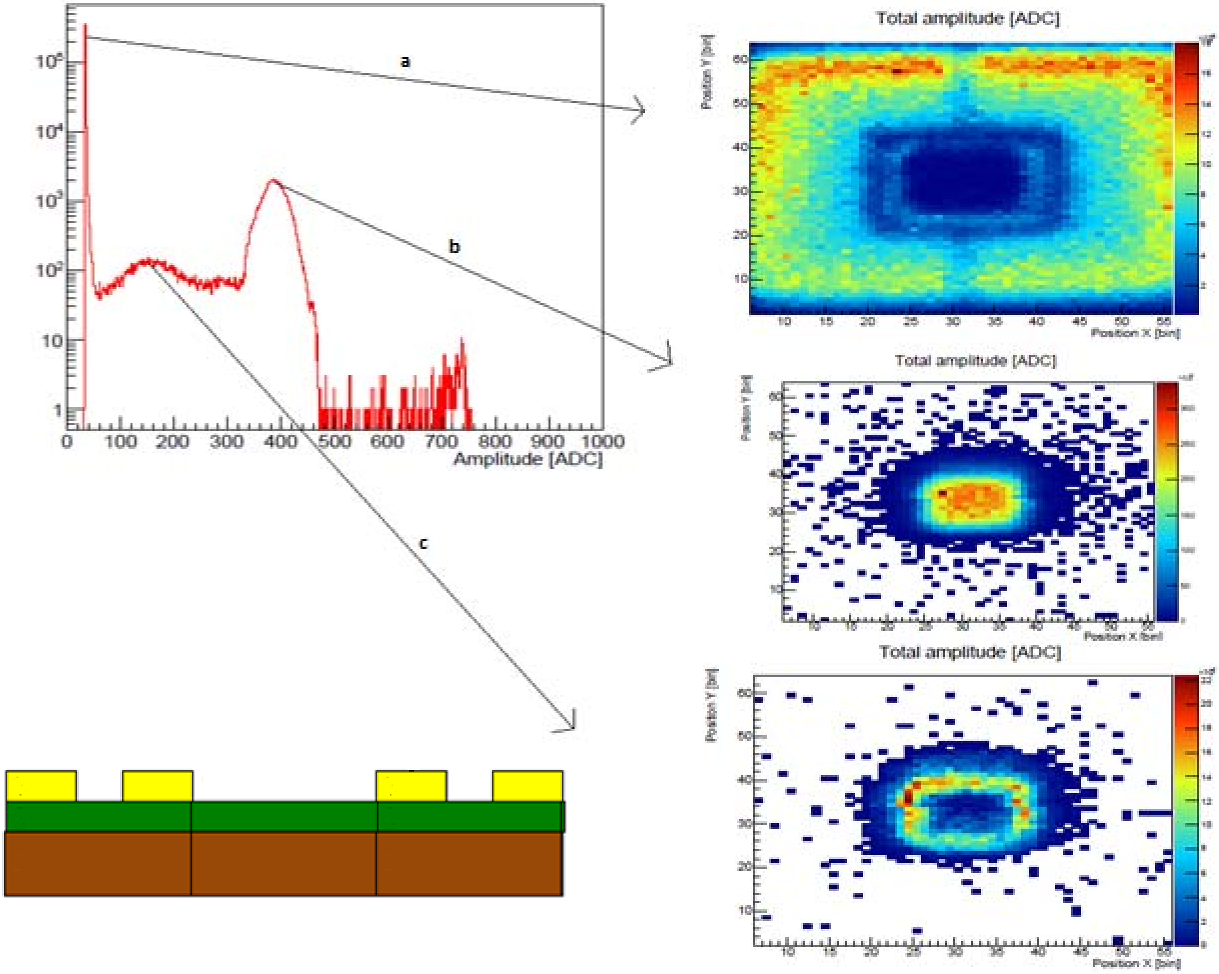






# (X,Y = AIFIRA coordinates reconstruction)

## Alphas 2,2 MeV



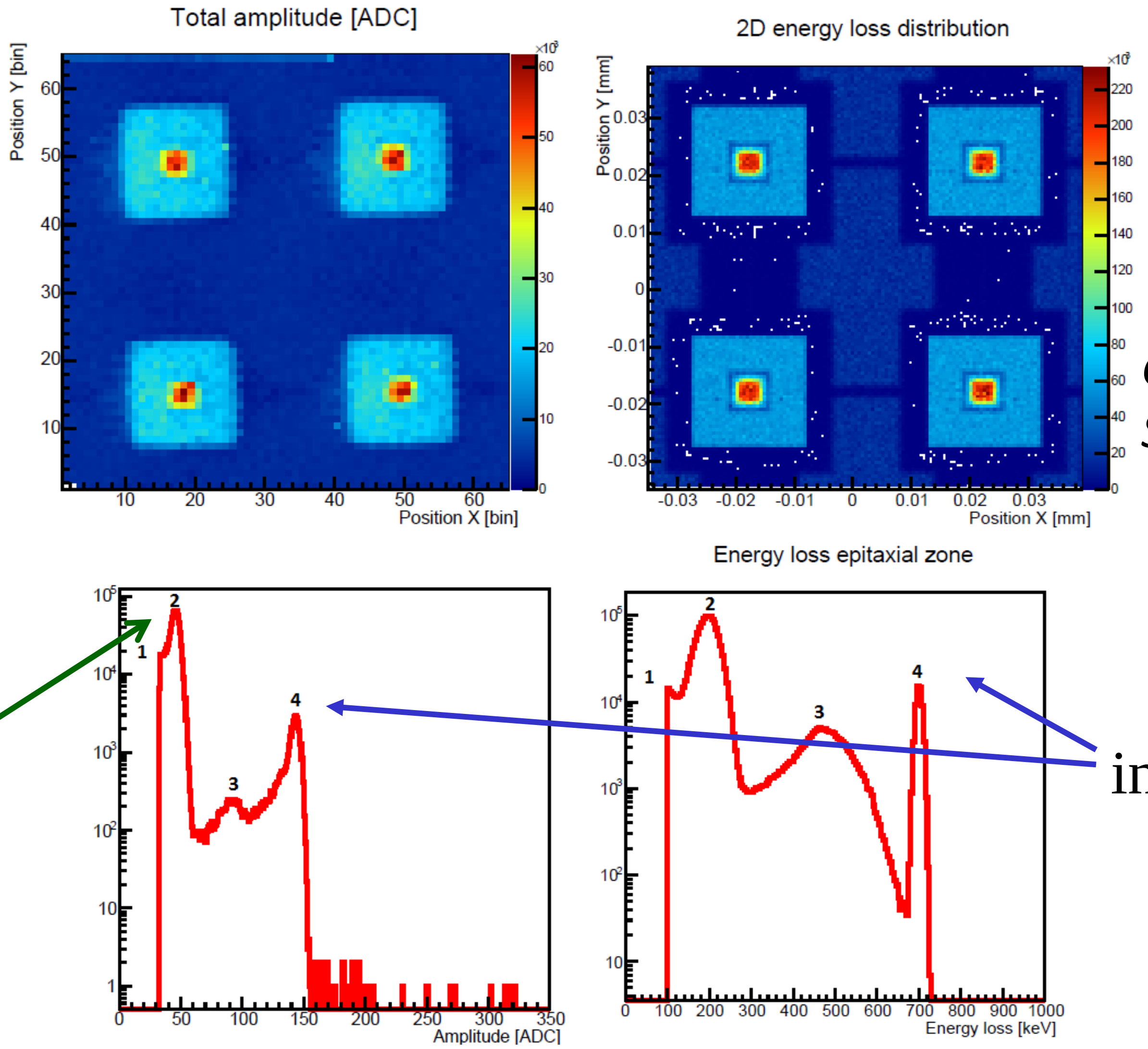
alphas through 7um oxide

alphas directly in diode

angular effects

# 0.7 MeV protons

*Data*



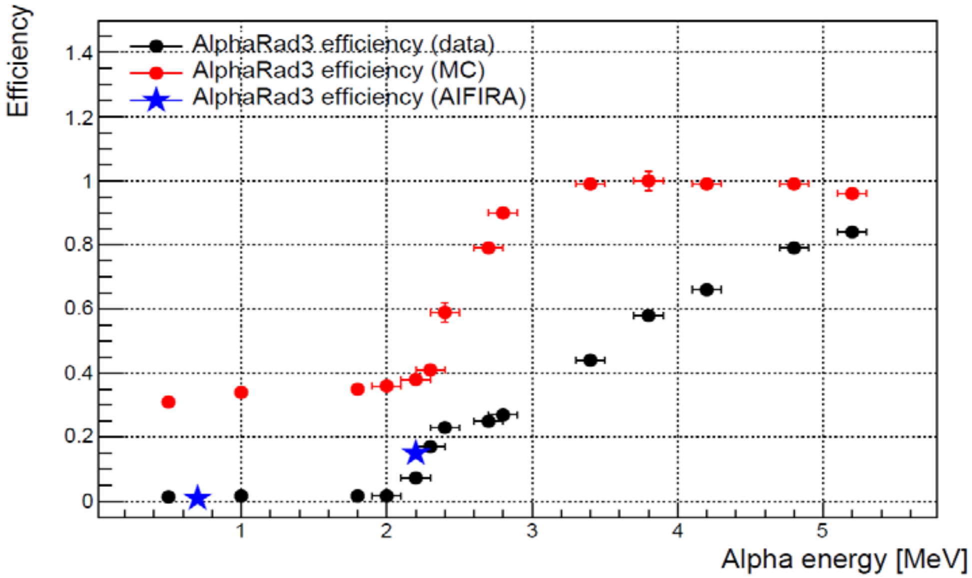
*G IV Simulations*

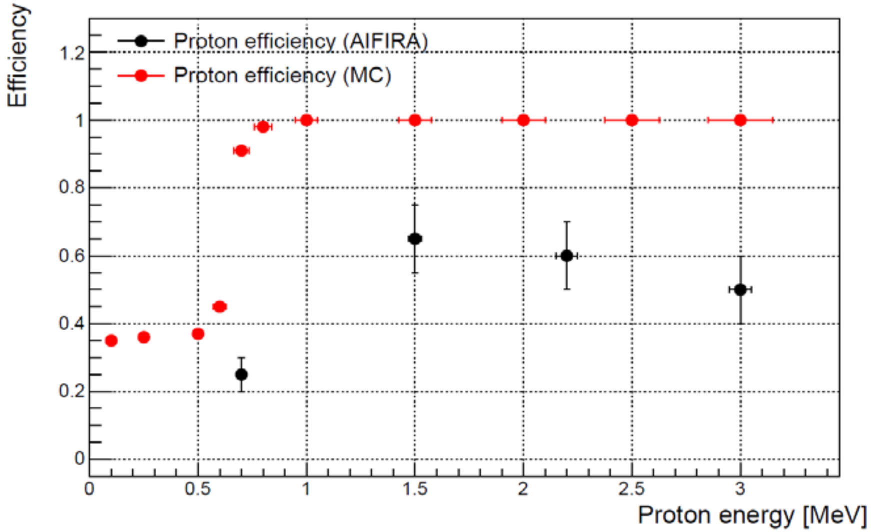
SiO$_2$ effect

in trench

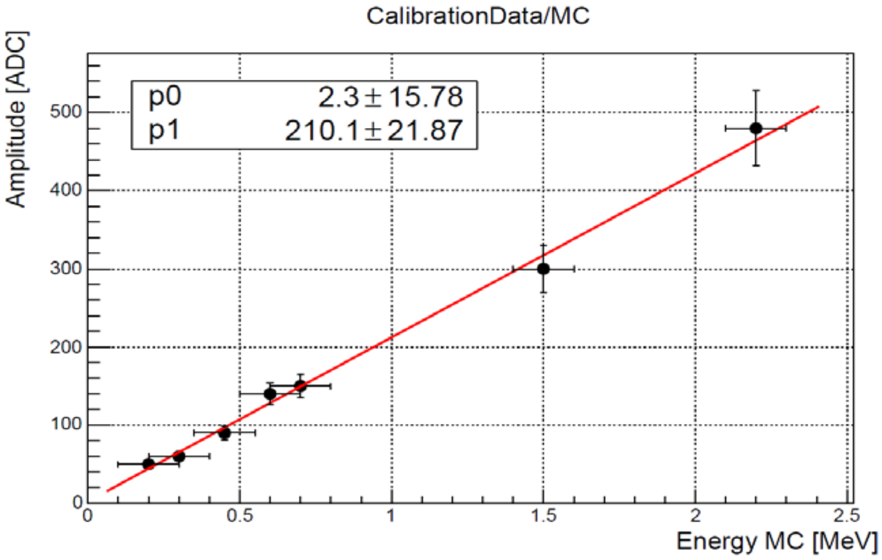
- Effects of all substructures well reproduced in simulation
- Design of the next chip OK

# Main results: 1) efficiency to alpha & protons (AIFIRA + 5,5 MeV source)





2) calibration



**Final Chip underway !**