Electron channeling at PRAE: investigation of Zitterbewegung and De Broglie internal clock of electrons

Denis Dauvergne[1,2], M. Bajard[2], R. Chehab[3], S. Dabagov[4], R. Kirsch[2], J-C. Poizat[2], J. Remillieux[2], E. Testa[2]

1. LPSC Grenoble
2. IPN Lyon
3. LAL Orsay
4. INFN Frascati

Zitterbewegung

Dirac (1957) and Schrödinger (1930):

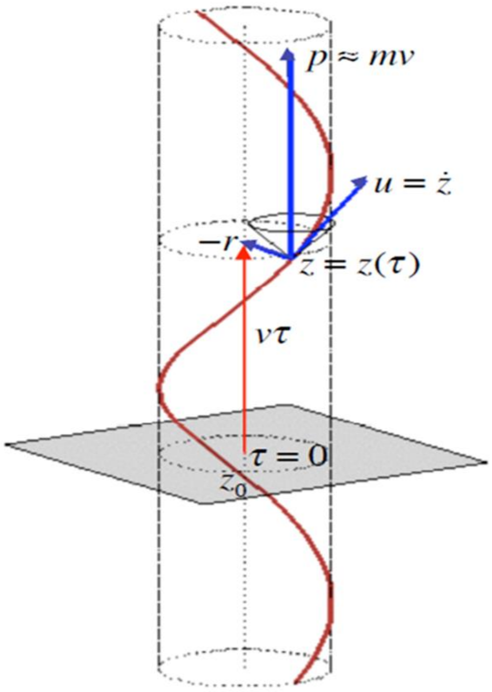
x(t)= *v.t* + "Zitterbewegung"

- *v.t* is the classical motion of a particle.
- the "Zitterbewegung" term is roughly:

$o(\lambda_c) \cos(\omega_z t/\gamma)$

$\lambda_c = \sim 10^{-10}$ cm for e- .

$\omega_z = 2 m_0 c^2/\hbar$.



Zitterbewegung frequency: ν_z = 1.55 ZHz

D.Hestenes. Zitterbewegung in Quantum Mechanics. *Found. Phys.*, 40 (2010)1
M.M. Asif, Eur. Phys. J. Plus 131 (2016) 37
W.Zawadzki and T.M. Rusin, J. Phys.: Condens. Matter 23 (2011) 143201
R. Gerritsma et al, Nature 463 (2010) 68

Internal clock (L. De Broglie thesis, 1924)

A particle is surrounded by a wave Ψ

- In its rest frame $\Psi = a_0 \exp(2\pi i \nu_0 t)$

$E = m_0c^2 = h\nu_0 \quad \rightarrow \quad \nu_0 = m_0c^2/h$

Internal Clock frequency: $\nu_0 = \nu_Z / 2$

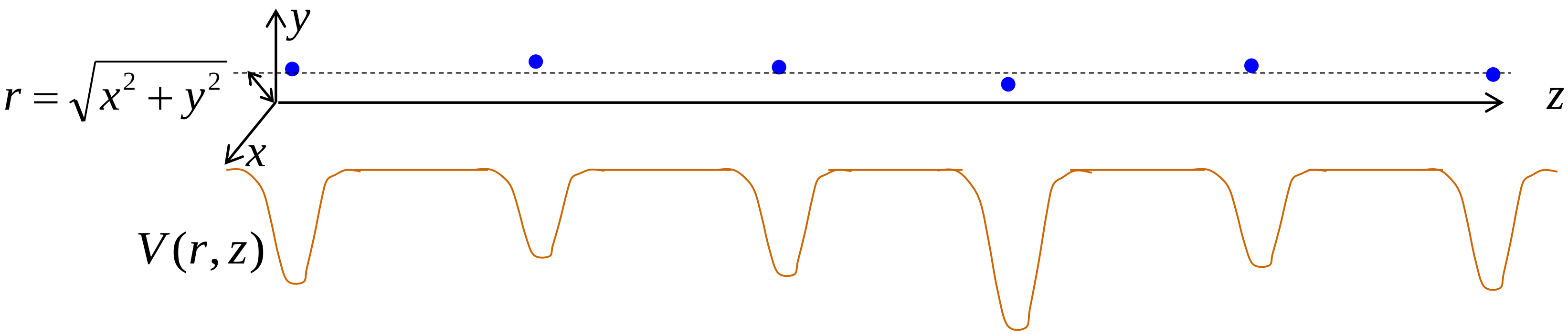
"A Clock Directly Linking Time to a Particle's Mass",
Shau-Yu Lan et al. Science 339, 554 (2013);

Experimental observation of Zitterbewegung?

- No direct observation so far
- Idea: could the trajectory be perturbed by its internal clock, when its velocity v is adjusted in order to fit the resonant condition $\nu_n = n\nu_0 = n\,\gamma\, v/d$ by a spatial periodic excitation?
- 10^{21} Hz ~ collision frequency along atomic string in a crystal by relativistic particles ($\gamma \sim 10^2$, d ~ few Å):

$$\nu = \gamma\, v/d$$

Charged particle channeling in the continuum potential approximation



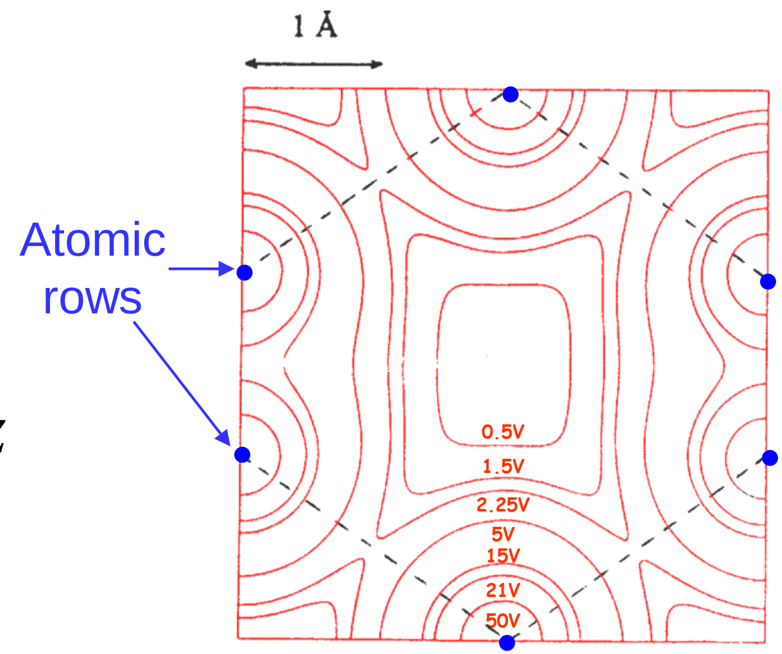
$$V(r,z) = U(r) + \delta V(r,z)$$

U(r): continuum potential

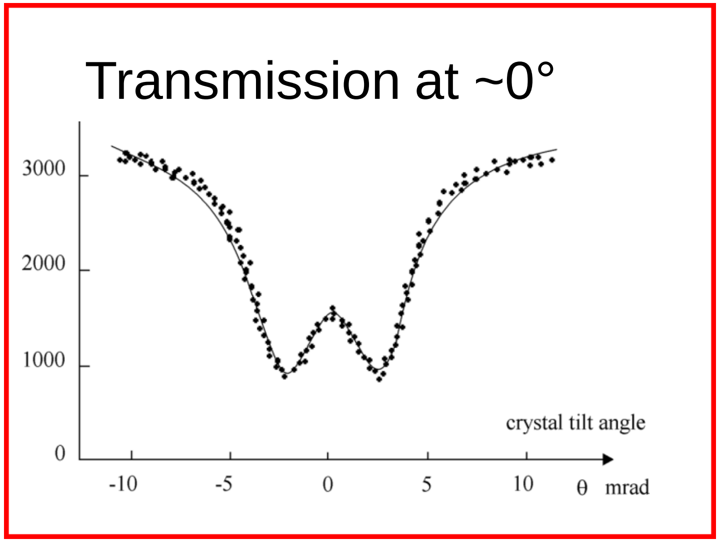
$$U(r) = \frac{1}{d}\int_{-\infty}^{+\infty} V\left[\left(r^2 + z^2\right)^{1/2}\right] dz$$

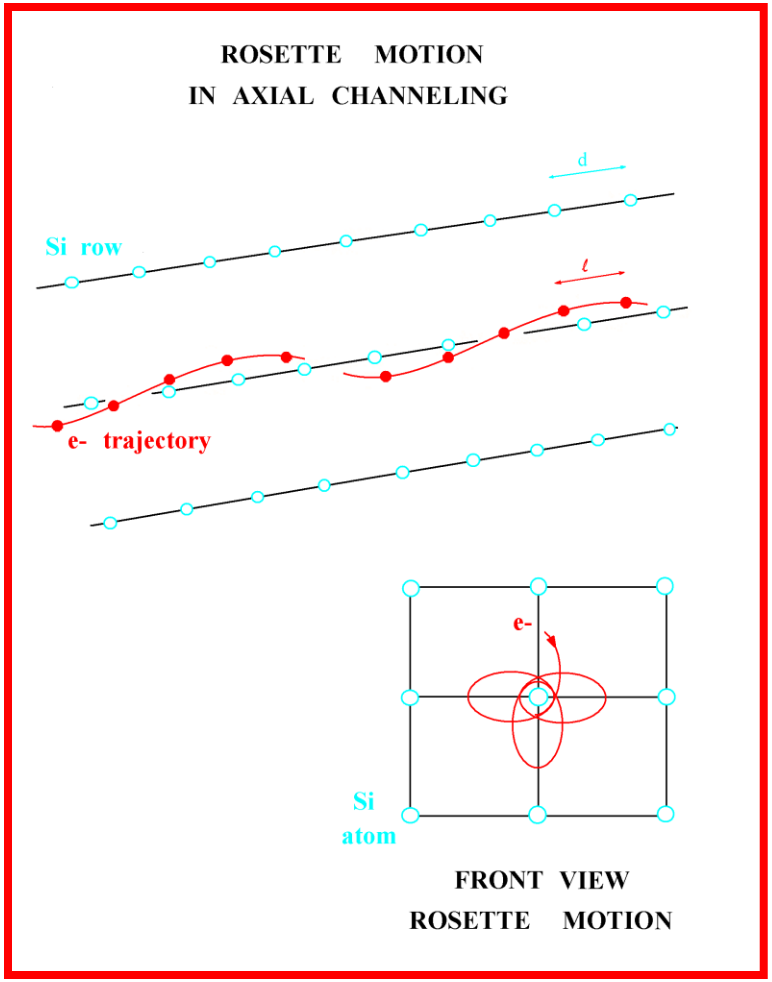
$$\langle \delta V \rangle = 0$$

Silicon <110> axis



Electron channeling at tens of MeV





- Attractive potential: electrons scattered away from axial direction
- A fraction of the incoming electron beam undergoes rosette motion: bound orbitals around a single string
- Characteristic critical angle :

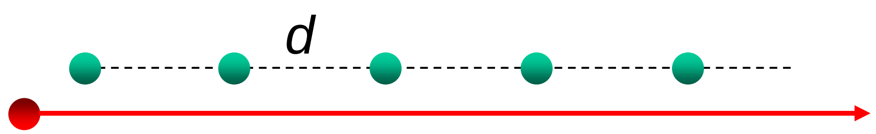
Lindhard: (1965)

$$\begin{cases} \Psi_{c\ axial} = \left(\dfrac{4QZ_2e^2}{pvd}\right)^{1/2} \\ \Psi_{c\ planar} = \left(\dfrac{4QZ_2e^2Nd_pCa}{pv}\right)^{1/2} \end{cases}$$

Resonant Coherent Excitation

- Resonance condition along a string (1D-RCE)

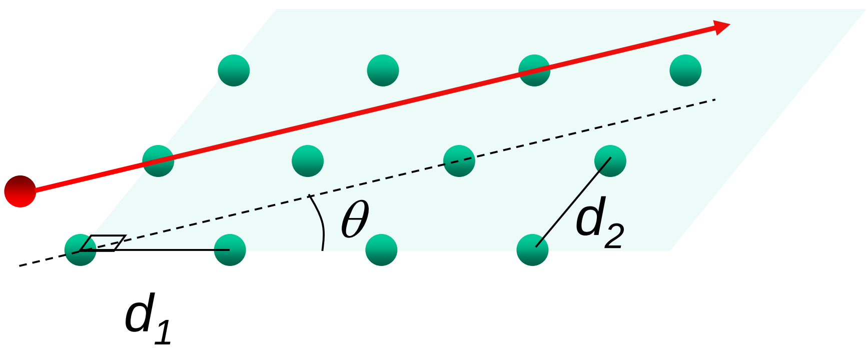
V. Okorokov (1965)
S. Datz et al. (1978)



$$\Delta E_{ij} = h\nu_k = k\,h\frac{\gamma v}{d} \qquad k = 1,2,\ldots$$

- Parallel to a plane (2D-RCE)

S. Datz et al., NIM 170 (1980) 15

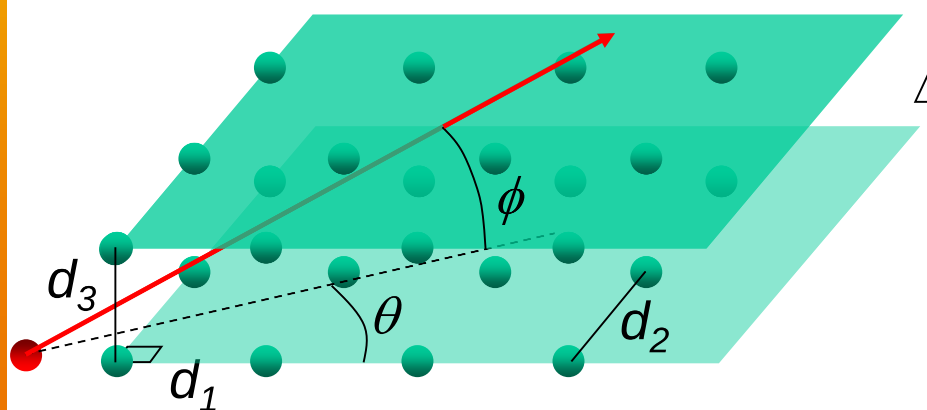


$$\Delta E_{ij} = h\gamma v\left(\frac{k\cos\theta}{d_1} + \frac{l\sin\theta}{d_2}\right)$$

k,l integers

- In a volume (3D-RCE)

K. Komaki et al., ICPEAC 2005

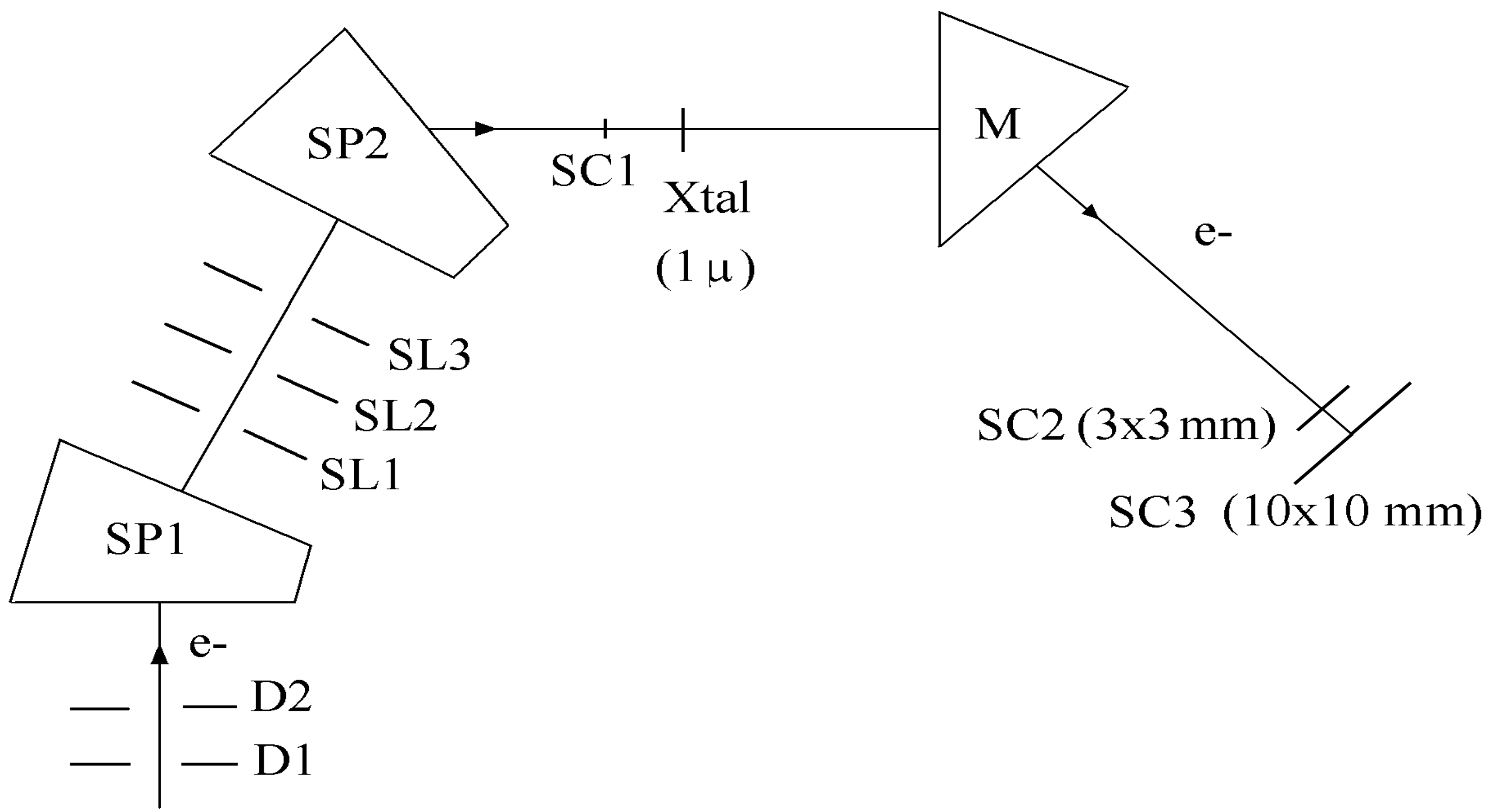


$$\Delta E_{ij} = h\gamma v\left(\frac{k\cos\theta\cos\phi}{d_1} + \frac{l\sin\theta\cos\phi}{d_2} + \frac{m\sin\phi}{d_3}\right)$$

k,l,m integers

No more channeling

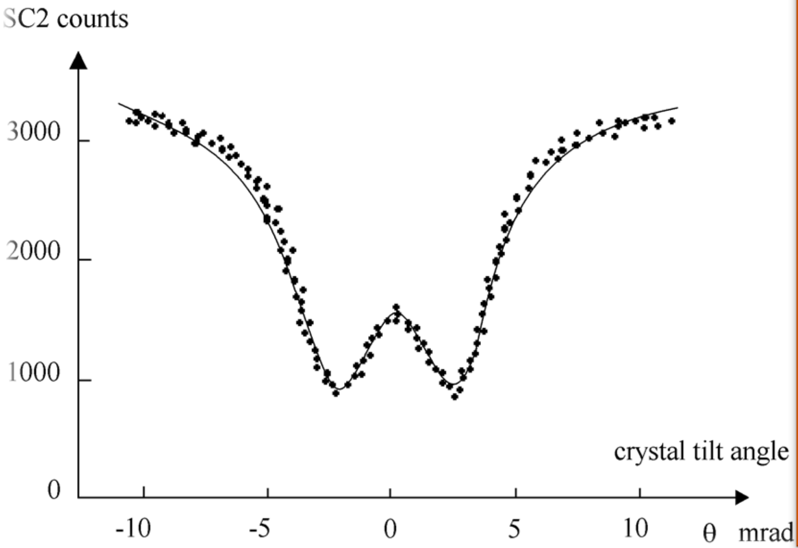
Experimental setup (ALS-Saclay)



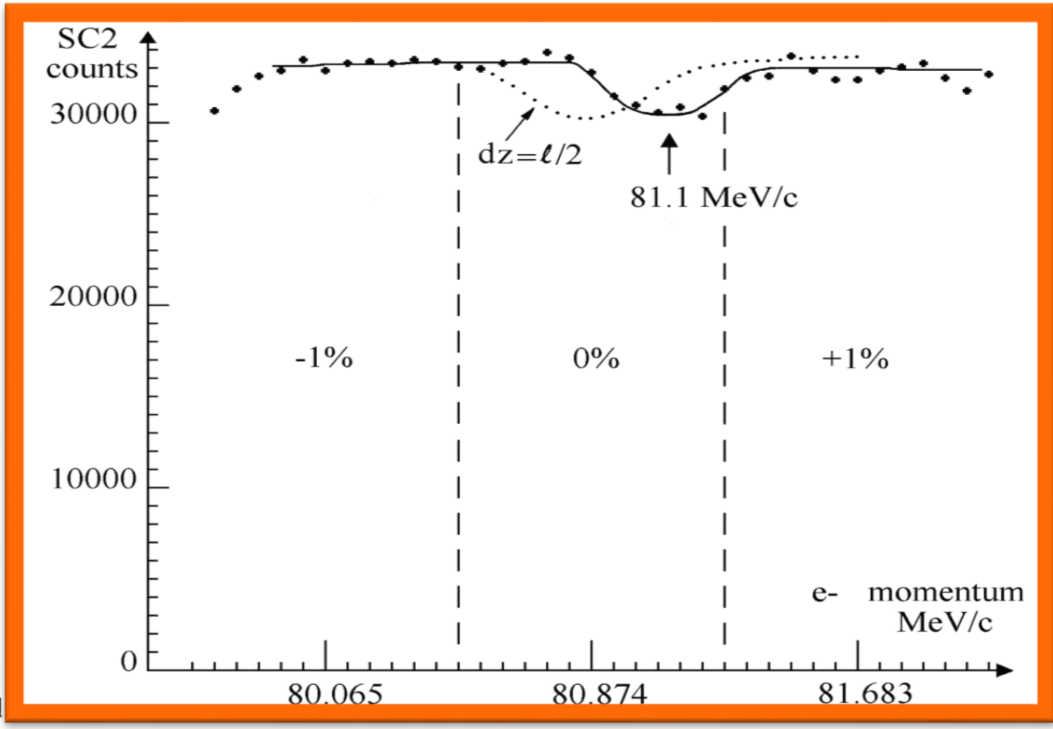
P.Catillon, N.Cue, M.J.Gaillard, R.Genre, M.Gouanère, R.G.Kirsch, J.C.Poizat, J.Remillieux, L.Roussel and M.Spighel. *Found.Physics* **38** (2008) 659.

Electron energy scan along <110> axis
First signature of IC at ALS

- Rosette motion signature
  in a 1µm thick Si crystal



- Expected resonance
  at ≈ 81 MeV/c



Catillon et al, 2008

Resonance energy

Zitterbewegung
ΔE=1022 keV
$= n\, hp/m_e d$

p (MeV/c)

	Diamond <110>	Si <110>
n=1	106,21	161,76
2	53,11	80,88
3	35,40	53,92
4	26,55	40,44

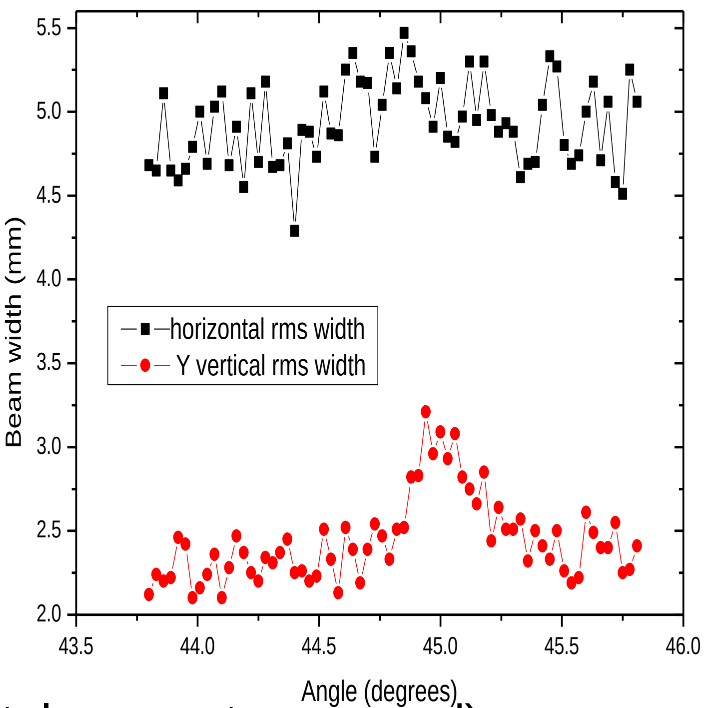
Internal clock (DB)
ΔE=511 keV

p (MeV/c)

	Diamond <110>	Si <110>
n=1	53,11	80,88
2	26,55	40,44
3	17,70	26,96
4	13,28	20,22

Further attempts (RICCE collaboration)

- BTF-Frascati



→ Channeling barely observable (horizontal momentum spread)

- SAGA-LS Japan (250 MeV protons) Takabayashi et al
  - Planar channeling
  - High index axial channeling

  → No resonance reported

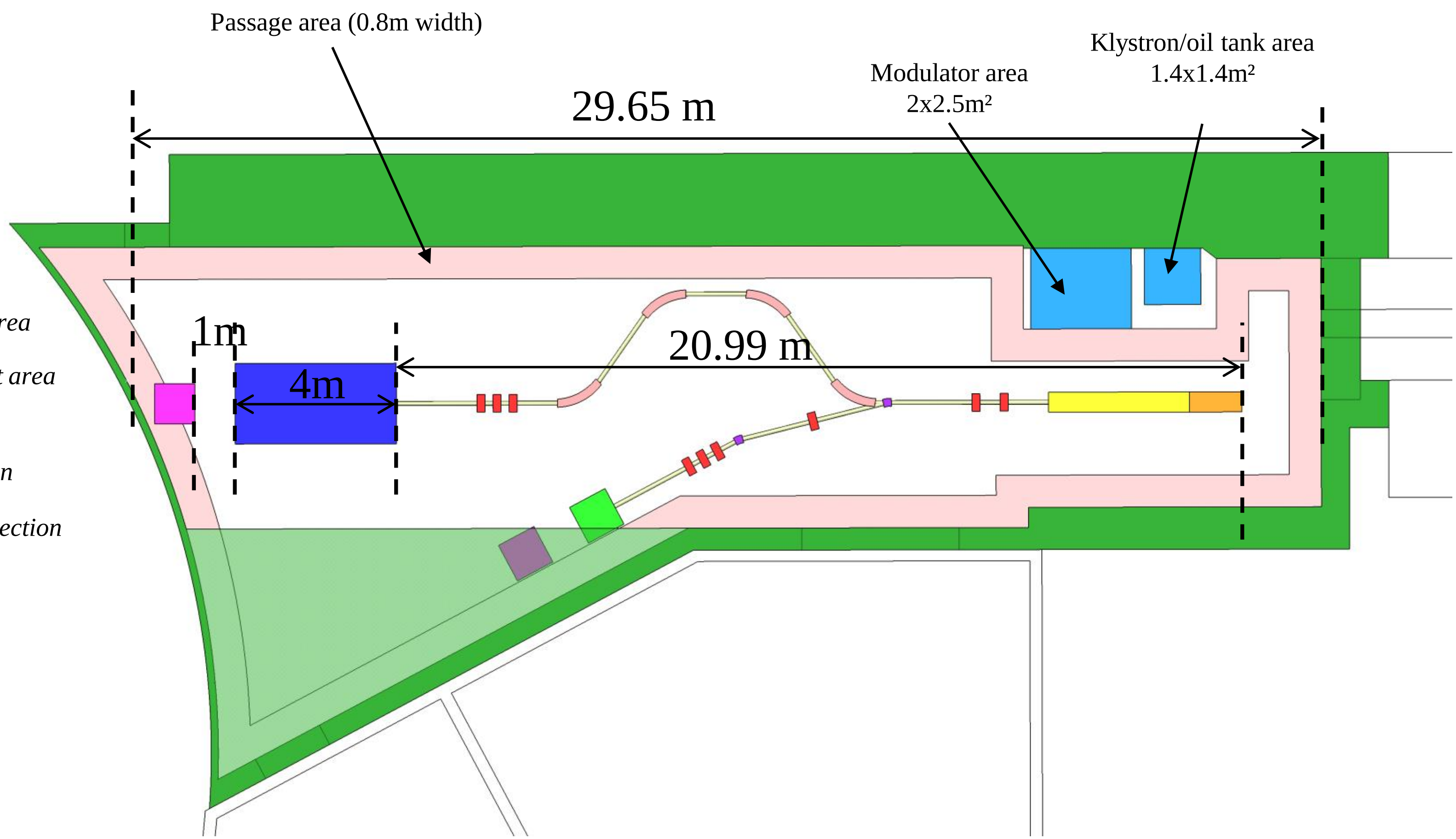
Experimental setup at PRAE

- Beam requirements:
  - Low emittance beam:
    - Angular divergence << channeling critical angle : 0.1 mrad in x and y
    - Beam spot size < 1 mm

    → Collimation?
  - Low longitudinal momentum dispersion: $dp/p = 10^{-3}$
  - Energy steps $\delta p/p \sim 10^{-3}$ with constant beam parameters
  - Low intensity (10^2 – 10^3 e-/s)

- Exprimental setup:
  - Emittance reduction (slits?) + beam focusing (parallel beam)
  - Goniometer (2 rotations) under vacuum
  - Flight line for angular distribution measurement (3m ideal, 1m minimum)
  - Position sensitive detector

    1 mm pitch x,y scintillating fibers hodoscope with 64-channel PMT
  - Transmission scintillator (single, pair and trident identification)



Wall
Passage area
Equipment area
RF Gun section
Accelerating section
Quadrupole
Dipole 45°
Dipole 14°
Beam dump
Pro Rad
Radiobiology/ Instrumentation platform

Alternative interpretation / byproduct

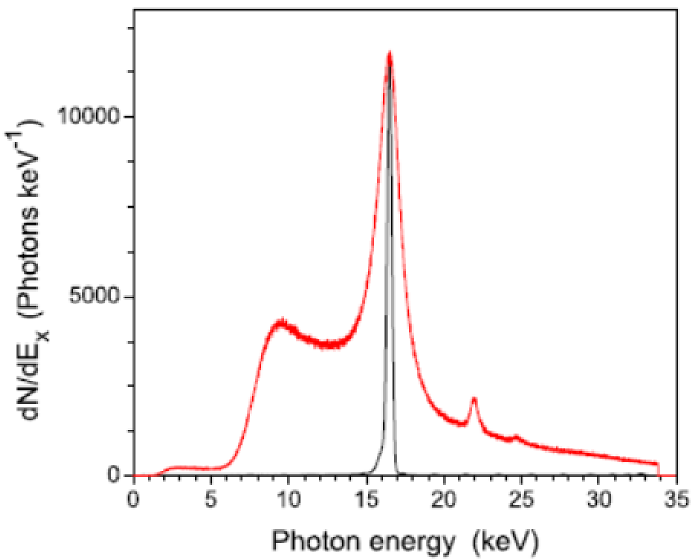
- Crystal assisted Trident production
  - at the energy threshold for ($e^- e^+ e^-$) production in channeled states
  - Pseudo-resonance and/or harmonics
  - → multiplicity measurement

- Channeling radiation studies

  Hard x-rays emission at forward angles ($1/\gamma$)

  Transmitted electrons to be swipped out by magnet.

  (see eg Brau et al, FERMILAB-PUB-12-503-APC)



Channeling radiation by 14 MeV electrons in diamond

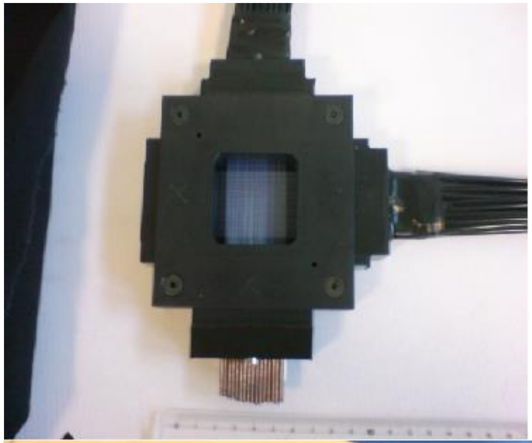
Hodoscope 2 prototypes

Objectif :

- Résolution spatiale : 1mm
- Résolution temporelle : 1ns
- Taux de comptage : 10^8 1/s

Prototypes :

- Fibres scintillantes croisées (1x1mm2 BCF 10/12)
- 2 prototypes: 2x32 et 2x128 fibres
- couplés à des MP hamamatsu H8500 par
  l'intermédiaire de fibres optiques FORETEC.



Petit hodoscope:

2x32 voies de lecture

Zone active de 3.2 x 3.2 cm

Grand hodoscope:

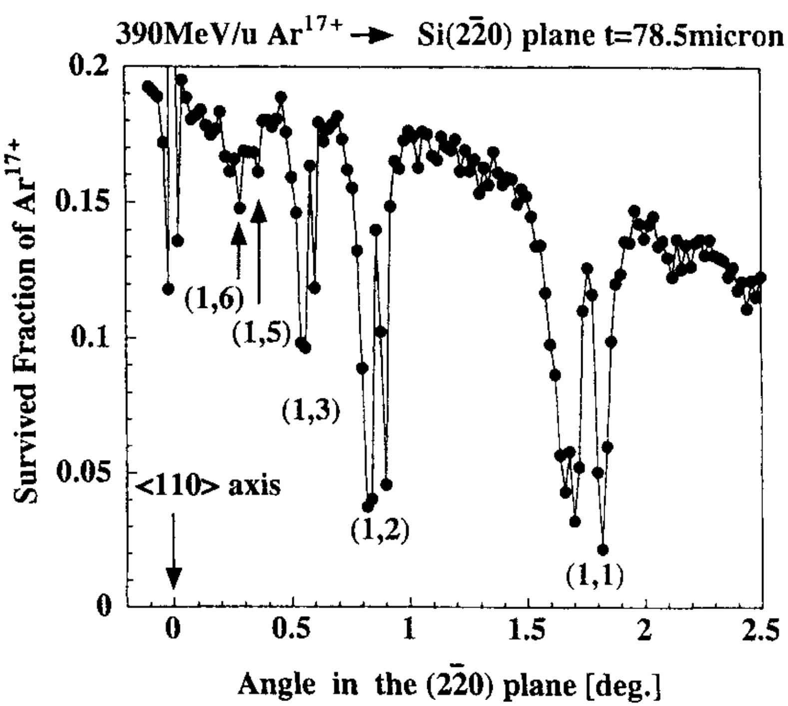
512 voies de lecture

Zone active de 12.8 x 12.8 cm

Resonant Coherent Excitation

Periodic term δV of the potential

- Perturbation frequency along a string $\nu_n = n\frac{\gamma v}{d}$ $n = 1,2,\ldots$
- Resonance when $h\nu_n = \Delta E_{ij}$ of the projectile



K. Komaki et al., NIM B146 (1998) 19

Application to atomic and nuclear spectroscopy