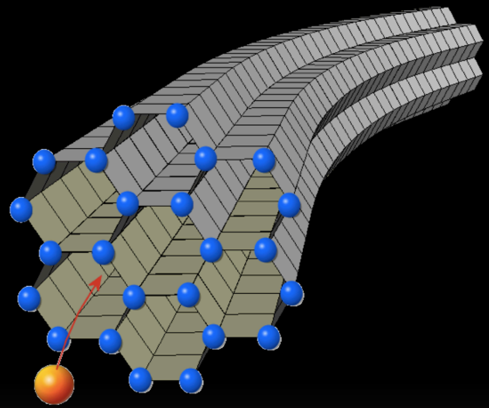
Ion channeling at intermediate energies:
- Experiments at GANIL and GSI
- Beam bending simulations



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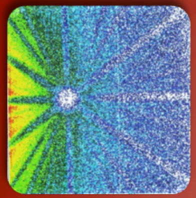
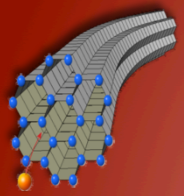
Summary

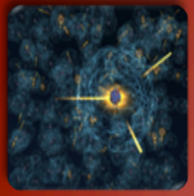


1 .Introduction

2. Heavy ion experiments



3. Proton and C ion bending simulations



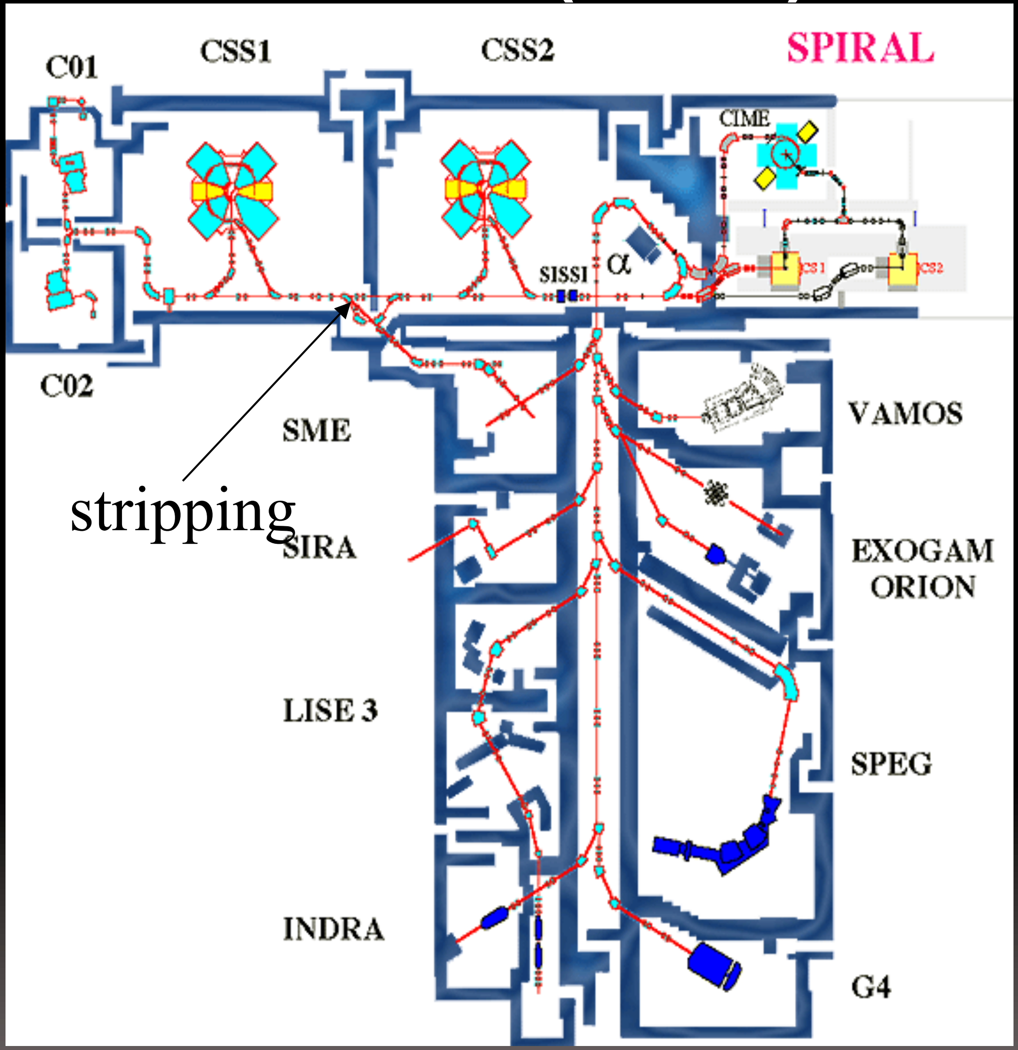
4. Conclusion

Introduction

Ion channeling at intermediate energies

- Ions: protons to uranium
- Energies: from 10 to 400 MeV/u
  - ✓No or little relativistic effects
  - ✓Fast ions: $v >> v_0$, but $v \sim v_0 Z^{1/3}$: Charge exchange
- Channeling: effects related to ion-electron interaction:
  - ✓Energy loss
  - ✓Impact parameter dependent charge exchange
  - ✓Blocking : lifetime during nuclear reactions
- Critical angles ~ 1 mrad
  - ✓Large bending radii: large angle deflection with bent crystals

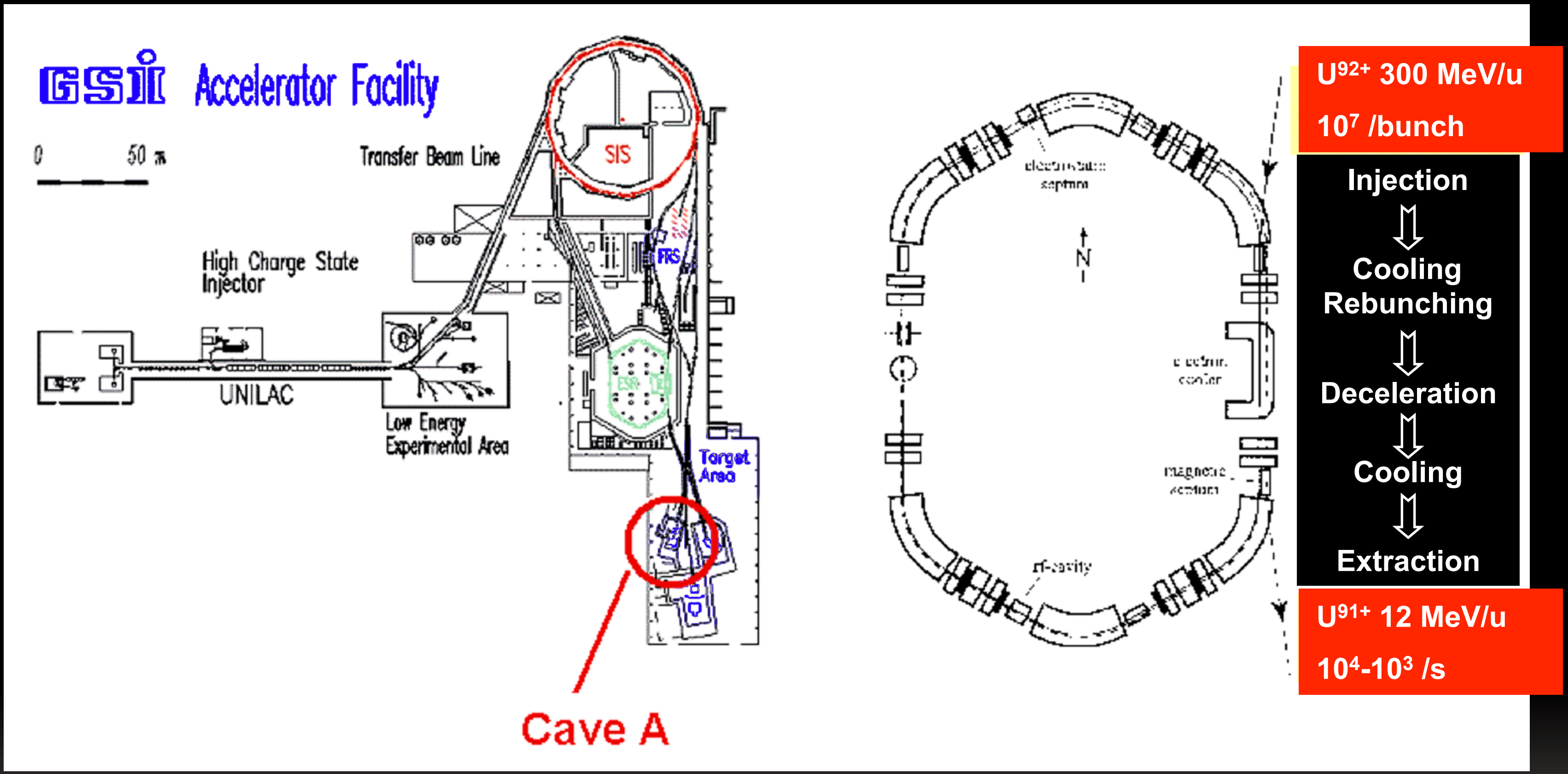
GANIL (Caen)



High energy
Ar: 95 MeV/u
Kr: 60 MeV/u
Pb^{56+}: 29 MeV/u

Stripping before last acceleration stage: ions with electrons in excess

SIS - ESR at GSI (Darmstadt)



H-like ion beams:

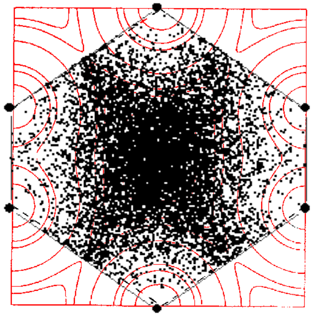
U^{91+} 20 MeV/u: $\eta_K = (v/v_K)^2 \approx 0.085, \eta_L \approx 0.35, \eta_M \approx 0.8$

U^{91+} 12 MeV/u: $\eta_K \approx 0.051, \eta_L \approx 0.21, \eta_M \approx 0.48$

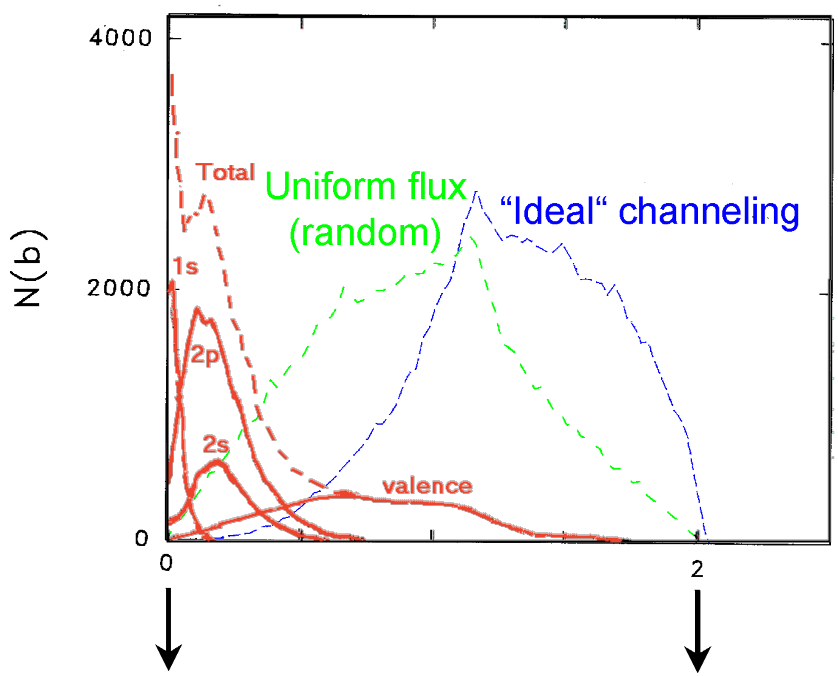
Stripping before deceleration: ions lacking of electrons

Ion channeling
interaction with the non-uniform electron gas

Flux redistribution simulation



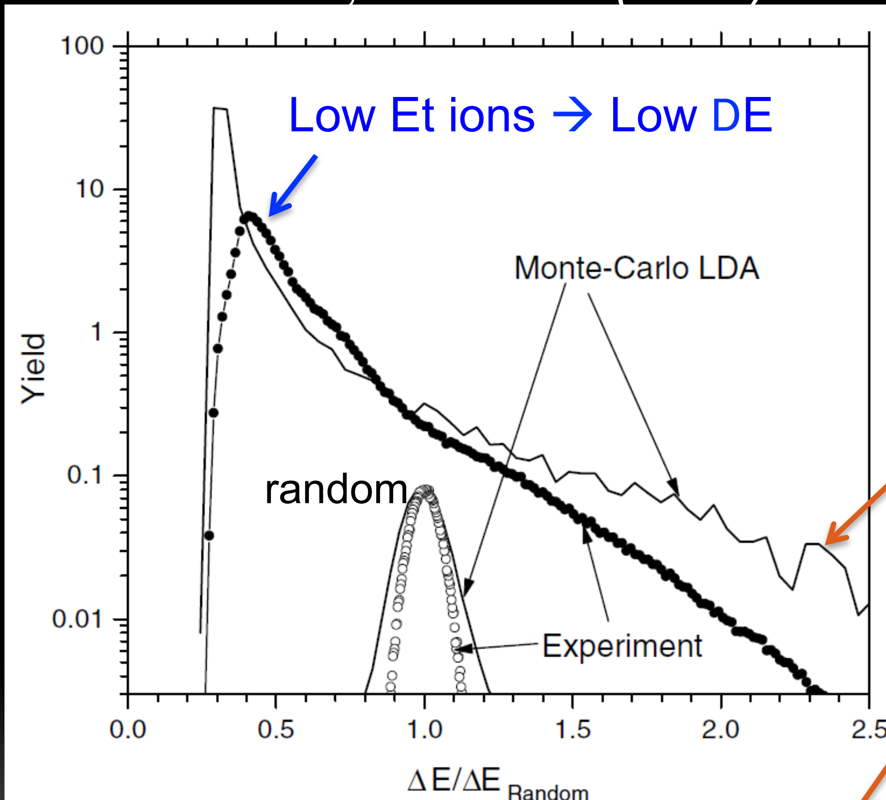
Silicon <110>



Energy loss

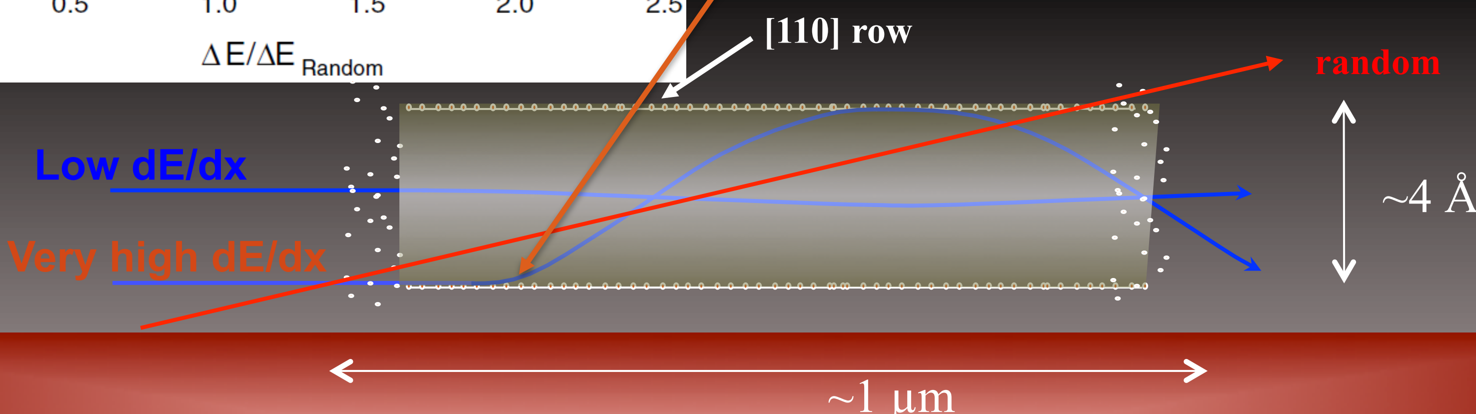
Pb 29 MeV/u on Si <110> 1.1 µm (GANIL: SPEG spectrometer)

L'Hoir et al., NIMB 245(2006)1



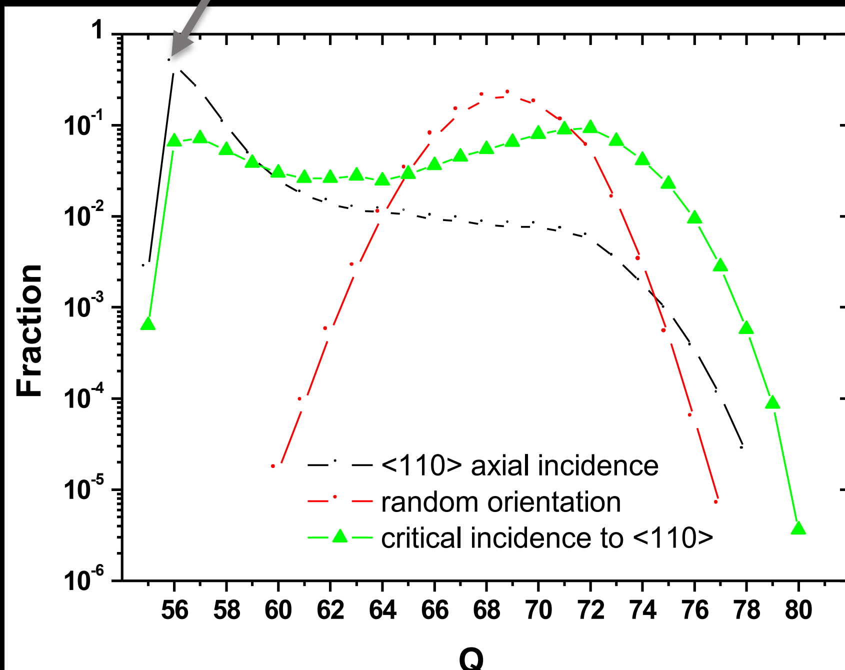
High Et ions:
close collisions along strings at entrance
Averaged DE~2 × DE_{random}

Locally, DE~10 x DE_{random}

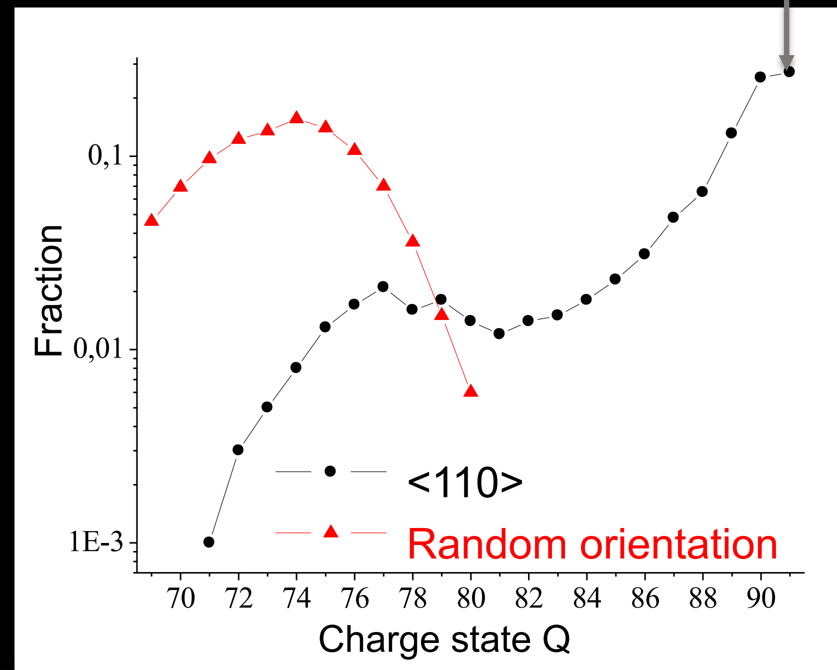


Charge state distributions (Magnetic spectrometers)

Pb^{56+} 29 MeV/u ? 1.1 µm Si (GANIL)



U^{91+} 20 MeV/u ? 11.7 µm Si (GSI)



Incident ions far from charge equilibrium

- "Random" orientations: 3-body capture (MEC) and Nuclear Impact Ionization ? Equilibrium
- Axial orientation : $F(Q_{out})$ linked to $F(E_{\wedge})$

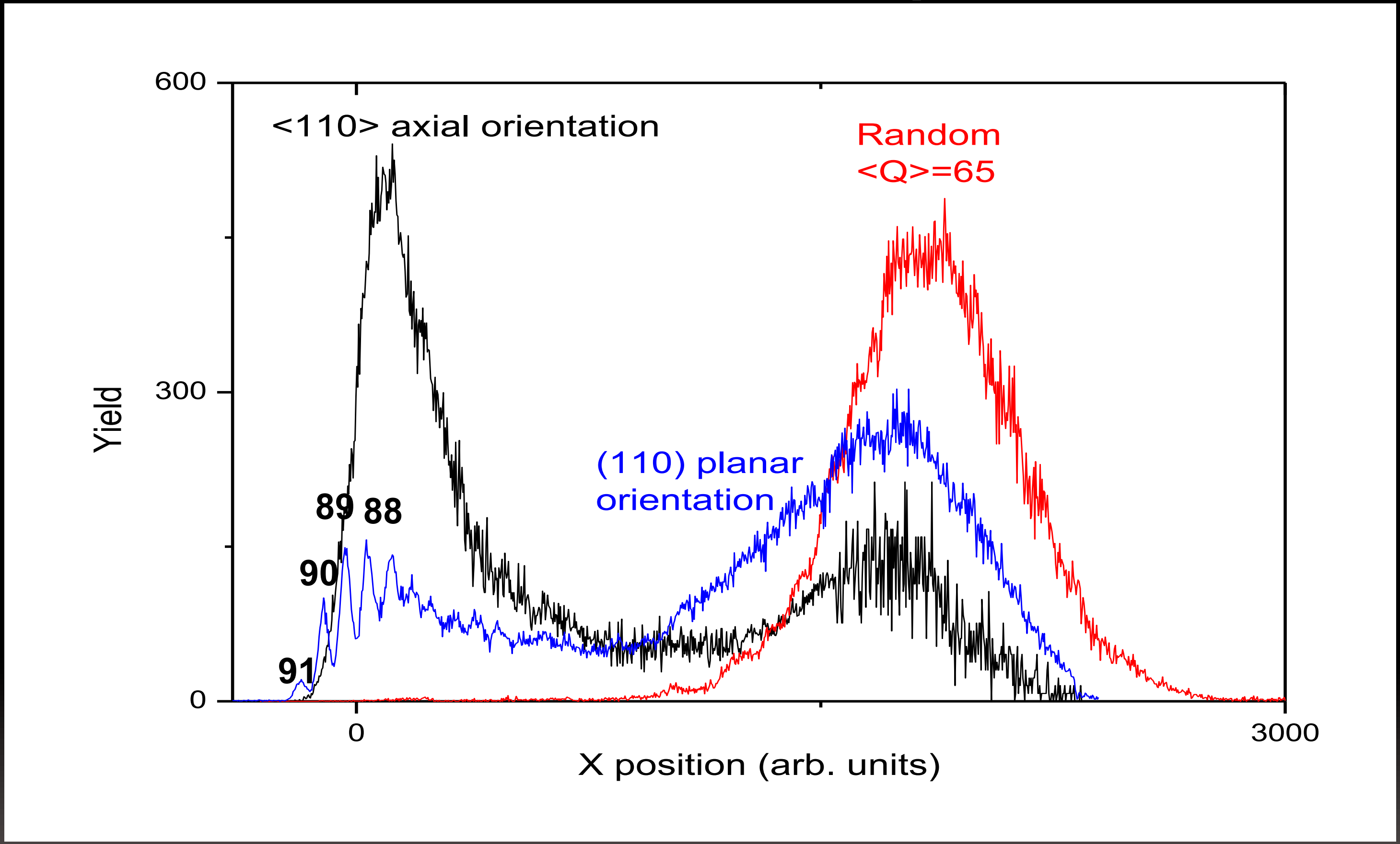
  Broad distributions, large "frozen" ion fraction

Superdensity effect: $Q_{out} > Q_{out}$(random), enhanced ionization close to strings

Critical incidence : $Y \sim Y_c$: superdensity effect maximum

Deceleration of highly charged uranium ions in a silicon crystal

U^{91+} 12 MeV/u ® 18 µm Si

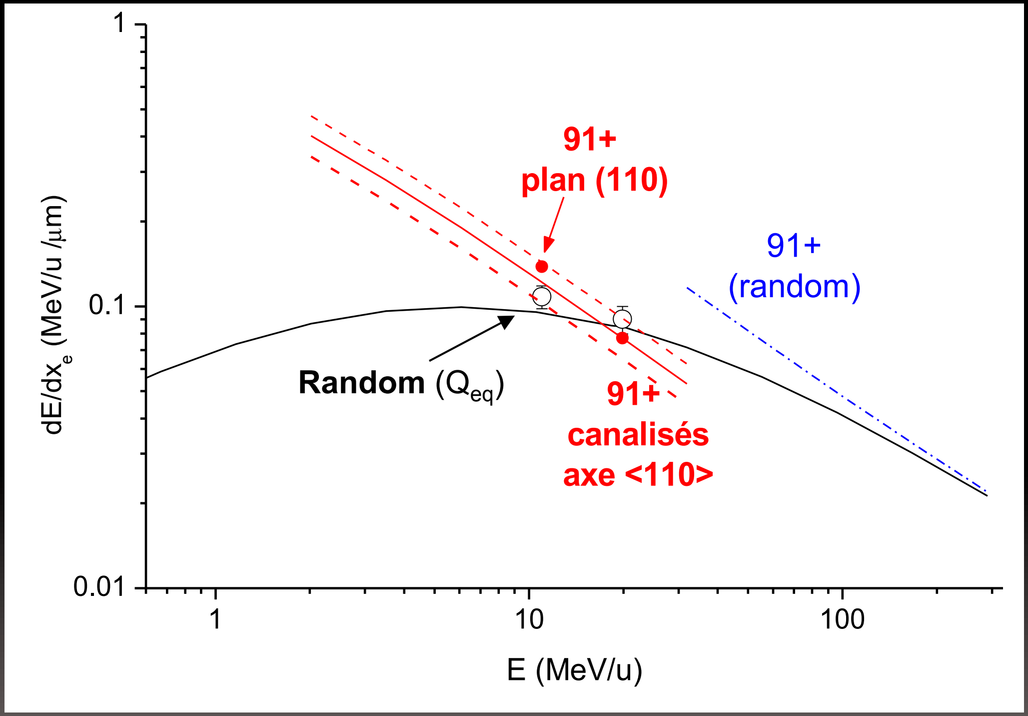


Frozen **transmitted U^{91+}** ions ~ 0.3% for (110) planar channeling

~1.5 % for <110> axial channeling

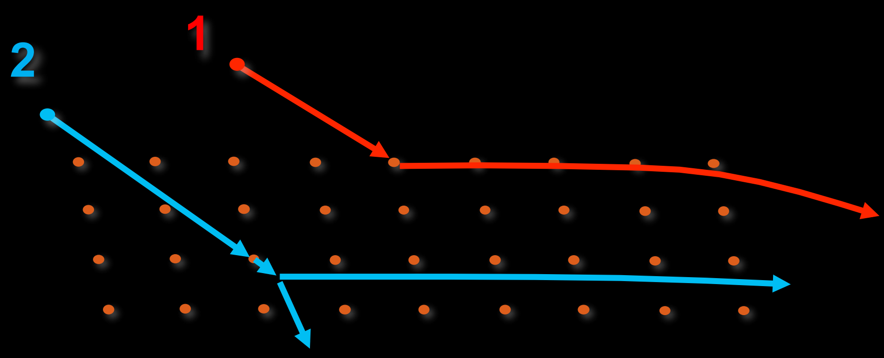
Crystal deceleration of heavy ions

- 12 MeV/u U^{91+} deceleration in 18 µm Si
  - Ion transmission U^{91+} ~0.3%; E_{final} = 9.4 MeV/u (110) plane
  - ?E(110)=2,6 MeV/u > ?E(random)=1.9 MeV/u

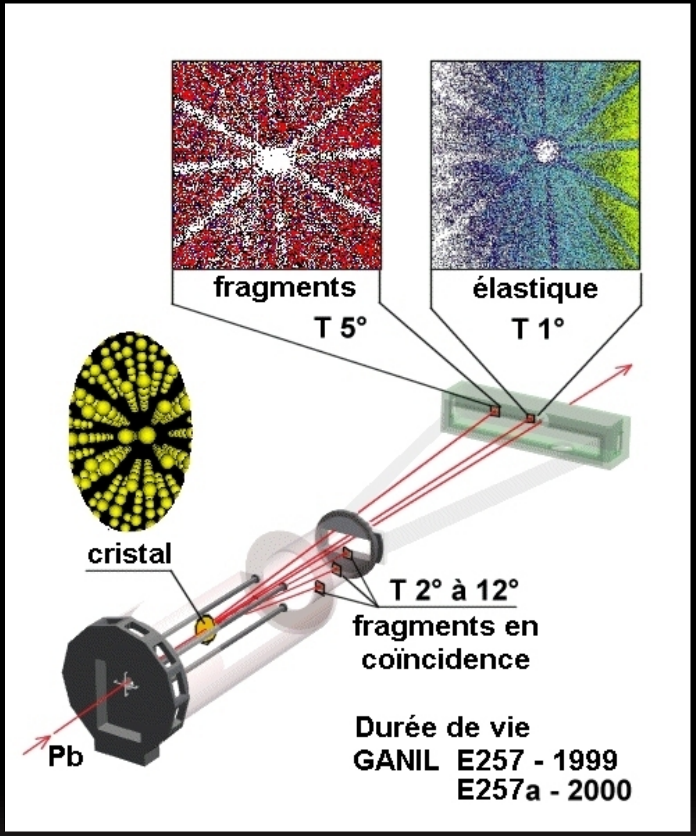


C. Ray et al., Physical Review B 84 (2011) 024119

Fission time measurement by crystal blocking

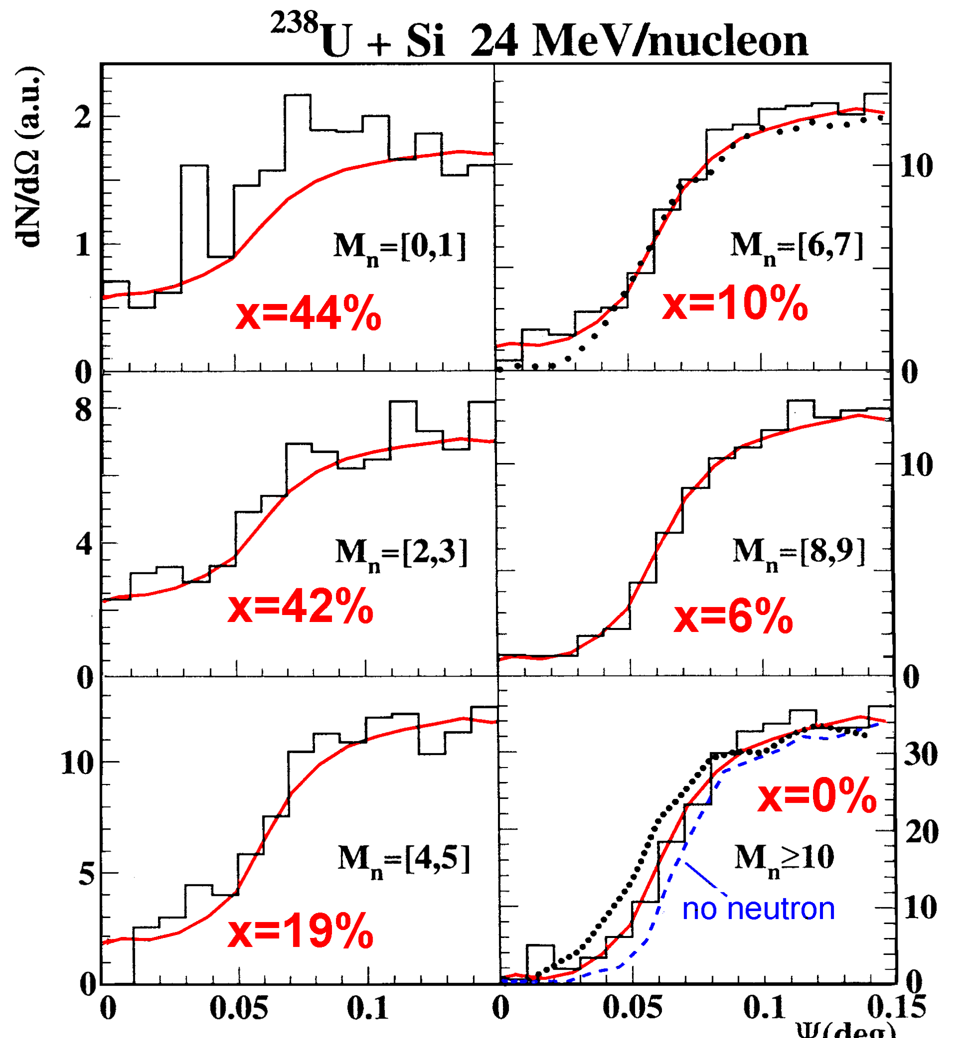


$r_{\perp} = v_{\perp} t_{fiss}$: compound nucleus transverse recoil

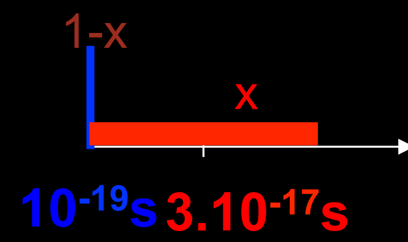


- Fission time measurement
  - Long time [?] filling of the blocking dip
  - simulations [?] long time fraction

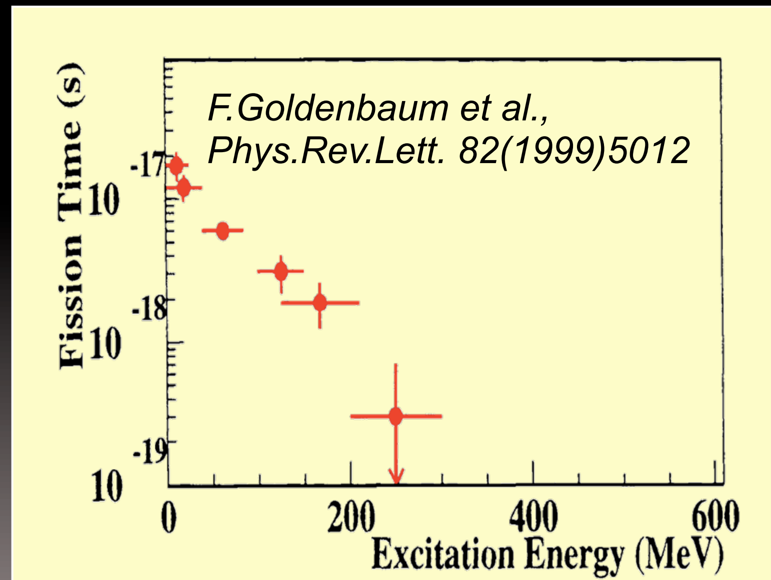
Uranium fission times as a function of excitation energy



C.Cohen and D.Dauvergne, NIM B 225 (2004) 40



x = long time component fraction deduced from simulated dips



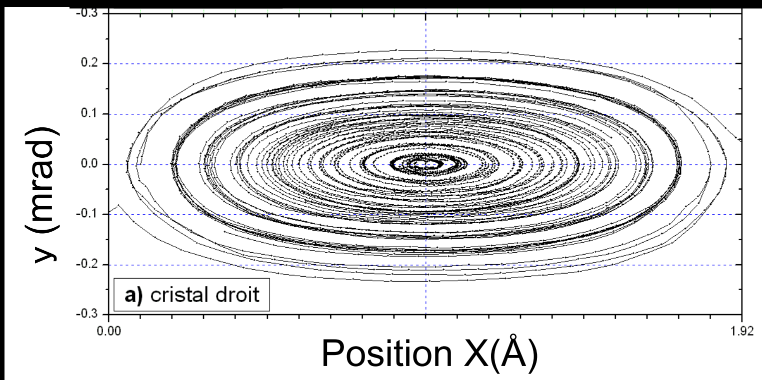
Simulations

Full trajectory simulations are needed for:

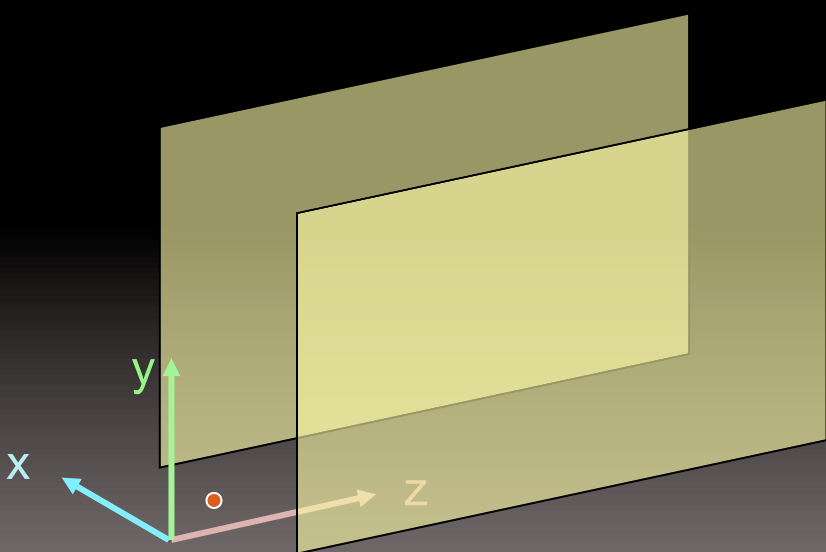
- Blocking experiments
  - ✓ Delayed neutron evaporation by fragments inside crystal
  - ✓ Angle at exit is required
- Energy loss or charge exchange when correlated collision dynamics play a role
  - ✓ Superdensity effect
- Dechanneling in thick crystals
  - ✓ Bent crystals

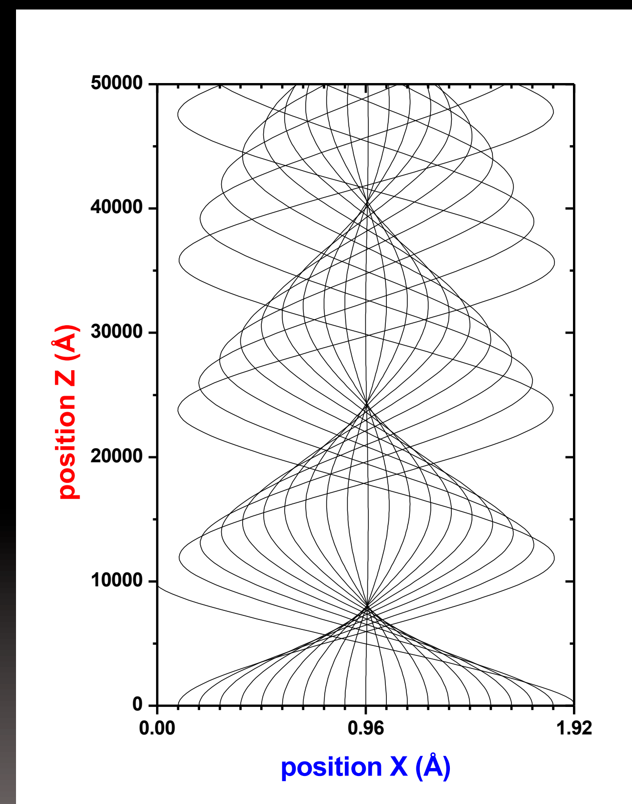
Planar channeling trajectory simulations

^{12}C @ 400 MeV/u ? Si ; L = 5 µm



Oscillation between 2 planes

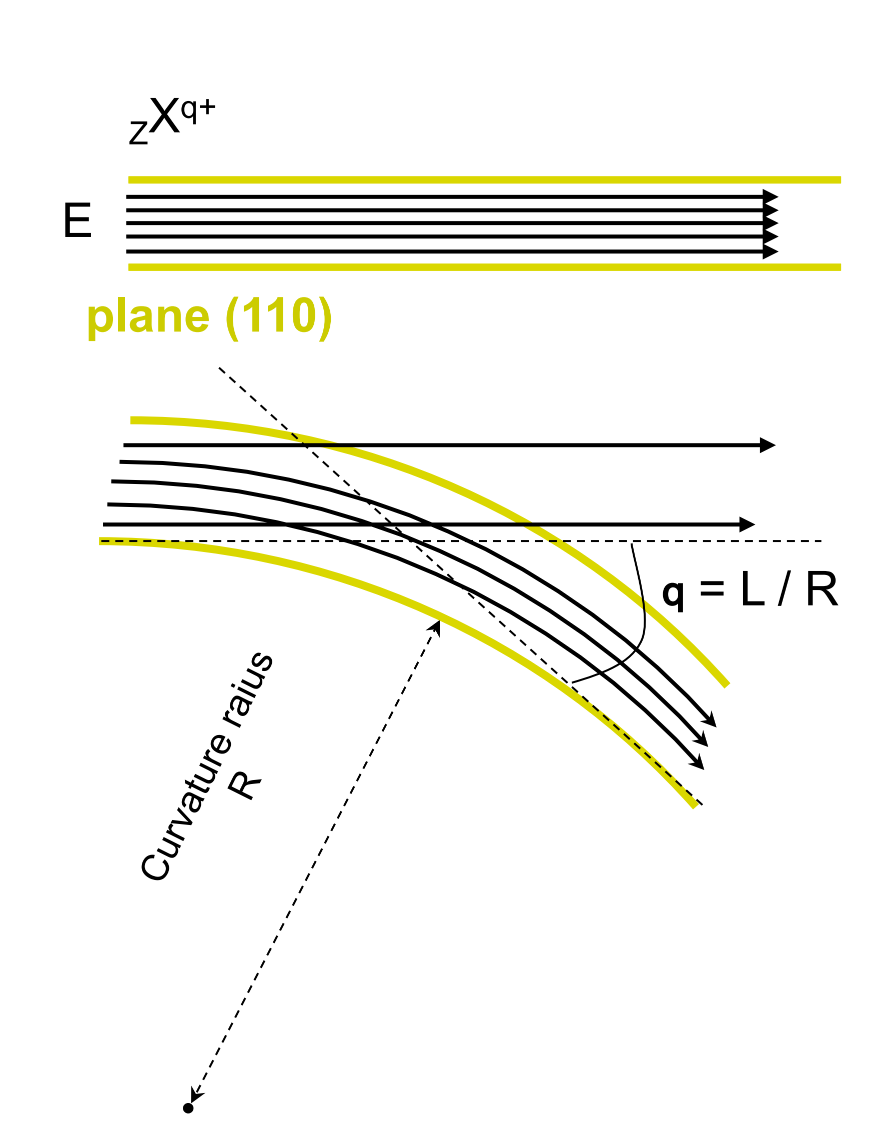




^{12}C @ 400 MeV/u ? Si ; L = 5 µm

Bent crystal : a minimal overview

- First experiments 70's – and 80's
  - High energies and small deviations
    - Proton 70 GeV, 450 GeV
      q : 80 mrad (4°)
    - Pb^{82+} : 22 – 33 TeV
      q : 4-9 mrad (0.2-0.5°)
    - Proton 3,5,10 MeV
      q : 1 mrad (0.08°)
    - Proton 7 TeV
      q : 2-20 µrad (0.1-1 $\times 10^{-3}$ °)



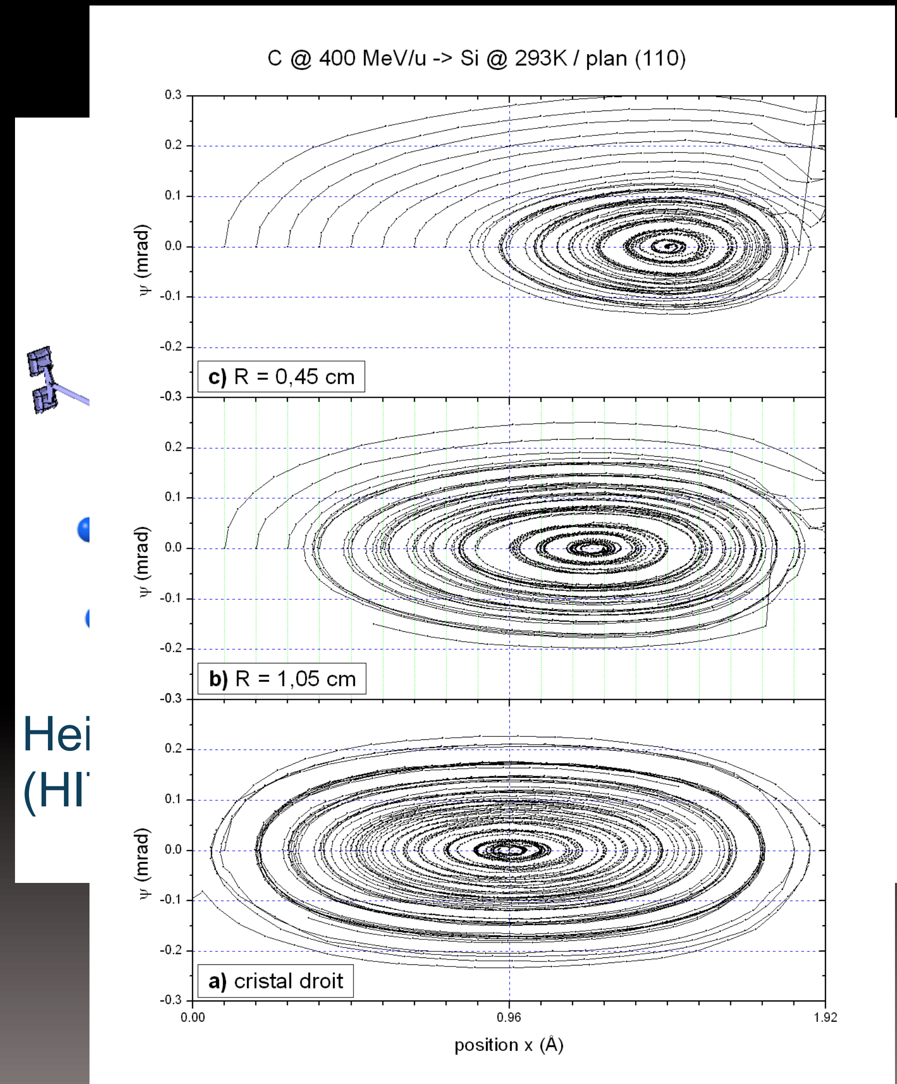
Ion therapy applications ?

- Medical constraints
  - Multi entrance ports
  - No rotation of the patient
- « Gantry »
  - Beam deviation
- Carbon gantry ~ 600t (proton ~30t)

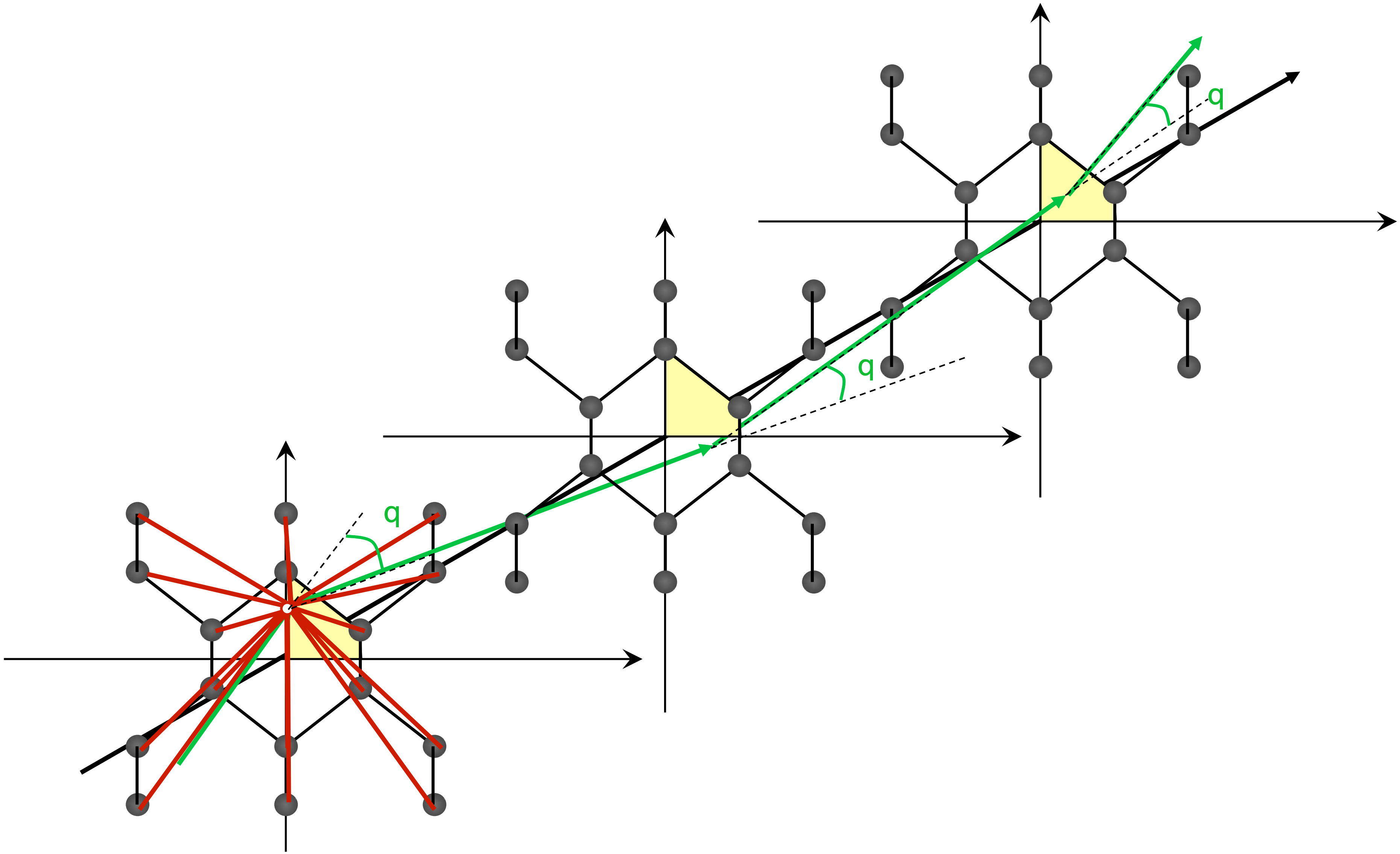
→ bent crystal <1g

  - Large deviations
    - 45° ? 90° ?
  - Ion survival yield
- Curvature influence
  - Critical radius (R_c)

^{12}C @ 400 MeV/u ? Si ; L= 5 µm

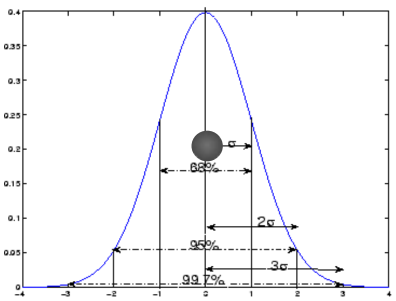


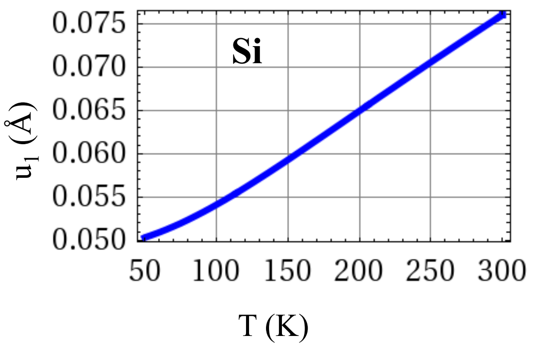
Monte Carlo simulations



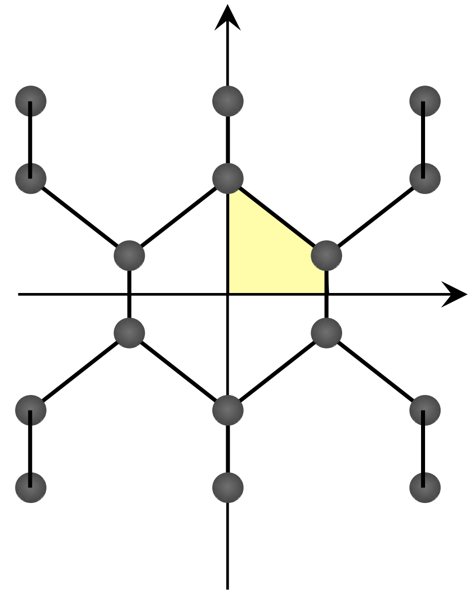
Monte Carlo simulations

- Thermal vibration

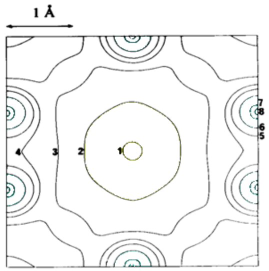




- Use of the crystal symmetry



- Electronic local density



- Energy loss

$$\frac{dE}{dx} \propto 1/v^2$$

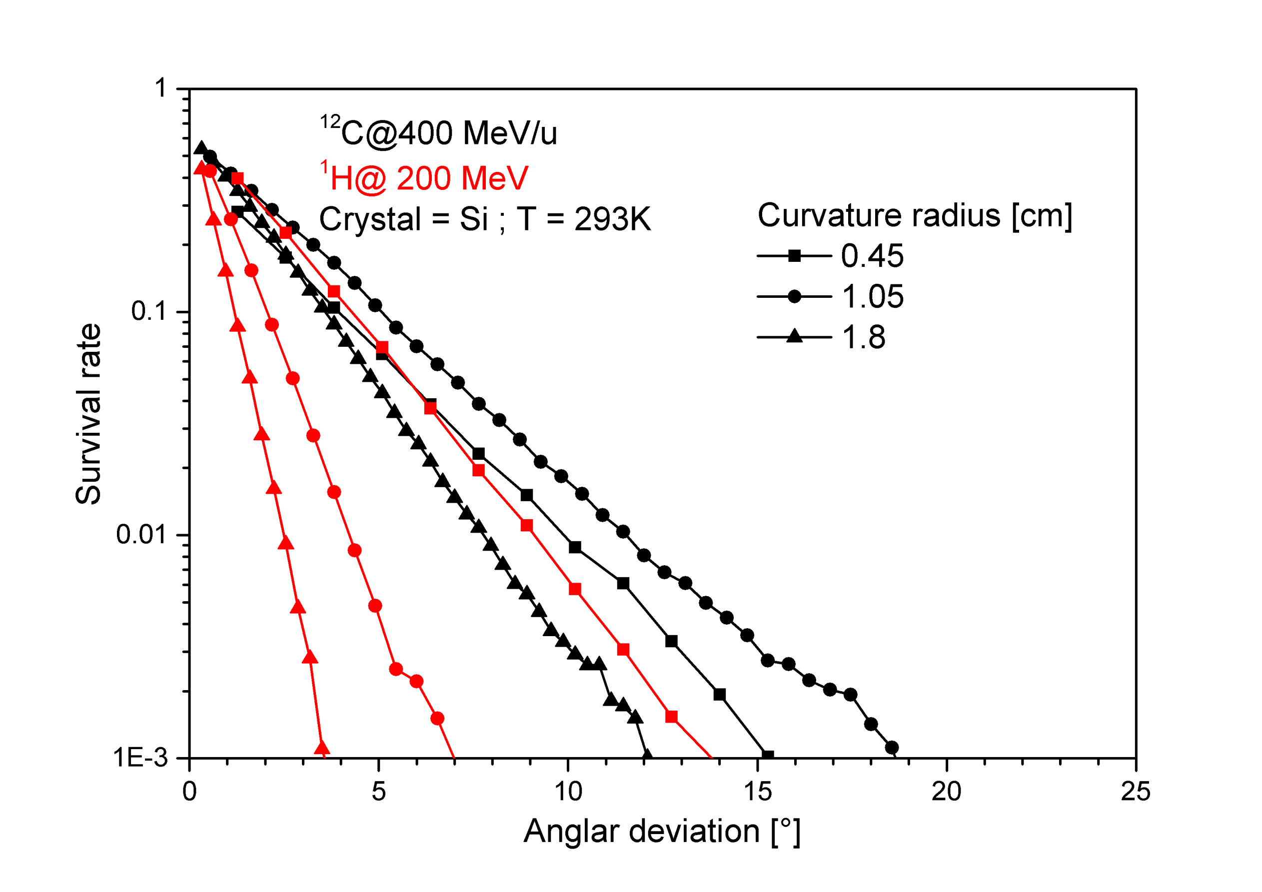
- Multiple scattering on electrons

$$\left\langle \frac{d\Omega^2}{dz} \right\rangle = \frac{m_e}{2 \cdot E \cdot m_1} \cdot \left(\frac{dE}{dx} \right)_{Rd} \cdot \frac{\rho(z)}{\rho_{Rd}}$$

- Relativistic speed

Simulation results

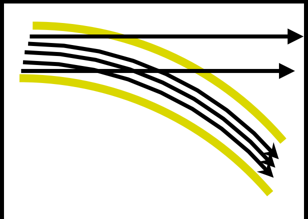
Survival : - [?]c < angle < [?]c relative to crystal plane

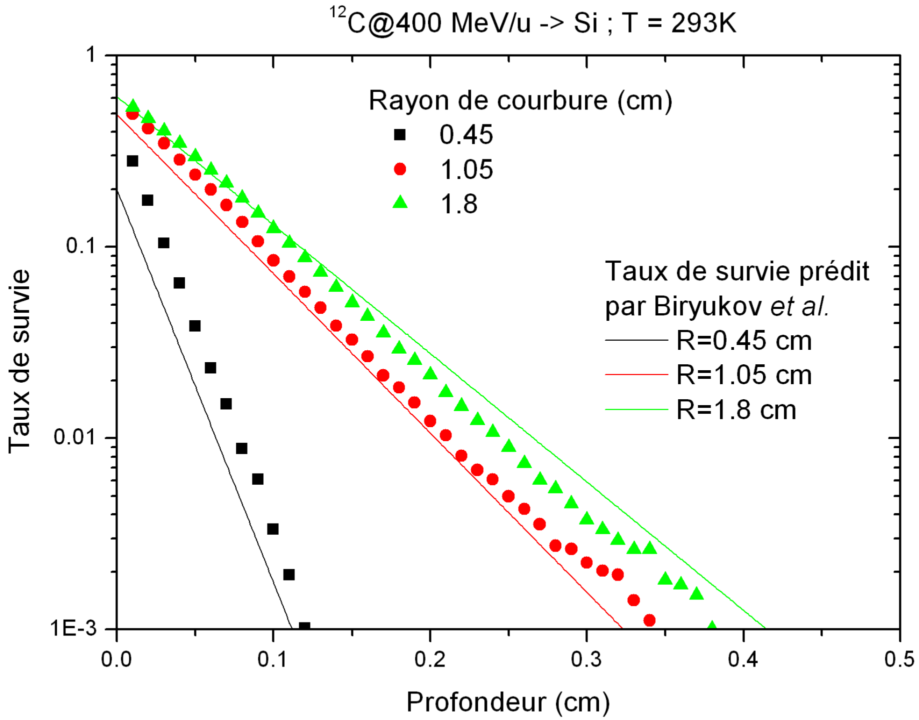


Simulation results

- Comparison with predictions

^{12}C @ 400MeV/u





$$T(\theta, R_C/R) = A_S^* \cdot \left(1 - \frac{R_C}{R}\right)^2 \cdot \exp\left(-\frac{L}{L_D \cdot \left(1 - \frac{R_C}{R}\right)^2}\right)$$

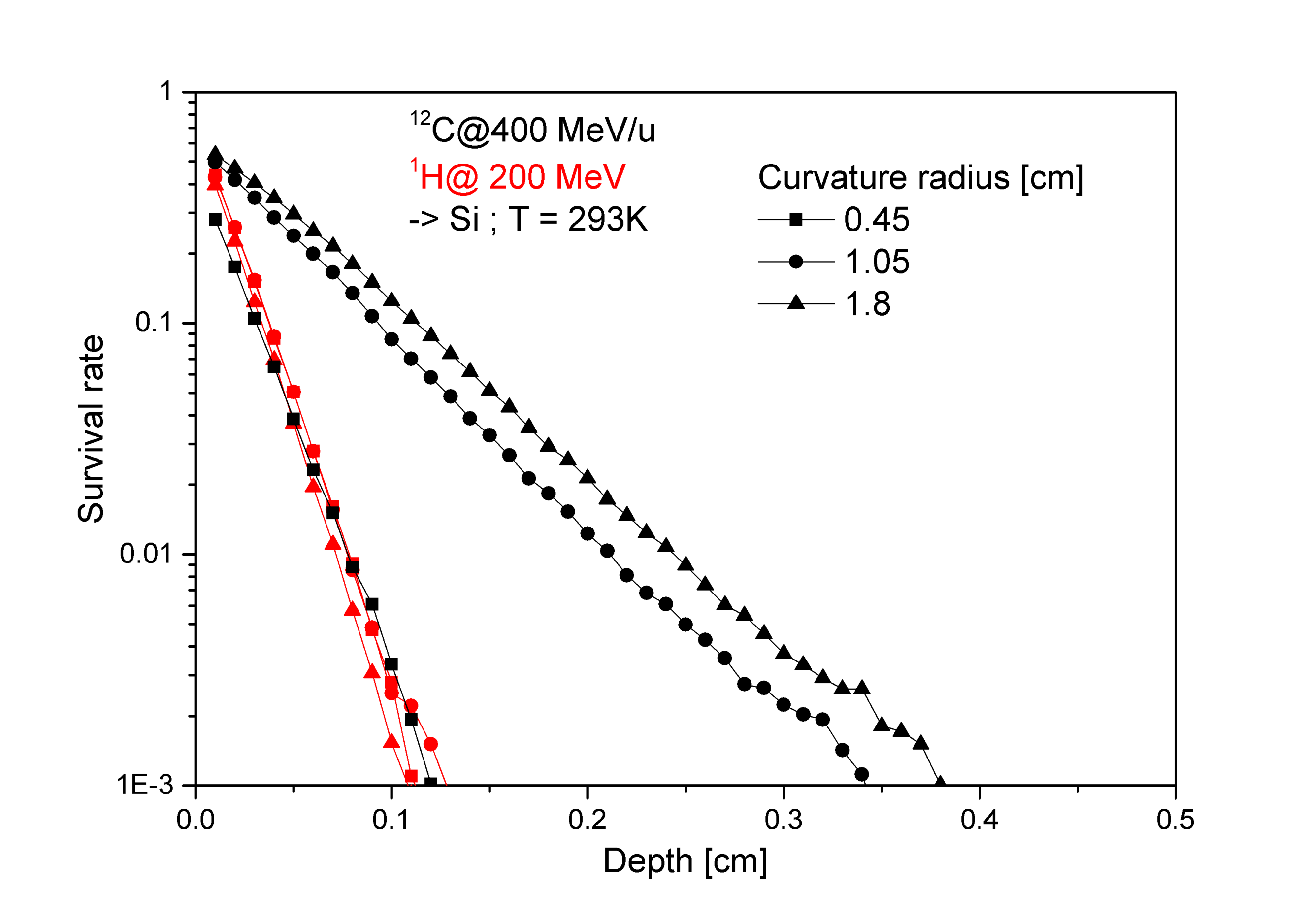
L : crystal length
R : bending radius
q : deviation angle
L_D : dechanneling length (from simulation)
R_C : critical bending radius

$$L = R \cdot \theta$$

$R_C = 0{,}225\ \text{cm}$ $L_D = 0{,}087\ \text{cm}$

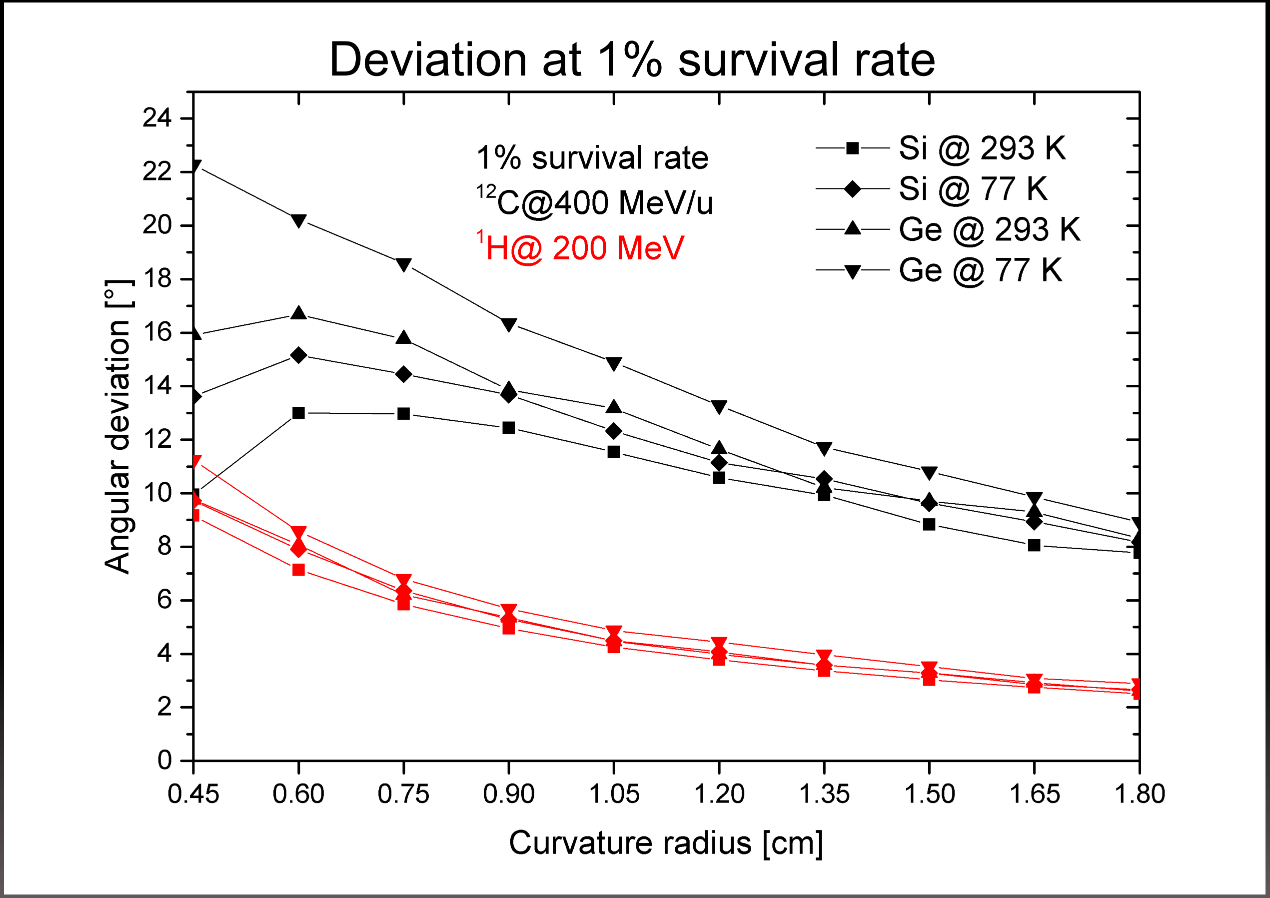
Simulation results

- Survival rate vs crystal depth



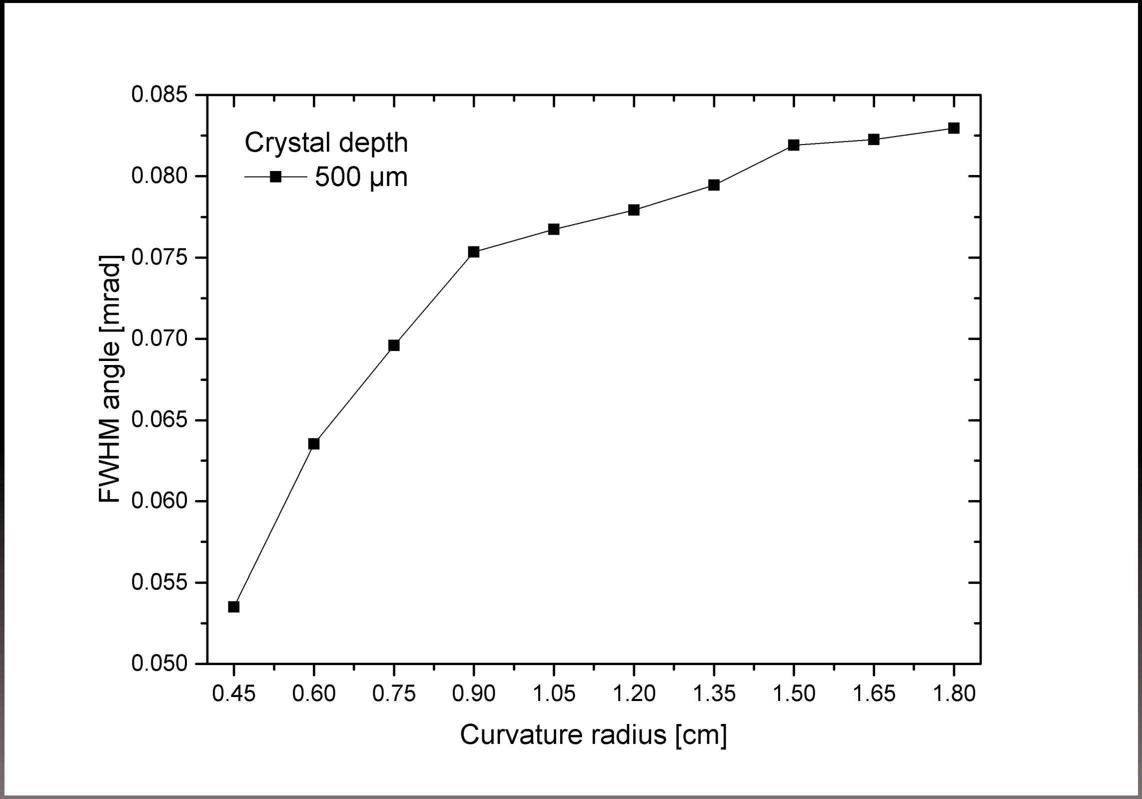
Simulation results

- Influence of crystal type and temperature



Simulation results

- Angular distribution of surviving ions
  (C ions at 400 MeV/u in Si 293 K)



Conclusions

- Simulation work based on previous work with heavy ions at GANIL and GSI
- Deflection angles above 10° achievable in planar channeling conditions

  But hardly convenient for demanding applications such as hadrontherapy
- Experiments needed to validate simulations (and extrapolation at higher energies)