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STUDY OF BEAM STEERING AND RADIATION EMISSION IN THE INTERACTION OF SUB-GEV ELECTRONS WITH SI AND GE THIN BENT CRYSTALS

The XII International Symposium

«Radiation from Relativistic Electrons in Periodic Structures»

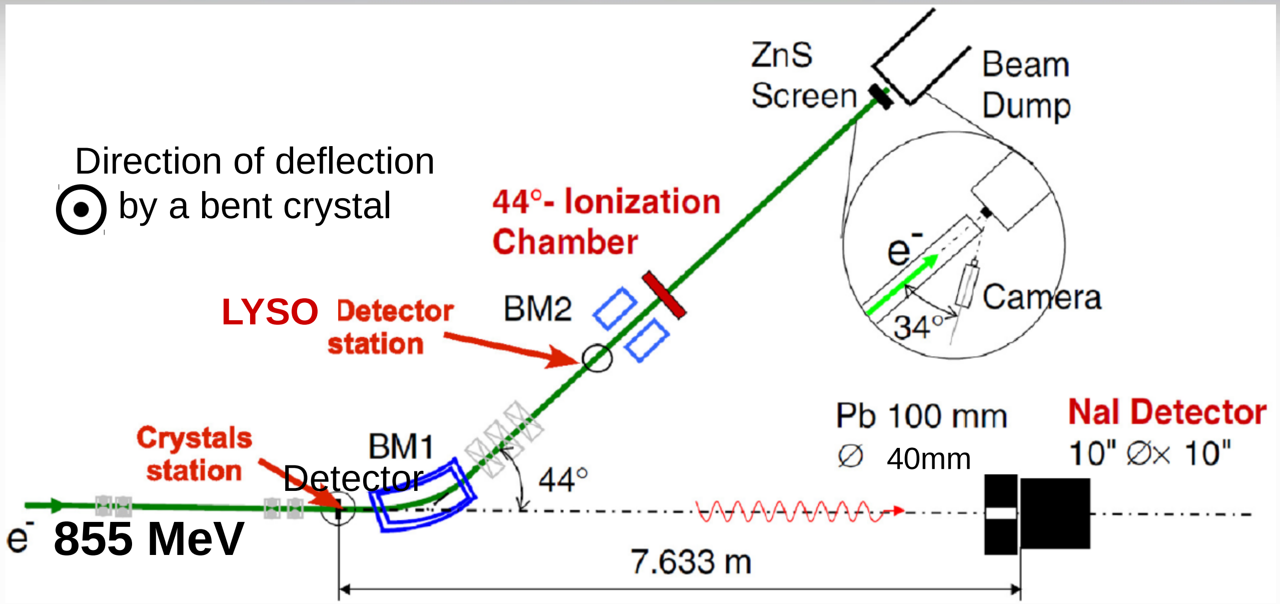
RREPS-17

DESY, Hamburg, September 18-22, 2017

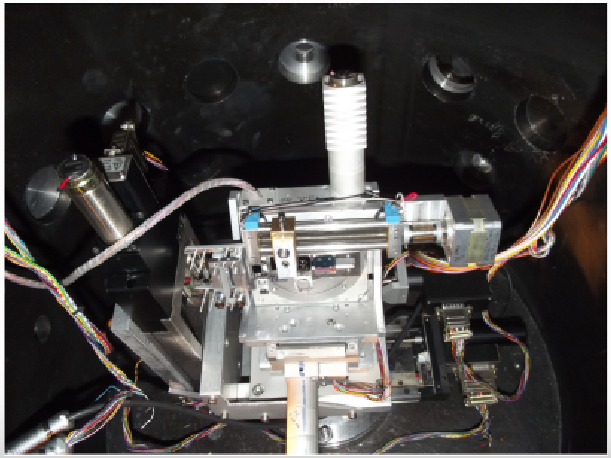
Outline

- **Experimental setup at MAinzer Mikrotron MAMI**
  - Experimental layout
  - Bent crystal manufacturing
  - Dynamical holder
  - **Silicon** and **Germanium** bent crystals
- **CRYSTAL** simulation code for particle tracking in crystal
- **Experimental** and **simulation** results
  - Angular distributions
  - Fitting model and influence of overbarrier particles
  - **Channeling efficiency** and **dechanneling length**
  - **Volume reflection**
- **Radiation** emitted by **sub-GeV electrons** in a bent crystal
  - First study of **Z influence** on **radiation production rate**

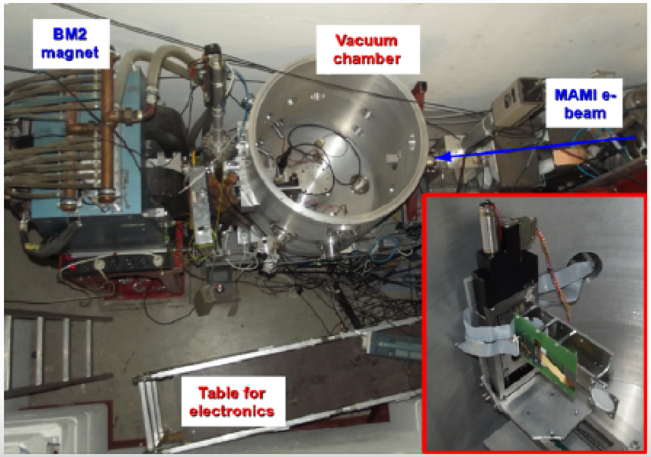
Experimental setup at Mikrotron MAMI



Crystal station

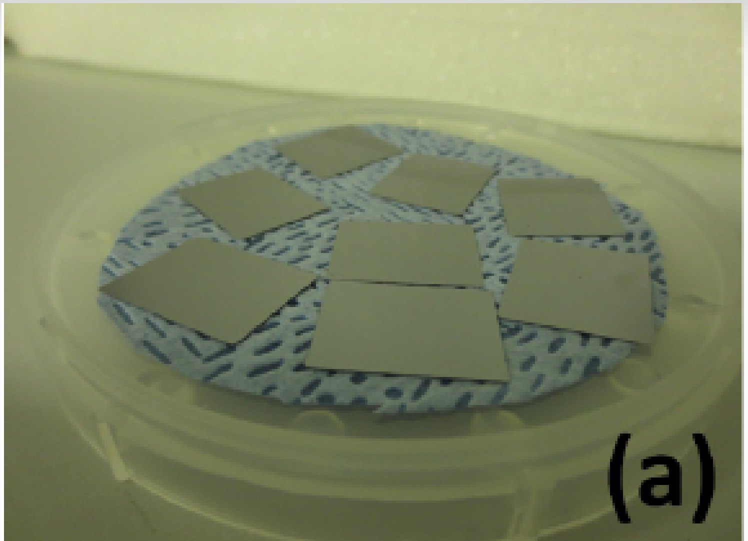


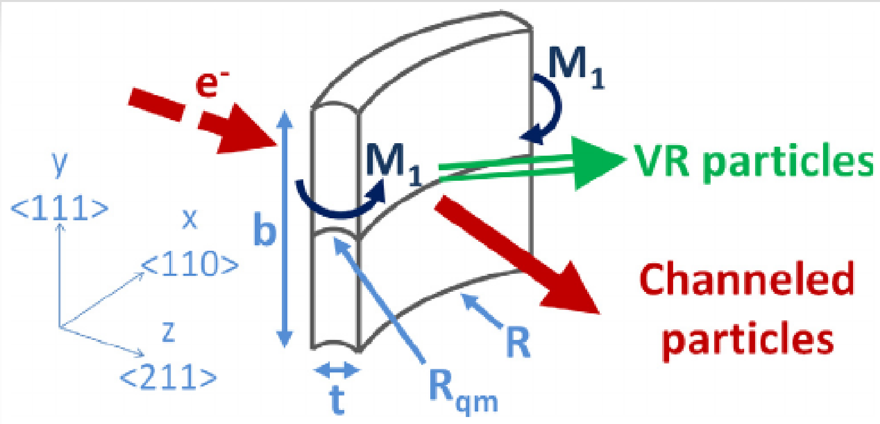
Detector station

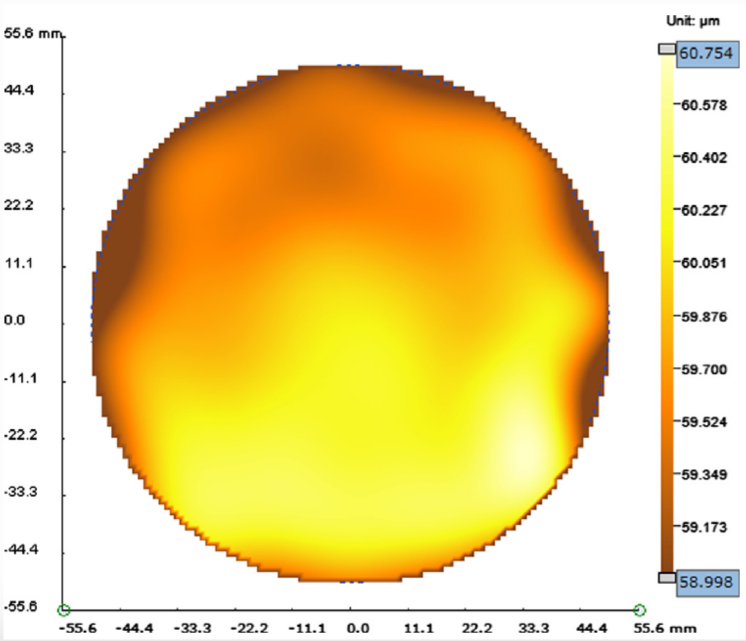


D.Lietti et al. Rev. Sci. Instrum. 86, 045102 (2015)

Manufacturing and characterization of bent silicon crystals

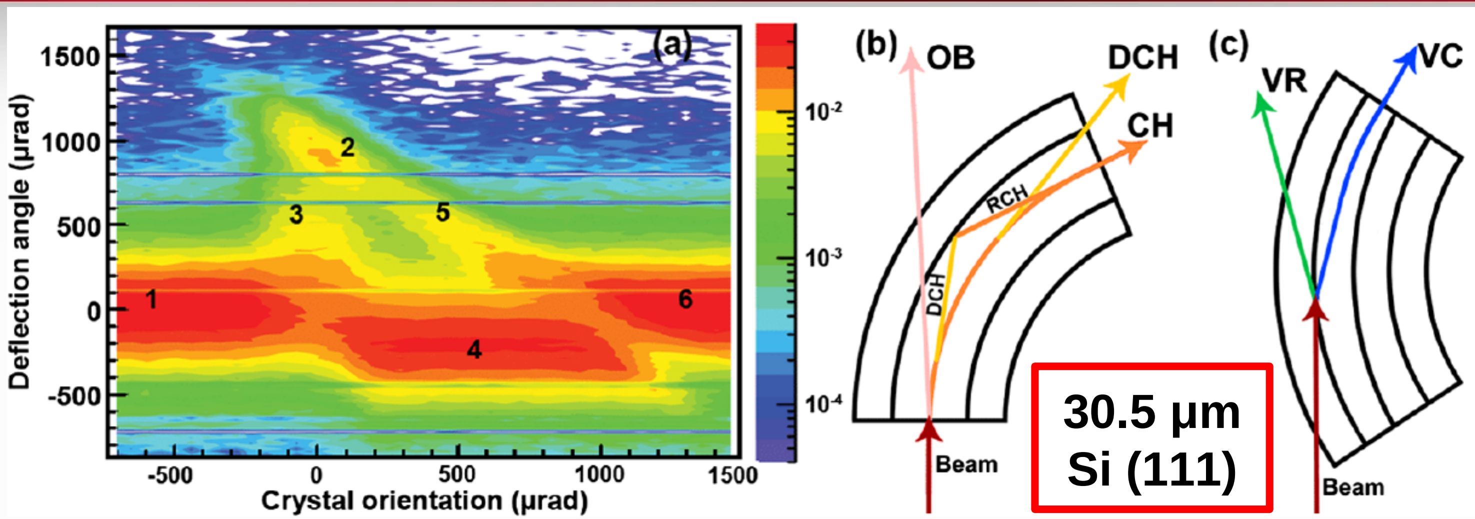


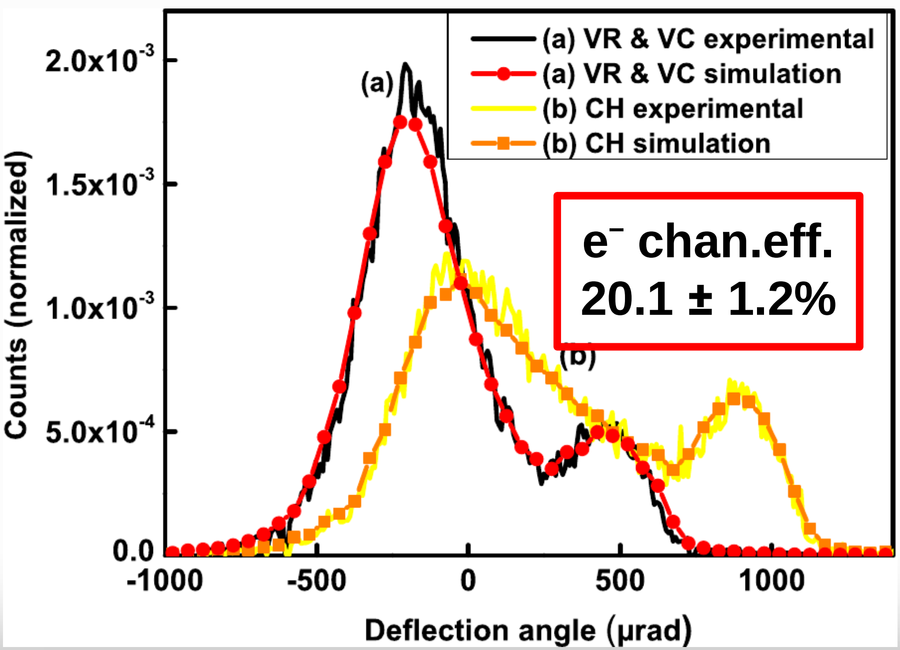


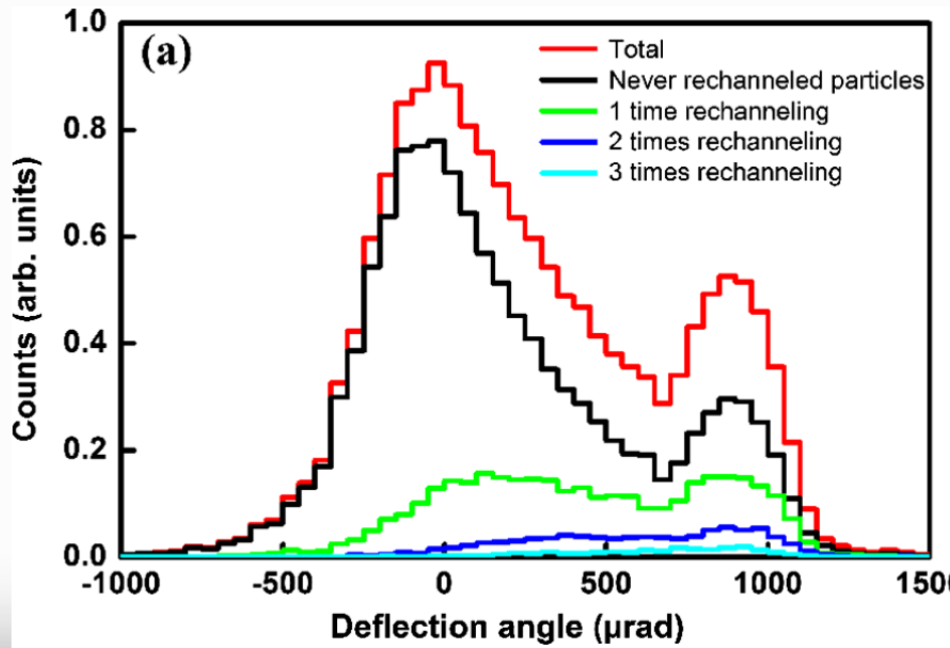


G. Germogli et al. NIM B 355 (2015) 81–85

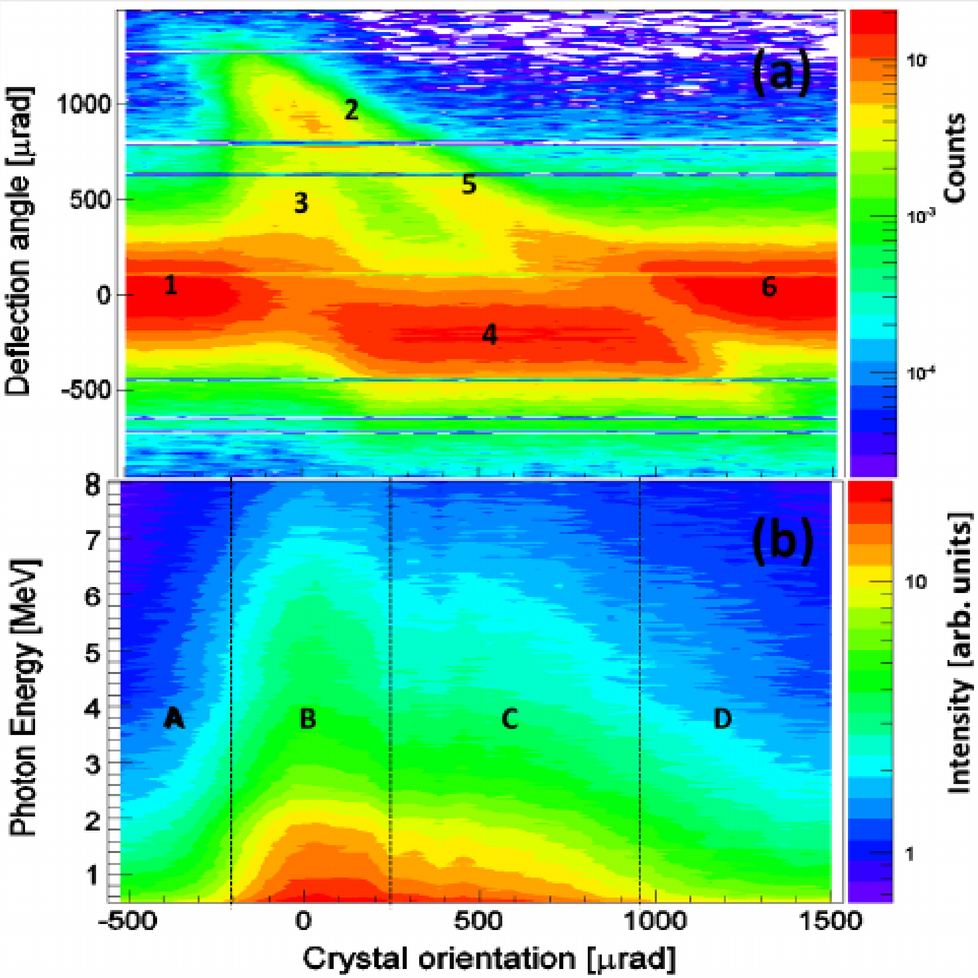
Steering of a Sub-GeV Electron Beam through Planar Channeling Enhanced by Rechanneling

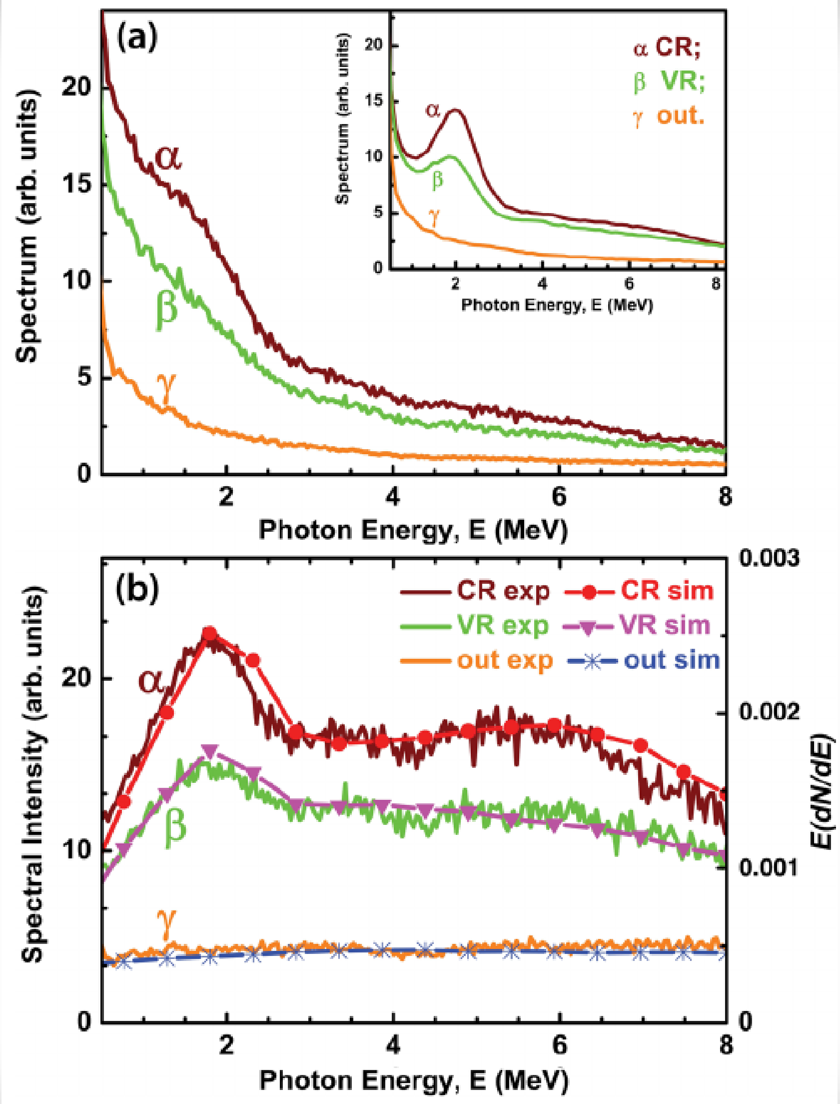






Investigation of the Electromagnetic Radiation Emitted by Sub-GeV Electrons in a Bent Crystal





CRYSTAL simulation code*

Main conception – tracking of charged particles in a crystal in averaged atomic potential

Program modes:

- **1D** model – particle motion in an interplanar potential
- **2D** model – particle motion in an interaxial potential

Simulation of the different physical processes:

- Multiple and single **Coulomb scattering** on nuclei and electrons.
- **Nuclear scattering**
- **Ionization energy losses**
- **Crystal geometry**

Advantages:

- High calculation speed (up to **10^3 particles/s/core**)
- **MPI** parallelization for high performance computing

Max number of cores used simultaneously by CRYSTAL

- **FERMI: 2048**
- **GALILEO: 768**
- **MARCONI: 2152**

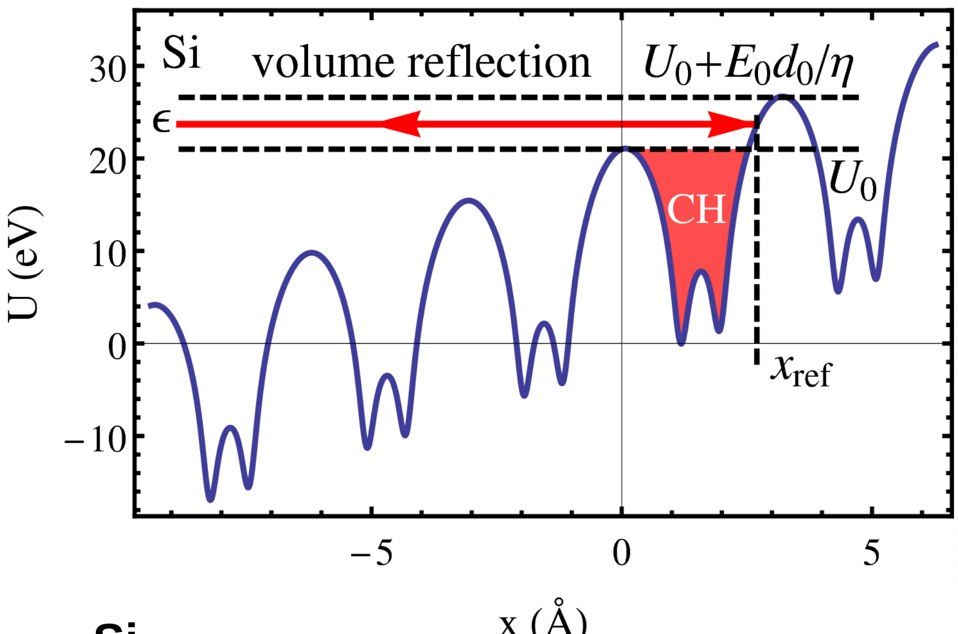
What have we been granted by?

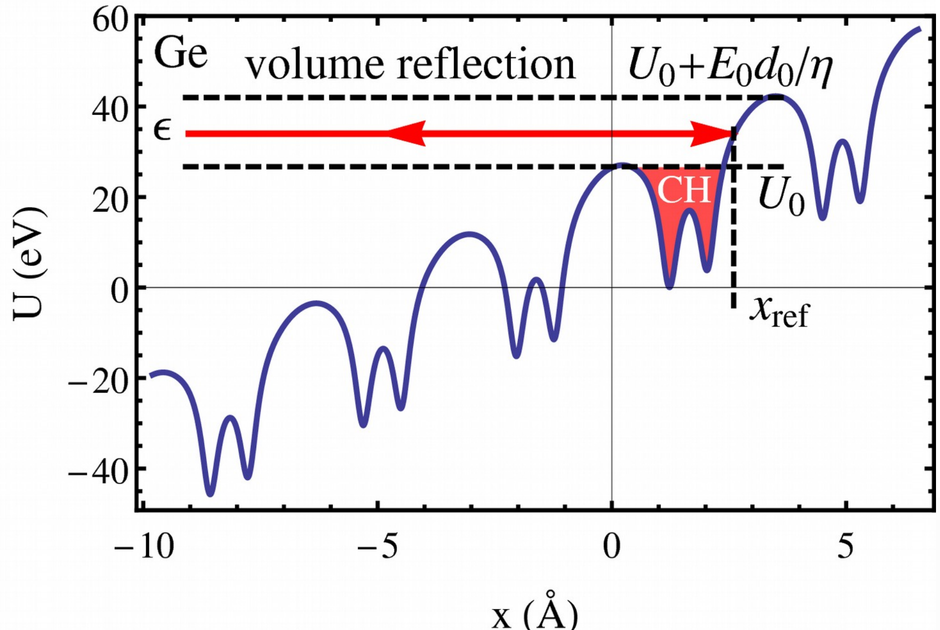
- **FERMI: 200 kh**
- **GALILEO: 100 kh**
- **MARCONI: 400 kh**

*A.I. Sytov, V.V. Tikhomirov. NIM B 355 (2015) 383–386.

Bent crystals: Si and Ge

Interplanar potentials for lowest curvature values





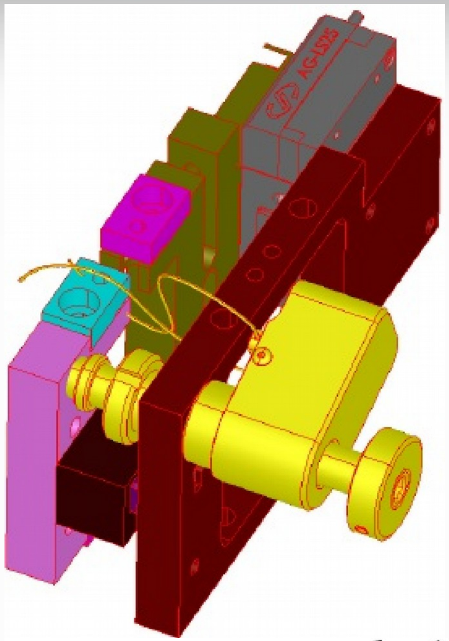
Si

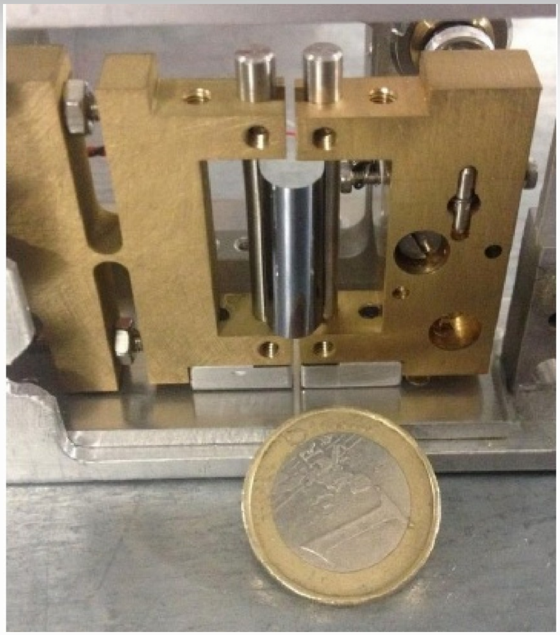
- Crystal length: **15 μm**
- Bending angles:
  - 315 μrad
  - 550 μrad
  - 750 μrad
  - 1080 μrad

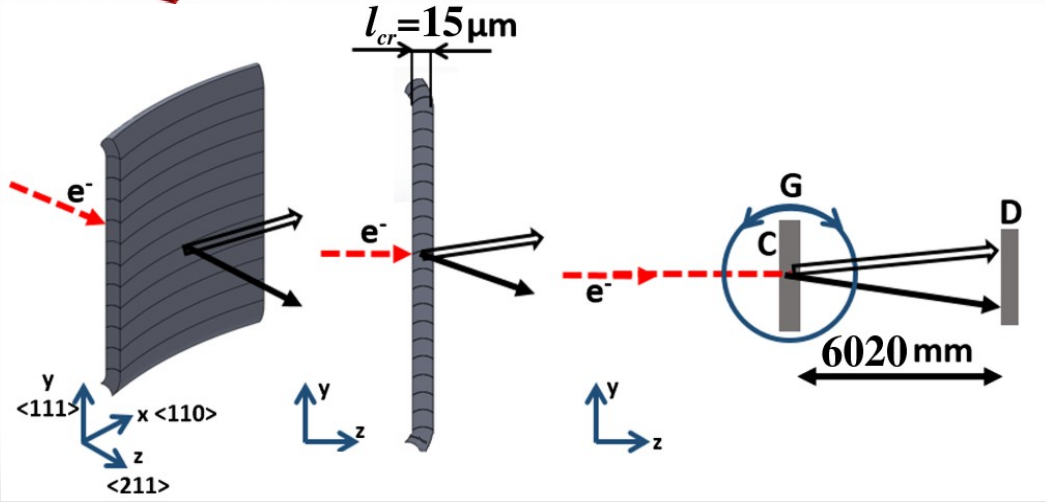
Ge

- Crystal length: **15 μm**
- Bending angles:
  - 820 μrad
  - 1200 μrad
  - 1430 μrad

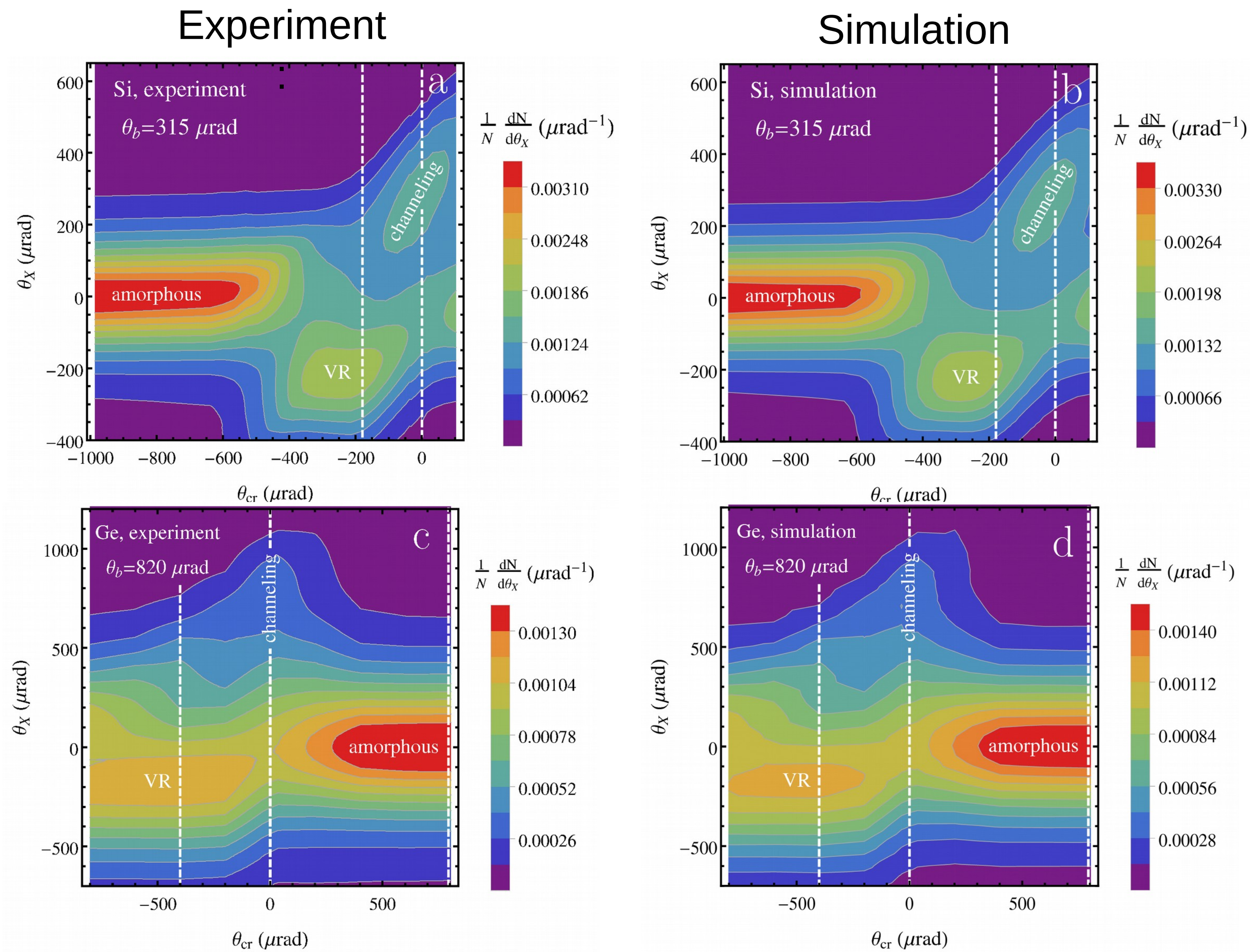
Dynamical holder: bending without breaking of vacuum





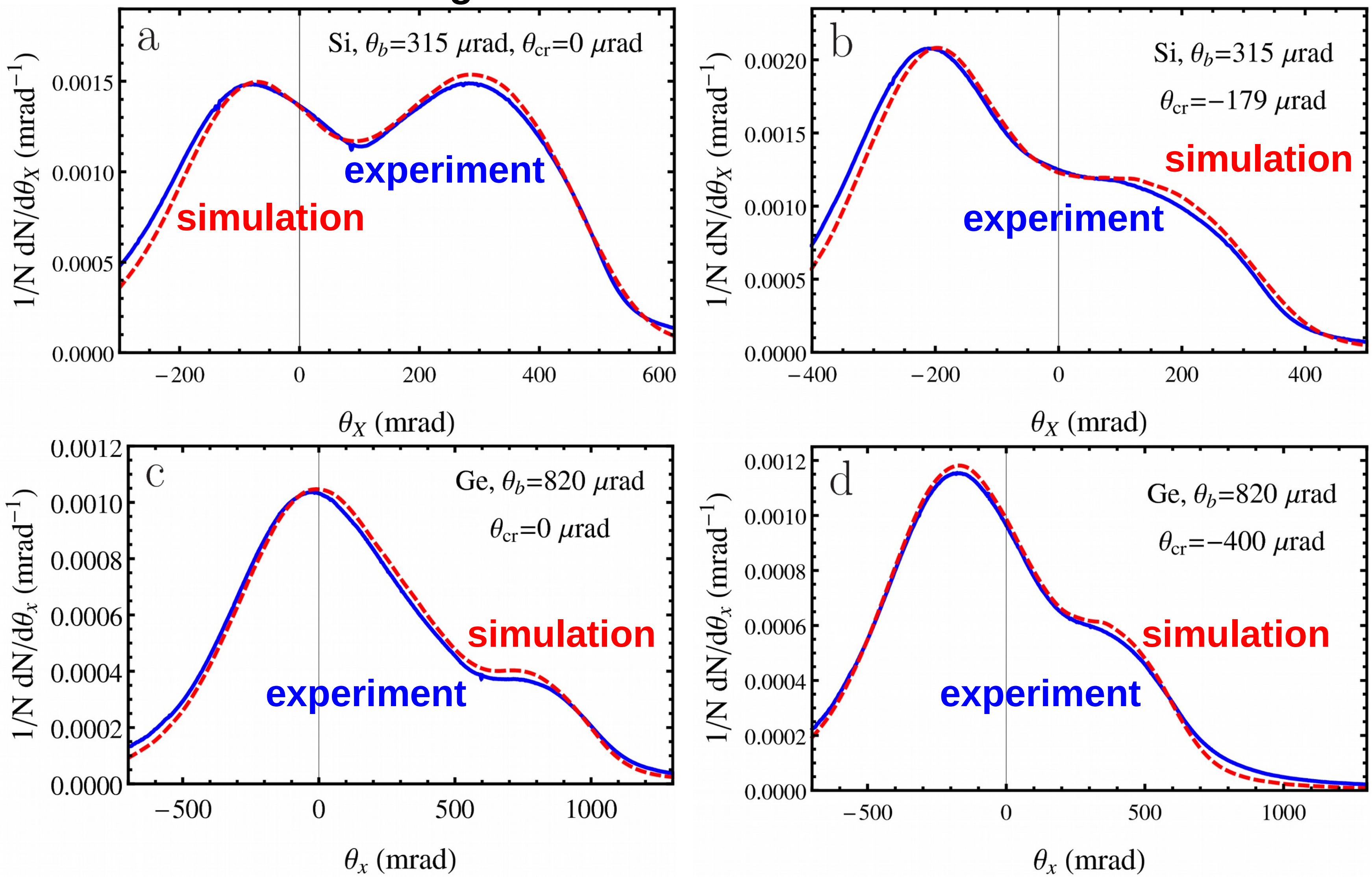


Angular scans for lowest curvatures

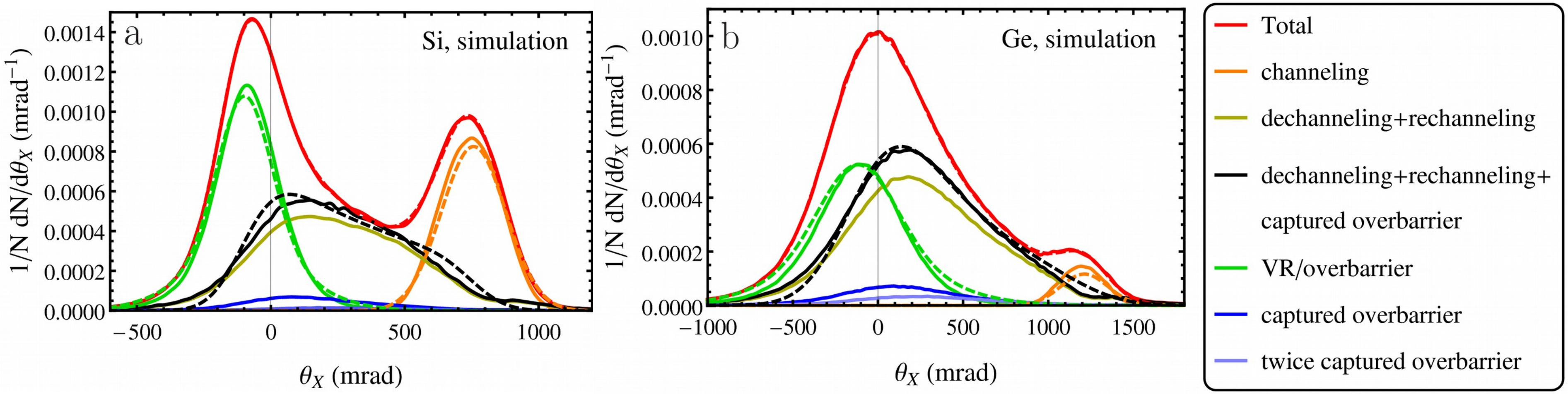


Beam distributions for lowest curvatures

channeling | **volume reflection**



Fitting model



$$\frac{1}{N}\frac{dN}{d\theta_X} = \frac{df_{ch}}{d\theta_X} + B_{VR}\frac{df_{VR}}{d\theta_X} + \frac{df_{dech}}{d\theta_X}$$

By using:
T.N. Wistisen et al. Phys. Rev. Acc. and Beams 19, 071001 (2016)

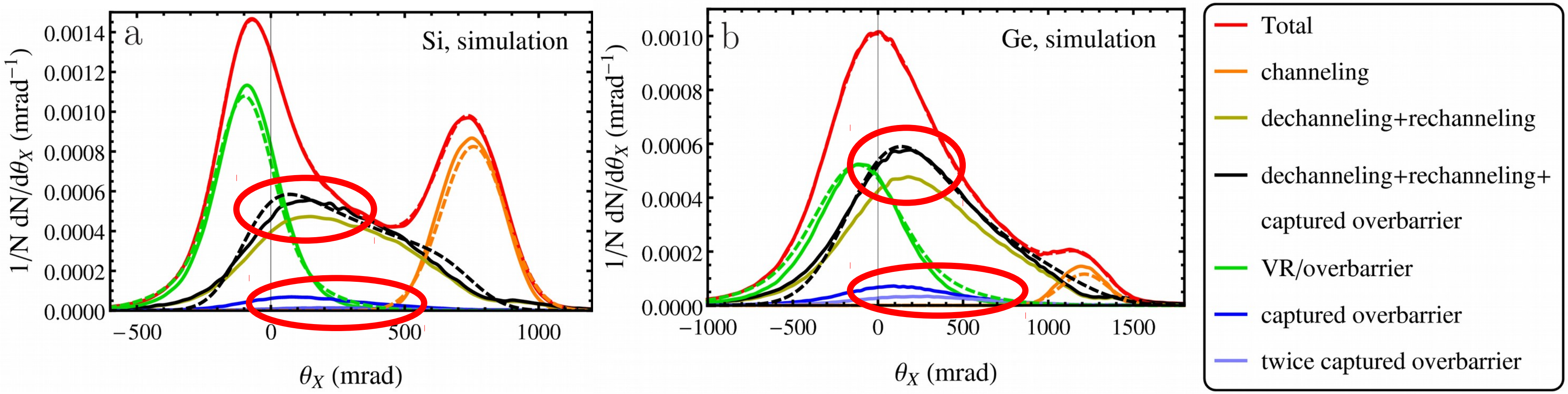
What's new?
The normalizing coefficients A_{ch}, A_{dech} and B_{VR} are treated independently
Why?

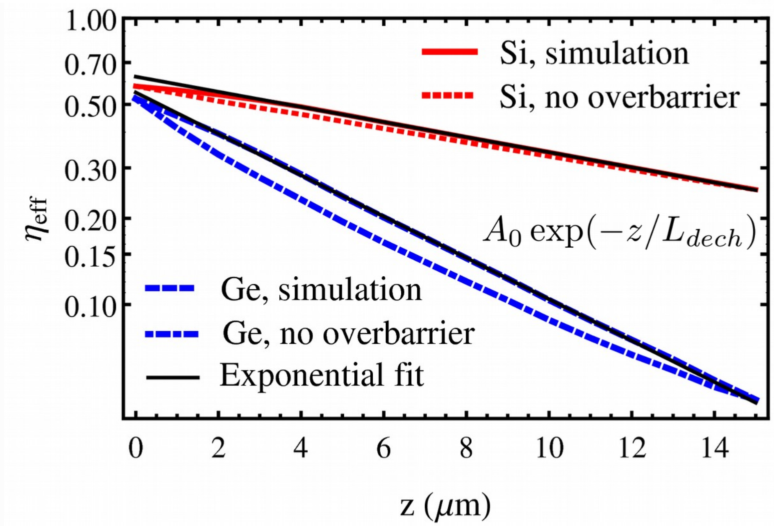
$$\frac{df_{ch}}{d\theta_X} = \frac{A_{ch}}{\sigma_{ch}\sqrt{2\pi}} \exp\left(-\frac{(\theta_X - \theta_{ch})^2}{2\sigma_{ch}^2}\right)$$

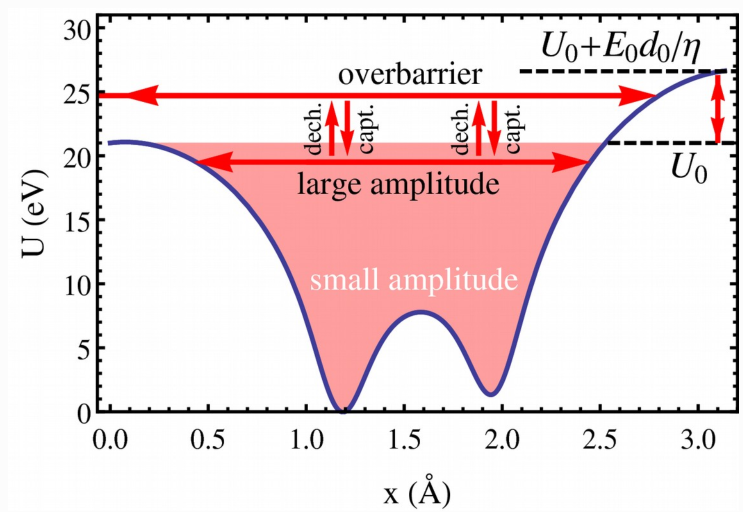
$$\frac{df_{dech}}{d\theta_X} = \frac{A_{dech}}{2\theta_{dech}} \exp\left(\frac{\sigma_{VR}^2}{2\theta_{dech}^2} + \frac{\theta_{ch} - \theta_X}{\theta_{dech}}\right)\left(\mathrm{erf}\left(\frac{\theta_{VR} - \theta_X + \frac{\sigma_{VR}^2}{\theta_{dech}}}{\sqrt{2}\sigma_{VR}}\right) - \mathrm{erf}\left(\frac{\theta_{ch} - \theta_X + \frac{\sigma_{VR}^2}{\theta_{dech}}}{\sqrt{2}\sigma_{VR}}\right)\right)$$

$$\frac{df_{VR}}{d\theta_X} = \frac{A_{VR}}{\sigma_{VR}\sqrt{2\pi}} \exp\left(-\frac{(\theta_X - \theta_{VR})^2}{2\sigma_{VR}^2}\right) + \frac{1 - A_{VR}}{r\sigma_{VR}\sqrt{2\pi}} \exp\left(-\frac{(\theta_X - \theta_{VR})^2}{2r^2\sigma_{VR}^2}\right)$$

Fitting model: overbarrier particles contribution

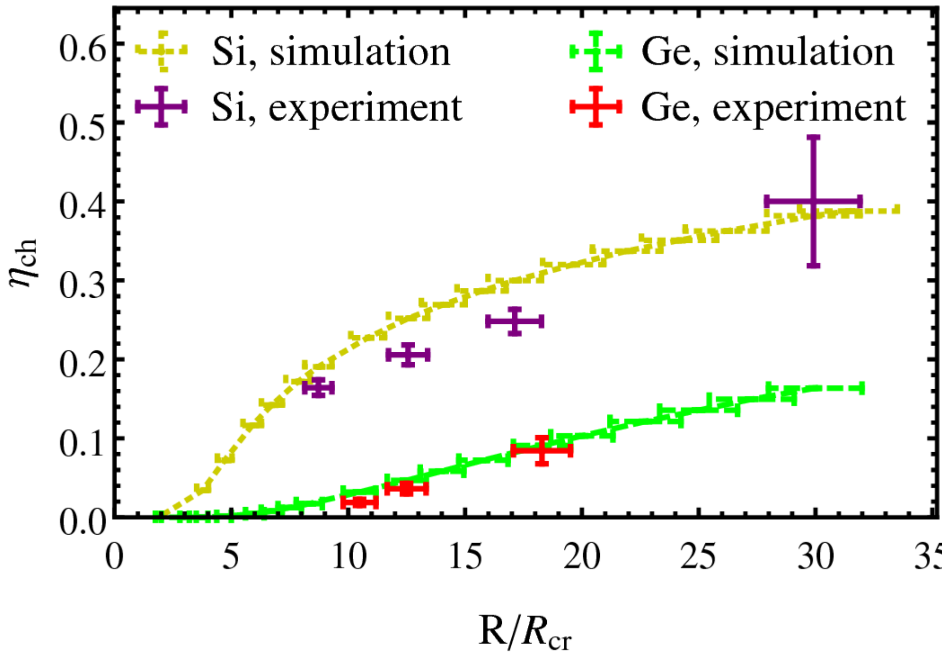


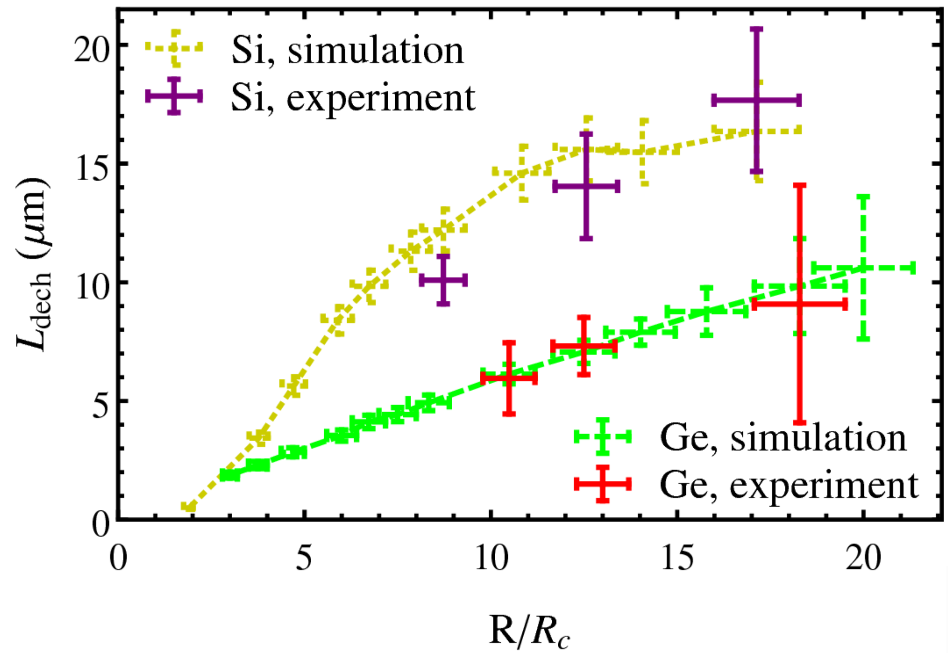




Initially **overbarrier** particles cause a **reduction** of the **dechanneling length**, if it is comparable with the crystal thickness. Therefore, it **influences** on the **angular distribution shape**, reducing correlation between normalizing coefficients.

Channeling efficiency and dechanneling length



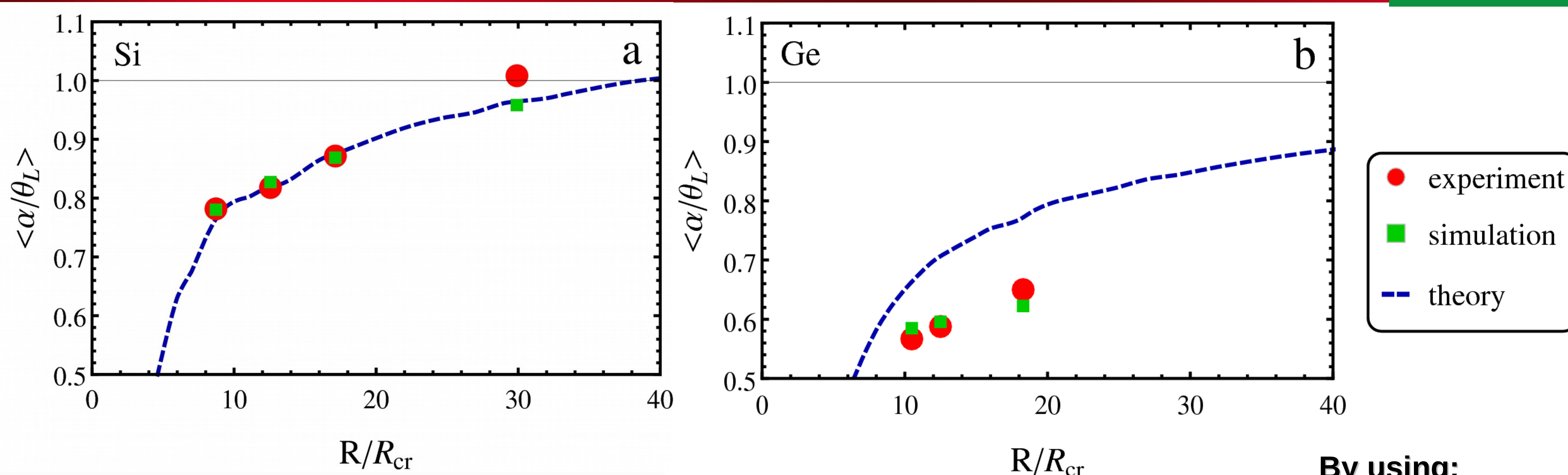


Material	θ_b (μrad)	$\frac{R}{R_{cr}}$	θ_{VR}^{Exp} (μrad)	η_{ch}^{Exp}	θ_{VR}^{Sim} (μrad)	η_{ch}^{Sim}	$L_{dech\ Exp}$	$L_{dech\ Sim}$	$L_{dech\ DSim}$	$L'_{dech\ DSim}$
Si	315	29.9	224	0.40 ± 0.08	235	0.3818 ± 0.0004				
Si	550	17.1	204	0.248 ± 0.016	203	0.3000 ± 0.0004	17.7 ± 3.0	16.4 ± 2.1	18.96 ± 0.05	21.14 ± 0.10
Si	750	12.6	194	0.206 ± 0.013	190	0.2519 ± 0.0003	14.0 ± 2.2	15.6 ± 1.4	16.48 ± 0.05	18.05 ± 0.07
Si	1080	8.72	183	0.165 ± 0.010	182	0.1907 ± 0.0003	10.1 ± 1.0	12.2 ± 0.9	13.62 ± 0.05	14.73 ± 0.06
Ge	820	18.3	172	0.084 ± 0.017	178	0.0909 ± 0.0002	9 ± 5	10 ± 2	7.97 ± 0.07	8.95 ± 0.26
Ge	1200	12.5	165	0.036 ± 0.007	161	0.0468 ± 0.0002	7.3 ± 1.2	7.1 ± 0.5	6.02 ± 0.03	6.46 ± 0.11
Ge	1430	10.4	162	0.019 ± 0.004	156	0.0320 ± 0.0002	5.9 ± 1.5	6.1 ± 0.4	5.29 ± 0.03	5.58 ± 0.09

New **record** of **channeling efficiency** for negative particles **> 35%**

channeling in a **Ge bent crystal:** never done before for **sub-GeV electrons**

Volume reflection



By using:
V.A. Maisheev, Phys. Rev. STAB 10, 084701 (2007)
S. Bellucci and V.A. Maisheev, Phys. Rev. STAB 18, 114701 (2015)

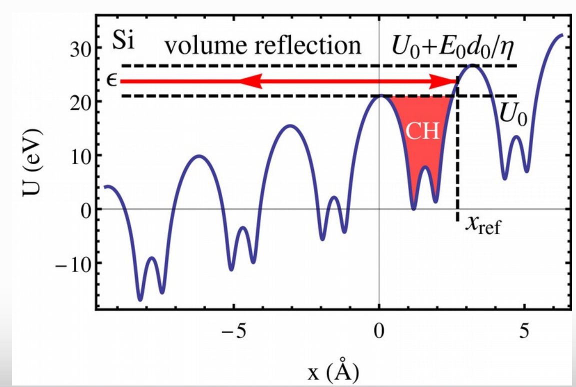
$$\frac{\alpha}{\theta_L} = \frac{E_0}{\eta\sqrt{U_0}} \int_{x_0}^{x_c(\epsilon)} \left[\frac{1}{\sqrt{\epsilon - U(x) - \frac{E_0}{\eta}x}} - \frac{1}{\sqrt{\epsilon - U(x_c(\epsilon)) - \frac{E_0}{\eta}x}} \right] dx$$

$$< \frac{\alpha}{\theta_L} > = \frac{\eta}{E_0 d_0} \int_{U_0}^{U_0 + \frac{E_0}{\eta} d_0} \frac{\alpha}{\theta_L} d\epsilon$$

where: $\theta_L = \sqrt{\frac{2U_0}{pv}}$

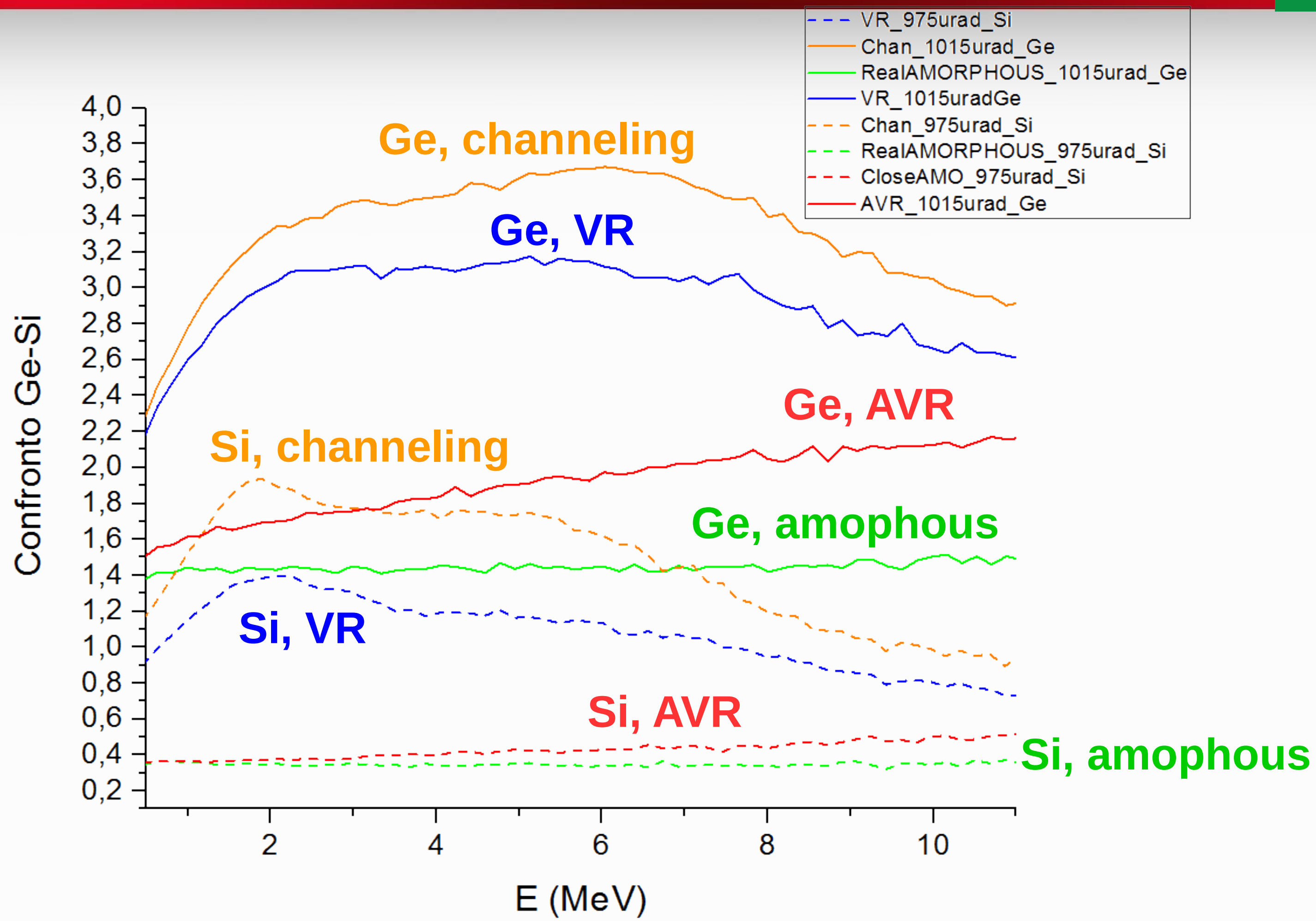
$$R_{cr} = \frac{pv}{E_0} \qquad \eta = R/R_{cr}$$

E_0 – maximal strength of the interplanar field



$< \frac{\alpha}{\theta_L} >$ doesn't depend on the energy

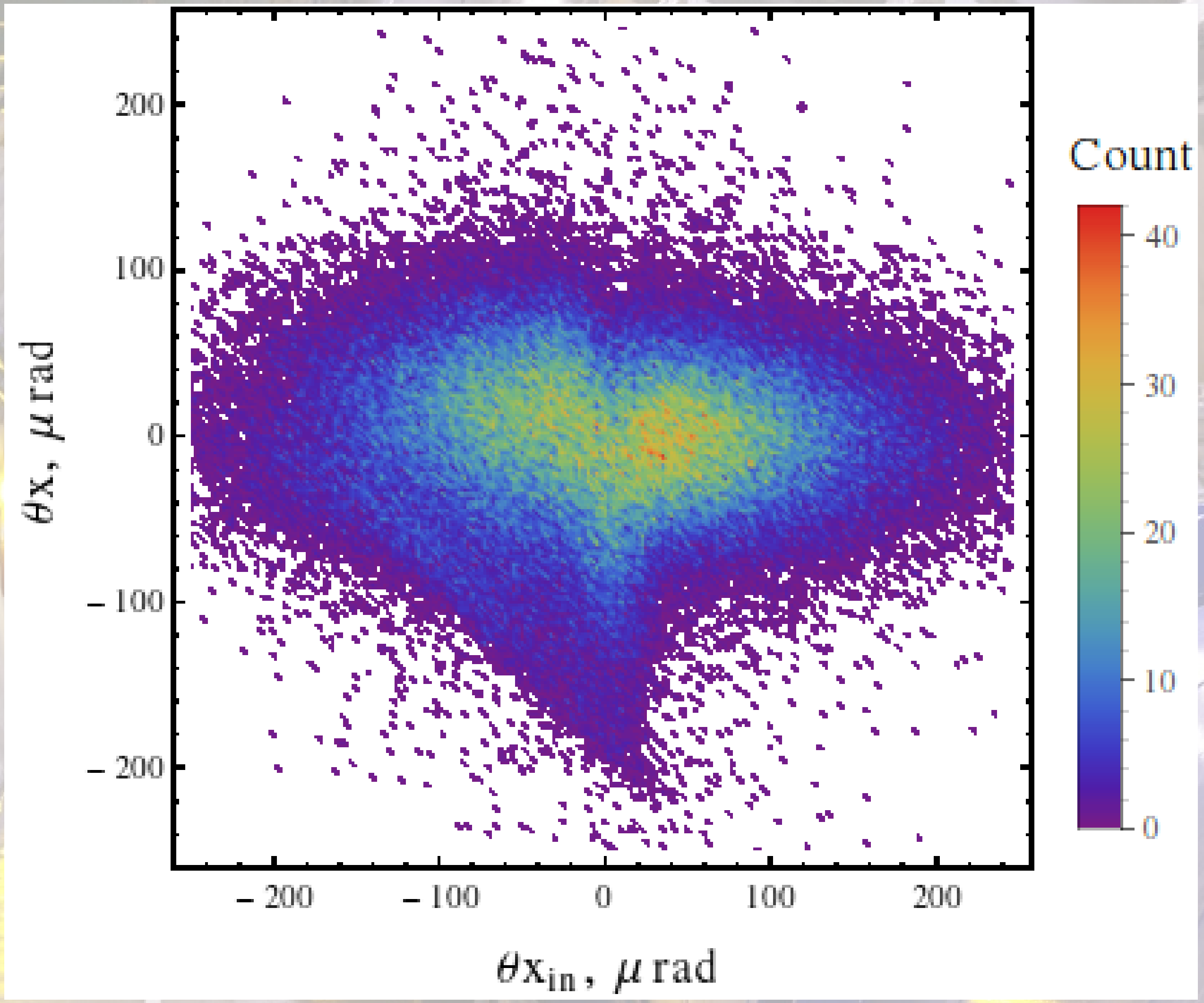
Planar channeling and volume reflection radiation vs Z in a bent crystal, preliminary results



If we compare the radiation emitted by the silicon crystal with that emitted by the **germanium crystal** the **increase in the radiation production rate is very evident and the channeling peak occurs at higher energy** for germanium.

Conclusions

- An **experiment** on beam steering of **855 MeV electrons** by using **15 µm** bent **Si** and **Ge** crystals has been carried out at the **Mainzer Mikrotron**.
- Through the exploitation of an **innovative piezo-actuated dynamical holder**, both **channeling efficiency** and **dechanneling length** have been measured for **several radii** of **curvature** of the **same crystal**.
- An **unprecedented** level of steering **efficiency** of about **40%** in a Si crystal for an **electron** beam has been achieved.
- The **evidence** of beam **steering** of **sub-GeV electrons** in a **Ge crystal** has been demonstrated for the **first** time.
- The influence of **initially non-channeled particles** on the **dechanneling** processes has been highlighted.
- The dependence of the **ratio** between the **VR** angle and the **Lindhard angle** vs the $\mathbf{R/R_c}$ has been investigated, demonstrating that it does **not depend** on the **energy**, being useful to make predictions at different energies.
- A study of **generation** of **radiation** at **different curvature** values for both **silicon** and **germanium crystals** has been carried out.



Thank you for attention!