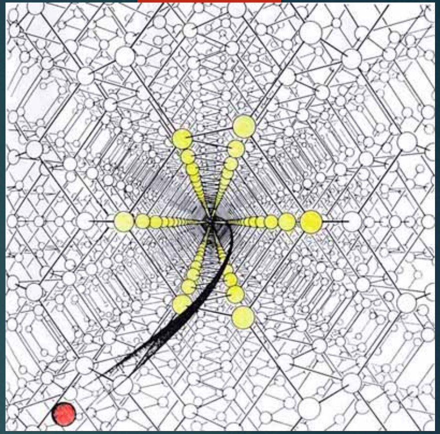
Channeling 2016, 25 / 9 / 2016, Sirmione, Italy



The chaotic discovery of ion channeling and channeling radiation

Joseph REMILLIEUX

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University of LYON, France

1912, Johannes STARK

104 years ago: the first prediction of angular effects in the penetration of particles in crystal targets

by the future Nobel Prize, Johannes **Stark**, at Aachen in Germany.

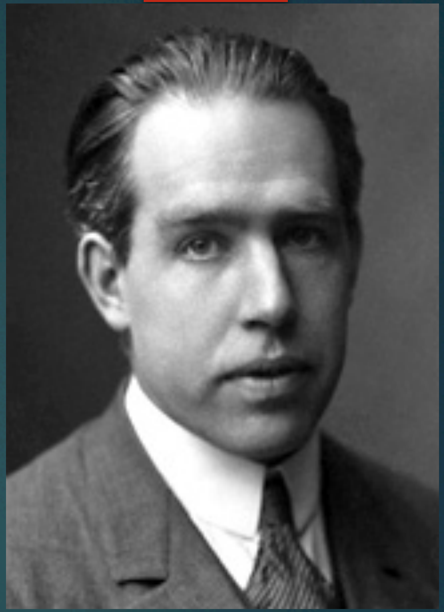
→ but for 50 years … nobody paid attention to this prophetic message !

(1874 – 1957)

1948, Niels BOHR

Everything needed by nuclear physicists
about ion-solid interactions,
was in the paper published by N. Bohr in 1948 at Copenhagen :

- energy loss rate
- multiple scattering
- charge exchanges
- free electron wake, …

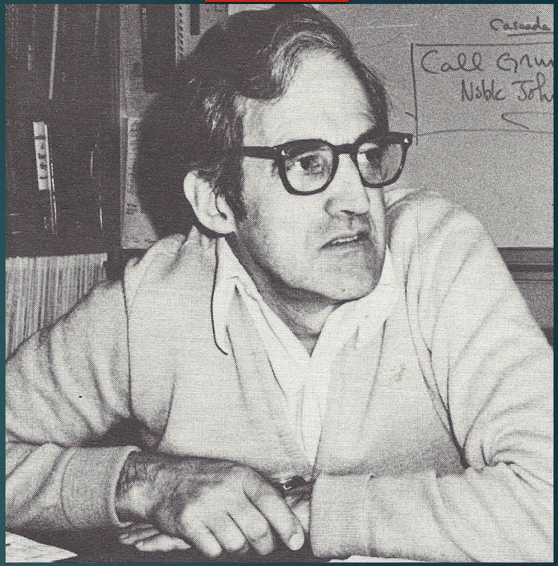


(1885 _ 1962)

→ but only in amorphous solids !
hopefully, Niels Bohr had, in that field, very good collaborators
Jens Lindhard, Werner Brandt, ...

ION CHANNELING

1960, John DAVIES and coworkers at Chalk River, in Canada



(✝ 2016)

They measured range distributions of ions
in a variety of polycrystalline metals
They observed very long tails
and suspected the role played
by aligned crystallites in the target

→ that was the first observation of directional effects

1962, a (slow) computer discovery !

At Oak Ridge, *M.T. Robinson* and *O.S. Oen* simulated ion ranges in fictive targets made of atoms arranged, for simplicity, … like a cubic lattice

IBM 7090

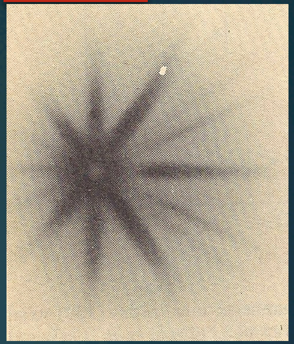
Unexpectedly, for some incident trajectories, the computing time exploded !

They made a correlation between these long computed ranges and the long tails measured earlier by *Davies et al.*

They call this anomalous penetration : particle "channeling"

→ ion channeling is definitively demonstrated

1963, transmission effects through thin crystals



Star pattern

Context: Si diodes are more and more used by nuclear physicists:

thick detectors, calorimeters, for total energy measurements (E),

and doublets (thick (E) + thin (ΔE)) detectors,

for ion masses (M) determination, since the product (E. ΔE) ∝ M

At Harwell (GB), *G.Dearnaley et al.*, observed orientational effects

in the amplitude of the ΔE signals delivered by thin Si crystals

That was the subject of my first thesis (1966) in Lyon:

a study of the reduced energy loss rate of channeled protons in crystals

→ the first channeling experiments in transmission through thin crystals

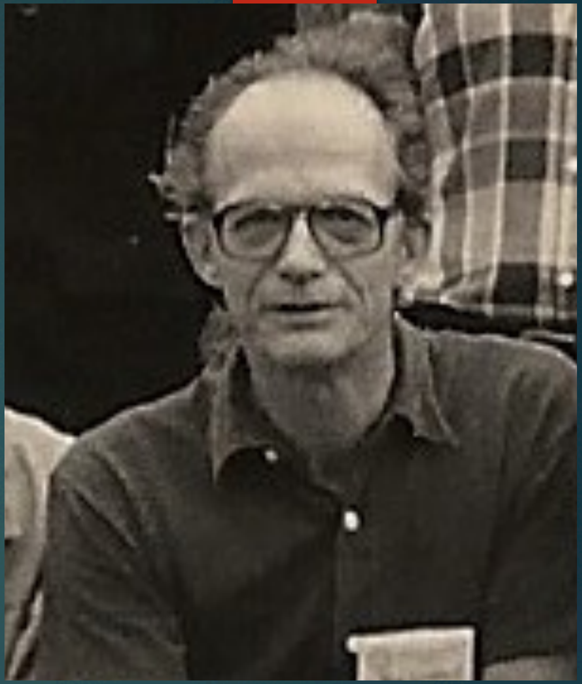
1965, Jens LINDHARD gives an extenstive theory of channeling

At Aarhus, the team of *Jens Lindhard (J.U.Andersen, E.Bøgh, E.Uggerhøj, …)* extends the work of *Niels Bohr* (1948) to channeling conditions.

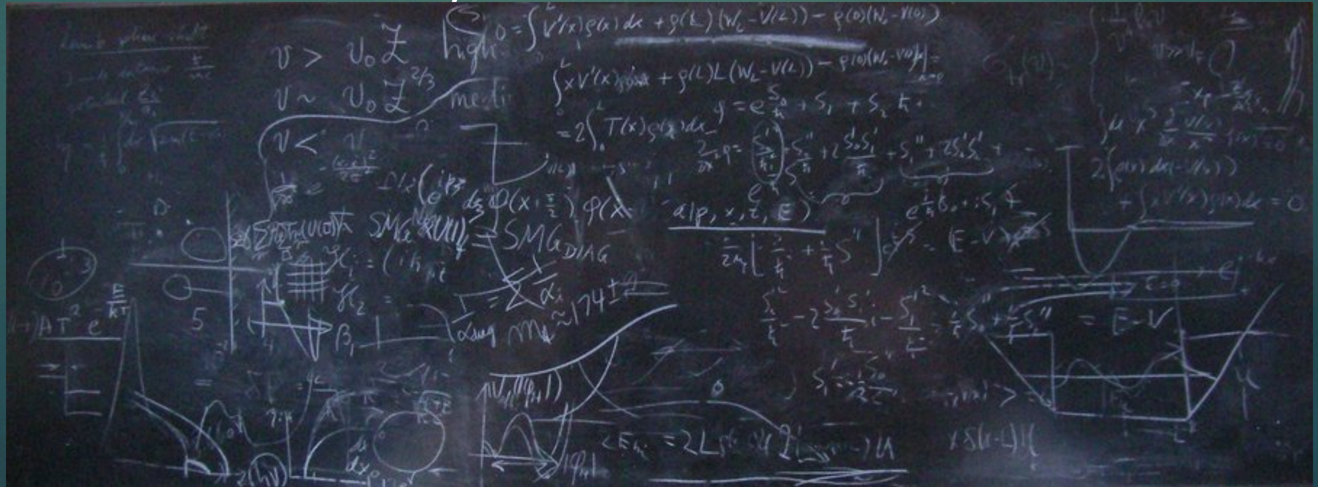
The 1965 *Lindhard* ‘s paper in *K. Dan. Vidensk. Selsk. Mat.-Fys. Med.* becomes “the bible” for all workers in the field.

With this theoretical basis, the number of experiments and simulations increases rapidly around the world.

In meetings and conferences *Jens Lindhard* is the theoretical reference but it was sometimes … not so easy to follow him !



(1922 – 1997)



1967-1973, channeling at Lyon

(*J.-C. Poizat, R. Kirsch, J.R. et al.*)

We developed new tools for transmission channeling studies

- the elaboration of ultra-thin self-supporting gold crystals
- the use of incident molecular ion beams

→ It opened for us long range collaborations and discussions, particularly with

- *W.Brandt, R.Ritchie* (New York and Oak Ridge Nat. Lab.)
- *D.S. Gemmell, R.E. Holland* (Argonne Nat. Lab.)
- *W.Gibson,* (Bell Laboratories)
- *S. Datz* (Oak Ridge)
- *A.F. Tulinov, V.V. Okorokov* (Moscow)

Werner BRANDT (N.Y. Univ) and Rufus RITCHIE (Oak Ridge)

R Ritchie

In the frame work of the *Bohr* electron-wake they developed a new way of calculation, in channeling alignment, of the interaction of ion beams and molecular-ion beams

→ energy loss rates
charge exchanges cross sections
coulomb explosion (molecular ions)
and wake-effects on the fragments

(1925 – 1983)

D.S. GEMMELL (Argonne Nat. Lab.)

Shadow effects

named “Blocking” by *R.Holland*

Charge changing effects in channeling

with ($\pi+/\pi-$) pion beams

Molecular-ion channeling

Coulomb-explosion of fragments

wake-effects on the fragments trajectories

→ A complete review paper on channeling

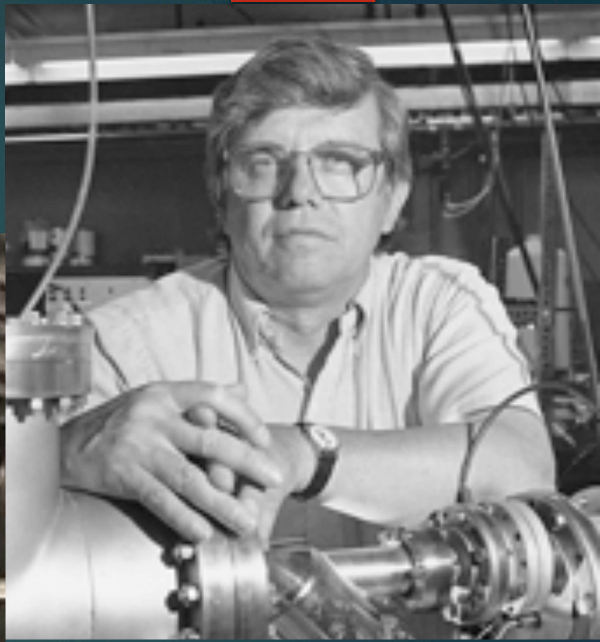
Rev. of Modern Physics (1974)

(1934 – 2013)

Walter GIBSON (Bell Lab.)

At Bell Lab. *W. Gibson* worked on applications of channeling to solid-state physics and material analysis (with *L. Feldman*, speaker at *Channeling 2014*)

- ion implantation
- lattice positions of impurities
- surfaces and interfaces characterizations



(1930 – 2009)

Then at Albany, *W.Gibson* worked with *Nelson Cue*

Later on *N. Cue* collaborated for many years with us, mainly on

- heavy ions channeling
- electron channeling

→ *N. Cue* wrote with *J.C.Kimball* a review paper on *QED and channeling (Phys. Report* 1985)

Sheldon DATZ, Oak Ridge Nat. Lab.

With his close collaborators

C. Moak, T. Noggle, C. Erginsoy B. Appleton, …

S. Datz was the first to explore

- heavy ions channeling
- hyper-channeling
- frozen charge states
- coherent excitation of ions
  - as first predicted in 1965 by *V. Okorokov*

(1927 – 2001)

LIGHT PARTICLE CHANNELING

Before Muradin Kumakhov

(1941 – 2014)

Electron and positron channeling at MeV incident energies:

1969 -1972, a balance between diffraction and classical channeling, the axial rosette-motion of electrons *(F. Fujimoto et al.)*

1966-1970, a test of charge changing channeling properties (e^+ / e^-) with β^+ and β^- emitters crystals (*E. Uggerhøj et al.)*

Pion channeling

1976, a measure of the reversibility (π^+ / π^-) in the channeling of (70-225 MeV) pions *D.S. Gemmell et al. (at Los Alamos)*

At higher electron energies, prediction of the channeling radiation by *Muradin Kumakhov* (1976)

1980, electron channeling radiation at medium energies (MeV - GeV)

Channelled electrons oscillate in the transverse-energy space

1D oscillators for planar channeling, 2D oscillators for axial channeling

Transitions happen between the quantum transverse-energy states

with a relativistic amplification of the radiated energy, by a factor $(2\gamma^2)$ => 20 000 at 50 MeV

→ Channeling radiation spectra with lines: a tuneable photon source

Major experimental programmes at medium energies:

1 MeV electrons (*J.U. Andersen et al.*) at Aarhus

16 - 56 MeV electrons (*R.Swent, et al*) at Stanford

54 - 110 MeV electrons (*M. Gouanère et al.*) at Saclay

Channeling radiation
at ultra-relativistic energies

At ultra-relativistic energies

no more lines in the radiation spectrum

(since there is a too large number of transverse energy states)

a radiation spectrum which looks like synchrotron radiation

(since electrons are bent in the macroscopic transverse electric field)

When "super-critical fields" are reached

channelled electrons radiate the larger part of their incident energy

(the non-linear QED theory of super-critical fields is involved)

→ programmes at CERN at ultra-relativistic energies (40-150 GeV)

E.Uggerhøj et al and *A.Belcacem et al*

Two major meeting points at the beginning of ion channeling

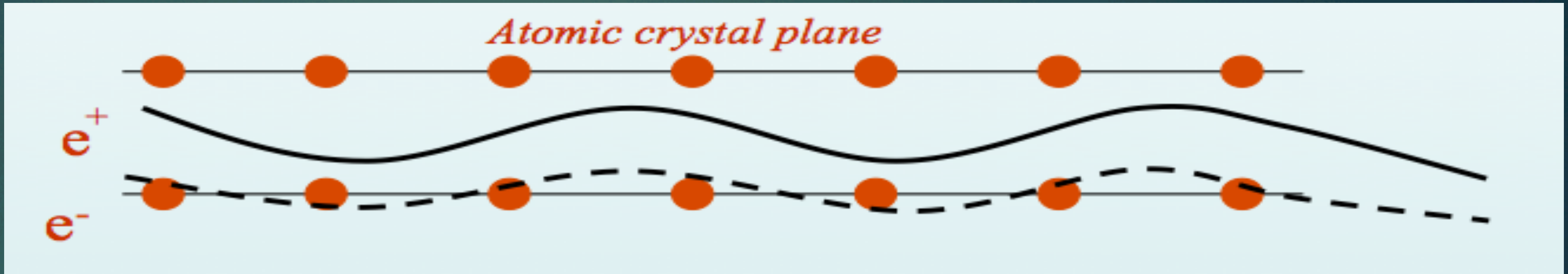
The series of International Conferences
on *Atomic Collisions in Solids*
- Brighton 1969, Gausdal 1971, Gatlinburg 1973,
- Amsterdam 1975, Moscow 1977, Lyon 1981, Okayama 1987, …

The series of *Gordon Conferences*
on *Ion-Solid Interactions*
- New Hampshire

→ Today, ***Channeling 2016***

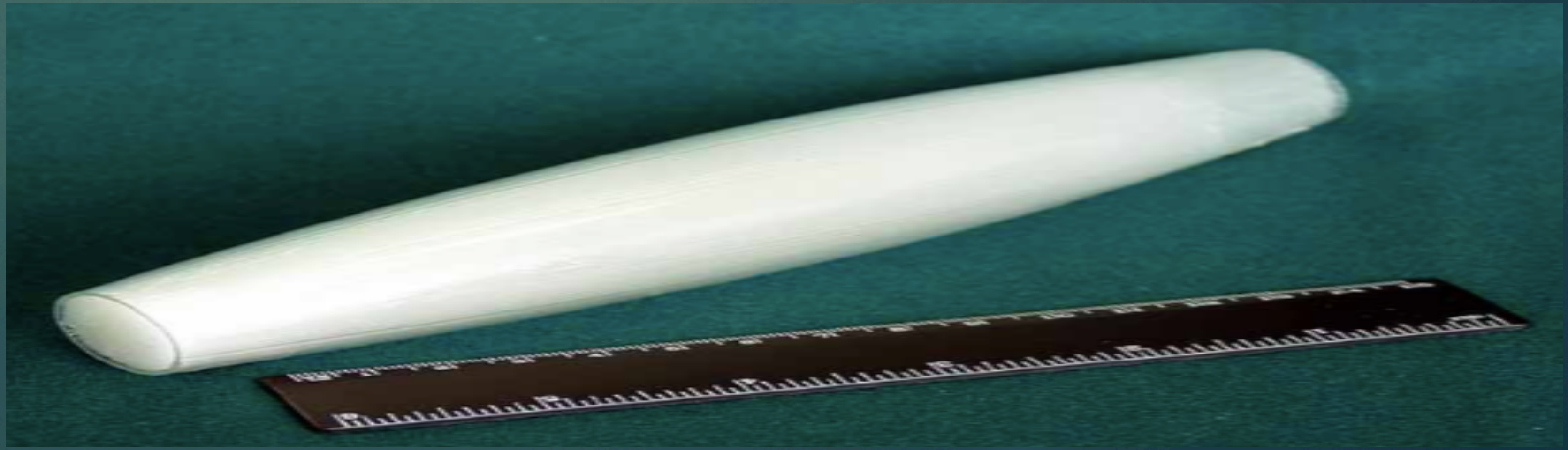
- pioneering works on channeling radiation:
  - ”Kumakhov effect”, “Kumakhov radiation”;

1974-1976



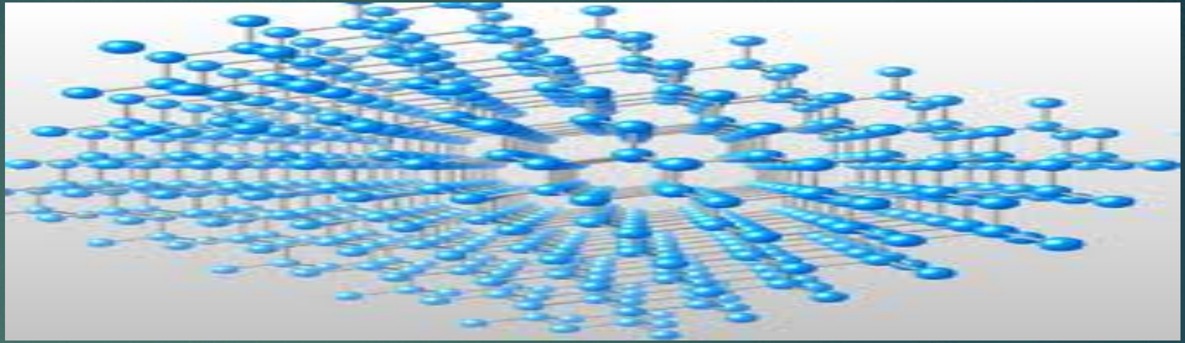
- pionnering works on polycapillary X-ray optics:
  - ‘Kumakhov lens”

1984-1986



@ Channeling: from Crystal to Capillary guides

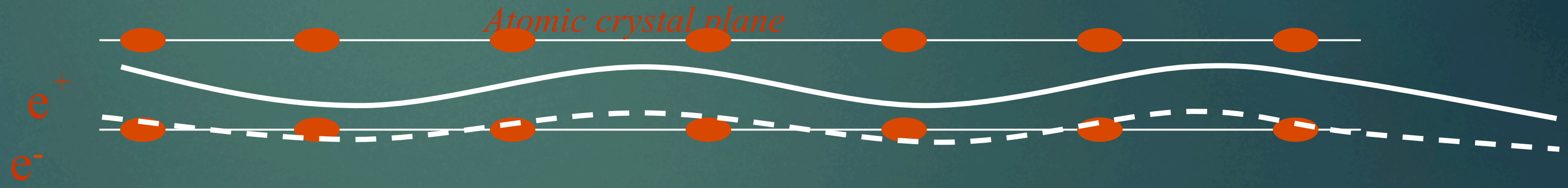
- Crystal Channeling
  - beam shaping
  - micro-undulator



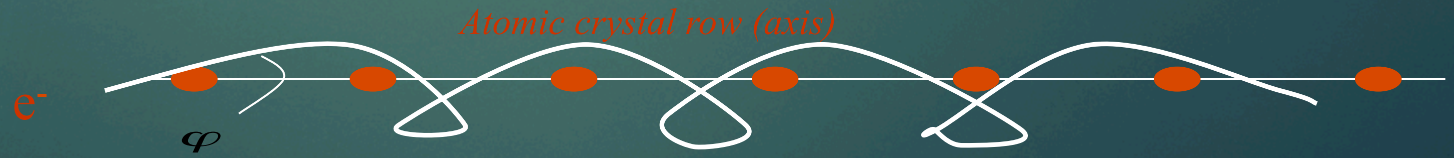
@ Amorphous:

@ Channeling:

planar channeling



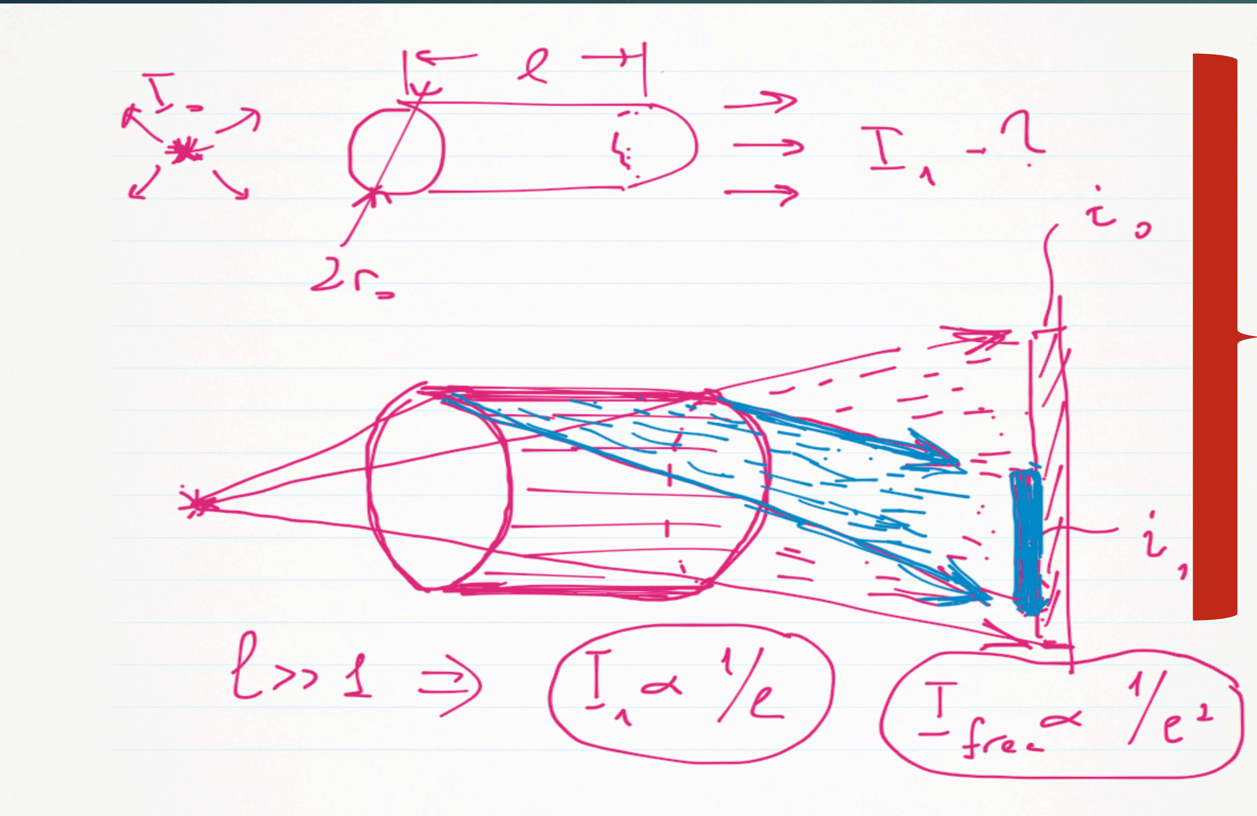
axial channeling



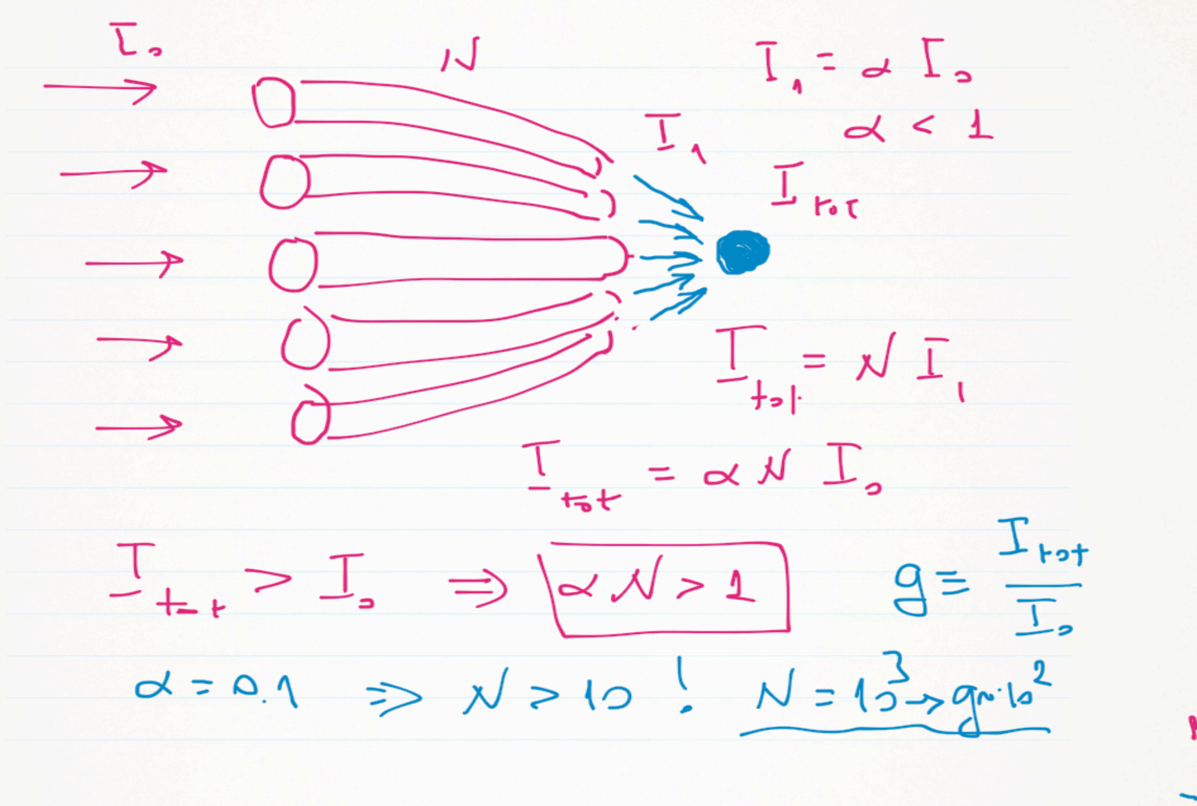
$$\varphi << 1 \qquad (\varphi < \varphi_L \sim \sqrt{U/E})$$

- the Lindhard angle is the critical angle for the channeling

@ 1984: first discussion on polyCO at the Minsk's School on charged particles interaction in crystals



Kumakhov's task:
a night work for the feasibility of mono/multichannel optics



@ polycapillary optics

Basic idea of polycapillary optics is very close to the phenomenon of charged particle channeling

@ deflection by large angles

@ divergent -> convergent

@ divergent -> quasiparallel e vs

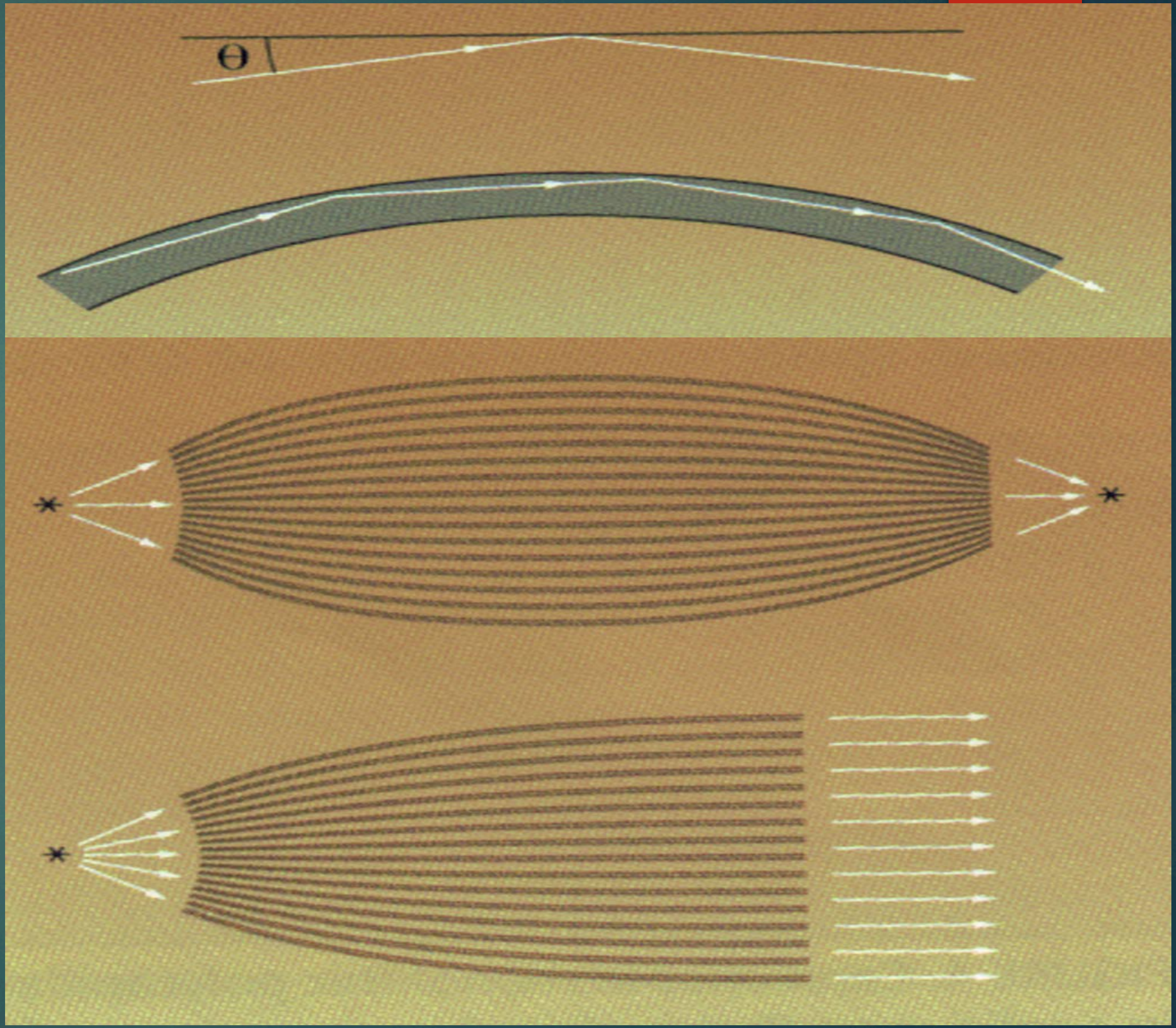
Number of applications

@ scientific instrumentation (XRF, XRD)

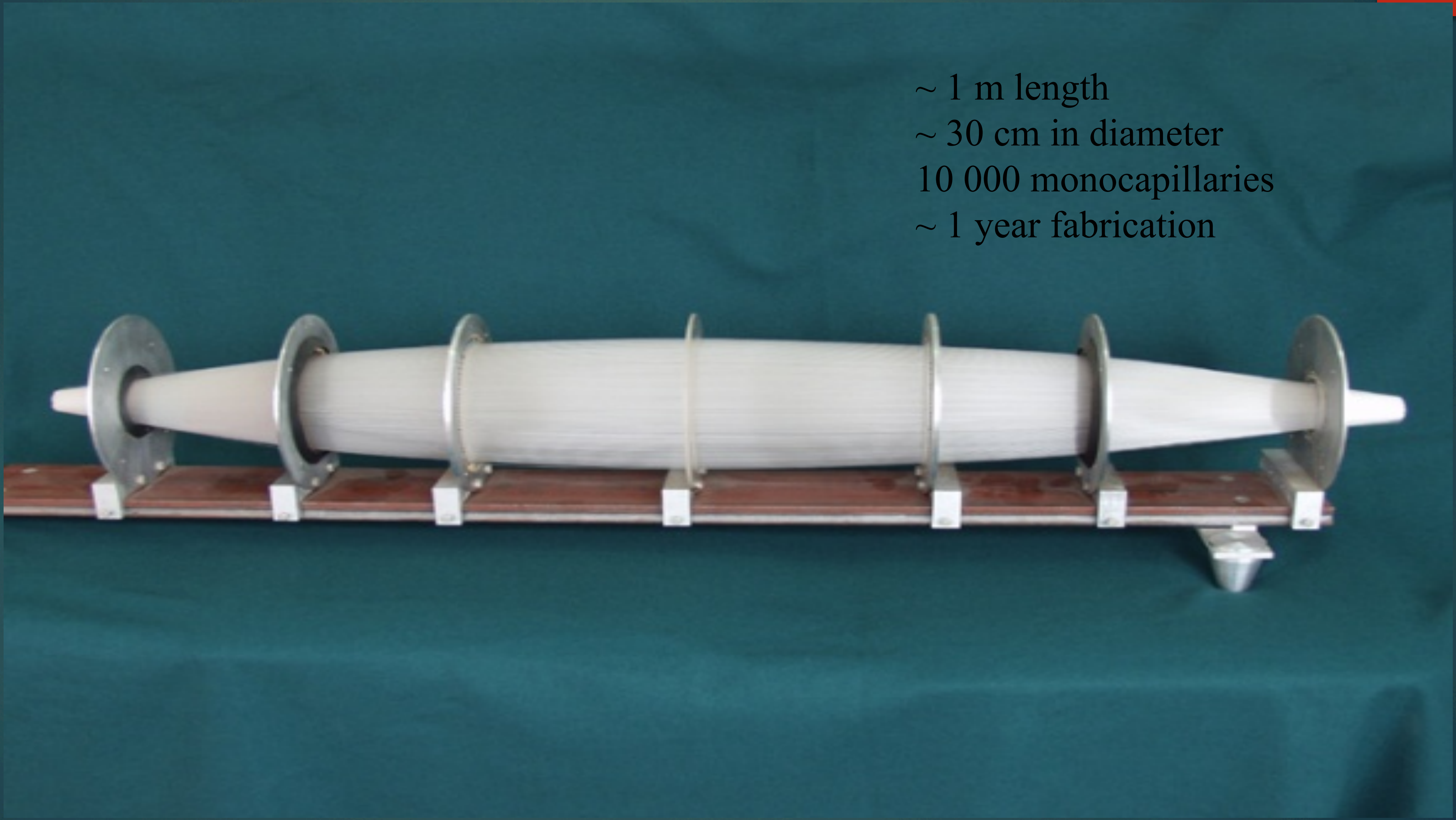
@ fluorescence & diffraction

@ medicine (diagnostics & therapy)

@ astrophysics

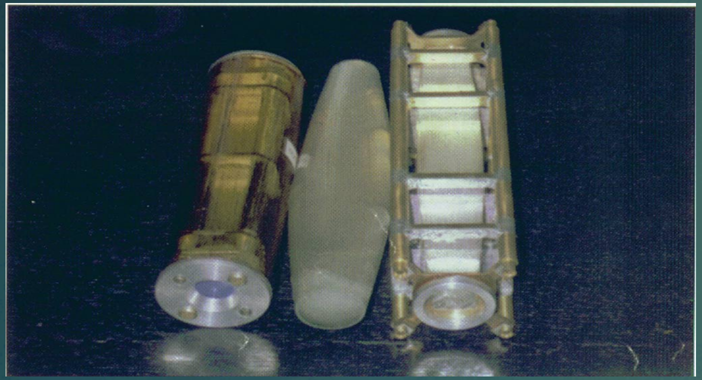


@ 1986: first polyCO => monocapillary semifabricated lens

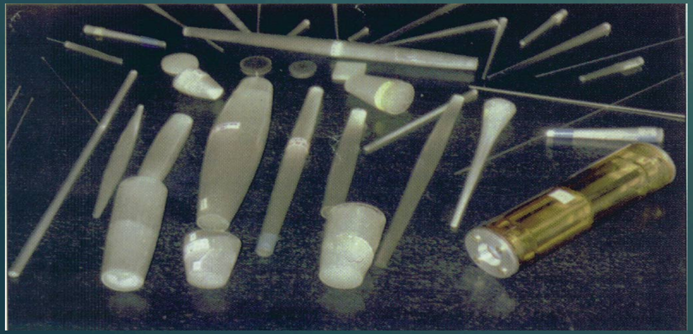


@ polyCO Evolution: "from micro- down to nano"

Generation	Kind of optics	Sizes: length & channel & energy
1^{st}		*1 m & 1 mm & ≤ 10 keV*
2^{nd}		*10-30 cm & 0.1-1 mm & ≤ 10 keV*
3^{rd}		*10 cm & 10-50 mm & ≤ 20 keV*
4^{th}		*4-10 cm & 1-10 mm & ≤ 50 keV*
5^{th}		*1-3 cm & 0.3-1 mm & ≤ 100 keV*

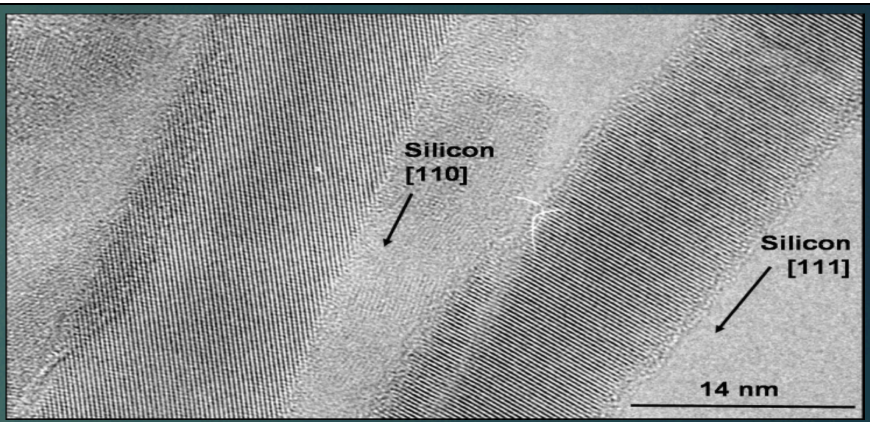


Micro-capillaries

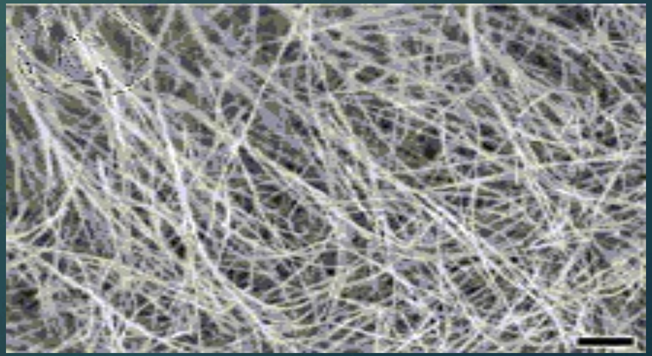


Micro X-rays

Nano g-rays (?)

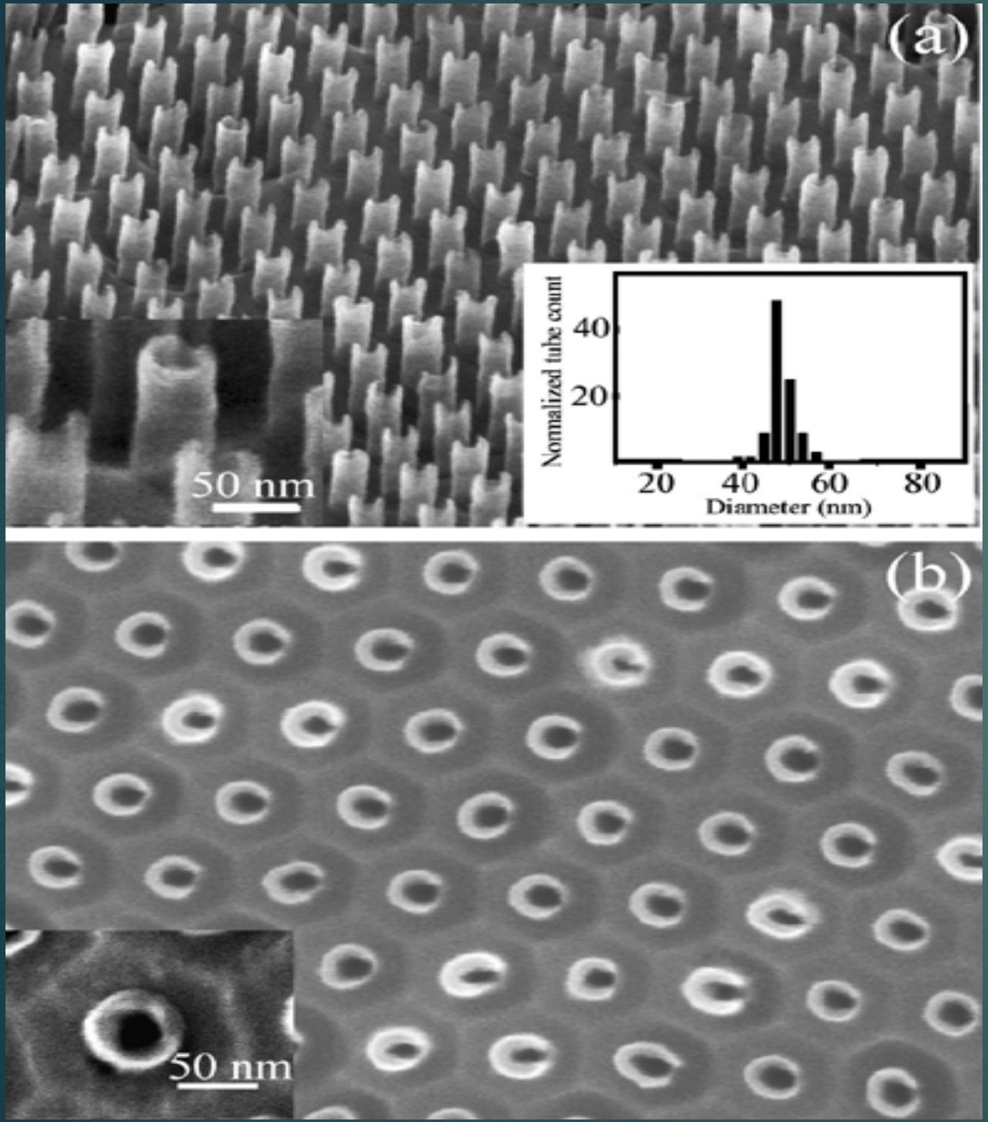


Nanotubes & Nanochannels



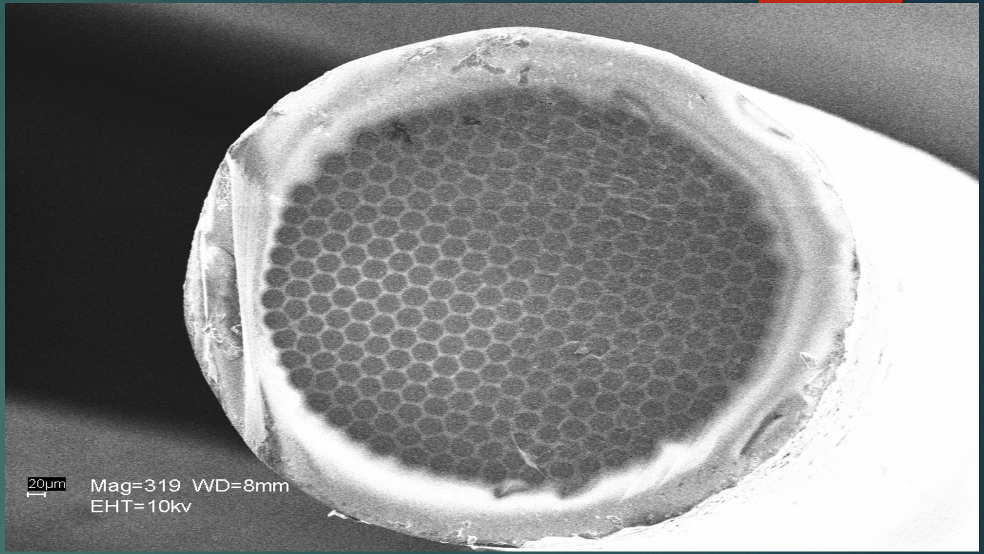
@ Samples of Nanostructures: various openness

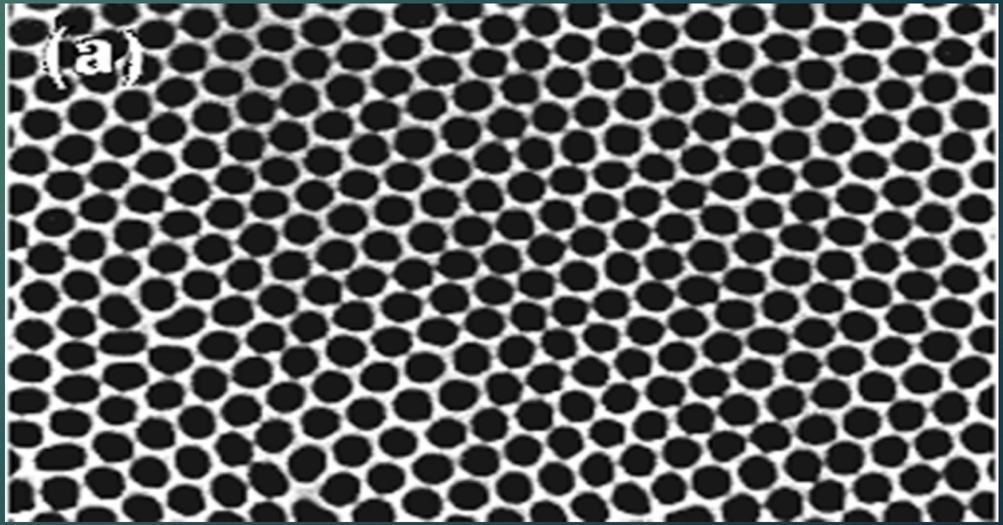
growing



laser burned

polycapillary technology





All-Union conferences on Interaction of Relativistic Particles in Crystals

Elbrus Valley, 1983

All-Union conferences on Interaction of Relativistic Particles in Crystals

Elbrus Valley, 1990

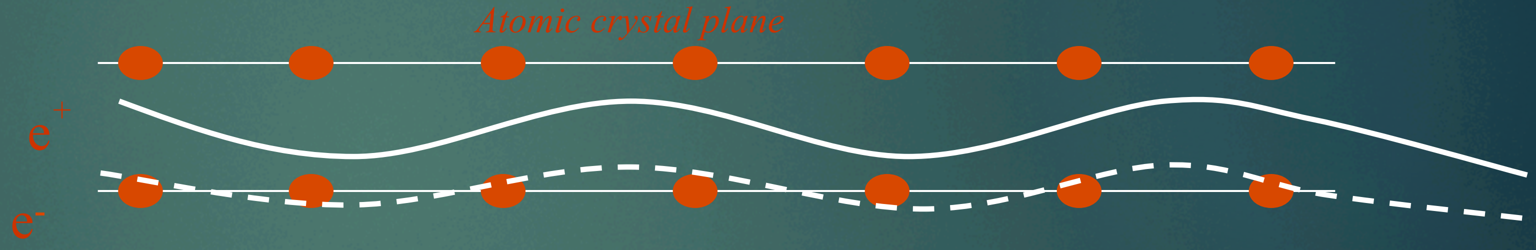
Channeling 2004, Frascati, 2-6 November

@ Channeling of Charged Particles

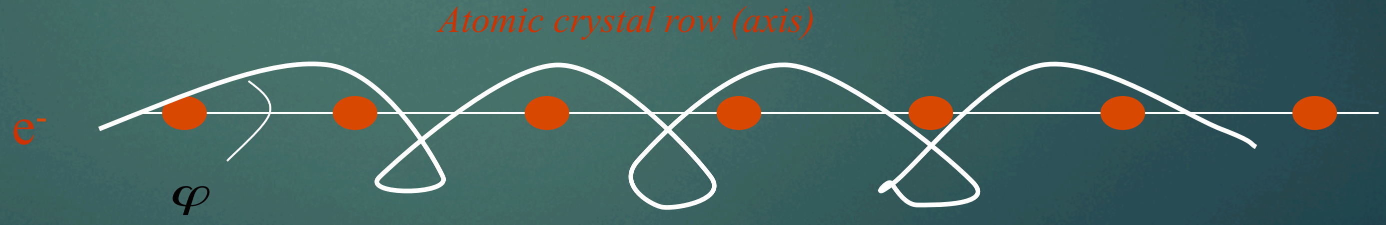
@ Amorphous:

@ Channeling:

planar channeling



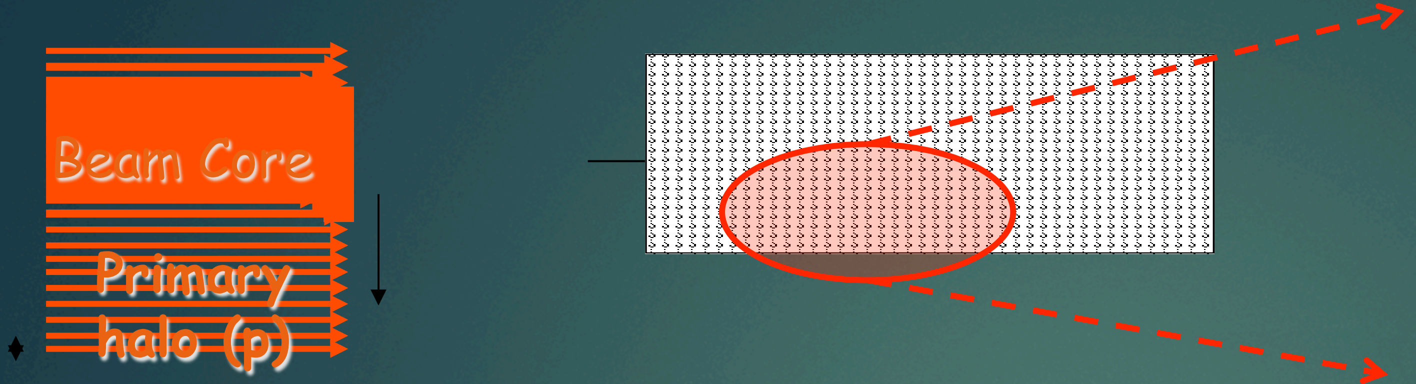
axial channeling

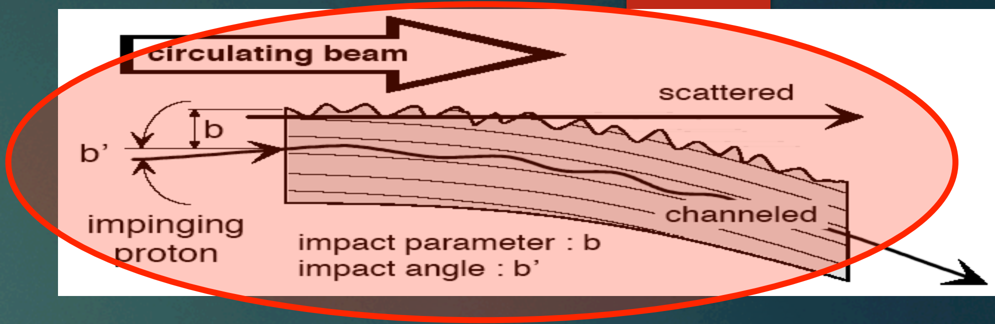


$$\varphi << 1 \qquad (\varphi < \varphi_L \sim \sqrt{U/E})$$

- the Lindhard angle is the critical angle for the channeling

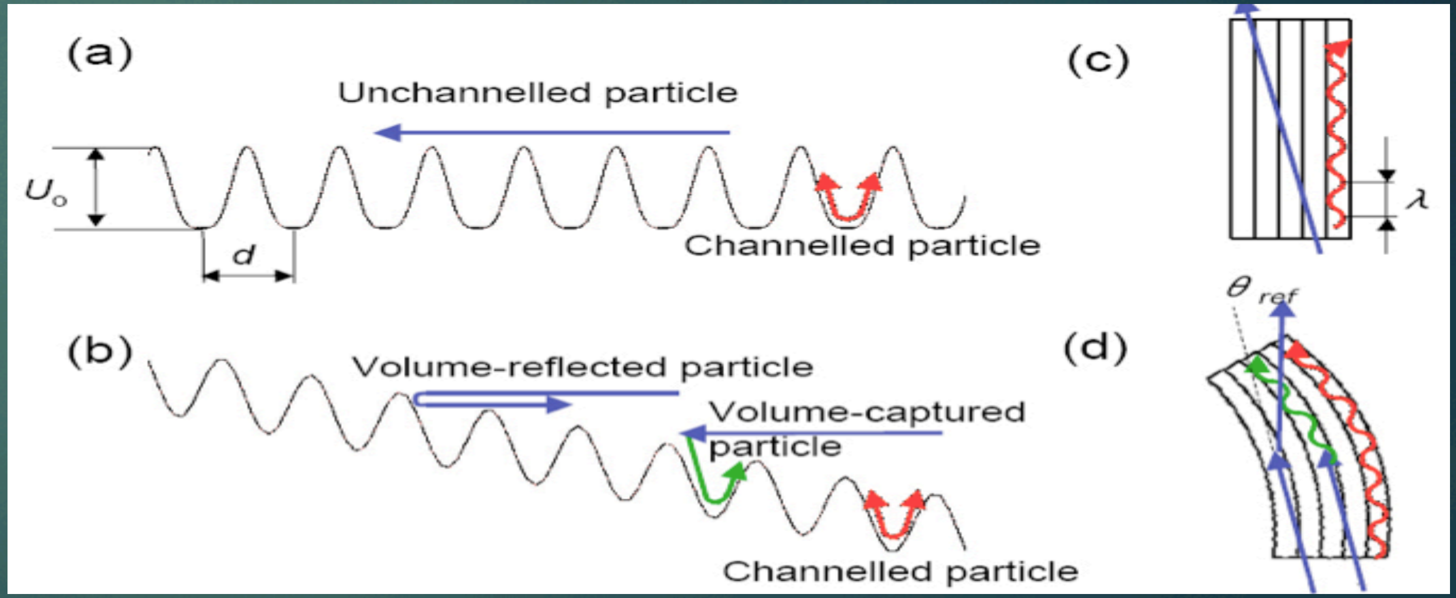
@ Crystal collimation at CERN





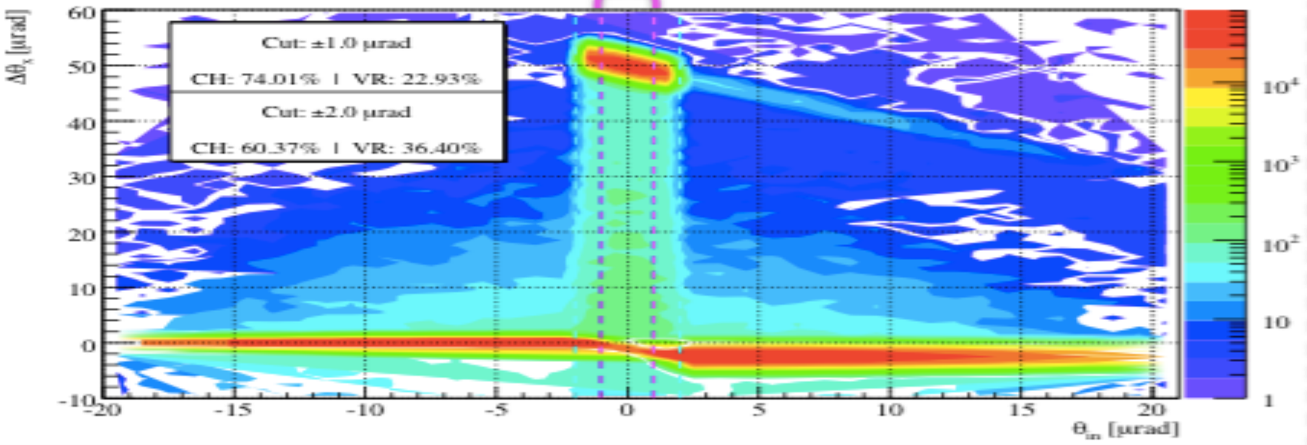
Possible processes:

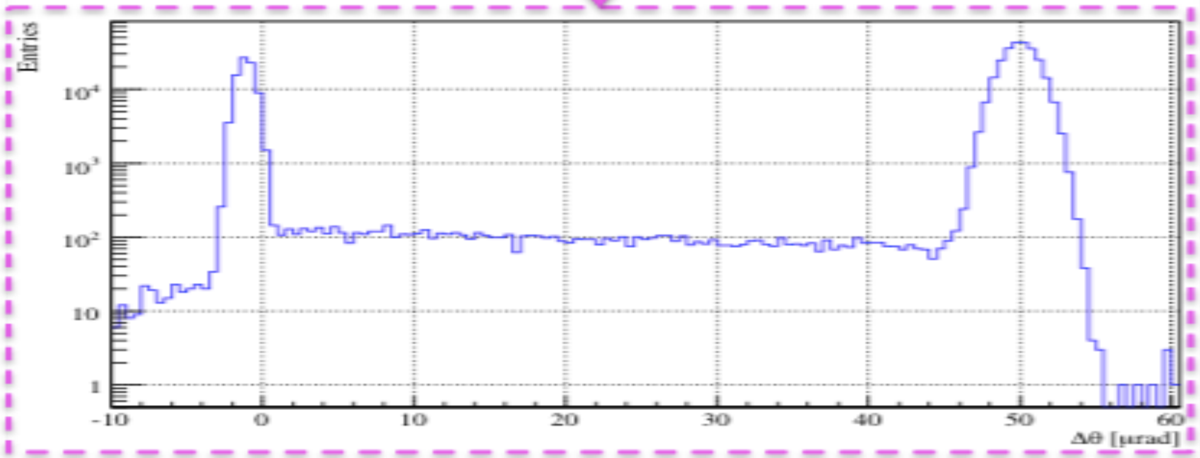
- multiple scattering
- channeling
- volume capture
- de-channeling
- *volume reflection*



@ deflection efficiency for TeV energies

Simulated deflections & efficiency for crystals installed in the LHC: 4 mm long, 50 μrad bending
Gaussian beam of 7 TeV with σ_x=1mm, $\sigma_{x'}$=10μrad.

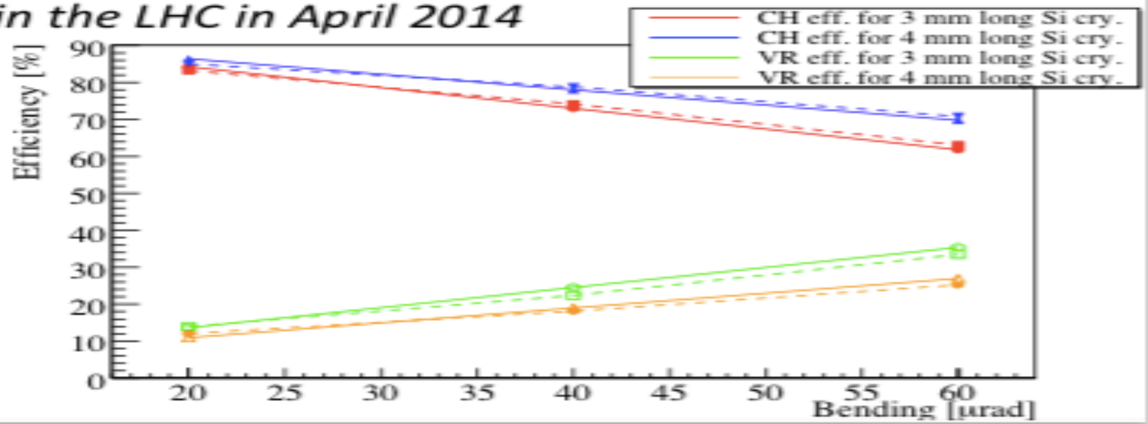




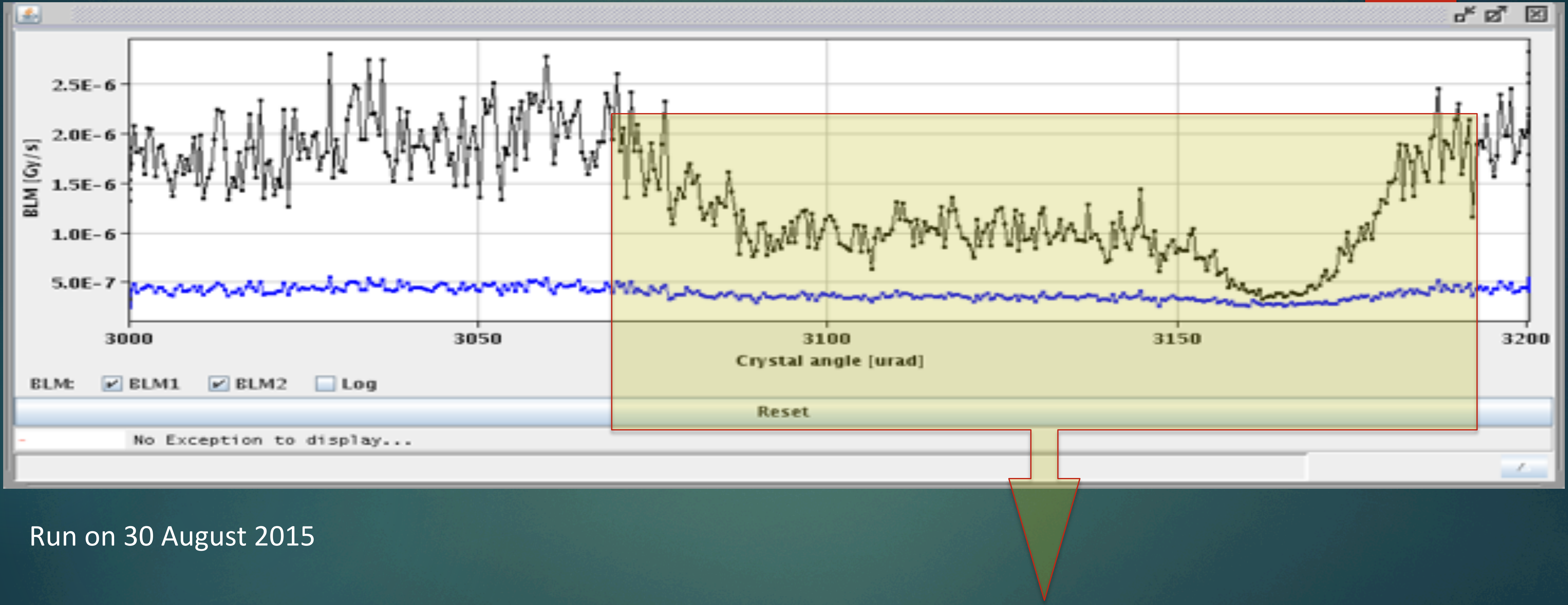
Parametric comparisons made with respect to Taratin's code at 7 TeV for studies related to the choice of crystals installed in the LHC in April 2014

7 TeV beam with a uniform distribution ±1 μrad.
Trend of CH & VR efficiency are compared.

Dashed line: **Fully analytical crystal simulator**
Solid line: **Crystal emulator in SixTrack**



@ first experience at LHC



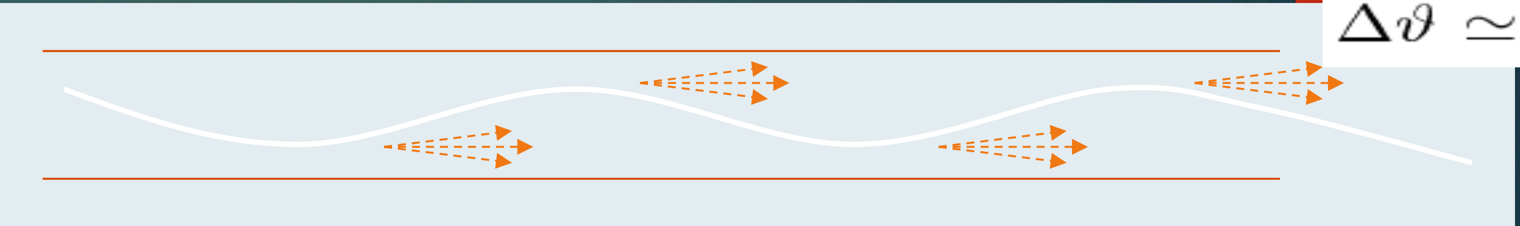
Run on 30 August 2015

evidence for crystal channeling at LHC

@ Channeling Radiation

@ Channeling Radiation:

$$\omega = \omega(\theta) = \frac{\omega_{fi}}{1 - \beta_{||}\cos\theta}$$



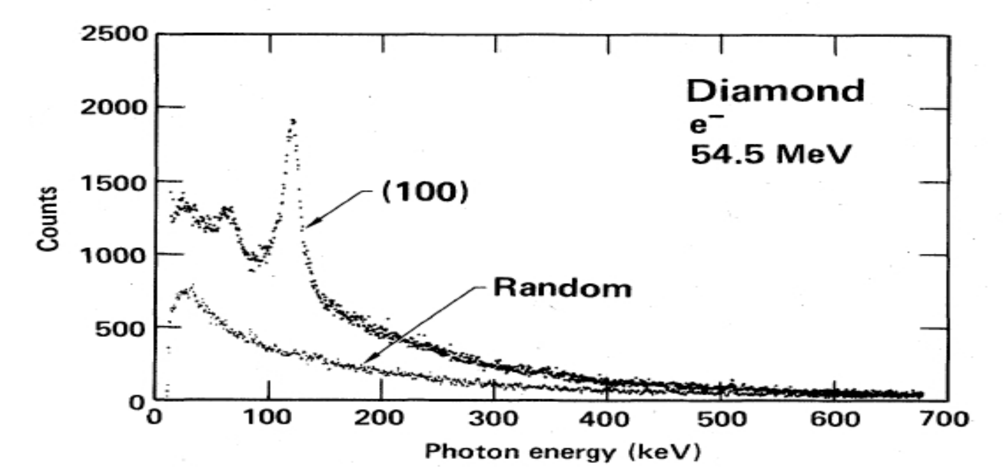
$\Delta\vartheta \simeq \gamma^{-1}$

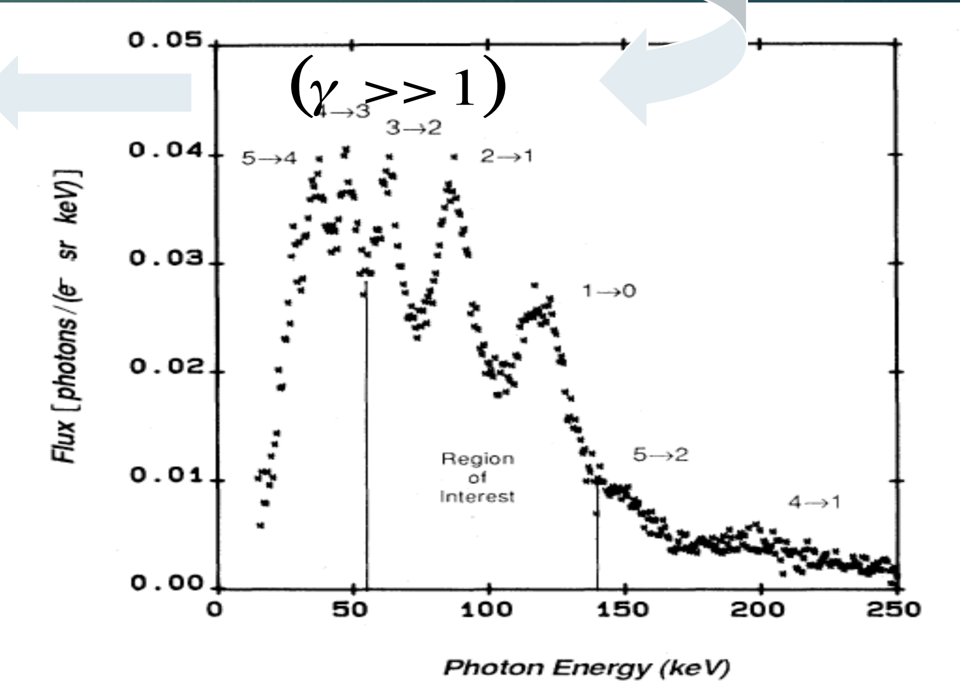
ω_{fi} - *optical frequency* ⟶ *Doppler effect* ⟶ $\omega_0\gamma^{3/2}$ - $\omega_0\gamma^2$

$(\gamma >> 1)$

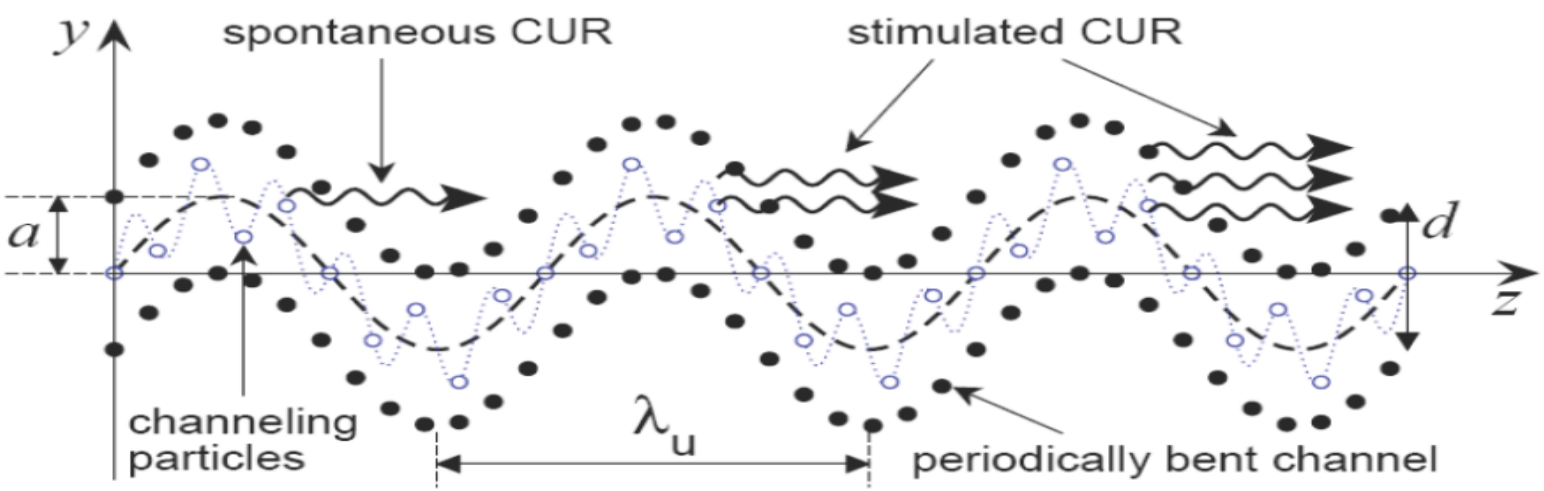
Powerful radiation source of X-rays and ?-rays:

- polarized
  - tunable
    - narrow forwarded





@ Crystalline Undulator



$d = 1\ldots2$ Å — the interplanar spacing
$a = (1\ldots50)d$ — the amplitude of bending
$\lambda_u = 10\ldots100$ μm — the period of bending

⇒ $d << a << \lambda_u$

tion of
UR:

es are shifted

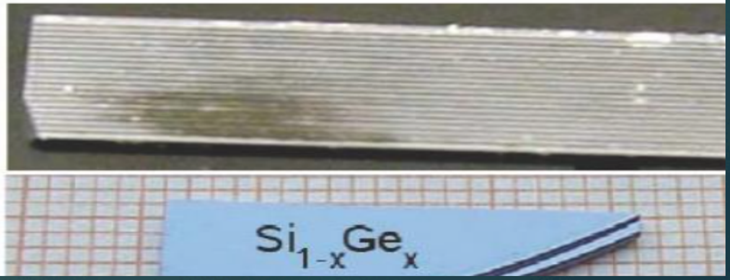
huge scale factor →

Magnetic undulator:

$\lambda_u \sim 1$ cm, $\hbar\omega \sim 10$ keV

Crystalline undulator:

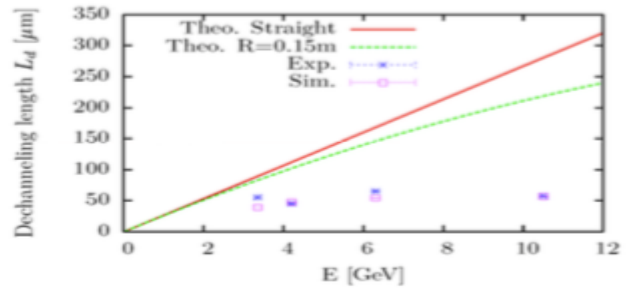
$\lambda_u \sim 10$ μm, $\hbar\omega \sim 0.1 \ldots 10$ MeV



@ channeling at SLAC: courtesy of U. Wienands

Channeling Experiments at SLAC

- Aarhus-Ferrara-CalPoly-SLAC Collaboration formed 2013
- 3 separate experiments, at FACET and ESTB
  - T513 (complete): Channeling and VR of multi-GeV e^- in a bent Si crystal (60 μm, ρ=0.15 m)
    - Ferrara crystal
    - dechanneling length independent of energy
    - scattering in "free" direction increased by about √3 compared to mult. scatt.

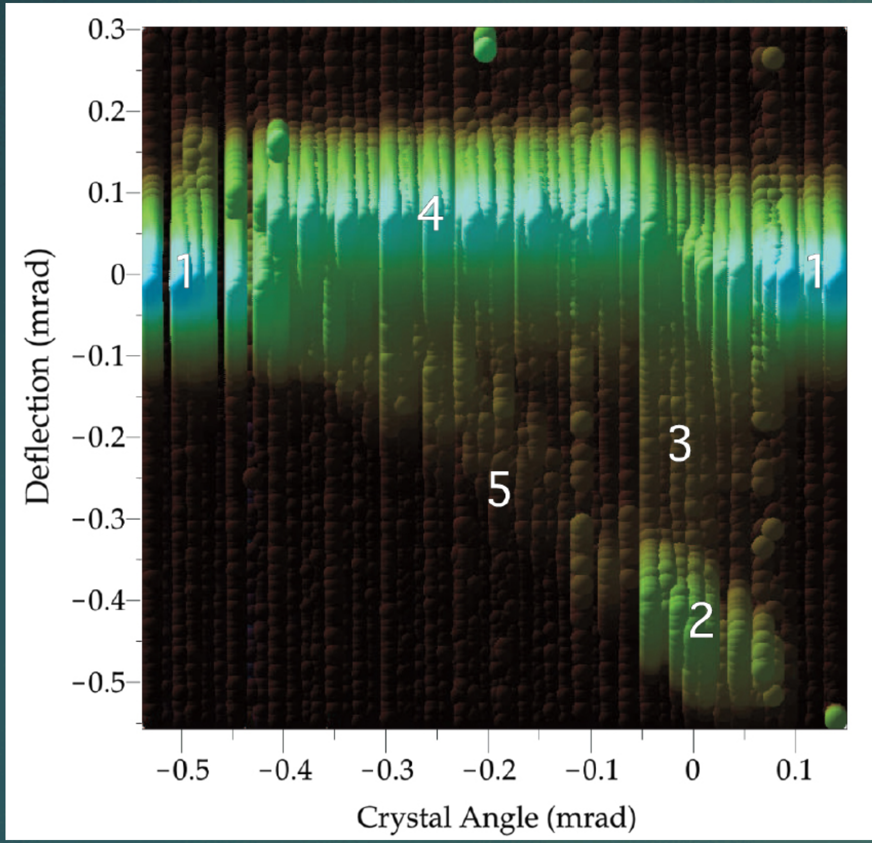


Wienands et al., PRL 114, 074801 (2015)
Wistisen et al., submission to PRB.

  - E212 @ FACET: comparison of 20 GeV e^+ and e^- data (in analysis)
  - T523 @ ESTB: first attempt to spectroscopy gamma rays from 14 GeV e^- in the T513 crystal (in analysis)
    - gamma-rays seen; VR spectrum relatively hard, consistent with synch. radiation
    - data quality not quite there yet; will improve experiment and try again.

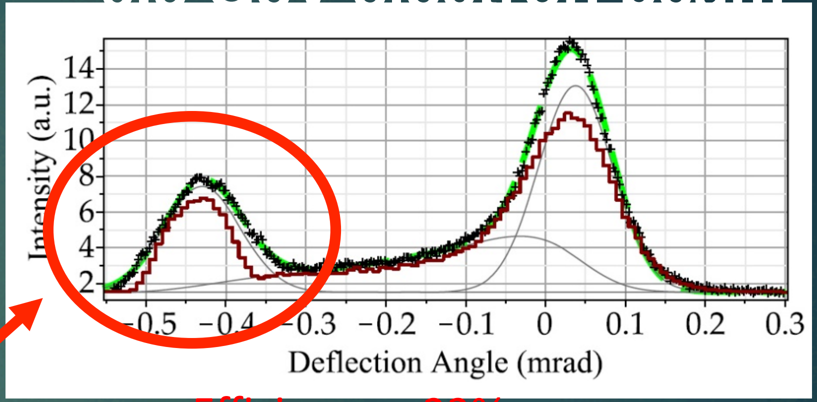
@ Multi-GeV electron beam steering (SLAC):
courtesy of A. Mazzolari

6.3 GeV electron beam



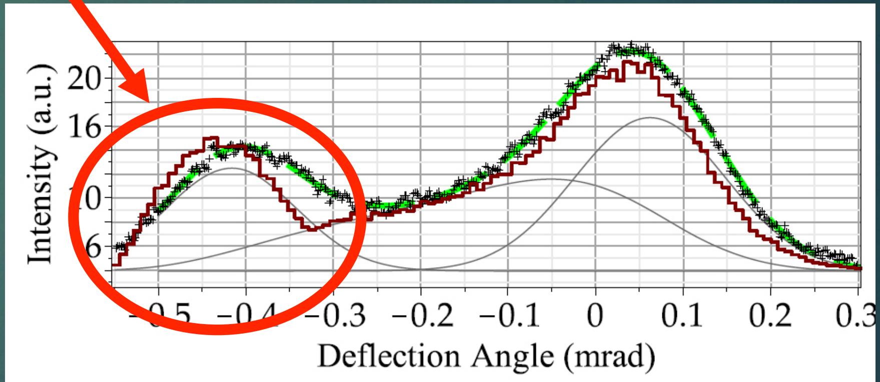
Channeling

6.3 GeV electron beam



Efficiency ~ 23%

3.5 GeV electron beam

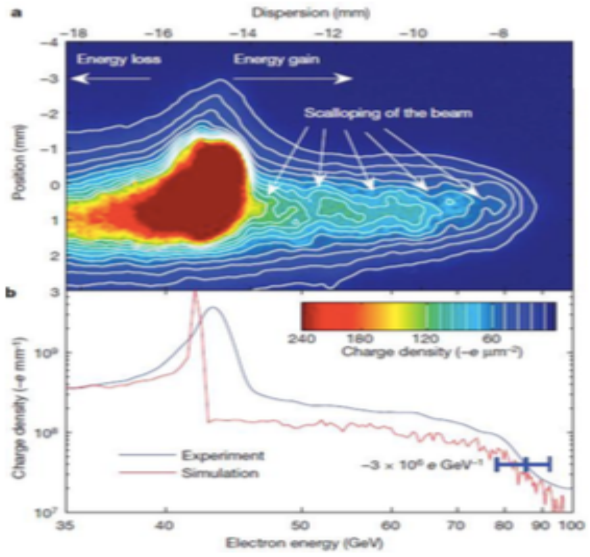


Efficiency ~ 22%

U. Wienands et al., PRL 114 074801 (2015)

@ Nano-Channeling at Fermilab: i courtesy of Shin

Gas-State Plasma

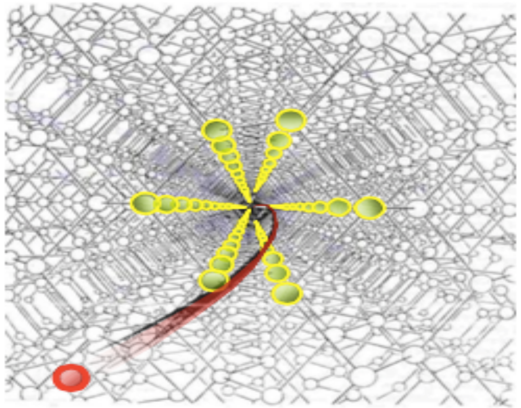


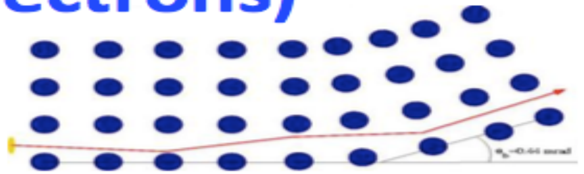
$10^{16} - 10^{18} cm^{-3} \rightarrow 10 \sim 100$ GeV/m

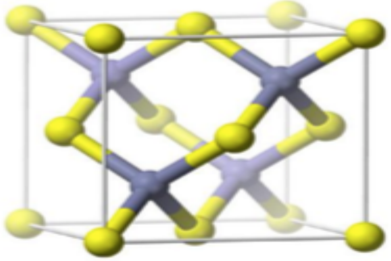
Nature 445, 741-744 (2007)

Energy Doubling: ~ 52 GV/m (@ 42 GeV)

Solid-State Plasma (Conduction Electrons)







$$E_0 = \frac{m_e c \omega_p}{e} \approx 100[\frac{GeV}{m}] \cdot \sqrt{n_0[10^{18} cm^{-3}]}$$

$10^{20} - 10^{23} cm^{-3} \rightarrow 1 \sim 30$ TeV/m

@ Nano-Channeling at Fermilab: i courtesy of Shin

$$\Delta E_{max} = \left(\frac{M_b}{M_p}\right)^2 (\Lambda G)^{1/2} \left(\sqrt{\frac{G}{z^3 \times 100[GV/cm]}}\right) \cdot 10^5 [TeV]^*$$

(M_b *and* M_p are the mass of the beam particle and mass of the proton respectively, Λ is the de-channeling length per unit of energy, G is the accelerating gradient, and z is the charge of the beam particle)

- 0.3 TeV for electrons/positrons,
- 10^4 TeV for muons,
- 10^6 TeV for protons

*P. Chen and R.J. Noble, in: Relativistic Channeling, eds. R.A. Carrigan, Jr and J.A. Ellison (Plenum, New York, 1987) p. 517.

	Dielectric based	Plasma based	Crystal channeling
Accelerating media	micro-structures	ionized plasma	solid crystals
Energy source: option 1 option 2	optical laser e^- bunch	e^- bunch optical laser	x-ray laser particle beam
Preferred particles	any stable	e^-, μ^-	μ^+, p^+ (e+, e-)
Max acc gradient	1-3 GV/m	30-100 GV/m	0.1-10 TV/m
c.m. energy in 10 km	3-10 TeV	3-50 TeV	10^3-10^5 TeV
# stages/10 km: option 1 option 2	10^5 - 10^6 10^4 – 10^5	~100 10^3 - 10^4	~ 1

- V. Shiltsev, Physics-Uspekhi (2012)
- F. Zimmermann, “The future of highest energy accelerators”, CERN, Geneva, Switzerland