Crystal Channeling Radiation and Volume Reflection Experiments at SLAC

Robert Noble, Andrei Seryi, Jim Spencer, Gennady Stupakov
SLAC National Accelerator Laboratory

4th Crystal Channeling Workshop
CERN, March 27, 2009

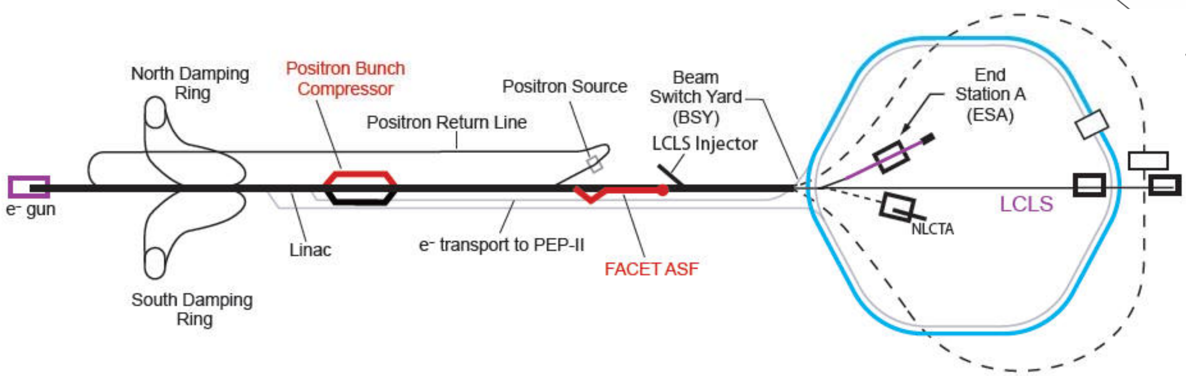
With the anticipated FACET start-up at SLAC in March 2011, we are studying the feasibility of two related crystal experiments:

- Physics of volume reflection (VR) by e- and e+ in crystals.
  - This will test the standard continuum model of VR for light particles of both charge signs
  - Explore the harmful effects of multiple scattering on VR
  - Possible application of VR to beam halo cleaning in Linear Colliders

- Physics of volume reflection radiation by e- and e+ in crystals.
  - This will test the radiation models for channeled light particles in the regime where “undulator parameter” K = E/m * deflection angle ~ 1
  - Explore possible applications of VR as a new photon source and an energy degrader/collimator for halo particles in colliders

FACET: Facility for Advanced Accelerator Experimental Tests

23 GeV e- , March 2011 (e+ later)



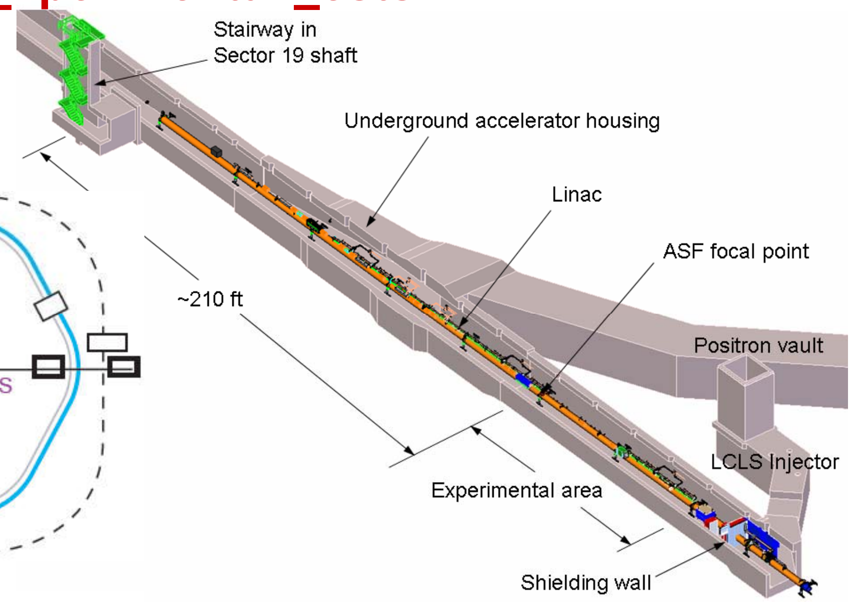


Table 1-1. FACET beam parameters

Energy	23 GeV with full compression and maximum peak current.
Charge per pulse	>2 x 10^{10} (3 nC) e^- or e^+ per pulse with full compression.
Pulse length at IP (σ_z)	25 µm with 4 % fw momentum spread with full compression and 40 µm with 1.5 % fw momentum spread with partial compression.
Spot size at IP ($\sigma_{x,y}$)	<10 µm nominal.
Momentum spread	4 % full width with full compression; (3% FWHM); < 0.5 % full width without compression.
Momentum dispersion at IP (η and η')	0
Drift space available for experimental apparatus	2 m from last quadrupole to focal point; approximately 23 m from the focal point to the beam dump.
Transverse space available for experimental apparatus	3 x 3 m

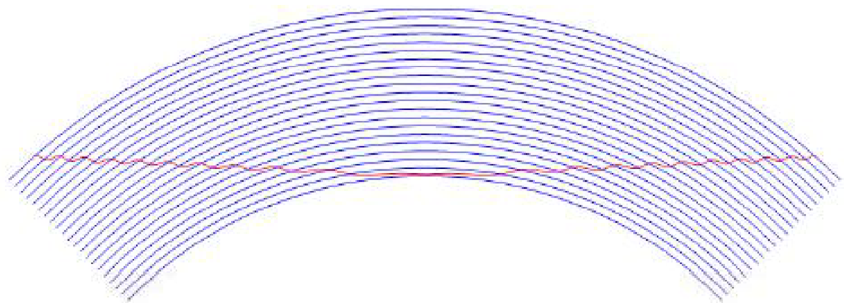
Uncompressed beam:
$\Delta p/p < 5E\text{-}3$ FW, $\sigma_z > 40\mu m$

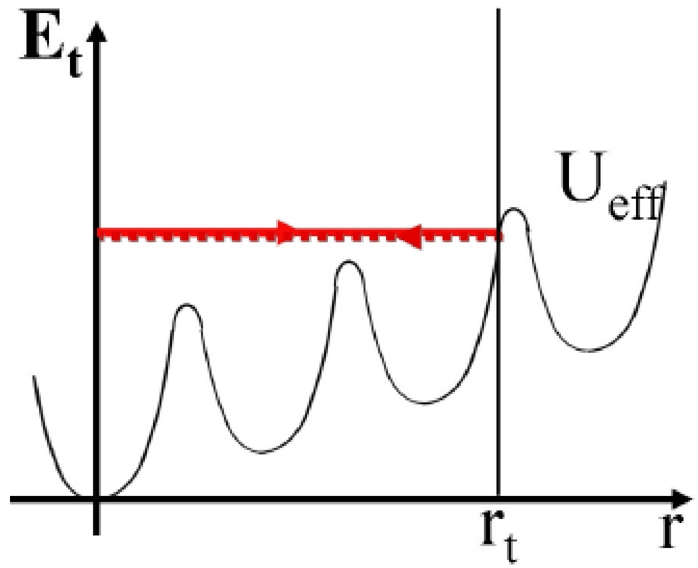
ε_n =30 mm mrad
σ_θ = 100 µrad at 10µm spot
σ_θ = 10 µrad at 100µm

For Si at 23 GeV
θ_c = 44 µrad

FACET beam is just right as crystal channeling probe

Bent crystal and volume reflection





- The wiggle periods are smaller further away from the reflection point
- The amplitude of the wiggles diminishes with the distance from the reflection point

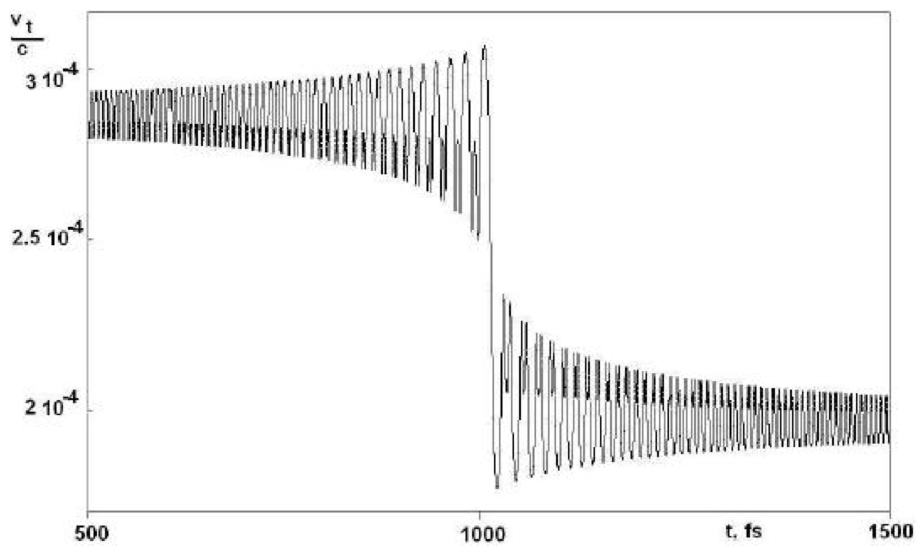


Figure 2. Behaviour of the transversal particle velosty (divided on c) as a function of time (in femptoseconds). (Time t=0 corresponds to enter point in single crystal.)

Critical channeling angle:

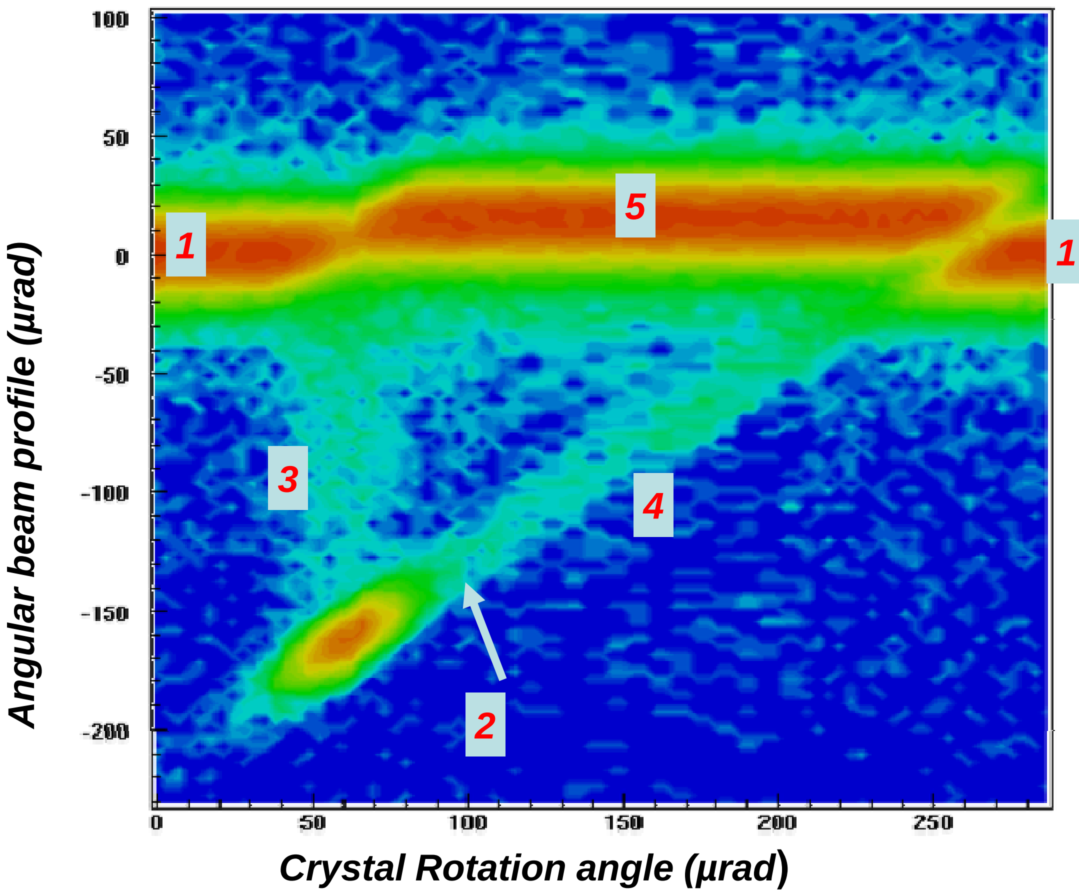
$$\theta_c = \sqrt{\frac{2U_{max}}{pv}}$$

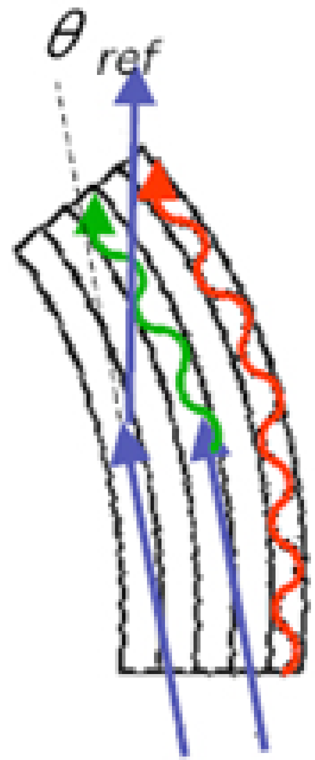
(Particle with KE = ½ pvθ_c^2 = max potential)

VR angle:

$$\theta_r \simeq 2\sqrt{\frac{2U(d_p/2)}{pv}} = 2\theta_c$$

Effects in bent crystals: New experimental work may lead to useful applications!



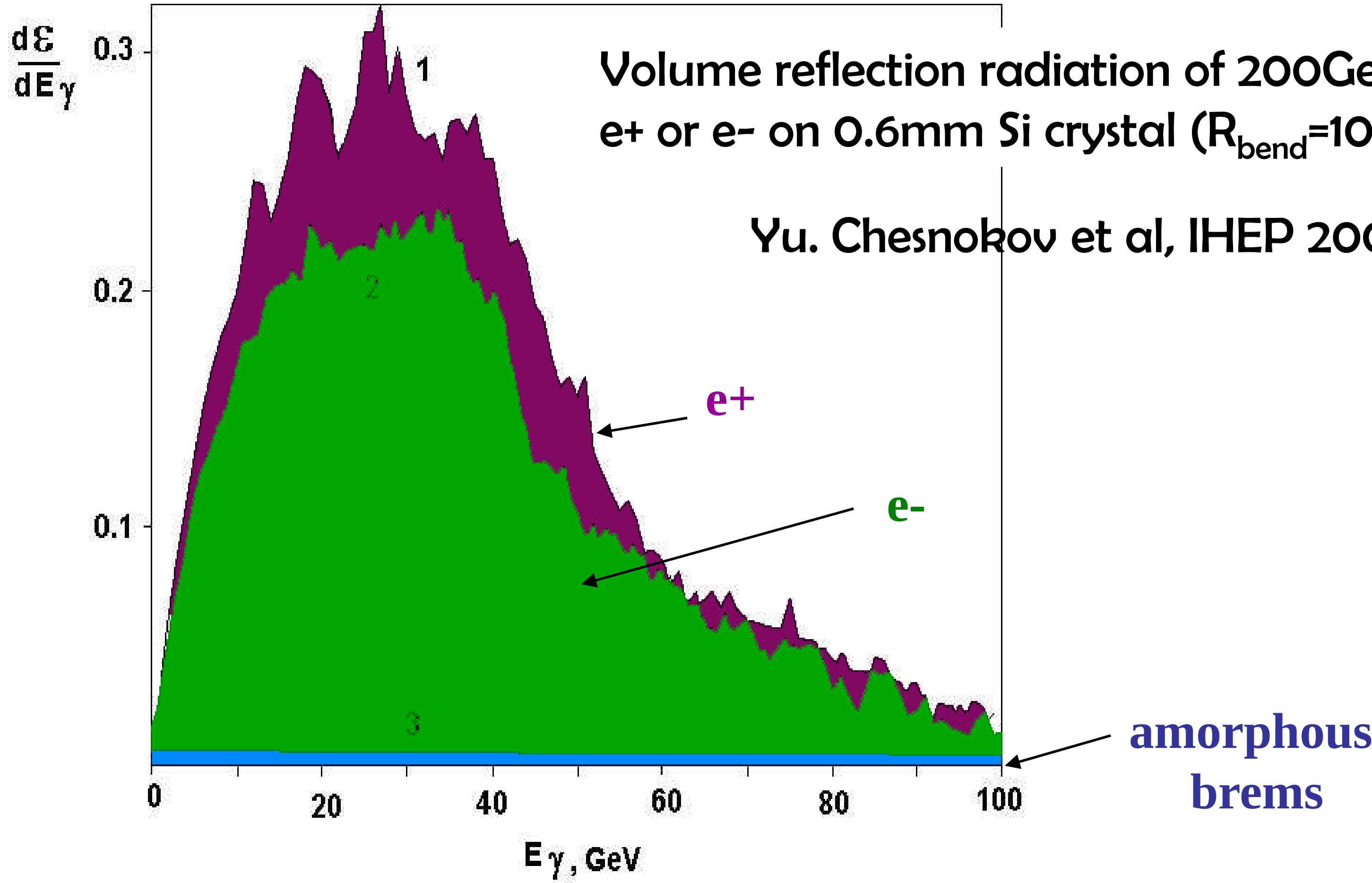


1 - “amorphous” orientation
2 - channeling
3 - de-channeling
4 - volume capture
5 - volume reflection

Deflection Angle of Protons after passing the crystal vs Crystal Rotation Angle.
Data plot from Walter Scandale et al

Light charged particles: Volume Reflection Radiation

(radiated energy per unit frequency range)



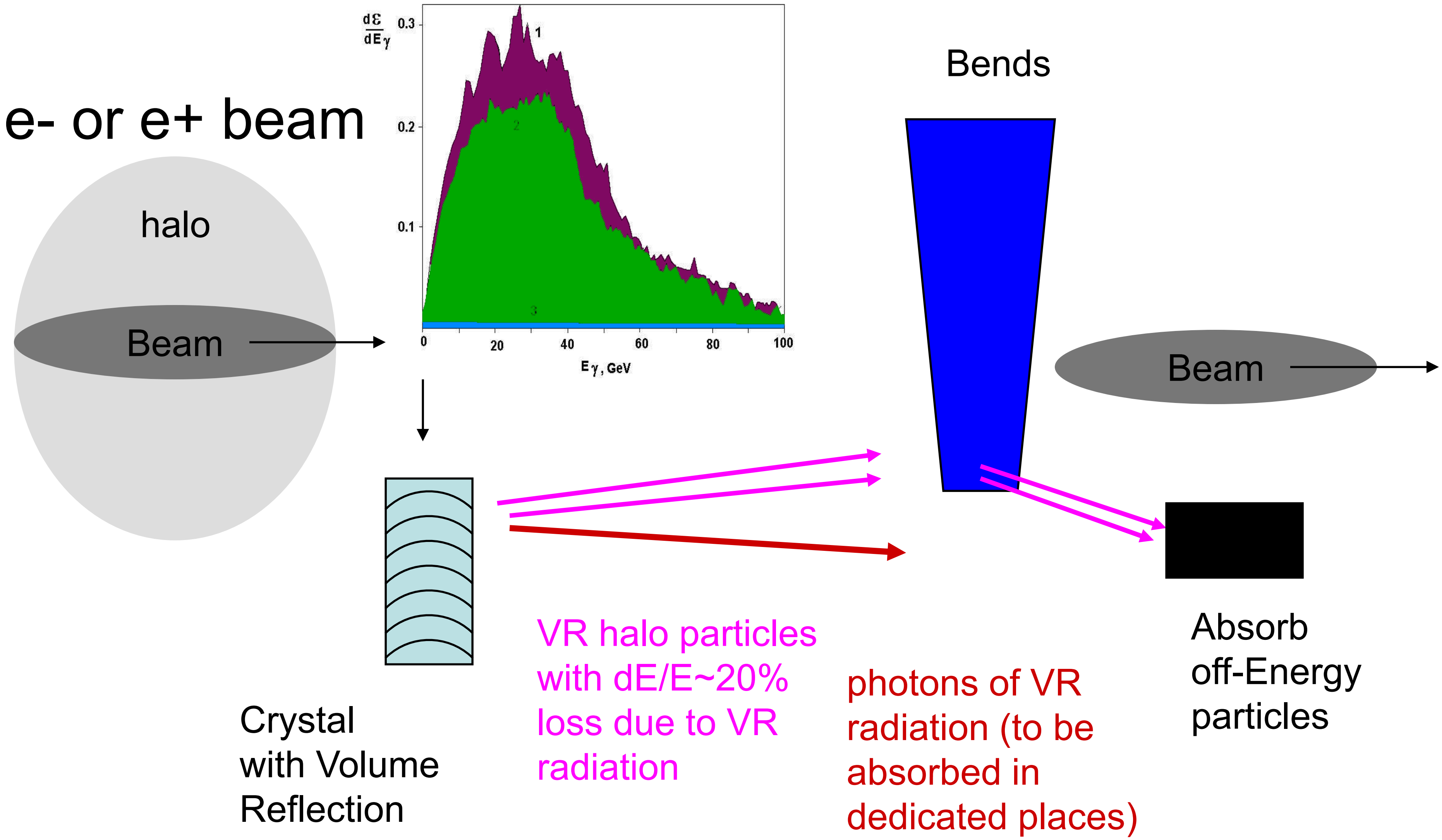
Volume reflection radiation of 200GeV e+ or e- on 0.6mm Si crystal (R_{bend}=10m)

Yu. Chesnokov et al, IHEP 2007-16

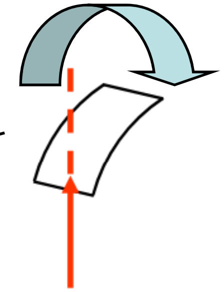
Scaling E_γ with E: ~$E^{3/2}$ for E<<10GeV and E^2 for E>>10GeV (Gennady Stupakov)

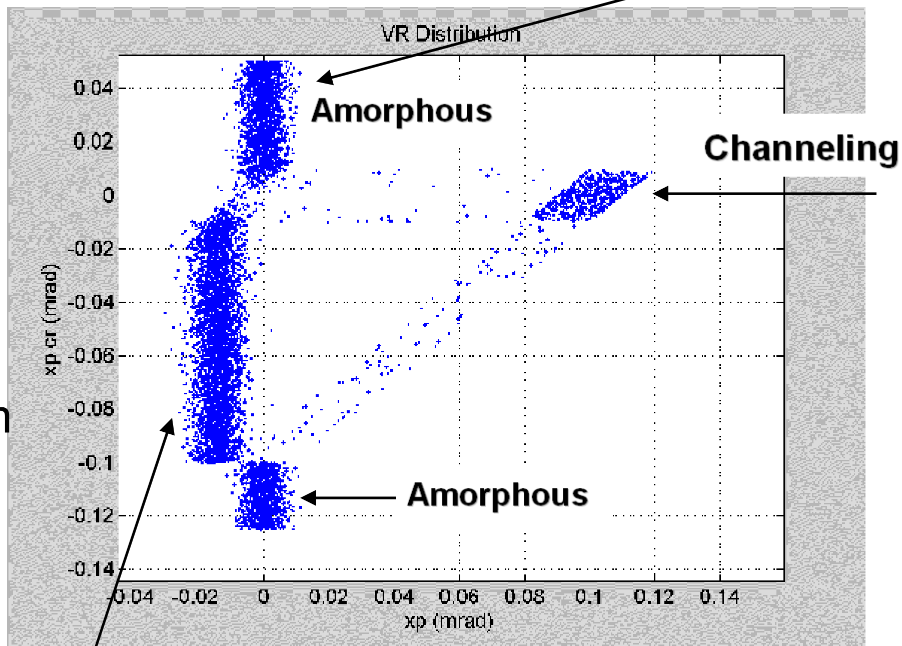
VR radiation is very similar for both e+ and e-, and has large angular acceptance – it makes this phenomena good candidate for collimation system of linear collider.

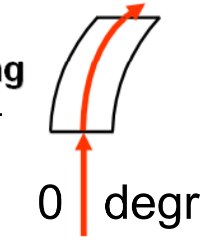
LC Collimation concept based on VR radiation
A. Seryi et al



Volume Reflection angles: Igor Yazynin's codes
Example: 400 GeV protons, Si(110),
crystal R = 10 m, length=1mm

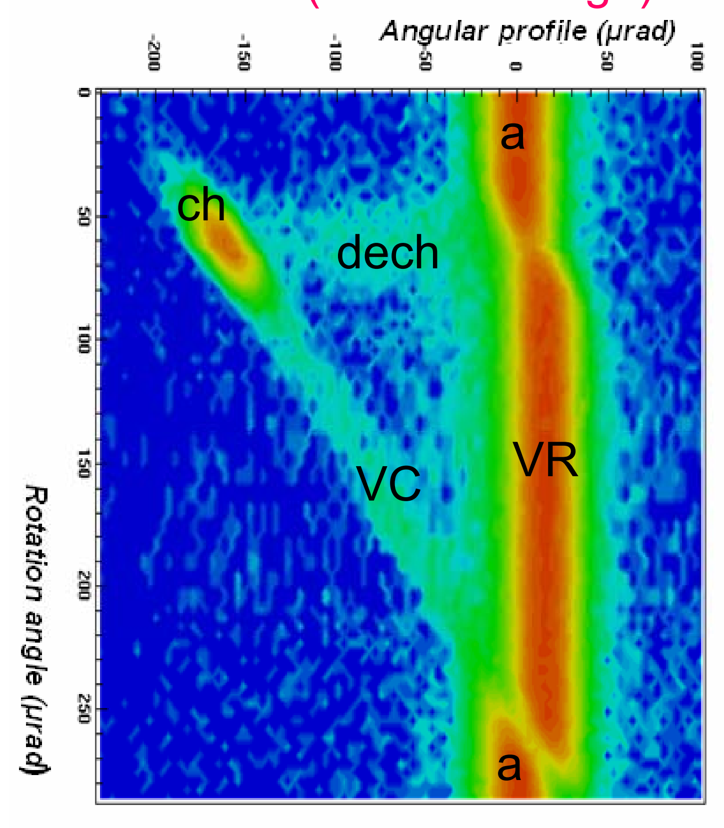




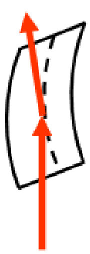


"Rotation Angle"-
crystal orientation rel. to beam initial direction

Experimental plot
(other than sign)

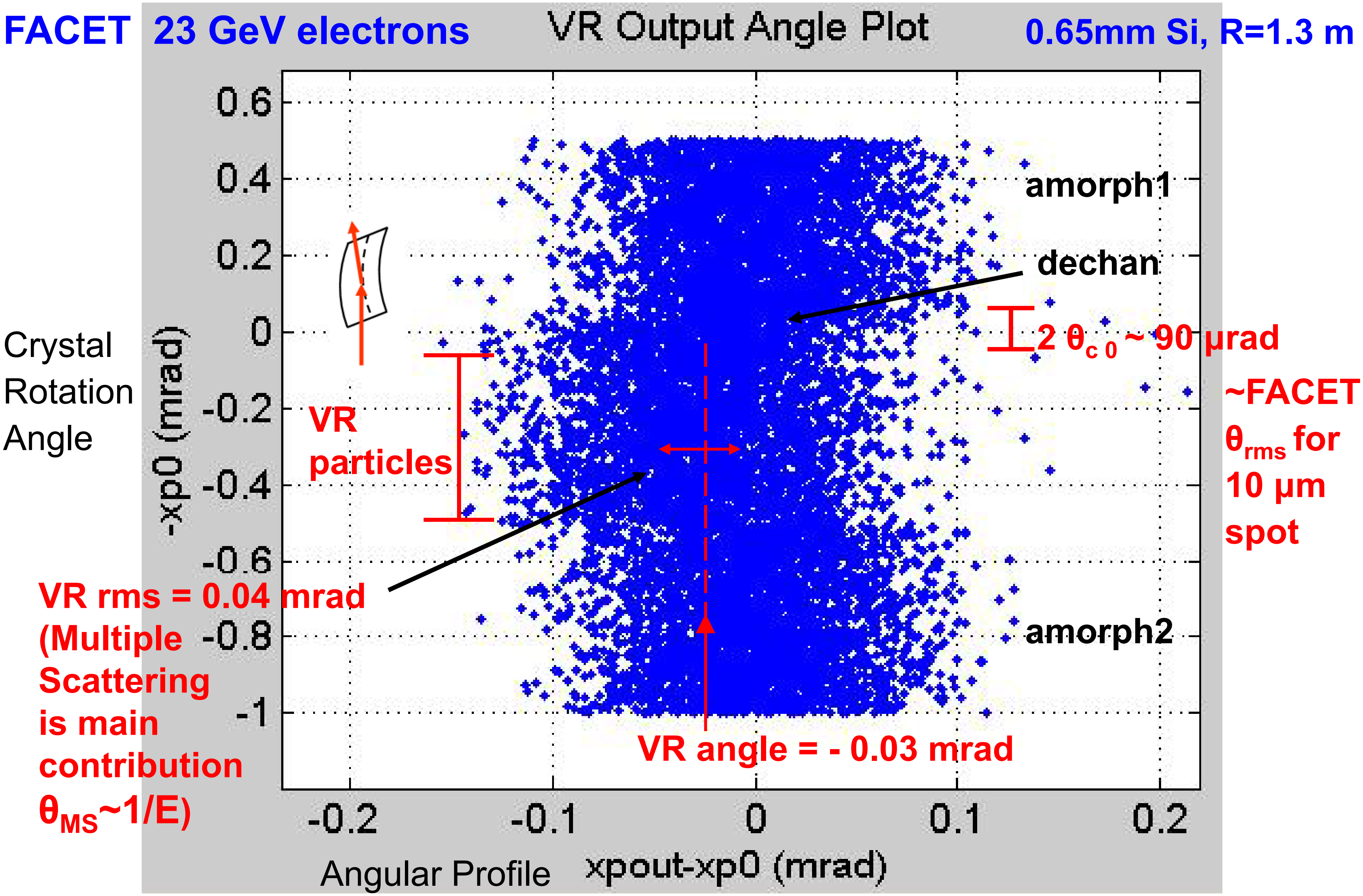


Volume Reflection



"Angular Profile"
- change in particle angle relative to initial beam direction

Max crystal angle for VR to occur
= crystal thickness / R



23 GeV: $\theta_{c\,0}$ (~ $E^{-1/2}$)=0.044 mrad, R_{crit} (~ E)=0.05 m, L_{dech} (~ E)=0.75 mm

A.G. Afonin, V.T. Baranov, G.I. Britvich, A.P. Bugorskiy,
Yu. A. Chesnokov, V. N. Chepegin, $\boxed{\text{V.I. Kotov}}$, A.E. Kushnirenko,
V.A. Maisheev, V.A. Pikalov, I.A. Yazynin
Institute for High Energy Physics, Protvino, Russia

Yu.M. Ivanov, V.V. Skorobogatov
Petersburg Nuclear Physics Institute, Gatchina, Leningrad Region, Russia

OBSERVATION OF RADIATION FROM 10 GEV POSITRONS AT VOLUME REFLECTION IN BENT SILICON MONOCRYSTAL

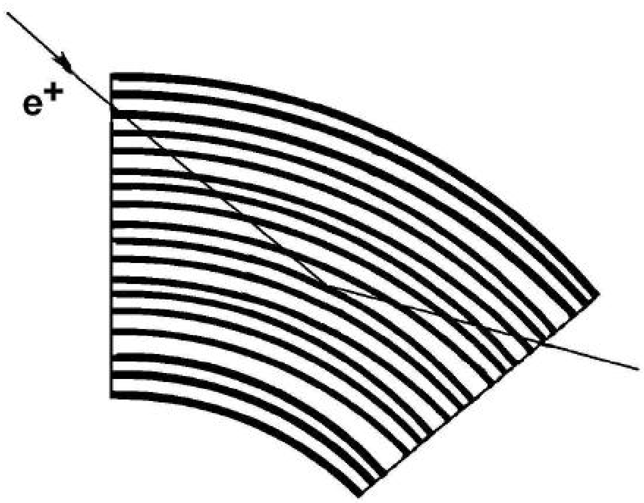


Figure 1. Scheme of volume reflection process in bent single crystals.

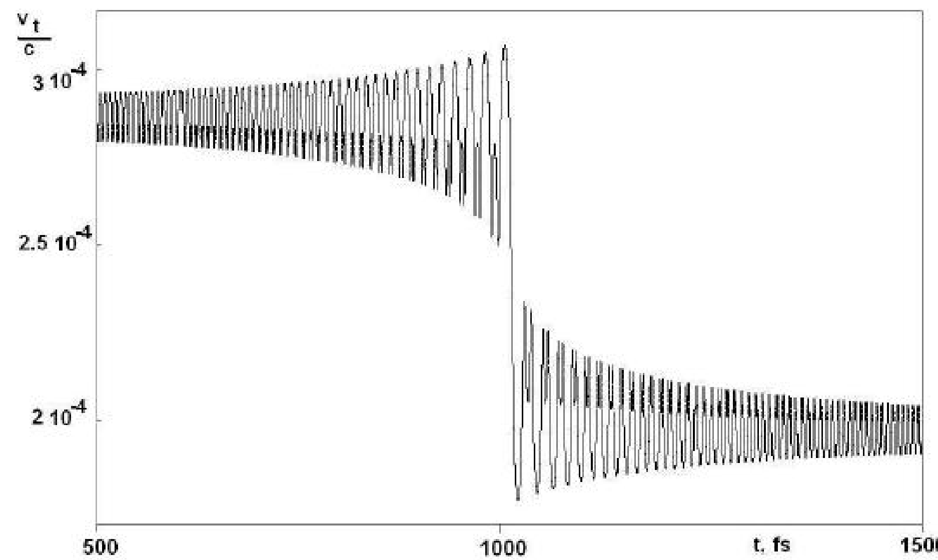
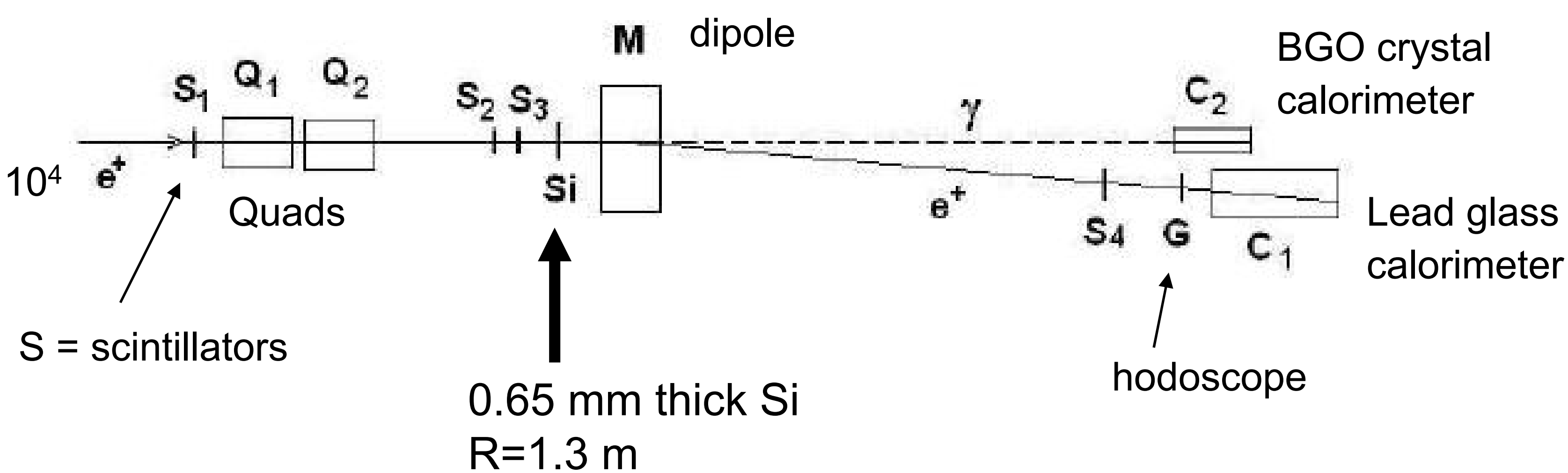


Figure 2. Behaviour of the transversal particle velosty (divided on c) as a function of time (in femptoseconds). (Time t=0 corresponds to enter point in single crystal.)

OBSERVATION OF RADIATION
FROM 10 GEV POSITRONS AT VOLUME REFLECTION
IN BENT SILICON MONOCRYSTAL

2. Experimental setup

Experiment was carried out on 22 beam line of IHEP accelerator. Fig. 3 illustrates the experimental layout.



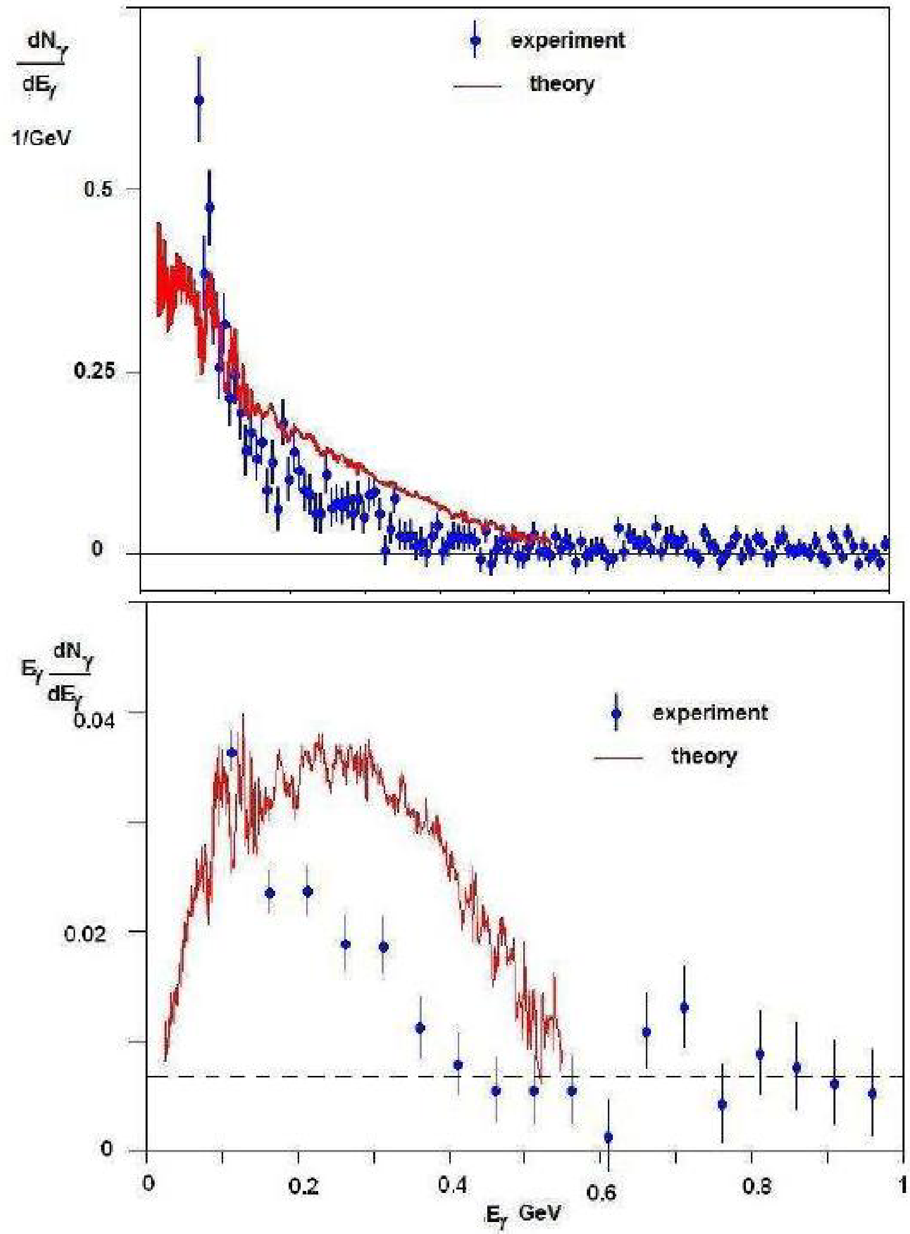


Figure 5. The coherent part of γ-quanta spectrum (a) and corresponding energy losses of positrons (b) in silicon single crystal. Points are experiment and solid line is calculation. The dashed curve is calculated energy losses in nonoriented single crystal.

10 GeV e+

Photon energy spectrum prominent at ~100 MeV. Scales as ~$\gamma^{3/2}$

At 23 GeV, we would expect this spectrum to shift >200 MeV

23 GeV e- & e+ VR radiation at FACET

- A possible experiment would be a collaboration in which we use the IHEP-NPI Si crystal (if available) from the IHEP experiment at FACET.

- VR radiation experiment at FACET would first involve e- and in the future e+, both at 23 GeV.

- The FACET results could be compared to the 10 GeV positron IHEP-NPI results for the same crystal.

- If agreeable to our IHEP colleagues, we would like to use their VR radiation code at SLAC to do some detailed radiation calculations for the FACET beams.

- At present we use a simple wiggler model of Gennady Stupakov for estimating VR spectrum.

Gennady Stupakov's Wiggler Model for Estimating VR Radiation

Potential energy in crystal

Channeling in a crystal is similar to motion in a wiggler—the transverse oscillations are confined by the potential energy U. I assume that the oscillations are at the energy $U_{\rm max}/2 \approx 10$ eV, with the amplitude $x_0 \approx 0.7$ Angstrom. Then

$$\psi_0 = \sqrt{U_{\rm max}/E}.$$

We also have

$$k_w = \psi_0/x_0.$$

Scalings: $\psi_0, k_w \propto 1/\sqrt{\gamma}$ and $K \propto \sqrt{\gamma}$. One can compute all parameters of the wiggler motion and the corresponding radiation.

Si channel potential

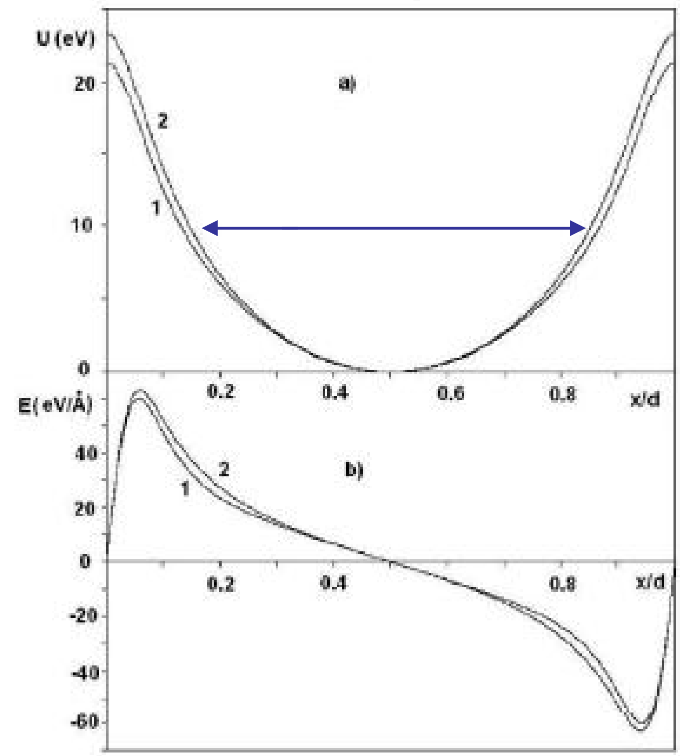
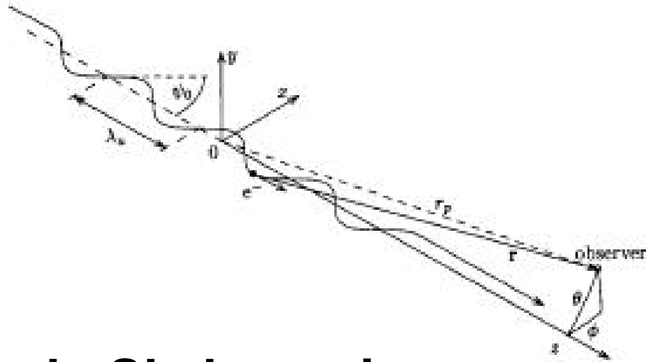


FIG. 2. One-dimensional potential (a) and electric field (b) in the (110) plane of a silicon single crystal (at the room temperature), as functions of the relative coordinate x/d, where $d =$ 1.92 Å is the interplanar distance. Curves 1 and 2 correspond to calculations based on the atomic form factors from x-ray measurements and the Moliere model.

Wiggler radiation



For 23 GeV particle in Si channel:

λ_w—period of the sinusoidal orbit **= 14.3 micron**

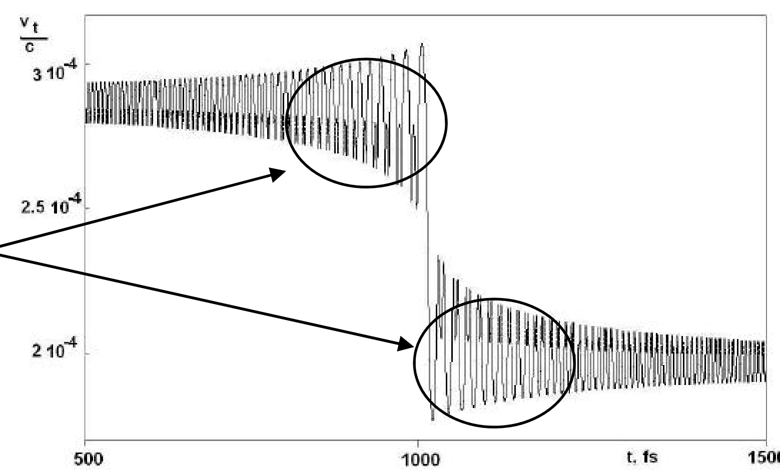
$k_w = 2\pi/\lambda_w$ **= 0.44 / micron**

ψ_0—max (amplitude) deflection angle **= 29.5 micro-radian**

$x_0 = \psi_0/k_w$—amplitude of the deviation **= 0.672 angstrom**

The undulator parameter $K = \gamma\psi_0$. **= 1.33**

VR radiation intensity is determined by effective number of wiggles. In the range 10 – 200 GeV, most of the radiation comes from 10-20 wiggles.



Spectrum of the wiggler radiation

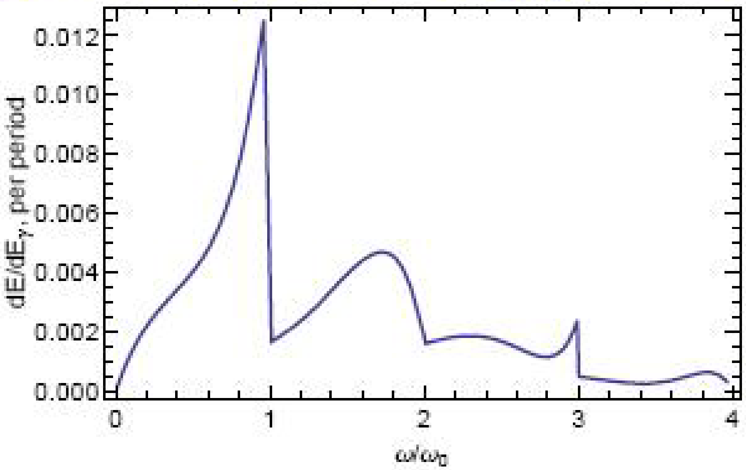


Figure: $K = 1$ (10 GeV)

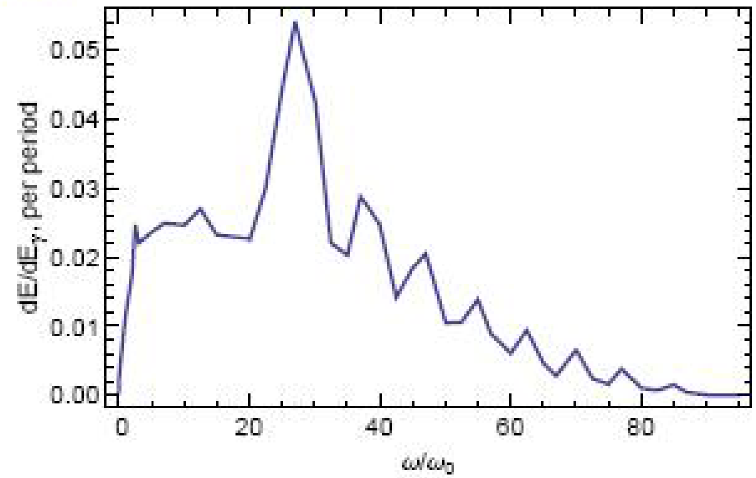


Figure: $K = 4$ (200 GeV)

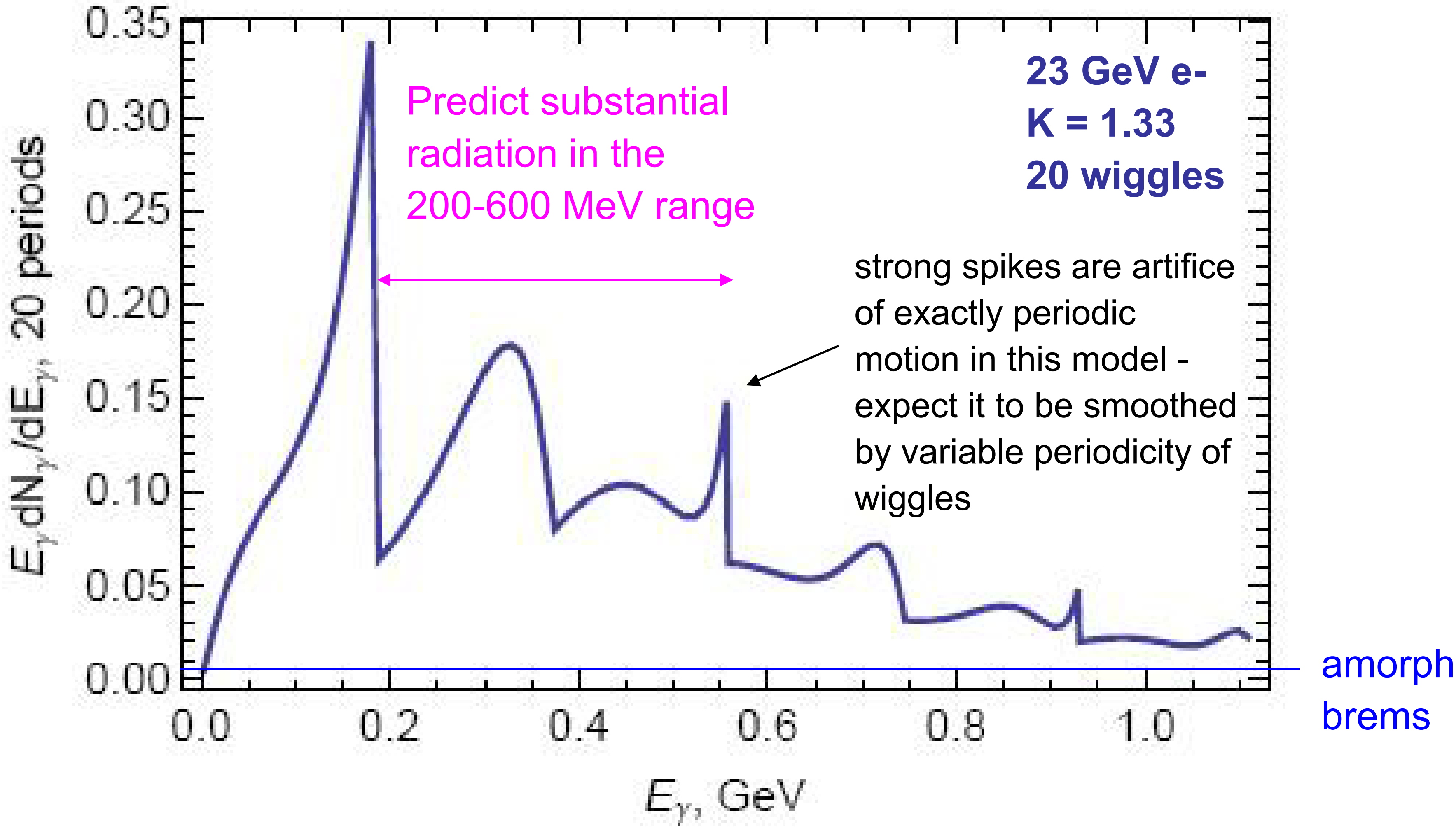
The frequency

for 23 GeV (K=1.33): $\omega_0 = \dfrac{2\gamma^2 c k_w}{1 + K^2/2}$. **= 2.83X10^{23} /sec or 187 MeV**

The vertical axis is the radiated energy E per unit frequency range $E_\gamma = \hbar\omega$ of the photon spectra per unit period of the wiggler.
For large $K \gg 1$, the spectrum extends to $\omega \sim \omega_0 K^3$.

Wiggler Model Estimate of 23 GeV e- VR Radiation

G. Stupakov



- **We need detailed calculations with full radiation code as next step.**

Summary

1. We have begun a study of possible VR physics and radiation experiments at the planned FACET facility of SLAC, with beam expected in March 2011. Such experiments would benefit from a wide collaboration of experienced researchers.

2. FACET 23 GeV e- and e+ beams will have θ_{rms} ~ 10-100 μrad for 100-10 μm spot sizes, well-matched to the channeling critical angle in Si, and a good probe for VR effects.

3. If we use the IHEP-NPI Si crystal, 0.65 mm thick, R= 1.3 m, the VR angles are about 30 μrad, but multiple scattering gives an rms spread of 40 μrad. VR angle can still be clearly identified from the distributions.

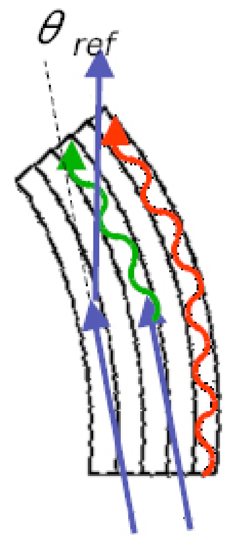
4. The VR radiation spectrum for this case is estimated to have structure in the range 200 – 600 MeV using a simple wiggler model, with about 20 channel wiggles providing most of the radiation. A collaboration to perform better estimates using state-of-the-art radiation codes from our IHEP colleagues would significantly help this feasibility study.

Extra slides

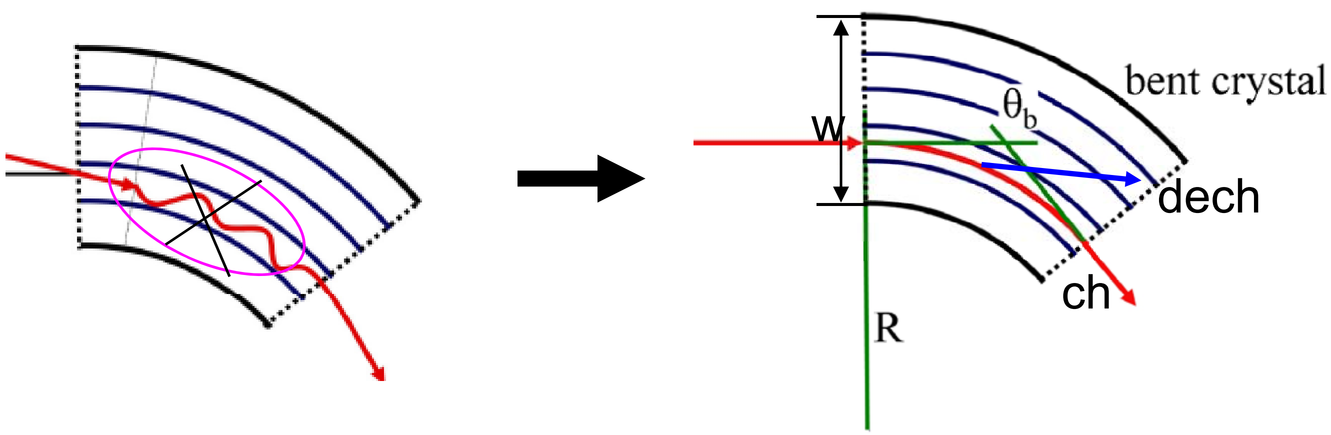
This is a "decision-tree" code, not full Monte Carlo.

Yazynin Code includes processes:

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

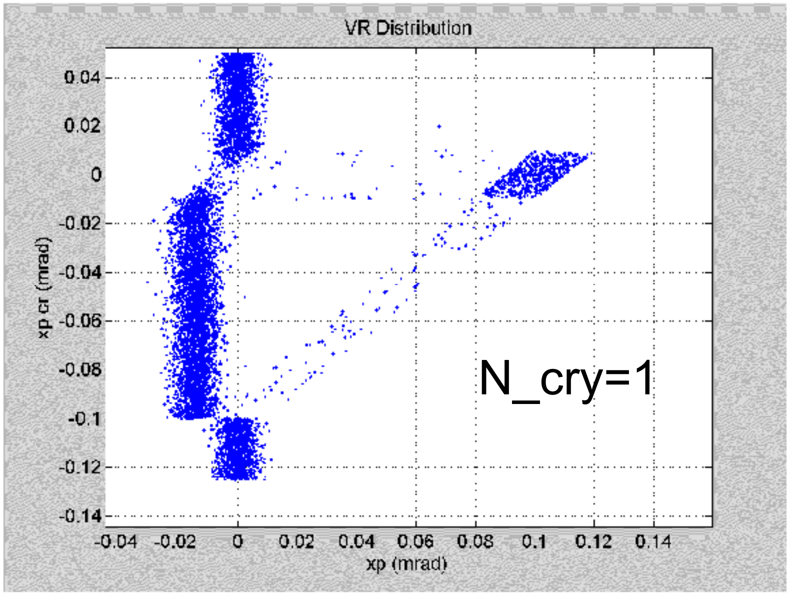


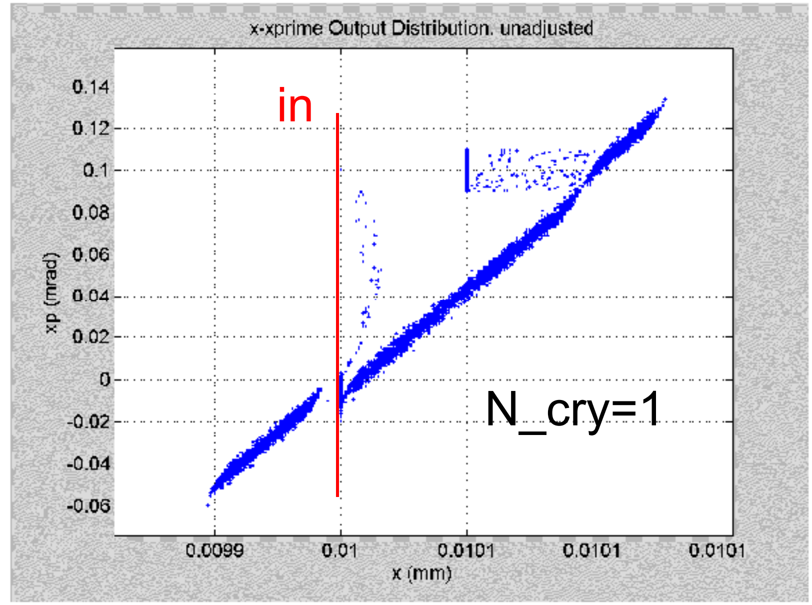
Basic approx: Code replaces details of particle orbits with Monte Carlo fits based on distribution fcns and analytic formulas for trajectories over long distances (not on scale of betatron motion in bent crystal). It applies probabilities to dechanneling, volume capture, volume reflection, amorphous transport, Coulomb and nucl scattering angles, energy loss, etc. Both proton and electron versions of code exist.

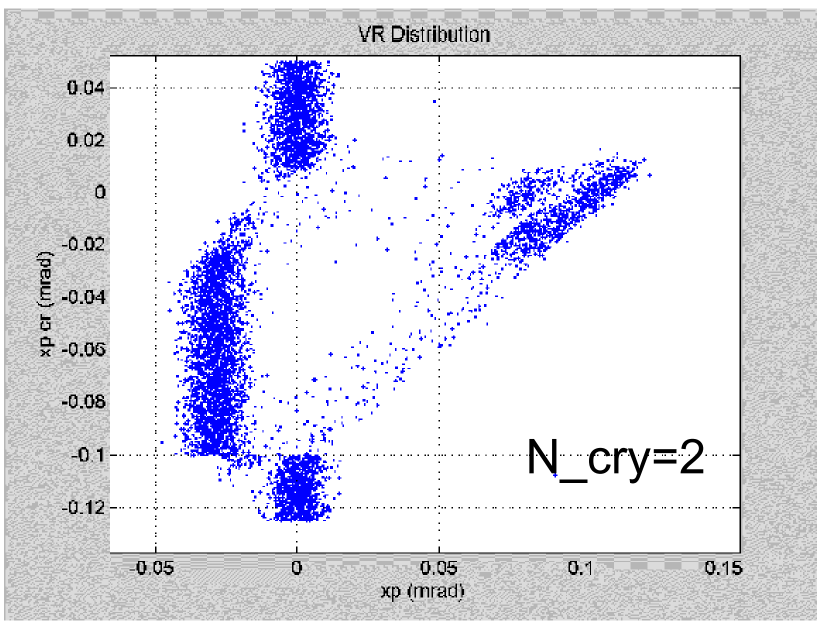


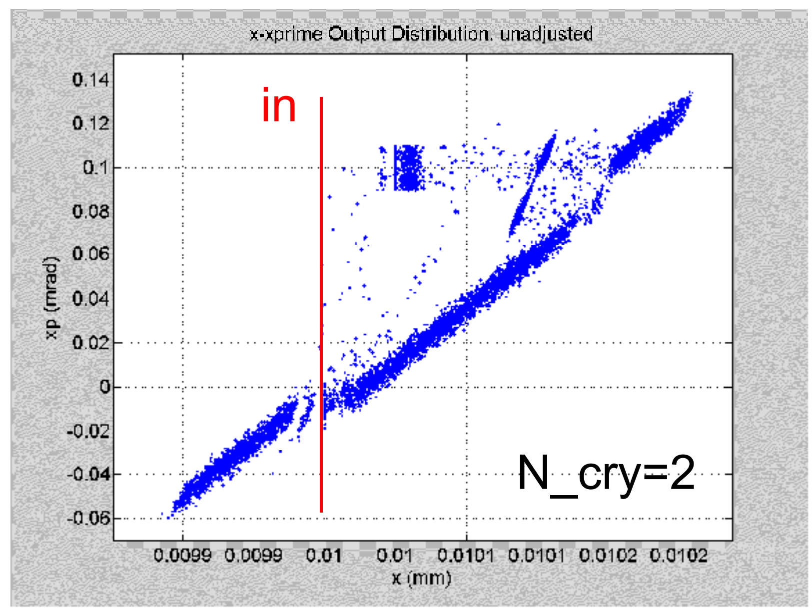
Profile plots

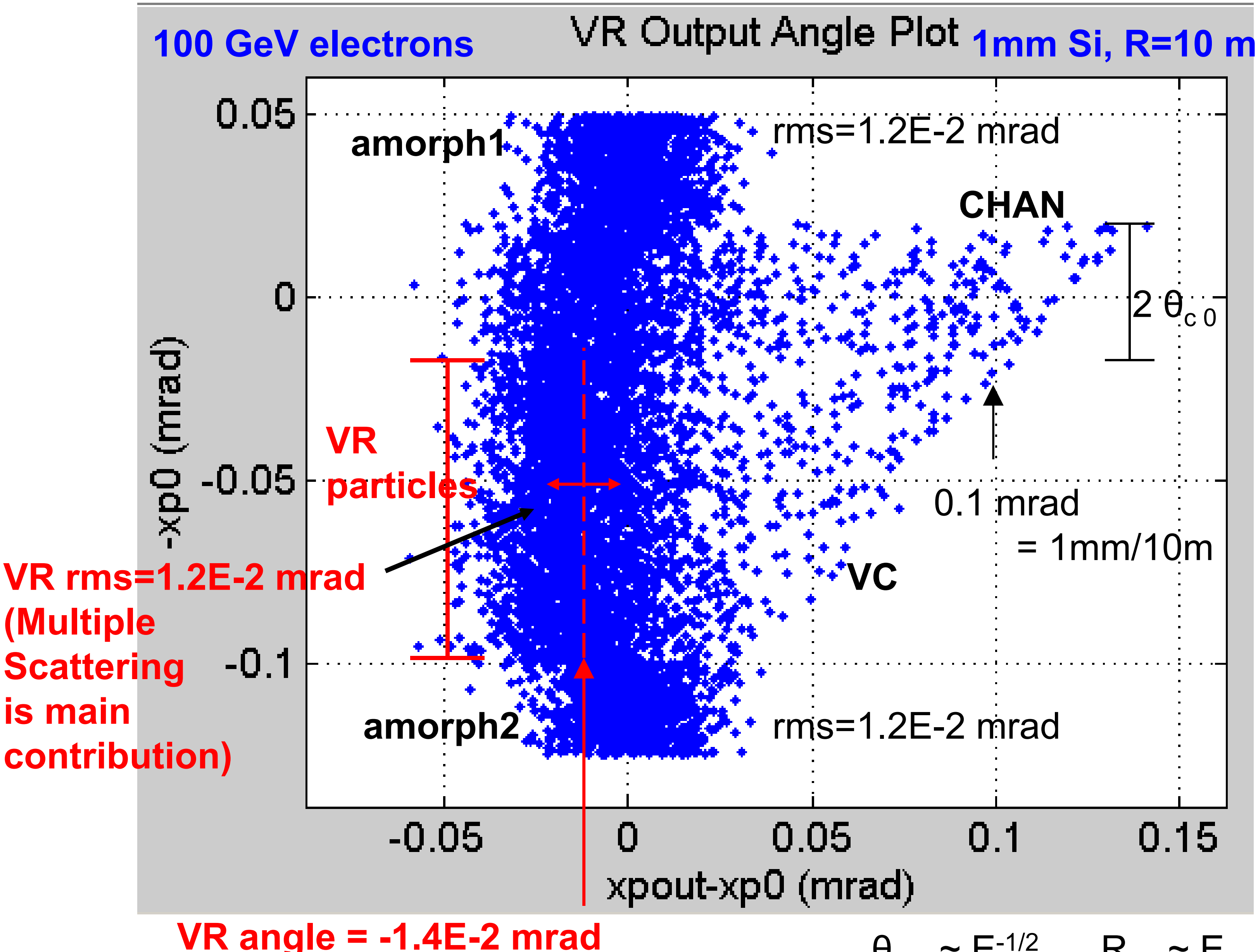
Phase space plots











$\theta_{c\,0} \sim E^{-1/2}$ $\quad R_{crit} \sim E$ $\quad L_{dech} \sim E$

Code VR: $\theta_{refl} = -0.8\,\theta_{c\,0}\,(1 - 2.55\,(R_{crit} / R))$ $\quad$ (0.02 mrad) $\quad$ (0.21 m) $\quad$ (3 mm)