Selective amplification of x-rays in the energy range 50-65 keV

J.E. Fernández, [1,2] V. Scot, [1]
D. Sivieri,[3] and A. Guidetti [3]

(1) Laboratory of Montecuccolino (DIENCA)
Alma Mater Studiorum University of Bologna, Italy

(2) Istituto Nazionale di Fisica Nucleare (INFN)
(3) IMAL srl, Modena, Italy

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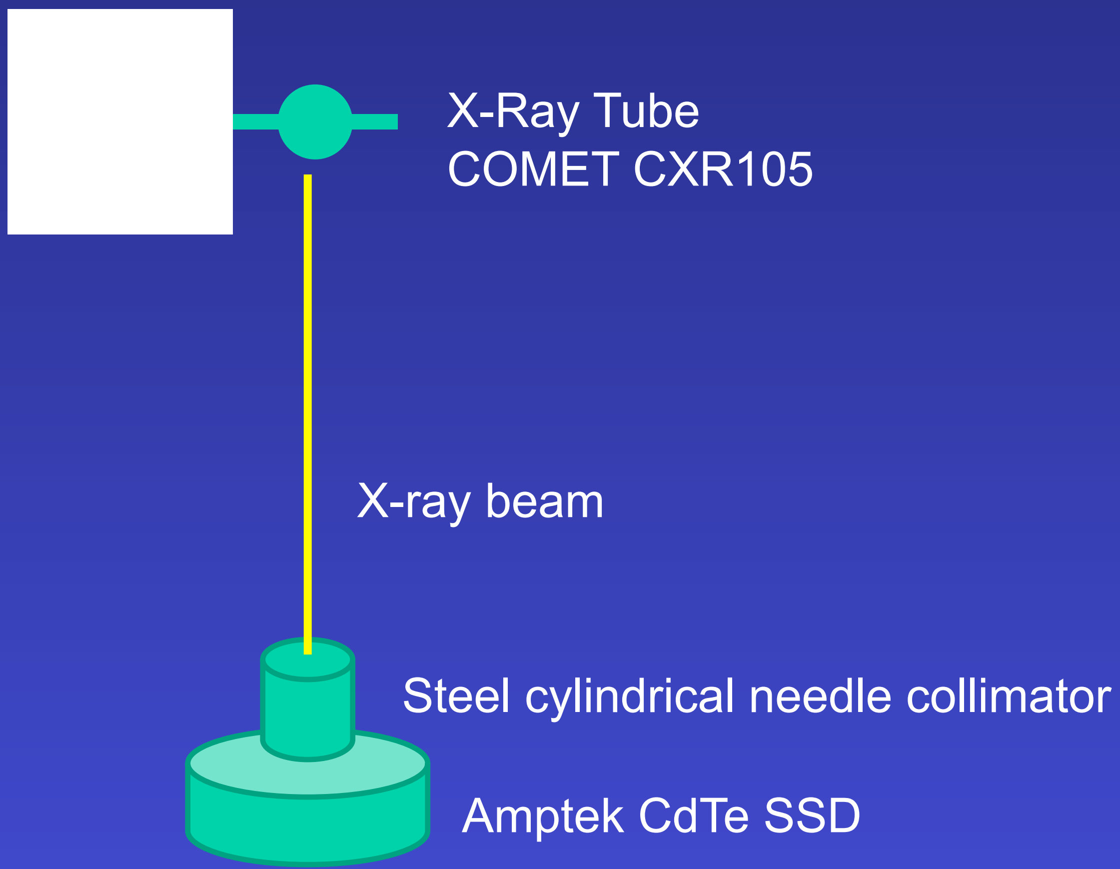
OUTLOOK

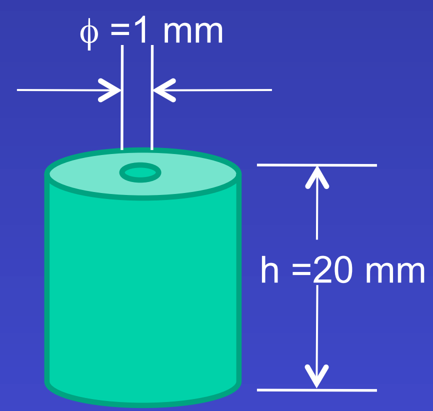
- Experimental results
- Theoretical Model
  - Description of Polarization
  - Scalar and Vector Models
  - The Codes
- Interpretation of Experimental Data

EXPERIMENTAL RESULTS

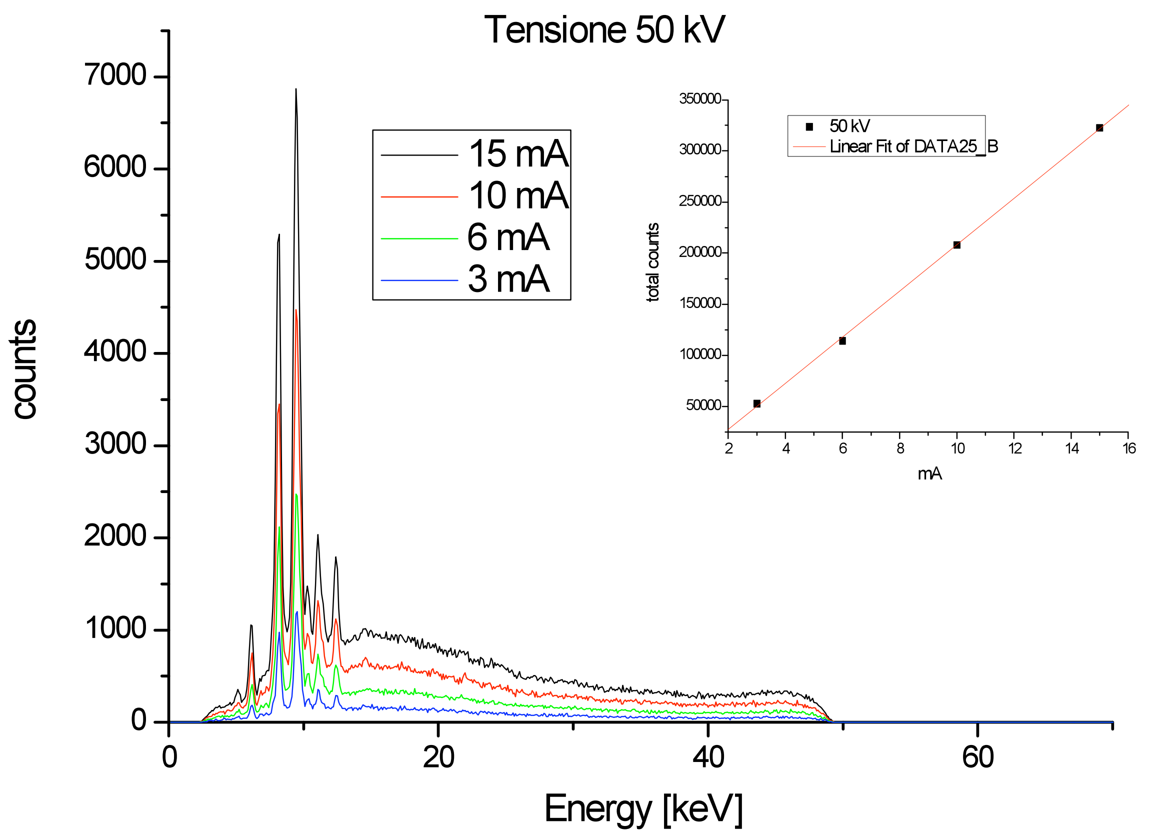
Direct Measurement of X-Ray Spectra



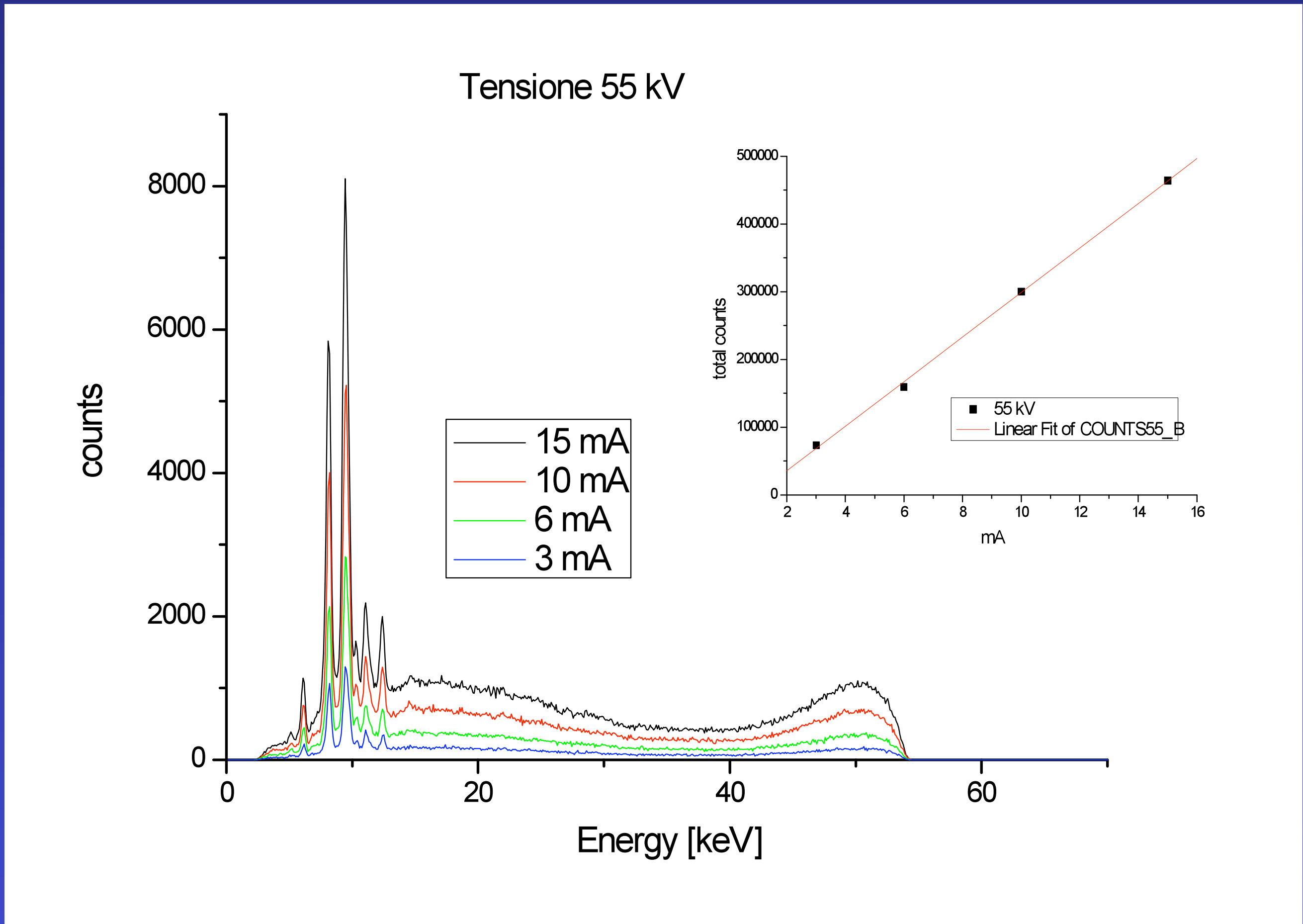
Set-up #1 Cylindrical Collimator



50 kV

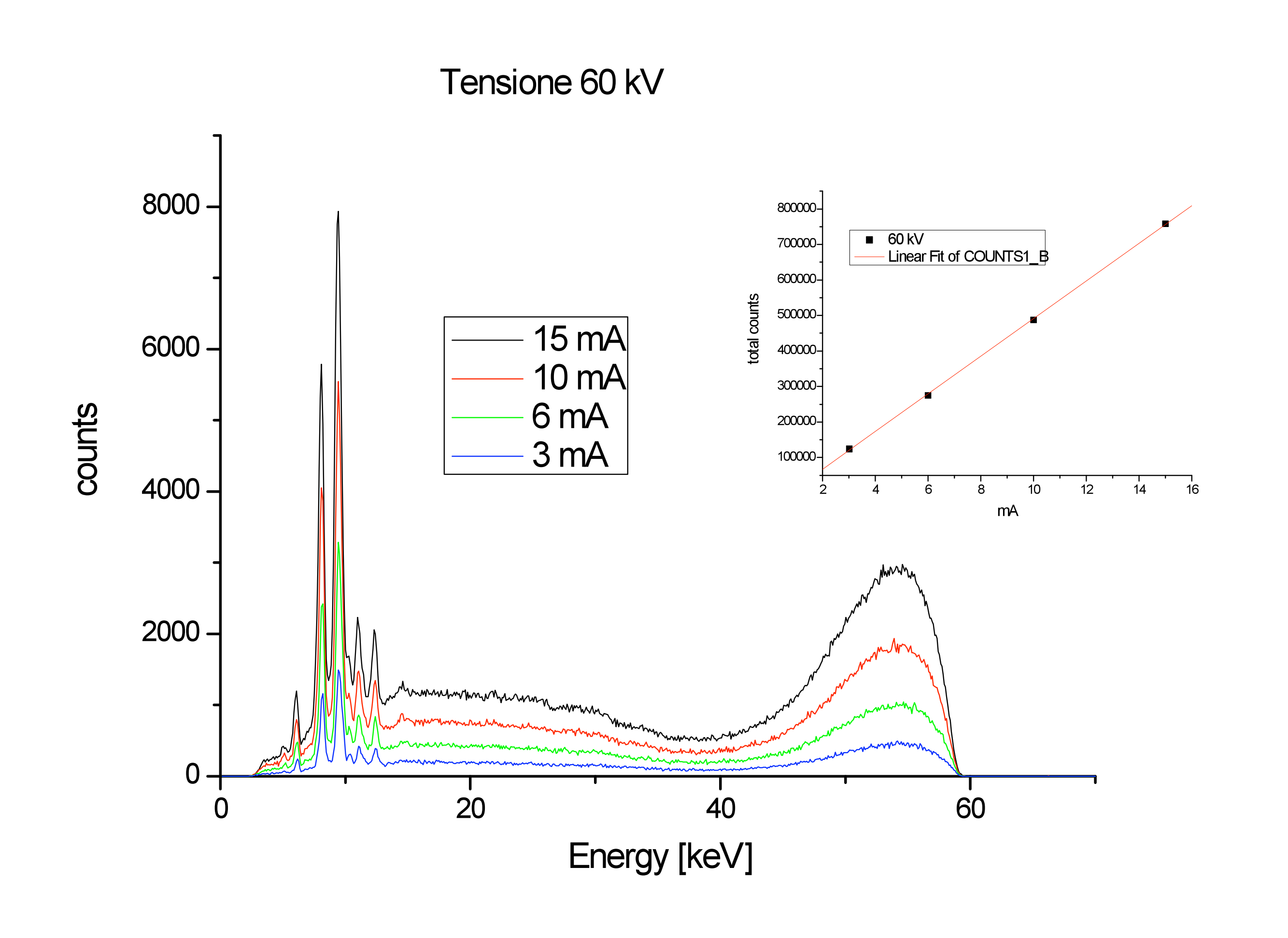

Tensione 50 kV
counts
7000
6000
5000
4000
3000
2000
1000
0
0
20
40
60
Energy [keV]
15 mA
10 mA
6 mA
3 mA
total counts
350000
300000
250000
200000
150000
100000
50000
2
4
6
8
10
12
14
16
mA
50 kV
Linear Fit of DATA25_B

55 kV



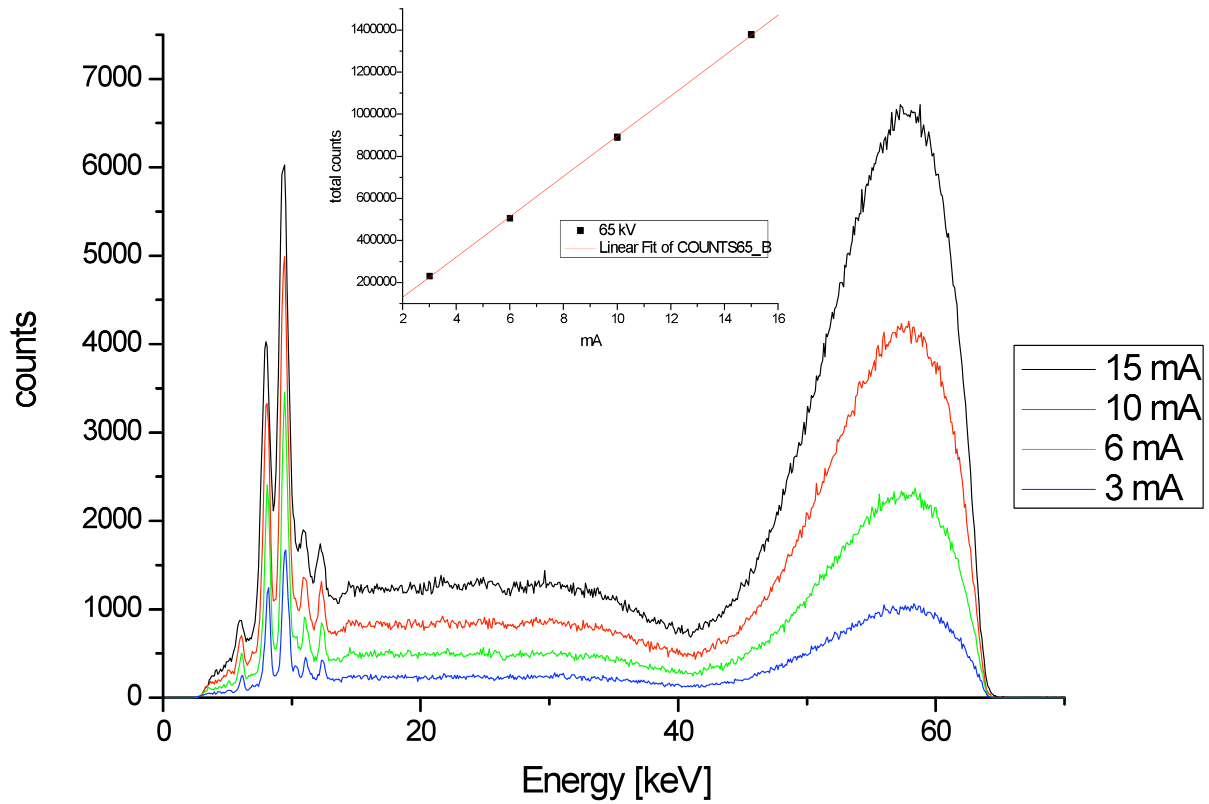
Tensione 55 kV
counts
8000
6000
4000
2000
0
0
20
40
60
Energy [keV]
15 mA
10 mA
6 mA
3 mA
total counts
500000
400000
300000
200000
100000
0
2
4
6
8
10
12
14
16
mA
55 kV
Linear Fit of COUNTS55_B

60 kV



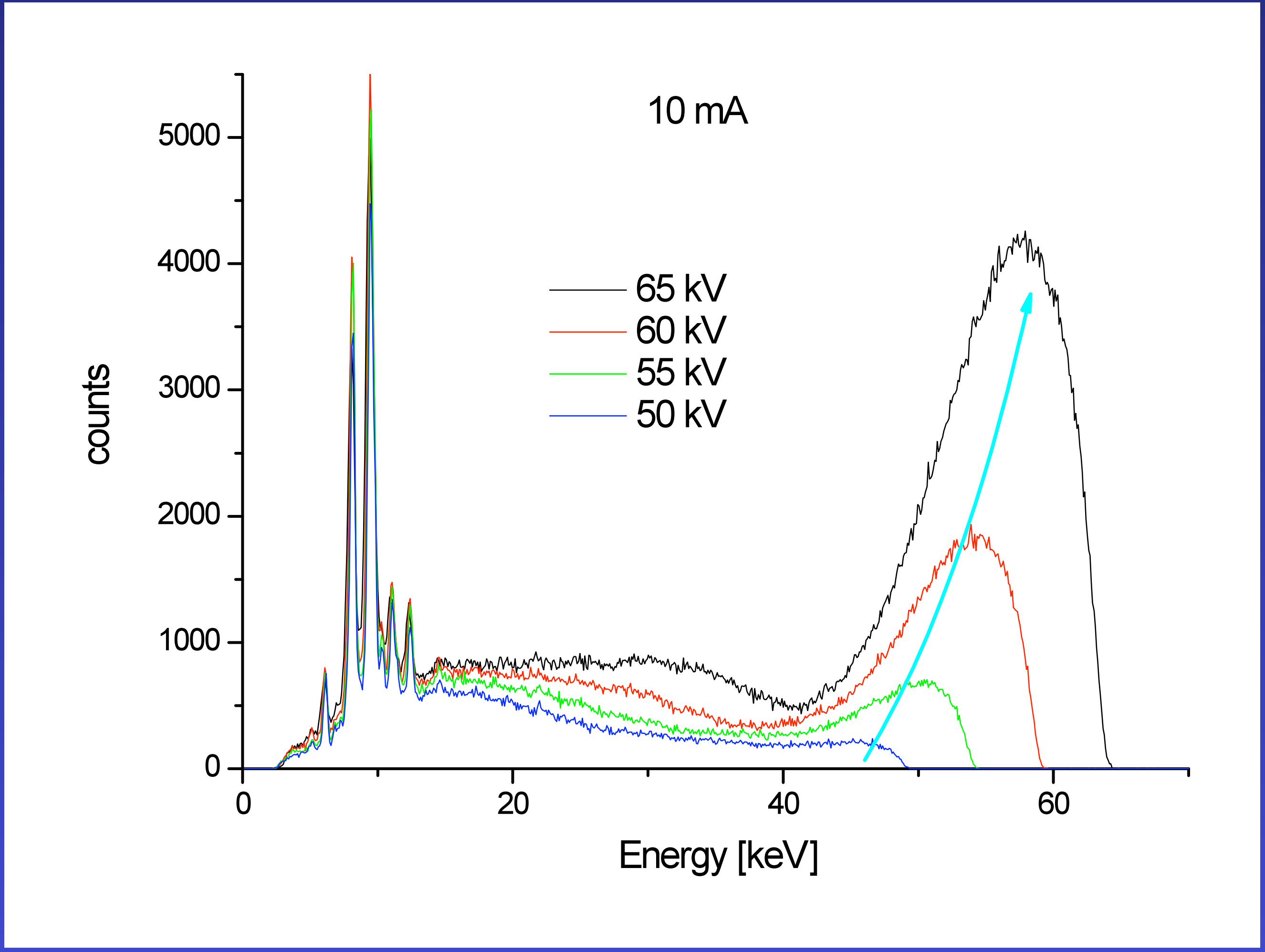
Tensione 60 kV
counts
Energy [keV]
15 mA
10 mA
6 mA
3 mA
0
2000
4000
6000
8000
0
20
40
60
60 kV
Linear Fit of COUNTS1_B
total counts
mA
100000
200000
300000
400000
500000
600000
700000
800000
2
4
6
8
10
12
14
16

65 kV

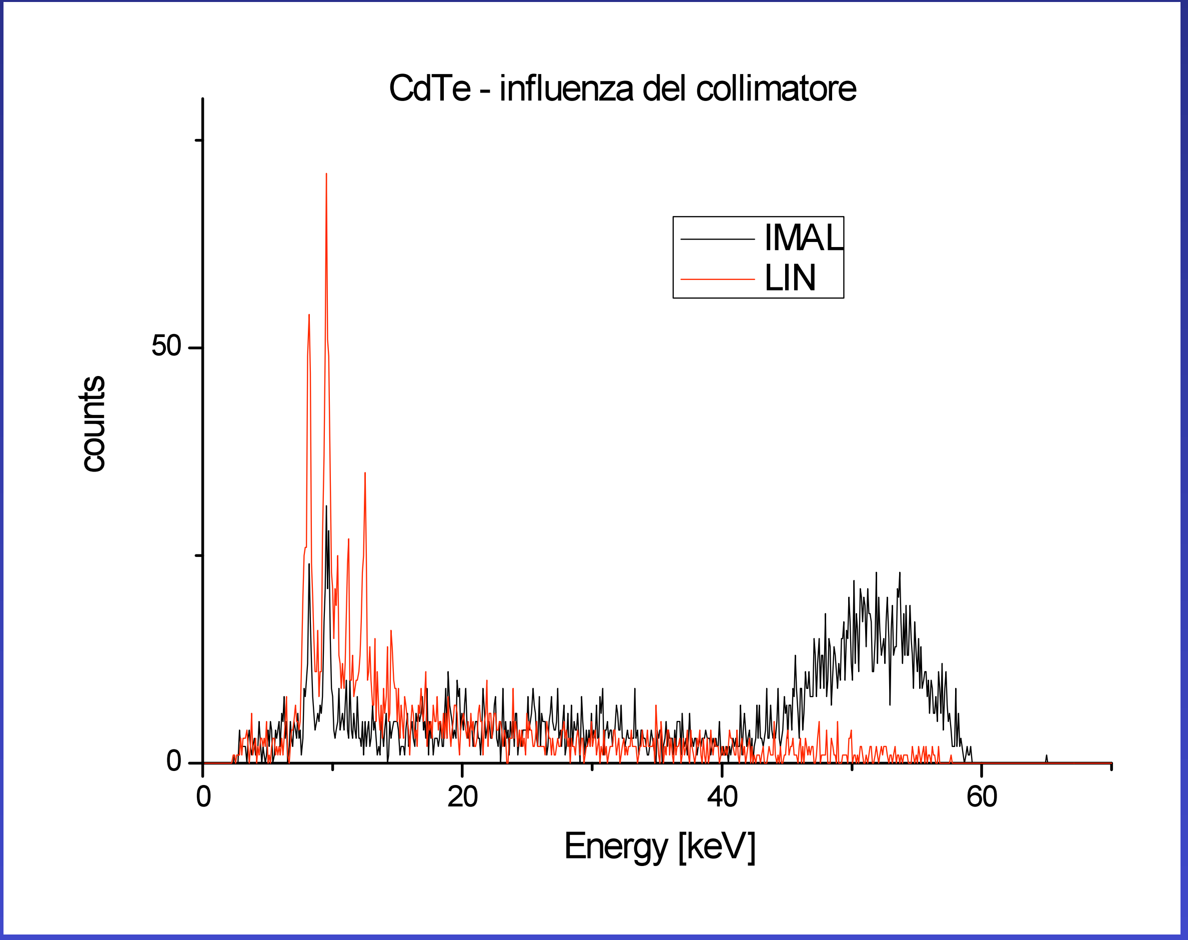


counts
7000
6000
5000
4000
3000
2000
1000
0
0
20
40
60
Energy [keV]
15 mA
10 mA
6 mA
3 mA
total counts
1400000
1200000
1000000
800000
600000
400000
200000
2
4
6
8
10
12
14
16
mA
65 kV
Linear Fit of COUNTS65_B

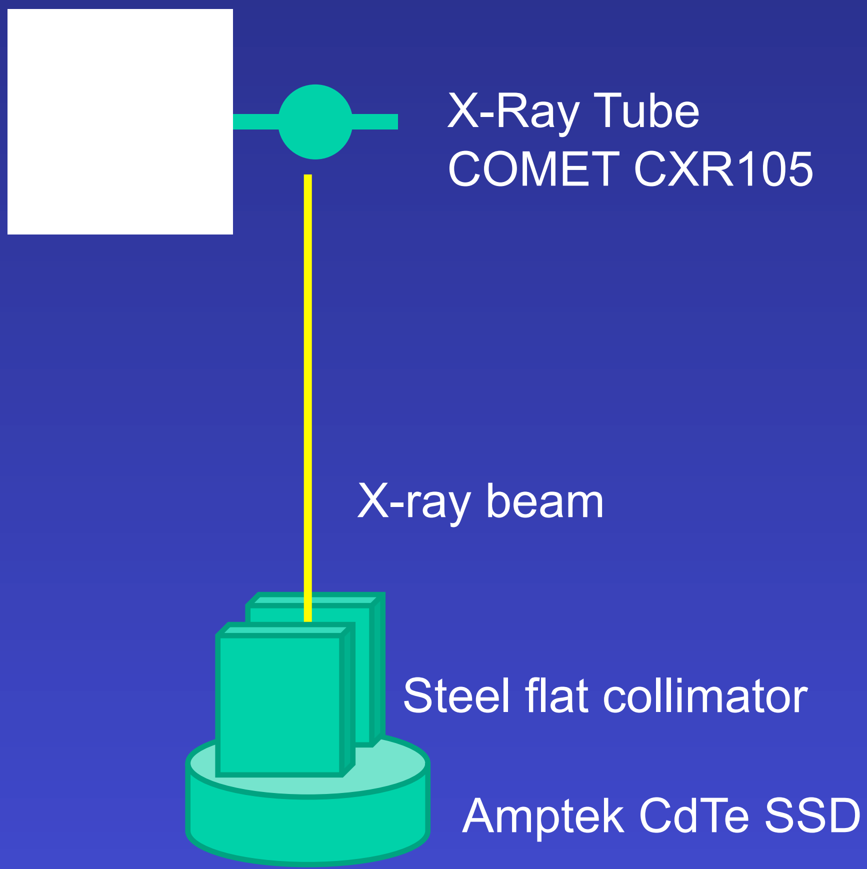
Variation with KV



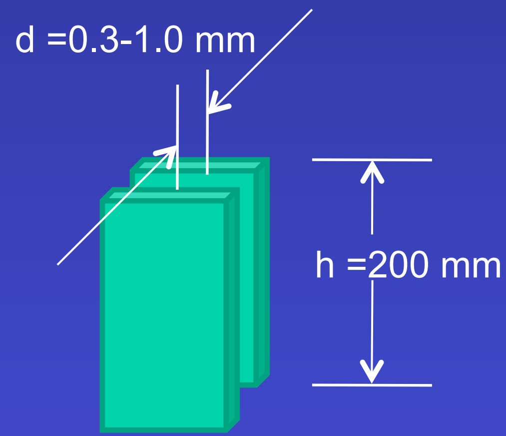
Comparison between needle and trap collimators



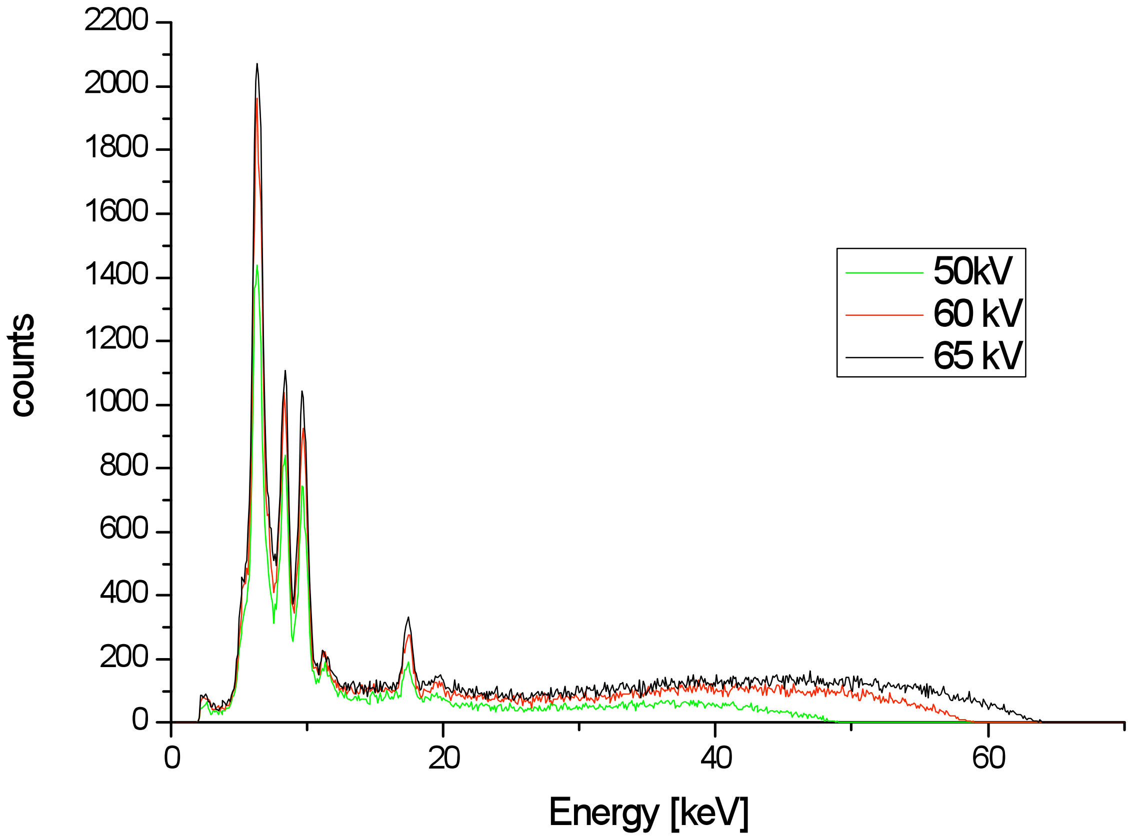
Direct Measurement of X-Ray Spectra



Set-up #2 Plate Collimator



Variation with KV

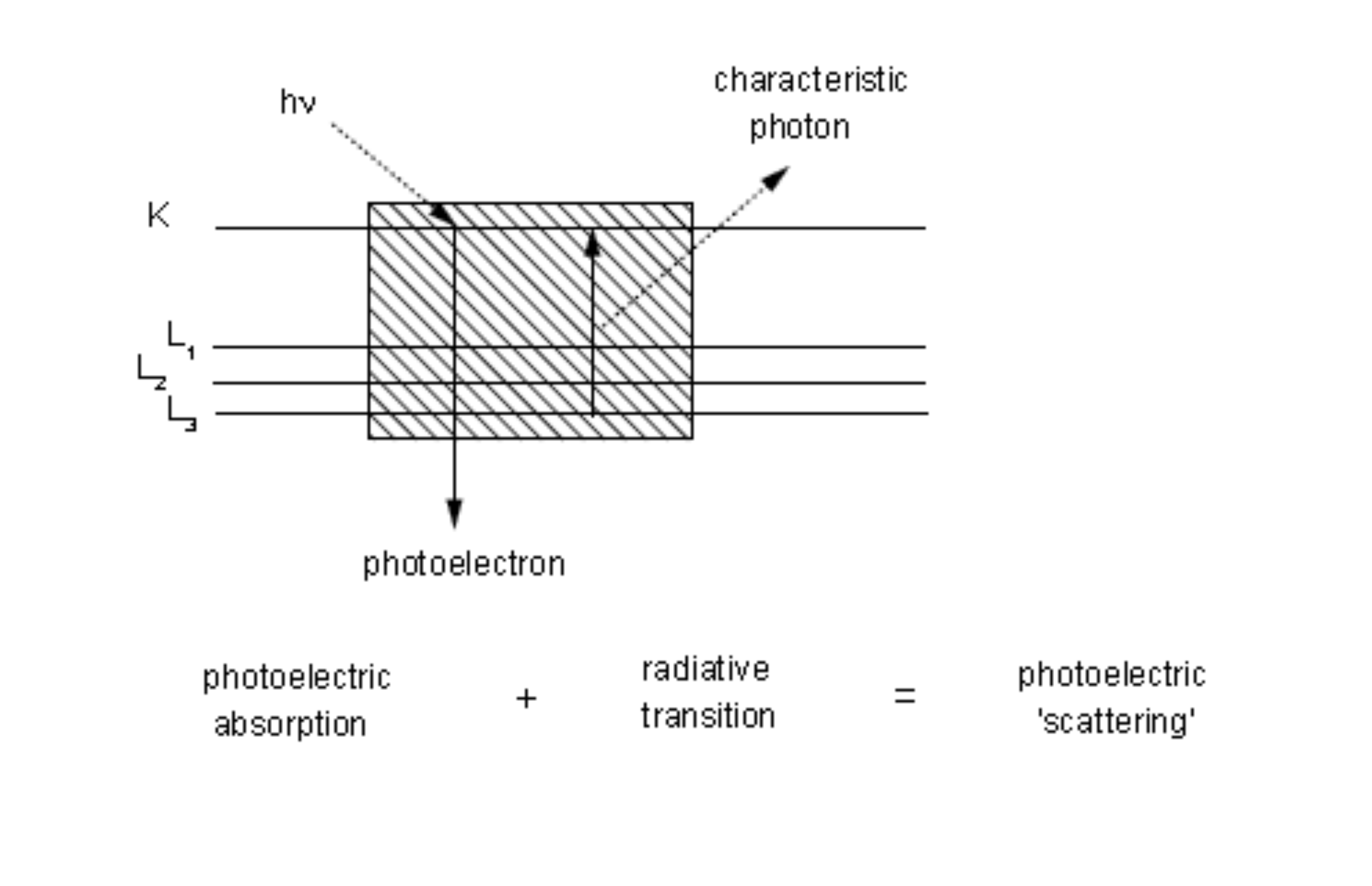


THEORETICAL MODEL

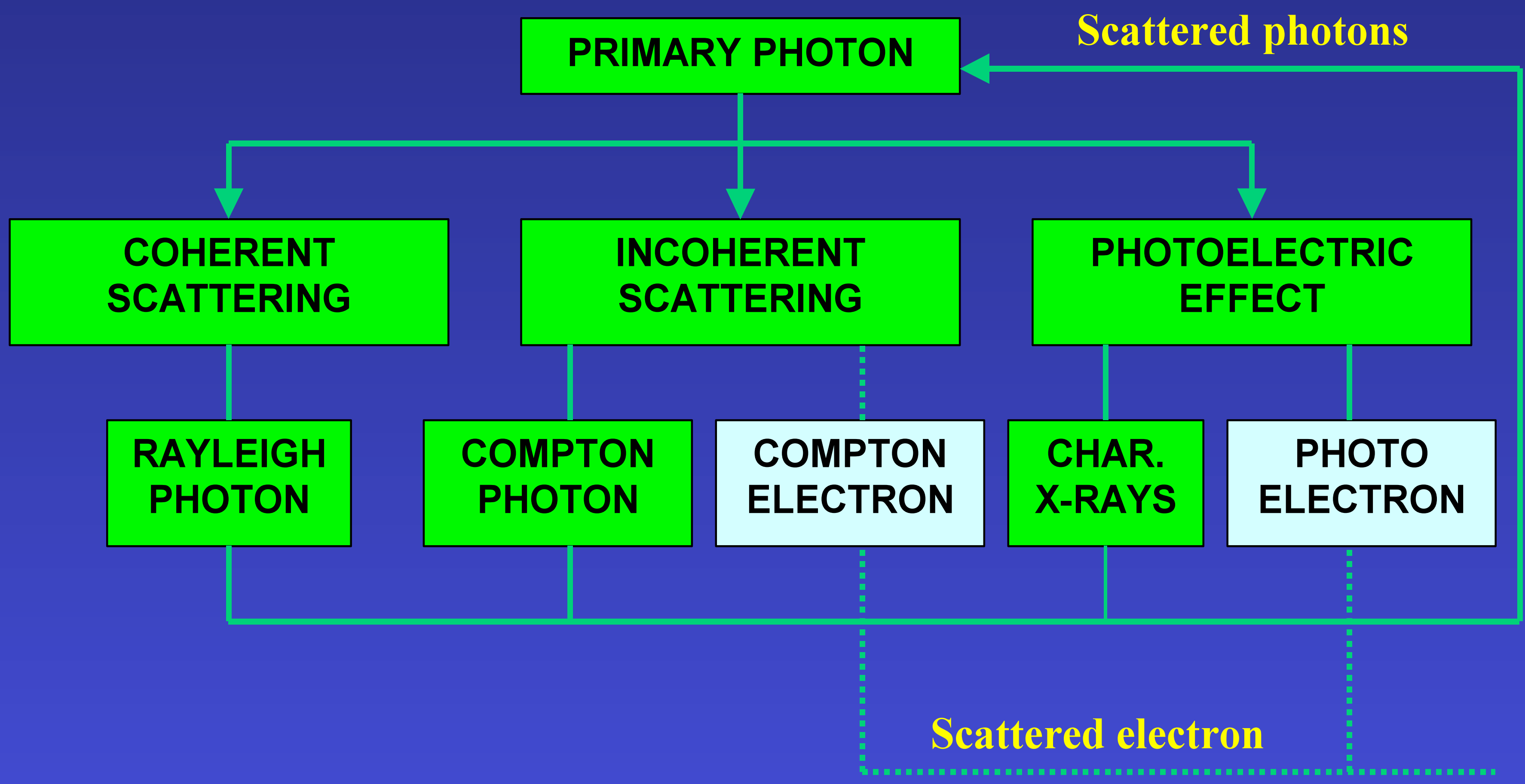
MULTIPLE SCATTERING

- X-rays penetrate deeply into the matter, and, in a thick medium, give place to a phenomenon known as multiple scattering (i.e, multiple collisions).
- Multiple scattering models describe the influence of the prevailing interactions in the x-ray regime (photoelectric effect, Compton scattering and Rayleigh scattering)

Photoelectric effect as 'scattering'



PREVAILING INTERACTIONS IN THE *X-RAY* REGIME



DESCRIPTION OF POLARIZATION

WHY POLARIZATION?

Polarization state → wave nature of photons

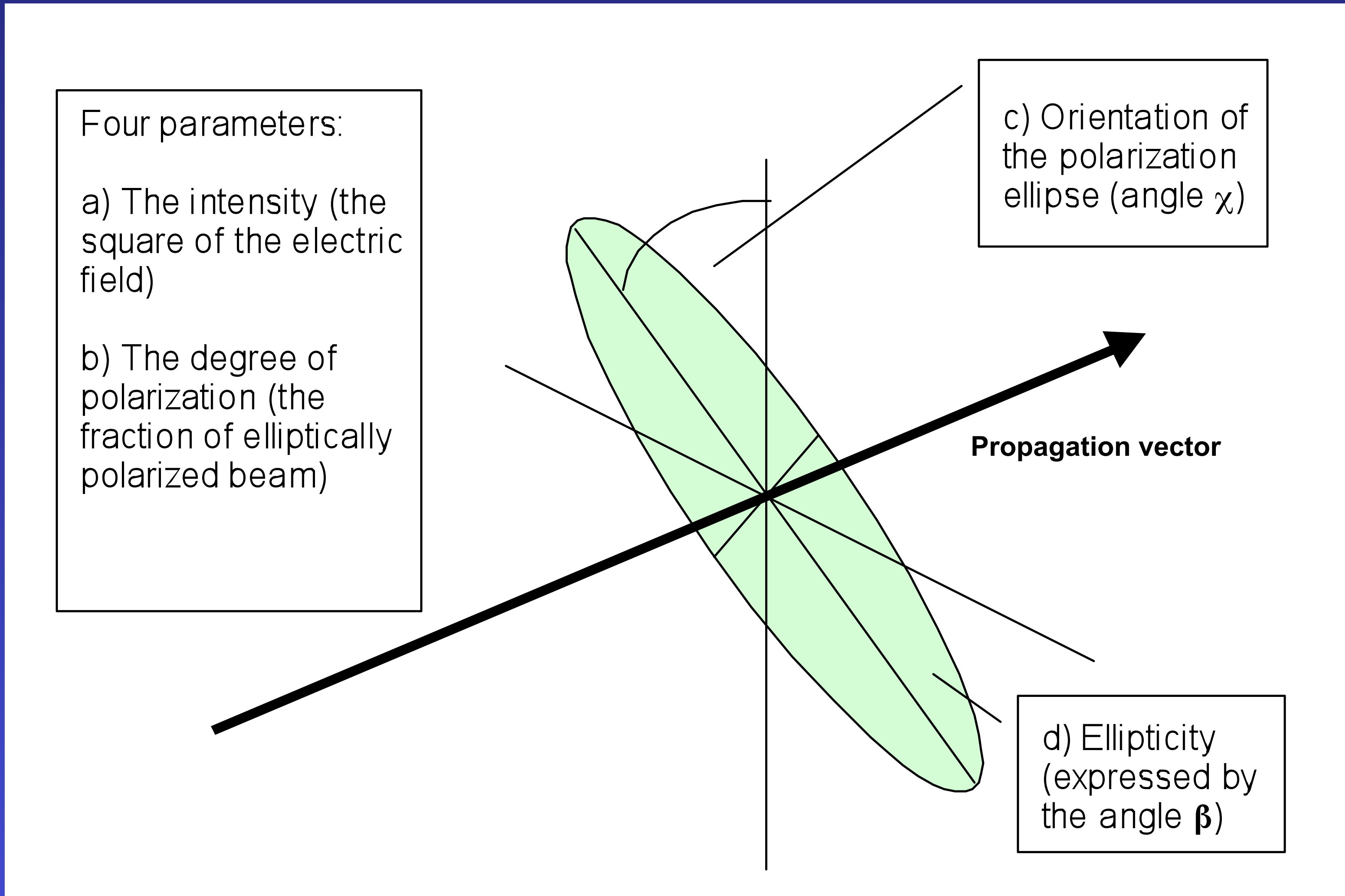
By considering polarization we improve the model of photon diffusion

Without polarization photons are considered only as a particles

⬇

a good approximation in many cases, but not for phenomena that are influenced by their wave properties

Polarization state definition



REPRESENTATION OF POLARIZED RADIATION

Stokes parameters I,Q,U,V (having the dimension of an intensity) can specify the physical magnitudes:

- **Intensity of the beam**
- **Degree of polarization**
- **Orientation of the ellipse of polarization**
- **Ellipticity**

COLLISION SCHEME

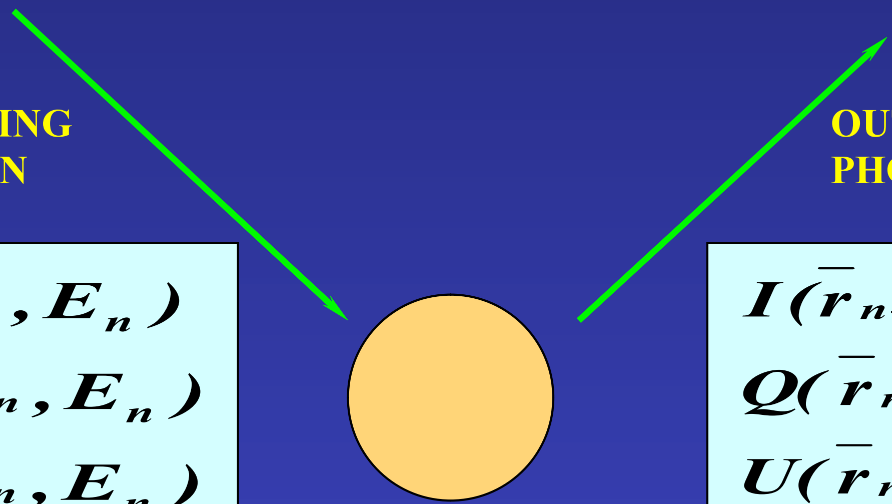
$\overline{\omega_n}, E_n$

INCOMING PHOTON

$\overline{\omega_{n+1}}, E_{n+1}$

OUTGOING PHOTON

$I(\overline{r}_n, \overline{\omega}_n, E_n)$
$Q(\overline{r}_n, \overline{\omega}_n, E_n)$
$U(\overline{r}_n, \overline{\omega}_n, E_n)$
$V(\overline{r}_n, \overline{\omega}_n, E_n)$



ATOM

$\overline{r_{n+1}}$

$I(\overline{r}_{n+1}, \overline{\omega}_{n+1}, E_{n+1})$
$Q(\overline{r}_{n+1}, \overline{\omega}_{n+1}, E_{n+1})$
$U(\overline{r}_{n+1}, \overline{\omega}_{n+1}, E_{n+1})$
$V(\overline{r}_{n+1}, \overline{\omega}_{n+1}, E_{n+1})$

Modification of the polarization state due to a collision (Stokes representation)

TWO RELEVANT ASPECTS

- A collision always changes the polarization state
- The angular distribution for scattered unpolarized and polarized photons is different

PHOTON DIFFUSION IS DESCRIBED BY A "VECTOR" TRANSPORT EQUATION (THE 3-D EQUATION IS SHOWN HERE)

$$\vec{\omega}\cdot\nabla\vec{f}^{(S)}(\vec{r},\vec{\omega},\lambda) = -\mu(\vec{r},\lambda)\,\vec{f}^{(S)}(\vec{r},\vec{\omega},\lambda) + \int_0^\infty d\lambda' \int_{4\pi} d\omega'\; H^{(S)}(\vec{r},\vec{\omega},\lambda,\vec{\omega}',\lambda')\,\vec{f}^{(S)}(\vec{r},\vec{\omega}',\lambda') + \vec{S}^{(S)}(\vec{r},\vec{\omega},\lambda)$$

where

$$\vec{f} = \begin{bmatrix} I(\vec{r},\vec{\omega},\lambda) \\ Q(\vec{r},\vec{\omega},\lambda) \\ U(\vec{r},\vec{\omega},\lambda) \\ V(\vec{r},\vec{\omega},\lambda) \end{bmatrix}$$

VECTOR TRANSPORT EQUATION (CONT.)

where

$$H^{(S)}(\vec{r},\vec{\omega},\lambda,\vec{\omega}',\lambda') = L^{(S)}(\pi-\psi)\, K^{(S)}(\vec{r},\vec{\omega},\lambda,\vec{\omega}',\lambda')\, L^{(S)}(-\psi')$$

$H^{(S)}$ = kernel matrix in the meridian plane of reference

$K^{(S)}$ = scattering matrix in the scattering plane of reference

IMPORTANT PROPERTIES OF THE "VECTOR" TRANSPORT EQUATION

- Describes the evolution of the full polarization state (not only the intensity of the beam)
- Is linear (for the Stokes representation)
- Requires the simultaneous solution of the whole set of transport equations
- Cannot be transformed in a scalar equation !! (due to the coupling in the scattering term)

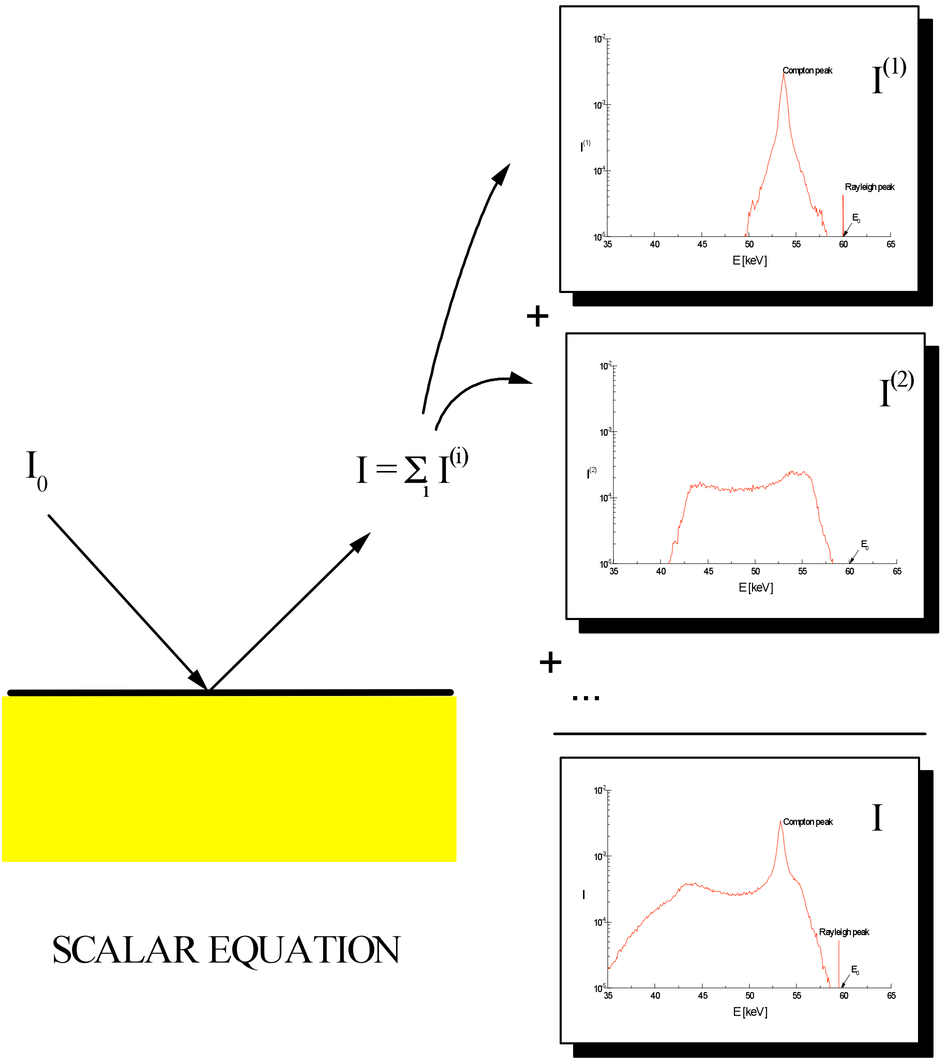
SCALAR and VECTOR MODELS

MODELS

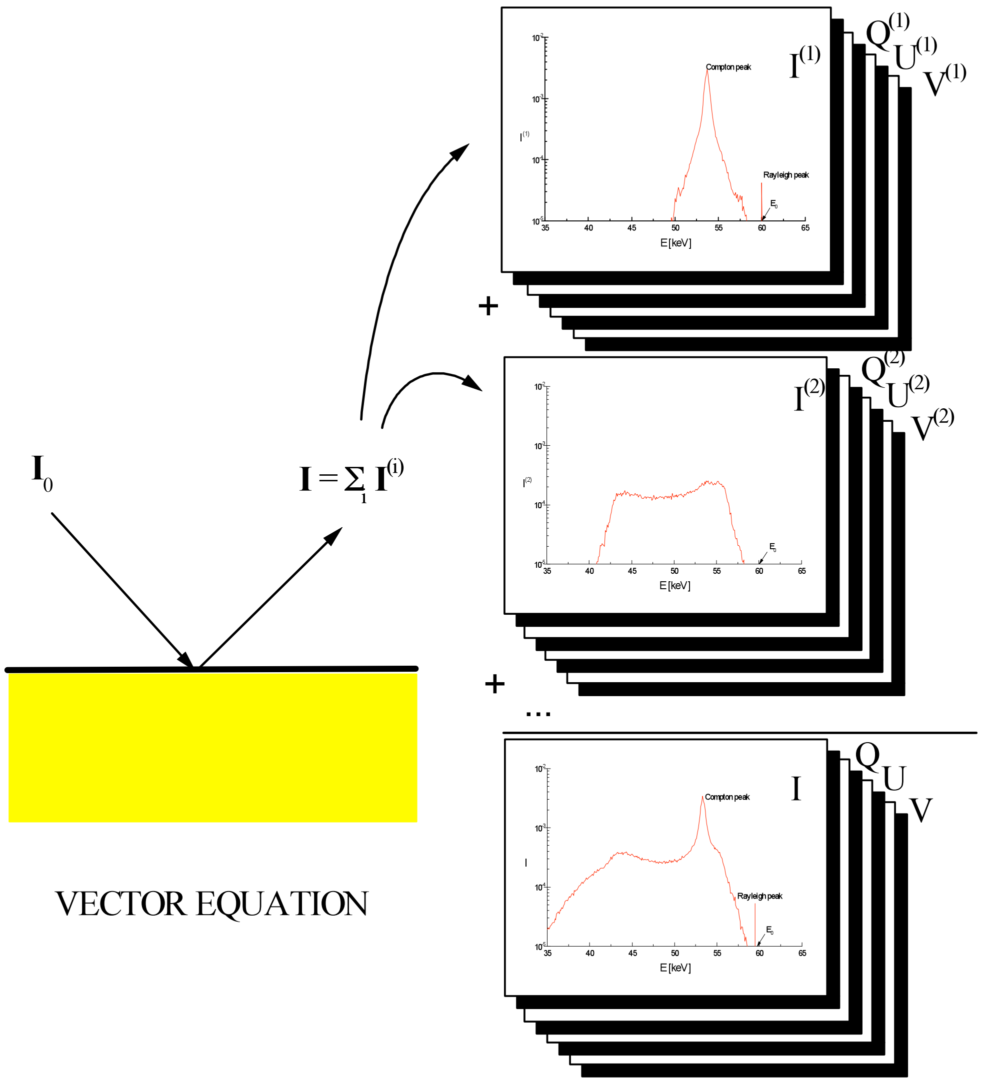
Different degrees of approximation to describe the diffusion photons:

- ***scalar model***: photons never modify an average polarization state
- ***vector model***: transport of photons starting with arbitrary polarization state

Scalar transport equation



Vector transport equation



THE CODES

SOLUTION TECHNIQUES

The transport equation is solved using an order-of-collisions scheme

comparable results for deterministic and Monte Carlo solutions

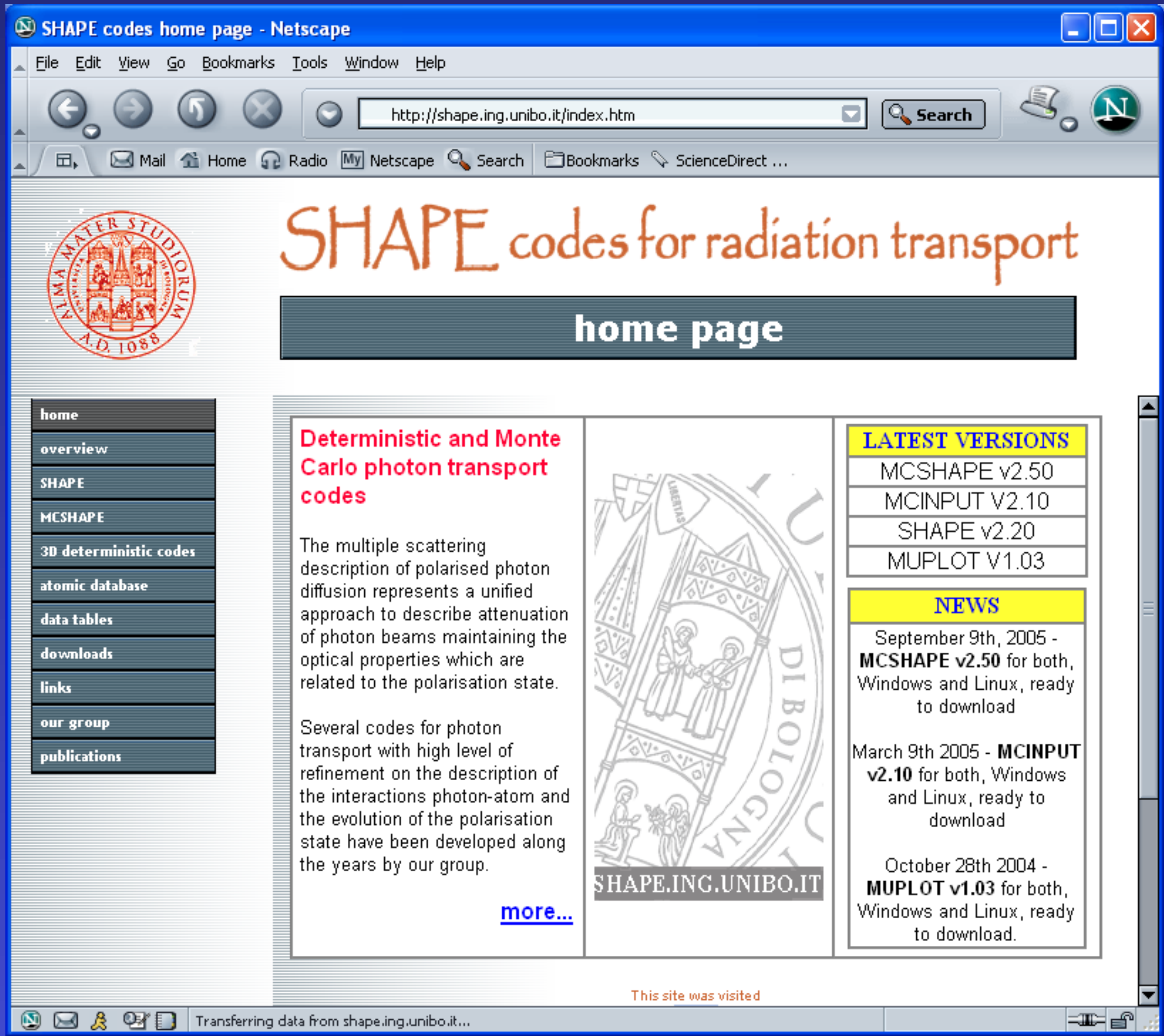
Deterministic vs. Monte Carlo

Solution	Deterministic	Monte Carlo (statistical)
Scope of the solution	Global	Local
Accuracy	↑	↓
Capability to describe the geometry	↓	↑
Number of collisions	↓	↑
Developed codes	SHAPE	MCSHAPE

CHARACTERISTICS OF THE CODE MCSHAPE

- Arbitrary polarization state of the source
- Multi-layer multi-component homogeneous targets
- Monochromatic or polychromatic source
- Doppler broadening (for Compton scattering)
- Full description of the polarization state
- N-collisions

WEB SITE http://shape.ing.unibo.it



CODES COMPARISON (part 1: Physics)

Features	Details	SHAPE v2.20	MCSHAPE v2.62
Physics	photoelectric effect	☒	☒
	~1000 characteristic lines	☒	☒
	line width	☒	☒
	atomic Rayleigh scattering	☒	☒
	atomic Compton scattering	☒	☒
	Compton profile	first collision only	☒
	electron bremsstrahlung	foreseen in v3	foreseen in v3
	open data bases	☒	☒
	user defined elements		foreseen in v3
	infinite thickness targets	☒	☒
	finite thickness targets		☒
	multilayer targets		☒
	polarization representation	Stokes	Stokes
	source polarization state	**linear/ unpolarised**	**arbitrary**
	calculated spectrum	intensity component only	**full polarization state**
	monochromatic source	☒	☒
	polychromatic source	postprocessor	☒
	external detector	solid state Si/Ge	☒
	reflection geometry	☒	☒
	transmission geometry		☒

UNIQUE FEATURES!

CODES COMPARISON (part 2: model and programming)

Features	Details	SHAPE v2.20	MCSHAPE v2.62
Miscellaneous	selective computation of single interaction chains	☒	partial
Transport model	particle	photons	photons
	scalar equation	☒	☒
	vector equation	☒	☒
	solution	deterministic	Monte Carlo
	collisions	3	100
	1-D spatial geometry	☒	☒
	3-D spatial geometry		**using MCSHAPE3D**
Code	language	DELPHI	FORTRAN 90
	additional libraries	graphics	WINTERACTER
	platform	WINDOWS	WINDOWS / LINUX
	distribution	web site	web site
	parallelization		MPICH v1.0 (only Linux)
Applications	spectroscopy	☒	☒
	analytical chemistry	☒	☒
	radiation metrology	☒	☒
	x-ray optics		with MCSHAPE3D
	dosimetry		with MCSHAPE3D
	radiation transport teaching	☒	☒

NEW!!
3D version
of MCSHAPE

INTERPRETATION OF EXPERIMENTAL DATA

SIMULATIONS WITH MCSHAPE 1-D

The simulation was performed using the following parameters:

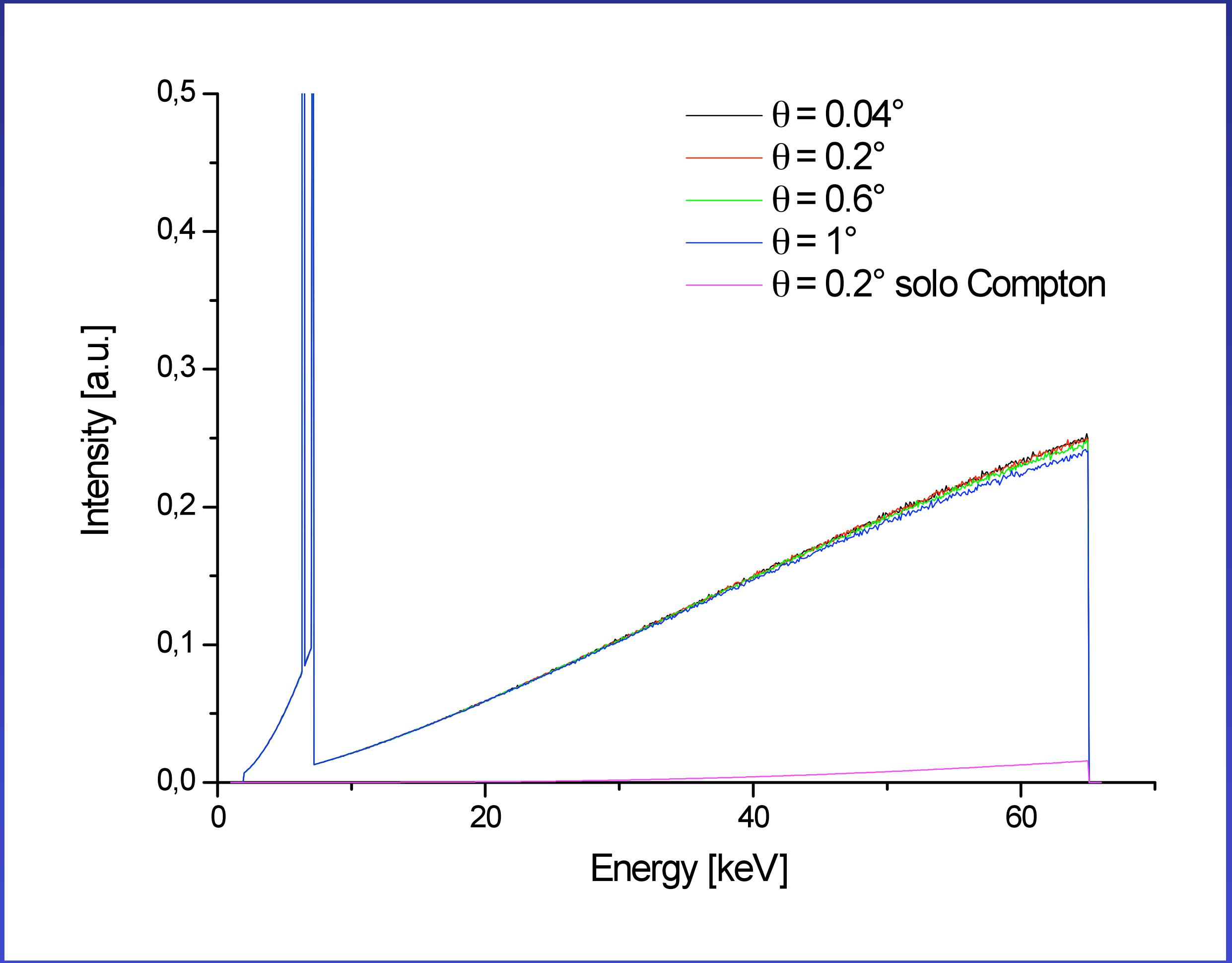
(1) Pure iron flat collimator

(2) Incidence and take-off angles in agreement with a scattering angle of:

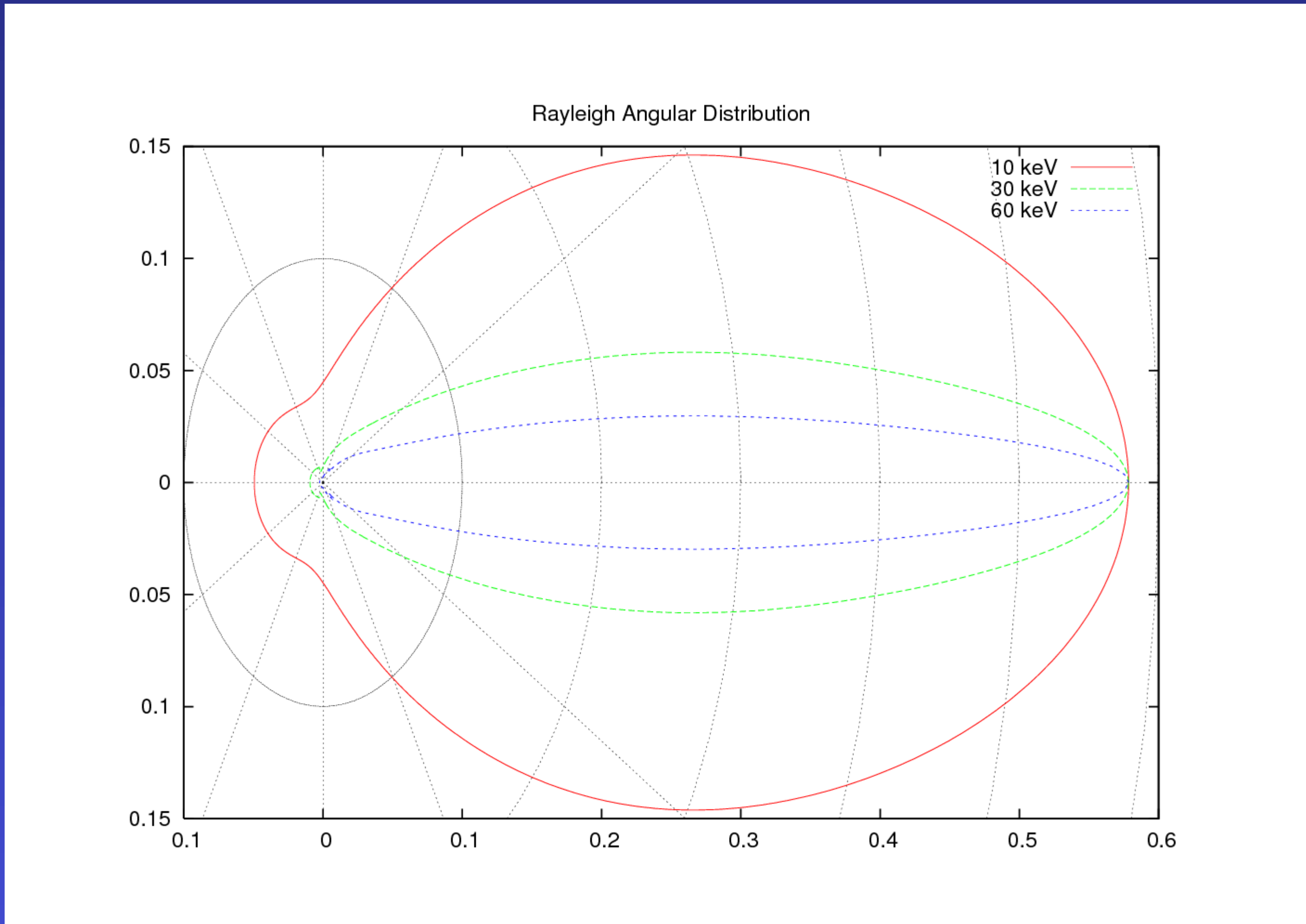
$$\theta \approx tg\theta = \frac{\frac{1}{2}\,\text{collimator diameter}}{\text{distance collimator} - \text{tube}} = \frac{\frac{1}{2}(1mm)}{(2000mm)} \approx 2.5\,10^{-4}\,rad$$

(3) Polychromatic excitation from 2 to 65 keV

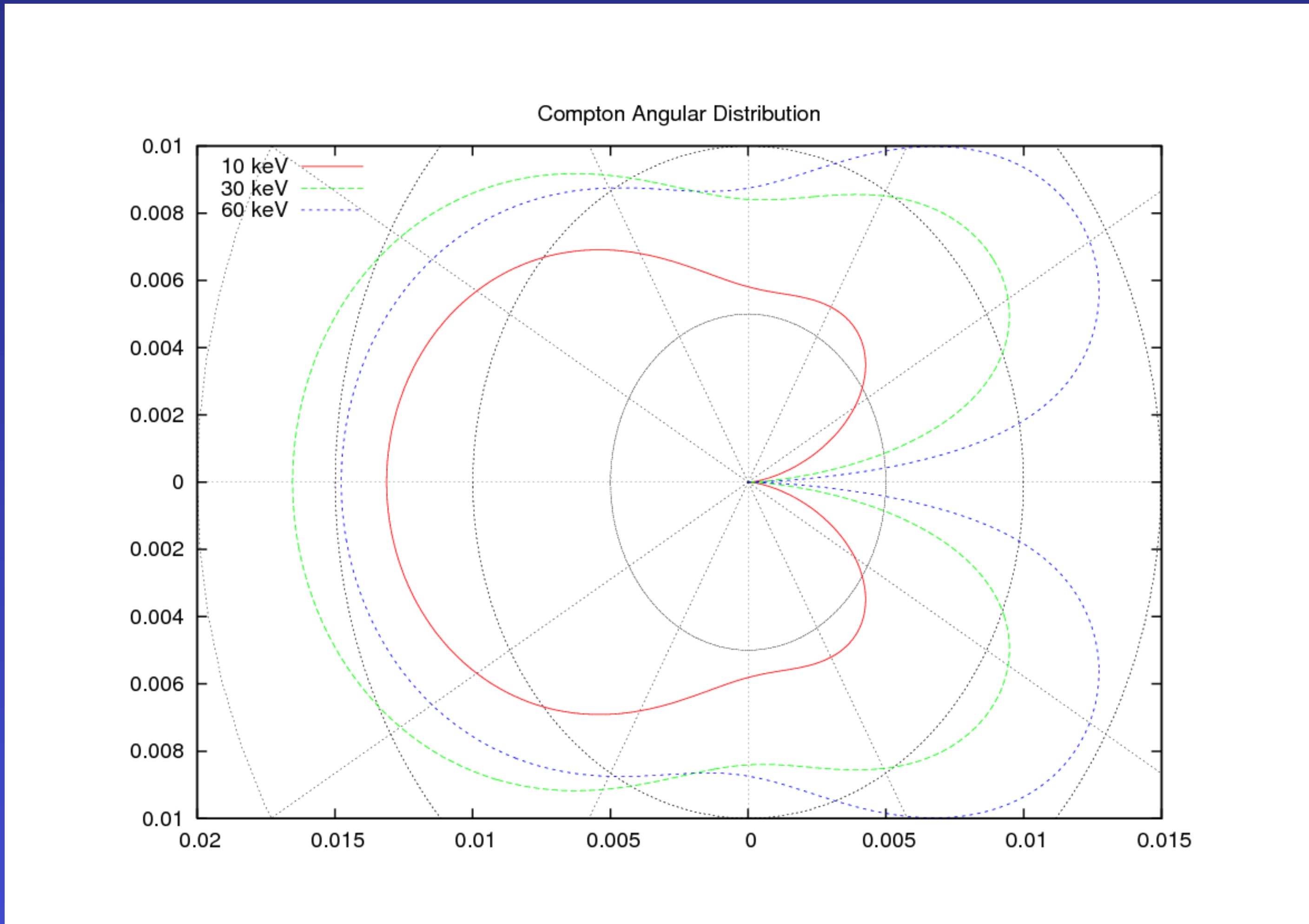
SIMULATION WITH MCSHAPE 1-D



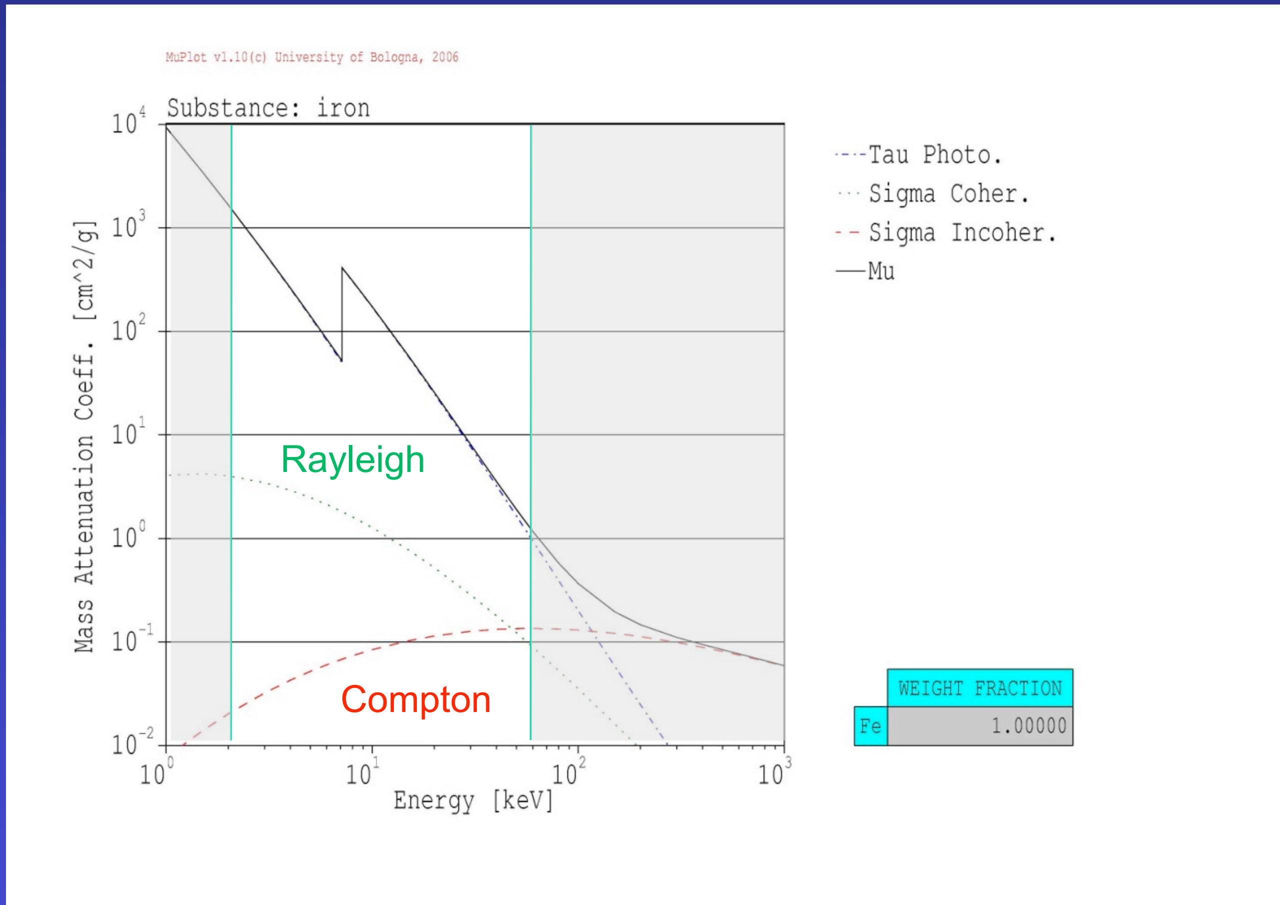
Atomic Rayleigh scattering always prevails in forward scattering



Atomic Compton scattering is negligible in forward scattering



In addition, Rayleigh scattering prevails (or is equivalent) to Compton in the energy range considered



CONCLUSIONS

CONCLUSIONS (1/2)

- Needle collimators can be used to remarkably enhance the intensity of the x-ray beam in the high energy side of x-ray spectra
- At 65 kV operation, the enhancement of the spectrum is equivalent to the whole incident spectrum and is concentrated on the high energy side.
- Plate collimators produce a similar but weaker effect.
- The effect has been tested in the range 50-65 keV

CONCLUSIONS (2/2)

- The MCSHAPE 1-D code was used to interpret the physical reasons of this effect.
- The enhancement can be explained as due to multiple scattering, in particular, atomic Rayleigh scattering in the forward direction (small angle scattering).
- The measured enhancement exceeds the theoretical prediction of the 1-D code but is consistent with a 3-D estimation.

Thank you for your attention!