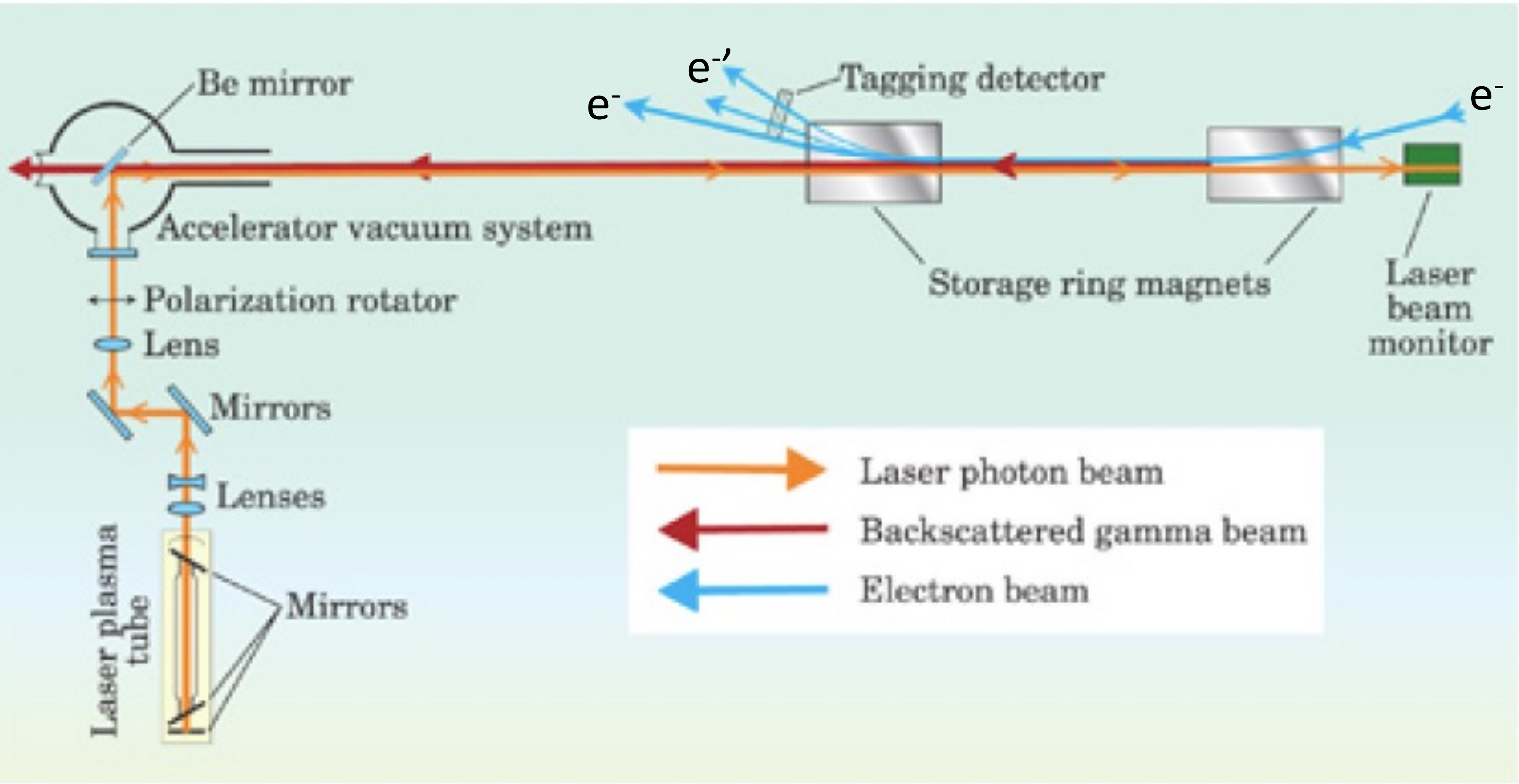
Ladon Beam Optics on Adone



Scattering of polarized Laser photons on ultra-relativistic electrons in a storage ring

$\overrightarrow{\gamma_L} + e \rightarrow e + \overrightarrow{\gamma}$

eV GeV GeV GeV

$$E_\gamma = \frac{4\gamma^2 E_\ell}{1 + \frac{4\gamma E_\ell}{m_e} + \theta^2\gamma^2}$$

$(\theta_\gamma = 180^o) \quad \theta = 0^o$

$k_{max} = E_{\gamma max} = E_e\, Z/(1+Z)$

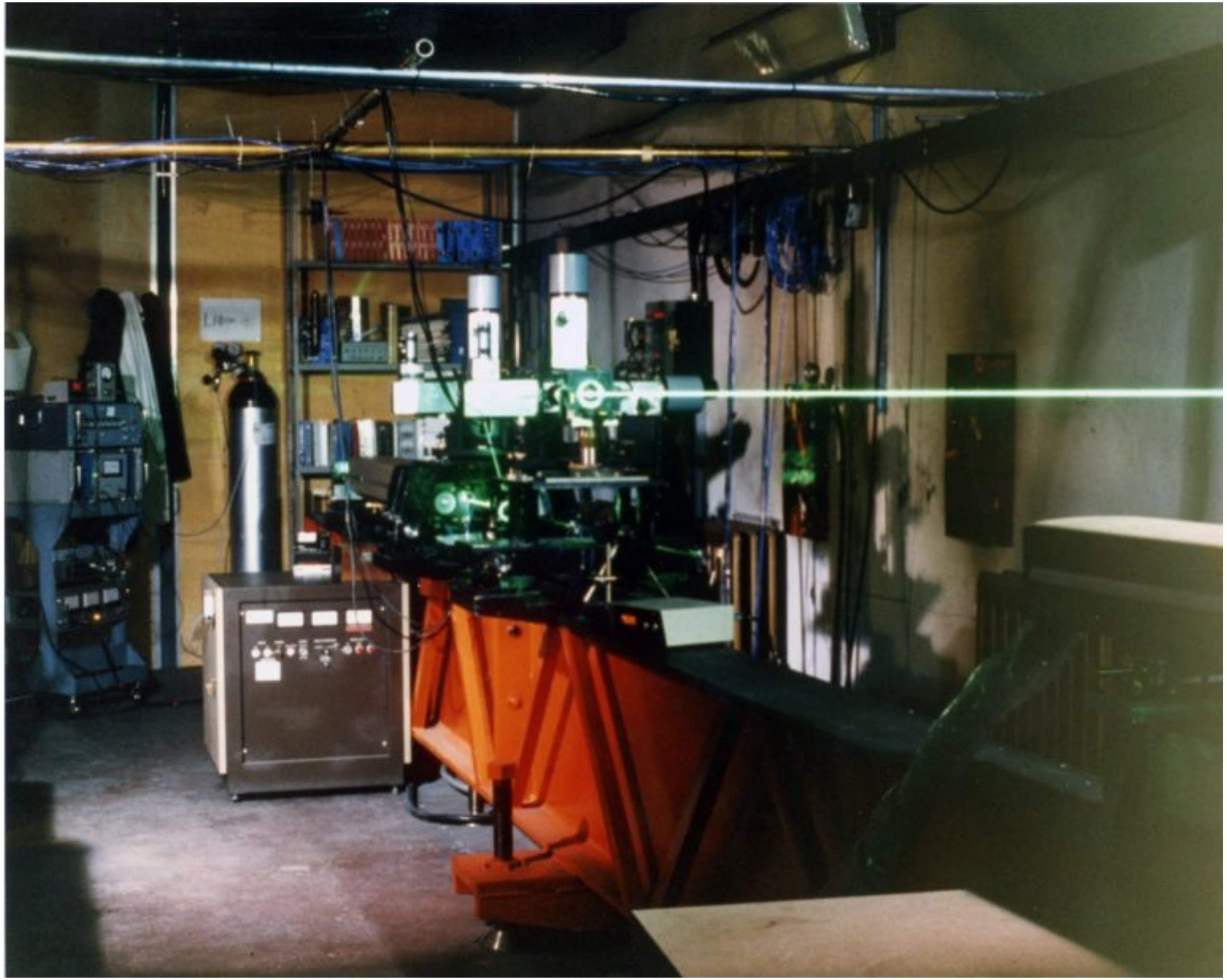
$k_{max} = E_e^2\, E_L/(1+Z)m_e$

$Z = 4\, E_e\, E_L/m_e^2$

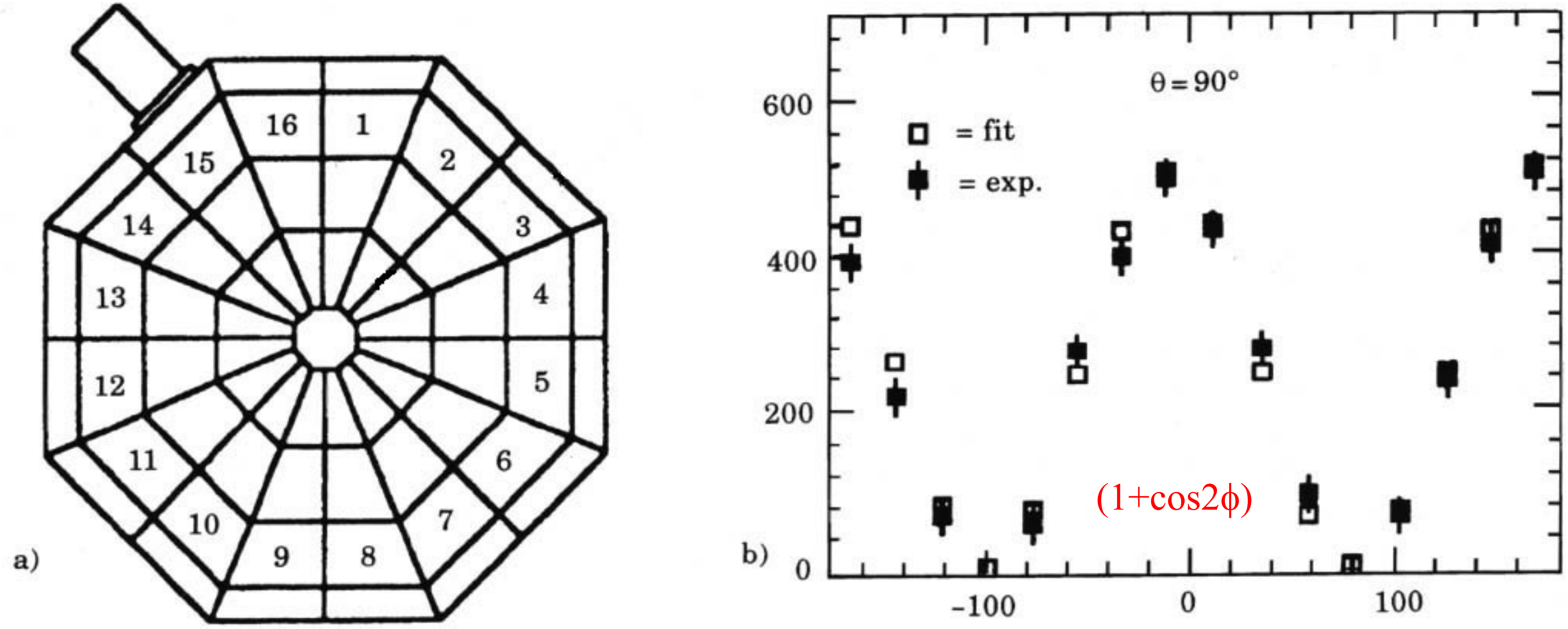
$Z = 4\, \gamma\, E_L/m_e$

$\gamma = E_e/m_e$

Ladon Beam Laser Apparatus



Ladon Beam Polarization Verification



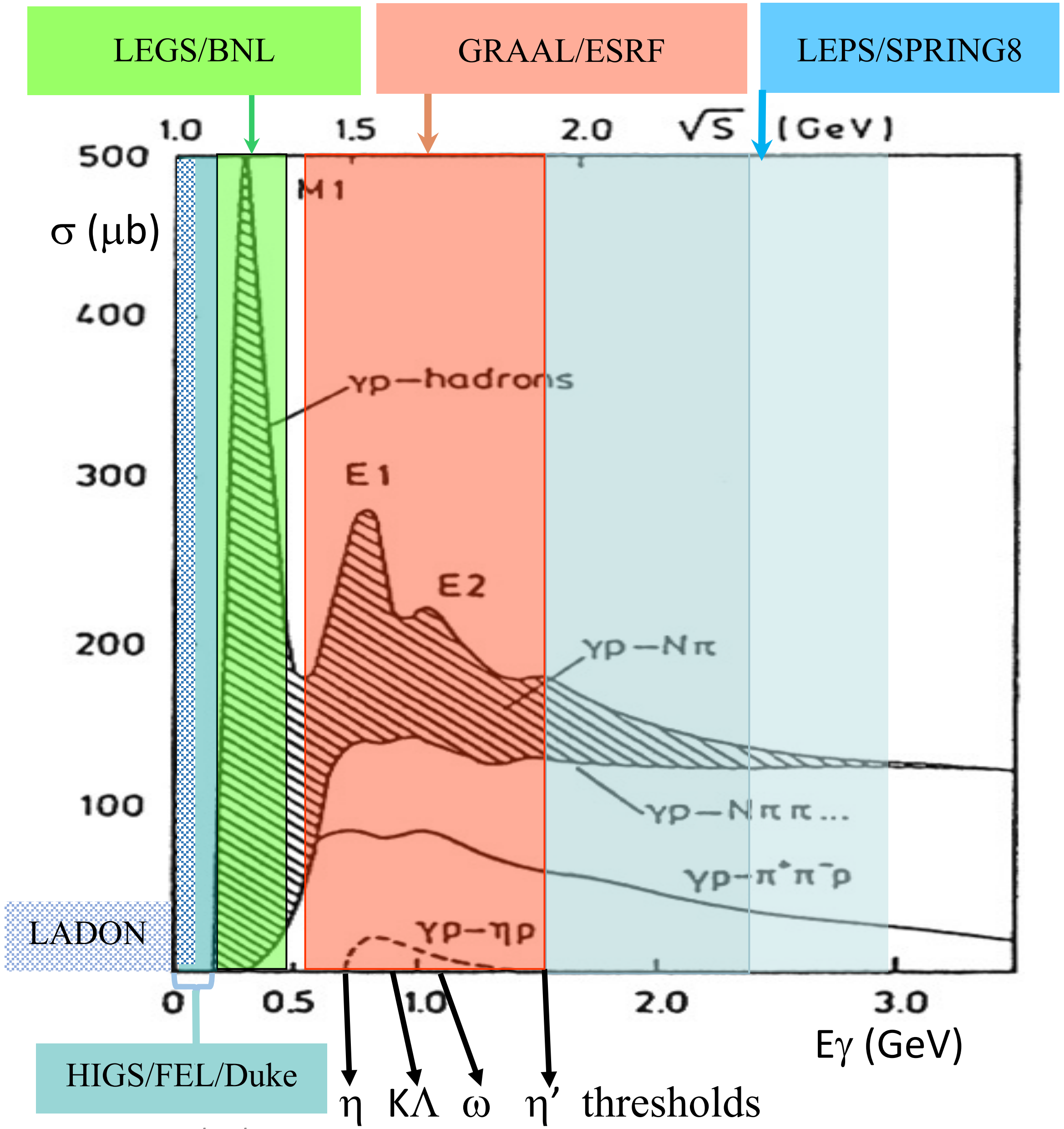
The first verification of the polarization of Ladon beams was performed at Frascati with the elastic scattering of the Ladon gamma-ray beam on the **15.1 MeV level of ^{12}C** using the small NaI crystal ball (7_θ x 16_ϕ) of the University of Rome "La Sapienza". The experimental points reproduce very well the (1+cos2ϕ) law expected for a fully polarized beam on a perfect polarization analyzer.

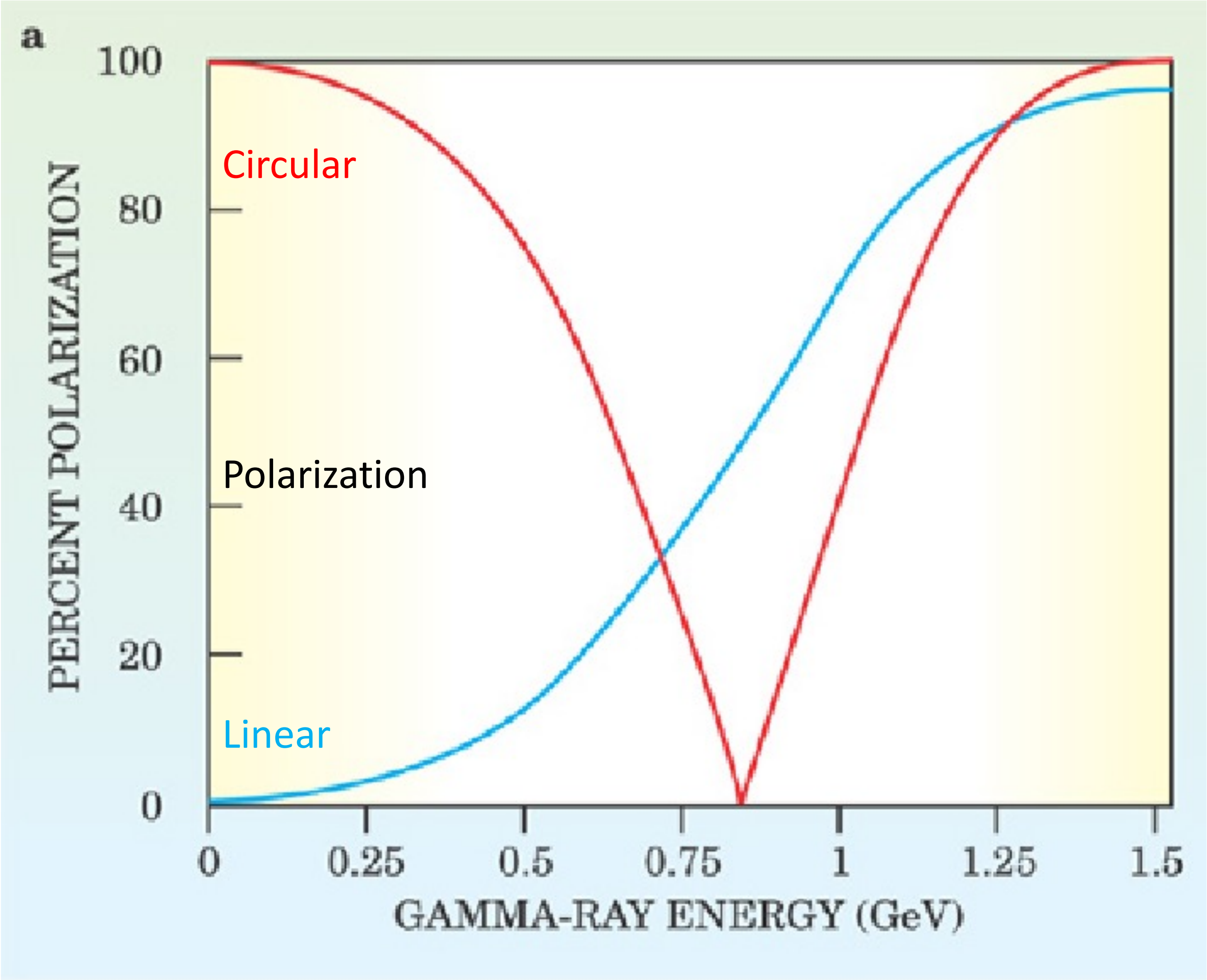
Ladon Beams in the World

Project name	Ladon°	Taladon+	ROKK-1Δ	ROOK-2	ROKK-1M	LEGS*	LEGS-2	Graal**	LEPS†	HIGS⊕
Location	Frascati (LNF-INFN)		Novosibirsk (BINP)			Brookhaven (BNL)		Grenoble	Harima	Durham
Storage ring	Adone		VEPP-4	VEPP-3	VEPP-4M	NSLS		ESRF	SPring-8	TUNL-FELL
Energy defining method	collimation	internal tagging		tagging		external tagging		internal tagging	internal tagging	collimation
Electron energy GeV	1.5	1.5	1.8-5.5	0.35-2.0	1.4 - 5.3	2.5	2.8	6.04	8	0.237-1.03
Photon energy eV	2.45	2.45	2.34-2.41	2.41-2.53	1.17-3.51	3.53	4.71	3.53	3.53	6.42
Gamma-ray energy MeV	5-80	35-80	100-960	140-220	100-1200	180-320	285-470	550-1470	1500-2400	1-95
	variable	simultaneous								variable
Energy resolution %	1.4-10	5	--	1.5	0.5	1.6	1.1	1.1	1.25	0.8-5
(FWHM) MeV	0.07-8	4-2	1.5-2	4	--	5	5	16	30	
Electron current A	0.1	0.1	0.2	0.2	0.1	0.2	0.2	0.2	0.1	100
Gamma intensity s^{-1}	10^5	$5\ 10^5$	$2\ 10^5$	$2\ 10^6$	$2\ 10^6$	$4\ 10^6$	$2\ 10^6$	$2\ 10^6$	$2\ 10^6$	10^6-10^8
Year of operation	1978	1989	1982	1987	1993	1987	1999	1996	1999	1999

°**L**aser **ADON**e, +**TA**gged **LADON**, Δ **ROKK** is a russian abbreviation for Backscattered Compton Gamma, * **L**aser **E**lectron **G**amma **S**ource, ** **GR**enoble **A**nneau **A**ccelerateur **L**aser, † Laser-Electron Photons at SPring-8, ⊕ High Intensity Gamma-ray Source.

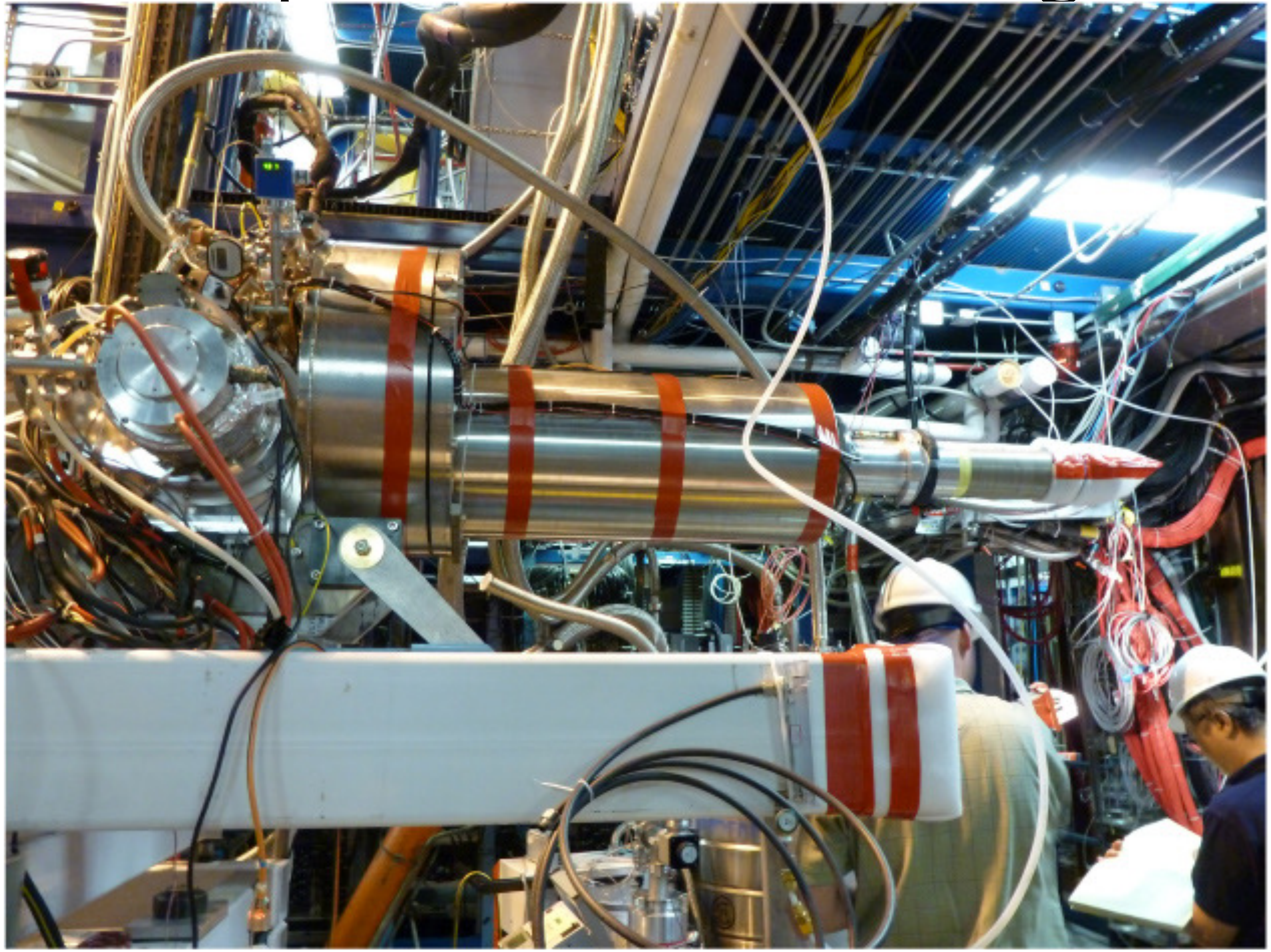
Ladon Beams in the World



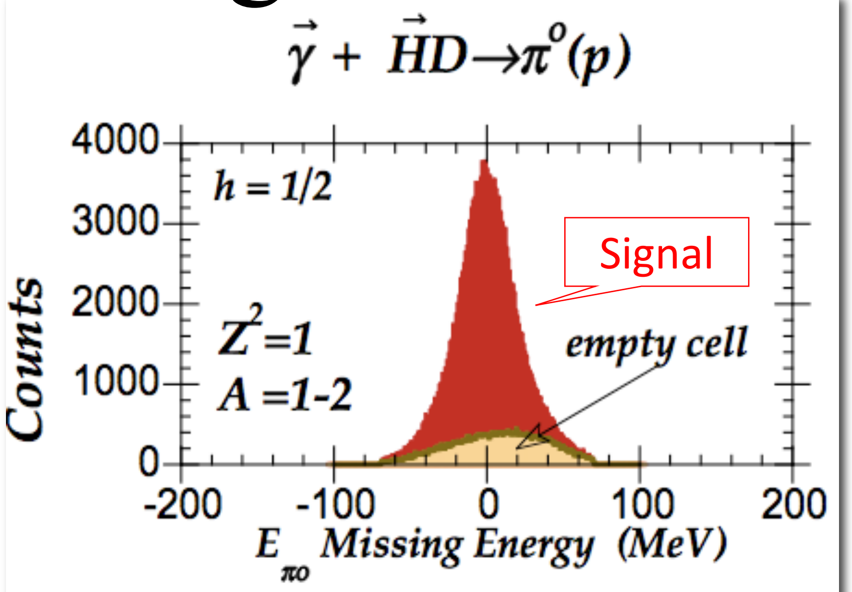


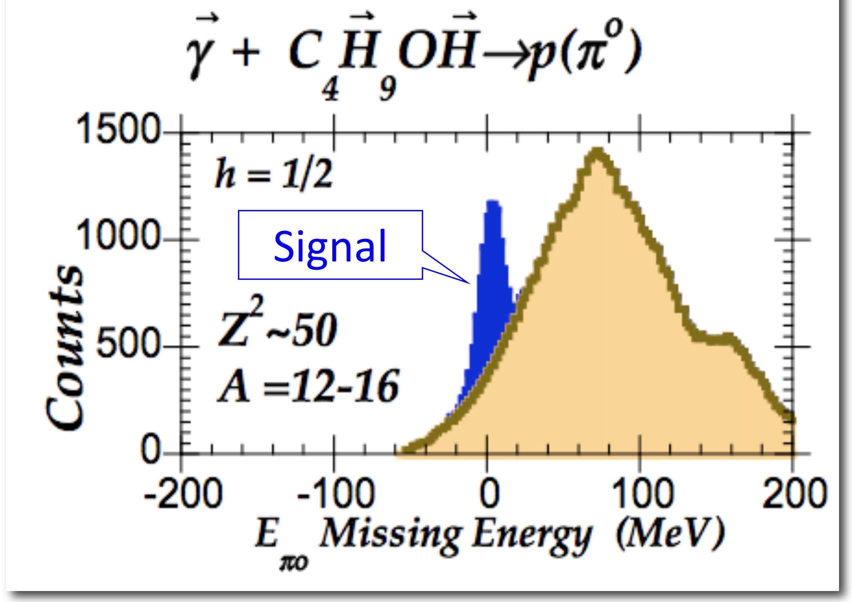
The calculated fractional polarization of the gamma-ray beam at the **Graal** facility, as a function of energy. The red and blue curves indicate, respectively, circular (absolute value) and linear polarizations.

The Frozen Spin Polarized HD Target at LEGS



Signal and Background with Polarized Targets

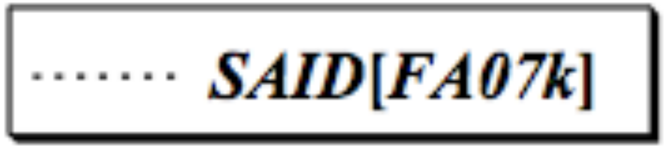


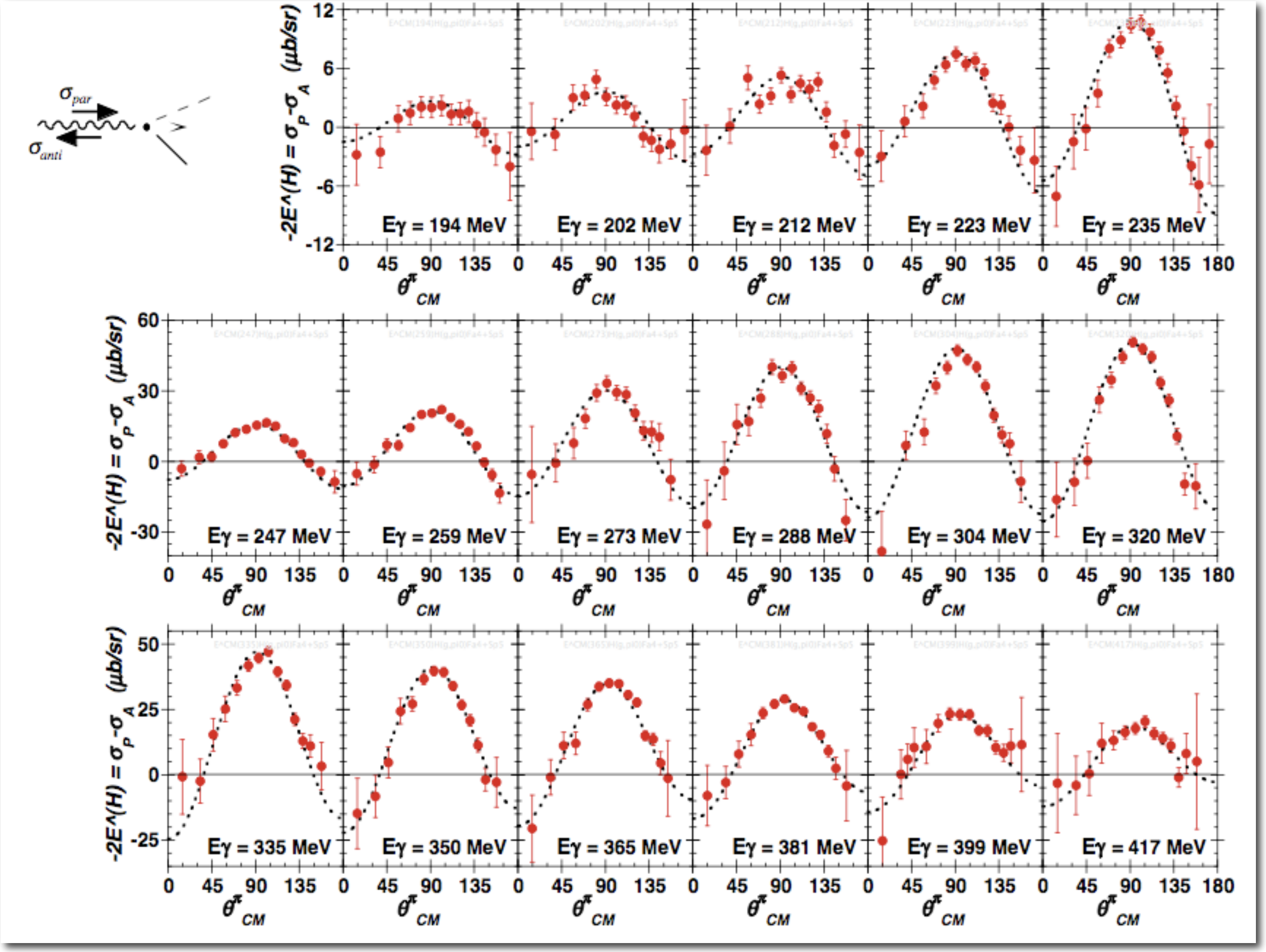


HD targets use a Hydrogen gas in which each molecule is made of one one proton and one deuteron. Since protons and deuterons are different particles, the deuteron is a boson, the molecular system is not subject to the exclusion principle and therefore the proton and the deuteron can be polarized independently.

HD target cell

Double Polarization Asymmetries at LEGS





Gerasimov, Drell, Hearn (GDH) Sum Rule

$$\int_{\omega_0}^{\infty} \frac{\vec{\vec{\sigma}}_P - \overleftarrow{\vec{\sigma}}_A}{\omega} d\omega = 4S\pi^2\alpha \left(\frac{\kappa}{m}\right)^2 = 204\ \mu\text{b}$$

Gerasimov, Drell, Hearn Sum Rule from Dispersion Relation.

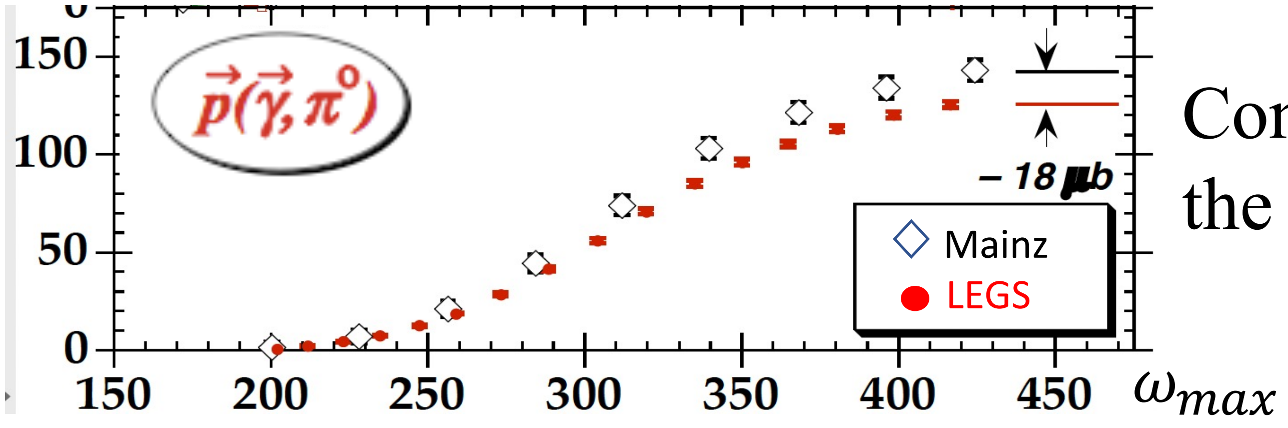
Cicularly polarized photons on longitudinally polarized target.

$\kappa = 1.793$ anomalous magnetic moment of the proton; Spin S = ½

For the convergence of the integral:

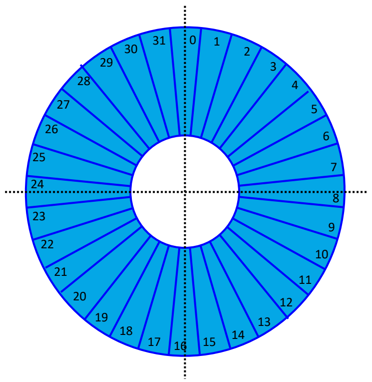
$$\sigma_P \xrightarrow[\omega \to \infty]{} \sigma_A \qquad \sigma = \sigma^{\pi^0} + \sigma^{\pi^+}$$

$$\int_{\omega_0}^{\omega_{max}} \Delta\sigma^\circ d\omega$$

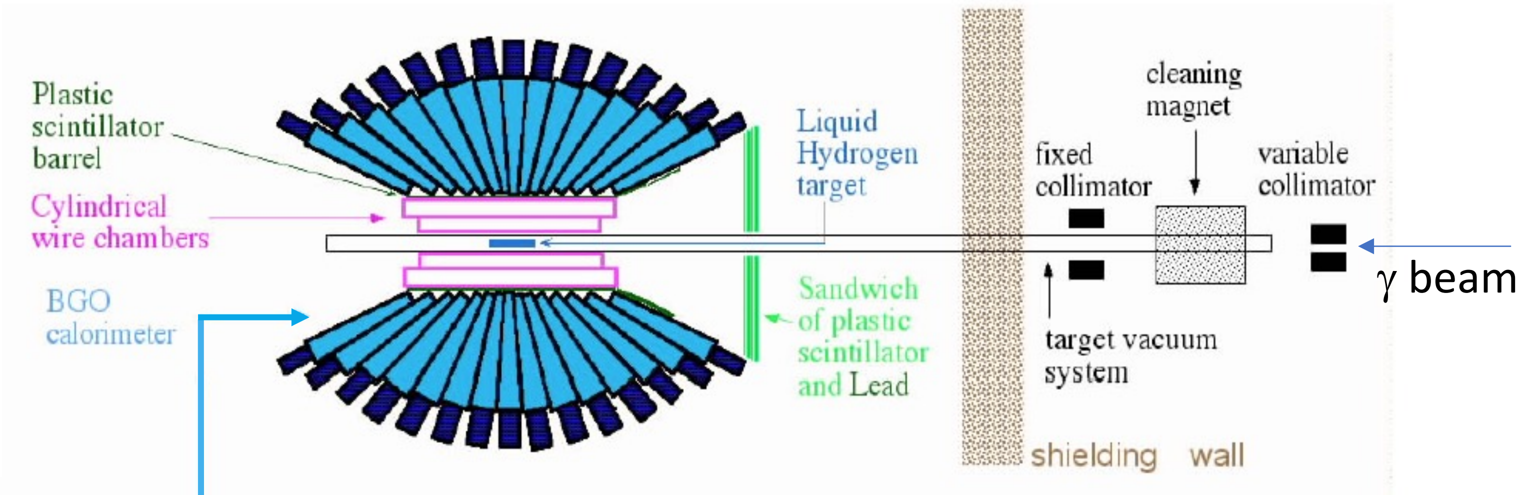


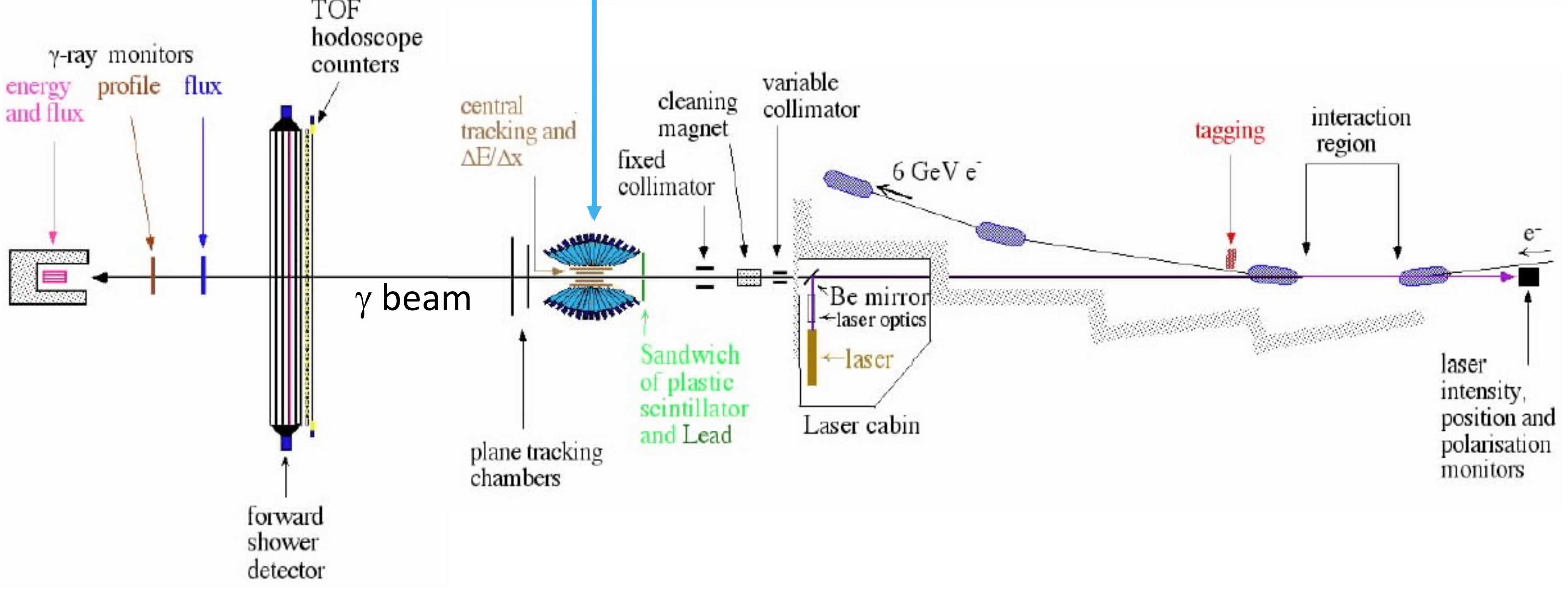
Convergence of the GDH integral

Graal Apparatus

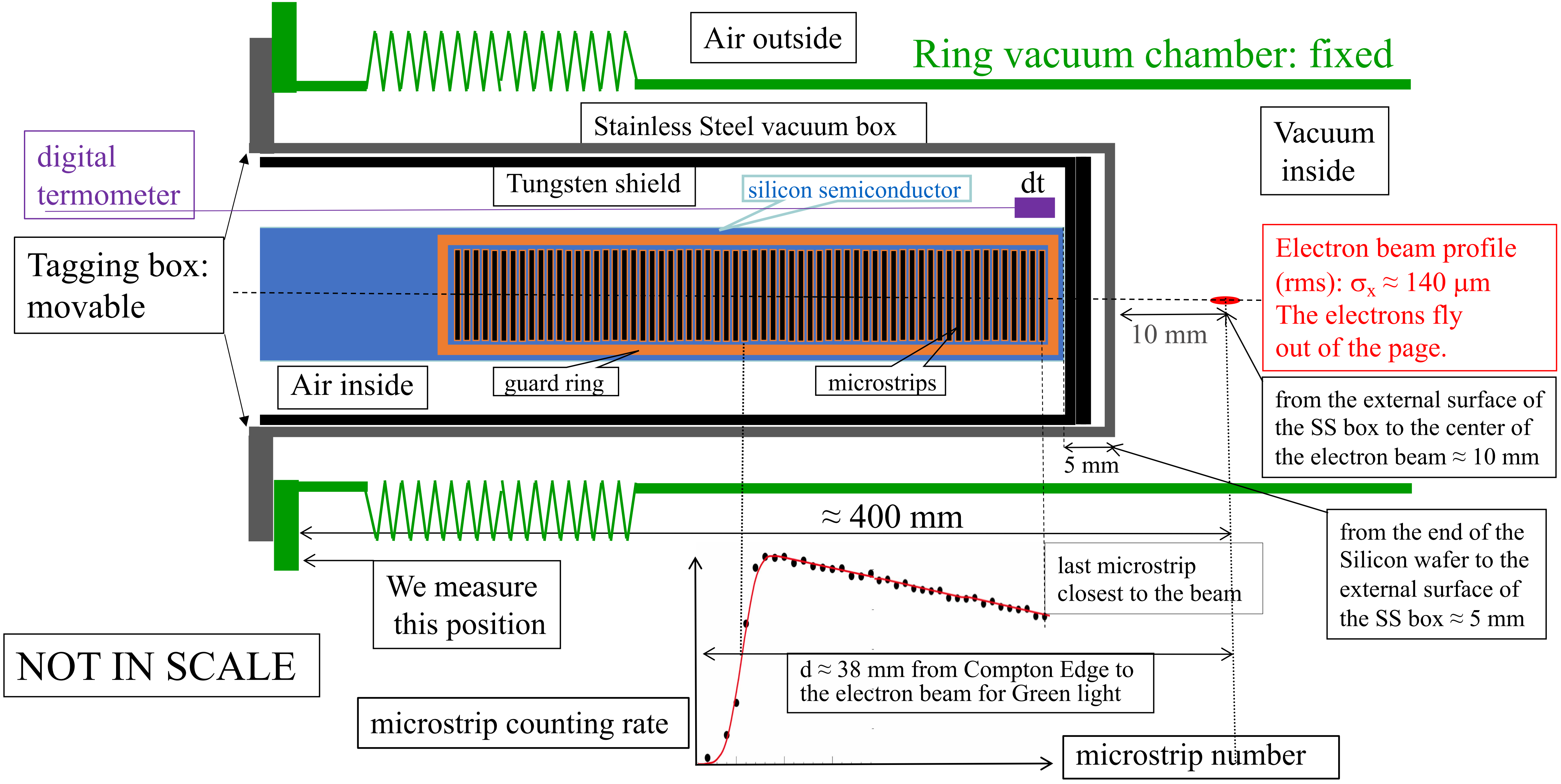


Cross section of the BGO ball 15 x 32=480

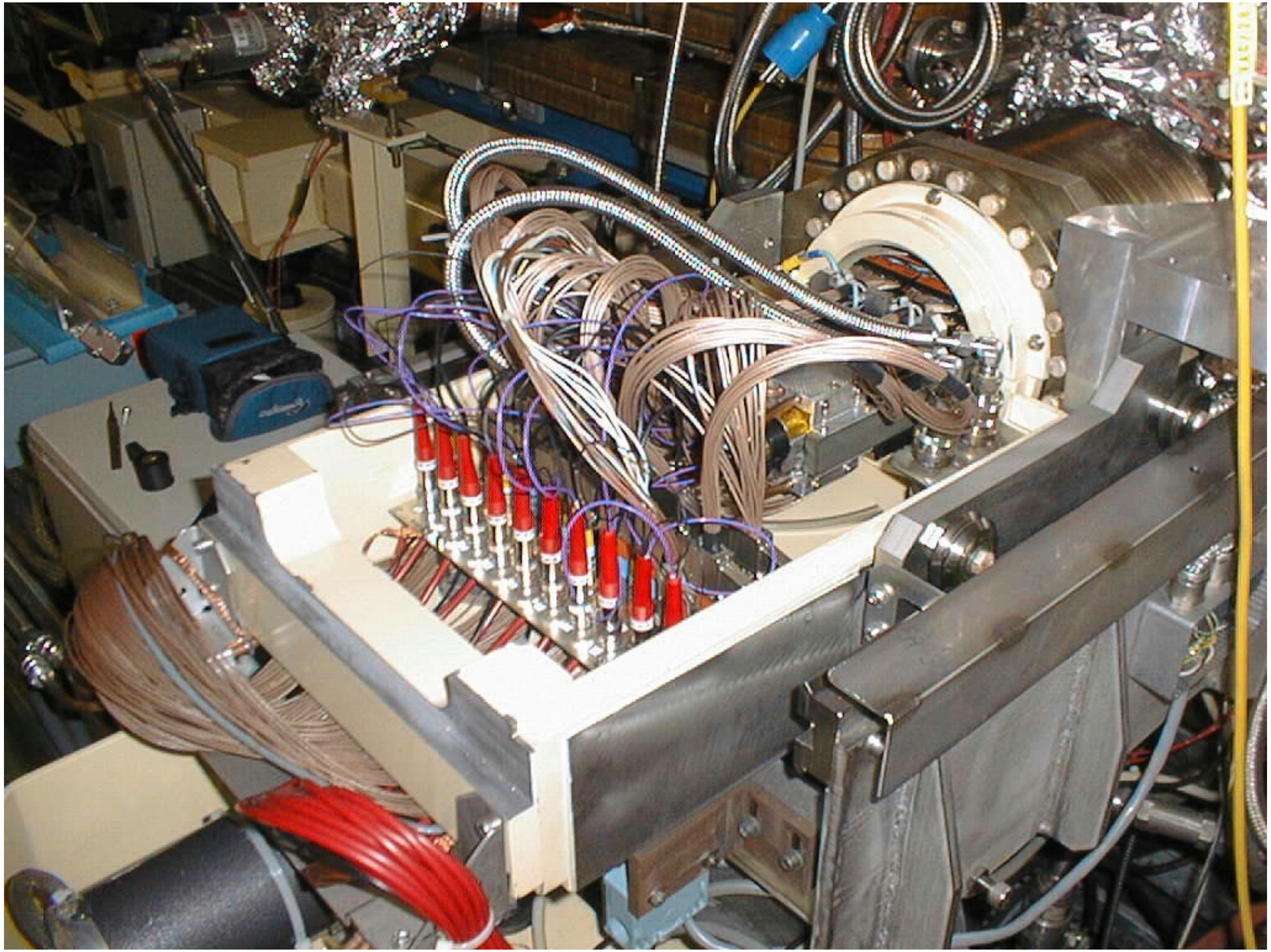




Graal Tagging Box



Graal Tagging Box

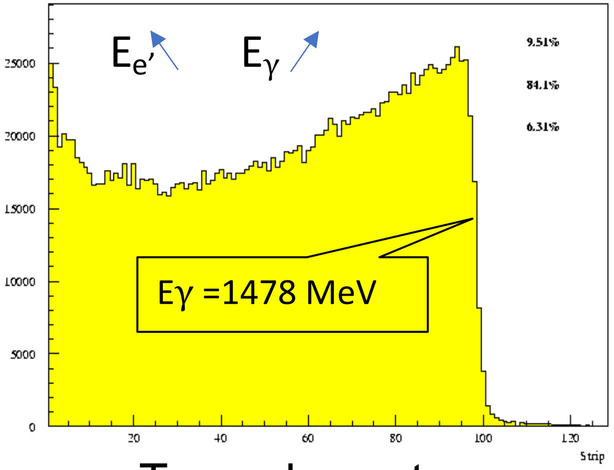


Energy and Timing Resolution 1 UV Line

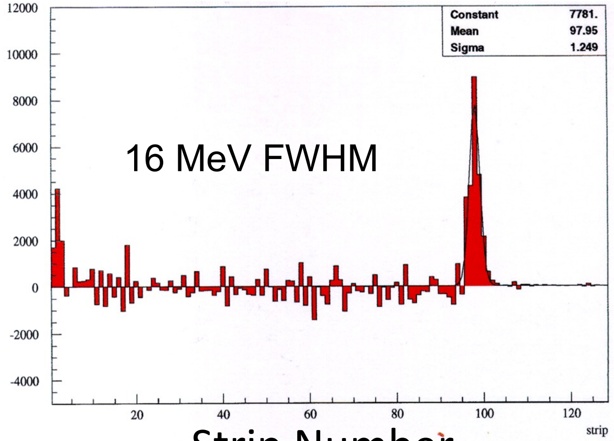
The energy resolution provided by the internal tagging technique:

μ-strip silicon detector → energy resolution of 16 MeV (FWHM) (1.1%)

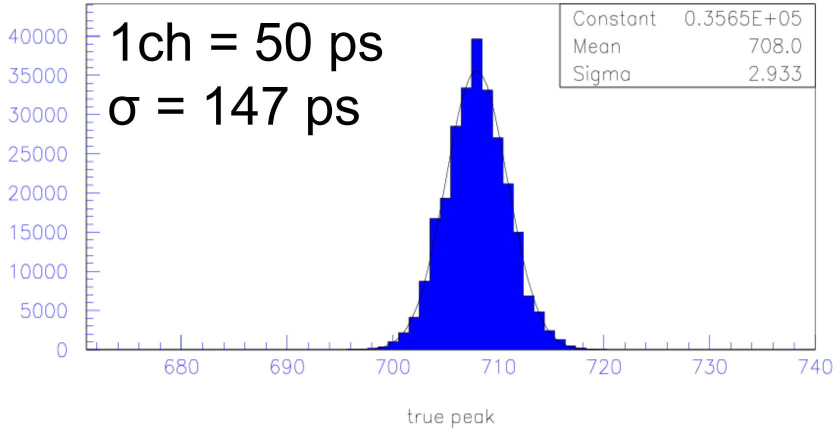
plastic scintillators → time resolution better than 500 ps (FWHM)



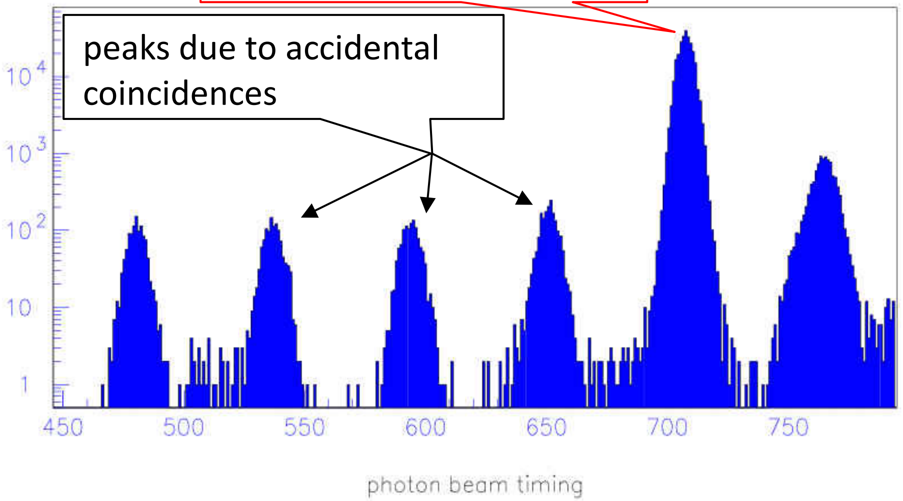
Tagged spectrum



Strip Number

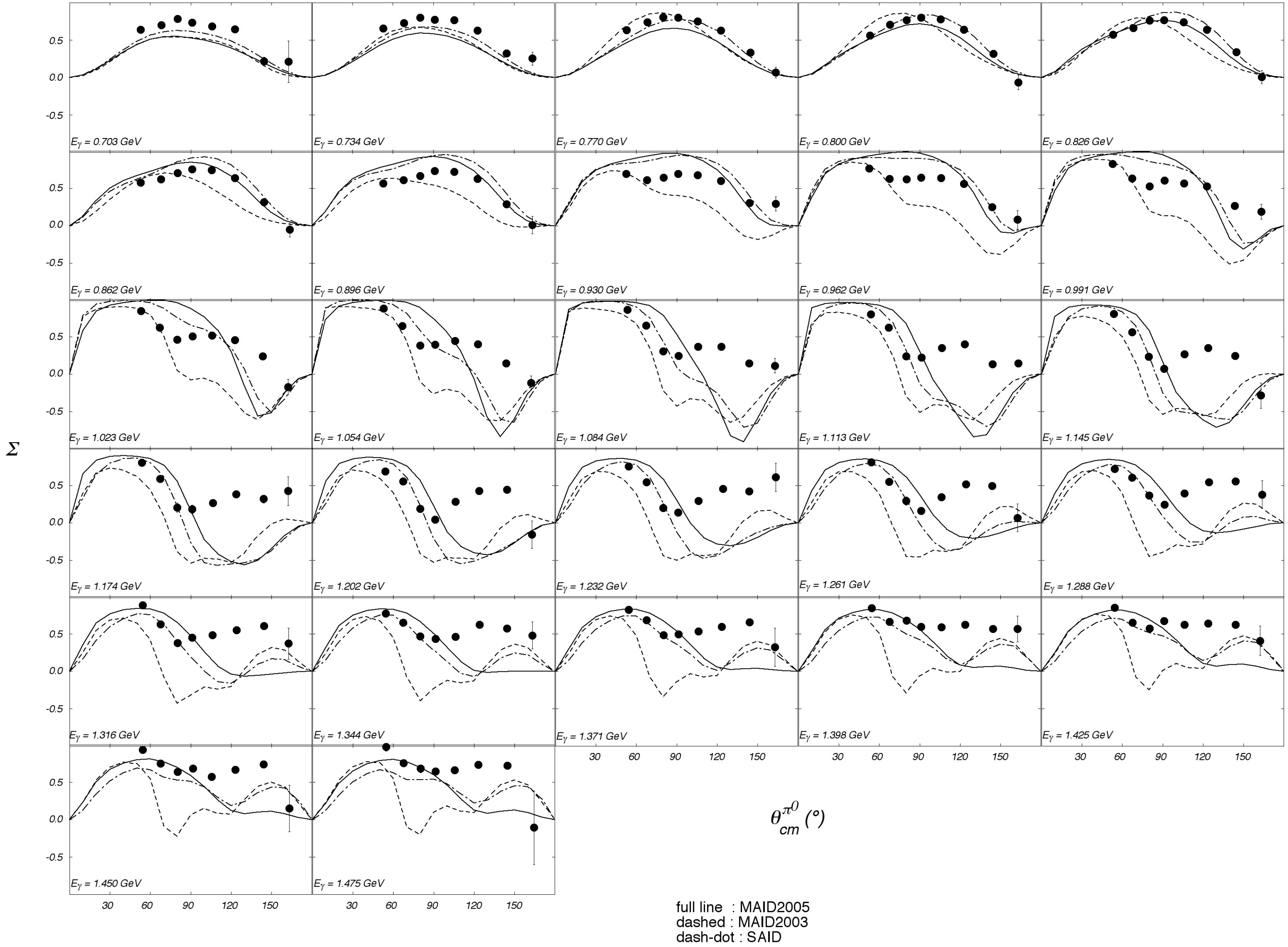


true events peak



Beam Polarization Asymmetries

Graal: $\gamma + d \rightarrow \gamma + n\ (+p) \rightarrow \pi^0 + n\ (+p)$



qfn

quasi-free neutron

(neutron in deuteron)

Full line: MAID2005
Dashed line: MAID2003
Dash-dot: SAID
Despite the availability of thousands of data points on pion photoproduction at these energies the Graal photon polarization asymmetries have required substantial changes to the existing models.
Beam polarization asymmetries have been produced for π^+, π^0, η, and ω on free protons (Hydrogen target) and on bound protons and neutrons (Deuterium target).

Our “Absolute” Velocities

(Velocity of light: c = 299 792 km/s)

Rotation of the earth around its axis (Grenoble) ≈ 0.32 km/s ≈ 10^{-6}c

Revolution of the earth around the sun ≈ 30 km/s ≈ 10^{-4}c

Velocity of the Solar System in the Galaxy ≈ 215 km/s ≈ 10^{-3}c

Motion relative to the Last Scattering Surface ≈ 371 km/s ≈ 10^{-3}c

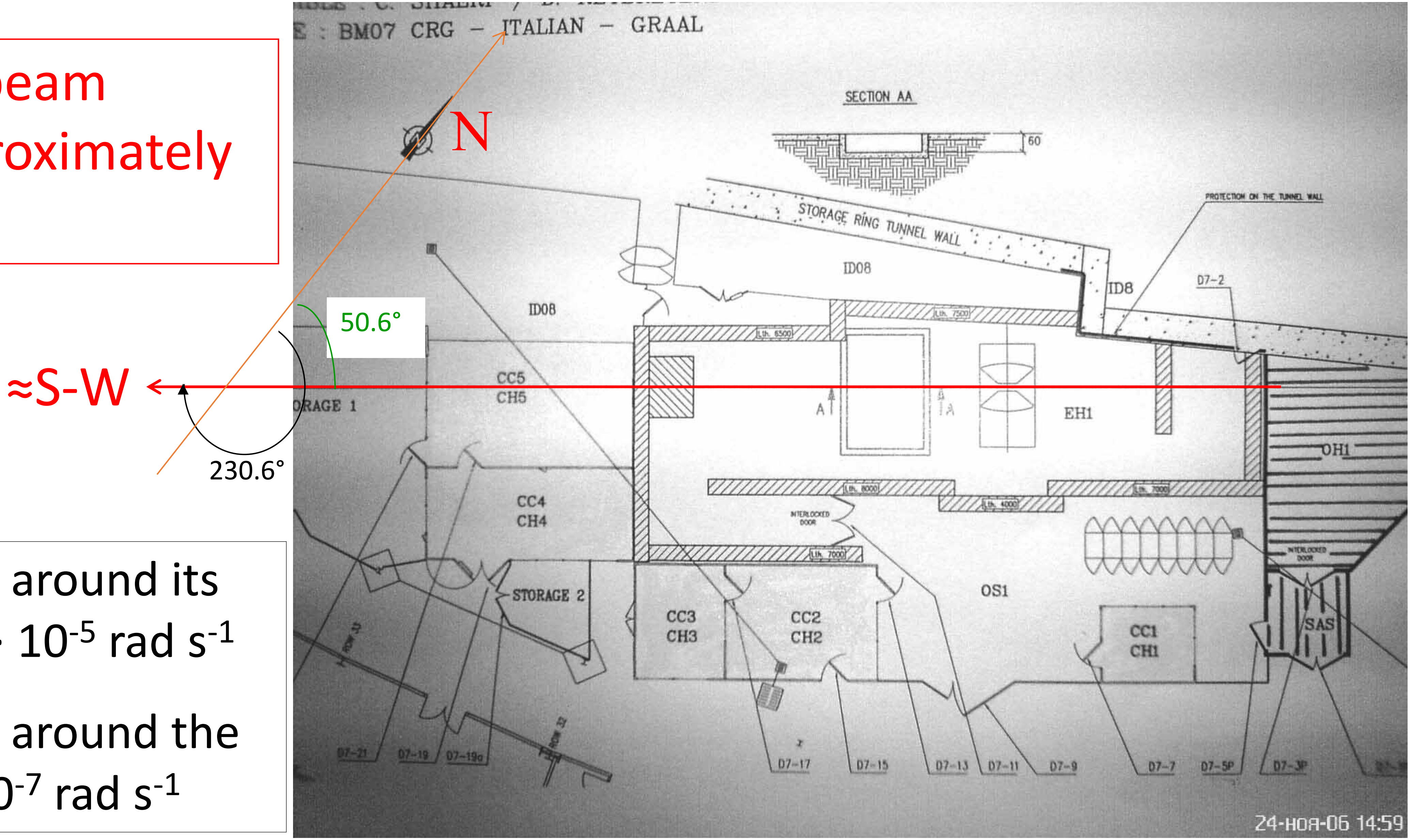
Cosmic Microwave Background distribution:

$$\frac{\delta T(\vartheta)}{T} = \frac{\mathrm{v}}{c}\cos\vartheta + \frac{\mathrm{v}^2}{2c^2}\cos 2\vartheta + O\left(\frac{\mathrm{v}^3}{c^3}\right)$$

$$\frac{\mathrm{v}}{c} = 0.000122 \pm 0.00006\mathrm{v} = 365 \pm 18 kms^{-1}$$

Graal Beam Orientation on the Earth

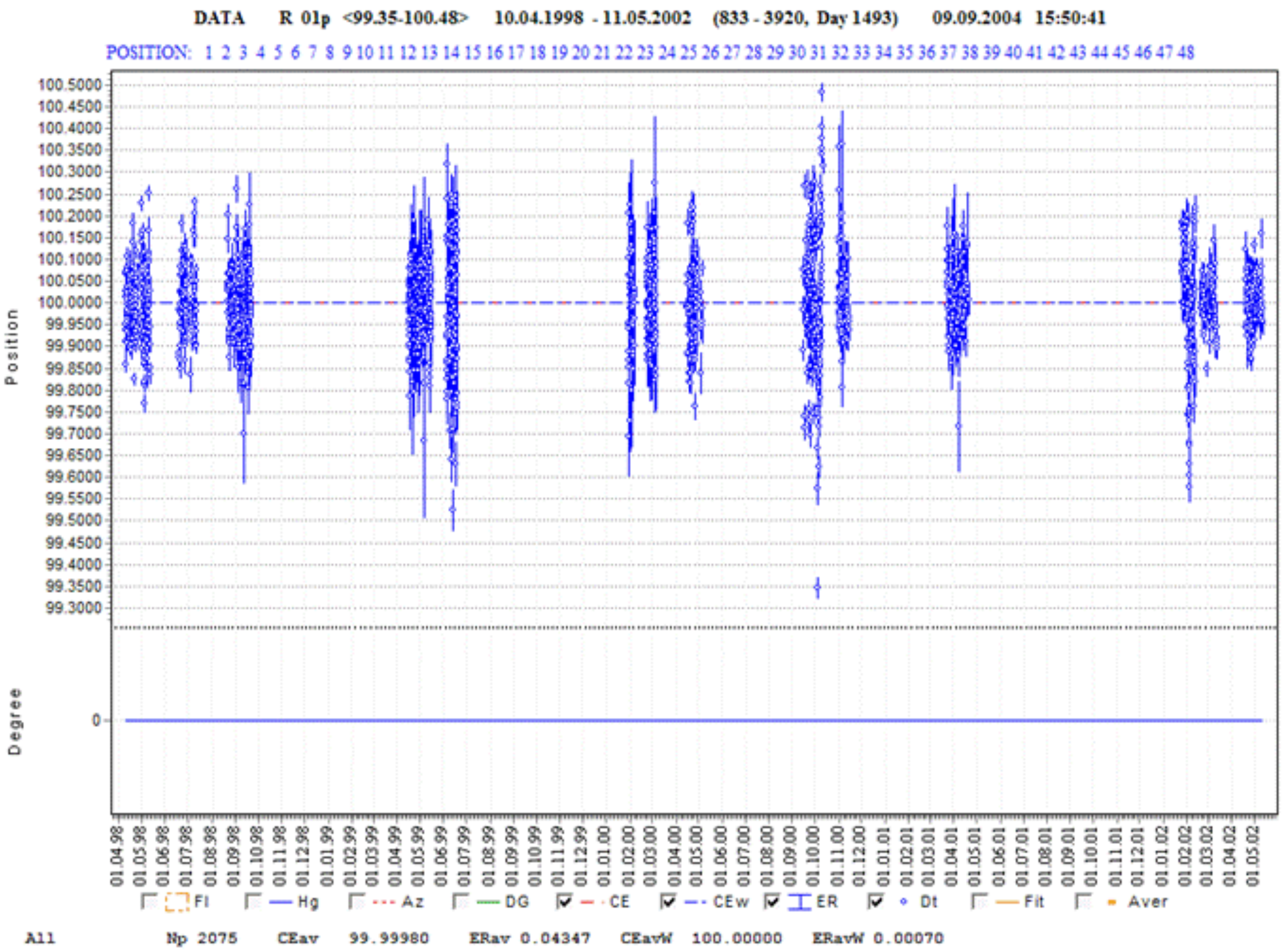
The Graal beam points approximately to the S-W



Earth rotation around its axis: $\omega = 7.3 \cdot 10^{-5}$ rad s^{-1}

Earth rotation around the sun: $\omega = 2 \cdot 10^{-7}$ rad s^{-1}

Distribution of Graal Data



Compton Scattering Kinematics

From the relativistic kinematics of Compton scattering:

($\theta_\gamma = 180^o$) $$E_{\gamma\max} = \frac{4\gamma^2 E_{laser}}{1+\dfrac{4\gamma E_{laser}}{m_e}} \approx 4\gamma^2 E_{laser}$$ and $$\frac{dE_\gamma}{E_\gamma} \approx 2\frac{d\gamma}{\gamma}$$ or $$\frac{d\gamma}{\gamma} \approx \frac{1}{2}\frac{dE_\gamma}{E_\gamma}$$

and in general from relativistic kinematics:

$$\beta d\beta = \left(\frac{1}{\gamma^2}\right)\frac{d\gamma}{\gamma} \approx \frac{1}{2}\left(\frac{1}{\gamma^2}\right)\frac{dE_\gamma}{E_\gamma} \quad \text{or} \quad \Delta\beta \approx \frac{1}{2}\left(\frac{1}{\gamma^2}\right)\frac{\Delta E_\gamma}{E_\gamma}$$

since at the ESRF:

$$\gamma = \frac{E_e}{m_e} = \frac{6030}{0.511} = 11\,800; \qquad \gamma^2 \approx 1.4\cdot 10^8$$

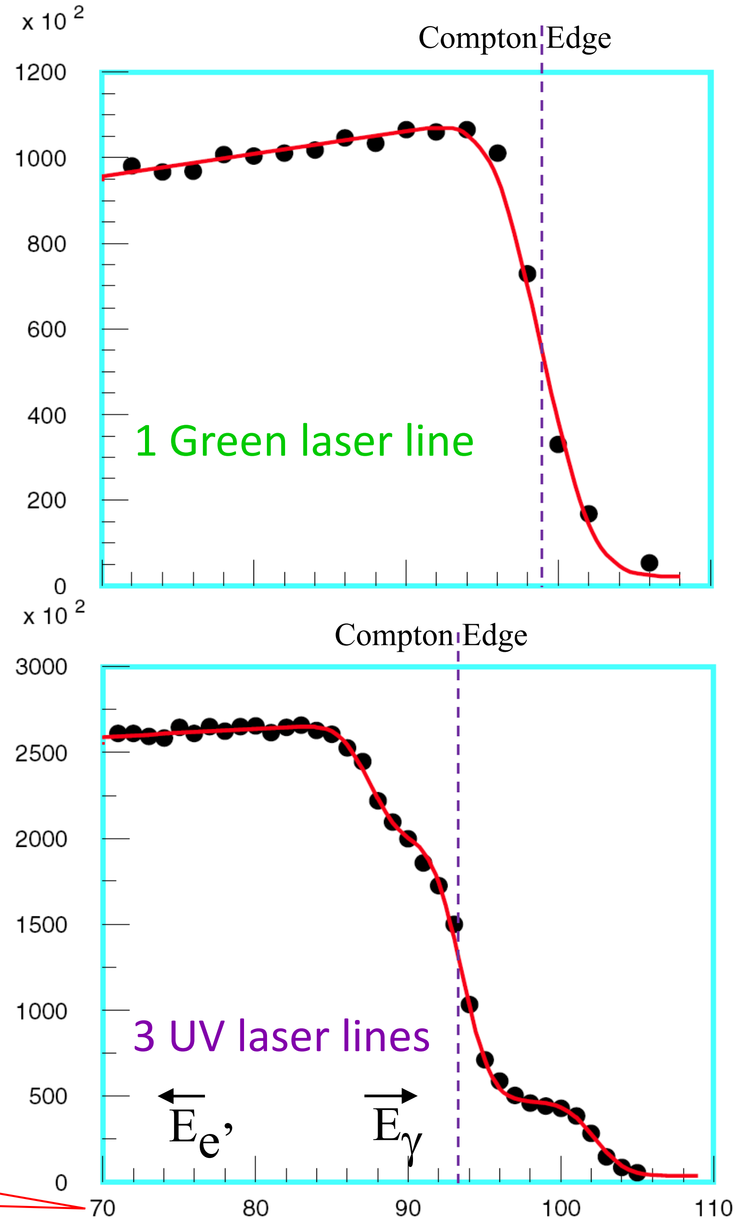
we have:

$$\Delta\beta_e = \Delta\frac{\mathrm{v}_e}{c} \qquad \Delta\beta \approx \frac{1}{2}\left(\frac{1}{\gamma^2}\right)\frac{\Delta E_\gamma}{E_\gamma} \approx \frac{1}{2}\frac{1}{1.4\cdot 10^8}\cdot\frac{\Delta E_\gamma}{E_\gamma} \approx 0.4\cdot 10^{-8}\frac{\Delta E_\gamma}{E_\gamma} \approx 0.4\cdot 10^{-8}\frac{\Delta d}{d}$$

The error in **β** is reduced by eight orders of magnitude with respect to the relative error in ***d*** (the displacement of the scattered electrons from the main orbit). For the ESRF electron energy of 6.03 GeV and a UV laser line of 3.53 eV, the energy loss is 1.487 GeV that corresponds to an electron displacement at the position of the Graal tagging detector: ***d* ≈ 52.3 mm**.

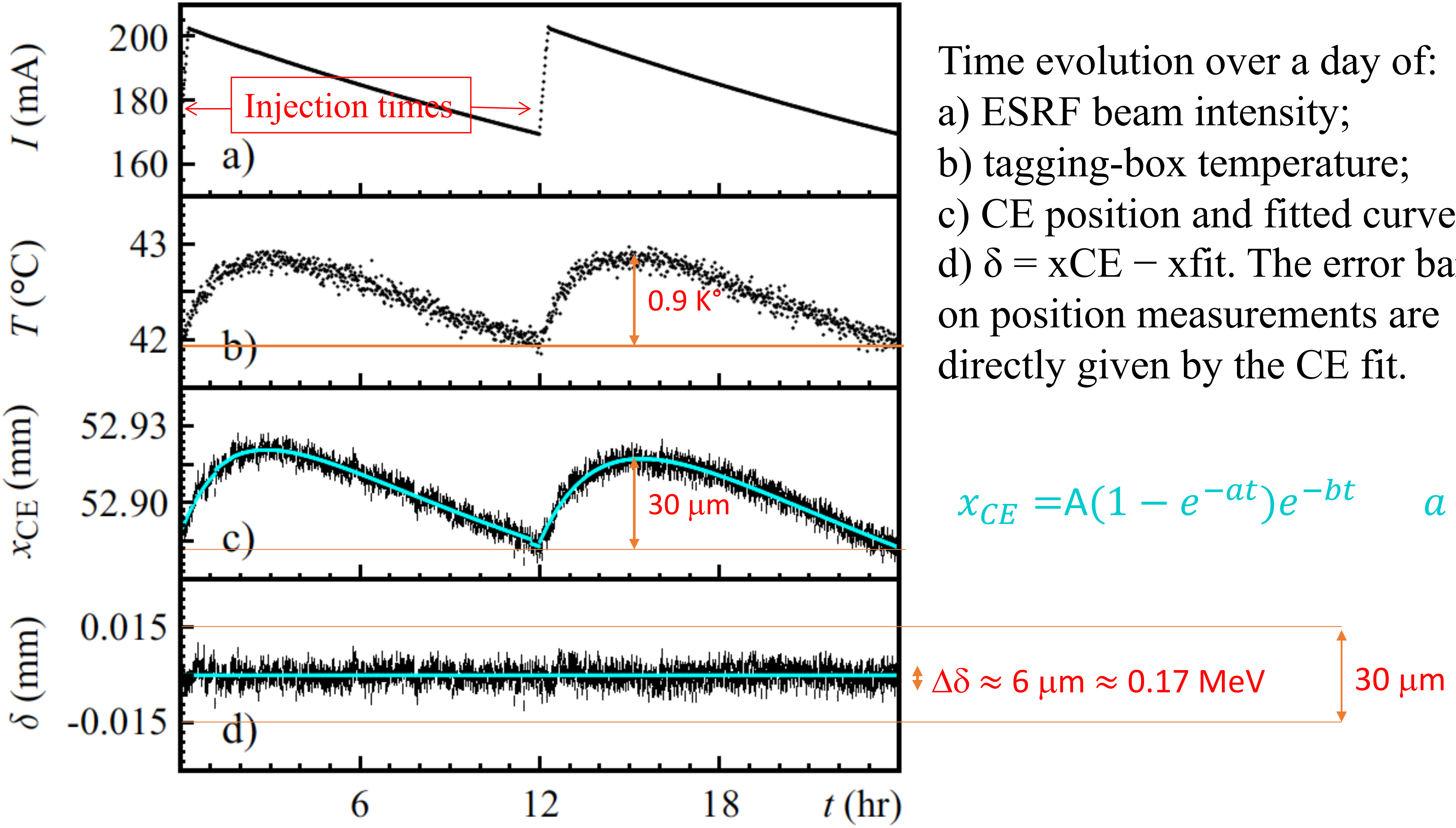
Electron Distributions and Compton Edge

Typical spectra of scattered electrons are given in the top and bottom figures. The top figure has been obtained with the Green laser line (2.41 eV) and the lower one with three UV lines around 3.53 eV. The abscissa indicates the microstrip number. One microstrip has a width of 300 μm corresponding approximately to an energy bin 7 MeV wide. The higher microstrip numbers correspond to the larger electron energy loss. The abrupt drop to the right corresponds to the maximum energy loss allowed by relativistic kinematics. We call it the "Compton Edge = CE" and its slope is given by the energy resolution of our tagging system: ≈16 MeV (FWHM). This resolution is determined mostly by the ESRF magnetic structure and the electron beam emittance. The microstrip pitch (300 μm) was chosen with the condition that it would not deteriorate appreciably the intrinsic energy resolution of the system.



Microstrip channel numbers
1 channel = 0.3 mm ≈ 6.6 MeV

ESRF Electron Beam Current and Compton Edge



Time evolution over a day of:
a) ESRF beam intensity;
b) tagging-box temperature;
c) CE position and fitted curve;
d) δ = xCE − xfit. The error bars on position measurements are directly given by the CE fit.

$$x_{CE} = A(1 - e^{-at})e^{-bt} \qquad a > b$$

Compton Edge Position

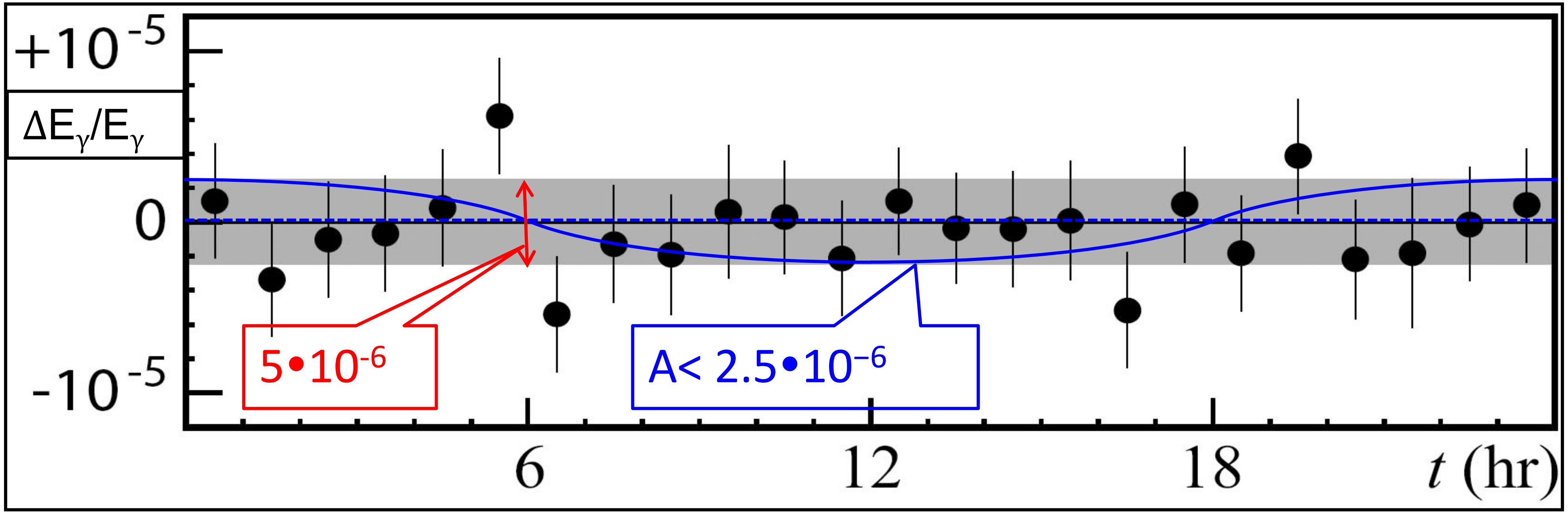
The position of the Compton Edge as a function of microstrip number depends on the position of the tagging detector with respect to the electron beam. This position can be remotely changed to cover the largest part of the gamma-ray spectrum. Normally the CE provides us with the absolute normalization of our energy scale.

Conversely the distance (***d* ≈ 52.3 mm**) between the position of the Compton Edge on the microstrip detector and the electron beam could be used as a check of the validity of the relativistic kinematics used for the derivation of the energy lost by the electrons if a careful estimate of the systematic error is made.

The Graal acquisition system has collected hundreds of events per second and more then 10^6 events per two-four hours run over the interesting part of the gamma-ray spectrum. Therefore the position of the Compton Edge has been measured, for each run, with a statistical precision, **Δ *d* ≈ 10 μm**, corresponding to ≈ 3% of the microstrip pitch of 300 μm. In five years Graal has collected more than two thousands measurements and therefore the statistical error, $(\Delta\, \boldsymbol{d})_{\mathrm{stat}}$, in the average position of the Compton Edge on the microstrip, for each group of about 100 runs, is of the order of one-two microns.

$$\frac{(\Delta d)_{stat}}{d} \approx \frac{1.5\,\mu m}{52.3\,mm} \approx \quad 3\cdot 10^{-5} \quad \approx \quad \frac{(\Delta E_\gamma)_{stat}}{E_\gamma}$$

Average Results over a Sidereal Day



14765 CE spectra grouped in 24 bins, with about 600 measurements each, corresponding to the hours of the sidereal day and averaged. The error bars are purely statistical and agree with the dispersion of the data points (χ^2 =1.04 for the unbinned histogram). The blue line is a fit of the form: $A \sin(\Omega t+\varphi)$. [$\Omega \simeq 2\pi/(23\text{ h }56\text{ min})$] and at 95% Confidence Level yields:

$$\Delta E_\gamma/E_\gamma = A < 2.5 \bullet 10^{-6}$$

$$\Delta\beta = 0.4\ 10^{-8}\ \frac{\Delta E_\gamma}{E_\gamma} \approx 0.4\ 10^{-8} \cdot 2.5\ 10^{-6}\ \approx\ 10^{-14}$$

Minimal Standard-Model Extension - mSME

The minimal Standard-Model Extension, mSME, for the photon energy-momentum four-vector, predicts a change given by:

$$\omega_\gamma = \left(1 - \vec{\kappa} \cdot \hat{k}_\gamma\right) k_\gamma + \mathrm{O}(\kappa^2)$$

$E_\gamma = \omega_\gamma$ energy of the photon

$p_\gamma = k_\gamma = \left|\vec{k}_\gamma\right|$; $\vec{k}_\gamma$ three - momentum of the photon; $\hat{k}_\gamma$ direction of the photon

$\vec{\kappa}$ specifies a preferred direction which violates Lorentz symmetry

Our measurement, based on the search for sidereal modulations in the CE of the scattered electrons, sets an upper limit: $\sqrt{\kappa_x^2 + \kappa_y^2} < 1.6\ 10^{-14}\ (95\%\ C.L)$

and shows no evidence for a signal **improving the previous limits by a factor of ten.**

Limits on Light-Speed Anisotropies from Compton Scattering of High-Energy Electrons, PRL 104, 241601 (2010)

Light Speed Anisotropy

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PROBING THE LIGHT SPEED ANISOTROPY WITH RESPECT TO THE COSMIC MICROWAVE BACKGROUND RADIATION DIPOLE

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Received 9 November 2004

We have studied the angular fluctuations in the speed of light with respect to the apex of the dipole of Cosmic Microwave Background (CMB) radiation using the experimental data obtained with GRAAL facility, located at the European Synchrotron Radiation Facility (ESRF) in Grenoble. The measurements were based on the stability of the Compton edge of laser photons scattered on the 6 GeV monochromatic electron beam. The results enable one to obtain a conservative constraint on the anisotropy in the light speed variations $\Delta c(\theta)/c < 3 \times 10^{-12}$, i.e. with higher precision than from previous experiments.

1. Introduction

The study of the light speed anisotropy with respect to the dipole of the Cosmic Microwave Background (CMB) radiation as suggested in Ref. 1, is the modern analog of the Michelson–Morley experiment. CMB, besides being a unique cosmological messenger, also determines the hierarchy of inertial frames and their relative motions, and is defining an "absolute" inertial frame of rest, i.e. the one where the dipole and quadrupole anisotropies vanish.

IL NUOVO CIMENTO Vol. 122 B, N. 5 Maggio 2007
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Lowering the light speed isotropy limit: European Synchrotron Radiation Facility measurements(*)

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(ricevuto il 10 Dicembre 2007; pubblicato online il 13 Febbraio 2008)

Summary. — The measurement of the Compton edge of the scattered electrons in GRAAL facility in European Synchrotron Radiation Facility (ESRF) in Grenoble with respect to the Cosmic Microwave Background dipole reveals up to 10σ variations larger than the statistical errors. We now show that the variations are not due to the frequency variations of the accelerator. The nature of Compton edge variations remains unclear, thus outlining the imperative of dedicated studies.

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The inverse Compton scattered electron energy spectrum, as suggested in [1], provides a way to study the light speed anisotropy within the energy scales and monochromaticity reachable in existing synchrotrons. The study of such anisotropy *vs.* the frame, when the dipole of the Cosmic Microwave Background (CMB) radiation is vanishing, *i.e.* with respect to the apex of the CMB dipole, is of particular interest. It is due to the "absolute"

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Limits on Light-Speed Anisotropies from Compton Scattering of High-Energy Electrons

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The possibility of anisotropies in the speed of light relative to the limiting speed of electrons is considered. The absence of sidereal variations in the energy of Compton-edge photons at the European Synchrotron Radiation Facility's GRAAL facility constrains such anisotropies representing the first nonthreshold collision-kinematics study of Lorentz violation. When interpreted within the minimal standard-model extension, this result yields the two-sided limit of 1.6×10^{-14} at 95% confidence level on a combination of the parity-violating photon and electron coefficients $(\tilde{\kappa}_{o+})^{YZ}$, $(\tilde{\kappa}_{o+})^{ZX}$, c_{TX}, and c_{TY}. This new constraint provides an improvement over previous bounds by 1 order of magnitude.

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Properties of the speed of light c, such as isotropy and constancy irrespective of the motion of the source, play a key role in physics. For example, they are instrumental for both the conceptual foundations as well as the experimental verification of special relativity, and they currently provide the basis for the definition of length in the International System of Units. It follows that improved tests of, e.g., the isotropy of light propagation remain of fundamental importance in physics.

Experimental searches for anisotropies in c are further motivated by theoretical studies in the context of quantum gravity: it has recently been realized that a number of approaches to Planck-scale physics, such as strings, spacetime-foam models, noncommutative field theory, and varying scalars, can accommodate minuscule violations of Lorentz symmetry [1]. At presently attainable energies, such Lorentz-breaking effects can be described by the standard-model extension, an effective field theory that incorporates both the usual standard model and general relativity as limiting cases [2]. To date, the minimal standard-model extension (MSME), which contains only relevant and marginal operators, has provided the basis for numerous tests of special relativity in a wide variety of physical systems [3,4].

In this work, we will study photons and electrons in an environment where gravity is negligible. Lorentz violation is then described by the single-flavor QED limit of the flat-spacetime MSME [2,5]. This limit contains the real, spacetime-constant MSME coefficients $(k_F)^{\mu\nu\rho\lambda}$, $(k_{AF})^{\mu}$, b^{μ}, $c^{\mu\nu}$, $d^{\mu\nu}$, and $H^{\mu\nu}$, which control the extent of different types of Lorentz and *CPT* violation. Note, however, that $c^{\mu\nu}$ and $\tilde{k}^{\mu\nu} \equiv (k_F)_{\alpha}{}^{\mu\alpha\nu}$ are observationally indistinguishable in a photon-electron system: suitable coordinate rescalings freely transform the $\tilde{k}^{\mu\nu}$ and $c^{\mu\nu}$ parameters into one another [5,6]. Physically, this represents the fact that the speed of light is measured *relative* to the speed of electrons. We exploit this freedom by selecting the specific scaling $c^{\mu\nu} = 0$ in intermediate calculations. However, we reinstate this coefficient in the final result for generality.

From a phenomenological perspective, the dominant MSME coefficient is k_F, which causes a direction- and polarization-dependent speed of light [6]. Various of its components have been tightly bounded with astrophysical observations [7], Michelson-Morley tests [4,8], and collider physics [5]. We will bound the $\tilde{\kappa}_{0+}$ piece of $\tilde{k}^{\mu\nu}$, which is an antisymmetric 3×3 matrix; it currently obeys the weakest limits, so all other MSME coefficients can be set to zero in what follows. A MSME analysis then reveals

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