Synchrotron Radiation – a Tool for Precise Beam Energy Measurements at the ILC

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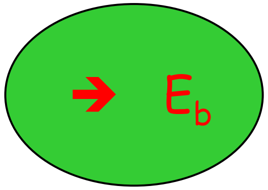
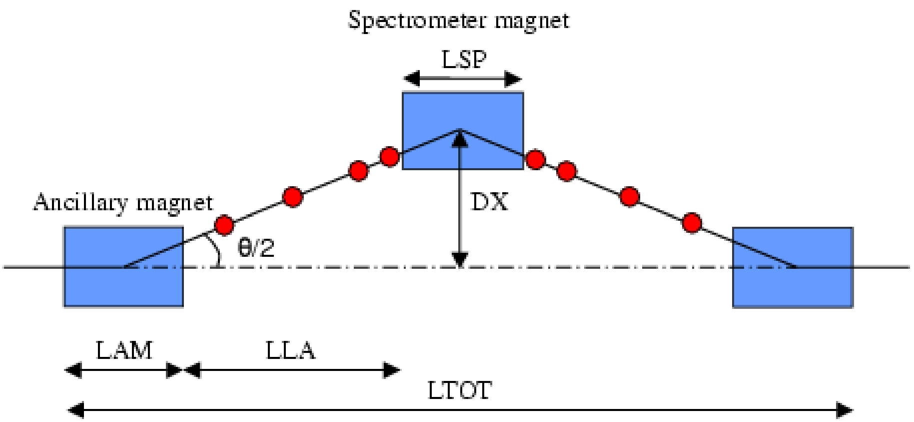
a BPM based magnetic spectrometer

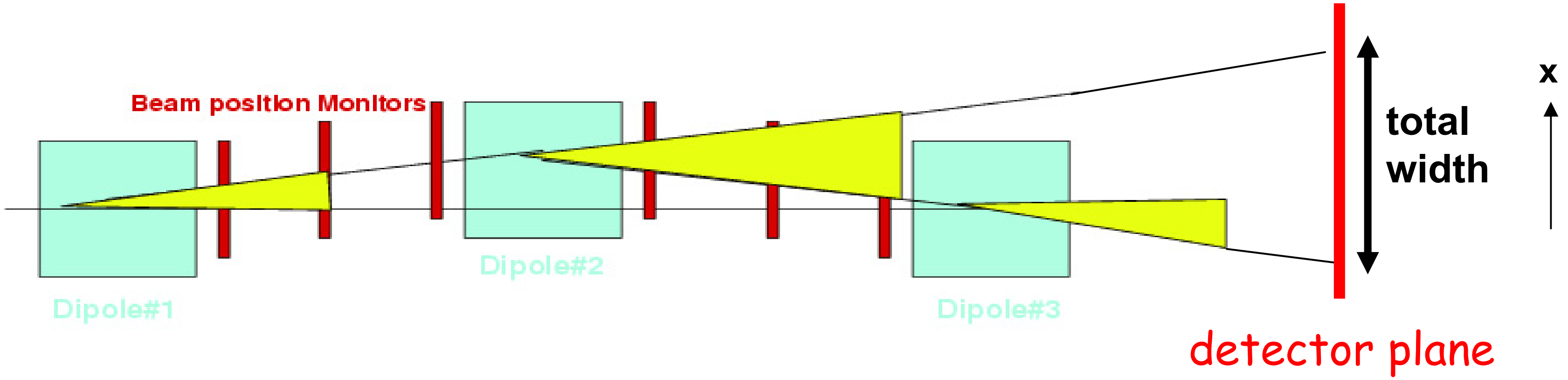


example



see LC-DET-2004-031

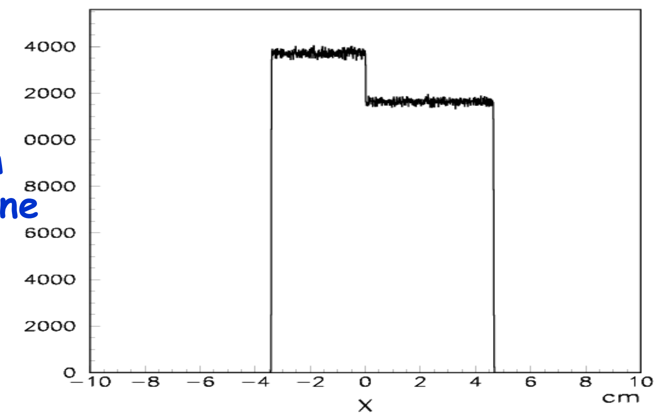
Three SR fans are generated when the beam particles pass through the magnets



width of SR yield in bending plane

~ $1/E_b$!

80 m downstream of the chicane



while in the vertical direction the divergence of SR fan

$$\theta_{vert} \approx (E_b / mc^2) \approx 2\mu rad$$ for photons with E_γ close to the critical energy of ~11 MeV

or

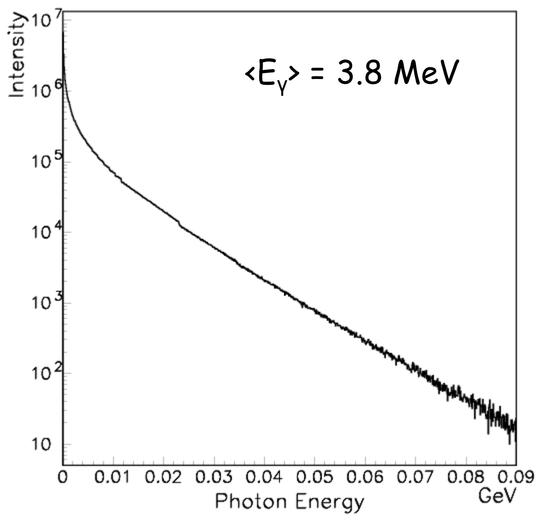
$$\theta_{vert} \approx 0.5 \cdot (\lambda / R)^{1/3} \approx 12\mu rad$$ for photons with E_γ <20 keV

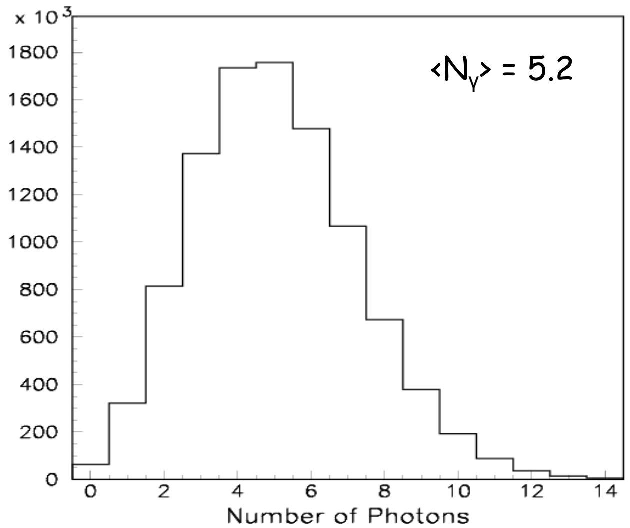
and vertical width varies with $(1/E_b)^{1/3}$ ➔ **weak beam energy dependence**

rely on bending plane variation

Vertical spot size $\Delta y \approx L \cdot \theta_{vert} \approx 1.1mm$ for L=80 m ➔ vertical spot size not very useful

basic characteristics of the synchrotron radiation expected:





For our example of the spectrometer and E_b = 250 GeV, # of e-/bunch = 2 10^{10}

➔ # of SR photons per bunch crossing ~(2-3) 10^{11}

➔ **huge amount of radiation !**

Precision achievable on E_b

$$\Delta E_b / E_b = \sqrt{(\Delta Bl / Bl)^2 + (\Delta L / L)^2 + (\Delta x / x)^2}$$

$(\Delta Bl / Bl)$	$(\Delta L / L)$	$(\Delta x / x)$
$2\ 10^{-5}$	$5\ 10^{-6}$	?

$2\ 10^{-5}$ and $5\ 10^{-6}$: **feasible !**

$\Delta x/x$ – precision of SR fan width or the endpoints of the fan

Bl – integrated B-field;
L – distance to detector

If $\Delta E_b/E_b = 5\ 10^{-5}$ is anticipated

→ **$\Delta x/x$ ~ few micrometer !**

i.e. high-spatial resolution synchrotron radiation detector needed which integrates over all incoming photons for a bunch crossing

Schemes of Measurement of E_b

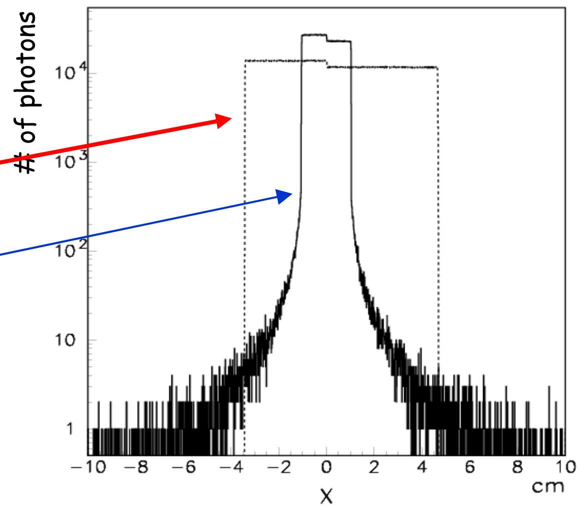
Due to the divergence of SR in bending plane

➔ interaction of photons with beam pipe wall should be avoided

with beam pipe radius 1 cm

no interactions

with interactions



no precise edge position measurement possible

solution: **dedicated vacuum chamber with increasing aperture in beam direction**

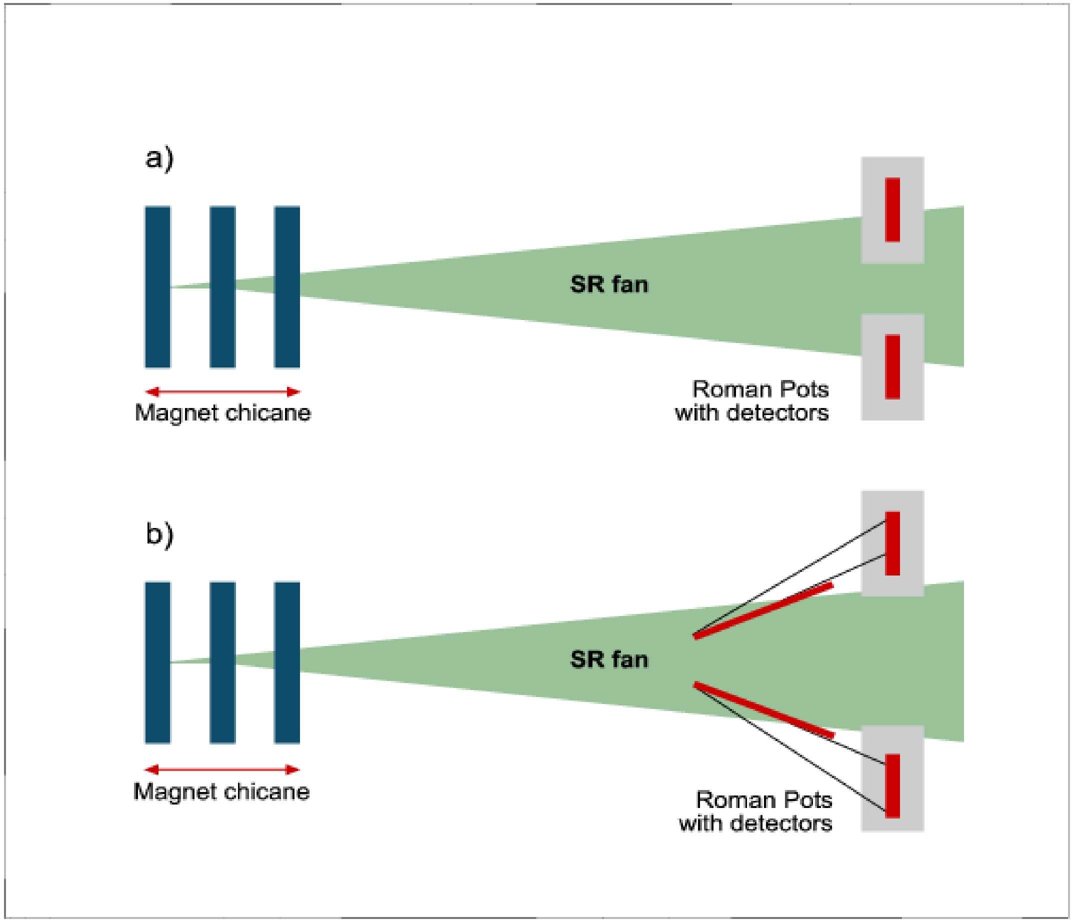
Scheme 1

edges of SR are measured by detectors installed in Roman Pots, separated by thin windows from main vacuum

➔ simple, no further devices except detectors needed

disadvantage: large radiation !

➔ damage or performance degradation of detectors



Scheme 2

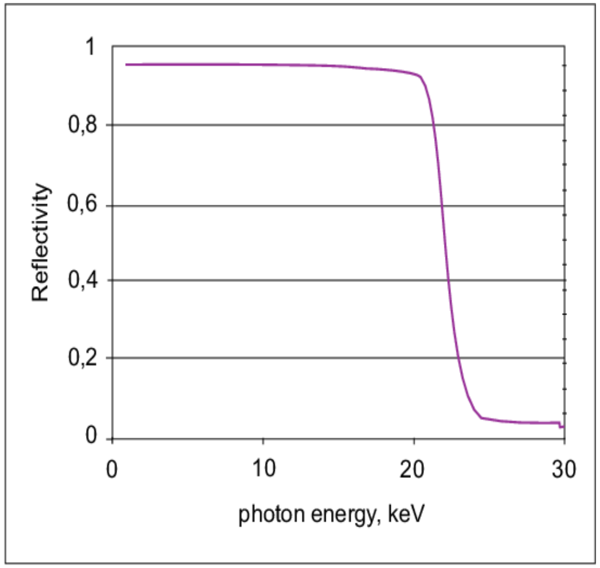
two mirrors are added

- to reflect a small part of the SR to the detectors
- the light reflected consists of only low energy photons (<20 keV)

amount of SR in detectors is suppressed by orders of magnitude

Possible mirrors:

Rhodium (Rh) mirrors are proposed,
and when installed into the beam line
with an angle less than 4 mrad,
very large reflectivity (>95%) is achieved
for photons with energies < 25 keV



Length of mirrors should be at least ~50 cm
➔ stability issues
and heat load investigations

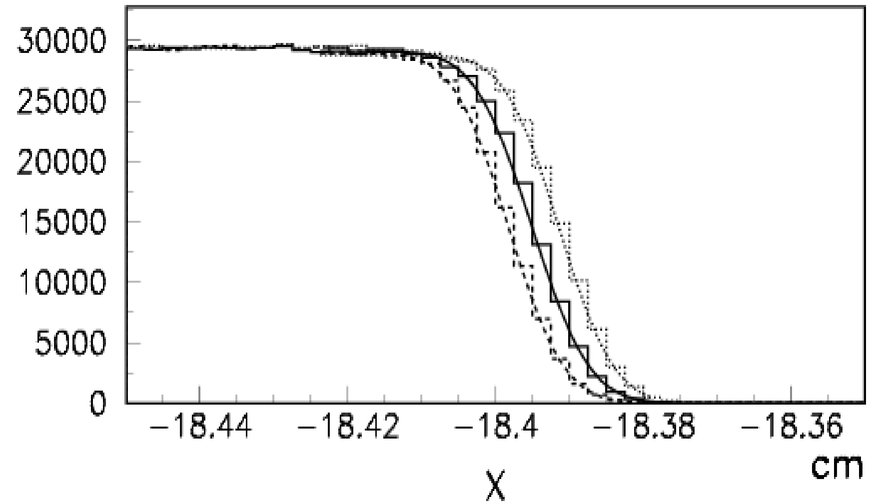
Both schemes

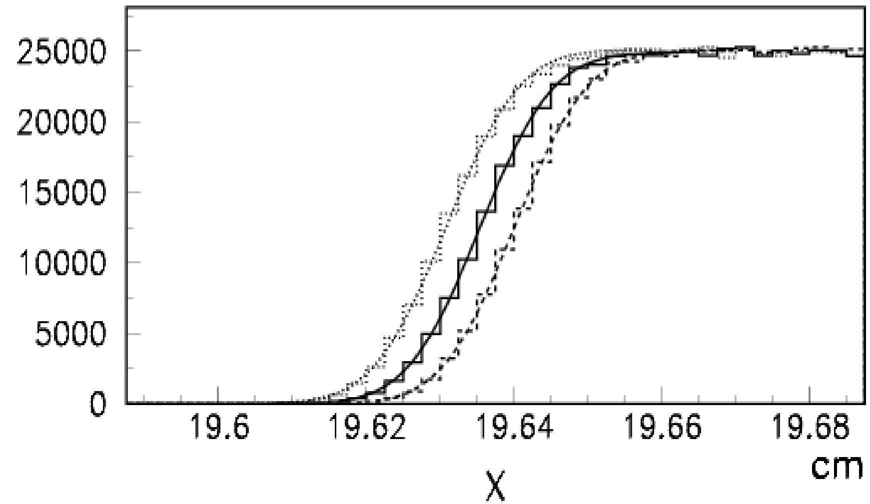
➔ **GEANT simulations with**

- internal beam energy spread (0.15%)
- fringe fields of the magnets
- reasonable transverse beam size

Endpoints of mirror reflected SR for E_b = 250.0 (solid histogram) and 250.0±0.250 GeV

80 m downstream of the spectrometer; mirrors 30 m upstream of the detectors





One notices

- significant variation of spectra with the beam energy on both sides of SR fan
- no sharp cut-off → edge dilution

➔ reasons:

- Eγ-dependent angular spread in the bending plane (→ few hundred μm)
- finite transverse beam size (→ 20 … 100 μm)
- internal energy spread (→ 40 μm)
- fringe fields (→ 50 … 100 μm)
- optical surface errors of the mirrors (→ 20 … 50 μm)
- uncorrelated ground motion of magnets (→ ???)

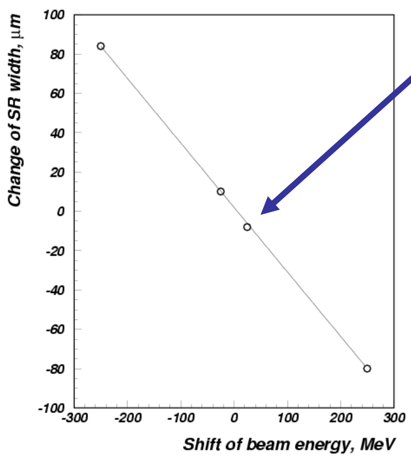
} **not in simulation**

The curves in the plots are the results of a fit to estimate the **endpoints of the SR fan**

fit function: step function folded by a Gaussian

$$f(x, p_1 \ldots p_4) = \frac{1}{2}(p_2(x - p_0) + p_3) + erf\left[\frac{x - p_0}{\sqrt{2}p_1}\right] - \frac{p_1 p_2}{\sqrt{2\pi}} \cdot \exp\left[-\frac{(x - p_0)^2}{2p_1^2}\right] - p_4(x - p_0)$$

with p_0 - edge position;
p_1 – edge width;
p_2 – slope left;
p_3 – edge amplitude;
p_4 – edge right



Results:

- very good X^2/NDF
- errors of edge position – few micrometer
- for 25 MeV beam energy increase ($1\ 10^{-4}$) edge values change by Δx_L = 4 μm resp. Δx_R = 6 μm; in total 10 μm shift of the width of the SR fan

➔ demands for SR detectors

SR detection

Processes of photon conversion in matter

- for photons with $E_\gamma < 100$ keV ➔ photoelectric effect
- … $E_\gamma = 100$ keV … 10 MeV ➔ Compton scattering
- … $E_\gamma > 10$ MeV ➔ pair production

↷ If no mirror ➔ all 3 processes contribute
while with mirror ($E\gamma < 25$ keV) only photoelectric effect

Furthermore, selecting low energy photons

- their spatial distribution is small (not spoiled) as for high energy photons
- mean path of photons is very small (e.g. in Al: 2.6 µm for 20 keV photons)
  ➔ **precision position detection possible**
- acceptance region of detectors ~5 mm of both sides of the SR fan in order to account for possible jitter of beam position, angle and energy

Examples of possible detectors

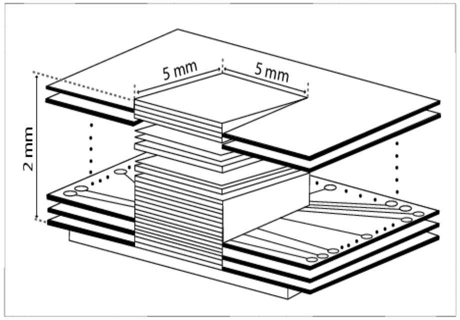
- Silicon strip detectors

  - well known, often used in particle physics experiments
  - with pitch of e.g. 25 μm ➔ spatial resolution of 25 μm/sqrt(12) for binary readout; improvements possible

  but radiation hardness is a critical issue
  ➔ only applicable for scheme 2 with mirrors (?)
  ➔ prove needed

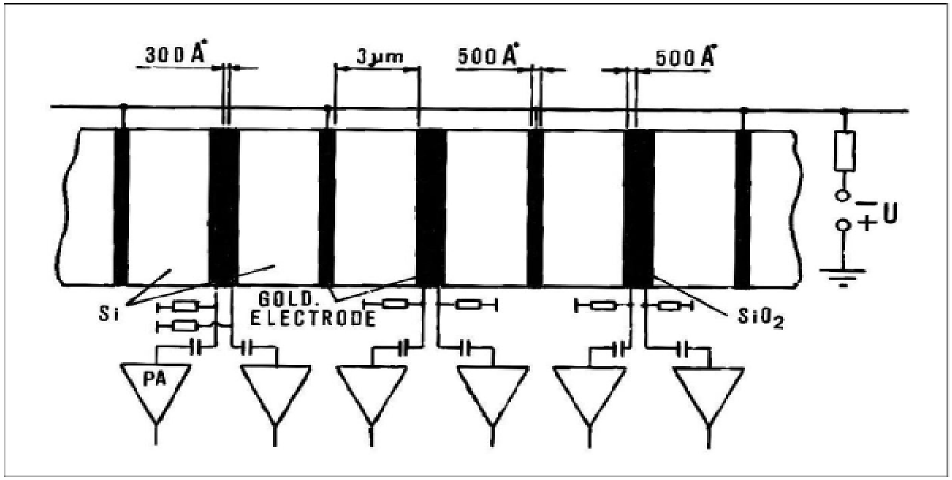
- novel high resolution Si detector (Dubna)

  the 5mm effective acceptance region
  2500 Si layers ($5*5$ mm^2 in size, 2 μm thick)
  interleaved by 0.05 μm SiO dielectric



Readout of each layer

- simple and compact close to readout of cathode strips for ATLAS muon chambers



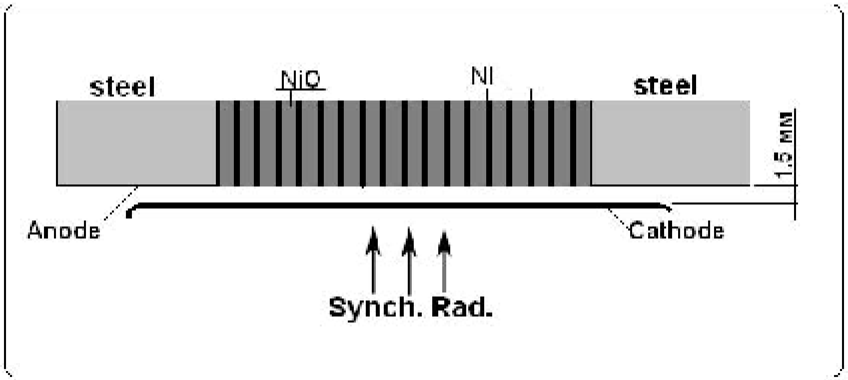
The large relaxation time of Si

→ proper adjustment of amplifier resistance → no problem so that bunch-to-bunch E_b measurement is possible

Such a detector radiation hard ➔ no damage expected (?) even for scheme 1

• Avalanche amplification detector (Dubna)

Plane-parallel avalanche detector with gas/liquid amplification in the range 10 … 100



Example: - 1.5 mm anode-cathode gap filled with xenon at 60 atm (liquid)
- entrance window: 1 mm Be
- anode plane consists of of 1 μm Ni layers separated by 2 μm NiO

Large number of photoelectrons expected → large signal of ~100 mV for 5 mV/pC amplifier conversion factor

Radiation hard ➔ suitable for scheme 1 ➔ need to be proven

LC-DET-2006-...

ILC Beam Energy Measurement based on Synchrotron Radiation from a Magnetic Spectrometer

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Abstract

We propose to measure, on a bunch-to-bunch basis, the beam energy at the International Linear e^+e^- Collider by monitoring synchrotron radiation (SR) light emitted in the magnets of an energy spectrometer based on beam position monitors. Measuring the width of the horizontal SR fan permits to determine the relative beam energy with a precision better than 10^{-4}. There are two different measuring schemes possible. The first one is based on edge measurements of the direct SR fan, while the second option includes mirrors to deflect soft SR light to detectors located sufficiently off the beamline. Three possibilities for high-spatial resolution detectors are considered: a standard silicon strip detector, a novel-type Si detector with exceptional position resolution and a gas amplification detector. The main issue of the first scheme is the high radiation dose expected in the direct SR fan. If mirrors are used this dose is strongly reduced and allows application of any of the three detectors proposed.

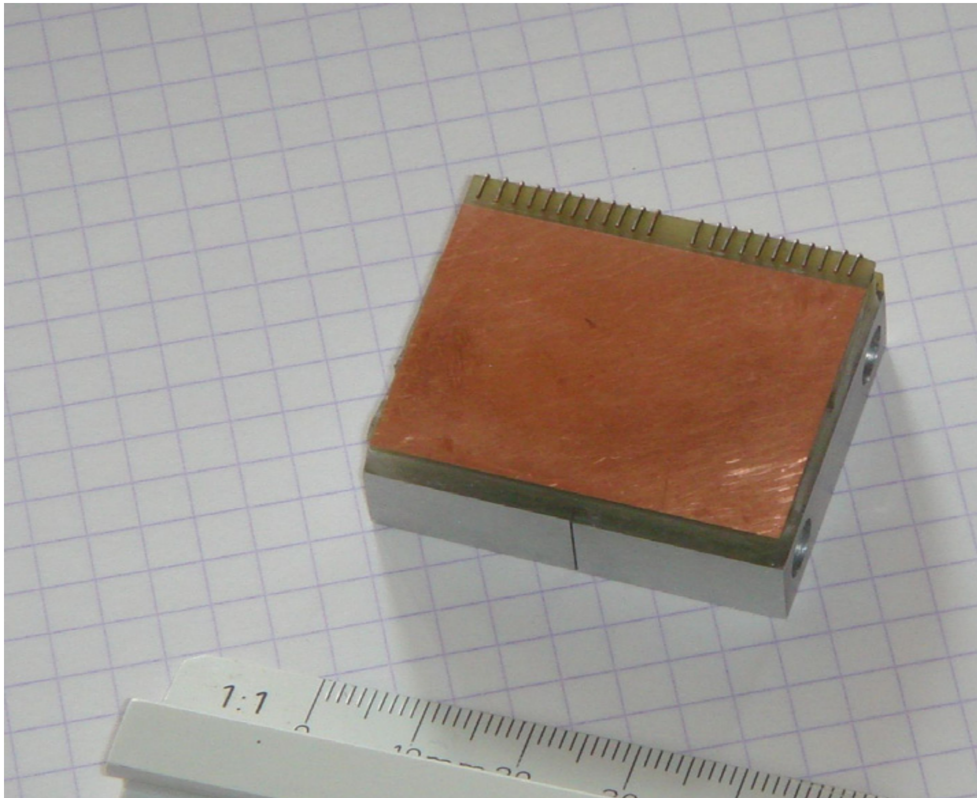
Present and future activities anticipated

- Dubna: - prototype of gas amplification detector with 48 channels, a pitch of 3 μm and a pressure of 150 atm

  construction → end of 2006

  - improved GEANT simulation w.r.t. 'real' bunch passing through BDS and improved detector response

  ➔ **real world is not Gaussian**



- DESY: launched an R&D detector program for XFEL to develope position sensitive detectors applied in a regime very similar to that at the ILC