Development of a compact single shot electron spectrometer

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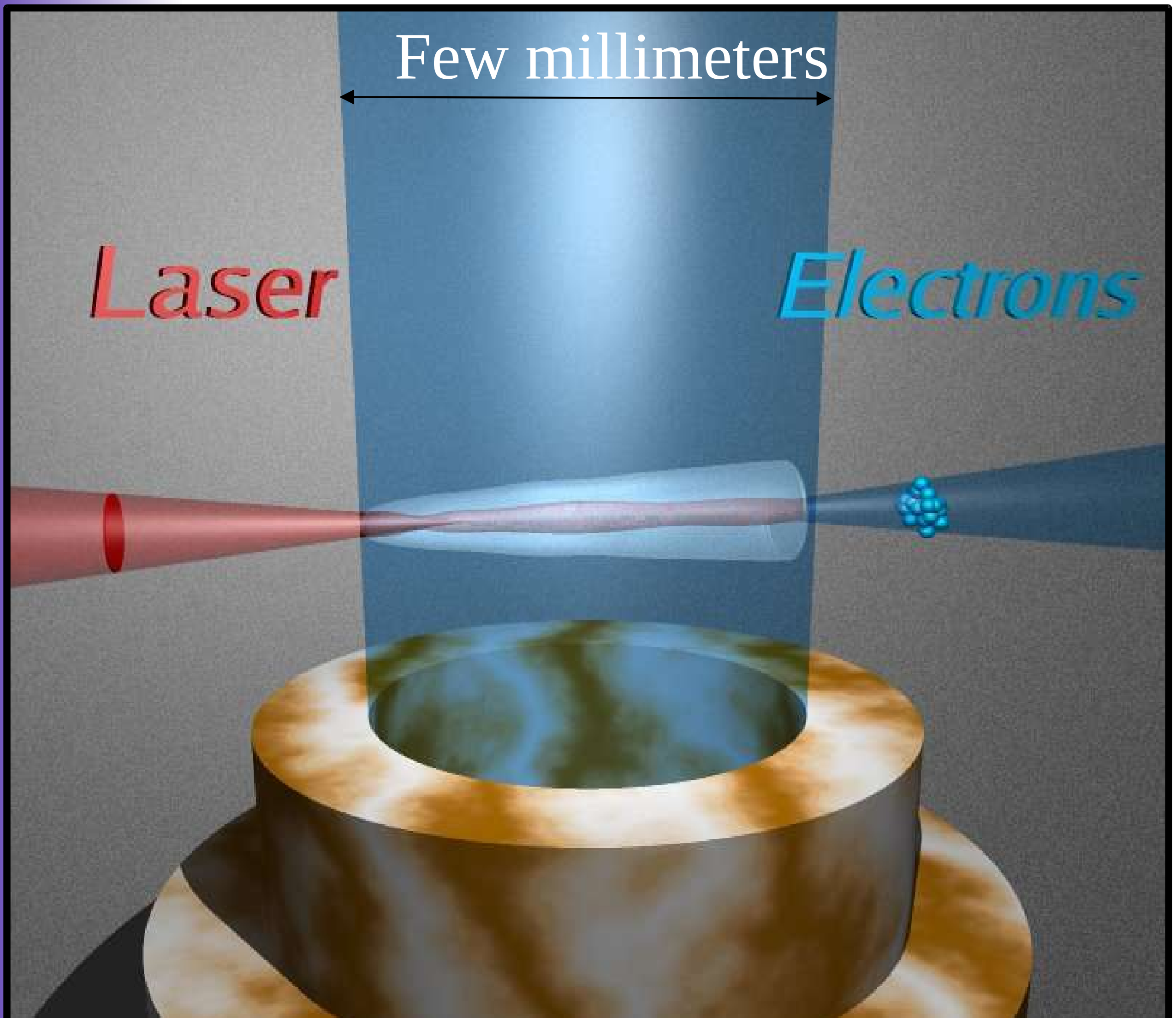
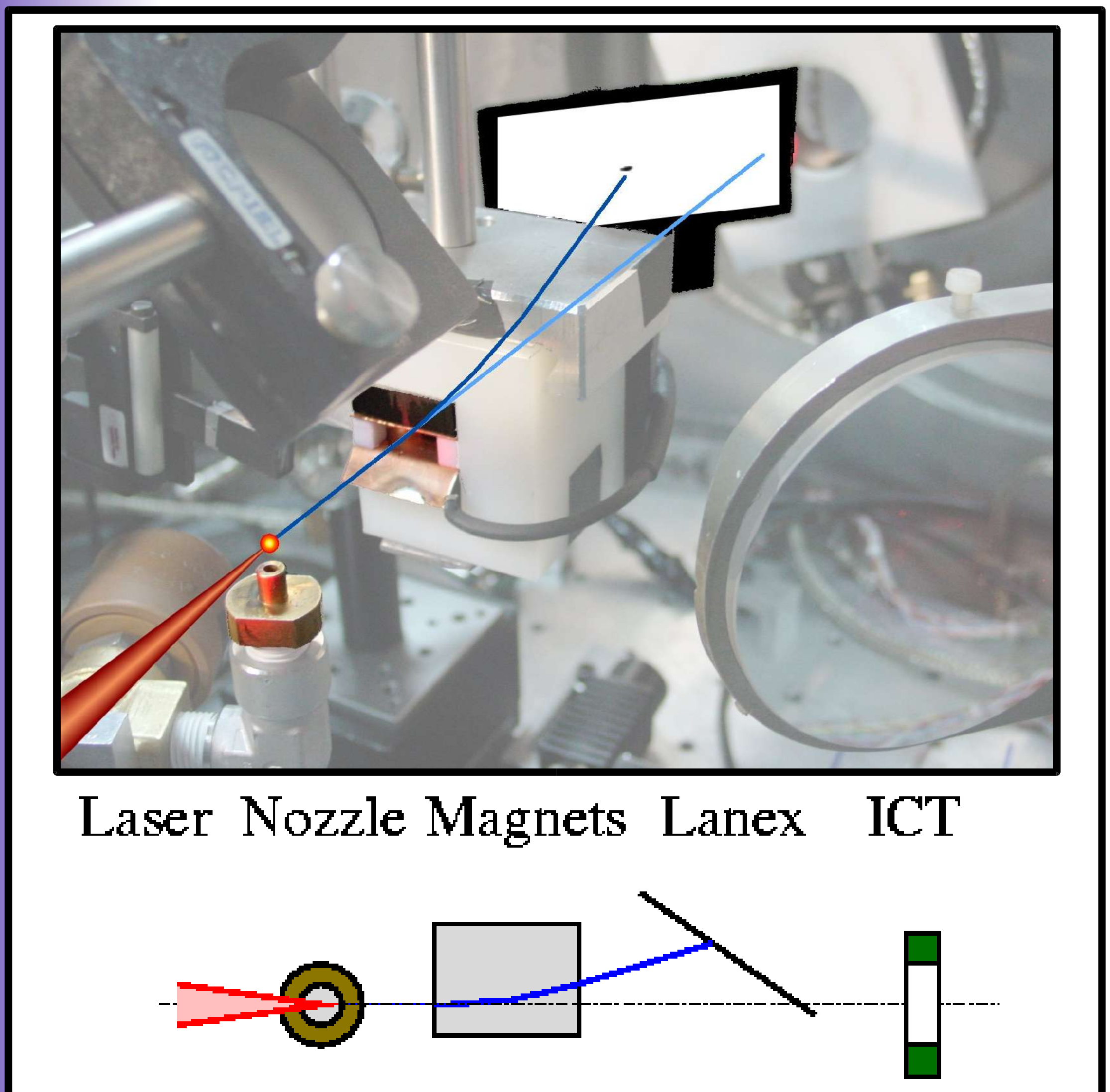
Compact electron accelerator



Major enhancements of the electron beam properties :

- Small source size
- Low divergence
- Quasi-monoenergetic
- Short duration
- High charge

In the interaction chamber

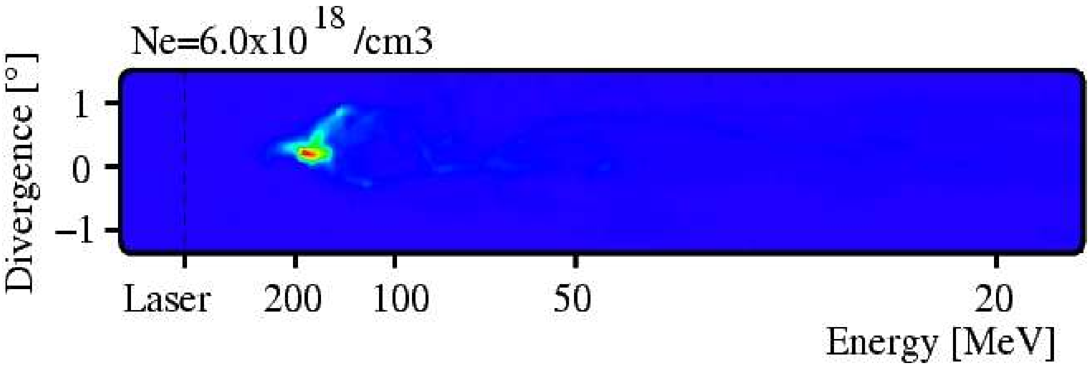


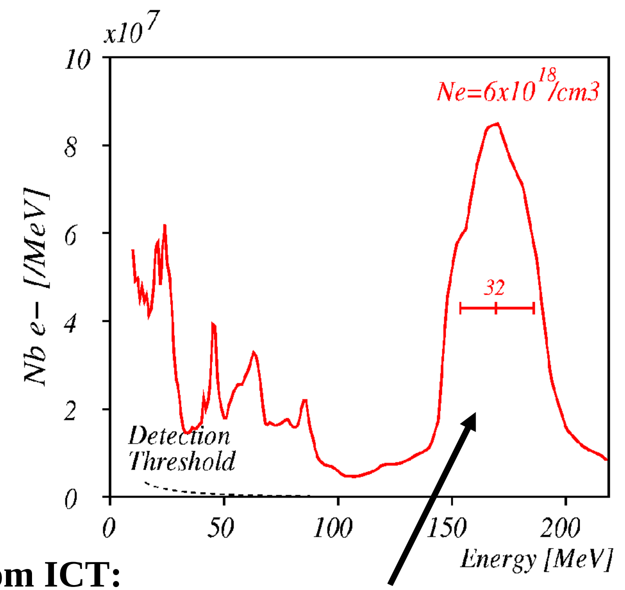
New spectrometer :

- Single shot measurement
- Spectrum and divergence
- Measurement of the charge at high energy

This diagnostic can be used because the electron beam is very collimated.

Measurement of a quasi-monoenergetic electron beam





From ICT:
500 pC +/-200 pC in the bump at 170 MeV

Limitation due to the spectrometer resolution

Faure *et al.*, Nature **431**, p541 (2004)

Outline

I – Design of a spectrometer for higher energies

- Permanent magnetic field.

II – Analytical calculations

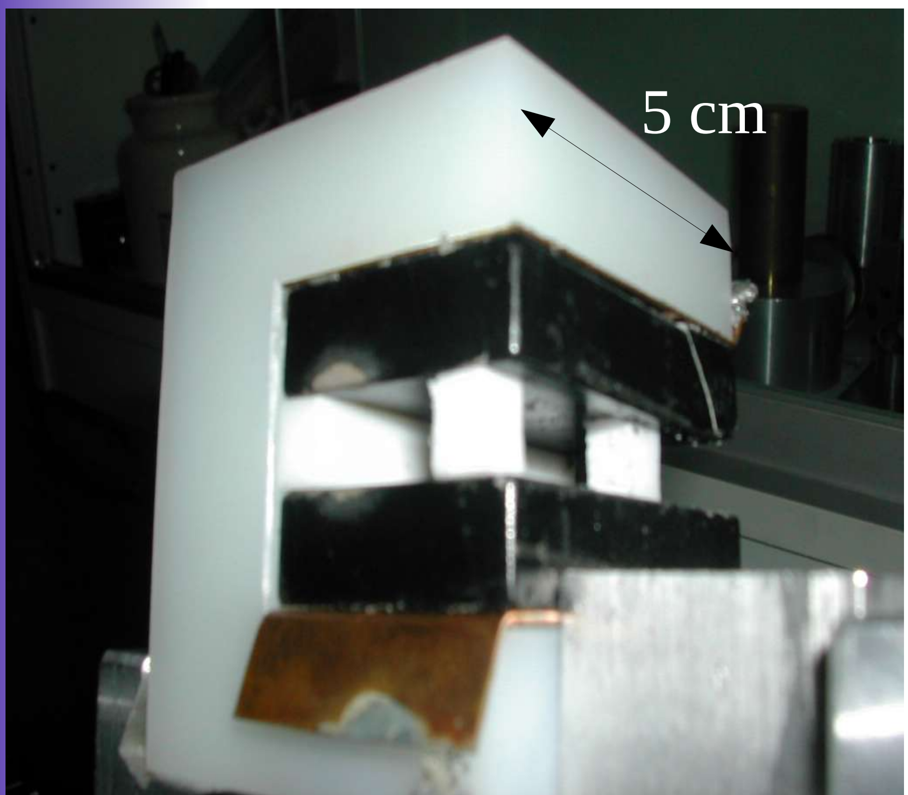
- Trajectories of electrons
- Spectrometer resolution
- Relative and abolute calibration of the number of electrons

III – Application to an experimental electron beam

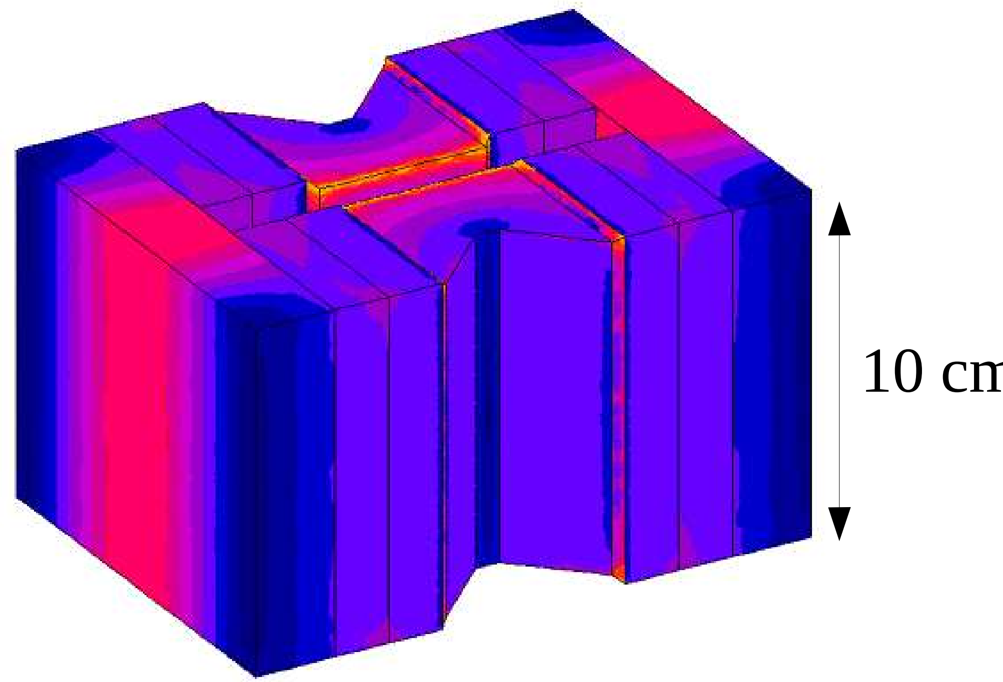
- Quasimonoenergetic electron spectrum

Comparison of the two magnets

B=0.41 T



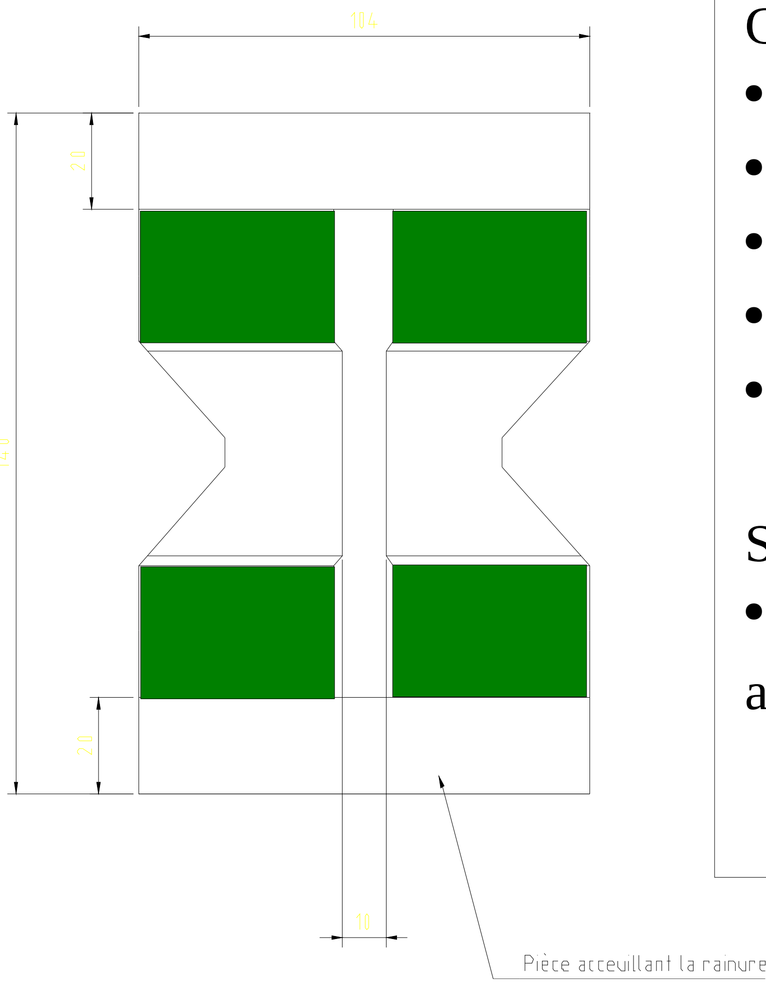
B=1 T



Previous Magnet
home made, up to 100 MeV

Design of a new magnet
up to 400 MeV

Datasheet



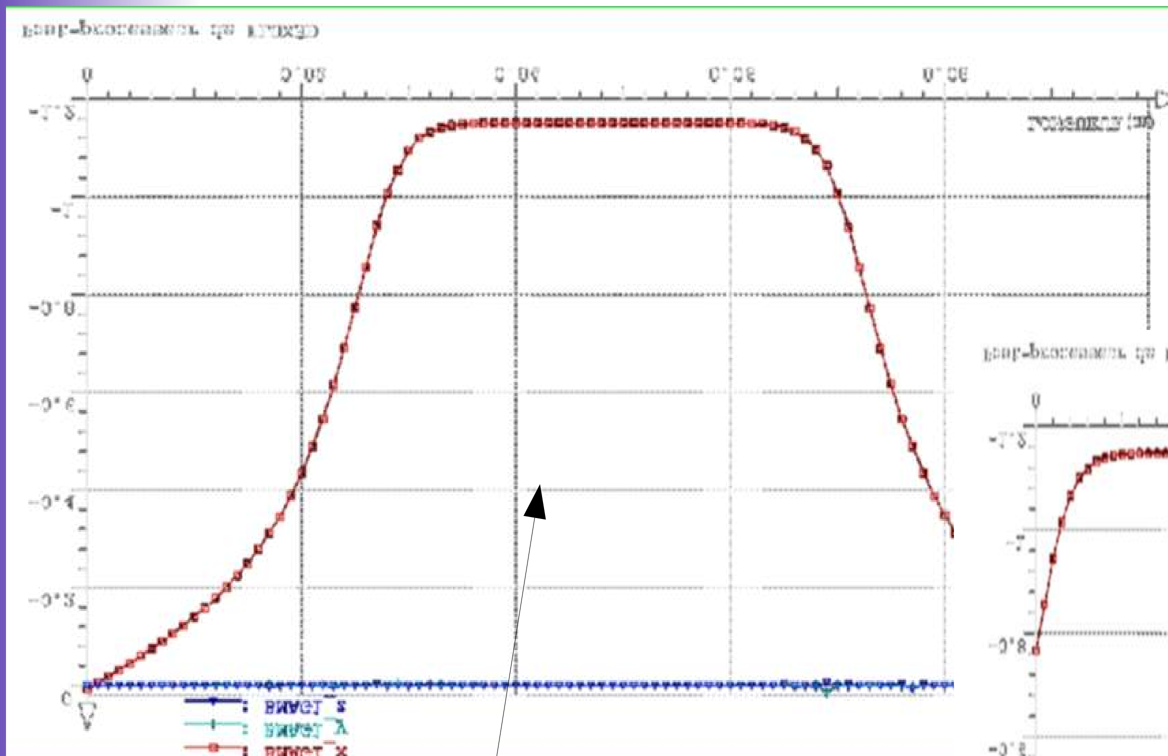
Constraints :

- Gap = 1cm
- Magnetic field ~ 1T
- Length = 10 cm
- Large slit required
- Compact spectrometer

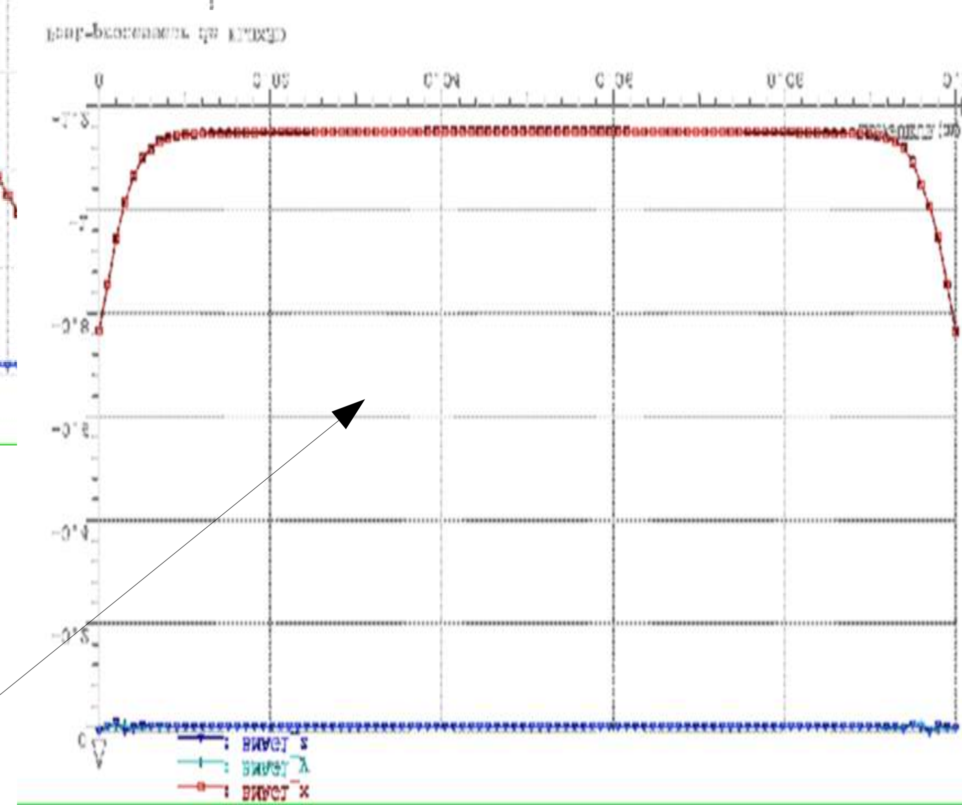
Solution :

- Good homogeneity due to a special arrangement of magnet poles

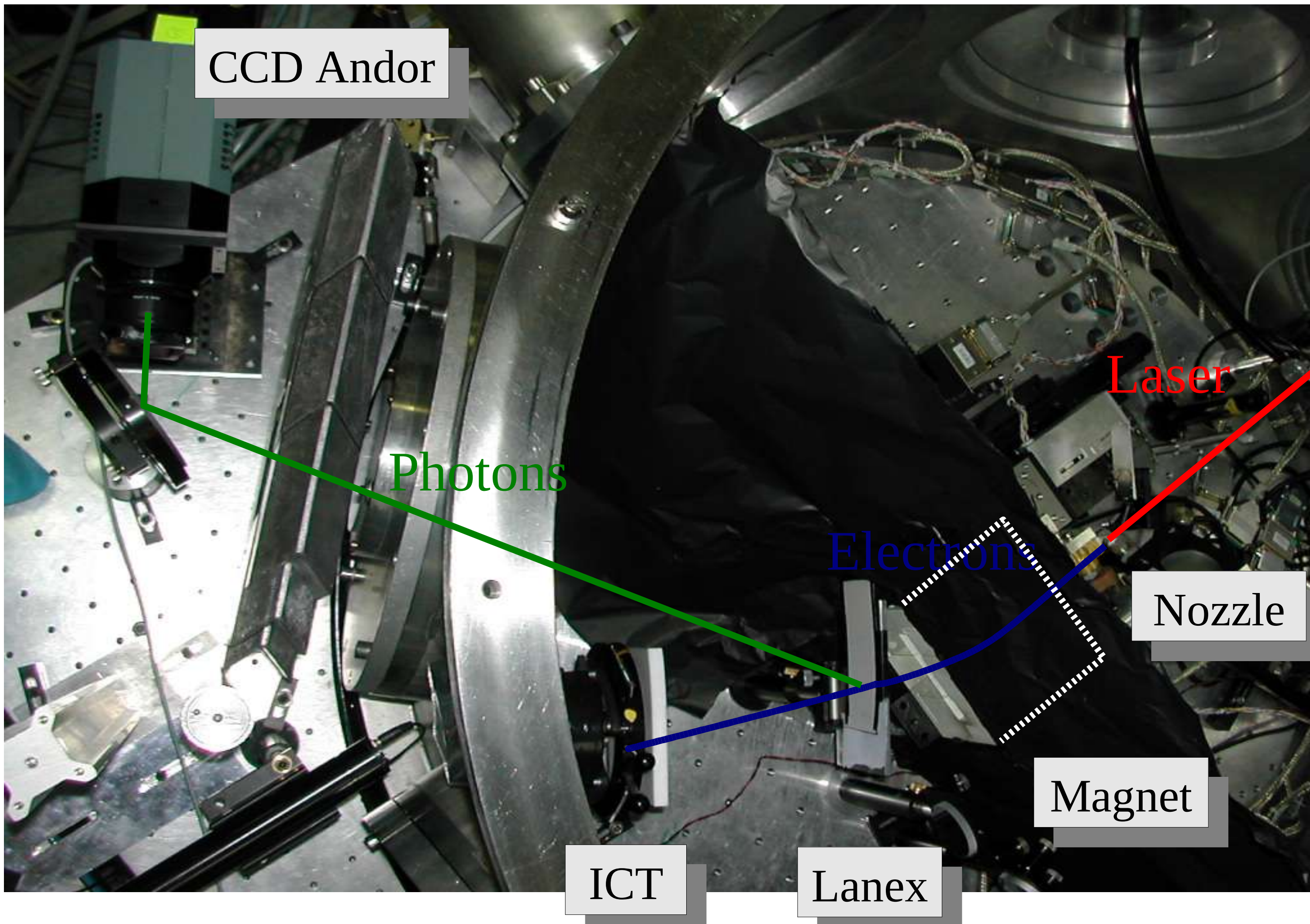
Data from the manufacturer



Simulations of the longitudinal magnetic field



Transverse magnetic field


CCD Andor
Photons
Laser
Electrons
Nozzle
Magnet
ICT
Lanex

Analytical calculations

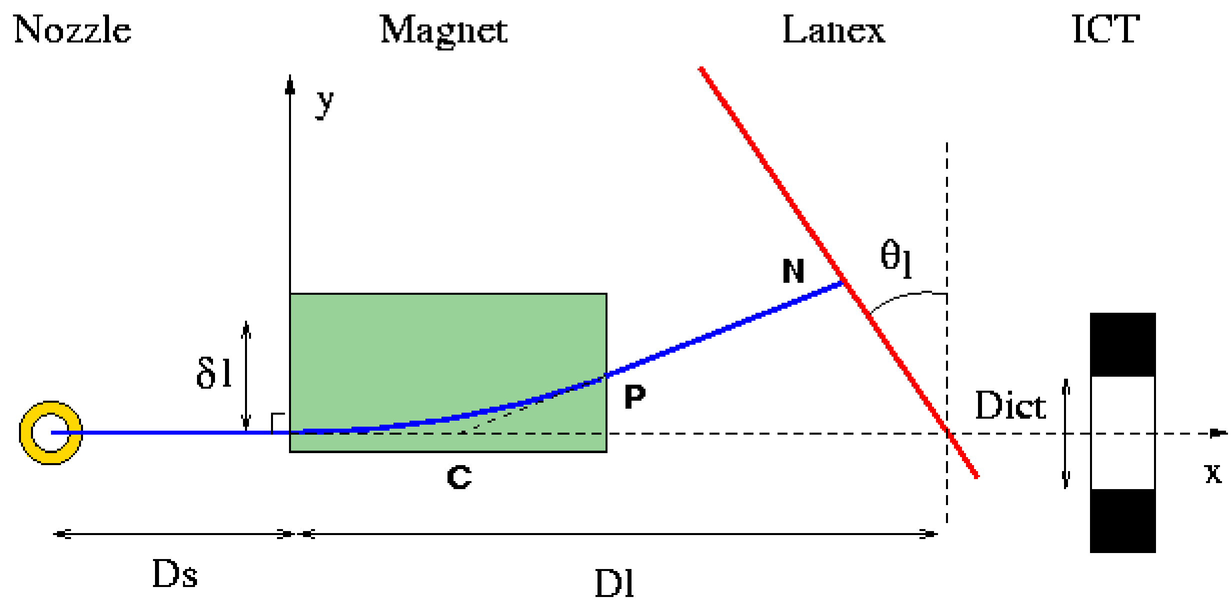
- Trajectories of an electron in a permanent magnetic field
  - Radius of curvature (relativistic electron):

$$R = \frac{E_0}{B_m e c}$$

E_0 Initial kinetic energy
B_m Magnetic field
e Charge of the electron
c Celerity of light

- Assumptions :
  - The magnetic field is uniform in a rectangular area
  - The relativistic incomming electron is perpendicular to the magnet's surface.

Coordinates



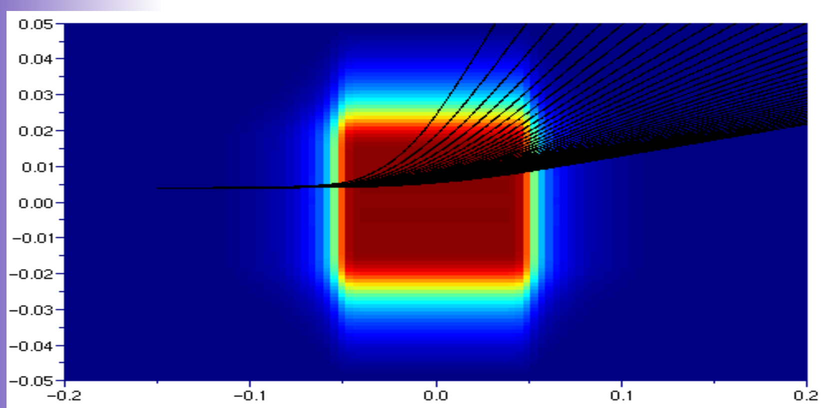
$$\begin{pmatrix} x_P \\ y_P \end{pmatrix} = \begin{pmatrix} L_m \\ R-\sqrt{R^2-L_m^2} \end{pmatrix}$$

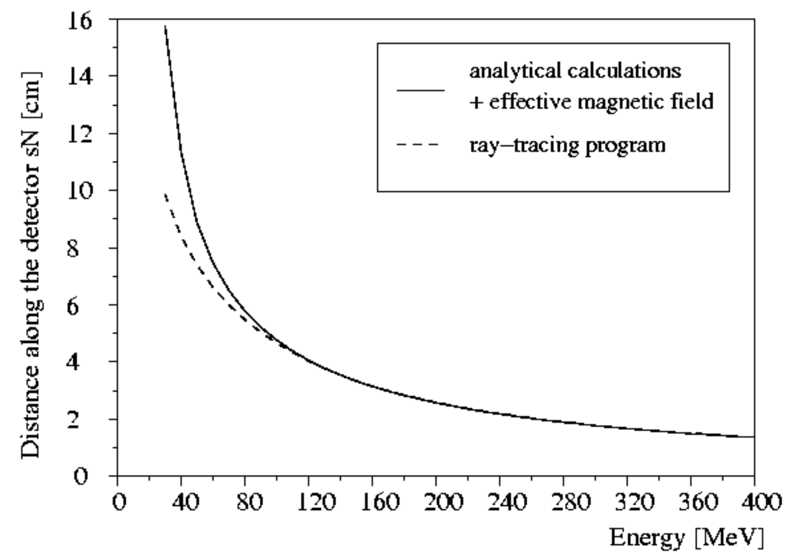
$$\begin{pmatrix} x_C \\ y_C \end{pmatrix} = \begin{pmatrix} \frac{x_P^2+y_P^2}{2\ x_P} \\ 0 \end{pmatrix}$$

$$\begin{pmatrix} x_N \\ y_N \end{pmatrix} = \begin{pmatrix} D_l - y_l \tan(\theta_l) \\ \frac{(D_l - x_C)\, y_P}{x_P - x_C + y_P \tan(\theta_l)} \end{pmatrix}$$

Equivalent magnetic field

- The real magnetic field spreads outside the magnet. The introduction of an equivalent magnetic field allows the use of analytical formulaes.





$$B_m^{max} = 1.0\,T \longrightarrow B_m^{eff} = 1.2\,T$$

- Not valid for electrons below 100 MeV who travel in the gradient of the magnetic field

Resolution

- The resolution is limitted by the size of the electron beam on the detector. The corresponding energy range at a given energy E_0 is :

$$\frac{\delta E_0}{E_0} = \frac{\delta_s}{E_0} \div \frac{d s_N}{dE_0}$$

$s_N = y_N / \cos(\theta_l)$ the distance along the Lanex

δ_s the size of the electron beam on the detector

- The equivalent at high energy is

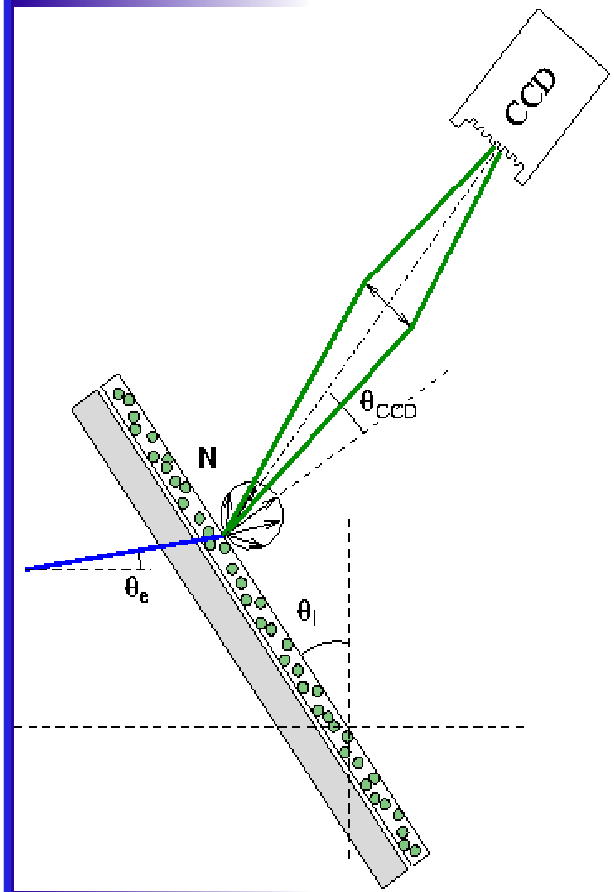
$$\frac{\delta E_0}{E_0} \sim \frac{(D_s + D_l) R \theta_s}{(D_l - L_m/2) L_m} \propto R \propto E_0$$

θ_s divergence

Energy [MeV]	20	50	100	200	400
«home-made» magnet	6%	14%	27%	53%	-
10cm magnet	-	-	5%	10%	20%

Resolution for two different configurations

Detector composition



Item	*Material*	*Density (g/cc)*	*Thickness (cm)*
Laser Shielding			
Shielding	Aluminium	2,70	0,0100
Kodak Lanex Fine Screen			
protective coating	cellulose acetate	1,32	0,0010
plastic subtrate	Poly(ethylene terephtalate)	1,38	0,0178
scintillator	Gd2O2S + urethane binder	4,25	0,0084
protective coating	cellulose acetate	1,32	0,0005

Composition of the scintillating screen

The surface loading of Gadolinium Oxysulfide in the urethane binder is 33 mg/cm^2

Schach von Wittenau *et al.*, Med. Phys. **29** pp. 2559-2570 (2002)

Absolute calibration

Phosphor layer : conversion

We assume that the conversion into visible light is proportionnal to the energy deposited in the scintillator layer

$$\frac{dN_{cr}}{dN_{el}} = \frac{1}{E_{ph}} \varepsilon \frac{dE}{dx} \delta x$$

$\delta x = h_s / \rho_{GOS}$ effective phosphor thickness

ε efficiency

Transport : photon collection

The transmission at the phosphor boundary and the number of photons collected by the lens of the Andor CCD

$$\frac{dN_{coll}}{dN_{cr}} = \zeta\, g(\theta_{CCD})\, \delta\Omega\, q_l q_Q q_{IF}$$

ζ output transmission factor

$g(\theta_{CCD})$ lambertian law

Detection by the CCD : number of counts

The yield of the Andor CCD camera

$$\frac{dN_{count}}{dN_{coll}} = \frac{QE}{r}$$

$$\frac{dN_{el}}{dE} dE = Counts \div \left(\frac{dN_{counts}}{dN_{coll}} \frac{dN_{coll}}{dN_{cr}} \frac{dN_{cr}}{dN_{el}} \right)$$

List of parameters

Parameter	Symbol	Value
Spectrometer		
Magnet		
Equivalent magnetic field	Bm	0.41 T
Magnet length	Lm	5 cm
Magnet width	Lm	2.5 cm
Magnet shift	δlm	1.3 cm
Magnet-Lanex length	Dl	17 cm
Lanex		
Lanex angle	θl	55°
Efficiency	ε	0,034
Surface Loading	hs	33 mg/cm2
Phosphor density	ρ_{GOS}	7.44 g/cm3
Photon energy	Eph	2.27 eV
Transmission factor	ζ	0,22
ICT		
ICT diameter	Dict	10 cm

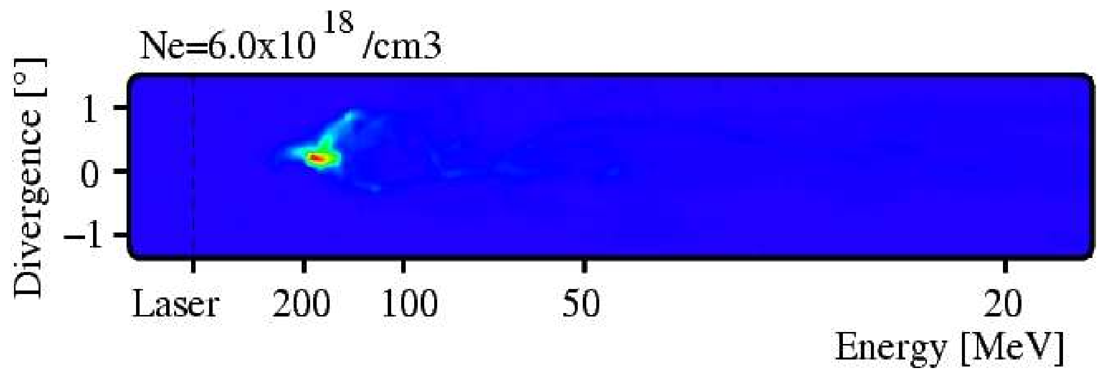
Parameter	Symbol	Value
Detection System		
Solid Angle	δΩ	2.0e-3 sr
CCD angle	θ_{ccd}	15°
Lens	q_l	0,95
Quartz	q_q	0,95
Interference filter	q_{IF}	0,2
Pixel size on the lanex	L_{pix}	0.28 mm
Electron Source		
Source-Magnet length	Ds	6 cm
Divergence	θs	10 mrad

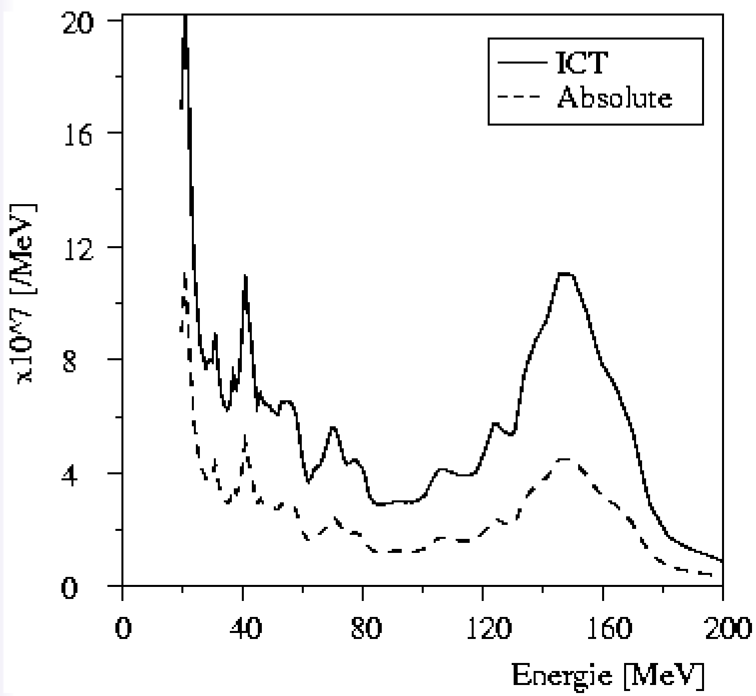
Private discussions with M. Kando

Needs further investigation

Example of image analysed

The quasi-mono energetic spectrum





Mismatch of the two curves for several reasons :

- ICT sensitive to electrical noise
- Efficiency of the lanex estimated from data of collabaorators
- Saturation effects in the phosphor film

Conclusion and Perspectives

I – Needs of a compact single shot spectrometer

- Requirements
  - Acceleration of electrons up to 200 MeV.
  - Adapted to high repetition rate : no film processing.
- Solution chosen
  - Design and purchase of a strong permanent magnet
  - Purchase of 16 bits Andor CCD cameras.
  - Development of analytical formulaes for spectrum deconvolution
  - Purchase of a hall probe for magnet characterization

II – Further developments

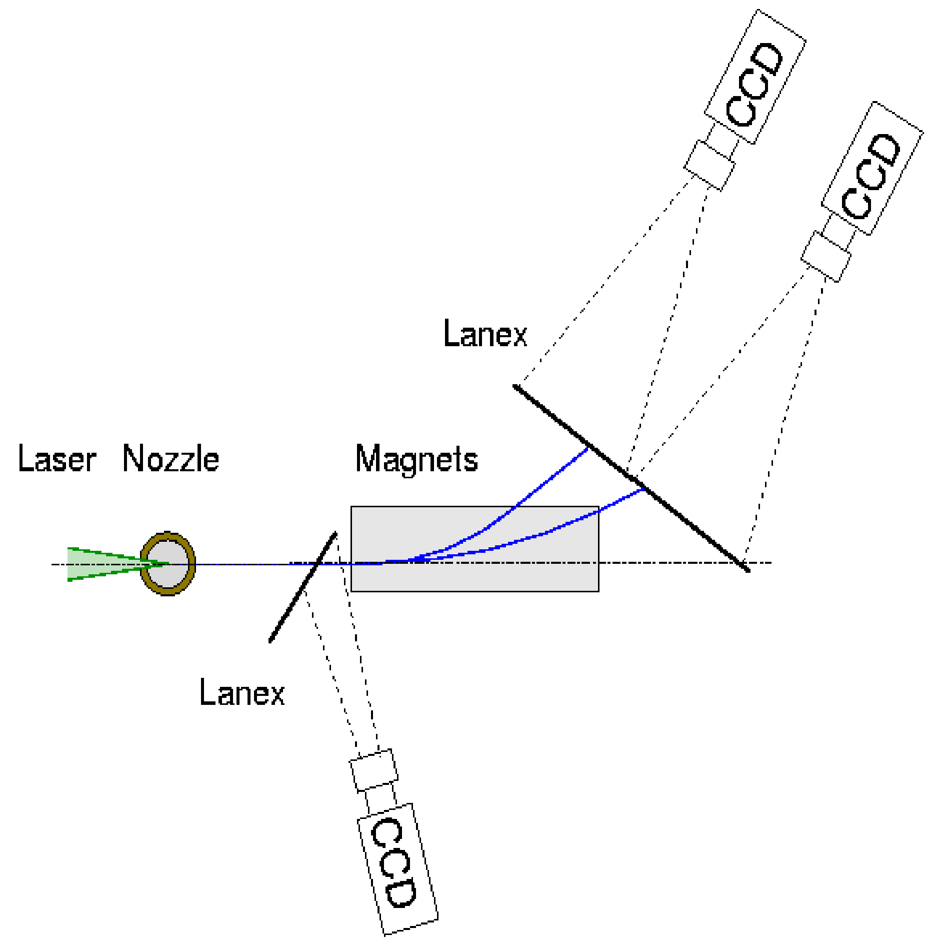
- The present work will help to design a larger magnet for GeV acceleration experiments
- Estimation of the efficiency of the scintillator

Example of possible configuration for a 1 GeV-energy electron spectrometer

- Longer magnet requires larger detector to get the full spectrum

- The electrons may exit the magnetic field by the edges, in order to reduce the deflection angle for low energies
  - Beware that the each pixel on the detector corresponds to a single energy.

- A third camera with less pixel depth to monitor the electron beam axis before the magnets.
  - Valid if the scattering angle is smaller than the natural divergence. Depends on the phosphor thickness. OTR may be required.



Transmission of the interference filter