MEASUREMENT OF THE BEAM ENERGY USING RESONANT ABSORPTION OF LASER LIGHT

- a novel method to determine the beam energy with high precision ?

DESY – Dubna – Yerevan Collaboration

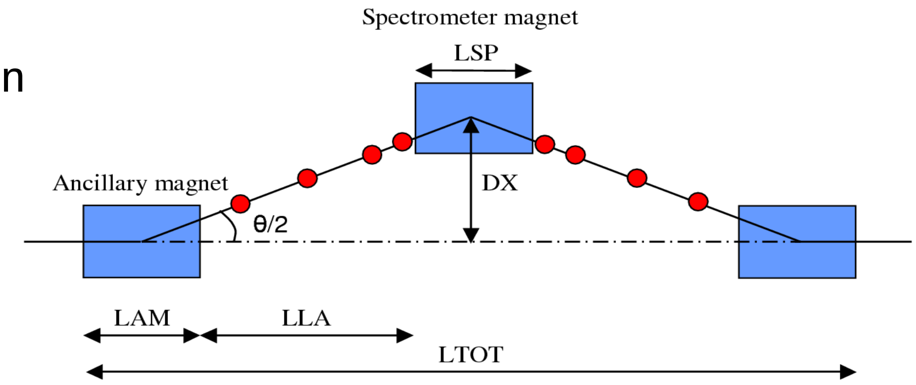
The canonical method to determine the beam energy relies on a magnetic spectrometer, a chicane:

Concept:

determination of the bending angle Θ
of charged particles through a magnet
whose B-field integral is precisely known

$$E_b = \frac{ce}{\Theta} \int_{magnet} B dl$$

Θ = bending angle
B = magnetic field



3 magnets (one analyzing, two ancillary) and a series of BPMs with high precision

For details see the note **LC-DET-2004-031**

Method of ***Resonance Absorption*** was introduced in theoretical papers

- D.P. Barber and R. Melikian, DESY Report 98-015 and hep-ph/9903007;
- D.P. Barber and R. Melikian, Proceedings of EPAC 2000, Vienna, Austria;
- R. Melikian, several ‘energy spectrometer’ meeting contributions by R.Melikian

→ Summary:

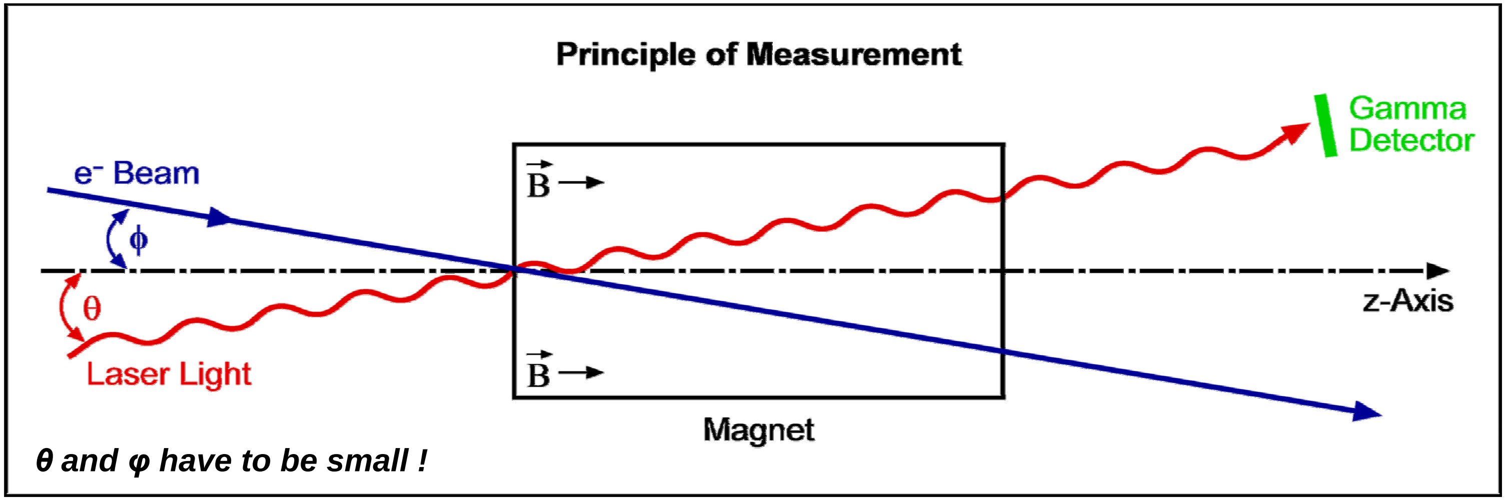
Absorption of circular polarized laser light by the beam particles in a static magnetic field permits to measure the beam energy with high precision, $\Delta E_b/E_b = 10^{-4} \ldots 10^{-5}$

The energy of the beam particles in a magnetic field has a discrete spectrum that allows the laser photons to be absorbed. During the absorption process transitions between different energy levels of the electrons occur.
At the point of largest absorption, i.e. at resonance absorption, the beam energy depends on few quantities, which are basically in our hand, so that

→ *determination of the beam energy and*
*its continuous monitoring during an experiment should be possible (**?**)*

This process is denoted as ***Resonance Absorption (RA)*** in the literature.
Theory behind this idea is ***QED***.

The basic experimental set-up is relatively simple:



RA can be detected by measuring the ratio of the number of absorbed laser photons to the number of incident laser photons, i.e. the drop of the laser light intensity in the detector, as a function of a suitable quantity (e.g. the B-field) during the time of interaction of the beam particles with the laser light within the magnet.

The (relative) accuracy of E_b can reach ***10^{-4} … 10^{-5}*** ***(?)*** if certain conditions resp. requirements can be fulfilled.

Now, we assume that ***only*** the following transitions between different energy levels of the electrons occur:

- without spin-flip (i.e. the e^--helicity is unaltered)
- and on the main harmonic, n' – n = 1 (n being an integer)

} other transitions are negligible **!**

resonance absorption condition, which can be written as

$$\gamma_0 = \frac{\Omega \pm \cos\varphi \cos\theta \sqrt{\Omega^2 - (1 - \cos\varphi^2 \cos\theta^2)}}{1 - \cos\varphi^2 \cos\theta^2} \qquad \textbf{(1)}$$

with $\gamma_0 = E_b / mc^2$ and $\Omega = \frac{\omega_c}{\omega} = \frac{eB}{m\omega}$

i.e. the **resonance absorption condition (1)** links the beam energy $\mathbf{E_b}$, i.e. $\boldsymbol{\gamma_0}$, the strength of the magnetic field **B**, the laser light frequency $\boldsymbol{\omega}$ and the two angles $\boldsymbol{\theta}$ and $\boldsymbol{\varphi}$ to each other **!**

Eq.(1) requires that the laser photon energy a) $\hbar\omega << E_b$ **(ok)**

and

b) $\Omega^2 \geq 1-(\cos\varphi\cos\theta)^2$ (**Ω** = function (**B,ω**))

The last condition restricts the possible multidimensional parameter space,
but for practical values of **B-fields** (0.05 – few Tesla)
and **ħω, the photon energy,** (0.1 to few eV)
and (very) small **θ** and **φ** values

$\longrightarrow$ **solutions can be found !**

An other so far not discussed important aspect concerns the ***significance of Resonance Absorption effect*** which is related to

the ***power of the laser***,

the ***length of the magnet***

and the ***laser light detection device***

If absorption occurs within the B-field, the electron gets some acceleration.
If the number of photons absorbed by a given electron is denoted by n_γ

The ***energy growth of the electrons*** near the resonance condition can be expressed by

$$E_b - E_b^0 \cong n_\gamma E_\gamma \approx mc^2 \xi \omega \sqrt{\frac{2\Omega}{\gamma_0}} \cdot t_i$$

within a classical approach !

where $\xi = e\varepsilon / mc\omega$ **a non-dimensional parameter of the laser intensity, with $\xi \ll 1$!**

ε = **amplitude of energy vector of the laser [V/cm]**

ω = **frequency of the laser**

$\omega_c = eB/m$

} with $\omega/2\omega_c \ll \gamma_0$

If each electron absorbs an integer number of photons n_γ

$$n_\gamma \cong \xi \frac{L}{\lambda_C} \sqrt{\frac{2\Omega}{\gamma_0}} = \xi \frac{L}{\lambda_C} \sqrt{\frac{2eB}{m\omega\gamma_0}} = 1,2,\ldots$$

(2)

L – length of the magnet;
λ_C – Compton wavelength of the electron

If eq.(2) is resolved for **ξ**, a parameter proportional to the laser energy amplitude, we can derive a **limit for the minimum laser power,** which in turn determines the ***number of incident laser photons* per cm² and sec**

$$N_{I,\gamma}\left[cm^{-2}\sec^{-1}\right]=\frac{Power[W/cm^{2}]}{E_{\gamma}[eV]}*\frac{1}{1.6022\cdot 10^{-19}} \quad \textbf{(3)}$$

Now, the ***total number of photons absorbed by the beam particles (N_e)*** during traveling in the magnet is given by

$$N_{\gamma}=N_{e}\cdot n_{\gamma}$$

(***n_γ*** – number of photons absorbed by one electron)

This number has to be confronted with the incident number of photons ***$N_{I,\gamma}$*** to estimate the significance of the RA method expressed as the ratio

$$N_{\gamma}/N_{I,\gamma}$$

→ ***try to find conditions which ensure a large figure for this ratio !***

Parameters: ***laser frequency and power, B-field, length of magnet, the angles θ and φ, laser light detector***

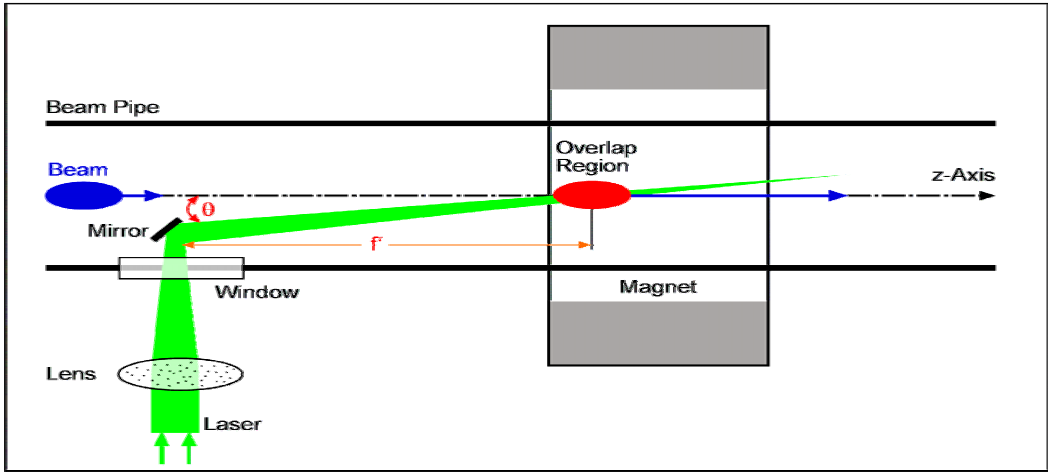
Due to the ***boundary conditions involved in the method***

* the angles ***θ and φ*** have to be very small, ***10^{-3} …10^{-4} rad***

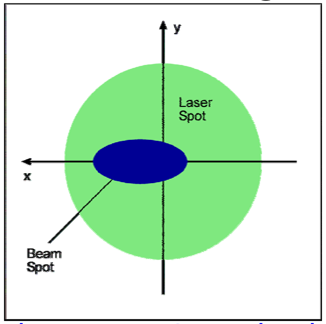
* ***length of the magnet*** somewhere between ***0.3 to 1.0 m*** (or so) and its ***B-field*** in the order of ***0.05 … 6 T,*** or even somewhat larger

* the ***power of the laser*** needed is within the range of modern lasers, e.g. ***CO_2 laser*** (with λ=10.6 µm) or ***Nd:YAG laser*** (with λ=1.064 µm, λ=0.532 µm or λ=0.266 µm)

Sketch of a possible laser beam line:



ensure an ***optimal*** overlay of both the laser and the beam spots during collision in the magnet



each spot has some Gaussian intensity profile

Simple example of a possible, ***idealistic*** experiment:

- E_b = 250 GeV, i.e. $\gamma_0 = 5\ 10^5$
- consider a full pulse (=train) at the ILC with N_e/bunch = $2\ 10^{10}$, # of bunches/train = 2820 with a length of 1 msec ***(old TESLA numbers)***
- L (magnet) = 1 m , B-field = 2 T
- φ = 0. (for simplicity), and $\theta = 2\ 10^{-4}$ rad, i.e. the angle between the laser and the beam is $2\ 10^{-4}$ rad
- a continuous CO_2 laser with a power of 0.1 W/cm^2 focused onto the beam spot with a diameter of 3 mm

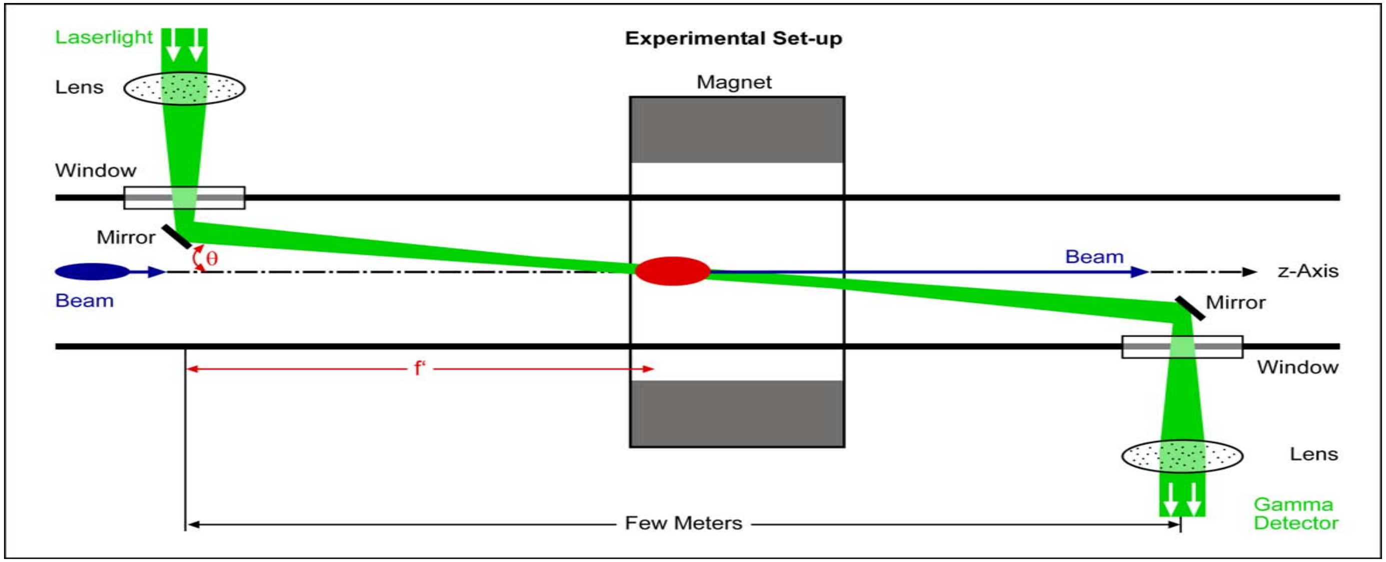
  → $\boldsymbol{N_{l,\gamma} = 5.1\ 10^{14}}$ $msec^{-1}$
- assume perfect overlay of both beams and absolute stability

→ $\boldsymbol{N_\gamma / N_{l,\gamma} = 5{,}6\ 10^{13} / 5.1\ 10^{14} \approx 0.1}$,i.e. we would observe a 10% laser light loss in a perfect gamma detector

MANDATORY: ***demonstrate the feasibility of the experiment and optimize the parameters***

FIRST SCHEMES FOR BEAM ENERGY DETERMINATIONS

Basic experimental set-up:



What about an absolute or relative E_b determination ?

Precise determination of the ***absolute value of the beam energy***, with the RA method is ***difficult***, because it is ***difficult to know the angles θ and φ*** with the ***necessary precision***.

However, if a reference energy E_r (γ_r) is well known with the corresponding value of Ω_r, the energy to be measured E_m (γ_m) can be determined from

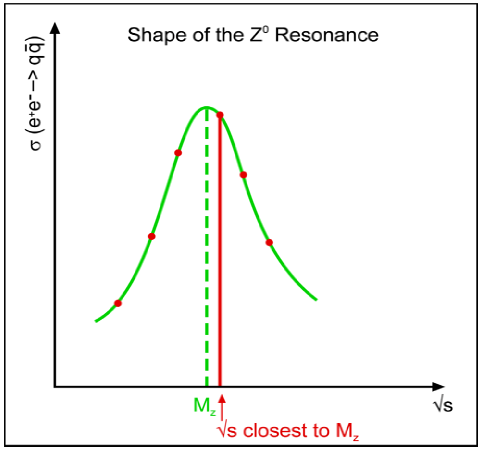
$$\frac{\gamma_m - \Omega_m}{\sqrt{\gamma_m^2 - 1}} = \frac{\gamma_r - \Omega_r}{\sqrt{\gamma_r^2 - 1}} \quad \Longrightarrow \quad E_m = E_r \cdot \frac{B_m}{B_r} \qquad \textbf{(4)}$$

Relative beam energy measurement !

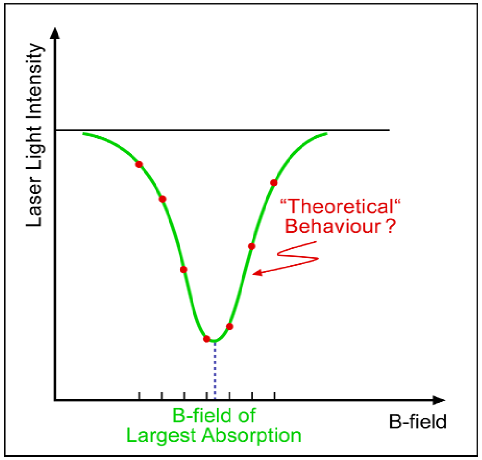
by ***adjusting Ω_r and Ω_m, i.e. the corresponding B-fields*** (*$\Omega = eB/m\omega$*) *to the resonance absorption point, i.e.* ***to the point of maximum laser light absorption***

Note, eq.(4) does not depend on θ and φ !

1.step: find E_r from e.g. a Z-line shape scan:
- select an energy close to M_Z with an error determined by the Z mass error
→ precise reference energy E_r relative to M_Z



2.step: find for the energy E_r the RA point by searching for the B-field with largest laser light absorption, B_r



3.step: repeat step 2 to find B_m , the B-field for largest absorption at the unknown energy E_m , and determine E_m

- ***during these measurements stable beam conditions are needed;***
- ***very good knowledge of the laser light drop vs. B-field to extract B_r resp. B_m***

.

If the reference energy $\boldsymbol{\gamma_r}$ close to $\boldsymbol{M_Z}$
with ***Δ√s = ΔM$_Z$ = 2.2 MeV*** is known
and a B-field error of ***ΔB/B = 3 10^{-5}*** is assumed,
the beam energy (at e.g. E_b = 250 GeV) can be determined with
a precision of

$$\frac{\Delta E_m}{E_m} = \sqrt{\left(\frac{\Delta\Omega_r}{\Omega_r}\right)^2 + \left(\frac{\Delta\gamma_r}{\gamma_r}\right)^2 + \left(\frac{\Delta\Omega_m}{\Omega_m}\right)^2} = (6-7)\cdot 10^{-5}$$

systematic errors ?

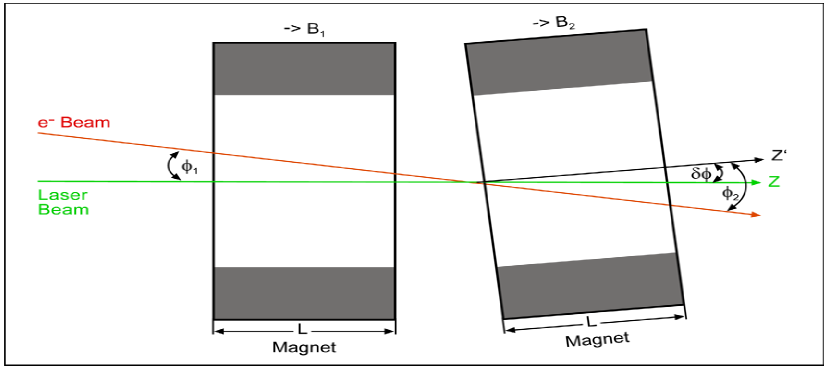
(with ΔΩ/Ω fixed by the B-field error ΔB/B)

Note that more than 50 % of this error comes from the error
of the reference energy $\Delta E_r/E_r$.
Repeated measurements at stable beam conditions would reduce this error;
for example, 10 cycles of measurements lower the (statistical) error to (2-2.5) 10^{-5}.

Discussions on absolute beam energy determination are ongoing
→ so far only rough ideas exist

Robert Melikian proposed ***two possibilities***:

1) use ***two solenoids with fields B_1 and B_2*** having identical lengths, and an ***angle $\delta\theta$*** between them



A ***two-step procedure*** determines the **absolute** beam energy:

- B_1 on and B_2 off: find absorption maximum → Ω_1 (by varying the B_1-field)
- B_1 off and B_2 on: find absorption maximum → Ω_2 (by varying the B_2-field)

$$\delta\varphi = \sqrt{\frac{2}{\gamma}}\left(\sqrt{\Omega_2} - \sqrt{\Omega_1}\right)$$

-- relays on additional assumptions ! ***CHECK carefully!***

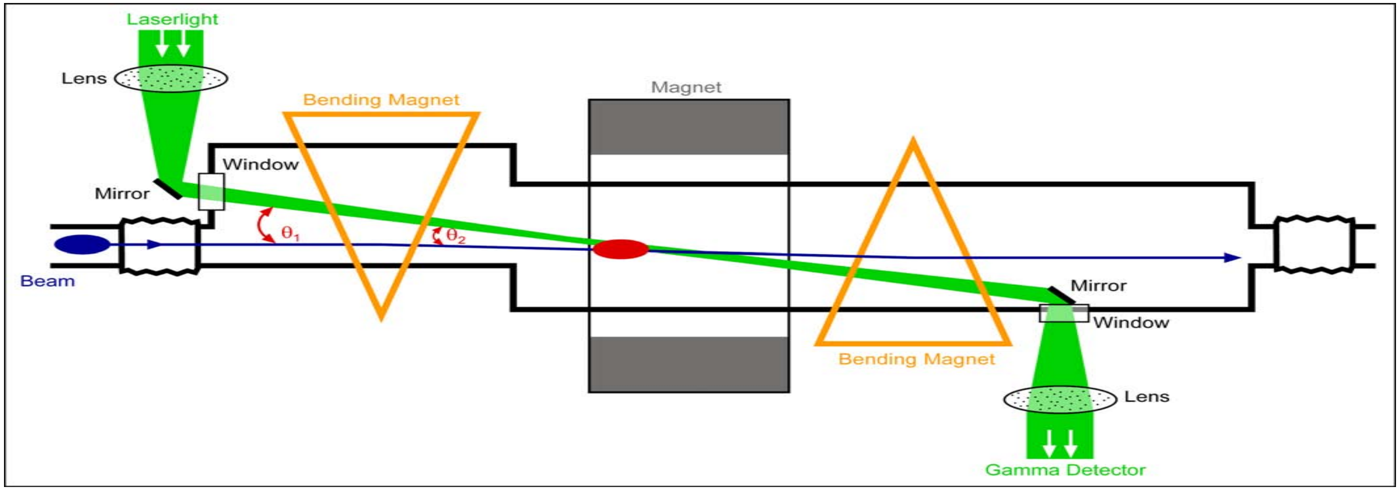
or $\delta\varphi$ is well known from alignment procedures

and

$$E_b = 2mc^2\left[\frac{\sqrt{\Omega_2} - \sqrt{\Omega_1}}{\delta\varphi}\right]^2$$

with a **precision determined by the errors of Ω_1, Ω_2 (resp. the B-fields) and $\delta\varphi$**

2) the ***angle between the laser and the beam is varied*** by means of an ***additional bending magnet***, while all other setup-parameters are kept fix



By changing the B-field in the first bending magnet, φ of the beam is changed, which in turn changes θ ($\theta_1 \rightarrow \theta_2$), the angle between the laser and the beam, by an amount δθ.

Again, after a **two-step procedure** to fix $\mathbf{\Omega_1}$ (for zero-bending field) and $\mathbf{\Omega_2}$ (with bending field on) and **δθ** known from the bending field

$$E_b = 2mc^2 \left[\frac{\sqrt{\Omega_2} - \sqrt{\Omega_1}}{\delta\theta} \right]^2$$

with a **precision determined by the errors of $\mathbf{\Omega_1}$, $\mathbf{\Omega_2}$ (resp. the solenoid B-field) and δθ**

Preliminary summary on absolute beam energy determinations:

- each option complicates the basic set-up by additional magnets
- careful evaluation is needed to select the most reliable solution
- is that the end of any further suggestions for absolute beam energy determination ? Probably not.

Is all that science fiction or a reliable idea ?

Resonance Absorption condition, γ_0 vs. Ω, in form of a picture