French-Ukrainian Workshop on the instrumentation developments for high energy physics

ProRad

An electron-proton scattering experiment

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Outline

- **Physical motivations**
- **The ProRad experiment**
- **Summary**

The proton radius puzzle

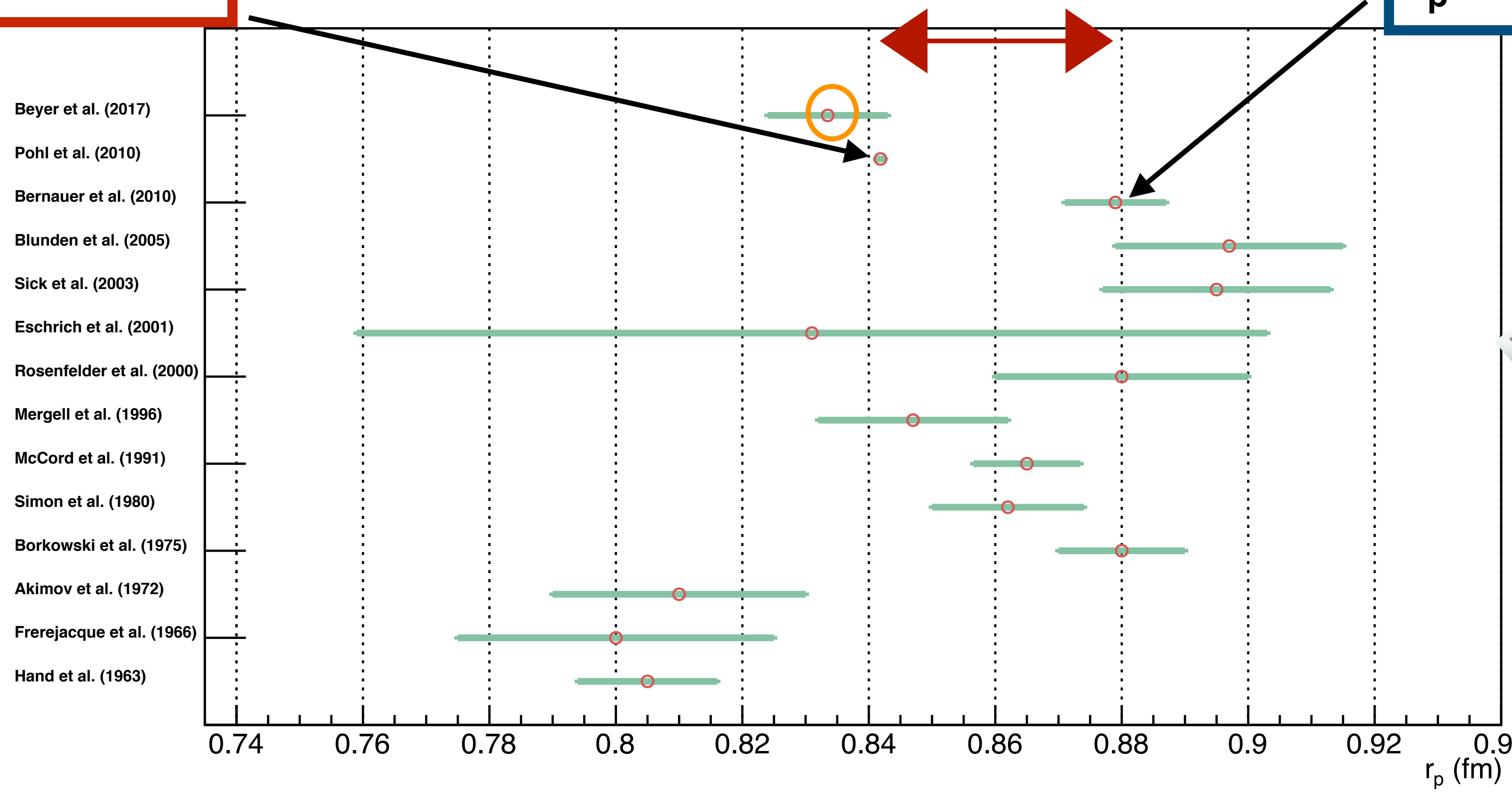
Muonic hydrogen spectroscopy

$r_p = 0.84184 \pm 0.00067$ fm

5σ

Electron scattering experiments*

$r_p = 0.87900 \pm 0.00800$ fm



The **proton** looked **smaller** to **muons** than it did to **electrons**

The measurement of the **2S-4P** transition frequency in ordinary hydrogen

$r_p = 0.8335 \pm 0.0095$ fm

Beyer, A. *et al. Science* **358**, 79–85 (2017).

3.3 σ smaller than the previous electron world data and consistent with muonic hydrogen

A proton radius puzzle for ordinary hydrogen all by itself!

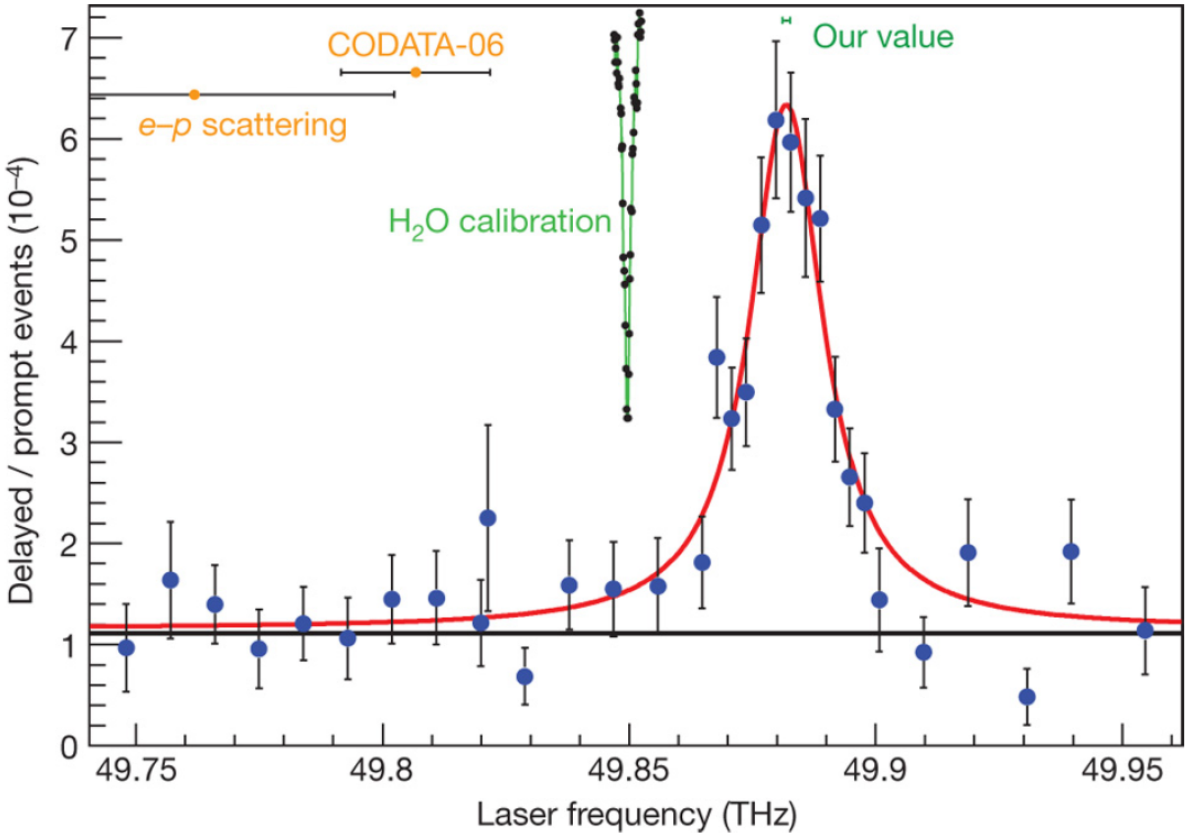
The proton charge radius from hydrogen spectroscopy

Measure the transition frequency between two energy levels

$$E_{nl} \sim -\frac{R_\infty}{n^2} + \delta_{l0}\frac{r_p^2}{n^3}$$

Direct measurement of the proton radius

R. Pohl et al. Nat. 466 (2010) 213



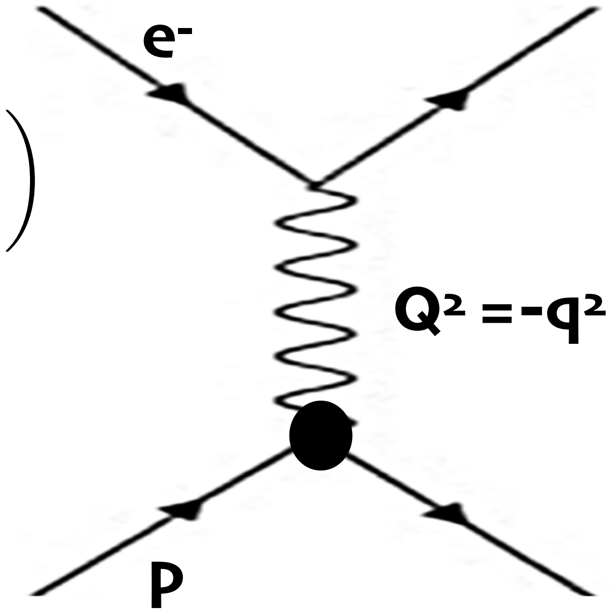
Muonic hydrogen is ~200 times smaller than ordinary hydrogen

Proton radius from muonic hydrogen is 10 times more precise than in ordinary hydrogen

The proton charge radius from electron-proton scattering experiments

Measurement of the e-p scattering cross section

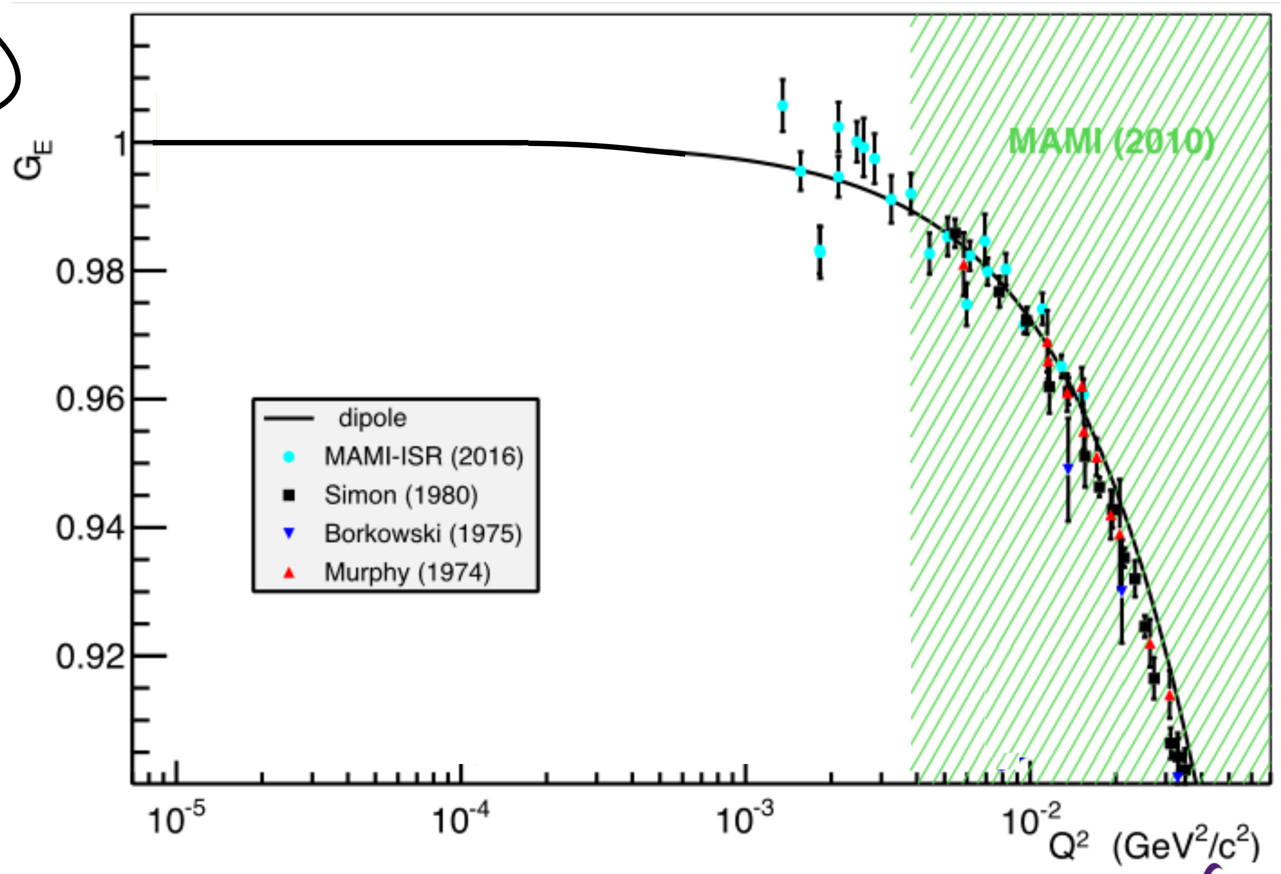
$$\frac{d\sigma}{d\Omega} = \frac{d\sigma}{d\Omega}\Big|_{Mott} \times \left(\frac{G_E^2(Q^2) + \tau G_M^2(Q^2)}{1+\tau} + 2\tau \tan^2\left(\frac{\theta}{2}\right) G_M^2(Q^2) \right)$$



$$\boxed{r_p = \sqrt{< r^2 >} = \sqrt{-6 \frac{\partial G_E^2(Q^2)}{\partial Q^2}\Big|_{Q^2=0}}}$$

Indirect measurement of the proton charge radius through extrapolation of the form factor to zero momentum transfer

Current experimental data are in a region that is not linear in Q^2 **extrapolation is inexact**



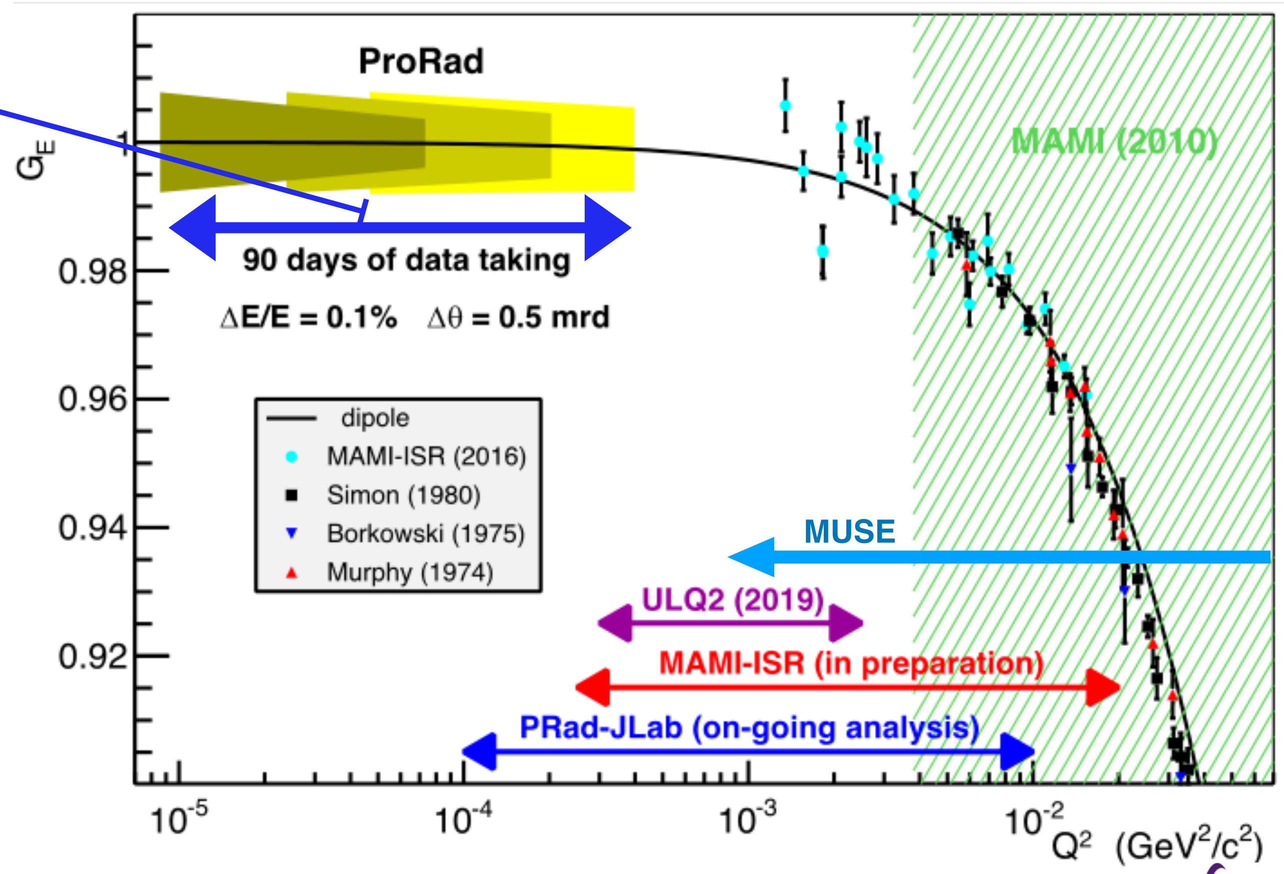
Need for low Q^2 experimental data that is in a region where extrapolation is linear

ProRad@PRAE: a never-before explored domain in momentum transfer

Elastic electron proton scattering at ProRad (Proton Radius):

- Incident electron energies varying between 30-70 MeV
- Angular range of (6^o-15^o) for scattered electron
- Precise measurement of the electric form factor $G_E(Q^2)$ in the momentum transfer range of 10^{-5}-10^{-4} $(GeV/c)^2$

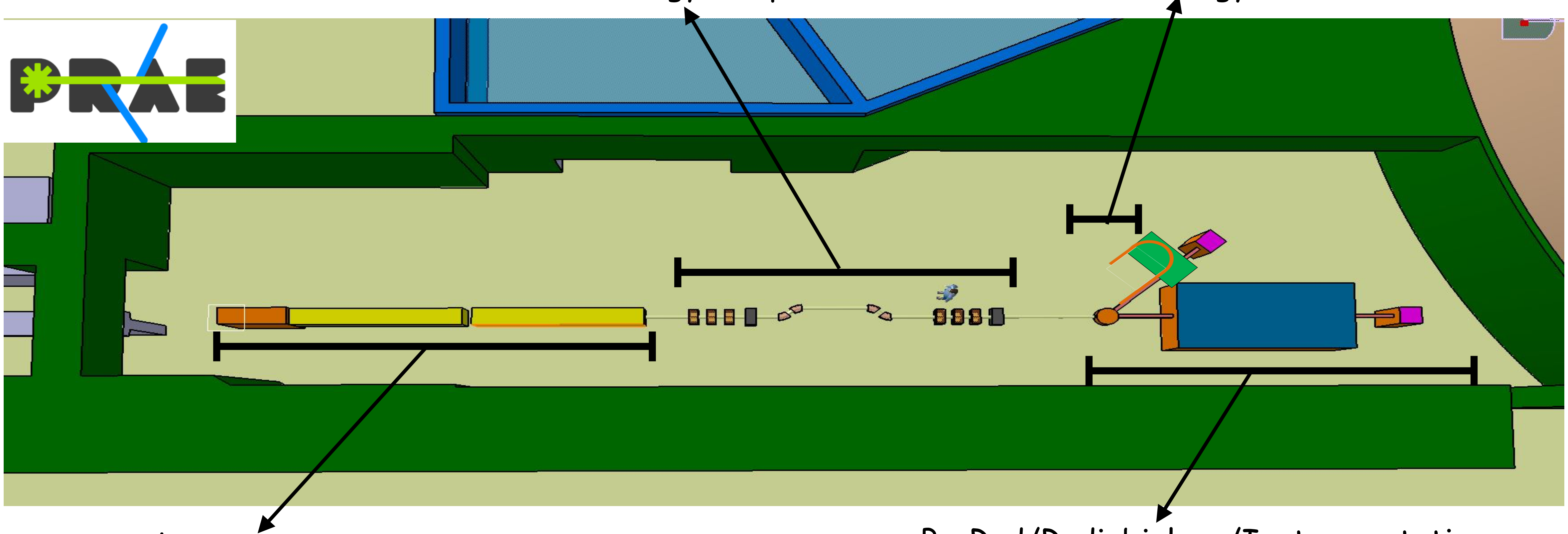
A linear region in $G_E(Q^2)$:
'Exact extrapolation'



Foreseen results:

- **A better knowledge of the dependence of G_E on Q^2**
- **A significant impact on the measurement of the proton charge radius**

Experimental requirements



Beam energy compression

Beam energy measurement

Accelerator:
2-phase implementation

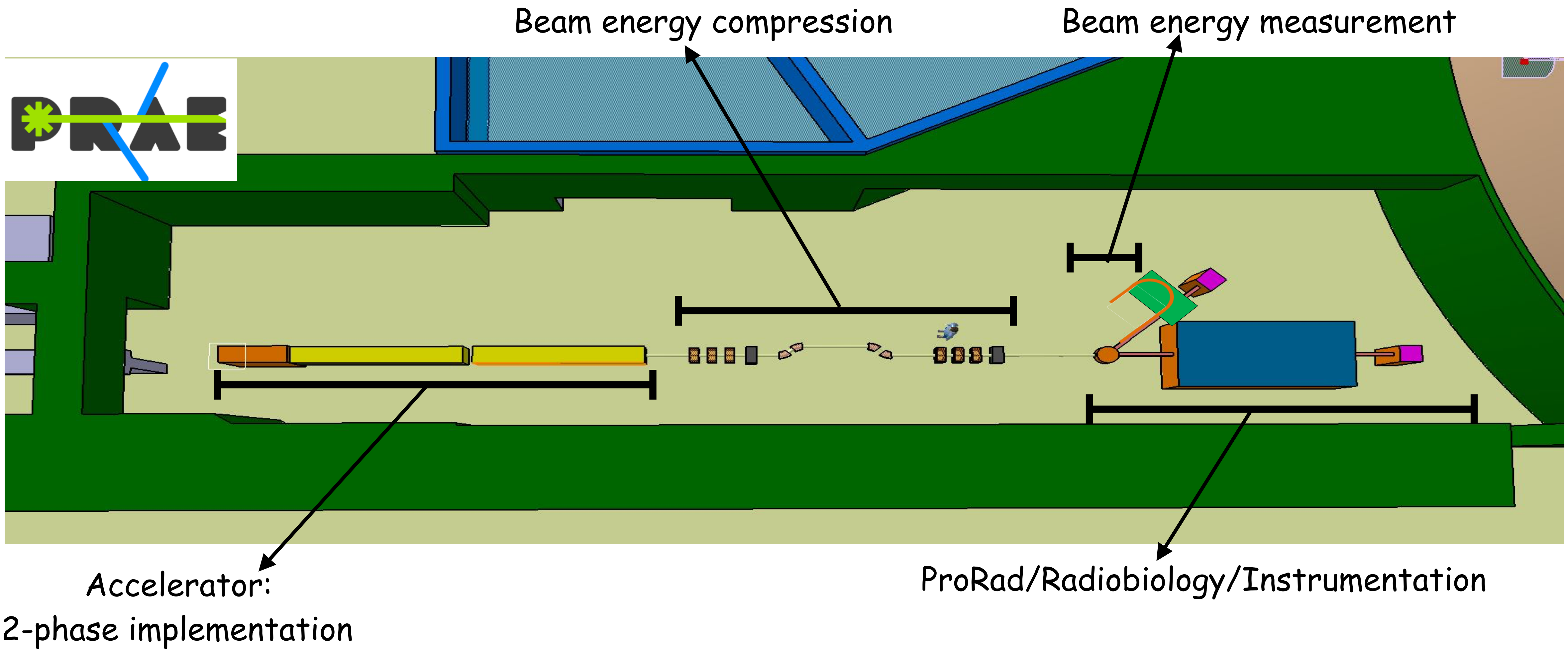
ProRad/Radiobiology/Instrumentation

The Platform of Research and Applications with Electrons at Orsay, France: a multi-disciplinary site based on the high-performance electron beam with energy range 30 MeV - 140 MeV

- Instrumentation
- Radiobiology
- Precision measurements: Proton Radius (ProRad) measurement

The ProRad experiment

Experimental requirements


Beam energy compression

Beam energy measurement

Accelerator:
2-phase implementation

ProRad/Radiobiology/Instrumentation

A high precision measurement of the proton electric form factor

ProRad experiment requirements:

- High precision beam
- Precise knowledge of the beam energy
- A stable target
- Optimised measurement of the scattered electron energy and position

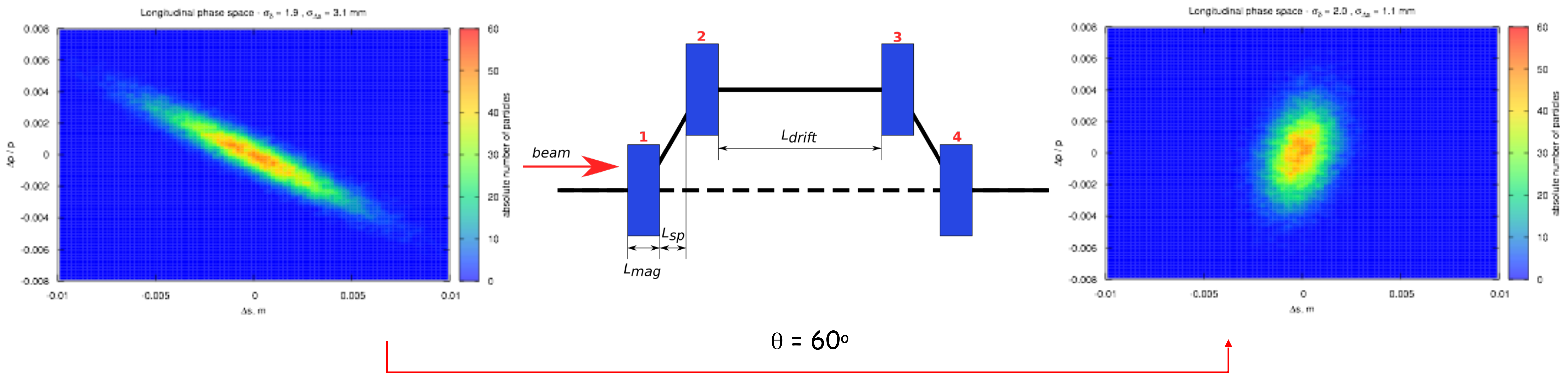
Beam energy compression system

High precision measurement: advanced equipment to control and measure the beam energy

Required beam characteristics

- **Reduced energy dispersion** (**5×10^{-4}**)
- Precise knowledge of the **energy** (**5×10^{-4}**)

A **chicane** of **4 identical dipoles** to reduce the phase space of the beam



➢ The association of a **RF** cavity to the chicane helps to reduce by a factor ~10 the dispersion in momentum (technique used at Mainz, Glasgow, Bates…).

➢ Alternative solution is to add a **passive structure** based on magnetic field created by the beam flow in tubes (**wakefield**). The form of this structure is essential to generate the field necessary to compress the beam to a dispersion of **5×10^{-4}**.

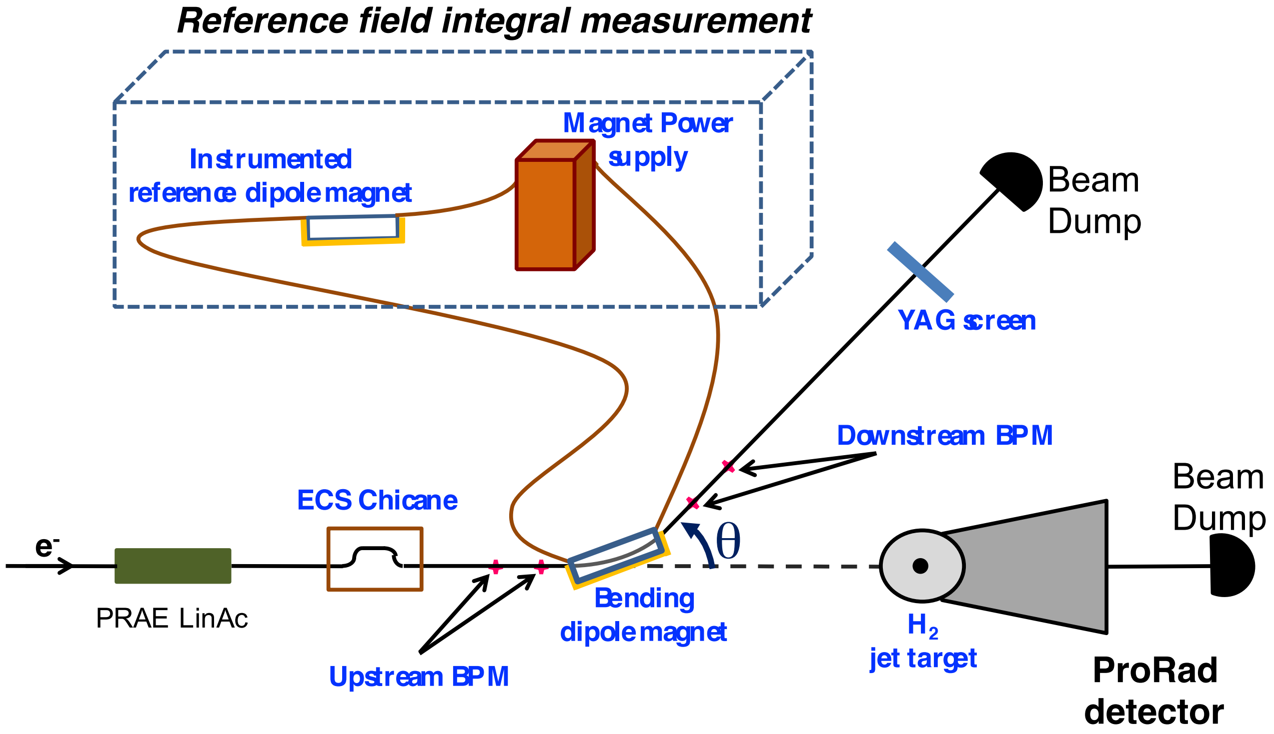
Beam energy measurement

The **precise knowledge** of the beam energy value is crucial to obtain a sub-percent uncertainty on $G_E(Q^2)$

Deviate the beam in a **controlled magnetic field**: an **absolute knowledge of the beam energy**

$$\boxed{E = \frac{c}{\theta}\int B\,dl = \frac{c\,I_B}{\theta}}$$

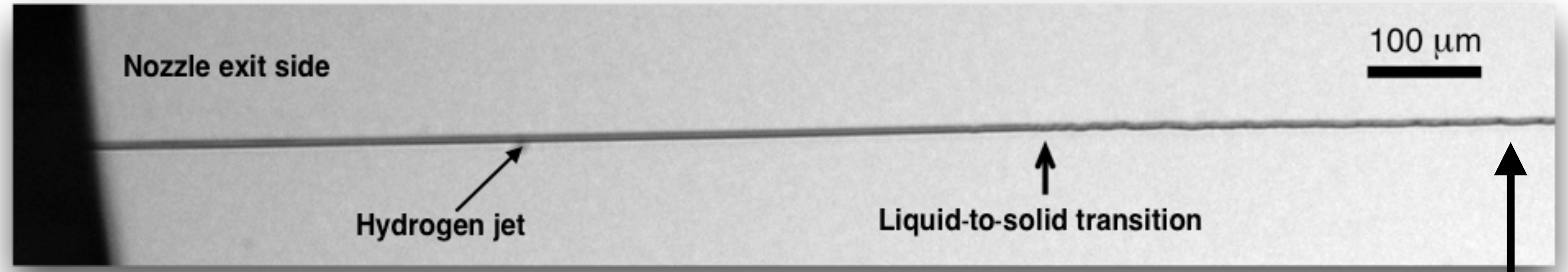
$$\boxed{\frac{\delta I_B}{I_B} = \frac{\delta\theta}{\theta} = 2\times10^{-4}} \rightarrow \boxed{\delta E/E = 3\times10^{-4}}$$



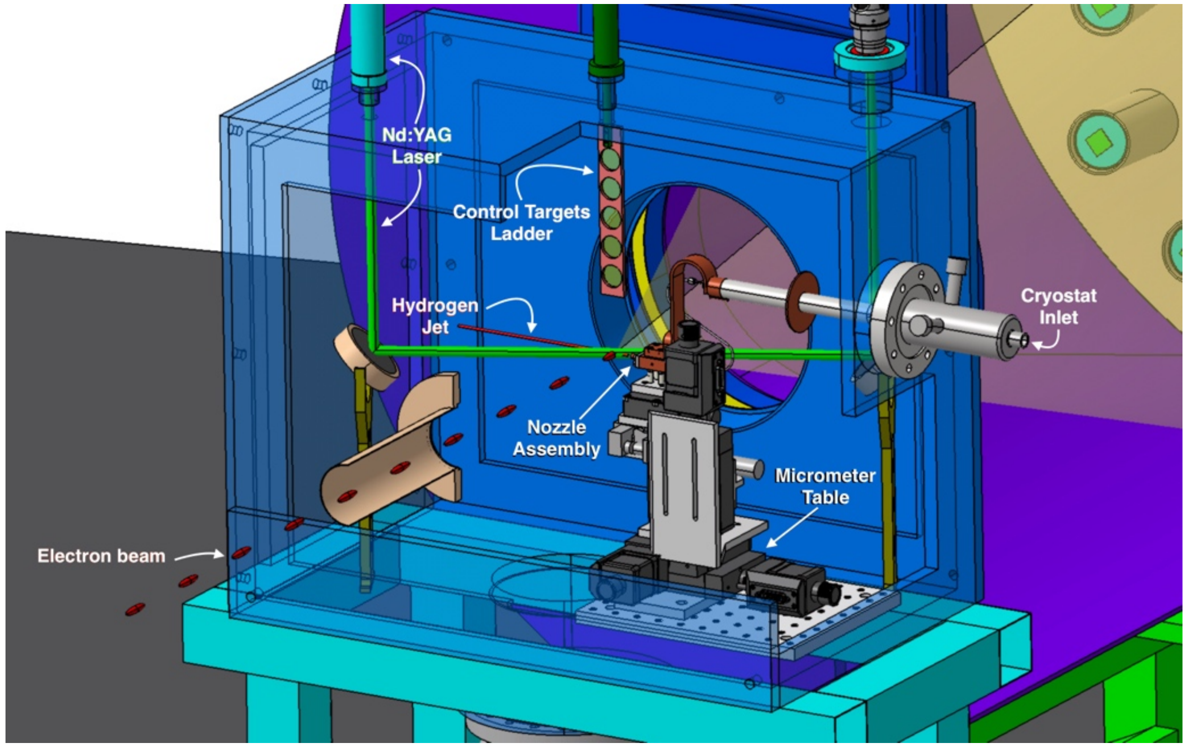
- Beam Position Monitors to measure **θ**
- A control magnet connected serially with the dipole magnet insures a precise measurement of the field integral
- A YAG screen to measure the energy dispersion of the beam

The Hydrogen target

R.A. Costa Fraga et al. RSI 83 (2012) 025102



Beam-target interaction region



Requirements:

A very stable windowless and self-replenishing target of 15 μm diameter

Windowless target: reduced background
Thin target: precise knowledge of interaction vertex

Ultra cold liquid technology developed at Frankfurt University

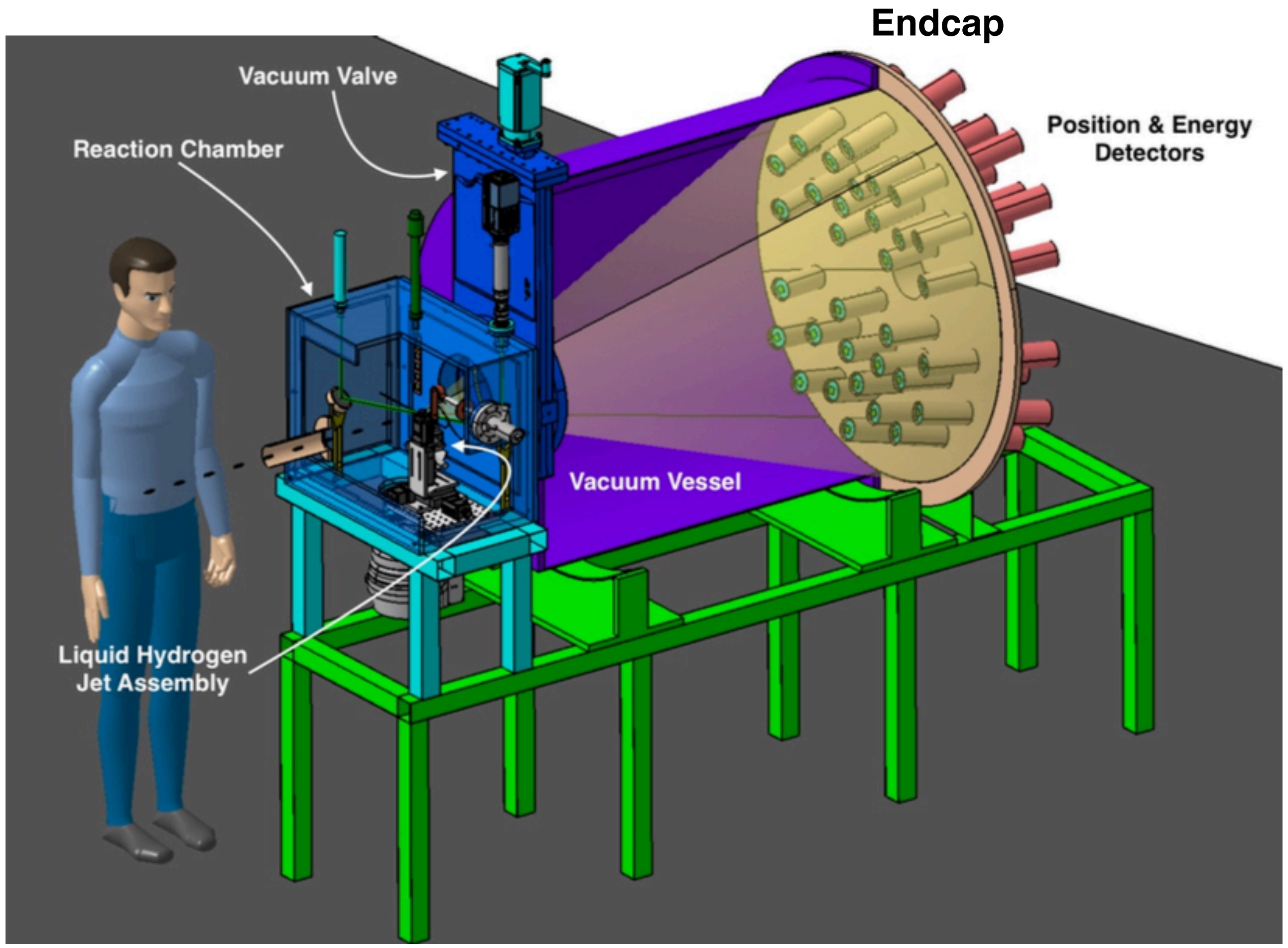
GOETHE UNIVERSITÄT
FRANKFURT AM MAIN

The experimental setup: a full view

Reaction chamber with the **target assembly**

Vacuum vessel featuring the **elementary detectors** placed on a spherical endcap

Each elementary detector made of
- 2 planes of scintillating fibres
- A cylindrical BGO crystal ($\pi 2.5^2 \times 15$ cm^3)

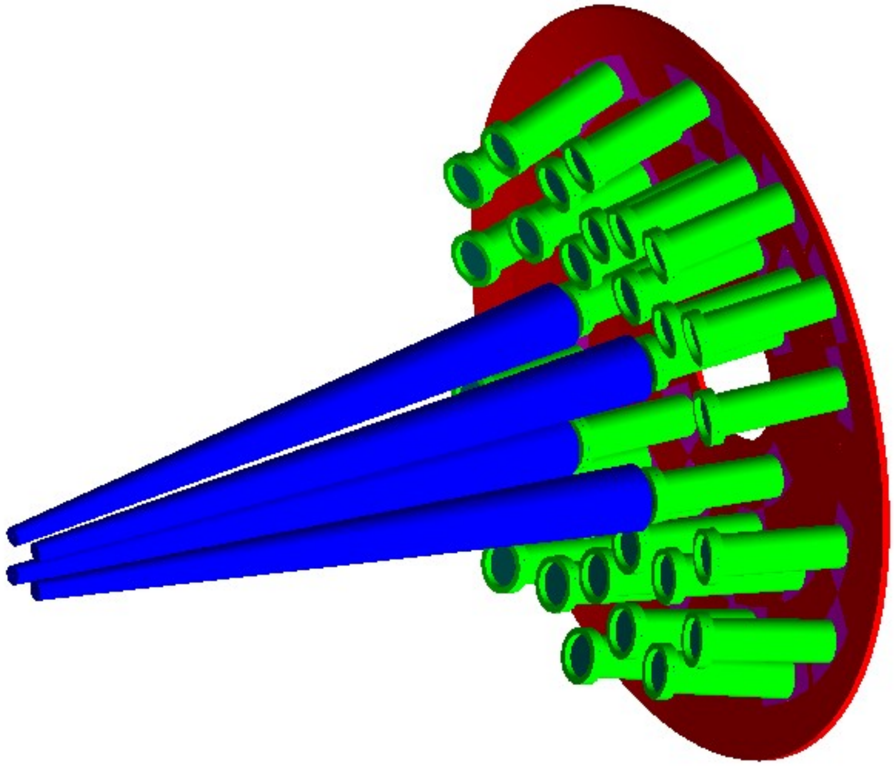


32 elementary detectors placed at 5 different scattering angles at a distance of 1.5 m from the target

The experimental setup: a zoom in

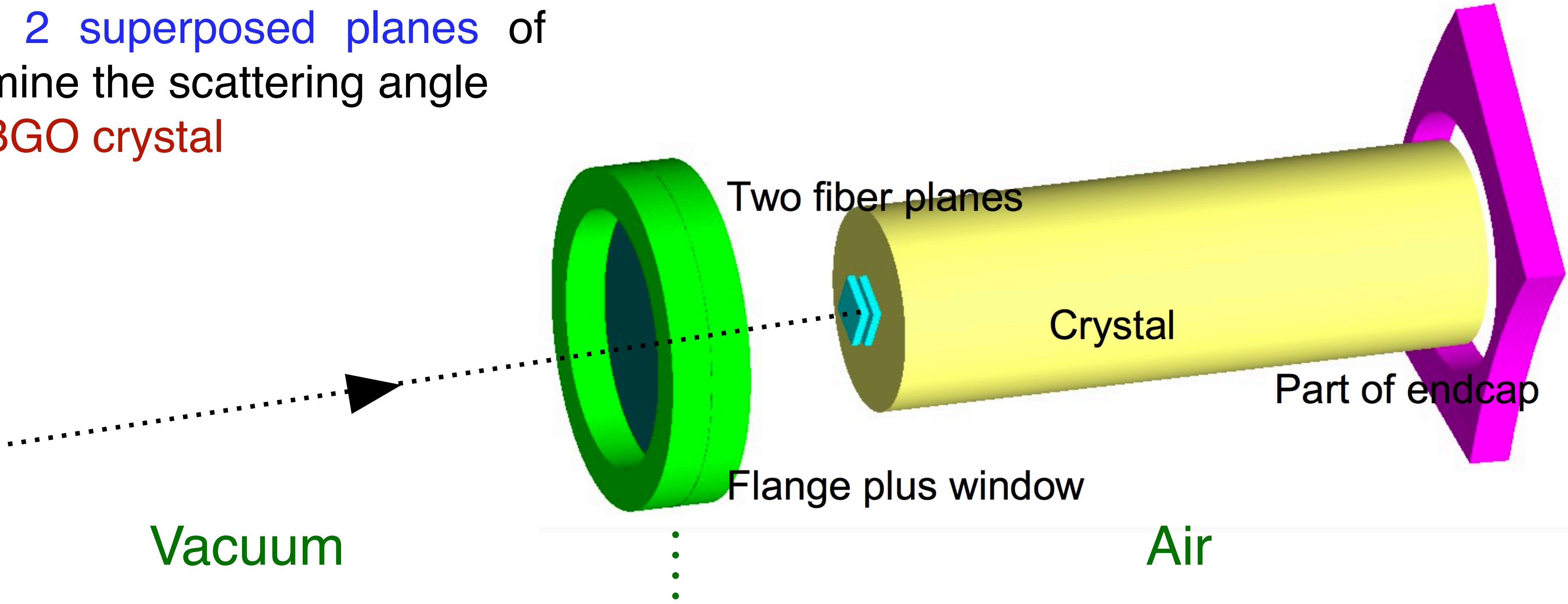
At (6^{o}): steel **tubes** (1 m) as a **collimator** of **1 cm** diameter

- Maintain a reasonable counting rate at low angles to avoid event pile-up



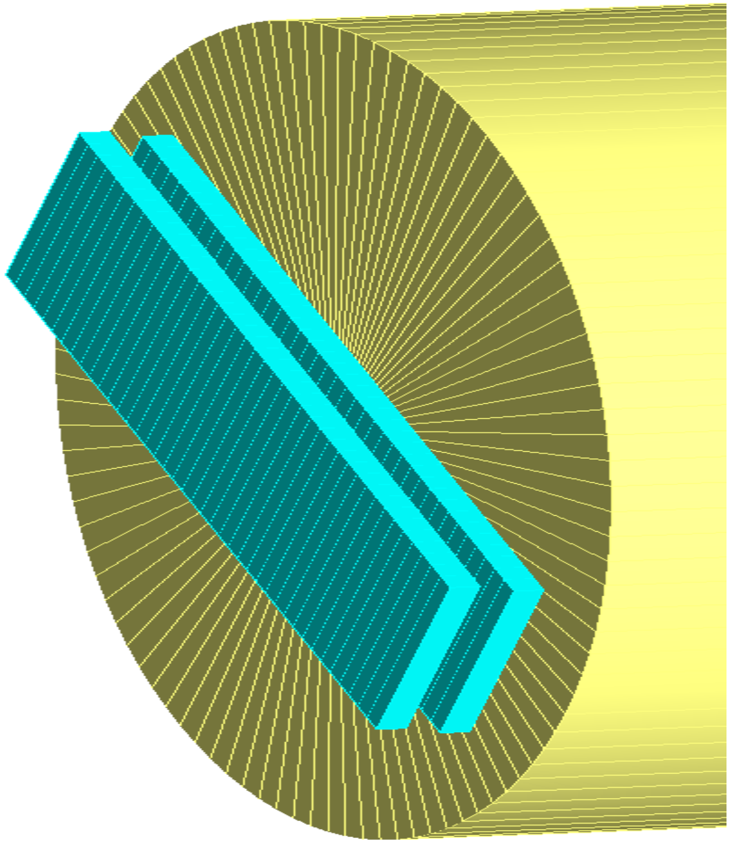
Elementary detector:

- Measure the position with 2 superposed planes of scintillating fibres and determine the scattering angle
- Measure the energy with a BGO crystal



Position measurement concept

✓ Position detector made of 2 **interleaved planes of scintillating fibres** of **1x1 mm²** read by SiPMs.



$$\boxed{\left(\frac{\delta G_E^2}{G_E^2}\right)^2 \sim \left(\frac{\delta\sigma_{Exp.}}{\sigma_{Exp.}}\right)^2 + 4\left(\frac{\delta E}{E}\right)^2 + 16\left(\frac{\delta\theta}{\theta}\right)^2}$$

❖ This configuration provides a precision of **0.35 mrad** on the scattering angle θ

❖ Two different geometries (**12x12** mm² et **40x20** mm²) at **small** & **large** angles to compensate the variation of the cross section

Energy Measurement

R&D started on crystals

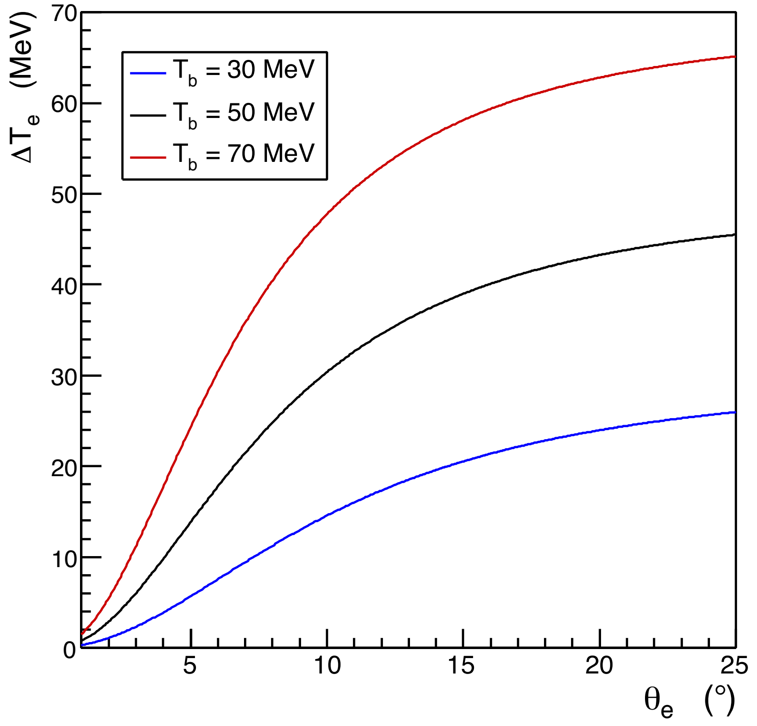
Energy measurement is done with a BGO crystal read out by a PMT

Both Moeller & elastic scattered electrons are detected: elastic cross section is normalised to the Moeller one to reduce systematics

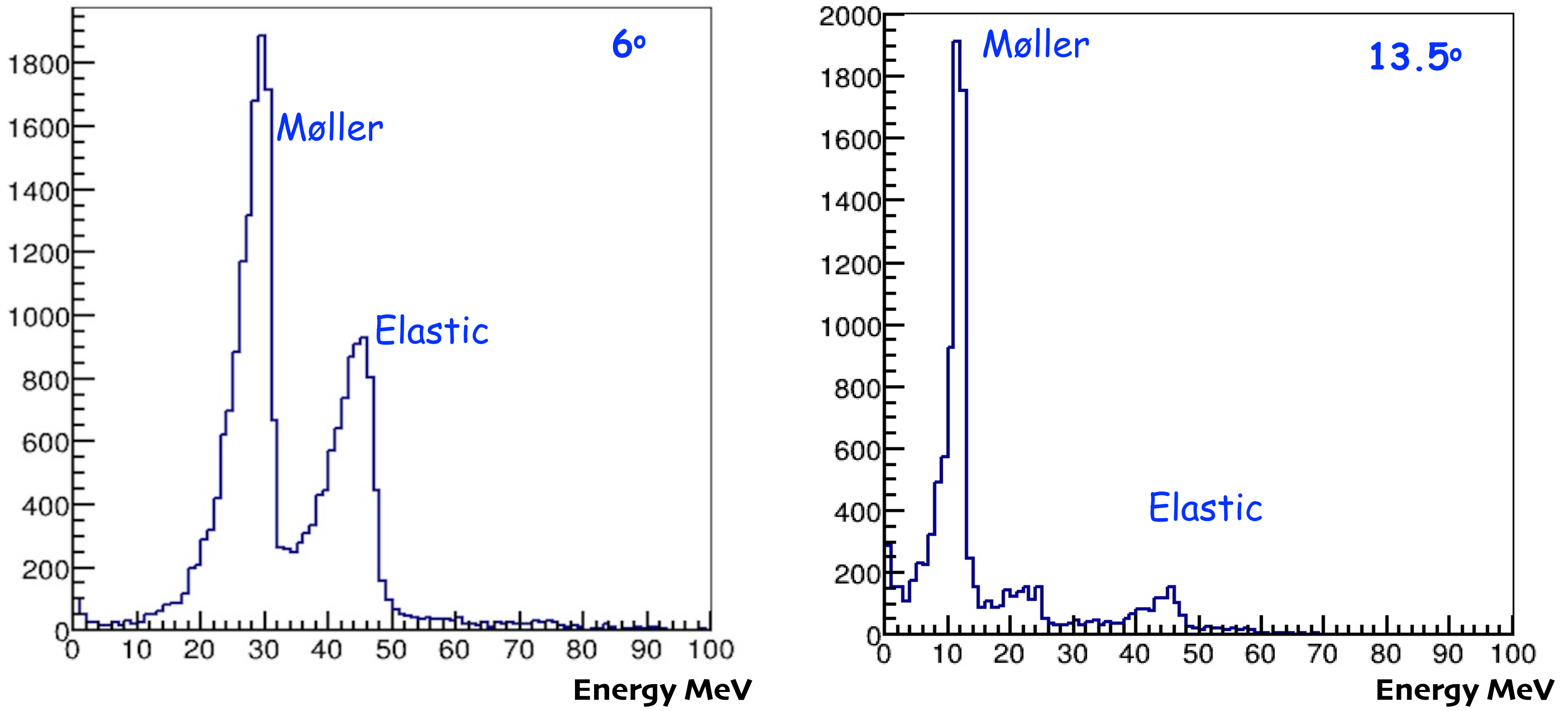
- ✓ At the same scattering angle, the difference between the energies of elastic and Moeller scattered electrons is a key element to identify each process

- ❖ At low angles, the elastic and Moeller spectrums overlap but can still be separated
- ❖ At high angles the separation is more clear

Energy Separation



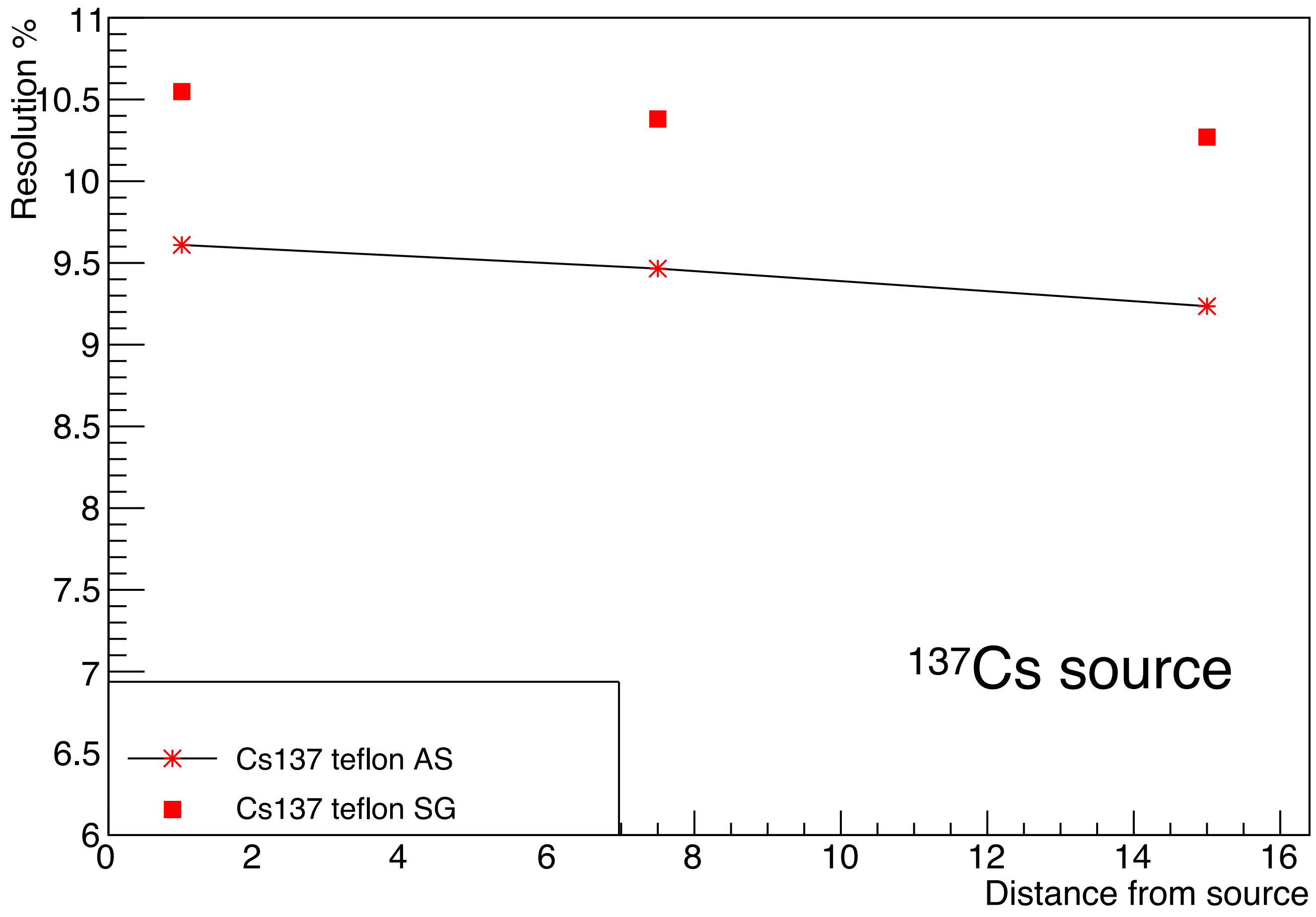
Geant4 simulations



Crystals tests

We are testing two BGO Crystals from different manufacturers (Alpha Spectra & Saint-Gobain)

Compare the resolution of the two crystals



Alpha Spectra crystal has a better resolution

We are also comparing two PMTs from Hamamatsu: R1306 (8 stage) and R2154-02 (10 stage)

Ongoing: Preparing for test with electron beam at ALTO (50 MeV electrons, real case test)

Summary

- **ProRad will contribute significantly to the proton radius puzzle**
- **Detector conception is in a very elaborated phase**
- **Data taking is foreseen in second half 2020**
- **Precision on all aspects is a key point for ProRad to reach its goals**