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Measuring the proton Zemach radius with the FAMU experiment at RIKEN-RAL

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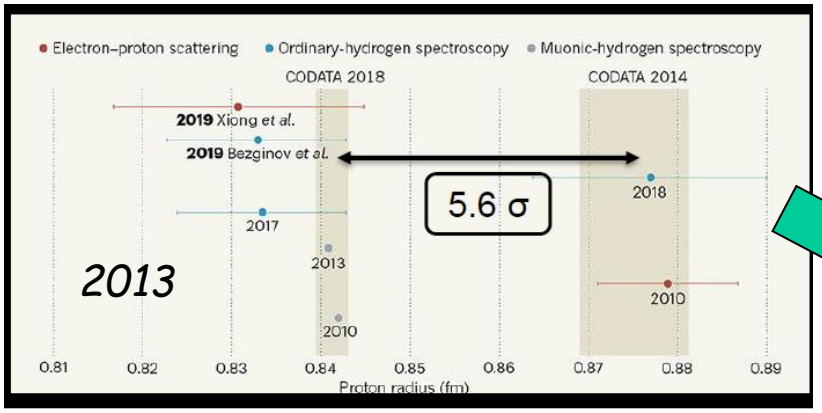
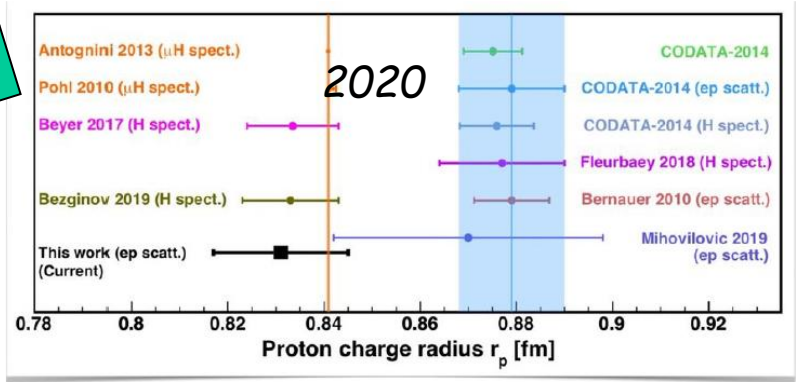
On behalf of the FAMU Collaboration

The proton radius puzzle



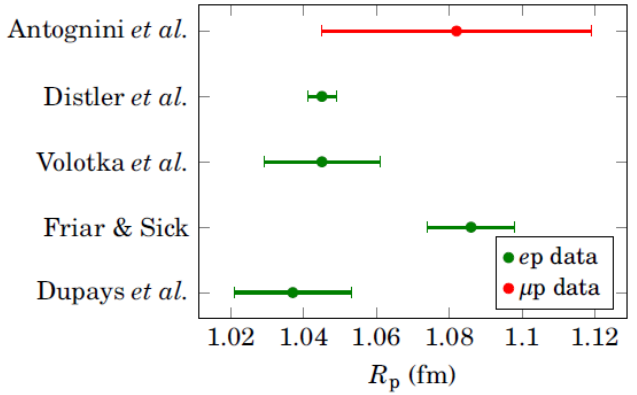
5.6 σ discrepancy on r_{ch} has vanished, but still problems around



Spatial charge and magnetic moment distributions $\rho_E(r)$, $\rho_M(R)$ in non-relativistic picture .

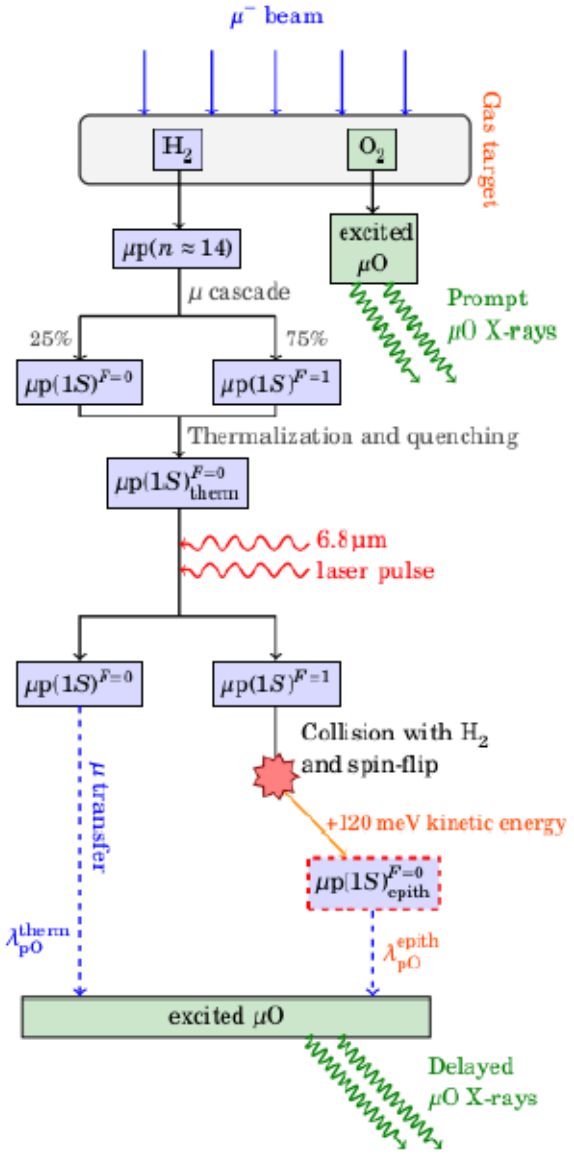
The complete set of moments $R^{(k)}_{E,M}=\int \rho_{E,M}(r) r^k d^3r$ is related to the observable quantities:

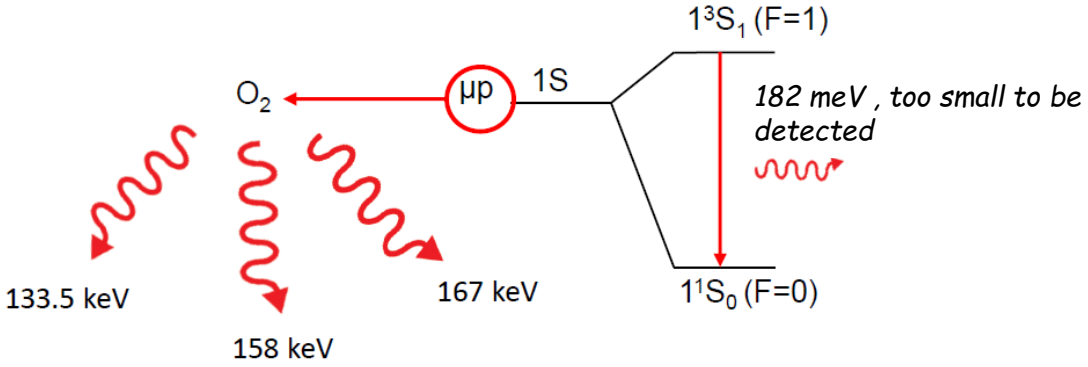
$$r_{ch}=(R^{(2)}_E)1/2$$
$$R_Z=\int \left(\int \rho_E(r')\rho_M(r-r')d^3r'r\right)d^3r$$



Large errors on R_Z → we need new measurements

The FAMU experimental method





1. Create muonic hydrogen in a hydrogen gas target and wait for its thermalization;

2. Laser shot at resonance wavelength (λ_0 ~6.8μ): spin state of μ^-p from 1^1S_0 to 1^3S_1, spin is flipped: $\mu^-p(\uparrow\downarrow) \rightarrow \mu^-p(\uparrow\uparrow)$;

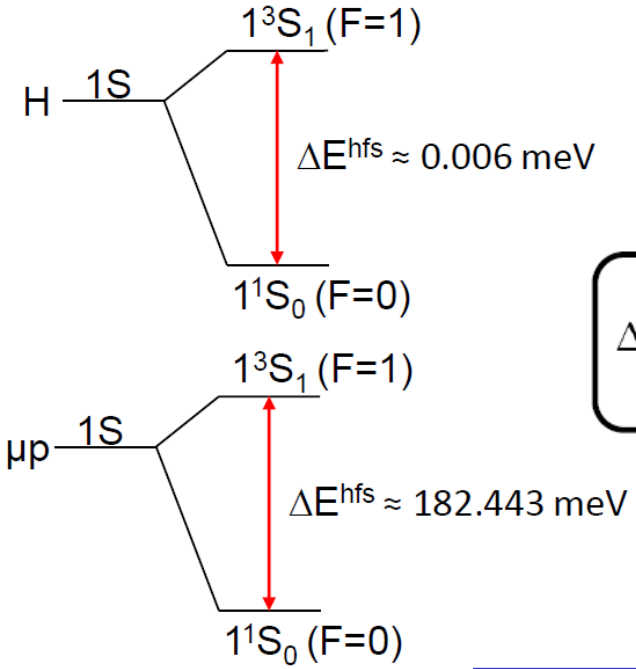
3. De-excitation and acceleration: $\mu^-p(\uparrow\uparrow)$ hits a H atom. It is depolarized back to $\mu^-p(\uparrow\downarrow)$ and is accelerated by ~120 meV ~2/3 ΔE^{hfs}_{1S};

4. μ^- are transferred to heavier gas contaminant (O_2) with energy-dependent rate;

5. λ_0 is determined by maximizing the time distribution of μ^- transferred events.

6.At this point ΔE_{HFS} is determined from: $\lambda_0 = hc/\Delta E^{1S}_{HFS}$ ~ 6.8 μ ~ 0.183 eV and then R_Z with a precision ~ 1%.

The FAMU experimental method (II)

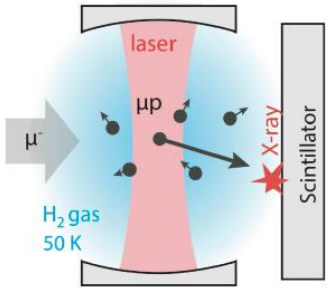


$_{RZ}$ is then determined via QED with a precision up to 1%, more than enough to discriminate between different Hypothesis

$$\Delta E_{hfs} = \frac{16}{3}\alpha^2 cR_\infty \left(\frac{\mu_2}{\mu_1}\right)\left(\frac{\mu_1}{\mu_1^0}\right)^2\left(1+\frac{m_e}{m_p}\right)^{-3}\times\left[1+\frac{3}{2}\alpha^2-2\frac{<r>_{Zemach}}{a_0}+\beta+\delta\right]$$

Other μp HFS projects

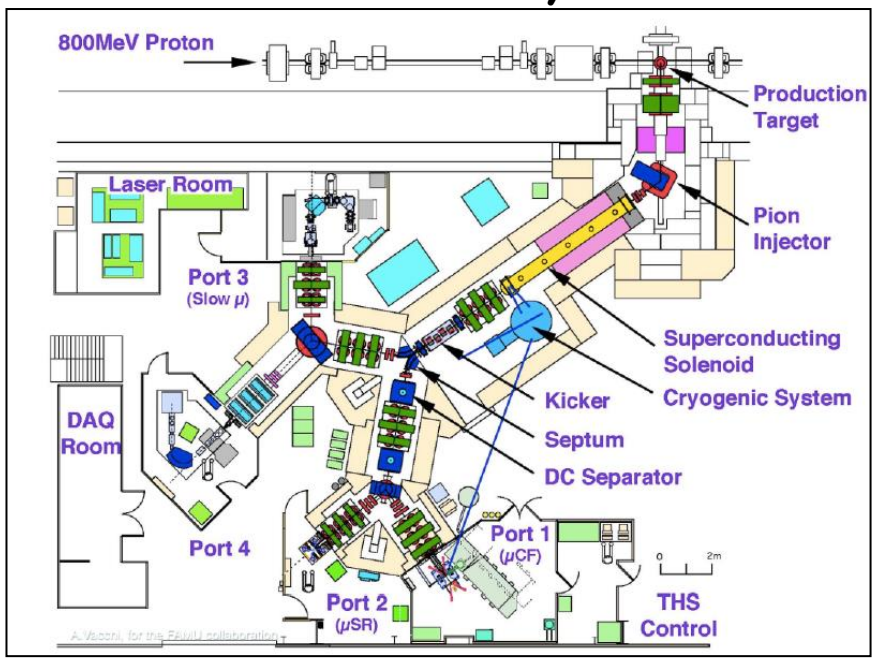
PSI



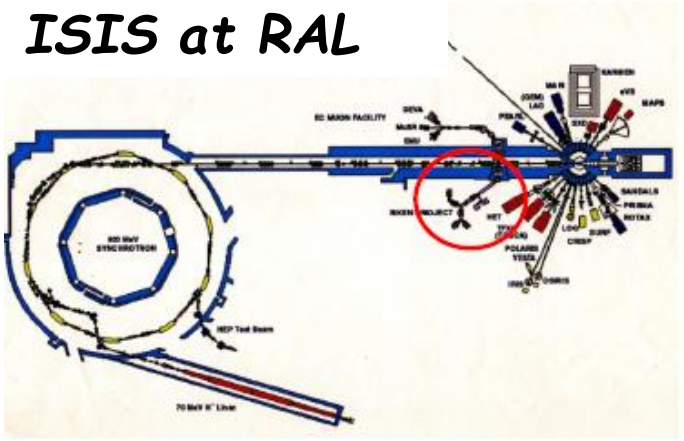
	FAMU (UK)	PSI (CH)	RIKEN (JP)
Method	transfer	diffusion	asymmetry
Laser	DFG-MIR 1-5 mJ		QCL-seeded ZGP-OPO > 20 mJ in development
Detection	X-rays	X-rays	electrons
Beam	pulsed	continuos	Pulsed

The RIKEN-RAL muon facility at RAL

RIKEN-RAL facility

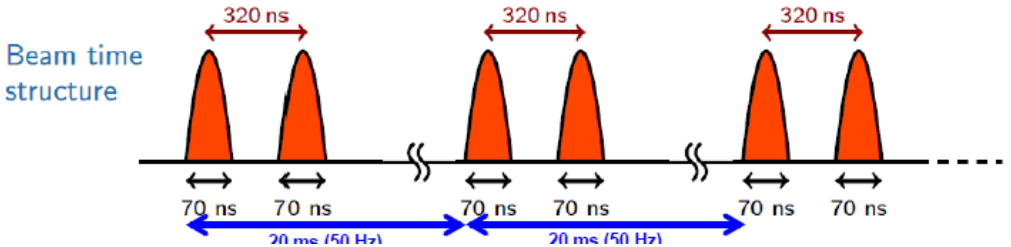


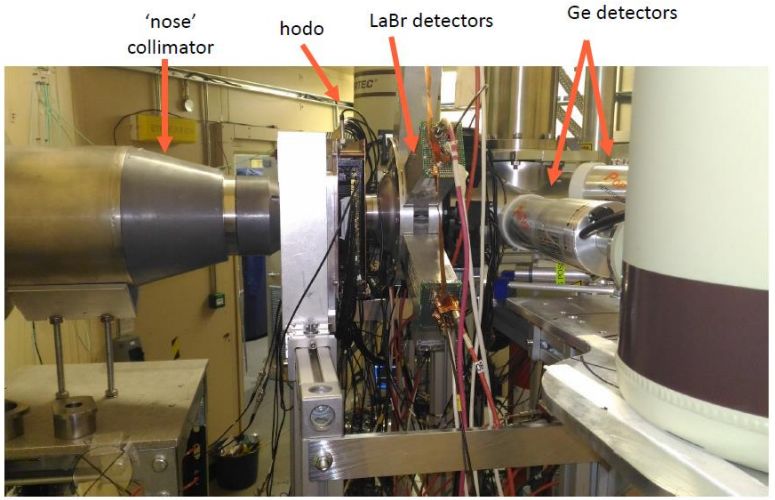
ISIS at RAL



800 MeV p accelerator , 200 mA, 50 Hz

Typical beam size ~10 cm²
Δp/p FWHM 10% (decay), 5% (surface)
Double pulse structure (see below)





The RIKEN-RAL facility: 4 experimental ports. FAMU presently use port 1 and has used port 4 for previous runs .

The FAMU essential ingredients

1. *Validation of X-rays detector system based on LaBr3:Ce in a noisy environment. Detection of X-rays both in the prompt and delayed component*

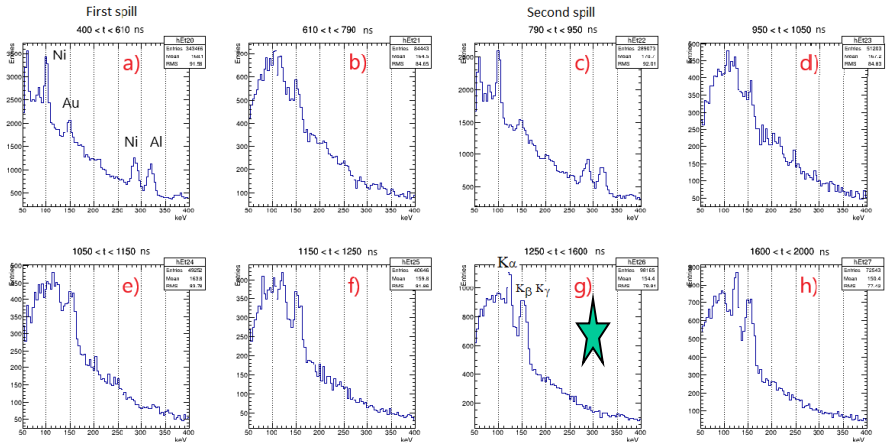
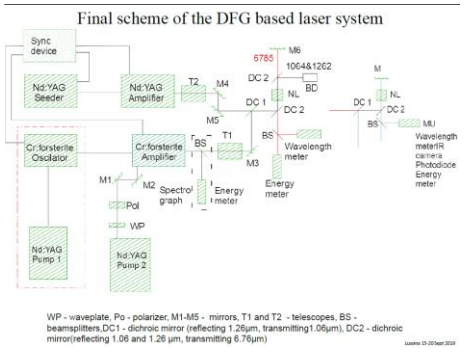
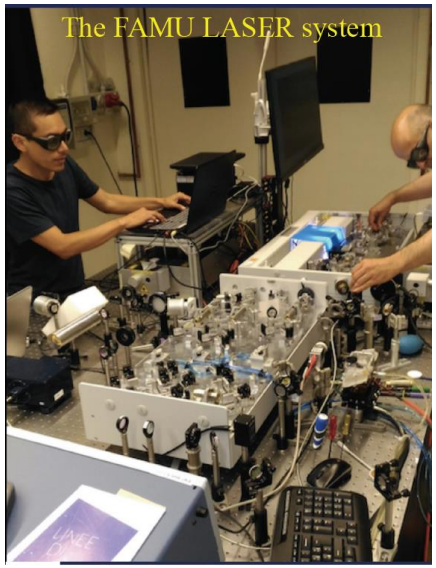


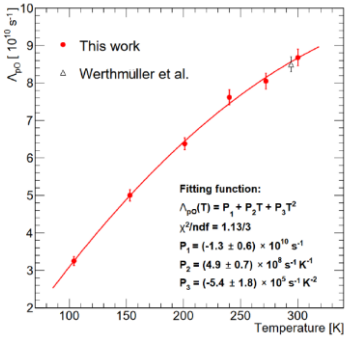
Fig. 2. The evolution of the energy spectra registered by one $LaBr_3(Ce)$ detector (real data) at different times during and after the arrival of the double pulsed muon beam spill (see sec. 3.1).

2. *Development of a high energy MIR laser system*
   - *Wavelength ~6780 nm*
   - *Line width < 0.07 nm*
   - *Tunability ~0.007 nm*
   - *Repetition rate 50 Hz*
   - *Energy ~ 1 mJ*



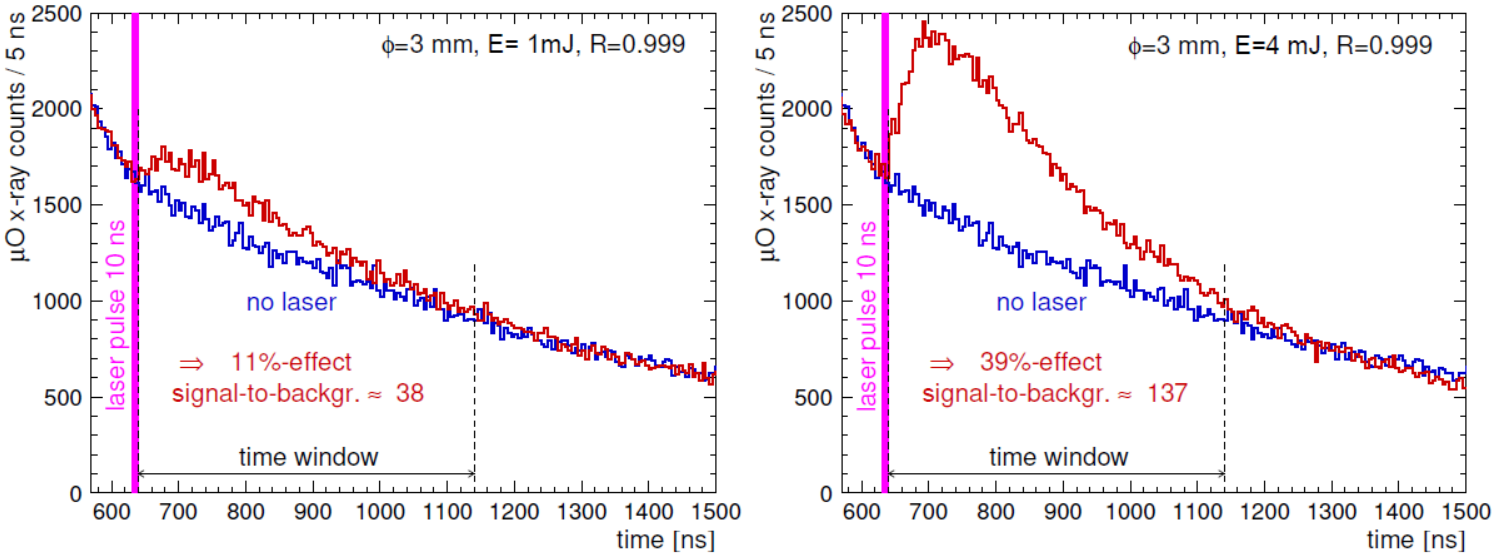


3. *Optimization of run conditions: best gas mixture at temperature T and pressure p (to be determined) to observe and measure the transfer rate energy dependence*



At this point the validity of the method to measure HFS is demonstrated

Expected results from the final run & conclusions



Expected results with a 1 mJ/ 4 mJ laser energy

- ***All preliminary steps done and working***
- ***Final data taking foreseen for March 2020. Delayed in steps to June 2021 due to COVID-19 pandemia***
- ***We hope to have results soon on r_Z with 1% accuracy***

Backup slides

Determination of r_Z from ΔE^{hfs}

The determination of the Zemach radius from the experimental value of the hfs is based on the theoretical relation between the hyperfine splitting , the lowest order Fermi hyperfine energy E_F and the corrections to it δ^{QED} due to QED effects, δ^{rec} recoil, δ^{Z} the static electromagnetic structure of the proton, δ^{pol} to dynamical proton polarizability and δ^{hvp} to hadron vacuum polarization respectively:

$$\Delta E^{hfs} = E_F(1 + \delta^{QED} + \delta^{rec} + \delta^{Z} + \delta^{pol} + \delta^{hvp})$$

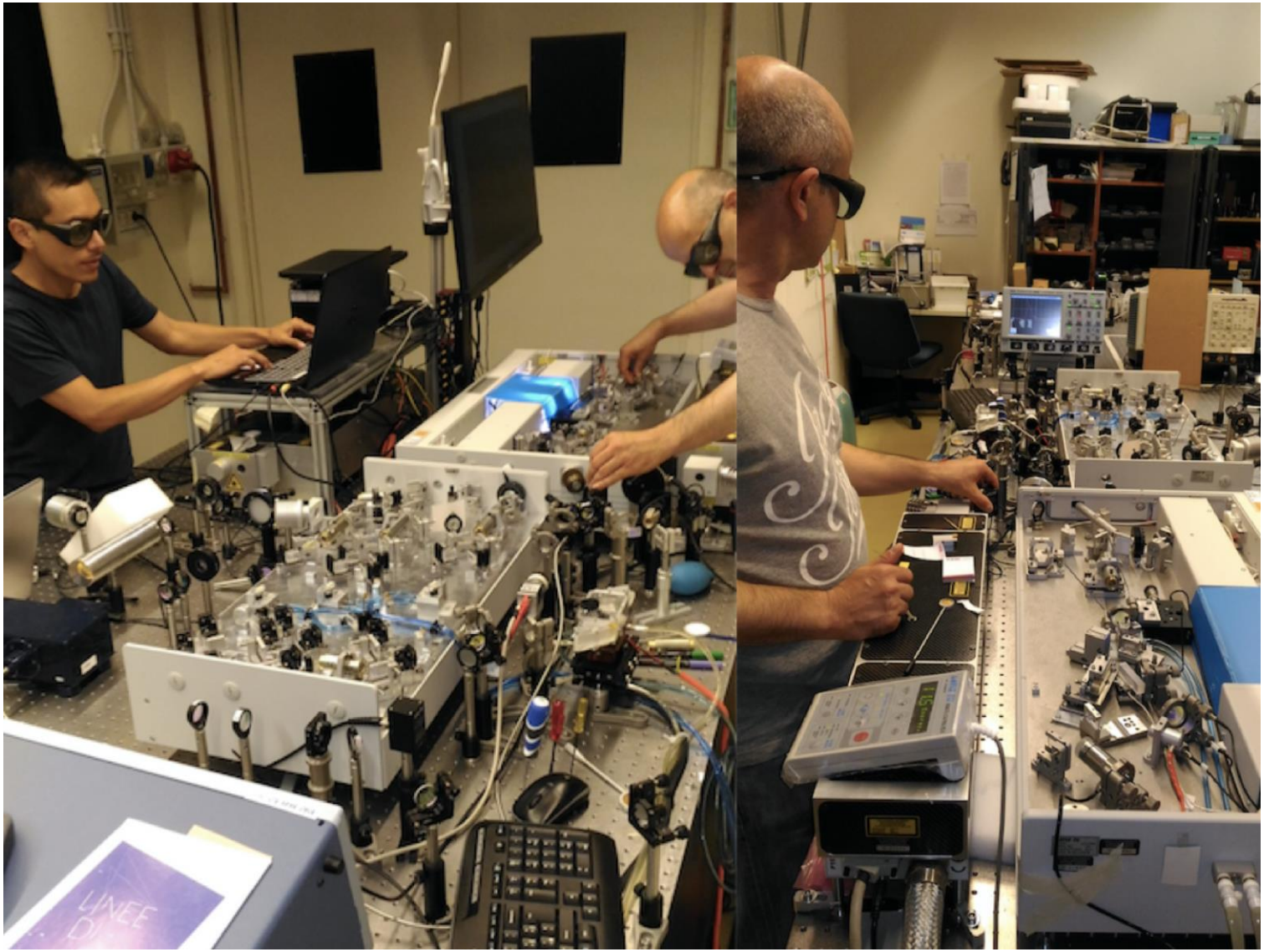
of these quantities E_F , δ^{QED} and δ^{rec} are known or calculable with accuracy 10^{-6} or better, and δ^{hvp} is small and may be neglected.
this relations δ^{Z} is related to the Zemach radius r_Z by means of

$$\delta^{Z} = 2\alpha(1+k)\cdot\frac{M_\mu M_p}{M_\mu + M_p}\cdot r_Z$$

where M_μ and M_p are the particle masses and k = 0.0152 is a QED correction, approximately $\delta^{Z} = -7.3\ \ 10^{-3}$.
Using phenomenological data the proton polarizability term δ^{pol} was evaluated to $\delta^{pol} = (4.6 \pm 0.8)\ \ 10^{-4}$

the uncertainty in the value of the Zemach radius is limited by the uncertainty of δ^{pol} to about 1%.

The MIR laser system

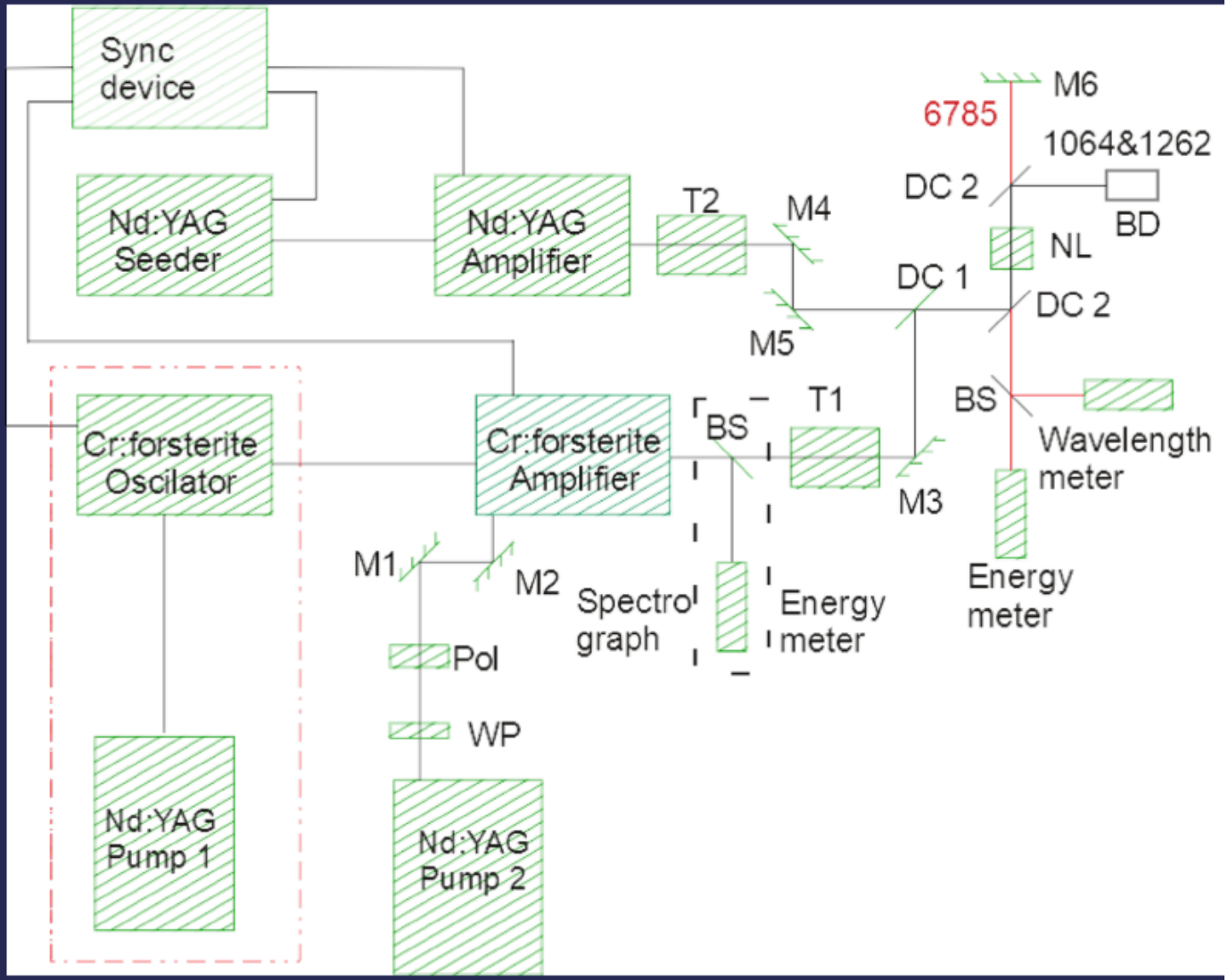


Final scheme of the DFG based laser system

The Nd:YAG will be at "fixed" wavelength 1064.14nm with linewidth max - 0.34pm (90MHz) and min - 0.11pm (30MHz).

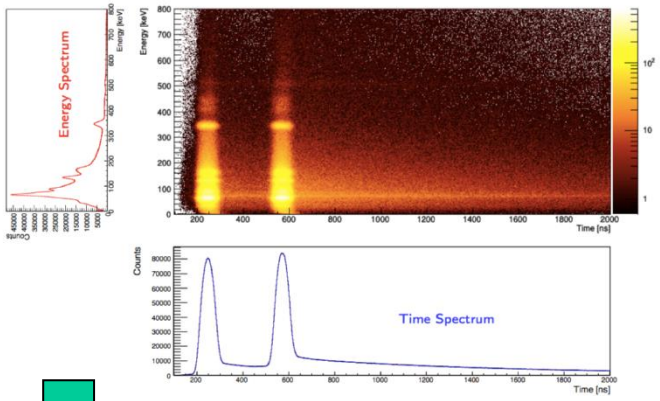
The Cr:forsterite will have linewidth max - 1pm (188MHz) and min - 0.5pm (90MHz).

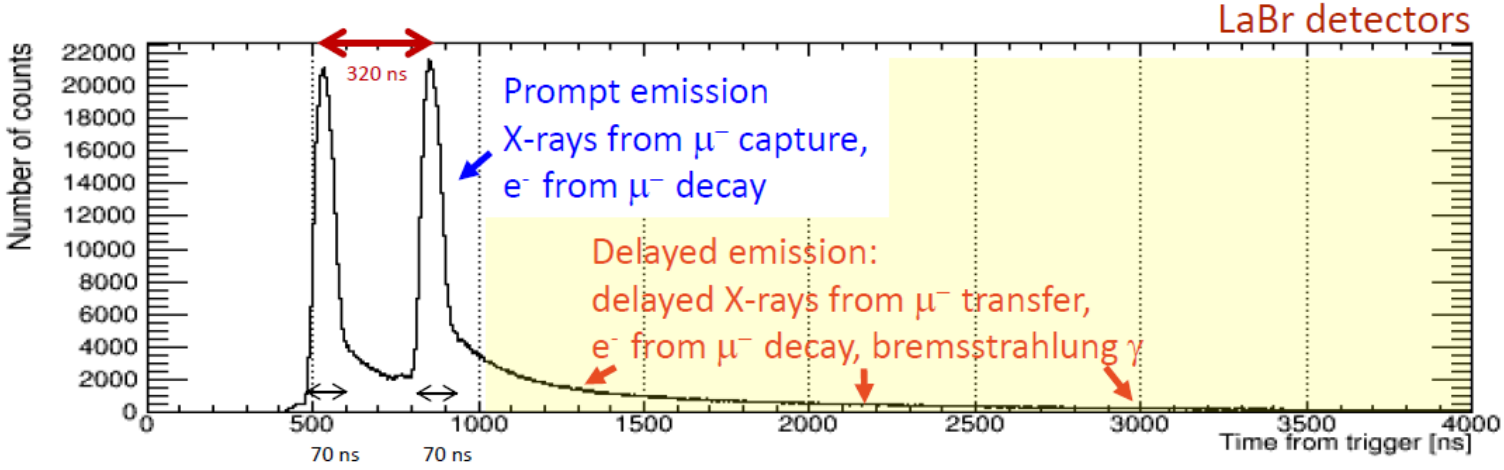
The Cr:forsterite will be tunable from 1252nm to 1272 nm which corresponds to tunability from 6500nm to 7090nm, which is 3765GHz. The required tunability 6760nm ±3nm corresponds to tunability range ~ 39GHz.



Physics measurements: transfer rate μp→ μO

- Transfer rate measured as a function of temperature
  - Target filled H_2+(120 ppm)O_2 at 41 bar at 300 K
  - Six temperatures (300, 272, 240, 201, 153, 104 K)
  - Each temperature kept stable for three hours each
- At each trigger we acquire a window of 10 microsecond
  - Produce μp's and wait for their thermalization (about 150 ns)
  - Study the time evolution of Oxygen X rays





Some references for further infos

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