Paving the way for bound-state QED tests in singly ionized helium

Julian J. Krauth

Vrije Universiteit Amsterdam

FFK Conference, Tihany, Hungary

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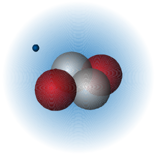
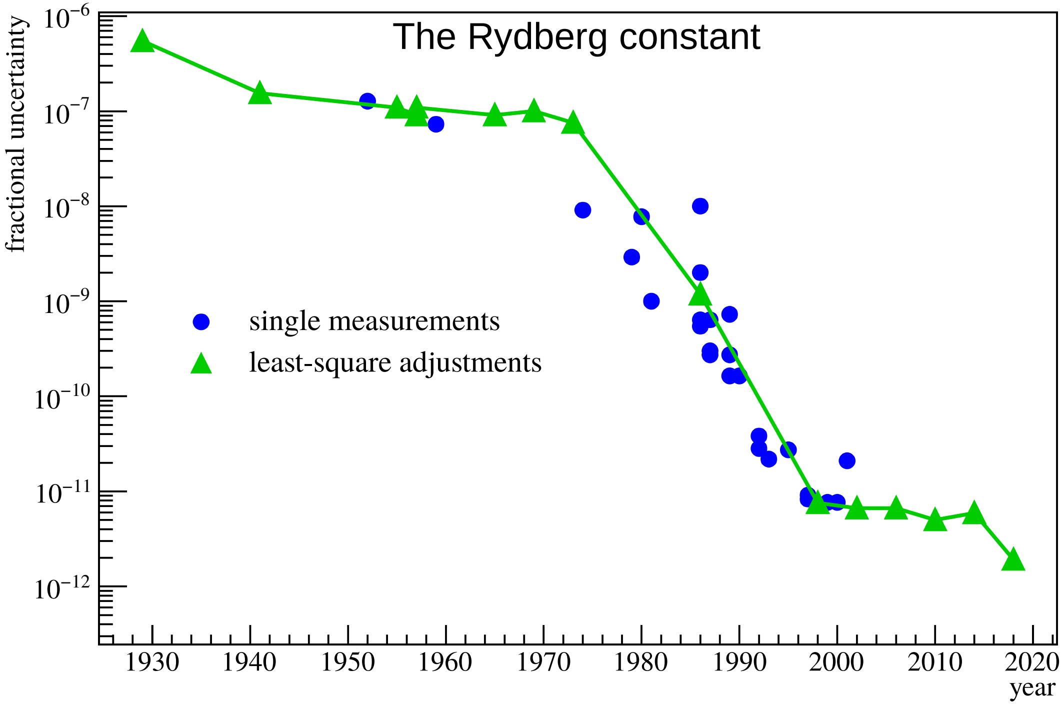


Testing bound-state QED



Simple systems are the ideal probe:

- **Atomic hydrogen**
- Other hydrogenlike systems
  - Positronium, Muonium,
  - D, **He^+**, …
- Other light atoms:
  - He
- Simple molecules
  - H_2, HD, HD^+, ...

- Can be calculated to high precision!
- Nuclear effects are small!

Limitations due to the nuclear charge radius?
→ Use **muonic** atoms!

Situation for He^+:
- Narrow 1S-2S transition
- Better sensitivity to higher-order QED terms (compared to H)
- Can be trapped
- Charge radius has been measured

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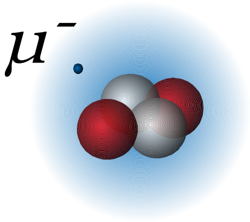
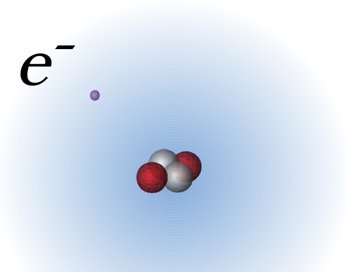
Helium ion spectroscopy



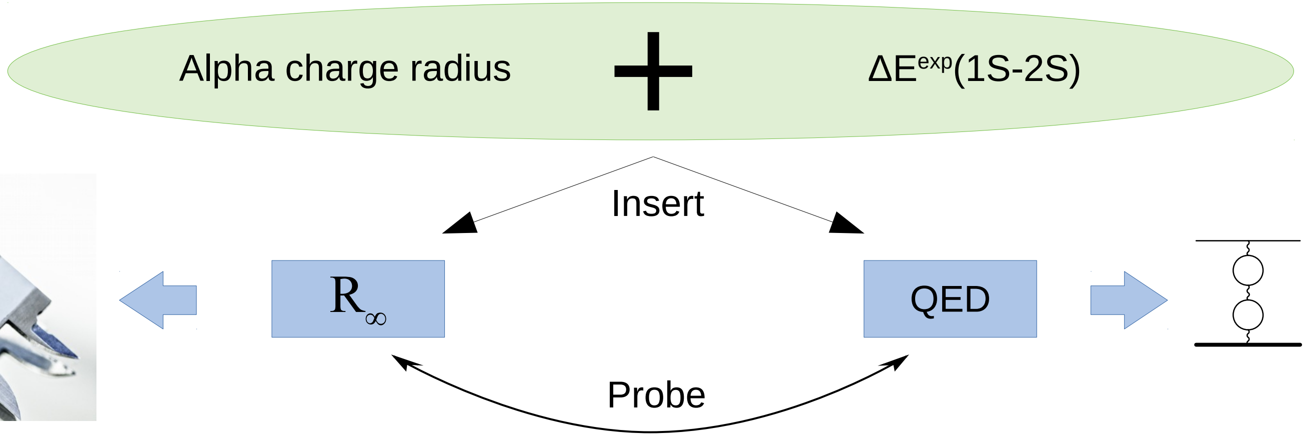
muonic He^+

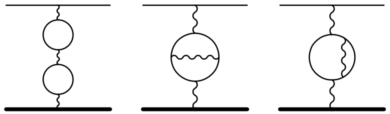
Large mass of bound lepton!
→ sensitive to nuclear properties
→ determine polarizab. or charge radius



electronic He^+

Can be measured with high precision!
→ determination of Rydberg constant
→ test $(Z\alpha)^{6..7}$ QED terms





Situation in Hydrogen-like Helium

Uncertainties which enter the theory determination of the 1S-2S transition frequency

Bohr term (Rydberg constant R_∞)	QED (higher order 2- and 3-loop)	Nuclear Size (alpha charge radius)	Measurement
R_∞ from CODATA14/18	current status	r_α from scattering	Current status
57 kHz / 19 kHz (PRP: 320 kHz)	110 kHz	295 kHz	✗
$R_\infty[\mu p$+H(1S-2S)]	future	r_α from μ^4He^+	projected
9 kHz	~10 kHz	~60 kHz preliminary	~1 kHz

[Theory numbers from He+ Workshop at MPQ, May 2018]

~10kHz if pol. could be calculated to higher precision

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High-precision spectroscopy at XUV wavelengths

Laser source in the XUV range

Upconvert a frequency comb (FC)

High-precision spectroscopy at XUV wavelengths

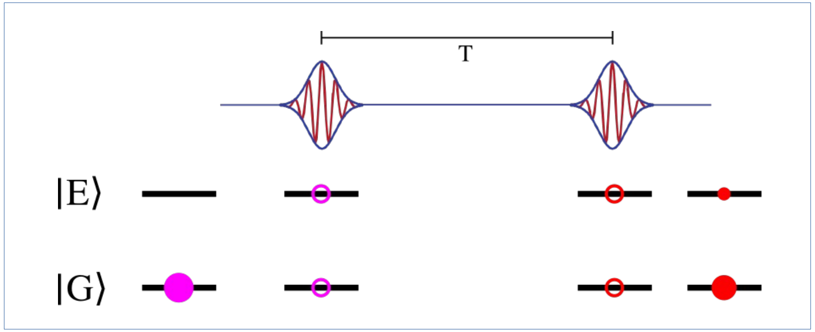
Laser source in the XUV range

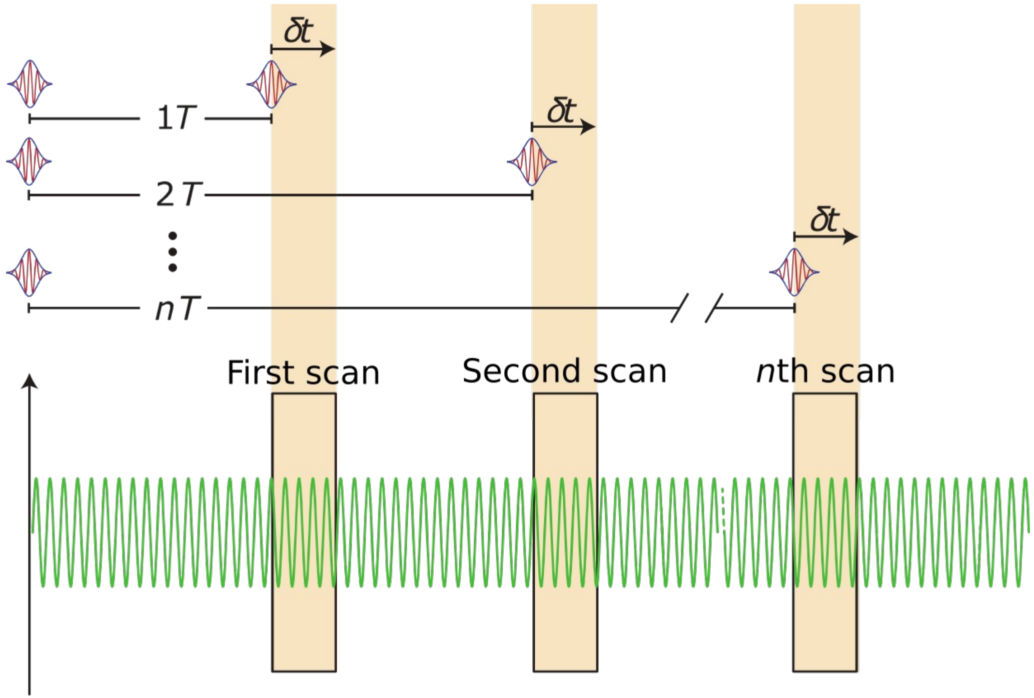
↳ Upconvert a frequency comb (FC)

↳ Need high peak intensities for upconversion

Pure direct FC spectroscopy	Ramsey-comb spectroscopy
Amplify **full repetition rate** FC and upconvert via intra-cavity HHG → Very challenging to reach required Peak-intensities → Comb-structure is maintained → 2x 60nm MPQ, Garching	Select, amplify and upconvert **only 2 pulses** of a FC and perform a Ramsey type measurement → High peak intensities achievable → Narrow-band comb-structure restored by measuring at different delays. → 790nm + 32nm VU, Amsterdam

Ramsey-Comb Spectroscopy



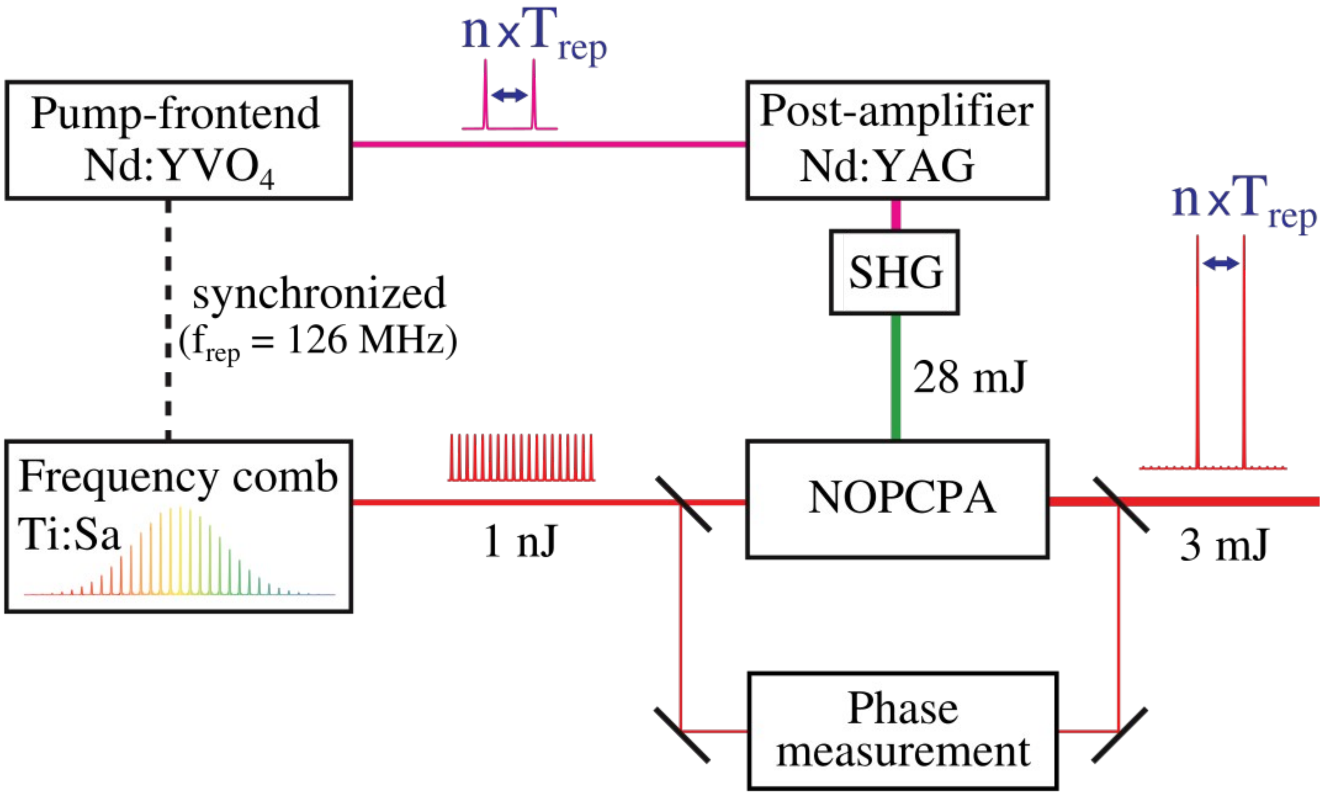


$$signal \propto \cos\left(2\pi f_{tr} T_{delay} - \Delta\phi\right)$$

Measure relative phase evolution:
→ Constant systematic phase shifts cancel
as e.g. AC Stark shift

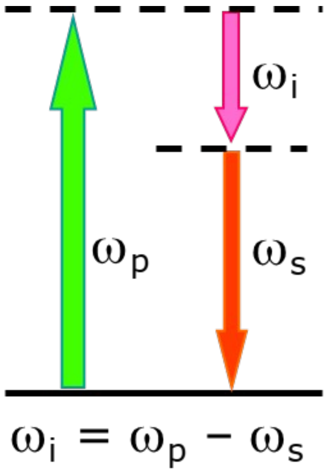
Morgenweg et al. - Nat. Phys. **10**, 30-33 (2014)

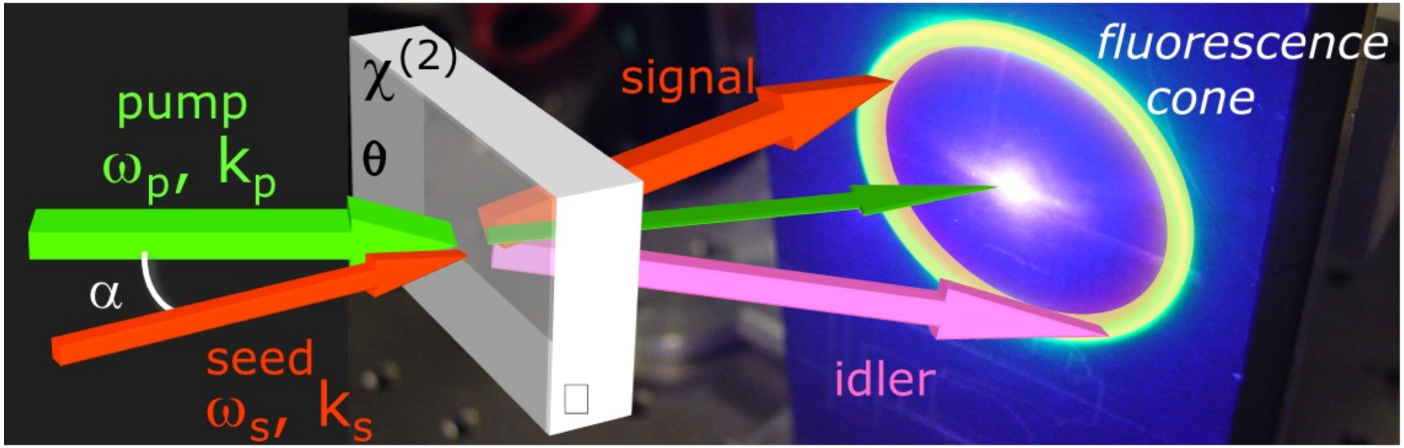
Ramsey-Comb Laser



NOPA

Noncollinear Optical Parametric Amplification

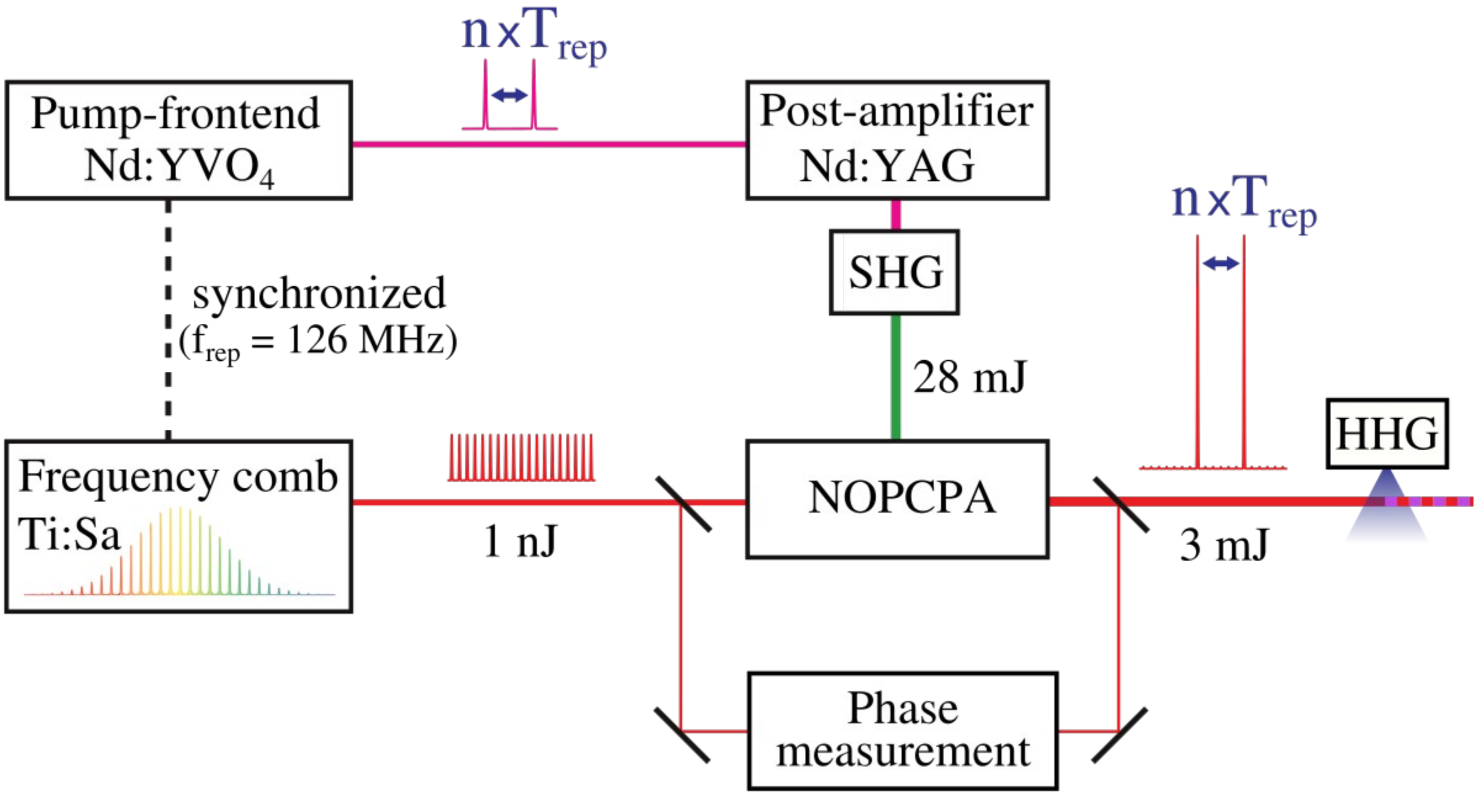




3 passes though BBO crystals pumped by 532 nm 50 ps @ 5 GW/cm^2

- Tuning over 700-1000nm with little effort
- Output ~3mJ
- Bandwidth adjustable from 300nm to 0.2nm
- No memory effect (no inversion)
- Phase of pump beam does not influence the phase of the signal, but the amplitude does

Ramsey-Comb Laser



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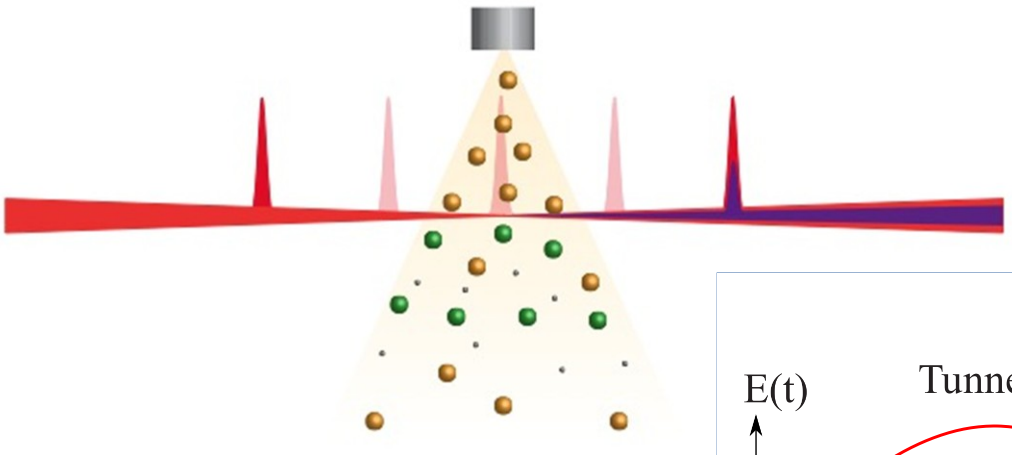
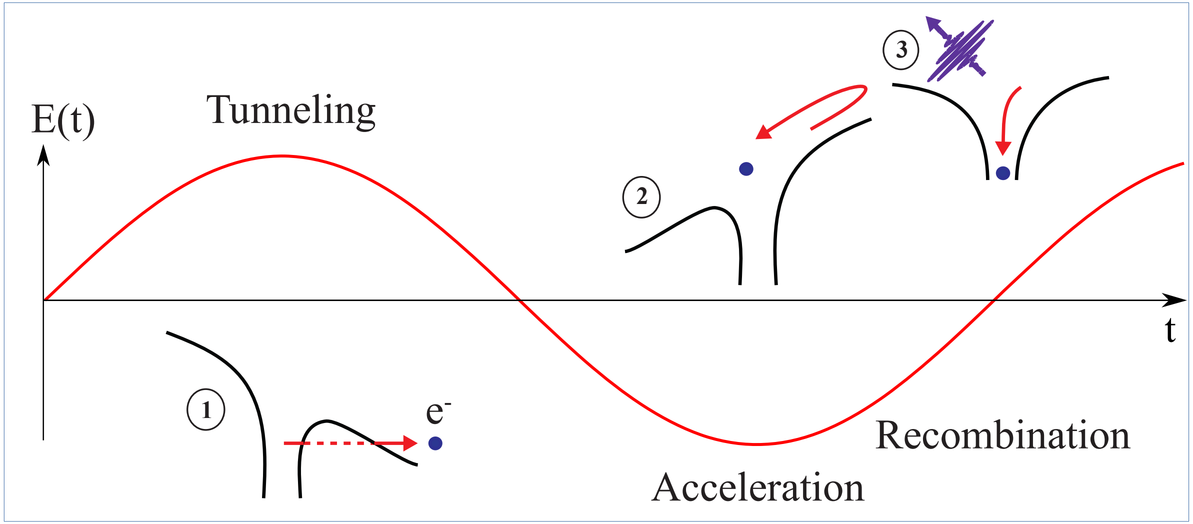
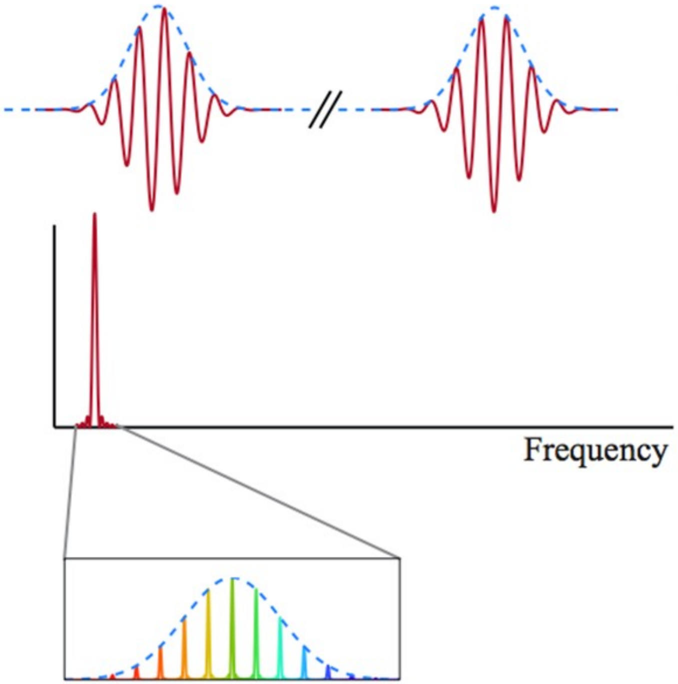
High-harmonic generation

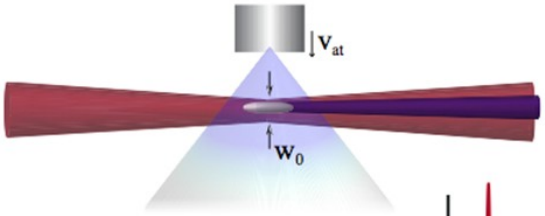


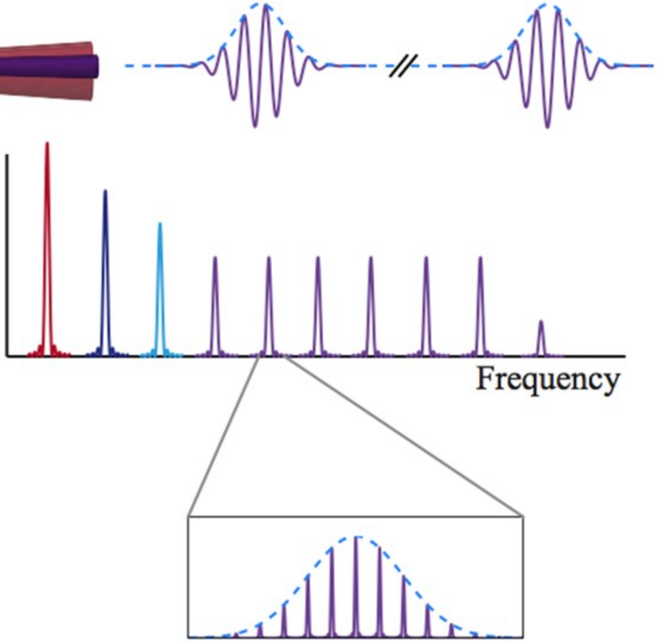
Required Intensity: 10^{14} W/cm^2



A comb in the XUV







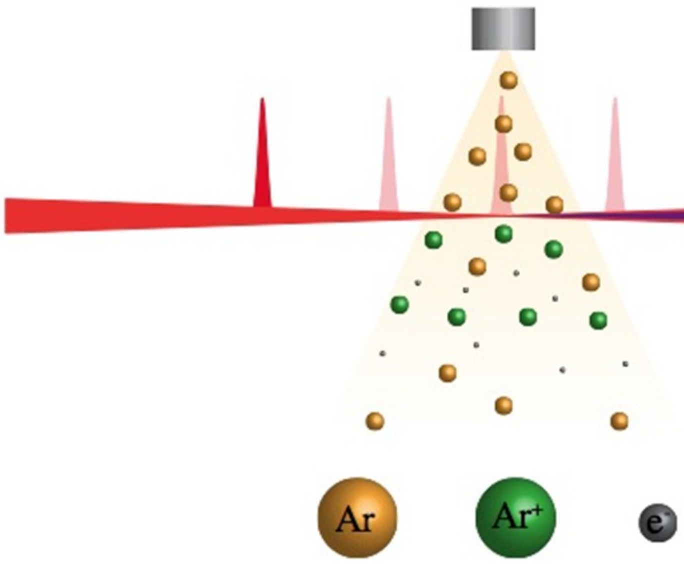
Coherent process

Efficiency $<10^{-6}$

Fundamental: $f_n = f_{ceo} + n\, f_{rep}$

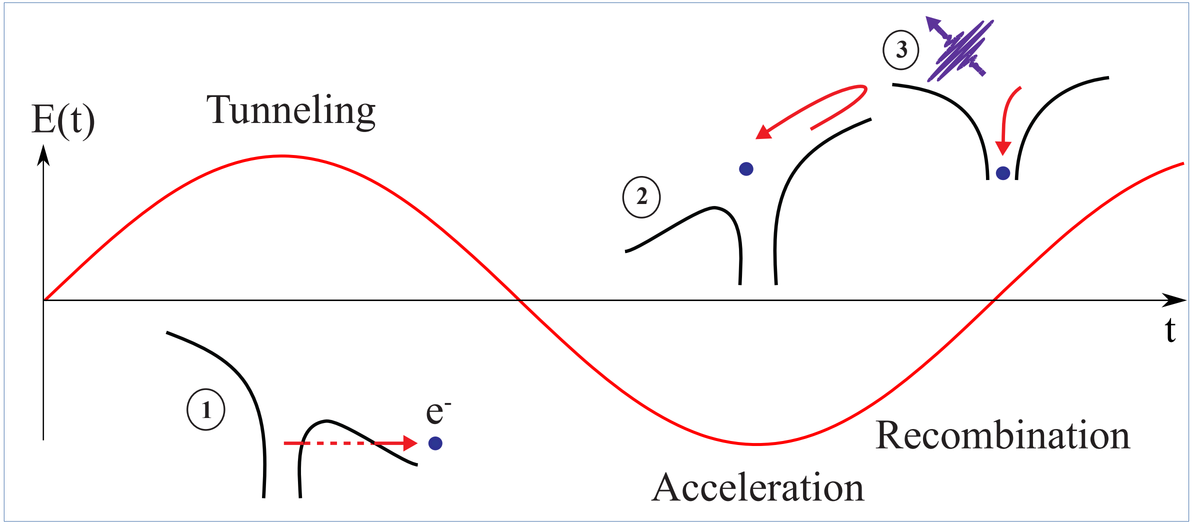
q^{th} harmonic: $f_m = q\, f_{ceo} + m\, f_{rep}$

Plasma creation in argon jet



Plasma formation might introduce delay-dependent phase shifts!

Allison et al., PRL **107**, 183903 (2011)



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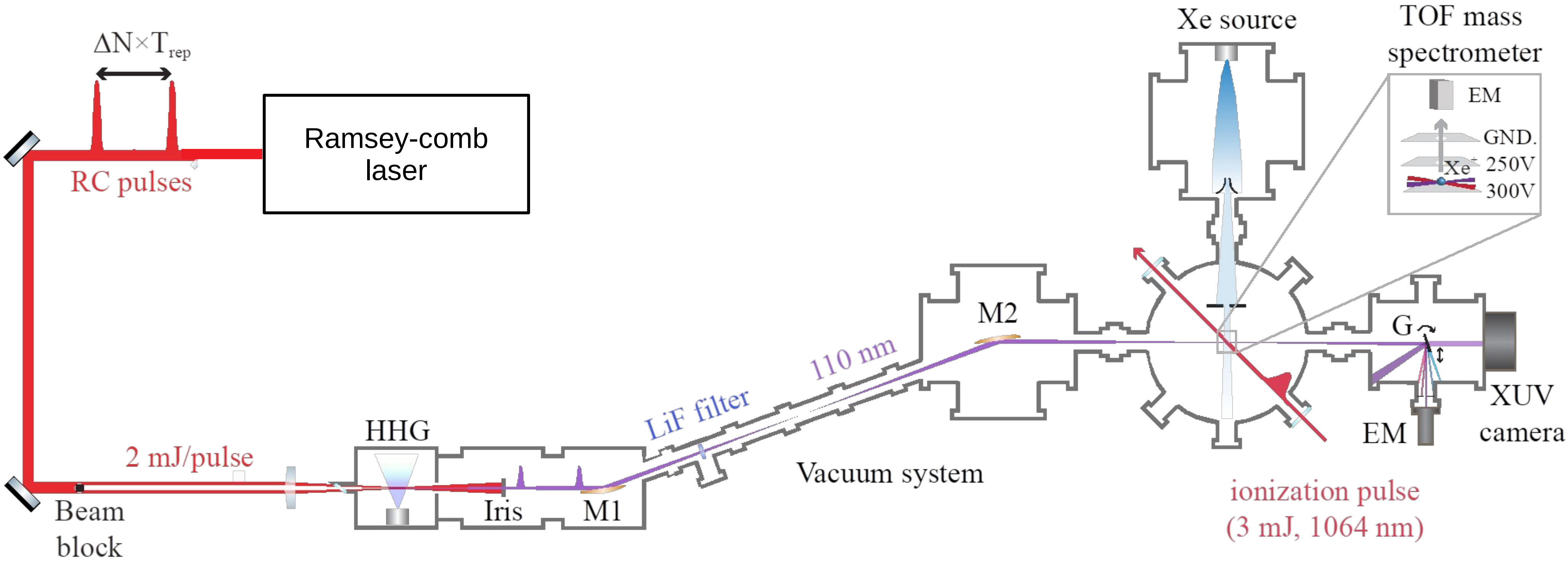
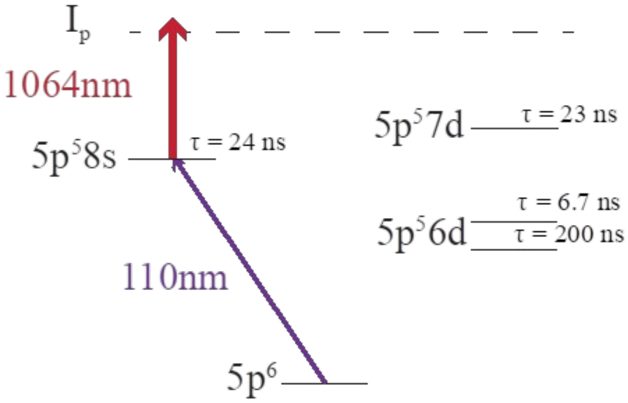
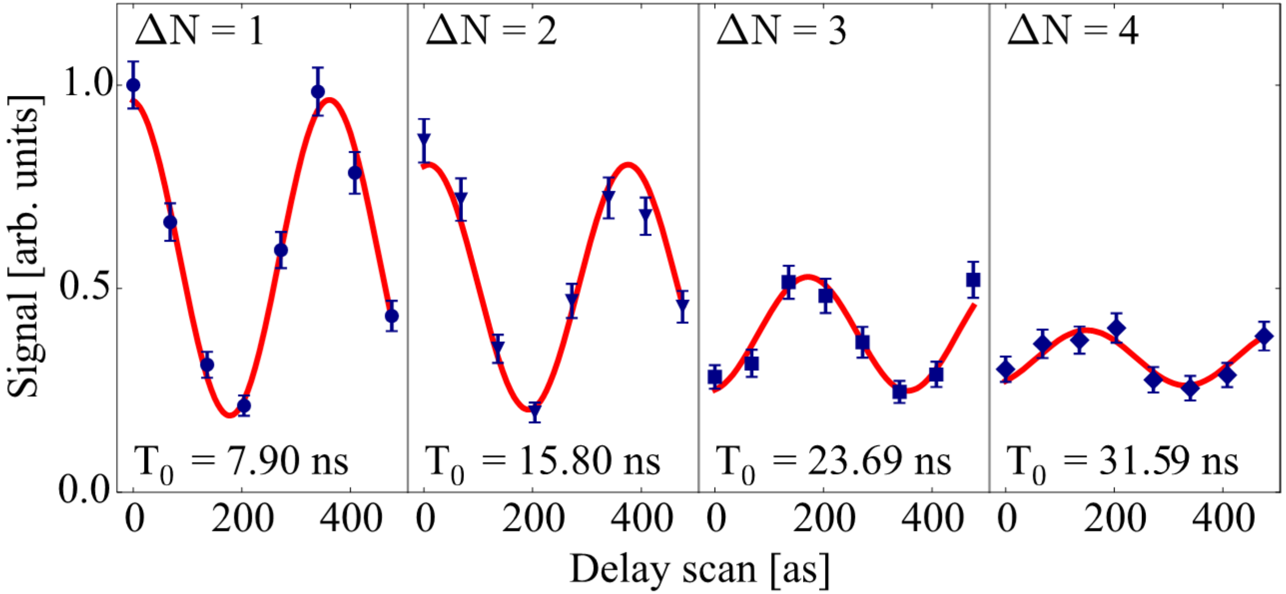
Measurement in xenon



Measurement in xenon

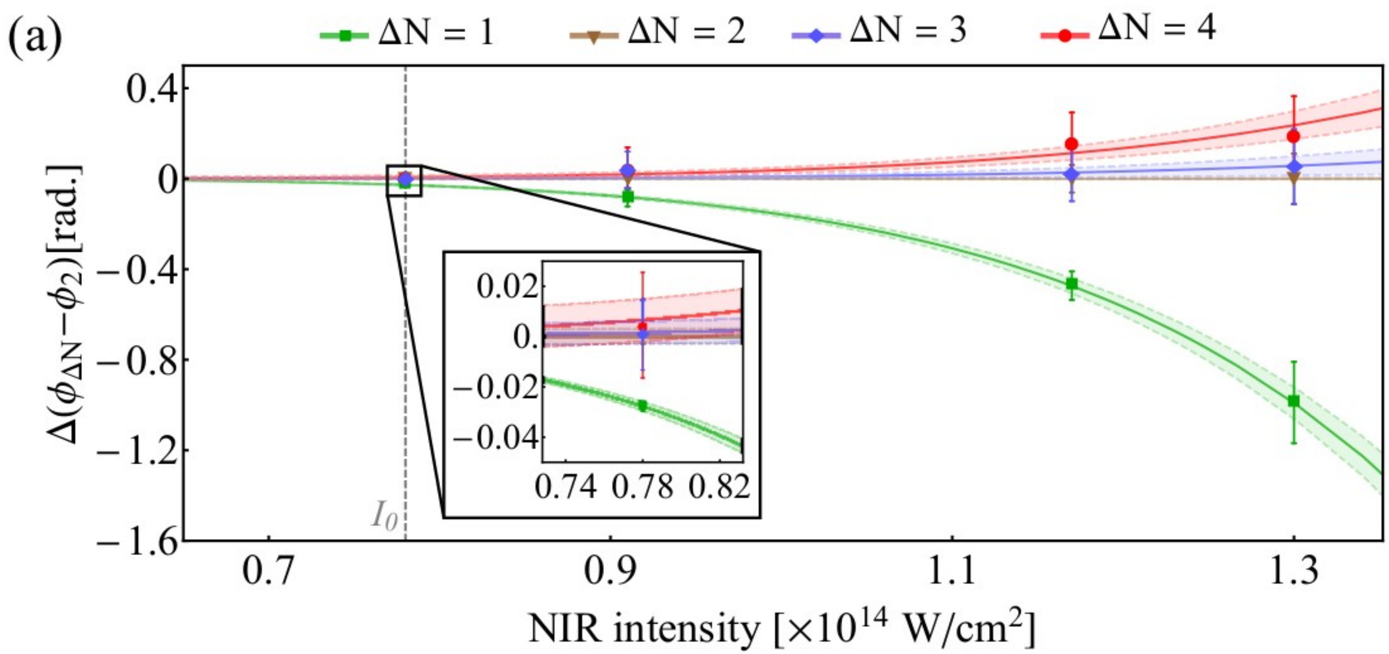
First Ramsey-comb measurement using a high-harmonic generation source





Laura Dreissen

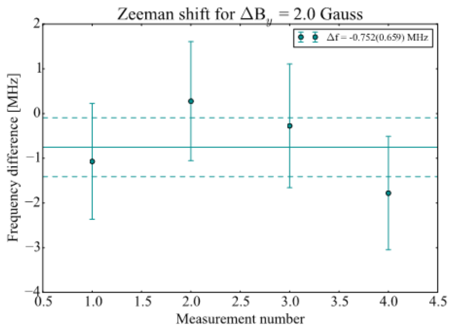
Plasma induced phase shift

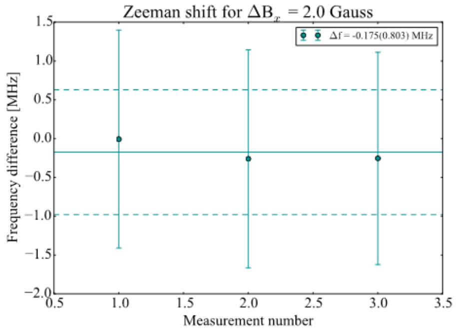


The effects on the phase are negligible: e.g. 7(9)mrad between ΔN=2 and ΔN=4

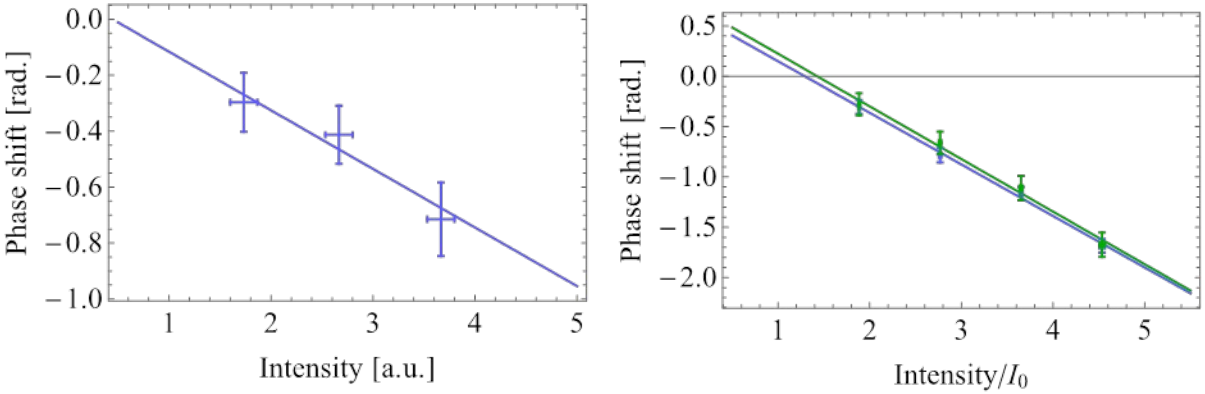
Systematics

Zeeman shift:

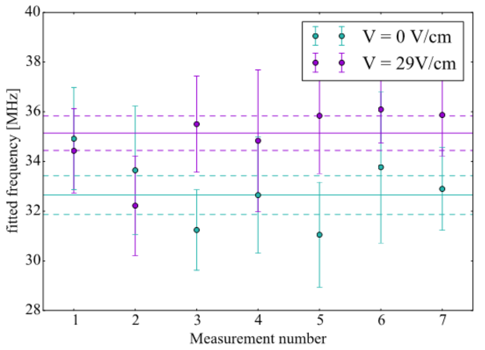




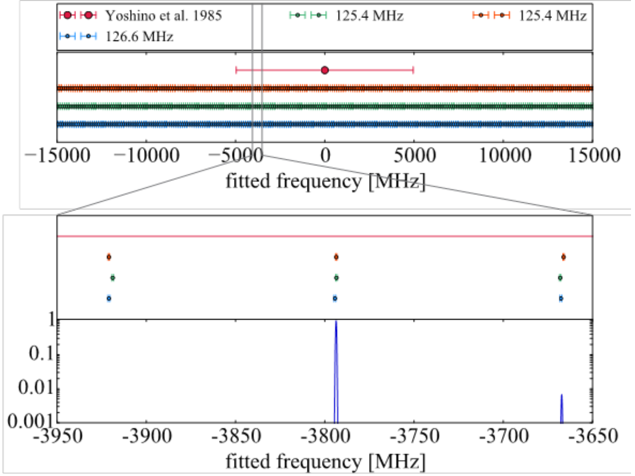
AC-Stark shift



DC-Stark shift



Mode determination

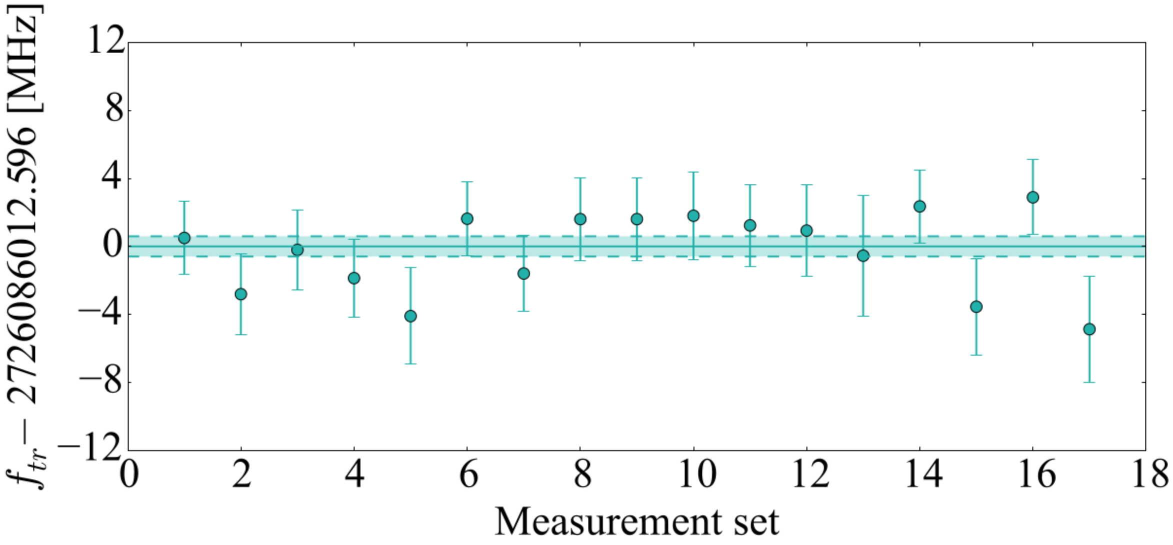


Absolute frequency calibration

Preliminary results:

$f = 2\ 726\ 086\ 012\ 473\ (630)$ kHz
$\mathrm{d}f\,/\,f = 2.3 \times 10^{-10}$

- The **most accurate** frequency measurement with a HHG source!
- **Improvement of 10^4** with respect to previous measurement [1]

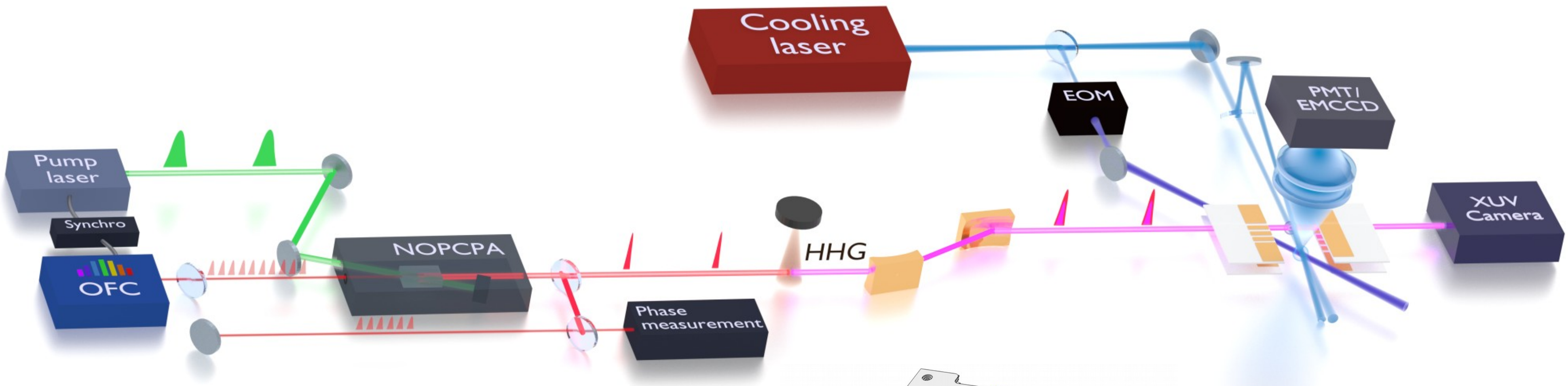


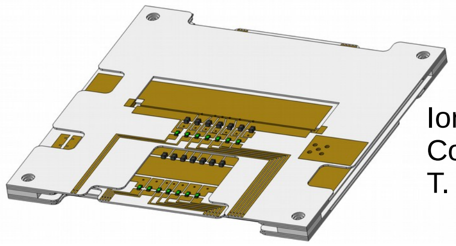
[1] Yoshino et al., J. Opt. Soc. Am. B **2**, (1985)

Conclusions from xenon measurements:

- HHG and RCS go well together, HHG shifts can be avoided
- We have performed the most accurate frequency measurement with a HHG source
- The accuracy is limited by the limited interaction time with the xenon atoms
- Future experiments in the helium ion are feasible

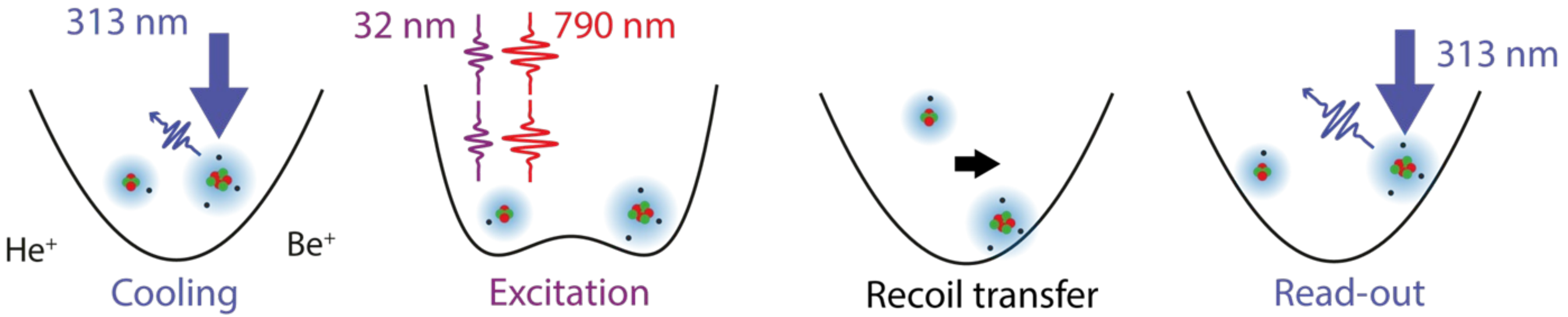
Setup for the He^+ measurement



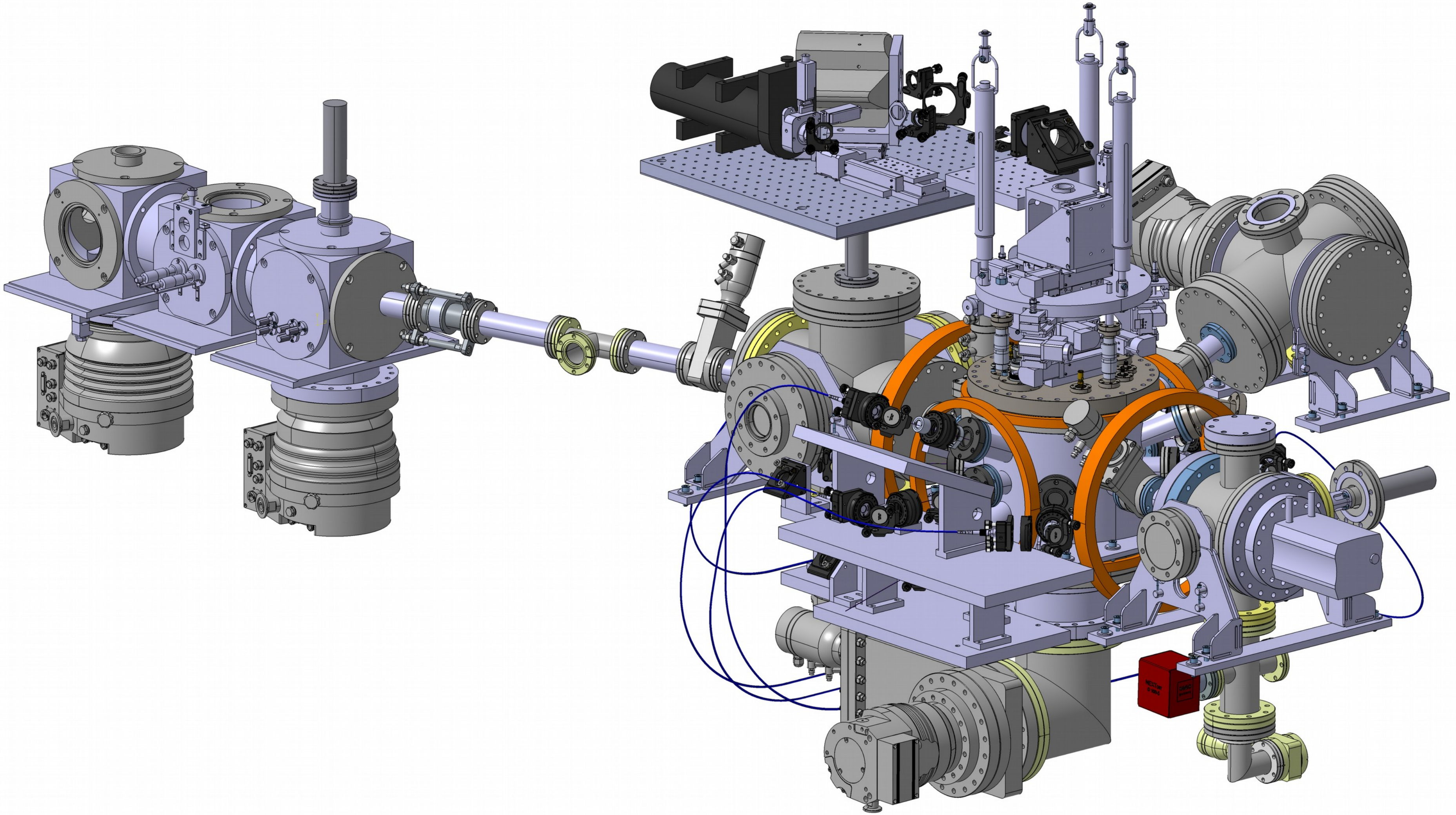


Ion trap from PTB:
Collaboration with
T. Mehlstäubler, P. Schmidt

Measurement principle



1) Sympathetic ground-state cooling
2) Ion separation and Ramsey-comb excitation
3) When He^+ is excited it gains momentum due to the high recoil of the XUV photon
4) Motional quanta from He^+ are coupled to Be^+, which is read out by state-dependent fluorescence



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Roadmap towards the He^+ measurement:

- Set up cooling laser for ground state cooling
- Build new improved RCS laser setup to reduce phase-noise
- Install the trap provided by PTB

Thank you for your attention!

The He^{+} group

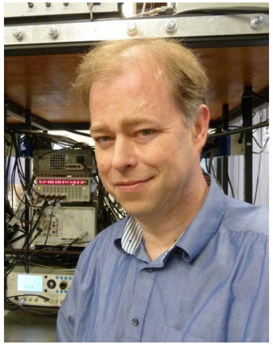

Laura Dreissen


Charlaine Roth


Elmer Gründeman


Mathieu Collombon


Julian Krauth


Kjeld Eikema

Netherlands Organisation for Scientific Research

European Research Council
Established by the European Commission

Collaborators on the ion trap:
Piet Schmidt and Tanja Mehlstäubler (PTB)