Towards High-Precision Spectroscopy of the 1S–2S Transition in He^+

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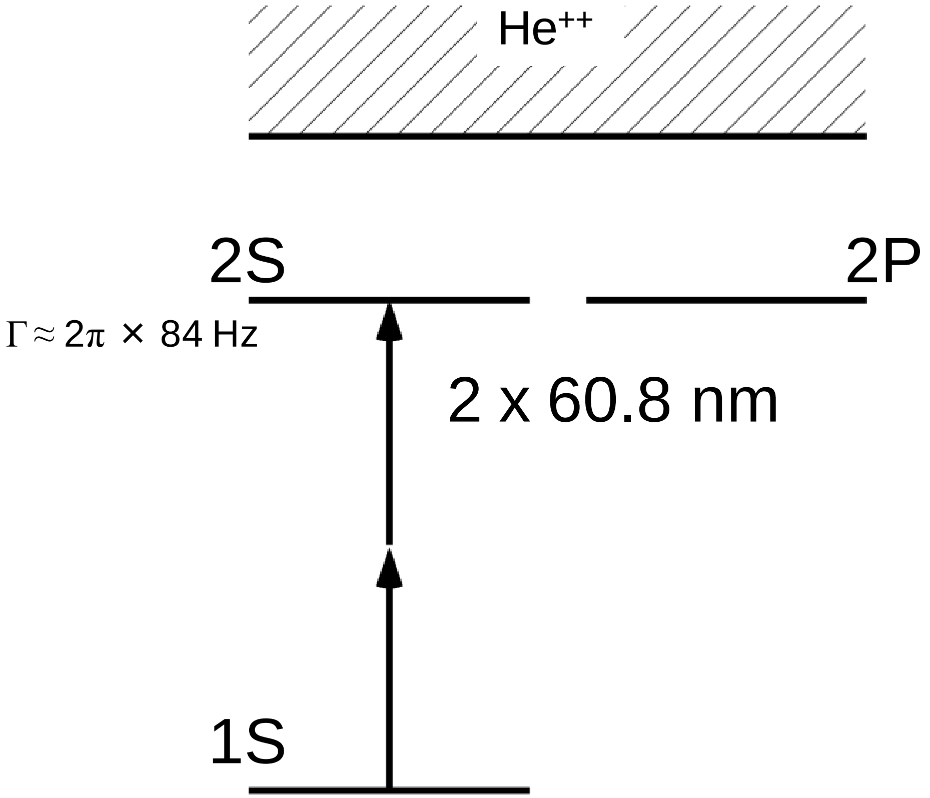
Spectroscopy of the 1S–2S Transition in He^{+}



Difference from Hydrogen spectroscopy:

- Trapped and cooled target → smaller systematics
- QED test for Z=2 system
- Frequency comb spectroscopy in XUV (extreme ultraviolet) wavelength

QED for He^+

$$E_{nlj} = R_\infty f_{nlj}\left(\alpha, \frac{m_N}{m_e}, \frac{r}{\lambda_C}\right)$$

- State energy in SI units (m^{-1}) → E_{nlj}
- Rydberg constant → R_∞
- Fine structure constant → α
- Nucleus/electron mass ratio → $\frac{m_N}{m_e}$
- Normalized nuclear charge radius → $\frac{r}{\lambda_C}$

Parameters	Contribution to Uncertainty (He^+ 1S2S)	
Rydberg constant R_∞	1.9×10^{-12} (19 kHz)	← Hydrogen spectroscopy μ-H + H (1s-2s), CODATA2018
Nuclear charge radius $\frac{r}{\lambda_C}$	6×10^{-12} (61 kHz)	← μ-He spectroscopy J. Krauth et al. Nature (2021)
Nucleus/electron mass $\frac{m_r}{m_e}$	5×10^{-15} (45 Hz)	← Mass ratio measurements in Penning trap
Fine structure constant α	2×10^{-14} (166 Hz)	← Atomic recoil (atom interferometer) g-2 measurement

Uncertainty due to QED theory for He^+ 1S-2S transition

[1] Physics Letters B 795, 432–437 (2019)
[2] Phys. Rev. A 100, 032515 (2019).
[3] Phys. Rev. A 98, 022522 (2018)
[4] Physics Letters B 800, 135137 (2020).
[5] Annalen der Physik 531, 1800324 (2019).
[6] Phys. Rev. A 94, 060501 (2016).
[7] Phys. Rev. A 93, 062514 (2016).

CODATA 2014

Contribution	Uncertainty (in kHz)
Relativistic Recoil	11
Nuclear Polarizability	3
Self Energy	0
Vacuum Polarization	1
Two Photon Corrections	111
Three Photon Corrections	28
Nuclear Size Correction to Self Energy	0
Nuclear Size Correction to Vacuum Polarization	0
Radiative Recoil	9
Nuclear Self Energy	0.6
Total	**116 kHz ($1x10^{-11}$)**

Recent improvements
(Not all are included in CODATA2018)

→ ~ 0 kHz — Yerokhin. A and Shabaev V. M [7]

→ <30 kHz — Karshenboim, S. G et al. [1,2,3]; V. Yerokhin et al. [5]; A.Czarnecki st al. [6]

→ <10 kHz — Karshenboim, S. G et al. [1,2]

Four loop (photon) corrections S. Laporta [4]

→ < 40 kHz ($4x10^{-12}$)

Total QED uncertainty : 40 kHz = $4x10^{-12}$ (preliminary)

He^+ spectroscopy for testing QED

- Measuring the 1S-2S transition

better than 400kHz (4×10^{-11})

⟶ Determine R_∞ and contribute to the proton charge radius puzzle

better than 60 kHz (6×10^{-12})

⟶ Determine charge radius, which can be compared with μ-He measurement

better than 40 kHz (4×10^{-12})

⟶ QED theory uncertainty will be a limitation

- Measuring other transitions in $^4He^+$ ⟶ QED test more independent from μ-He and Hydrogen
- Measuring $^3He^+$ ⟶ Charge radii difference, which can be compared with neutral He spectroscopy

$^4He^+$ Nuclear charge radius

$r_\alpha = 1.681(4)$ — Scattering, I.Sick (2008)

$r_\alpha = 1.67824(13)_{exp}(82)_{theo}$ — μ-He spectroscopy, J. Krauth et al. (2021)

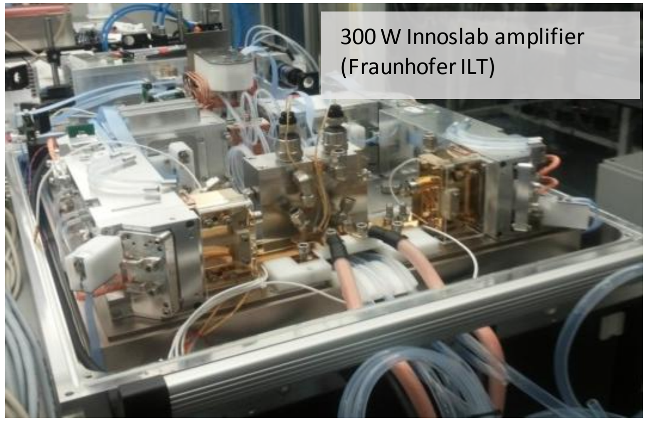
r_α uncertainty J. Krauth et al. (2021)		**Contribution to He^+ 1S-2S uncertainty**
QED (r-independent)	0.04 am	2.9×10^{-13}
2PE	0.70 am	5.2×10^{-12} =52 kHz
3PE	0.42 am	3.1×10^{-12}
1PE	0.06 am	4.5×10^{-13}
Theory Total:	0.82 am	6.1×10^{-12}
Experiment (statistics) :	0.13 am	9.7×10^{-13} = 9.6 kHz

4×10^{-12}: He^+ QED theory uncertainty

He⁺ spectroscopy setup: overview

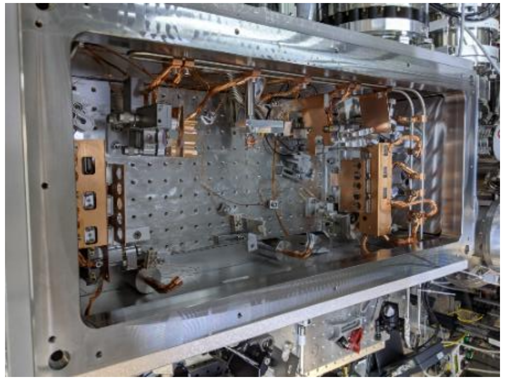
High-power IR frequency comb

Yb:KYW laser + amplifiers
@1030 nm

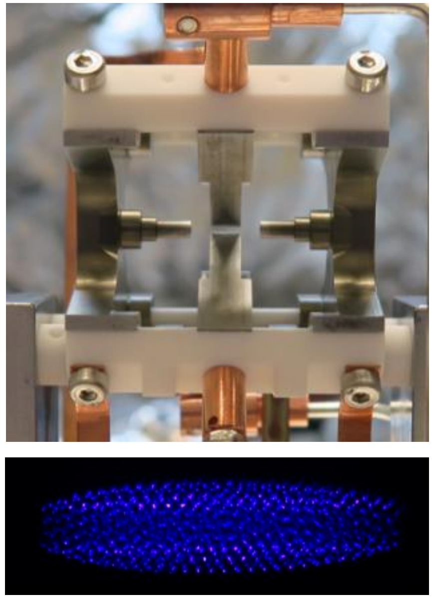


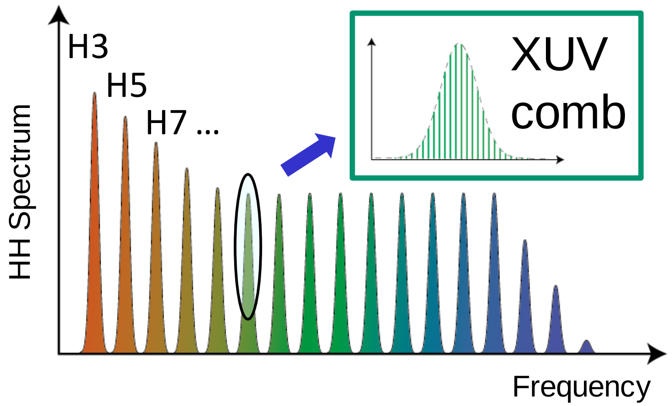
Frequency comb at 60.8 nm

Intracavity HHG
17^{th} harmonic

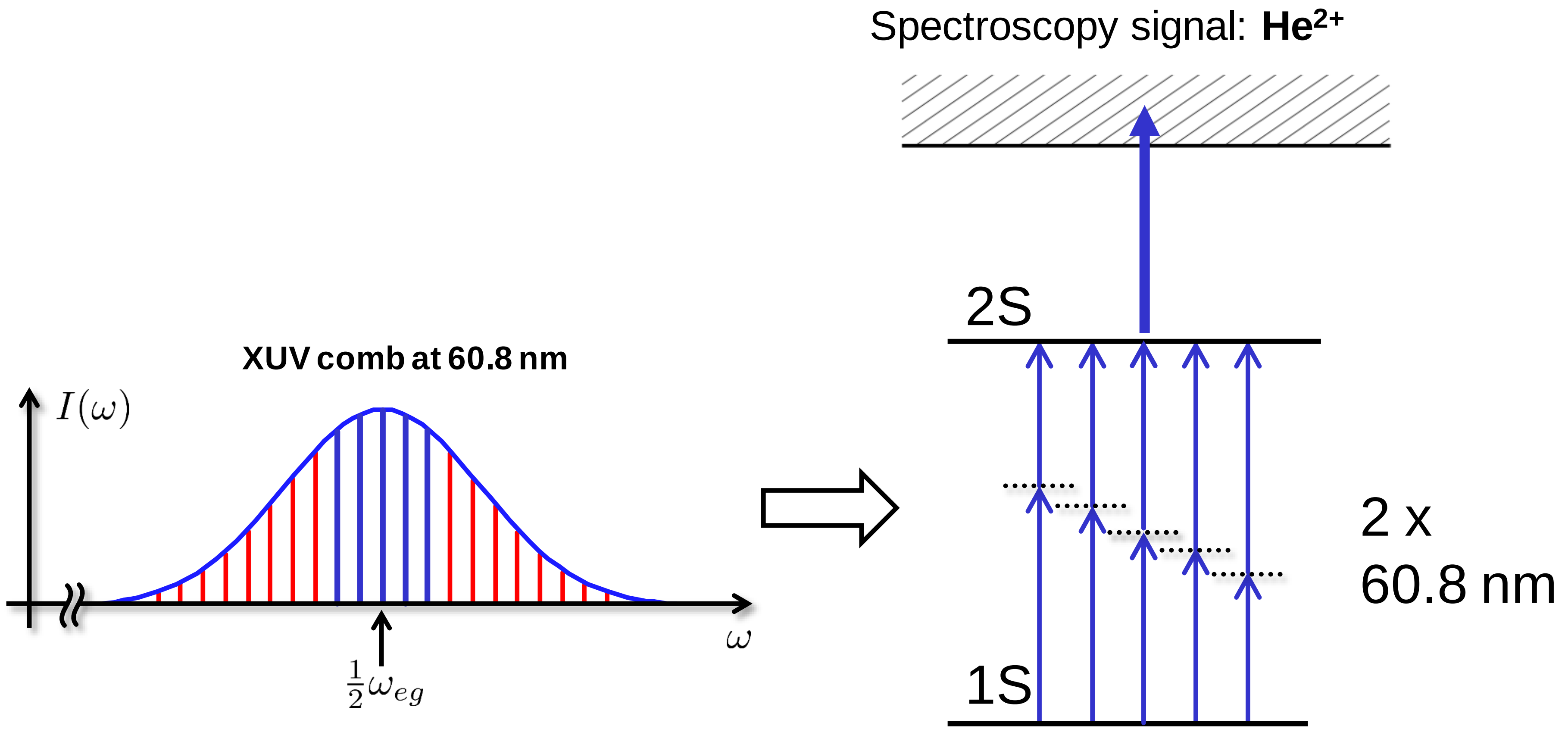


Trapped He^+ ions

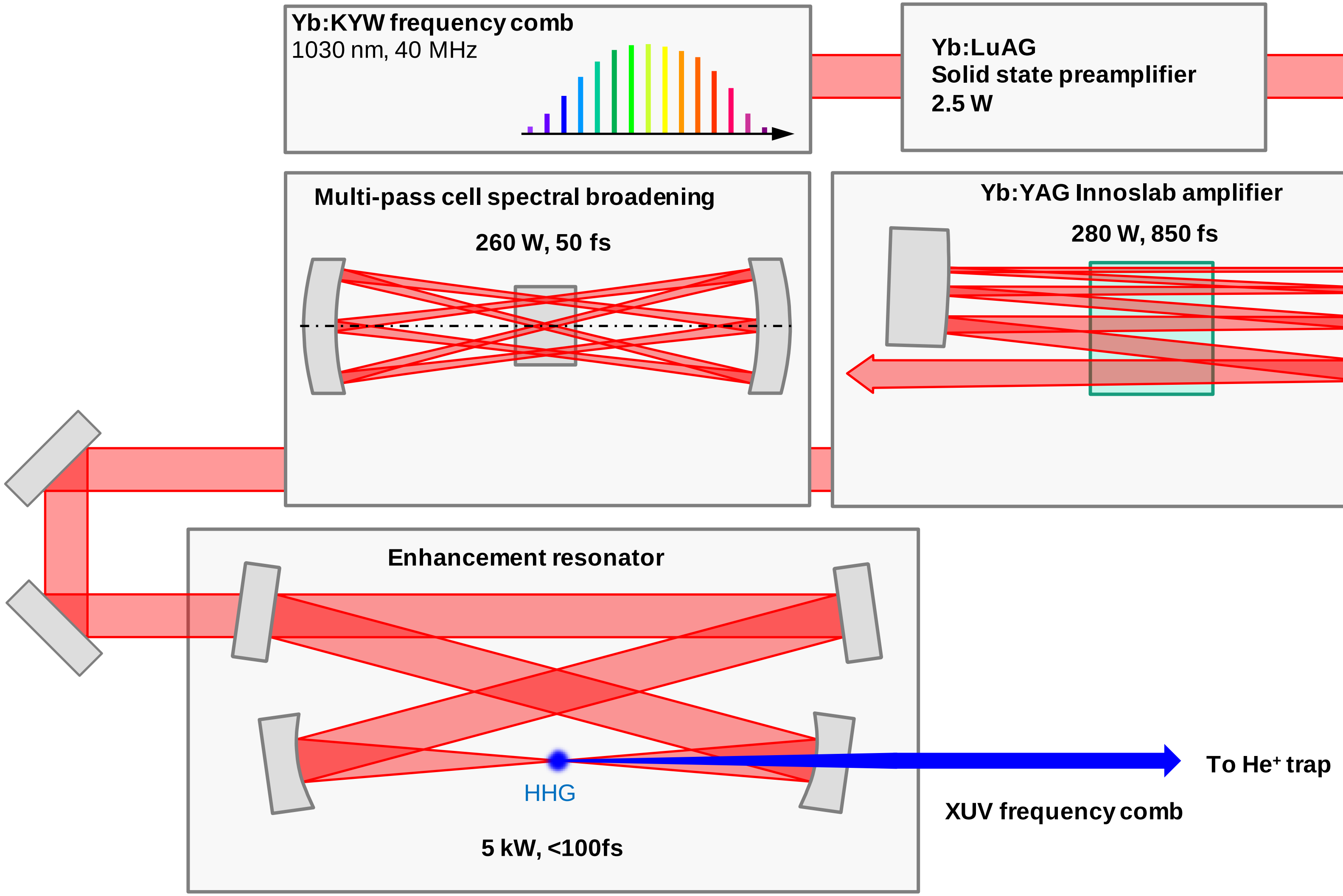




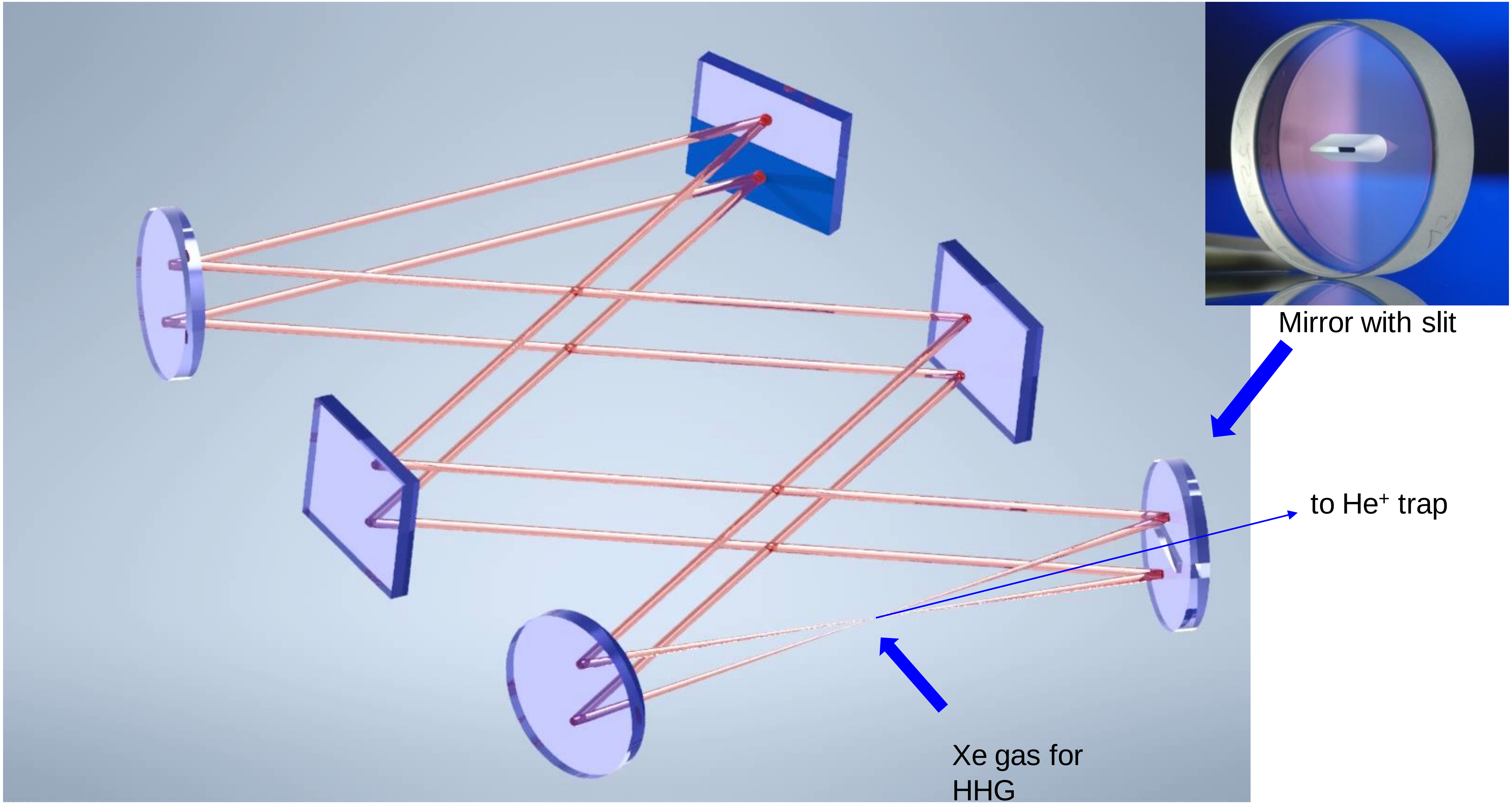
Direct frequency comb spectroscopy



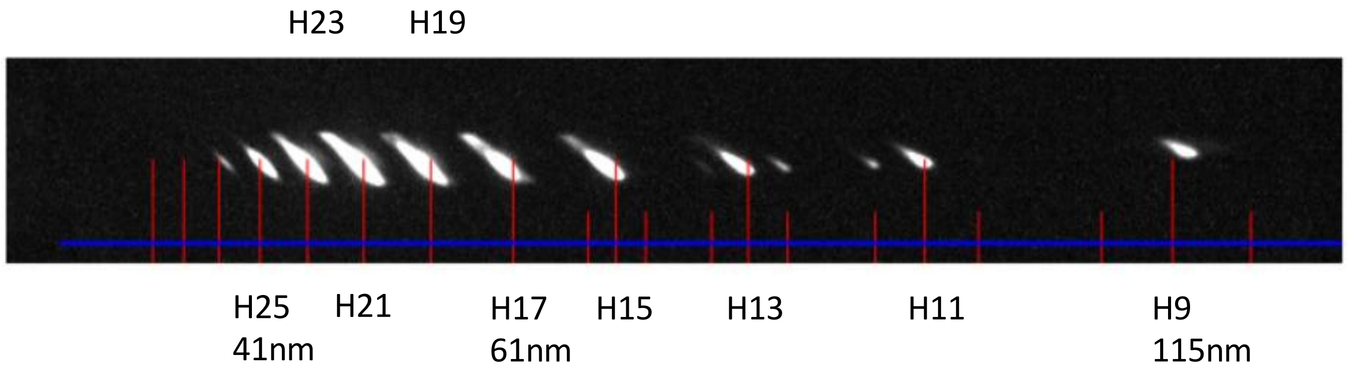
61nm Laser system

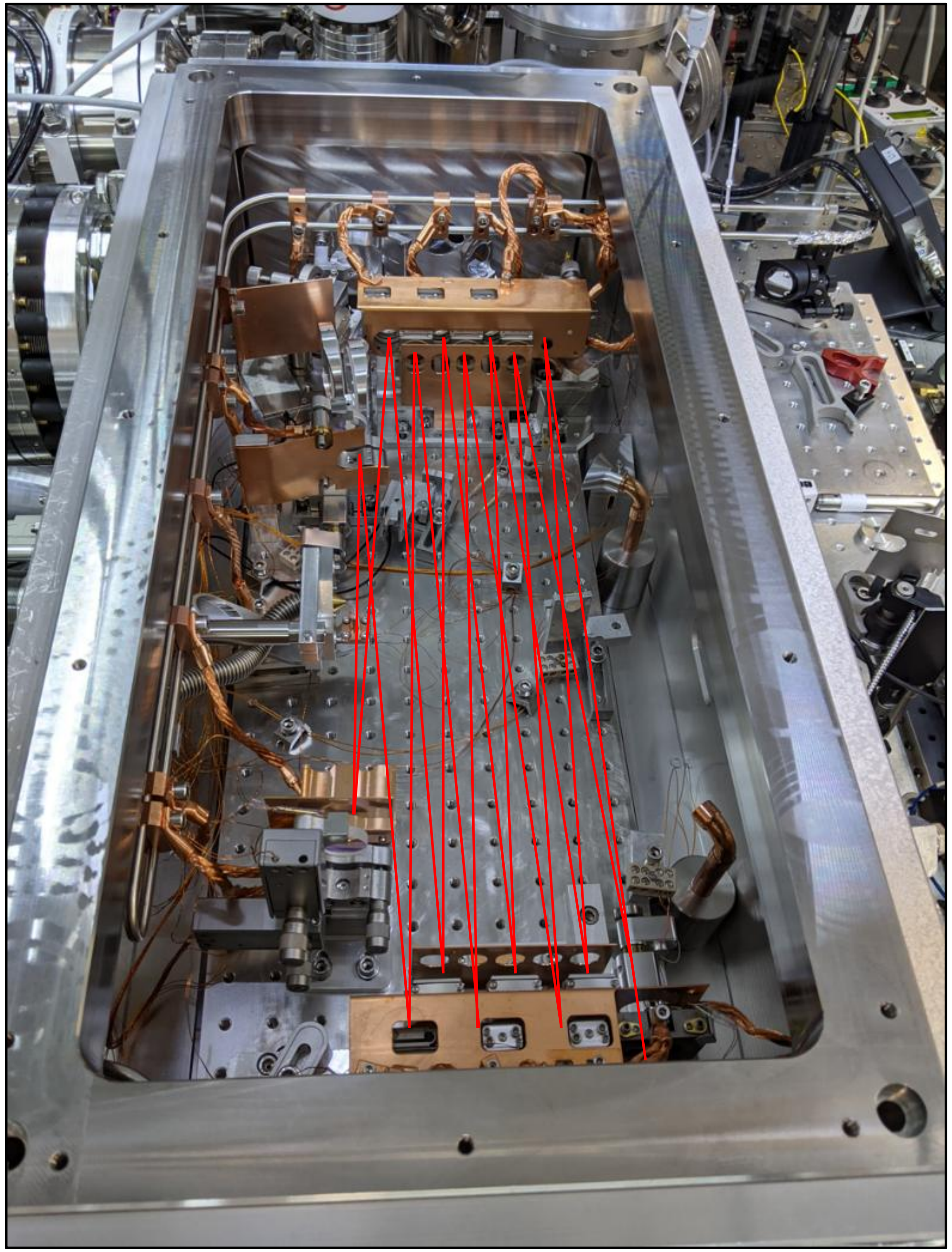


Enhancement Resonator for HHG



Enhancement Resonator for HHG

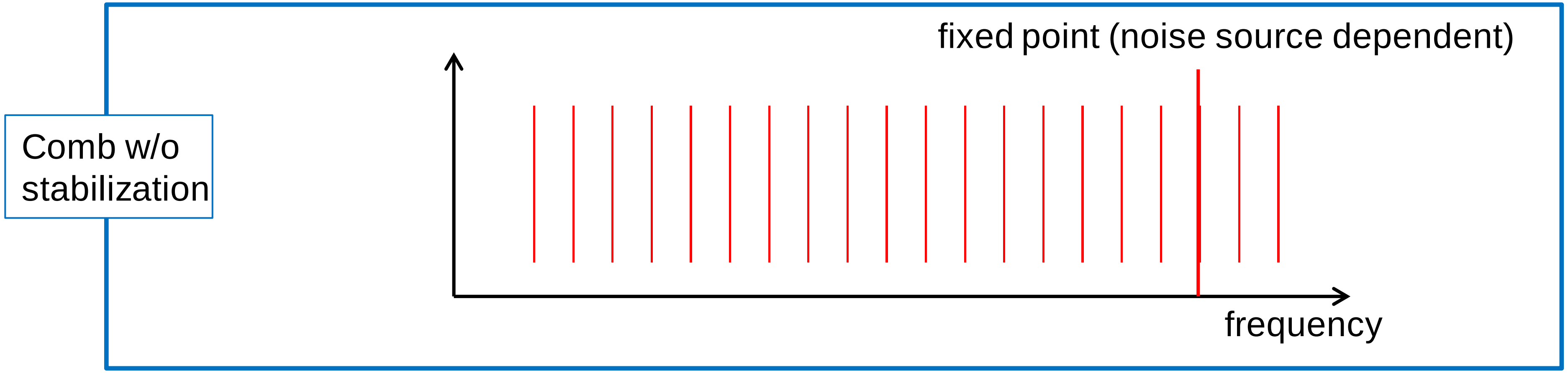


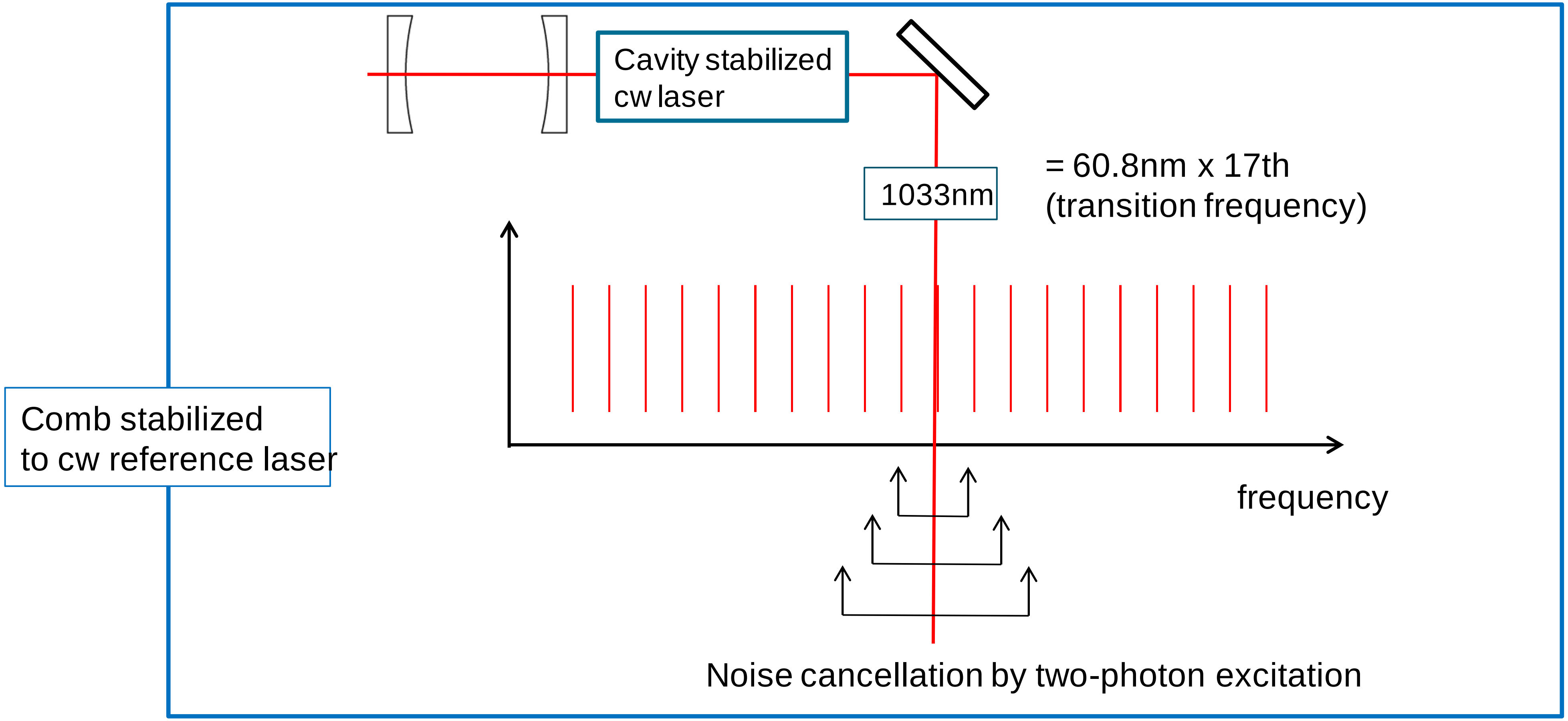


~30 µW at 60.8 nm (preliminary)

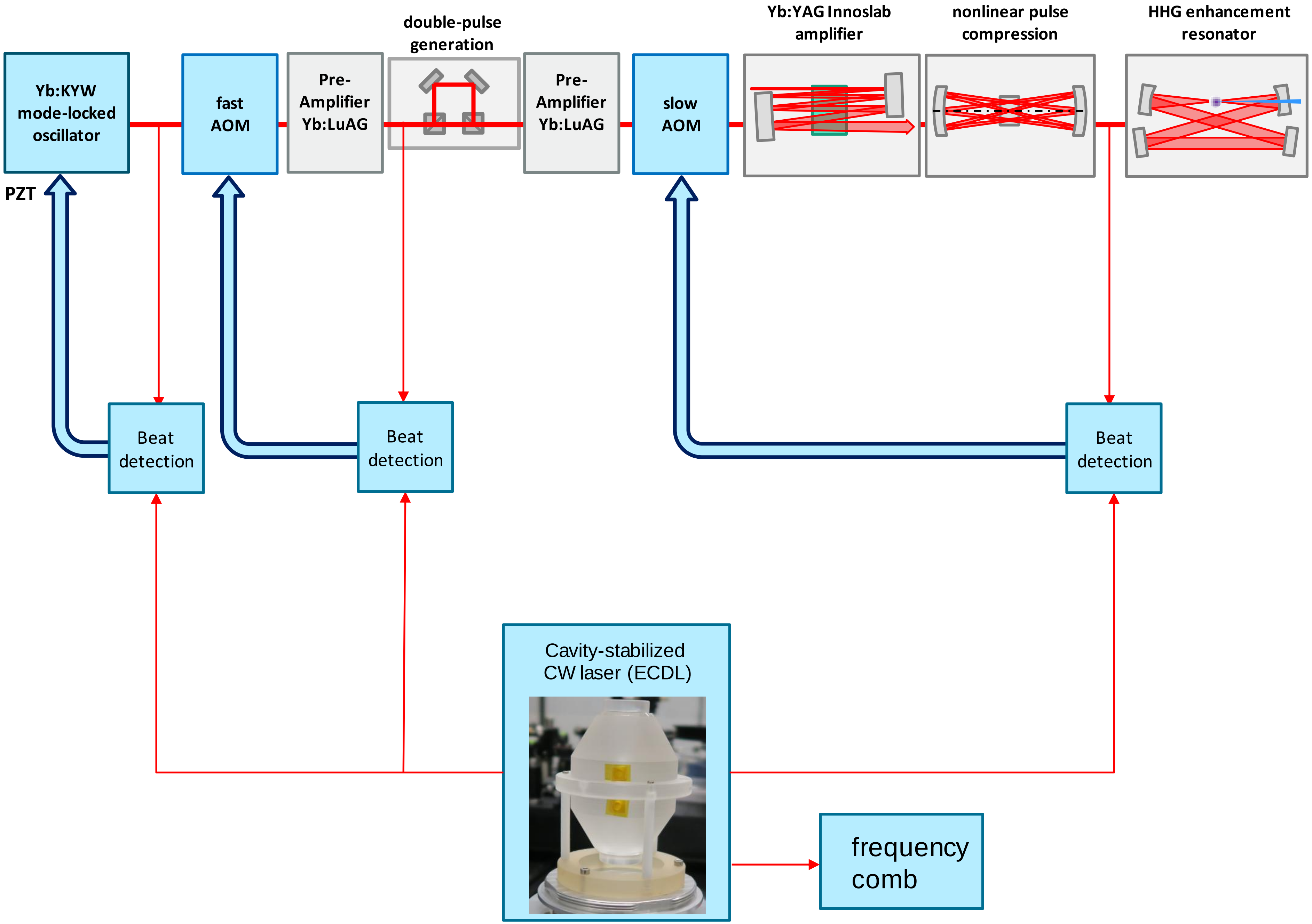
→ ~ 0.1 Hz signal rate (ionization)

Stabilization of frequency comb

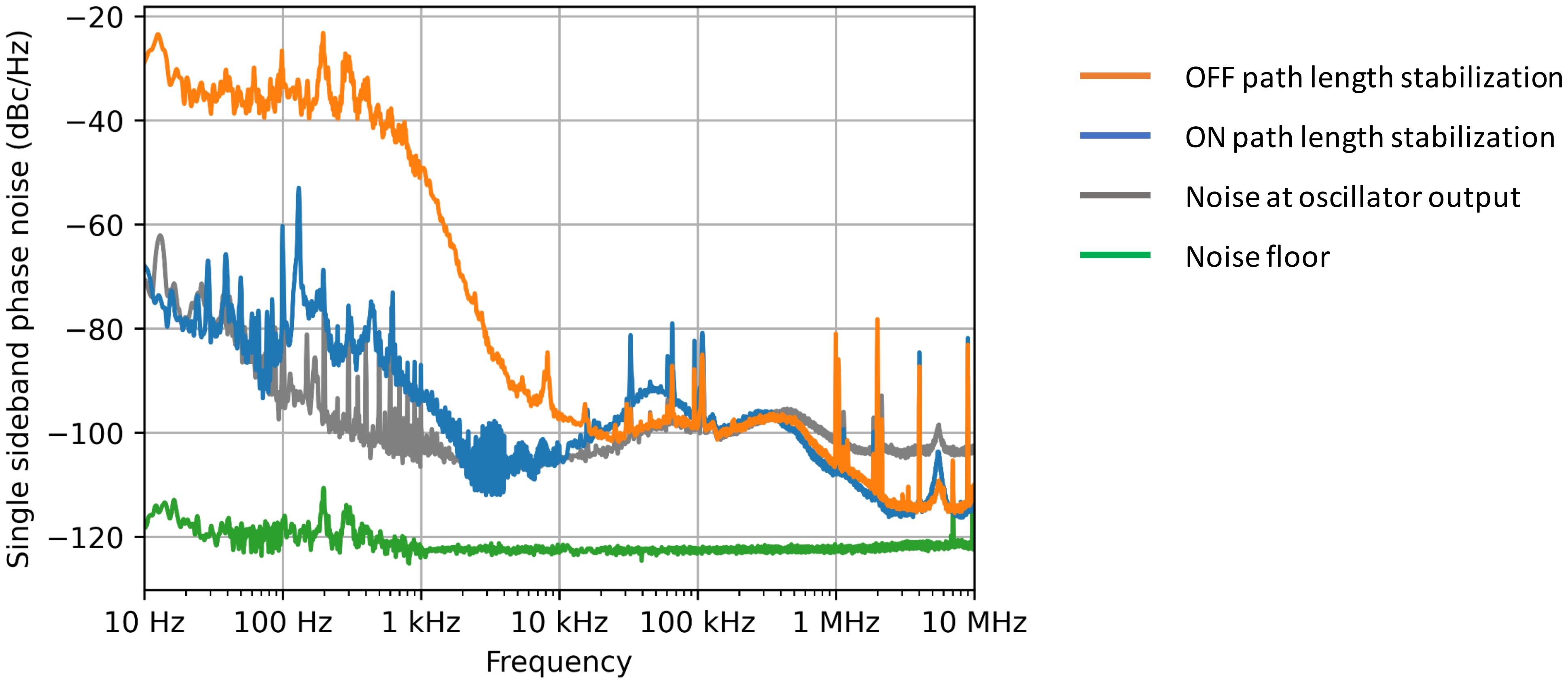




Stabilization of frequency comb



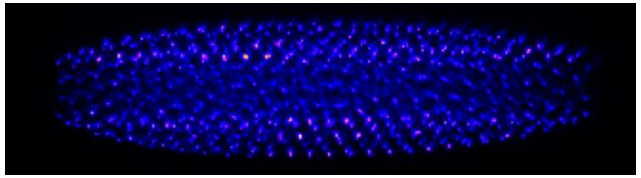
Stabilization of frequency comb

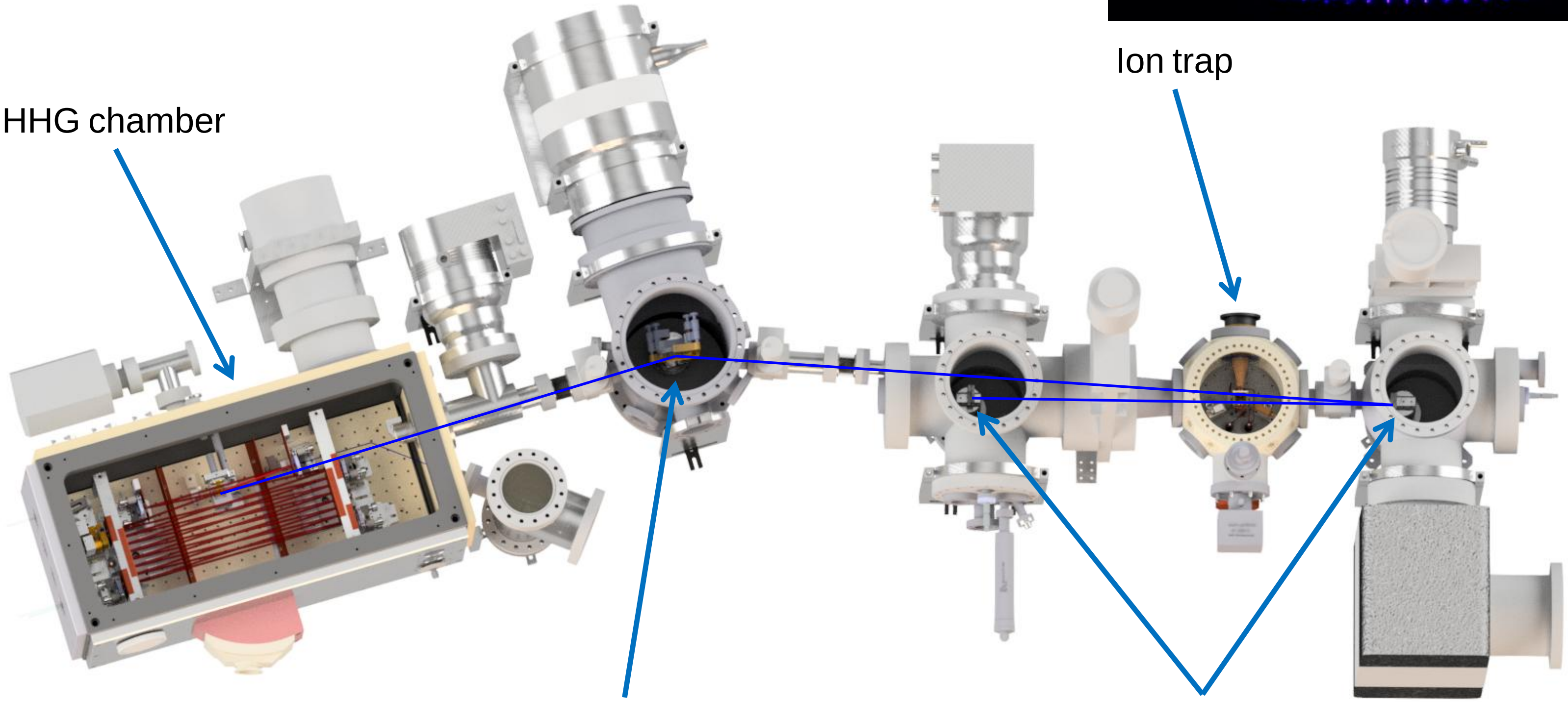


- 80% of power in carrier at XUV
- Less than 20% of signal loss due to phase noise

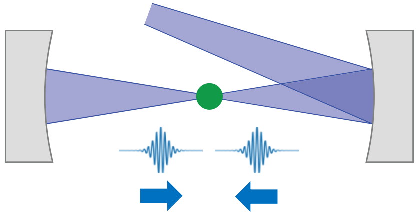
XUV beam delivery to trapped He^+

Sympathetically cooled He^+
in mixed ion crystal (He^+/Be^+)

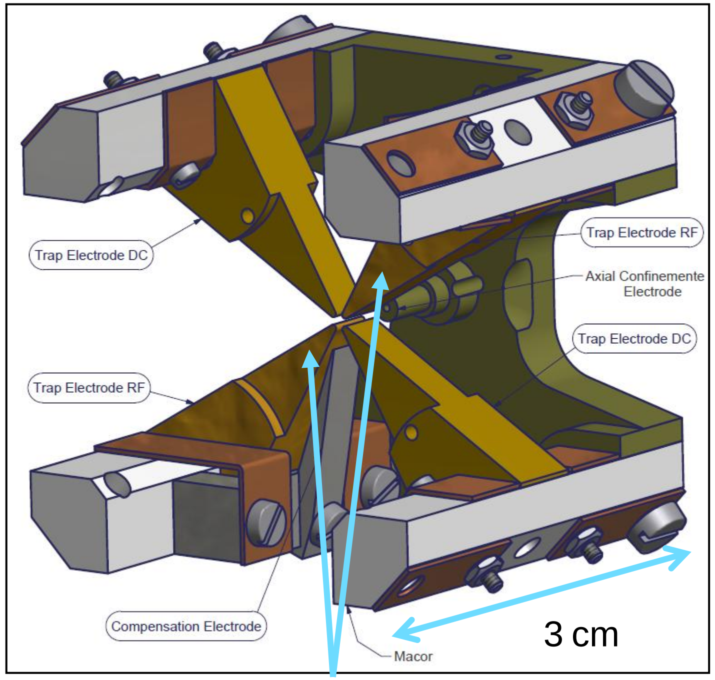




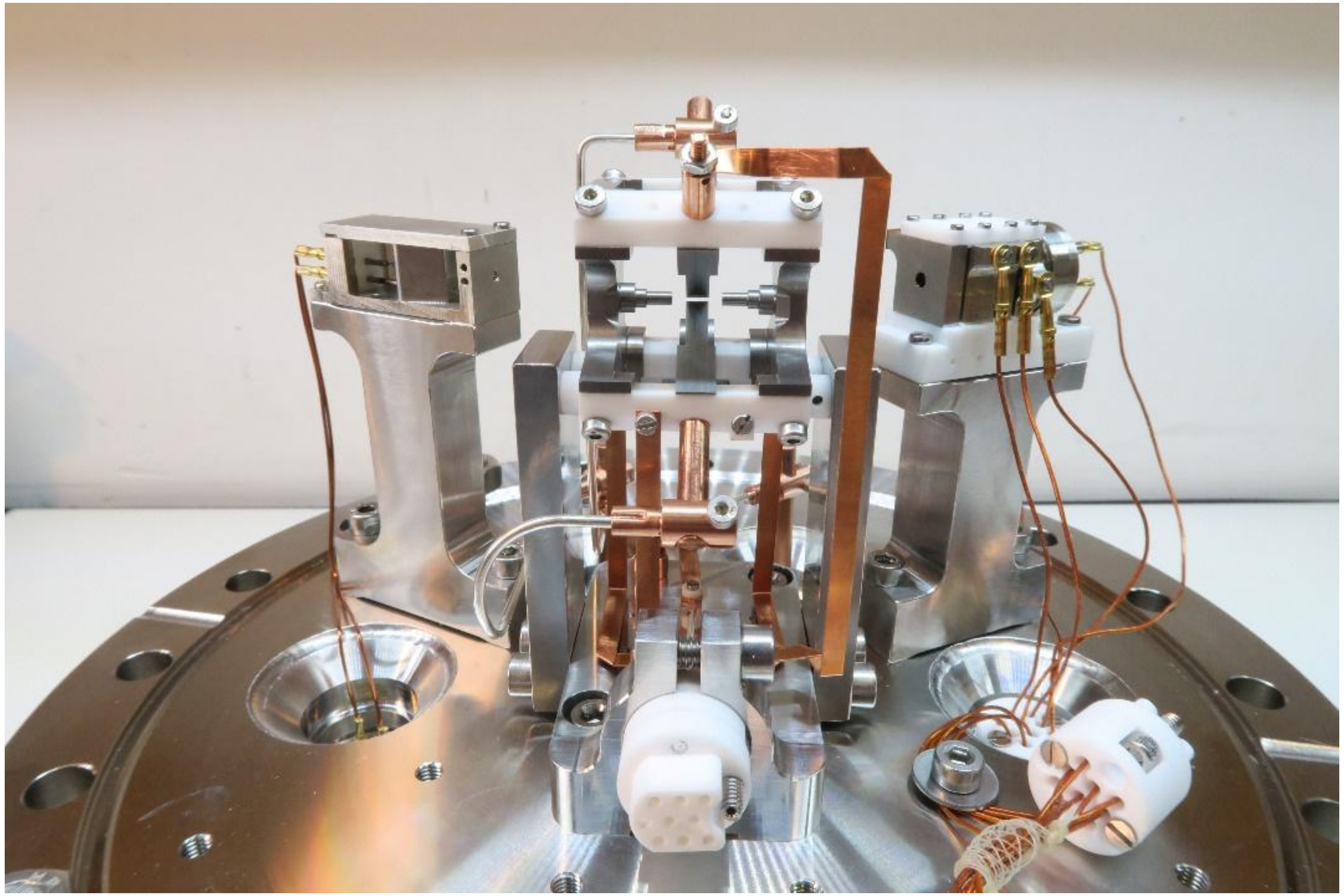
Doppler-free
Anti-collinear excitation



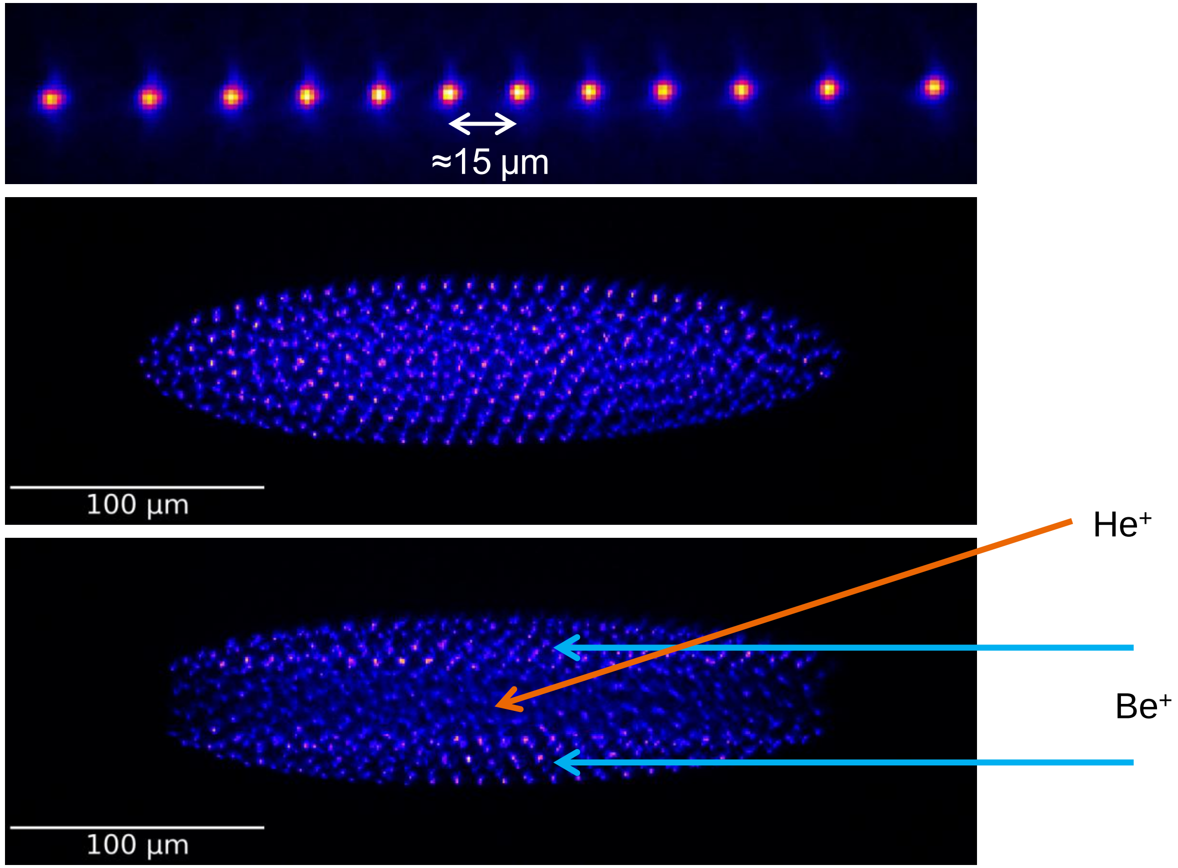
Be^+/He^+ ion trap



RF
electrodes



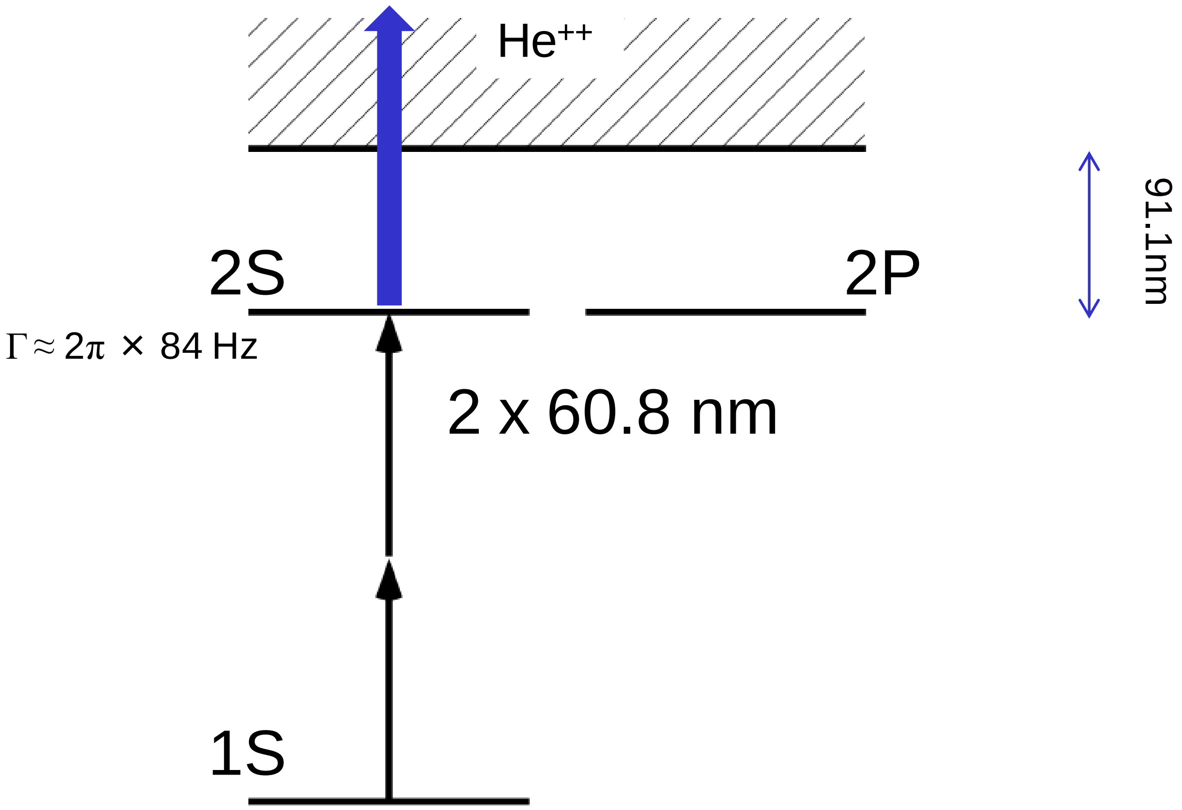
Ion crystals and sympathetic cooling



Be^+ laser cooled to a few mK

He^+ sympathetically cooled

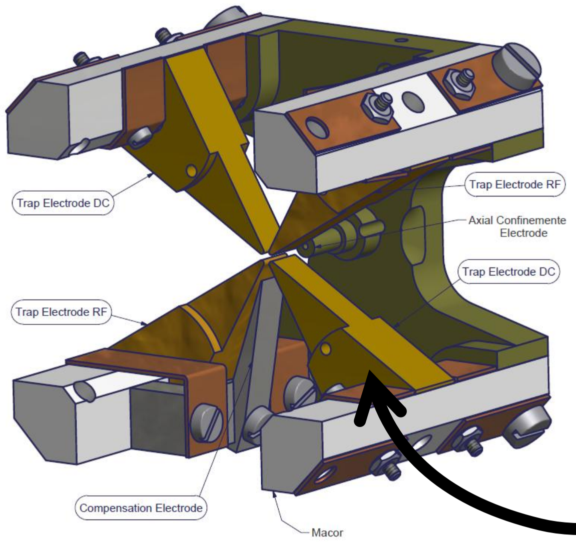
Spectroscopy signal



Spectroscopy signal:
Secular excitation detection

Motional resonance : $\omega_{\mathrm{sec}} \approx \frac{U_0}{\sqrt{2}\Omega r_0^2} \frac{Q}{m}$

Trap Species



PMT

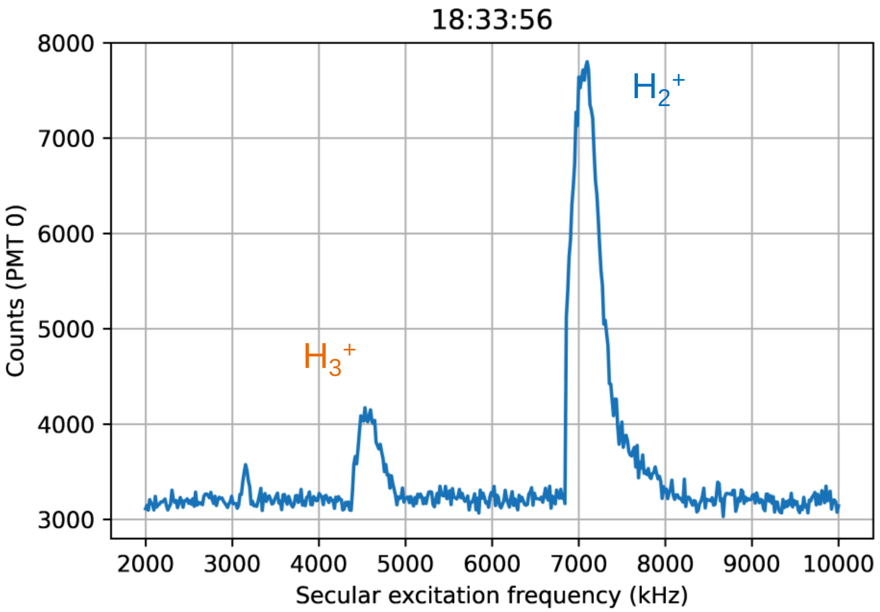
Signal: fluorescence from Be^+ ions

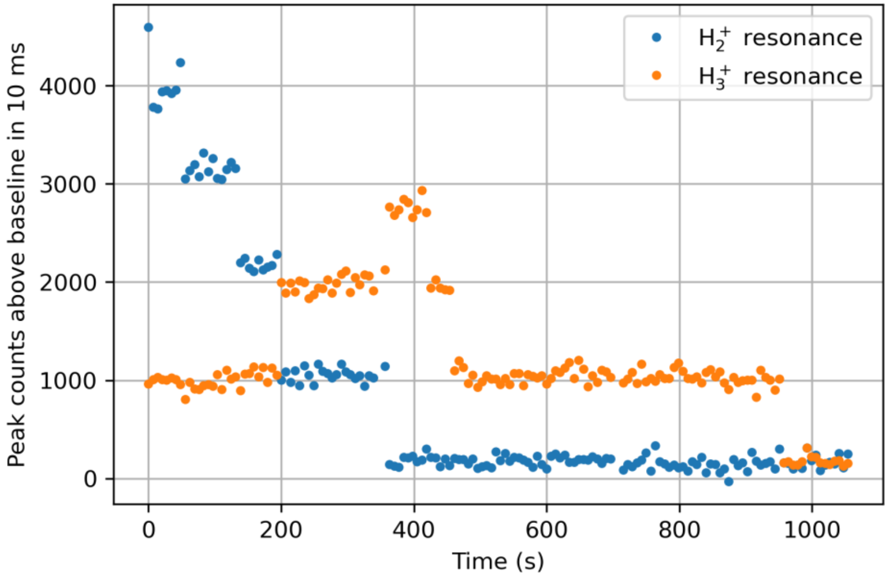
Signal generator:
scan frequency

Testing secular excitation detection

H_2^+: Same charge-to-mass ratio as He^{2+}

$$H_2^+ + H_2 \Rightarrow H_3^+ + H$$





Single event sensitive detection

Achieved:

- Generation of 61nm comb
- Trapped and cooled He^+
- Demonstrated sensitive He^{2+} detection

Plans :

- Optimization of 61nm comb
  (power, spectrum)

- Testing spectroscopy setup with easier transition
  (Two-photon transition at 204 nm with Be^+)

- Finding He^+ 1S-2S signal:
  QED predication: ~ 70 kHz
  Expected linewidth of signal: ~ 1 kHz

The He^+ team

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Thomas
Udem