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

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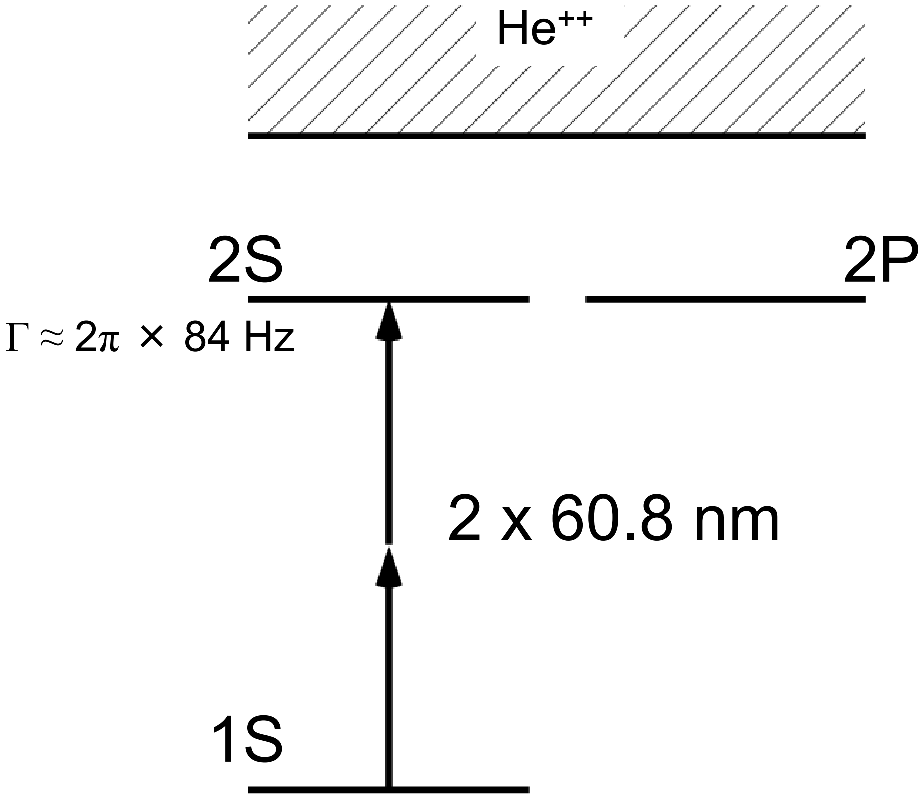
Spectroscopy of the 1S–2S Transition in He^+



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^+

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

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

Parameters	Contribution to Uncertainty (He^+ 1S2S)	Source
Rydberg constant R_∞	2×10^{-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

45% larger uncertainty In Pachucki et al. arXiv (2023)

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

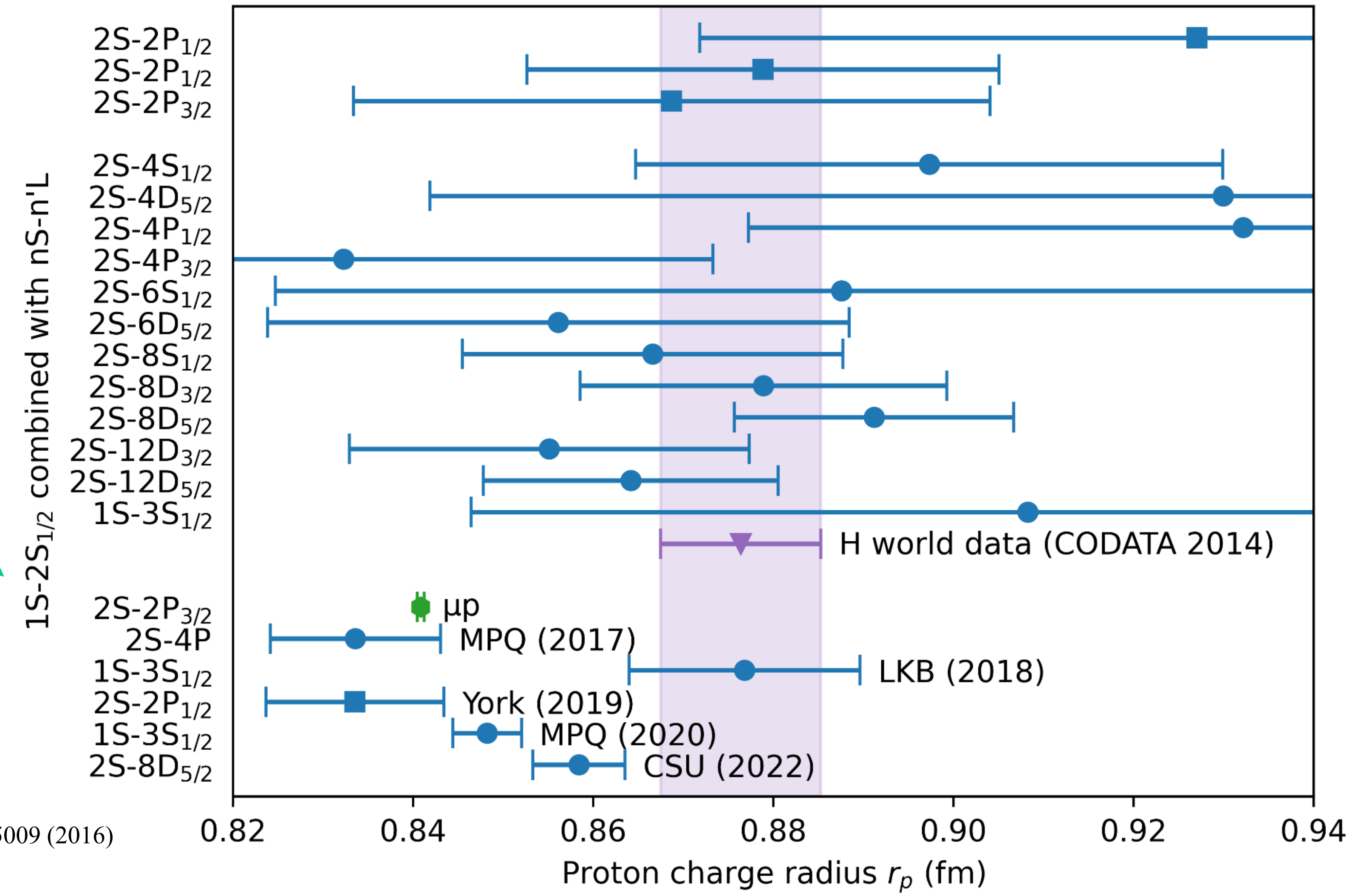
[1] Yerokhin. A and Shabaev V. M , Phys. Rev. A 93, 062514 (2016).
[2] Karshenboim, S. G et al. , Physics Letters B 795, 432–437 (2019)
[3] Karshenboim, S. G et al. , Phys. Rev. A 100, 032515 (2019).
[4] Karshenboim, S. G et al. , Phys. Rev. A 98, 022522 (2018)
[5] V. Yerokhin et al. , Annalen der Physik 531, 1800324 (2019).
[6] A.Czarnecki et al. , Phys. Rev. A 94, 060501 (2016).
[7] S. Laporta, Physics Letters B 800, 135137 (2020).
[8] Karshenboim, S. G and Shelyuto V. A. , Phys. Rev. A 100, 032513 (2019)

Contribution	Uncertainty (in kHz)	
Relativistic Recoil	0	[1]
Nuclear Polarizability	3	
Self Energy	0	
Vacuum Polarization	1	
Two Photon Corrections	32	[2-6]
Three Photon Corrections	9.5	[2,3]
Four Photon Corrections	0	[7]
Nuclear Size Correction to Self Energy	0	
Nuclear Size Correction to Vacuum Polarization	0	
Radiative Recoil	12	[8]
Nuclear Self Energy	0.6	
Total	**~36 kHz**	

Total QED uncertainty : 36 kHz ($4x10^{-12}$) (preliminary)

Proton radius puzzle

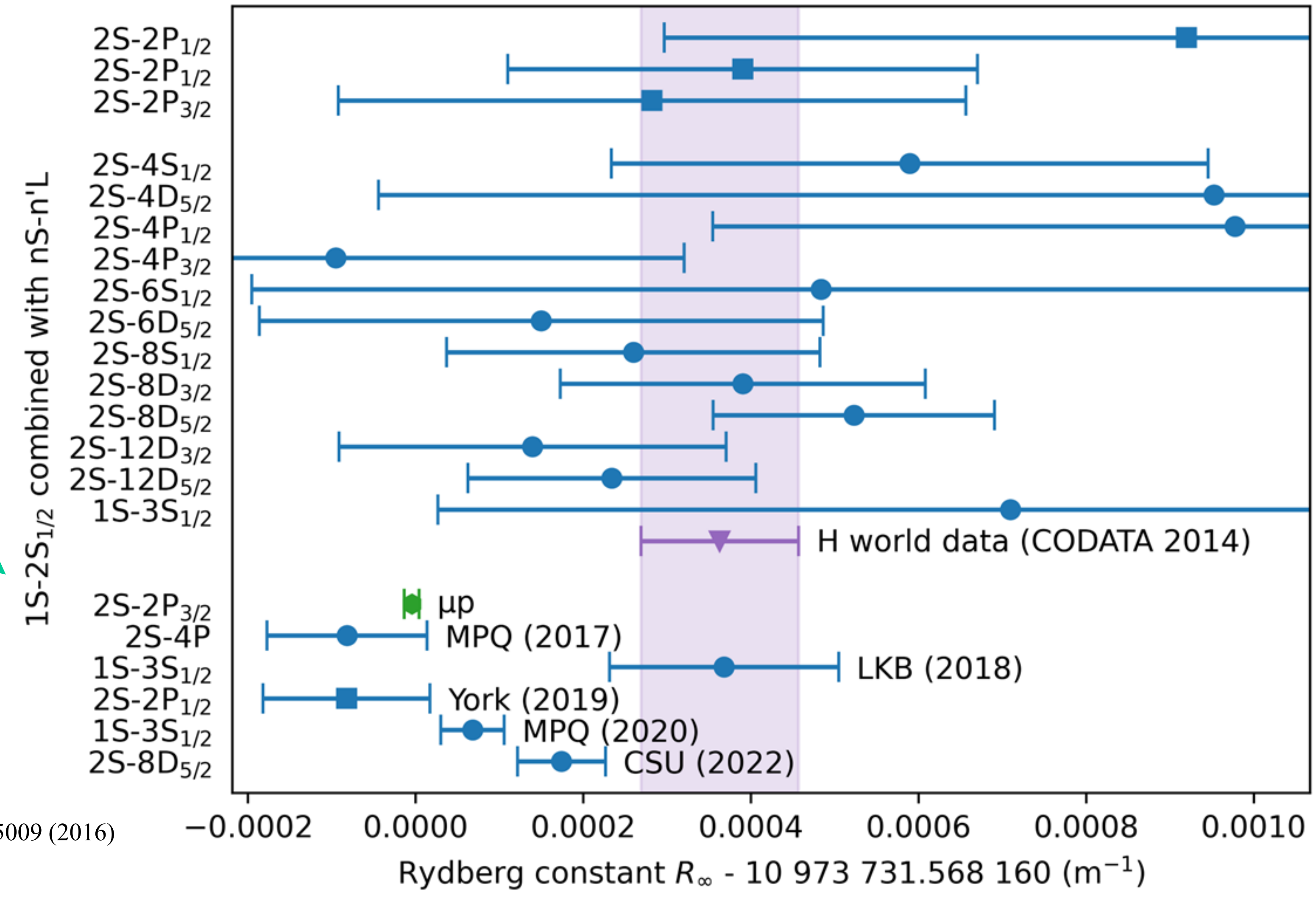
Known to 4 x 10^{-15}



P. Mohr *et al.*, Rev. Mod. Phys. **88**, 035009 (2016)
R. Pohl *et al.,* Nature 466, **213** (2010)
A. Beyer *et al.,* Science **358**, 79 (2017)
H. Fleurbaey *et al.*, Phys. Rev. Lett. **120**, 183001 (2018)
N. Bezginov *et al.*, Science **365**, 1007 (2019)
A. Grinin *et al.*, Science **370**, 1061 (2020)
A. D. Brandt *et al.,* Phys. Rev. Lett. **128**, 023001 (2022)

Rydberg constant puzzle

Known to 4 x 10^{-15}



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He^+ spectroscopy for testing QED

- Measuring the 1S-2S transition

better than 400kHz ($4x10^{-11}$)

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

better than 60 kHz ($6x10^{-12}$) [90 kHz from Pachucki et al. arXiv (2023)]

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

better than 36 kHz ($4x10^{-12}$)

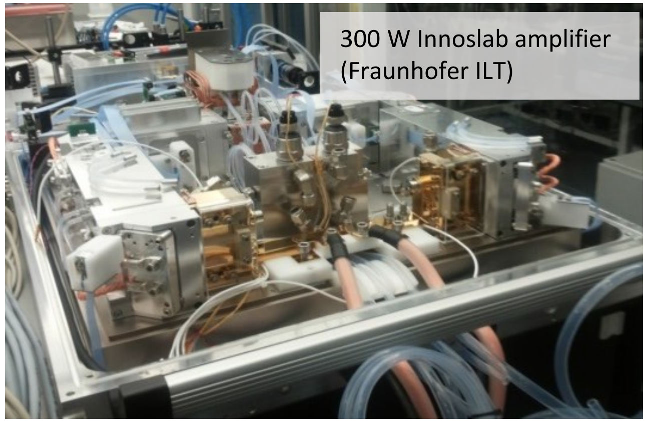
⟶ QED theory uncertainty will be a limitation

- 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

He$^+$ spectroscopy setup: overview

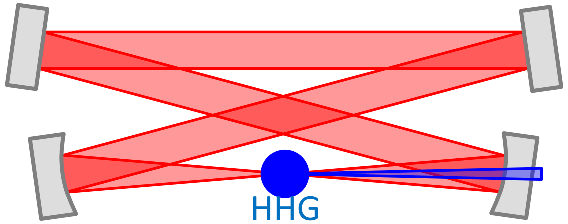
High-power IR frequency comb

Yb:KYW laser + amplifiers
@1030 nm

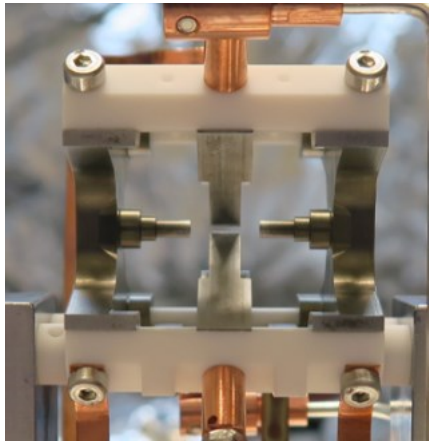


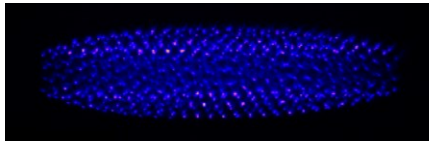
Frequency comb at 60.8 nm

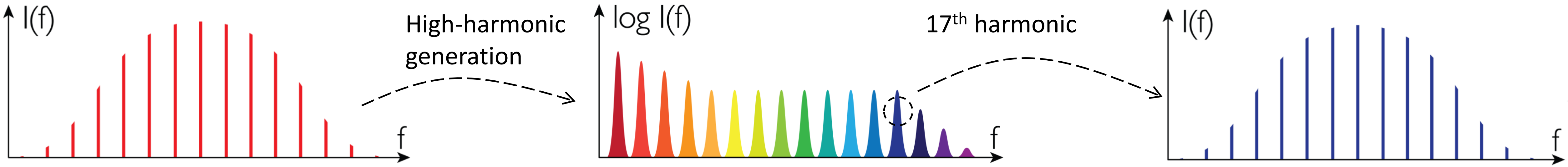
Intracavity
high-harmonic generation
17th harmonic



Trapped He$^+$ ions







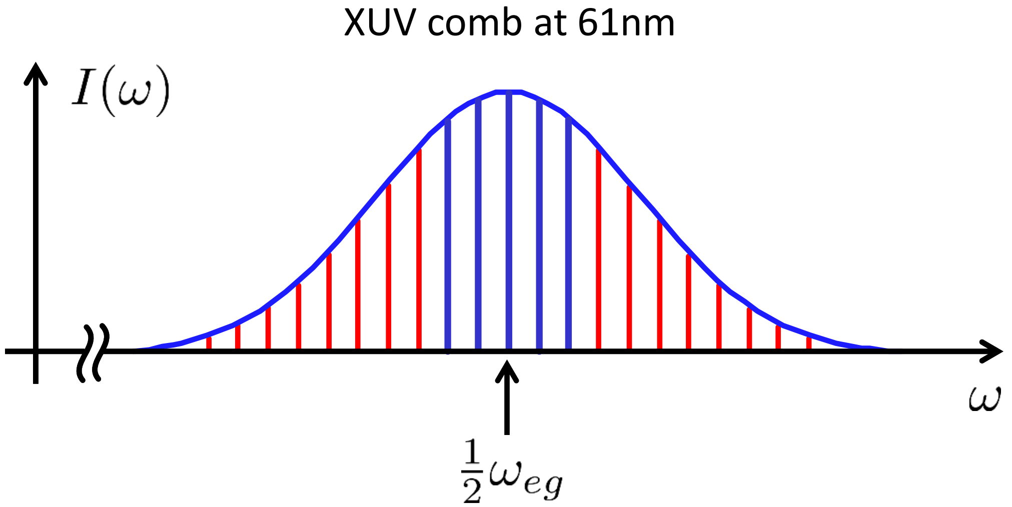
IR frequency comb
1030 nm

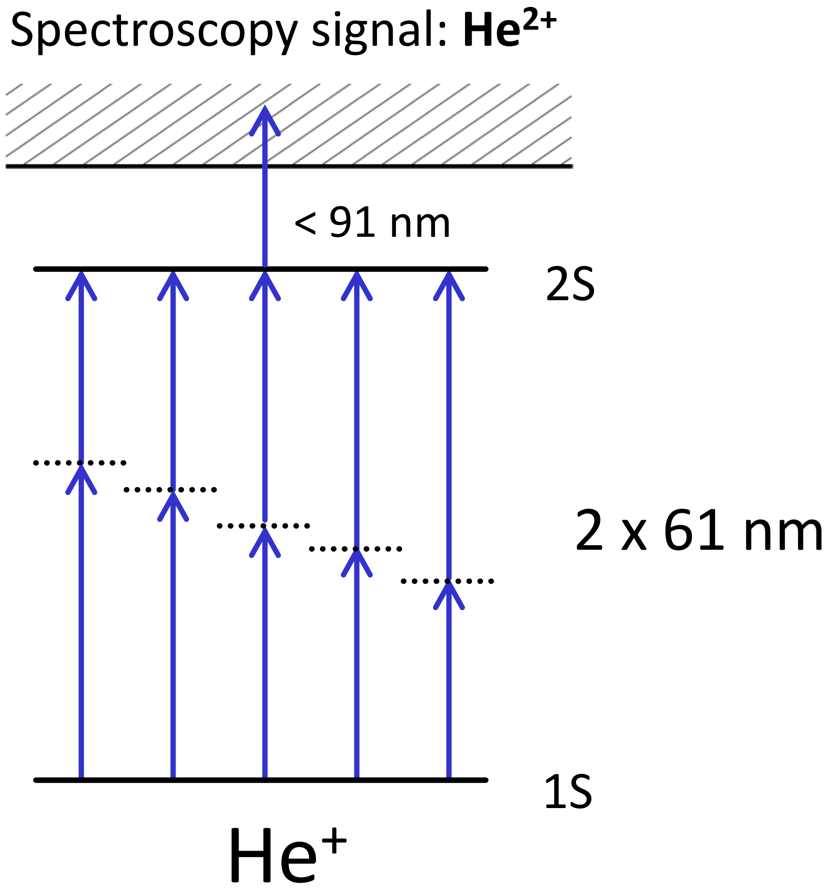
Odd-order
harmonics

XUV frequency comb
61 nm

Direct frequency comb spectroscopy

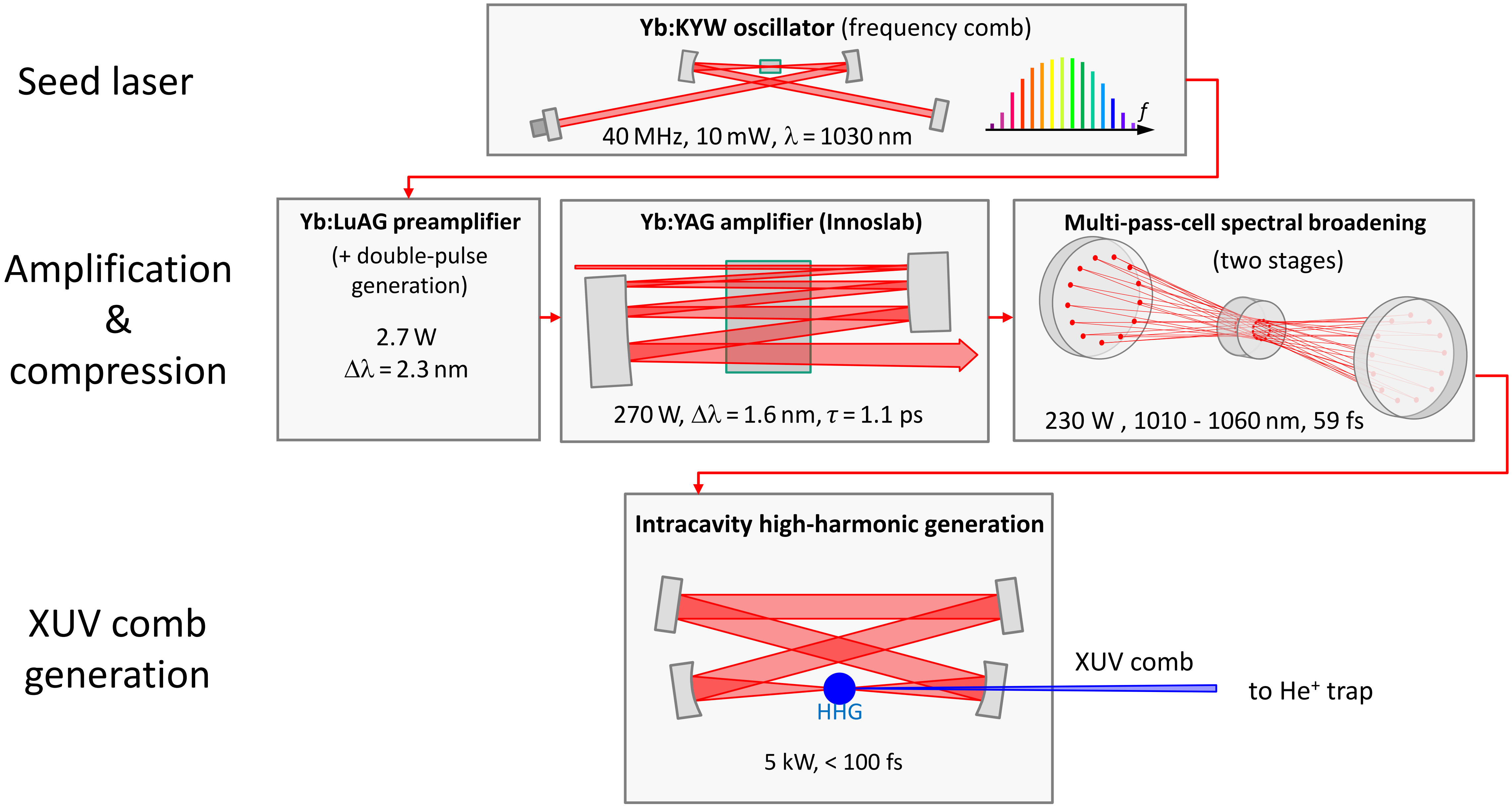
- Line width of a single laser mode
- Efficient nonlinear frequency conversion due to high peak power of pulsed laser
- As efficient as CW laser of same average power



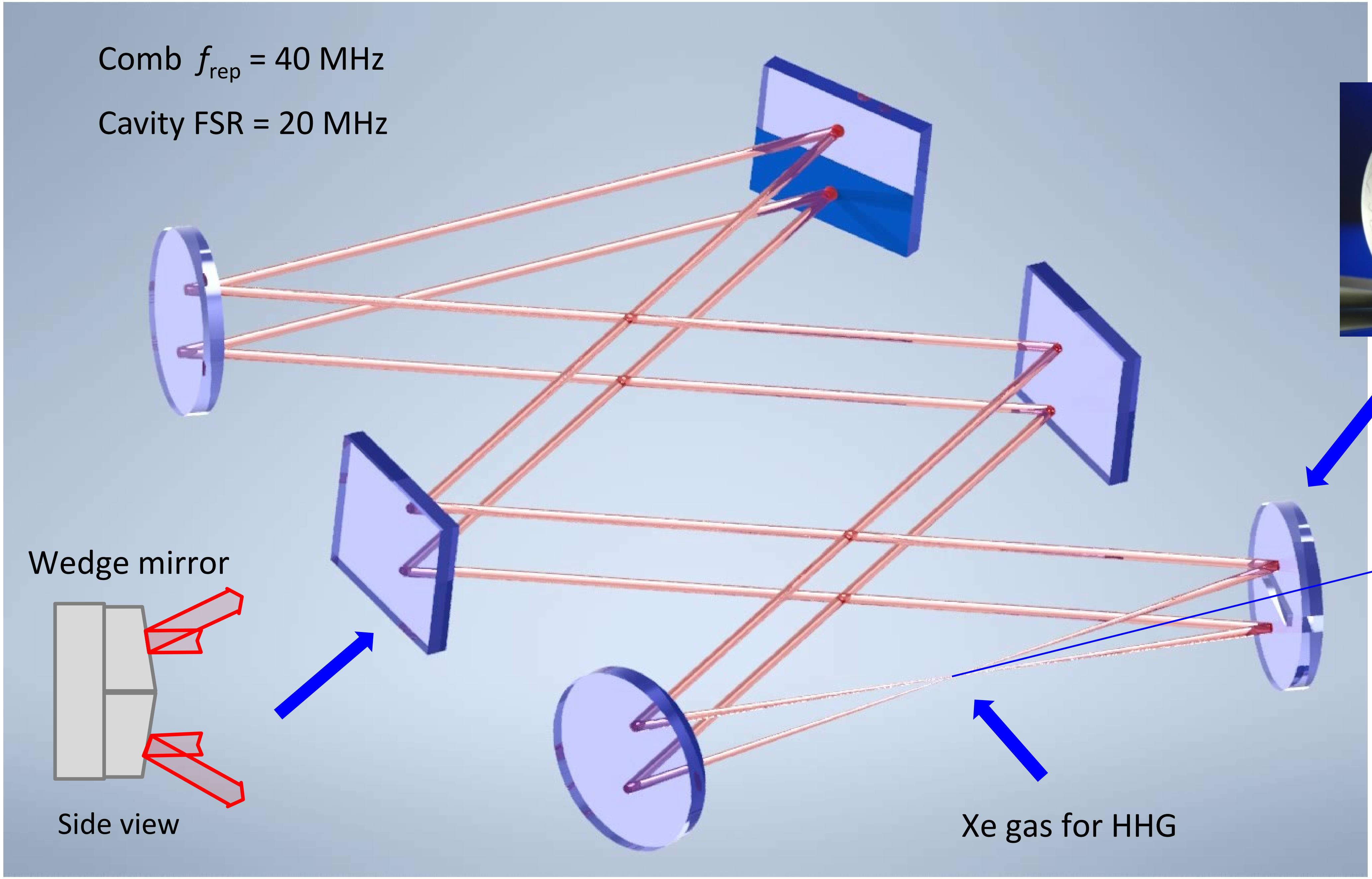


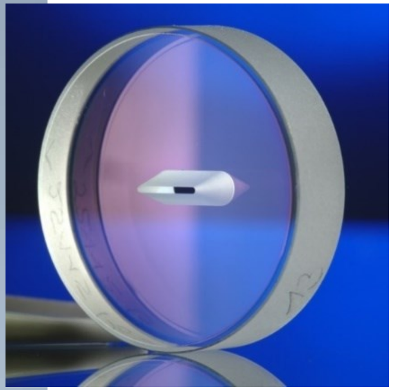
Pioneered by: Ye. V. Baklanov and V. P. Chebotayev, Appl. Phys. 12, 97 (1977)
Hydrogen 1S-3S: A. Grinin *et al.*, Science **370**, 1061 (2020)

61 nm laser system



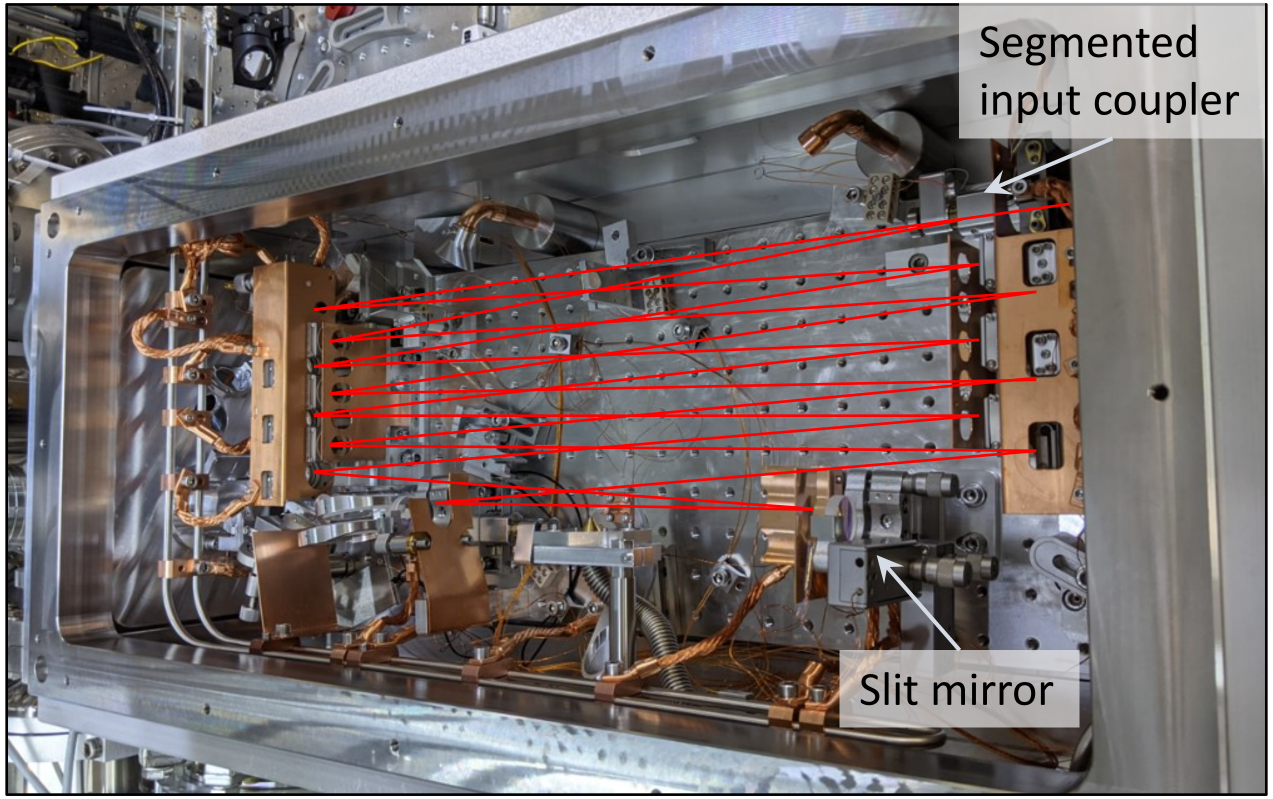
Enhancement Resonator for HHG

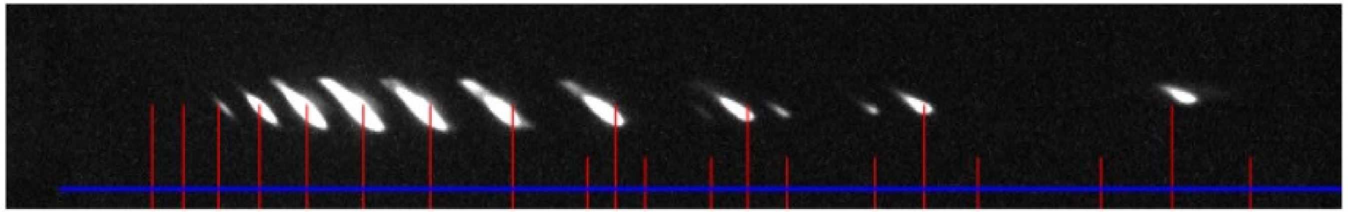




Mirror with slit

Enhancement Resonator for HHG

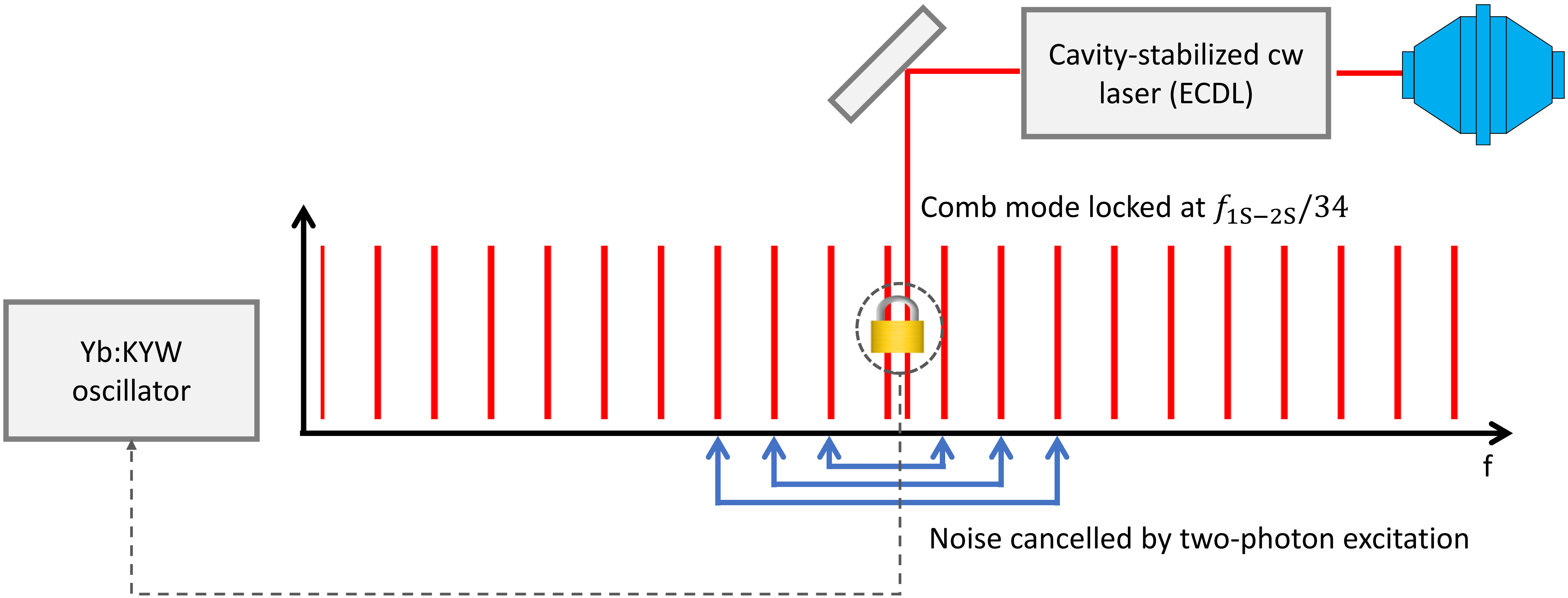




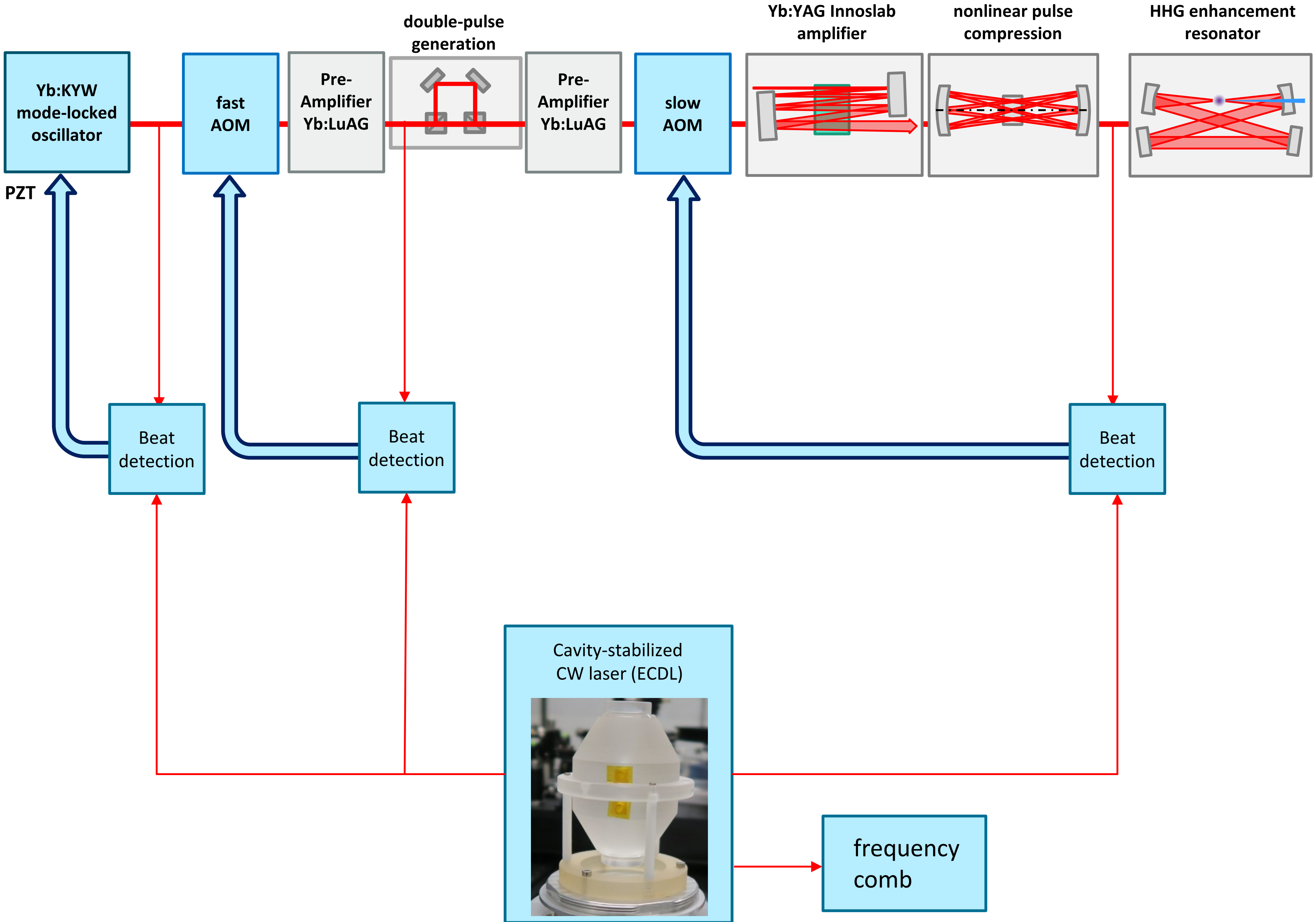
~30 μW at 60.8 nm (preliminary)

⟶ ~ 0.1 Hz signal rate (ionization)

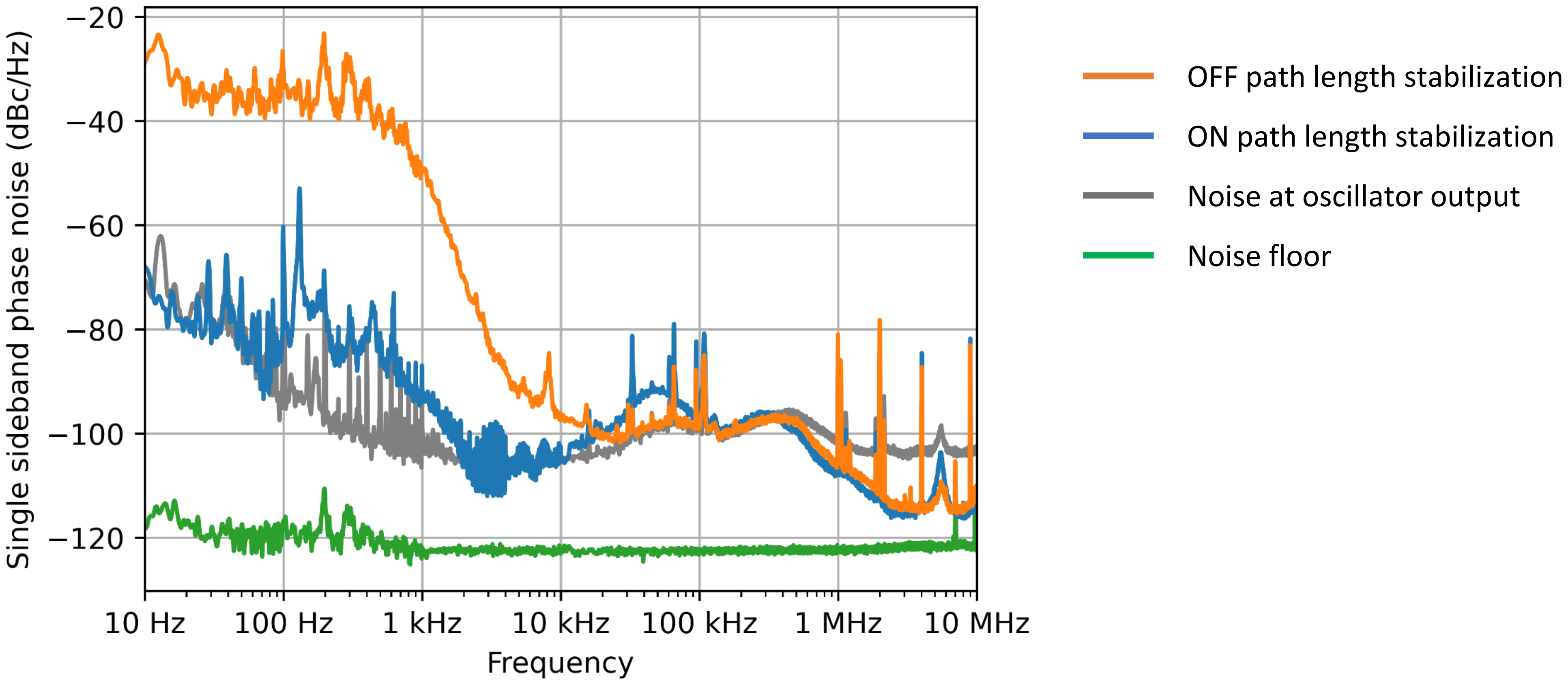
Comb stabilization



Stabilization of frequency comb



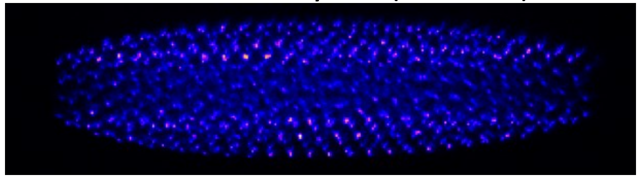
Stabilization of frequency comb

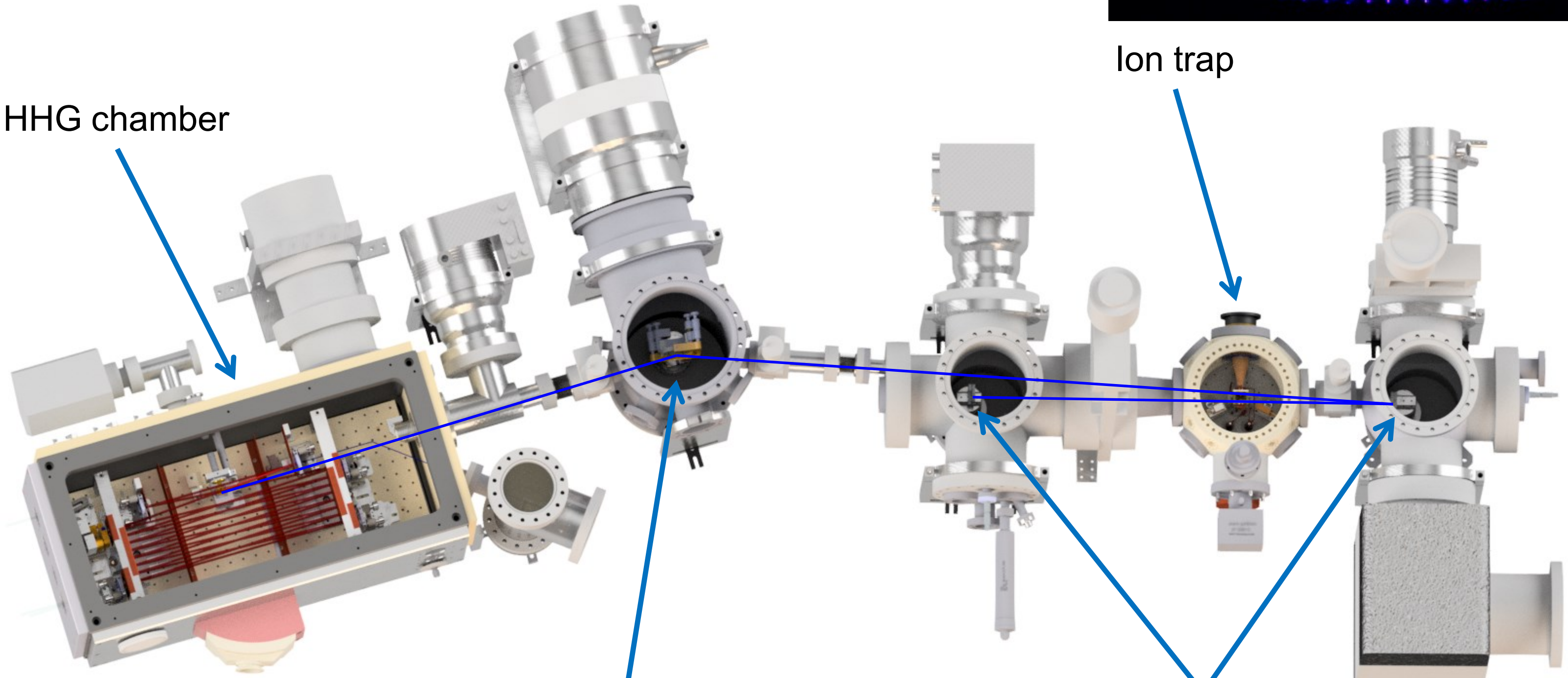


- 80% of power in carrier at XUV
- Less than 20% of signal loss due to phase noise

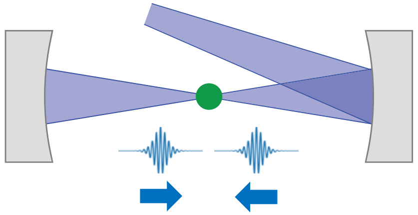
XUV beam delivery to trapped He^+

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

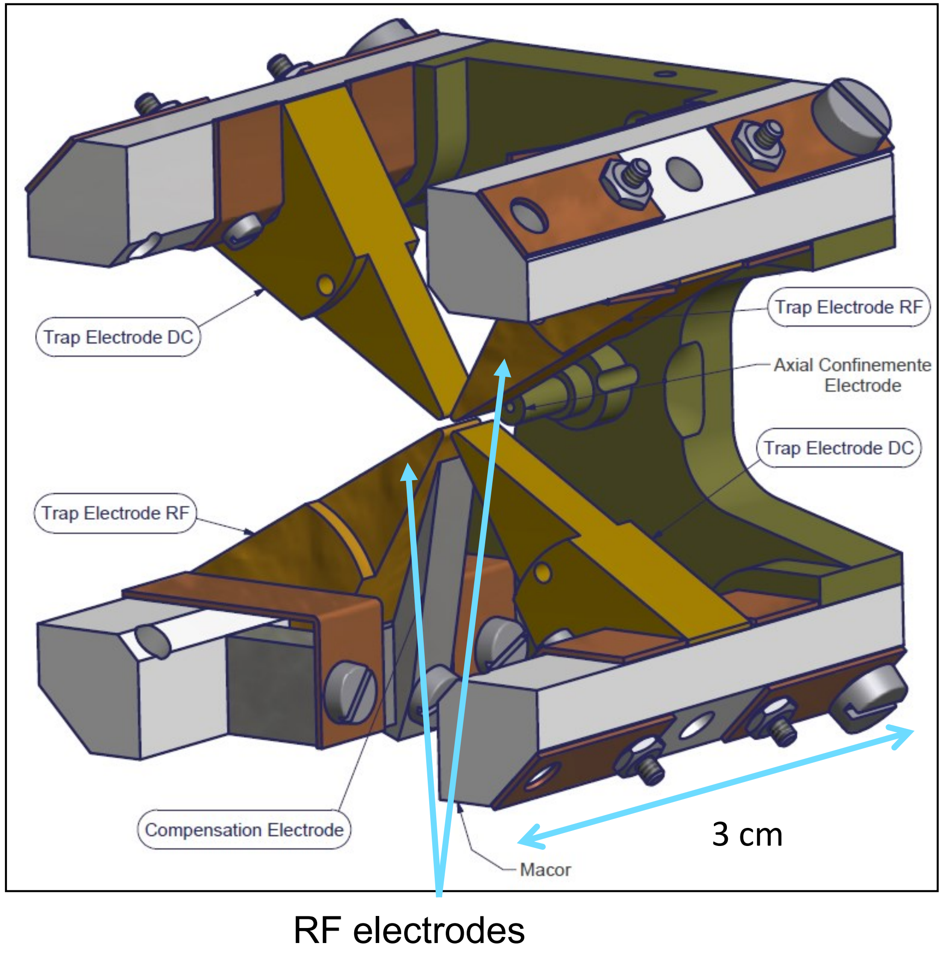


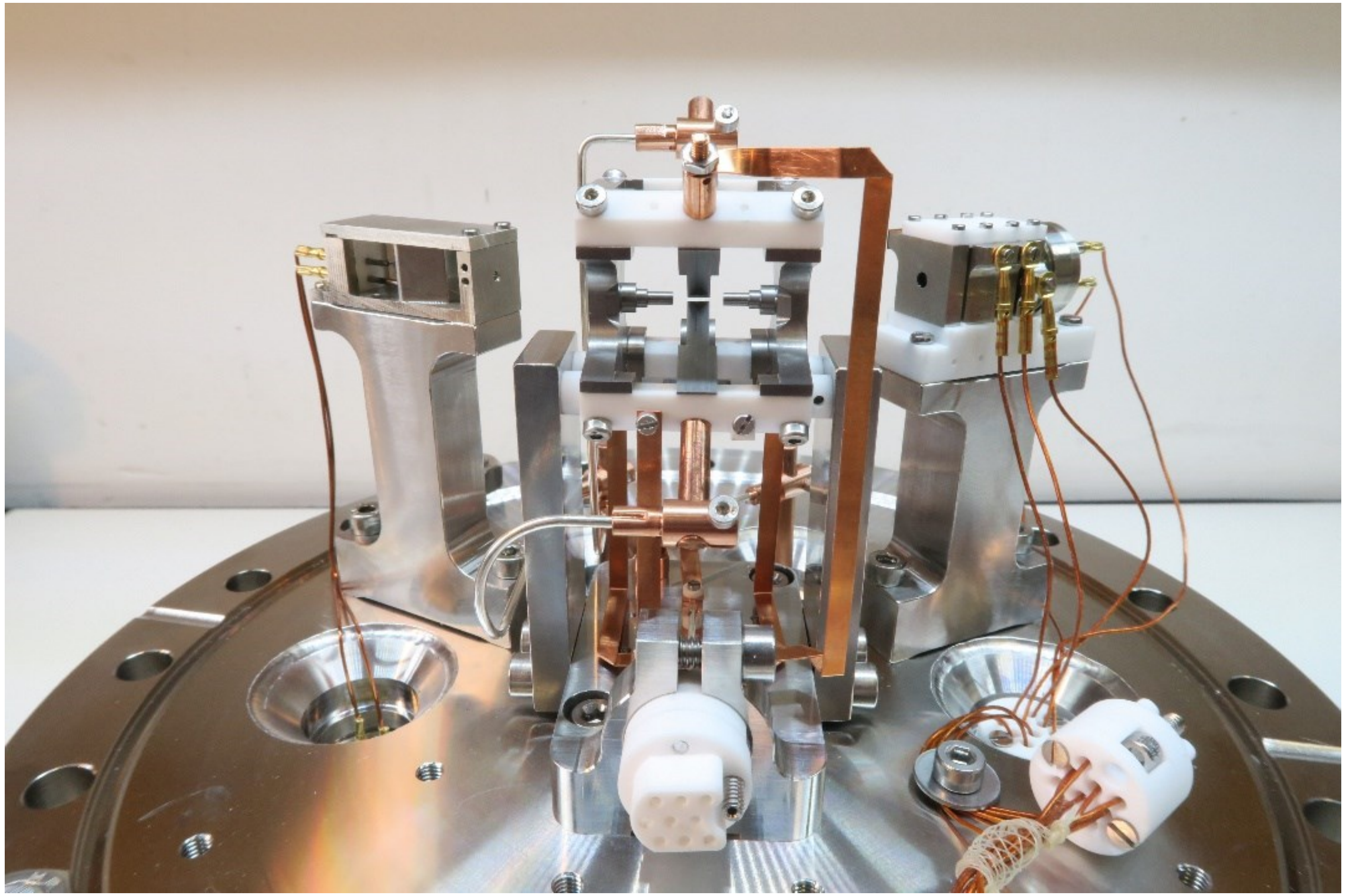


Doppler-free
Anti-collinear excitation



Be$^+$/He$^+$ ion trap

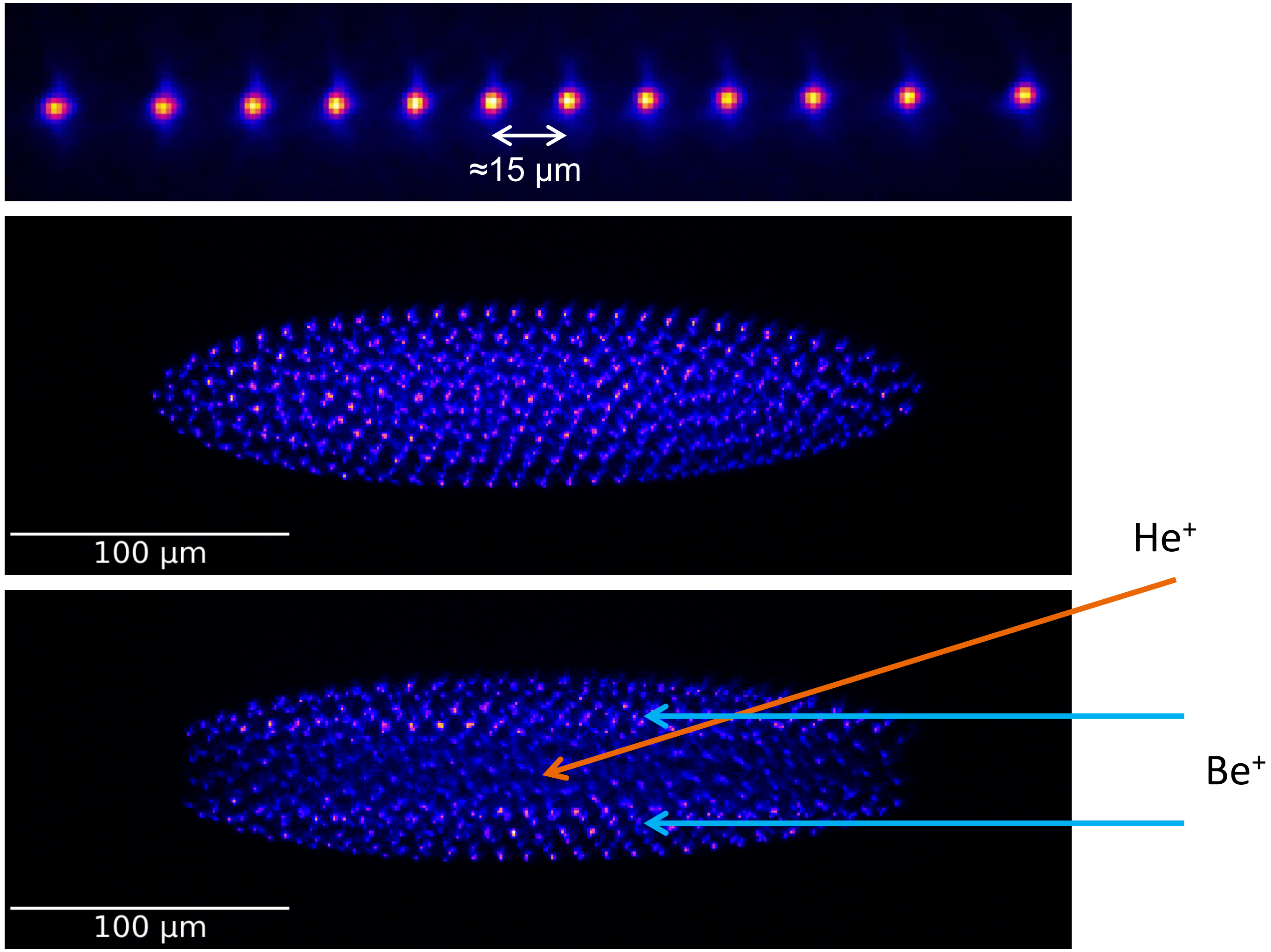




Ion crystals and sympathetic cooling

Be⁺ laser cooled to a few mK

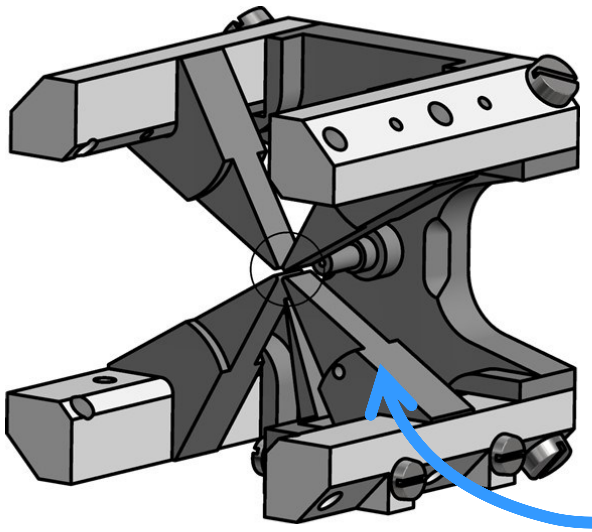
He⁺ sympathetically cooled



Spectroscopy signal:
Secular excitation detection

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

Trap   Species



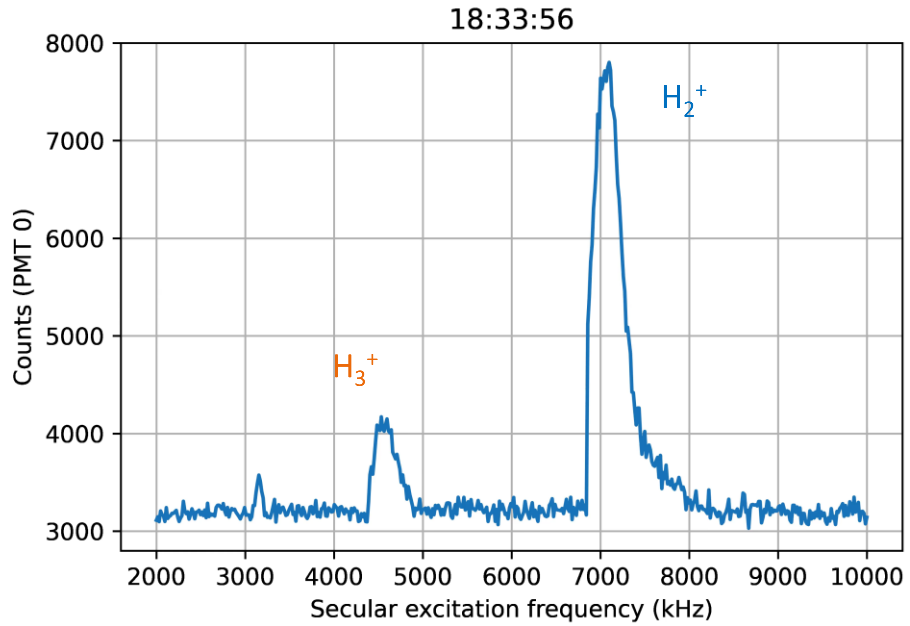
PMT → Signal: fluorescence from Be^{+} ions

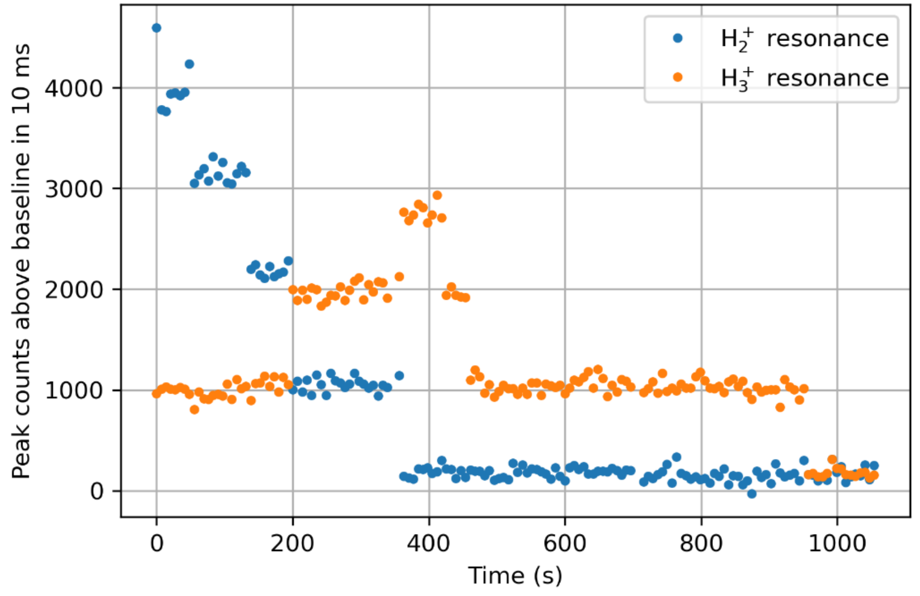
Signal generator:
scan frequency

Testing secular excitation detection

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

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

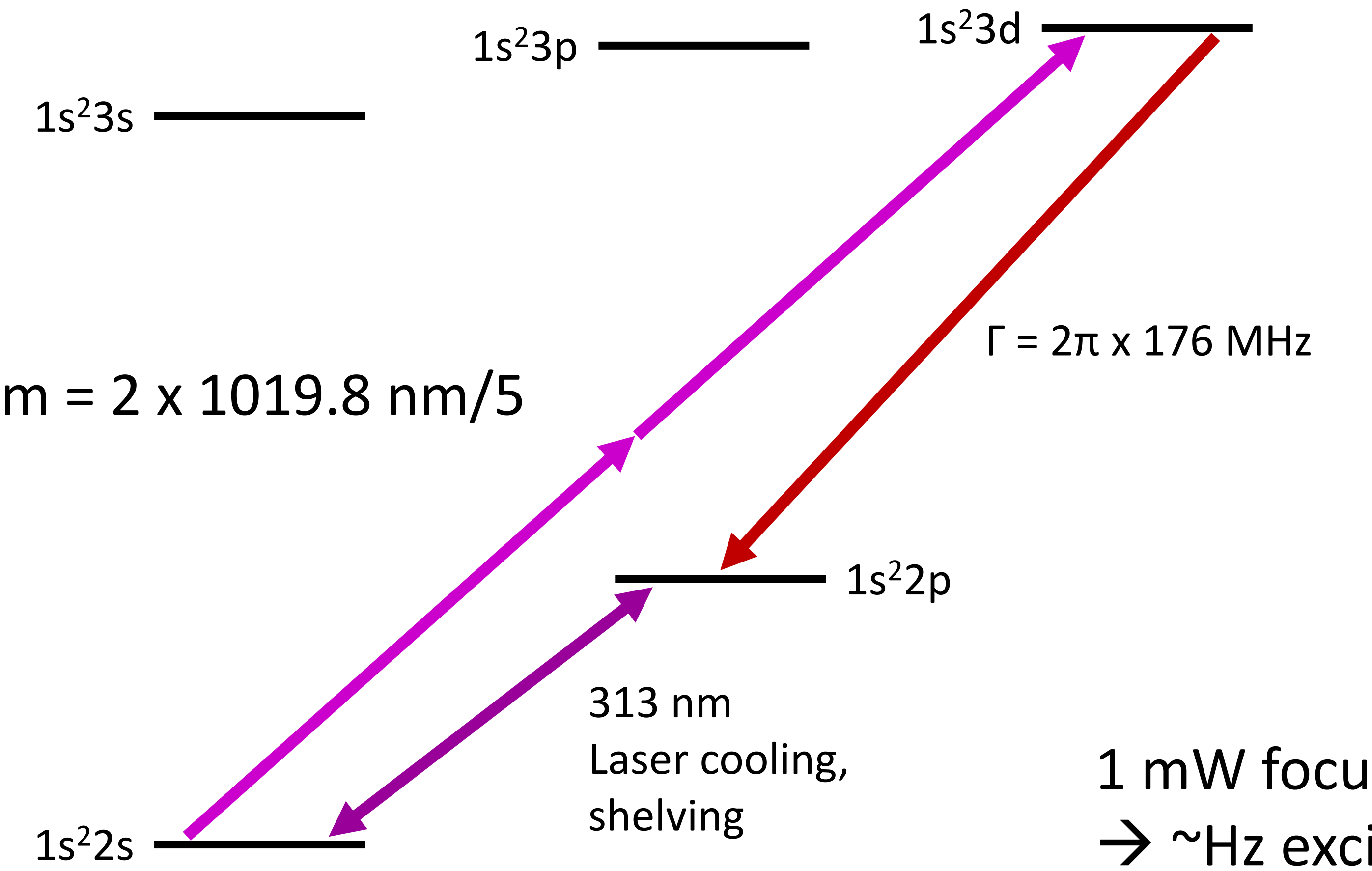




➡ Single event sensitive detection

F. Schmid *et al.*, Phys. Rev. A **106**, L041101 (2022)

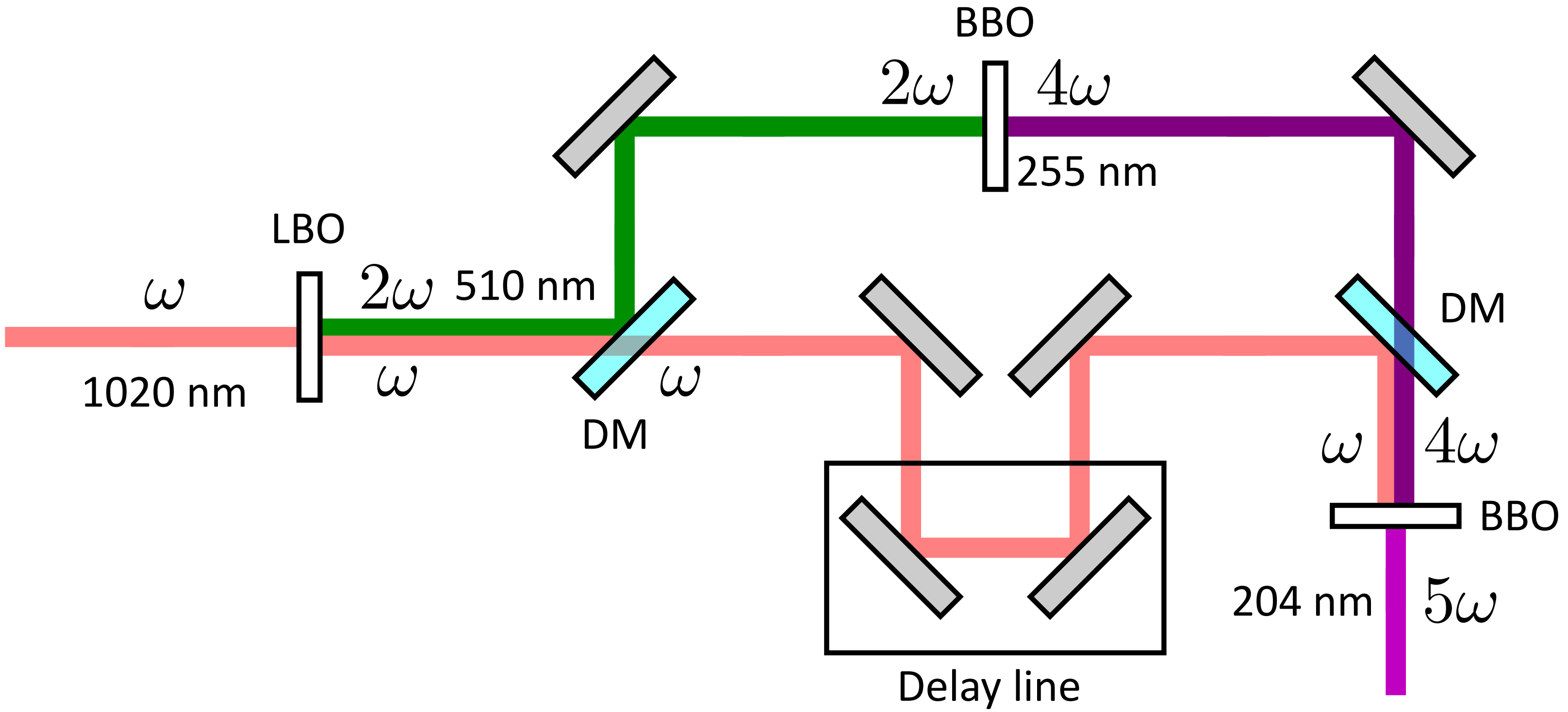
Driving two-photon transition in Be^+



2 x 203.97 nm = 2 x 1019.8 nm/5

1 mW focused to 5 µm
→ ~Hz excitation rate

5th harmonic generation in crystals



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 prediction: ~ 70 kHz

  Expected linewidth of signal: ~ 1 kHz

The He^+ team

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Weitenberg

Theodor
W. Hänsch

Thomas
Udem

Thank you for your attention!