Accurate High Voltage Measurements Based on Laser Spectroscopy

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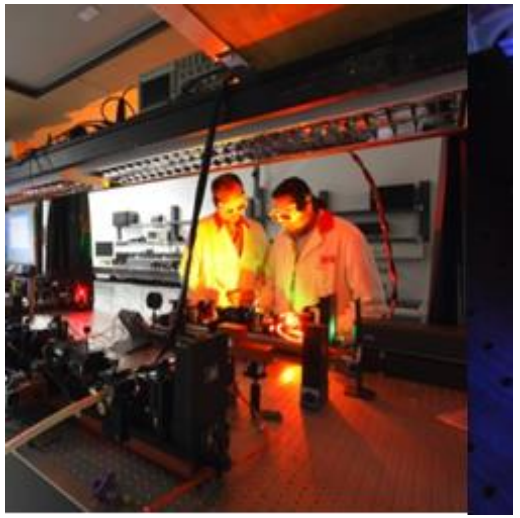
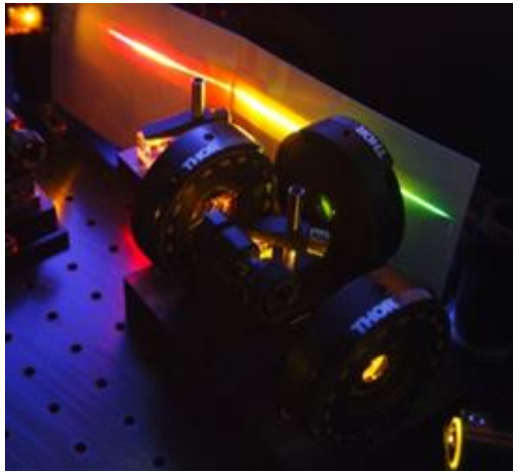
LASER SpHERe





Outline

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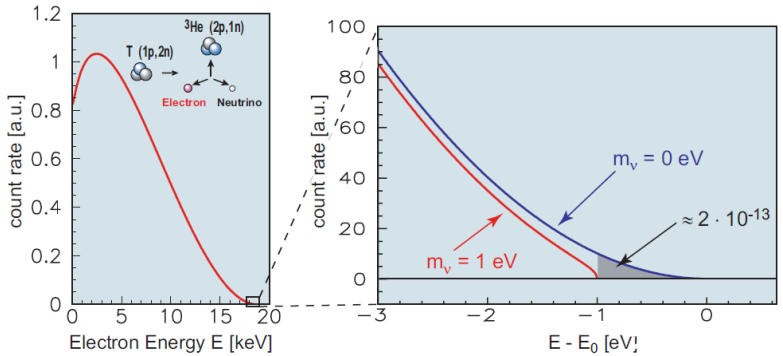
- Motivation
- Collinear Laser Spectroscopy for Voltage Metrology
- Experimental Setup
- Results from Calcium Spectroscopy
- Summary & Outlook

Motivation – High Voltage in Precision Experiments

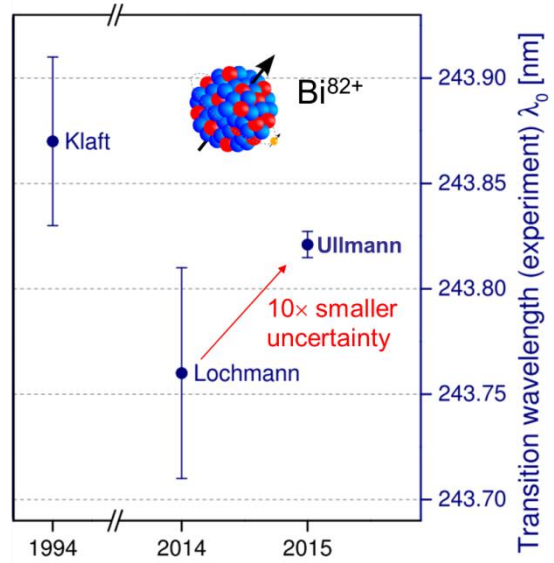
KATRIN experiment (KIT)



https://www.katrin.kit.edu/79.php

- end-point energy of tritium beta decay spectrum: E_0 = 18.6keV
- required voltage stability and reproducibility of retardation spectrometer: 3 ppm / 2 months

LIBELLE experiment (GSI)



Ullmann et al., J. Phys. B: At. Mol. Opt. Phys. 48 (2015) 144022

- Measurement of ESR electron cooler voltage with PTB HV dividers
- 10x reduced systematic uncertainty in absolute transition frequency

Standard HV measurement technique: HV divider

The world´s best high voltage divider:
1ppm / year

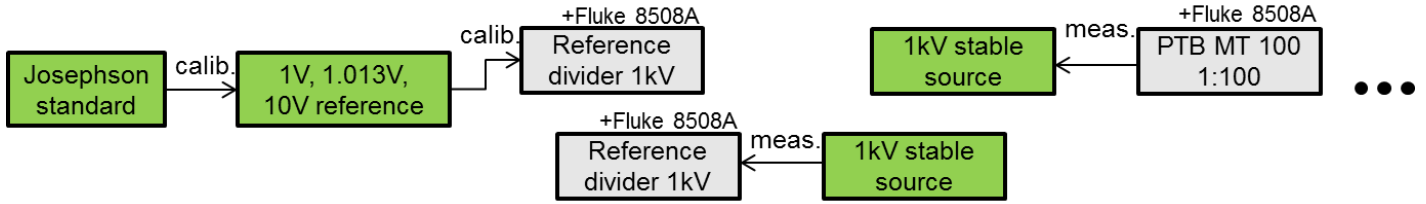
Th. Thümmler, R. Marx and Ch. Weinheimer,
NJP 11 (2009) 103007

PTB MT100:
2ppm / year

rel. uncertainty limited to 1ppm

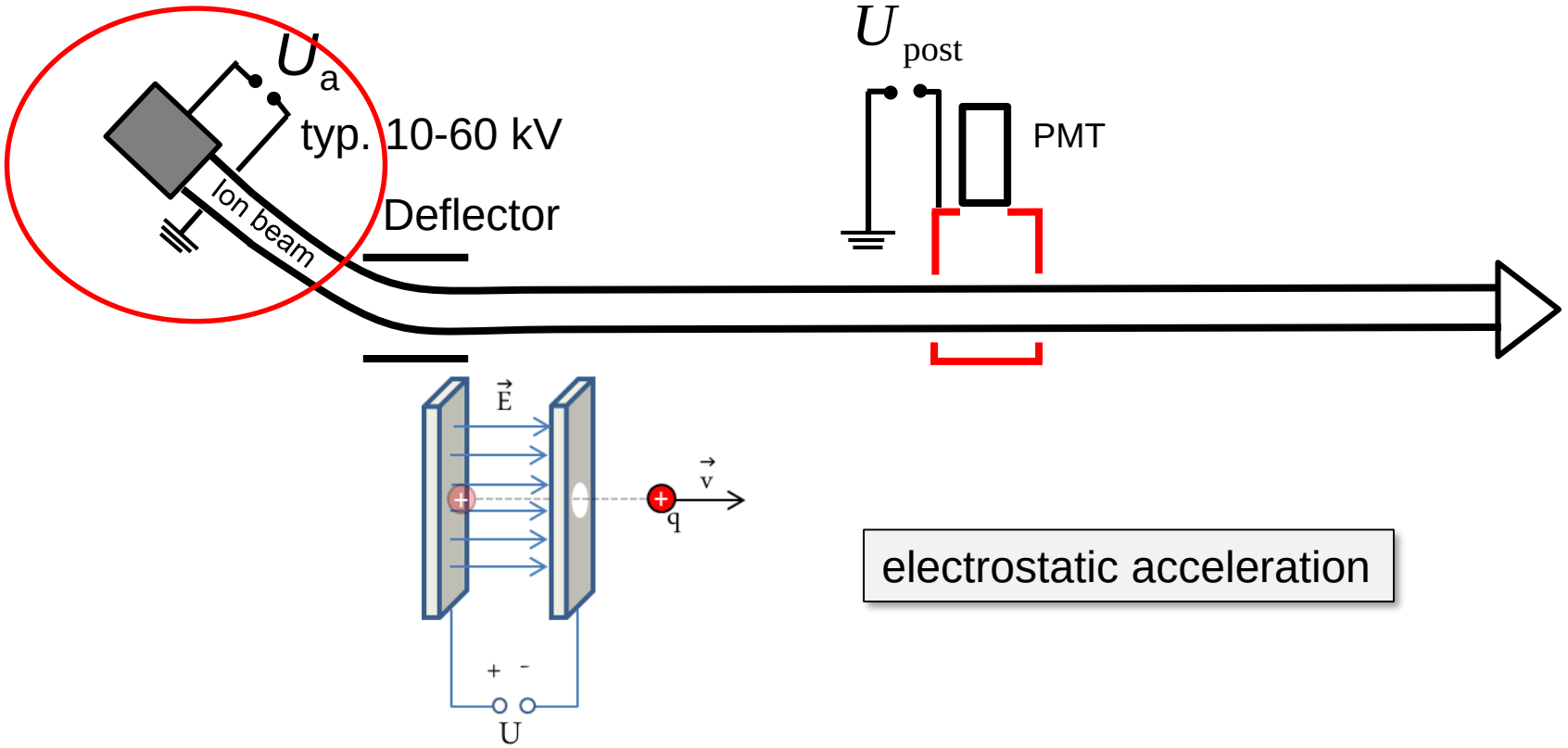
Tracing back:

- „Step up method“ method



direct comparison to „quantum standard“ desirable!

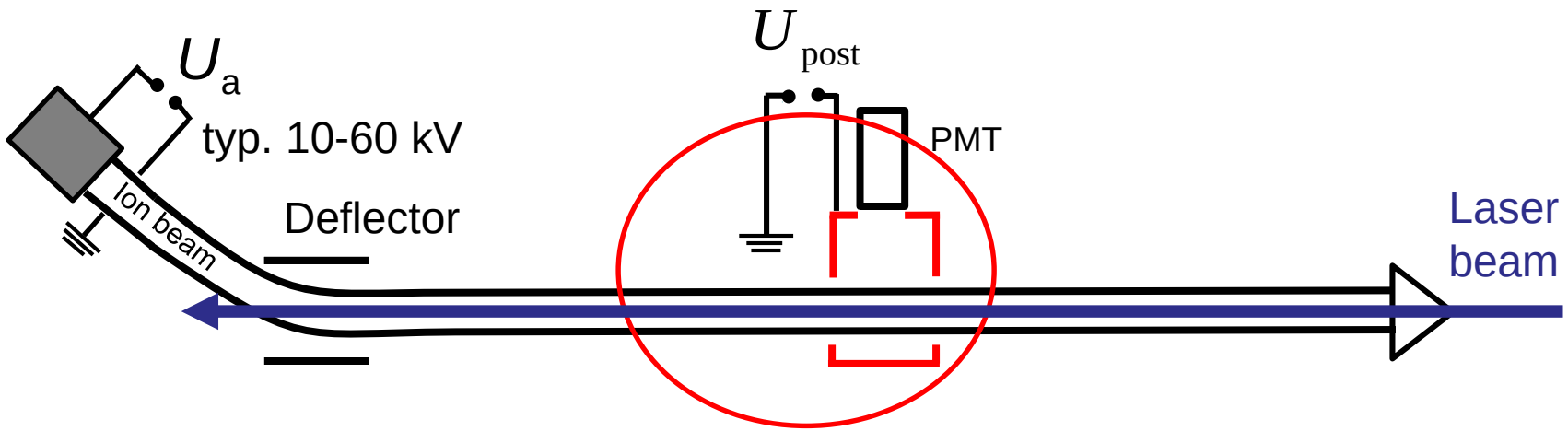
Collinear Laser Spectroscopy for Voltage Metrology

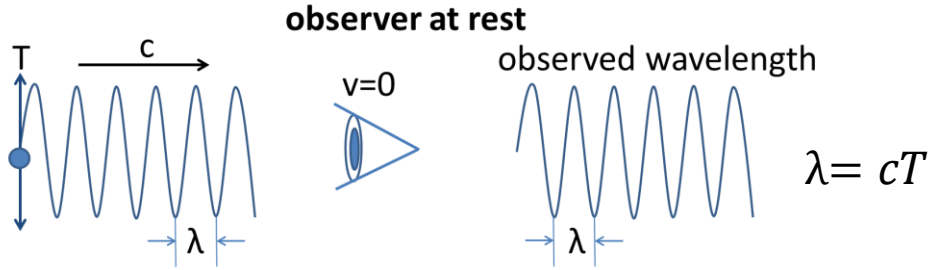


electrostatic acceleration

$$qU = mc^2\,(\gamma - 1)$$

Collinear Laser Spectroscopy for Voltage Metrology

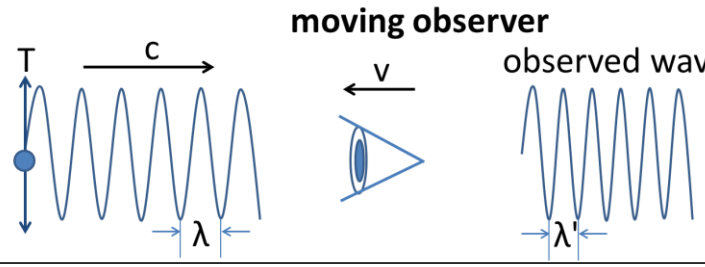




$$\lambda = cT$$

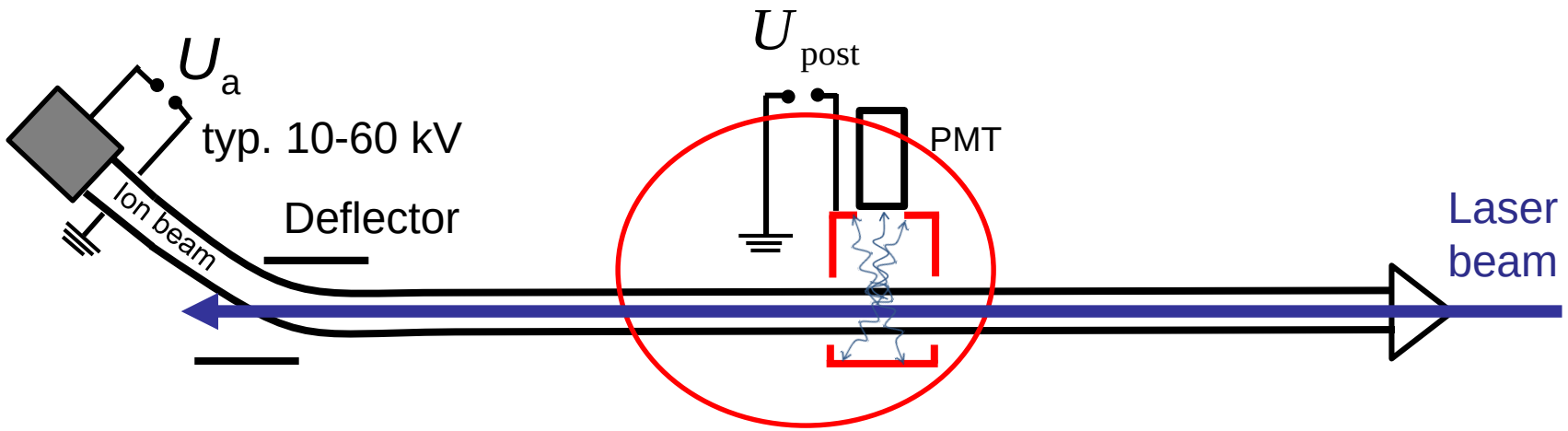
optical Doppler effect

$$\nu_{a/c} = \nu_L \gamma (1 \pm \beta)$$



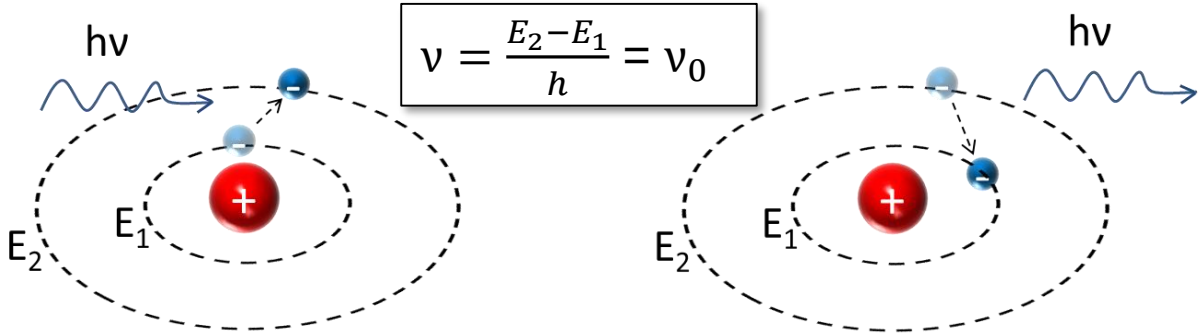
$$\lambda' = \lambda - vT = \lambda(1-\beta)$$

Collinear Laser Spectroscopy for Voltage Metrology



resonant excitation

fluorescence



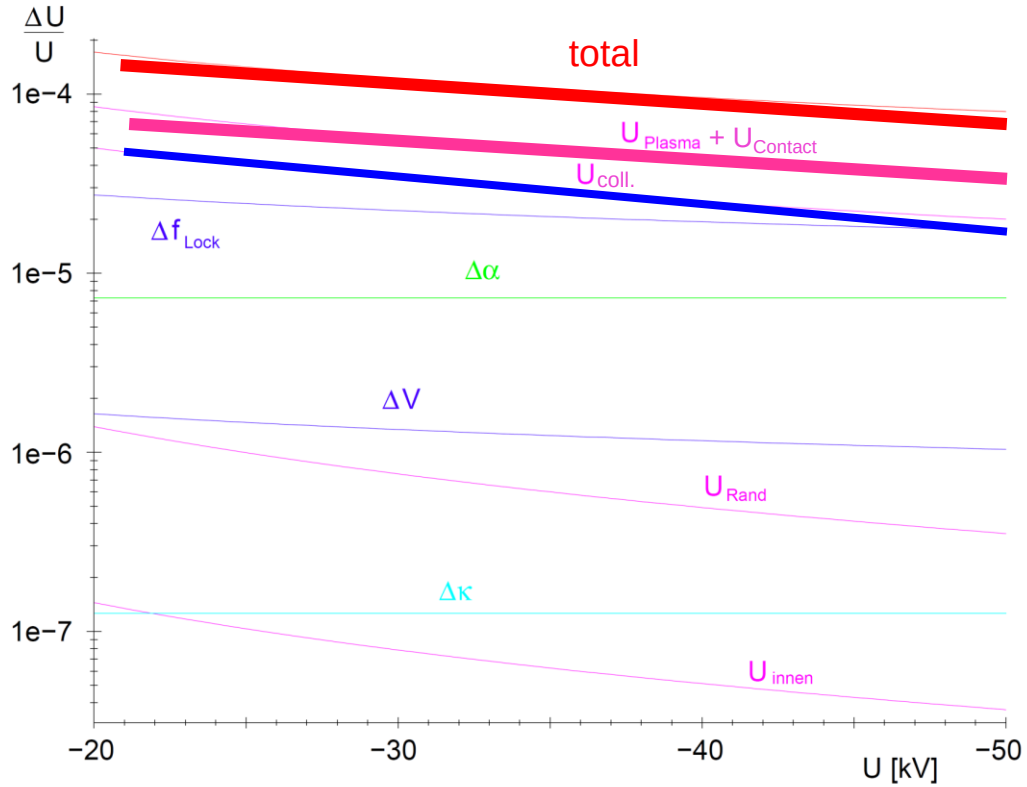
$$\nu = \frac{E_2 - E_1}{h} = \nu_0$$

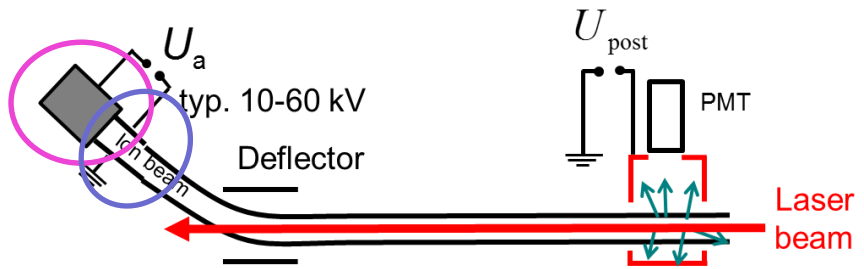
measure accurately with frequency comb

Literature value, atomic properties

$$U = -\frac{m_0 c^2}{2q}\frac{(\nu_0 - \nu_\pm)^2}{\nu_0 \nu_\pm}$$

Limits of the Classical Approach



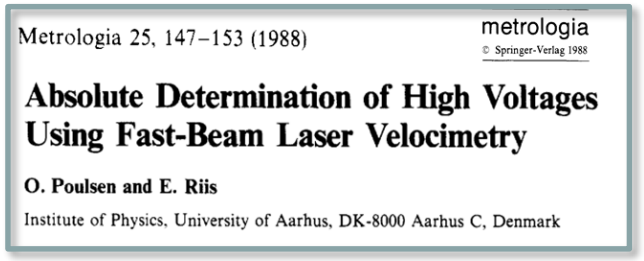


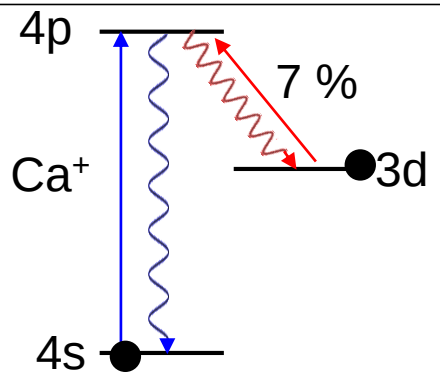
S. Götte et al. RevSciInstr75,4(2004)

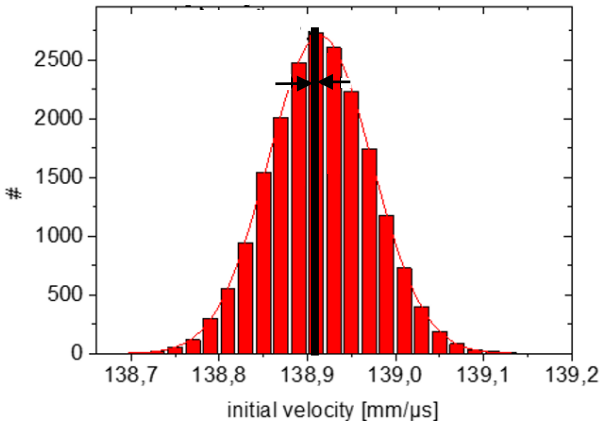
LUST experiment @ Mainz/GSI

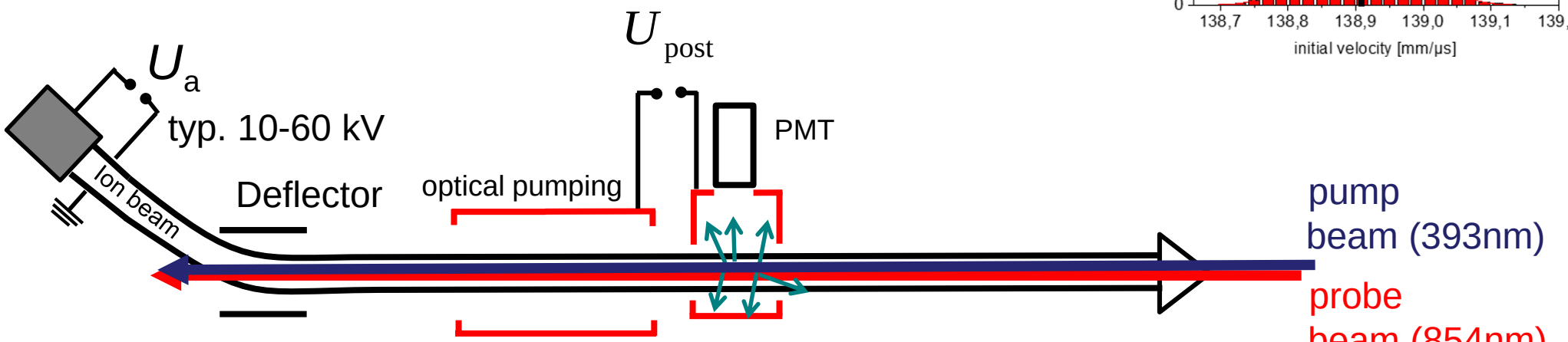
LaserUnterstützte SpannungsmessTechnik

The Two-Chamber Approach



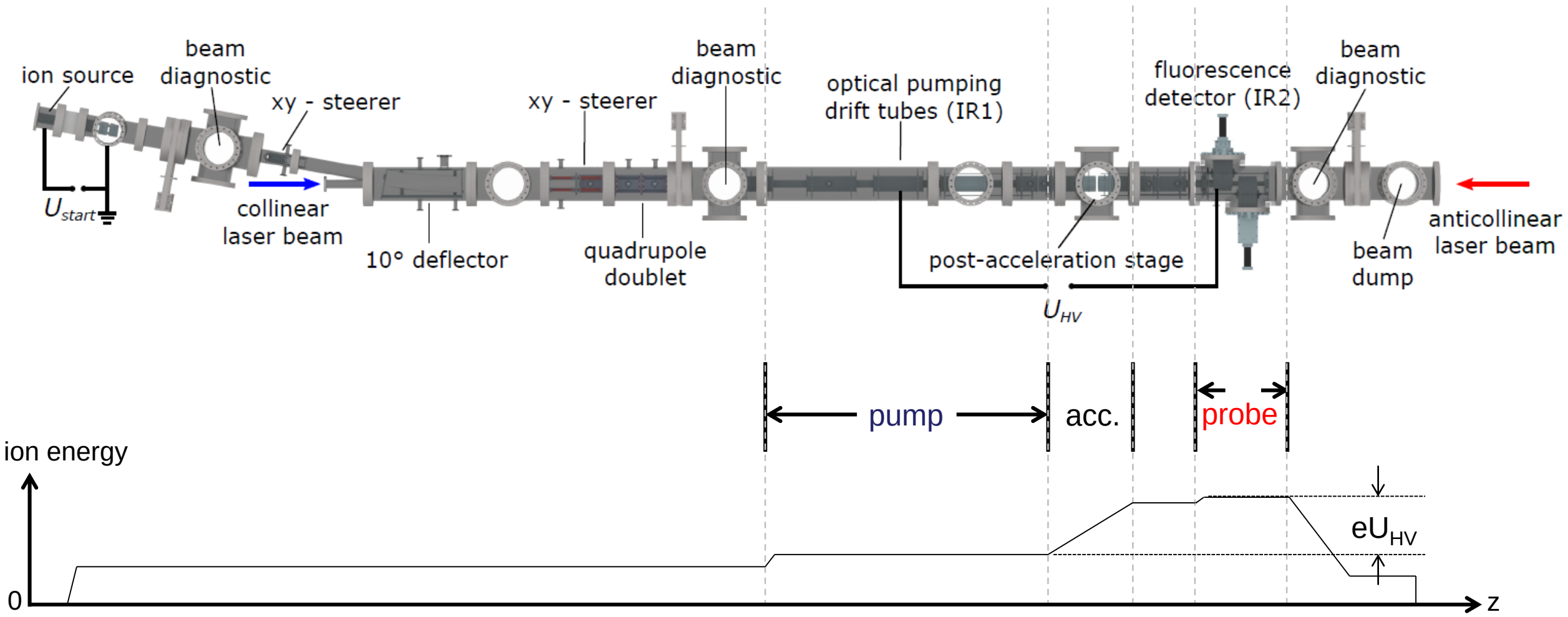






- independent of ion`s starting potential
- collisions near the ion source have no effect
- direct access to contact potentials as source of systematic uncertainty

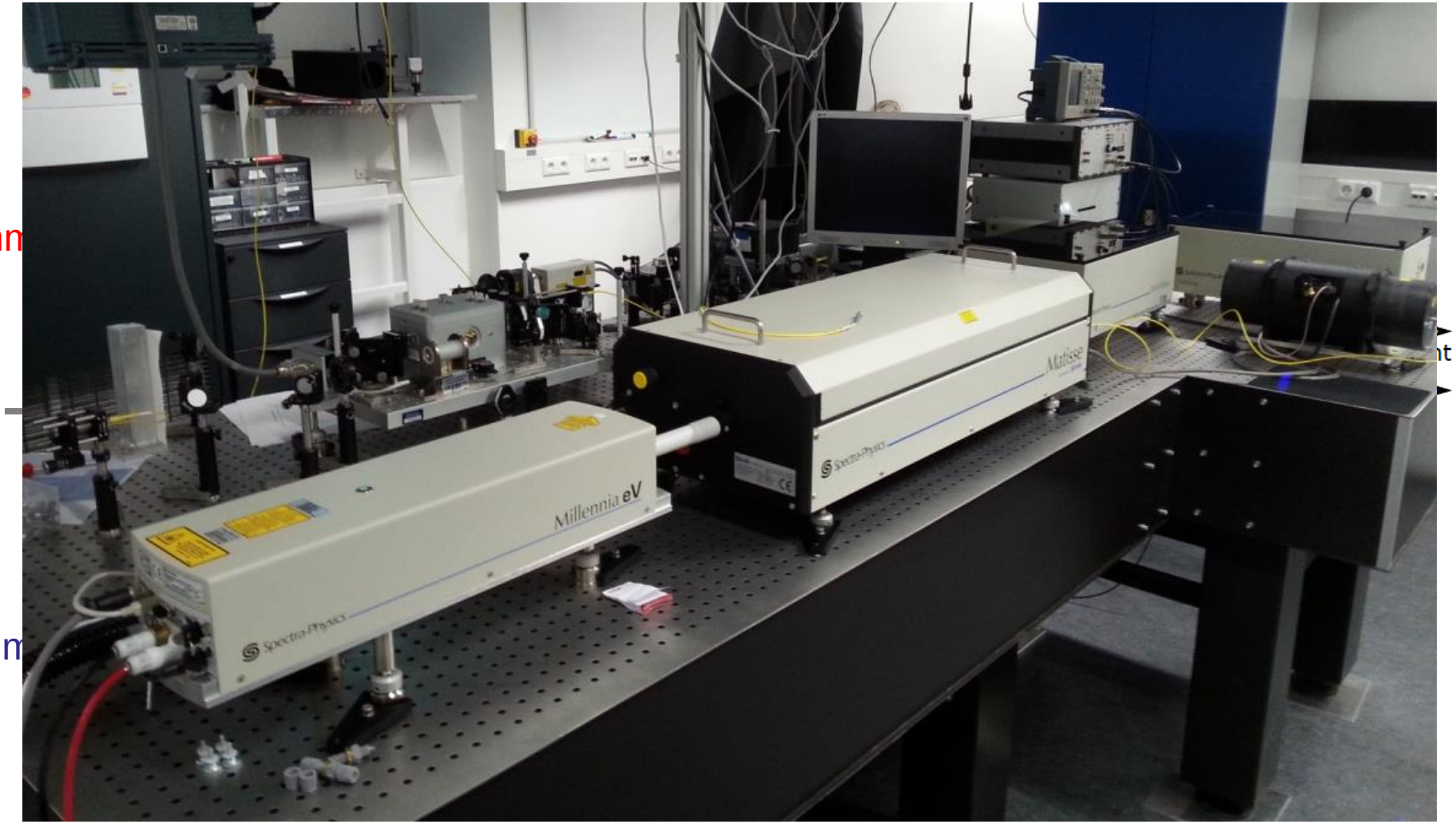
Vacuum beamline



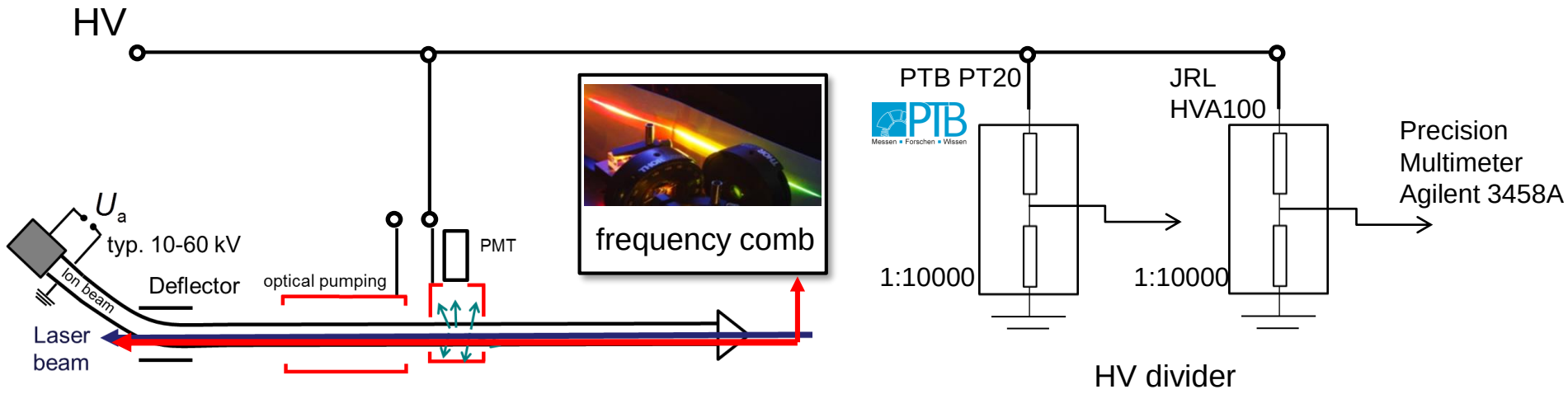
Laser System

probe (854nm

pump (393nm



Measurement Procedure



- Determine resonance voltage (blue), apply to pumping tube
- **0V measurement**, detection stage „grounded“
- Apply HV, tune laser frequency to corresponding frequency (wait for stable voltage)
- **HV measurement**, measure voltage with HV dividers in parallel

- Contact potential (≈1V) and other (constant) offset voltages cancel out
- Exact frequency measurement of the blue pump laser is not needed

Systematics I: Beamline Alignment

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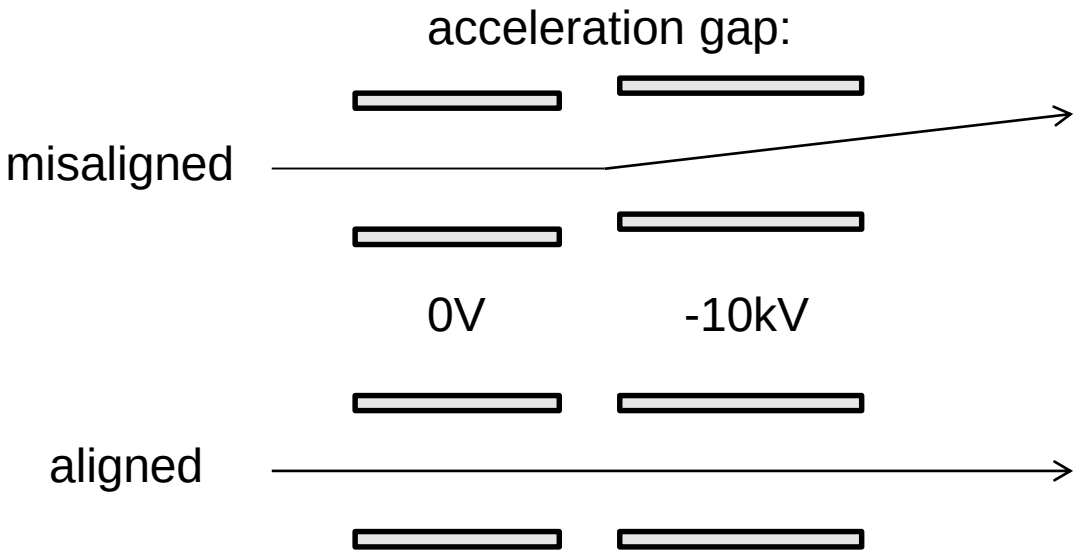
$$\nu_{ion} = \nu_{laser}\gamma\,(1 + \beta\,\mathbf{cos}\,\boldsymbol{\alpha})$$

Any angle between laser/ion:
-> reduced Doppler shift
-> peak shifted to smaller voltages



All parts aligned to < 1mm (limited by stiffness of electrode mounting frame)

⇒ Systematic uncertainty < 3 ppm

Systematics II: Ion beam divergence

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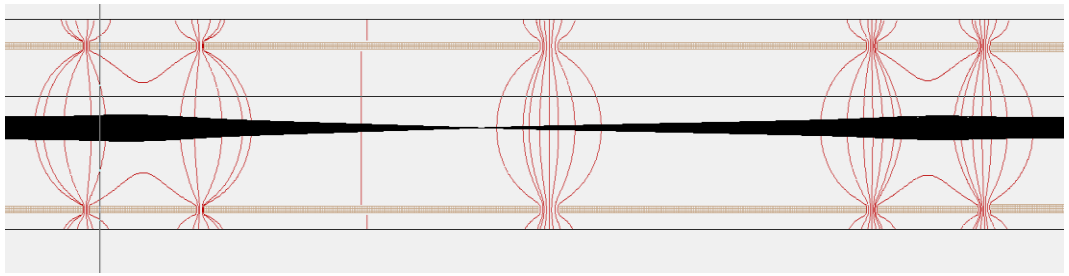
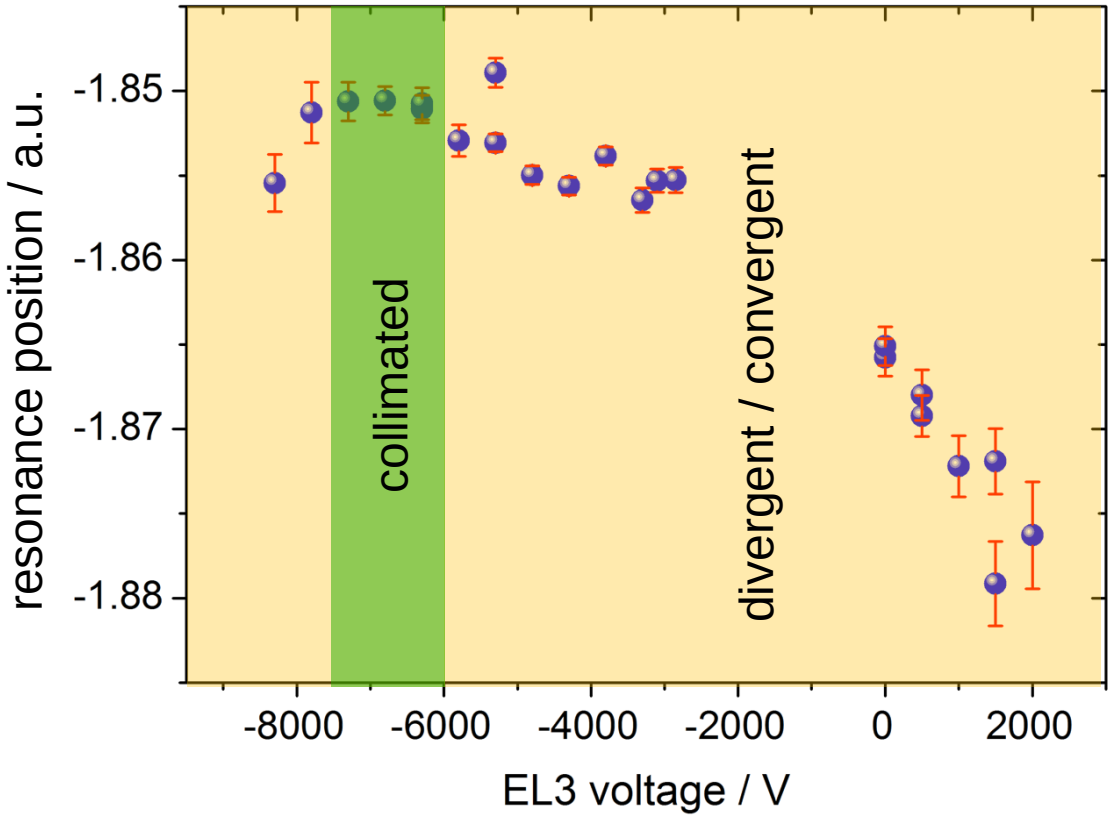
$$\nu_{ion} = \nu_{laser}\gamma\,(1 + \beta\,\mathbf{cos}\,\boldsymbol{\alpha})$$

Any angle between laser/ion:
-> reduced Doppler shift
-> peak shifted to smaller voltages

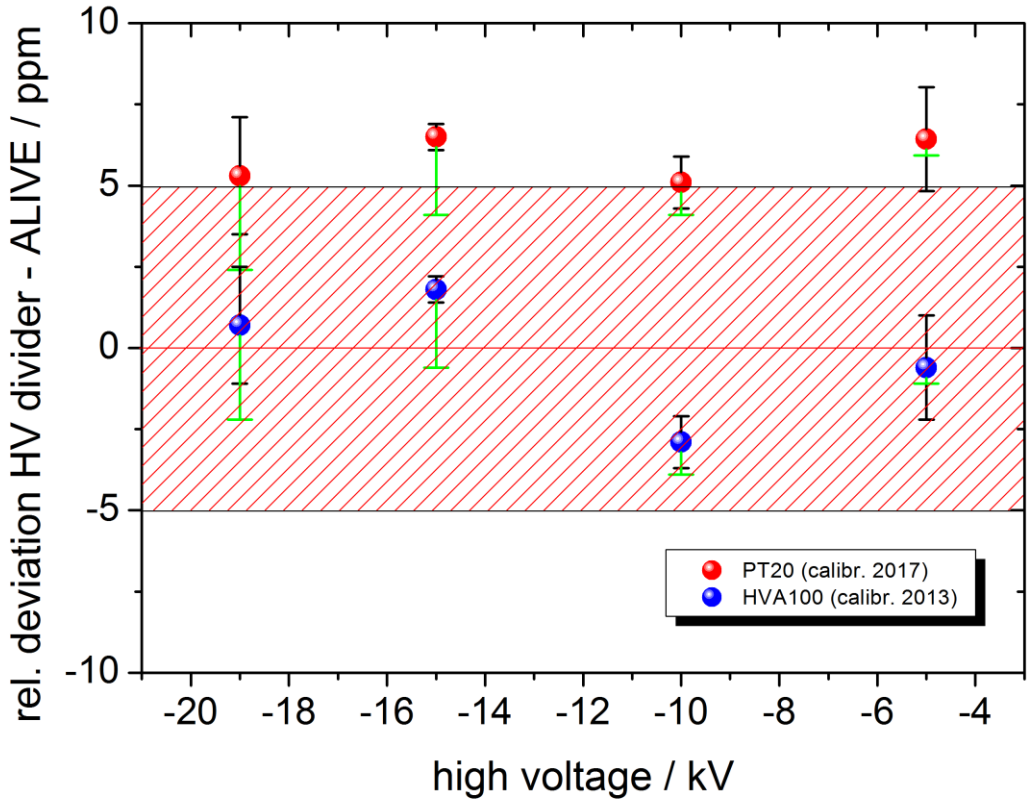
einzel lens „EL2“ | acc. gap | einzel lens „EL3“





optimization procedure:
tune lens voltage to maximize Doppler shift (= minimize divergence/angular deviation)

Results



J. Krämer, K. König et al., Metrologia 55 (2018) 268-274

error budget:

systematic	(-19kV)
electrode alignment	**+3 ppm**
Ion/laser beam angle	+0.2 ppm
laser beam divergence	+0.2 ppm
electric field penetration	+0.2 ppm
transition frequency	±0.15 ppm

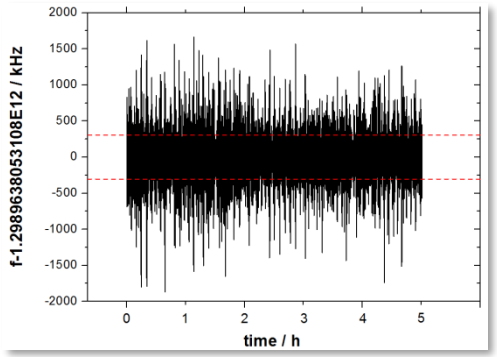
statistical	(-5kV)
laser frequency stability (blue pump laser)	**±4 ppm**
voltage stability	±1 ppm

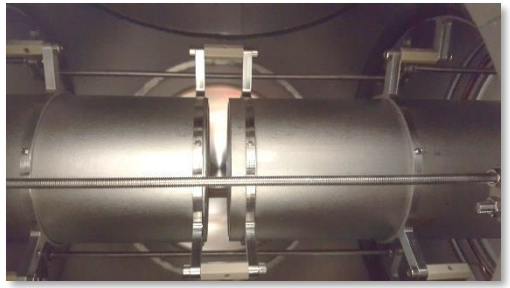
20x improvement compared to previous attempts!

Summary & Outlook

- Laser-based HV measurement: Alternative approach for accurate high voltage metrology
- Successful measurements with Ca^+ performed
- 5 ppm rel. uncertainty for HV up to -19 kV reached (20x improvement)

- Improved beamline alignment (especially acceleration stage)
- Lasers stabilized directly to frequency comb





⇨ Prepared for comparison with 1ppm divider (envisaged for late 2018)

Thank you for your attention!

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