Interferometer-based white light measurement of neutral rubidium density and gradient at AWAKE

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CERN / TUM / Max-Planck-Institute for Physics

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AWAKE

CERN

Technische Universität München

Outline

- Motivation and requirements
- Measurement method
- Achieved accuracy
- Measurements at AWAKE
- Summary

Motivation

- Central part in AWAKE: 10 m long rubidium plasma source, n = 10^{14} - 10^{15} cm^{-3}
- Full laser-ionization of Rb vapor -> plasma with same density

  → Measure instead vapor density at both ends
- Linear density ramp of 0-10 % in plasma cell used to optimize e^- acceleration process
- Gradient set and controlled by Rb reservoir temperatures at both cell ends with better 1 % accuracy

→ **Goal: Measure optically Rb vapor density at both ends with ± 0.5% relative accuracy and in a fully automated way**

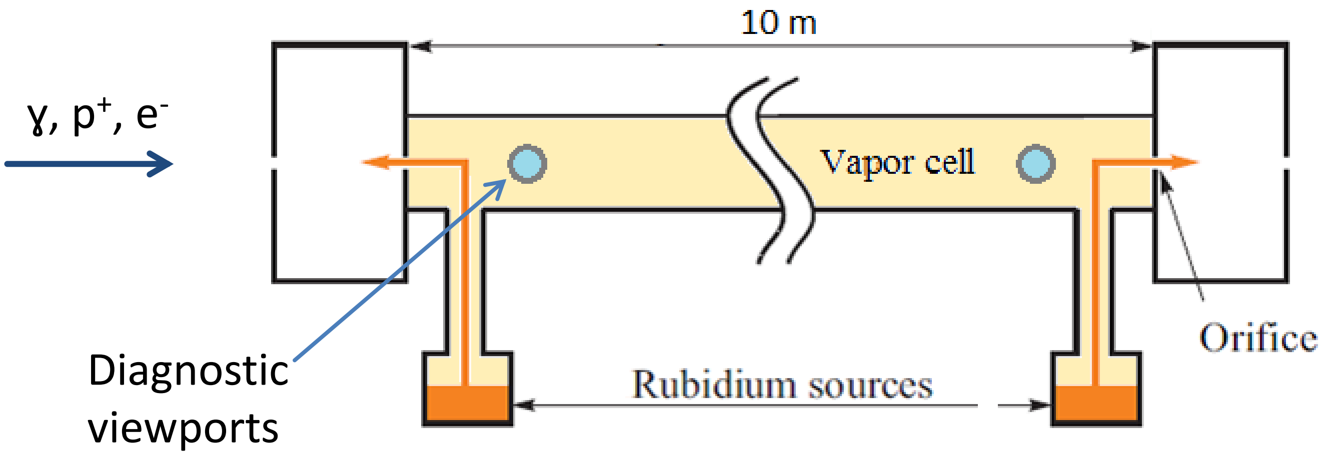

Fig.
Drawing of the Rb vapor source (by G.Plyushchev)

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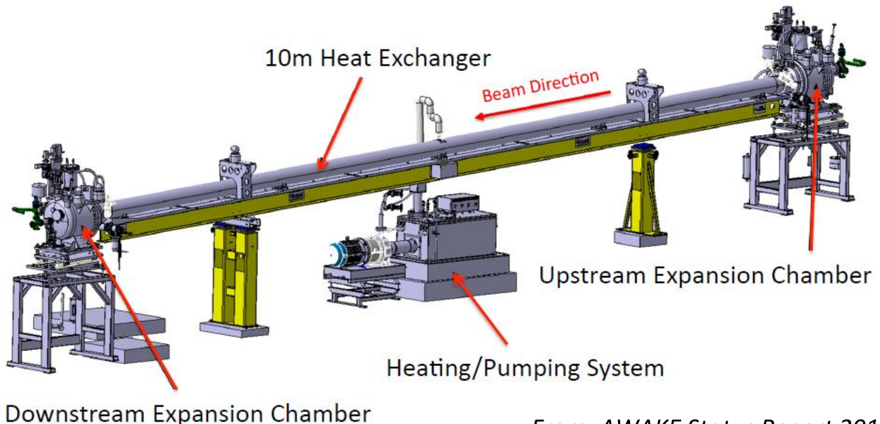
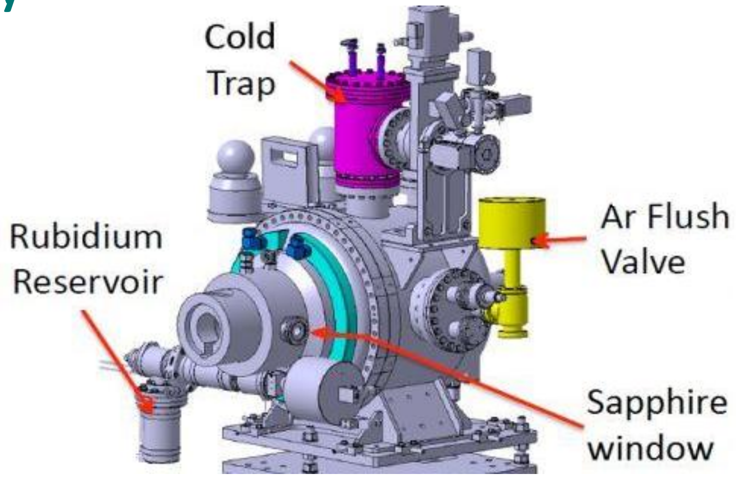


From: AWAKE Status Report 2016



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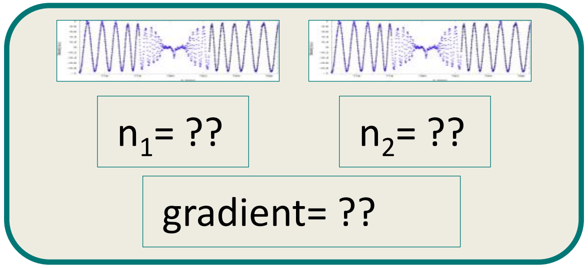

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Properties of Rb Vapor

- Vapor temperatures of 150°C to 200°C, corresponding to a density range of 10^{14} - 10^{15} cm^{-3}
- Vapor density n(T) from vapor pressure curve (5% abs. accuracy):

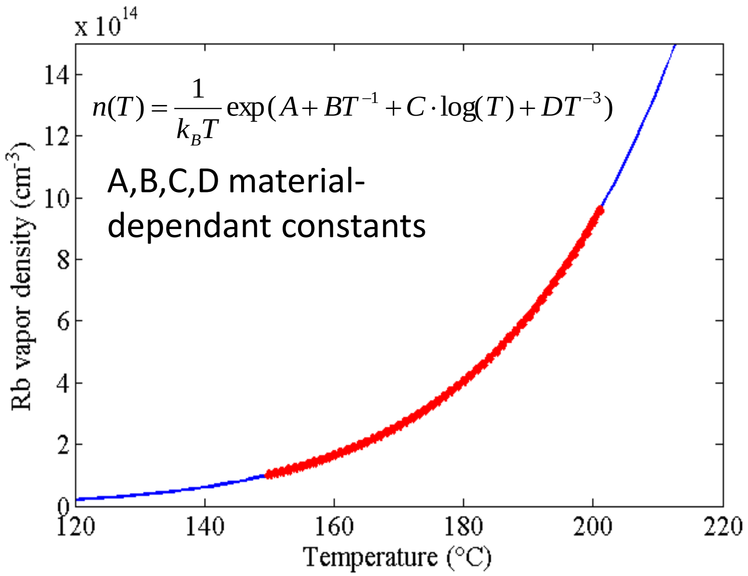


Fig. Rb Vapor temperature plotted versus its density

- Optical transitions from ground state at 780.24 nm (D_2 line) and 794.98 nm (D_1)
- Anomalous dispersion and absorption in their vicinity
- Real and imaginary parts for relative permittivity ε change

$$n_{ir} = \sqrt{\varepsilon} = \sqrt{1+\chi}$$

$$\chi \propto N_{GS} = N_{Vapor}$$

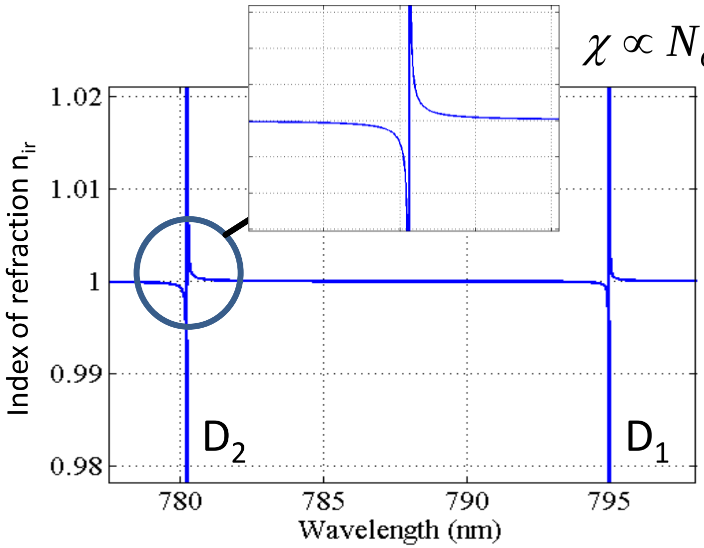


Fig. Index of refraction for n= $9.8 \cdot 10^{14}$ cm^{-3}

Measurement Method

- Use interferometry and the hook method adapted to vertical fringes
- Main set-up components: coherent white light source, Mach-Zehnder-interferometer and spectrometer
- Optical single mode fibers guide light
- Fiber collimators allows for free space travel through Rb

$I_1(\lambda)$

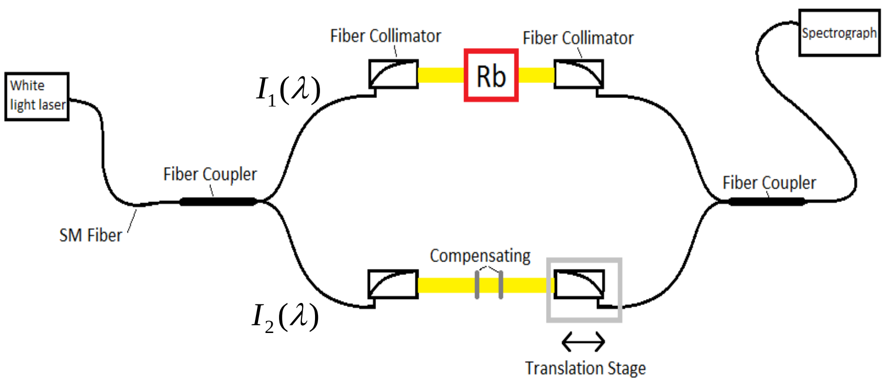
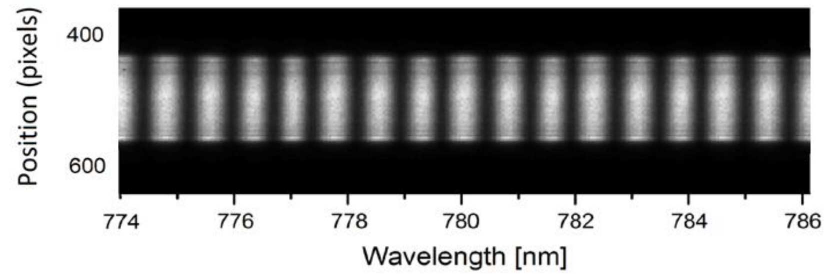
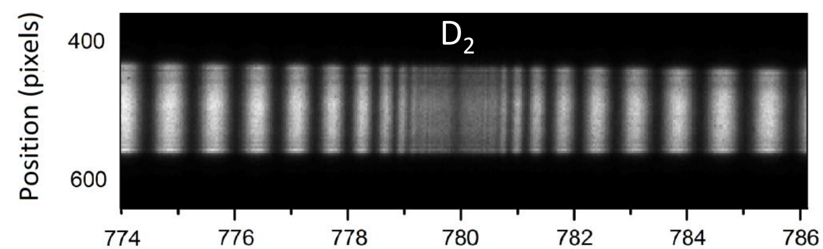


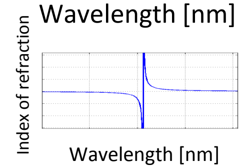
Fig. Setup of the fiber-based Mach-Zehnder Interferometer

- Fringes equidistant for $n_{Rb} = 0$



- With Rb vapor, anomalous dispersion causes density-dependant change in periodicity of interference maxima.

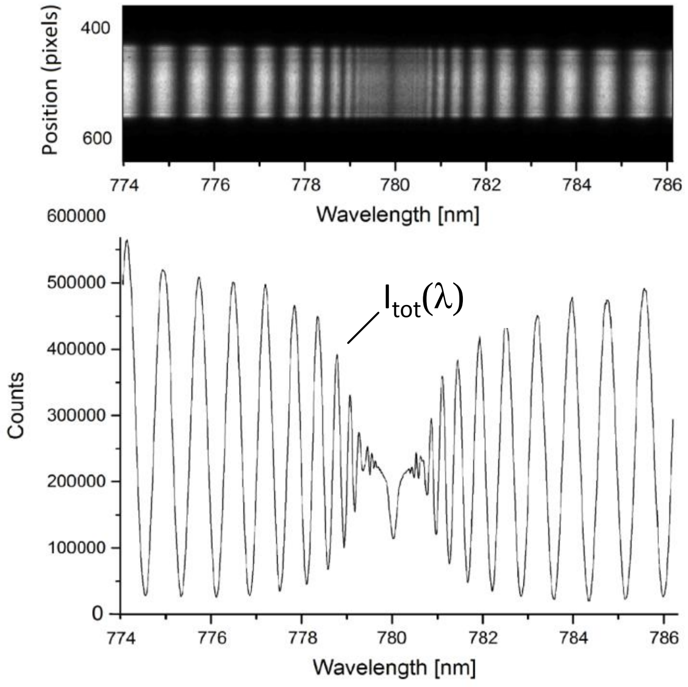




$$I_{tot}(\lambda) = I_1(\lambda) + I_2(\lambda) + 2\sqrt{I_1 I_2}\cos(\Delta\varphi)$$

Determine density by fitting

- Analyze intensity spectrum I_{tot} :
  Use 1D spectrograph



$$I_{tot}(\lambda) = I_1(\lambda) + I_2(\lambda) + 2\sqrt{I_1(\lambda) I_2(\lambda)} \cos(\Delta\varphi)$$

- Before fit, normalize intensity spectrum to compensate inhomogeneous light distribution (caused by light source, light transport in fiber):

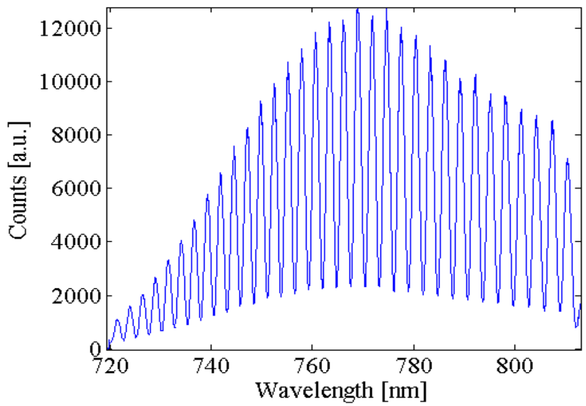
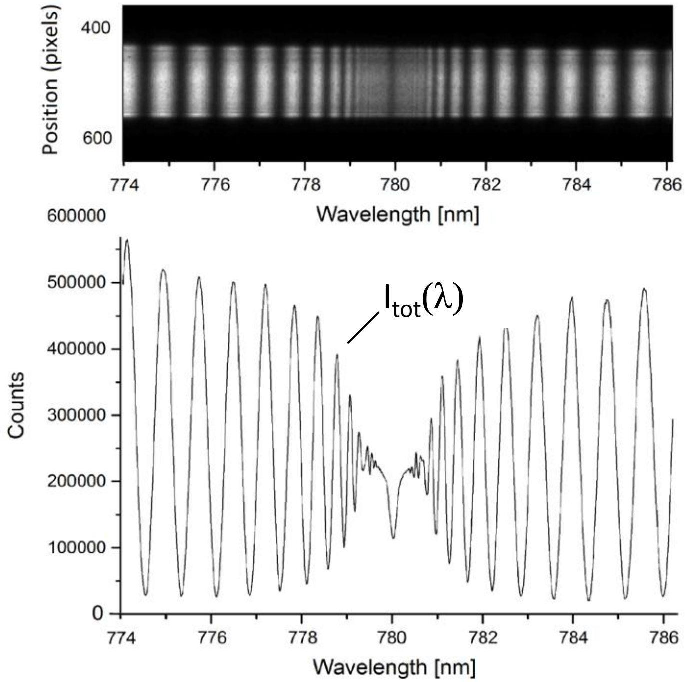


Fig. Interferogram for n= 0 cm^{-3}

- Normalization by recording arm spectra or by spectrograph signal conditioning using FFT (by M. Martyanov, does not require reference spectra / noise filtered) possible

Determine density by fitting

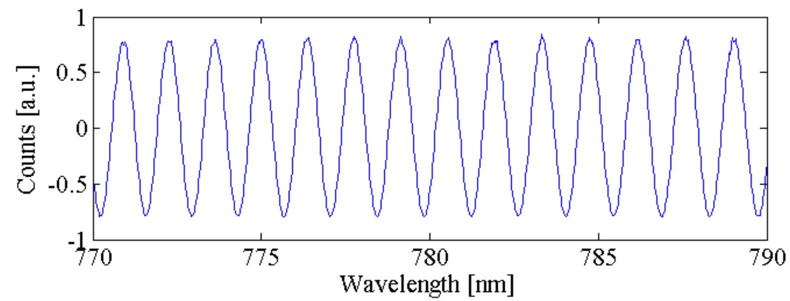
➢ Analyze intensity spectrum I_{tot} :
Use 1D spectrograph



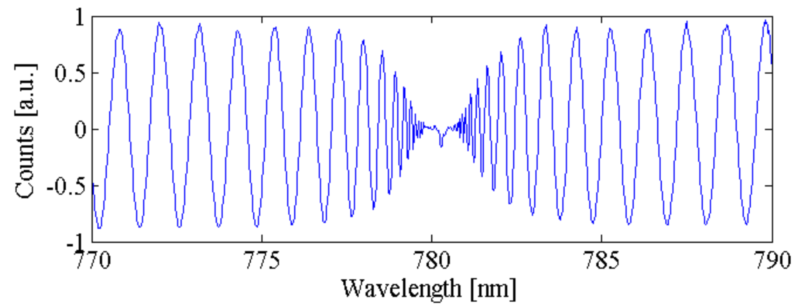
$$I_{tot}(\lambda) = I_1(\lambda) + I_2(\lambda) + 2\sqrt{I_1(\lambda) I_2(\lambda)} \cos(\Delta\varphi)$$

➢ Before fit, normalize intensity spectrum to compensate inhomogeneous light distribution (caused by light source, light transport in fiber):

- for $n_{Rb} = 0$



- for $n_{Rb} = 5 \times 10^{14}$ cm^{-3}



Determine density by fitting

- Look at both transition lines for analysis
- Intensity function *S* described by:

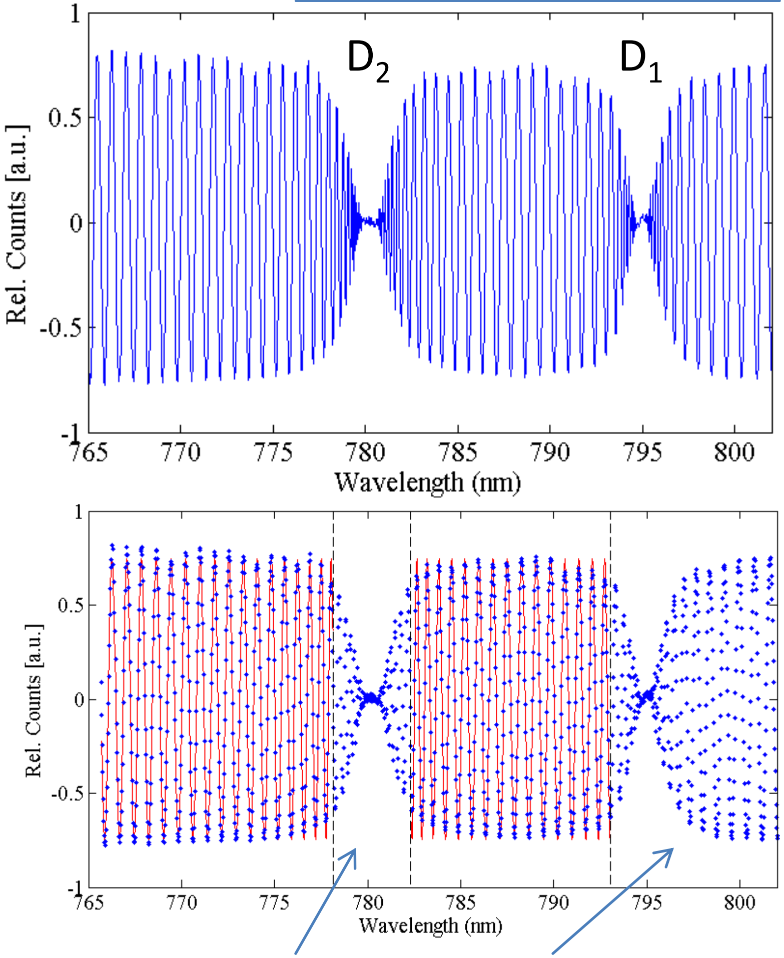
$$S(\lambda)=\tilde{A}\cdot\cos\left(\frac{2\pi}{\lambda}\cdot\left[\frac{\tilde{n}l\cdot r_0 f_1\lambda_1^3}{4\pi(\lambda-\lambda_1)}+\frac{\tilde{n}l\cdot r_0 f_2\lambda_2^3}{4\pi(\lambda-\lambda_2)}+\tilde{\xi}\right]\right)$$

with
- A the amplitude,
- nl the density-length product
- $\lambda_{1,2}$ transition wavelength
- r_0 classical e^- radius
- $f_{1,2}$ oscillation strength
- ξ path length difference in interferometer

Fitting parameters marked with ~

- Density value obtained by fitting intensity spectrum near transition line , with A, n , ξ fitting parameters

Norm. by arm spectra



Areas ignored by fit

Determine density by fitting

- Look at both transition lines for analysis
- Intensity function S described by:

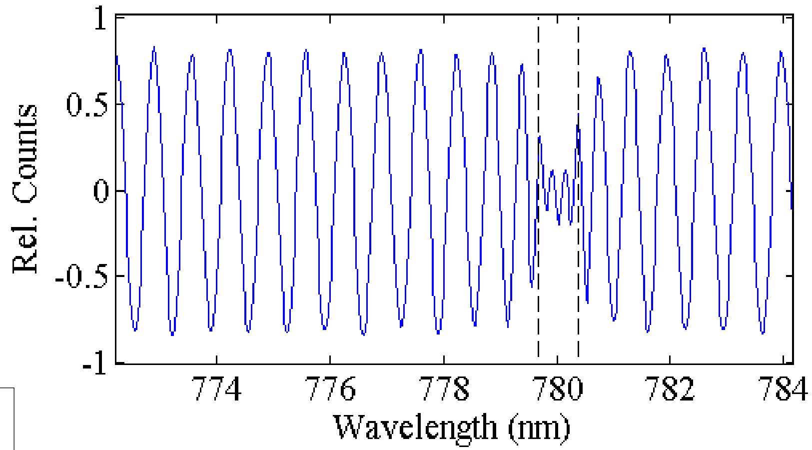
$$S(\lambda) = \tilde{A} \cdot \cos\left(\frac{2\pi}{\lambda} \cdot \left[\frac{\tilde{n}l \cdot r_0 f_1 \lambda_1^3}{4\pi(\lambda - \lambda_1)} + \frac{\tilde{n}l \cdot r_0 f_2 \lambda_2^3}{4\pi(\lambda - \lambda_2)} + \tilde{\xi} \right] \right)$$

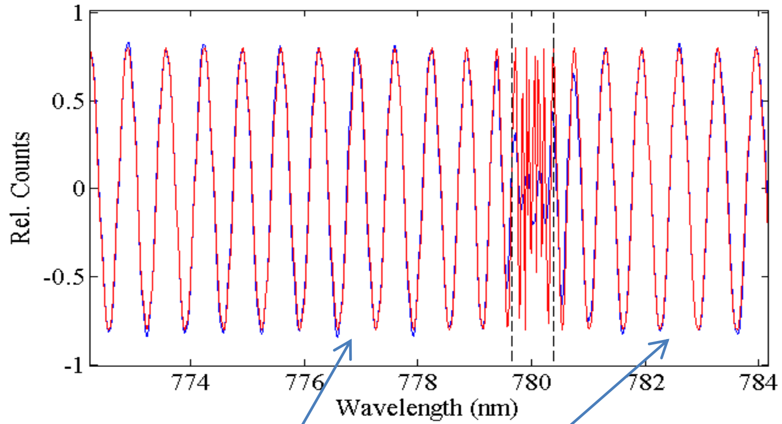
with A the amplitude,
nl the density-length product
$\lambda_{1,2}$ transition wavelength
r_0 classical e$^-$ radius
$f_{1,2}$ oscillation strength
ξ path length difference in interferometer

Fitting parameters marked with ~

- Density value obtained by fitting intensity spectrum near transition line, with A, n , ξ fitting parameters
- Dispersion might effect fitting -> completely equal arms

Norm. by FFT





Areas ignored by fit

Automation of the system at CERN:

- **Laser:** runs with constant power 24/7
- **Interferometer**: Flippers in both arms, to block and record arms separately, path length difference constant for all measurements
- **Spectrograph**: Remotely controlled, software acquires data with both spectrographs simultaneously, saved on local computer
- **Data analysis**: CERN FileReader reads-in up- and downstream data for density calculation (done in a FESA class) -> density displayed in control room, density-time file saved in data base (implementation ongoing)

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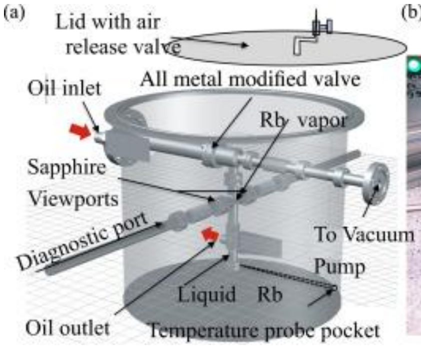
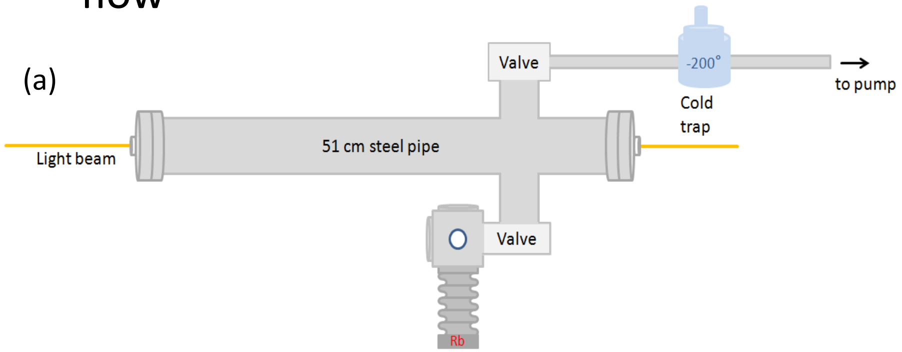
Two different Rb test cells at MPP:

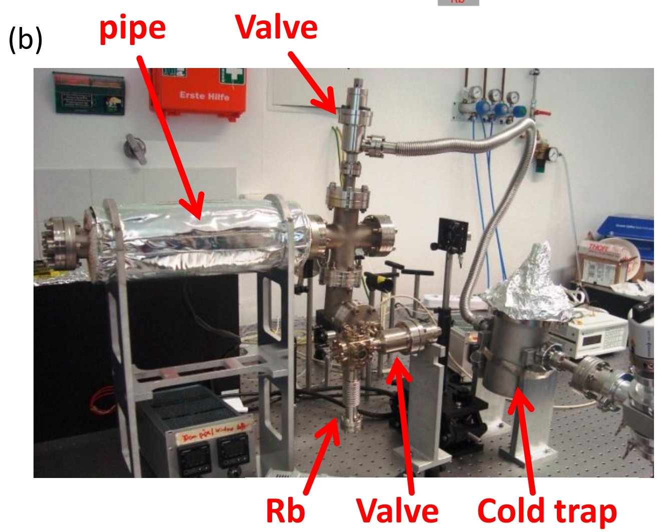
- Oil-heated Rb reservoir with a temperature stability of 0.1 K
- Vapor column length l = 8 cm



E. Öz, F. Batsch, P. Muggli, Nuclear Instruments & Methods in Physics Research A (2016), http://dx.doi.org/10.1016/j.nima.2016.02.005

- Electrically heated pipe system with l = 51 cm and valves to control Rb flow



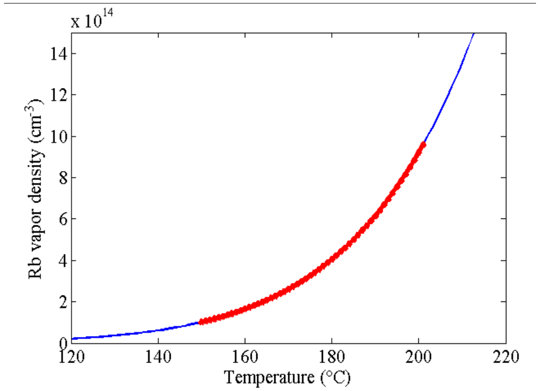


Evaluation of the absolute accuracy

Norm. by arm spectra

- Absolute accuracy measured by using a temperature - stabilized Rb vapor source:

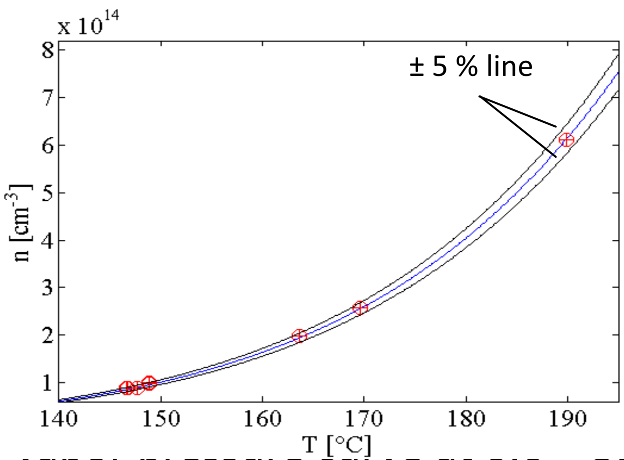
<u>From vapor pressure curve</u>:



$$n(T) = \frac{1}{k_B T} \exp(A + BT^{-1} + C \cdot \log(T) + DT^{-3})$$

A,B,C,D material-dependant constants

<u>Measured n_{Rb} vs. *T*:</u>

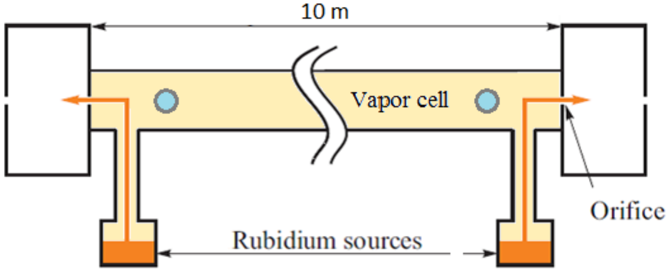


✓ Measured values tracks .8 % level

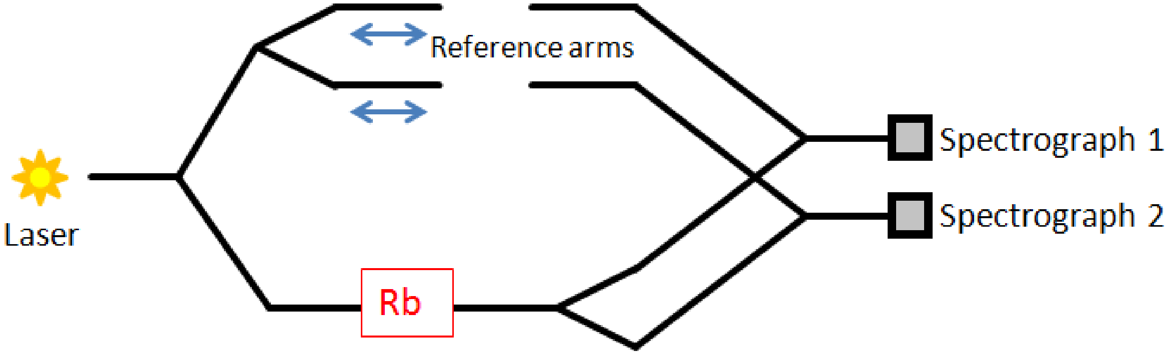
Gradient determination accuracy:

Norm. by arm spectra

- Crucial point: Measure not one, but two density - length products with the same accuracy < ± 0.5%   <-> determine density gradient at (sub-) % level



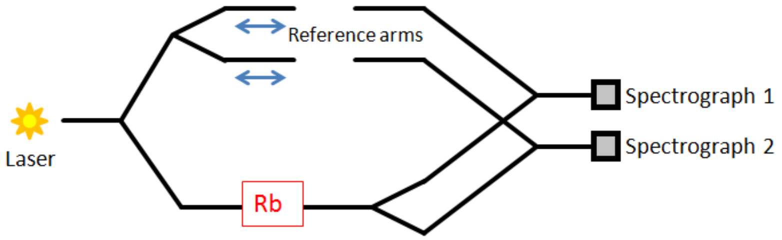
- Idea: Probing the same Rb vapor with two independent measurement setups to simulate to equal vapor column length
- Interferometer test setup:



Results for the relative accuracy:

Norm. by arm spectra

- Record images at const. n, arm 1 (2) corresponds to spectrograph 1 (2):



- ✓ Result: Both measurements differ by 0.1 % (up to 0.3 % , depending on temperature):

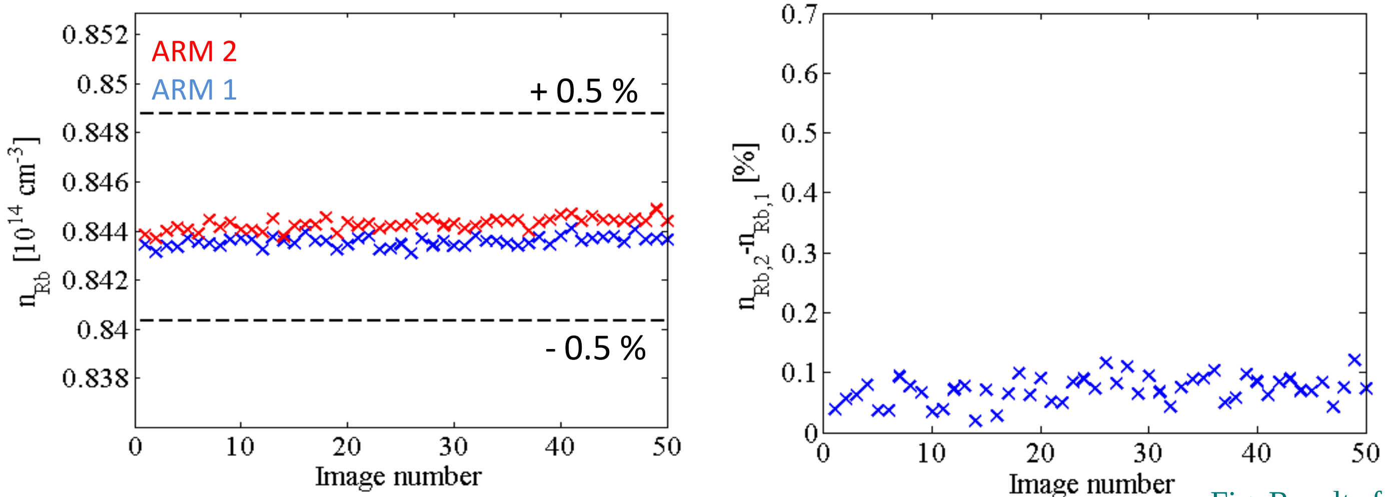


Fig. Results for T = 190°C, l=51 cm

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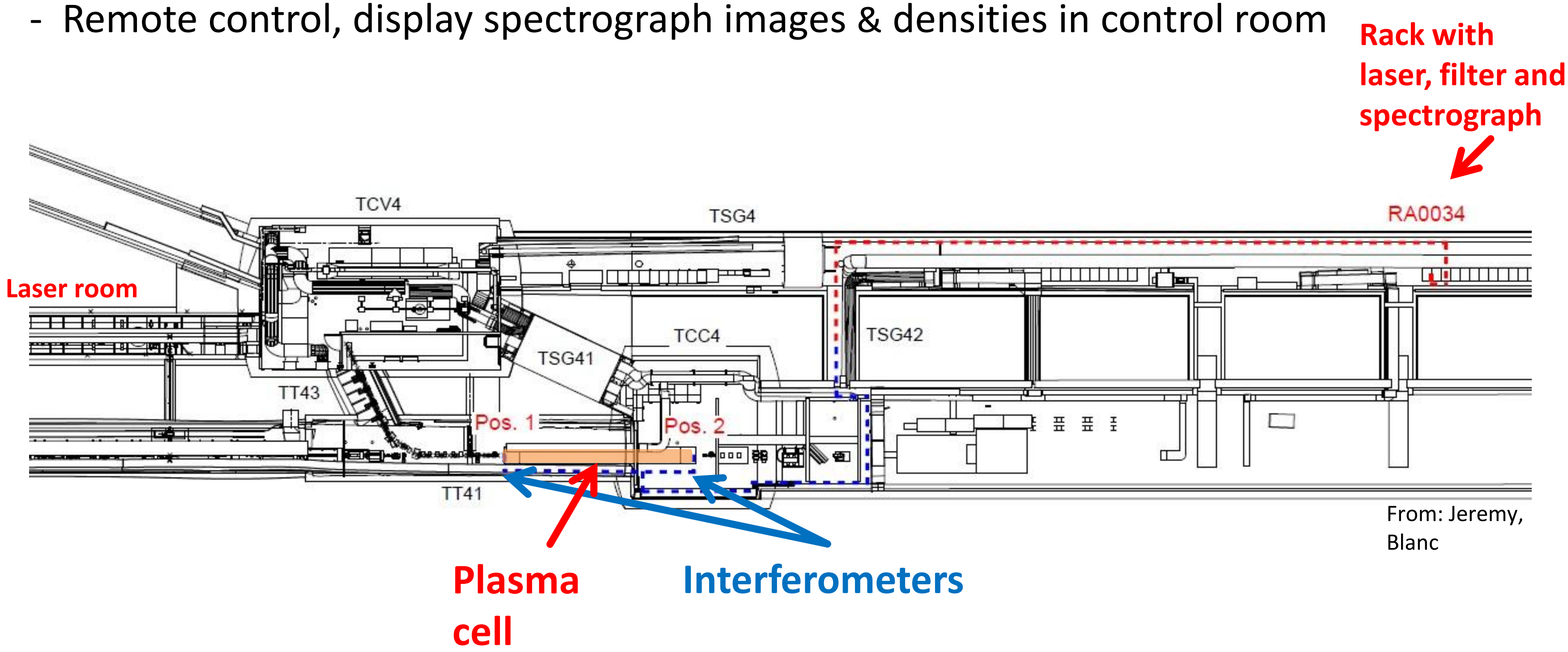
The AWAKE facility:

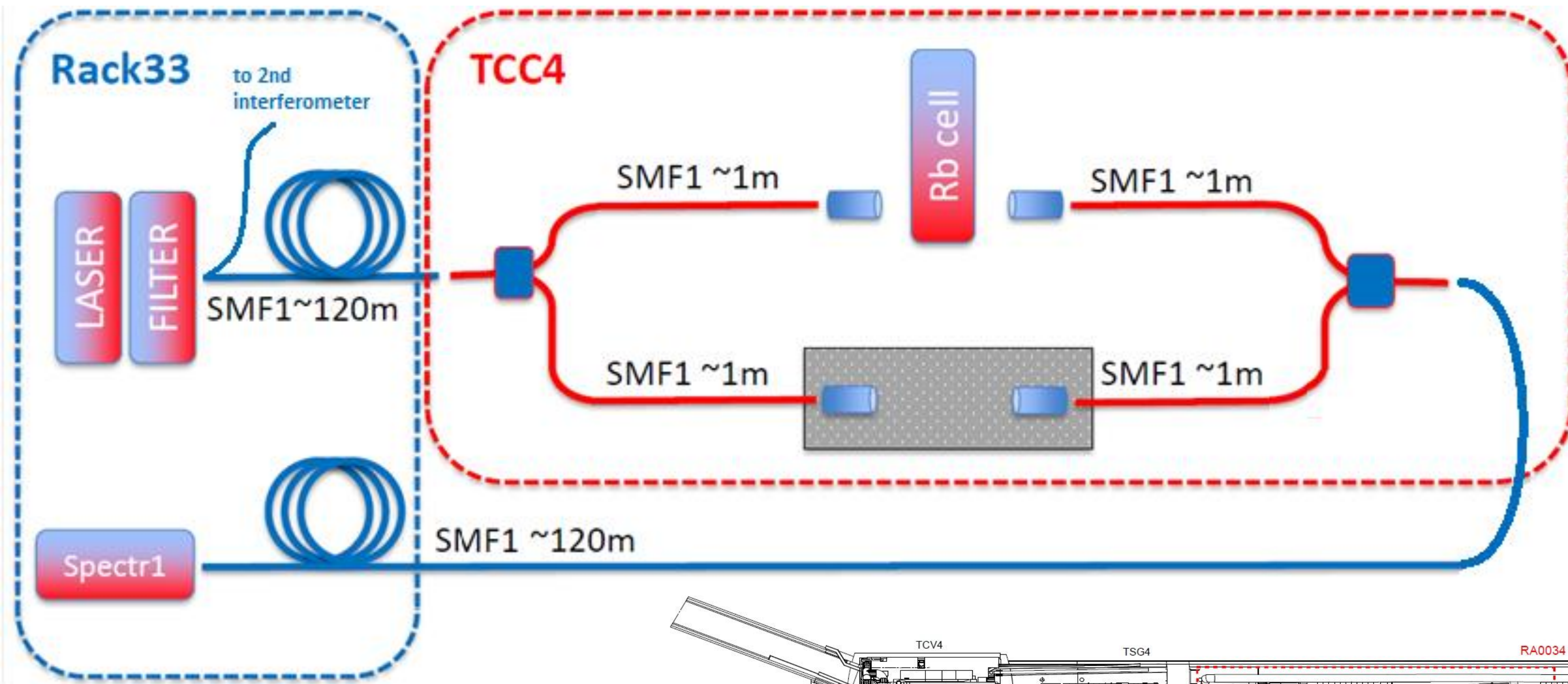
- Basic setup:
  - Two interferometer at each cell end
  - Laser and spectrographs located in electronics gallery to protect hardware from radiation, 120 m fiber length guide light between rack and cell ends
  - Remote control, display spectrograph images & densities in control room

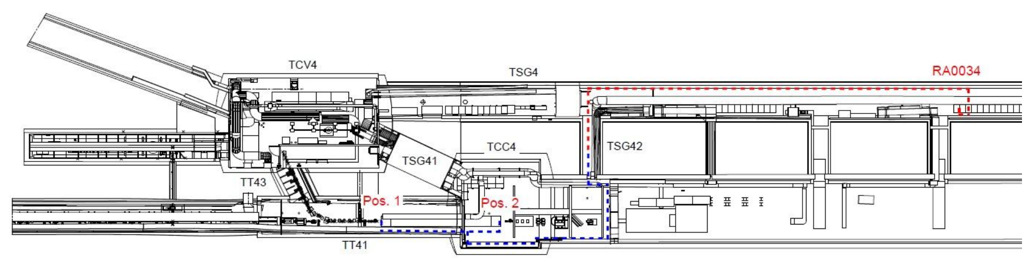


From: Jeremy, Blanc

Fiber path schematic:

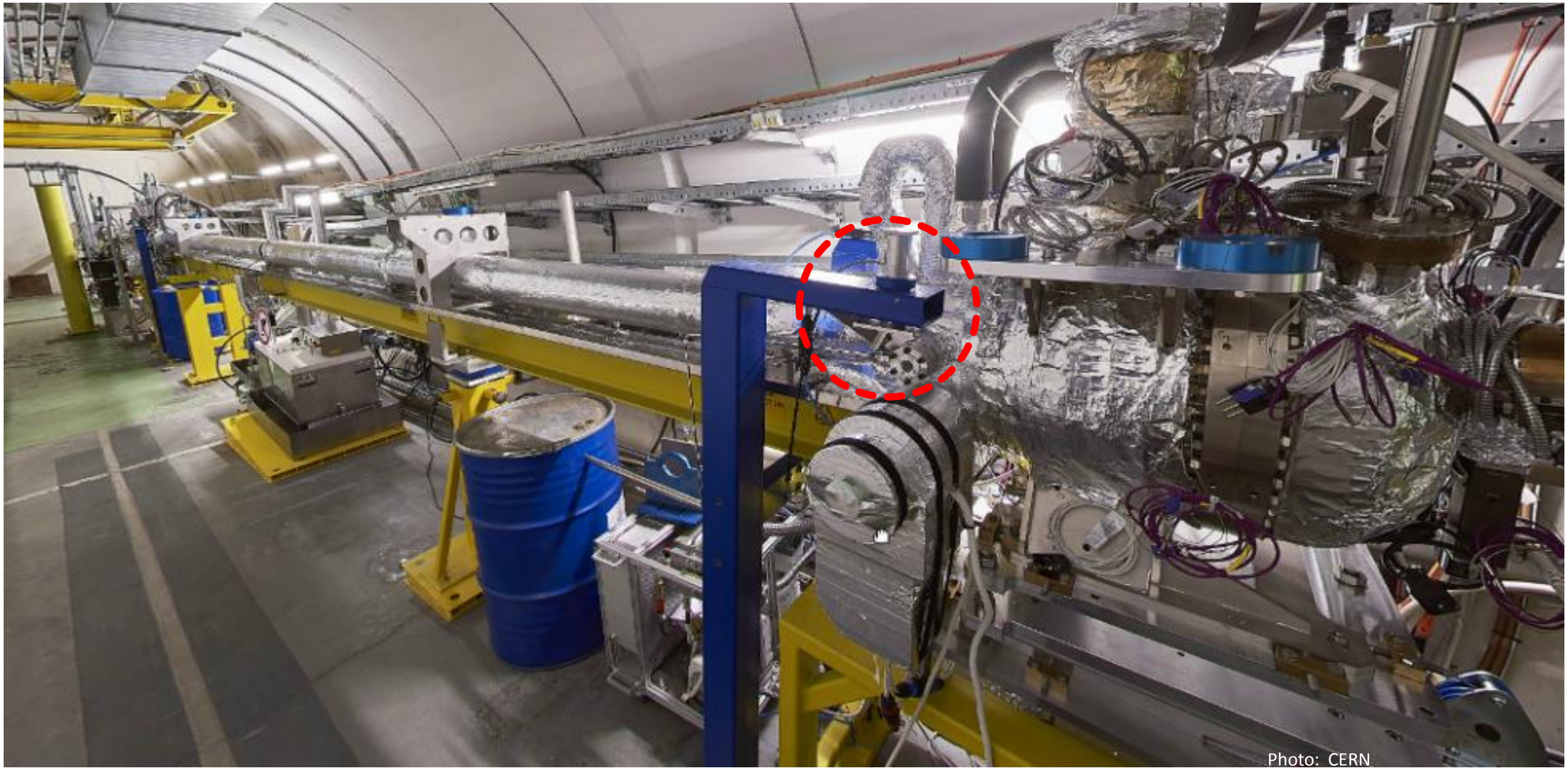
- Situation equivalent for both ends:





Installation at AWAKE:

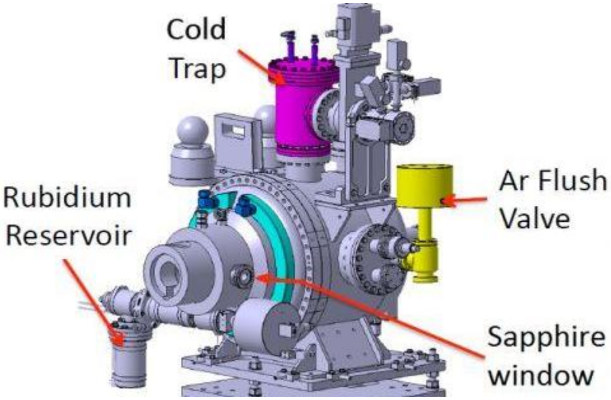
Optic holder legs and diagnostic window:



Setup photos downstream:

Applications:

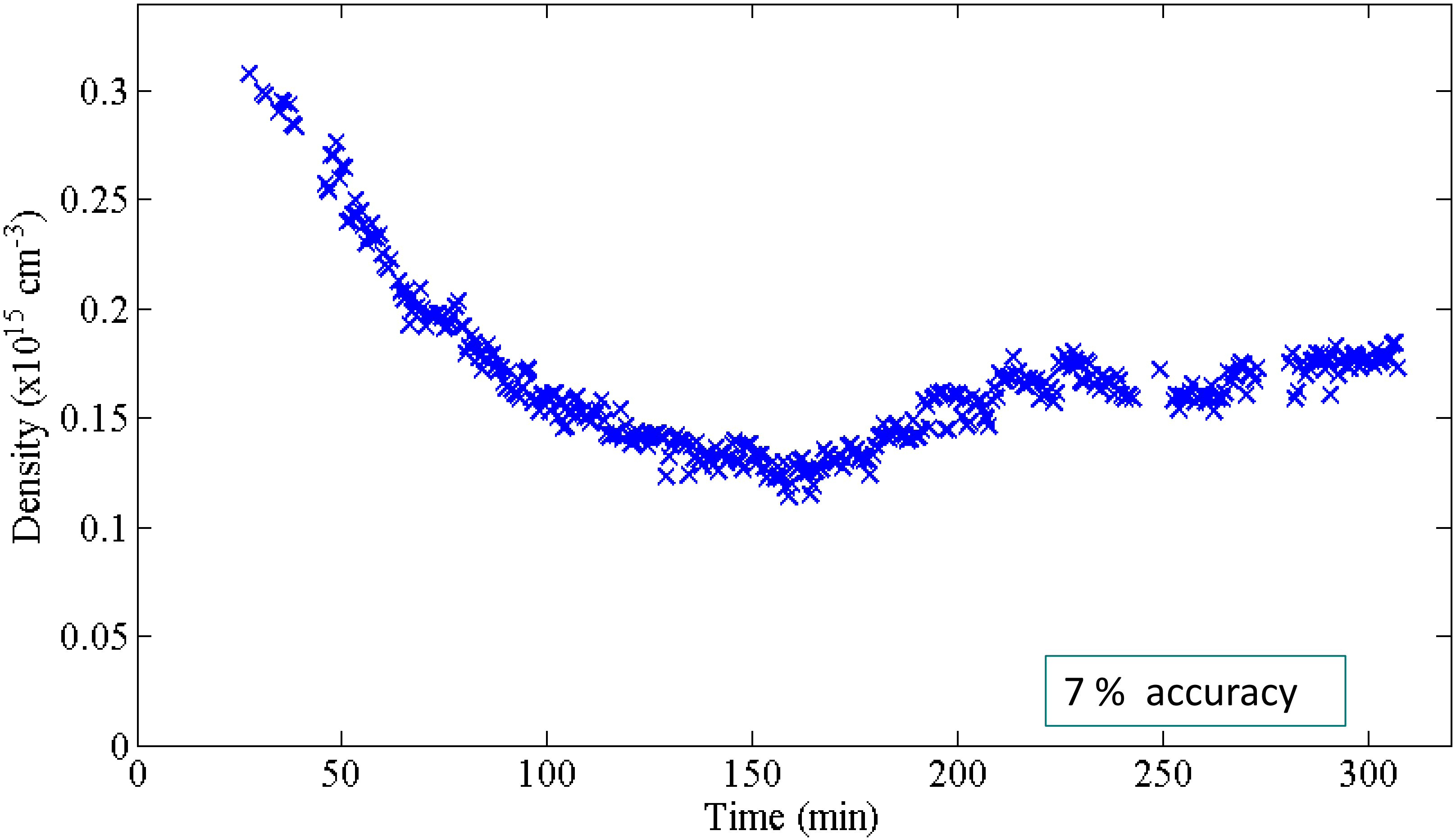
- Measured Rb density downstream during Dec run
- Determine vapor cells (long-term) density stability
- Vapor cell calibration: set temperature in reservoir – measured density in the beam pipe



- During run: density live on fixed display in control room

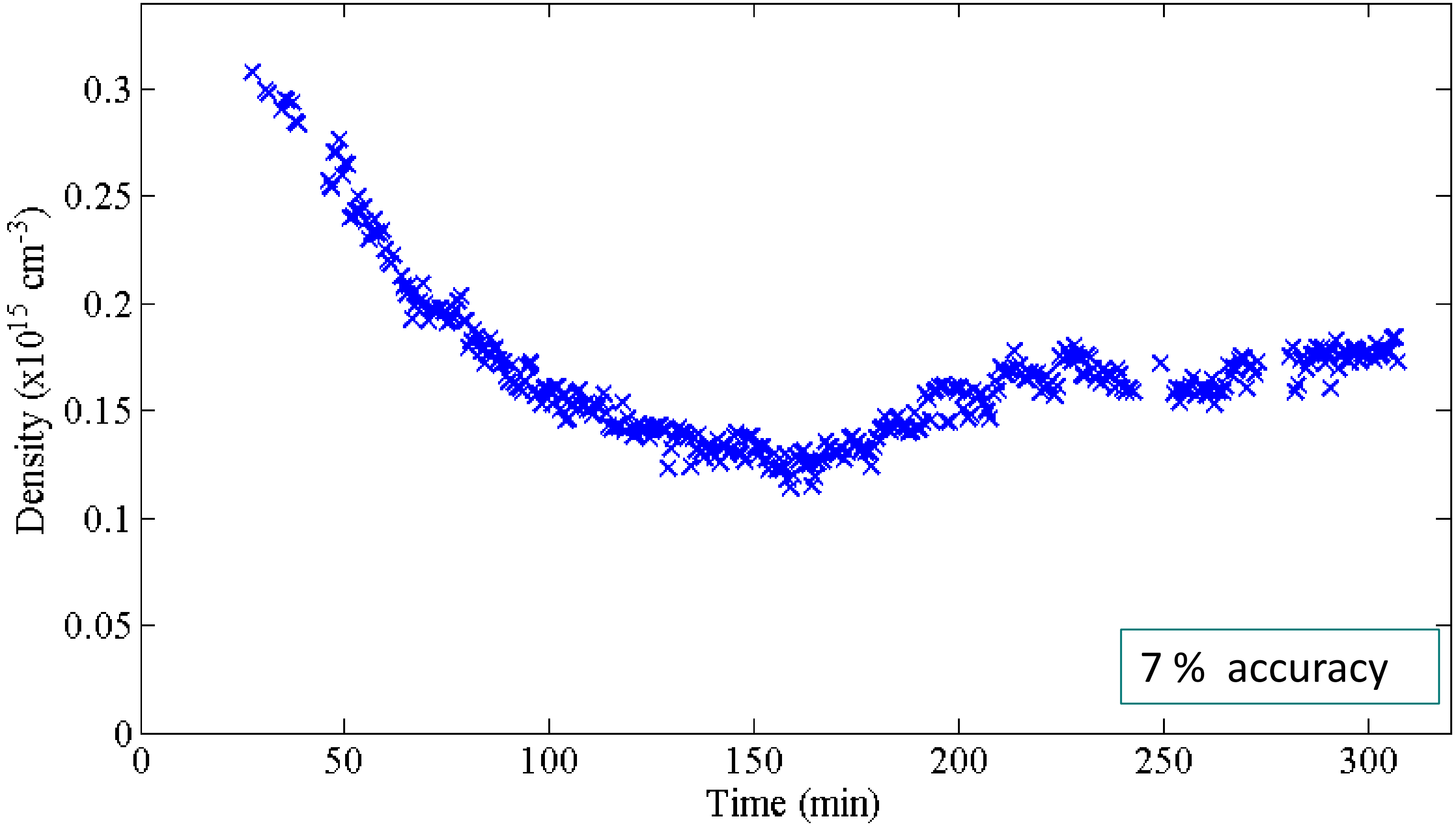
Results from Dec run:

- Measured density vs time (t = 0 ~ 12/12/16, 00:00 Geneva time)



Results from Dec run:

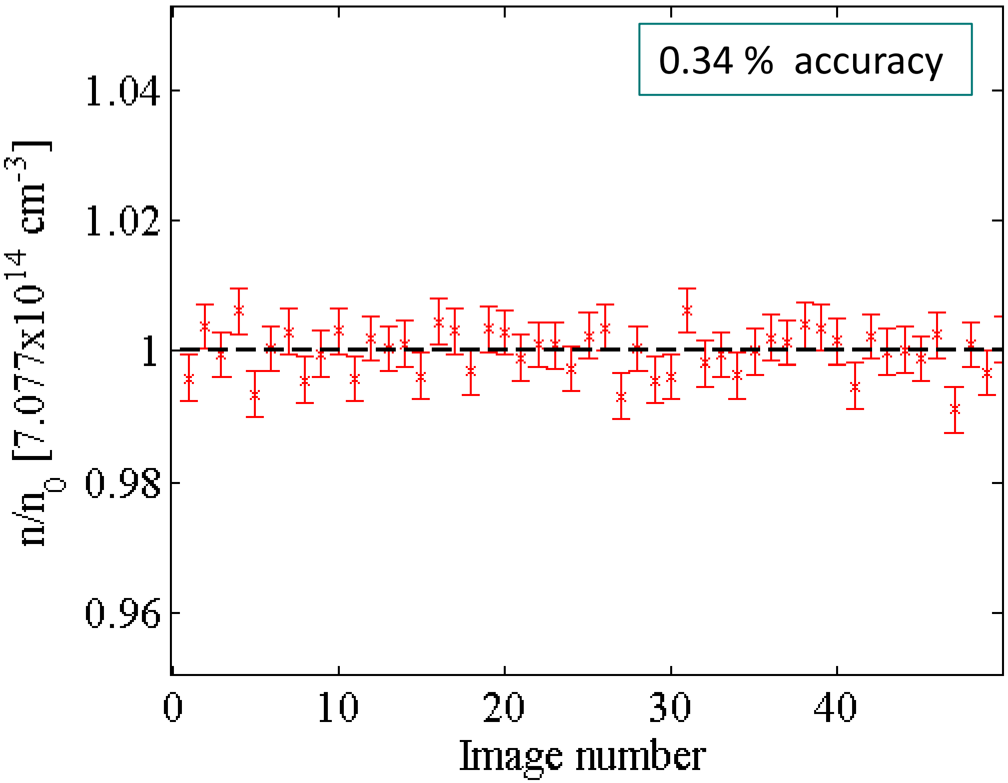
- Measured density downstream over time (t = 0 ~ 12/12/16, 00:00 Geneva time, every 40 sec)



Measurements:

Norm. by FFT

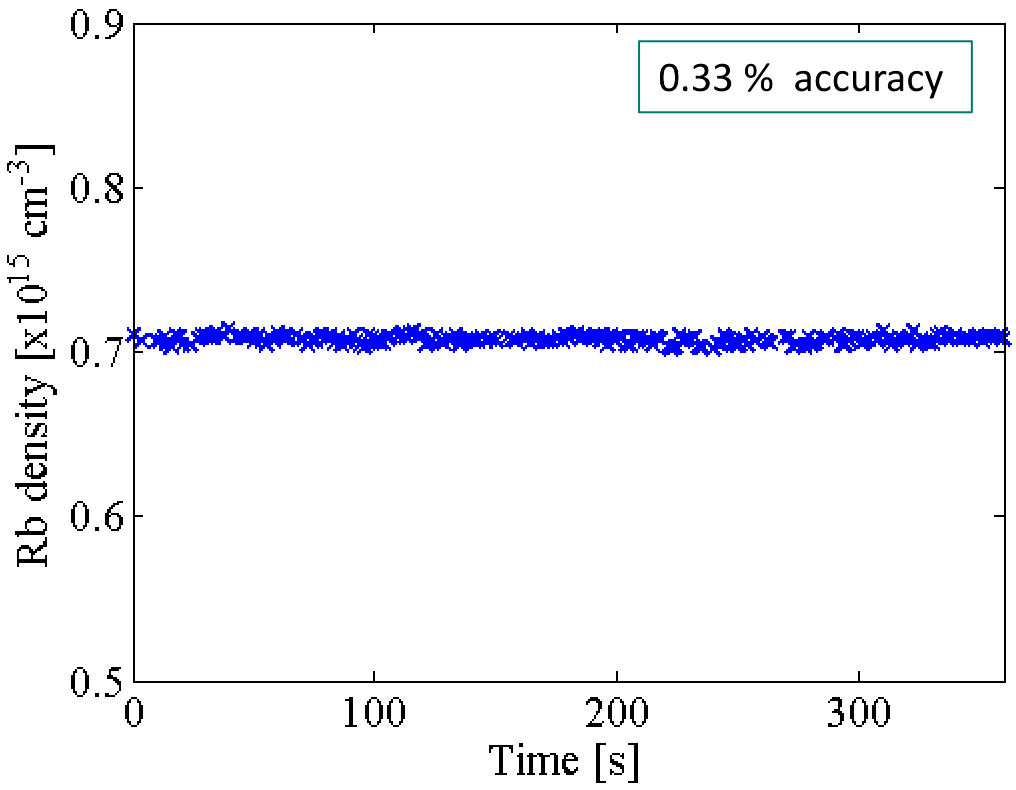
- Determine measurement uncertainties at stable density by recording 50 images over short time (< 10 sec)



Measurements:

Norm. by FFT

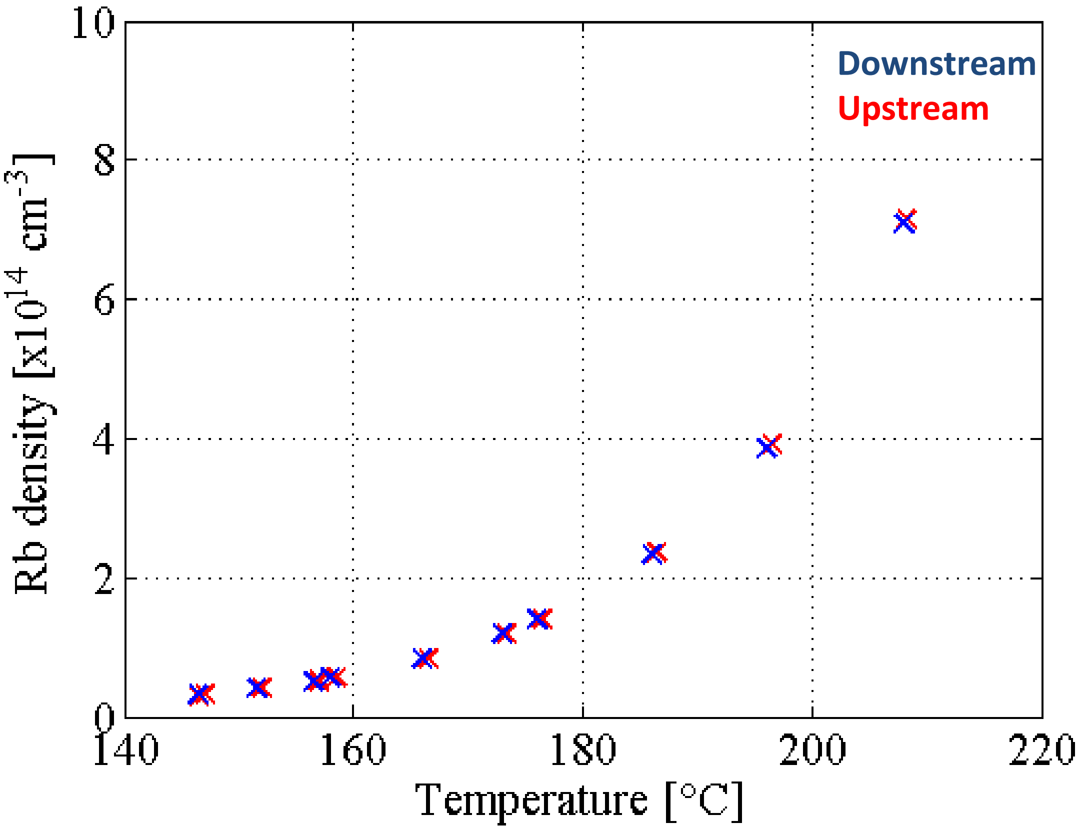
- Long-term stability:

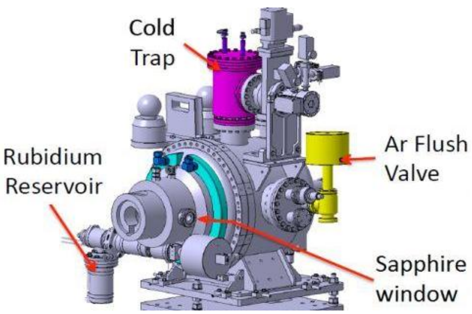


Measurements:

Norm. by FFT

- Vapor cell calibration: correlation between temperature set in Rb reservoir and measured Rb vapor density

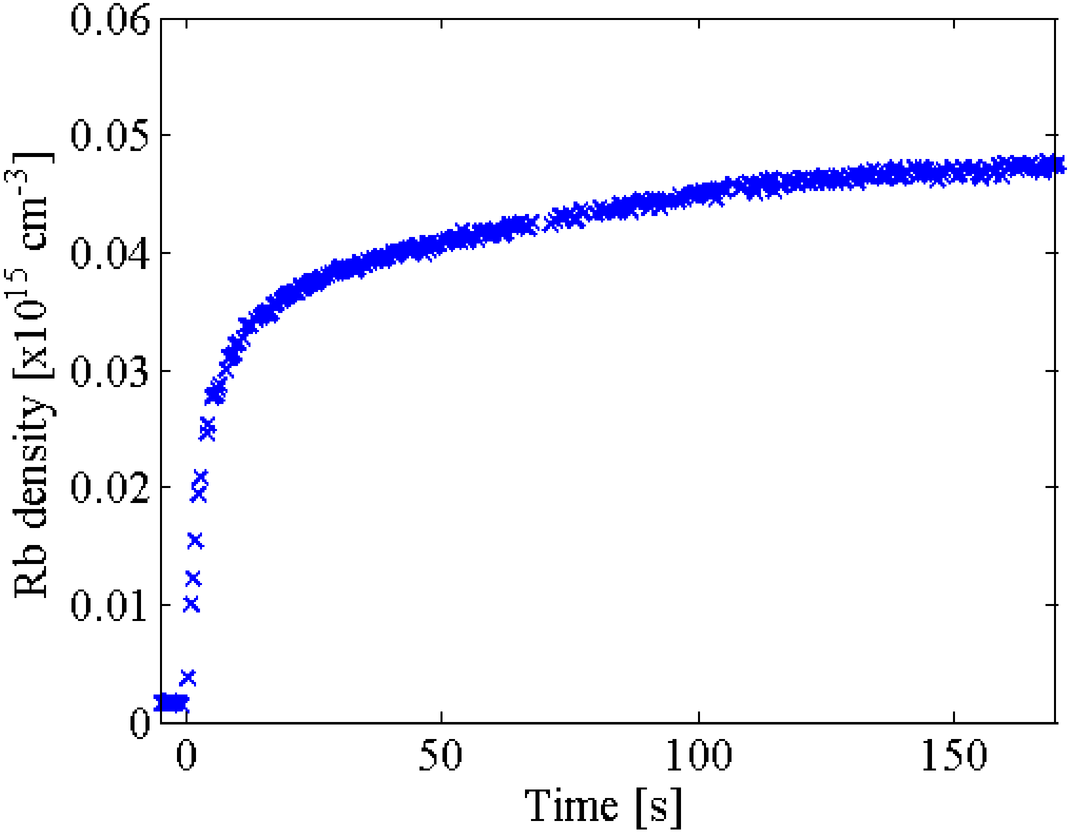




Measurements:

Norm. by FFT

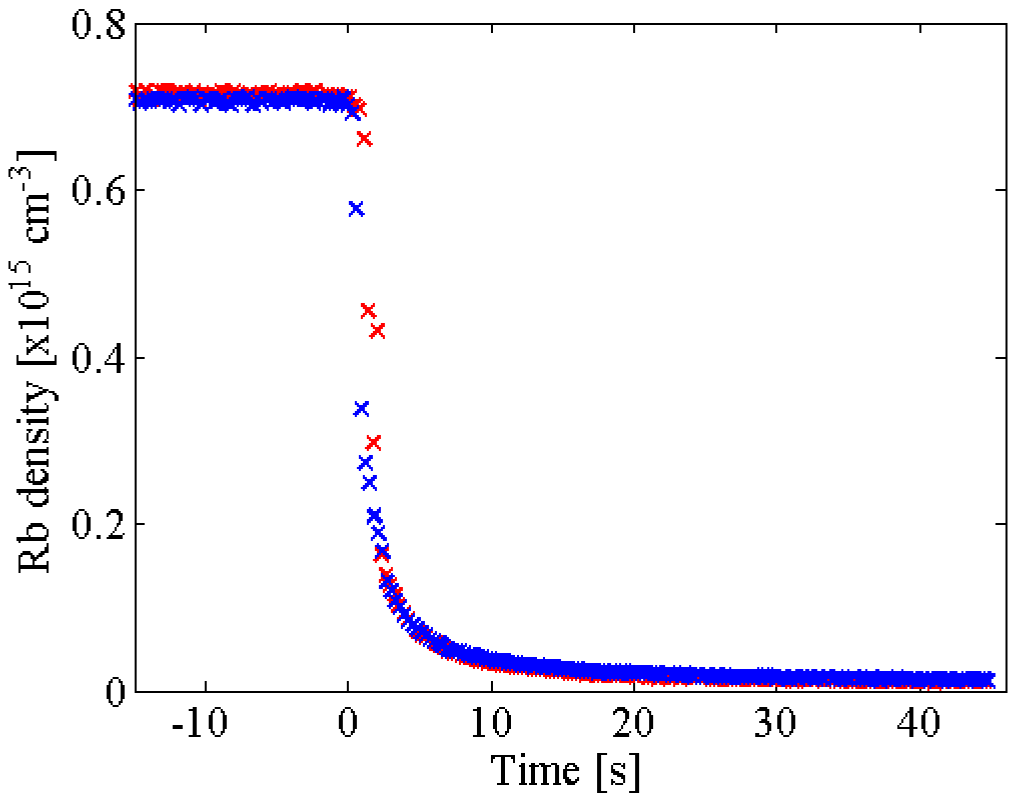
- Density over time: cell filling (cell hot, open Rb valves (1% accuracy))



Applications:

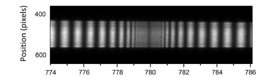
Norm. by FFT

- Density over time: cell emptying for both ends (0.25% accuracy)



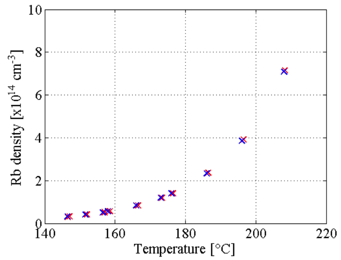
Summary:

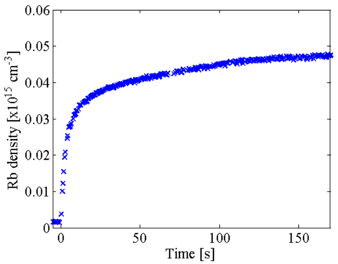
- Use Mach-Zehnder Interferometer / White light interferometry

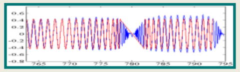


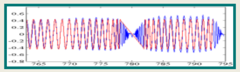
- Normalization of spectra + nonlinear least-square fitting routine, giving 0.3 % rel. accuracy.
- Measure Rb vapor density gradient with two interferometers at both ends, laser / spectrograph and cell separated -> light transport in 120 m fibers

- Use at AWAKE: last Dec, now remotely controlled. E.g for cell characterization
- Automated and density diagnostic during future runs.









n_1= 7.08

n_2= 7.14

gradient= + 0.89 %

x 10^{14} cm^{-3}

Thank you!

Back-up slides

Fiber specification :

- Nufern 780-HP:

Optical Specifications

Operating Wavelength	780 – 970 nm
Core NA	0.130
Mode Field Diameter(Gaussian)	5.0 ± 0.5 μm @ 850 nm
Cutoff	730 ± 30 nm
Core Attenuation	≤ 4.0 dB/km @ 780 nm

Geometrical & Mechanical Specifications

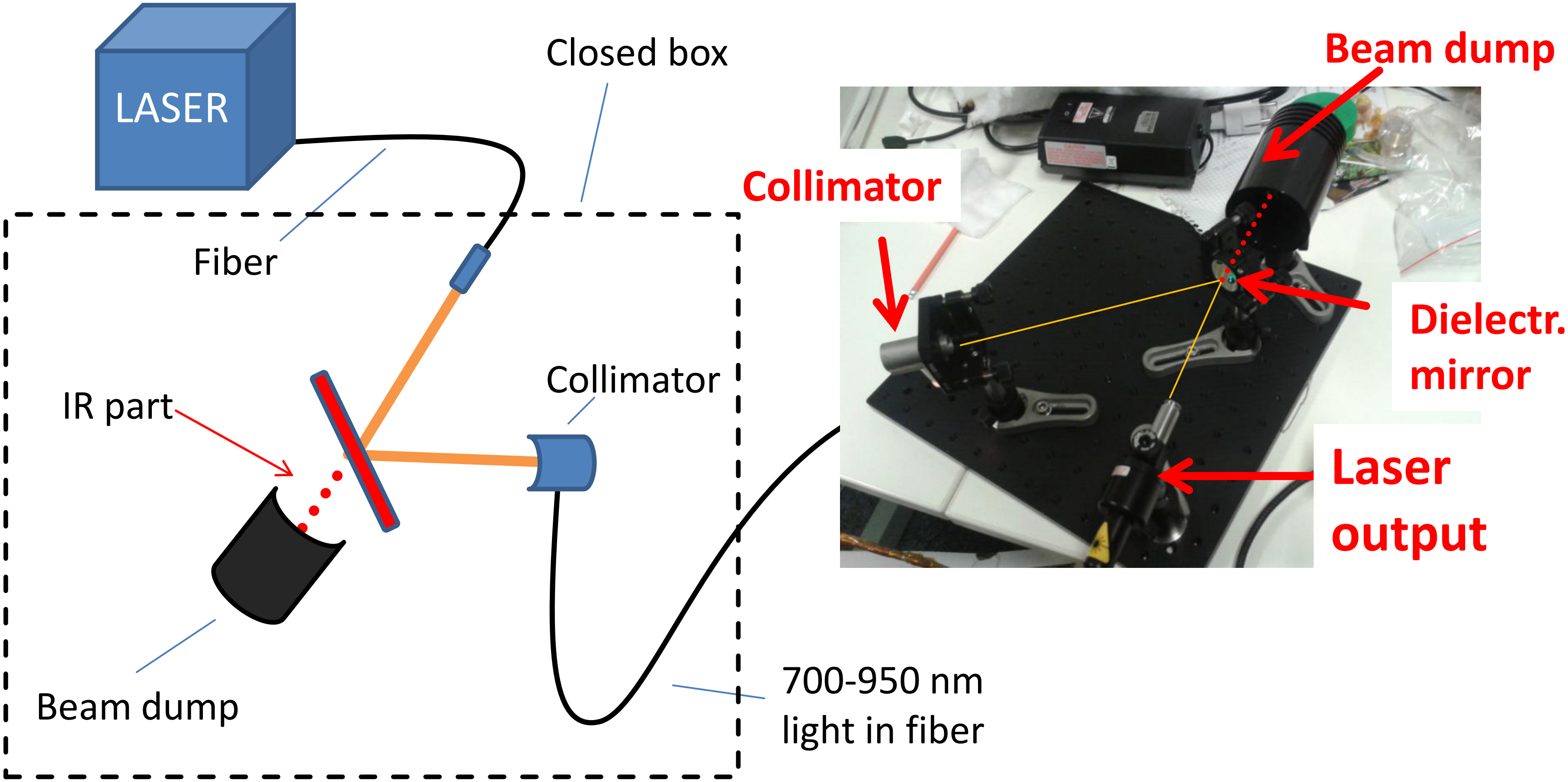
Cladding Diameter	125.0 ± 1.0 μm
Core Diameter	4.4 μm
Coating Diameter	245.0 ± 15.0 μm
Coating Concentricity	< 5.0 μm
Core/Clad Offset	≤ 0.50 μm

NKT SuperK Compact Laser

Optical Spectral Range	450-2400 nm
Total output power	> 110 mW
Total VIS power (450-850 nm)	> 25 mW
Output power stability (1 hour)	± 2.0 %
Repetition rate	Variable 1 Hz to minimum 20 kHz
Output pulse width	< 2 ns
Pulse-pulse jitter (Std. Dev.)	< 2 µs (rep rate dependent)
Output fiber	Single mode

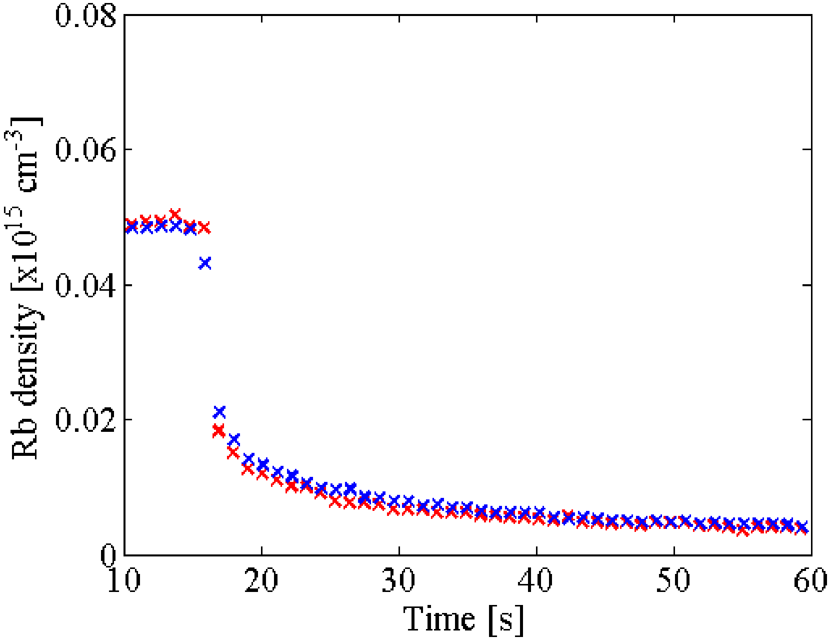
Appendix: IR light filtering

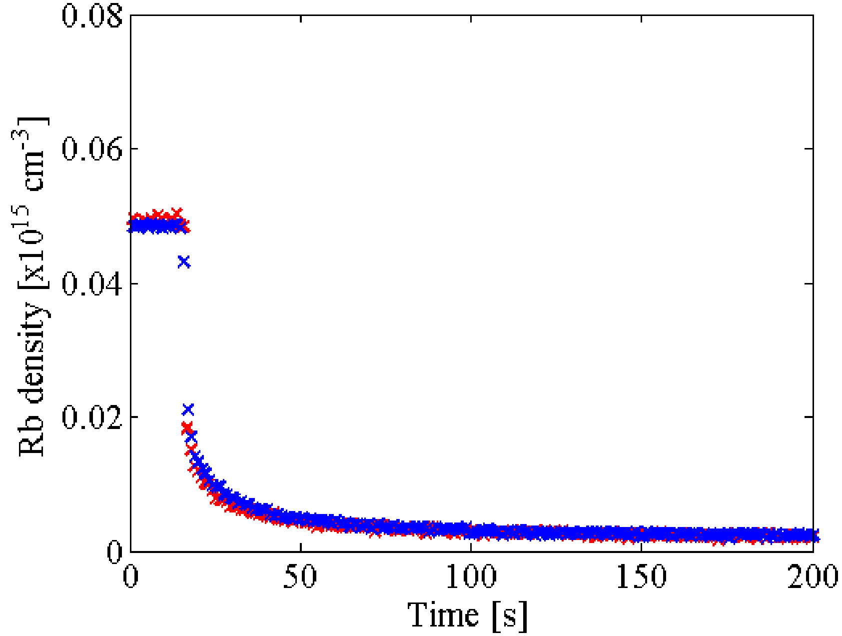
- Select wavelength range around 780 nm to avoid high-intensity laser light > 950 nm for safety (peak in laser intensity at 1064 nm)



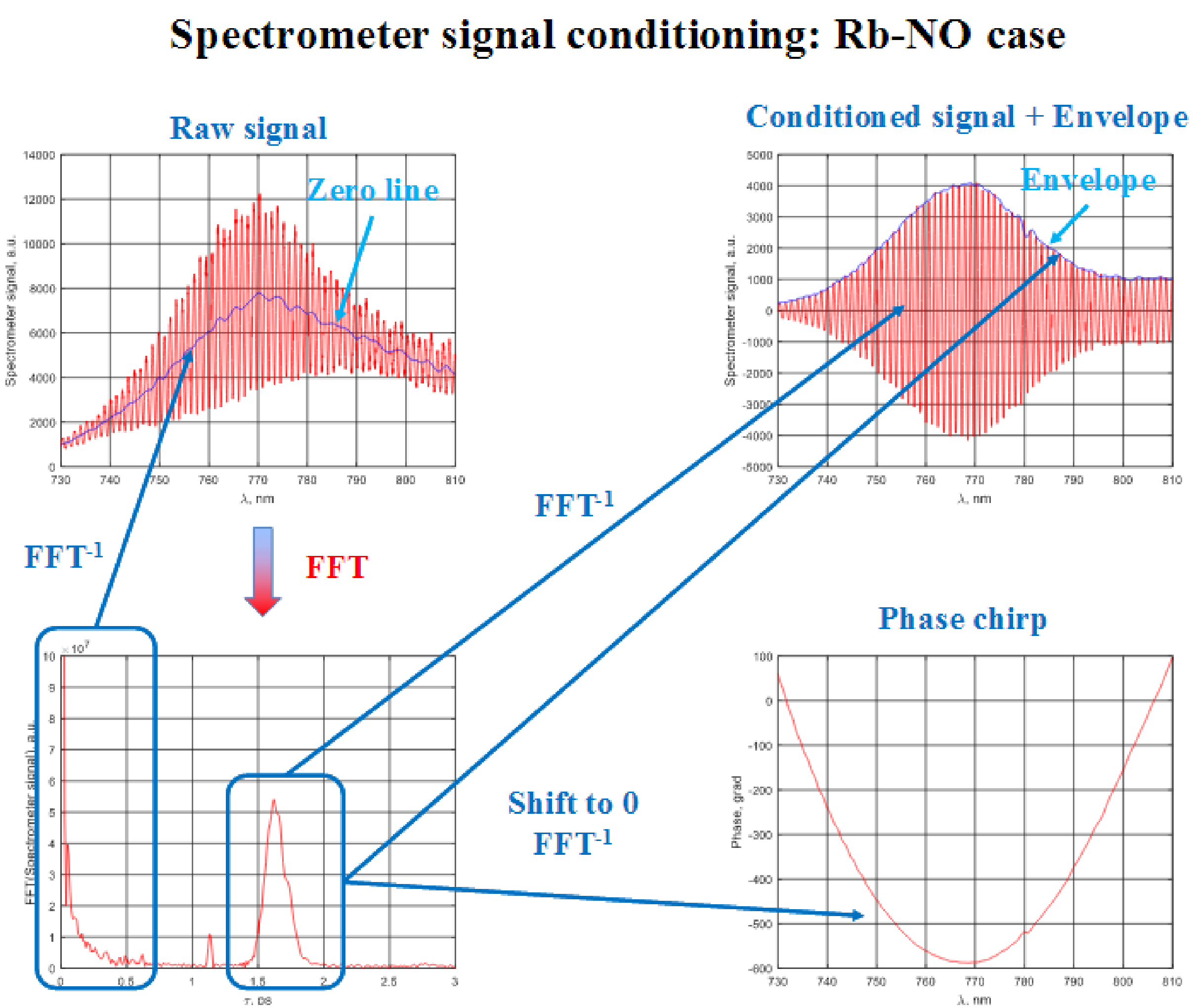
Applications:

- Density over longer time for emptying process

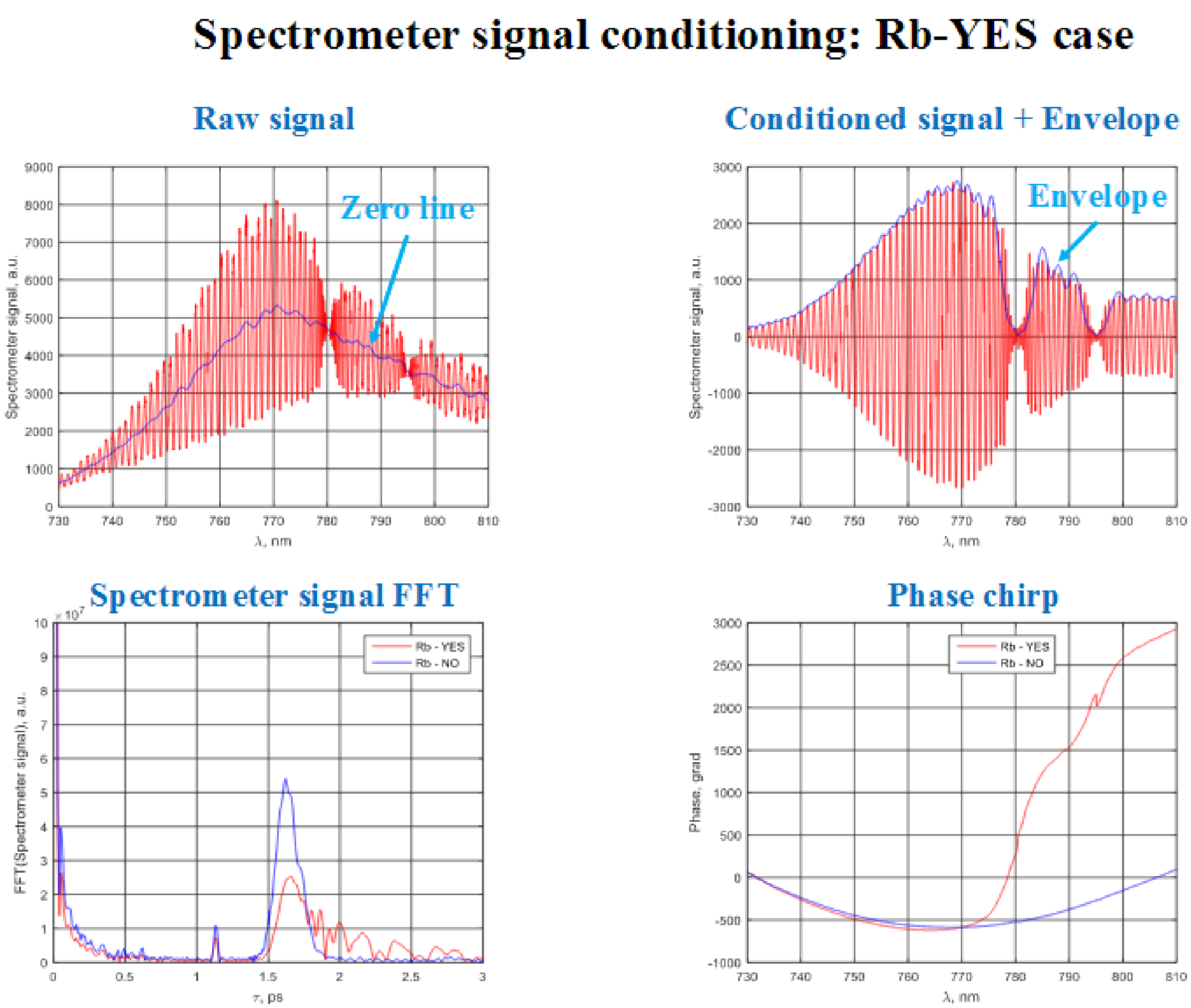




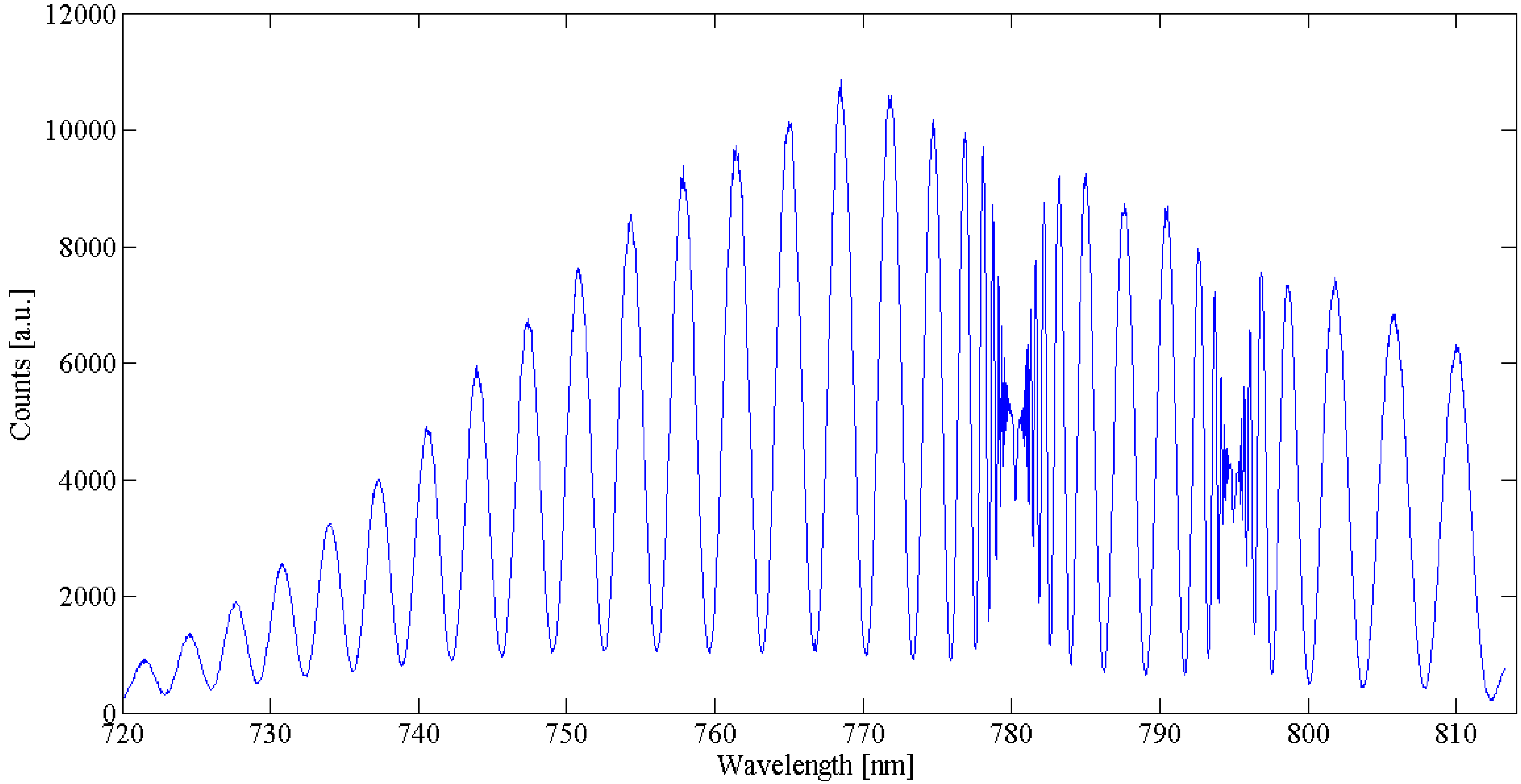
FFT data conditioning by M. Martyanov:



FFT data conditioning by M. Martyanov:

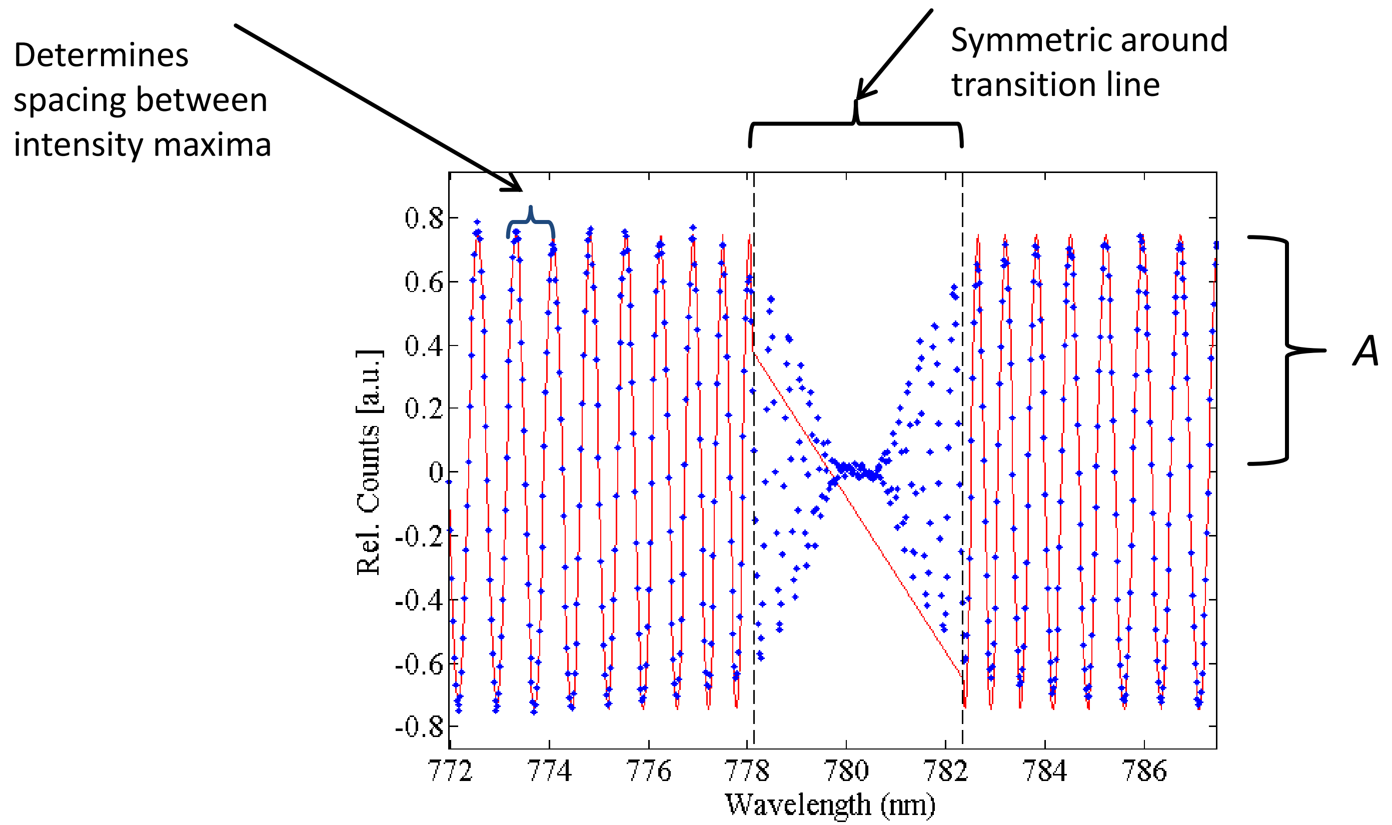


Raw data image:



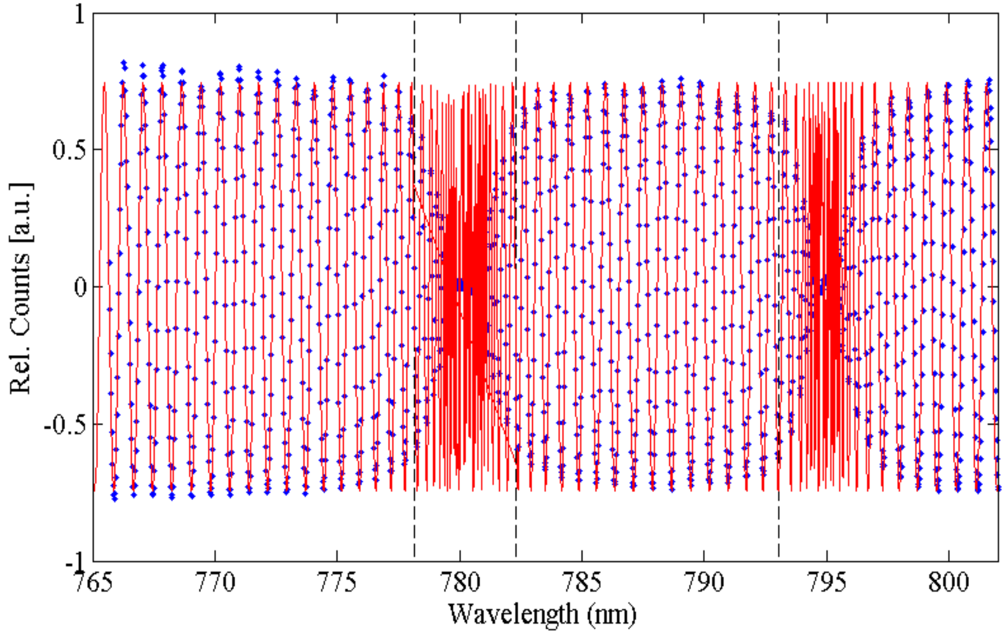
Influence of other fit parameter errors

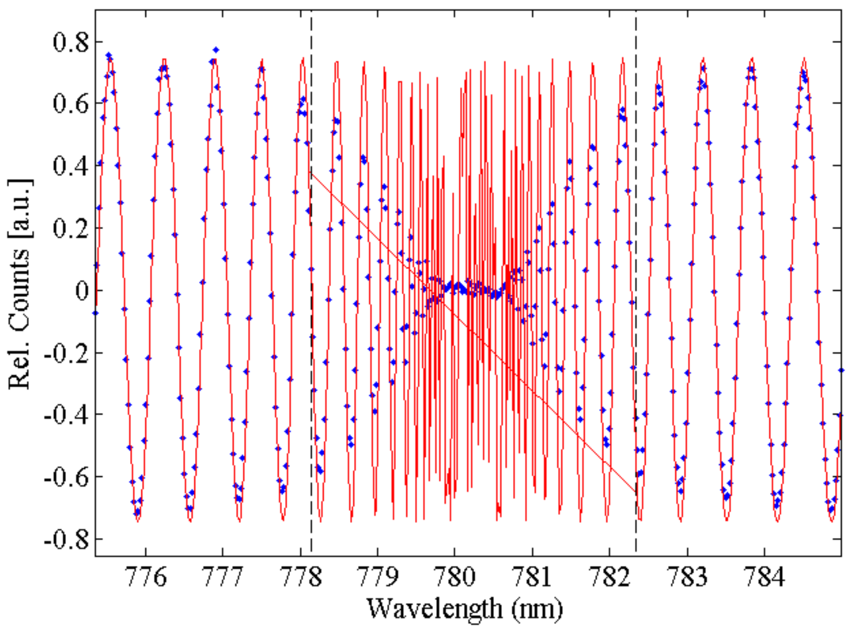
- Results have to be independent from all others parameters:
  Path length difference (pld), Amplitude *A* and Size of excluded data around transition line.



Comparison Fit - Data

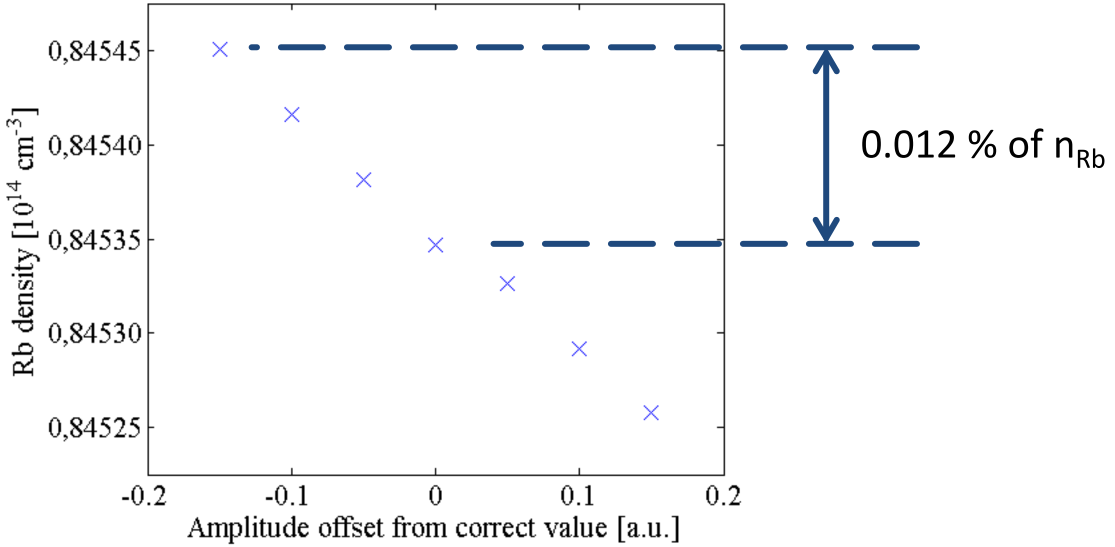
Fit results plotted over excluded image regime:





Effect of amplitude errors

- Results have to be independent from all other fitting parameters:
  Path length difference, Amplitude A and Size of excluded data around transition line.
- Calculating n_{Rb} by varying the amplitude *A* manually from *A* = 0.79 to false values:



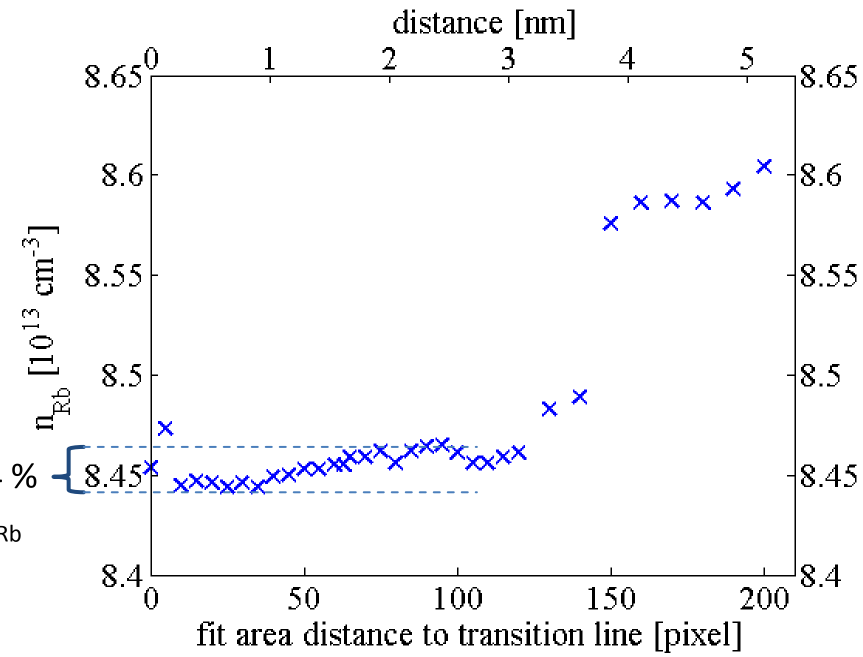
→ An error of Δ A = 0.15 ≙ 19 % in amplitude leads to an error of 0.012 % in n_{Rb}

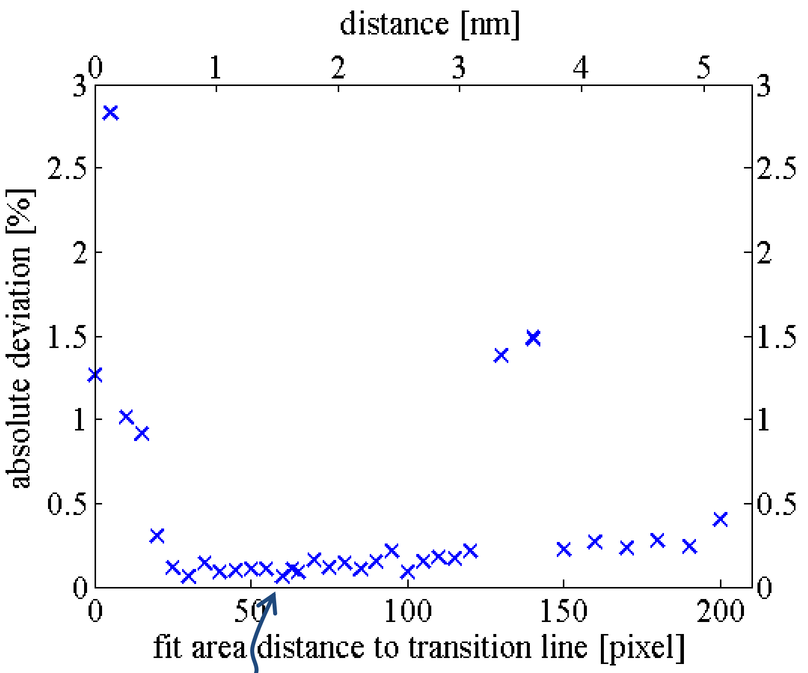
✓ Negligible

Size of excluded data

- Results have to be independent from all others fitting parameters:
  Path length difference, Amplitude and Size of excluded data around transition line.
- Calculating n_{Rb} by changing the size of the ignored area in spectrograph image:

0.24 % of n_{Rb}



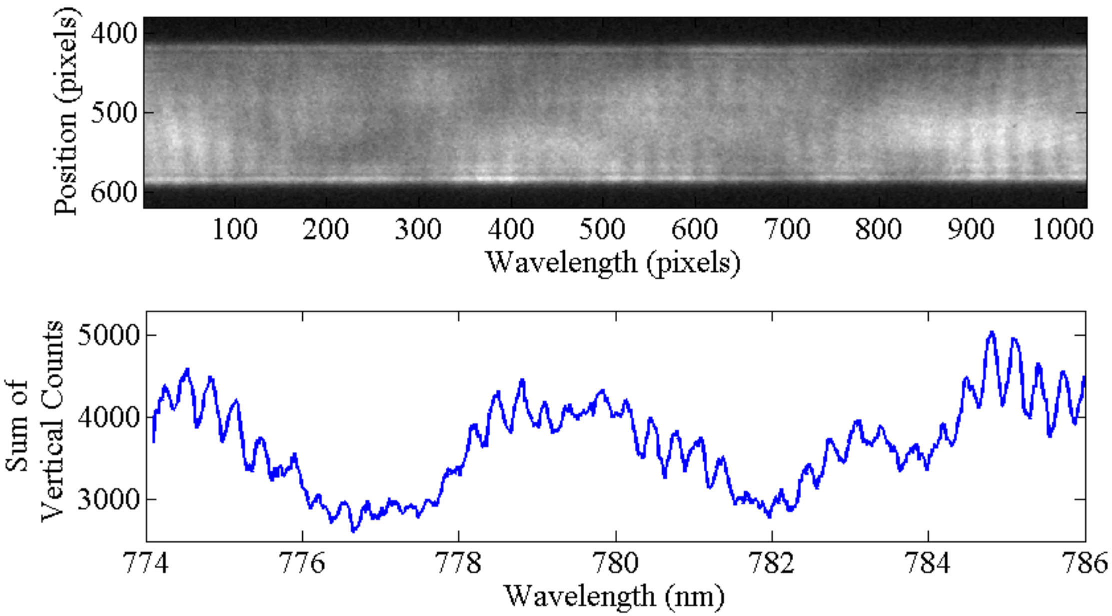


- Between 30 and 100 px, n_{Rb} is in ± 0.12 %
  -> change on a small scale for some px

~ 60 px chosen to be optimal, with n_{Rb} ± 0.07 %

Speckles in MM fibers

- In multi mode fibers, different modes interfere randomly, forming speckles.



The hook method

- The original hook method uses not fibers, but mirrors
- Form not vertical, but oblique fringes (set to an angle wrt. the spectrograph slit)