Interferometer-based white light measurement of neutral rubidium density for the AWAKE experiment at CERN

Fabian Batsch

Max-Planck-Institute for Physics

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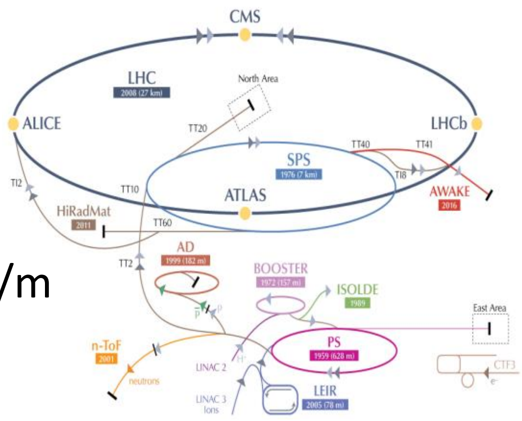
Outline

- Motivation and the AWAKE experiment
- Measurement method
- Achieved accuracy
- Summary + Outlook

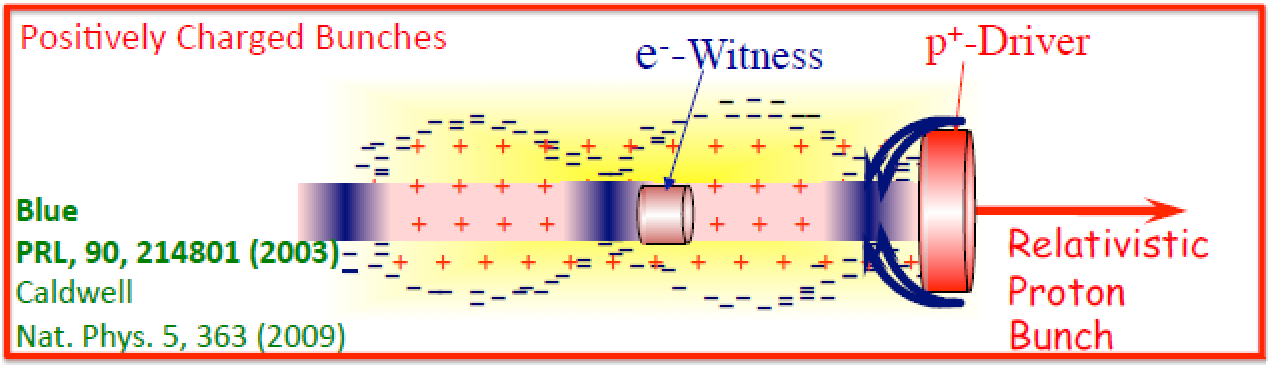
The AWAKE Experiment



- Advanced Wakefield (AWAKE) experiment @ CERN
- Goal: pave the way for short high-energy e^- accelerators
- Conventional RF cavities: E< 100 MV/m, L >10 km for 1 TeV

  <-> Plasma waves can sustain accelerating fields up to 100 GV/m

  → Acceleration length for 1 TeV is only 10 m!
- First proton driven wakefield experiment, will start 12/2016
- Uses 400 GeV/c SPS proton beam as driver



Motivation

- Central part in AWAKE: 10 m long rubidium plasma source, n = 10^{14} - 10^{15} cm^{-3}
- Laser-ionization of Rb vapor -> plasma with same density
- 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 1 % accuracy

→ Measure optically and fully automated Rb vapor densities at both ends with ± 0.5% relative accuracy

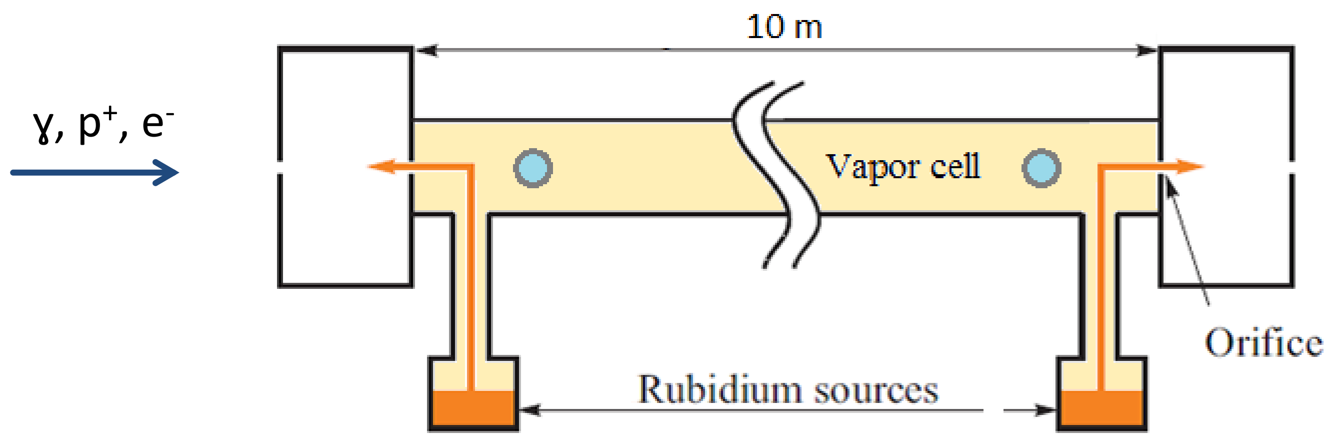


Fig.
Drawing of the Rb vapor source (by G.Plyushchev)

Motivation

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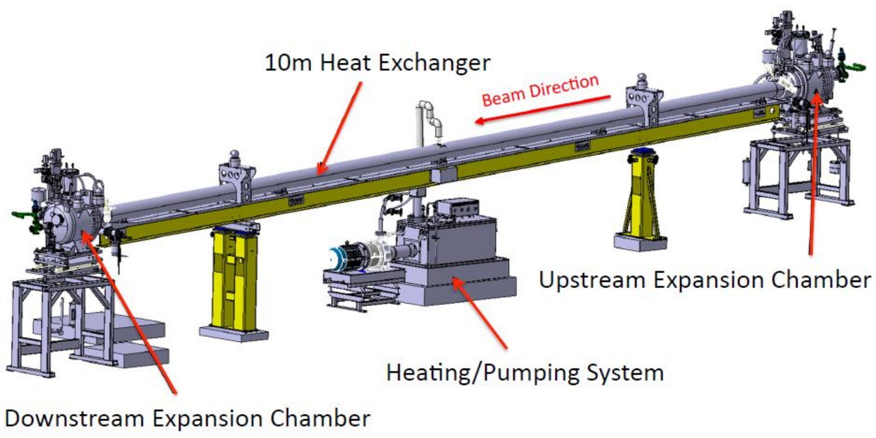
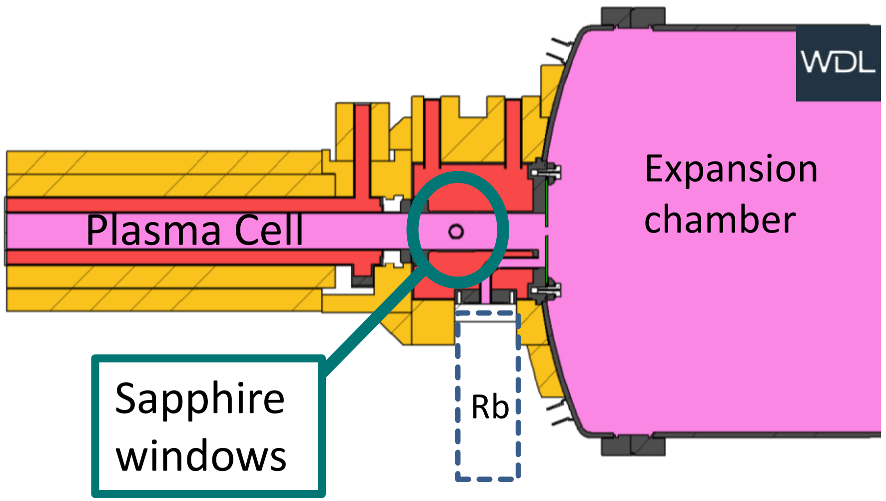




Properties of Rb vapor

- 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):

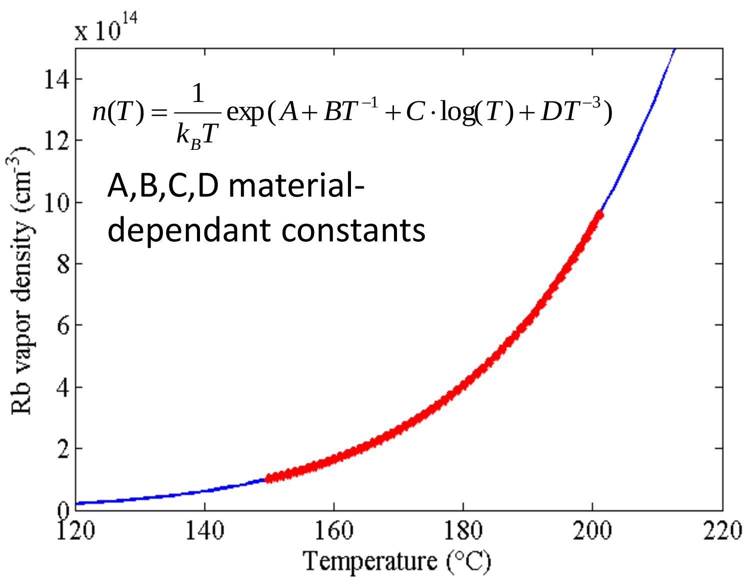


Fig. Rb Vapor temperature plotted versus its density

- 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

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

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

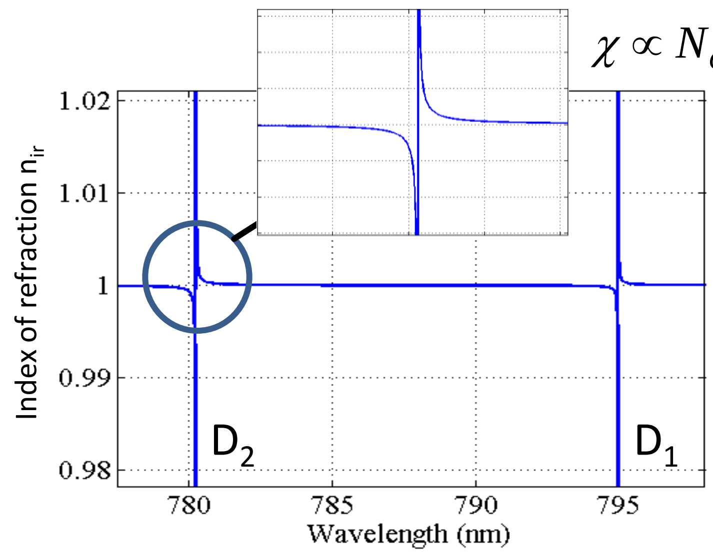


Fig. Index of refraction for n= $9.8 \cdot 10^{14}$ cm^{-3}

Measurement method

- Use interferometry and the <u>hook method adapted to vertical fringes</u>
- 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

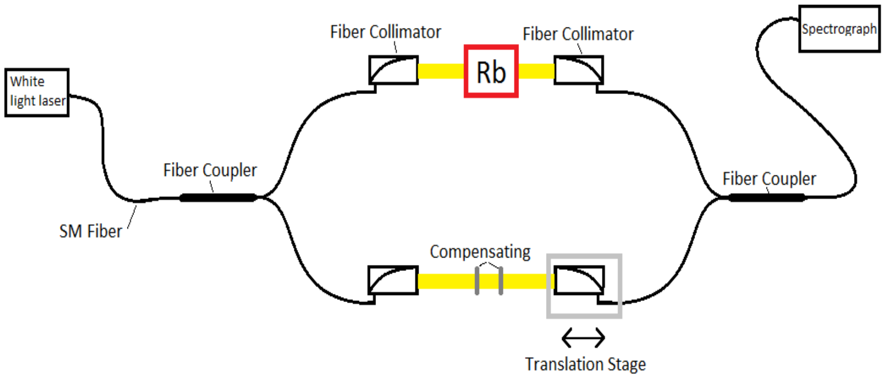
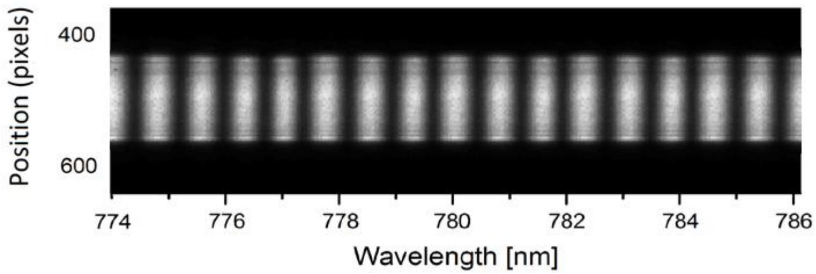
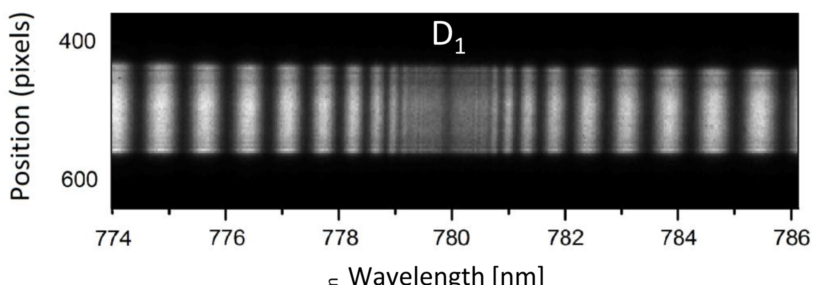


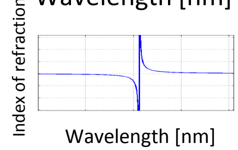
Fig. Setup of the fiber-based Mach-Zehnder Interferometer

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



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





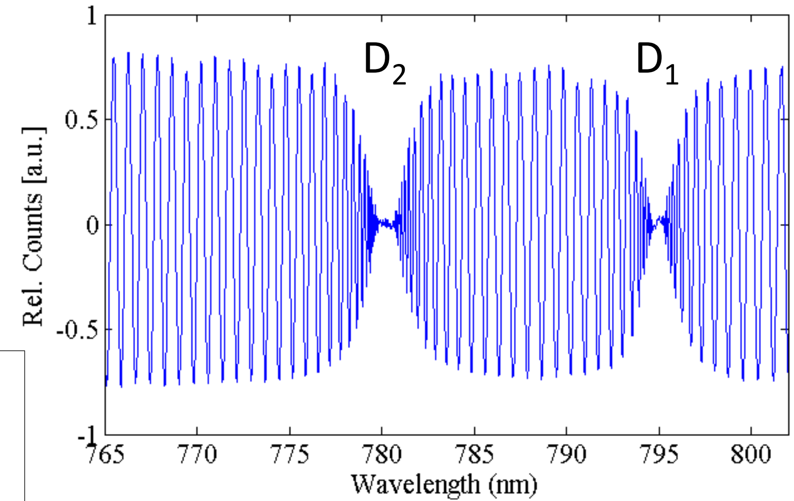
Determine density by fitting

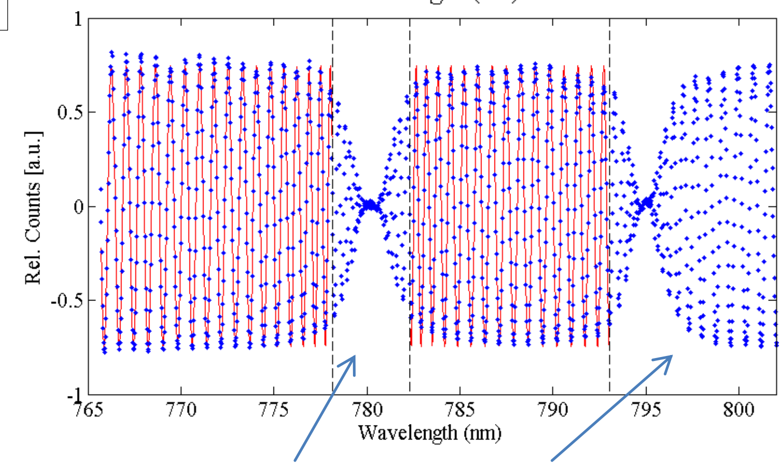
- Summing counts per wavelength or use 1D spectrograph, then normalize to get intensity profile
- Intensity function *S* given by:

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

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 ~



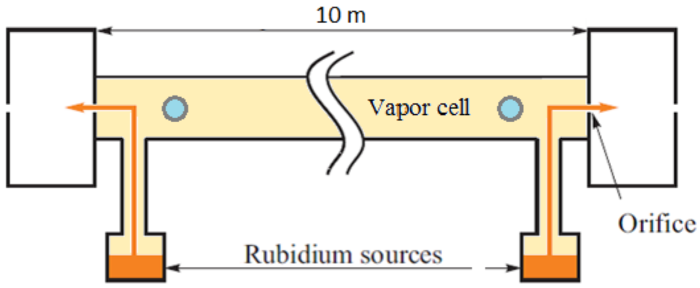


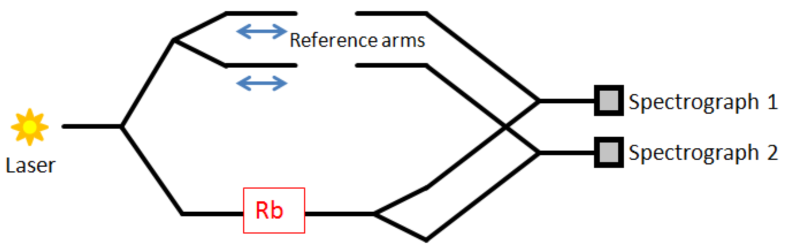
Areas ignored by fit

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

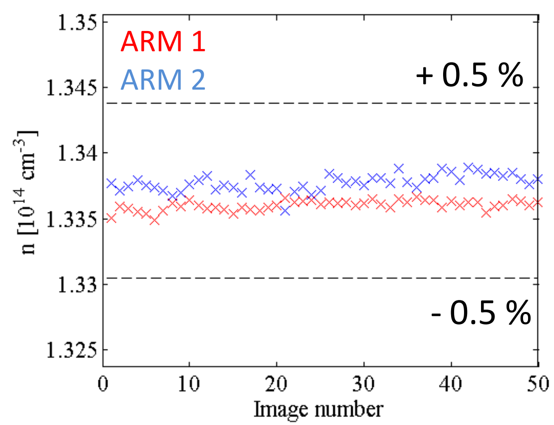
Gradient determination accuracy:

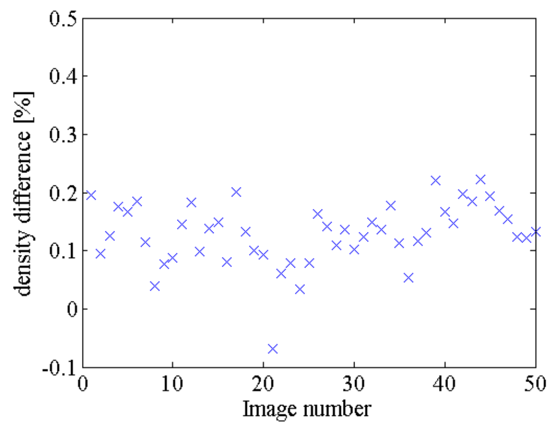
- Crucial point: Measure not one, but two two density - length products with the same accuracy < ± 0.5%   <-> determine density gradient at % level
- Idea: Probing the same Rb vapor with two independent measurement setups





✓ Both measurements differ by 0.1 – 0.2 % , depending on temperature and goodness of the spectrometers calibration



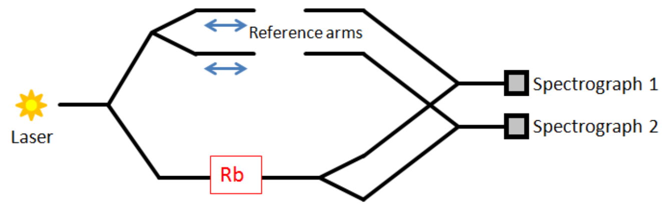


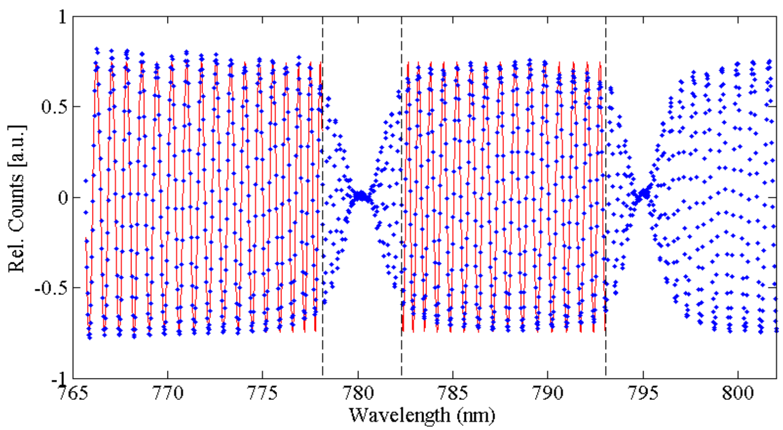
Fitting challange:

- Measurement of equal density-length products not trivial :

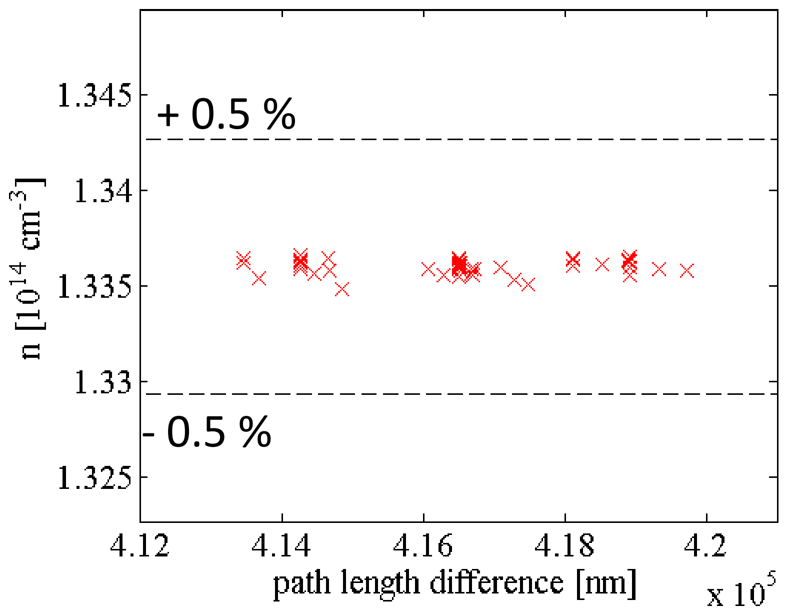
  Vibrations causing changes in path length differences (pld) can be misinterpreted as changes in density

→ n_{Rb} for several events at T = const. are within 0.08 %, although pld changes





Result:

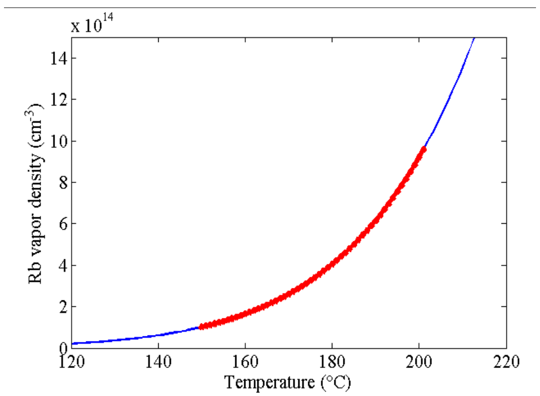


$$S(\lambda) = \tilde{A} \cdot \cos\left(\frac{2\pi}{\lambda} \cdot \left[\frac{\boxed{\tilde{n} l} \cdot r_0 f_1 \lambda_1^3}{4\pi(\lambda - \lambda_1)} + \frac{\boxed{\tilde{n} l} \cdot r_0 f_2 \lambda_2^3}{4\pi(\lambda - \lambda_2)} + \boxed{\tilde{\xi}} \right] \right)$$

Evaluating the absolute accuracy

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

Expected:

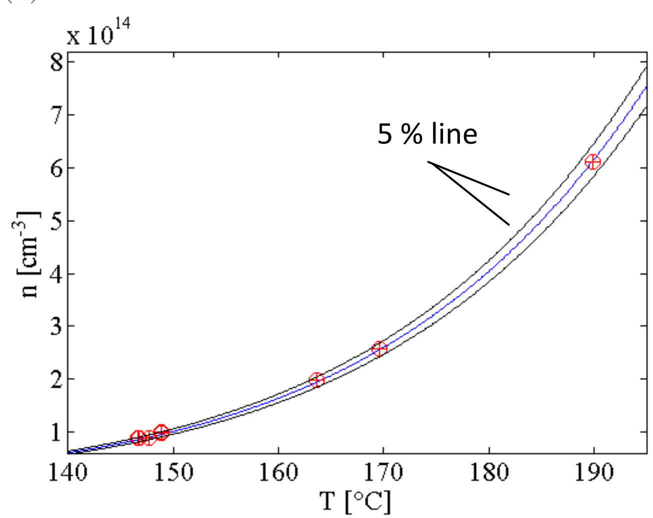


$$n(T)=\frac{1}{k_B T}\exp\left(A+BT^{-1}+C\cdot\log(T)+DT^{-3}\right)$$

A,B,C,D material-dependant constants

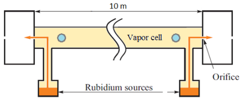
Fig. Rb Vapor temperature plotted versus its density

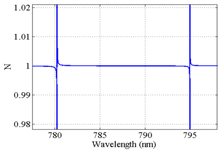
Measured n_{Rb} vs. T:

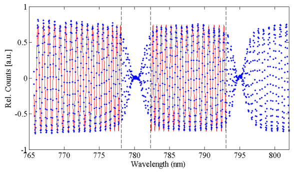
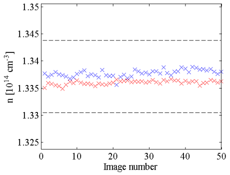


✓ Measured values tracks vapor pressure curve at 0.6 – 3.8 % level

Summary:

- Measuring Rb vapor density with < 0.5 % accuracy is critical for AWAKE 

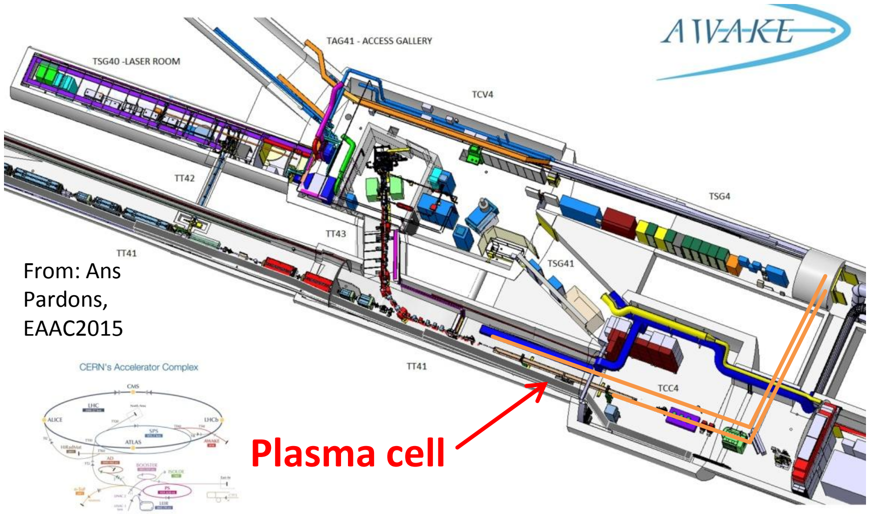
- Used anomalous dispersion around D_2 line of Rb 

- Developed a method to retrieve density to ± 0.1 – 0.2 % < 0.5 % with two interferometers  

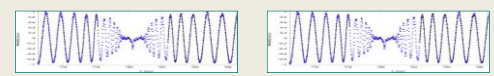
→ Requirements for gradient calculation reached

Outlook:

- Diagnostic will be installed at AWAKE as online density and gradient measurement



AWAKE fixed display:



n_1= 1.00

n_2= 1.02

gradient= 2%

Thank you for your attention!

Back-up slides

The different setups at MPP:

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

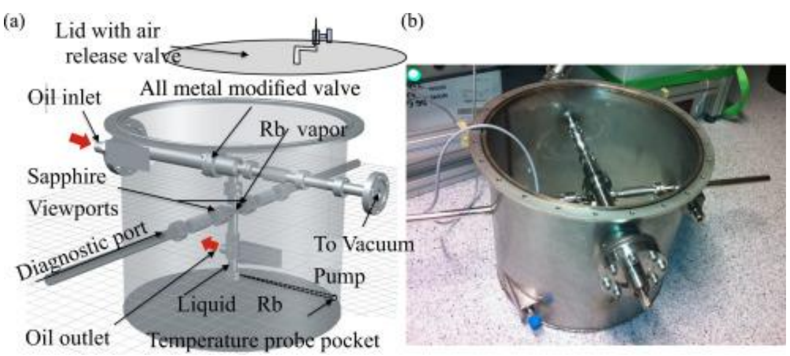


Fig. (a) Schematic and photo (b) of the oil heated Rb reservoir.

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

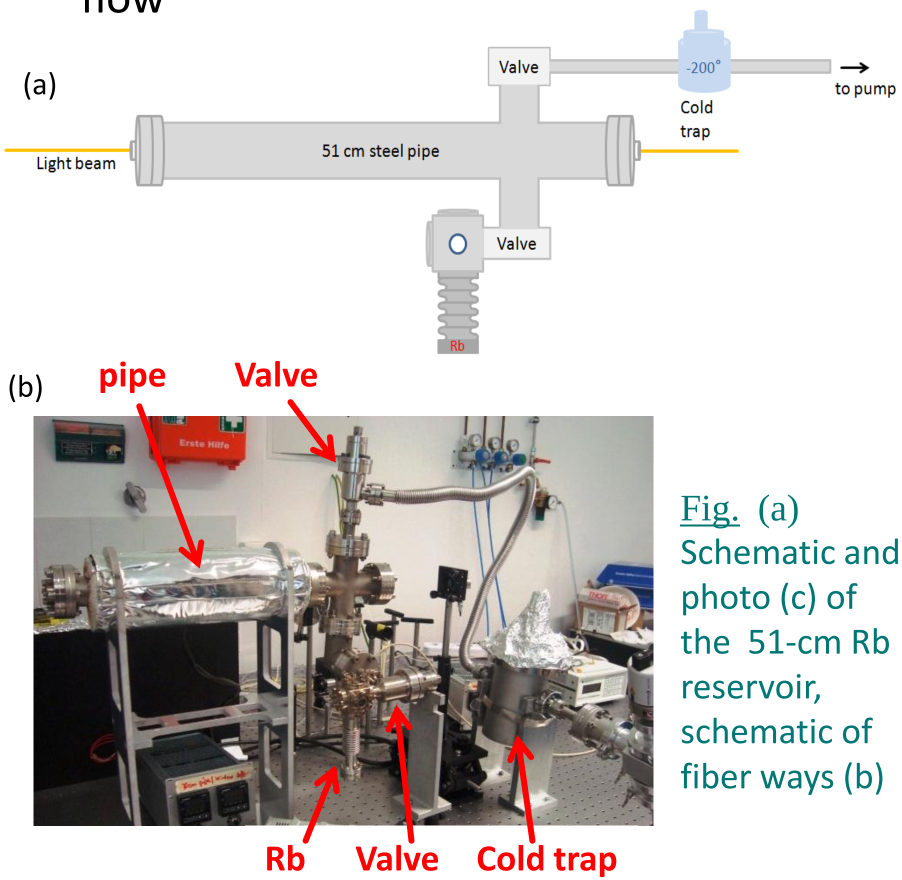
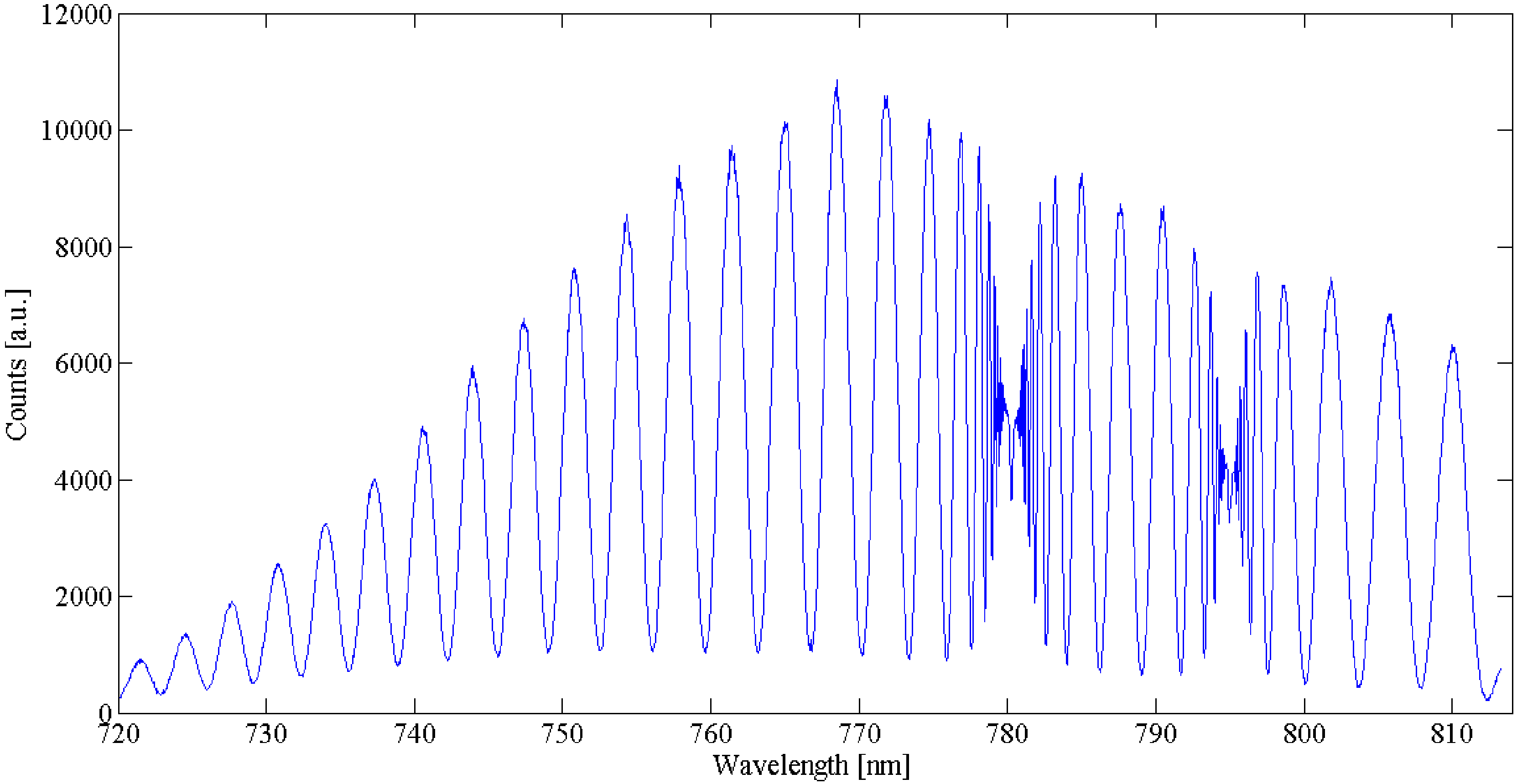


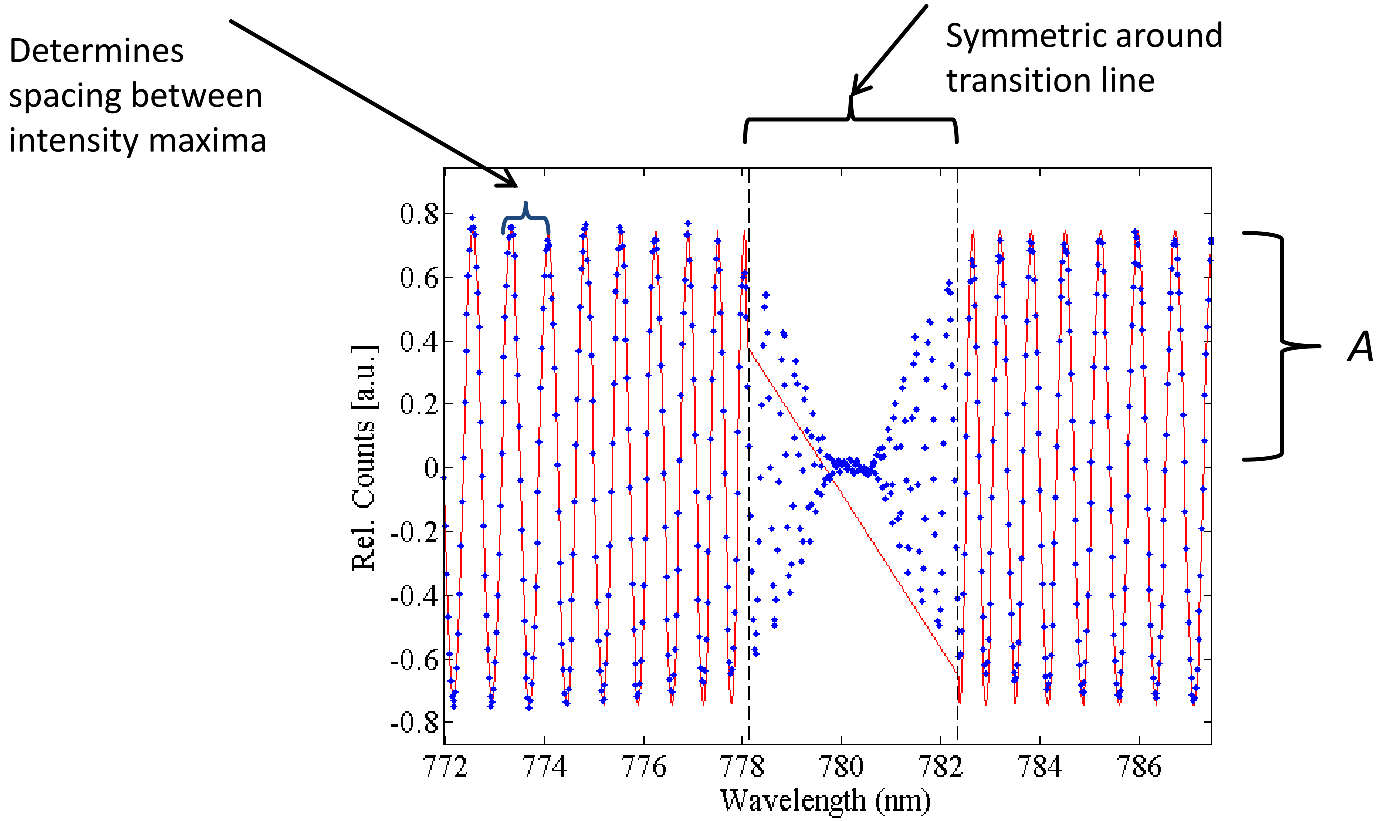
Fig. (a) Schematic and photo (c) of the 51-cm Rb reservoir, schematic of fiber ways (b)

Raw data image:



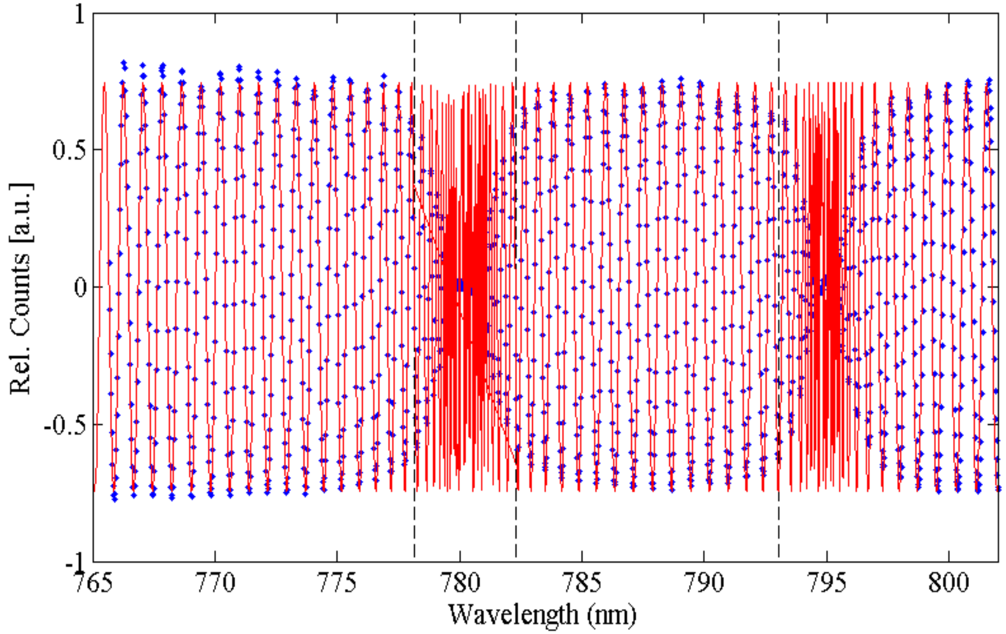
Influence of other fit parameter errors

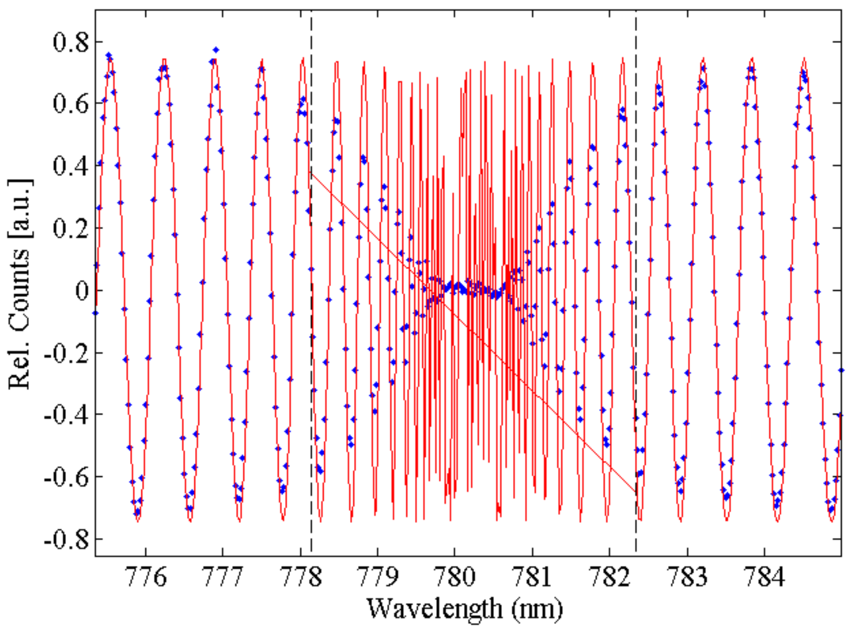
- Results have to be independent from all others parameters:
  Path length difference (pld), Amplitude *A* and Size of excluded data around transition line.



Comparison Fit - Data

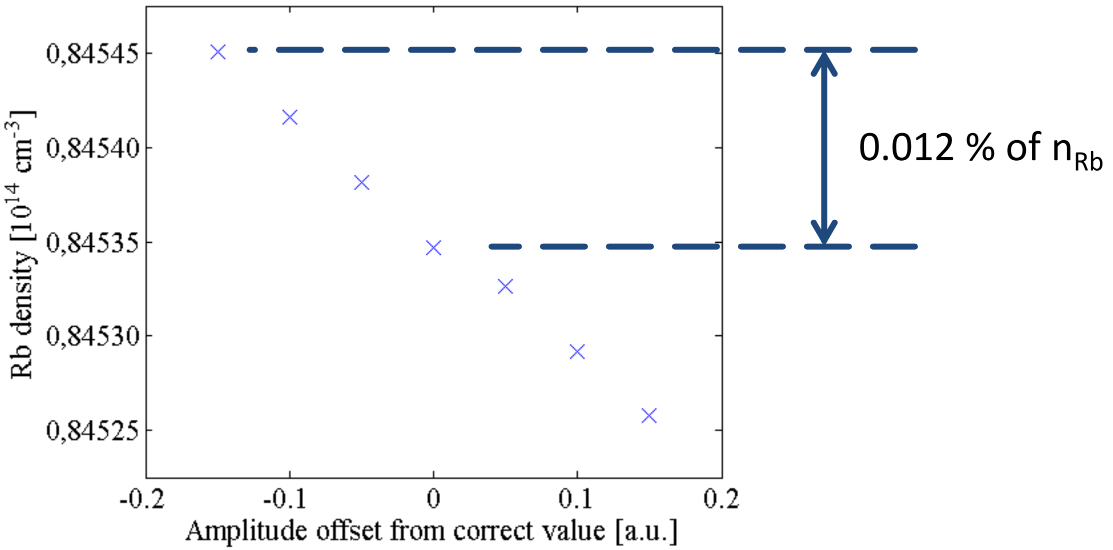
Fit results plotted over excluded image regime:





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:

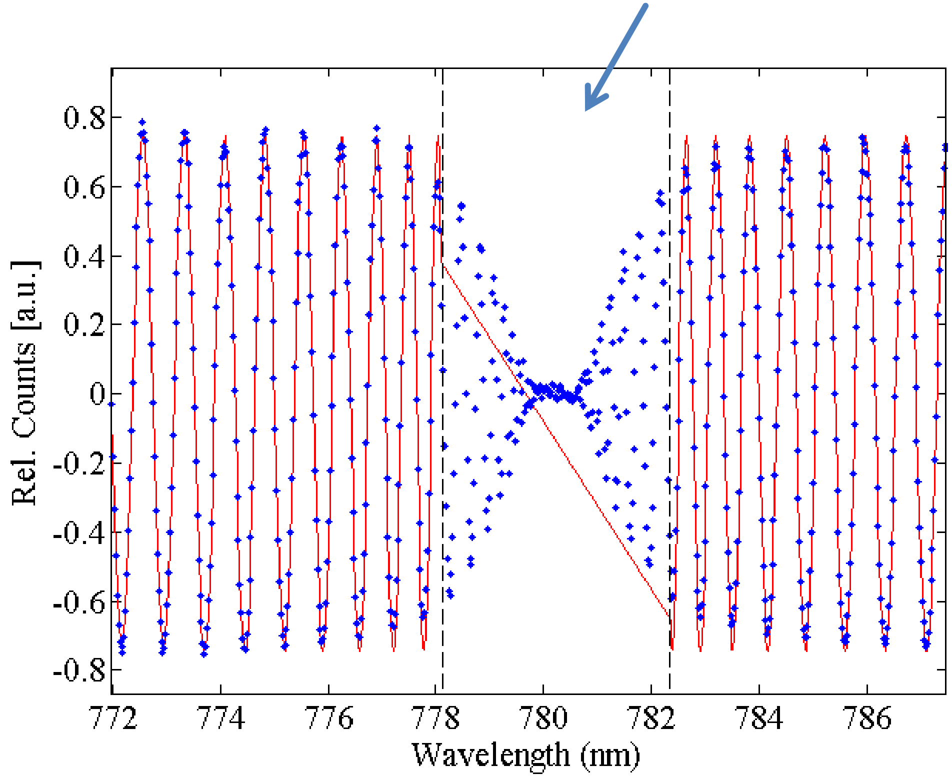


→ An error of Δ A = 0.15 ≙ 19 % in amplitude leads to an error of 0.012 % in n_{Rb}

✓ Negligible

Size of excluded data

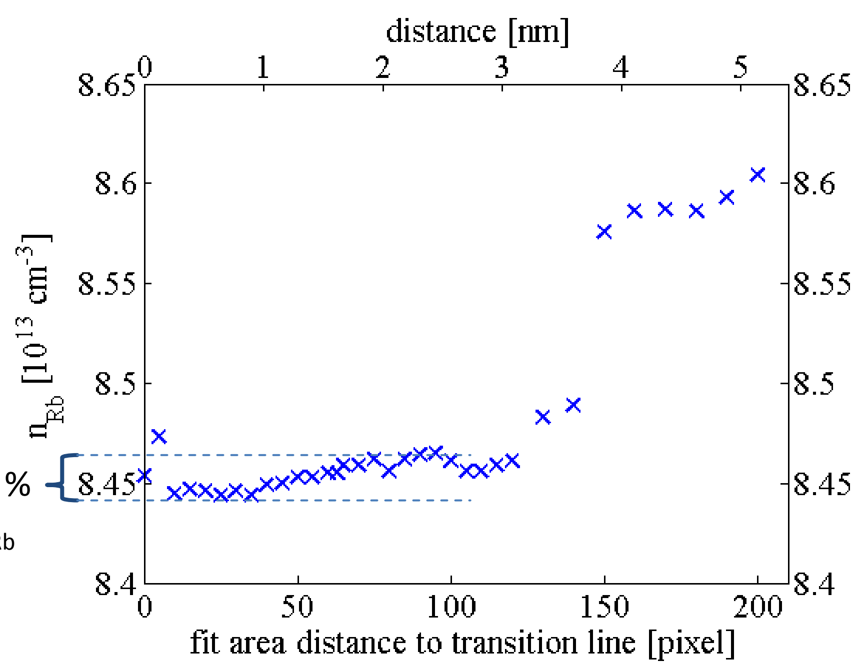
- Results have to be independent from all others fitting parameters:
  Path length difference , Amplitude and Size of excluded data around transition line.
- Calculating n_{Rb} by changing the size of the ignored area in spectrograph image:

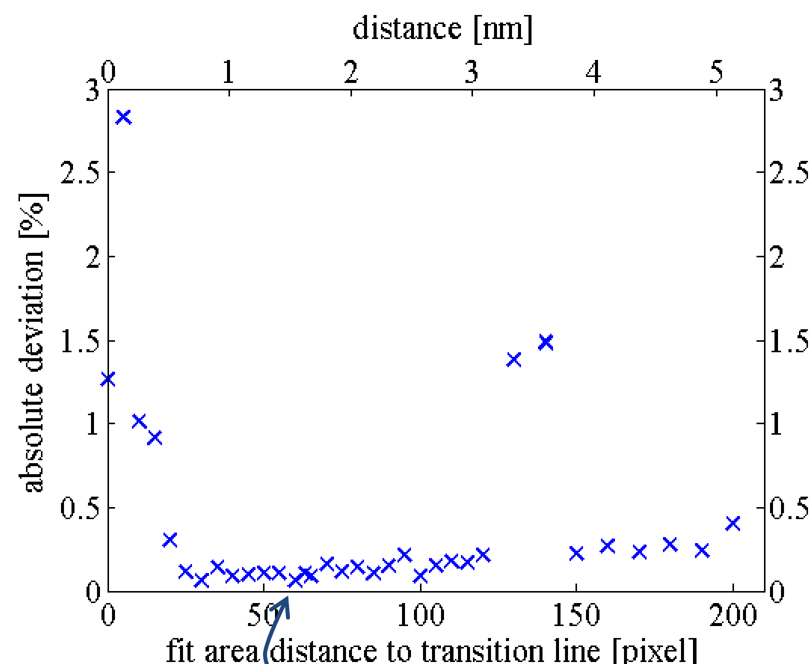


Size of excluded data

- 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}



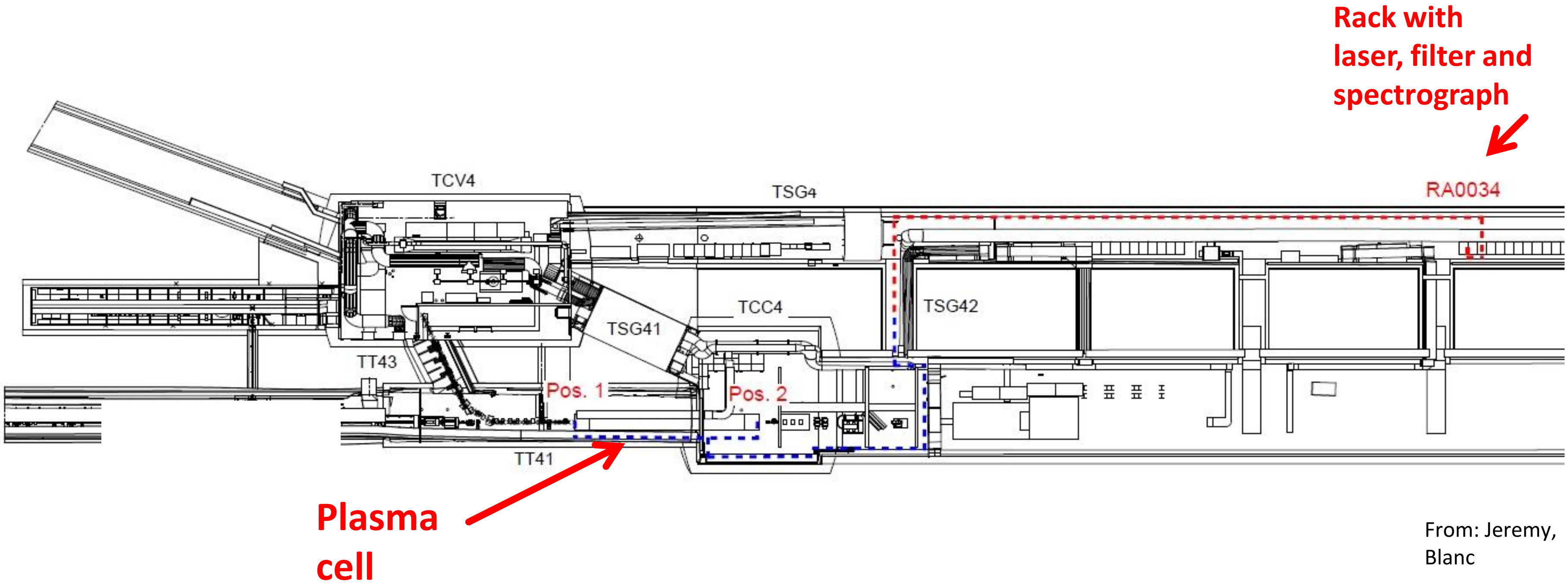


- Between 30 and 100 px, n_{Rb} is in ± 0.12 %
  -> change on a small scale for some px

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

Appendix: Location at CERN

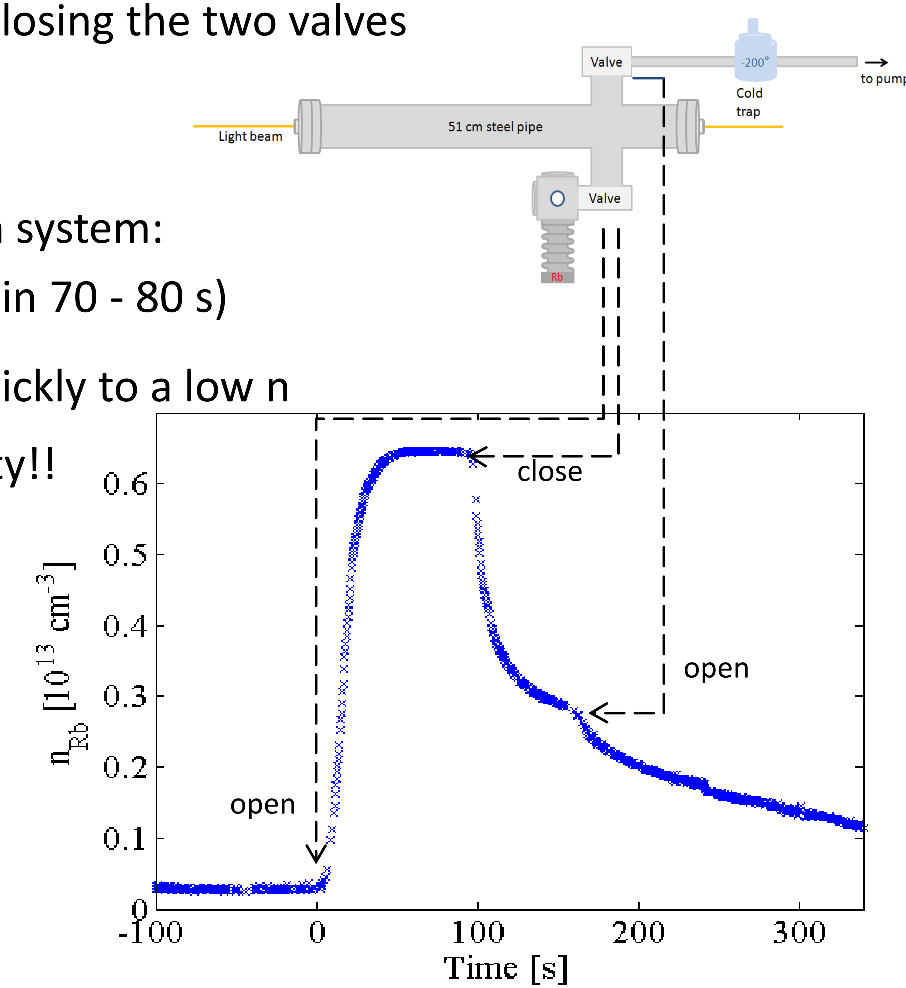
- Light source: white light laser to ensure sufficient light intensity for 2 interferometers and long fiber distances
- Laser/spectrograph and plasma cell separated: 120m fibers to guide light from rack-mounted laser to vapor cell and back to spectrographs in the rack



From: Jeremy, Blanc

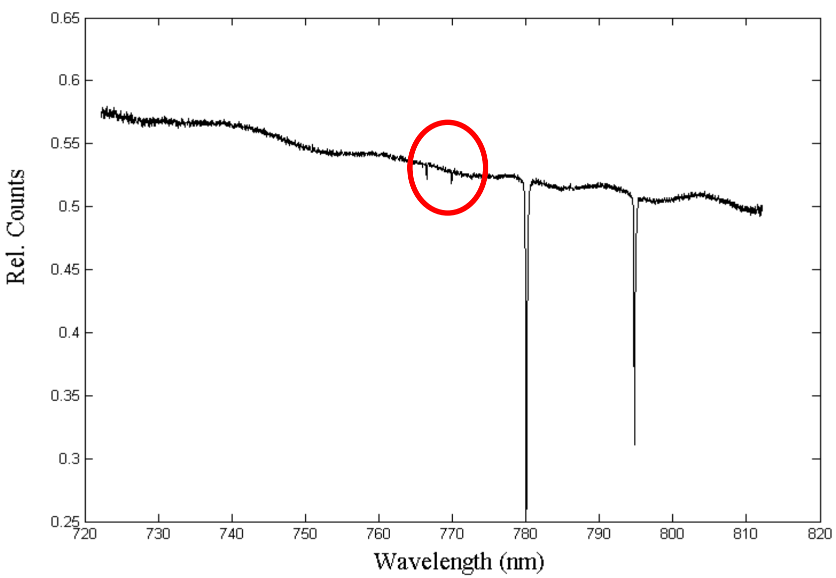
Tracking changes in n_{Rb}

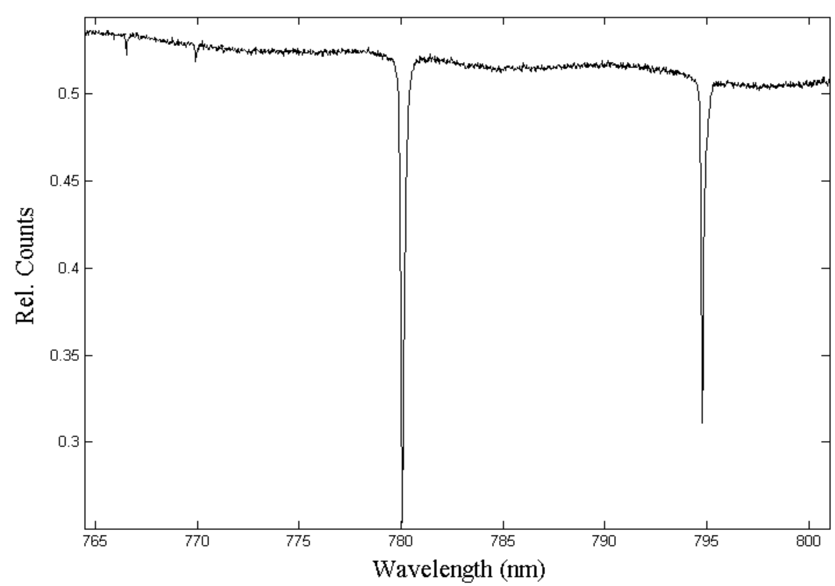
- Code should track density – time – line over full density range (0- 10^{15} cm^{-3})
- Fill and empty 51-cm pipe by opening and closing the two valves
- Rb density measured with time stamp
- ✓ Able to track n(t) curve over wide range
- → Results show important results for the 10 m system:
  - Filling a pipe with Rb vapor works (within 70 - 80 s)
  - After closing Rb valve, density drops quickly to a low n
  - → Coldest spot influences Rb vapor density!!
  - Excess to cold trap empties pipe
  - → Collect Rb on cold spot for recycling



Rb cell transmission spectrum

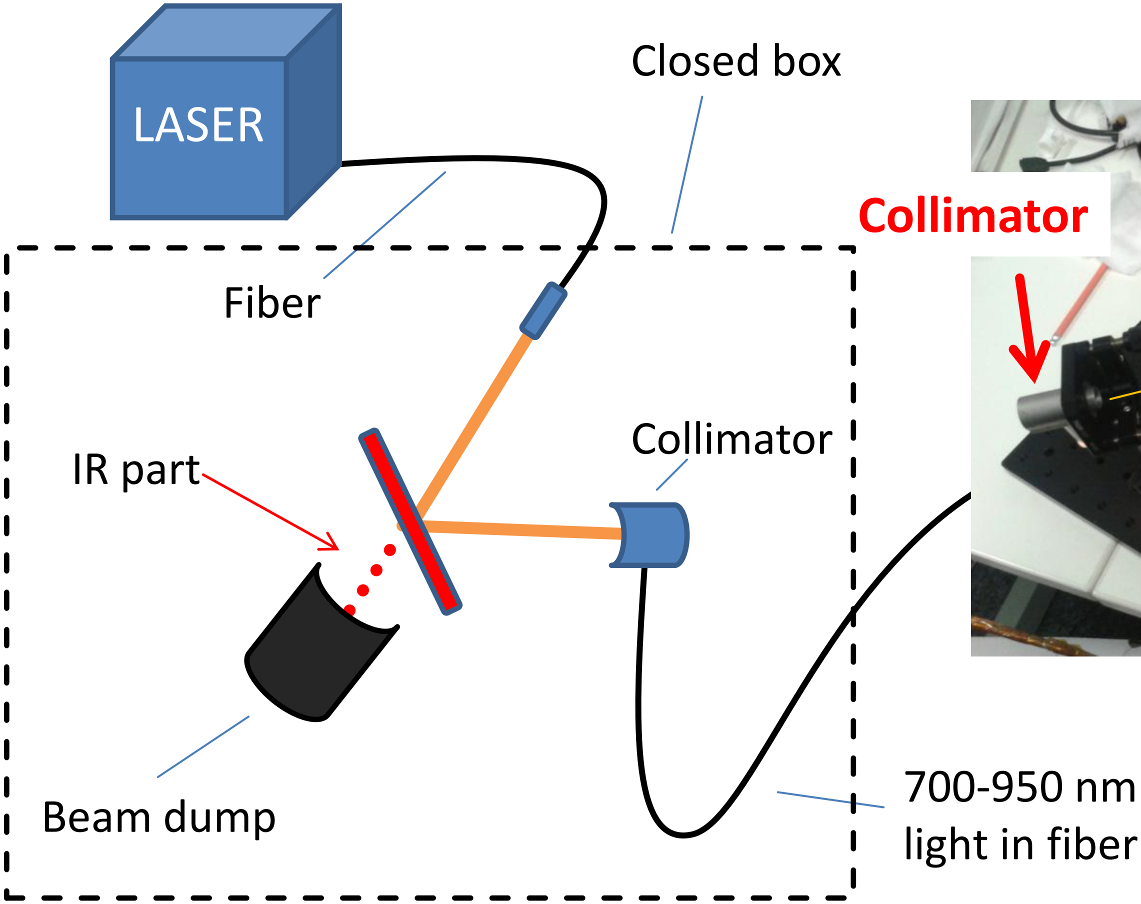
- Sending light only through Rb vapor, reference arm blocked
- Discovered 2 additional absorption peaks !!!
-           <-> not from rubidium
- Comparing with NIST lines shows:
- Potassium has to weak lines at 766.49 nm and 769.90 nm

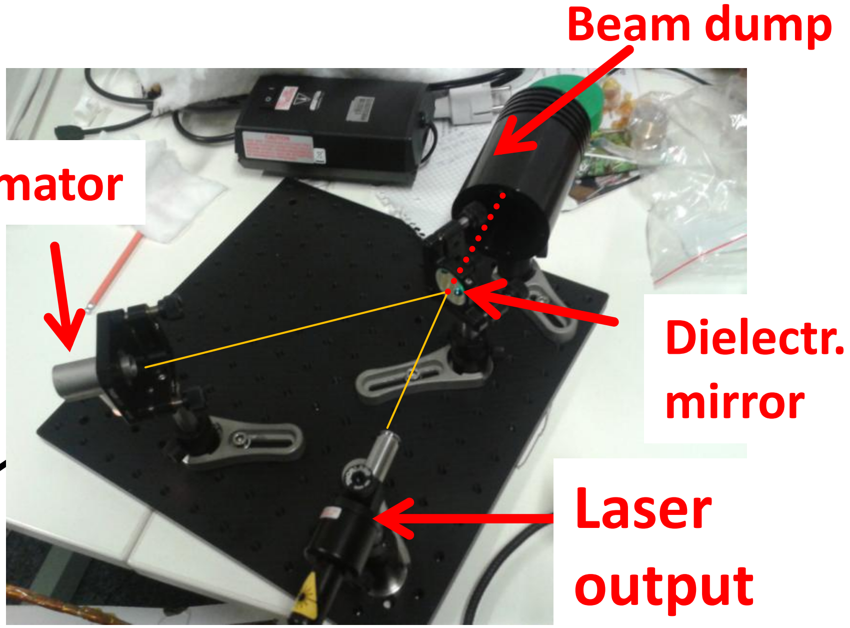




Appendix: IR light filtering

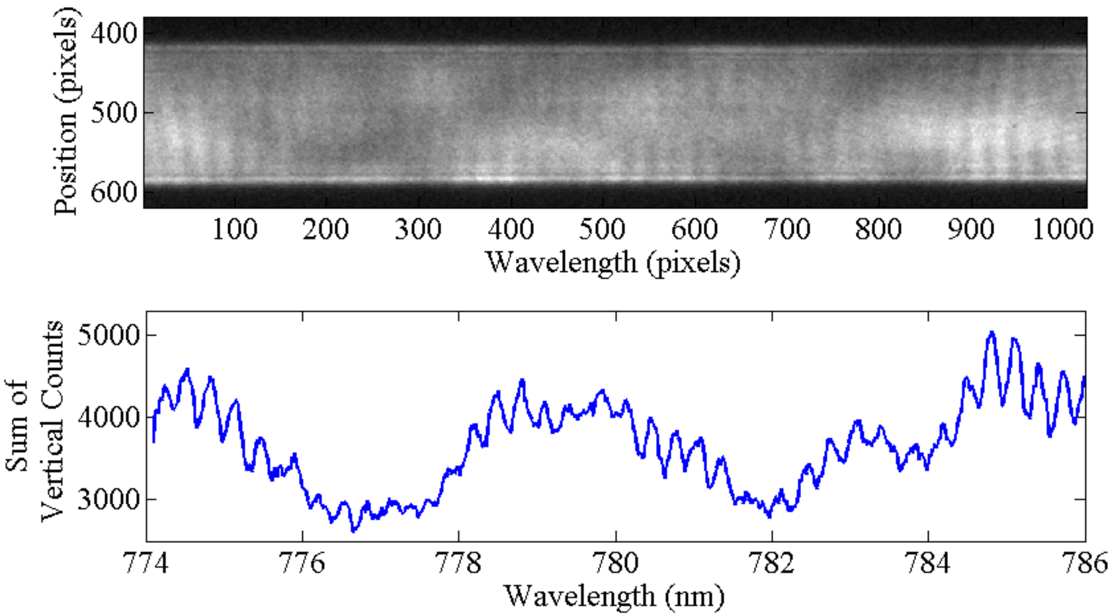
- Select wavelength range around 780 nm to avoid high-intensity laser light > 950 nm for safety (peak in laser intensity at 1064 nm)





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)