Experimental set Helium-Neon Laser

08656.93

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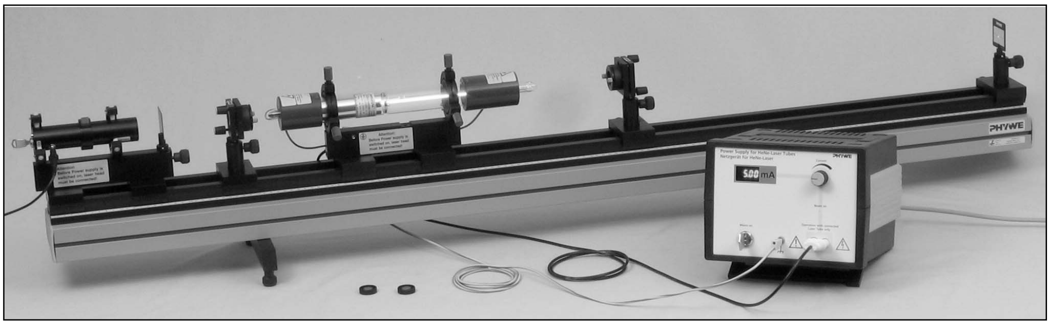


Operating Instructions

Fig. 1: He-Ne-laser, basic set 08656.93.

CONTENT

1 SAFETY INSTRUCTIONS

Class 3B

Laser radiation
Avoid direct exposure to beam
Laser Class 3B
according to DIN EN 60825-1 (VDE 0837-1)

Caution!
According to DIN EN 60825-1

- Carefully read these operating instructions completly before operating this experimental set. This is necessary to avoid damage to it, as well as for user-safety.
- Only use the instrument in dry rooms in which there is no risk of explosion.
- Do not start up this instrument in case of visible signs of damage.
- Only use the instrument for the purpose for which it was designed.

Class 3B laser equipment according to DIN EN 60825-1!
He-Ne laser power $\leq$ 8 mW
λ = 611…640 nm.
Avoid direct exposure to beam!
Do not look into the beam!

The resonator mirrors and the Brewster windows (reflections!) are laser beam apertures! Equipment placed on the optical bench may be laser beam aperture!
Regard the notes on operation.
Green laser class 2:
λ = 532 nm 0.2 / 1 mW

Hazardous electrical voltage!
High voltage circuits in use for the plasma tube. These voltages can be deadly.
Hazardous mains voltage.
Refer servicing to qualified servicing personnel.
Regard the notes on operation.

2. NOTES ON OPERATION

Read and follow the operation instructions supplied with the alignment laser, the He-Ne laser and the power supply for He-Ne laser tubes.
These instruments are only to be put into operation under supervision of specialists or persons who have undergone special training with respect to hazards of laser radiation.
The equipment may only be operated according to the rules concerning class 3B lasers:

- Never look directly into the laser beam!
- Avoid skin exposure to the laser beam!
- Wear suitable eye protection!
- Control the access to area of laser operation. Limit the access to this area to persons required to be there and those who have been instructed in the safe operation of lasers.
- Post warning signs in prominent locations near the laser area.
- Do not set up experiments at eye level.
- Provide enclosed paths for laser beams when possible.
- Keep the beam path as short as possible.
- Keep the number of changes of the direction of the beam as low as possible.
- The laser beam should not cross areas where persons walk along.
- Set up beam targets (e.g. black V-shaped material).
- Shield reflections which go beyond the experiment.

3. INSTALLING THE HE-NE LASER

3.1. Adjustment of the alignment laser

Place the optical bench on a plane and stable surface.
Adjust the leveling screws in a way that the optical bench stands firmly (Fig.2).
Mount the alignment laser on the left end of the optical bench and insert the diaphragm in front of the laser with the label "left" facing the laser. Turn on the alignment laser. Loosen the grub screws on the adjustment screws of the alignment laser and position the laser so that the green laser beam passes the hole in the left diaphragm (Figs. 3, 4).
Put the diaphragm with the label "right" on a slide mount on the right end of the optical bench.

Adjust the green laser's position so that the beam passes exactly through the middle of the right diaphragm – the hole of the diaphragm in the centre of the beam (Figs. 5, 6).
Don’t loosen the ring on the diaphragms – it is adjusted by the manufacturer such that the holes in the diaphragms have exactly the same height.

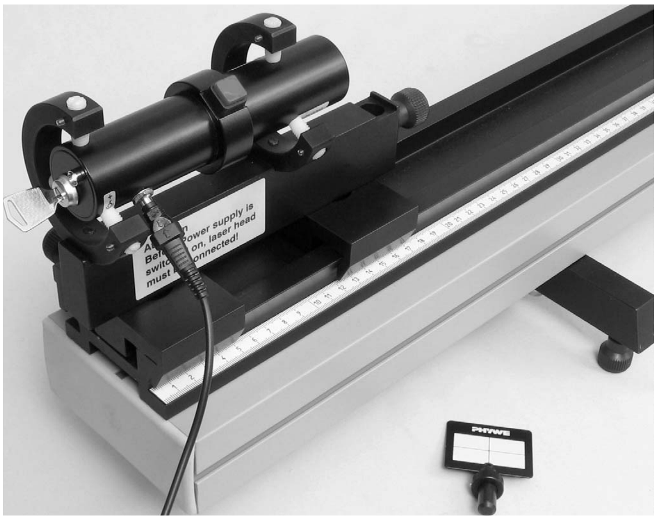


Fig. 3: Alignment laser.

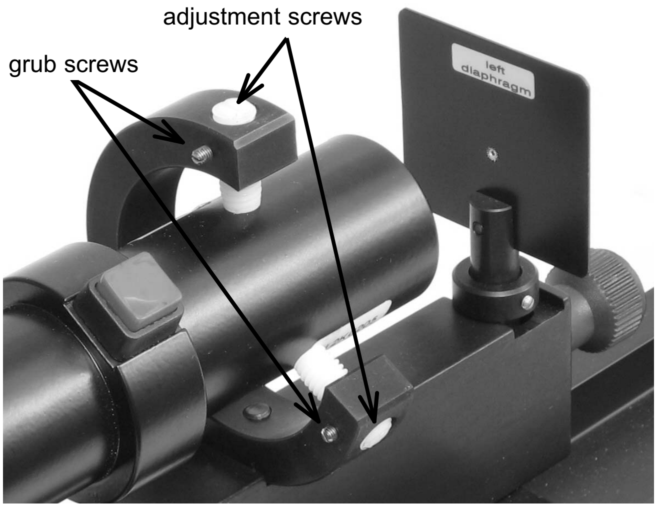


Fig. 4: Adjustment screws.

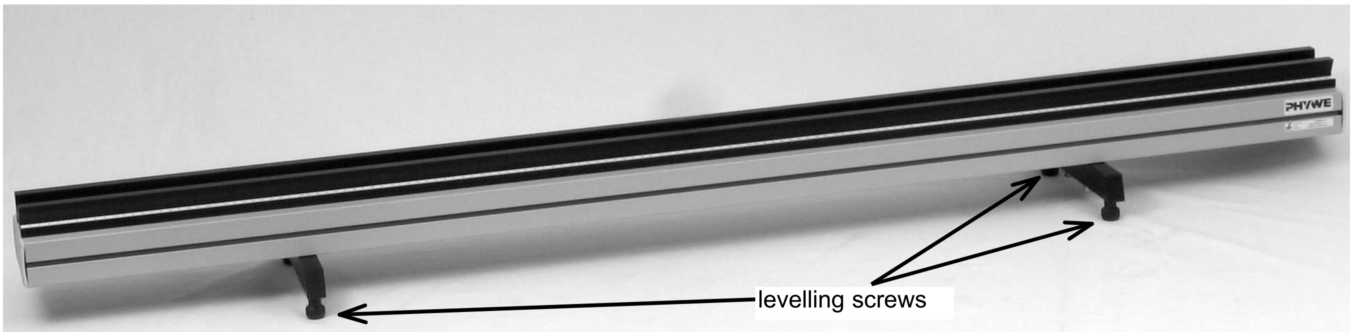


Fig. 2: Levelling screws of the optical bench.

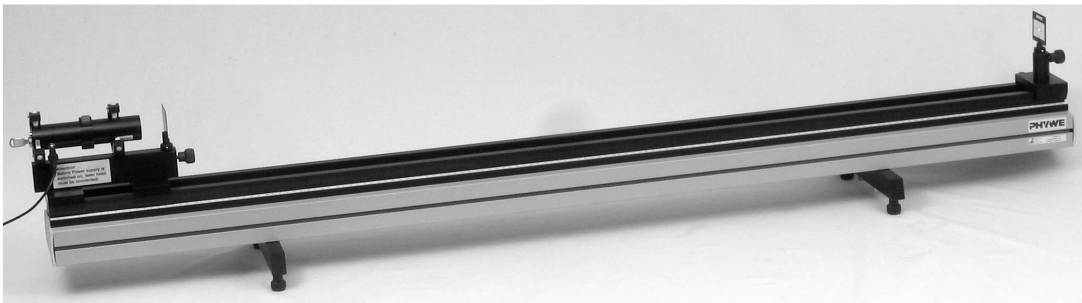


Fig. 5: Adjusting the alignment laser.

Fig. 6: Correct adjustment.

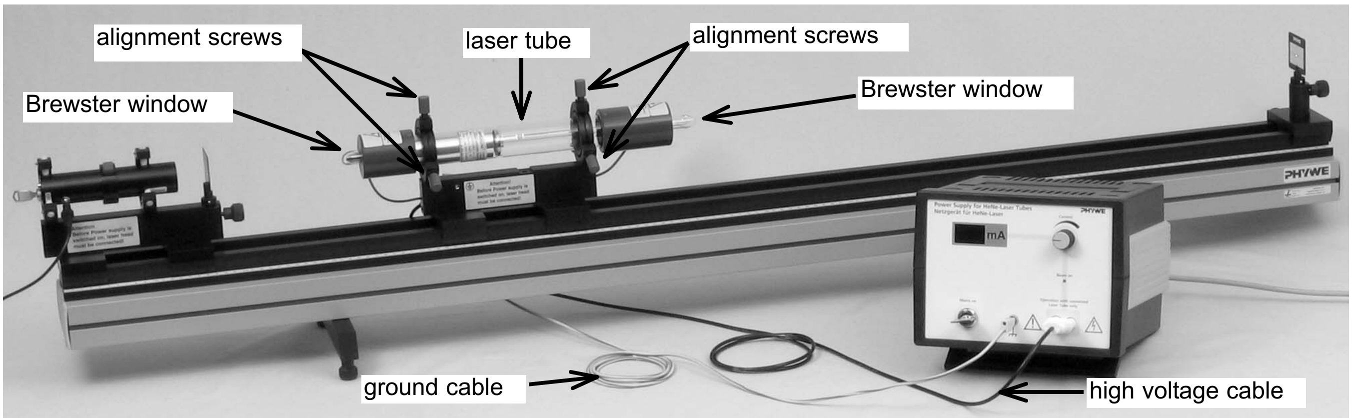


Fig. 7: Mounting the laser tube.

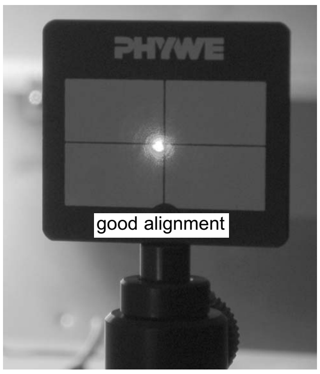
3.2. Adjustment of the laser tube

Mount the laser tube with it's holder onto the optical bench and connect both ground and high-voltage cable to it's power supply (Fig. 7).

Position the tube with the alignment screws in a way that the alignment beam passes the centre of both Brewster windows and does not touch the inner tube. The light spot on the right diaphragm has to be undistorted and should not be surrounded by reflections (Fig. 8). No reflection should be visible on the left diaphragm.

The laser tube may displace the light spot slightly on the right diaphragm as seen on Fig. 8.

In case a precise alignment of the laser beam is necessary for following experiments, the He-Ne laser beam may be readjusted by "beam walking" later on so that the beam impinges upon the middle of the right diaphragm again.



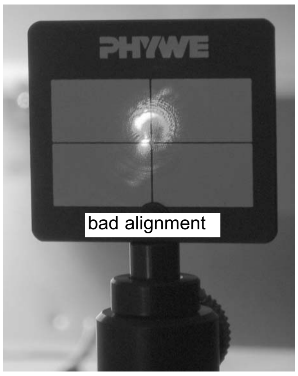


Fig. 8: Adjustment of the laser tube.

3.3. Adjustment of the right resonator mirror

Take the concave high reflective mirror (high reflective = HR, out coupling = OC) with 1000 mm radius (HR flach/1000 mm) and insert it into a xy-adjusting support on a slide mount.

The labeled side of the mirror is the high reflective concave one and has to face the laser tube (Figs. 9, 10).

Adjust the mirror in a way that the light spot of the reflection of the adjustment laser on the left diaphragm is undistorted and precisely in the centre.

There may be two reflection spots visible – one from the concave front side and one reflection of the back of the mirror. They may be distinguished by their size. Which of them has the bigger size depends on the distance between mirror and diaphragm – the focal length of a mirror with 1000 mm radius is 500 mm – so moving the mirror along the optical bench will reveal the correct spot. The reflex of the concave front side of the mirror is the one that has to be centered precisely. For starting a laser in a hemispheric resonator cavity, start with a mirror spacing less than ca. 70% of the radius of the concave mirror and the laser tube near the flat mirror.

3.4. Adjustment of the left resonator mirror

Take the flat high reflective mirror (HR flach/flach) and insert it into a xy-adjusting support on a slide mount. The labeled side of the mirror is the high reflective one and has to face the laser tube.

Adjust the mirror in a way that the light reflex of the adjustment laser on the left diaphragm is undistorted and precisely in the centre (Fig. 11).

Fig. 9: Assembling the resonator mirror.

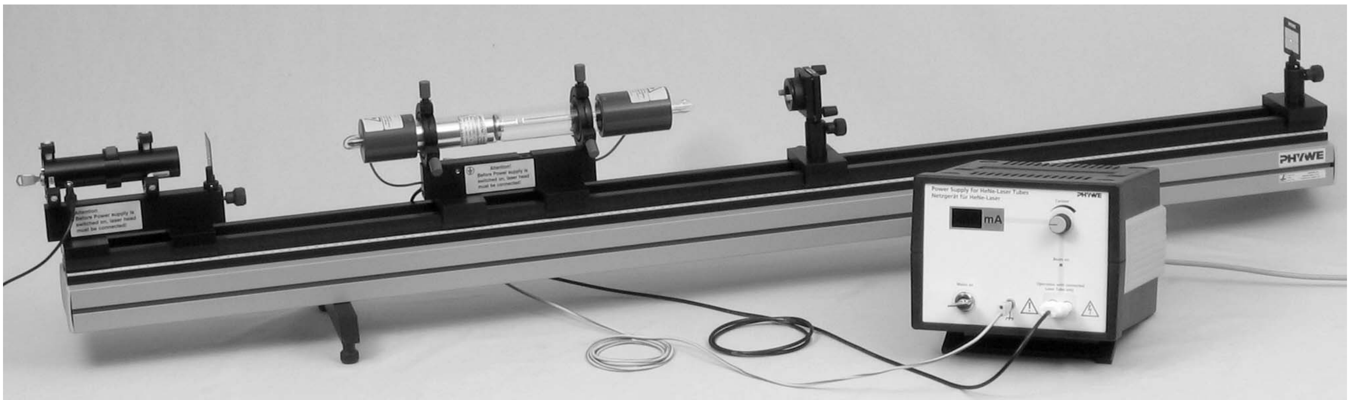


Fig.10: Right resonator mirror.

3.5. Starting the laser process
Turn on the He-Ne laser power supply with the key switch and set the tube current to 6.5 mA.
Wobble the adjustments screws on the right resonator mirror – one of them slowly and the other one faster – scanning the xy-range. E.g. keeping an eye on the alignment beam reflection on the left diaphragm turn the screw for horizontal adjustment of the right hand mirror very slowly first to the right and then to the left side of the assumed centre position while turning the screw for vertical adjustment fast up and down from the assumed centre position. When a laser flash is seen, optimize the laser power by readjusting both mirrors and the tube position. Repeat the optimization process readjusting all the components.
If the laser process starting position can not be found, check on all the adjustments made before. Check the cleanness of the optical components. If the laser still does not ignite, disassemble the set-up and start the adjustment over again.

If the set-up of the laser is changed, e.g. the laser is to be moved along the optical bench, all changes have to be done step by step: Perform a change on one component only and then start the laser process and optimize the output power of the laser before you alter another component. Otherwise it might be hard to find a position where the laser starts if more than one component is maladjusted.
Readjustment of the alignment of the laser beam is done by "beam walking" mentioned before. If the output power is already optimized, the left resonator mirror is turned in the direction that the light spot moves in the desired direction as far as possible without extinguishing the laser. Then the output power is raised again readjusting the left mirror and the laser tube position. This procedure is repeated until the desired position is achieved.

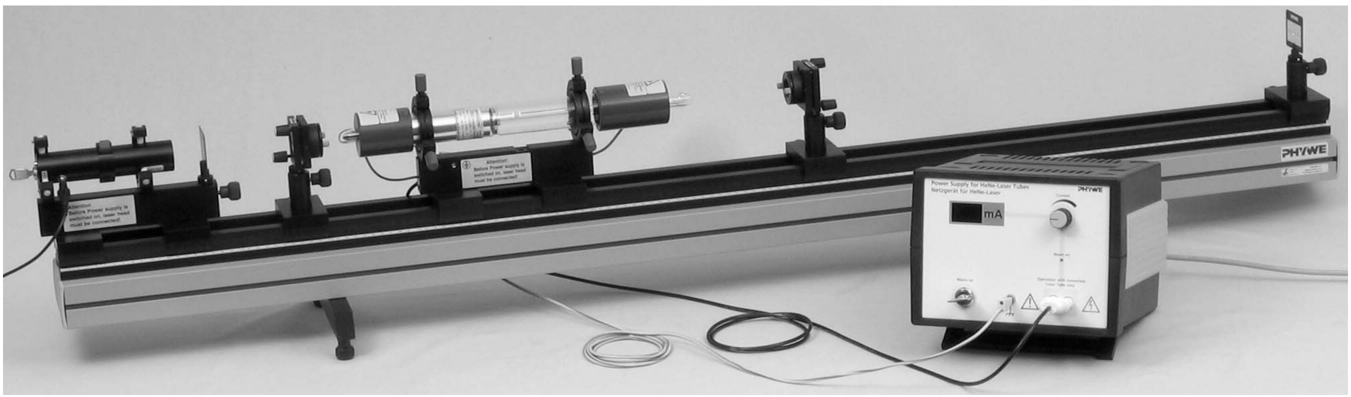


Fig. 11: Left resonator mirror.

4. CLEANING THE OPTICAL COMPONENTS

Optimal cleanness of the Brewster windows and the resonator mirrors is the precondition for optimal output power and stable continuous operation of the He-Ne laser and thus correct measurement results. The high electric field strength inside the resonator may support the adhesion of dust.
The optical surfaces are coated and the coating is sensitive to touching and scratching and can easily be damaged. They must not get in contact with hard objects and may not be touched with the fingers. Optical instruments are fragile and have to be handled with care.
The cleaning has to be carried out with caution and may be done in the following way:
Acetone, a syringe, plastic tweezers and a lens cleaning tissue are taken from the PHYWE cleaning set for lasers Nr. 08582.00.
The syringe is filled with some acetone.
A lens cleaning tissue is cut into half (Fig. 12). Wash your hands before touching the tissue – touch it as few as possible and especially not in the region that is to get in contact with the optical surfaces.

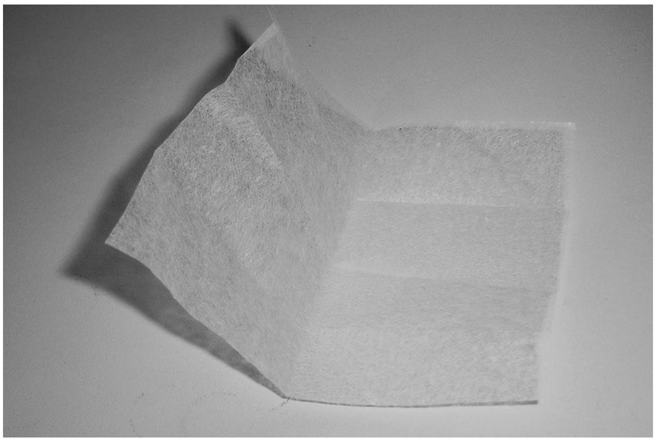


Fig. 12: Cleaning tissue.

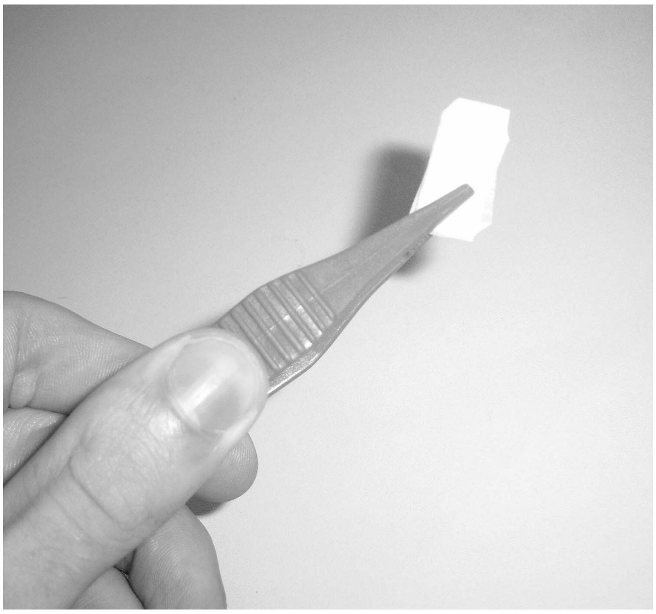


Fig. 13: Holding the cleaning tissue.

The half tissue is folded to 1 cm x 3 cm.
The folded tissue is held by the plastic tweezers (Fig. 13).
Some drops of acetone are dripped with the syringe onto the tissue (Fig. 14). Excess acetone is removed by shaking the tissue.

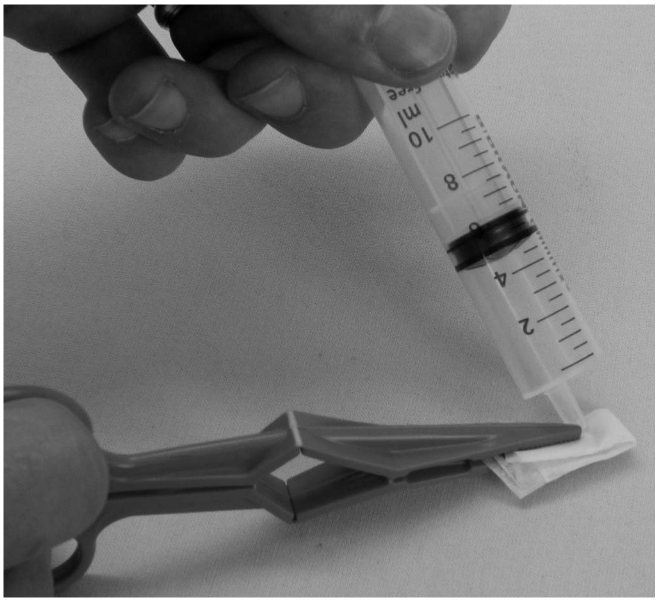


Fig. 14: Application of the acetone.

The optical surfaces are wiped with the tissue without the tweezers touching them.
Wipe only in the indicated direction (Fig. 15).

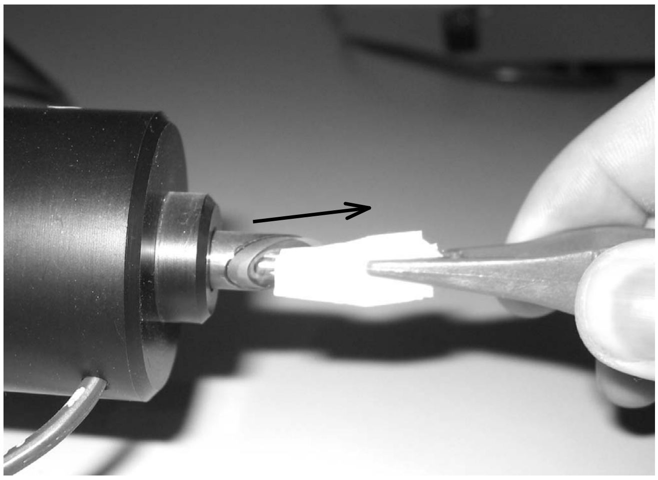


Fig. 15: Cleaning the brewster window.

Acetone may dissolve plastic, varnish, synthetics and adhesives. So bring only the optical surfaces you want to clean in contact with acetone!

5. FUNCTION PRINCIPLE OF THE HE-NE LASER

5.1. Introduction

The Helium-Neon laser was the first continuous laser. It was invented by Javan et al. in 1961 and is still in widespread use. Javan's first He-Ne laser oscillated at a wavelength of 1.5 µm, since the amplification at this wavelength is considerably higher than at the red 632.8 nm line which is nowadays commonly used. The first red He-Ne laser was built one year later by White and Ridgen.
The similarity between the manufacturing techniques of He-Ne lasers and electron valves helped in the mass production and distribution of He-Ne lasers.
He-Ne lasers will have to increasingly compete with laser diodes in the future. But He-Ne lasers are still unequalled as far as beam geometry and purity of modes are concerned. Laser diodes will have to be improved to a great extend before they pose a serious threat to He-Ne lasers.

5.2. Light amplification

Light amplification is possible by stimulated emission of radiation. For the possibility of stimulated emission exceeding the light input a population inversion of two energy states with an optical transition between them is necessary, i.e. there have to be more states occupied in the higher energy level than in the lower one. So only systems far away from thermodynamic equilibrium may possibly be amplifiers. For continuous lasers at least three states are involved in the process.

Feedback turns an amplifier into an oscillator. An amplifier together with a resonator with a resonance frequency inside the frequency range where the gain of the amplifier exceeds unity represents a stabilized oscillator. In the case of gas lasers the gain profile of the amplifier is the Doppler broadened line profile of the optical transition. The optical resonator modes are the standing waves that are possible in an optical cavity consisting of some mirrors.

The principle underlying stimulated emission of photons is Bose-Einstein statistics. While for fermions it is strictly forbidden to occupy the same quantum state (exchanging two fermions in a multi-particle state reverses the sign of the wave function) for bosons it is the more likely to be found in a state the more populated the state already is. So a system with population inversion releases its photons into an already crowded resonator mode – the resonator mode completely describing the photon state (quantum numbers e.g. the TEM_{ijk} numbers).

5.3. He-Ne Energy-level diagram

The fascination for inert gases and their clear atomic structure formed the basis for many spectroscopic investigations. The knowledge of the spectroscopic data was extremely helpful in deciding to choose helium and neon for the first lasers, using the criterion of Schawlow and Towne of 1958 to estimate whether a population inversion was feasible for laser operation. The lifetime of the s- and p-states were well known. Those of the s-states were 10 times longer than those of the p-states. The inversion condition can therefore be fulfilled.

Fig. 16 shows the reduced energy-level diagram for helium and neon. Only those levels important in the discussion of the excitation and laser processes at a wavelength of 632 nm are indicated.

The left side of the representation shows the lower levels of the helium atoms. Notice that the energy scale is interrupted and that there is a larger difference in energy in the recombination process than is evident in the diagram. Paschen's names for the neon energy levels are used (Racah's term descriptions are often found as well). The terms are simply numbered consecutively, from bottom to top. A characteristic of helium is that its excited states with lowest energy, 2^3S_1 and 2^1S_0, are metastable, i.e. optical transitions to the ground state 1^1S_0 are not allowed because of the selection rules for optical transitions. These excited states are populated by electron collisions in a gas discharge (collision of the second type, Fig. 17).

A collision is called a collision of the second type if the internal energy of the colliding particles is changed in the reaction e.g. a transition from one energy state to another of one or both of the particles takes place. Apart from the electron collision of the second type there is also the atomic collision of the second type. In the latter, an excited helium atom state decays without photon emission transferring its energy to a neon atom which is then excited. Both these processes form the basis for the production of a population inversion in the neon system.

If we look at Fig. 16 we can see that the 2^1S_0 level of Helium is slightly below the 3s level of neon. However, the additional thermal energy kT is sufficient to overcome this gap.

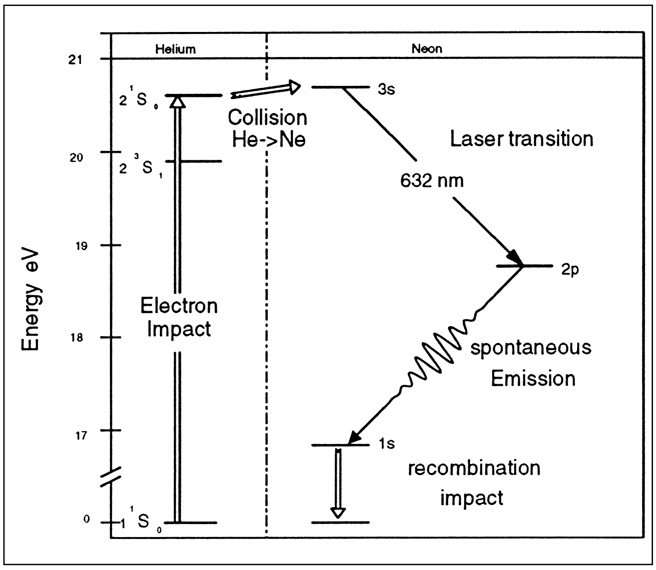


Fig.16: Excitation and laser process for the visible laser emission

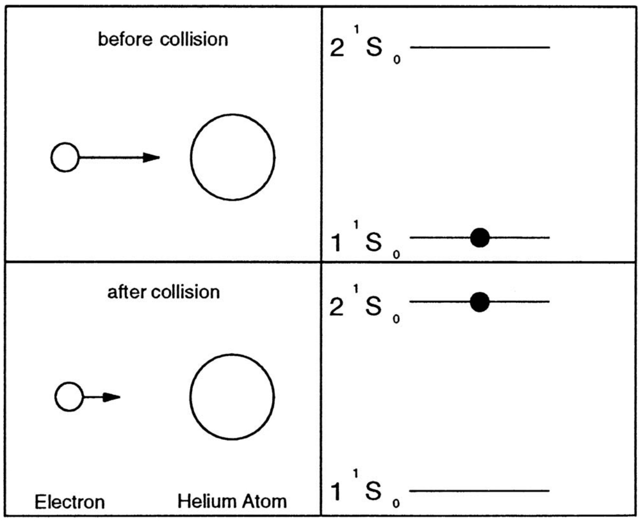


Fig. 17: Electron collision of the second kind

As already mentioned, the lifetime of the s-states of the neon is approximately 10 times longer as the one of the p-states. An immediate population inversion between the 3s and the 2p levels will therefore be generated. The 2s level is emptied due to spontaneous emission into the 1s level. This state decays into the ground state primarily through collisions with the tube wall (capillary), since an optical transition is not allowed. This process is the bottle neck in the laser cycle. It is therefore advisable to choose a capillary diameter that is as small as possible. On the other hand an active volume as big as possible is desirable for high output power. Modern He-Ne lasers work at an optimum of these contradictory conditions. This bottleneck is the main reason for the comparatively low output of He-Ne lasers. We have discussed the laser cycle of the commonly known red line at 632 nm up to this point. However the neon has several other transitions, used to produce about 200 laser lines in the laboratories. The following explanation describes the energy-level diagram for further visible lines. After that infrared laser transitions will be discussed.

The 3s state of Neon is populated by Helium atoms of the

2^1S_0 state as a result of an atomic collisions with Neon atoms in the ground state. The 3s state consists of 4 sub-states. Of these it is primarily the $3s_2$ state which has been populated through the collision process. The population density of the other 3s sub-states is approx. 400 times less than that of the $3s_2$ state. The 2s state is populated with Helium atoms in the 2^3S_1 state, as a result of an atomic collision.

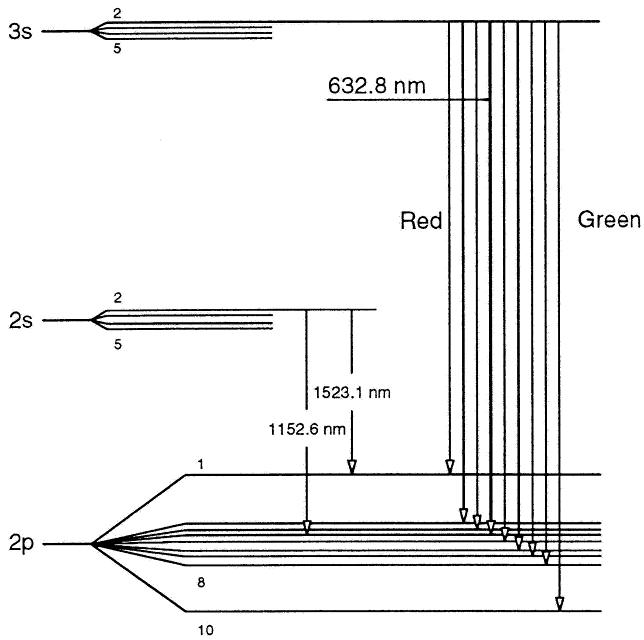


Fig. 18: The most important laser transitions in the neon system

The four sub-states of the 2s group are all populated in a similar way. Visible (VIS) optical transitions and laser processes are taking place between the $3s_2 \rightarrow 2p_i$ and infrared (IR) between the $2s_i \rightarrow 2p_i$ energy levels.
Table 1 shows the most important laser transitions. The Einstein coefficients A_{ik} are given for the visible lines and amplification is indicated as percentage per meter.
Further laser transitions are known, which start at the $3s_2$ level and terminate at the 3p level of neon. However, these laser transitions lie even further within the infrared spectral range and dielectric resonator mirrors for visible light are not suitable for infrared light. Those transitions are not particularly suitable for experiments. Notice that these lines originate from the same level as the visible lines and are therefore competing with them. Since the cross-section of the stimulated emission is increasing with λ^3 as well, the amplification of these lines is therefore very strong. This applies to the 3.39 µm line in particular, which in case of a sufficiently long capillary may show laser activity (so called superfluorescence) even without an optical resonator.

5.4. Light amplification profile of the neon atoms
The Neon atoms move more or less freely in the laser tube but at different speeds. The number N of neon atoms with the mass m, within a speed interval of *v* to *v+dv* is described according to the Maxwell-Boltzmann distribution (Fig. 19).

$$\frac{n(v)}{N} = \frac{4}{\sqrt{\pi}} \cdot \frac{v^2}{\sqrt[3]{(2kT/m)^2}} \cdot e^{-\frac{mv^2}{kT}} \, dv$$

T is the absolute temperature and k Boltzmann's constant. The above equation is applicable for all directions in space. However, we are only interested in the distribution of speed in the direction of the capillary. Using $v^2 = vx^2 + vy^2 + vz^2$ we obtain for the direction x:

$$\frac{n(v_x)}{N} = \frac{4}{\sqrt{\pi}} \cdot \sqrt{2kT/m} \cdot e^{-\frac{mv^2}{kT}} \, dv_x \qquad (1)$$

A resting observer will now see the absorption or emission frequency shifted, due to Doppler's effect (Ch. Doppler: Abh. d. K. Boehmischen Ges. d. Wiss. (5). Vo1.II (1842) P.4b5), and the value of the shift will be:

$$f = \frac{f_0}{1 \pm v/c} \qquad \text{assuming } v \ll c \qquad (2)$$

Table 1: Transitions and laser lines

Transition	Wavelength [nm]	A_{ik} [10^8 s^{-1}]	Gain [%/m]
3s2→2p1	730.5 ③	0.00255	1.2
3s2→2p2	640.1 ①	0.0139	4.3
3s2→2p3	635.2 ①	0.00345	1.0
3s2→2p4	632.8 ①	0.0339	10.0
3s2→2p5	629.4 ①	0.00639	1.9
3s2→2p6	611.8 ①	0.00226	1.7
3s2→2p7	604.6	0.00200	0.6
3s2→2p8	593.9	0.00255	0.5
3s2→2p9	★		
3s2→2p10	543.3	0.00283	0.52
2s2→2p1	1523.1 ②		
2s2→2p2	1177.0 ③		
2s2→2p3	1160.5		
2s2→2p4	1152.6 ③		
2s2→2p5	1141.2 ③		
2s2→2p6	1084.7 ③		
2s2→2p7	1062.3		
2s2→2p8	1029.8		
2s2→2p9	★		
2s2→2p10	886.5		
2s3→2p2	1198.8③		
2s3→2p5	1161.7③		
2s3→2p7	1080.1③		

(1) Possible laser transitions if laser tube is supplied with perpendicular or Brewster windows
(2) Possible laser transitions if laser tube is supplied with Brewster windows and special set of mirrors
(3) Possible laser transitions if laser tube is supplied with Brewster windows and IR mirror set
★ Transition not allowed

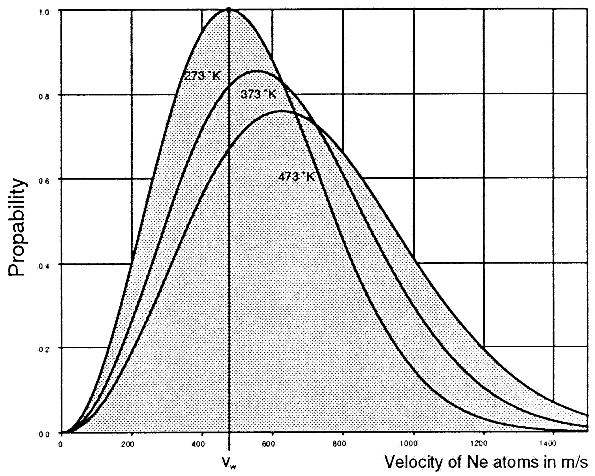


Fig. 19: Maxwell-Boltzmann speed distribution.

f_o is the absorption or emission frequency of the resting neon atom and c the speed of light. If the Doppler equation (2) is used to substitute the velocity v in the Maxwell-Boltzmann's velocity distribution (1) the line broadening produced by the movement of neon atoms can be found. Since the intensity is proportional to the number of absorbing or emitting neon atoms, the intensity distribution will be:

$$I(f) = I(f_0) \cdot e^{-(c \cdot \frac{f - f_0}{f_0 \cdot v_w})} \tag{3}$$

with v_w the most likely speed $v_w = \sqrt{\frac{2kT}{m}}$

The full width at half maximum is calculated by setting $I(v) = 1/2\, I(v_o)$ and the result is:

$$\Delta f_{Doppler} = \sqrt{4 \cdot \ln 2} \cdot \frac{v_w}{c} \cdot f_0 \tag{4}$$

We can conclude from (4) that the line broadening caused by Doppler's effect is larger in the case of:

higher resonance frequencies f_o
or smaller wavelengths ($f_o = c / \lambda_o$, UV-lines)
higher most likely velocity v_w that means higher temperature T

and smaller in the case of:

a larger particle mass.

The line profile also corresponds to a Gaussian distribution curve (3). Fig. 20 shows this kind of profile. The histogram only approaches the distribution curve when the speed intervals dv are small.

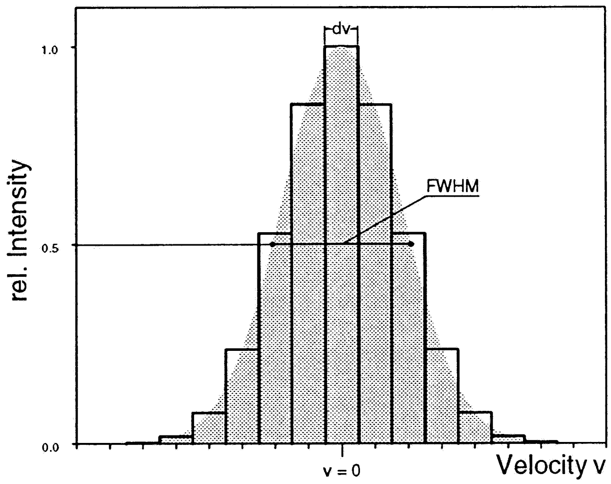


Fig. 20: Inhomogenous line profile, speed intervals *dv.*

On closer observation we can see that a line broadened by the Doppler effect actually does not have a pure Gaussian distribution. The natural linewidth due to the lifetime of the state has to be taken into account. Consider an ensemble of Ne atoms with speed component of value v in the direction we are looking at. All these atoms emit light not only with the same frequency f or wavelength λ but their emission lies in the range of the natural linewidth of the transition. The shorter the lifetime, the broader the emission line profile (time-energy uncertainty). The population n_2 of a state *2* decays spontaneously into a state *1* with lower energy with a time constant T_s following the equation:

$$n_2(t) = n(t=0) \cdot e^{-A_{21} \cdot t} \quad \text{with} \quad \tau_s = 1 / A_{21} \quad \text{and } A_{21}$$

the Einstein coefficient for the spontaneous emission.
The ensemble of Ne atoms then emits a frequency spectrum represented by a Lorentz profile (Fig. 18).

$$\delta(f) = \frac{1}{4\pi \cdot (f - f_0)^2 + (1/2 \cdot \tau_s)^2}, \quad f_0 \equiv f_{21}$$

The exact profile can be determined from the convolution of the Gaussian profile with the individual Lorentz profiles. The result obtained in this manner is called Voigt profile. Since one group of particles in an ensemble can be assigned to a given speed v, these groups have characteristics that makes them distinguishable. Every group has its own frequency of resonance. Which group a photon interacts with depends on the energy (frequency) of the photon. This does not affect the other groups which are not resonant on this interaction. Therefore such kind of a gain profile is termed inhomogeneous.
Gain occurs in a medium when it shows inversion. This

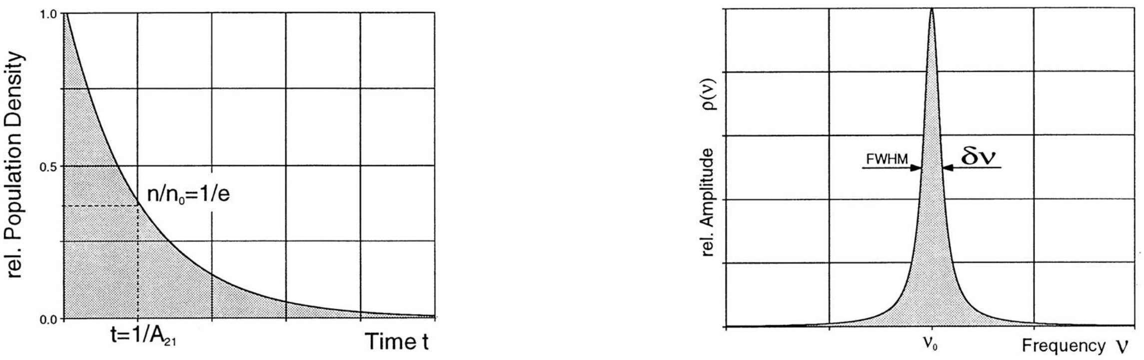


Fig. 21: Decay of the population of state 2 into state 1 and natural linewidth.

means that the population density of the upper level n_2 (3s in the Ne-system) is larger than the population density of the lower state n_1 (2p). Transition can only take place between sub-ensembles which have the same velocity v because the optical transition does not change the speed of the particular Ne atom. Besides some specific other constants the gain is proportional to the difference $n_2 - n_1$. Now we will place the inverted ensemble of Ne atoms into an optical cavity, which is formed by two mirrors having the distance of L. Due to the spontaneous emission photons are generated which will be amplified by the inverted medium and reflected back from the mirrors undergoing a large number of passes through the amplifying medium. If the gain compensates for the losses, a standing laser wave will build up inside the optical resonator. Such a standing wave is also termed as oscillating mode of the resonator also eigenmode or simply mode. Every mode must fulfill the following condition because of field constraints on the surfaces of the mirrors:

$$L = n \cdot \frac{\lambda}{2} \quad \text{or} \quad L = n \cdot \frac{c}{2f}$$

L represents the length of the resonator λ the wavelength, c the speed of light, f the frequency of the generated light and n is an integer number. Thus every mode has its frequency

$$f(n) = n \cdot \frac{c}{2L}$$

E.g. a He-Ne-Laser with a resonator length of 30 cm at an emission wavelength λ of 632.8 nm will have the following value for n:

$$n = \frac{f}{c} \cdot 2 \cdot L = 2 \cdot \frac{L}{\lambda} = 2 \cdot \frac{0.3}{632.8 \cdot 10^{-9}} \approx 950000$$

The difference in frequency of two neighbored modes is:

$$\Delta f = f(n+1) - f(n) = (n+1) \cdot \frac{c}{2L} - n \cdot \frac{c}{2L} = \frac{c}{2L}$$

In the above example the frequency difference between modes would be

$$\Delta f = \frac{3 \cdot 10^8 \; m/s}{2 \cdot 0.3 \; m} = 5 \cdot 10^8 \; Hz = 500 \; MHz$$

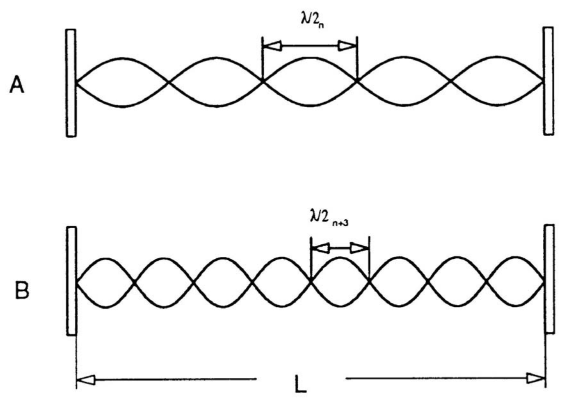


Fig. 22: Standing longitudinal waves in an optical resonator. A with *n* nodes and B with *n+3* nodes.

If the active laser material is now brought into the resonator standing waves will be formed and energy will be extracted from the material. However, the resonator can only extract energy for which it is resonant. The resonator has an indefinite amount of modes, whereas the active material only emits in an area of frequency determined by the emission line width. Fig. 23 shows the situation in the case of material with a line that is inhomogeneously broadened.

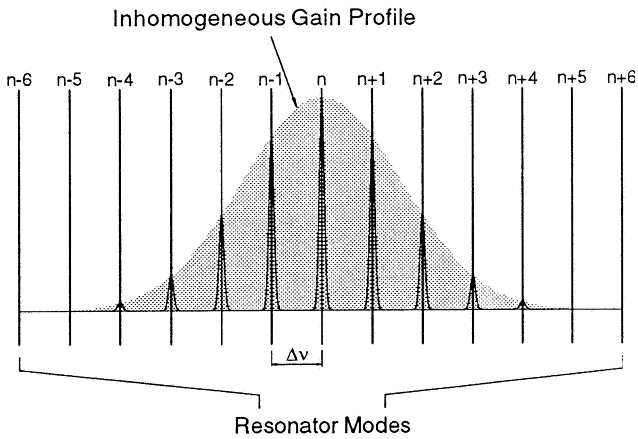


Fig. 23: Inhomogeneous gain profile (Gaussian profile) interacting with an optical resonator.

If the laser is operating in a steady state, it may emit in several longitudinal modes. Since only the modes within the emission profile may be amplified and the frequency difference of the modes depends on the resonator length, the number of oscillating modes increases with the resonator length. Single-mode He-Ne lasers usually have a resonator length of only 12.7 cm (5 inch). Since the modes are fed by an inhomogeneous emission profile they can also exist independently.

5.5. Resonators

In the following section some fundamentals used in the description and calculation of optical resonators will be introduced. Stability diagrams, the beam radius and beam sizes for the resonator types used in later experiments will be calculated and discussed. The investigations and calculations will be carried out for an empty resonator ignoring particular influences on the characteristics of the resonator (e.g. thermal lenses, abnormal refractive index etc.). The ABCD law will be introduced and used in this context. Just like the Jones matrix formalism this type of optical calculation is an elegant method of following the beam (ray tracing) in a complex optical system. Fig. 24 shows that an equivalent lens system can be constructed for every optical resonator. The beam path of the resonator can be traced using the ABCD law, aided by an equivalent lens system. So, how does the ABCD law work ?

First we must presume that the following calculations are correct for the limits of geometric optics. Additionally the beam angle is < 15° to the optical axis, so sin $\alpha \approx \alpha$ is valid. This is fulfilled for laser resonators. A light beam is clearly defined by its height X to the optical axis and the slope at this point (Fig. 25).

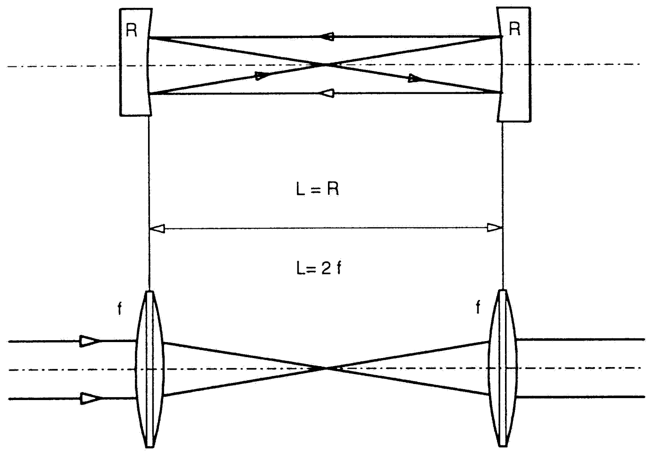


Fig. 24: Spherical resonator with equivalent lens guide.

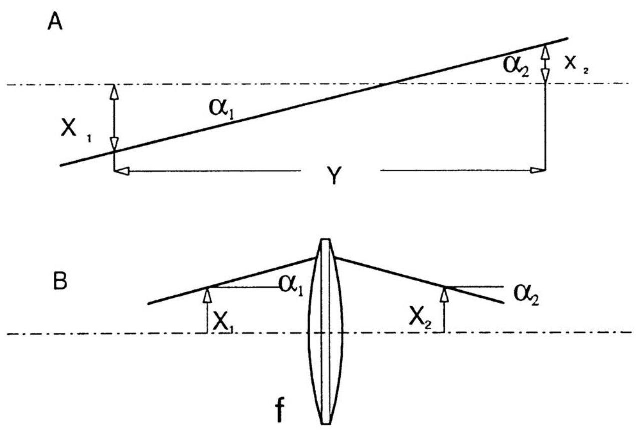


Fig. 25: A: light beam with the characteristic sizes,
B: trace through a lens

The matrix to be introduced is called the beam transfer matrix or ABCD matrix. When this matrix is applied to the input quantities X_1 and α_1 the resulting output quantities will be X_2 and α_2 :

$$\begin{pmatrix} X_2 \\ \alpha_2 \end{pmatrix} = \begin{pmatrix} A & B \\ C & D \end{pmatrix} \cdot \begin{pmatrix} X_1 \\ \alpha_1 \end{pmatrix}$$

Example A in Fig. 24 shows the free propagation of a beam, from which we can deduce that $\alpha_1 = \alpha_2$ and $X_2 = X_1 + \alpha_1$ Y. So, the ABCD matrix in this case is:

$$\overline{\overline{A}} = \begin{pmatrix} 1 & Y \\ 0 & 1 \end{pmatrix}$$

In example B for a thin lens the matrix is:

$$\overline{\overline{B}} = \begin{pmatrix} 1 & 0 \\ -1/f & 1 \end{pmatrix}$$

The combination of example A and B is a result of free beam propagation with subsequent focusing with a thin lens

$$\overline{X}_2 = \overline{\overline{B}} \cdot \overline{\overline{A}} \cdot \overline{X}_1$$

A series of ABCD matrices for different optical elements can be drawn out with this method. They have been compiled by Kogelnik and Li [H. Kogelnik and T. Li, Laser Beams and Resonators, Appl. Optics 5, 1550. (1966)]. The above examples are sufficient for the calculation of a resonator. Beams in an optical resonator have to pass through the same optical structure several times. After passing through it *n* times the ABCD law for a particular place Z of the lens guide (Fig. 22) would be:

$$\begin{pmatrix} X_f \\ \alpha_f \end{pmatrix} = \begin{pmatrix} A & B \\ C & D \end{pmatrix}^n \cdot \begin{pmatrix} X_i \\ \alpha_i \end{pmatrix}$$

In this case the ABCD matrix is the equivalent lens guide given to the resonator. The *n*-th power of a 2 x 2 matrix is calculated as follows:

$$\begin{pmatrix} A & B \\ C & D \end{pmatrix}^n = \frac{1}{\sin\theta} \begin{pmatrix} a & b \\ c & d \end{pmatrix} \quad \text{with}$$

$$\theta = \arccos((A+D)/2) \quad \text{and}$$

$$a = A\sin(n\theta) - \sin((n-1)\theta)$$

$$b = B\sin(n\theta)$$

$$c = C\sin(n\theta)$$

$$d = D\sin(n\theta) - \sin((n-1)\theta)$$

The trace of the above ABCD matrix |A+D| has to be less or equal than one if the beams are to remain within the lens guide. So the criterion of stability for the lens guide and therefore also for the accompanying resonator is

$$|A+D| \leq 1 \tag{5}$$

Conclusion: An equivalent lens guide system can be linked to every resonator. The ABCD matrix may be determined for this optical structure (several simple lenses). The stability diagram for the different mirror intervals with given mirror radii can be deduced using (5).

For a resonator with
radius of curvature of left mirror: b_1
radius of curvature of right mirror: b_2
resonator length: d
we define

$$g_i = 1 - \frac{d}{b_i}$$

Then the criterion of stability is

$$0 < g_1 \cdot g_2 < 1$$

Table 2: Some special types of resonators

Type	Mirror radius	Stability parameter
Confocal	$b_1 + b_2 = 2d$	$g_1 + g_2 = 2 g_1 g_2$
Concentric	$b_1 + b_2 = d$	$g_1 g_2 = 1$
Symmetric	$b_1 = b_2$	$g_1 = g_2 = g$
Sym. confocal	$b_1 = b_2 = d$	$g_1 = g_2 = 0$
Sym. concentric	$b_1 = b_2 = ½ d$	$g_1 = g_2 = -1$
semi confocal	$b_1 = \infty$, $b_2 = 2d$	$g_1 = 1$, $g_2 = ½$
plane	$b_1 = b_2 = \infty$	$g_1 = g_2 = 1$

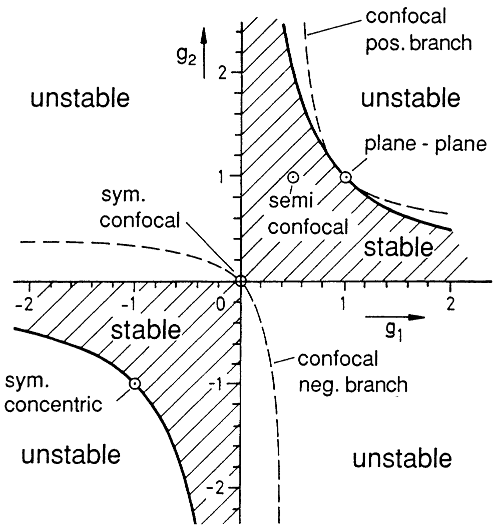


Fig. 26: Range of stability of resonators

5.6. Laser tubes and Brewster windows

Brewster windows have two functions. They hermetically seal the tube, as well as ensure that there is a definite polarization in laser oscillation without additional losses.

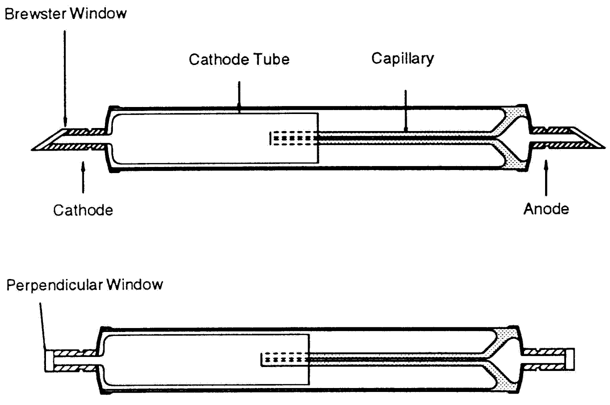


Fig. 27: Laser tube with Brewster windows and perpendicular windows with highly anti reflection coating

Brewster windows are soldered on to a special metal (Vacon). The tube being used has a ignition voltage of approx. 8 kV and an operating voltage of approx. 2 kV. The optimal current for the 632 nm line is 5 mA.

The Brewster windows of the laser tube are arranged in a way that enables compensation for beam displacement by the windows.

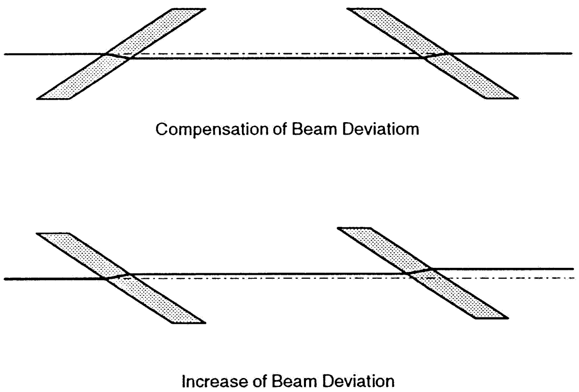


Fig.28: Two possible arrangements of Brewster windows. The one above compensates for displaced beams.

6. TECHNICAL DATA

Alignment laser:

Wavelength 532 nm	linearly polarized
Reduced output power	0.2 mW
Maximum output power	1.0 mW
Beam divergence	< 2 mrad
Safety class acc. to IEC 60825-1	Laser Class 2
Input voltage of the laser module	max. 3 VDC
Current consumption	approx. 50 mA
Housing dimensions (mm)	approx. 45 x 155 (OD, L)
Weight	approx. 0,610 kg

Power supply for alignment laser:

Line voltage	100…240 VAC
Supply frequency	50/60 Hz
Output voltage	max. 3 VDC
Power consumption	approx. 5 VA

Laser tube

Brewster windows	on both ends
Capillary size	Ø 1.1 mm
Length	408 mm
Nominal current	6.5 mA DC
Holder	two xy-adjusters

Power supply for laser tube:

Operating temperature range	5...40°C
Relative humidity	< 80%
Mains supply connecting voltage	110...240 V
Mains frequency	50/60 Hz
Power consumption	95 VA
Mains fuse (5 mm x 20 mm)	see type plate
Output	Special high voltage socket
Trigger voltage	> 10 kVDC
Output voltage	2000 - 2700 VDC
Output current	4 - 10 mA
Max. output power	20 W
Housing dimensions (mm)	230 x 170 x 240 (W, H, D)
Weight	approx. 3.2 kg
recommended laser:	He/Ne Laser 5 mW, 08701.00 with holder

Resonator mirrors:

Size		12.7 mm (1/2")
Surface finish		< lambda / 10 @ 632.8 nm
Mirror coating		dielectric
Flat mirror	HR (high reflective) R > 99%	flat / flat
Concave mirror	HR (high reflective) R > 99%	r = 1000 mm / flat
Concave mirror	HR (high reflective) R > 99%	r = 1400 mm / flat
Concave mirror	OC (out coupling) T 1.5…1.8%	r = 1400 mm / flat

7. SCOPE OF DELIVERY

Alignment laser with holder:	
- frequency doubled green alignment laser 0.2 / 1 mW	1
Optical bench on carrier rail 1500 mm	1
Diaphragms for laser alignment	2
Slide mount for optical bench	3
Holder for D = 25.4 mm with xy-fine adjustment	2
Dielectric laser mirror for red light HR flat / flat	1
Dielectric laser mirror for red light HR R = 1400 mm / flat	1
Dielectric laser mirror for red light OC R = 1400 mm / flat	1
Dielectric laser mirror for red light HR R = 1000 mm / flat	1
He-Ne laser tube in adjustable holder	1
Power supply for He-Ne lasers, 4 kV continuous / 12 kV ignition, 4…10 mA	1
Connecting cable, 4 mm plug, 32 A, green-yellow, 2000 mm	1

8. ACCESSORIES

General recommended accessories:	
Protective glasses for He-Ne laser	08581.10
Danger sign –LASER–	06542.00
Screen, 150 mm x 150 mm	09826.00
Cleaning set for lasers	08582.00
Accessories for laser power measurement:	
Photo element, silicon	08734.00
Digital multimeter	07128.00
Advanced accessories:	
Lyot plate on carrier and slide mount	08656.10
Littrow prism on carrier and slide mount	08656.20
Fabry-Perot etalon on carrier and slide mount	08656.30
He-Ne laser advanced experimental set containing Lyot plate, Littrow prism and Fabry-Perot etalon	08656.02

9. ACCOUNT OF CONFORMITY

This laser system is an assembly of elementary components. These elementary components are individual passive or active electrical or electronic elements and do not come under the EMC Law. They are not tested, and are neither given an EC declaration of conformity nor, as a rule, a **CE** mark.

System set-ups and set-ups from experimental construction sets must be in accordance with the directives in the EMC Law.
An exception to this is made, however, in the case of such **systems** that, as a pure combination of components, only contain individual components that cannot be separately operated, as long as these are exclusively supplied to research, **teaching and training places** (institutes, schools, universities), in which it can be assumed that the experiments will be carried out under the supervision of **qualified (EMC skilled) staff** in appropriate technical rooms, and that all necessary measures (e.g. screening, short connecting cables, brief operation times) will be taken so that the proper functioning of other equipment that is operated outside of the technical room, or in the immediate electromagnetic vicinity, is not impaired.

10. GUARANTEE

We guarantee the instrument supplied by us for a period of 24 months within the EU, or for 12 months outside of the EU. This guarantee does not cover natural wear nor damage resulting from improper handling.
The manufacturer can only be held responsible for the function and technical safety characteristics of the instrument, when maintenance, repairs and changes to the instrument are only carried out by the manufacturer or by personnel who have been explicitly authorized by him to do so.

11. WASTE DISPOSAL

The packaging consists predominately of environmental compatible materials that can be passed on for disposal by the local recycling service.

Should you no longer require this product, do not dispose of it with the household refuse. Please return it to the address below for proper waste disposal.

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