Monochromator

For a monochromator, diffraction from a crystal is used [slide]. As we learned before, for a given angle only a specific wavelength will fulfil the diffraction condition. Even for the case of undulators, monochromators are still needed, as the bandwith of the undulator is often too large and higher harmonics need to be supressed. Very often, Si crystals are used, as here large, perfect crystals can be obtained and shaped. Using diffent planes, a wide range of energies can be covered [slide]. There a various designs in use with diffent properties, for example a double crystal monochromator where the beam does not move when the energy is changed. [slide]

Mirrors

X-ray lenses cannot be easily build with high optical quality. Therefore, very often mirrors are used to focus the beam, based on total reflection from surfaces below the critical angle [slide]. Focussing and collimation is then achieved by bending the magnet actively.

Free electron laser

The most advanced light source available since a couple of years is the free electron laser (FEL). They provide unprecedented x-ray brightness ($> 10^{10}$ times greater than in conventional synchrotrons) in pulses of very short duration. Short, intense pulses are especially needed in pump-probe experiments. (slide) A FEL does, for example, allow the probe to be x-ray diffraction. In such a machine, intensity can be high enough to record a diffraction pattern before the sample is destroyed by the beam. (diffract and destroy). The photons are obtained by accelerating a rather large number of electrons and then pass them through a long undulator. When the electrons start emitting photons, they still are travelling together with the electromagnetic field. This causes the electrons to bunch together so that later a large number of electrons will emit photons coherently, which again enhances the process (like in a laser). This is called spontaneous amplified self emission (SASE).

Ultra-high vacuum technology

A lot of modern experimental in solid state physics request vacuum or even ultra-high vacuum (UHV). One reason is that only under UHV surfaces stay clean sufficiently long, the other reason is that electron beams (occuring in a lot of techniques) need vacuum to travel far enough.
Let us first look at the contamination of surfaces with adsorbing gases. From kinetic gas theory, one can calculate that the flux I of molecules impinging on a surface from the environment is given by:

$$I = \frac{p}{\sqrt{2\pi m k_B T}}$$

(p: pressure; m: mass of particle; T: temperature)

This flux has to be compared to the areal density of atoms in the surface n_0. One often assumes that every atom or molecule impinging on a surface also sticks there and calls the number of particles needed to cover every surface atom with one gas atom a monolayer. The time constant to form a monolayer is then given as:

$$\tau = \frac{n_0}{I} = \frac{n_0 \sqrt{2\pi m k_B T}}{p}$$

From the ideal gas equation one knows:

$$pV = NkT$$

$$\Leftrightarrow \quad n = \frac{N}{V} = \frac{p}{k_B T}.$$

Finally, the mean free path of a particle is given as:

$$\lambda = \frac{k_B T}{\sqrt{2}\,\pi\,\sigma^2\,p}$$

(σ: molecular cross section)

To illustrate these quantities, let us look at N_2 (main ingredient of air) at room temperature. For n_0 we assume $10^{19}\ m^{-2}$ (≙ nearest neighbor distance on square lattice: 3 Å). For N_2, we assume a diameter of 6 Å. The results are shown in the slide. Several things should now become clear:

- even at 10^{-6} mbar, a clean surface stays clean for roughly 1 s. For surface sensitive experiments, much lower pressures are therefore needed.
- in this pressure regime, the mean free path is usually much longer than the size of your machine. Therefore, for the individual gas atom, the vacuum seems perfect.
- Still, due to the particle density still appears very large.

In consequence, experiments where (i) the technique is intrinsically surface sensitive like PES or (ii) you are even particularly interested in surfaces, are performed under UHV condition ($p \leq 10^{-10}$ mbar) 1 slide

A second, somewhat weaker request for vacuum is the mean free path of electrons 1 slide. Good vacuum conditions are needed in, e.g., a TEM. Due to the very long path of the electrons, a synchrotron needs UHV as well. Methods based on visible light, X-rays, or neutrons, as well as scanning probe microscopies, do not need vacuum.

Special pumps have to be used to reach UHV-conditions. The two most prominent are the turbomolecular pump and the ion pump. The turbomolecular pump 1 slide operates in the 10^{-4} to 10^{-11} mbar range and consequently a roughing pump is needed. Basically, a turbo pump resembles a jet engine: a stack of rotors with multiple blades with angled leading edge is rotated at very high speed (50 000 to 100 000 rpm) and sweeps the gas molecules in the direction of the exhaust connected to the foreline. Turbo pumps are clean and reliable, but due to induced vibrations they are not suitable in systems with precise positioning, for example STM.

Ion pumps work in the 10^{-3} mbar to 10^{-11} mbar regime. [slide] The basic configuration of an ion pump includes two plates made of Ti (cathode), mounted close to the open ends of short stainless steel tubes (anode), a strong magnetic field being applied parallel to the tube's axis. When an electron is situated inside the tube, the applied high voltage accelerates it towards the anode. The magnetic field forces them on a helical (and thus rather long) path. Collision of the electrons with gas molecules causes ionization. The gas ions are accelerated towards the cathode and are buried in the reactive Ti. At the same time, Ti is sputtered and coats the surfaces of the pump. Consequently, the reactive Ti binds additional gas atoms. The major advantages of ion pump are cleanliness, vibration free operation, and long operating life (no moving parts).

Special care has to be taken when selecting materials used in a UHV chamber.

A lot of materials have a <u>vapor pressure</u>, which is actually higher than the desired pressure inside your system [slide]. This includes almost all plastic or rubber materials, but also many metals. Today, all vacuum chambers are built out of steel and use copper gaskets [slide]

The base pressure that can be reached is given as:

$$p = \frac{L}{S_{eff}}.$$

Here, S_{eff} is the combined effective pumping speed of your pumps (measured in mbar·l/s) and L is the leak rate. It consists of three parts: (i) real leaks, i.e. little openings to atmosphere, (ii) virtual leaks, i.e. small volumes of gas trapped in your chamber or brought in by unsuitable materials, and (iii) outgassing. Outgassing is due to the fact that under ambient conditions, all surfaces are fully covered by adsorbate (mostly water). In vacuum, this gas slowly desorbs. However, the amount of gas is so high and the desorption rate is so low that you can pump for months on a system and not reach UHV. The solution is to bake-out your system, i.e. to raise the temperature to 150° – 200° for a few days in order to remove the adsorbed gas layer. Only there after the pressure will drop down to the 10^{-10} mbar regime.

Also the determination of these low pressures needs special devices. The standard tool to determine pressures lower than 10^{-3} mbar is the ionization gauge. (Stick). Its operation is based on the ionization of molecules.

As the ionization rate and, hence, the ion current are directly dependent on the gas pressure, the pressure can be determined. The Bayard-Alpert gauge depicted here uses electrons which are accelerated from a filament towards a grid which is at a high potential than the filament. These electrons ionize atoms and molecules, which are then attracted towards the fine wire grounded collector situated at the center of the gauge. Finally, the collector current is converted to a pressure indication. The low pressure limit of the gauge arises mainly from the excitation of x-rays by the electrons bombarding the grid, which, in turn, excite disturbing photo electrons. Ion gauge measurements are seriously affected by the gas composition.

Finally, there is a whole little industry supplying additional vacuum equipment, like valves, feed throughs for current or liquids, or devices enabling movement of parts inside the vacuum. A large UHV-system can quickly become quite complicated.