Introduction to Plasma Physics

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Physics in Greifswald

Research:
Plasma physics
Soft matter
Complex quantum systems

Teaching:
Bachelor of Science (3 years)
Master of Science (2 years)

Ph.D. Programme:
International Max-Planck-Research School Bounded Plasmas

Summer School „Plasma Physics in Science and Technology“

Hansestadt Greifswald
Home town of Caspar David Friedrich

Marktplatz

Characterisation of Plasma

Plasmas are characterised by charged particles, in particular
- Electrons (negative)
- Ions (mostly positive).

Most plasmas contain as many postive as negative charges, i.e. the total plasma charge is zero (quasi-neutrality).

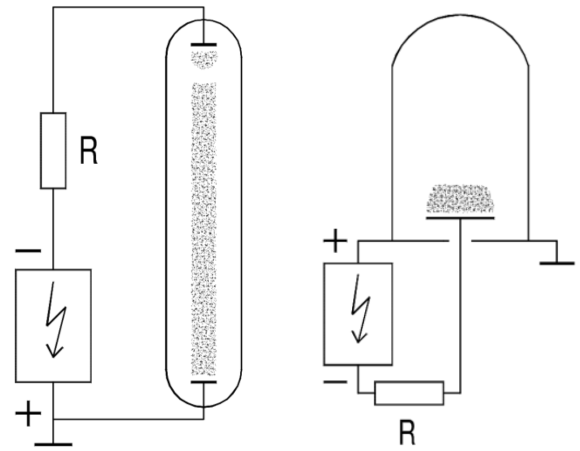
There are numerous ways to characterise plasmas, i.e., with respect to
- Plasma (electron, ion) temperature, e.g.,
    - Low temperature plasmas
    - High temperature plasmas
- Plasma (electron, ion) density
- Production/Vicinity of Plasmas, e.g.,
    - Laboratory Plasmas
    - Terrestrial Plasmas
    - Astrophysical Plasmas

Plasma Sources

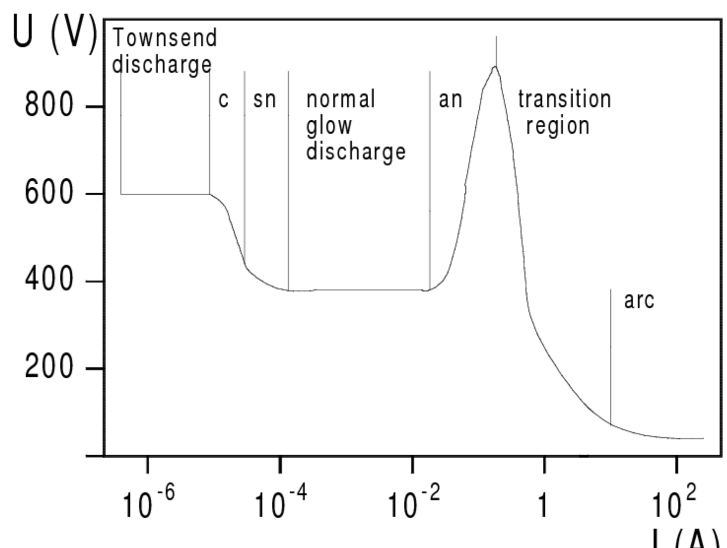
- Direct current discharges
- Pulsed direct current discharges
- Radiofrequency discharge
    - Capacitively coupled plasmas (CCP)
    - Inductively coupled plasmas (ICP)
- Microwave discharge
- Electron and ion beam plasmas
- Dielectric barrier discharge

Direct current discharges

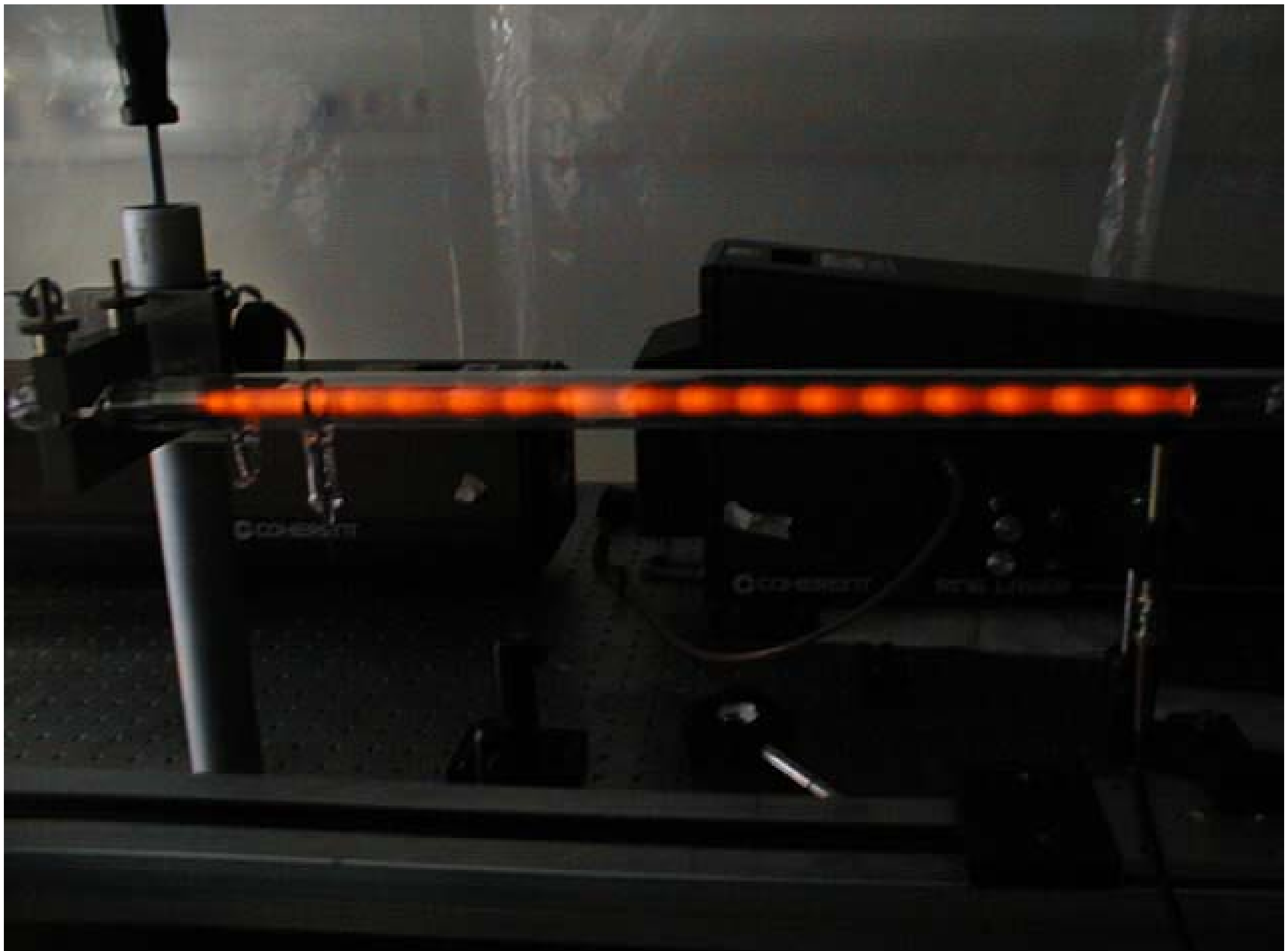
Direct current discharges are created by an electric field between two electrodes (cathode and anode). Various operation modes, e.g., Townsend discharge, corona, subnormal, normal, and abnormal glow, and arc discharge, depending on the applied voltage can be distinguished.



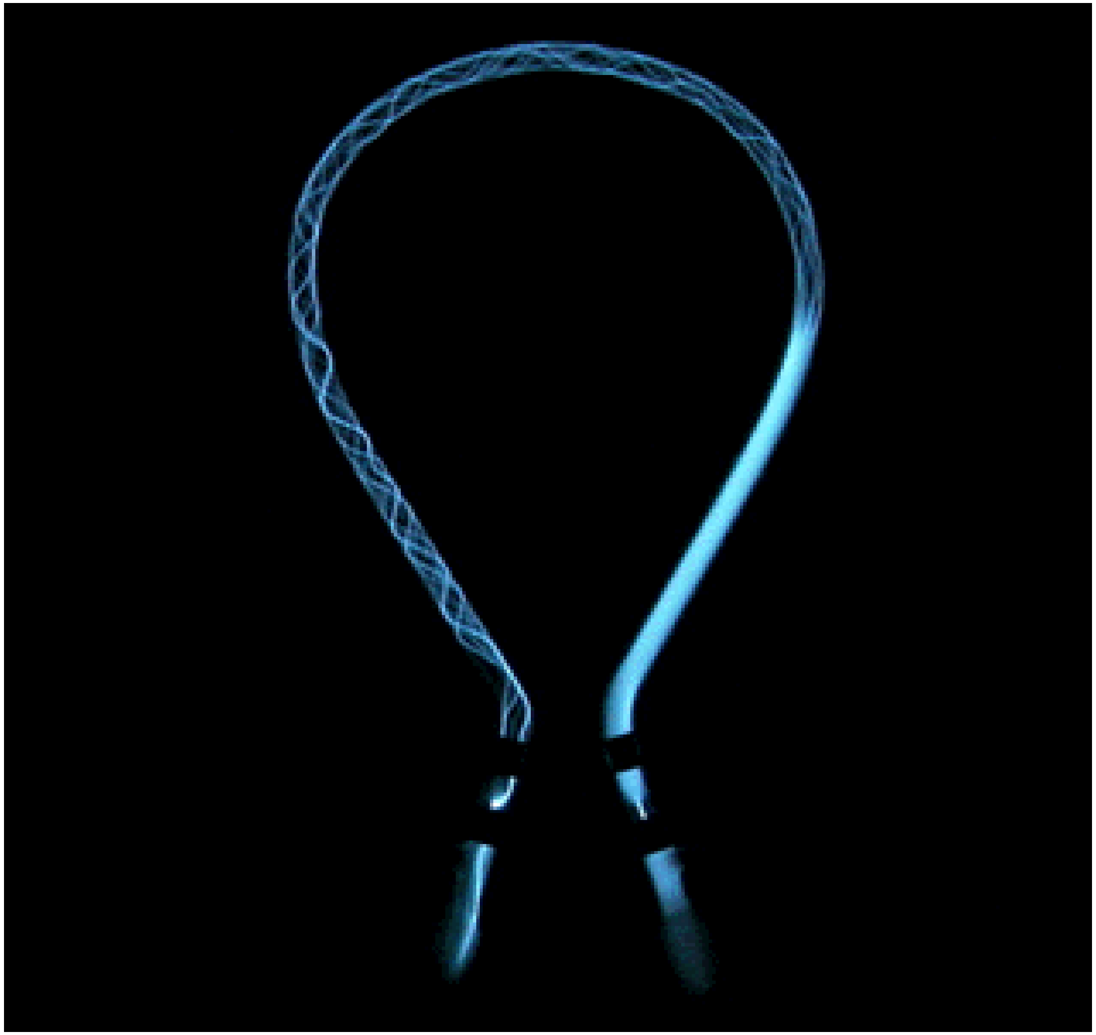
Electrons are produced by energetic ion bombardment of the cathode. The electrons are accelerated in the cathode fall and produce new ions in the negative glow region which again hit the cathode. Electrons are further accelerated in the positive glow region where excited atoms and ions are formed.



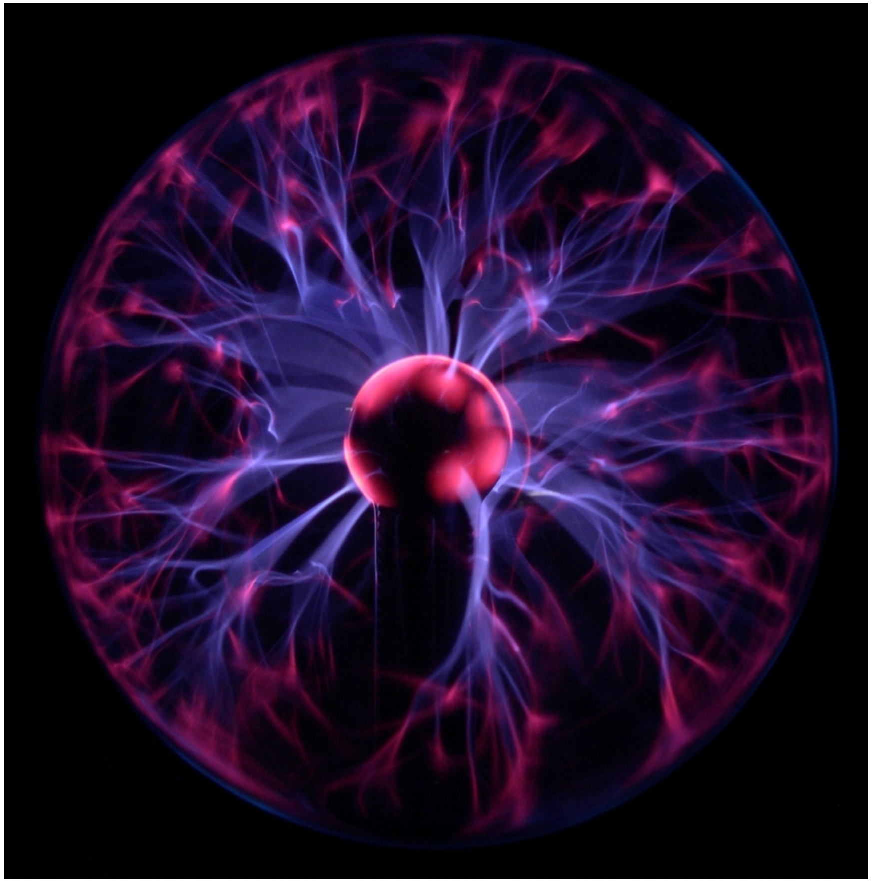
Layered Neon Discharge



Filamentary Discharge



Corona discharge

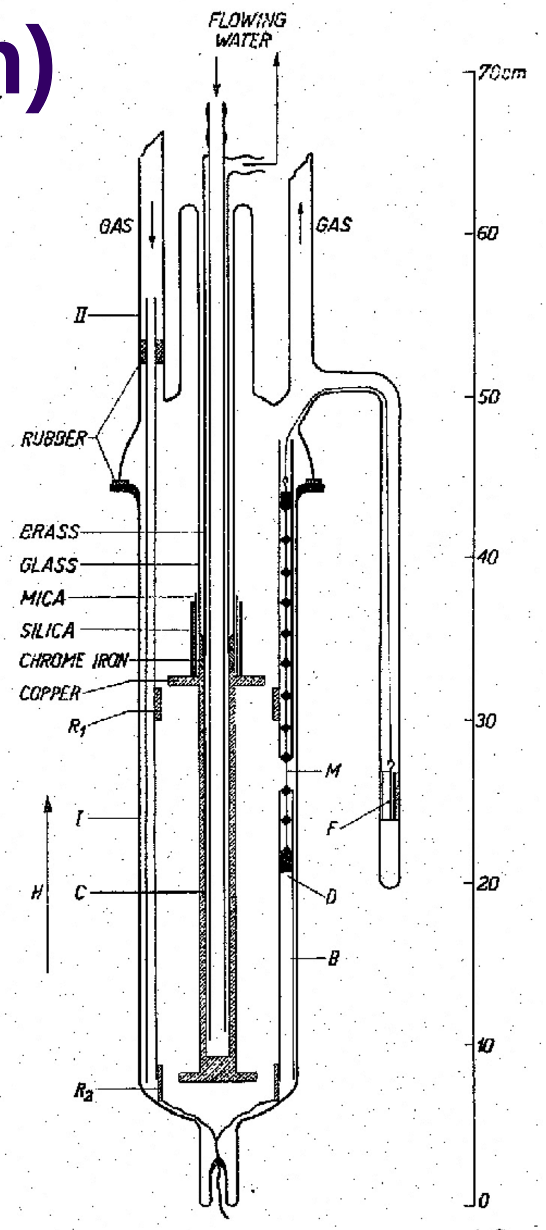


Penning (magnetron) discharge

- Cylindrical magnetron discharge
- Utilizes an external magnetic field
- Lower ignition pressure, and
- Increase of the discharge current at the same discharge voltage.

C water-cooled cathode (Al, Cu, ..)
R1, R2 rings fixing the anode
Deposition has been carried
out onto mica plates M which could be changed
in situ by magnetically moving the weight F.

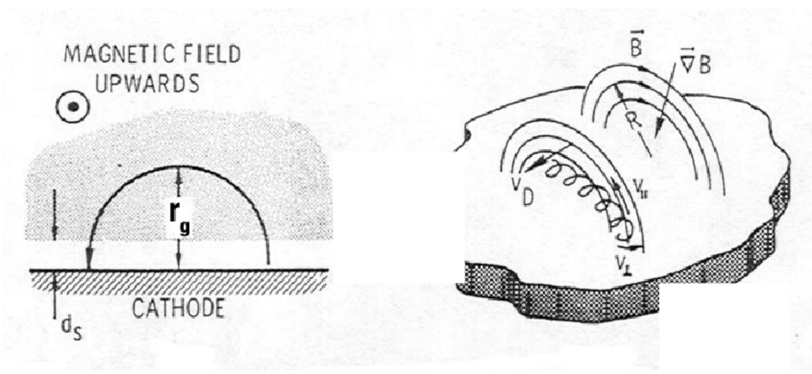
The whole tube was placed within a coil, providing a magnetic field H (arrow) parallel to the axis of C.

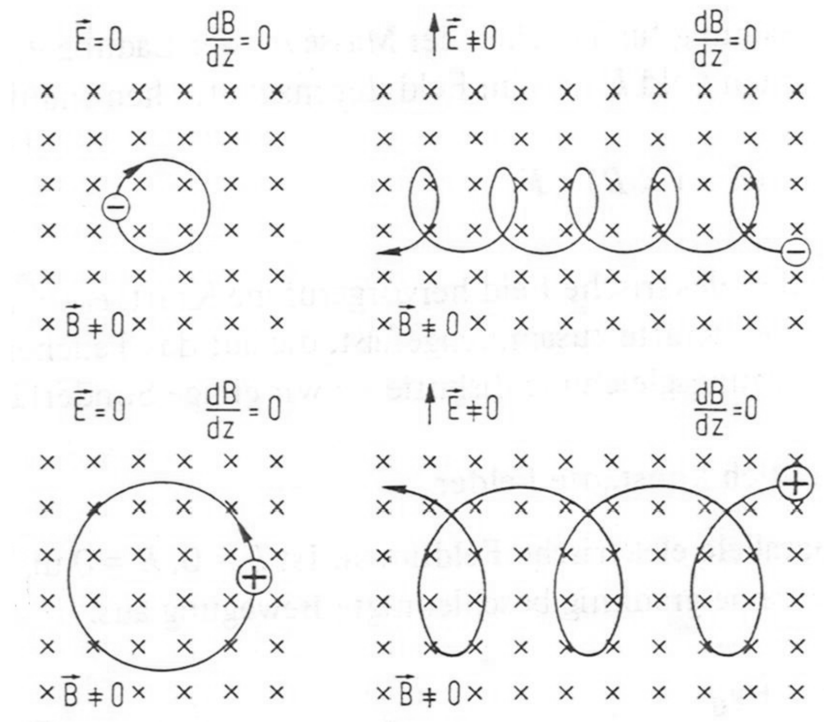


Charged particles in a Magnetic Field

The Lorentz force equation of motion of a particle of charge q ($q = -e$ for electrons and $n \times e$ for n-times ionized atoms, e is the elementary charge), mass m, and velocity v in an electric field $\vec{E}$ and a magnetic field $\vec{B}$ is given by (see, e.g., [22,48]):

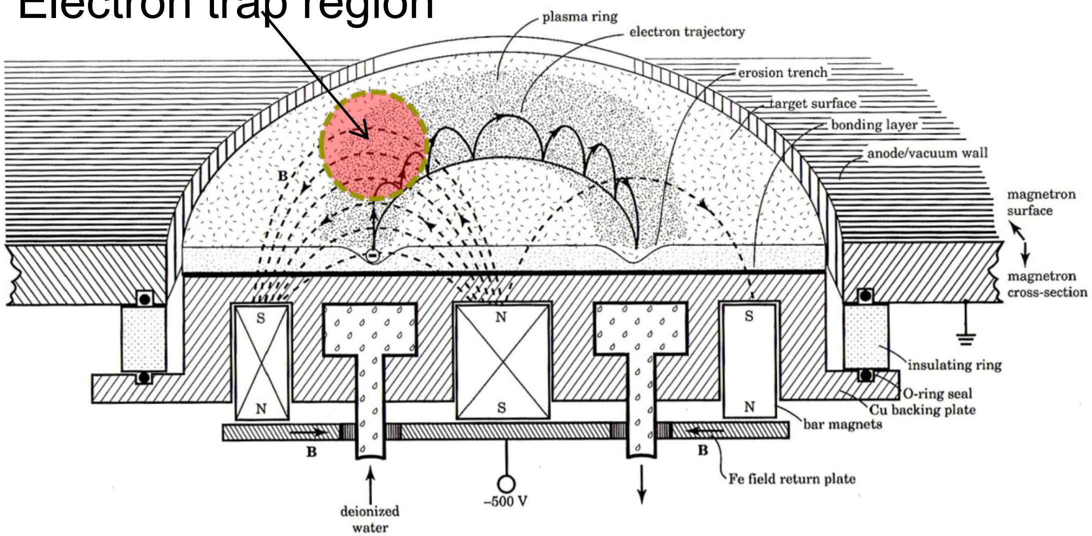
$$\frac{\mathrm{d}\vec{v}}{\mathrm{d}t} = \frac{q}{m}(\vec{E} + \vec{v} \times \vec{B}) \tag{26.1}$$

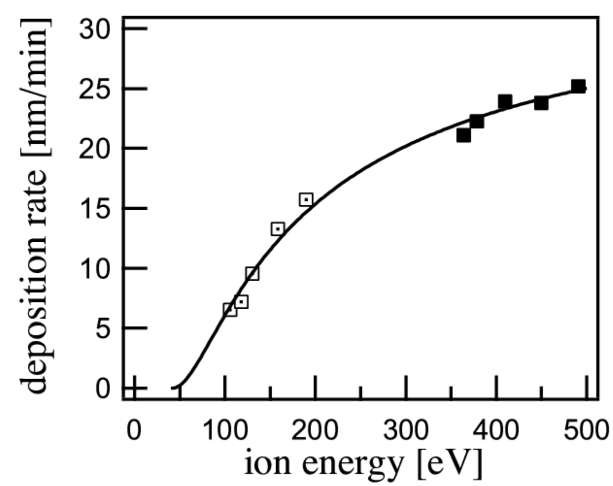




Planar magnetron

Electron trap region



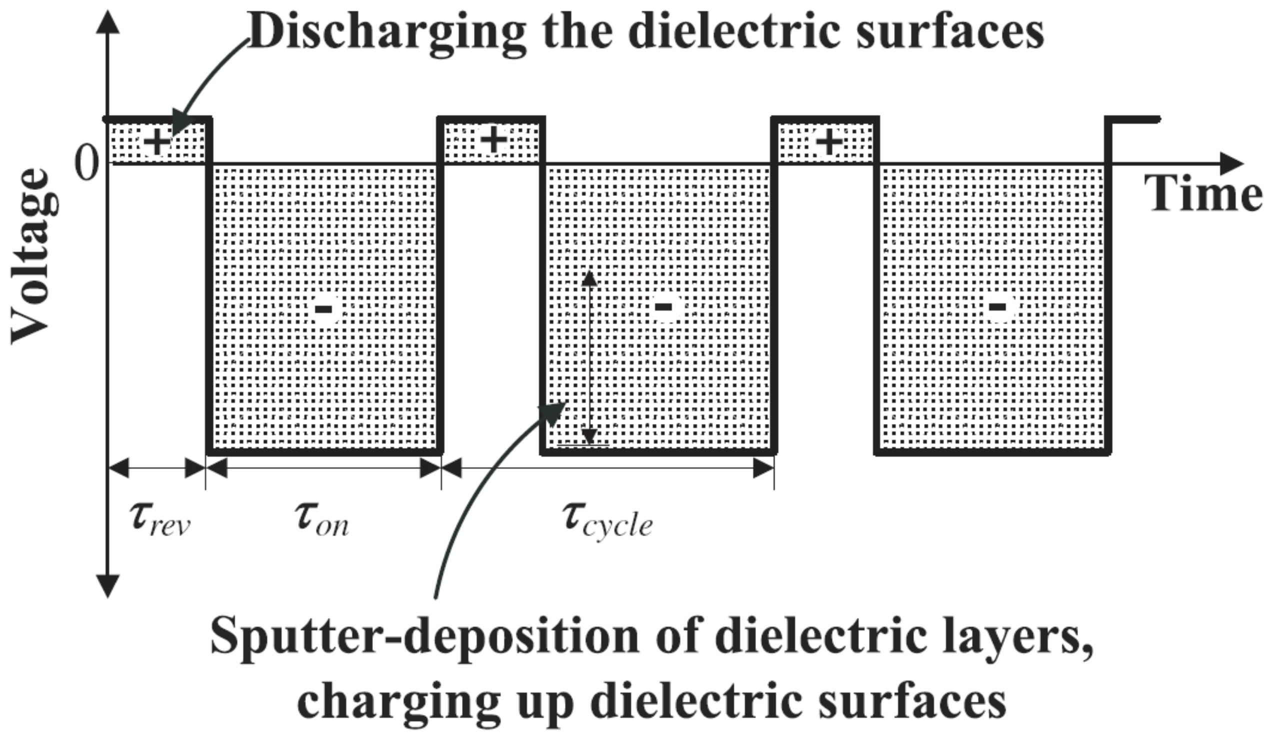


Positve Ions impinging on negatively biased cathode with kinetic energy E ≤ e U produce

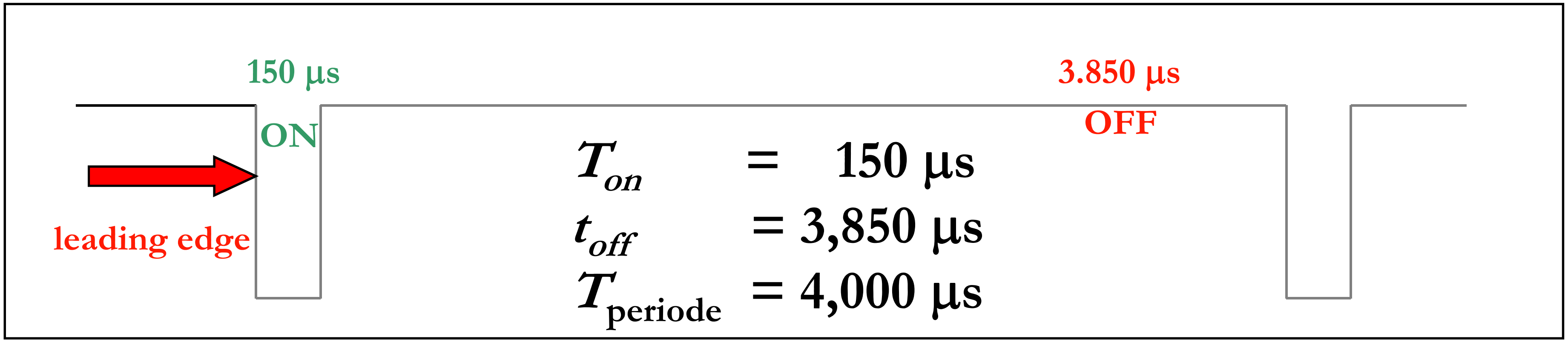
- Sputtered target atoms and ions, sputtering yield Y ≈ 0.5
- Secondary electrons, emission coefficient $\gamma \approx 0.05$.
- Secondary electrons gain energy equal to cathode potential and become trapped in the trap region of perpendicular electric and magnetic fields where each energetic electron produces $1/\gamma \approx 20$ ions.

Pulsed direct current discharge

Frequently used for sputter deposition in reactive plasmas of, e.g., metal oxide films, when cathode becomes insulating.



Pulsed mode operation
high discharge currents

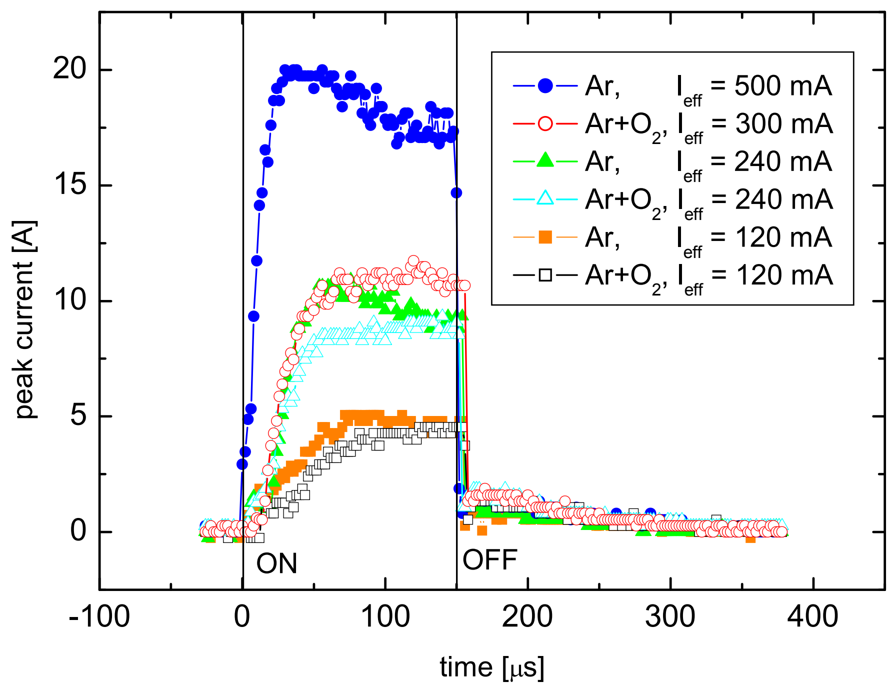


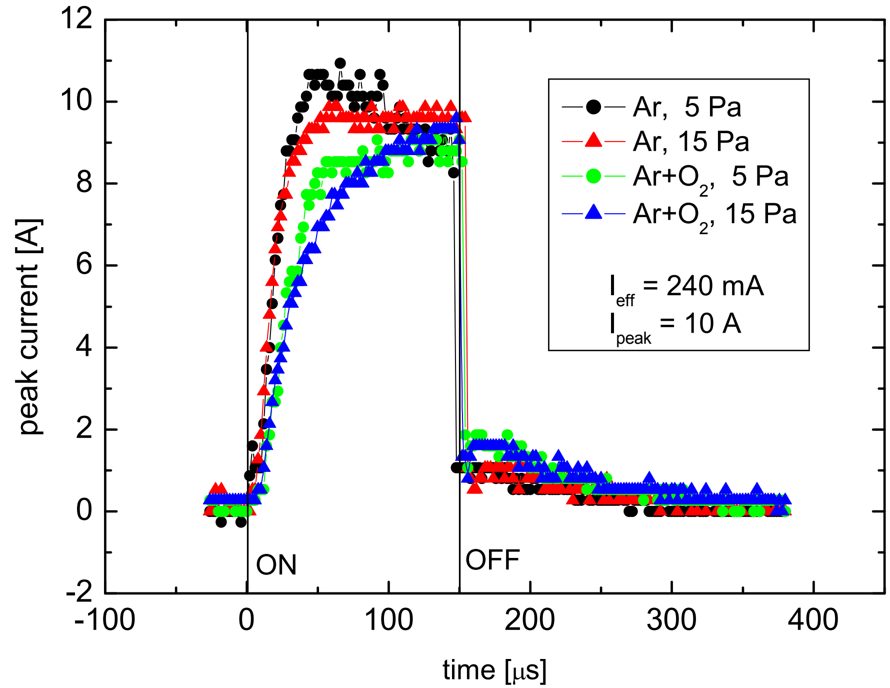
$$T_{on} = 150\ \mu s$$
$$t_{off} = 3{,}850\ \mu s$$
$$T_{periode} = 4{,}000\ \mu s$$

$$i_{eff} = \frac{1}{T}\int_0^T i(t)\,\mathrm{d}t$$

$$I_{\text{eff}} = 300\ \text{mA} \rightarrow I_{\text{peak}} \approx 15\ \text{A}$$

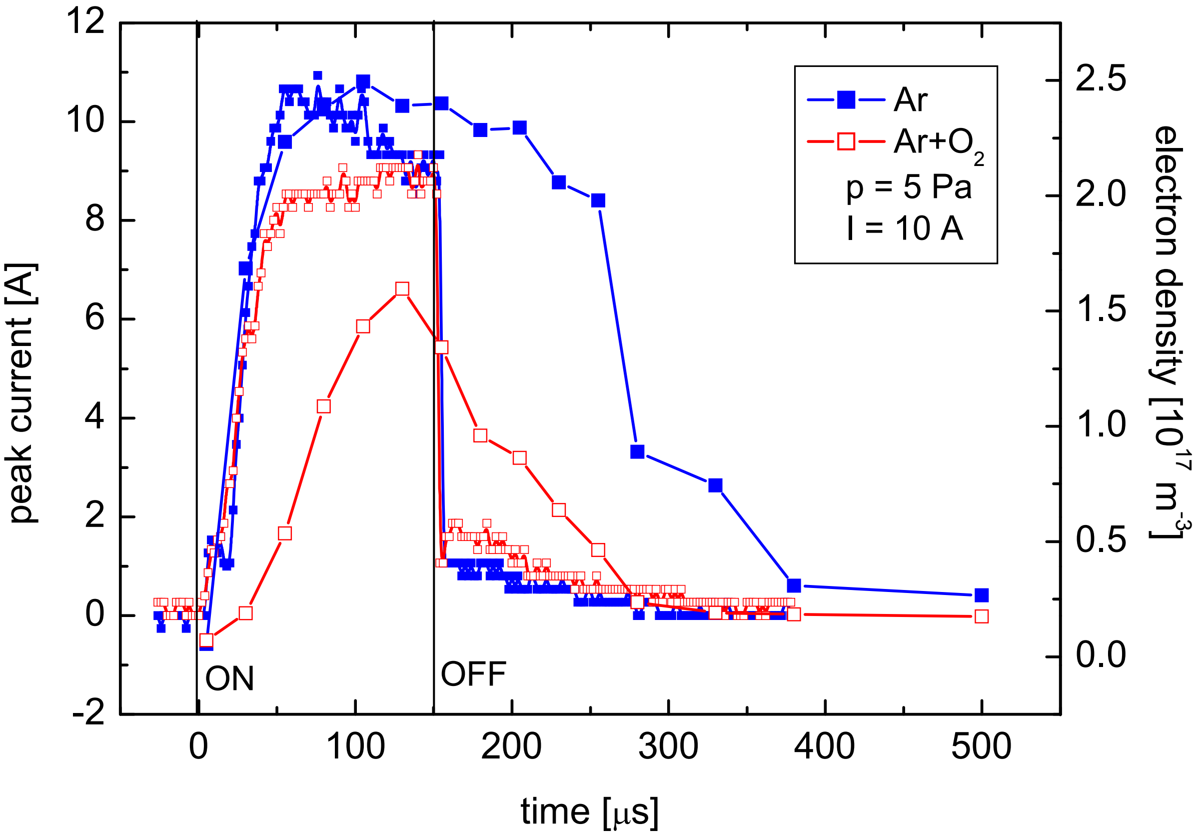
Discharge current





- real data (calculated by the help of Ohm law) from the oscilloscope
- measured between the output and input of pulsed source resistance
- determined plasma parameters are influenced by current behaviour

Electron density



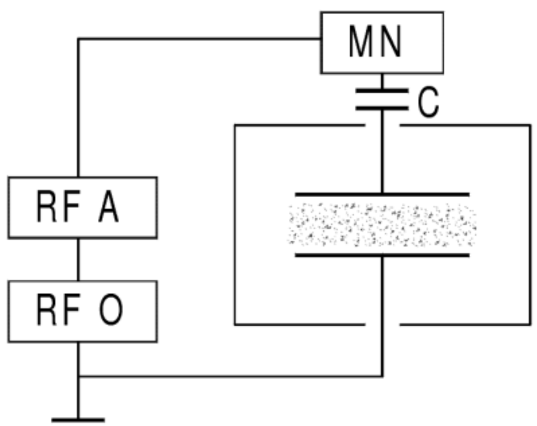
Electron density temporarily enhanced: up to $10^{18}/m^3$ i.e., factor of 100 compared to dc operation.

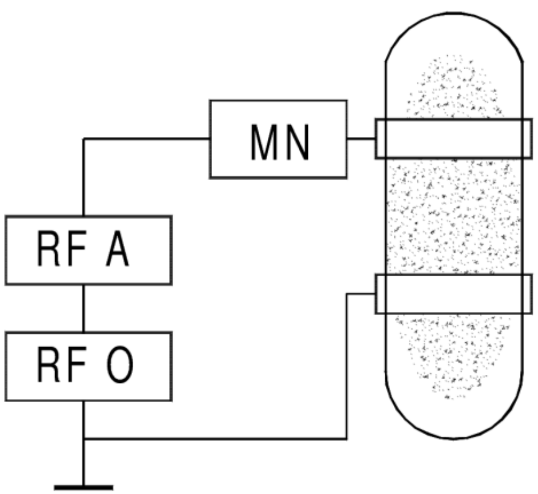
Radiofrequency discharge

Operated at radio frequencies (e.g., 13.56 MHz or 27.2 MHz)
Here we have:

- Capacitively coupled plasmas (CCP)
- Inductively coupled plasmas (ICP), and
- Helicon discharges.

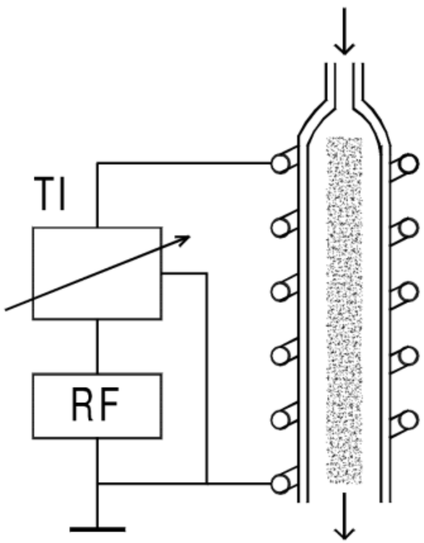
Capacitively coupled plasmas (CCP)

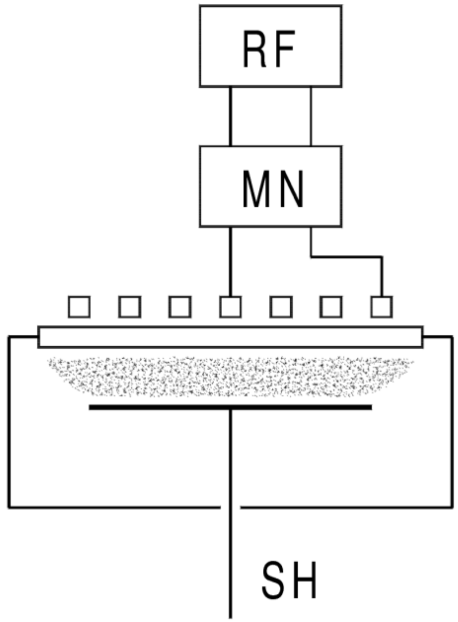




Radiofrequency discharge

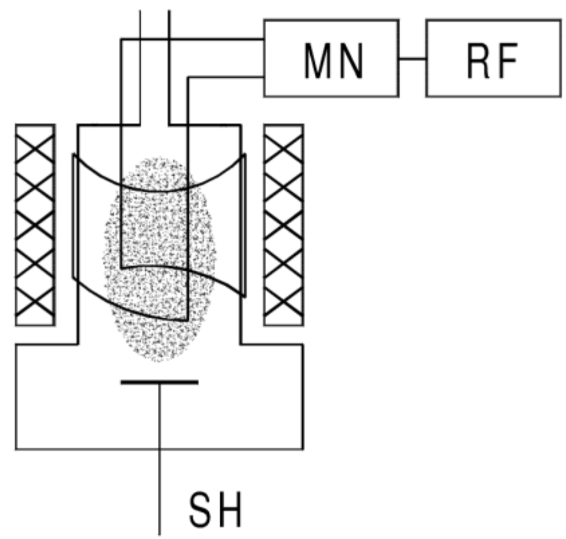
Inductively coupled plasmas (ICP)





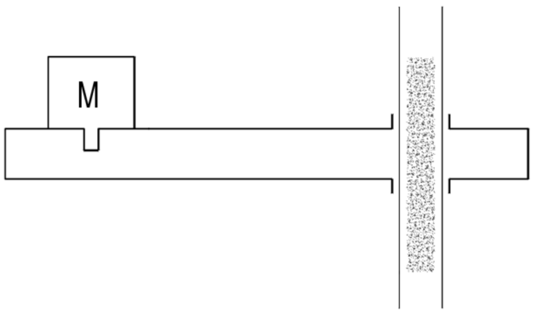
Helicon discharge

Additionally utilizing a longitudinal magnetic field

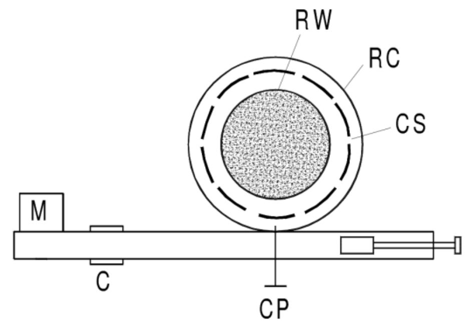


Microwave discharge

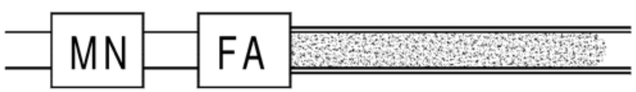
- Utilizes microwaves (typically 2.45 GHz)
- Can be operated at higher pressures up to atmospheric pressures



Microwave coupled to a discharge via a rectangualr waveguide



Slot antenna (SLAN) plasma source. A homogeneous power distribution is achieved by the resonant ring cavity (RC). Microwave power is transmitted by coupling slots (CS), with M magnetron, C circulator, CP coupling probe, RW reactor wall, and the plasma inside the reactor.



Surfatron. The surface wave propagates on the plasma surface in the dielectric discharge tube, with matching network (MN) and field applicator (FA).

Electron and laser beam plasmas

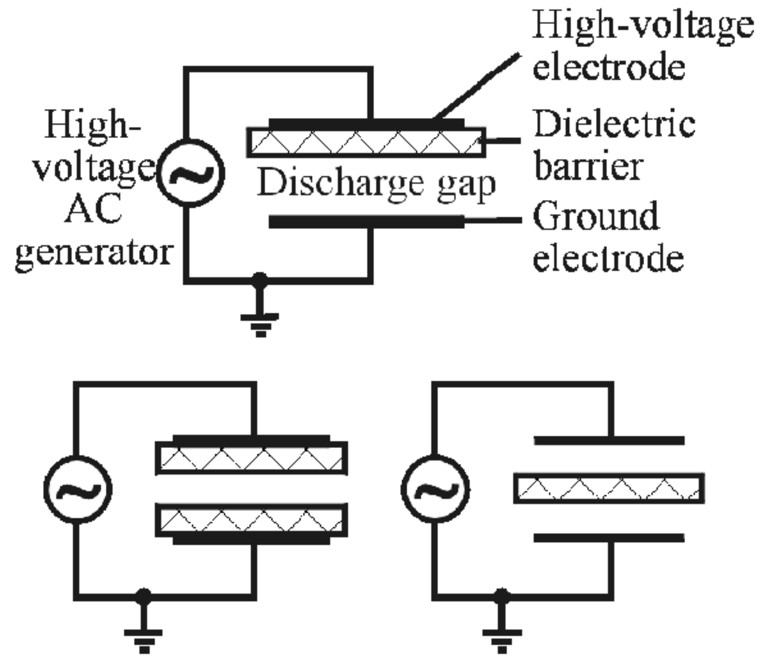
A beam-produced plasma discharge is sustained, e.g., by the interaction of an electron beam with a gaseous medium. The energy transfer is very effective as up to 70% of the beam energy can be transferred to the plasma. It is possible to create plasmas with high degrees of ionization in low-pressure environments. The plasma properties may be controlled by the electron beam current, the acceleration voltage, the gas pressure, and by the shape of the beam.

Electron-beam generated plasmas are being used for large-area material processing. For process gas pressures between 1 and 100 Pa, plasmas with electron densities up to $10^{12}/cm^3$ and electron temperatures of about 1 eV can be obtained.

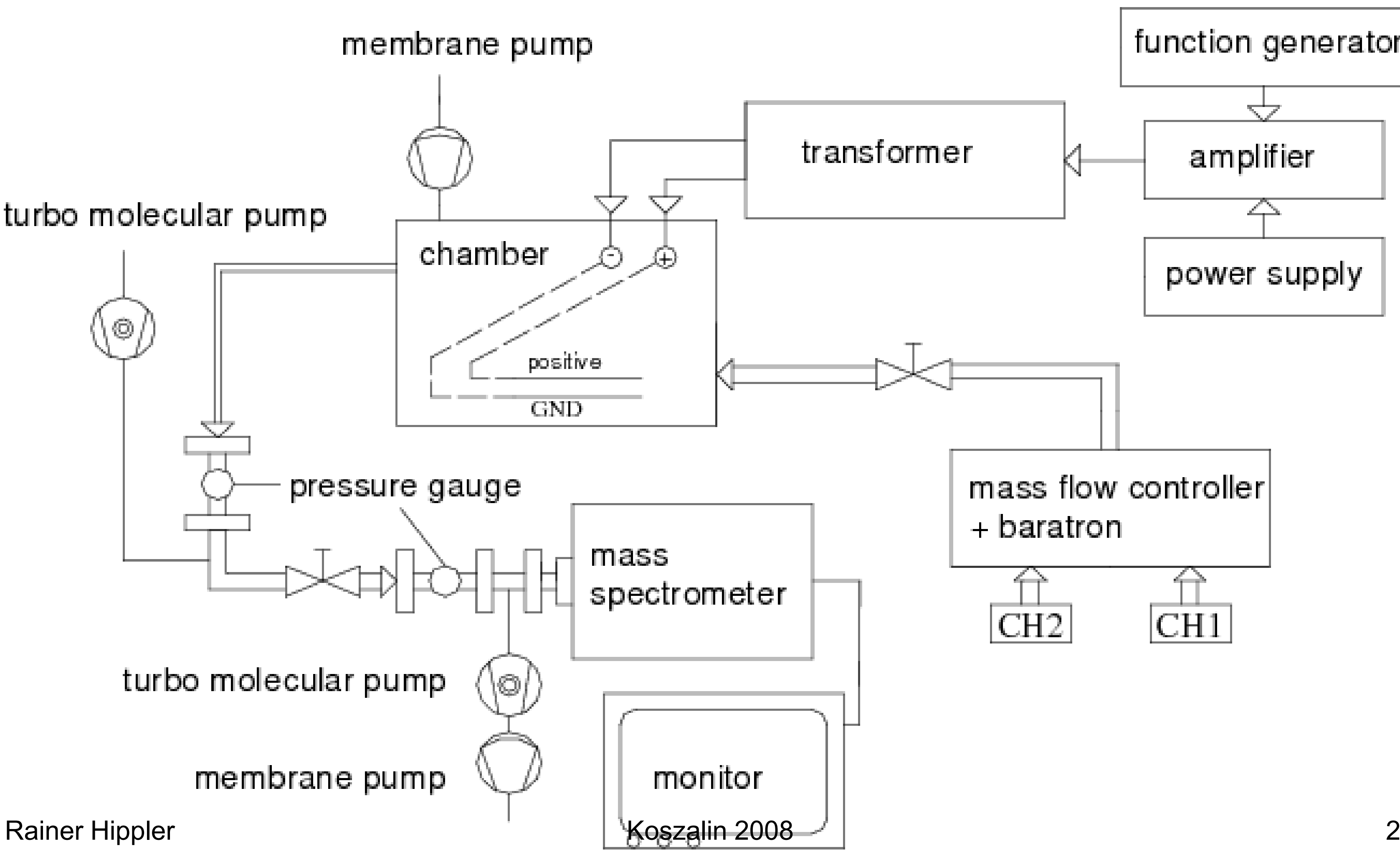
The interaction of laser beams of sufficient energy with matter is connected with the formation of plasmas. It is used, e.g., for fusion research, for cutting of metal, and for chemical analysis of evaporated solid state materials by optical spectroscopy or mass spectrometry.

Dielectric barrier discharge

Dielectric barrier discharge (DBD) have a dielectric barrier that allows for ignition but suppresses the sustainment of a discharge as no current can flow through the barrier. DBDs are operated at normal pressure in pulsed or alternating current (AC) mode and frequently have a filamentary character, ie., the discharge consists of filament of short duration (ns).



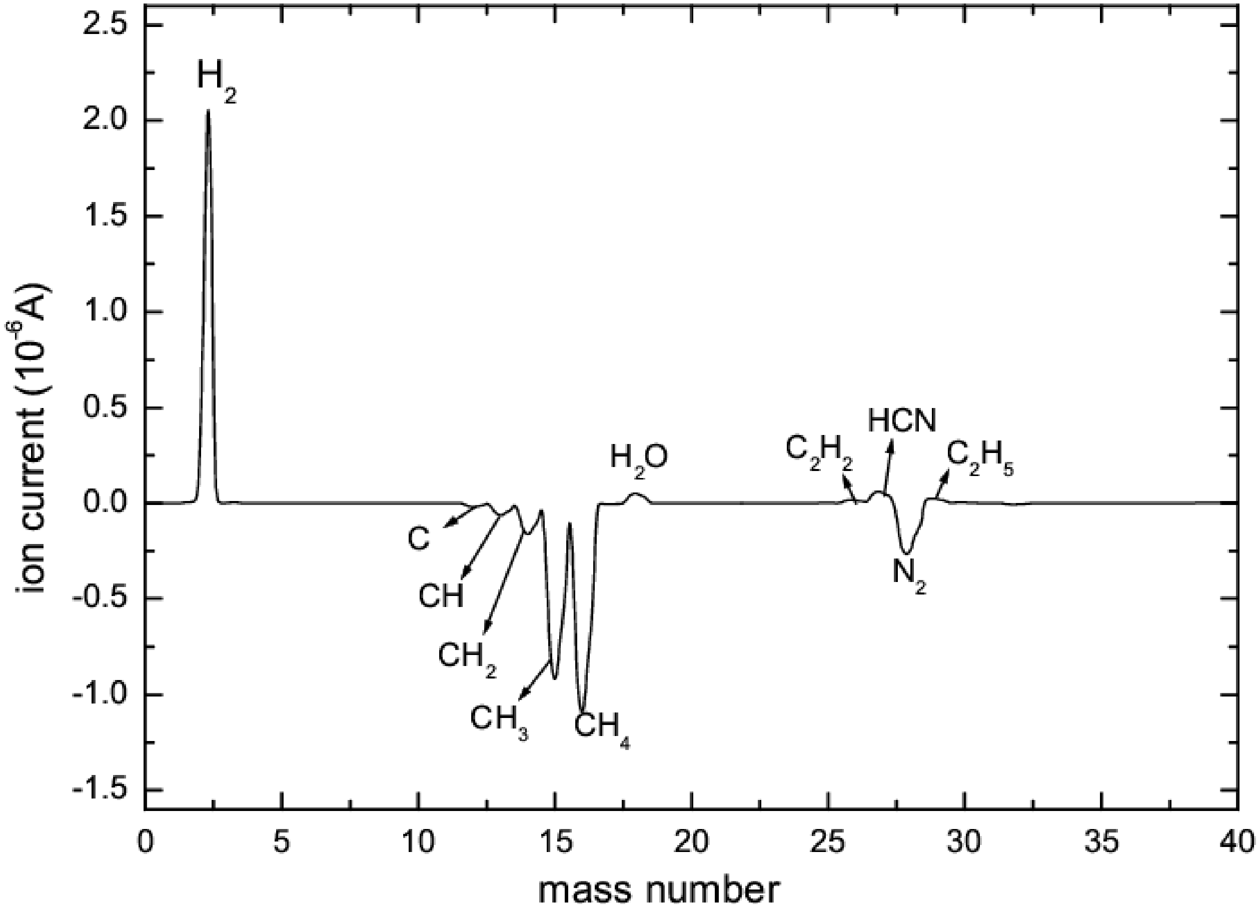
DBD Set-up



membrane pump
function generator
transformer
amplifier
turbo molecular pump
chamber
power supply
positive
GND
pressure gauge
mass flow controller
+ baratron
mass
spectrometer
CH2
CH1
turbo molecular pump
membrane pump
monitor

Chemical reactions in N_2/CH_4

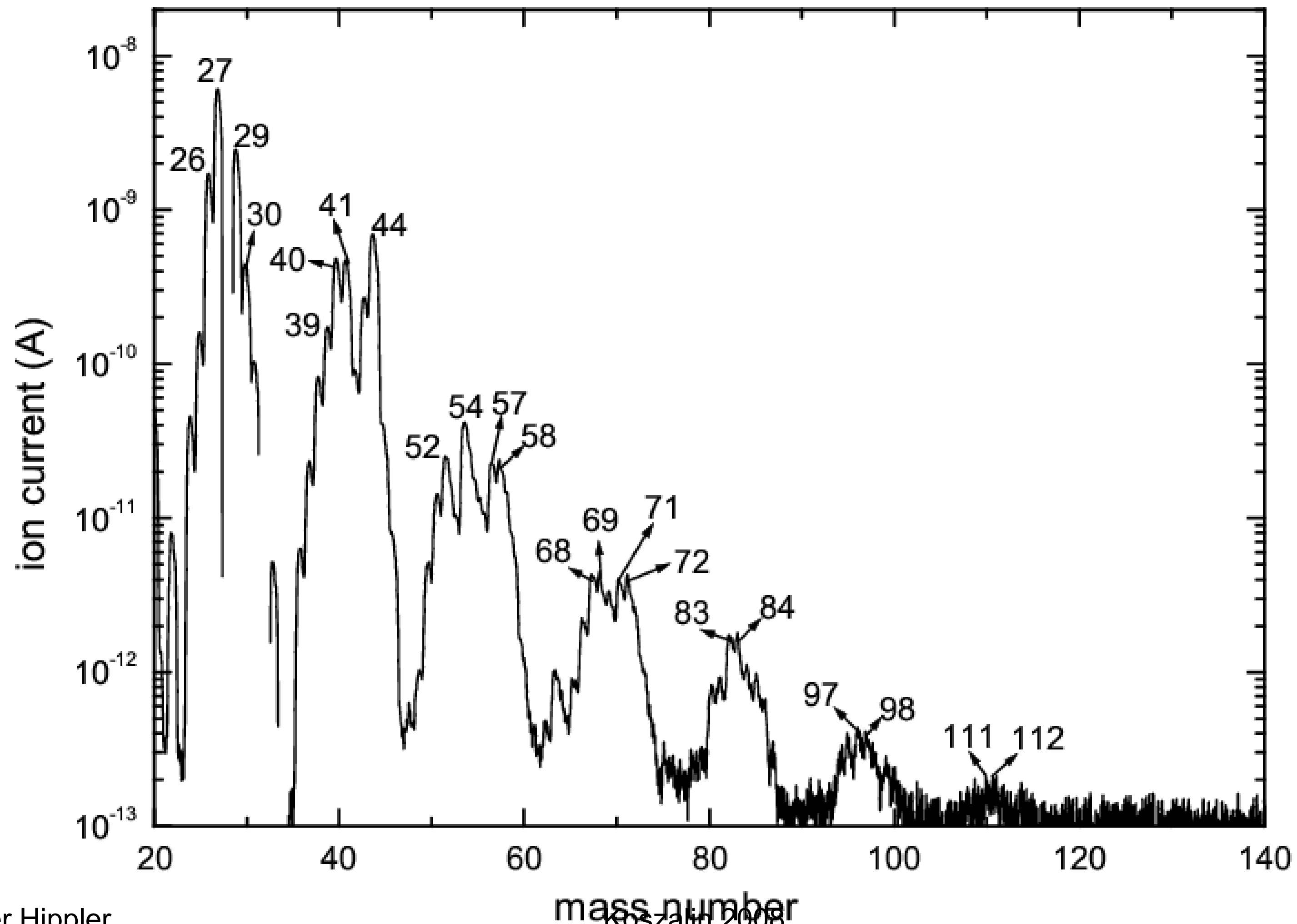
Production of hydrogen from methane



Difference
mass spectrum

Chemical reactions in N_2/CH_4

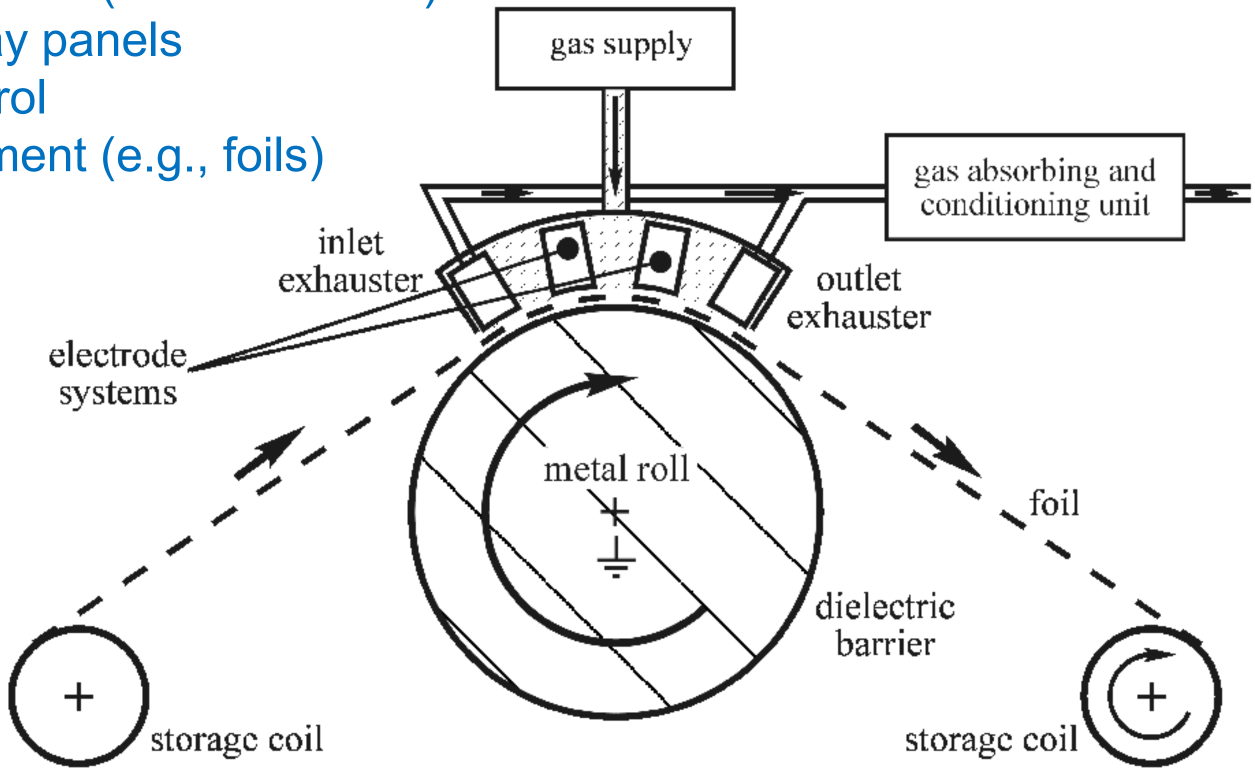
Formation of larger molecules from methane



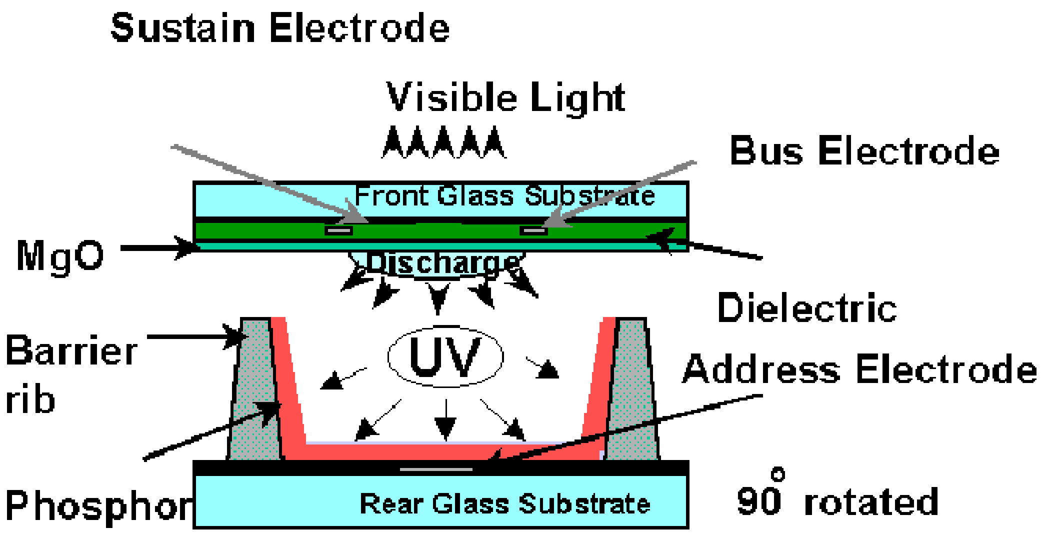
Dielectric barrier discharge

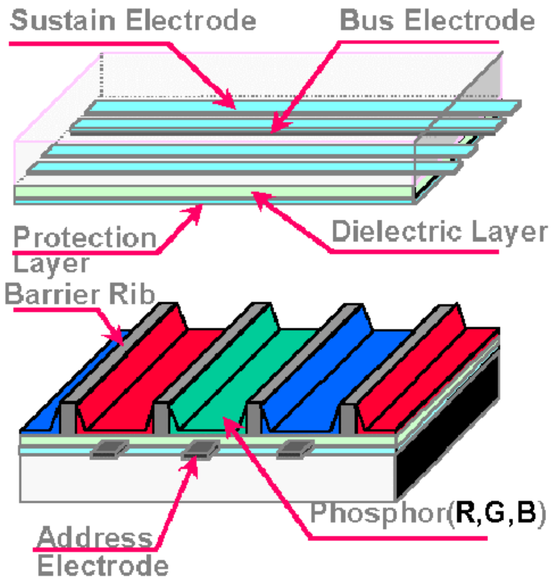
Applications

- Ozone generation (Siemens 1857)
- Plasma display panels
- Pollution control
- Surface treatment (e.g., foils)



Plasma Display Panel



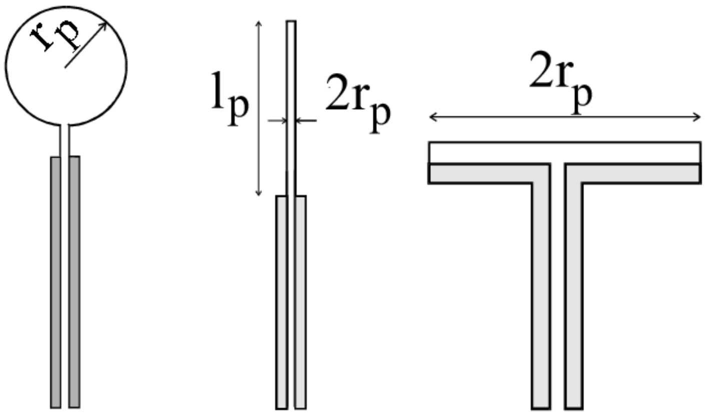


Plasma Diagnostics

- Langmuir probe
- Optical emission spectroscopy
    - Cross correlation spectroscopy
- Laser spectroscopy
    - Absorption spectroscopy
    - Laser-induced fluorescence
- Mass spectrometry
    - Energy resolved mass spectrometry

Langmuir probe

- Simple configuration (wire)
- Electrical probe measures current as function of applied voltage
- Allows determination of fundamental plasma parameters:
    - Floating potential (= zero probe current, ie., ion flux = electron flux)
    - Plasma potential (from second derivative)
    - Electron temperature (from second derivative)



Langmuir probe

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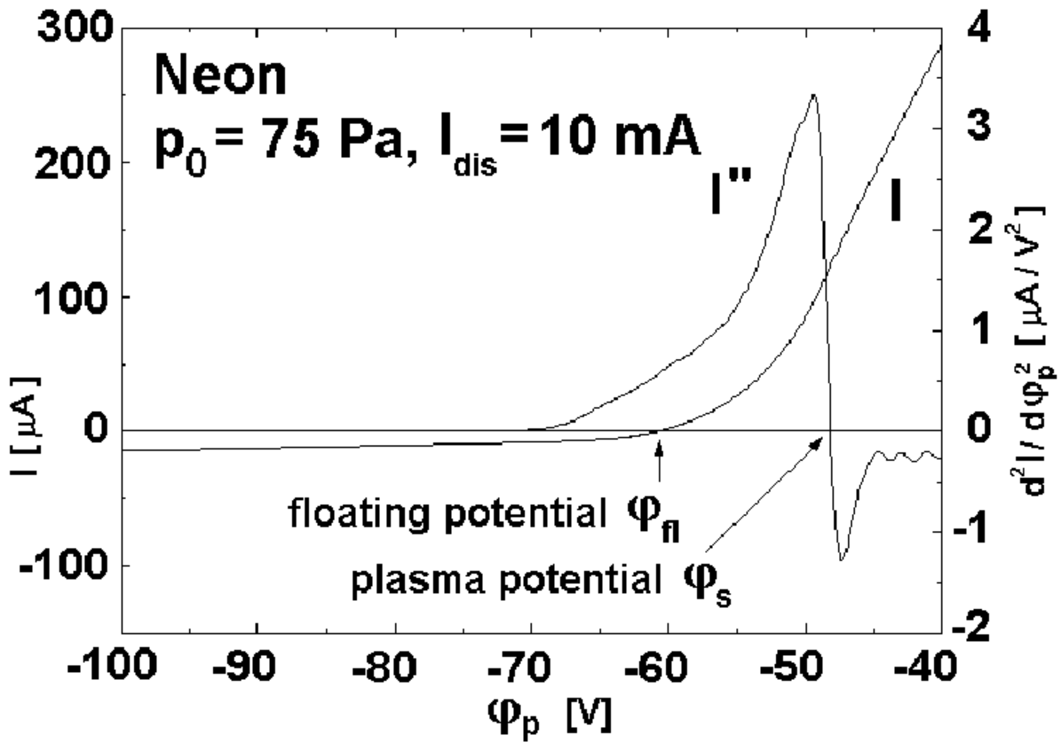
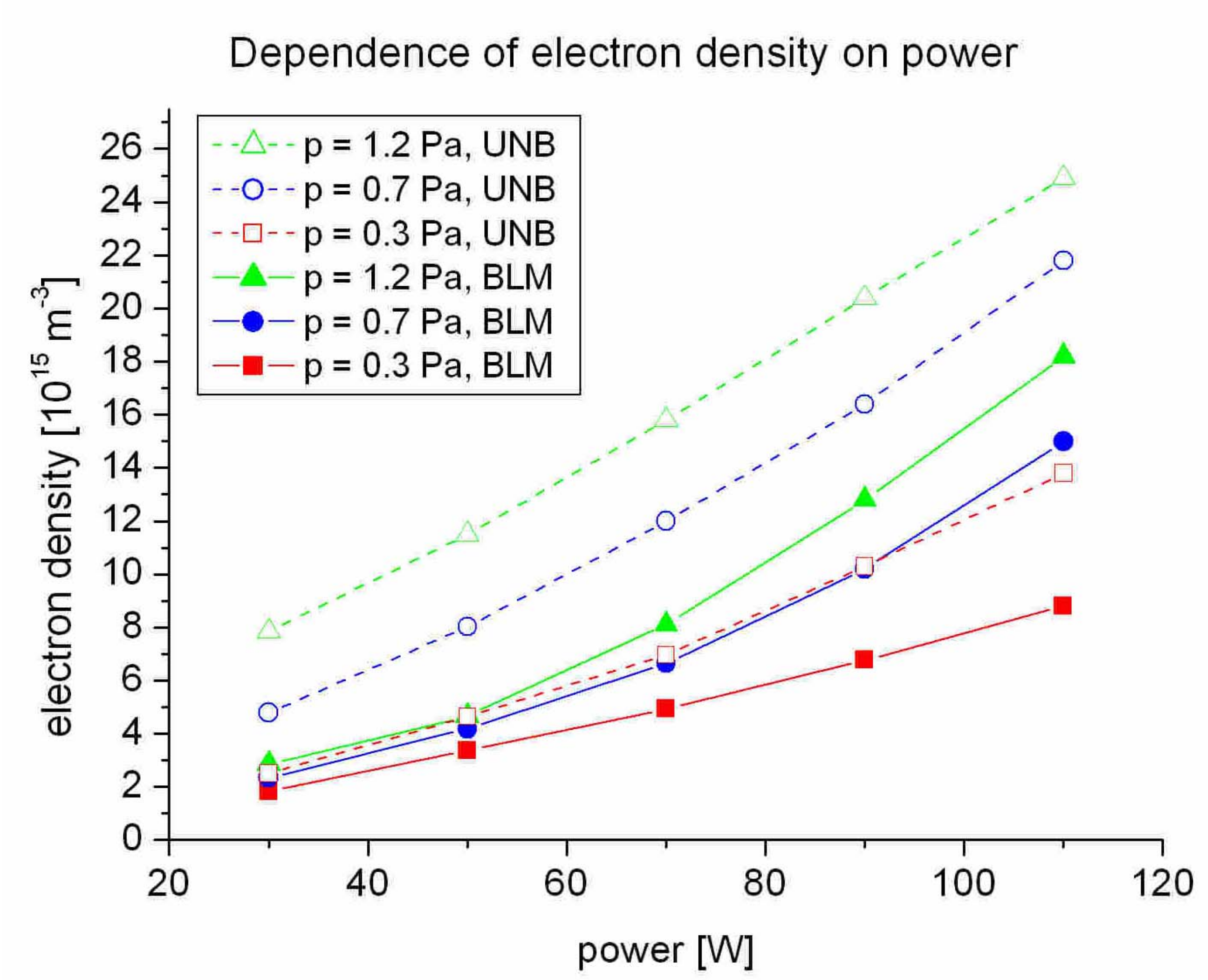
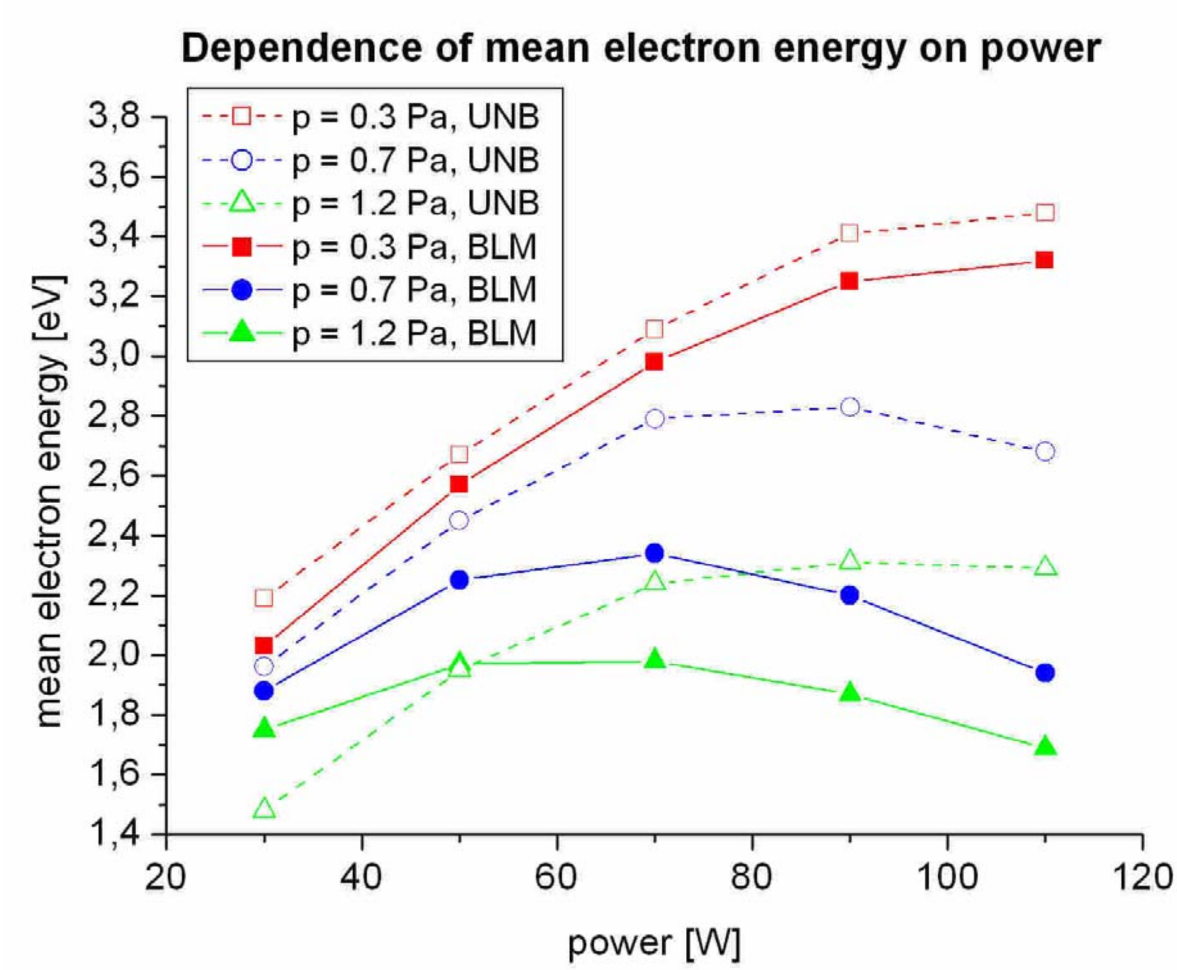


Langmuir probe:
electron density



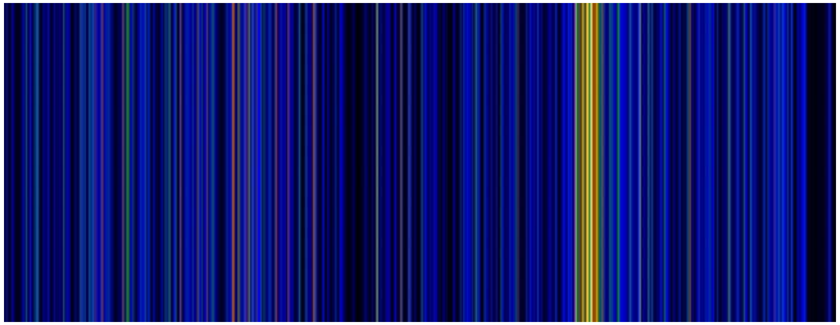
Mean electron energy

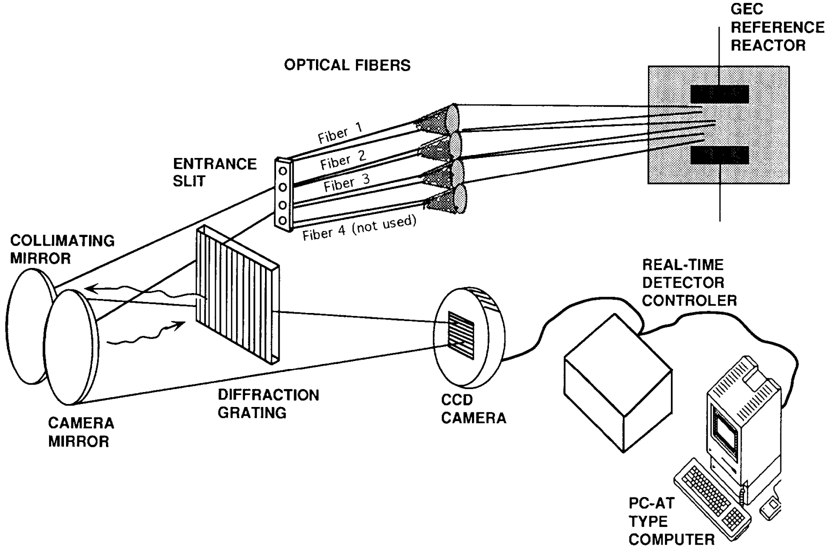


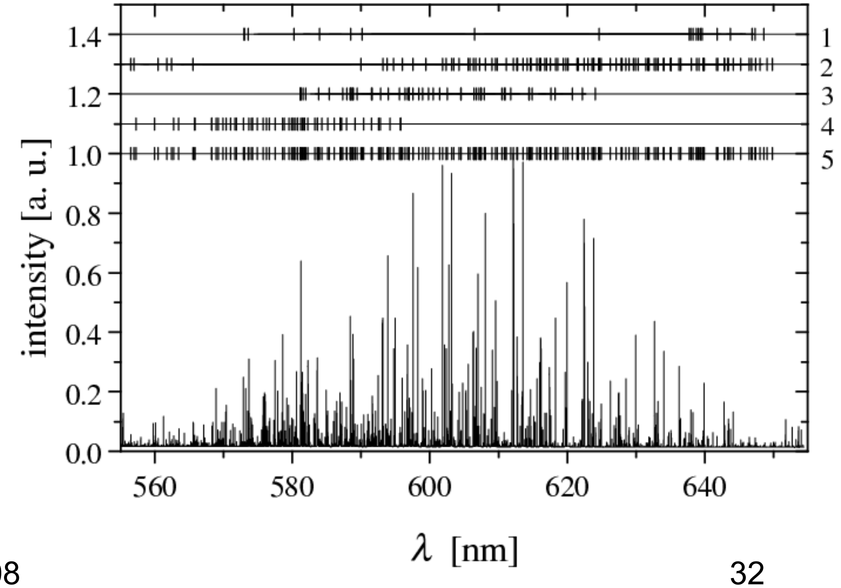
Decrease caused by „cooling“ due to sputtered metal atoms in a magnetron discharge

Optical emission spectroscopy

- Utilizes a wavelength-dispersive element (grating) which determines the resolution, and
- a light sensitive element (e.g., camera)
- which is connected to a PC.

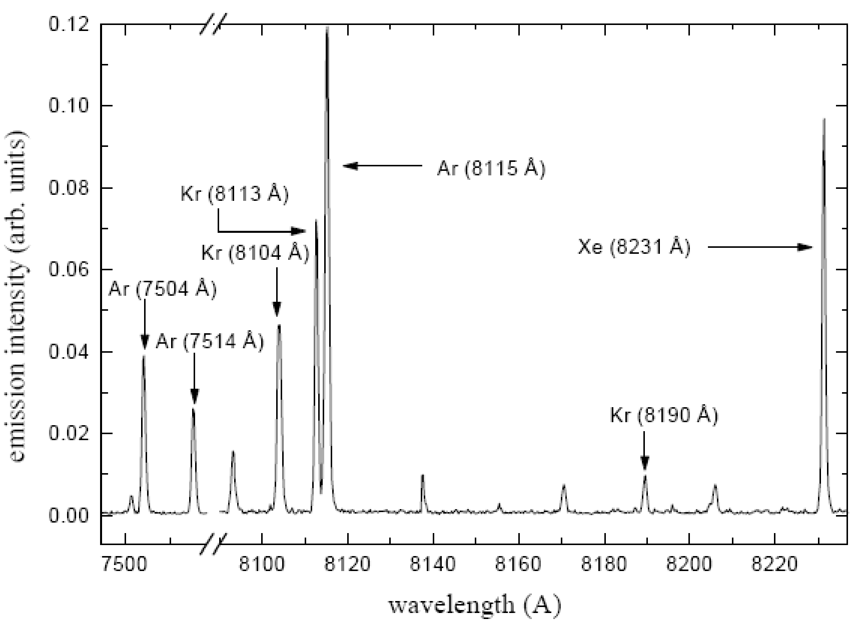


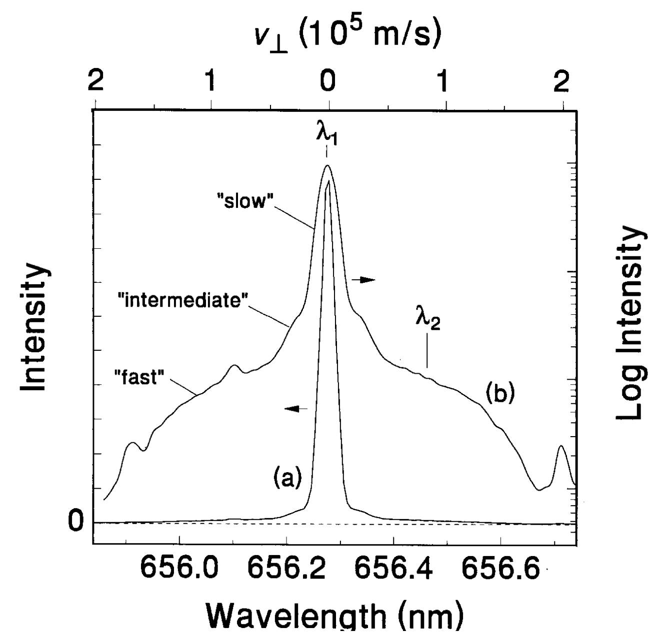




Optical emission spectroscopy

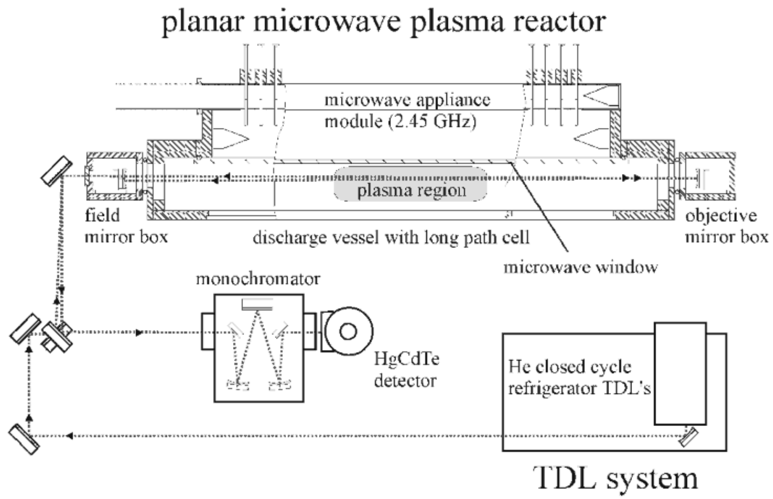
• Measures light emitted by excited atoms to determine the density of light emitting species by identification of specific transitions,
• Velocity (temperature) of excited species from width of emission profile.





Laser spectroscopy

- Laser-induced fluorescence
- Absorption spectroscopy
- others…..



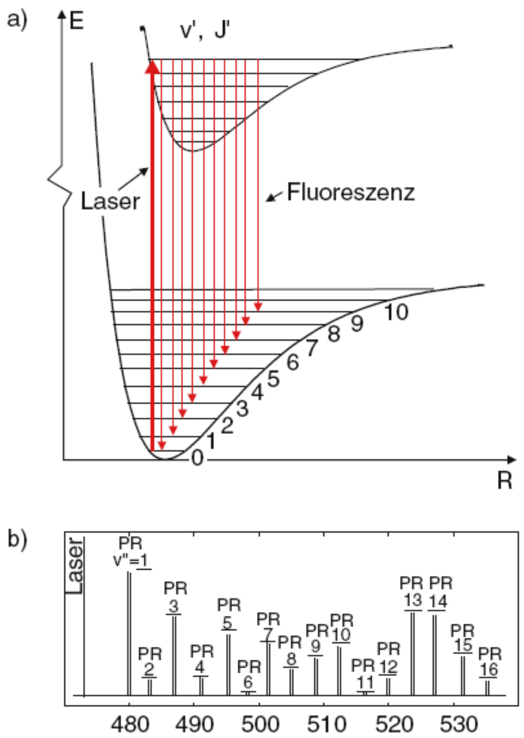
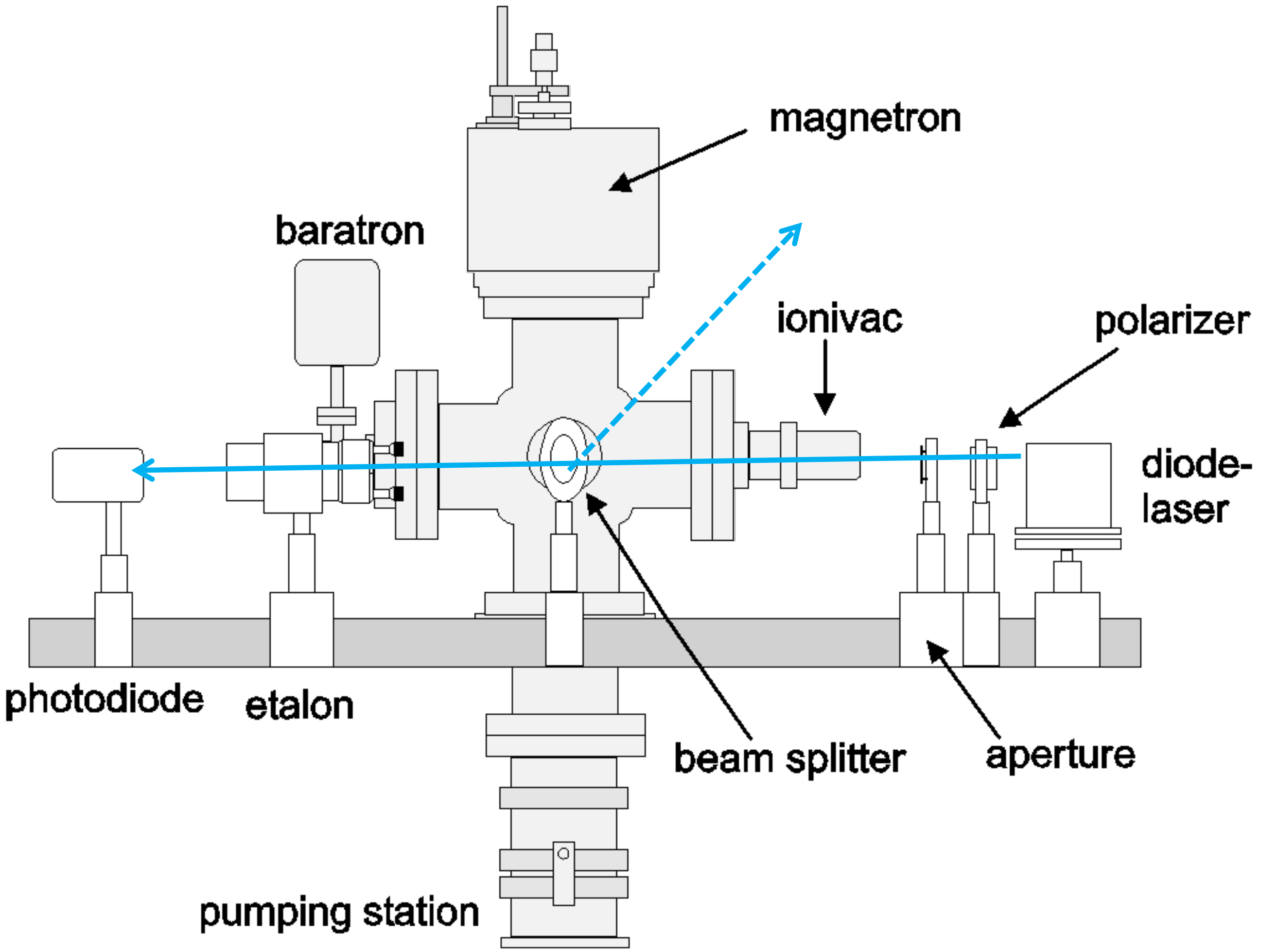
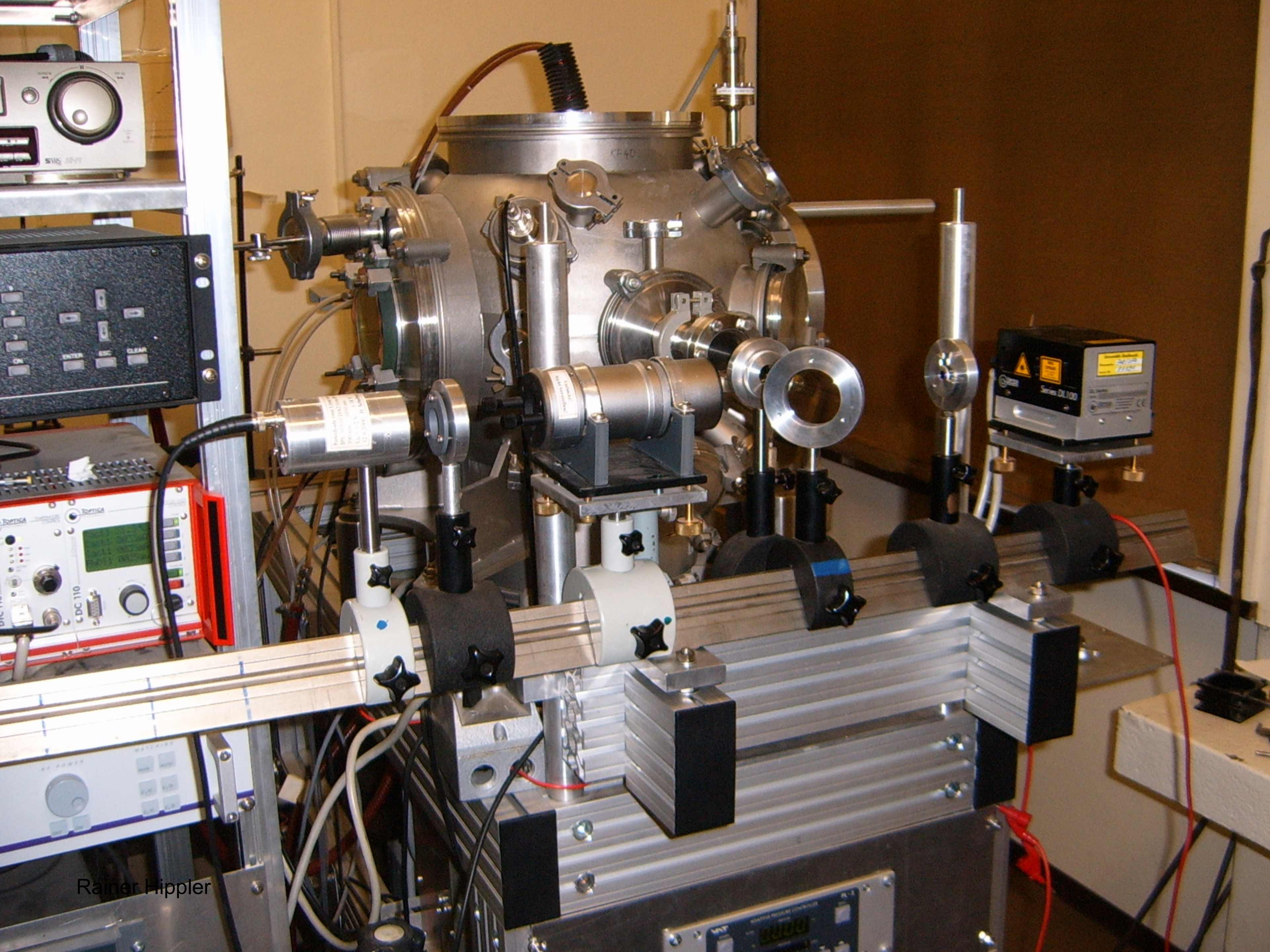


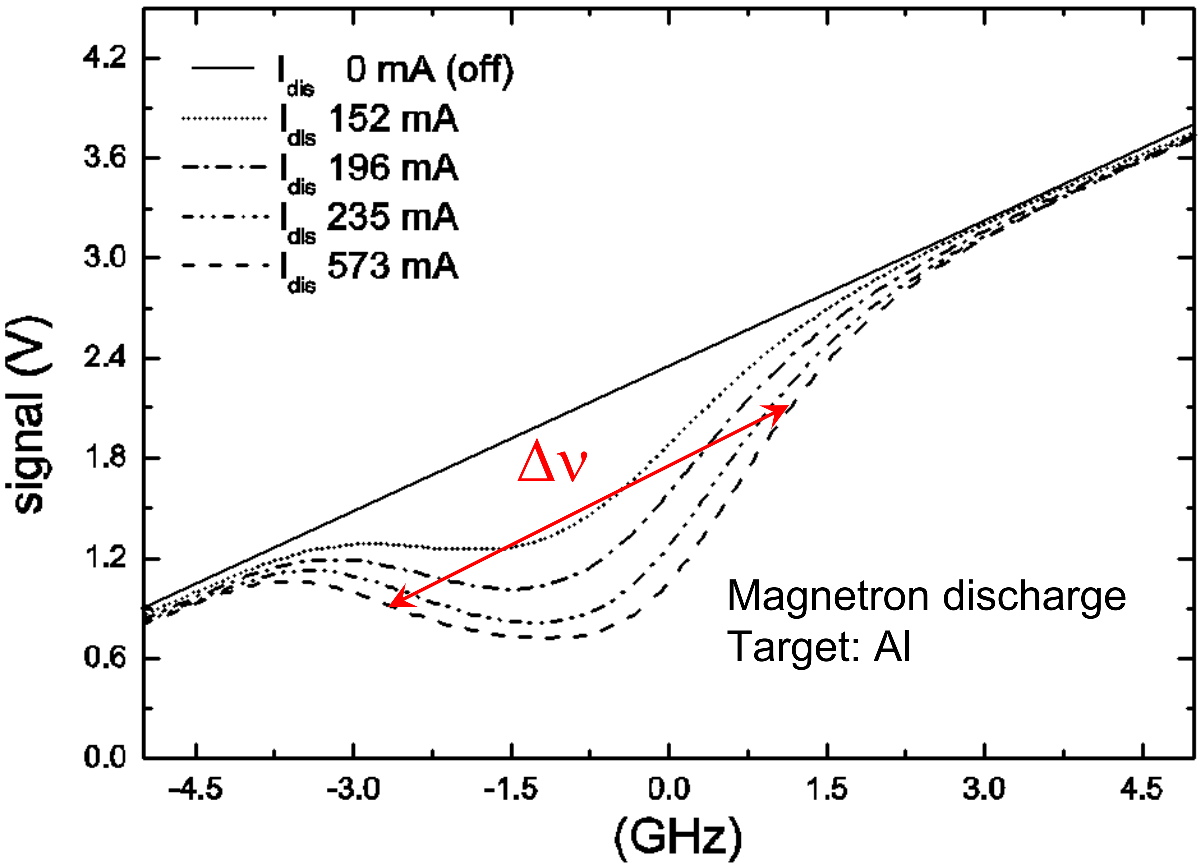
Abb. 10.16a,b. LIF (Laserinduzierte Fluoreszenzspektroskopie). (**a**) Termschema; (**b**) LIF-Spektrum des $Na_2(B^1\Pi_u)$-Zustandes in dem das Niveau ($v' = 6$, $J' = 27$) selektiv von einer Argonlaserlinie bei $\lambda = 476,5$ nm angeregt wurde

Blue Tunable Diode Laser Absorption Spectroscopy




KF40
ENTER
ESC
CLEAR
ON
TOPTICA
DC 110
Series DL100
Rainer Hippler

Laser absorption profile

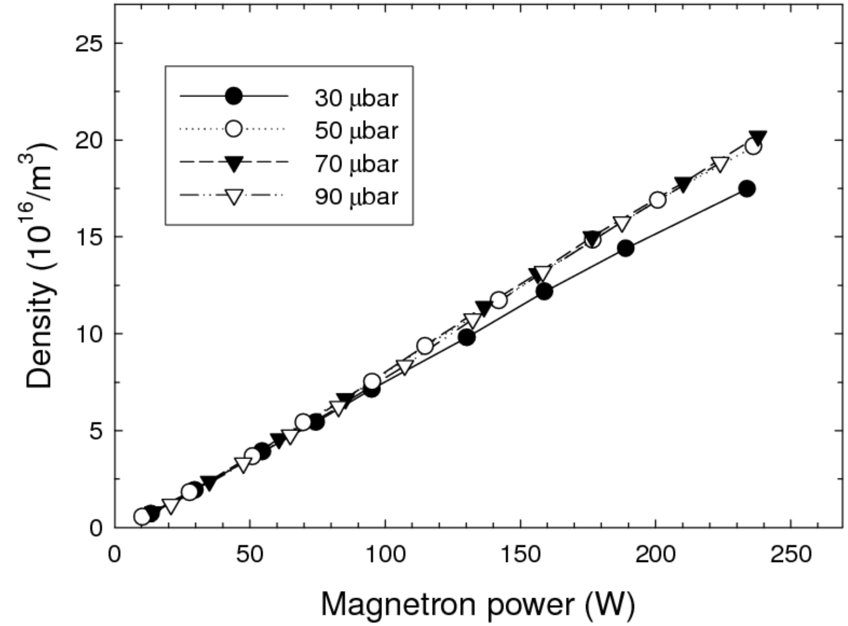


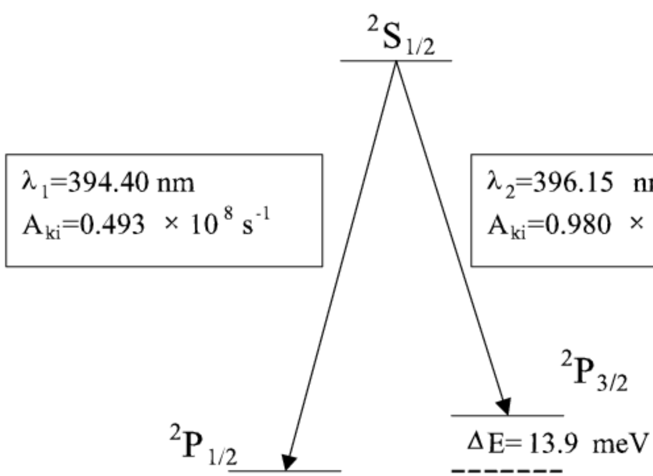
Density:
proportional to integral of absorption profile

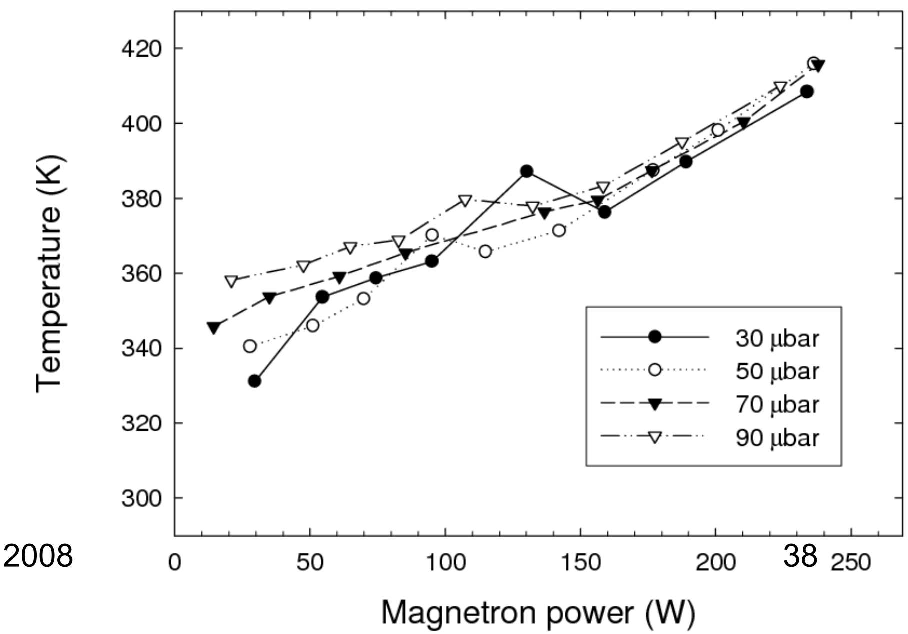
Temperature:
Proportional to width $\Delta\nu$ of absorption profile

Aluminum

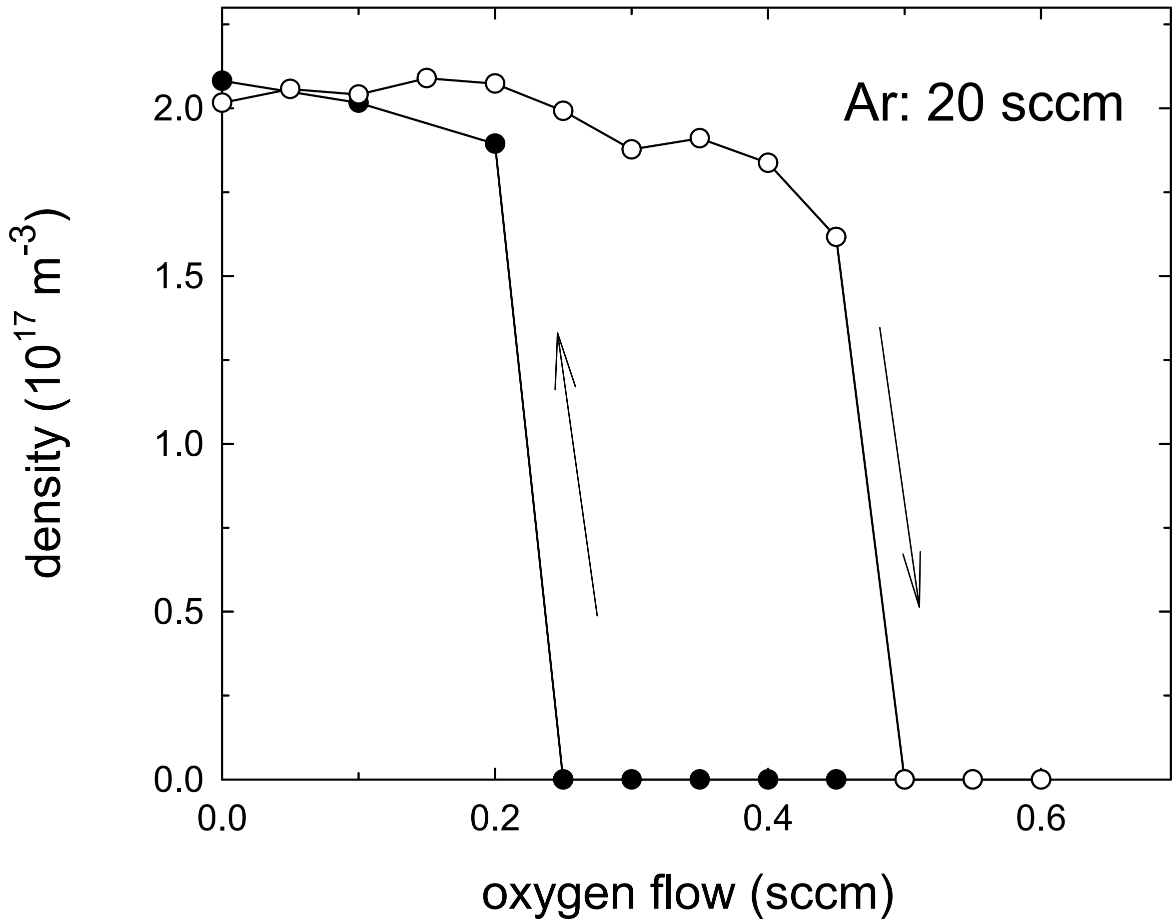
Density and Temperature







Al density vs. Oxygen flow

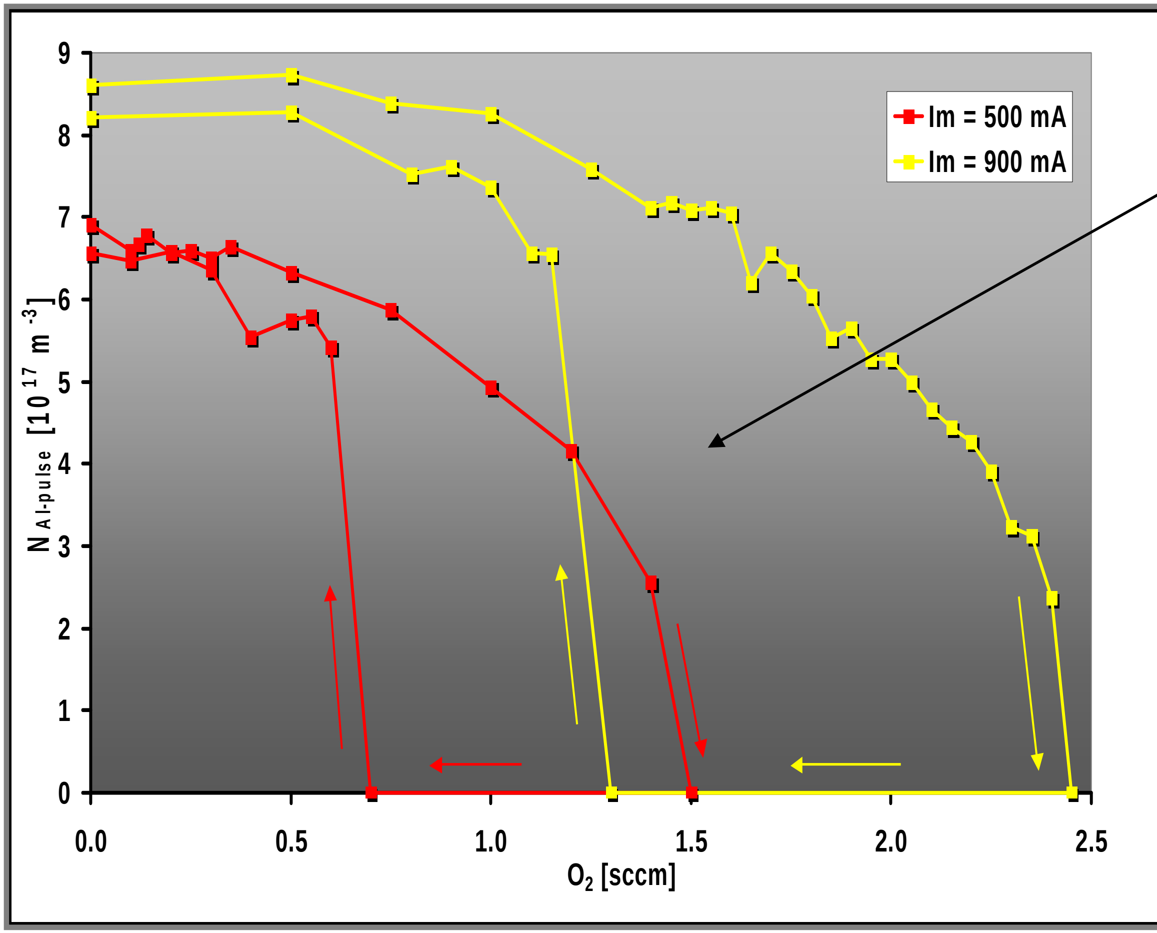


Target oxidation is responsible for the dramatic drop (factor of 30) in Al atom density

Most likely, electron emission is drastically reduced

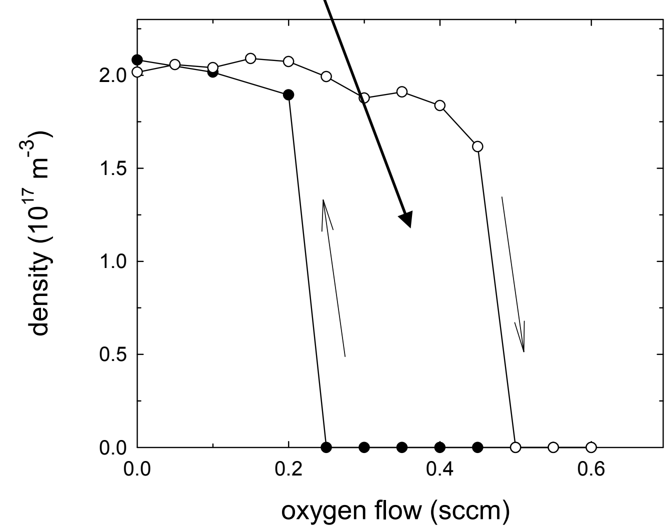
To overcome target poissening, operate magnetron in ac or pulsed mode

Al density vs. Oxygen flow



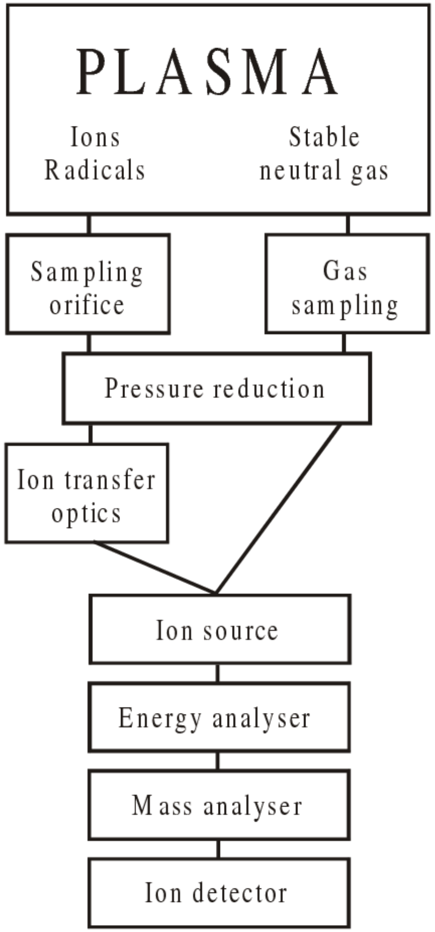
Pulsed operation

dc operation



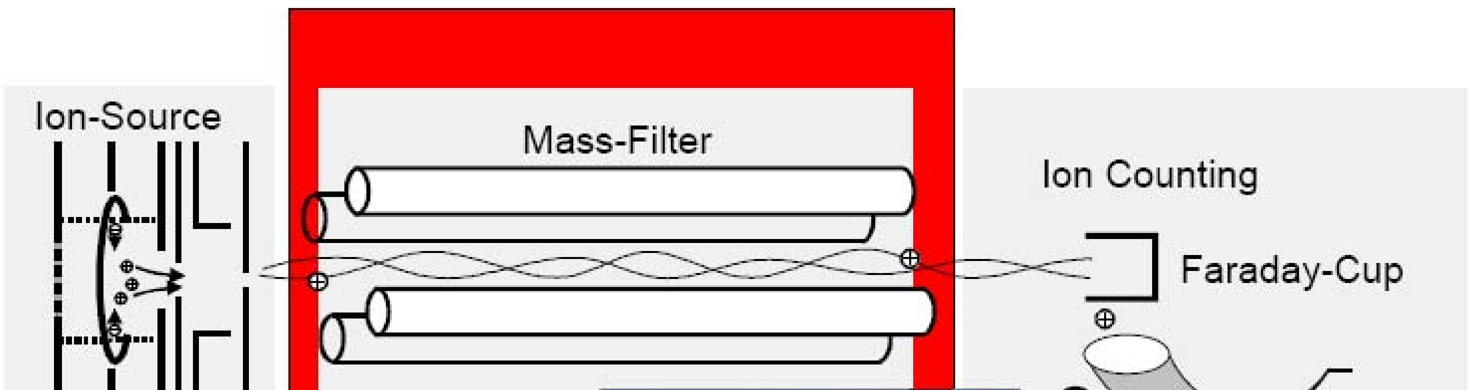
Mass Spectrometry

A typical mass spectrometer, e.g., for gas analysis, consists of
- ion source to ionize gaseous species
- mass filter, and
- ion detector.
- Optional: energy filter

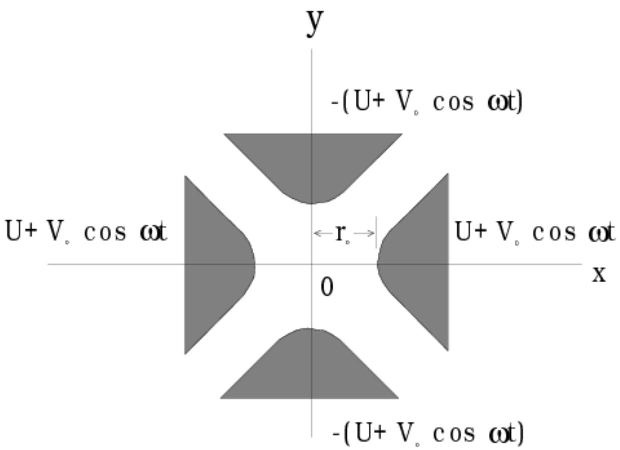


Quadrupole mass analyzer

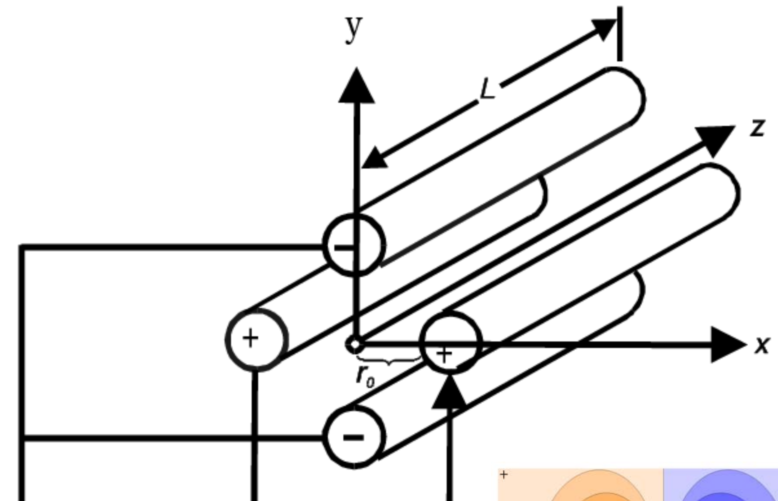
Quadrupole Mass Filter

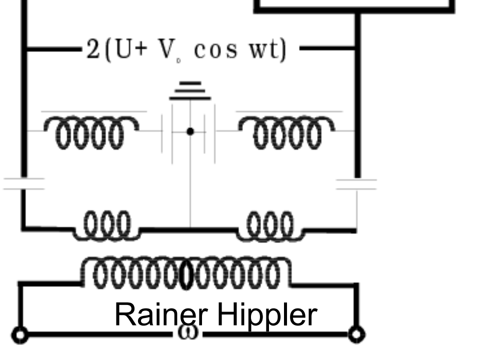


Quadrupole mass analyzer

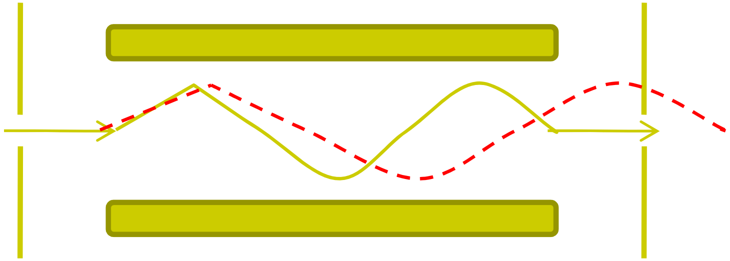


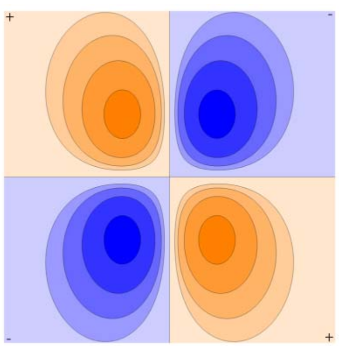
(a)





(b)

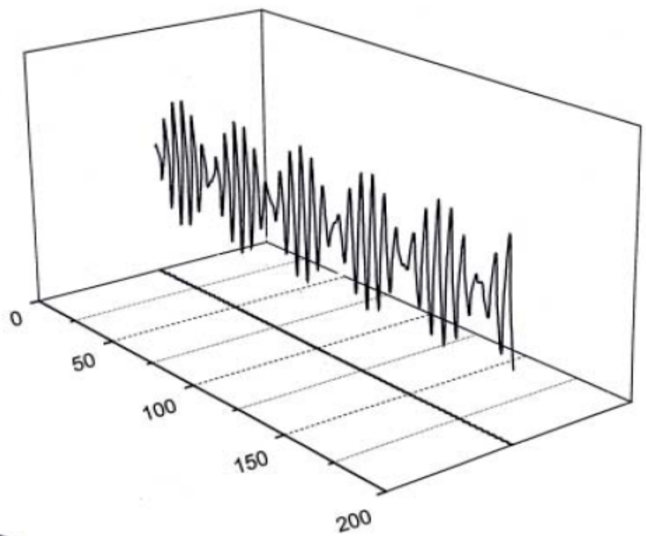




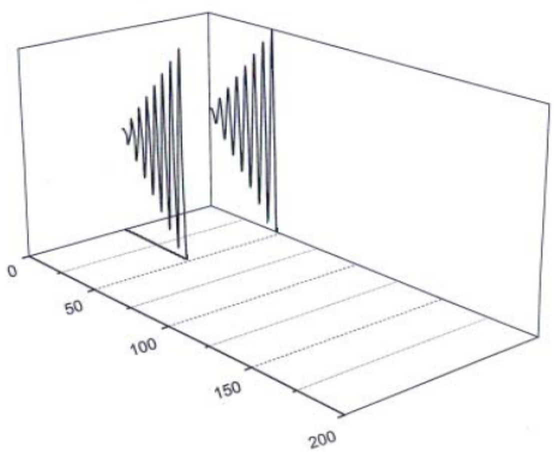
Contour Plot of an electric quadrupole. The lines depict the equipotential surfaces.

Flight pass of ions through mass analyzer

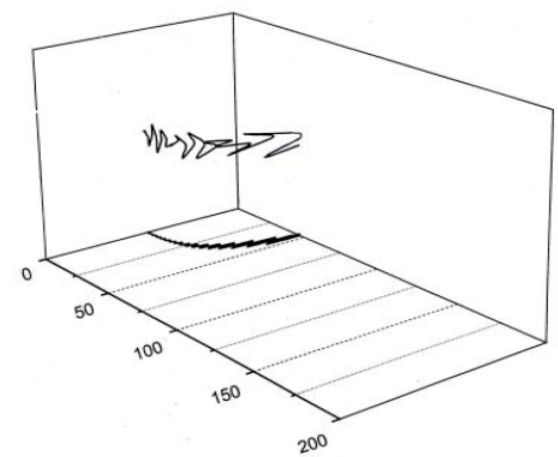
→ Ion mass identical to set mass



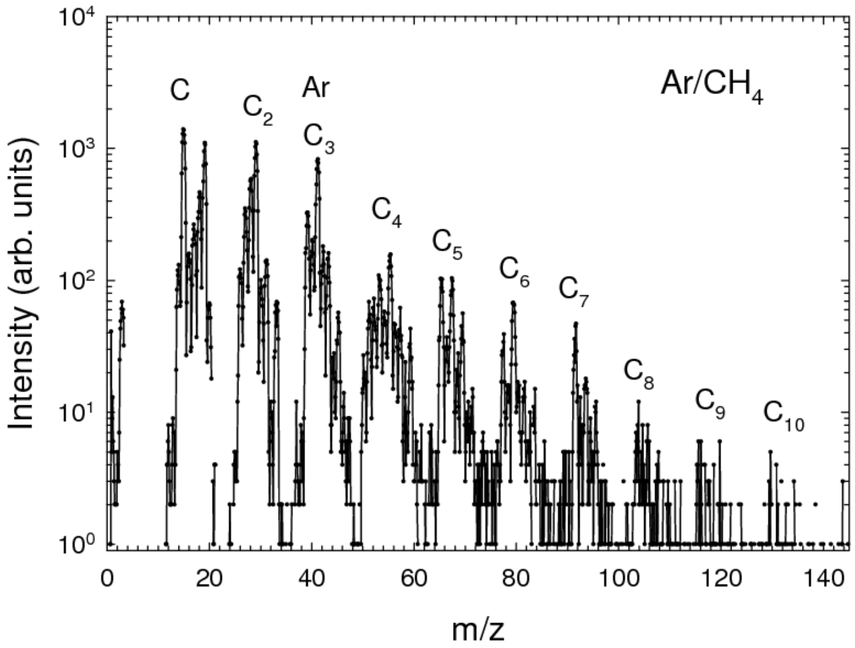
→ Ion mass lower than set mass

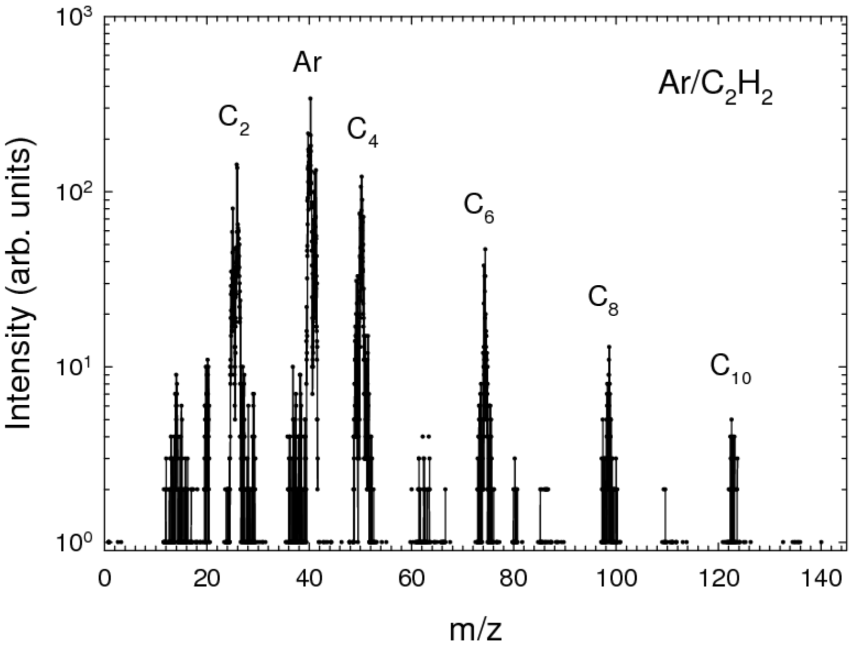


on mass higher than set mass

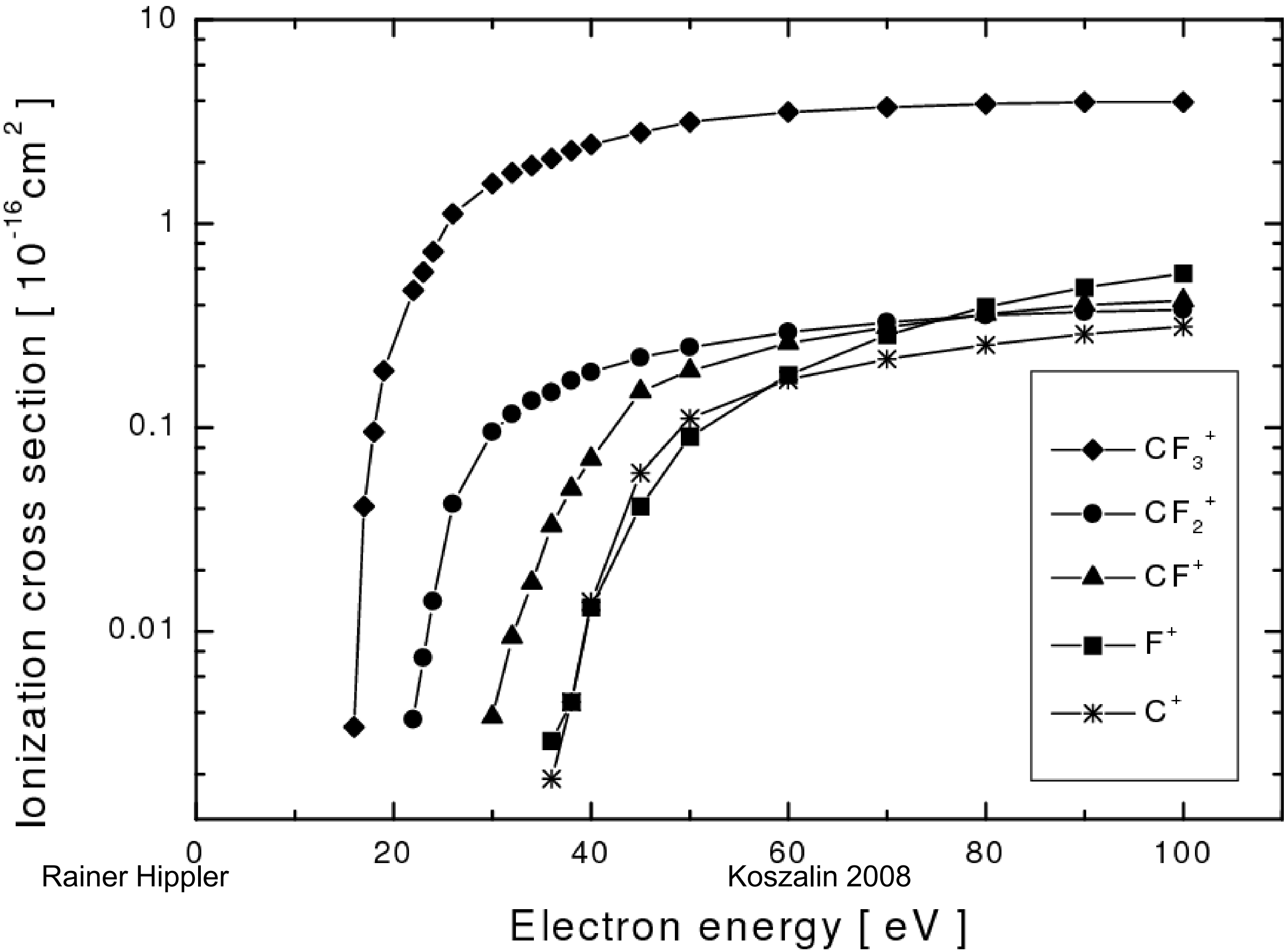


Mass spectra
Ar/CH_4 and Ar/C_2H_2





Ionisation efficiency

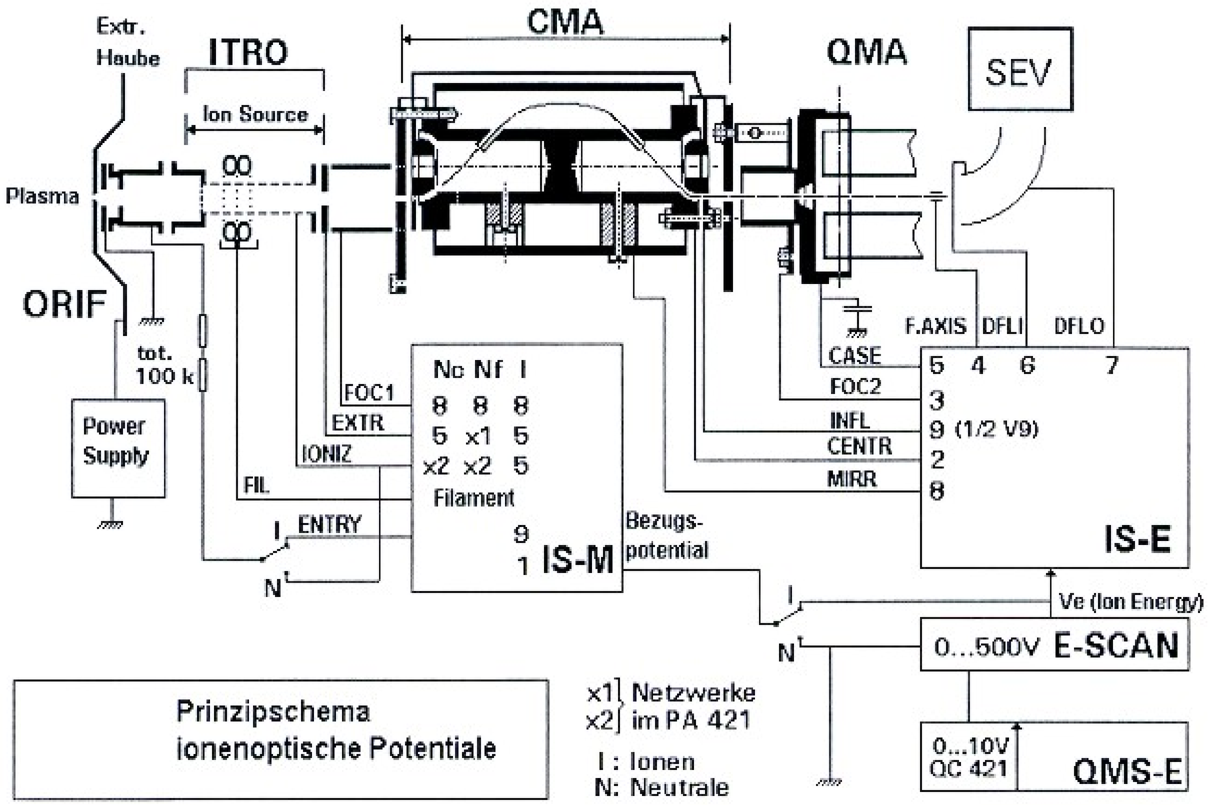


Plasma diagnostics: Energy-resolved mass spectrometry

Plasma process Monitor

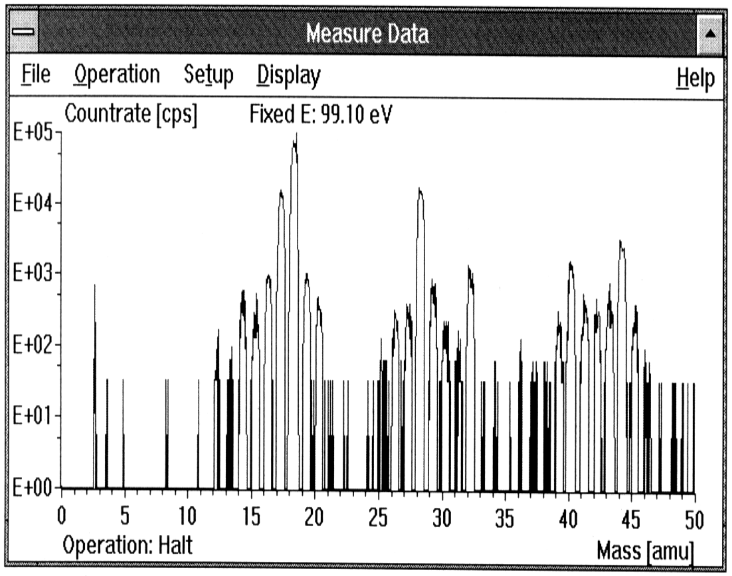
- Mass spectrometer
- Energy filter

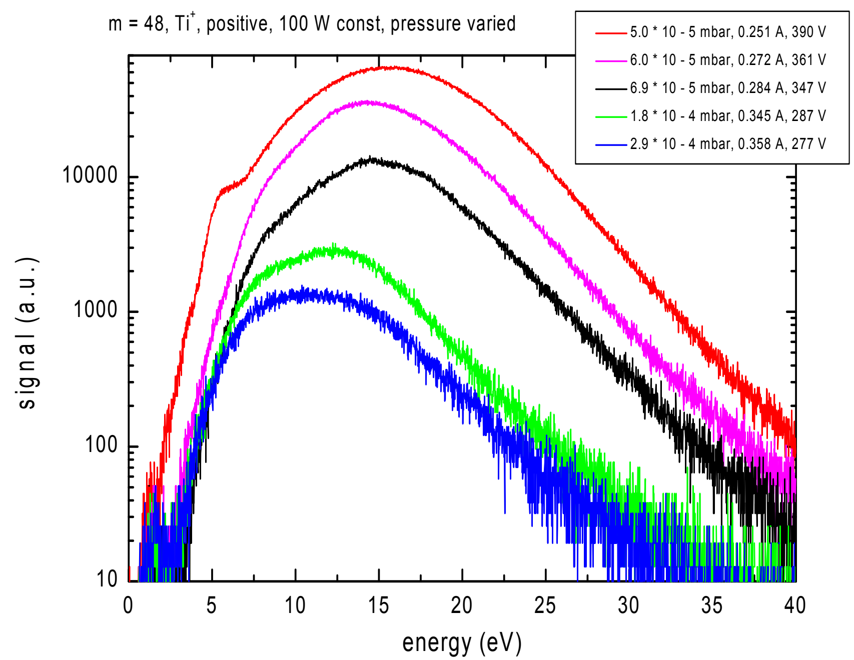
Plasma process monitor



- Ion source
- Energy filter (Cylindrical mirror analyzer, CMA)
- Mass filter (Quadrupole mass analyzer, QMA)

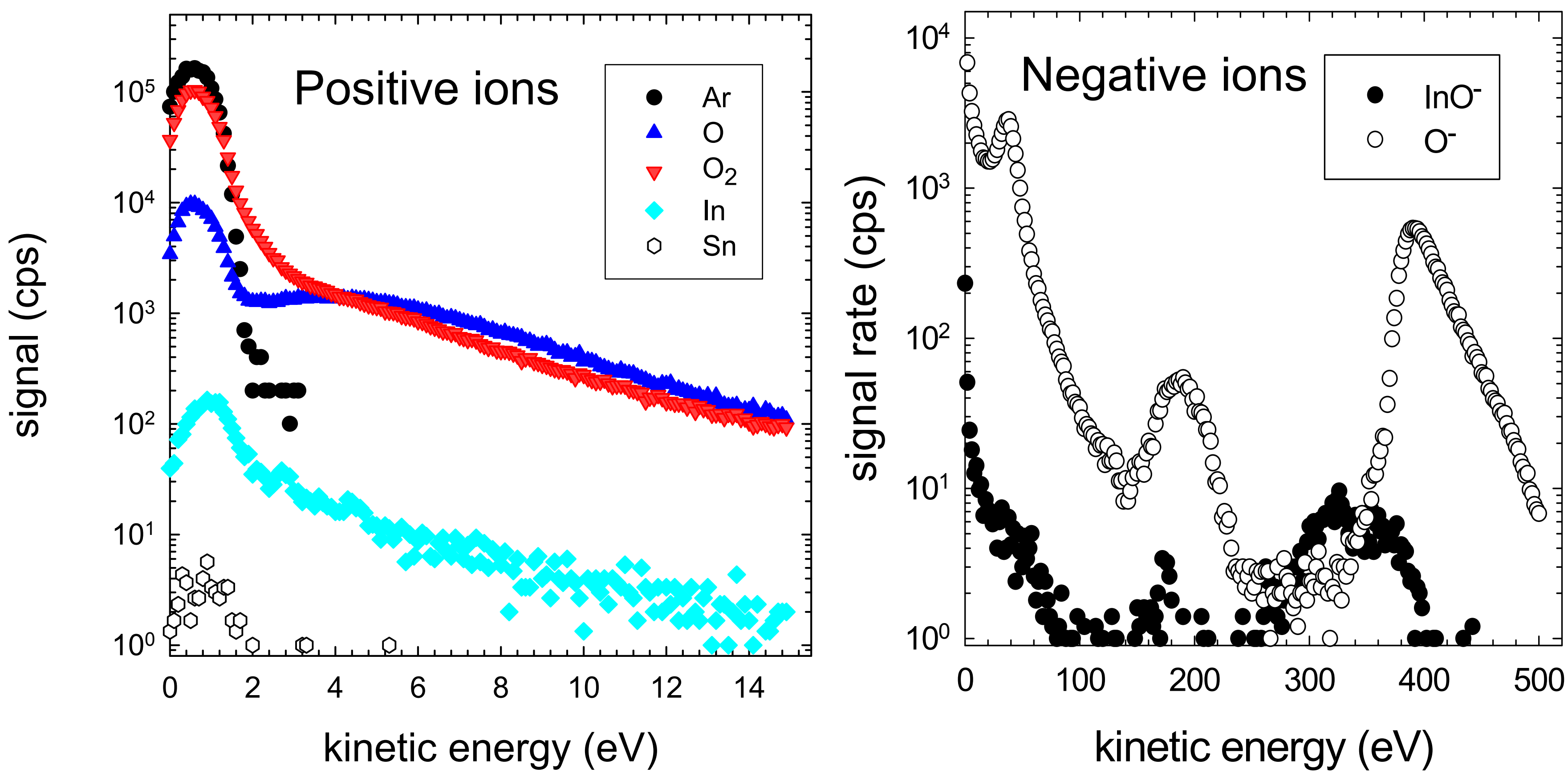
Mass and energy spectra



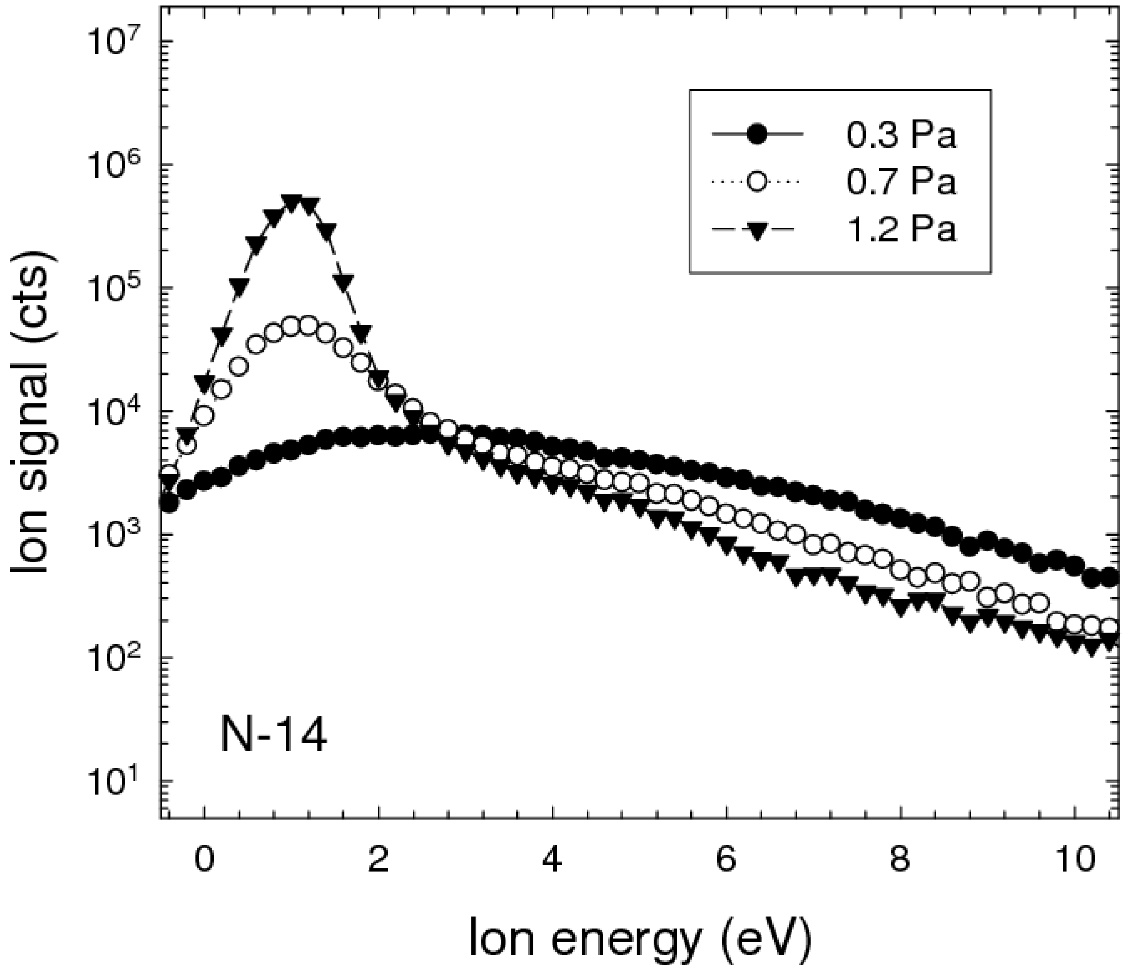


Ion energy distributions

Target: In/Sn (9:1)   Ar: 20 sccm; O_2: 2 sccm



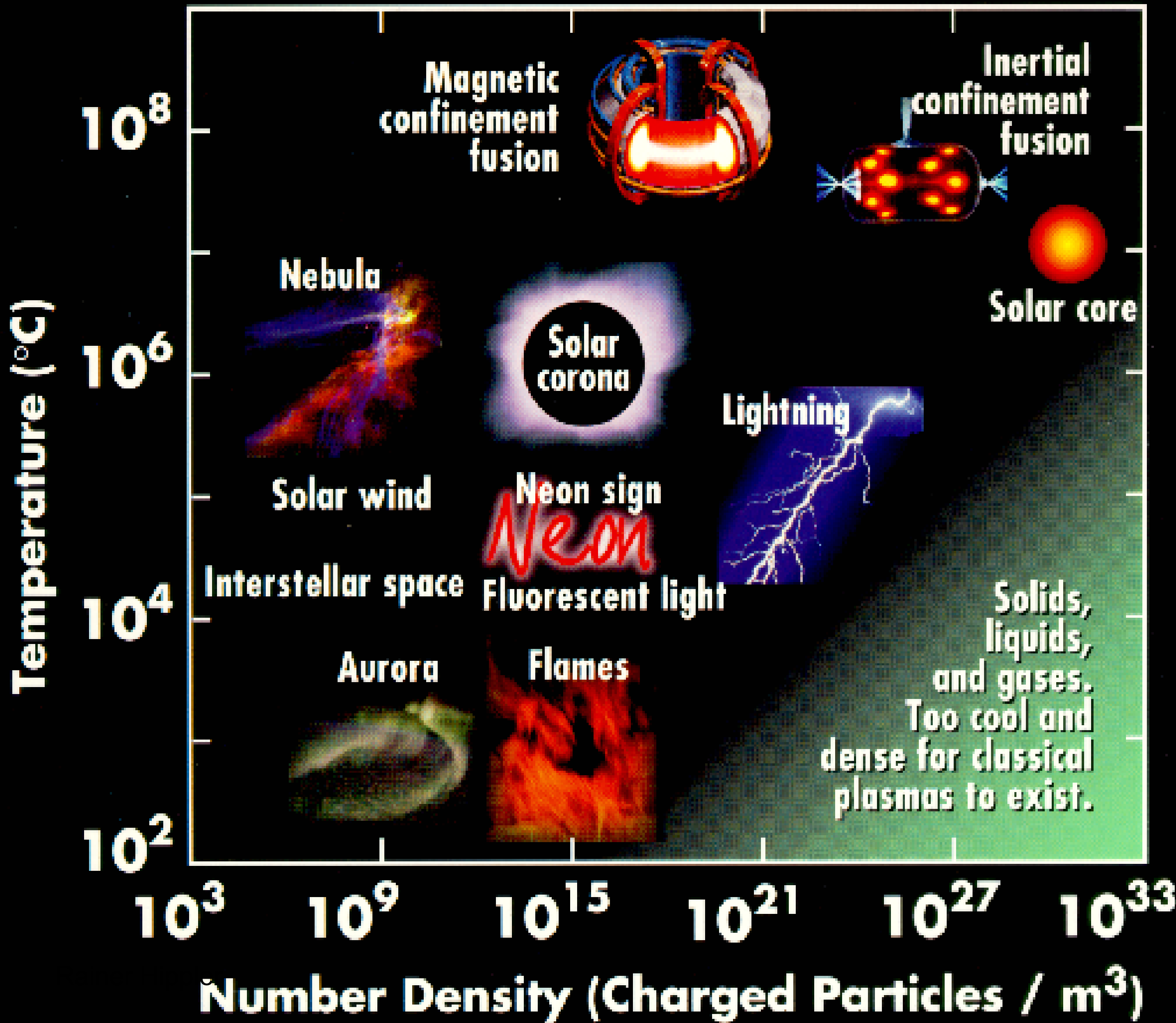
Ion energy distribution of N^+ ions vs. pressure



Applications

- Fluorescent lamps, lighting
- Plasma display panels
- Plasma etching
- Dusty plasmas
- Corona discharge
- Dielectric barrier discharge (Ozone generator)
- Plasmas used in semiconductor device fabrication:
    - Reactive Ion Etching,
    - Sputtering,
    - Plasma Enhanced Chemical Vapor Deposition
- Fusion plasmas

PLASMAS – THE 4th STATE OF MATTER

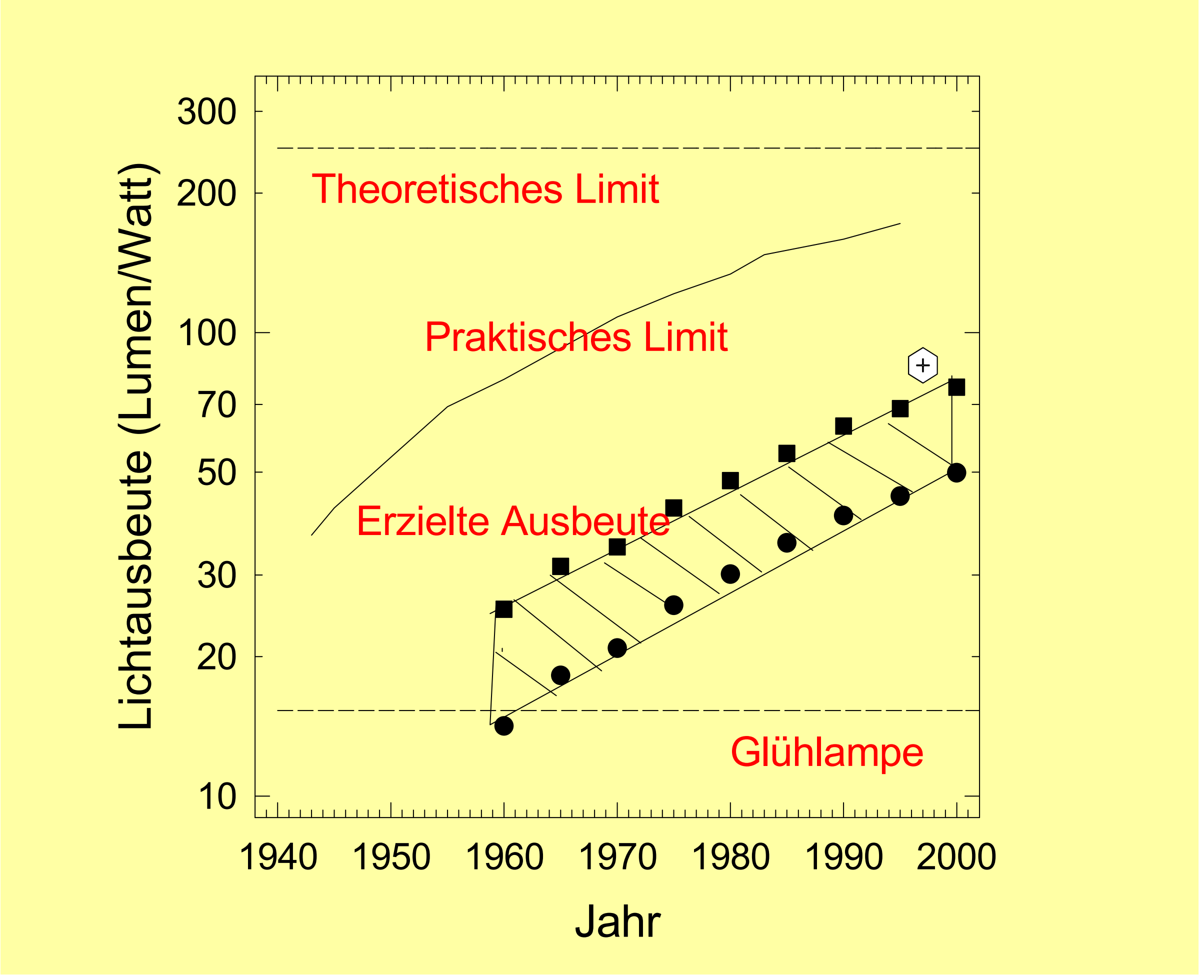


Light Sources

Lighting is a major application of plasma physics.

Light sources consume about 40 GWh/year, ie. about 10% of all electricity. This corresponds to the energy provided by 10 coal-fired power plants. Increasing the efficiency of light sources by only 10% would thus save the emissions of one coal-fired power plant.

Efficiency of light sources



Plasma light sources

Fluorescence lamps (neon light) belong to the popular light sources. Advantages in comparison to incandescent lamps are

- larger light efficiency
- longer lifetime
- lower costs.

Fluorescence lamps are available in many design and with different spectral emissions, e.g., „true light".

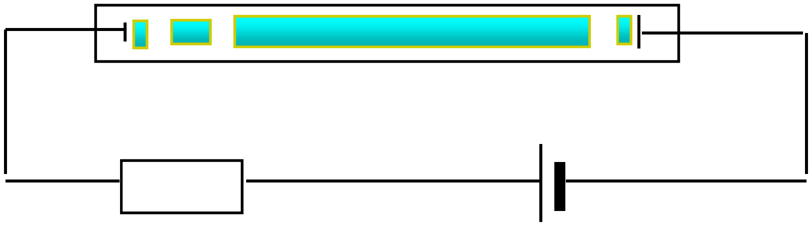
Fluorescence lamps

Fluorescence lamps essentially consist of

• Anode and

• Cathode

at opposite ends of a partially evacuated glass tube.

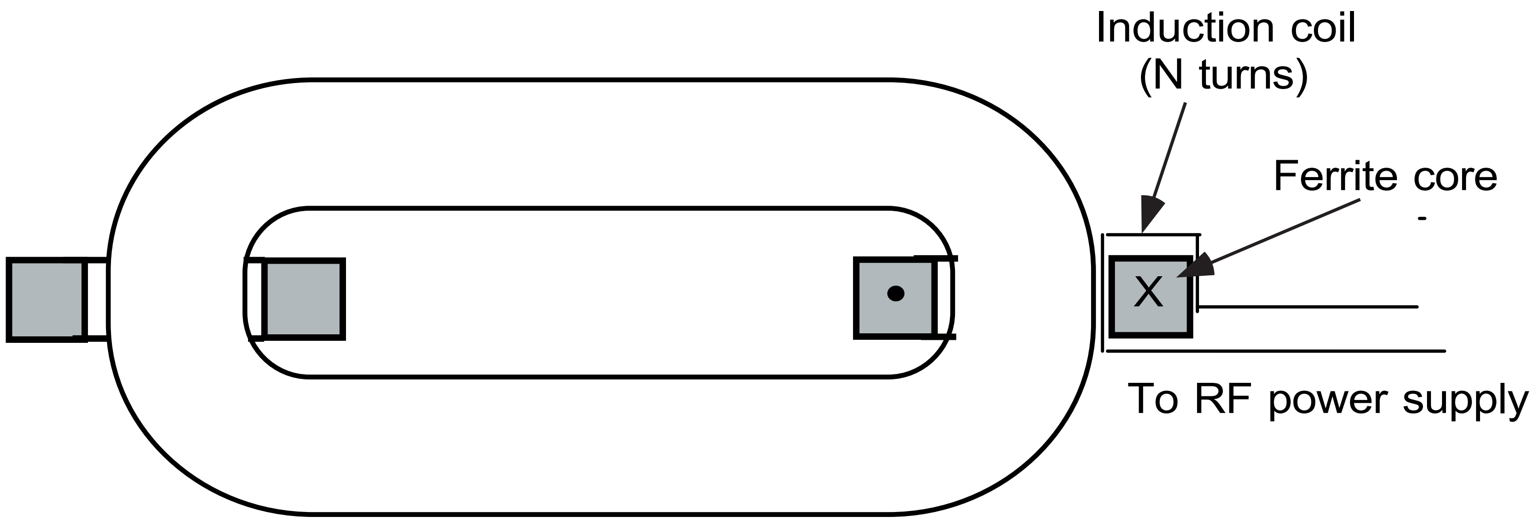


Most fluorescence lamps contain an inert gas (Ar, Kr) with a small admixture of mercury (Hg). Mercury is the dominant light emitter. The majority of the emitted light lies in the far ultraviolet (254 nm) and is thus invisible. Therefore, the inner surface of the glass tube is coated with a fluorescent material (phosphor) to convert the UV into visible light. The phoshor determines the „colour“ of the light.

Lifetime of fluorescence lamps

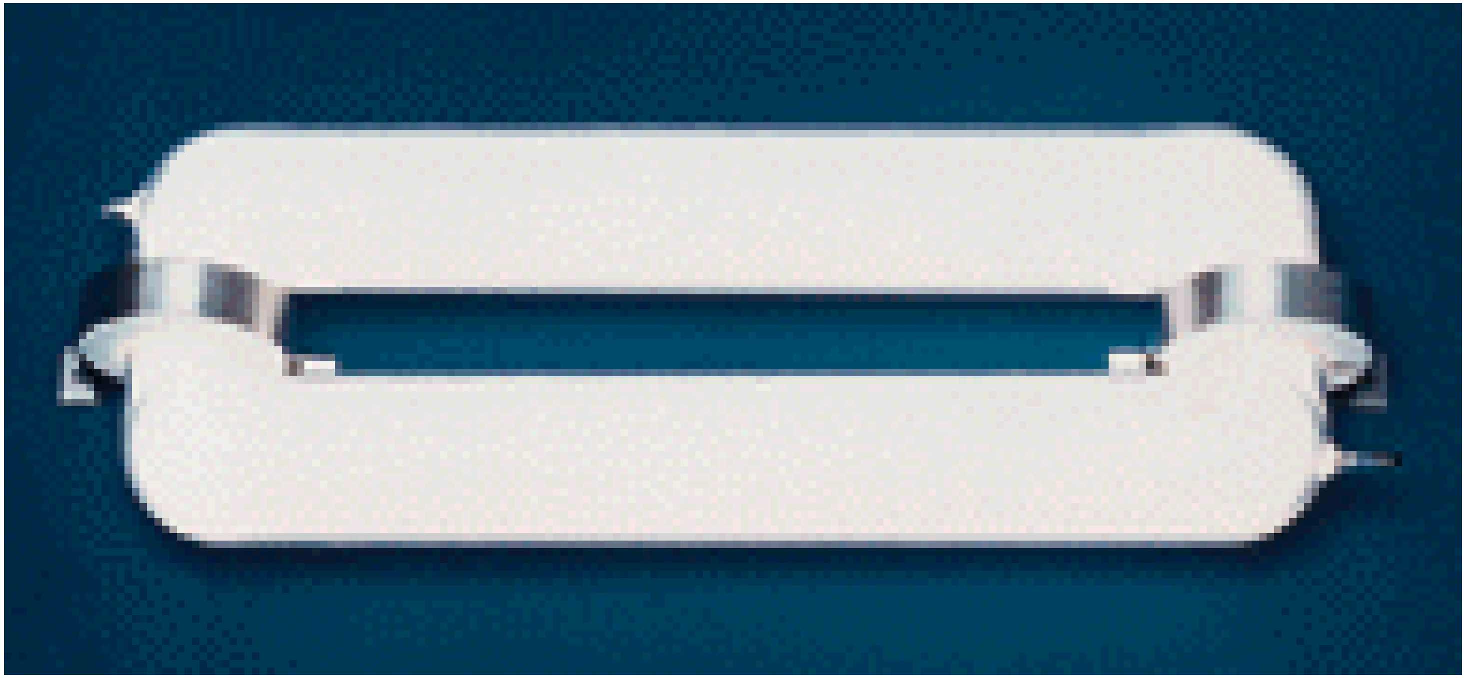
Fluorescence lamps have a good light effciency (about 60 Lumen/Watt) and a long life time of typically 8,000 h (≈1 year). The finite life time is determined by erosion of electrodes (cathode) due to ion bombardment.

Elektrode-less flourescence lamps with inductive coupling Endura (Osram)



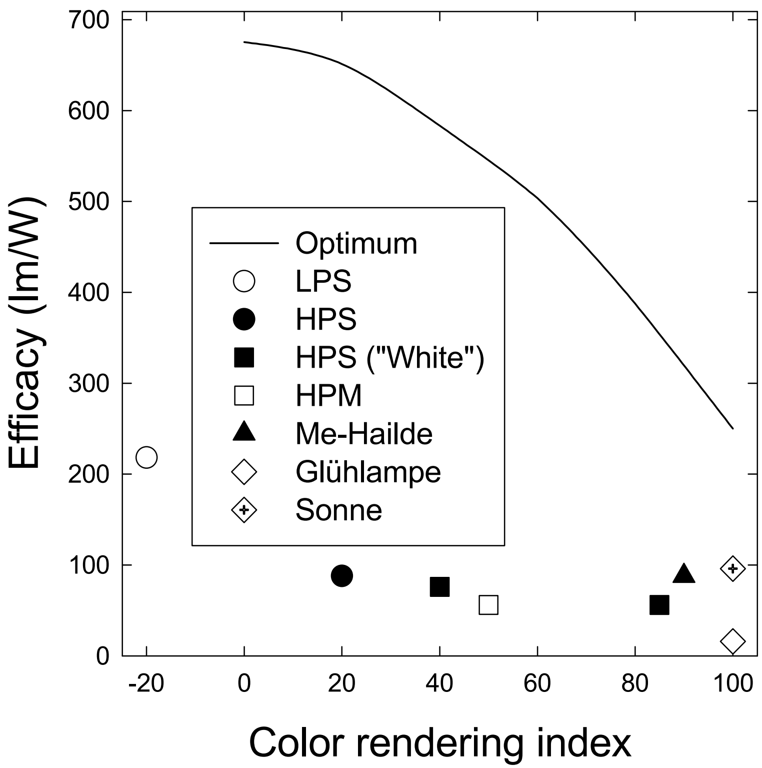
Adaption of frequency (several 100 kHz) in order to achive an optimum energy consumption.

Elektrode-less flourescence lamps with inductive coupling Endura (Osram)



Advantage: long life time (60.000 h) and improved light efficiency (85 Lumen/Watt)

Efficiency vs. „Colour“



Further impovements are required with respect to the lamp‘s „color“.

High pressure sodium lamp

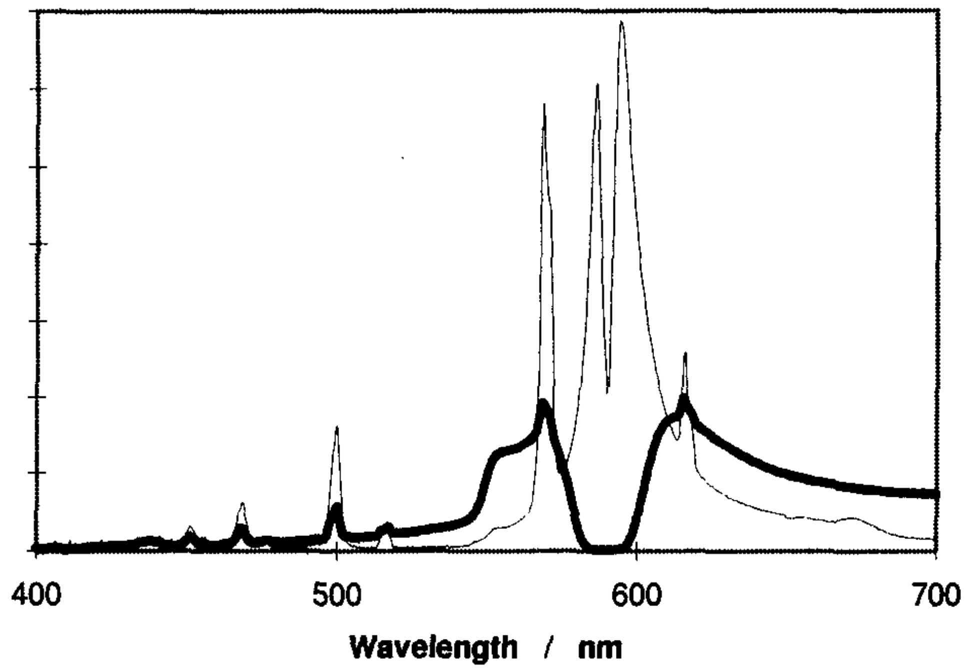


Figure 1.8: Spectra of HPS lamps at different sodium pressures. Thin line: low sodium pressure with CCT = 1900 K, CRI = 10, h = 89 lm/W; solid line: high sodium pressure with CCT = 2500 K, CRI = 84, and h = 48 lm/W.

Metall halide lamp

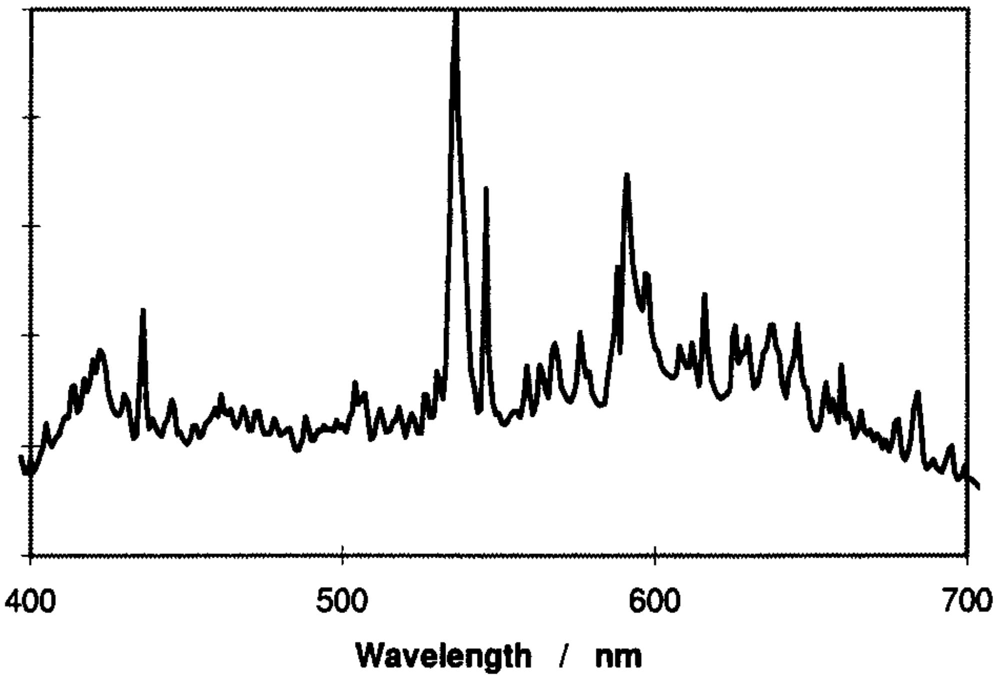


Figure 1.7: Spectrum of a ceramic MH lamp with CCT = 4200 K and CRI = 95.

Surface modifications

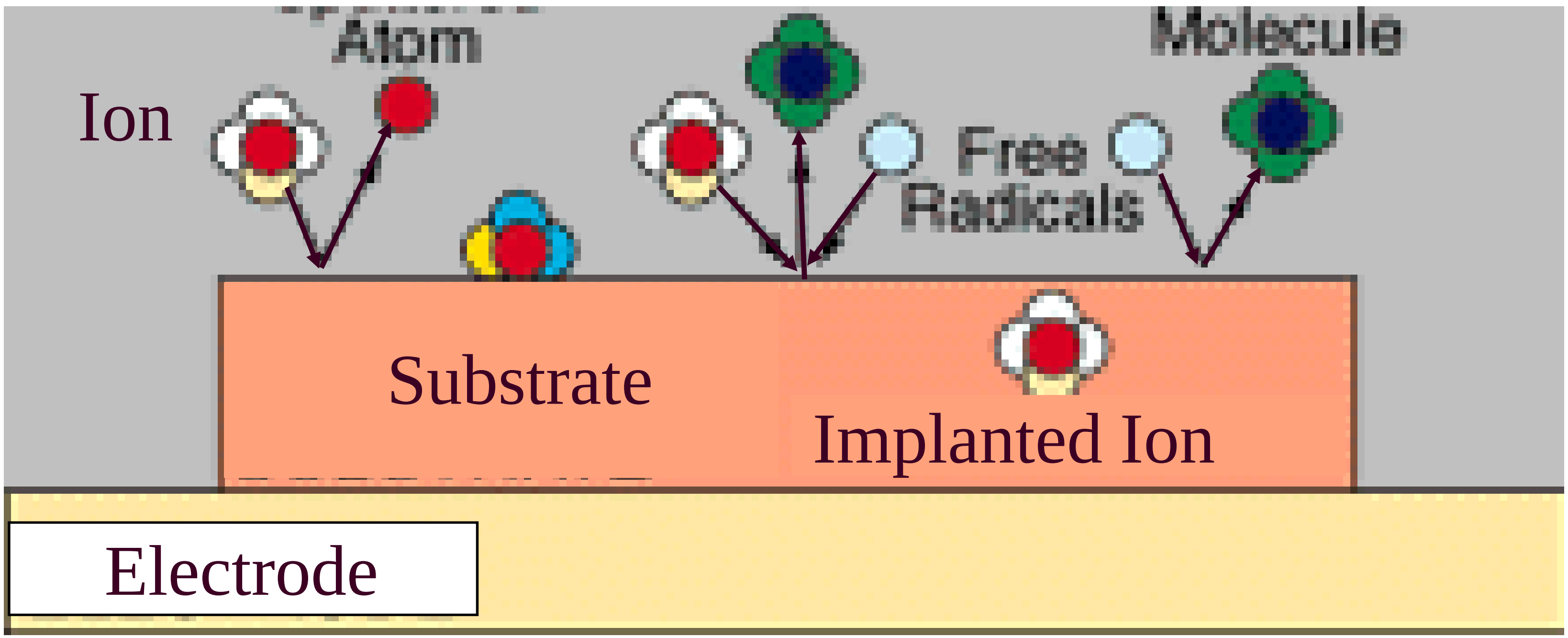
- Etching
  - Cleaning
  - Trench etching
- Deposition
  - Thin solid films on surfaces for surface modification and surface protection
- Functionalisation
  - Hydophilic surfaces
  - Hydrophobic surfaces

Plasma Etching Reactions

Sputtering

Plasma etching

Chemical etching



Plasma etching reactions

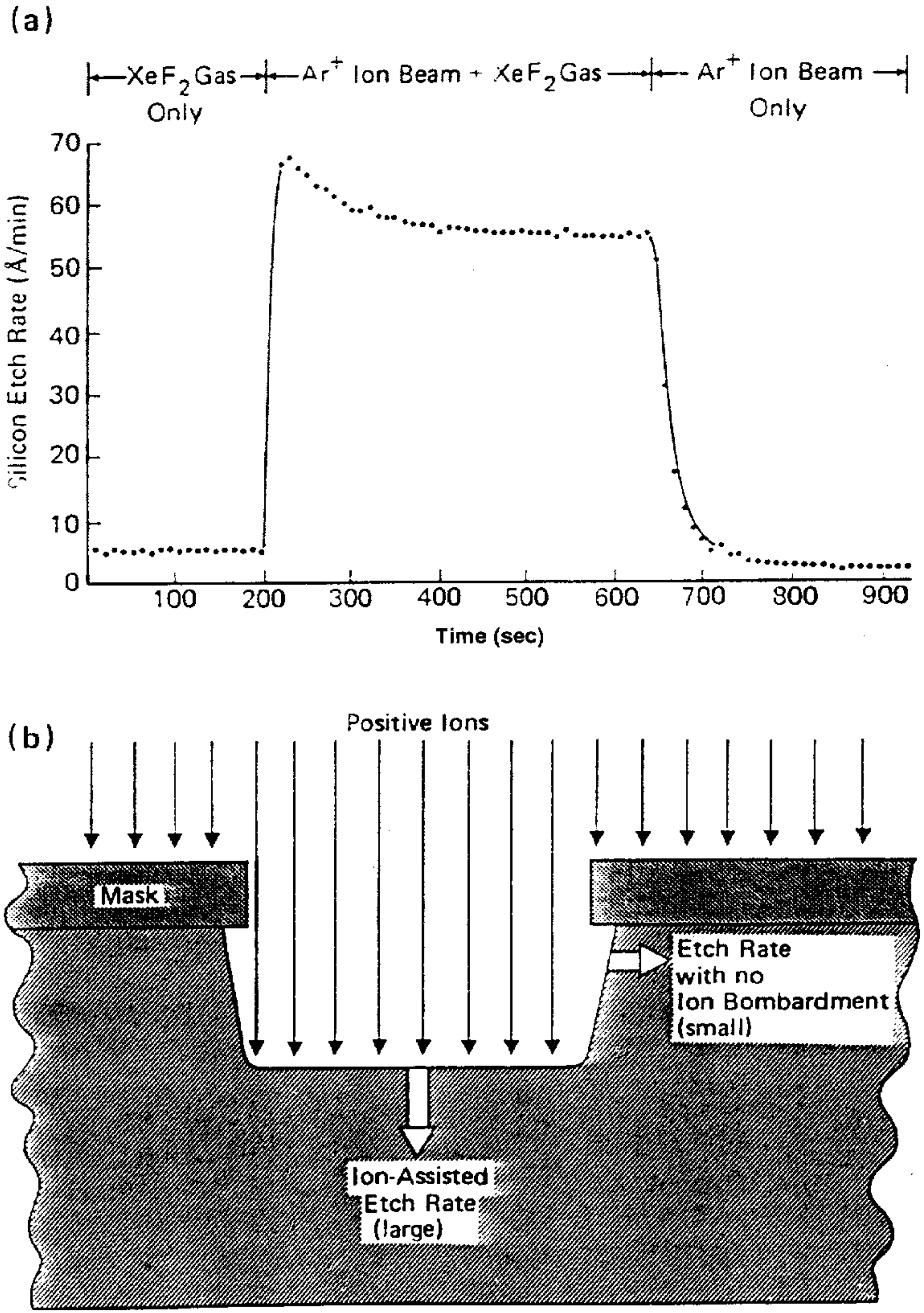
- Chemical reactions: Reactive atom - surface interaction, e.g.,

$$2\,F_2 + Si\ (solid) \rightarrow SiF_4\ (gas)$$

- Physical reactions: Energetic ion-surface interaction (sputtering), e.g.,

$$Ar^+ + Si\ (solid) \rightarrow Si\ (gas\ phase)$$

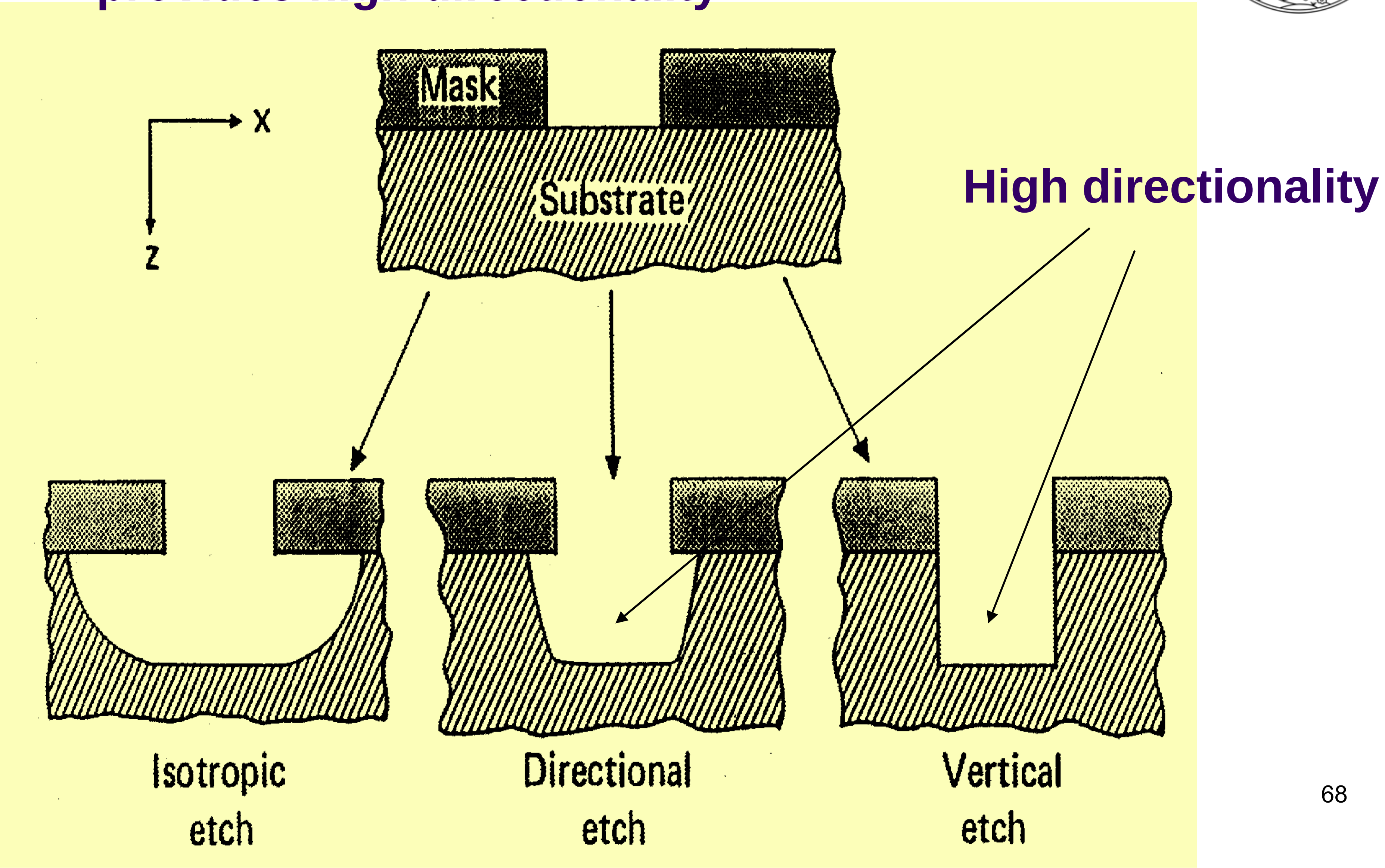
- Plasma etching: Combination of physical and chemical etching reactions



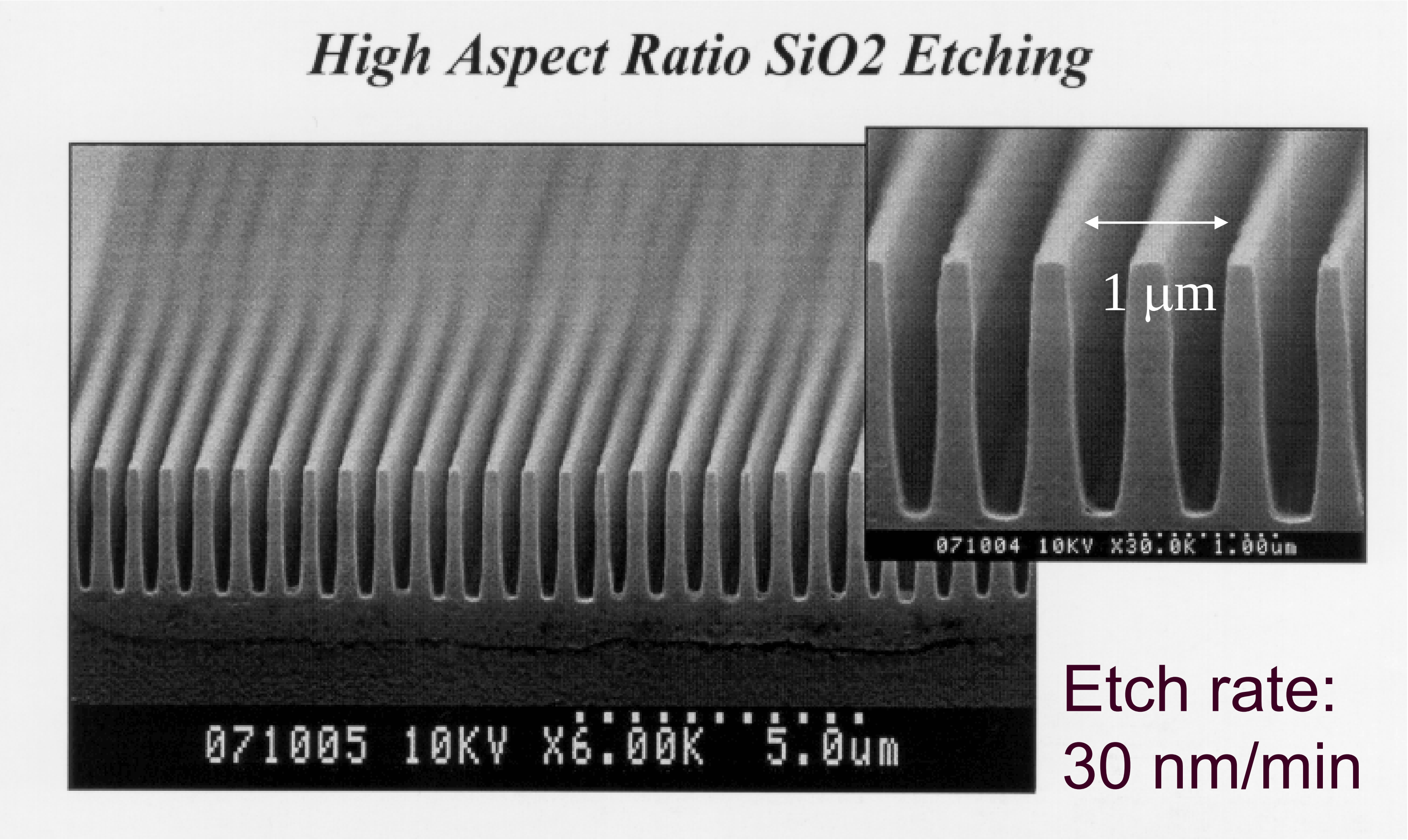
Plasma etching of Si with Ar^+/XeF_2

Plasma etching

provides high directionality



SiO_2 Plasma Etching in F_2

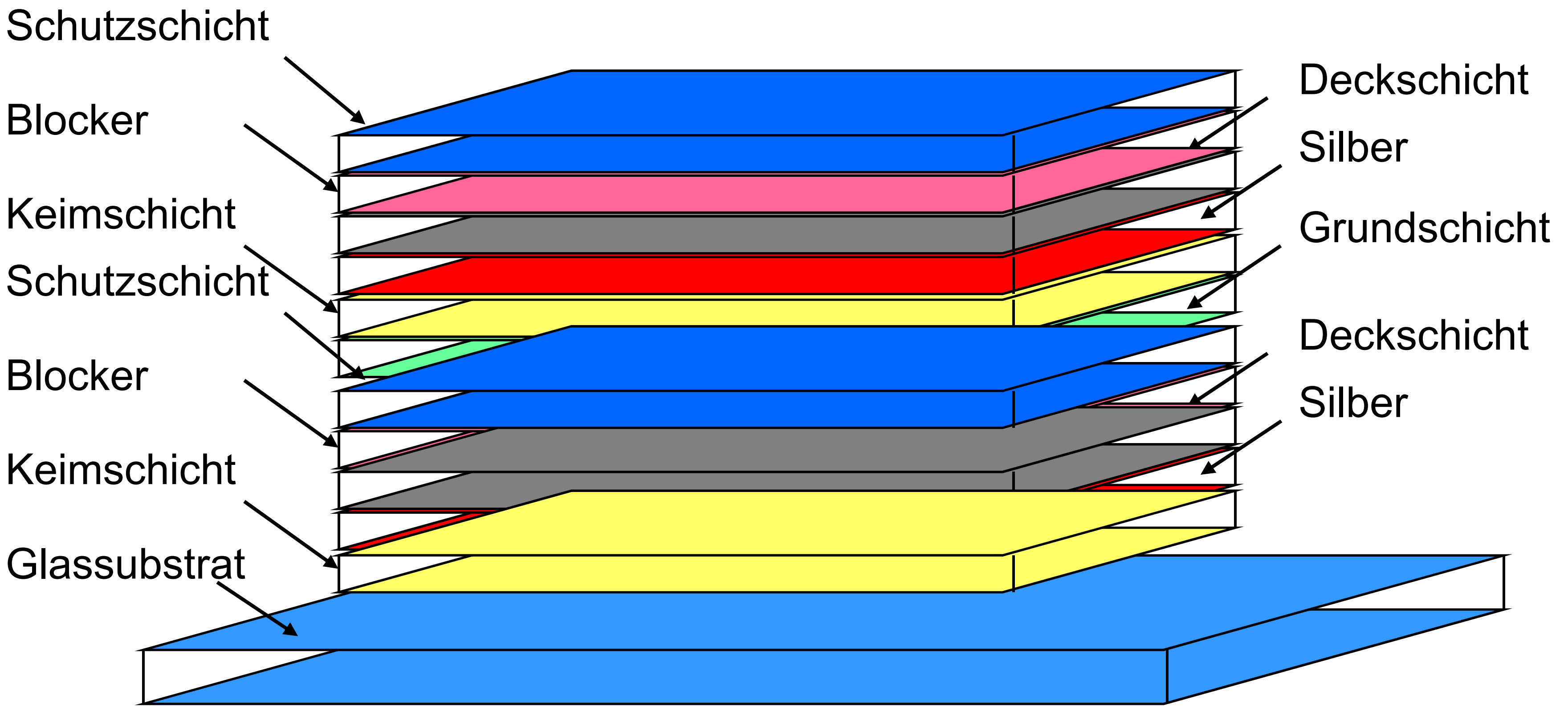


Plasma-assisted deposition
e.g., Thin metal oxide films

- Optically transparent
- Electrically conducting
- Large number of potential applications:
  - Glas with low heat conductivity
  - Solar cells
  - Optical coatings
  - Liquid crystal and plasma display panels
  - optoelectronical elements

Deposition of Functional layers

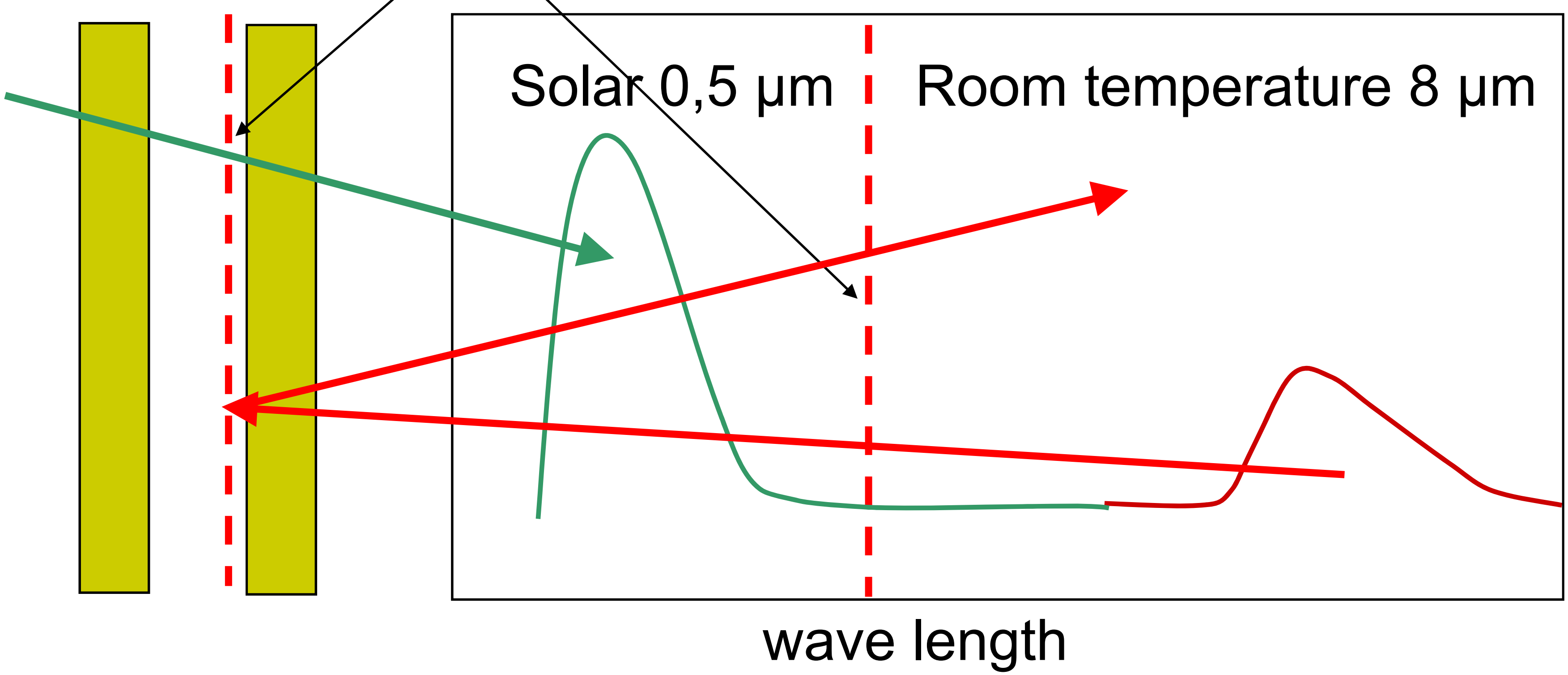
on Glas with low heat conductivity



Thermo-Glas

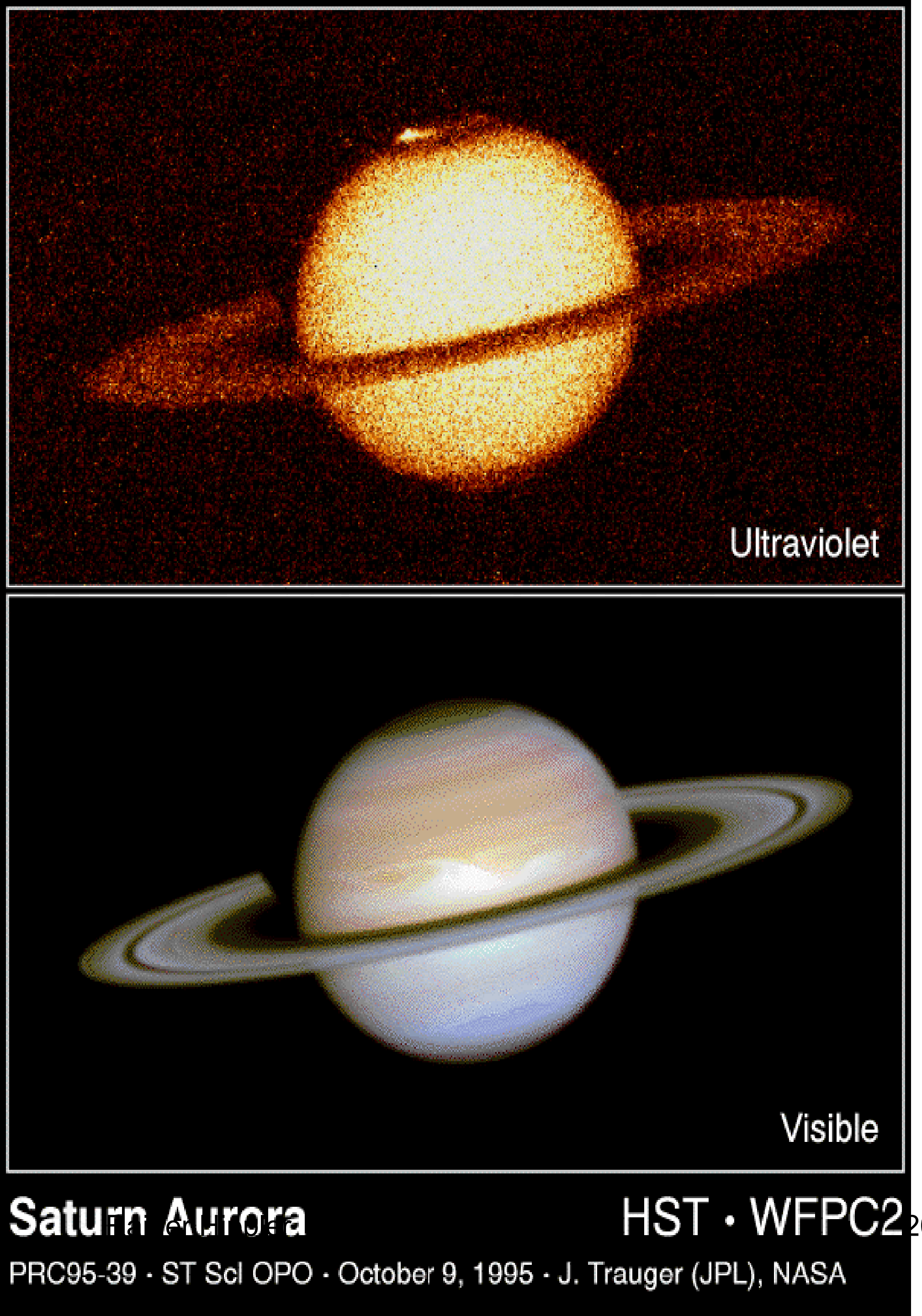
Heat transport = heat conductivity + Radiation

Glas/Argon/Blocker/Glas



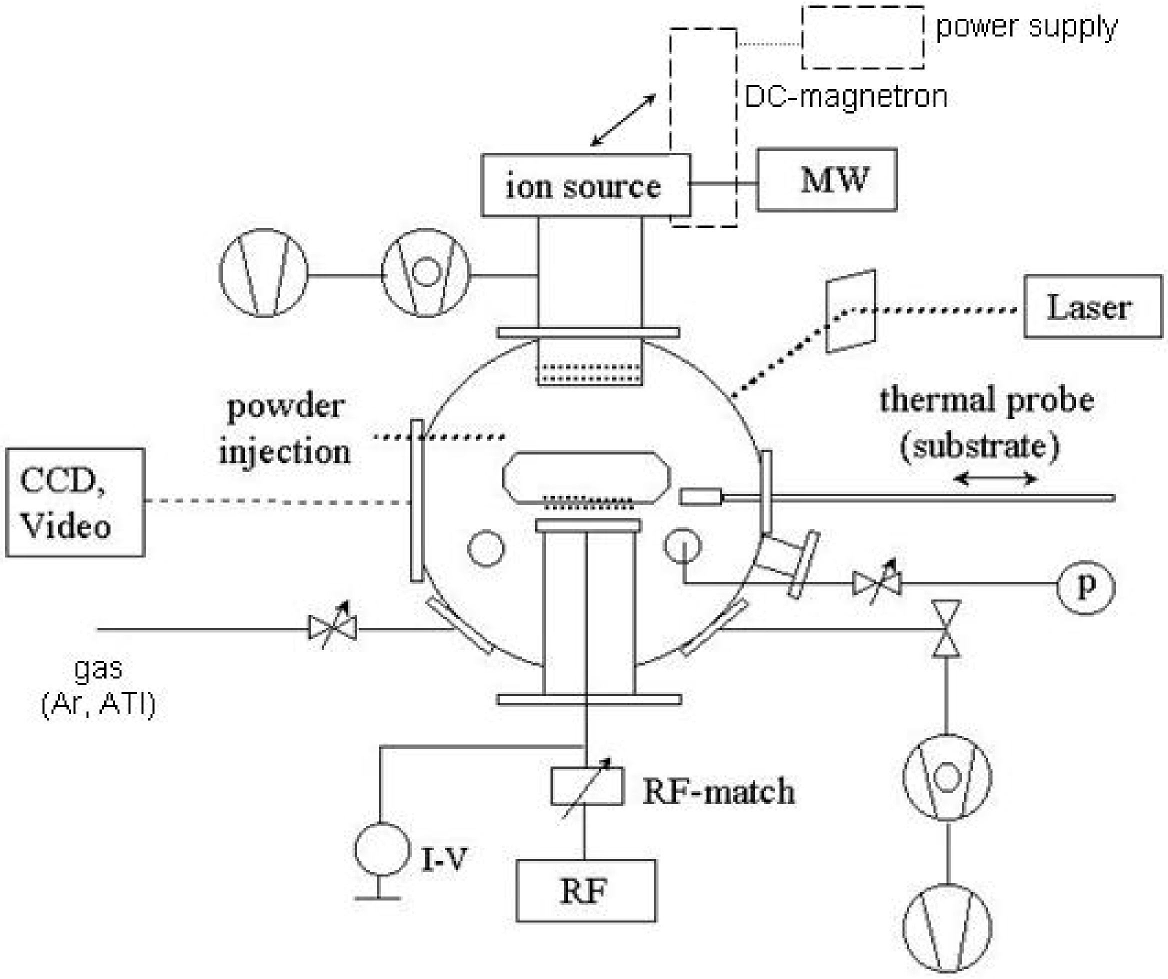
Dusty (complex) plasmas

- Particle-containing plasma
- Inside the plasma the particles become negatively charged (typically 10^3....10^4 elementary charges)
- Dusty plasma contain small particles (typically, few nm to several µm)
- Due to the positve plasma potential, the particles become trapped inside the plasma and cannot leave the plasma.
- There are natural and technical dusty plasmas



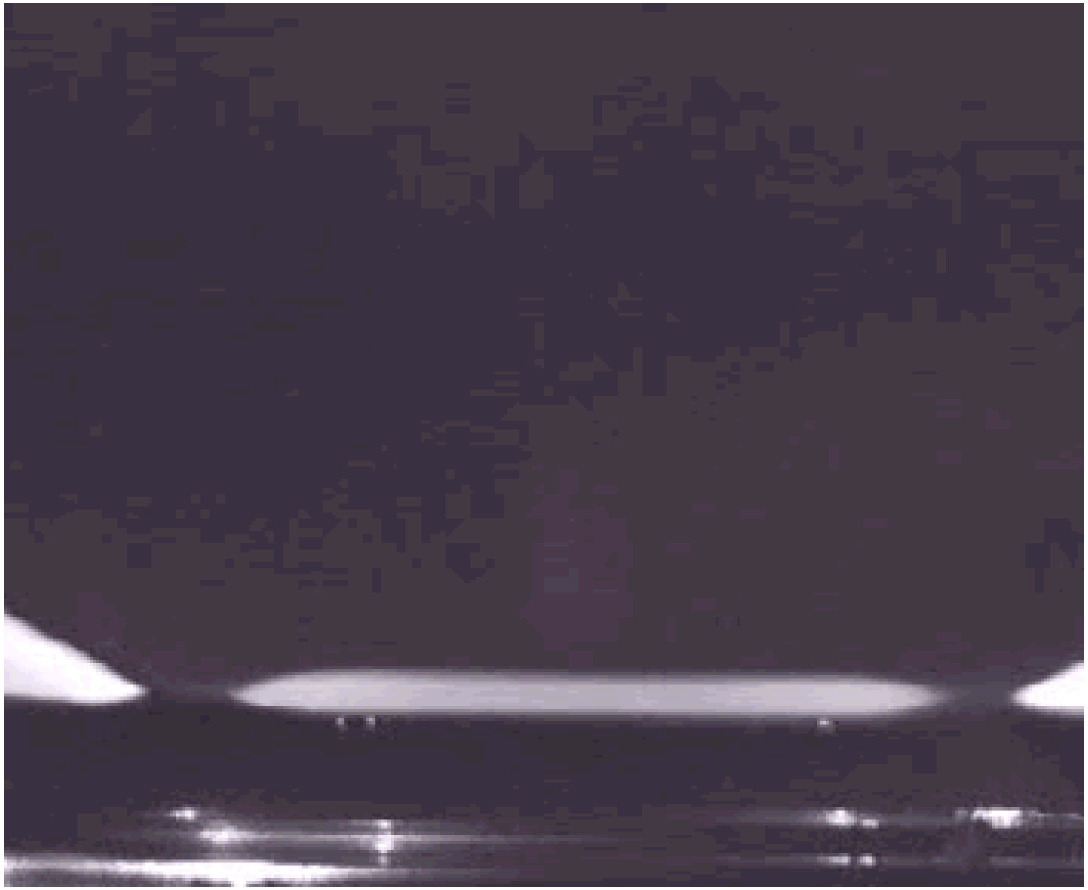
Saturn and its rings

Formation and modification of nano-size powder particles



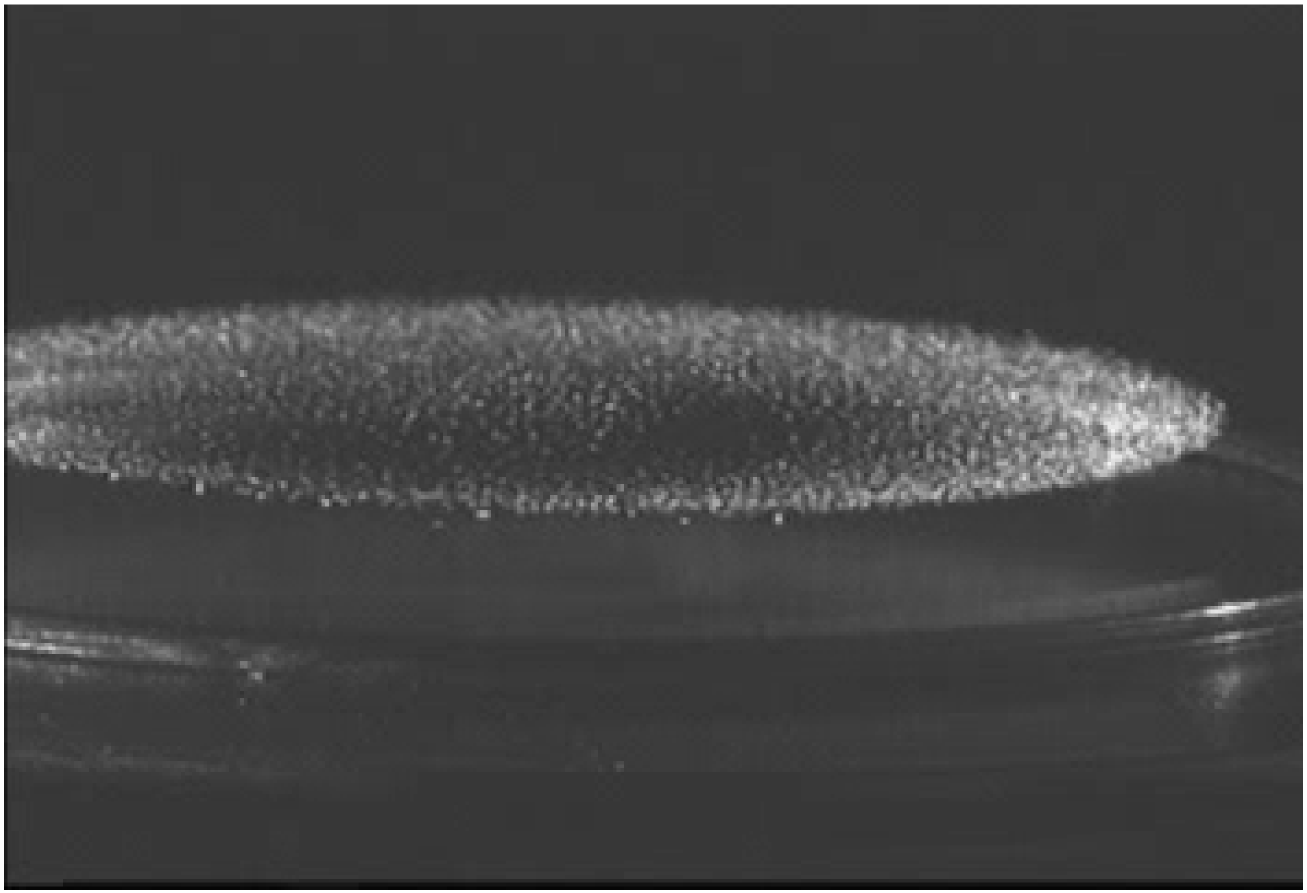
PULVA

Radiofrequency discharge: Growing dust particles



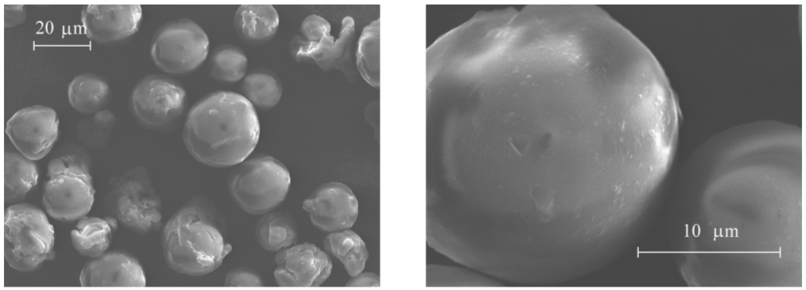
Ar/C_2H_2

Radiofrequency discharge:
Rotating dust cloud (large particles)

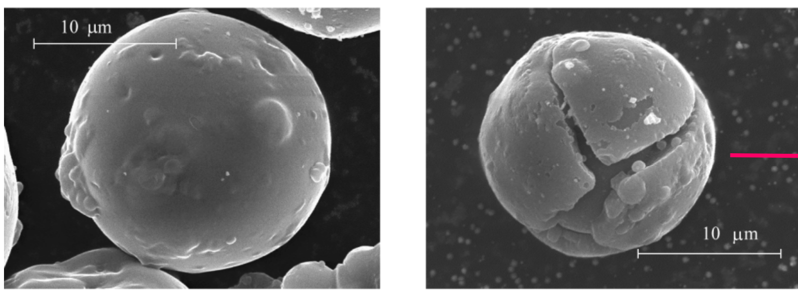


Ar

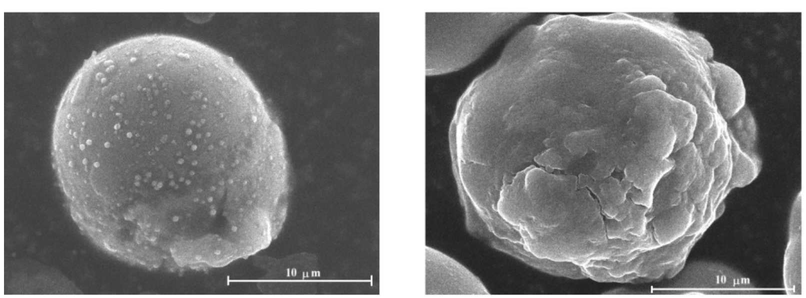
Radiofrequency discharge: Coating of micro-particles



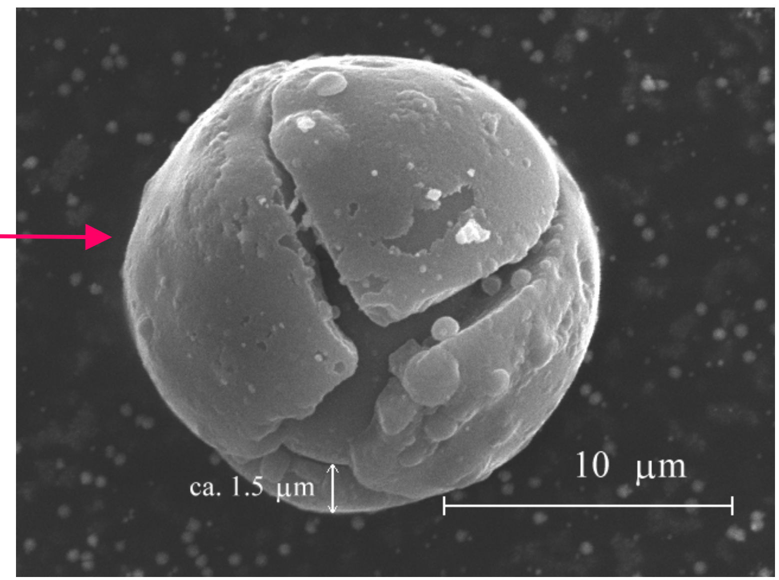
(a) Silicon oxide particles uncoated (b)



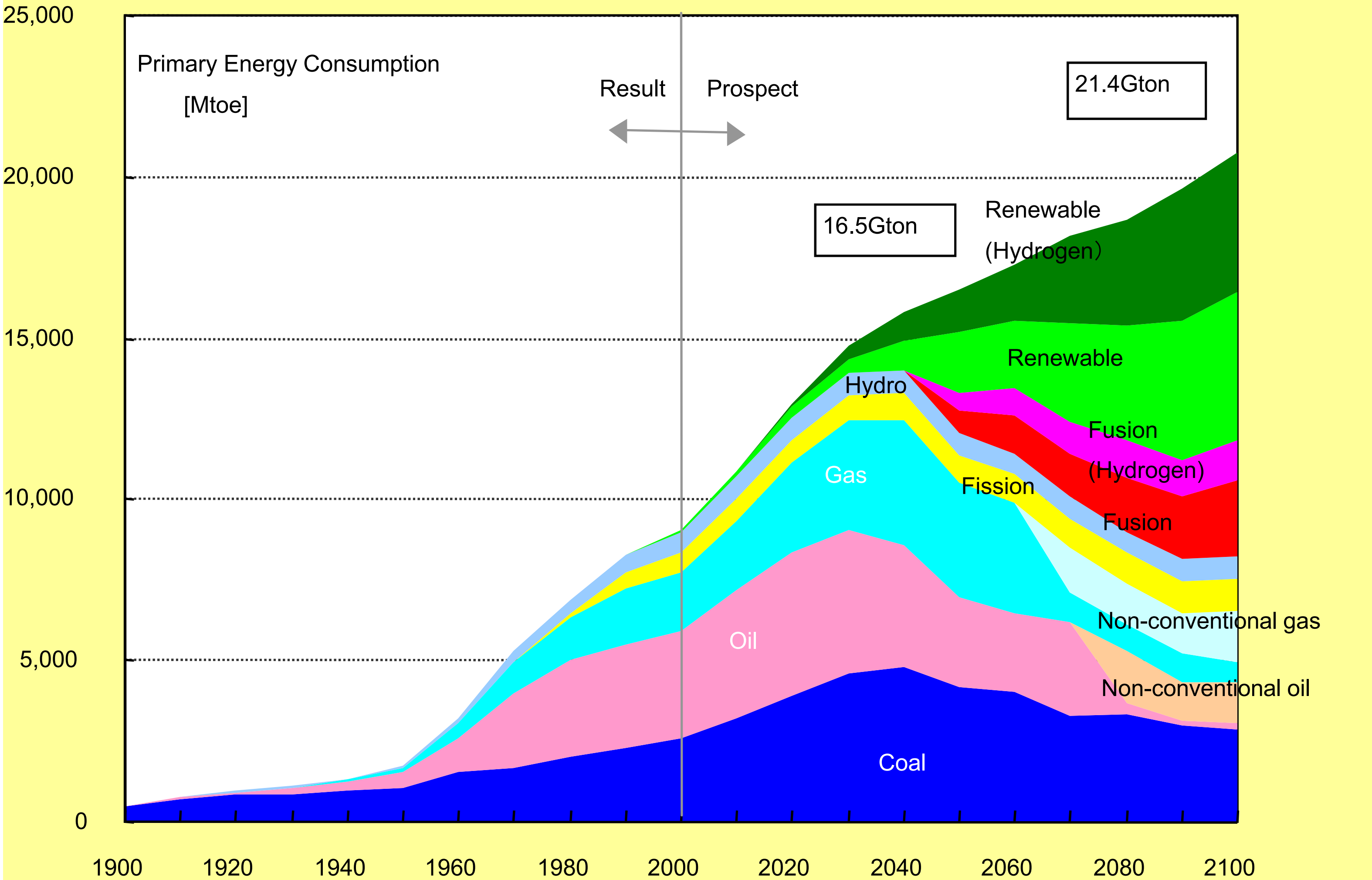
(c) Cu-coated (d)



(e) Ti-coated Al-coated (f)



Energy consumption



Fusion plasmas

Nuclear fusion may one way out of the upcoming energy crisis, ie., the fusion, of deuterium (d^+) and tritium (t^+) nuclei:

$$ {}_1^2d^+ + {}_1^3t^+ \rightarrow {}_2^4He^{++} + {}_0^1n + 17{,}8\,MeV $$

In order to achive nuclear fusion, an energy barrier of 0.5 MeV has to be overcome. It is therefore required to accelerate the nuclei to sufficiently large kinetic energy which reqires sufficiently large temperatures of typically 10^8 K.

Lawson-Kriterium

A fusion reactor has to meet several requirements, one of which beside a sufficently large temperature is the Lawson-criteria regarding density *n* and confinement time τ:

$$n \times \tau \geq 10^{20}\ \mathrm{sec/\,m^3}$$

Confinement

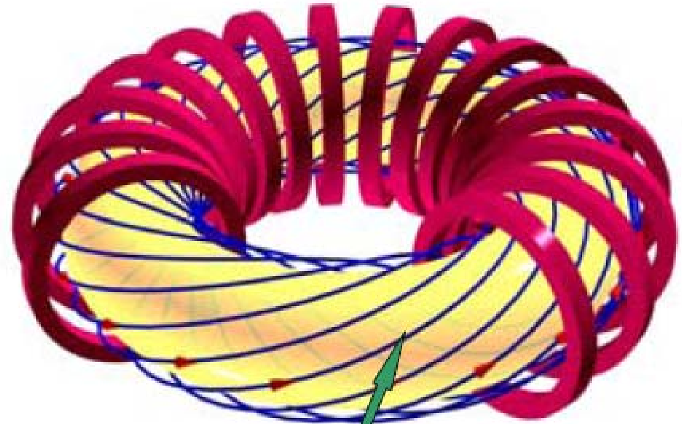
As realistic confinement one considers

- momentum confinement (Laser, ion beam)
- magnetic confinement.

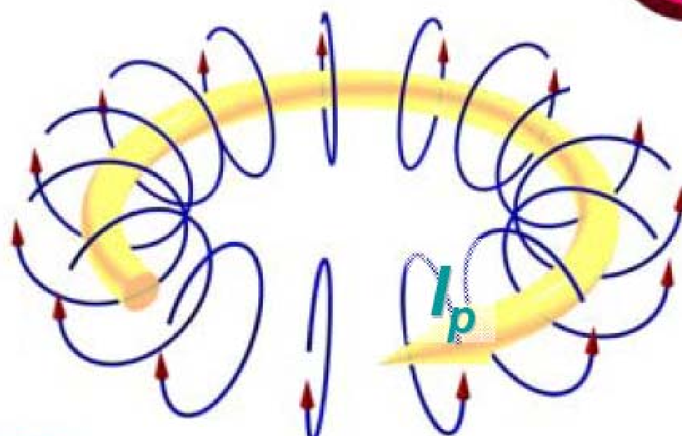
Confinement	n (cm^{-3})	τ (sec)
Momentum	10^{25}	10^{-11}
Magnetic	10^{14}	1

The Tokamak

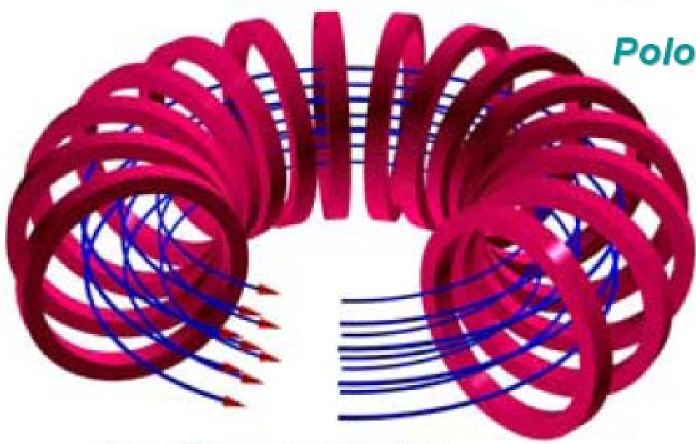
In Russian
Tok: current
Mak: machine



Total field



Poloïdal field created by I_p

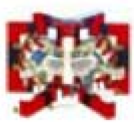
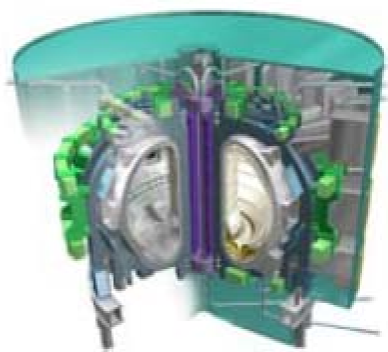
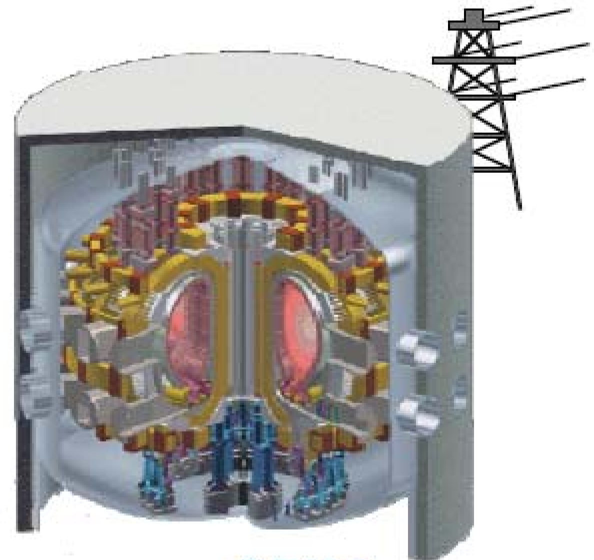


Toroïdal field coils

- Plasma ions and electrons spiral tightly around field lines
- Magnetic field lines map closed toroïdal surfaces
- Plasma is confined within closed toroïdal surfaces, plasma pressure balanced by $B^2/2\mu_0$

Thermal isolation :
➔ size essential

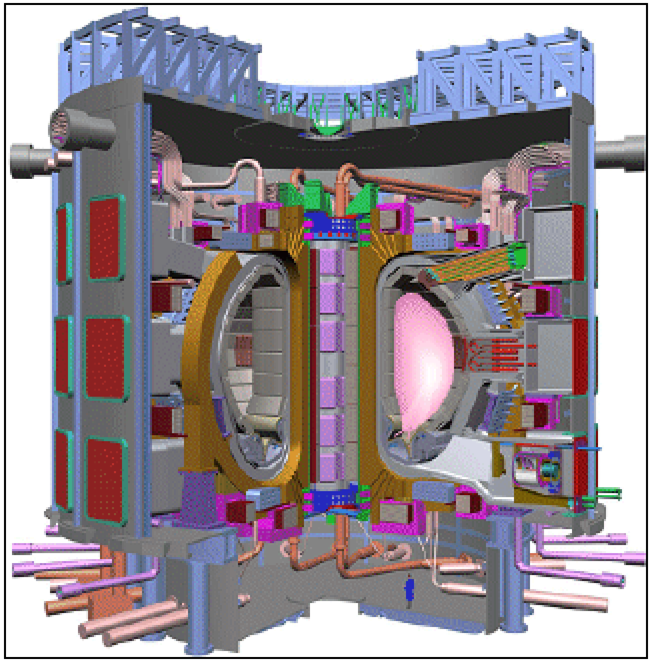
ITER : an essential step towards the reactor

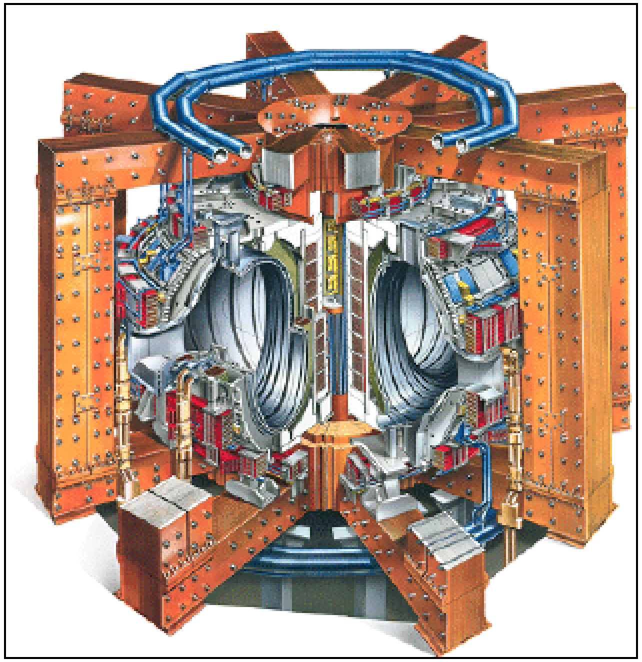
			
Tore Supra	***JET***	***ITER***	**DEMO**
25 m³	***80 m³***	***800 m³***	***~ 1000 - 3500 m³***
~ 0	***~ 16 MW_{th}***	***~ 500 MW_{th}***	***~ 2000 - 4000 MW_{th}***
Q ~ 0	**Q ~ 1**	**Q ~ 10**	**Q ~ 30**
6 minutes	**10 sec**	**10' to CW**	**CW**

------- Dominant self heating -----------

International Thermonuclear Reactor (ITER)

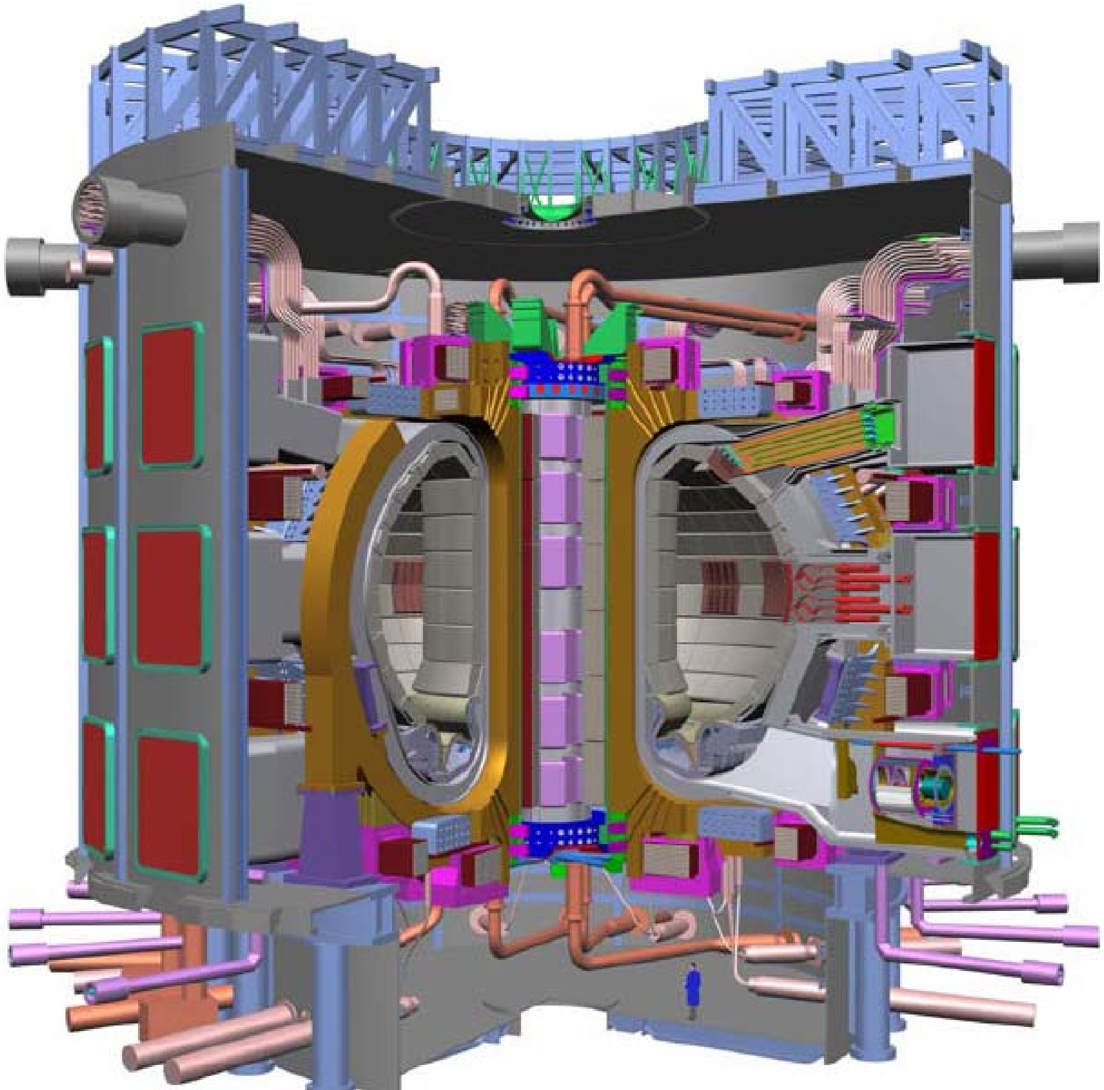
EFDA-JET: ITER





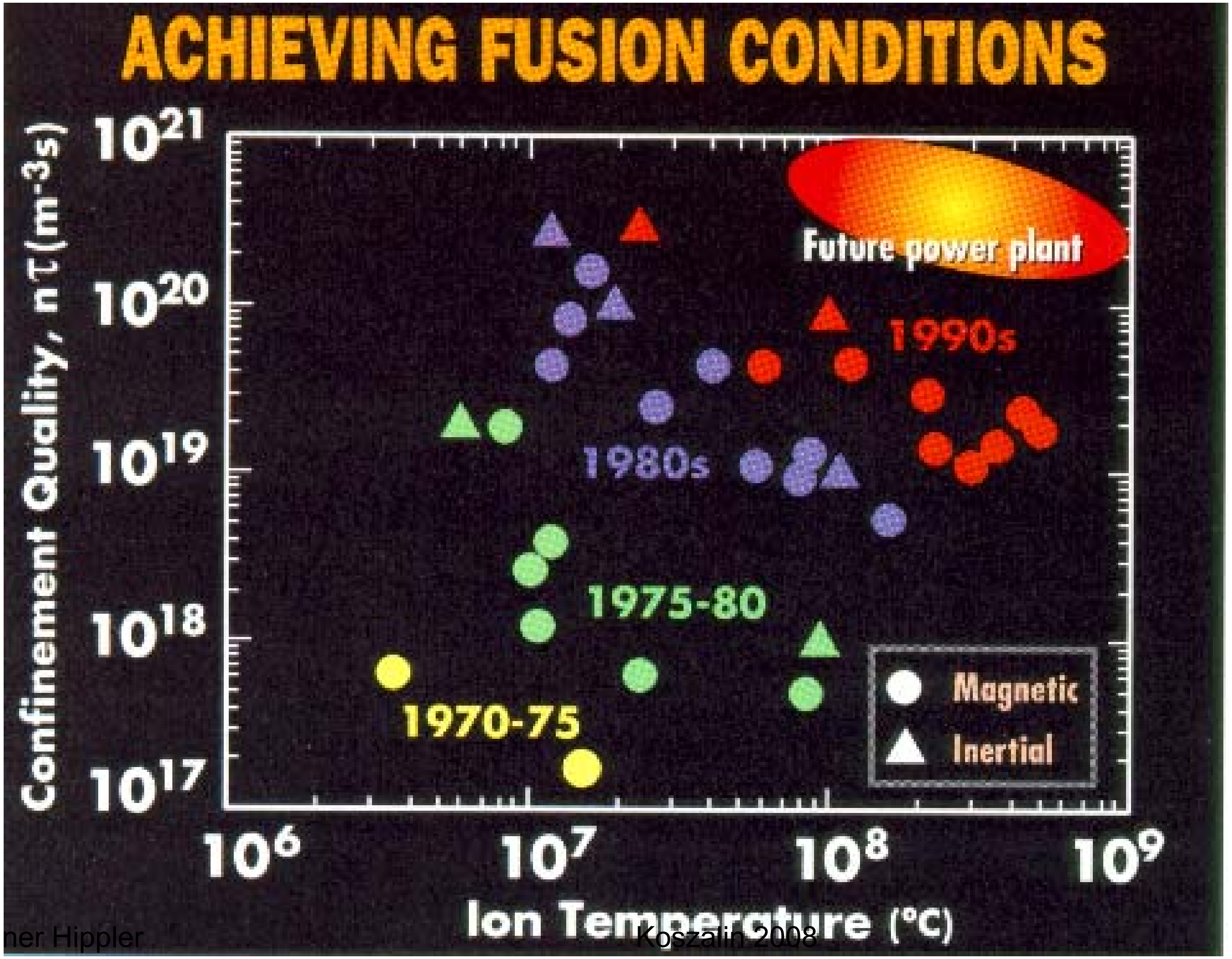
- **ITER**: hydrogen plasma torus operating at 10^8 K
- Aiming for 500 MW fusion power
- Large international collaboration (EU, China, India, Russia, USA …); site - Cadarache, France

International Thermonuclear Reactor (ITER)

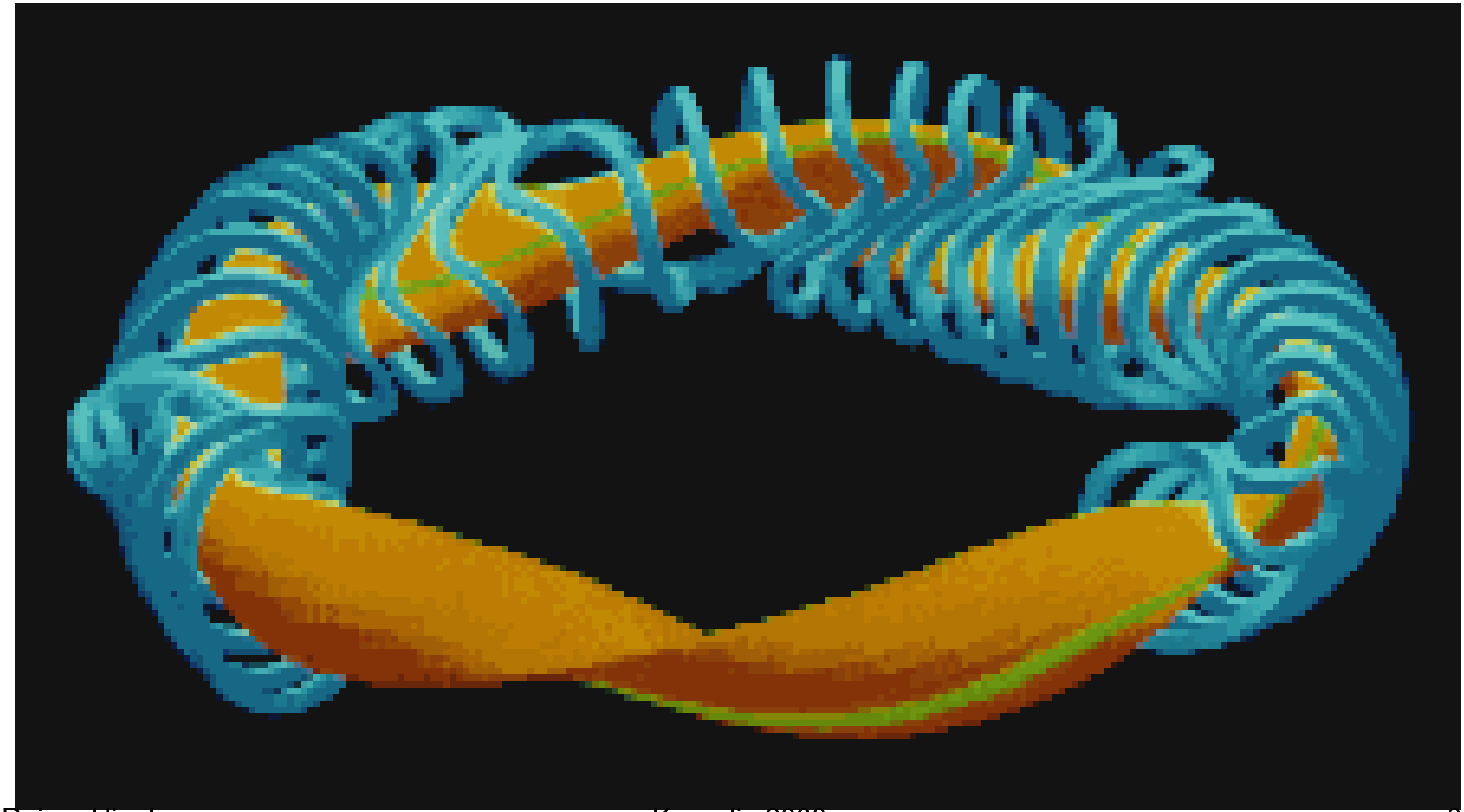


ᴧW fusion
r

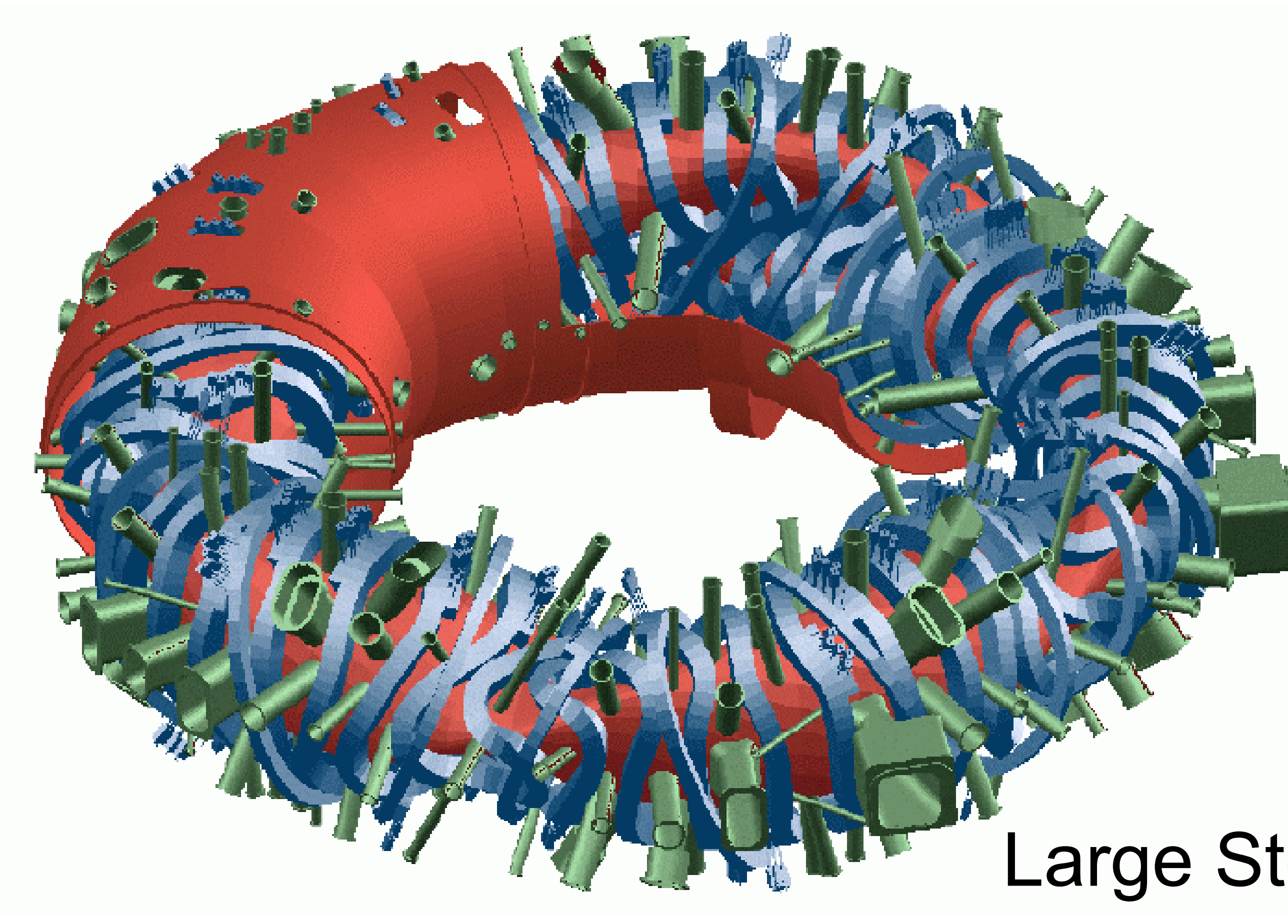
Road to Fusion



Stellerator: Wendelstein 7-X (Greifswald)



Wendelstein-7-X Greifswald



Large Stellarator
for Fusion Research


Thank you
Plasma Physics for Appications


Thank you