INSTITUTE OF PLASMA PHYSICS
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THERMAL PLASMAS: Properties, Generation, Diagnostics and Applications

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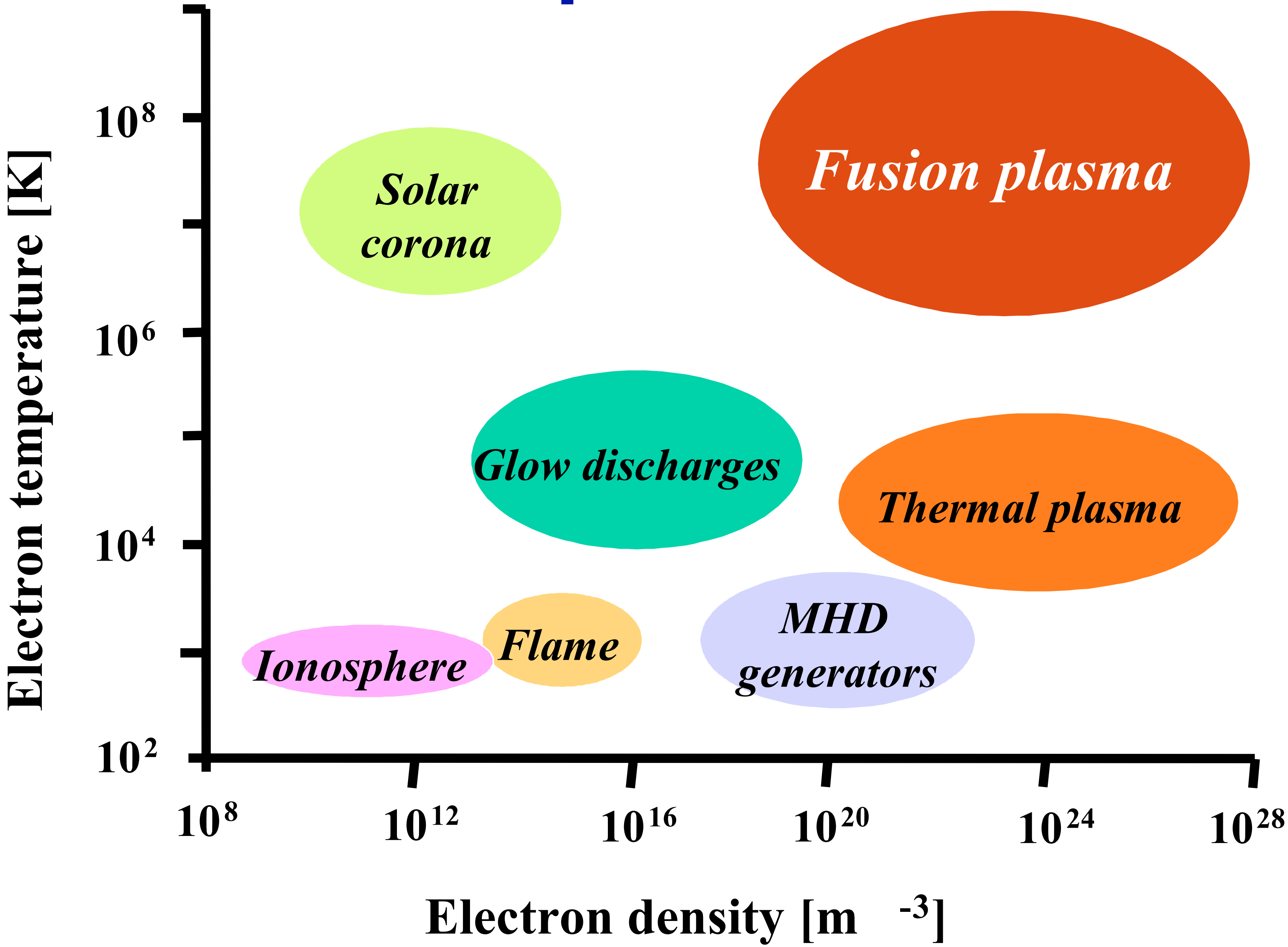
OUTLINE

- Thermal plasma and non-thermal plasma
- Composition, thermodynamic and transport properties of thermal plasmas
- Modeling of thermal plasma flows, arc modeling
- Generation of thermal plasmas
- Basic principles of arc plasma torches
- Factors influencing properties of plasma jet in arc plasma torches (design of the torch, properties of plasma gas)
- Plasma jet fluctuations
- Diagnostics of thermal plasma jets
- Thermal plasma processing

Electron temperatures and densities in plasmas



Nonequilibrium plasmas

$$T_e \neq T_i \qquad (T_e > T_i)$$

- plasma is not in thermodynamic equilibrium
- high values of E/p
- low pressures
- low densities of electric current

Thermal (equilibrium) plasmas

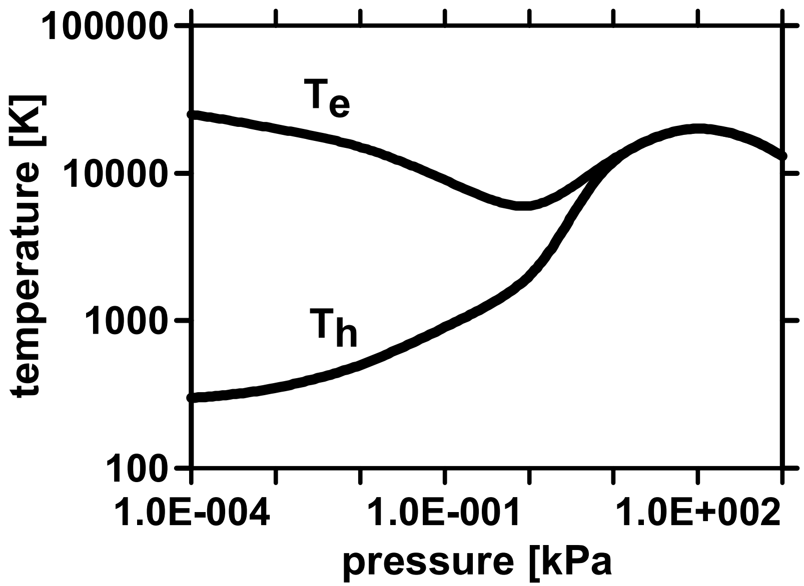
$$T_e \cong T_i$$

- plasma is in thermodynamic equilibrium - LTE
- low values of E/p
- higher pressures
- high densities of electric current

Thermal plasmas

Basic plasma properties

Local thermodynamic equilibrium
Temperatures $T_e = T_h \sim 8 - 50.10^3$ K
Pressures 10 kPa - 1 Mpa
E/p ~ 1 – 100 V/m.kPa



Common sources of thermal plasmas

- **Inductively coupled discharges in gases**
- **Electric arcs – stabilized by gas flow**
  – stabilized by vortex of liquid (Gerdien arcs)

Plasma in LTE

Properties of plasma in thermodynamic equilibrium are determined by pressure and temperature

Thermodynamic and transport properties of plasma depend on plasma composition

Composition of plasma

Monoatomic gas – electrons, ions, atoms

Eggert-Saha Equation:

$$\frac{n_e n_i}{n} = \frac{2Q_i}{Q}\left(\frac{2\pi m_e kT}{h^2}\right)^{3/2} \exp\left(-\frac{E_i}{kT}\right)$$

Dalton´s Law:

$$p = \left(n_e + n_i + n\right)kT$$

Quasineutrality:

$$n_e = n_i$$

Thermal plasmas - composition

Monoatomic gases: atoms, ions, electrons

Argon: Ar, Ar^+ , Ar^{++}, ... , e

Molecular gases: molecules, atoms, molekular ions, atomic ions, electrons

Nitrogen: N_2 , N, N_2^+ , N^+ , N^{++}, ... , e

Air: N_2 , O_2 , Ar, NO, N_2O, NO_2 , N, O, N_2^+, N^+, O_2^+, O^+, Ar^+, N^{++}, O^{++}, Ar^{++}, ... , e

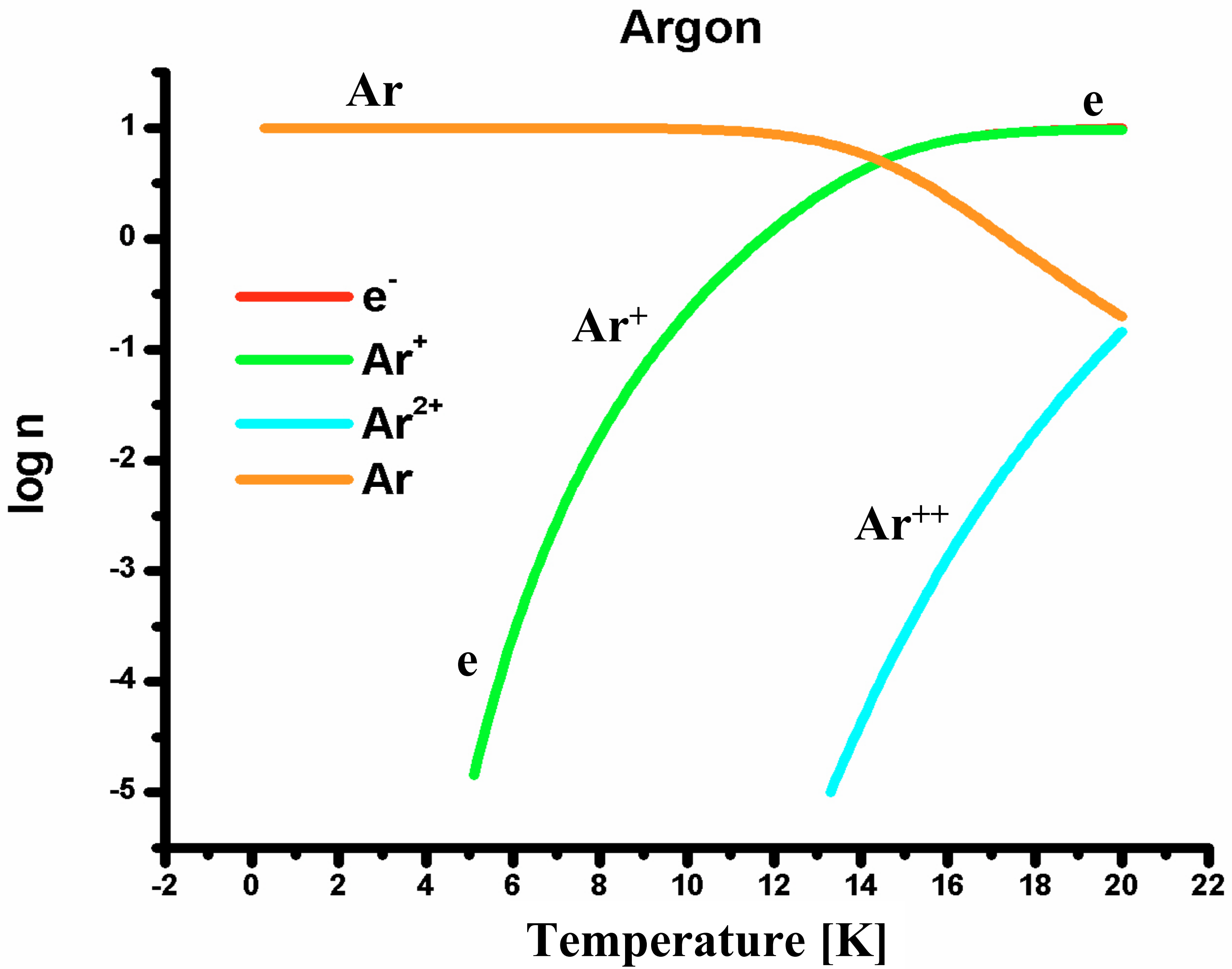
Calculation of composition:

Equilibrium between dissociation, ionization and recombination

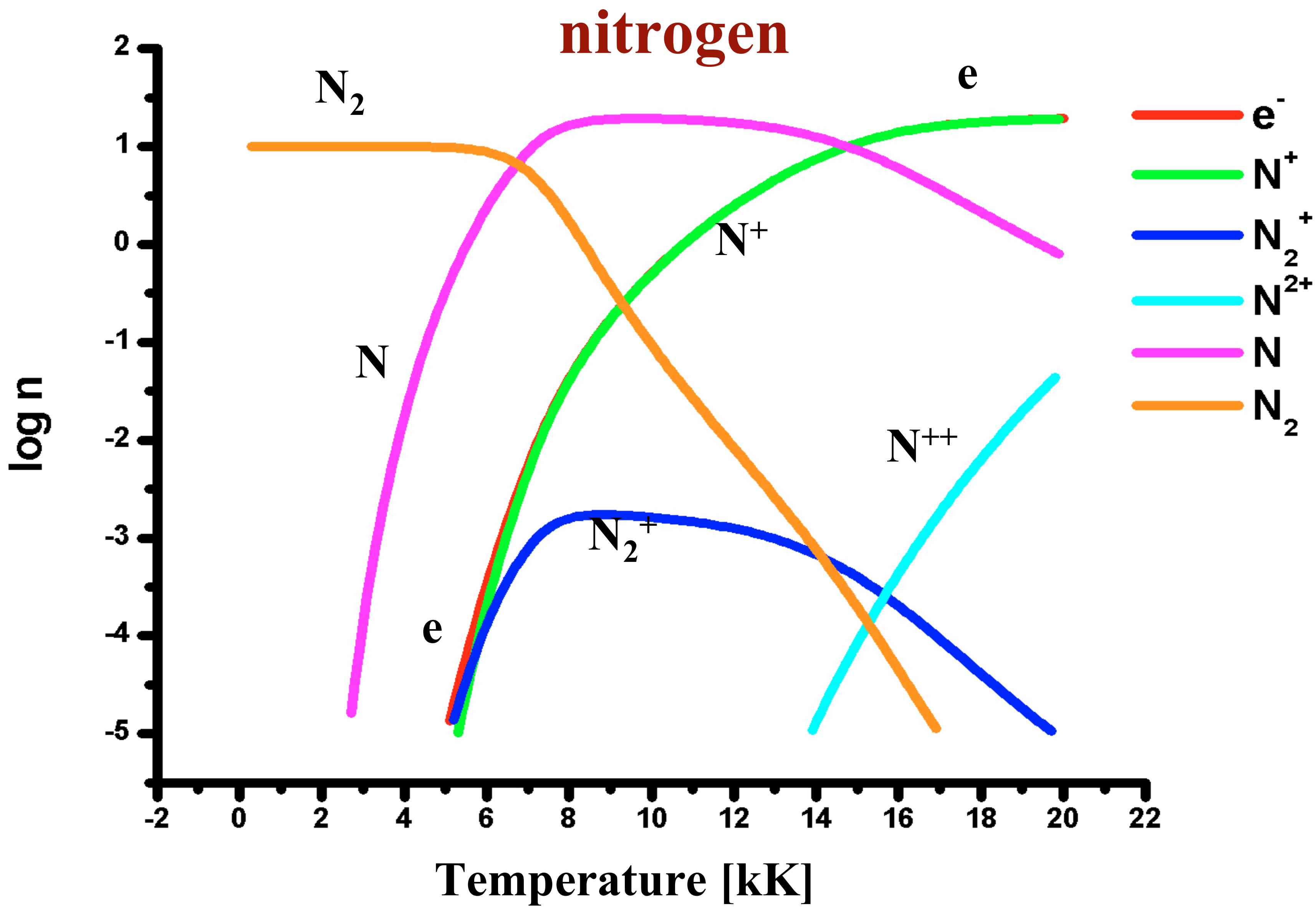
Minimization of Gibbs free energy

Depends on chemical potentials of different species present in plasma – can be determined from thermodynamic considerations

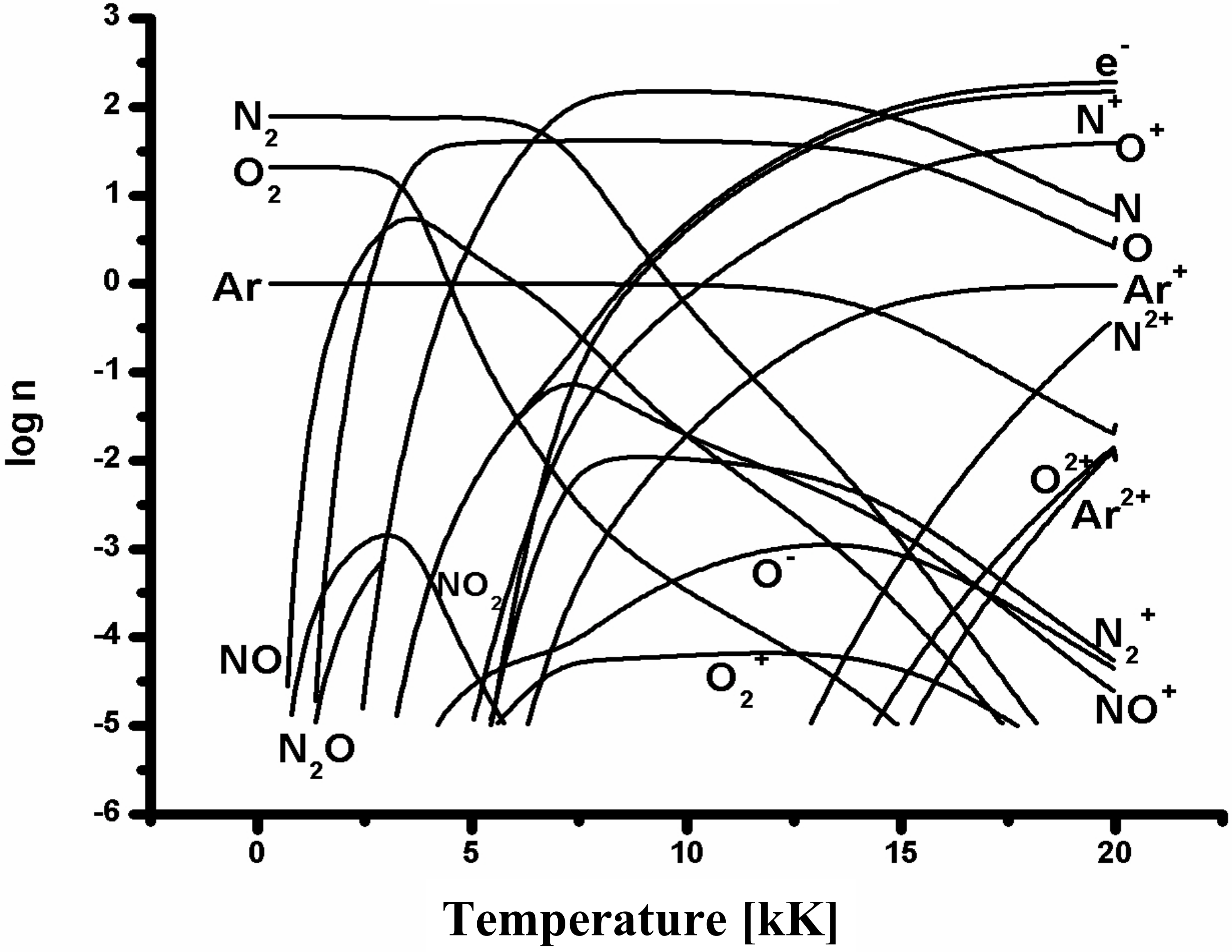
Plasma composition – monoatomic gas



Plasma composition-molecular gas



Composition of air plasma



Thermodynamic properties

Mass density
Enthalpy
Internal energy
Specific heat
Entropy

Evaluated for given plasma composition by methods of thermodynamics

The evaluation of thermodynamic properties is based on calculated partition functions for all species:

$$Q = \sum_s g_s \exp\left(-E_s / kT\right)$$

Plasma density

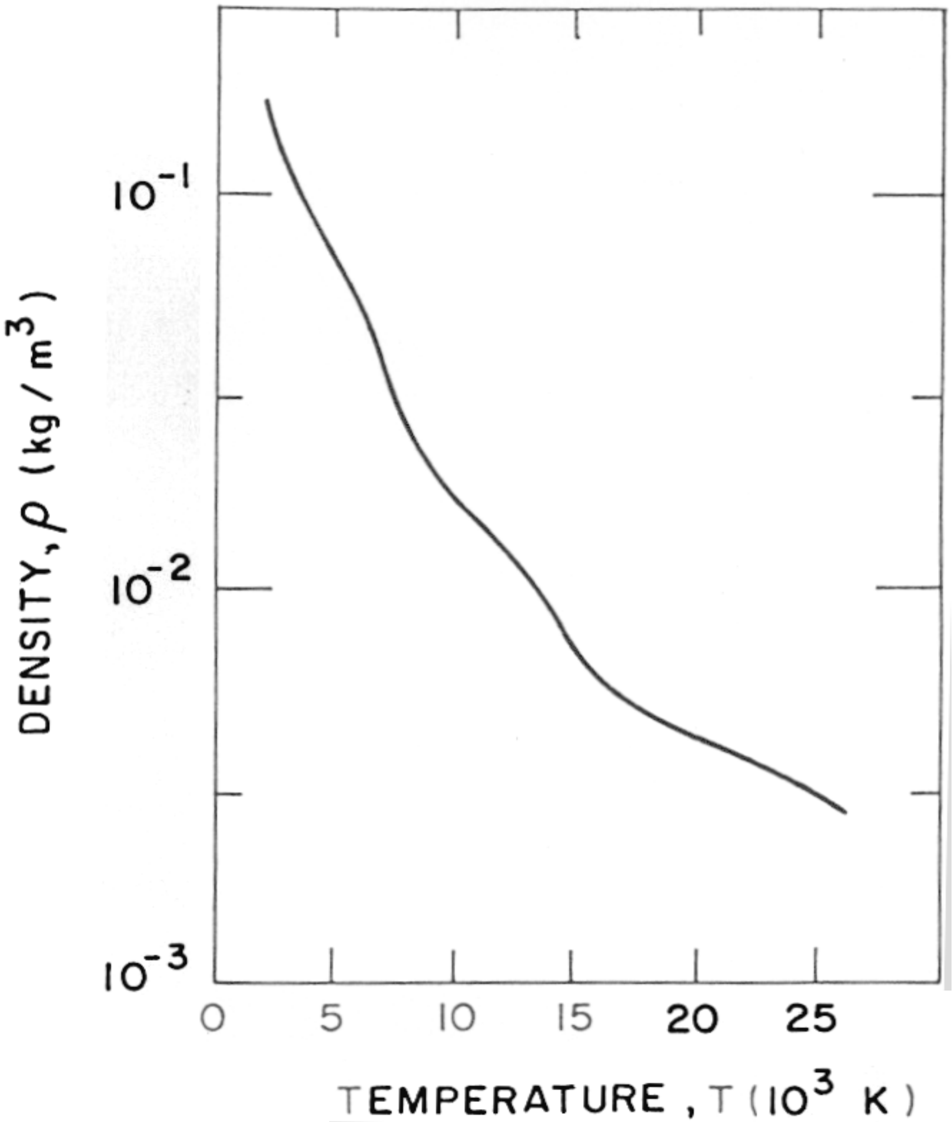
$$\rho = \sum n_i m_i$$

Temperature increase

➢ **Decrease of particle concentration**
➢ **Disociation, ionisation**

Increase of number of particles with low mass

Density of nitrogen plasma



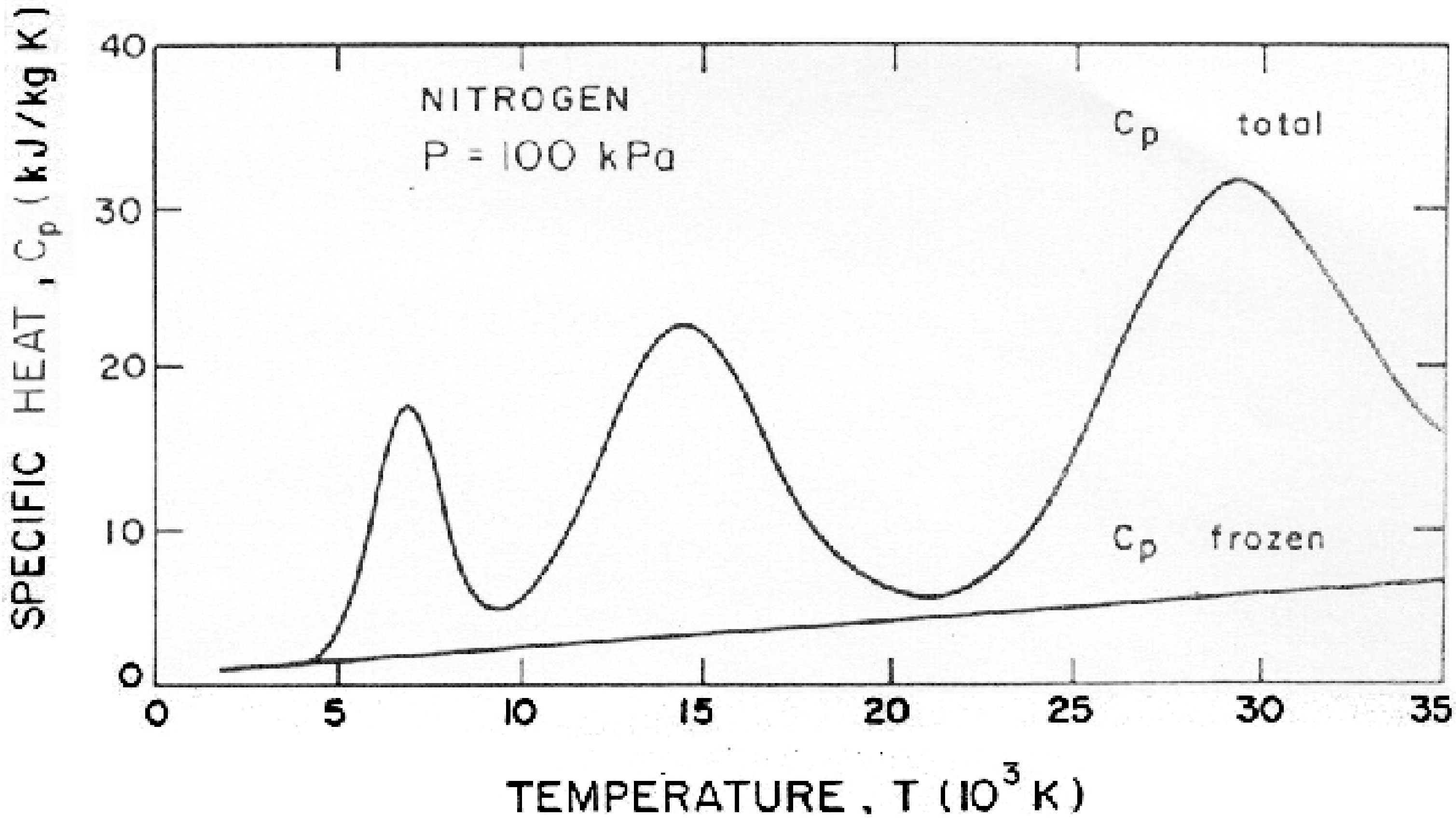
Specific heat capacity

Increase of temperature ⇒

- **Increase of kinetic energy of thermal motion - C_f**
- **Dissociation**
- **Ionization**

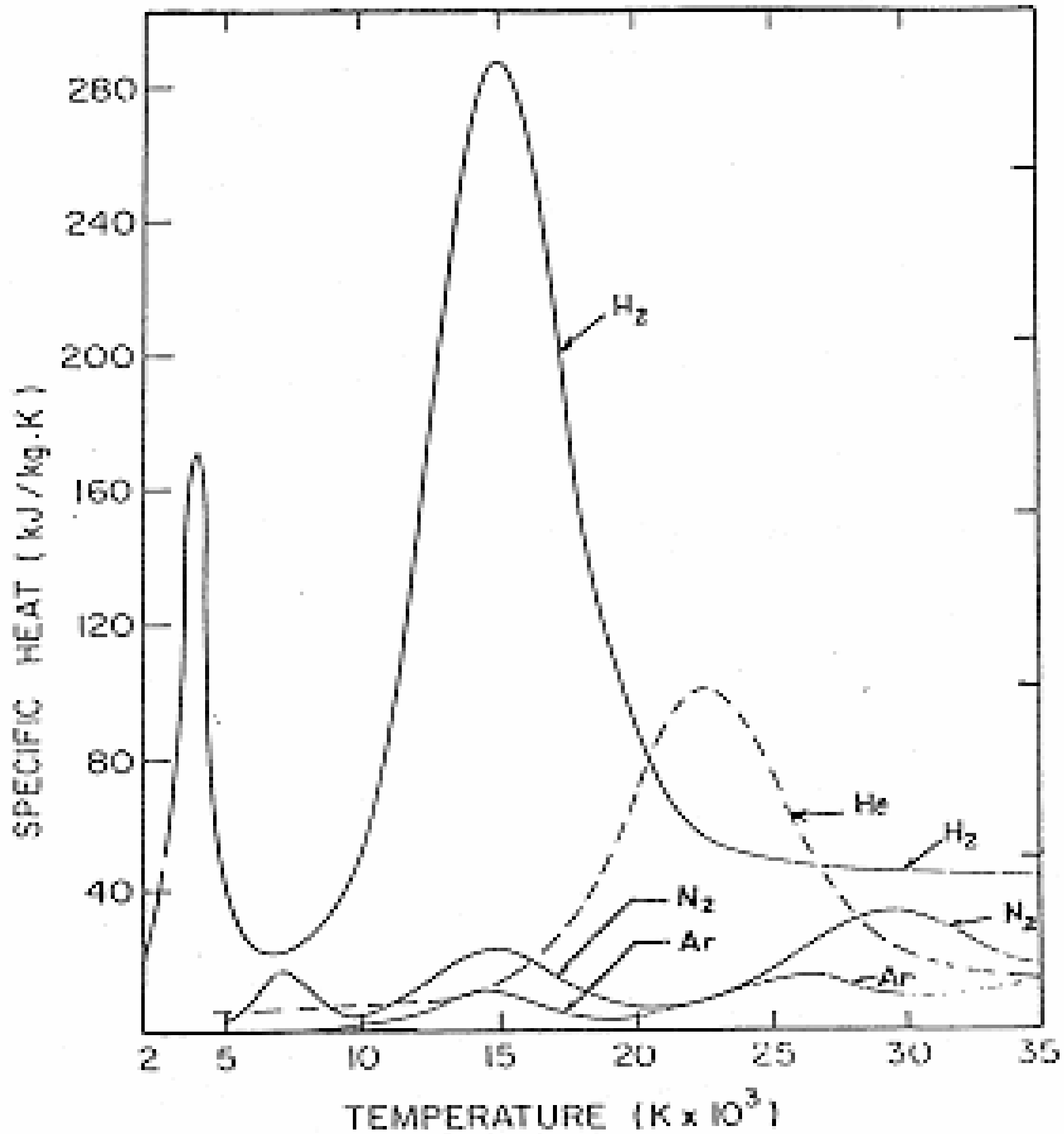
$\left.\begin{matrix}\textbf{Dissociation}\\ \textbf{Ionization}\end{matrix}\right\}$ **- C_r**

$$C_p = C_f + C_r$$



Specific heat capacity of various gases

Hydrogen
Helium
Nitrogen
Argon



Transport properties

Diffusion coefficient D $\vec{\Gamma} = D \text{ grad } n$

Thermal conductivity k $\vec{q} = k \text{ grad } T$

Electrical conductivity σ $\vec{j} = \sigma \text{ grad } V$

Viscosity μ $\vec{f}_x = \mu \text{ grad } v_x$

Computations of transport coefficients is based on solution of Boltzmann equation. Knowledge of collision cross sections for all collisional interactions between particles is crucial. Transport coefficients for more complex mixtures are frequently unknown.

Thermal conductivity

$$k = k_m + k_a + k_i + k_e + k_D + k_I$$

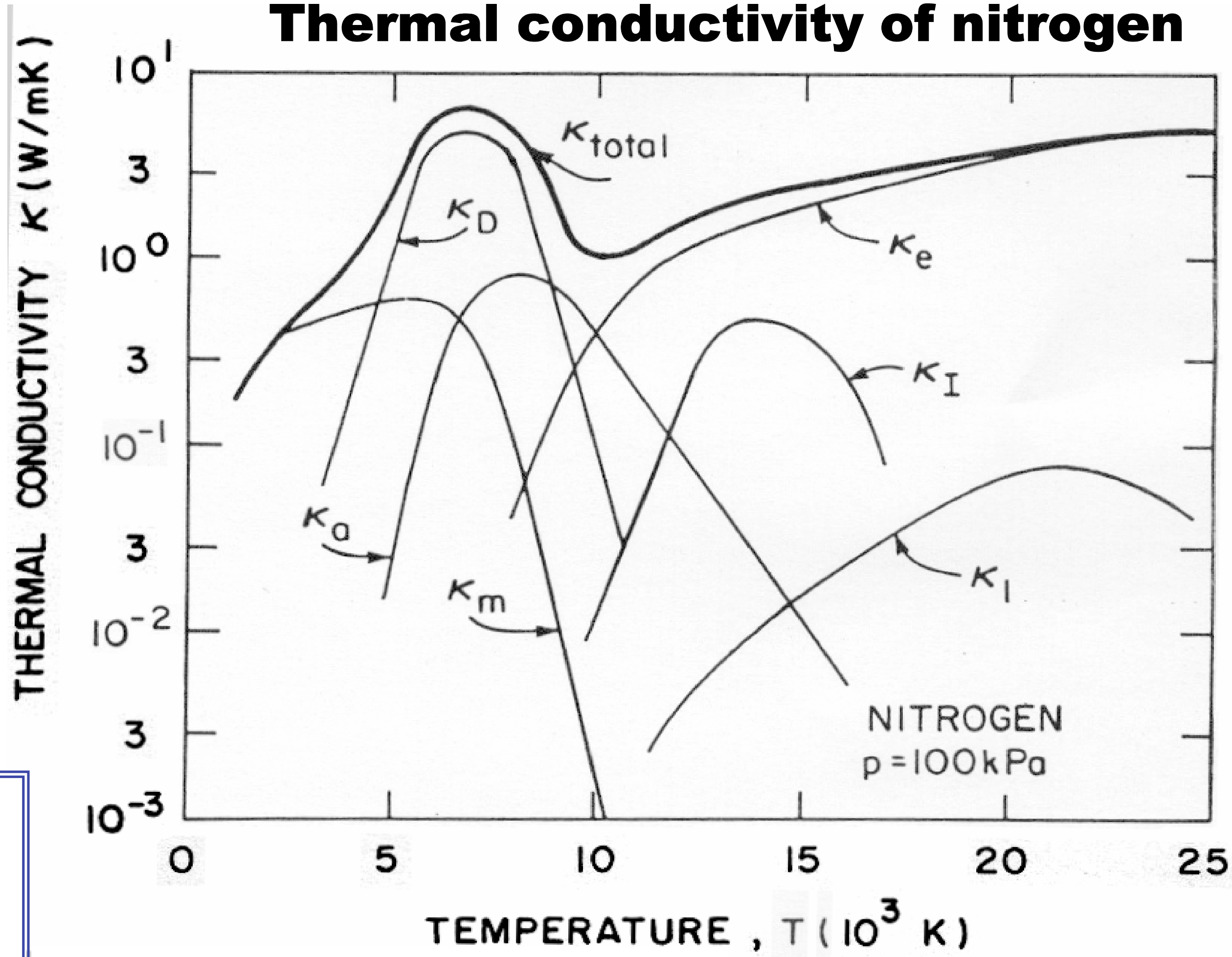
Heat transfer

- **Molecules – k_m**
- **Atoms - k_a**
- **Ions - k_i**
- **Electrons - k_e**

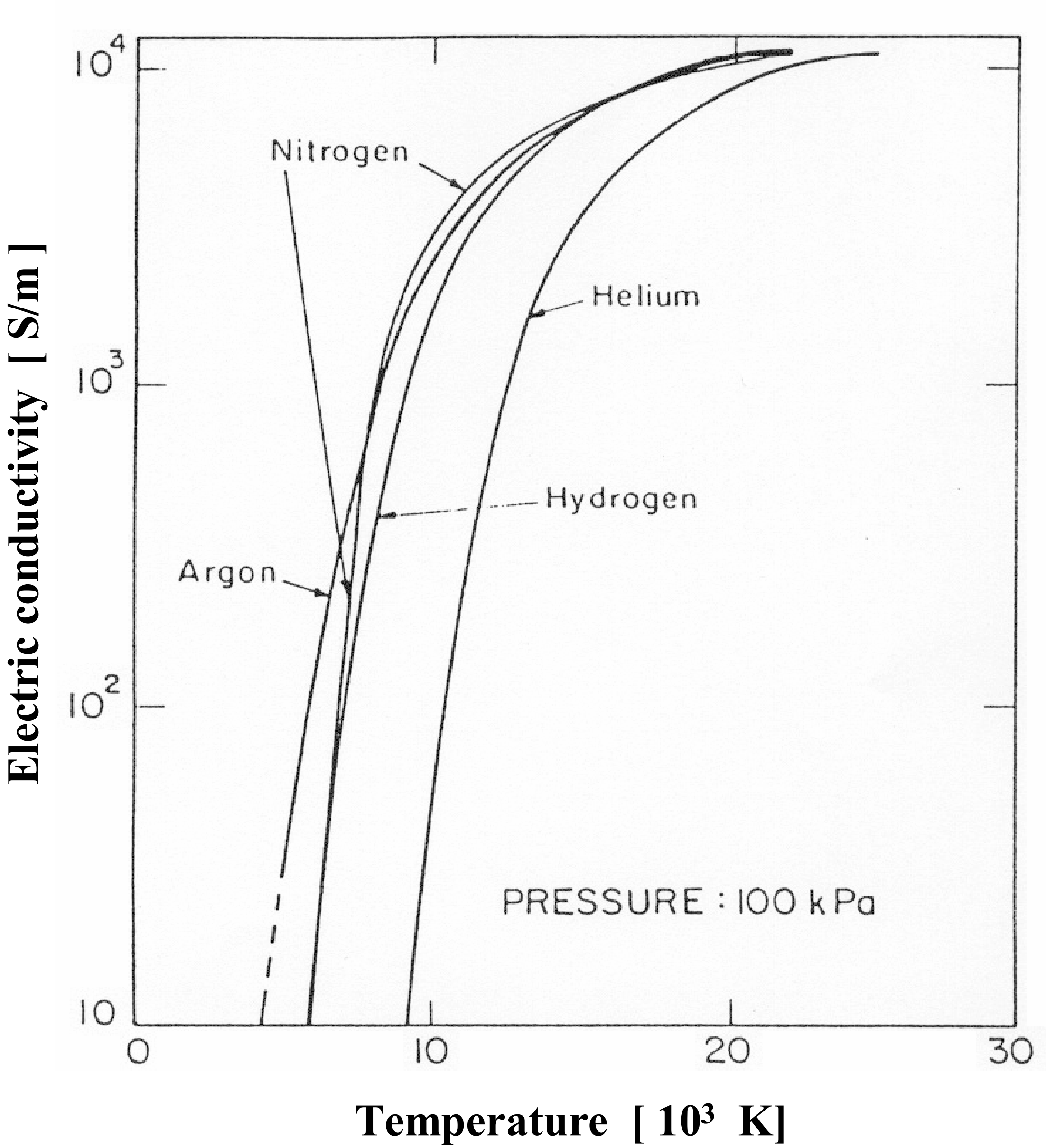
- **Dissociation – k_D**
- **Ionization - k_I**

Copper	**k = 390 W/mK**
Iron	**k = 75 W/mK**
Water	**k = 0,6 W/mK**

Thermal conductivity of nitrogen



Electric conductivity

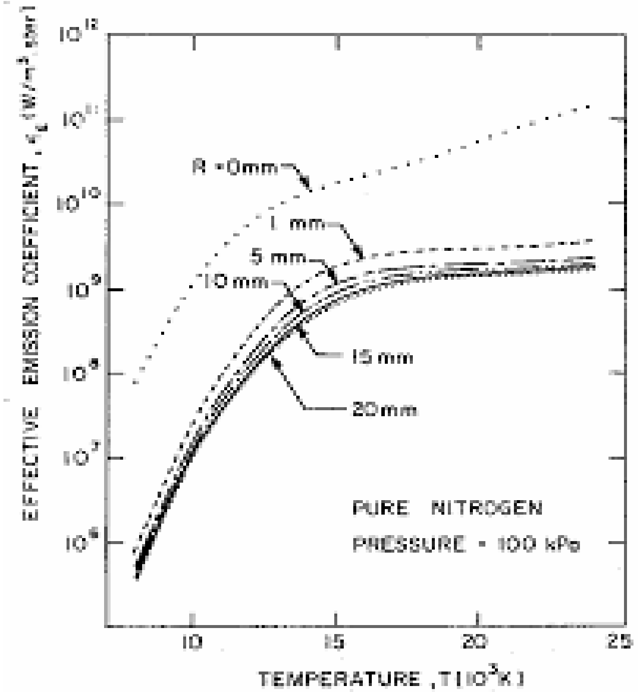


Copper σ = 5,8 .10^7 S/m
Iron σ = 9,5 .10^6 S/m
Graphite σ = 1,0 .10^5 S/m

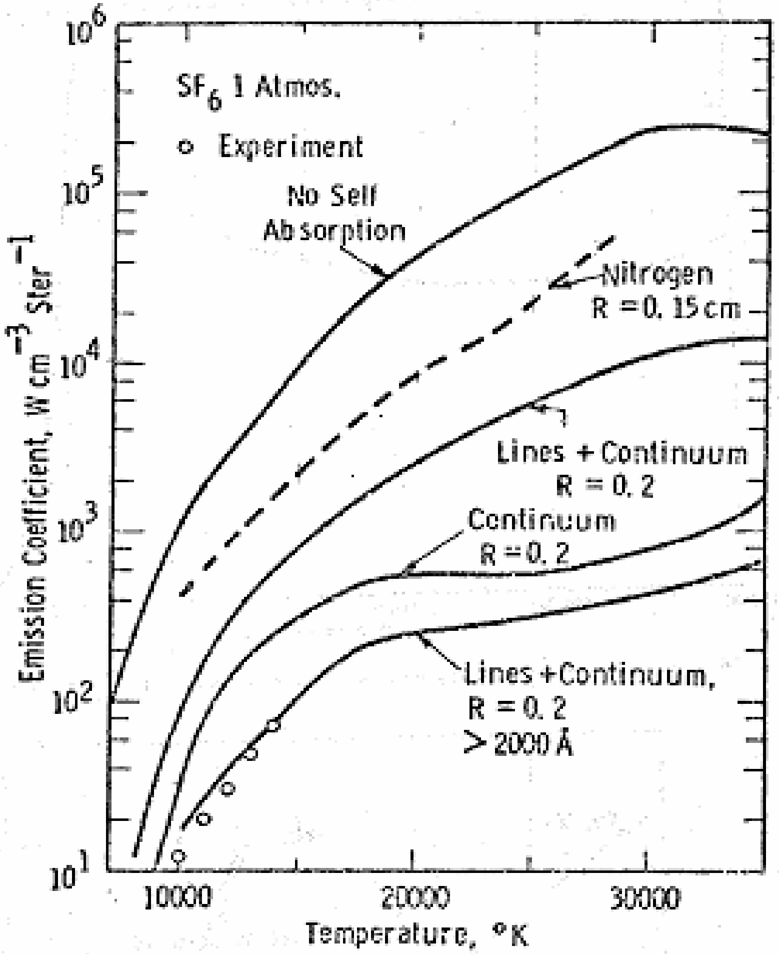
Plasma radiation

Complex modeling of radiation transfer in plasma with high spatial gradients of temperature is extremely difficult due to strong dependence of absorption and emission coefficients on temperature. Integration over all wavelengths along the optical path in plasma is necessary. Re-absorption of emitted light is main problem.

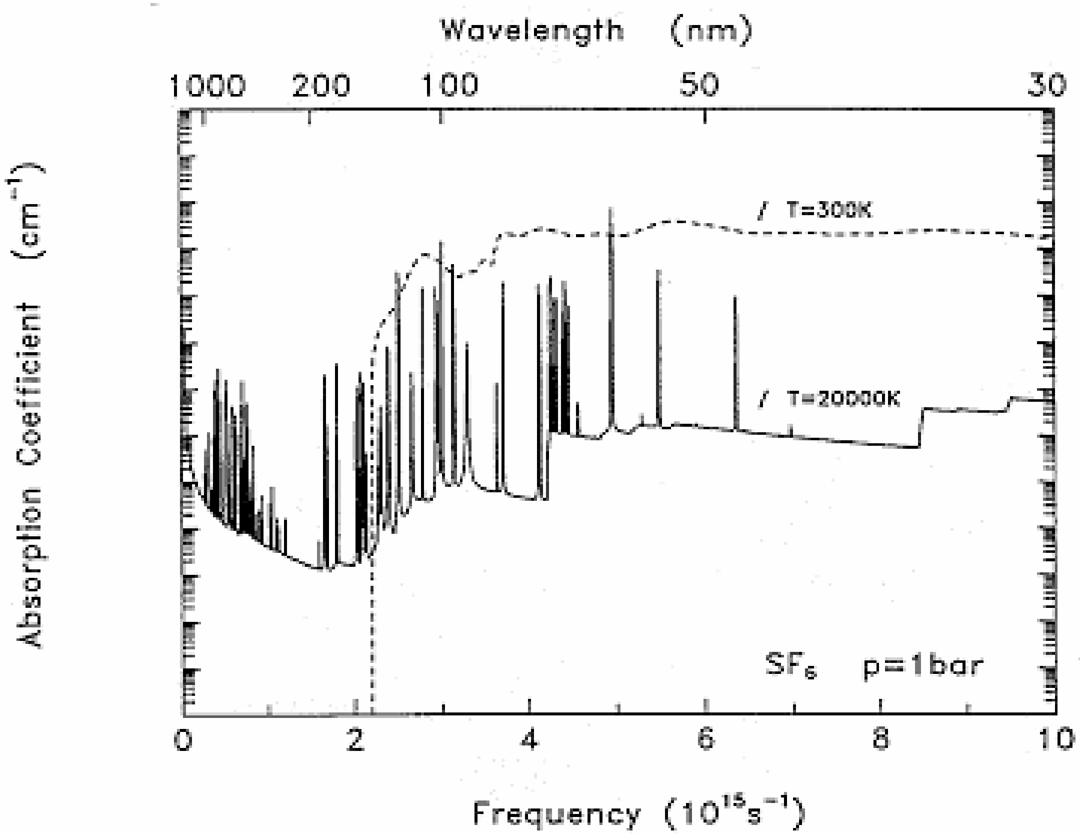
Concept of net emission coefficient is frequently used. Net emission coefficient represents radiation from isothermal cylinder of plasma with radius R.



Components of plasma radiation



Components of total radiation emission coefficient fo SF_6 at 1 atm.



Absorption coefficient of SF_6 for temperatures of 300 K and 20 000 K

Non-equilibrium effects

Deviations from LTE are caused by various mechanisms in thermal plasma flows.

- **Flows with high spatial gradients of temperature in the direction of flow**
  - **"frozen" plasma composition corresponding to the upstream position**
- **High spatial gradients of temperature – diffusion of species**
  - **Higher concentrations of electron in fringes of thermal plasma jets**
  - **De-mixing of plasma gases-ambipolar diffusion of ions with different coefficients of diffusion**
- **Rapid changes of plasma temperature**
  - **effect of kinetics of reactions (dissociation, ionization, recombination) in plasma**

Modeling of thermal plasma flows

Plasma can be described as a fluid with thermodynamic and transport properties depending on pressure and temperature

Models of thermal plasma flows are based on solution of equations of balances of mass, momentum and energy. Equations of fluid dynamics are used with terms representing dissipation of energy by Joule heating, radiation energy transfer and effect of electromagnetic forces.

Plasma properties are represented by transport and thermodynamic coefficients often calculated separately and given in tables giving dependence on temperature and pressure.

Model of arc column in axial gas flow

continuity equation:

$$\frac{\partial}{\partial t}\rho + \frac{1}{r}\frac{\partial}{\partial r}(\rho v r) + \frac{\partial}{\partial x}(\rho u) = 0 \quad ,$$

momentum equations:

$$\rho\frac{\partial u}{\partial t} + \rho v\frac{\partial u}{\partial r} + \rho u\frac{\partial u}{\partial x} = -\frac{\partial p}{\partial x} + j_r B_\theta - \frac{2}{3}\frac{\partial}{\partial x}\left[\eta\left(\frac{1}{r}\frac{\partial}{\partial r}(rv) + \frac{\partial u}{\partial x}\right)\right] + \frac{\partial}{\partial x}\left(2\eta\frac{\partial u}{\partial x}\right) + \frac{1}{r}\frac{\partial}{\partial r}\left[r\eta\left(\frac{\partial u}{\partial r} + \frac{\partial v}{\partial x}\right)\right]$$

$$\rho\frac{\partial v}{\partial t} + \rho v\frac{\partial v}{\partial r} + \rho u\frac{\partial v}{\partial x} = -\frac{\partial p}{\partial r} - j_x B_\theta - \frac{2}{3}\frac{\partial}{\partial r}\left[\eta\left(\frac{1}{r}\frac{\partial}{\partial r}(rv) + \frac{\partial u}{\partial x}\right)\right] + \frac{\rho w^2}{r} + \frac{1}{r}\frac{\partial}{\partial r}\left(2\eta r\frac{\partial v}{\partial r}\right) - \frac{2\eta v}{r^2} + \frac{\partial}{\partial x}\left[\eta\left(\frac{\partial u}{\partial r} + \frac{\partial v}{\partial x}\right)\right]$$

$$\rho\frac{\partial w}{\partial t} + \rho v\frac{\partial w}{\partial r} + \rho u\frac{\partial w}{\partial x} = \frac{1}{r}\frac{\partial}{\partial r}\left(\eta r\frac{\partial w}{\partial r}\right) + \frac{\partial}{\partial x}\left(\eta\frac{\partial w}{\partial x}\right) - \frac{\rho v w}{r} - \frac{\eta w}{r^2} - \frac{w}{r}\frac{\partial \eta}{\partial r} \quad ,$$

energy equation:

$$\rho c_p\frac{\partial T}{\partial t} + \rho v c_p\frac{\partial T}{\partial r} + \rho u c_p\frac{\partial T}{\partial x} - \frac{\partial p}{\partial t} = u\frac{\partial p}{\partial x} + v\frac{\partial p}{\partial r} + j_r E_r + j_x E_x +$$

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\lambda\frac{\partial T}{\partial r}\right) + \frac{\partial}{\partial x}\left(\lambda\frac{\partial T}{\partial x}\right) + \frac{5}{2}\frac{k}{e}\left(j_x\frac{\partial T}{\partial x} + j_r\frac{\partial T}{\partial r}\right) - \dot{R}$$

charge continuity equation:

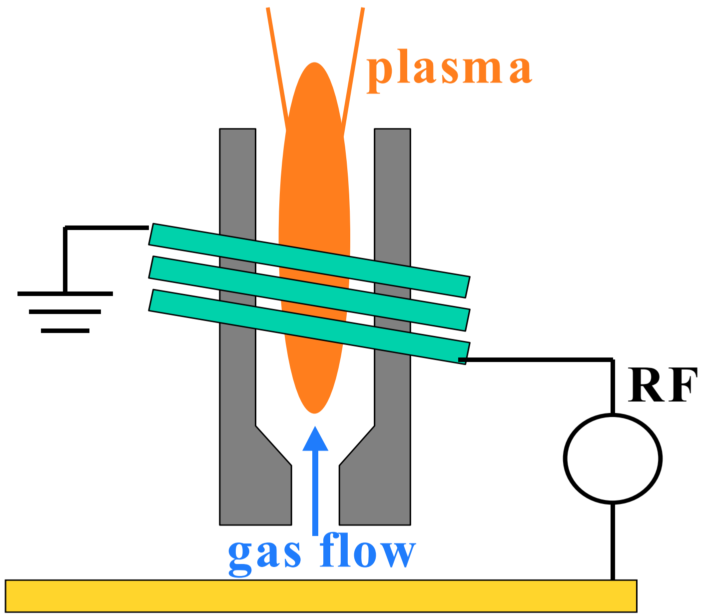
$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\sigma\frac{\partial \Phi}{\partial r}\right) + \frac{\partial}{\partial x}\left(\sigma\frac{\partial \Phi}{\partial x}\right) = 0 \quad ,$$

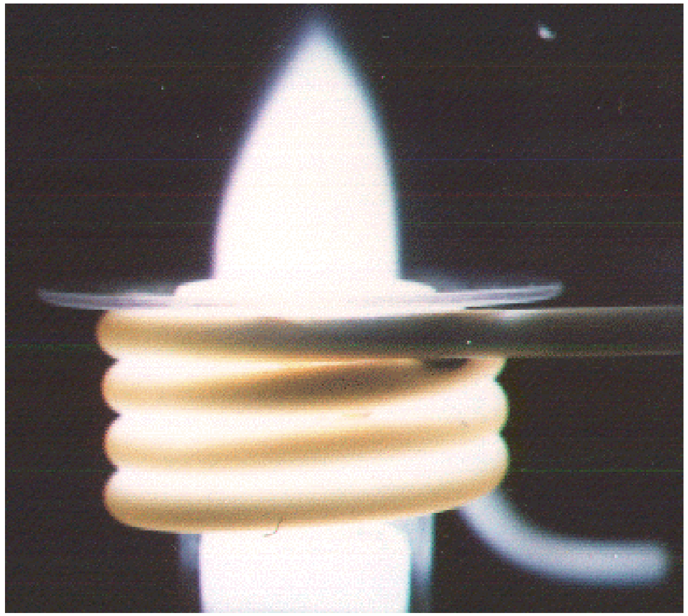
Thermal plasma generation

Inductively coupled plasma torches

Inductively coupled discharge is maintained in an open tube in the presence of streaming gas. Low velocity plasma jet is formed at the exit.

Frequencies: 100 kHz – 100 MHz
Power: 1 kW – 1 MW
Pressure: 10^4 – 10^6 Pa
Plasma temperature: 6 000 – 10 000 K
Plasma velocity: 10 – 10^2 m/s





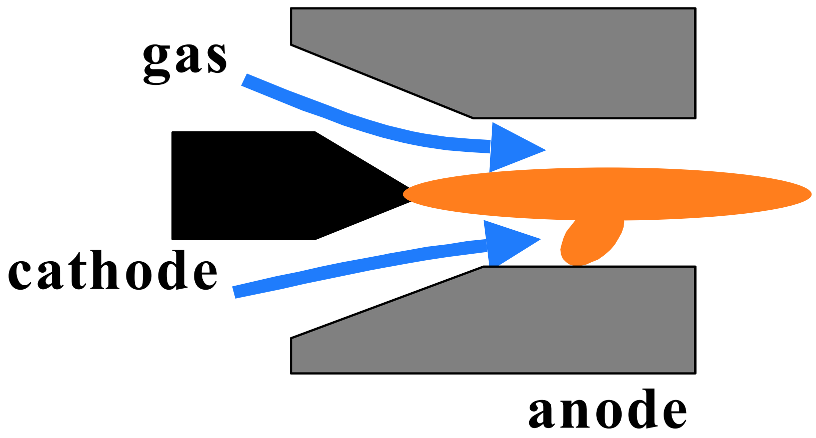
Electric arcs

- High current densities
  - arc column ~ 100 A/cm^2
  - electrode spots ~> 10^6 A/cm^2
- High radiation intensity
- Low electrode potential drops $V_c \sim 10$ V
- Discharge current often limited only by power supply
- Arc currents 1 A – 10^6 A
- Intensity of electric field 1 V/cm – 10^3 V/cm
- Arc column length 1 mm – 10^1 m

Principles of arc stabilization

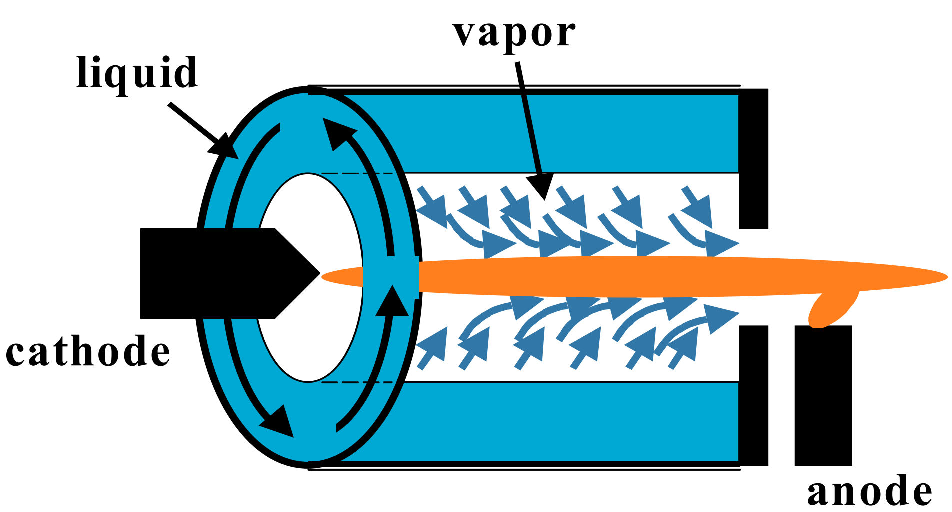
Gas-stabilized arc

- Gas flows along the arc in the nozzle
- Usually gas flow has vortex component for better stabilization and for anode spot movement
- Anode created by exit nozzle or transferred arcs
- Power level: 1 kW – 10 MW
- Plasma temperatures: 6 000 – 20 000 K



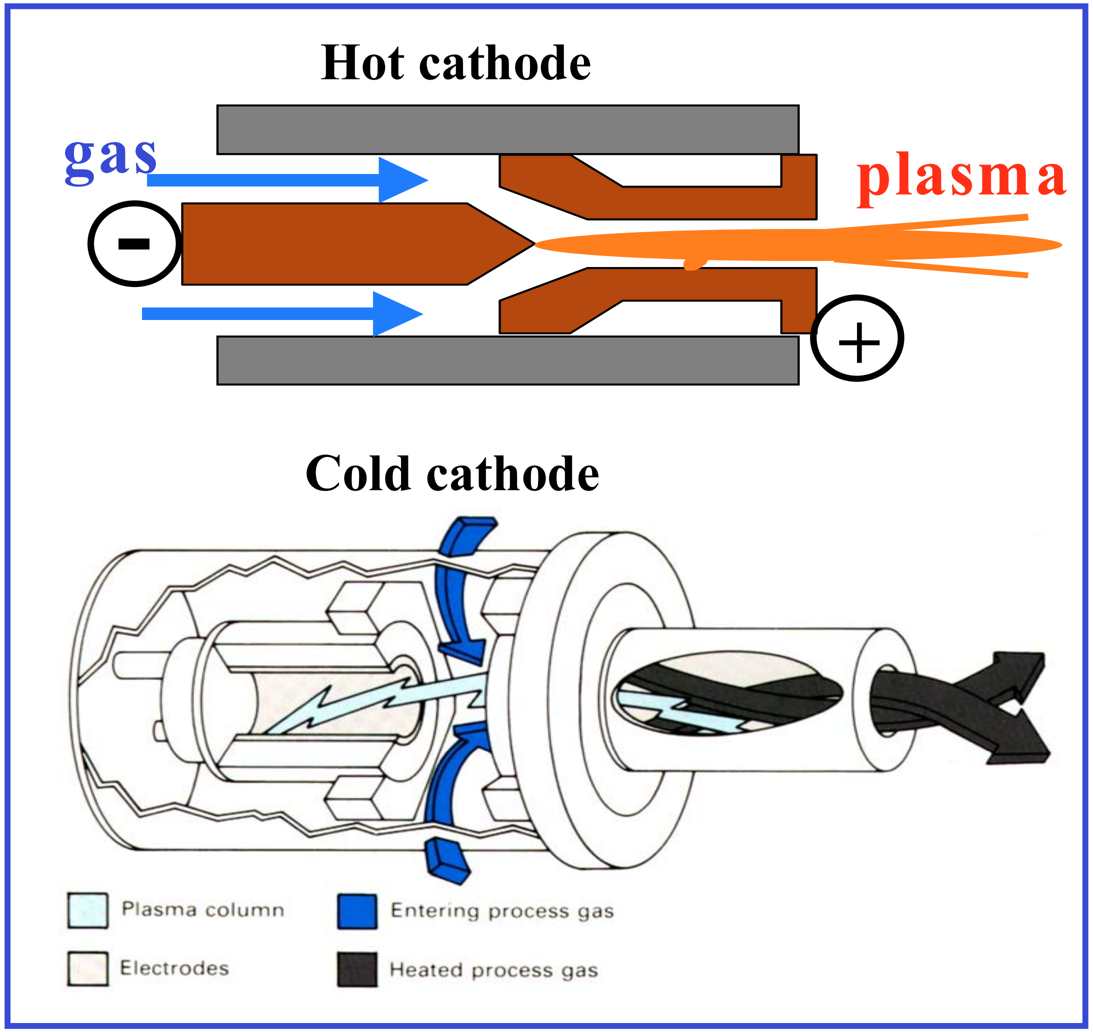
Liquid-stabilized (Gerdien) arc

- Liquid vortex is created in cylindrical chamber with tangential injection
- Arc is stabilized by its interaction with the vortex
- Anode is outside of arc chamber
- Power level: 10 – 200 kW
- Plasma temperatures: 8 000 – 50 000 K

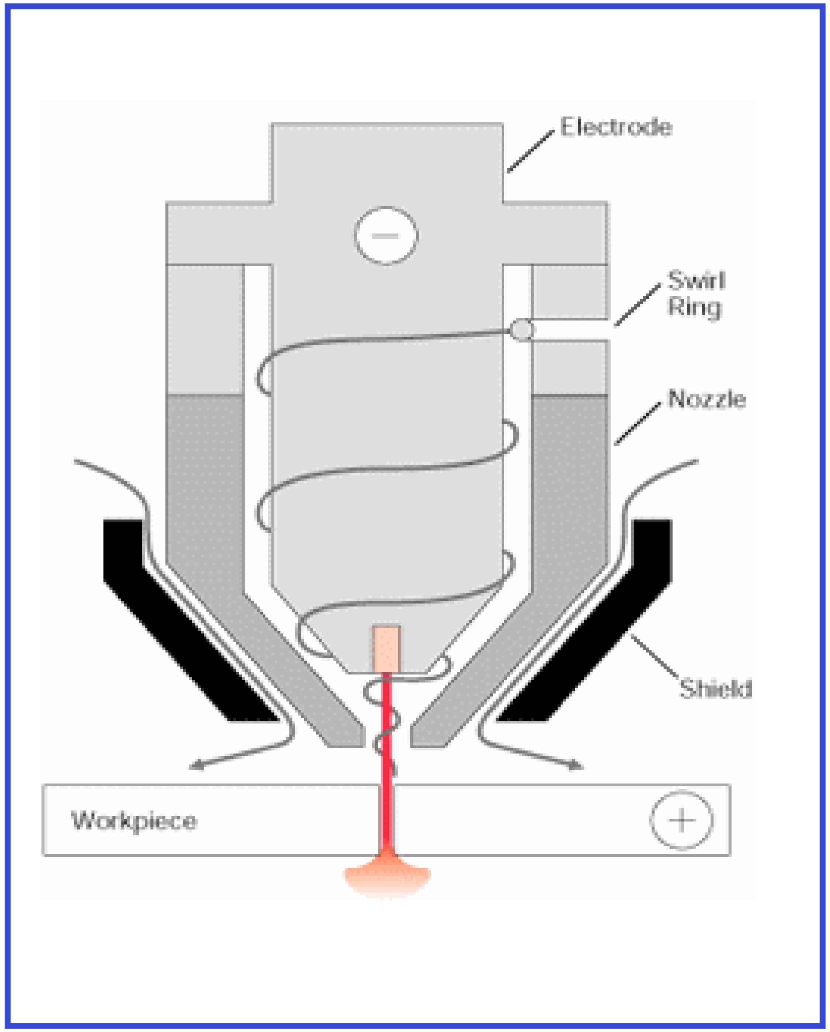


Gas-stabilized arc plasma torches

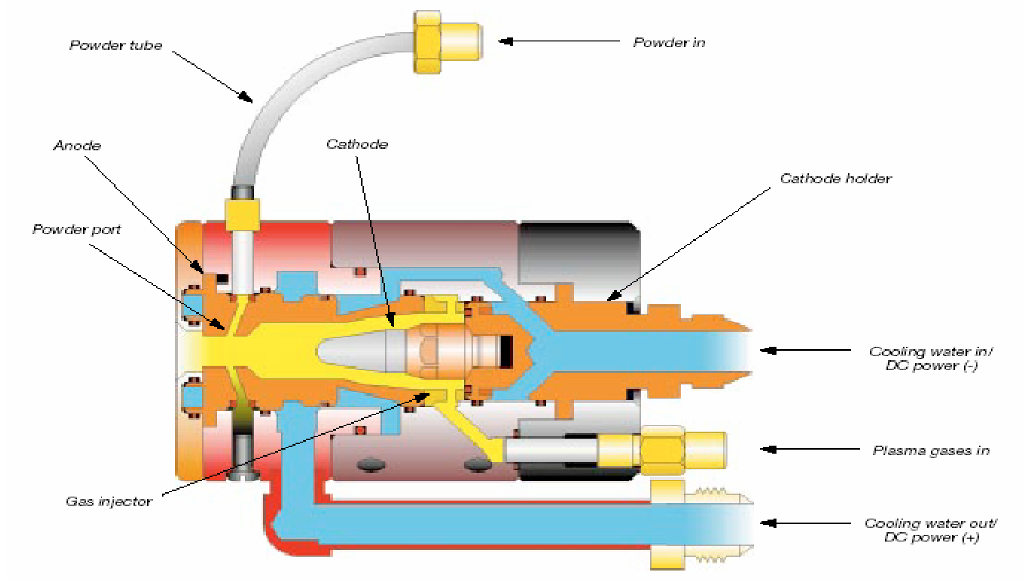
Non transferred arcs

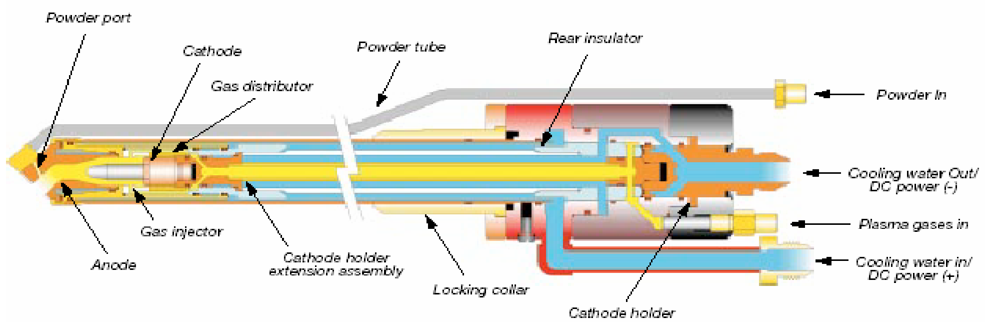


Transferred arcs

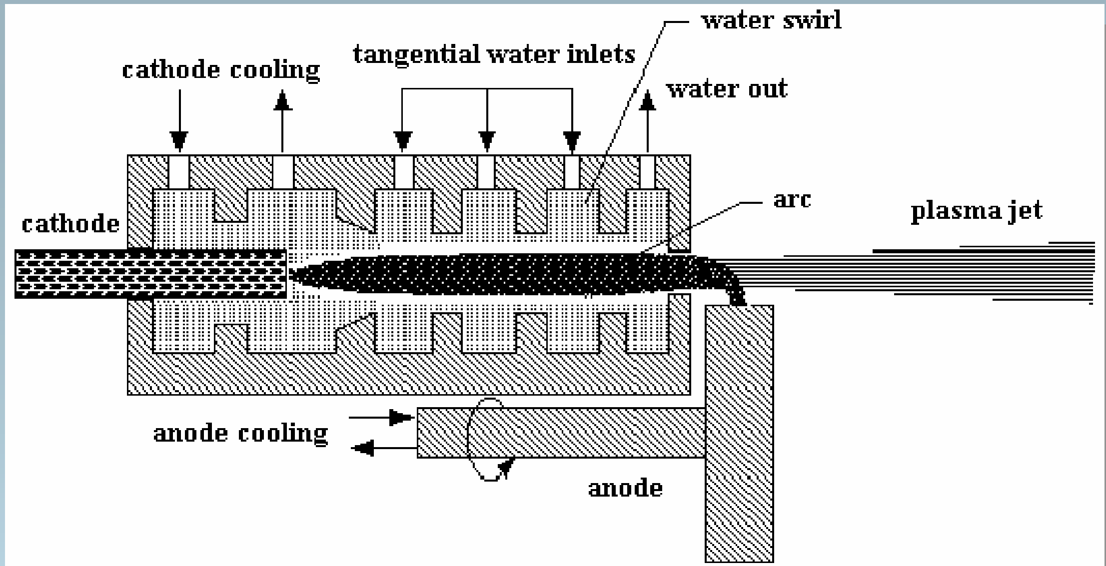


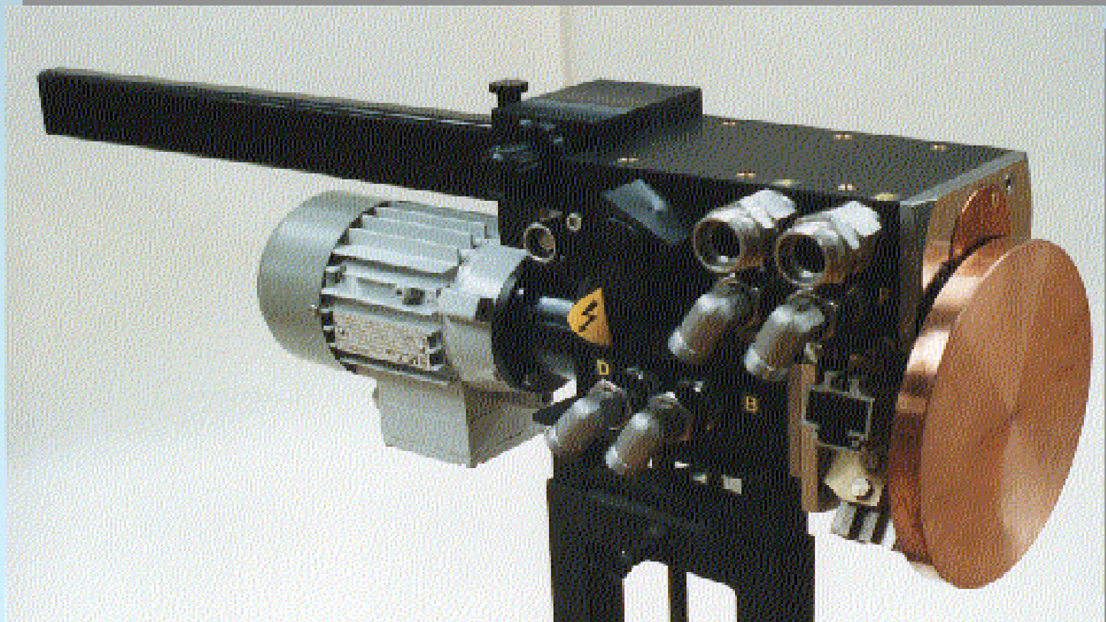
Gas-stabilized plasma torches





Water Stabilized Plasma Torch





arc current: 300 - 600 A
arc power: 80 - 176 kW
arc voltage: 267 - 293 V

exit centerline temperature:
19 000 - 28 000 K
exit centerline velocity:
2500 - 7000 m/s
centerline plasma density:
0.9 - 2.0 g/m^{-3}

Basic factors determining properties of plasma jet in arc torches

Principal design factors: arc chamber geometry, arc current
plasma gas, gas flow rate

Dominant mechanisms of energy balance of unit length of arc column in axial flow:

Energy dissipation by Joule heating = Increase of axial enthalpy flux + Power loss by radial conduction + Power loss by radiation

Following simple relations can be derived from energy balance equation for basic torch parameters:

Torch Efficiency:

$$\eta = \left(1 + \frac{4\pi^2\theta_G}{\theta_F} \frac{R^2 L}{G} \frac{\varepsilon_n}{h} + \frac{2\pi\theta_G}{\theta_F} \frac{L}{G} \frac{S}{h} \right)^{-1}$$

design factors

plasma gas properties

Torch Power:

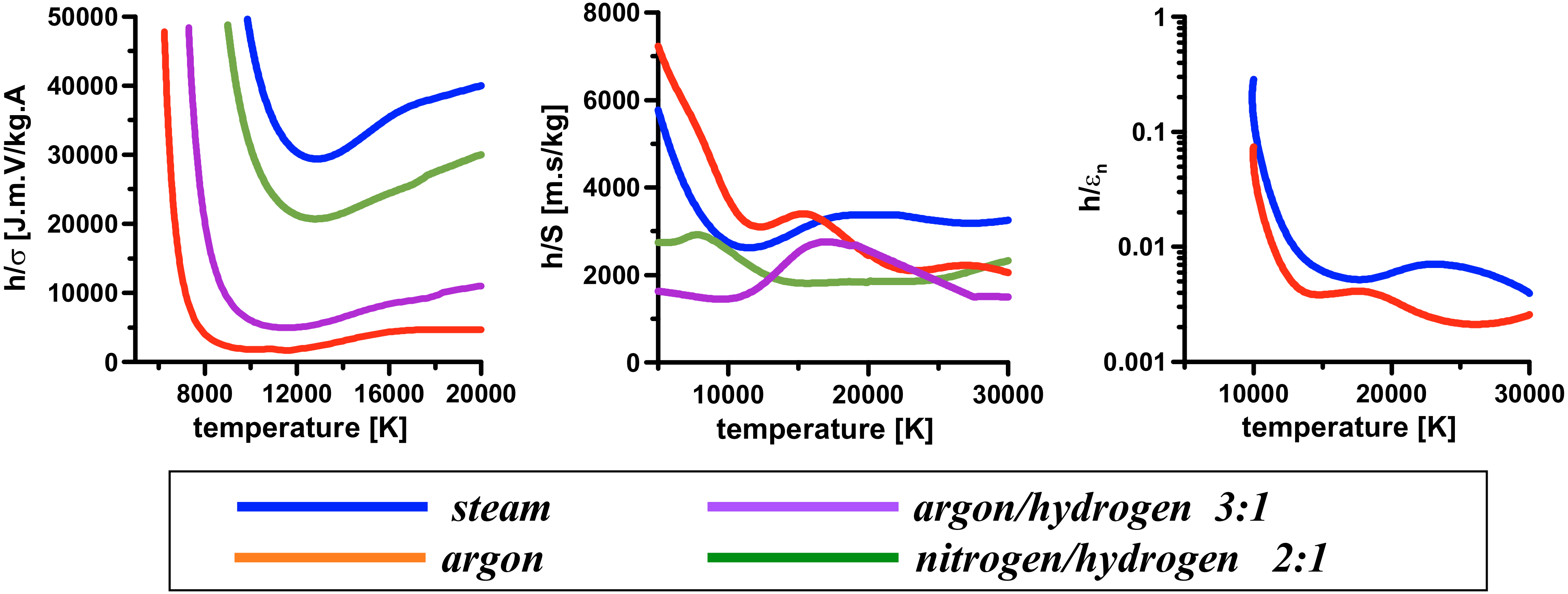
$$\mathbf{P = I.U = I.\left(\frac{\theta_F \theta_\sigma}{\eta \theta_G} \frac{L.G}{\pi R^2} \frac{h}{\sigma} \right)^{\frac{1}{2}}}$$

Properties of plasma gases

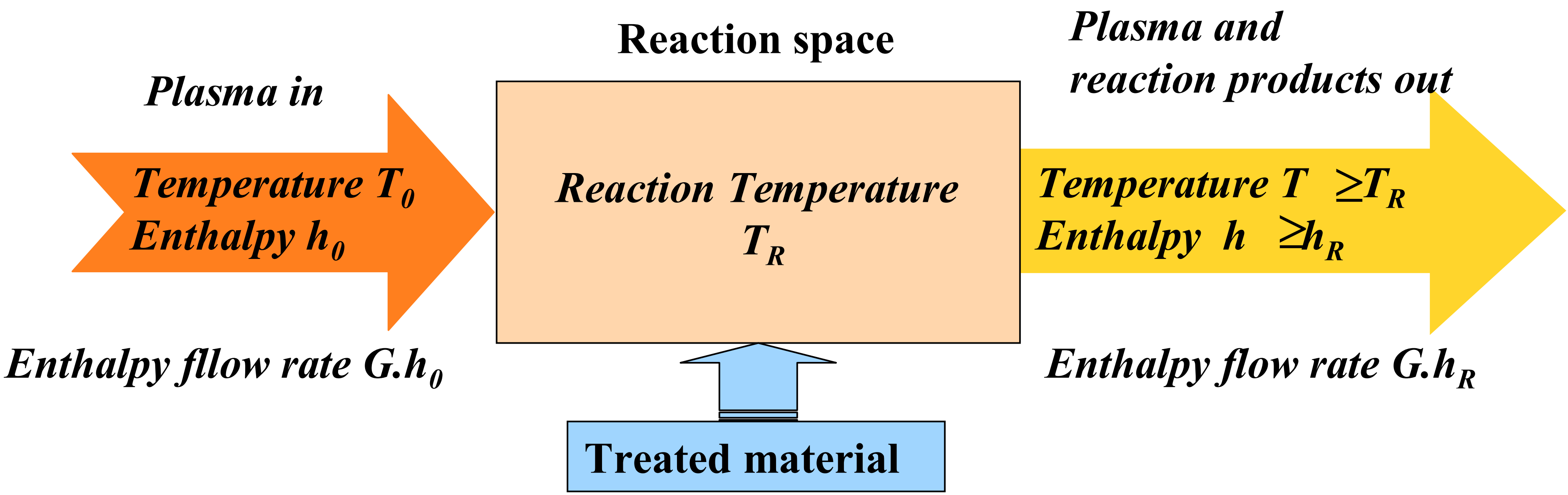
Torch operation parameters are determined by physical properties of plasma gas.
Decisive gas properties:

Power:
ratio between enthalpy and electrical conductivity

Efficiency:
Ratio between enthalpy and heat conductivity
Ratio between enthalpy and radiation emissivity



Efficiency of utilizing plasma enthalpy for processing



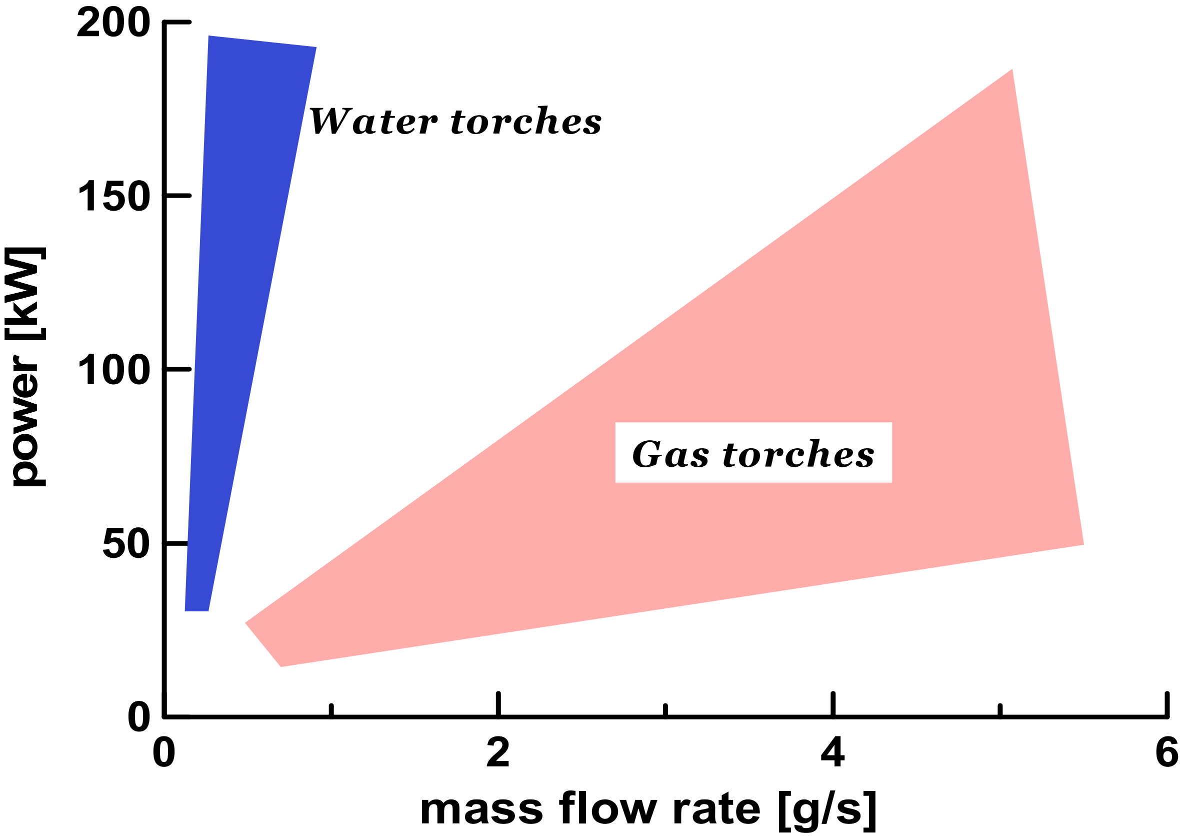
Only enthalpy $\Delta H = G.h_0 - G.h_R$ can be used for the treatment of material

Process efficiency:

$$\eta_R = \frac{G.(h_0 - h_R)}{G.h_0} = 1 - \frac{h_R}{h_0}$$

Operation regimes of gas-stabilized and water-stabilized dc arc torches

Operation regimes are expressed by the relation between arc power and mass flow rate



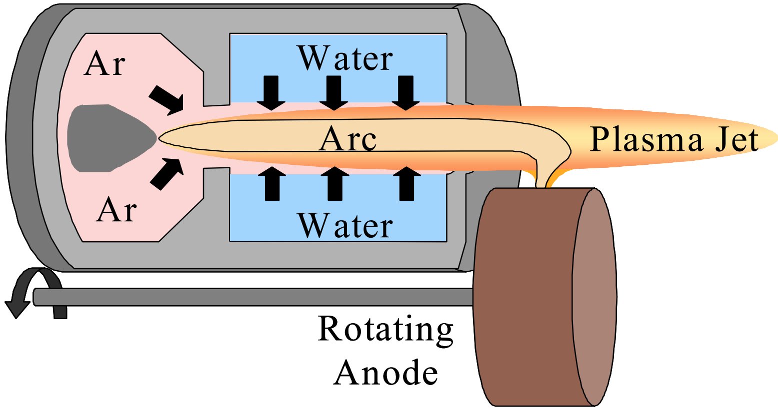
Mean plasma enthalpy:

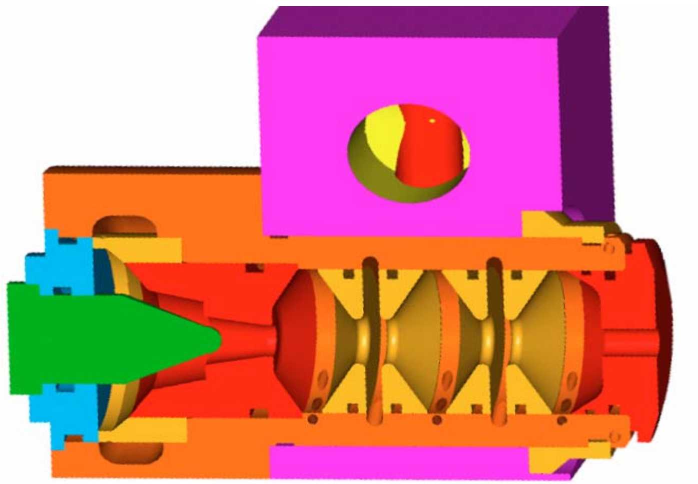
Gas torches:
10 – 40 MJ/kg

Water torches:
100 – 300 MJ/kg

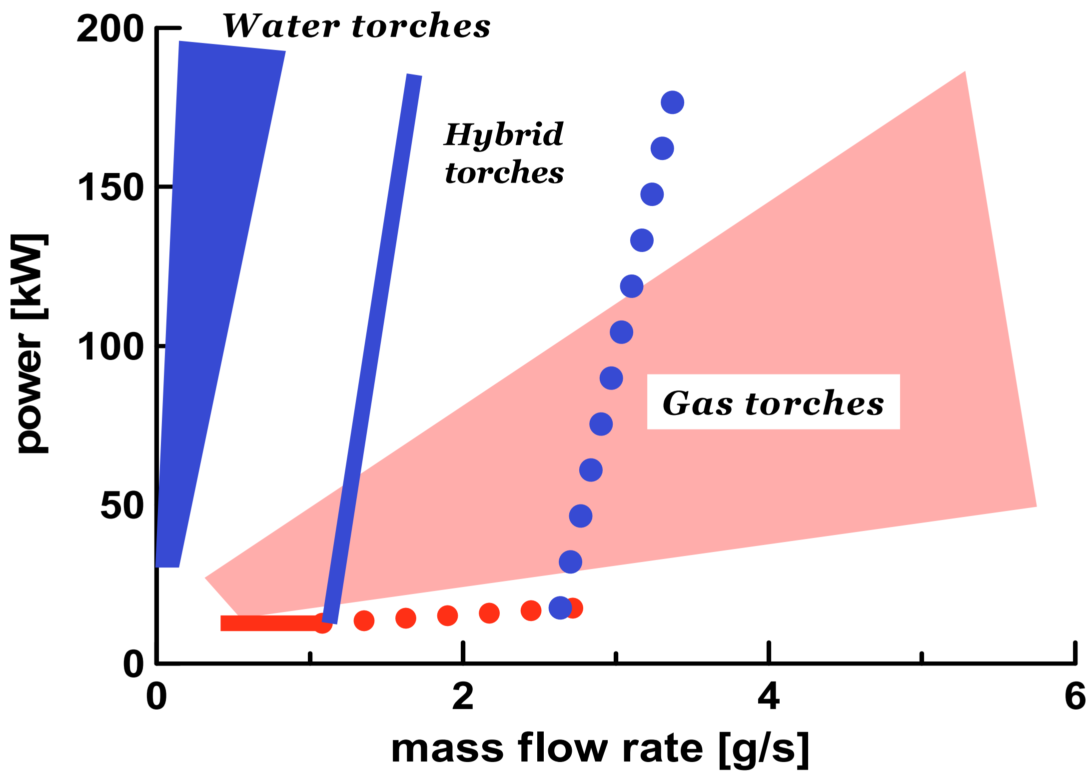
Hybrid gas/water dc arc plasma torch

Principle of hybrid gas/water plasma torch





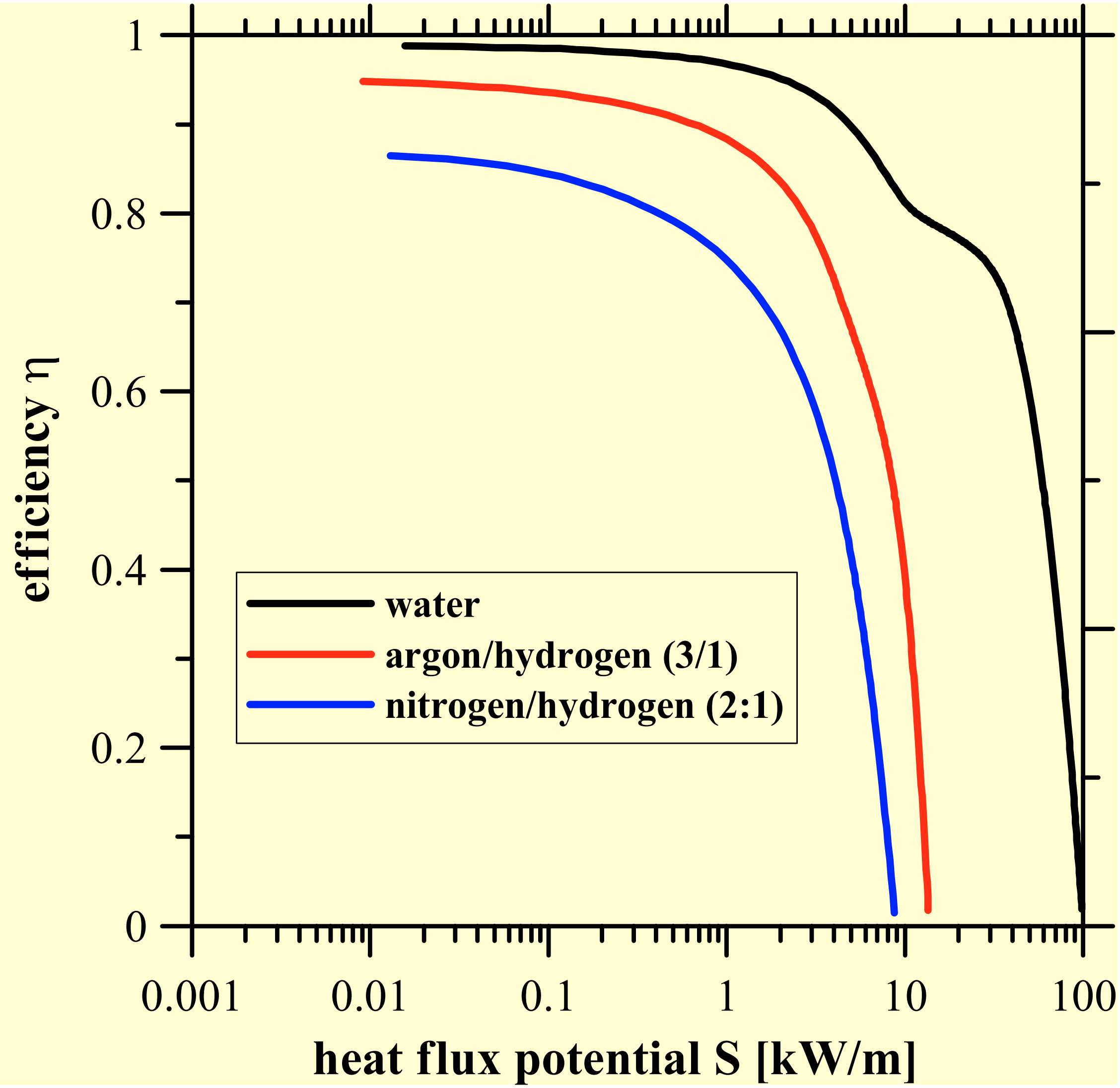
Operation regimes of dc arc plasma torches



Typical parameters of dc arc plasma spraying torches

Plasma gas	Current [A]	Power [kW]	G [g/s]	G/L [kg/s.m]	H_{bulk} [MJ/kg]	T_{bulk} [K]
N_2	700	180	40	8.0	3.6	3 000
N_2	300	115	32	6.4	2.9	2 500
Ar/H_2 (65/3)	500	44	1.93	0.15	15.3	10 800
N_2/H_2 (235/94)	500	200	5.0	0.10	24	6 200
Ar/H_2(33/10)	750	25	0.98	0.08	13.5	12 100
water	300	84	0.2	0.004	252	15 800
water	600	176	0.33	0.006	320	17 500

Thermal efficiency of water-stabilized and gas-stabilized torches



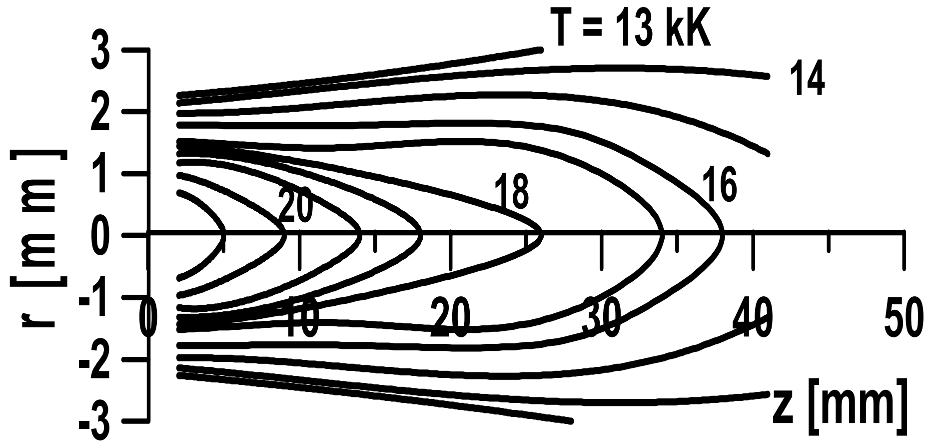
$$\eta = (P_{jet} - G.h_T)/\ P_{jet}$$

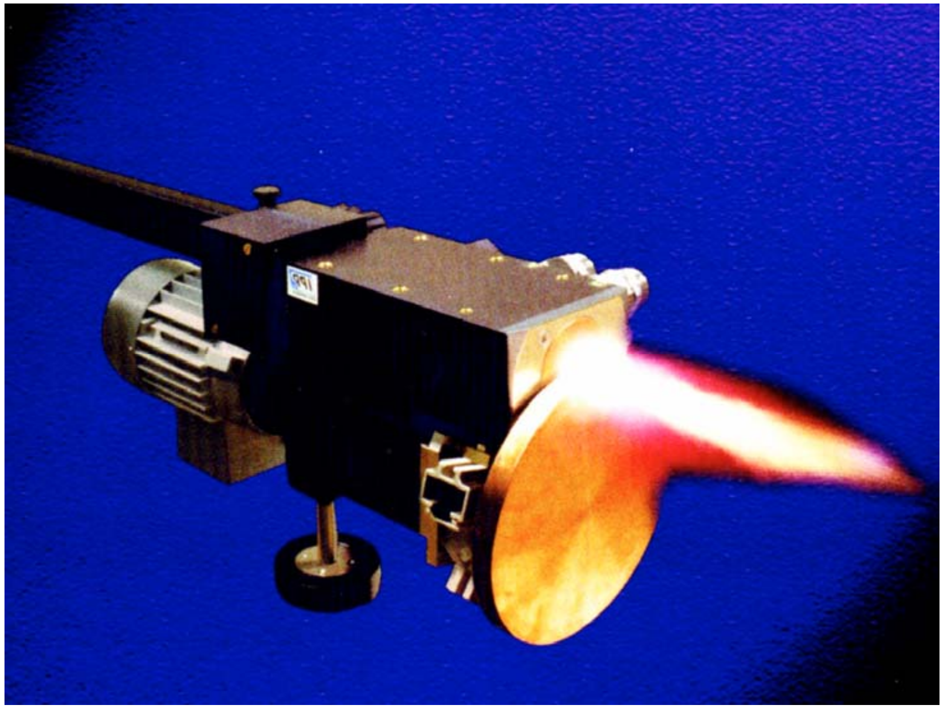
$$= (1 - h_T\ .\ G/P_{jet})$$

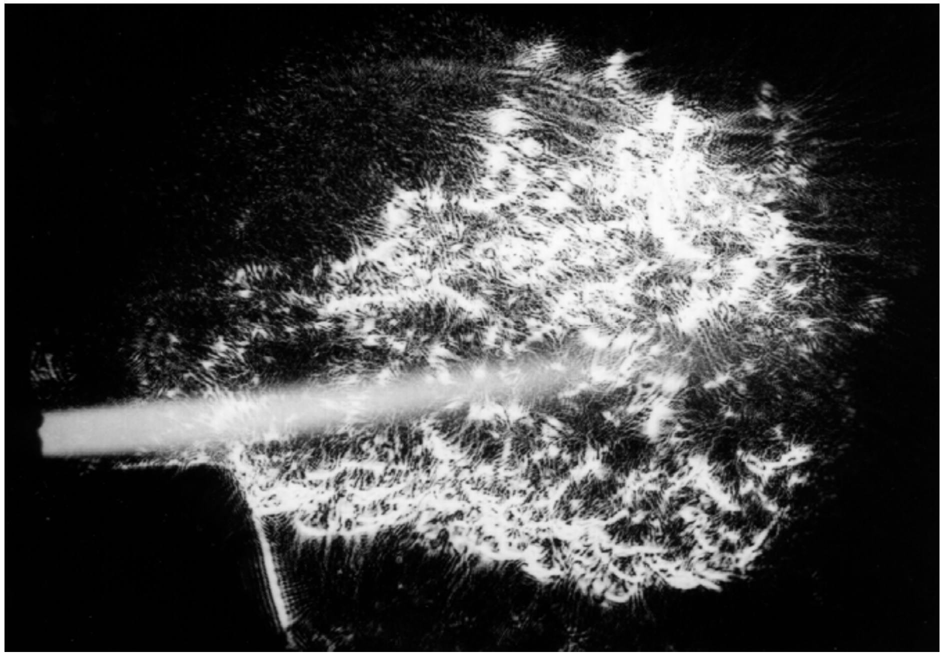
$$h_T = h(T)\ \ldots\ T\ \ldots S(T)$$

Thermal Plasma Jets

In most plasma generators gas (water) is supplied into the discharge chamber and plasma jet is produced at the exit nozzle





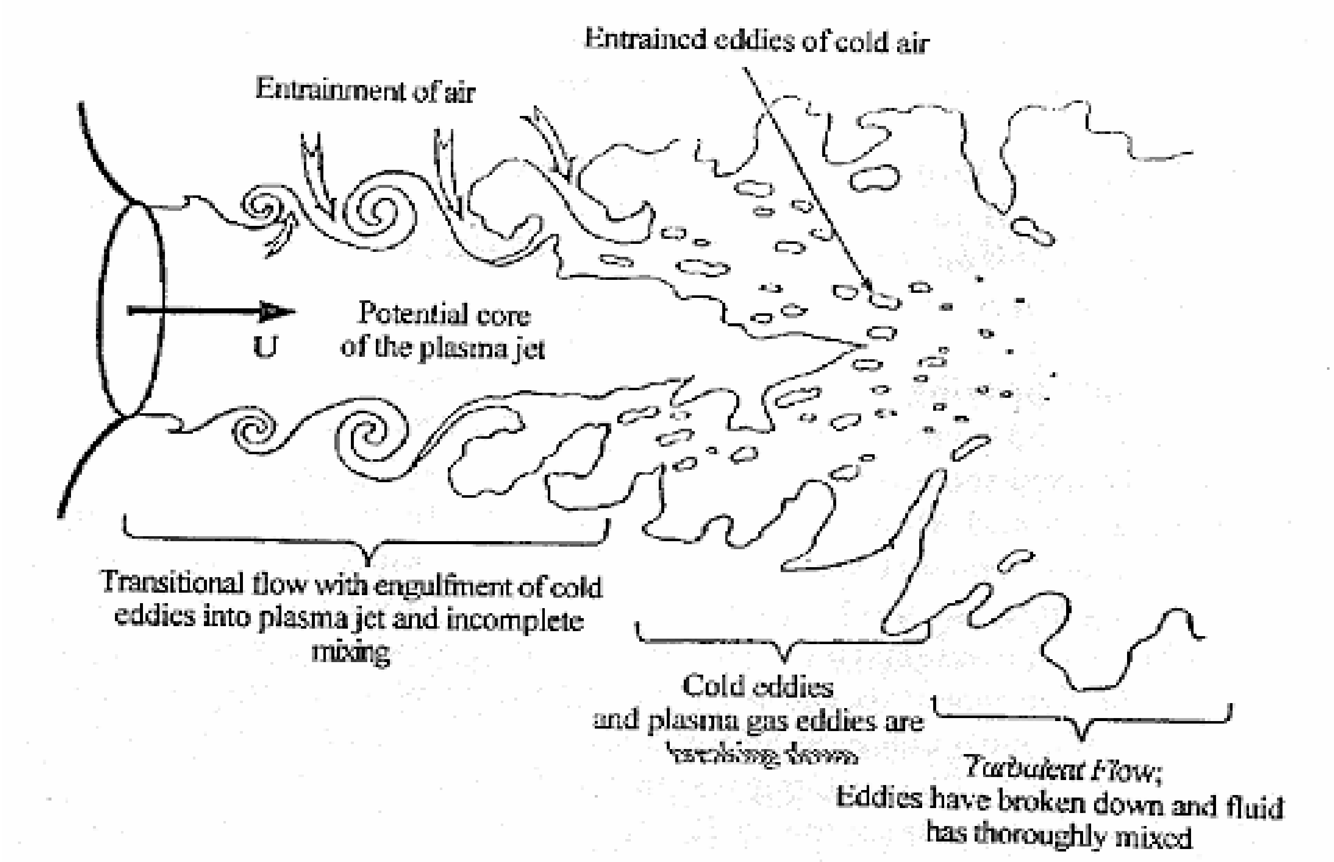


Plasma Jet Instabilities

- **Gas dynamic instabilities:**
  - **Fluctuations and turbulences in the arc chamber**
  - **Interaction of plasma jet with ambient gas outside the arc chamber**
- **Arc instabilities:**
  - **Fluctuations of arc power due to ripple of rectifiered arc current**
  - **Arc column instabilities, changes of arc length**
  - **Instabilities caused by electrode processes**

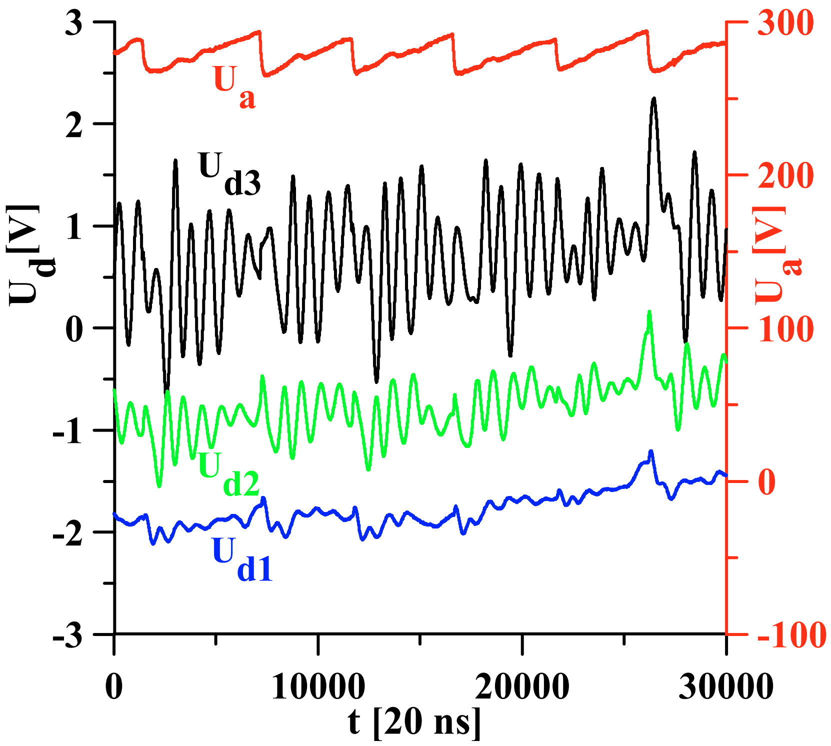
Plasma jet interaction with ambient gas

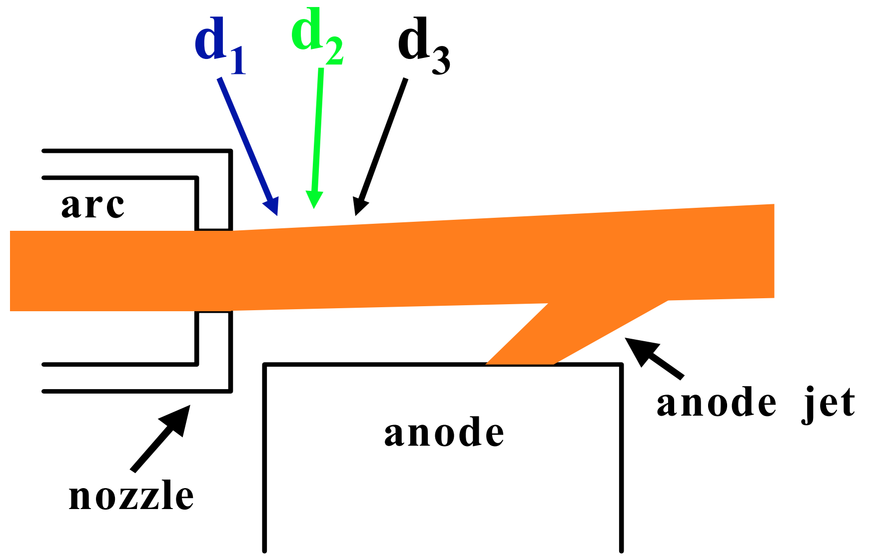
Production of vortex structures at the jet boundary
Entrainment of cold gas into plasma flow
Formation of plasma flow turbulence



Development of gas-dynamic instability and effect of anode attachment

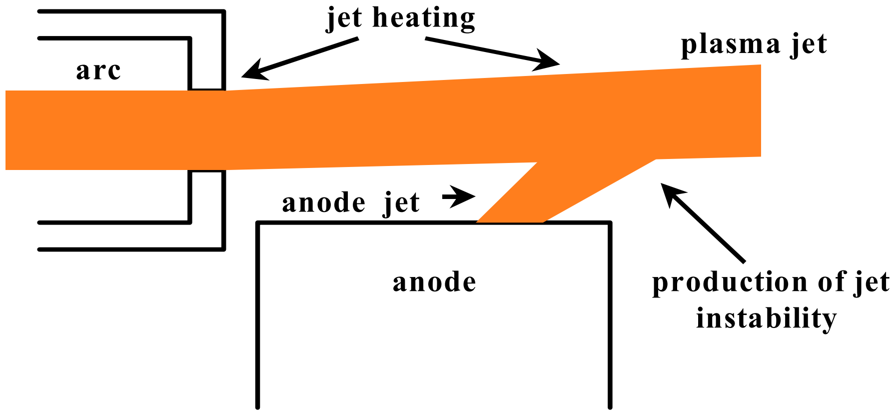
Arc voltage and light fluctuations at various axial positions.



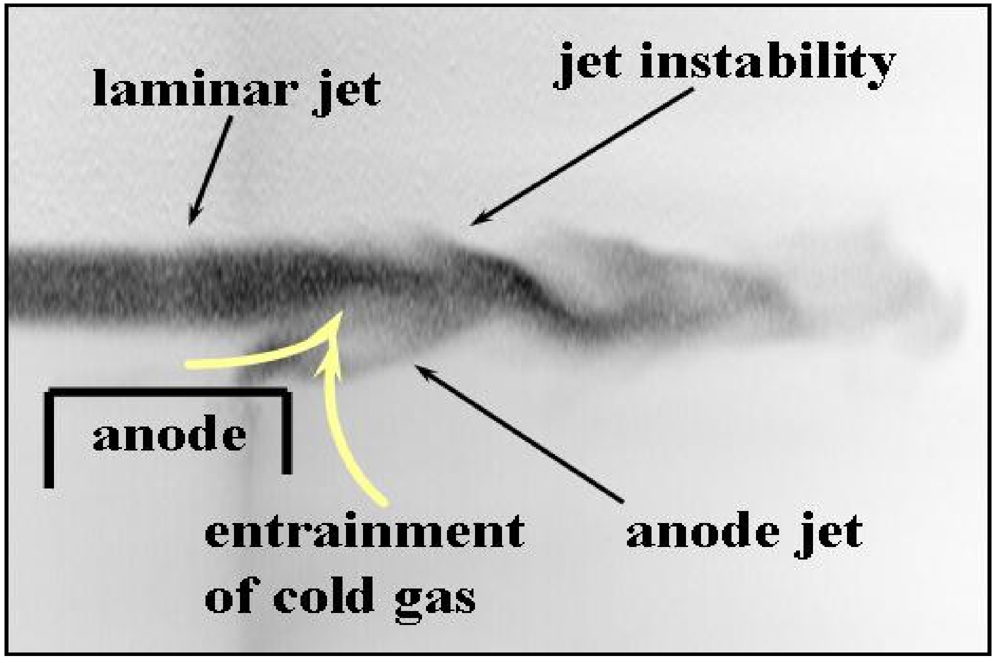


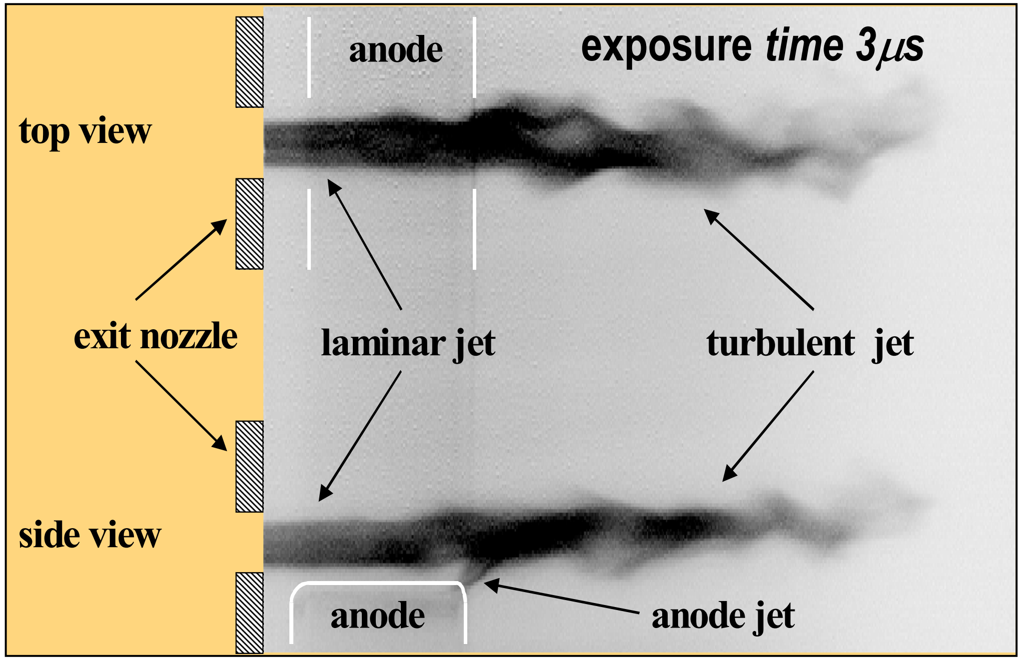
Positions of diodes: $z_{d1} = 2.4$ mm
$z_{d2} = 4.3$ mm
$z_{d3} = 6.2$ mm

Jet instability caused by anode attachment



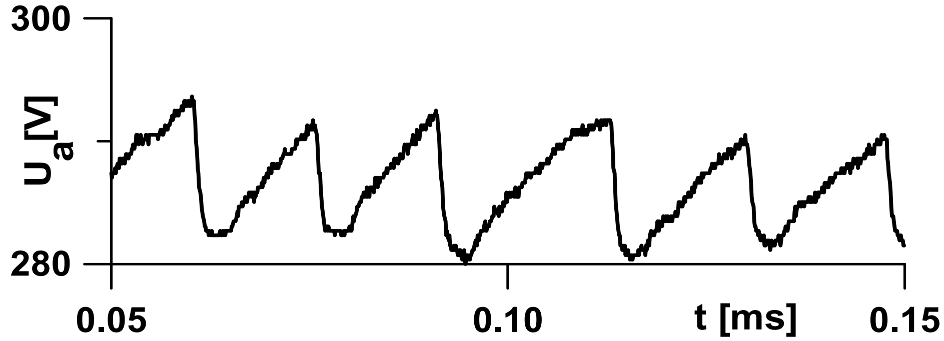
Arc anode attachment:
-anode jet
-movement in the restrike mode



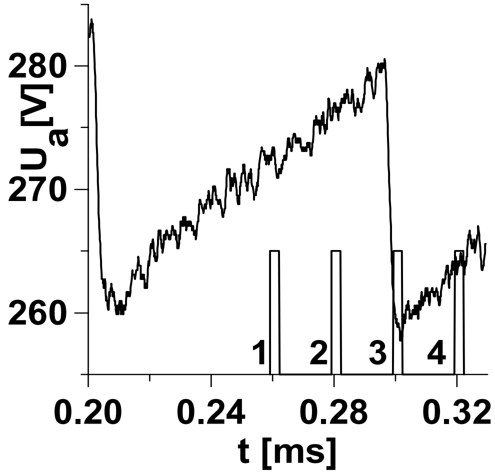


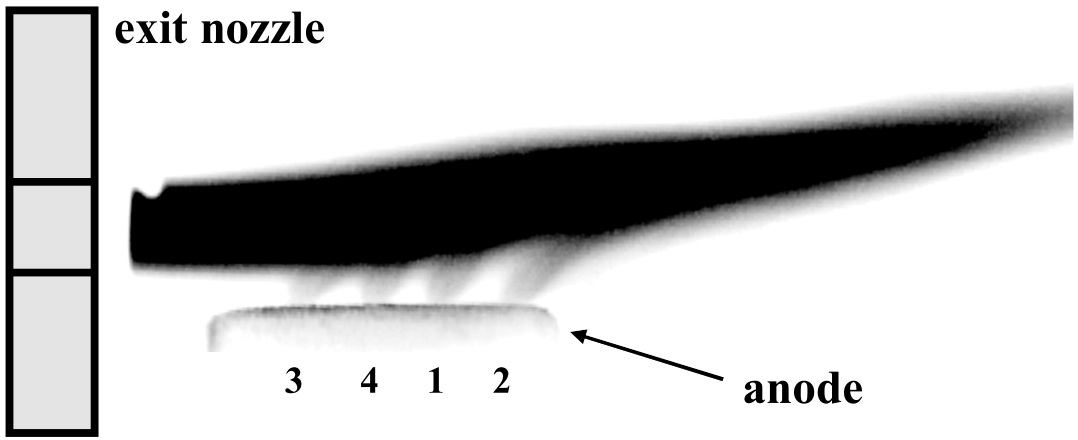
Anode restrike and movement of anode attachment

Fluctuations of arc voltage → **Fluctuations of arc power**

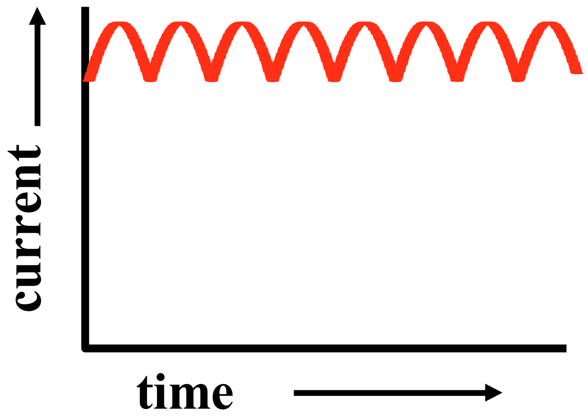


Sequence of four images of anode region of plasma jet





Effect of fluctuations of arc current



For classical 6-way rectifiers:
$\Delta I/I = 0.1 - 0.15$
Frequency : 300 Hz

Time constant of current changes $\tau_I = \left(\frac{1}{I}\frac{dI}{dt}\right)^{-1}$

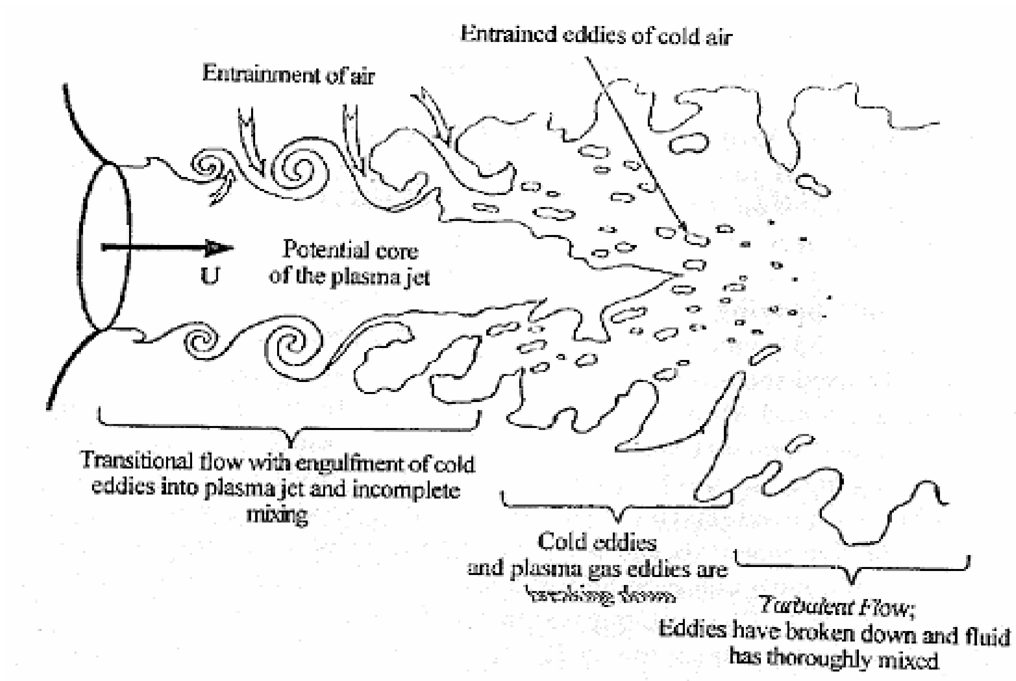
Arc time constant $\tau_a = \left(\frac{1}{g}\frac{dg}{dt}\right)^{-1}$ **~ $10^{-4} - 10^{-2}$ s**

Amplitude of fluctuations of arc power depends on relation between τ_I and τ_α

1. $\tau_I << \tau_a$ **Arc has constant conductance:** $U = U + R_s \cdot \Delta I$
   Amplitude of fluctuations of arc power: $\Delta P/P = 2\,\Delta I/I + (\Delta I/I)^2$
   For $\Delta I/I = 0.1 - 0.15$ ………. $\Delta P/P = 0.21 - 0.32$

2. $\tau_I >> \tau_a$ **Arc voltage follows static characteristic:**
   Constant arc voltage : $\Delta P/P = \Delta I/I$
   Falling static arc characteristic: $\Delta P/P < \Delta I/I$

Diagnostics of thermal plasma jets



Plasma jet core:
- **High gradients of temperature and velocity**
- **Laminar flow**

Turbulent jet:
- **Smooth T and v profiles**
- **Heterogeneous mixture of plasma and cold gas**

Time averaged characteristics:
- ***Temperature profilers***
- ***Velocity profiles***
- ***Plasma compositon***

Fluctuations:
- ***Spatial distribution***
- ***Frequency spectra***
- ***Phase velocity of oscillations***

Shape of the jet
Jet structure

Emission spectroscopy

Basic plasma characteristics evaluated from measurements:

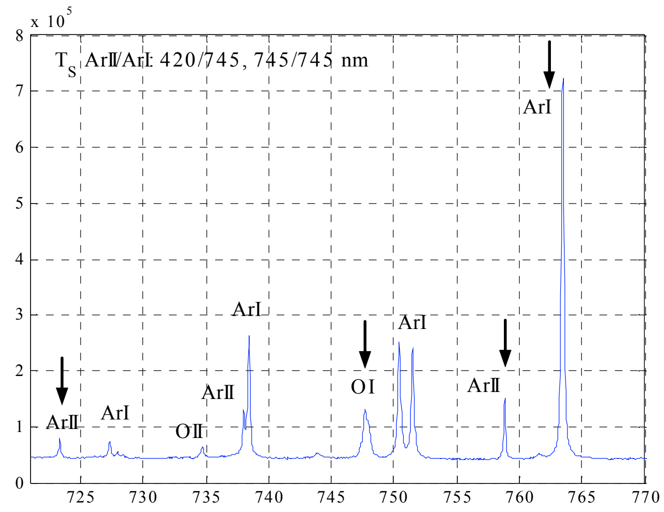
- ***Electron number density***
- ***Temperature***
- ***Molar concentrations of components***

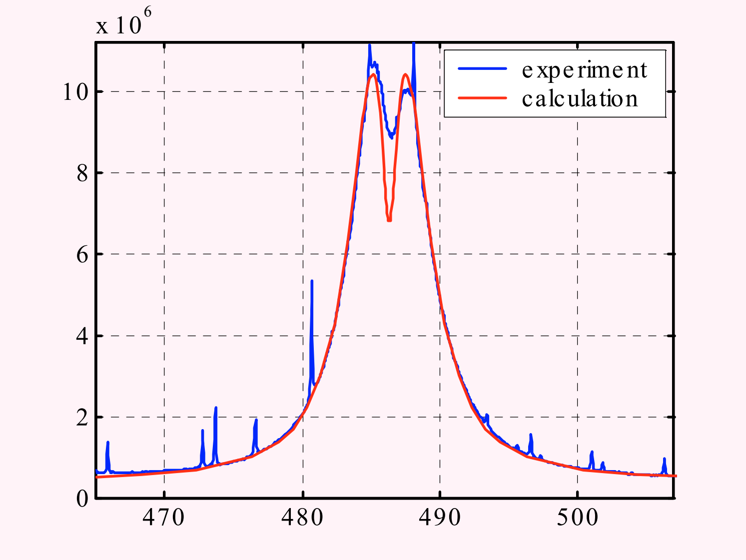
Basic methods:

- **Absolute intensities of spectral lines**
- **Line intensity ratios**
- **Stark Broadening**

Problems:

- **Non LTE conditions**
- **High gradients of temperature**
  electron diffusion
  de- mixing of plasma gases
- **Non symmetrical cross section of the jet**

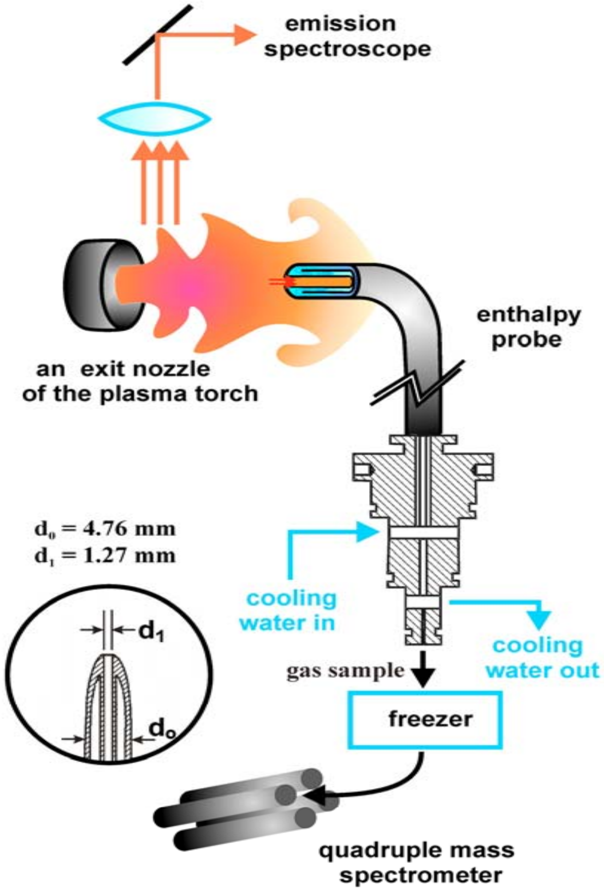




Enthalpy probe

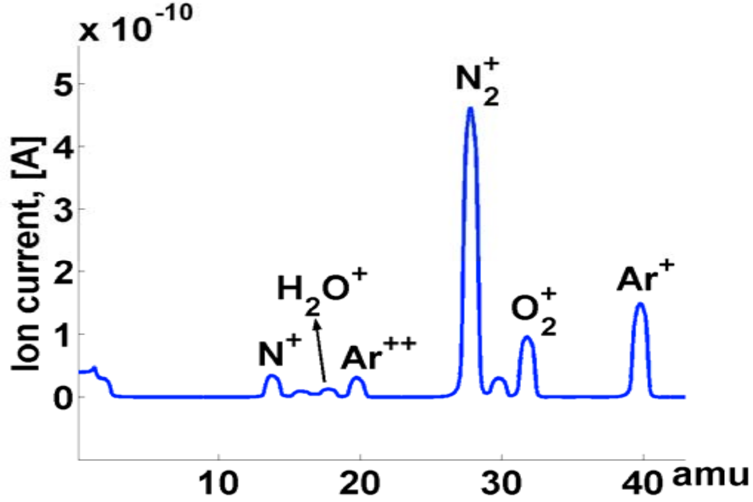
Isokinetic coefficient

$$K_{iso} = G / \pi R^2 \rho_p v_p$$



Measurements:

1. *Tare – no plasma flow*
   Q – Heat flow rate
   P – Pressure
2. *Sampling – plasma flows into the probe*
   Q – Heat flow rate
   G – plasma flow rate
3. *Mass spectrum*



Evaluation of plasma jet characteristics from enthalpy probe measurements

Plasma enthalpy:

$$h_0 = \frac{Q_{sample} - Q_{tare}}{G_g} + C_{pg} T_g$$

Plasma composition

Plasma temperature
Thermodynamic and transport coefficients

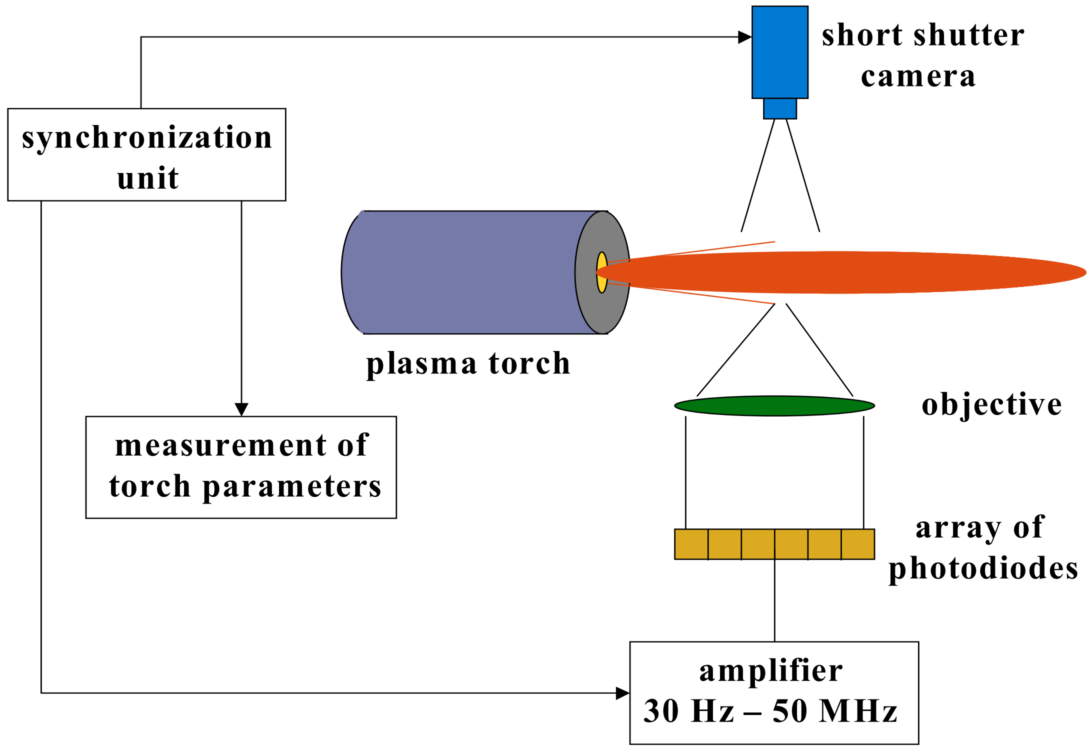
Local plasma velocity

$$V = \sqrt{\frac{2(P_s - P_a)}{\rho(T)}}$$

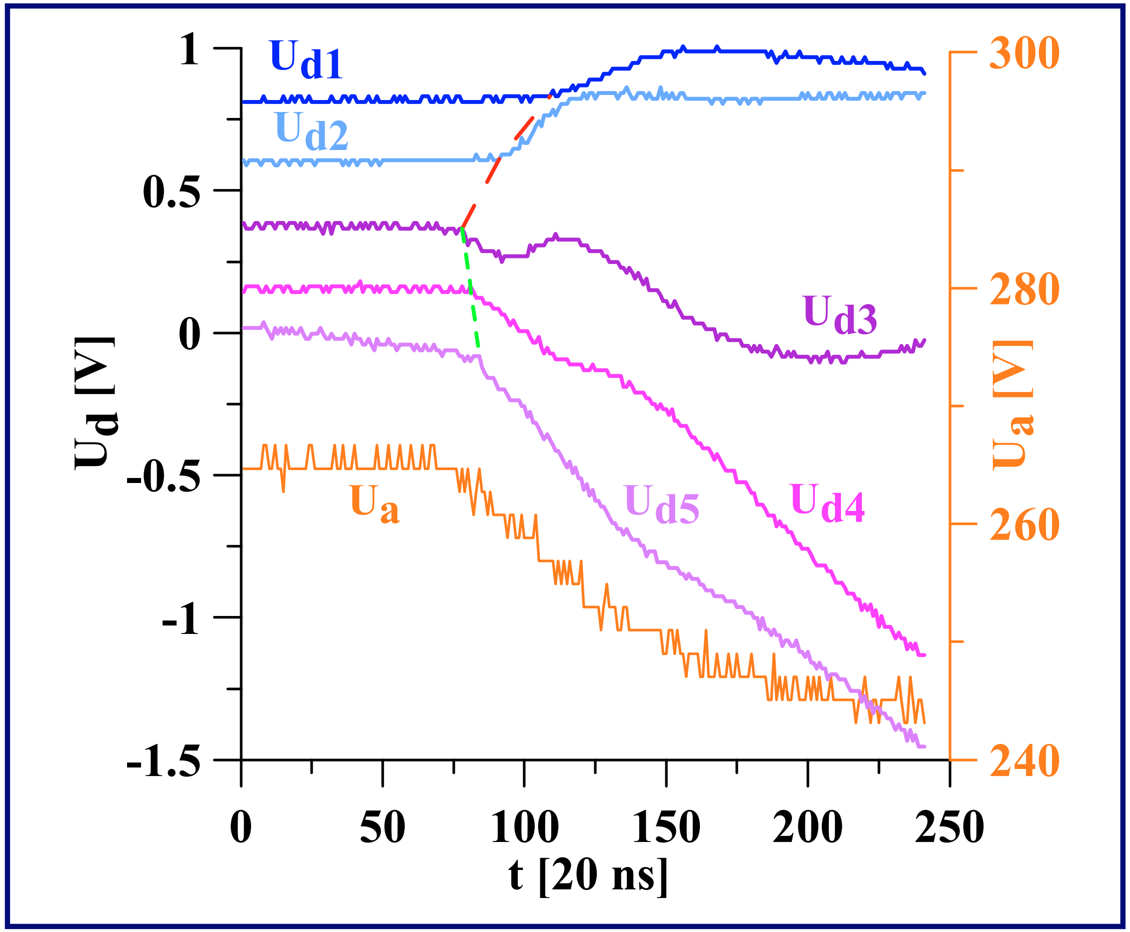
Measurement of flow velocity

Enthalpy probe - Pitot tube
Time of flight of fluctuations - emitted light
- electric probe current
Propagation of waves in plasma

Diagnostics of jet fluctuations and instabilities



Determination of flow velocity from propagation of disturbance caused by an anode restrike



Anode restrike in the position d3

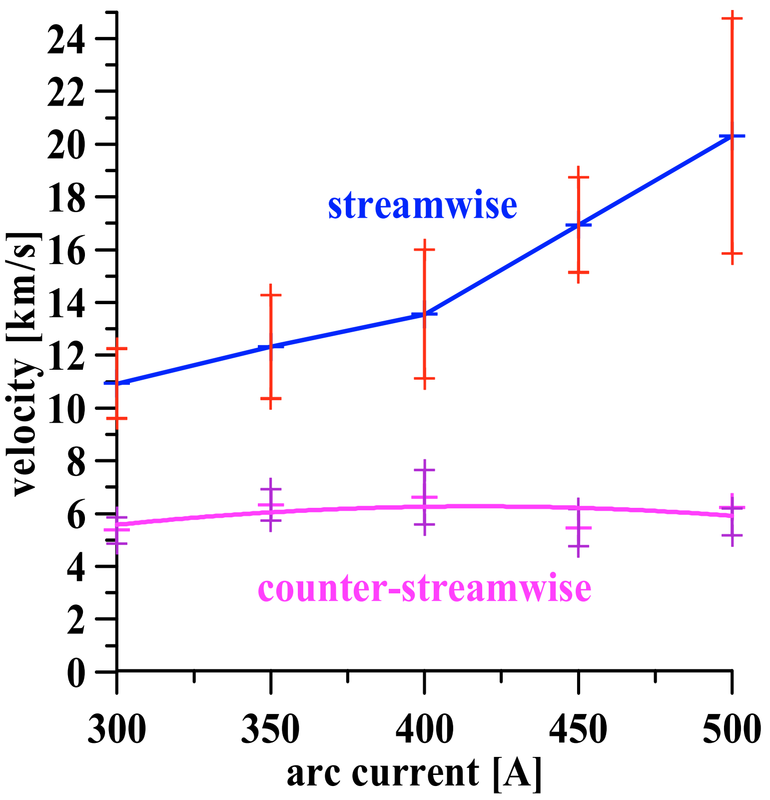
Ua - Arc voltage

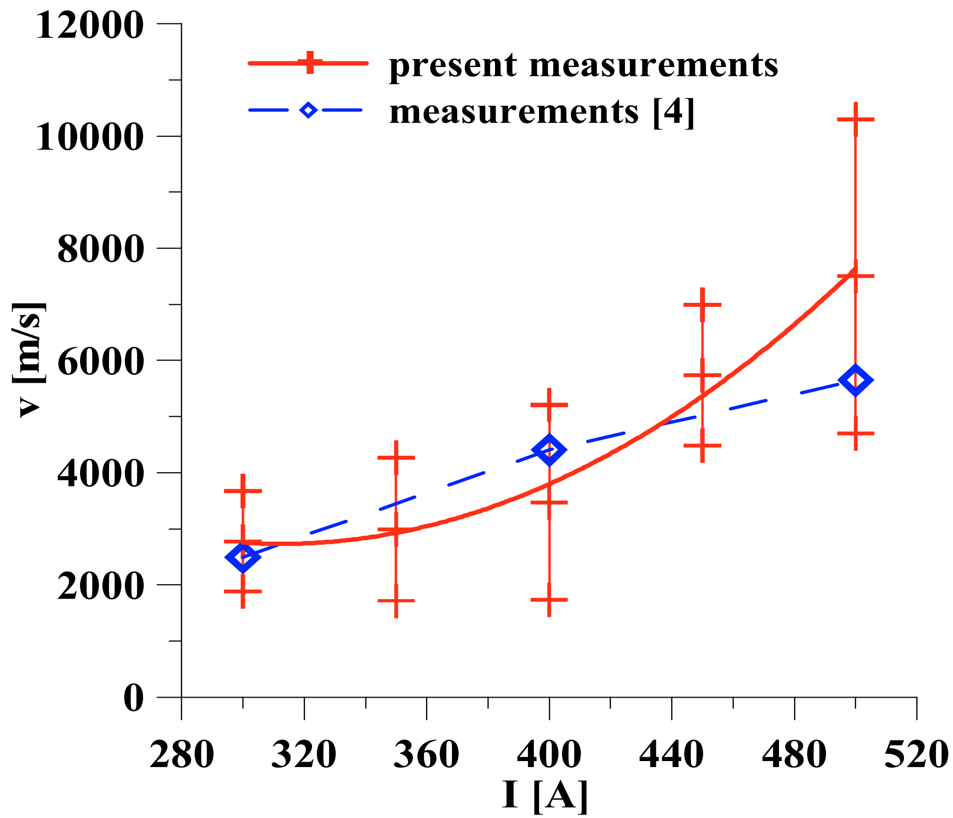
Signals of photodiodes:

d1 = 1 mm (z/D = 0.167)
d2 = 4.3 mm (z/D = 0.717)
d3 = 7.7 mm (z/D = 1.28)
d4 = 11 mm (z/D = 1.83)
d5 = 14.3 mm (z/D = 2.38)

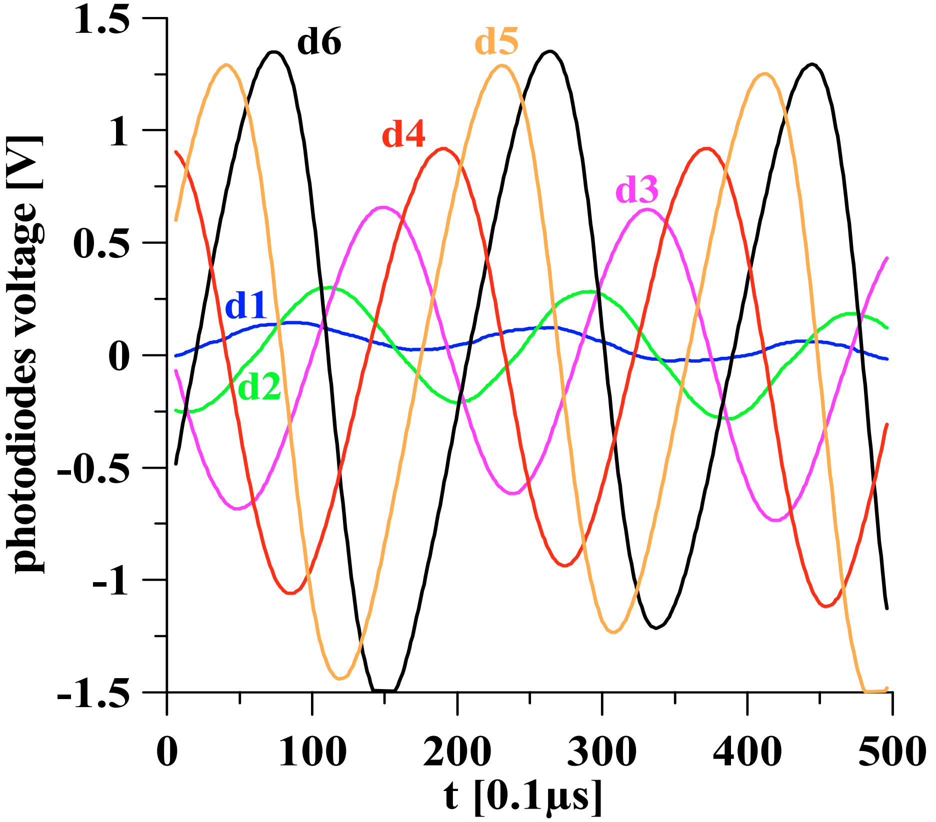
Determination of flow velocity

Stream-wise and counter-stream-wise velocities of perturbations caused by a formation of new anode spot and flow velocity evaluated as their difference





Determination of flow velocity from phase shift of jet fluctuations



Fluctuations of emitted light at various distances from the torch exit

D - Distance between points

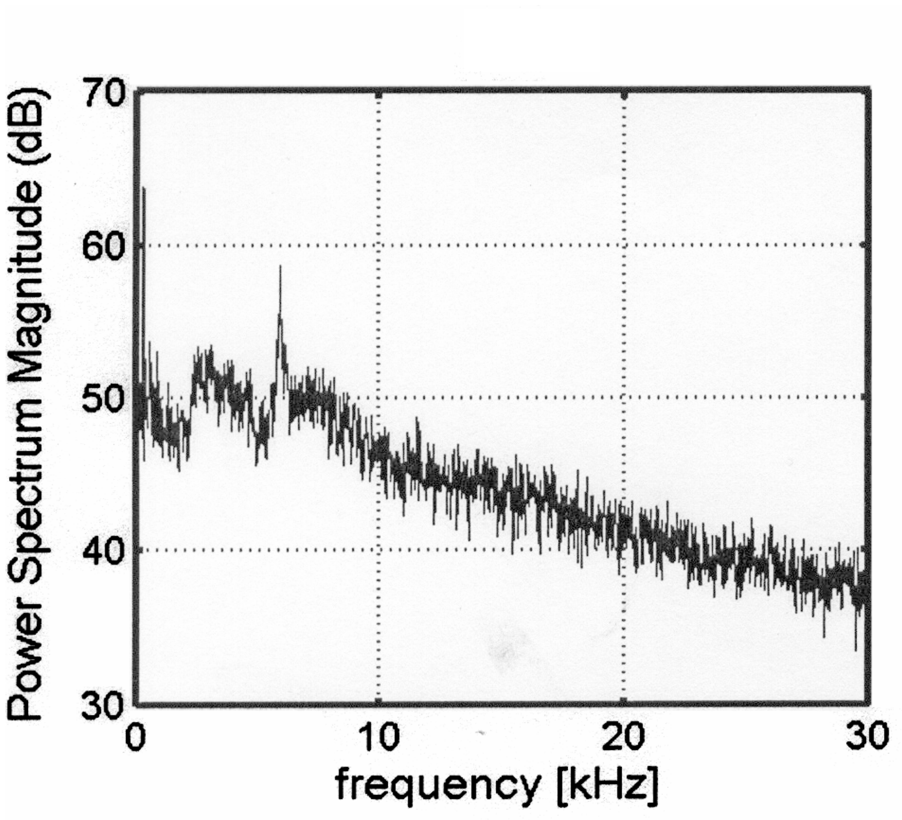
$\Delta\Phi$ - Phase shift

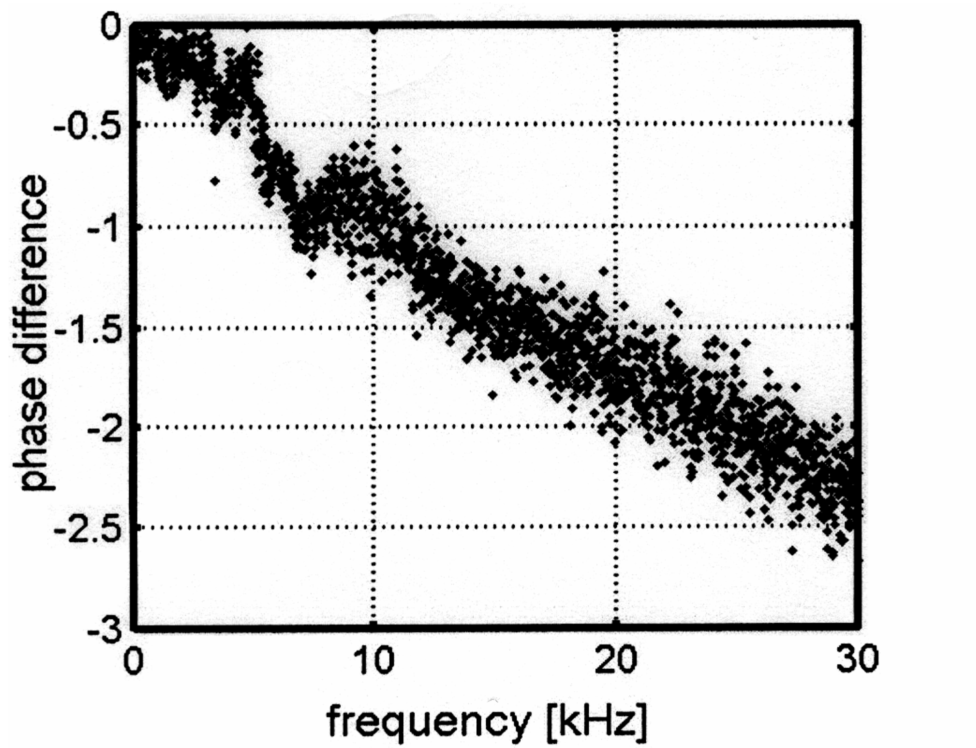
Velocity of movement of oscillations

$$v = 2\pi D \frac{f}{\Delta\Phi}$$

Determination of flow velocity

Fourier spectrum and dependence of phase shift of oscillations on frequency – argon, 10 kW

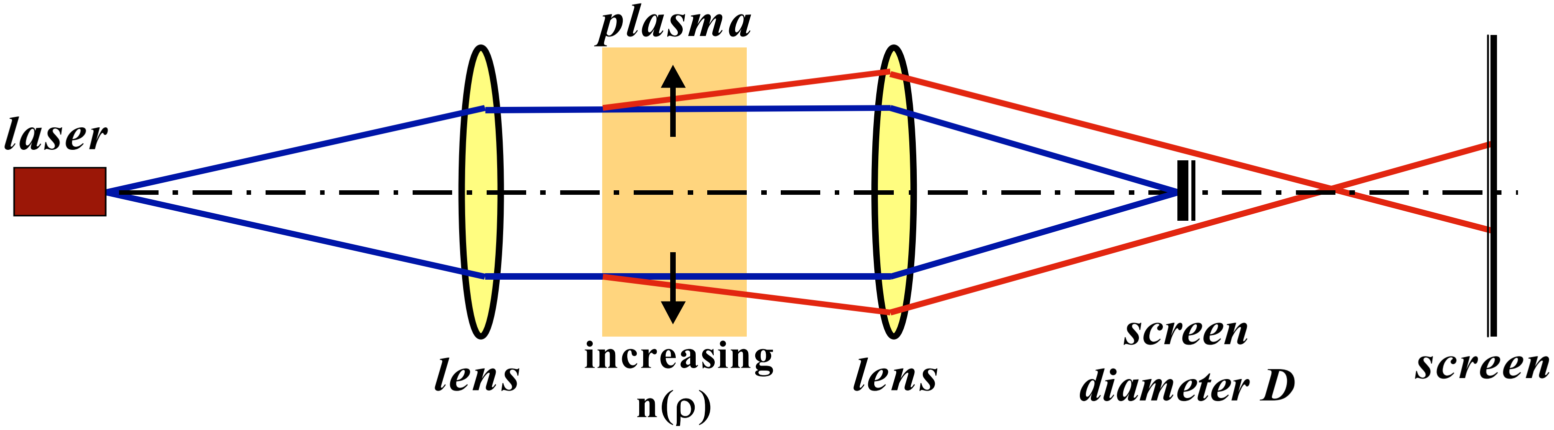




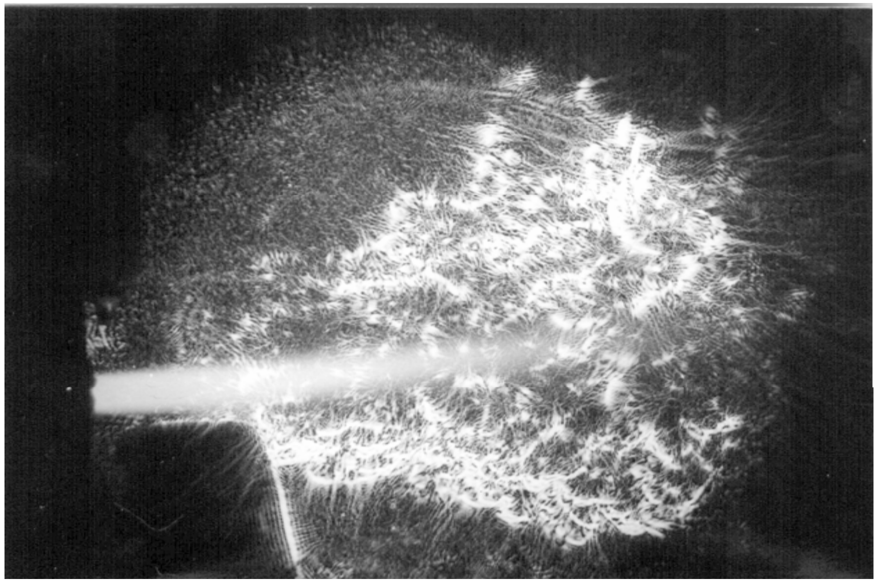
$$v = 2\pi D \frac{f}{\Delta\Phi} = 300\, m / s$$

F3 / 8

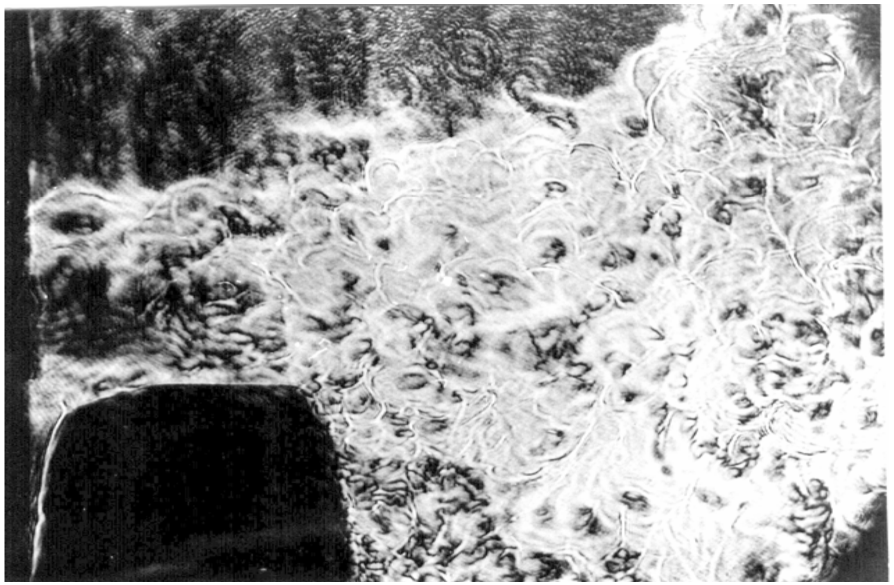
Schlieren photography



plasma jet produced in water stabilized arc



D = 5 mm

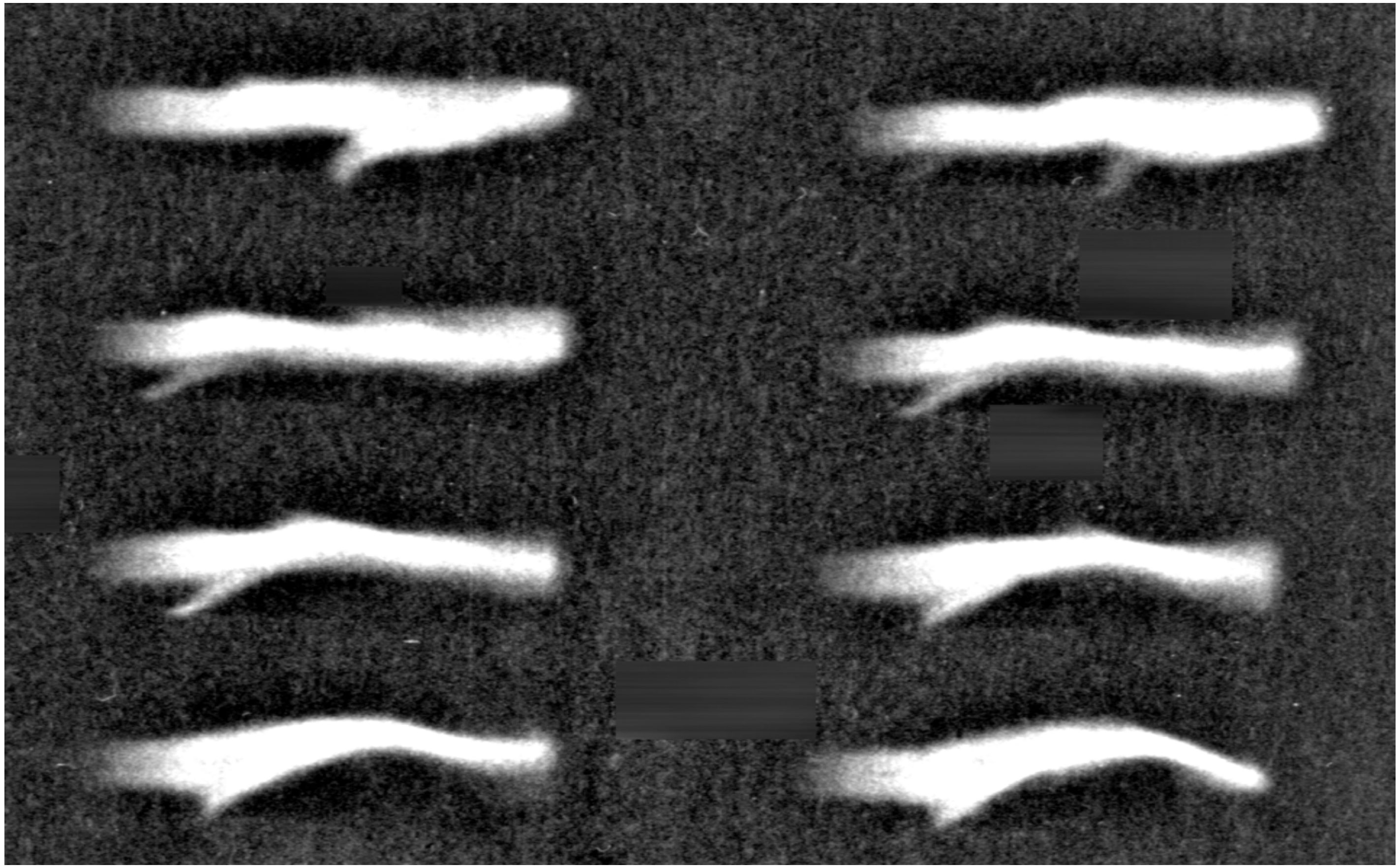


D = 1 mm

High speed photography

Interaction of plasma jet with arc anode attachment

t [μs]:



0 **5**

10 **15**

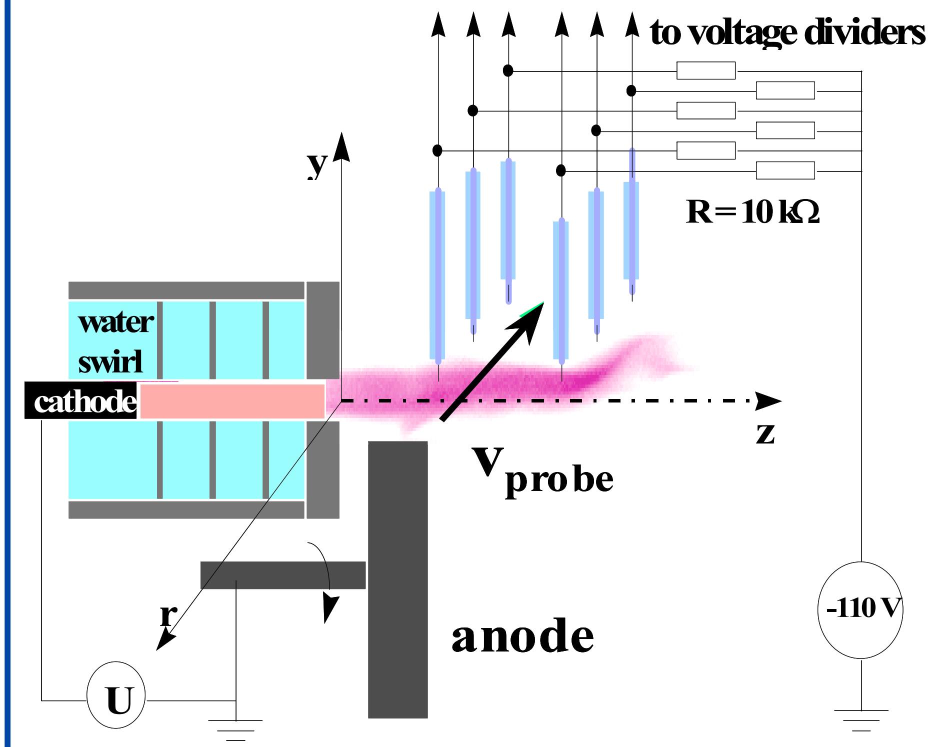
20 **25**

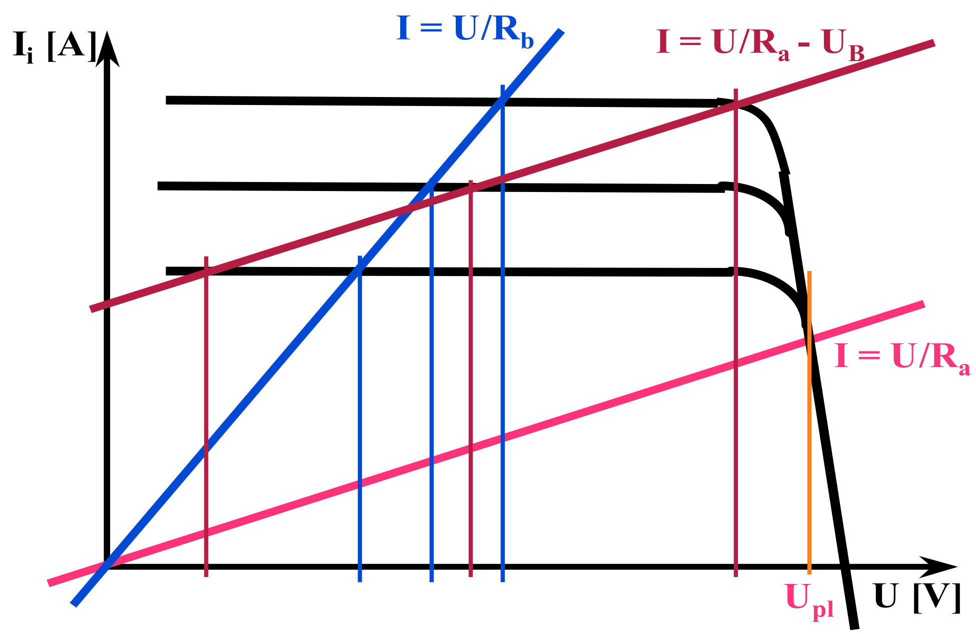
30 **35**

Electric probes in thermal plasma jets

Ion collecting electric probes are used for study of structure of plasma flow

High biasing resistance – probe potential close to floating potential
Low biasing resistance – probe current close to ion saturation current
Negative biasing voltage increases sensitivity of probe measurement

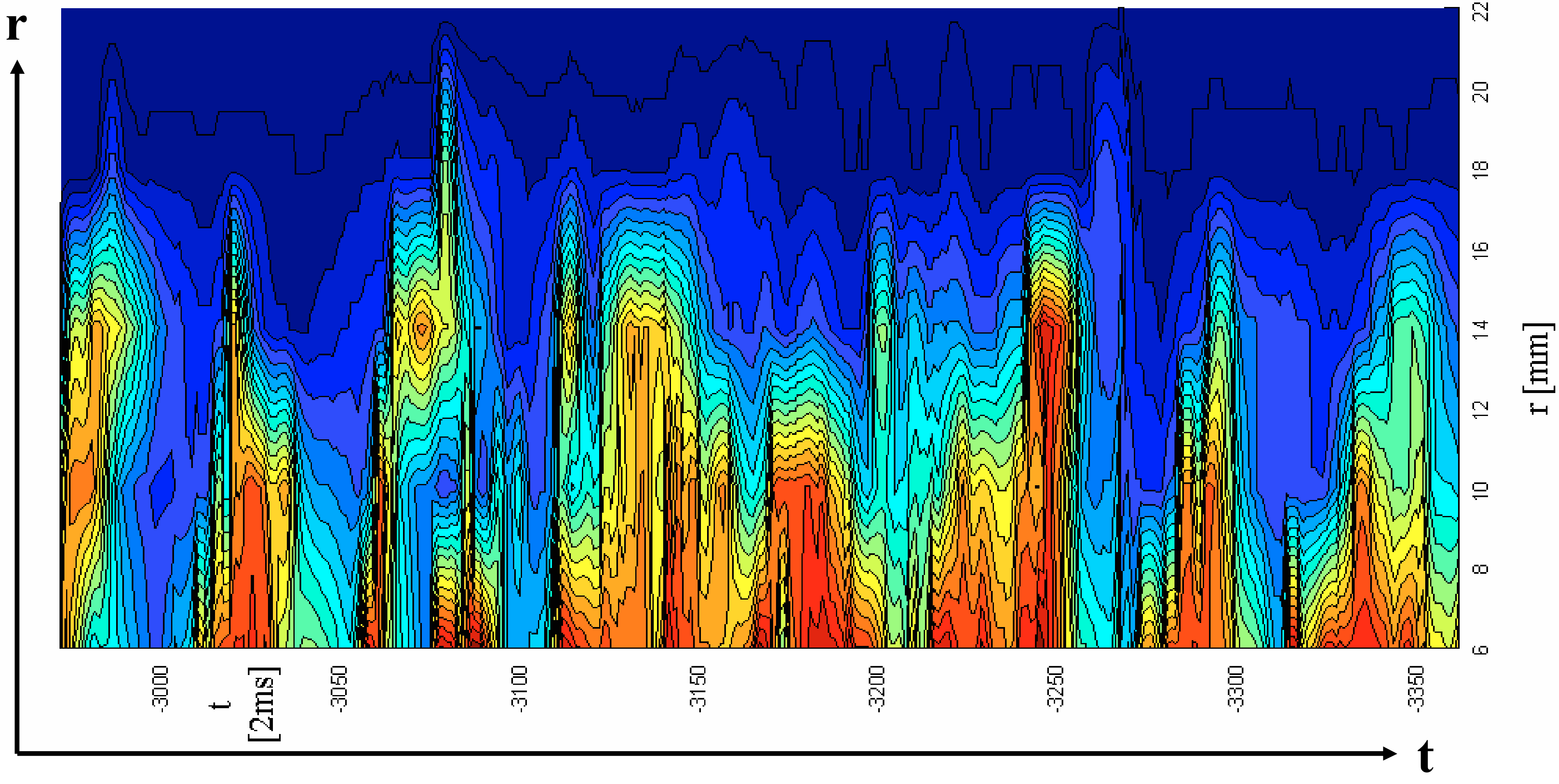




Determination of probe potential

Structure of the jet boundary

Lines of the same probe current at the plasma flow in the jet boundary



Thermal plasma processing

Plasma technologies and decisive mechanisms

Heat transfer

- ❑ Plasma melting
- ❑ Plasma cutting

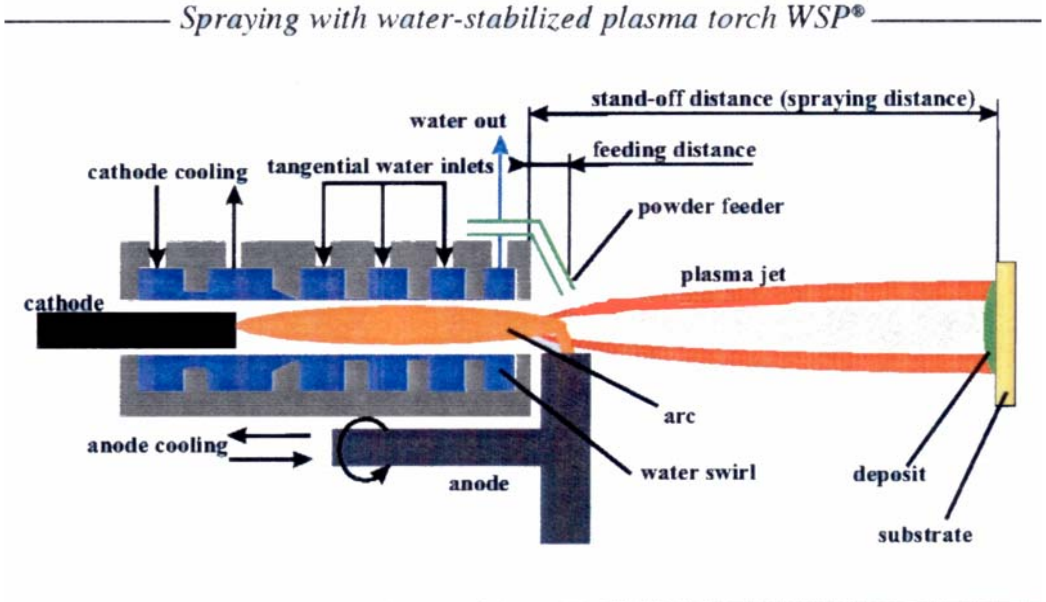
Heat and momentum transfer

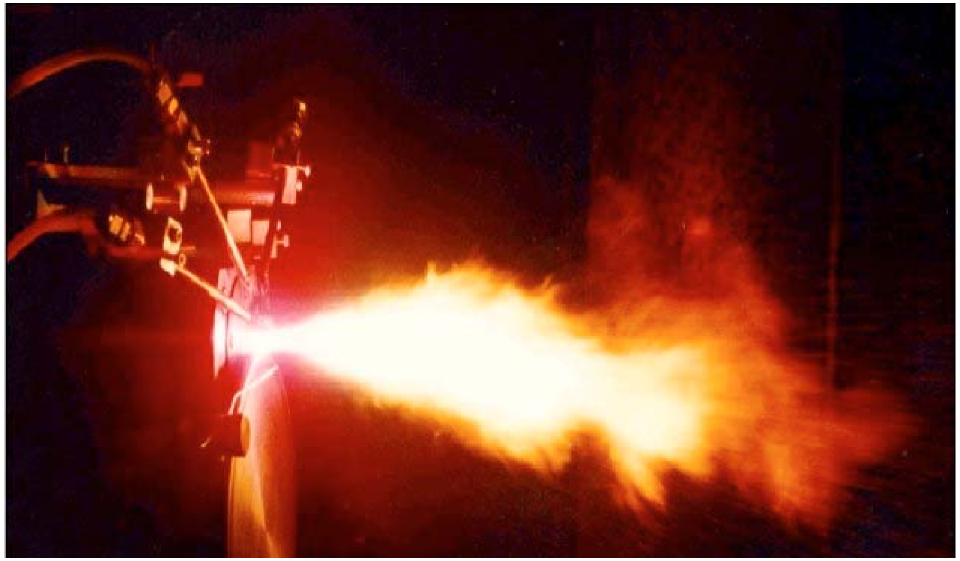
- ❑ Plasma spraying
- ❑ Surface modifications

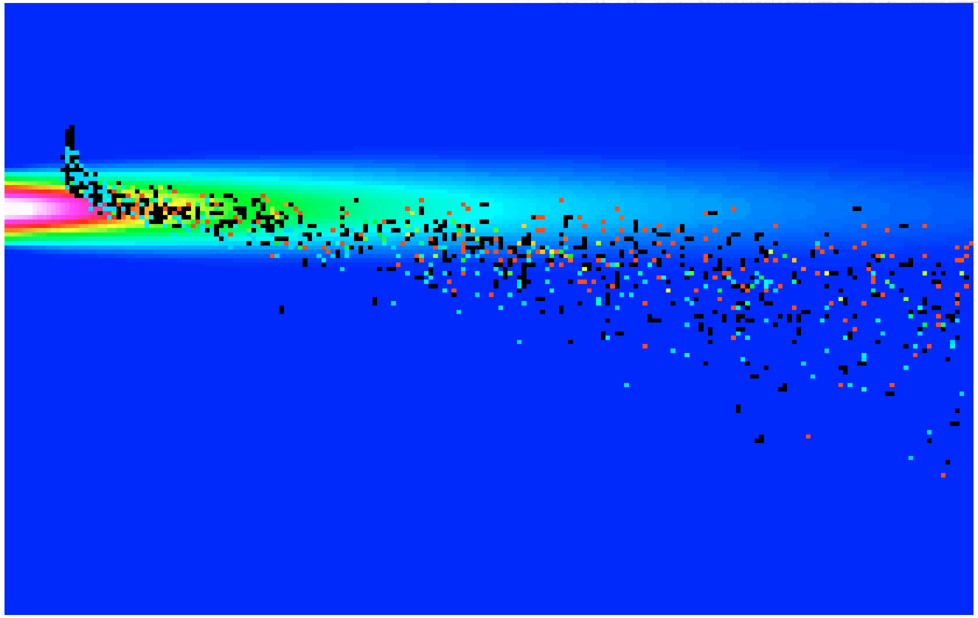
Chemical processes – decomposition and/or synthesis

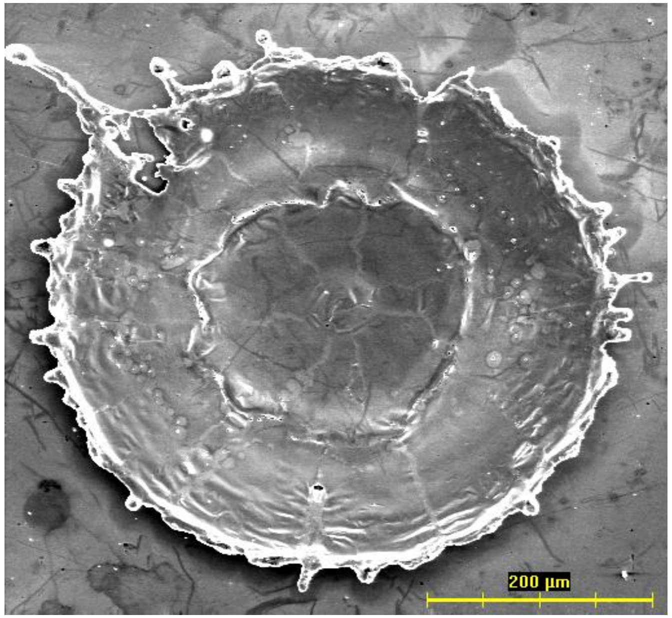
- ❑ Waste treatment, gasification, vitrification
- ❑ Plasma CVD – production of films
- ❑ Plasma synthesis

Plasma spraying

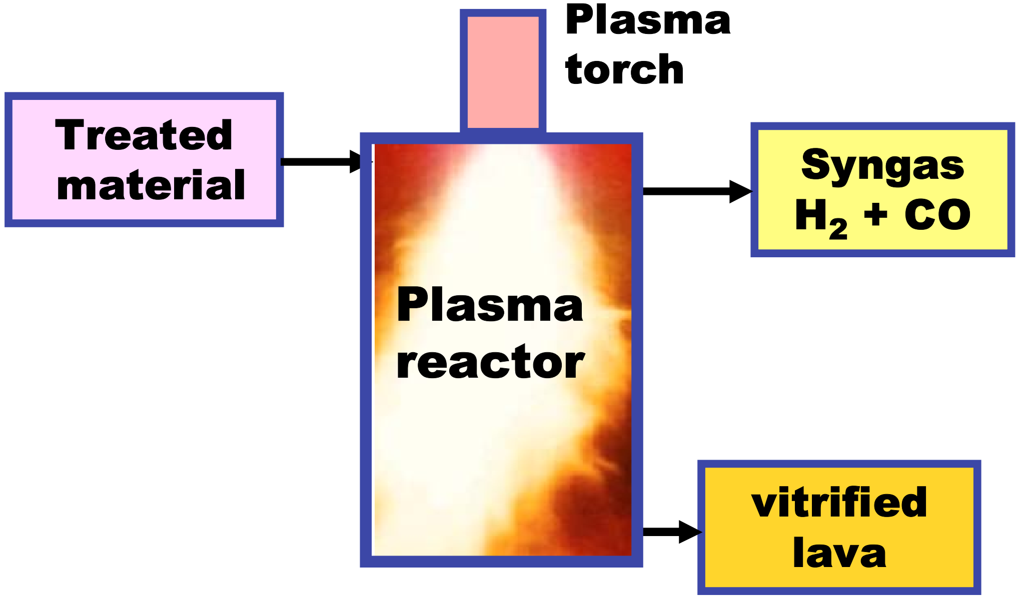




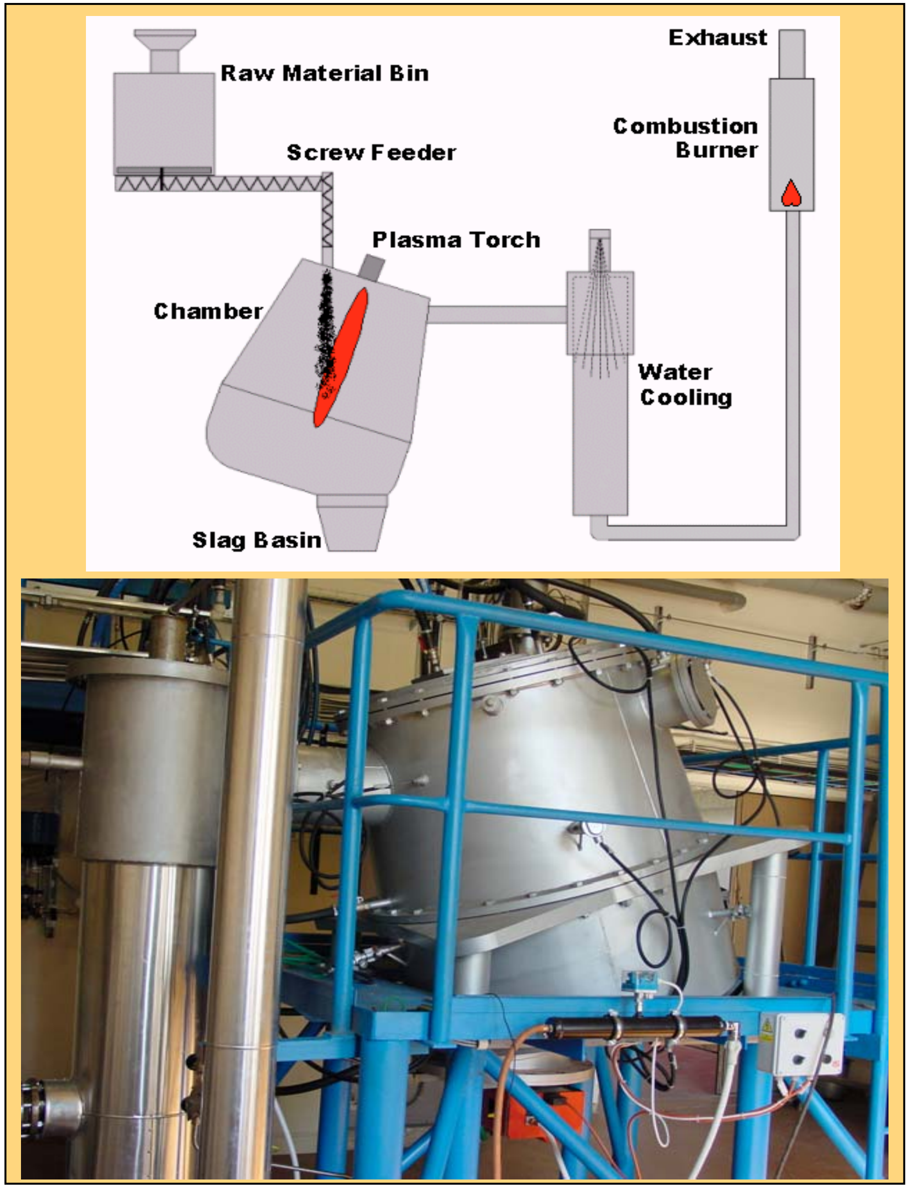




Decomposition of Persistent Chemical Compounds and Waste Treatment



Gasification
+
vitrification



Operating Experience – Commercial Project
Toxic Waste Destruction Project at Plasma Center, Madison, PA

- Project using Pyroplasma Trailer Commenced in 1986
- Destruction of Liquid Toxic Waste
- MARC-11H Torch
  - 1 active, 1 spare
- Nominal Power:
  - Total System: 800 kW
  - Individual Torch: 600 – 800 kW
- Process gas: Oxygen
- Electrode Life:
  - Anode: 900 Hours
  - Cathode: 200 Hours

CONCLUSIONS

- **Basic thermal plasma jet properties:**
  - **Temperature and velocity profiles, plasma enthalpy, plasma composition**
  - **Flow structure and (in)stability**
- **Basic plasma torch design parameters:**
  - **Arc chamber geometry, length and diameter**
  - **Gas composition, gas flow rate**
- **Basic diagnostics for thermal jets**
  - **Spectroscopy**
  - **Enthalpy probes**
  - **High speed photography, schlieren photography**
  - **Electric probes**
- **Thermal plasma applications:**
  - **Metallurgy, welding, cutting**
  - **Surface modifications, coatings**
  - **Materials synthesis**
  - **Decomposition, waste treatment**