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Thermal plasma jets generated in dc arc plasma torches - generation, properties, diagnostics

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OUTLINE

- Generation of thermal plasma jets
- Basic principles of arc plasma torches
- Factors influencing properties of plasma jet in arc plasma torches (design of the torch, properties of plasma gas)
- Water and hybrid gas/liquid plasma torches
- Special diagnostic tools for thermal plasma jets

Thermal plasmas

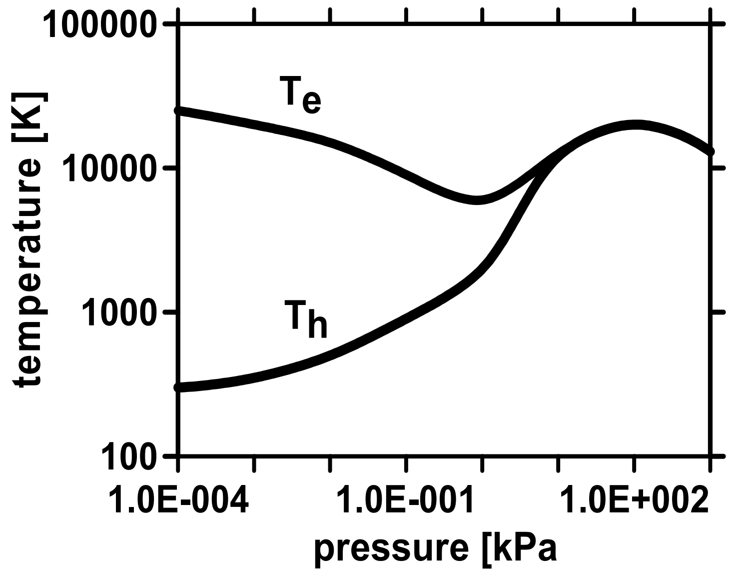
Basic plasma properties

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

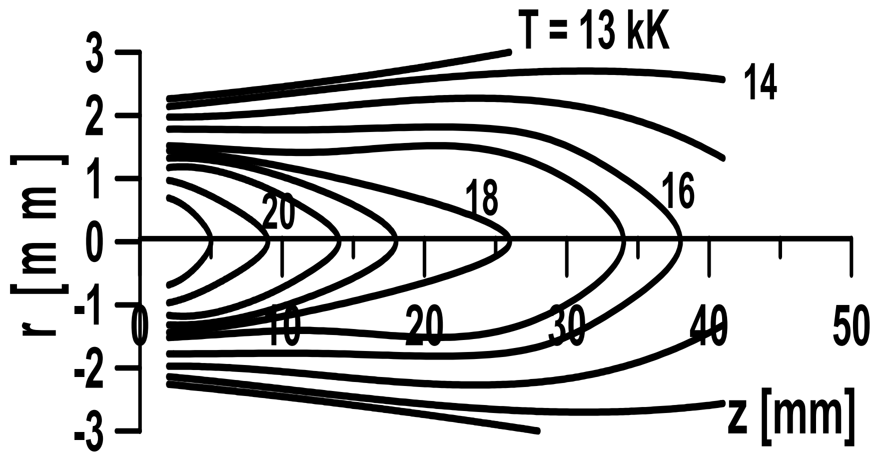


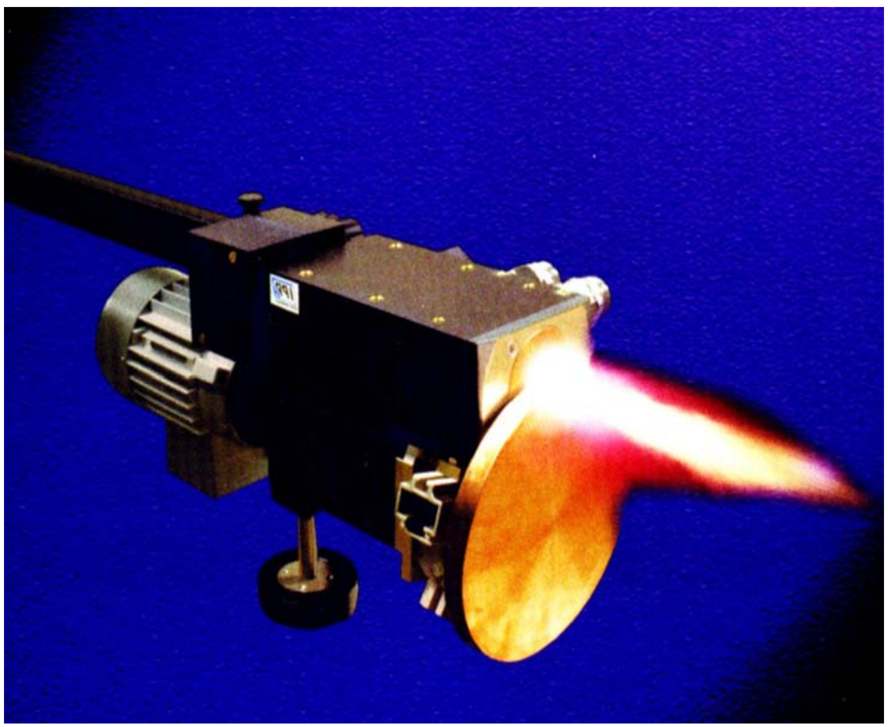
Common sources of thermal plasmas

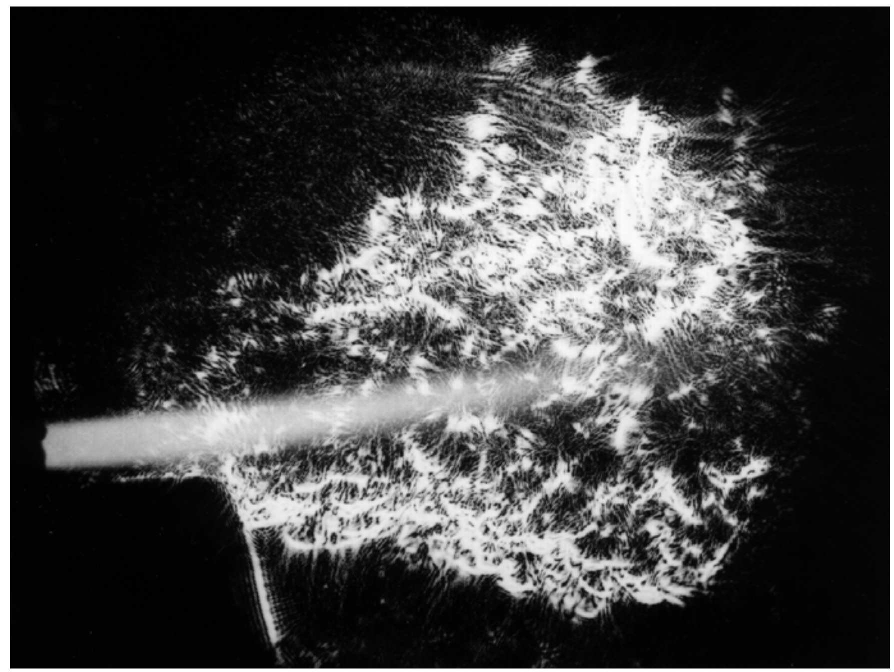
- **Inductively coupled discharges in gases**
- **Electric arcs – stabilized by gas flow**
  – stabilized by vortex of liquid (Gerdien arcs)

Thermal Plasma Jets

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







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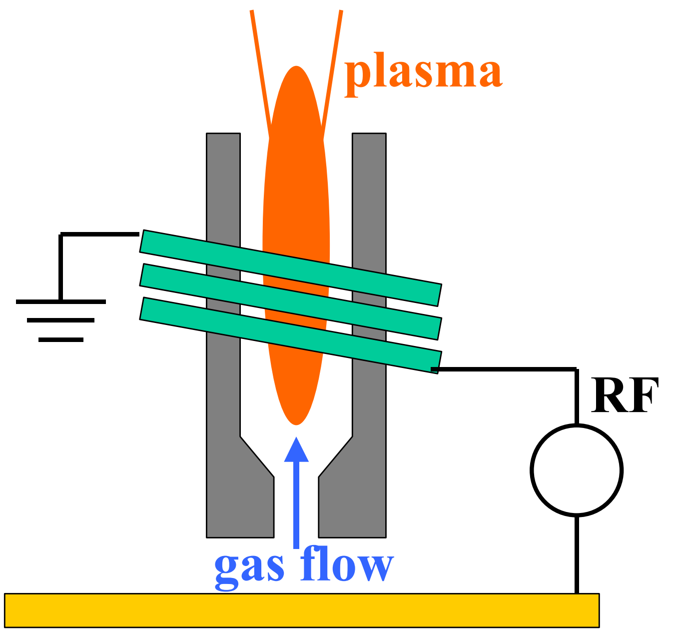
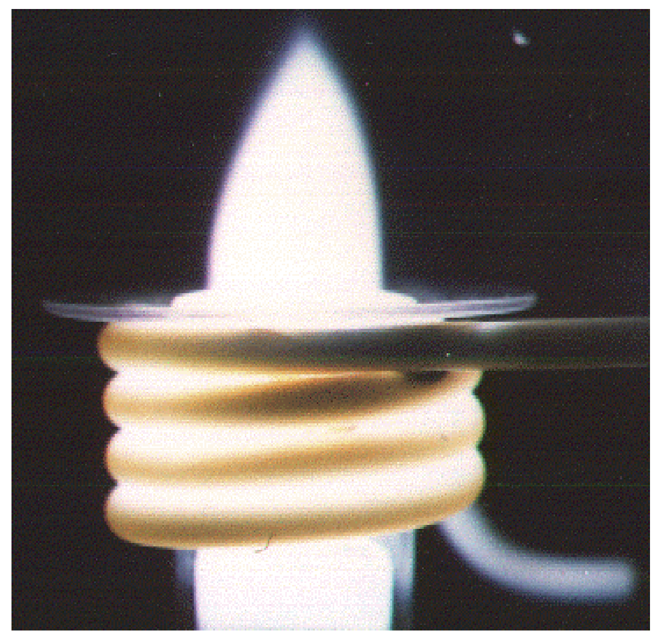
Inductively coupled plasma torches

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

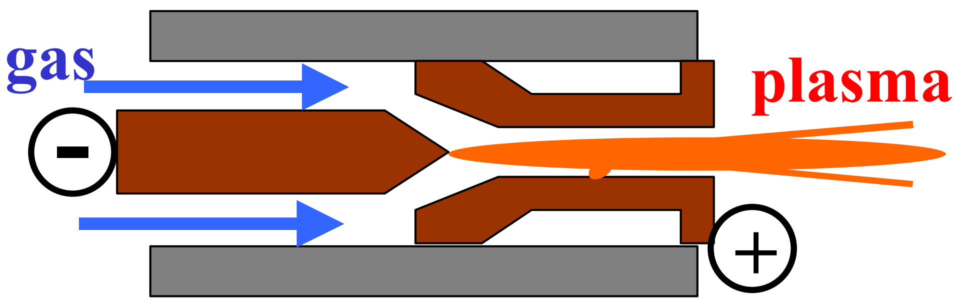




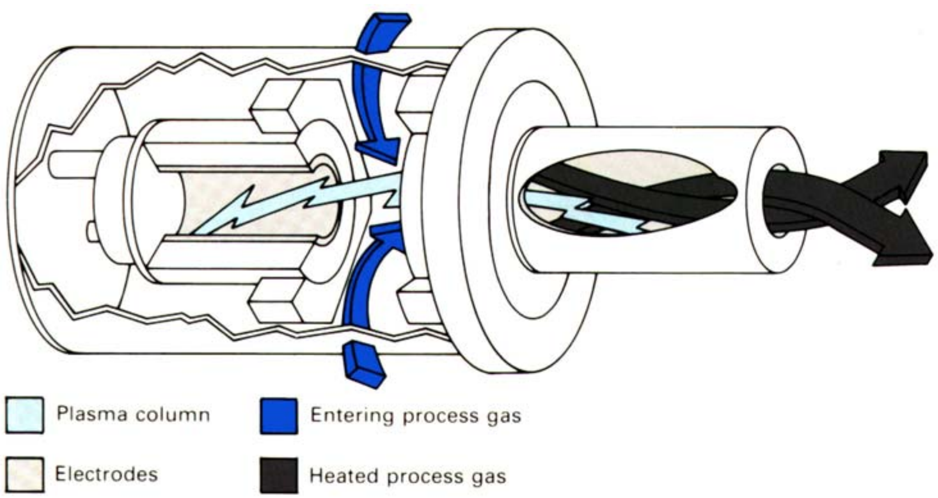
Arc plasma torches

Non transferred arcs

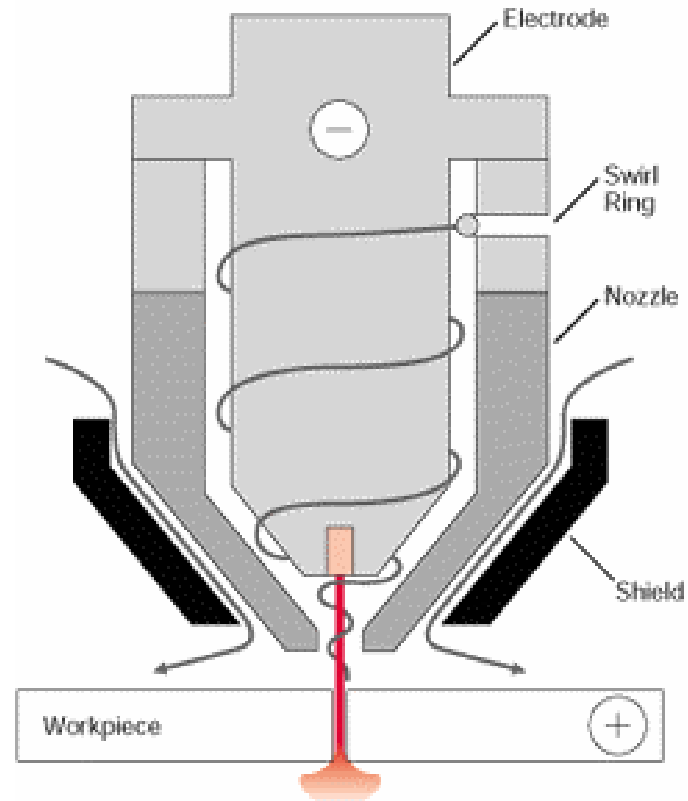
Hot cathode



Cold cathode



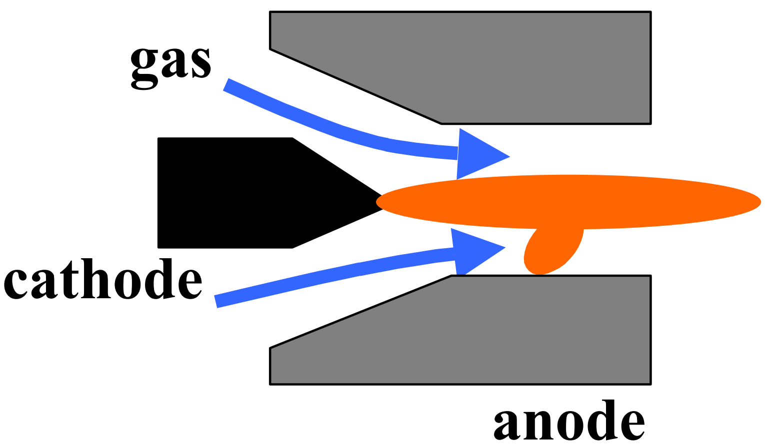
Transferred arcs



Principles of arc stabilization

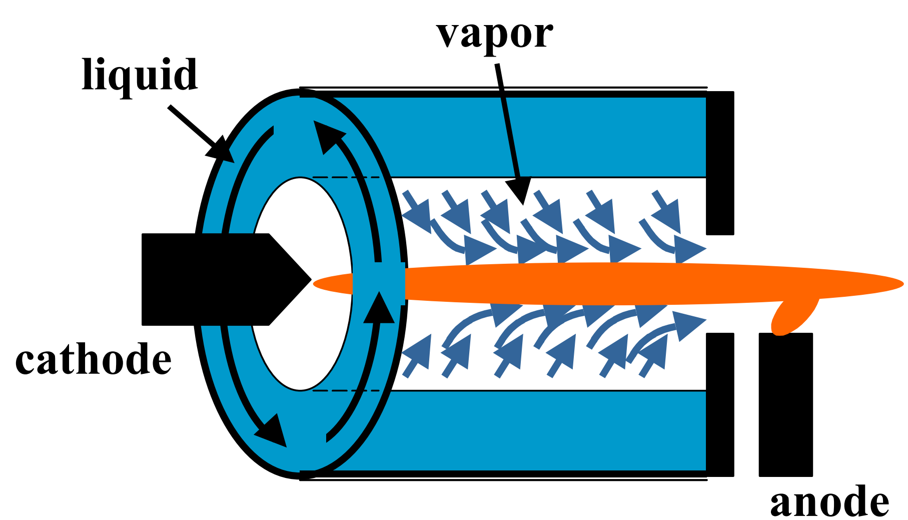
Gas-stabilized arc

- 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



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:

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

design factors

plasma gas properties

Torch Power:

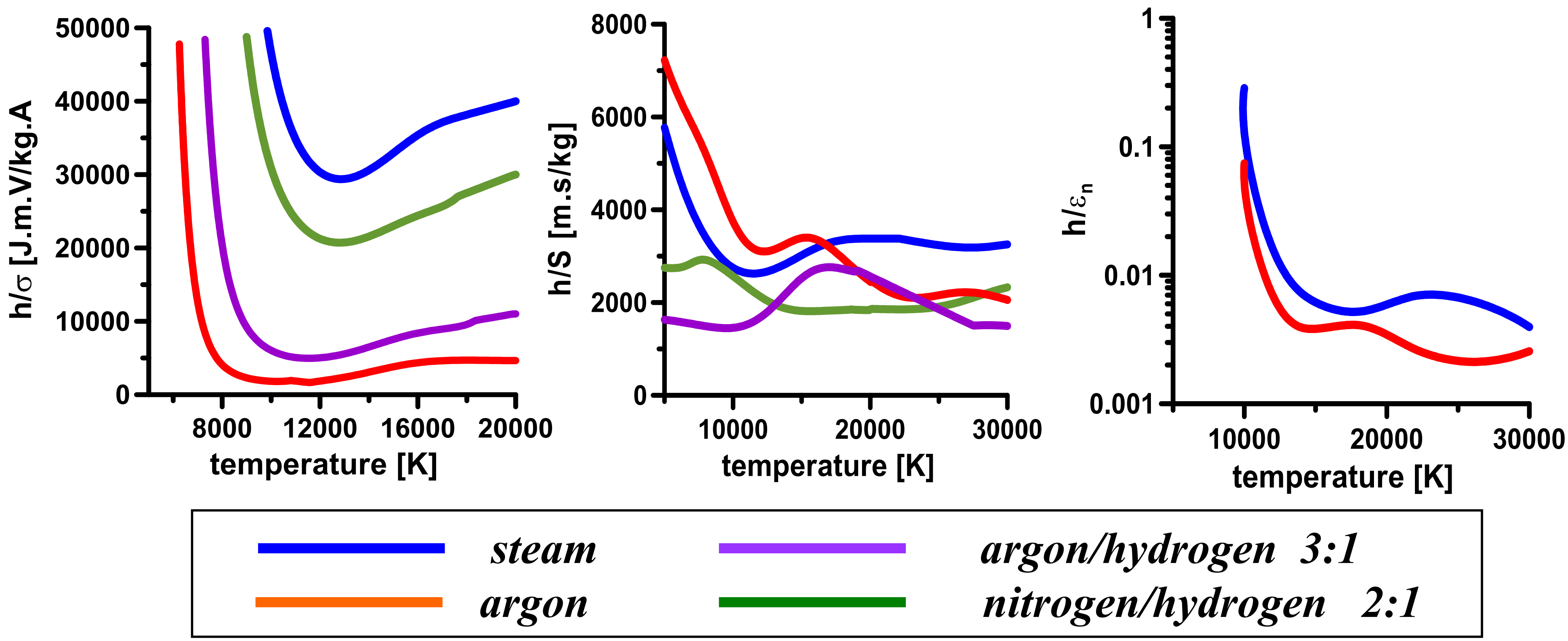
$$P = I.U = I.\left(\frac{\theta_F\theta_\sigma}{\eta\theta_G}\frac{L.G}{\pi R^2}\frac{h}{\sigma} \right)^{\frac{1}{2}}$$

Properties of plasma gases

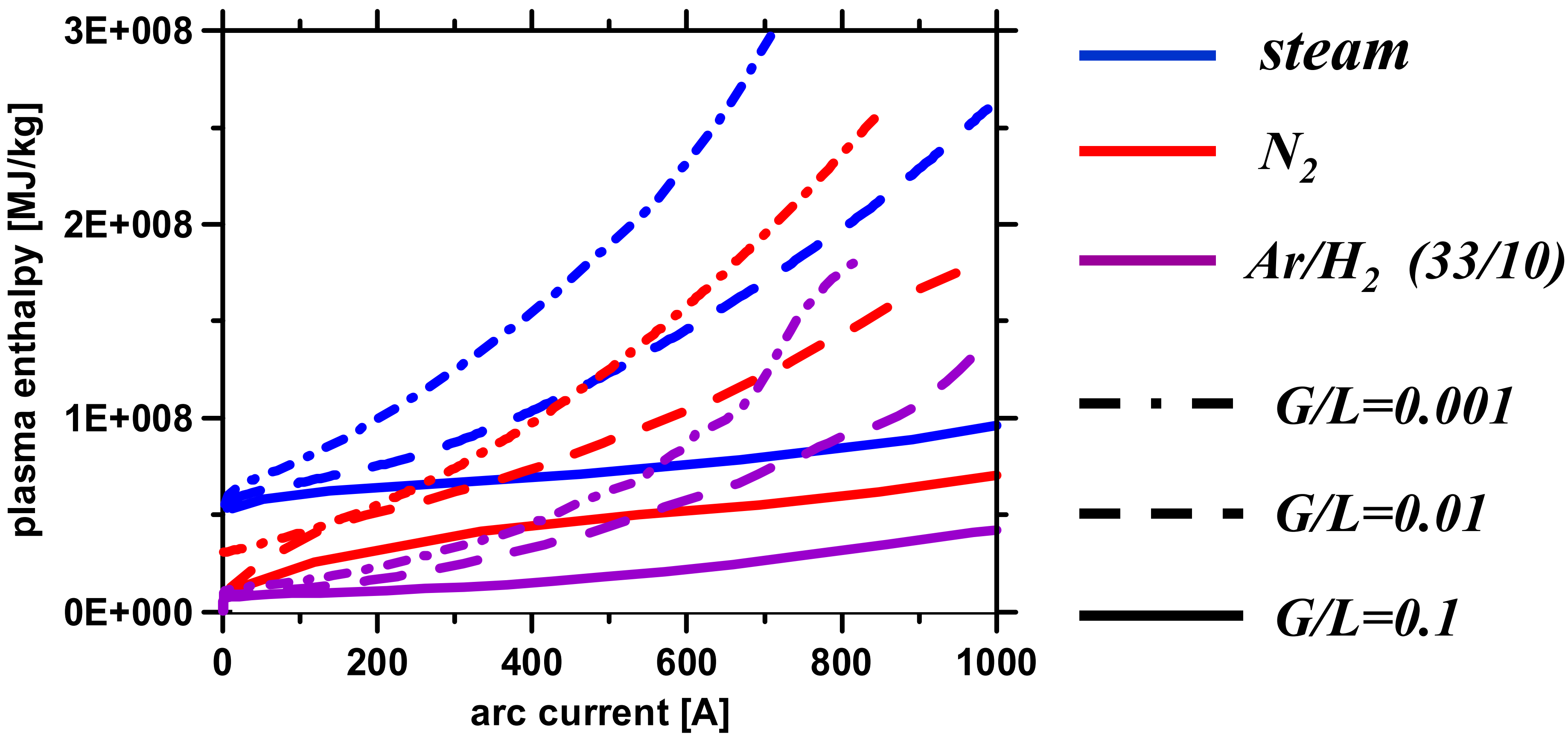
Torch operation parameters are determined by physical properties of plasma gas.
Decisive gas properties:

Power:
ratio between enthalpy and electrical conductivity

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



Plasma enthalpy in dependence on arc current



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

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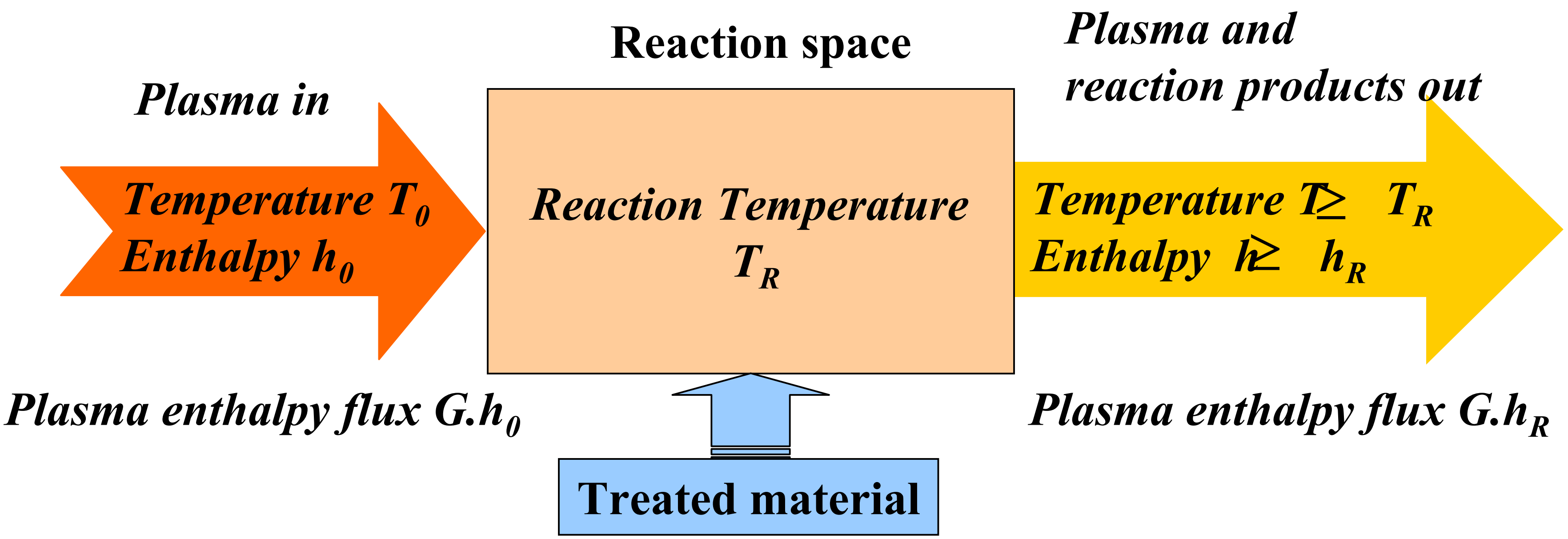
Efficiency of utilizing plasma enthalpy for processing

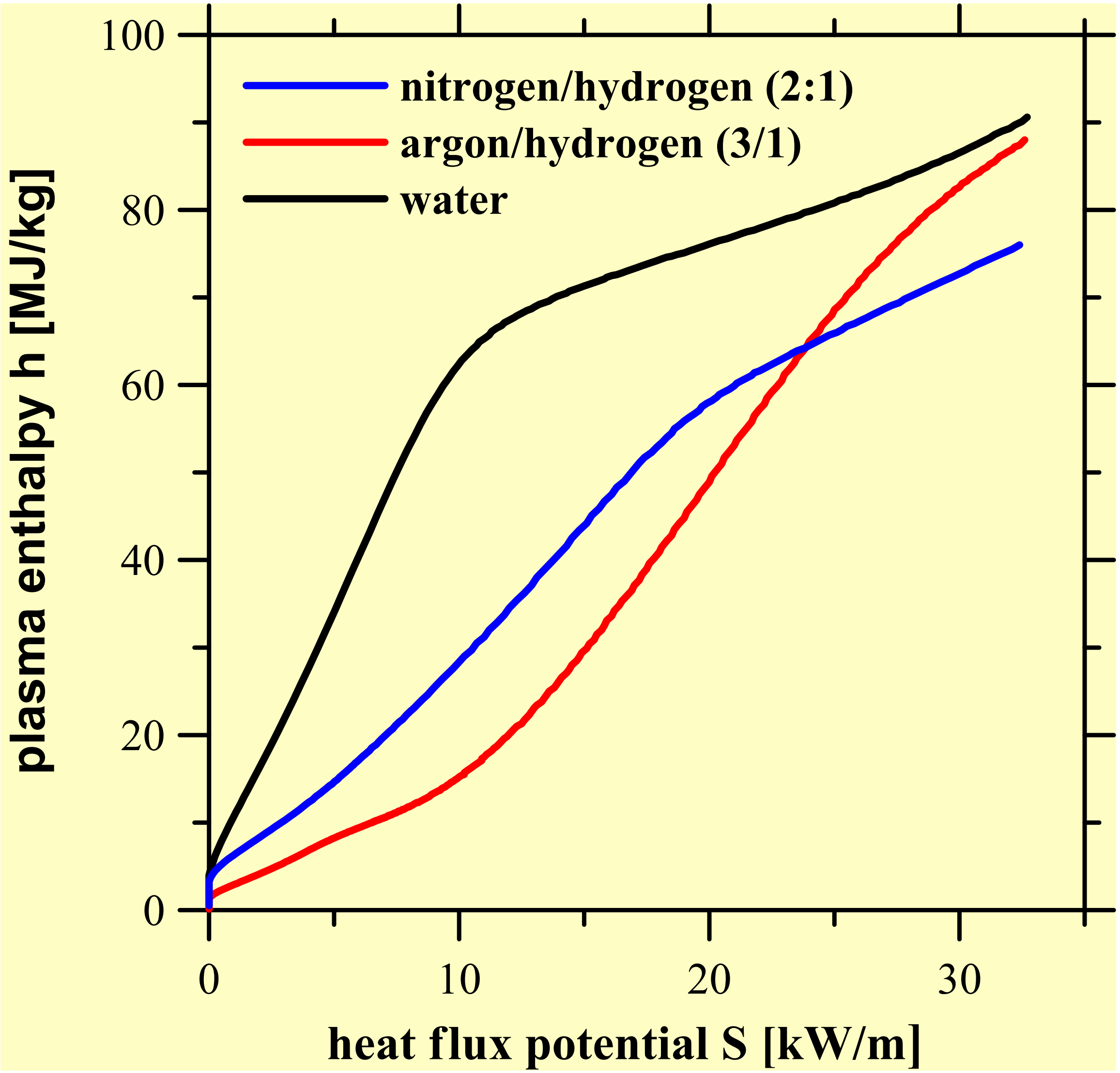


Only enthalpy ΔH = $G.h_0 - G.h_R$ can be used for the treatment of material

Process efficiency:

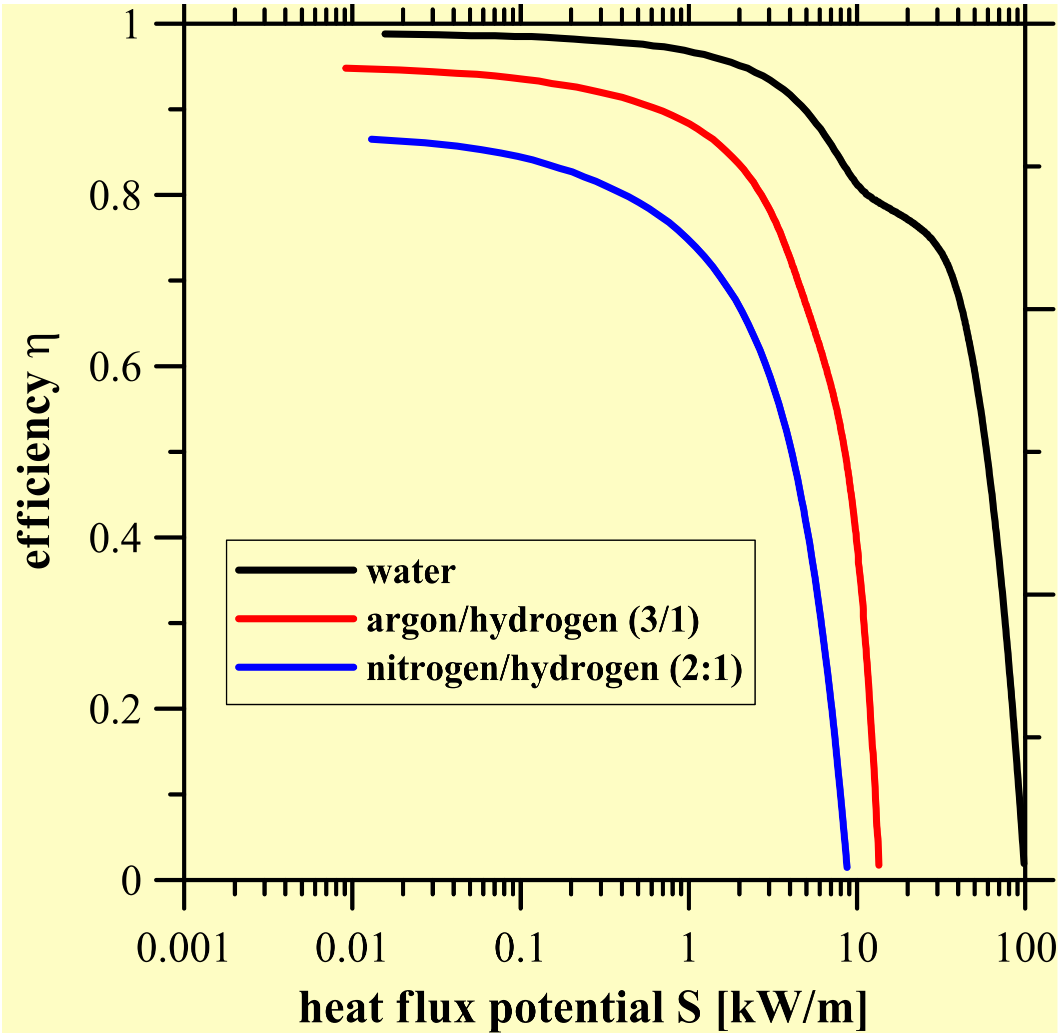
$$\eta_R = \frac{G.(h_0 - h_R)}{G.h_0} = 1 - \frac{h_R}{h_0}$$

Relation between enthalpy and heat flux potential for common plasma gases



$$S = \int_{T_0}^{T} k(T)\, dT \qquad T_0 = 2000\ K$$

Thermal efficiency of water-stabilized and gas-stabilized torches



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

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

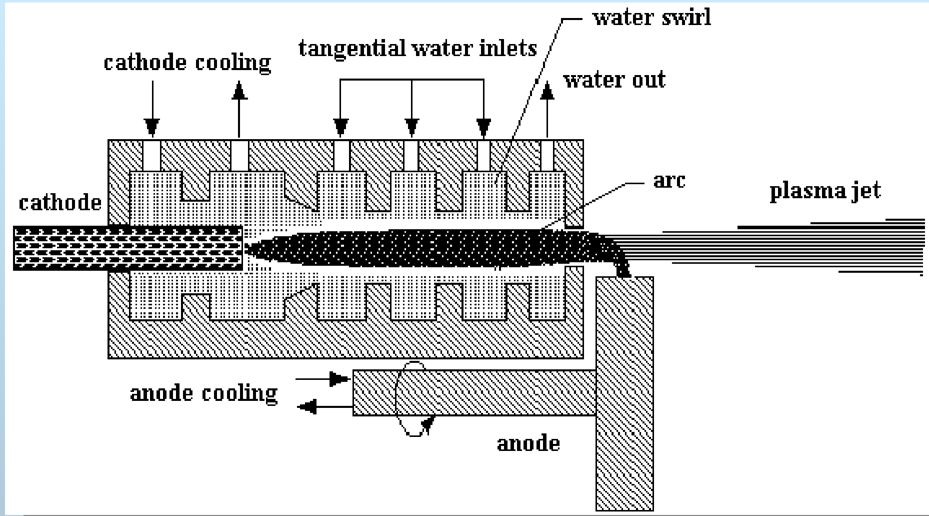
$h_T = h(T)$ … T …S(T)

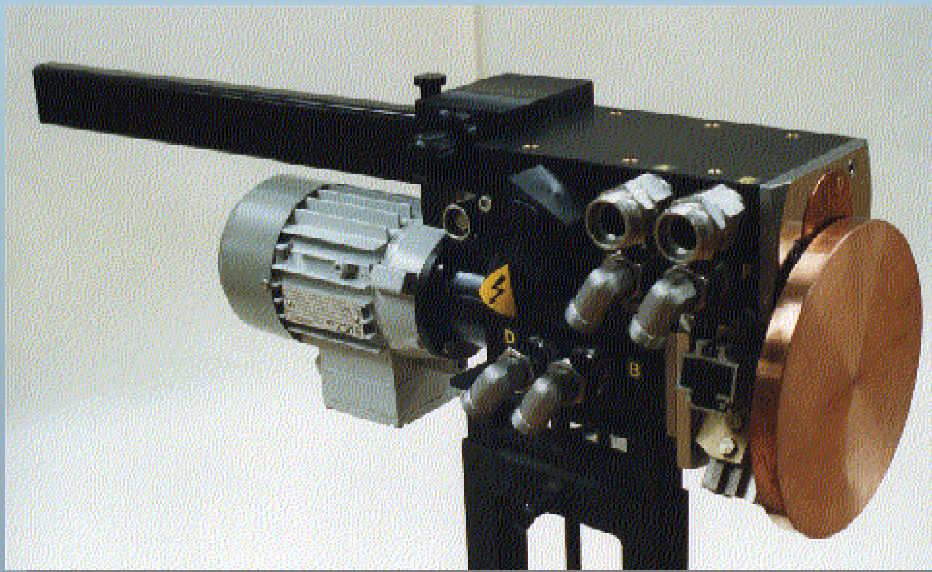
Typical spray rates for dc arc plasma torches

plasma medium	arc power [kW]	spray rate [kg/h]	
		ceramics	metals
water	160	25-45	80-100
gas - N_2/H_2	200	5-8	25-45
gas-$Ar/H_2/He$	50	2-4	6-8

Spray rates in kg of powder per hour for water torch WSP-500 and for gas spraying torches Plasmatechnik F4 and PlasJet.

Water Stabilized Plasma Torch



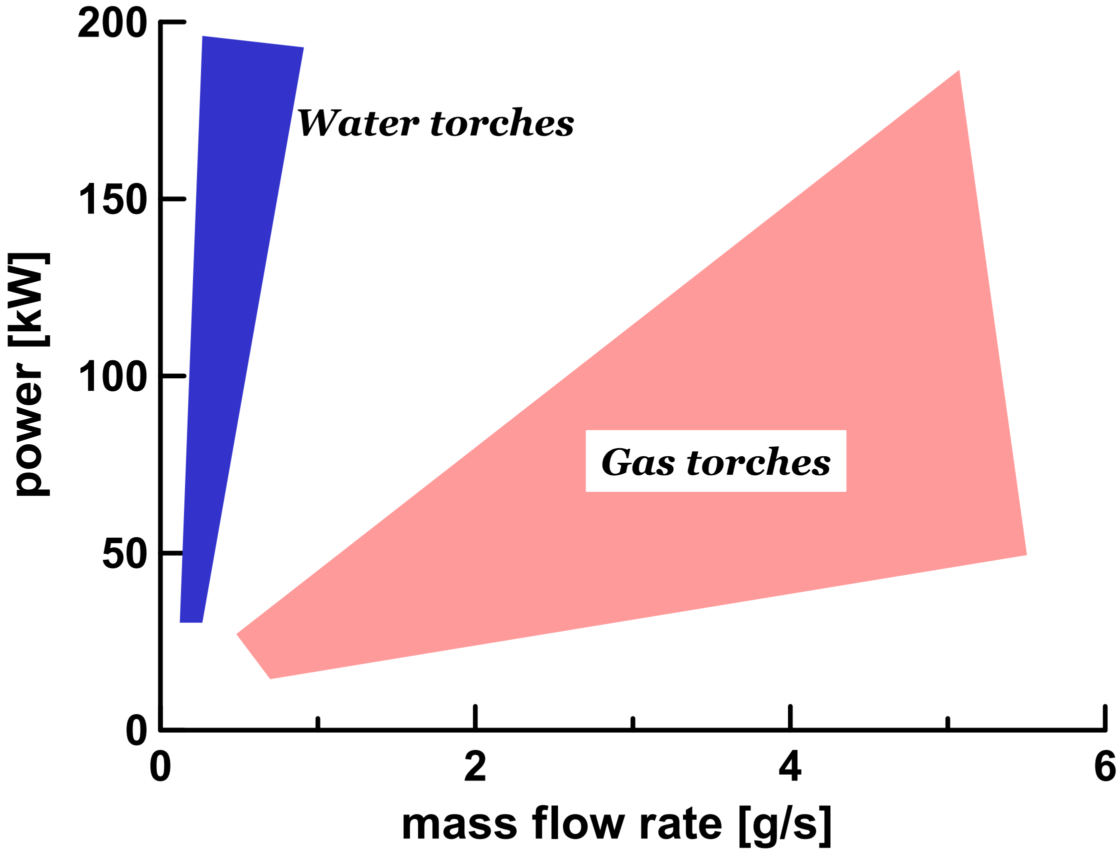


arc current: *300 - 600 A*
arc power: *80 - 176 kW*
arc voltage: *267 - 293 V*

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}

Operation regimes of gas-stabilized and water-stabilized torches

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

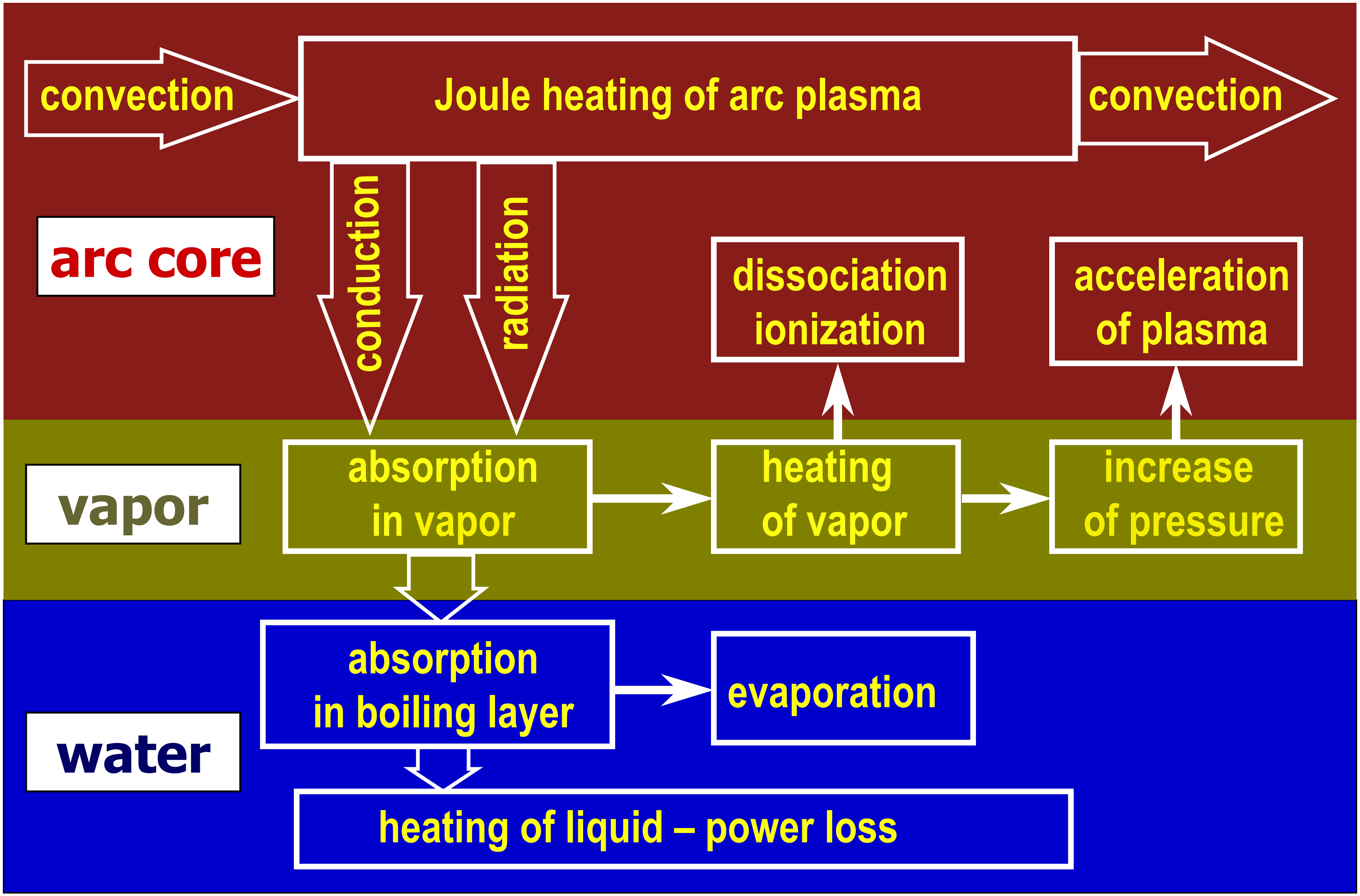


Mean plasma enthalpy:

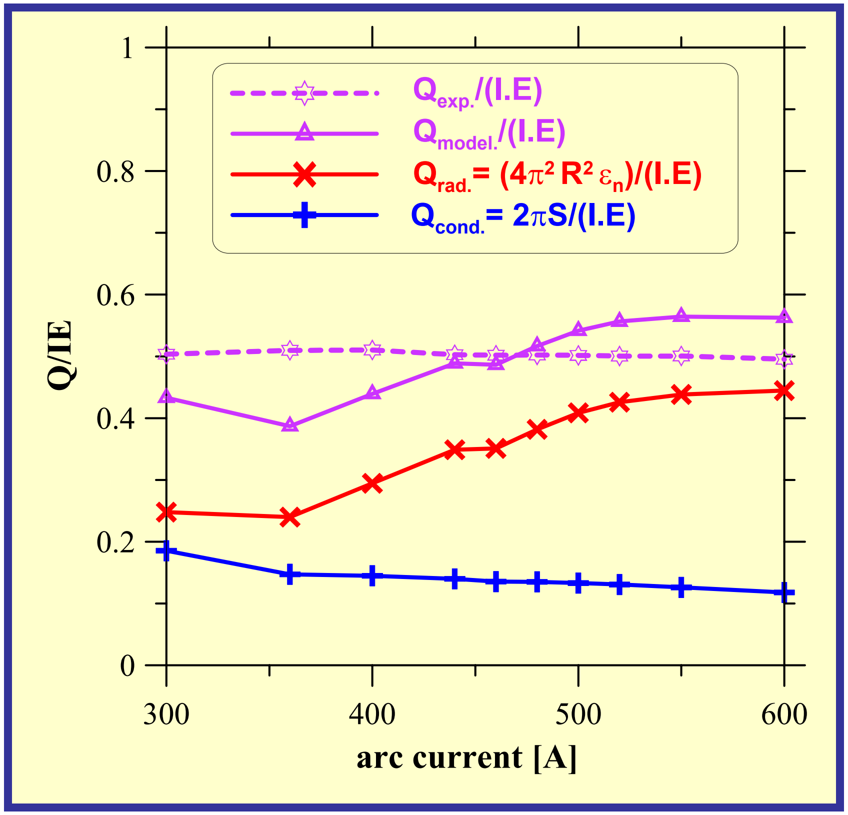
Gas torches:
10 – 40 MJ/kg

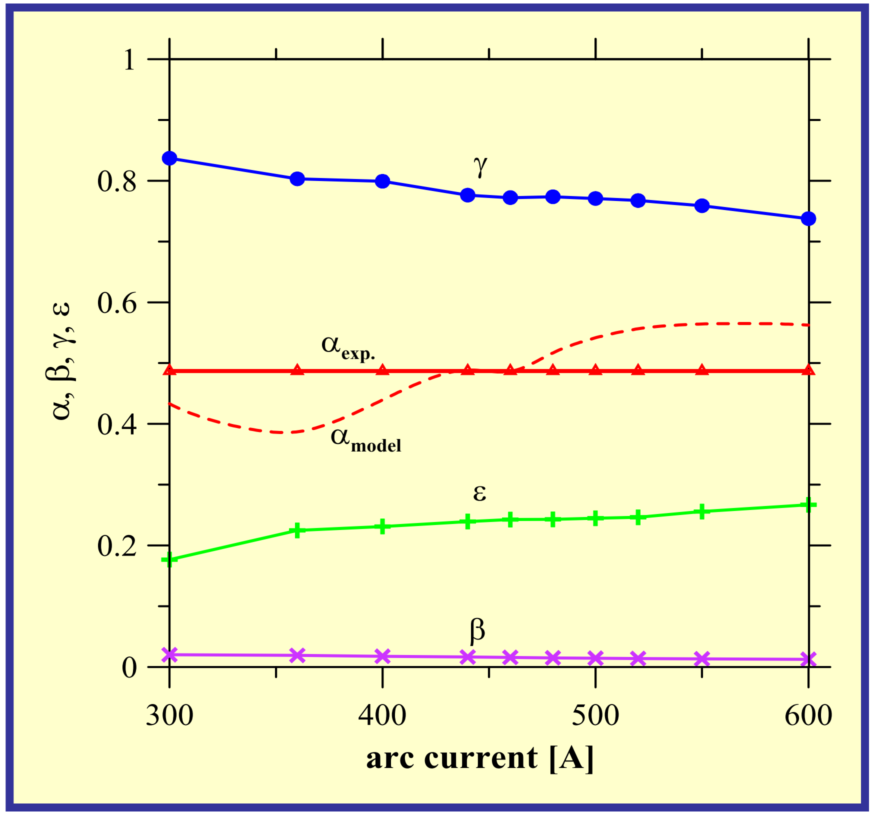
Water torches:
100 – 300 MJ/kg

Basic Processes in Liquid-Stabilized Arc



Components of radial heat transfer





$Q_{exp.}$, $Q_{model.}$-total radial heat flux
$Q_{cond.}$- heat transferred by conduction
$Q_{rad.}$- heat transferred by radiation

$$\alpha_{model} = (4\pi^2 R^2 \varepsilon_n + 2\pi S) / I.E_{model.}$$
$$\varepsilon = k_m.m$$
$$\beta = m.Q_{ev.} / (\alpha.I.E)$$
$$\gamma = \frac{P_w}{\alpha.I.E}$$

Effect of balance of radial transfer of energy on arc plasma properties.

For high arc plasma temperatures radiation energy transfer is dominant
Most of radiation in UV waveband is absorbed in vapor sheath due to photodissociation and photoionisation.
Low fraction of radiation is absorbed in boiling water layer.

- low part of radially transferred energy is spent for water evaporation
- high part of radially transferred energy is spent for vapor heating

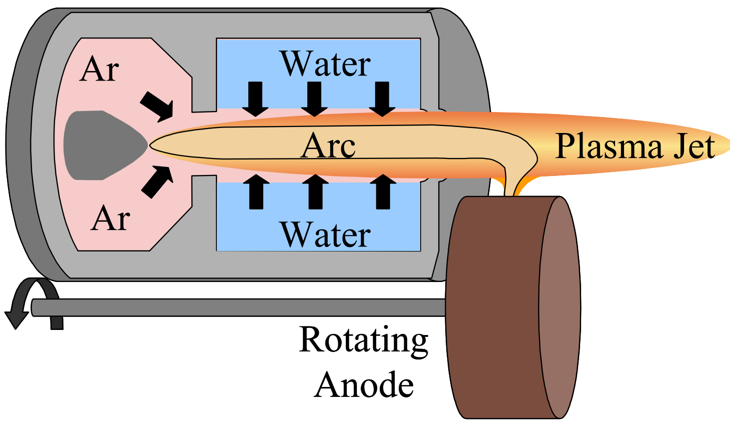
⇓

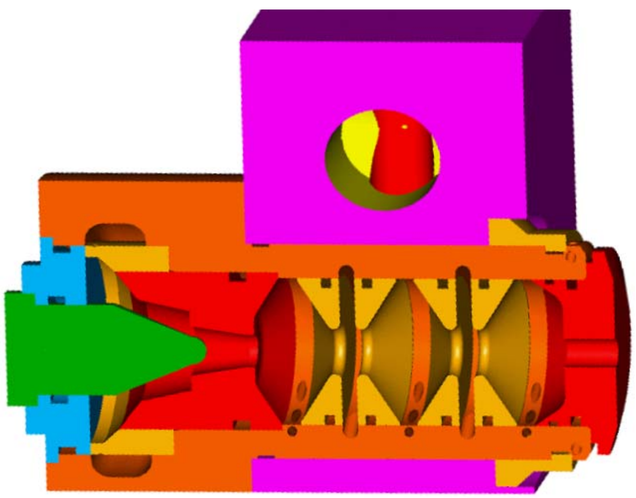
plasma with high enthalpy and temperature and low density is generated

The balance of energy transfer and thus arc characteristics and plasma properties can be changed by changing boiling temperature or latent heat of evaporation of liquid.

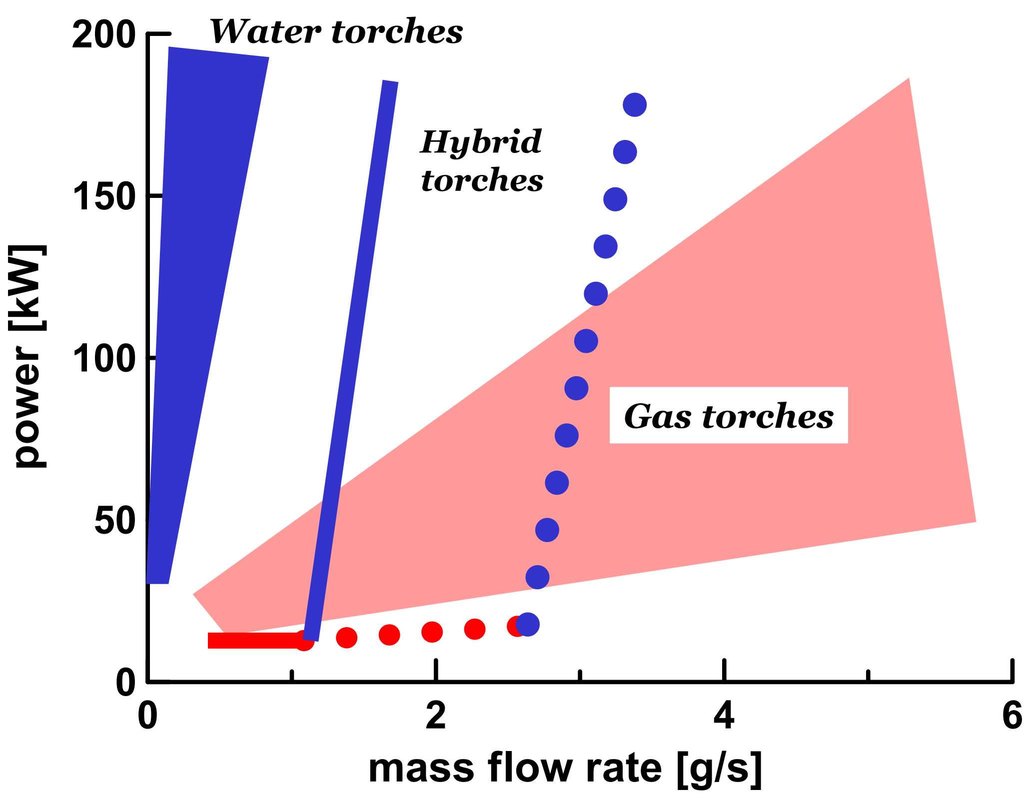
Hybrid gas/water dc arc plasma torch

Principle of hybrid gas/water plasma torch



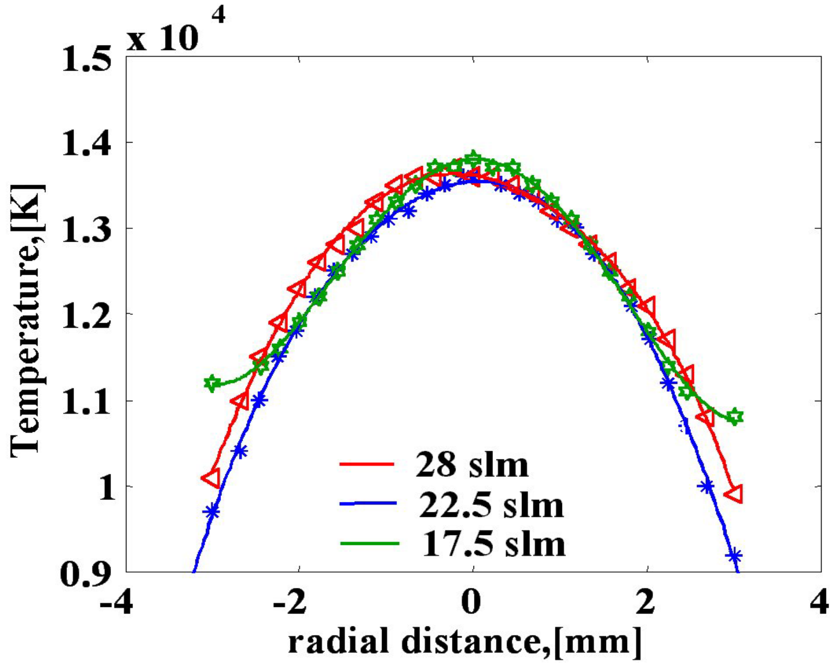


Operation regimes of dc arc plasma torches

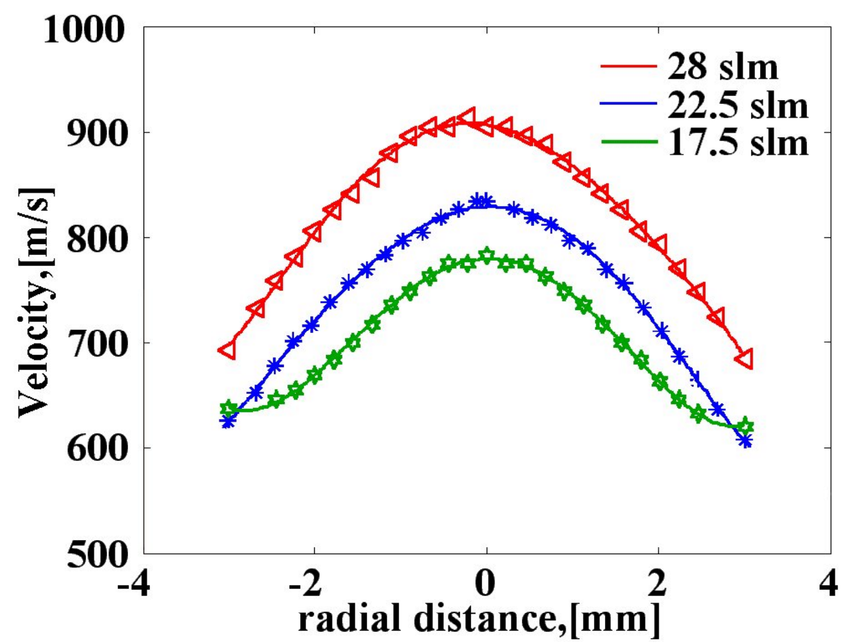


Profiles of plasma temperature and velocity at the exit nozzle

Profiles of plasma temperature for arc current 150 A and three argon flow rates, z = 2 mm

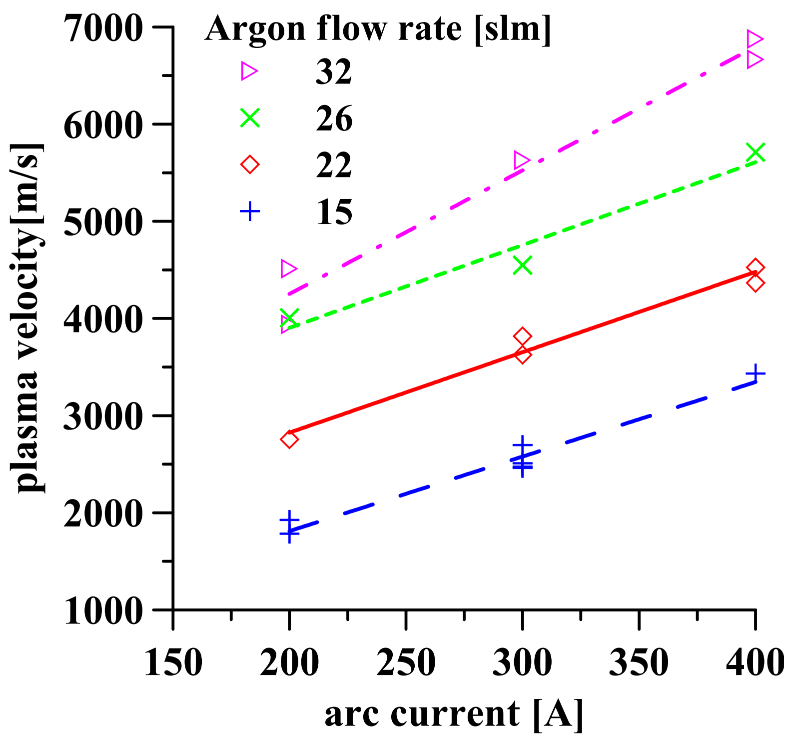


Profiles of plasma velocity for arc current 150 A and three argon flow rates, z = 2 mm

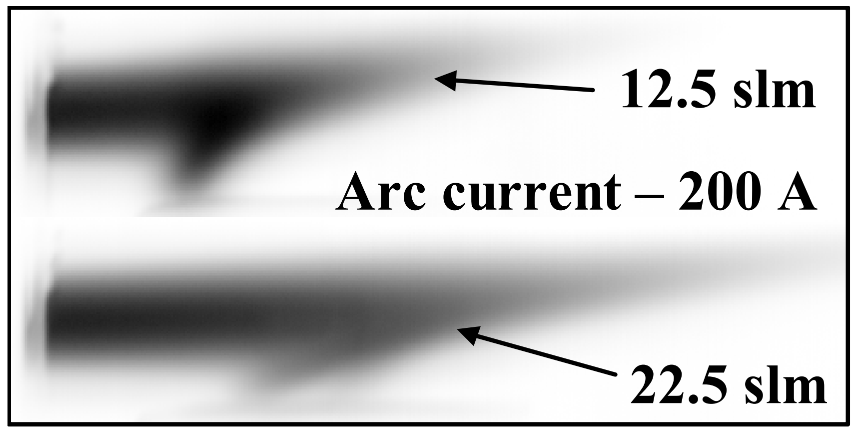


Effect of argon flow rate and arc current on plasma velocity and shape of the jet

Centerline plasma velocity in the anode region as a function of arc current for various argon flow rates.

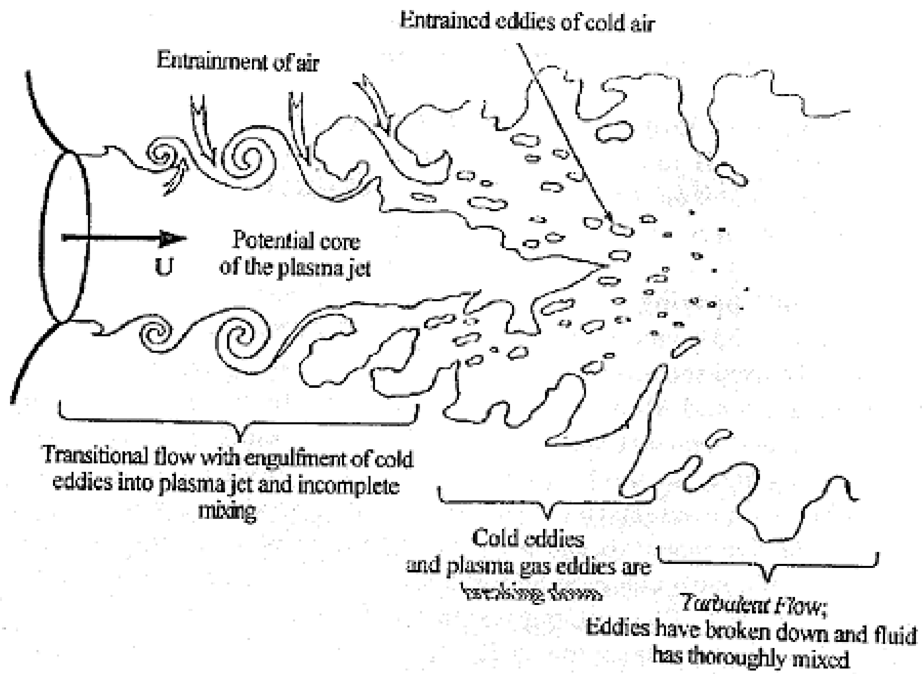


Images of luminous jet core recorded by short shutter camera and spread angles of the jet for various flow rates of argon



Argon flow rate	*Spread angle*
12.5	6.45°
17.5	8.35°
22.5	9.46°

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

Evaluation of mass flux at the exit nozzle

Temperature profile from optical spectroscopy

Equilibrium calculations of transport and thermodynamic coefficients of plasma

↓

Profiles of plasma enthalpy h, density ρ and sound velocity c

Power balance of arc inside the arc chamber

↓

Mach number at the exit nozzle

$$M = \frac{W - P}{\int_0^{R_E} 2\pi r \rho c h \, dr + (1 - f_{Ar}) \, [\lambda + C_w (T_B - T_0)] \int_0^{R_E} 2\pi r \rho c \, dr}$$

↓

Velocity profile

v (r) = M . c(r)

↓

Mass flow rate at the exit nozzle

$$G_N = M \int_0^{R_E} 2\pi r \rho c \, dr$$

Emission spectroscopy

Basic plasma characteristics evaluated from measurements:

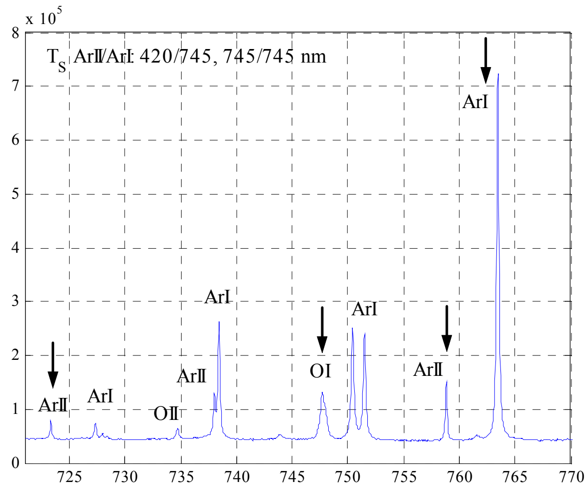
- *Electron number density*
- *Temperature*
- *Molar concentrations of components*

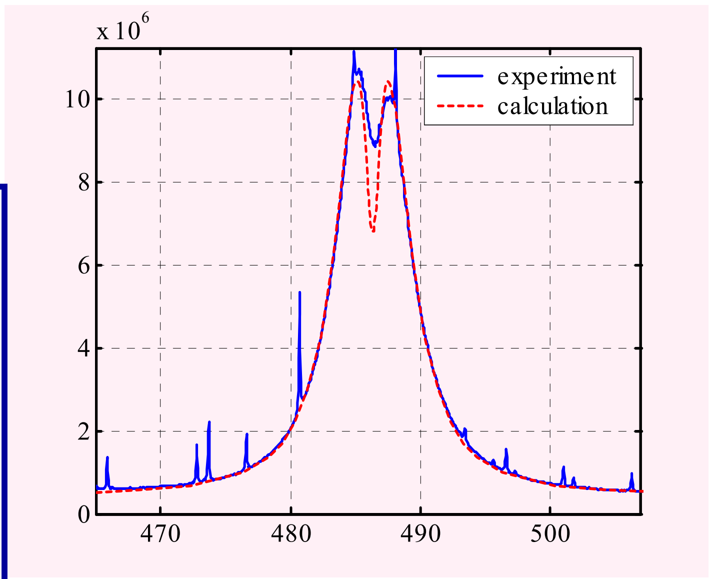
Basic methods:

- **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**

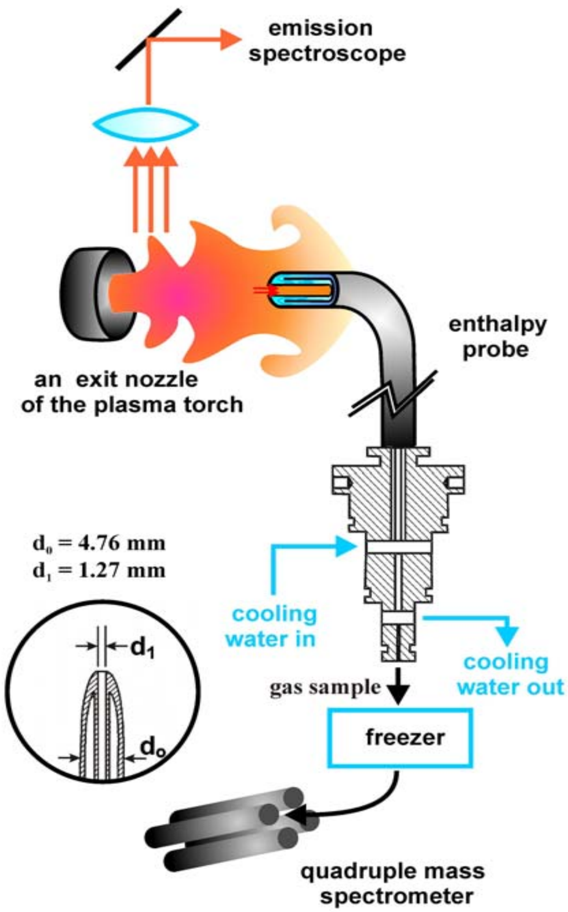




Enthalpy probe

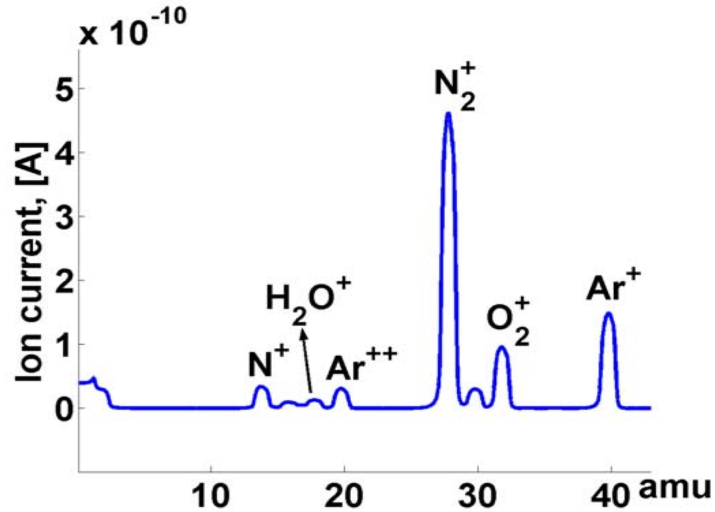
Isokinetic coefficient

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



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

Plasma enthalpy:

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

Plasma composition

Plasma temperature

Thermodynamic and transport coefficients

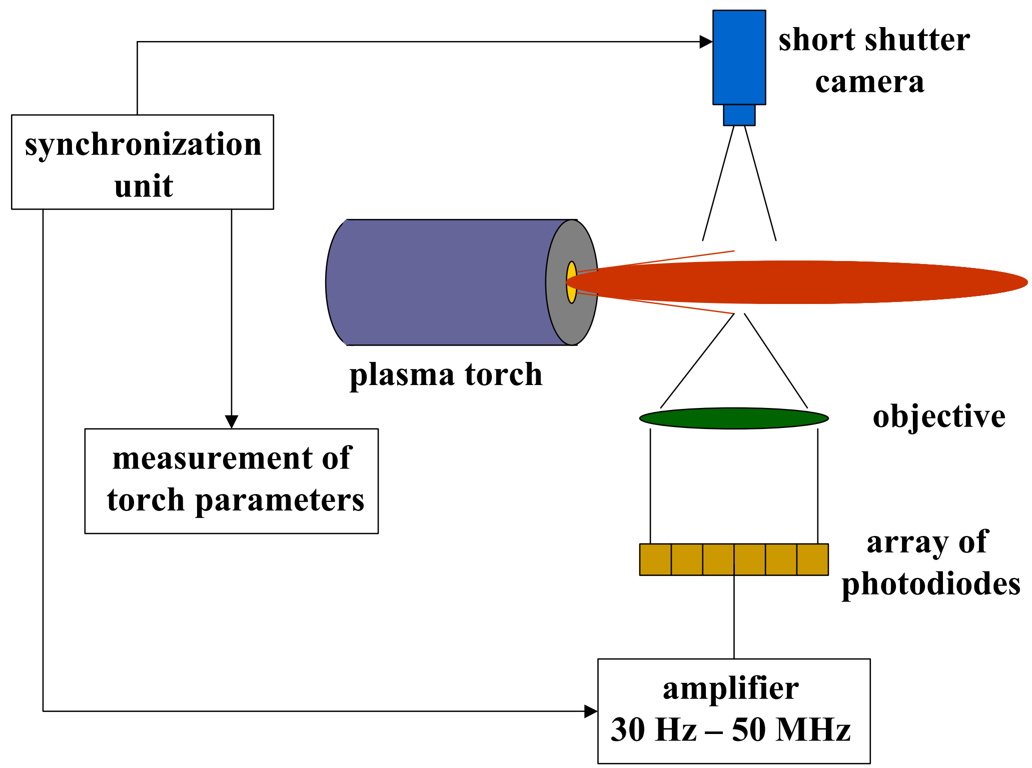
Local plasma velocity

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

Measurement of flow velocity

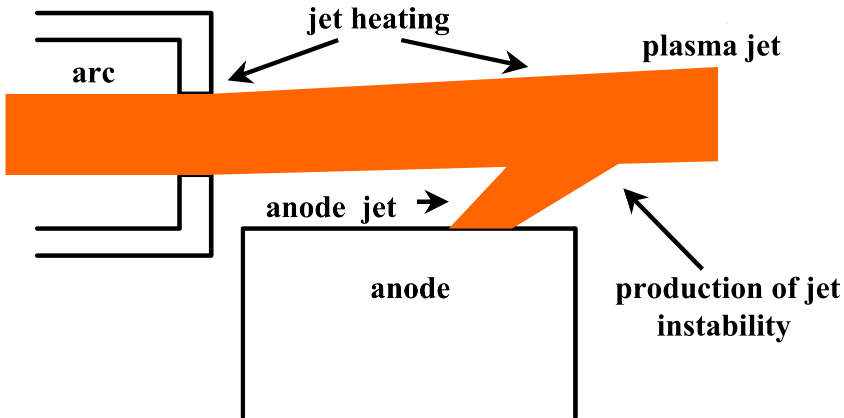
Enthalpy probe-Pitot tube
Time of flight of fluctuations - emitted light
- electric probe current
Propagation of waves in plasma

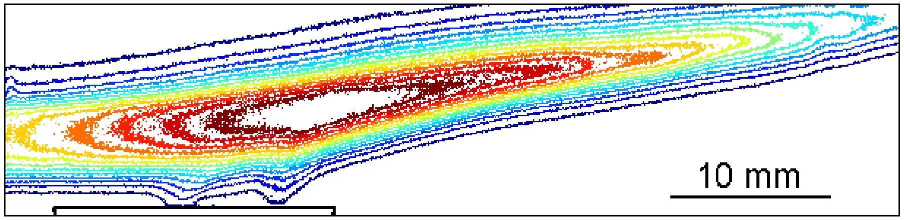
Diagnostics of jet fluctuations and instabilities



Main sources of plasma flow instabilities

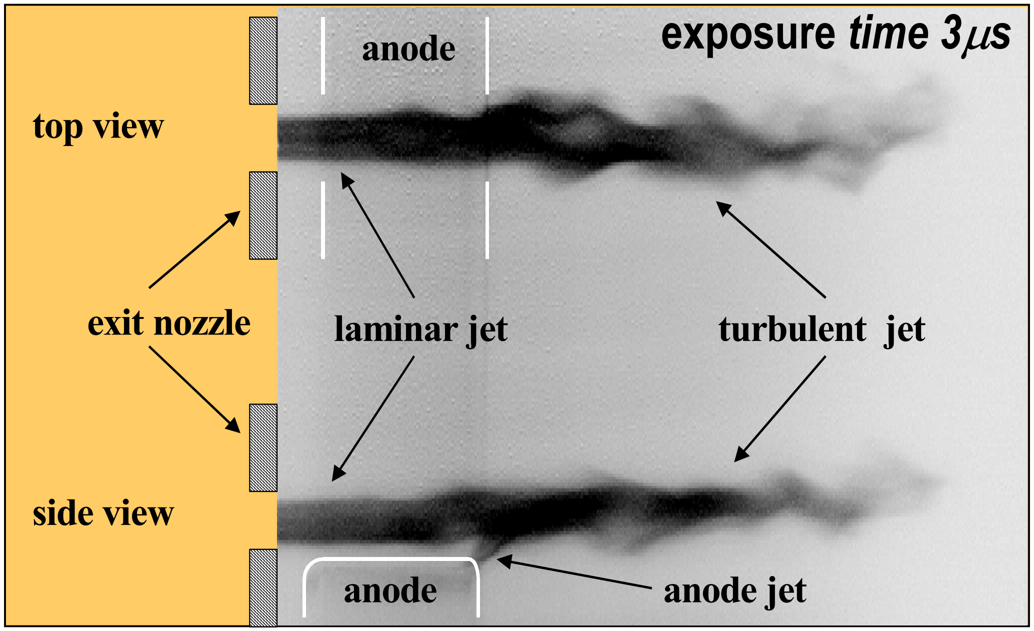
Arc phenomena





I = 400 A, argon flow rate F_{Ar} = 8.5 slm

exposure time t = 700 ns.

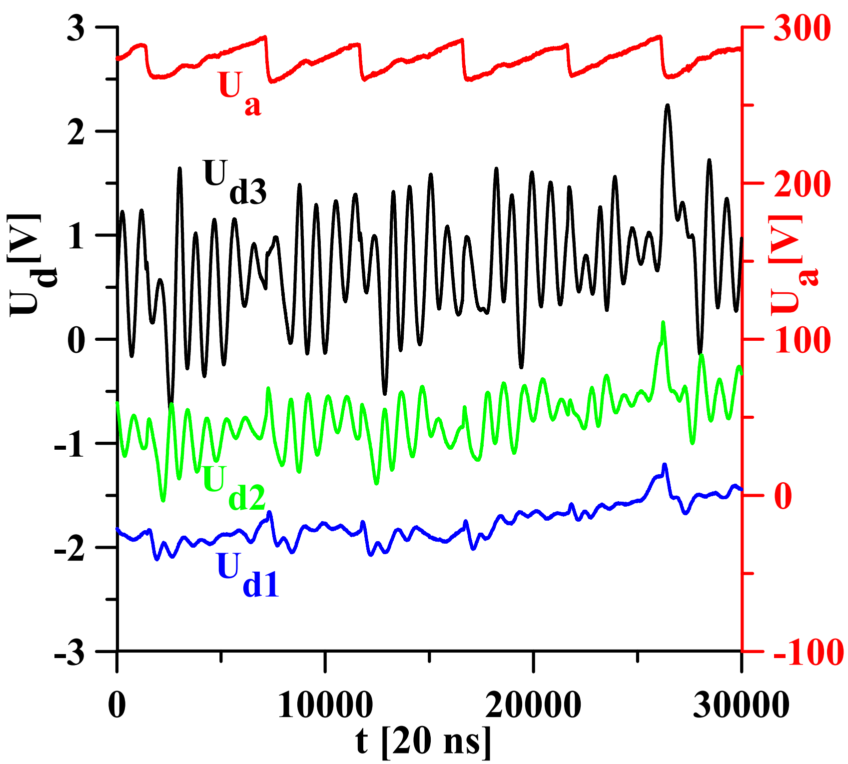


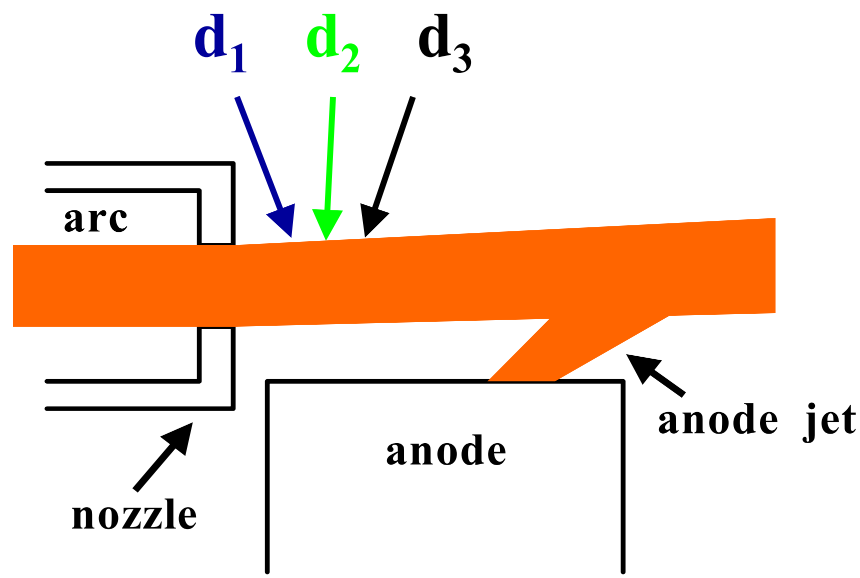
Arc anode attachment:
-movenet in the restrikeš mode
-anode jet

Main sources of plasma flow instabilities

Gas-dynamic instability

Arc voltage and light fluctuations at various axial positions.





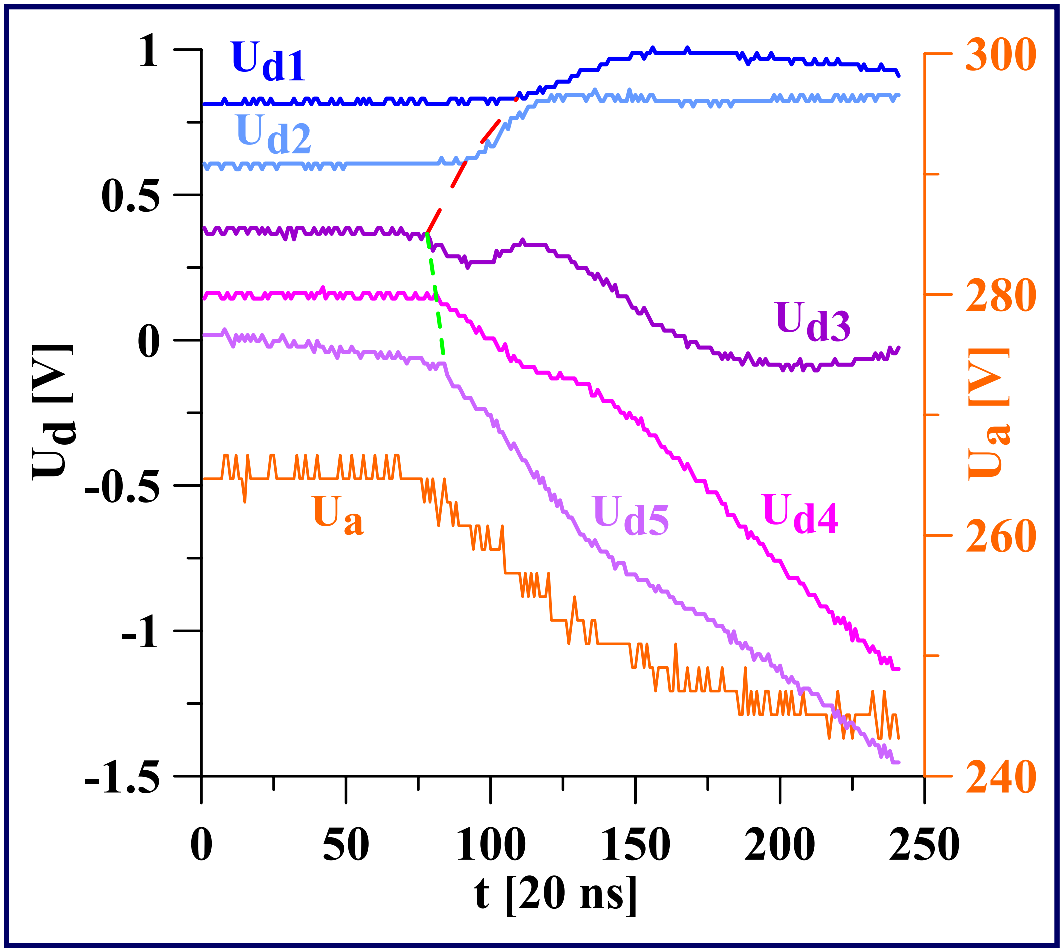
Distances from the nozzle:

$z_{d1} = 2.4$ mm

$z_{d2} = 4.3$ mm

$z_{d3} = 6.2$ mm

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)

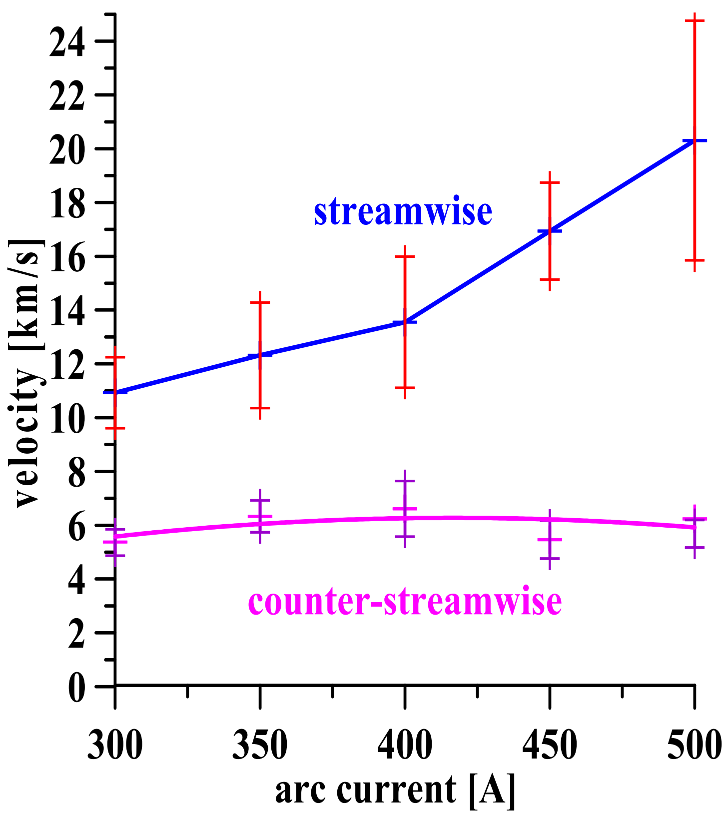
d3 = 7.7 mm (z/D = 1.28)

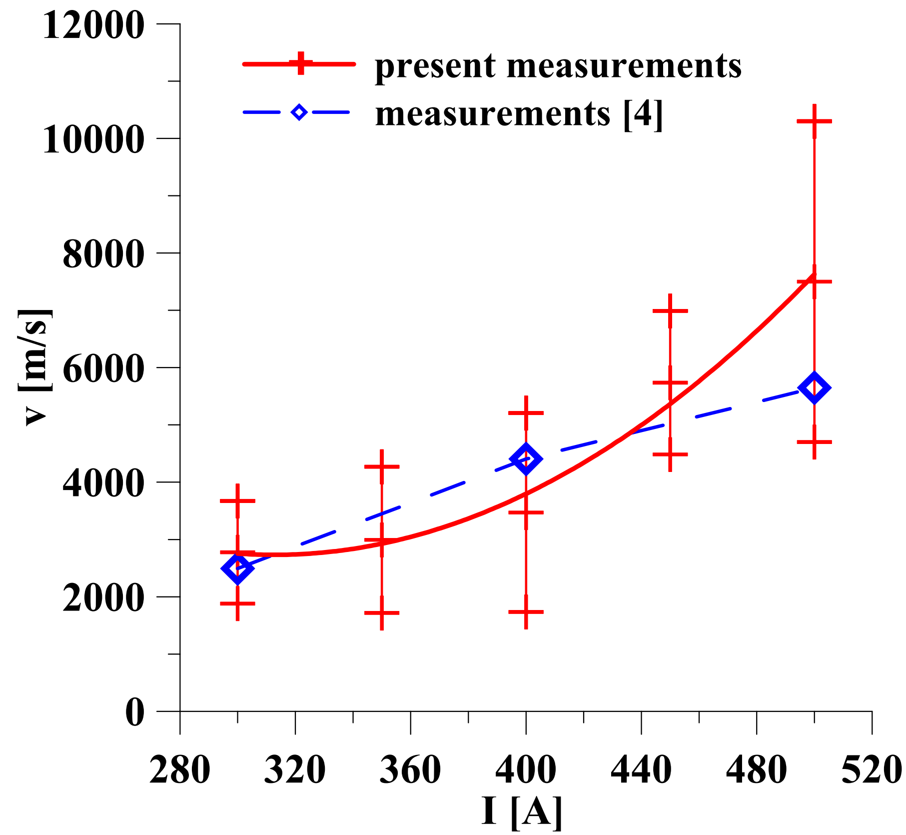
d4 = 11 mm (z/D = 1.83)

d5 = 14.3 mm (z/D = 2.38)

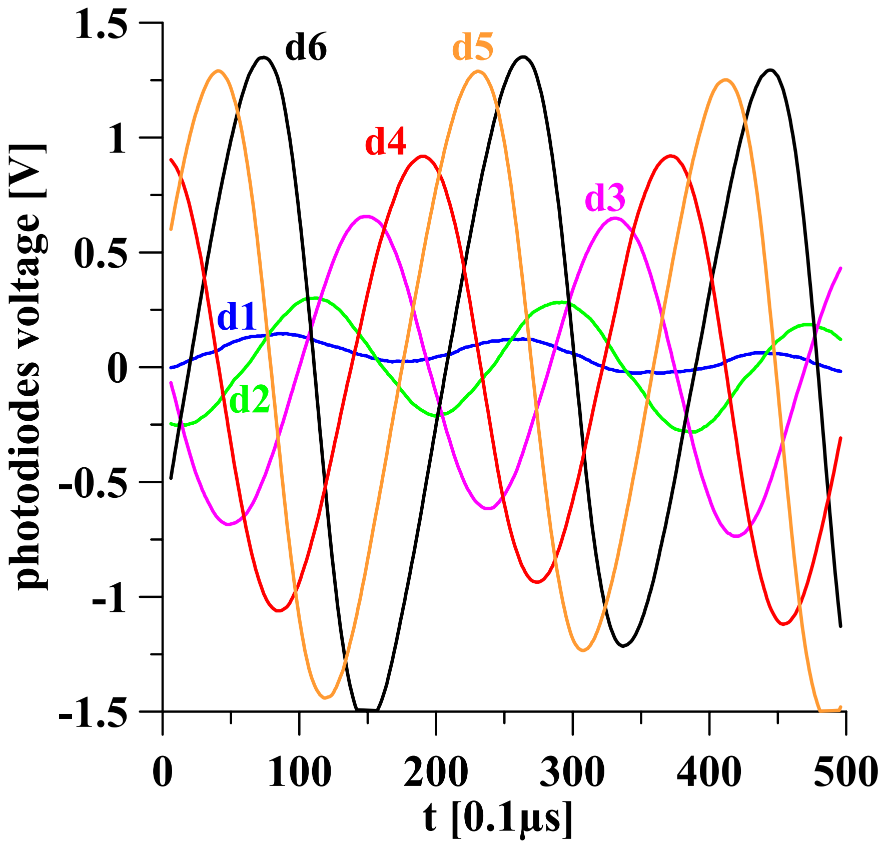
Determination of flow velocity

Streamwise and counter-streamwise velocities of perturbations caused by a formation of new anode spot and flow velocity evaluated as their difference





Determination of flow velocity



Fluctuations of emitted light at various distances from the torch exit

D - Distance between points
ΔΦ - Phase shift

Velocity of movement of oscillations

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

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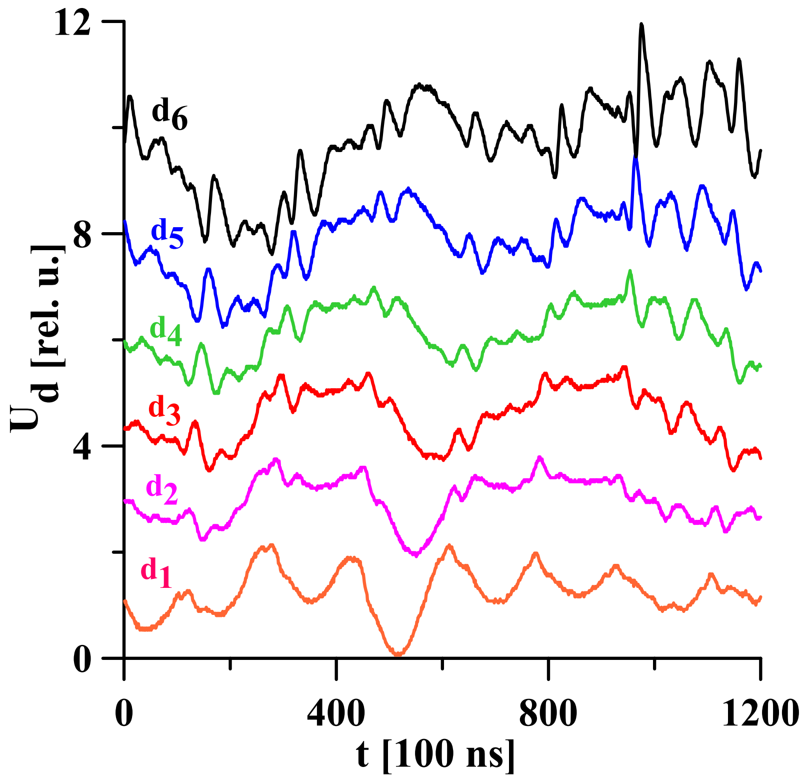
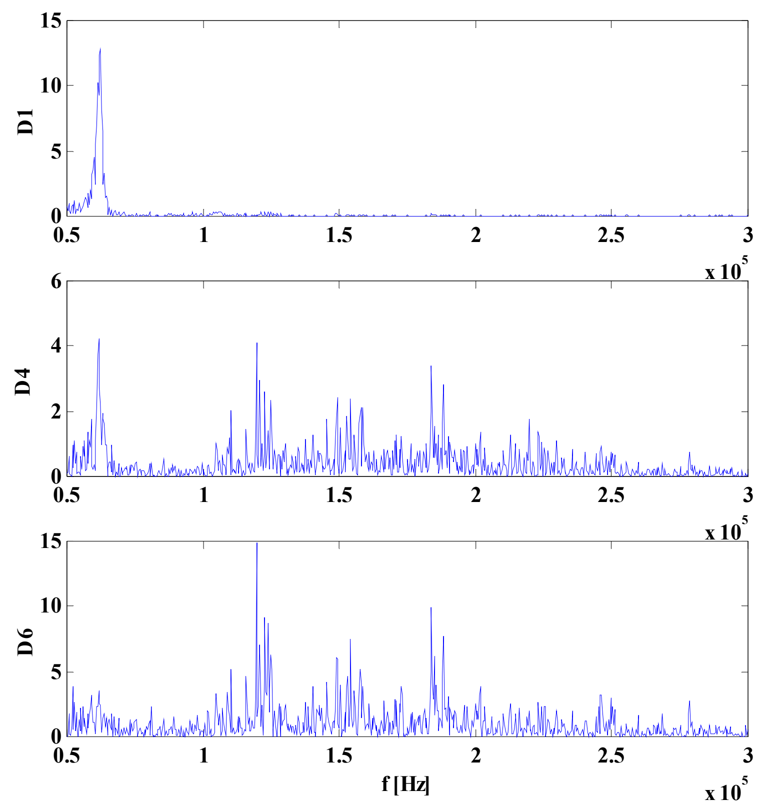
Fourier spectra of oscillations at various axial positions along the jet



z=17.5 mm
z/D=2.92

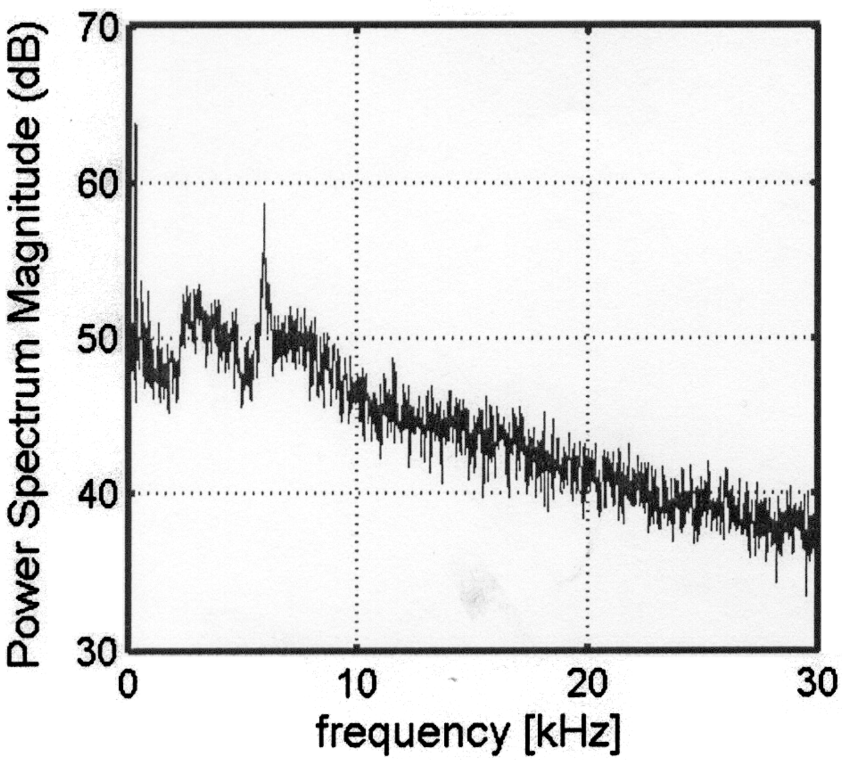
z=26.1 mm
z/D=4.35

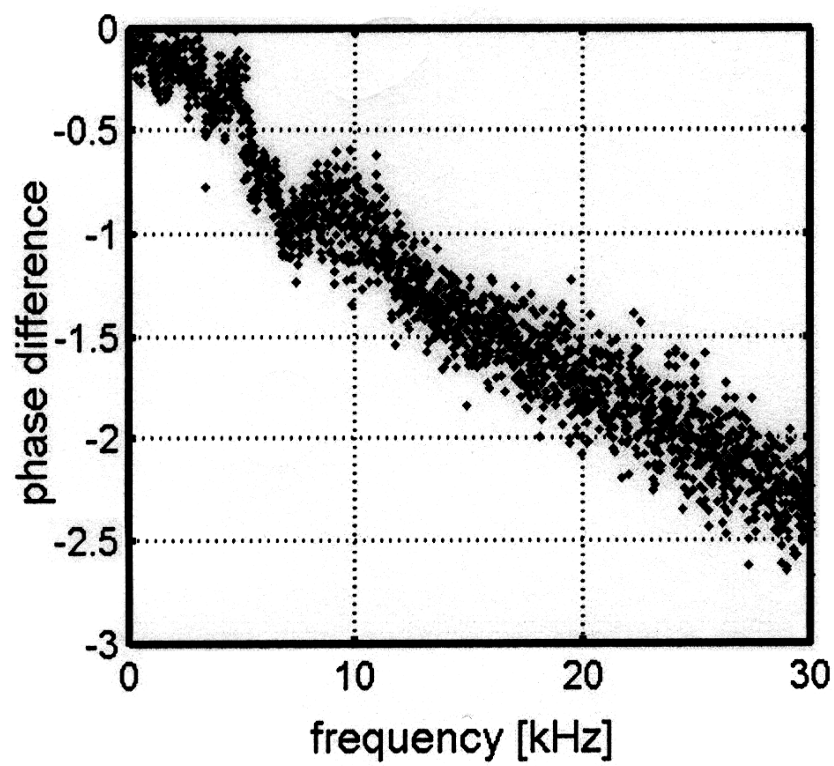
z=31.7 mm
z/D=5.28



Determination of flow velocity

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



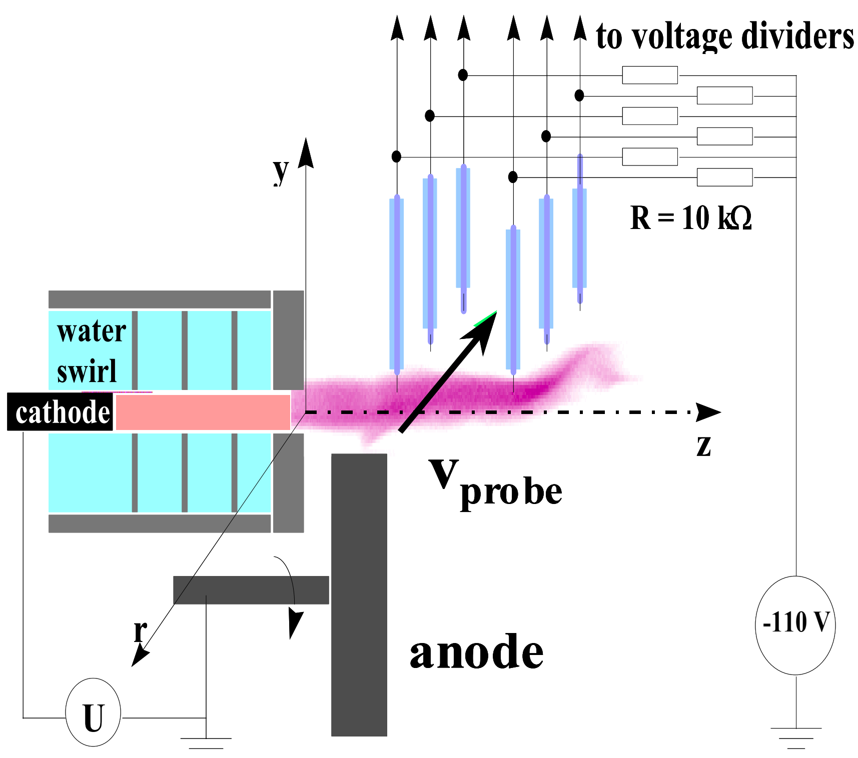


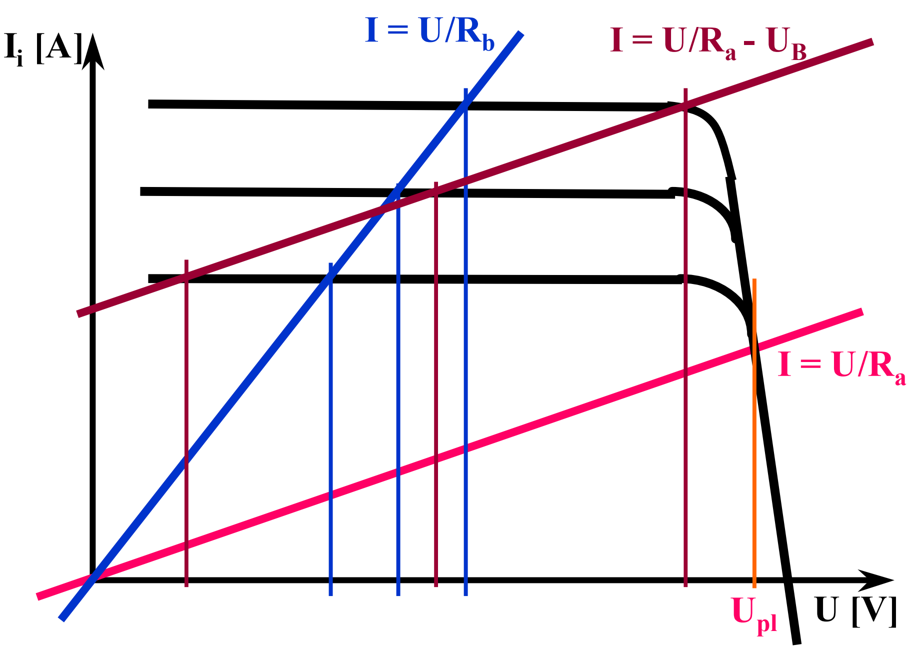
$$v = 2\pi D \frac{f}{\Delta\Phi} = 300\, m/s$$

F3/8

Electric probes in thermal plasma jet

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

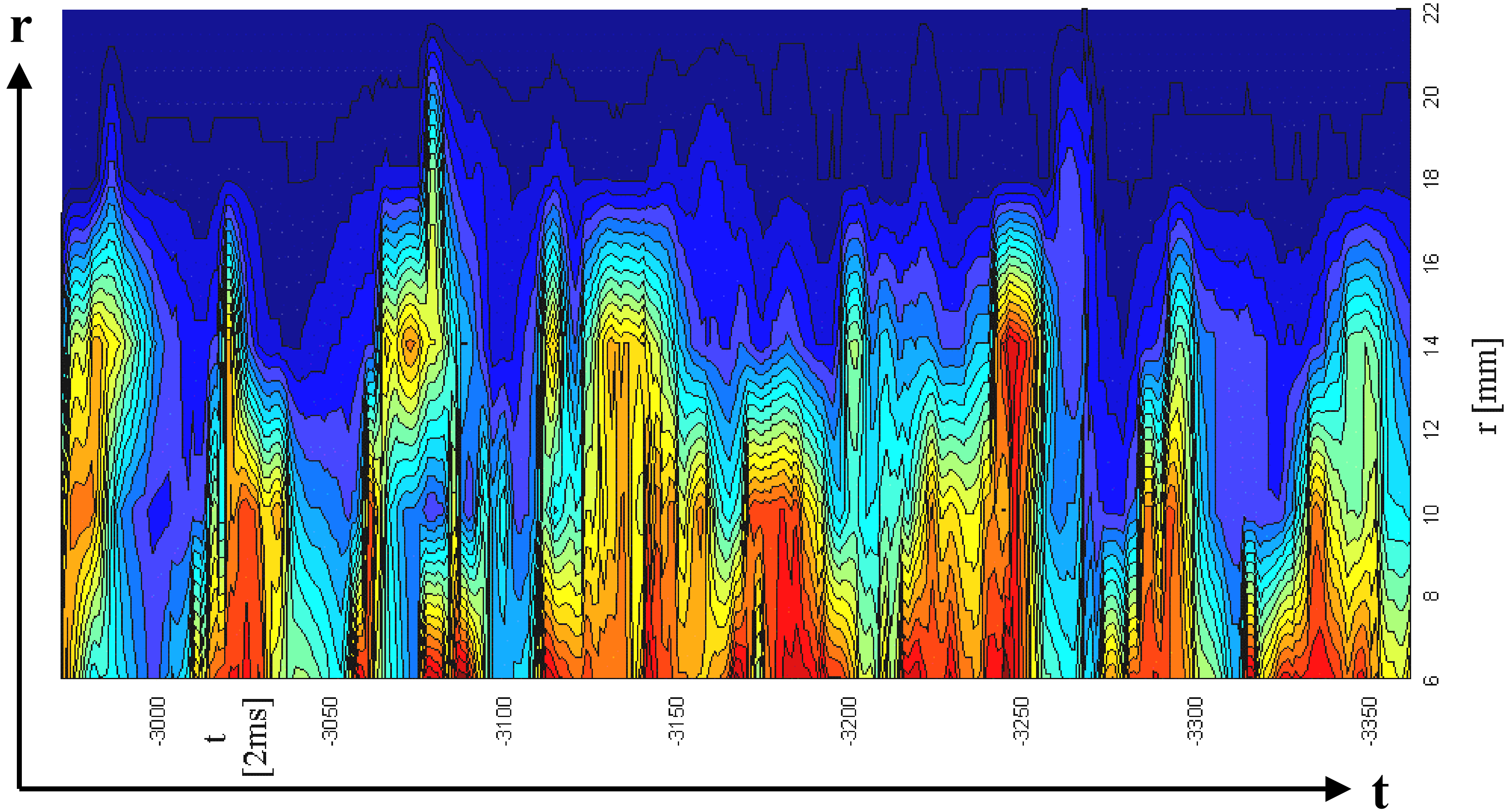




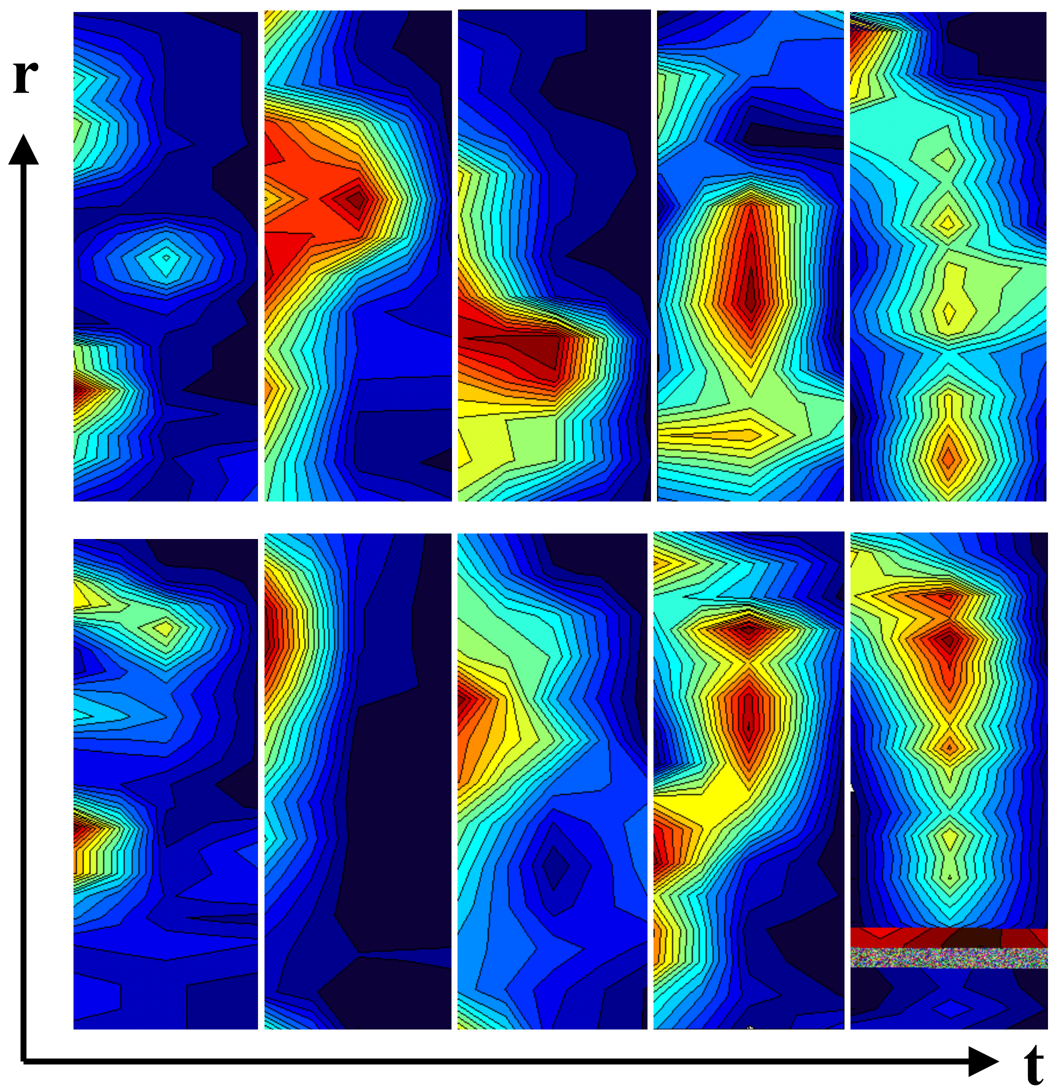
Determination of probe potential

Structure of the jet boundary

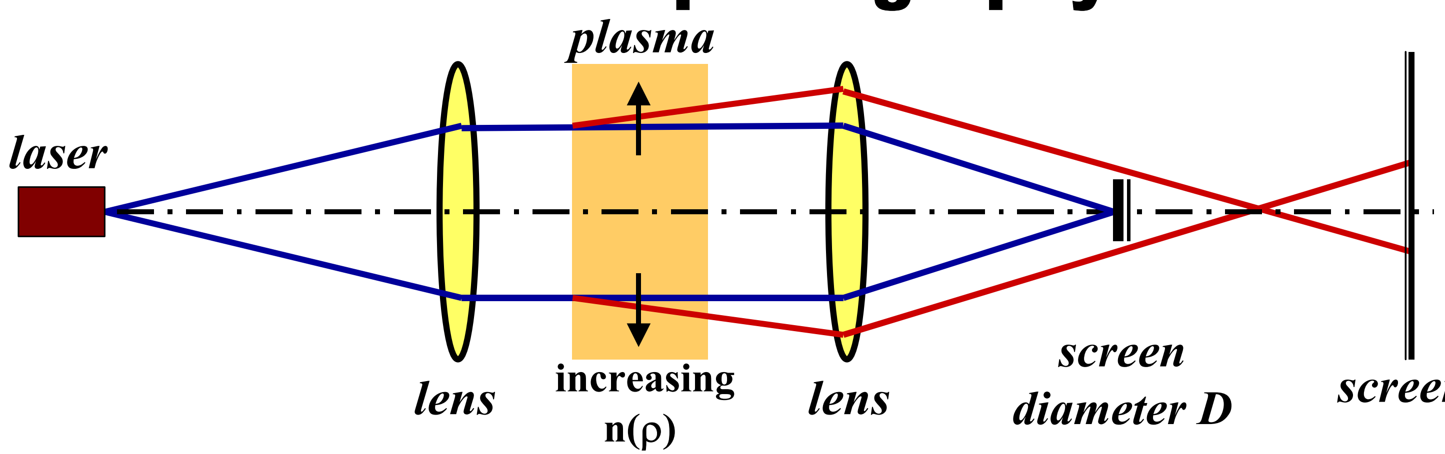
Lines of the same probe current at the plasma flow in the jet boundary



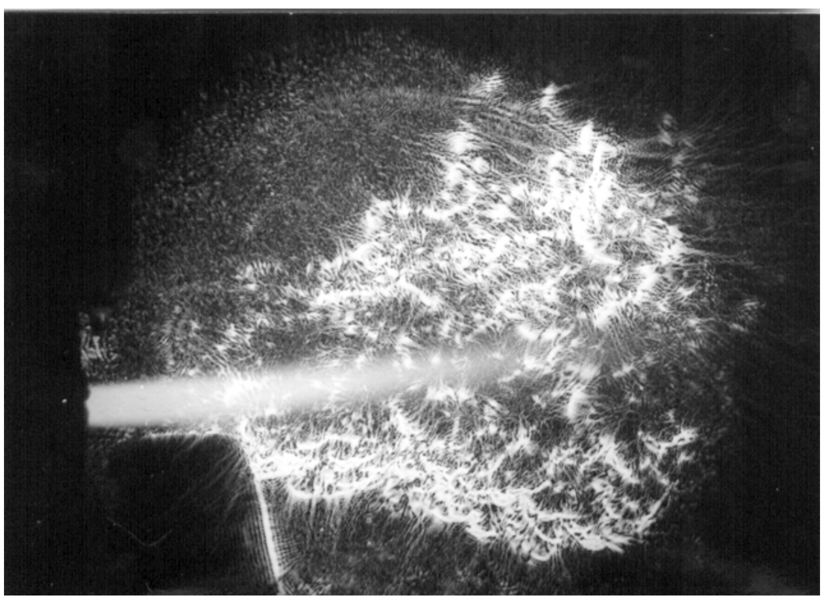
Development of shape of structures at the jet boundary



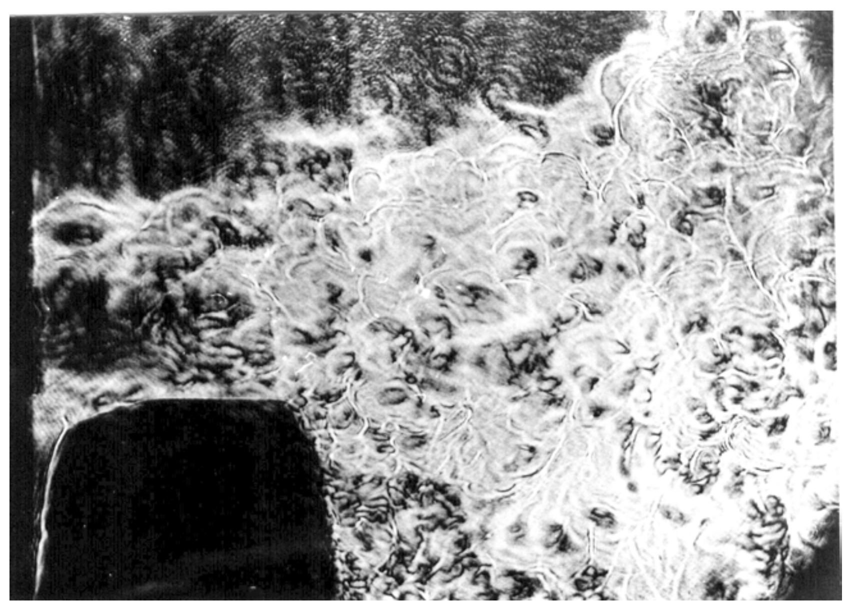
Schlieren photography



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