RF Ion Sources

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Outline

- Introduction
- Simple theory
  - Power absorption
  - Skin effect
  - Electron temperature
- Capacitive discharges
- Inductive discharges
  - High power
  - Low pressure
- Design of RF sources for different applications
- Helicon wave sources

RF discharges

Principle:

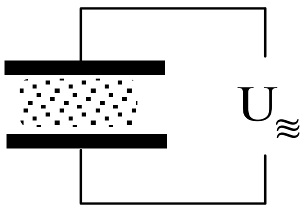
- Acceleration of electrons in an oscillating electric field with amplitudes < source dimensions
- Electrons gain energy, if there is “friction” (i. e. collisions)
- Ionizing collisions
- Equilibrium between ionisation and loss rates

Frequency range: 0.1 – 30 MHz

Power range: 50 W – 800 kW

Three different ways of RF coupling

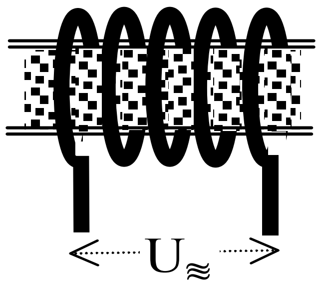
Capacitive coupling



f = 1 – 30 MHz

P = 0.05 – 0.1 kW

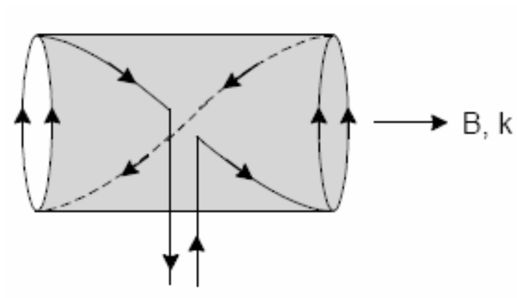
Inductive coupling



f = 0.1 – 13.5 MHz

P = 0.1 – 100 kW

Wave Coupling (Helicon)



f = 2 – 13.5 MHz

P = 0.1 – 1 kW

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Power absorption

Equation of motion of the electrons

$$m_e \cdot \ddot{x} + \underbrace{\nu_{Coll} \cdot (m_e \cdot \dot{x})} = -e \cdot E_0 \cdot e^{i\omega t}$$

Friction = Collision frequency x momentum

Solution

Current

$$j_0 = n_e \cdot \frac{e^2 \cdot E_0}{m_e} \cdot \left\{ \frac{\nu}{\nu^2 + \omega^2} \quad + \quad i \cdot \frac{-\omega}{\nu^2 + \omega^2} \right\}$$

Conductivity

$$\sigma_{HF} = n_e \cdot \frac{e^2}{m_e} \cdot \left\{ \frac{\nu}{\nu^2 + \omega^2} \quad + \quad i \cdot \frac{-\omega}{\nu^2 + \omega^2} \right\}$$

Absorbed power

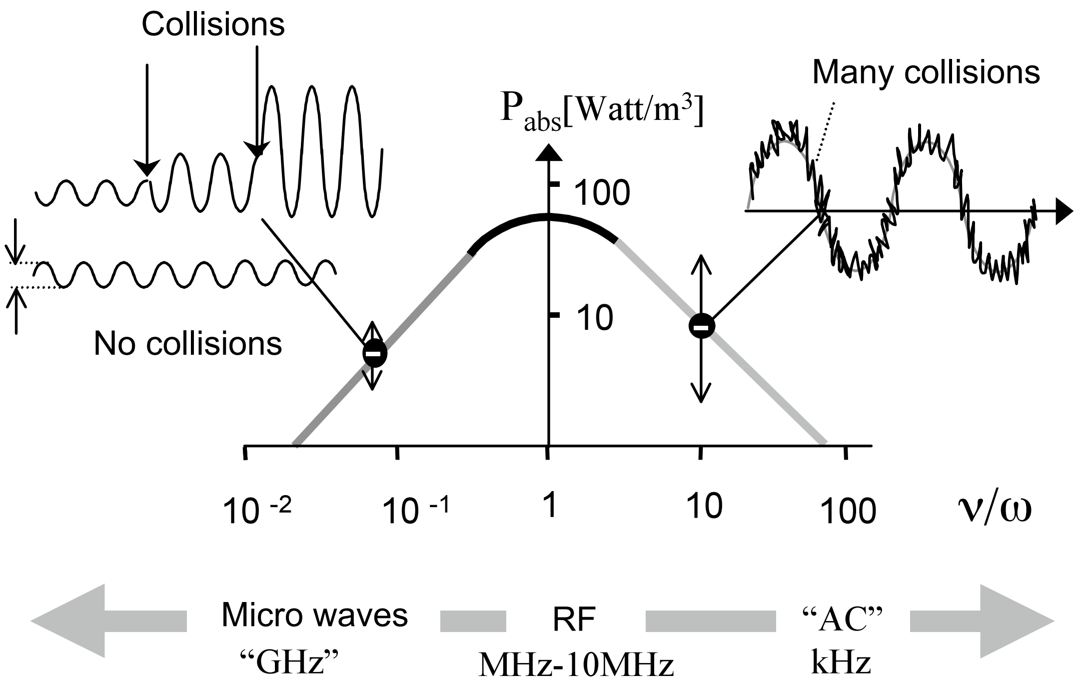
$$P_{abs} = n_e \cdot \frac{e^2 \cdot E_0^2}{2m_e} \cdot \left(\frac{\nu}{\nu^2 + \omega^2} \right)$$

Collisions necessary $\nu > 0$

P_{abs} maximal at $\nu \sim \omega$

P_{abs} decreases at high frequency

Illustration of the RF absorption



Limitations of the model

- Local E_{RF} field in has to be known
- E_{RF} field constant (not dependent on the plasma parameters)
- Low power, because B_{RF} field not considered (50 -100 G at 100 kW)
- No Coulomb collisions
- E_{RF} field homogenous (no skin effect)

Skin effect

The e.m wave vary as

$$\propto e^{i(kx-\omega t)}$$

If the RF frequency is much smaller than the plasma frequency the wave decays exponentially

$$\omega << \omega_p$$

$$\propto e^{-x/\delta_s - i\omega t)}$$

Decay length is the

Skin depth

Collisionless

$$\delta_s = c/\omega_p = (\frac{m_e}{e^2 \mu_0 n_e})^{1/2}$$

Collisional

$$\delta_s = (\frac{2}{\omega \mu_0 \sigma})^{1/2}$$

Typically **0.5 – 2 cm**, decreases at high frequency(!) and conductivity σ

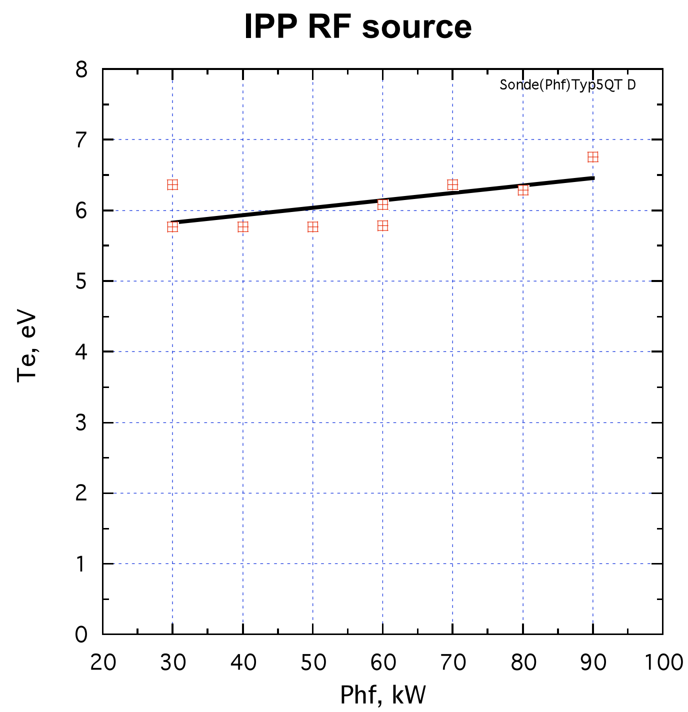
Electron temperature

Particle balance in uniform low density discharges with Maxwellian electron temperature

$$\cancel{n_e} \cdot n_0 \cdot \langle \sigma_{ion} \cdot v_e \rangle \approx \frac{\cancel{n_e} \cdot L}{c_s}$$

Ion production by electron–neutral collisions

Wall losses
L = effective plasma size



v_e and c_s depend on Te

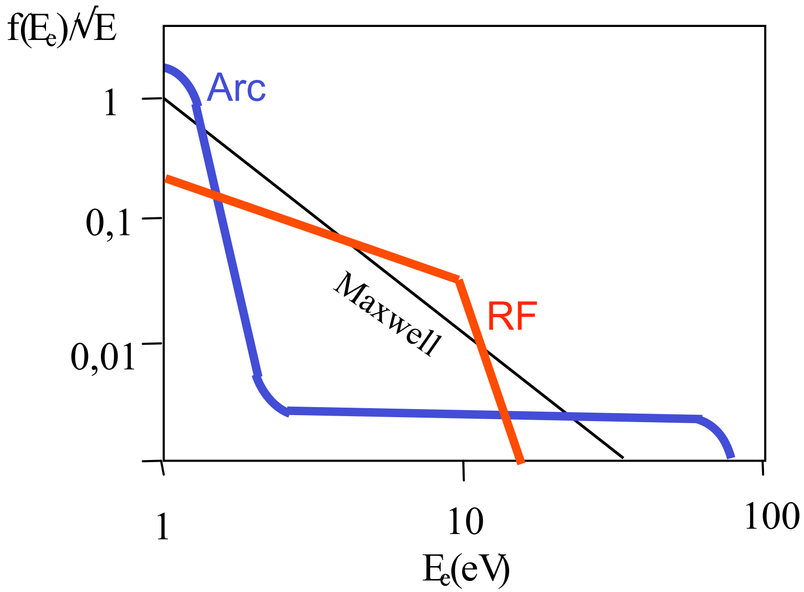
=> **T_e is independent of the plasma density n_e and therefore independent of the input power**

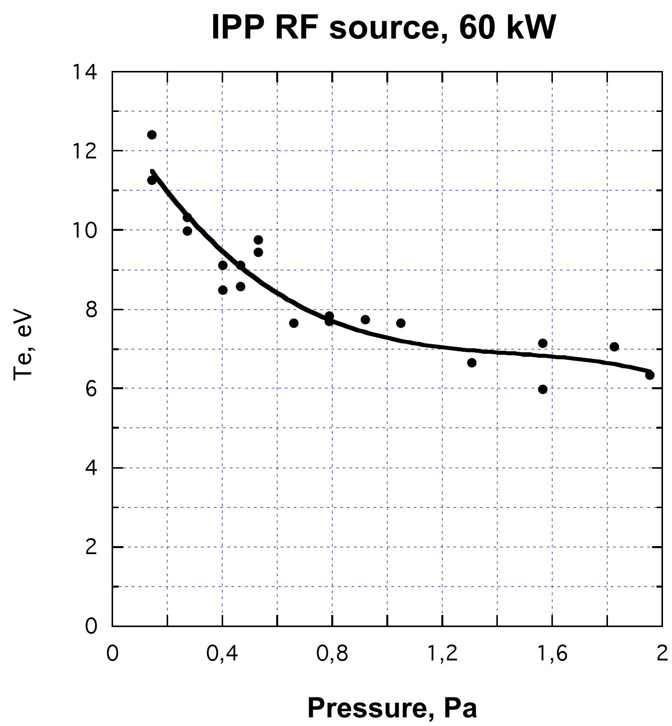
Electron temperature distribution

- Depends on the distance to the coil
- Determined by the gas density (pressure)

No Maxwell distribution

At high energy reduced by inelastic collisions



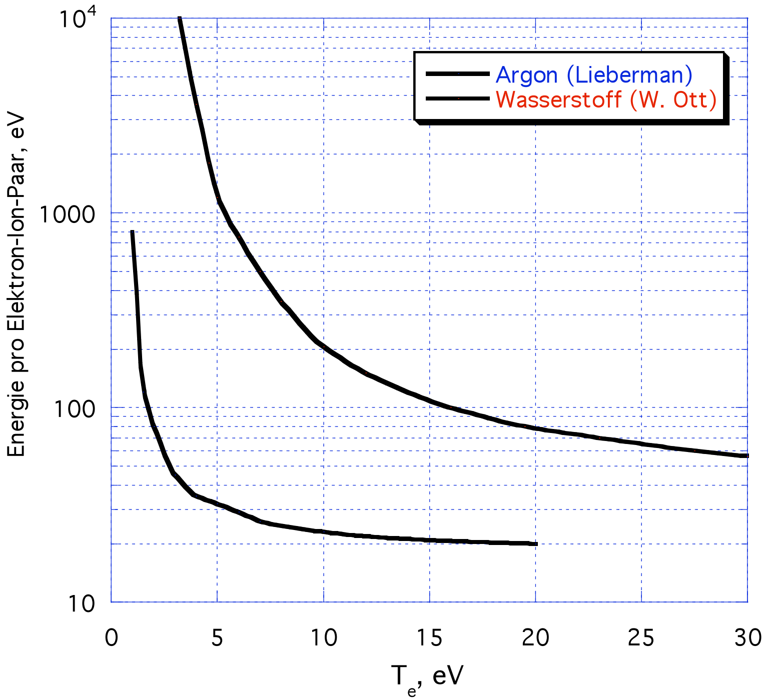


Energy loss per electron-ion pair created

Power balance

$$P_{loss} = \frac{n_e}{\tau_p} \cdot (m \cdot E_{ion}) = P_{abs}$$

m represents energy losses by excitation of vibrational and rotational energy levels, molecular dissociation, energy loss at the wall



***mE**$_{ion}$* : energy needed for an electron-ion pair

- Can be measured by the decay time of the plasma
- Is for molecular gas one order of magnitude higher than the ionisation energy

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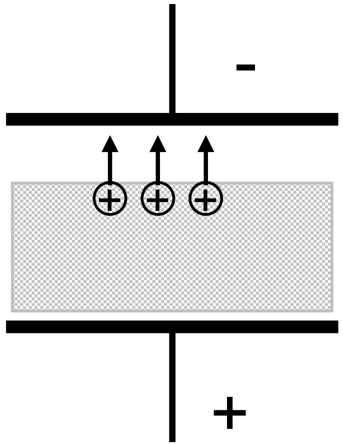
Capacitive discharges

"Electron cloud" ozillates between the electrodes

=> High RF voltage drop in the cathode sheath



RF frequency << ion plasma frequency

⇒ Ions are accelerated in the sheath

⇒ most of the RF power goes for the ion acceleration

⇒ bombardement of the electrodes by energetic ions of some keV

=> Used for surface treatment in the plasma technology

RF frequency >> ion plasma frequency

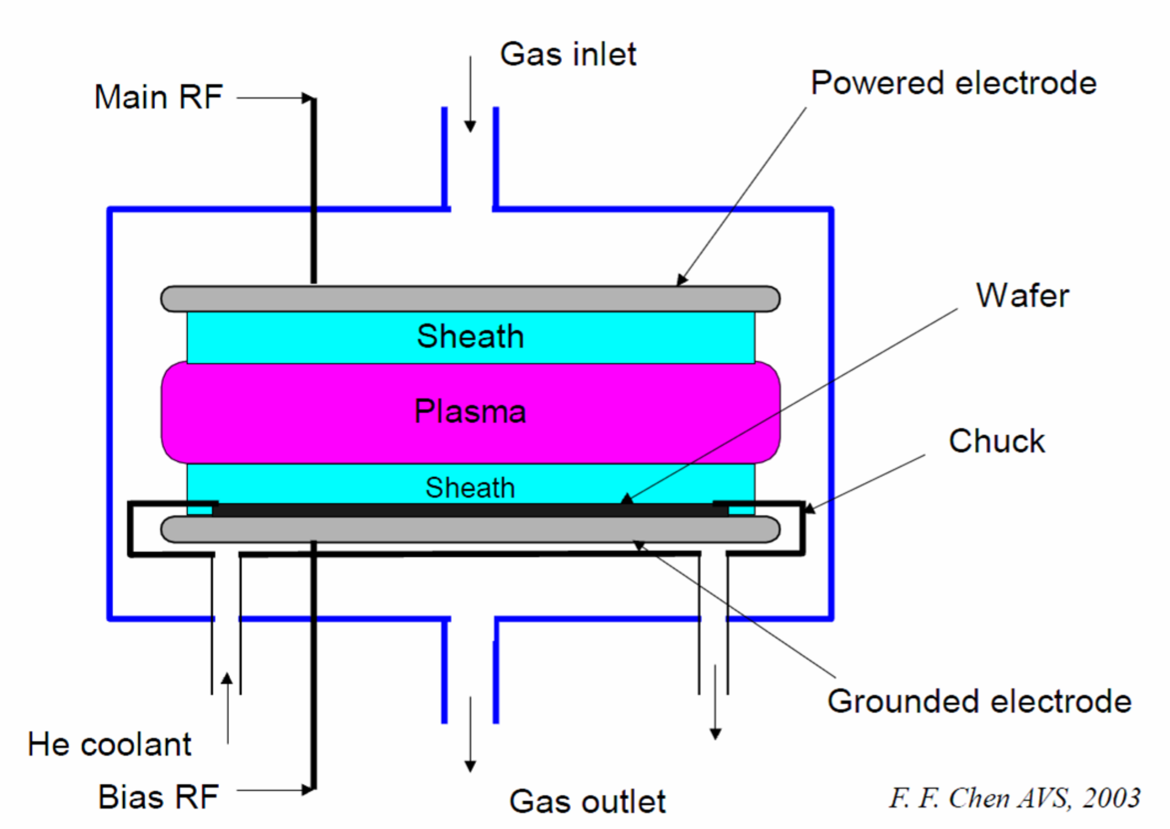
⇒ Ions cannot follow the RF field

⇒ Low ion energy of some 10 eV

Transition region 5 – 10 MHz

$$\omega_{pi} = \sqrt{\frac{Z^2 e^2 \cdot n_e}{\varepsilon_0 \cdot m_i}}$$

Schematic of a CCNP Processing Chamber



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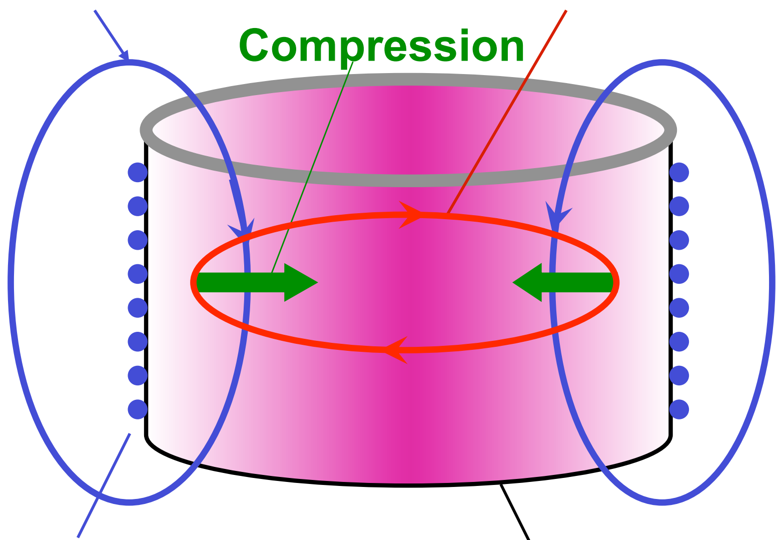
Inductive discharges

1. RF current in the coil I_{RF} produces an axial magnetic field

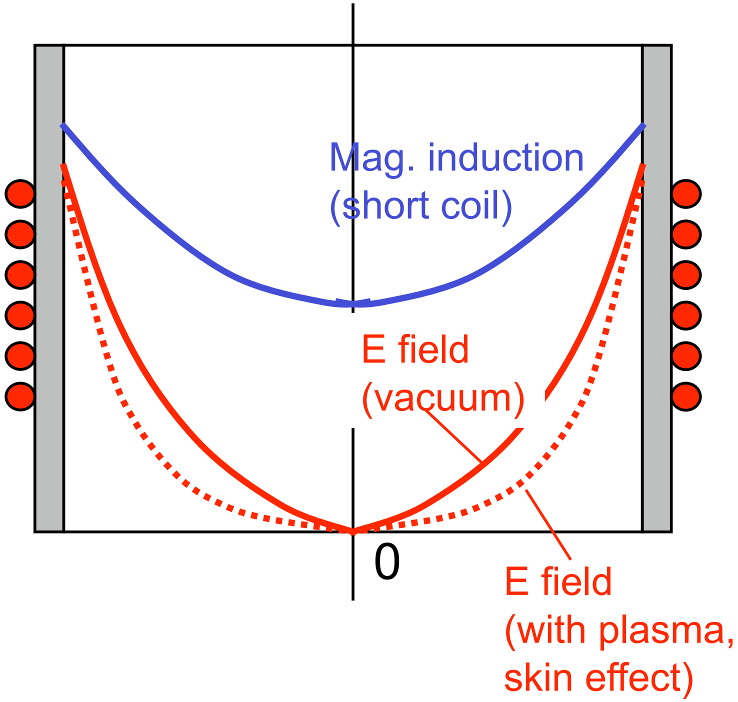
2. Magnetic field induces an electric field

3. Acceleration of the electrons and ionizing collisions with the neutrals

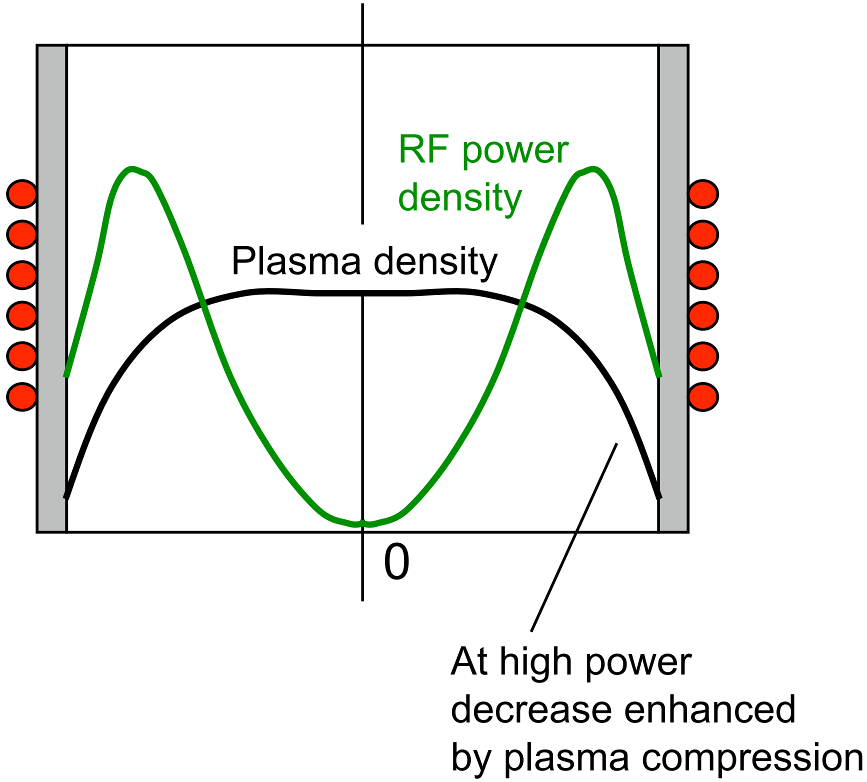
4. Plasma compression by Lorentz force
   => reduces skin effect
   => better coupling at high power



RF fields



Mag. induction
(short coil)
E field
(vacuum)
0
E field
(with plasma,
skin effect)



RF power
density
Plasma density
0
At high power
decrease enhanced
by plasma compression

Limits of the classical theory in powerful inductive discharges

- Collisions needed for the power absorption
- Electron temperature not dependent on the plasma density or power
- Skin depth decreases at high conductivity i. e. increasing plasma density

  => saturation of the power coupling, reduced energy transfer to the center of the source

- Collisionless power absorption possible

$\Rightarrow$ Stochastic heating

- At high power induced E-field sufficient for ionisation
- T_e increases at high power due to neutral depletion
- No saturation observed due to plasma compression

Low pressure: Stochastic heating

Power absorption without collisions by

- Inhomogenous RF field (skin depth)
- Static magnetic fields

Reduction of the Gyration radius of the electrons in the stronger B field

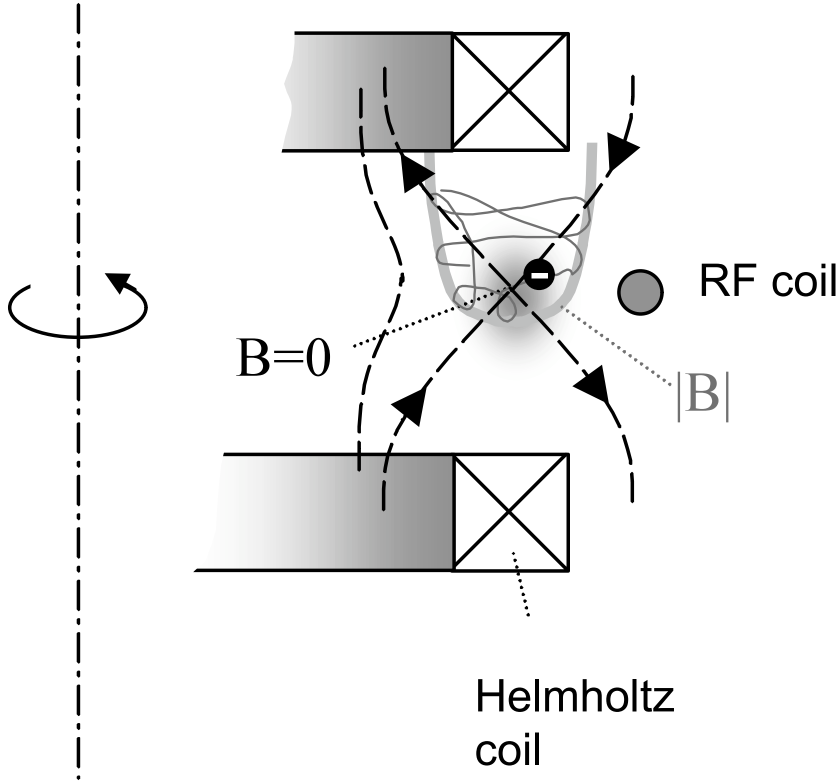
⇒ Reflection

⇒ "anomal collision frequency"

Enables operation with low gas density

Example

Neutral loop discharge



High Power: Neutral depletion

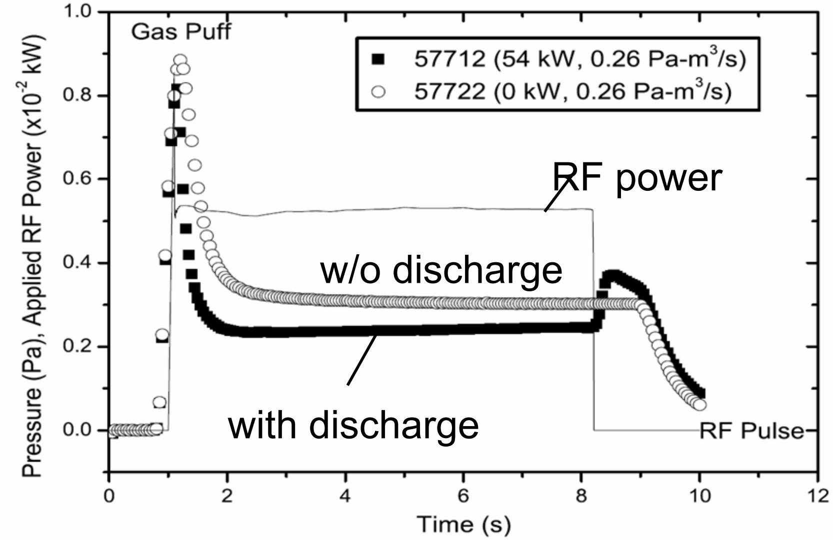
Most Ion Source modeling assumes:

- Neutral gas is at room temperature
- Neutral gas is uniformly distributed
- Degree of ionization is small

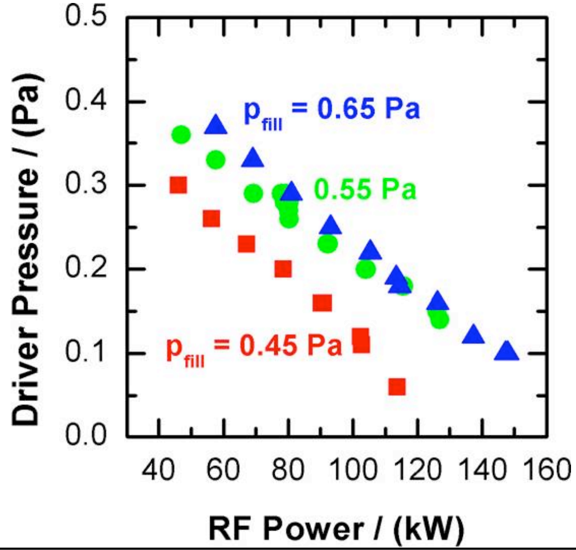
  Theory: Neutral gas represents a constant background

  Holds only when n_e, T_e are low and $T_e >> T_i$

  Reality: After the discharge ignites temperature and density change => RF coupling at high powers, i.e. low driver pressure difficult



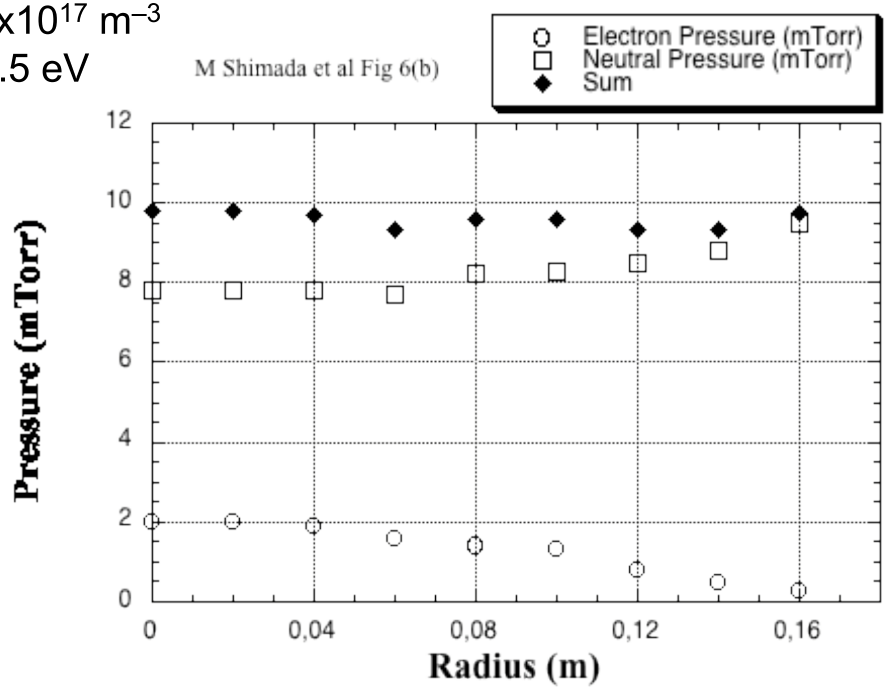
Measured pressure drop during the discharge



Pressure balance at high power

Ar/5%N_2
n_e: 6×10^{17} m^{-3}
T_e: 2.5 eV

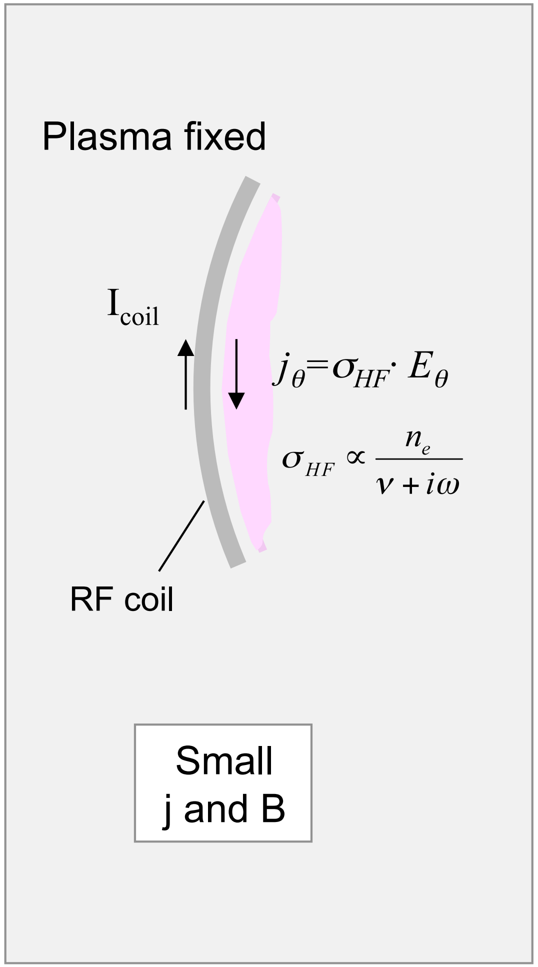
The **neutral pressure is depleted** due to the pressure balance when the plasma pressure (electron pressure) becomes comparable to the neutral pressure



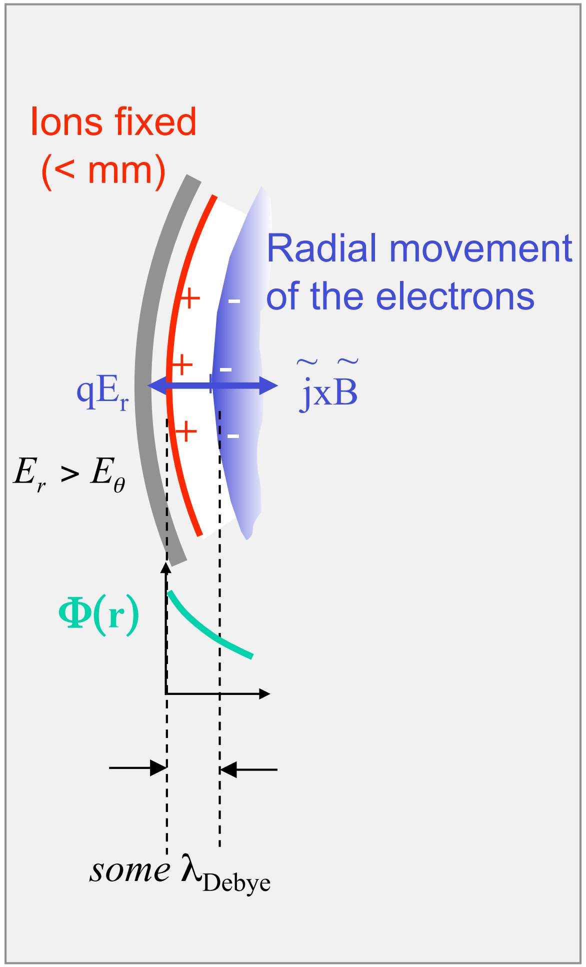
$$n_{n,w}kT_w = n_nkT_n + n_ekT_e + n_ikT_i$$

High power: Plasma compression by E x B forces

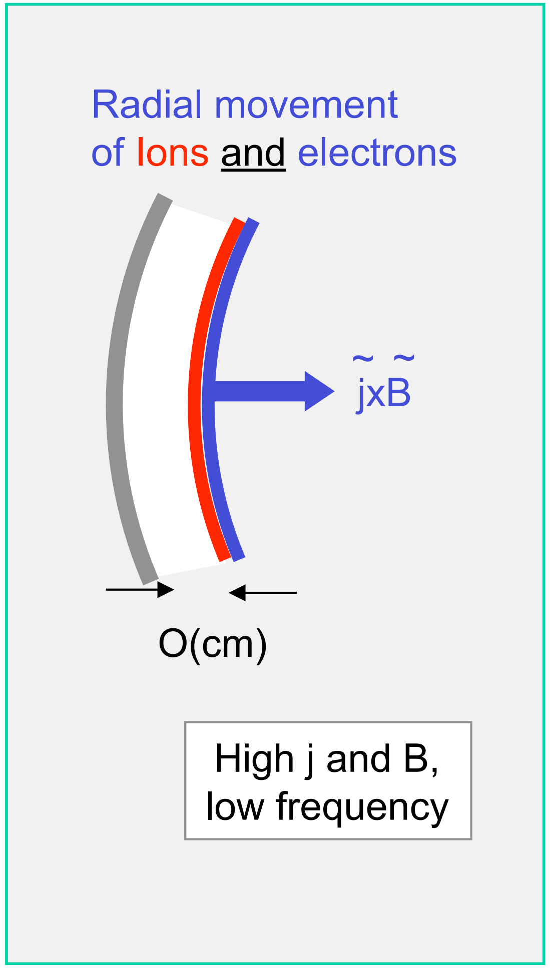
Low power (0.1 kW)



Medium power (some kW)



High Power (10 - 100 kW)



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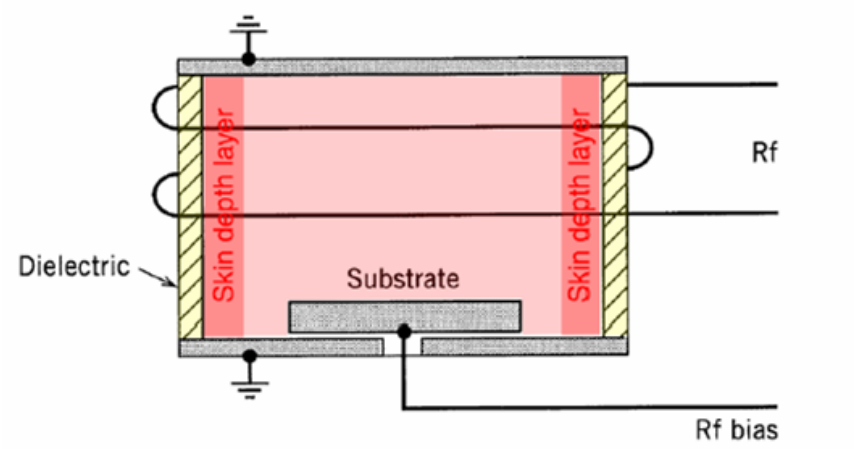
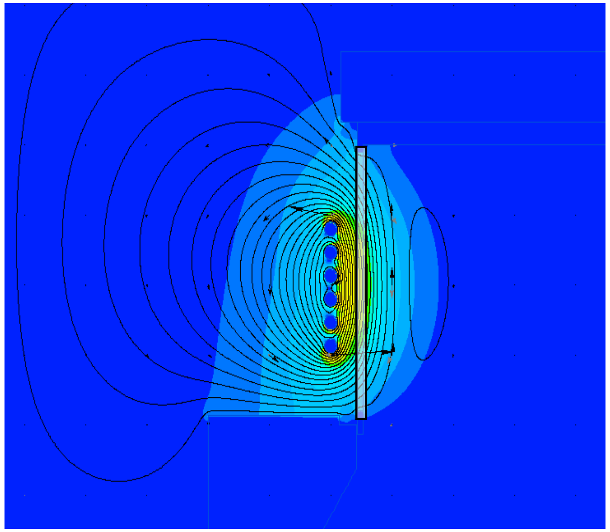
Main ICP topologies in industrial applications

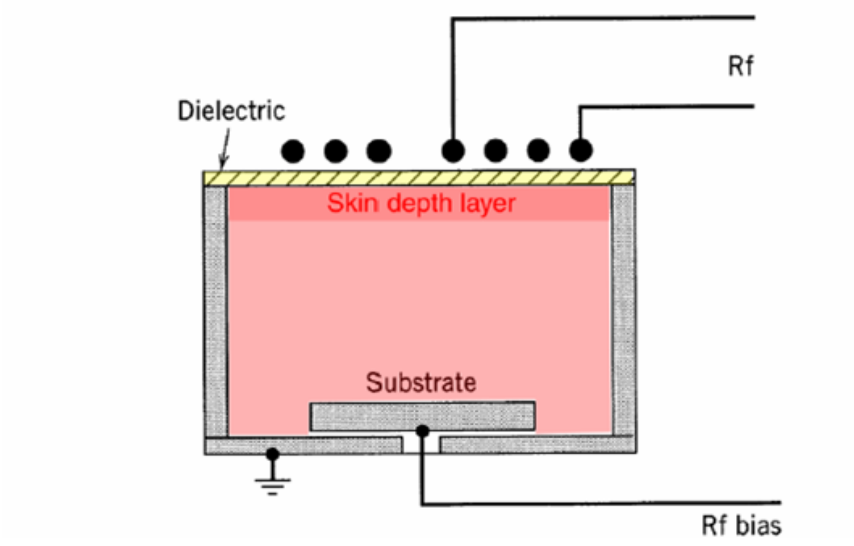


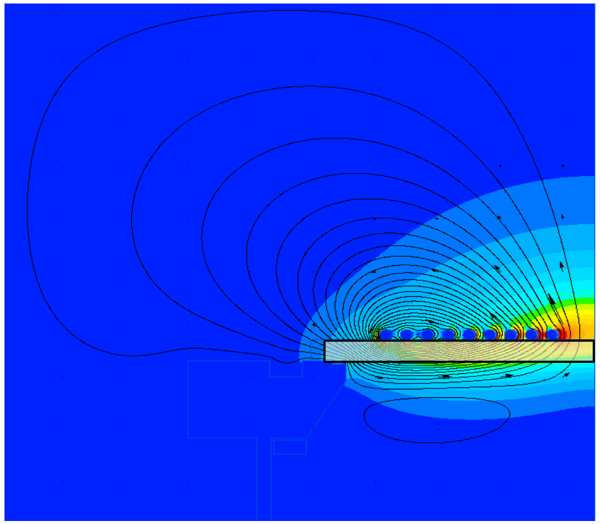


Cylindric

Insulator

0.2 - 0.6 cm





B_{RF} field distribution

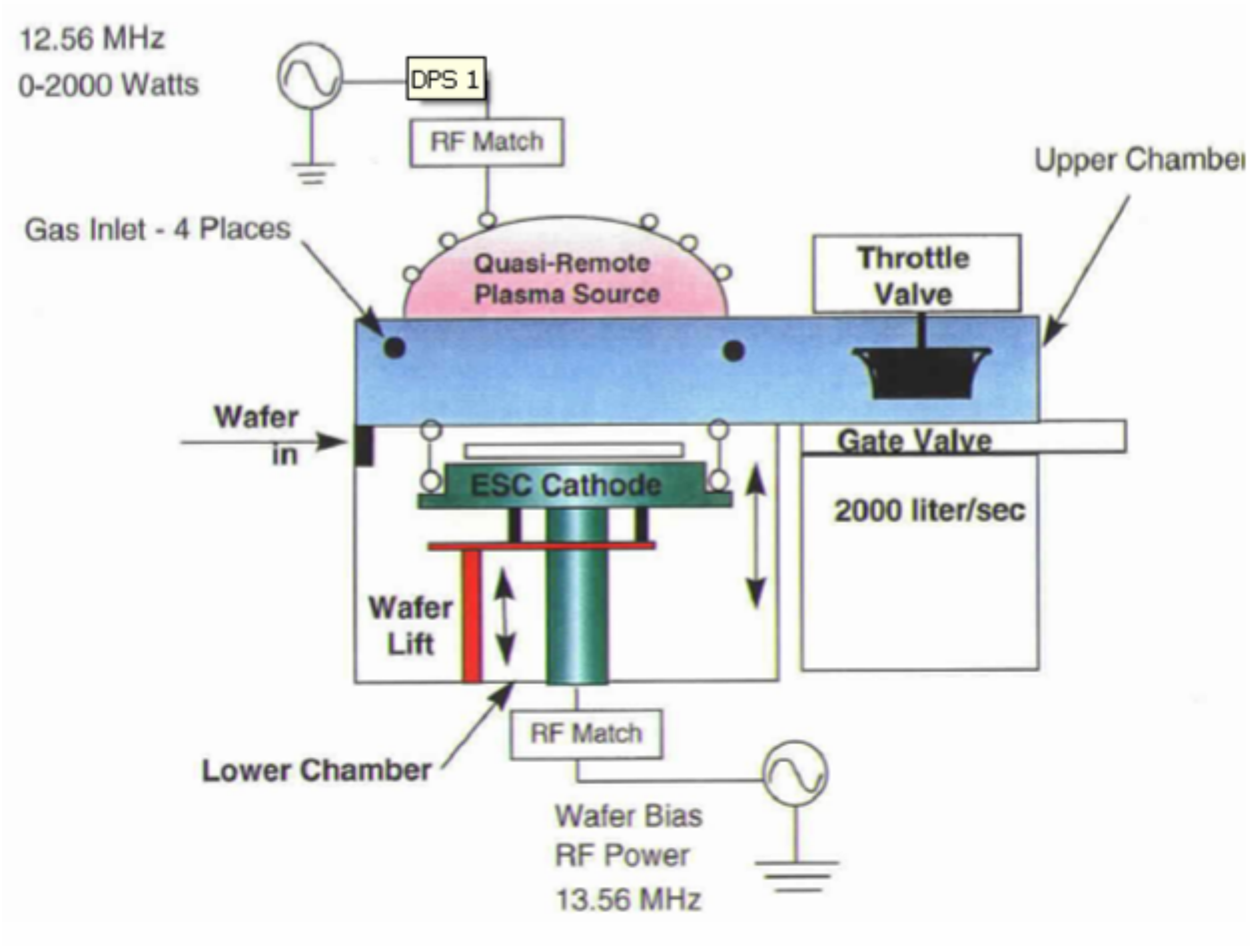
Plate

Insulator

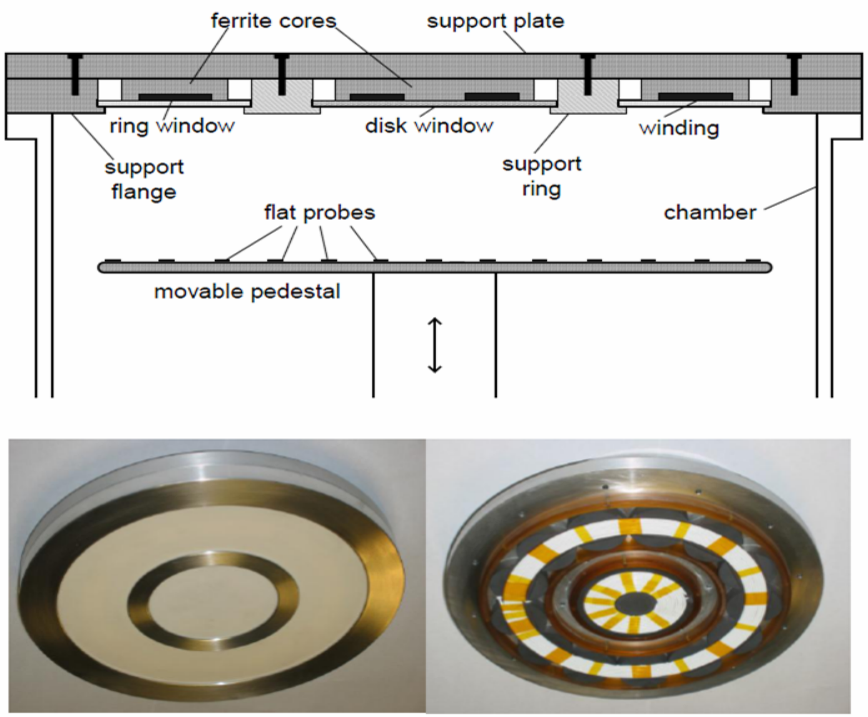
1-2 cm

=> Poor coupling

ICP based plasma processing tool

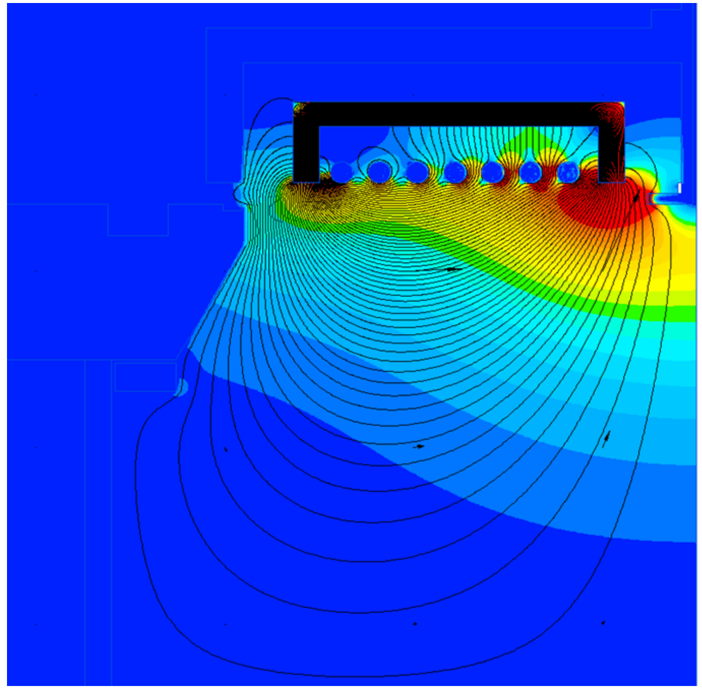


ICP Enhanced with Ferrite Core



V. Godyak, PSST ***20****, 025004, 2011*

B_{RF}



Ferrite cores for

- Concentration of the RF field => better coupling to the plasma
- RF shielding => support plate => thin insulator => better coupling to the plasma

Internal antenna

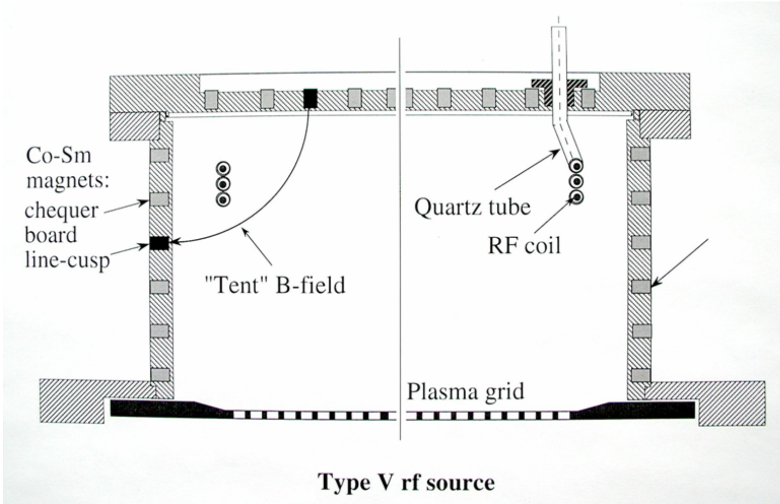
- **Better coupling to the plasma**
- **Lower wall losses due to larger area of magnetic cusps**

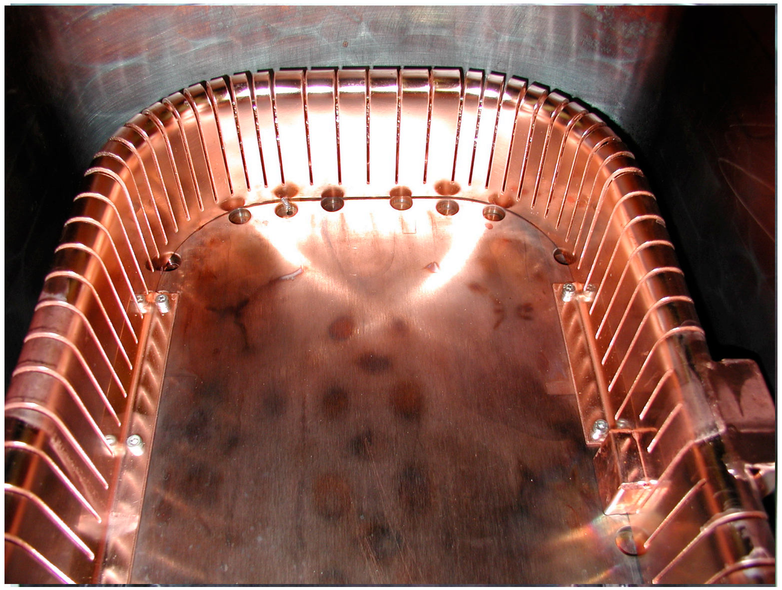
Insulation

- Porcelain coating
- Quartz tubing

Problem: Lifetime of the insulation

- RF breakdowns,
- Sputtering
- Difficult to protect it by a Faraday shield

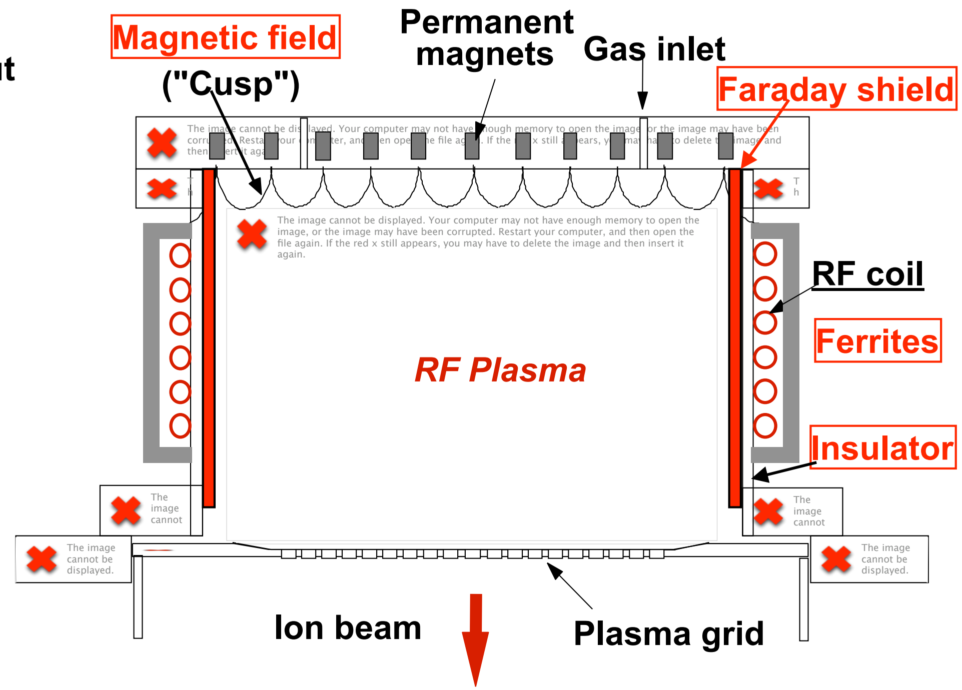




Design of high power ICPs

Insulator

- Quartz or Pyrex (**low expansion coeff. but chemically active)**
- Al_2O_3 (**chemically stable, high temperature)**
- AlN (**high thermal conductivity)**



Magnetic cusp field

- Improves the plasma confinement
- Reduces plasma losses

Faraday shield

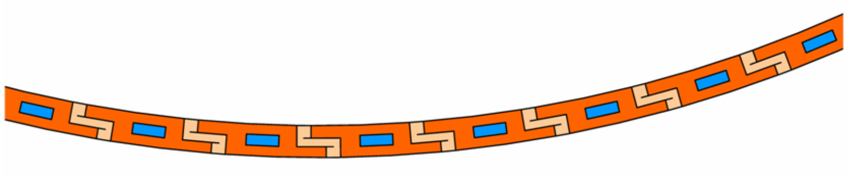
- Shields capacitive coupling
- protects insulator from chemical and physical sputtering

Ferrites

- Shields RF fields
- Improves the coupling to the plasma

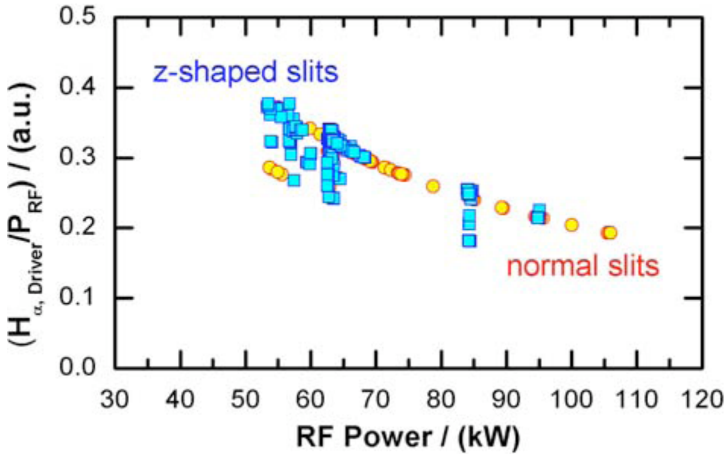
Internal Faraday shield for high power ICPs

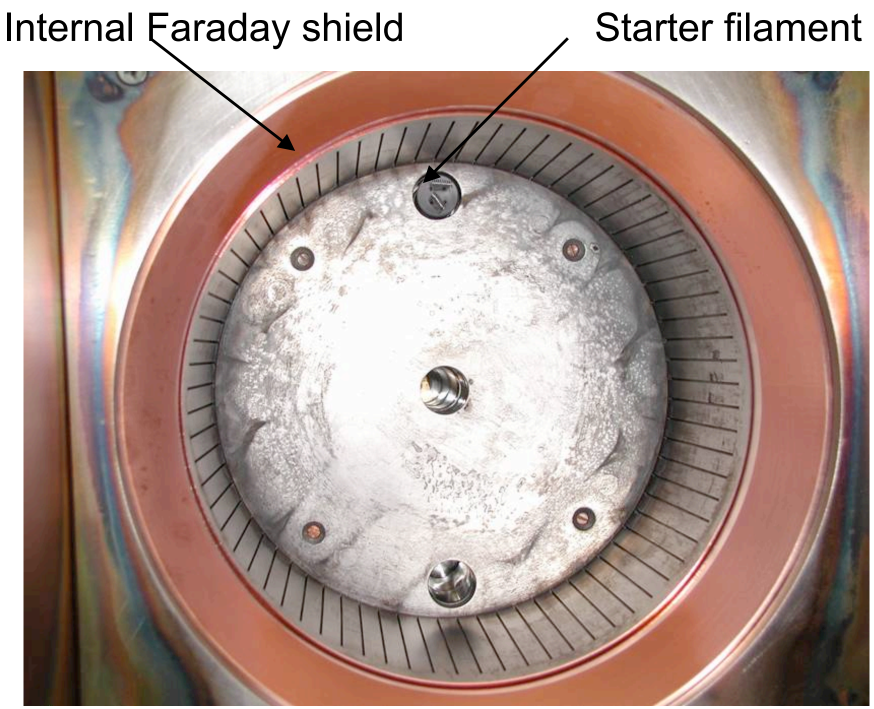
B_{RF} field penetrates through the slits even when they are Z-shaped



- No power load on the insulator
- H_α radiation in the driver not changed

⇒ No additional power losses by eddy currents





Ignition of the plasma

Condition for the ignition

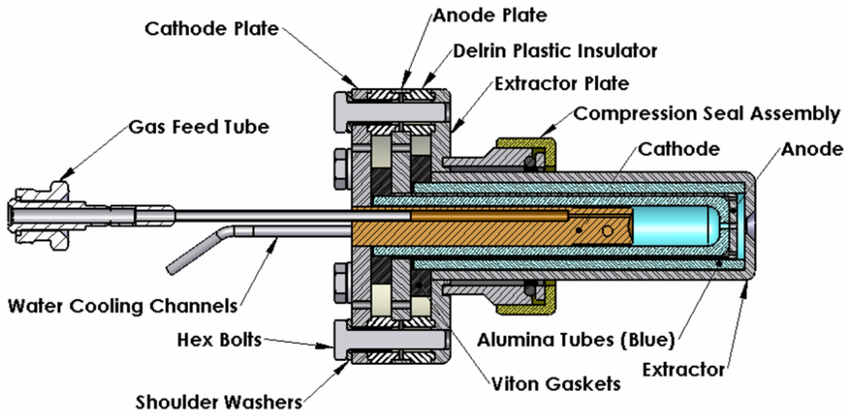
Ionisation rate > rate of wall losses

More difficult without capacitice coupling,

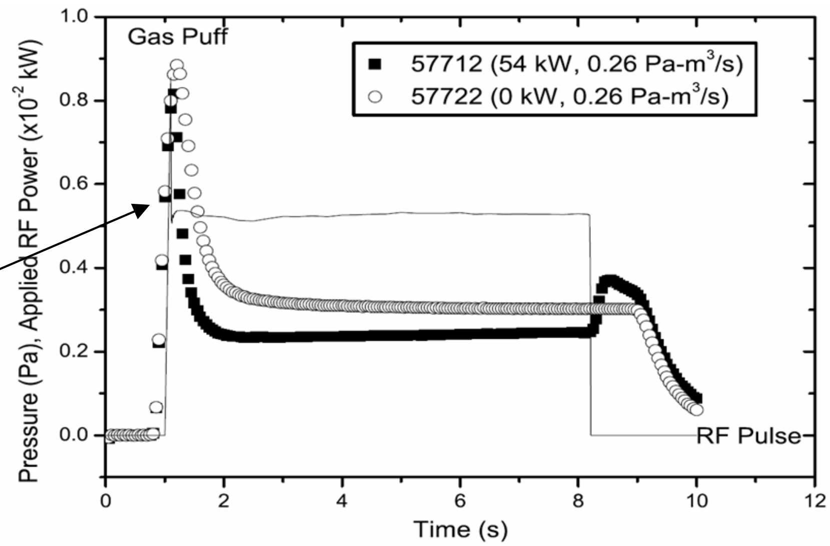
i.e. with Faraday shield

Additional electron source necessary

- Electron gun
- Filament and/or pressure pulse



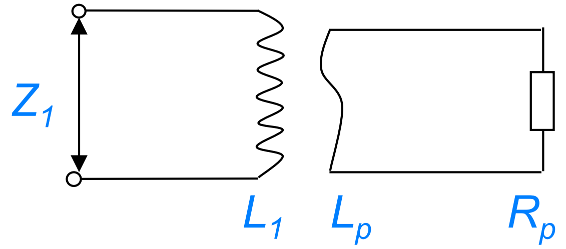
Electron gun (ORNL)



Matching circuit

RF coil and plasma are a transformer

Transformation of the plasma impedance depends on coil inductance



$$Z_1 = j\omega\left(L_1 - \frac{(\omega M)^2 L_p}{R_p^2 + \omega^2 L_p^2}\right) + R_p \frac{(\omega M)^2}{R_p^2 + \omega^2 L_p^2}$$

$M = k\sqrt{L_1 L_p}$

= mutual inductance, k = coupling

Matching to 50 Ω by a parallel and a (variable) series capacity or by frequency matching

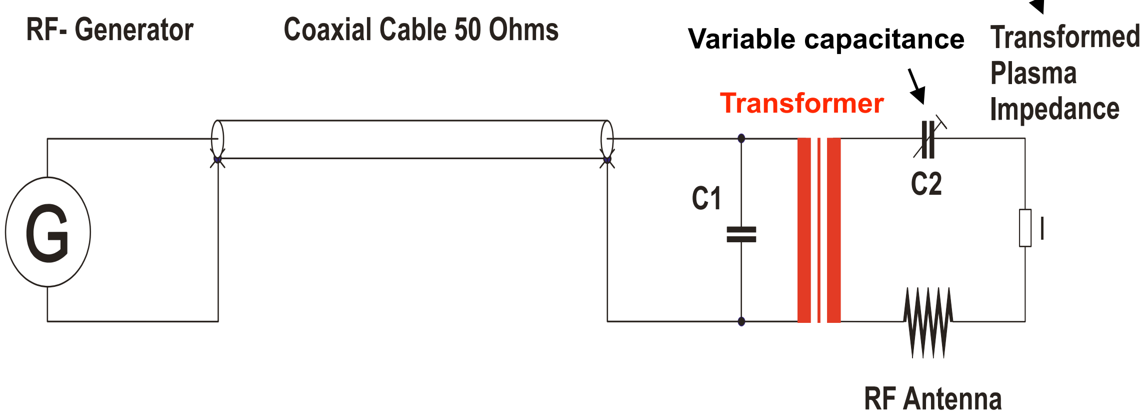
Frequency mostly 13.56 MHz

Low frequency is advantageous

- larger skin depth $\propto \sqrt{\omega L}$

  => lower ohmic losses
- lower coil voltage

  => less capacitive coupling, less breakdowns



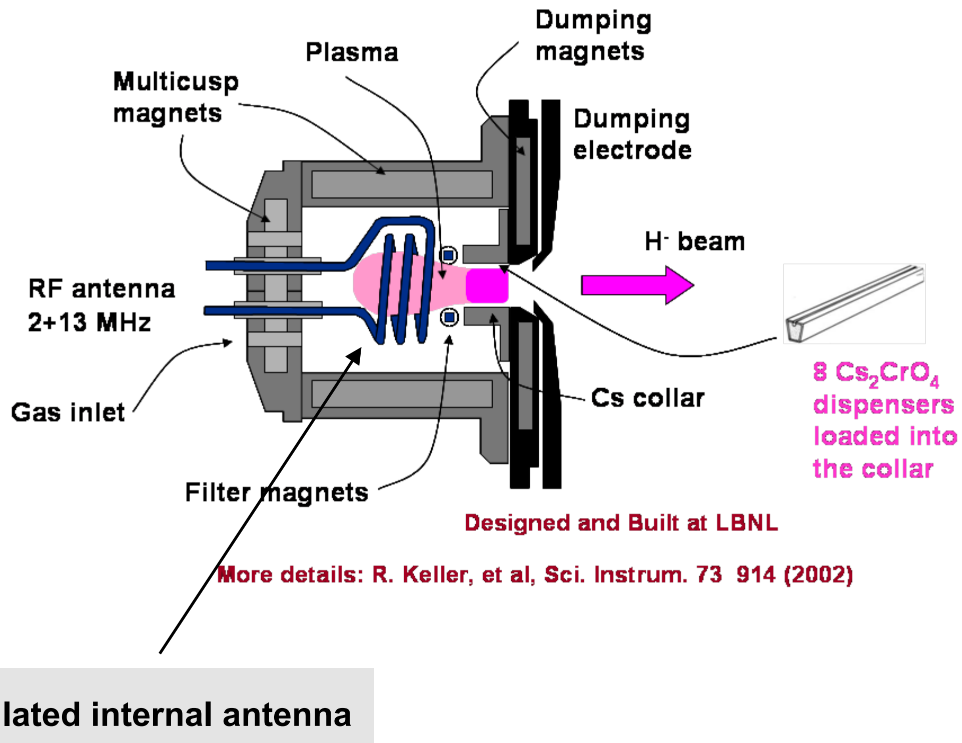
RF sources for accelerators

Up to 100 kW at 2 MHz in small volumes (L ~10 cm, Ø~ 5 cm)

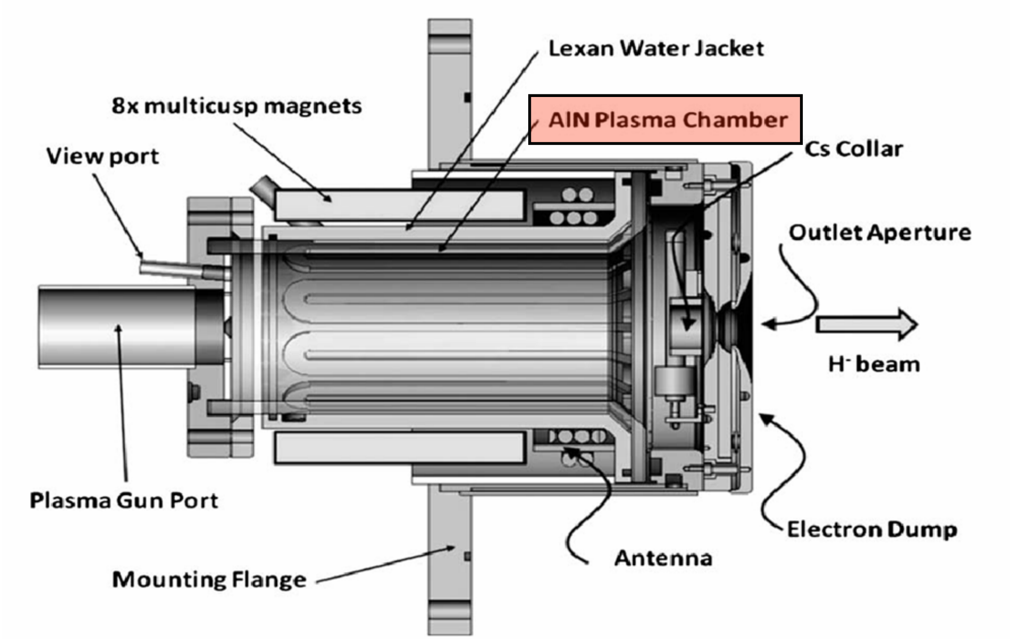
Pulse duration 0.5 ms with a repetition rate of 4 - 60 Hz

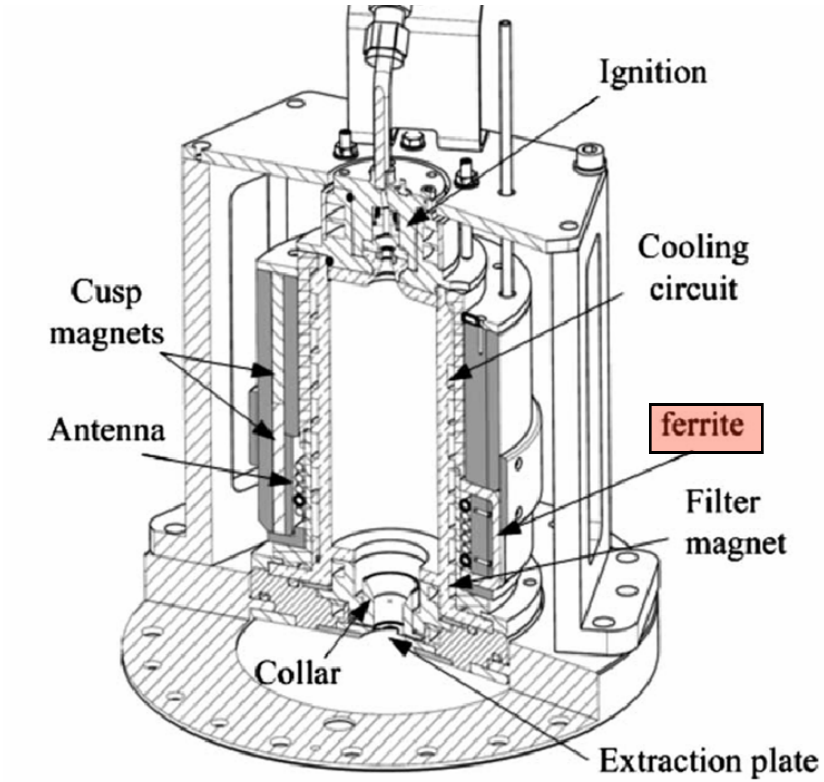
40 -80 mA H^-current produced by surface conversion on Caesium surfaces

First design by LBL (Berkeley, USA)



RF sources for accelerators: present design





Ion source of the spallations neutron source (ORNL Oakridge National Laboratory)

100kW/2MHz RF source of the LINAC4 accelerator (CERN)

Ion thrusters for spacecraft propulsion

Tsiolkovsky rocket equation:

$$v_e = v_T \ln \frac{m_0}{m_e}$$

Maximum speed = exhaust velocity x ln(Initial mass/final mass)

Chemical thrusters		small	large
Electrical thrusters	**up to 25 x larger**	large	small

- Small thrust (0.1 - 1 N) but
- Very reliable
- High propellant capacity
- propulsion energy provided by an electric source
- exact control of the thrust

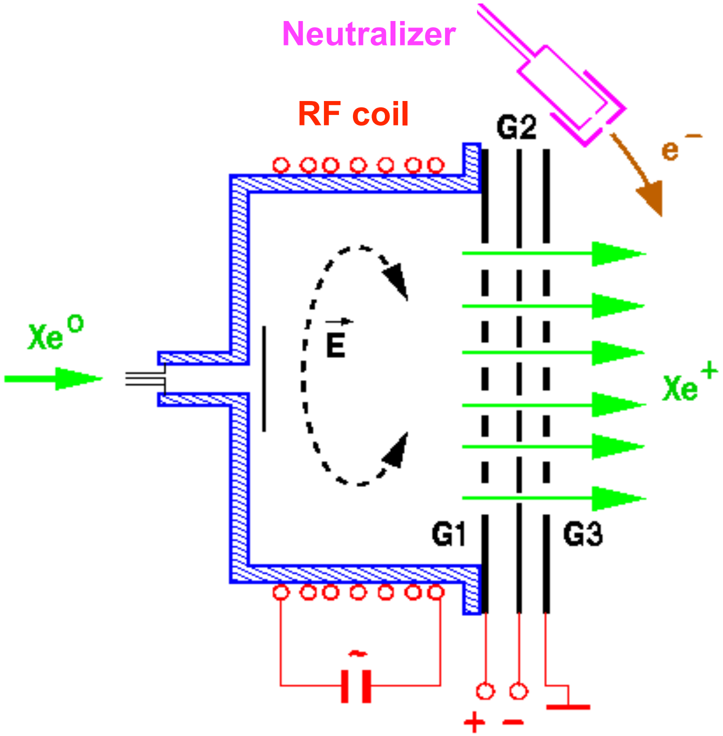
  => used for

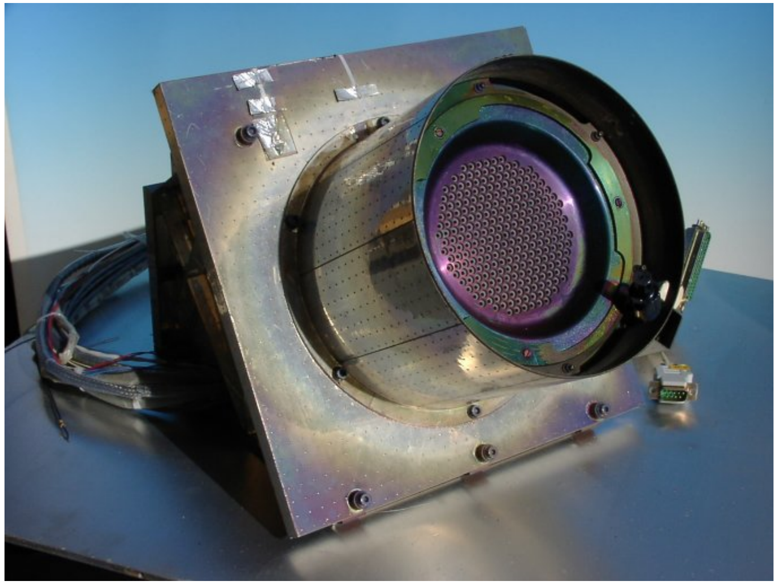
  space missions, space probes

  orbit control of satellites

RF ion thrusters

RIT 10
Giessen university





Propellant: **Xenon**
(high mass => high momentum => high thrust)
10 cm diameter,
Thrust: 0.01 – 1 N

Acceleration voltage: ca 2 kV
Power supply: solar
4 MHz, few 100 W,

RF ion sources for the Neutral Beam Injection systems of Fusion Reactors

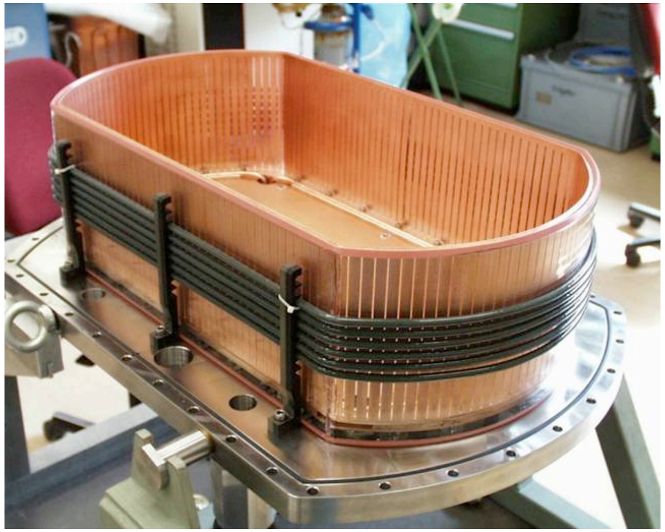
IPP

Positive H/D ions

ASDEX-Upgrade, 1997

100 kW / 1MHz,

32 x 59 cm^2



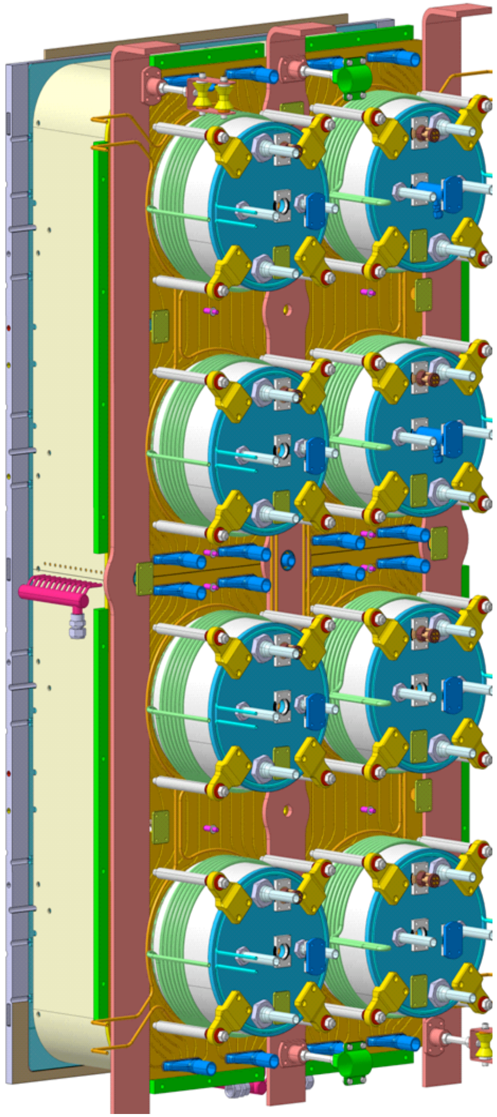
Negative H/D ions

ITER, 2015

800 kW / 1MHz,

8 “drivers”,

190 x 90 cm^2



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Helicon wave sources

RF antenna launches a wave, the **helicon wave**, that propagates along an static **B-field** with a phase velocity comparable of a 50 – 200 eV electron

- Very efficient ionisation
- Plasma density one order of magnitude higher than in ICPs

Helicon waves are **whistler waves** confined to a cylinder

RH polarized e. m. waves propagating along B_0, wave vector k at an angle Φ to B_0

Dispersion relation of whistler waves

$$\frac{c^2k^2}{\omega^2} = 1 - \frac{\omega_p^2}{\omega^2}\frac{1}{1 - \frac{\omega_c}{\omega}\cos\phi}$$

$$\omega_c, \omega_p >> \omega$$

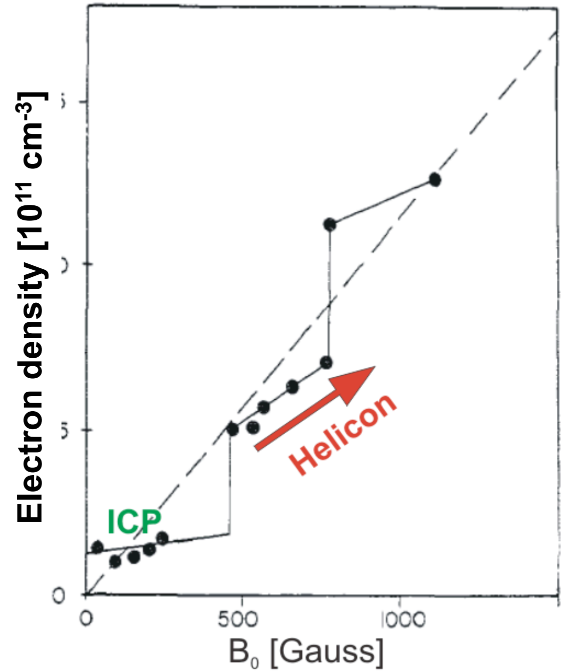
$$k^2 = k_z^2 + k_\perp^2$$

Helicon dispersion relation

$$k = \frac{\omega}{k_z} \frac{e n_e \mu_0}{B}$$

At fixed ω, radius of the source (=> $k_\perp$), wavelength 2π/k

=> **Density n_e proportional to the magnetic field**



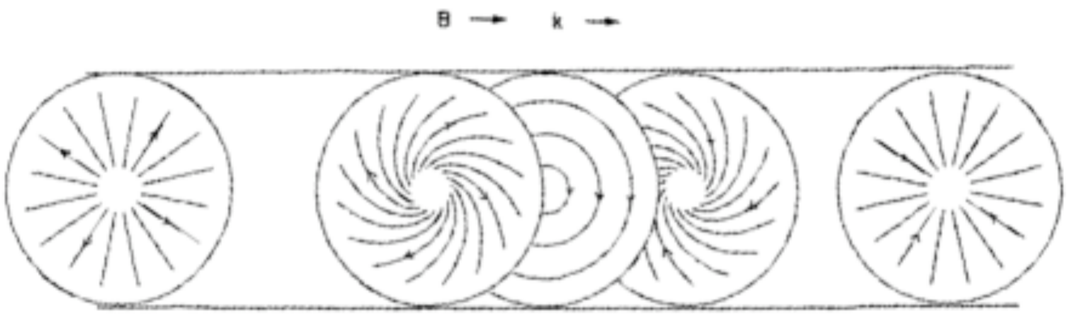
Boundary conditions in a cylindrical discharge for the wave which varies like

$$\vec{B} = \vec{B}(r) e^{i(m\phi + k_z z - \omega t)}$$

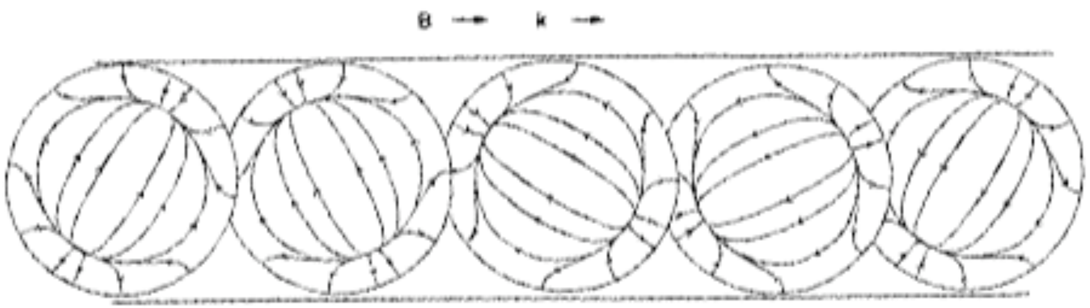
fulfilled by **azimutal wave numbers m**

Helicon modes in a cylindrical discharge

m = 0: changes from electrostatic (radial E) to electromagnetic (azimuthal E-lines)



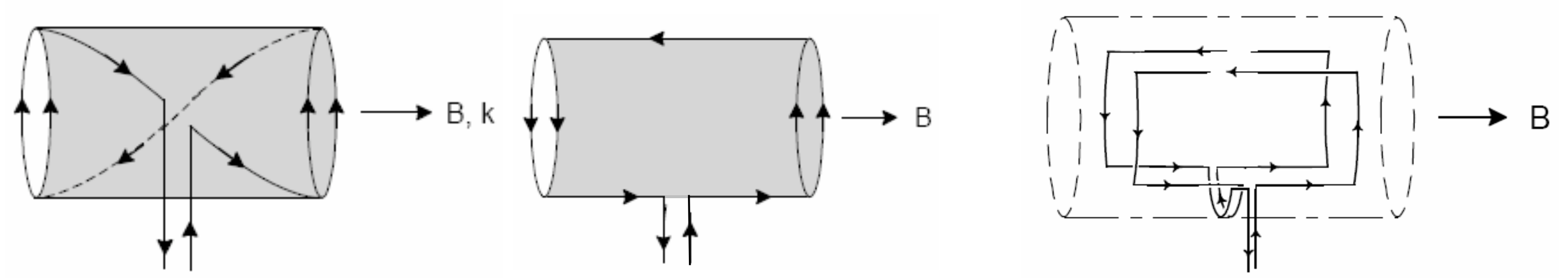
m = 1: rotating E-field pattern, mostly right hand polarized observed (m=+1)



Helicon antennas and energy transfer

For m = 0: Ring antennas

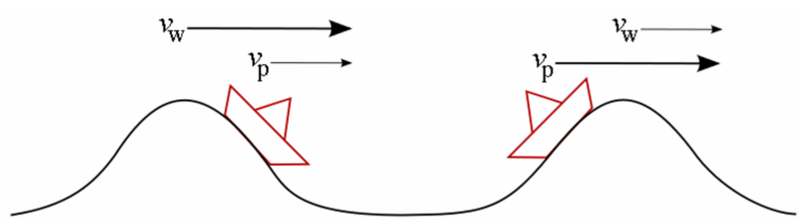
For m = 1



Half helical | Nagoya Type III | Double saddle (Boswell)

Energy transfer mechanism is not yet clear:

Landau damping: electrons with phase velocity below wave velocity gain energy (surfing boat)



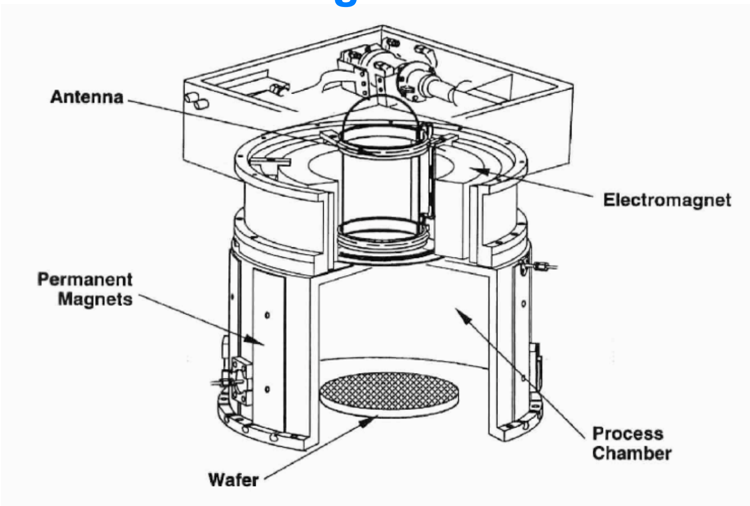
Not consistent with EEDF measurements!

Alternative explanation: electron cyclotron waves **Trivelpiece-Gould modes**

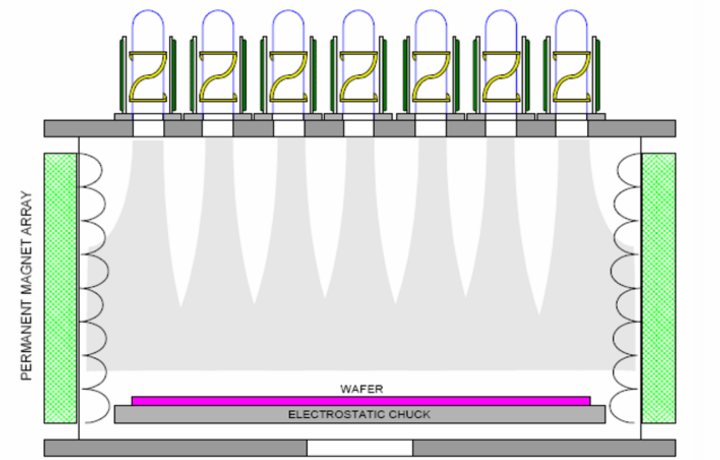
Applications

M = 0 or 1, B = 100 – 400G

Plasma etching



MORI source

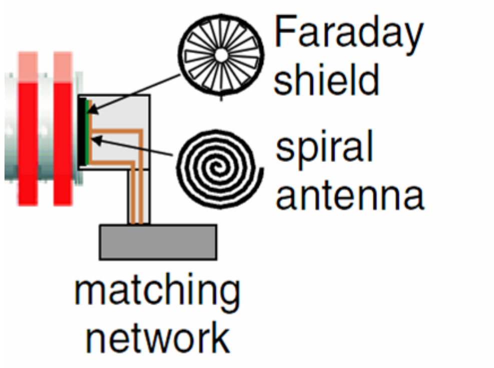


Multiple helicon source (Chen) for uniform plasmas

Accelerator (VENETA)

m = 0 with spiral antenna

(Windisch)



Conclusion

Chen & Chang ("Principles of plasma processing")

"In (source) plasma physics classical treatments like the above are doomed to failure, since plasmas are tricky and more often than not are found experimentally to disobey the simple laws of electromagnetics."