Production of High Intensity, Highly Charged Ions – I

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Fundamental aspects of ion generation and ion sources

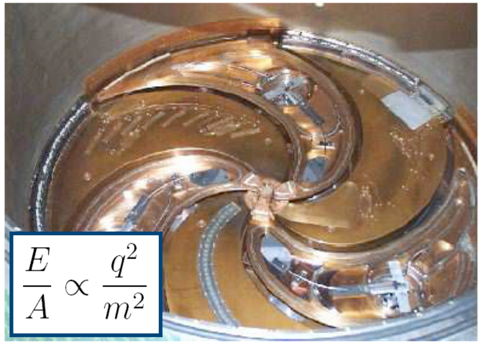
The main goal of ion sources is the production of high quality ion beams to be injected into particle accelerators, minimizing beam losses and maximizing the overall reliability

The requirements of Ion sources employed for accelerators like LINACS or Cyclotrons are:

- ❑ High stability and long-time operations without significant maintenance
- ❑ Production of intense beams of highly charged ions
- ❑ Low emittance.
- ❑ For pulsed operations, the number of particles per pulse must be as high as possible.

MOTIVATIONS

ION SOURCES: Their development is crucial to boost the accelerator performances



$$\frac{E}{A} \propto \frac{q^2}{m^2}$$

INFN-LNS Cyclotron

Increase of Ion Charge States → Higher energies attainable by Accelerators

Increase of Ion Current → Decrease of acquisition times for rare events

Increase of Ion Sources performances allow to enhance the Accelerators ones without hardware modifications

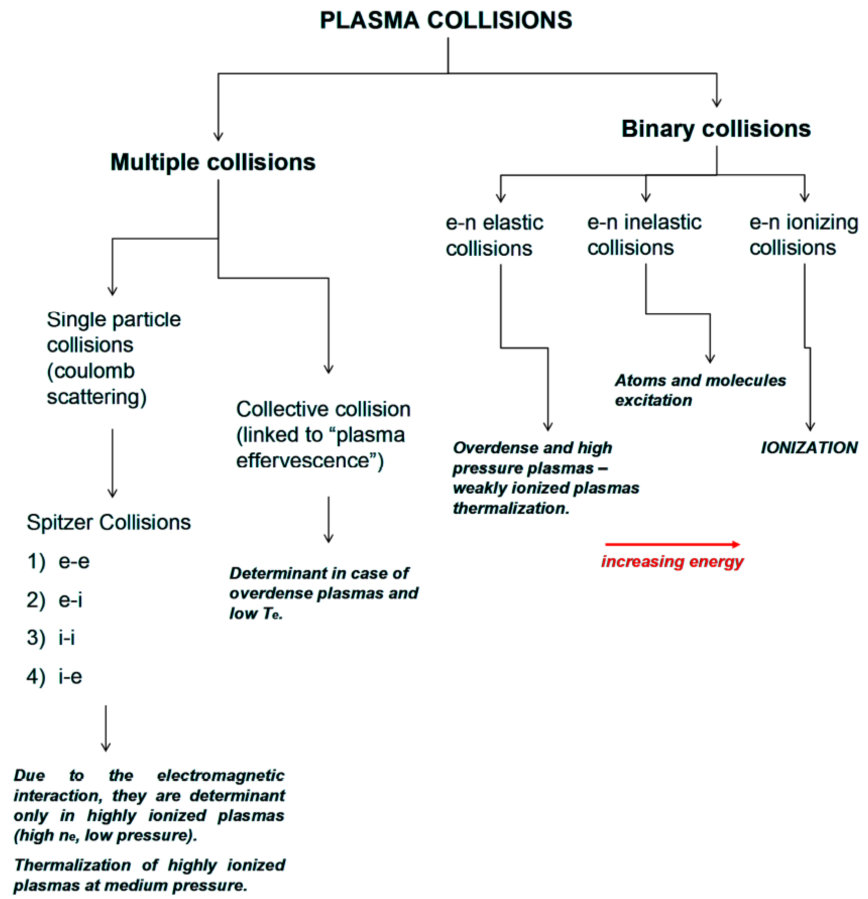
That’s one of the reason why some institutions have invested more than others in the development of HCI ion sources.

Direction to follow:

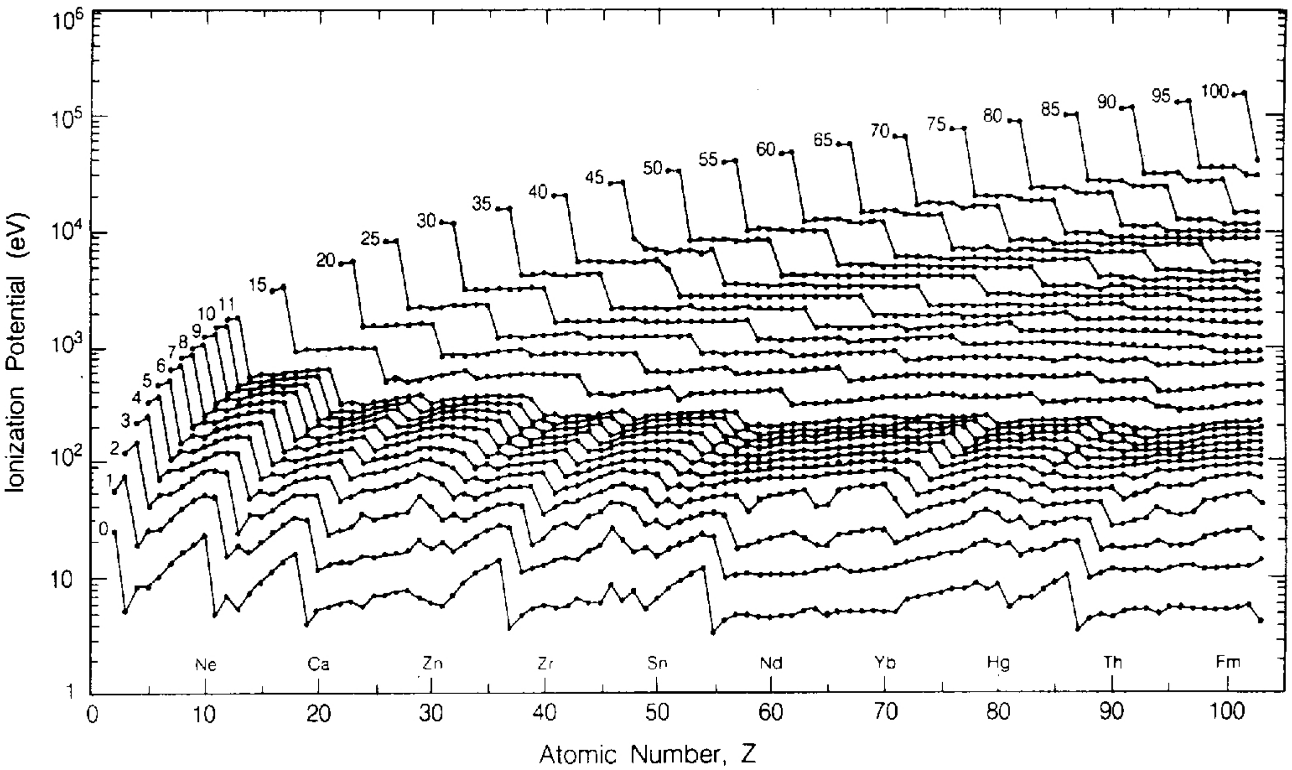
- Ionization process knowledge
- Ability to manage the Plasma microscopic parameters (through the magnetic trap)
- Ability to create the basic conditions (vacuum, beam transport and matching)

Atomic Physics background in Ion Sources Science

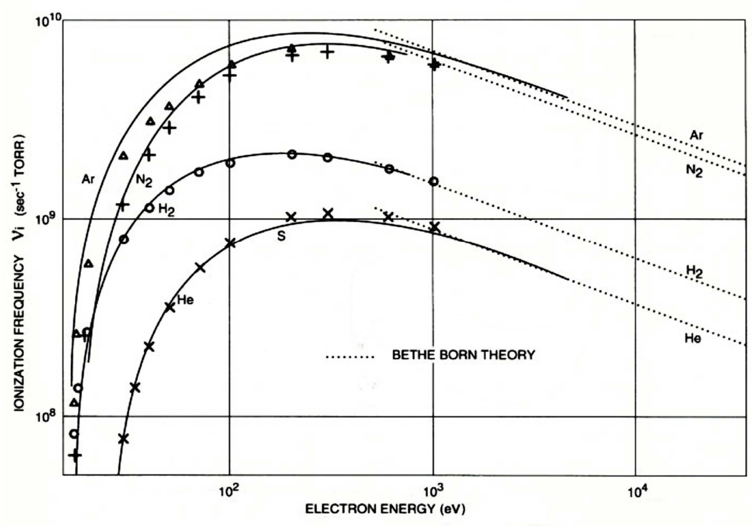
General Principles for the generation of multicharged ions


PLASMA COLLISIONS
Multiple collisions
Binary collisions
Single particle collisions (coulomb scattering)
Collective collision (linked to “plasma effervescence”)
Spitzer Collisions
1) e-e
2) e-i
3) i-i
4) i-e
Due to the electromagnetic interaction, they are determinant only in highly ionized plasmas (high n_e, low pressure).
Thermalization of highly ionized plasmas at medium pressure.
Determinant in case of overdense plasmas and low T_e.
e-n elastic collisions
e-n inelastic collisions
e-n ionizing collisions
Overdense and high pressure plasmas – weakly ionized plasmas thermalization.
Atoms and molecules excitation
IONIZATION
increasing energy

Atomic physics background



Atomic physics background



✓ The figure shows the trend of the ionization frequency versus the electron energy for different ion species;

✓To determine the real ionization rate, we have to multiply the frequency by the operating pressure of our ion source. ν_i refers to all the possible ionizing events.

Dynamical (Non-stationary)) balance equations for multi-charged ions (Shirkov 1991) $dn/dt \neq 0$

$$\frac{dn_0}{dt} = \frac{S}{V} v_0 (n - n_0) - n_0 \left(\sum_{i=2}^{z} \sigma_i^{ex} n_i v_i + \sum_{i=3}^{z} \sigma_i^{2ex} n_i v_i (\sigma_1^i + \sigma_1^{2i}) n_e v_e \right)$$

$$\frac{dn_1}{dt} = n_0 \left(\sigma_1^i v_e n_e + \sigma_2^{ex} n_2 v_2 + \sigma_2^{2ex} n_3 v_3 + \sum_{i=2}^{z} \sigma_i^{ex} n_i v_i \right) - n_1 \left(\sigma_2^i v_e n_e + \sigma_2^{2i} v_e n_e + \frac{1}{\tau_1} \right)$$

$$\frac{dn_2}{dt} = n_0 \left(\sigma_1^{2i} v_e n_e + \sum_{i=3}^{z} \sigma_i^{2ex} n_i v_i \right) + n_1 \sigma_2^i v_e n_e + (\sigma_3^{ex} n_3 v_3 + \sigma_4^{2ex} n_4 v_4) n_0 - n_2 \left((\sigma_3^i + \sigma_3^{2i}) v_e n_e + (\sigma_2^{ex} + \sigma_2^{2ex}) v_2 n_0 + \frac{1}{\tau_2} \right)$$

$$\frac{dn_i}{dt} = \sigma_i^i v_e n_e n_{i-1} + \sigma_{i-1}^{2i} v_e n_e n_{i-2} + \left(\sigma_{i+1}^{ex} n_{i+1} v_{i+1} + \sigma_{i+2}^{2ex} n_{i+2} v_{i+2} \right) n_0 - n_i \left((\sigma_i^{ex} + \sigma_i^{2ex}) v_i n_0 - (\sigma_{i+1}^i + \sigma_{i+2}^{2i}) v_e n_e + \frac{1}{\tau_i} \right)$$

$\boxed{3 \leq i \leq z-2}$

$$\frac{dn_{z-1}}{dt} = (\sigma_{z-1}^i n_{z-2} + \sigma_{z-2}^{2i} n_{z-3}) v_e n_e + \sigma_z^{ex} n_z v_z n_0 - n_{z-1} \left(\sigma_z^i v_e n_e + (\sigma_{z-1}^{ex} + \sigma_{z-1}^{2ex}) v_{z-1} n_0 + \frac{1}{\tau_{z-1}} \right)$$

$$\frac{dn_z}{dt} = (\sigma_z^i n_{z-1} + \sigma_{z-1}^{2i} n_{z-2}) v_e n_e - n_z \left((\sigma_z^{ex} + \sigma_z^{2ex}) v_z n_0 + \frac{1}{\tau_z} \right)$$

$$\frac{dn_e}{dt} = \left(\sum_{1}^{z-1} \sigma_i^i n_{i-1} + 2 \sum_{1}^{z-2} \sigma_i^{2i} n_{i-1} \right) v_e n_e - \frac{n_e}{\tau_e}$$

$$\Delta\phi = \frac{p}{2} e n_e R^2 f \left(1 + 2 \ln \frac{l}{R} \right) \qquad f = \frac{\sum_{i=1}^{z} i n_i - n_e}{n_e}$$

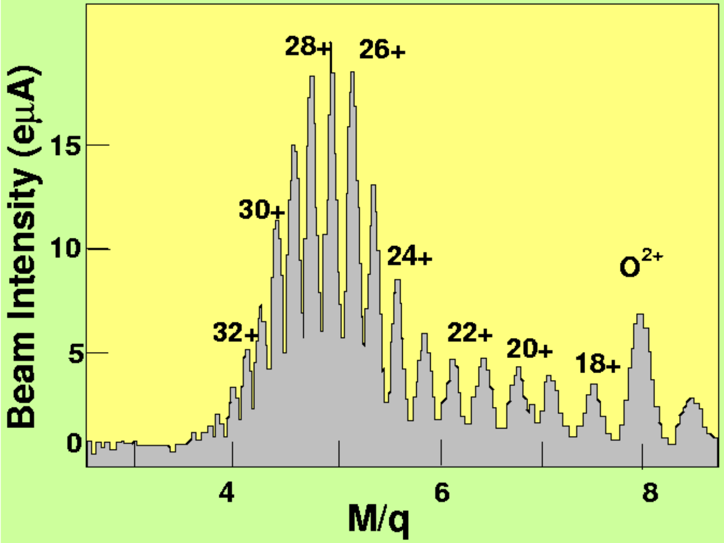
n_0 = density of neutrals inside the plasma
n = density of neutrals outside the plasma
τ_e = electron lifetime determined by the loss cone of the longitudinal magnetic field
l and R = length and radius of the cylindrical source
$\Delta\phi$ = potential
f = factor of plasma neutralization
v_0, v_i and v_e = mean velocities of neutrals, ions and electrons

σ_i^{ex} and σ_i^{2ex} = single – and double – charge – exchange cross sections for the ions with charge state i

σ_i^i and σ_i^{2i} = single – and double – ionization cross sections of the ions with charge state $i-1$

Typical Charge State Distribution

First result of Liquid He free SC-ECRIS



Parameters

Gas

^{136}Xe(85% enriched)+ O_2

Vacuum

injection 1.9×10^{-7} Torr

extraction 9.4×10^{-8} Torr

Magnetic field

B_{inj}	1.84 T
B_{center}	0.396 T
$B_{extraction}$	1.24 T

RF

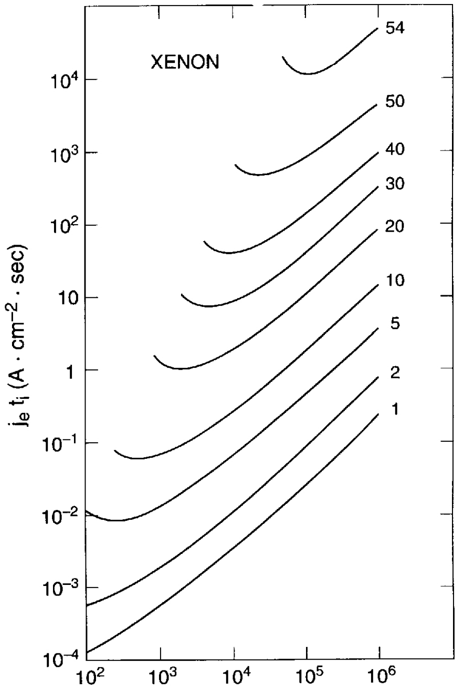
Freq	14.5 GHz
Power	771W

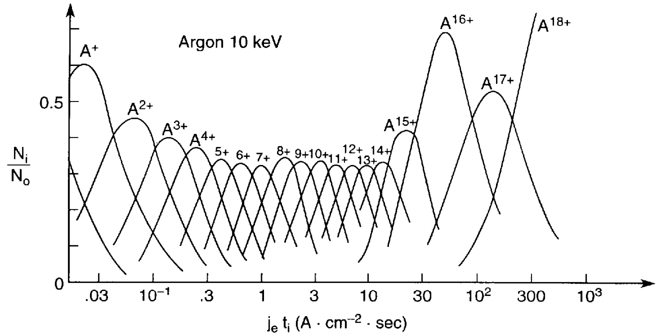
extraction	15kV

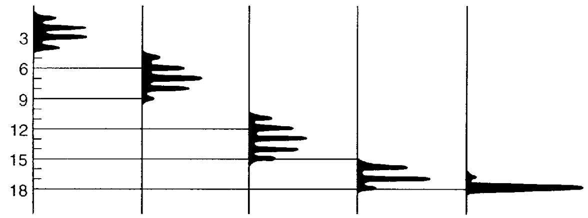
Bias Disc

voltage	-225 V
position	0.5 cm

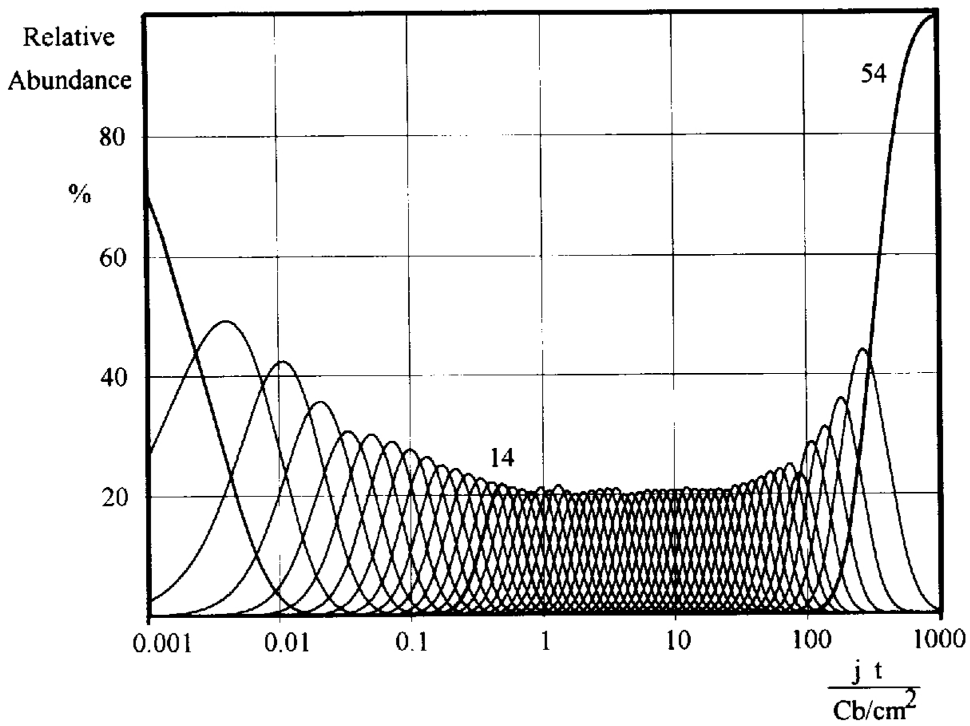
Electron density and confinement time





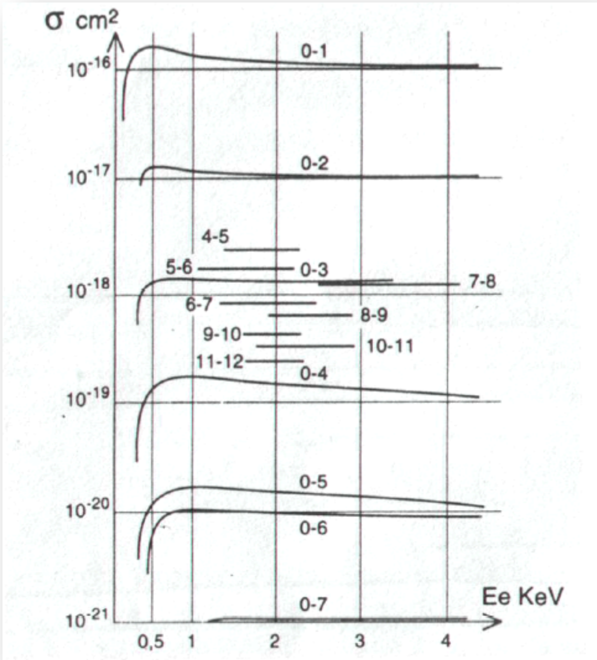


Atomic physics background



Atomic physics background

Step by step ionization



The cross section for ionizing processes like $z \rightarrow z{+}x$ as a function of energy features a maximum value when $x=1$. This means that the ionization proceeds expelling one by one electrons from atomic shells.

The ionization mechanism is therefore a slow process which requires long plasma lifetime to produce highly charged ions

Atomic physics background

The ionization up to high charge state is a step by step process

If τ_i is the ion confinement time, then:

$$\boxed{n_e \tau_i \geq \frac{1}{[S_z(T_e)]}} \Rightarrow$$

Multiply charged ion formation criterion

By taking into account the electron temperature:

(we need warm electrons but cold ions)

$$\boxed{n_e \tau_i \geq 5 \cdot 10^4 \left(T_e^{opt}\right)^{\frac{3}{2}}}$$

$T_e^{opt} \simeq 5W_{thr}$ being W_{thr} the ionization energy of the particular charge state to be achieved

For fully stripped light ions

$$\boxed{n_e \tau_i \cong 10^{10}\ cm^{-3}\ \mathrm{sec} \qquad T_e^{opt} = 5\,keV}$$

High density – long lifetimes are required!!

$$I_{ext} \propto \frac{n_e}{\tau_i} \; ; \qquad < q > \propto n_e * \tau_i$$

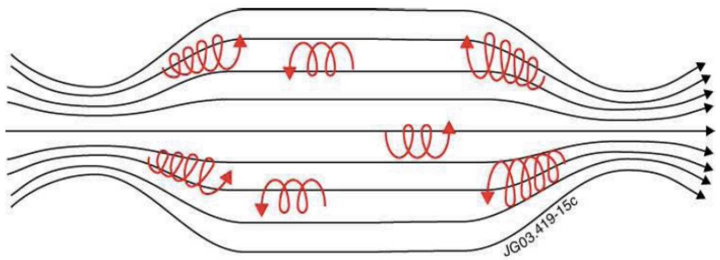
Plasmas at high electron density and characterized by long ion lifetimes are specifically required. They can be produced by high intensity electron beams or sustained by microwaves

Principles of magnetic confinement

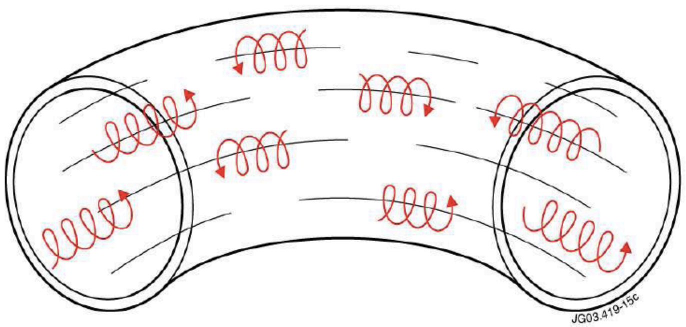
Stabilization of electron and ion confinement is mandatory to achieve highly charged ions

Magnetic Confinement

Magnetic fields intrinsically force charged particles to reduce the degrees of freedom: the electrons follow a spiral trajectory around the field lines and can be trapped for several ms in mirror machines or toroidal structures.



MIRROR STRUCTURES have axial symmetry and they can be produced by sequences of room temperature or SC coils.
They are commonly used in ion sources field



Toroidal confinement is typical of Fusion Machines like TOKAMAKS or STELLARATORS

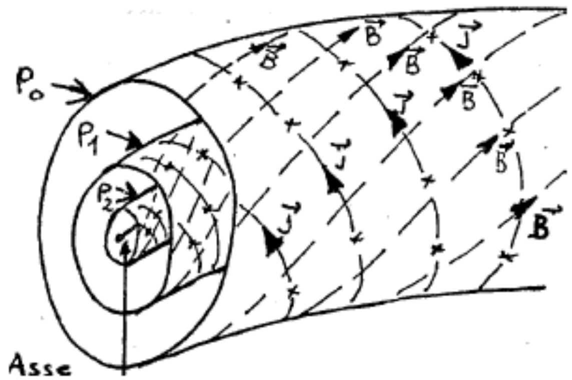
Stability of magnetic confinement

$$\vec{J} \times \vec{B} = \vec{\nabla} p$$

$$\downarrow$$

$$\boxed{\mathbf{B} \cdot \nabla P = 0}$$

$$\boxed{\mathbf{J} \cdot \nabla P = 0}$$



1. Magnetic field lines lie on surfaces which also correspond to isobaric surfaces
2. In addition, lines of particles currents lie on isobaric surfaces.
3. B and J are both solenoidal fields, therefore the field lines are closed for each one.

The confinement places some stringent conditions on plasma equilibrium and stability

By a physical point of view, the plasma can be viewed as a fluid. Therefore the confinement and its equilibrium and stability can be investigated by looking to the equilibrium between the plasma kinetic pressure and the magnetic (confining) field pressure.

$$p + \frac{B^2}{2\mu_0} = c$$

The stability of the confinement can be studied as a function of the β parameter, which is the ratio between the kinetic and magnetic pressures.

$$\beta \equiv \frac{\sum nkT}{\frac{B^2}{2\mu_0}}$$

The condition for a stable plasma is that $\beta \ll 1$

Stability of magnetic confinement

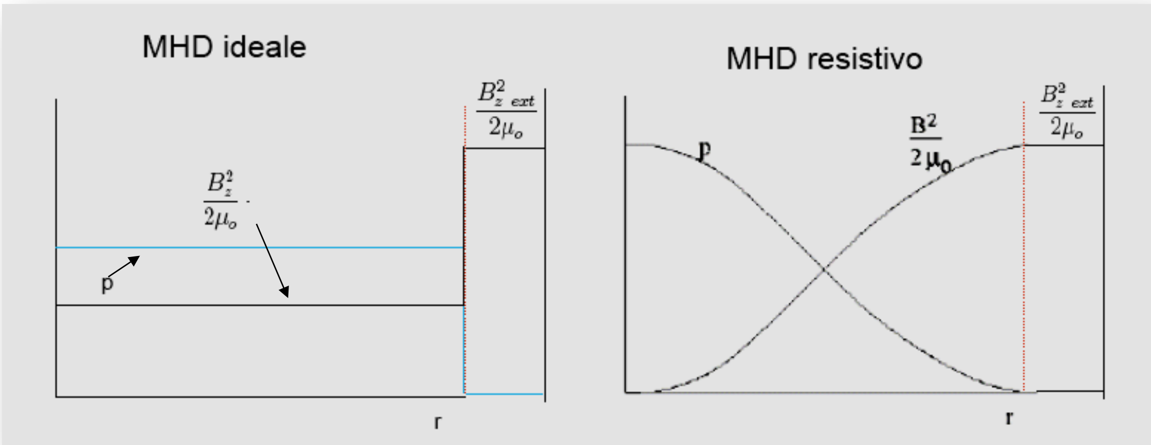
The magneto-hydro-dynamics equation gives:

$$\nabla p = \frac{1}{\mu_0}(\nabla \times \boldsymbol{B}) \times \boldsymbol{B} = \frac{1}{\mu_0}\left[(\boldsymbol{B}\cdot\nabla)\boldsymbol{B} - \frac{1}{2}\nabla \boldsymbol{B}^2\right]$$

$$\Rightarrow \quad \nabla\left(p + \frac{B^2}{2\mu_0}\right) = \frac{1}{\mu_0}(\boldsymbol{B}\cdot\nabla)\boldsymbol{B}$$

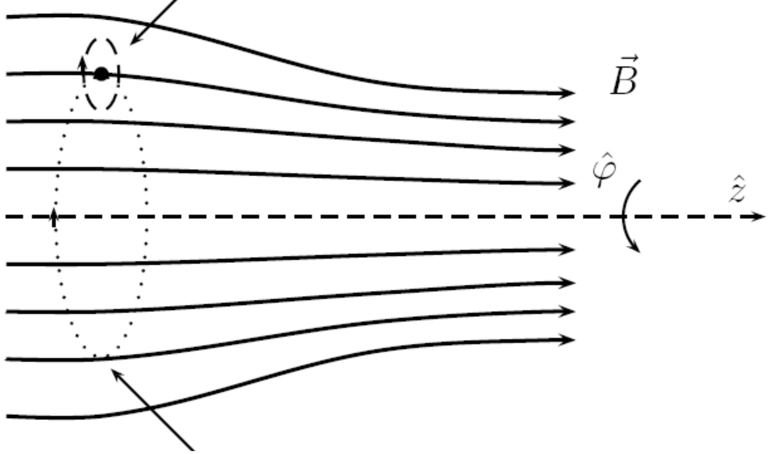
In case B is smoothly variable along its own direction, the right hand term can be neglected, yielding:

$$p + \frac{B^2}{2\mu_0} = \text{costante}$$



Principles of magnetic mirrors

Magnetic mirrors are largely employed in ion sources field since allow the construction of compact-size machines. Some ingredients are needed to ensure efficient trapping:



Adiabatic Invariant

- A magnetic gradient must exist along the direction of B:

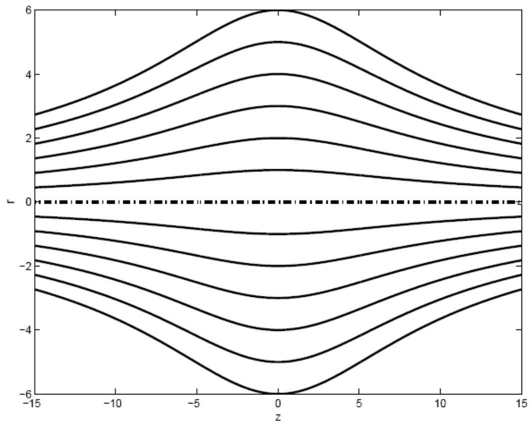
$$\vec{F}_{\parallel} = -\mu \frac{\partial B}{\partial s} = -\mu \vec{\nabla}_{\parallel} B$$

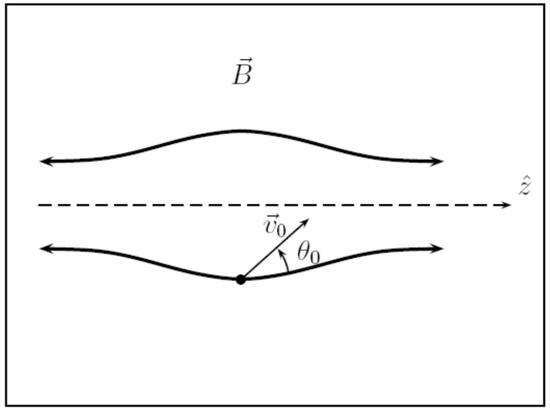
$$\mu \equiv \frac{1}{2} \frac{m v_{\perp}^2}{B}$$

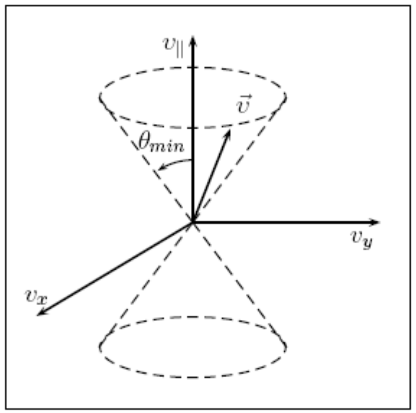
- Radial component of the magnetic field;
- The angle formed by the particle velocity w.r.t B must be as large as possible.

Confinement can be explained by means of μ invariance.

Principles of magnetic mirrors





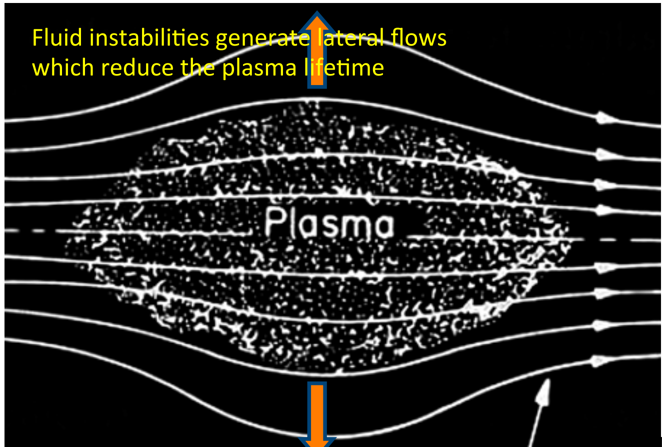


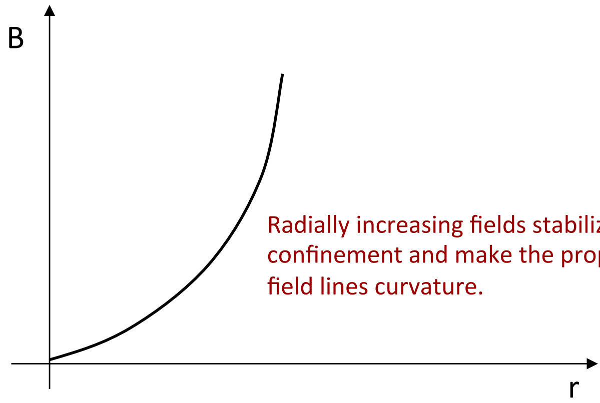
$$\theta_{min} = \arcsin \sqrt{\frac{B_0}{B_m}}$$

- Efficient confinement by a single-particle point of view.
- Considering a fluid approach, MHD instability arises because of the bad curvature of the field lines in the midplane, causing the onset of flute instability.

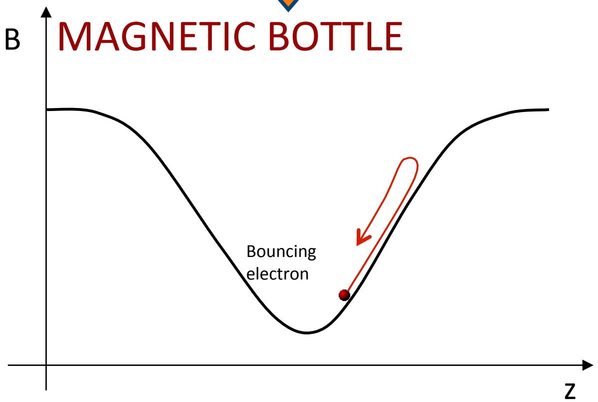
Principles of magnetic mirrors

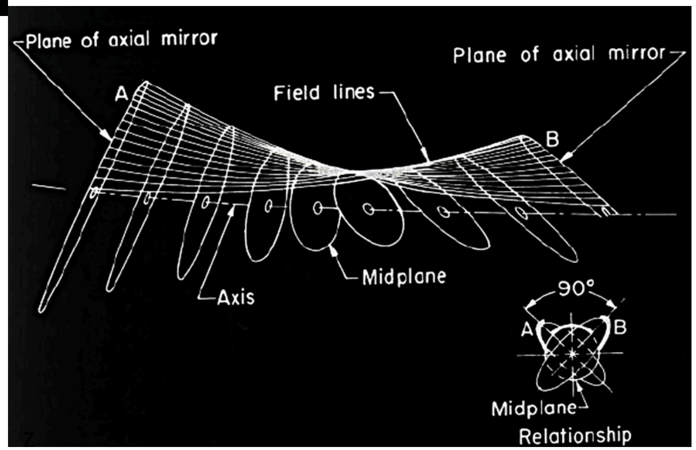
The necessity of the minimum B structure





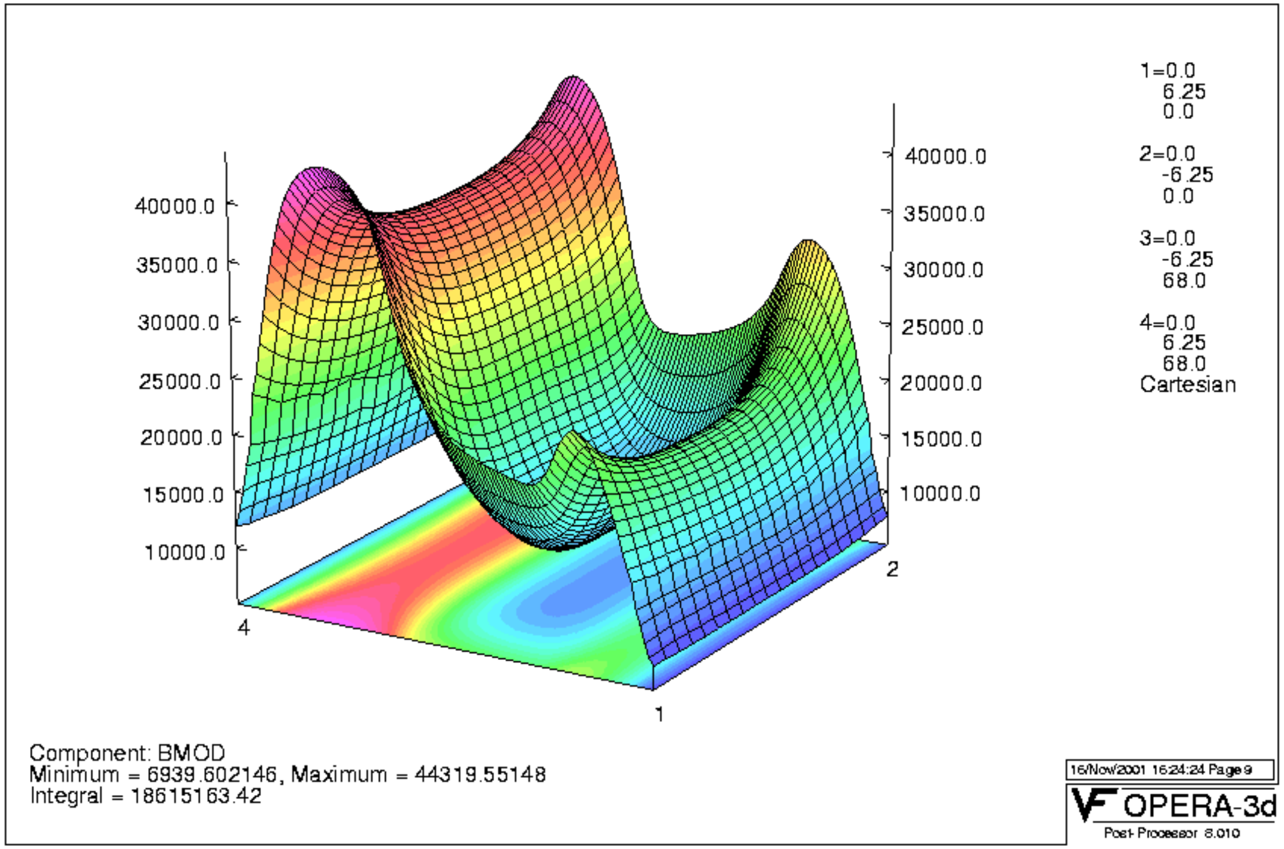
Radially increasing fields stabilize the confinement and make the proper field lines curvature.



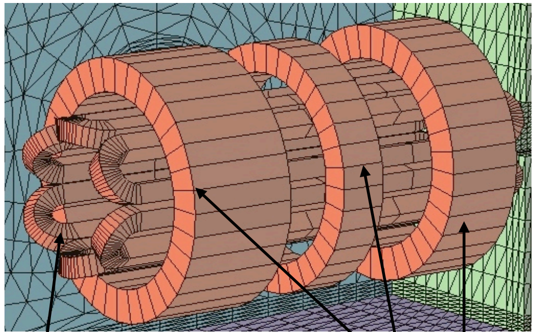


ECRIS case: magnetic structure

The necessity of the minimum B structure



ECRIS case: magnetic structure



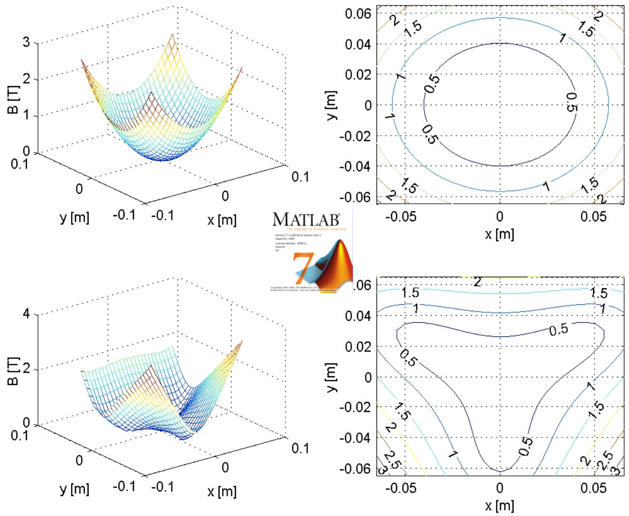
Hexapole for radial confinement

Solenoids for axial confinements

Minimum B magnetic field structure

$$
\begin{aligned}
B_x &= -B_1 x z + 2 S x y \\
B_y &= -B_1 y z + S\left(x^2 - y^2\right) \\
B_z &= B_0 + B_1 z^2
\end{aligned}
$$

$$
\vec{\nabla} \cdot \vec{B} = 0
$$



The ability to confine a plasma for a longer time than μs is required for HCI production

$$I_{ext} \propto \frac{n_e}{\tau_i} \; ; \qquad < q > \propto n_e{}^{*}\tau_i$$

According to different values of electron density and ion confinement time, different classes of ion sources are available, intense or low current, HCI or low charge

Four types of ion sources

EBIS (Electron Beam Ion Sources): easy production of beams at high charge states (very long plasma lifetime), unavailable for high intensity ion beams (too long plasma lifetime)

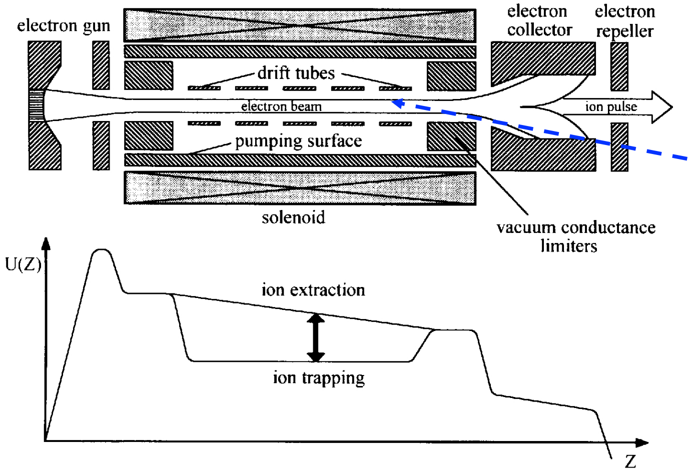
MDIS (Microwave Discharge Ion Sources): simplified version of ECRIS for high intensity proton (or low charge state ion) beams.

LIS (Laser Ion Sources): intense beams of medium and high charge states, but unable to produce stable beams in CW mode and high quality beams

ECRIS (Electron Cyclotron Resonance Ion Sources): intense beams of low charge states, moderate intensity of highly charged ions

EBIS Sources

(Electron Beam Ion Sources)



Production of ion beams

at high charge states

A solenoid, producing a quasi constant magnetic field along the axis, focalizes a very intense electron beam

The electron beam in turn produces, due to space charge, a radial potential well confining the ions. The electrostatic trap is axially closed by an anode. Once fluxed the gas, ions are then ionized by electron impact, are trapped by the potential well and ionized many times by the passing, high energy electrons

The highest obteinable charge states were Xe^{53+} and Xe^{54+}, with currents of some fraction of nA (JINR, Dubna - Russia). EBIT – Electron Beam Ion Trap, are able to produce 10 pps of U^{92+}.

$$I_{ext} \propto \frac{n_e}{\tau_i} \; ; \qquad < q > \propto n_e{}^{*}\tau_i$$

The number of electrons may be large, and so for the confinement time, which means that it’s the best solution for the HCI production, even though the high intensity condition cannot be met

EBIS Sources

(Electron Beam Ion Sources)

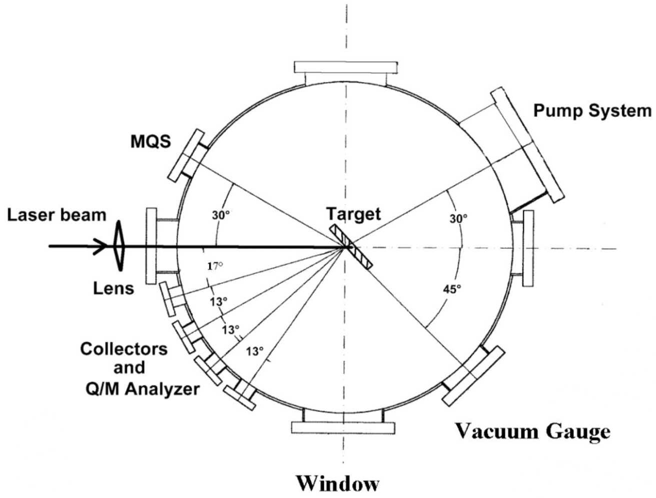
Advantages

- Extremely high charge states
- Excellent beam quality
- Possibility of either CW and pulsed mode
- No limitations due to average lifetime

Disavantages

- Low currents (too long confinement times)
- Complex and expensive devices

LIS - Laser Ion sources



✓In Laser Ion Sources a laser is optically focalized on a solid target and the plasma is generated through laser-matter interaction.

✓The laser energy is used to vaporize the target and then to create the plasma through avalanche ionization.

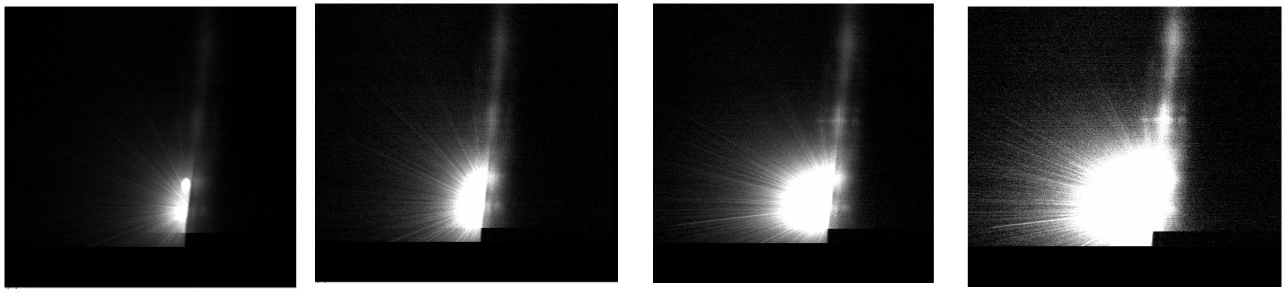
✓Electrons can be energized up to several hundreds of keV. Electron density fluctuation may generate large accelerating field

✓Plasma temperature and charge state distribution depend strongly on the laser power:

$$\boxed{T_e \sim (P\langle Z\rangle)^{2/7}.}$$

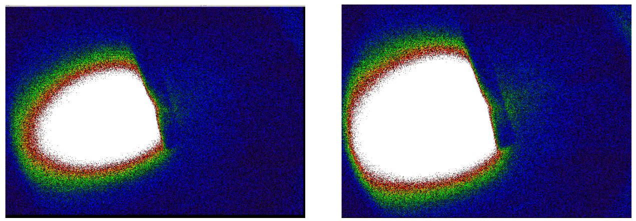
The source layout can be divided into three different subsystems: the laser beam generator, the optical focusing system and finally the vacuum chamber which hosts the target.

Plasma evolution

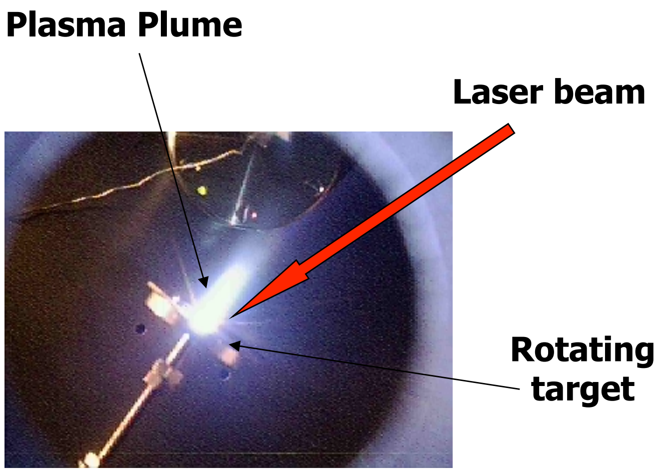


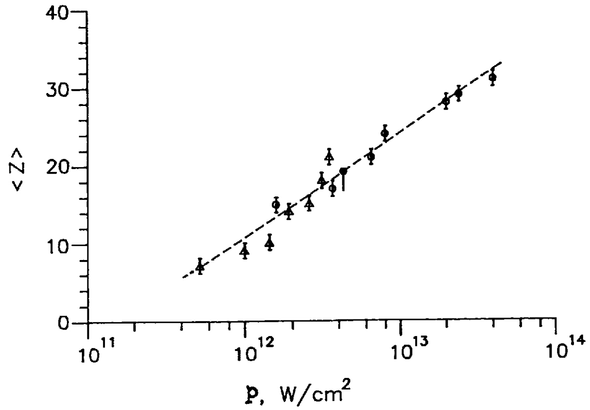
2 µsec 4 µsec 6 µsec 8 µsec

Expansion velocity ~ 10^4 m/s
Density ~ 10^{18}/cm^3



LIS - Laser Ion sources





High charge state vs. laser power

$$I_{ext} \propto \frac{n_e}{\tau_i} \; ; \qquad < q > \propto n_e{}^{*}\tau_i$$

Large electron density at the early stage but we cannot define a confinement time, nor a plasma temperature. High intensity HCI production condition can be met, but the 'brutal' plasma generation reflects on large energy spread, poor stability, large emittance

LIS - Laser Ion sources

Advantages

- Simple and compact source for production of intense beams in pulsed mode
- Ions can be produced by any solid material, with low – medium – high charge states, depending on laser power;
- Extremely high beam currents;
- Moderate operations costs.

Disadvantages

- Short pulse width;
- Low repetition rate;
- Powerful laser are not table-top ones;
- Large emittance
- Wide energetic spread.

MDIS – Microwave Discharge Ion sources

$$I_{ext} \propto \frac{n_e}{\tau_i} \; ; \qquad < q > \propto n_e * \tau_i$$

Large electron density is generated in 2.45 GHz plasma generators but poor confinement time and plasma temperature is achieved. High intensity ion beam production condition can be met, but not the conditions for HCI production.

Four types of ion sources for multicharged ions production or single-charged intense ion beams

EBIS (Electron Beam Ion Sources): easy production of beams at high charge states (very long plasma lifetime), unavailable for high intensity - single charge ion beams (too long plasma lifetime)

MDIS (Microwave Discharge Ion Sources): simplified version of ECRIS for high intensity proton (or single charge state ions) beams.

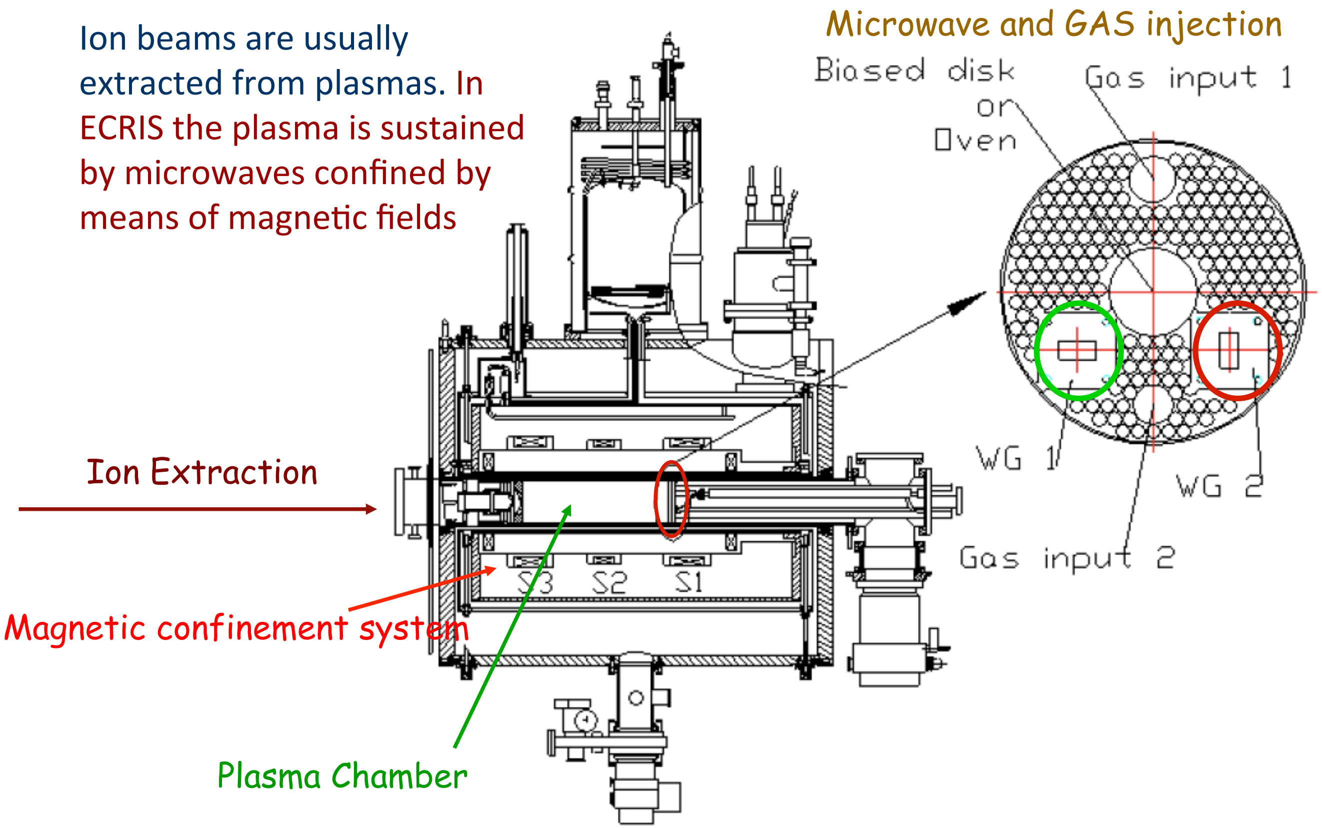
BEST COMPROMISE for production of intense beams of highly charged ions

LIS (Laser Ion Sources): intense beams of medium and high charge states, production of metallic ions from refractive materials, but unable to produce beams in CW mode

ECRIS (Electron Cyclotron Resonance Ion Sources): intense beams of low charge states, moderate intensity of highly charged ions

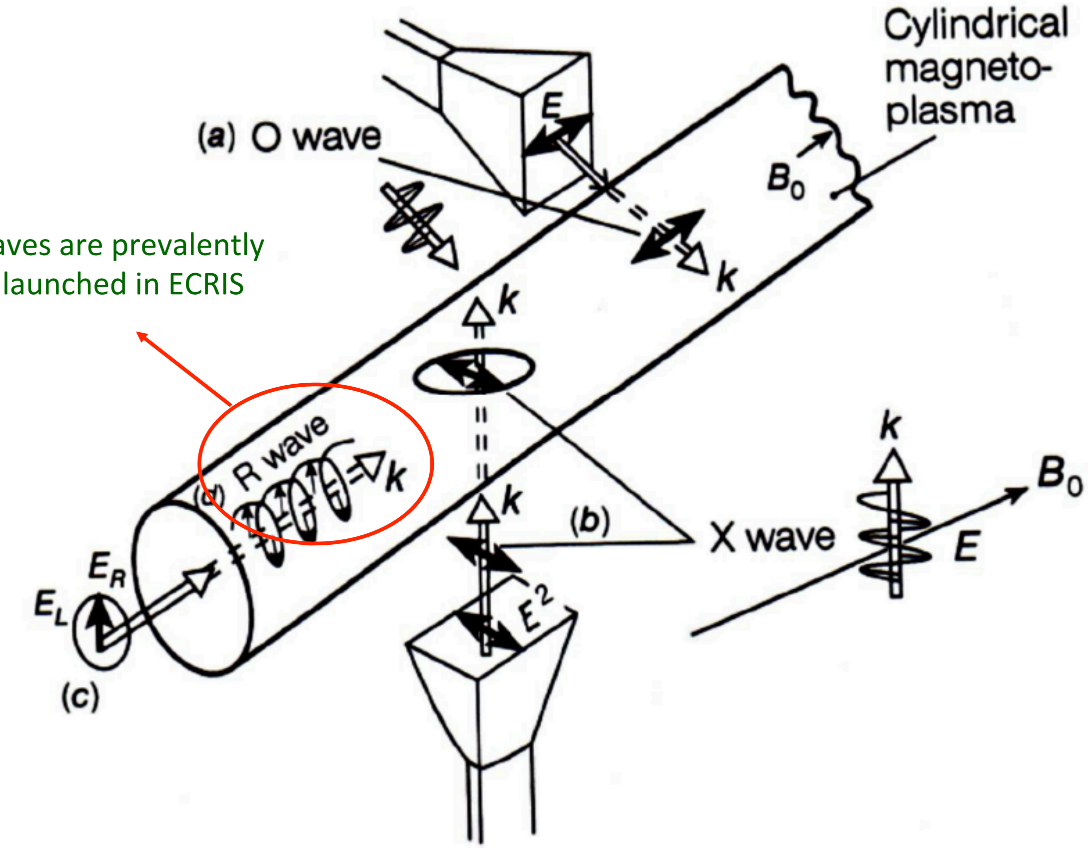
ECRIS subsystems

Ion beams are usually extracted from plasmas. In ECRIS the plasma is sustained by microwaves confined by means of magnetic fields



Wave propagation in magnetized plasmas

R waves are prevalently
launched in ECRIS



The creation of the ECR Plasma

During plasma start-up a modest number of free electrons exists

Magnetic Field

Electrons turn around the magnetic field lines with the frequency:
$\omega_g = qB/m$

A circulary polarized electromagnetic wave transfers its energy to the electrons by means of the ECR :
$\omega_{RF} = \omega_g$

The energetic electrons ionize the gas atoms and create a plasma.

The ionization up to high charge state is a step by step process which requires long ion confinement times and large electron densities.

100 μA of Xe^{30+} or more can be obtained in 3rd generation ECRIS

The cutoff density

$$\boxed{\epsilon(\omega) \sim 1 - \frac{\omega_p^2}{\omega^2}}$$

The propagation of e.m. waves is possible if ε>0

$$\boxed{\omega_p^2 = \frac{4\pi n_e e^2}{m_e}}$$

The plasma frequency is connected to self-generated plasma oscillations which strongly affect the wave propagation.

Above the cutoff the wave cannot propagate:

$$\boxed{n_{cutoff} = 4\pi^2 \frac{m\epsilon_0}{e^2} f_p^2}$$

ECRIS Standard Model

Scaling Laws

(R. Geller-1987):

For many years they represented the guideline for ECRIS development

$$I \propto \frac{\omega_{RF}^2}{M} \qquad \langle q \rangle \propto \log \omega_{RF}^{3.5}$$

1. We have to increase the Microwave frequency to attain higher electron densities
2. The confinement is essential but no conditions on magnetic field distribution

High-B Mode

(G. Ciavola-S.Gammino, 1990)

It doesn't conflict with Scaling Laws, but it limits their efficiency to high confined plasmas

High mirror rations ensure the MHD stability exploiting the density increase.

$$\boxed{\frac{B}{B_{ECR}} > 2}$$

B>4T for future ECRIS !

Overcoming the current limits of ECRIS

Roadmap indicated by the ECR Standard Model:

- High Frequency Generators;
- High Magnetic Fields;

$$< q > \sim n_e \tau_i$$

$$I \sim n_e / \tau_i$$

Investigations about RF energy transfer to the electrons may allow to overcome the limits

By quickly replacing the loss hot electrons we can increase the Electron Density and the heating rapidity

The optimization of the wave-electron energy transfer allow to slightly relax the confinement conditions

Overcoming the current limits of ECRIS

Alternative Methods for Plasma Heating? (L. Celona)

A breakthrough in magnets & microwaves technology?

$$\langle q \rangle \sim n_e \tau_i$$

$$I \sim n_e / \tau_i$$