Ion Sources (a glance..)

Heavy Ion Therapy Masterclass School, 17-22 May 2021, Sarajevo-Online

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This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101008548

Overview

PART1: General Overview Ion Sources: today

PART2: ECR Ion Sources: Friday

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Overview – PART2

- Recap from previous time
- Introduction to ECR Ion Sources
- Hystory of ECRIS
- ECRIS for Medical Applications
- Physics of ECRIS
- Summary

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Recap

- The ion source is the first important element of any accelerator
- It generates the beam which needs to have specific requirements in terms of the fundamental parameters that were introduced on previous talk (i.e. particle type, charge state, intensity, energy, emittance)
- Depending on the application, the best source can be selected
- For medical applications, Electron Cyclotron Resonance Ion Sources (ECRIS) are good candidates to produce stable beams (charge states from 1+ to 4+, currents on the order fo hundreds of uA)
- Compromise between high charge state and intensity must be always found…

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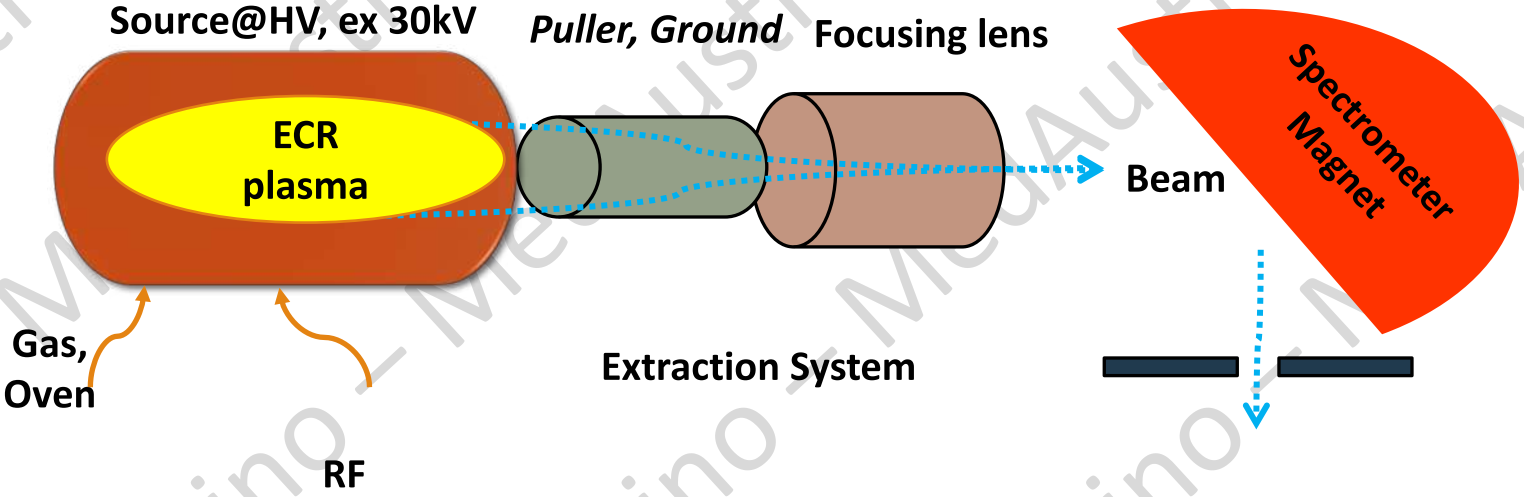
What is an ECRIS?

An Ion Source where the ions are created via **Electron Cyclotron Resonance** by making us of:

1. A vacuum vessel where we inject a material/a neutral gas to create those ions
2. An RF generator to trigger the ionization process and a state of **Plasma**
3. A **sophisticated magnet** to confine the plasma (permanent, coils, superconducting..)
4. An extraction system to pull out the generated ions



Beside that: cooling systems, magnets, vacuum pumps, racks, power supplies etc…

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ECRIS – a bit of History

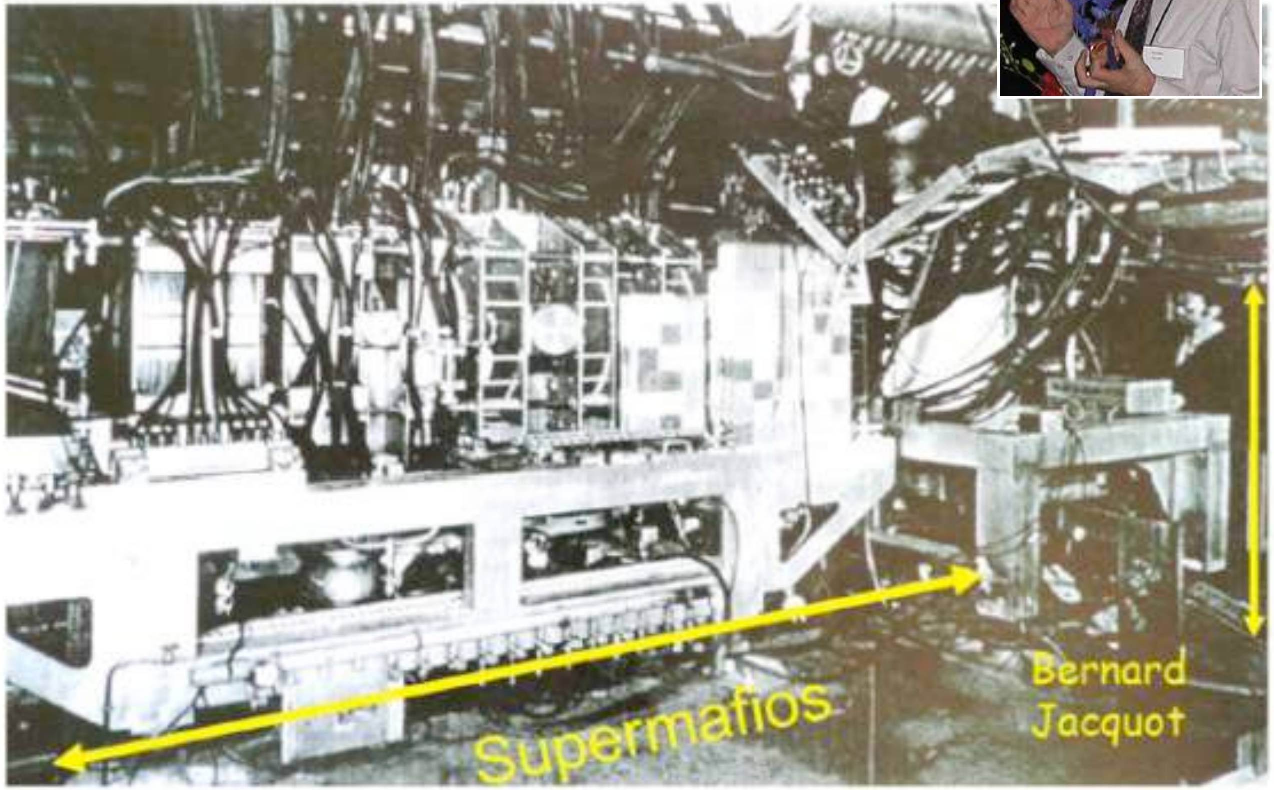
Richard Geller

•Invented in 1972 by R. Geller in Grenoble: converted a 3MW fusion plasma devices into ECR ion sources and succeeded in 1974 with “Supermafios” to produce 15 µA of O6+ and Ar8+

•The legend says that, at first power switching, an electrical black out, occurred on half of Grenoble city!

•ECRIS classified in “generation” (first, second etc.) depending on the operative conditions (RF frequency) and on the magnetic field configuration (permanent or superconductive magnets)

•There is a limitation in the performance of the ECRIS (frequency and power) so today many studies are focused on how to optimize the heating mechanism with a given frequency



Supernanogan (II GEN, 14 GHz)

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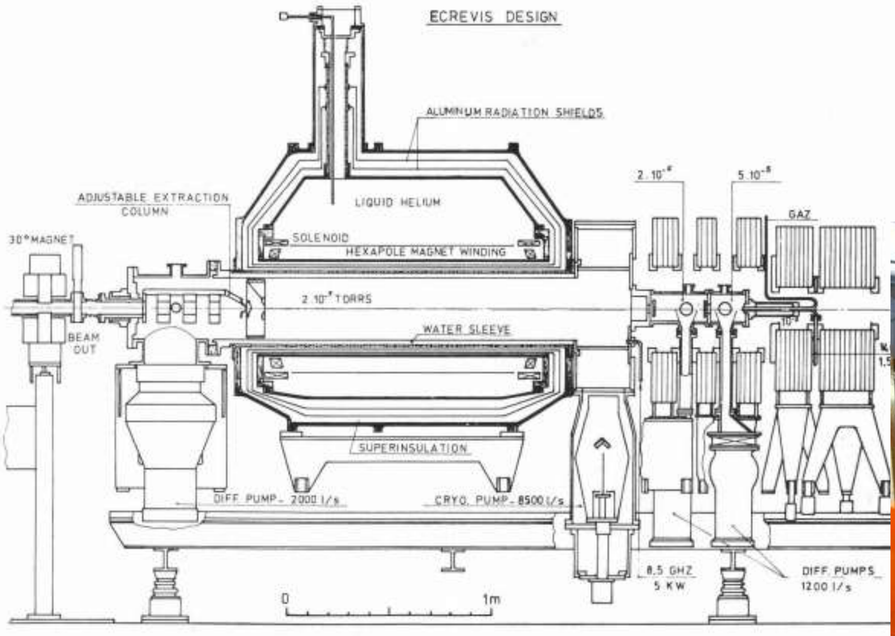
Venus Ion Source a LBNL (III GEN , 28 GHz)

ECRIS – I, II, II Generation

ECRIS classified in “generation” (first, second etc.) depending on the operative conditions (RF frequency) and on the magnetic field configuration (permanent or superconductive magnets)

- First generation, Minimafios, ECREVIS source, (1970-1980) , 100 uA, 6^{+}-8^{+},
- Second generation (1980-2003), ramp-up of performances, currents mA!
- Third Generation (2003…), 18-28 GHz, 3 mA O^{6+}, 0.86 mA Ar^{12+}



THE ECREVIS SOURCE STATUS REPORT Y. Jongen, C. Pirart, G. Ryckelaert

Supernanogan (II GEN, 14.5 GHz)

Venus Ion Source a LBNL (III GEN , 28 GHz)

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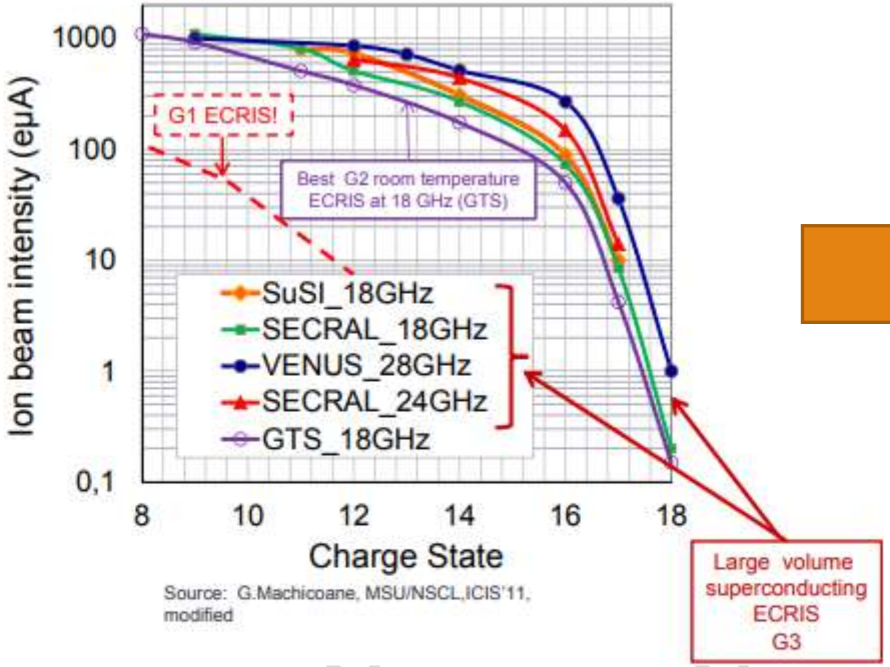
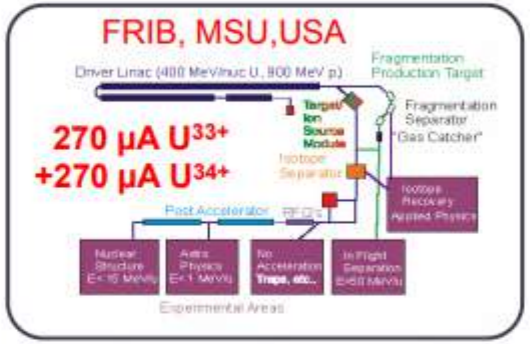
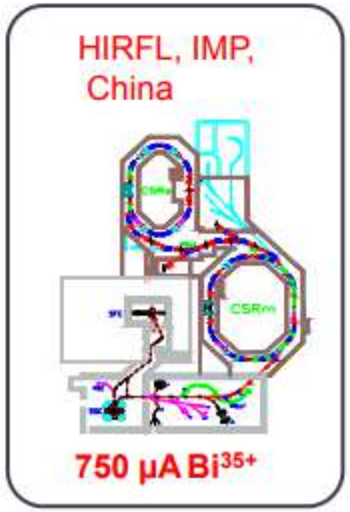
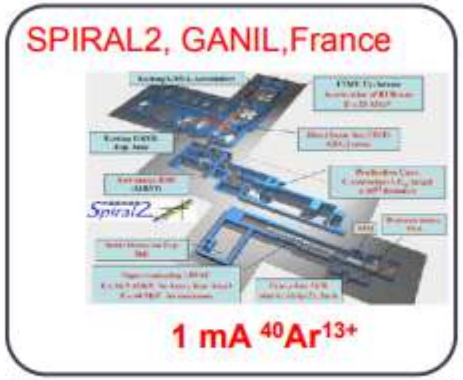
Towards IV Generation









Source: ELECTRON CYCLOTRON RESONANCE ION SOURCES – II, Thuillier, CAS school 2012

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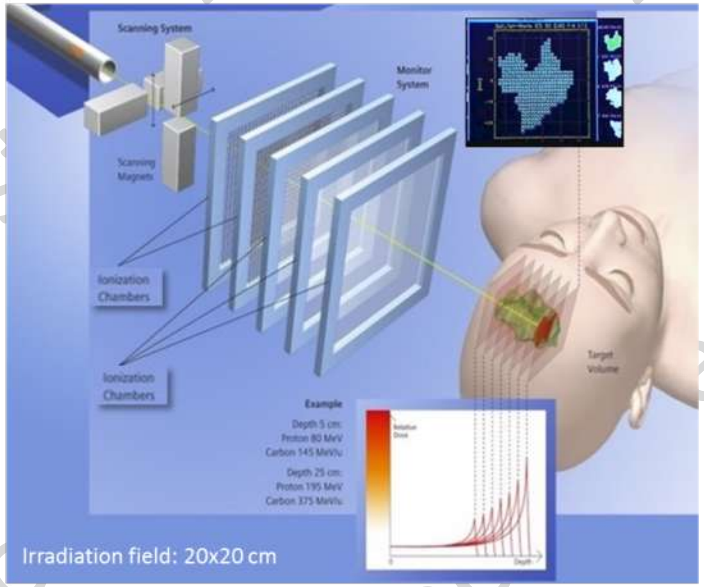
Which IS do we need to met the Medical Requirements?

- Capable of generating a **stable** and reproducible beam 24/24 hours
- Charge state & extracted currents for clinical treatment
- “Smaller” beam emittance in order to match the beam further in the accelerator (LINAC)
- Low maintenance IS with minimum component failure and low electrical consumption
- User friendly for the Operators



<u>High intensity and high charge state is not the main requirement for us, II Generation already meet the requirements</u>

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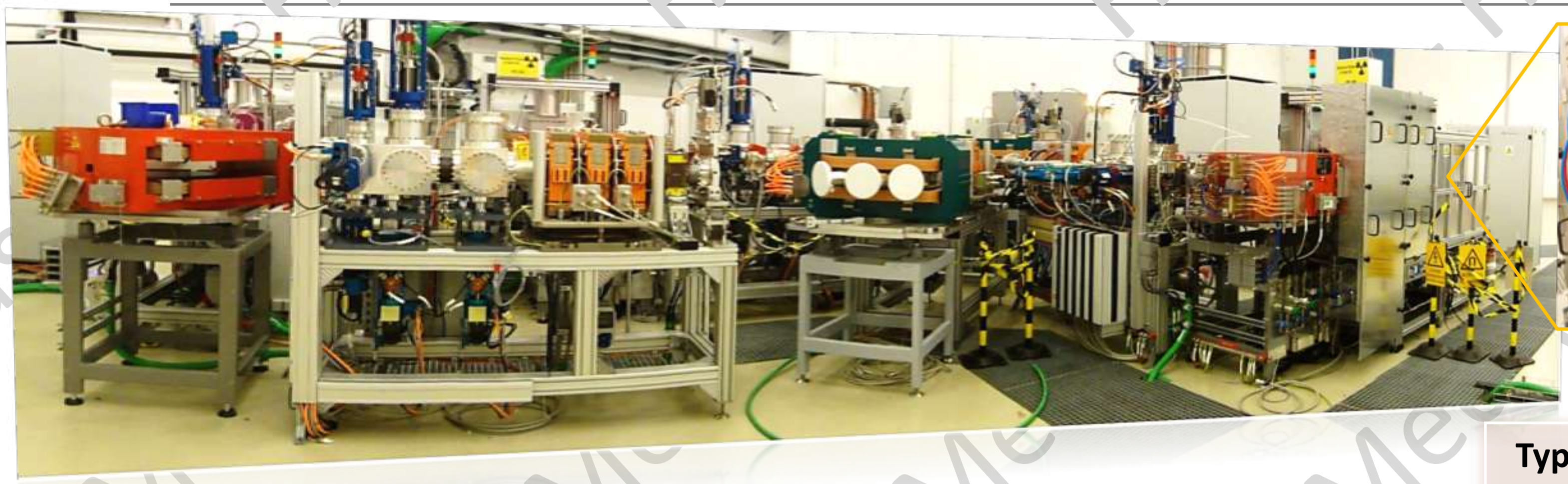
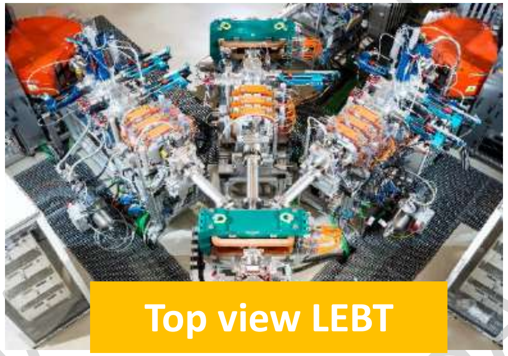
Example: Supernanogans at MedAustron





- Three identical ECRIS from Pantechnik always accessible
  - One dedicated to proton ion beam generation
  - One dedicated to carbon ion beam generation
  - Third source for future non-clinical research with helium
- Possibility of source switching for treatment by a switching magnet

Typ. Parameters used at MedAustron	H^+ Source	C^{4+} Source
RF Frequency (GHz)	14.451	14.455
RF Power (W)	8-10	80-90
B_{ECR} (T)	0.5	0.5
Gas Mix	H_2	CO_2+He
Ex. current	670 uA	100 uA

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Physics of ECRIS

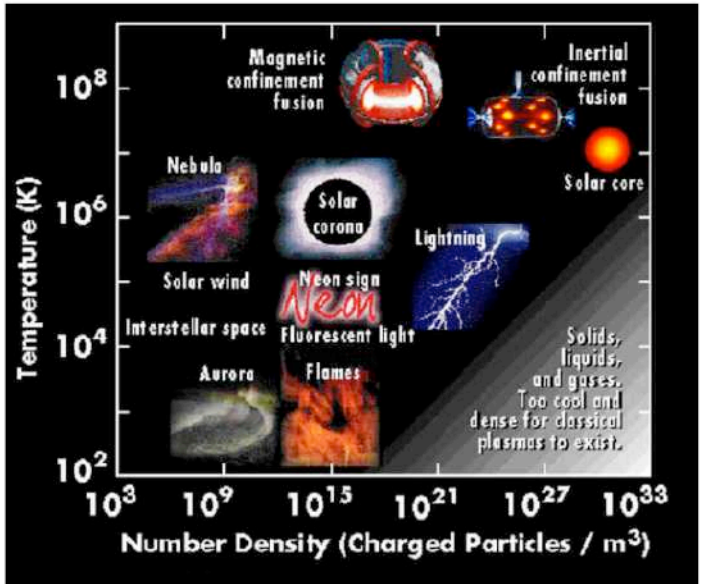
Combines the use of an RF EM forse and magnetic confinement via creating a **plasma state**

The plasma is mixture of ion, electrons and atoms with specific properties

highly ionized gas with property of “quasi-neutrality” out of a certain λ_D (Debye length) , Plasma Length must be $L >> \lambda_D$

mixture behaves like an oscillator: ions and electrons oscillate in layers with their own oscillation frequency ω_P and their own plasma potential

To create the plasma, we use an EM field (for example an RF Generator) we need to go above the critical density N_{cr} to have an efficient heating



Plasmas always classified in terms of n_e and

$$\lambda_D = \left(\frac{\epsilon_0 k_B T_e}{n_e \cdot e^2}\right)^{0,5} \qquad \omega_p = \omega_{pi} = \left(\frac{e^2 n_e}{m_0 \epsilon_0}\right)^{\frac{1}{2}} \qquad N_{cr} = 4\pi^2 \frac{m\epsilon}{e^2} f_p^2$$

complex physics behind plasma formation (collective phenomena, atomic physics, plasma waves, ExB drifts, EM Theory)

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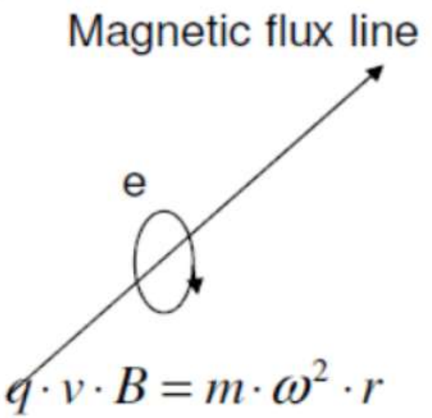
How do we trigger the ECR?

- The neutral gas injected into the vacuum vessel contains few free electrons
- The few free electrons gain energy from the RF electromagnetic wave having a certain ω_{rf} and start to collide with the neutral atoms
- The presence of the magnetic field makes the electrons spiraling around the magnetic field lines (Lorentz Force) with a certain ω_e
- Electron Cyclotron Resonance happens for:

$$\boxed{\omega_e = \frac{e \cdot B}{m} = \omega_{rf}}$$

Plasma is formed



$$q \cdot v \cdot B = m \cdot \omega^2 \cdot r$$

$$\omega = \frac{v}{r}$$

$$r_c = \frac{m \cdot v}{q \cdot B}$$

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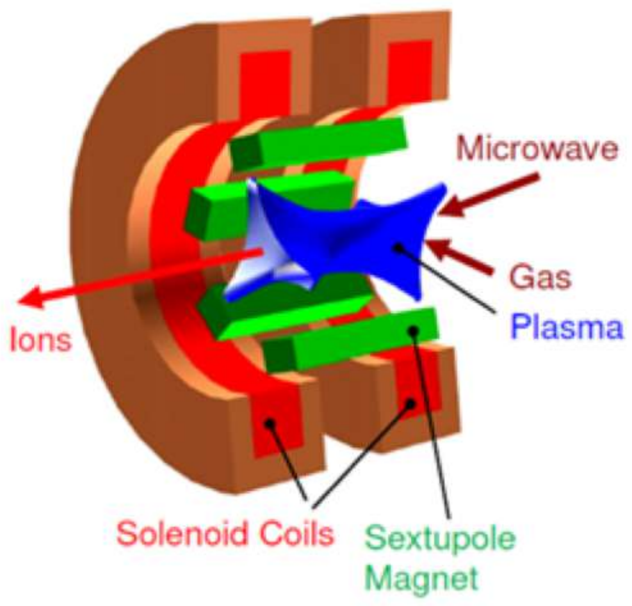
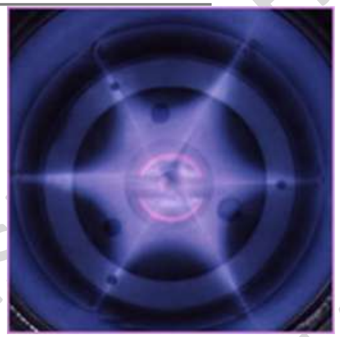
Magnetic Field Structure

- B field creates the ECR resonance, but it also confines the plasma
- B field created by a pair of solenoid (axial field) is inherently instable as the plasma fluid can 'escape' radially (**B_{min} field**)
- **Solution**: add a radial field (sextupole) that creates a 'mirror field' in the radial direction by adding a multipole to the confinement field (can define loss cones)
- Combination of sextupole and solenoid field shapes the magnetic field lines to form a twisted triangular shape on each end of the source





Source: USPAS- Fundamentals of Ion Sources 8./9. Electron Cyclotron Resonance Ion Sources Daniela Leitner

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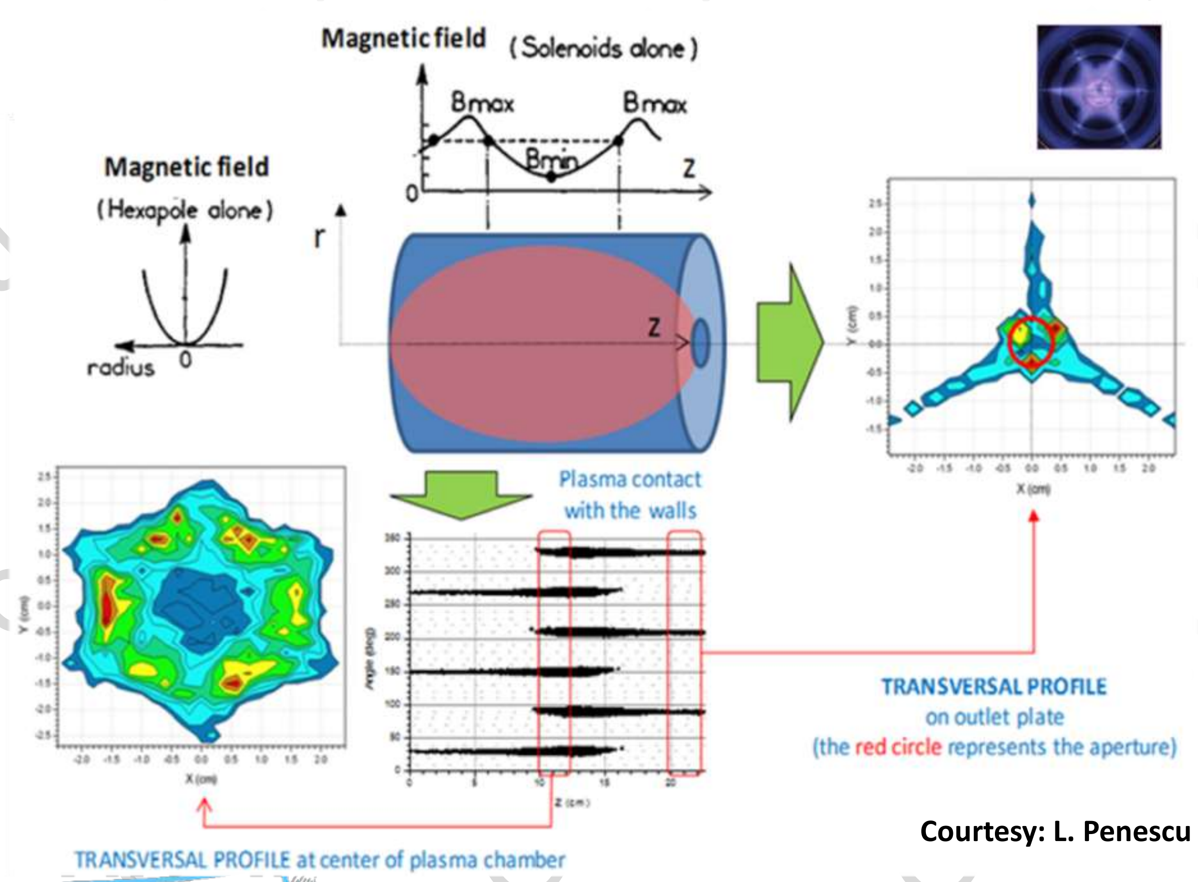
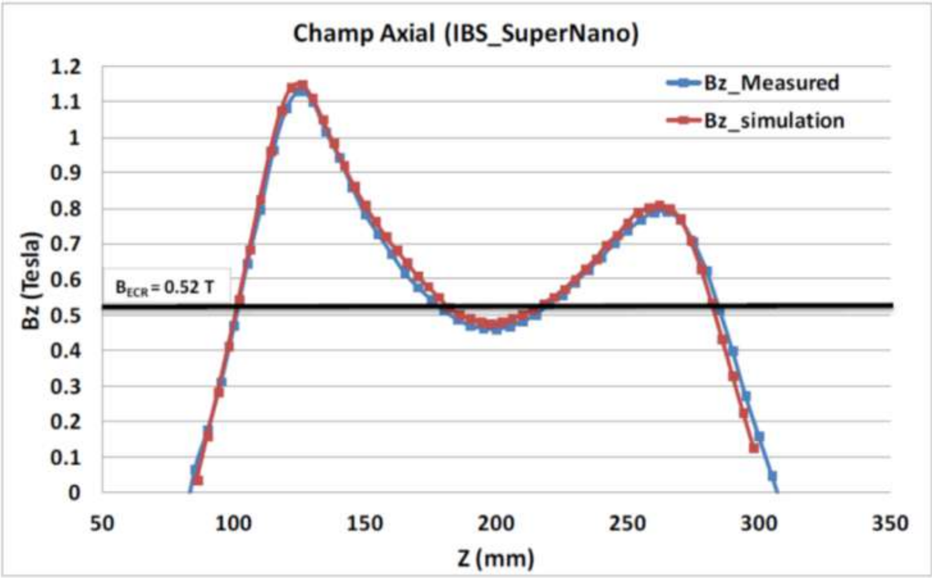
Magnetic Field Structure in Supernanogans



Courtesy: L. Penescu



Courtesy Pantechnik/GANIL

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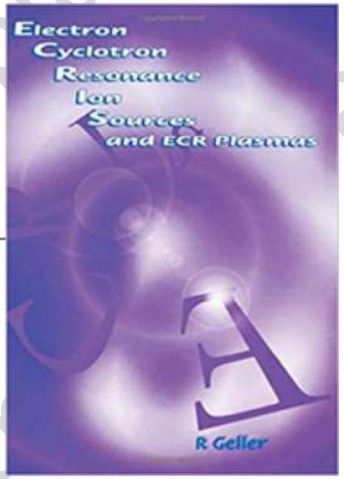
Magnetic FIELD Structure



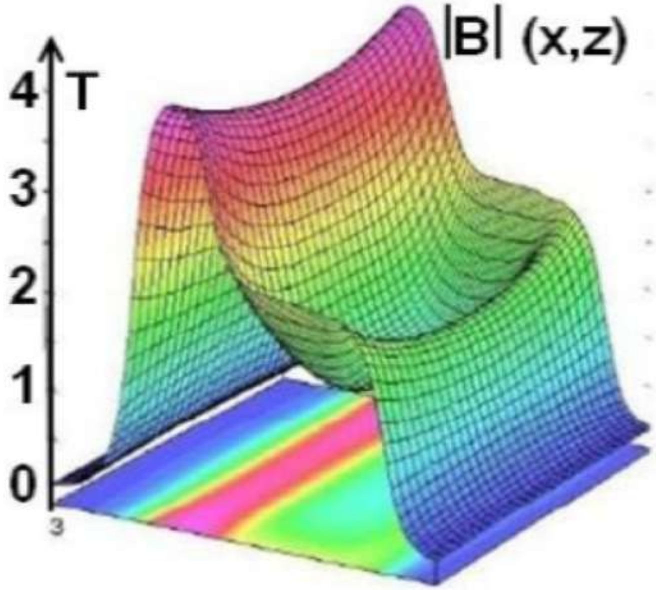
The magnetic field strengths need to fulfill specific laws (scaling laws from R. Geller) in order to have a stable plasma

$$B_{inj} \sim 4 \cdot B_{ecr}$$

$$B_{min} \sim 0.8\, B_{ecr}$$

$$B_{ext} \sim B_{rad}$$

$$B_{rad} \geq 2\, B_{ecr}$$



Source: USPAS- Fundamentals of Ion Sources 8./9. Electron Cyclotron Resonance Ion Sources Daniela Leitner

- For medical requirements we are borderline with these laws, but it is not critical for low intensities

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Plasma Stability

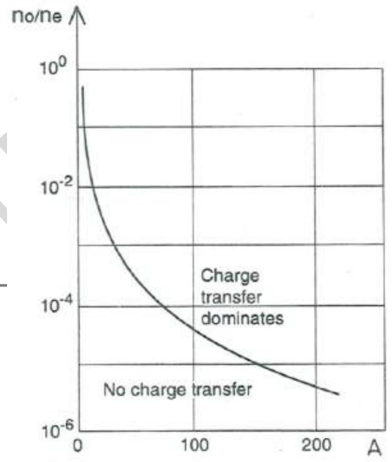
- The plasma needs to be well sustained in terms of density and temperature (atom injection)
- The amount of gas vs. the rf power (and the shape of the magnetic field are the key components for such stability:

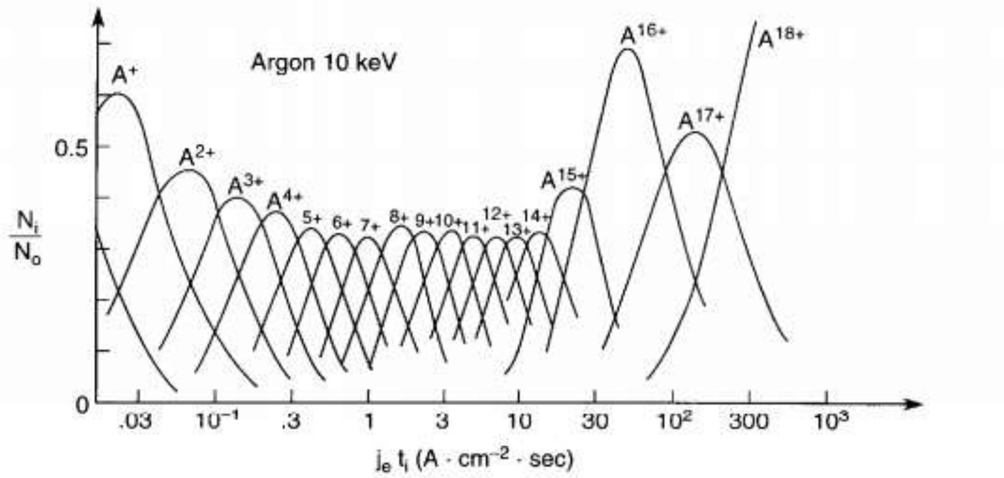
$$\boxed{\text{Eff} \sim \frac{n_i}{n_0}}$$

- **Product of $n_e \tau_i$ can be increased with increasing microwave power, but at the cost of lower intensity..**

- Compromise has to be found in between charge state $< q >$ and Intensity I

$$\boxed{\begin{array}{c} < q > \sim n_e \tau_i \\ I \sim \dfrac{n_e}{\tau_i} \end{array}}$$





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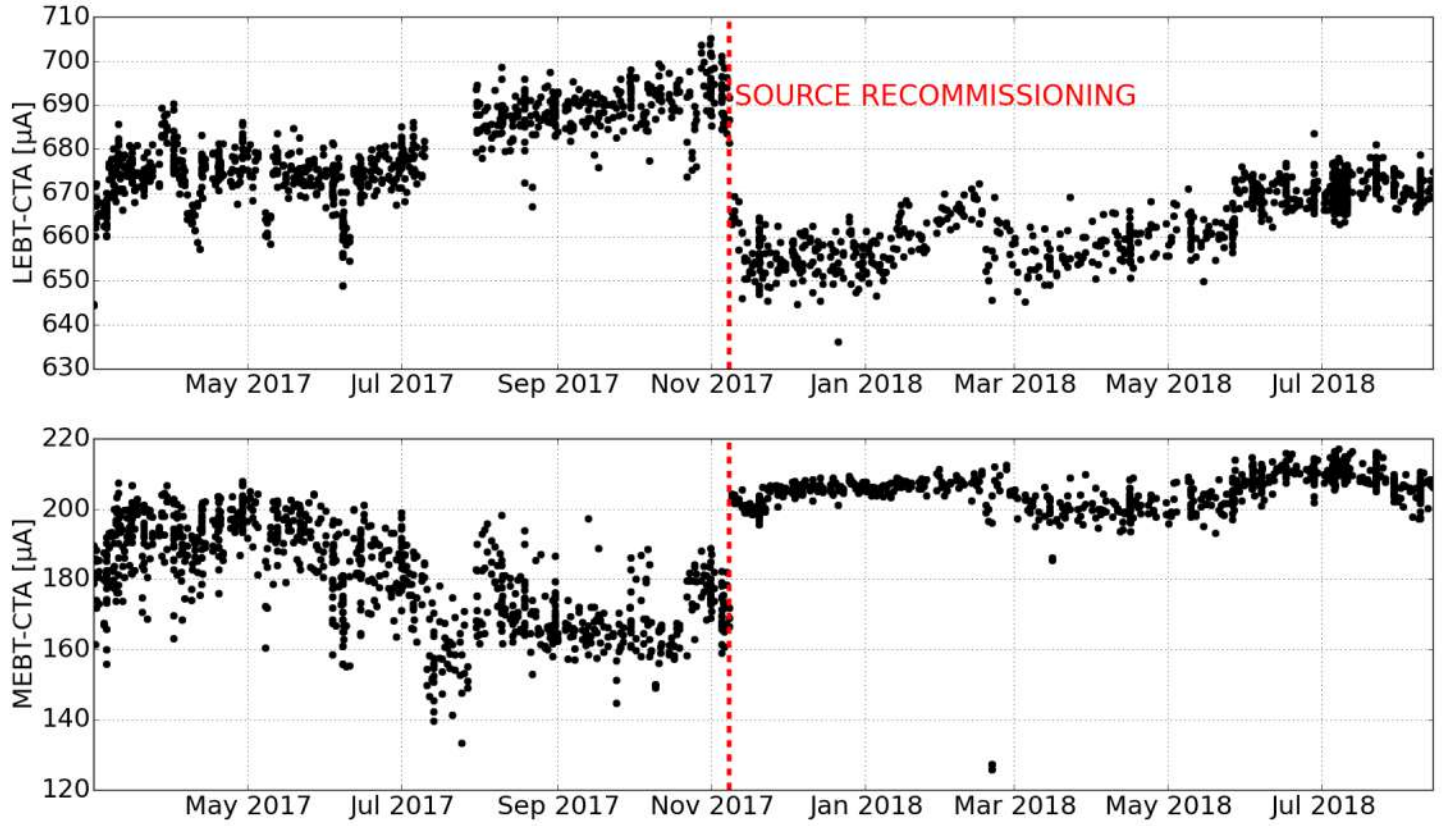
IS Stability for us translate in machine perfomances



- Low intensity drifts occurs over time
- Low intensity leads to longer treatment time
- Emittance can grow over time
- From time to time source has to be recommissioned in order to recover the needed intensity and improve the **shot to-shot stability**

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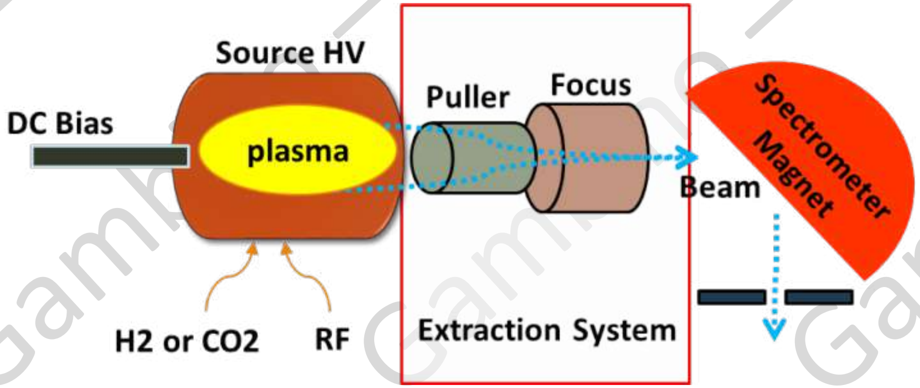
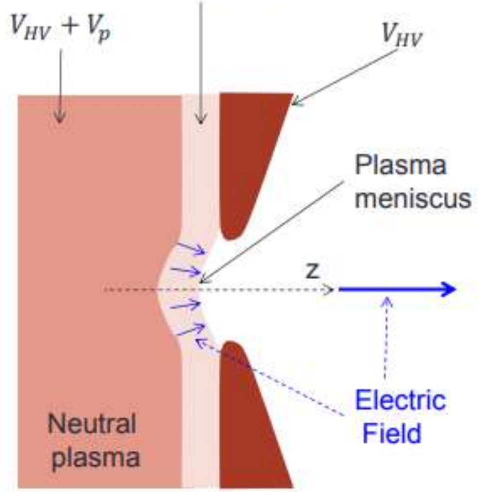
Extraction of the beam

- Ions from the loss cone are extracted via a high potential
- Source body placed at positive HV (≈24 kV, i.e. 8 KeV)
- An electrode (**puller**) at ≈2 kV is grounded and placed at negative lower potential to favour the extraction with circular hole, an electric field generates between the source and the puller
- An electrode (**focus**) at ≈1.5 kV adapts the beam size to the focal point of the dipole magnet for good transmission into the beam line
- Additionally a **Bias** adds electrons to the plasma and lowers the plasma potential reducing ion losses towards the injection
- The longitudinal beam profile depends mainly on extraction parameters with respect to the plasma potential





Source: ELECTRON CYCLOTRON RESONANCE ION SOURCES – II, Thuillier, CAS school 2012

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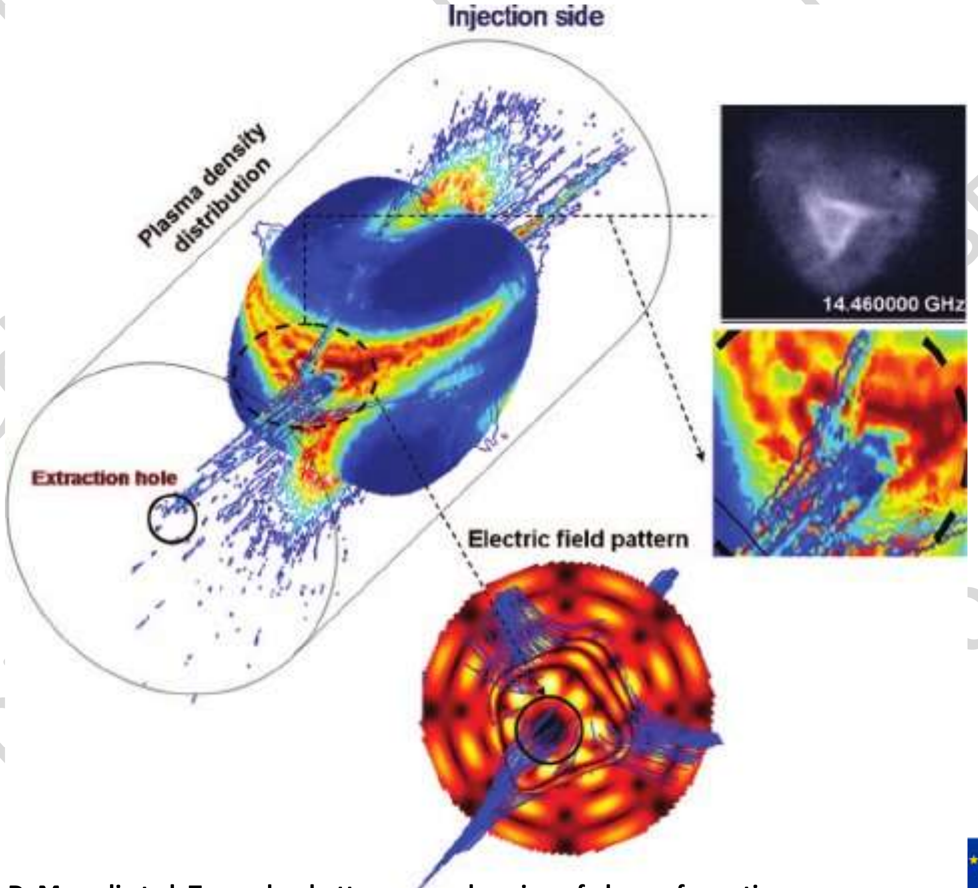
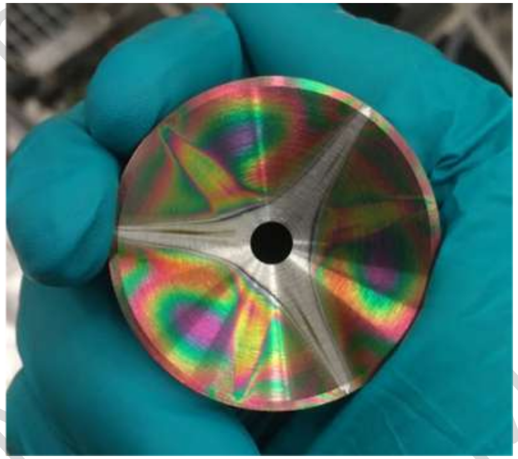
Follow the Field Lines and find the Ion Beam

Some ions will always escape (loss cone), these are the ions that we extract

The hot electrons of ECRIS are a key aspect in:

- At early plasma formation, when the ions have very low energy
- Partially neutralize the space charge induced by the ions during extraction gap penetration, until a point where they are reflected back to the source





Plasma Lens, Ion Beam Clearly visible at the extraction hole

Source: D. Mascali at al. Towards a better comprehension of plasma formation and heating in high performances electron cyclotron resonance ion sources

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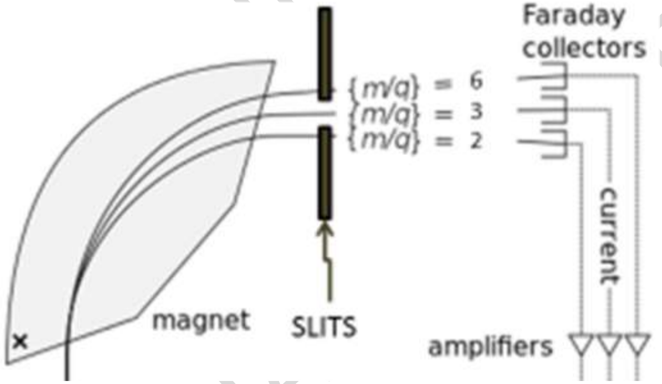
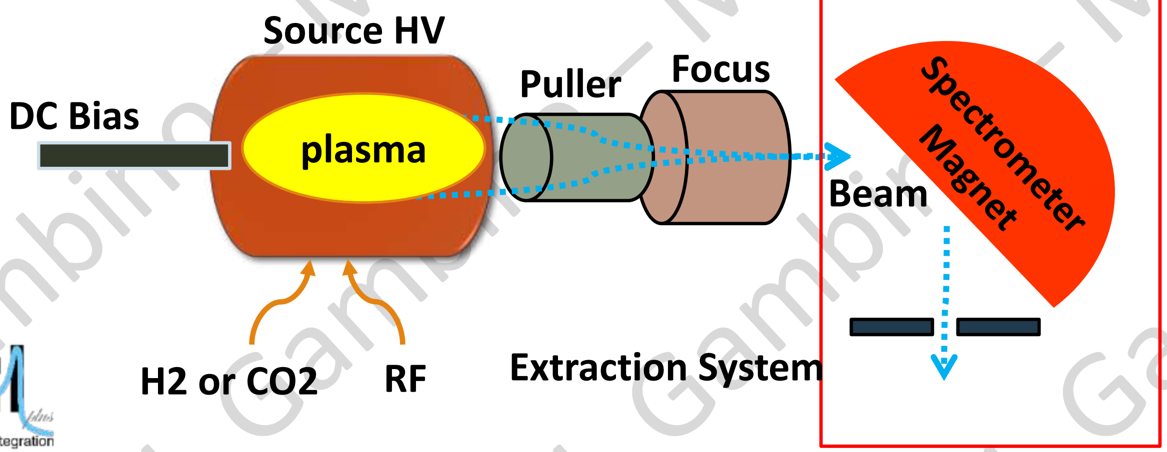
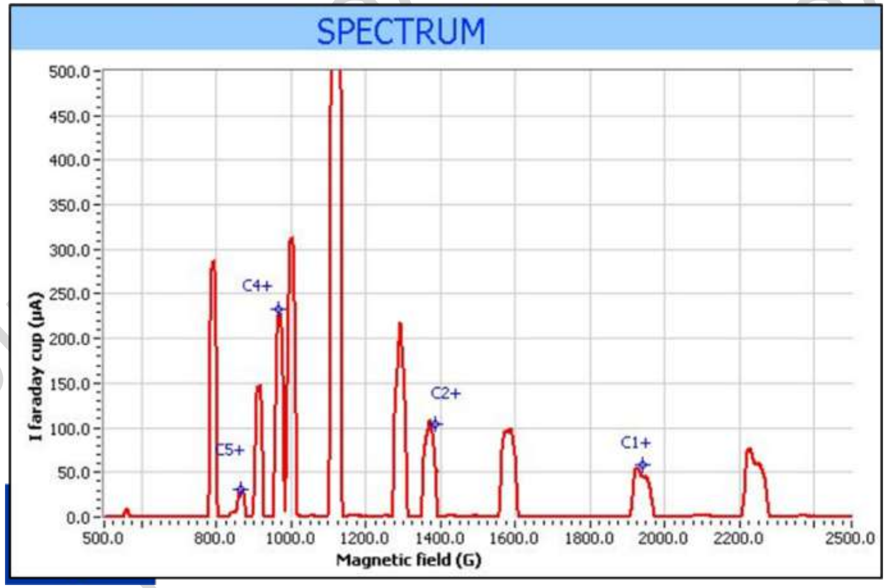
Selection of species

- Beam is sent to dipole for charge state selection (from source all charge states)
- Extracted current is checked with FCN (invasive, blocks the beam).
- Wire scanners to check the beam profile (H and V)
- Slits to cut out the oxygen peak for carbon
- Emittance measured with slits and wire scanners







To Summarize

- ECRIS are well suited IS for medical treatment requirements
- The combination of gas injection, RF frequency and power and magnetic field creates the condition for the plasma heating
- The magnetic field profiles needs to fulfill the scaling laws in order to sustain and confine the plasma (confinement of hot electrons that ionize the atoms and confinement of the ions long enough to get multiple ionizations)
- The beam is extracted via a high potential and ion species are selected via a spectrometer magnet
- Overall source has to be built already for a specific range of charge states and intensities
- Perfomances can also be improved via pulsed mode operation or double frequency heating

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Thanks for your attention!

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