Heavy Ion Therapy Research Integration

Ion Sources (a glance..)

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

NADIA GAMBINO-MEDAUSTRON

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 – PART1

- What is and how do we build an ion source?
- Which are the relevant parameters?
- Types of Ion Sources
- Which physics is involved?
- Some applications and challenges

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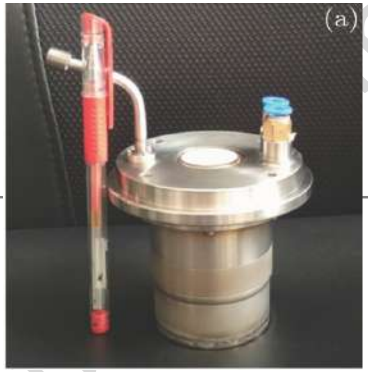
What is an Ion Source?

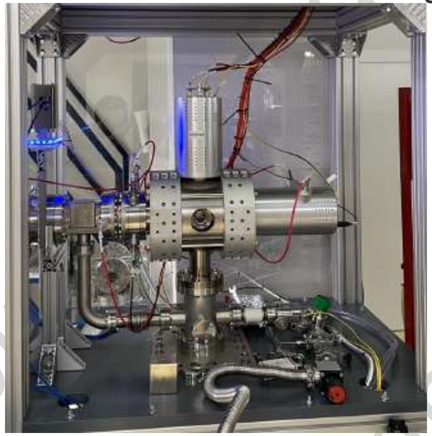
- It is the first fundamental element of any accelerator that allows to generate the ion beam
- Needs to fulfill strict requirements based on desired ion species, charge state, intensity and energy
- Many applications (research, industry, medical) and several types availble



A miniaturized 2.45 GHz ECR ion source at Peking Universit, Wen Jia-Mei et.al.

Supernanogan from Pantechnik 14.5 GHz ECR Ion Source installed at MedAustron

Xenon Focussed Ion Source (FIB) at IST Austria, from ThermoFisher, Credit: S. Bagiante



Electron Beam Ion Source Installed at TUWien Austria, Credit: R. Willhelm

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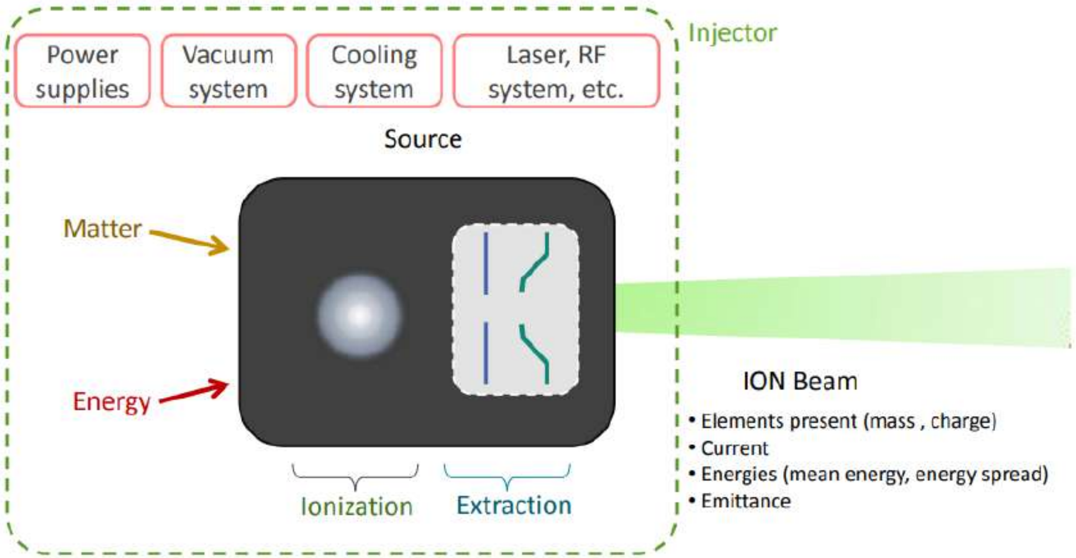
What is an Ion Sources?

We need to produce charged ions from a neutral gas:

1. A vacuum vessel where we inject a material/a neutral gas to create those ions
2. A power source to generate the ions (via discharge or plasma creation)
3. Eventually a sophisticated magnet to confine the plasma
4. An extraction system to pull out the generated ions

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



Source: Gabriel Gaubert, OMA School on Medical Accelerators, CNAO, Pavia, Ion Sources – June 5-9th 2017

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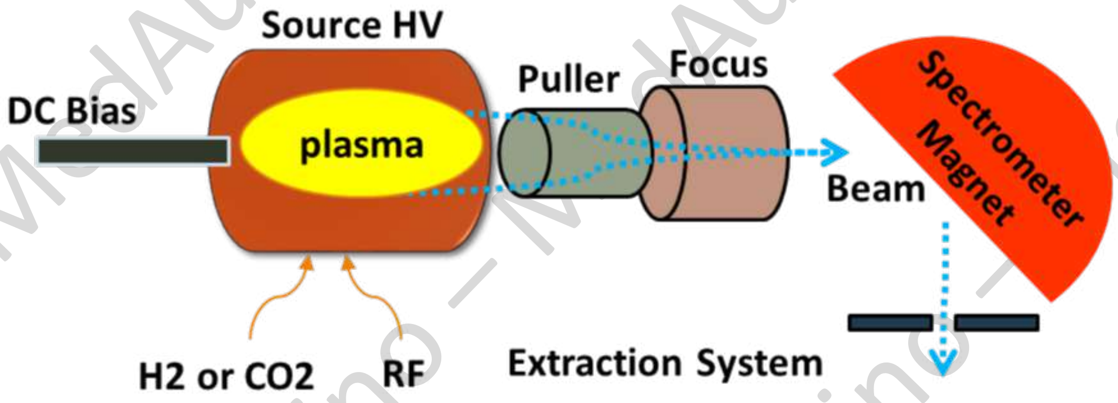
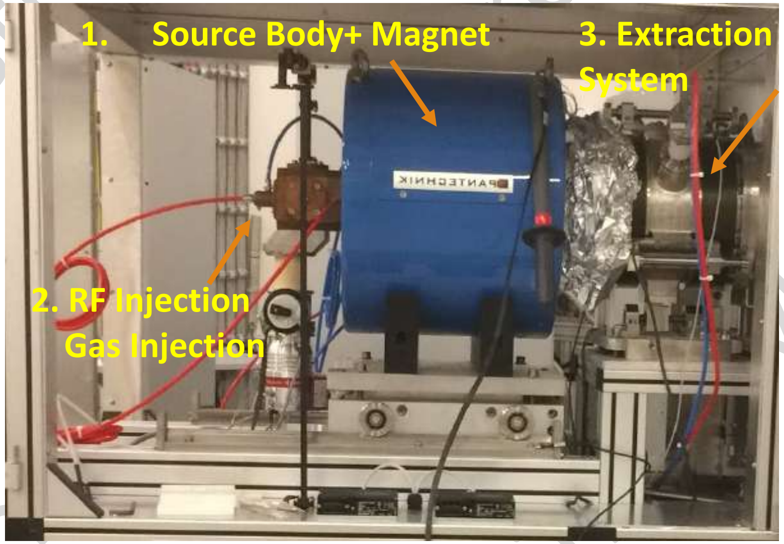
Real Example: Supernanogan

1. A vacuum chamber and a magnet
2. An RF System
3. An extraction system
4. Spectrometer magnet to extract the desired ion species





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Relevant Parameters

- The ion source needs certain characteristics, i.e. it needs to able to generete ions:
  - from different species and charge states, H^{+}, He^{2+}, C^{4+}…Ar^{18+}, Xe^{30+}
  - with certain intensity (from uA to tens of mA)
  - with certain stability requirements

Compromise between high charge state and intensity must be found…

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Relevant Parameters

Intensity $$I_{particle\_current} = \frac{eN_{ions}}{t} = \frac{I_{electrical\_current}}{q}$$

Total Ion Energy after extraction $$E_{total} = qeV$$

Energy Per Nucleon $$E/nucleon = qeV/A$$

Extraction Voltage $$E_{extraction} = V\ (\mathrm{kV})$$

Energy Spread $$\Delta E$$

Emittance $$\varepsilon$$

Example: $_{12}C^{4+}$
E= 8 KeV/u
at 24kV extraction potential

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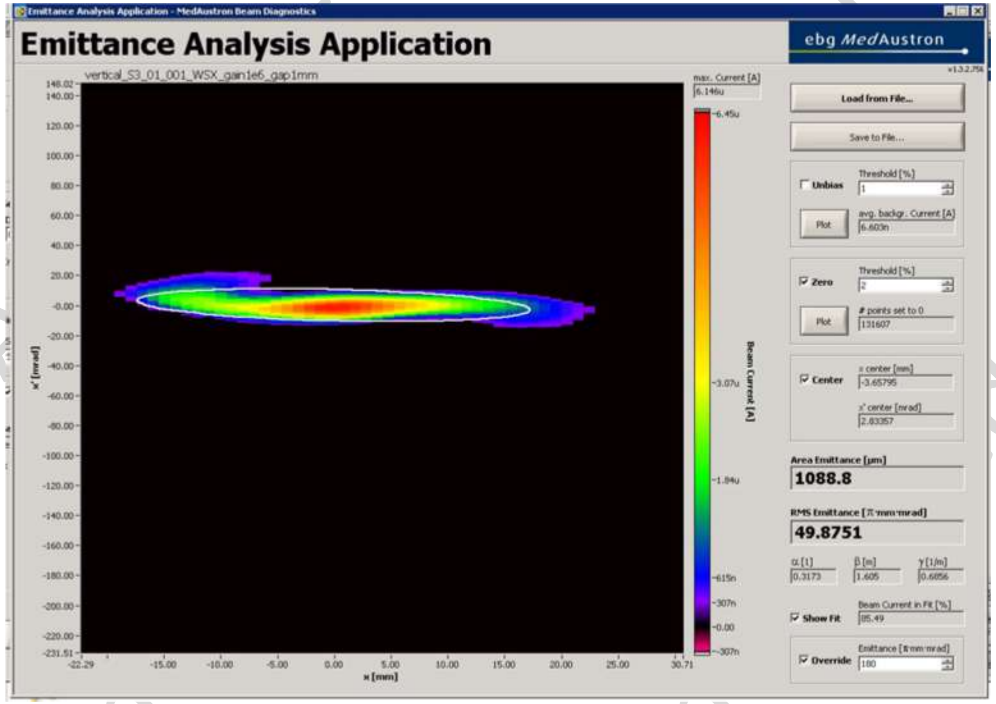
Emittance

Traditionally the emittance is defined as the 6-dimensional volume limited by a countour of particle density in the (x, px, y, py, z, pz) phase space. This volume obeys the Liouville theorem and is constant in conservative fields.

Practically the emittance is the reference parameter for:

- the transmission efficiency in accelerators (example from the source to the next acceptance aperture, example an RF Quadrupole)
- the spot size requirements, brightness, in particle experiments, ion milling etc.
- the luminosity for colliders

A whole lecture would be needed only for the emittance..



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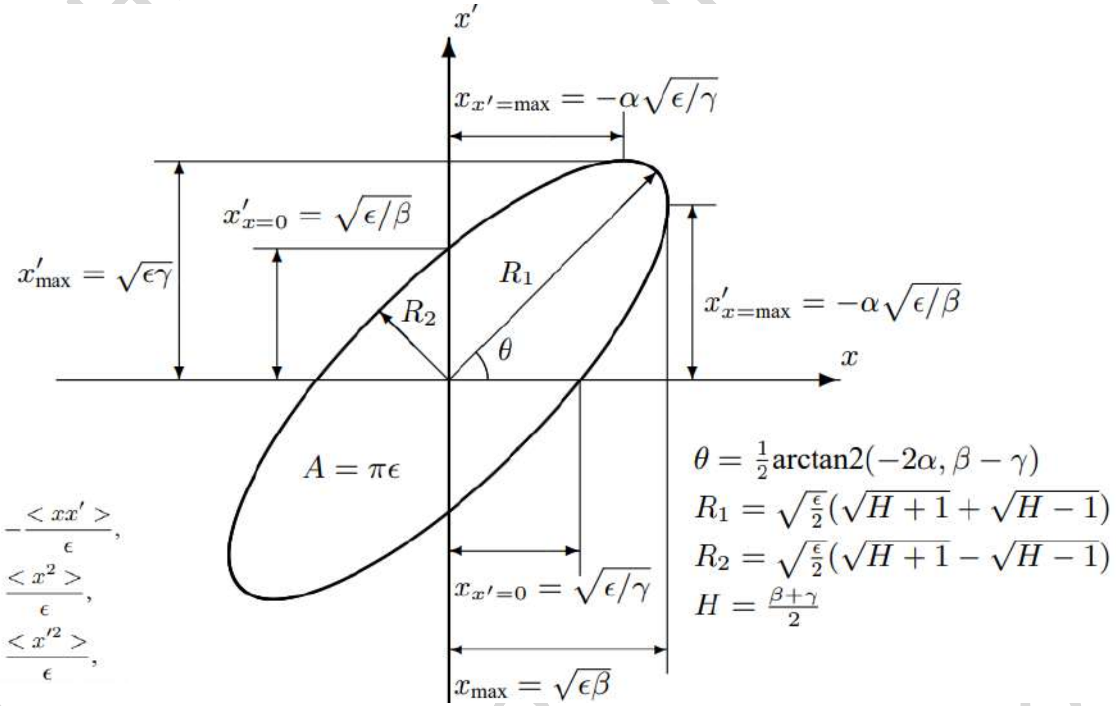
Geometrical Emittance



$$\alpha = -\frac{<xx'>}{\epsilon}, \quad \beta = \frac{<x^2>}{\epsilon}, \quad \gamma = \frac{<x'^2>}{\epsilon},$$

$$\theta = \tfrac{1}{2}\arctan2(-2\alpha, \beta-\gamma)$$
$$R_1 = \sqrt{\tfrac{\epsilon}{2}}(\sqrt{H+1}+\sqrt{H-1})$$
$$R_2 = \sqrt{\tfrac{\epsilon}{2}}(\sqrt{H+1}-\sqrt{H-1})$$
$$H = \tfrac{\beta+\gamma}{2}$$

$$\gamma x^2 + 2\alpha x x' + \beta x'^2 = \varepsilon$$

Emittance ellipse

$$\varepsilon_{rms} = \frac{1}{N^2}\left\{\left[N\sum x^2 - \left(\sum x\right)^2\right]\left[N\sum x'^2 - \left(\sum x'\right)^2\right] - \left[N\sum xx' - \sum x \sum x'\right]^2\right\}^{1/2}$$

$$\varepsilon_{rms} = \frac{1}{N}\left(\sum x^2 \sum x'^2 - \left(\sum xx'\right)^2\right)^{1/2}; \quad \bar{x} = \bar{x}' = 0$$

N: Total number of particles

$$\beta_x \varepsilon_{rms} = \langle x^2 \rangle \quad \alpha_x \varepsilon_{rms} = \langle xx' \rangle \quad \gamma_x \varepsilon_{rms} = \langle x'^2 \rangle$$

Twiss parameter – for calculating beam transport
Note: Subscripted are Twiss, not relativistic

For plasma sources the ion temperature and source outlet aperture give the minimum emittance.

$$\varepsilon_n = \beta\gamma\sigma_{x'}\sigma_x \qquad \varepsilon_n = \frac{\gamma(\beta m_0 c \sigma_{x'})\sigma_x}{m_0 c} \qquad \varepsilon_{th} = r_{out}\sqrt{\frac{2E_{th,ion}}{3m_0c^2}}$$

Small apertures and low (ion) temperature plasmas are good.

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References:
T. Kalvas, CAS School lecture, Ion Sources, Senec, 2012

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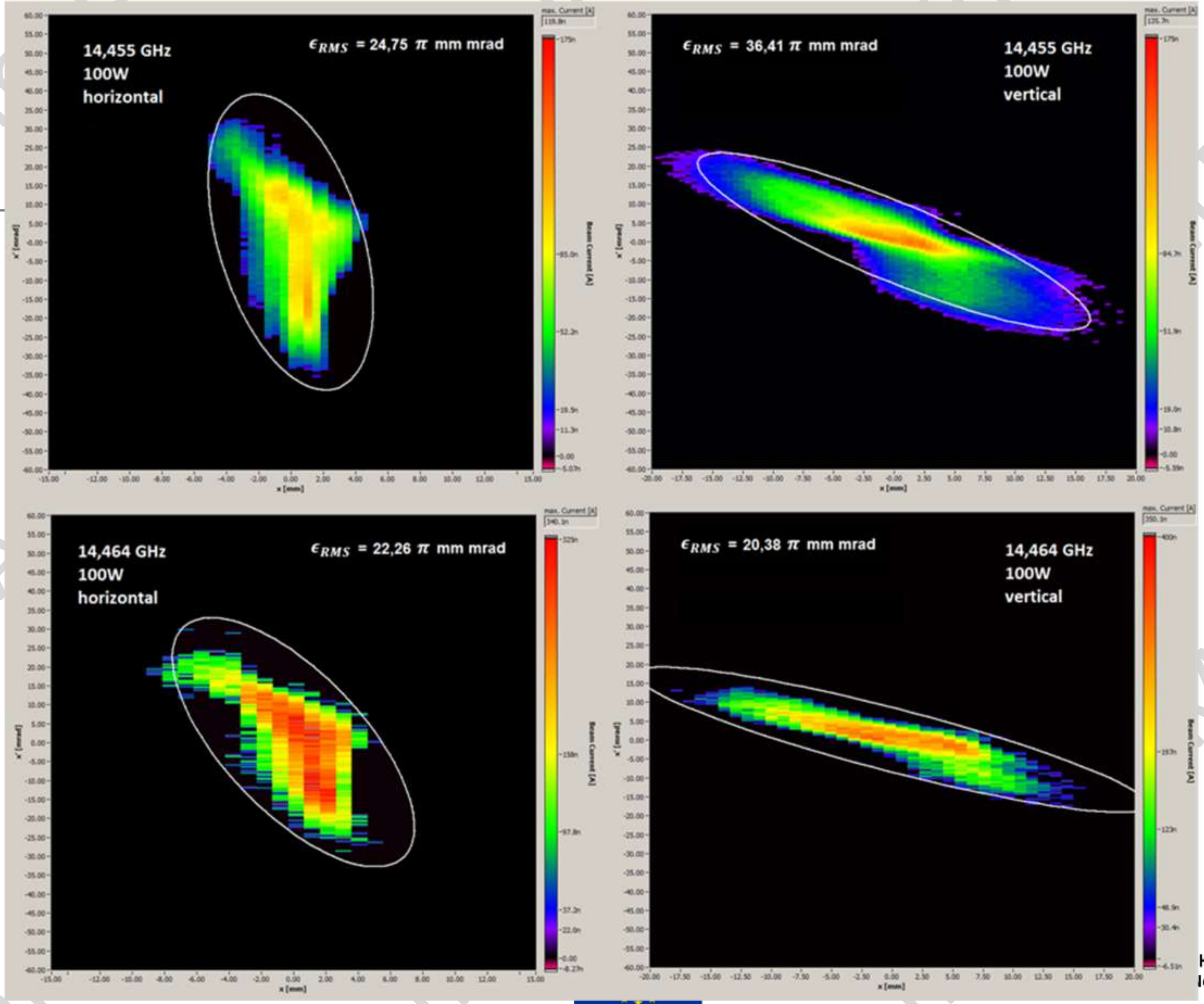
Emittance, the reality

- Real shapes are not as in theory….
- Critical aspect for proper transmission into the accelerator



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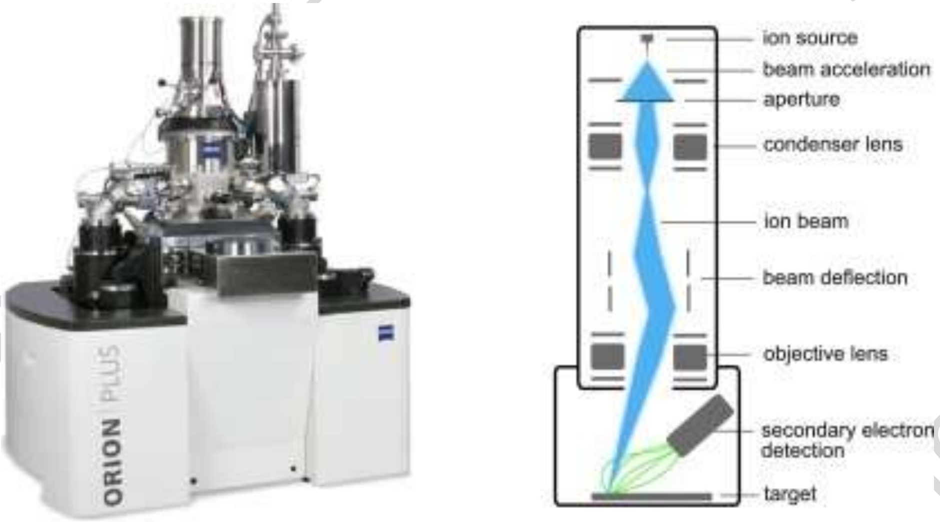
Horizon 2020
No 101008548

Other Relevant Parameters

- Brightness $$B_b = \frac{I_b}{\pi^2 \varepsilon_x \varepsilon_y}$$
- Purity $$\kappa = \frac{N_{ions}}{N_{beam}}$$
- Efficiency $$\eta = \frac{N_{ions}}{N_{atoms}}$$



(A) (B)

Advances in Imaging and Electron Physics
Volume 212, 2019, Pages 181-216

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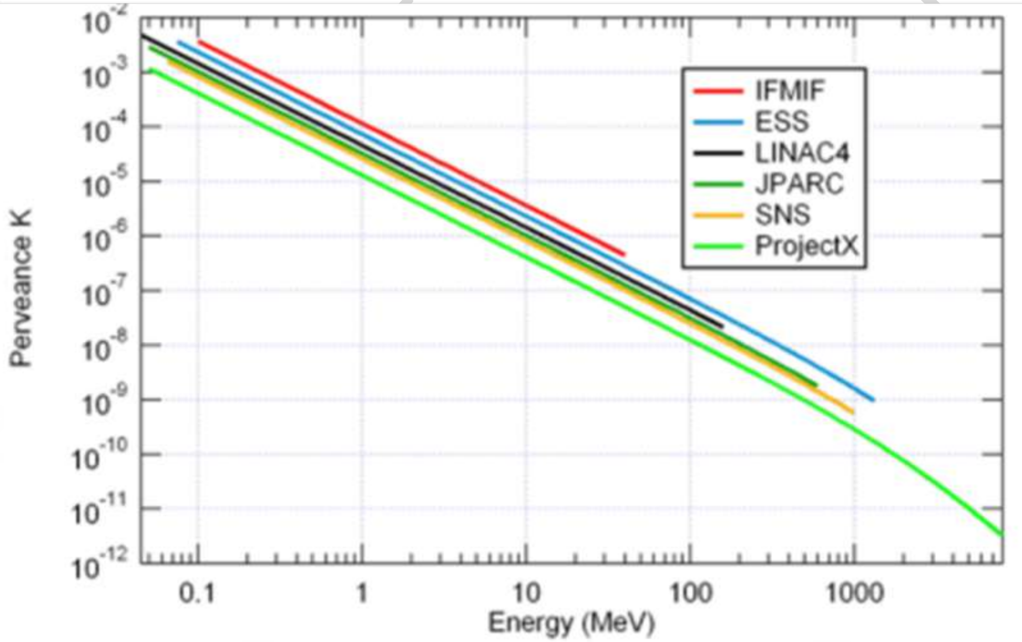
Space Charge

- Space charge effects are generated from electromagnetic repulsion in moving ion beams
- On Low Energy Ion Beams space charge will have a <u>defocusing effect</u>
- It will affect the emittance (emittance growth)
- It can be compensated by focussing elements

STUDY ON SPACE CHARGE COMPENSATION OF LOW ENERGY HIGH INTENSITY ION BEAM IN PEKING UNIVERSITY, S. X. Peng1 et. Al.



Space Charge Effectsm N. Chauvin
CAS Lecture Senec, 2012

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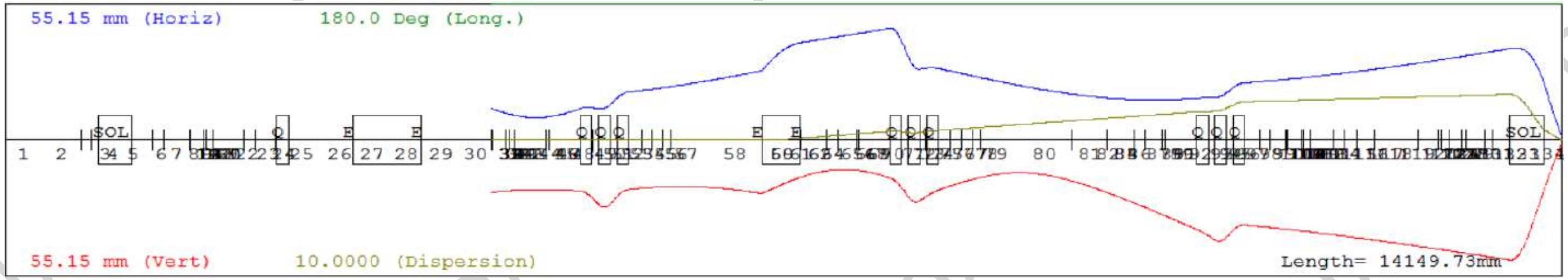
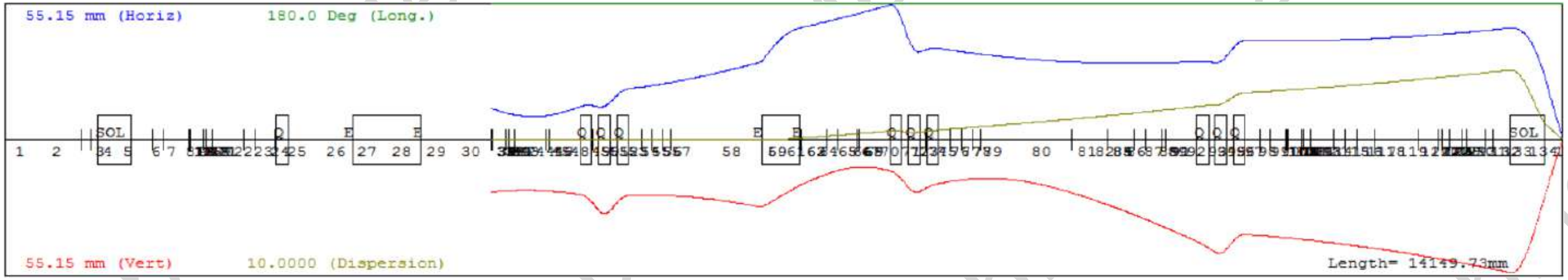
Example: Space Charge in Beam Dynamics Simulations

Simulated beam envelopes (Trace3D):

- I = 0 mA (no space charge)



- I = 0.2 mA



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Courtesy of M. Kausel

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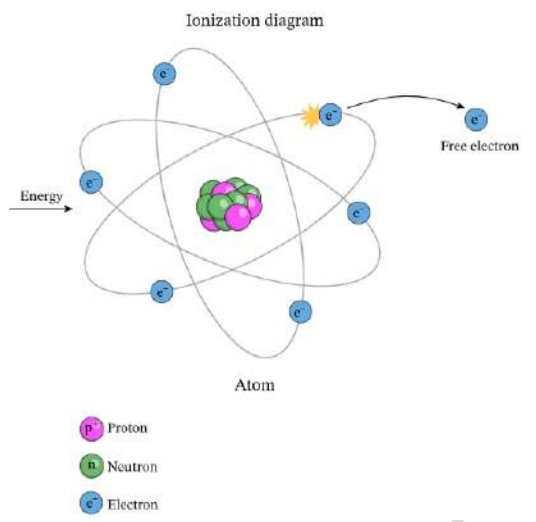
Type of Ion Sources

1. We need to triggger the ionization process, i.e. the ion formation by gain or loss of an electron from an atom
2. We need a driving force, i.e. an electromagnetic force to generate the ions

- RF
- Laser
- Discharge
- …



This will define the type of Ion Source and the underlying physics that we need to understand it (type of ionization process, therefore atomic physics, plasma physics, EM theory)

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Main type of Ion Sources

- **DC, RF, Plasma Discharges**
  - Plasmatron, Magnetron, Duoplasmatron, Penning
- **ECRIS**
- **EBIS**

1. Electron Impact Ionization

The ones of our interest for medical applications

- **Laser Ion Source (LIS)**

2. Photo Induced Ionization

- **SIS**

3. Surface and
4. Thermal Ionization
5. Charge Exchange

References:
Classification of Ion Sources R. Scrivens CERN, Geneva, Switzerland

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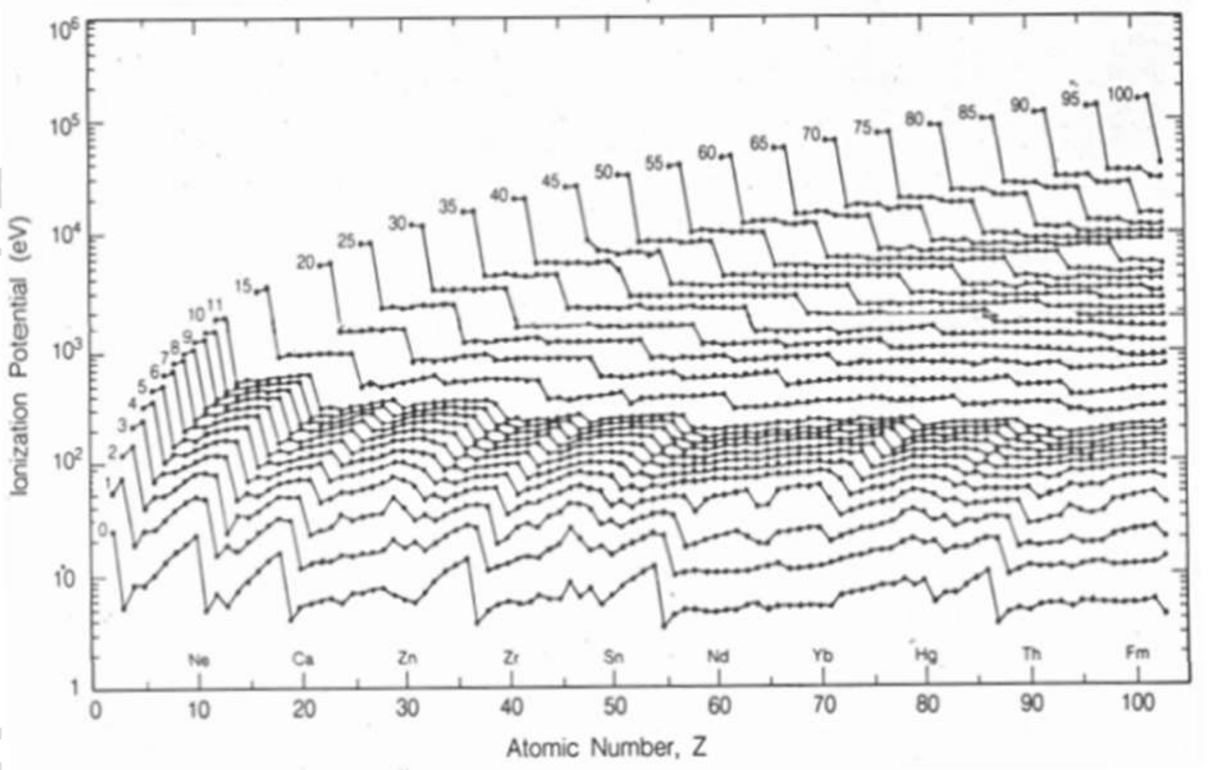
Ionization Potential



- The electron energy needs to be sufficiently high in order to overcome the ionization potential
- Beside the gain of energy via electron impact ionization we will have losses generated by:
  - Collisions with the wall
  - Radiative Recombination
  - Dieletric Recombinations
  - Charge Exchange collisions
- Some of these losses can be limited via tuning of the operating pressure
- Certain optimizations are needed..

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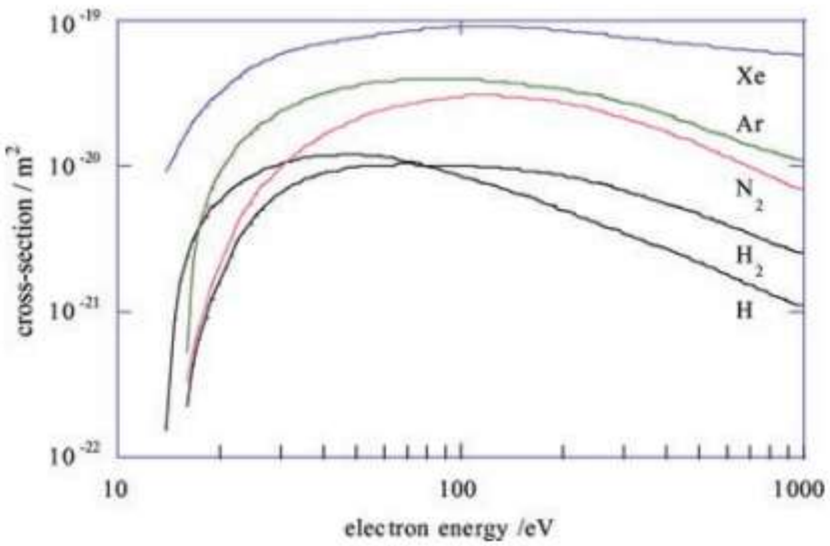
Ionization Cross Sections



Plasma Sources Sci. Technol. **9** (2000) 517–527.

$$\sigma n_{\text{atom}} = \frac{1}{L_{\text{collision}}}$$

- Any reaction has a certain probability to happen, this is why we calculate cross sections for every element!
- Cross sections can be very small
- Use of step by step ionization, to make some needed collisions more probable and generate highly charged ions
- Ions need to get sufficient time to get the proper charge state (confinement time within the ion source vessel)
- A good enviroment where these conditions apply can be created by **generating a plasma** in the vacuum vessel

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Plasma State

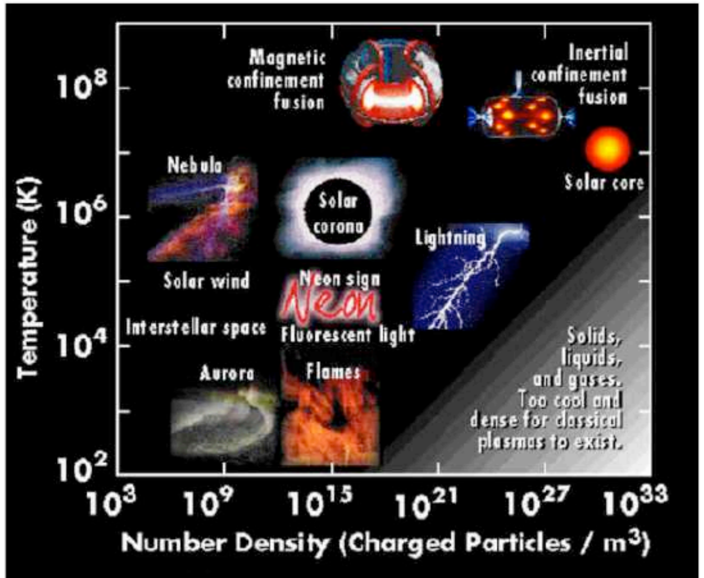
Called *fourth state of matter*, can be studied as a liquid or a gas

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 $L \gg \lambda_D$

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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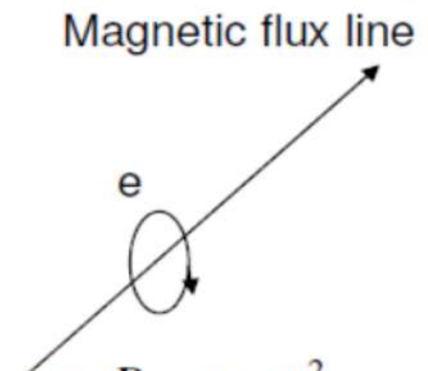
Magnetic Confinement (helps)

- The neutral gas 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:

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

$\Downarrow$

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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Plasma Stability

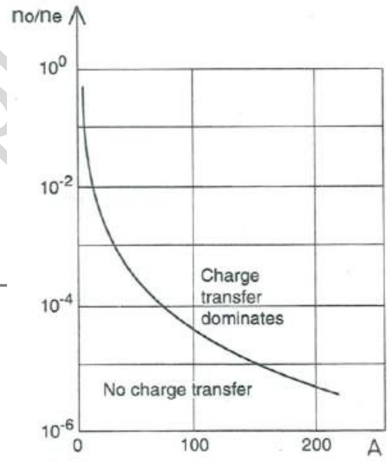
- The plasma needs to be well sustained in terms of density and temperature (atom injection)
- The amount of gas vs. the rf power (and the shape of the magnetic field are the key components for such stability:

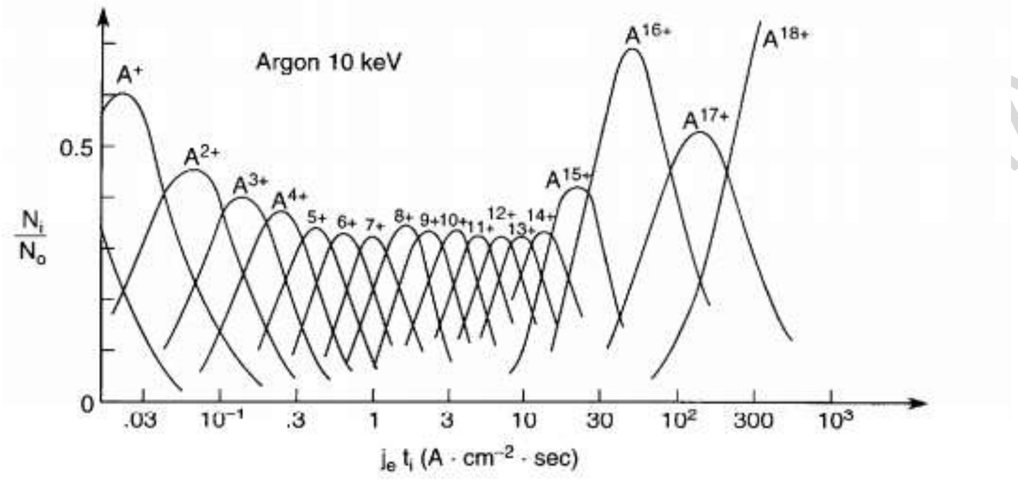
$$\boxed{\text{Eff} \sim \frac{n_i}{n_0}}$$

- **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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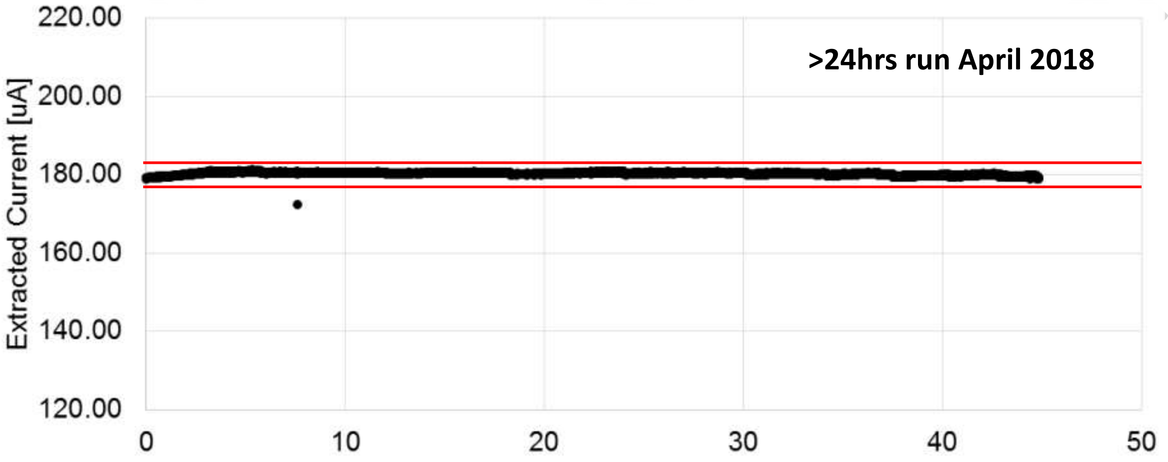
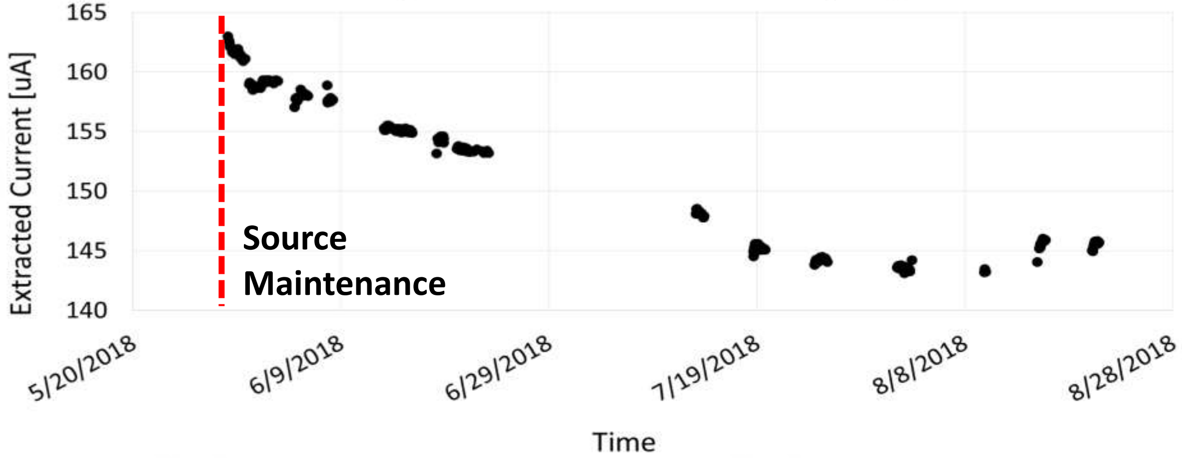
Challenges For Medical Treatment

- Does the source produces the needed charge state?
- Does the source produce the needed charge state with sufficient intensity?
- Is the beam stable over time? Time means days..
- Is the emittance good enough for optimal tranmission further into the accelerator?



Degradation of Carbon Current May-August



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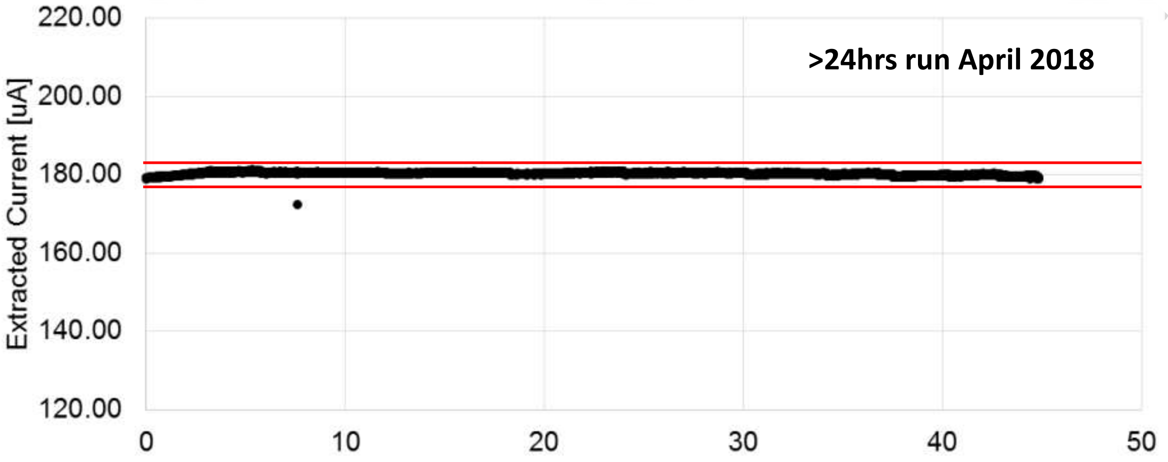

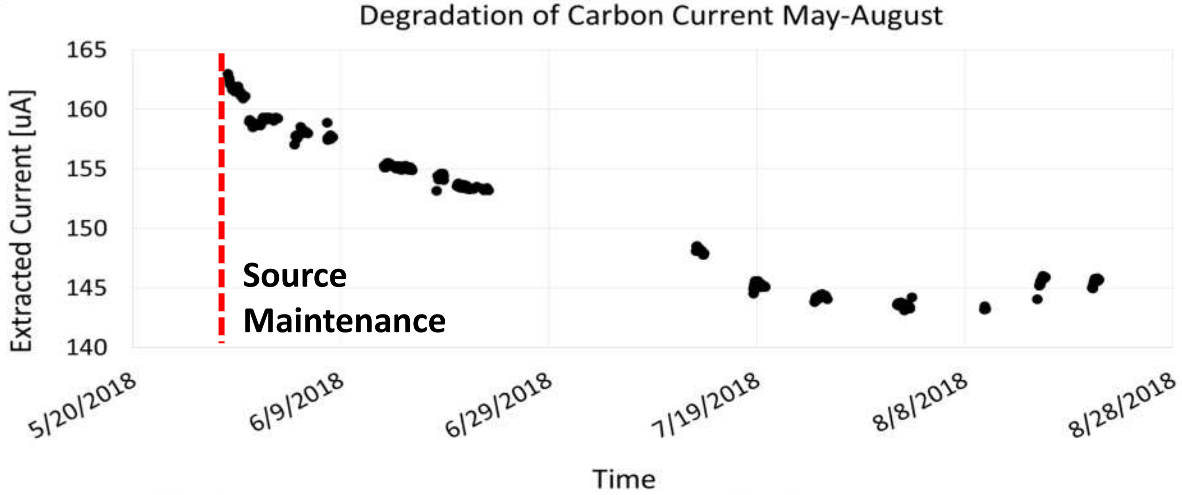

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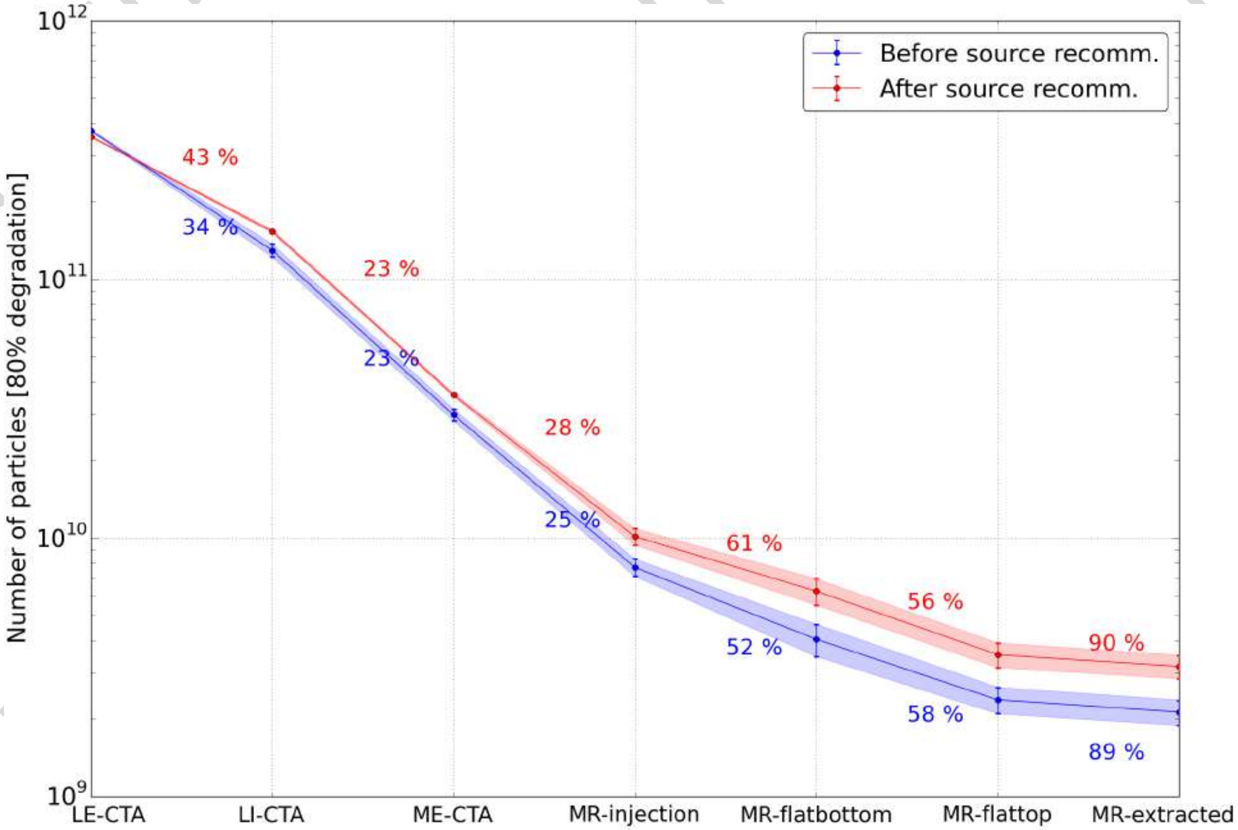
Challenges For Medical Treatment



Transmission from LEBT to LINAC, from LINAC to MEBT, from MEBT to synchrotron injection (MR-injection), from injection to capture (MR-Flatbottom), from start to end acceleration (MR-Flattop), from end acceleration to extraction (MR-extracted).

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To Summarize

- A glance inside the Ion Sources Physics was given today
- Many physical process were shown together with some technological aspects
- Depending on the application the right ion source has to be chosen (intensity, charge state, emittance)
- For medical application we need a source delivering stable beam and with low maintenance
- For further reading dig in the CAS lectures:
- Ion sources, 29 May 2012 - 08 June 2012, Senec, Slovakia (link)

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Thanks for your attention and see you on Friday!

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