JOINT UNIVERSITY ACCELERATOR SCHOOL

PARTICLE SOURCE ADD-ON :

ION BEAM EXTRACTION AND LEBT

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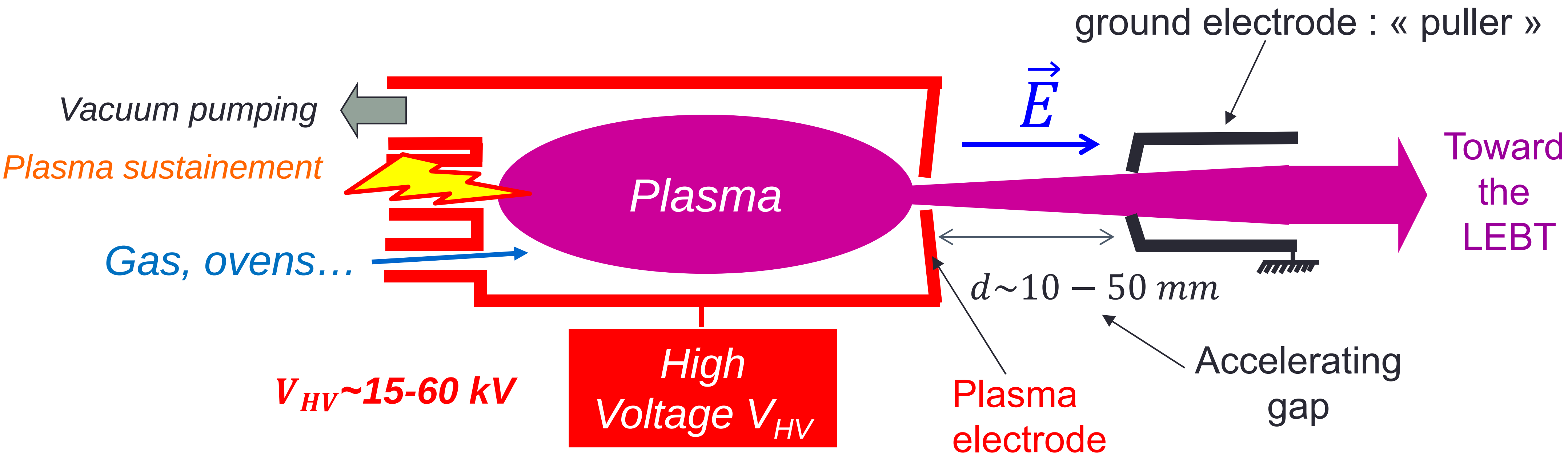
Beam Extraction from a plasma Ion Sources - Overview

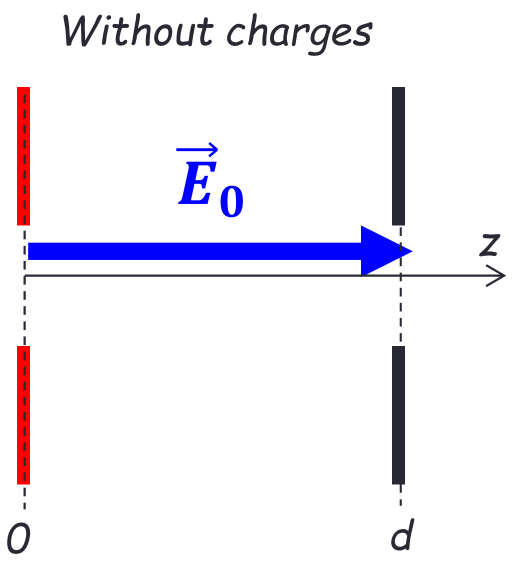
- The ion beam is extracted by setting the plasma chamber to a high voltage V_{HV}~15-60 kV
- A plasma electrode is closing the chamber on the extraction side, it is equipped with a circular hole with diameter Ø~5-13 mm or aset of small holes
- A puller electrode, set to ground potential, is placed in front of the plasma electrode
- The electric field in the gap, $E \sim \frac{V_{HT}}{d} \sim 10-100\ \mathrm{kV/cm}$, enables to accelerate the low energy ions from the
- Kinetic energy of ions on axis after the acceleration, with atomic number A and charge Z :

$$\mathbf{T} = \frac{1}{2} m_A A v^2 = ZeV_{HV}$$



The Child Langmuir Law (1/3)

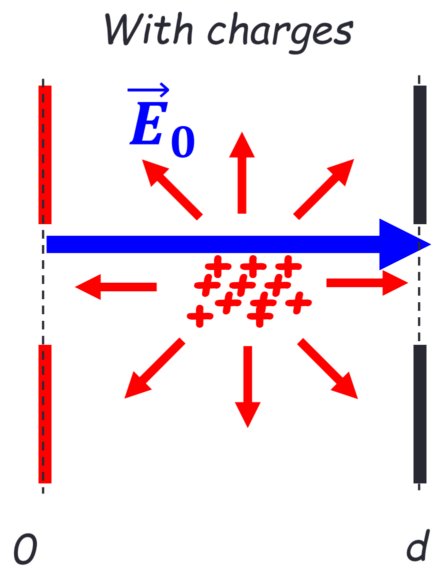
- When a beam current ***I*** of charged particle is extracted in a static electric field $\vec{E}_0 = \frac{V}{d}\vec{z}$, the particle charges in the beam generate a space charge electric field $\vec{E}_{SC}(\vec{r})$ that perturbates $\vec{E}_0$



$$\vec{E}_{SC}(x,y,z) = \iiint \frac{Ze}{4\pi\epsilon_0}\frac{\vec{r}-\vec{r'}}{\|\vec{r}-\vec{r'}\|^3}dx'\,dy'dz'$$

$$\vec{J}_{SC} = \rho(\vec{r})\vec{v}(r)$$

Beam Current density



- The resulting electric field in the gap is: $\vec{E}(x,y,z) = \vec{E}_0 + \vec{E}_{SC}(x,y,z)$
- At z=0, $E(x,y,0) = E_0 - |E_{SC}(x,y,0)| < E_0$ (fields are opposed!)

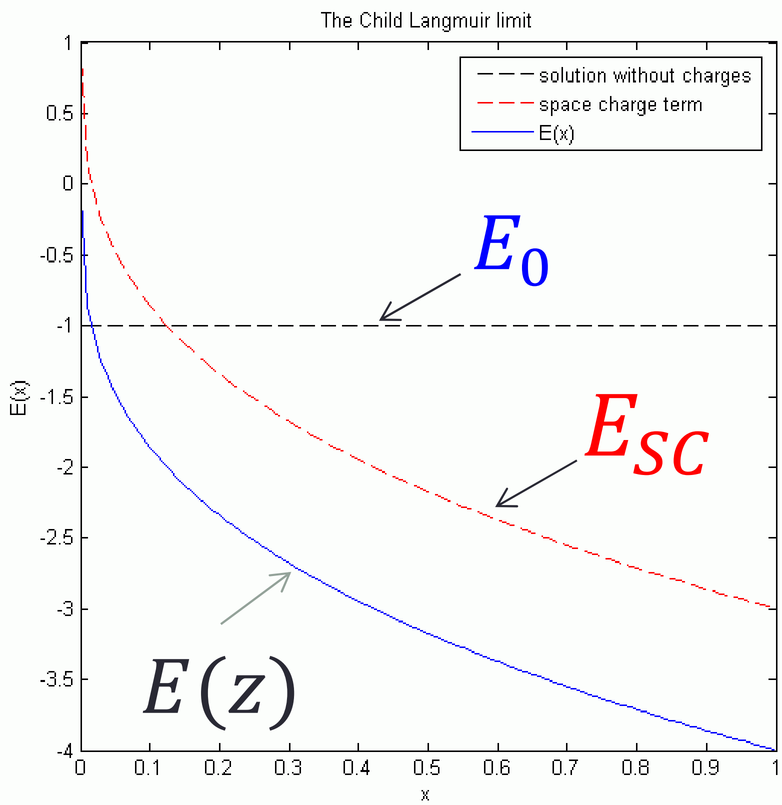
The Child Langmuir Law (2/3)

- When the extracted current *I* increases:

$\vec{E}_{SC}(z,r)$ increases,

so $E(x,y,0) = E_0 - |E_{SC}(x,y,0)|$ decreases

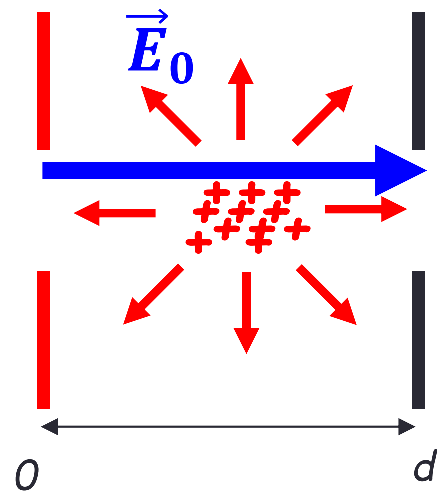
- A limit current density J is reached when E$(x,y,0) \rightarrow 0$
  - Then, particles cannot be extracted any more from the plasma, as there is no more electric field to accelerate low energy particles!



- This gives the Child Langmuir Law: $J \leq \frac{4\epsilon_0}{9}\sqrt{\frac{Z}{A}}\sqrt{\frac{2e}{m_A}}\frac{V^{3/2}}{d^2}$
  - Increase J requires:
    - increase High Voltage *V*

  and/or
    - reduce gap *d* (caution with breakdowns!)

Law valid For 1D infinite planar extraction



The Child Langmuir Law (3/3)

- The general limit current density that can be extracted from a real 3D extraction system can be expressed as:

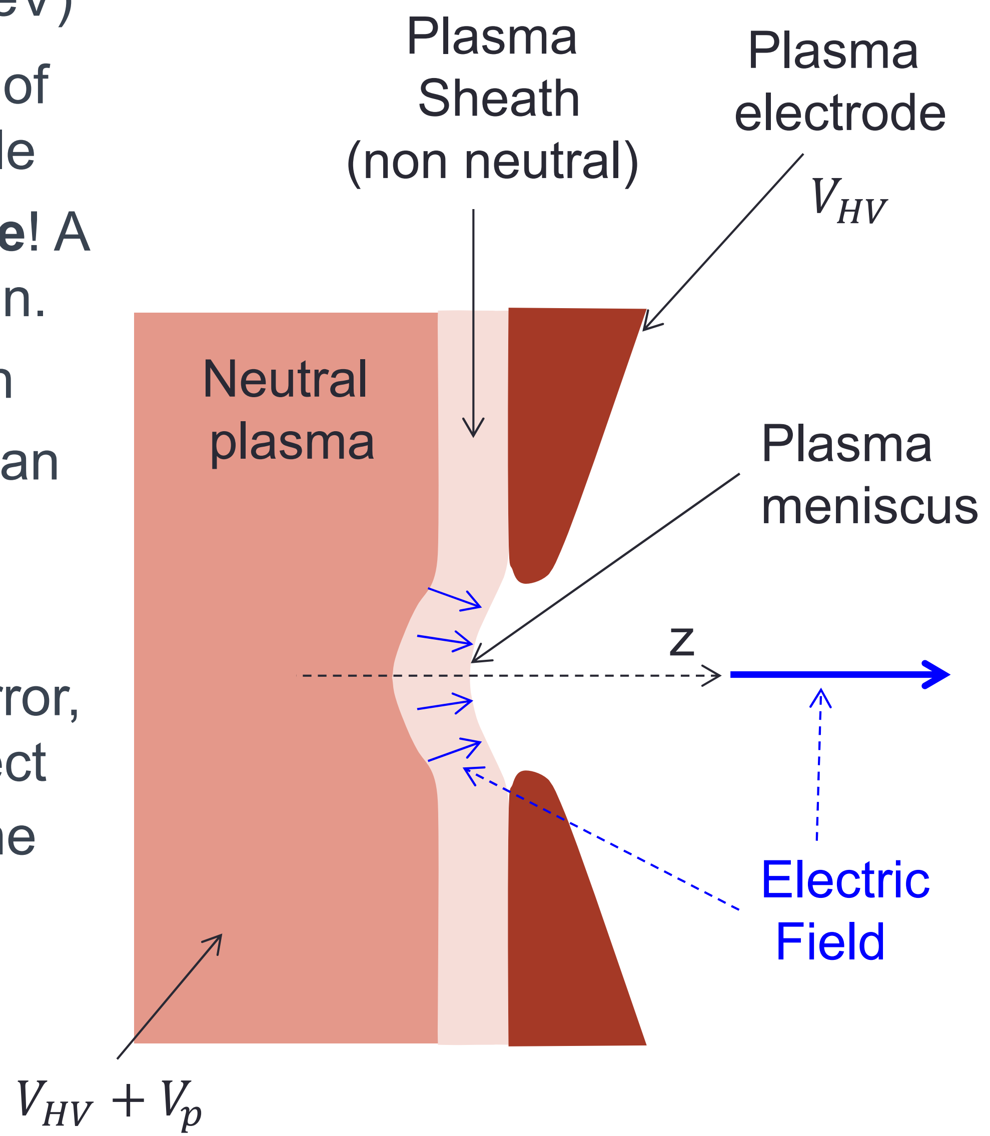
$$J = P.U^{3/2}$$

  - J= limit current density (A/m^2)
  - P=perveance of the extraction system
  - U=extraction voltage (Volts)

- The perveance is a function of the extractor geometry
- For a usual axi-symetrical extraction, $P \sim \frac{K}{d^2}$, where d is the accelerating gap and K a constant

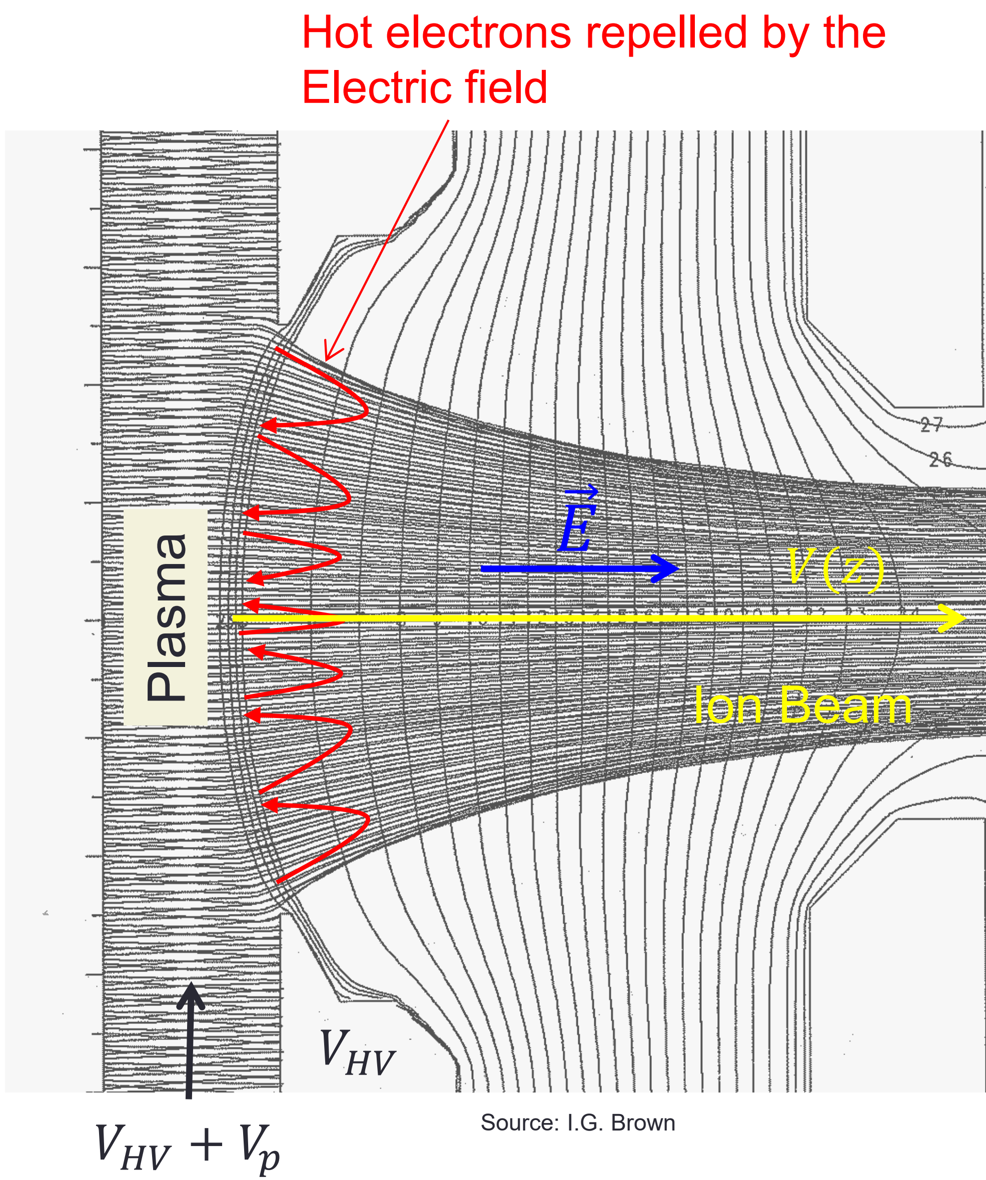
Zoom on the Ion Extraction from the plasma Sheath

- The plasma potential is $V_p > 0$ (usually ~5-50 eV)
- The plasma meniscus is the natural curvature of the plasma in front of the circular electrode hole
- The plasma meniscus shape is **not predictible**! A concave meniscus is optimum for ion extraction.
- The ions are extracted from the plasma sheath
- The ions incident velocity in the early sheath can be modelized by the Bohm criterion:
  - $v_{\mathrm{i}} = \sqrt{kT_e/m_i}$
- Ions extracted have escaped the magnetic mirror, so their initial velocity pitch angle θ with respect to $\vec{B}$ are distributed in the loss cone ruled by the Axial Mirror ratio $R = \sqrt{B_{max}/B_{min}}$:
  - $v_{\parallel} = v \cos\theta$
  - $\sin\theta \leq \frac{1}{\sqrt{R}}$



Hot Electrons contribution to the emittance

- The hot electrons of Heavy Ion ECRIS play an important role in the early beam formation, when the ions have very low energy
- Hot electrons ($kT_e \sim 1 - 5\ keV$) penetrate into the extraction gap and neutralize partially the space charge induced by the ions, until a point where they are reflected back to the source.
- The electron density in the ECR plasma sheath is usually approximated by the Boltzmann distribution function, assuming a gaussian electron distribution function:
- $n_e = n_{e0} e^{\frac{e(V(z) - V_{HV} - V_p)}{kT_e}}$
  - n_{e0} is the electron density in the neutral plasma
  - $V(z)$ is the local electrostatic potential at position z in the extraction area
  - V_p and V_{HV} are respectively the plasma potential and the High Voltage



Source: I.G. Brown

Ion Beam Emittance from an ECRIS

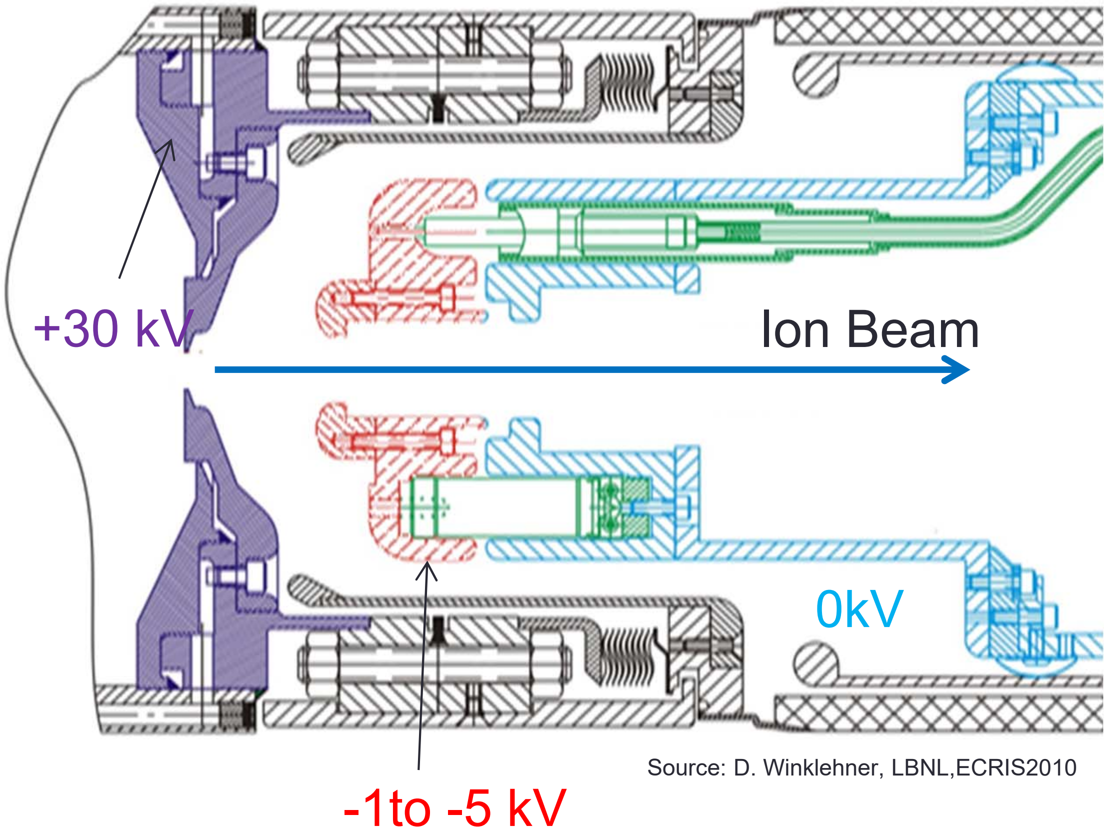
- The beam emittance from an ECRIS has mainly two origins:
  - **Thermal emittance** induced by ion beam temperature (OFTEN NEGLIGIBLE)
  - $\boldsymbol{\varepsilon_T}^{\boldsymbol{xx'-rms-norm}} = \mathbf{0.016r}\sqrt{\frac{\boldsymbol{kT_i}}{\boldsymbol{M/Q}}}$
    - kT_i ion temperature (~1/40 eV)
    - r electrode radius (mm)
    - M/Q mass over charge in amu
  - **Magnetic emittance** induced by the beam rotation due to the decreasing magnetic field seen by the beam when it exits the source: THIS IS THE DOMINANT TERM
  - $\boldsymbol{\varepsilon_B}^{\boldsymbol{xx'-rms-norm}} = \mathbf{0.032}\boldsymbol{r^2 B}\frac{\mathbf{1}}{\boldsymbol{M/Q}}$
    - B magnetic field intensity at the plasma electrode
    - r electrode radius (mm)
    - M/Q mass over charge in amu
    - This effect is a direct consequence of the Busch Theorem that says that the azimuthal canonical particle momentum $p_\theta = \mathrm{m}r^2\dot{\theta} + \frac{1}{2}qB(z)r^2$ is a constant of the motion in an axi-symmetrical magnetic field (see appendix for details)

High intensity Heavy Ion ECRIS Extractor

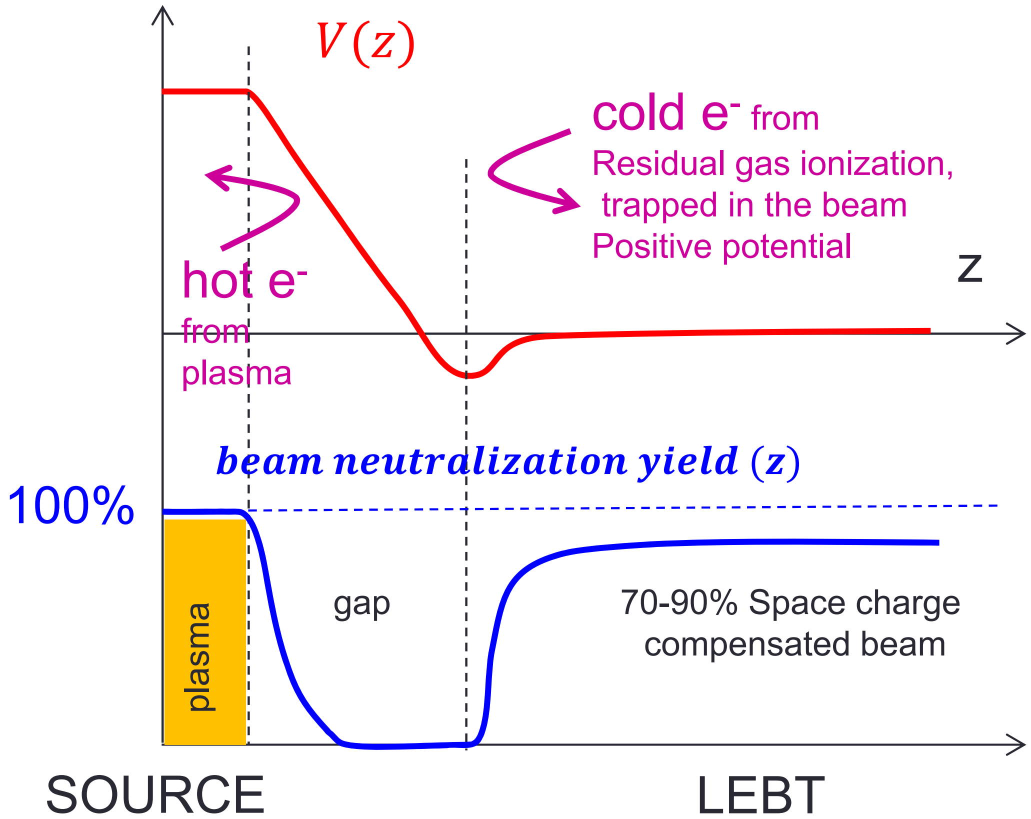
- For ECR ion sources used to extract I~1-2 mA of Ion beams,with a low divergence and negligible space charge effects:
  - A classical extraction featuring a simple **diode** system with a plasma electrode and a grounded puller is enough (as shown earlier in slide 3)
  - V_{HT}~15-25 kV is enough
- For new generation high performance ECRIS producing high intensity beams of multicharged ions: the total current extracted increases typically to the range I~2-20 mA where the **space charge effect is highly dominant**
  - ECRIS extractor is usually modified to a **Triode** system including a negative electrode to prevent cold electrode captured by the beam in the LEBT to be attracted by the source High voltage (see next slide)
  - V_{HT}>30-40 kV is recommended

Triode Extraction system for heavy ion source

- Prevent cold electrodes trapped in the beam potential to be attracted by the ECRIS High Voltage => more stable in operation
- May slightly improve the beam transmission if it is space charge limited…

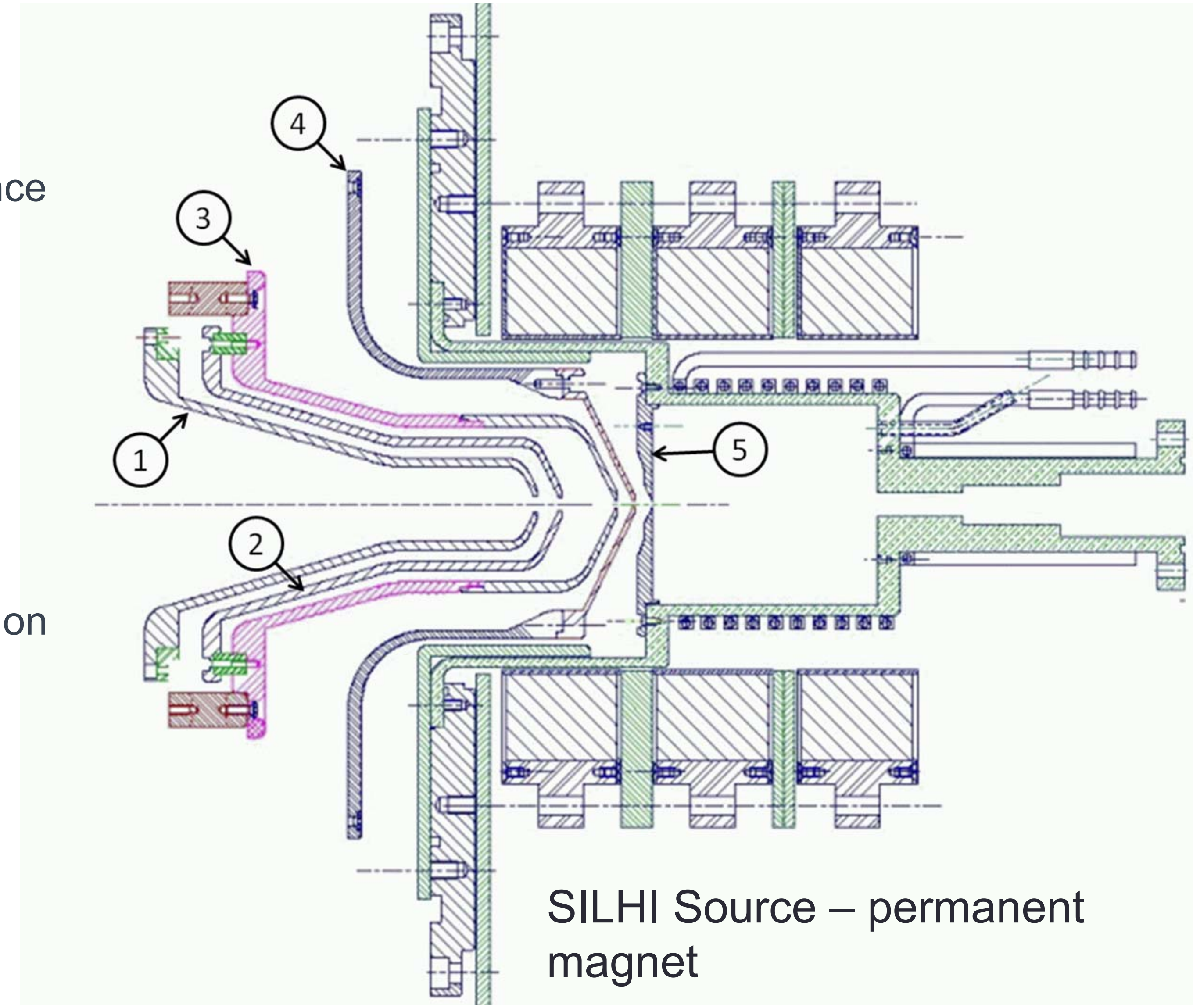


Source: D. Winklehner, LBNL,ECRIS2010



Pentode extraction for Light Ion source (100 mA H^+)

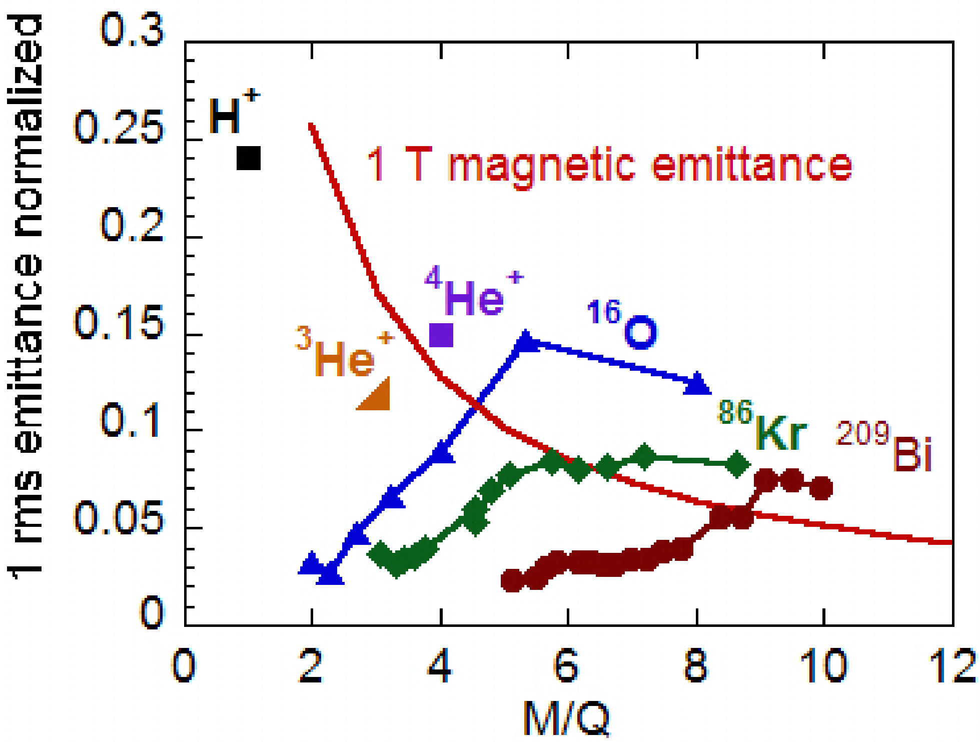
- The world reference is the SILHI extraction system
  - Geometry Optimized by simulation
  - 100 mT magnetic field=> Low emittance
- Pentode system:
- (5) plasma electrode 100 kV
- (4) puller electrode ~50-90 kV
  - Very small gap d_{45}=> allow high current extraction (Child Langmuir)
  - Tuning the puller voltage also allows to adapt beam focusing in the extraction
- (3) ground electrode (0 V)
  - Avoid direct sparks between 2 and 4
- (2) negative electrode (-5 kV)
  - Same function as in Triode system
- (1) ground electrode (0V)



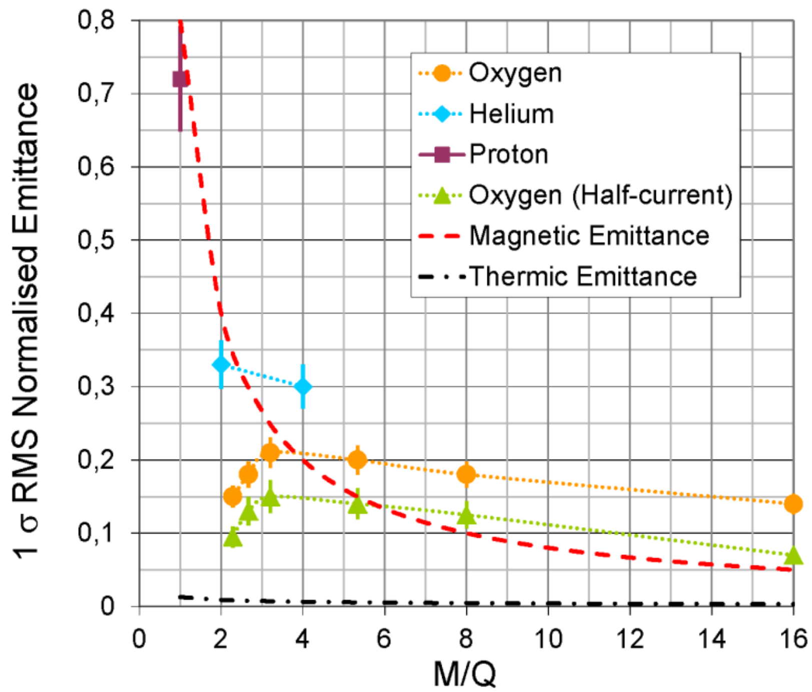
SILHI Source – permanent magnet

Experimental beam emittance measurements

- Systematic experimental emittance measurements performed on Heavy Ion ECRIS confirms that the **Magnetic Emittance is dominant**
  - VENUS Plot left
  - PHOENIX Plot right
- It also shows other interesting features…



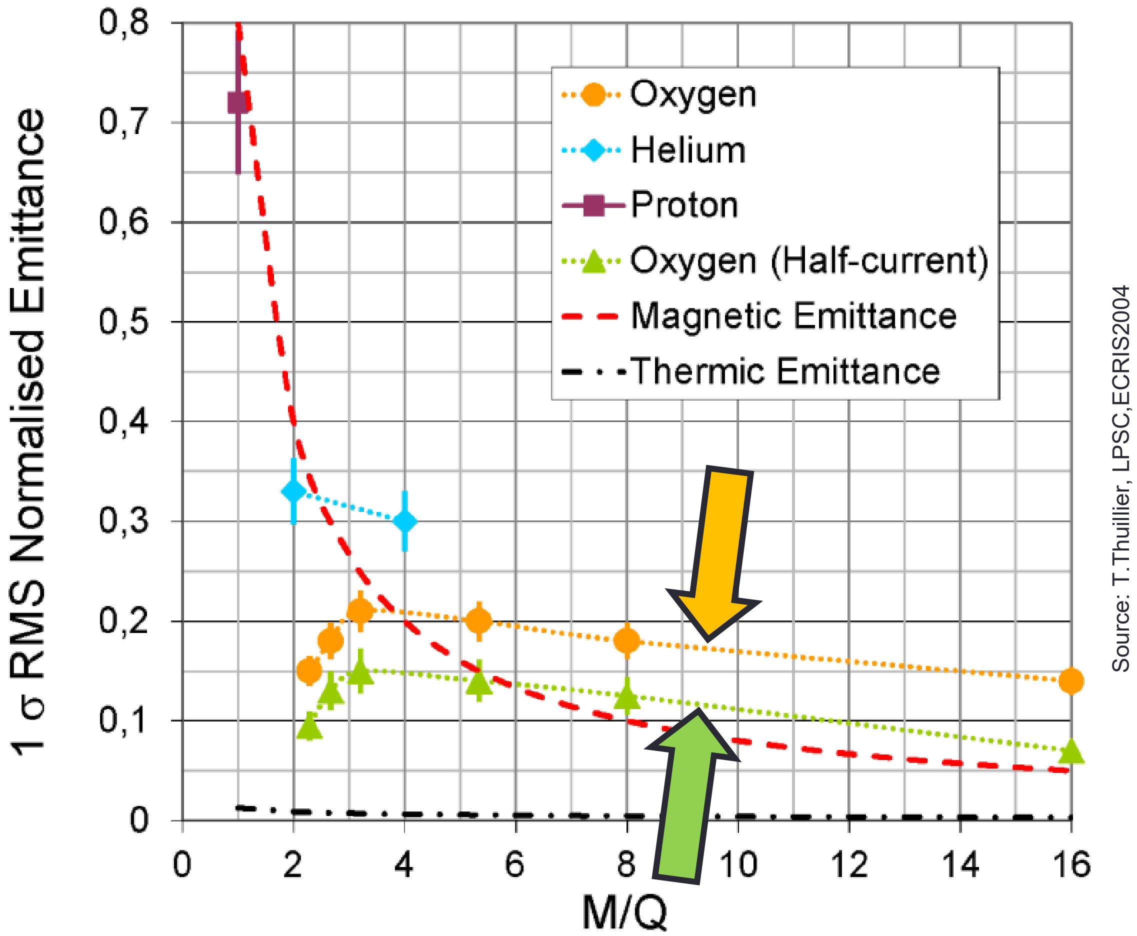
Source: D. Winklehner, LBNL,ECRIS2010



Source: T.Thuillier, LPSC,ECRIS2004

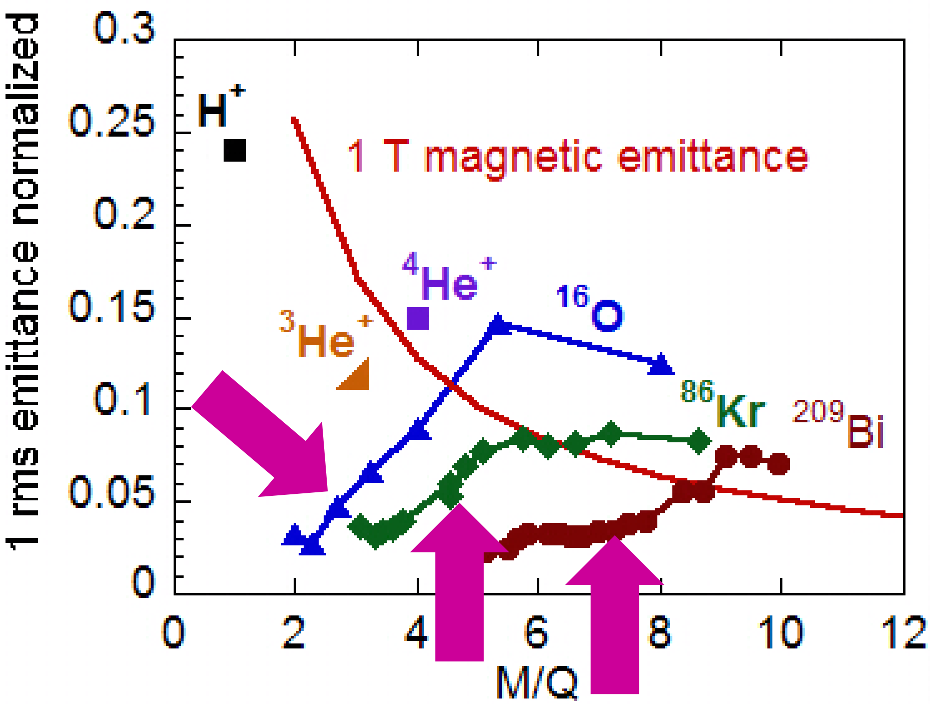
Experimental beam emittance measurements

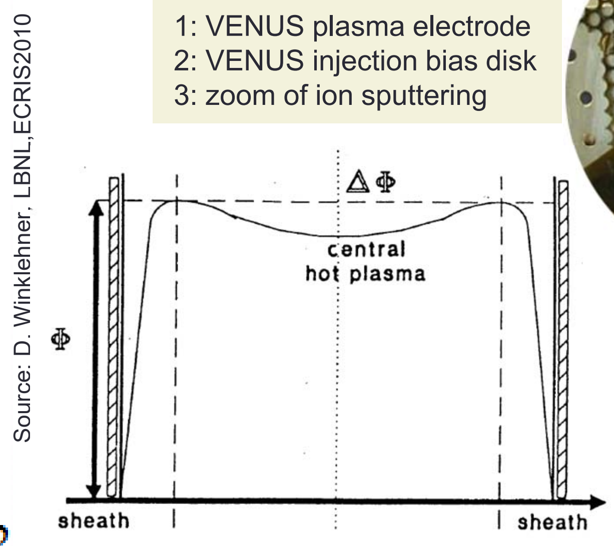
- High intensity beams extracted (I_{tot}>2 mA) induce space charge effects that may **inflate the final beam emittance** in the LEBT
- PHOENIX Orange plot:
  - Orange1 mA O^{6+}
  - Green: 0.5 mA O^{6+}

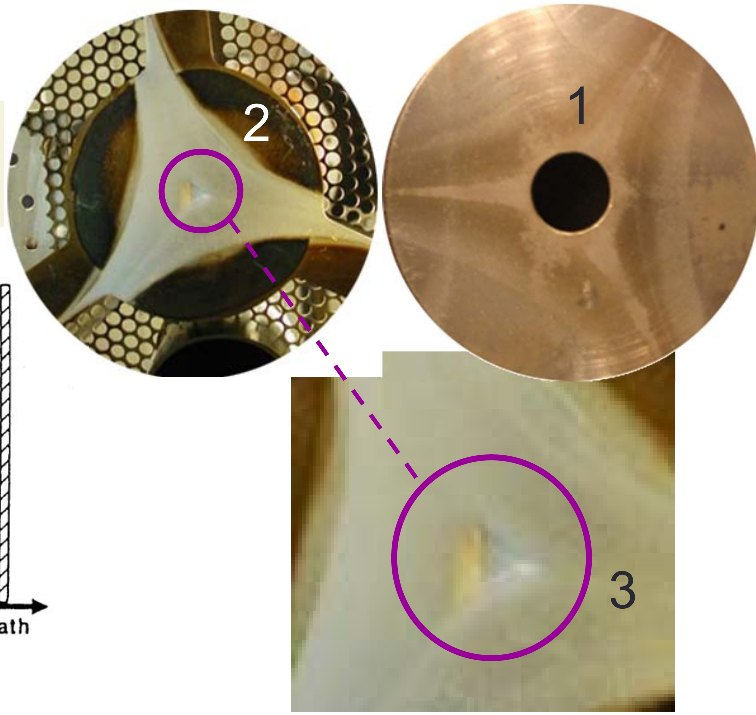


Experimental beam emittance measurements

- The Emittances of All High Charge states are smaller than expected
  - High charge state ions are extracted from a radius lower than the plasma electrode one => Magnetic emittance reduction
  - Effect due to the potential dip (generated by hot confined electrons) that confine electrostatically the ions near to the ECRIS axis
  - Experimental evidences exist of small triangular beams for high charge state





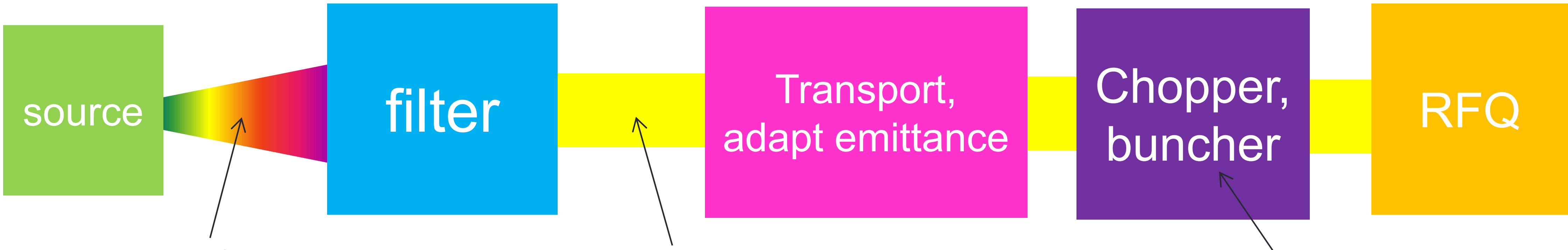


Discussion on the High Intensity current from an heavy ion ECRIS

- The total ion beam current extracted from a new generation high performance heavy ion ECRIS is:
  - $I \sim 5 - 20\ mA$
- This total current is composed of several chemical elements and several charge states:
  - $I = \sum_{A=1}^{n_A} \sum_{Z=1}^{n_z(A)} I_{A,Z(A)}$
  - n_A number of different mass numbers A in the beam
  - $n_z(A)$ number of charge states for a given mass A
- ECRIS are very efficient ionizers and **all** the chemical elements present in the plasma chamber will be jointly extracted with the element of interest:
  - Pollution from atmospheric gases (C,N,O,H, He,Ar, Kr,Xe …)
  - Pollution from the plasma chamber compounds will be there(Al, Fe…)
  - Pollution from vacuum cleaning detergents used…

Today Low Energy Beam Transport Requirements

- Extract ions with a as high as possible High Voltage to reduce the time during which space charge acts on the beam in the LEBT (V>30-40 kV)
- Filter as fast as possible the mixed beams from the source to keep only the beam of interest and thus reduce space charge effect
- Water cool the Filter part pipe walls as 90% of the power may be deposited there
- Minimize any emittance growth / distorsion of the beam of interest by designing oversized optics
- Have a low vacuum pressure UNDER OPERATION to minimize the charge exchange process with the residual gas (P~few 10^{-8} mbar)
- Transport the beam and adapt its emittance to match the RFQ one
- Chop/bunch the beam if required by RFQ/LINAC
- Have Faraday Cups to TUNE THE SOURCE and check transmission through filter, have emittance measurements (Pepper Pot or Allison scanner), beam profiler to monitor the beam, and steerers to correct misalignement



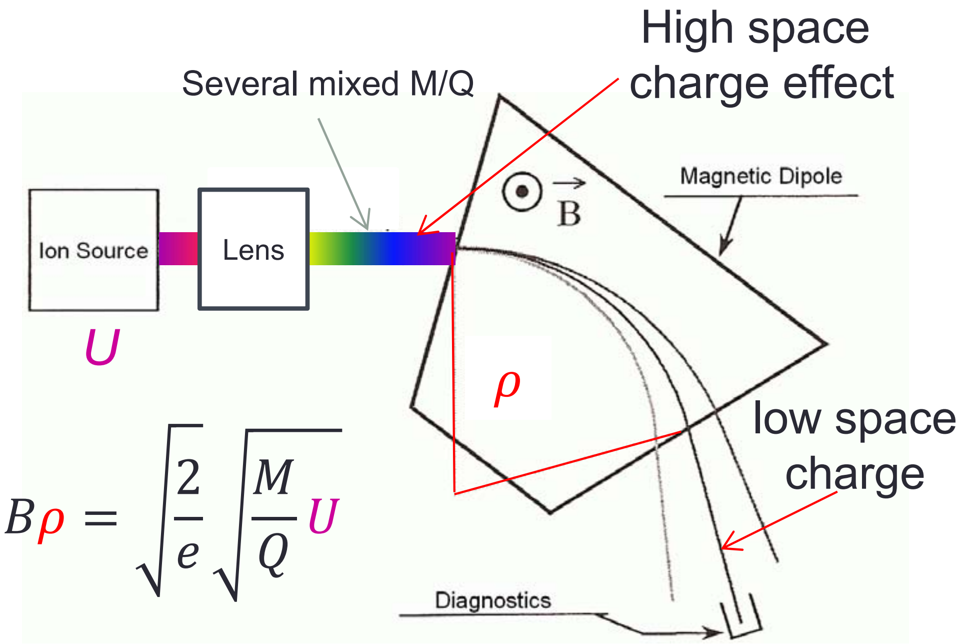
A horrible Mixture of 10 to 50 beam currents I(A,Z) up to I_{tot}=20 mA, With a global space charge compensation of~70-90%

0.1-1 mA of the beam of Interest with the minimum emittance growth (space charge compensation still ~70-90%)

Adapt the time/power structure of the beam to the RFQ and/or LINAC

The simplest Heavy Ion LEBT making the job

- A **Magnetic** Focusing lens is located as close as possible from the source extraction
  - Separate spatially as soon as possible the different M/Q beams to reduce the space charge effect
  - Adapt the beam of interest to the following bending magnet
- A bending magnet is placed as close as possible from the extraction
  - Reduce the length of action of space charge before magnet
  - Filter the beams and keep only the M/Q of interest
  - Make ionic spectrum to **TUNE THE SOURCE**
  - Have M/dM~100 to cleanly separate the beam with high transmission

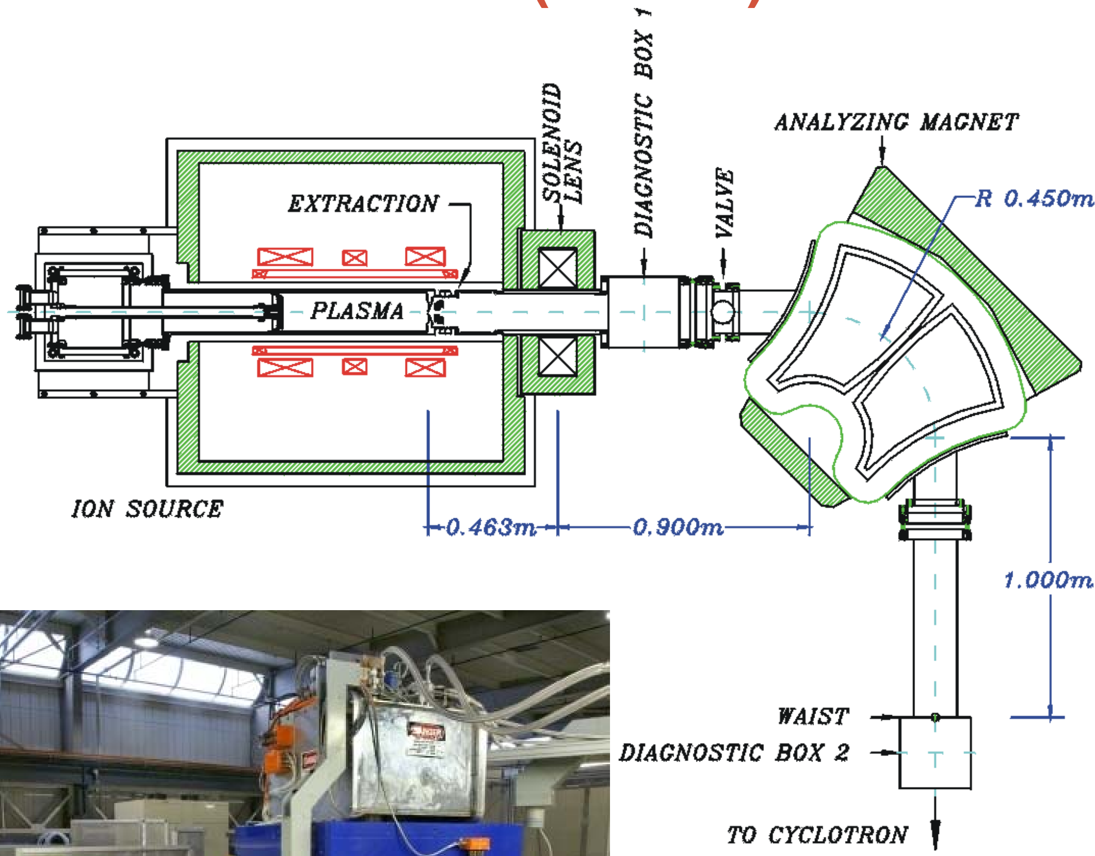


$$B\rho = \sqrt{\frac{2}{e}}\sqrt{\frac{M}{Q}U}$$

- Some accelerators have chosen a first electrostatic focusing lens …
  - Advantage: low power consumption
  - Inconvenient: do not separate M/Q beams and keeps space charge until the dipole!
  - No evidence of good transmission with such a LEBT for space charge dominated beams=> be careful…

Example of the VENUS LEBT at LBNL (USA)

- A large gap Solenoid lens
  - Ø150 mm
- A large gap bending magnet
  - Vertical Gap in vacuum 160 mm
  - Bending radius 510 mm
  - Horizontal aperture 300 mm
  - M/dM resolving power~100
  - 90° bending
  - Double focusing
  - Maximum rigidity 0.18 T.m
  - More on next slide…
- Used to inject beam in the 88'' cyclotron

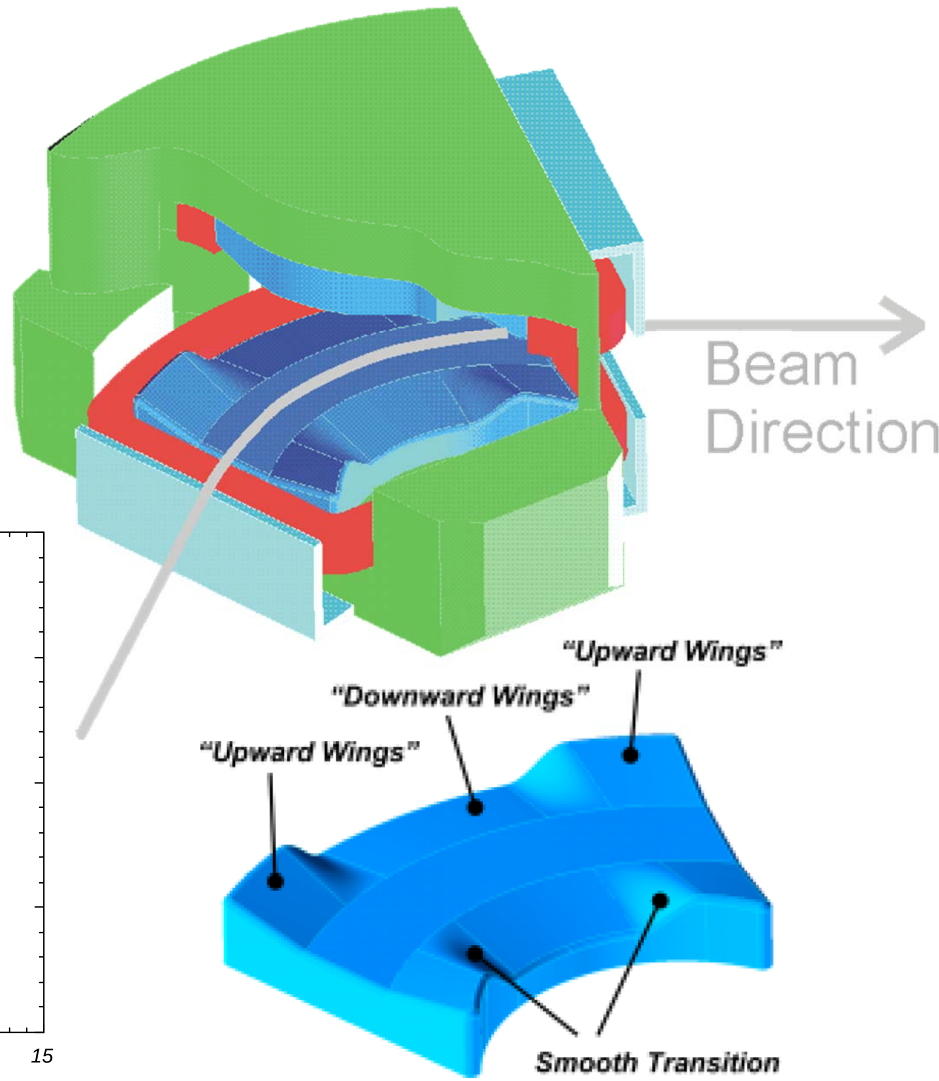


Example of the VENUS LEBT dipole (USA)

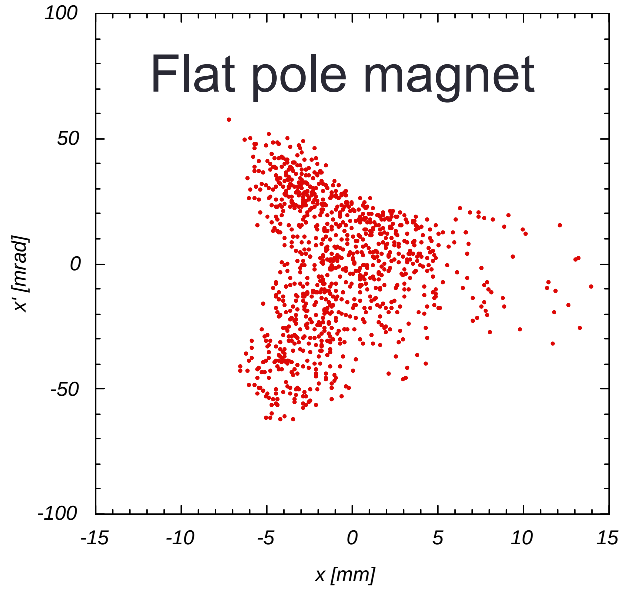
- Bending magnet corrected from second order aberration term

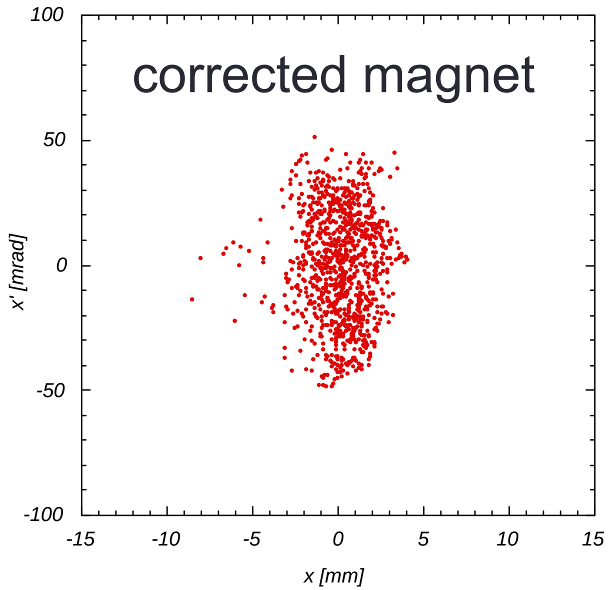
  => no increase on the emittance even with

  A large beam going through it



22 mA He Horizontal emittances plot

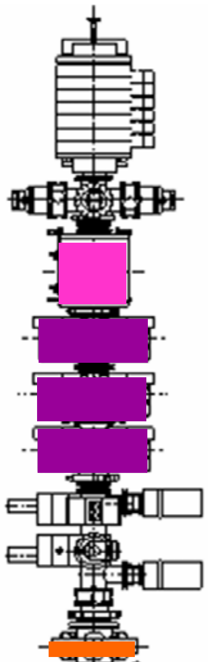


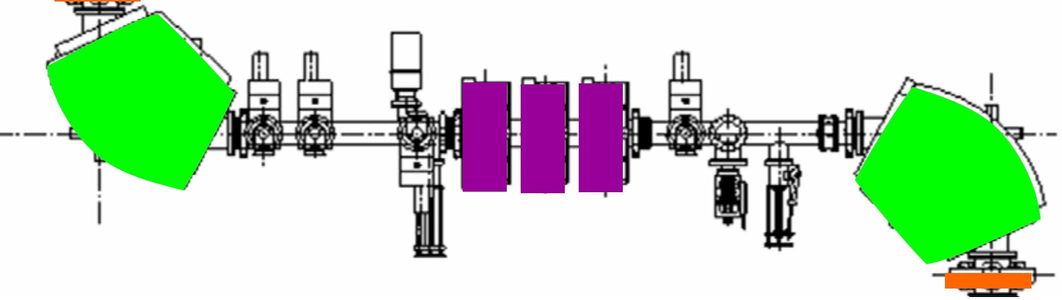


Example of the Spiral2 Heavy Ion LEBT (France)

- Operational LEBT, commissioned during 2010-2012
  - Large beam pipe (Ø 150 mm)
  - **1st large and long magnetic solenoid**
    - to minimize beam aberrations through it and split M/Q to reduce space charge effect
  - 1st Quadrupole triplet
    - To adapt any beam to the dipole and maximize dM/M separation in the magnet
  - **flat pole dipole + Sextupole** to compensate the second order correction
  - 2nd Quadrupole triplet
  - **Second Dipole + Sextupole** ….toward the RFQ (=> achromatic line)
- Low pressure $P{\sim}2 \times 10^{-8}\ mbar$
- Excellent beam transmission **~90-100%** for high intensity, space charge dominated, beams
  - Experimental neutralisation rate 70-80%

60 kV



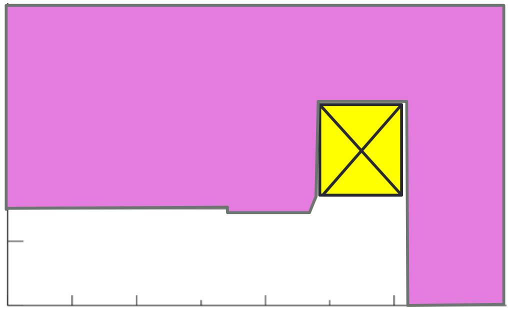


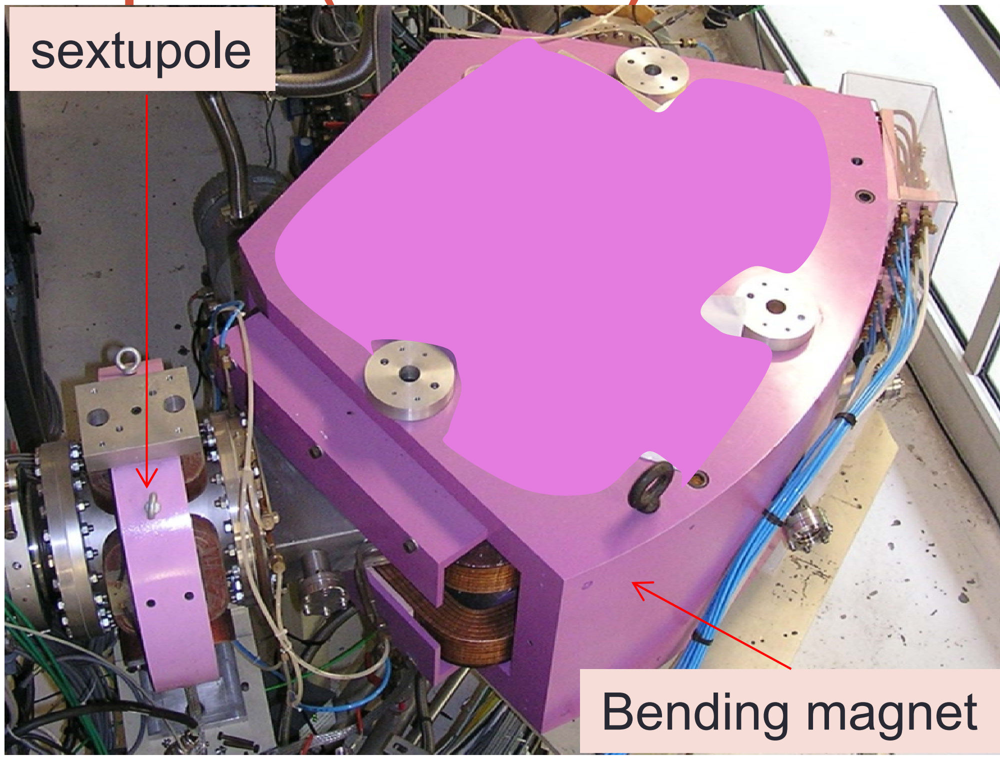
1st solenoid, as big as the ion source!

Example of the Spiral2 LEBT dipole (France)

- A low current sextupole compensates the second order aberration occuring in the flat pole bending magnet
- dM/M~100
- Bending radius 600 mm
- Rigidity 0.16 T.m
- Double focusing
- 100 mm vertical gap

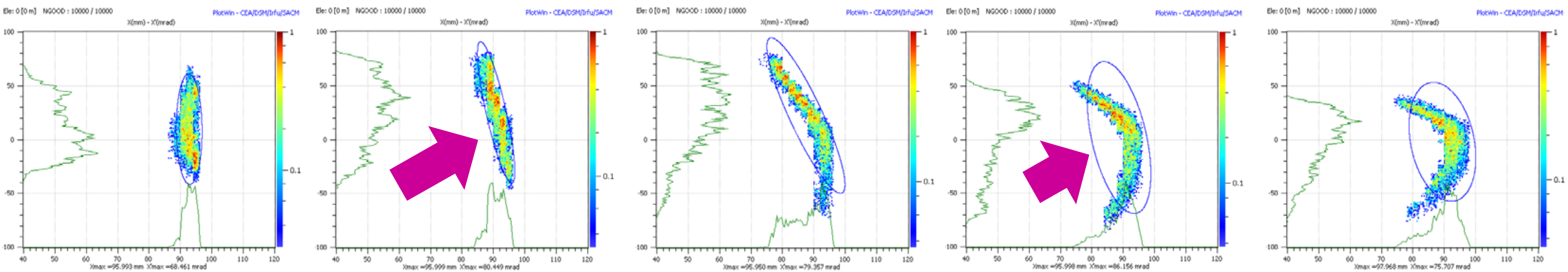
Flat pole design





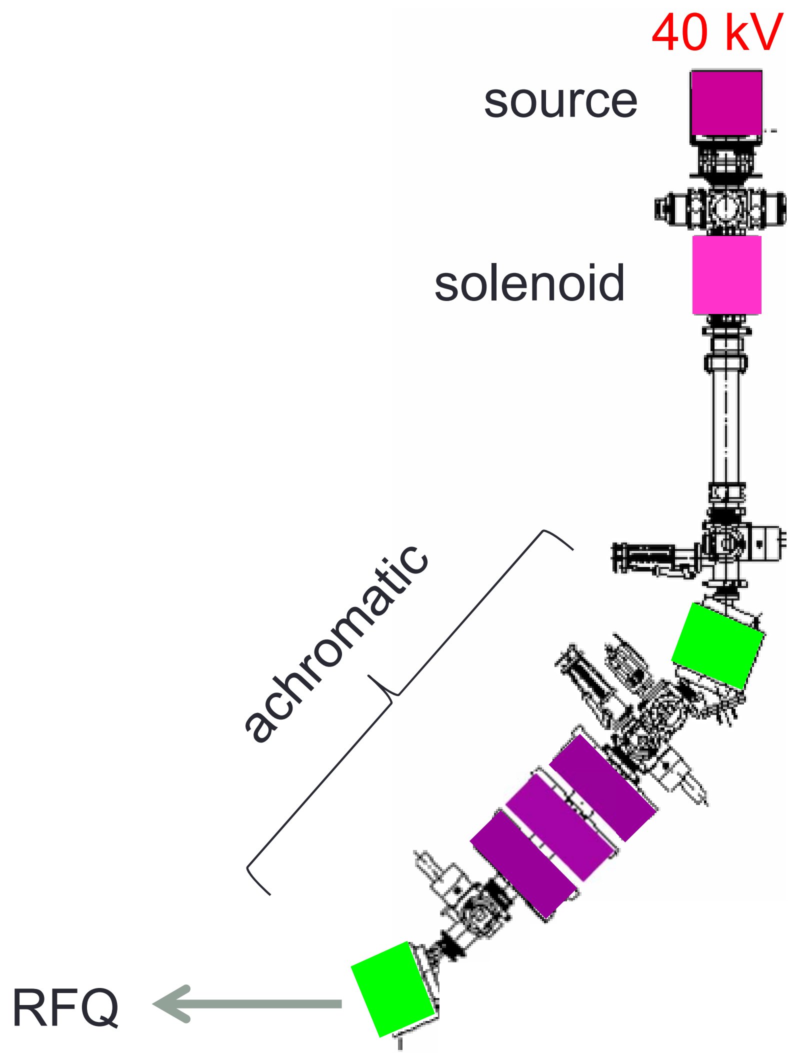
Horizontal emittance plot after the dipole vs current in the hexapole lens

-5A 2 A -2A 0A 10 A

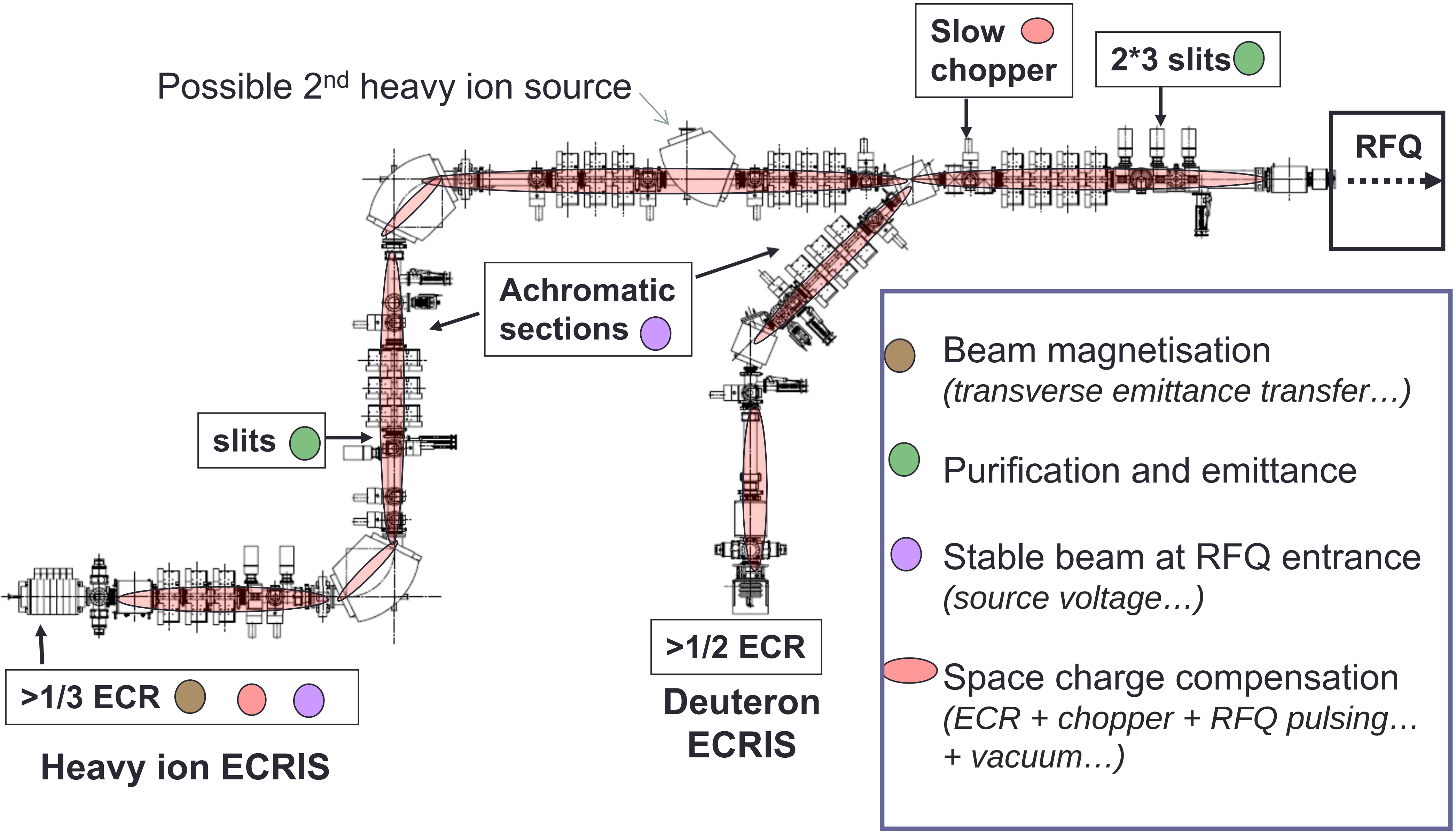


Light Ion LEBT - 5 mA D^+ - Spiral2 (France)

- Large 1st Solenoid
  - Separate spatially ionic species to reduce space charge
- 45° Bending magnet
  - to filter the D^+ from D_2^+, D_3^+
- Quadrupole triplet +second 45° bending magnet toward the RFQ
  - Achromatic line
- High pressure in the source ($P \sim 10^{-5}$ mbar)
  - Important pumping necessary to screen the high pressure before the RFQ entrance

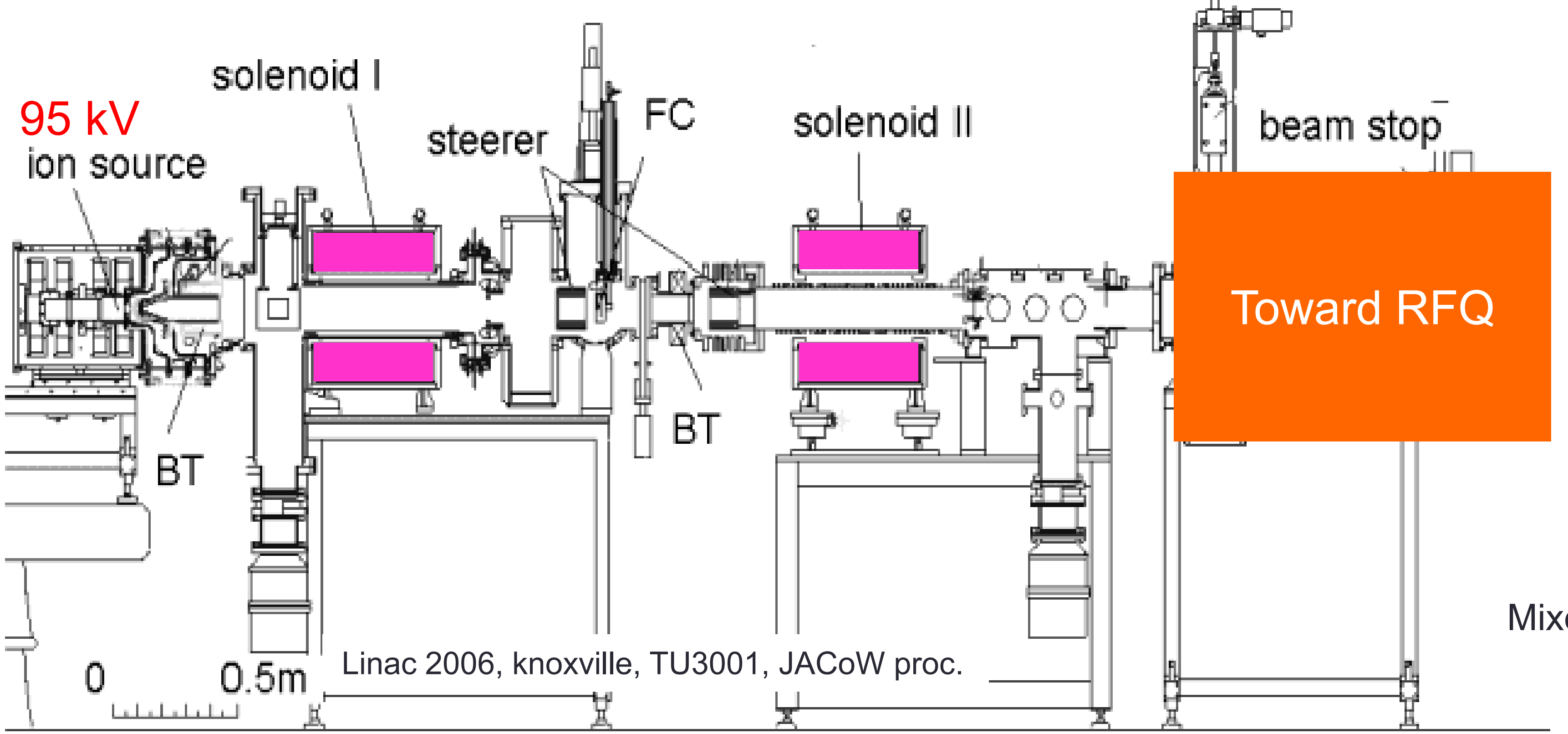


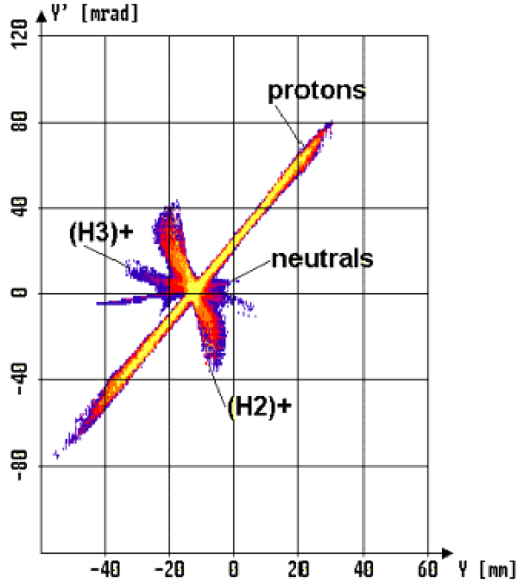
The whole Spiral2 LEBT (GANIL, France)



Light Ion LEBT – 100 mA H^+ - SILHI (France)

- The LEBT is straight to ensure achromatism
- The H^+,H_2^+,H_3^+ separation is done **online** through a set of two solenoids tuned to transport the H+
  - So H_2^+,H_3^+ are defocused and beam is progressively lost along the pipe wall
  - The RFQ accelerates H^+, but do not H_2^+,H_3^+ remnants beams which are too slow=> RFQ acts as the final filter

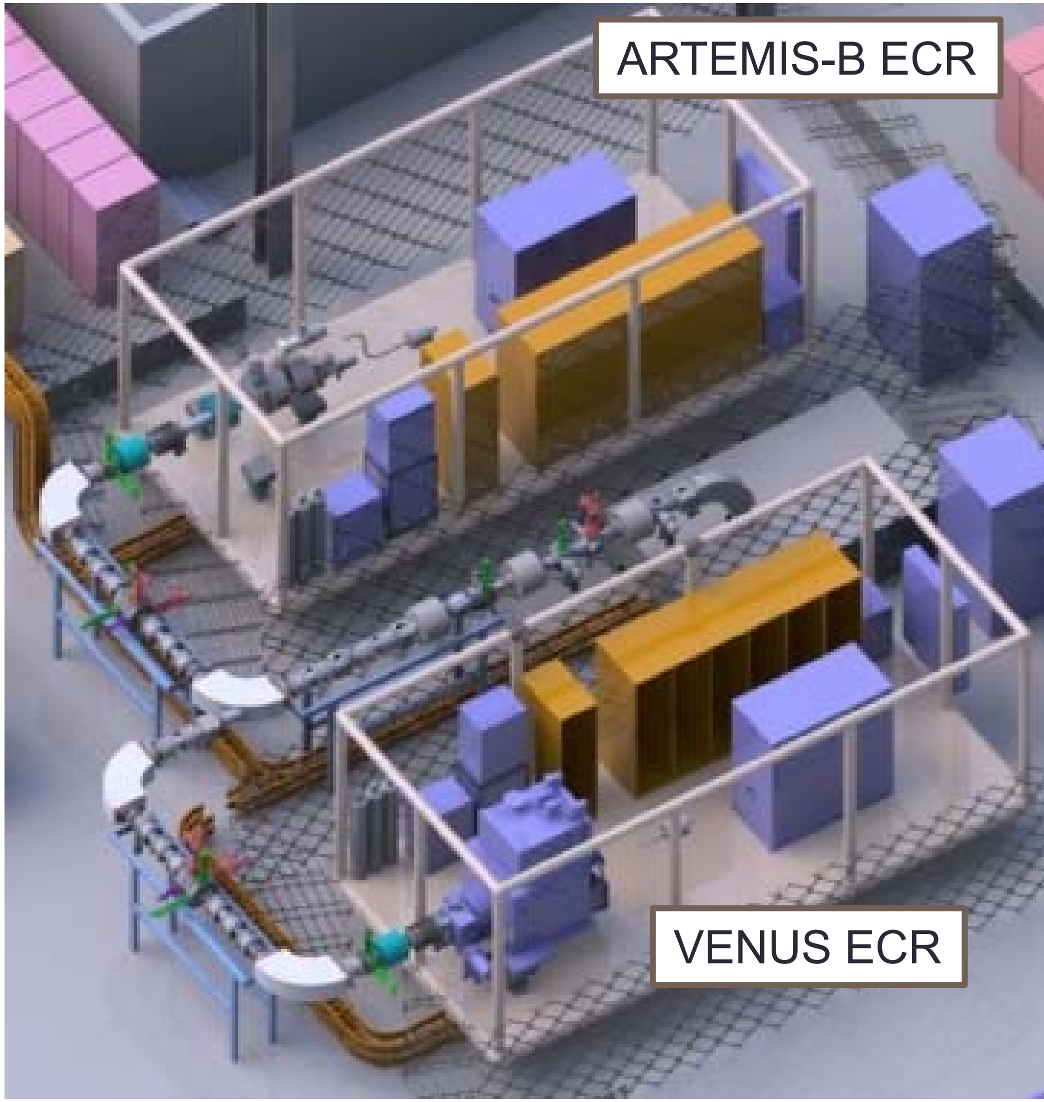




Mixed emittances a the entrance of the RFQ

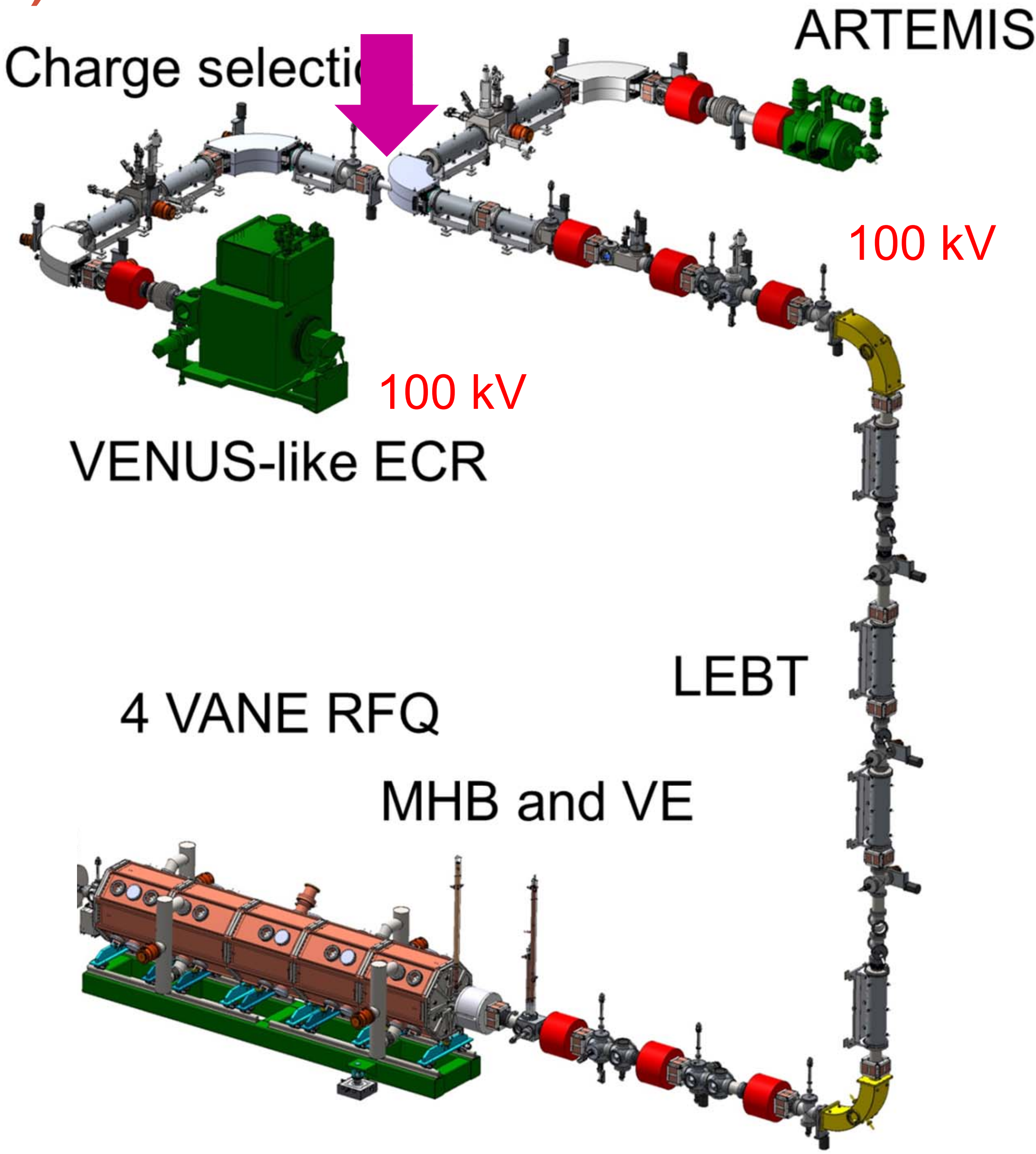
The FRIB LEBT (MSU/USA)

- The whole LEBT is **achromatic** to allow the transport of both U^{33+} and U^{34+} beams
- Two Ion sources on 50-60 HV platforms
  - ECRIS at V_{HT}~30-40 kV
  - 1st solenoid lens on the platform
  - Accelerator tube
  - 2nd solenoid lens
- Achromatic filter
  - Able to transport U^{33+}+U^{34+} beams
  - 2x90° bending magnet
  - 2xelectrostatic quadrupole Triplet
  - Diagnostic box in between



The FRIB LEBT (MSU/USA)

- Beam pipes merging, then transport
  - 2xquadrupole triplet (electrostatic)
  - 3 solenoids
- Vertical electrostatic beam line
  - 90° electrostatic magnets
  - Quadrupole triplets
- Transport through 3 solenoids
- Final line toward the RFQ
  - 3 Solenoids
  - Chopper
  - Buncher
- Low vacuum level required to limit charge exchange losses



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The Bush Theorem (emittance magnetization)

- The potential vector $\vec{A}$ of a static axisymetric magnetic Field $\vec{B}$ can be integrated from $\vec{B} = curl(\vec{A})$:
  - $\vec{A} = \frac{1}{2} Br\vec{e}_\theta = A_\theta \vec{e}_\theta$
- The Lagrangian of a charged particle in such a magnetic field is (in cylindrical coordinates):
  - $L = \frac{1}{2} mv^2 + q\vec{A}\vec{v} = \frac{1}{2m}\left[\dot{r}^2 + r^2\dot{\theta}^2 + \dot{z}^2\right] + qA_\theta r\dot{\theta}$
- The Hamiltonian derived from this Lagrangian is:
  - $H = \frac{1}{2m}[(\frac{p_\theta}{r} - qA_\theta)^2 + {p_z}^2 + {p_r}^2]$
  - where $p_r = {\partial L}/{\partial \dot{r}}$, $p_z = {\partial L}/{\partial \dot{z}}$, $p_\theta = {\partial L}/{\partial \dot{\theta}}$ are the associated canonical momentum
- $\dot{H} = 0 \rightarrow$ the energy in constant in a magnetic field
- Most important: since H is not depending on θ, a general property can be derived:
- $\dot{p}_\theta = -\frac{\partial H}{\partial \theta} = 0 \rightarrow p_\theta = const$

- $p_\theta = \frac{\partial L}{\partial \dot{\theta}} = \mathrm{m}r^2\dot{\theta} + \frac{1}{2} qBr^2 = const$ <= THIS IS THE BUSH THEOREM
  - On the plasma electrode, an ion is extracted at $r = r_0$ and $B = B_0$; Since the ions are cold in the source (T_i~$300\ K$), the initial ion velocity is negligible with respect to $\frac{1}{2} qBr^2$
  - So $p_{\theta 0} = \mathrm{m}{r_0}^2\dot{\theta}_0 + \frac{1}{2} qB_0{r_0}^2 \sim \frac{1}{2} qB_0{r_0}^2$
- Once accelerated in the beam line where $B \rightarrow 0$, the azimuthal momentum becomes: $p_\theta \rightarrow \mathrm{m}r^2\dot{\theta} = \frac{1}{2} qB_0 r_0$