USPAS - Fundamentals of Ion Sources
8./9. Electron Cyclotron Resonance Ion Sources

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Content

Electron Cyclotron Resonance Ion Sources (ECRIS) – Part I

- ECR Ion Source Fundamentals
- Brief History
- Atomic Physics of ECR Ion Source

Tuesday Afternoon (1:30 PM – 3:30 PM)

Electron Cyclotron Resonance Ion Sources (ECRIS) – Part II

- Plasma Confinement – Magnetic Field
- Scaling Laws
- ECR Heating
- Gas Mixing
- Operations of ECR Ion Sources and Examples

References used for the lecture

- Thullier, T., https://cas.web.cern.ch/cas/Slovakia-2012/Lectures/
- Geller, R., *Electron Cyclotron Resonance Ion Source and ECR Plasmas*. 1996: Bristol, Institute for Physics Publishing.
- Leitner, D. and C.M. Lyneis, *Electron Cyclotron Ion Sources*, in *The Physics and Technology of Ion Sources*. 2005Wiley-VCH Verlag GmbH & Co. KGaA.

High Charge State Ion Sources

- Driven by the need to use high charge states to increase the final energy for the accelerator

$$LINAC \qquad \frac{E}{M} = Q \cdot e \cdot V$$

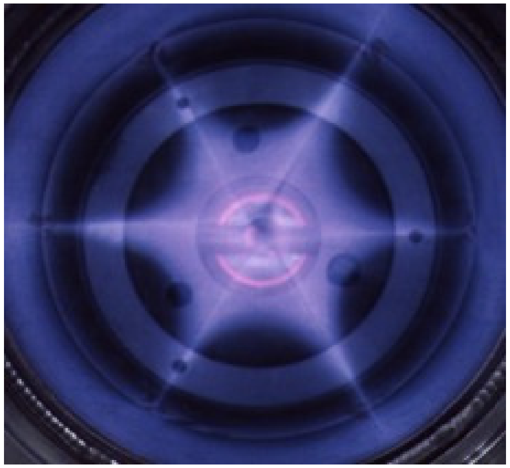
Energy increases linear with charge state

$$Cyclotrons \qquad \frac{E}{M} = \frac{Q^2}{M^2} \cdot \frac{(B \cdot \rho \cdot e)^2}{2m_\mu}$$

Energy increases quadratic with charge state

- High charge state ion sources
  - Classic sources (medium to low charge states): PIG, MEVVA (Metal Vapor Vacuum Arc) , CHORDIS (GSI), Duaplasmatrons..
  - Electron Cyclotron Resonance Sources (ECRIS)
  - Electron Beam Ion Sources (EBIS, Thursday)
  - Laser Ion Sources (not discussed here)

Recap – Plasma Properties

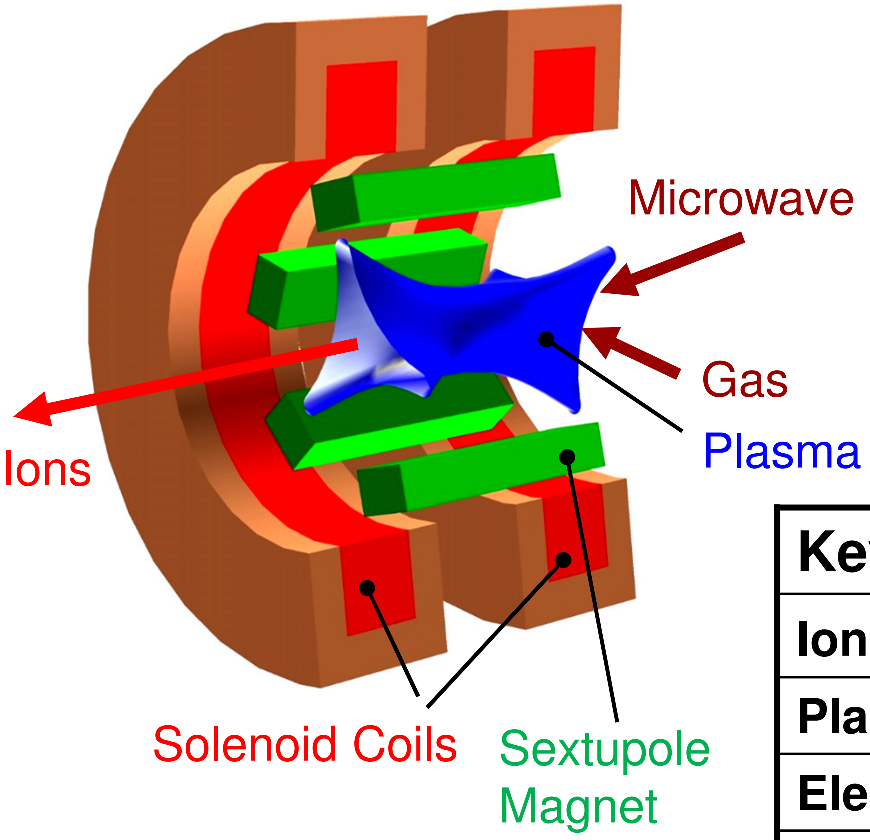


- ECR ion sources are plasma ion sources, so plasma fundamentals apply: charge neutrality, plasma temperature, plasma sheath, plasma confinement
- Plasma needs to be constantly heated to be sustained
- Must be confined if it should be sustained for some time (gravity in stars, on earth with magnetic fields)

ECR source plasma physics is highly complex: RF heating, collective effects, atomic physics, plasma waves, microwave coupling …. Simulations are still not able to predict the ECR parameters but can show trends

ECR ion sources fundamentals

Ingredients of an ECR-Ion Source

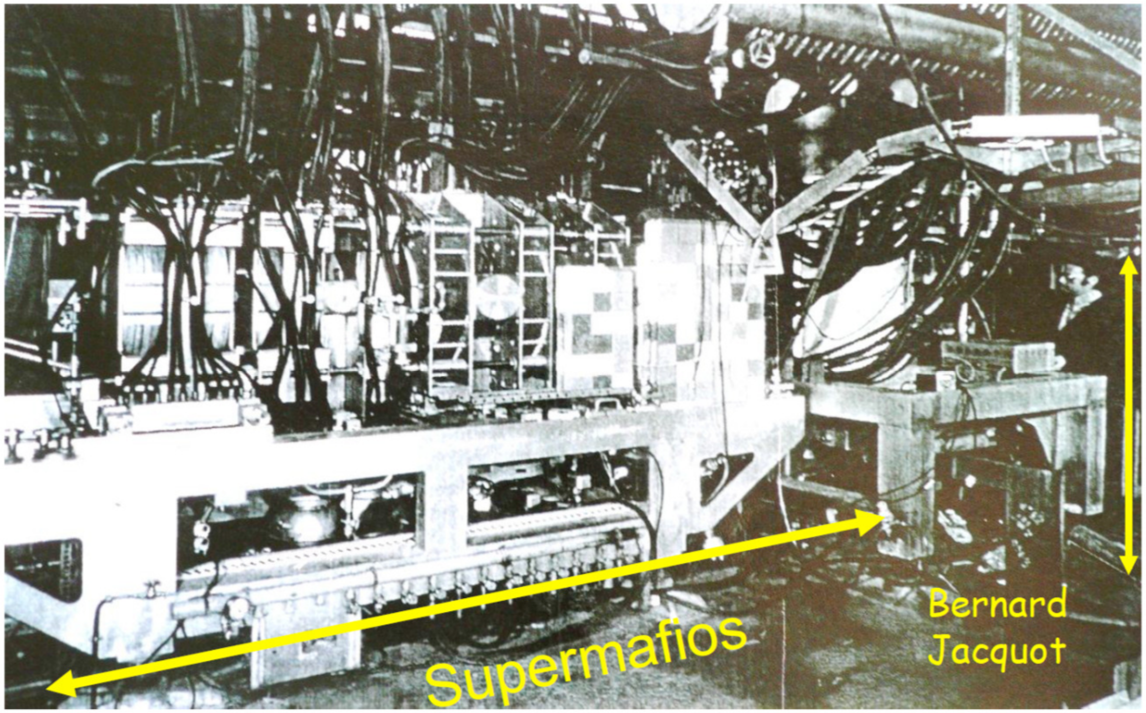


- Plasma Heating: Microwaves
- Plasma Ions: Gas injection, vapor from external devices (e.g. ovens), sputtering
- Charge balance is determined by the neutral gas pressure in the source, electron temperature and confinement time

Key parameters	
Ion confinement times τ_i	**~ms**
Plasma densities n_e	**10^9 - 10^{12} /cm^3**
Electron temperature T_e	eV to MeV
Charge exchange/ neutral gas density σ_{ex}	$q^{1.17} \cdot I_p^{-2.76} \cdot 10^{-12} cm^2$

ECR- History

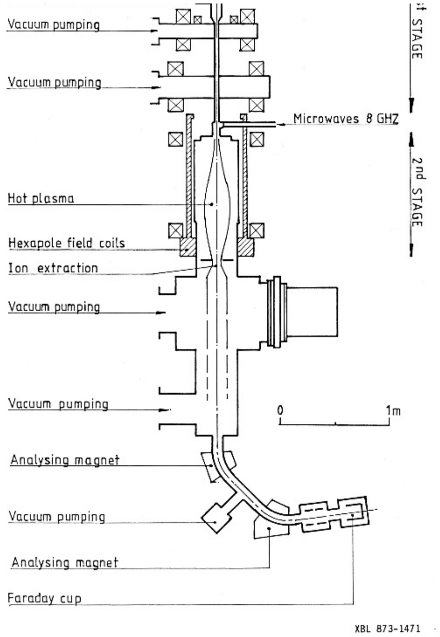
- Starting in 1972 R. Geller in Grenoble converted fusion plasma devices into ECR ion sources and succeeded in 1974 with “Supermafios” to produce 15 μA of O^{6+} and Ar^{8+}.

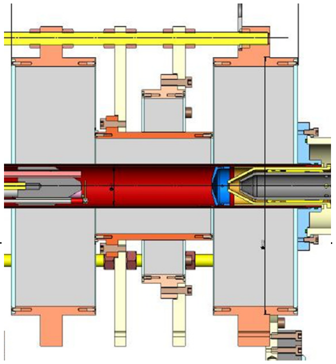


- A 3 MW modified fusion machine (CIRCE) to produce ion beams
- The legend says that, at first power switching, an electrical black out occurred on half of Grenoble city!

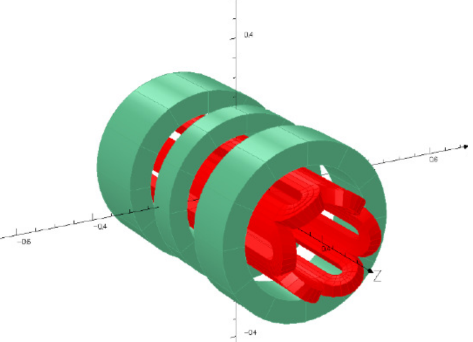
Electron Cyclotron Resonance Ion Source Development

Supermafios (Geller, 1974)
15 eμA of O^{6+}

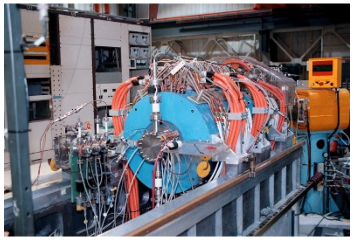




Superconducting ECRs
VENUS, SUSI, SECRAL, SC-RIKEN
>3000 eμA of O^{6+}



Electron Magnet Solenoid, Permanent Magnet Sextupole
Minimafios (1979), Grenoble
Caprice, Grenoble
GTS, PHOENIX,…….
AECR (1990), LBNL

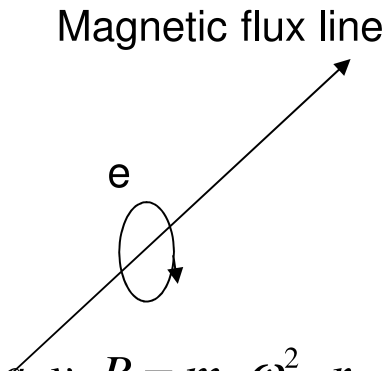


Permanent Magnet Sources:
Nanogun, Supernanogun, Grenoble
Compact Source

The plasma is heated resonantly with microwaves

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

The electron cyclotron frequency is matched with the microwave frequency – heating is mainly transverse

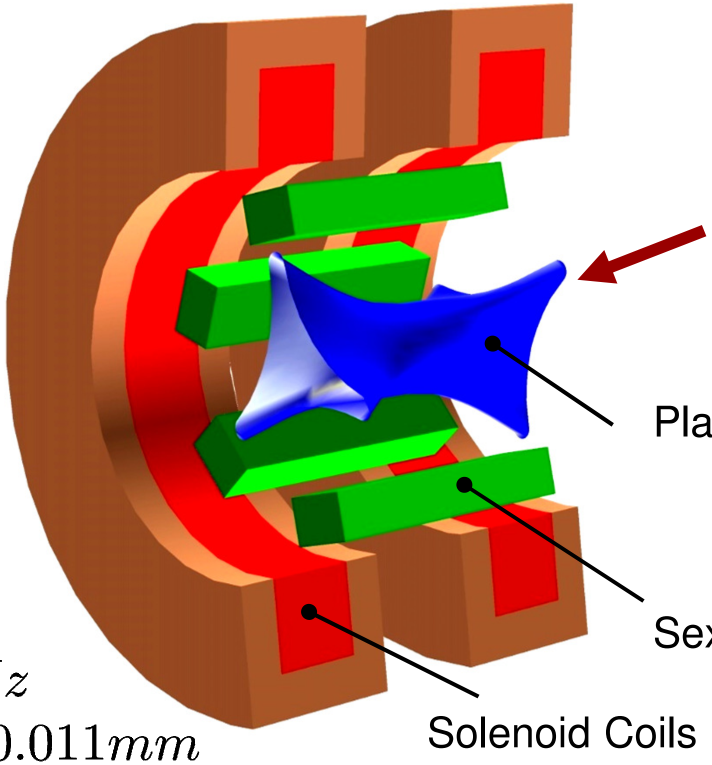


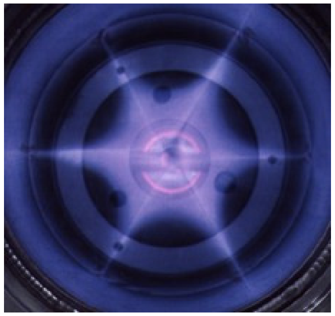
$$q \cdot v \cdot B = m \cdot \omega^2 \cdot r$$

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

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

$$B = 1T$$
$$f = 28GHz$$
$$r_{Lamor} = 0.011mm$$





ECR Performance Criteria/Design Guide

- The magnetic field design needs to match the chosen microwave frequency

Recap: Plasma Oscillations –Plasma Frequency

- Macroscopic the plasma is charge neutral, microscopic the imbalance of charges leads to micro instabilities, fluctuations and oscillations

$$E = \frac{e}{\epsilon_0} n x$$

$$F = eE = \frac{e^2}{\epsilon_0} n x$$

$$F = m_e \frac{d^2 x}{dt^2}$$

- Local electric field is created by shifting a charge cloud along distance x
- The charge unbalance leads to a restoring force !
- Equation of and harmonic oscillator with eigenfrequency ω!

$$\boxed{\omega_e = \sqrt{\frac{e^2 n_e}{\epsilon_0 m_e}}}$$

Plasma frequency GHz range !

$$\boxed{\omega_i = \sqrt{\frac{e^2 n_e}{\epsilon_0 m_i}}}$$

Plasma frequency MHz range !

Plasma Heating

$$\boxed{\omega_e = \omega_p = \sqrt{\frac{e^2 n_e}{\epsilon_0 m_e}}}$$

The plasma frequency ω_p is the natural oscillation frequency of a plasma as a response to a pertubation

The simplest dispersion relation of an EM wave in the plasma is $\omega^2 = \omega_p^2 + k^2 c^2$

EM wave propagates if $\omega > \omega_p$

ECR Cut-off density $\omega > \omega_p \rightarrow n_e < \frac{\epsilon_0 m_e \omega^2}{e^2}$

At a given ECR density, the plasma density is limited by $n_e \propto \omega_p^2$

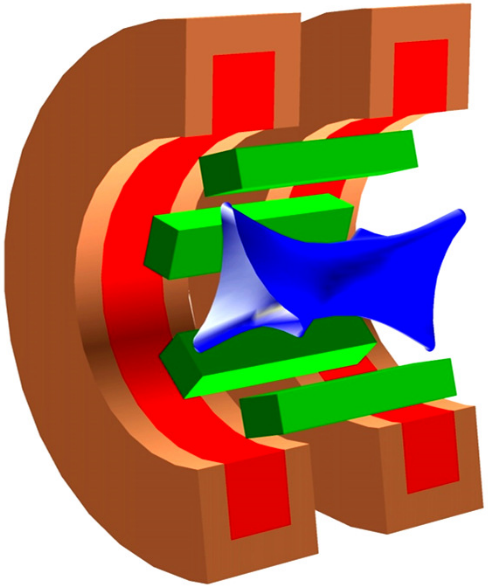
Overdense heating is possible, but the plasma is highly turbulent – no high charge states, used in 1+ microwave sources

ECR Performance Criteria/Design Guide

- The magnetic field design needs to match the chosen microwave frequency
- The maximum electron density that the source can be operated (and therefore the maximum extracted current) is proportional to the frequency square!

Electron temperatures

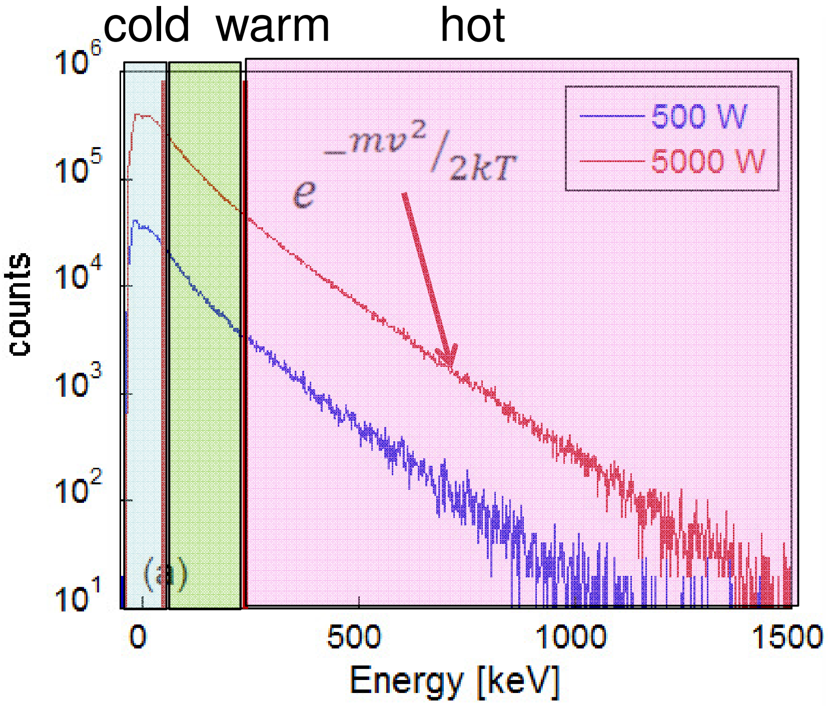
- Can be described through several Maxwell-Boltzmann Distribution in the simplest model (however a plasma has long-range interactions so modeling needs more complexity, Vlasov equation, fluid modeling)



Cold (< 200eV)	Most abundant, ionization for lowest charge states, lowest confinement time – important for confinement through the plasma neutrality criteria, Reason for the plasma potential
Warm (< 300 keV)	ionization process, main source of bremstrahlung
Hot (> 300 keV):	highly confined population, non collisional very little role for ionization, source bremsstrahlung, very important for electrostatic confinement

Observation of energy spectrum

The Electron Energy Distribution can be observed by measuring the bremsstrahlung spectra from ECR ion sources



By line fitting to the inverse slope of the energy calibrated x-ray spectra data in a certain energy window one can determine an “spectral temperature “ in keV.

Relative measure of the energy in the plasma

De-convolution is difficult

Atomic Processes in ECRs

Charge balance

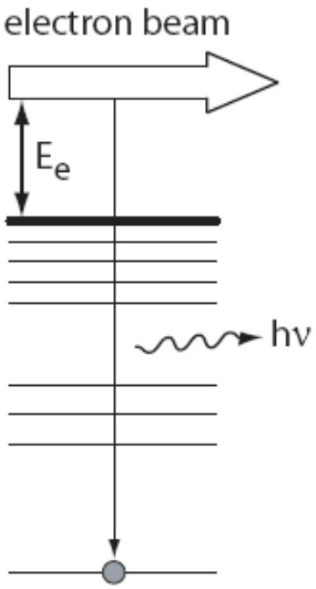
- Ionization through electron impact (step-by-step) until charge state balance is reached
- The final Charge State Distribution (CSD) is a balance between Charge Generation Processes Versus Charge Destructive Processes
- Main Atomic processes are
  1. Electron Impact Ionization (single)
  (2. Electron Impact Ionization (multiple) for higher charge states)
  3. Charge Exchange
  (4. Radiative Recombination)

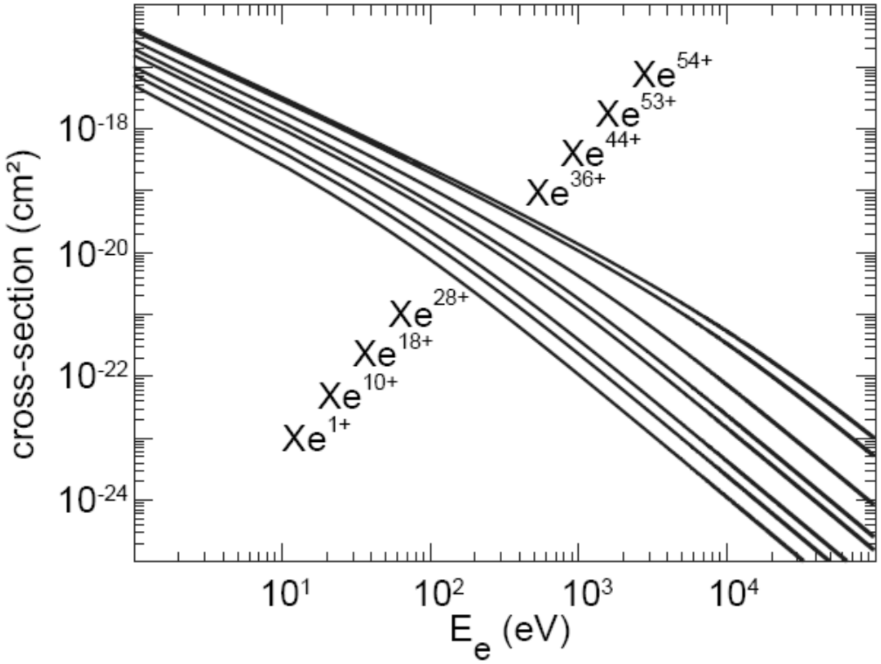
Radiative Recombination Processes

$$\boxed{\frac{J_e}{e} \cdot \left(N_{i+1} \cdot \sigma_{i+1}^{RR} \cdot f_{e,i+1} - N_i \cdot \sigma_i^{RR} \cdot f_{e,i}\right)}$$

$$X^{q+} + e^- \rightarrow X^{(q-1)+} + h\omega$$

This cross section decreases with increasing electron energy and increases with charge state





$$\sigma_{i\rightarrow i-1}^{RR} \sim Q^2$$

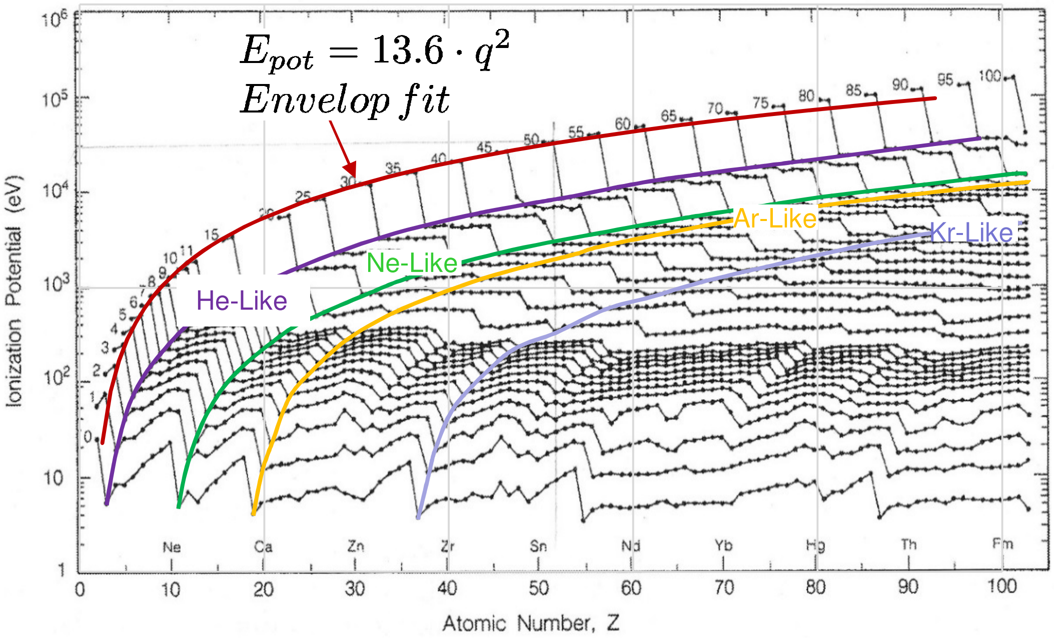
G. Zschornack, et.al, *Electron Beam Ion Sources*, in *CAS - CERN Accelerator School, Ion Sources*. 2013, CERN-2013-007.

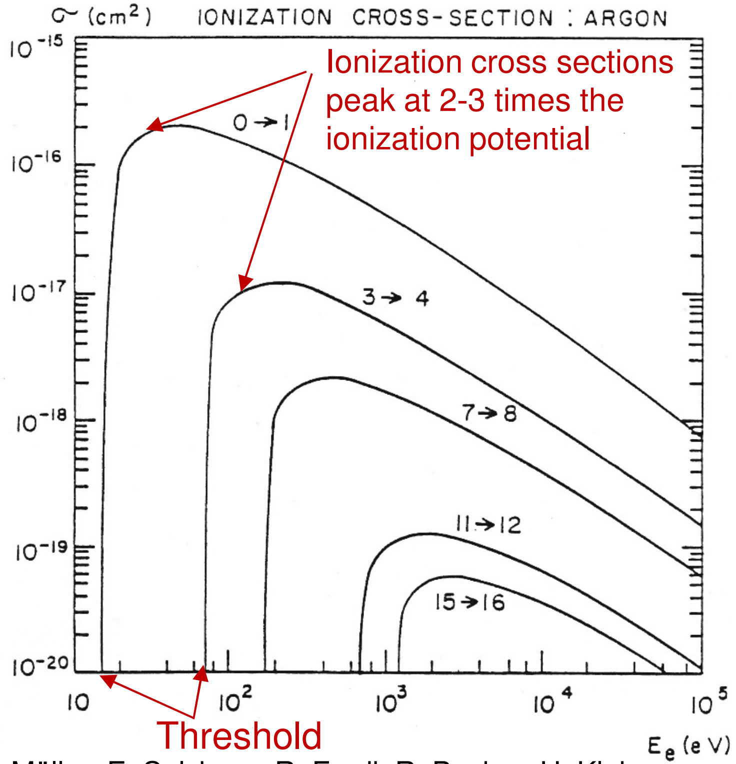
Electron Impact Ionization

$$X^{q+} + e^- \rightarrow X^{(q+1)+} + 2e^-$$

$$\boxed{\frac{J_e}{e}\cdot\left(N_{i-1}\cdot\sigma^{EI}_{i-1}\cdot f_{e,i-1} - N_i\cdot\sigma^{EI}_{i}\cdot f_{e,i}\right)}$$

Ionization Potentials





Ionization cross sections peak at 2-3 times the ionization potential

Threshold

A. Müller, E. Salzborn, R. Frodi, R. Becker, H. Klein, and H. Winter, J. Phys., 1980. B 13: p. 1877.

$$\sigma_{i,i+1} = 1.4\cdot 10^{-13}\frac{ln\frac{E_e}{E_i}}{E_e E_i}(eV)^2 cm^2$$

E_e: E-beam energy

E_i: Ionization potential

Charge Exchange

$$\boxed{n_0 \cdot (N_{i+1} \cdot < \sigma_{i+1}^{CX} \cdot v > \cdot f_{e,i-1} - N_i \cdot < \sigma_i^{CX} \cdot v >)}$$

$n_0 \ldots neutral\,gas\,pressure!$

$v \ldots relative\,velocity$

$\sigma_{i+1}^{CX} \ldots charge\,exchange\,cross\,section$

neutral-ion charge exchange

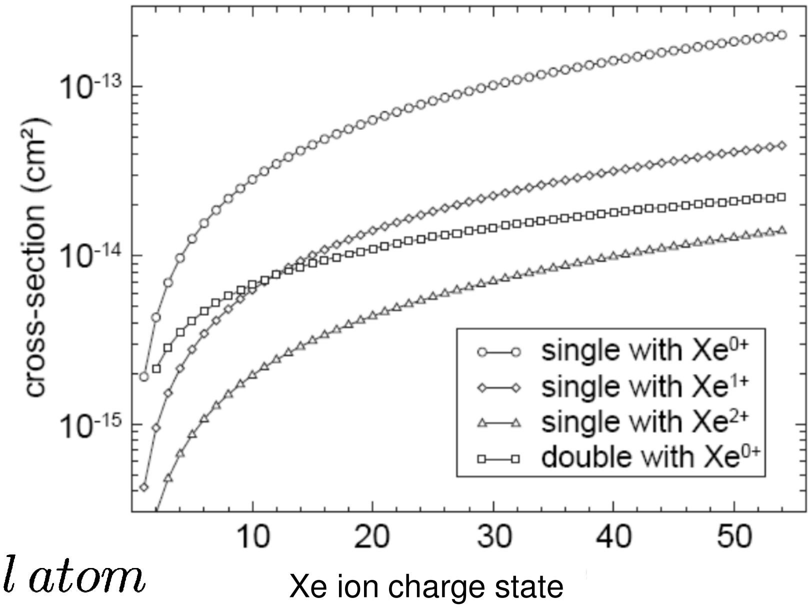
$$X^{q+} + X \rightarrow X^{(q-1)+} + X^{+}$$

Increases with Charge State!!

$$\sigma^{CX} = 1.43 \cdot 10^{-12} \cdot q^{1.17} \cdot E_i^{-2.76}$$

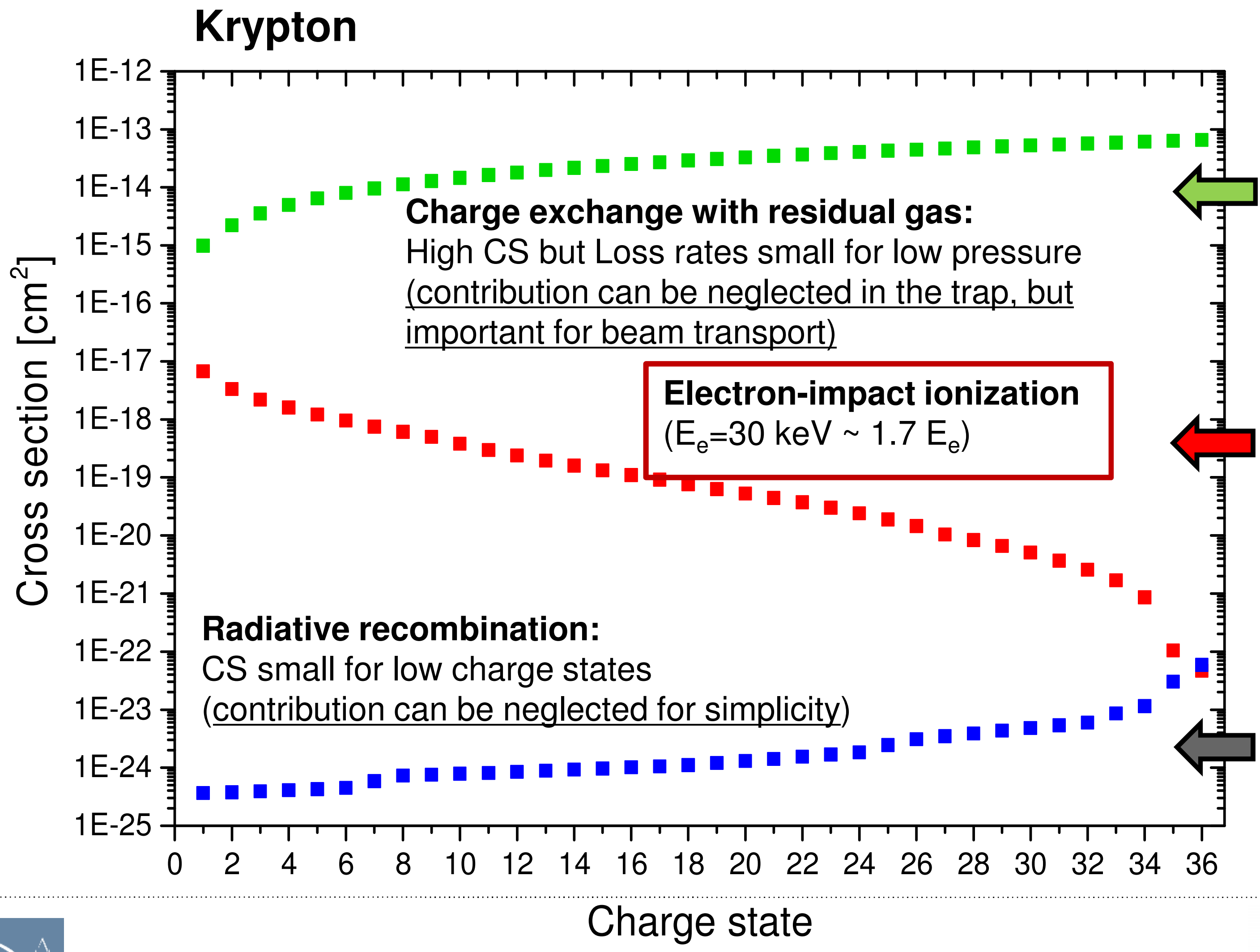
$E_i \ldots Ionization\,potential\,of\,the\,neutral\,atom$

$q \ldots Charge\,State$



A. Müller and E. Salzborn, Phys. Lett., 1977. **62A**: p. 391.

Example: Ionization for Krypton (assumption is electron temperature is 30keV)



Charge exchange with residual gas:
High CS but Loss rates small for low pressure
(contribution can be neglected in the trap, but important for beam transport)

Electron-impact ionization
(E_e=30 keV ~ 1.7 E_e)

Radiative recombination:
CS small for low charge states
(contribution can be neglected for simplicity)

$$\sigma^{CX}_{i\to i-1} \sim Q$$

$$\sigma^{ion}_{i\to i+1} \sim \frac{1}{Q^4}$$

$$\sigma^{RR}_{i\to i-1} \sim Q^2$$

Courtesy: A. Lapierre

Rate equation

Electron density

Ion confinement time

Electron temperature

$$\begin{cases} \dfrac{dn_0}{dt} = -n_e \chi^{\text{ion}}_{0\to 1} n_0 + n_{\text{gas}} \xi^{\text{ex}}_{1\to 0} n_1 - \dfrac{n_0}{\tau_0} \\ \vdots \\ \dfrac{dn_i}{dt} = +n_e \chi^{\text{ion}}_{i-1\to i} n_{i-1} - n_e \chi^{\text{ion}}_{i\to i+1} n_i - n_{\text{gas}} \xi^{\text{ex}}_{i\to i-1} n_i + n_{\text{gas}} \xi^{\text{ex}}_{i+1\to i} n_{i+1} - \dfrac{n_i}{\tau_i} \end{cases}$$

Ionization

$$\chi^{\text{ion}}_{i\to i+1} = \left\langle \sigma^{\text{ion}}_{i\to i+1}(v_e) v_e \right\rangle$$

$$\chi^{\text{ion}}_{i\to i+1} = \int \sigma^{\text{ion}}_{i\to i+1} v_e \frac{2}{\sqrt{\pi}} \left(\frac{E_e^{1/2}}{T_e^{3/2}} e^{-E_e/T_e} \right) dE_e$$

$$= \frac{9.37\times 10^{-6}}{I_i T_e^{1/2}} \int_{I_i}^{\infty} \ln \frac{E_e}{I_i} e^{-E_e/T_e} \frac{dE_e}{T_e} \left[\text{cm}^3\text{s}^{-1}\right]$$

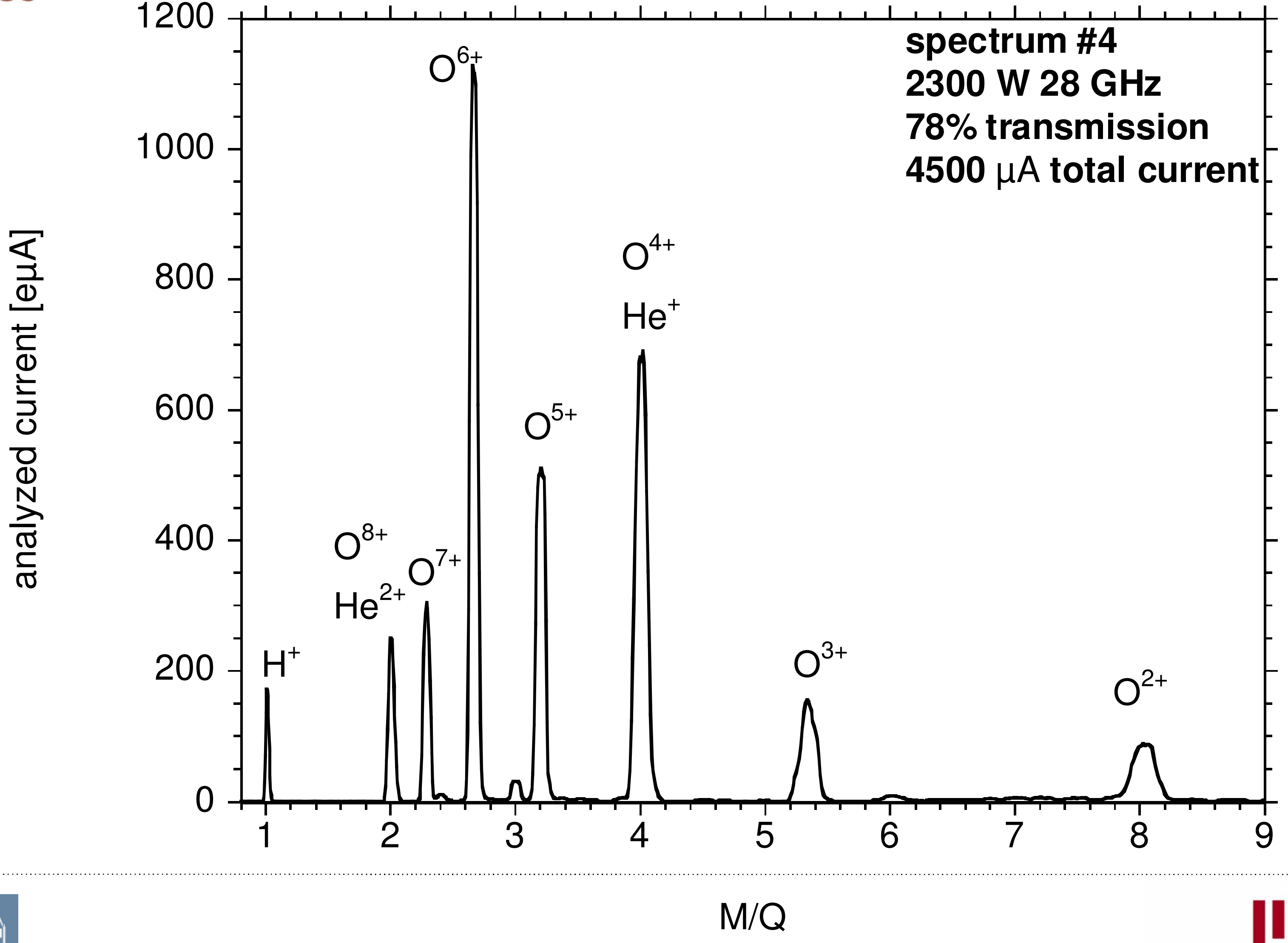
Charge exchange

$$\xi^{\text{ex}}_{i\to i-1} = \left\langle \sigma^{\text{ex}}_{i\to i-1}(v_i) v_i \right\rangle$$

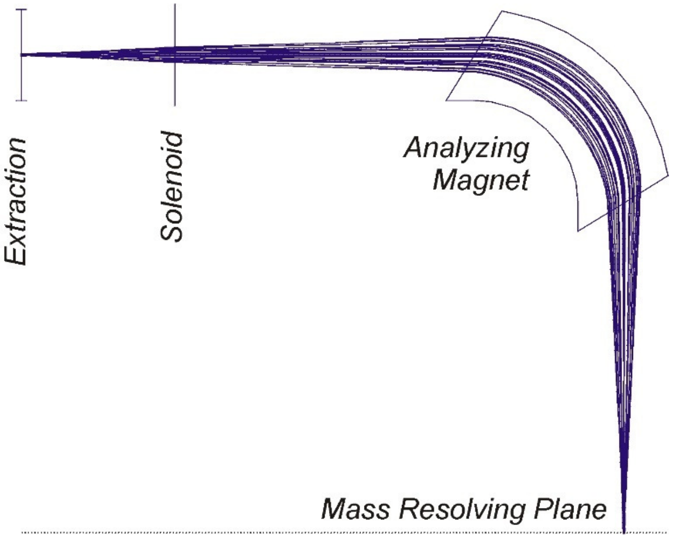
$$\xi^{\text{ex}}_{i\to i-1} = \int_0^{\infty} \sigma^{\text{ex}}_{i\to i-1} v_i \frac{2}{\sqrt{\pi}} \left(\frac{E_i^{1/2}}{T_i^{3/2}} e^{-E_i/T_i} \right) dE_i$$

$$= 3.15\times 10^{-6} i^{1.17} I_{\text{gas}}^{-2.76} \sqrt{\frac{T_i}{A_i}} \quad \left[\text{cm}^3\text{s}^{-1}\right]$$

Equilibrium state in the ECR ion source plasma will consist out of a Charge State Distribution (CSD)



Sector Magnet, Analyzing Magnet



$$R = \frac{M \cdot m_p \cdot v}{Q \cdot q_e \cdot B} \qquad v = \sqrt{\frac{2 \cdot Q \cdot q_e \cdot V_{ext}}{M \cdot m_p}}$$

$$M \approx A,\ q_e = 1.6022 \cdot 10^{19}\, coul, \quad m_p = 1.67 \cdot 10^{-27}\, kg,$$

$$V_{ext} \text{.....extraction voltage}, R\text{....bend radius},$$

$$B\text{...magnetic field}, Q\text{..charge state}, A\text{...Atomic Mass}$$

$$\frac{M}{Q} = \frac{q_e \cdot B^2 \cdot R^2}{2 \cdot V_{ext} \cdot m_p},$$

or

$$\sqrt{\frac{M}{Q}} = C \cdot B$$

C....const. for given accelerator voltage V_{ext} and bend radius R

By changing the magnetic field different ions are transported into the Faraday Cup -> Spectrum

Ionization Factor: **Product of the electron density and the time of bombardment required to reach a desired charge state**

Probability for Ionization:

$$P_{q\rightarrow q+1} = \sigma_{q\rightarrow q+1} \cdot v_e \cdot n_e \cdot \tau_i \rightarrow 1$$

$$\tau_i = \frac{1}{\sigma_{q\rightarrow q+1} \cdot v_e \cdot n_e \cdot}$$

Time required to remove the i-th electron for a specific ion for a given n_e

$$\tau_q n_e = \sum_{k=1}^{q} \frac{1}{\sigma_k^{EI} v_e}$$

Time required to reach a charge state q for a given electron density, and T_e

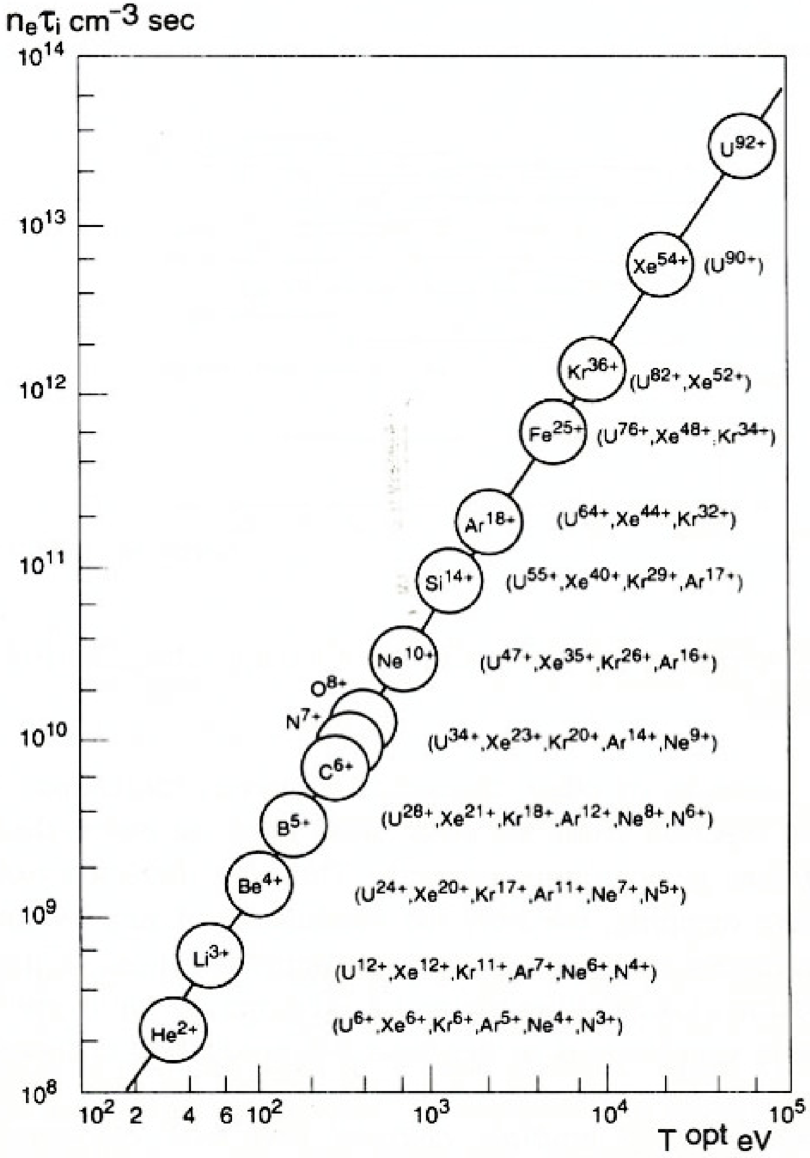
$$\overline{v} = \sqrt{\frac{8kT}{\pi m}}$$

$j\tau$: quality factor/ tuning factor for an EBIT ion source is the combination of the electron density (electron gun current + compression)
Depending on the ionization potential of the desired charge state and electron beam density, the minimum confinement time can be calculated

Golovanivsky's plot

$$\tau_q n_e = \sum_{k=1}^{q} \frac{1}{\sigma_k^{EI} v_e}$$

- Golovanivsky's plot of the ($n_e \tau_i$) is a criteria for the production of highly charged ions in an ECRIS
- Plots the optimum electron temperature for creating fully ionized ions
- The presents an upper limit for the creation of charge states that have a similar Ionization potential



Geller, R., *Electron Cyclotron Resonance Ion Source and ECR Plasmas*. 1996: Bristol, Institute for Physics Publishing, page 89

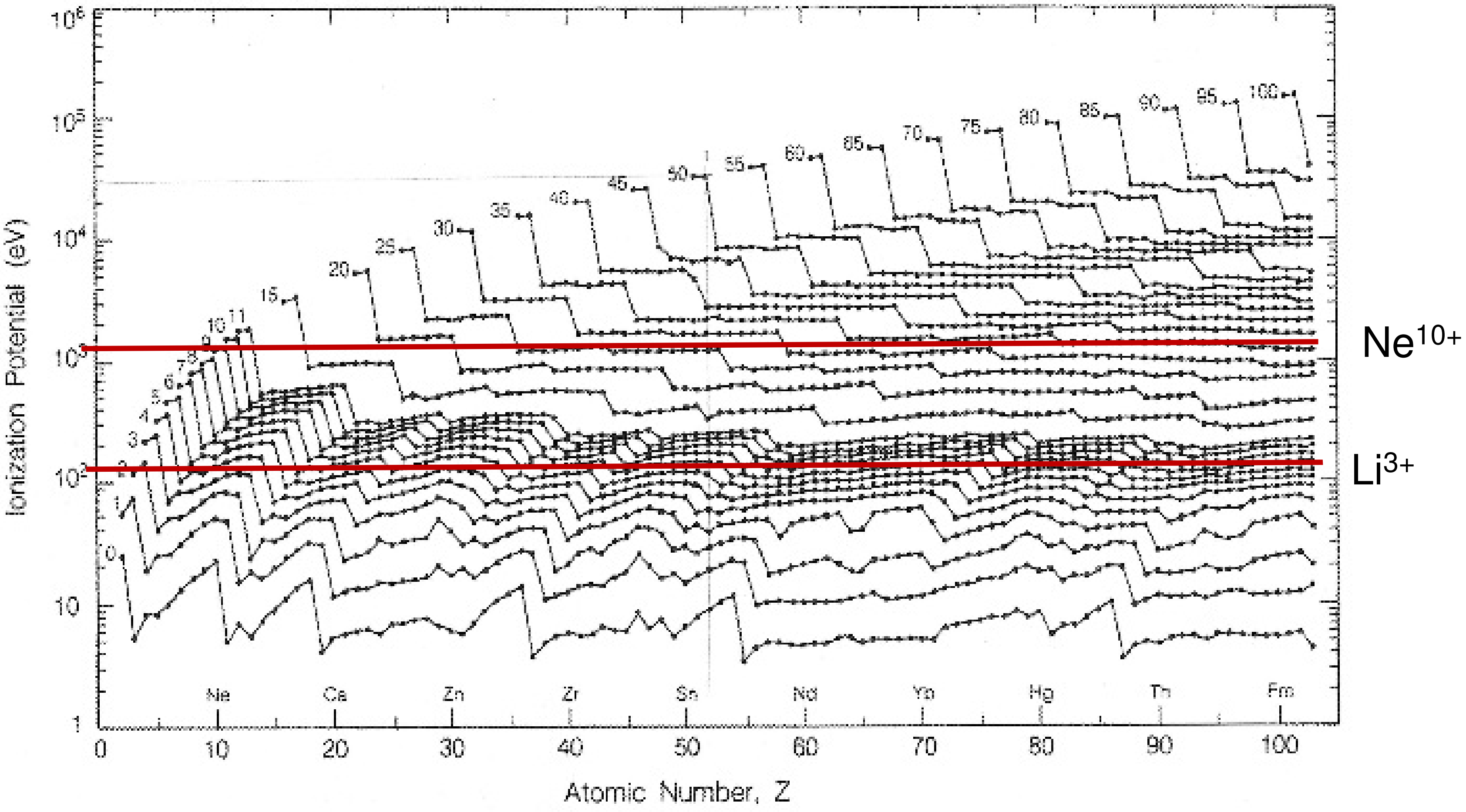
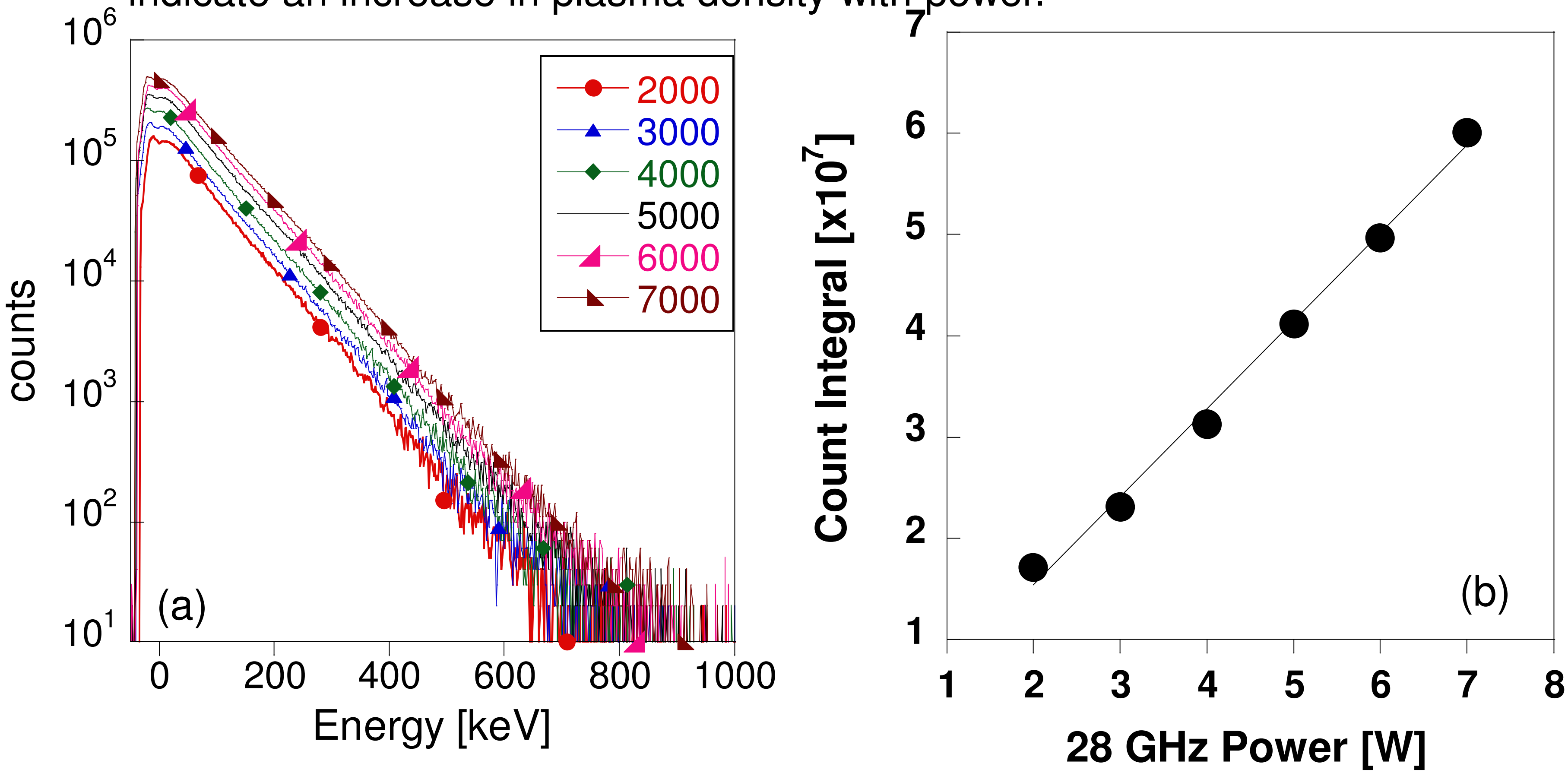


Figure 2.3 Ionization potentials for multiply charged ions of all of the elements [15].

Product of $n_e \cdot \tau_i$ can be increased with increasing microwave power

Axial bremsstrahlung measurements in VENUS and other ECR ion source indicate an increase in plasma density with power.



D. Leitner, et.al "Measurement of the high energy component of the x-ray spectra in the VENUS electron cyclotron resonance ion source," Rev. Sci. Inst. **79** 033302 (2008)

Vacuum Criteria

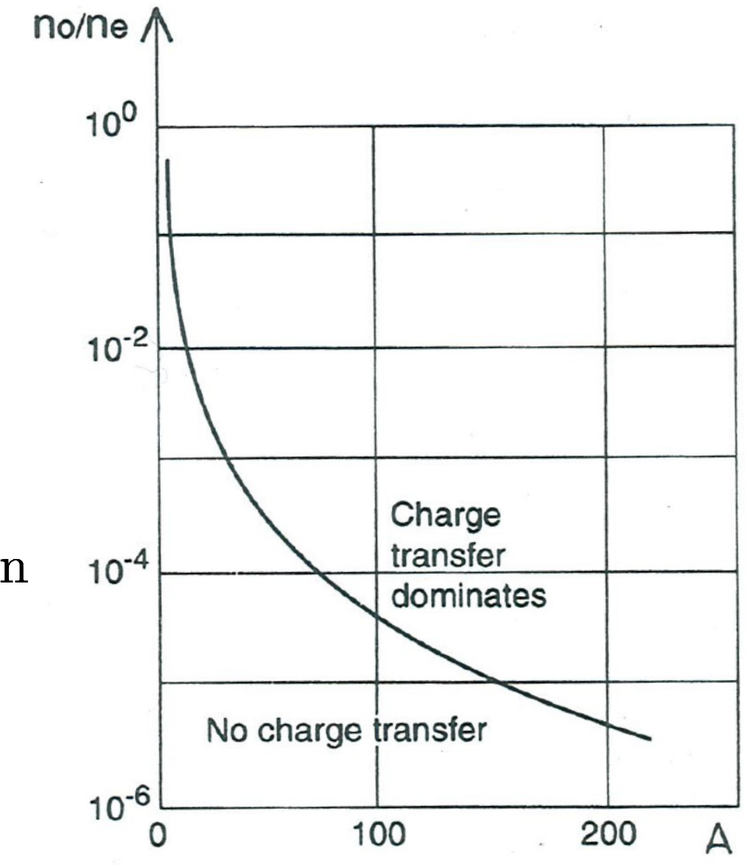
- The electron temperature is one threshold criteria
- The second threshold criteria is neutral gas level in the plasma (charge exchange!)

$$\tau_{q\rightarrow q-1} = \frac{1}{\sigma_{q\rightarrow q-1}\cdot v_i \cdot n_0\cdot} > \tau_{q-1\rightarrow q}$$

$\sigma_{q\rightarrow q-1}$...Charge Exchange Cross Section

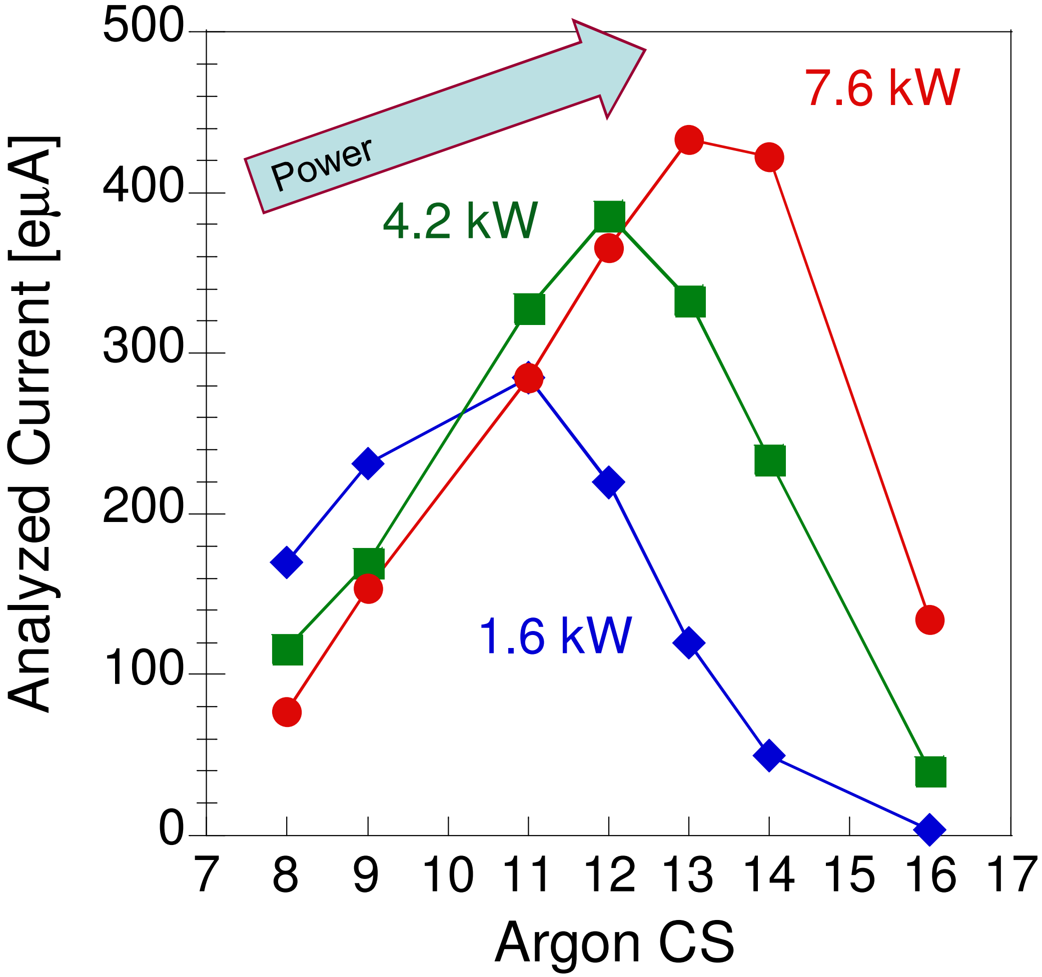
- For example to achieve Ar^{18+}, with an $n_e=3\cdot10^{11}/cm^3$, requires a neutral gas pressure in the plasma of $3\cdot10^8/cm^3$ or a vacuum of better than $1\cdot10^{-8}$ torr !

Golovanivsky Boundary Conditions



Geller, R., *Electron Cyclotron Resonance Ion Source and ECR Plasmas*. 1996: Bristol, Institute for Physics Publishing, page 92

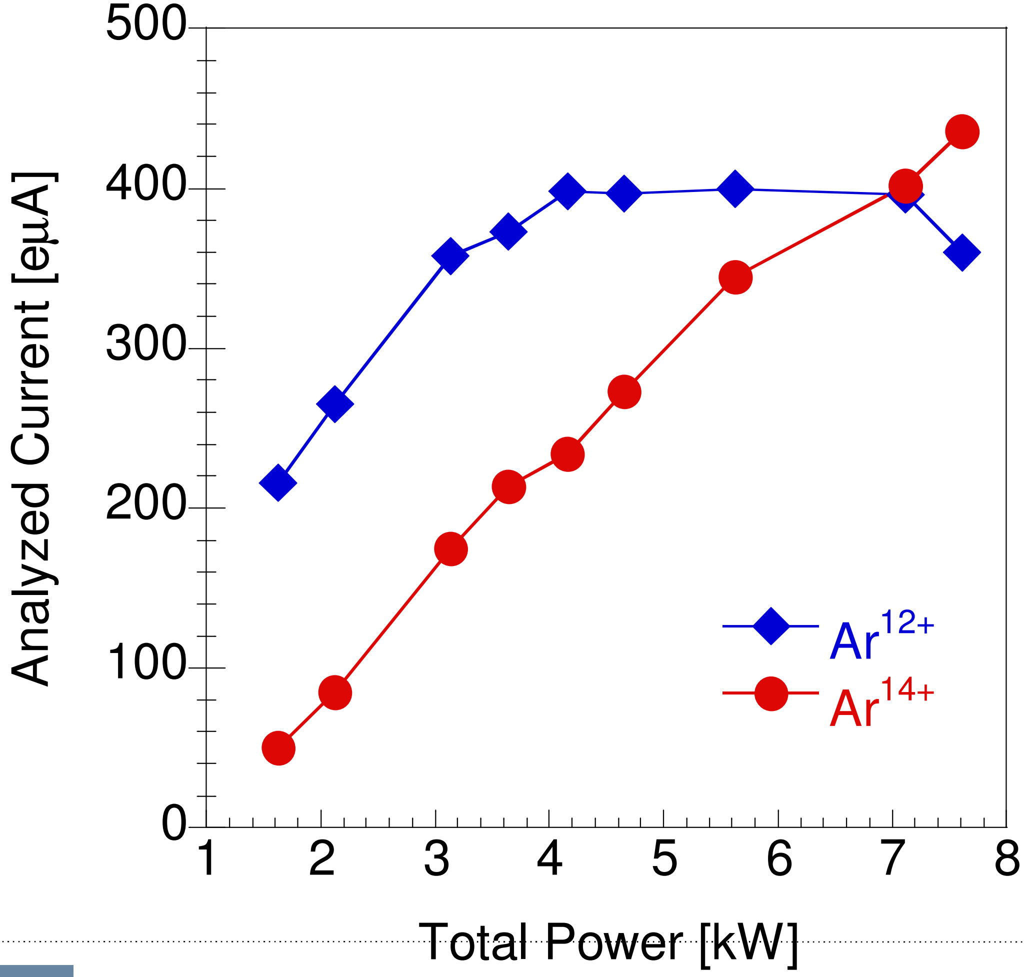
The charge state distribution (CSD) increases with increasing electron density



The Argon CSD shifts from lower charge states to higher charge state for constant gas flow and same confinement fields as the power coupled to the plasma increases.

Product of $n_e \cdot \tau_i$ increases with power

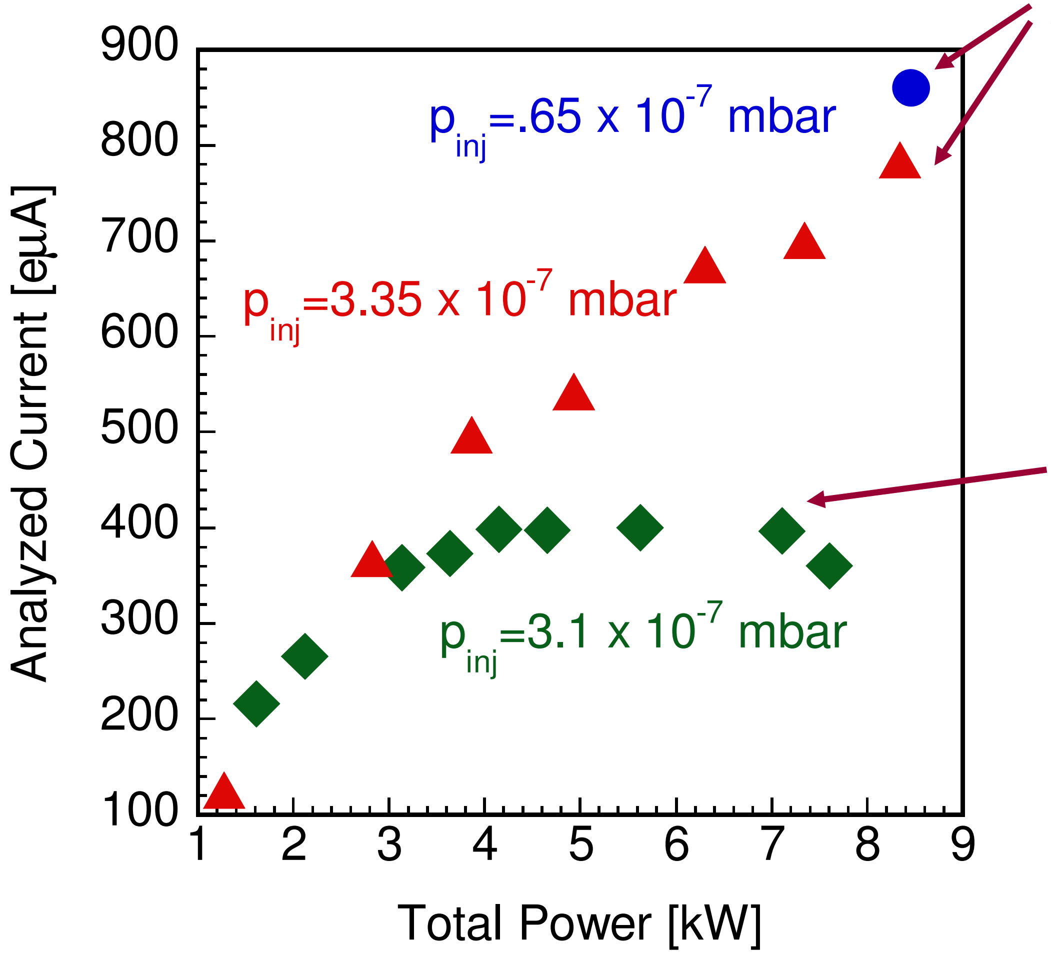
Dependence of Ar^{12+} and Ar^{14+} on microwave heating power with constant gas flow rates and unchanged confinement field



The ionization rate for Ar^{12+} into higher charge states increases with power, but levels off as the CSD shifts to higher charge states

Ar^{14+} continues to increase as n_e is further increased

The equilibrium CSD

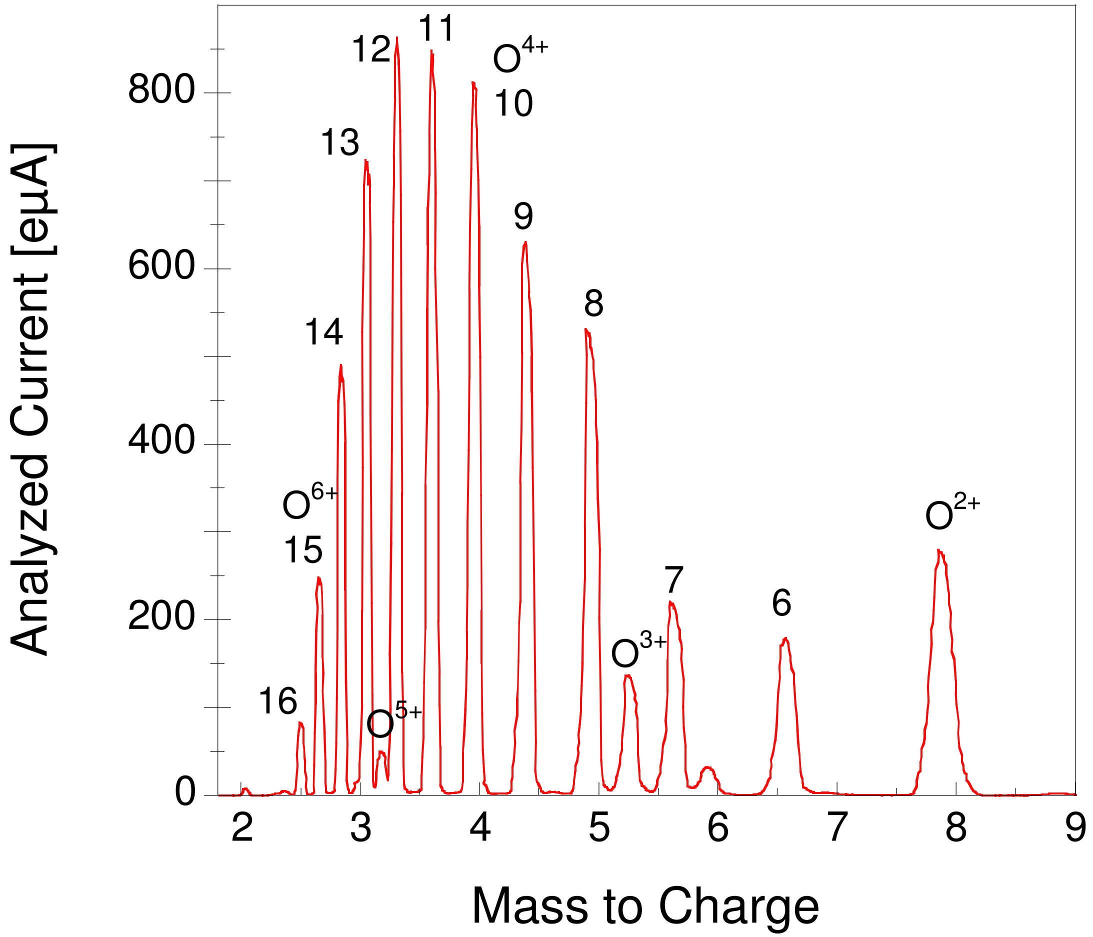


To keep the CSD peaked on Ar^{12+} more gas needs to be added to the plasma

CSD is shifted to higher charge states

Ar^{12+} CSD for well ‘tuned’ the plasma parameters

Argon charge state distribution from VENUS using oxygen as mixing gas



Ar	VENUS (28GHz) eμA
12^+	860
14^+	514
16^+	270
17^+	36
18^+	1

ECR Performance Criteria/Design Guide

- The magnetic field design needs to match the chosen microwave frequency

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

- The electron density of the ECR plasma (and therefore the maximum extracted current) is proportional to the frequency square!

$$n_e \propto \omega_p^2$$

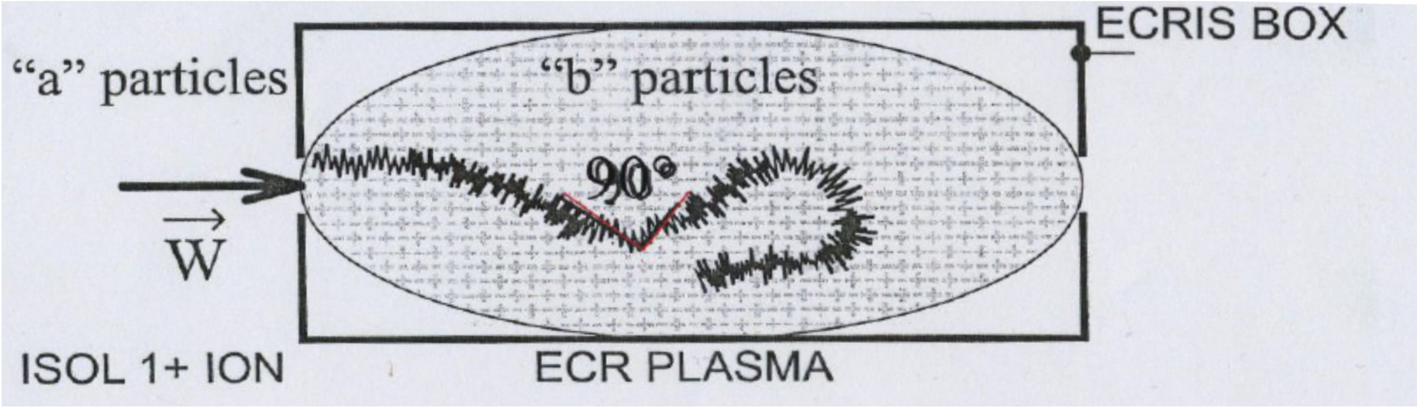
- The product of n·τ in dependence of the optimum electron temperature must reach a critical value to obtain a certain charge state
- The ratio of n_0/n_e must be low enough to keep the charge exchange recombination rate sufficiently low to achieve the desired CSD – the lower the pressure in the plasma the higher the charge state that can be achieved

$$\tau_{q \to q-1} > \tau_{q-1 \to q}$$

Plasma Confinement and Plasma Heating

Recap: Collisions in plasma are governed through long range collective effects

- Collision are fundamentally different between charge particles in the plasma – they are governed through collective effects
- Collisions in plasma are governed through long range interactions (coulomb collisions between charged particles – takes several interactions to deflect an ion- usually the characteristic time is calculated for a **collective 90˚ scattering (Spitzer collisions)**



Spitzer Collisions: Fundamental relations to interpret source performance

$$\frac{1}{\tau_{ee}} = \nu_{ee} = 5 \cdot 10^{-6} n_e ln[\frac{\Lambda_D}{b}] \frac{1}{T_e^{\frac{3}{2}}}$$

$$\frac{1}{\tau_{ei}} = \nu_{ei} \approx 2 \cdot 10^{-6} z n_e ln[\frac{\Lambda_D}{b}] \frac{1}{T_e^{\frac{3}{2}}}$$

$$\frac{1}{\tau_{ii}} = \nu_{ii} \sim z^4 \sqrt{\frac{m_e}{m_i}} n_e \left(\frac{T_e}{T_i}\right)^{\frac{3}{2}} \cdot \nu_{ee}$$

$$\nu_{ee}^{90} > \nu_{ii}^{90}$$

In most regions of the plasma, electrons losses dominate over ion losses parallel to the magnetic field

T_i .... Ion temperature
z .... Ion charge
m_i .... Ion mass
T_e .... Electron temperature
m_e .... Electron mass
n_e .... plasma density
ν_{ii} .... 90° collision rate
τ_{ii}, τ_{ei}, τ_{ee} .... mean time between 90° deflection
$ln[\frac{\Lambda_D}{b}]$ .... Coulomb Logarithm

Important factor: Ion temperature, electron temperature, ion mass, ion charge state!!

Recap: Diffusion processes in magnetized plasmas (Spitzer Collisions!)

- In the direction of the fields there is no force, transverse the particles are bend into the circular motion

$$F = q\vec{v} \times \vec{B} \qquad r_c = \frac{mv}{eQB} \longrightarrow \begin{array}{l} f_{ce} = 28 \cdot GHz \cdot B(T) \\ f_{ci} = 15.2 \cdot MHz \cdot \frac{Q}{A} B(T) \end{array}$$

A....atomic mass number

Q....Charge state

- Therefore the transport // to the field is different than ⊥ !
- // to the field the transport dominated by 90˚ collisions

$$\nu_e^{90} > \nu_i^{90} \longrightarrow \frac{D_{\parallel e}}{D_{\parallel i}} \propto \sqrt{\frac{m_i}{m_e}}$$

Electron loss dominantly // to the field

- ⊥ to the field the transport is dominated by the gyrotron motion.

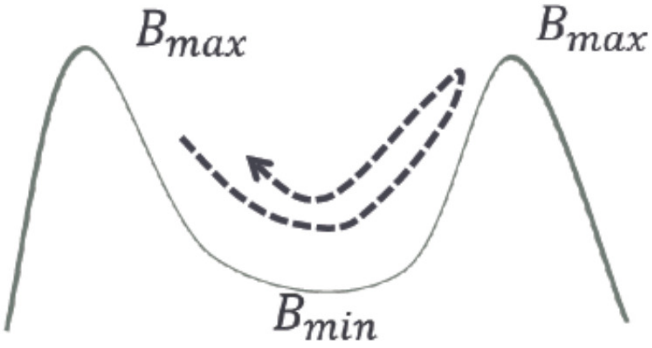
$$f_c >> \nu_i^{90} \qquad r_{ci} >> r_{ce} \longrightarrow \frac{D_{\perp e}}{D_{\perp i}} \propto \sqrt{\frac{m_e}{m_i}}$$

Loss is dominated by hoping from one field line to the next

Ion loss dominantly ⊥ to the field

ECR Confinement
Magnetic confinement in a mirror field

- In a growing magnetic there is an adiabatic exchange between the parallel velocity component (decreases in the growing magnetic field) and the transverse one (increases to keep µ constant)
- The confinement is not perfect: if v⊥/v is too small the particle will be lost – the loss cone is determined by the ratio of the minimum to the maximum field



$$\mu = \frac{W_\perp}{B} = \frac{\frac{1}{2}mv_\perp^2}{B} = \text{constant}$$

$$W_\perp + W_{||} = \text{constant}$$

$$\sin(\theta_{min}) = \sqrt{\frac{Bmin}{Bmax}} = \sqrt{\frac{1}{R_m}}$$

θ_{min} ... defines the loss cone

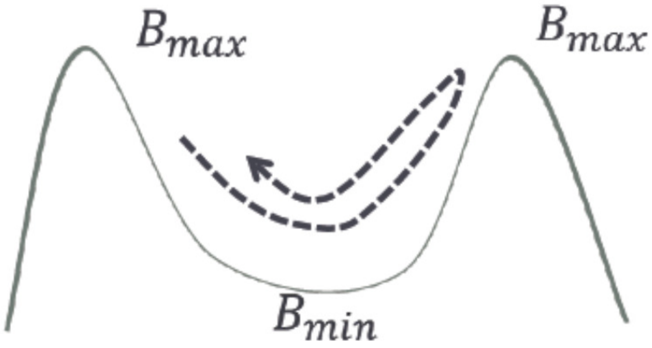
R_m ... mirror ratio

$$\Rightarrow \quad \frac{v_\perp}{v} > \sqrt{\frac{1}{R_m}}$$

Thullier, T., https://cas.web.cern.ch/cas/Slovakia-2012/Lectures/

Plasma losses in the magnetic mirror

- The confinement is not perfect: if v⊥/v is too small the particle will be lost – the loss cone is determined by the ratio of the minimum to the maximum field
- Electrons get heated mostly transverse as the wave is coupled to the transverse velocity of the ion



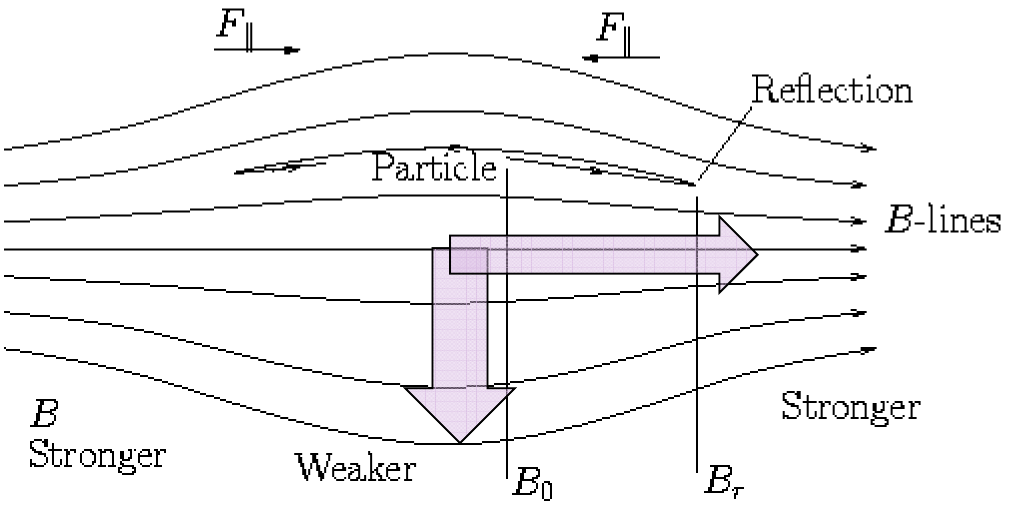
- Electrons that are scattered into the loss cone will leave the plasma

$$\frac{1}{\tau_{ee}} = \nu_{ee} = 5 \cdot 10^{-6} n_e ln[\frac{\Lambda_D}{b}] \frac{1}{T_e^{\frac{3}{2}}}$$

- The confinement increases with increasing electron temperature since the collision rate decreases

ECR Confinement

Recap – Magnetic Pressure



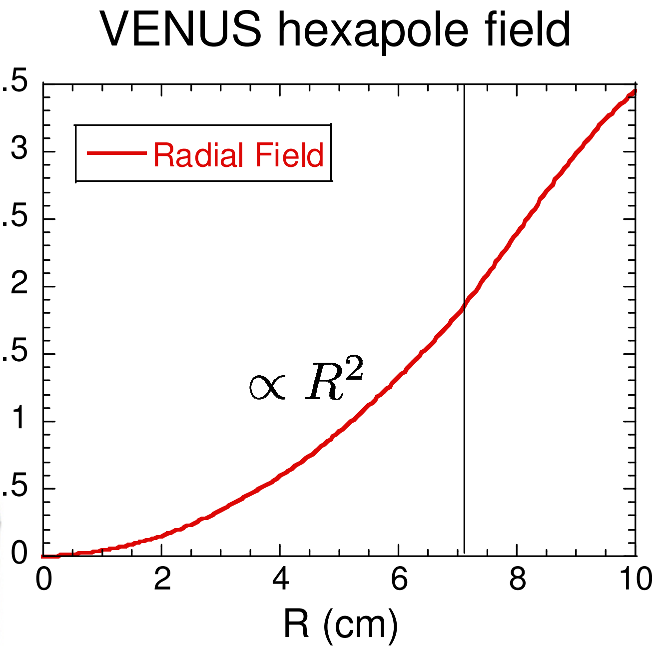
Magnetic pressure gets stronger (stable confinement axially)

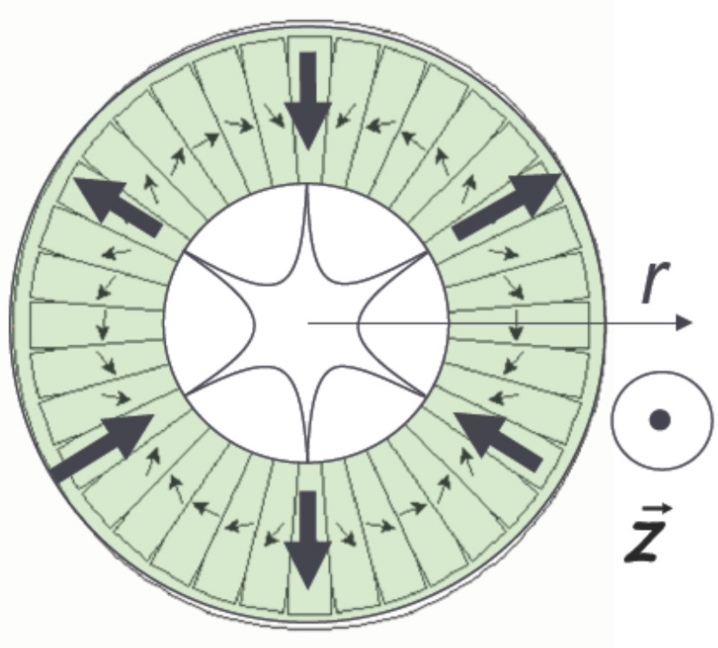
Magnetic pressure gets weaker (unstable confinement radially)

- The field created by a pair of solenoid is inherently instable as the plasma fluid can ‘escape’ radially
- **Solution: add radial confinement field**

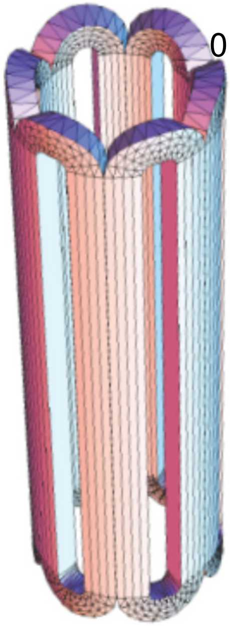
Radial Confinement Field

- Create a ‘mirror field’ in the radial direction by adding a multipole to the confinement field (can define loss cones)
- Typically a hexapole is used (sometimes an Octopole)

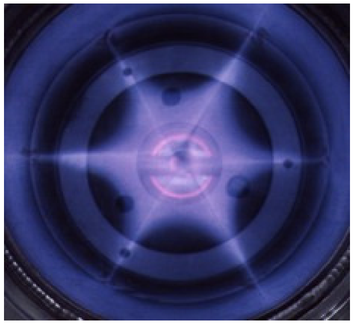




(HallBach Hexapole
With 36 permanent magnets
30° rotation/magnet)

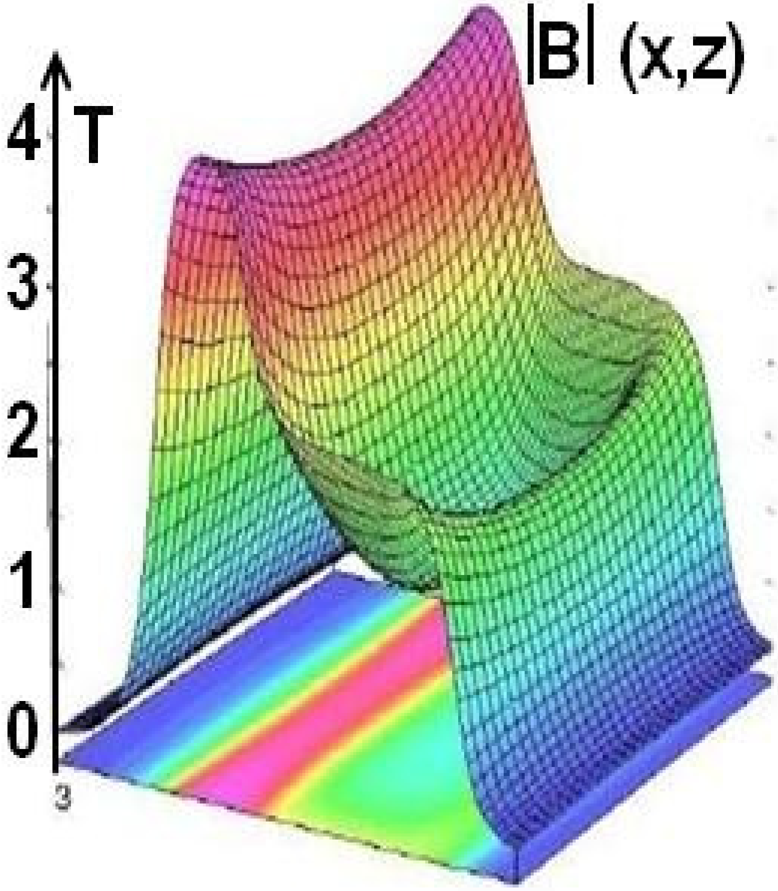


Superconducting hexapolar coil

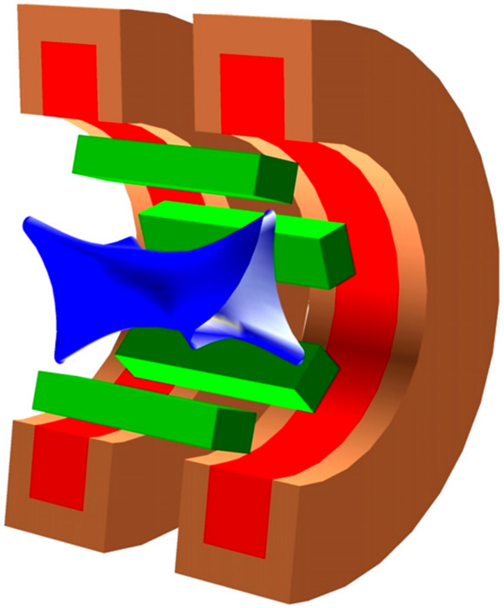


Plasma Chamber Wall

Minimum-B field confinement structure: Magnetic field strength increases in every direction from the center of the plasma



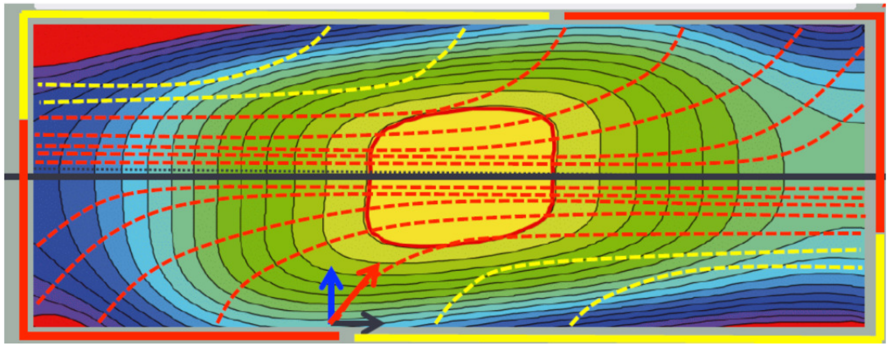
- The combination of a solenoid field with the sextupole field creates a minimum-B field configuration

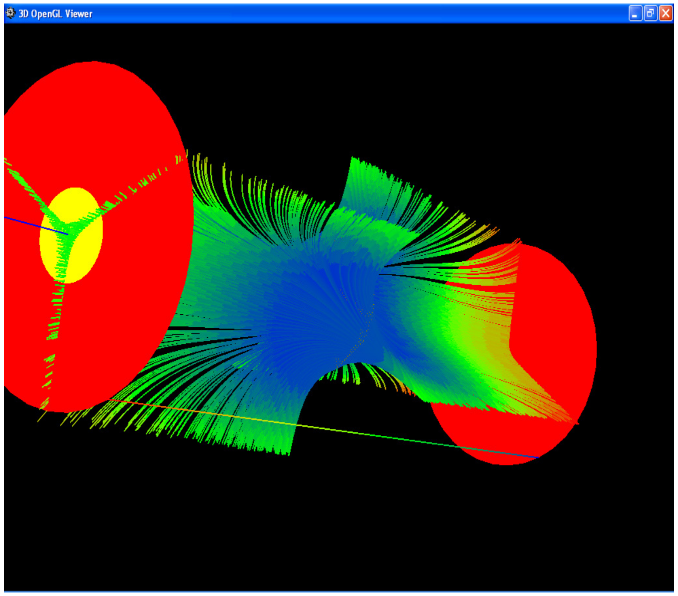


Thullier, T., https://cas.web.cern.ch/cas/Slovakia-2012/Lectures/

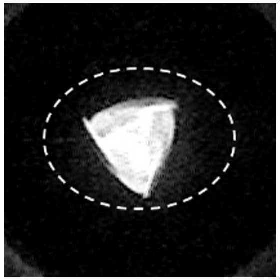
The famous shape of the ECR plasma (and the ion beam extracted from it)

- In order to understand the plasma shape – one must follow the field lines !



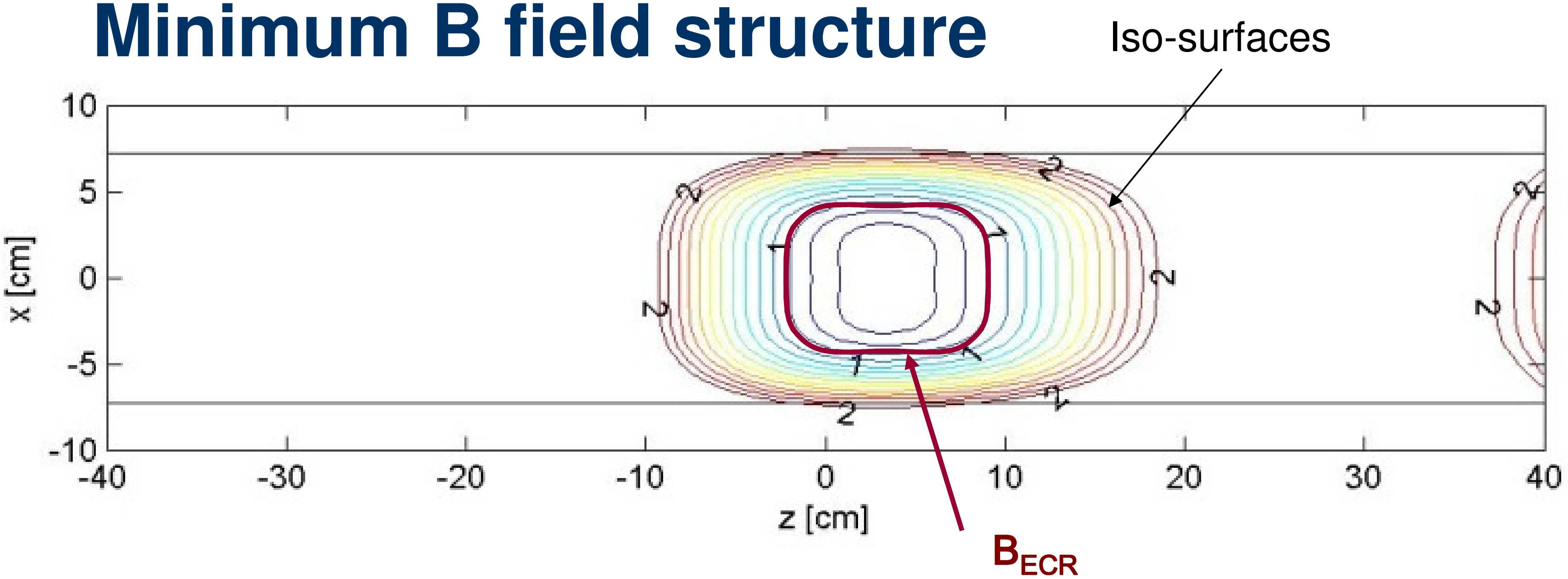


The combination of the sextupole field and the mirror field (that has a radial component) shapes the magnetic field lines to form a twisted triangular shape on each end of the source



Extracted beam

Minimum B field structure



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

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

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

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

The heating surface is well separated from the plasma chamber wall!
Using a second or (third) heating frequency adds heating surfaces to the plasma and increases the overall performance of the source

Standard ECR model for high performance ECR ion sources

Courtesy of Damon Todd

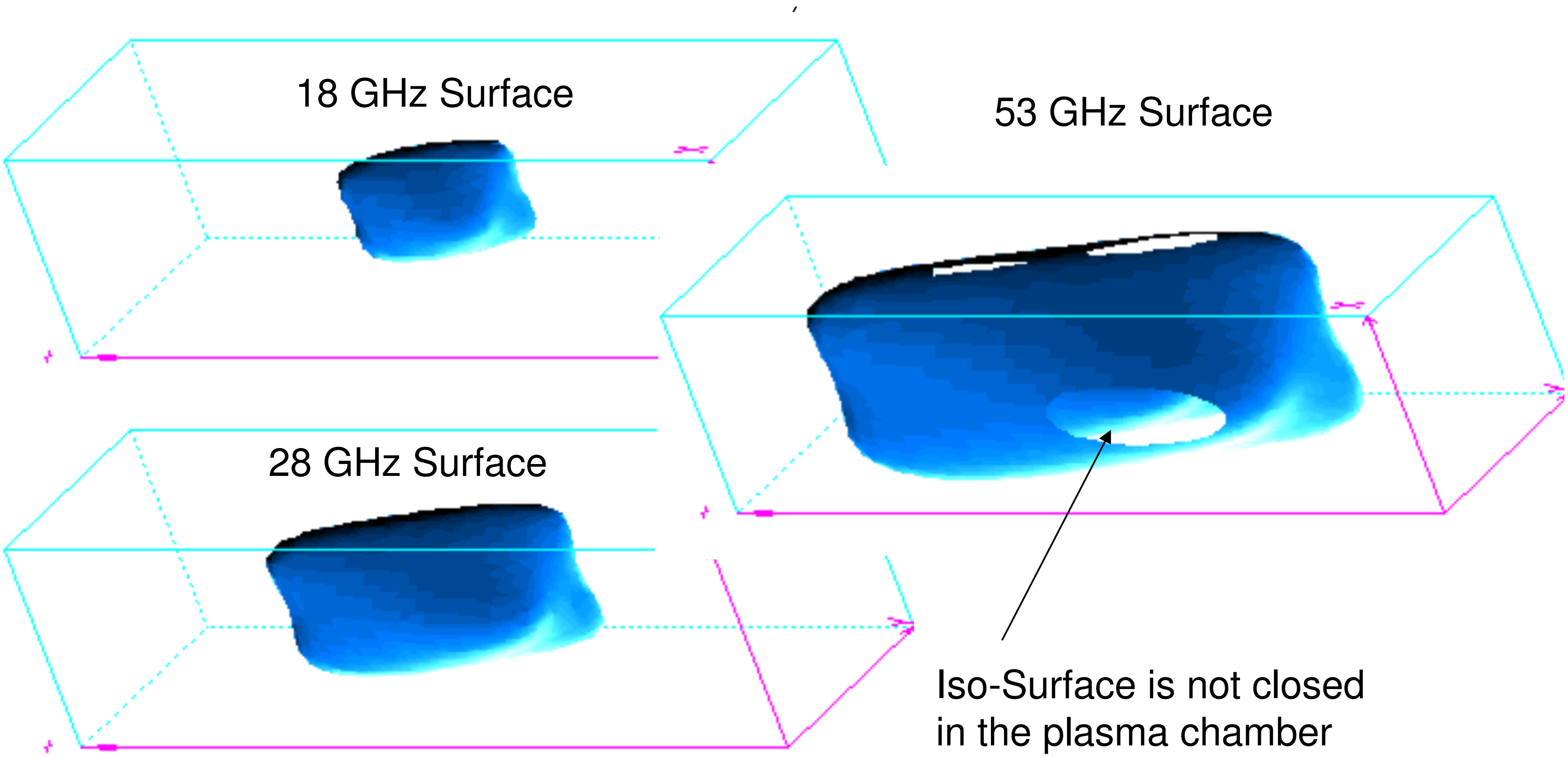
‘Standard’ Model for an optimized ECR ion source magnetic confinement field

	28 GHz (VENUS)	14 GHz (AECR-U)
$B_{inj} \sim 4 \cdot B_{ecr}$	4T	1.8T
$B_{min} \sim 0.8\ B_{ecr}$	.5-.8 T	.45 T
$B_{ext} \sim B_{rad}$	2T	1.1T
$B_{rad} \geq 2\ B_{ecr}$	2T	0.85-0.9T

14 GHz B_{ECR}= 0.5 Tesla

28 GHz B_{ECR}= 1 Tesla

Iso-Surfaces in VENUS



18 GHz Surface

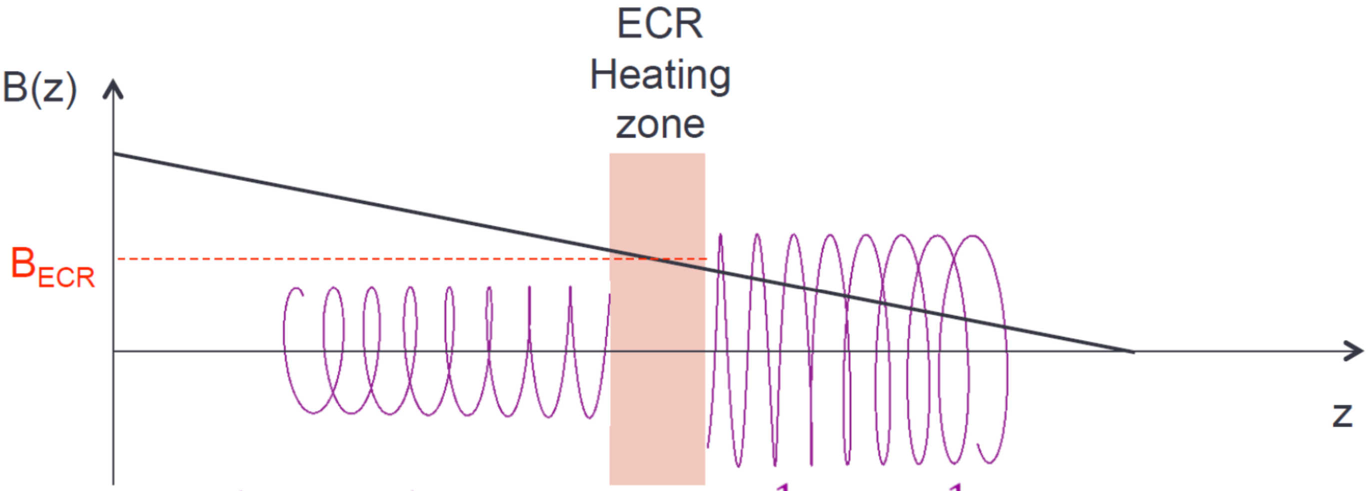
28 GHz Surface

53 GHz Surface

Iso-Surface is not closed
in the plasma chamber

ECR Heating and Magnet Field Gradient

- When electrons pass through the ECR surface they are slightly accelerated (in mean), the parallel velocity is unchanged while the transverse velocity increases
- The ECR surface thickness is correlated to the slope of the ECR confinement field
- Shallow magnetic field slope increases the interaction time of the electron with wave and will lead to more efficient ECR heating

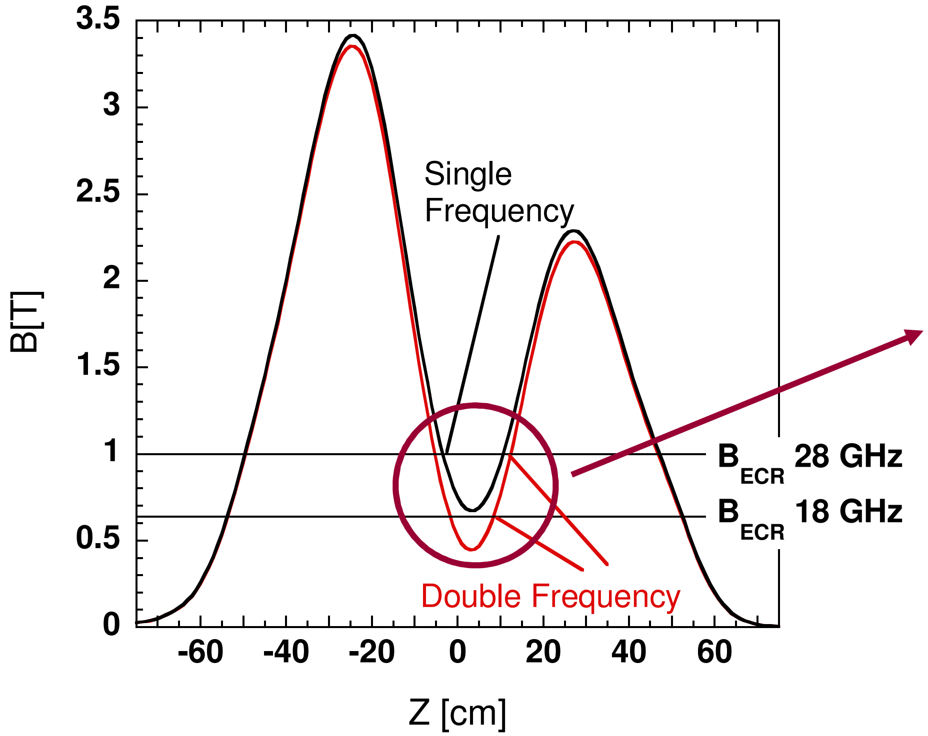


$$\frac{1}{2}mv_{\parallel}^{2}+\frac{1}{2}mv_{\perp}^{2} \Rightarrow \frac{1}{2}mv_{\parallel}^{2}+\frac{1}{2}m(v_{\perp}+\delta v_{\perp})^{2}$$

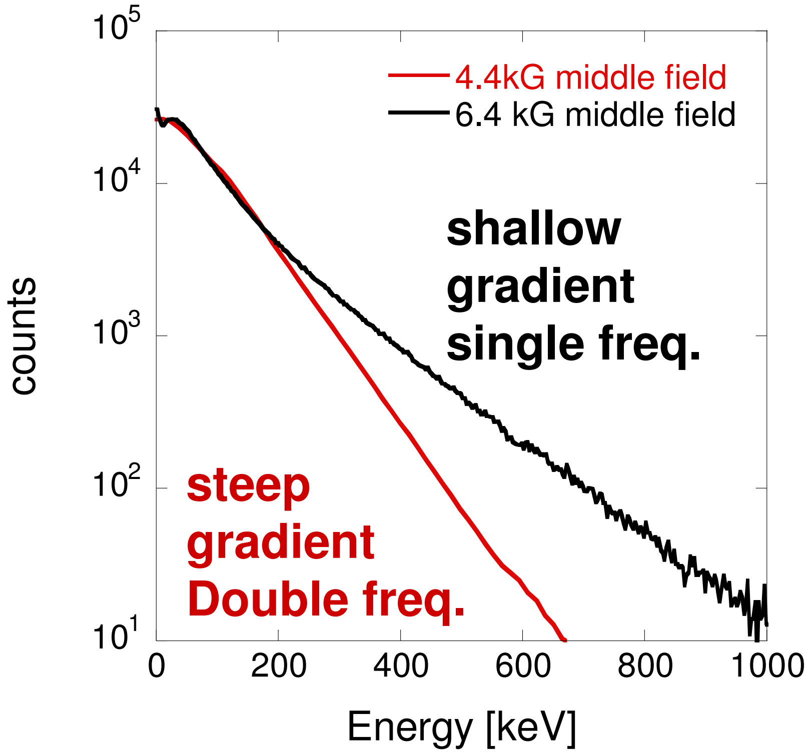
Thullier, T., https://cas.web.cern.ch/cas/Slovakia-2012/Lectures/

X-ray Spectra: shallow gradient versus a steep gradient (measurement at VENUS)

Magnetic field configuration for optimized single and double frequency heating.



Axial Bremstrahlung spectra from VENUS for the two field configuration



The bremsstrahlung spectrum with a shallow magnetic field gradient at the resonance contains much higher x-ray energies.

ECR Performance Criteria/Design Guide

- The magnetic field design needs to match the chosen microwave frequency

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

- The electron density of the ECR plasma (and therefore the maximum extracted current) is proportional to the frequency square!

$$n_e \propto \omega_p^2$$

- The product of n·τ in dependence of the optimum electron temperature must reach a critical value to obtain a certain charge state
- The ratio of n_0/n_e must be low enough to keep the charge exchange recombination rate sufficiently low to achieve the desired CSD – the lower the neutral pressure in the plasma the higher the charge state that can be achieved

$$\tau_{q \to q-1} > \tau_{q-1 \to q}$$

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ECR Performance Criteria/Design Guide

- The plasma confinement is related to the ratio B_{min} to B_{max} and $B_{average}=\frac{1}{2}(B_{min}+B_{max})$
- Shallow magnetic field gradients are more efficient for ECR plasma heating – long plasma chambers are beneficial!
- Hot electrons are essential for electrostatic plasma confinement

Role of hot electrons in the plasma

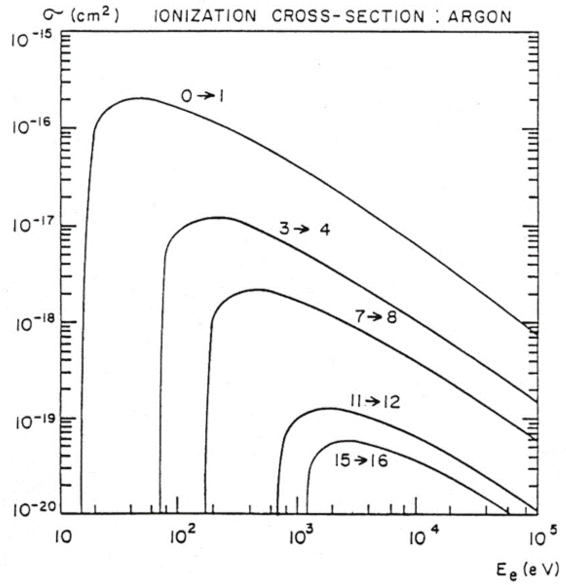
- Hot electrons are highly confined in the magnetic bottle, since v⊥ component is large

$$\frac{v_\perp}{v} > \sqrt{\frac{1}{R_m}}$$

- The hot electrons are non collisional
  - the collision rates (Spitzer collisions into the loss cone) decrease with increasing temperature

$$\nu_{ee}, \nu_{ei} \propto \frac{1}{T_e^{\frac{3}{2}}}$$

- Ionization Cross Sections declines with energy
  - hot electrons play a very little role for ionization !
- Hot electrons are a major contributor to the x-ray flux from the source



XBL 8611-4404

Role of hot electrons in the plasma – lets go back to Spitzer!

- **For the core (not everywhere!!)** of the plasma with $T_e >> T_i$ the Spitzer collisions **ion** scattering rate into the loss cone can dominate over the scattering rate of the very hot electrons confined in the plasma core.

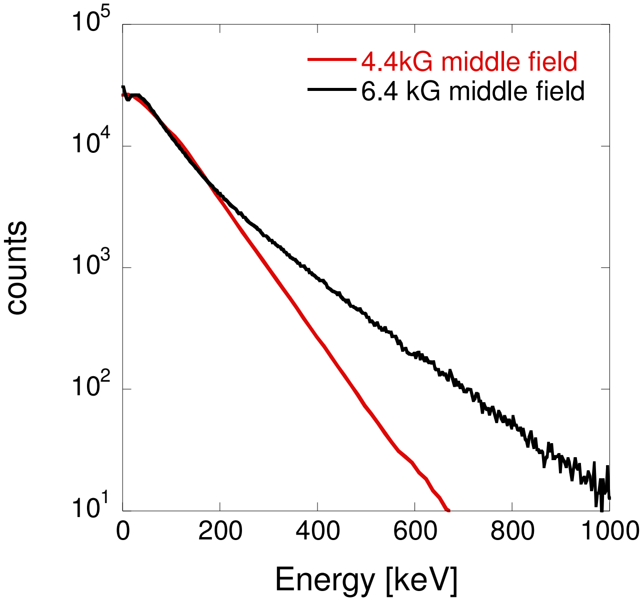
$$\frac{1}{\tau_{ee}} = \nu_{ee} = 5 \cdot 10^{-6} n_e ln[\frac{\Lambda_D}{b}] \frac{1}{T_e^{\frac{3}{2}}}$$

$$\frac{1}{\tau_{ei}} = \nu_{ei} \approx 2 \cdot 10^{-6} z n_e ln[\frac{\Lambda_D}{b}] \frac{1}{T_e^{\frac{3}{2}}}$$

$$\frac{1}{\tau_{ii}} = \nu_{ii} \sim z^4 \sqrt{\frac{m_e}{m_i}} n_e (\frac{T_e}{T_i})^{\frac{3}{2}} \cdot \nu_{ee}$$

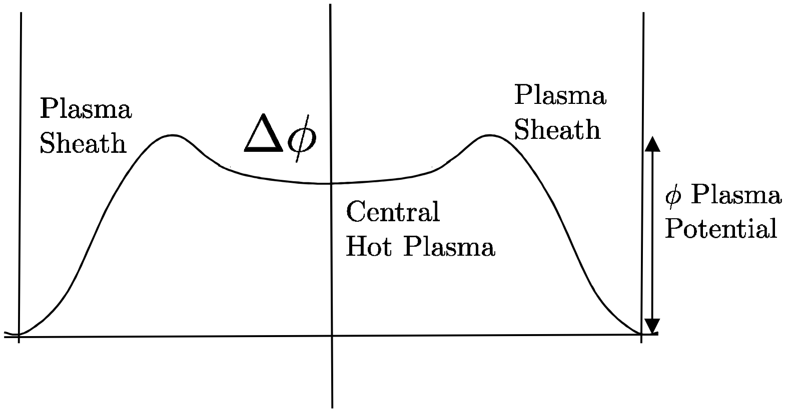
$\frac{\tau_{ei}}{\tau_{ii}} > 1$ for $T_e \gg T_i$
in the hot core

T_i .... Ion temperature
z .... Ion charge
m_i .... Ion mass
T_e .... Electron temperature
m_e .... Electron mass
n_e .... plasma density
ν_{ii} .... 90° collision rate
$\tau_{ii}, \tau_{ei}, \tau_{ee}$ .... mean time between 90° deflection
$ln[\frac{\Lambda_D}{b}]$ .... Coulomb Logarithm



Role of hot electrons in the plasma

- **For the core (not everywhere!!)** of the plasma with $T_e >> T_i$ the Spitzer collisions ion scattering into the loss cone can dominate
- Model: Highly confined electron beam is created on source axis that forms a negative space charge potential well thus electrostatically confining highly charged ions.
- The space charge potential of these highly confined electrons create a radial confinement field for the high charge state positive ions

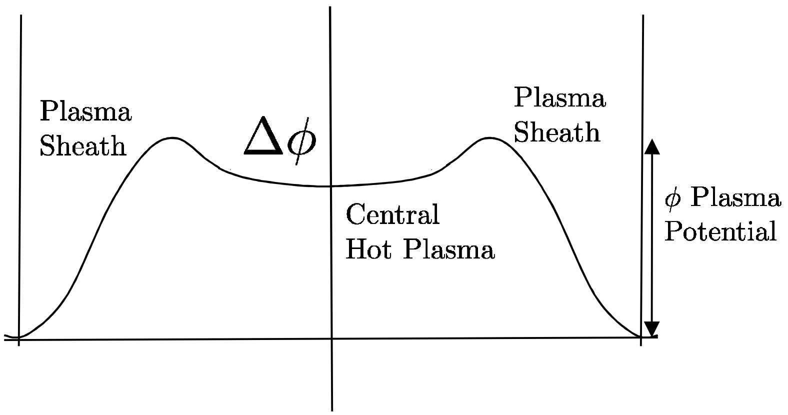


$$\Delta\phi \propto \frac{-T_i}{z \cdot e}$$

Negative potential is proportional to the ion temperature!

Role of hot electrons in the plasma

- Model: Highly confined electron beam is created on source axis that forms a negative space charge potential well thus electrostatically confining highly charged ions.
- The negative potential has important consequence for the ion confinement and extracted ion beams!!!
- When ECR ion sources are pulsed – a burst of high charge state ions are released (afterglow effect), $I_{afterglow} \sim 4\text{-}10\text{x}\ I_{cw}$



$$\Delta\phi \propto \frac{-T_i}{z \cdot e}$$

Negative potential is proportional to the ion temperature!

Recap: Diffusion processes in magnetized plasmas

- In the direction of the fields there is no force, transverse the particles are bend into the circular motion

$$F = q\vec{v} \times \vec{B} \qquad r_c = \frac{mv}{eQB} \quad \longrightarrow \quad \begin{array}{l} f_{ce} = 28 \cdot GHz \cdot B(T) \\ f_{ci} = 15.2 \cdot MHz \cdot \frac{Q}{A} B(T) \\ \text{A....atomic mass number} \\ \text{Q....Charge state} \end{array}$$

- Therefore the transport // to the field is different than $\perp$!
- // to the field the transport dominated by 90˚ collisions

$$\nu_e^{90} > \nu_i^{90} \quad \longrightarrow \quad \frac{D_{\parallel e}}{D_{\parallel i}} \propto \sqrt{\frac{m_i}{m_e}}$$

Electron loss dominantly // to the field

- $\perp$ to the field the transport is dominated by the gyrotron motion.

$$\begin{array}{l} f_c >> \nu_i^{90} \\ r_{ci} >> r_{ce} \end{array} \quad \longrightarrow \quad \frac{D_{\perp e}}{D_{\perp i}} \propto \sqrt{\frac{m_e}{m_i}}$$

Loss is dominated by hoping from one field line to the next
Ion loss dominantly $\perp$ to the field

Ion Confinement Times Increases With Decreasing Ion Temperature !

Mathematical description depends on the collision regime

- For collisionless plasma (Pasthukov regime)

$$\tau_P = \frac{\sqrt{\pi}}{2}\ln\left(2R+2\right)\frac{qe\,\Delta\,\phi}{kT_i}\frac{R+1}{R}\frac{\exp\left(\frac{qe\Delta\phi}{kT_i}\right)}{1+\frac{qe\Delta\phi}{2kT_i}}\tau_{ii}$$

- For collisional plasma

$$\tau_f \simeq Rl\sqrt{\frac{A_i m_p}{kT_i}}\exp\left(\frac{qe\,\Delta\phi}{kT_i}\right)$$

- For highly collisional plasmas

$$\tau_D \simeq \frac{r^2}{v_{T_i}^2\,\tau_{ii}}$$

$R = \frac{Bmax}{Bmin}$

l...... plasma mirror length

T_i.... Ion temperature

v_i.....Ion velocity

τ_{ii}....90° time between ion-ion collisions

r ..... plasma chamber radius

$\Delta\phi$ ..... negative potential well

→ Ion Cooling !

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$$n_e \propto \omega_p^2$$

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- The ratio of n_0/n_e must be low enough to keep the charge exchange recombination rate sufficiently low to achieve the desired CSD – the lower the neutral pressure in the plasma the higher the charge state that can be achieved

$$\tau_{q \to q-1} > \tau_{q-1 \to q}$$

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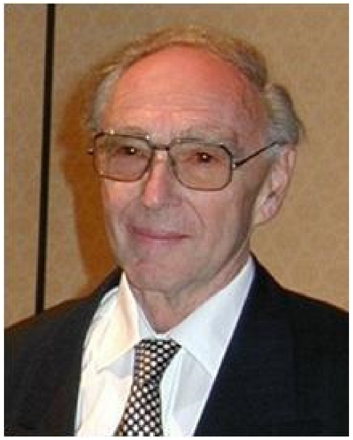
- The plasma confinement is related to the ratio B_{min} to B_{max} and $B_{average}=\frac{1}{2}(B_{min}+B_{max})$
- **Shallow magnetic field gradients** are more efficient for ECR plasma heating – long plasma chambers are beneficial!
- Hot electrons are essential for electrostatic plasma confinement
- Plasma ion confinement is proportional to the **plasma mirror length**, the mirror ration, and to the **square of the radius – larger plasma chamber**
- But power density available is related to the volume – plasma density is proportional with the power density! Compromise!

Trends for ECR Ion Sources
Higher magnetic fields and higher frequencies



R. Geller

Empirical Scaling Laws

$n_e \propto \omega_{rf}^2$

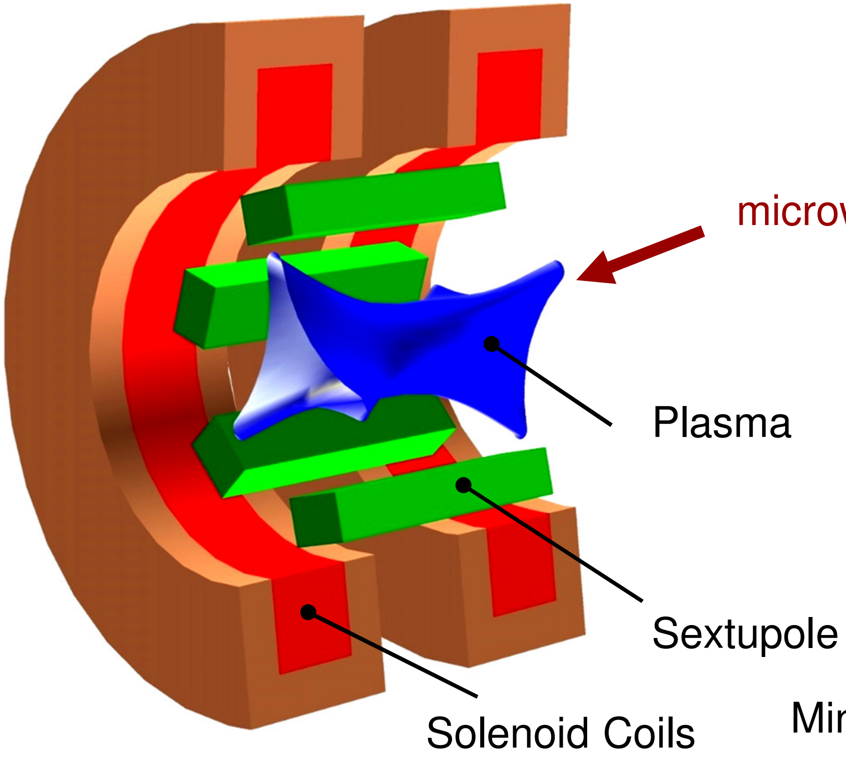
$\tau_{ion} \propto B_{max}/B_{min}$

$q_{opt} \propto \log(B_{avg})$

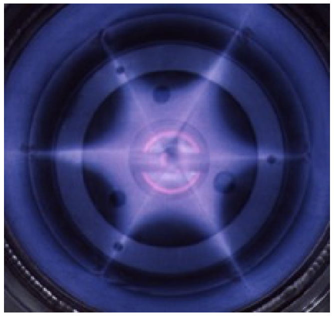
$I \propto \omega_{rf}^2 M^{-1}$

$I \propto P_{rf}^{1/3}$

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

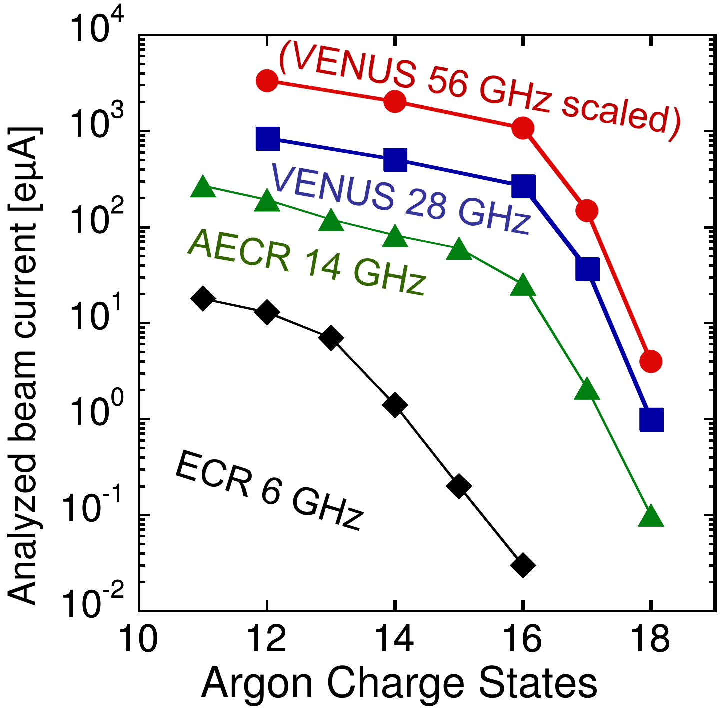


microwave, gas



Minimum-B field

Higher magnetic fields and higher frequencies are the key to higher performance

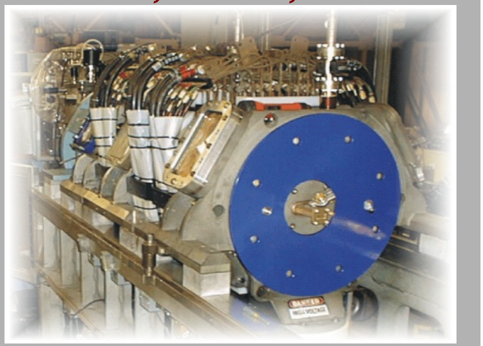


Normal conducting

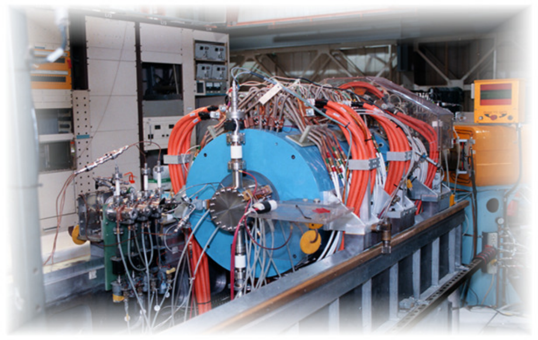
⇓

Super conducting

ECR (1983)
0.4 T, 0.6 kW, 6.4 GHz

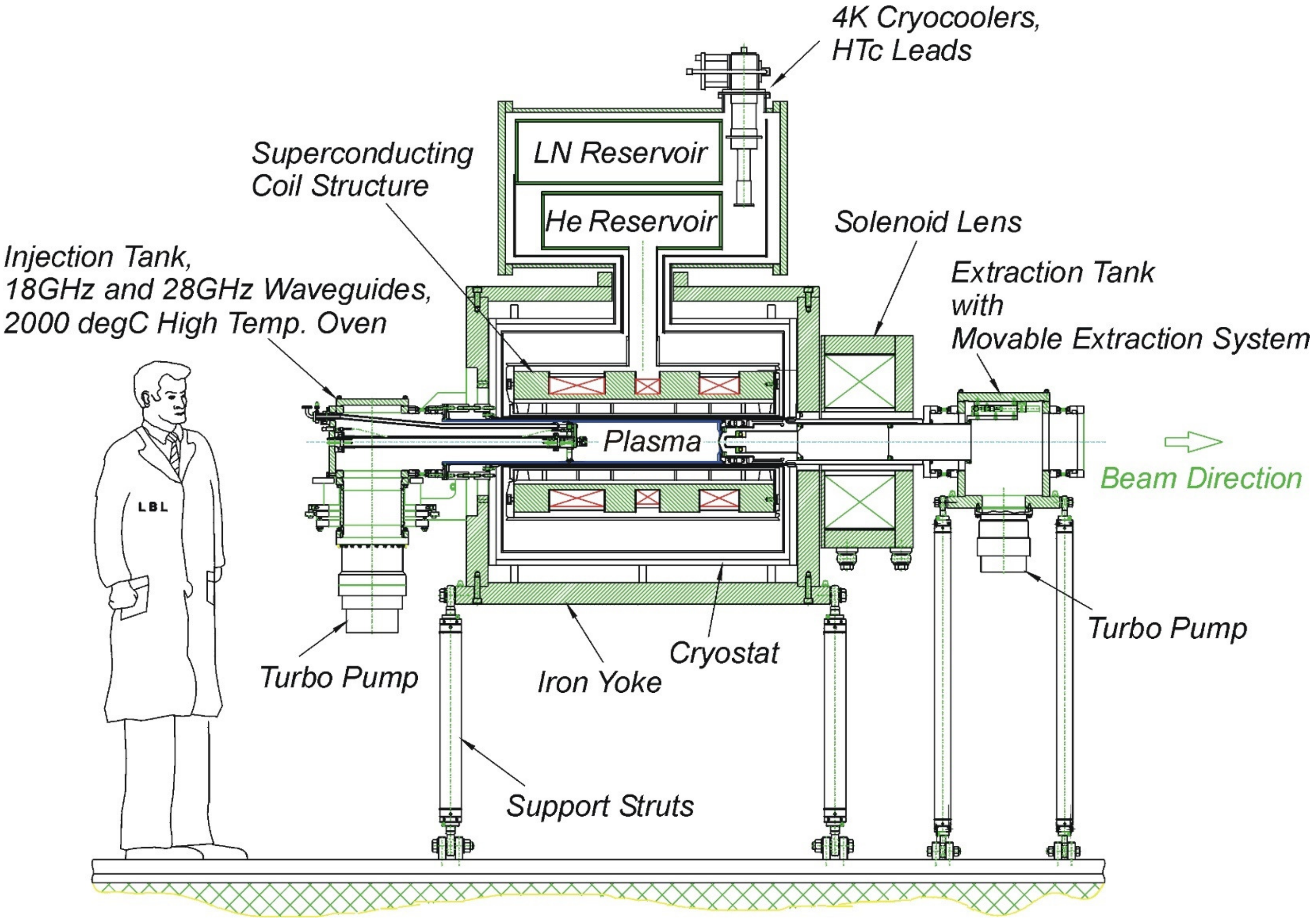


AECR-U (1996)
1.7 T, 2.6 kW, 10 + 14 GHz



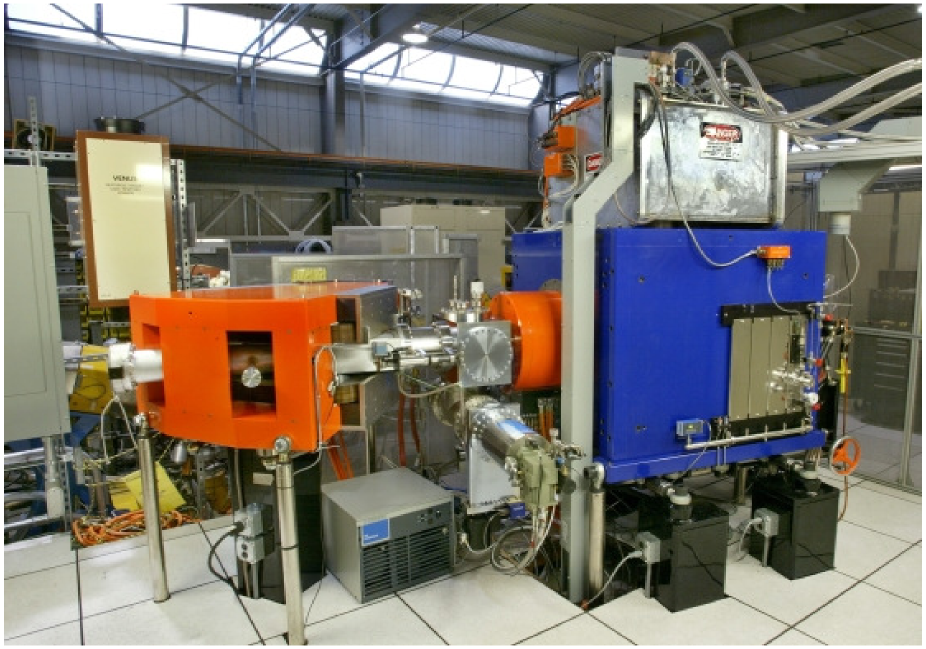
VENUS (2001)
4.0 T, 14 kW, 18 + 28 GHz

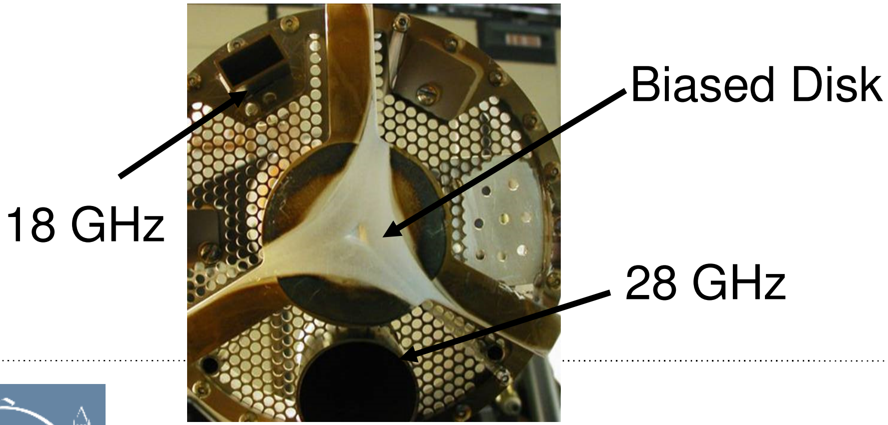
VENUS ECR Ion Source

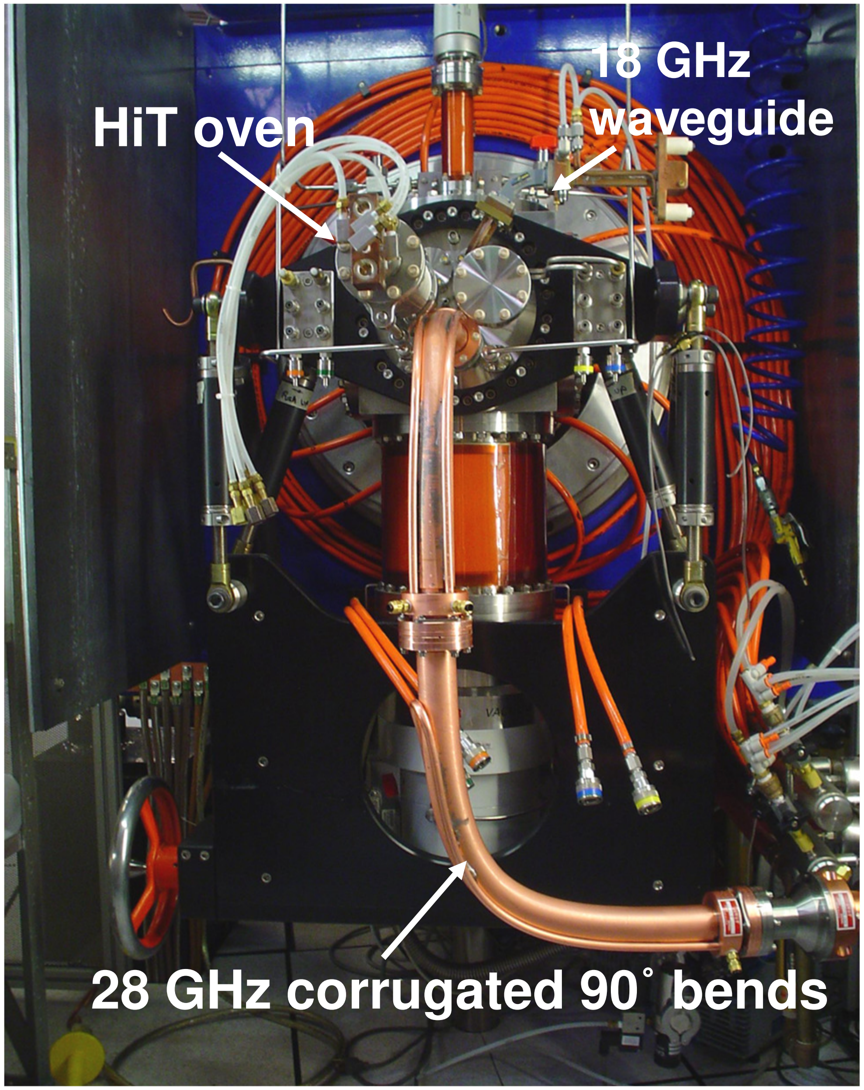


VENUS: **V**ersatile **E**CR for **NU**clear **S**cience

Pictures from VENUS



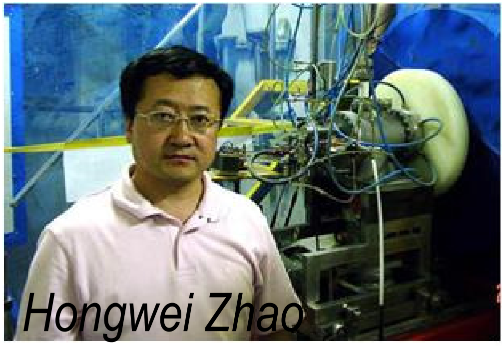




SECRAL, the Lanzhou ECRIS

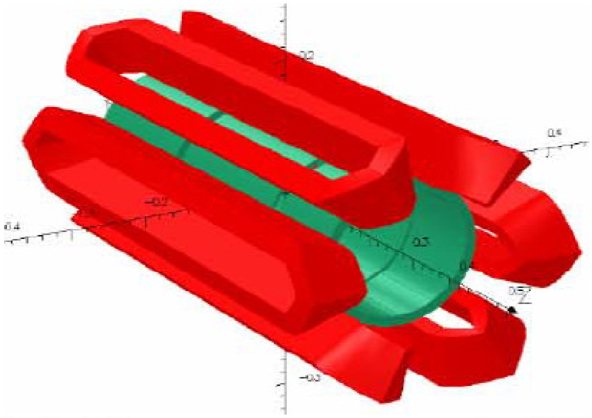
Lanzhou: SECRAL
high field solenoids inside the hexapole.

Klystron	3 kW 18 GHz
Gyratron	7 kW 24 GHz


Hongwei Zhao


L.T. Sun

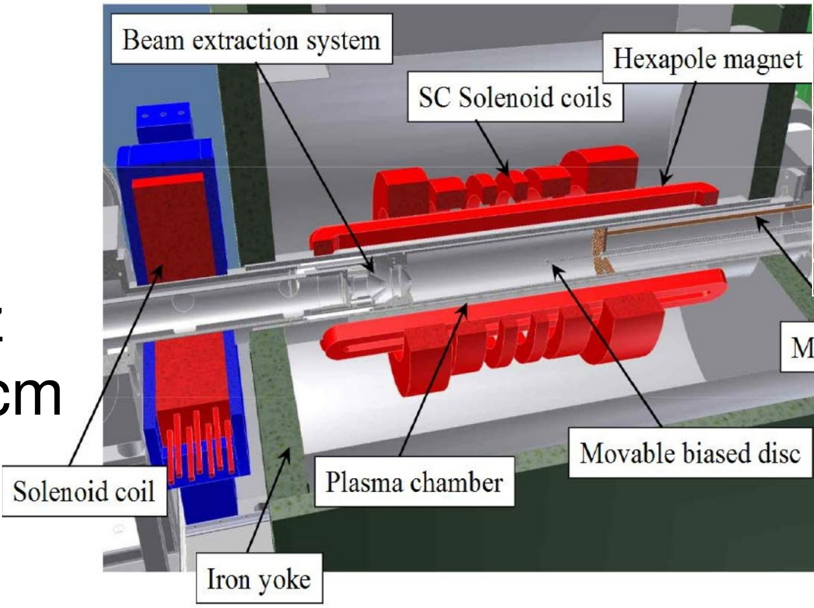
& D. Xie



The RIKEN SC-ECRIS

6-solenoid superconducting

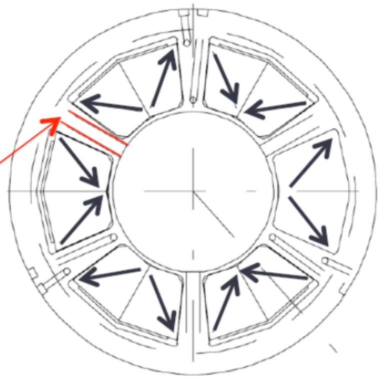
Klystron:	2kW 18GHz
Gyratron:	10 kW 28 GHz
Plasma volume:	15 x ~52 cm




T. Nakagawa

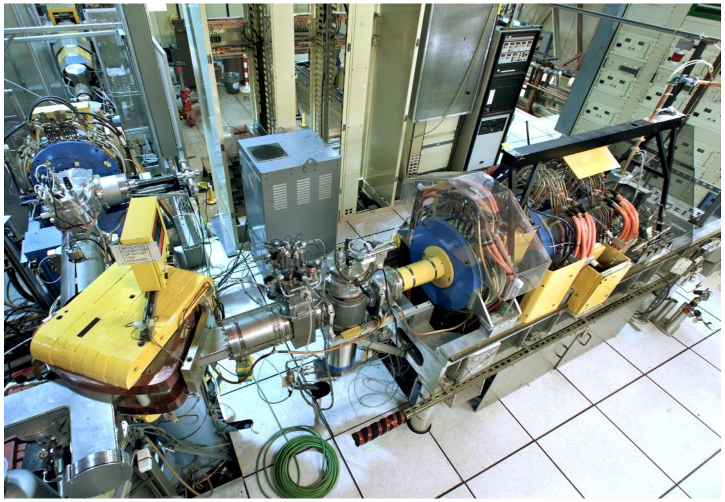
AECR-U (LBNL, 1990), 14 GHz second

- Introduction of double frequency heating (+10-20% beam),
- 14 GHZ / 2 kW and 1kW 10GHz
- TWT: 1kW 10-13.5GHz
- Volume (Ø =76 mm, L=30 cm) V~1.36 liter
- Permanent magnet hexapole with radial slots access between poles for pumping
- Aluminum plasma chamber (higher charge state)



Radial slots to reduce n_0 in the chamber

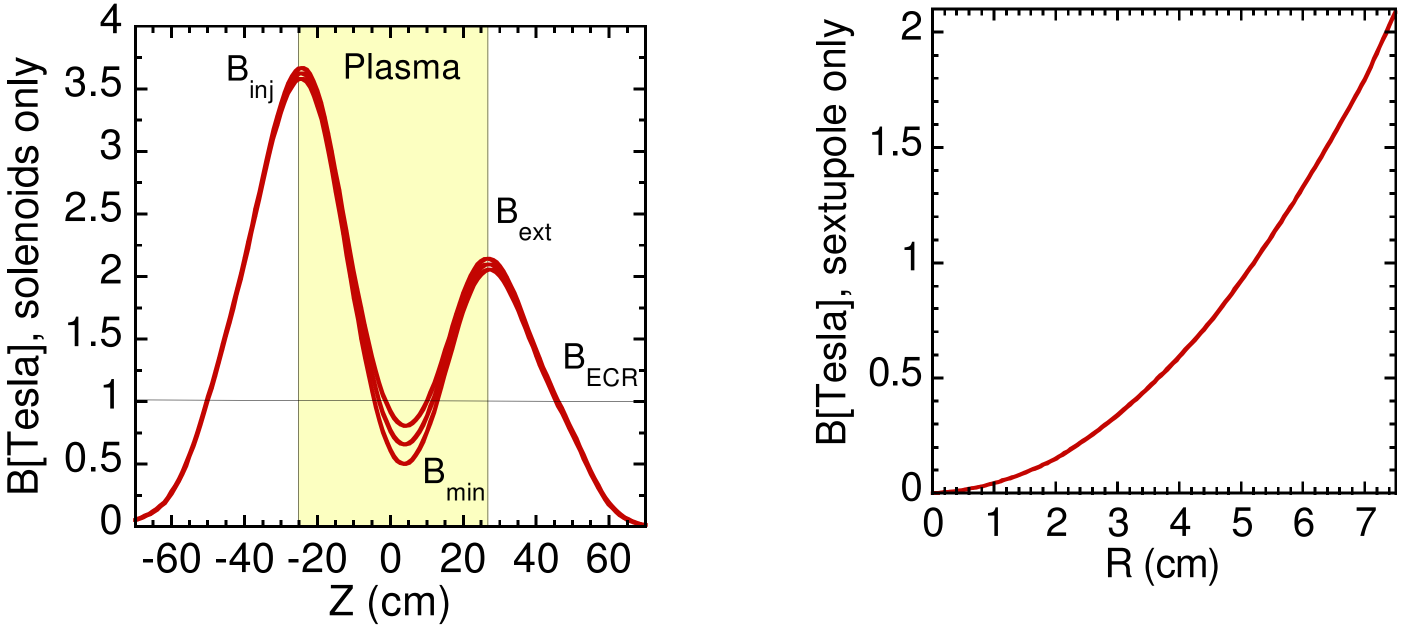
hexapole



Next step in ECRIS?

Superconducting Magnets: ECR Design ‘Standard Model’

28 GHz VENUS Tune



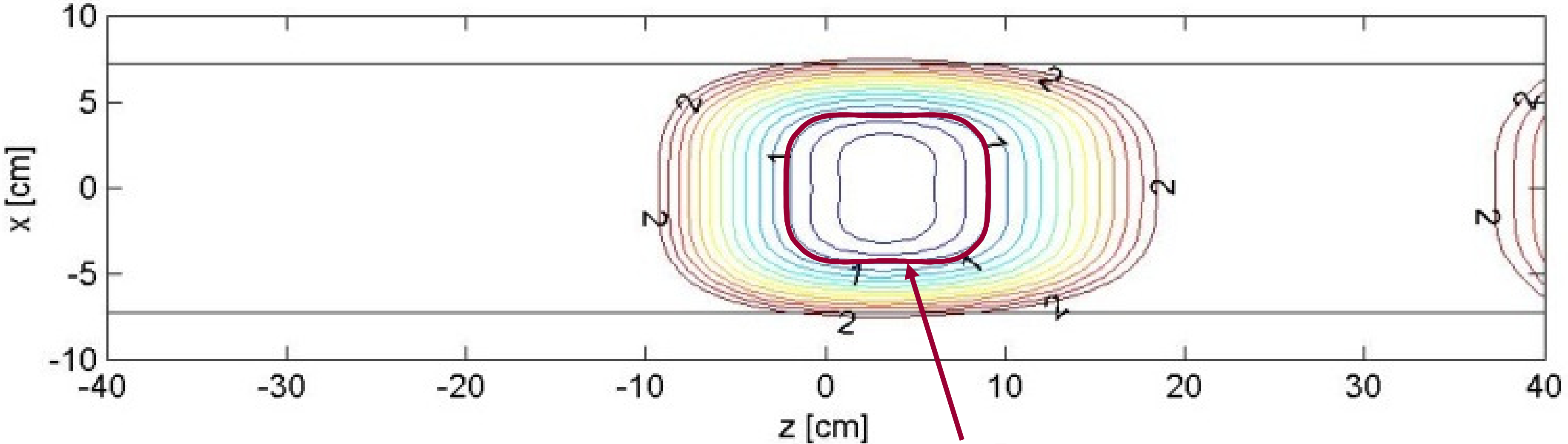
$B_{inj} \sim 4 \cdot B_{ecr}$

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

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

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

Superconducting Magnets: ECR Design ‘Standard Model’



B_{ECR}

28 GHz B_{ECR}= 1 Tesla

56 GHz B_{ECR}= 2 Tesla

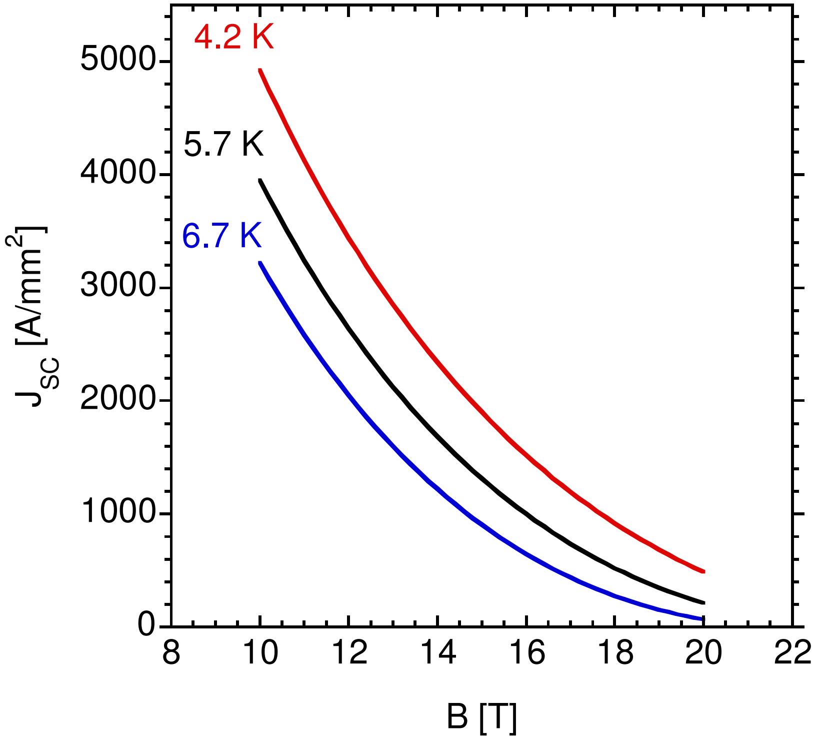
	28 GHz	56 GHz
$B_{inj} \sim 4 \cdot B_{ecr}$	**4T**	**8T**
$B_{min} \sim 0.8\ B_{ecr}$	**.5-.8 T**	**1-1.6 T**
$B_{ext} \sim B_{rad}$	**2T**	**4T**
$B_{rad} \geq 2\ B_{ecr}$	**2T**	**4T**

Magnetic Design		28 GHz	56 GHz
Max solenoid field	on the coil	6 T	12 T
	on axis	4 T	8 T
Max sextupole field	on the coil	7 T	15 T
	on plasma wall	2.1 T	4.2 T
Superconductor		NbTi	Nb_3Sn

Superconducting Magnet Structure: Magnetic Analyses

Critical line and magnet load lines

Current Density through the superconductor



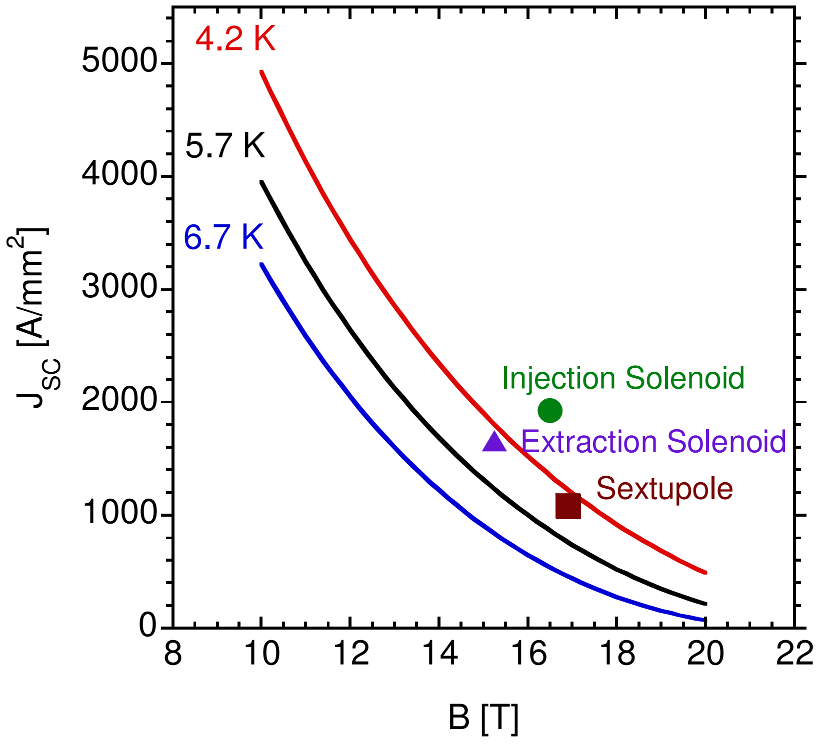
Magnetic Field on the conductor

Superconducting Magnet Structure: Magnetic Analyses

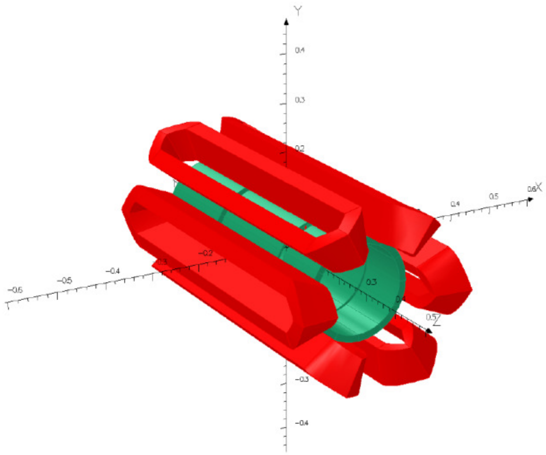
Goal: Achieve 4.2T on the plasma chamber wall radially
and 8 T and 4 T on axis

Solenoid-in-Sextupole

Current Density through the superconductor



Magnetic Field on the conductor



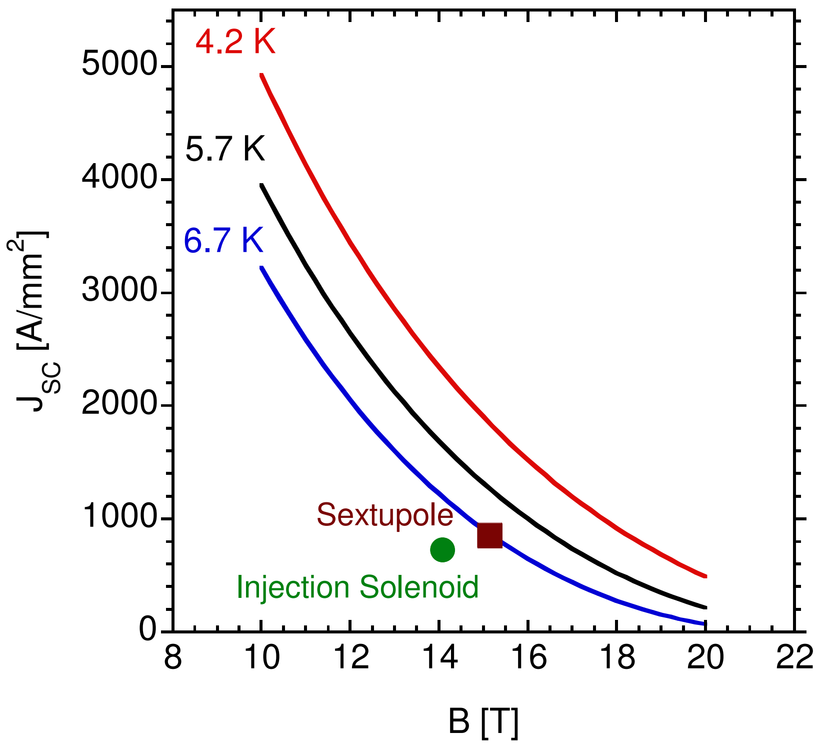
- Magnetic field and current density requirements exceed the capability of $NbSn_3$

This geometry can be ruled out as candidate for a 56 GHz ECR ion source

Superconducting Magnet Structure: Magnetic Analyses

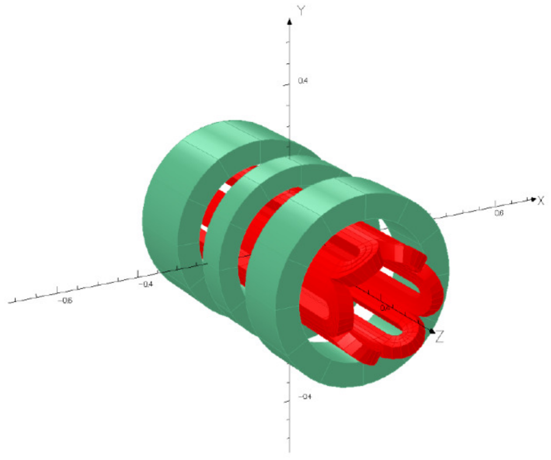
Goal: Achieve 4.2T on the plasma chamber wall radially
<u>and</u> 8 T and 4 T on axis

Sextupole-in-Solenoid



Current Density through the superconductor

Magnetic Field on the conductor



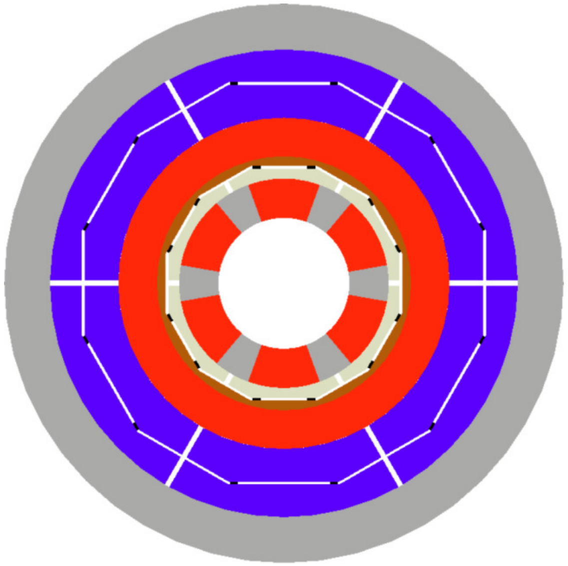
- 2.5 Kelvin temperature margin for the Sextupole
- Operates at 86% of current limits

This geometry is challenging but feasible with current $\mathrm{NbSn_3}$ technology

BERKELEY LAB

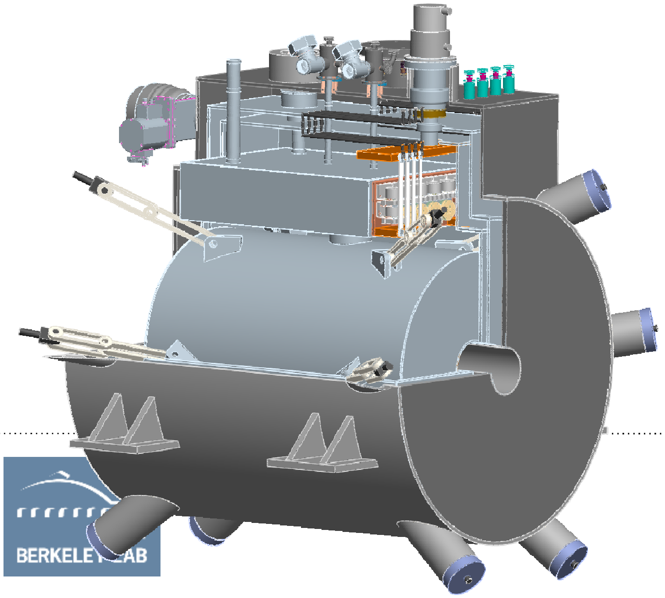
Massachusetts Institute of Technology

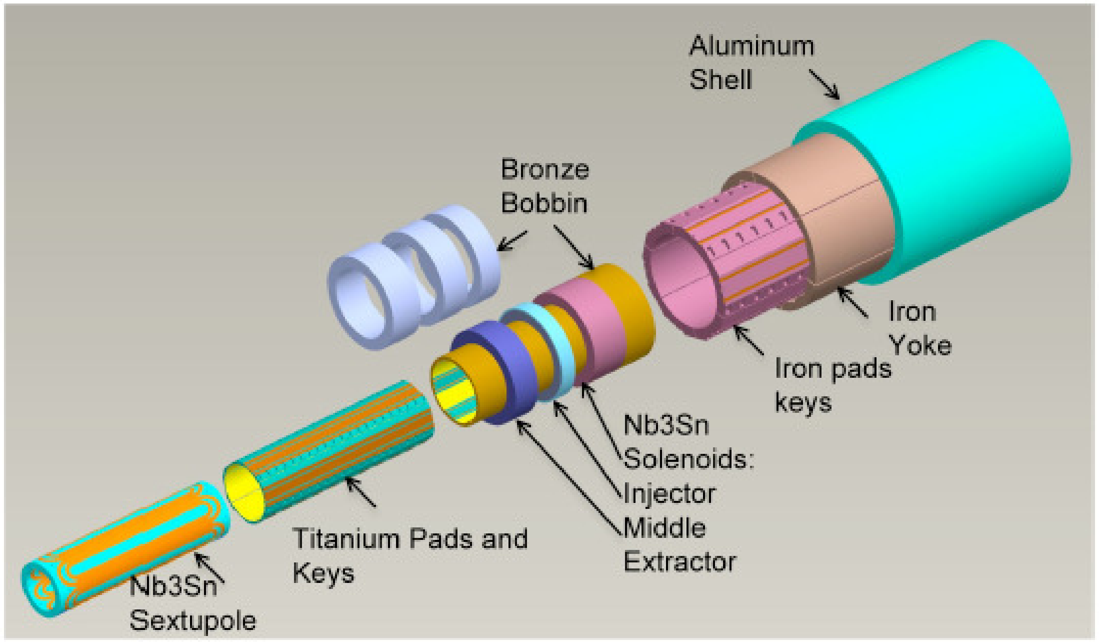
Sextupole-in-Solenoid: Clamping Structure



56 GHz concept (LBNL)

- A shell-based structure using bladders and keys provides a mechanism for controlled room temperature pre-stress.
- Pre-stress is then amplified by the contraction of an aluminum shell during cool-down.
- The method was developed at Superconducting magnet group at LBNL and successfully applied to high field magnets.



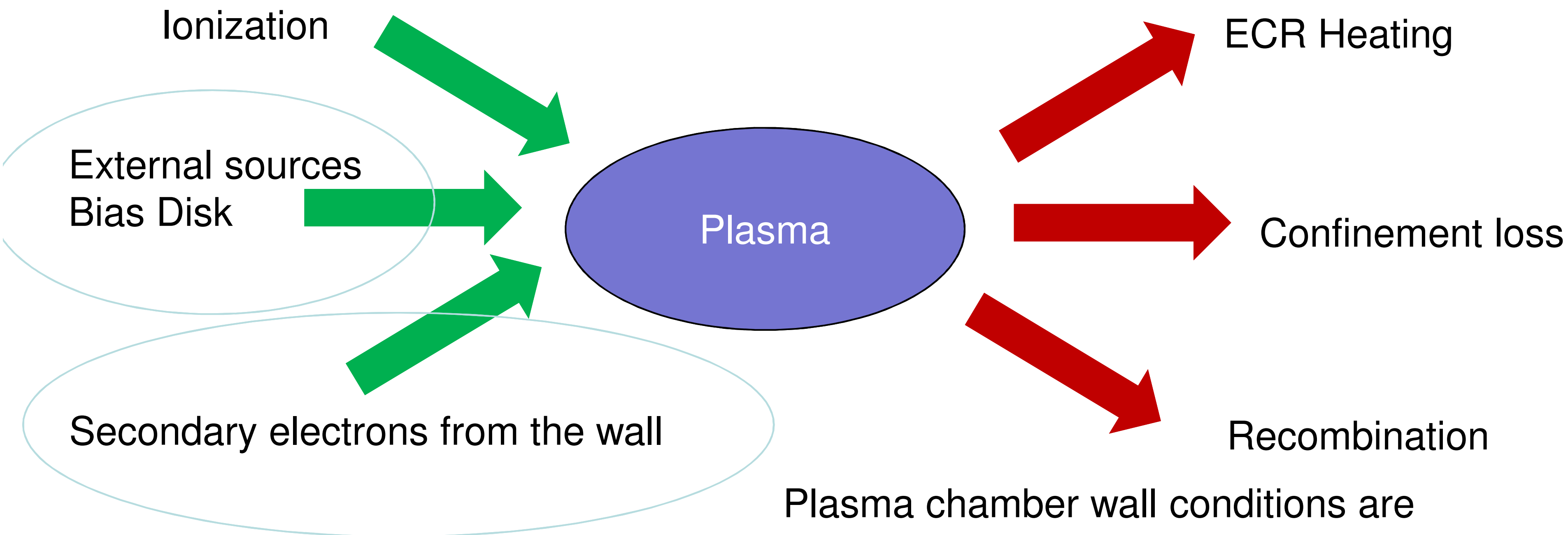


Tuning and Operations
ECR- “tricks”

Adding Electron Sources to the plasma

Plasma is starving of low energy electrons!
If we replace them the ion confinement time will increase

Low energy electron sources and losses



Ionization

External sources
Bias Disk

Secondary electrons from the wall

Plasma

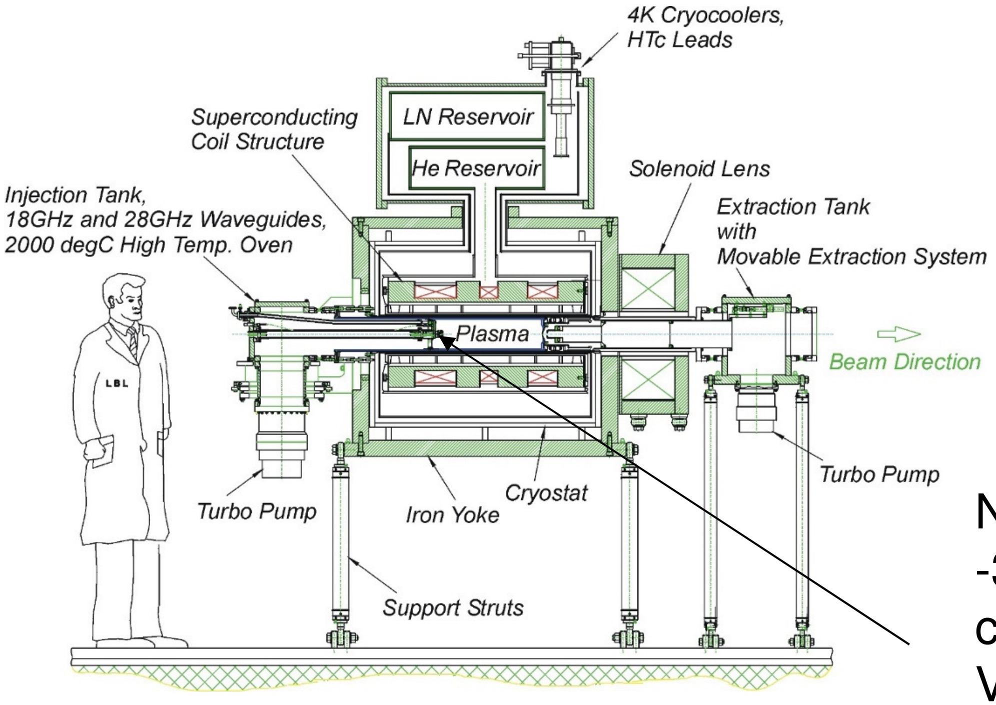
ECR Heating

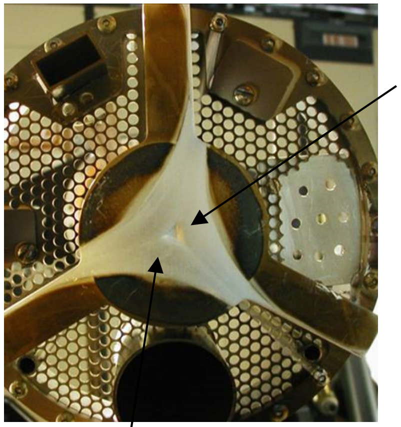
Confinement loss

Recombination

Plasma chamber wall conditions are extremely important for ECR performance (performance enhancements or decrease (mostly) are possible)

Bias Disk





Sputter mark from ion impact

Negatively Biased Plate (-10V to -300V) in respect to the plasma chamber voltage

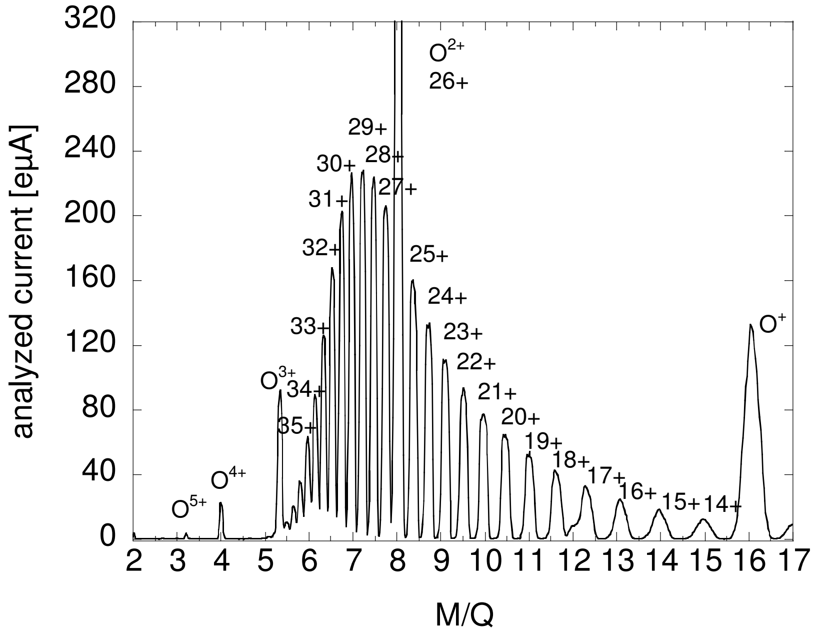
Very sensitive parameter for high charge state ions!

It supplies low energy electrons to the plasma!

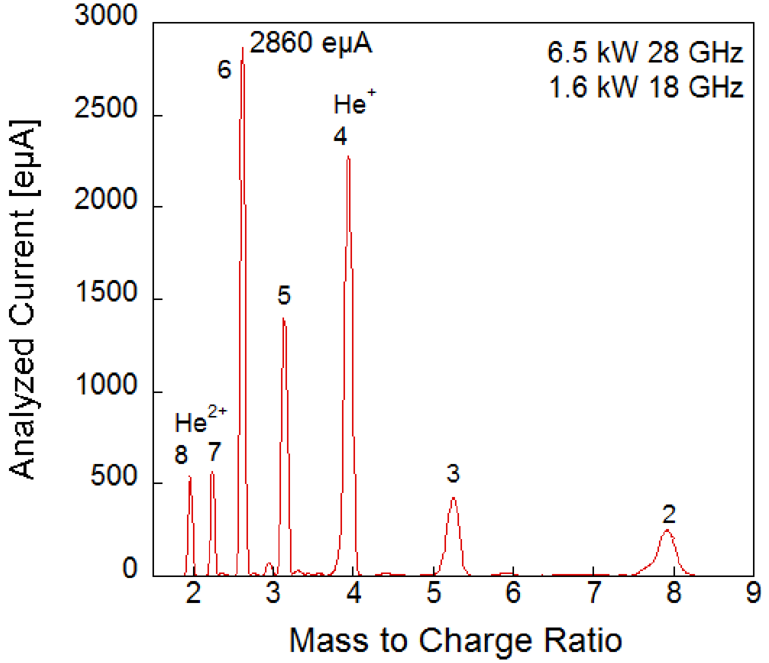
The biased disk has largely replaces other external electron sources such as cathodes or plasma injector

Gas Mixing (experimental observations)

- Discovered and explored extensively in KVI (Drentje)
- The mixing gas should always be lighter than the desired ion



Bismuth spectrum using oxygen as buffer gas, the oxygen CSD is suppressed



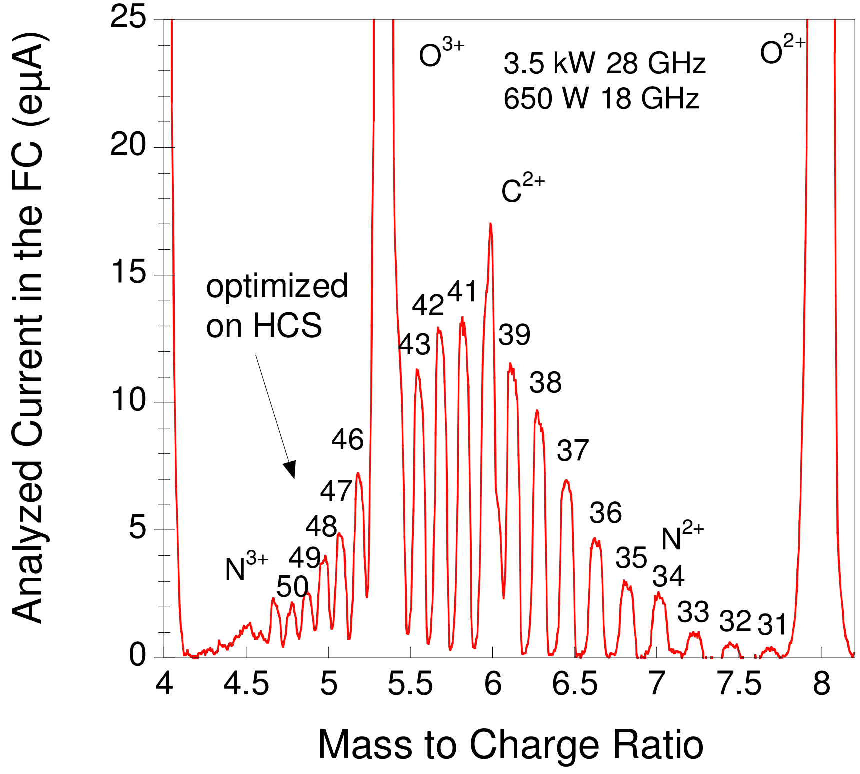
Oxygen spectrum using helium as buffer gas, the oxygen CSD peaks on high charge states

Gas Mixing (experimental observations)

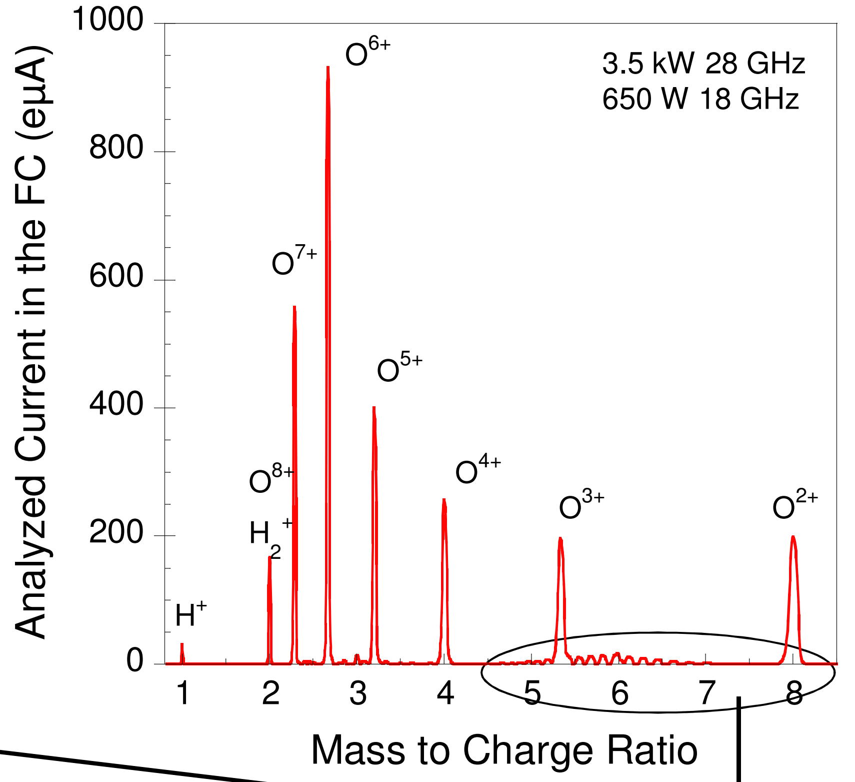
- Discovered and explored extensively in KVI (Drentje)
- The mixing gas should always be lighter than the desired ion
- Add He or O_2 gas helps improving high charge state production in an ECR Ion Source
  - Usually He is used for mixing with atomic masses $A<16$ (O)
  - Usually O_2 is used to mixing with heavy masses $A>16$
  - ^{18}O is more effective than ^{16}O (mixing gas anomaly)
- The extra O_2 or He injected is used as the main buffer gas that sustains the plasma
- The other compound to be highly ionized is injected in low quantity with respect to the buffer gas
- The charge state distribution of the atom of interest shifts to very high charge state

High Charge State Uranium Production using Gasmixing!

Uranium High Charge States



Oxygen Mixing Gas Spectrum



Spectrum Detail

Oven temperature at 1700° C,
4.2 kW microwave power

Gasmixing Effect – 'ECR tricks'

When a light gas is mixed into a heavy ion plasma the charge state distribution shifts to higher charge states

Qualitative Explanation:

- Light ion get heated by the multiple collisions with heavy ions and are more likely to loose confinement (carry ion thermal energy away from the plasma and effectively cool the heavy ions (therefore ^{18}O better than ^{16}O)

$$\tau_i \propto \sqrt{\frac{m_i}{T_i}}$$

- Confinement time for the heavy ions increases with decreasing temperature
- The overall charge in the plasma is lower – so if an ion get lost not as any electrons have to follow, electron confinement increases as $q_{average}$ decreases !

$$q_{av} \downarrow \qquad \tau_e \uparrow$$

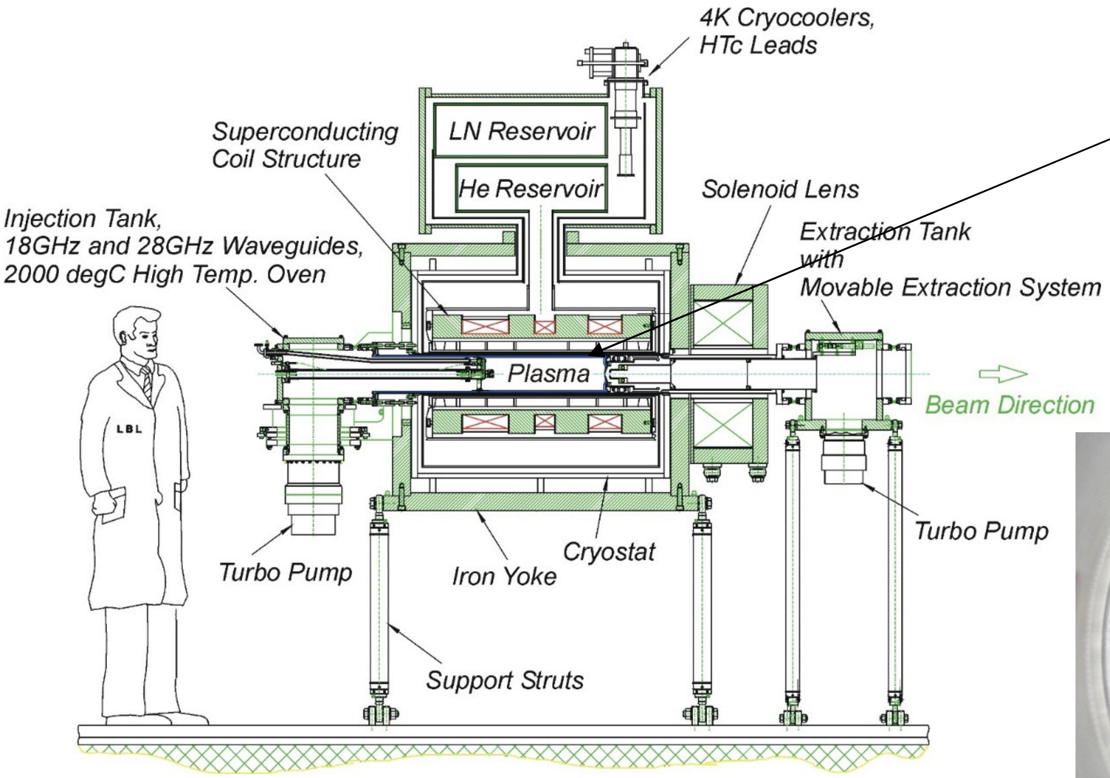
- As the plasma confinement time increases the neutral pressure can be lowered

$$n_0 \downarrow$$

Plasma Chamber Wall

- Gas mixing is very effectively used in most ECR ion sources
- But some gases work better than others
- Oxygen is particular effective (but Fluor is terrible!)
  - The plasma chamber wall role plays an important role as source for secondary electrons!
  - Aluminum Chamber with oxygen plasma → Al_2O_3
  - Other materials: SiO_2
- Fluor, Selenium, Sulfur, Carbon ‘poisons’ the chamber wall – secondary electron production is suppressed and the confinement time is reduced
- When the source is operated with various metals, the plasma chamber needs to be reprocessed with oxygen or cleaned to regain performance

Most modern ECR use aluminum plasma chambers or liners



Aluminum Plasma Chamber

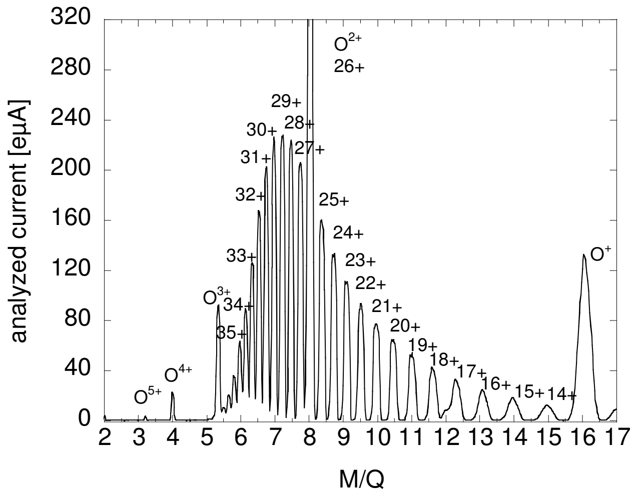
Al_2O_3 has a high secondary electron coefficient

ECR “tricks” summary

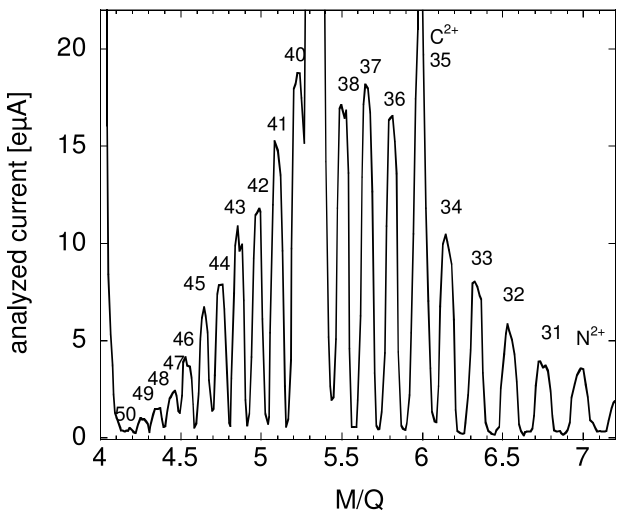
- Bias disk – injection of cold electrons
- Gas mixing
  - Ion cooling (increased ion confinement)
  - Lowering the average charge in the plasma (increase electron confinement!)
- Plasma chamber wall
  - Use material with high secondary electron coefficient (aluminum in combination with oxygen plasmas

Changing the tune of the plasma – using what we have learned

Low/medium charge states



Very high charge states



Higher neutral pressure in the chamber

Lower Power

Lower confinement fields

Ion source will be less sensitive

Secondary electron flux (bias disk, first stage) not very sensitive

Lower gas flux pressure

Higher Power

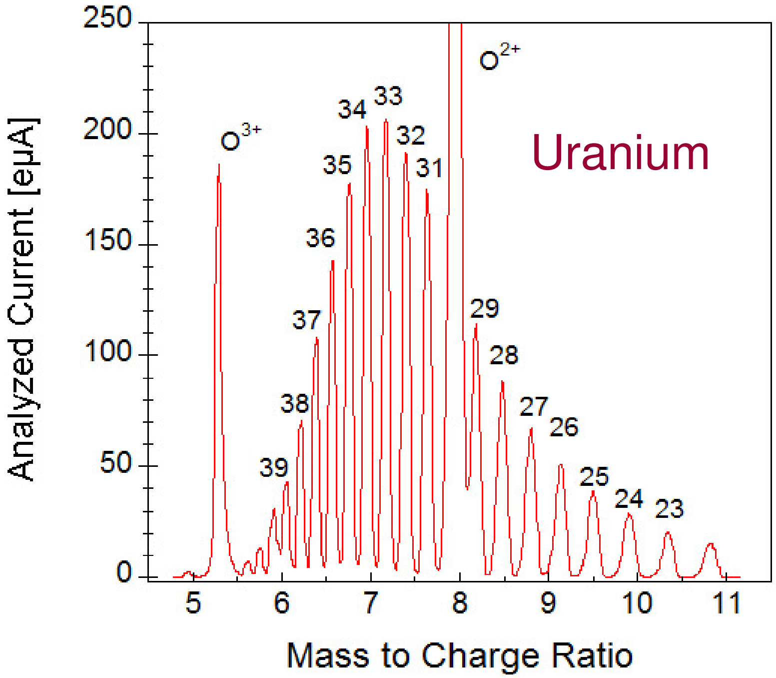
Higher confinement fields

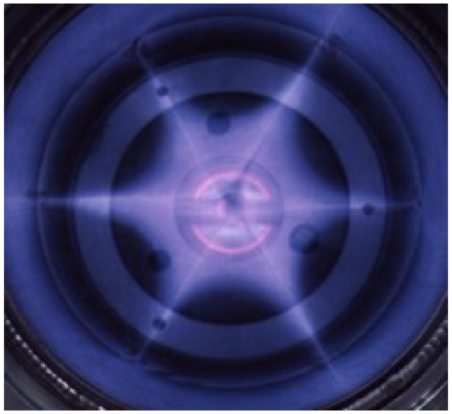
Add lighter component gas for ion ion cooling (= gas mixing)

Secondary electron flux (bias disk) very sensitive

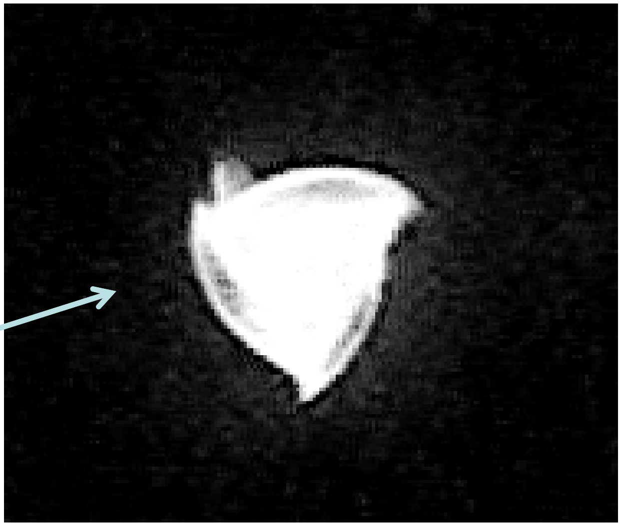
ECR – Extraction Simulations

Beams produced by ECR ion sources are complex



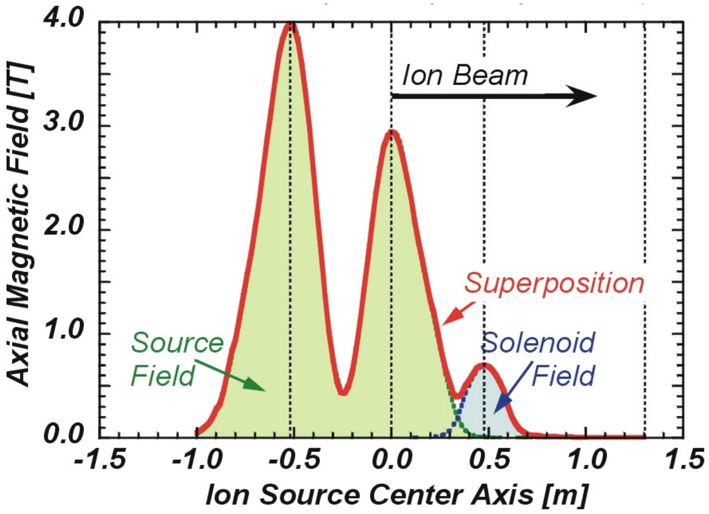


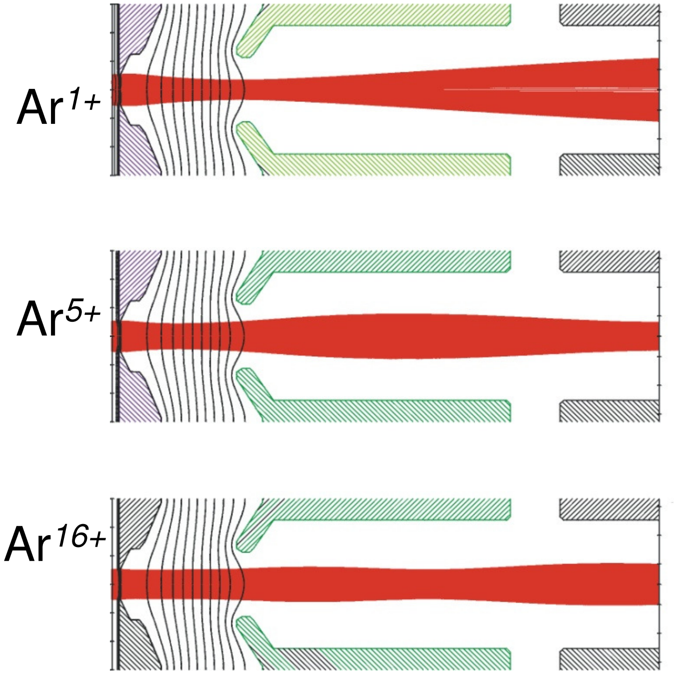
- Extracted from a multispecies and charge state plasma
- The distribution across the extraction aperture is inhomogeneous and not rotational symmetric
- Initial conditions at the emitting surface can vary widely for different beams

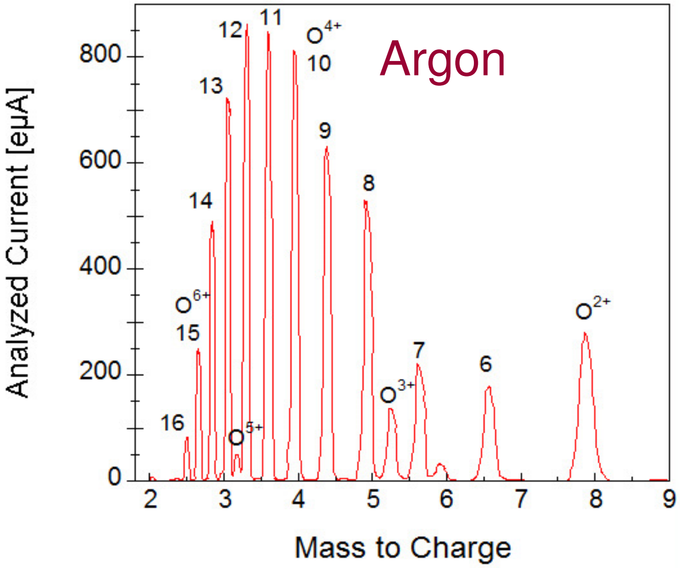


Daniel Winklehner measurement on VENUS He beam

Ions are extracted from the peak of the extraction mirror







Due to their different magnetic rigidity each component in the multispecies beam is differently focused

Magnetic field adds a rotational component to the ion velocity (emittance growth)

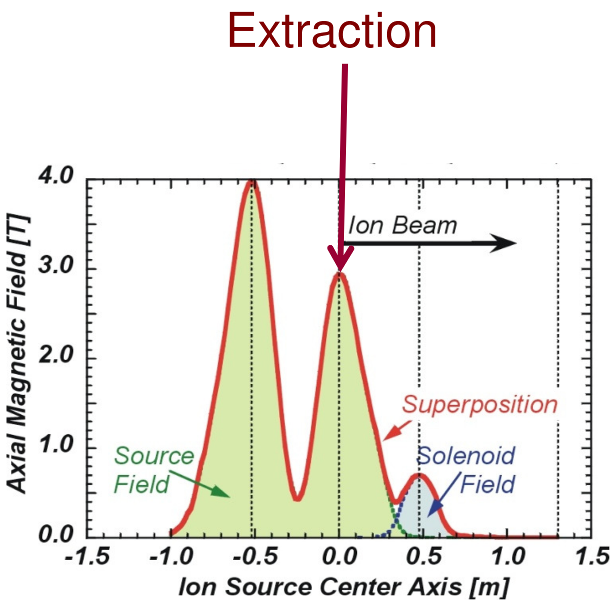
The emittance value is influenced by the ion temperature and the magnetic field at the extraction region

- Energy of the ions in the plasma (a few eV)

$$\varepsilon^{xx'-rms-norm}_{TEMP} = 0.016 \cdot r \cdot \sqrt{\frac{kT_i}{M}}$$

- Magnetic field in which the ions were born

$$\varepsilon^{xx'-rms-norm}_{MAG} = 0.032 \cdot r^2 \cdot B_0 \cdot \frac{1}{M/Q}$$



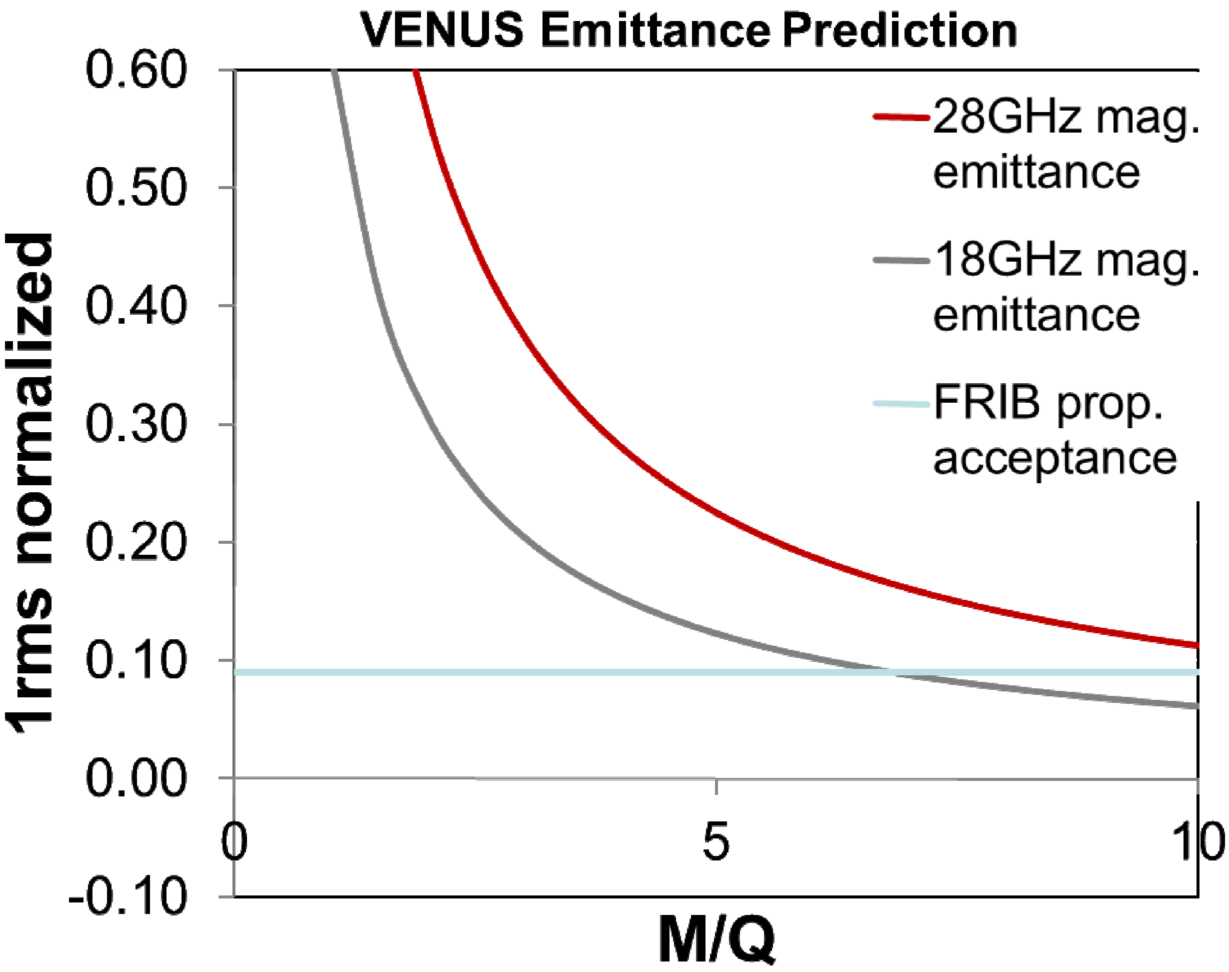
Magnetic Field Dominates Emittance:

M/Q=1	H^+	$B_0 > 0.18$ T
M/Q=5	Ar^{8+}	$B_0 > 0.40$ T
M/Q=7.21	U^{33+}	$B_0 >$ 0.47 T

ε…norm. x-x’ rms emittance [π mm mrad]
r…plasma outlet hole radius [mm]
kT_i…ion temperature [eV]
M/Q…amu/charge [dim.less]
B_0…axial magnetic field [T]
(PAC’01, M. Leitner et.al, http://accelconf.web.cern.ch/accelconf/)

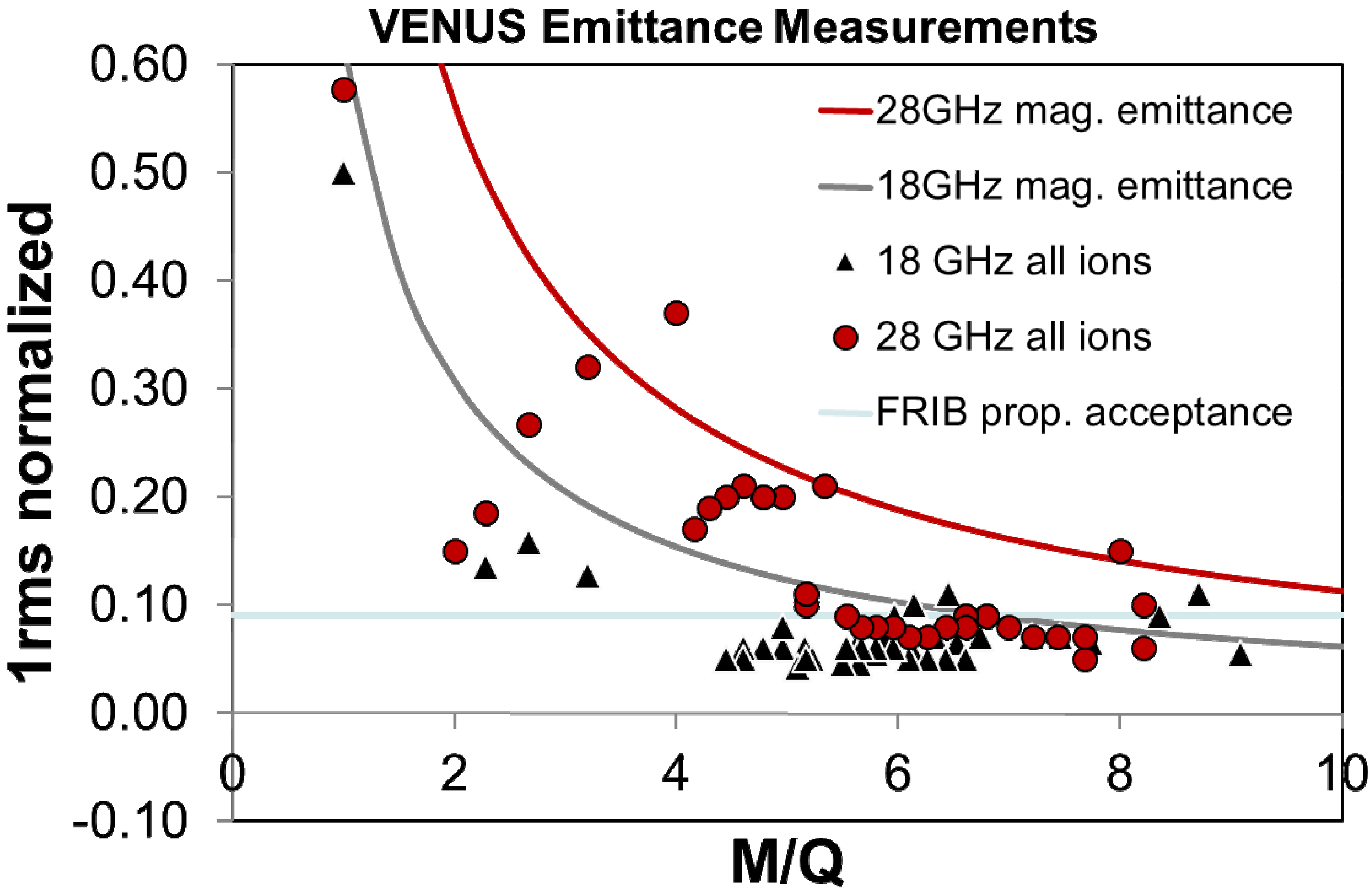
For B fields is the main contributor to the emittance value in ECR ion sources

Predicted emittance using the magnetic field strengths on axis



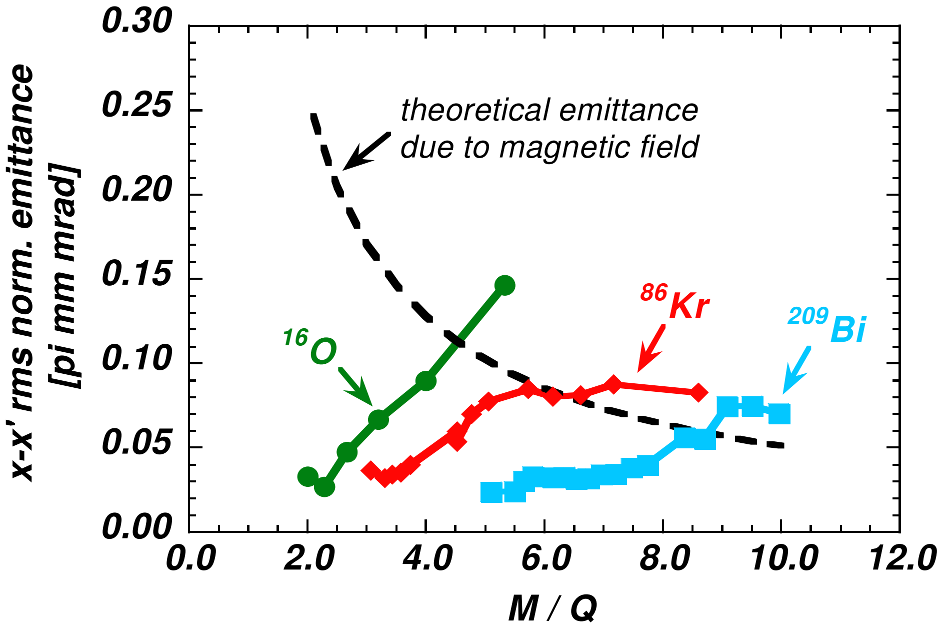
Measured emittance for VENUS

Magnetic emittance is a good upper boundary but does not describe the measured data



Emittance Values for ECR ion sources

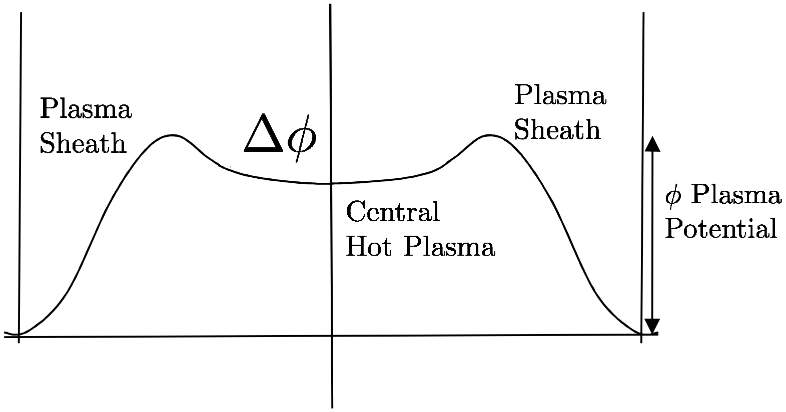
- For the same M/Q the emittance
  values are lower heavier masses
- Emittance decline for higher charge states (in many cases)



The highly charged heavier ions appear to be more concentrated on the ion source axis.

Recap: Role of hot electrons in the plasma

- Model: Highly confined electron beam is created on source axis that creates a negative space charge potential – electrostatically confining highly charged ions.
- **The negative potential has important consequence for the ion confinement and extracted ion beams!!!**

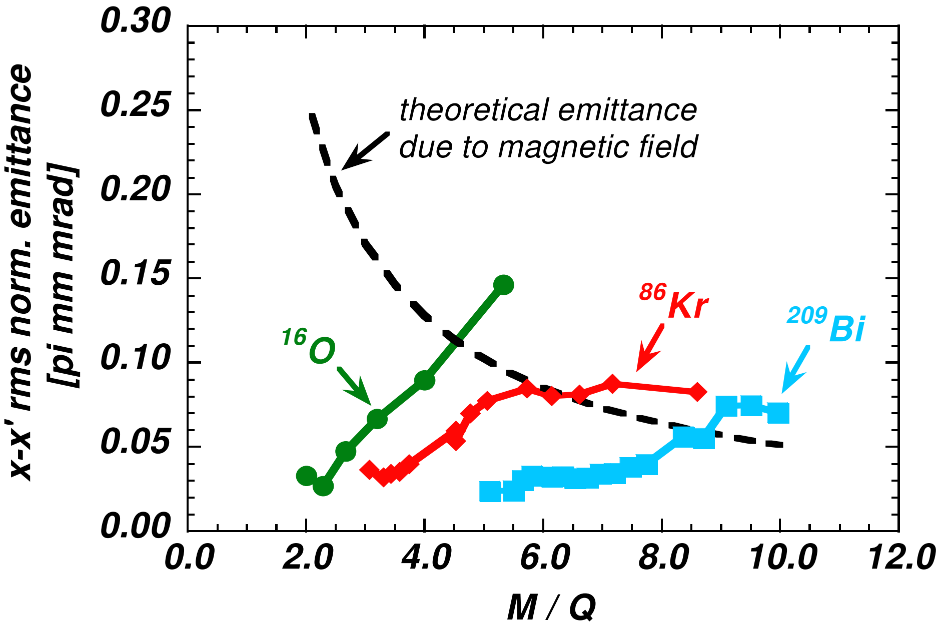


$$\Delta\phi \propto \frac{-T_i}{z \cdot e}$$

Negative potential is proportional to the ion temperature!

Emittance Values for ECR ion sources

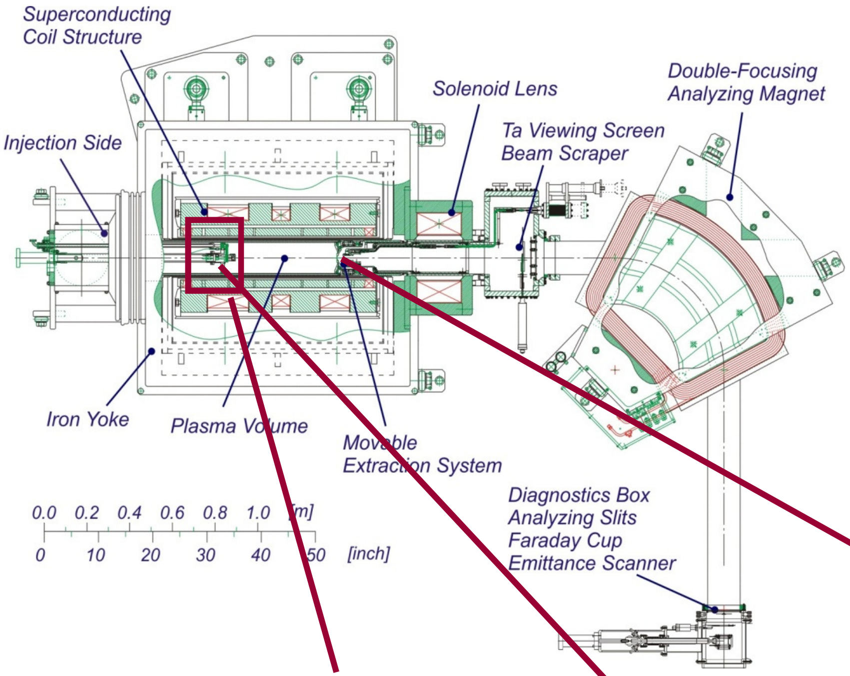
- For the same M/Q the emittance values are lower heavier masses
- Emittance decline for higher charge states (in many cases)



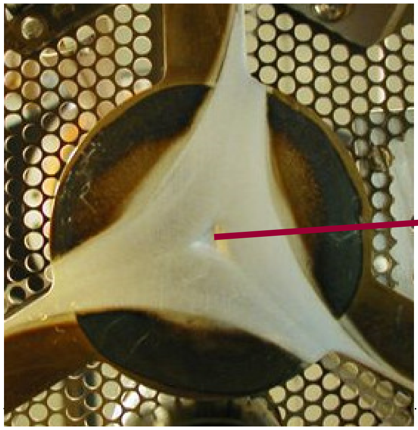
The highly charged heavier ions appear to be more concentrated on the ion source axis.
Use effective radius or more realistic ion distribution at the plasma boundary to simulate the true emittance of the ions!

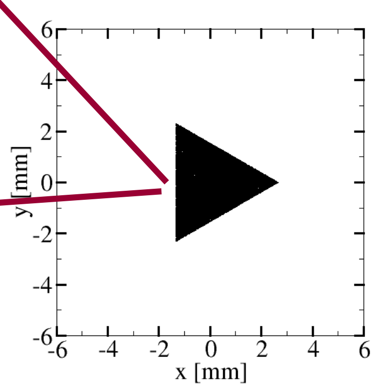
$$\varepsilon_{MAG}^{xx'-rms-norm} = 0.032 \cdot r_{eff}^{2} \cdot B_0 \cdot \frac{1}{M/Q}$$

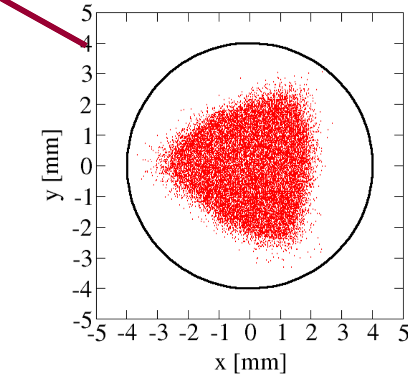
Possible semi empirical model for the initial conditions



- Ion sputter marks opposite to the extraction aperture show clear triangular structure
- Distribution should be the same on the other side
- When traced through the magnetic field of the source triangular pattern doe not fully fill the extraction aperture

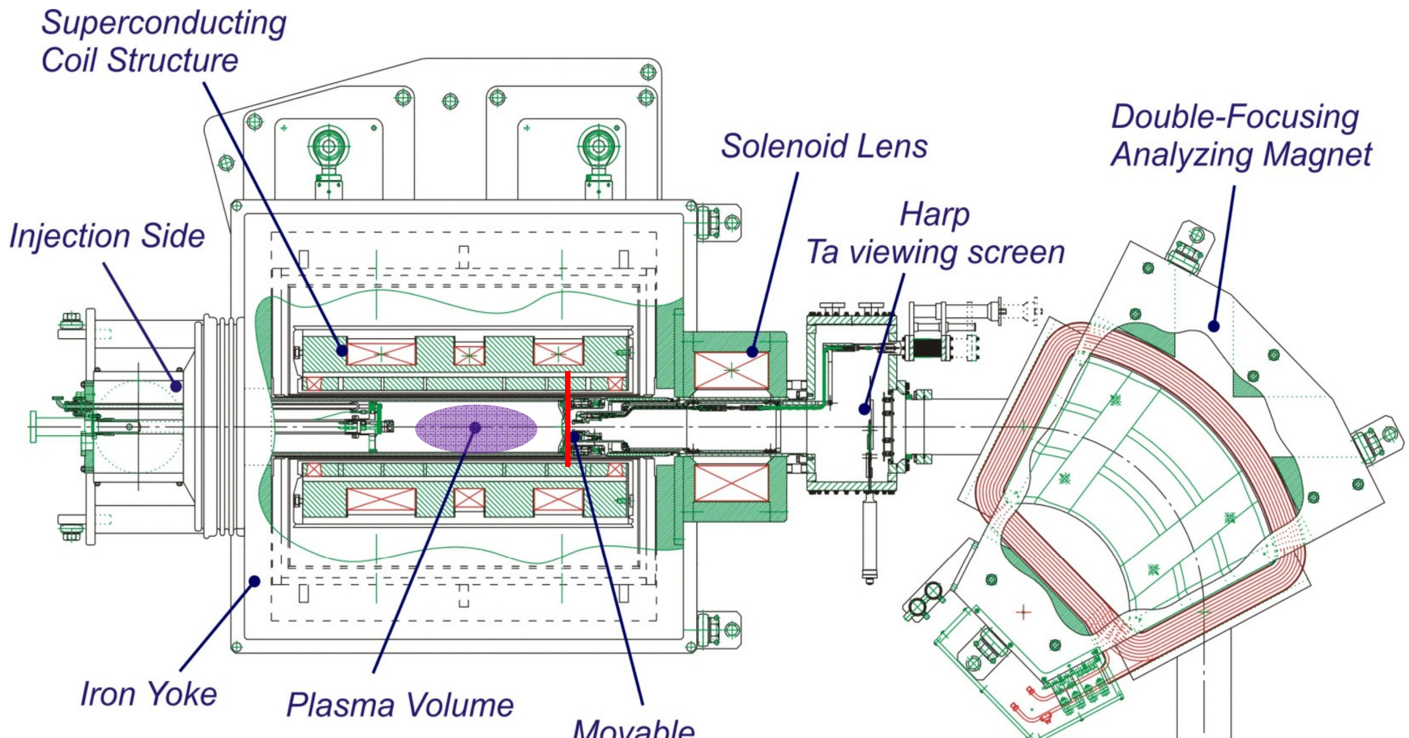


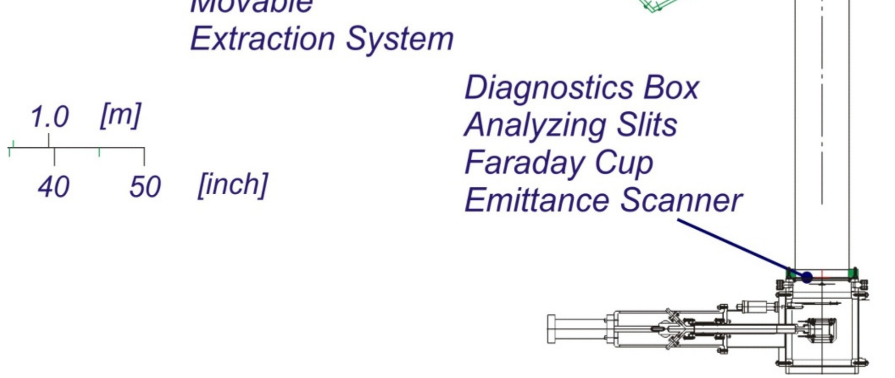


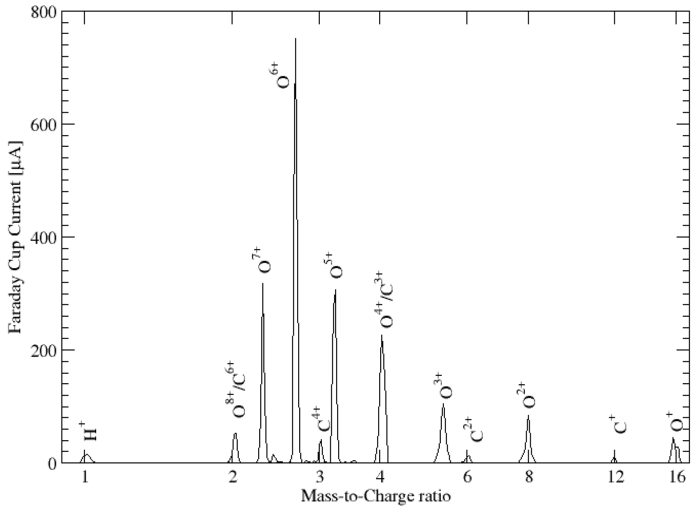


D.S. Todd, D. Leitner, C. Lyneis, and D. P. Grote, RSI. 79, 02A316 (2008).

How does the model compare with experiments?





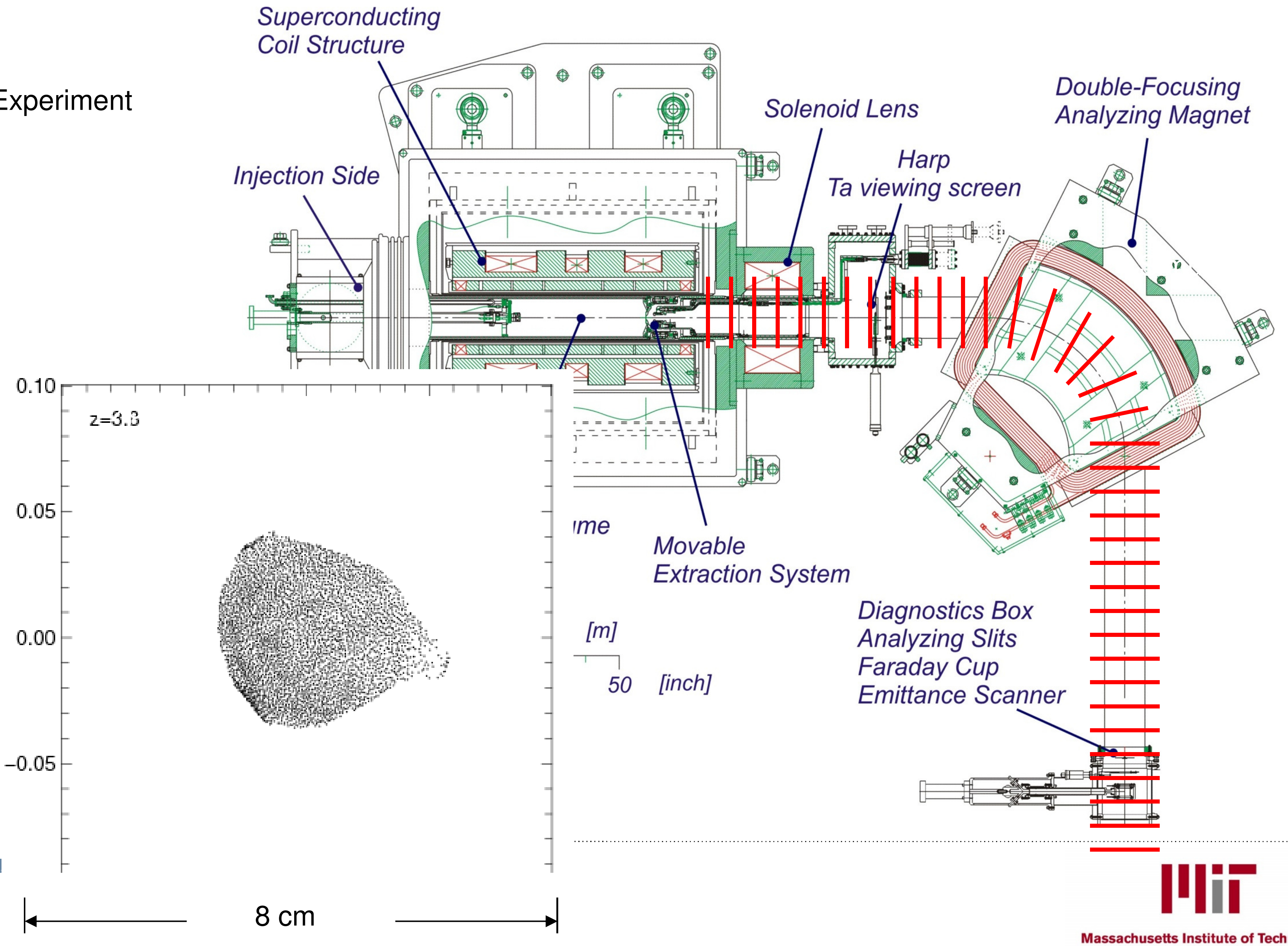


Todd et al., Rev. Sci. Inst. 79 02A316

Massachusetts Institute of Technology

Simulation of Oxygen Beam Extraction and Transport

Experiment


Superconducting Coil Structure

Injection Side

Solenoid Lens

Harp
Ta viewing screen

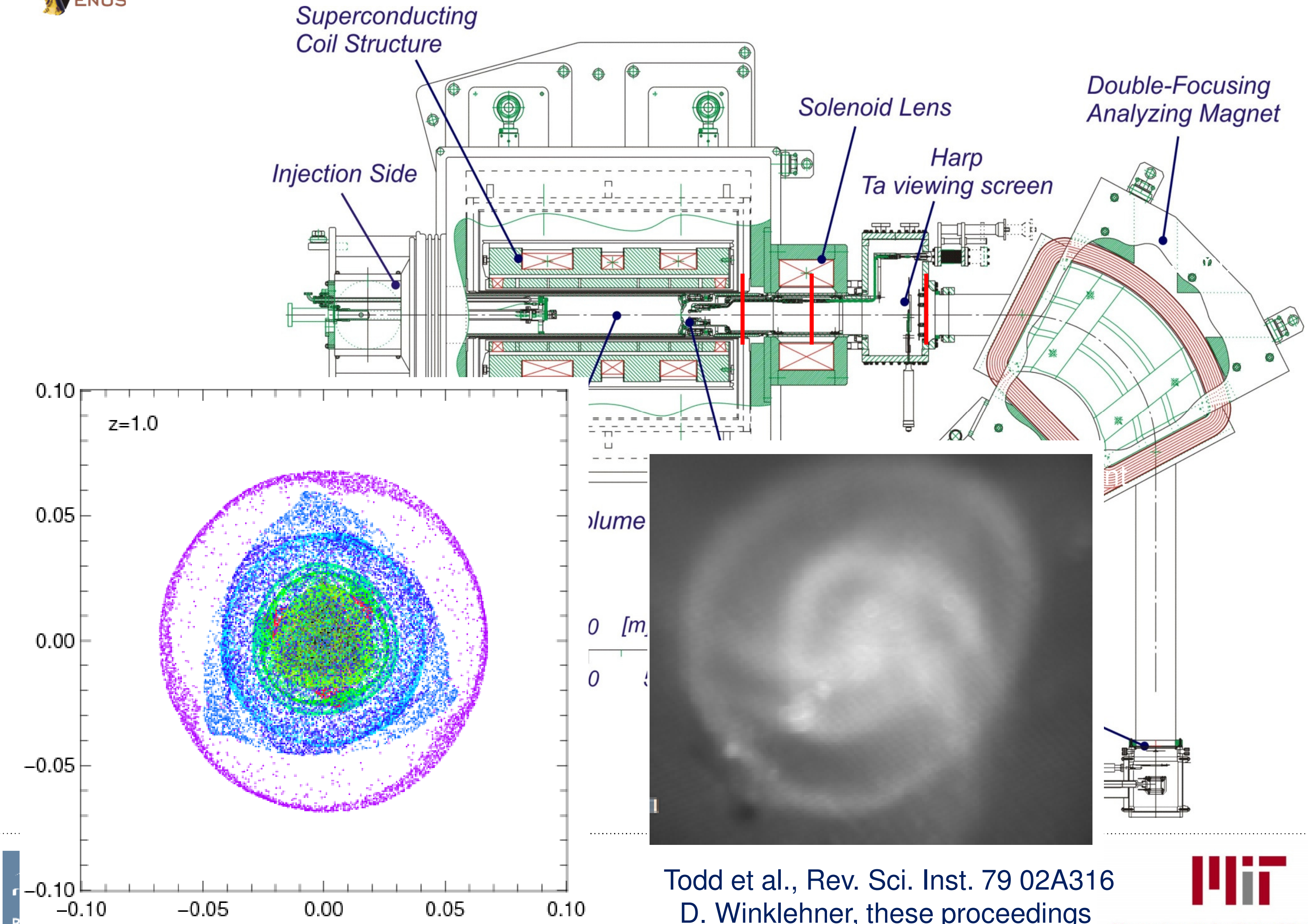
Double-Focusing Analyzing Magnet

Movable Extraction System

Diagnostics Box
Analyzing Slits
Faraday Cup
Emittance Scanner

8 cm

Simulation of Oxygen Beam Extraction and Transport



Todd et al., Rev. Sci. Inst. 79 02A316
D. Winklehner, these proceedings

Simulation of Oxygen Beam Extraction and Transport