CERN ACCELERATOR SCHOOL 2012:

ELECTRON CYCLOTRON RESONANCE ION SOURCES - II

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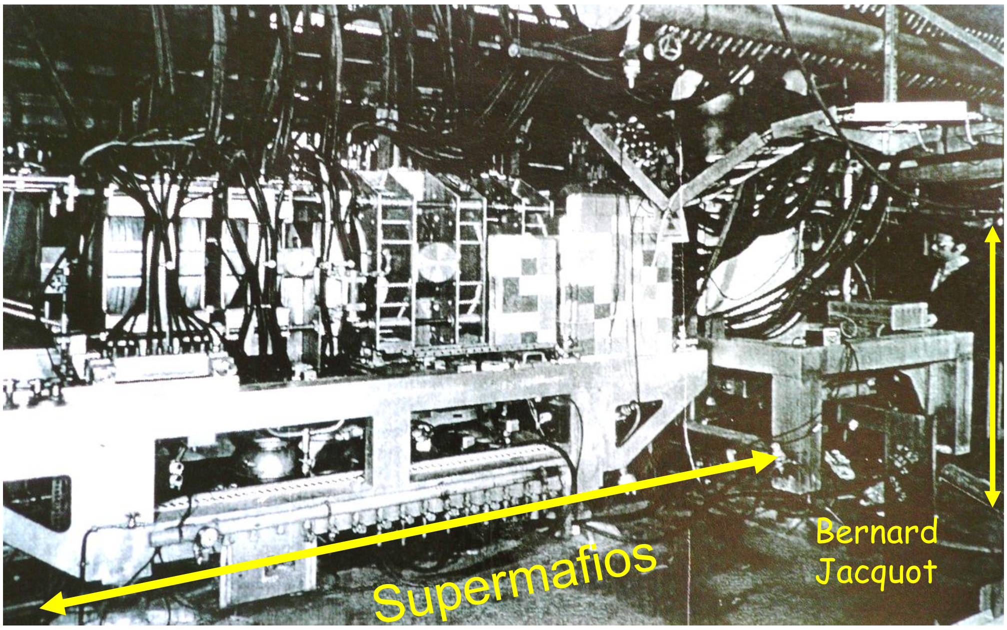
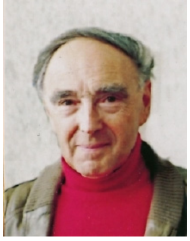
OUTLINE

- **Electron Cyclotron Resonance Ion Sources - 2**
  - **Evolution of Multicharged ECR Heavy Ion Source**
    - **The pionneers – First generation (1970-1980)**
    - **Second generation (1980-2003)**
    - **Third Generation (2003…)**
    - **Prospects toward the Fourth Generation**
  - **Ligh ECR Ion Sources Operated at 2.45 GHz**
  - **Techique to Improve Performance: Gas Mixing**
  - **Techniques to Produce Metallic Ion Beams**
  - **Basics of ECRIS Charge Breeding (1+/N+)**
  - **Pulse Mode Operation**
  - **Beam Extraction**
  - **Requirements for Beam Separation**
  - **Bibliography**
  - **Appendix**

The First Multicharged ECR Ion Source : SUPERMAFIOS 1975

- Invented at CEA Grenoble by R. Geller team (France)




R. Geller

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

The First Multicharged ECRIS: SUPERMAFIOS (1975)

- SUPERMAFIOS, a Two Stage ECR Ion Source
  - The first ECRIS were very long (≥ 1m) and featured a complicated two stage ECR plasma
  - Stage 1: high frequency, high pressure plasma in an axi-symetric magnetic field to pre-ionize the atoms
  - Plasma diffusion between stage 1 and stage 2 in a magnetic gradient
  - Stage 2: main plasma heated at a lower frequency but in a large volume chamber equipped with a min-B structure (Iofee bar hexapole + axial coils mirror) providing good confinement time for ions.
  - The ion extraction was done very far away from the last magnetic mirro peak (never do that!)

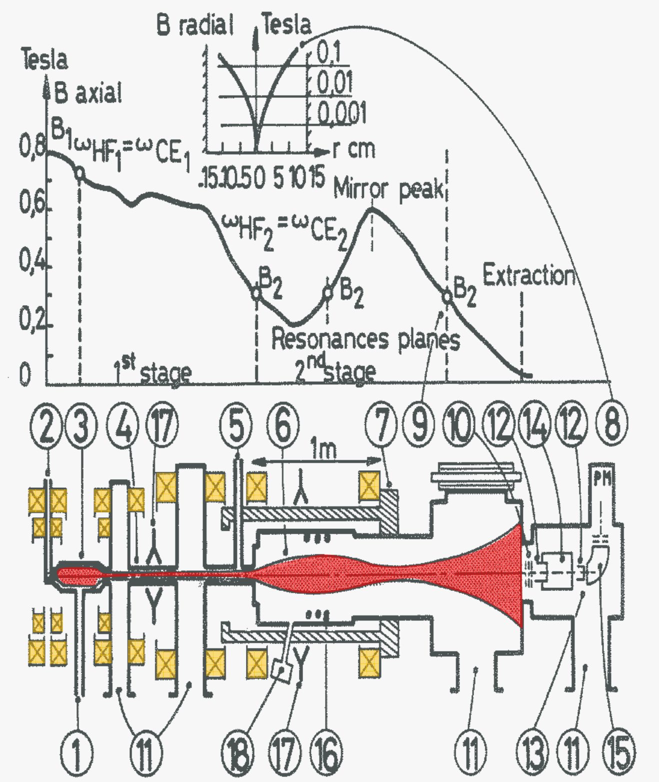


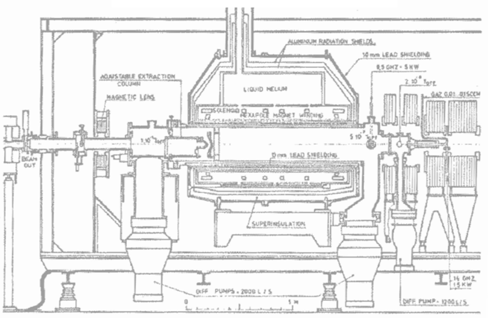
Fig. 1. 1) Gas injection; 2) Wave guide for RF_1 (16 GHz); 3) UHF cavity – source of plasma to be injected; 4) Diffusion zone; 5) Wave guide for RF_2 (8 GHz); 6) Accumulation zone for hot plasma; 7) Hexapole field coils; 8) Radial magnetic field; 9) Axial magnetic field; 10) Ion extraction; 11) Vacuum pumping; 12) Retractable faraday cup; 13) Ion abundance measurement; 14) Wien filter; 15) Energy analyzer; 16) Diamagnetic loop; 17) Microwave 8 mm interferometer for density measurements; 18) Beryllium window for X ray measurements.

The 70 & 80's Pioneers – First Generation Ion Sources

- MINIMAFIOS – ECREVIS– LBL ECR …

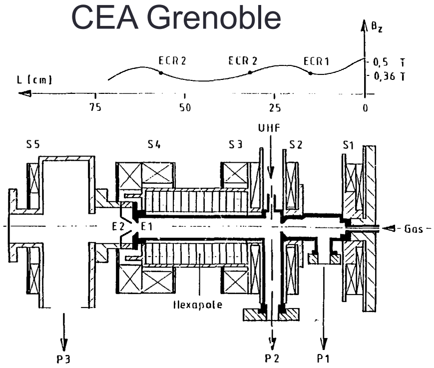
ECREVIS

Louvain la Neuve

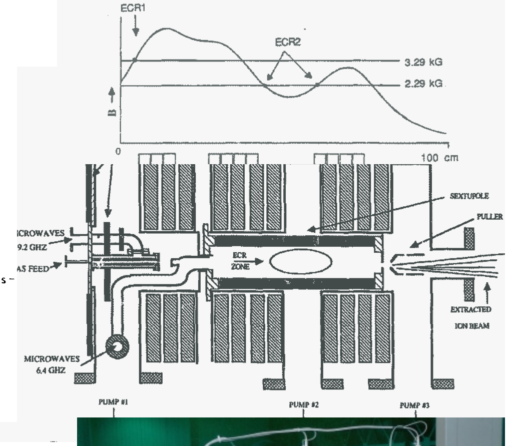


MINIMAFIOS

CEA Grenoble

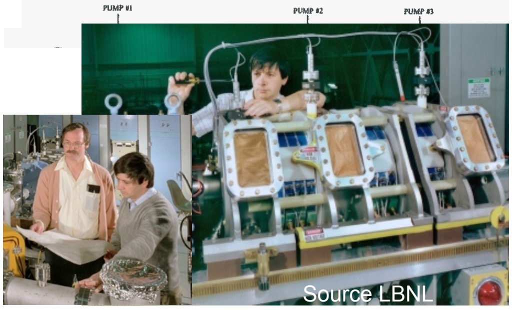


LBL ECR



1st Superconducting ECRIS at L-L-N

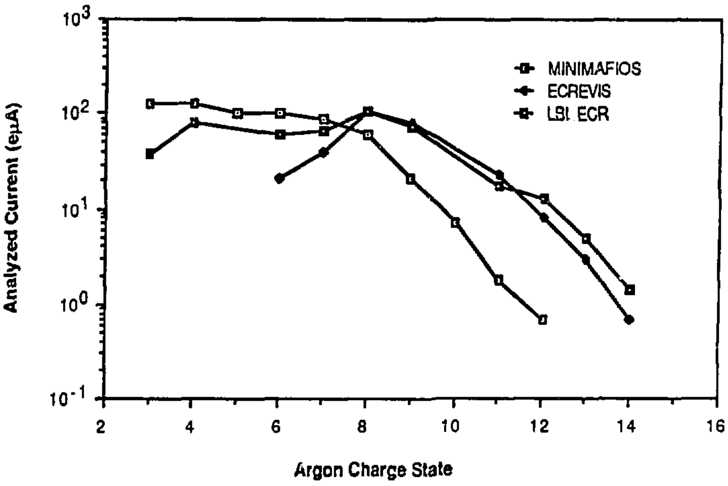
The First ECR beam in A cyclotron was achieved at Louvain La Neuve (B)

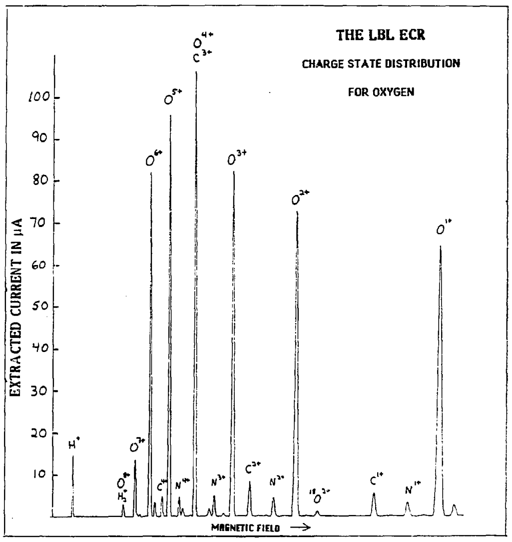


Source LBNL

First Generation ECRIS performances

- International competition for results was already there!
- First International Workshop on Ion sources in





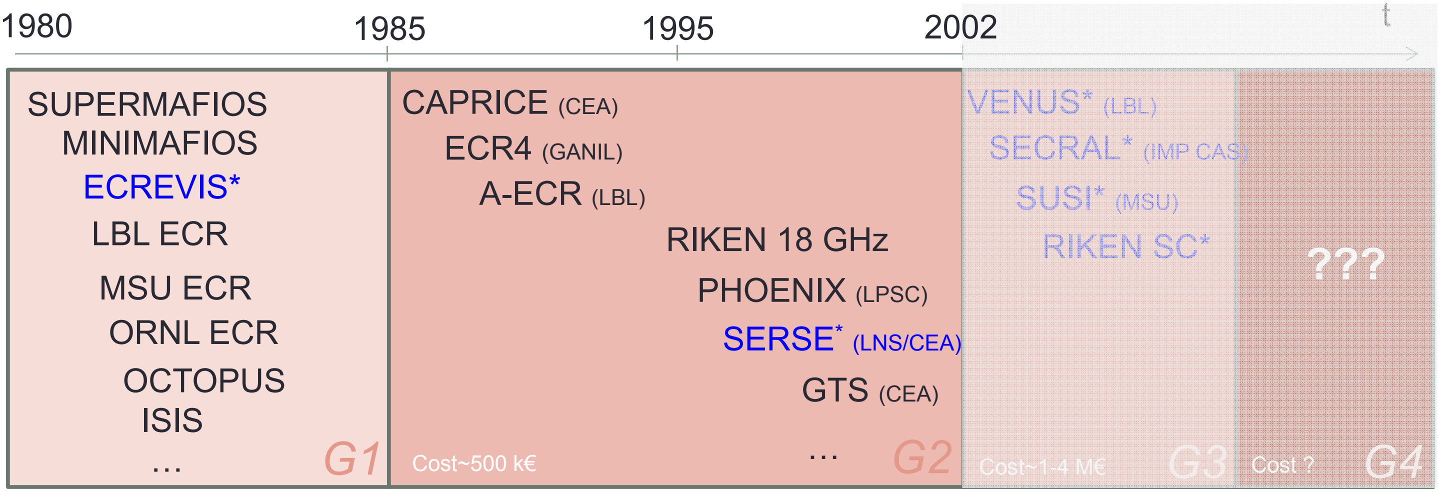
Typical beam performance of G1:

~100 μA Ar^{8+}

~100 μA O^{6+}

Second Generation ECRIS

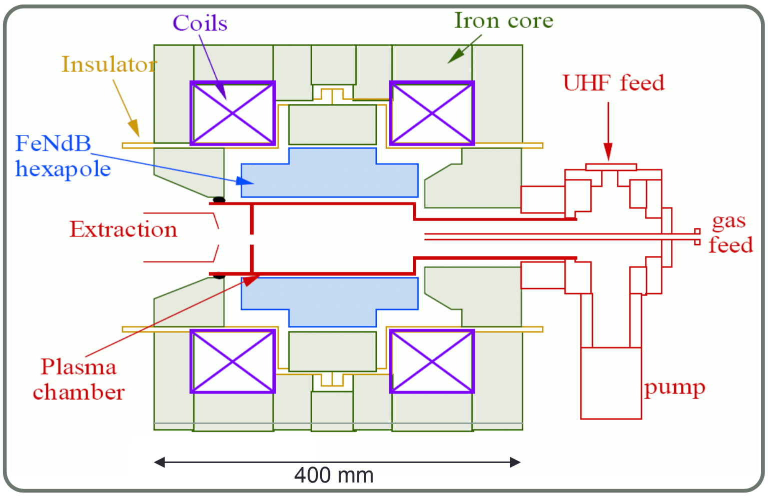
- Generalization of ECRIS used as cyclotron injectors or low energy atomic physics facility in the 80's and the 90's
    - Dramatic increase of plasma performance by improving the know-how in RF injection, magnetic confinement and ion beam extraction
    - The first plasma stage is abandonned => simplification of the design
    - It is the time for more compact an economical ion source using permanent magnets for hexapole
    - Numerous nuclear physics results obtained thanks to ECR Ion Sources

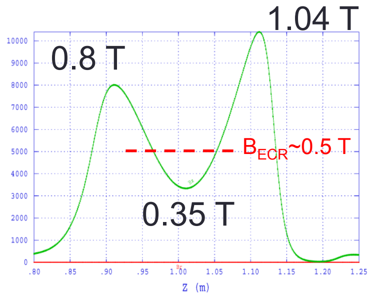


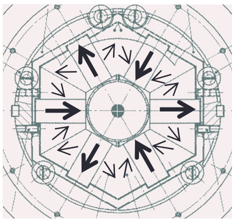
*Superconducting ECRIS

Example of ECR4, GANIL (1989)

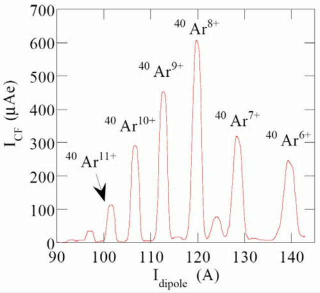
- f=14.5 GHz-1.5 kW (B_{ECR}=0.64 T)
- Coaxial RF coupling from a cube located outside the source, equipped with a movable rod (not shown) able to adapt RF impedance to the ECR cavity, inherited from CAPRICE source design.
- Axial Mirror: 1.04 T – 0.35 T – 0.8 T
- Hexapole: 1 T FeNdB HallBach type
- Typical Ion Beam: ~650 μA Ar^{8+}
- Chamber volume (Ø64 mm×L200 mm) V~0.5 liter

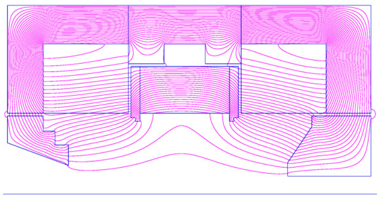






FeNdB hexapole

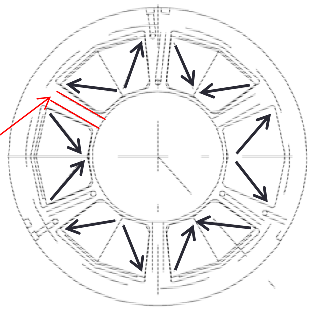




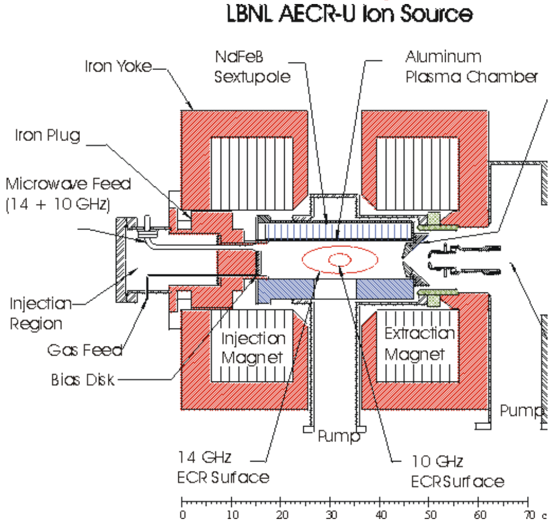
Axial Magnetic field lines (ECR4M)

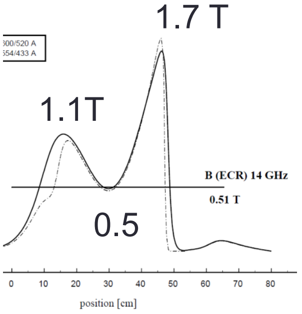
AECR-U LBNL(1996) (upgrade of A-ECR 1990)

- Introduction of double frequency heating (+10-20% beam)
  - f=10+14 GHZ / 2 kW
- Volume (Ø =76 mm, L=30 cm) V~1.36 liter
- Hexapole with radial slots access between poles for pumping.
- Iron Plug at injection to boost injection field to 1.7 T
- Bias disk to boost charge states (see picture next slide)
- Aluminum plasma chamber (higher charge state)
- Axial field 1.7-0.5-1.1 T
- Radial Field 0.85 T
- Movable extraction system
- Typical beam 840 µA O^{6+}, 120 µA Ar^{13+}

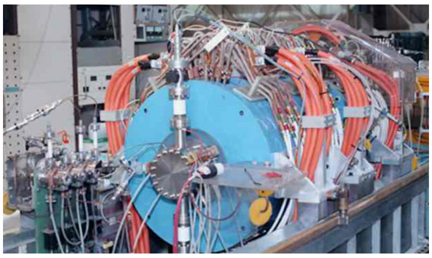


hexapole



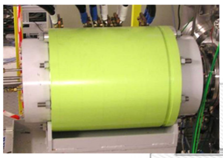


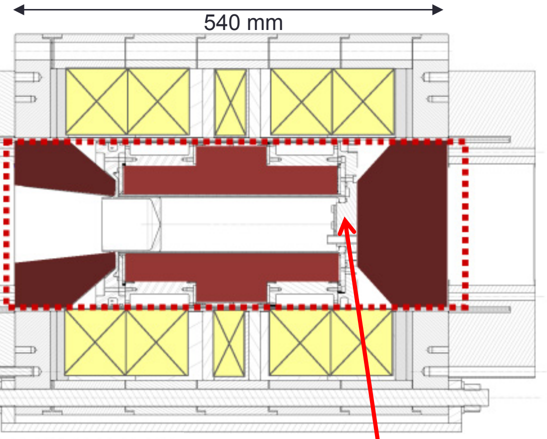
Axial magnetic field

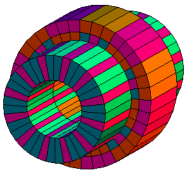


A 18 GHz Modern ECRIS: PHOENIX V2, LPSC/SPIRAL2 (2004)

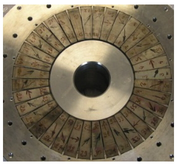
- f=18 GHz- 2 kW (B_{ECR}=0.64 T)
- Direct Wave guide coupling
- 3 room temperature coils to tune more efficiently the plasma (central in opposition)
- Optimised Hexapole:1.35 T FeNdB, 2 layers
- Axial Mirror: 2-0.5-1.25 T
- Chamber Volume~0.6 liter
- Typical beam 1.3 mA O6+ ; 20 µA Ni^{19+}

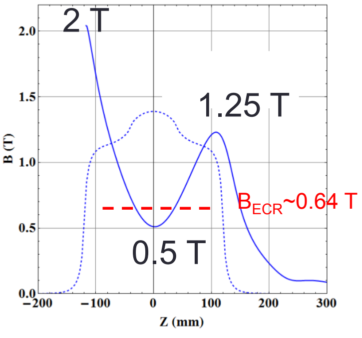


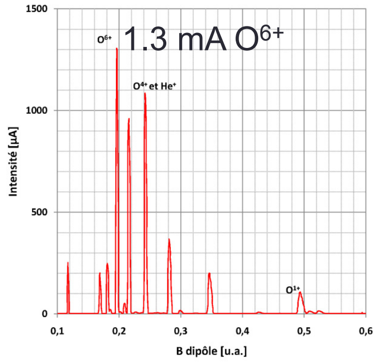


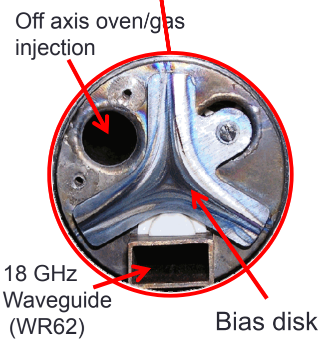


Optimized hexapole









Third Generation ECR Ion Sources

- The new high performance ECR ion sources are optimized for ECR frequency 18 <f< 28 GHz
- The high magnetic field intensity required to confine the plasma (~2-4×B_{ECR}~2-4) makes the use of copper coil technology unreasonable in term of electrical power consumption (2T hexapole in Cu technology=> 3-4 MW electrical power).
- New ECRIS are preferably fully superconducting, with a large plasma volume to produce very high charge states for Cyclotrons or High intensity LINAC
- The beam current dramatically increases when the source is operated at higher frequency, and new technical challenges have arisen….

1980 – 1985	1985 – 1995 – 2002	2002 – ?	? – t
SUPERMAFIOS MINIMAFIOS ECREVIS* LBL ECR MSU ECR ORNL ECR OCTOPUS ISIS …	CAPRICE (CEA) ECR4 (GANIL) A-ECR (LBL) RIKEN 18 GHz PHOENIX (LPSC) SERSE* (LNS/CEA) GTS (CEA) …	VENUS* (LBL) SECRAL* (IMP CAS) SUSI* (MSU) RIKEN SC*	???
G1	G2 Cost~500 k€	G3 Cost~1-4 M€	G4 Cost ?

*Superconducting ECRIS

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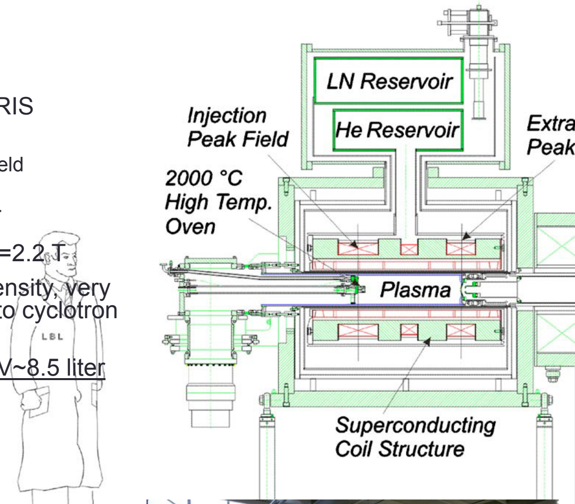
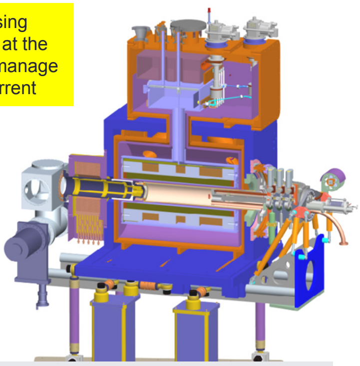
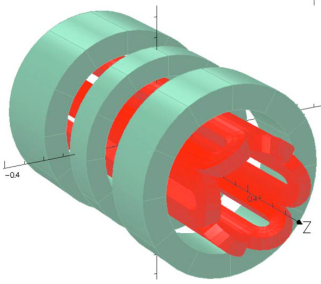
the first 28 GHz ECRIS VENUS, LBNL (2002)

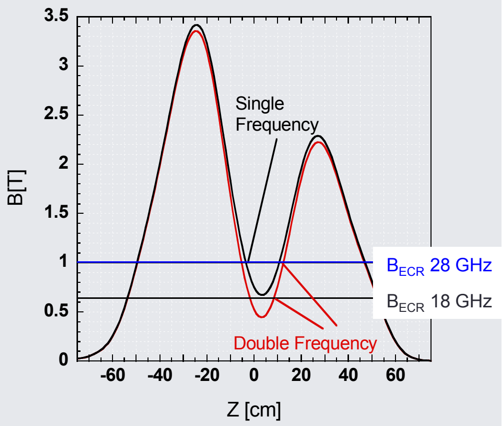
- f=18+28 GHz - (2+6) kW
- B_{ECR}=1 T
- Fully superconducting ECRIS
  - NbTi:Cu wire technology
  - 4K LHe + thermal 40 K shield
  - 4×1.4 W cryocooling
- Axial profile 3.5-0.35-2.2 T
- Radial hexapole at wall Br=2.2 T
- Dedicated to very high intensity, very high charge state applied to cyclotron acceleration
- Plasma Chamber volume V~8.5 liter
  - Ø~15 cm , L~50 cm
- V~25 kV
- Typical beams: 3 mA O^{6+}, 0.86 mA Ar12+





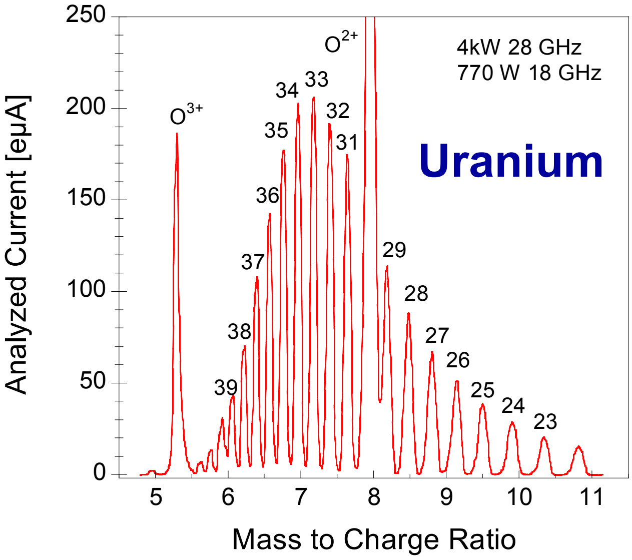
Note the focusing Solenoid right at the Extraction to manage High beam current

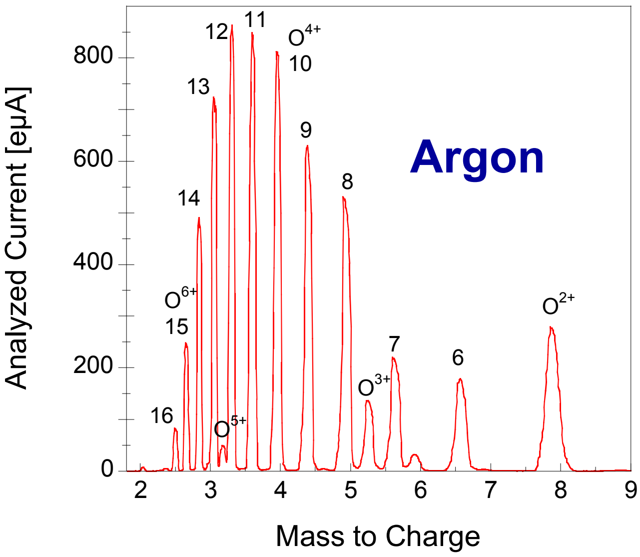




VENUS Performances – example of ion spectrums

- High intensity, high charge state ion spectrums

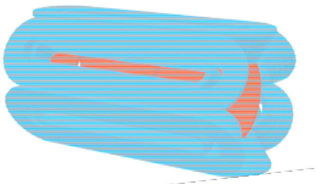




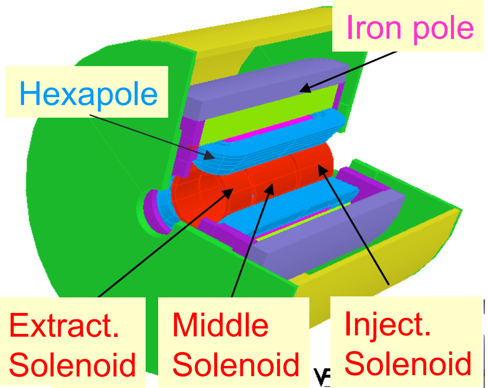
Source: D.Leitner, LBNL, 2007

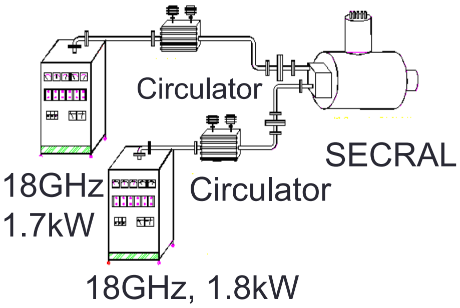
SECRAL 24 GHz (IMP CAS, Lanzhou)

- Fully Superconducting ECRIS (2004)
- Original design hexapole outside the axial coils
  - Magnetic intensity boosted by large iron yoke around the large hexapole
- f=18+24 GHz / ((1.7+1.8)+7) kW
- Brad=1.8 T
- Axial Field 3.7-0.82-2.2 T
- Ø120 mm, L 42 cm ; V~4.7 liter
- Typ. beam: 2.3 mA O6+ ; 510 μA Ar12+

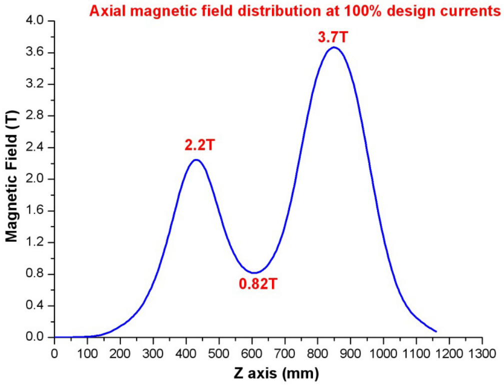


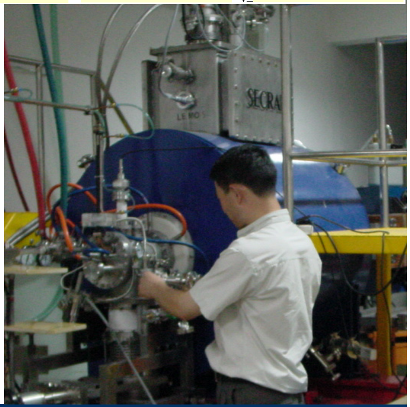
SC Hexapole outside
The solenoids





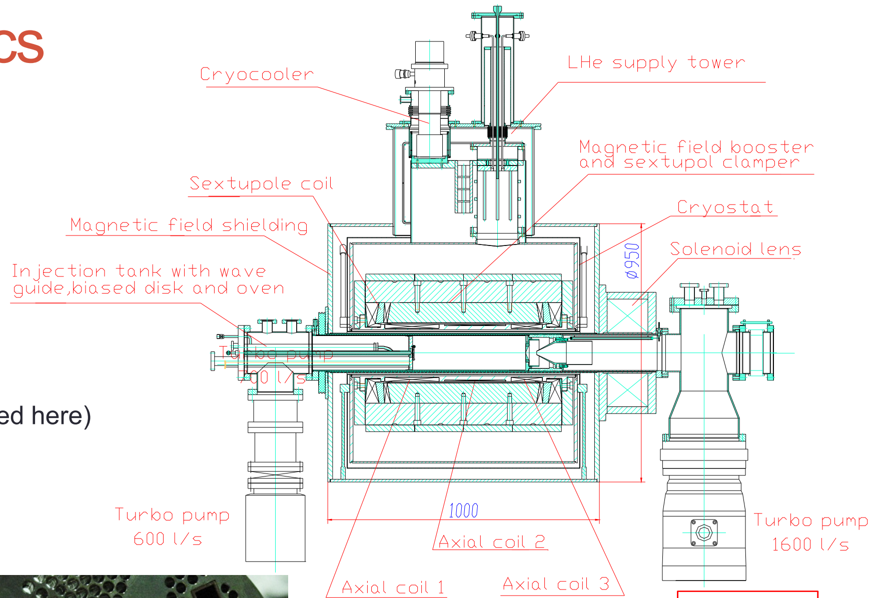
Sum of 2 ×18 GHz Klystron power

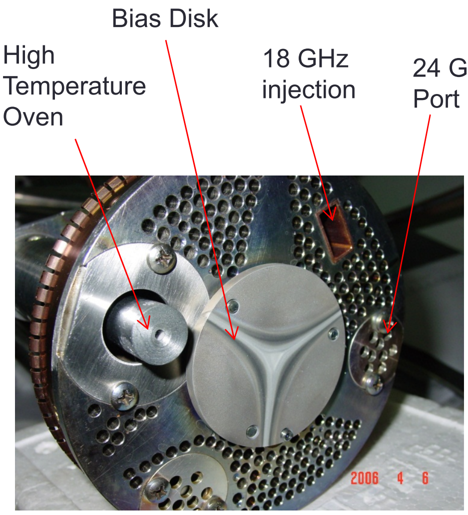




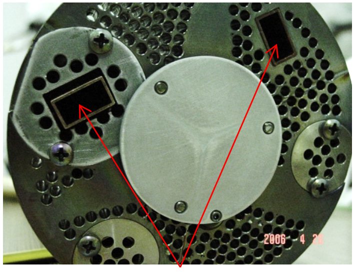
SECRAL Mechanics

- Uses of all the up to date techniques
  - Note the large pumping to work at low pressure, improve charge state and reduce background

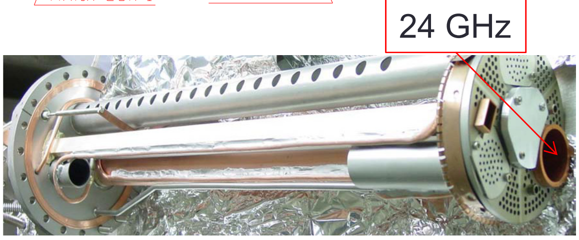




Removable UHV Injection system

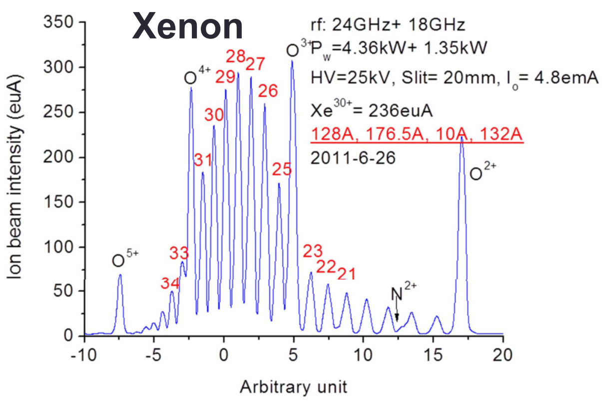


Double 18 GHz Injection here

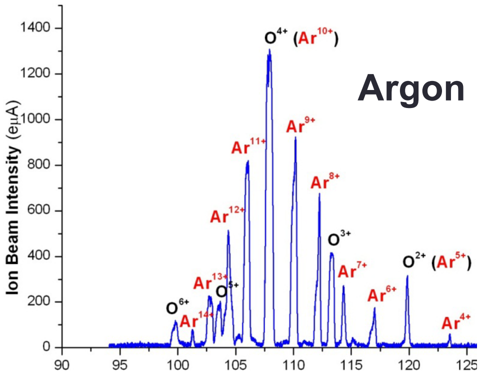


Removable UHV Injection system with 18+24 GHz

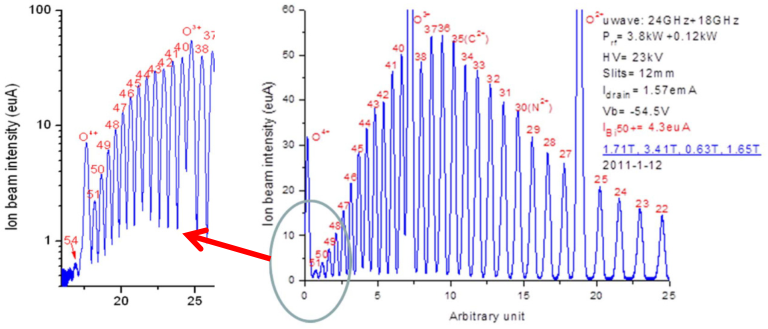
SECRAL – typical Beam performance



rf: 24GHz+ 18GHz
P_w=4.36kW+ 1.35kW
HV=25kV, Slit= 20mm, I_o= 4.8emA
Xe^{30+}= 236euA
128A, 176.5A, 10A, 132A
2011-6-26



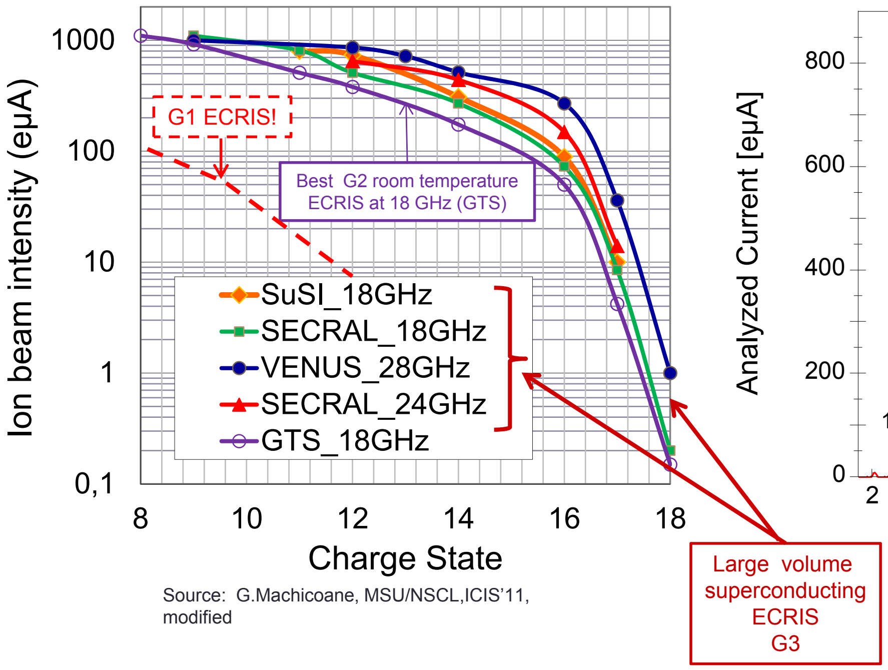
Bismuth



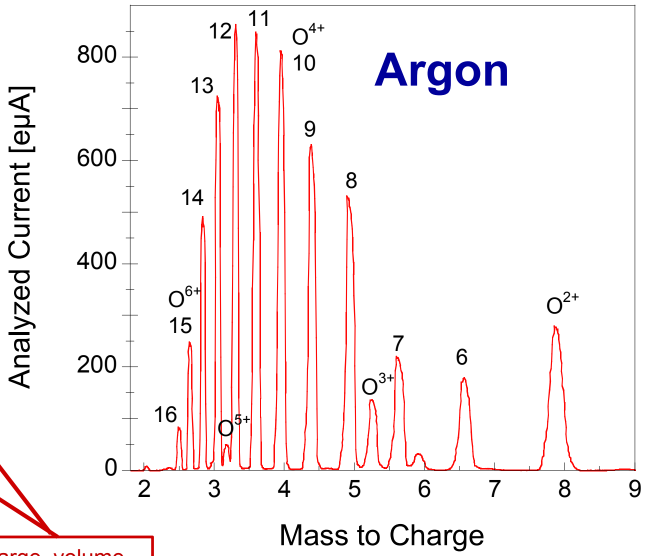
uwave: 24GHz+18GHz
P_{rf}= 3.8kW +0.12kW
HV= 23kV
Slits= 12mm
I_{drain}= 1.57emA
Vb= -54.5V
$I_{Bi^{50+}}$= 4.3euA
1.71T, 3.41T, 0.63T, 1.65T
2011-1-12

Example of Today High Charge state production

- Today ECRIS Argon beam performance



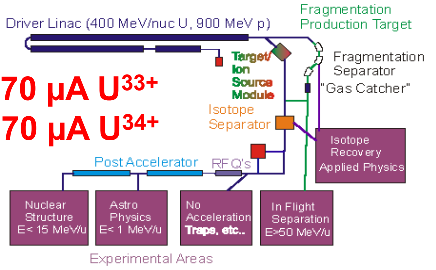
Source: G.Machicoane, MSU/NSCL,ICIS'11, modified



ECRIS prospects – Accelerators demands

- Many new accelerator projects are requiring high intensity, high charge state ion beams → Condition to start 4th Generation ECRIS R&D are met

FRIB, MSU,USA

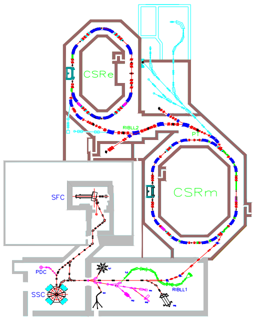


270 μA U^{33+} +270 μA U^{34+}

FAIR, GSI, Germany

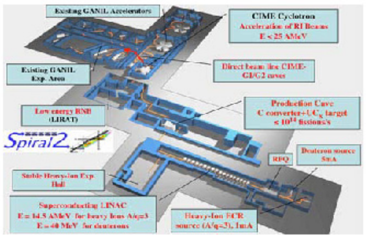
1 mA U^{28+}

HIRFL, IMP, China



750 μA Bi^{35+}

SPIRAL2, GANIL,France



1 mA $^{40}Ar^{13+}$

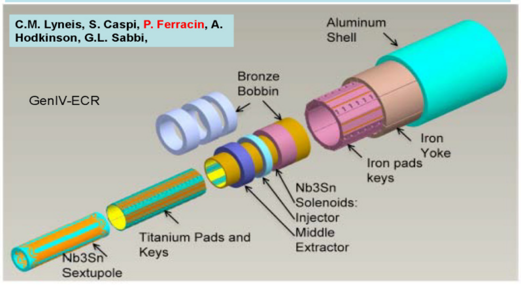
RIKEN, Japan

525 μA U^{35+}

LBNL preliminary 56 GHz magnetic design study

- Magnet design study (Nb3Tn) presented at ICIS’11, Italy.

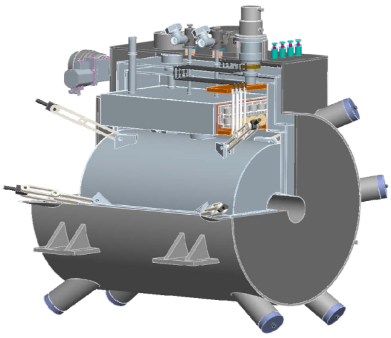
Concept for a Fourth Generation ECR Ion Source



Lawrence Berkeley National Lab

GenIV-ECR Cryostat Design

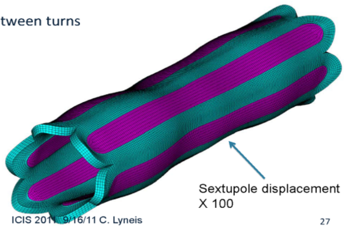
- Two 5 W GM-JT cryocoolers at 4.2 K
- One shield cryocooler 6 W at 20 K and 120 W at 77 K
- High Tc leads
- Static heat load 1.5 W
- Magnets on + 0.15 W
- Warm bore 170 mm ID
- Designed for HV platform
- No LN cooling



ICIS 2011 9/16/11 C. Lyneis 28

3D analysis with real structure

- All the components of the impregnated coil bonded
  - Both sextupole and solenoids
- Output
  - Peak stress --OK
  - Bonding tension between turns and pole
    - <20 Mpa--OK



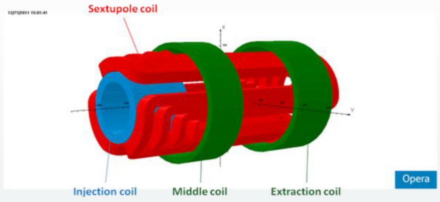
ICIS 2011 9/16/11 C. Lyneis 27

- Complicated engineering with Nb3Tn
- Feasibility is demonstrated

IMP Lanzhou 50 GHz design

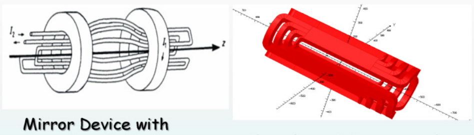
- NbTi is used, relaxing coil stress thanks to « fusion like » coils use (D. Xie at ICIS’11)

The Best of Combination (c)



All of the Azimuthal Currents Flows in the same Directions! No Repulsions between the Solenoids and the Sextupole Ends!

New Sextupole: A Close-loop with Six Rectangular Ioffe Bars.



Mirror Device with Open-loop Ioffe Bars

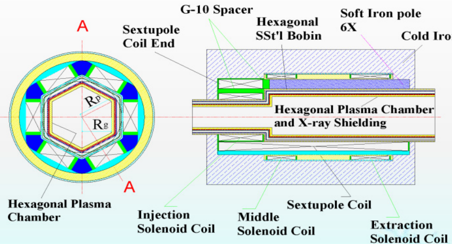
Only the radial fields are used, not the axial fields generated by the end turns.

Close-loop with rectangular Ioffe Bars

Will use both the radial and the axial fields generated by the end turns.

MK-I

The Embodiment Of the New Magnet Structure



Rp > Rg

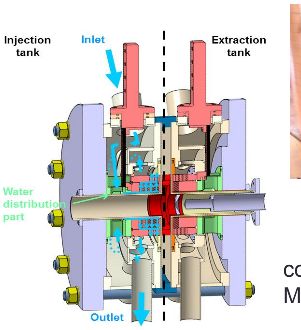
Bp = Bm(Rp/Rm)**2
> Bg = Bm(Rg/Rm)**2

Hexagonal Chamber of maximum ID 206 mm

- Use of a sophisticated hexapole directly generating a min-B field
- NbTi Wire used
- forces on coil reduced, but complicated engineering for winding and plasma chamber

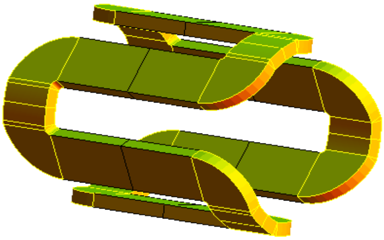
ECR (exotic) Prospects at higher frequency

- High frequency ECR R&D with MegaWatt Magnets (LPSC & GHMLF, Grenoble)
    - Design and build of several copper coils prototypes to study innovative magnetic structures
    - Test at the Grenoble High Magnetic Field Laboratory on a dedicated test bench equipped with a 60 GHz Gyrotron
        - Coil building is simple
        - Allow fast R&D: build, test & improve
    - First prototype is axysymetric (SEISM) « CUSP » presented earlier
    - Next prototypes should feature a classical minimum-B structure
    - Ioffe bar style hexapole (Xie) is part of the plan for a long time (CERN EURISOL meeting slides 2006).
    - Once studied and validated, the goal is to switch the source to a superconducting version



copper coil with turns
Machined by electro erosion

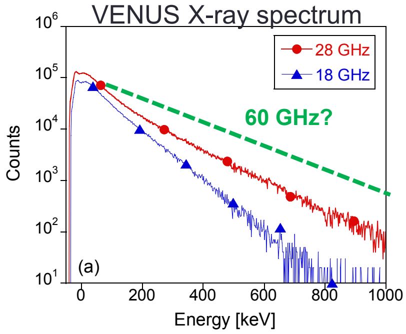
SEISM applied to Beta Beams R&D

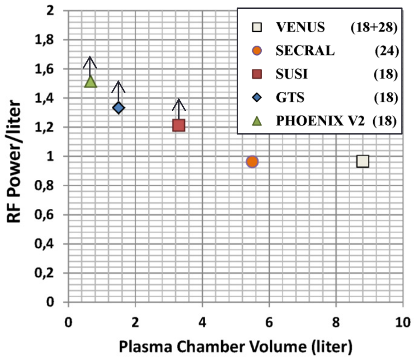


Min-|B| hexapole foreseen,
as presented in 2006 at CERN

The challenges of 4th generation ECRIS (50-60 GHz)

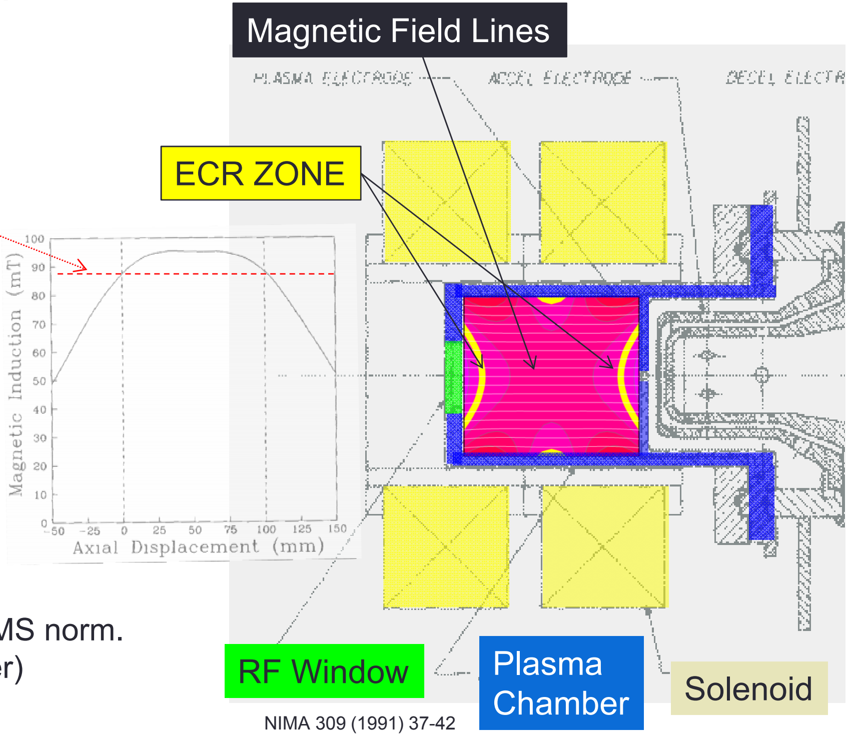
- 4th generation ECRIS Magnetic Field at SC coil surface is above NbTi superconducting wire performance
    - This likely Requires the use of another SC wire…Nb3Sn? A strong R&D is necessary
- 3rd generation ECRIS shows an intense parasitic X-ray flux, generated by the Bremstrahlung of hot electrons impinging the plasma chamber wall, inducing a dramatic extra heat load of the SC cold mass of ~1 W/ kW RF at 24 or 28 GHz… What about a 60 GHz plasma???
- Today total current extracted (I~5-15 mA) from 3G ECRIS is highly space charge dominated … How to manage a 60 GHz beam with I×4 (I~20-50 mA)???
- In high performance ECRIS, an experimental limitation on RF power injected is observed with P~1 kW/chamber liter. How to go further to improve performances?





2.45 GHz High Intensity Light Ion Source

- **The TAYLOR Source (1991)**
  - Still a reference in the field
- f=2.45 GHz / 2 kW ECR frequency
  - BECR=0.087 T (easy to do)
  - Monomode cavity
- 2 open ECR surface
  - Purely axial field
  - NO MAGNETIC CONFINEMENT
- One single electron pass through ECR
  - Te~1-20 eV
  - **$\Lambda_{0\to1+}$ ~ 7 cm**
- 1+ Ion Source
- Very high intensity: ~25 mA of H+
  - Ø4 mm hole only
  - « High » pressure P~10^{-5} mbar
- Proton Fraction: H+~90%
- H_2^+ & H_3^+ ~ 10%
- Low emittance ~0.07 π.mm.mrad 1σ RMS norm. (low B, Triode: see extraction slides later)



Magnetic Field Lines

ECR ZONE

RF Window

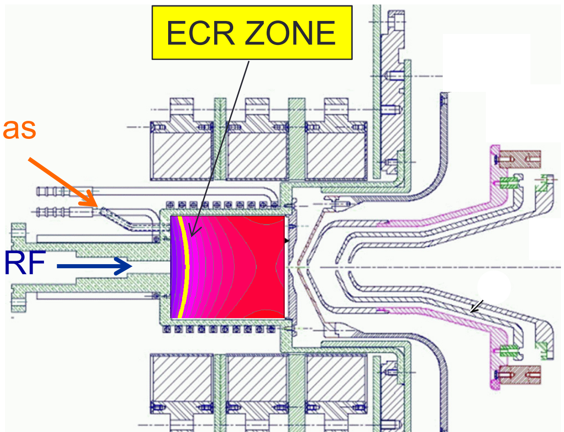
Plasma Chamber

Solenoid

NIMA 309 (1991) 37-42

SILHI with permanent magnets (CEA/IRFU)

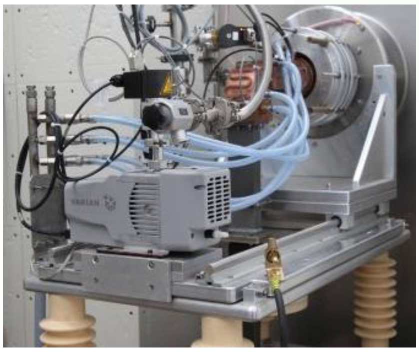
- A single ECR resonance in the chamber
  - located at the maximum of RF electric field, near to RF input.
  - The second resonance is out of the chamber in the extraction system
- WR340->WR284->double ridge RF transition
- Complicated 5 electrodes extraction to manage very high ionic currents
- I H^+~100 mA, 80% Fraction
- High current is obtained by increasing extraction hole Ø

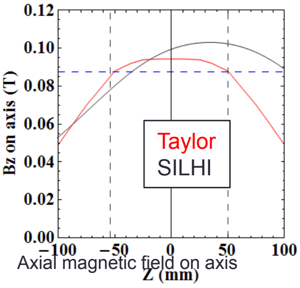


ECR ZONE

Gas

RF

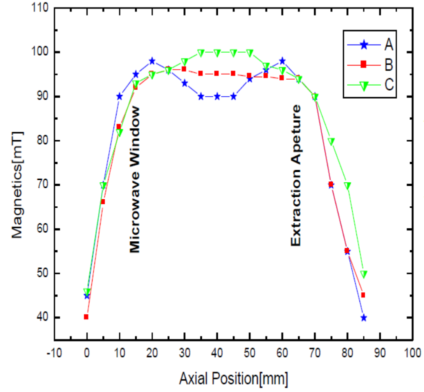


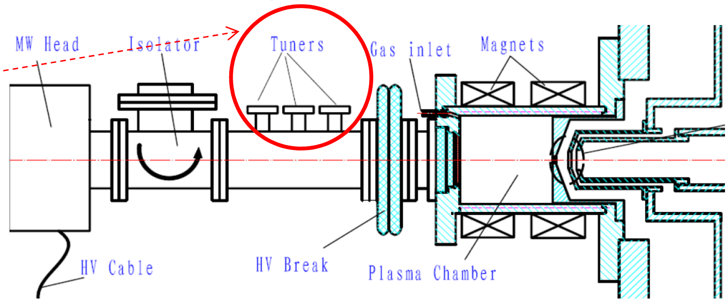


Axial magnetic field on axis

Very Compact 2.45 GHz (Peking University)

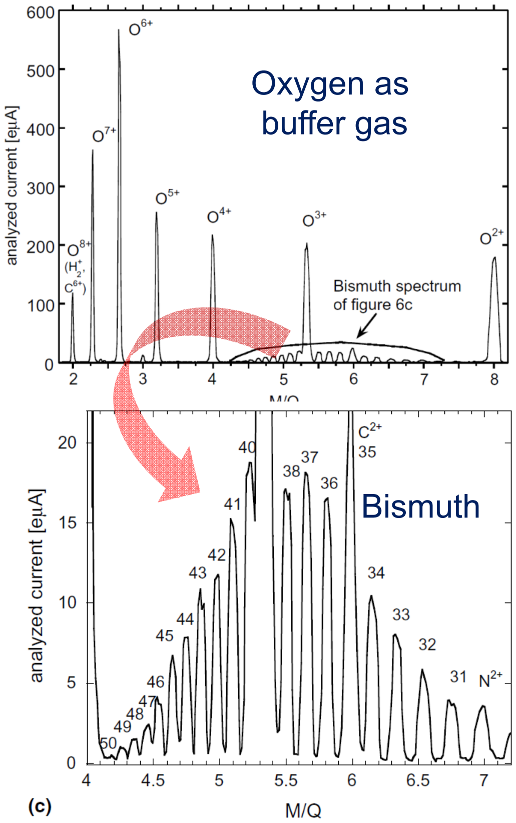
- A half length cavity with respect to Taylor
  - L= 50 mm
- A quarter wave diameter chamber
  - Ø ~40 mm
- Permanent magnets
- 50 mA H^+ with a triode extraction
- Direct Waveguide coupling (no transition)
- By the way: RF Tuners are mandatory in 2.45 GHz ECRIS to optimize the power coupled to the ECR plasma!





Gas Mixing

- Discovered at KVI (Holland)
- 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 is used to mixing with heavy masses A>16
- The extra O 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 (eg fully stripped Ar^{18+} beam)

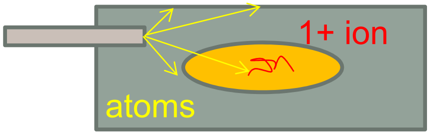


Very high charge states obtained in VENUSwith the gas mixing technique

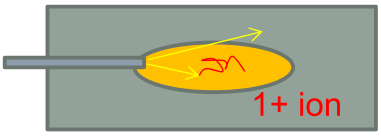
Condensable Ion Beam production in ECR Ion Sources

- The high plasma density of ECR ion Sources features a short mean free path for 1st ionization of atoms: $\lambda_{0\rightarrow 1+} \sim 1-10\ cm$
- On flight ionization of condensable or refractory atom can be performed by severa techniques in ECRIS
  - **Oven technique**: An miniature oven is inserted in front of the ECR plasma and heated up to the temperature at which a condensable atom evaporates under vacuum
  - **Sputtering technique**: when the evaporation temperature is unreachable, a sample of condensable is introduced inside the plasma which sputters the material. The sample can be biased to negative voltage to increase sputtering yield.
  - **MIVOC technique** (Metal Ions from VOlatile Compounds): condensable atoms are chemically inserted in an organic molecule that is gaseous under vacuum. The gas diffuses to the plasma.
  - **Wall heating**: It is complementary of oven or sputtering technique. A refractory cylindrical metallic liner (Mo, Ta, W) is placed around the plasma chamber with a weak thermal interaction with the water cooled wall. The liner temperature increases due to RF and plasma heating. The sticking time of condensable is reduced, which allows wall recycling and improve the global ionization efficiency.

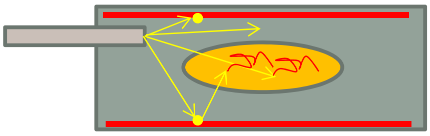
Oven technique

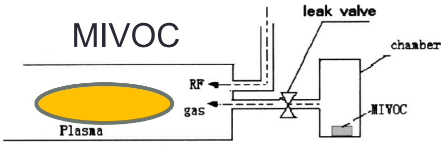


Sputtering technique



Hot Wall liner

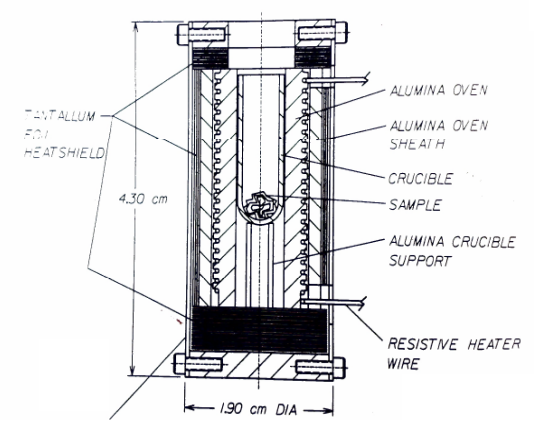




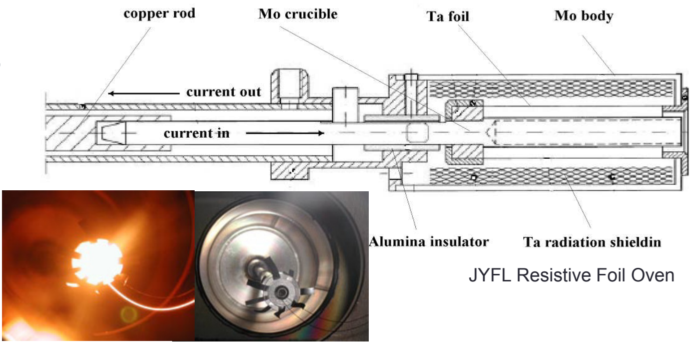
Lanzhou, IMP, china

Metallic ovens for ECRIS

- **Resistive Filament Oven**
  - Helicoidal W filament inserted bewteen an inner and outer insulator (alumina)
  - Can be very compact (Ø~10-20 mm)
  - T~1400-2000°C max
    - Depending on design
    - The Alumina crucible melts at 2050˚C
  - Possibly radiation reflector foil on the outside to improve heating
- **Resistive Foil Oven**
  - The filament is replaced by a Ta Foil
  - The alumina crucible is replaced by a Mo one
  - T_{MAX}~2000-2600°C (Mo melting)
  - Ø~20 mm
  - Requires a careful thermal design study



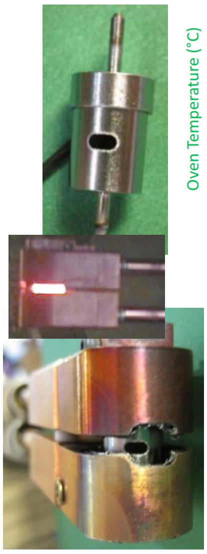
MSU Resistive Filament Oven



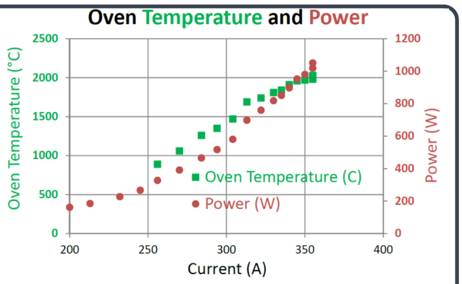
JYFL Resistive Foil Oven

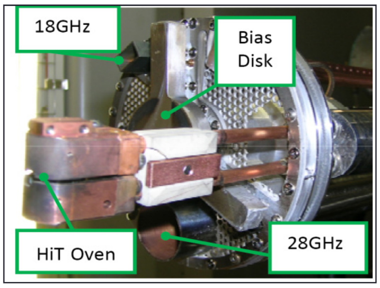
Metallic ovens for ECRIS

- **Massive resistive oven**
  - The crucible is directly the heated resistor (Tungsten)
  - Large oven (~4 cm), large metal capacity
  - Requires large DC current 350 A/3V
  - T_{MAX}~2000-2300°C
  - Large current through leads may generate electromagnetic force in the magnetic field of the ECRIS:
    - F~IB
    - Thermo-mechanical calculation required
- **Inductive oven**
  - The metallic crucible is inductively heated by a water-cooled excitation coil
  - T_{MAX}~2000-2600°C (Mo melting)
  - The tricky part is the external pulsed current generator to excite the coil (f~100-200 kHz P~1 kW)
  - Ø~25 mm



LBNL Massive Resistive Oven





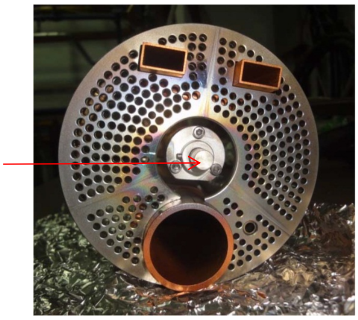
Rev. Sci. Instrum. 83, 02A311 (2012)

JYFL inductive oven

Typical metallic beam intensities

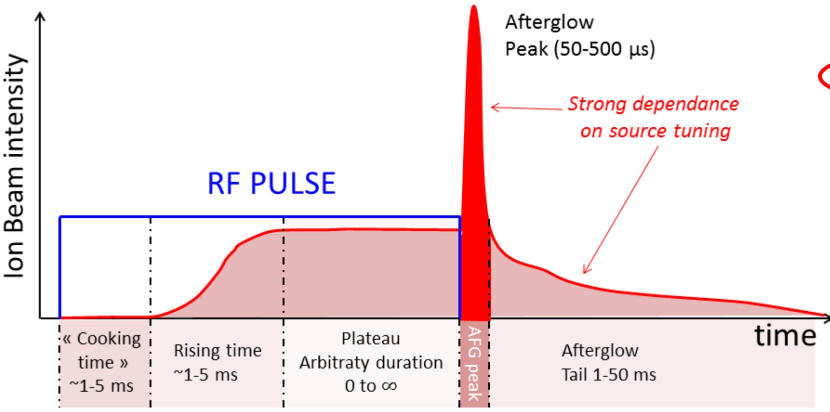
- Metal consumption~0.1-10 mg/h depending on the tuning and the source
  - Consumption is a concern when expensive elements like ^{48}Ca is requested
- Global ionization efficiency of oven is ~10%
- Hot liner Recycling helps to reach ~ %
- Run duration ~days to ~weeks depending on the crucible volume and the metal consumption

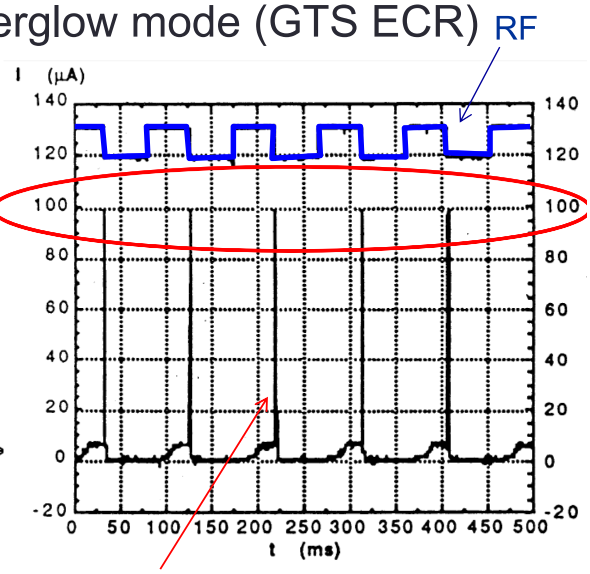
Uranium Sputtering stick
Inserted on the plasma
Axis to make U beam
On SECRAL



Pulse Mode operation for Synchrotrons: The Afterglow

- When the RF is pulsed, ECRIS can be tuned to produce a high intensity peak with a duration $\delta t \sim 50 - 400\ \mu s$, suitable for multi-turn Synchrotron injection
- LHC Lead beams are produced in Afterglow mode (GTS ECR)





Pb^{28+} pulses (ECR4 GANIL)

The Afterglow mechanism

- The ECR is tuned to provide High plasma confinement
  - Bext~Binj ⇒ very small loss cone

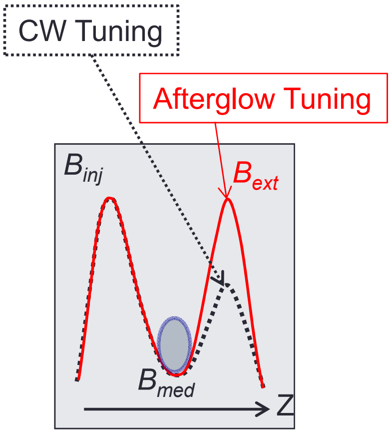
  ⇔ Very low extracted current in CW mode
- The hot confined electrons population, maintained by the RF, build a large potential dip $\Delta\Phi$ around the axis
  - Pastukov, 1974

  ⇒ Accumulation of ions trapped at the center of the source
- At RF stop: the electron heating stops brutally:

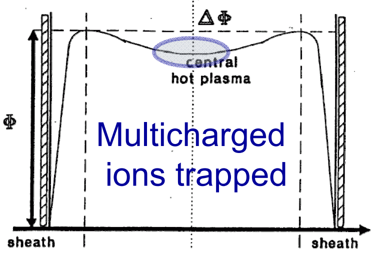
  ⇒ Fast destruction of the potential dip $\Delta\Phi \rightarrow 0$

  ⇒ Deconfinement of multicharged ions

  ⇒ High intensity peak of multicharged ions

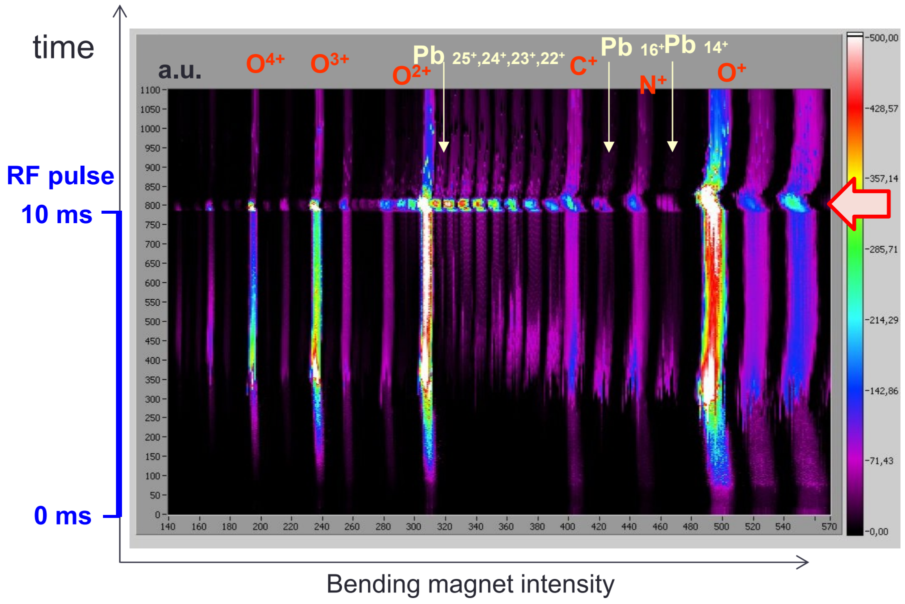


Axial Magnetic Mirror



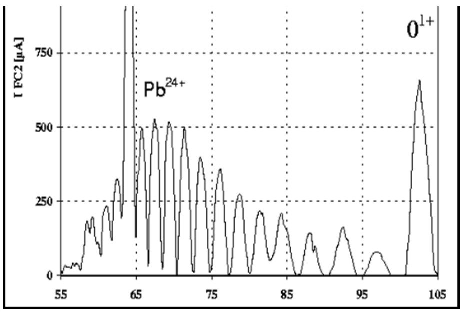
Lead Afterglow Spectrum

- 650 µA Pb25+ - 28 GHz- PHOENIX V1 SOURCE (LPSC) - 10 ms/10 Hz



AFTERGLOW

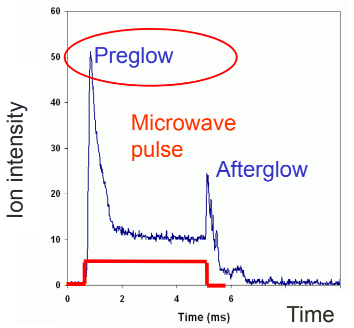
Very stable tuning at 500 µA

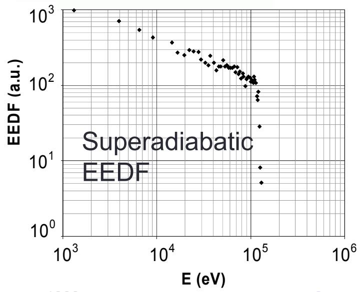


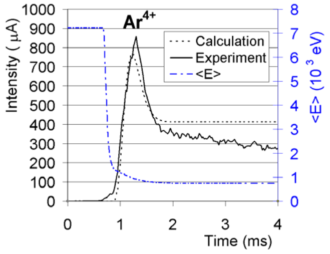
The Preglow mode (under R&D)

- Discovered by chance at LPSC during afterglow studies
  - Intense transient peak occuring at plasma breakdown
  - Studied at 18 and 28 GHz ECR frequency
- The Preglow is reproduced with a 0D model developped at IAP (Russia)
  - Main assumption: build up of a superadiabatic high energy electron distribution function (EEDF) at early plasma breakdown, when n_e is low
    - The confined electrons absorb all the RF power and reach high energy
  - When n_e increases, plasma leaks and collisions with ions become dominant and the superadiabatic EEDF damps brutally to a lower energy one (maxwellian).
  - during the EEDF damping, high Transfer of energy from electrons to ions occur (through electron impact ionisation)

  ⇒ transient Preglow peak

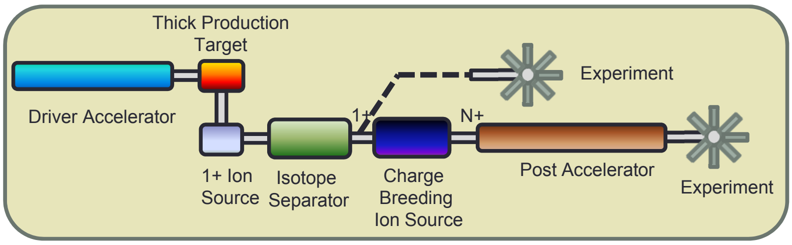




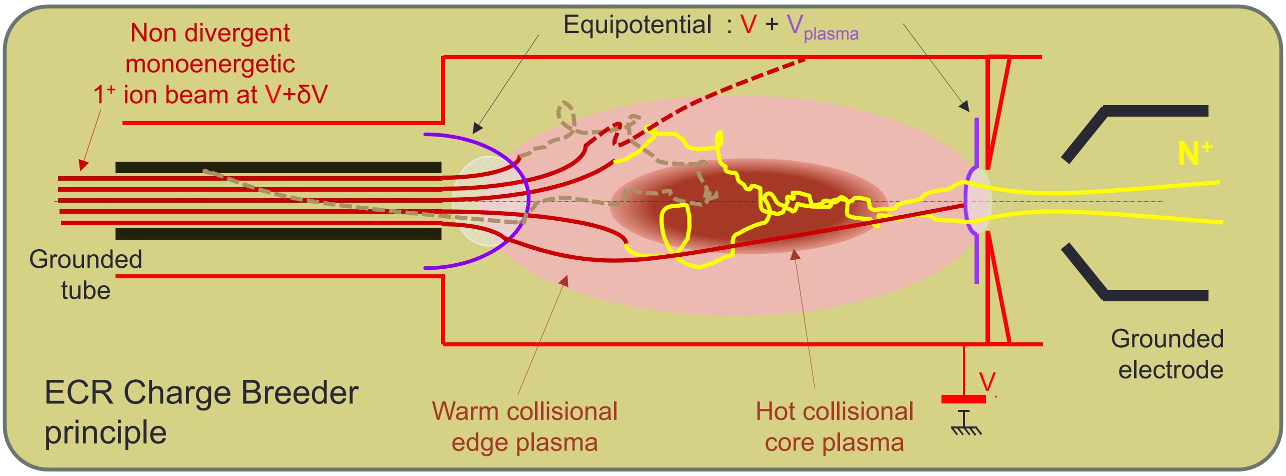


1+N+ Method in ECRIS

- Dedicated to Radioactive Ion Beam post-acceleration

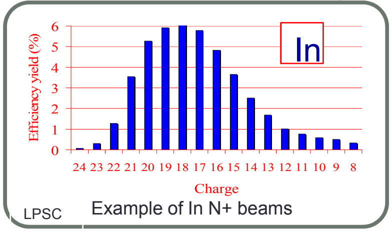


- Invented by R. Geller at Grenoble
- Method under development in many laboratories GANIL(SPIRAL1→2), ANL(CARIBU), TRIUMF (ISAC2), KEK(TRIAC), LNL(SPES)…

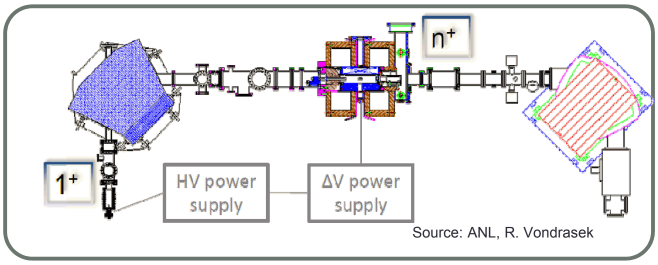


ECR Charge Breeder principle

ECR Charge Breeding – efficiency - ΔV

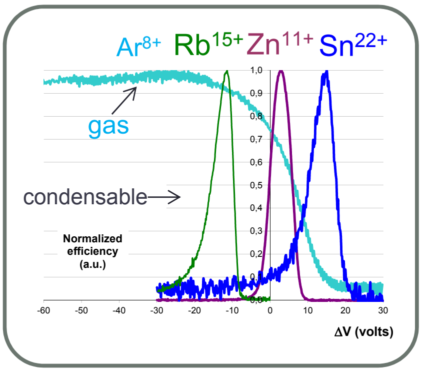


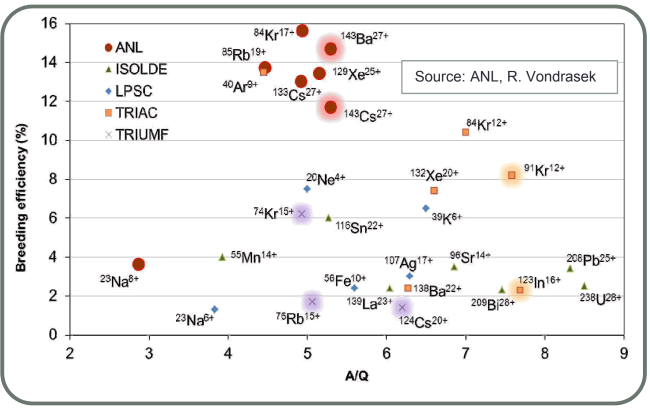
Example of In N+ beams



Source: ANL, R. Vondrasek

- Efficiency for n+ ion: $\eta_n = \frac{I^{n+}}{n.I^{1+}}$
- The 1+ ions should be accurately decelerated to match the plasma capture condition (ΔV curve=function of both source plasma potential)
- Today, the main limitation comes from the beam contamination with impurities (from plasma chamber walls)
- Small intensity RIBS may be hidden by a nearby Q/A contaminant

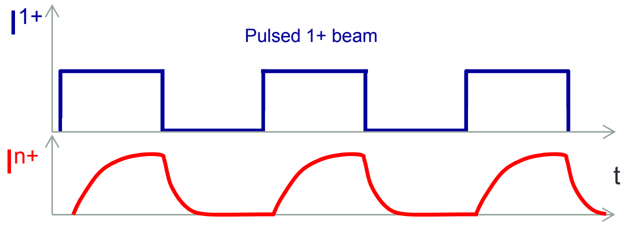


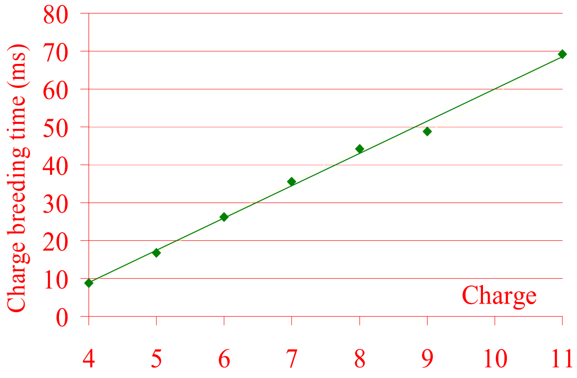


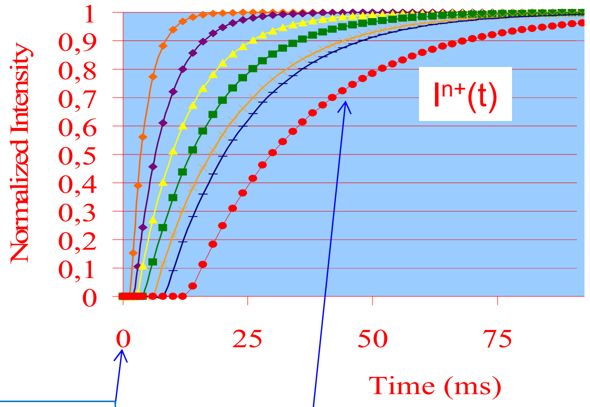
Source: ANL, R. Vondrasek

ECR Charge breeding as a plasma probe

- Evidence of step by step ionization process in the ECR plasma







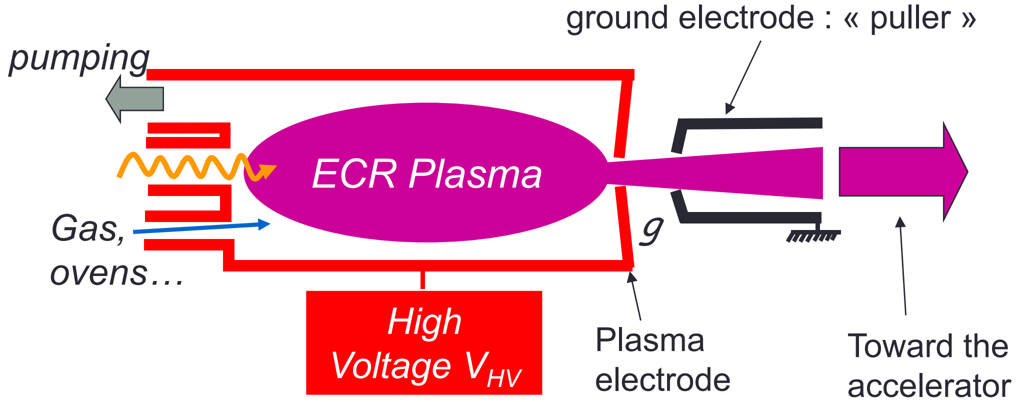
1+ beam injection

Charge Breeding time=
time for 1+→ N+ ionization +
Time for plasma escape
(confinement time)

Experiments done with the PHOENIX Charge Breeder (LPSC)

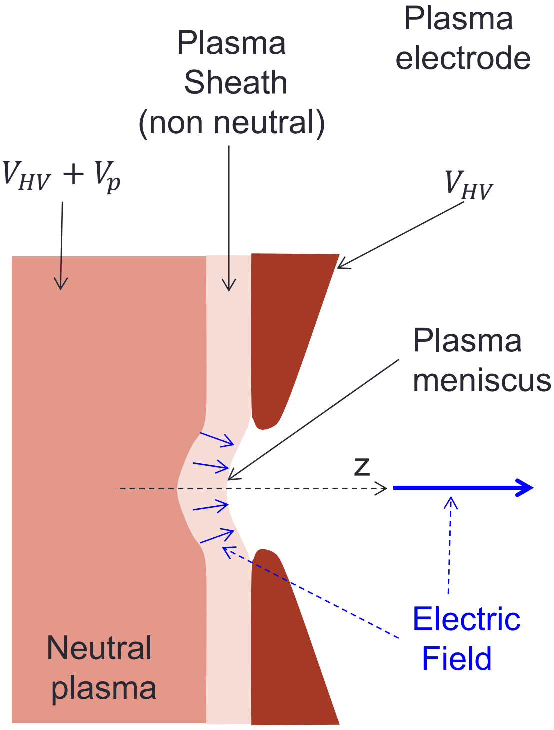
Beam Extraction from ECR Ion Sources

- The ion beam is extracted by setting the plasma chamber to high voltage V_{HV}~15-60 kV
- A plasma electrode is closing the cavity on the extraction side, it is equipped with a circular hole with diameter Ø~5-13 mm
- A puller electrode, set to ground potential, is placed in front of the plasma electrode
- The electric field in the gap d enables to accelerate the low energy ions from the plasma while hot electrons are repelled back to the source



Ion Extraction from the plasma

- 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 (non neutral area, see appendix).
- 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 angle θ with respect to $\vec{B}$ are distributed in the <u>loss cone</u> ruled by the Axial Mirror ratio $R = \sqrt{B_{max}/B_{min}}$:
  - $v_\parallel = v\cos\theta$
  - $\sin\theta \leq \frac{1}{\sqrt{R}}$



Plasma electrode

Plasma Sheath (non neutral)

$V_{HV} + V_p$

V_{HV}

Plasma meniscus

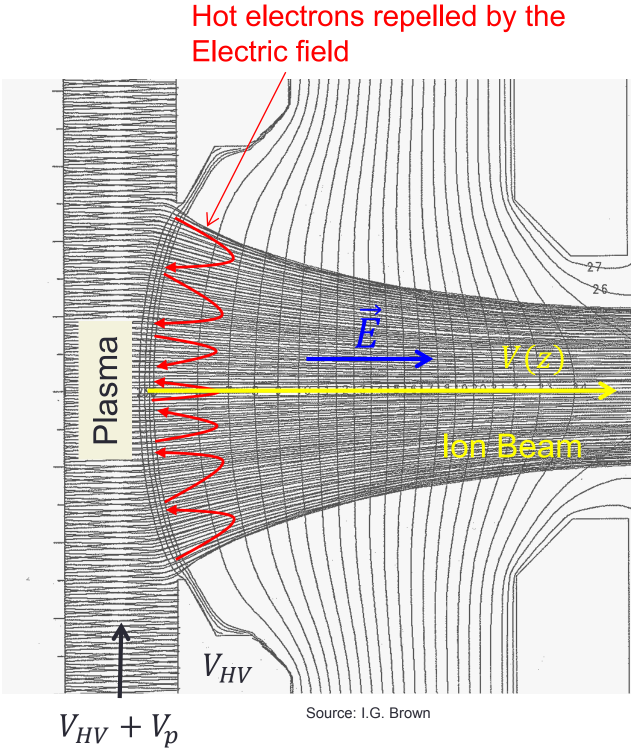
z

Electric Field

Neutral plasma

Hot Electrons contribution to the emittance

- The hot electrons of ECRIS play an important role in the early beam formation, when the ions have very low energy
- Hot electrons (k$T_e \sim 1 - 5\ keV$) 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 potential at position z in the extraction area
  - Vp is the plasma potential, V_{HV} the High Voltage



Hot electrons repelled by the Electric field

$V_{HV} + V_p$

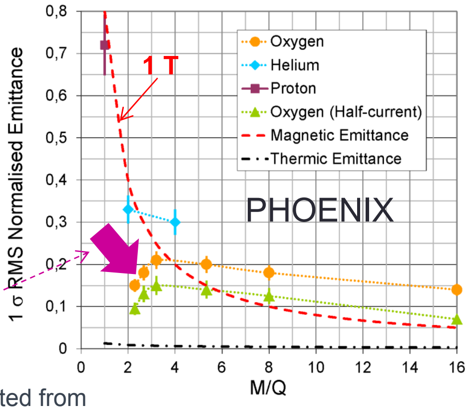
Source: I.G. Brown

Ion Beam Emittance from an ECRIS

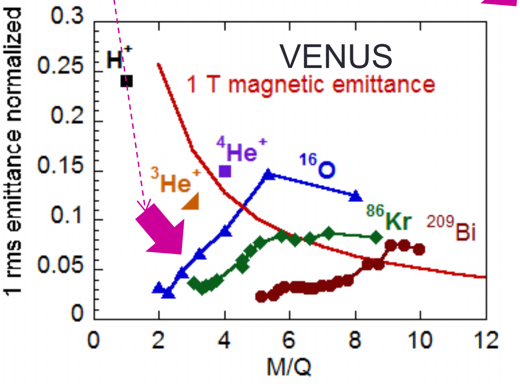
- The beam emittance from an ECRIS has mainly two origins:
  - **Thermal emittance** induced by ion beam temperature (OFTEN NEGLIGIBLE)
  - $\boldsymbol{\varepsilon_T{}^{xx'-rms-norm} = 0.016r\sqrt{\frac{kT_i}{M/Q}}}$
    - kT_i ion temperature (~1/40 eV)
    - r electrode radius (mm)
    - $^{M}/_{Q}$ mass over charge in amu
  - **Magnetic emittance** induced by the beam rotation due to the decreasing magnetic field when the beam exits the source: THIS IS THE DOMINANT TERM
  - $\boldsymbol{\varepsilon_B{}^{xx'-rms-norm} = 0.032r^2B\frac{1}{M/Q}}$
    - 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-symmetric magnetic field (see appendix for more details)

Experimental beam emittance measurements

- Systematic experimental emittance measurements performed on Heavy Ion ECRIS confirms that Magnetic Emittance is dominant
  - VENUS Plot below
  - PHOENIX Plot right
  - Light Ions emittances is consequently very large
- High intensity beams extracted (Itot~3-15 mA) induce space charge effects that inflate final beam emittance
  - PHOENIX Orange plot: 1 mA O^{6+} - Green: 0.5 mA O^{6+}
- The Emittances of High Charge states are smaller than expected

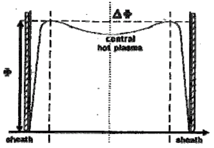


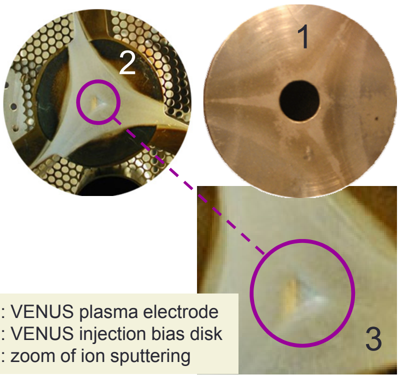
Source: T.Thuillier, LPSC,ECRIS2004



Source: D. Winklehner, LBNL,ECRIS2010

- 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 the ECRIS axis
- Experimental evidences exist of small triangular beams for high charge state

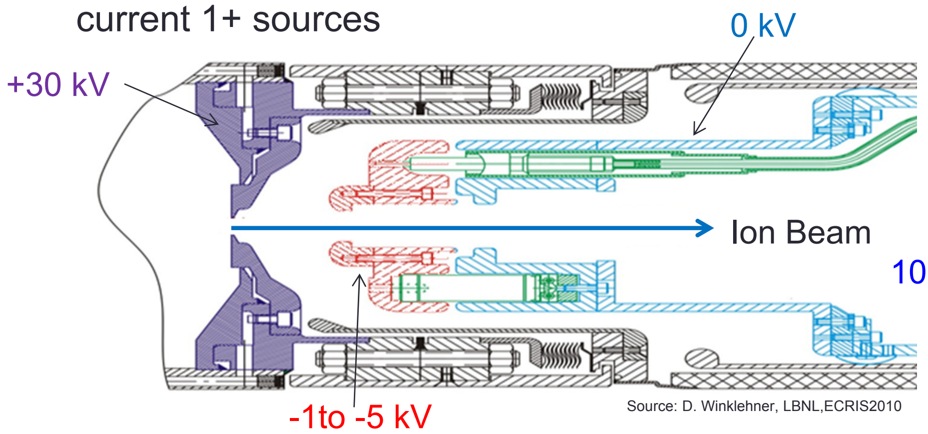




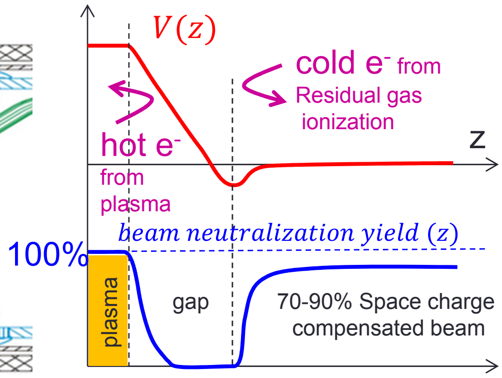
1: VENUS plasma electrode
2: VENUS injection bias disk
3: zoom of ion sputtering

High intensity ECRIS Extractor

- ECR ion sources used to extract I~1-2 mA of Ion beams,with a low divergence and negligible space charge effects
  - Classical extraction feature diode system with a plasma electrode and a grounded puller (as shown earlier)
- New generation high performance ECRIS produce high intensity beams of multicharged ions: the total current extracted increases typically to the range I~2-20 mA where the space charge is highly dominant
- ECRIS extractor was modified to a Triode system used fo decades in high current 1+ sources

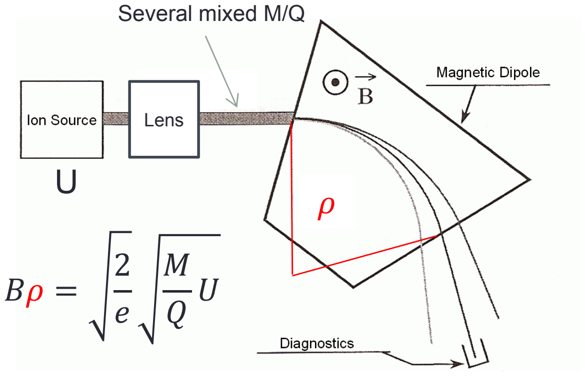


Source: D. Winklehner, LBNL,ECRIS2010

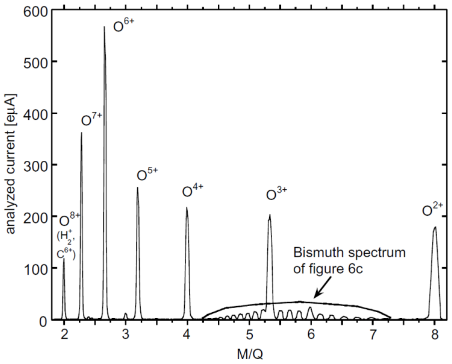


ECRIS requirements for Beam separation and transport

- The ECRIS beams are composed of several charge states of several atomic species. These beams are extracted all together, and their number is in the range ~10-50. A bending magnet with a mass separation $M/_{\delta M} \sim 100$ is necessary to cleanly separate the beam of interest from its M/Q neighbours.
- The dramatic increase of total current extracted from today high performance multicharged ECRIS (I~5-20 mA) requires a dedicated high performance Low Energy Beam Transfer Line, usually equipped at least with a focusing lens right at the exit of the source, a large acceptance beam line (Ø$_{pipe}$≥100 mm), and a large bending magnet (~100 mm vertical gap and a large ~200 mm horizonthal aperture).



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



Example of an ion spectrum from VENUS, LBNL

NIMB 235 (2005) 486–493

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Appendix

- Bush Theorem
- Motion of charged particule in E & B static field
- Plasma Sheath and Plasma Potential
- Plasma Wall Interactions

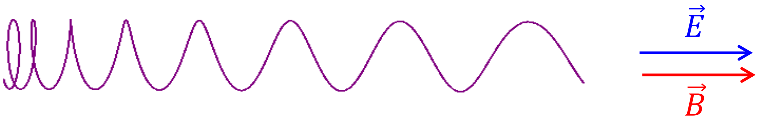
The Bush Theorem (emittance magnetization)

- 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 ($T_i \sim 300\ K$), 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: $p_\theta \rightarrow \mathrm{m}r^2\dot{\theta} = \frac{1}{2}qB_0r_0$

Motion of a particle in a static Magnetic and Electric Field

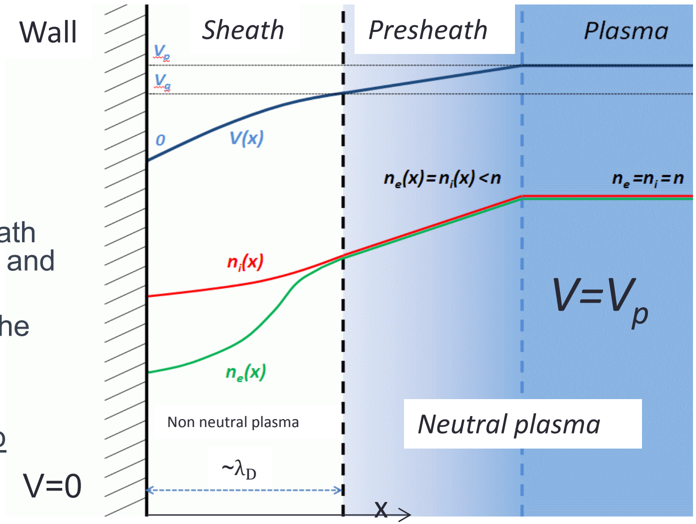
- Motion with B // E
  - $m\frac{d\vec{v}}{dt} = q\vec{v}\times\vec{B} + \vec{E} \rightarrow \begin{cases} m\frac{d\vec{v}_\perp}{dt} = q\vec{v}_\perp \times\vec{B} \\ m\frac{d\vec{v}_\parallel}{dt} = q\vec{E} \end{cases} \rightarrow \begin{cases} rotation\ with\ v_\perp = \rho\omega \\ v_\parallel = \frac{qEt}{m} \end{cases}$
  - $\rightarrow$ helix with radius ρ, angular frequency ω, variable pitch $p = \frac{2\pi v_\parallel(t)}{\omega}$



- Motion with B ⊥ E
  - $m\frac{d\vec{v}}{dt} = q\vec{v}\times\vec{B} + \vec{E} \rightarrow \vec{v} = \frac{E}{B}(\cos\omega t.\vec{e}_{\perp 1} + \sin\omega t.\vec{e}_{\perp 2}) - \frac{E}{B}.\vec{e}_{\perp 1}$
  - with $\vec{e}_{\perp 1} = \frac{\vec{E}\times\vec{B}}{EB}$ and $\vec{e}_{\perp 2} = \frac{\vec{E}}{E}$
  - $\rightarrow$ a cycloïd with a drift velocity $\vec{v}_D = \frac{\vec{E}\times\vec{B}}{}$
  - T$_{kin}$ is not constant!

The Plasma Sheath and The Plasma Potential

- In a laboratory plasma, the presence of walls forces the Plasma to auto-adapt to keep its global quasi-neutrality
- The whole plasma globally charges to reach the **Plasma Potential V_p**>0 to slow down electrons and accelerate ions to the wall in the **Plasma Sheath**
  - The sheath width is ~λ_D (Debye Length)
  - $V_p \sim 1-50$ *Volts*
- The plasma sheath is not neutral and an electric field $E \sim V_p/\lambda_D$ acts on particles
- In the plasma:
  - $n_e = n_i$, $v_i \ll v_e$, so $\varphi_i \ll \varphi_e$
- In the Sheath:
  - $\varphi_i = \mathrm{n_i}(x) v_i(x) = \varphi_e = \mathrm{n_e}(x) v_e(x)$



- **The Bohm Criterion**
  - A stable sheath implies the presence of a pre-sheath where the plasma is still neutral but local potential and densitites starts to decrease linearly.
  - Bohm has shown that the ultimate ion velocity at the boundary of the neutral plasma is :

$$v_g \geq \sqrt{kT_e/m_i}$$

  - This value should be used as an initial condition to simulate ion beam extraction from an ion source

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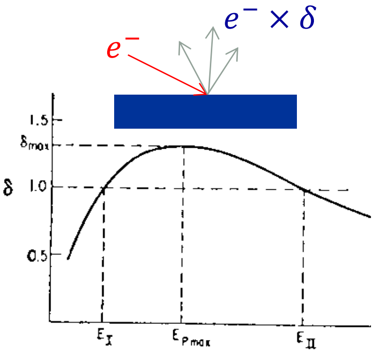
Plasma-Wall interactions

Secondary Electron Emission

- Impinging electrons to the wall generate secondary electrons flux that are accelerated toward the plasma
  - Excellent feedback effect on plasma density
  - The Yield Strongly depends on material



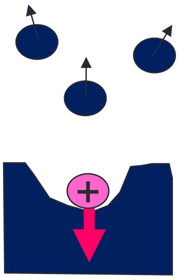
Secondary electron Yield δ vs primary electron energy

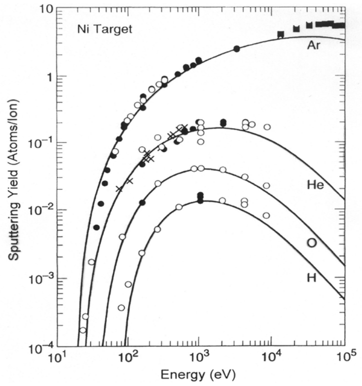
Source J. Arianer, IPNO

Element	δ_{max}	E_p (eV)
Cu	1.3	600
Fe	1.3	600
Pt	1.8	700
Ta	1.3	600
W	1.4	650
Compound	δ_{max}	E_p (eV)
NaI (crystal)	19	1300
Al2O3 (layer)	2 - 9	
MgO (crystal)	20 – 25	1500

Ion Sputtering

- Ions escaping the plasma are accelerated in the sheat to E=ZVp eV
  - Atoms are sputtered and contaminate the plasma
  - A high concern in Tokamak…





Source J. Arianer, IPNO