U.S. DEPARTMENT OF ENERGY | Office of Science

MICHIGAN STATE UNIVERSITY

FRIB

PHY862
Introduction to Ion Sources

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Facility for Rare Isotope Beams

Outline

- Overview of ion sources for accelerator and industrial applications
- Basic Physics Principles supporting ion creation
  - Design feature common to all ion sources
- Some examples of ion sources found in major US accelerator facilities
  - Electron Cyclotron Resonance Ion Source
  - Electron Beam Ion Source
  - Negative ion sources

Suggested Literature - Books

- Resources for ion source literature
  - The Physics and Technology of Ion Sources , Ian Brown.
  - Ion Sources, Huashun S. Zhang, Jianrong Zhang, Springer-Verlag, 2000
  - Handbook of Ion Sources, Bernhard H. Wolf, CRC Press, 1995
  - Electron Cyclotron Resonance Ion Sources, R. Geller, IOP Pub, 1996
  - CERN Accelerator School – *CAS* (2013), CERN-2013-007

Working on Ion source is a mix of physics and engineering

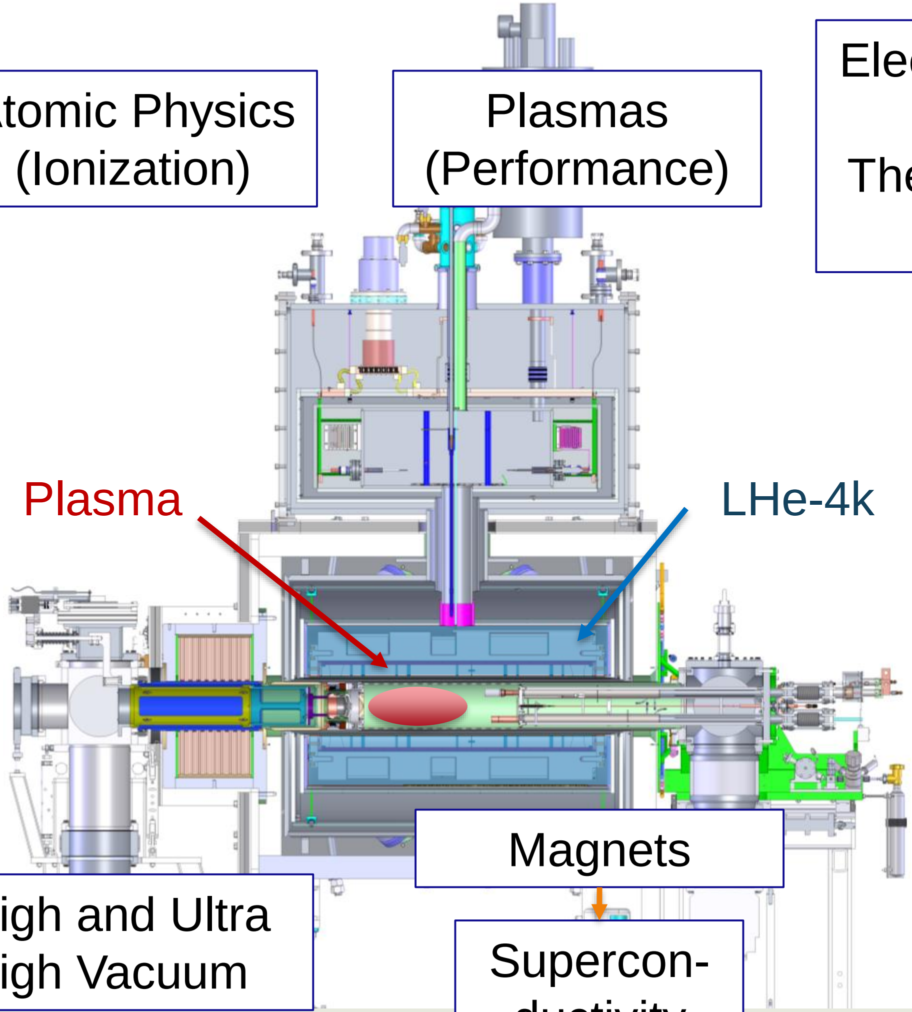
- FRIB Electron Cyclotron Resonance Ion Source

Atomic Physics
(Ionization)

Plasmas
(Performance)

Electromagnetism
and
Thermodynamics
(Design)

Beam Dynamics
(Accelerator)



Magnets

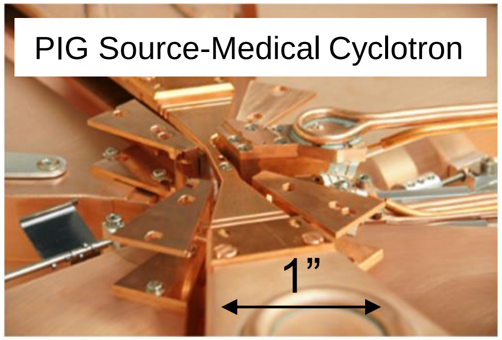
Supercon-ductivity

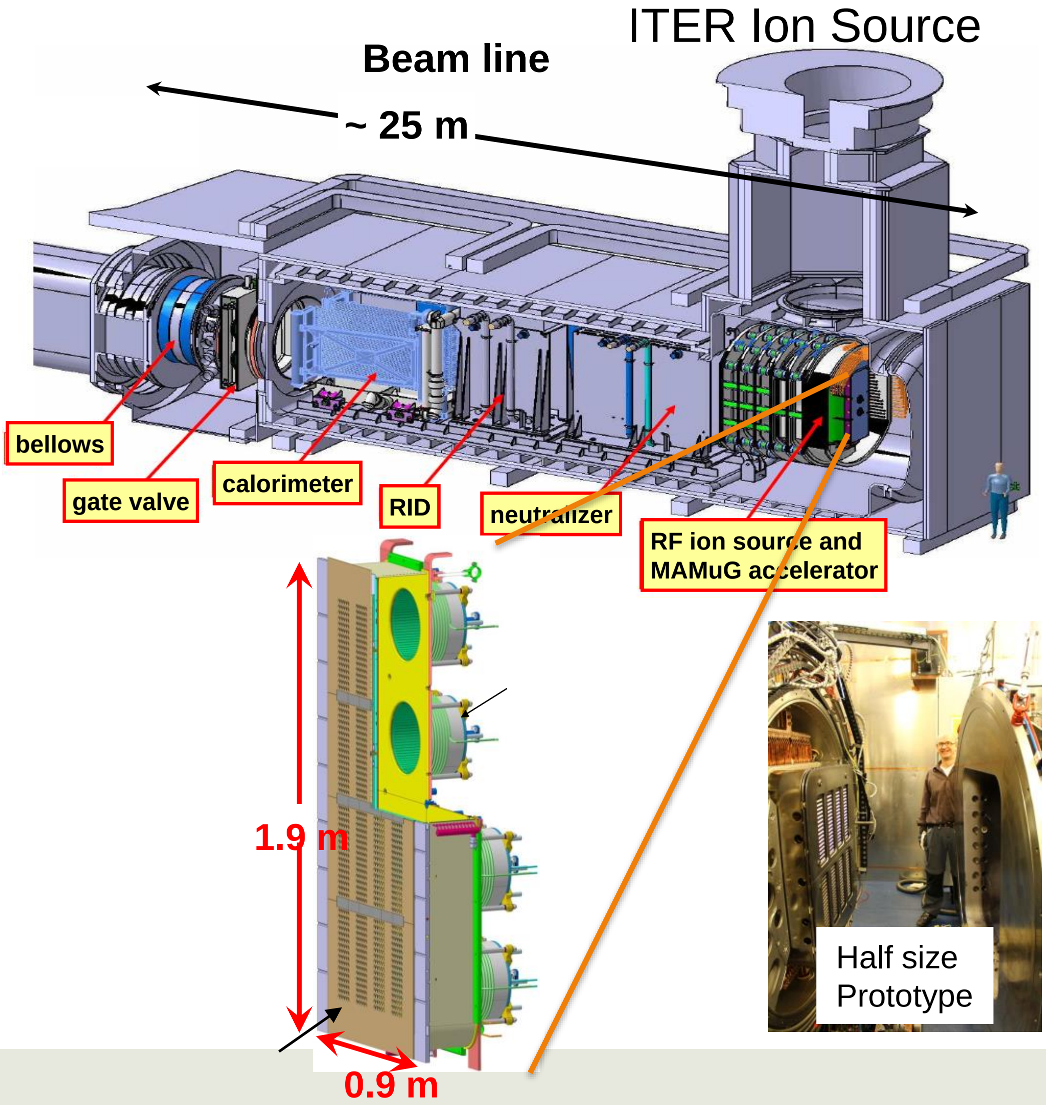
High and Ultra
High Vacuum

Microwave
Generation

High Voltage

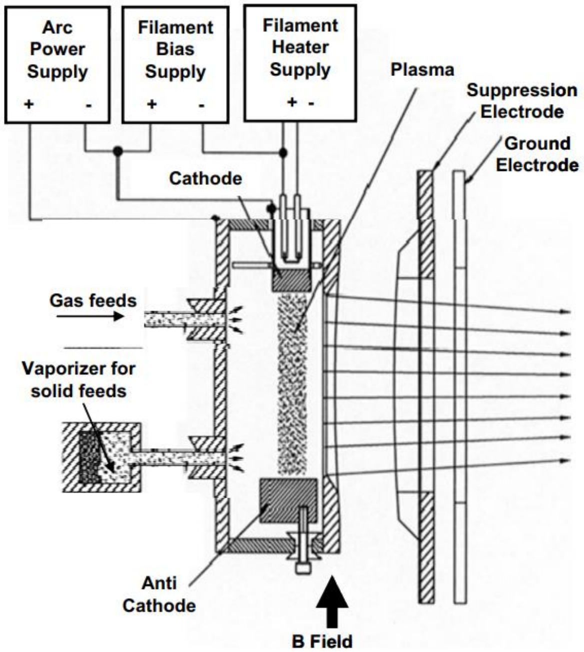
Ion Sources come in all sizes





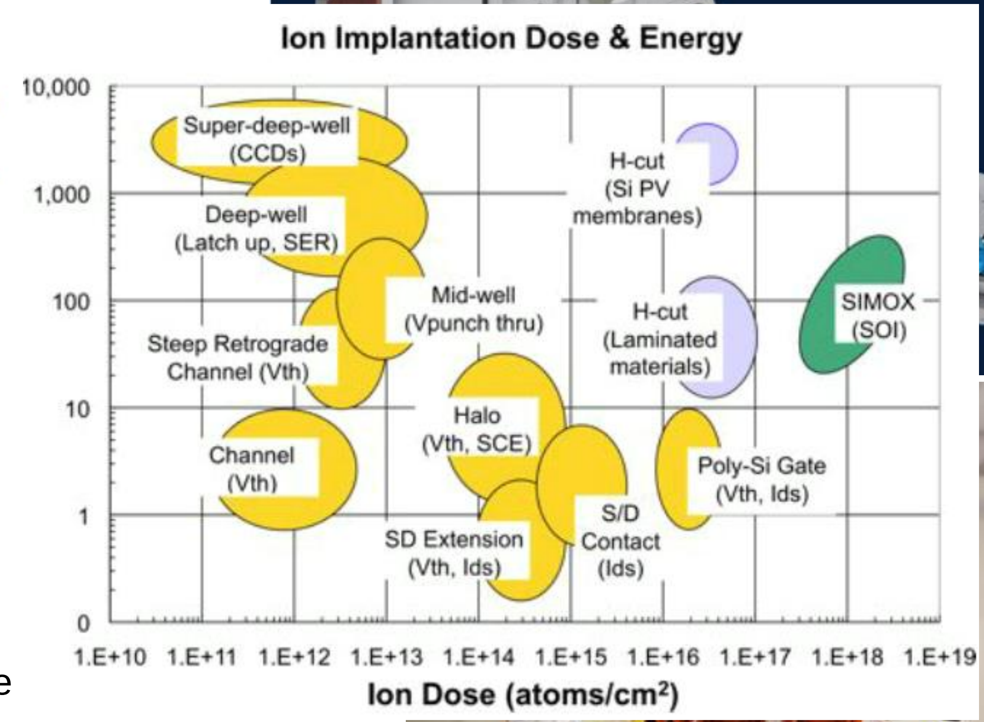
Ion Sources for Implantation

Freeman Ion Source → Bernas Ion Source → IHC Ion Source



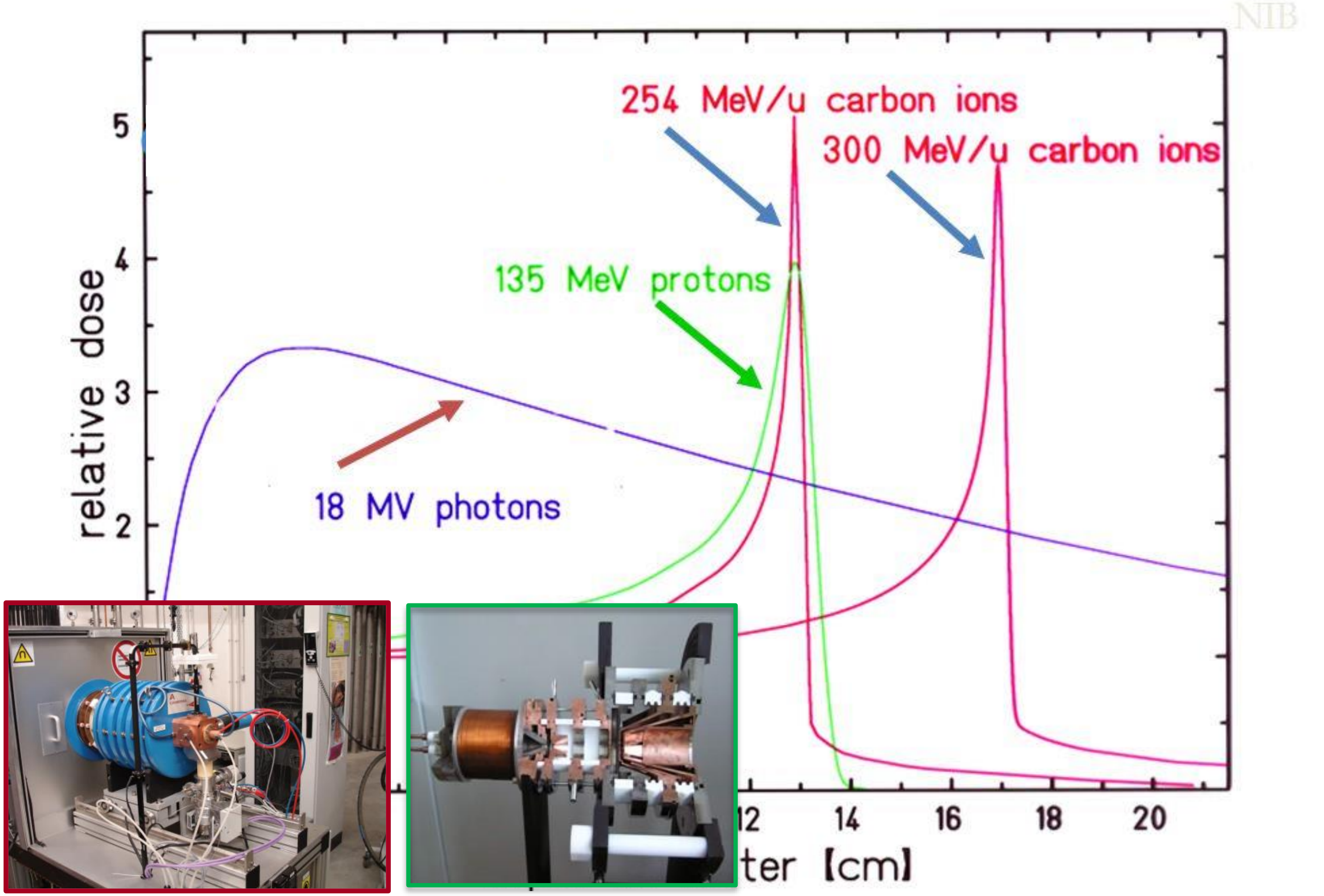
Indirectly Heated Cathode (IHC) Source

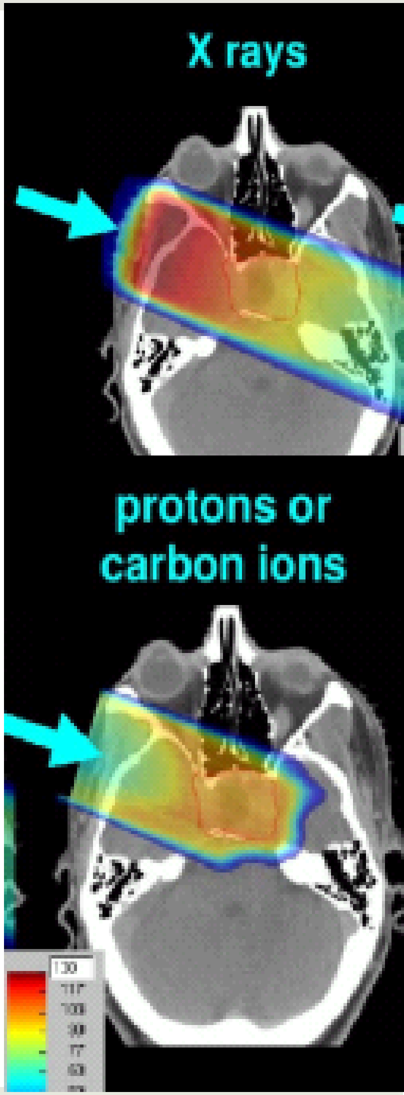
~200-400hr lifetime



Boron (Z=5) : **BF3, B2H6**
Phosporus (z=15) : **PF3, PH3**
Arsenic (z=33) : **AsH3**

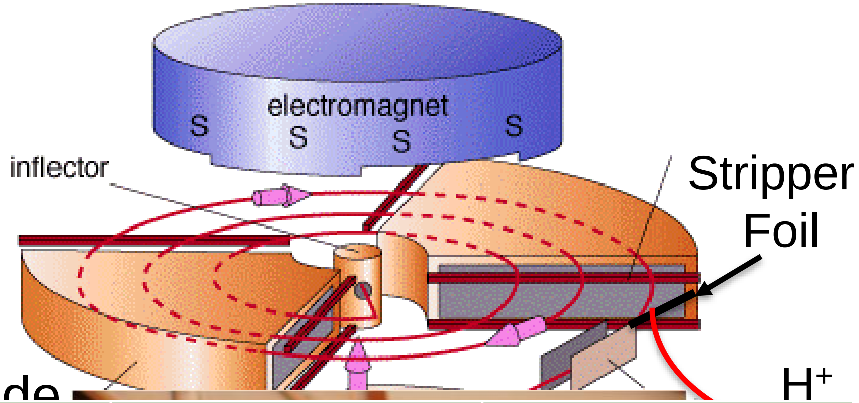
Basis of hadron use for Radiotherapy





Radioisotopes Production with Cyclotrons [2]

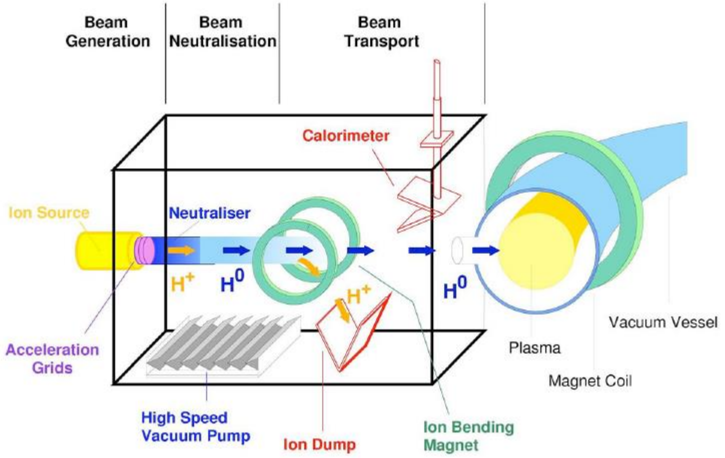
- Commercial cyclotrons are typically negative ion machines (H-)
  - Stripping foil at extraction to remove 2 electrons (H+)
  - Internal Penning Ion Gauge (PIG) ion source prefered cost effective solution (<200euA)
  - Negative ions are produced on the cathode

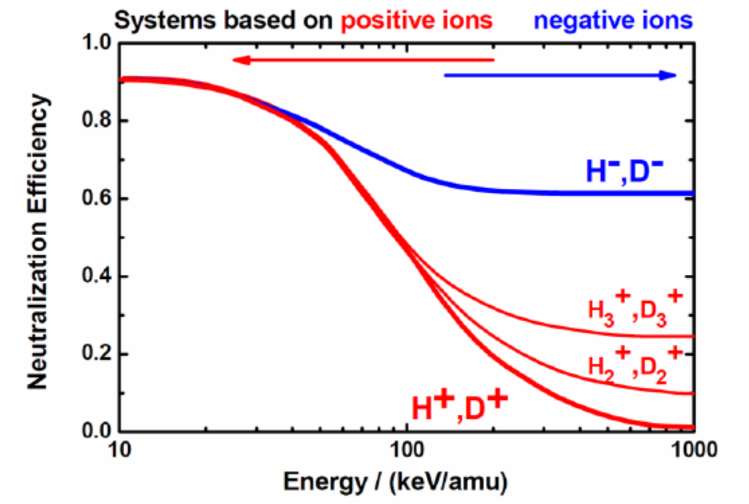


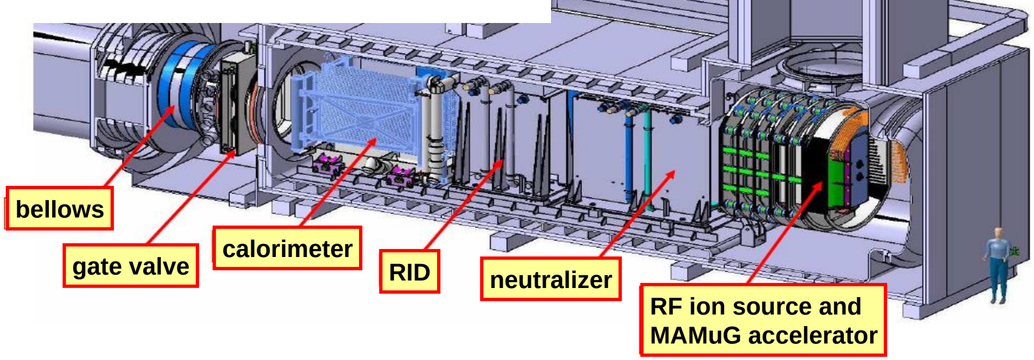
Energy	Current (euA)	Usage	Isotope	Production Location
<15 MeV	<200	Short-Lived PET Isotope	^{18}F, ^{11}C, ^{13}N, ^{15}O	On-Site (Hospital)
15-30 MeV	>400	SPECT Isotope	^{99m}Tc, $^{123\text{-}124}$I, ^{111}In, ^{103}Pd	Hospital-Local Distributor
>30 MeV	>1000	Therapy	^{77}Br, ^{186}Re, ^{211}At	Research lab/industry

Neutral Beam Injection for Fusion

- Tokamac requires heating using H^0, D^0
  - Beam Power: 15-40 MW (~1MeV-40A)

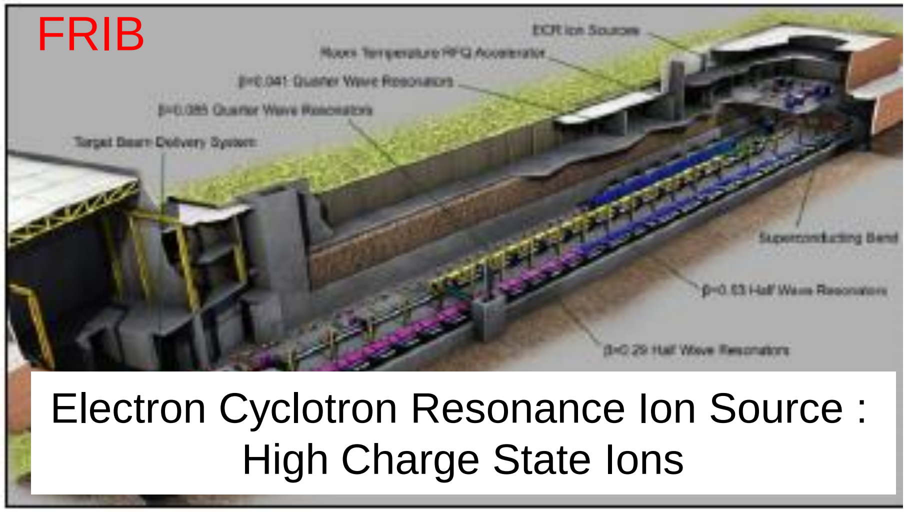




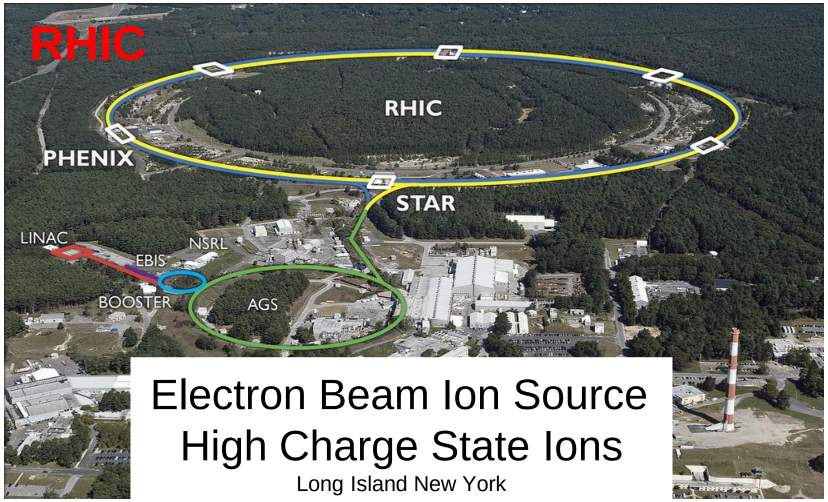


Example of ITER
▸**33 MW** injected power from 2 injectors
▸ 3600 s, **1 MeV Deuterium**

Ion Sources used for US Accelerator (Driver)



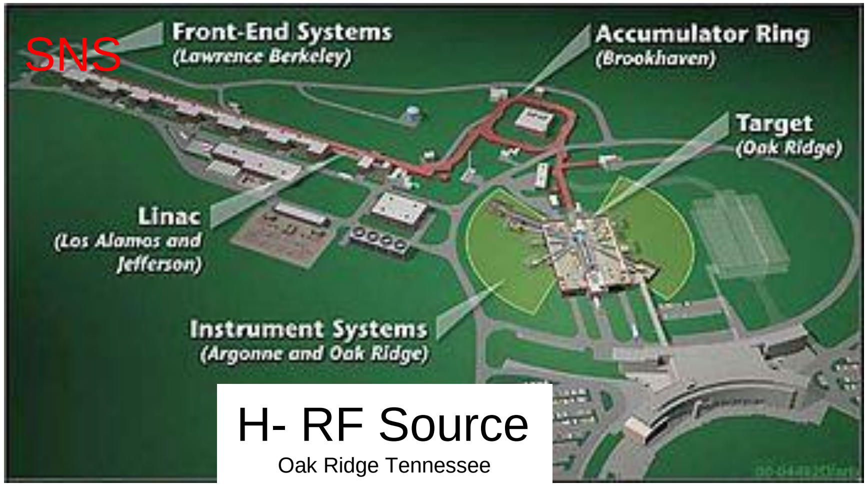
Electron Cyclotron Resonance Ion Source : High Charge State Ions



Electron Beam Ion Source High Charge State Ions

Long Island New York

- Also ECRs used at:
  - ATLAS ANL (Argonne Illinois),
  - 88' Cyclotron at LBNL (Berkeley Ca),
  - Texas AM (College Station, TX)



H- RF Source

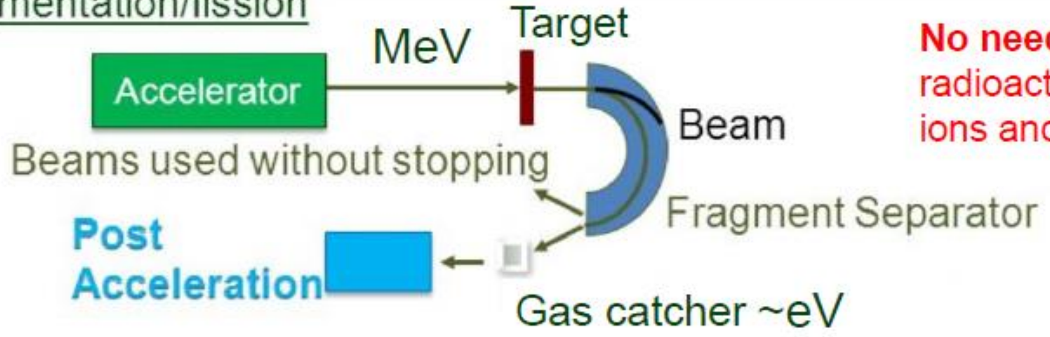
Oak Ridge Tennessee

Ion Sources for Radioactive Isotopes (RIB)

There exists a few techniques and facilities to produce radioactive beams

NSCL/FRIB

- In-flight Separation following nucleon transfer, fusion, projectile fragmentation/fission



No need for an ion source. The radioactive isotopes are produced as ions and decelerated in a gas catcher

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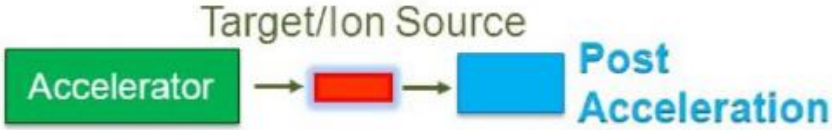
Next Slide

Target spallation and fragmentation by light ions (ISOL – Isotope separation on line)



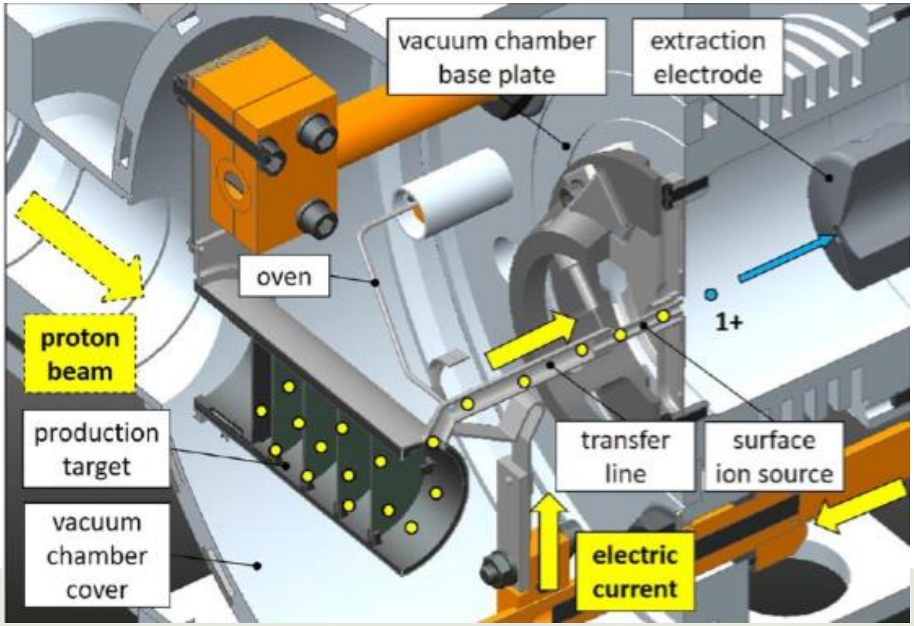
An ion source is needed to ionize radioactive isotopes produced as neutral atoms

Ion Sources for Radioactive Isotopes (RIB)

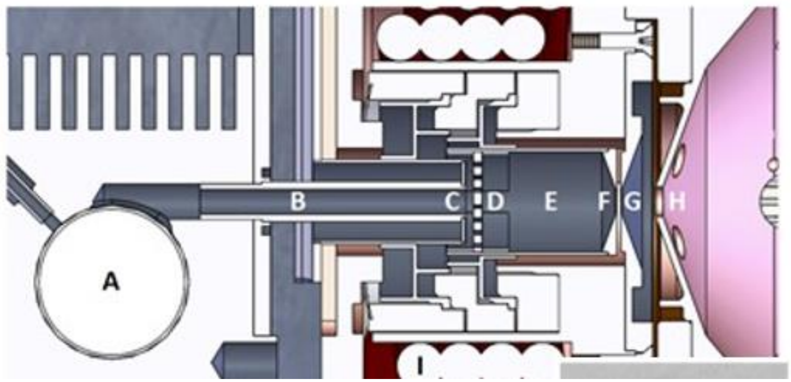
Mostly Found in CERN and TRIUMF (Canada)

- Unl
ion sources are not a separate design but they are sources optimized for radioactive beam production
- The entire system from isotope production, to particle transfer to the ion source, to ionization, and ion extraction is all optimized for maximum efficiency
- That is because unlike stable isotopes that are abundant, radioactive isotopes are typically produced only in minute quantities and can decay with short half-lives

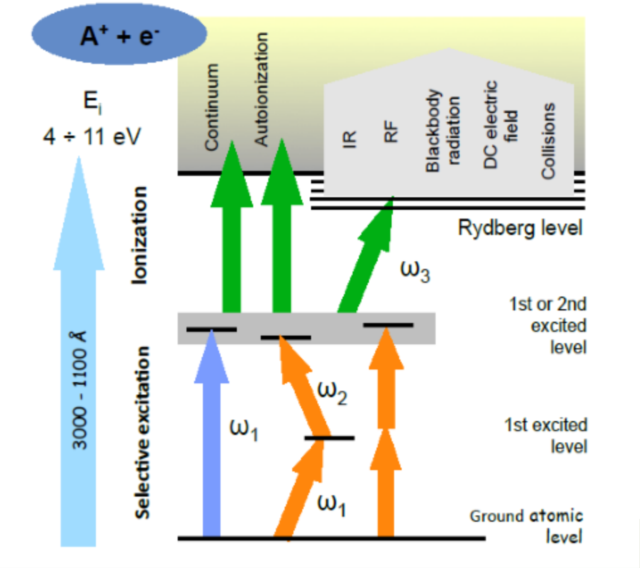
Surface Ionization



FEBIAD ion source at TRIUMF

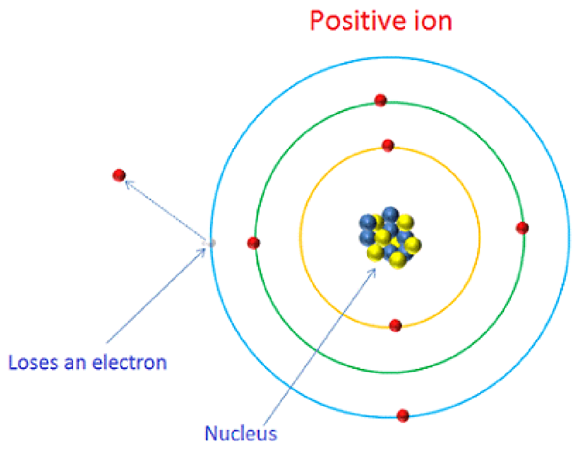


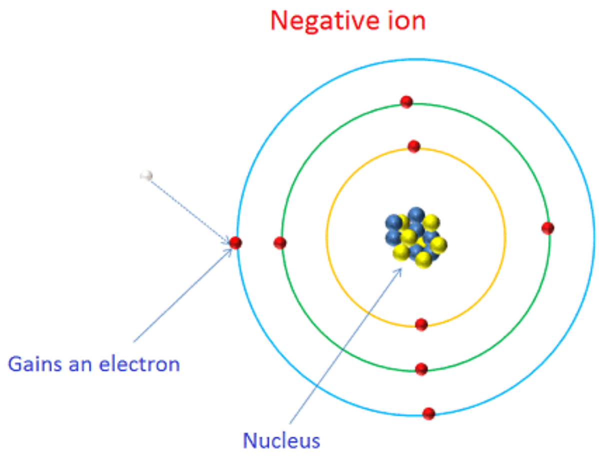
Resonant ionization laser ion source (RILIS)



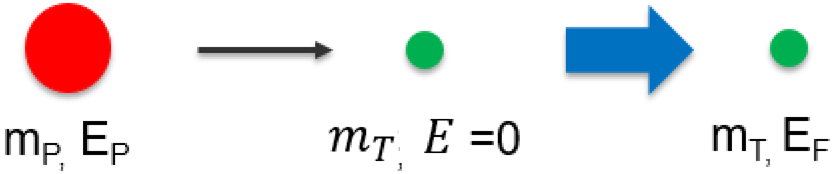
Ion Definition

- An **ion** (/ˈaɪən, -ɒn/) is an atom or molecule that has a non-zero net electrical charge due to the removal or addition of one or more bound electrons
- Mechanism for ionization:
  - **electron impact ionization**,
  - photo-induced ionization
  - surface ionization..
- Definition of electron impact ionization :
  - **removal of electrons bound to an atom using free electrons as projectiles**
- Definition of ionization energy (E_I)
  - Energy needed to free bound electron from atom potential with zero kinetic energy





Why electron are good projectiles for ionization?



Maximum Energy Transferred to Target for elastic collision:

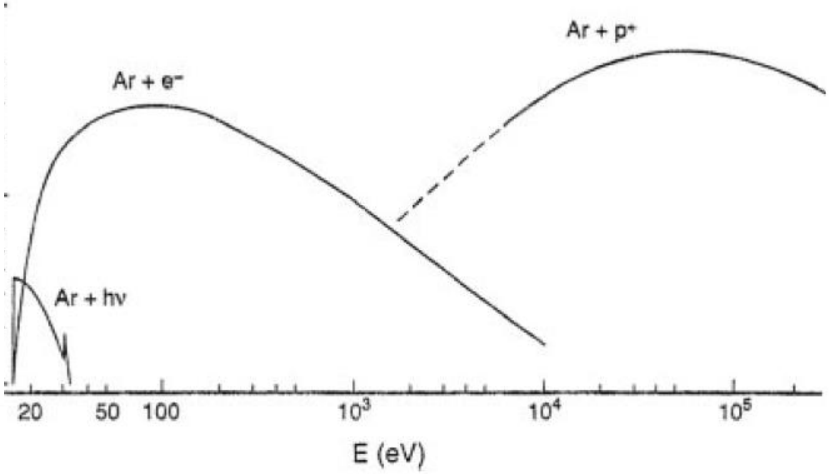
$$\boxed{E_F = \frac{4 m_T m_P}{(m_T + m_P)^2} E_P}$$

Proton to electron

$$m_P \gg m_T \, ; E_F \approx 2.10^{-3} E_P$$

Electron to electron

$$m_P = m_T \, ; \underline{E_F = E_P}$$

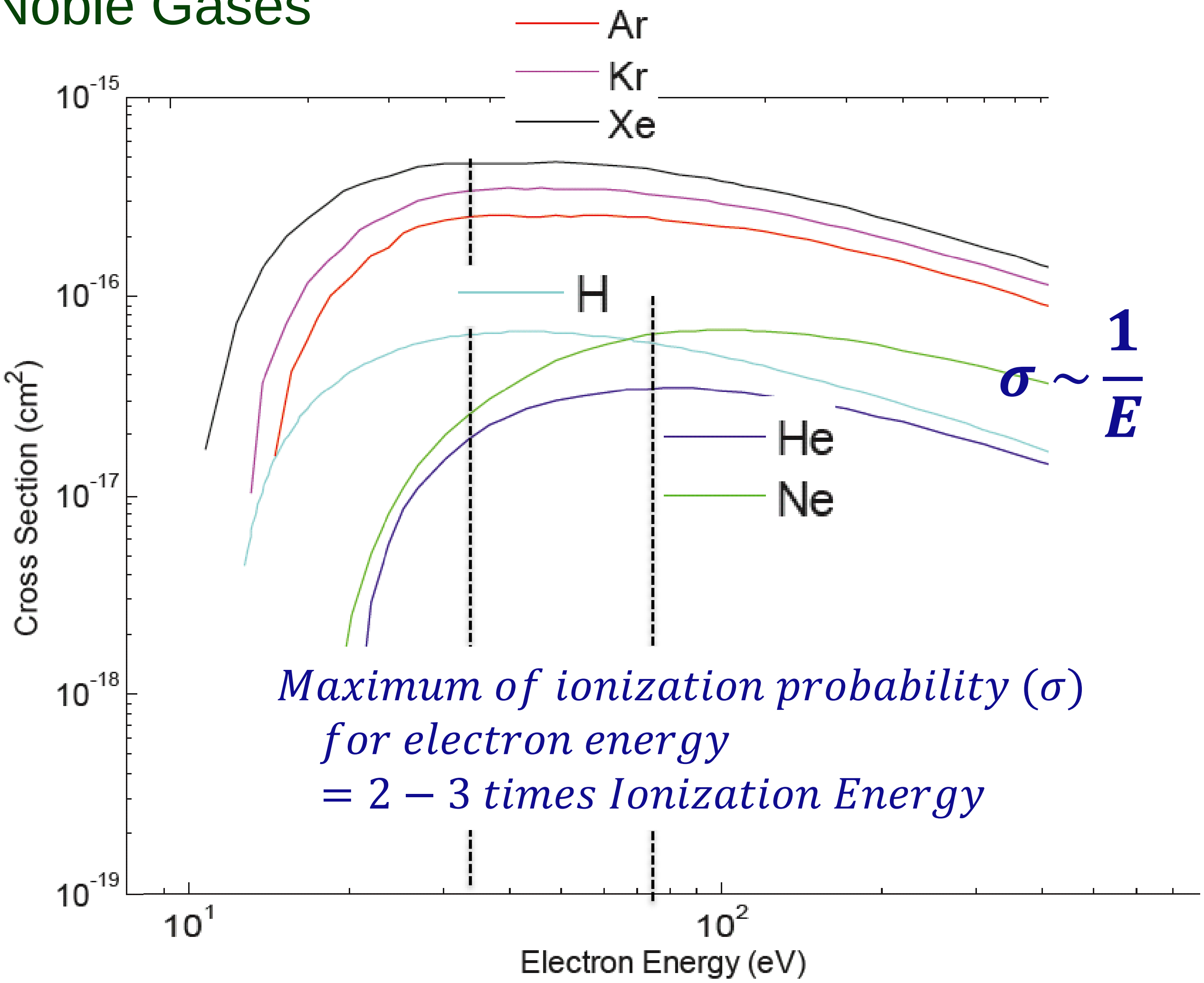


Ionization cross sections for Ar as a function of energy for ionizing collisions with electrons, protons, and photons. (From H. Winter, in Experimental Methods in Heavy Ion Physics, Springer-Verlag, Berlin, 1978). ***Ian Brown Handbook***

Electron impact ionization cross section

- Singly charged ions: Noble Gases

Element	Ionization Energy(eV)
Xenon	12.13
Hydrogen	13.6
Krypton	14.00
Argon	15.76
Neon	21.56
Helium	24.59



$$\sigma \sim \frac{1}{E}$$

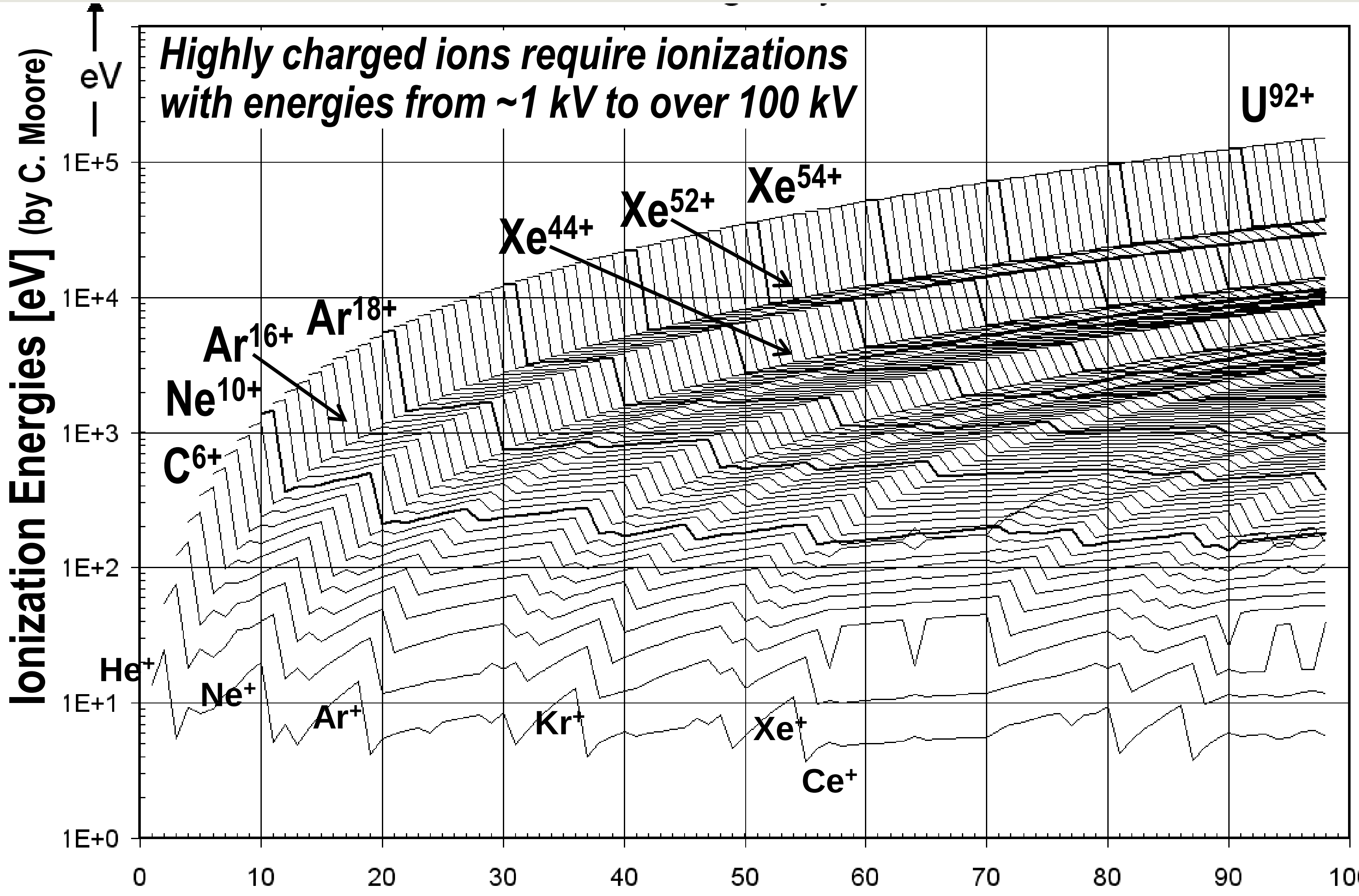
$Maximum\ of\ ionization\ probability\ (\sigma)$
$for\ electron\ energy$
$= 2 - 3\ times\ Ionization\ Energy$

Ionization energy increased quickly with charge State

Highly Charged Ions

Multiple Charged Ions

Singly Charged Ions



Ionization Cross Section for higher Charge State

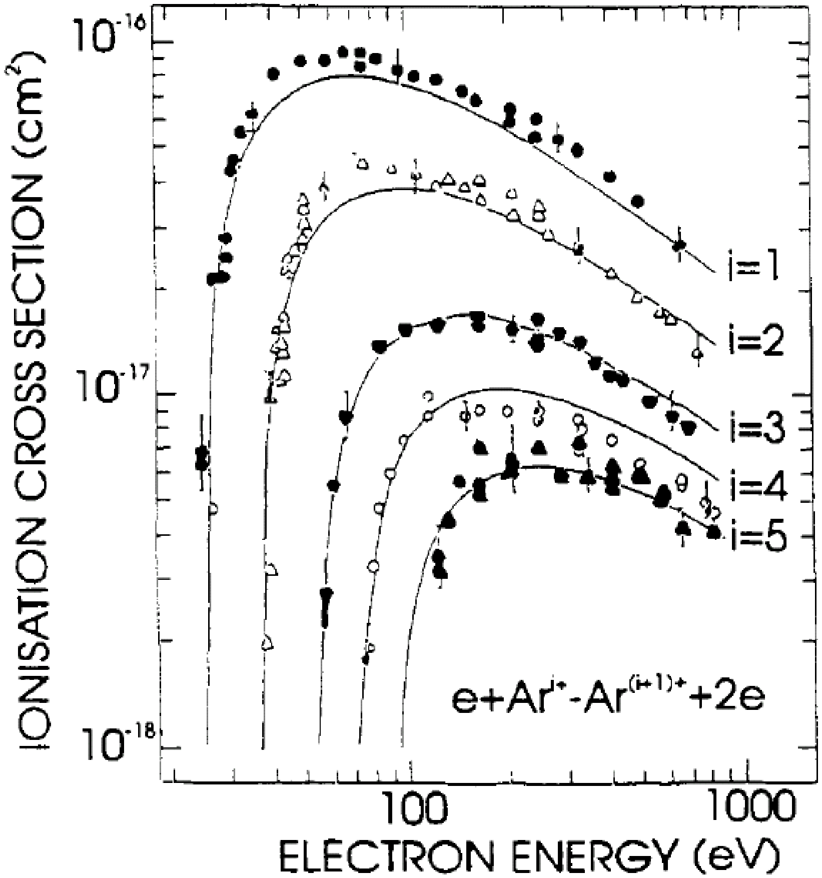


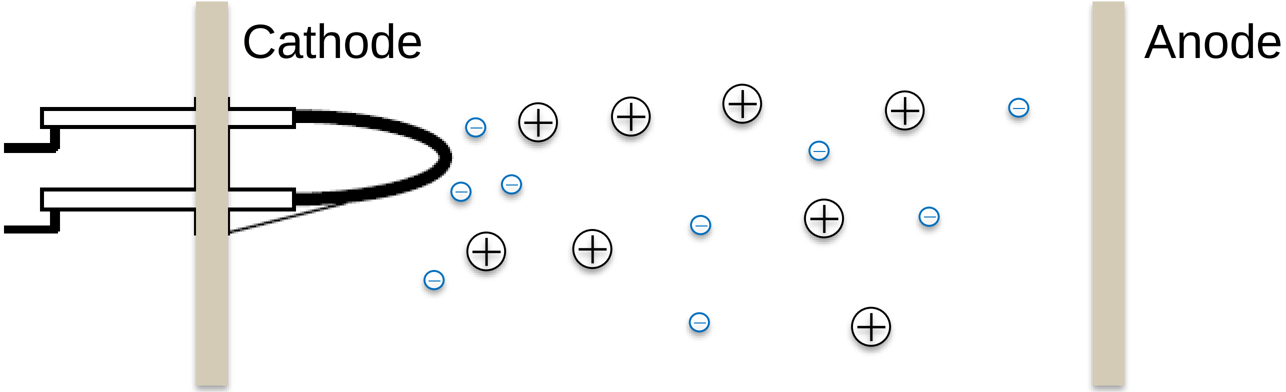
Fig. 2 Ionization cross-section versus bombarding electron energy for different charge states

Ionization cross section decrease quickly with charge state

The projectile is getting smaller With higher charge state!

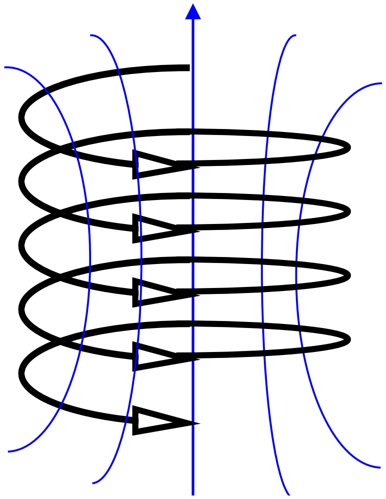
Generating and Accelerating Electrons Lead to Sustained Discharge

- Many sources work on the principle of a cathode – anode gas discharge
  - Electrons from a hot cathode are accelerated into the gas by a cathode to anode voltage, and ionize the gas atoms / molecules with electron impact ionization.
  - The creation of significant numbers of ions and electrons from the initial gas will lead to the possibility of sustaining a discharge i.e., the current flowing between cathode and anode electrodes is no longer dominated by the thermionic electrons from the cathode, but by new ions and electrons created from the gas, as well as secondary electrons from ion impact on the cathode surface.

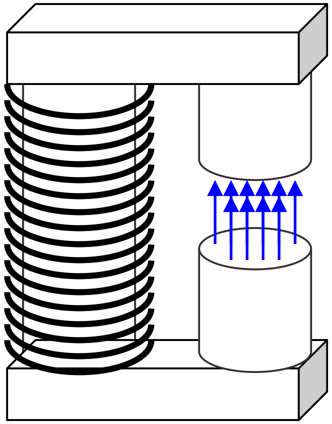


Confining charged particles

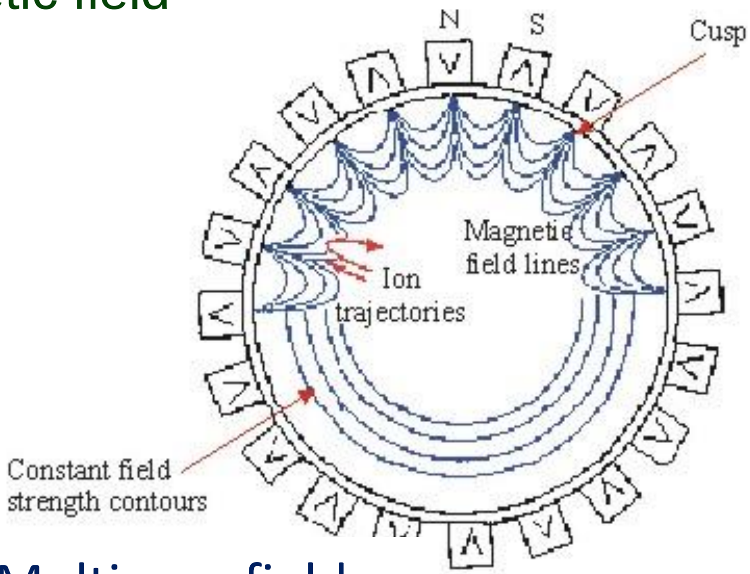
- In the direction of the fields there is no force, transverse the particles are bend into the circular motion
- Helical motion increases the time the electron send in the discharge chamber- field lines can only be crossed through collisions – wall losses are reduced
- Add strongly increasing magnetic field as the confinement mechanism: Particles get reflected by an increasing magnetic field



Solenoidal field

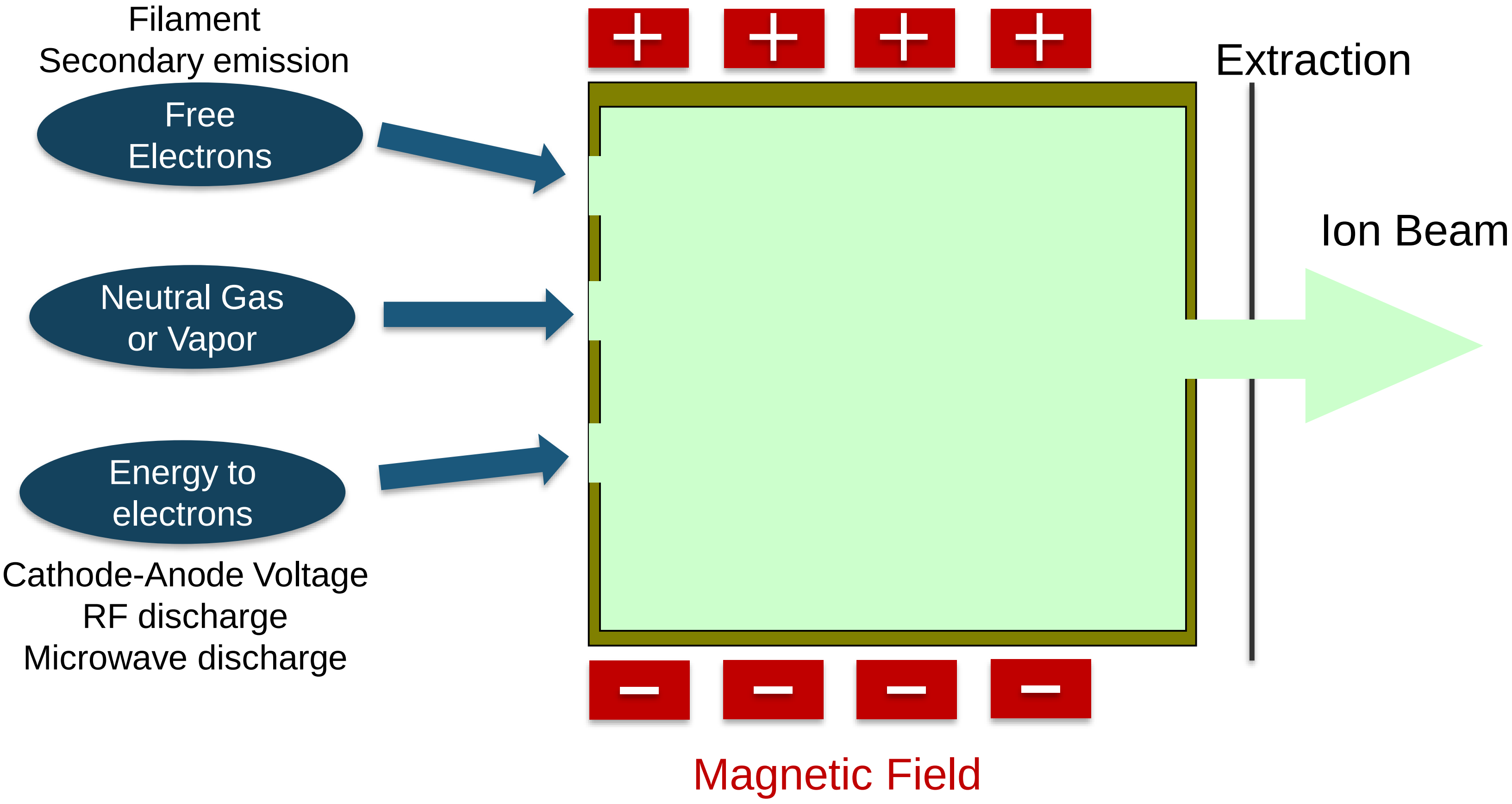


Dipole field



Multicusp field

Ion Source Components



Filament
Secondary emission

Free Electrons

Neutral Gas or Vapor

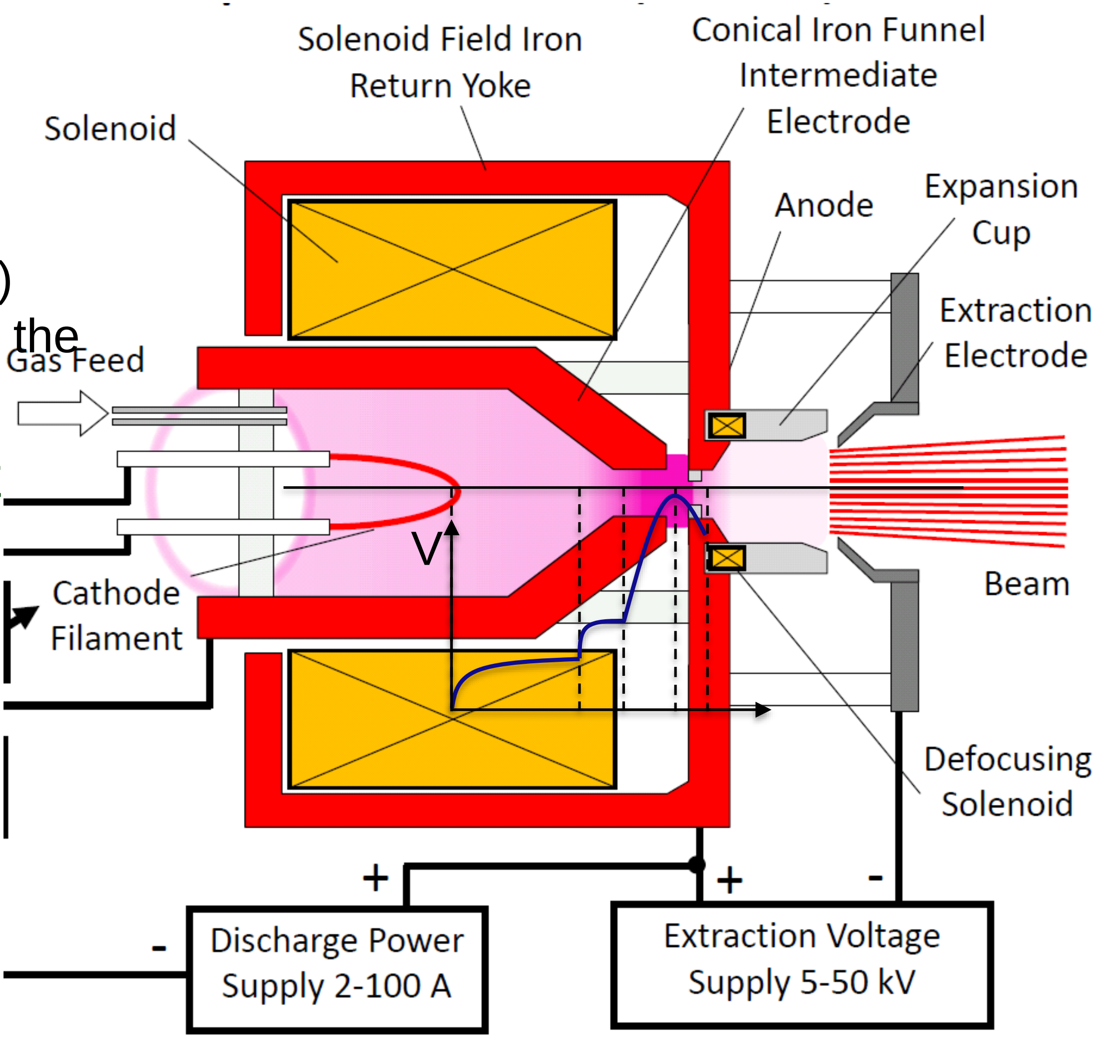
Energy to electrons

Cathode-Anode Voltage
RF discharge
Microwave discharge

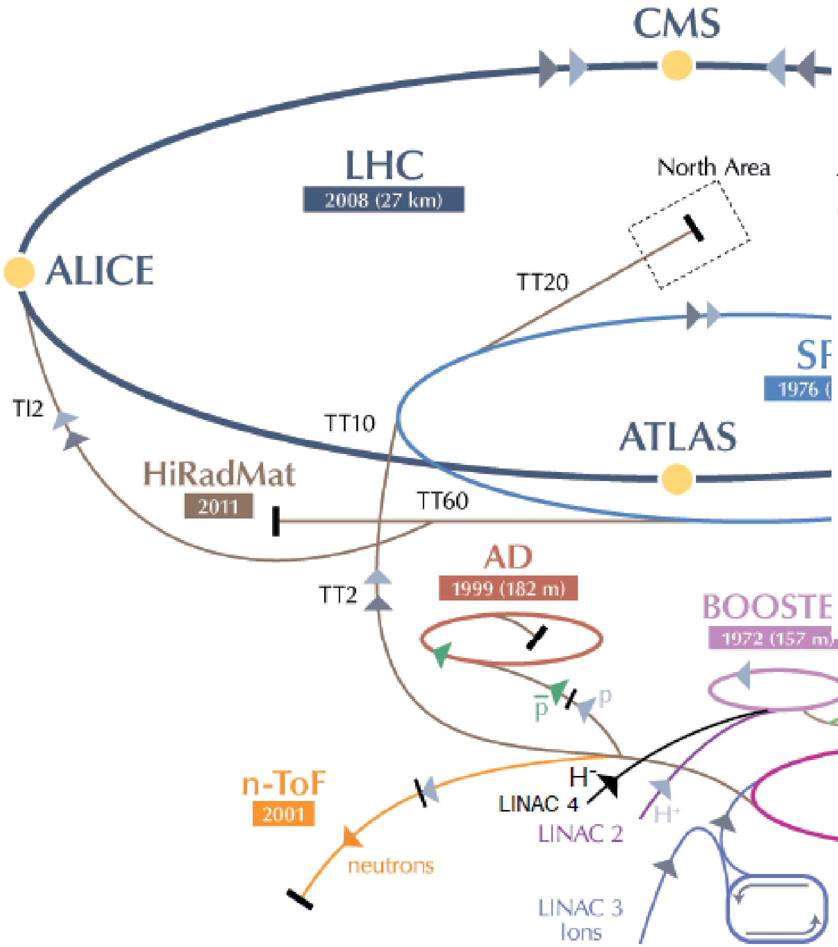
Magnetic Field

Duoplasmatron

- Developed by Ardenne 1956
  - 2^{nd} constriction of discharge through strong magnetic field. This increase:
    - The plasma density (10^{14} cm^{-3})
    - The potential difference across the restriction
- Main tuning knob is to adjust the electron emission to optimize potential profile
- Used in many accelerator facility: CERN, GSI
- Can be used for positive or negative ions
- Can extract 100emA



CERN Accelerator



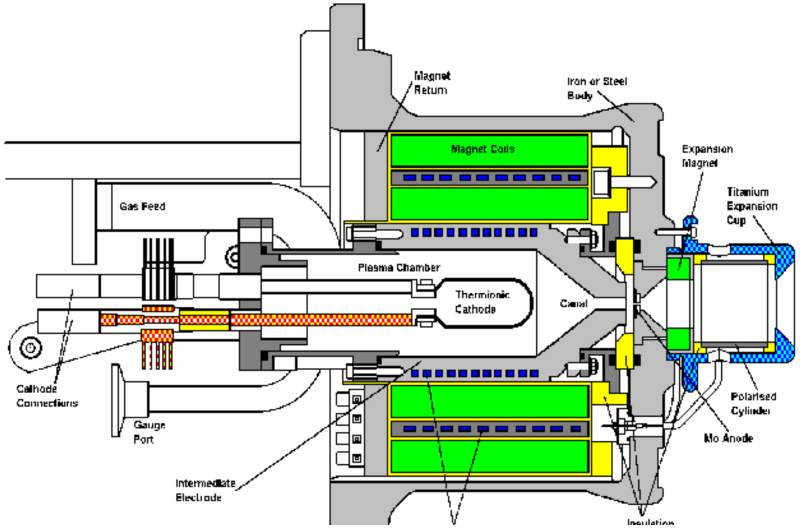
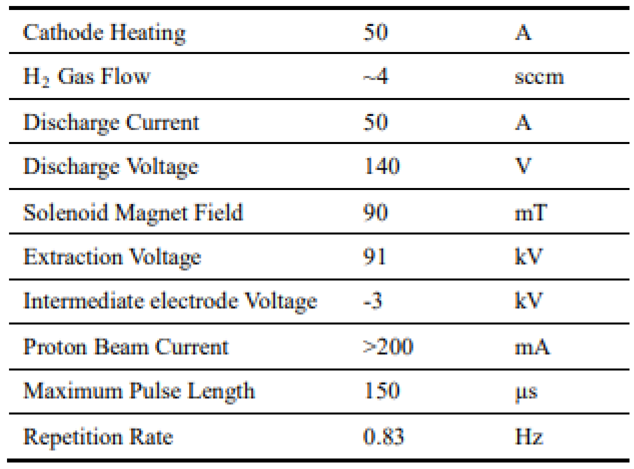


Table 1. Parameters of the Duoplasmatron proton source at CERN's Linac2



Cathode Heating	50	A
H_2 Gas Flow	~4	sccm
Discharge Current	50	A
Discharge Voltage	140	V
Solenoid Magnet Field	90	mT
Extraction Voltage	91	kV
Intermediate electrode Voltage	-3	kV
Proton Beam Current	>200	mA
Maximum Pulse Length	150	µs
Repetition Rate	0.83	Hz

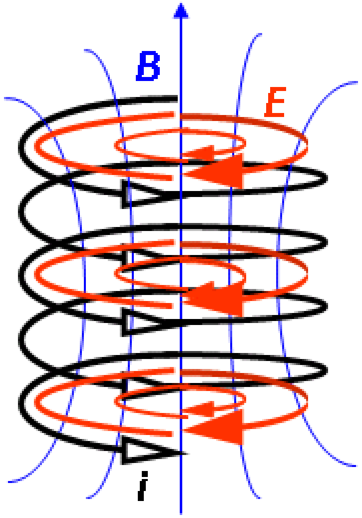
RF Driven Ion Sources

- The 2nd Maxwell Equation describes a curling *E* field generated by a changing magnetic field in absence of any charges!

$$\Delta \times E = -\frac{\partial B}{\partial t}$$

- A changing magnetic field *B* can be produced with an alternating current $i = i_0 . \cos(\omega t)$ in N windings with radius r_0:

$$B = \frac{1}{2}\mu_0 \frac{N.i}{r_0}$$



- Now integrate Maxwell's equation to get Faraday's law and solve for *E*

$$\int E.ds = -\frac{d\phi_B}{dt} = -\frac{d}{dt}\int B.dS$$

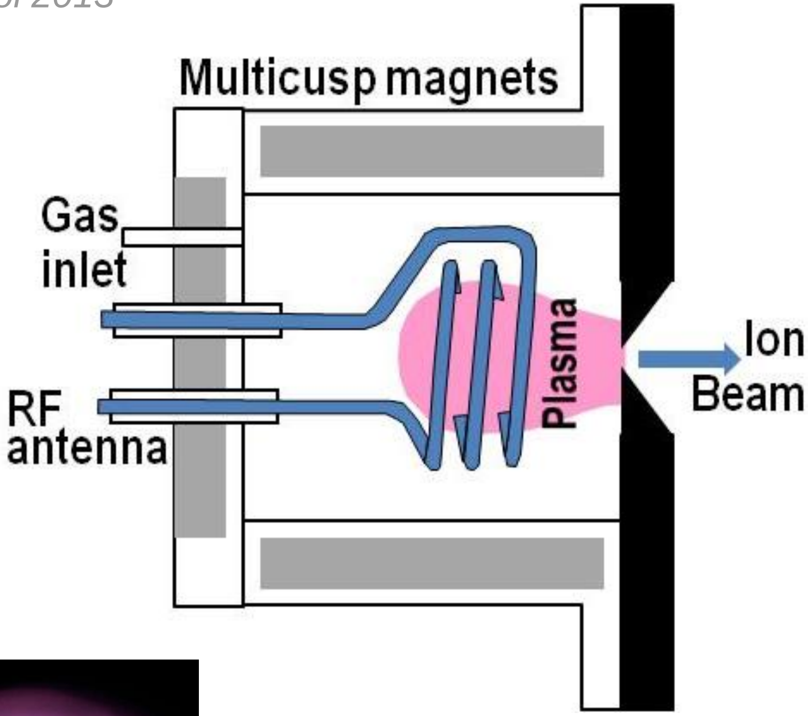
$$E(r,t) = \frac{1}{4}\frac{r}{r_0}.\mu_0 \omega N i_0 . \sin(\omega t)$$

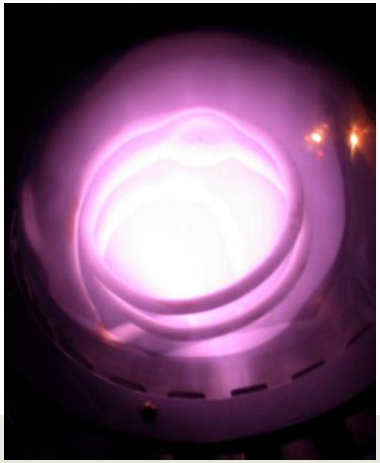
(Adapted from: M. Stöckli, US-CERN-Japan Accelerator School 2013)

Example LBNL RF driven Multicusp Ion Source

Adapted from: M. Stöckli, US-CERN-Japan Accelerator School 2013

- In 1990 LBNL replaced the filament in their multicusp ion source with a 3-turn antenna, driven by 2 MHz.
- In 1992-1994 this source was tested for SSC yielding up to 100 mA for 0.1 ms at 10 Hz.
- 1999-2001 LBNL developed this source for SNS, hoping to eventually reach the 7% duty factor.

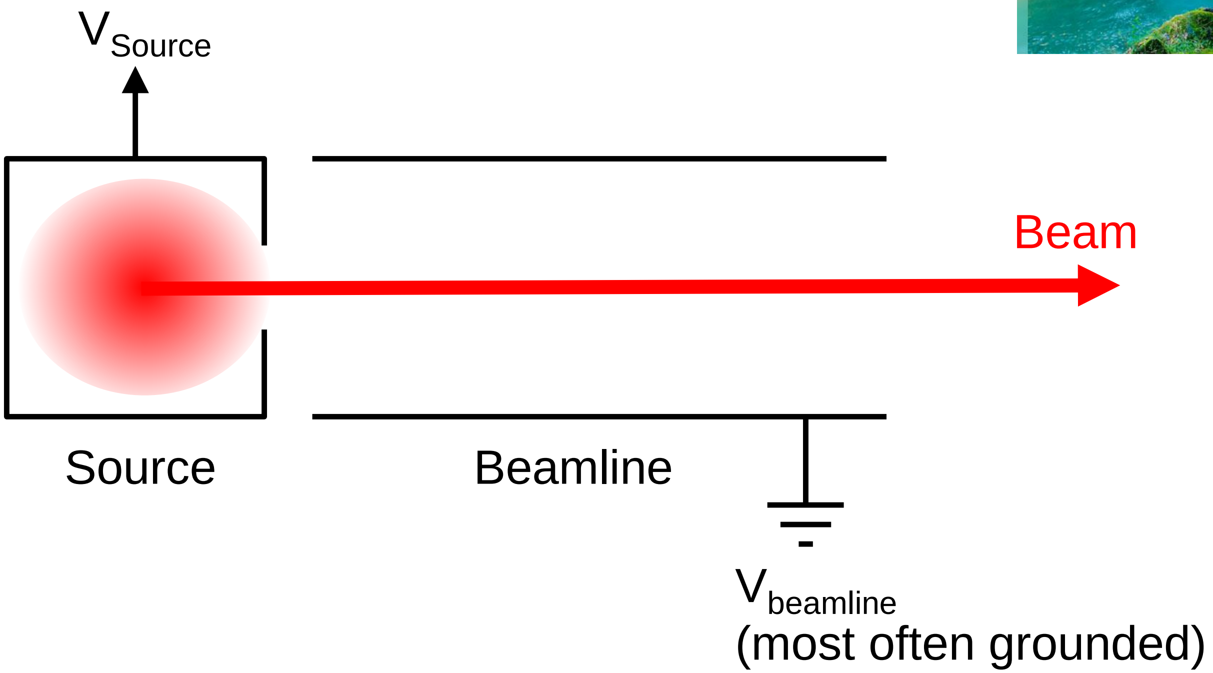




In 2001 the plasma was visualized by replacing the stainless steel source chamber with a glass dome surrounded by identical cusp magnets

Beam Extraction [1]

- The extraction of the ion source is here to produce a beam from the plasma generator.
  - Done by Applying a high voltage between plasma boundary and an extraction electrode



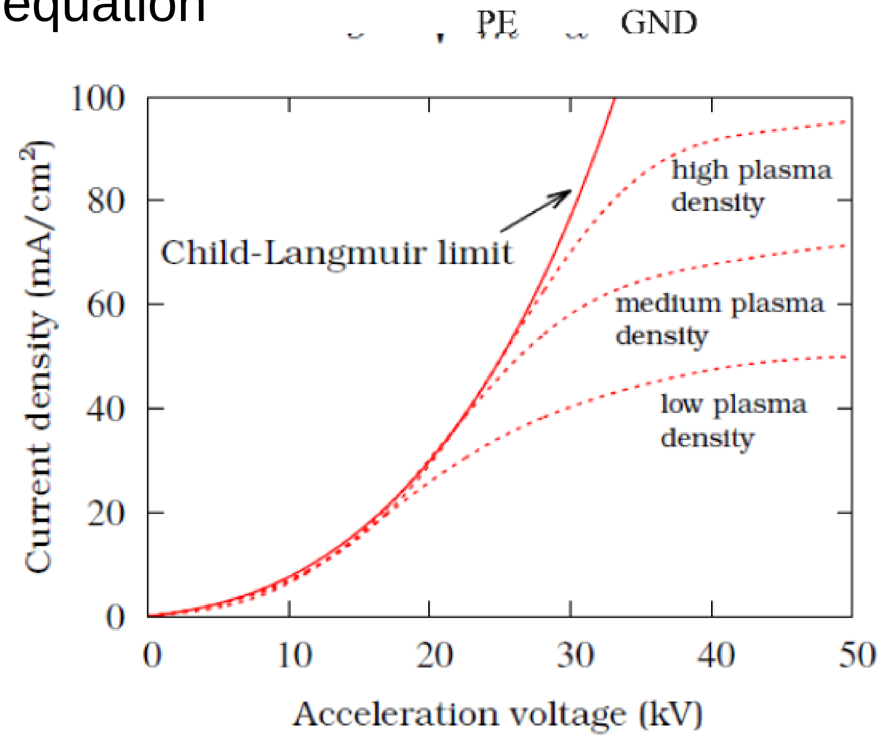
$$E_{kin} = q(V_{Source} - V_{Beamline})$$

$$\boxed{E_{kin} = qV_{Source}}$$

Child-Langmuir Law

- As the current density extracted from the ion source increase, the space charge of the beam in front of the meniscus slows the extraction of ions within the plasma to the point that it will eventually cancels out the extraction field.
  - This is given by the Child-Langmuir equation

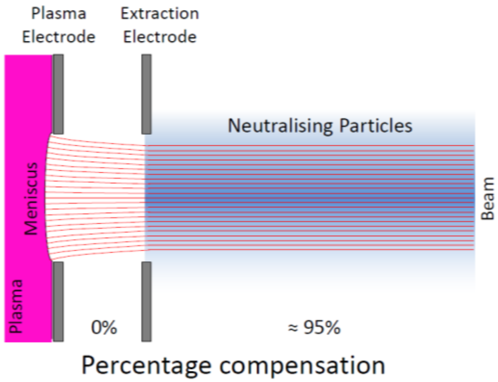
$$J_{Lim} = \frac{4}{9}\varepsilon_0 \frac{\sqrt{\frac{2eq_i}{m_i}}V^{\frac{3}{2}}}{d^2}$$

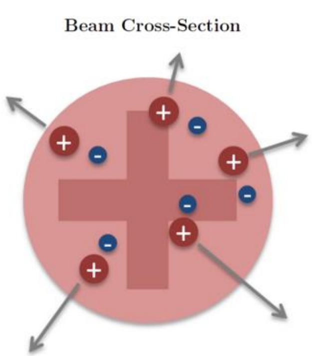


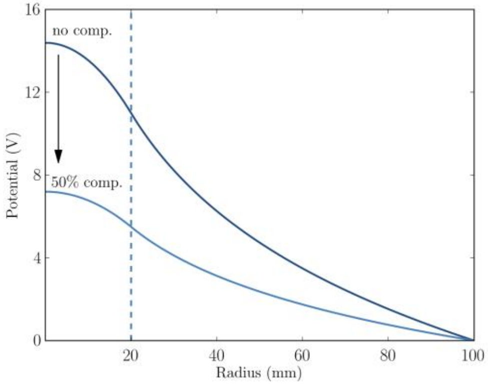
  - V is the acceleration voltage, d gap suppression electrode, m_i, q_i the ma

Notion of emittance and Space Charge

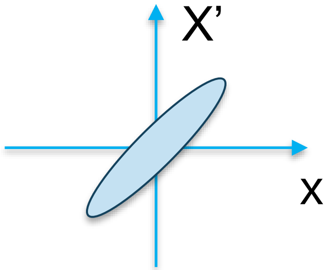
- Space charge
  - Coulomb repulsion between positive particle of ion beam







- Emittance
  - Defined as the product of beam size and divergence angle and is represented as plots of divergence angle versus transverse position
  - Calculation usually made for area that enclosed 95% of particle or r.m.s



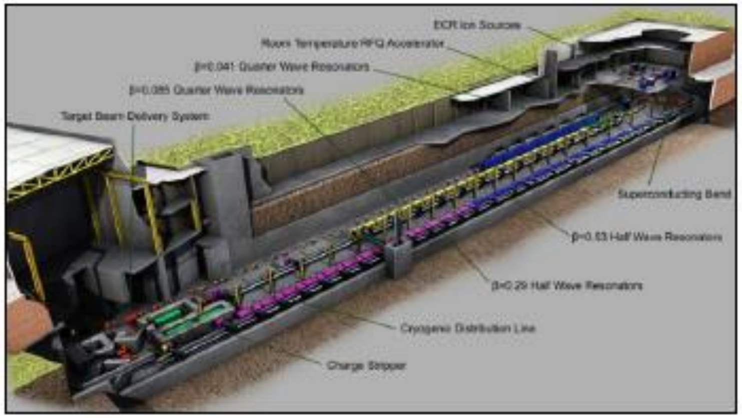
$$\epsilon_{rms} = \sqrt{\langle x^2\rangle\langle x'^2\rangle - \langle xx'\rangle^2} \quad [mm\text{-}mrad]$$

$$\langle x^2\rangle = \frac{\iiiint x^2 f(x,y,x',y')dxdydx'dy'}{\iiiint f(x,y,x',y')dxdydx'dy'}$$

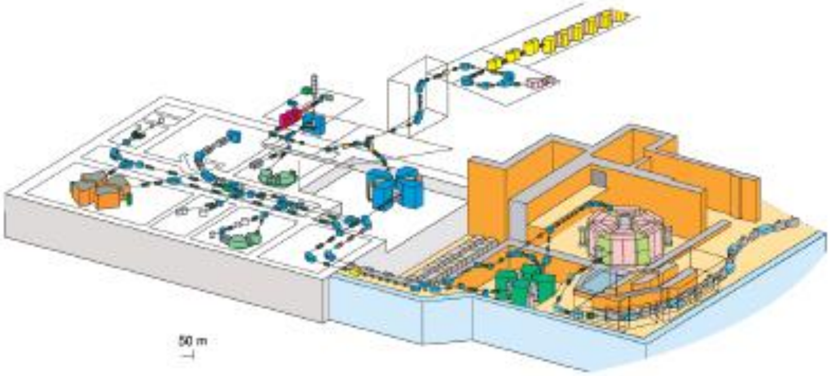
- Ion temperature and Magnetic Field are main contribution to emittance

Electron Cyclotron Resonance Ion Source (ECRIS)

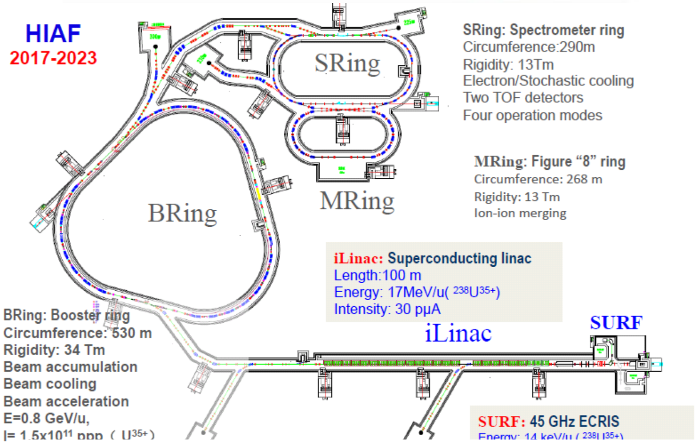
Projects worldwide that needs high intensity high charge state ion beams



MSU FRIB U^{33+} + U^{34+} 13 pμA/ CW



RIKEN RIBF U^{35+} 15 pμA/ CW



SRing: Spectrometer ring
Circumference:290m
Rigidity: 13Tm
Electron/Stochastic cooling
Two TOF detectors
Four operation modes

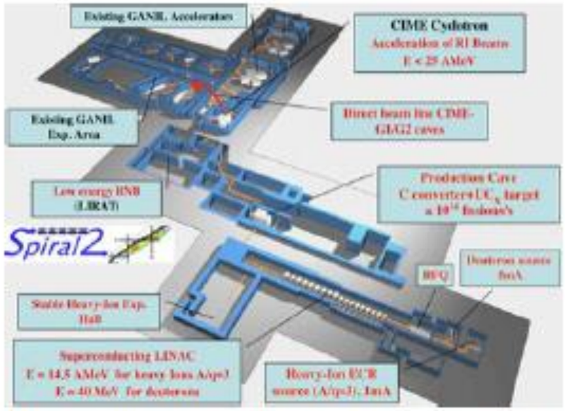
MRing: Figure “8” ring
Circumference: 268 m
Rigidity: 13 Tm
Ion-ion merging

iLinac: Superconducting linac
Length:100 m
Energy: 17MeV/u($^{238}U^{35+}$)
Intensity: 30 pμA

BRing: Booster ring
Circumference: 530 m
Rigidity: 34 Tm
Beam accumulation
Beam cooling
Beam acceleration
E=0.8 GeV/u,
I= $1.5x10^{11}$ ppp（U^{35+}）

SURF: 45 GHz ECRIS
Energy: 14 keV/u ($^{238}U^{35+}$)

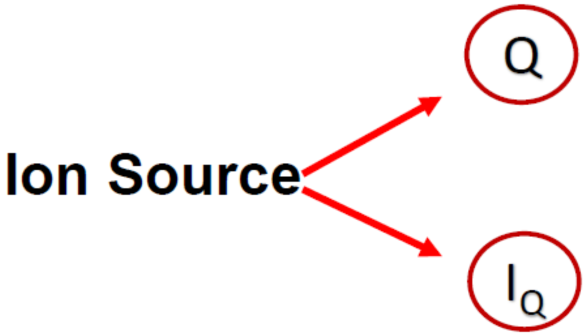
HIAF China,
U^{35+} $20p\mu A\ CW, 50\ p\mu A\ Pulsed$



1.0 emA q/A=1/3 and intense heavy ion beams of q/A=1/6~1/7 (optional)

! Very Challenging Projects

Advantages of high charge states for injector

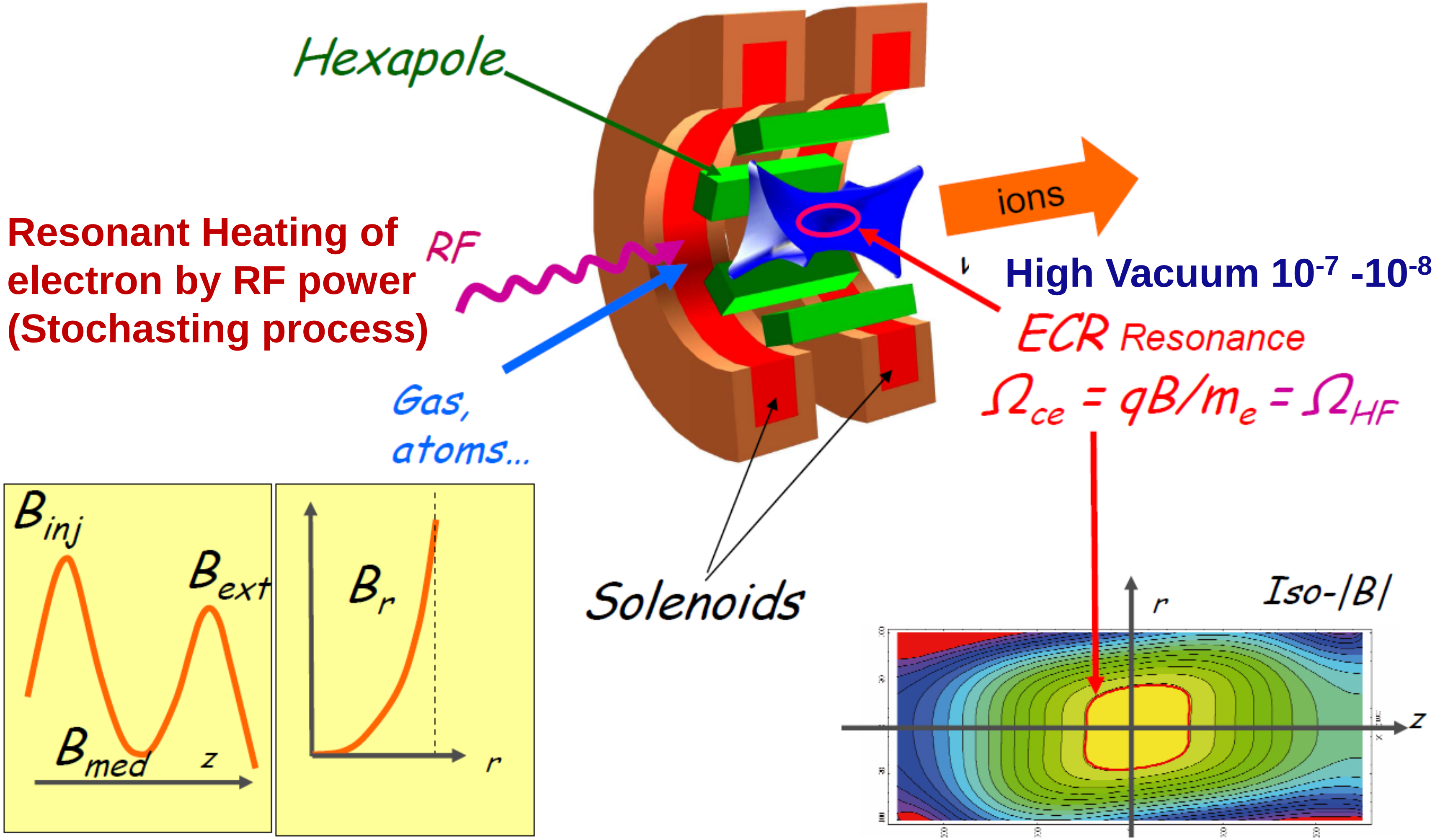


$E \sim Q^2$ for cyclotrons
$E \sim Q$ for linac

Higher power
Simpler injection mode

Developing intense highly charged ion source is both **performance-effective** and **cost-effective**

ECR Principle of Operation



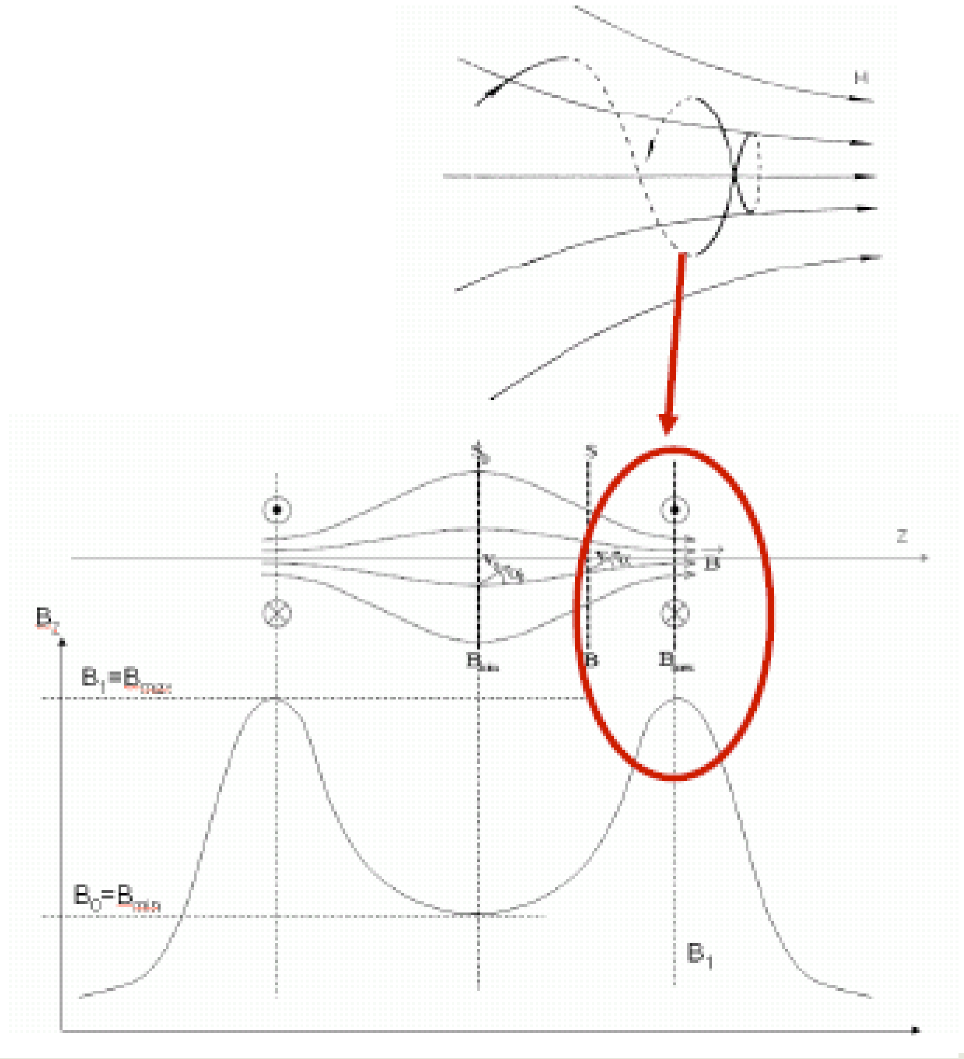
Resonant Heating of electron by RF power (Stochasting process)

High Vacuum 10^{-7} -10^{-8} Torr

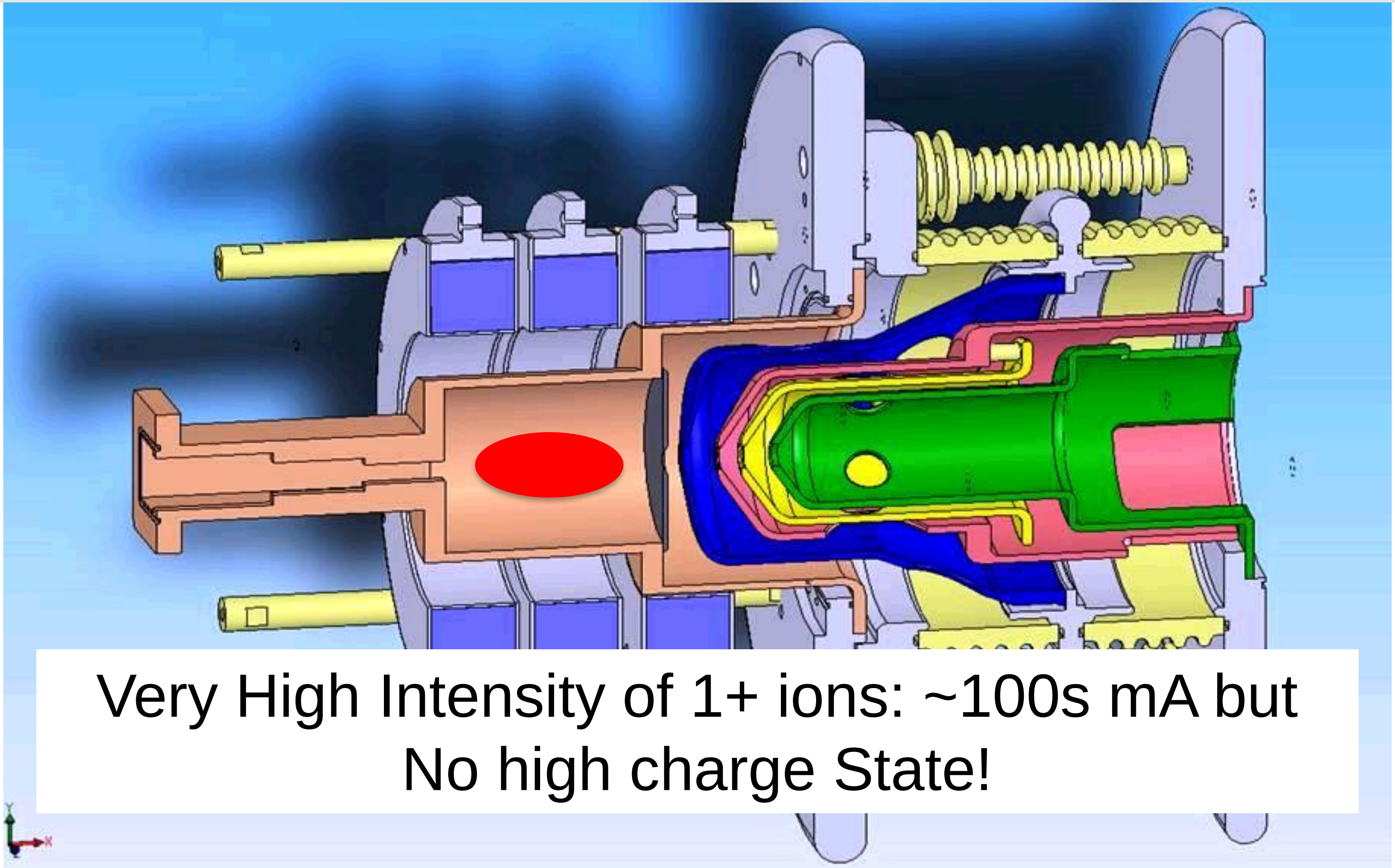
Magnetic Mirror effect

- When a charged particle propagates along the source axis toward a region with a higher magnetic field, it may be reflected back
  - $T_{kin}(z) = T_{\parallel} + T_{\perp} = \frac{1}{2}mv_{\parallel}^2(z) + \frac{1}{2}mv_{\perp}^2(z) = const$
  - Magnetic moment $\mu = \frac{mv_{\perp}^2}{2B} = \frac{T_{\perp}}{B} = const$
- $T_{kin}(z) = \frac{1}{2}mv_{\parallel}^2(z) + \mu B(z) = const$
  - When B is increases the velocity is transferred from $v_{\parallel}\ to\ v_{\perp}$
  - The particle is stopped at $z = z_1$ where $v_{\parallel} = 0$

An ECR has a high gradient of magnetic field in all directions resulting in a long confinement (ms) and high density of electrons



1+ ECR No radial Field



Very High Intensity of 1+ ions: ~100s mA but No high charge State!

Charge Exchange and Radiative Recombination

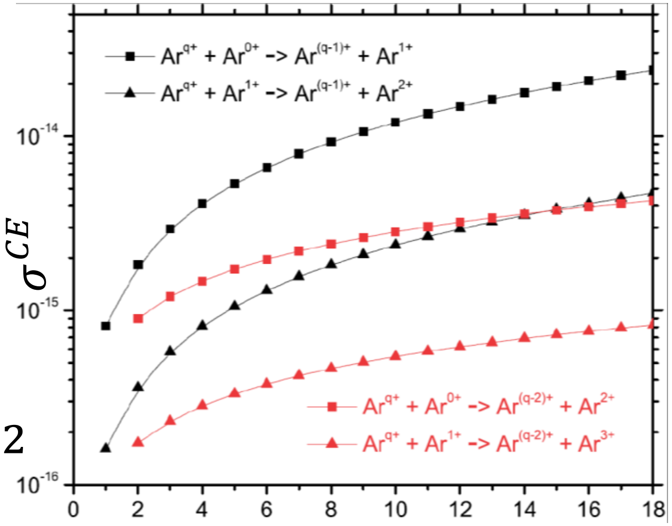
- Charge Exchange reduce Ions charge state through atom-ion collision

$$B^0 + A^{n+} \longrightarrow A^{(n-1)+} + B^+$$

  - Cross section for single or multiple electron capture are large and increase with charge state (Q)

$$\sigma^{CE}_{q\to q-1} \sim 1.43.10^{-12} Q^{1.17} \ (E_i\,[eV])^{-2.76} cm^2$$

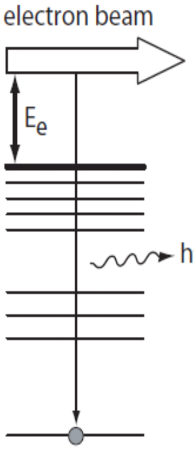
Müller Salzborn (1977)

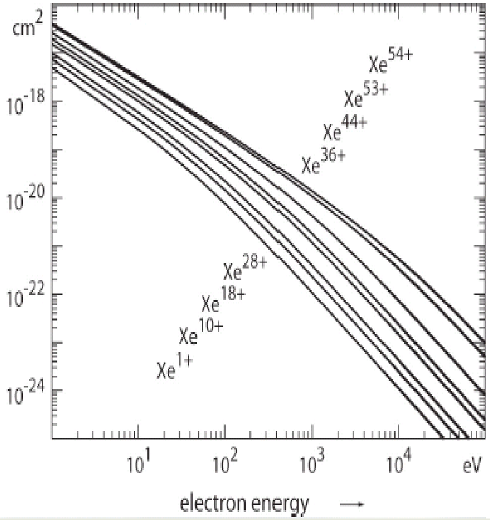


- Radiative Recombination

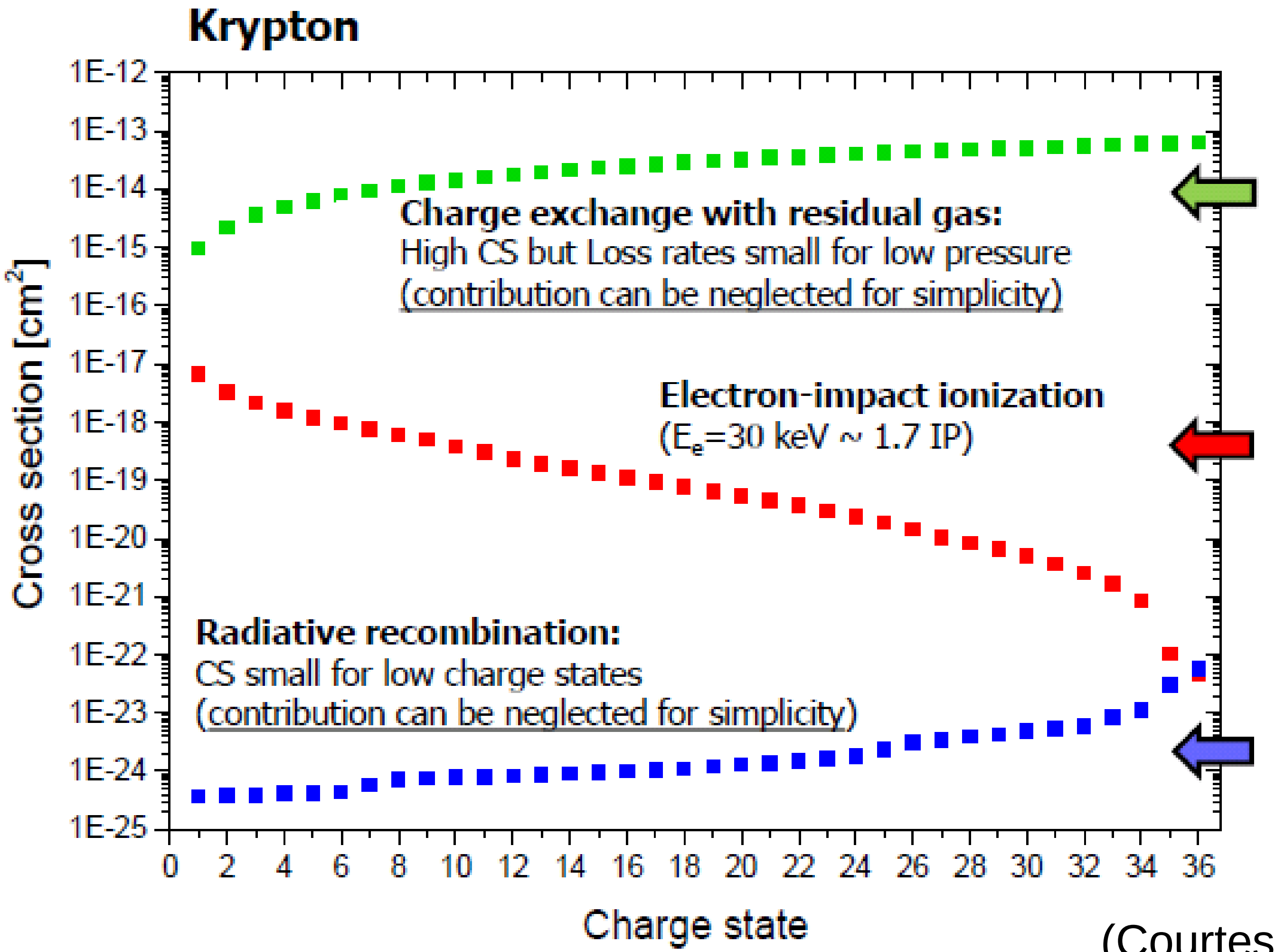
$$e^- + A^{n+} \longrightarrow A^{(n-1)+} + \hbar\omega$$

  - Cross section high a low electron energies
  - $\sigma^{RR}_{q\to q-1} \sim Q^2$





Balance of Atomic Processes for Krypton



Charge exchange with residual gas:
High CS but Loss rates small for low pressure
(contribution can be neglected for simplicity)

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

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

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

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

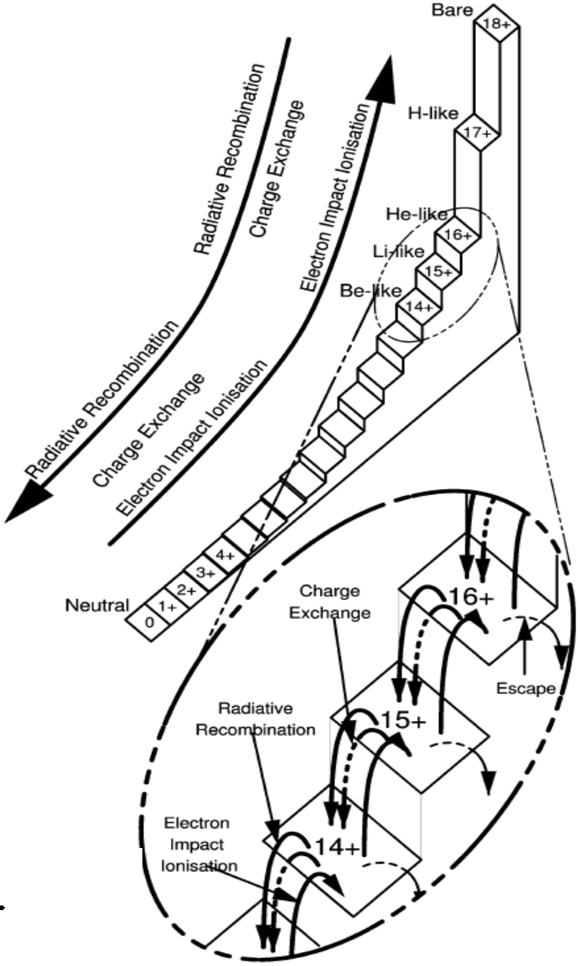
$$\sigma^{RR}_{i\rightarrow i-1} \sim Q^2$$

(Courtesy A. Lapierre)

Charge dynamics

- The competition between the charge generation processes and the charge destruction processes can be visualized as a staircase…
- Electron impact increases the charge state
- Charge exchange and radiative recombination decrease the charge state

Example of Argon

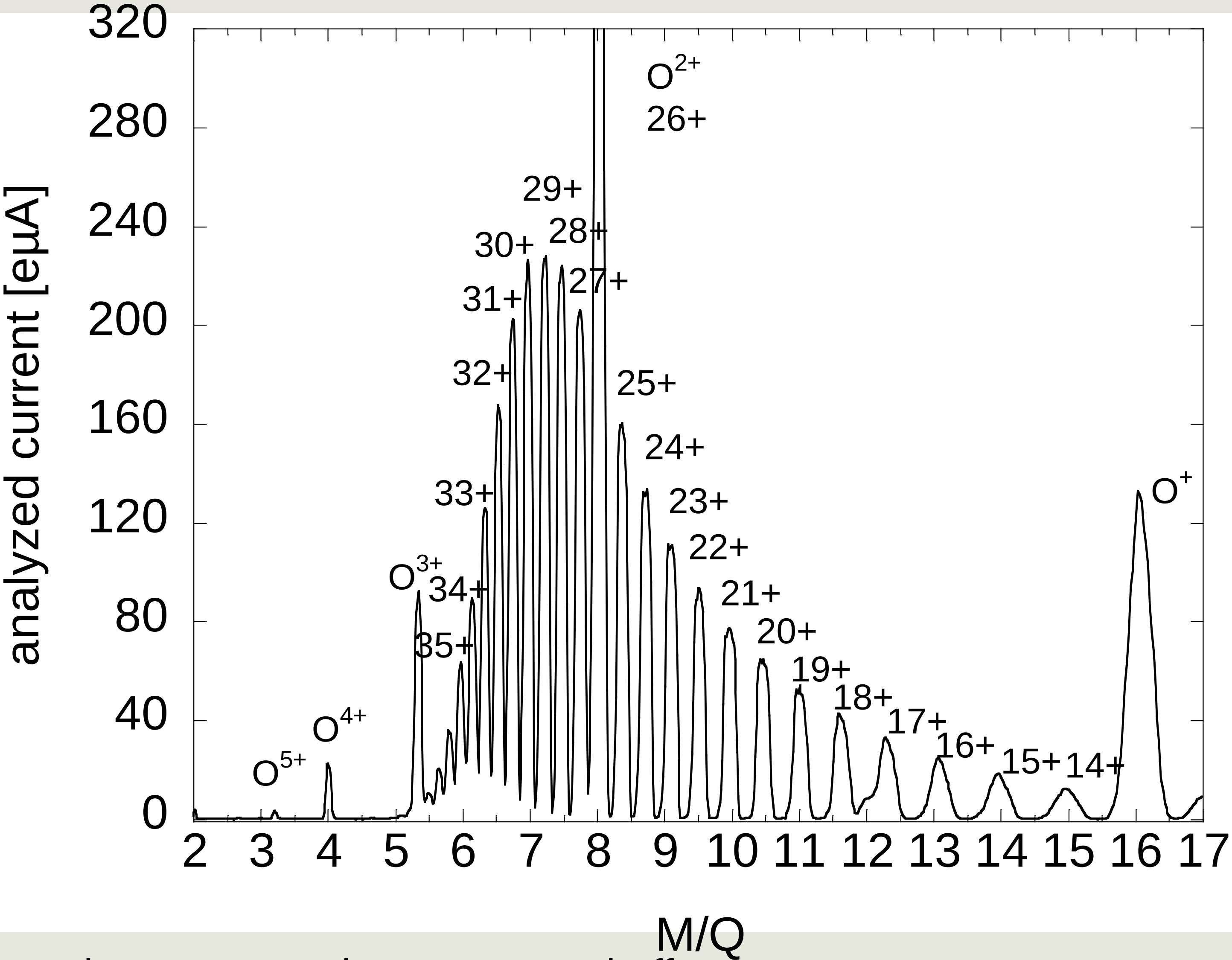


creation

$$\frac{\partial n_i}{\partial t} = \underbrace{\sum_{j=j_{\min}}^{i-1} n_e n_j \left\langle \sigma^{EI}_{j\to i} v_e \right\rangle + n_0 n_{i+1} \left\langle \sigma^{CE}_{i+1\to i} v_{i+1} \right\rangle}_{\text{Creation}}$$

$$\underbrace{- n_0 n_i \left\langle \sigma^{CE}_{i\to i-1} v_i \right\rangle - \sum_{j=i+1}^{j_{\max}} n_e n_j \left\langle \sigma^{EI}_{i\to j} v_e \right\rangle}_{\text{Destruction}} \underbrace{- \frac{n_i}{\tau_i}}_{\text{Losses}}$$

Charge State Distribution from an ECR



Bismuth spectrum using oxygen as buffer gas

ECR-Performance: Frequency Scaling

- $n_e\tau_i \geq\propto T_e^{3/2}$ gives a condition on what charge states can be reached.

- $I_i^q = \frac{1}{2}\frac{n_i^q qeV_{ecr}}{\tau_i^q}$

$$\sum_{i,q} n_i^q q_i = n_e$$

(Plasma neutrality)

n_i^q Ion density

τ_i^q Confinement time

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

Increasing excitation frequency principal way to improve performance of ECR

- Scaling with Magnetic field
  - Stability condition expressed as kinetic pressure<< Magnetic pressure

$$\beta = \frac{n_e kT_e}{\frac{B^2}{2\mu_0}} \ll 1$$

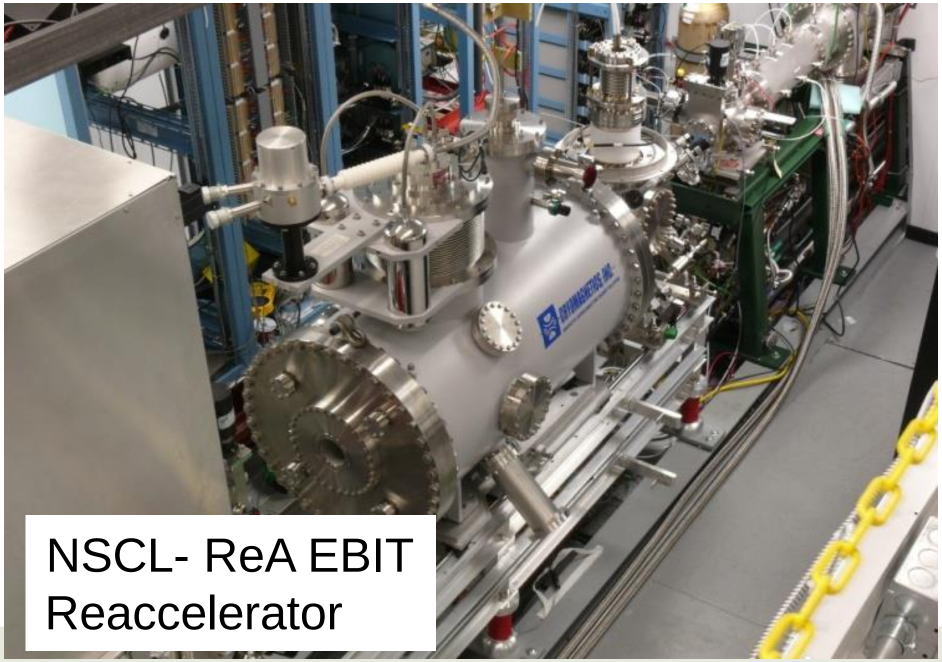
$$\boxed{I_Q \propto n_e \propto B^2}$$

Need to increase magnetic field to keep up with increased density

EBIS/EBIT

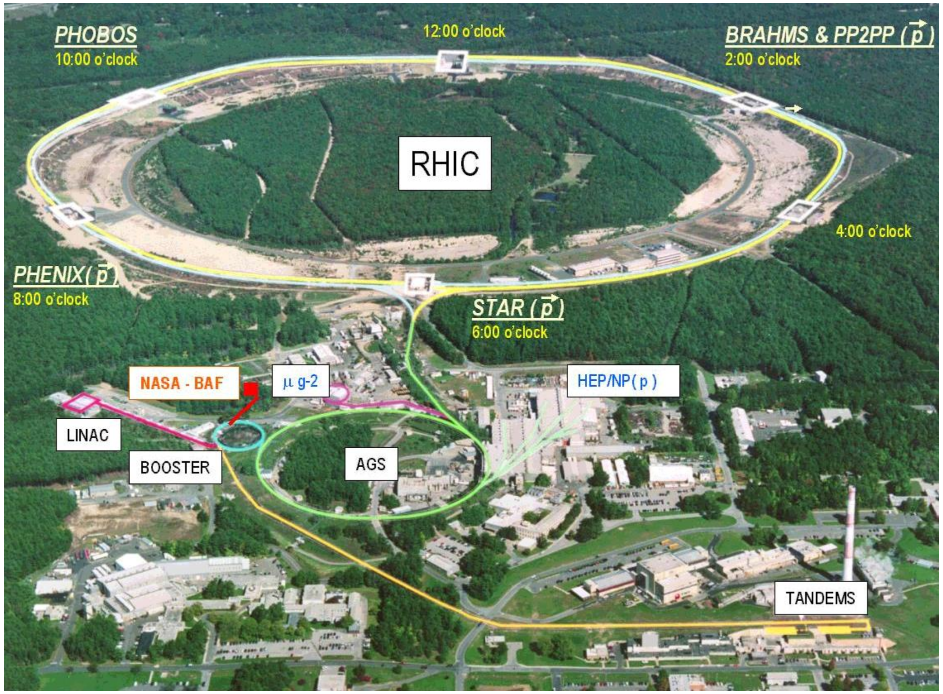
EBIS/T overview

- Electron Beam Ion Sources like Electron Cyclotron Resonance Ion Source ionize atoms to a high degree to extract high charge state ions
  - Injector for synchrotrons: RHIC EBIS
  - Charge breeder for post-accelerators: REX-ISOLDE (CERN), CARIBU (ANL), ReA (FRIB/NSCL), and others.


NSCL- ReA EBIT
Reaccelerator


BNL-RHIC EBIS
Synchrotron Injector

EBIS of RHIC: Relativistic Heavy Ion Accelerator (collider) at the Brookhaven National Laboratory



The EBIS is an injector of stable isotopes for:

- High-energy heavy ion collisions (e.g., Au-Au)
- NASA radiation facility

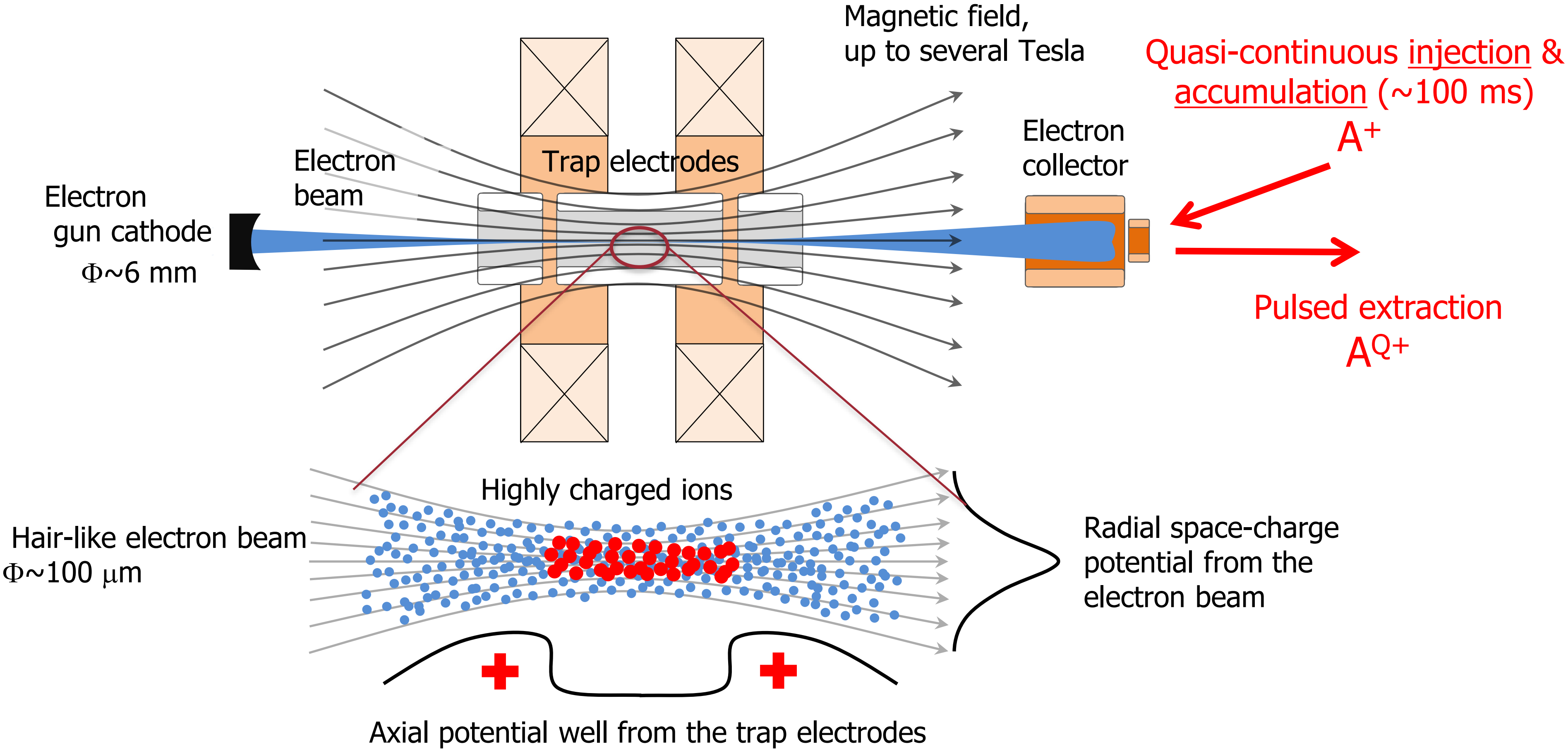
- 2 indep. intersecting storage rings
- Chain of accelerators
  - 3 injectors: EBIS source + linac, Tandem injector, proton linac
  - Booster Synchrotron
  - Alternating Gradient Synchrotron
  - 2.4 miles circumference storage ring

- EBIS is an ideal source for synchrotrons because of the sharp pulse structure of the beam: multi-turn injection for accumulation in intense peaks for high signal-to-noise ratio.

Basic working principle -1-

What is an Electron-Beam Ion Source/Trap and how does it work?

- Produces & traps **highly charged ions** with a high-current density electron beam
- 3 Parts: e-gun, trap + magnet , e-collector
- Strong magnetic field: Electron-beam compression & Ionization by electron impact
- Trap electrodes (**drift tubes**) → Axial ion confinement
- Electron beam → Radial ion confinement



Magnetic field,
up to several Tesla

Quasi-continuous injection &
accumulation (~100 ms)
A^+

Electron
gun cathode
Φ~6 mm

Electron
beam

Trap electrodes

Electron
collector

Pulsed extraction
A^{Q+}

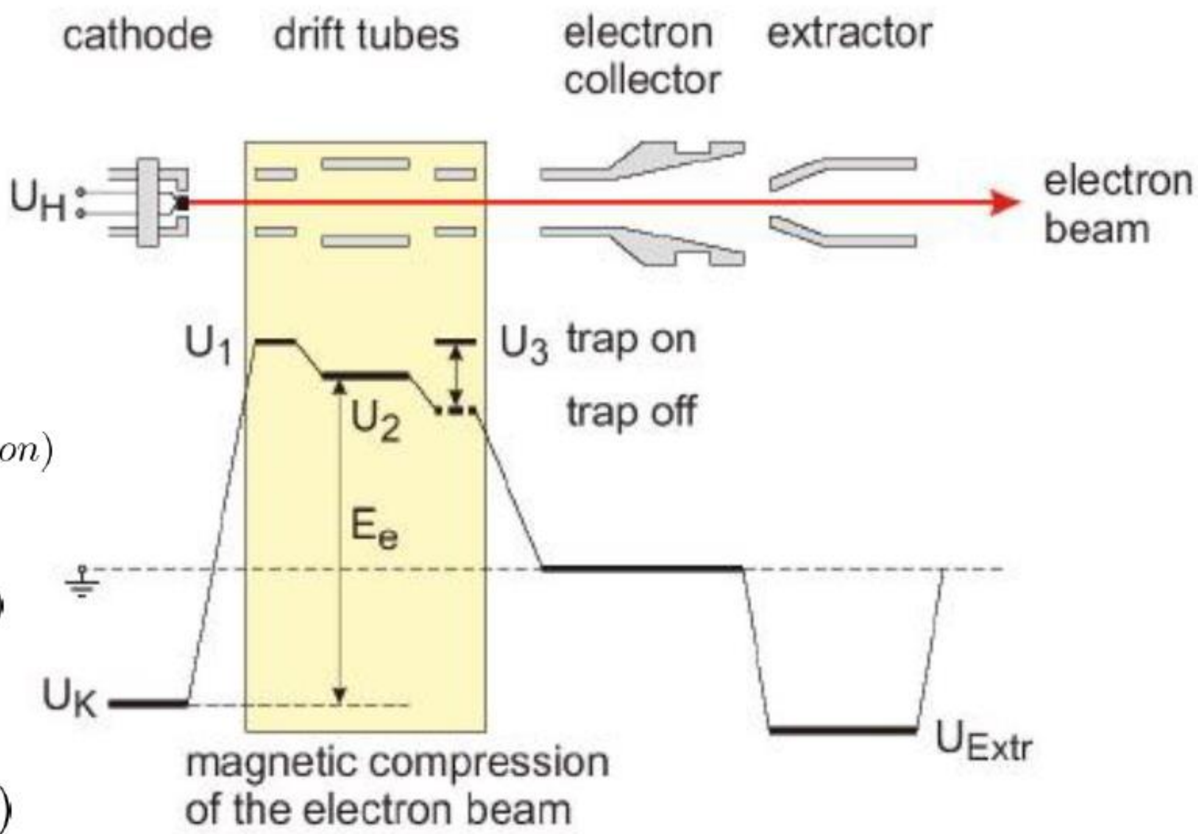
Highly charged ions

Hair-like electron beam
Φ~100 μm

Radial space-charge
potential from the
electron beam

Axial potential well from the trap electrodes

Basic working principle -2-



$U_1 ... Trapping\ Potential (e - gun)$

$U_2 ... Middle\ Electrode\ Potential$

$U_3 ... Trapping\ Potential\ (Extraction)$

$U_k ... Cathode Potential (neg)$

$U_{sp} ... Space\ Charge\ Potential (neg)$

$$U_{elec} = e \cdot (U_2 - U_k + U_{sc})$$

$U_{elec}\ ranges\ from\ 500\ eV\ to\ 200\ keV$

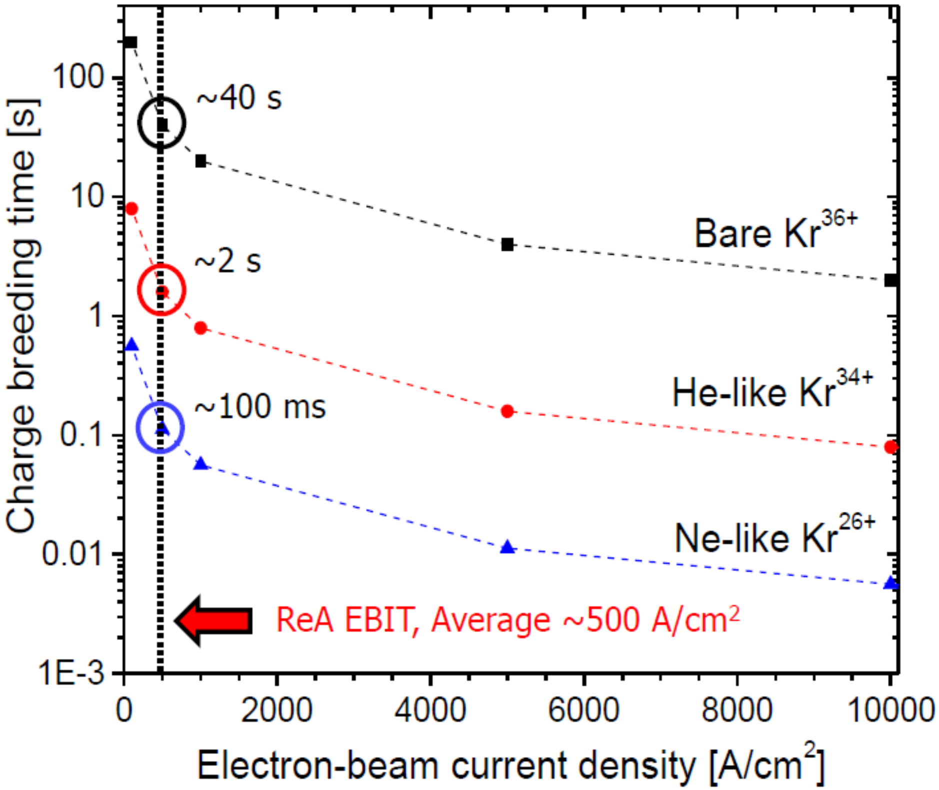
Electron energy defined by applying voltages to the electron gun (-) and the electrodes of the trap (+)

Charge Breeding Times

From the ionization factor, we can estimate the breeding time of a charge state knowing the current density and cross sections →

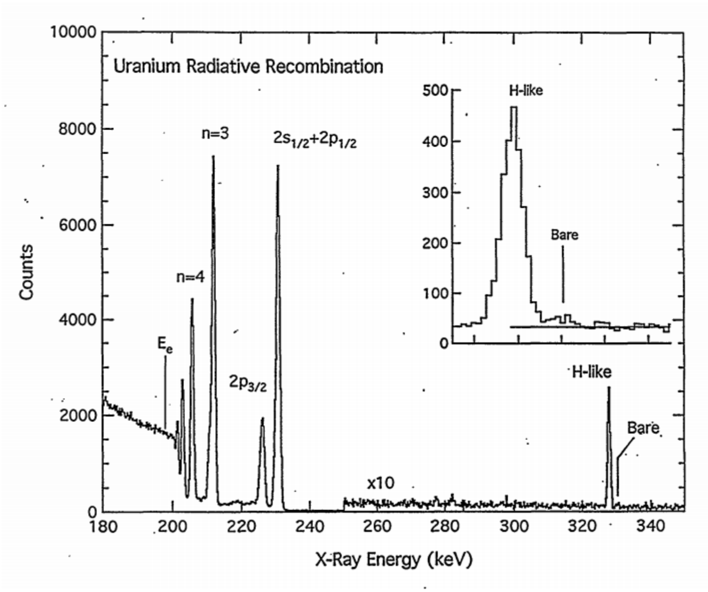
$$\tau_{Q+} \sim \frac{e}{j_e} \sum_{n=0}^{Q+} \frac{1}{\sigma_{EI}}$$

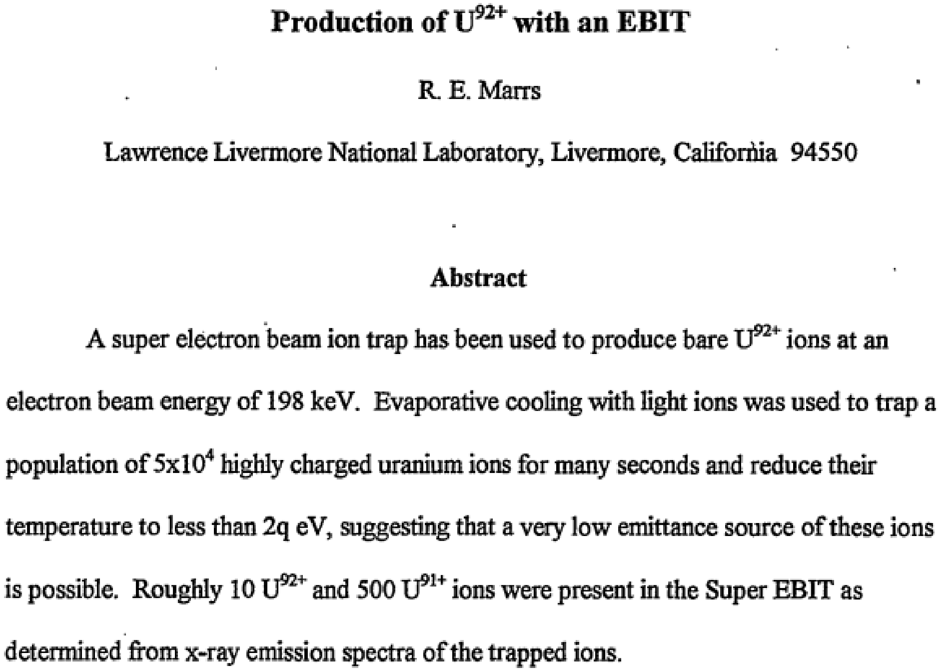
The breeding time is inversely proportional to the e-beam current density (j_e), and e-impact ionization cross sections (σ_{EI}) (neglect all other processes)



High Charge State Record obtained in 1995 with an EBIT

- U 92+ Produced within the Electron Beam Ion Trap at Lawrence Livermore National Laboratory





Production of U^{92+} with an EBIT

R. E. Marrs

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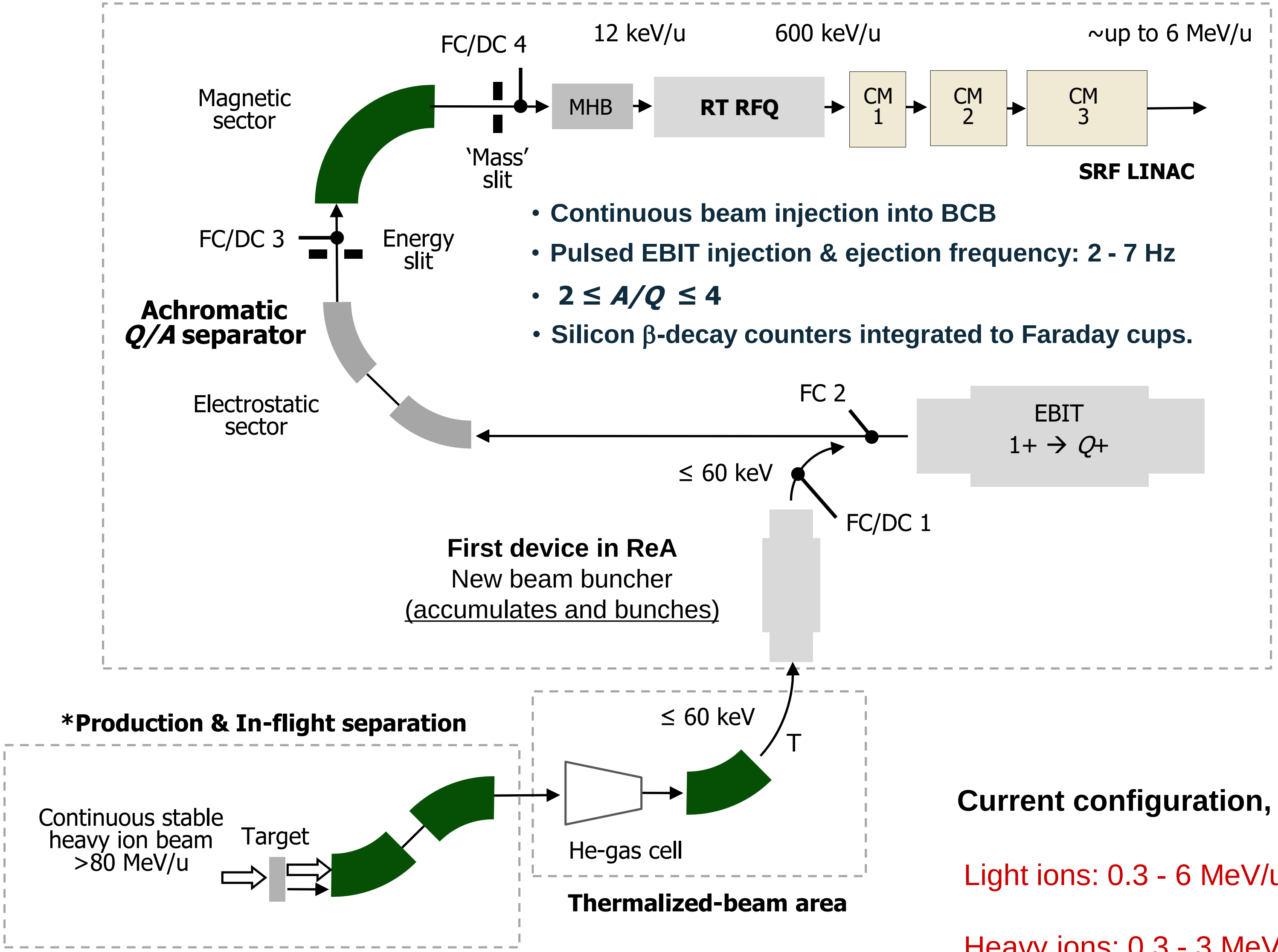
Abstract

A super electron beam ion trap has been used to produce bare U^{92+} ions at an electron beam energy of 198 keV. Evaporative cooling with light ions was used to trap a population of 5×10^4 highly charged uranium ions for many seconds and reduce their temperature to less than 2q eV, suggesting that a very low emittance source of these ions is possible. Roughly 10 U^{92+} and 500 U^{91+} ions were present in the Super EBIT as determined from x-ray emission spectra of the trapped ions.

The ReA post-accelerator of rare isotopes at the NSCL/FRIB

ReA post-accelerator



- **Continuous beam injection into BCB**
- **Pulsed EBIT injection & ejection frequency: 2 - 7 Hz**
- **$2 \leq A/Q \leq 4$**
- **Silicon β-decay counters integrated to Faraday cups.**

Current configuration, ReA3

Light ions: 0.3 - 6 MeV/u (^{48}Ca)

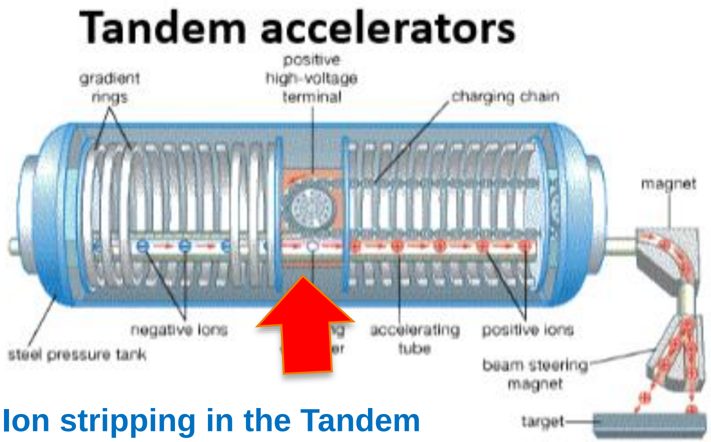
Heavy ions: 0.3 - 3 MeV/u (^{238}U)

Negative Ion Sources

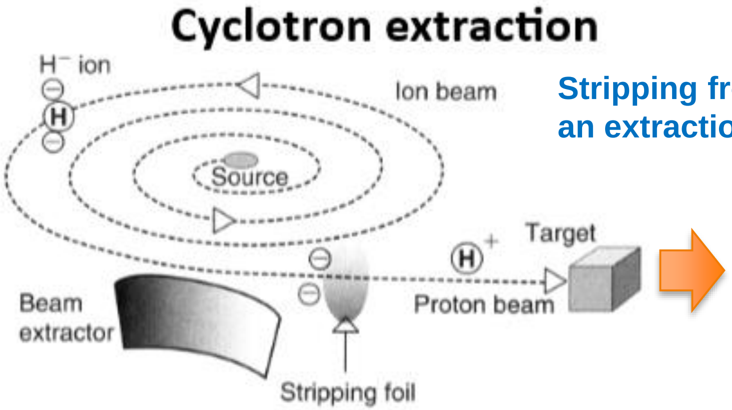
Need for negative ion beams has grown significantly over the last decades

→ Atomic Mass Spectrometry (AMS); key to carbon dating (^{14}C); ^{14}N does not form a stable negative ion

→ Production of radioactive ion beams with a intense, high-energy proton beam (TRIUMF)



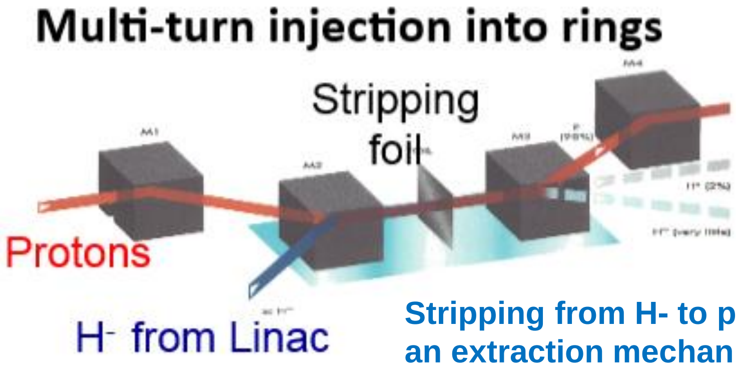
Ion stripping in the Tandem



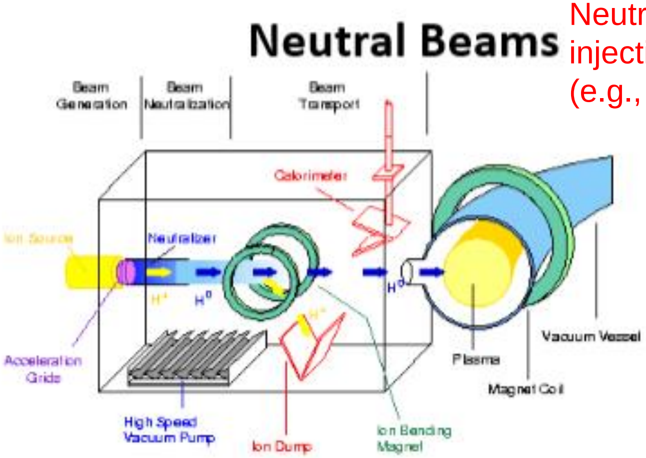
Stripping from H- to p+ as an extraction mechanism

Heating of fusion plasmas: Neutralization to H for injection into fusion devices (e.g., Tokamak, ITER)

→ Production of neutron beams (SNS)



Stripping from H- to p+ as an extraction mechanism



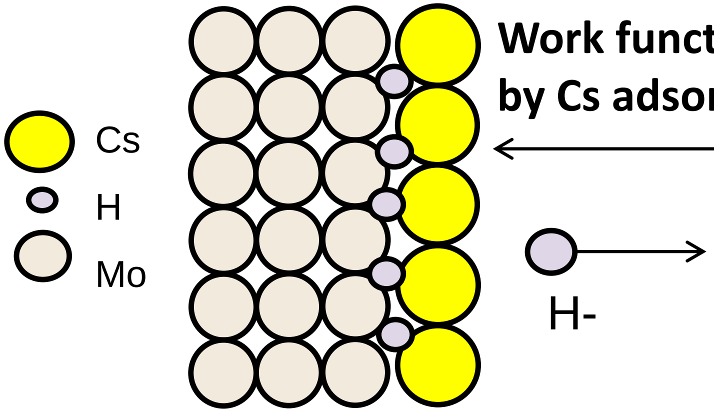
Production mechanisms of negative ions

- A negative ion is formed when an atom or molecule captures an electron into a bound state: “electron affinity level”
  - **Electron affinity energy**: minimum energy needed to remove the electron of a negative ion to form a neutral atom
  - Similar to the ionization potential: minimum energy to remove an electron from a neutral atom (or a position ion)
  - EA are smaller than ionization energies: 3.6 eV for Cl-; 0.75 eV for H-
  - Neutralizing a negative ion is called “**electron detachment**”

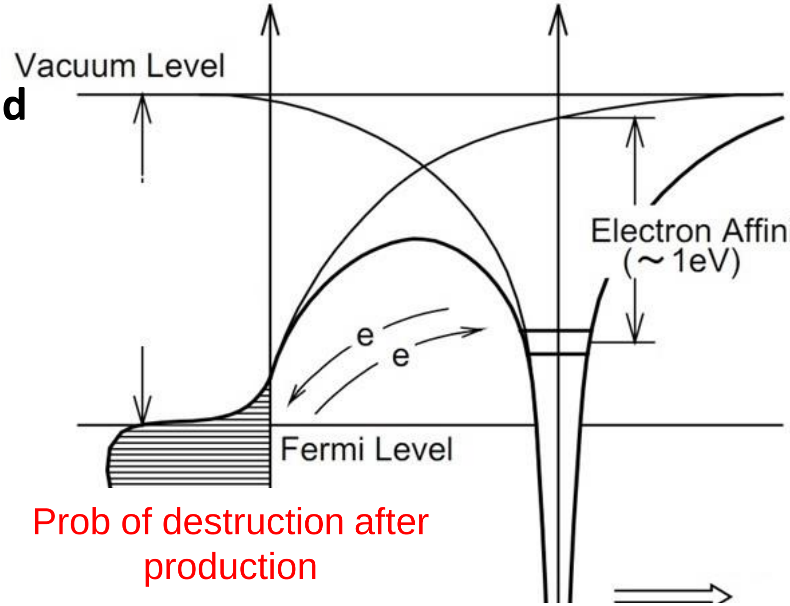
- The production mechanisms can be classified in terms of where the electrons come from…(the electron source)
  - Electrons in the conduction band of a metal → ***Surface Effect***
  - Plasma electrons → ***Volume production of H-***

Surface effect

- **An atom emitted from a surface of a metal of a low work function has a high probability to leave the surface as a negative ion**
- **What happens here is:** electron capture occurs due to quantum tunneling of an electron from the Fermi level to electron affinity level



Work function reduced by Cs adsorption



Prob of destruction after production

$$I^- = I^+ A\eta^- \exp\left(-n_0 L\sigma_d\right)$$

ce

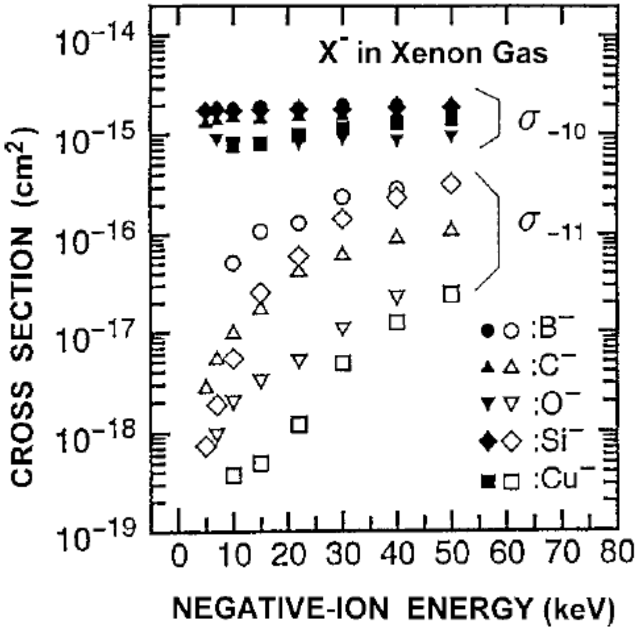
A :Reflection/Sputtering yield (Probto reflect or be sputtered)

η-:Production efficiency (Prob an atom captures an electron)

n_0: Neutral gas particle density
L: Transport length
σd: Electron detachment cross section

Many processes that can destroy H– ions

- After leaving the surface, negative ions can be destroyed to neutral atoms or positive ions due
  - Mutual neutralization $H^- + H^+ \rightarrow H^0 + H^0$
  - Electron Detachment (ED) $H^- + e \rightarrow H^0 + 2e$
  - Associative detachment $H^- + H^0 \rightarrow H_2{}^* + e$
- The destruction probability depends on…
  - The gas pressure in the source
  - The transport length (L) to the extraction
  - The detachment cross sections by collisions.
- As well as being fragile and easily destroyed it is much more likely to be hit.
  - » The H^- ion collision cross section with electrons is 30 times larger than neutral H0 atom
  - » The H^- ion collision cross section with ions is 100 times larger than neutral H0 atoms



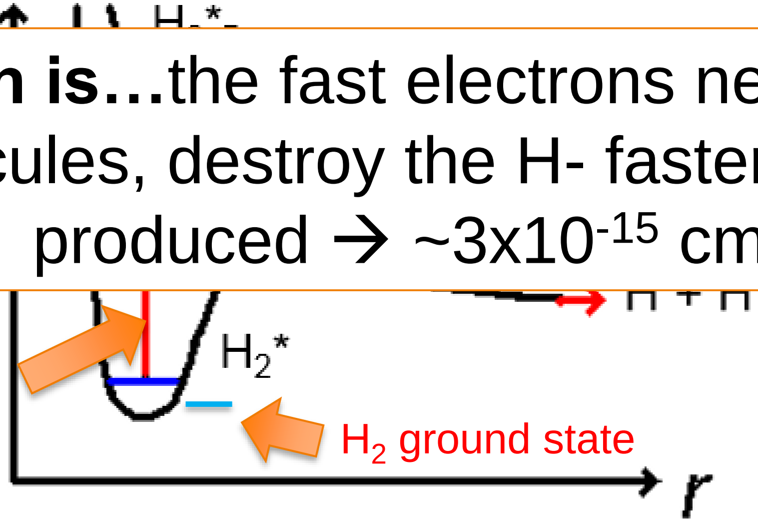
Single and double ED cross sections in Xe

Volume Production of H- By Dissociative Electron Attachment

- Volume production of H- (more in the next slide…)
  - Hydrogen molecules (H_2) are excited to high rotational and vibrational levels (H_2^*) by high-energy electrons (>15 eV)

$$H_2 + e(\text{fast}) = H_2^* + e$$

  - The excited molecules capture low-energy electrons (<1eV) to form an unstable molecules that breaks apart to form a negative hydrogen (H-) through "**dissociative electron attachment**" → $H_2^* + e \rightarrow H_2^{*-} \rightarrow H + H^-$



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The catch is…the fast electrons needed to excite the molecules, destroy the H- faster than they are produced → ~3×10^{-15} cm^2 for H-

Capture of slow e

H_2 ground state

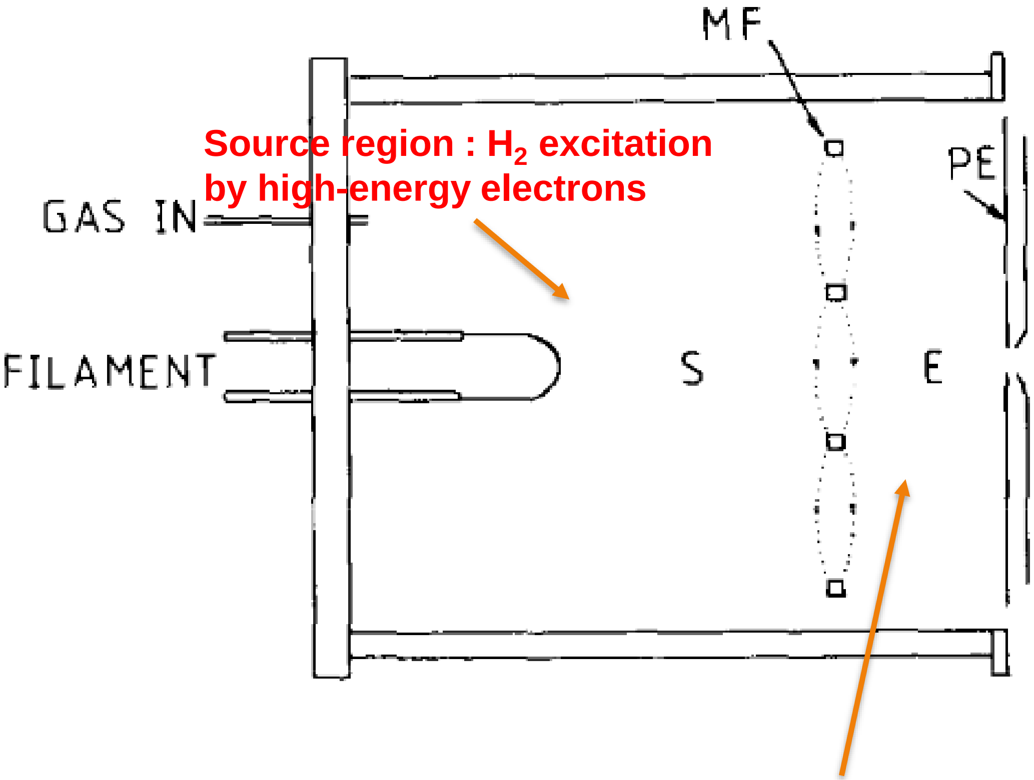
Inter-nuclear distance
(distance between protons)

$$H_2^* + e(\text{slow}) = H + H^-$$

Volume production of H- :Tandem H- Source

- **In the source (S),** electrons emitted by a filament are accelerated to ~100 eV to form a plasma with a non-Maxwellian electron energy distribution
- **The extraction (E)** is characterized by the **absence of energetic electrons** and a low-electron temperature (~1 eV)
- The two regions are separated by a **magnetic filter** to allow transfer to the extraction region of slow electrons, but **not energetic electrons**
- The first electrode of the extractor (plasma electrode) (PE) can be biased to help equalize the potentials of the two plasma regions.
- Cold electrons captured by excited molecules near the outlet produce the extractable H- ions

$$H_2^* + e(<1eV) = H + H^-$$

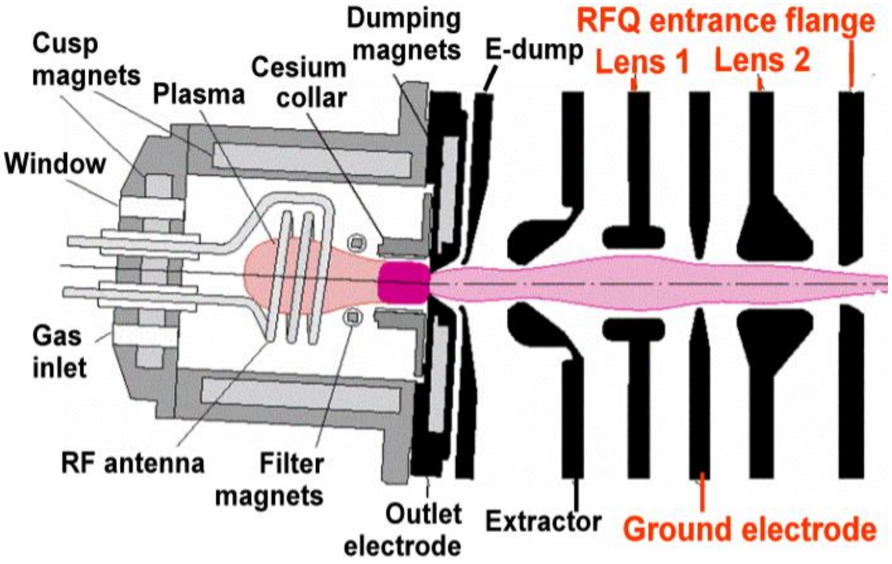


Source region : H_2 excitation by high-energy electrons

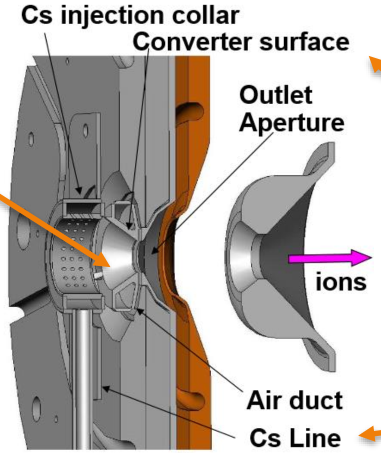
Extraction region: H_2 electron capture of low-energy electrons and dissociation

Most recent (volume + surface) negative ion source for H-

- Another H- source is the SNS (Spallation Neutron Source) source that uses **volume and surface** production



Positive ions (H+) interact with the converter surface to become H-



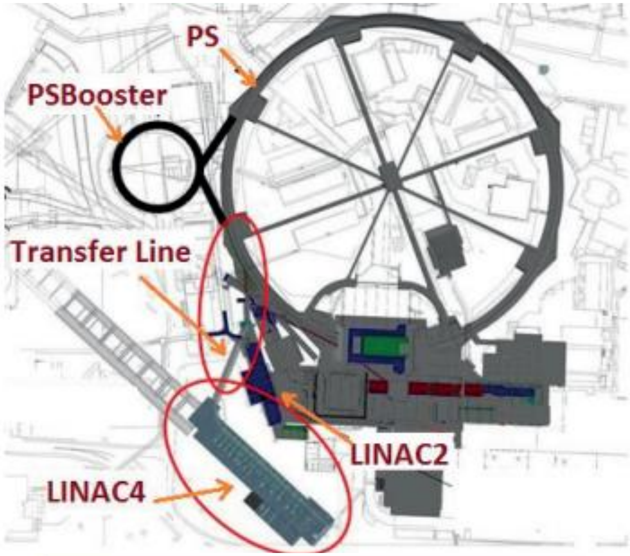
Mo surface covered with Cs

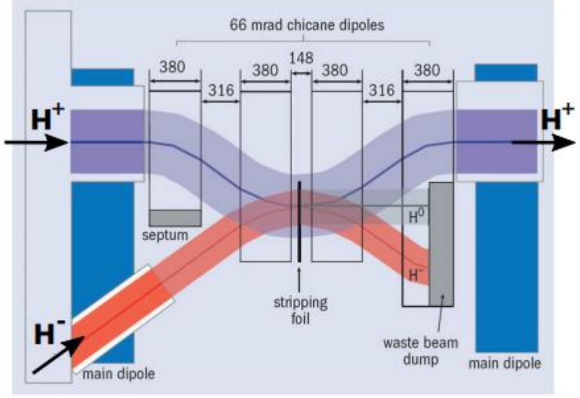
Cs from an oven passes thru the line and passes through the collar to coat the converter

- Developed by LBNL based on the RF H- concept (see previous slide)
- Typically 300 W…
- ~50 mA being injected into the RFQ under nominal conditions.
- ~230 C of H- ions per day !
- Recent paper: Martin P. Stockli, Robert F. Welton, and Baoxi Han, REVIEW OF SCIENTIFIC INSTRUMENTS 89, 052202 (2018) **(Winner of the ICIS 2017 Brightness Award)**

CERN new H^- Ion source for Linac 4

- CERN Linac 4 is now using an H^- source for injection into Proton booster ring
  - X2 intensity (50emA from ion source)





- Design similar to SNS H^- sources that uses **volume and surface** production