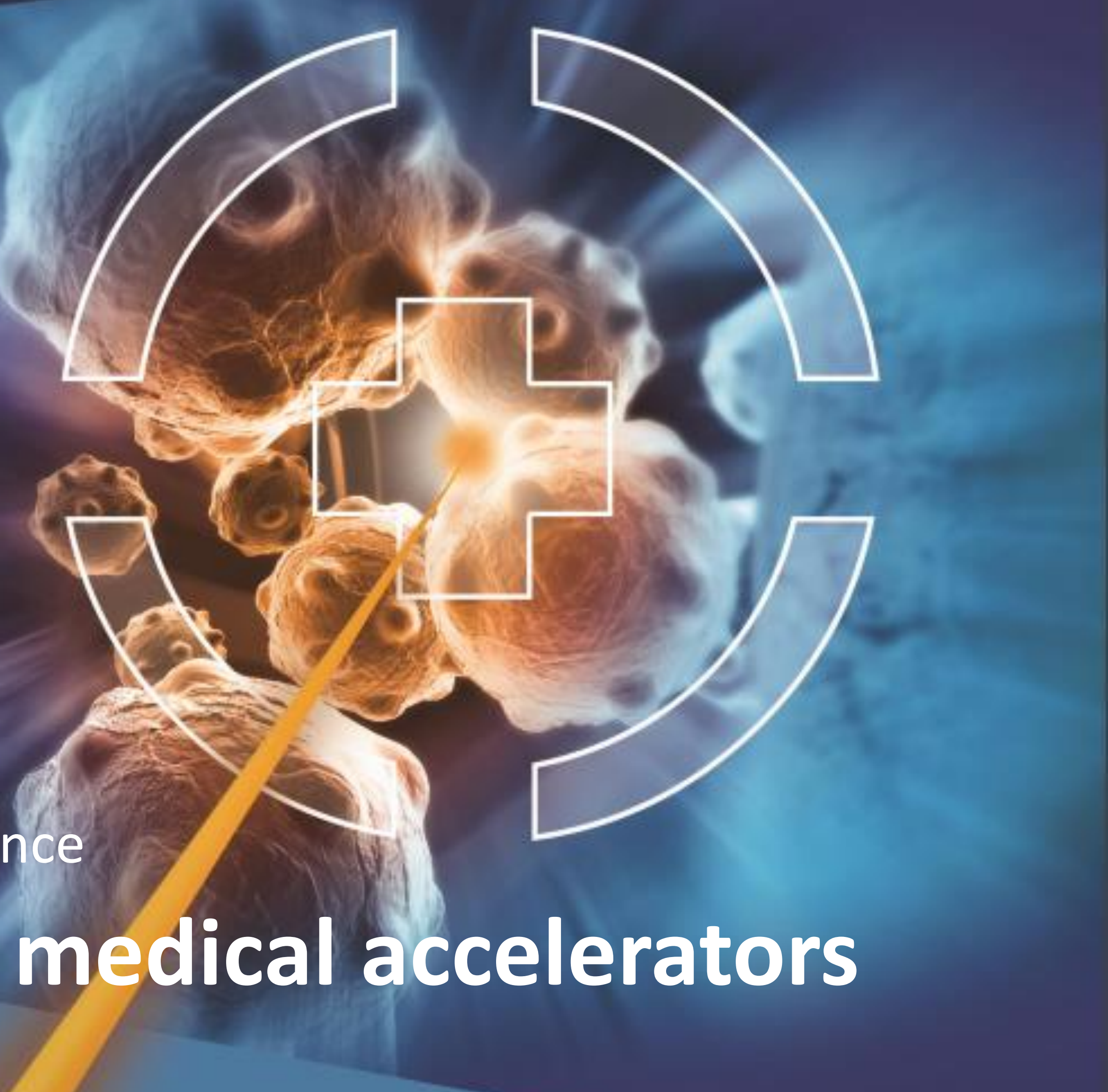

School on Medical Accelerators

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PANTECHNIK, Bayeux, France

Ion sources for medical accelerators

5th - 9th June 2017
Fondazione CNAO
Pavia, Italy

Main purpose

Ion sources are widely use in an amazing number of applications, not only for accelerators but also for chemical analysis, lights, flat screens, space thrusters etc…
They can be few mm^3 small up to m^3 in fusion machines !

Today this lecture focusses on the ion sources used for particle medical accelerators

The medical applications of ion accelerators are classified into two categories: treatment and diagnosis.

Overview

- ☑ Ion Source Requirements
- ☑ Ionization process, plasma, motion & confinement basics
- ☑ **Review of Ion Sources for medical accelerators**
    - ➢ Proton radiotherapy IS
    - ➢ Heavy Ion radiotherapy IS
    - ➢ IS Developments for future radiotherapy
    - ➢ Boron Neutron Capture Therapy IS
    - ➢ Radioisotope production
- ☑ Conclusion

Overview

☑ Ion Source Requirements

☑ Ionization process, plasma, motion & confinement basics

☑ **Review of Ion Sources for medical accelerators**

- ➢ Proton radiotherapy IS
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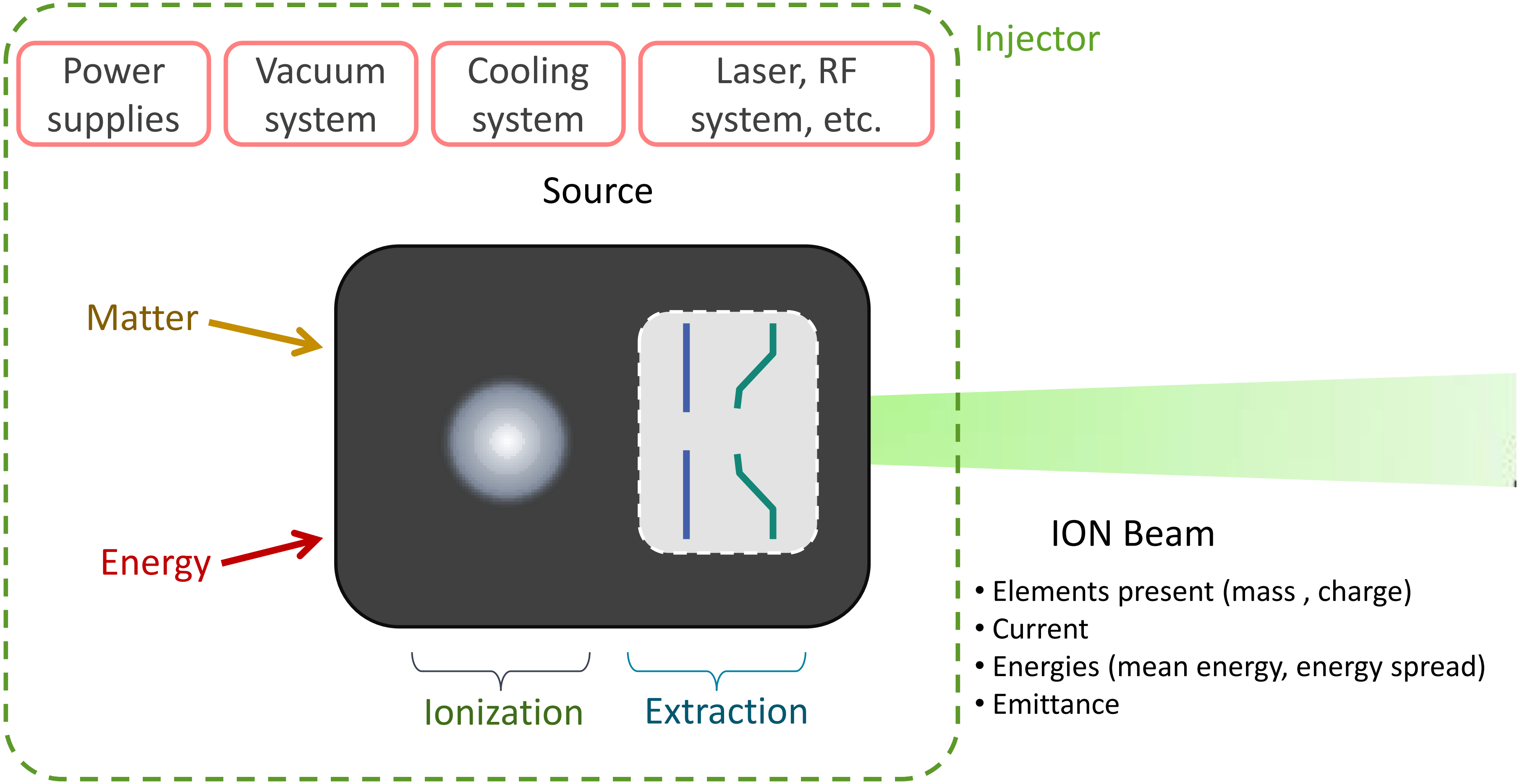
- ➢ IS Developments for future radiotherapy
- ➢ Boron Neutron Capture Therapy IS
- ➢ Radioisotope production
- ➢ Particle therapy IS injector in-site examples

☑ Conclusion

☑ Ion Source Requirements

- Ion Source definition
- Involved technologies
- What are the first questions ?
- Parameters

Ion Source definition



ION Beam

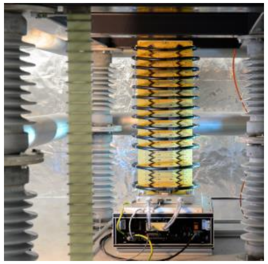
- Elements present (mass , charge)
- Current
- Energies (mean energy, energy spread)
- Emittance

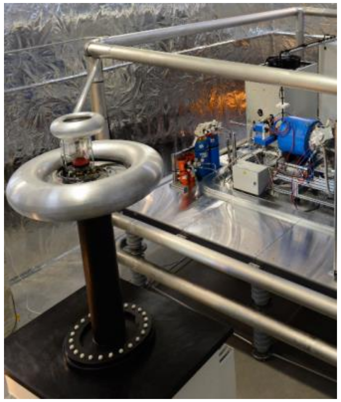
☑ Ion Source Requirements

Involved technologies

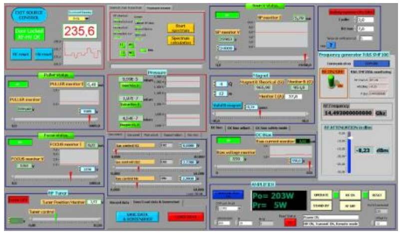
Power supplies

Laser, RF system, HV etc.

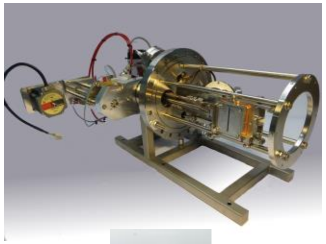




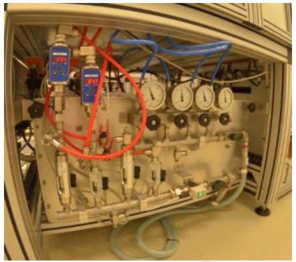
C&C system and software



Beam diagnostics



Cooling system



Vacuum system

Interlock & safety systems

Plasma diagnostics

What are the first questions ?

Particle type:

Choose the element of interest and the way to bring it as “neutral” in the IS (gas, evaporation, sputtering, gas mixing)

Do I need proton? H^+, $_2H^+$, $_3H^+$ or isotope like Deuterium or Tritium

Do I need carbon? C^+, C^{2+}, C^{n+} or CO^+ … or isotope like ^{11}C … or isotopologue like $^{11}C^{18}O^+$

Do I need a range of different elements ? What is the switching cycle frequency and speed ?

Is another element can do the job ? He^+ instaed of H^+ ?

☑ Ion Source Requirements

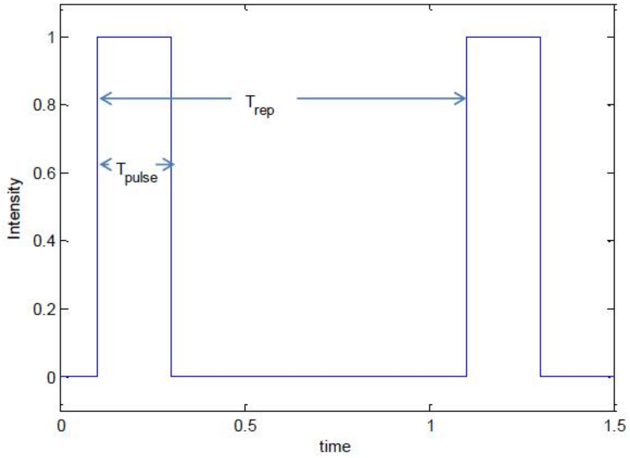
Parameters

Intensity:

Beam current extracted from the IS: $$I_{electric\_current} = \frac{qeN_{ions}}{t}$$

In case of multiplate charge state: $$I_{particle\_current} = \frac{eN_{ions}}{t} = \frac{I_{electrical\_current}}{q}$$

In case of pulsed beam the current is to be given with its time structure



$$\text{Repetition Rate} = \frac{1}{T_{rep}}$$

$$\text{Pulse length} = T_{pulse}$$

$$\text{Duty factor} = \frac{T_{pulse}}{T_{rep}}$$

Parameters

Intensity order of magnitude (examples):

Carbon therapy: around 200µAe of C^{4+} and 800µA of $_{3}H^{+}$

Proton therapy: from 10 to several 100µAe of H^{+} or H^{-} cw or pulsed

BNCT: many mA of H^{+} or H^{-}

Isotope production: as large as possible depending on target reliability

Parameters

Energy:

Total energy after extraction ?	$E_{total} = qeV$
Energy per nucleon ?	$E/_{nucleon} = qeV / A$
Energy spread ?	ΔE
Extraction voltage ?	$E_{extraction} = V$ (kV)

Parameters

Energy:

High beam energy advantages:

- Space charge effect reduced – higher beam current
- Energy spread ratio reduced ($\Delta E/E$)
- Geometrical emittance reduced
- High velocity makes it easier to inject into downstream accelerator (RFQ, DTL ...)

High beam energy disadvantages:

- technical complexity to work with very high HV
- sparks with their consequences on equipments
- high energy together with higher beam power to manage for beam dignostics

Parameters

Emittance :

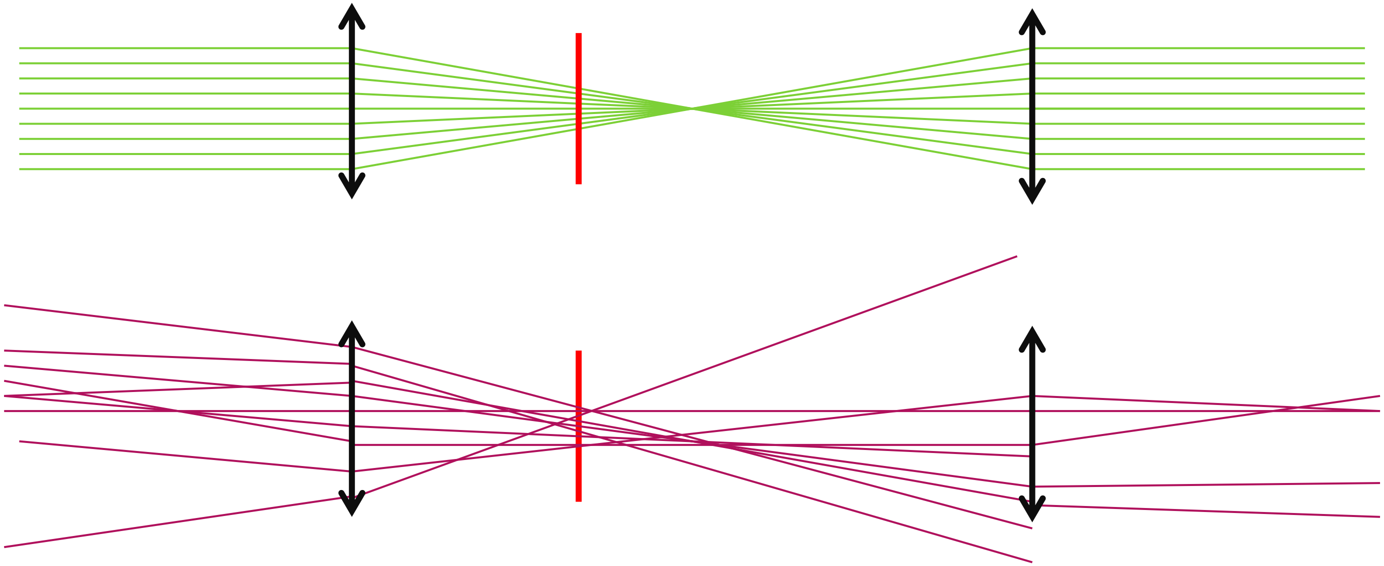
Need to produce a beam with an emittance lower the the accelerator acceptance

But what is emittance ?

Parameters

Emittance :

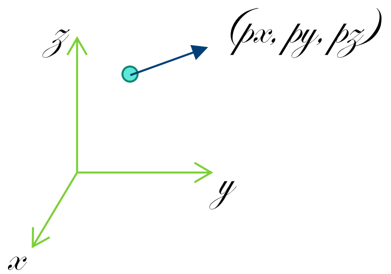
How to define a beam quality (independently of the position of measurement)?
Will the beam be transported (without significant losses) in the rest of the beam line?



- It is not possible to define the quality of the beam with just its profile.
- Its is not possible to define the acceptance of a beam line with just an input profile.

Parameters

Emittance :



Each particles of a beam can be define by 6 parameters :

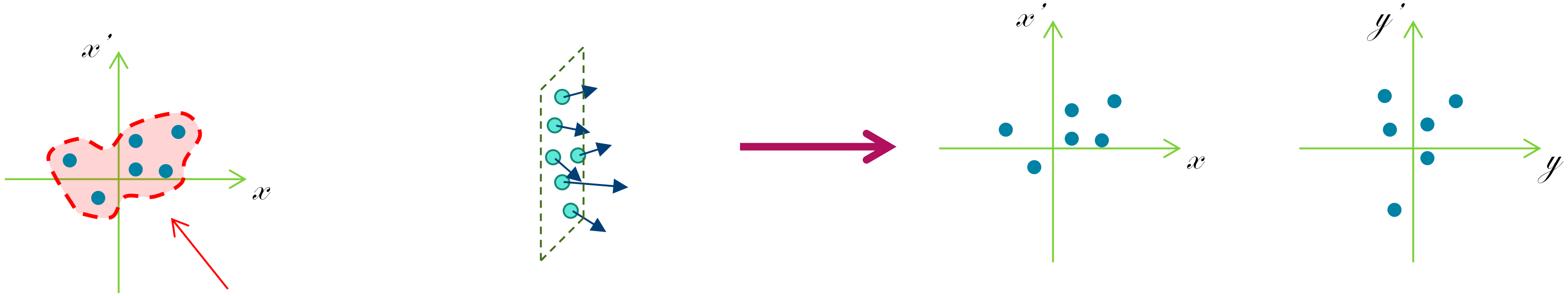
(x , y , z, px , py , pz)

In most cases the beam are continuous, with the longitudinal direction along the z axis.

Total beam *One transverse slice of the beam* If no coupling between the *(x , x')* and *(y , y')*

6D → 4D → 2 x 2D

(x , x') *(y , y')*



Emittance *x-x'* = Area

Parameters

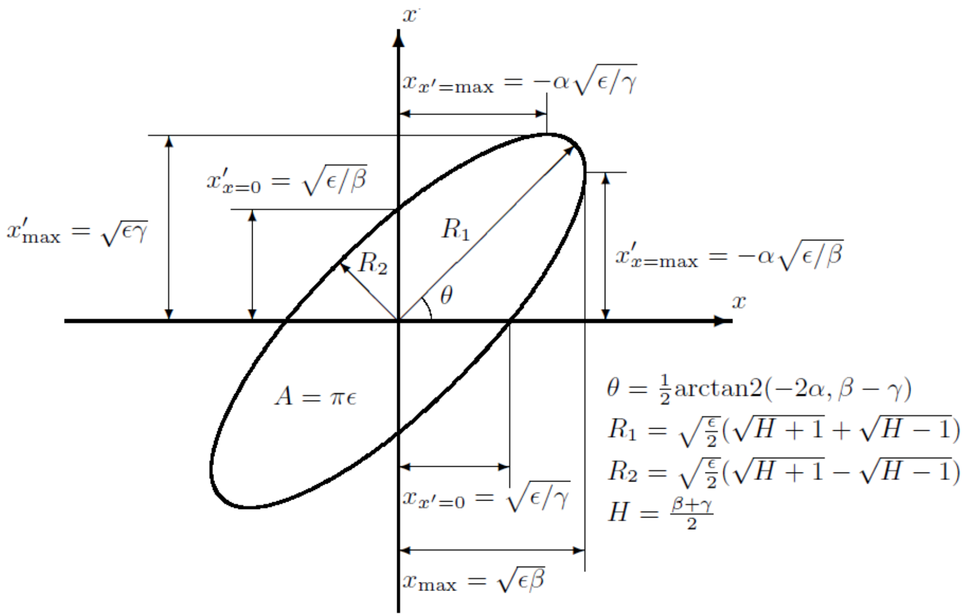
Emittance :

- The beam emittance can be “easily” approximate by an ellipse.

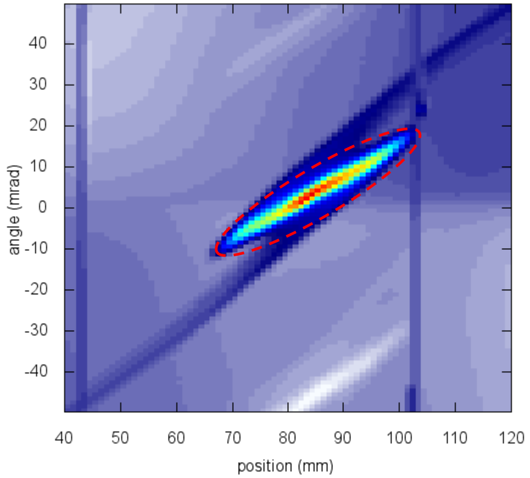
- An ellipse is a simple shape, easy to parameter :

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

Twiss parameters : α,β,γ



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



$$\boxed{\varepsilon_{total,geometric} = \frac{Area}{\pi}}$$

Parameters

Emittance : which definition ? What unit ?

$$\varepsilon_{normalised} = \beta\gamma\varepsilon_{geometric}$$

The normalized emittance conserved with acceleration

$$\varepsilon_{rms} = \varepsilon_{\sigma}$$

Produces an ellipse that extends to +/- 1σ

$$\varepsilon_{4rms} = 4\varepsilon_{rms} = \varepsilon_{2\sigma}$$

… another definition !

$$\varepsilon_{th} = r_{out}\sqrt{\frac{2E_{th,ion}}{3m_0c^2}}$$

For plasma sources the ion T° and the source exit aperture give the minimum emittance

Emittance UNIT : mm.mrad (but often expressed in π.mm.mrad !)

Parameters

- Space charge and Child-Langmuir limits

$$J_{CL} = \frac{4}{9}\varepsilon_0\sqrt{\frac{2qe}{m}}\cdot\frac{U_d^{3/2}}{d^2}$$

- Space charge compensation
- Brightness = intensity per emittance

$$B_b = \frac{I_b}{\pi^2\varepsilon_x\varepsilon_y}$$

- IS Efficiency : from atom to ion

$$\eta = \frac{N_{ions}}{N_{atoms}}$$

- Beam purity: contaminant level
  - material choices
  - gas mixing
  - sputtering

$$\kappa = \frac{N_{ions}}{N_{beam}}$$

Parameters

- Operating pressure: from 10^{-10} mbar to 1 mbar !
  - recombination or stripping losses
  - breakdowns in extraction system and accelerating fields

- Stability
  - from +/- 1% up to +/- 2,5 % around the beam intensity
  - feed back loop required ?
  - run IS at medium performance

Parameters

- Operating scheme & reliability
  - Uptime / Availability: key element for medical application
  - Mean Time Between Failures (MTBF)
  - Mean Time To Repair (MTTR)
  - Maintenance plan
  - Number of spare parts and complexity : as low as possible
  - Number of IS on the same injector

- Space
  - contraints on the available space for the IS influence the design
  - internal sources in cyclotrons
  - compactness of the accelerator injector vault

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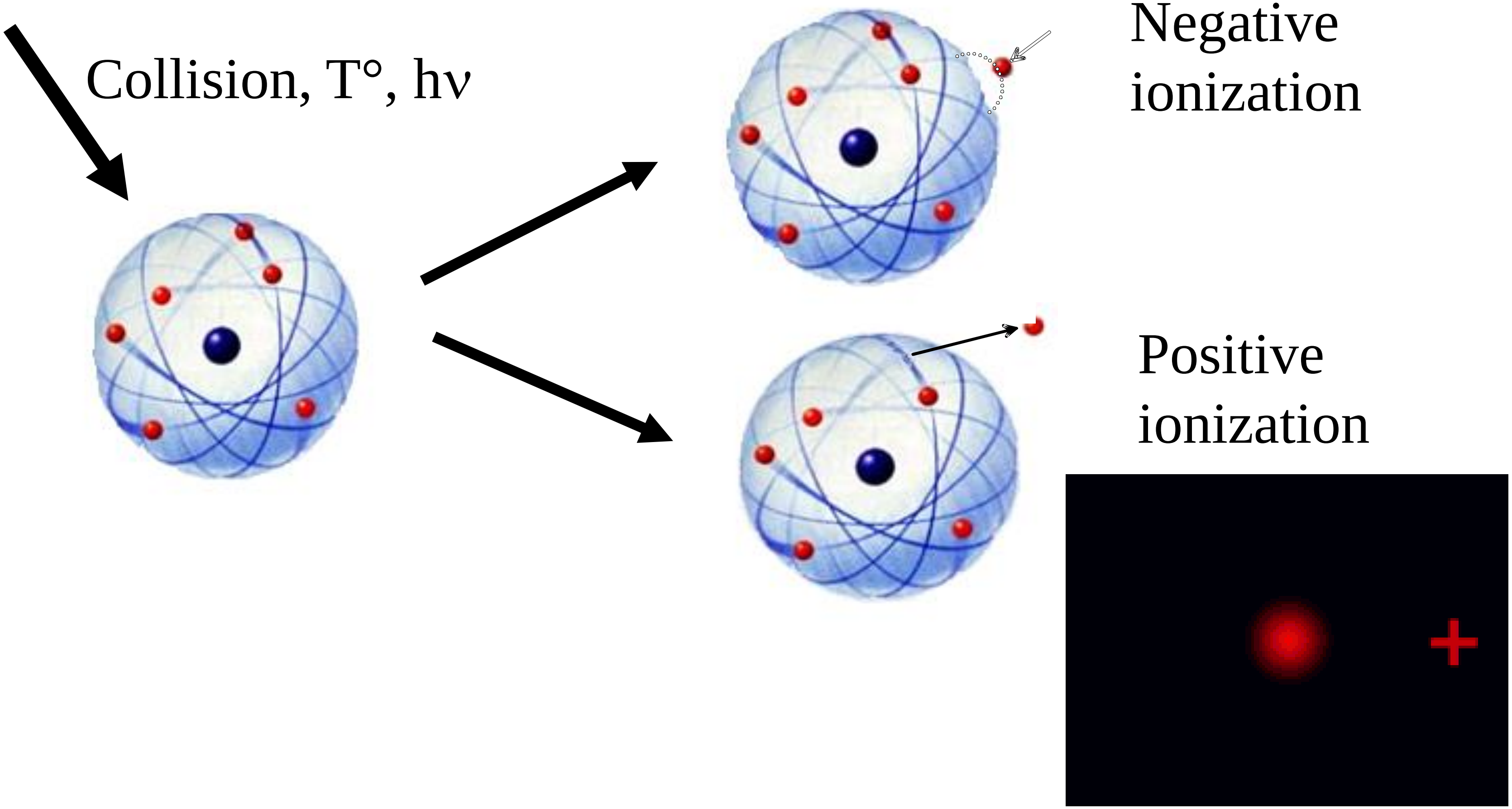
☑ Conclusion

- Positive – Negative Ions
- Classification of Ion Sources
- Electron impact ionization
- Plasma basics
- Motion of charged particles
- Confinement of charges particles

Positive – Negative Ions

Ionizing one atom is modifying its number of electrons by...

…perturbing the electron cloud



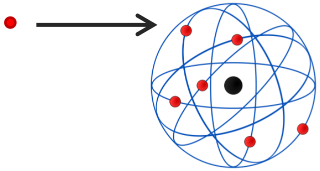
Collision, T°, hν

Negative ionization

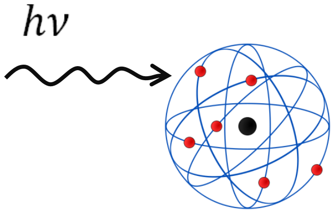
Positive ionization

Positive – Negative Ions

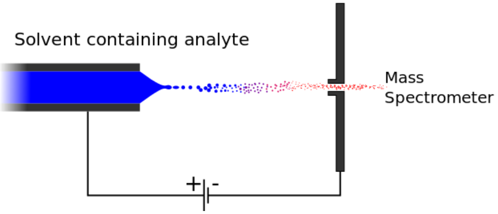
- Electron impact ionization



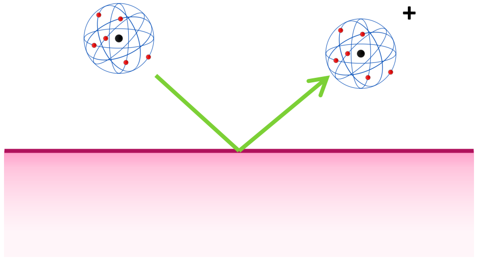
- Photoionization



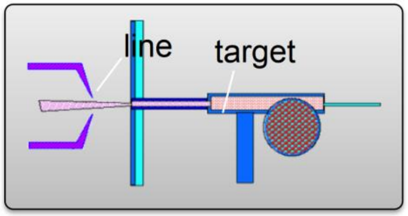
- Field ionization



- Hot surface



- Thermal ionization

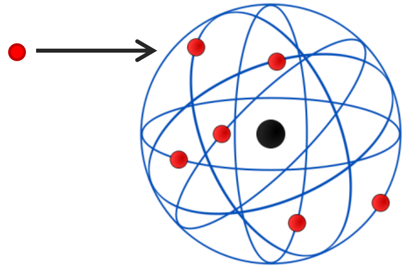


Classification of Ion Sources

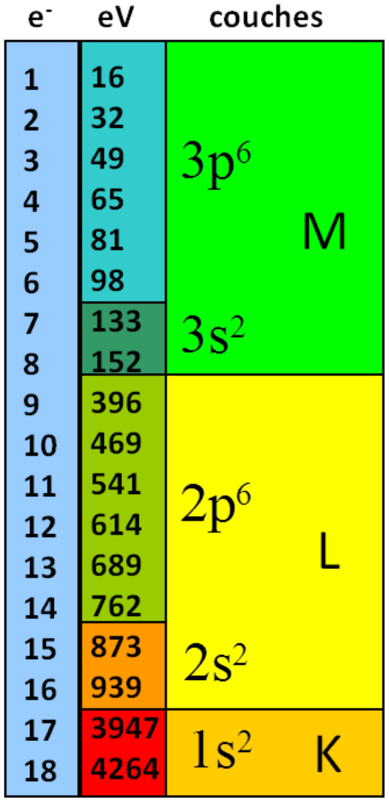
Electron Impact ionization	**DC discharge**	**Arc**	Duoplasmatron PIG FEBIAD Cathode Kaufman Nier Freeman Magnetron etc…
	RF discharge	**RF**	Helicon Thonemann
		µ-wave	**ECRIS**
	Without discharge	**e- beam**	EBIS
		photon	LIS
Without electron impact ionization	**Surface ionization**		SIS
	Field ionization		LIS Electrospray
	Charge Exchange		Stripping
	Thermo-ionization		Thermospray

- IS for medical accelerators are mostly based on the **Electron impact ionization**

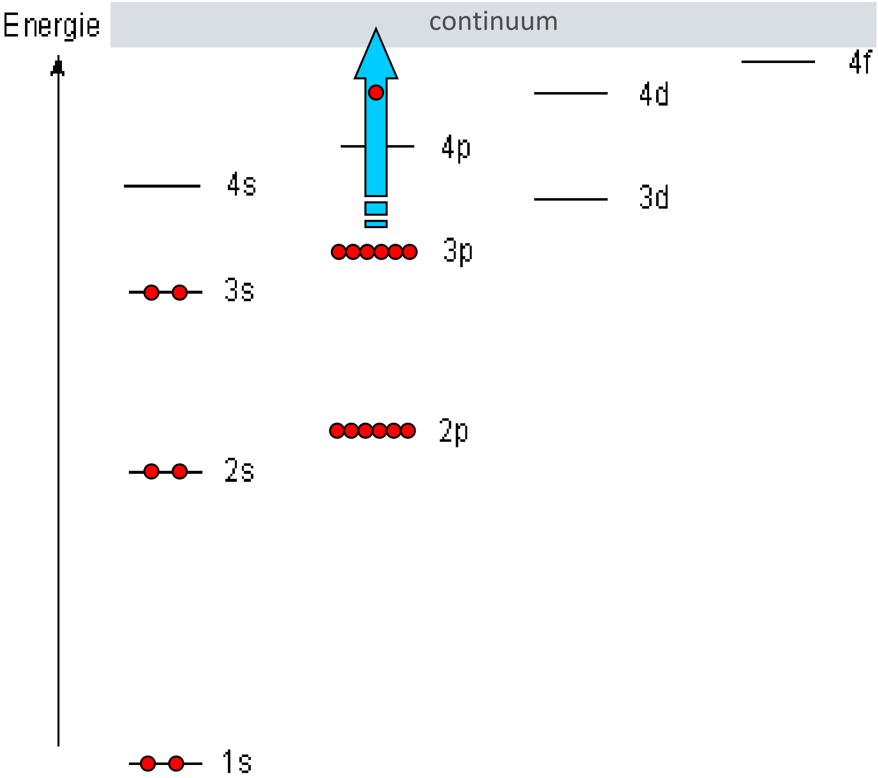
Electron impact
Ionization Potential



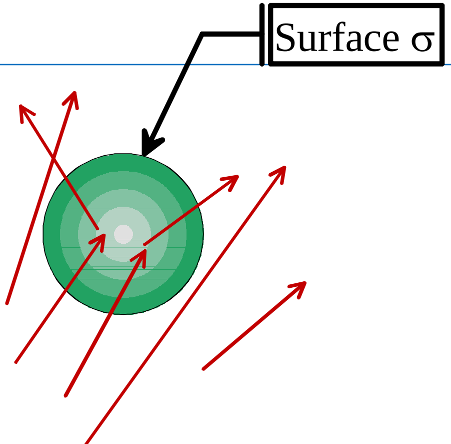
Example for argon: $^{40}Ar^{18}$

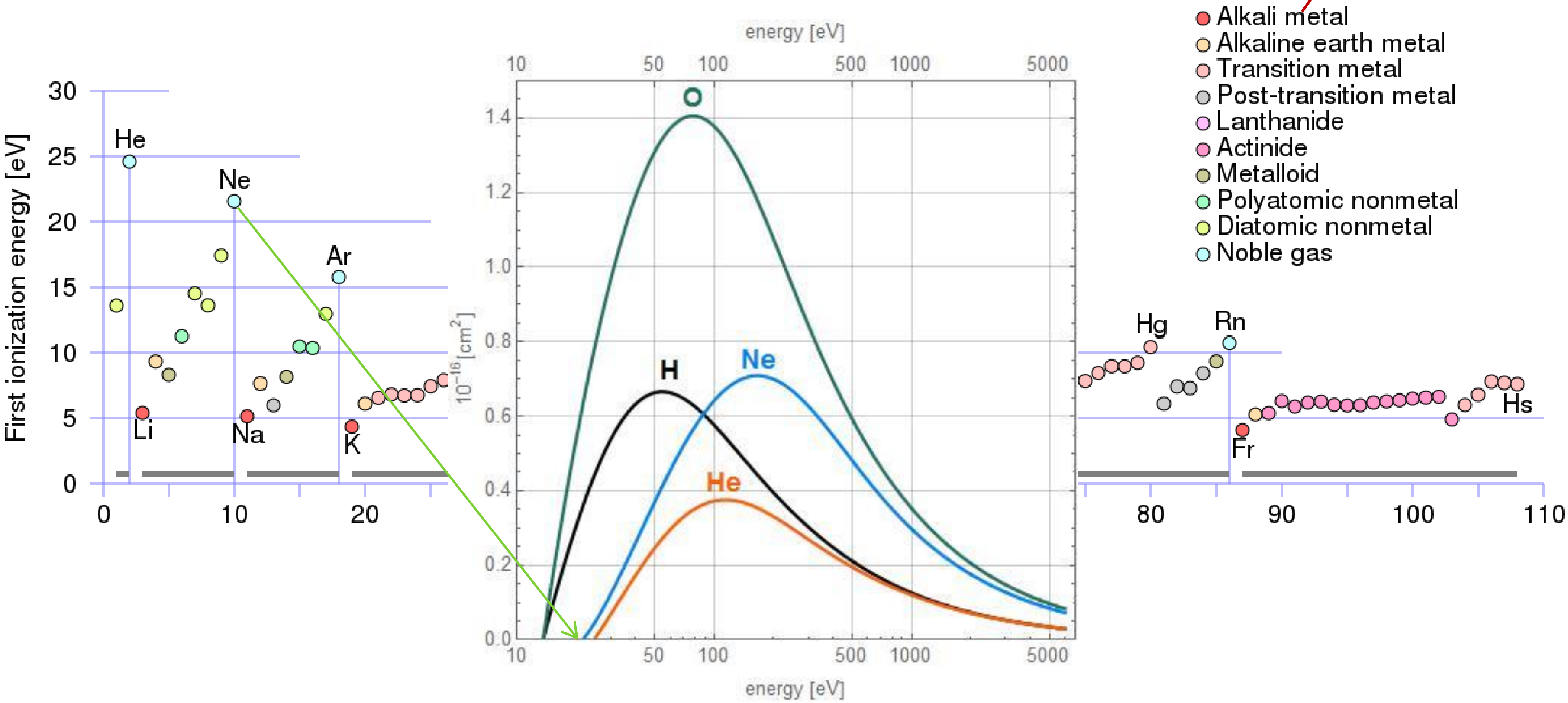


e^-	eV	couches	
1	16	$3p^6$	M
2	32		
3	49		
4	65		
5	81		
6	98		
7	133	$3s^2$	
8	152		
9	396	$2p^6$	L
10	469		
11	541		
12	614		
13	689		
14	762		
15	873	$2s^2$	
16	939		
17	3947	$1s^2$	K
18	4264		



Electron impact
Ionization Potential & cross section





Source : Wikicommons

Electron impact
Ionization Potential & cross section

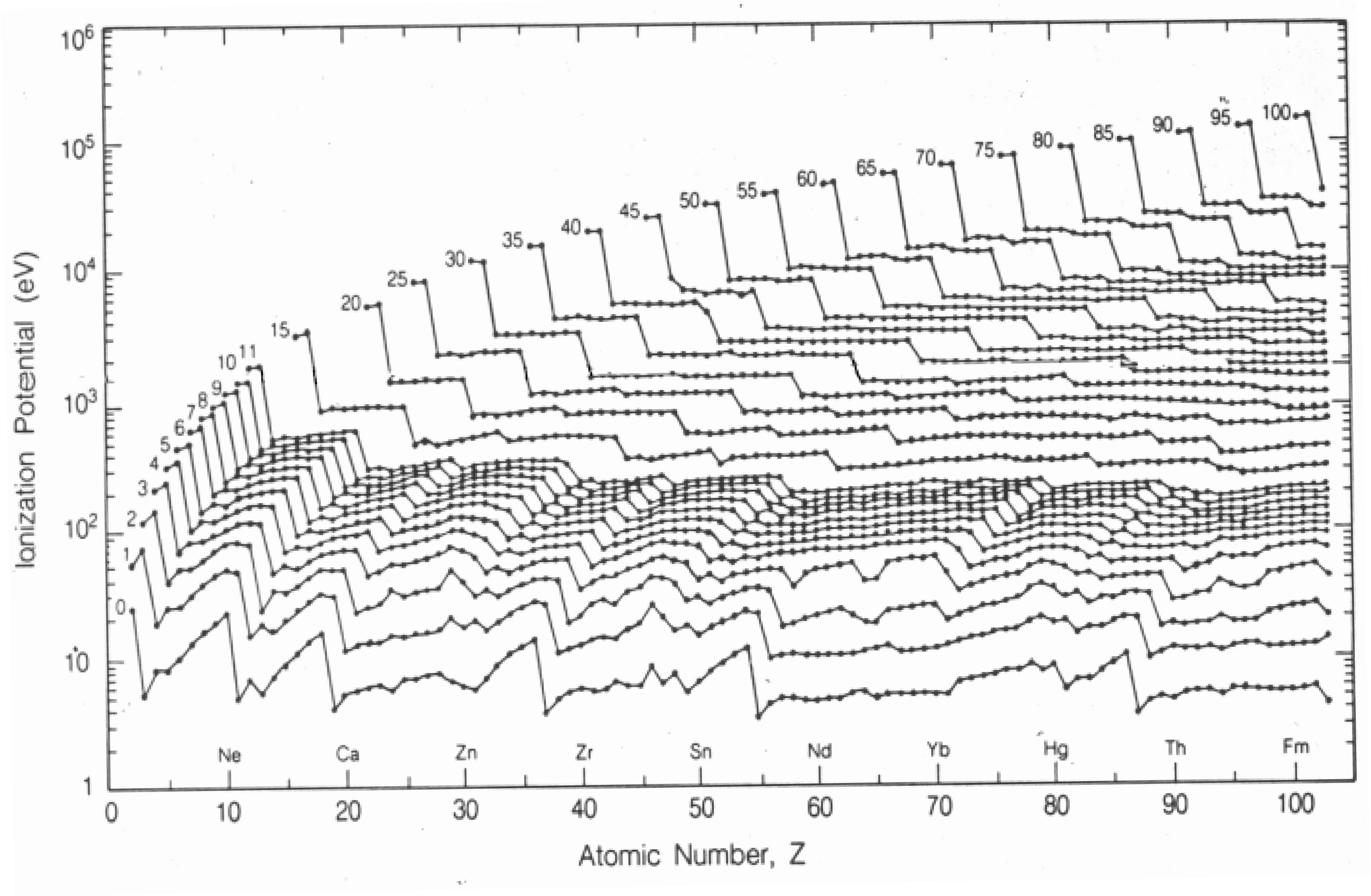
Reaction	**σ_{200eV} (cm²)**
e- + He => He^+ +2e-	$3{,}2.\ 10^{-17}$
e- + He+ => He^{2+} +2e-	$4{,}6.10^{-18}$
e- + He => He^{2+} +3e-	$1{,}4.10^{-19}$

⇳ Step by step ionization to get multi-charged ions

Source : Wikicommons

Electron impact

Ionization potentials of the atom can be very high !

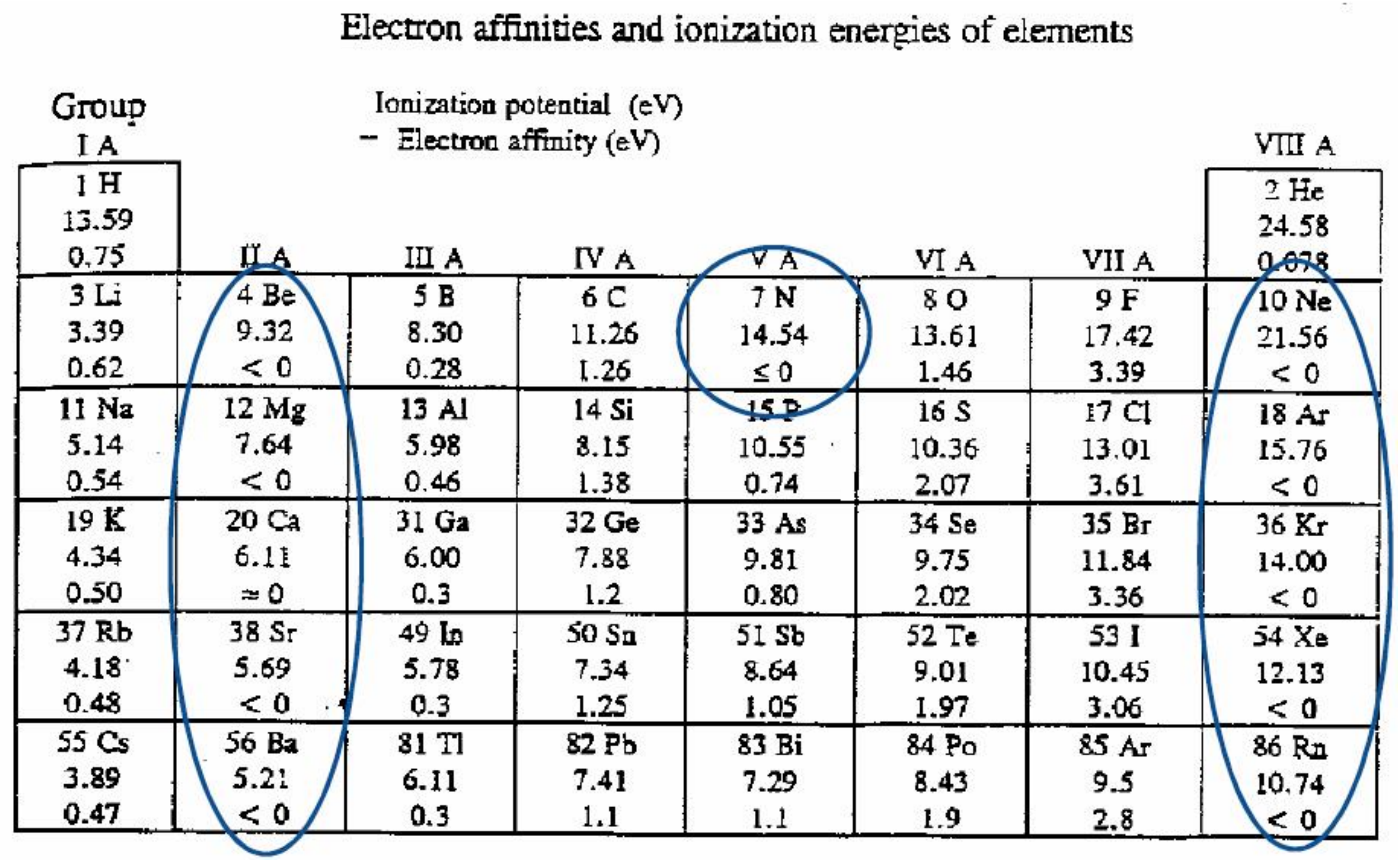


Carlson et al., http://dx.doi.org/10.1016/S0092-640X(70)80005-5

Electron impact

Electron Affinity (EA) for negative Ions

Definition of EA: energy given off when neutral atom in gas phase gains extra electron to form *negatively charged ion*



Electron affinities and ionization energies of elements

Ionization potential (eV)
– Electron affinity (eV)

Group I A	II A	III A	IV A	V A	VI A	VII A	VIII A
1 H 13.59 0.75							2 He 24.58 0.078
3 Li 3.39 0.62	4 Be 9.32 < 0	5 B 8.30 0.28	6 C 11.26 1.26	7 N 14.54 ≤ 0	8 O 13.61 1.46	9 F 17.42 3.39	10 Ne 21.56 < 0
11 Na 5.14 0.54	12 Mg 7.64 < 0	13 Al 5.98 0.46	14 Si 8.15 1.38	15 P 10.55 0.74	16 S 10.36 2.07	17 Cl 13.01 3.61	18 Ar 15.76 < 0
19 K 4.34 0.50	20 Ca 6.11 ≈ 0	31 Ga 6.00 0.3	32 Ge 7.88 1.2	33 As 9.81 0.80	34 Se 9.75 2.02	35 Br 11.84 3.36	36 Kr 14.00 < 0
37 Rb 4.18 0.48	38 Sr 5.69 < 0	49 In 5.78 0.3	50 Sn 7.34 1.25	51 Sb 8.64 1.05	52 Te 9.01 1.97	53 I 10.45 3.06	54 Xe 12.13 < 0
55 Cs 3.89 0.47	56 Ba 5.21 < 0	81 Tl 6.11 0.3	82 Pb 7.41 1.1	83 Bi 7.29 1.1	84 Po 8.43 1.9	85 Ar 9.5 2.8	86 Rn 10.74 < 0

Electron impact: ion production

The Kinetic energy of one electron Ec must be larger than the ionization potential of the atom I.

$Ec > I \quad e + X \rightarrow e + X^+ + e$

$Ec > I_{n+} \quad e + X^{n+} \rightarrow e + X^{(n+1)+} + e$ Successive ionization

$Ec > I_{n+} \quad e + X^{n+} \rightarrow e + X^{(n+j)+} + je$ Multiple Ionization

N_e monokinetic electrons travelling a L path in a gas will product N^+ ions as below:

$$N^+ = \sigma N_0 N_e L$$

N_0 is the density of neutral particles

Electron impact but ion destruction …

Radiative recombination : $X^{n+} + e \rightarrow X^{(n-1)+} + h\nu$

Charge exchange $X^{+} + Y \rightarrow X + Y^{+}$

Dielectronic recombination: $X^{(n+1)+} + e \rightarrow X^{n+*}$

$X^{n+*} \rightarrow X^{n+} + h\nu$

Looses on the walls: $X^{n+} + \text{wall} \rightarrow X$

$$\frac{\partial n_i}{\partial t} = \underbrace{\sum_{j=j_{\min}}^{i-1} n_e n_j \left\langle \sigma_{j\to i}^{EI} v_e \right\rangle + n_0 n_{i+1} \left\langle \sigma_{i+1\to i}^{CE} v_{i+1} \right\rangle}_{\text{creation}} \underbrace{- n_0 n_i \left\langle \sigma_{i\to i-1}^{CE} v_i \right\rangle - \sum_{j=i+1}^{j_{\max}} n_e n_j \left\langle \sigma_{i\to j}^{EI} v_e \right\rangle}_{\text{destruction}} \underbrace{- \frac{n_i}{\tau_i}}_{\text{Losses (ion extraction, wall…)}}$$

n: density

S: cross section of a process

τ_i: confinement time

n_i / τ_i: current intensity (=losses)

Plasma Basics

Plasma is a quasi-neutral ionized gas

$$\mathbf{n^{+} = \sum n_i q_i = n_e}$$

Composition = (Ions + e^- + Atoms + Molecules)

Ionization ratio

$$\boxed{\boldsymbol{\alpha} = \frac{\mathbf{n^{+}}}{\mathbf{n^{+} + n_0}}}$$

- Low $10^{-9} < \alpha < 10^{-4}$
- High $10^{-4} < \alpha < 1$

Typical ECR parameters	n_e cm^3	E_e keV	Φ V	T_i eV	τ_e ms
Order Of magnitude	10^{10} à 10^{12}	5 à 50	few V to few tens	< 1	0,5 à 5

Plasma parameters:

n^+ : positive ion density

n_e : electron density

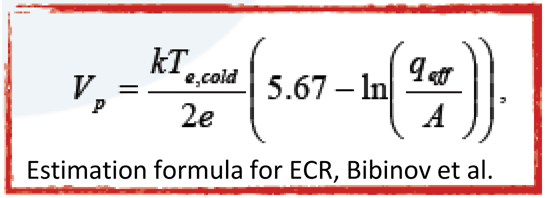
n_0 : neutral density

Ti : ion temperature

Te: electron temperature

τ_e : e^- confinement time

Φ : plasma potential



$$V_p = \frac{kT_{e,cold}}{2e}\left(5.67 - \ln\left(\frac{q_{eff}}{A}\right)\right),$$

Estimation formula for ECR, Bibinov et al.

Plasma Basics

- Typical total length scale L has to exceed the shielding length of the plasma: Debye Length

$$L \gg \lambda_{De} = \sqrt{\frac{\varepsilon_0 k T_e}{e^2 n_e}},$$

the collective interactions are dominated by bulk plasma rather than boundary effects

- Number of particles inside the Debye sphere must be sufficient

$$n_e \lambda_D^3 \gg 1.$$

collective interactions dominate over binary interactions at the mean interparticle separation distance

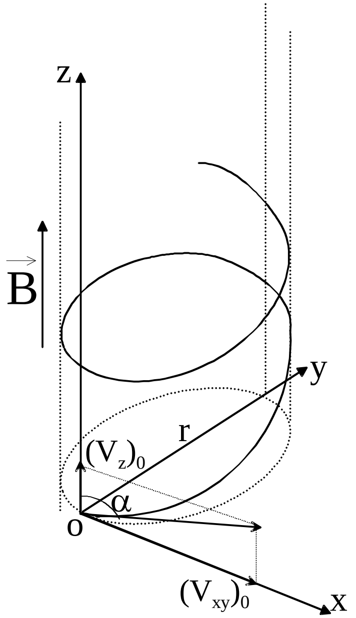
- Frequency of collective plasma (electron) oscillations must be higher than the collision frequency of electrons and neutrals

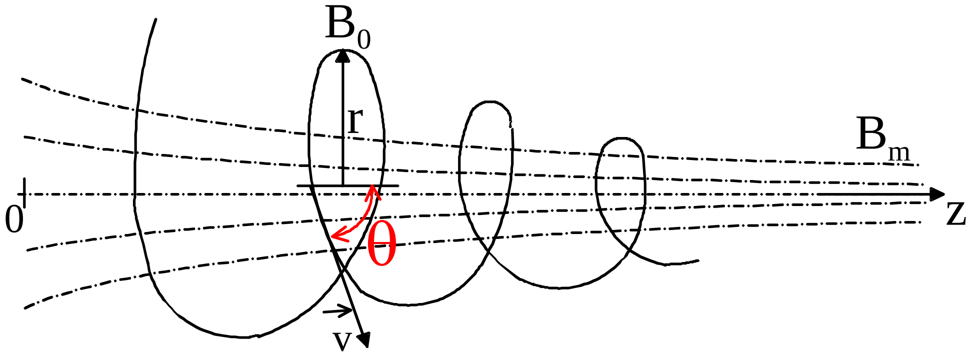
$$f_{pe} = \frac{\omega_{pe}}{2\pi} = \frac{1}{2\pi}\sqrt{\frac{n_e e^2}{\varepsilon_0 m_e}} > \nu_{en},$$

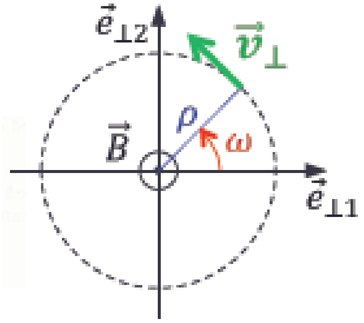
Motion of charged particles

Elementary motion of charged particle in static magnetic and electric field

Motion with B







$\boxed{\omega = \frac{qB}{m} \text{ is the cyclotronic frequency}}$

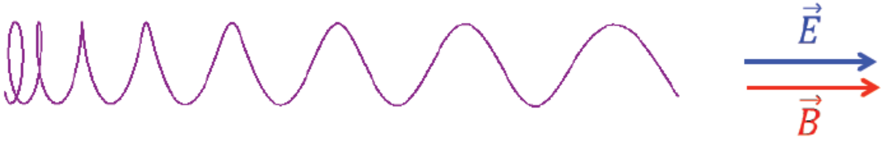
ρ is the Larmor radius

Motion of charged particles

Elementary motion of charged particle in static magnetic and electric field

Motion with B // E

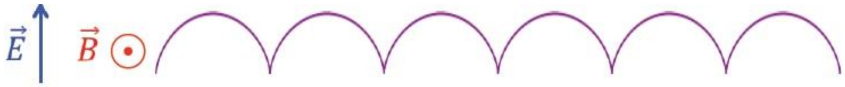
- $m\frac{d\vec{v}}{dt} = q\vec{v}\times\vec{B} + \vec{E} \rightarrow \begin{cases} m\frac{d\vec{v}_\perp}{dt} = q\vec{v}_\perp \times \vec{B} \\ m\frac{d\vec{v}_\parallel}{dt} = q\vec{E} \end{cases} \rightarrow \begin{cases} rotation\ with\ v_\perp = \rho\omega \\ v_\parallel = \frac{qEt}{m} \end{cases}$
- $\rightarrow$ 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 $\vec{e}_{\perp 2} = \frac{\vec{E}}{E}$

E x B azimuthal drift

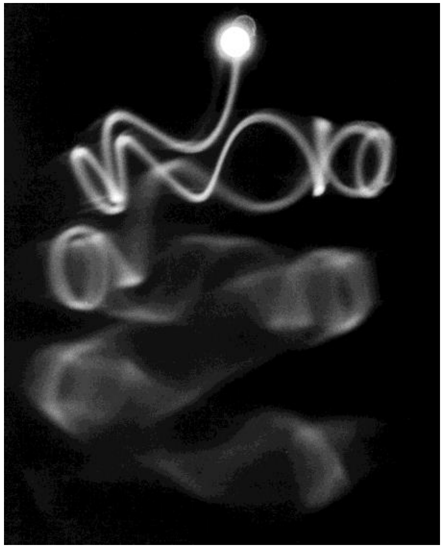


Confinement of charged particles
The magnetic mirror

$$E_c = E_\perp + E_{//} = \frac{1}{2} m_e \left(v_\perp + v_{//}\right)^2$$

$$\mu = \frac{E_\perp}{B}$$

CONSERVATION



when B ↗ $E_\perp$ ↗ $v_{//}$ ↘

when B ↘ $E_\perp$ ↘ $v_{//}$ ↗

REFLEXION

Overview

☑ Ion Source Requirements

☑ Ionization process, plasma, motion & confinement basics

☑ **Review of Ion Sources for medical accelerators**

- Proton radiotherapy IS
- Heavy Ion radiotherapy IS
- IS Developments for future radiotherapy
- Boron Neutron Capture Therapy IS
- Radioisotope production

☑ Conclusion

- Proton radiotherapy IS
- Heavy Ion radiotherapy IS
- IS Developments for future radiotherapy

Proton and Carbon Ions

- Boron Neutron Capture Therapy IS

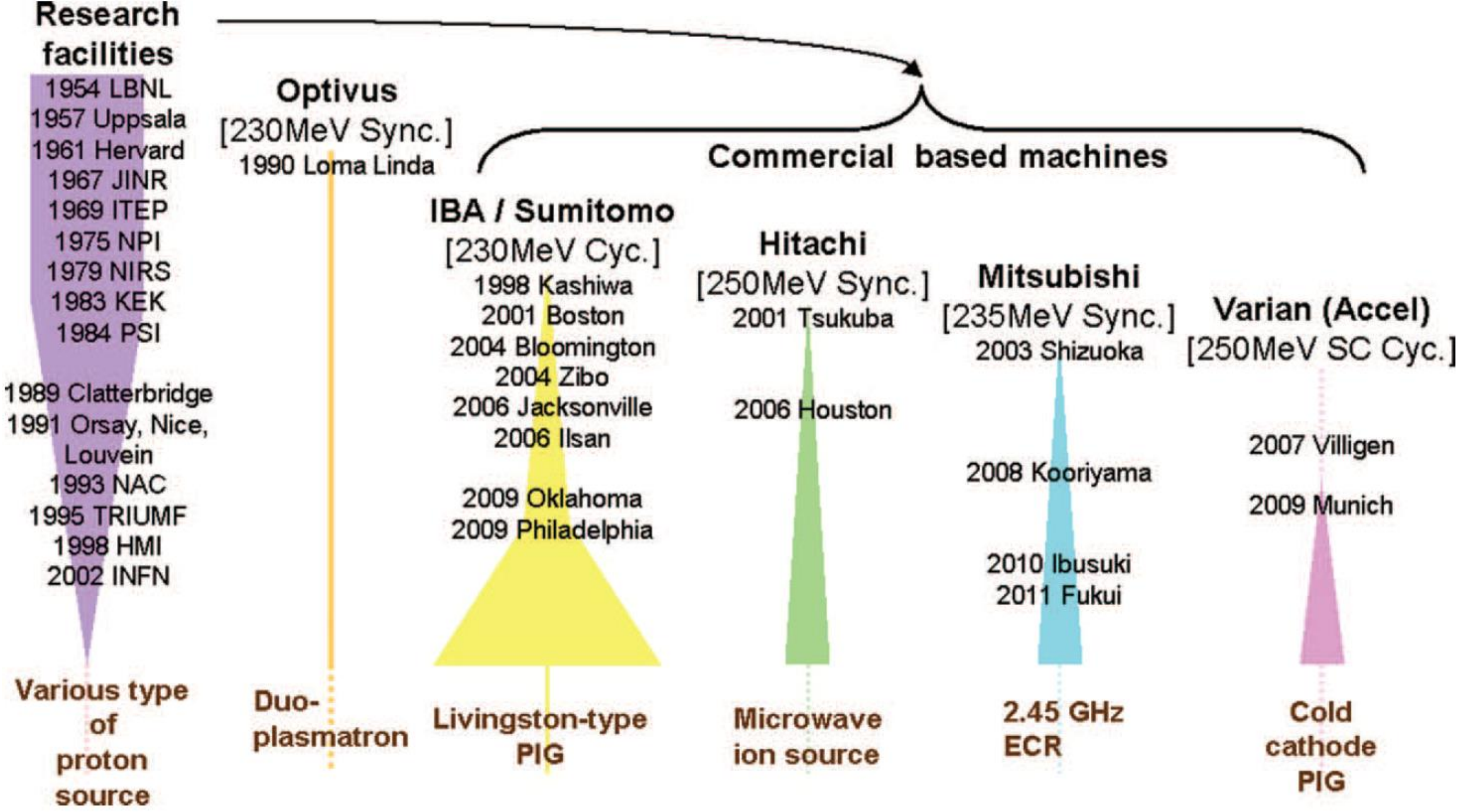
Protons

- Radioisotope production

Different ion species

Proton radiotherapy IS

Development and trend in radiotherapy



Research facilities
1954 LBNL
1957 Uppsala
1961 Hervard
1967 JINR
1969 ITEP
1975 NPI
1979 NIRS
1983 KEK
1984 PSI
1989 Clatterbridge
1991 Orsay, Nice, Louvein
1993 NAC
1995 TRIUMF
1998 HMI
2002 INFN

Various type of proton source

Optivus
[230MeV Sync.]
1990 Loma Linda

Duo-plasmatron

Commercial based machines

IBA / Sumitomo
[230MeV Cyc.]
1998 Kashiwa
2001 Boston
2004 Bloomington
2004 Zibo
2006 Jacksonville
2006 Ilsan
2009 Oklahoma
2009 Philadelphia

Livingston-type PIG

Hitachi
[250MeV Sync.]
2001 Tsukuba
2006 Houston

Microwave ion source

Mitsubishi
[235MeV Sync.]
2003 Shizuoka
2008 Kooriyama
2010 Ibusuki
2011 Fukui

2.45 GHz ECR

Varian (Accel)
[250MeV SC Cyc.]
2007 Villigen
2009 Munich

Cold cathode PIG

M. Muramatsu and A. Kitagawa, RSI 83, 02B909 (2012)

Proton radiotherapy IS

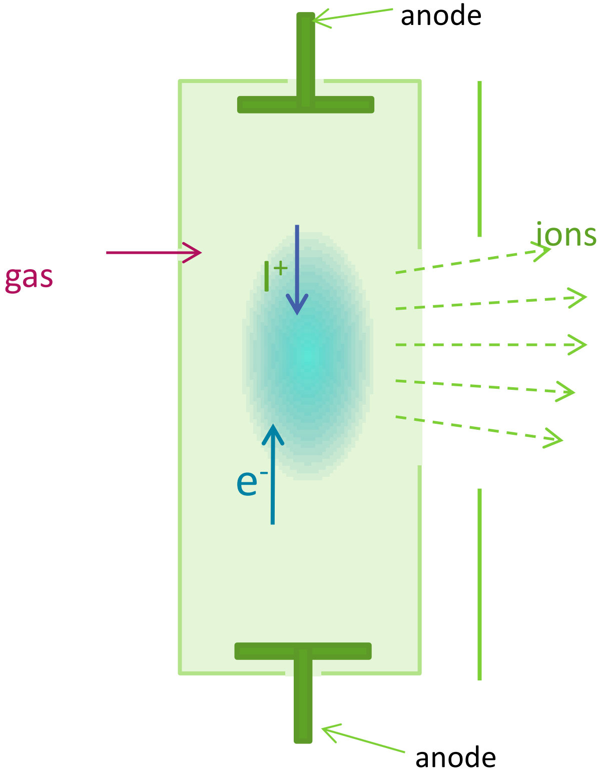
Development and trend in radiotherapy since 2011

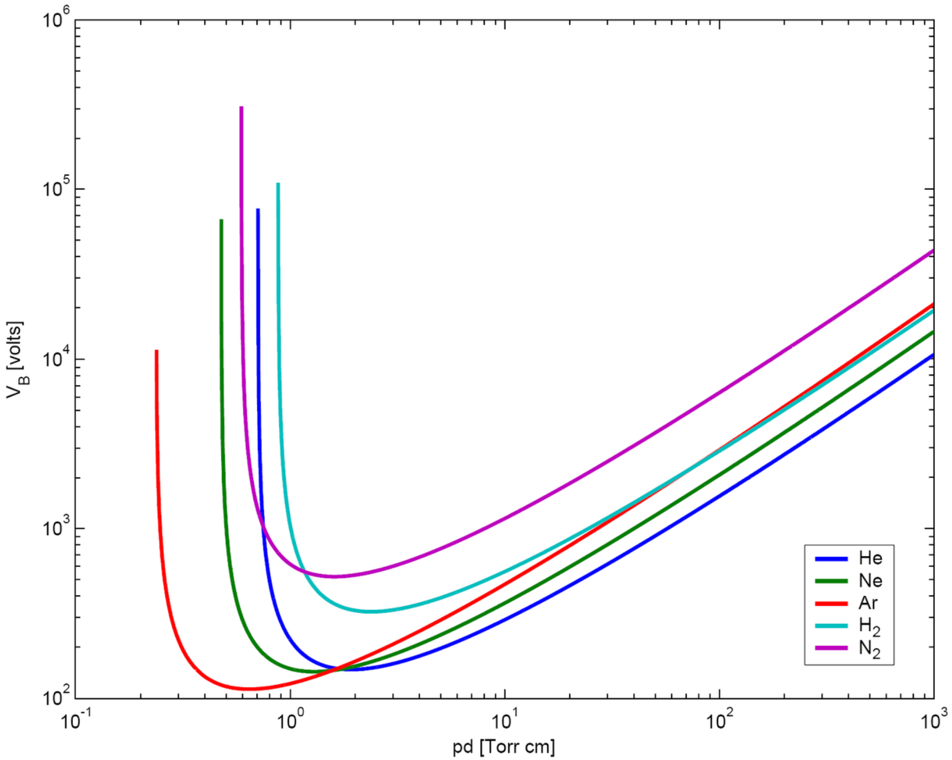
- about 30 new proton therapy facilities over the world

- new (improvement of) accelerators … new manufacturers:
  - S2C2 superconducting accelerator at IBA
  - compact 330MeV synchrotron at PROTOM
  - Gantry mounted accelerator at MEVION
  - compact LINAC at AVO-ADAM

Proton radiotherapy IS

DC Discharge





- Simple principle: breakdown of the gas using the Paschen low
- Many # configurations

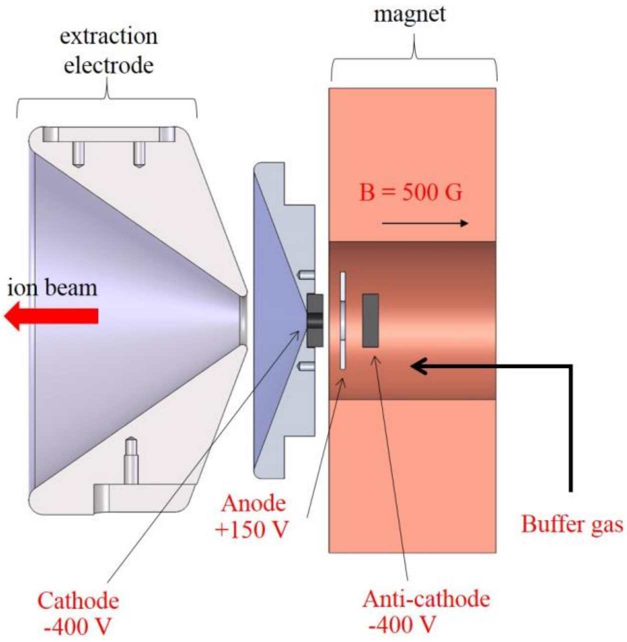
$$V_{\text{claquage}} = \frac{Bpd}{C + \ln(pd)}$$

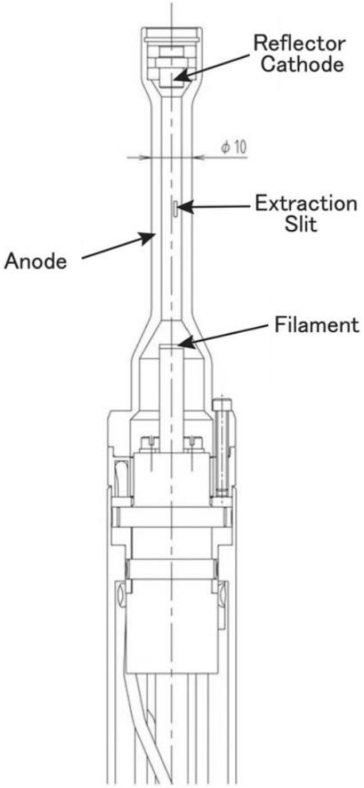
Source : wikimedia

Proton radiotherapy IS

Penning Ionization Gauge (PIG)

Ion Beam Applications (IBA) &
Sumitomo Heavy Industry (SHI)
for the 235 MeV cyclotron





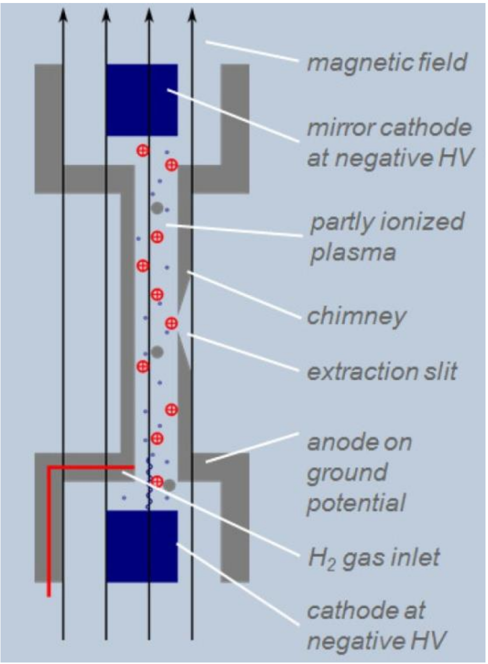
Type: Livongstone-type internal PIG
Arc voltage: 140 V
Arc current: 500mA
Max. beam current: 10 µA, H$^+$
Life time Ta filament: 5 to 7 days
Gas flow: 1 to 2 sccm

P. Cailliau et al., Proc. Of Cyclotrons2016, Zurich
http://jacow.org/cyclotrons2016/papers/tup02.pdf, 2017
M. Muramatsu and A. Kitagawa, RSI 83, 02B909 (2012)

Proton radiotherapy IS

Penning Ionization Gauge (PIG)

VARIAN's 250 MeV cyclotron



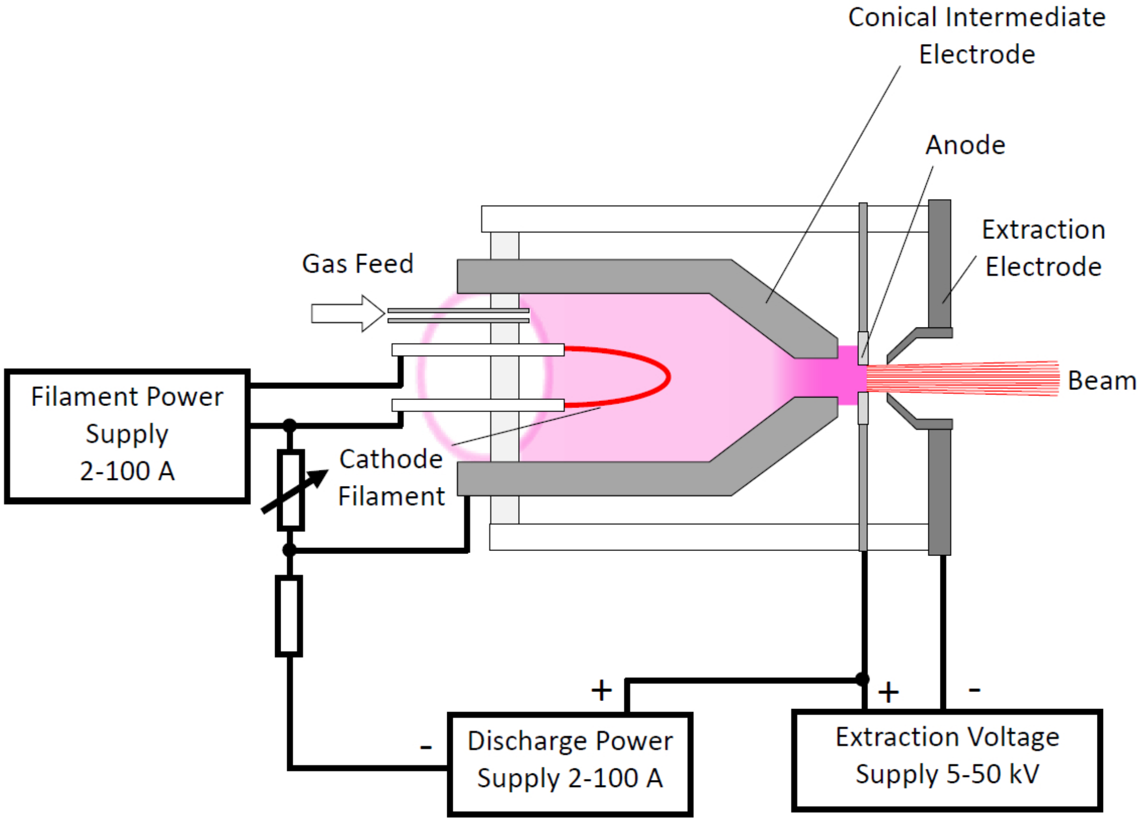
Type: Cold cathode PIG
Cathode voltage: -1 to -1,8kV
Discharge current: 300mA
Max. beam current: few 100 µA, H^+
Gas flow: few sccm

S. Busold et al., Proc. Of Cyclotrons2016, Zurich
http://jacow.org/cyclotrons2016/papers/thp06.pdf, 2017

Proton radiotherapy IS

DUOPLASMATRON FOR PROTONS

Original design of the Plasmatron by Manfred Von Ardenne (late 1940s)

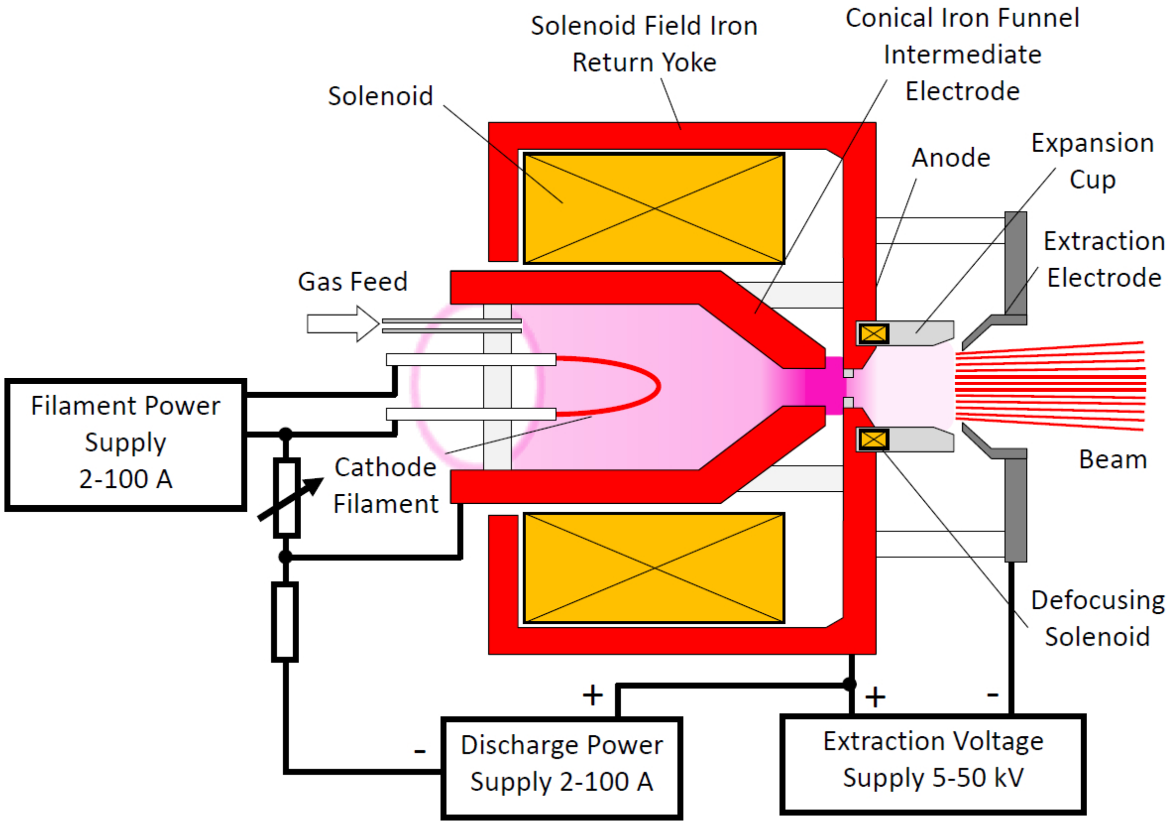


Dan Faircloth, CAS 2011, Bilbao, arXiv:1302.3745, 2013

Proton radiotherapy IS

DUOPLASMATRON FOR PROTONS

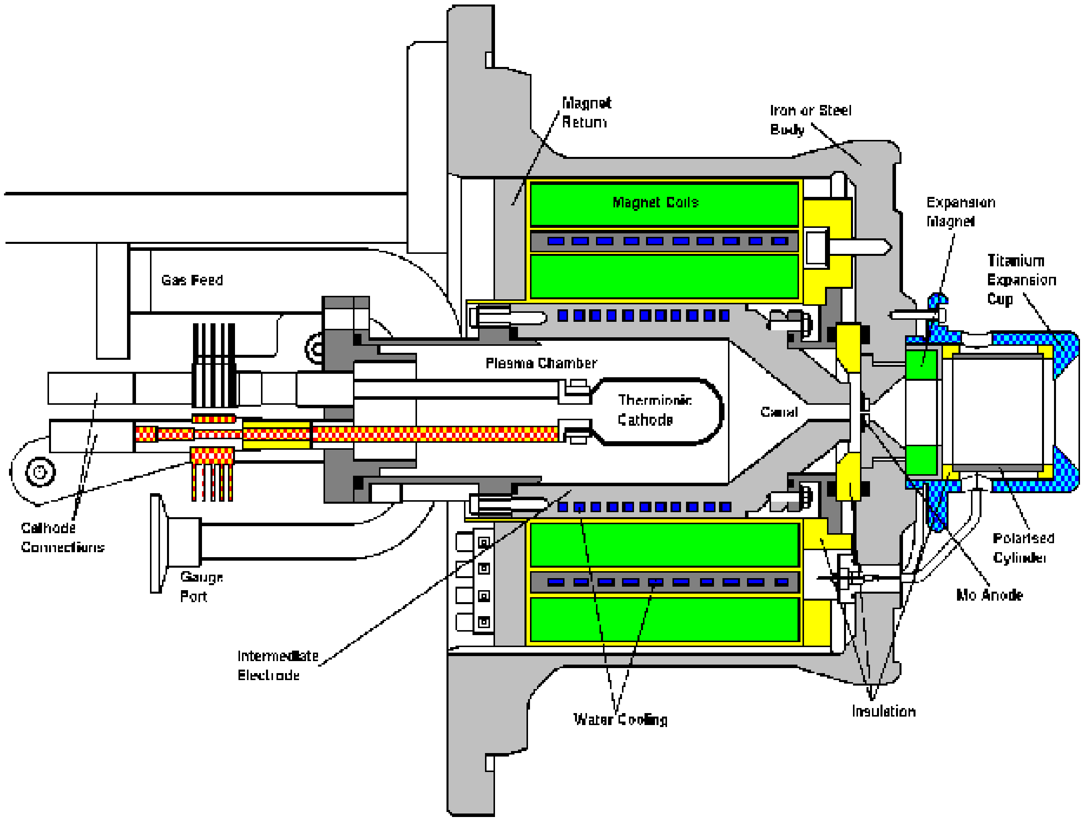
Duoplasmatron design improves the Plasmatron with magnetic field
Manfred Von Ardenne (late 1956s)



Dan Faircloth, CAS 2011, Bilbao, arXiv:1302.3745, 2013

Proton radiotherapy IS

DUOPLASMATRON FOR PROTONS



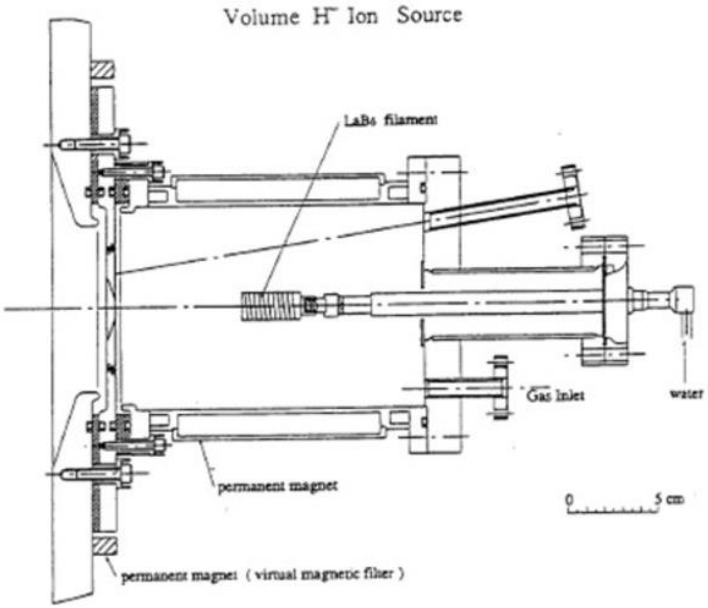
OPTIVUS 230 MeV synchrotron

Type: Duoplasmatron
Arc voltage: 100 V
Extraction: up to 50kV
Max. beam pos. current: several mA, H^+
Max. beam neg. current: few 10 µA, H^-
Off axis extraction for neg. operation
Life time > 1000 h

Dan Faircloth, CAS 2011, Bilbao, arXiv:1302.3745, 2013

Proton radiotherapy IS

Volume H^- multicusp IS



A filament driven plasma is confined by a multicusp field

Source: JPARC KEK Design.

TRIMPH Type DC Volume-Cusp H^- IS

Type: Multicusp
Arc voltage: 200 V
Filament supply: 400 A, 10V
Extraction: up to 30kV
Max. beam neg. current: 5 mA, H^-
Life time > 5200 h

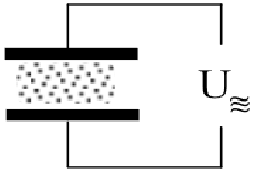
Source : http://www.d-pace.com

Proton radiotherapy IS

RF Discharge IS

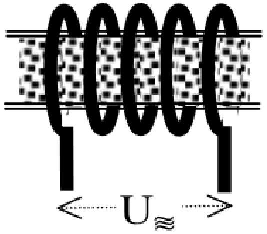
Frequency range 0.1 – 30 MHz
Power range 50 – 800 kW

Capacitive coupling



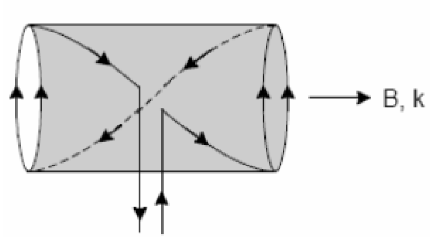
f = 1 – 30 MHz
P = 0.05 – 0.1 kW

Inductive coupling



f = 0.1 – 13.5 MHz
P = 0.1 – 100 kW

Wave Coupling (Helicon)



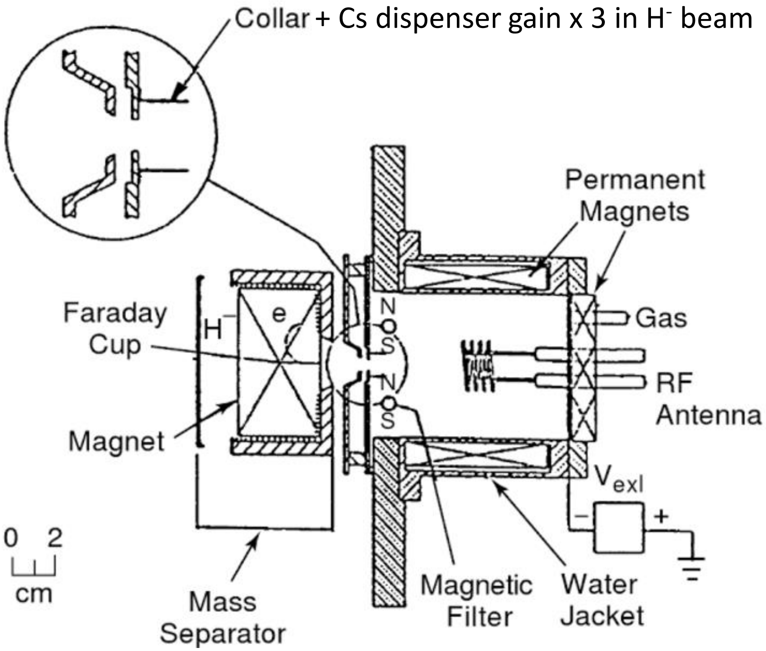
f = 2 – 13.5 MHz
P = 0.1 – 1 kW

source: Kraus 2012

Proton radiotherapy IS

RF Discharge IS

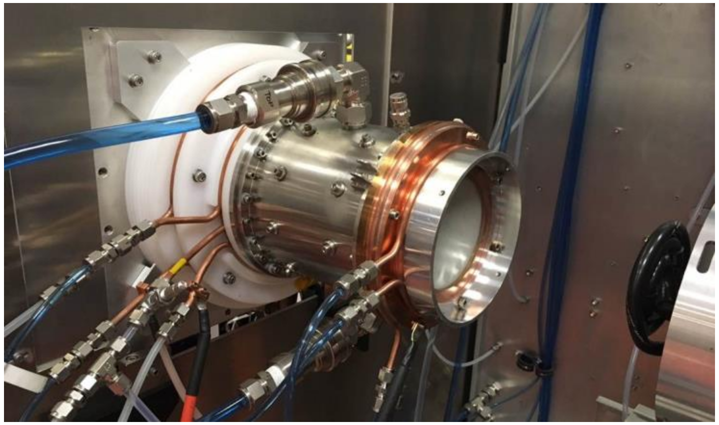
LBNL RF driven multicusp volume source



35kV, > 35mA 100µs at 10Hz

From K.N. Leung, RSI 62 (1991) 100

TRIMPH & Jyväskylä RF Volume Cusp source



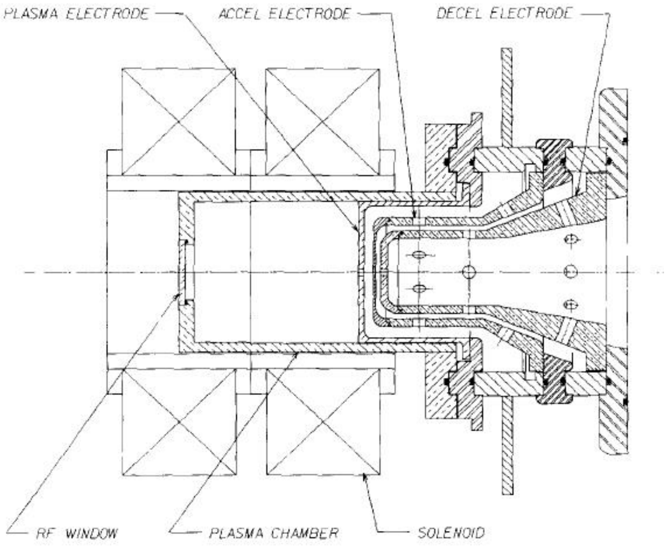
Type: RF Multicusp
No filament
Extraction: up to 30kV
Max. beam neg. current: 7,5 mA, H^-
Life time > 1 year

D-pace.com

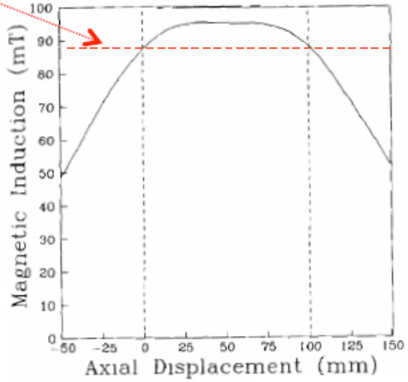
Proton radiotherapy IS

Microwave Discharge IS

Taylor type 2,45GHz ECR ion source



  - 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
  - **$\Lambda_{0\text{->}1+}$ ~ 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.



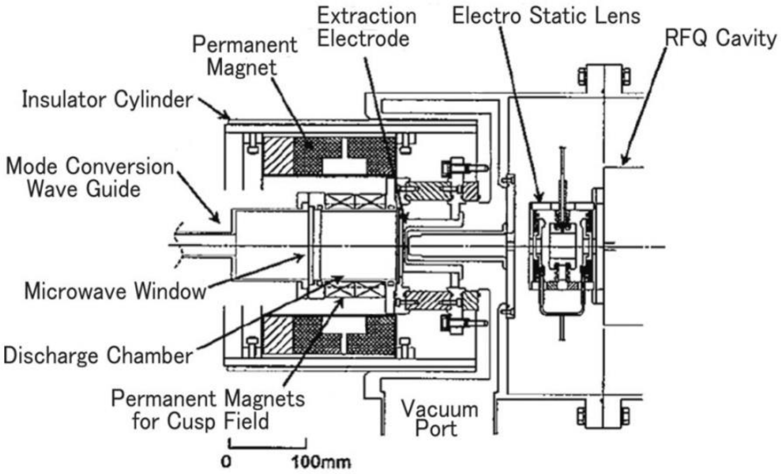
Source: NIM PR A309 (1991) 37-42

Source: T. Thuillier, CAS, Senec, 2012

Proton radiotherapy IS

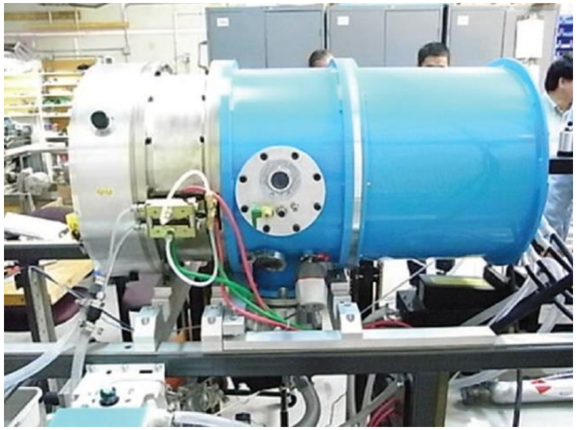
Microwave Discharge IS

HITACHI & AccSys
250 MeV synchrotron



Type: ECR discharge IS
Frequency: 2,45GHz
Max. current: 30mA DC, H^+

MITSUBISHI ELECTRIC Co. (MELCO)
250 MeV synchrotron



Type: ECR discharge IS
Frequency: 2,45GHz
Max. current: 25mA DC, H^+

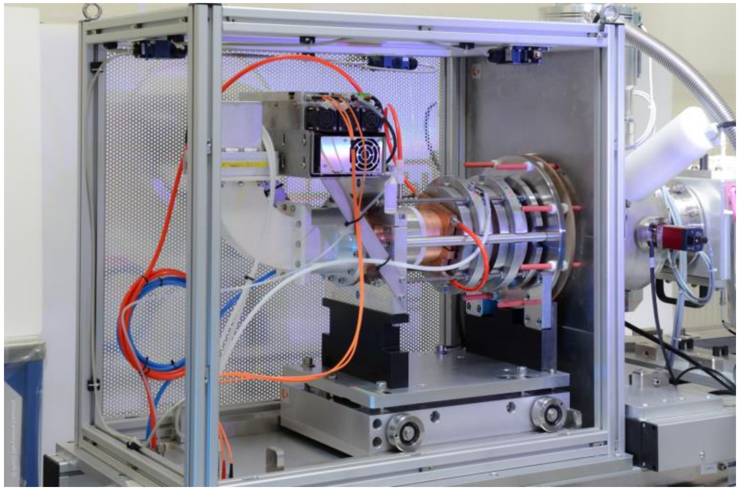
M. Muramatsu and A. Kitagawa, RSI 83, 02B909 (2012)

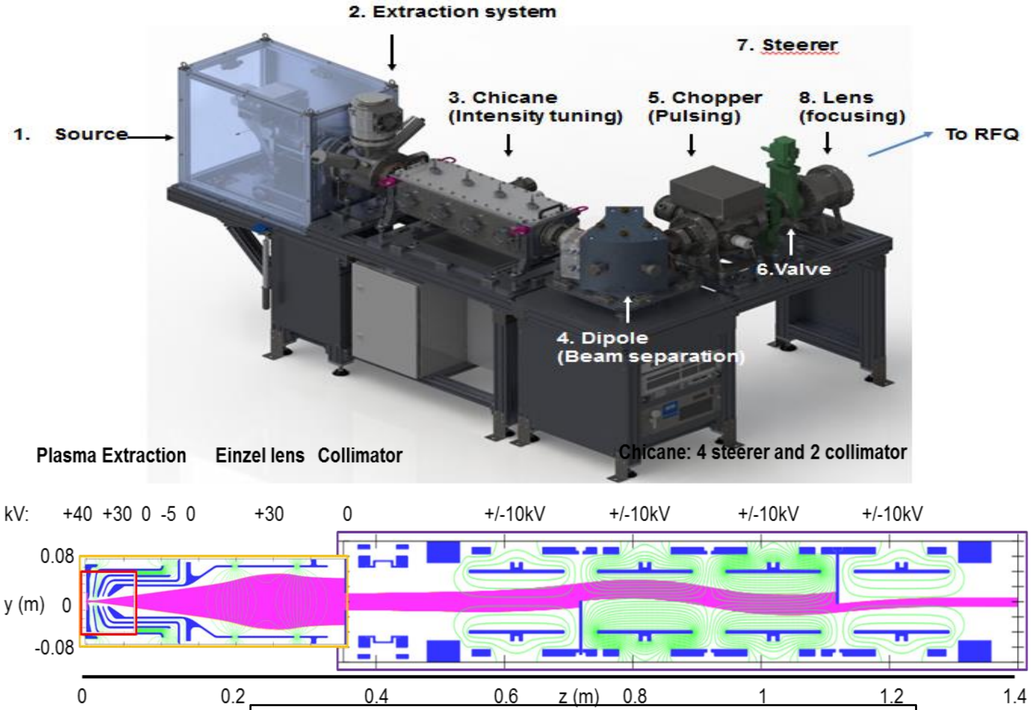
Proton radiotherapy IS

Microwave Discharge IS

Advanced Oncotherapy (AVO) /ADAM – LIGHT 230 MeV LINAC

Monogan M1000 from PANTECHNIK





Type: ECRIS
Extraction: 40kV
Frequency: 2,45GHz
Max. current: 1mA DC @80W RF, H^+

With chicane + chopper:
Current from 1 to 300µAe variation at 200Hz
Beam pulses from 5 to 20µs
PID controlled

Heavy Ion radiotherapy IS

Heavy Ion radiotherapy facilities (mostly) accelerate carbon ions

Final energy is up to 430MeV/u with several 10^8 or 10^9 pps

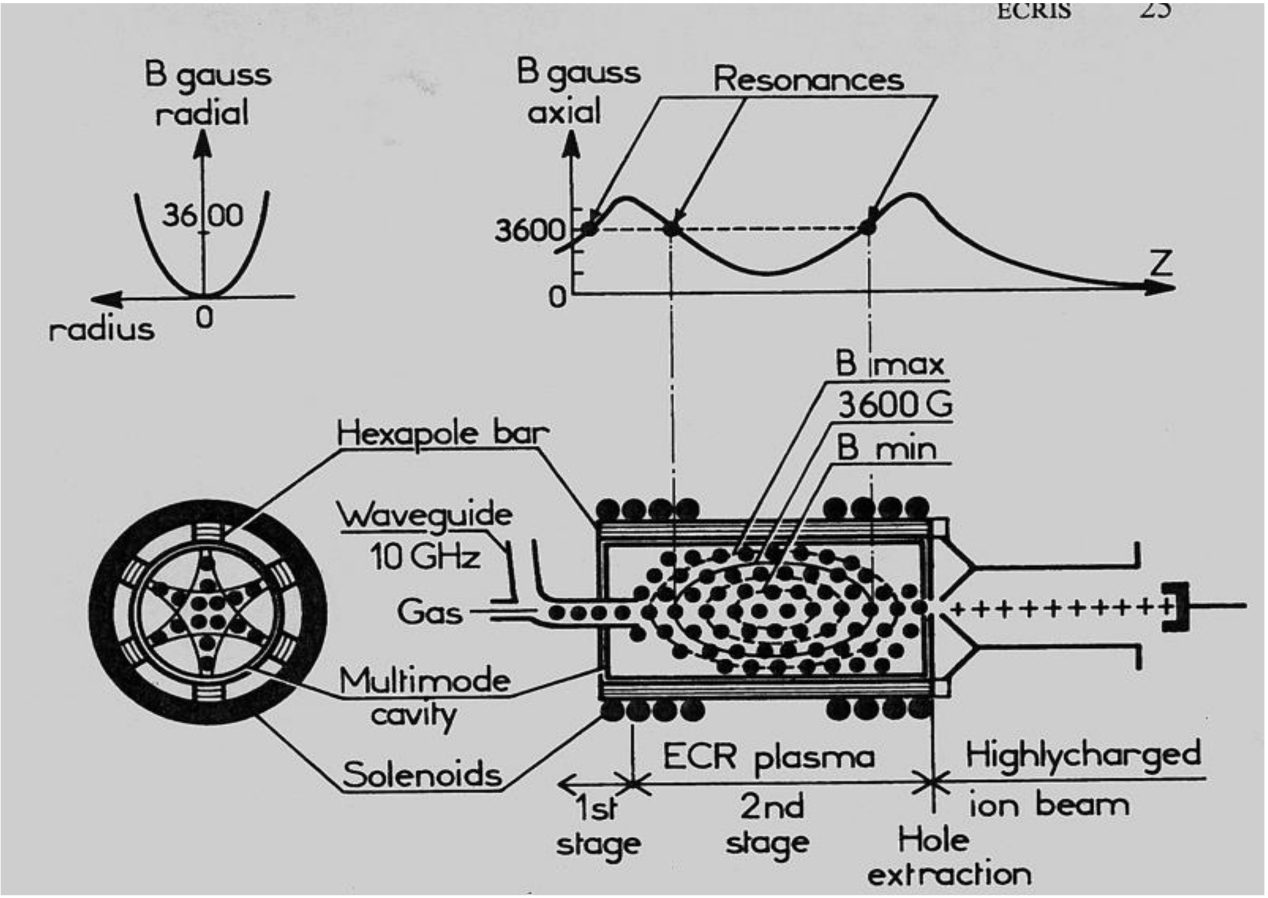
Only ECR ion sources can supply C^{x+} ion for this requirement

- ➢ First let's describe shortly ECR IS principle ….

Heavy Ion radiotherapy IS ECR basics

The first ECR Ion Source, named SUPERMAFIOS, was invented at CEA Grenoble by R. Geller team (France)

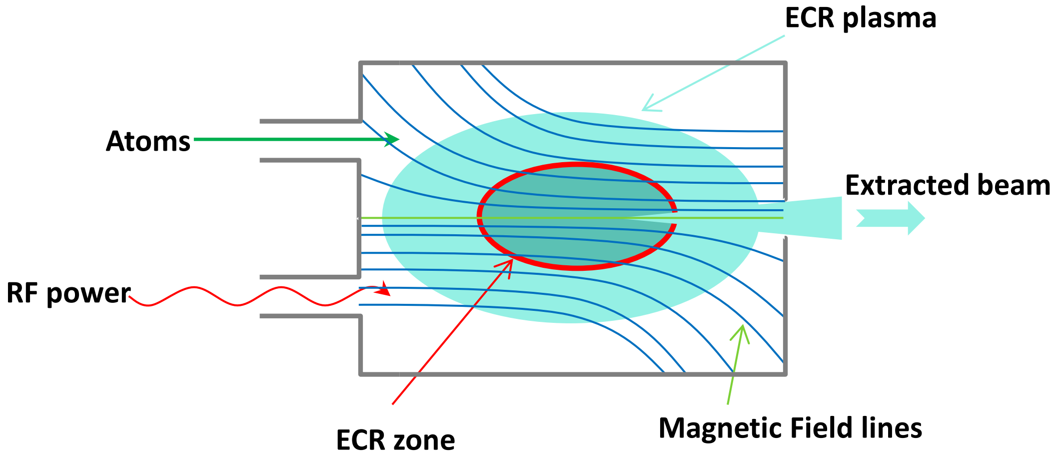
R. Geller



See: R. Geller, Ann. Rev. Nucl. Part. Science 40 (1990) 15.

Heavy Ion radiotherapy IS ECR basics

- A secondary vacuum level to allow multicharged ion production
- A RF injection into the cavity (multimode)
- A sophisticated magnetic field for
  - Transfer RF power to the electrons using the ECR mechanism
  - ensure the confinement of hot electrons that ionize the atoms
  - ensure the confinement of the ions long enough to get multiple ionizations
  - ensure the stability of the plasma
- An atom injection system to sustain the plasma density
- An extraction system to accelerate the ions from the plasma



Heavy Ion radiotherapy IS

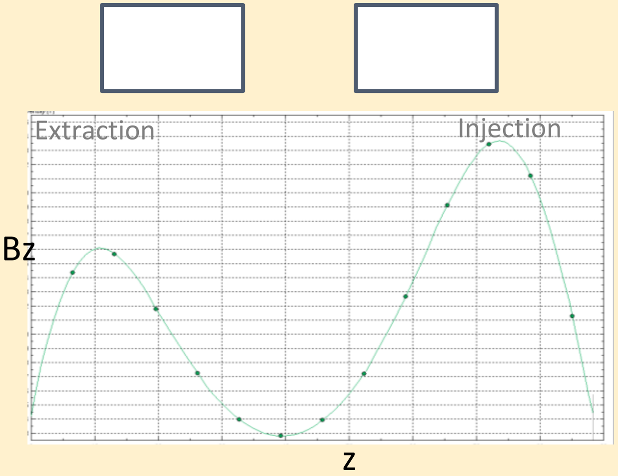
ECR basics

MAGNETIC CONFINEMENT

Axial magnetic structure

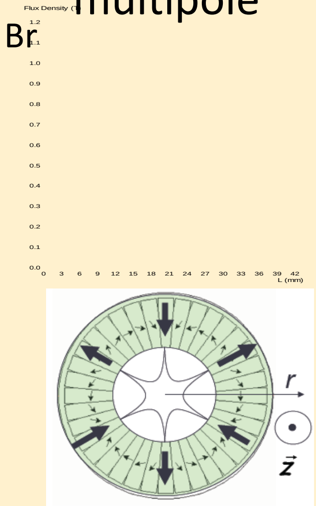
So called « minimum B »

Coils and/or Permanent Magnet



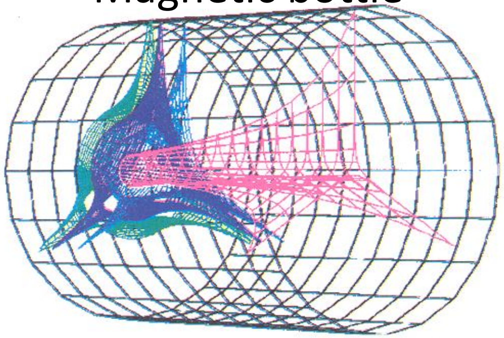
Radial magnetic structure

multipole



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

Magnetic bottle



Heavy Ion radiotherapy IS

ECR basics

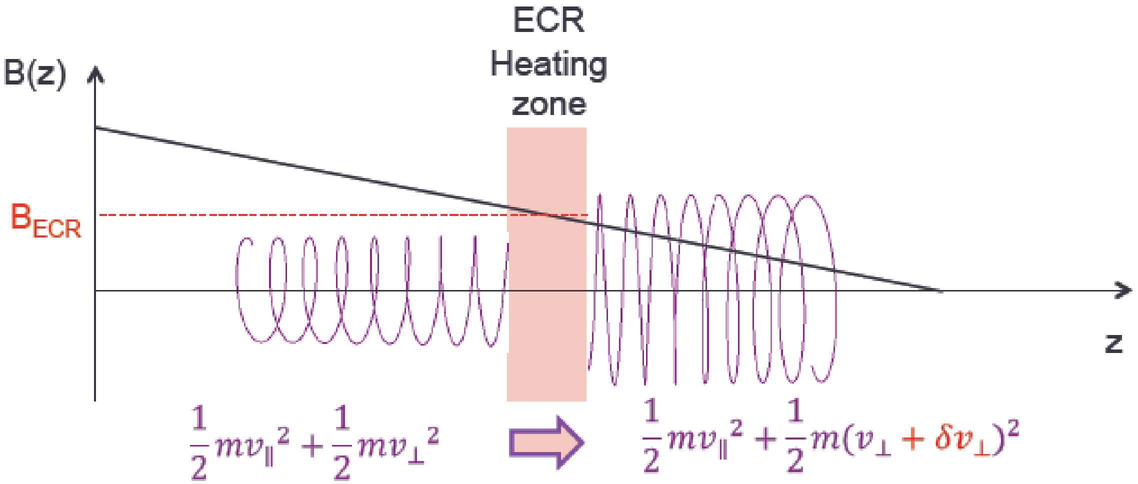
Electron heating

Electron frequency

$$f = \frac{q_e B}{2\pi m_e}$$

Resonance condition

$$B_{res} = \frac{2\pi m_e}{q_e} f_{HF}$$



Field/frequency matching:
0,036 Tesla / GHz

$B_{min} < B_{res} < B_{max}$

Heavy Ion radiotherapy IS ECR basics

Plasma oscillation & Cut-Off density

As a response to perturbation, the plasma shows a natural oscillation frequency:

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

Dispersion relation of an EM wave in a plasma:

$$\omega^2 = \omega_p{}^2 + k^2 c^2$$

The wave propagates if :

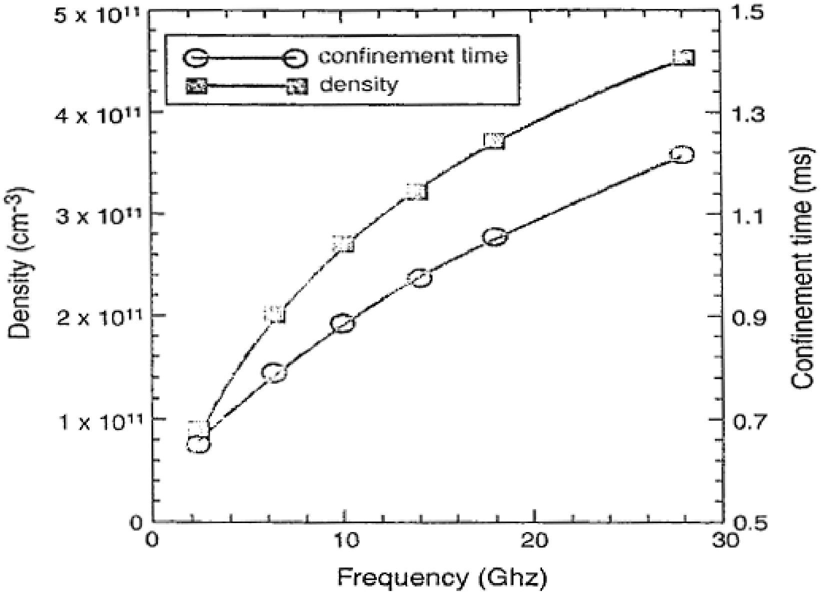
$$\omega > \omega_p$$

ECR CUT-OFF FREQUENCY:

$$\omega > \omega_p \Rightarrow n_e < \frac{m_e \varepsilon_0 \omega^2}{e^2}$$

Critical Density:

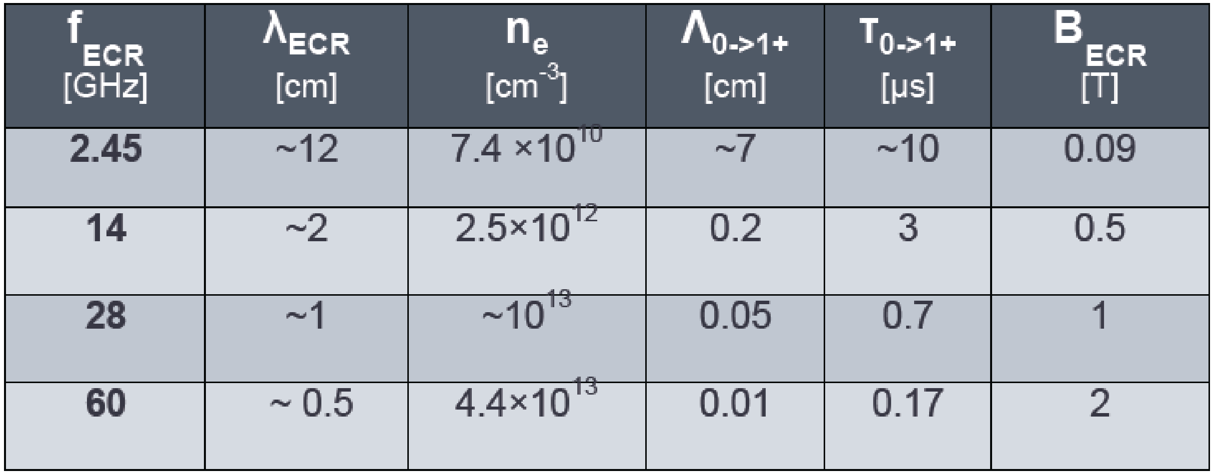
$$n_c = \frac{4\pi^2 \varepsilon_0 m_e}{e^2} f_{HF}^2$$



Heavy Ion radiotherapy IS ECR basics

ECR Scaling laws (R. Geller, 1987)

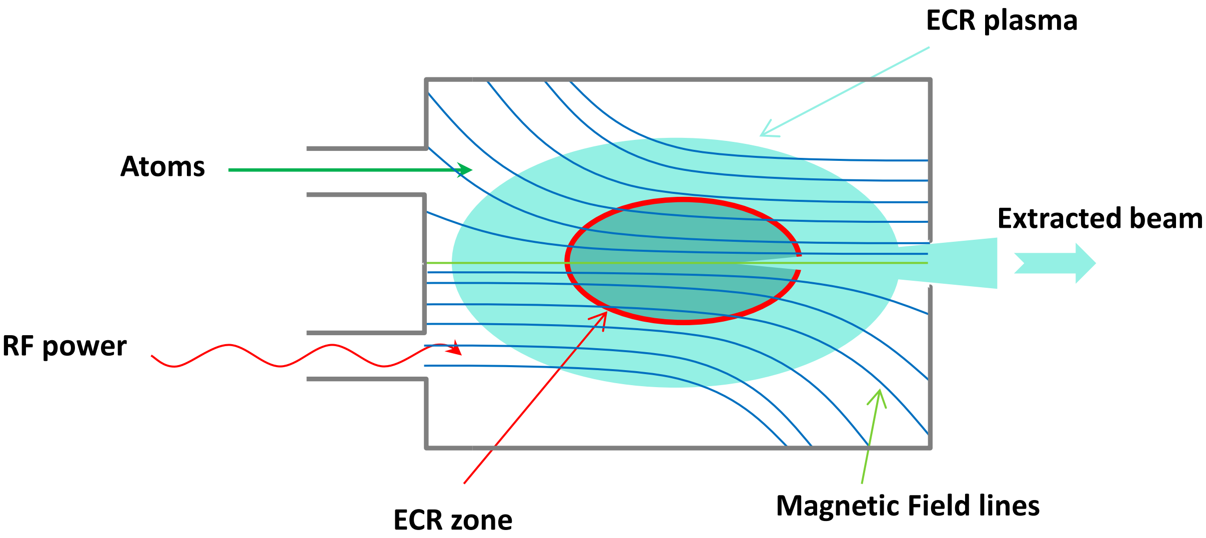
- The higher the frequency, the higher the beam current
- The higher the RF power, the higher the beam current
- Plasma density $n \sim f^2_{\mathrm{ECR}}$
- Beam current $I \sim n \sim f^2_{\mathrm{ECR}}$
- But the higher the ECR magnetic field required
- ECR magnetic field $B_{ECR} = \frac{f_{ECR\,[GHz]}}{28}\ Tesla$ (or 0,036 T / GHz)



f_{ECR} [GHz]	λ_{ECR} [cm]	n_e [cm^{-3}]	$\Lambda_{0\text{->}1+}$ [cm]	$T_{0\text{->}1+}$ [µs]	B_{ECR} [T]
2.45	~12	7.4×10^{10}	~7	~10	0.09
14	~2	2.5×10^{12}	0.2	3	0.5
28	~1	$\sim 10^{13}$	0.05	0.7	1
60	~ 0.5	4.4×10^{13}	0.01	0.17	2

Heavy Ion radiotherapy IS ECR basics

Ion beam Dynamics and formation



Atomic effusion* probability depends on:

- geometry of the chamber
- temperature of the atoms
- mass of the atoms

Ionic effusion * probability depends on:

- geometry of the magnetic field
- elastical collisions
- distribution of the plasma potential

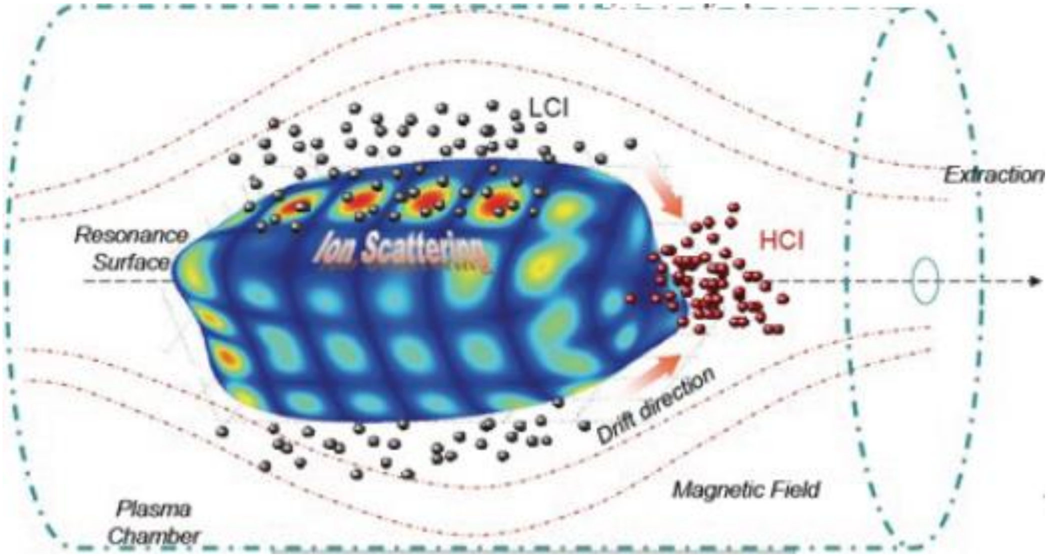
Sticking probability depends on:

- plasma feature
- element to ionise
- trajectory

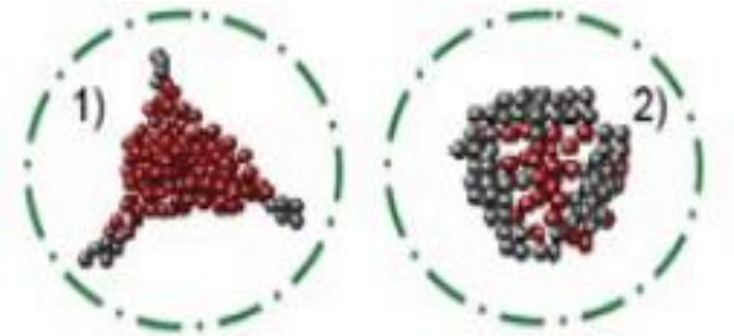
** effusion: particle motion inside the vacuum chamber*

Heavy Ion radiotherapy IS ECR basics

Ion beam Dynamics and formation



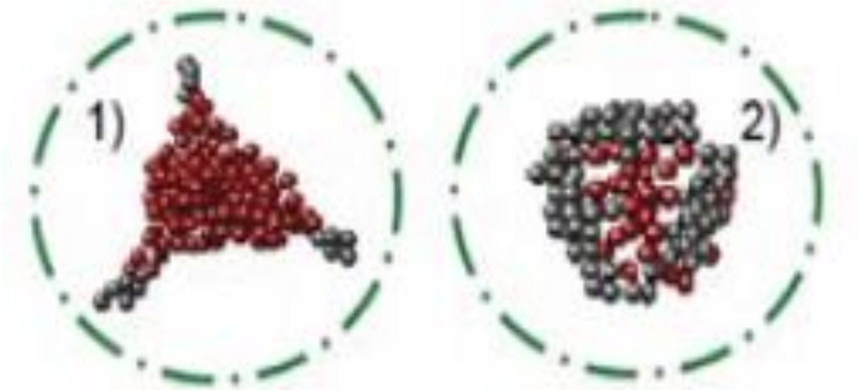
Perturbations of the Primary Plasma Potential (PPP), due to the electric field patterns, strongly influence the beam formation.



Distribution depends of the E field patterns inside the plasma

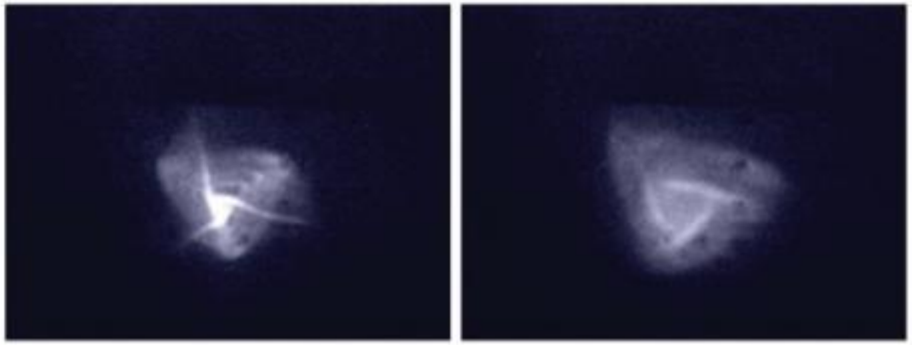
Heavy Ion radiotherapy IS ECR basics

Ion beam Dynamics and formation



1) Optimal Source performances: Higly Charged ions concentrated in the center of the extracted beam

2) Bad Source performances: ion scattering injects lowly charged ions in the loss cone. The beam periphery is populated by LCI

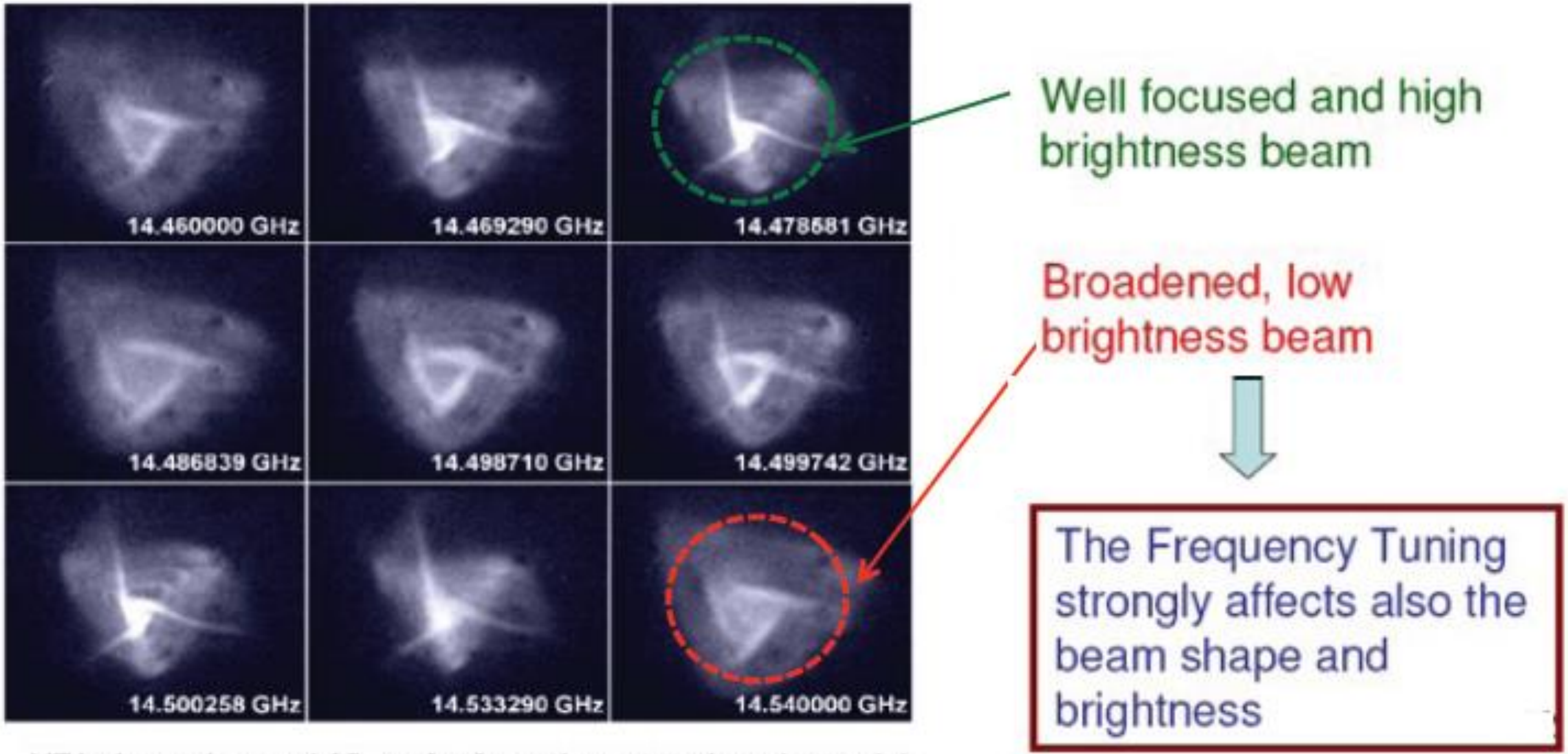


↓

Also Ion Dynamics may take advantage from Frequency Tuning

Heavy Ion radiotherapy IS ECR basics

Ion beam Dynamics and formation



Well focused and high brightness beam

Broadened, low brightness beam

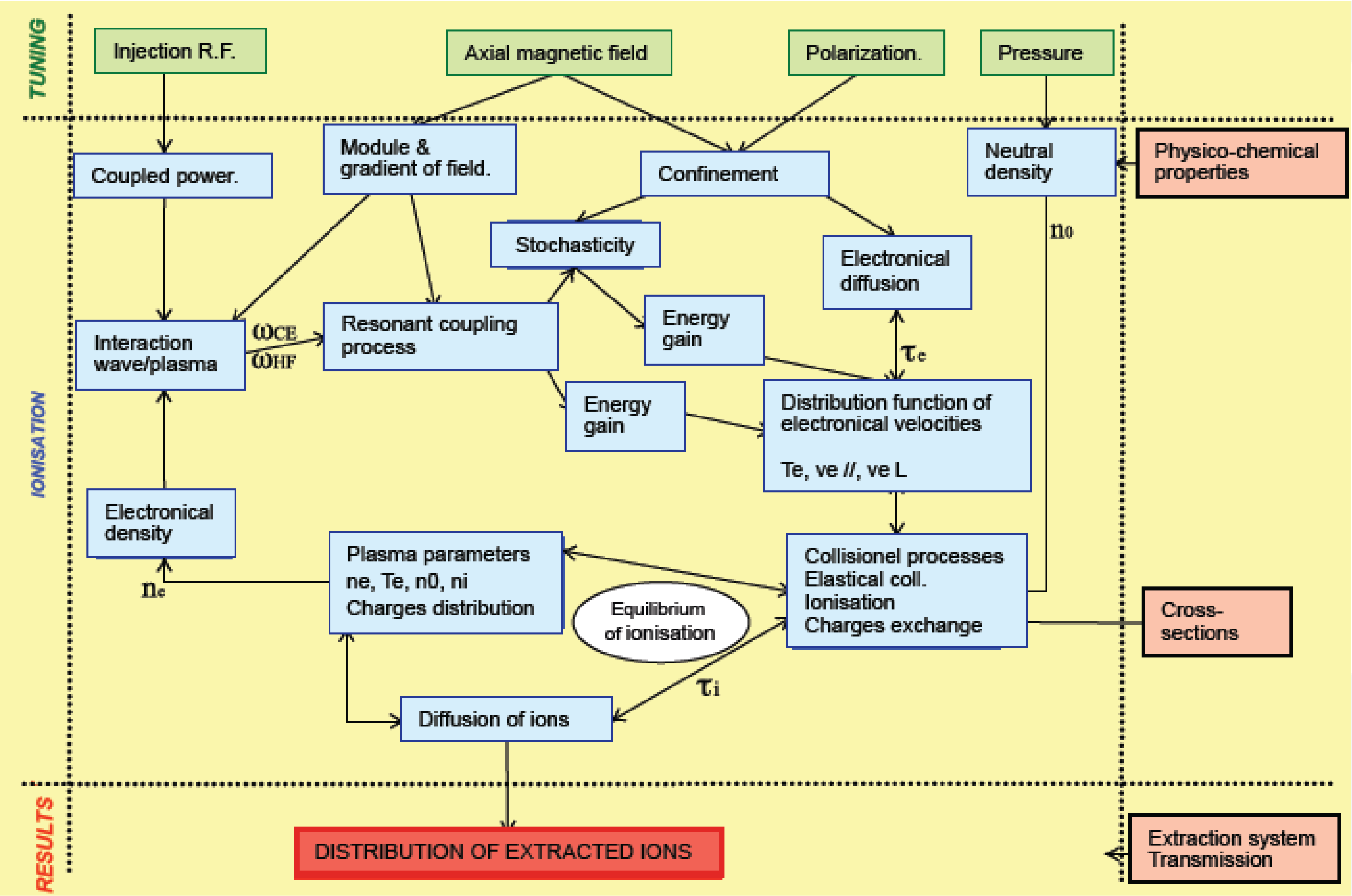
The Frequency Tuning strongly affects also the beam shape and brightness

VT1 viewer (around 25 cm far from the extraction electrode)

L. Celona, G. Ciavola, F. Consoli, S. Gammino, F. Maimone, D. Mascali,
P. Spaätke, K. Tinschert, R. Lang, J. Mäder, J.Roßbach, S. Barbarino, R.S. Catalano, Rev. Sci. Instrum., 79, 023305 (2008).

Heavy Ion radiotherapy IS ECR basics

Interdependency of parameters



TUNING

Injection R.F.

Axial magnetic field

Polarization.

Pressure

Coupled power.

Module & gradient of field.

Confinement

Neutral density

Physico-chemical properties

Stochasticity

Electronical diffusion

n_0

IONISATION

Interaction wave/plasma

ω_{CE}

ω_{HF}

Resonant coupling process

Energy gain

τ_e

Energy gain

Distribution function of electronical velocities

Te, ve //, ve L

Electronical density

n_e

Plasma parameters
ne, Te, n0, ni
Charges distribution

Equilibrium of ionisation

Collisionel processes
Elastical coll.
Ionisation
Charges exchange

Cross-sections

τ_i

Diffusion of ions

RESULTS

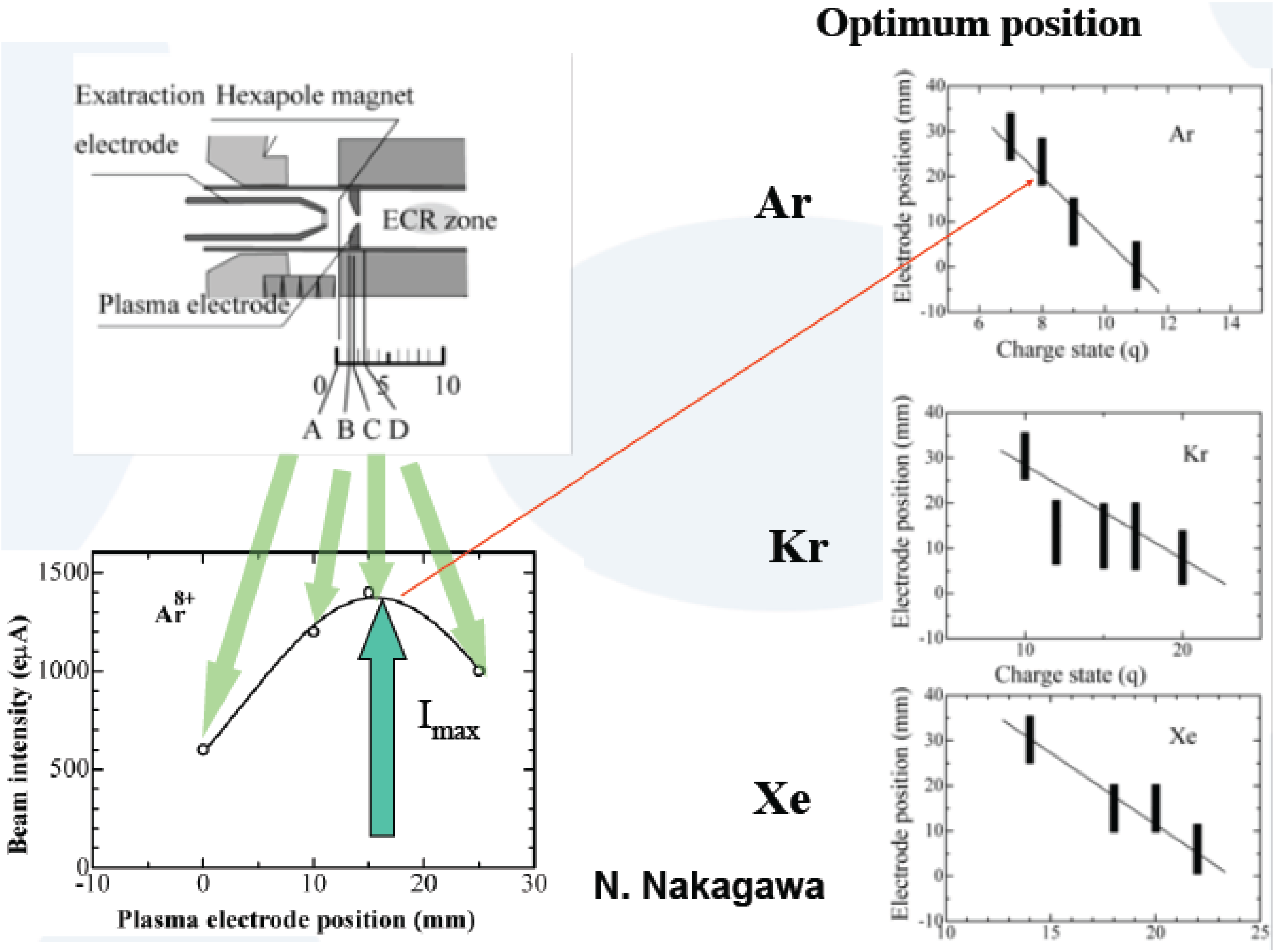
DISTRIBUTION OF EXTRACTED IONS

Extraction system Transmission

Heavy Ion radiotherapy IS

ECR basics

➲ Parameters of improvement of an ECRIS : **Plasma electrode location**

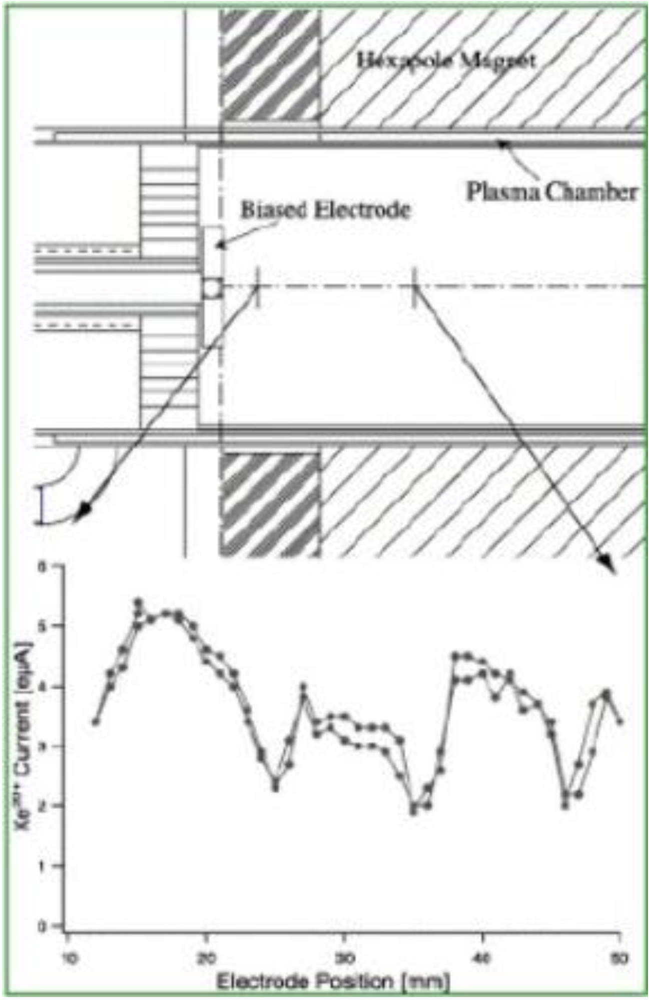


N. Nakagawa

Heavy Ion radiotherapy IS

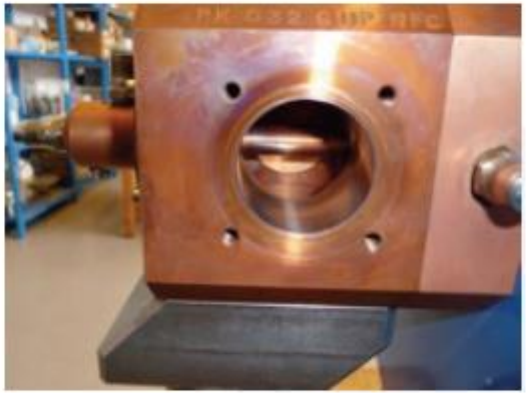
ECR basics

➲ **Parameters of improvement of ECRIS : DC biased disk/tube effect**



- ➢ The beam intensity is strongly dependent on the position of the DC biased disk
- ➢ Better to have an adjustable length of the plasma chamber to be able to change the matching conditions between the plasma and the microwaves

↳ Current gain by 2 to 10



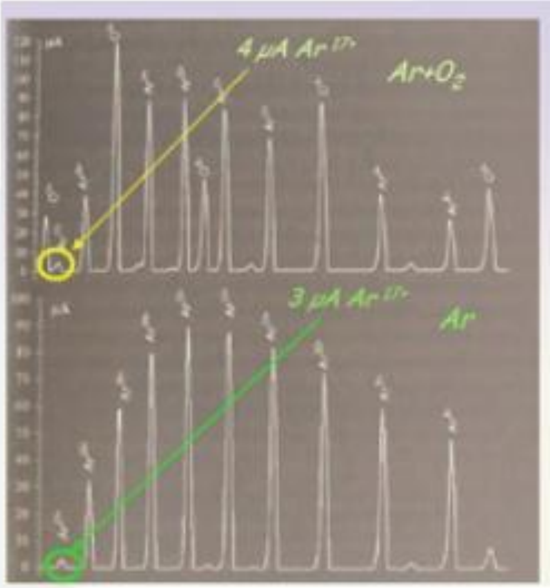
Heavy Ion radiotherapy IS

ECR basics

➲ **Parameters of improvement of ECRIS : Gas mixing effect**

Gas mixing technique (1983)

- ○ experimental technique to increase the output of multi-charged ions
- ○ Addition of a ligther gas than the gas (or metal) of interest :
  Example: I (Arq+) more intense with O than with Kr
- ○ Cooling effect on heavy ions by collision ion/ion
- ○ Diminution of the plasma potentiel



↳ Current gain by 1 to 5

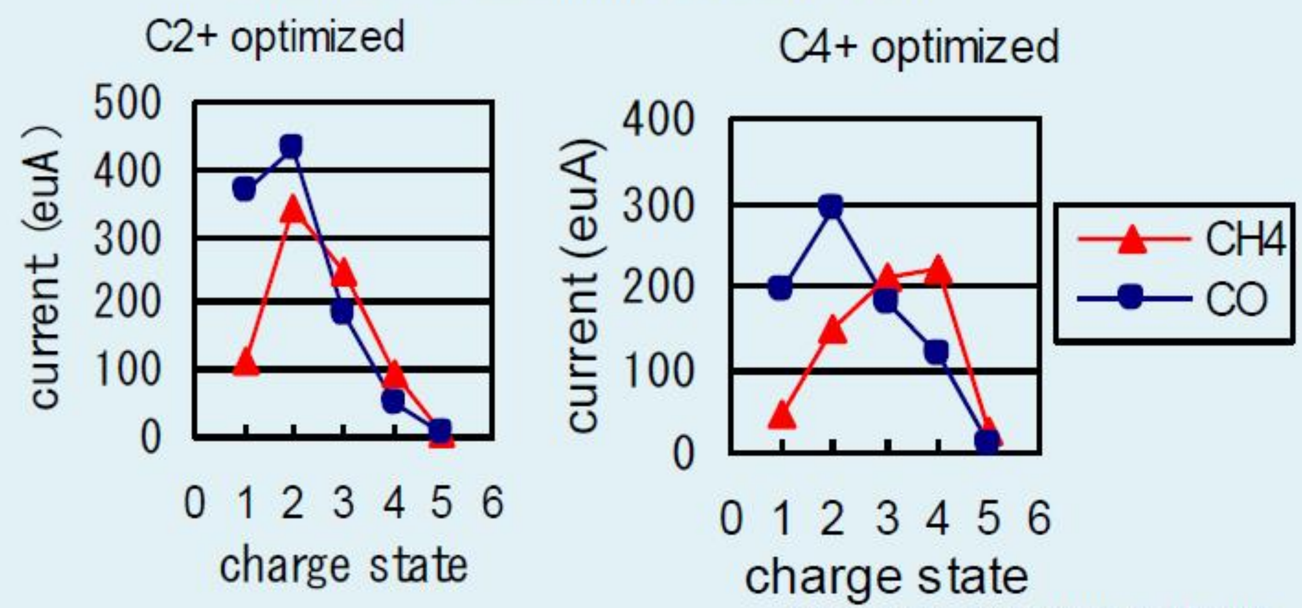
Pb1: I (Arq+, Krq+, Xeq+) are more intense with 18O than with 16O.

⇨ The gas mixing is still not well understood

Heavy Ion radiotherapy IS ECR basics

➲ **Parameters of improvement of ECRIS : Gas mixing effect**

Observation of gas mixing effect at NIRS-ECR



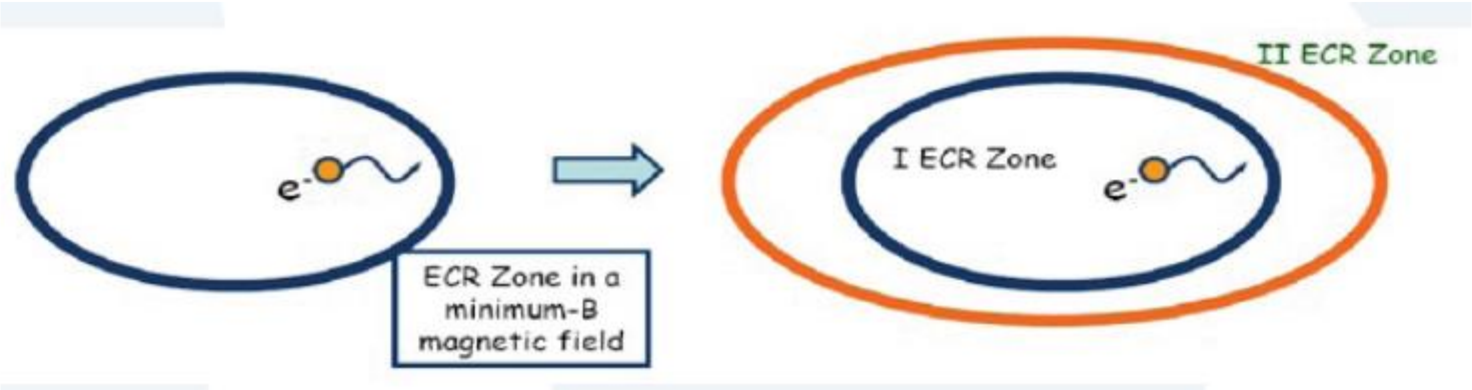
A. Kitagawa et al., Rev. Sci. Instrum. 71, 1061 (2000).

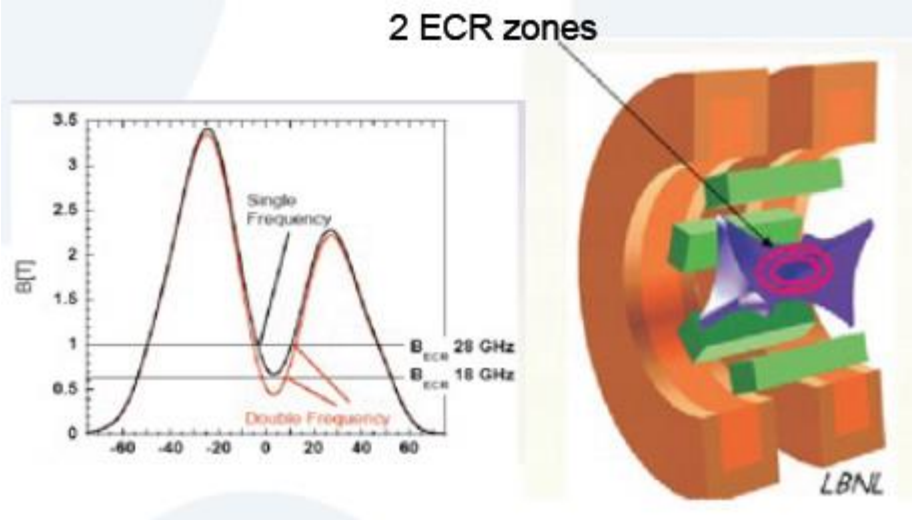
C^{4+} intensity is higher for CH_4 than CO.

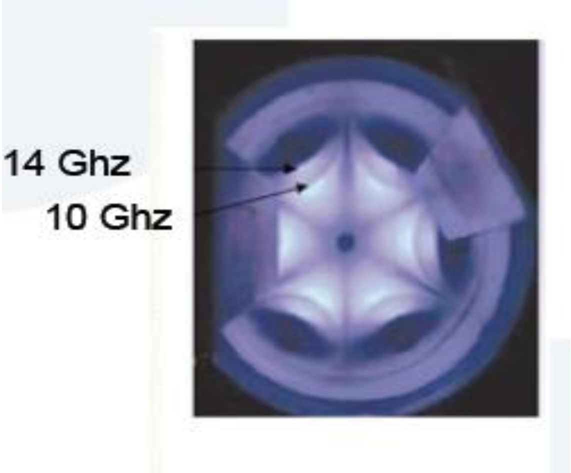
- ➢ CH_4 for higher beam intensity
- ➢ CO_2 + He enhance carbon recycling to the wall and gives high stability

Heavy Ion radiotherapy IS   ECR basics

➲ Parameters of improvement of ECRIS: **RF double frequency injection**





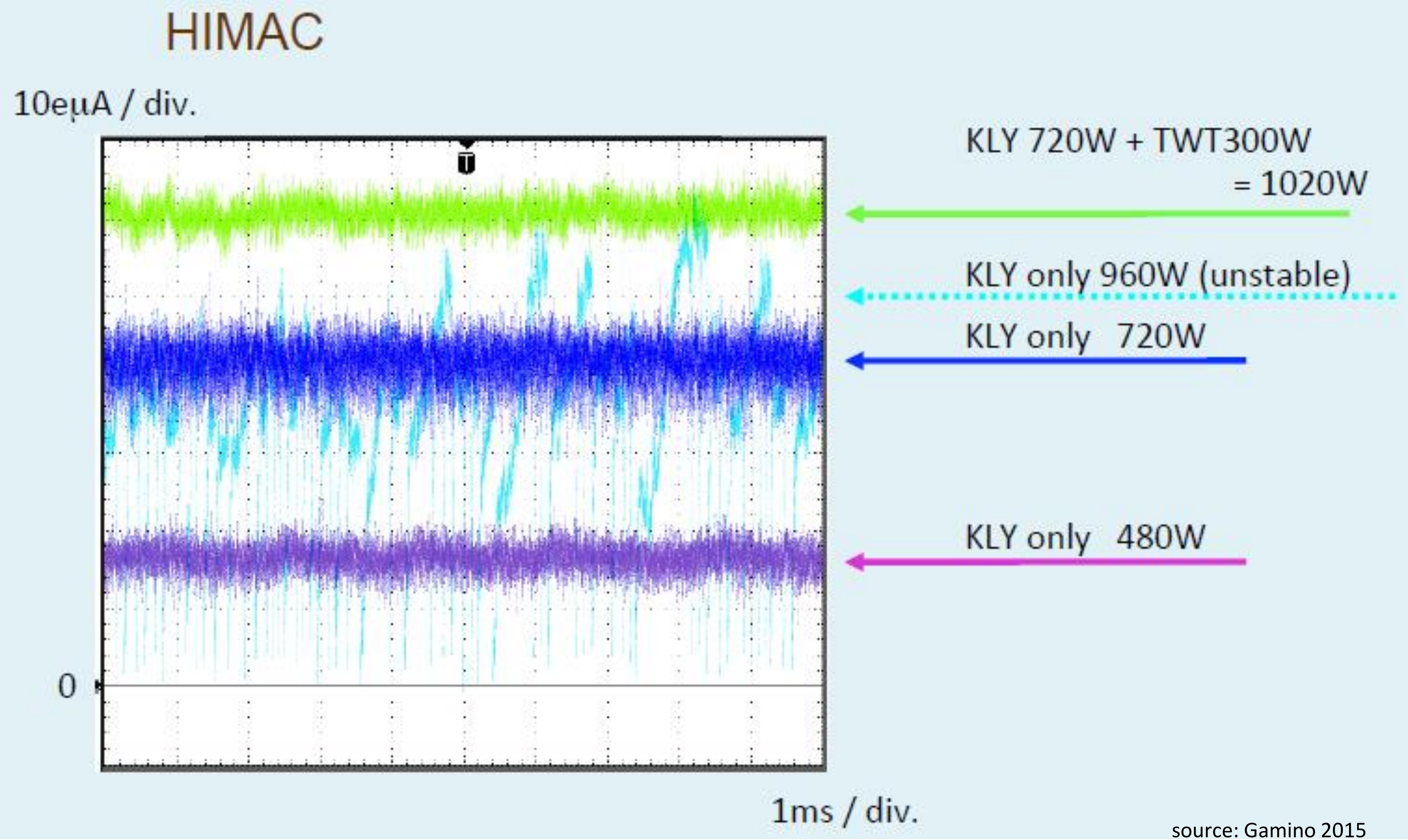


↳ Current gain by 1 to 2 for a constant total RF power

Heavy Ion radiotherapy IS

ECR basics

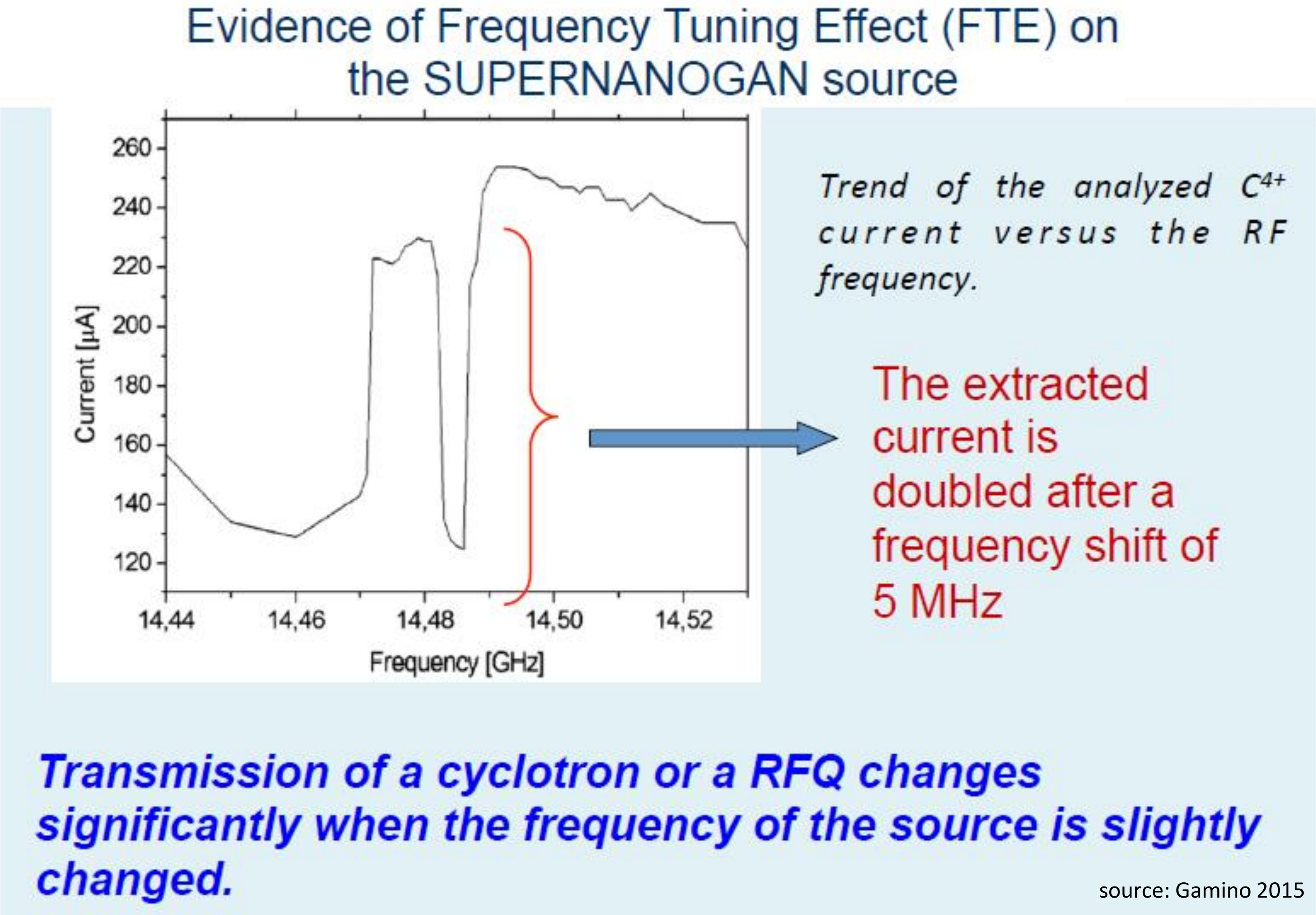
➲ **Parameters of improvement of ECRIS: RF double frequency injection**



source: Gamino 2015

Heavy Ion radiotherapy IS ECR basics

➲ **Parameters of improvement of ECRIS: RF frequency fine tuning**



Evidence of Frequency Tuning Effect (FTE) on the SUPERNANOGAN source

Trend of the analyzed C^{4+} current versus the RF frequency.

The extracted current is doubled after a frequency shift of 5 MHz

Transmission of a cyclotron or a RFQ changes significantly when the frequency of the source is slightly changed.

source: Gamino 2015

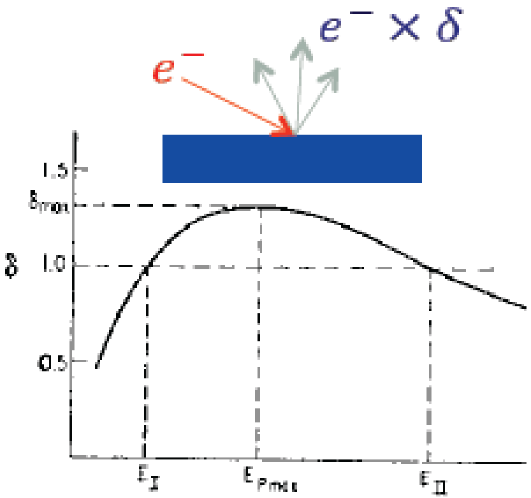
Heavy Ion radiotherapy IS

ECR basics

➲ **Parameters of improvement of ECRIS: Plasma chamber 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

Material	Al	C (soot)	Cu	SiO_2	Al_2O_3	MgO
δ	1.0 – 1.2	0.45	1.3	2.1 - 4	2 - 9	3 – 15
$E_{\delta max}$ [eV]	300	500	600	400	-	400 - 1500

Heavy Ion radiotherapy IS

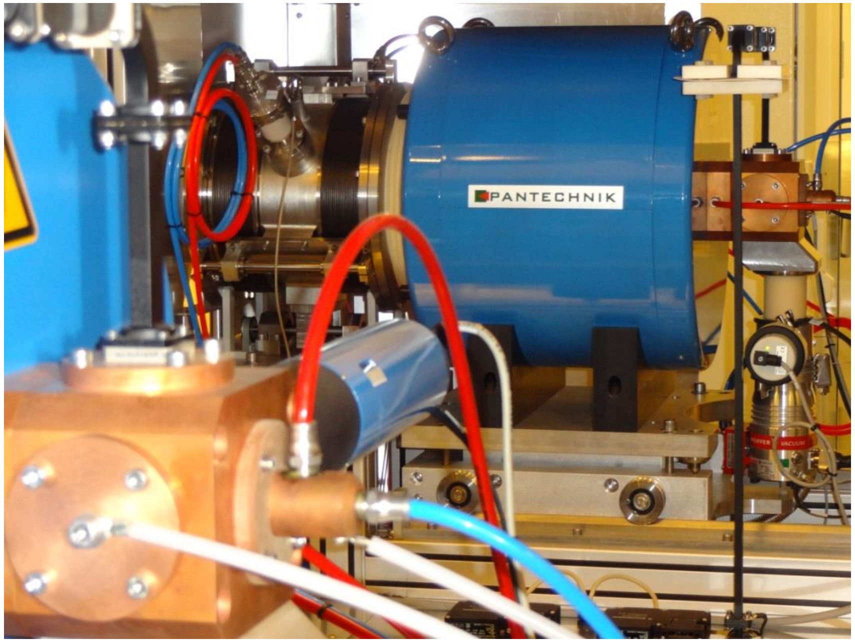
- The latest operational facilities are using full compact permanent magnet ECRIS

Source	SUPERNANOGAN	Kei series
Manufacturer	PANTECHNIK	NIRS – MELCO
TYPE	ECR	ECR
Ion	Carbon	Carbon
Charge	4+	4+
Required intensity	Low	High
Extraction Voltage	24kV	30kV
Purpose	Wide Use	C^{4+} production
Frequency	14.25-14.75 GHz	9.75-10.25 GHz
Operation	CW or pulsed mode	Pulsed mode
Gas	Carbon oxide (+He)	Hydrocarbon

- LECR3 Hybrid ECRIS from IMP produces C^{4+} beam for the Heavy Ion Research Facility in Lanzhou (HIRFL) Facility

Heavy Ion radiotherapy IS

SUPERNANOGAN



Heidelberg, CNAO, Marburg, Kiel, Shanghai, MedAustron, Kirams

ECRIS	All NdFeB permanent magnets
Frequency	14.25-14.75 GHz (~250 W)
Mode	CW or pulsed (10Hz – 5ms)
Ions	C^{4+} … and $_3H^+$, He^{2+}, O^{6+}, Ar^{x+}
Extraction voltage	24kV to 30kV
Emittance	< 0.3 π.mm.mrad for 200μA C^{4+}
Stability	< +/-2,5% in intensity
Uptime	> 98% (measured at HIT)
Maintenance	Parts replacement once a year

Heavy Ion radiotherapy IS

Kei series

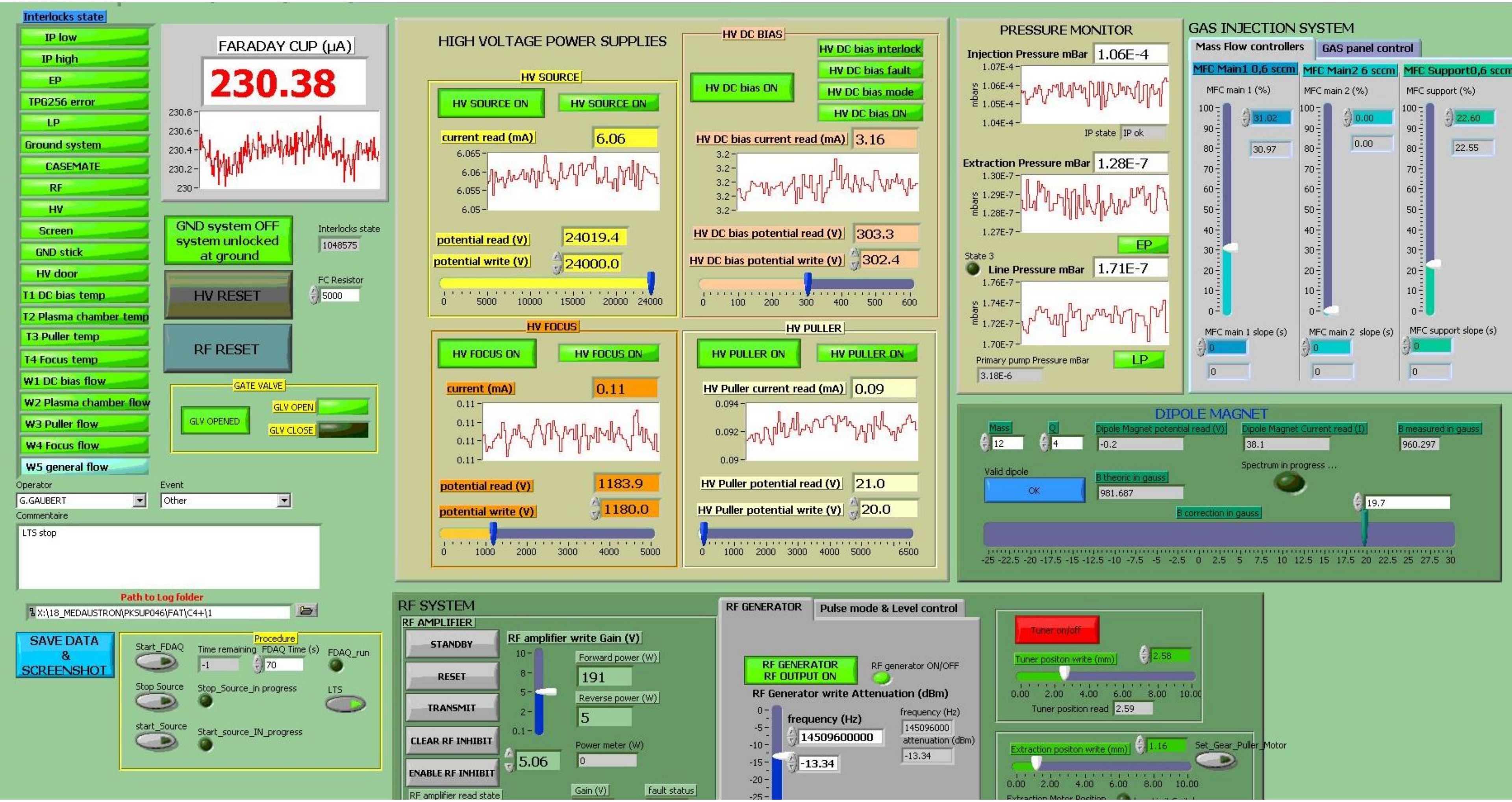
Kei2 KeiGM

HIMAC, Gunma U., Saga, iRock

ECRIS	All NdFeB permanent magnets
Frequency	9.75-10.25 GHz (~300 W)
Mode	pulsed
Ions	C^{4+} … and He^{2+}, O^{6+}, Ar^{8+}
Extraction voltage	30kV – 40kV
Emittance	< 0.3 π.mm.mrad for 300µA C^{4+}
Stability	< +/-2,5% in intensity
Uptime	-
Maintenance	Parts replacement once a year

Heavy Ion radiotherapy IS

SUPERNANOGAN: control panel



FARADAY CUP (µA): 230.38

Interlocks state: 1048575

FC Resistor: 5000

Operator: G.GAUBERT

Event: Other

Commentaire: LTS stop

Path to Log folder: X:\18_MEDAUSTRON\PKSUP046\FAT\C4+\1

Time remaining: -1

FDAQ Time (s): 70

HV SOURCE current read (mA): 6.06

HV SOURCE potential read (V): 24019.4

HV SOURCE potential write (V): 24000.0

HV DC bias current read (mA): 3.16

HV DC bias potential read (V): 303.3

HV DC bias potential write (V): 302.4

HV FOCUS current (mA): 0.11

HV FOCUS potential read (V): 1183.9

HV FOCUS potential write (V): 1180.0

HV Puller current read (mA): 0.09

HV Puller potential read (V): 21.0

HV Puller potential write (V): 20.0

Injection Pressure mBar: 1.06E-4

IP state: IP ok

Extraction Pressure mBar: 1.28E-7

State 3

Line Pressure mBar: 1.71E-7

Primary pump Pressure mBar: 3.18E-6

MFC main 1 (%): 31.02 / 30.97

MFC main 2 (%): 0.00 / 0.00

MFC support (%): 22.60 / 22.55

MFC main 1 slope (s): 0 / 0

MFC main 2 slope (s): 0 / 0

MFC support slope (s): 0 / 0

Mass: 12

Q: 4

Dipole Magnet potential read (V): -0.2

Dipole Magnet Current read (I): 38.1

B measured in gauss: 960.297

B theoric in gauss: 981.687

B correction in gauss: 19.7

RF amplifier write Gain (V): 5.06

Forward power (W): 191

Reverse power (W): 5

Power meter (W): 0

RF Generator write Attenuation (dBm): -13.34

frequency (Hz): 14509600000

frequency (Hz): 145096000

attenuation (dBm): -13.34

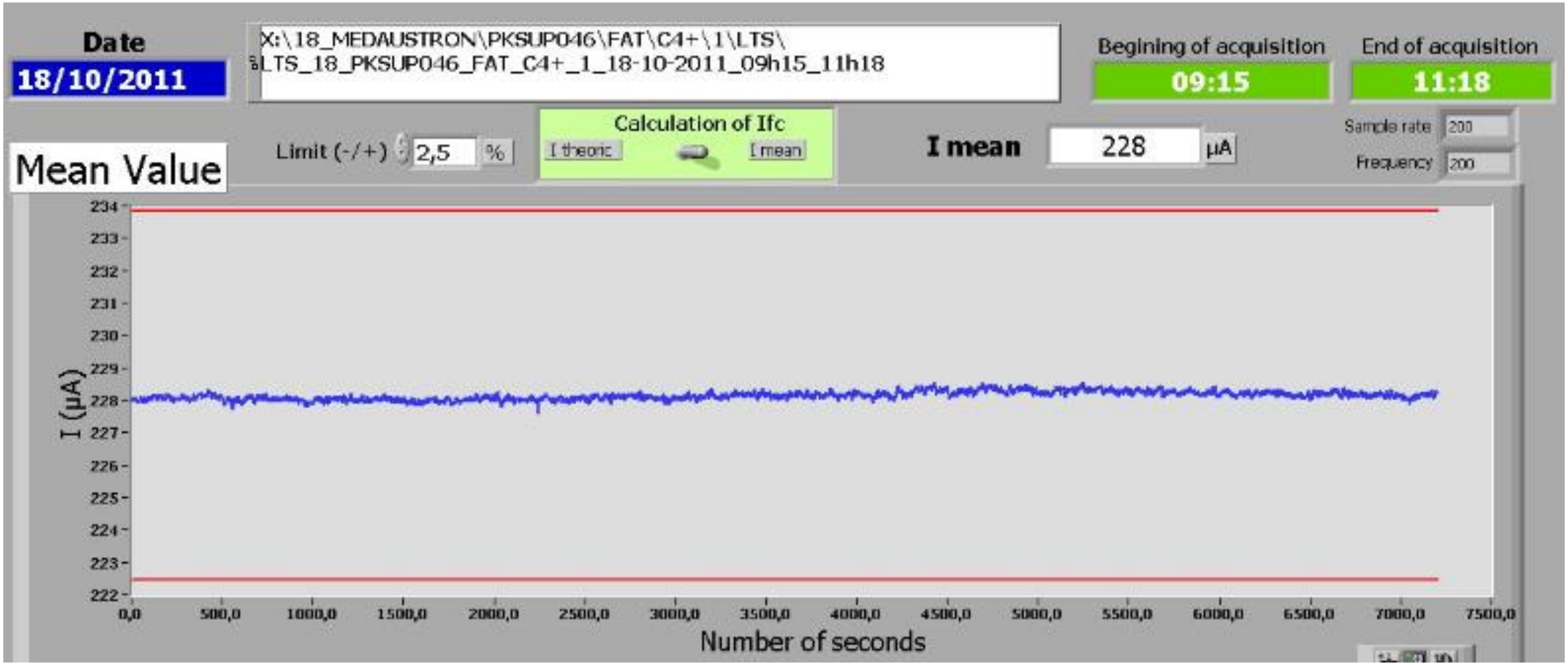
Tuner positon write (mm): 2.58

Tuner position read: 2.59

Extraction positon write (mm): 1.16

Heavy Ion radiotherapy IS

SUPERNANOGAN: C^{4+} stability over 2 hours



Date 18/10/2011

X:\18_MEDAUSTRON\PKSUP046\FAT\C4+\1\LTS\
LTS_18_PKSUP046_FAT_C4+_1_18-10-2011_09h15_11h18

Begining of acquisition: 09:15

End of acquisition: 11:18

Limit (-/+) 2,5 %

Calculation of Ifc: I theoric / I mean

I mean 228 µA

Sample rate 200

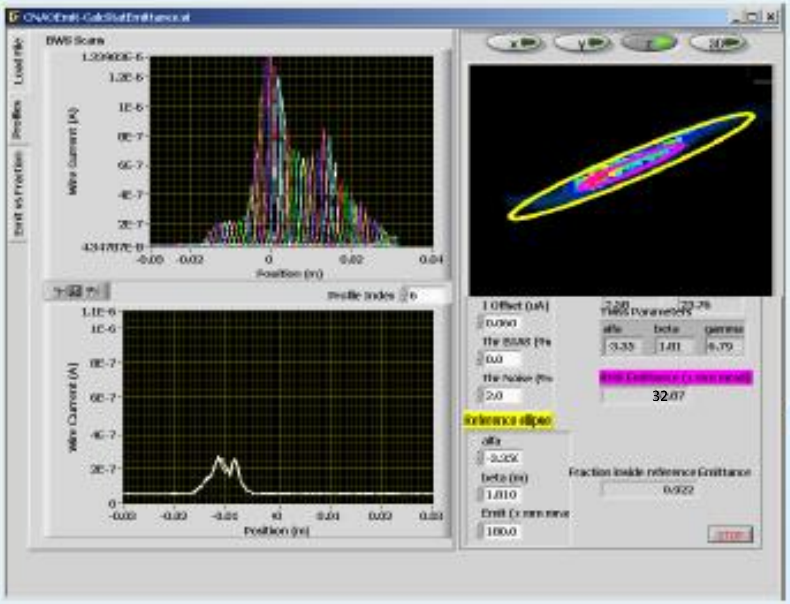
Frequency 200

Heavy Ion radiotherapy IS

SUPERNANOGAN: emittance at CNAO

H_3^+, 1.4mA
(design =800 μA)

Emittance measured
after spectrometer



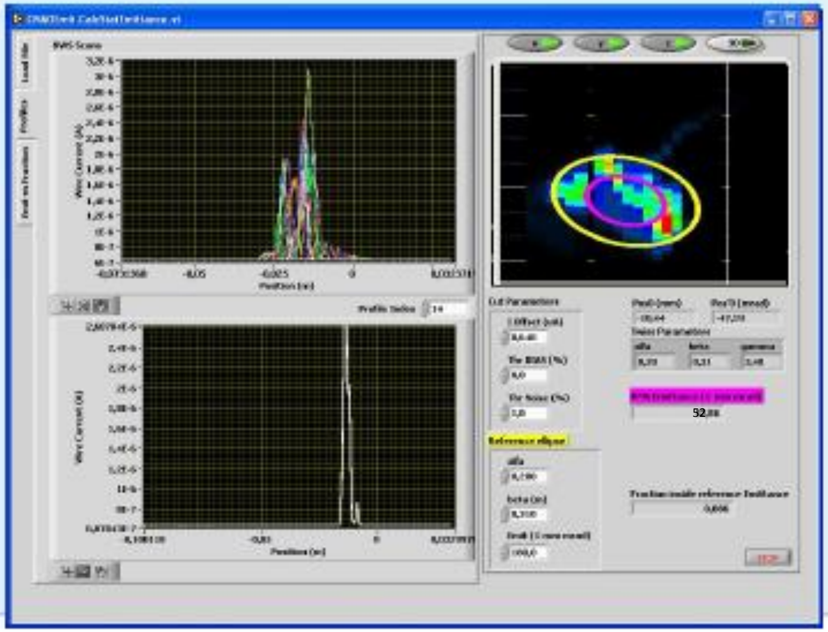
Twiss Parameters
alfa -3.33
beta 1.01
gamma 6.79

32.07

Reference ellipse
alfa -3.25
beta (m) 1.010

Fraction inside reference Emittance 0.922

Emit (π mm mrad) 100.0



52

C^{4+}, 250 μA
(design = 200 μA)

IS Developments for future radiotherapy

- Still further possible development to improve ECRIS:
  - ➢ fight against carbon deposition: material, gas mixing, pulsed operation
  - ➢ shorten the switch time from 2 beams without multiple IS (cost reduction)
  - ➢ RF injection improvment
  - ➢ Automatic feedback loop for long term operation

- Higher yields in C^{6+} for future cyclotron (C400 IBA, others ?)
  - ➢ 18GHz operation … but require high magnetic fied
  - ➢ Hybrid superconducting ECRIS are good candidates: PKISIS or Aisha

  … or other IS based on electron impact without discharge
  - ➢ EBIS
  - ➢ Laser Ion Soucre (LIS) developped by JAEA/NIRS/Kyoto University

18GHz ECRIS for future radiotherapy: PKISIS

ECR ion source with "He-free" 4 K Superconducting coils (axial field) + High performance Permanent Magnets (radial field)

Magnetic field:
- B injection variable < 2.1 T
- B extraction variable < 1.5 T
- B minimum variable 0.4 < B < 0.6 T
- B radial at chamber wall = 1.32 T

Radio Frequency:
- f = 18 GHz
- Available RF power = 2.5 kW

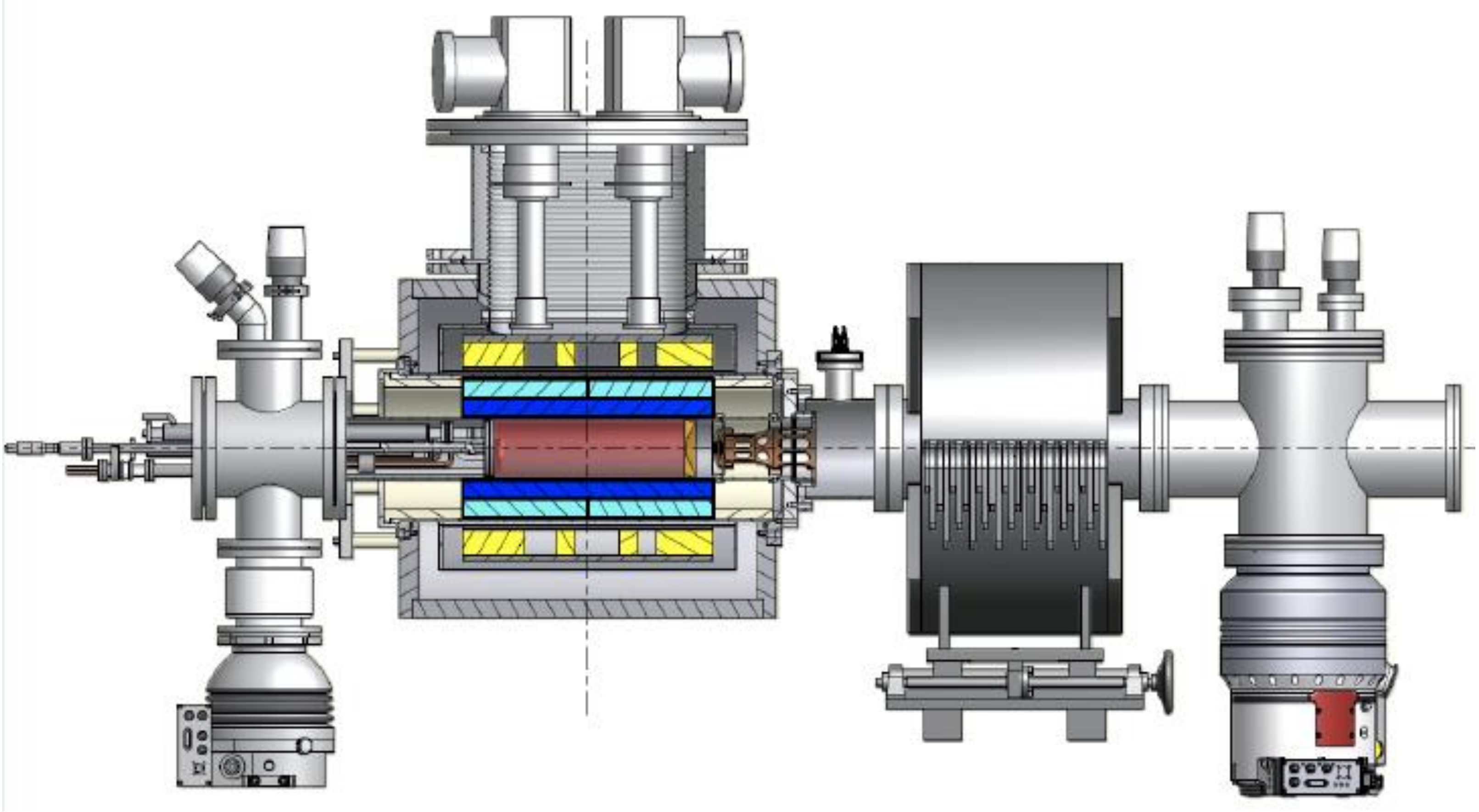
Mechanical dimensions
- Plasma chamber diameter = 82 mm
- Plasma chamber Length = 450 mm
- Yoke diameter = 680 mm
- Yoke length = 730 mm
- Weight = 1,500 kg

Insulation
- V max = 30 kV

Cryogenics
- (4.2-45) K Pulsed Tube cryo-cooler
- P = (1 - 40) W
- He free

Ion	Intensity (μA – electrical)
^{4}He (2+)	2,400
^{13}C (4+)	>500
^{13}C (6+)	50
^{14}N (5+)	>1,000
^{16}O (6+)	1,500
^{16}O (7+)	230
^{40}Ar (12+)	200
^{40}Ar (14+)	100
^{84}Kr (17+)	100
^{129}Xe (26+)	100
^{181}Ta (26+)	20
^{181}Ta (30+)	13
^{181}Ta (32+)	6
^{209}Bi (29+)	35
^{209}Bi (31+)	25
^{209}Bi (33+)	15

18GHz ECRIS for future radiotherapy: Aisha (CNAO / LNS)

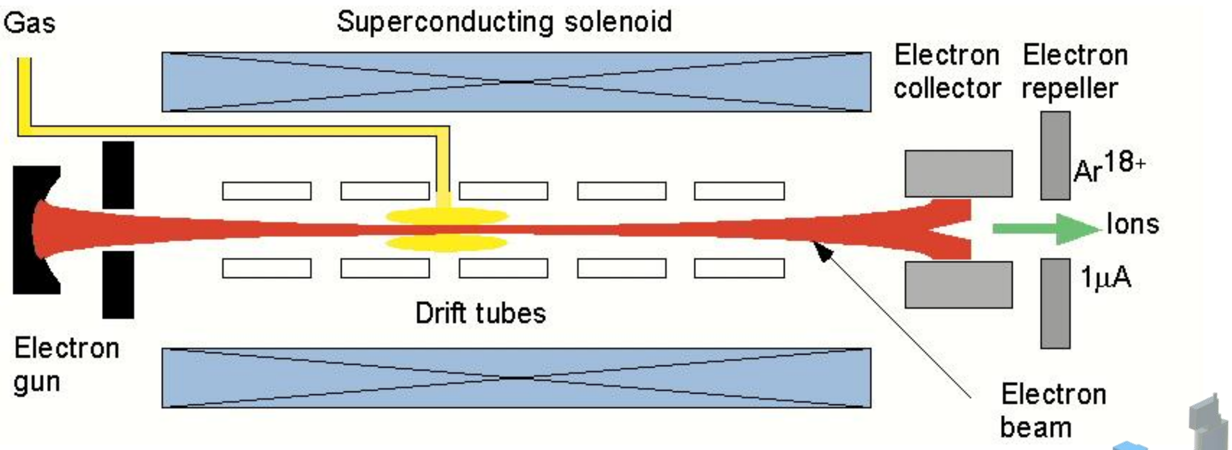


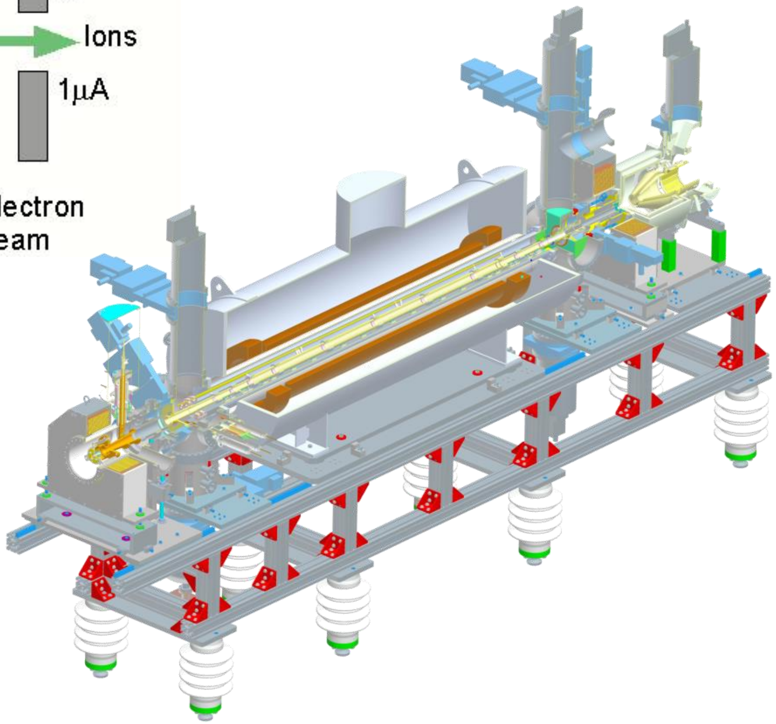
- Results to be announced at ICIS 2017 conference in October at Geneva

Source: Gamino, CAS, Wien 2015

IS Developments : EBIS

Electron beam ion source (EBIS) :

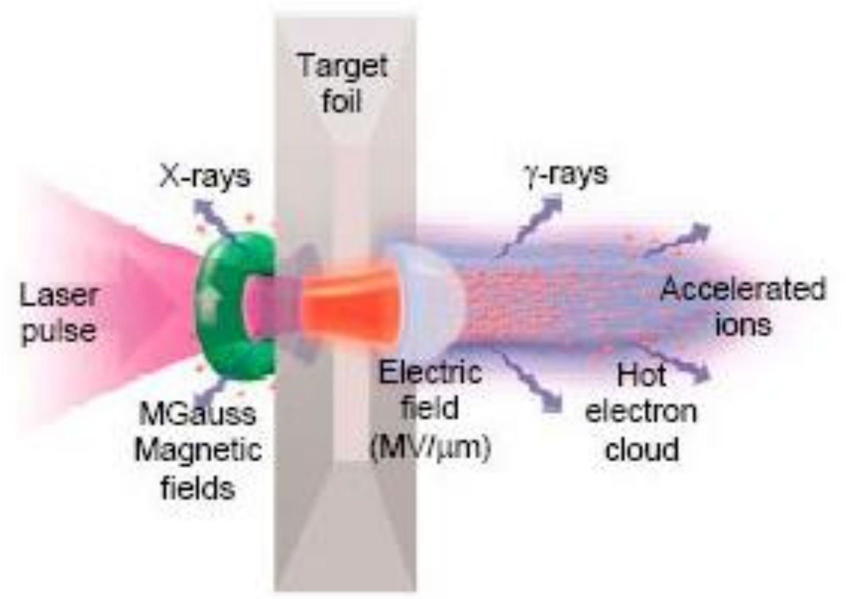




- Used for production of highly charged ion
- Low current
- Dedicated for laboratory uses
- Can be used for charge breeding
- Working pressure < 10^{-9} mbar

Source : BNL, Liljeby 2003

IS Developments : LIS



- See Dr Koji Noda yesterday's talk for NIRS HIMAC

Boron Neutron Capture Therapy Ion Source

- BNCT efficiency has been proven using neutrons from nuclear reactors
- Accelerators could advantageously replace reactors !

- BNCT accelerators need proton / deuteron beam to convert them into neutrons
  …. But very high beam current to get at least 1.10^9 particle/cm²/s

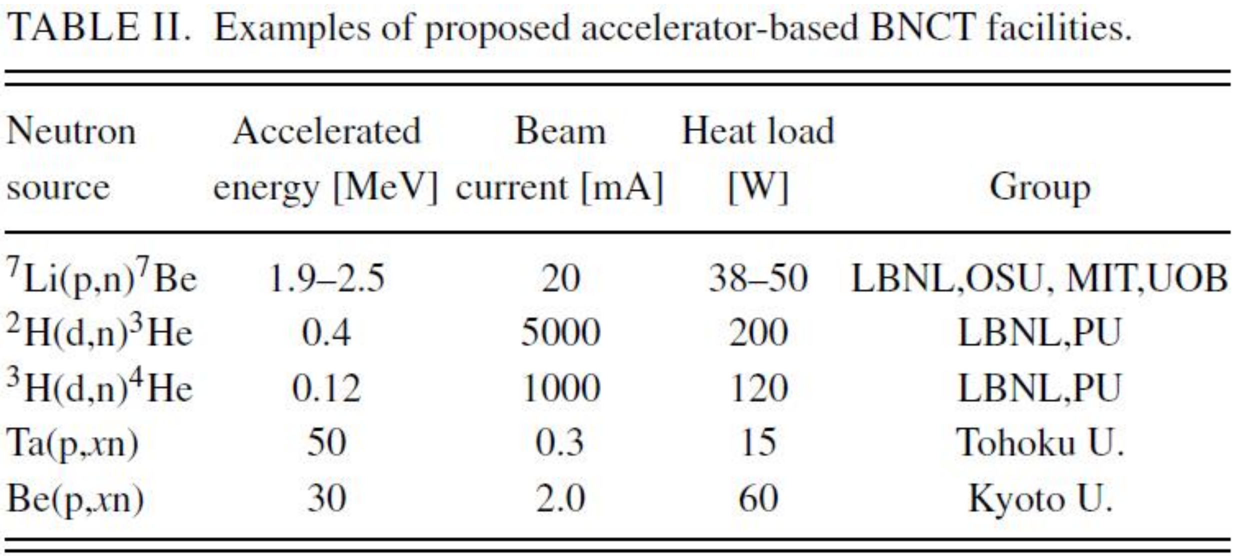


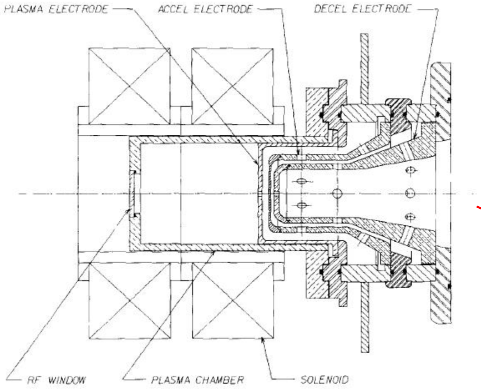
TABLE II. Examples of proposed accelerator-based BNCT facilities.

Neutron source	Accelerated energy [MeV]	Beam current [mA]	Heat load [W]	Group
^{7}Li(p,n)^{7}Be	1.9–2.5	20	38–50	LBNL,OSU, MIT,UOB
^{2}H(d,n)^{3}He	0.4	5000	200	LBNL,PU
^{3}H(d,n)^{4}He	0.12	1000	120	LBNL,PU
Ta(p,xn)	50	0.3	15	Tohoku U.
Be(p,xn)	30	2.0	60	Kyoto U.

M. Muramatsu and A. Kitagawa, RSI 83, 02B909 (2012)

Boron Neutron Capture Therapy Ion Source

Microwave Discharge IS



- IBA Dynamitron using a 2,45GHz Ion Source

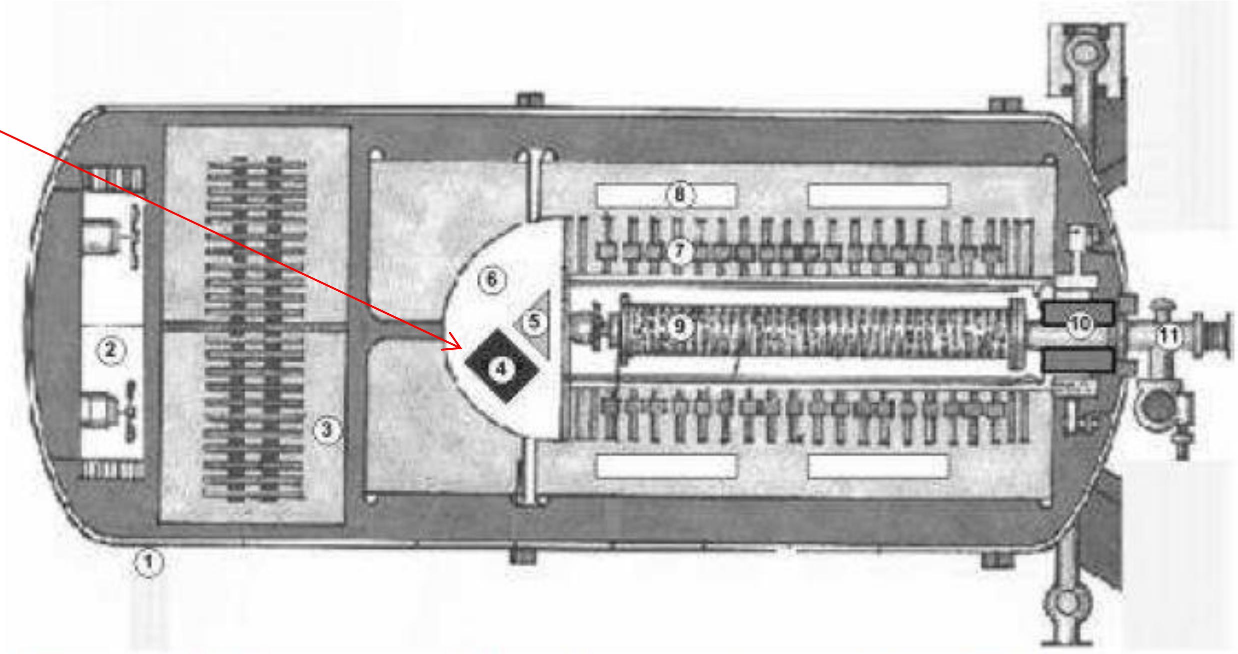


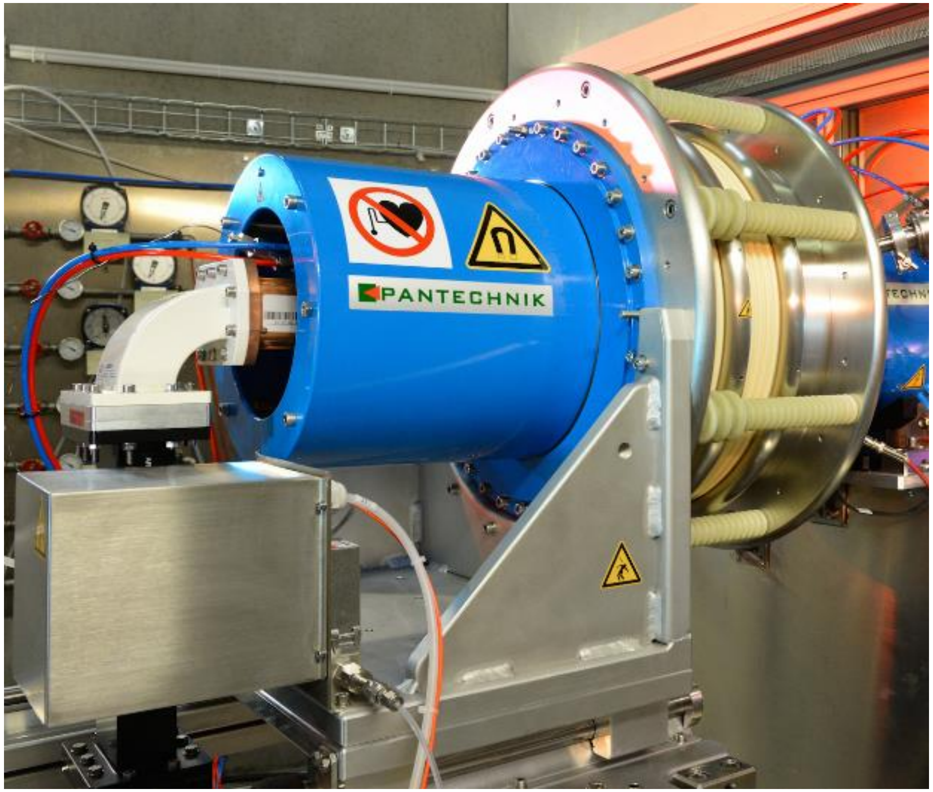
Figure 2: Layout of the dynamitron. The ECR source and selection magnet are pictured as a dark square and grey triangle, respectively.

E. Forton et al., DOI: 10.1016/j.apradiso.2009.03.099 · Source: PubMed

Boron Neutron Capture Therapy Ion Source

Microwave Discharge IS: SILHI from PANTECHNIK / CEA licensed

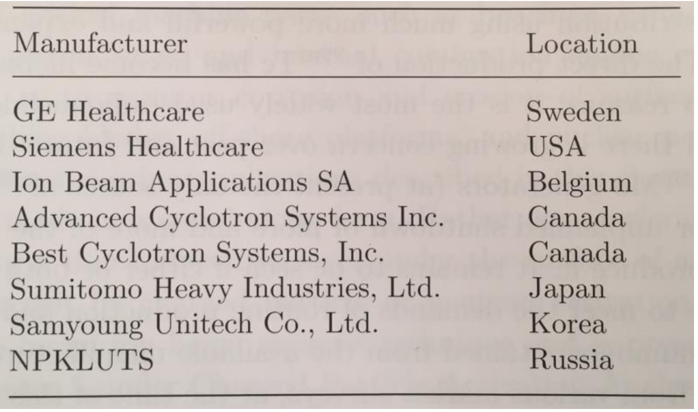
- ➢ could be a good candidate !



ECRIS	NdFeB permanent magnets
Frequency	2,45 Ghz
Mode	CW or pulsed
Ions	H^+ , D^+
Extraction voltage	60 kV to 100kV
Current	40 to 100 mA
Emittance	$< 0.2\ \pi$.mm.mrad

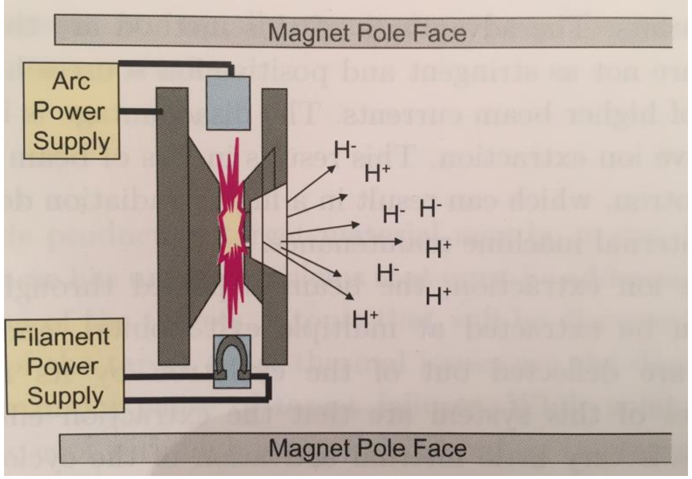
Radioisotope Production

- Cyclotrons are historically utilized for radioisotope production
- Many manufacturers, for more than 700 cyclotrons in operation in the world - 2010



Manufacturer	Location
GE Healthcare	Sweden
Siemens Healthcare	USA
Ion Beam Applications SA	Belgium
Advanced Cyclotron Systems Inc.	Canada
Best Cyclotron Systems, Inc.	Canada
Sumitomo Heavy Industries, Ltd.	Japan
Samyoung Unitech Co., Ltd.	Korea
NPKLUTS	Russia

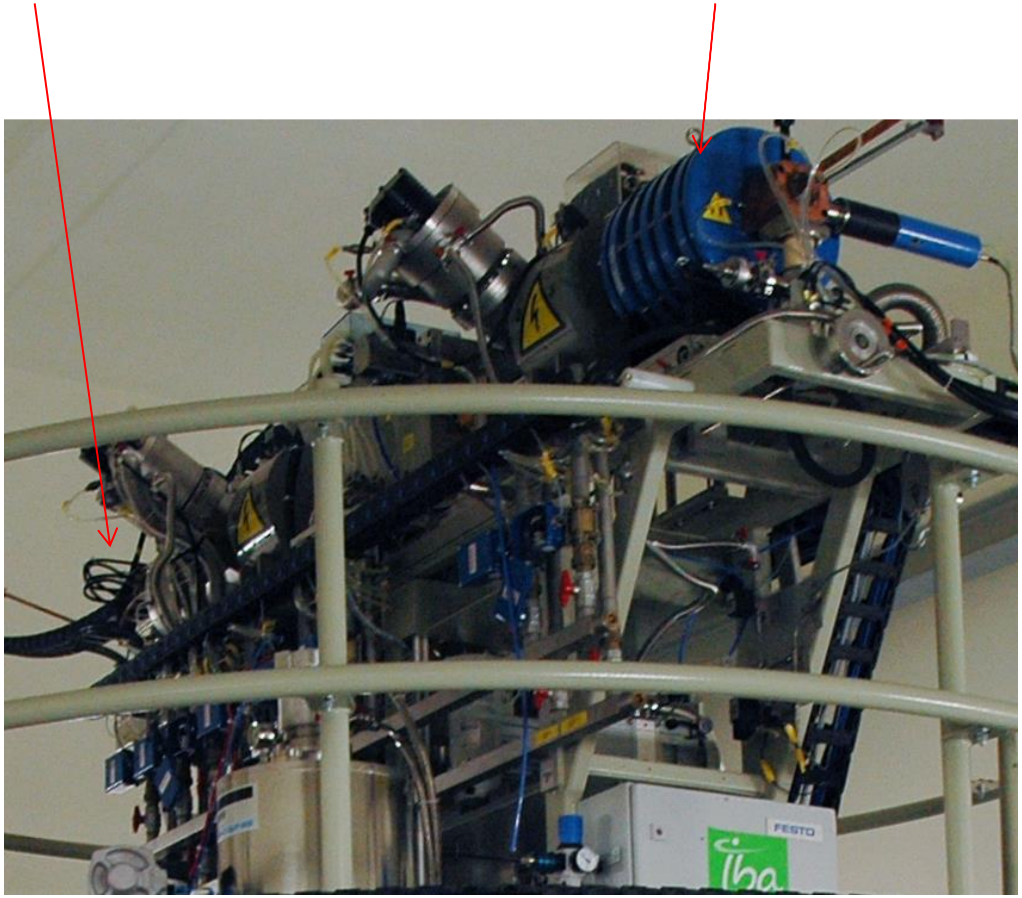
- mostly they use internal hot / cold cathode IS (similar than for proton therapy)



R. W. & M.E. Hamm,
Industrial accelerators and their applications ,
ISBN 978-981-4307-04-8

Radioisotope Production

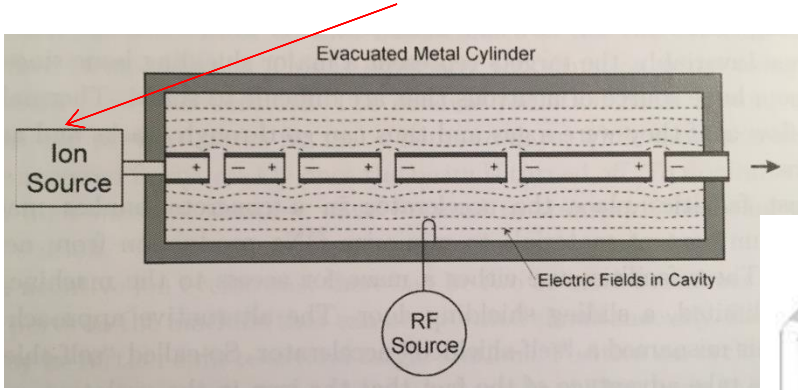
- external IS is also possible with cyclotrons using axial inflector
- C70 IBA for Arronax (France) is fed by one H^- multicusp source and one SUPERNANOGAN for $^4He^{2+}$ beam injection



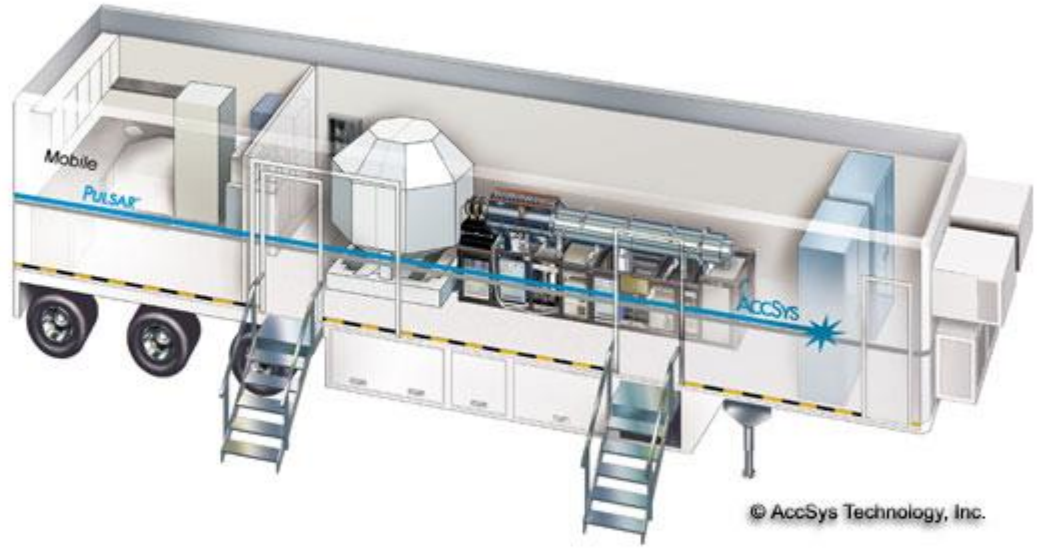
https://fr.wikipedia.org/wiki/Cyclotron_ARRONAX

Radioisotope Production

- LINAC are also commercially available (mainly AccSys Technology, Inc. USA)
- They can use any discharge source already described for high current



- Isotopes can eventually be produced and distributed close by the hospital ….



R. W. & M.E. Hamm,
Industrial accelerators and their applications ,
ISBN 978-981-4307-04-8

Ideal ion source for radioisotope production must have:

- beam current as large as possible, depending on the limits on target reliability
- an emittance < accelerator acceptance
- a good stability
- be user friendly
- a high MTBF and short MTTR
- low maintenance
- a moderate installation and maintenance cost

Overview

☑ Ion Source Requirements

☑ Ionization process, plasma, motion & confinement basics

☑ **Review of Ion Sources for medical accelerators**

- ➢ Proton radiotherapy IS
- ➢ Heavy Ion radiotherapy IS
- ➢ IS Developments for future radiotherapy
- ➢ Boron Neutron Capture Therapy IS
- ➢ Radioisotope production

☑ **Conclusion**

CONCLUSION

- Ion Source development is a never ending story

  … hope you are not lost in this jungle !!

- Ion Therapy, BNCT and radioisotope techniques still need improvments which start with the ion source in terms of robustness, simplicity of maintenance and operation

- High current ion source will make possible the production of radioisotopes for immunoradiotherapy

- It is a good mix of engineering, physics, passion to SAVE LIFES !

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