Ion sources for medical applications

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Ion sources for medical applications

Three types of applications will be described :

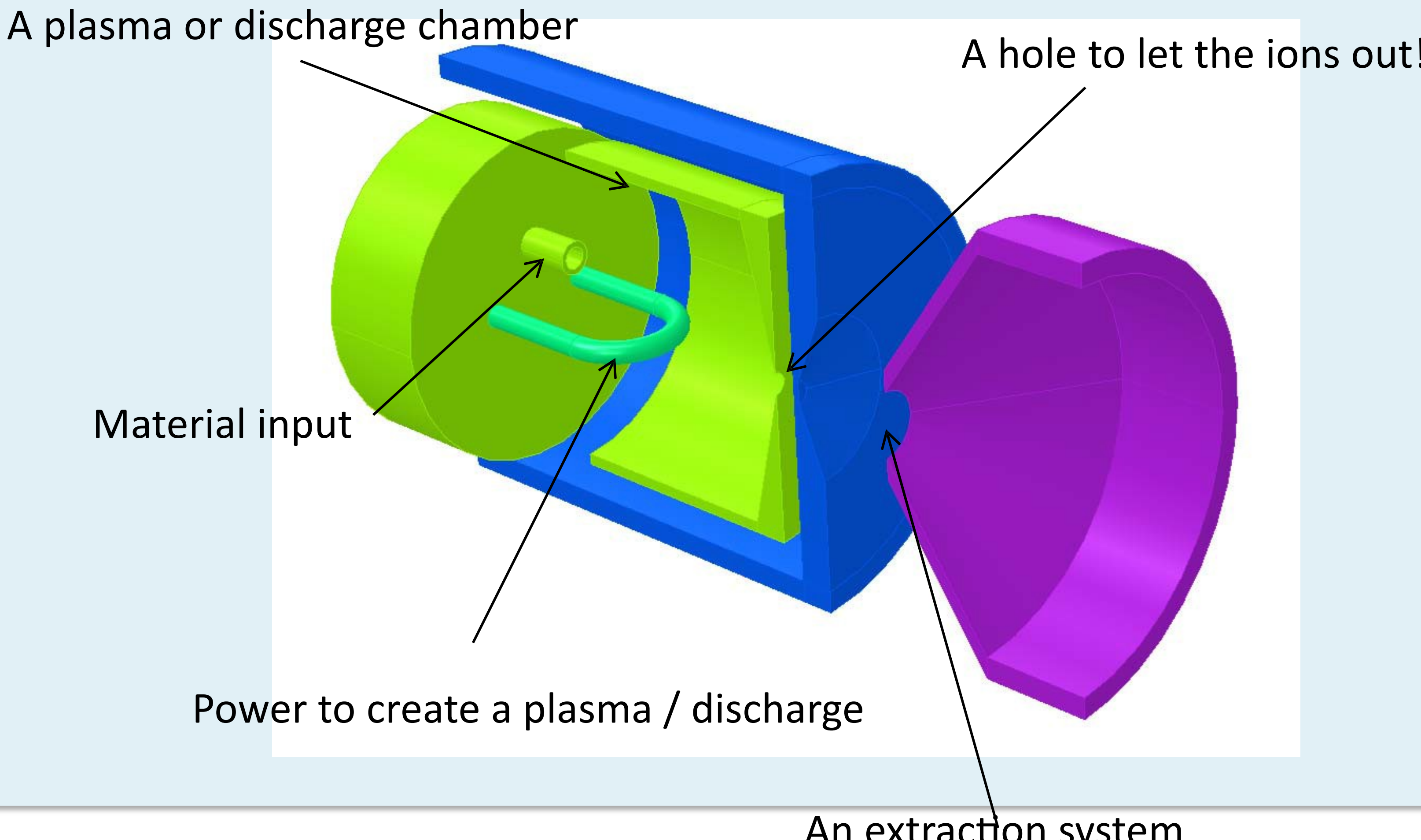
- hadron therapy facilities (protons and Carbon ions)
- BNCT (protons)
- isotope production (different ion species)

The three types of applications present also different requirements in terms of ion beam quality, reproducibility and beam availability.

Different characteristics of ion sources will be described, along with a more detailed description of a few particular sources which are particularly interesting or largely used. This lecture will not describe the variety of Ion Sources for medical application, which would require much more time.

What is a source made of?

There is no single drawing of an ion source, such are the variations in their approaches. But typically a source contains:



Reproduced from CERN Acc. School - Ion sources (2012)

What Else Is Needed...

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Power Source

Power Supplies / RF / Laser

Vacuum Pumping

+ Cooling
+ Computer Controls
+ LEBT
+ Beam Stop
+ Gate valve
etc.

Plasma diagnostics

Beam diagnostics

Interlocking + Safety Systems

Ideal ion source for hadrontherapy must :

- ✓ Produce the necessary beam current for the treatment (with a margin of 20% or more), i.e. 200-400 eμA for carbon ions, three times more for protons
- ✓ generate an emittance lower than accelerator acceptance;
- ✓ have high stability, low beam ripple and high reproducibility;
- ✓ be user friendly;
- ✓ high MTBF;
- ✓ low maintenance.

Ideal ion source for BNCT must have:

- ✓ the necessary beam current (with a margin of 20% or more), i.e. many mA of protons
- ✓ an emittance lower than accelerator acceptance;
- ✓ high stability and high reproducibility;
- ✓ user friendly;
- ✓ high MTBF;
- ✓ low maintenance.

Ideal ion source for isotope production must have:

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

Ideal ion source ?

- ✓ Some sources may be adapted for different application, i.e. a source producing multiply charged ions may work for hadrontherapy and some isotope productions, while intense beam of protons are for BNCT and for isotope production

- ✓ Often to minimize the spare parts and complexity the same type of ion source is chosen in two copies

- ✓ Uptime is a key element for medical applications, with stringent requirements w.r.t. the ion sources devoted to nuclear physics accelerators.

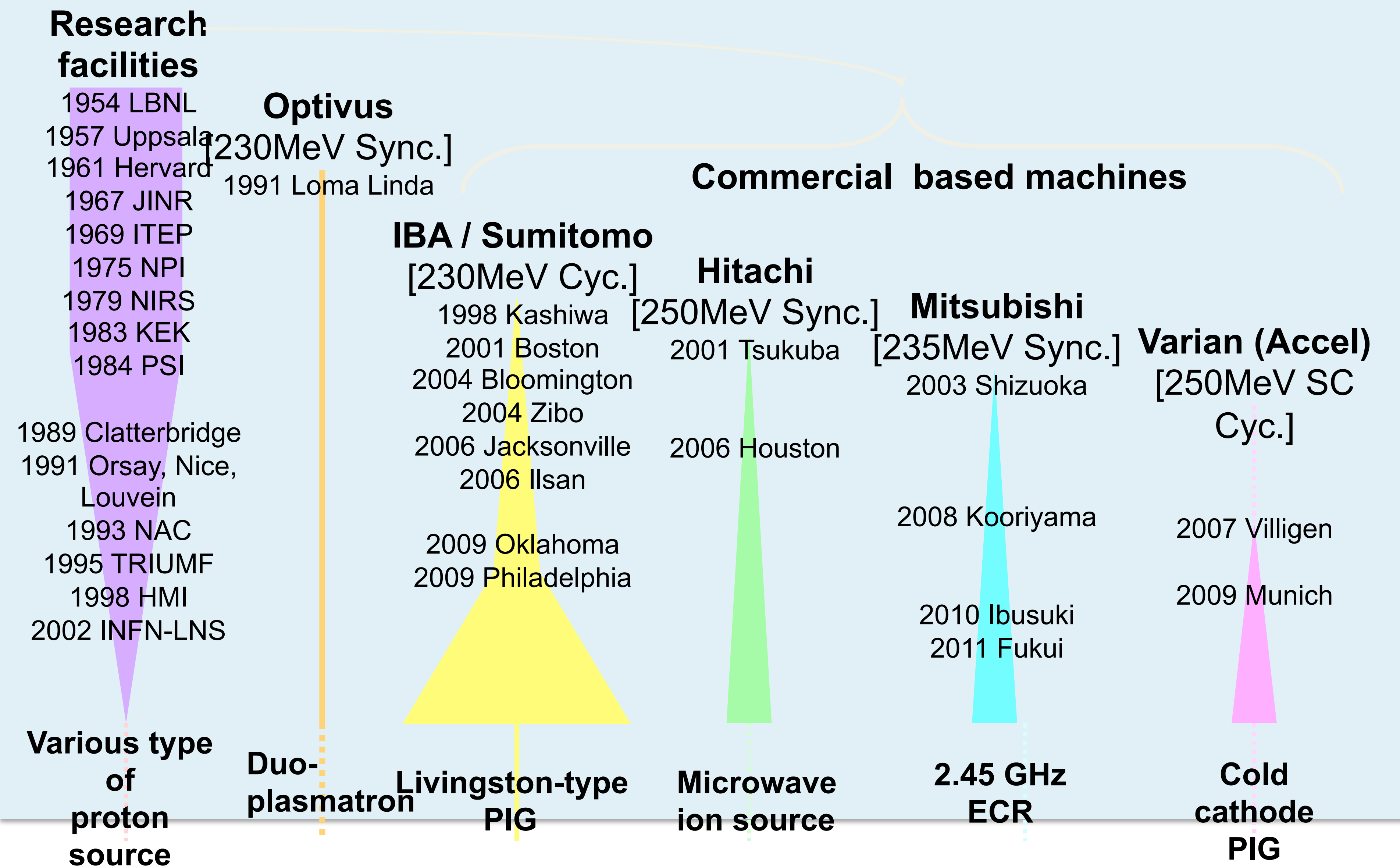
Ion source for hadrontherapy - Two cases:

- In the case of facilities which provide only protons (33), different ion sources can be chosen, that provide the needed current (in the order of 1-2 mA)

- carbon beams: highly charged carbon beams with the above said characteristics may be produced by Electron Cyclotron Resonance Ion Sources (3 facilities at NIRS, Chiba, Gunma and Lanzhou)

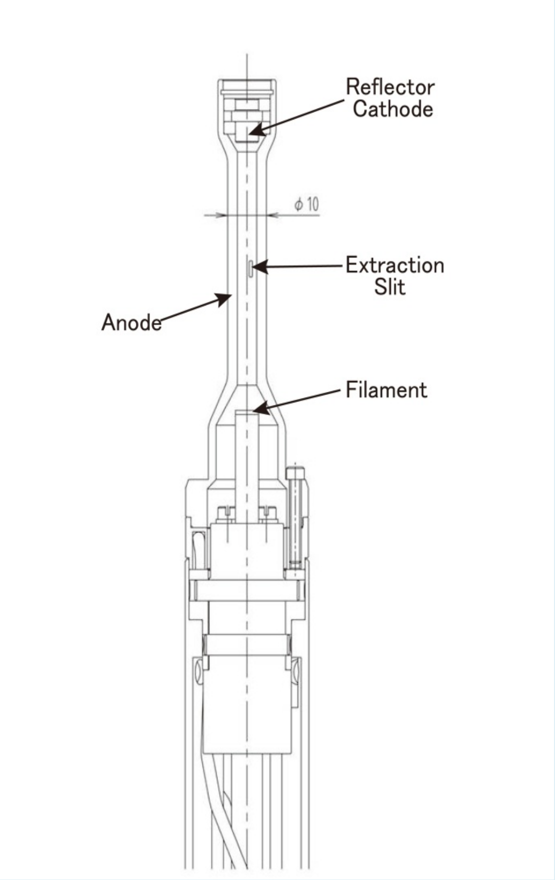
- In the case of facilities which provide both species, the best solution is anyway an ECRIS (3 facilities, at HIT Heidelberg, CNAO Pavia, Hyogo)

The trend of proton therapy



National Cancer Center (NCC)

Ion Beam Applications s.a. (IBA) and Sumitomo Heavy Industry, Co. (SHI)



235 MeV cyclotron

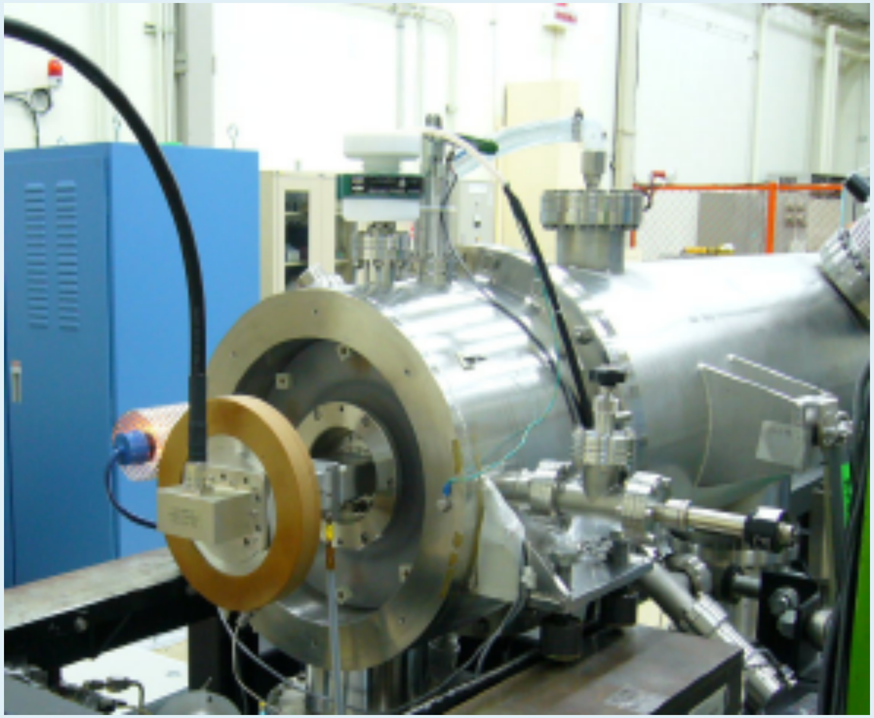
1998 Kashiwa
2001 Boston
2004 Bloomington
2004 Zibo
2006 Jacksonville
2006 Ilsan
2009 Oklahoma
2009 Philadelphia

Type: Livingston-type internal ion source
Arc voltage: 140 V
Arc current: 500 mA
Max. Beam intensity: 10 μA, H^+

Proton Medical Research Center (PMRC), University of Tsukuba

Hitachi Ltd.

http://www.pmrc.tsukuba.ac.jp/engOurFacility.html

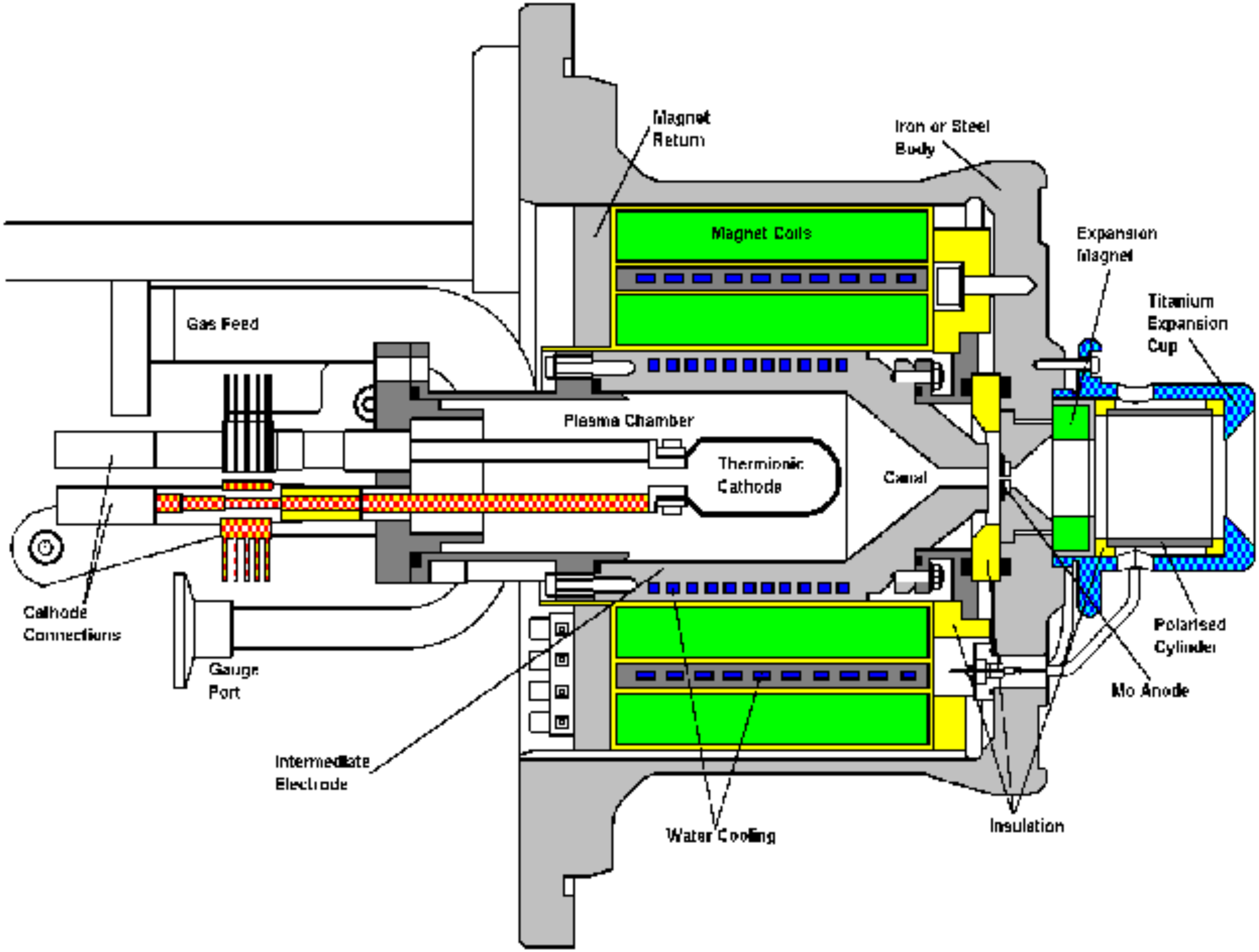


250 MeV Synchrotron

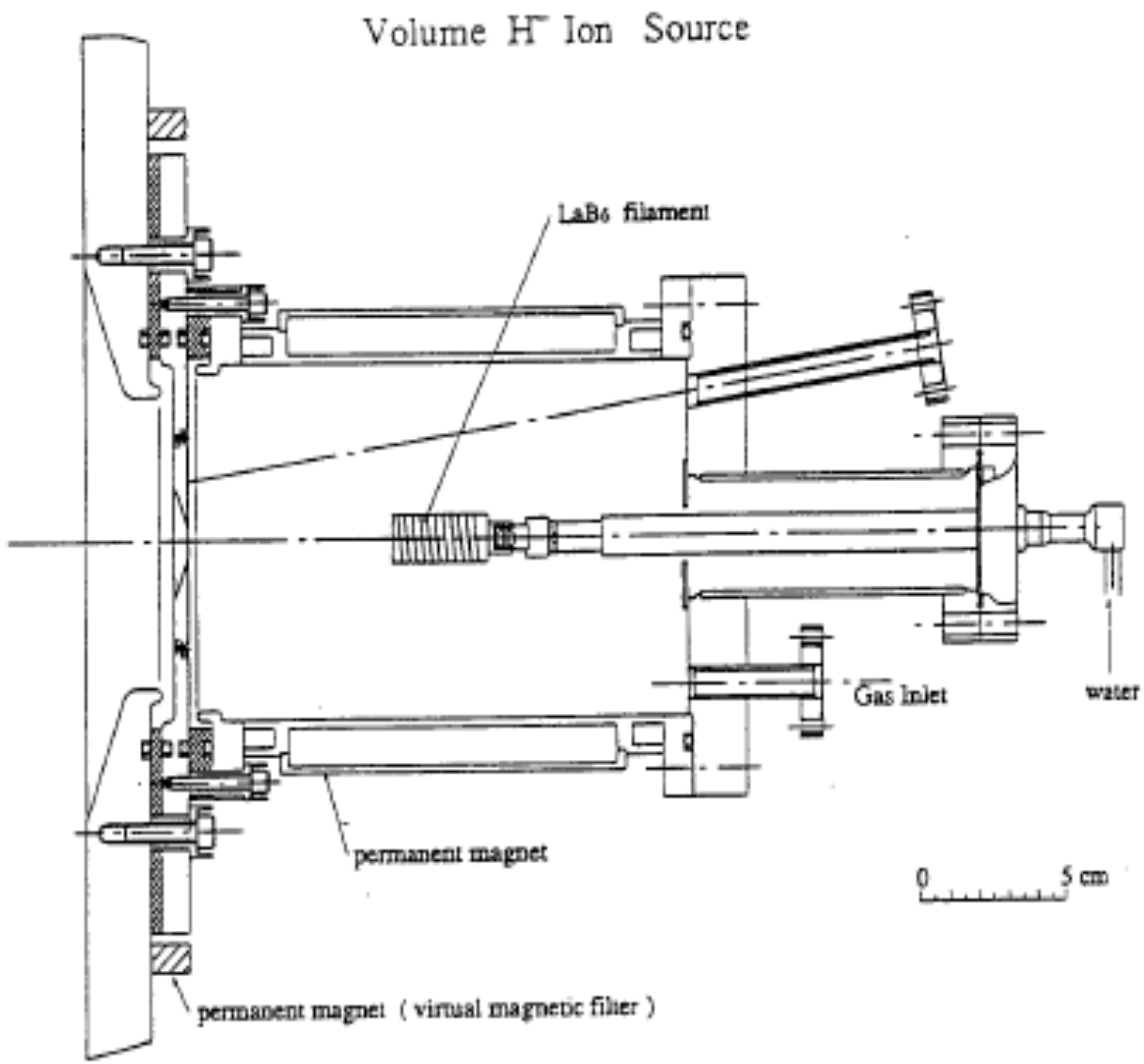
2001 Tsukuba
2006 Houston

Type: Microwave ion source
Microwave frequency: 2.45 GHz
Microwave power: 1.3 kW
Max. Beam intensity: 30 mA, H^+

DUOPLASMATRON FOR PROTONS (Loma Linda, etc)

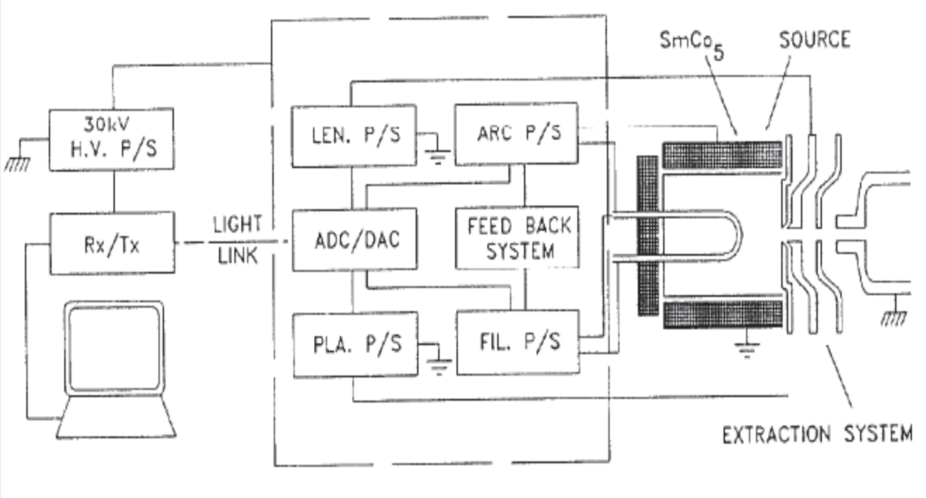


Multicusp Volume Production H- Ion Source



The TRIUMF H- Source

- *The TRIUMF H- source was developed ~1990 to inject H- into the TRIUMF Cyclotron.*
- *A filament driven plasma is confined by a multicusp field*
- *Filter field generated by two inverted cusp magnets near the outlet.*
- *A 6 mA, 5.8 keV copy was developed for Jyvaskyla.*



Beam Current:	15 mA continuous
Ion Energy:	20-30 kV
Filament:	340 A, 3.5 V; 1.2 kW
Arc supply:	29 A, 120 V; 3.5 kW
Normalized rms emittance	~0.22 n·mm·mrad
Plasma lens	30 A, 10 V; 0.3 kW
Efficiency:	~ 3 mA / kW
Filament lifetime: 14	days at peak current

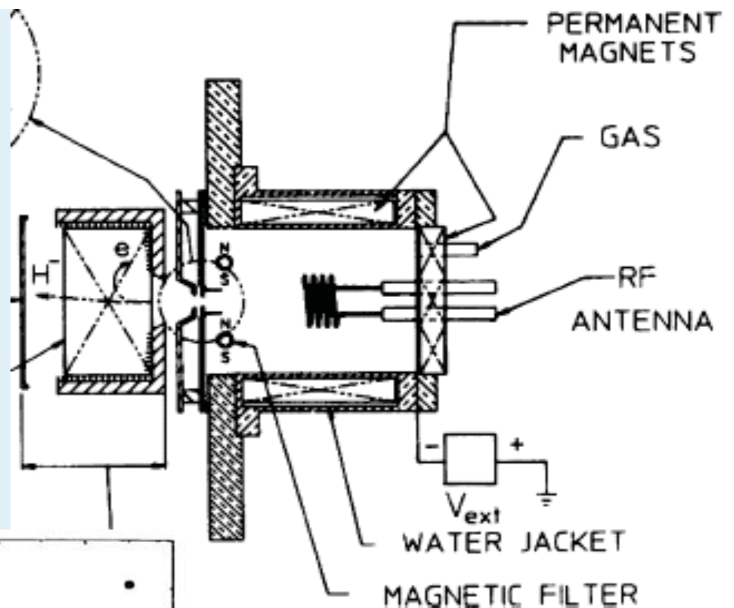
The Berkeley H^- developments-RF antennas

•*In 1990 Leung et al. report the use of inductively generated plasma for producing H^- beams "**with almost no lifetime limitation**".*
The efficiency is higher than their filament source.

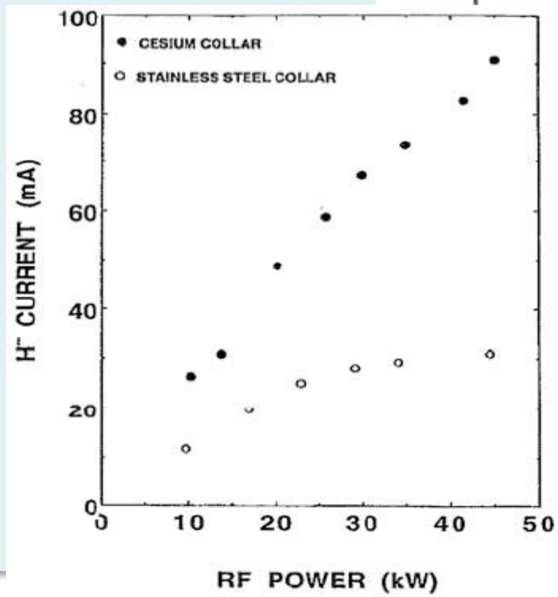
•*In 1993 Leung et al report a 3 fold gain in H^- beam using a collar with SAES Cs dispenser.*

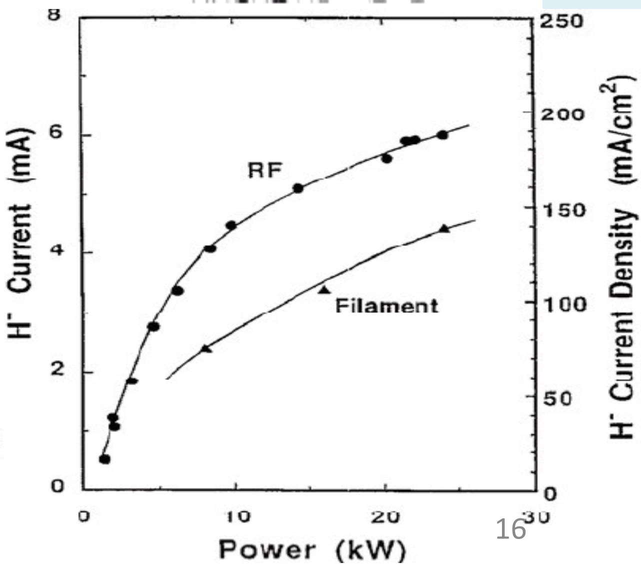
•*In 1996, Saadatmand et al. report 70-100 mA running at 10 Hz 0.1 ms with the SSC source modeled after the LBNL source. H- beam appeared to be stable for up to 8 hrs.*

From K.N. Leung, RSI 61 (1990) 1110



From K.N. Leung, RSI 64 (1993) 970



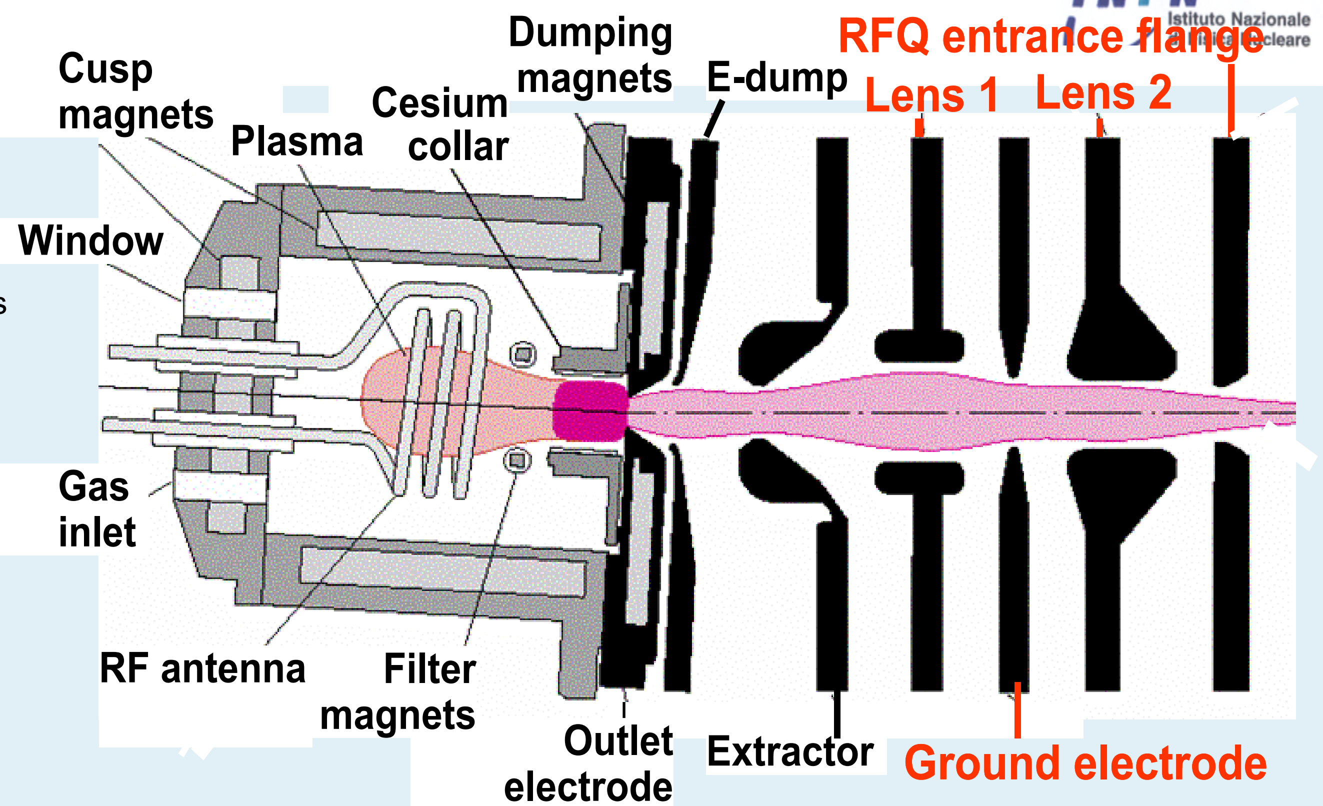


The SNS Baseline Ion Source and LEBT

•LBNL developed the SNS H^- ion source, a cesium-enhanced, multicusp ion source.

•Typically 300 W from a 600-W, 13-MHz amplifier generates a continuous low-power plasma.

•The high current beam pulses are generated by superimposing 50-60 kW from a pulsed 80-kW, 2-Mz amplifier.



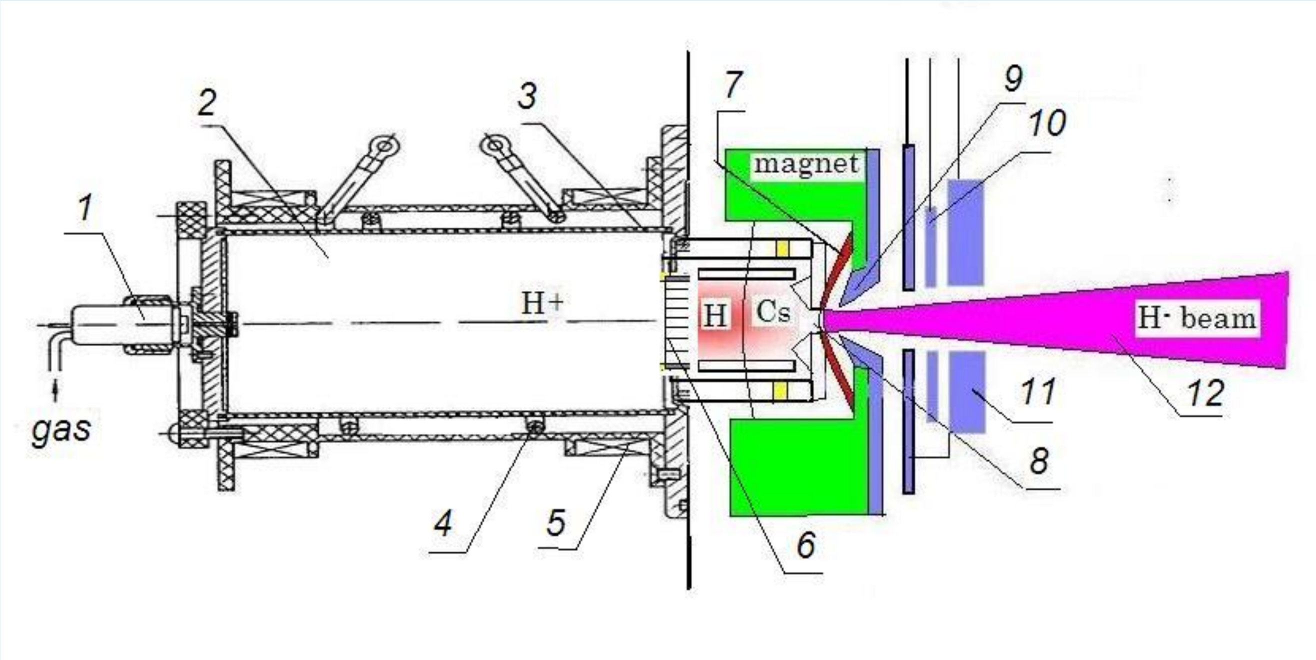
•The two-lens, electro-static LEBT is 12-cm long. Lens-2 is split into four quadrants to steer, chop, and blank the beam.

•The compactness of the LEBT constrains beam characterizations in front of the RFQ. The beam current is measured after emerging from the RFQ, which equals the LINAC beam current.

•Measuring the chopped beam on the RFQ entrance flange shows ~50 mA being injected into the RFQ under nominal conditions (= ~38 mA LINAC peak current).

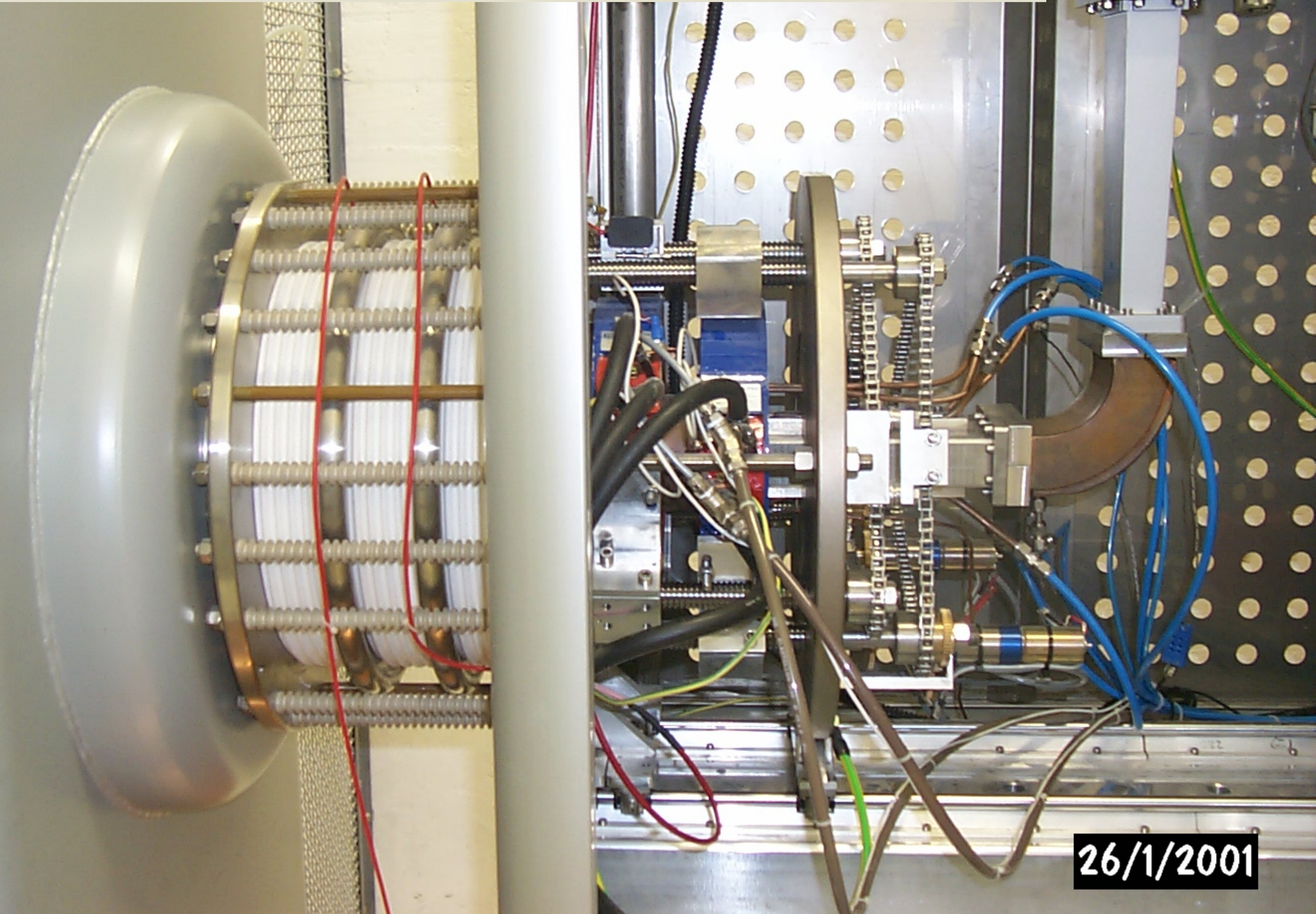
This is ~230 C of H^- ions per day!

Helicon Discharge Surface Plasma Source.



1- gas valve; 2- discharge volume; 3- discharge vessel; 4- helicon saddle like antenna; 5- magnetic coil; 6- ion/atom converter; 7- electron flux; 8- emission aperture (slit); 9- extraction electrode; 10-suppression /steering electrode; 11- ion beam.

2.45 GHz Microwave discharge ion source



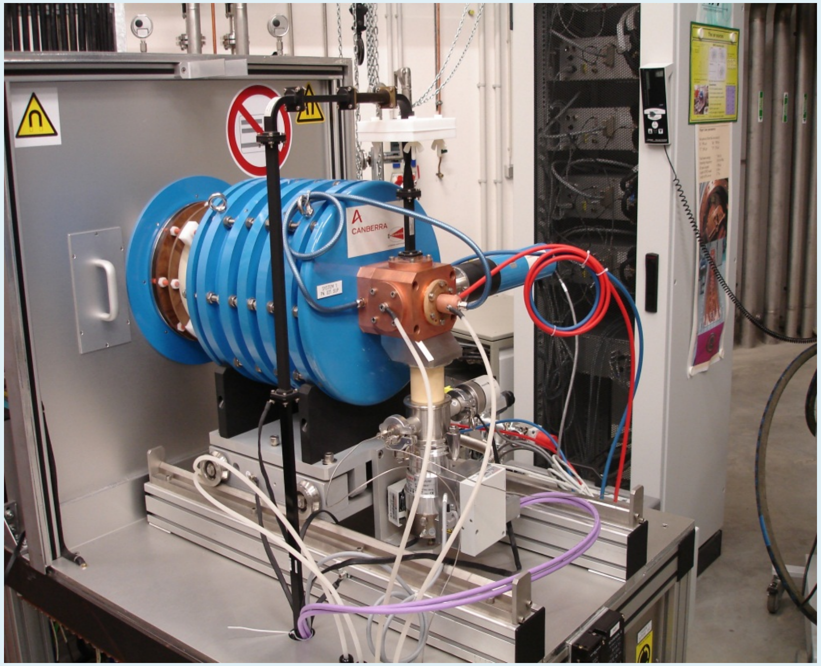
Ion sources for carbon ion therapy

Source	Supernanogan	Kei series
Type	ECR	ECR
Magnets	permanent	permanent
Ion	Carbon	Carbon
Charge	4+	4+
Required intensity	Low	High
(difference in irradiation method)		
Extraction voltage	24 kV	30 kV
Frequency	14.25-14.75 GHz	9.75-10.25 GHz
Operation	CW	Pulse
Gas	$C0_2$	CH_4

Supernanogan: beam stability

Kei series: intensity

Supernanogan

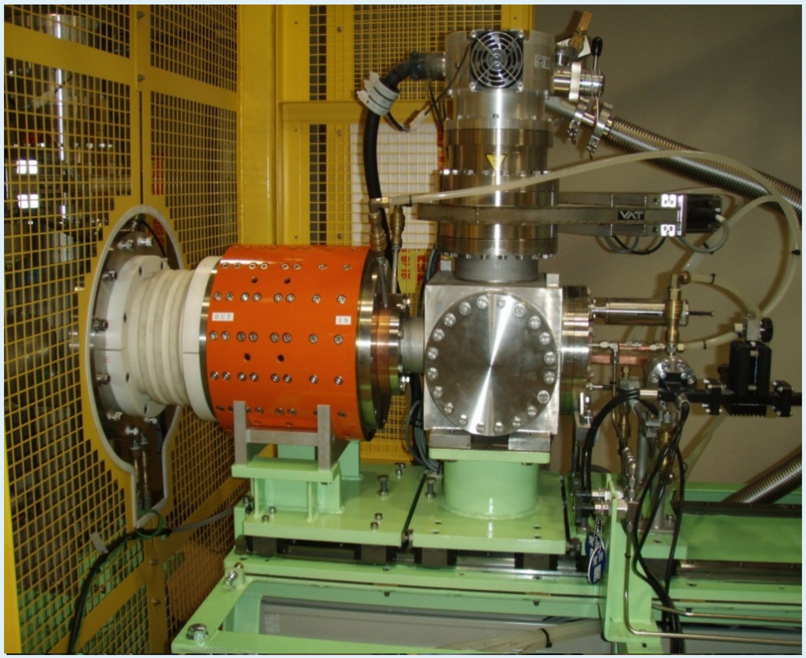


Magnetic field production	
All permanent magnet	
Microwave	
Frequency	14.25-14.75 GHz
Operation mode	CW
Extraction voltage	24 kV@C4+

Heidelberg, CNAO, Marburg,
Kiel, Shanghai, Med-Austron

Kei series

Kei2 source KeiGM

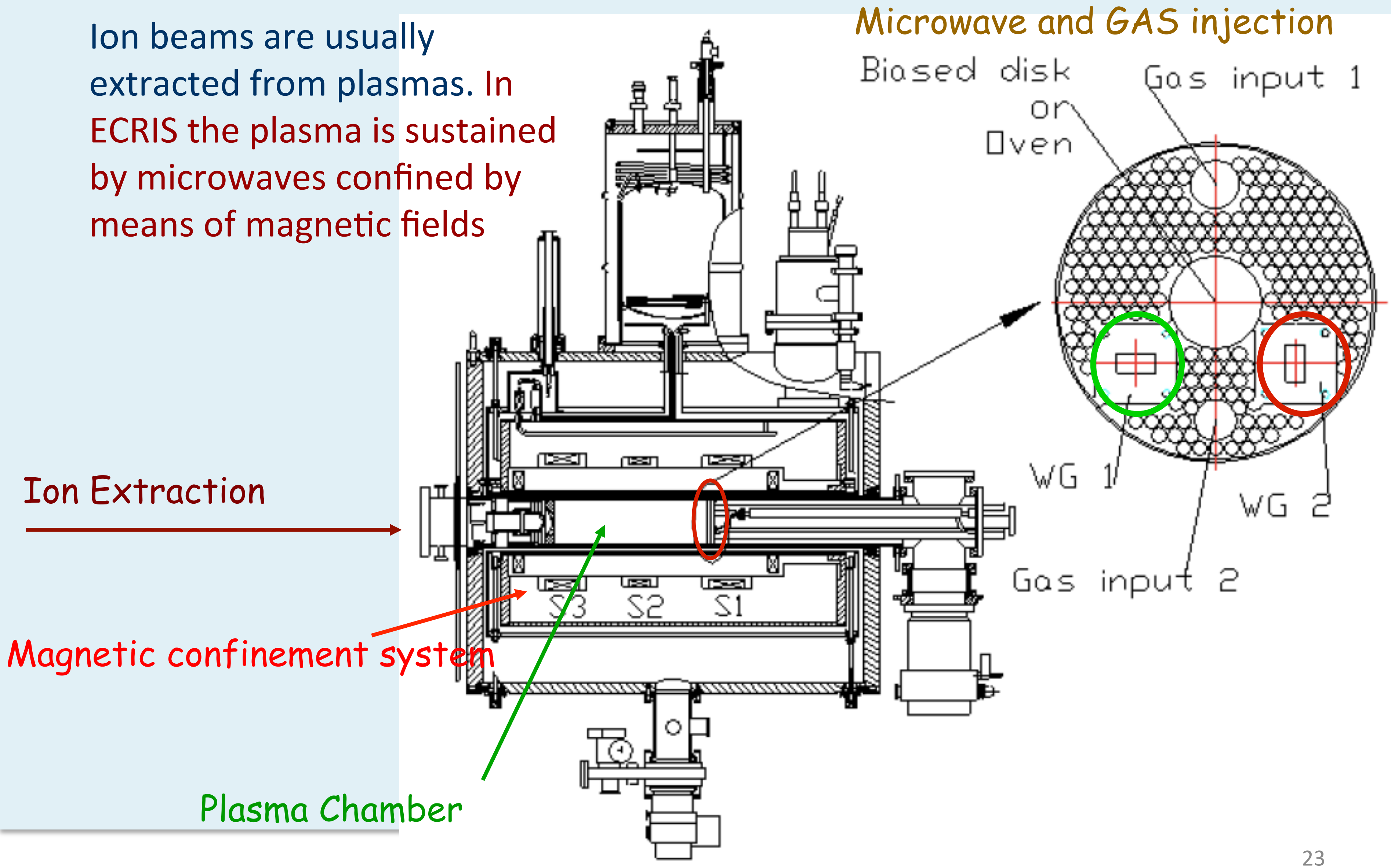


HIMAC, Gunma U., Saga

Magnetic field production	
All permanent magnet	
Microwave	
Frequency	9.75-10.25 GHz
Operation mode	pulse
Extraction voltage	30 kV@C4+

ECRIS subsystems

Ion beams are usually extracted from plasmas. In ECRIS the plasma is sustained by microwaves confined by means of magnetic fields



The creation of the ECR Plasma

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During plasma start-up a modest number of free electrons exists

→ Magnetic Field

Electrons turn around the magnetic field lines with the frequency:

$\omega_g = qB/m$

The ionization up to high charge state is a step by step process which requires long ion confinement times and large electron densities.

100 μA of Xe^{30+} or more can be obtained in 3rd generation ECRIS

A circulary polarized electromagnetic wave transfers its energy to the electrons by means of the ECR :

$\omega_{RF} = \omega_g$

The energetic electrons ionize the gas atoms and create a plasma.

The cutoff density

$$\epsilon(\omega) \sim 1 - \frac{\omega_p^2}{\omega^2}$$

The propagation of e.m. waves is possible if ε>0

$$\omega_p^2 = \frac{4\pi n_e e^2}{m_e}$$

The plasma frequency is connected to self-generated plasma oscillations which strongly affect the wave propagation.

Above the cutoff the wave cannot propagate:

$$n_{cutoff} = 4\pi^2 \frac{m\epsilon_0}{e^2} f_p^2$$

ECRIS Standard Model

Scaling Laws

(R. Geller-1987):

For many years they represented the guideline for ECRIS development

$$I \propto \frac{\omega_{RF}^2}{M} \qquad \langle q \rangle \propto \log \omega_{RF}^{3.5}$$

1. We have to increase the Microwave frequency to attain higher electron densities
2. The confinement is essential but no conditions on magnetic field distribution

High-B Mode

(G. Ciavola-S.Gammino, 1990)

It doesn't conflict with Scaling Laws, but it limits their efficiency to high confined plasmas

High mirror rations ensure the MHD stability exploiting the density increase.

$$\frac{B}{B_{ECR}} > 2$$

B>4T for future ECRIS !

Overcoming the current limits of ECRIS

Roadmap indicated by the ECR Standard Model:

- High Frequency Generators;
- High Magnetic Fields;

$$\langle q \rangle \sim n_e \tau_i$$

$$I \sim n_e / \tau_i$$

Investigations about RF energy transfer to the electrons may allow to overcome the limits

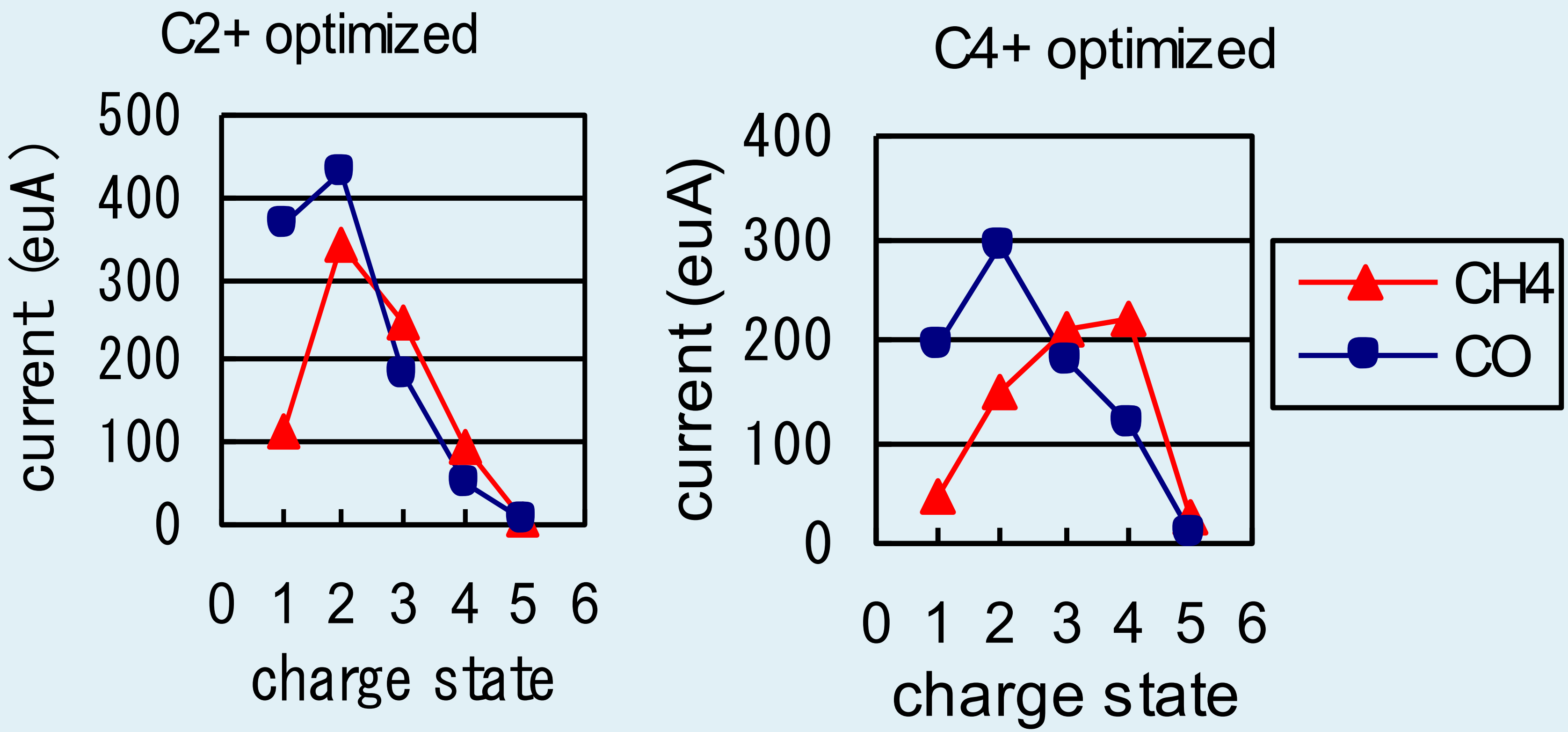
↓

By quickly replacing the loss hot electrons we can increase the Electron Density and the heating rapidity

The optimization of the wave-electron energy transfer allow to slightly relax the confinement conditions

Beam intensity of Carbon

Observation of gas mixing effect at NIRS-ECR

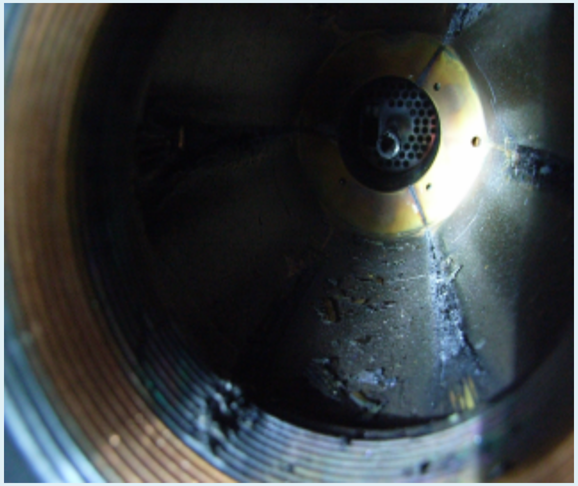


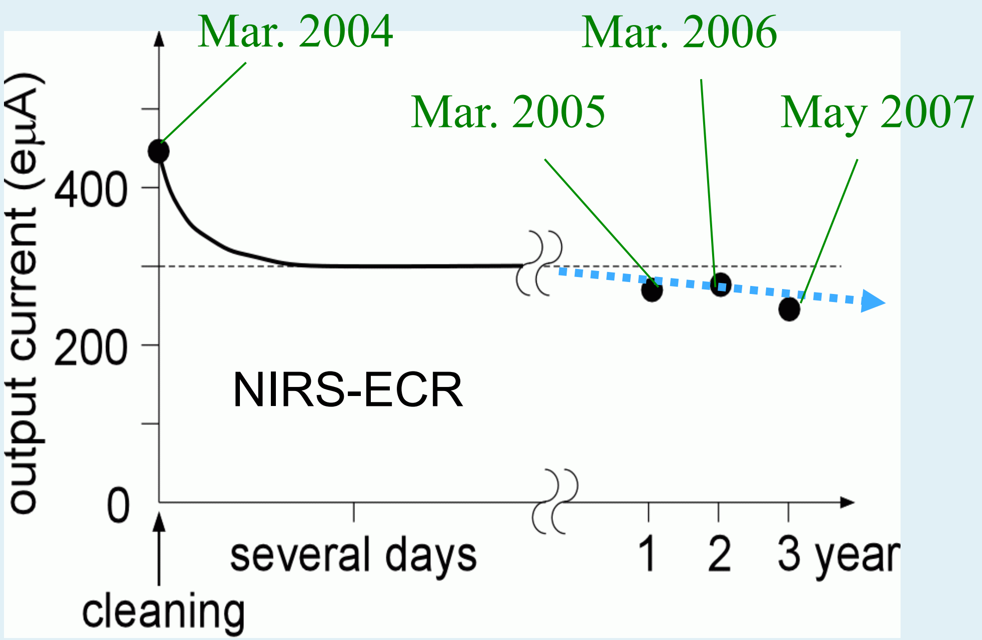
A. Kitagawa et al., Rev. Sci. Instrum. 71, 1061 (2000).

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

In this case, the deposition of carbon on the wall surface causes serious effects.

Maintenance-free ion source





- Carbon deposit on the wall increases
  - -> intensity decreases
  - -> stability and reproducibility worsen

Supernanogan: CO_2 for stability under the long operation

Kei series: low duty pulsed mode (reduce the carbon deposition)

Decreasing of intensity due to carbon deposition

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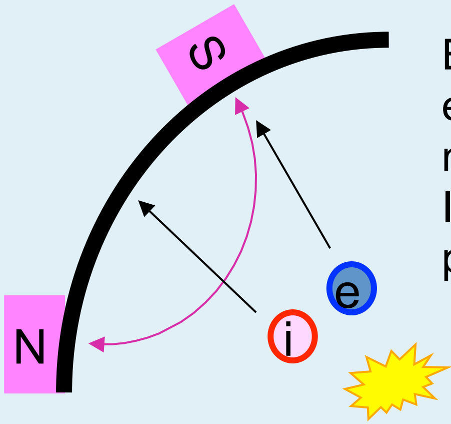
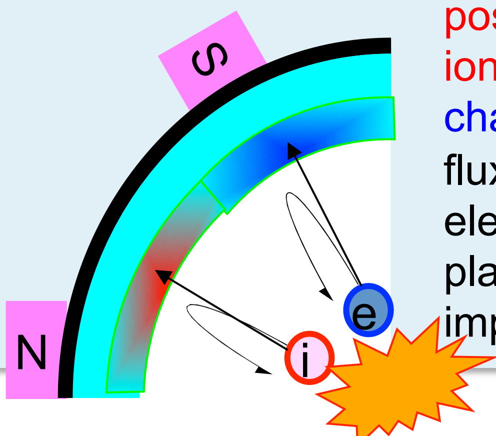
A) Normal metallic wall



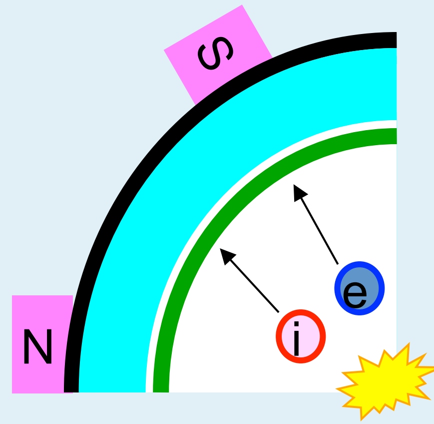
Electrons mainly escape toward to the magnetic field line.
Ions also escape to the perpendicular direction.

B) Dielectric wall (wall coating effect)

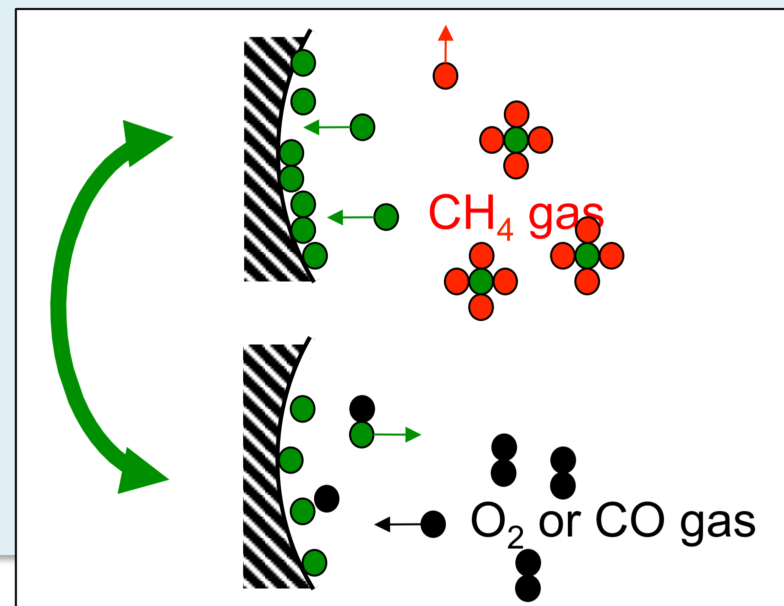


Positive and negative potential formed by positive charge-up of ion’s and negative charge-up of electron’s flux repel ions and electrons, thus the plasma confinement is improved.

C) Carbon deposition (Adverse wall coating effect)



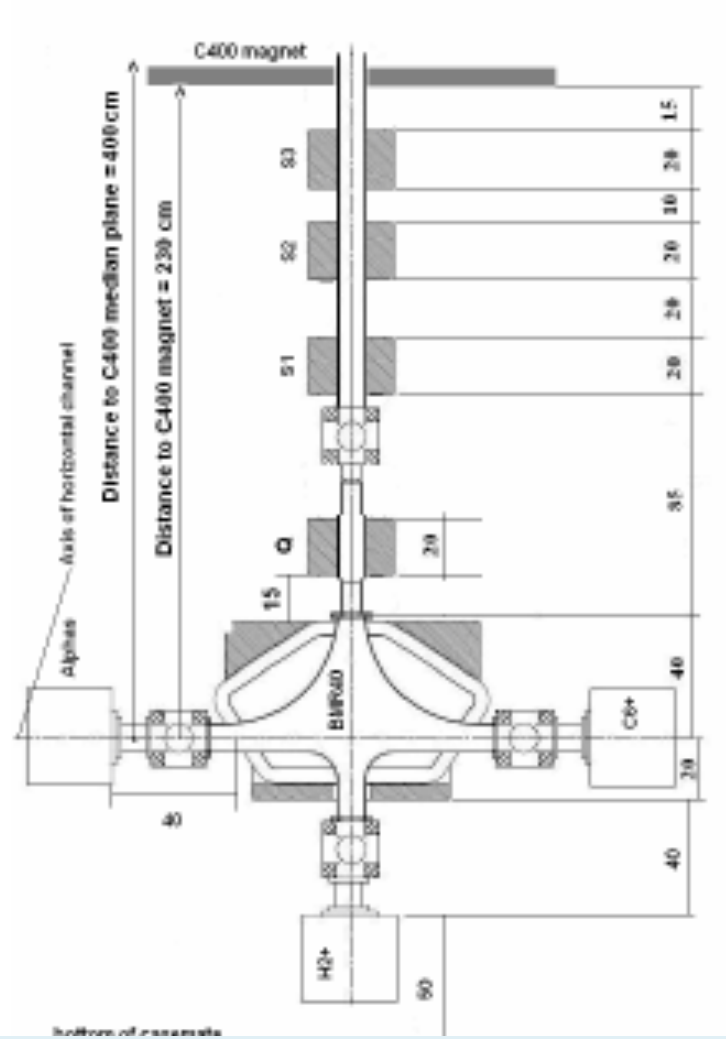
Carbon deposition on the wall prevents the form of potentials, thus the improvement is disappeared.



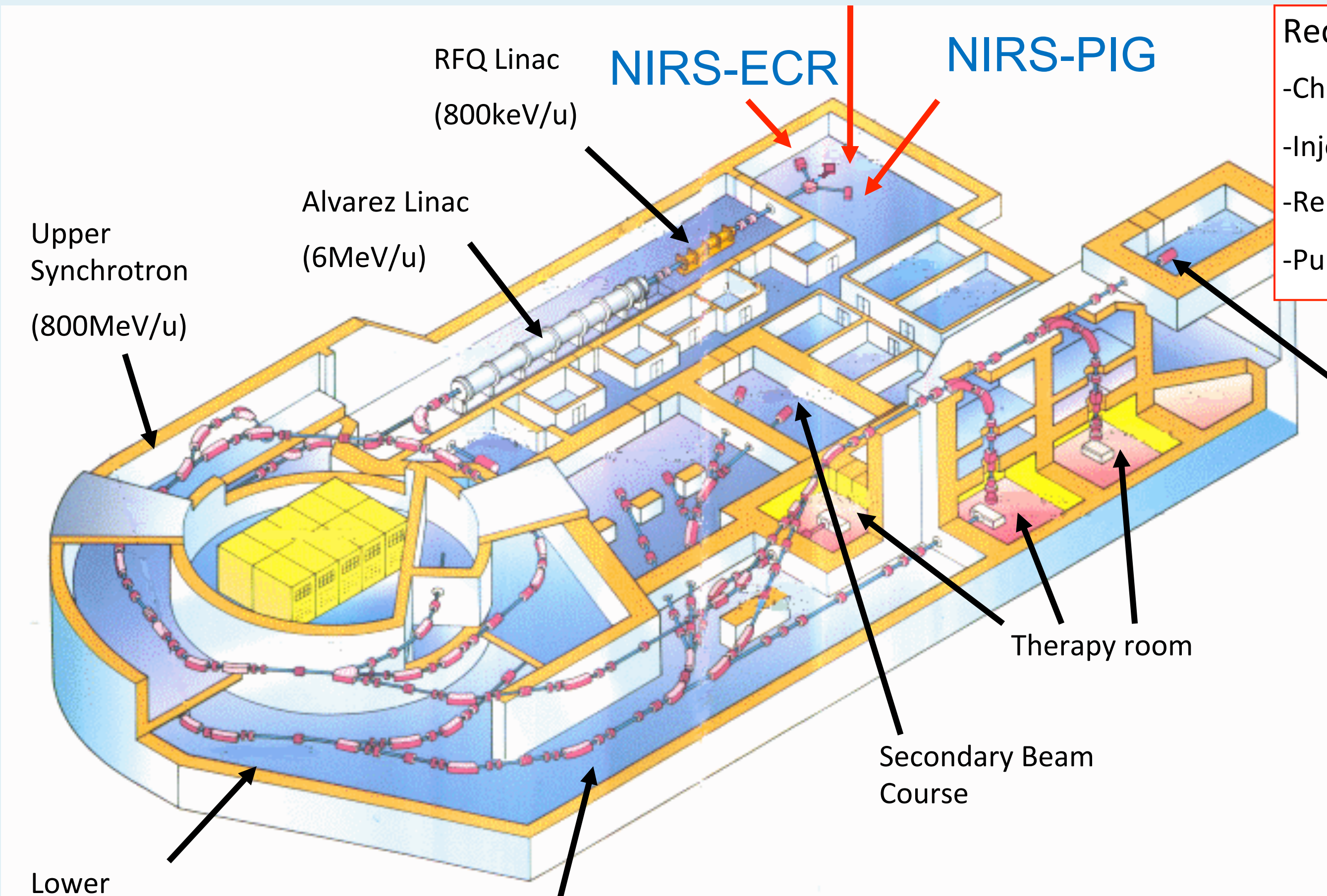
IBA C400

accelerated particles	H_2^+, $^4He^{2+}$, ($^6Li^{3+}$), ($^{10}B^{5+}$), $^{12}C^{6+}$
Injection energy	25 keV/Z
final energy of ions, protons	400 MeV/amu 265 MeV/amu

Three external ion sources are mounted on the switching magnet on the injection line located below of the cyclotron (see Fig. 1). $^{12}C^{6+}$ are produced by a high performance ECR, alphas are also produced by the ECR source, while H_2^+ are produced by a multicusp ion source. All species have a Q/M ratio of 1/2 and all ion sources are at the same potential, so that small retuning of the frequency and magnetic field change achieved by different excitation of 2 parts in the main coil are needed to switch from H_2^+ to alphas or to $^{12}C^{6+}$. We expect that the time to switch species can be not more than two minutes, as long as the time needed to retune the beam transport line between different treatment rooms.



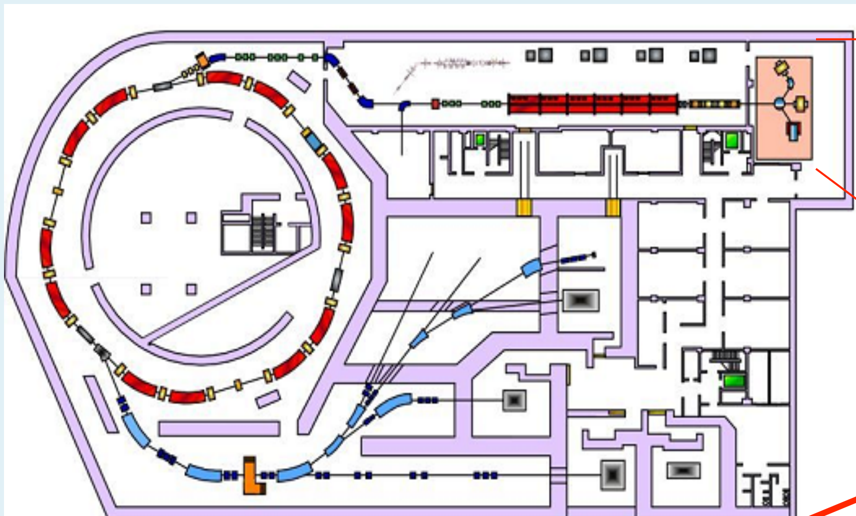
The HIMAC project



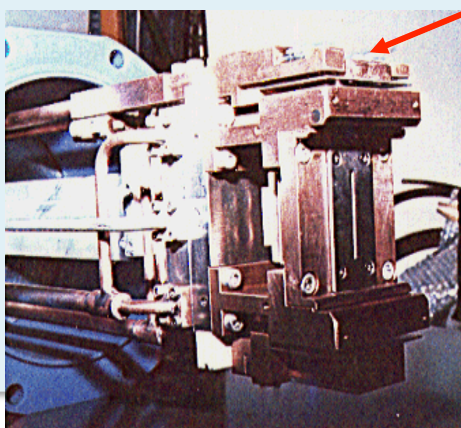
Requirement for ion sources	
-Charge to mass ratio≥1/7	
-Injection energy	8keV/u
-Repetition rate	≤3Hz
-Pulse width	≅0.5ms

HIMAC (Heavy Ion Medical Accelerator in Chiba)

Ion sources at HIMAC

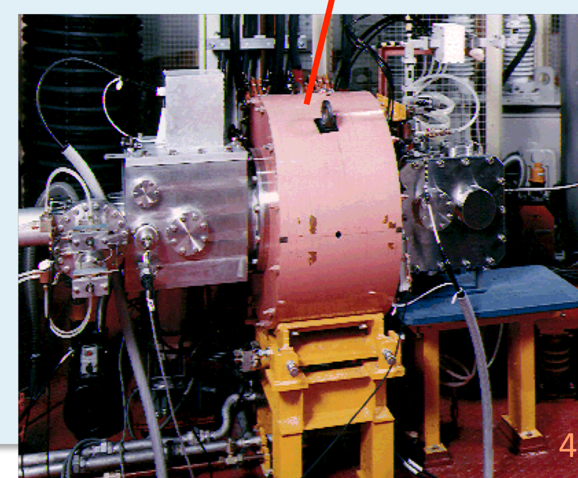


NIRS-PIG IS

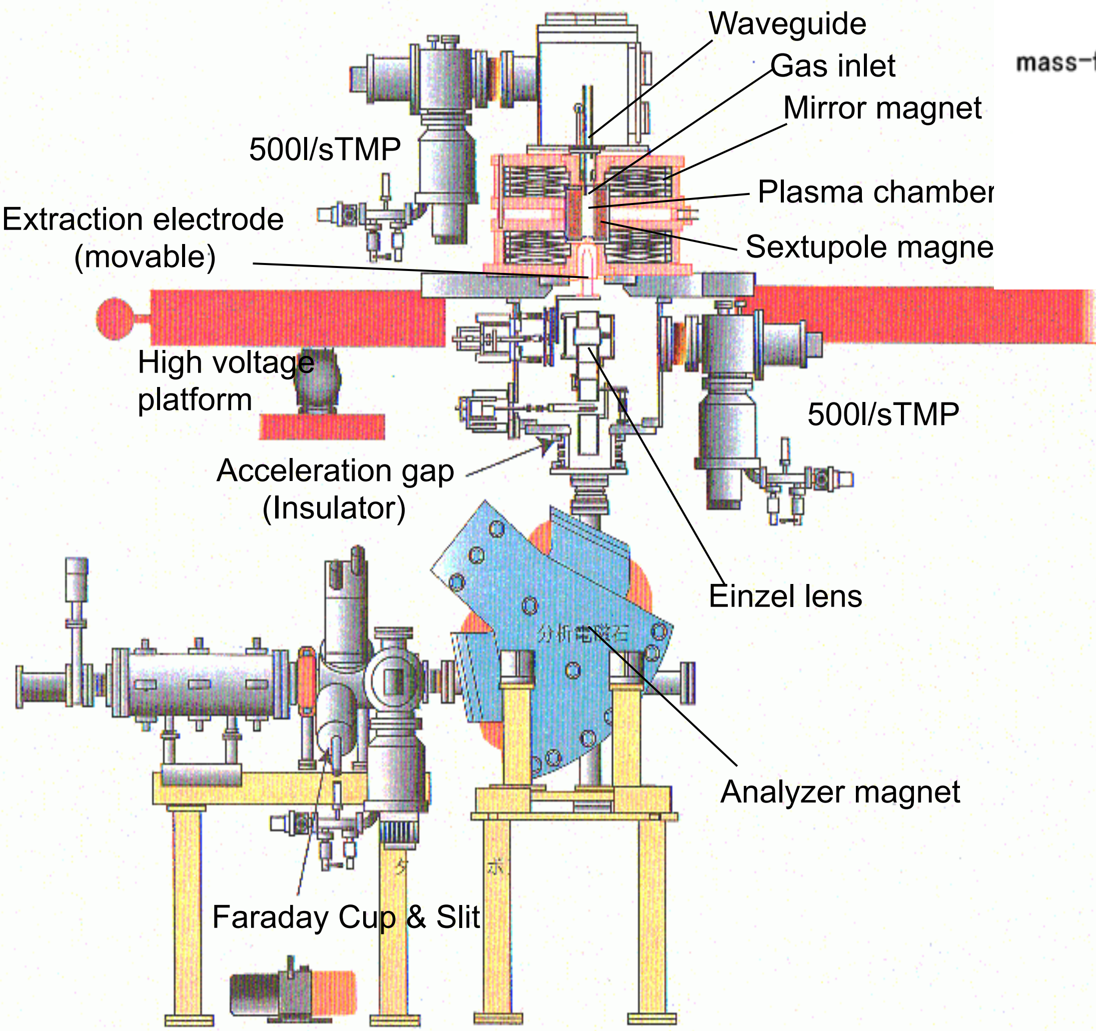


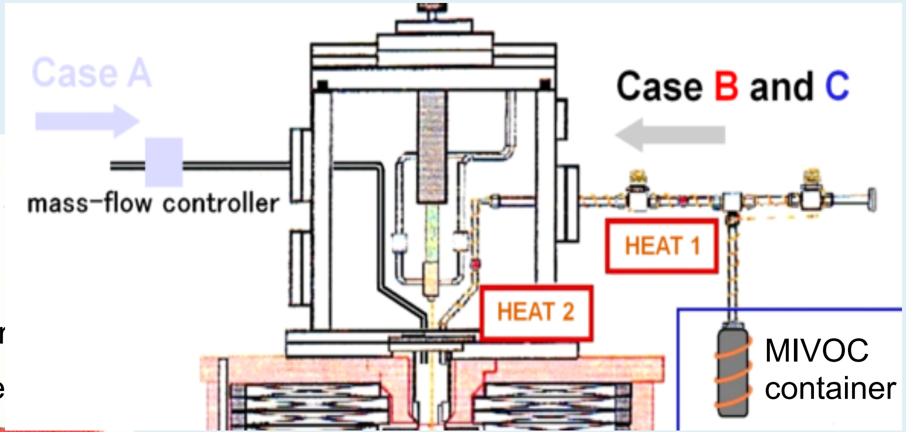
18GHz NIRS-HEC ECRIS

10GHz NIRS-ECR IS



18GHz NIRS-HEC



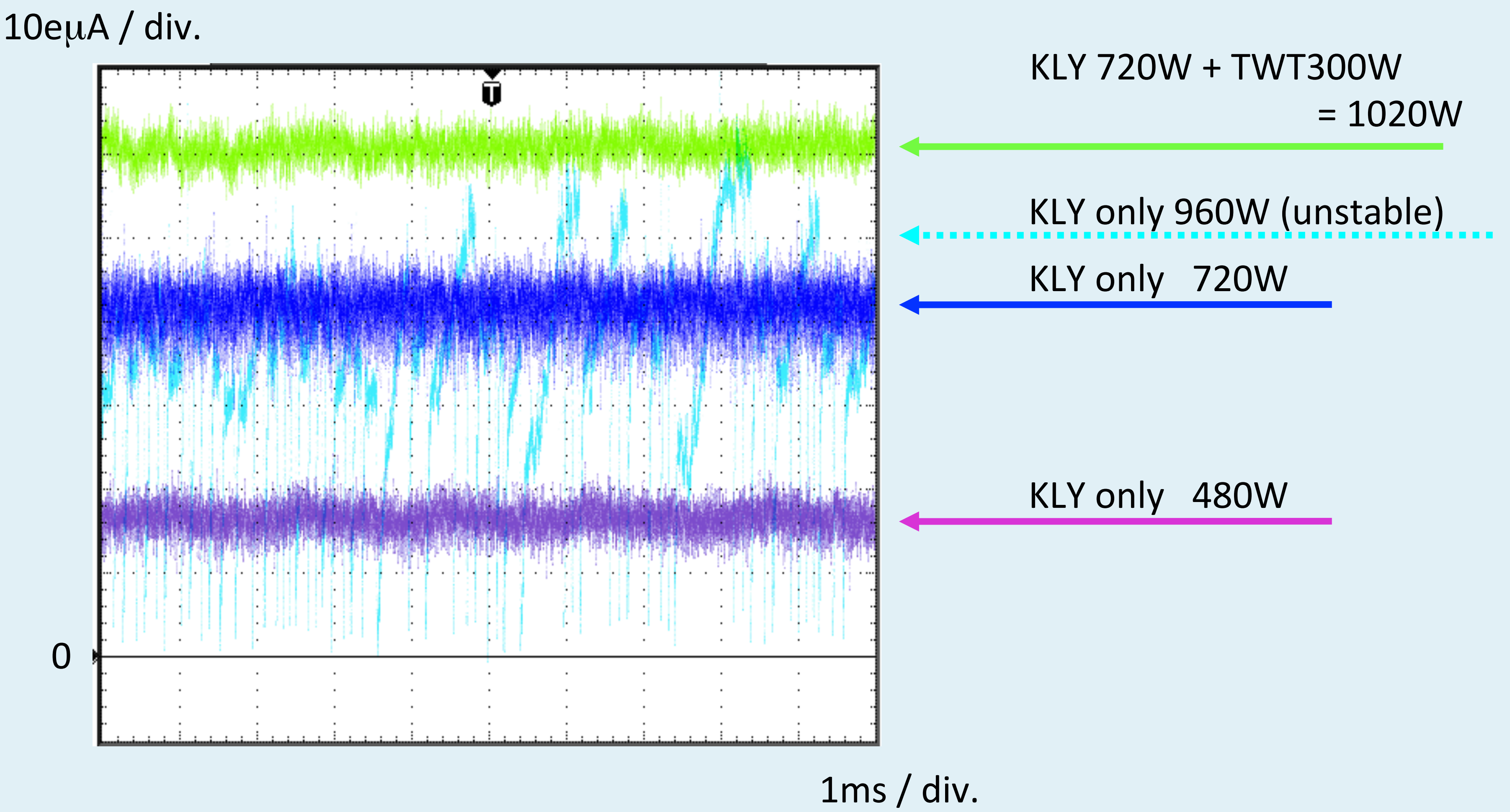


- <u>Features</u>
- Max. 60kV high extraction voltage
- Optimize the radial magnetic field for ion and electron fluxes
- MIVOC method with thermal control
- Backup for carbon-ion radiotherapy

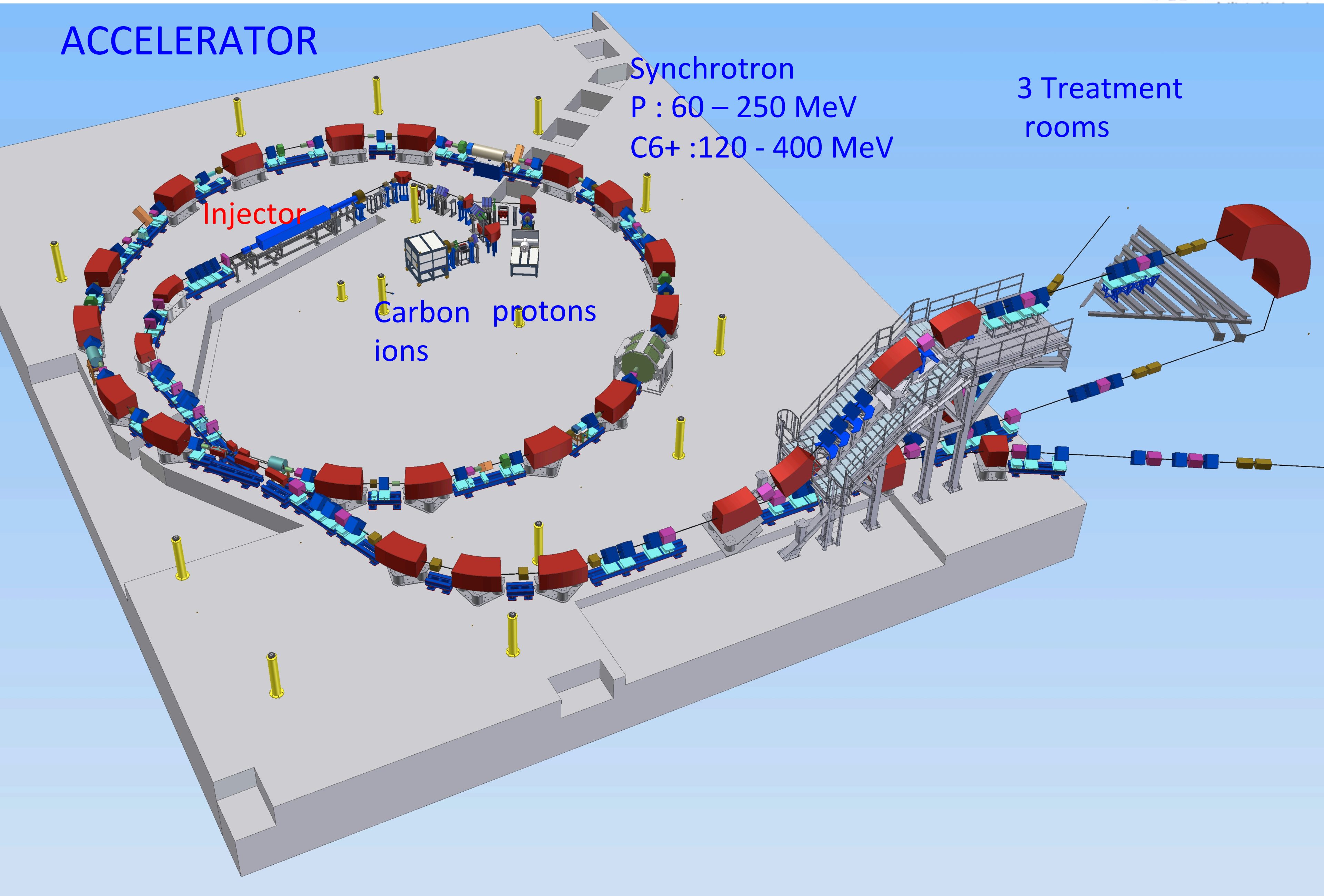
Improvement of plasma instability by two frequency heating

NIRS

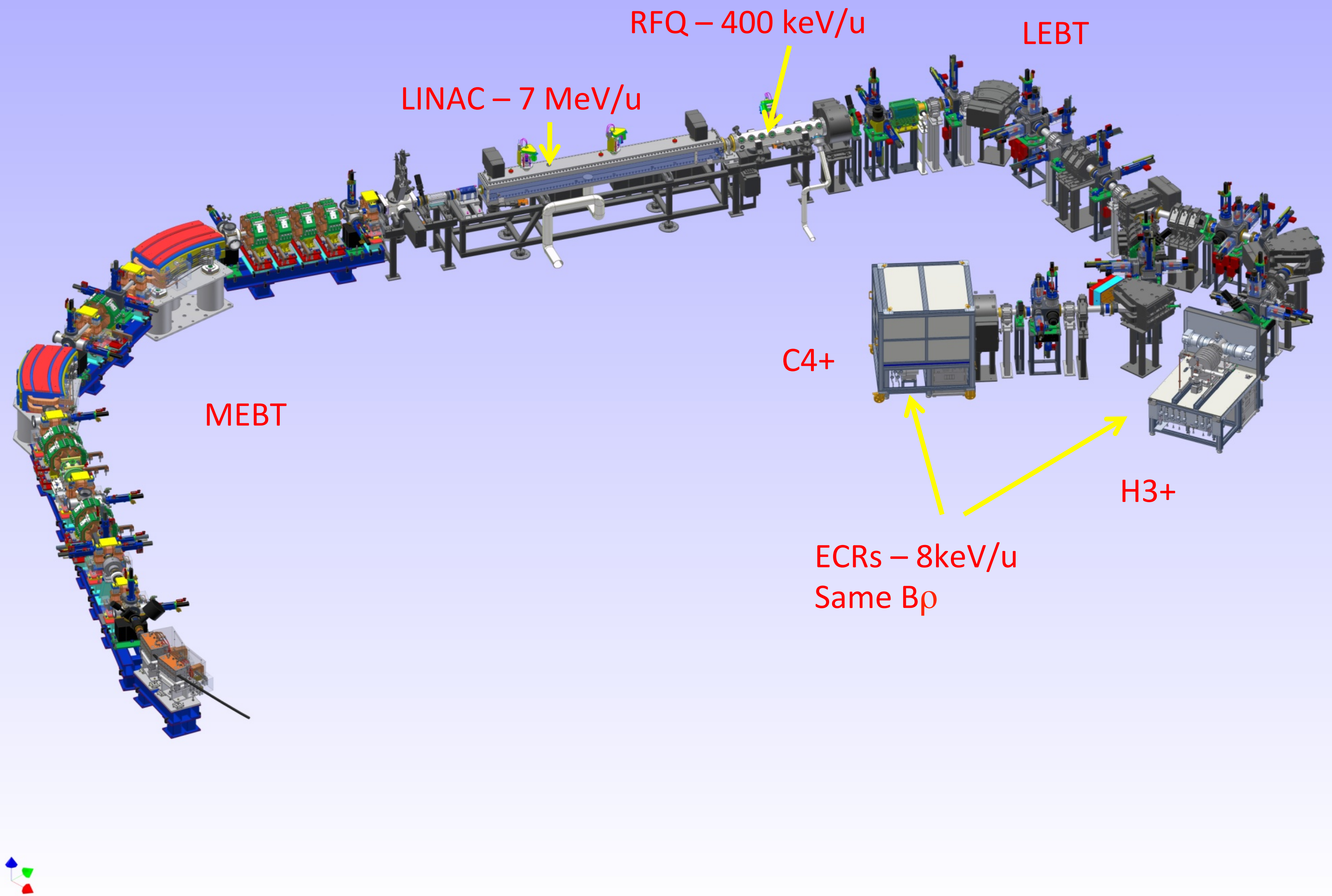
HIMAC

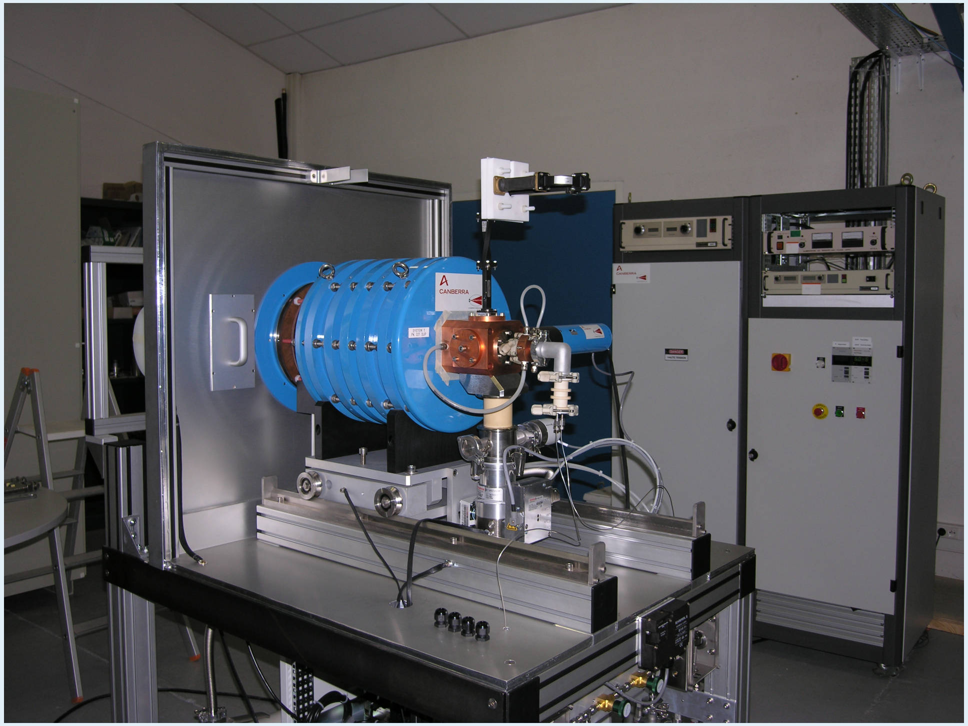


CNAO (National Center for Hadrontherapy, Pavia)



INJECTOR



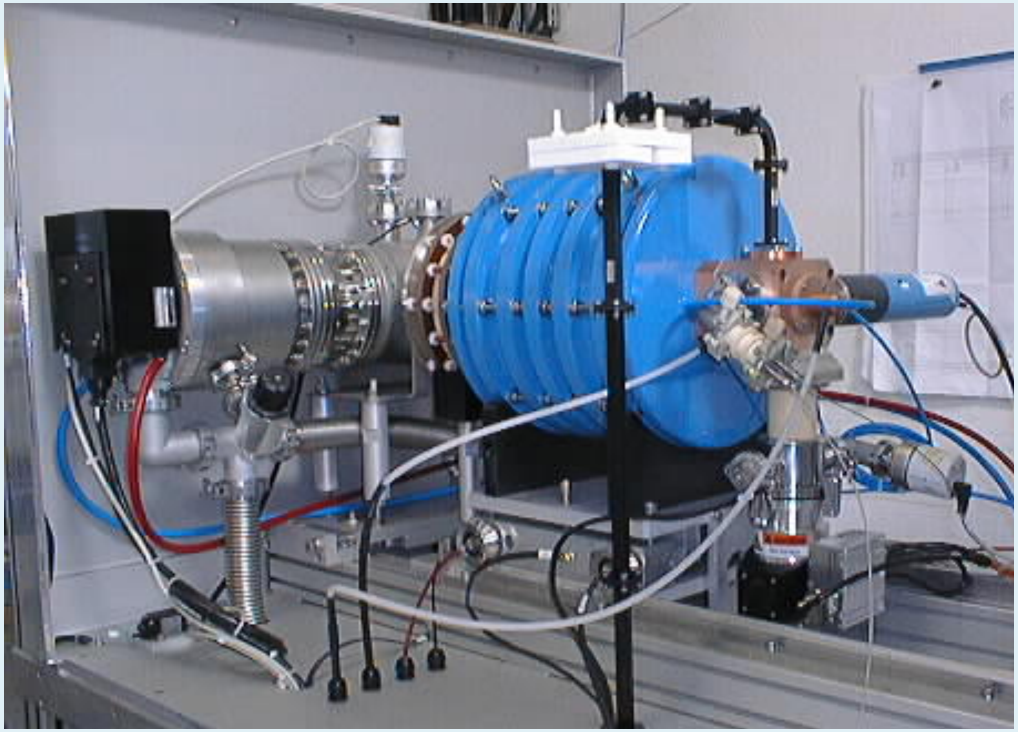


SUPERNANOGAN
ECR Ion Source

- Better sources can be built (GTS, SERSE,VENUS) but a hospital facility is not adapted to 'difficult' multi-parameters ECR sources that can be managed in a laboratory environment
- Even a "simple" Hypernanogan source requires a higher cost for electricity, which is not the case for a source with permanent magnets like Supernanogan
- Minimizing the number of components subject to failure in Supernanogan source, its reliability is in principle higher

ECR Ion Sources

Both can deliver H3+, C4+ and other species
14.5GHz



Built by Pantechnik on INFN-LNS Design

- Double wall, water cooled plasma chamber, 7 mm diameter aperture for beam extraction.
- Permanent magnets system providing the axialand radial confinement (axial field from 0.4 to 1.2 T, radial field i1.1 T)
- Copper made “magic cube” for microwave injection system = waveguide to coaxial converter with a tuner to minimize the reflected power.
- RF window for the junction between the magic cube at high vacuum and the waveguide at atmospheric pressure.
- A gas injection system.
- A DC bias system to add electrons to the plasma and decrease the plasma potential.
- An RF generator of about 400 W at 14.5 GHz (the effective power used in operation is below 300W).
- Flexible frequency variable travelling wave tubes amplifiers (TWTA) .

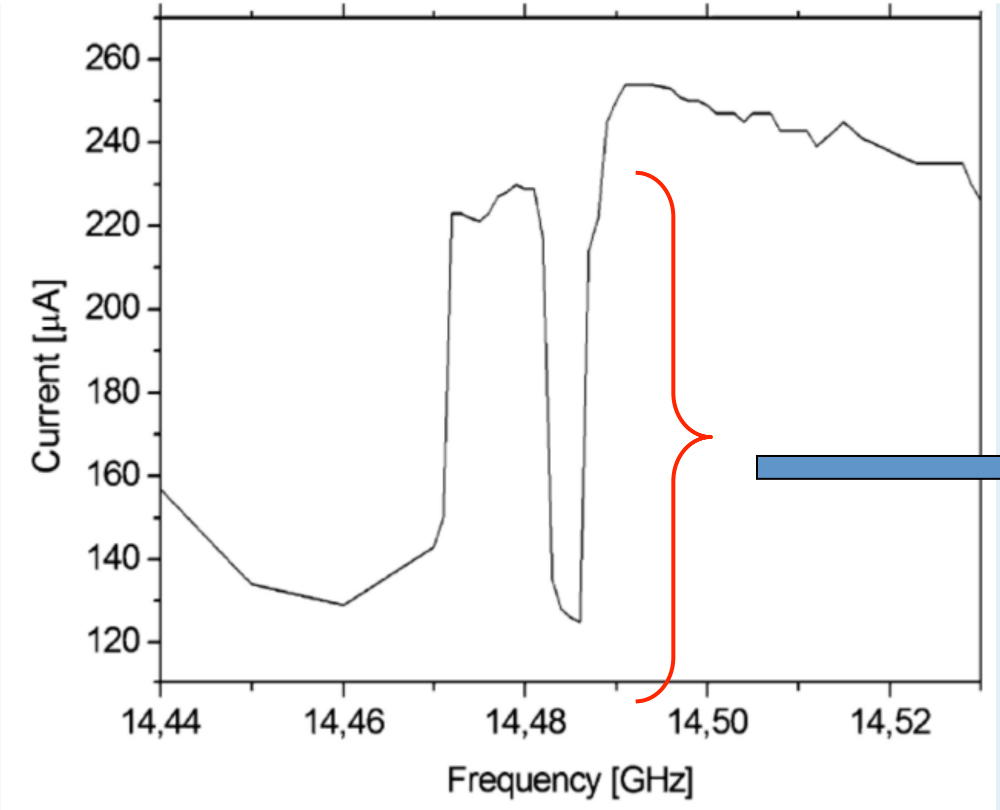
ECR Ion Sources

Ions	Current (requested) [μA]	Current (available) [μA]	After improvements by INFN-LNS [μA]	Emittance (requested) π mm.mrad	Emittance (new extractor) π mm.mrad	Stability [99,8%]
C^{4+}	200	200	250	0.75	0.56	36 h
H_2^+	1000	1000		0.75	0.42	2 h
H_3^+	700	600	1000	0.75	0.67	8 h
He^+	500	500		0.75	0.60	2 h

Major improvements

1) Frequency tuning for the microwave injection: improvement to beam intensity and emittance
2) New extraction system: improvement to beam emittance and stability
3) Changes to gas input system: much better stability

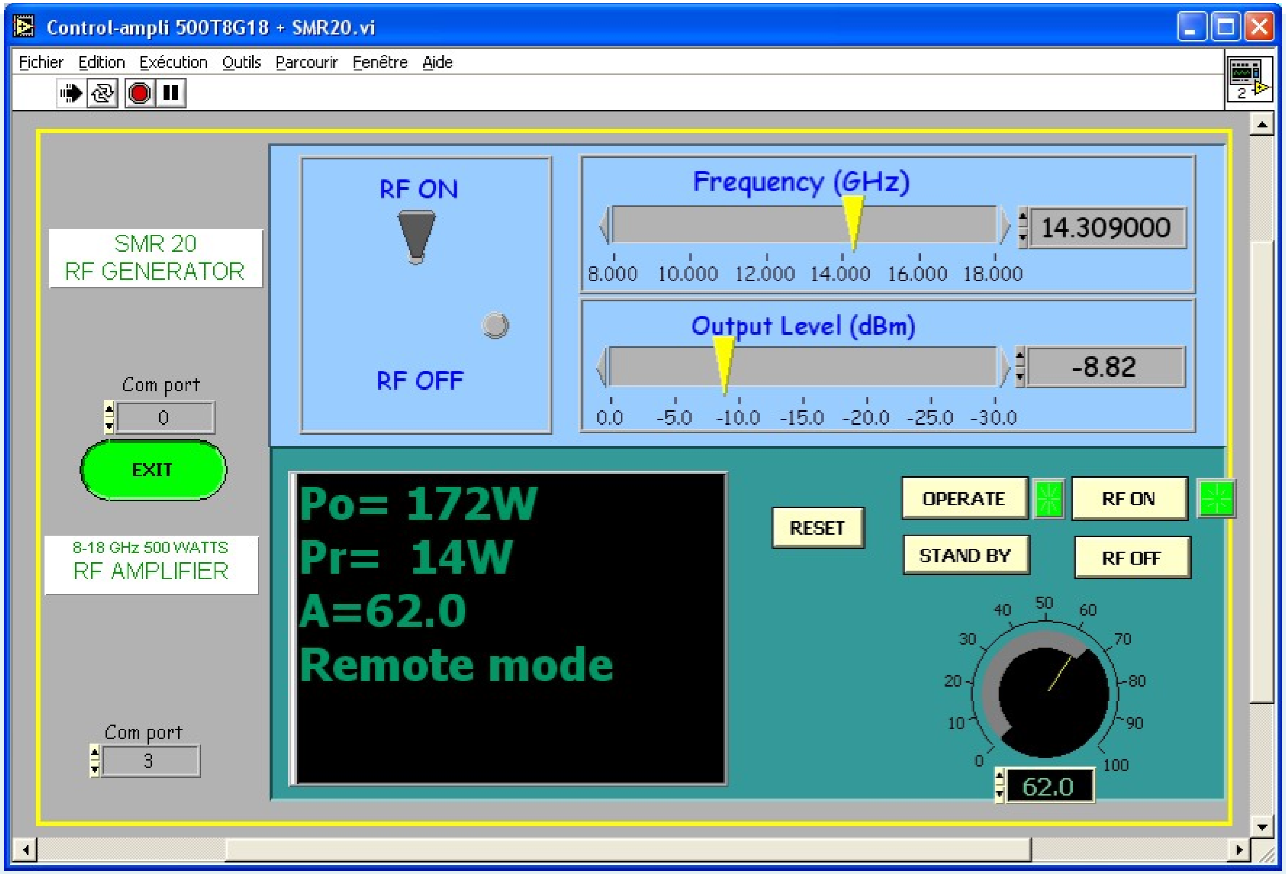
Evidence of Frequency Tuning Effect (FTE) on the SUPERNANOGAN source



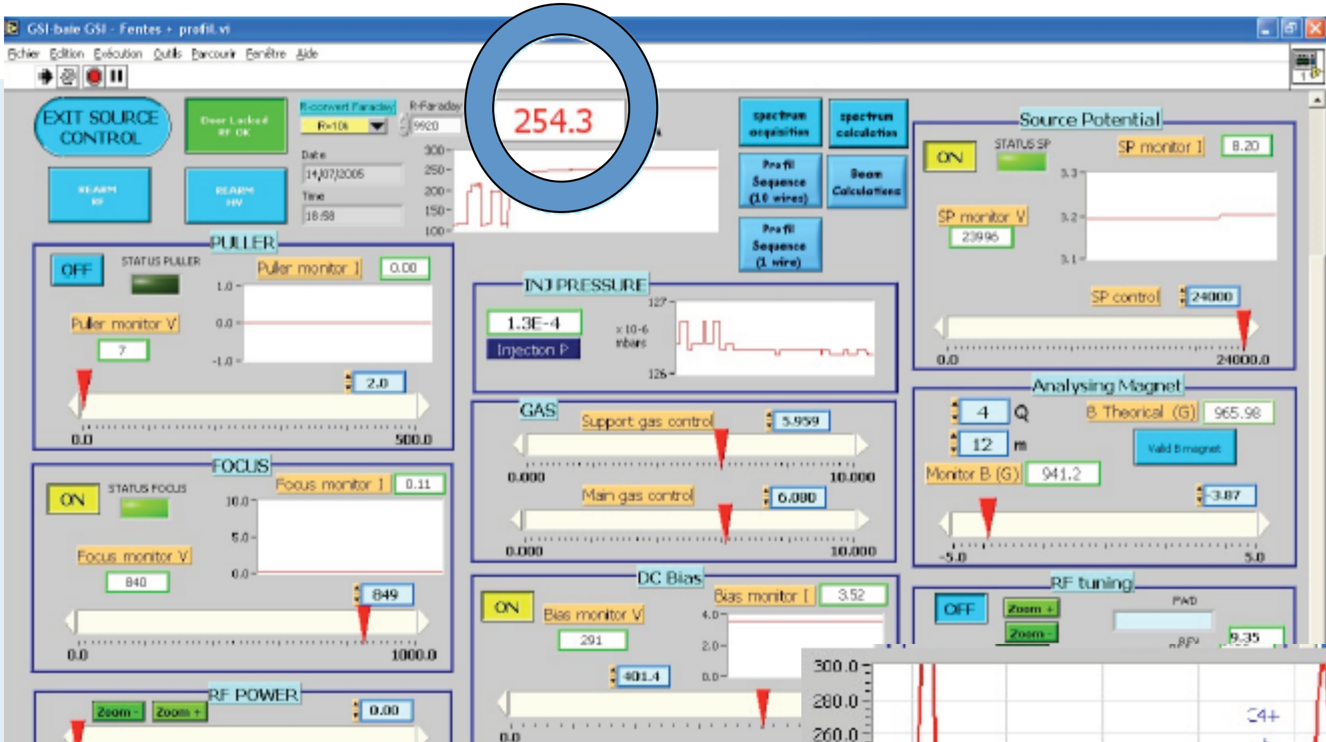
Trend of the analyzed C^{4+} current versus the RF frequency.

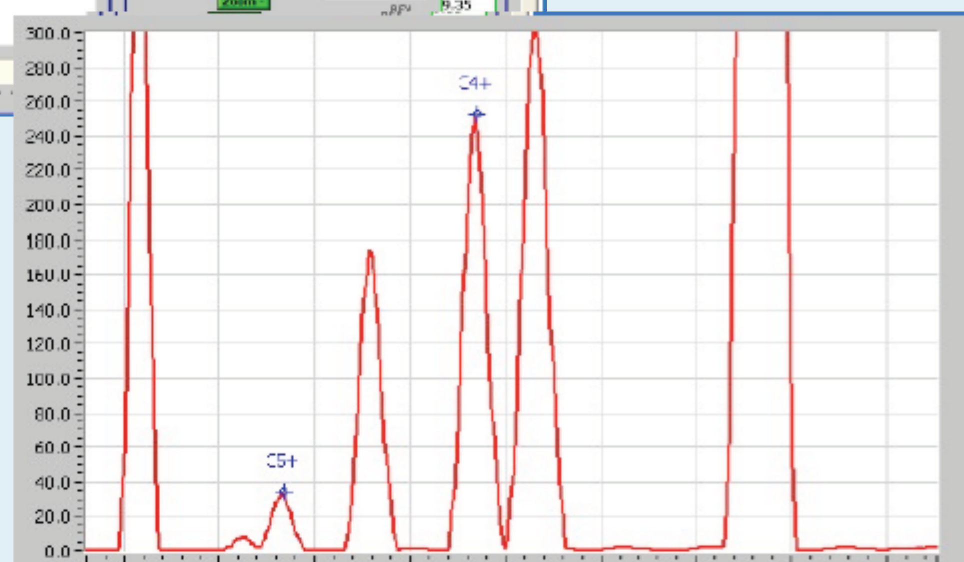
The extracted current is doubled after a frequency shift of 5 MHz

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



Frequency tuning: easy to be implemented





For C^{4+} the current provided by SuperNanogan was increased from 200 μA to 250 μA thanks to the frequency tuning (even better improvements obtained with H_3^+)

Sources currents and emittances

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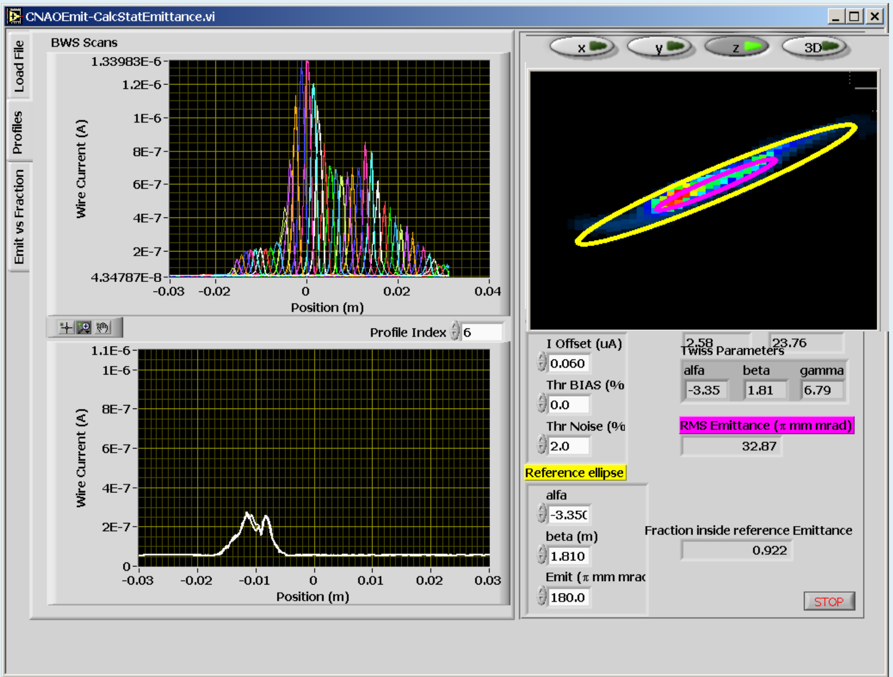
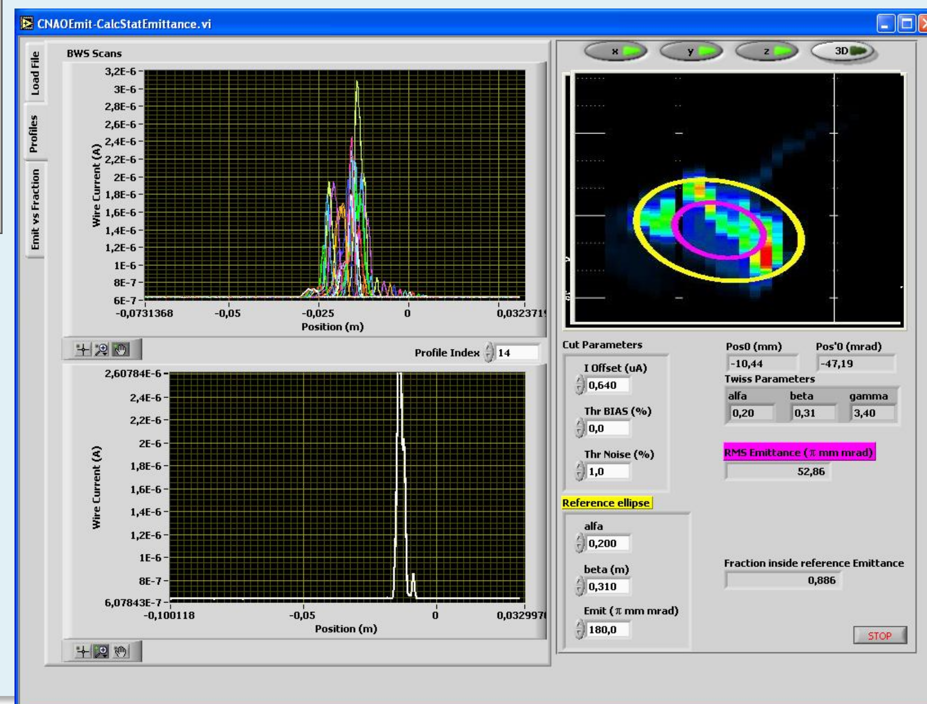


H_3^+, 1.4mA
(design =800 μA)

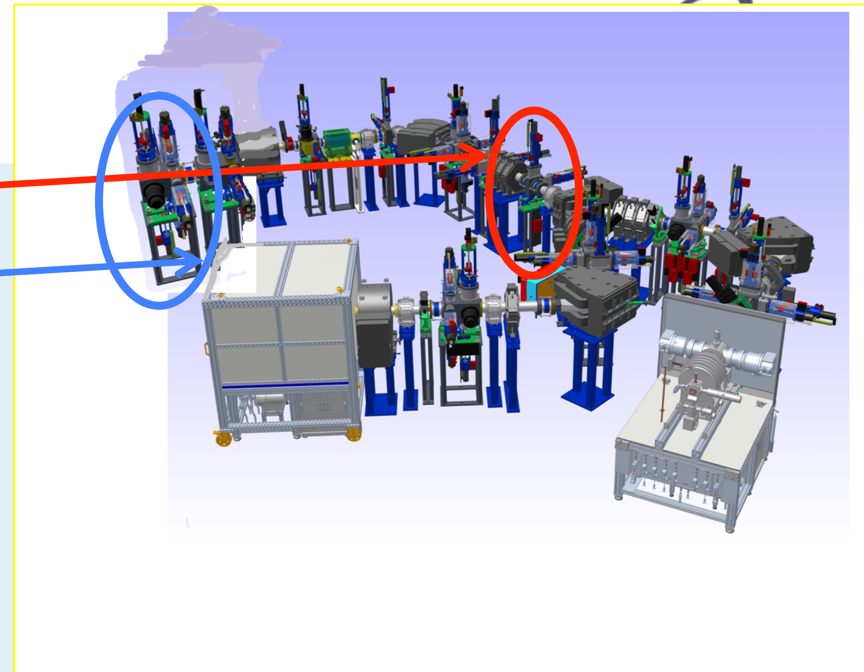
Emittance measured after spectrometer



C^{4+}, 250 μA
(design = 200 μA)

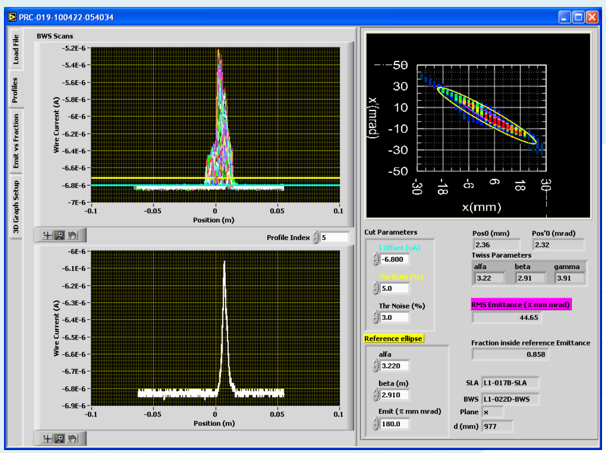
LEBT

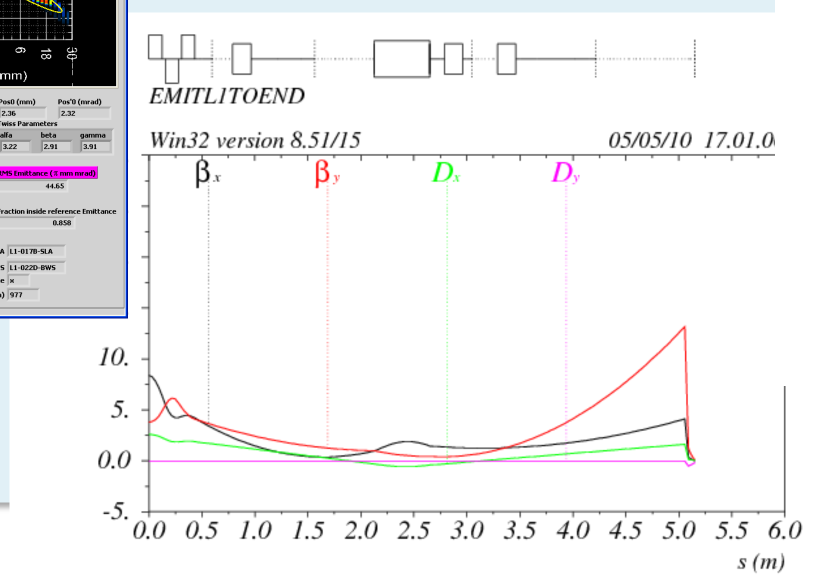
Diagnostic tanks containing
slits, wirescanners, faraday cups
Along the line + TB0

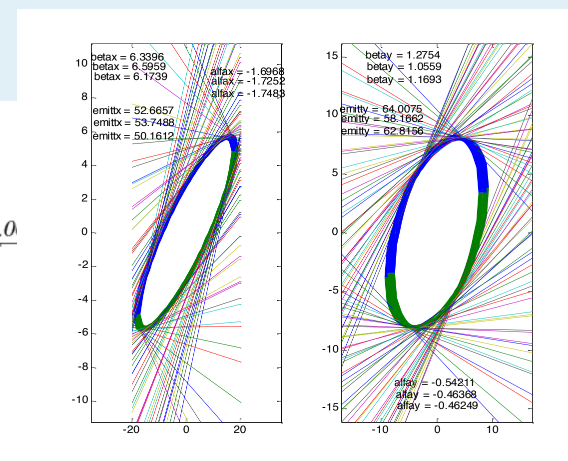


Emittance and Twiss Parameters measurementns

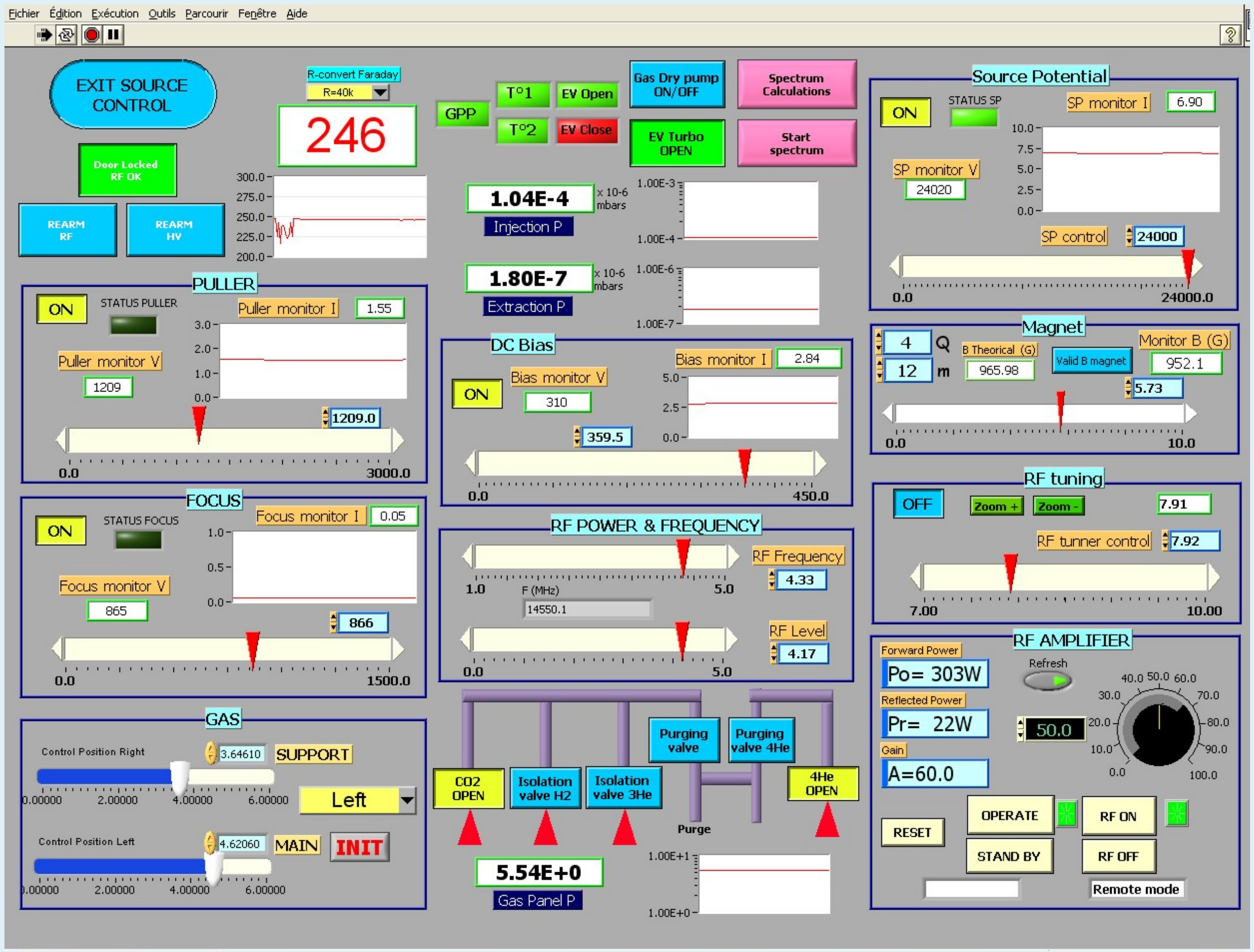
- With tank diagnostics
- With Quad scans
- Model Agreement better than ± 10%



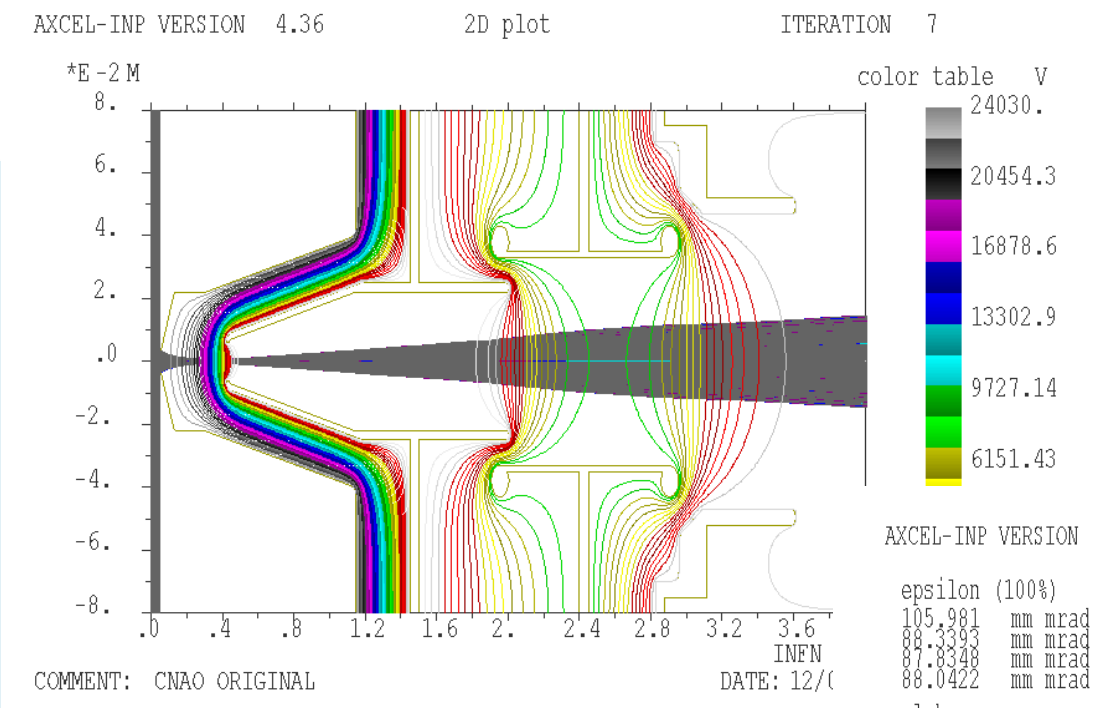


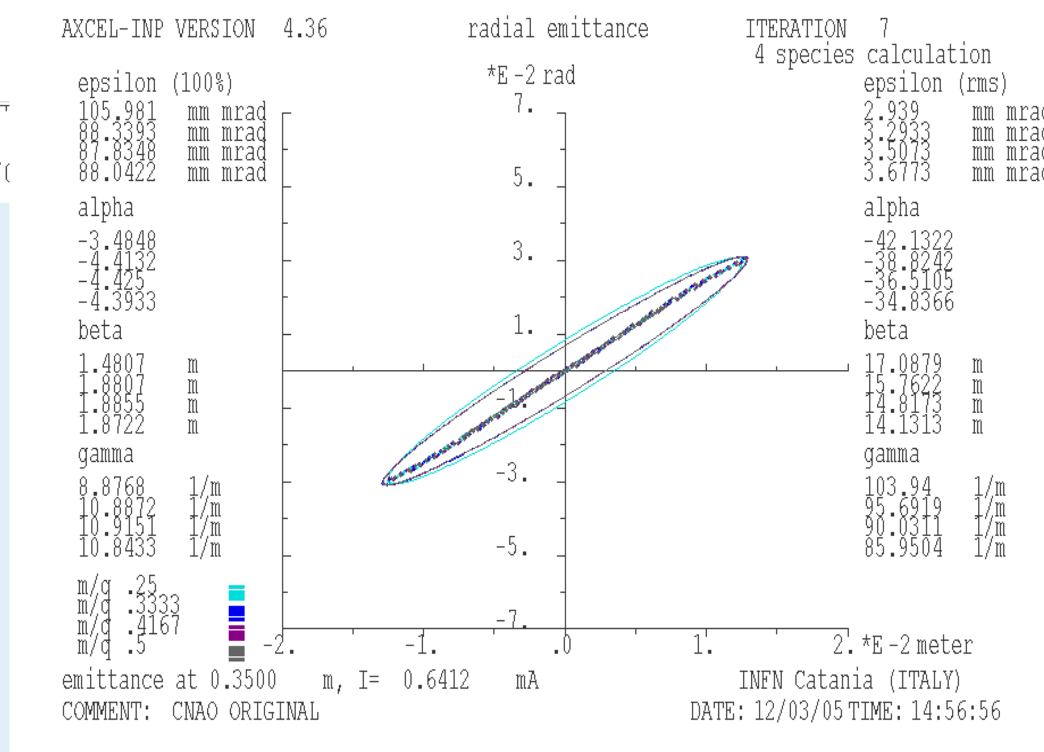


Easy control from operators (even non-PhD educated)

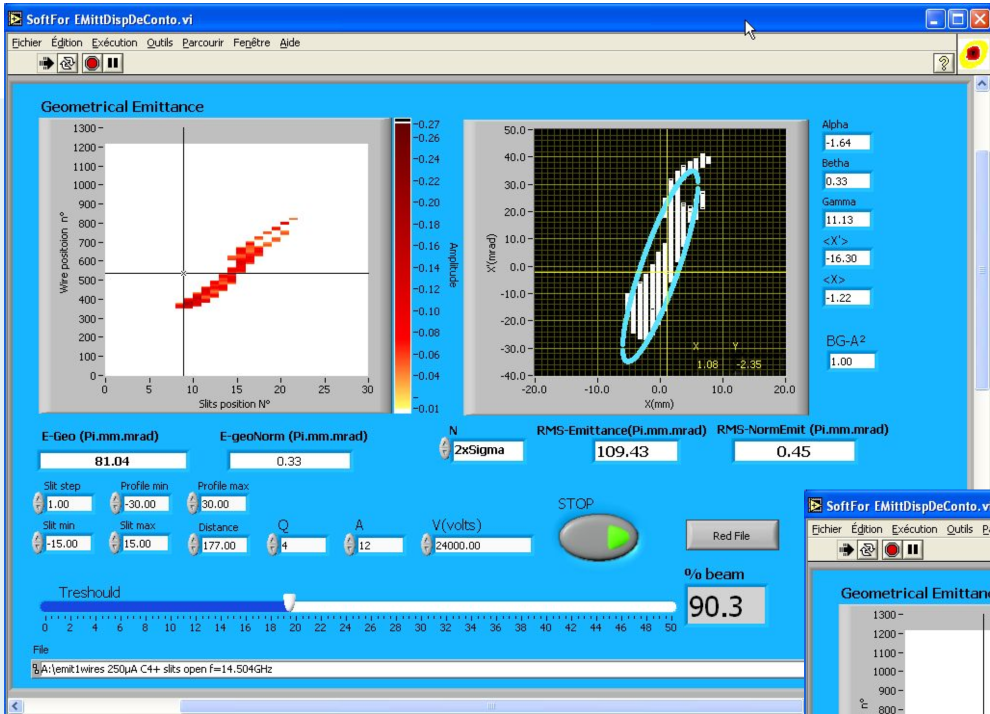


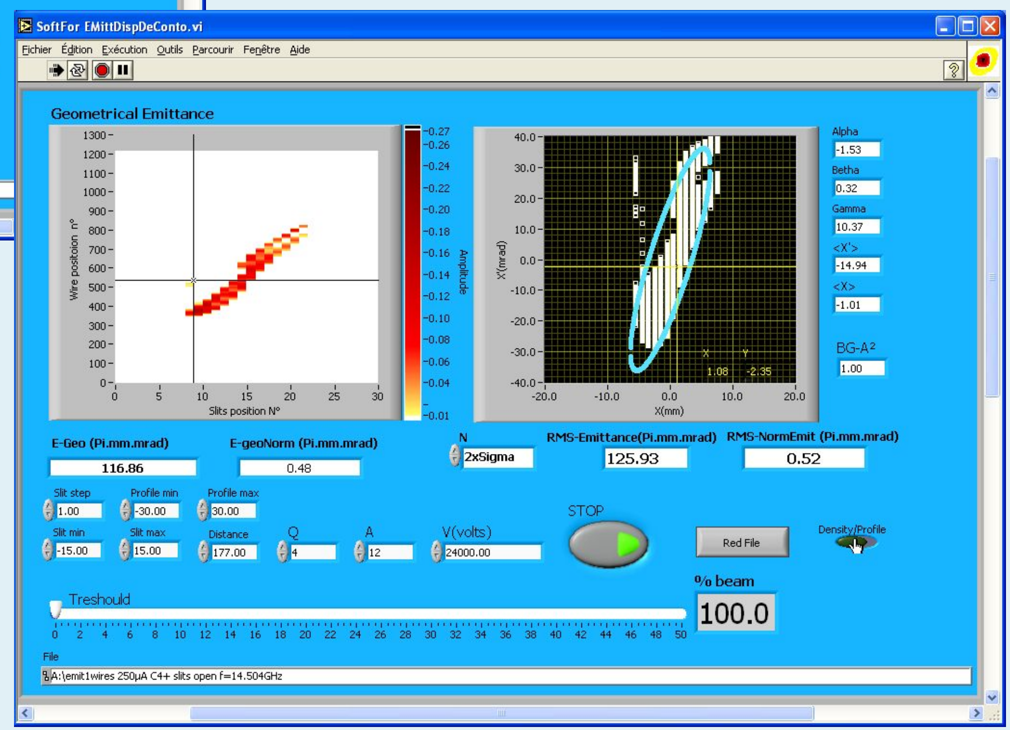
Control panel during C^{4+} tests





The simulations of the new extraction system installed in the SUPERNANOGAN source build for CNAO.





The emittance for the above case was good, 0.52π for 100% and 0.45π for 90% of the beam.

Reproducibility, stability issues not only for the current but also for the emittance

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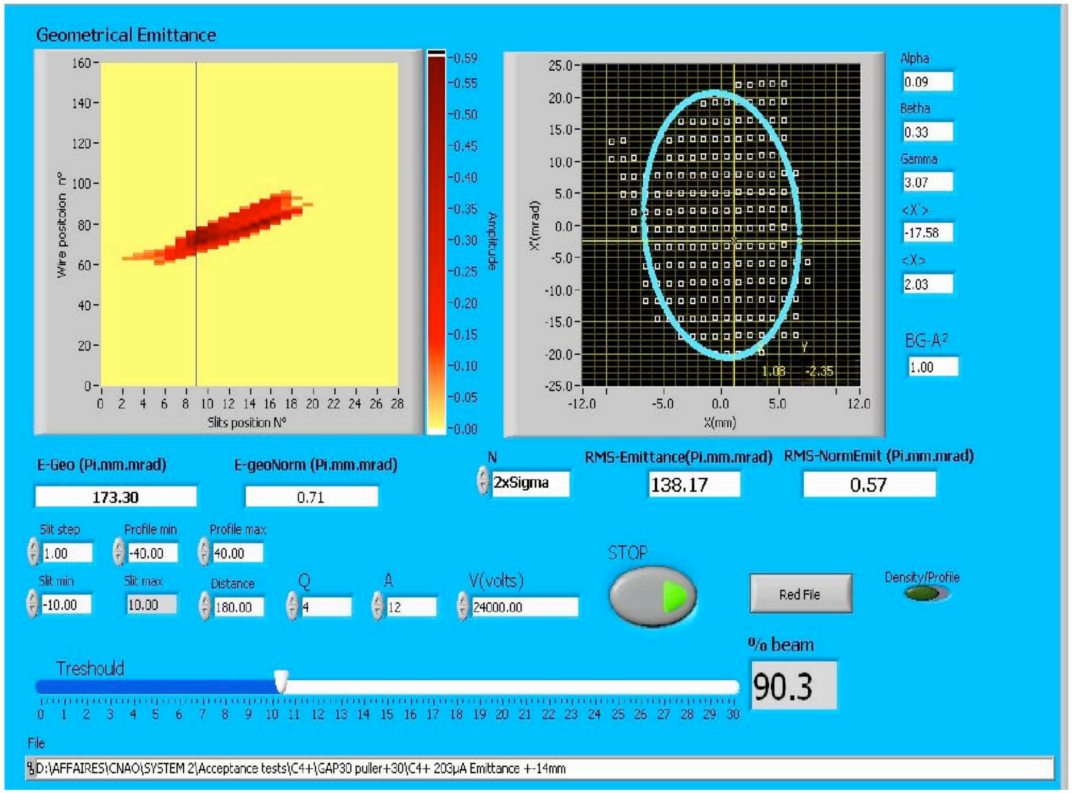


Figure 36: $12C^{4+}$ Emittance with the new gap.

Emittance for a typical C^{4+} beam

ECR Ion Sources

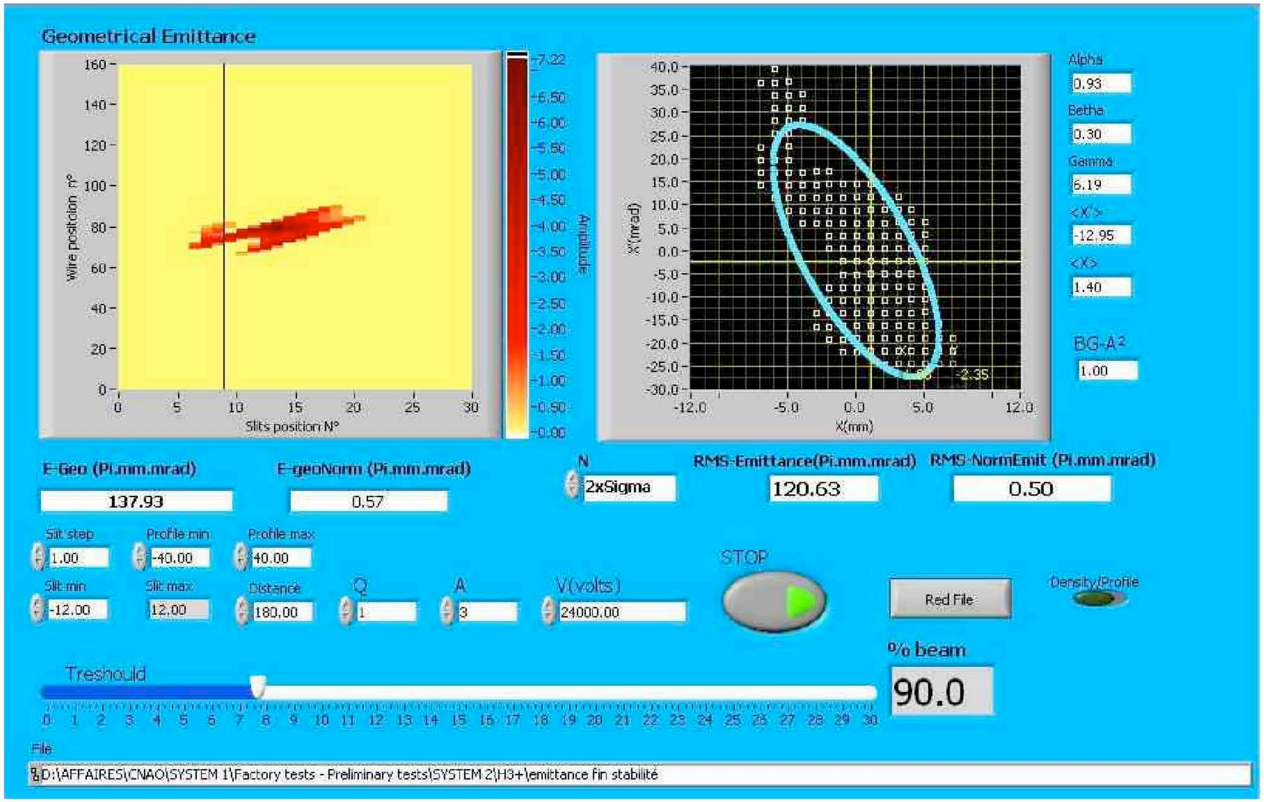


Figure 52: H_3^+ emittance at the end.

Emittance for a typical H_3^+ beam

ECR Ion Sources

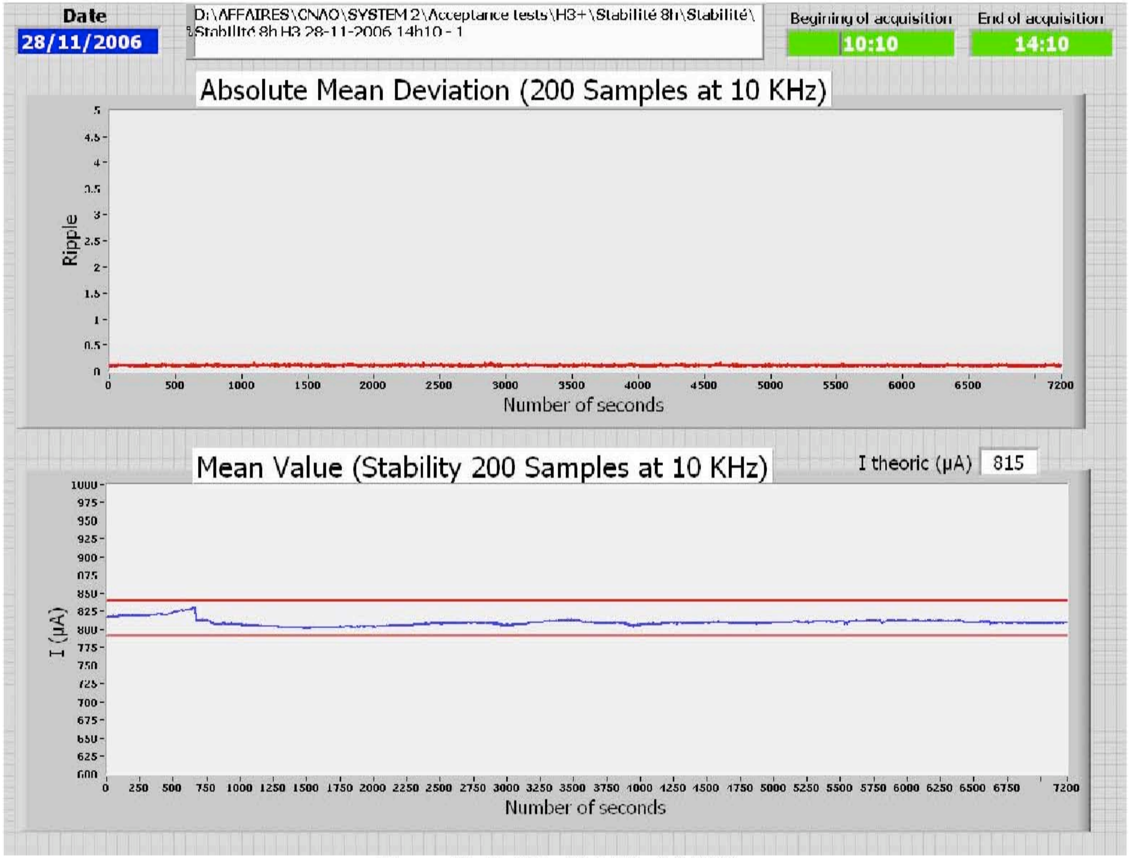
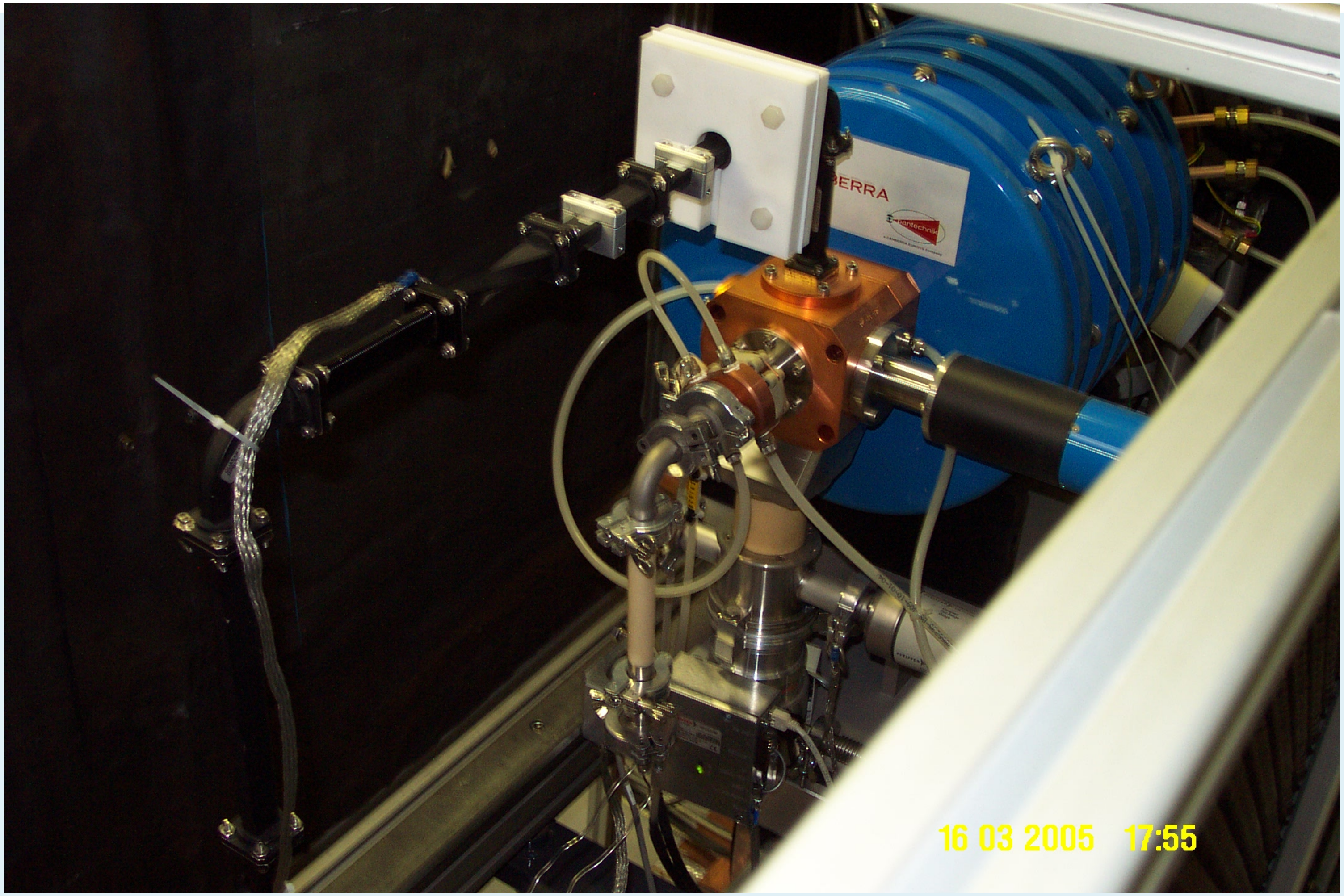


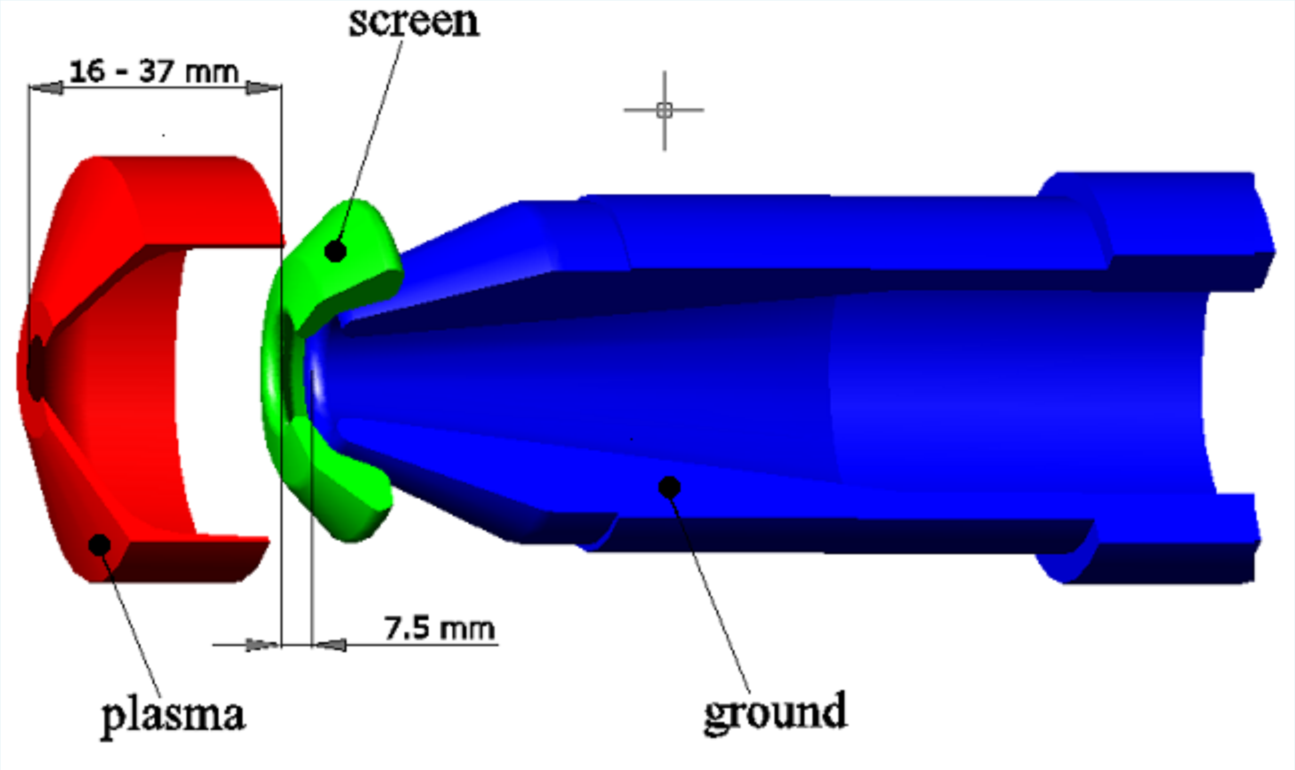
Figure 46: H_3^+ 8h: Stability 0→7200s.

Stability test for H_3^+

Technical limits

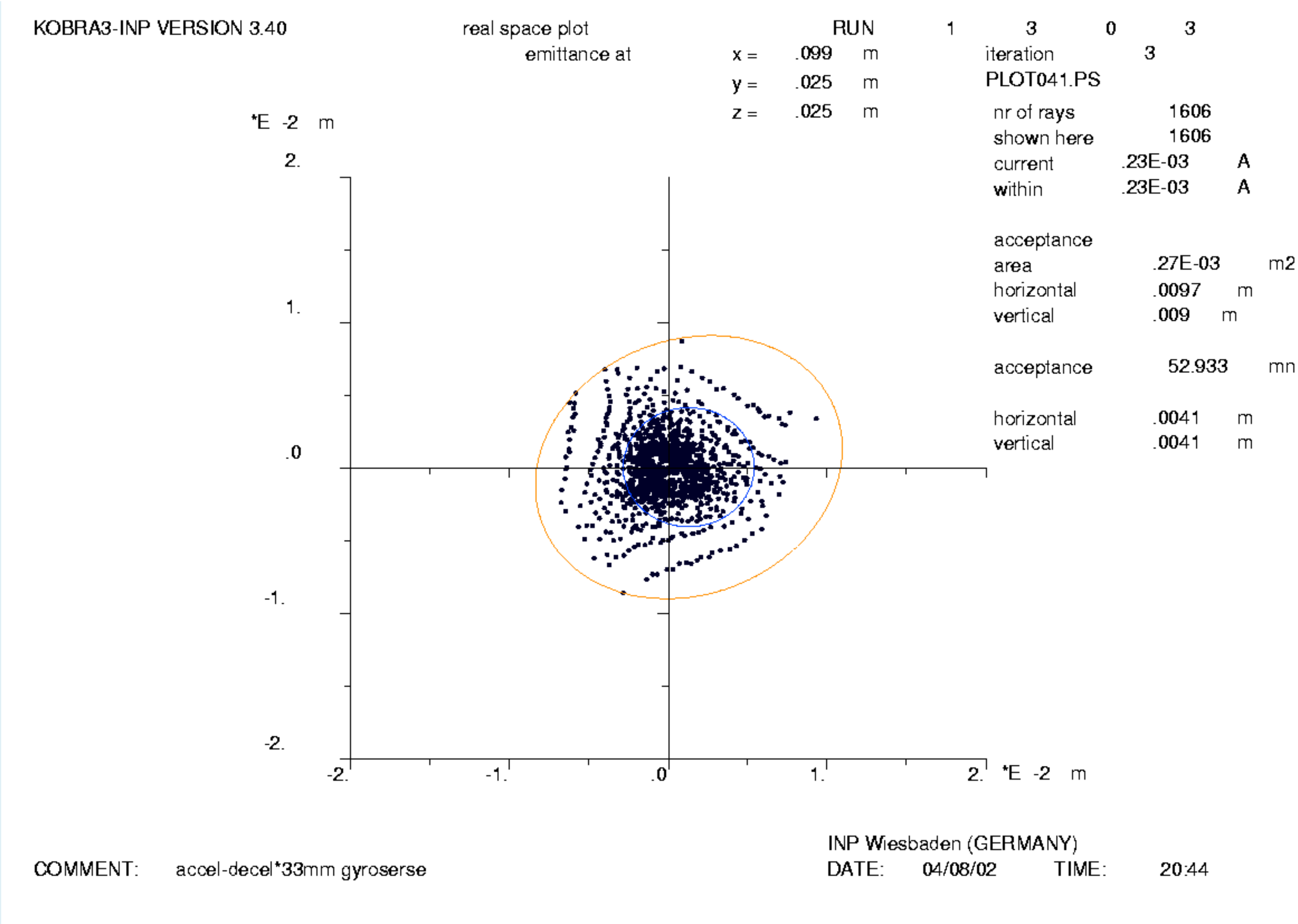


SUPERNANOGAN with RF injection



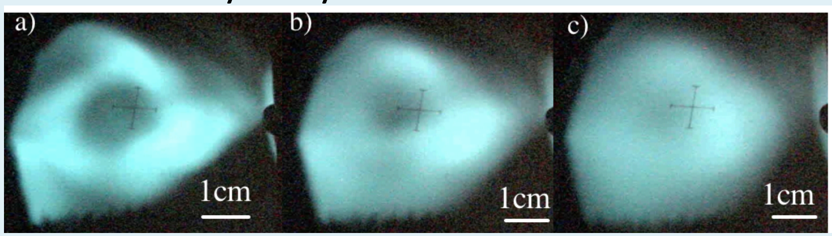
Accel-decel extraction needs to be improved

Evidence of hexapolar field effect

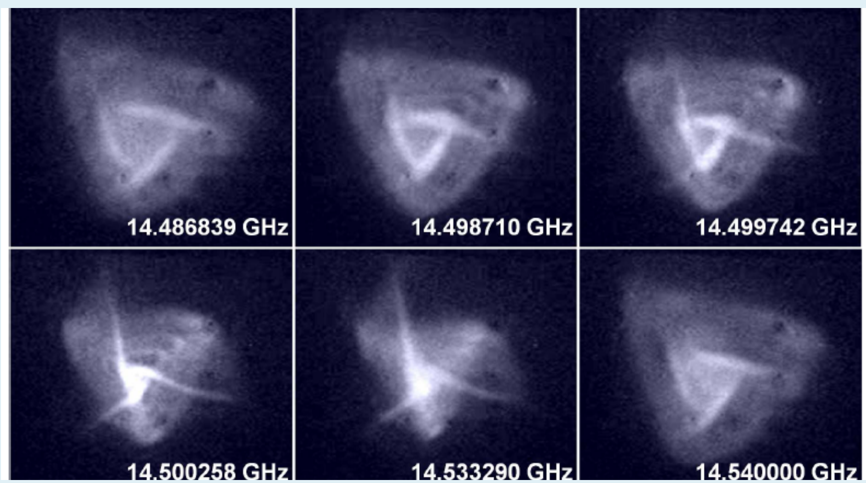


Huge impact of FTE on ion dynamics and beam formation

Jyvaskyla ECRIS

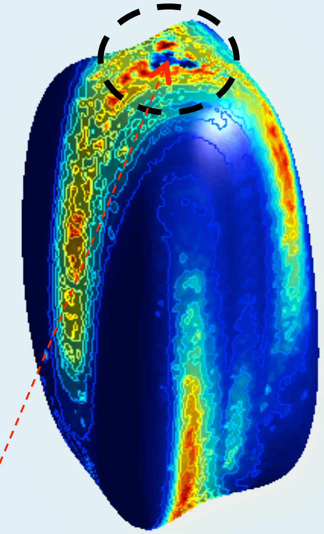


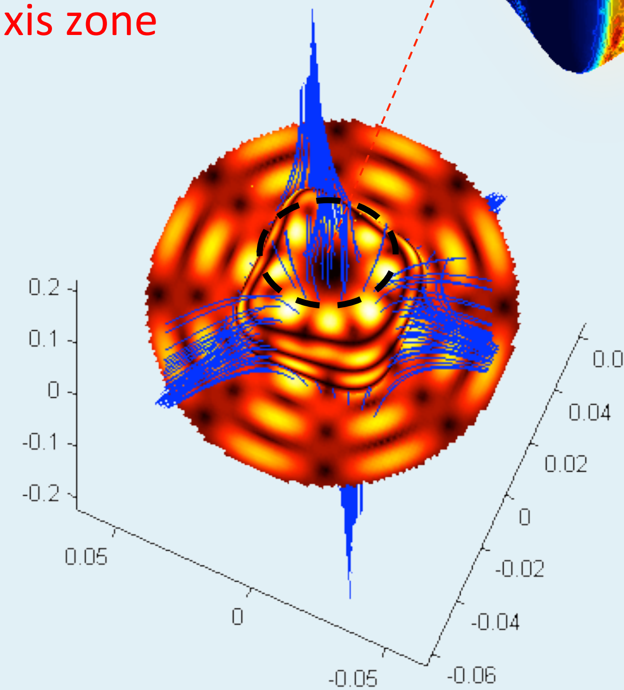
GSI-ECRIS (CAPRICE)



Hollow beam formation is a common feature of most of ECRIS.
Transversal beam shape confirms ions are magnetized in outer plasmoid region

Near axis density depletion takes place because of low EM field. Most of the resonant modes at f>10GHz exhibit holes in near axis zone





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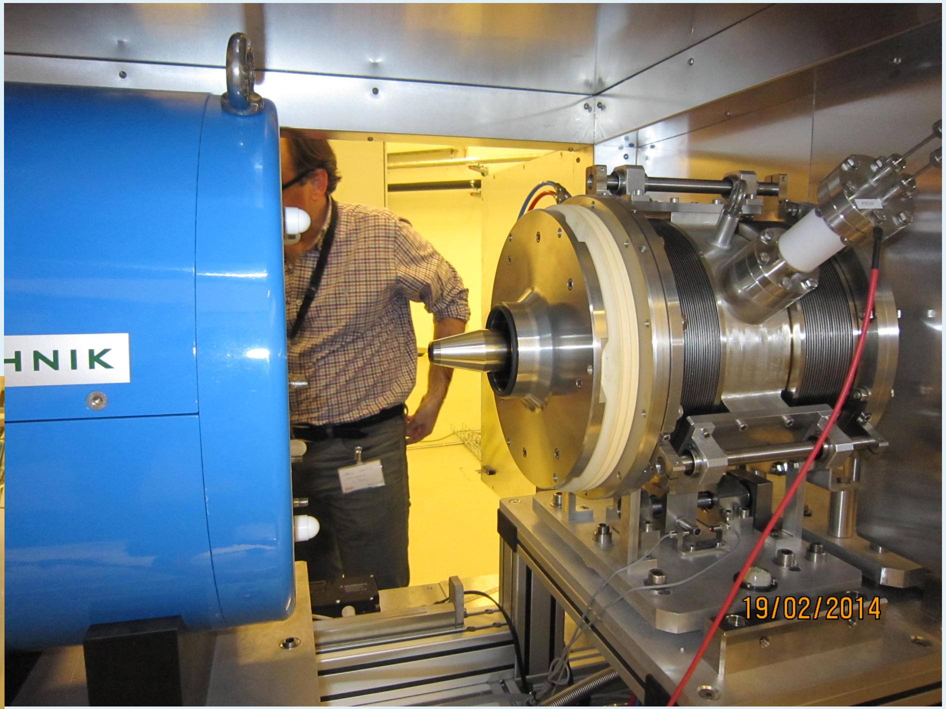
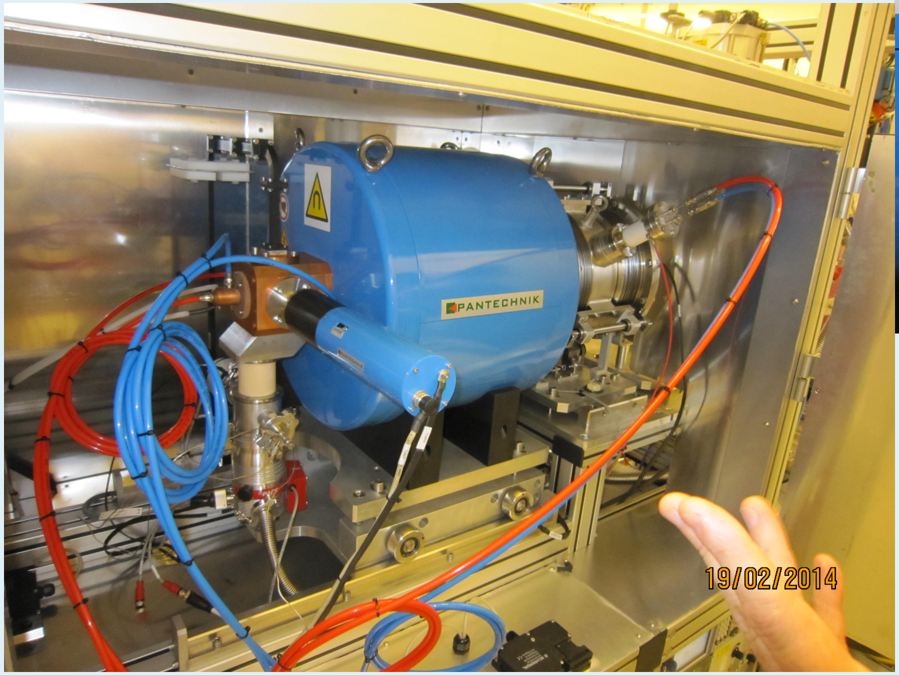
Sources for Med-Austron





Next step: AISHa

Advanced Ion Source for Hadrontherapy

CNAO SUPERNANOGAN PRO/CONS

- Very simple source with just a few parameters to set, important for installation in hospital environment.
- Currents limited by the limited power sustainable and from the rigid magnetic field structure.
- Lack of space in extraction to further optimize the extraction system
- Metal beams not available

AISHA
Advanced Ion Source for HAdrontherapy

- AISHA is a hybrid ECRIS: the radial confining field is obtained by means of a permanent magnet hexapole, while the axial field is obtained with a set of four superconducting coils.
- The **superconducting system will be Helium-free** at 4.2 °K, by using two cryocoolers.
- The magnetic field values are following the scaling laws (R. Geller) and the High-B-mode concept (G.Ciavola & S.Gammino), experimentally validated in ’90s at INFN-LNS and at MSU-NSCL.
- The **operating frequency of 18 GHz has been chosen** to maximize the plasma density taking into account the availability of commercial microwave tubes and the **specificity of the installation in a hospital** environments.
- The electric insulation is chosen to be 40 kV, for daily operation above 30kV.

AISHA
Advanced Ion Source for HAdrontherapy

- The set of four superconducting coils independently energized will permit to realize a ***flexible magnetic trap***, which is fundamental to study alternative heating schemes based on Bernstein waves excitation and heating in sub-harmonics.

- The use of a ***broadband microwave generator*** able to provide signal with complex spectrum content, will permit to efficiently tune the frequency increasing the electron density and therefore the performance in terms of current and average charge state produced.

- The experimental activity will be reinforced by ***numerical simulations*** to deeply understand the plasma heating in different conditions.

AISHA
Advanced Ion Source for HAdrontherapy

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- An adequate ***extraction system*** takes into account the production of high current and high charge states. The project will benefit of the experience gained with the design of high intensity sources (TRIPS, VIS, ESS).

- The chamber dimension and the injection system have been designed in order to ***optimize the microwave coupling*** to the plasma chamber taking into account the need of space to house the ***oven for metallic ion*** beam production.

- ***GOAL : 3 times more current than SUPERNANOGAN***

- ***Same emittance, reliability, stability***

- ***Possibility to produce metallic ion beams***

AISHA design features

Radial field	1.3 T
Axial field	2.6 T - 0.4 T - 1.5 T
Operating frequencies	18 GHz (TFH)
Operating power	1kW
Extraction voltage	40 kV
Chamber diameter / length	Ø 92 mm / 300 mm
LHe	Free
Iron yoke diameter/length	42 cm / 60 cm
Source weight estimation	480 kg

AISHA assembly

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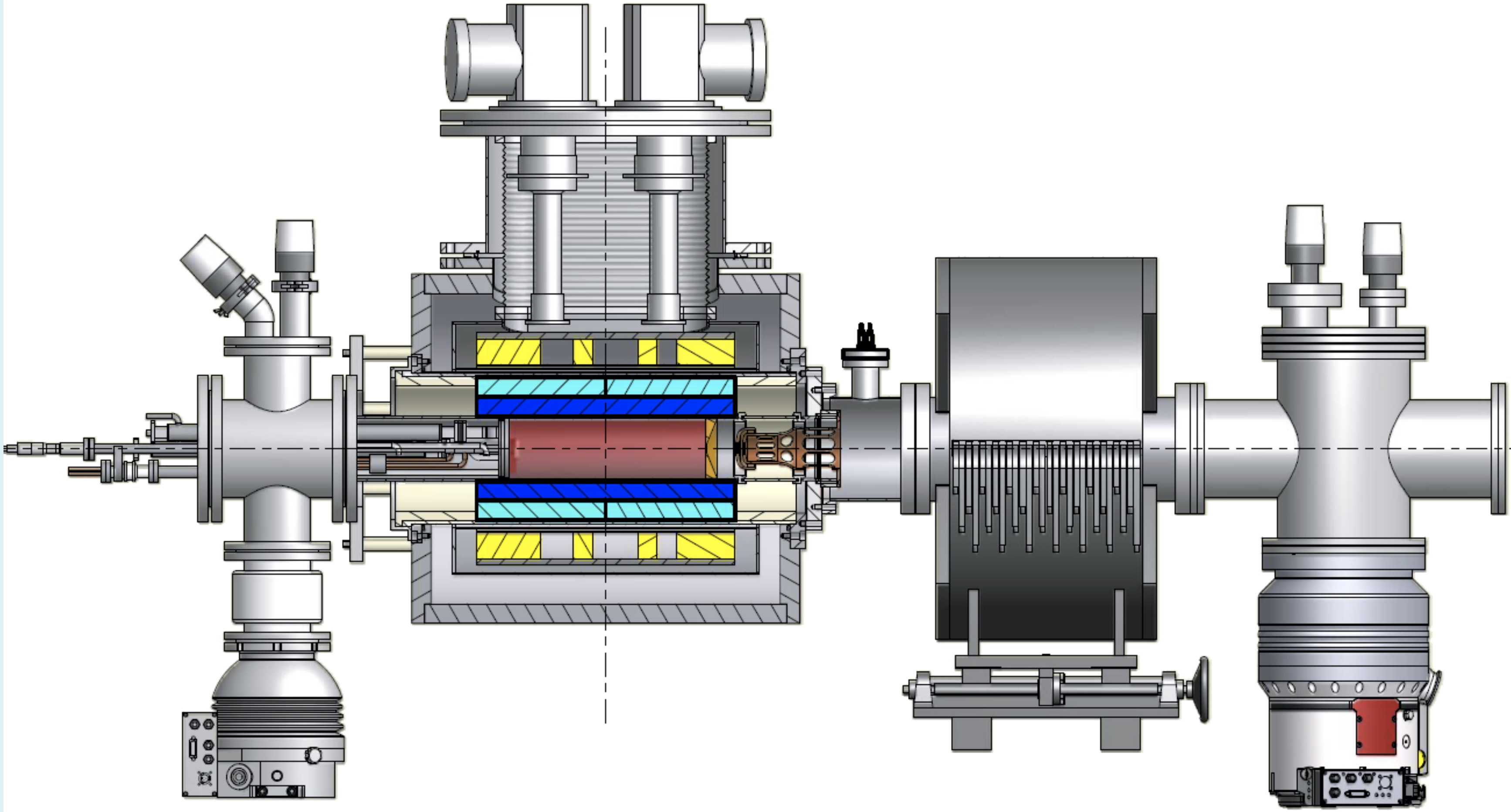
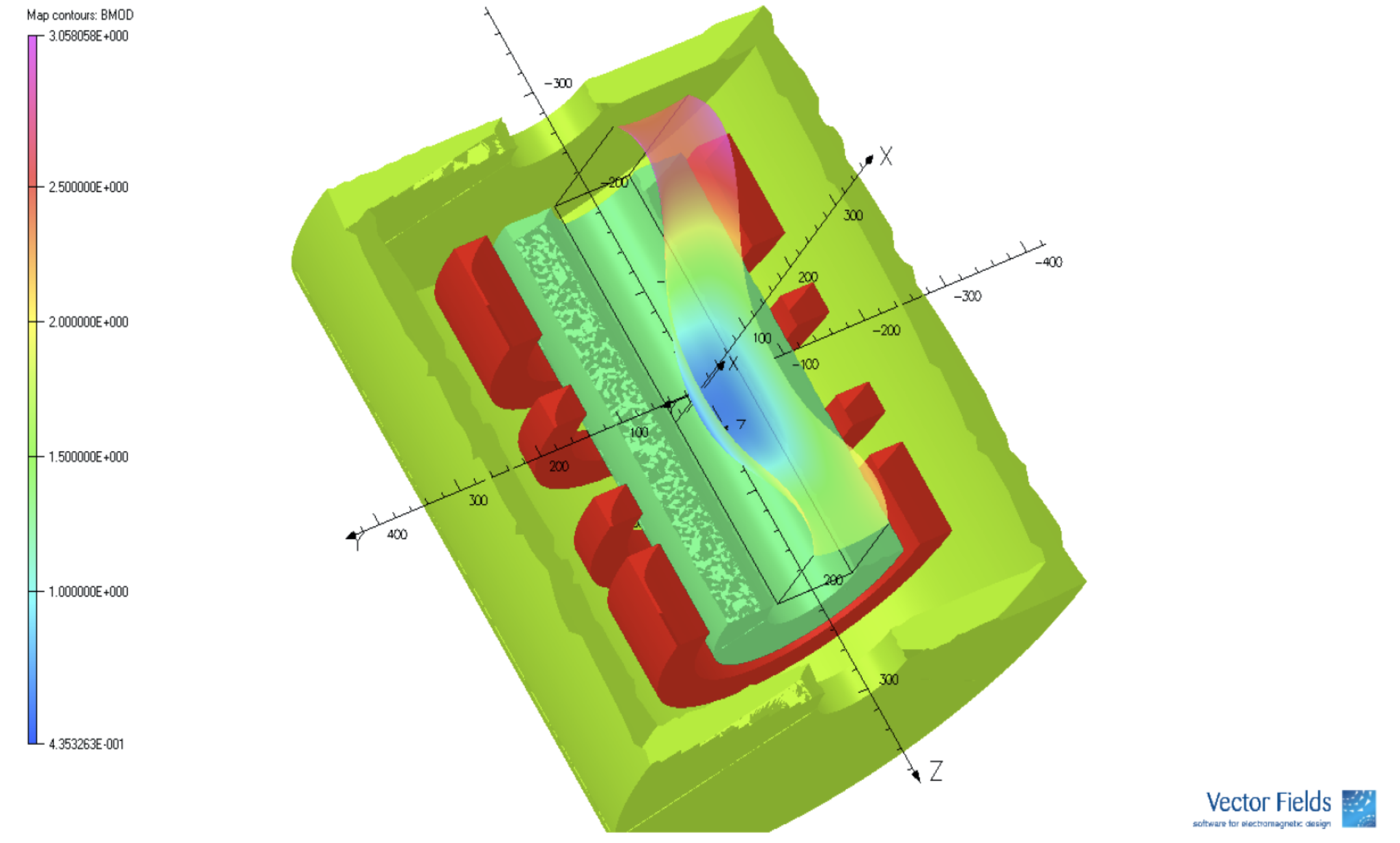


AISHA entire magnetic system



Ion sources for hadron therapy

- ✓ Ion sources satisfy the current accelerators' requirements
- ✓ Room for improvements is available
- ✓ Either in Europe and Japan there are interesting developments

Ideal ion source for isotope production must have:

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

Los Alamos Neutron Science Center (LANSCE)

800 MeV linear accelerator and proton storage ring

Isotope production facility

Proton radiography

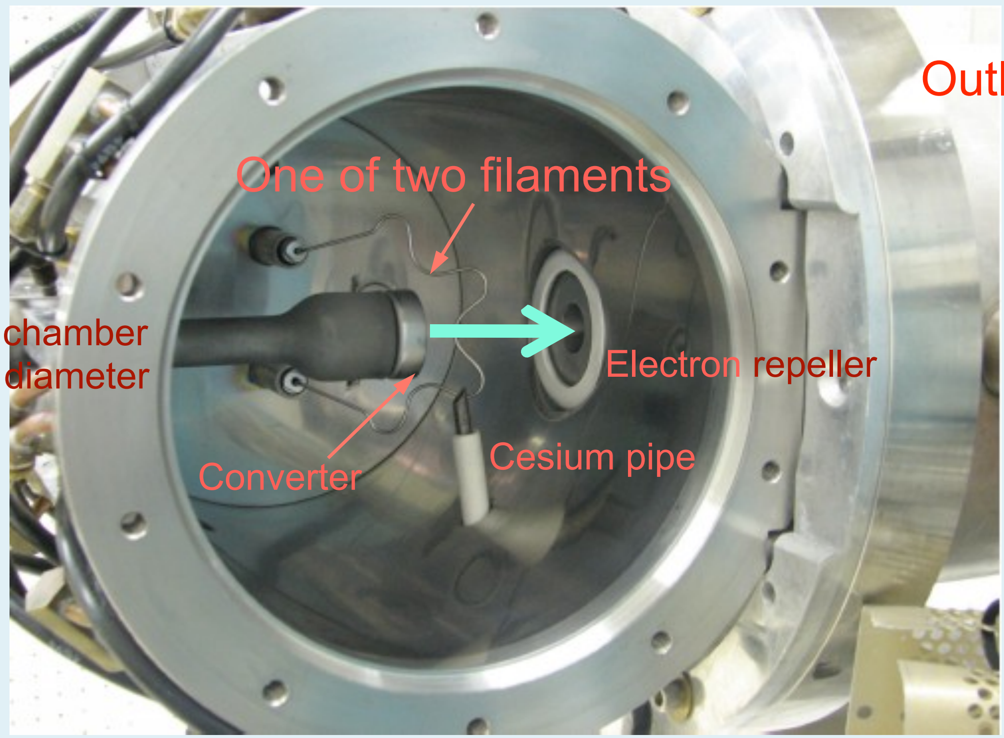
Lujan center (neutron scattering)

Weapons neutron research

Ultra-cold neutrons & Materials test station

Standard H⁻ ion source at Los Alamos Neutron Science Center (LANSCE)

- Charge-exchange injection into PSR accumulator ring at 800-MeV energy
- Multi-cusp discharge chamber
- Cesiated, biased converter for ion production



Negative (H^-) ion source at LANSCE

Beam current	16-18 mA (up to 30-40 mA)
Duty factor	6 %,1 ms pulses @ 60 (up to 12 %, 120Hz in future)
e/H^- ratio	< 5
Emittance	< 0.25 πmmmrad (95 % norm. rms)
Time-between-services	> 4 weeks (up to months)

H^- ion source development strategy at LANSCE

- Gradual development of the filament-driven surface conversion ion source
- Program for studying the feasibility of RF-driven ion sources for LANSCE linac
  - Helicon ion source development at LANSCE
- Other ion source options (HYBRIS-concept and ECR-driven surface conversion ion source)

Development of the filament-driven surface conversion ion source: Filament properties

- Filament strength and longevity depend on the material grain size
  - Impurities
  - Processing
- Adding 3 % of Rhenium into the Tungsten filaments have been proven to enhance the material properties (grain size → longevity) in other applications

Development of the filament-driven surface conversion ion source

- Improvement of the filament material
  - Longer lifetime @ the same performance level OR
  - Higher performance (current) @ the same lifetime
- Improvement of the source temperature control
  - Higher performance (current) BUT
  - Effect on the lifetime still unknown
- Improvements in beam current allow us to reduce the size of the extraction aperture
  - Lower emittance

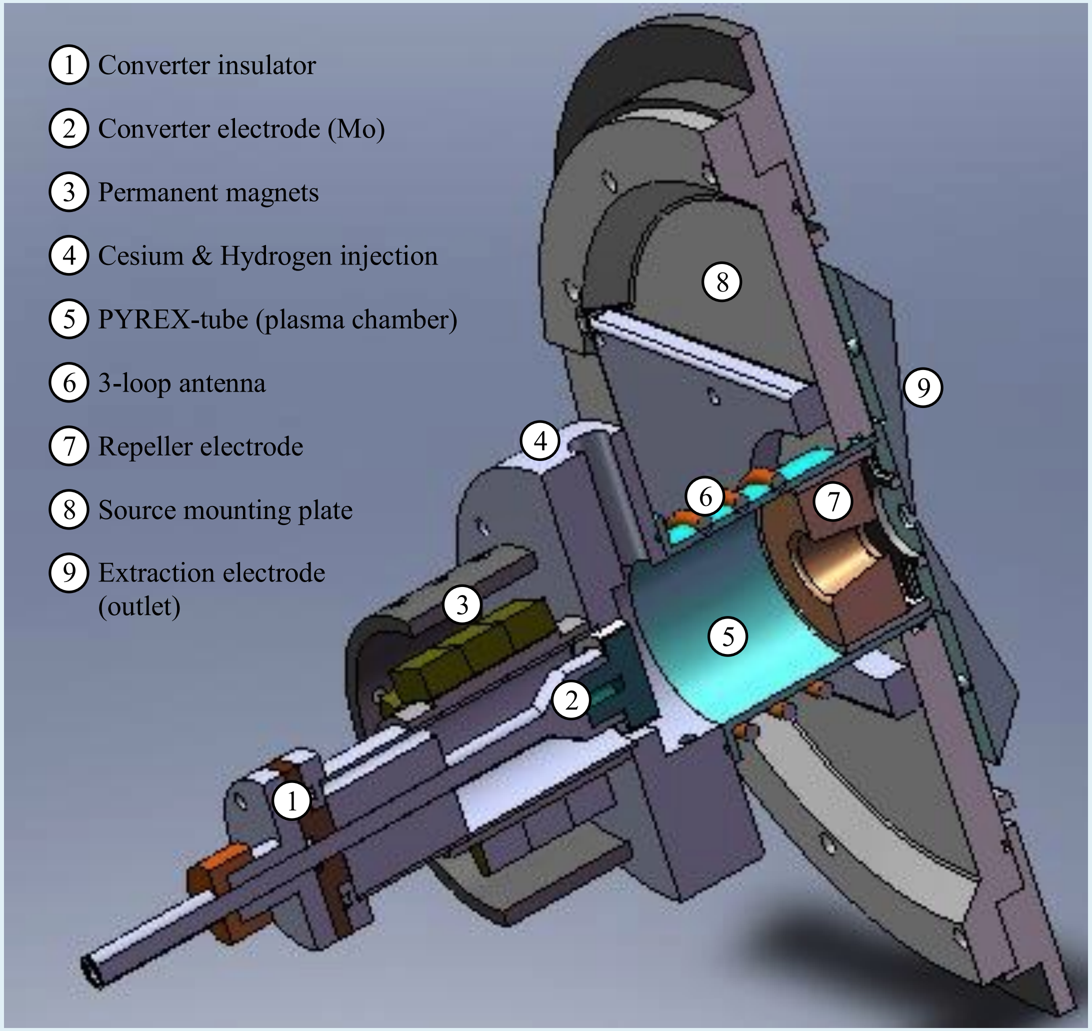
Development program for RF-driven H^- ion source(s)

- Why RF-driven sources
  - Long lifetime with external antenna
  - Higher plasma density
- Volume vs. surface production?
  - Surface production is more effective and technologically more simple
- Converter-type source or two-stage source with magnetic filter (SNS-type)?
  - Converter-type:

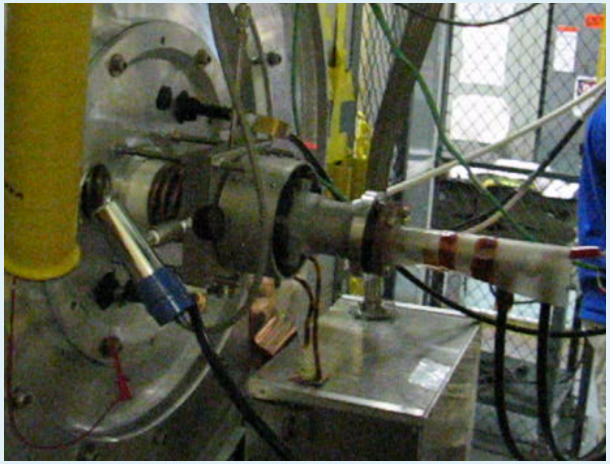
    “self-extracted beam” yields intrinsically lower emittance

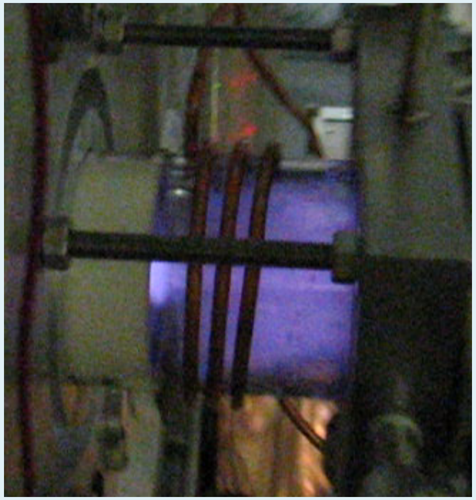
    higher duty factor easily attainable due to lower plasma density requirement (manageable temperature and Cesium control)

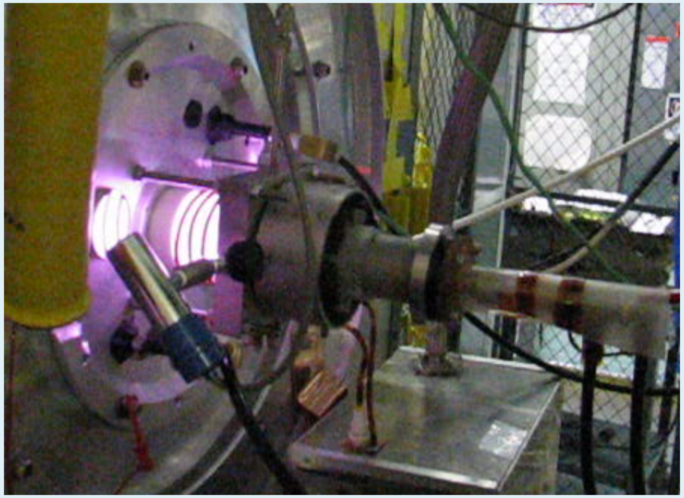
Helicon-driven surface conversion ion source

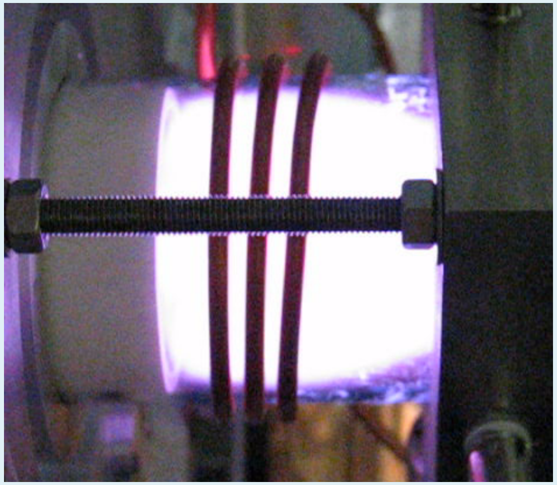


Helicon-driven surface conversion ion source



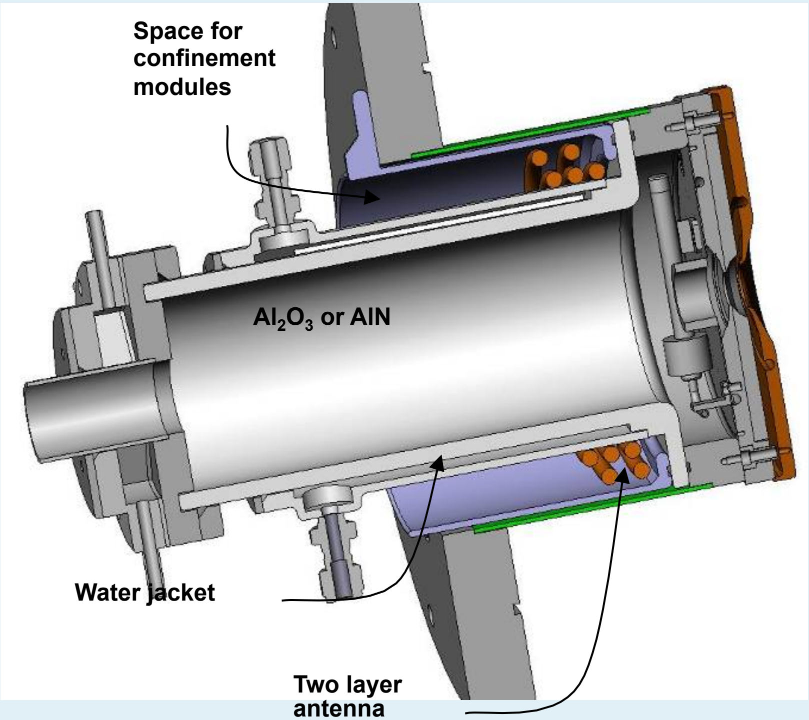






RF-driven H^- sources: Collaboration with SNS

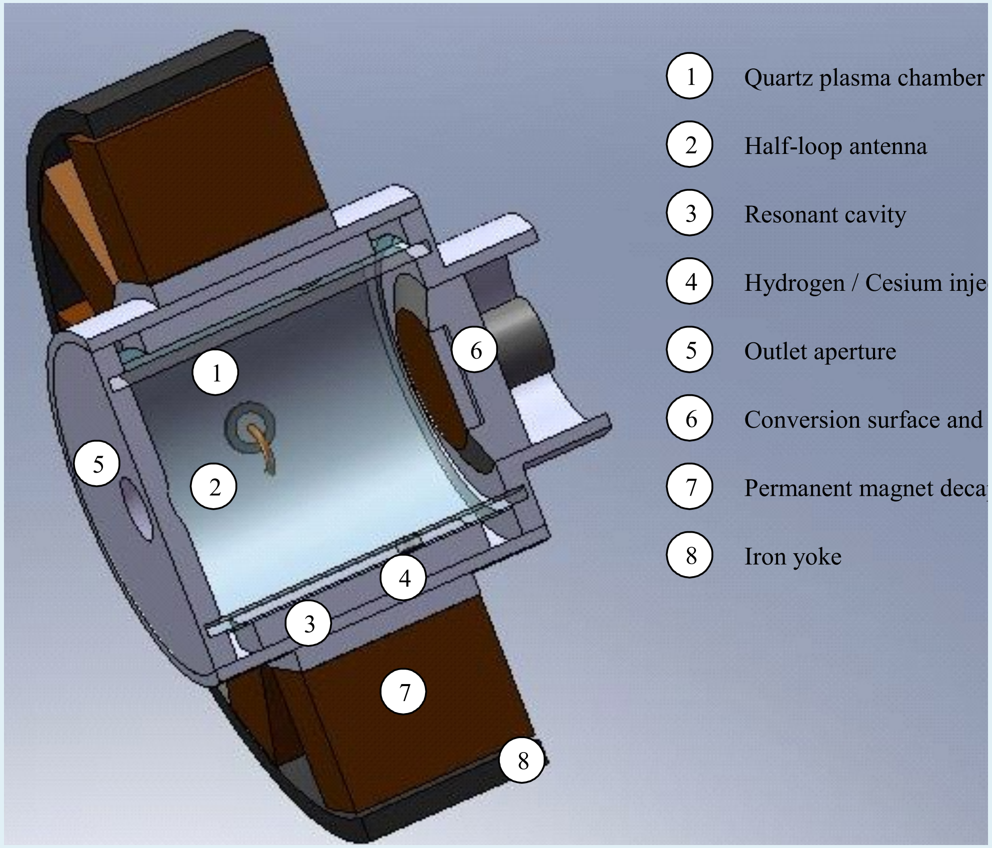
- Performance
  - 40-50 mA @ 5% duty factor (30-50 kW RF-power)
  - Emittance is unknown
- Studies of different plasma confinement techniques
  - Cusp-magnets
  - Solenoid magnet
  - Power density experiments
- Optimizing the power density
  - RF power vs. chamber dimensions
  - Avoid neutral starvation



The figure is courtesy of R.F. Welton, SNS

Other ion source concepts for LANSCE: NECRIS

The neutral pressure seems to be the limiting parameter in the case of the helicon surface converter source → Plasma ignition should be based on resonance → 2.45 GHz ECR heating

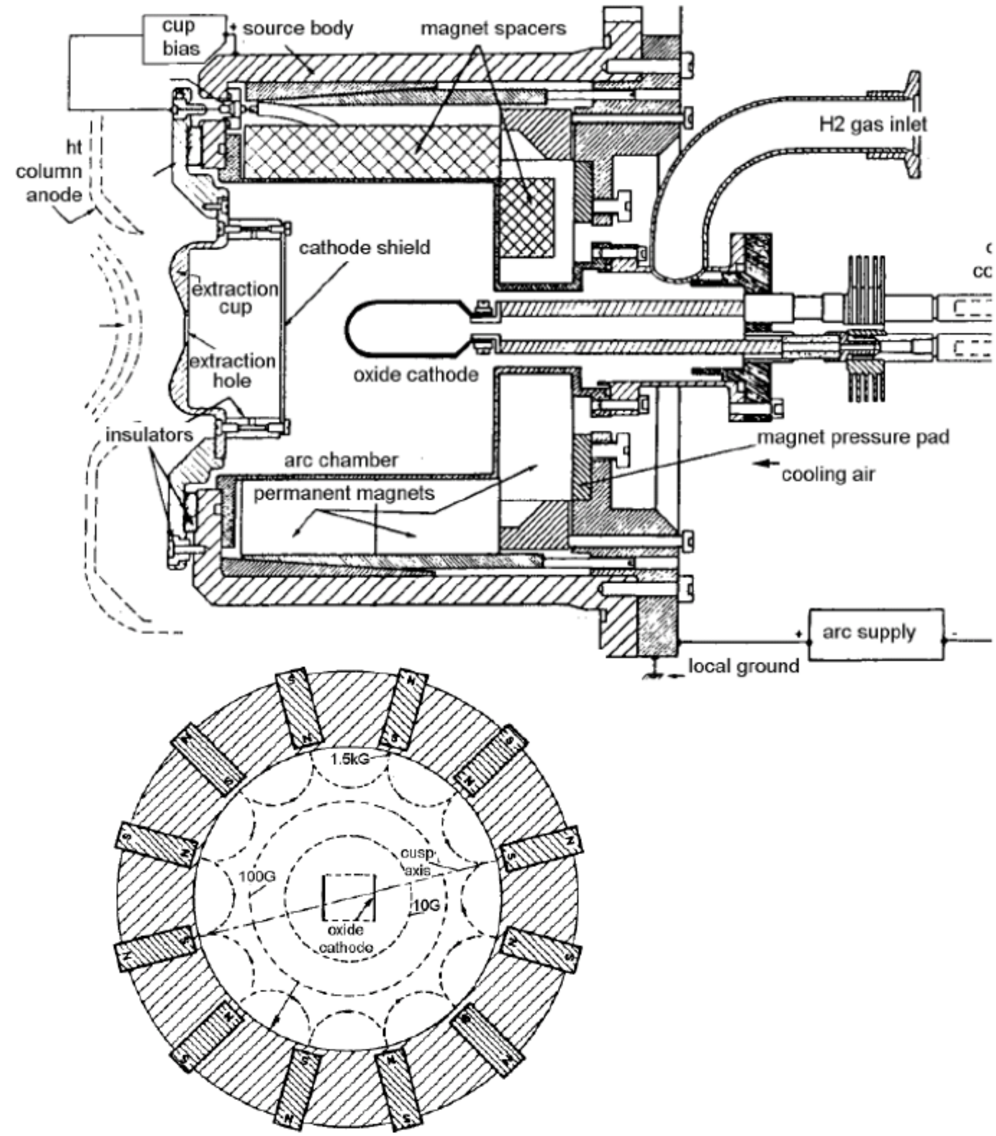


Multicusp sources

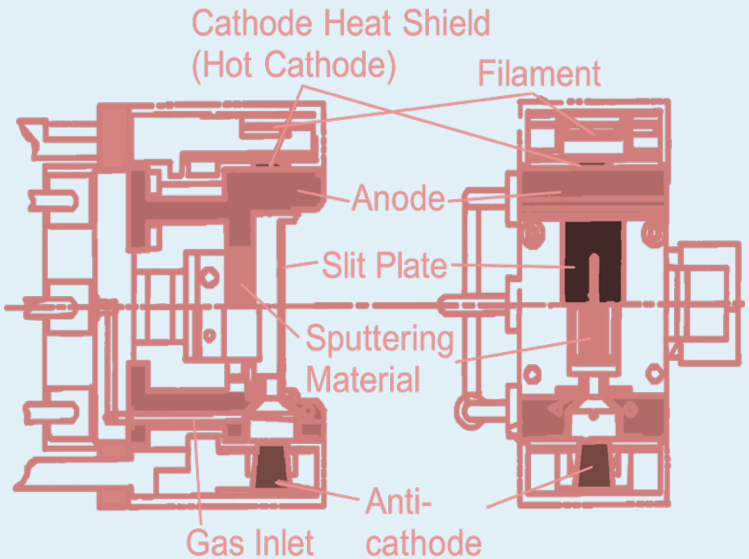
- **Iba: Dual source (internal) to enhance the uptime**

"the global ion source lifetime is greatly extended, the number of maintenance interventions reduced and personnel exposure is further limited"

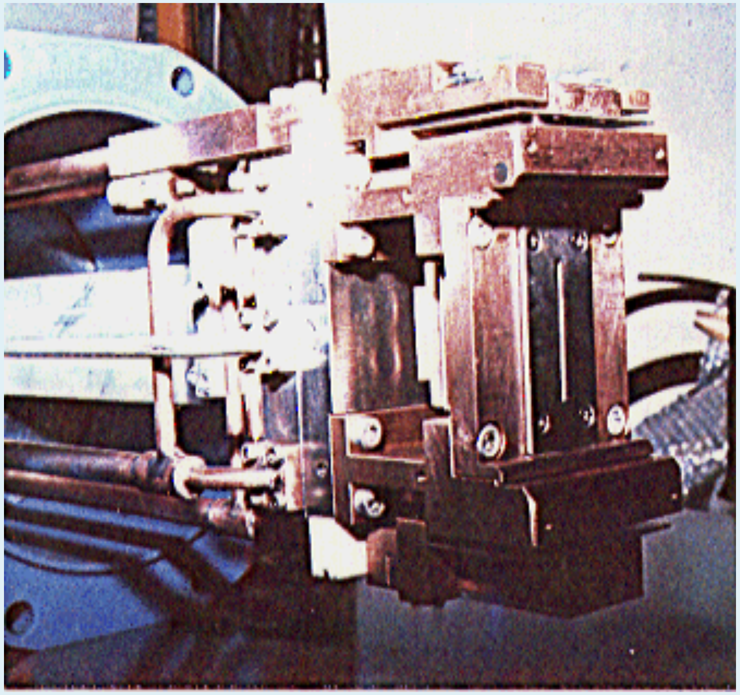
- The negative hydrogen ions are produced by an external multicusp arc discharge ion sources producing an H- beam. This external source is combined with axial injection. The use of an external source avoids the vacuum problems leading to beam losses and activation of cyclotrons with internal sources.
- Maintenance is easier and safer.



PIG ion source



- Feature
  - Indirectly heated cathode type.
  - Very low duty pulsed operation
    - long lifetime (over one week)
    - high intensities for highly charged ions



PIG

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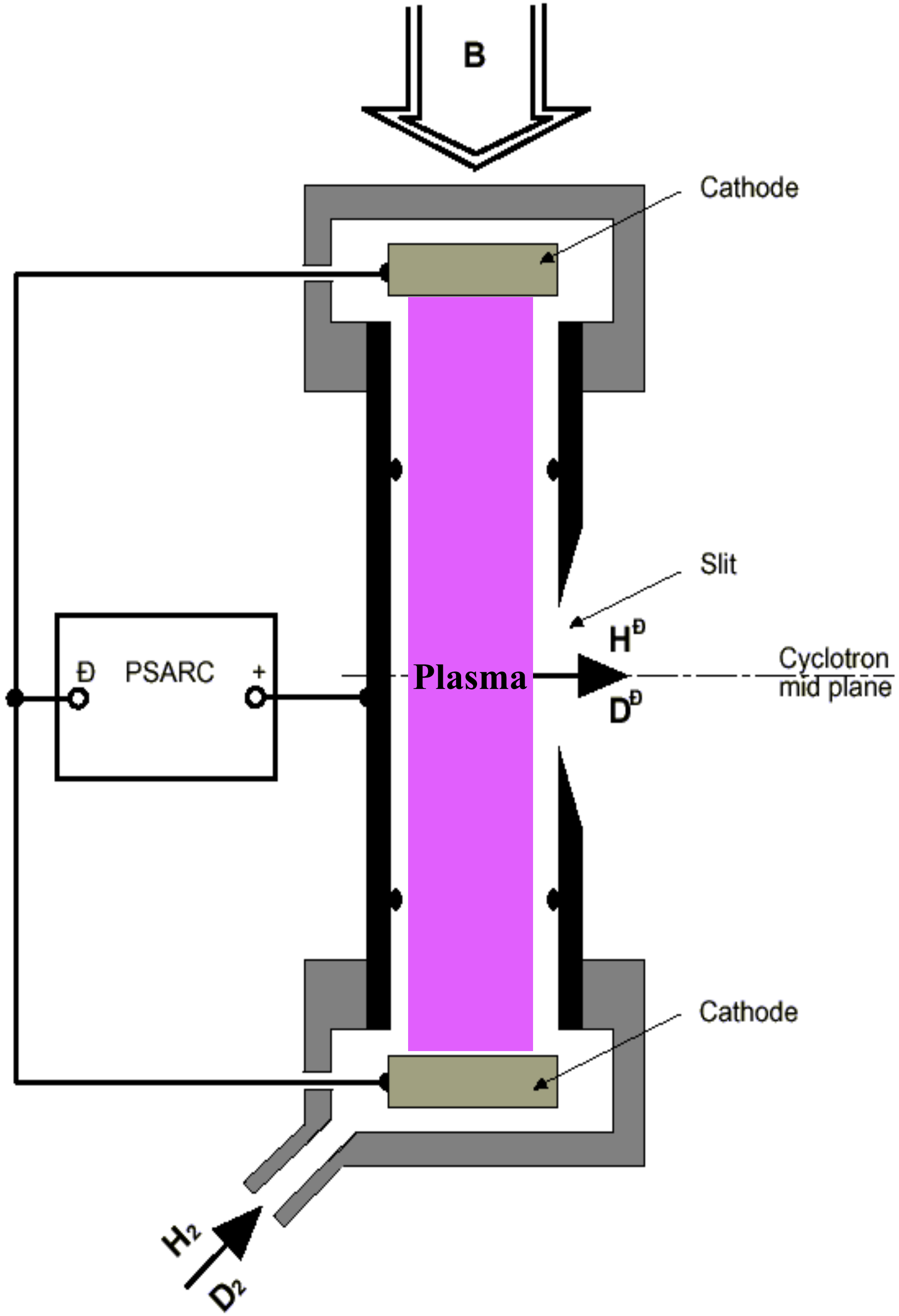

A plasma is built up between the two cathodes

The magnetic field keeps the plasma arc concentrated

The plasma column and the cathodes are put in a closed volume to maintain the gas pressure without loading the cyclotron vacuum system excessively

Ideal ion source for BNCT must have:

- ✓ the necessary beam current (with a margin of 20% or more), i.e. many mA of protons
- ✓ an emittance lower than accelerator acceptance;
- ✓ high stability and high reproducibility;
- ✓ user friendly;
- ✓ high MTBF;
- ✓ low maintenance.

Clinical Trial of reactor based BNCT

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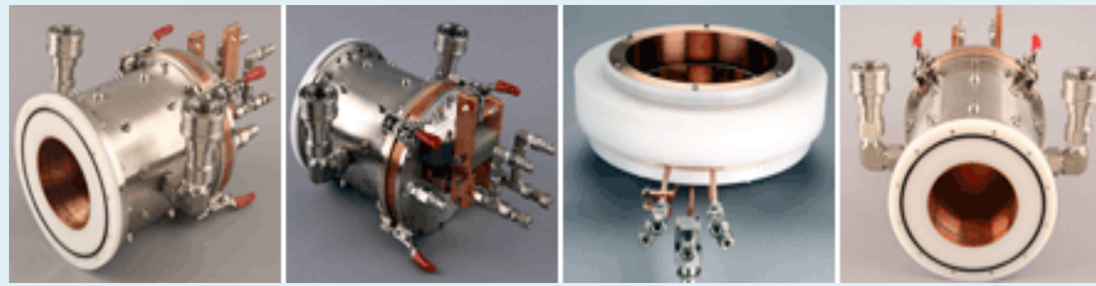
	Facility	Brain	Skin	Others	Total	Period
Argentina		0	0	7	7	2003-
Czech Republic	Nuclear Research Institute Rez plc (NRI-Rez)	2	0	0	2	2000-
Finland	Technical Research Centre of Finland (VTT)	272	0	0	272	1999-
Italy		0	0	2	2	2002-
Japan	Hitachi Co.	13	0	0	13	1968-1974
	Japan Atomic Energy Agency	1	0	0	1	1969
	Japan Atomic Energy Agency	33	0	0	33	1990-1996
	Japan Atomic Energy Agency	47	0	0	47	1999-2007
	Japan Atomic Energy Agency	30	4	24	58	2010-2011
	Musashi Institute of Technology	99	9	0	108	1977-1989
	Kyoto University	47	14	61	122	1977-1995
	Kyoto University	97	8	105	210	1996-2006
	Kyoto University	30	4	24	58	2010-2011
Sweden	Uppsala University	52	0	0	52	2001-2005
Taiwan		0	0	10	10	2010-
the Netherlands	HTR Pettern	22	0	0	22	1997-
USA	Brookhaven Graphite Research Reactor	28	0	0	28	1951-1958
	Brookhaven Medical Research Reactor	17	0	0	17	1959-1961
	Brookhaven Medical Research Reactor	54	0	0	54	1994-1999
	MIT Reactor	18	0	0	18	1959-1961
	MIT Reactor	18	6	0	24	1994-
	TOTAL	880	45	233	1158	

Accelerator based BNCT facility at Kyoto University



Specifications of accelerator	
Type	: Cyclotron
Ion	: H^-
Energy	: 30 MeV
Beam current	: 2 mA
Heat load	: 60 kW
Irradiation field	: 250mm×250 mm

Specifications Ion source	
Type	: multi cusp
Beam current	: H^- 15 mA
Max. extraction voltage	: 30 kV
Max. arc current	: 2.5 A
Gas	: H_2

Key technologies for a cw p or d linac (5-40 MeV)

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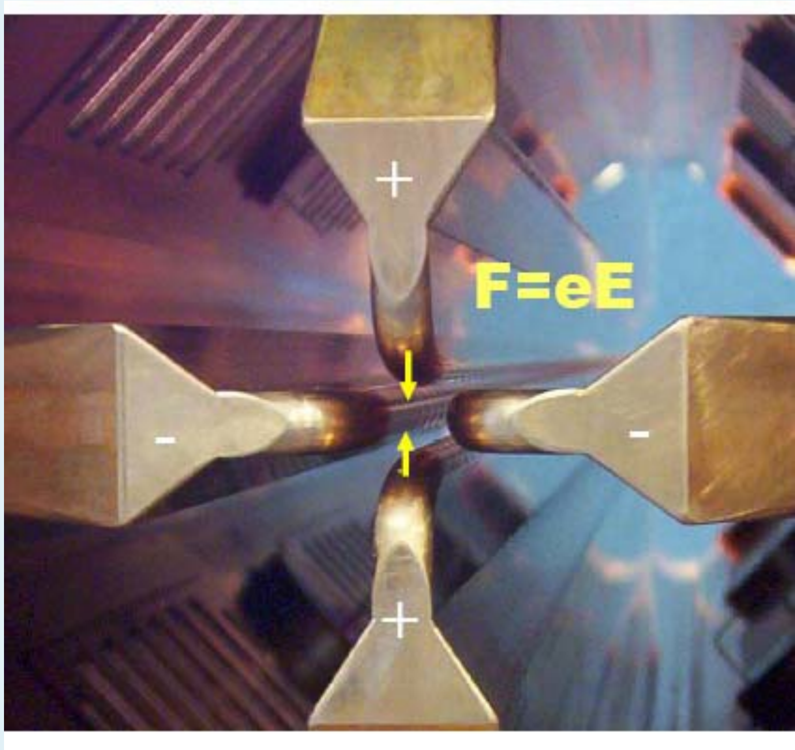
- **ECR sources (high intensity, high reliability continuous beam)**
- RFQ acceleration with high transmission (about 90%) of a continuous beam and preparation of time structure for RF acceleration.
- Superconducting cavities for cw linac operation (HWR or QWR derived from heavy ion linacs like ALPI)
- Solid state RF amplifiers for reliable cw operation (10-150 kW)
- High power targets (solid beryllium or carbon, liquid lithium). SPES BNCT and SPIRAL2 prototypes
- Dosimetry to characterize the neutron field



TRIPS *(TRasco Intense Proton Source)*

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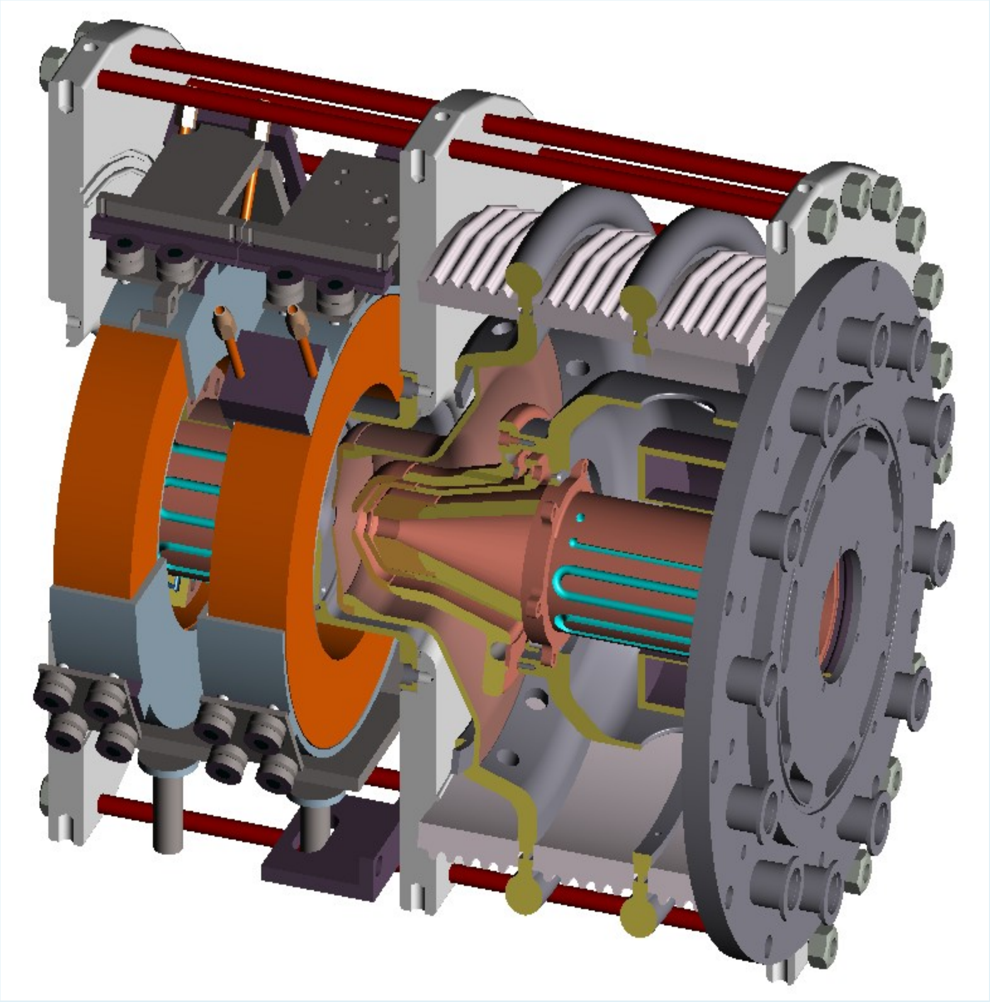
Proton beam current:
60 mA dc

Beam Energy:
80 keV

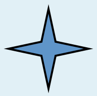
Beam emittance:
$\varepsilon_{RMS} \leq 0.12\ \pi\ \text{mm mrad}$

Reliability:
close to 100%

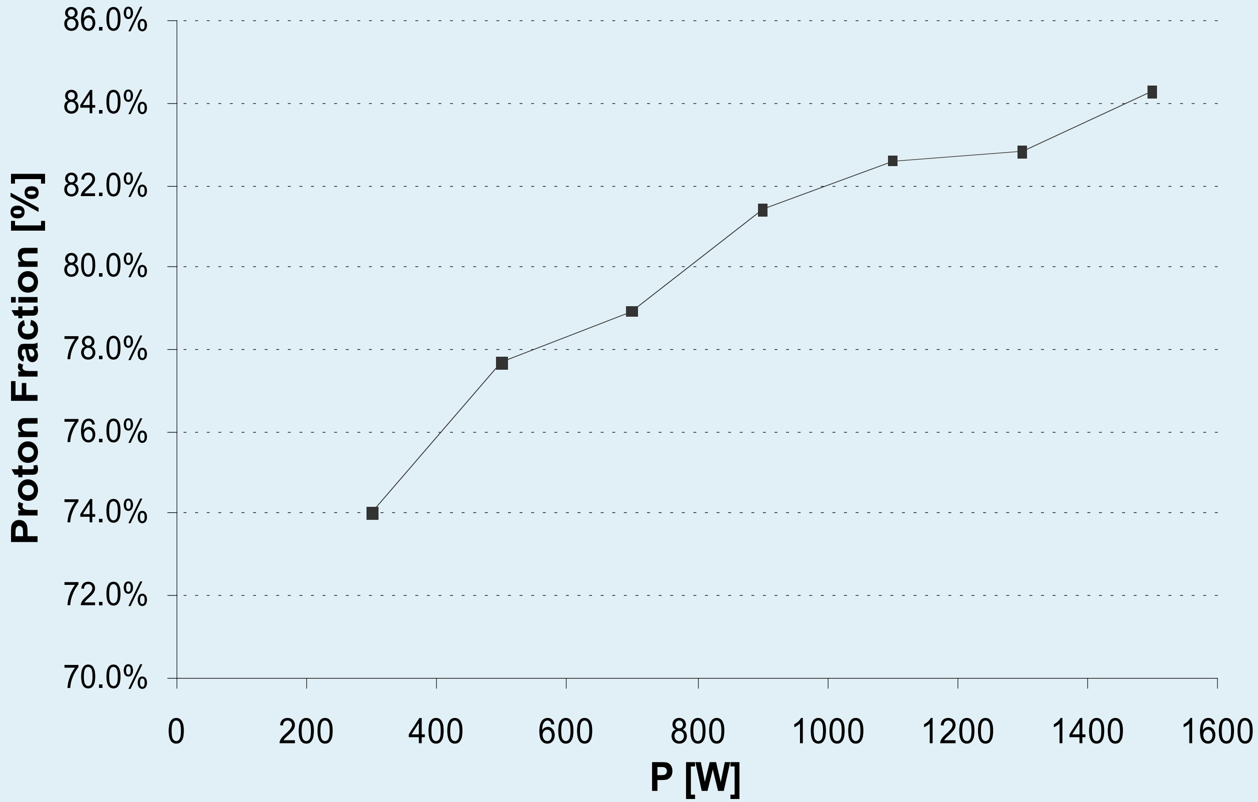


Built at INFN-LNS, then moved to INFN-LNL, now ready for BNCT facility

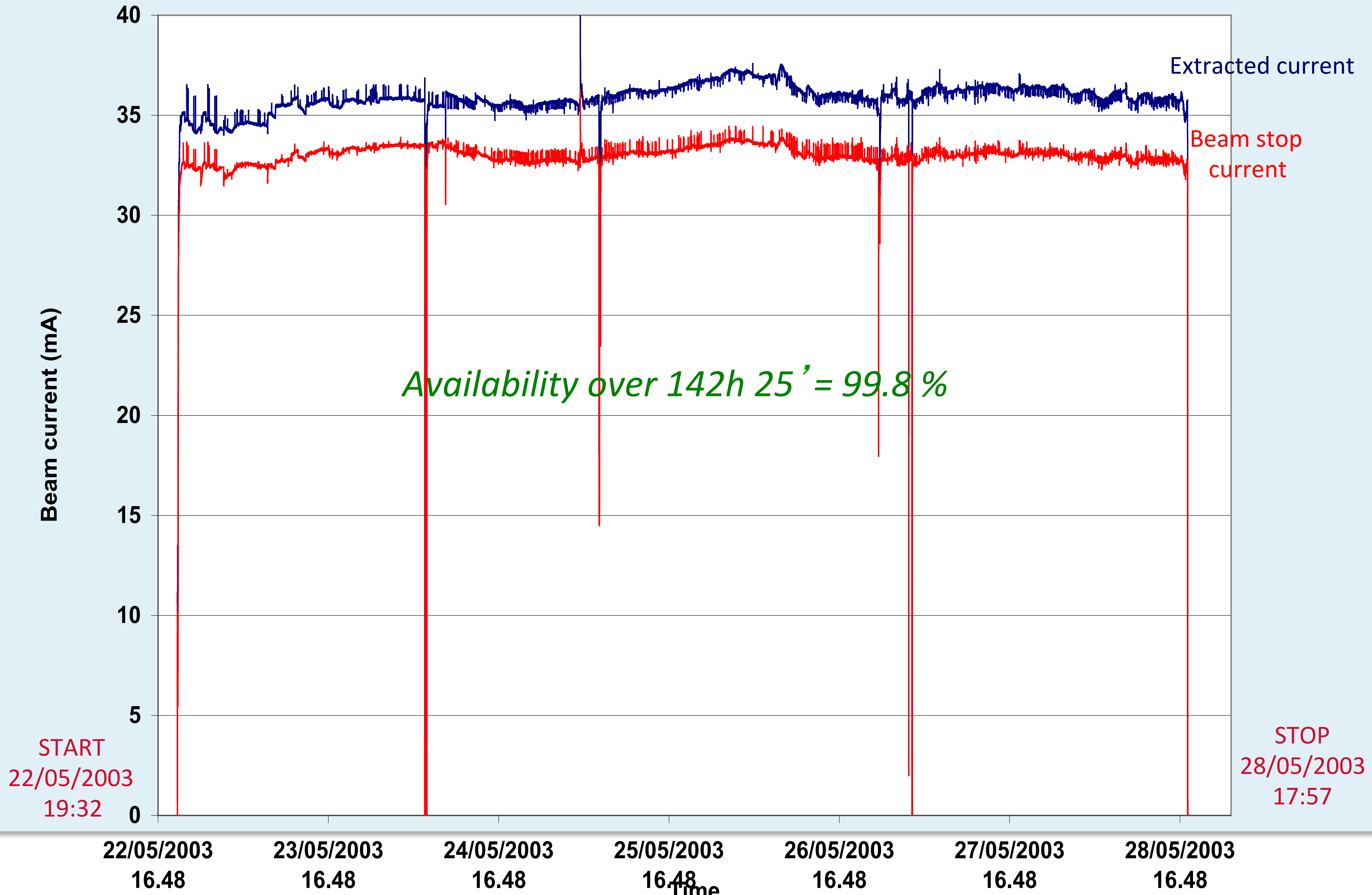
Proton fraction



90% was obtained in 2005 at 1 kW with Al_2O_3 tube



Parameter	
Extraction voltage	80 kV
Puller voltage	42 kV
Repeller voltage	-2.6 kV
Discharge power	435 W
Beam current	35 mA
Mass flow	≈0.5 sccm



TRIPS operating parameters

	Requirement	Status
Beam energy	80 keV	80 keV
Proton current	35 mA	55 mA
Proton fraction	>70%	80% at 800 W RF power
RF power, Frequency	2 kW (max) @2.45 GHz	Up to 1 kW @ 2.45 GHz
Axial magnetic field	875-1000 G	875-1000 G
Duty factor	100% (dc)	100% (dc)
Extraction aperture	8 mm	6 mm
Reliability	≈100%	99.8% @ 35mA (over 142 h)
Beam emittance at RFQ entrance	≤0.2 πmmmrad	0.07÷0.20 πmmmrad

Conclusions (?)

This lecture does not imply “conclusions” as it is a snapshot of “work in progress”.

The three different applications will become more convenient if they can be based on better ion sources than the ones existing nowadays, so further developments in the coming years are highly probable.

The presentation displayed a large variety of techniques that can be adapted to different needs, satisfying all present requirements.

The availability of mA range ECR ion sources for highly charged ions may change significantly the situation of isotope production facilities and will also improve significantly the operations of hadron therapy facilities.