CYCLOTRON 13

# ECR SOURCE DEVELOPMENT

Thomas Thuillier
LPSC
53 rue des Martyrs
38026 Grenoble cedex
France
e-mail: thuillier@lpsc.in2p3.fr

*LBL from 08/12 to 08/13*

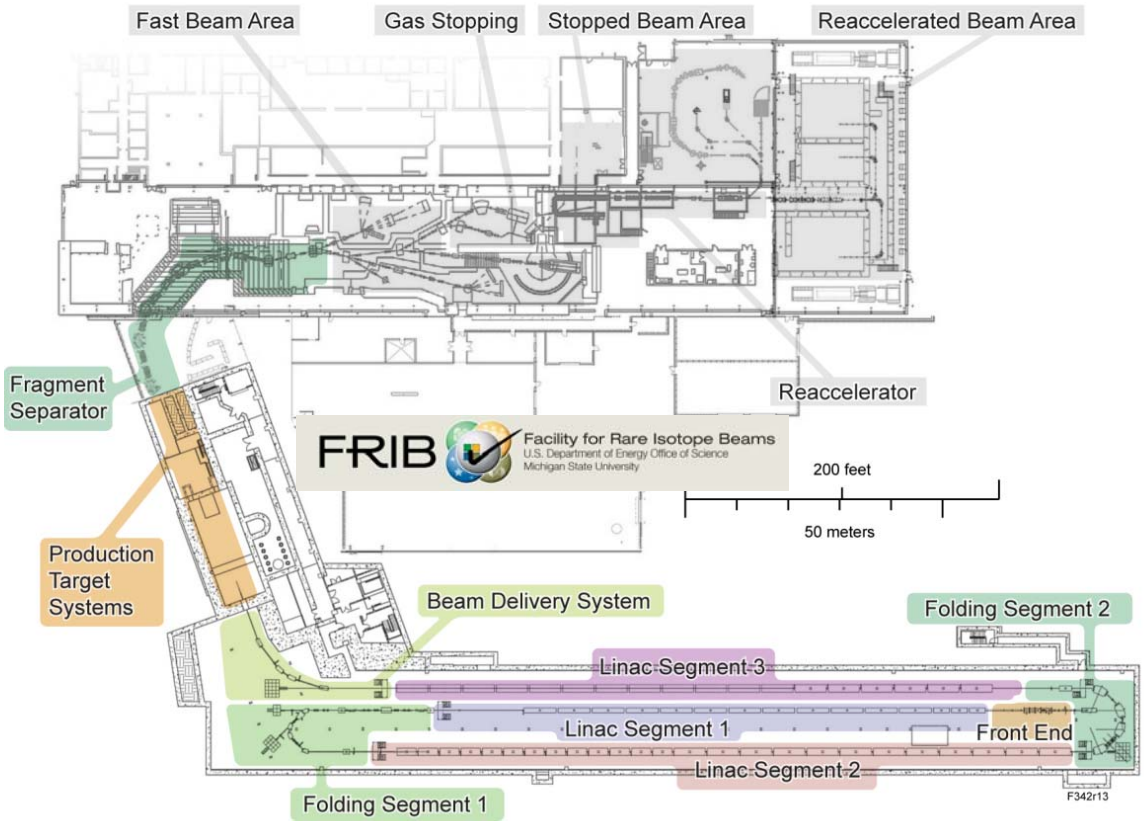
# Preamble

- The ECRIS'12 Workshop and the ICIS'13 Conference demonstrated that the ECR Ion Source field is still very active
- Many interesting new developments have been presented in the last years, but it 's unfortunately impossible to summarize all of them in 25 minutes
- The philosophy retained for this presentation is to focus on some
  - new challenging projects
  - newcomers
  - Original/exotic developments

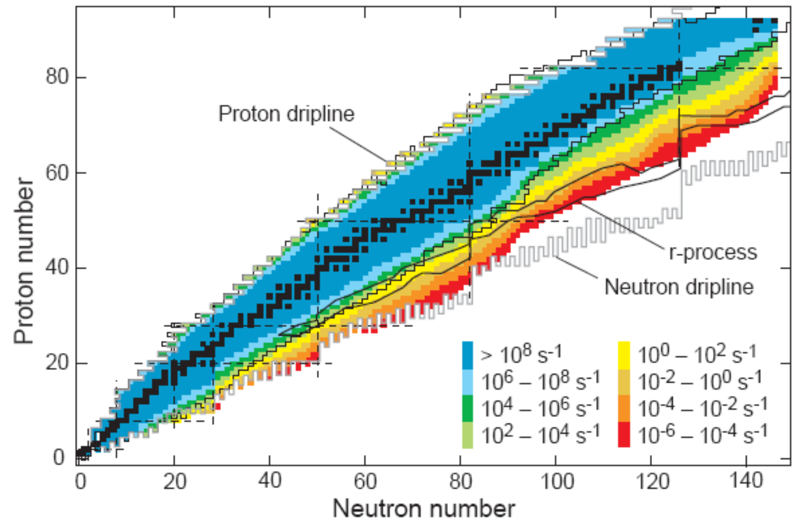
# OUTLINE

- **ECRIS DEVELOPEMENT FOR (non cyclotron) ACCELERATORS**
  - **FRIB (MSU)**
  - **SPIRAL2 (GANIL)**
  - **RISP (IBS)** *newcomer*
  - **KBSI (KBSI Busan)** *newcomer*
- **SOME ORIGINAL/EXOTIC ECRIS DEVELOPMENT**
  - **INTENSE PULSED PROTON BEAMS AT IAP (IAP RAS)**
  - **INDUSTRIAL APPLICATIONS WITH THE COMIC SOURCES (LPSC)**
  - **$TE_{01} \rightarrow HE_{11}$ MODE CONVERTER FOR THE VENUS ECR ION SOURCE (LBL)**
  - **MASS SPECTROSCOPY (ANSTO)** *newcomer*

# ECR developments for the FRIB project



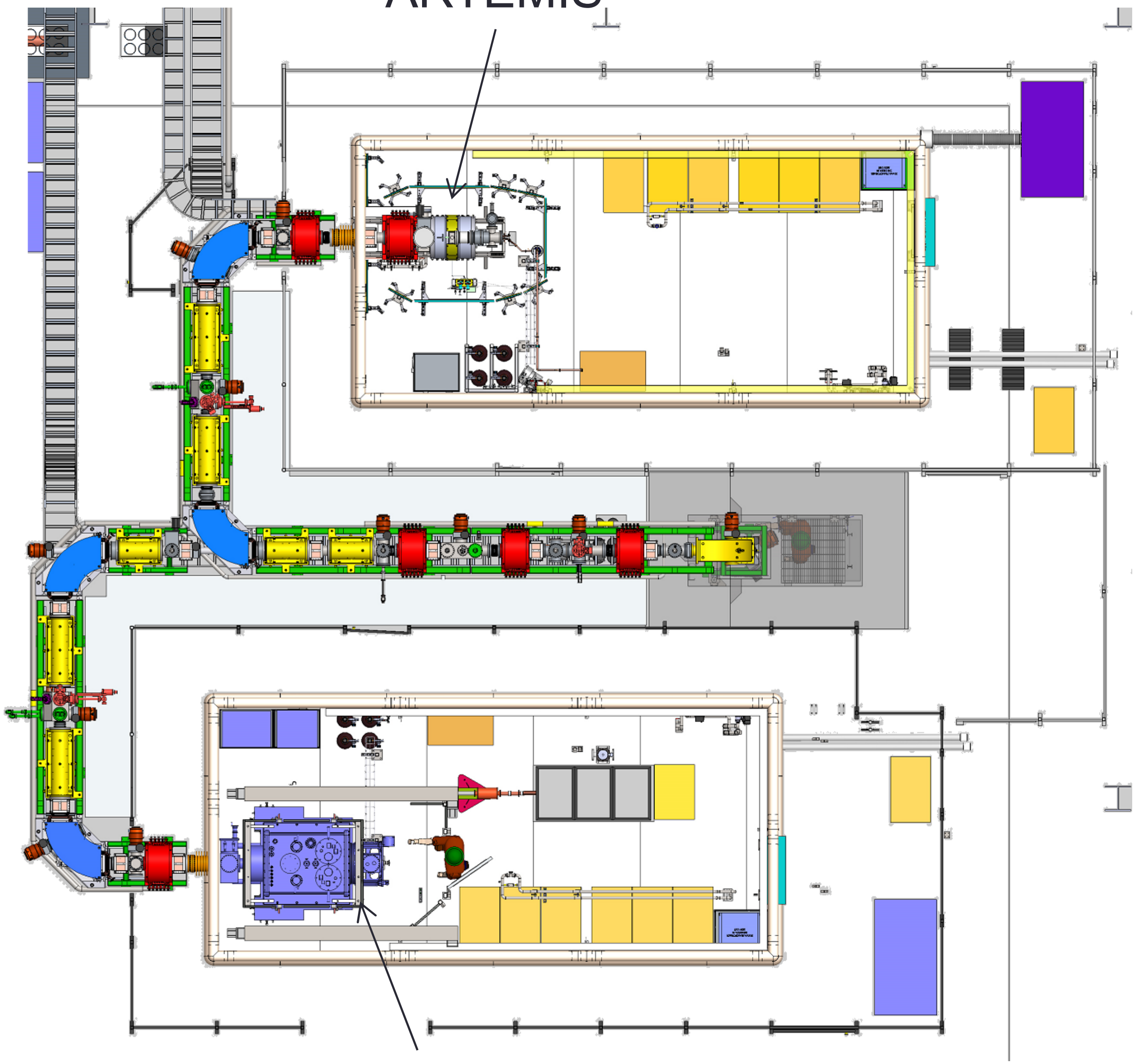

- A facility to study nuclei synthesis and properties far from stability by means of radioactive ion beams
- Accelerate ion species up to $^{238}U$ with energies of no less than 200 MeV/u
- Provide beam power up to 400 kW to the target



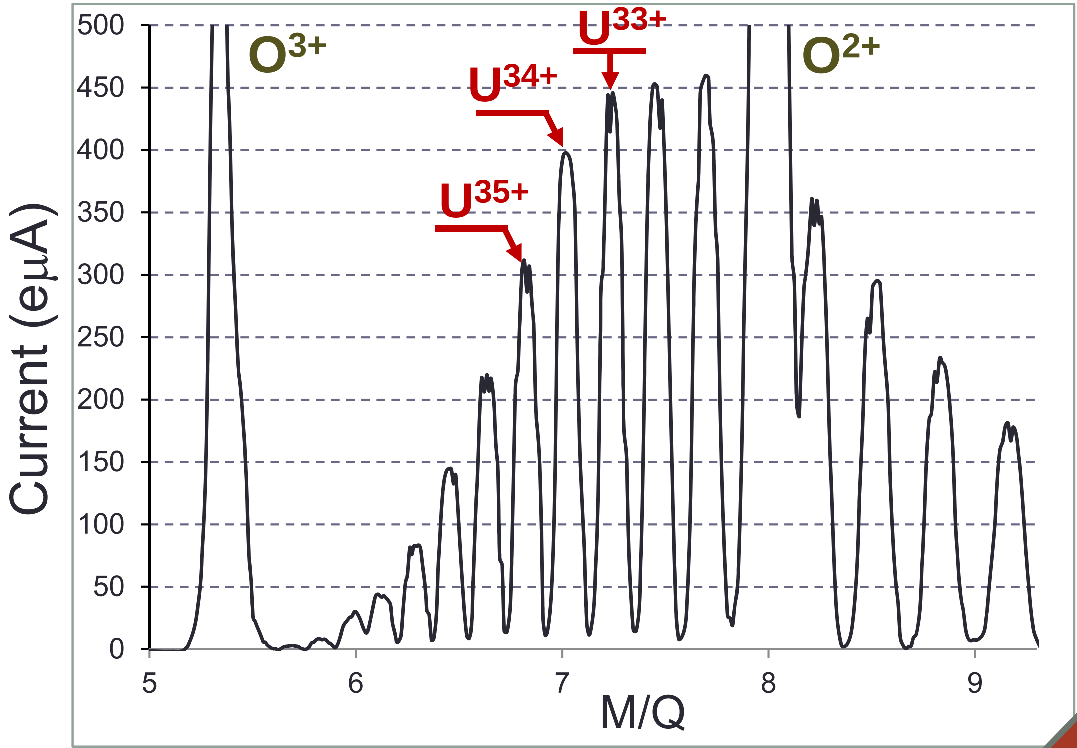

- 450 μA of $^{238}U^{33+}$+$^{238}U^{34+}$ required from the source
- Beam norm. emittance (99%):
  - <0.9 π.mm.mrad (for single charge)
  - <0.6 π.mm.mrad (for dual charge)

# FRIB ECR systems

- Two ECR on two 100 kV HV platforms:
  - Existing ARTEMIS ECRIS (room temp.))
    - For commissioning
  - An upgraded version of VENUS
    - For high intensity beam operation
    - Under design
- A complex achromatic LEBT to transport simultaneously $U^{33+}+U^{34+}$ beams
  - The LINAC is one floor below (not shown here)



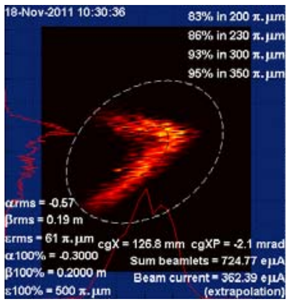
# Uranium production test with VENUS (LBNL+MSU)




- Impressive Uranium spectrum!
- Oven with a Rhenium crucible
  - U consumption~9 mg/h
- 2 kW 18 GHz+6.5 kW 28 GHz
  - VENUS tuned to its maximum experimental power
- LEBT transmission limited at 22 kV
  - HV drain 9 mA, FC tot~5mA
- No production limitation observed: source still responsive with power and oven temperature

- Emittance compatible with FRIB specification

H

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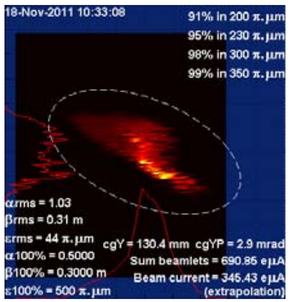
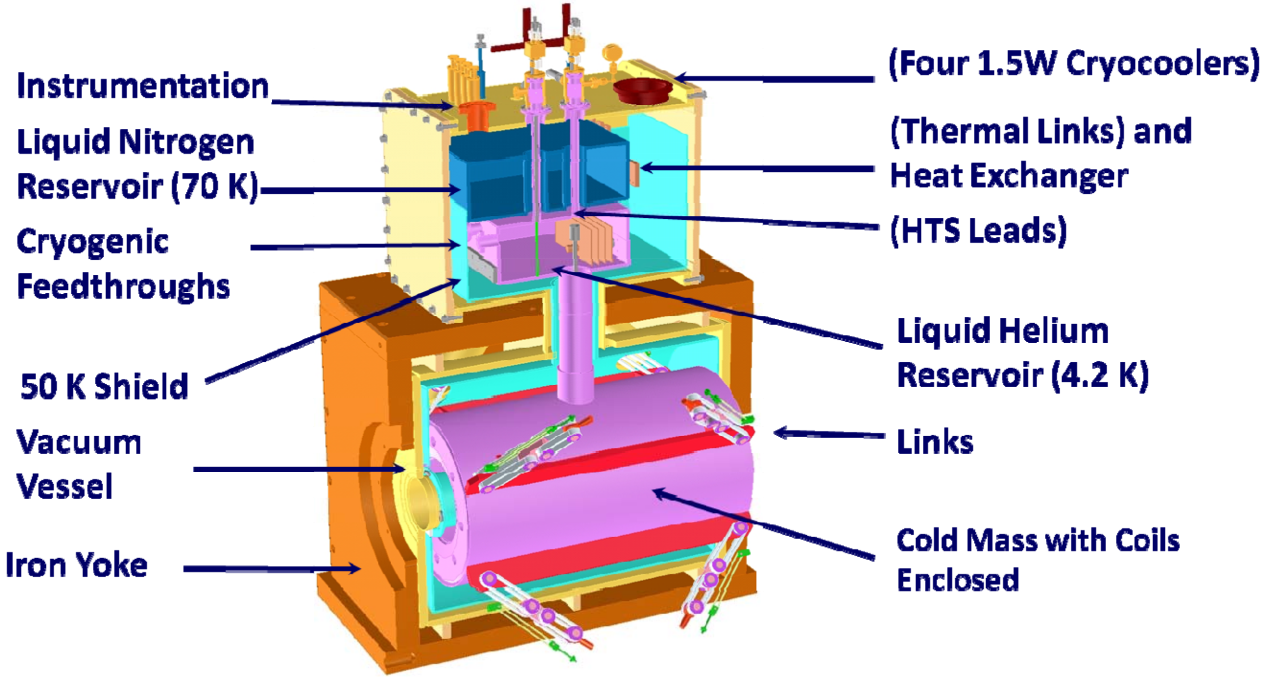



Validates the FRIB operation

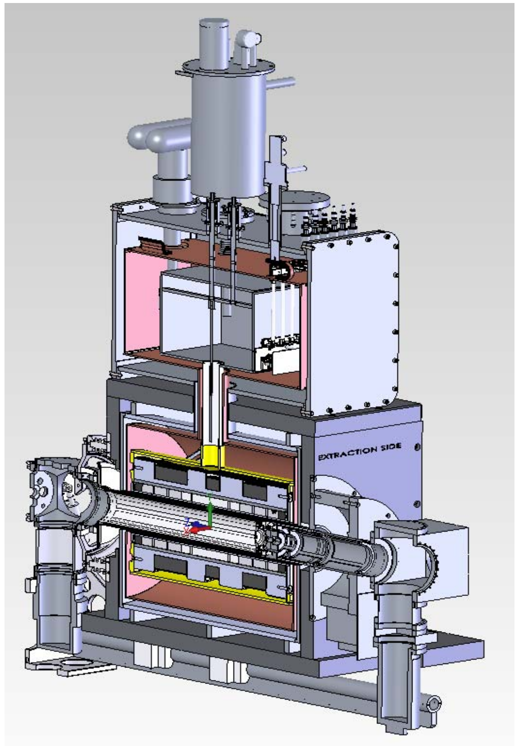
With 220 μA $U^{33+}$ + 220 μA $U^{34+}$

# VENUS upgrade for FRIB

- VENUS original design

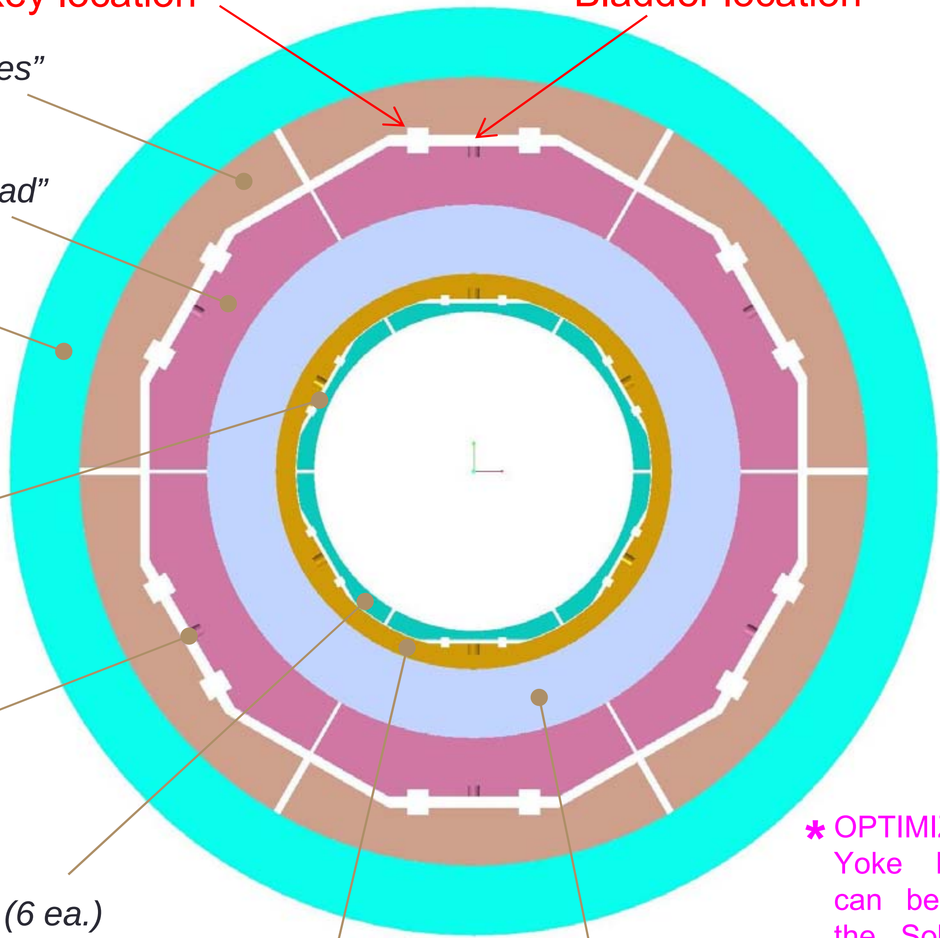



- VENUS upgrade for FRIB



- Cold mass of FRIB SC-ECR essentially identical to VENUS
  - re-design entrusted to LBL Superconducting Group (see next slides)
- Original VENUS Cryostat extensively modified (MSU)
  - Cooling rely only on cryocoolers
  - Added cooling capacity at 4.2 K (8 to 9W total vs. 5 to 6 W for VENUS)
  - Optimized material, and design to minimize heat leak and simplify maintenance

# FRIB / VENUS upgrade: possible new cold mass design



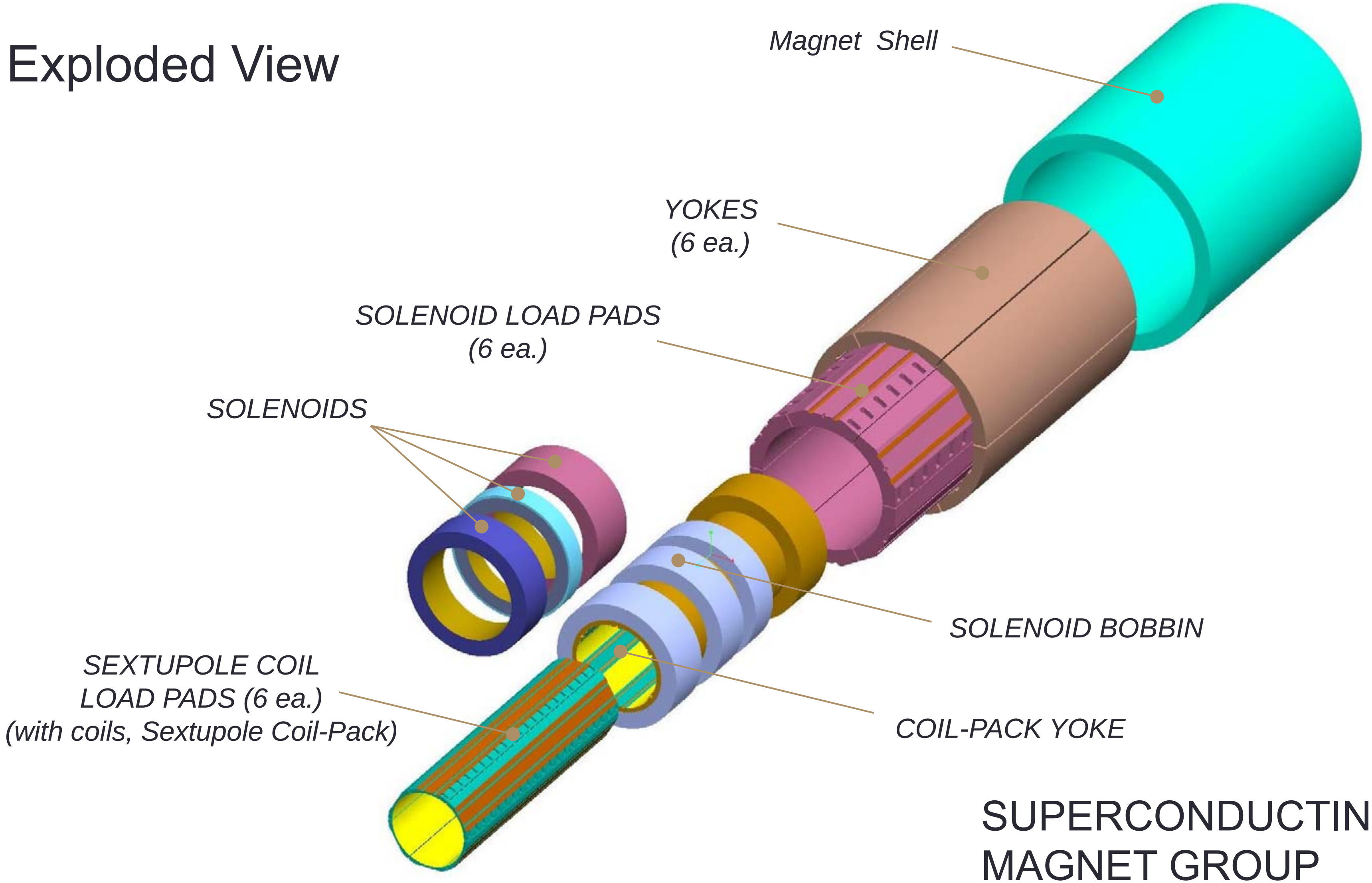

- New cold mass mechanics design for the coils
  - Bladders and Keys
- Each sextupole coil is dismountable
- Pre-stress can be modified/optimized
  - By changing the keys size

* OPTIMIZATION:
Yoke keyway features can be incorporated in the Solenoid Bobbin – eliminating a thin, cylindrical machining. Also, the Load Pads can be made thicker and structurally stable.

SUPERCONDUCTING MAGNET GROUP, LBL

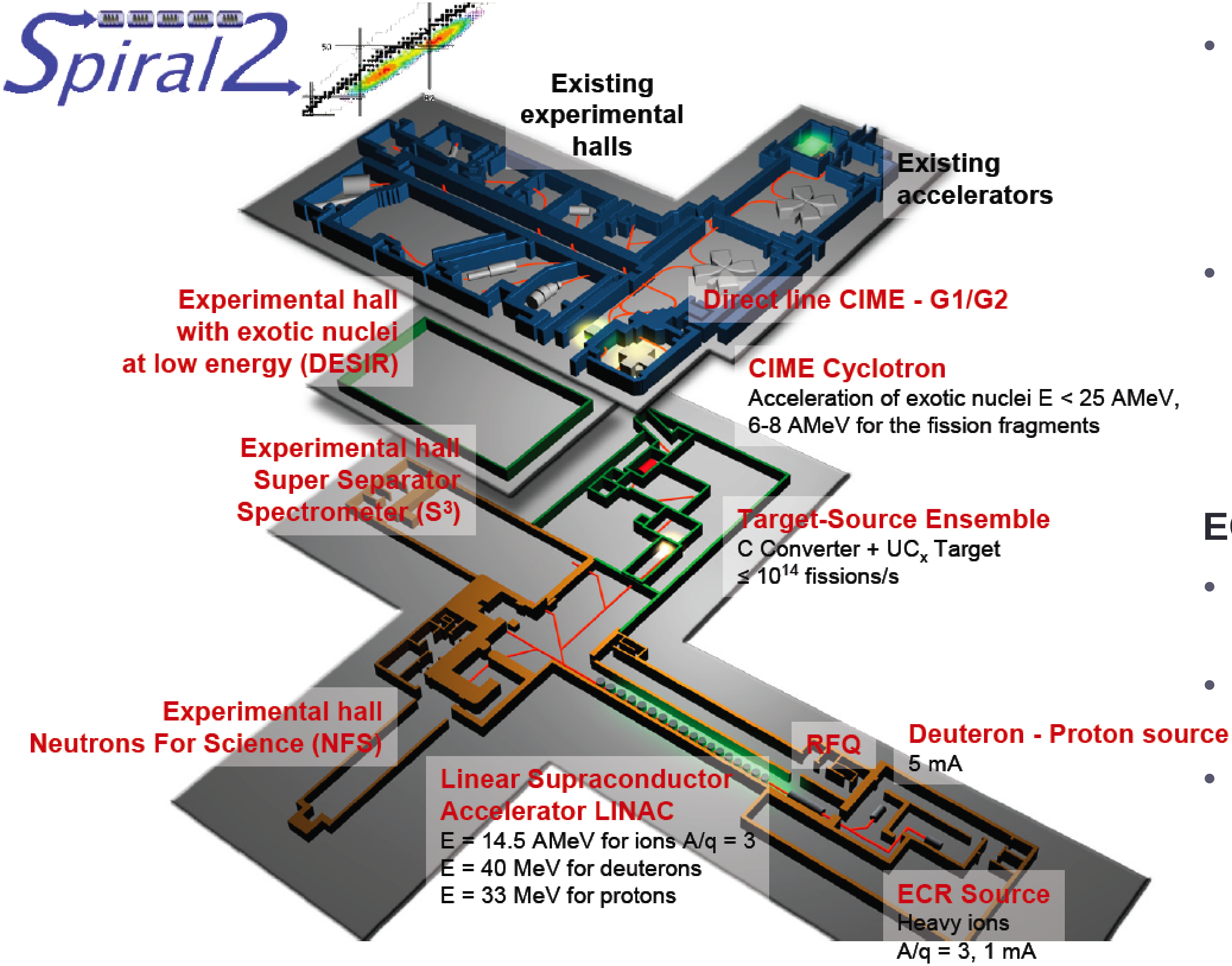
# FRIB / VENUS upgrade: possible new cold mass design

- Exploded View




SUPERCONDUCTING
MAGNET GROUP

# ECR development for the Spiral2 project




- GANIL extension to produce radioactive ion beams (RIB)
  - 5 mA Deuterons on target
  - Re-acceleration of RIBs in existing cyclotron
- Stable Heavy ion program with the LINAC
  - Super Separator Spectrometer
  - Neutron for Science

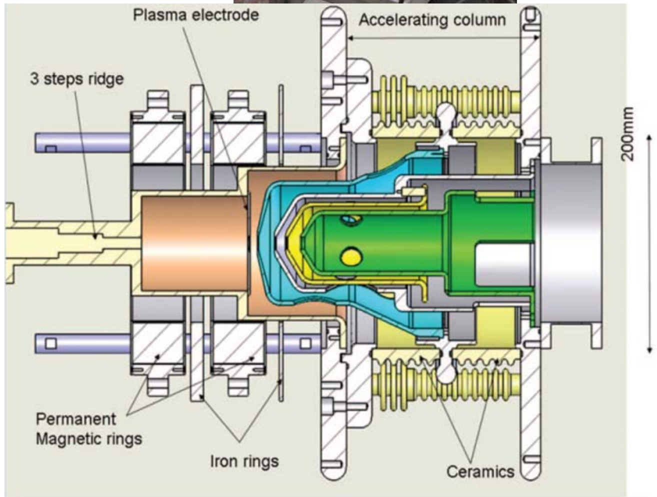
**ECR challenge:**

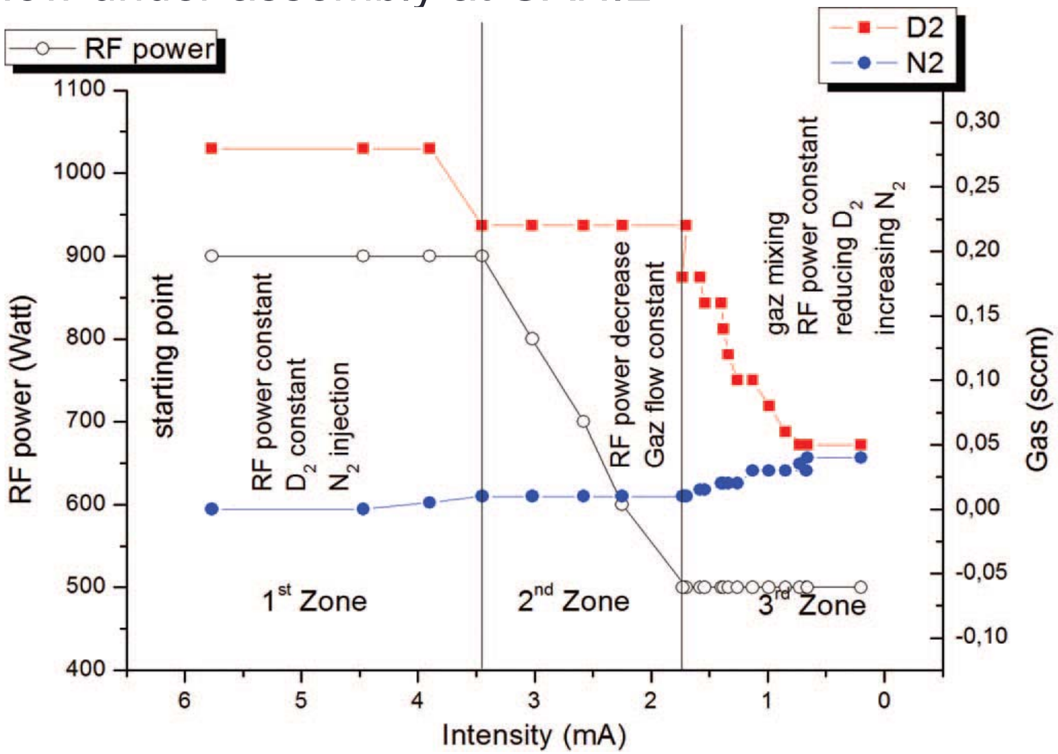
- Produce 1 mA A/Q=3 beams up to the argon mass at 60 kV
- Produce high intensity Metallic beams (Ni, Ca, S, Si, C…)
- Emittance 1σ norm. RMS<0.4 π.mm.mrad

# Deuteron Spiral2 LEBT commissioning

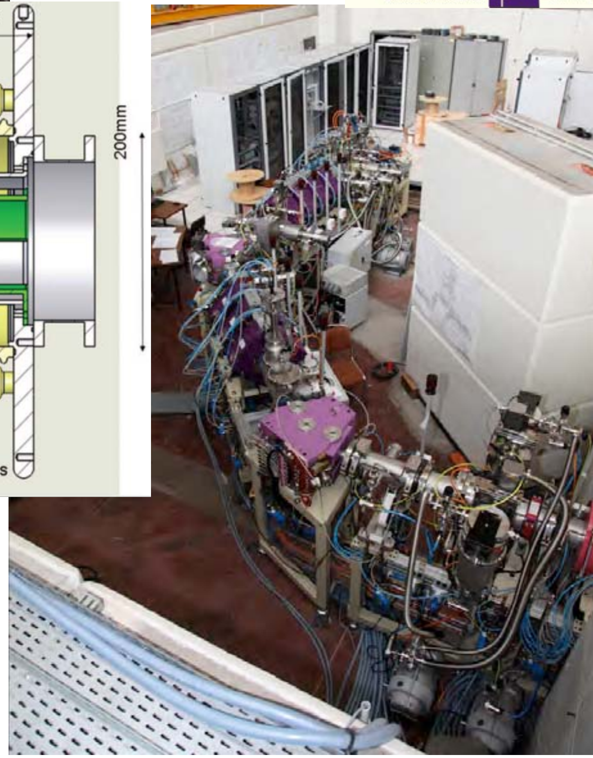
- A variation of the SILHI (Taylor) source
  - Permanent magnets
  - The source produces up to 100 mA of D+
  - 0.1 to 5 mA required @ 40 kV OK (see plot)
  - Emittance OK
- Source ant LEBT commissionned at CEA/IRFU Saclay
- Now under assembly at GANIL

*Deuteron ECR*



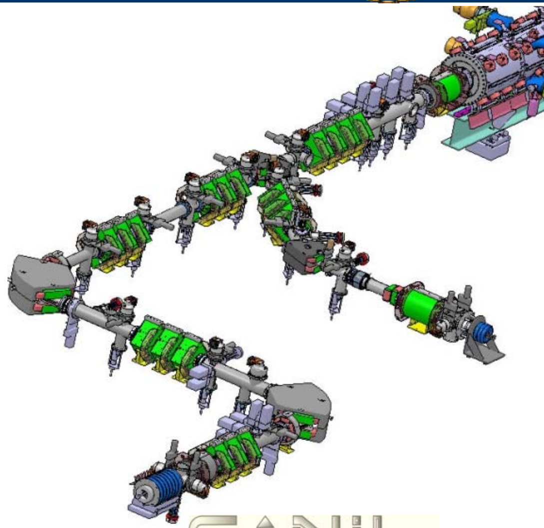




1: injection of $N_2$, P=cst
2: reduction of P, $N_2$=cst
3:D reduced,$N_2$ increased



*Deuteron LEBT @ IRFU*

# A/Q=3 ECR and LEBT commissioning



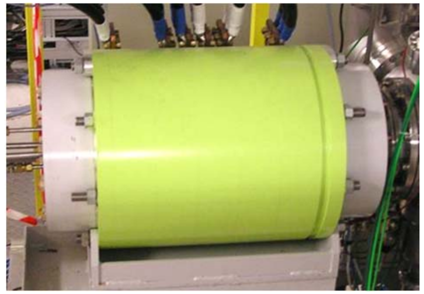
- Source and LEBT commissionned at LPSC, Grenoble
  - Excellent transmission (T>90%)
- Starter source is PHOENIX V2
  - Room temperature 18 GHz ECRIS
  - OK for LINAC commissioning at GANIL and first year experiments
  - Emittance OK
- But a new high performance ECRIS should be built (and financed) to fulfill the final beam requirement

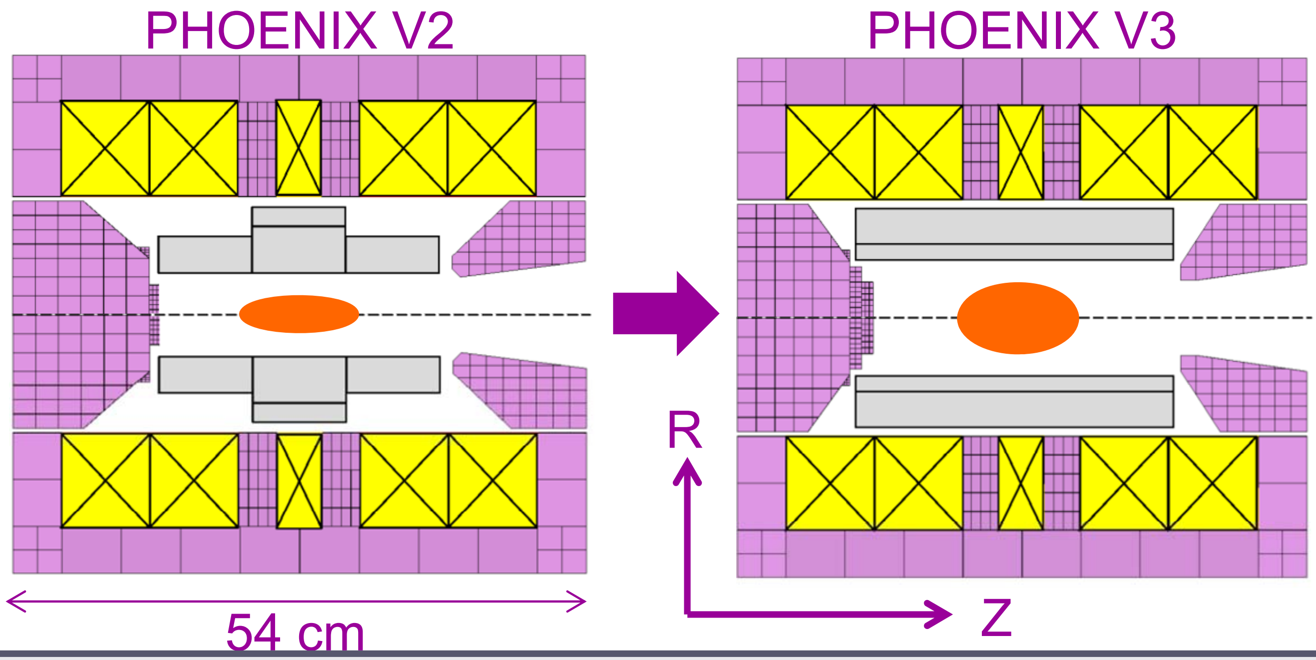
| Ion | Required (µA) | PHOENIX V2 (µA) | World record (µA) | Ref. |
|---|---|---|---|---|
| $O^{6+}$ | 1000 | 1300 | 3000 | VENUS |
| $S^{12+}$ | 240 | 55 | - | - |
| $Ar^{14+}$ | 420 | 50 | 514 | VENUS |
| $Ca^{16+}$ | 160 | 16 | 70 | SECRAL |
| $Ni^{19+}$ | 57 | 19 | 50 | SUSI |

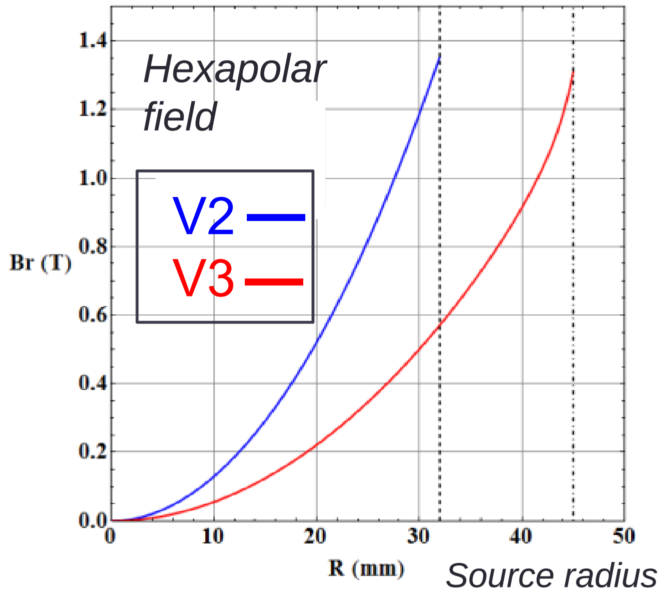
*Heavy ion LEBT @ LPSC*

# Spiral2 ECR A/Q=3 upgrade and prospect

- PHOENIX V2→PHOENIX V3 upgrade
  - Increase the plasma chamber volume : 0.7→1.4 litre
  - ECR Magnetic confinement kept identical
  - Expected shift of CSD: Gain expected +50-100% on A/Q=3
  - Under design, to be assembled and tested in 2014

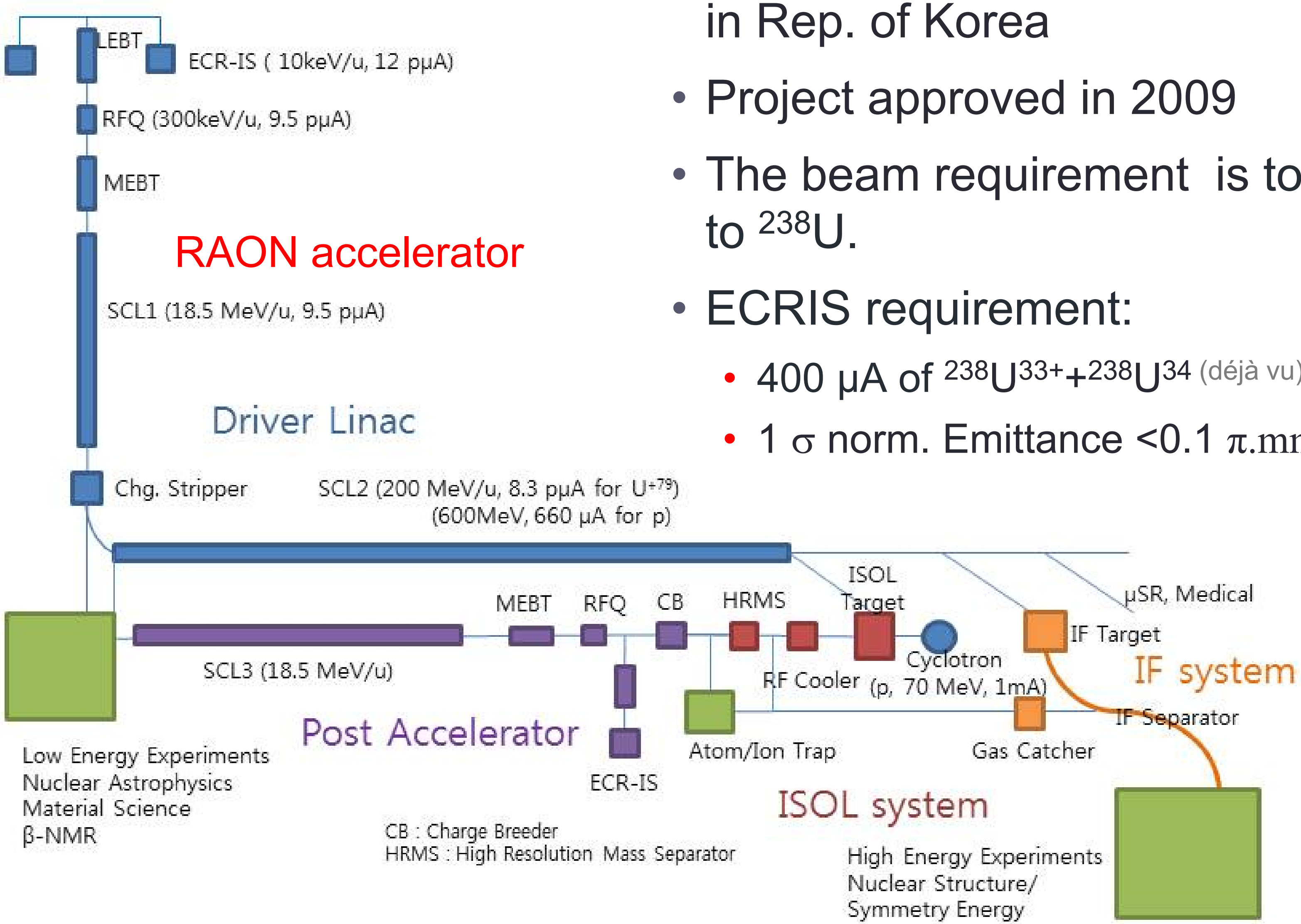





- Long term upgrade: design and build a superconducting 28 GHz ECRIS
  - Pending funding

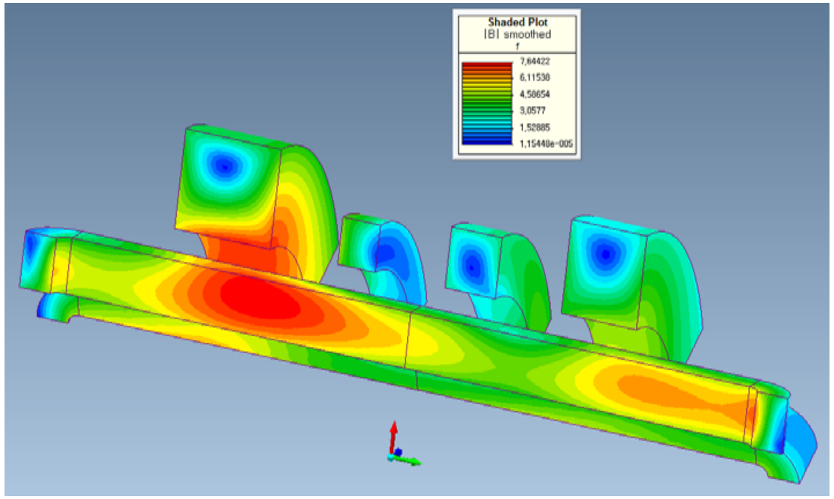
# The Rare Isotope Science Project (Institute of Basic Science)

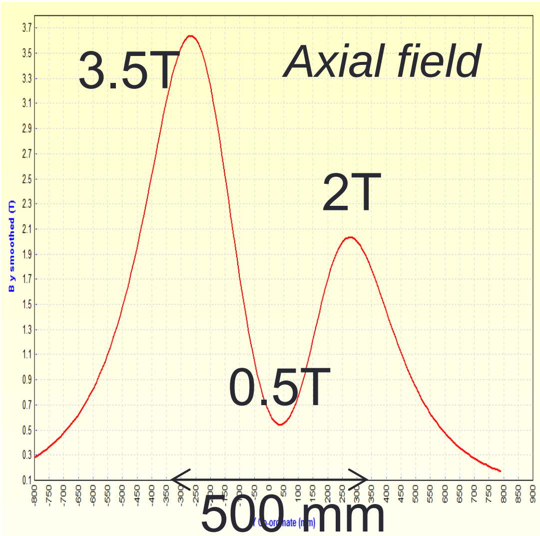


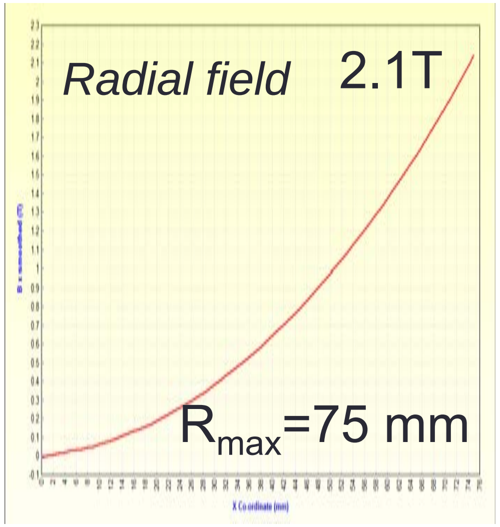

- A new RIB facility to study nuclei far from stability in Rep. of Korea
- Project approved in 2009
- The beam requirement is to accelerate ion from H to $^{238}U$.
- ECRIS requirement:
  - 400 μA of $^{238}U^{33+}$+$^{238}U^{34}$ (déjà vu)
  - 1 $\sigma$ norm. Emittance <0.1 $\pi$.mm.mrad

# ECRIS development for the RAON accelerator

- A Newcomer team in the ECRIS community from Daejeon
- A 28 GHz superconducting ECRIS is under development
  - Overal dimension and cryostat technology similar to VENUS
  - 4 axial coils instead of the usual 3 (inspired by the SUSI SC (MSU) with its 6 coils)



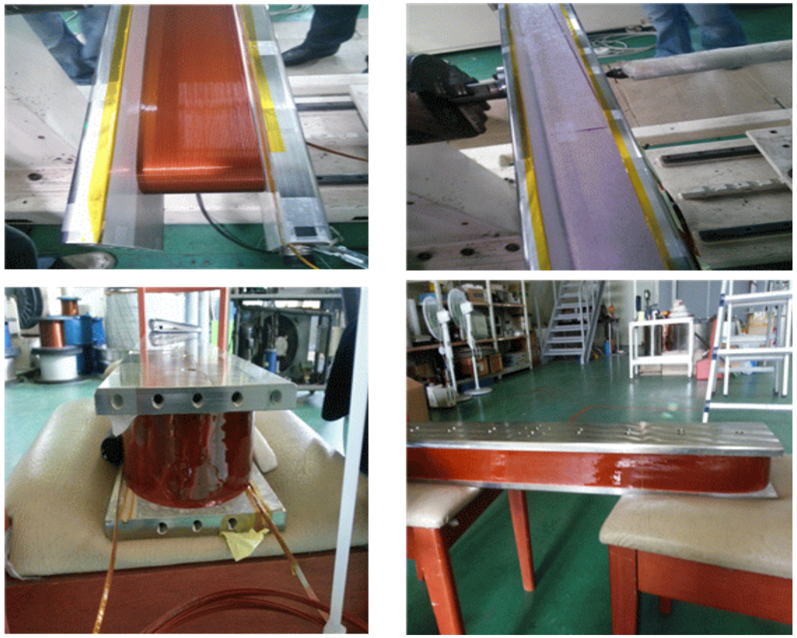




Boundary condition : $B_{inj} > 3.5 B_{ecr}$, $B_{ext} \sim 2B_{ecr}$, $B_r \sim 2B_{ecr}$, $B_{min} \sim 0.8B_{ecr}$

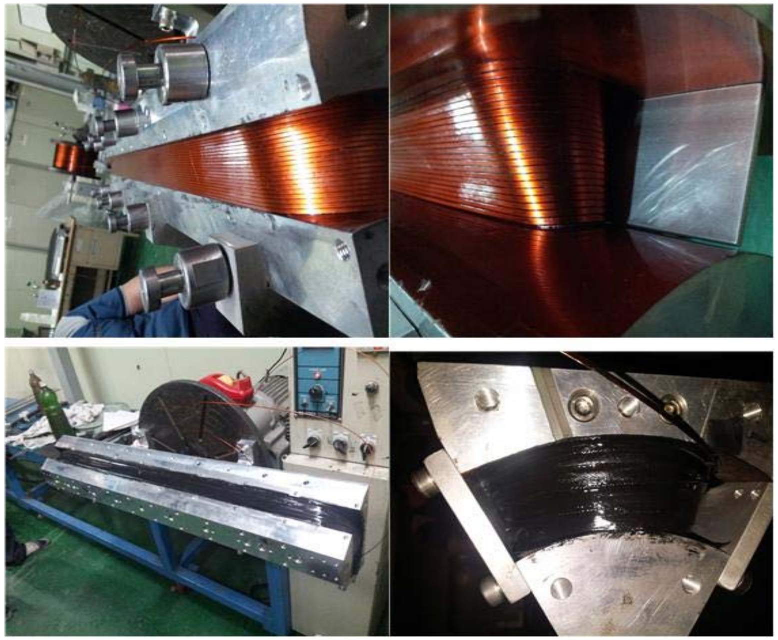
Design result : $B_{inj} = 3.61$ T, $B_{ext} = 2.07$ T, $B_r = 2.17\ B_{ecr}$, $B_{min} = 0.545$ T

# Superconducting coil prototyping

- 3 single hexapolar coils prototype have been built
  - Rectangular wire 1.9x1 $mm^2$ with Cu:NbTi ratio of 3:1
  - 1 saddle coil wet winding, no fiber cloth
  - 1 racetrack coil pre-preg impregnation (wet winding, fiber cloth)
  - 1 saddle coil, pre-preg impregnation => validated



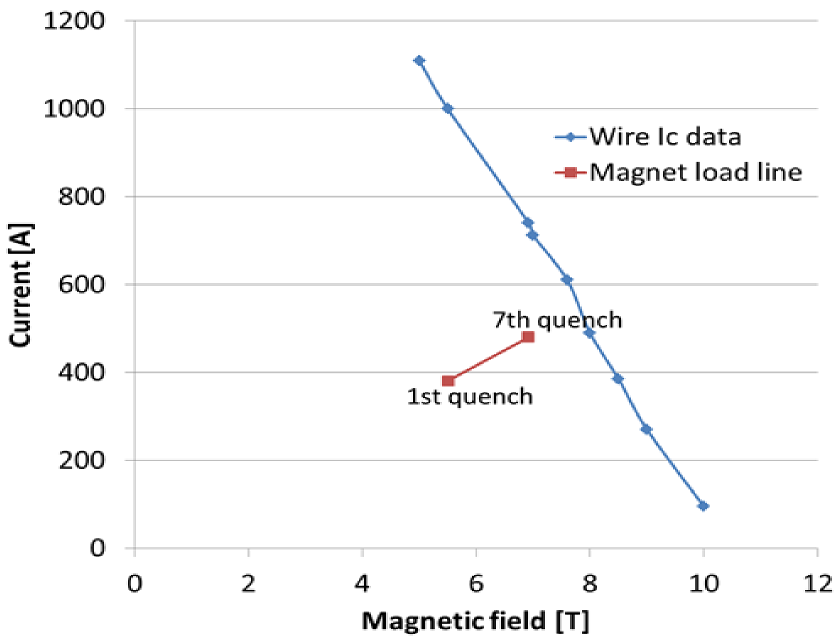
racetrack type



Saddle type

# Superconducting coil test performed in LHe

- The final saddle prototype reached 95% of wire Ic current data
  - Validation of the design
- Other coils under construction
- Final assembly and test will follow

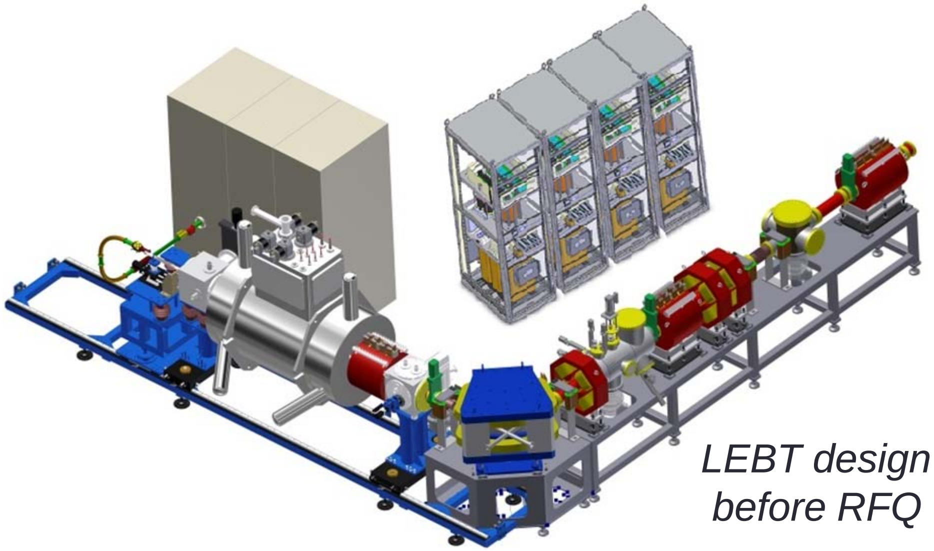



# A new compact LINAC at the Korean Basic Science Institute, (KBSI), Busan, South Korea

- Project started in 2009 *Unfortunately only a few papers available on the topic…*
- The goal is to produce intense fast neutron flux up $5 \times 10^{13}$ n/s applied to neutron radiography
- A LINAC accelerates 1 mA of $^{7}Li^{3+}$ to produce fast neutron flux in a windowless hydrogen target
  - LEBT equipped with a 28 GHz SC ECR Ion Source
  - RFQ 500 kV/u
  - DTL 3 MeV/u


Fig.a. X-ray and Neutron r… s that they are almost transparent for neutrons. Dark componets in the neutron radiograph are due to plastic components which in turn are almost transparent to x-rays.

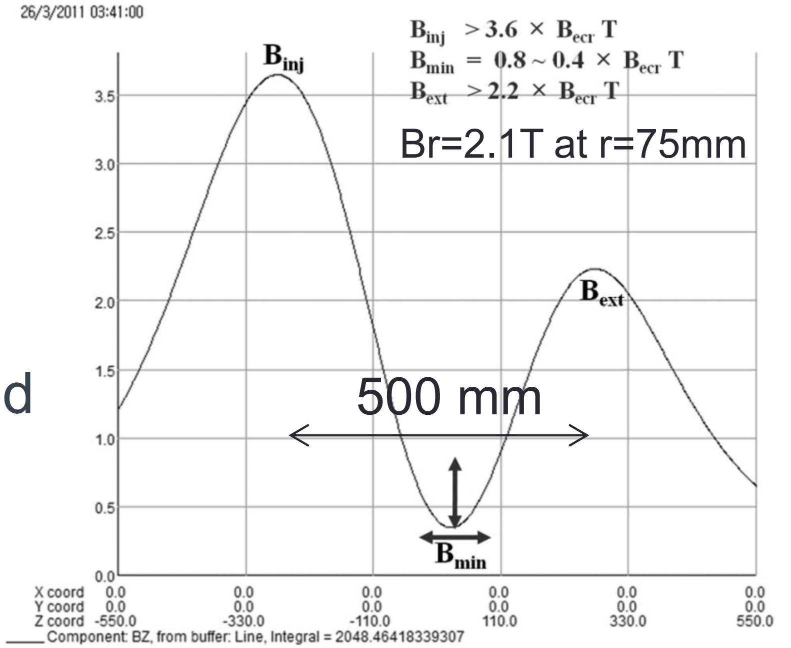
McClellan Nuclear Research Center, UC Davis



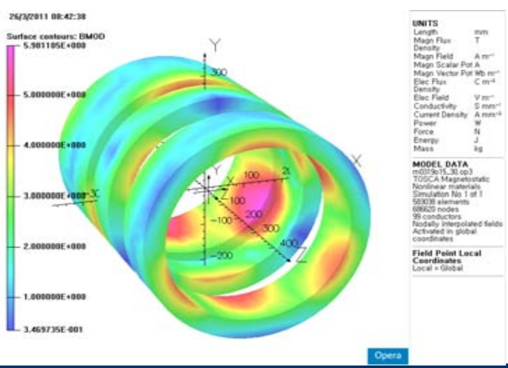
*LEBT design before RFQ*

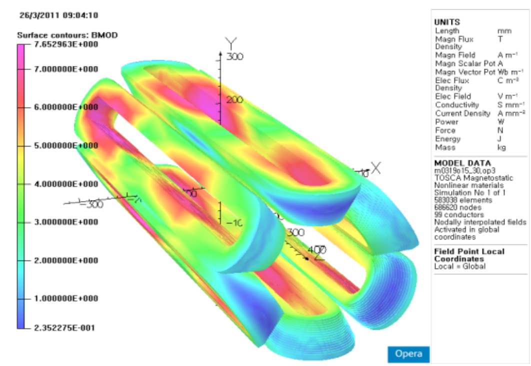
# A new 28 GHz ECRIS at KBSI

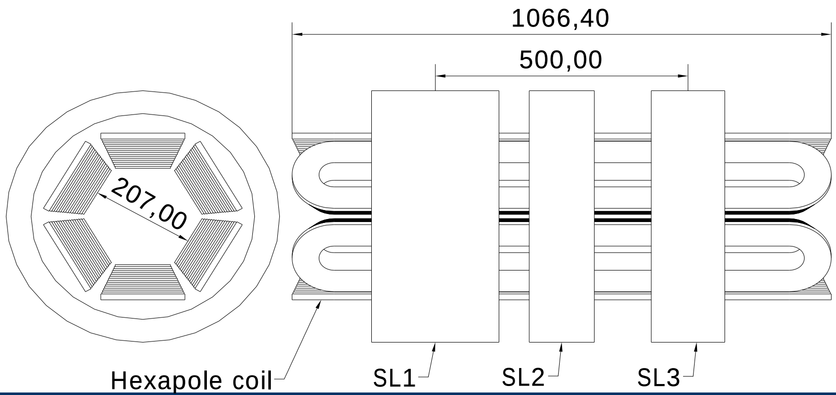
- Another Newcomer Team in the ECR community
- The ECRIS construction is well advanced
  - The ECRIS design and technology is close to VENUS (LBNL)
  - Except for the hexapole coils which are more inspired from SECRAL (IMP Lanzhou)
    - Racetrack coils with a trapezoid section




*KAERI 28 GHz ECRIS magnetic design*

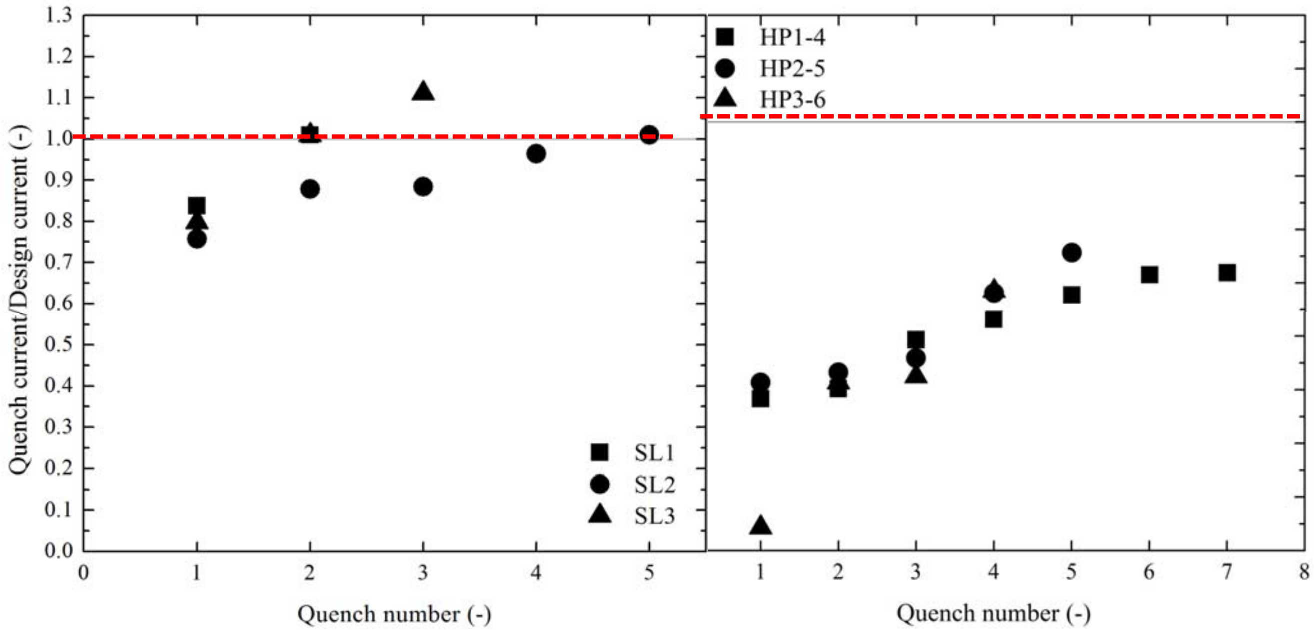






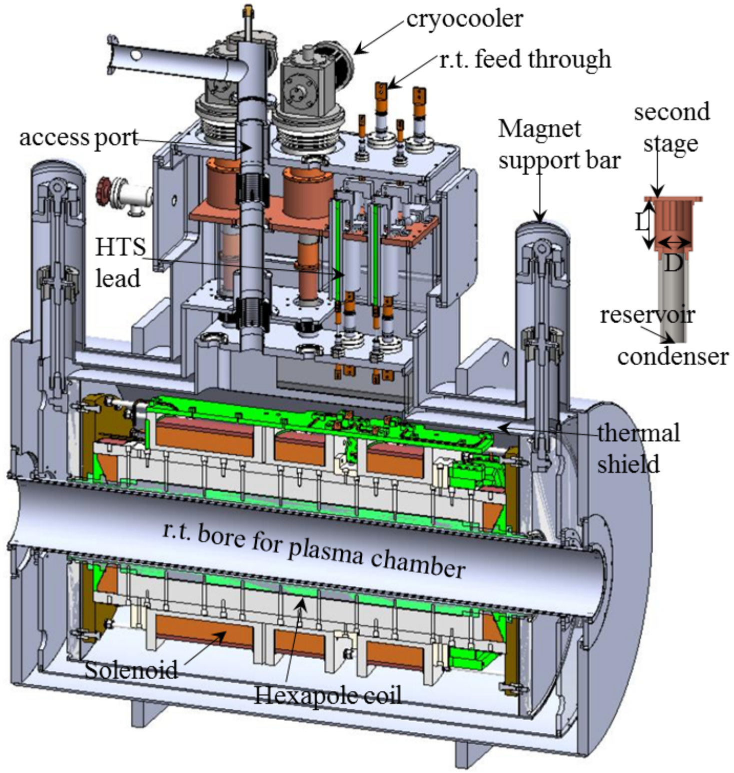
# A new 28 GHz ECRIS at KBSI

- Individual Coil test in a vertical cryostat
  - Axial coils OK
  - Hexapole reacetrack at 70% of design
    - At least suitable for a high performance 18 GHz operation (1.5T)
  - Tests stopped because of LHe shortage




# A new 28 GHz ECRIS at KBSI

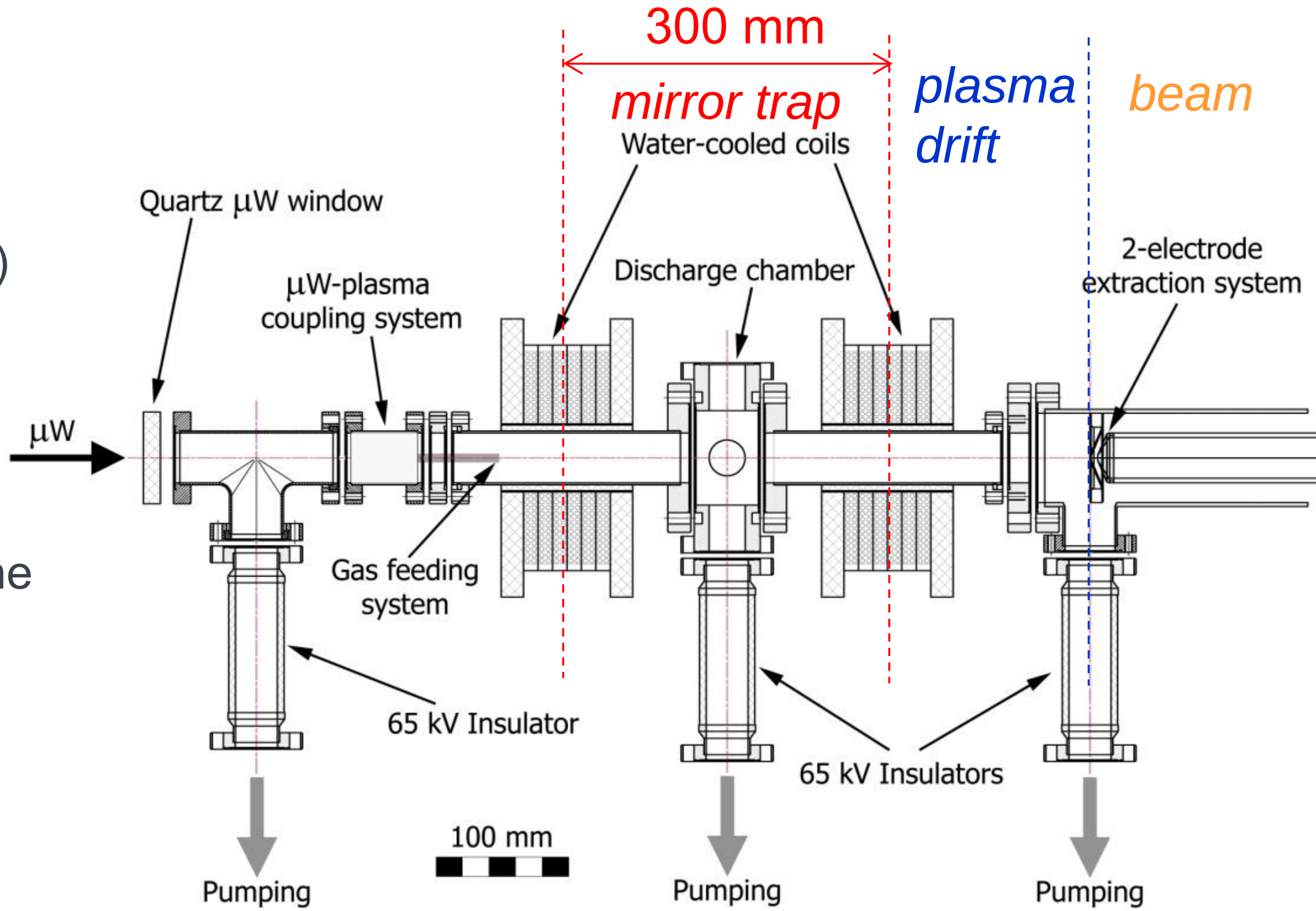
- The source has been assembled recently:
  - We wish them good luck with the final global magnetic test!



# Intense pulsed proton beam at IAP RAS

- SMIS 37 is a pulsed ECR operated at 37.5 GHz

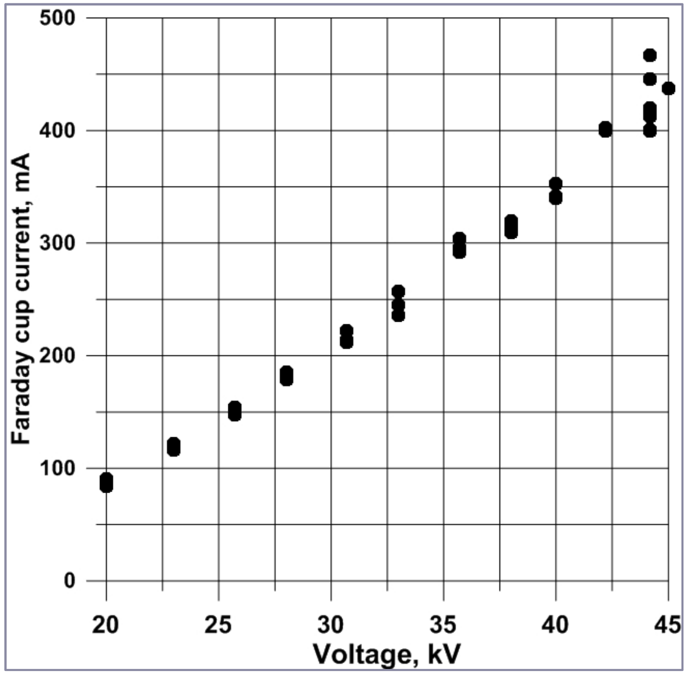
- RF power up to 100 kW
- pulse duration ≤ 1.5 ms
- Optical microwave coupling
- Gaussian beam (linear polarization)
- Fast pulsed gas valve (5 ms pulse)
- Water cooled pulsed coil
  - Capacitor discharge (T/2=11 ms)
  - Bmax~4 T
- HV ≤ 65 kV
- Beam Current measured right at the extraction in a Faraday cup
- Or current analyzed in a bending magnet
- Beam emittance measured with a pepper pot
- **Gasdynamic regime** (collisional plasma), P~$10^{-3}$-$10^{-4}$ mbar

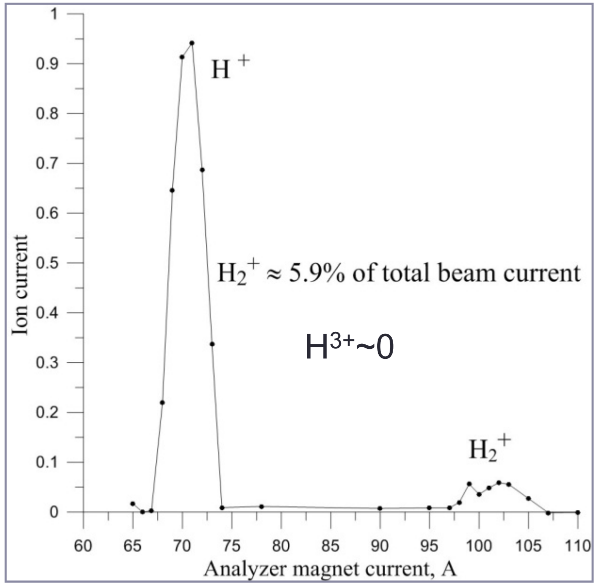


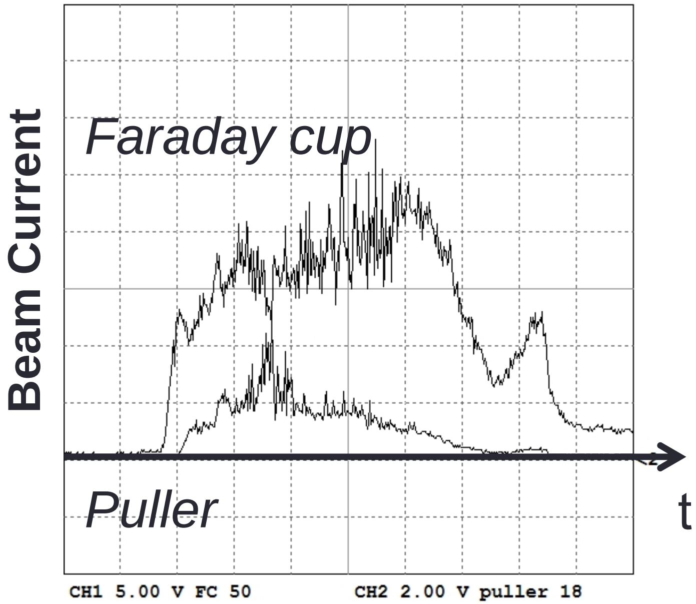

*SMIS 37 experimental setup*

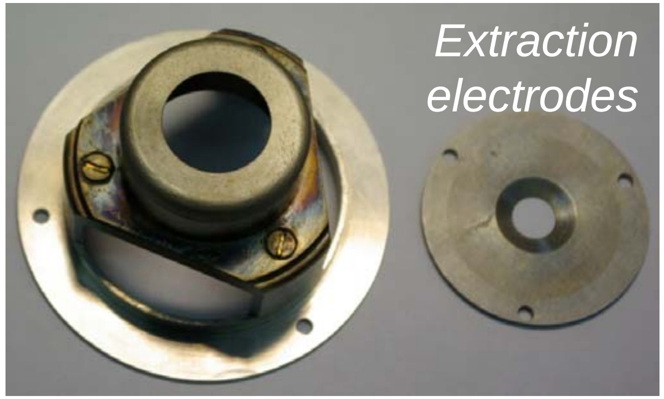
# 450 mA of $H^+$

- SMIS 37 produces pulses up to 450 mA of $H^+$
  - Diode Ion Extraction:
    - HV electrode Ø10 mm
    - ground electrode Ø22 mm
  - Proton fraction ~95%



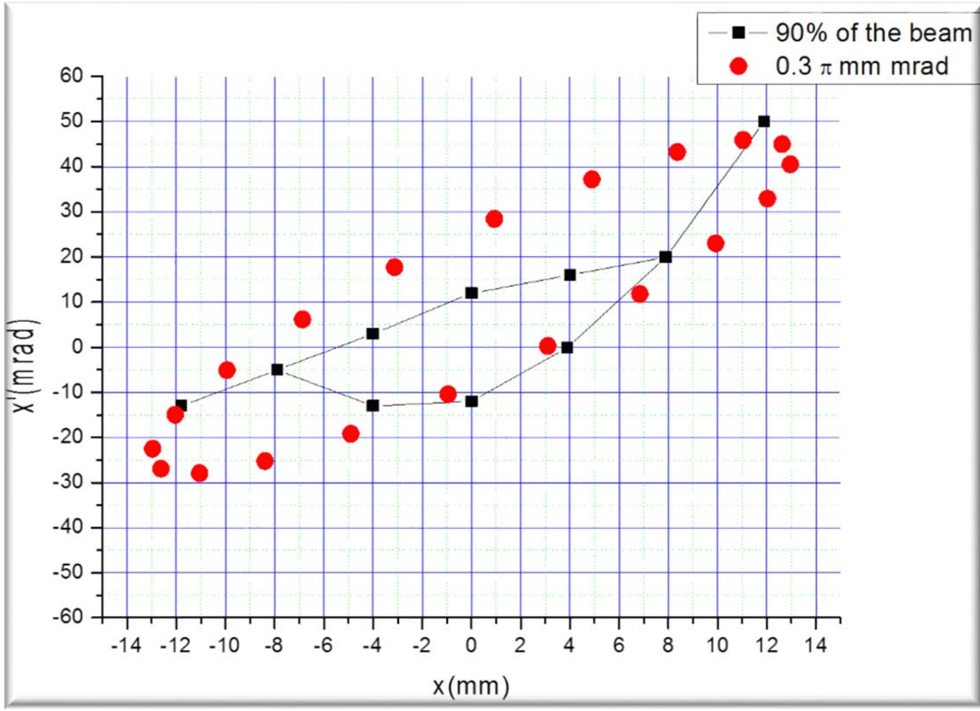



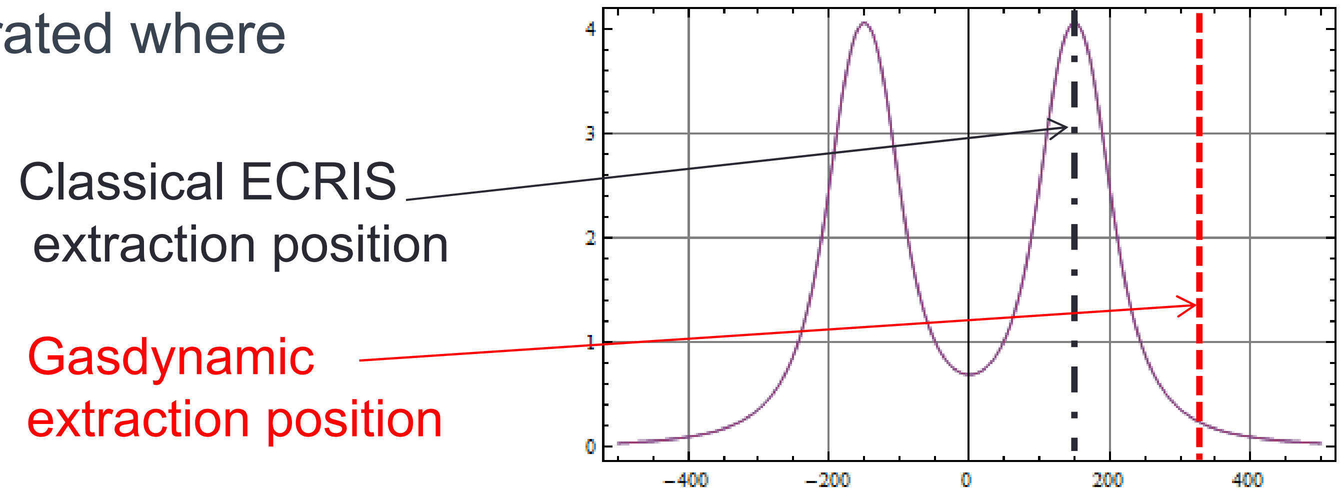



# $H^+$ Emittance measurement

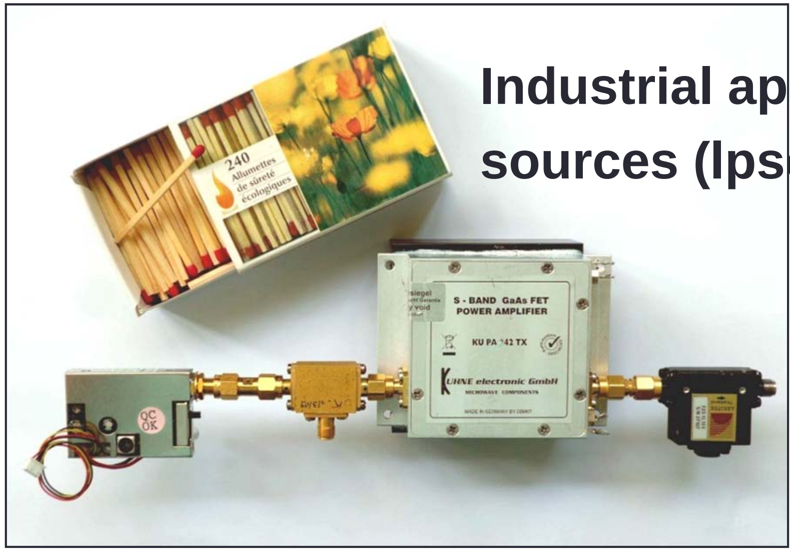
- SMIS 37 Beam emittance
  - 450 mA H+
  - Current density~600 mA/cm2
  - 90% norm. Emittance is 0.3 π.mm.mrad
    - So RMS norm. Emittance~0.06 π.mm.mrad
- Why is the emittance so small?
  - Because the magnetic emittance is small!
  - plasma drifts far out of the magnetic trap and the beam is accelerated where B<<Bmax



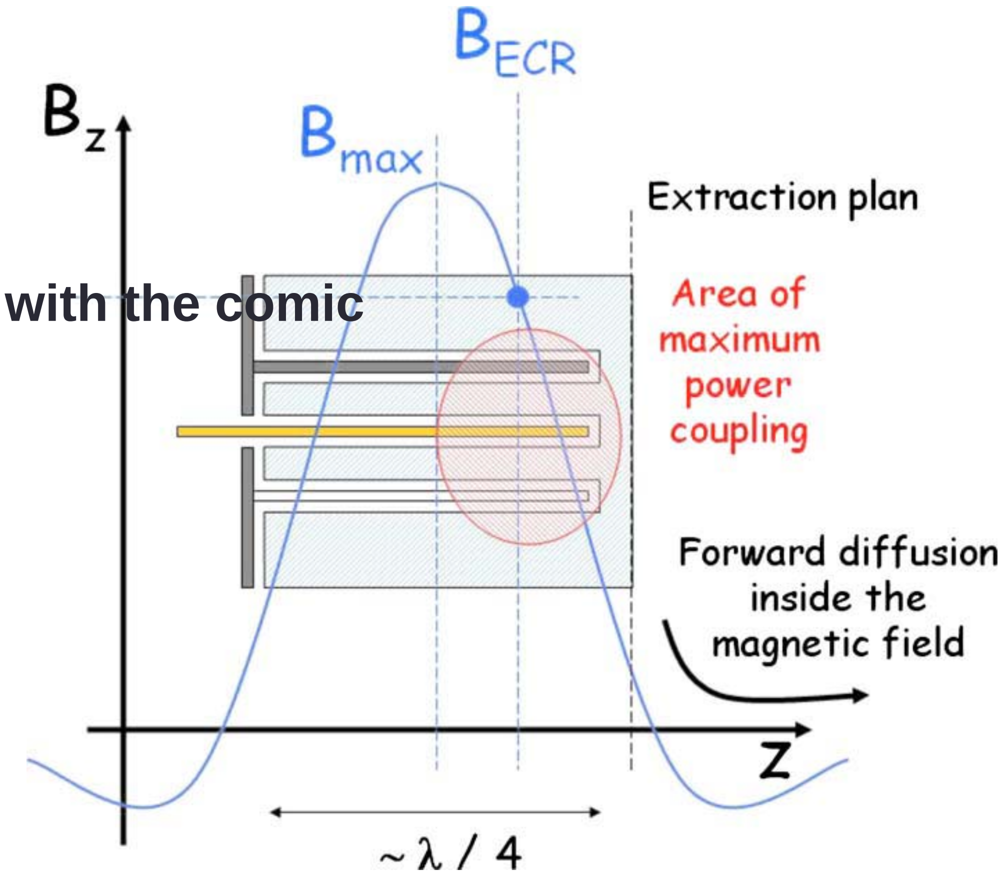



# COMIC sources at LPSC

- COMIC 2.45 GHz
  - Compact ECR source operated at low power
  - 10 W solid amplifier

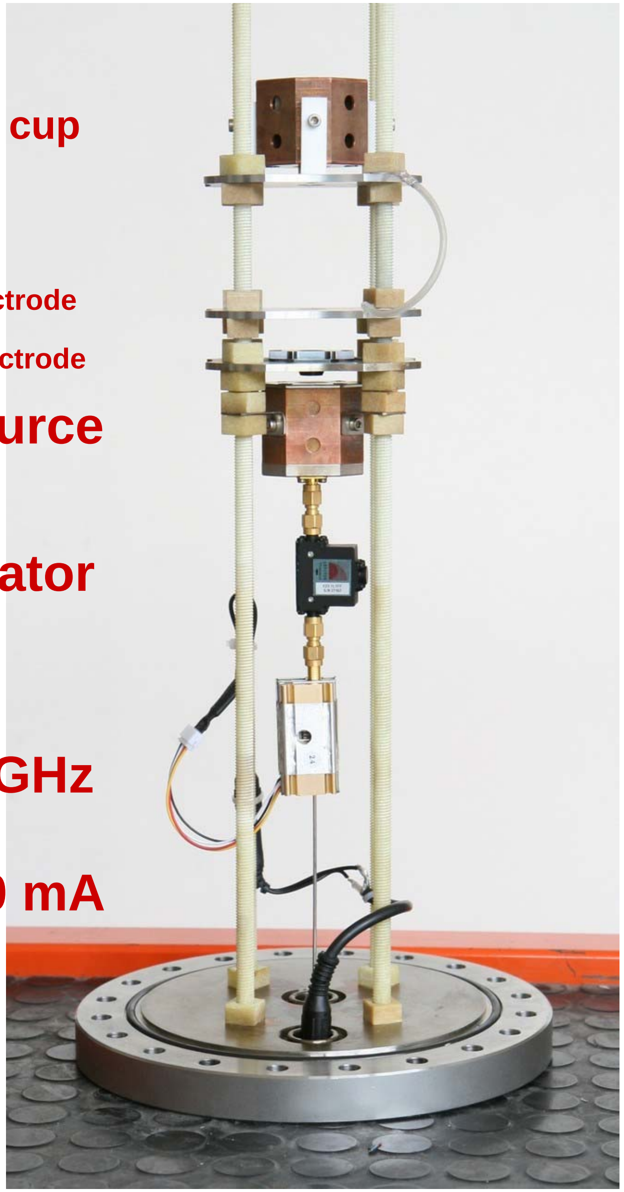



**Industrial applications with the comic sources (lpsc)**

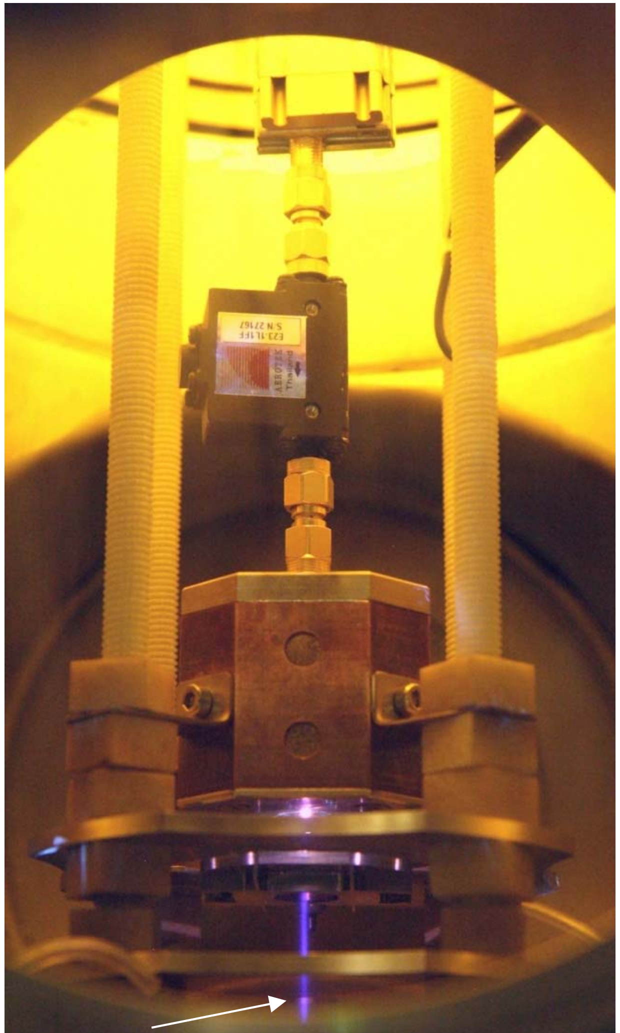



27 mm

# COMIC 2.45 GHz



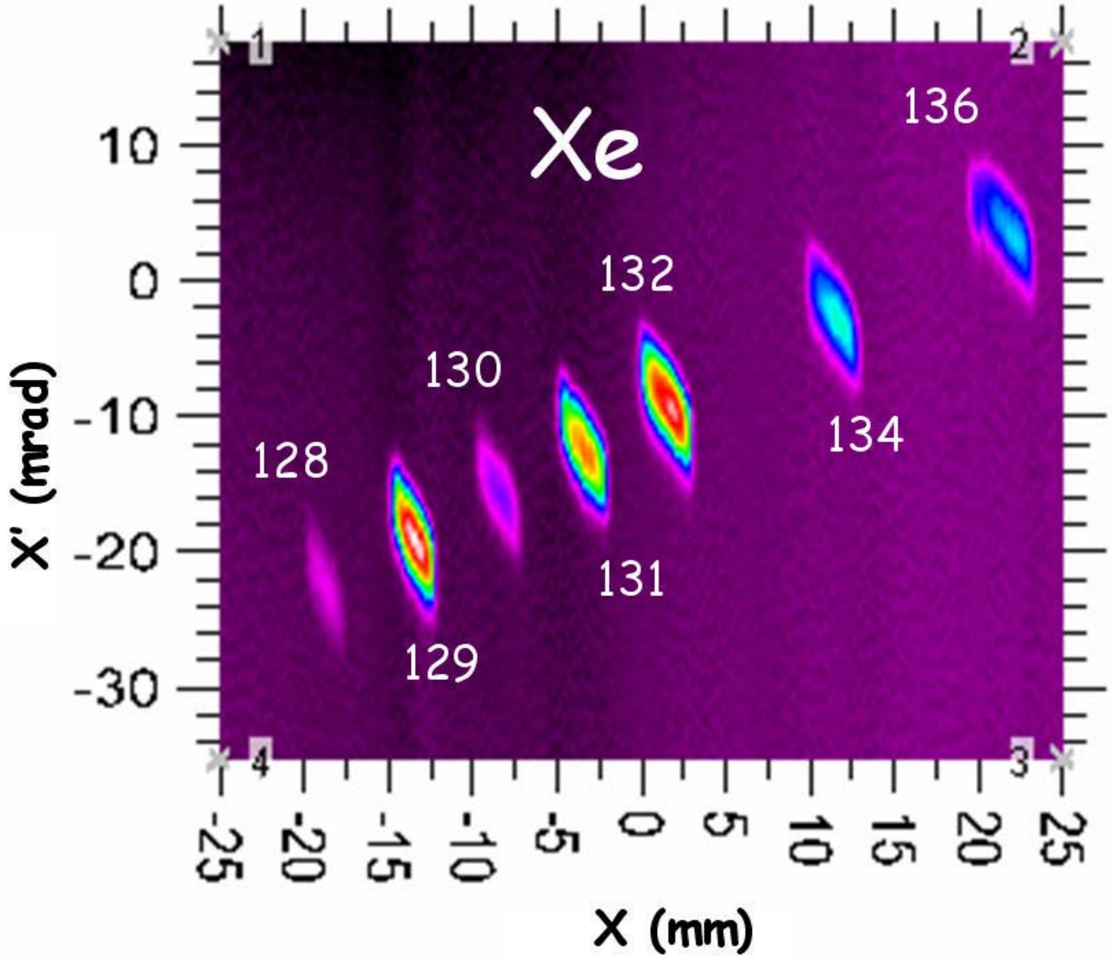

- 1W vacuum ECRIS



Ar - 24 µA - Φ 1 mm - 20 KV (18 KV) - 1 W- ~ 3 mA/cm²

# COMIC 2.45 GHz

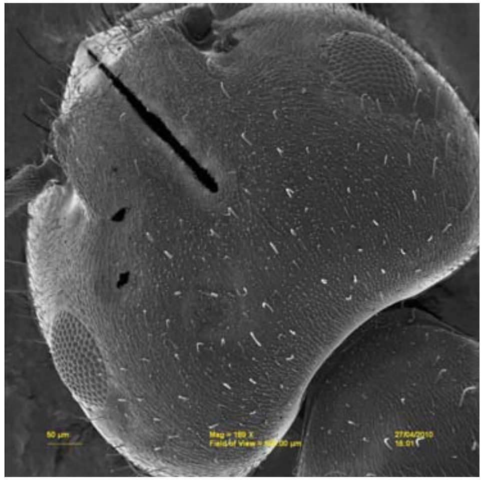
- Emittance - Xenon – 1.8 µA tot / 3 W / Ø 0.3 mm /15 kV



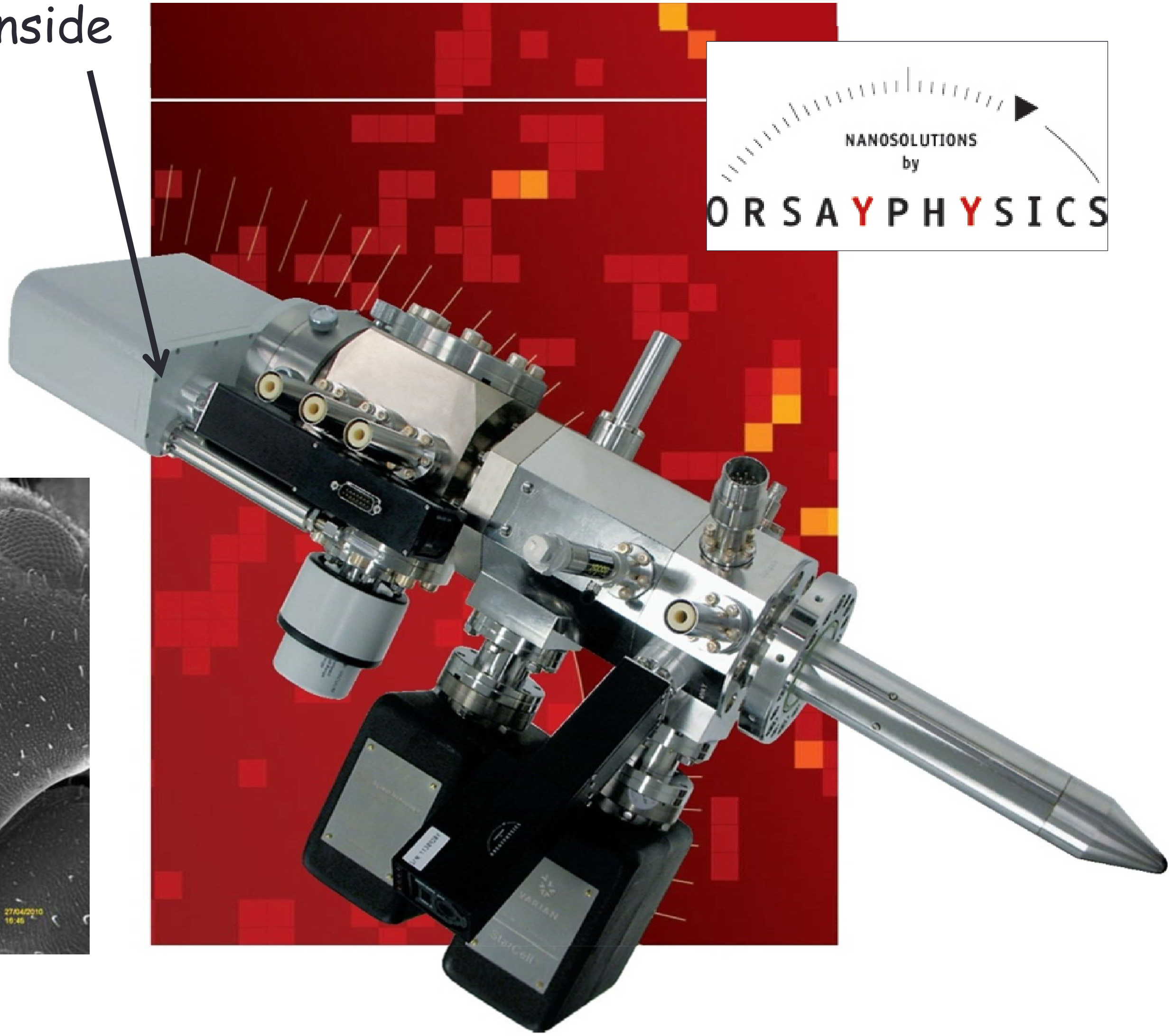

1 σ RMS
1.2 π.mm.mrad
15 KV
3/10 mm ext.

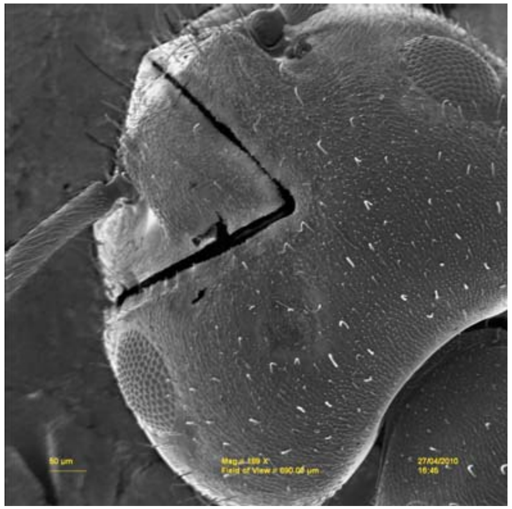
# COMIC Application on a Focusing Ion Beam

- Orsay Physics FIB



COMIC source inside

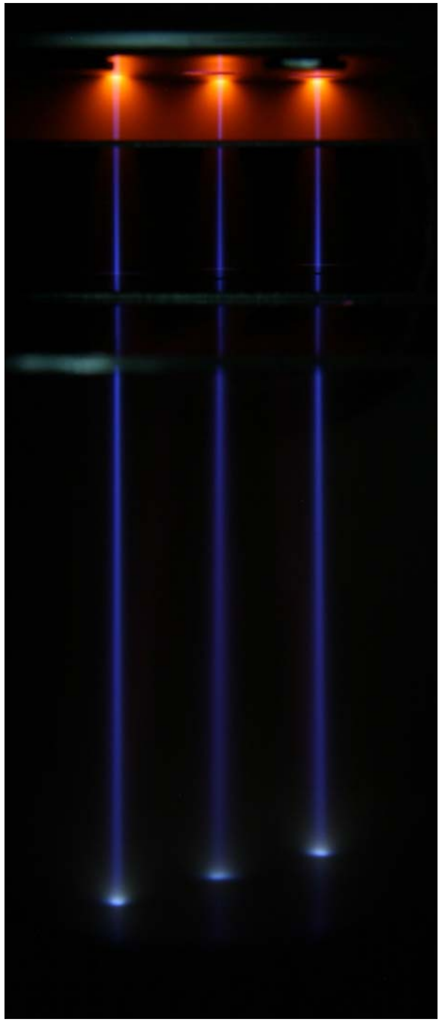


Microsurgery
Of an ant head

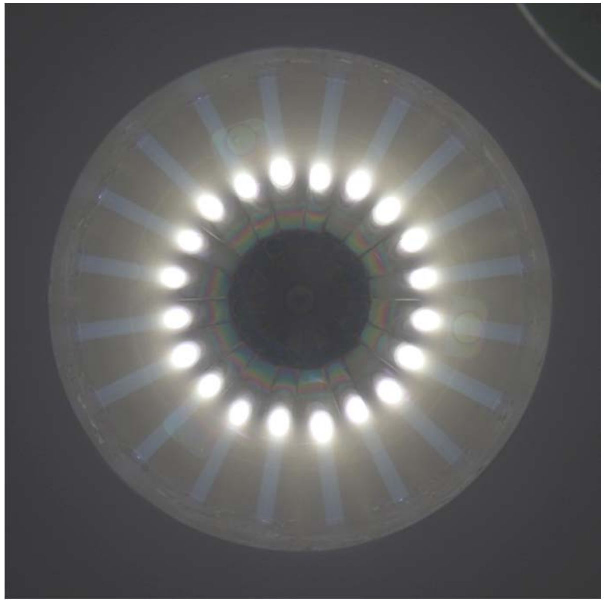
# COMIC Application for Implantation

- Multi-beam implanter 10 sources (HV>30 kV)

# COMIC Application for thin film deposition

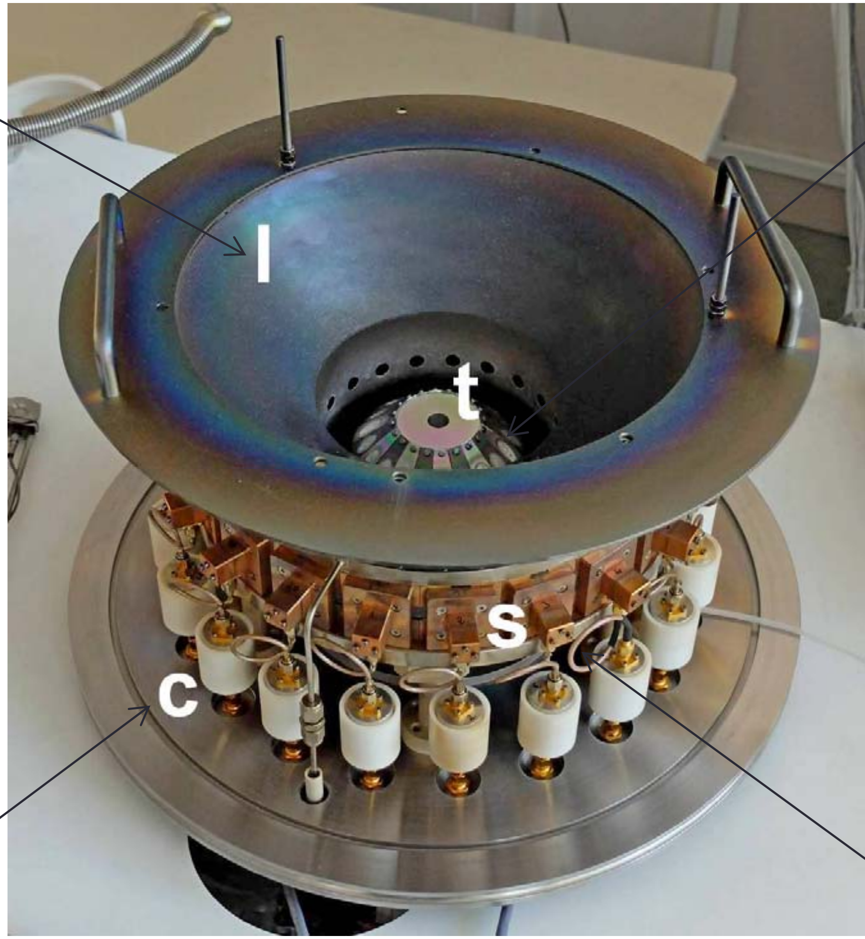
- Multi-Beam Sputtering  with 20 ECR sources



Ø100 mm
substrate

Liner

20Targets

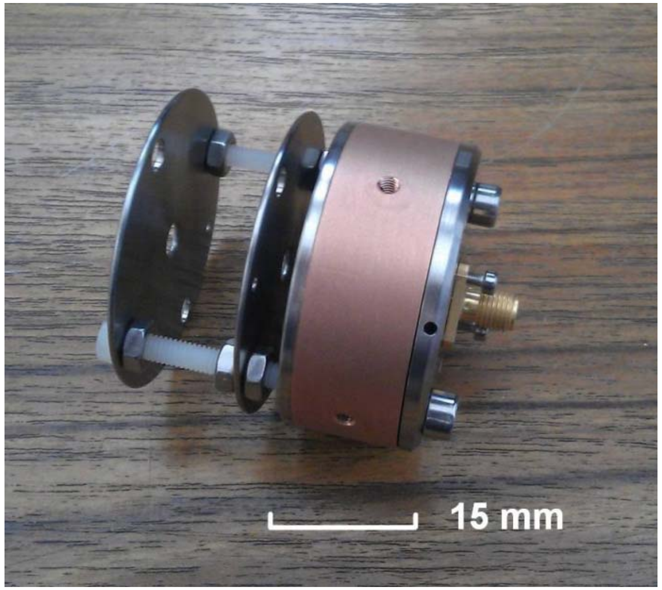


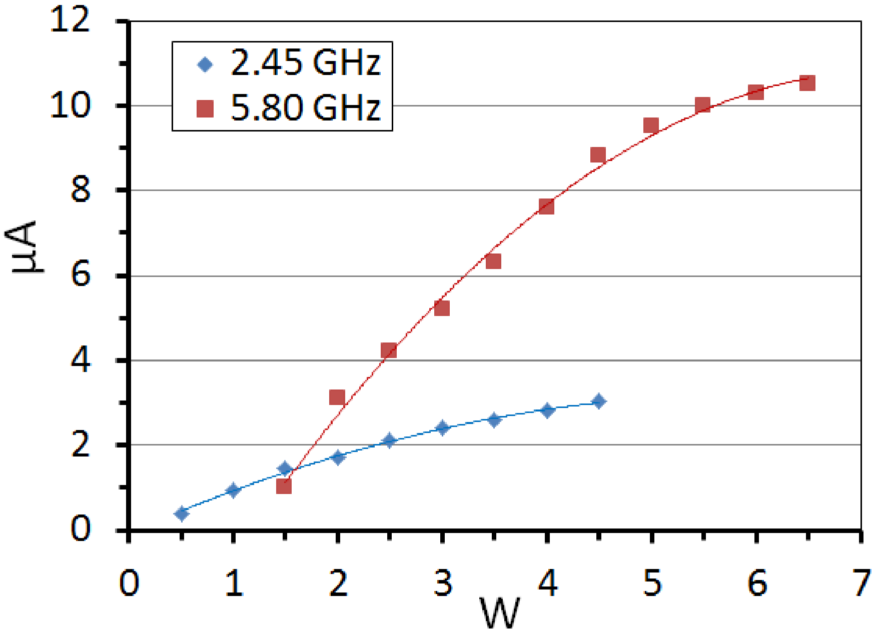

Coupler
insulator

20 ECR
sources

# COMIC 5.8 GHz

- The Goal is to improve the current density (ECR scaling law)
  - Quarter wave cavity down-scaled from 2.45 to 5.8 GHz
  - A clear current increase is observed
    - Higher plasma density

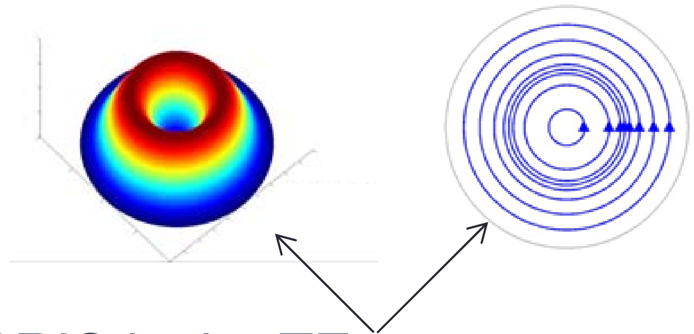


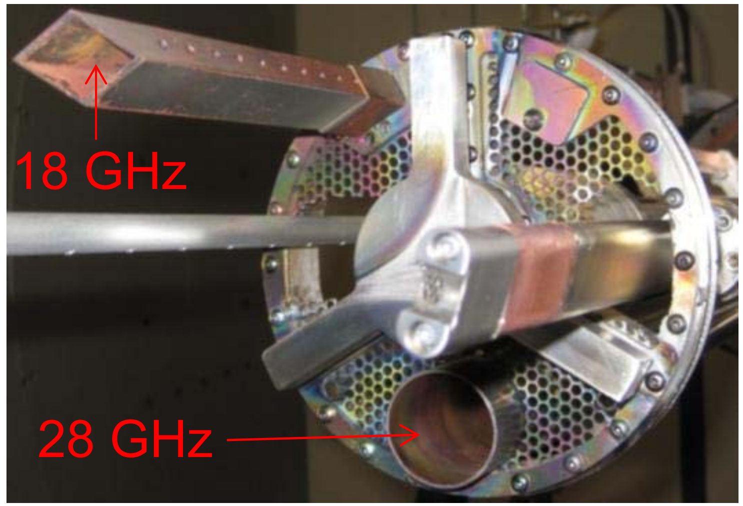




15 kV- Ø 0.3 mm extraction - Ar gas pressure:
$2\times10^{-6}$ mbar at 2.45 GHz
$1\times10^{-5}$ mbar at 5.8 GHz

# $TE_{01}$ to $HE_{11}$ Mode Converter for the VENUS ECR Ion Source

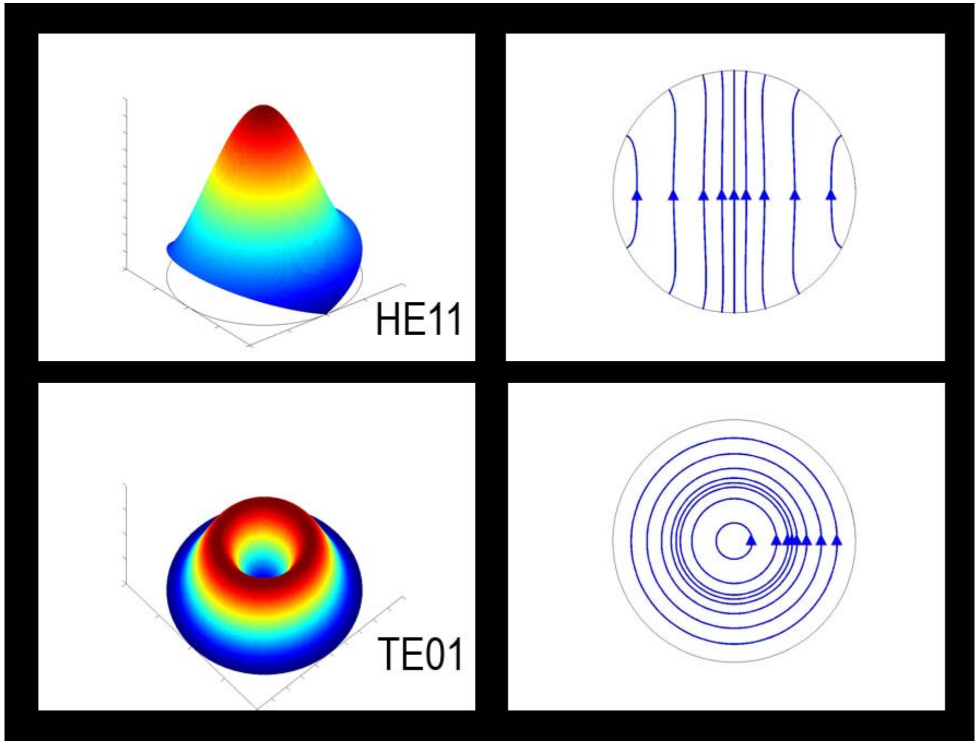
- Motivations:
  - The usual 18 GHz mode injected in an ECRIS is the $TE_{10}$
    - Transverse Electric, linearly polarized
    - Rectangular waveguide
    - Efficient plasma coupling
    - Excellent performance vs RF power
  - The 24/28 GHz mode injected in new generation ECRIS is the $TE_{01}$
    - Oversized circular waveguide
    - Transverse Electric circular polarization
    - The RF power density profile is hollow
    - Weaker performance vs power observed /18 GHz
  - Is this weaker performance coming from the $TE_{01}$ mode used?





# $HE_{11}$ mode vs $TE_{01}$

- The $HE_{11}$ mode is used in fusion research since the 80's
  - $HE_{11}$=Hybrid Electric~85%$TE_{11}$+15%$TM_{11}$
  - Quasi gaussian beam profile with a linear polarization



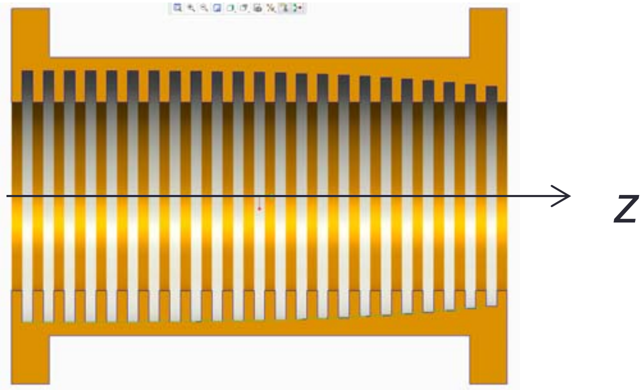

- The $HE_{11}$ @ 28 GHz is nearly equivalent to the $TE_{10}$ @ 18 GHz

# $HE_{11}$ conversion steps

- The mode conversion is done into two steps:

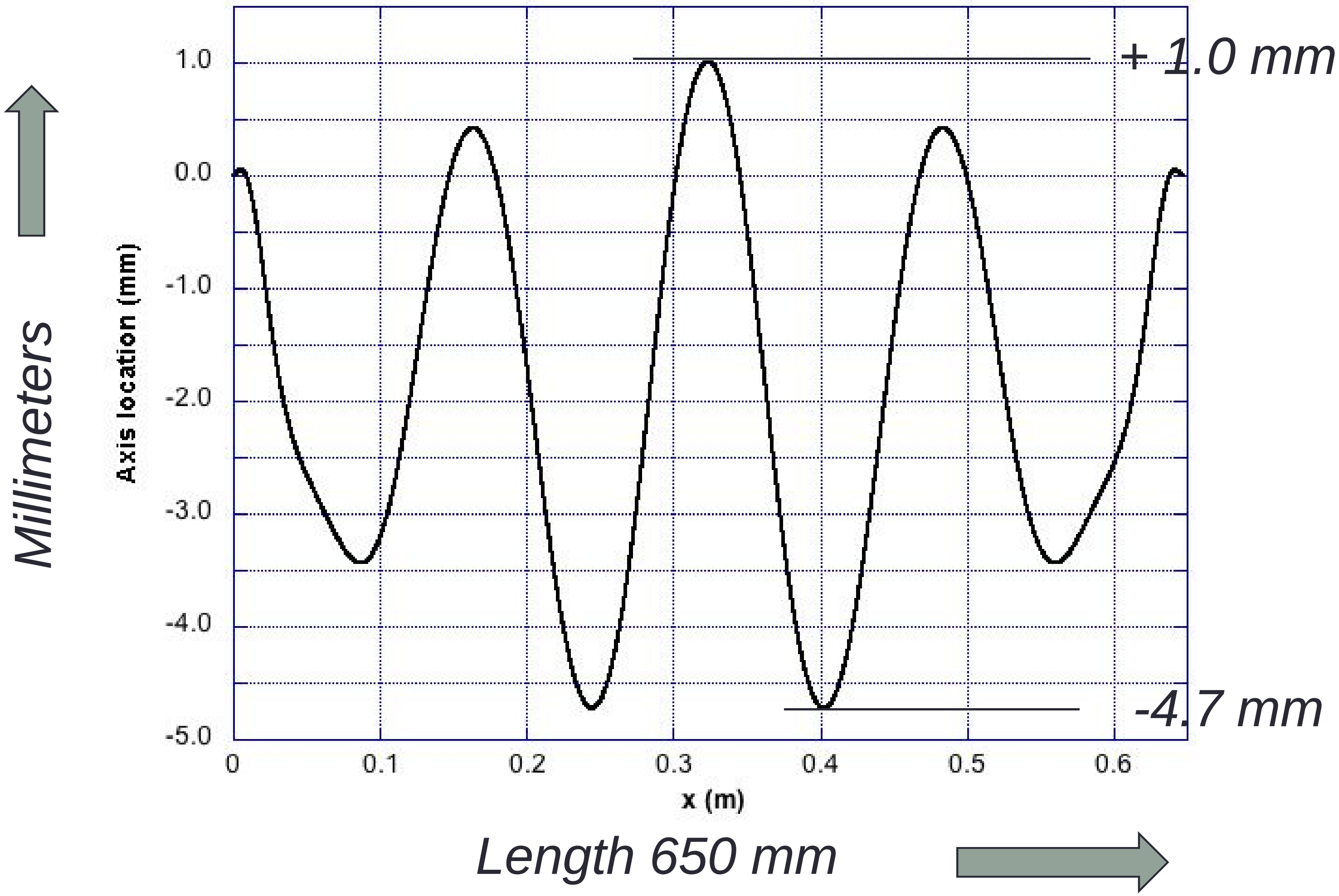
1) Convert the $TE_{01}$ to $TE_{11}$ using a circular waveguide whose center is wiggling in a direction perpendicular to the waveguide axis. This is the « **Snake** ».

2) Convert partially the $TE_{11}$ to $TM_{11}$ to build up the $HE_{11}$ in a corrugated waveguide whose groove depth is following a special curve from λ/2 to λ/4

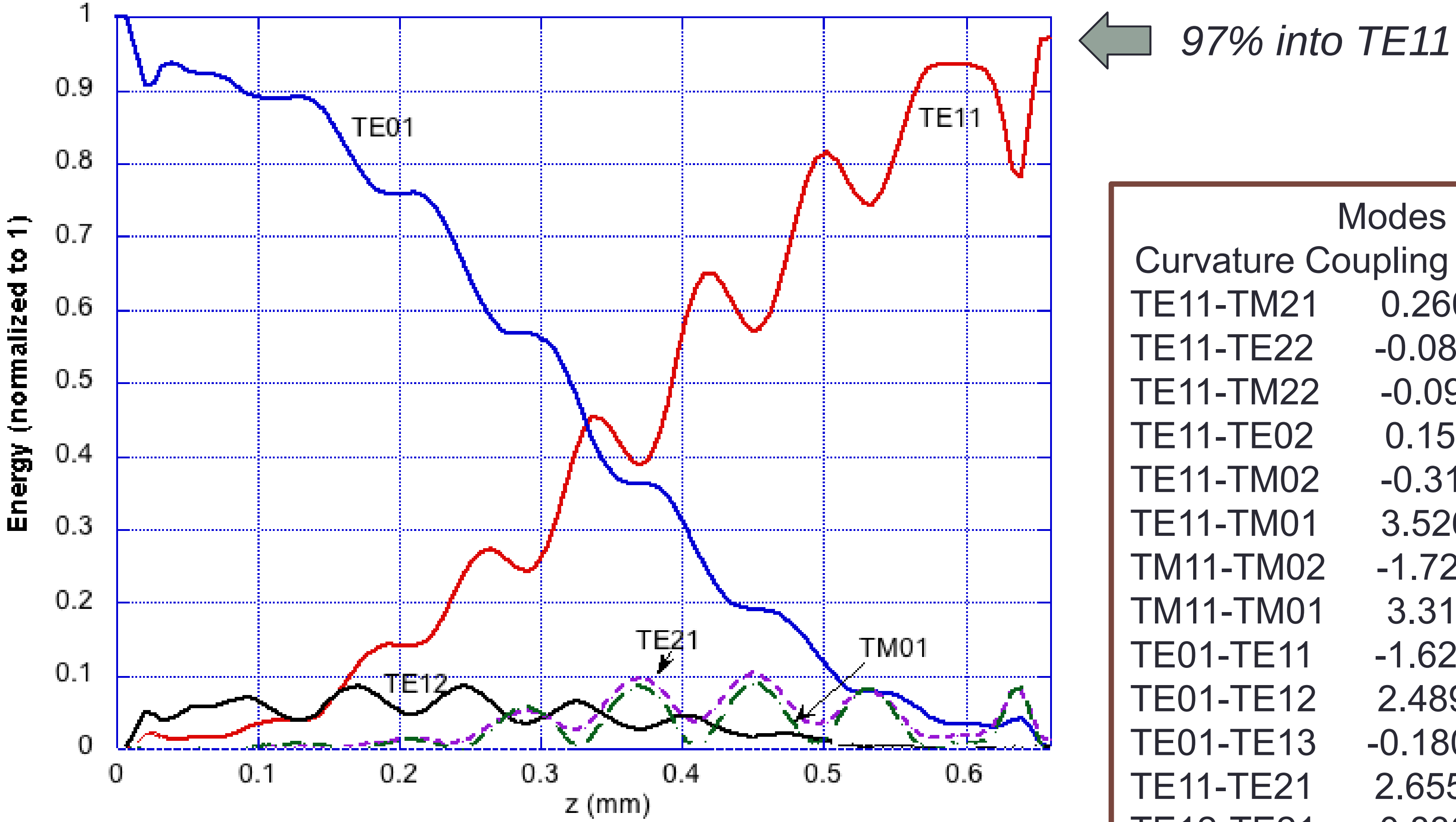


# Snake optimum profile

- Obtained by a simulation program

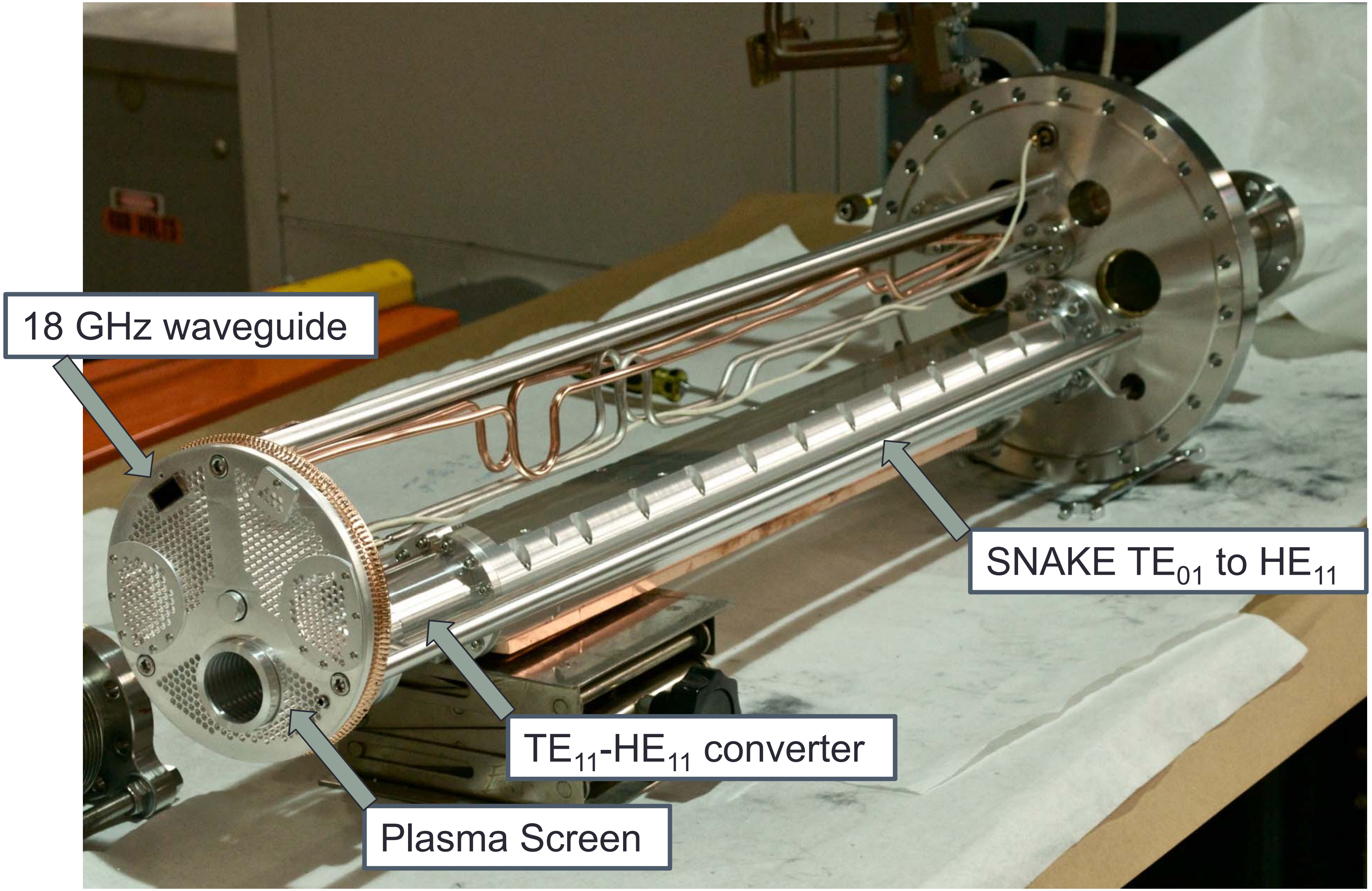


# Snake calculated mode conversion profile




| Modes | |
|---|---|
| Curvature Coupling Coefficients | |
| TE11-TM21 | 0.2605380 |
| TE11-TE22 | -0.0883540 |
| TE11-TM22 | -0.0970206 |
| TE11-TE02 | 0.1590250 |
| TE11-TM02 | -0.313236 |
| TE11-TM01 | 3.5267400 |
| TM11-TM02 | -1.724160 |
| TM11-TM01 | 3.3100900 |
| TE01-TE11 | -1.6289790 |
| TE01-TE12 | 2.489450 |
| TE01-TE13 | -0.1800641 |
| TE11-TE21 | 2.6557800 |
| TE12-TE21 | -0.8366008 |
| TE01-TM11 | 1.7056530 |
| TM11-TE21 | 1.4960860 |
| TM11-TM21 | 2.4503221 |

# New VENUS Injection Assembly

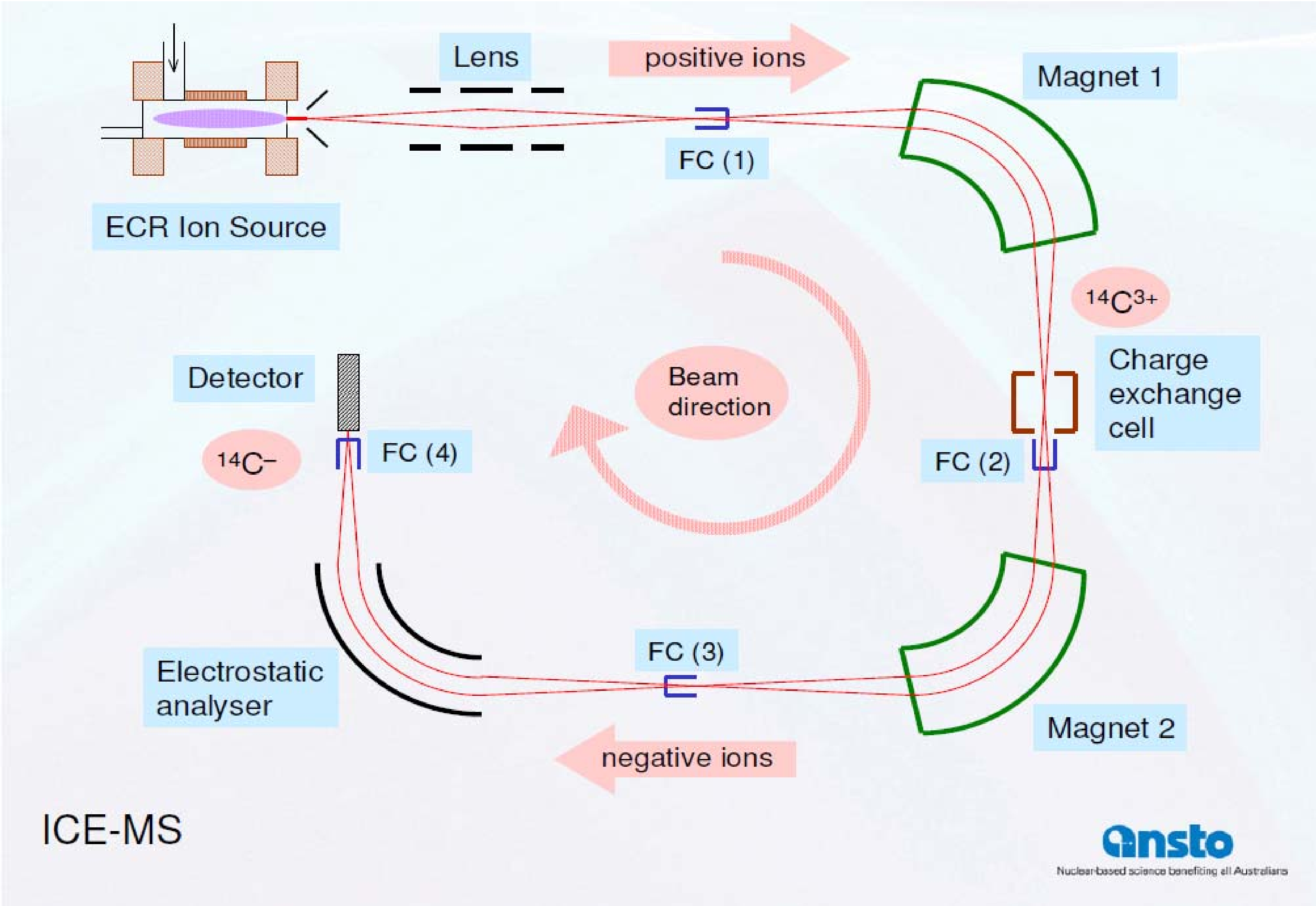


# Initial tests with the HE11 mode launcher

- Installation beginning of August 2013
- It has preformed very well in the early tests.
  - Up to 5 kW of power
  - No problems with arcing or parasitic mode generation
- Compared to the old system
  - Tuning appears to be broader
  - Smoother dependence on 28 GHz power (more monotonic)
  - Maximum $Xe^{27+}$ test at 5 kW of 28 GHz only
    - $TE_{01}$ mode launcher 330 μA
    - $HE_{11}$ mode launcher 370 μA
  - Some indications of improvements when used in two frequency mode with the 18 GHz
- Further development is needed see if $HE_{11}$ mode launching has significant advantages over $TE_{01}$ mode
  - VENUS has an enormous range of settings, ions and power levels
  - As Geller said, "Tuning an ECR ion source is searching for an island of stability in a sea of turbulence." This will take some time.

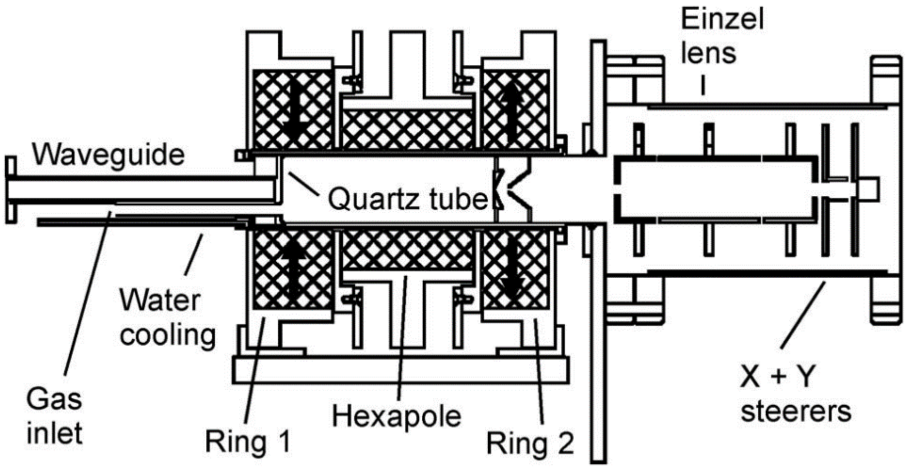
# The Ion Charge Exchange Spectroscopy at ANSTO

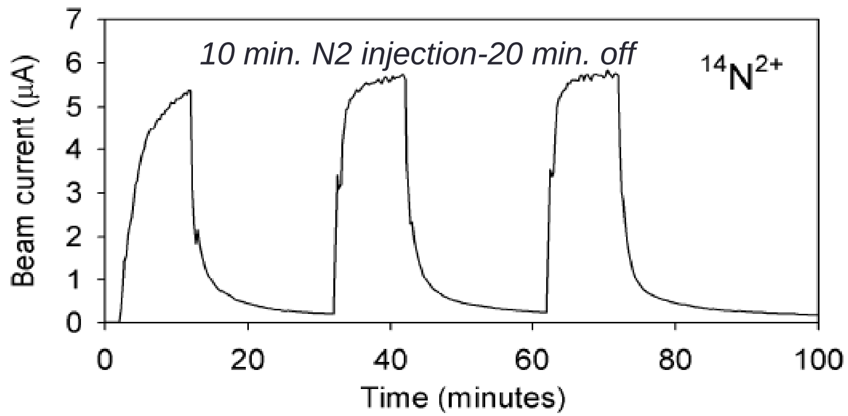
- 7 GHz ECRIS
  - Quartz tube
  - Volume 300 ml
  - P<100 W
- $^{14}C$:$^{12}C$ ratio measurement down to $10^{-9}$
- Charge 3+
  - $^{14}N^{3+}$ rejection
  - Molecule rejection ($^{13}CH$, $^{12}CH_2$..)
- Online transient $^{14}C$:$^{12}C$ ratio count foreseen for medical application
- Limitations:
  - Reproducibility
  - Ion residence time in plasma chamber
  - background

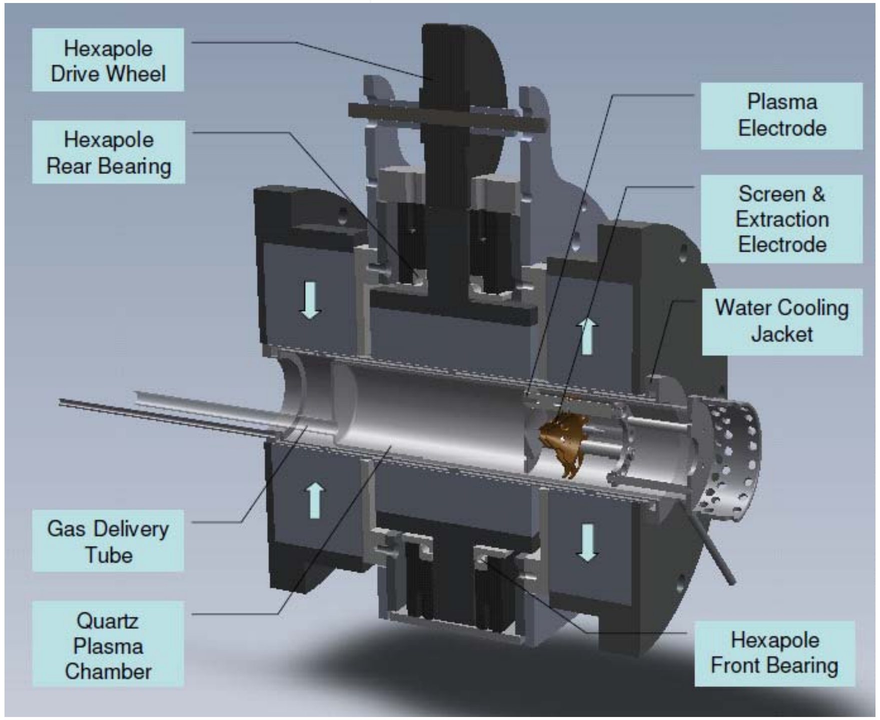


# Source upgrade

- Hexapole rotation to enhance desorption from the plasma chamber walls



# Thank you for your attention!