ECOS: European COllaboration on Stable ion beams

European Nuclear Science and Applications Research ENSAR Within the Seventh Framework Programme of the European Commission

Status and perspectives of high power ion sources

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CNRS IN2P3 Les deux infinis

Grenoble INP

High power ion sources

High power = high intensity and high charge state at a 'reasonable' extraction voltage

Ion source list from Martin Stockli (ORNL-SNS, USA)

- Bayard-Alpert type ion source
- Electron Bombardment ion source
- Hollow Cathode ion source
- Reflex Discharge Multicusp source
- Cold- & Hot-Cathode PIG
- Electron Cyclotron Resonance ion source (ECR)
- Electron Beam Ion Source (EBIS)
- Surface Contact ion source
- Cryogenic Anode ion source
- Metal Vapor Vacuum Arc ion source (MEVVA)
- Sputtering-type negative ion source
- Plasma Surface Conversion negative ion source
- Electron Heated Vaporization ion source
- Hollow Cathode von Ardenne ion source
- Forrester Porus Plate ion source
- Multipole Confinement ion source
- EHD-driven Liquid ion source
- Surface Ionization ion source
- Charge Exchange ion source
- Inverse Magnetron ion source
- Microwave ion source
- XUV-driven ion source
- Arc Plasma ion source
- Capillary Arc ion source
- Von Ardenne ion source
- Capillaritron ion source
- Canal Ray ion source
- Pulsed Spark ion source
- Field Emission ion source
- Atomic Beam ion source
- Field Ionization ion source
- Arc Discharge ion source
- Multifilament ion source
- RF plasma ion source
- Freeman ion source
- Liquid Metal ion source
- Beam Plasma ion source
- Magnetron ion source
- Nier ion source
- Bernas ion source
- Nielsen ion source
- Wilson ion source
- Recoil ion source
- Zinn ion source
- Duoplasmatron
- Duopigatron
- Laser ion source
- Penning ion source
- Monocusp ion source
- Bucket ion source
- Metal ion source
- Multicusp ion source
- Kaufman ion source
- Flashover ion source
- Calutron ion source
- CHORDIS

Main sessions of the last International Conference on Ion Sources September 2011, Giardini Naxos - Italy

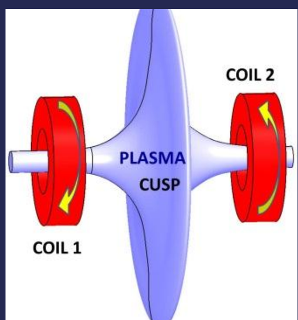
Negative Ion Sources	
Ion Sources for Fusion	
High intensity proton and deuteron ion sources	
Electron Beam Ion Sources	Pulsed
Laser Ion Sources	Pulsed
Electron Cyclotron Resonance Ion Sources	cw or pulsed
1+ ion sources for radioactive ions	
Charge breeders	cw or pulsed
Ion sources for industrial applications	

Scope of the talk

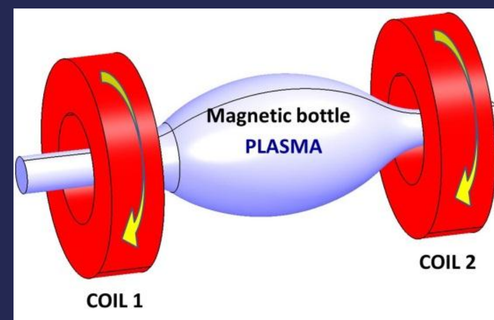
- Negative Ion Sources
- Ion Sources for Fusion
- High intensity proton and deuteron ion sources
- Electron Beam Ion Sources — Pulsed
- Laser Ion Sources — Pulsed
- Electron Cyclotron Resonance Ion Sources — cw or pulsed
- 1+ ion sources for radioactive ions
- Charge breeders — cw or pulsed
- Ion sources for industrial applications
- ...

How to build high power 'Minimum B' ECRIS

- Science demands :
  - Higher and higher intensities and charge states (1 mA Ar^{12+}, 500 µA U^{35+}...)
- Find a compromise (characteristics and costs) between
  - ECR frequency and power, plasma volume, magnetic field configuration and technology
  - Examples of magnetic field configurations

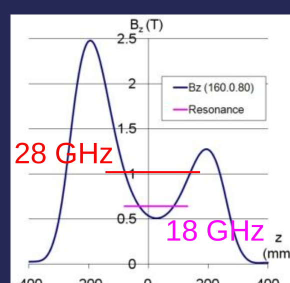


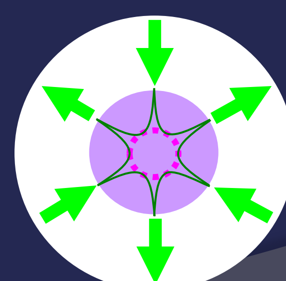
CUSP
Simple, low cost
MHD stable
Plasma leaks

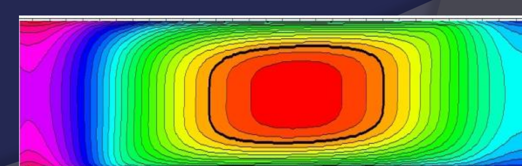


Magnetic bottle
MHD unstable

Minimum B magnetic bottle with radial field MHD stabilization, high confinement



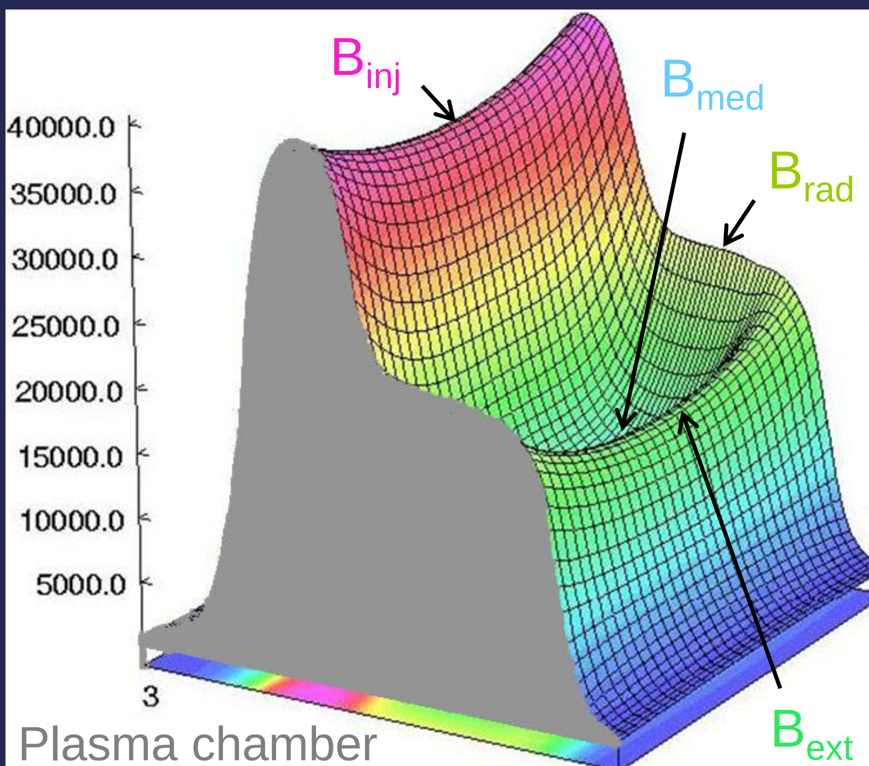




$\omega_{ce} = q_e B / M_e = \omega_{HF}$ | B axial | + | B radial | = | Minimum B

Towards high power ECR ion sources
Present status

- Minimum B magnetic structures
  - Ion extracted intensity I_i is
    - Proportional to plasma density (n_e) and plasma volume (V_p), $n_e \propto (\omega_{ce} = \omega_p)^2$ or B^2
    - Inversely proportional to ion life time (τ_i)
- Semi-empirical 'minimum B' scaling laws *to favor high <q> and I_i:*



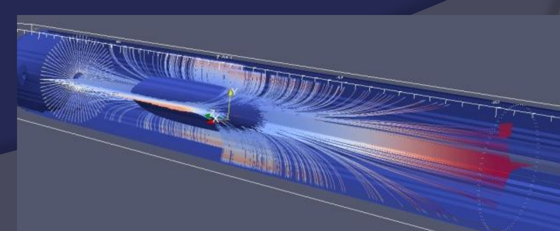
ECR scaling laws

$B_{inj} \approx 4 * B_{ECR}$

$B_{rad} \approx 2 * B_{ECR}$

$B_{med} \approx 0.6\ B_{ECR}$

$B_{ext} \approx 0.9\ B_{rad}$



Towards high power ECR ion sources
Present status

- Presently ‘almost’ no novel concept

$I_i \propto (\omega_{ce})^2$ so B^2...

  - ECR frequency increase in order to increase the plasma density
  - 10, 14, 18, 24, 28 GHz (the highest in a minimum B magnetic structure)...
  - 24, 28 GHz superconducting prototypes design and constructions
    - ✓ First 28 GHz ECR plasmas: PHOENIX LPSC-Grenoble and SERCE LNS-Catania

$\omega_{HF} = \omega_{ce} = 28$ GHz

$B_{ecr} = 1$T

$B_{inj} \approx 4$ T

$B_{rad} \approx 2$T

$B_{med} \approx 0.6$ T

$B_{ext} \approx 0.9$ T

Superconducting
Magnetic structures
But
High gradients
And
High mechanical stress

(~ 8 M€)

  - No one is decided to let us play with such expensive and sophisticated objects
  - The game is to develop a cost effective and confident magnetic structure
  - ‘Min B’ Prototypes design and simulations at 50-56 GHz, $B_{inj} > 7$ T, $B_{rad} > 3.5$ T

- Presently there is no ambitious **experimental discovery research** program

A few projects status...

Present status of high power ECR ion sources
USA VENUS (I)

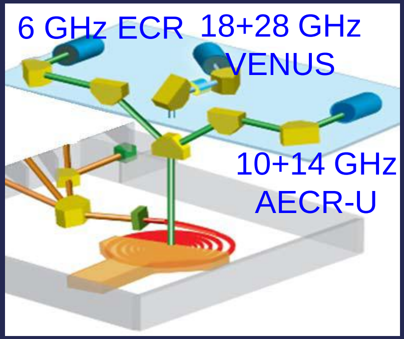
LBNL Berkeley, USA : J. Y. Benitez et al., Rev. Sci. Instrum. 83, 02A311 (2012)

B_{inj} Max = 4 T B_{ext} Max = 3 T B_{rad} Max = 2.2 T

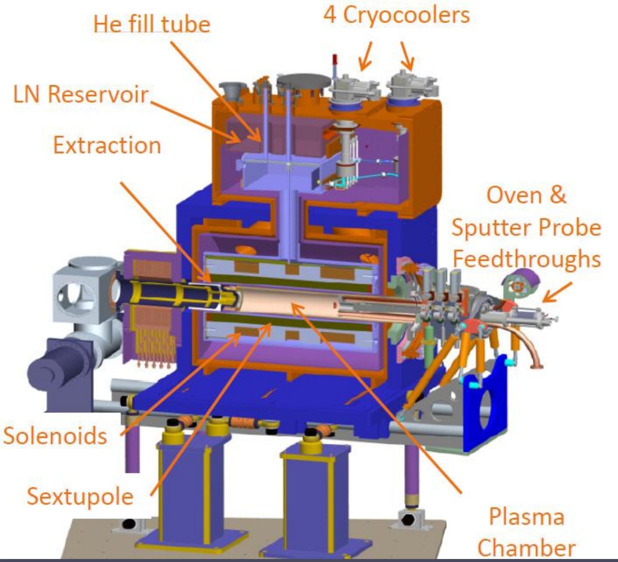
Plasma chamber Φ_{int} = 140 mm, L = 480 mm

P_{max} (18GHz) = 2kW - P_{max} (28GHz) =10kW (6.5 injected) (8.5 kW both)

88-Inch Cyc.

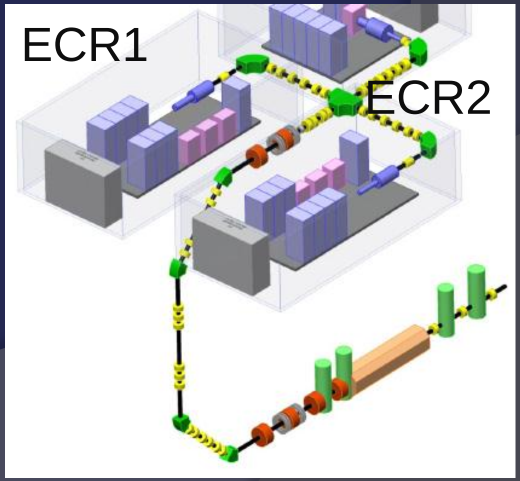


- Historically, first 3rd generation fully superconducting ECRIS
  - Excellent beam results (2.86 emA O^{6+}, 860 µA Ar^{12+})
  - 20 kV high voltage isolation
  - About 15 % of the cyclotron beam times since 2006



Considered as a prototype for FRIB
2 VENUS-like 28 GHz ECRIS will be installed

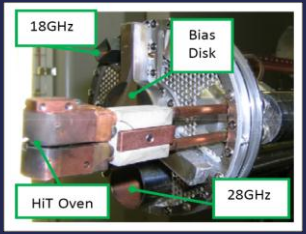
NSCL

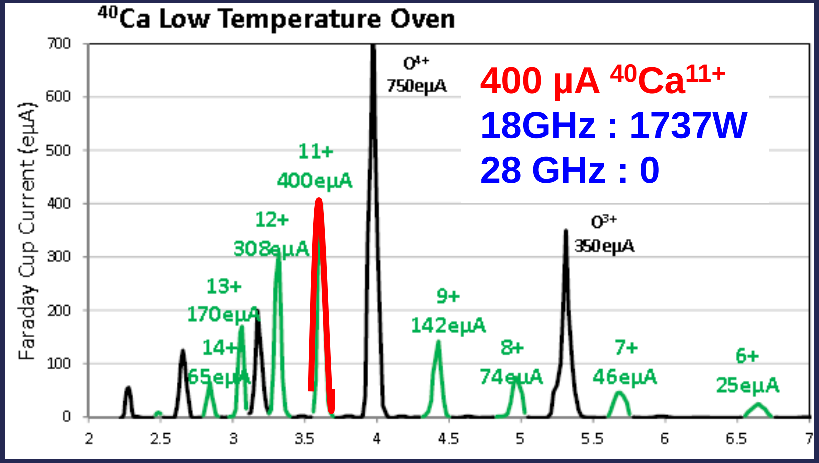


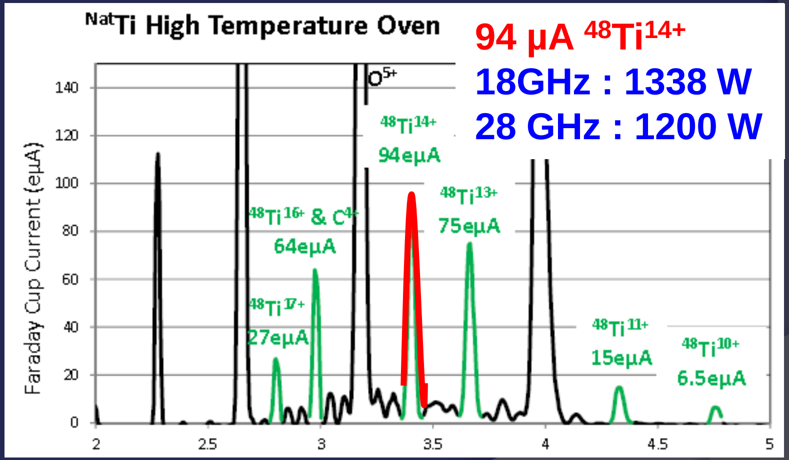
Present status of high power ECR ion sources
USA VENUS (II)

- Latest developments
  - Cocktail beams and high intensity metallic ion beams
    - ✓ Mixture of similar Q/A beams in the cyclotron (radiation and space effects testing)
    - ✓ Low (650°C) and high (2000°C) temperature ovens and sputter probe

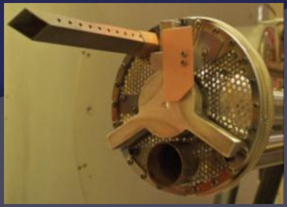






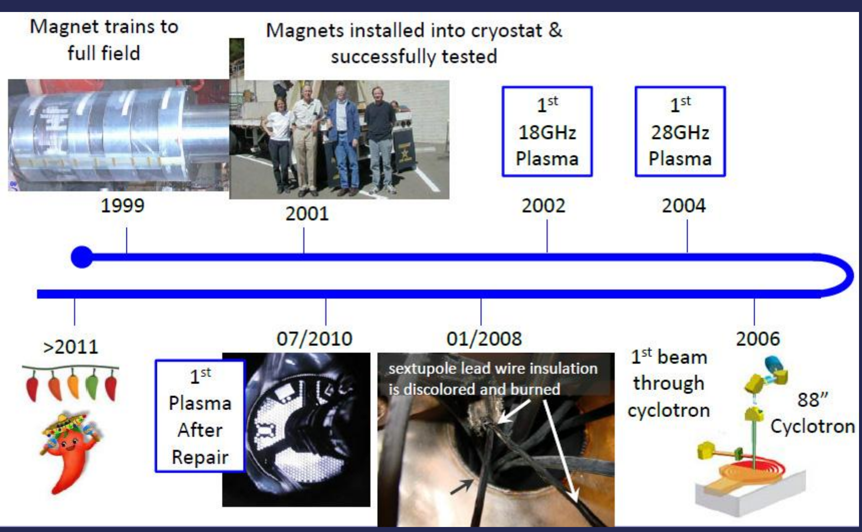


  - Experimental HF injection improvement
    - ✓ Objective : to improve the 28 GHz coupling



Present status of high power ECR ion sources
USA VENUS (III)

- VENUS operation (beams for the cyclotron : less than 19 months in 6 years)
  - ✓ Magnets reached full field 1999
  - ✓ First 18 GHz plasma 2002
  - ✓ First 28 GHz plasma 2004
  - ✓ Sept. 2006 : Production for cyclotron for 16 months
  - ✓ Jan. 2008 : sextupole leads destroyed (reparation 2.5 years)
  - ✓ 2010 about 3% of the beams delivered to the cyclotron, 2011 about 10 %



	Beam Current	Previous Record**	Method
$^{124}Xe^{30+}$	211eµA	152eµA	gas
$^{124}Xe^{42+}$	1eµA	0.4eµA	gas
$^{209}Bi^{31+}$	300eµA*		HiT Oven
$^{209}Bi^{50+}$	5.3eµA		HiT Oven
$^{16}O^{6+}$	3000eµA	2860eµA	Gas
$^{16}O^{7+}$	925eµA	850eµA	Gas
$^{40}Ca^{11+}$	400eµA		LoT Oven

*in collaboration with MSU

** before 07/2010

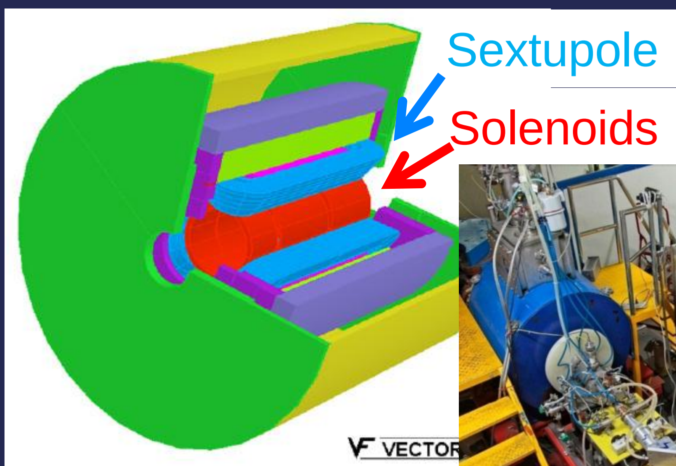
Present status of high power ECR ion sources
China SECRAL (I)

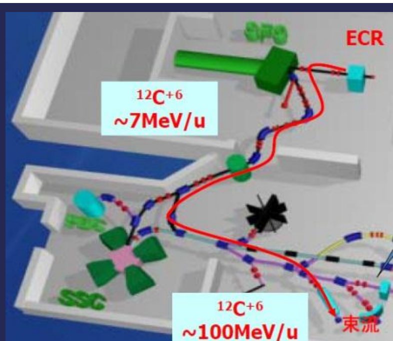
IMP Lanzhou, China: Zhao et al. Rev. Sci. Instrum. **83**, 02A320 (2012)

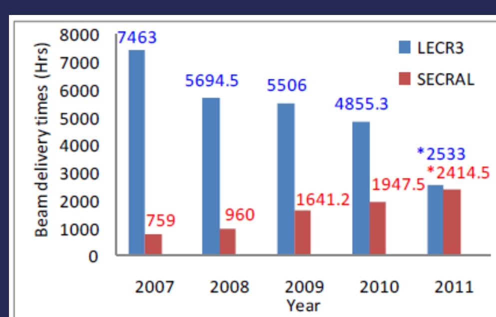
B_{inj} Max = 3.7 T B_{ext} Max = 2.2 T B_{rad} Max = 2 T

Plasma chamber Φ_{int} = 116 mm, L = 890 mm

P_{max} (18GHz) = 2kW - P_{max} (24GHz) =7kW







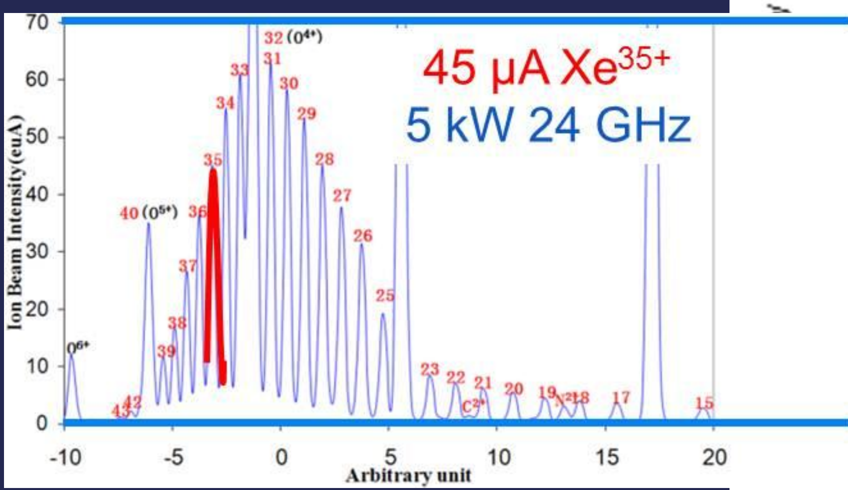
7720 hours cumulated

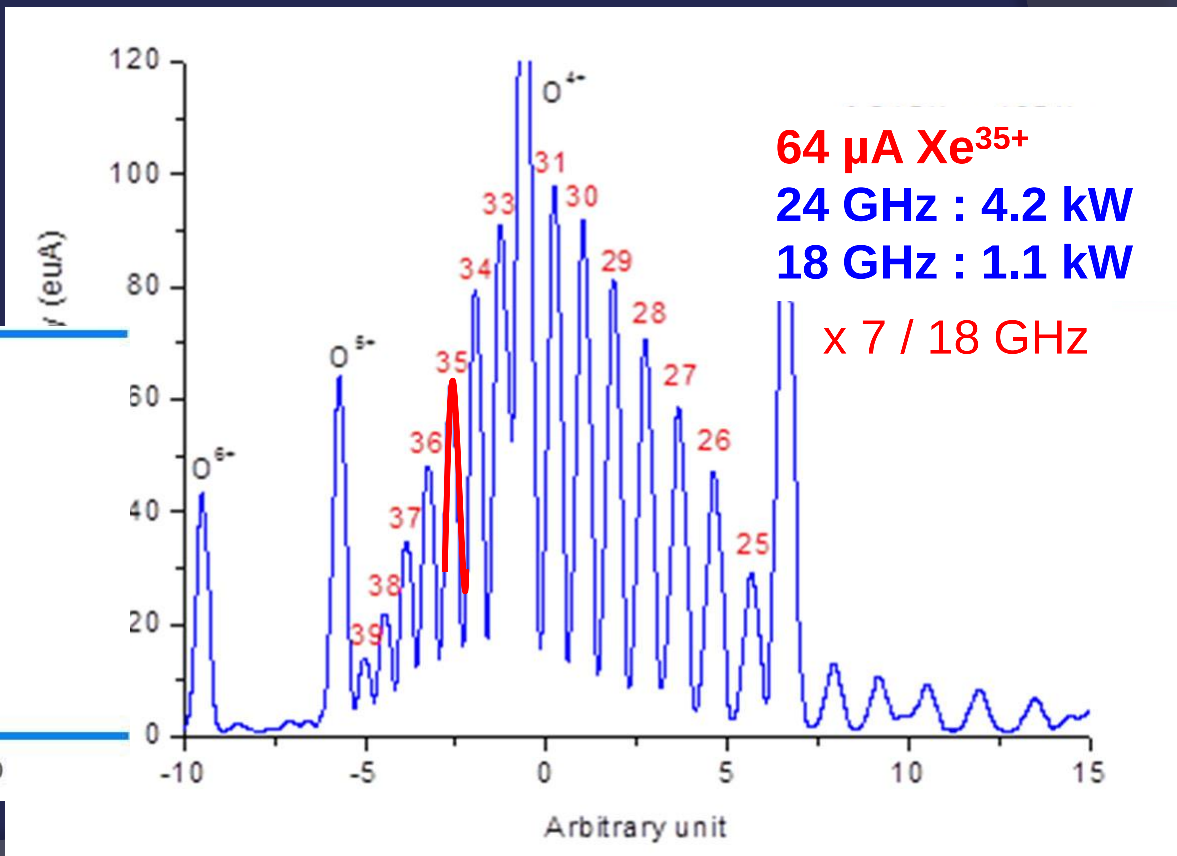
- In operation since 2007
  - Original superconducting structure (sextupole outside)
  - I(beams) comparable to VENUS but lower ω_{ce}
  - 30 kV high voltage isolation
- ECR frequency increase and multi frequencies
  - 18, 24, 18+24 (GHz)
  - Stainless steal or aluminum plasma chamber

Present status of high power ECR ion sources
China SECRAL (II)

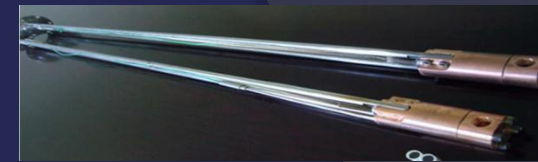
- Best results Xenon Binj = 3.4 T, Bmed = 0.65 T, Bext = 1.8 T, and Brad = 1.6 T
- (24+18) GHz + Al more stable than 24 GHz +St.S

9 µA Xe^{35+}	3.2 kW 18 GHz +St.S
14.5 µA Xe^{35+}	1.6 kW 18 GHz + 0.2 kW 14.6 GHz + Al

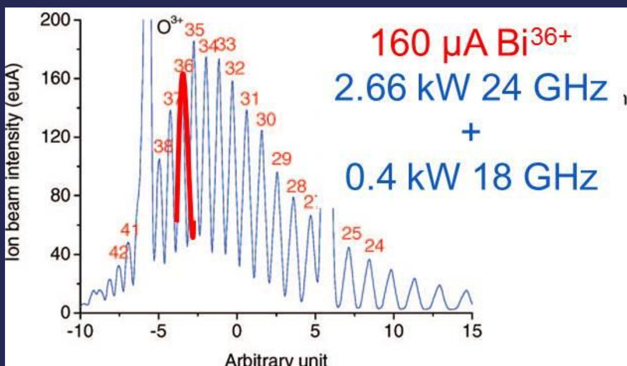


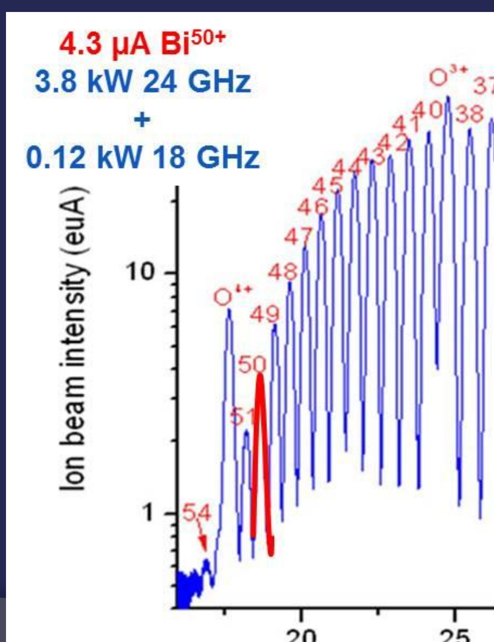


Present status of high power ECR ion sources
China SECRAL (III)



- Latest developments
  - high intensity metallic ion beams
    - Low (700°C), conventional (1600 °C) and high (2200°C) temperature ovens





Xe IONS	SECRAL 18GHz <3.2kW (eµA) 2007	SECRAL 24GHz-SS <5kW (eµA) 2009	SECRAL 24+18GHz-Al <6kW (eµA) 2011	VENUS 28+18GHz >6kW (eµA) 2010
26+	410			
27+	306	455		411
28+				
30+	101	152	236	211
31+	68	85	190	
33+				
34+	21			
35+	16	45	64	38
36+				
37+				
38+	6.6	17	22.6	12
42+	1.5	3		1

World records (may be not for normal operation)

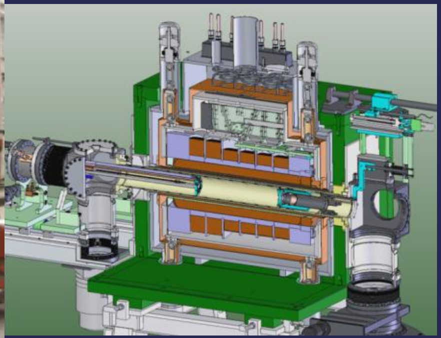
Present status of high power ECR ion sources
USA SuSI (I)

NSCL – MSU, USA : L. T. Sun. et al. Proceedings of ECRIS2010, Grenoble, France
http://accelconf.web.cern.ch/AccelConf/ECRIS2010/papers/mocoak02.pdf

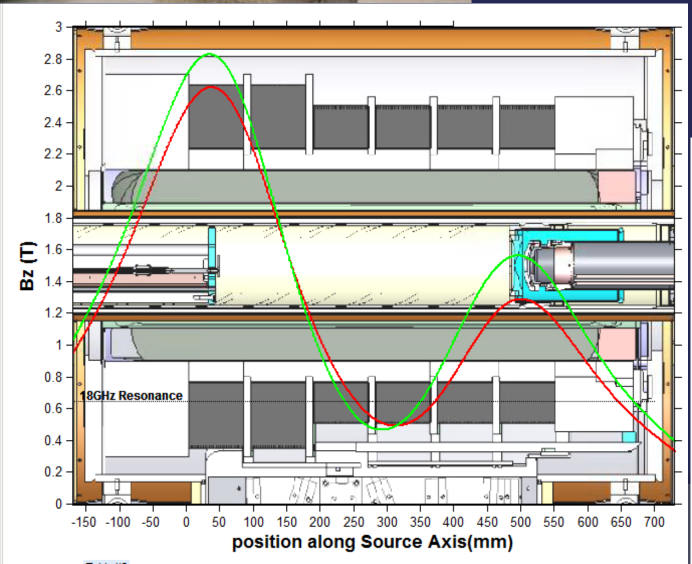
B_{inj} Max = 3.6 T B_{ext} Max = 2.2 T B_{rad} Max = 1.8 T

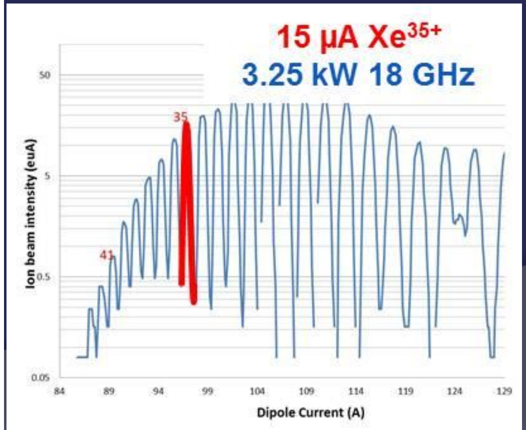
Plasma chamber Φ_{int} = 101 mm, L = up to 500 mm

P_{max} (18GHz) = 4 kW - P_{max} (24GHz) = 7 kW



- Versatile magnetic structure
  - 6 solenoids
    - ✓ Allow to vary length of the structure
    - ✓ 30 kV high voltage isolation
- 18 GHz HF power increase 2 to 4 kW
  - Performance increase like in SECRAL
- 24 GHz HF injection soon
  - ✓ Possibly the second source for FRIB



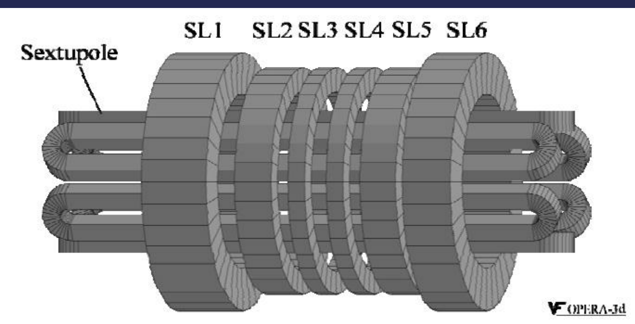


Present status of high power ECR ion sources
Japan SC-ECR (I)

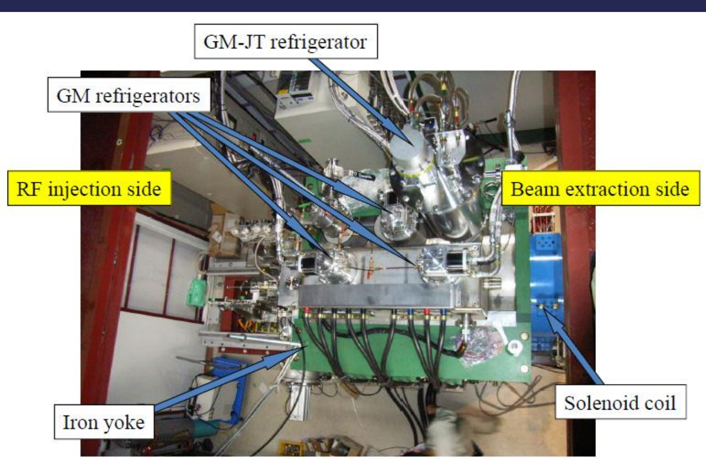
Riken, Nishina center, Japan : Y. Higurashi et al, Rev. Sci. Instrum. 83, 02A308 (2012)

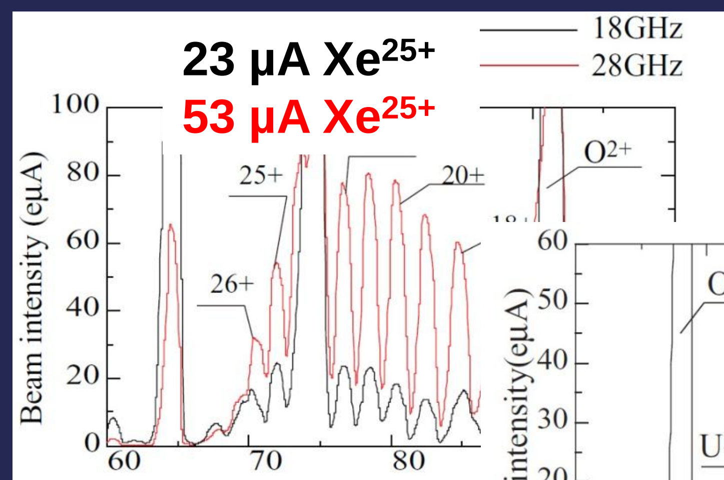
B_{inj} Max = 3.8 T B_{ext} Max = 2.3 T B_{rad} Max = 2.1 T

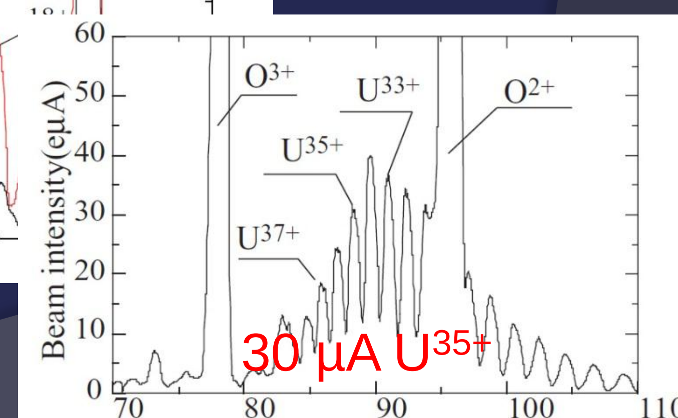
Plasma chamber Φ_{int} = 150 mm



- SuSI like ion source
  - 6 solenoids
    - ✓ Flat field possible
    - ✓ 40 kV high voltage isolation
- 18 GHz then 28 GHz







Present status of high power ECR ion sources
Europe MS-ECRIS (I)

Courtesy of G. Ciavola (INFN-LNS) and K. Tinschert (GSI)

K. Tinschert, et al., Rev. Sci. Instrum. 83, 02A319 (2012)

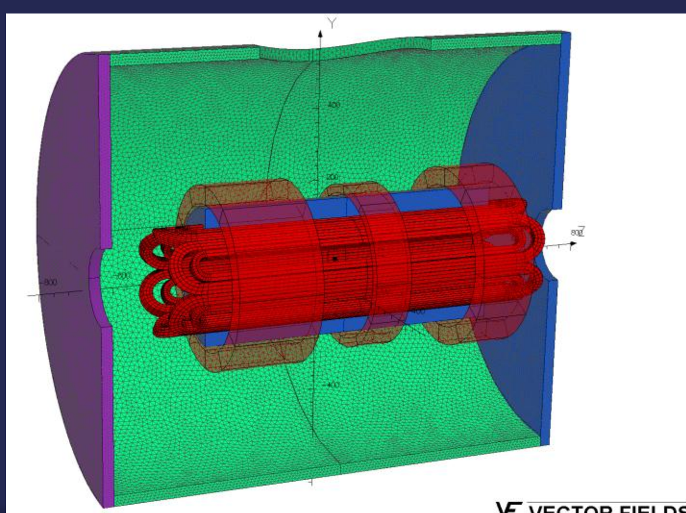
B_{inj} Max = 4.5 T B_{ext} Max = 3.2 T B_{rad} Max = 2.7 T

Plasma chamber Φ_{int} = 180 mm, L = 1162 mm

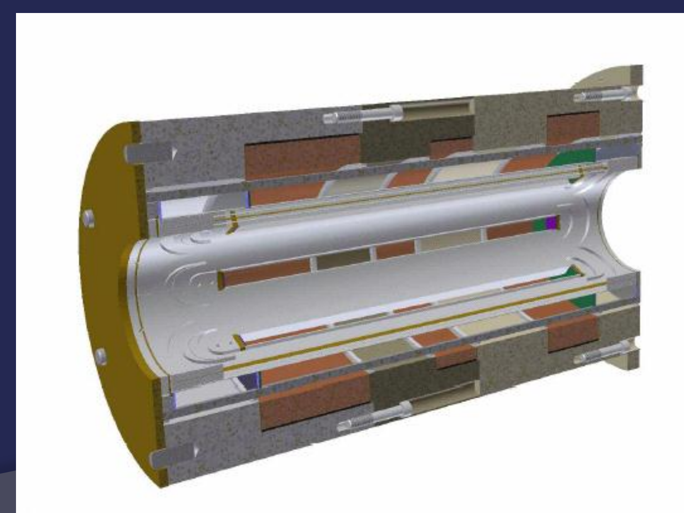
P_{max} (14 GHz) = 2 kW - P_{max} (28 GHz) = 10 kW

- Intense beams (≤ emA) O^{7+}, Ca^{10+}, Ni^{11+}, Xe^{20+}, Pb^{27+}...
- Very high charge state of heavy ion beams (≥ eμA) Kr^{32+}, Xe^{45+}...

Model for the magnet coil design



Schematic view of the cold mass

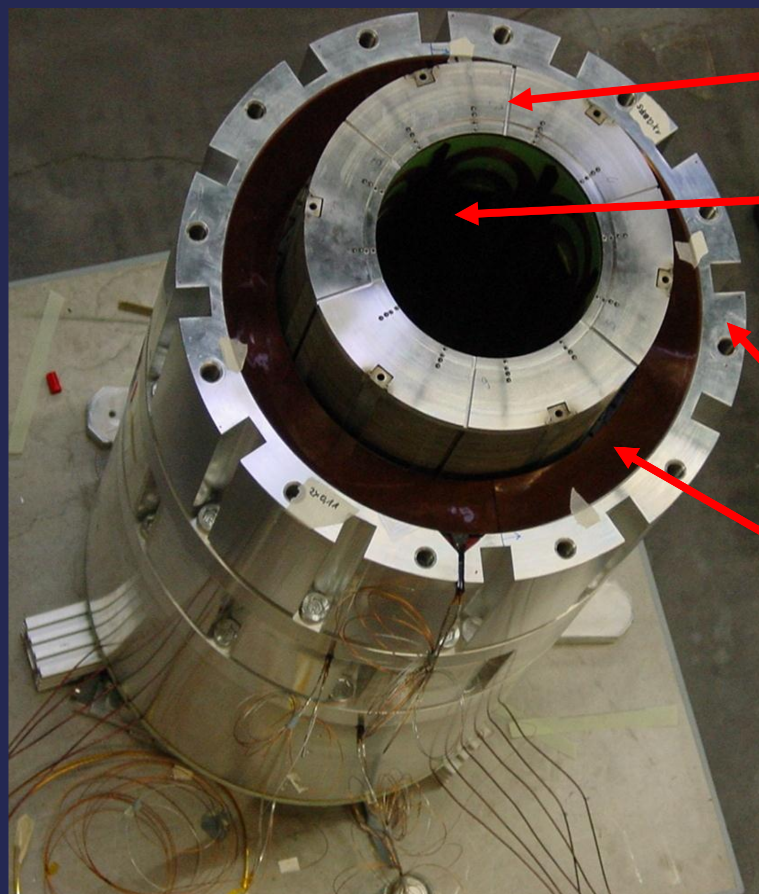


Present status of high power ECR ion sources

Europe MS-ECRIS (II)

Courtesy of G. Ciavola (INFN-LNS) and K. Tinschert (GSI)

Assembly of cold mass with sextupole and solenoids



Stack of ferromagnetic collar sheets clamping the sextupole coils (inside)

Al-housing of the solenoids with solenoid coils (inside)

Present status of high power ECR ion sources
Europe MS-ECRIS (II)

Courtesy of G. Ciavola (INFN-LNS) and K. Tinschert (GSI)

- Results of the first series of cold tests for commissioning
  - All 3 solenoids reached nominal field without quench
  - Sextupole alone also reached nominal field
  - Ramping all coils simultaneously ➔sextupole shows random quench behavior
  - A level of 40-50 % of its nominal field could be achieved
- Dedicated new design study
  - comprehensive structural analysis, magnetic field and force patterns calculations Analyze the interaction of the iron collar with the solenoidal fields
- Conclusion of the design study
  - Two classes of problems have been identified:
  - A complex pattern of magnetic forces exerted on the iron collars
  - Forces related to the radial magnetic fields generated at the ends of the solenoid coils independent of the magnetic or non-magnetic nature of the collars
- Work in progress
  - Improve clamping of the iron collar by mechanical machining and additional supporting of the collar package

A new cold test is upcoming and If will be successful, a new planning will be made

Present status of high power ECR ion sources

- Comparison of different fully superconducting ECR Ion Sources

	SUSI (NSCL-MSU)	SC-ECRIS (RIKEN)	SECRAL (IMP Lanzhou)	VENUS (LBNL)	MS-ECRIS (GSI)
Frequency	18-24 GHz	14-28 GHz	18-24 GHz	18-28 GHz	14-28 GHz
Maximum RF power	< 10 kW	<10 kW	10 kW	10 kW	10 kW
B_{radial}	1.8 T	2.1 T	2.0 T (2.2 T)	2.0 T (2.4 T)	2.7 T
B1 (injection)	3.6 T	3.8 T	4.0 T	4.0 T	4.5 T
B2(extraction)	2.2 T	2.2 T	2.0 T	3.0 T	3.2 T
ϕ chamber	102 mm	150 mm	126 mm	140 to 152 mm	180 mm
L chamber	> 500 mm	≥ 500 mm	804 mm	1030 mm	1162 mm
LHe consumption	> 0	0	1.5 l/h	0 (+LN_2 precool)	0

Courtesy of G. Ciavola (INFN-LNS)

Two over five have presented important problems

All tend 'more or less' towards the same intensities

JRA01-ARES
(Advanced Research on Ecr ion Sources)

INFN - GSI - GANIL - JYFL – KVI – ATOMKI - IFIN HH – IKF

Coordinator : G. Ciavola (INFN-LNS)
Deputy coordinator : K. Tinschert (GSI)

Steering Committee: L. Celona (INFN-LNS)
H. Koivisto (JYFL)
K. Tinschert (GSI)

TASK 1-Plasma heating, Wave-plasma interaction

Task Leader: INFN - Participants: INFN, JYFL, GSI, ATOMKI, IFIN-HH, IKF

TASK 2- Ion beam formation and transport

Task Leader: GSI- Participants: GSI, JYFL, INFN, KVI, ATOMKI, IKF

TASK 3- Production of metal ion beams

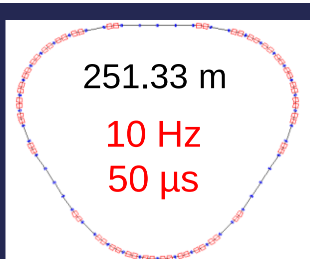
Task Leader: JYFL- Participants: JYFL, GANIL, GSI, INFN, KVI

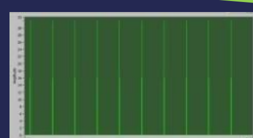
All activities are devoted to increase the intensities of high charge state ion beams

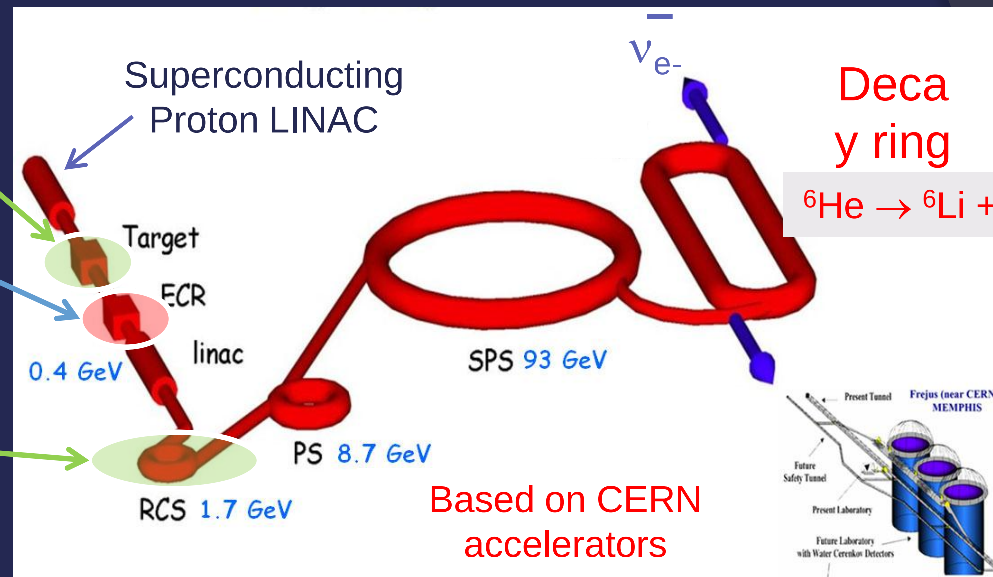
Experimental discovery research
The LPSC 60 GHz ECRIS prototype

^{6}He ($t_{1/2}$ = **807 ms**), ^{18}Ne, ^{8}B , ^{8}Li
Continuous production
5 . 10^{13} pps

For a 100 % ionization efficiency
$I(He^{2+})$ = 32 mA
I extracted ~ several 100 mA







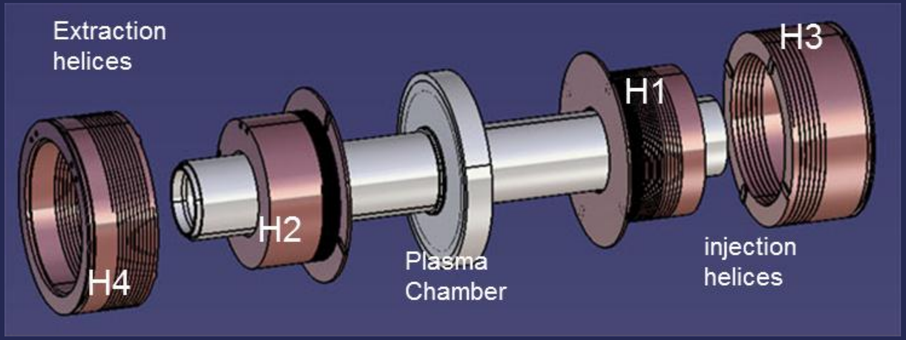
$^{6}He \rightarrow {}^{6}Li + e^{-} + \bar{\nu}_{e-}$

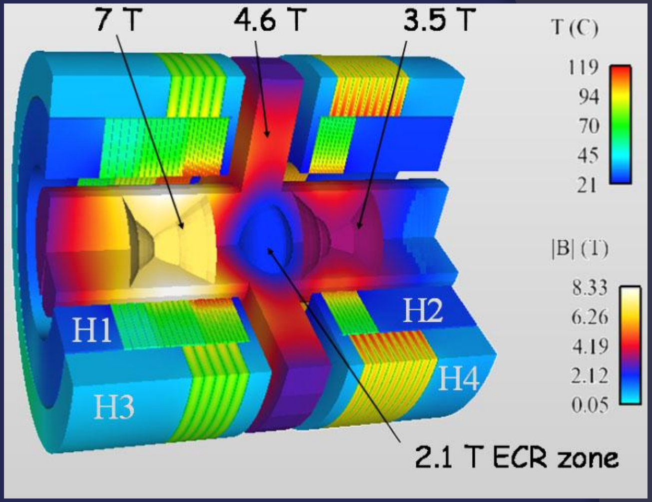
- Apply high field magnets technologies to ECR ion source
  - ✓ Radialy cooled Helix technique
- Collaborative context
  - National Laboratory for intense magnetic fields (LNCMI) Grenoble
  - Institute of Applied Physics, Russian Academy of Science Nizhniy Novgorod

60GHz Ion source : Highlights and results

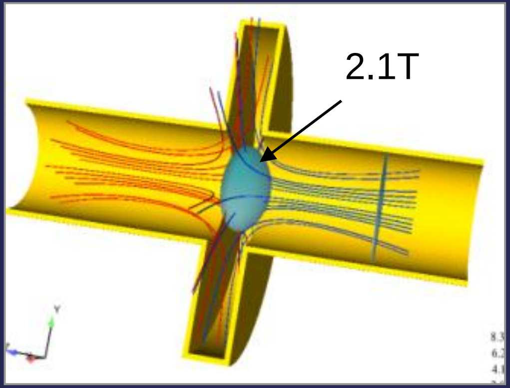
- Magnetic simulations, experimental validation

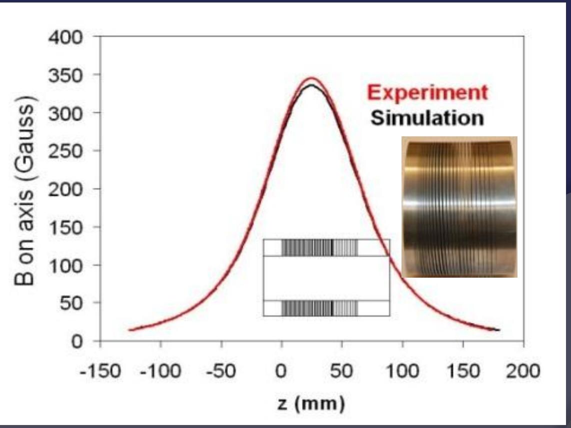
30000A, 6 MW





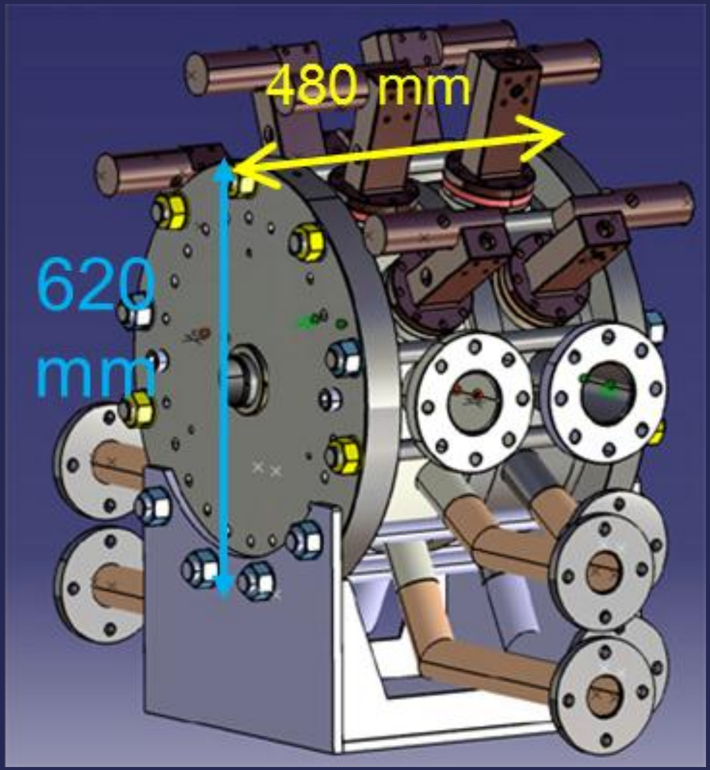
- Compact design
- Short time between design and prototype construction

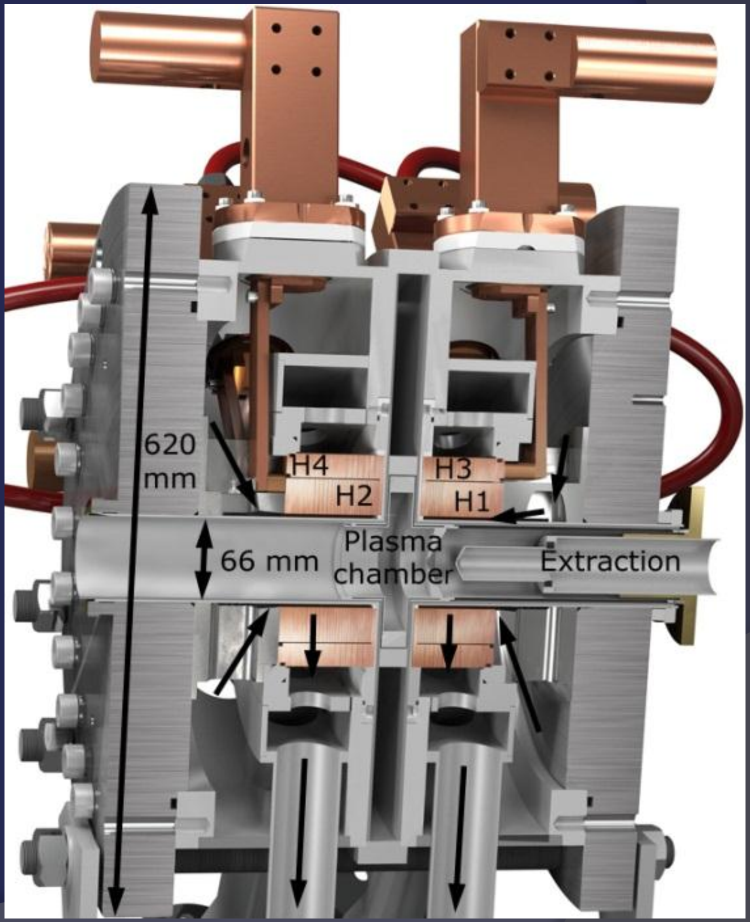




60GHz Ion source : Highlights and results

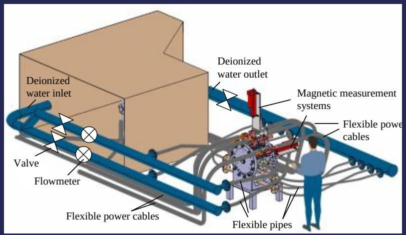
- Mechanical design and optimization of the magnetic structure prototype



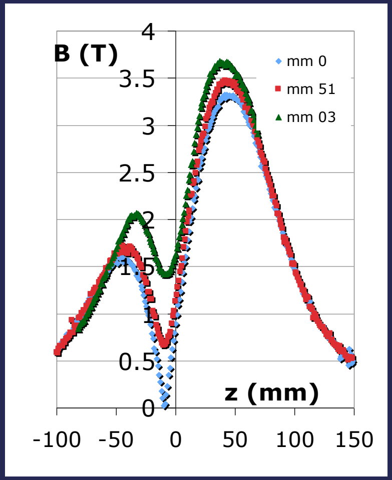


60GHz Ion source : Highlights and results

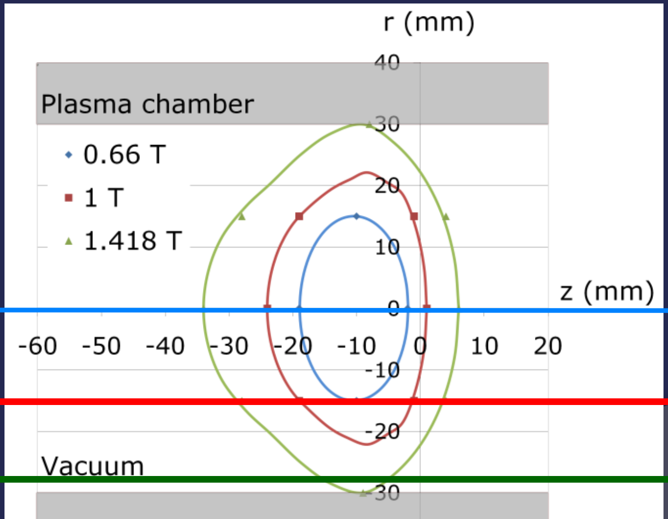
- Magnetic field structure prototype construction and installation on the M5 LNCMI site



- Magnetic field measurements from1500 up to 15000 A



Magnetic field along 3 axis at 15000 A

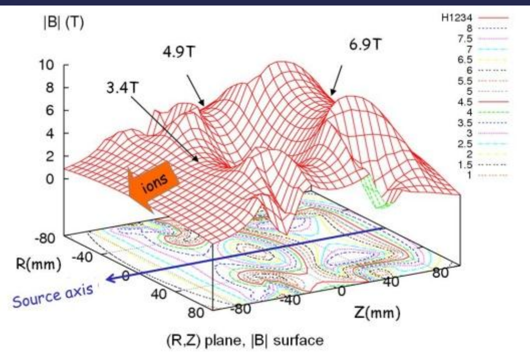


Iso-B in the prototype at 15000 A

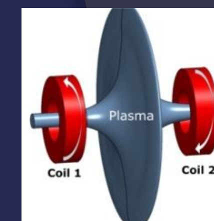
Prototype axis

60GHz Ion source : Highlights and results

- Next experiments ion beams @ 28 GHz, B for 60 GHz



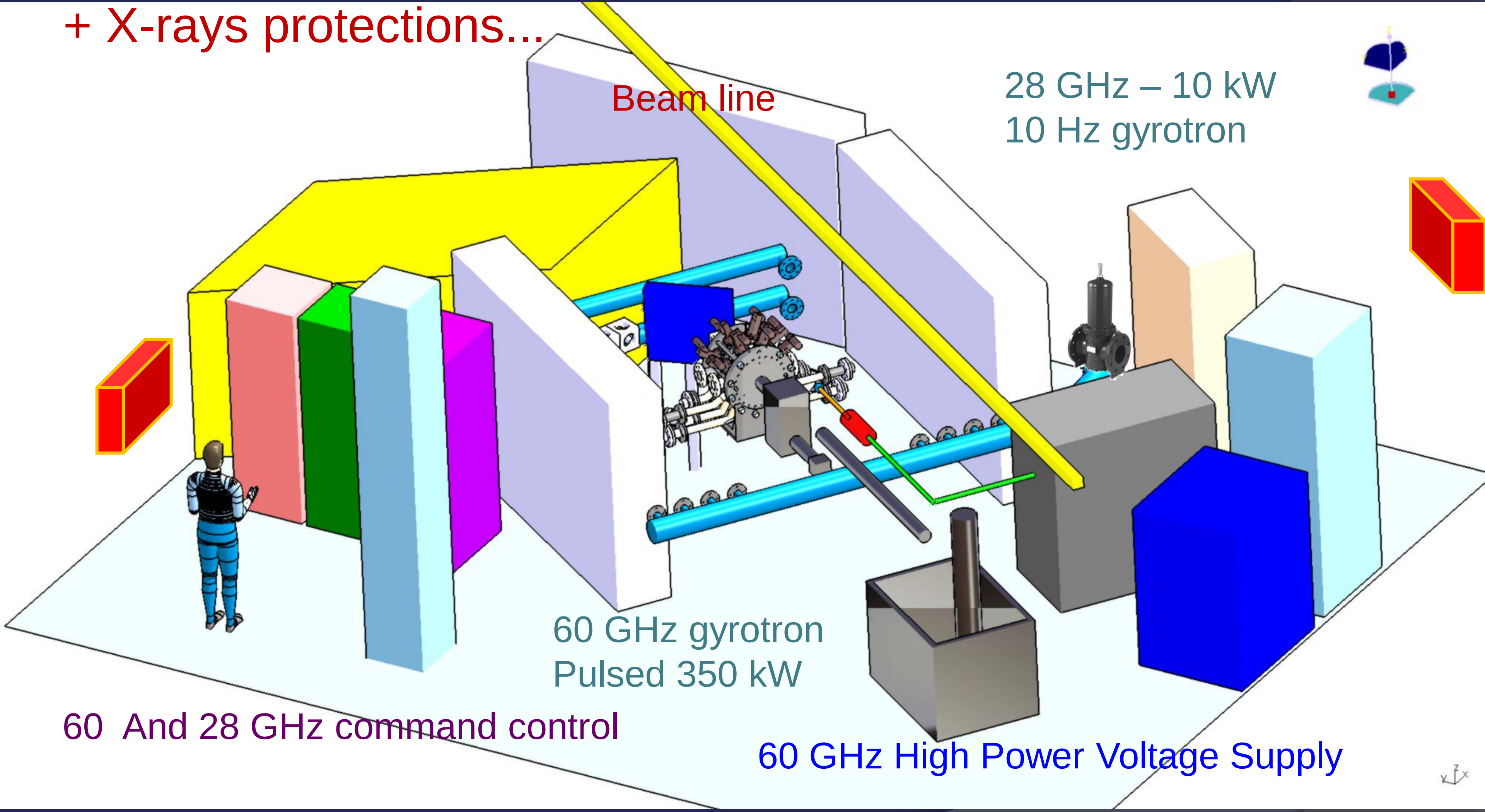
- Highest magnetic field in a cusp with a closed ECR zone
- Experiment accepted for 2*20 days
  - First beam scheduled in July or September



Previous experiment : M5

A new dedicated room : M3

60GHz Ion source : Highlights and results

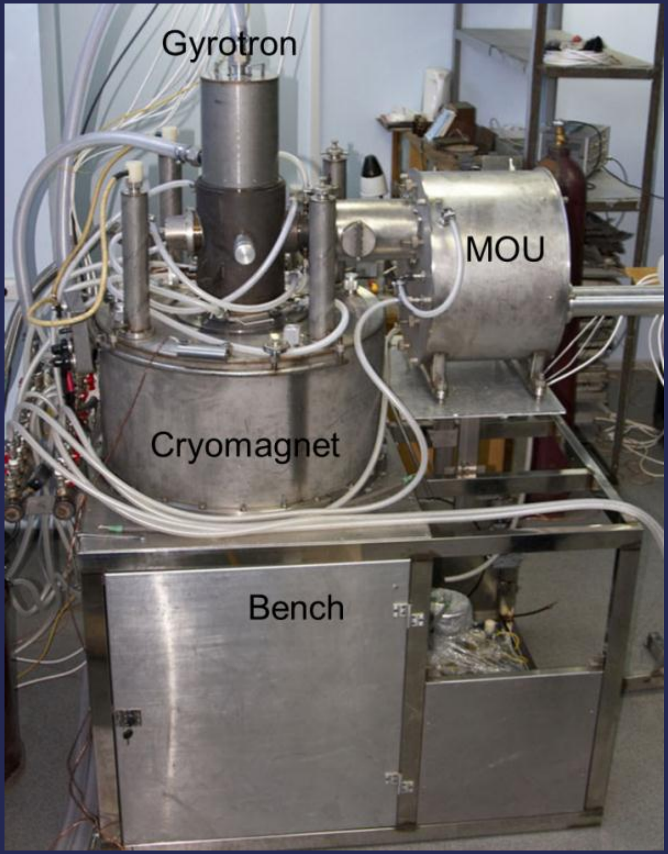


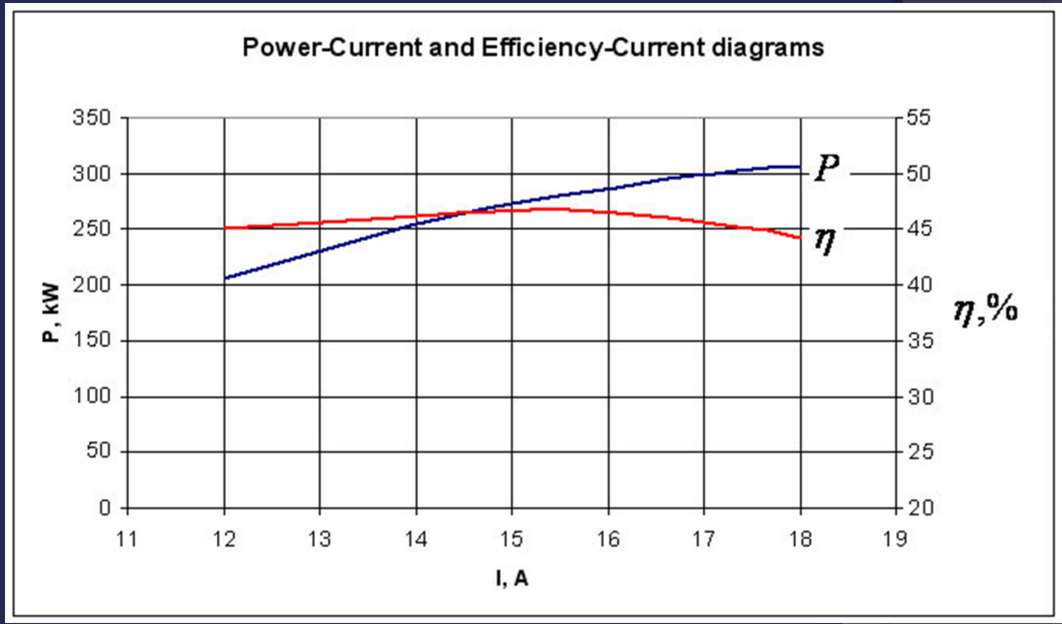
60GHz Ion source : Highlights and results

- 60 GHz gyrotron (10 - 350 kW / 5 Hz / 10µs - 10 ms)

  (Gycom Ltd, Nizhny Novgorod, Russia)

  - Should be delivered September 2012...
  - Tests have just begun

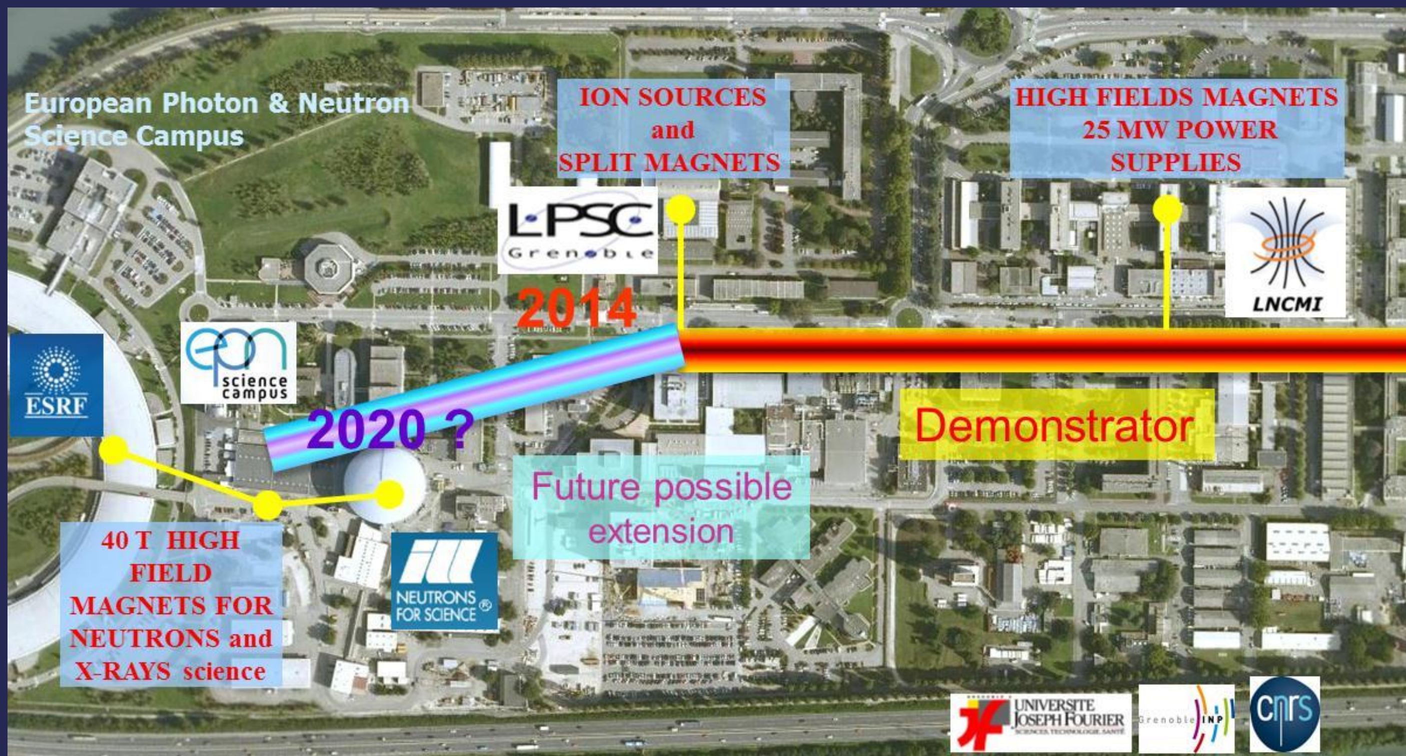




Cost of a 0 - 15 kW 60 GHz : 400 k€

COLOSSUS LNCMI + LPSC +(ESRF + ILL) ?

(4*15000 A) allowing future 28 and 60 GHz ion sources R&D, experimental studies on split magnets for ESRF and ILL



2 cryostats 600 meters long
Diameter PHI 163 mm

Synergies between stable beam facilities and accelerator technologies (Ion sources - I)

- Organization of ion sources developments in Europe (the same worldwide)
  - Ion source teams (generally not more than 10 persons) are often created for the construction of a specific accelerator
  - Once the accelerator is operational, these teams are in charge of:
    - The beam production
    - The sources operation improvements : easy tuning, stability, easy and fast maintenance...
    - Developments of specific instrumentation (ovens, bias disks, organometallic injection, extraction systems...
  - Advantages:
    - An operational team close to the accelerator guarantee an optimal operation of the facility
    - Continuity of the experimental knowledge on specific setups
    - Better communication between accelerator physicists and ion sources specialists
  - Disadvantages
    - Production is the priority, limited time dedicated to R&D
    - Excess of specialization prevents from ‘open minded’ R&D
    - Risk of scientific isolation

Synergies between stable beam facilities and accelerator technologies (Ion sources - II)

- Technological synergies
  - Intense magnetic fields with high gradients
  - RF coupling in cavities
  - Beam extraction and transport, characterization and simulation
  - Ultra high vacuum technologies, material science
  - Plama physics (i.e. plasma acceleration)
  - ....
- Efficient ion sources research and developments require
  - Expensive infrastructure and equipment (often forgotten)

    - Simulation and generation of intense magnetic fields

    - Simulation and generation of high frequency-high power HF (klystrons, gyrotrons)

    - Beam lines with magnetic spectrometers and diagnostics

    - Stabilized high voltage and power supplies

    - Pressurized demineralized water

    - Mechanics specialists (CAD, simulation, workshop, treatment of parts under vacuum...)

    - ...
  - Constant political (or financial) support from various physicists communities

    - The 60 GHz ECRIS development has been possible with the neutrinos community

Thank you !