60 GHZ ECR ION SOURCES

T. LAMY

LABORATOIRE DE PHYSIQUE SUBATOMIQUE DE DE COSMOLOGIE
UNIVERSITÉ GRENOBLE ALPES
CNRS-IN2P3

I warmly thank the International Advisory Committee for the invitation

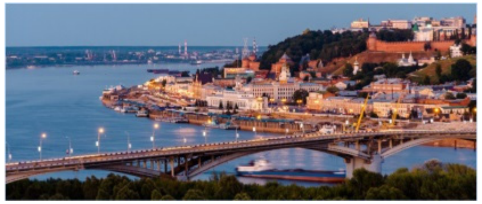
CO-AUTHORS OF THE COLLABORATION

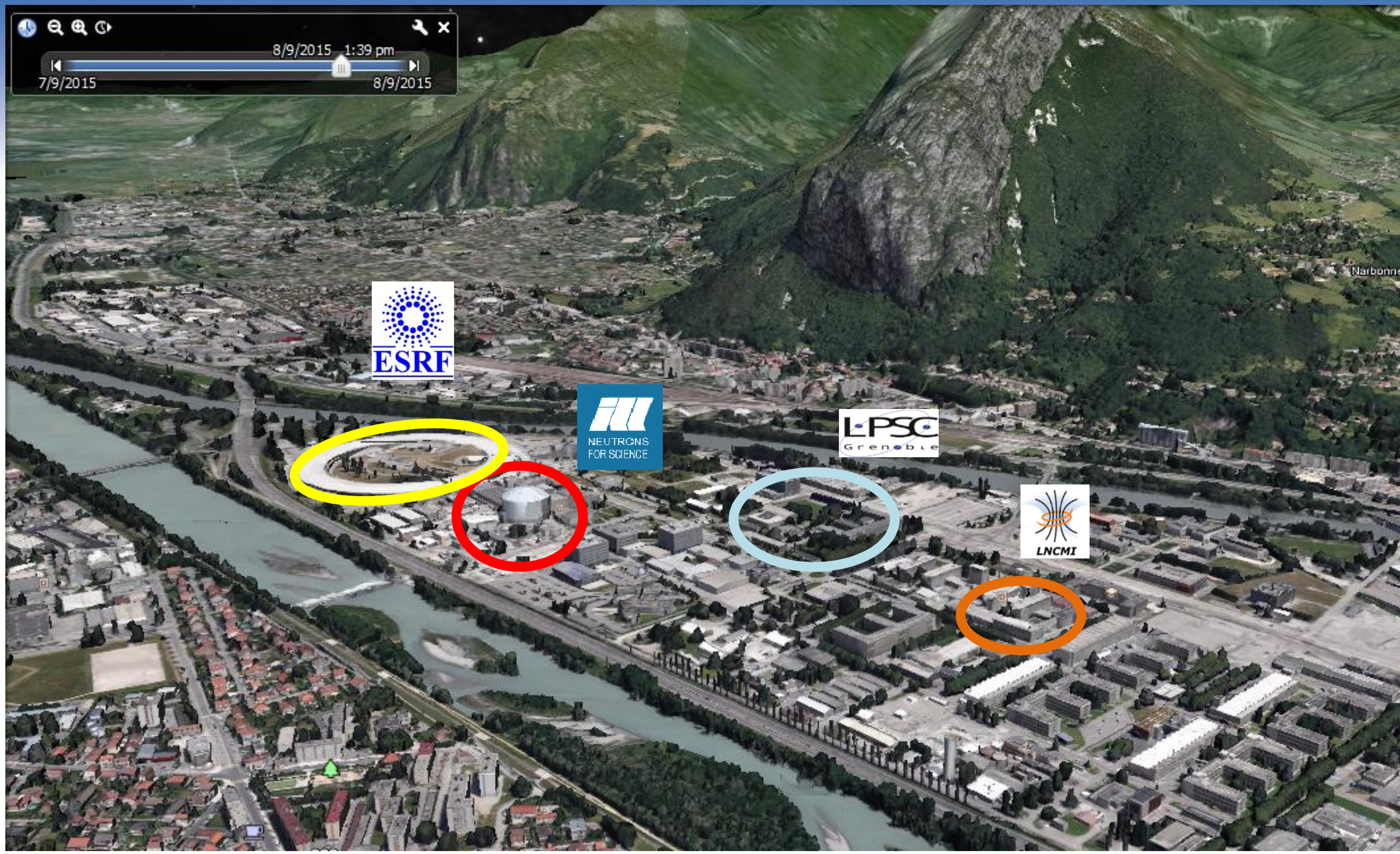
J. JACOB, J. ANGOT, P. SOLE, T. THUILLIER
LPSC, Université Grenoble - Alpes, CNRS/IN2P3, Grenoble, France

F. DEBRAY, C. GRANDCLEMENT, P. SALA, C. TROPHIME
LNCMI, Grenoble, France

A.G. EREMEEV, I. IZOTOV, B. MOVSHEVICH, V. SKALYGA
Institute of Applied Physics /RAS, Nizhny Novgorod, Russia

M. BAKULIN
GYCOM Ltd, Nizhny Novgorod, Russia




8/9/2015 1:39 pm
7/9/2015
8/9/2015
ESRF
NEUTRONS FOR SCIENCE
LPSC Grenoble
LNCMI

ECRIS BASIC PRINCIPLES

– Electron heating
  - **Electromagnetic** wave (frequency ω_{EM}) in a **cavity** under a **magnetic field**
  - ECRIS **resonance** condition insures an **energy transfer from the wave to the electrons**

    $\omega_{EM} = \omega_{ec}$, $\omega_{ec} = eB/m$ electron rotation frequency so $B_{ecr} = m\,\omega_{EM}/e$
  - Magnetic field insures **plasma confinement** and 'possibly' **stability** (MHD)

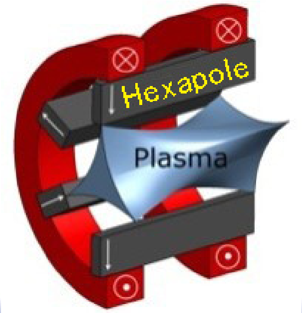
– 'Step by step' ionization, successive electron - ion collisions
  - **Highly charged** ion beams can be **produced** if ions are **confined for a sufficient time** (τ_i) in a **dense plasma** (n_e), for O^{8+} : $n_e \tau i \sim 10^{10}$ $s.cm^{-3}$
  - If we **increase** significantly the **density**, the **confinement time can be decreased**

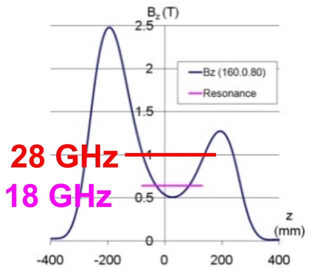
– Plasma density
  - The wave can't propagate in a too high electronic density : cut-off density, it depends on the magnetic field and on the electronic density
  - It is commonly admitted that in ECRIS $\mathbf{n_e \propto (\omega_{EM})^2}$ **or** $\mathbf{(B_{ecr})^2}$
  - A straightforward way to increase the ion intensities is to increase the EM wave frequency

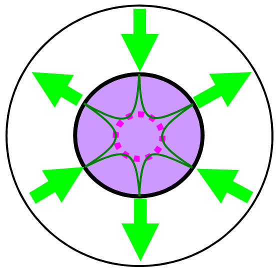
ECRIS STATE OF THE ART

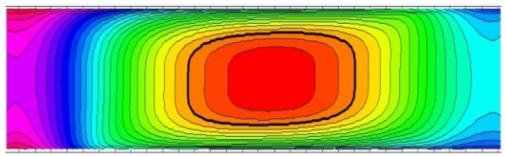
– Present most performing ECRIS (intensity and charge state)

- Minimum-B magnetic field, increase in every direction from the plasma center
- Superposition of an axial magnetic field (solenoids) with a radial one (hexapole)
- Follow scaling laws $B_{inj} \sim 4\ B_{ECR}$, $B_{rad} \sim 2\ B_{ECR}$...
- Double frequency heating: (24 +18) or (28 +18) GHz, 28 GHz : BECR~ 1T
- Are fully superconducting, (very) high cost, (very) long development
- Next step : about 60 GHz, 8T axial, 4T radial, technological limits of NbTi, so Nb_3Sn...
- Who is enough crazy (and rich) to build such a machine ?







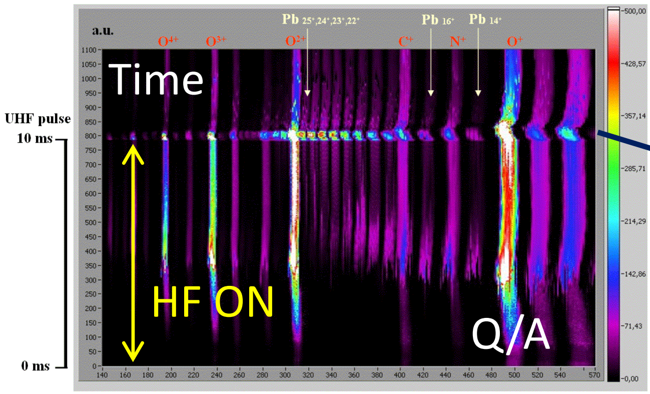


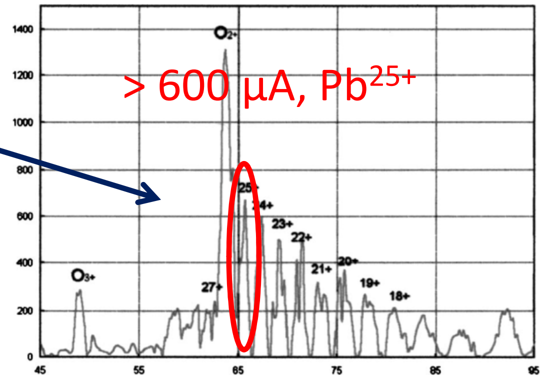
HIGH FREQUENCY ECRIS ORIGINAL IDEAS

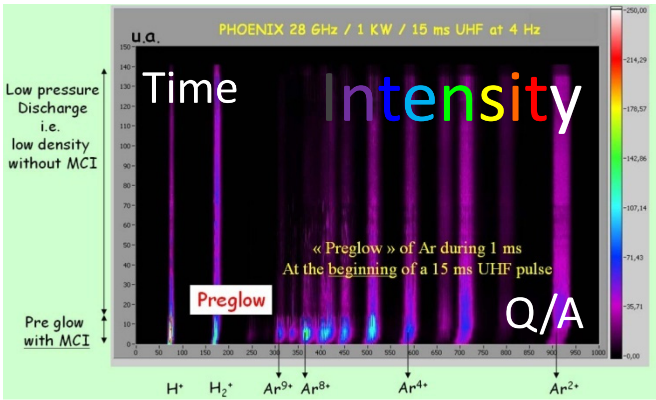
- Classical ECRIS (solenoids + hexapole)
  - A lot of **simulation work** to optimize magnetic structures, some doubts too...
    - (LBNL, Berkeley) and (IMP, Lanzhou) Nb3Sn 56 GHz; NbTi 40 GHz (ICIS 2015)
- From fusion machines to ECRIS... Let’s go back to fusion machines
  - **Yin-Yang** coil ARC-ECRIS (JYFL- Jyväskylä)
    - With NbTi given for **60 GHz**
  - **Torus stellarator style** (Dept. of App. Phys. and App. Math., Columbia University)
    - The plasma chamber is the poloidal coil **(0.73 V, 3.5 MA)**, the hexapolar field is provided by 6 coils **(30-300 kA)**, given for **at least 56 GHz**

LPSC INGREDIENTS TOWARDS 60 GHZ

- Activities with pulsed beams
  - Afterglow and preglow experimental development and characterization
  - 28 GHz PHOENIX source development for CERN-LHC lead beam
  - Collaboration with Institute of Applied Physics SMIS 37.5 GHz (Nizhny Novgorod-Russia)

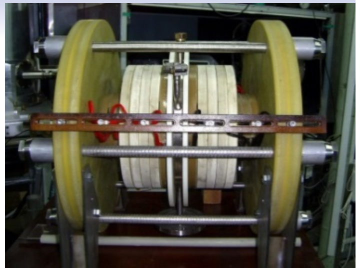


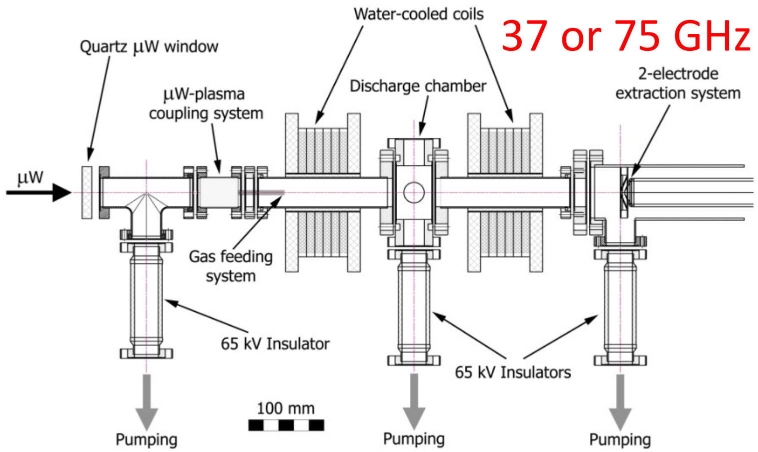


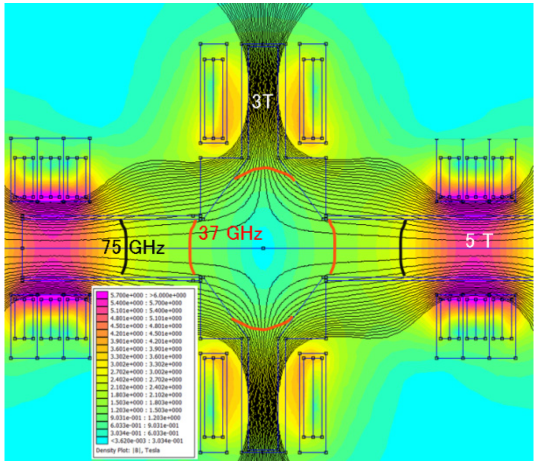


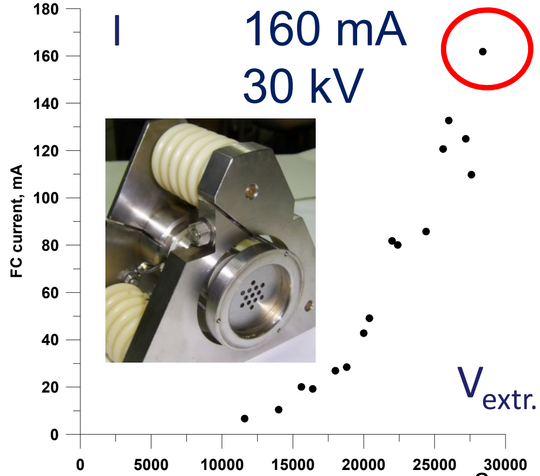
LPSC – IAP COLLABORATION

- Since more than 15 years
- Experimental studies with SMIS37
  - Cusp or magnetic bottle, non closed ECR surfaces at 37 or 75 GHz
- Experimental and theoretical work on preglow (LPSC PHOENIX)







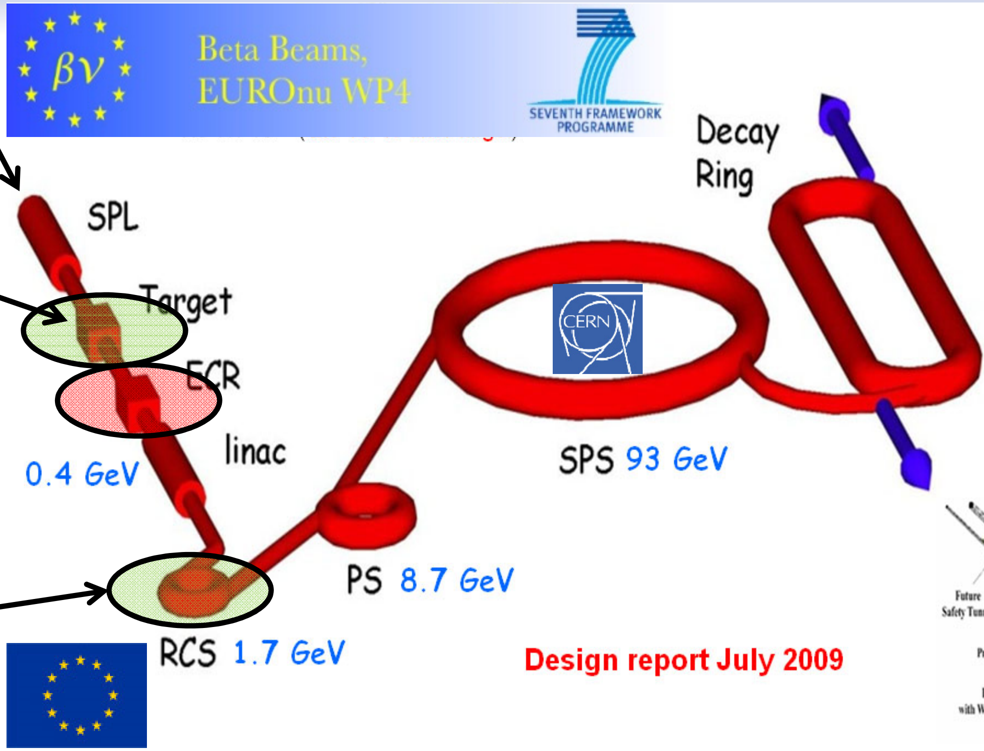


THE BETA BEAM PROJECT

Intense neutrinos beams from accelerated ions disintegrating by beta decay

protons

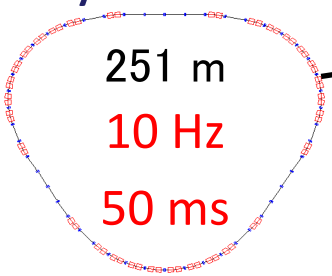
CW Production
^{6}He 5 . 10^{13} s^{-1}
($t_{1/2}$ = 807 ms)



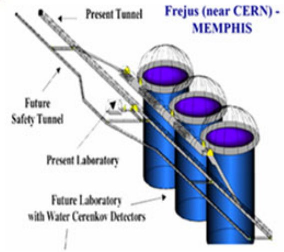
Decay ring
Bρ = 1500 Tm
B = ~6 T
C = ~6900 m
L_{ss} = ~2500 m
^{6}He: γ = 100
^{18}Ne: γ = 100

$^{6}_{4}He \rightarrow {}^{6}_{5}Li + e^{-} + \overline{\nu}_{e-}$

Rapid Cycle Synchrotron



High energy bunched neutrino beam



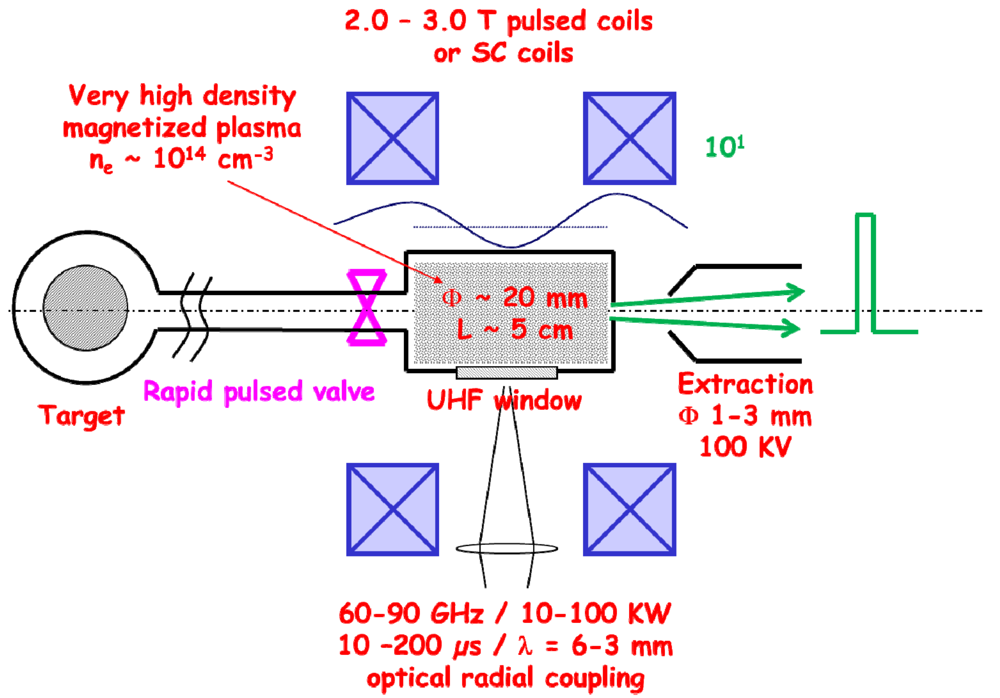
Design report July 2009

A 60 GHZ SOURCE FOR WHAT PURPOSE ?

2003: P. Sortais proposed a 60-90 GHz « ECR Duoplasmatron » for gaseous RIBs

CW Production

^{6}He 5 . 10^{13} s^{-1}



10 Hz – 20 µs

I(He+) = 40 mA

+

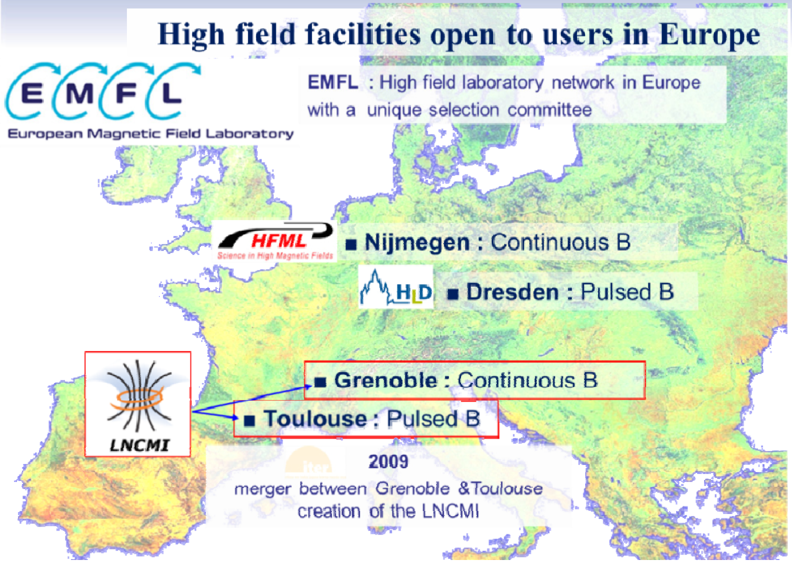
All others species produced...

the source may deliver

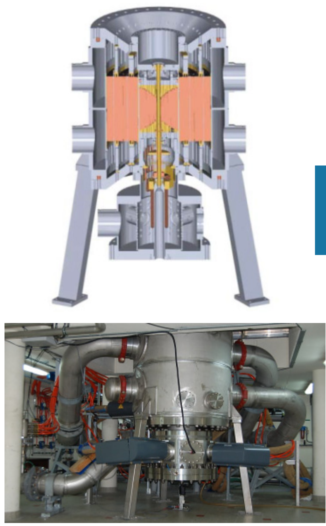
Several 100's mA

How we could build such a prototype ?

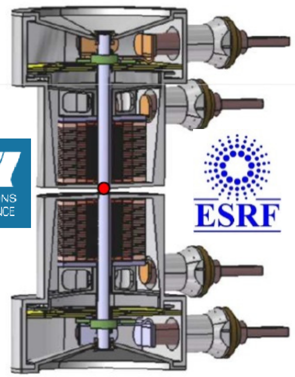
THE HIGH MAGNETIC FIELD LABORATORY



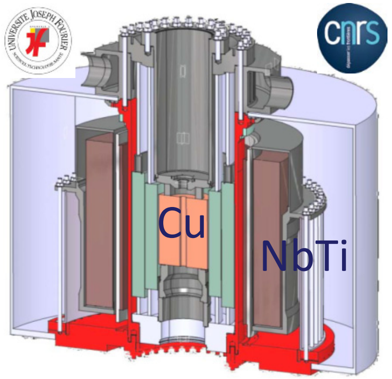
Continuous field 24 MW → 36 Tesla
30 scientists, 30 PhD & postdocs, 65 technical staff
200 access proposals/year



'**Classical**' magnet



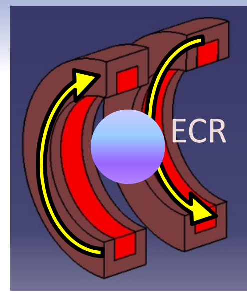
Split magnet
development



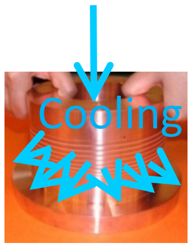
Hybrid magnet
NbTi : 9 T 800 mm
43 T / 34 mm
(24 MW)

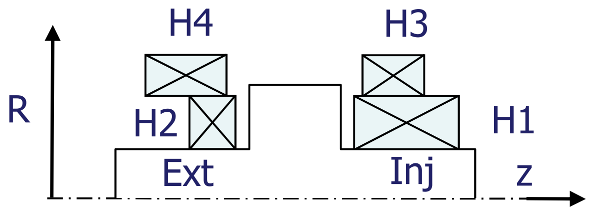
LPSC-LNCMI COLLABORATION

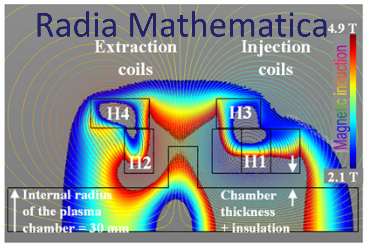
– Design of a 60 cusp GHz ECRIS with a closed resonance surface (2.14T) and a magnetic field respecting scaling laws

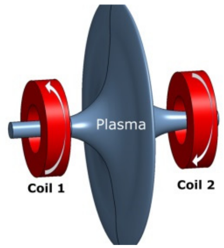


- An ECRIS is a split magnet (at least for the axial field)
- Use of the high field magnet technology
- A cusp is simple, we have to learn the technique...
- Allows the fine tuning of the current density during the design (variable width at each turn), and so, of the magnetic field
- 2D calculations : 4 radially cooled polyhelices are suitable for the design





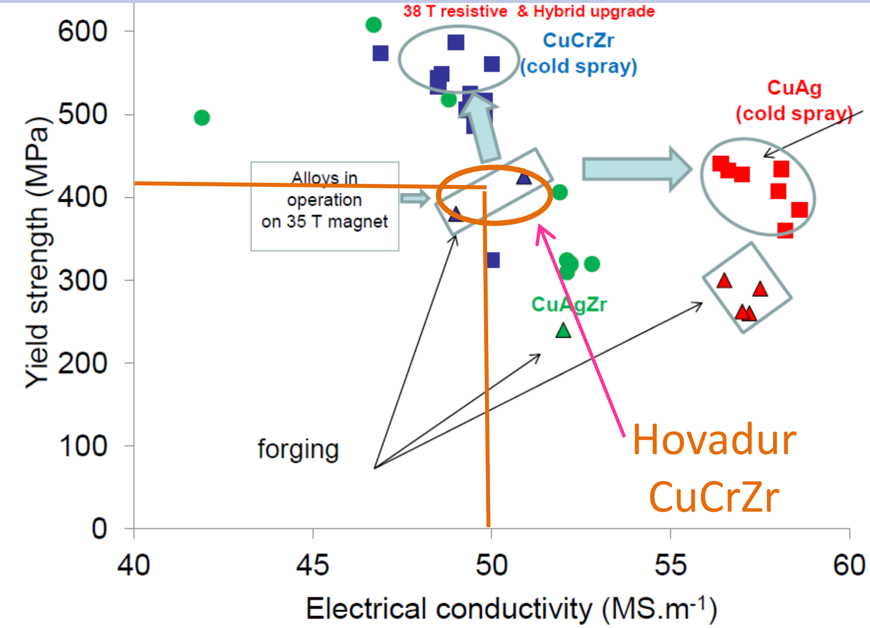


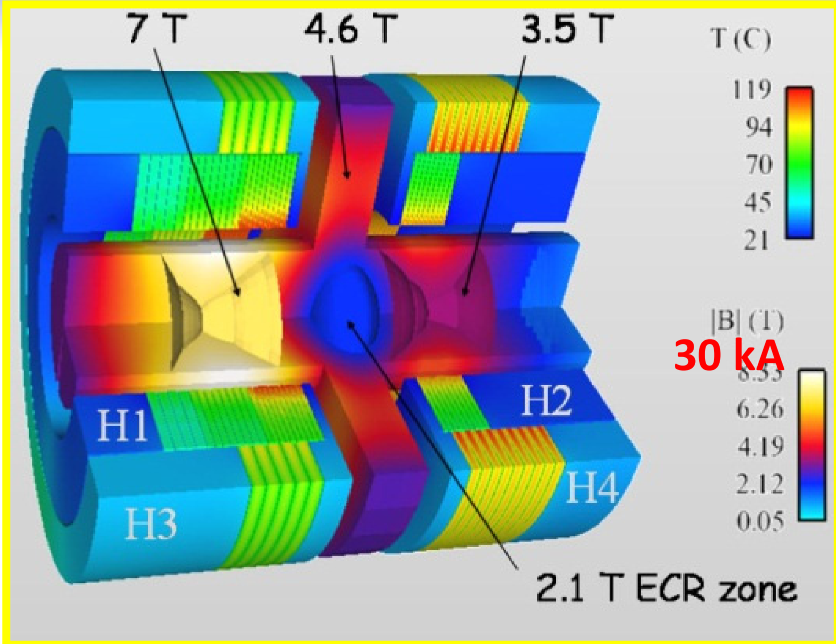


Good ! in 2D → 3D

60 GHZ SOURCE DESIGN

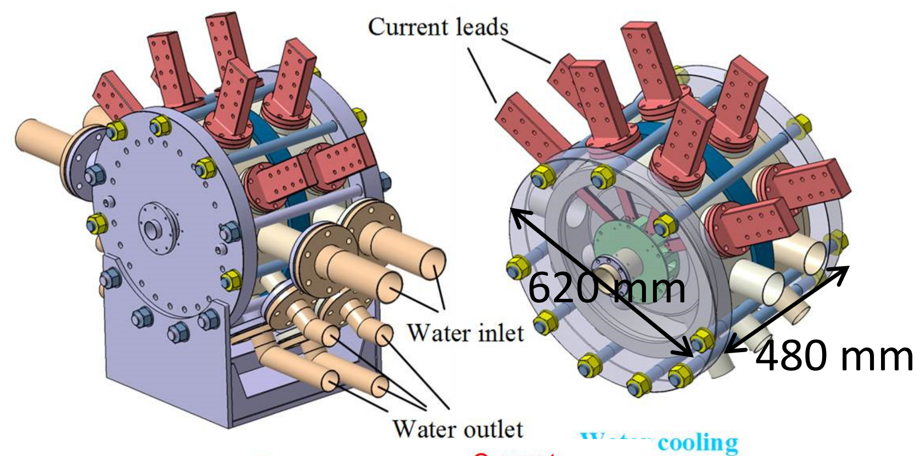
Magnetic and temperature simulation

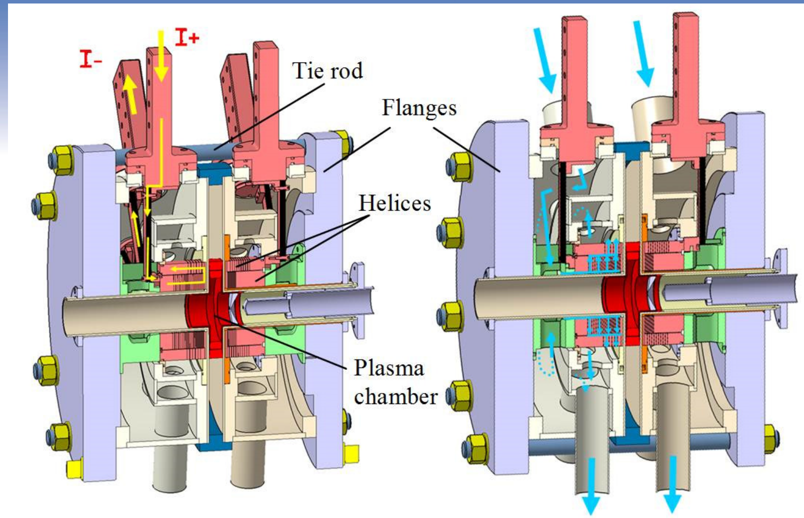


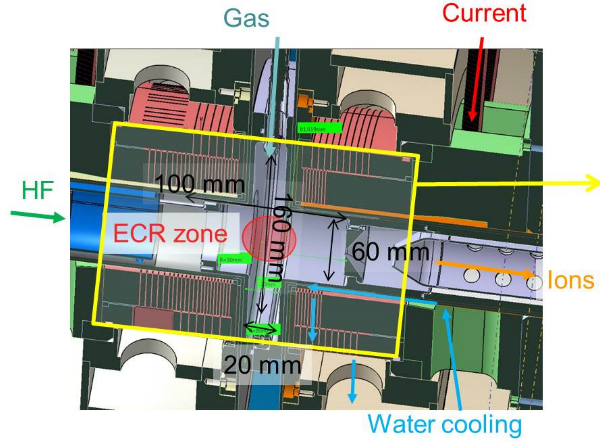


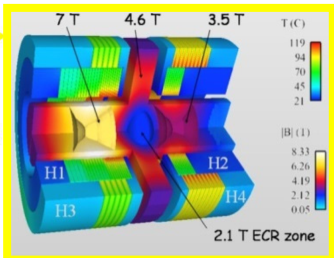
4 Hovadur helices : maximum current density 600 A/mm2(the highest ever performed)
Small volume plasma chamber : plasma < 100 cm3

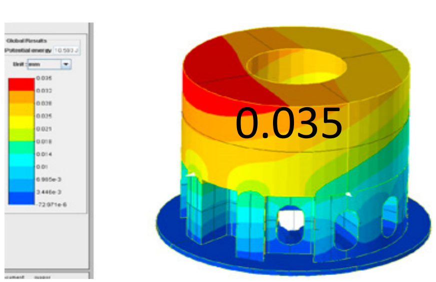
GENERAL DESIGN



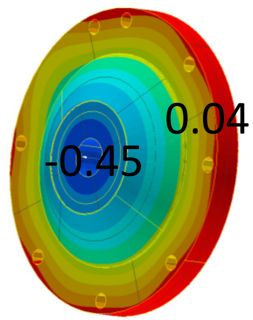








Helix support deformation

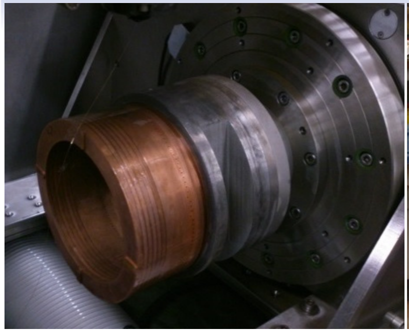


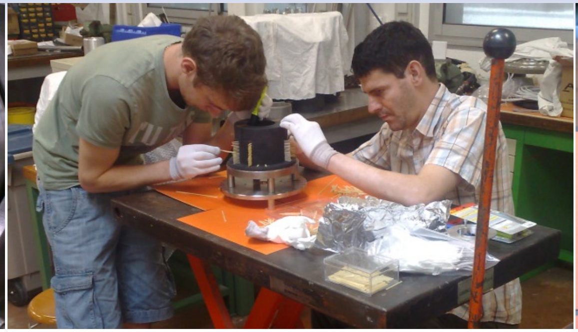
Flange

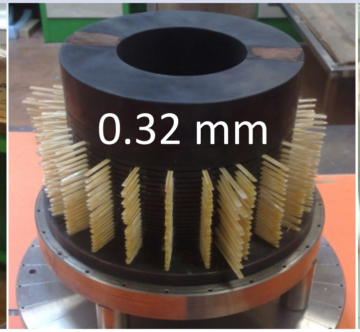
HELICES FABRICATION

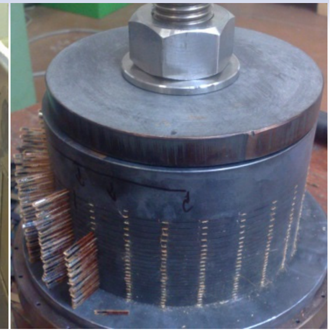
Slit electro erosion

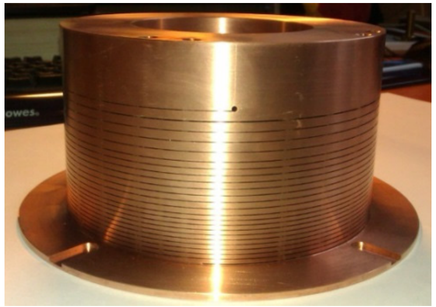
Computer-Aided Manufacturing

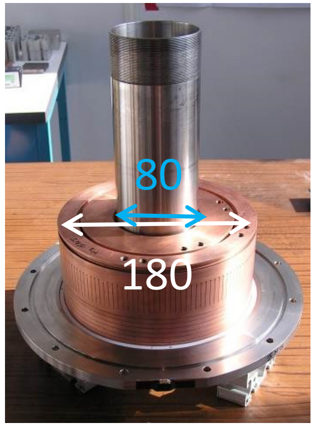


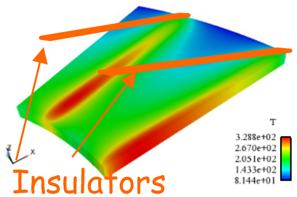








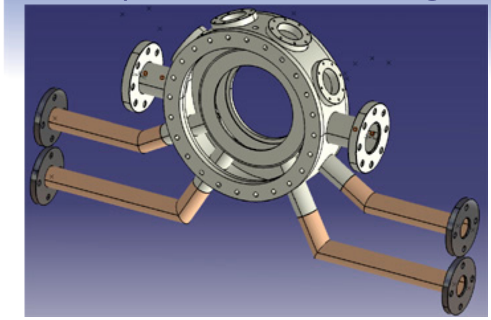


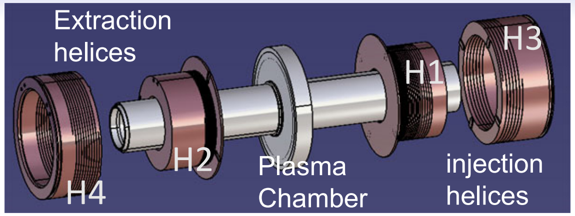


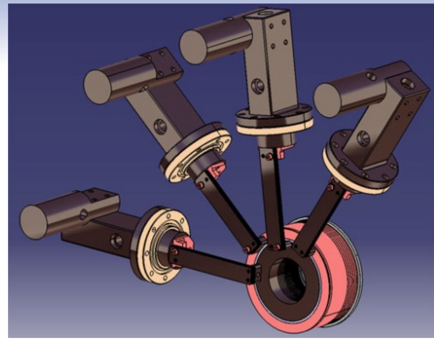
10 % of
the total surface

PROTOTYPE MOUNTING

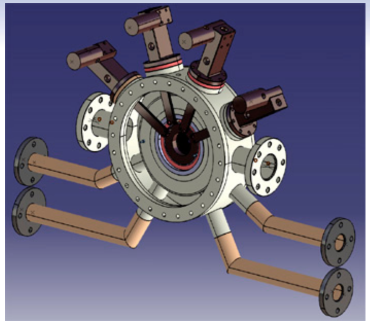
Basic part: heat exchanger

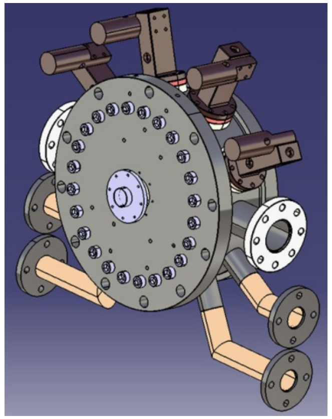


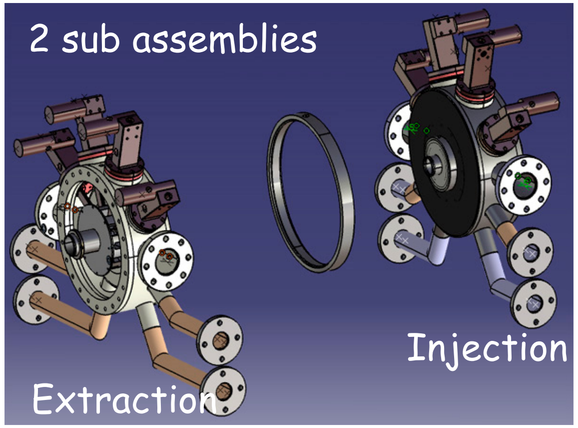


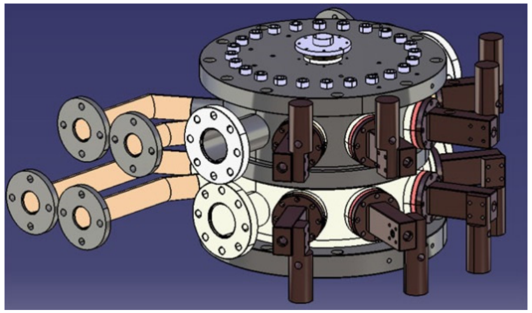


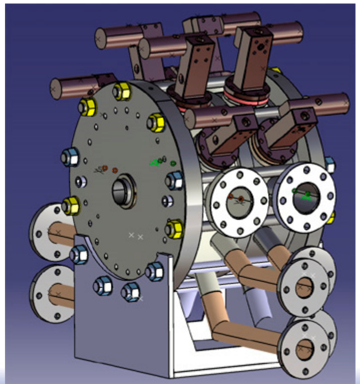
Helices and current leads



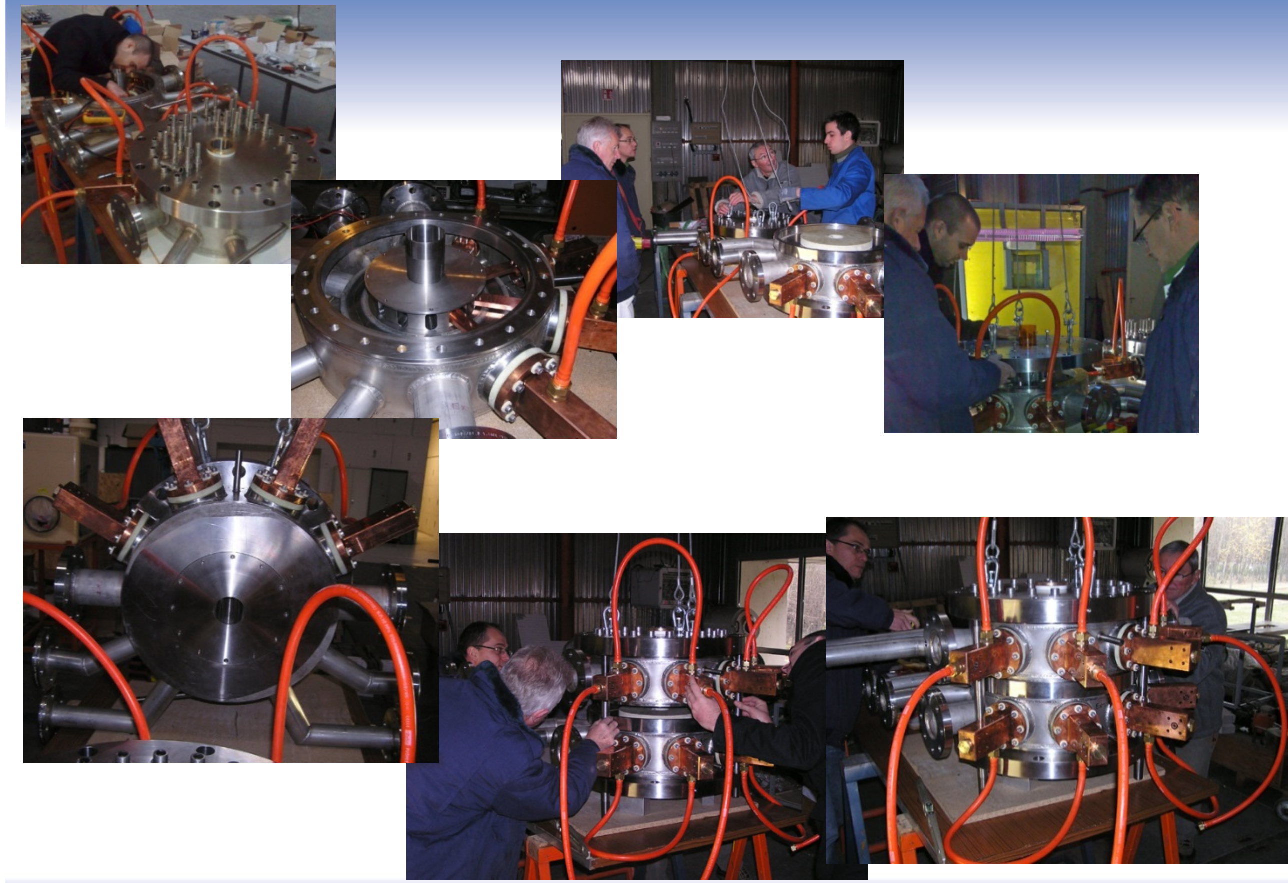






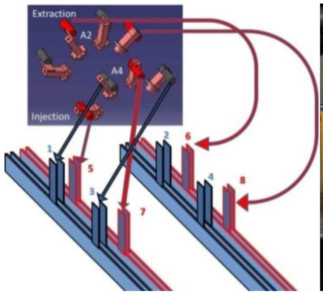


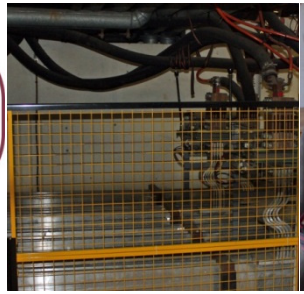
PROTOTYPE FABRICATION

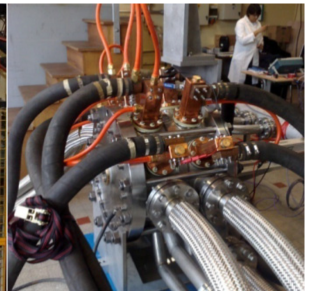


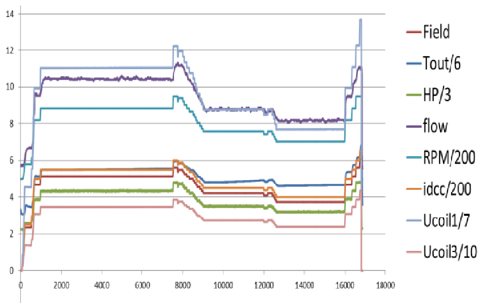
MAGNETIC FIELD MEASUREMENT…?

– Objective : to reach 26 kA (6T at the injection)
  - Radial and axial fields already measured at 15 kA (28 GHz)
  - Allows a significant variation of the 60 GHz resonance zone size (closed at about 20 kA)
  - Injection and extraction helices in series (only 2 DC convertors necessary (more flexibility for experiments) : no differential tuning between injection and extraction
  - 7500 A cooled down cables
  - Procedure to reach 26 kA, Multi ramping from 0 to a given Ig, increase Ig at each ramp and record U(I) until Imax is reached, the system checks for a deviation from the previous curves and set an alarm for abnormal deviations



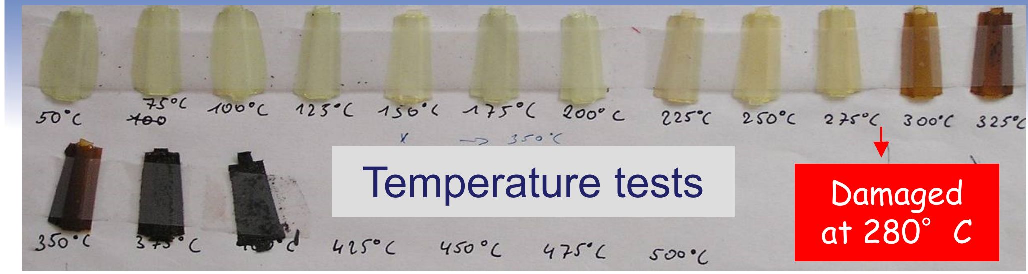




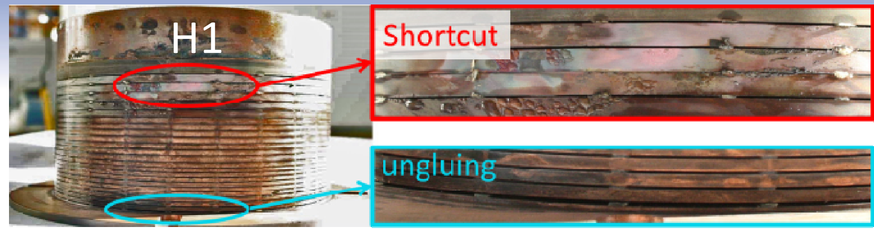


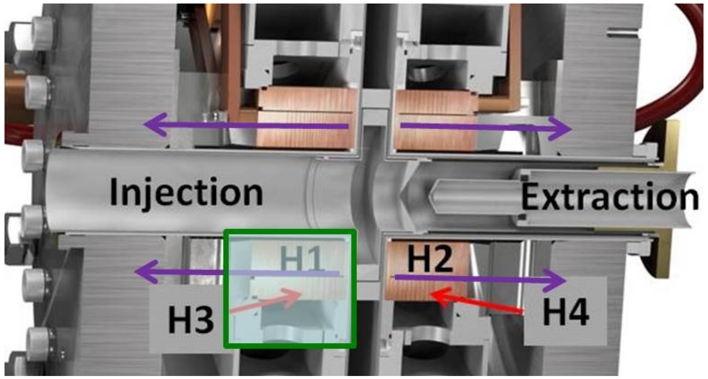
At 21 kA a voltage drop occurred…

21 KA MAGNET FAILURE ANALYSIS



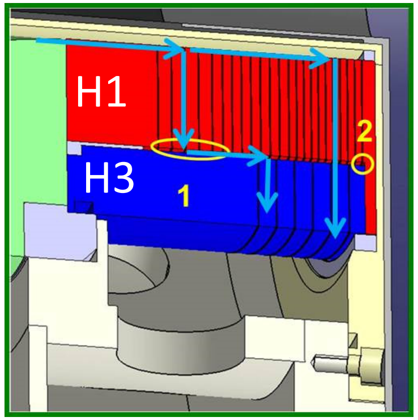
After disassembly





Repulsive force

@ 21000 A, total repulsive force : 300 kN



Cooling design problem

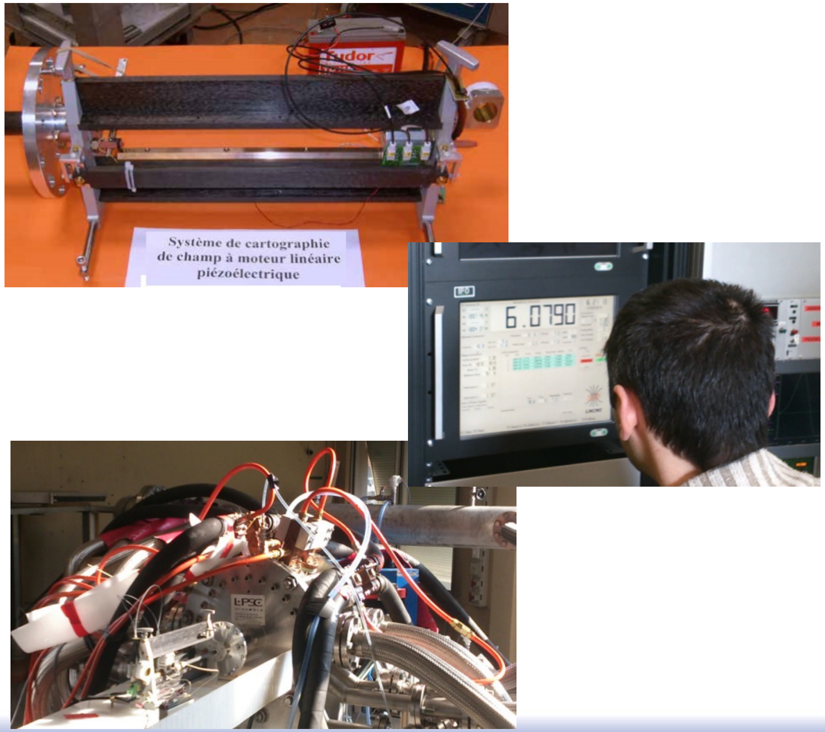
H3 modification

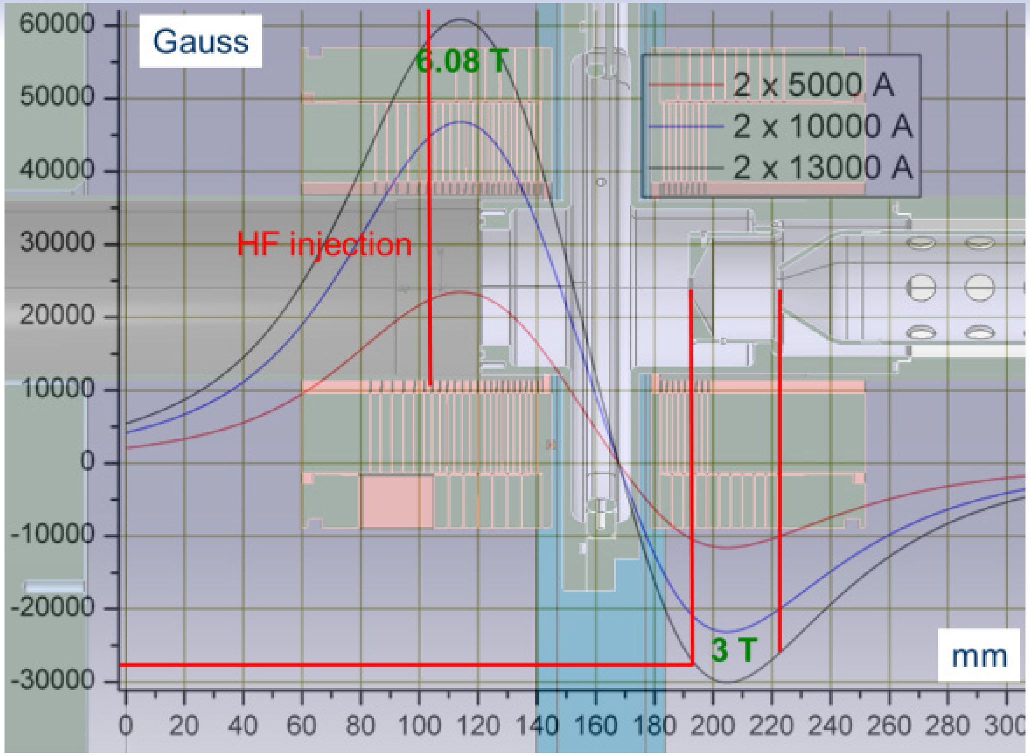
Since then, prototype run hours with no failure

SO, MAGNETIC FIELD MEASUREMENTS…!

LNCMI Flux integration measurement

Integration interval: 0.1mm





LPSC-IAP-GYCOM COLLABORATION

– International Science and Technology Center contract (2010-2012)

"Design, Manufacturing and Tests of Short Pulse ECR Multi-Charged Ion Source Prototype with High Ionization Efficiency"

Gyrotron to be delivered to LPSC-CNRS

Characteristics	Spécifications	Realized
Frequency	60 GHz	60.089 GHz
Power output	300 kW	313 kW
Pulse length	50µs – 10 ms	100µs – 1 ms
Repetition rate	10 Hz	2 Hz (5Hz @100 kW)
Efficiency	> 45 %	45.3 %

Cathode power supply

Pulses -20 to 40 Kv/3-18 A

1ms/3 Hz

Instability < 1%

Anode power supply

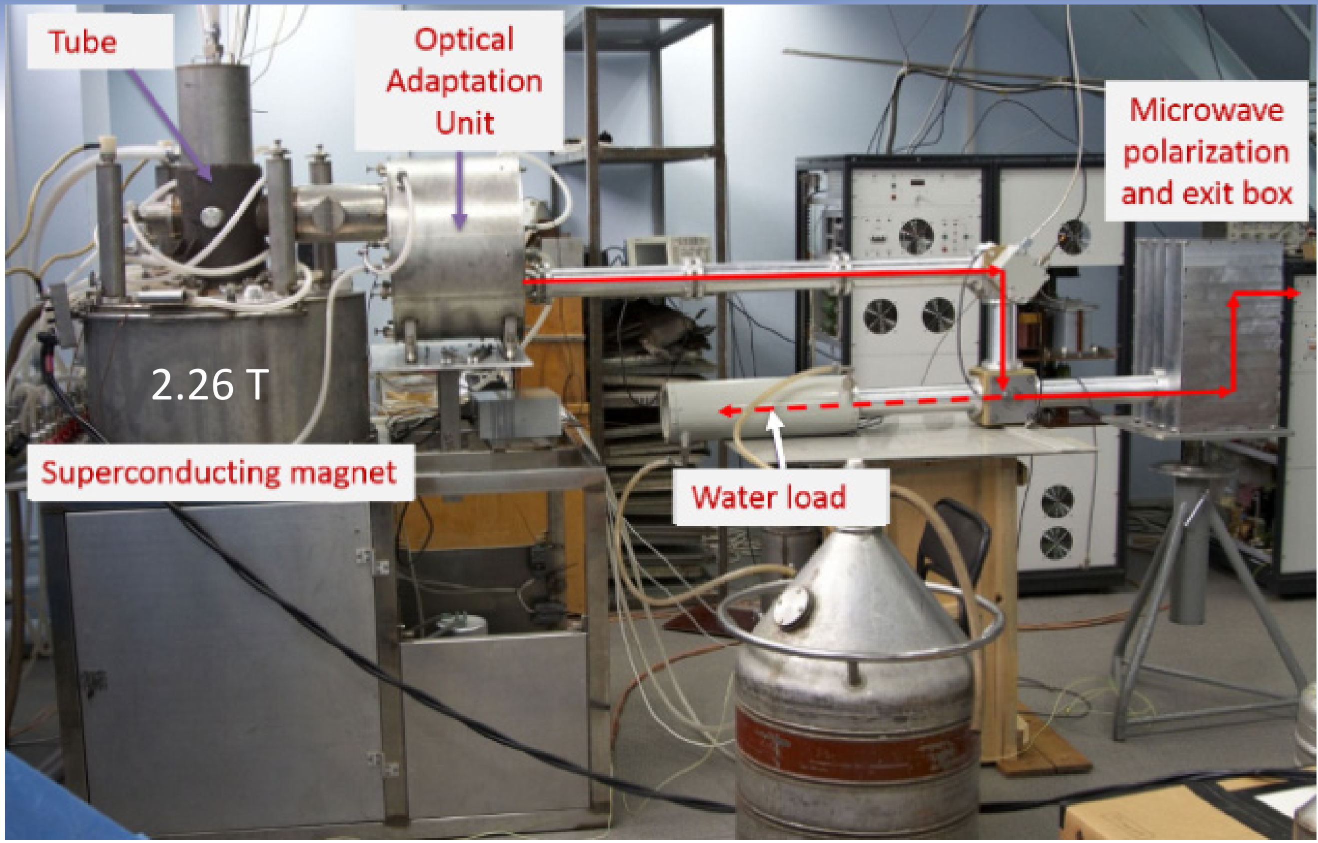
Pulses 2 to 20 Kv / 100 mA

0.5 - 1.0 ms/3Hz

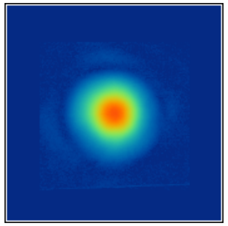
Instability < 1%

Rise and fall times < 20 ms

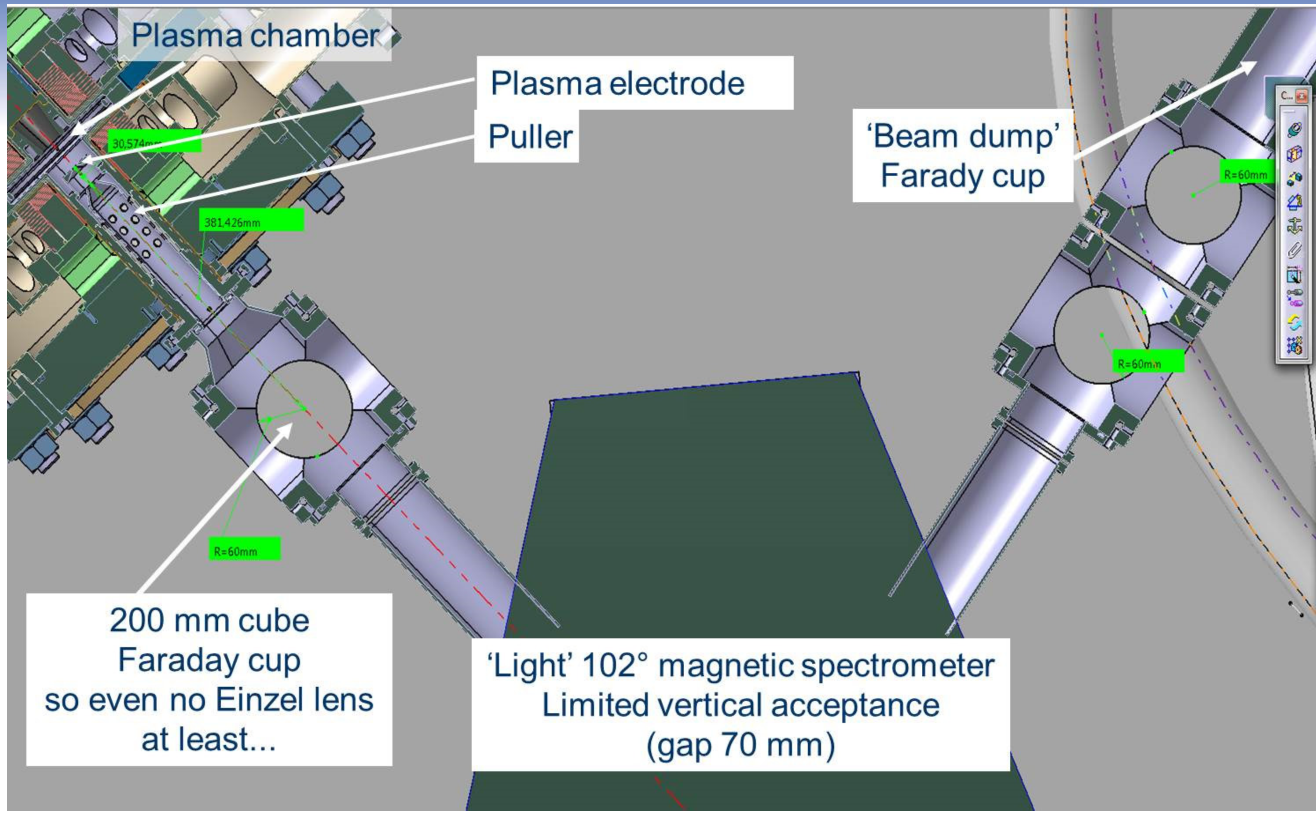
GYROTRON SYSTEM



Quasi Gaussian beam

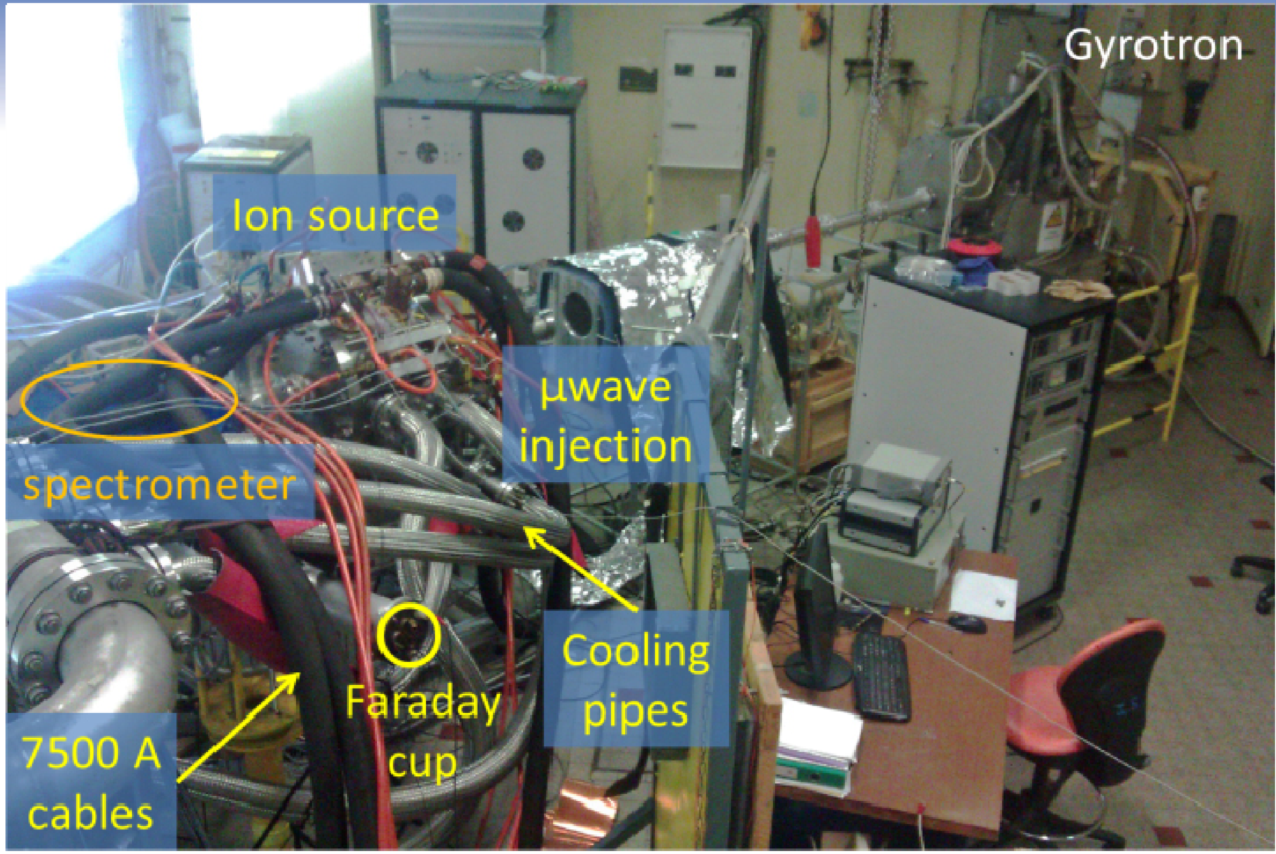


"THE (...TOO SIMPLE...) BEAM LINE"



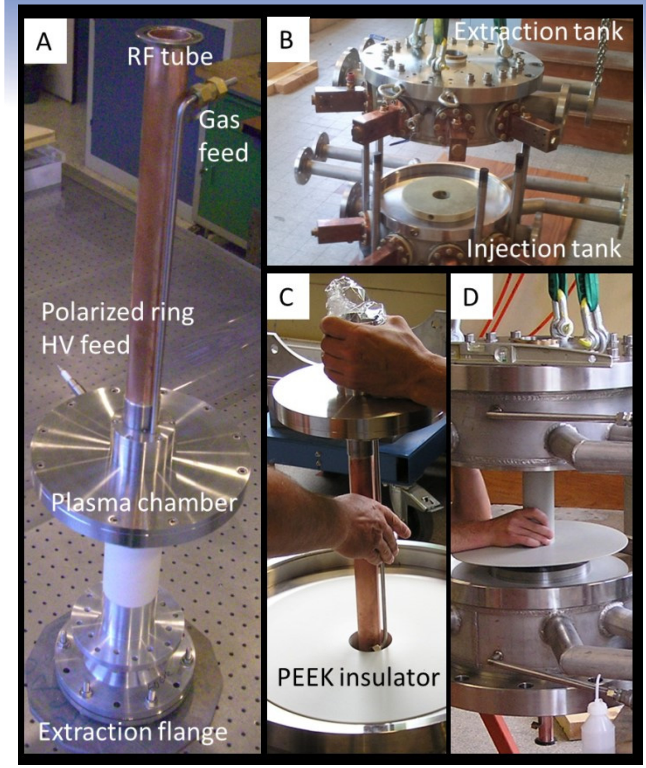
No optics...

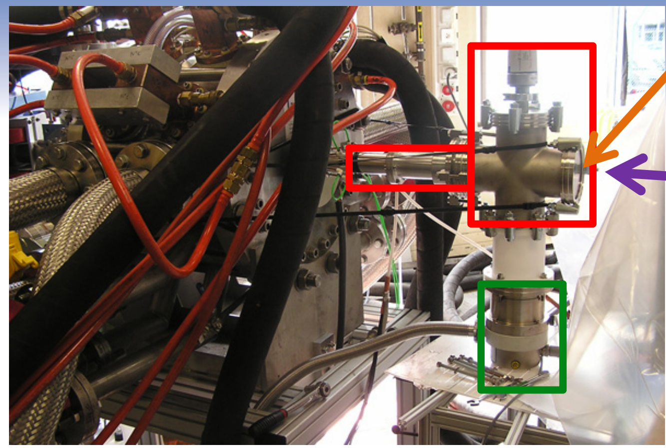
VIEW OF THE "EXPERIMENT"



Called
"The octopus"
by LNCMI
Staff...

"INSIDE THE SOURCE"

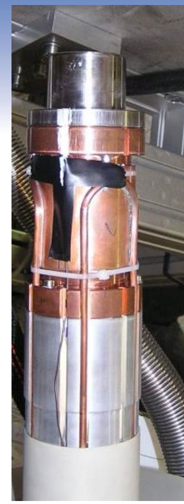


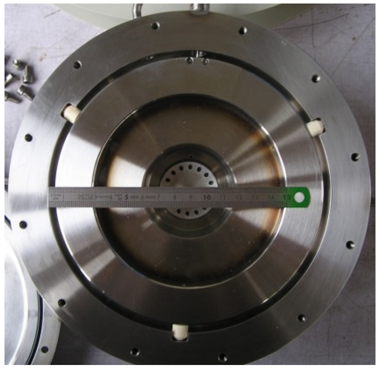


Quartz window

60 GHZ

No
DC breaker !





30 kV

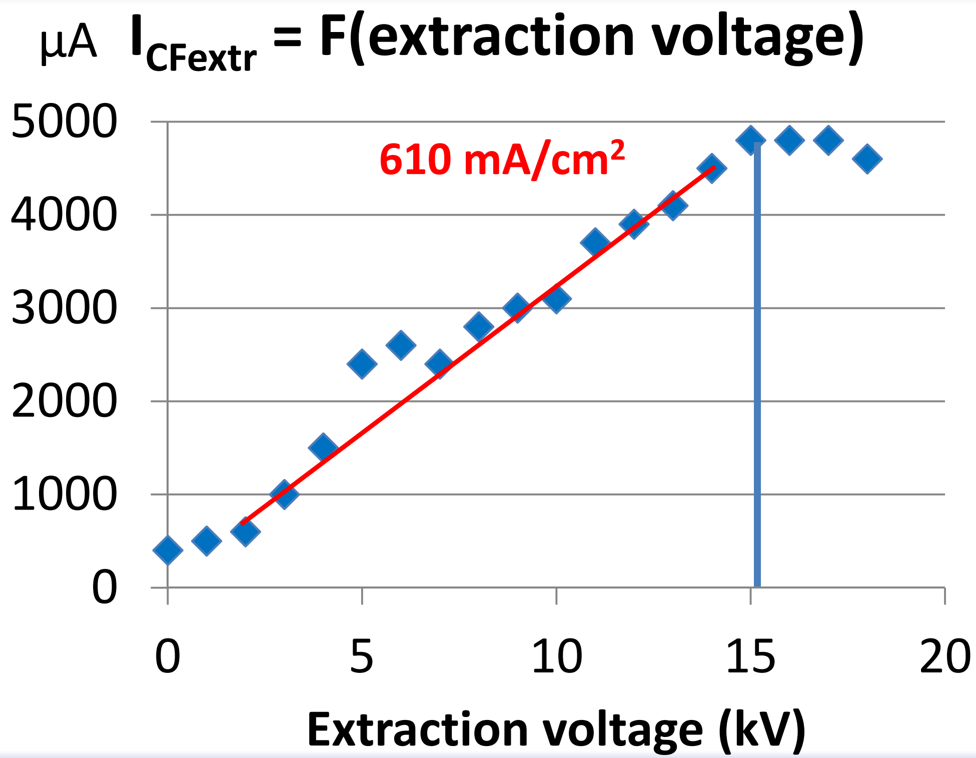
VERY FIRST PLASMA

Total current extracted

Maximum power due to X rays

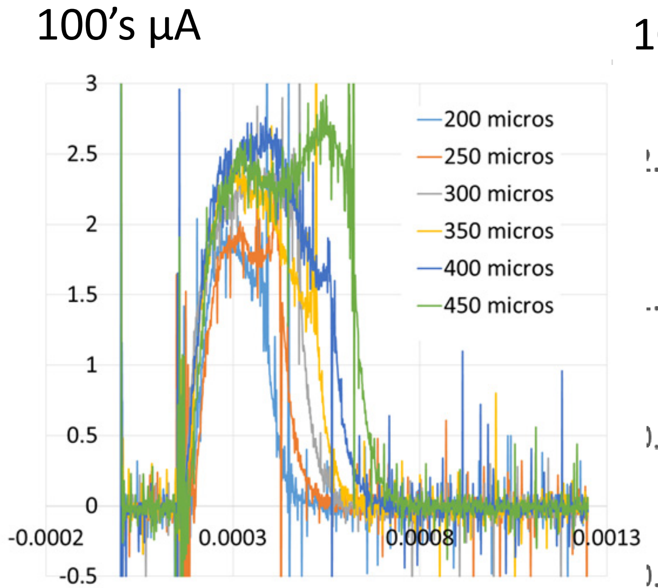
100 kW – 200 µs – 2 Hz
22 kA
1,1 E-05 mbar

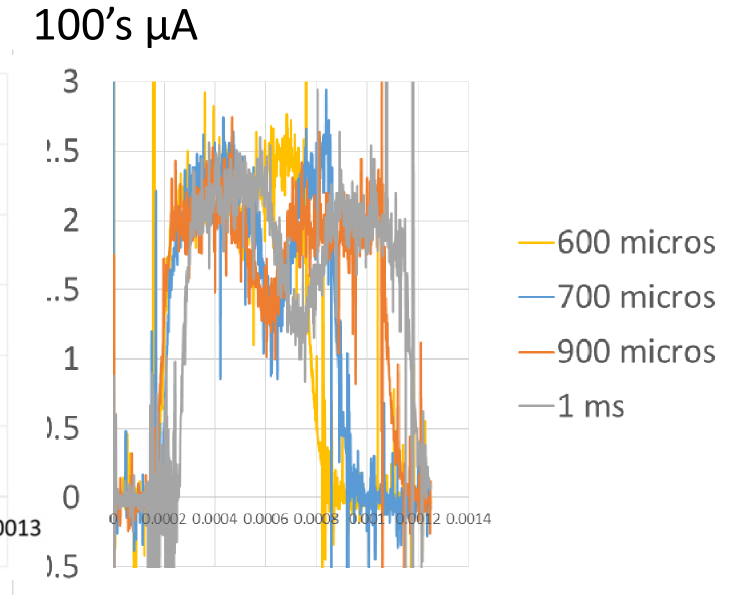
Plasma electrode hole
D = 1mm
Distance from puller 30 mm



HF PULSE LENGTH VARIATION

O^{2+} 15 kV / Helices 20 kA
6.3 E-06 mbar



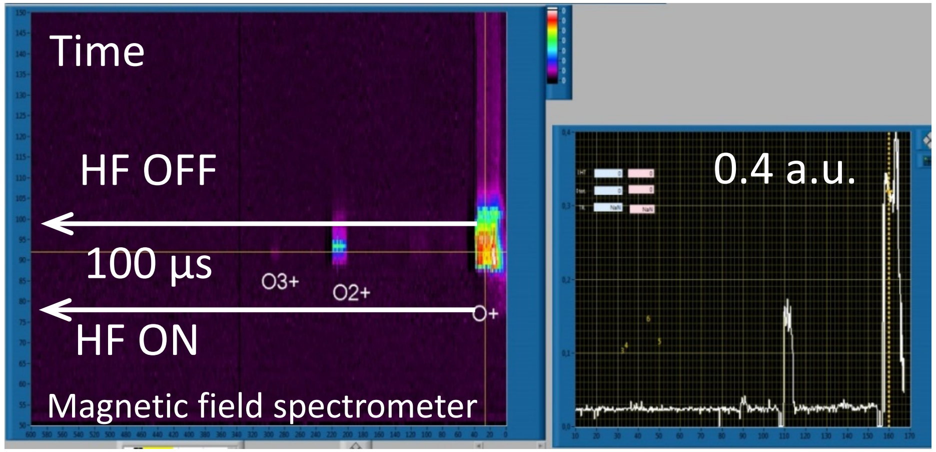


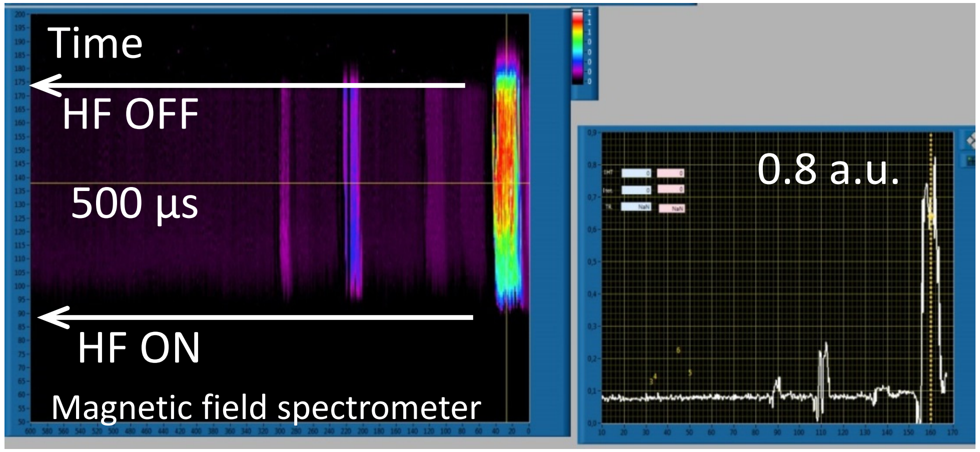
Intensity increases
then no gain

For longer pulses
some instabilities appear
decrease of the intensity

3D SPECTRA FOR DIFFERENT HF PULSE LENGTH

Intensity





All beam intensities increase with the pulse length up to 500 µs

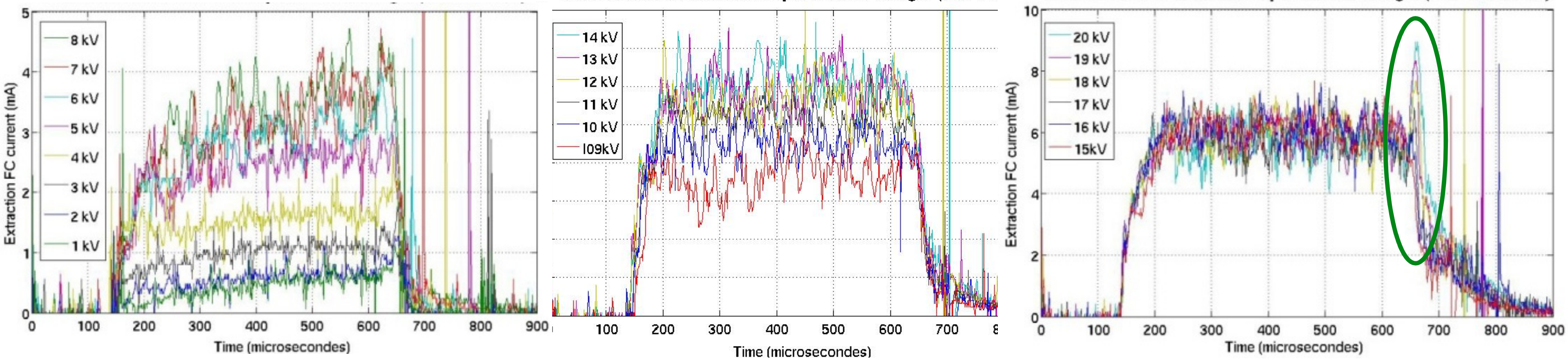
TIME EVOLUTION OF THE TOTAL CURRENT VERSUS EXTRACTION HIGH VOLTAGE

22kA - 80 kW / 500 µs - 1.1 E-05 mbar

From 1 to 8 kV

From 9 to 14 kV

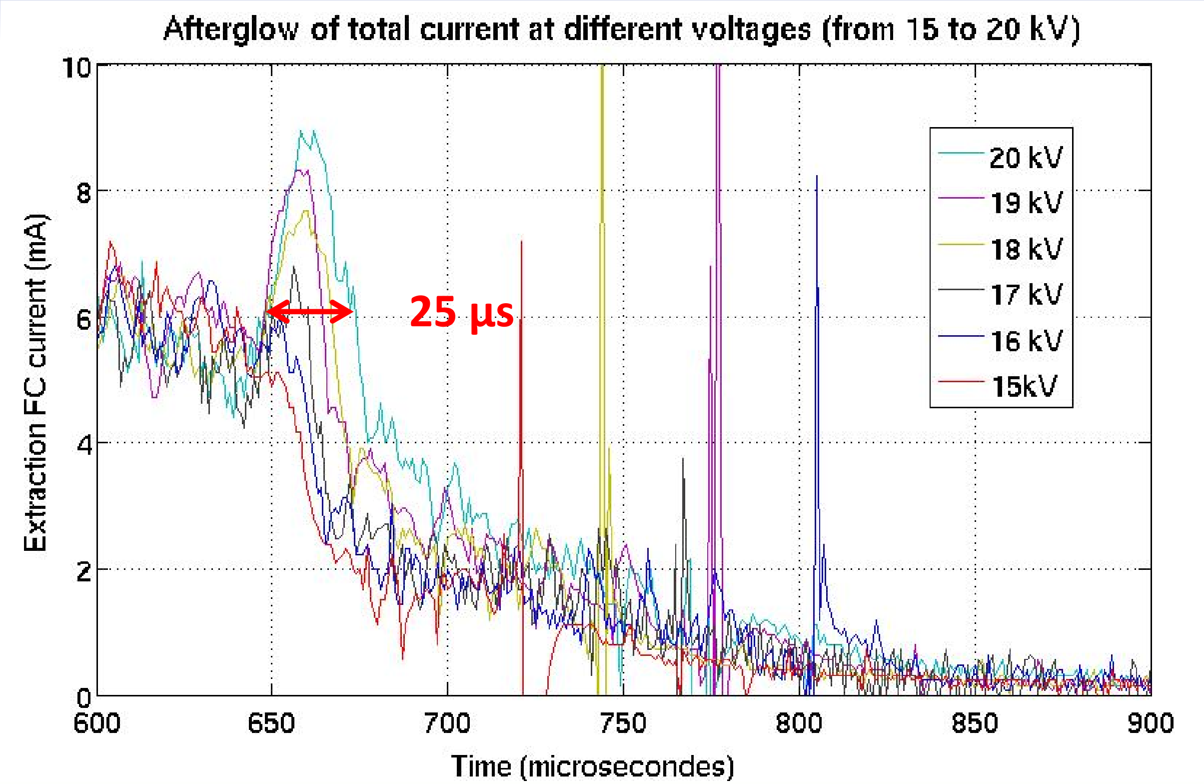
From 15 to 20 kV



The steady state intensity is reached in 50 µs (the rising time of the HF !)

Afterglows appear at voltages higher than 15 kV

ZOOM ON AFTERGLOWS



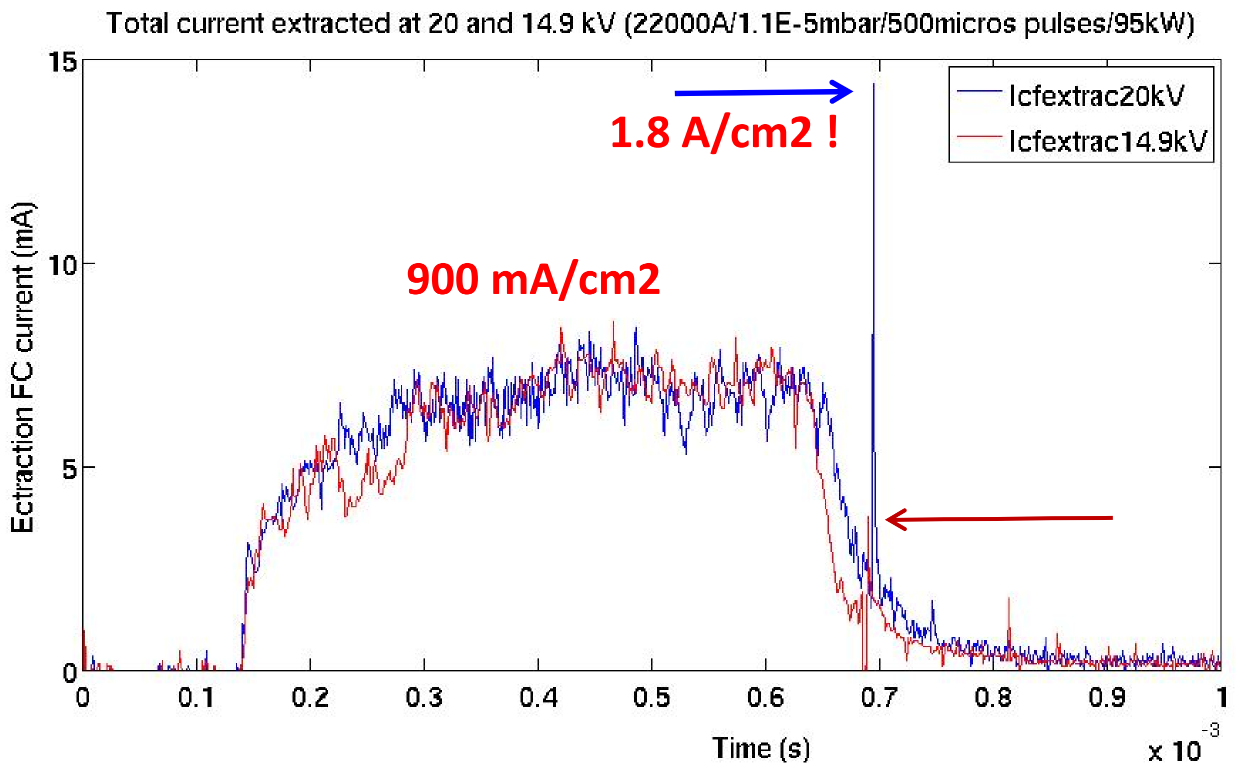
Afterglows appear at voltages > 15kV

Their intensity increase when increasing the extraction voltage

Width ~ 25 µs

(10 times shorter than the ones obtained in PHOENIX CERN 28 GHz)

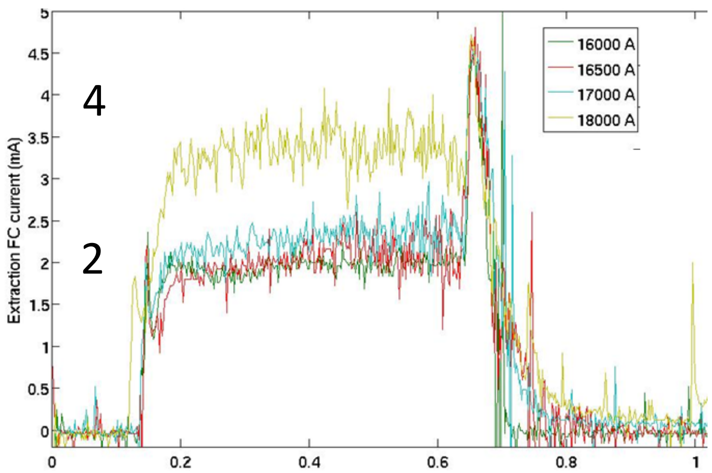
BEAM FLASHES



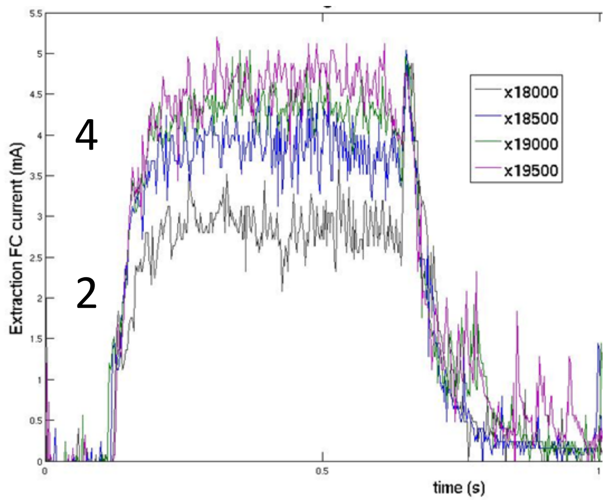
For some tunings
reproducible short peaks
appear with a
very high current density

TOTAL CURRENT VERSUS COILS INTENSITY

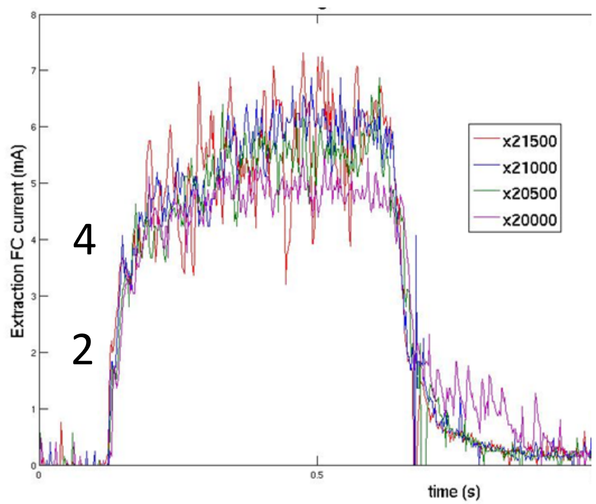
From 16 to 18 kA



From 18 to 19.5 kA



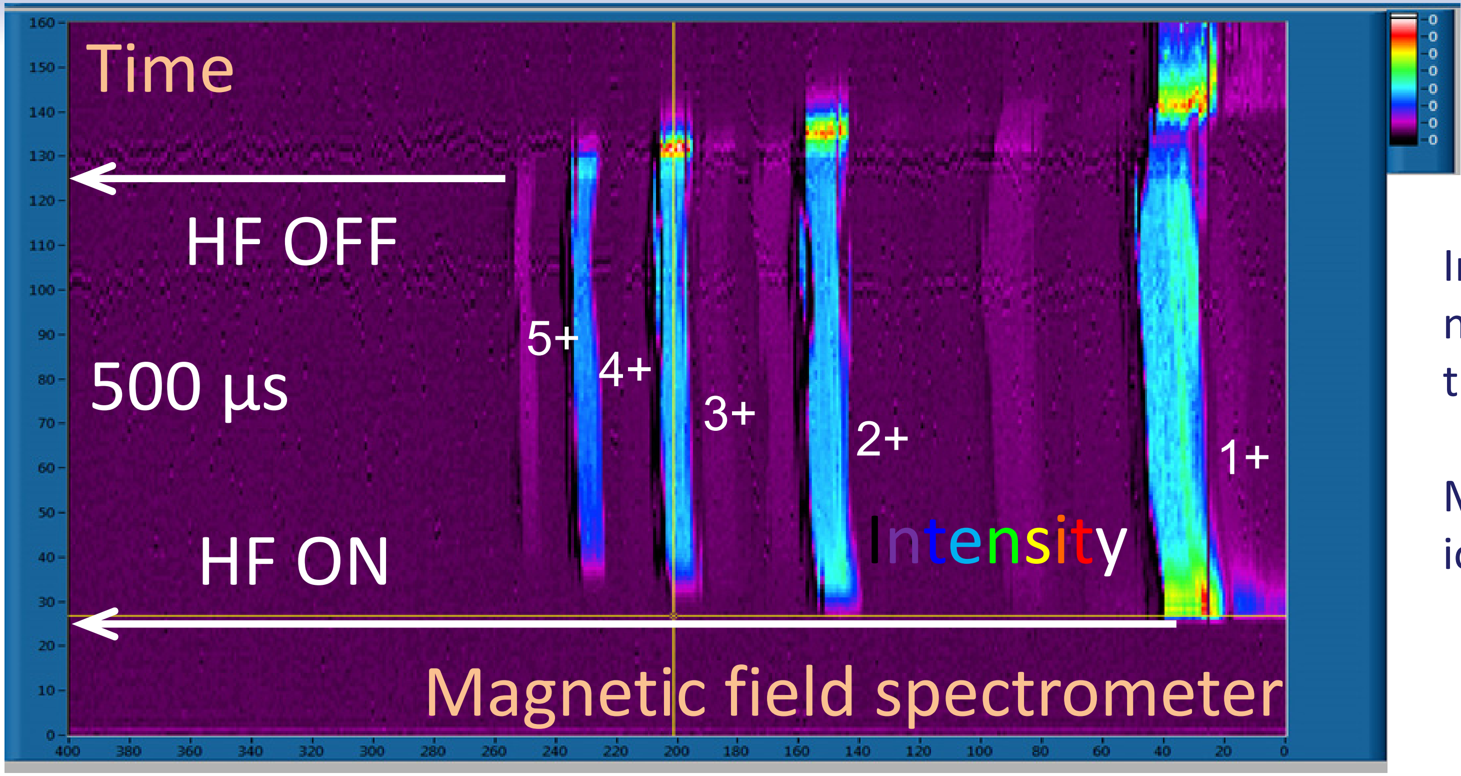
From 20 to 21.5 kA



The intensity of the steady state increases, the afterglows stays constant !

(opposite of classical ECRIS)

3D OXYGEN SPECTRUM

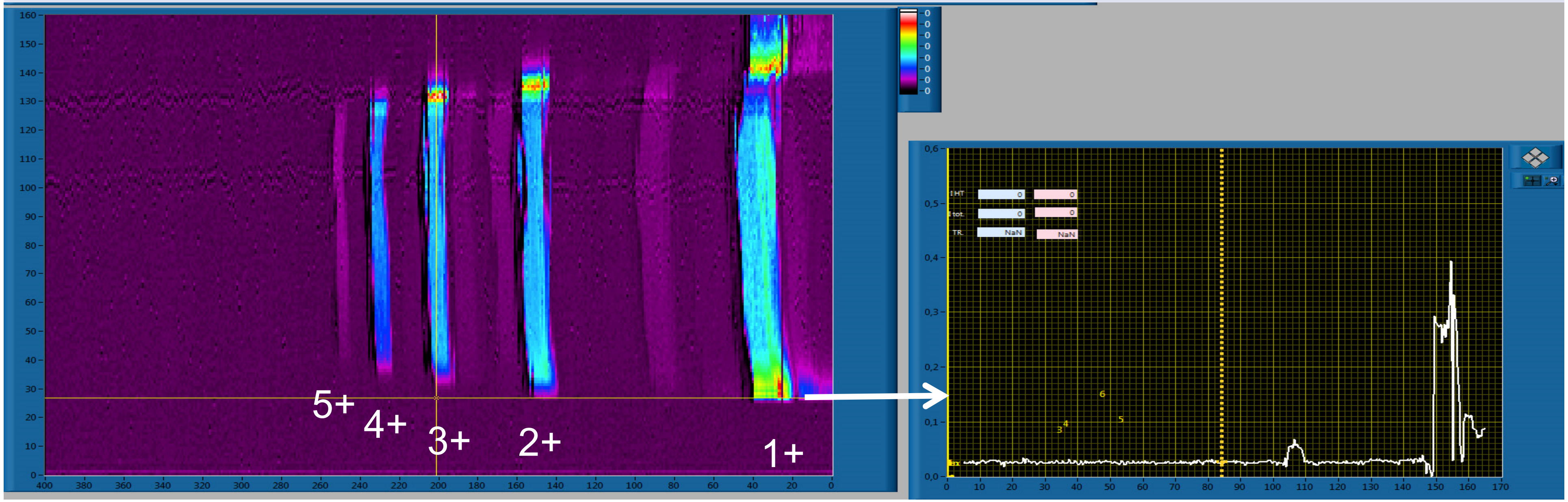


Intensity normalized to the highest one

Multicharged ions up to 5 +

3D OXYGEN SPECTRUM

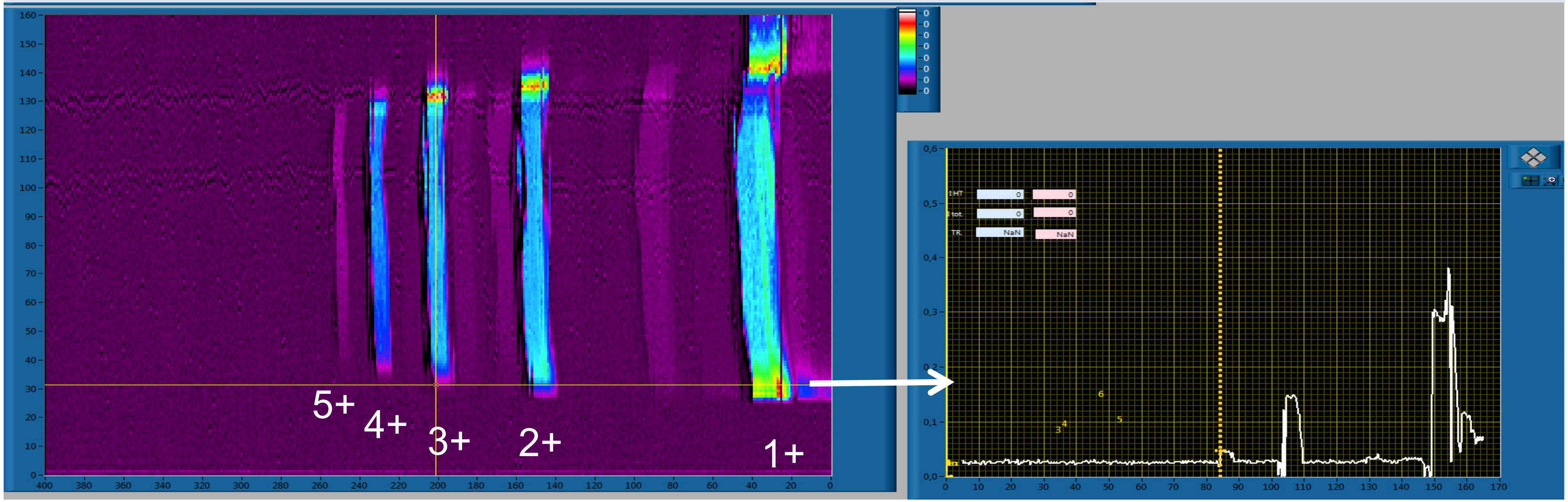
18000 A – 15 kV – 56 kW



Ion creation

3D OXYGEN SPECTRUM

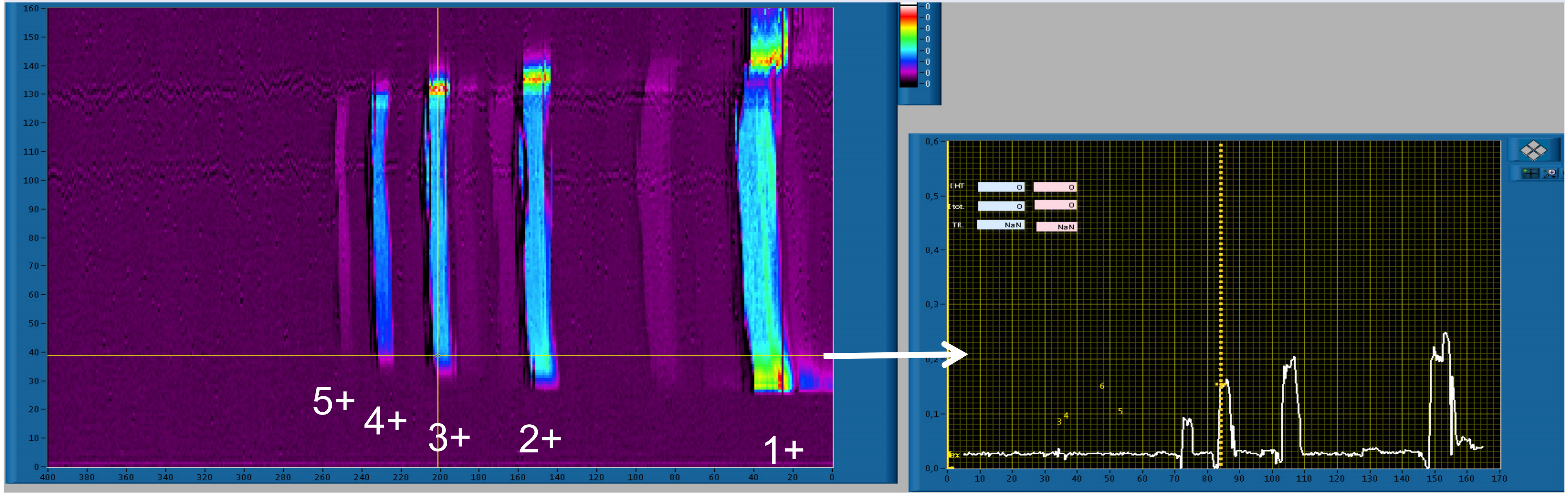
18000 A – 15 kV – 56 kW



Ion creation

3D OXYGEN SPECTRUM

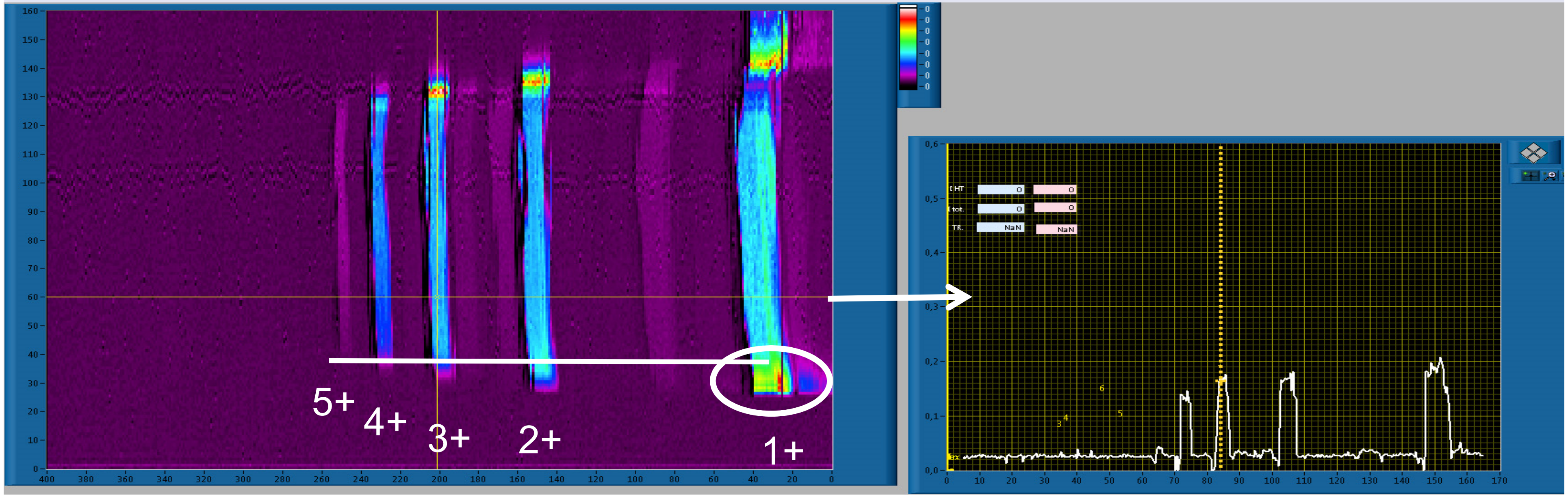
18000 A – 15 kV – 56 kW



Ion creation

3D OXYGEN SPECTRUM

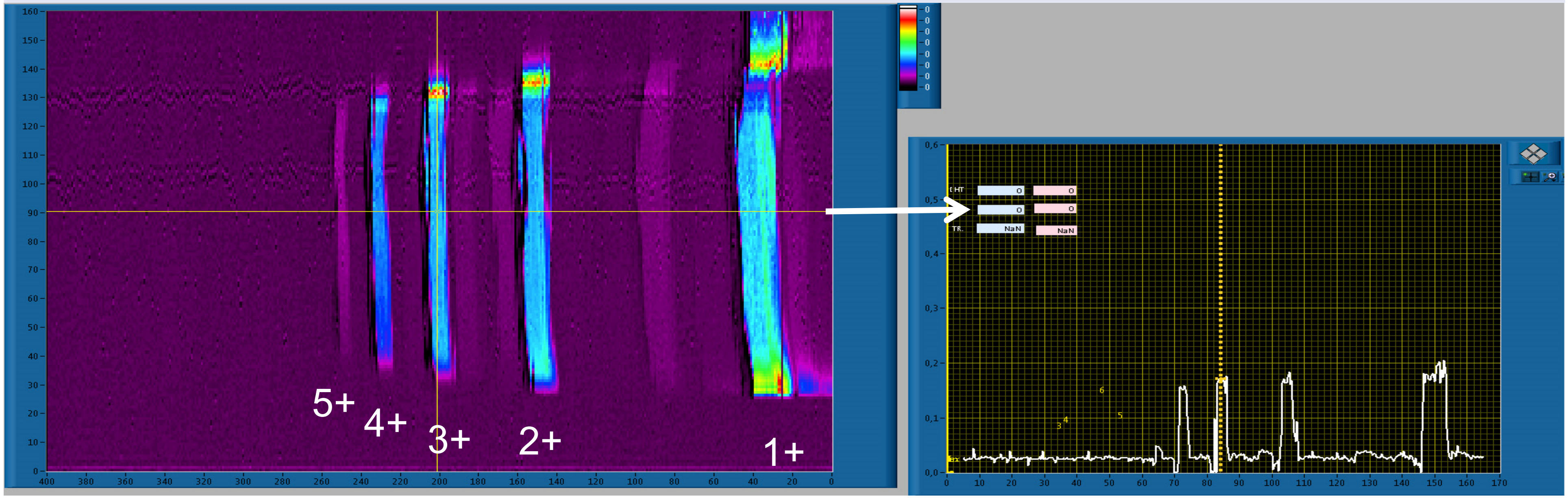
18000 A – 15 kV – 56 kW



Ionization equilibrium

3D OXYGEN SPECTRUM

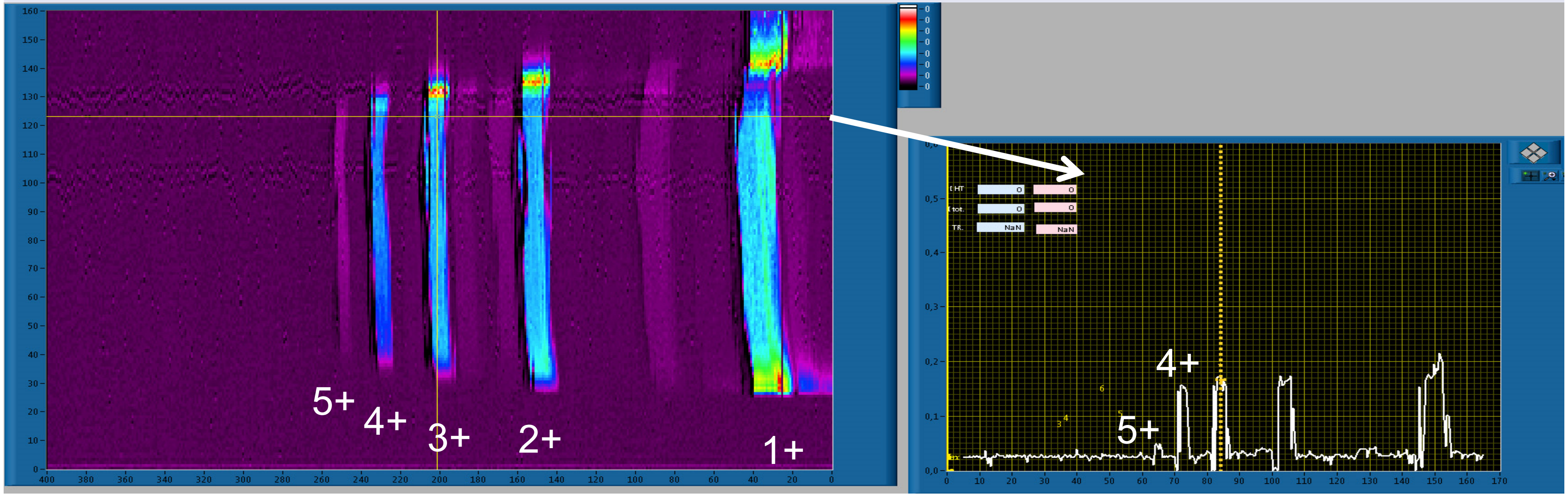
18000 A – 15 kV – 56 kW



Ionization equilibrium

3D OXYGEN SPECTRUM

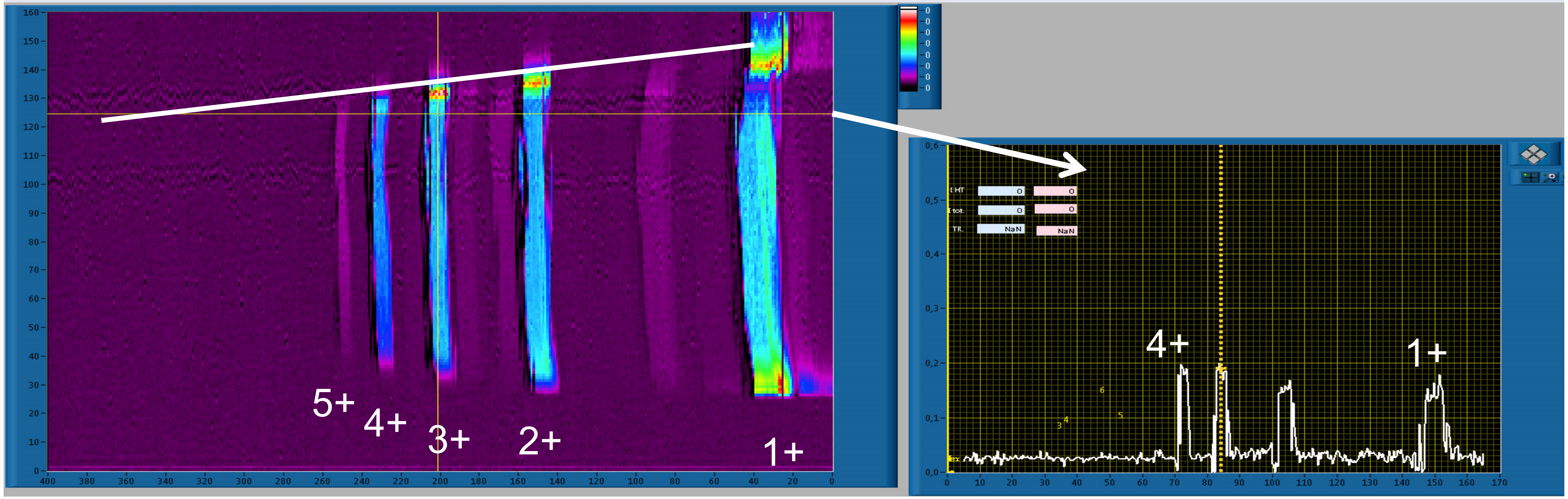
18000 A – 15 kV – 56 kW



Ionization equilibrium (and HF stop)

3D OXYGEN SPECTRUM

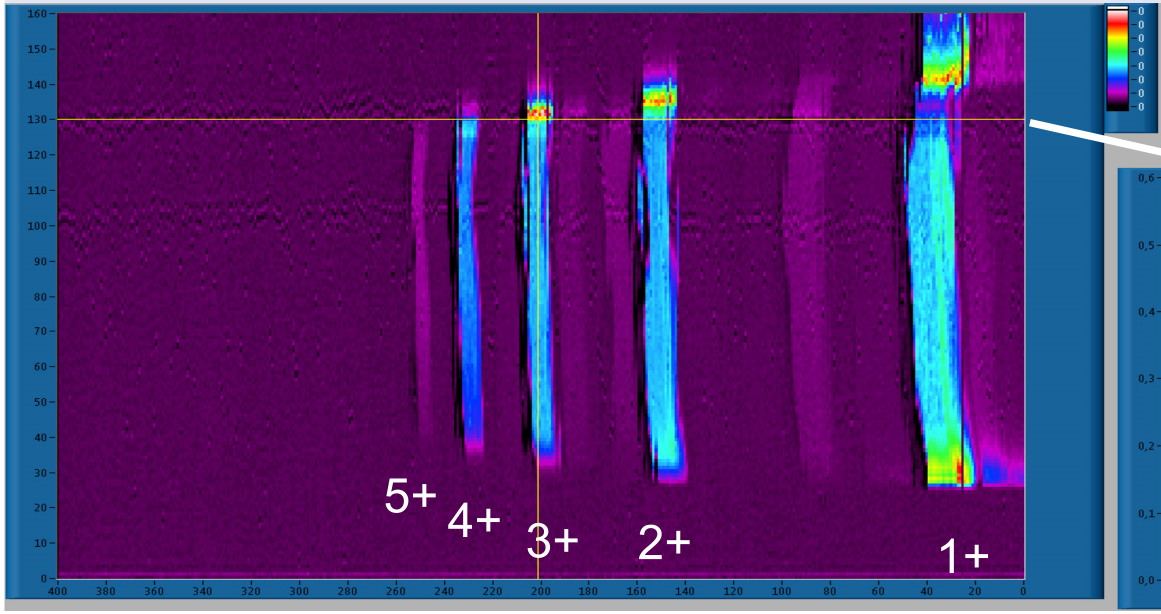
18000 A – 15 kV – 56 kW

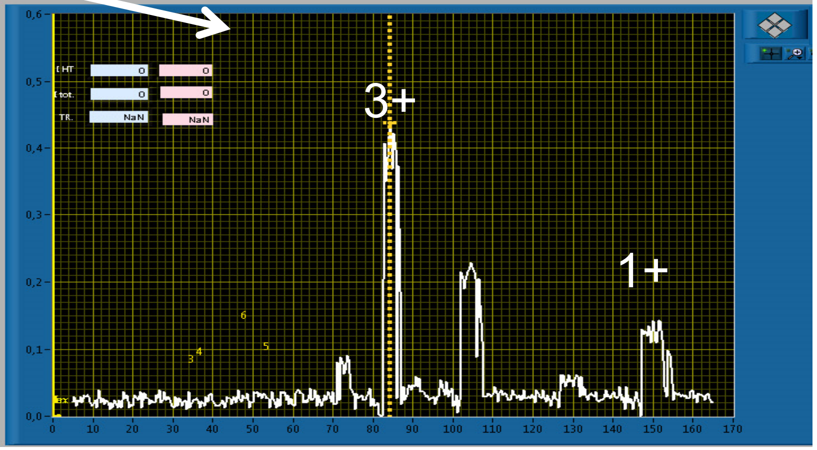


4+ Afterglow

3D OXYGEN SPECTRUM

18000 A – 15 kV – 56 kW

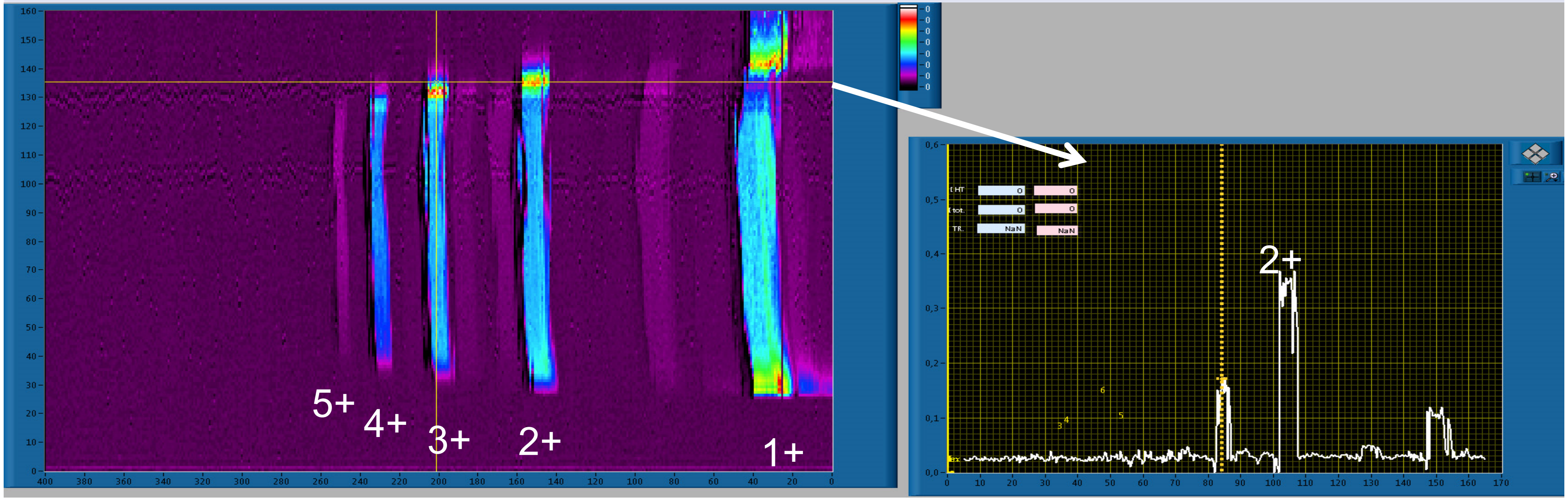




3+ Afterglow

3D OXYGEN SPECTRUM

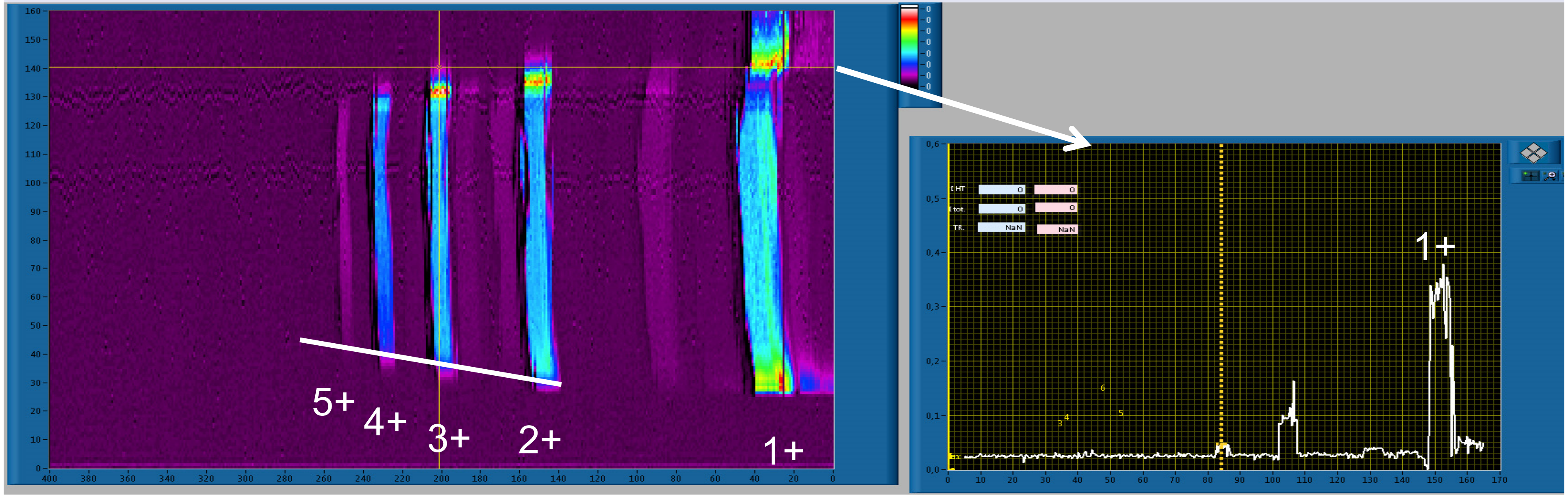
18000 A – 15 kV – 56 kW



2+ Afterglow

3D OXYGEN SPECTRUM

18000 A – 15 kV – 56 kW

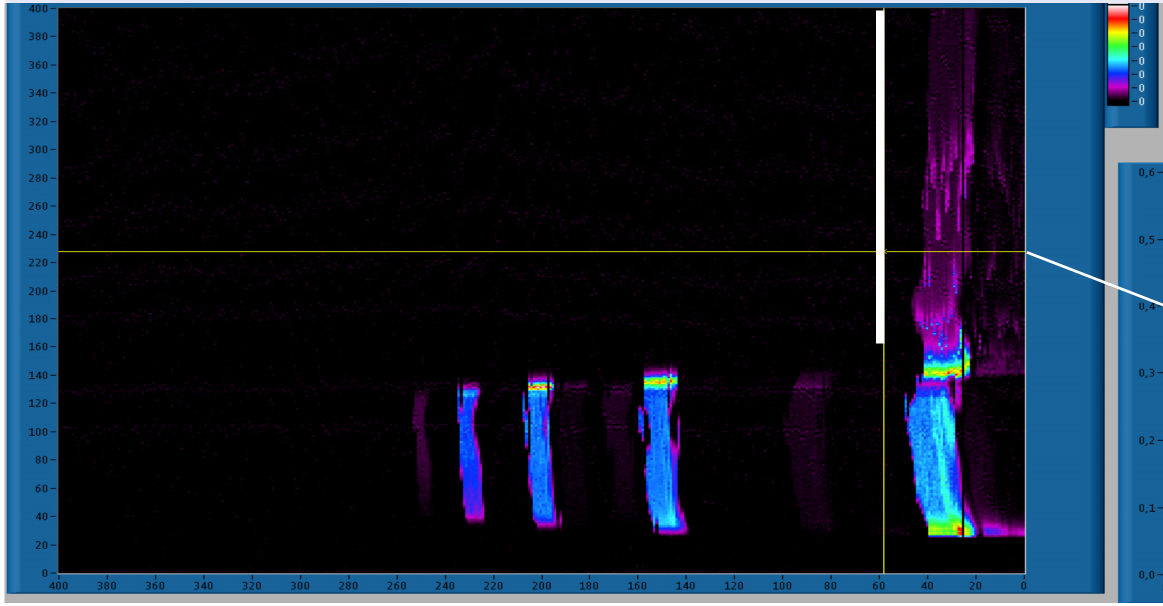


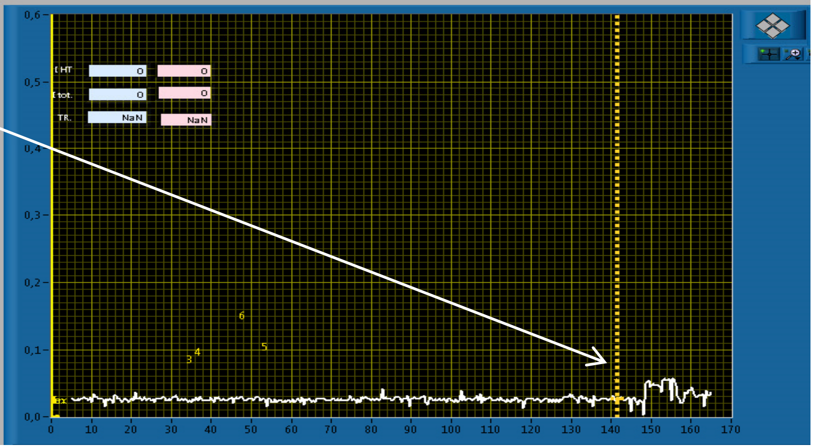
1+ Afterglow

3D OXYGEN SPECTRUM

18000 A – 15 kV – 56 kW

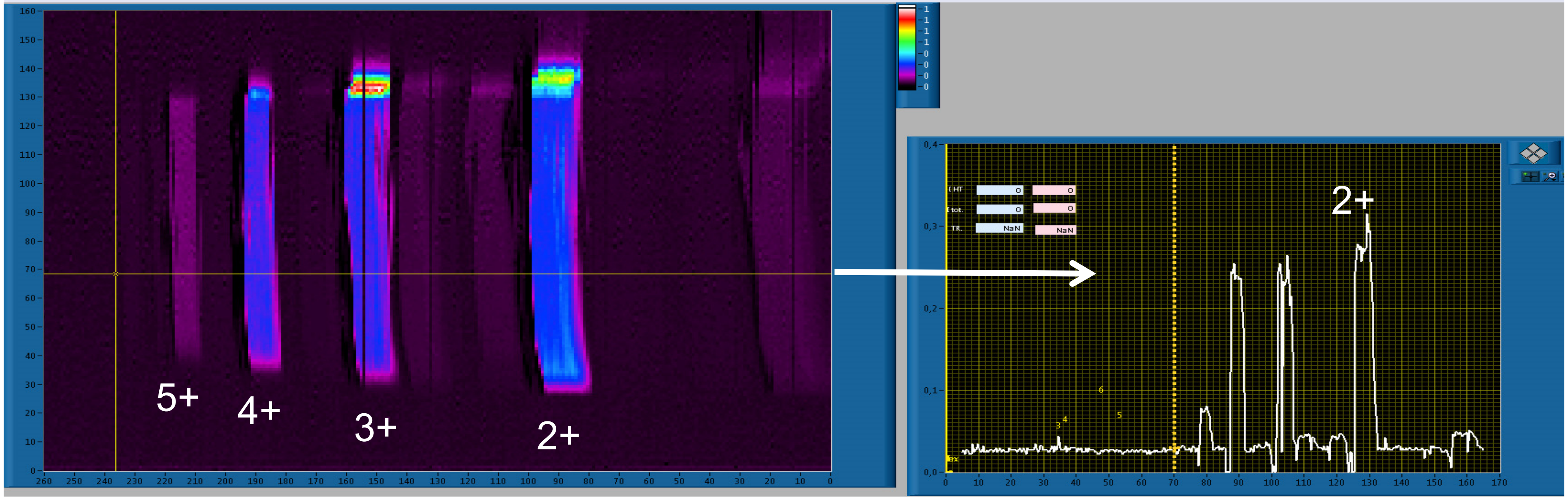
1+ tail





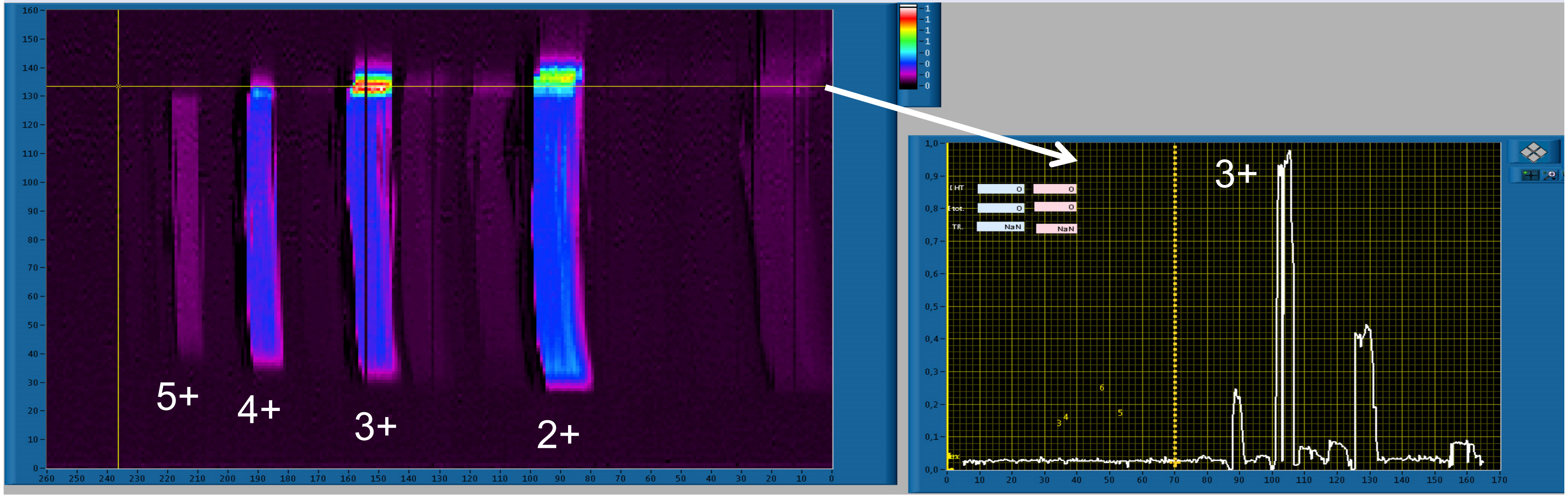
3D OXYGEN SPECTRUM

18000 A – 22 kV – 56 kW To maximize afterglows without too many breakdowns

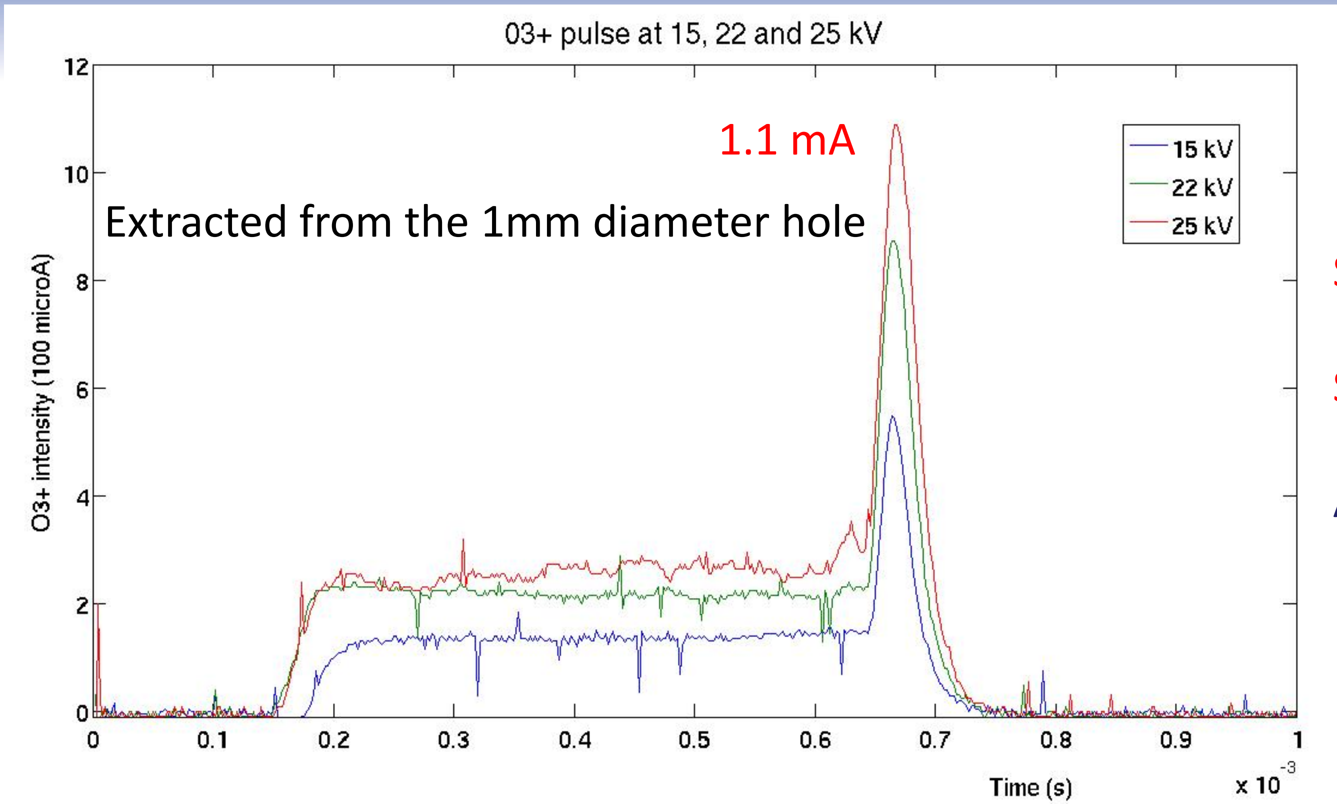


3D OXYGEN SPECTRUM

18000 A – 22 kV – 56 kW



O^{3+} SIGNAL AT DIFFERENT EXTRACTION VOLTAGES



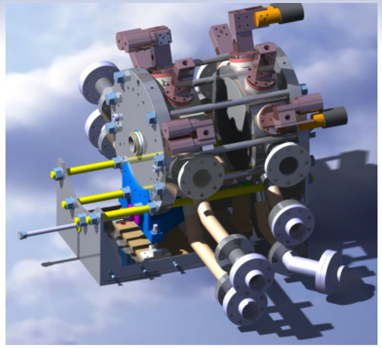
Such a stability !

Such beautiful afterglows !

About 50 µs duration

PERSPECTIVES

– Add electric switches to the LNCMI bus bars or build a 26000 A rheostat...
    - To tune the injection and extraction independently



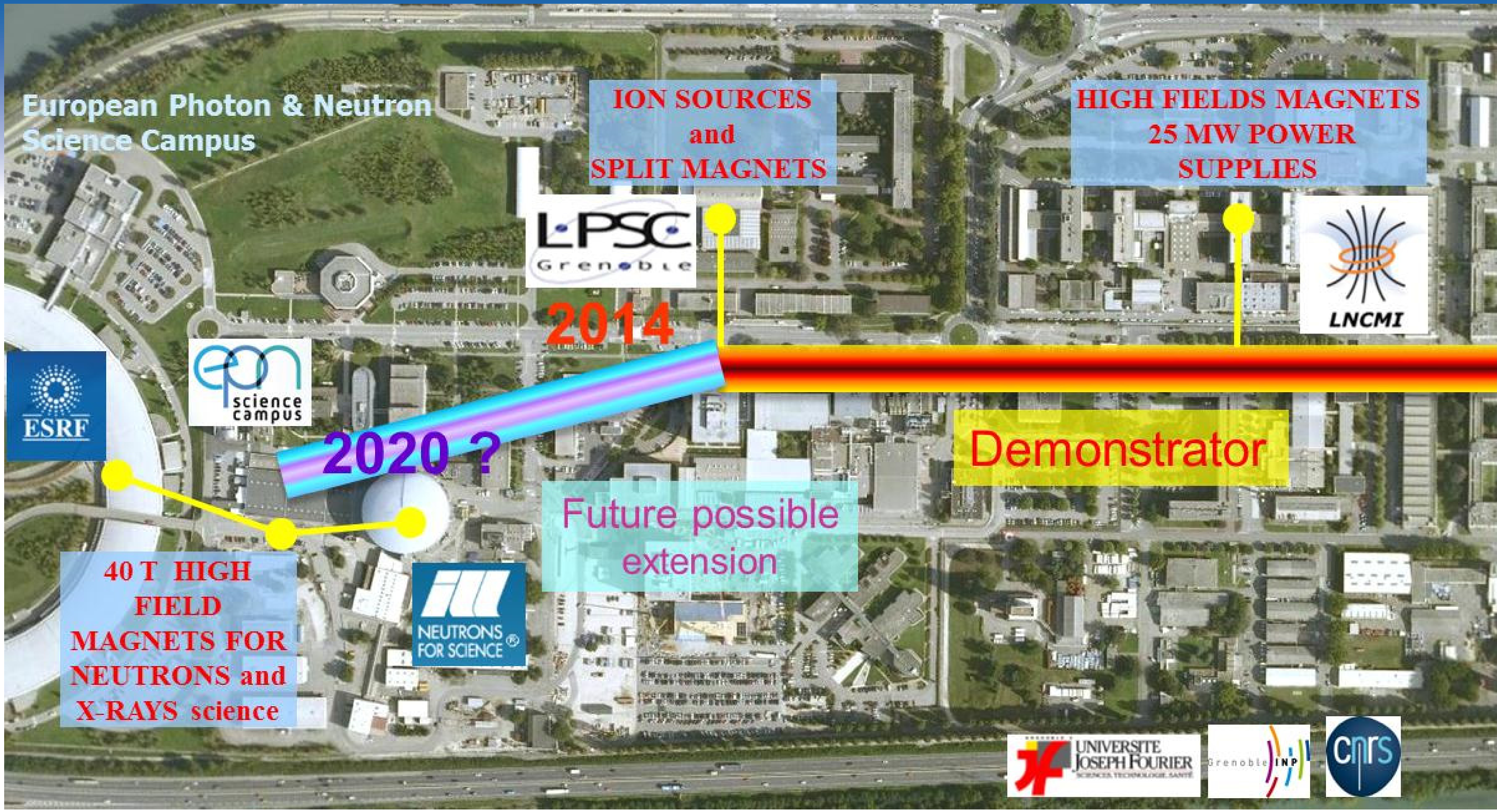
– Allow the variation of the cusp length
    - will allow too the study of the magnetic bottle
– Construct one helix with the cold spray method
    - Will improve the conductivity
– Find the funding for a European project (Grenoble – Nizhny Novgorod – Jyväskylä) with satisfying experimental conditions Study the feasibility of a 'classical' minimum-B 60 GHz ECRIS to study their physics
– Evaluate the feasibility of superconducting helices (solid MgB_2)
– Bring the LNCMI current to LPSC with MgB2 cables (600m)

CONCLUSIONS

- All the results presented have been obtained in 1.5 week, a few days of beam
- A high frequency ECR source based on a cusp with high magnetic field and a closed ECR zone has obvious confinement properties
- It is able to produce amperes of ion beams
- A lot of plasma physics studies can be considered...
- We have a unique opportunity to experiment 60 GHz ECRIS for the future

Vadim Skalyga invited tal at ICIS2015, New York City, USA
'New Progress of High Current Gasdynamic Ion Source'
The real performance of gasdynamic ECRIS for multicharged ions production should be demonstrated in Grenoble

Thank you so much for your attention !!


European Photon & Neutron Science Campus
ION SOURCES and SPLIT MAGNETS
HIGH FIELDS MAGNETS 25 MW POWER SUPPLIES
LPSC Grenoble
LNCMI
2014
ESRF
epn science campus
2020 ?
Demonstrator
Future possible extension
40 T HIGH FIELD MAGNETS FOR NEUTRONS and X-RAYS science
NEUTRONS FOR SCIENCE
UNIVERSITE JOSEPH FOURIER
Grenoble INP
cnrs

Zero-dimensional model of **gas breakdown** in an ECRIS magnetic trap with ^6He

$$\frac{\partial N_e}{\partial t} = N_e \cdot \sum_{\alpha=1}^{3} \sum_{i=0}^{q} k_{i,i+1}^{\alpha} N_i^{\alpha} - \frac{N_e}{\tau_e}$$

Electronic density (for 3 ionic species)

$$\frac{\partial N_i^1}{\partial t} = (k_{i-1,i}^1 N_{i-1}^1 - k_{i,i+1}^1 N_i^1) \cdot N_e - \frac{N_i^1}{\tau_i^1}$$

Ion density (buffer gas)

$$\frac{\partial N_i^2}{\partial t} = (k_{i-1,i}^2 N_{i-1}^2 - k_{i,i+1}^2 N_i^2) \cdot N_e - \frac{N_i^2}{\tau_i^2} - \frac{N_i^2}{\tau^*}$$

Ion density (^6He)

$$\frac{\partial N_i^3}{\partial t} = (k_{i-1,i}^3 N_{i-1}^3 - k_{i,i+1}^3 N_i^3) \cdot N_e - \frac{N_i^3}{\tau_i^3} + n_i^*$$

Ion density (^6Li)

Efficiency:
$\eta = N_{ion\ ext} / N_{atoms\ inj}$

$$\frac{dN_0^{\alpha}}{dt} = I^{\alpha}(t) - k_{0,1}^{\alpha} N_0^{\alpha} N_e$$

Neutral density

$$\frac{3}{2} \cdot \frac{d(N_e \cdot \langle E \rangle)}{dt} = P - \frac{N_e}{\tau_e}(\langle E \rangle + \varphi_0) - \sum_{\alpha=1}^{3} \sum_{i=0}^{q} k_{i,i+1}^{\alpha} N_e N_i^{\alpha} I_i^{\alpha}$$

Energy balance

$$\frac{1}{\tau_e} = \frac{1}{N_e} \sum_{\alpha=1}^{3} \sum_{i=1}^{q} \frac{i N_i^{\alpha}}{\tau_i^{\alpha}}$$

Quasi-neutrality condition