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DEVELOPMENT OF THE ECR ION SOURCES FOR THE FLNR (JINR) CYCLOTRONS

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FLNR (JINR) CYCLOTRONS WITH ECR ION SOURCES

U400 + ECR4M

U400M + DECRIS-2

CI-100 + DECRIS-SC

NEW CYCLOTRONS

DC-72

DECRIS-2m

DC-60

DECRIS-3

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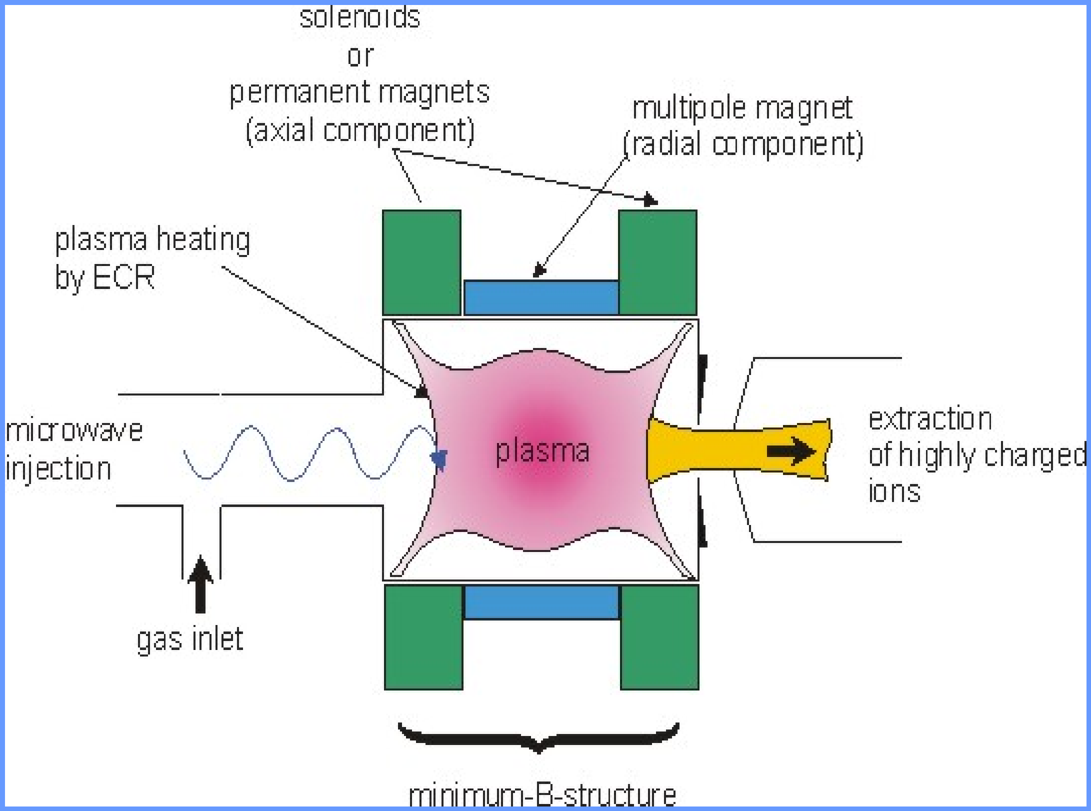
The ECR ion source



f [GHz]	B [T]	n_{ec} [cm^{-3}]
2.45	0.0875	7.44×10^{10}
6.4	0.23	5.08×10^{11}
10	0.36	1.24×10^{12}
14	0.5	2.43×10^{12}
16	0.57	3.2×10^{12}
18	0.64	4×10^{12}
28	1	10^{13}

$$\omega_{ECR} \sim B \times e / m_e$$

$$n_{ec} = \frac{m\omega^2}{4\pi e^2} = 1.24\times10^{10} \times (f[GHz])^2$$

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DECRIS - Dubna ECR Ion Sources

DECRIS-2, DECRIS-2m, DECRIS-3, DECRIS-4 are "room temperature" ECR ion sources. The axial magnetic field is created by two coils with independent power supplies. The radial magnetic field is created by permanent magnet hexapole, made from NdFeB.

DECRIS-SC – axial magnetic field is created by superconducting solenoids

DECRIS-2 – U-400M cyclotron – 1995

ECR-4M – U-400 cyclotron – 1996 (collaboration FLNR – GANIL (France))

DECRIS-3 – TESLA Accelerator Installation (Belgrade) -1997

DECRIS-2m – BIONT Inc. (Bratislava) – 2003

DECRIS-SC – CI-100 cyclotron - 2004

DECRIS-3 - DC-60 accelerator complex (Astana, Kazakhstan) – 2006

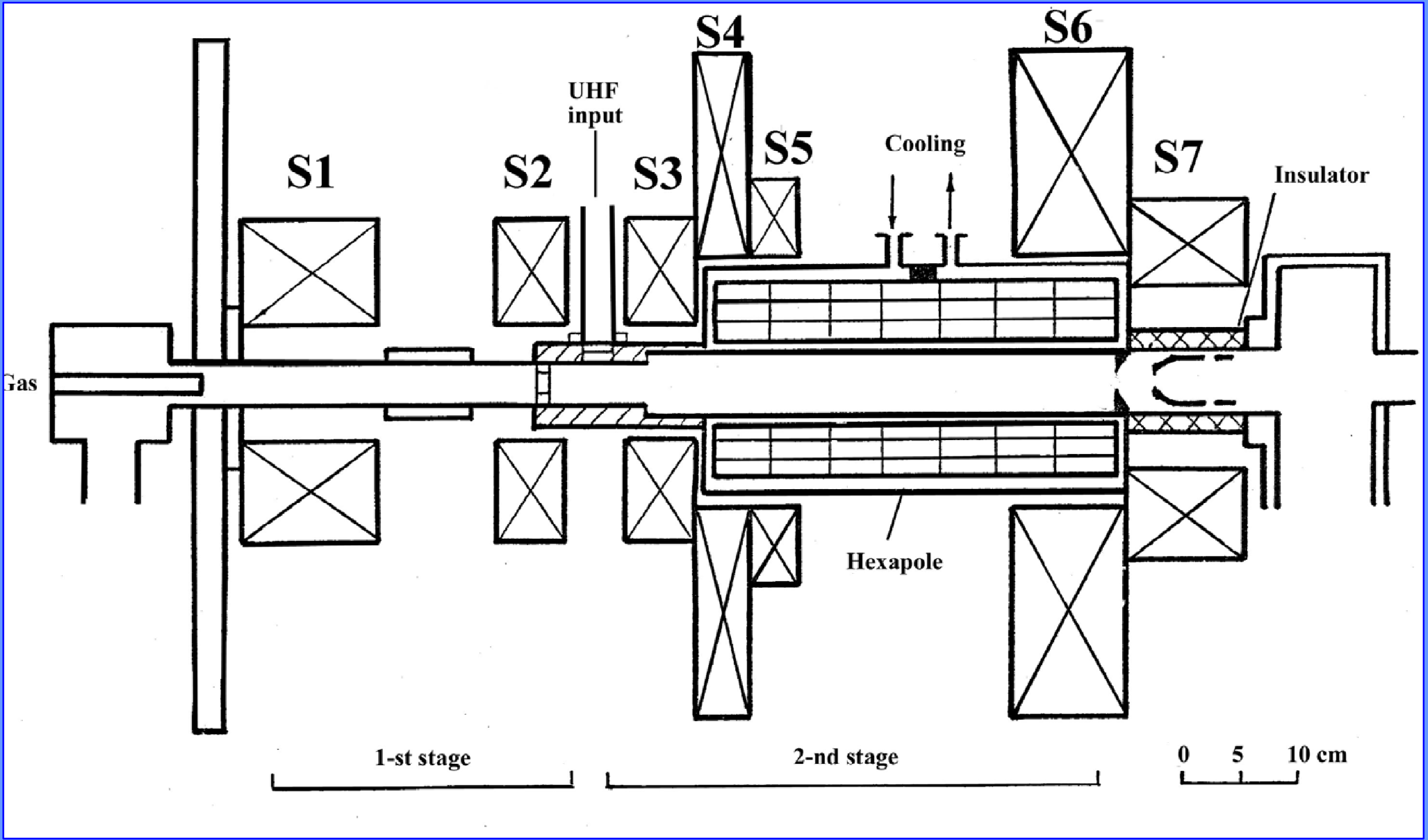
DECRIS-4 – in operation at the test bench - 2006

DECRIS-2m – tested → DC-72 cyclotron (Bratislava) – 2009

DECRIS-SC2 – new ion source for U-400M – under commissioning

DECRIS-SC3 – for DC-350 cyclotron - project

DECRIS -1



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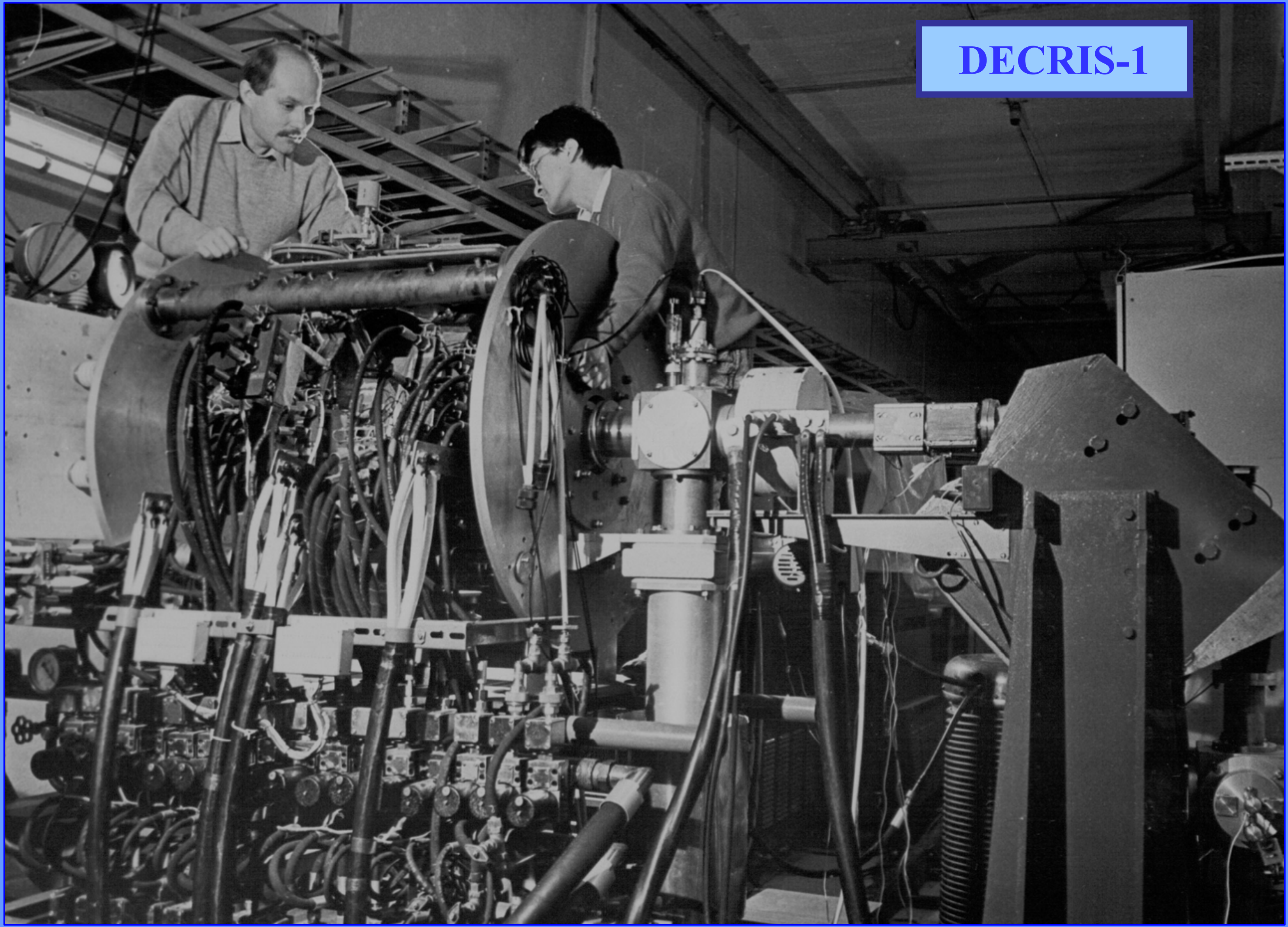

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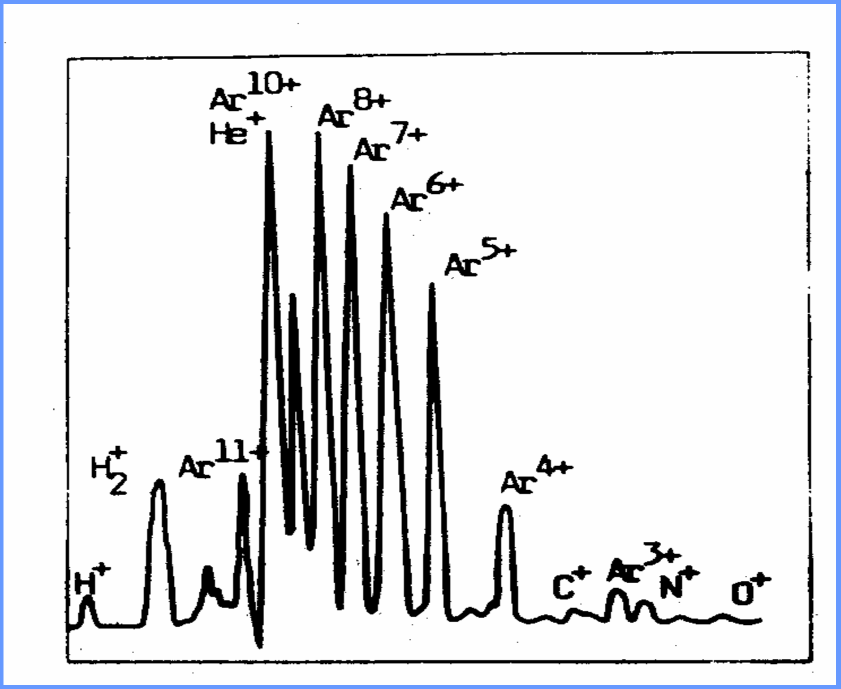
DECRIS-1



Charge state	4+	5+	6+	7+	8+	9+	11+	Support gas
N	270	92	17					
O		160	87	26				
Ar					70	24	5	
Ar					95	45	9	He
Ar					110	70	15	Oxigen

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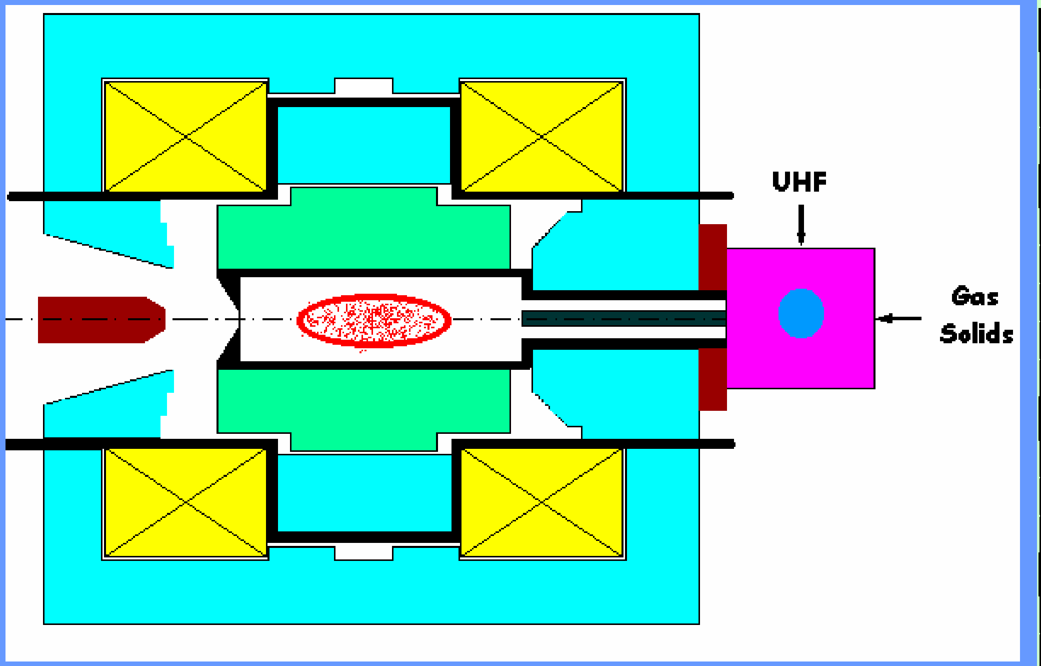
DECRIS-2



AXIAL MAGNETIC FIELD	
Peak on axis, injection side	1.2 T
Peak on axis, extraction side	0.85 T
Length of the main stage mirror	19 cm
HEXAPOLE	
External diameter, central part	19 cm
External diameter, end part	16 cm
Internal diameter	7 cm
Hexapole length	20 cm
Hexapole field on the chamber wall	1.1 T
PLASMA CHAMBER	
Internal diameter for the main stage	6.4 cm
Internal diameter for the injection part	2.9 cm
Length for the main stage	22 cm
SOLENOID	
Solenoid number	2
Internal diameter	18 cm
External diameter	34 cm
Typical coil current	950 A
Maximal coil current	1300 A
Typical power consumption	< 60 kW
Cooling water pressure	5 Bars

DECRIS-2 *U-400M cyclotron, 1995*
DECRIS-2m *BIONT Inc., 2003*
DECRIS-2m *DC-72 cyclotron, 2009*

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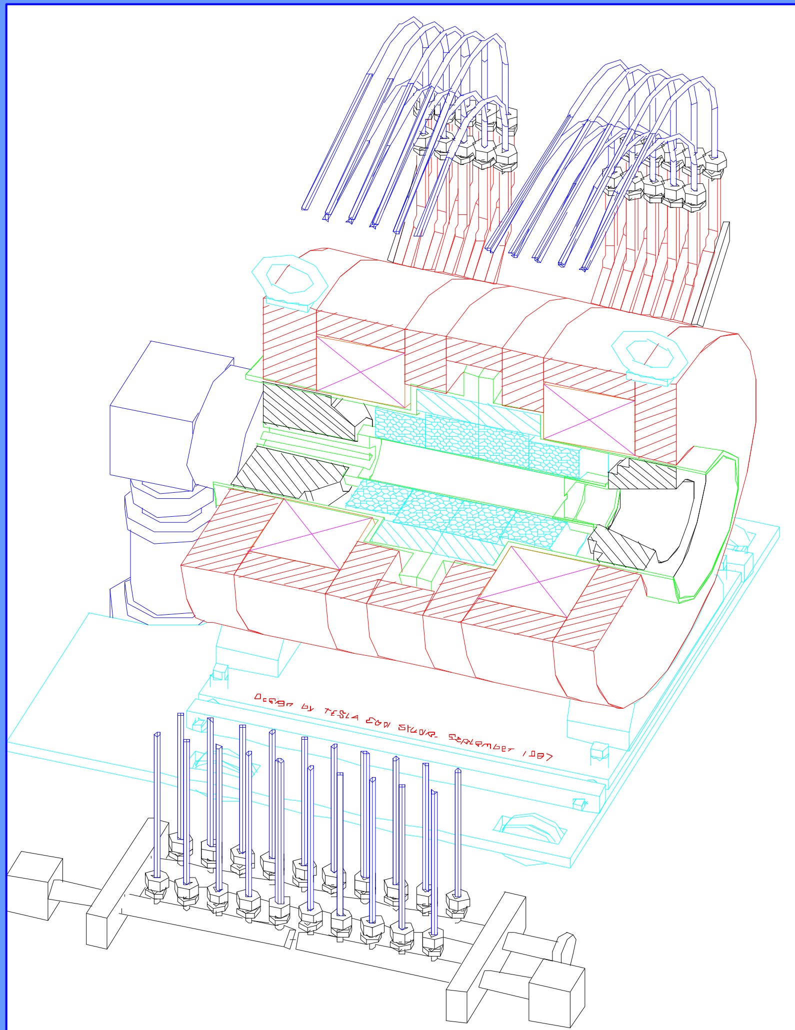
DECRIS-3



MAIN PARAMETERS		
f	14 GHz	18 GHz
W_{total}	68 kW	120 kW
B_{inj}	1.23 T	1.45 T
B_{min}	0.46 T	0.58 T
B_{extr}	1.04 T	1.25 T
L_{mirror}	20 cm	20 cm
Source length	40 cm	40 cm
Source diameter	44 cm	44 cm
Plasma chamber diameter	6.4 cm	6.4 cm
COILS		
Coils number	2	2
I_{max}	1000 A	1300 A
U_{max}	34 V	45 V
ΔP	≤ 10 Bars	≤ 15/≤ 20
ΔT	25^{0}	$32^{0}/27^{0}$
Cooling water consumption	2.5 m^3/h	3.5 m^3/h
HEXAPOLE		
Material	NdFeB	NdFeB
Internal diameter	7 cm	7 cm
Hexapole field on the chamber wall	1.1 T	1.1 T

DECRIS-3 "TESLA" Accelerator Installation, 1997

DECRIS-3 – DC-60 cyclotron, 2006

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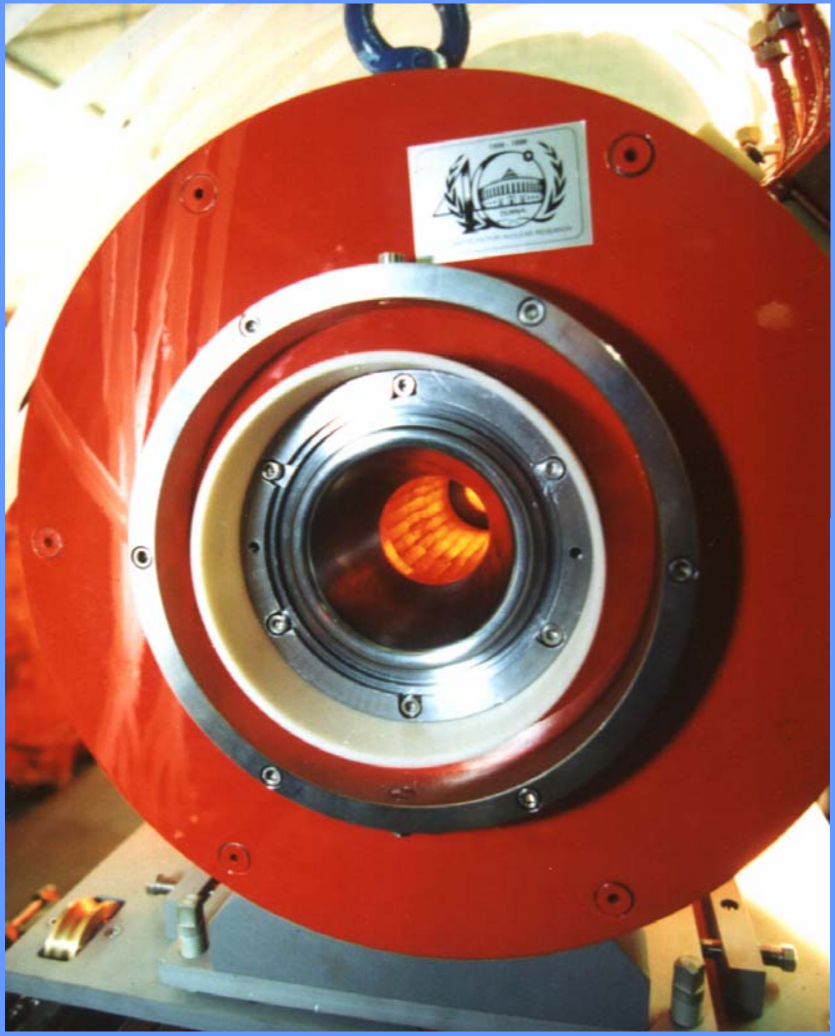
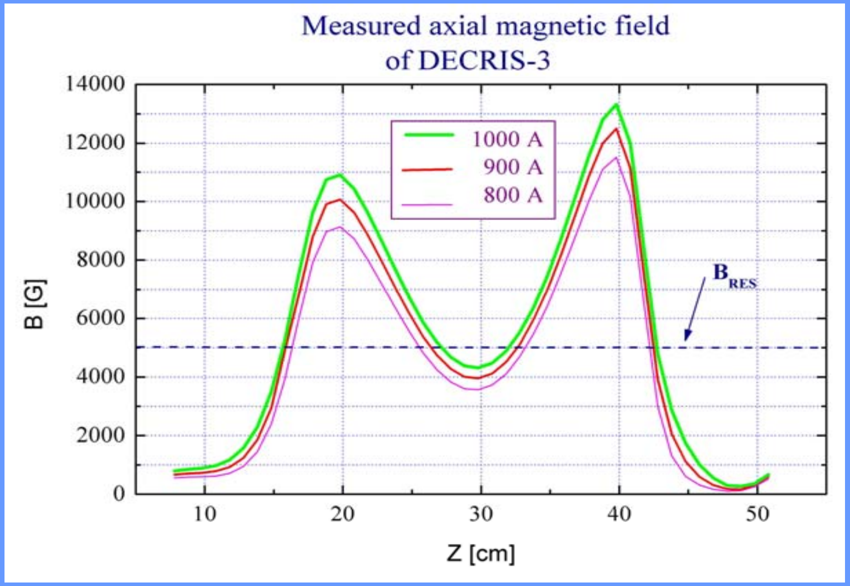
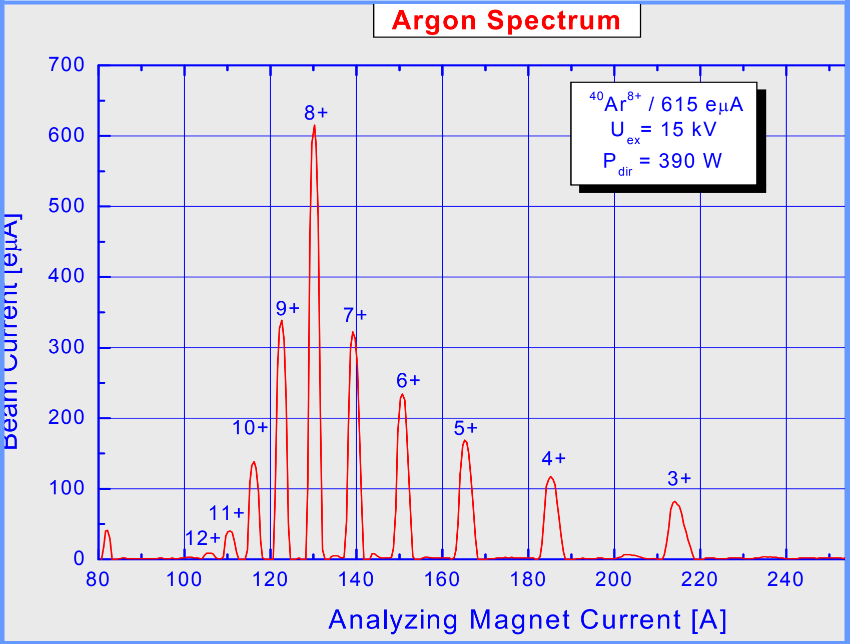
DECRIS-3







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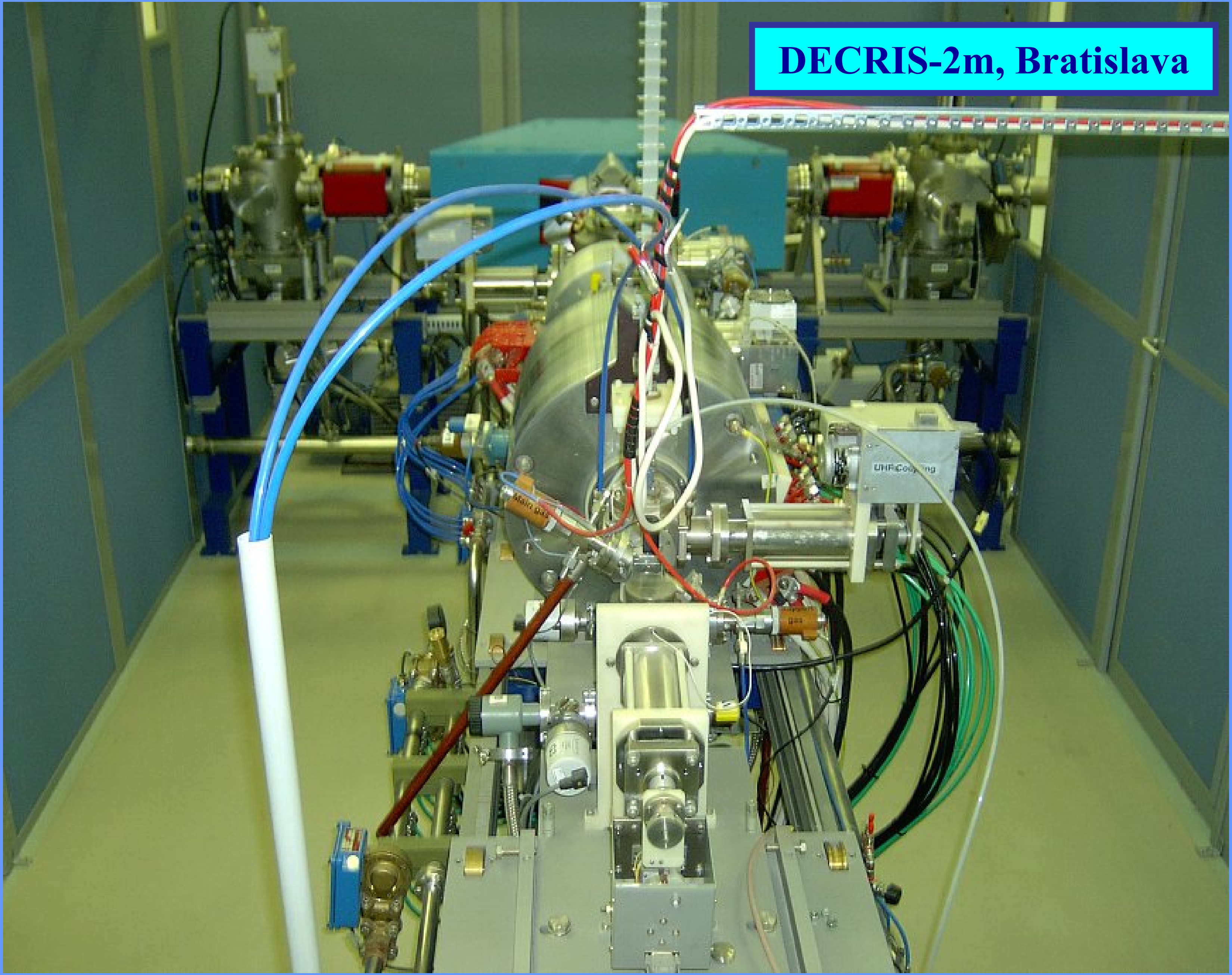
DECRIS-2m, Bratislava



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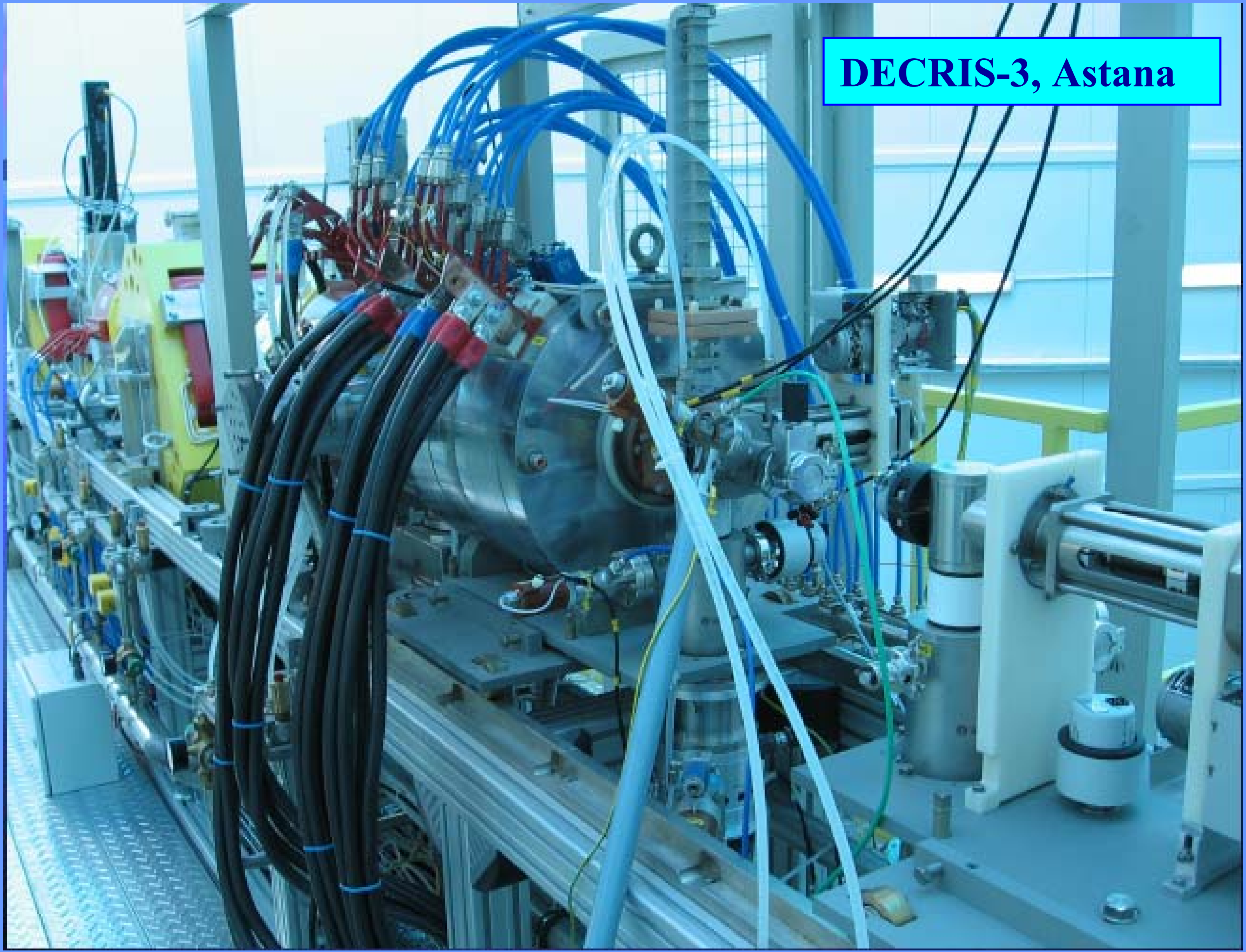

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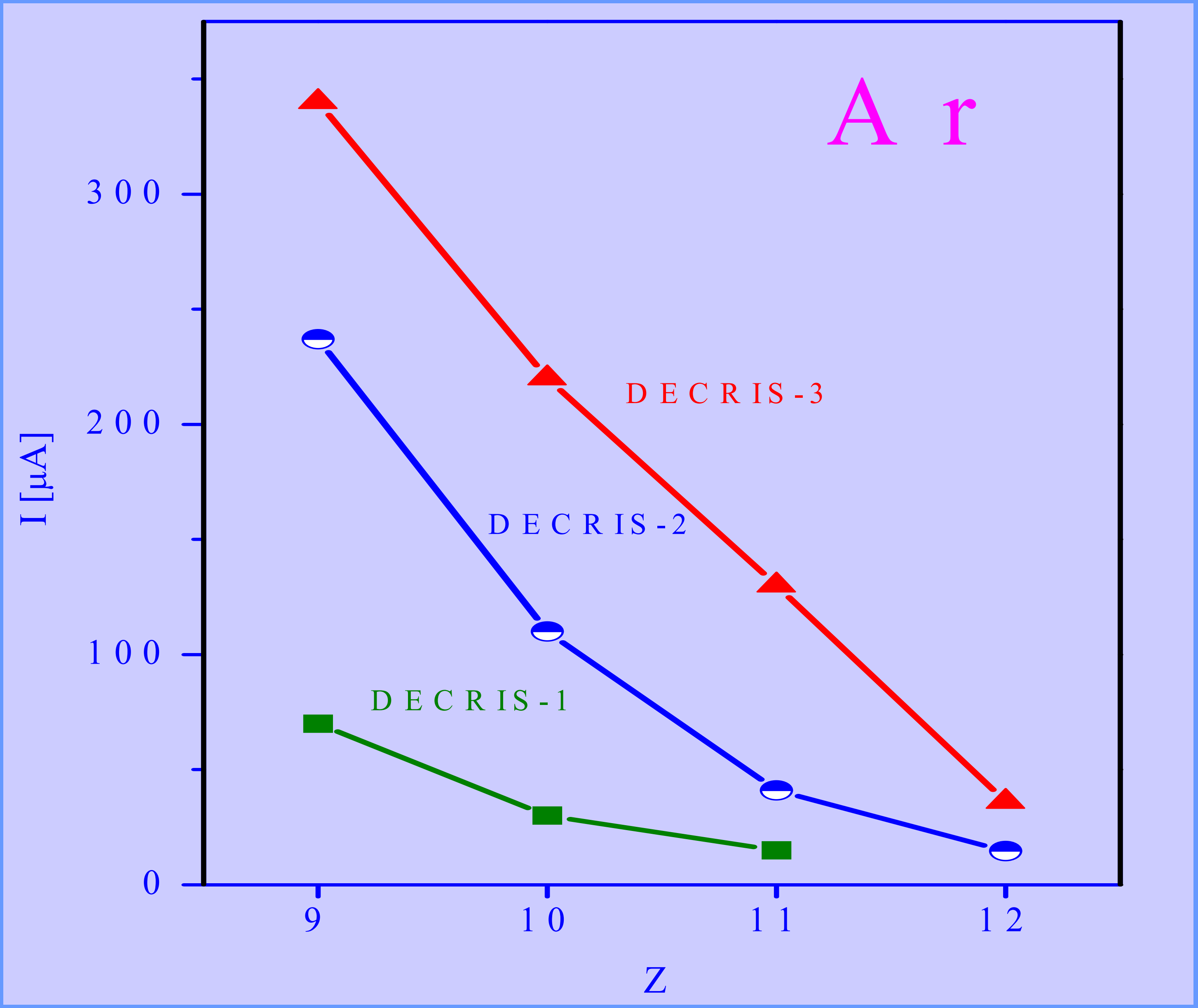
Development of DECRIS



TYPICAL ION CURENTS (eμA)

Ion	Li	B	O	Ar	Kr	Xe
2+	300					
3+	70	200				
4+		80				
5+			660			
6+			450			
7+			40			
8+				600		
9+				340	100	
18+						45
20+						40

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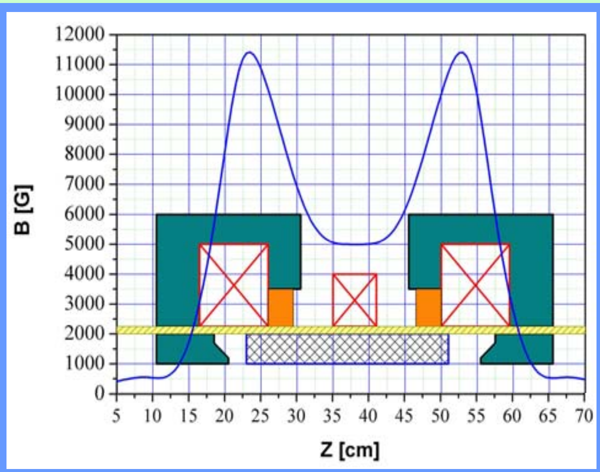
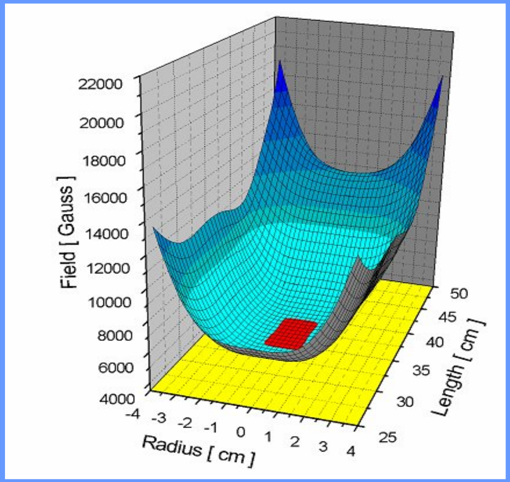
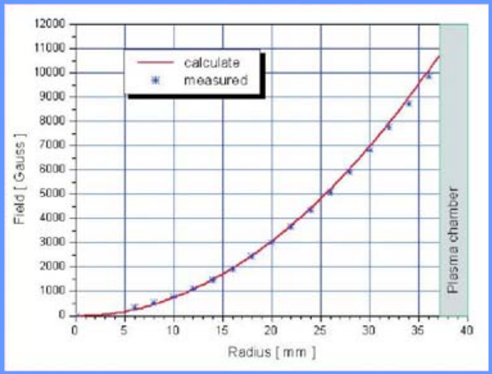
DECRIS-4

DECRIS-4 - a new injector of multiply charged ions for the U-400 cyclotron. The design of the magnetic structure of the source is based on the idea of the so-called “magnetic plateau”. The axial magnetic field is formed by three independent solenoids enclosed in separated iron yokes. The superposition of the coils and hexapole magnetic fields creates <u>the resonance volume.</u>

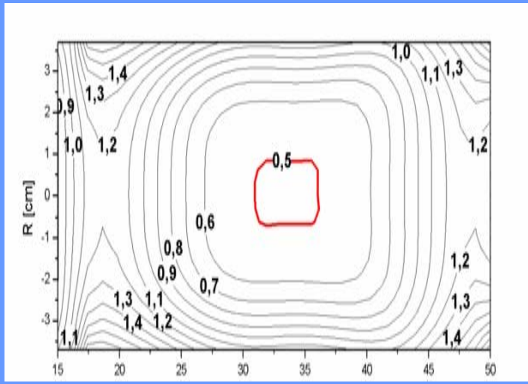


Axial magnetic field distribution





Radial magnetic field distribution



FLNR Ion Sources Group

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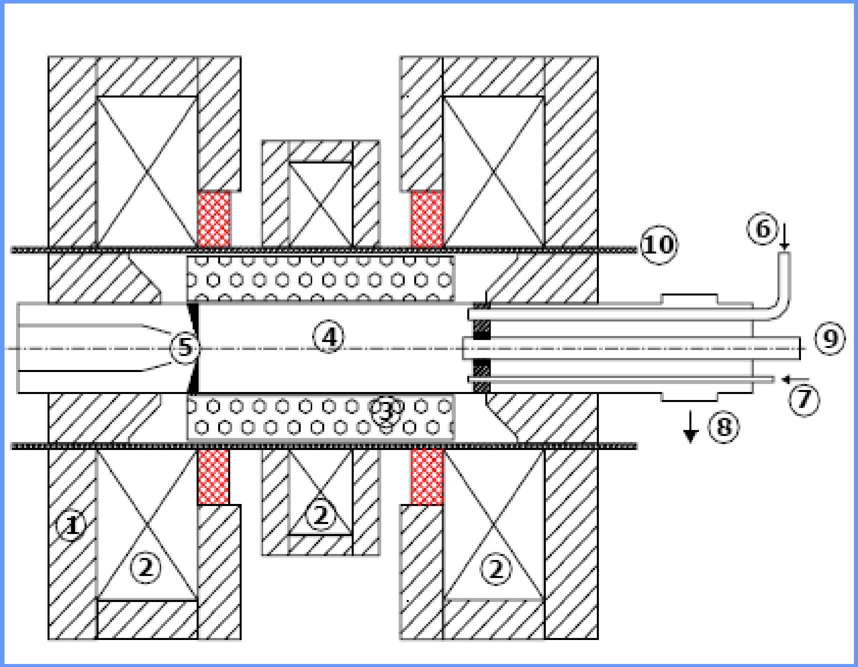
Structure of the DECRIS-4

DECRIS-4



1: Iron yoke. 2: Three independent coils.
3: Hexapole. 4: Plasma chamber.
5: extraction electrodes. 6: UHF input.
7 : Gas feeding. 8: Pumping.
9: Bias electrode. 10: Isolator

Main parameters	
UHF frequency	14 GHz
B_{inj}	1.29 T
B_{ext}	1.29 T
L_{mirror}	29 cm
Max. coil current	1000 A
Water cooling ΔP	15 bar
Plasma chamber Ø	74 mm
Hexapole field on the wall of plasma chamber	>1.0 T
Max. extraction voltage	30 kV

The whole magnetic structure is movable along the axis with respect to the plasma chamber to optimize the plasma electrode position during the source operation.

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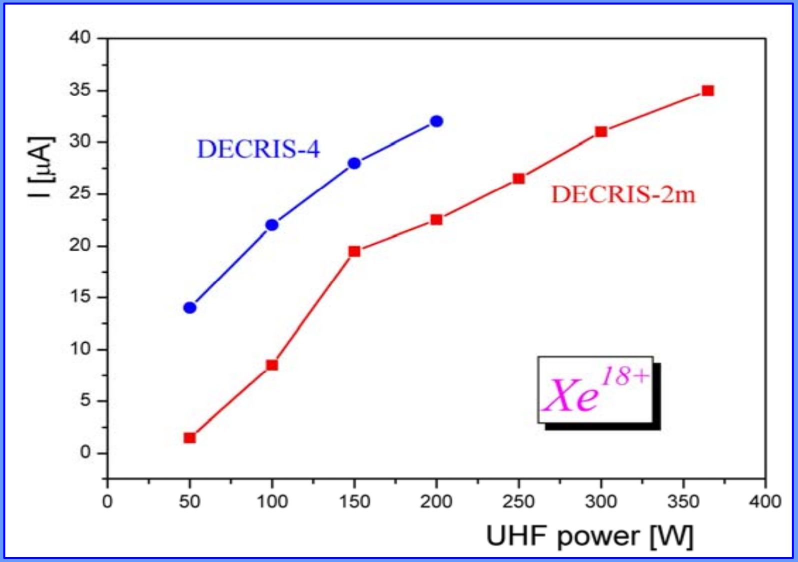
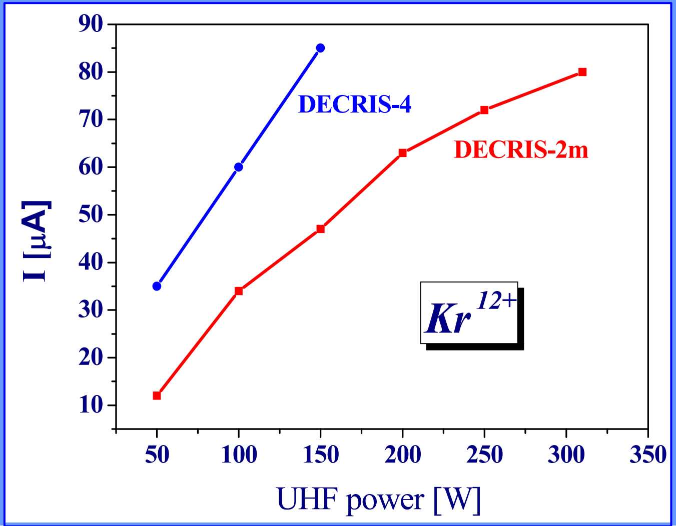
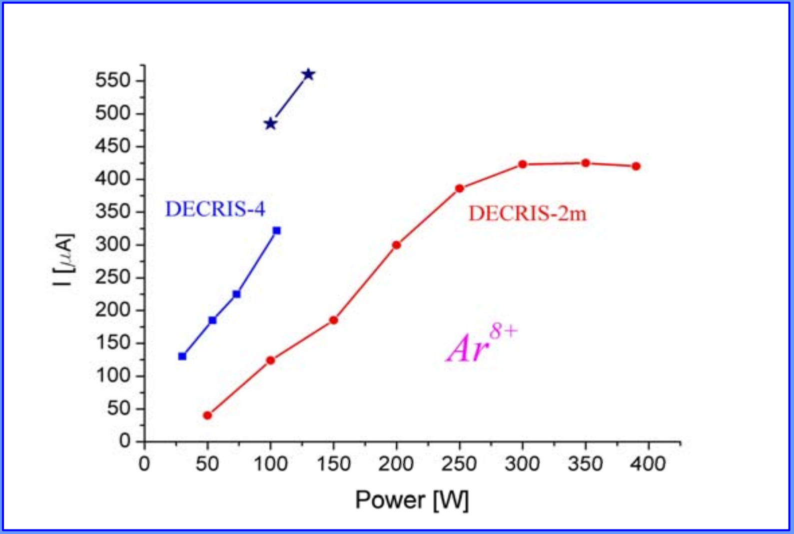
RESULTS

DECRIS-4

Ion	O	Ar	Kr	Xe
6+	400			
7+	80			
8+		400		
9+		220	80	
11+		125	110	
12+		65	85	
15+			35	55
18+				30
20+				25







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Production of ions of metals with an ECR ion sources

Many of the elements required for acceleration at the FLNR cyclotrons are available in the solid state form only.

Production of neutron reach light nuclei (^{6}He, ^{8}He,…)

Required beams -Li, B..

Synthesis of new super heavy nuclei

Required beams: ^{48}Ca-(0,19 %); ^{50}Ti - (5,2 %); ^{58}Fe–(0,3 %)

For the production of intense beams an expensive enriched isotopes are used

Efficiency of material consumption !!!

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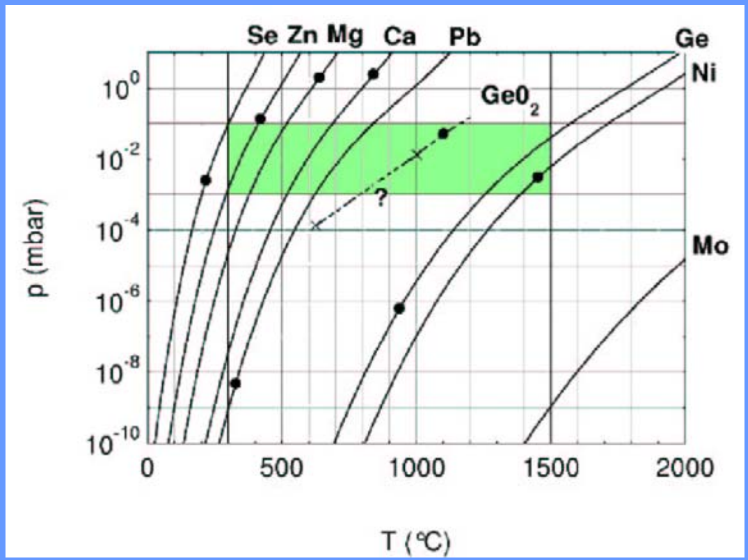
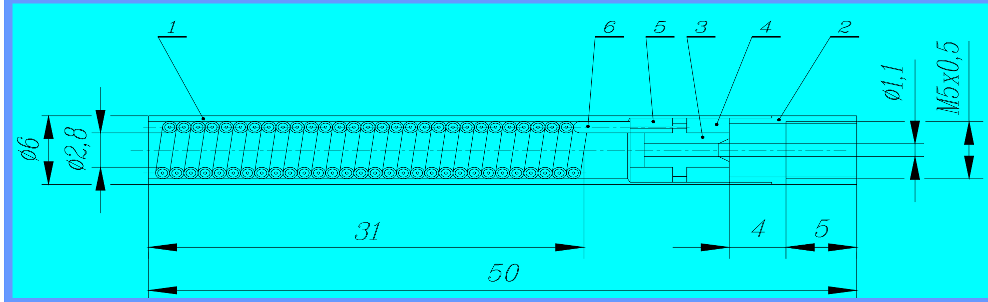
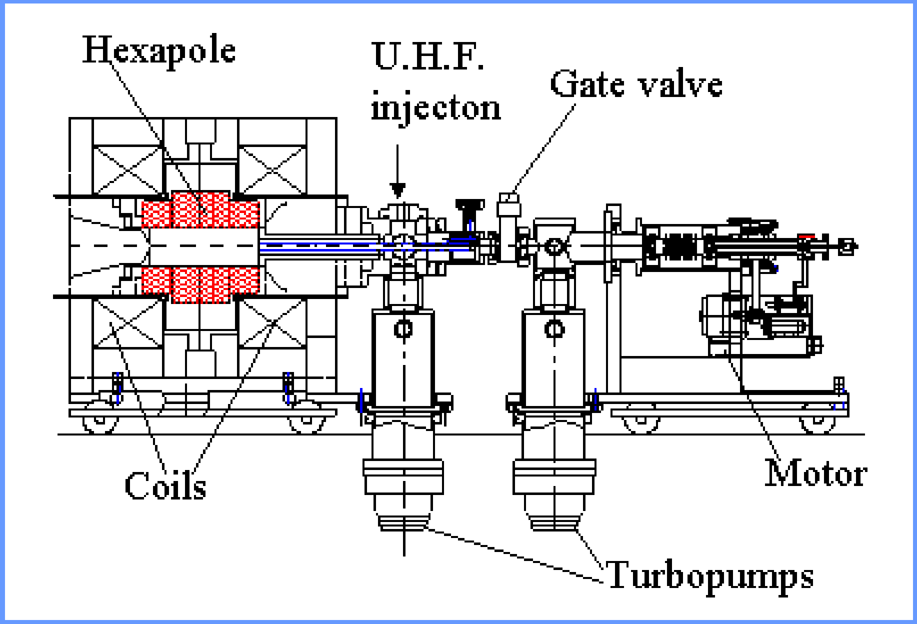
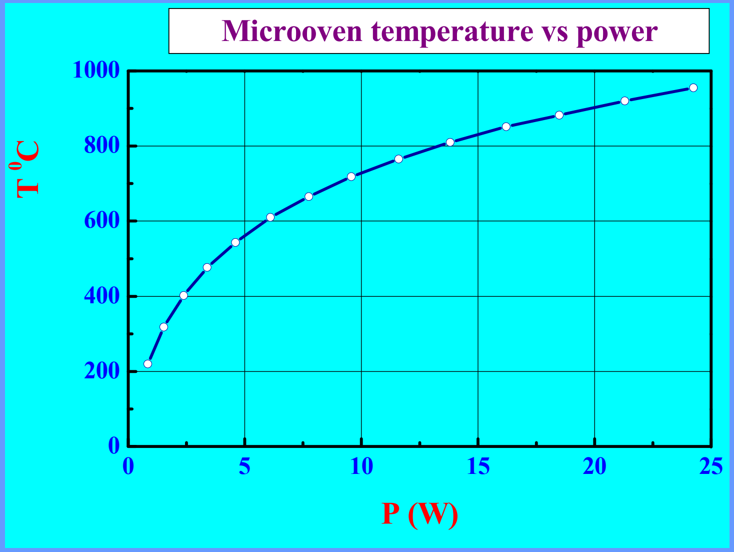
OVEN TECHNIQUE





Microoven: 1,2 - body, 3 - electrical connector, 4,5 - ceramic insulators, 6 – heater.





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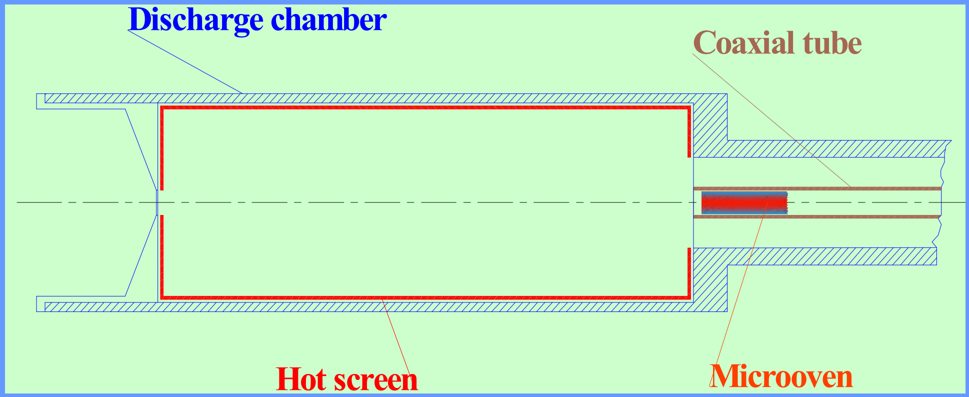
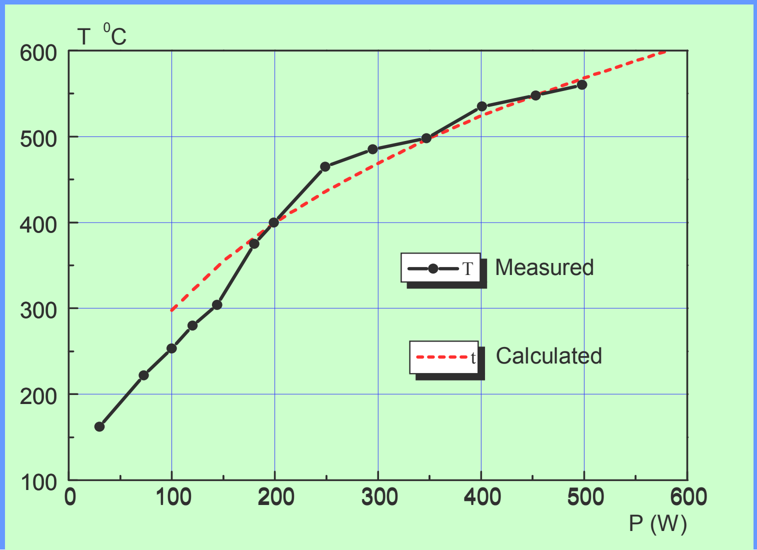
ECR ion sources: ionization efficiency for gases is high enough, ~ 70 ÷ 80 %. For metals the ionization efficiency is about 10 times smaller. The main part of the evaporated metal is condensed at the water-cooled plasma chamber wall.

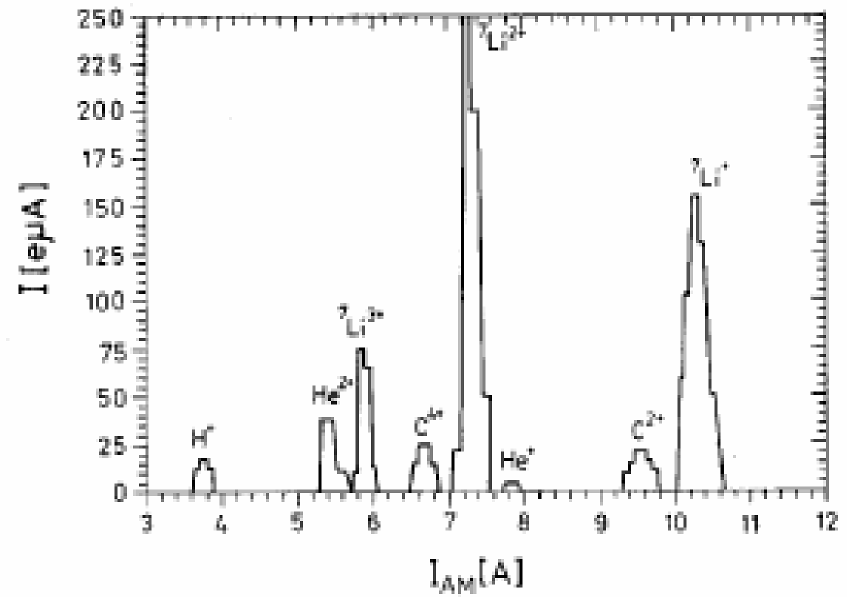
Hot screen inside the discharge chamber!!.



Li^{2+} - 50eμA
Li^{3+} - 25 eμA
Ion beam intensity without hot screen

The screen is heated by microwaves and plasma electrons.





Li spectrum with hot screen

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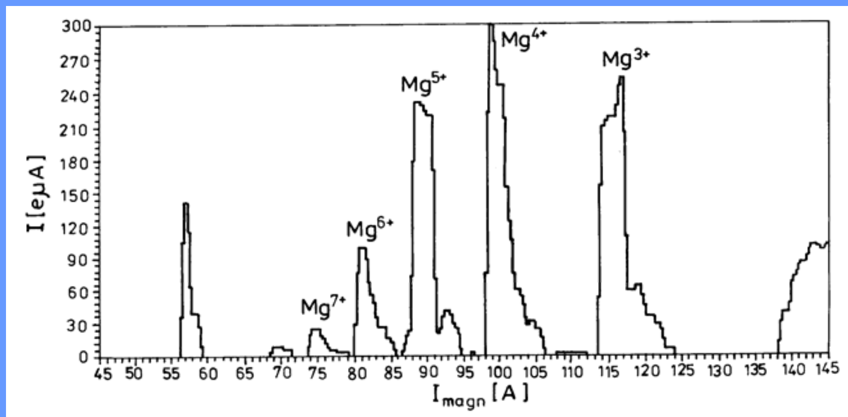
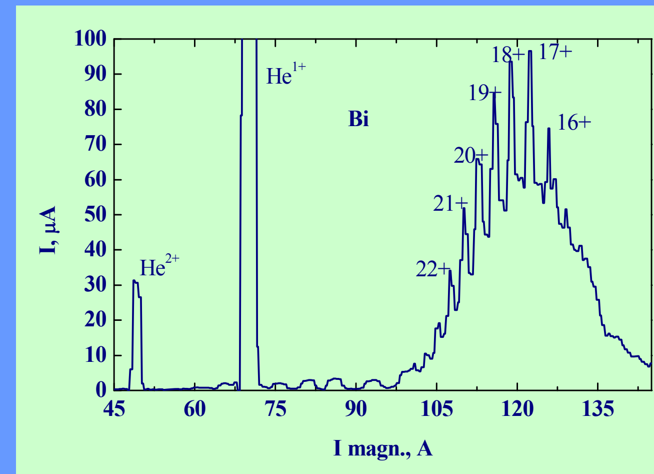
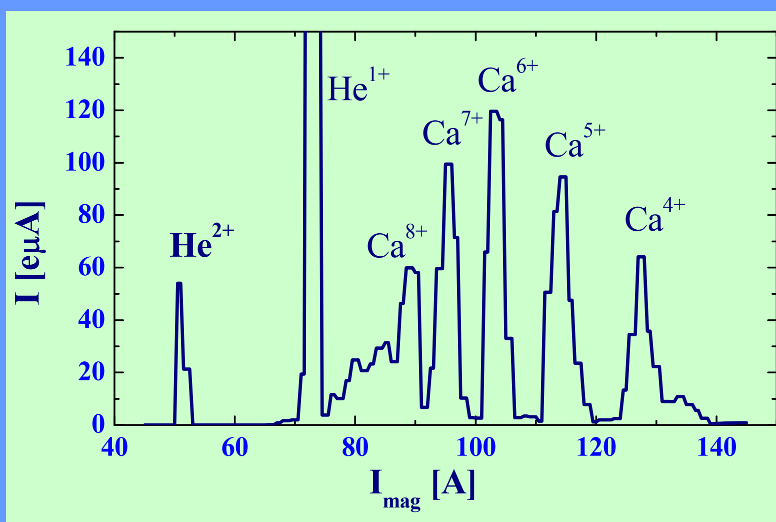
Ions of solids, produced with microoven and hot screen







Ion	Maximal current, eμA	Average material consumption, mg/h
Li^{2+}	290	0,7 - 2
Mg^{4+}	300	2,45
$^{40}Ca^{6+}$	120	0,8 – 1,0
Bi^{19+}	90	0,36

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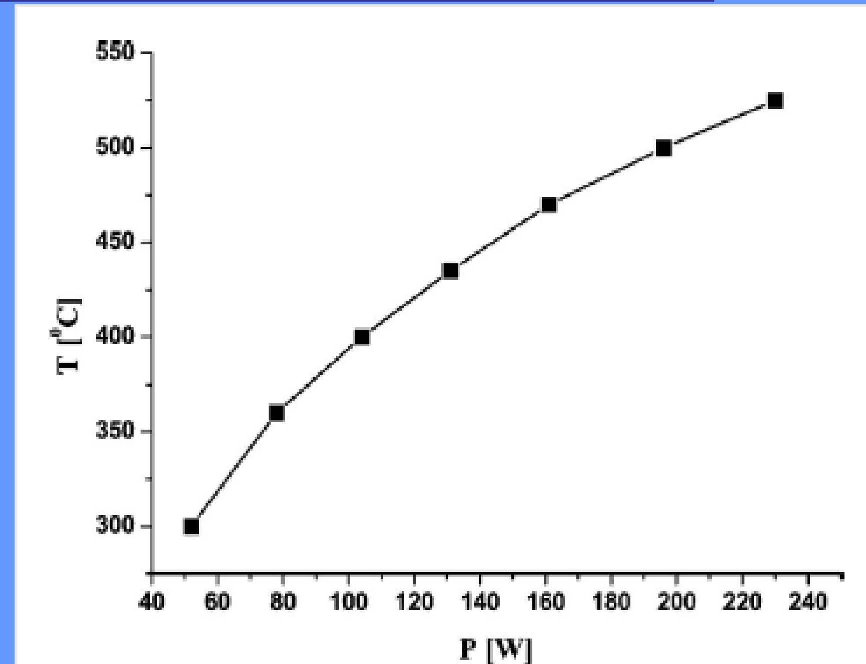
Resistively heated screen in DECRIS-4 ion source

The heater is winded on a thin stainless steel cylinder and screened by the Ta foil outside. The heater itself consists of NiCr wire with a mineral insulation contained in a stainless steel tube. The thickness of the whole assembly is of about 2 mm.



Measured screen temperature vs electric power.

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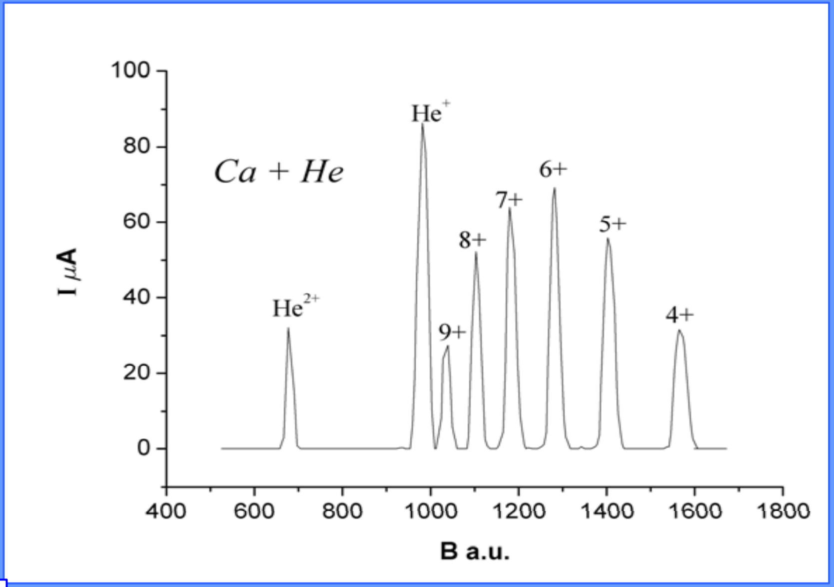
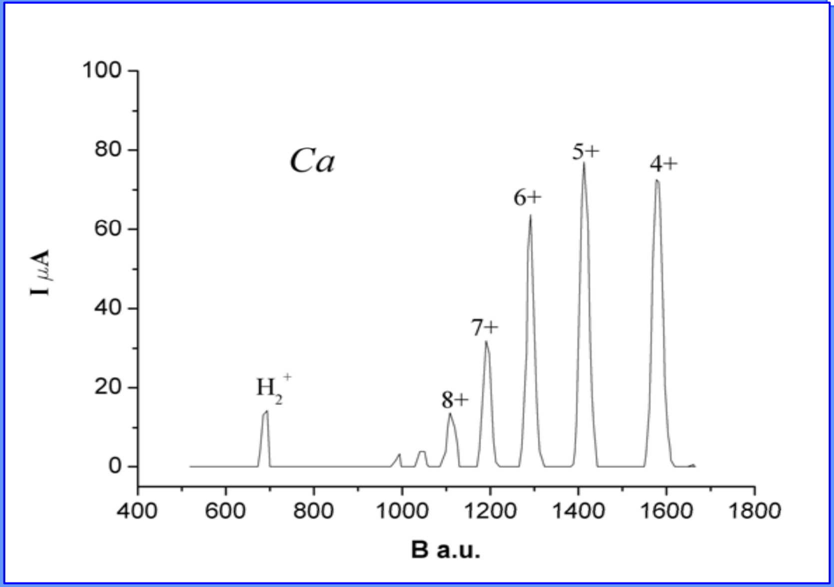
Ca ion spectra with resistively heated screen
UHF power ≤ 100 W

Ca+He



pure Ca



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MIVOC-method (Metal Ions from VOlatile Compounds)

- The vapour pressure of a compound should be about ≥ 10^{-3} torr at room temperature.
- Evaporation of a compound and its diffusion into the source take place without dissociation.
- The same feeding system as for gases is used.

B – $C_2B_{10}H_{12}$

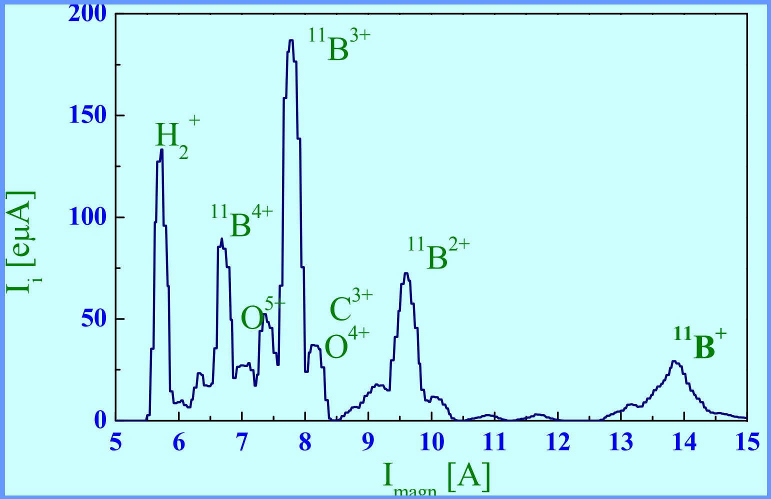
Ti – $(CH_3)_5C_5Ti(CH_3)_3$

$Ti\{OCH(CH_3)_2\}_4$

Fe – $Fe(C_5H_5)_2$;

Ni – $Ni(C_5H_5)_2$; Cr – $Cr(C_5H_5)_2$

Cr – $Cr(CO)_6$; W – $W(CO)_6$

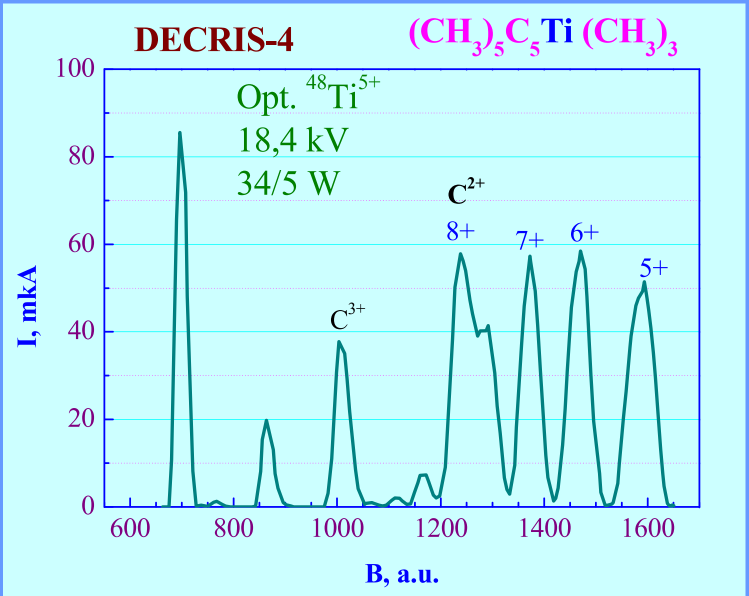


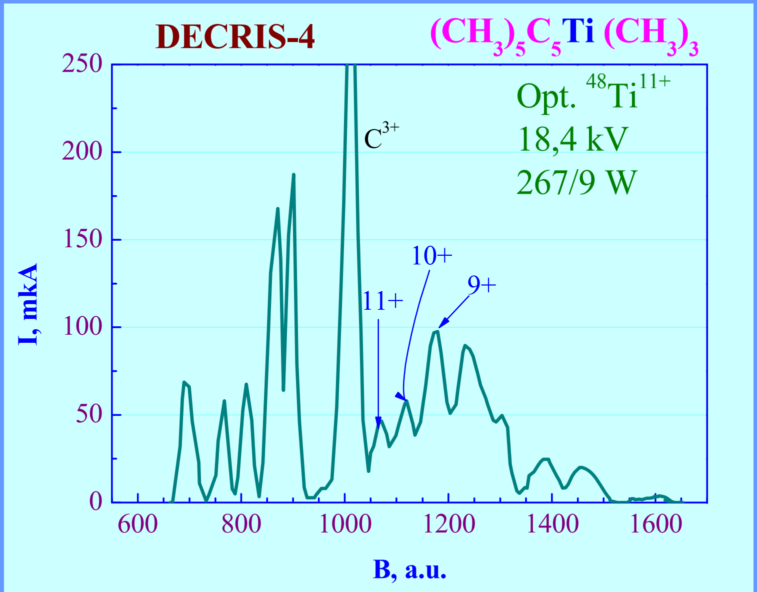
The spectrum of boron ions

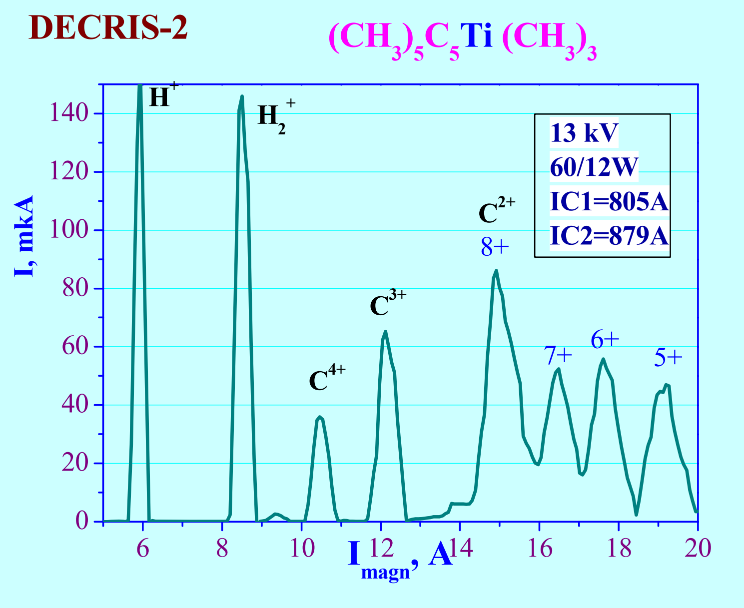
Working substance - $C_2B_{10}H_{12}$

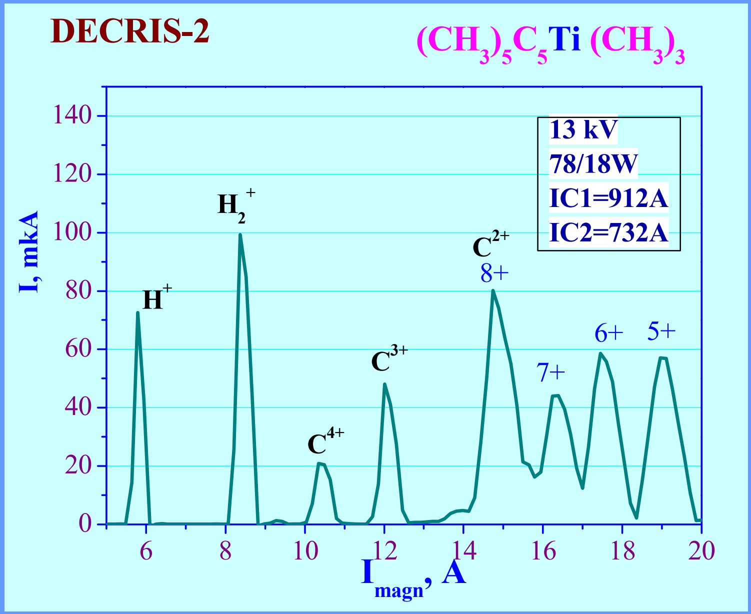
U-400 – $^{58}Fe^{7+}$ - 40÷50 μA
Material consumption ~ 3 mg/h
(~ 1.5 mg/h for ^{58}Fe)

MIVOC-method (Titanium ions)









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DECRIS-SC ion sources.

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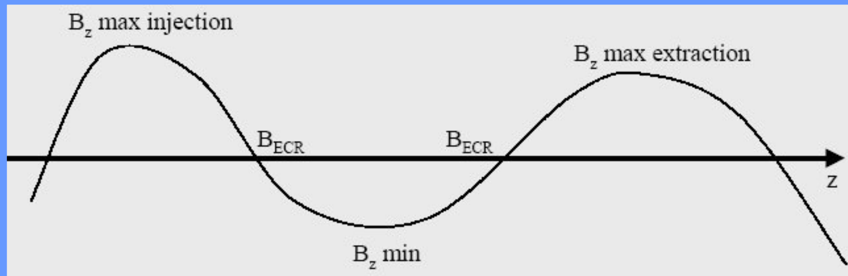

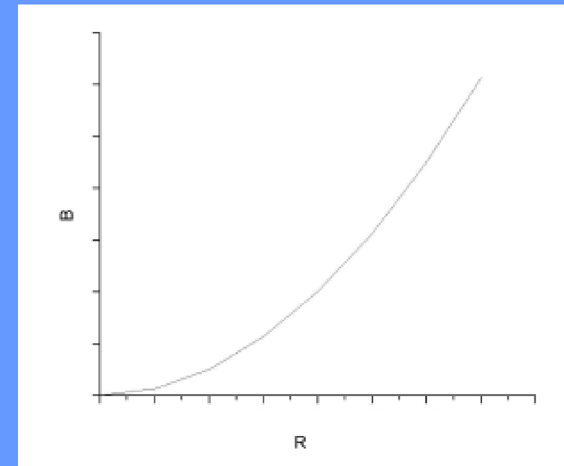

Scaling laws:

(1987 R. Geller)

$$\langle q \rangle \infty \log B_{max}$$

$$\langle q \rangle \infty \log B_{ECR}$$

$$I^q \infty \ \omega^2_{ECR}$$

Semiempirical design criteria:

B_{inj} ~3 - 4 B_{ecr}
$B_{rad} \geq 2\ B_{ecr}$
B_{min} ~ 0.5-0.8 B_{ecr}

f [GHz]	B [T]	n_{ec} [cm^{-3}]
2.45	0.0875	7.44×10^{10}
6.4	0.23	5.08×10^{11}
10	0.36	1.24×10^{12}
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28	1	10^{13}

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ECR ion source with superconducting magnet system

Modernization of CI-100 cyclotron:

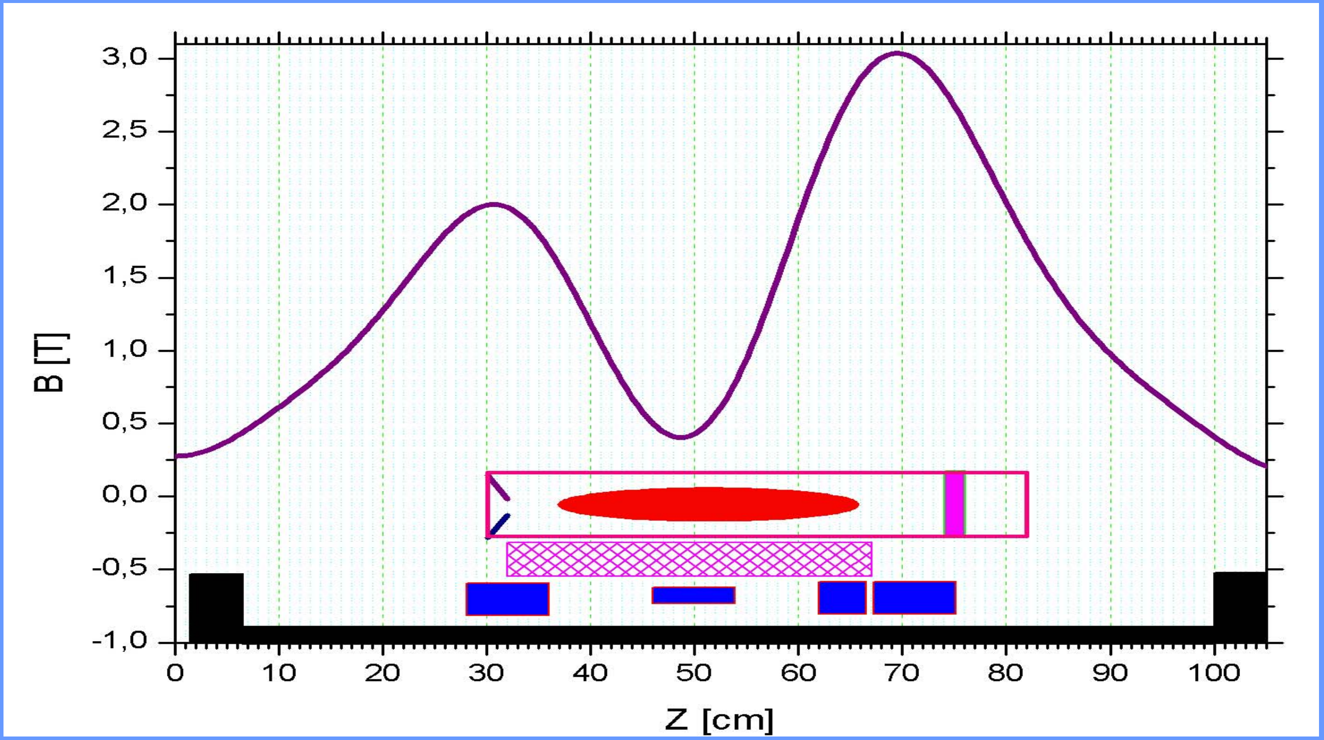
•accelerated ions - Kr^{15+}, Xe^{22+} energy 1 MeV/n

Kr^{20+}, Xe^{30+} 2 MeV/n

• **accelerated beam intensity** > 10^{12} pps

• The high enough requirements on charge and intensity of accelerated beams (Kr^{15+}, Xe^{22+}) demand the necessity of using the ion source with the large mirror ratio and a strong magnetic field.

• "Liquid He free" technology



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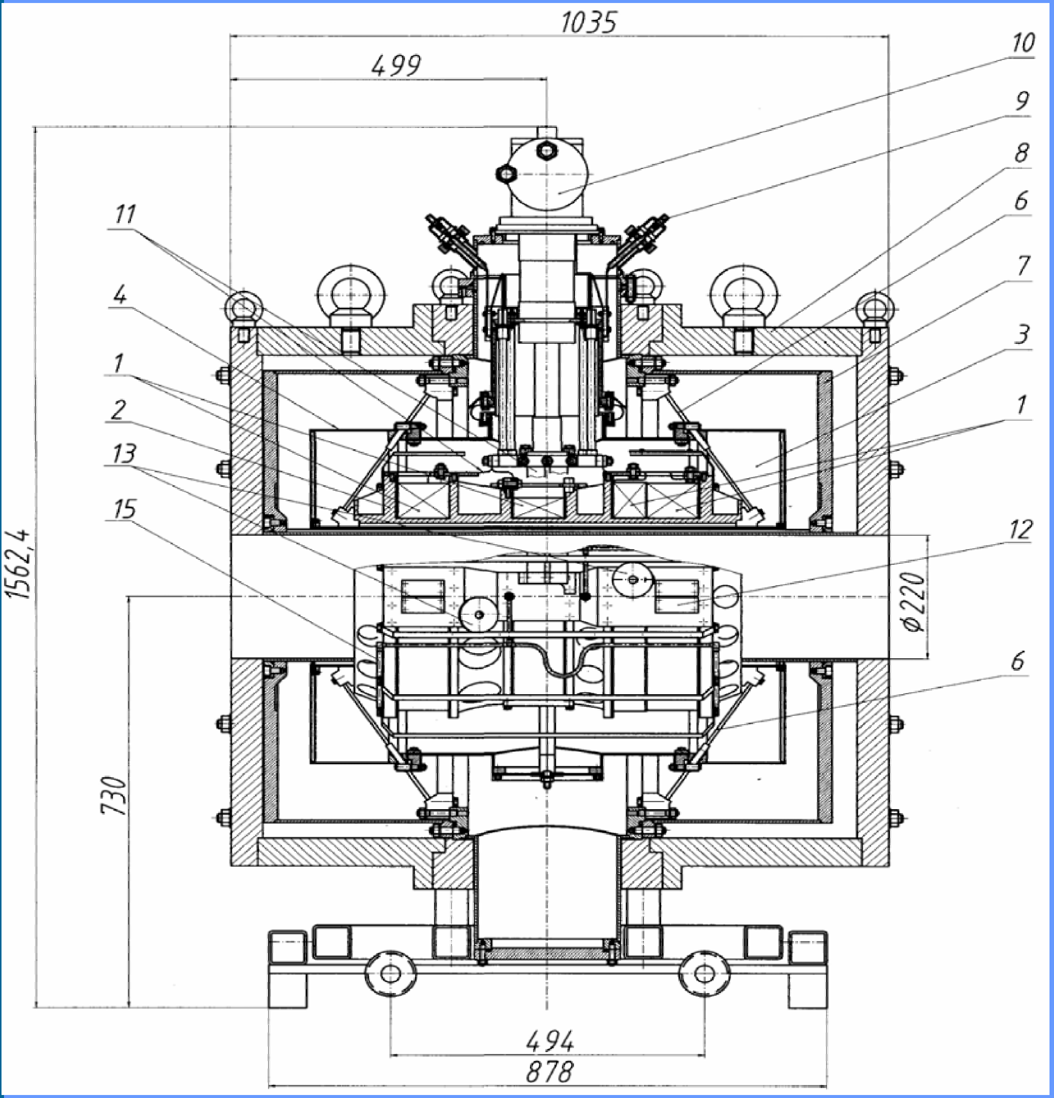
Parameters of DECRIS-SC

UHF frequency	18 ÷ 28 GHz
Mirror field on the axis: Extraction side Injection side	 2 T 3 T
Mirror to mirror distance	390 mm
Max. coil current	60 A
Radial field at the plasma chamber wall	1.3 T
Plasma chamber internal diameter	74 mm
Max. extraction voltage	30 kV

DECRIS-SC



The design of the SC magnet :

1 - superconducting solenoids; 2 - framework of solenoids; 3 - thermal screen; 4 - multilayer screen-vacuum isolation; 6 - support of cold mass; 7 - vacuum casing; 8 - magnetic shield; 9 – current lead; 10 - cryocooler; 11 - heat pipes; 12 - "cold" diodes; 13 - absorbing resistors; 15 - nitrogen heat exchanger.

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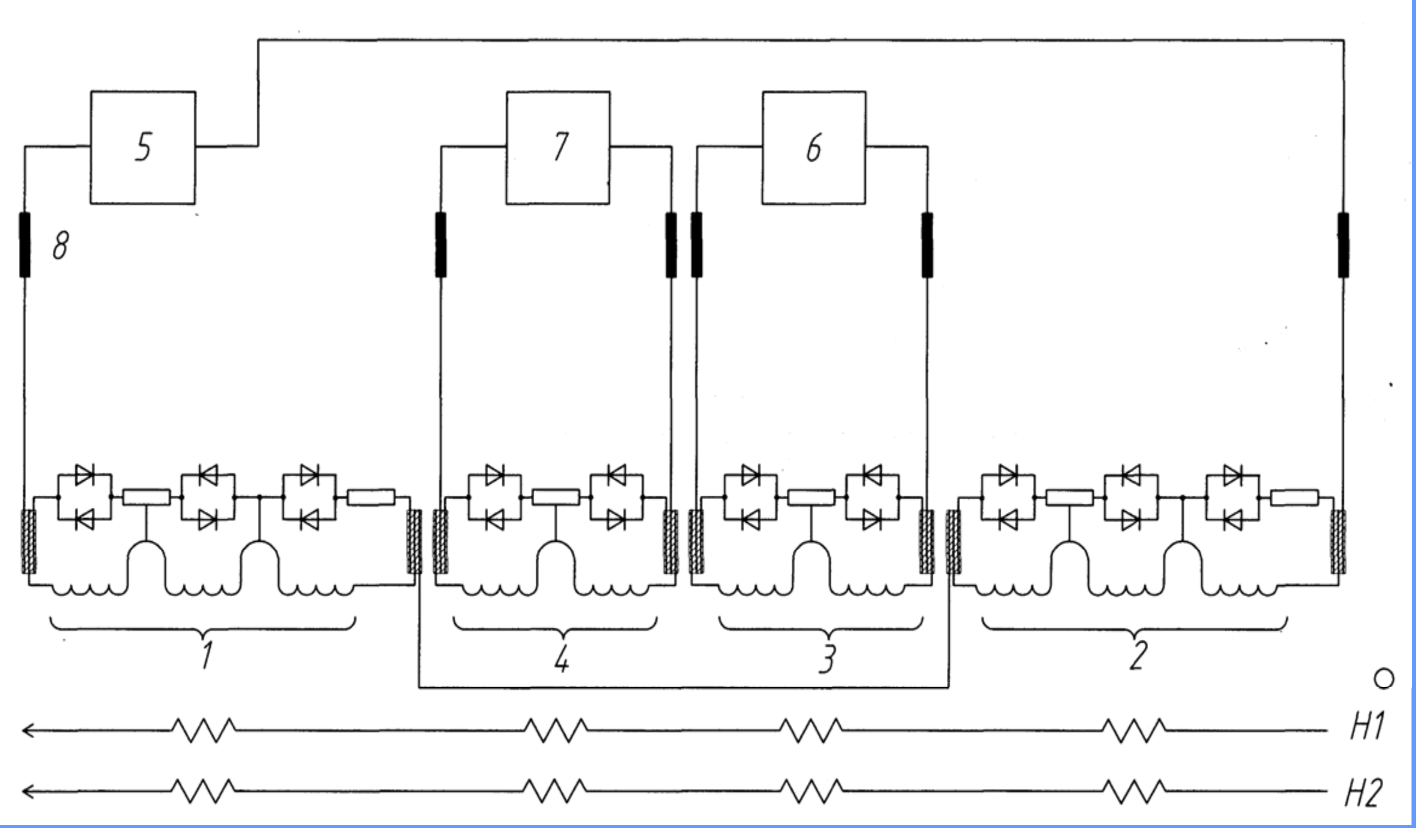
Electrical power supply and safety system:

Passive protection: sectionalization, "cold" diodes and absorbing resistors.
Active protection: three sensor units of the normal zone and eight resistive heaters, installed at the windings.



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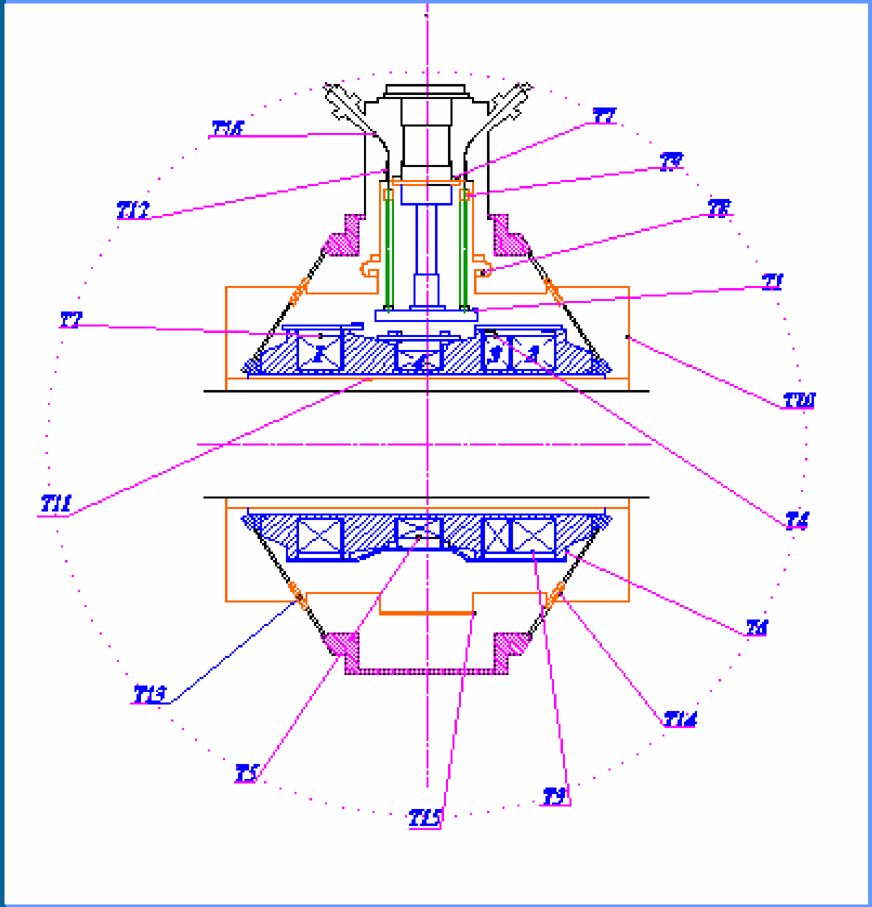
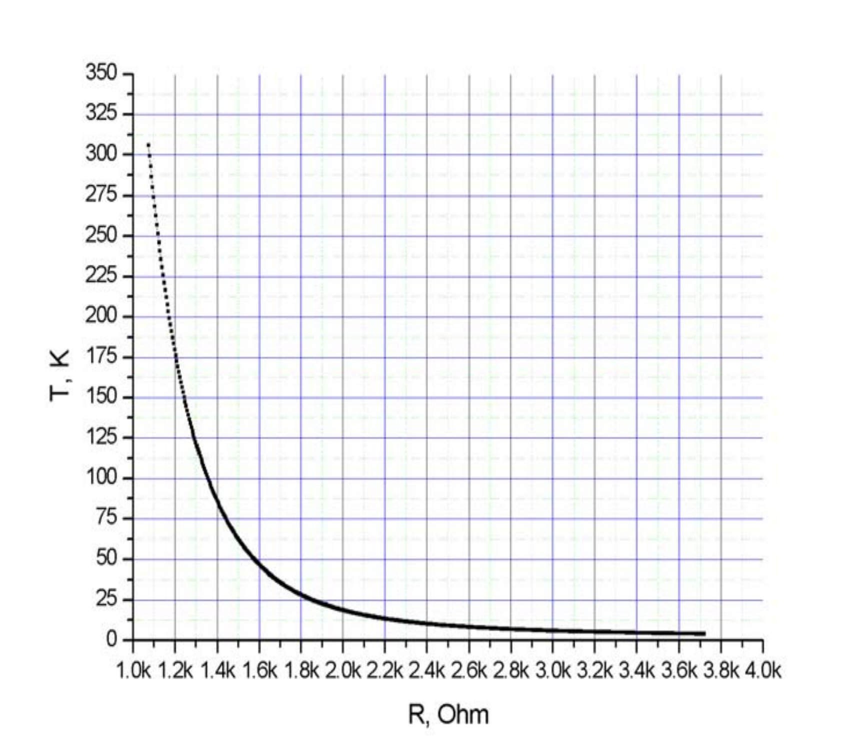
DECRIS-SC

Thermo control:

In the cold zone of the magnet 16 thermometers are located.

Calibrated TVO carbon resistors are used as thermometers





DECRIS-SC

Solenoids: a Nb Ti/Cu monolithic superconducting wire (bare diameter - 0.65 mm, insulated diameter - 0.7 mm). Compounding of the windings is realized with prepreg. Each winding is made from a single piece of wire, without internal junctions, but electrically is divided into 2 or 3 sections. The coils are posed on the framework, made from non-magnetic stainless steel, which is free-floating fixed inside a vacuum casing with the help of glass textolite supports. (Cold mass ~ 280 kg)

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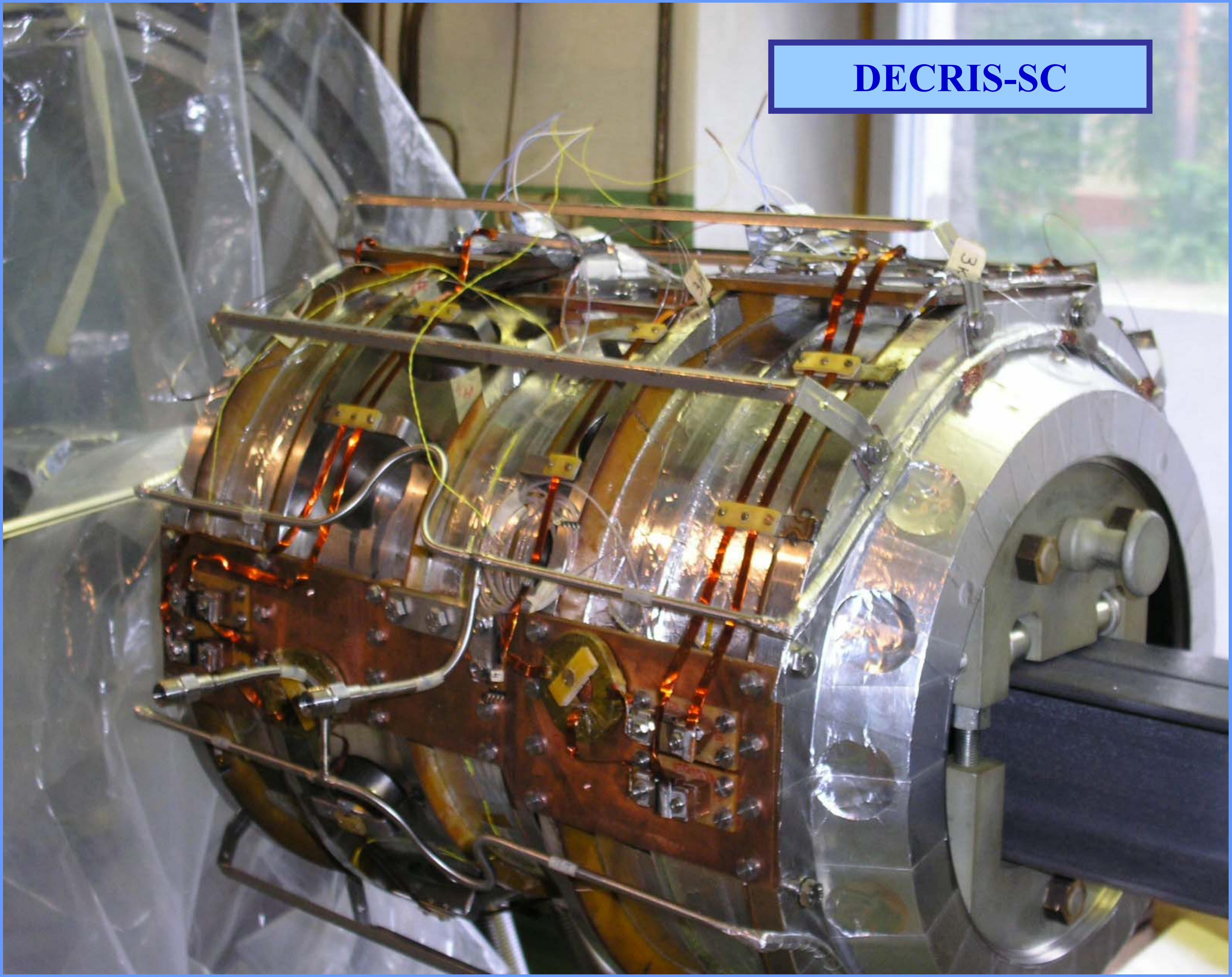

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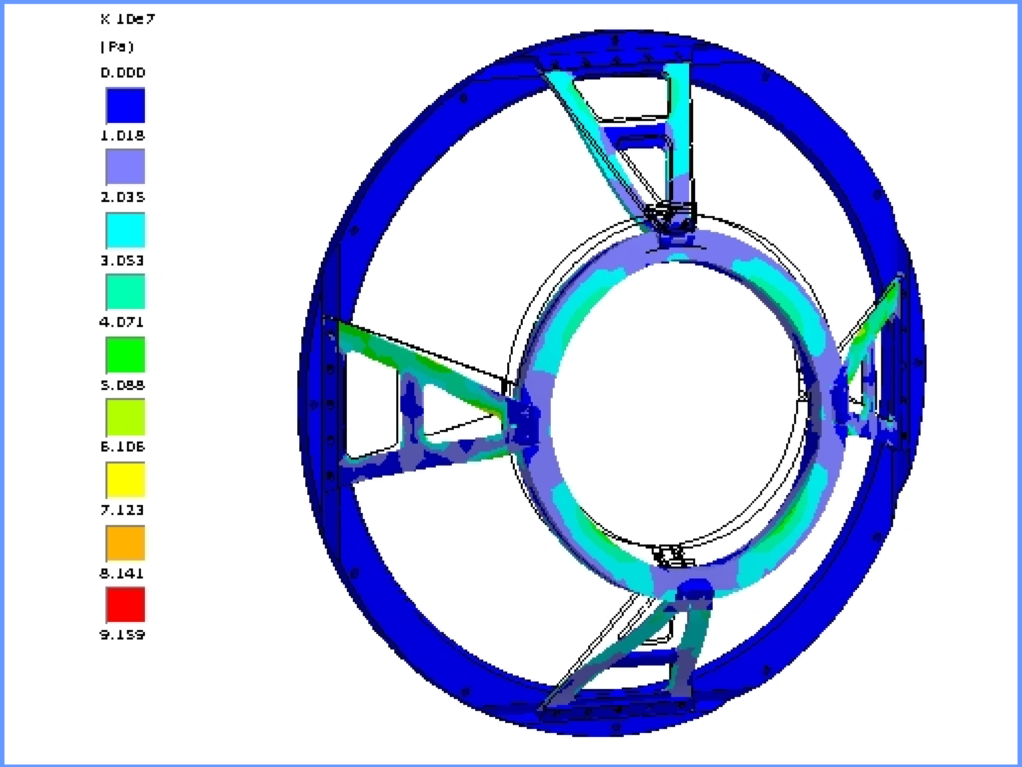
DECRIS-SC

Cold mass support consists of the glass textolite plates. The supports are designed to not only bear the weight of the cold mass but also to handle significant axial dynamic forces which can arise from unequal transitions of the windings during a quench. The supports are tested for durability using an axial load of 1,27 t and a radial load of 0,32 t.



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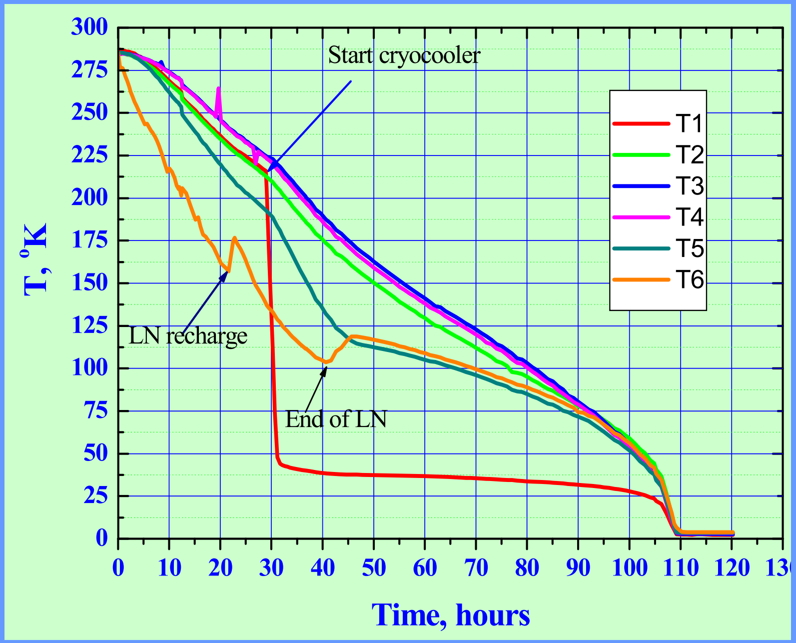
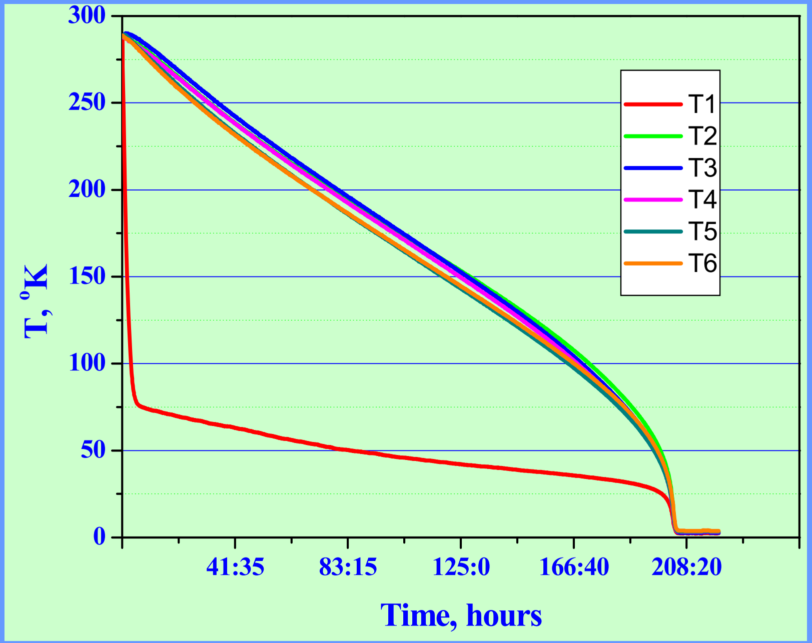
DECRIS-SC

DECRIS-SC

Cooling of the solenoids





With LN heat exchanger

With cryocooler only

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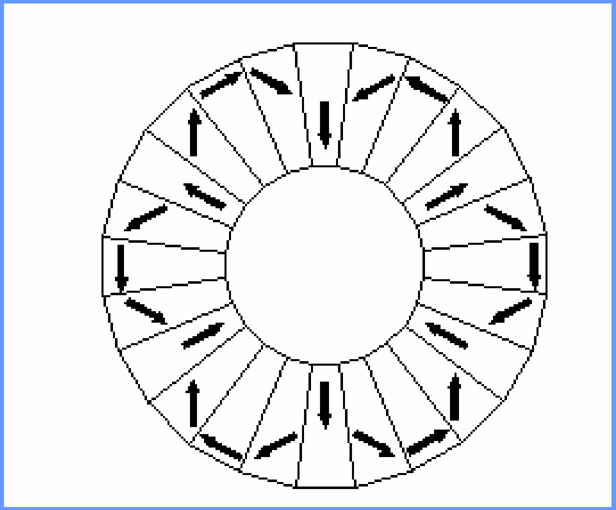
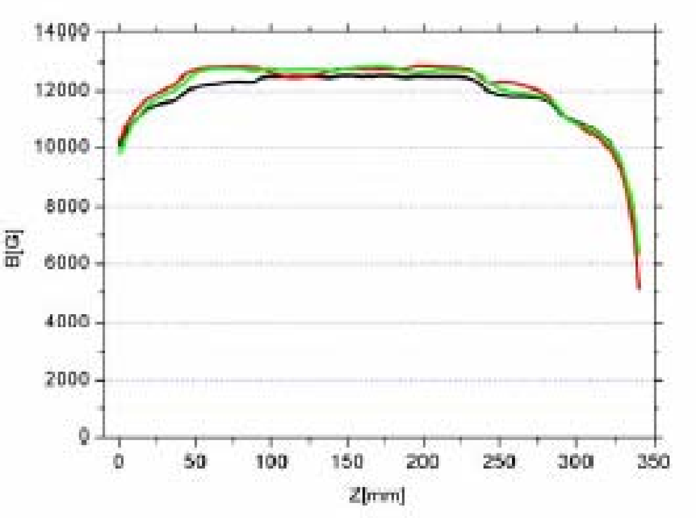
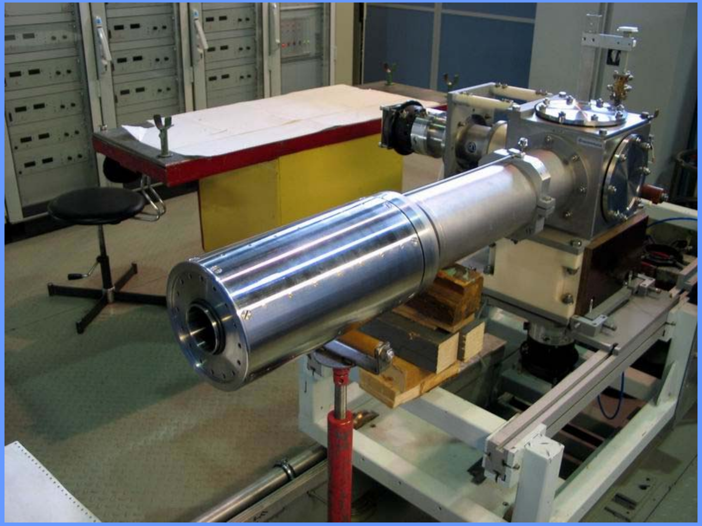
DECRIS-SC

Hexapole design







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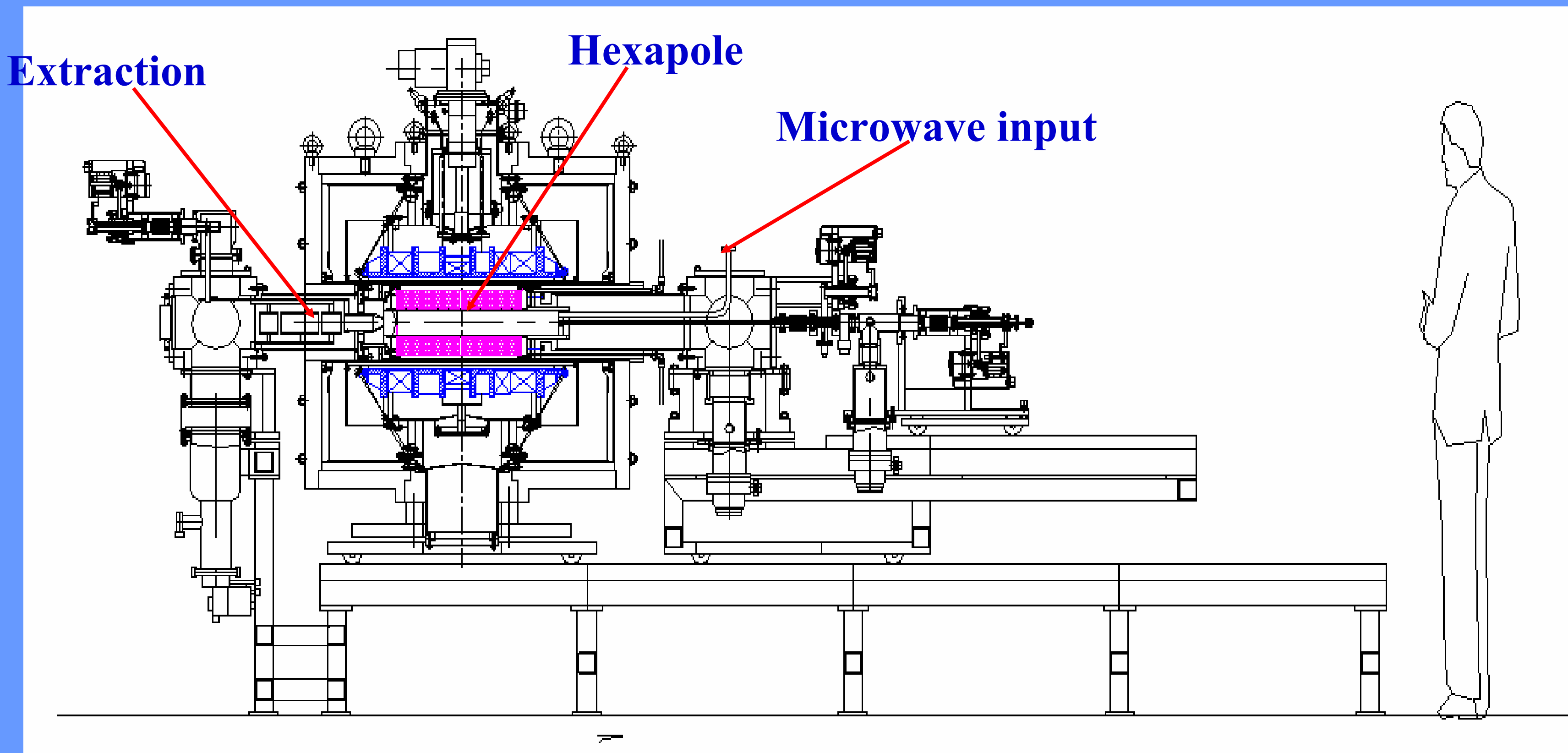
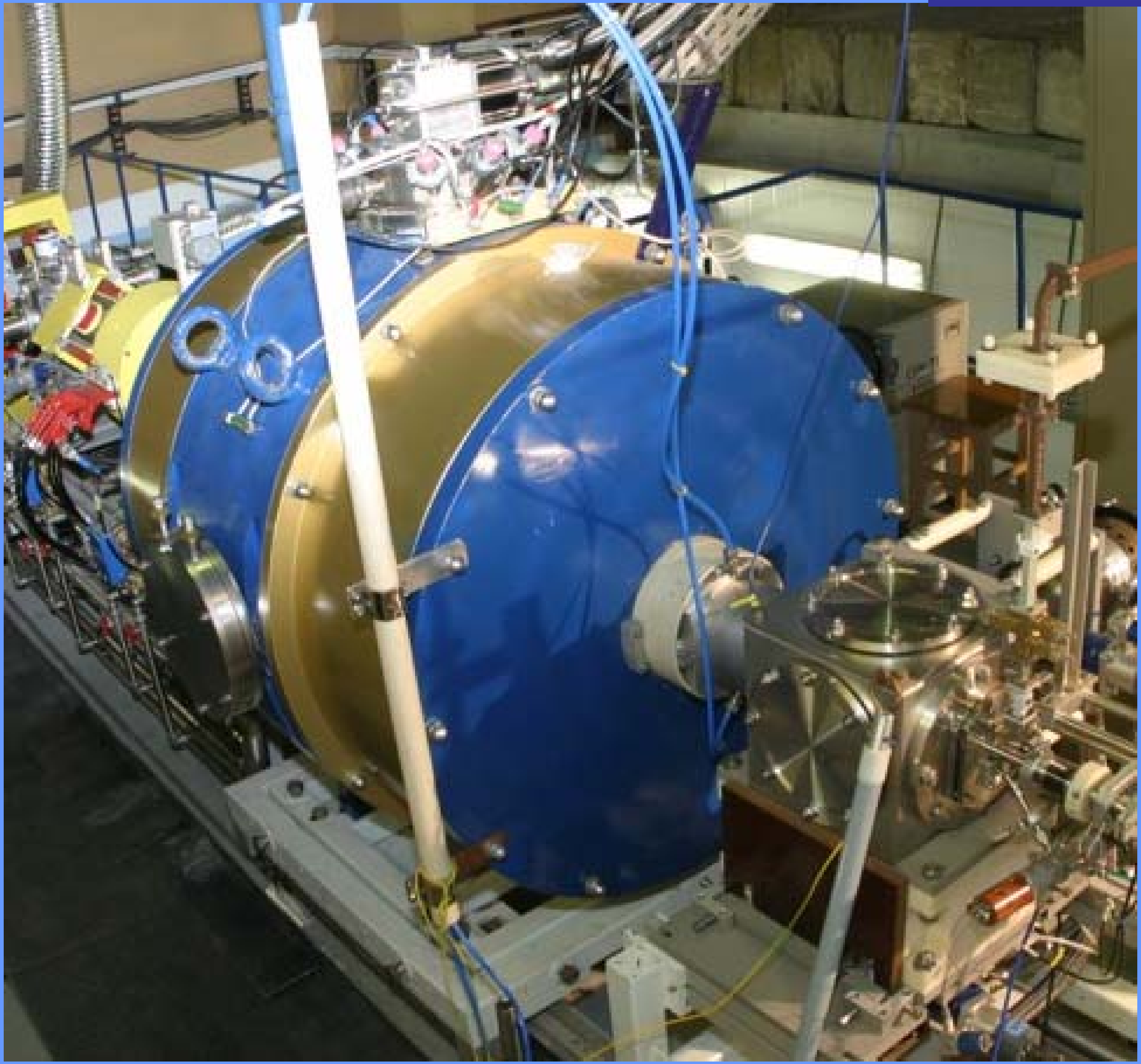
DECRIS-SC

General view of the source

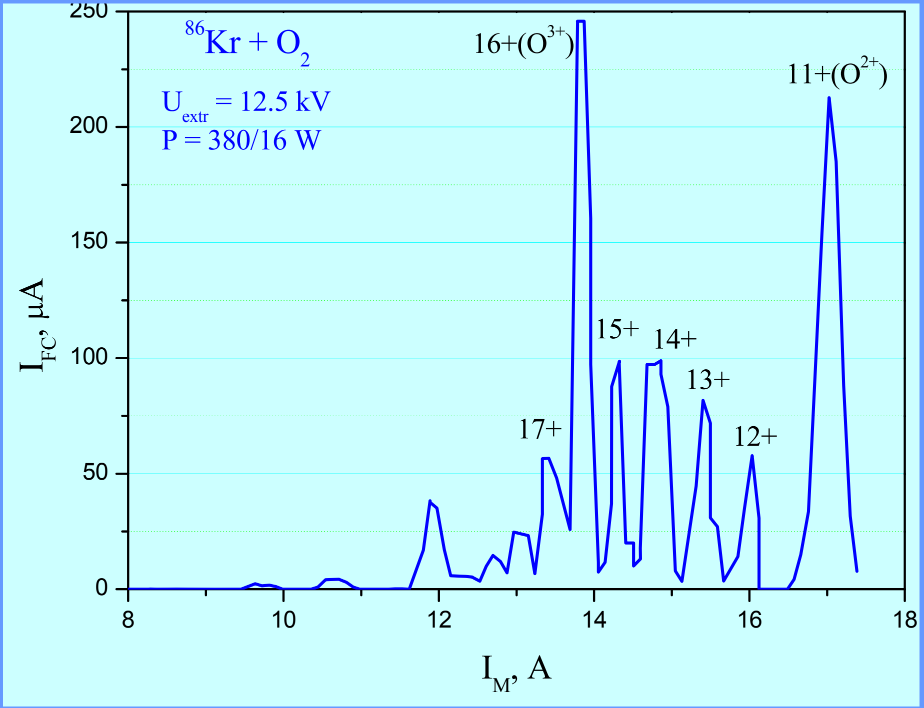


DECRIS-SC



DECRIS-SC and axial injection system of CI-100 cyclotron

DECRIS-SC



Krypton ion spectrum
May 2004

Element	A	Z	Target current eμA
Ne	22	+4	0.7
Ar	40	+7	2.5
Fe	56	+10	0.5
Kr	86	+15	3.5
I	127	+22	0.25
Xe	132	+23	3.7
Xe	132	+24	0.6
W	182	+32	0.015
W	184	+31	0.035
W	184	+32	0.017

Expected intensities

Kr^{15+} ~ 200 eμA, Kr^{20+} ~ 25 eμA

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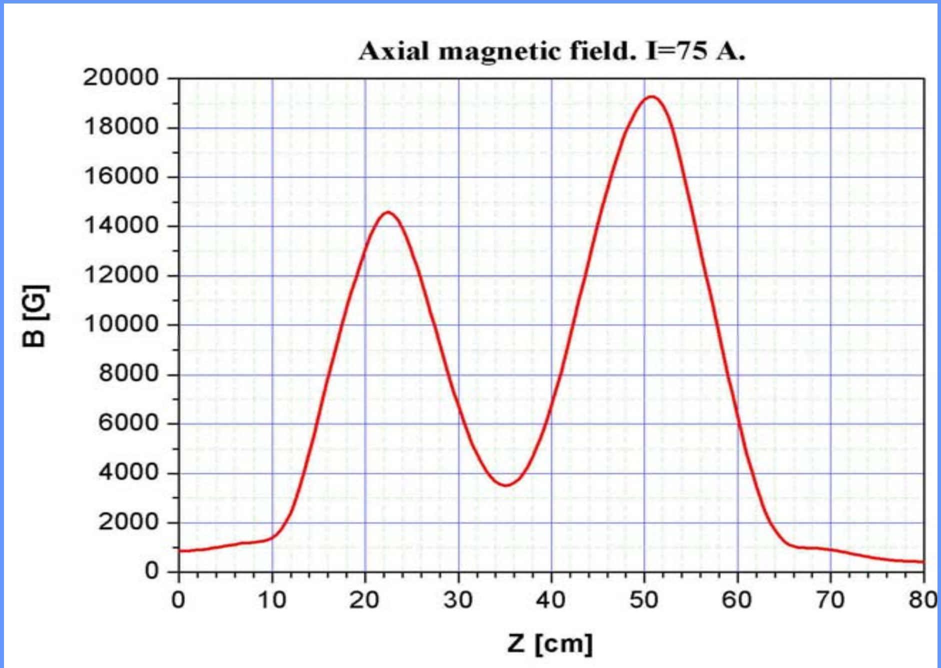
DECRIS-SC2 ion source for U-400M cyclotron

The main goal of the DECRIS-SC2 source is the production of more intense beams of heavy ions in the mass range heavier than Ar.

Table of main parameters.

Operating frequency	14 GHz
UHF power range	50 ÷ 700 W
Axial magnetic field (injection/extraction)	1.9 / 1.4 T
Coils power consumption	10 kW (cryocooler)
Coil current	75 A
Radial magnetic field	1.0 T
Plasma chamber diameter	74 mm
Source diameter / length	690 / 570 mm
Source weight	~ 700 kg



Expected intensities: Kr^{15+} ~ 100 eμA, Kr^{20+} ~ 10 eμA, Xe^{30+} ~ 5 eμA

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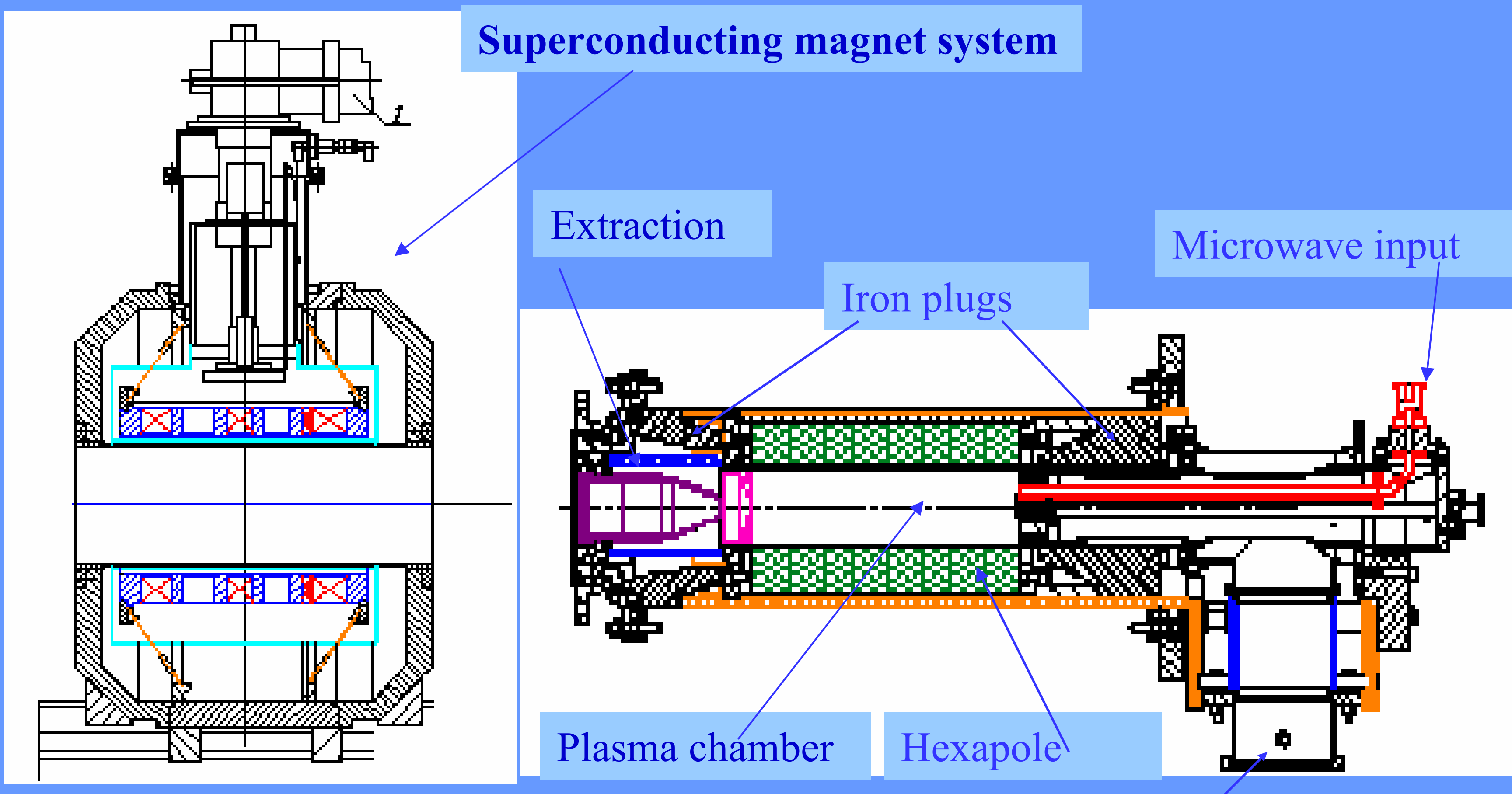
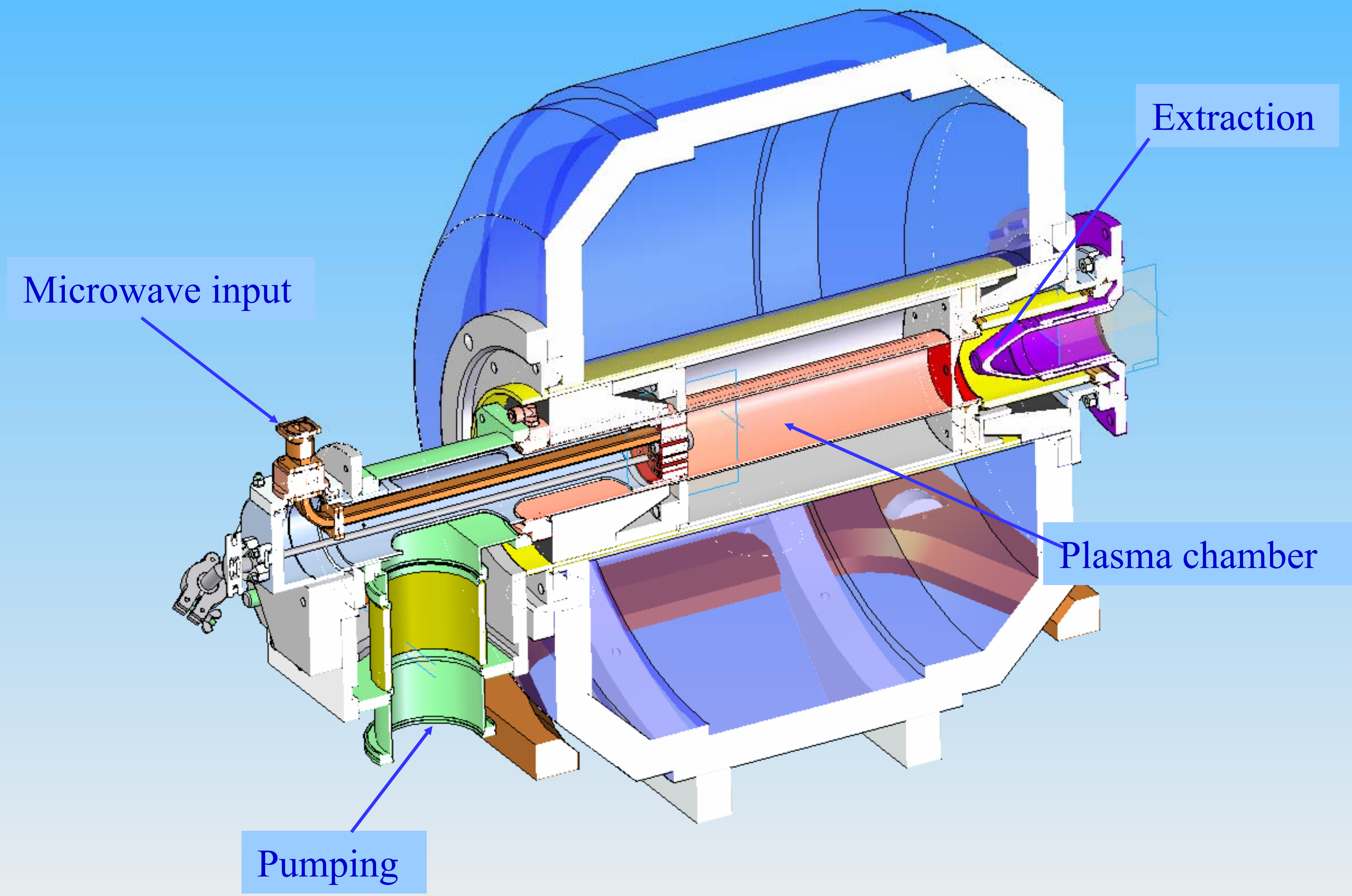
DECRIS-SC2

DECRIS-SC2 is the compact version of the “liquid He free” superconducting ion source. The axial magnetic field is created by superconducting coils and iron plugs. The radial magnetic field is formed by permanent magnet hexapole.



DECRIS-SC2



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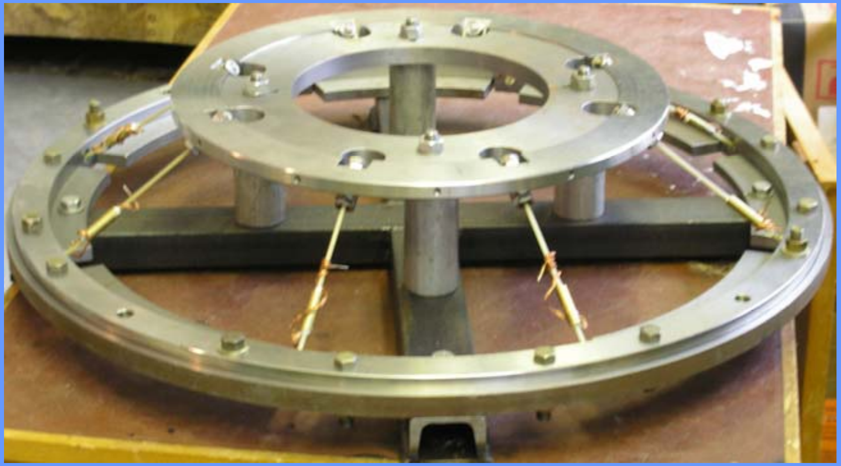
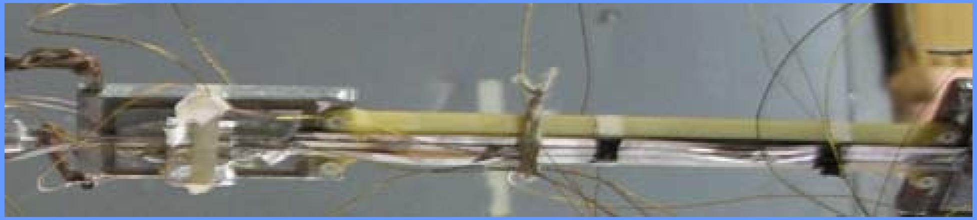
Components of DECRIS-SC2

Superconducting solenoid



Cold mass support

Thermal screen



HTSC current lead

DECRIS-SC2

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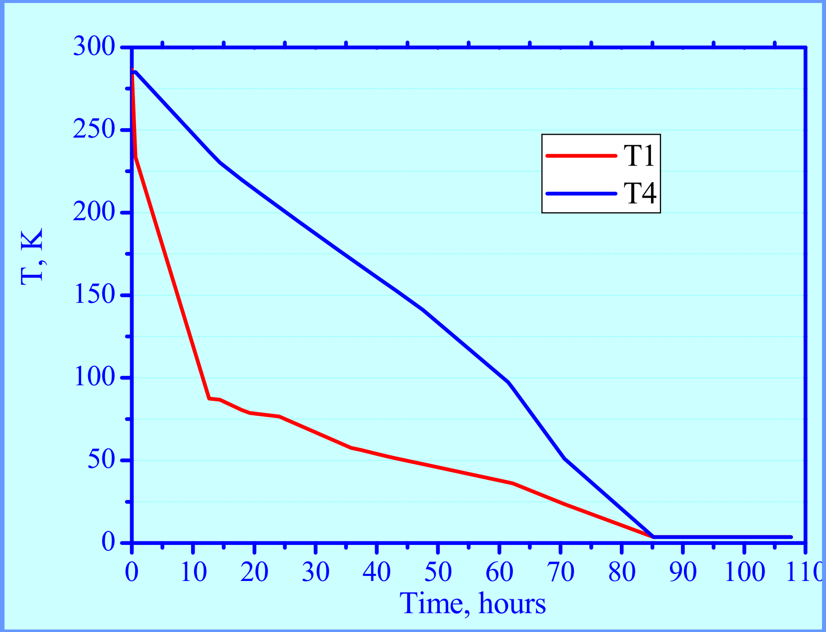
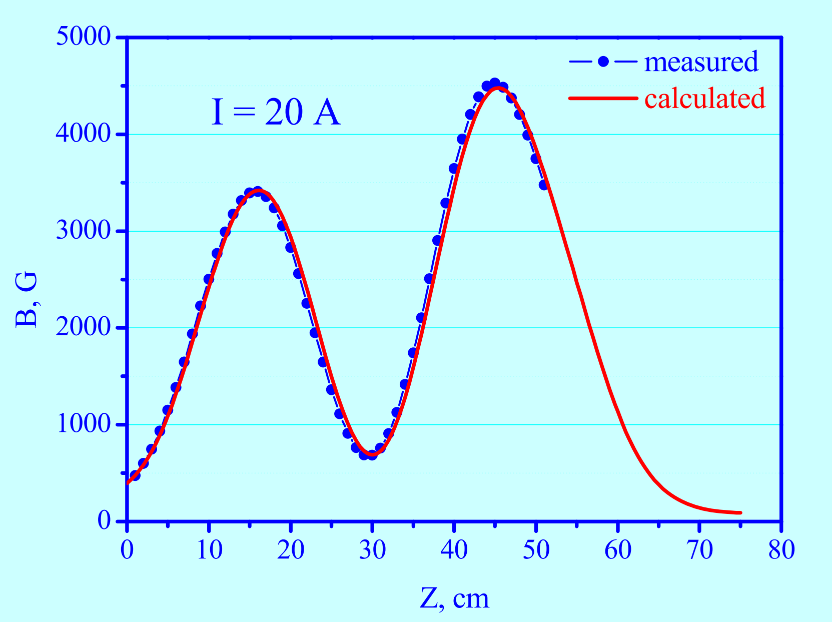
DECRIS-SC2

First tests of the superconducting magnet system september 2008



Cooling



Axial magnetic field measurement

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DC-350 cyclotron

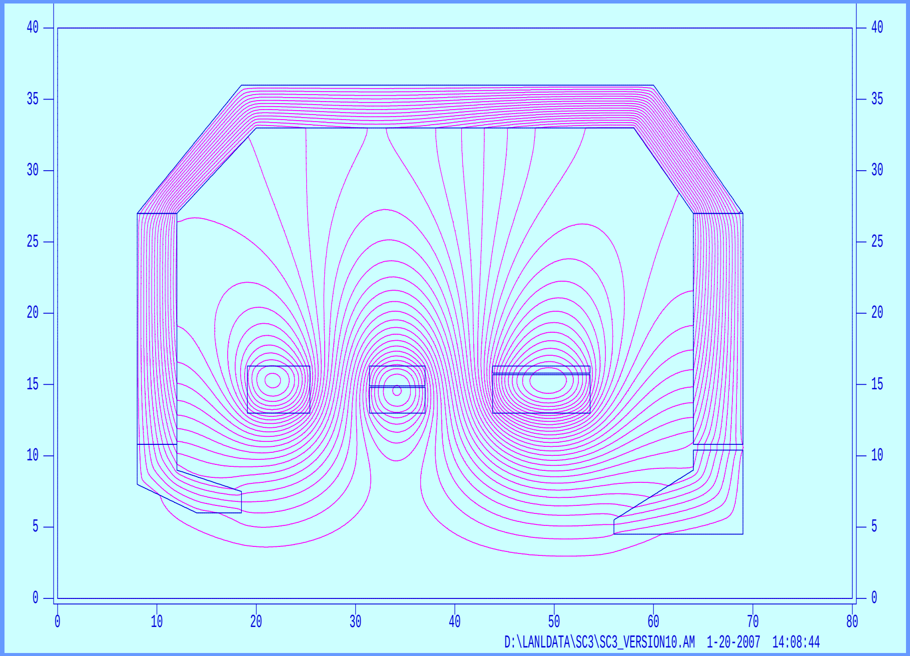
Intense ion beams of rare isotopes

Achieved intensities	Planned for DC-350 cyclotron ★
48Ca – 1,0 ÷ 1,5 pμA	48Ca – 2 ÷ 5 pμA
50Ti – 0,8 ÷ 1,6 pμA	50Ti – 2 ÷ 3 pμA
54Cr – 1,0 ÷ 1,25 pμA	54Cr – 2 ÷ 3 pμA
58Fe – 0,8 ÷ 1,0 pμA	58Fe – 2 ÷ 3 pμA
64Ni – 0,6 ÷ 0,8 pμA	64Ni – 2 ÷ 3 pμA

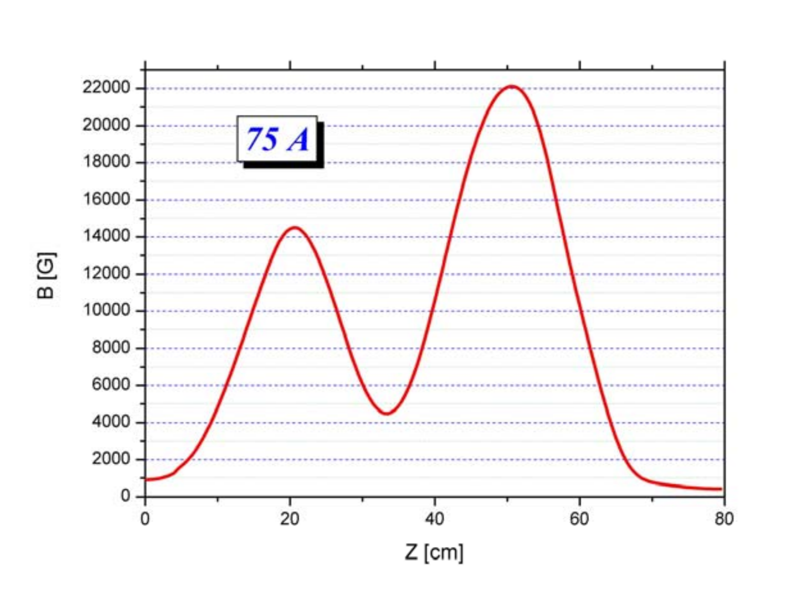
★ Smooth energy variation in the range of 4,5÷5,5 MeV/n

Project of DECRIS-SC3 source for DC-350 cyclotron

Operating frequency – 18 GHz



Computational model of the magnet system



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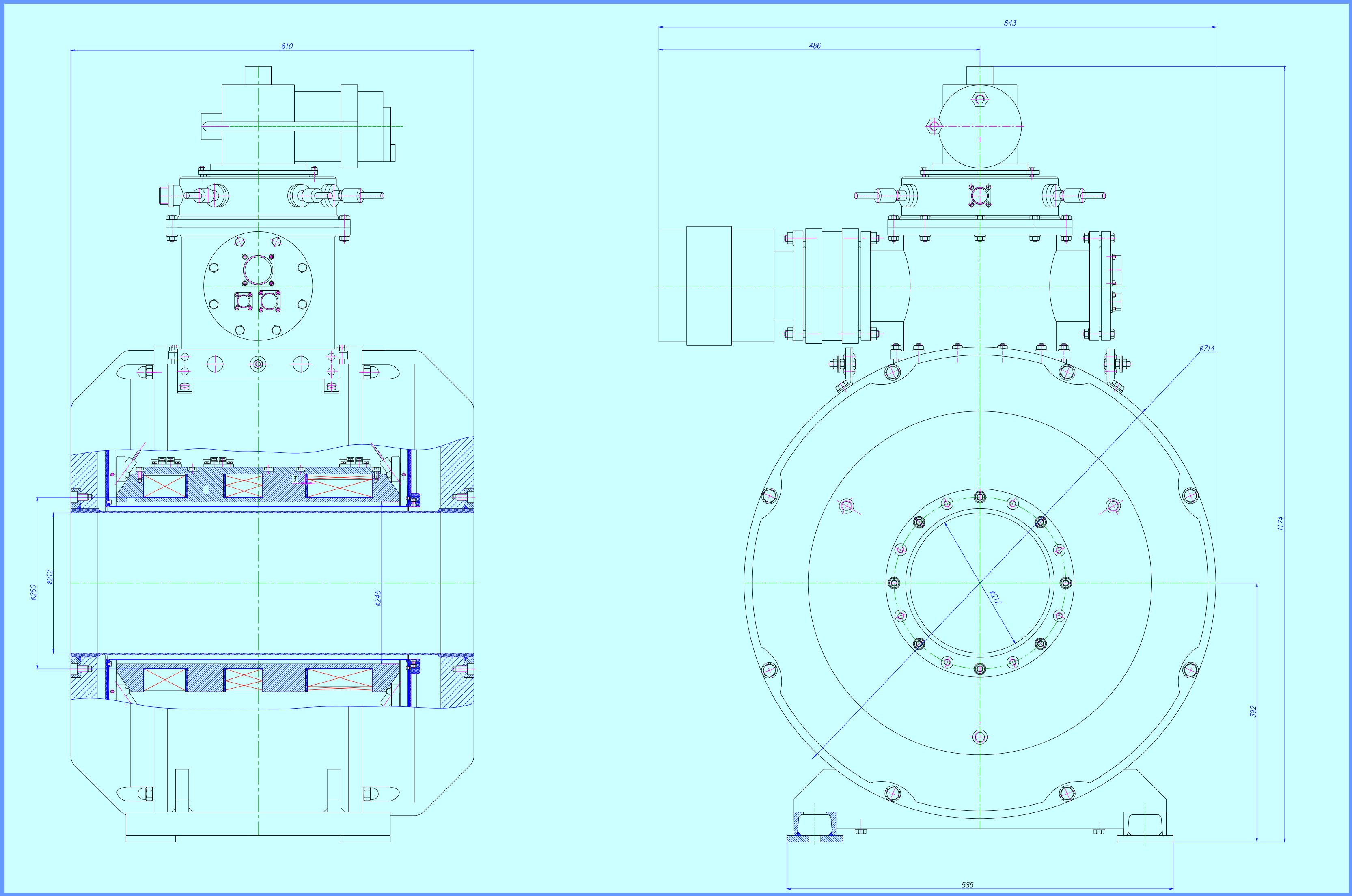
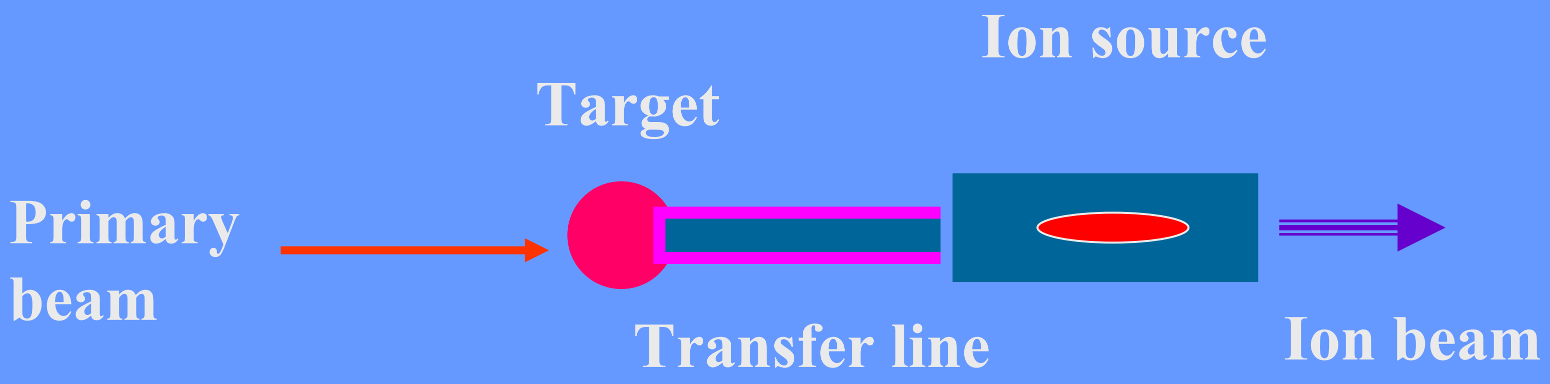
Superconducting magnet system for DECRIS-SC3



ECR ion sources for radioactive ion beams



$$I = N\,\varepsilon_1\varepsilon_2\varepsilon_3$$

N – number of products produced in the target

ε_1 - efficiency of products release

ε_2 – transport efficiency

ε_3 – ion source efficiency

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DRIBs (**D**ubna **R**adioactive ***I***on Beam**s**) project

- **First phase – production and acceleration of ^{6}He и ^{8}He beams.**
- Second phase – *production and acceleration of fission products (^{132}Sn).*

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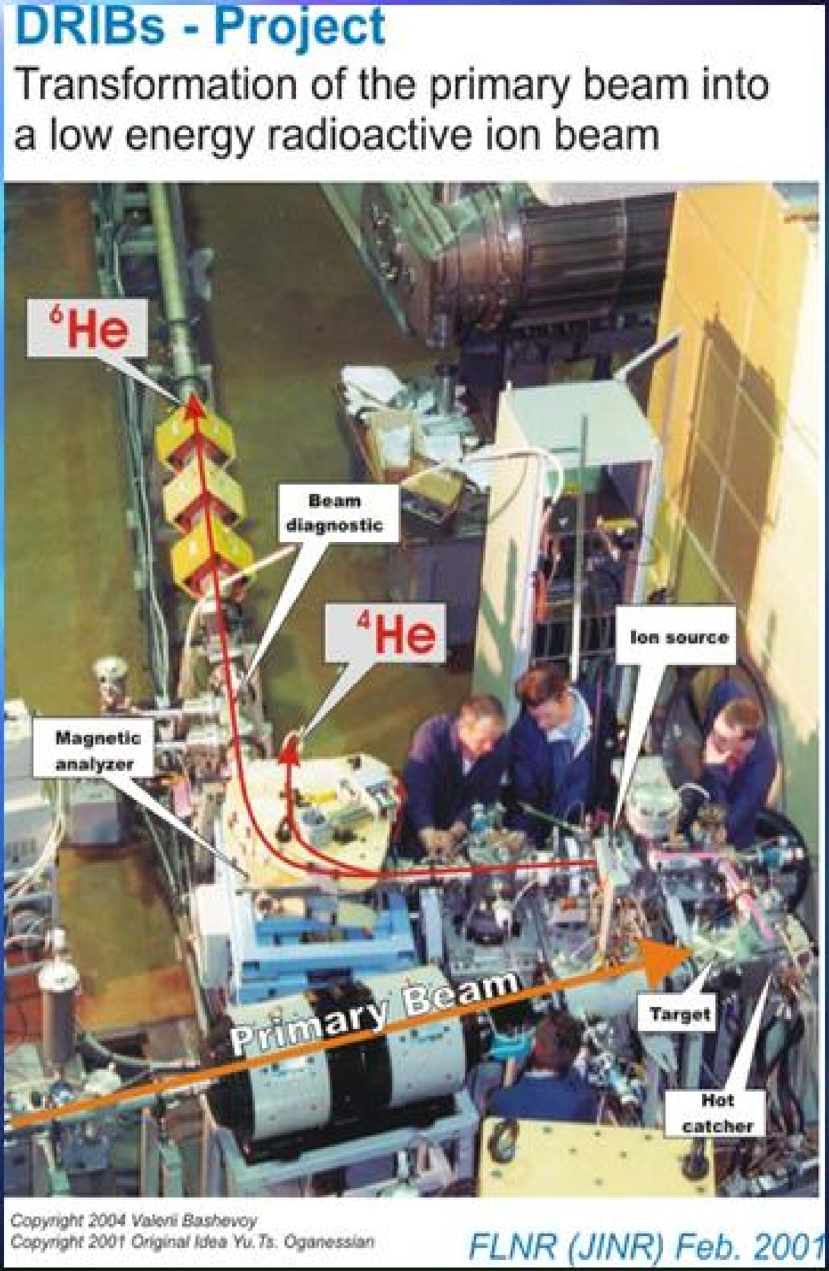

DRIBs - Project
Transformation of the primary beam into a low energy radioactive ion beam
^{6}He
Beam diagnostic
^{4}He
Ion source
Magnetic analyzer
Primary Beam
Target
Hot catcher
Copyright 2004 Valerii Bashevoy
Copyright 2001 Original Idea Yu.Ts. Oganessian
FLNR (JINR) Feb. 2001

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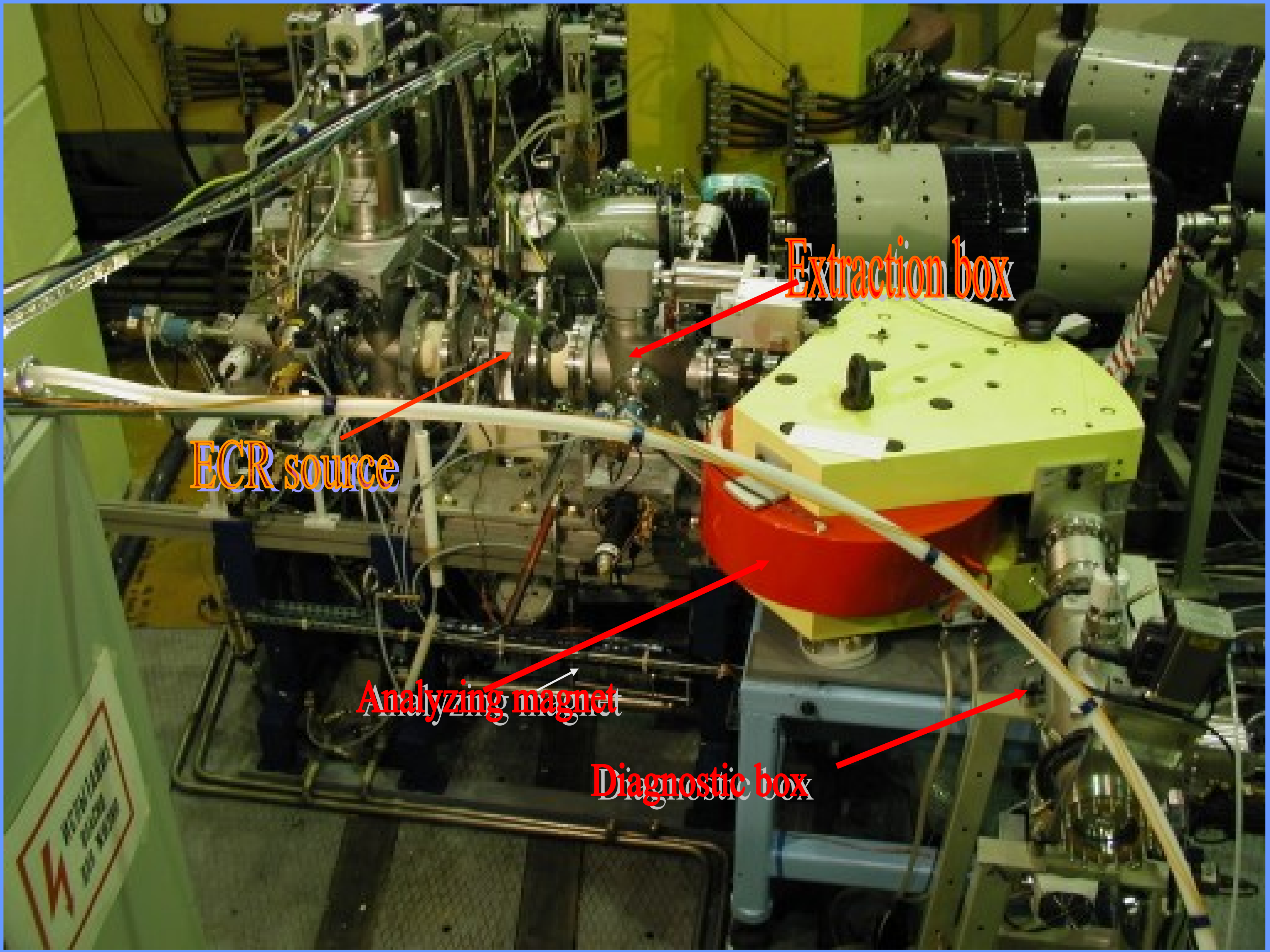
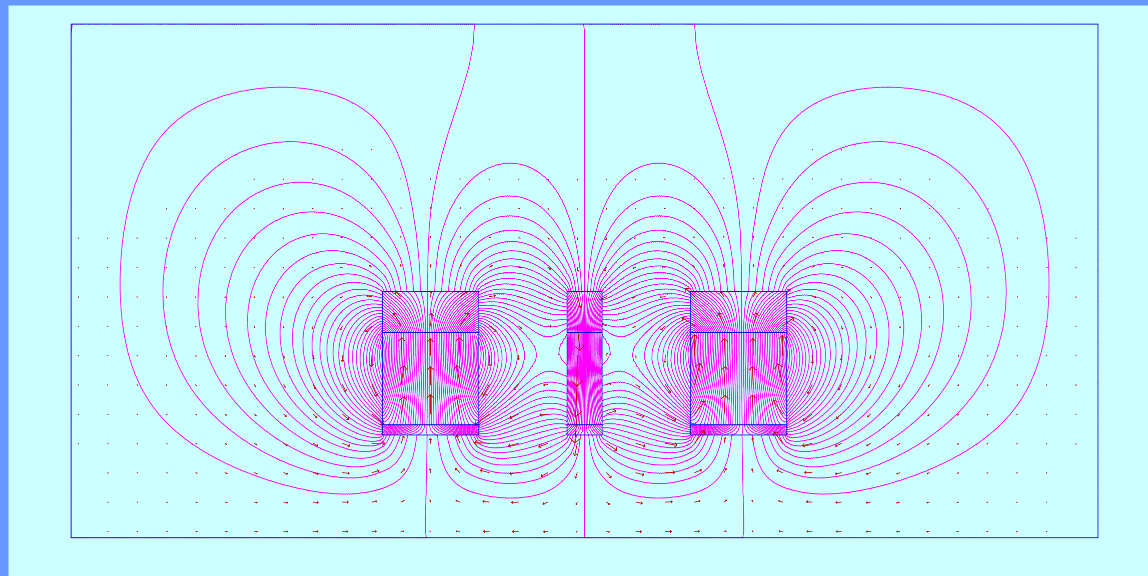
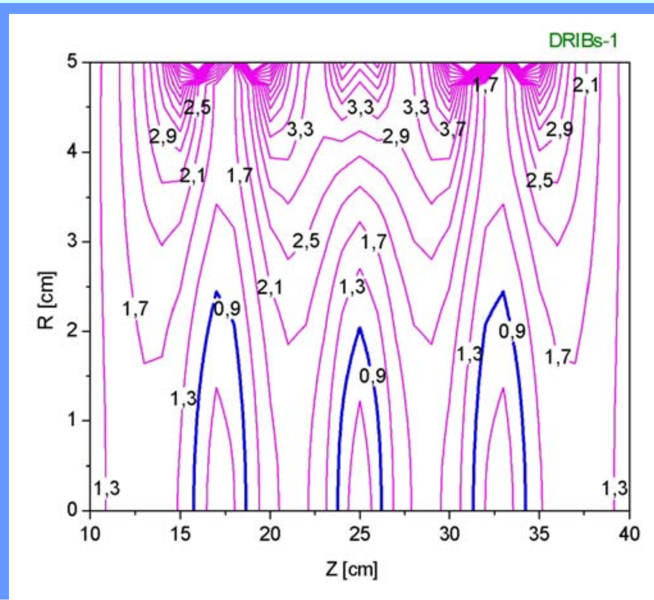

Extraction box
ECR source
Analyzing magnet
Diagnostic box

Magnetic structure of ECR ion source for DRIBs
(operating frequency 2.45 GHz)





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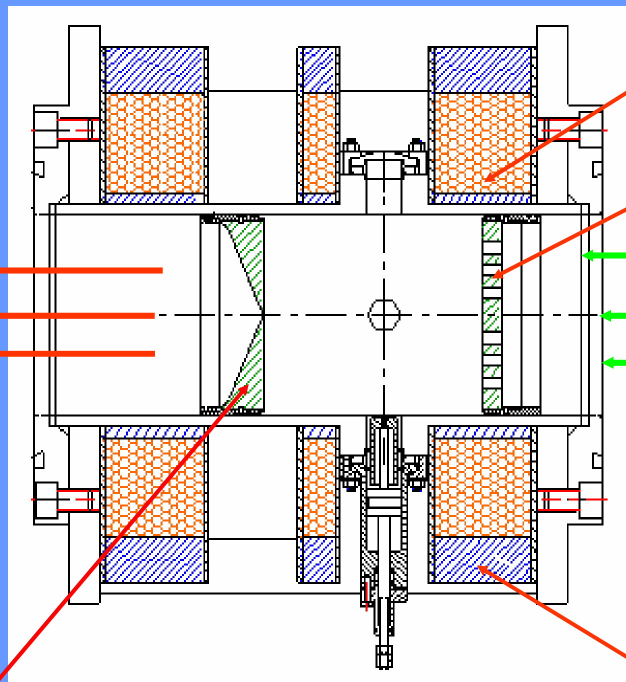
ECR ion source for DRIBs

Permanent magnets

Shorting plate

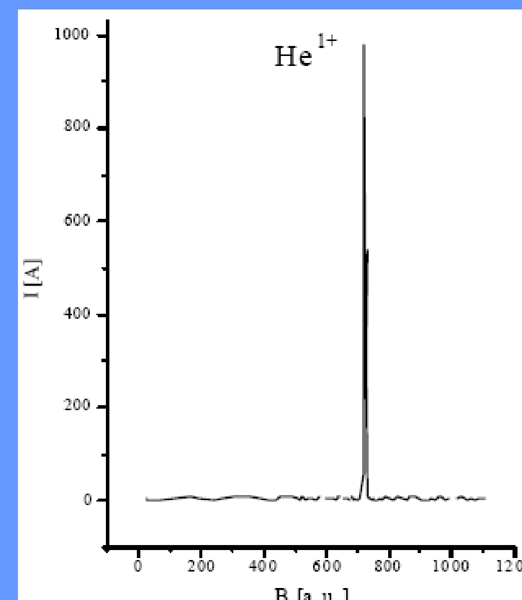


Beam

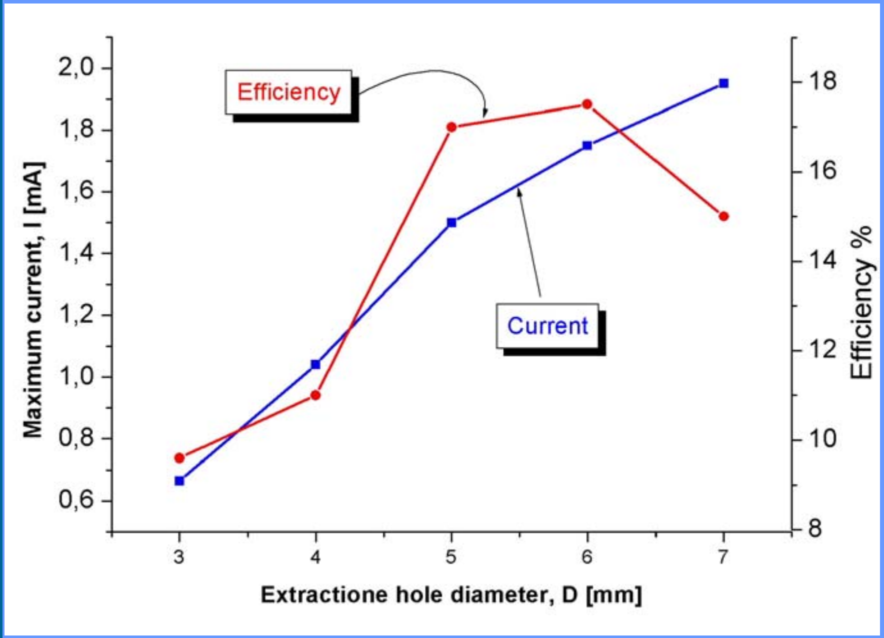
^{6}He atoms

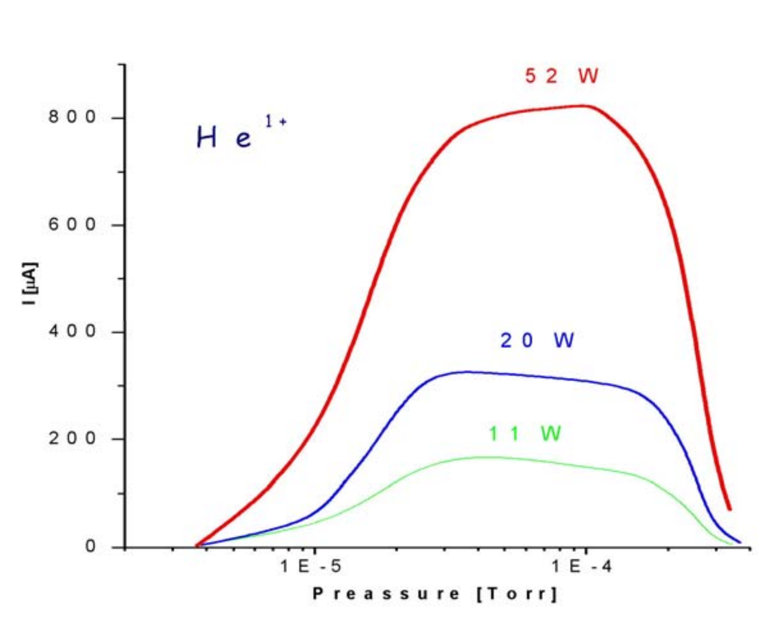
Plasma electrode

Soft iron



ECR ion source for DRIBs





Maximum extracted $^4He^{1+}$ current and global efficiency versus the diameter of the extraction hole.

Efficiency for Ar and Kr ≥ 80%

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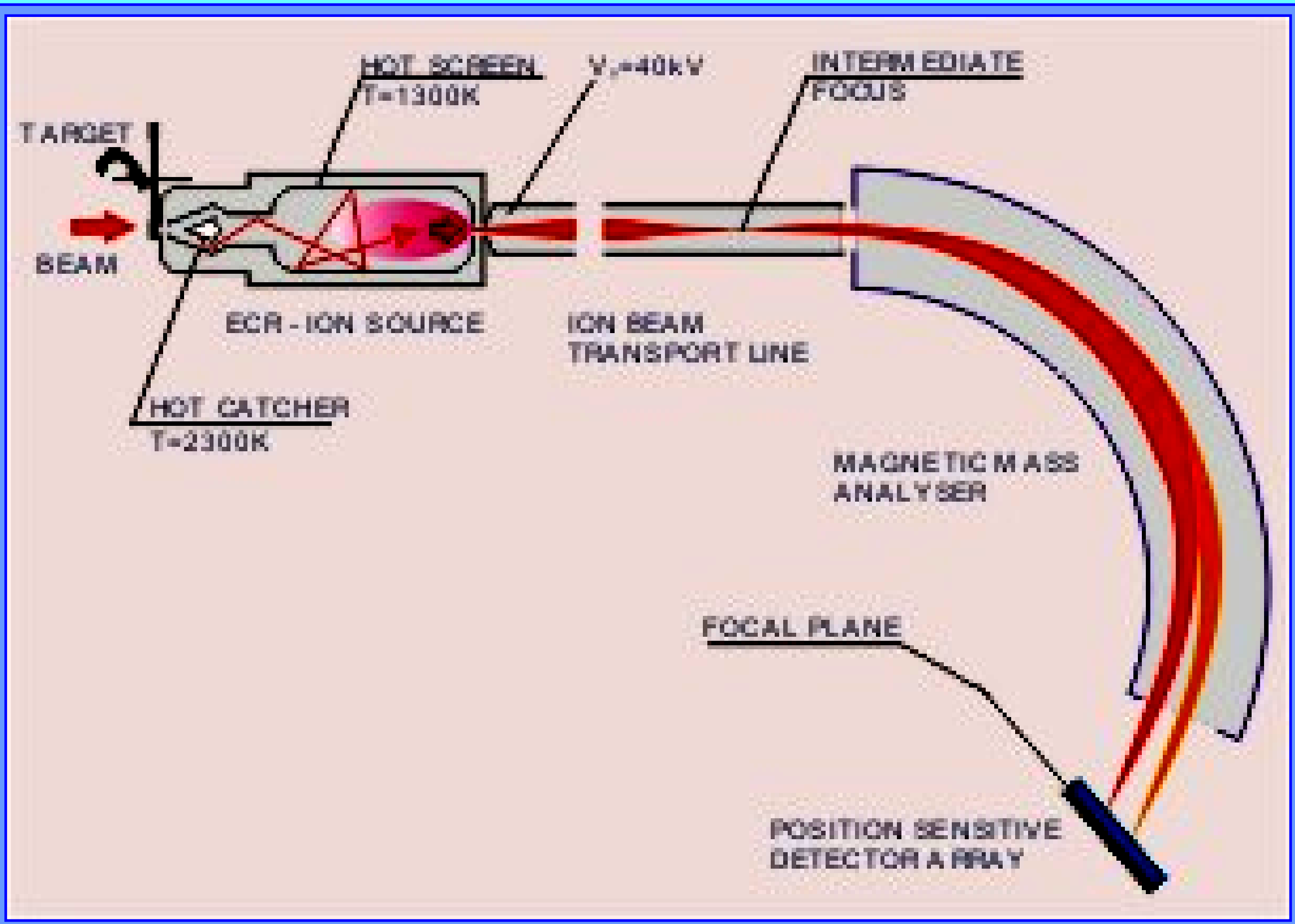
MASHA (Mass Analyzer of Super Heavy Atoms)

Mass identification of super heavy nuclei with a resolution better than 1 amu at the level of 300 amu.

Synthesized in nuclear reactions nuclides are emitted from an ECR ion source at energy E = 40 kV and charge state Q = +1. The set up can work in the wide mass region from A~20 to A 500, mass acceptance ±3%.



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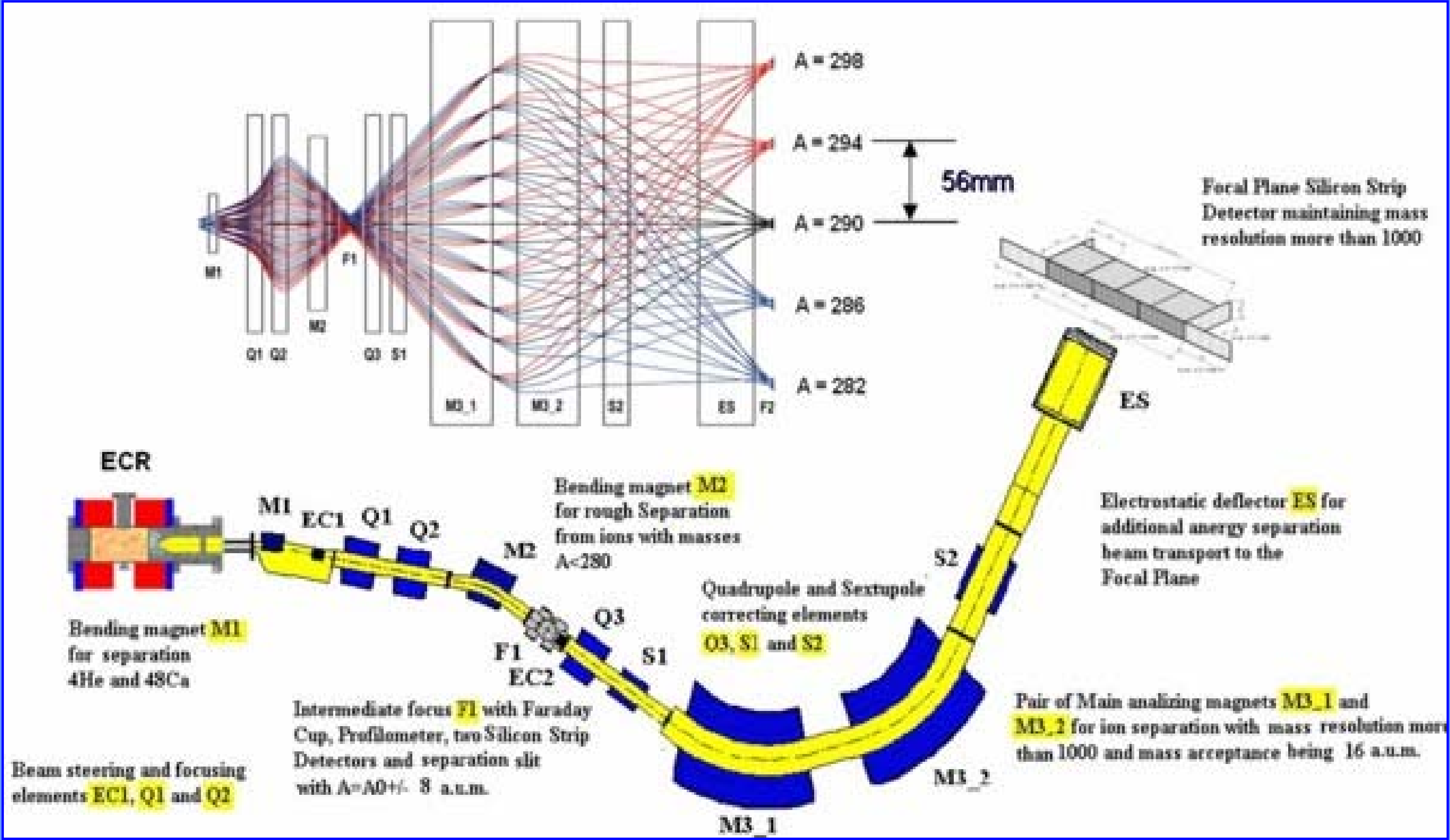
MASHA (Mass Analyzer of Super Heavy Atoms)



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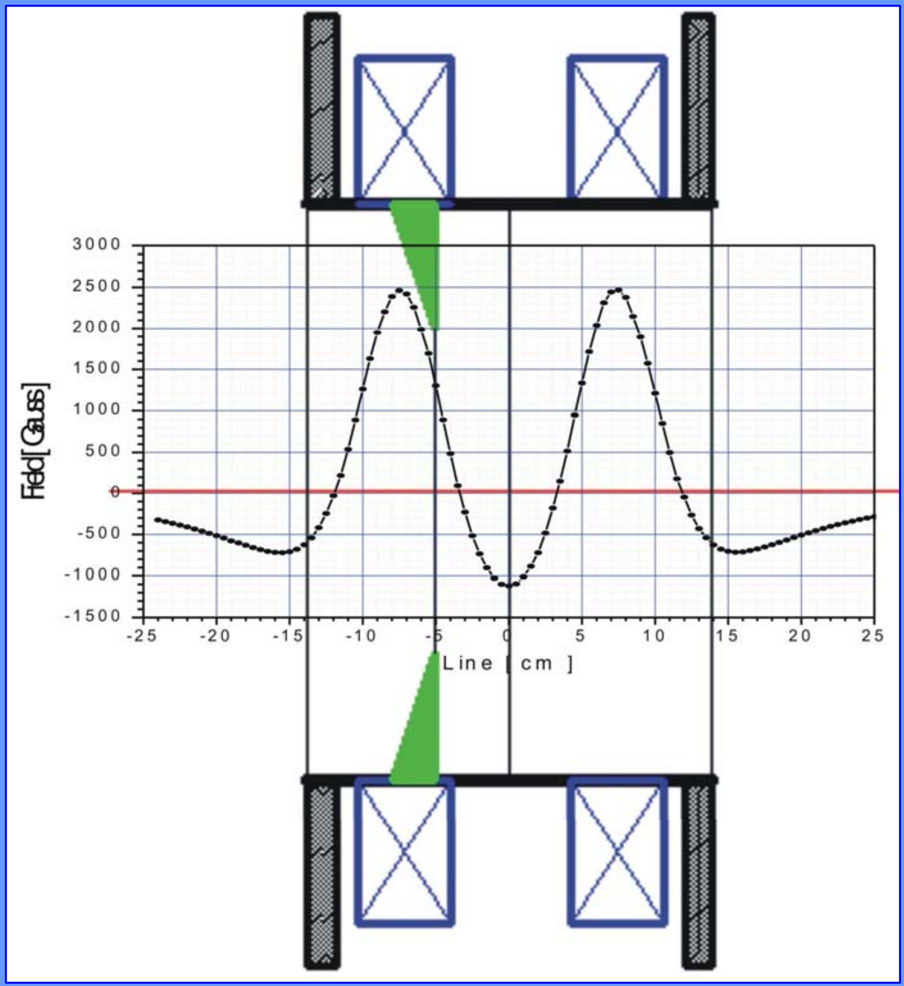
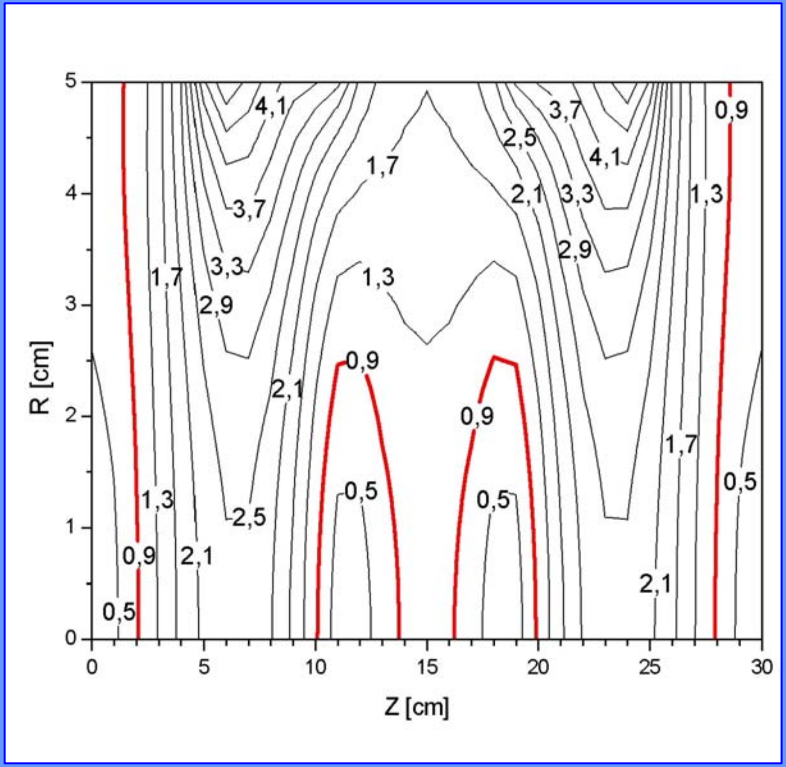
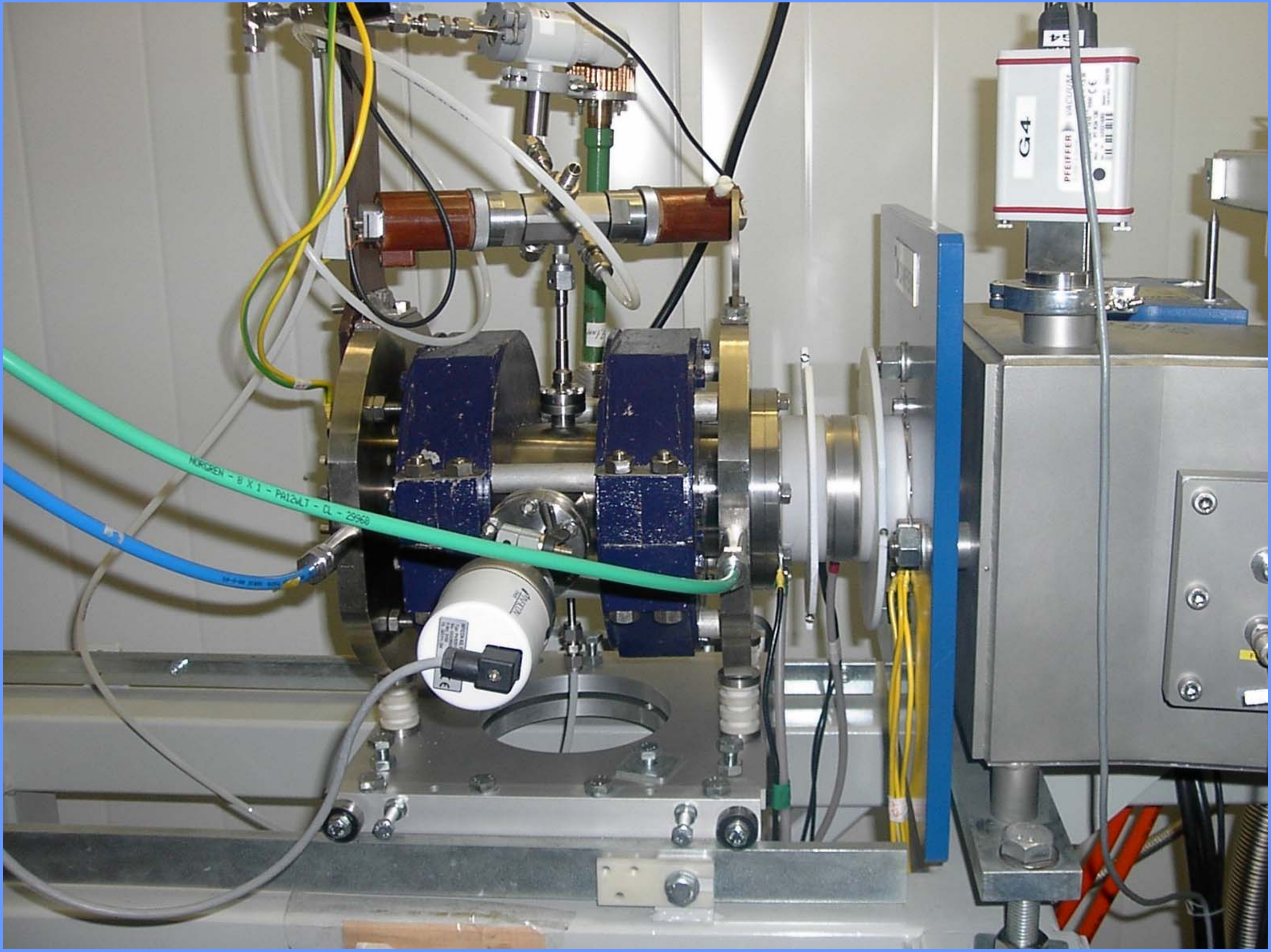
Magnetic structure of ECR ion source for MASHA (operating frequency 2.45 GHz)





ECR ion source for MASHA



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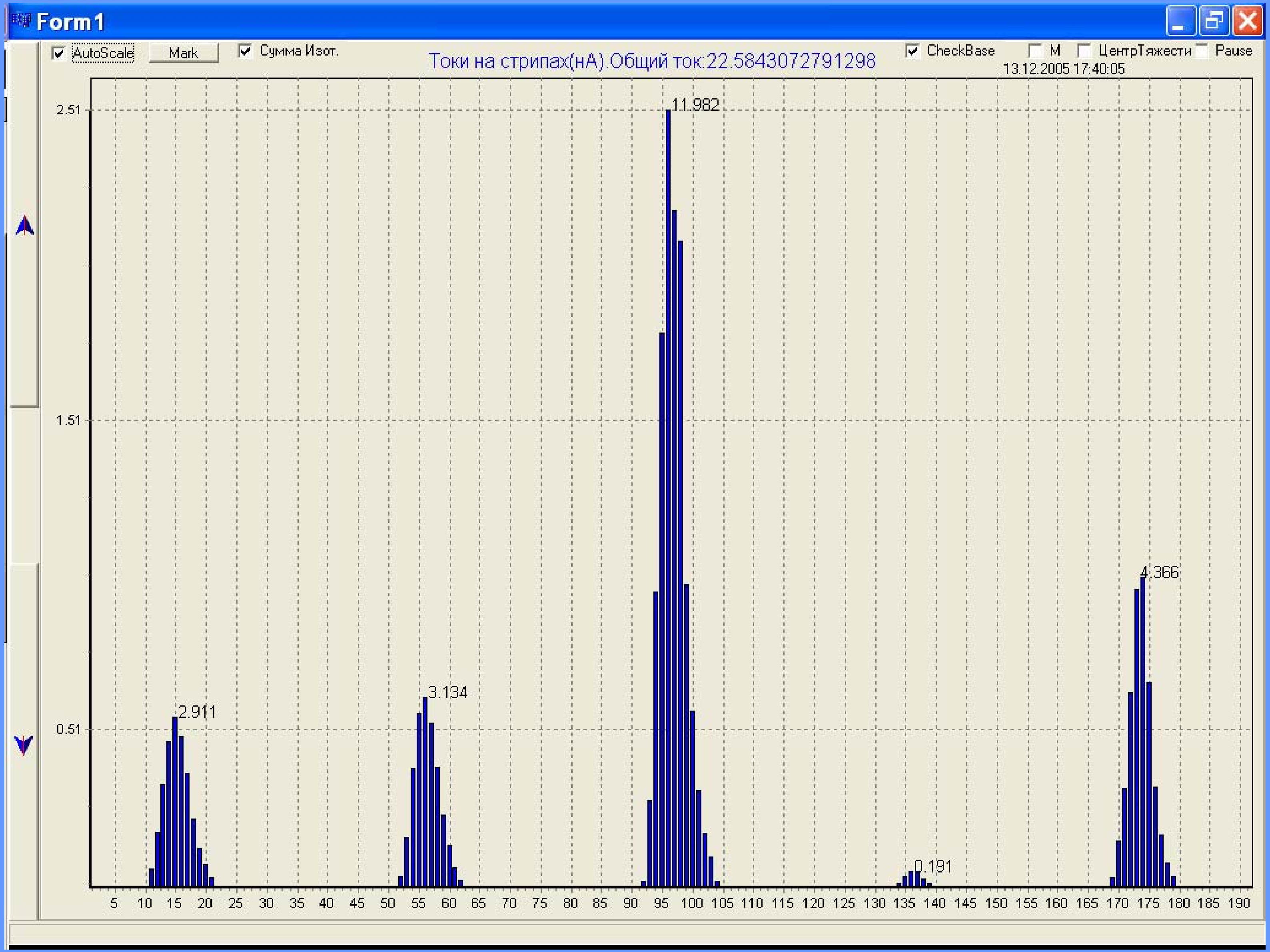
Kr spectrum



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THANK YOU!!