Development of FLNR JINR Heavy Ions Accelerator Complex (DRIBs III)

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FLNR's BASIC DIRECTIONS of RESEARCH

U-400 cyclotron (^{48}Ca, ^{50}Ti 5-6 MeV/n)

- Heavy and superheavy nuclei:

- synthesis and study of properties of superheavy elements;
- chemistry of new elements;
- fusion-fission and multi-nucleon transfer reactions;
- nuclear- , mass-, & laser-spectrometry of SH nuclei.

U-400M cyclotron (light ions ~50 MeV/n)

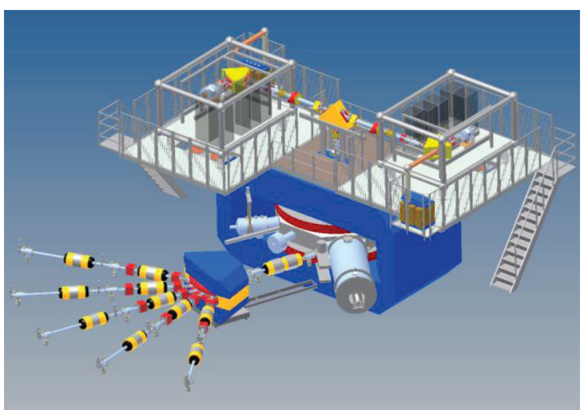
- Light exotic nuclei:

- properties and structure of light exotic nuclei;
- reactions with exotic nuclei.

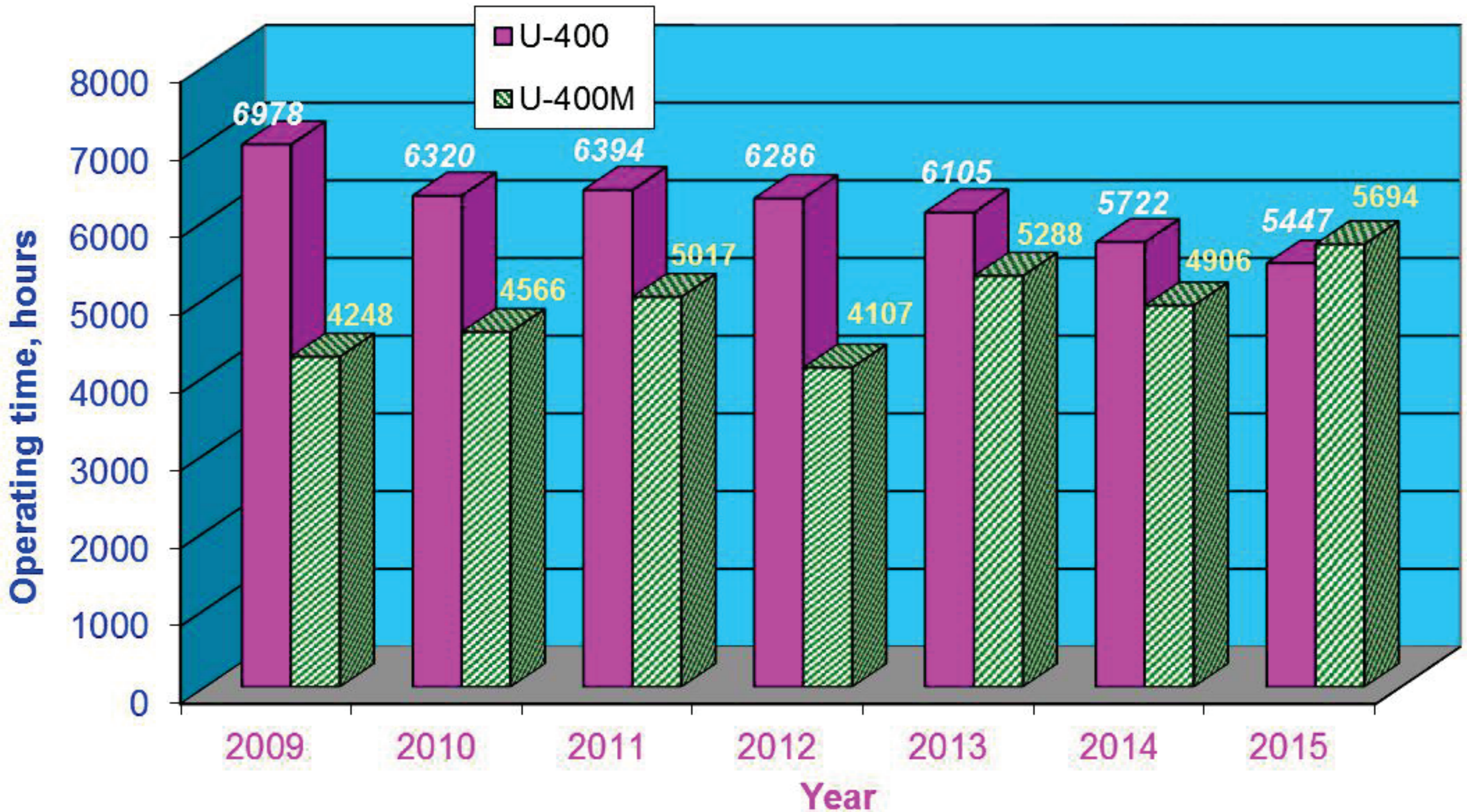
IC-100 (C ÷ Bi 1 MeV/n), U-400 (Ar ÷ Bi 3.5-5 MeV/n)

- Radiation effects and physical groundwork of nanotechnology.


DC-280
SHE factory
U-400
Heavy and superheavy nuclei
U-400M
Light exotic nuclei
IC-100
Applied research
NanoLab
DRIBs gallery
MT-25
Microtron



TOTAL OPERATION TIME OF U-400 AND U-400M ACCELERATORS

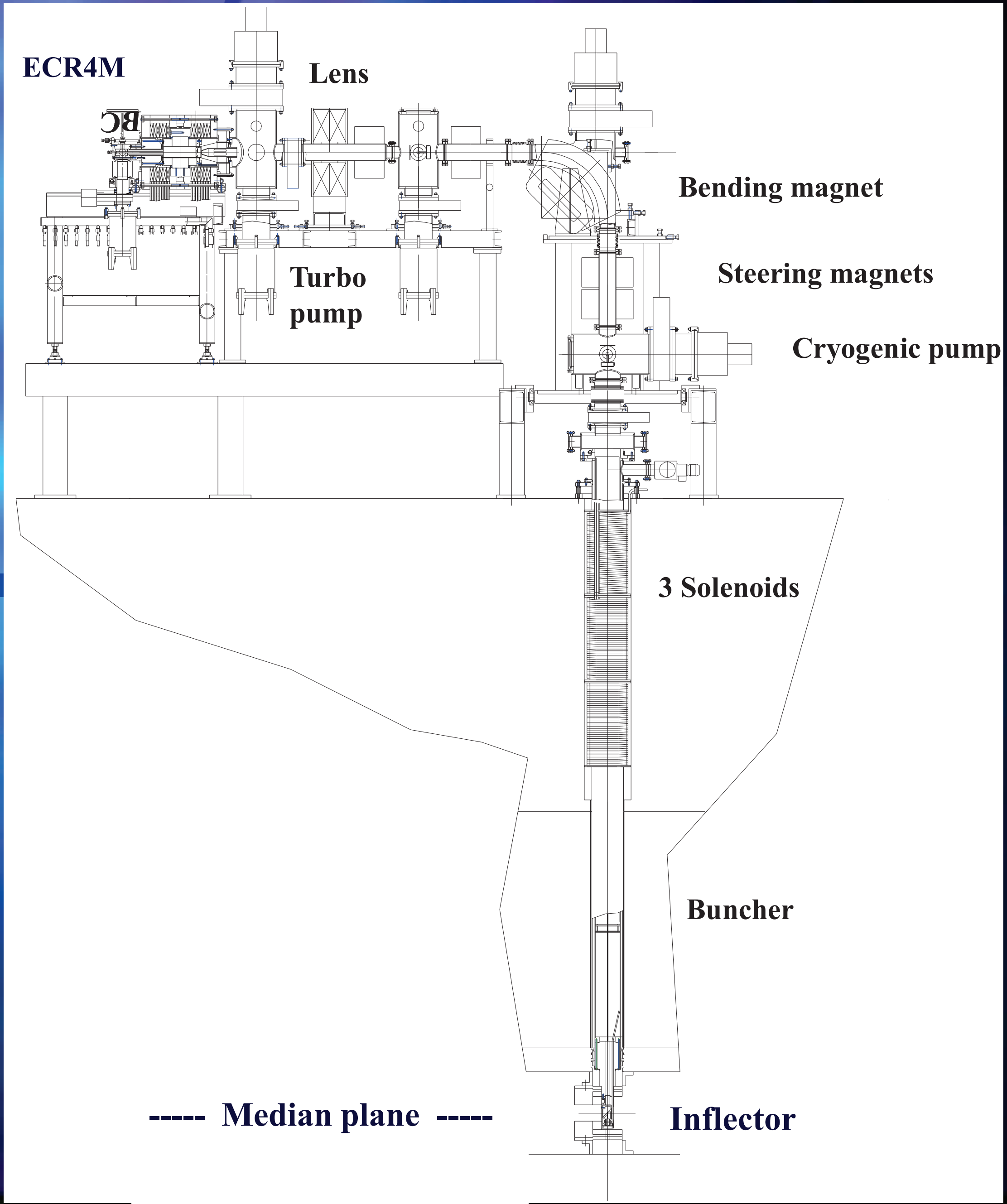


U400 Cyclotron (1978)

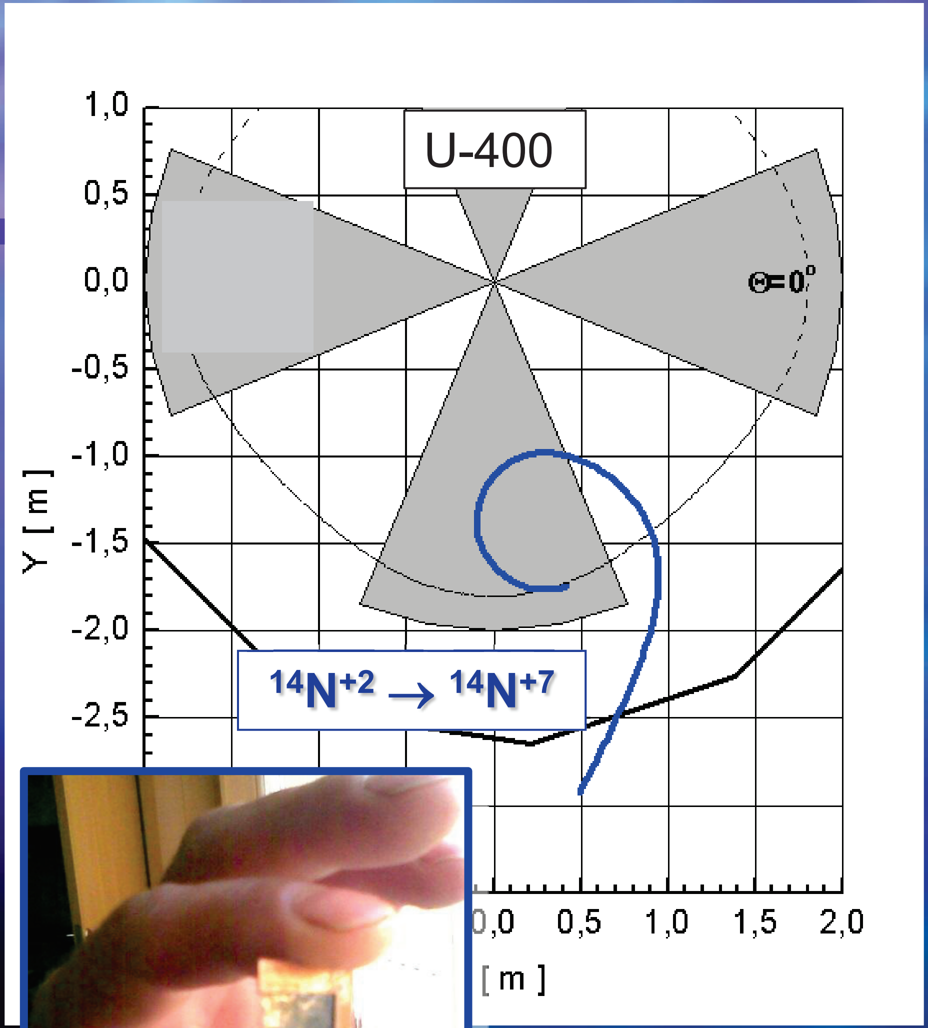
Axial injection system of U-400 Cyclotron

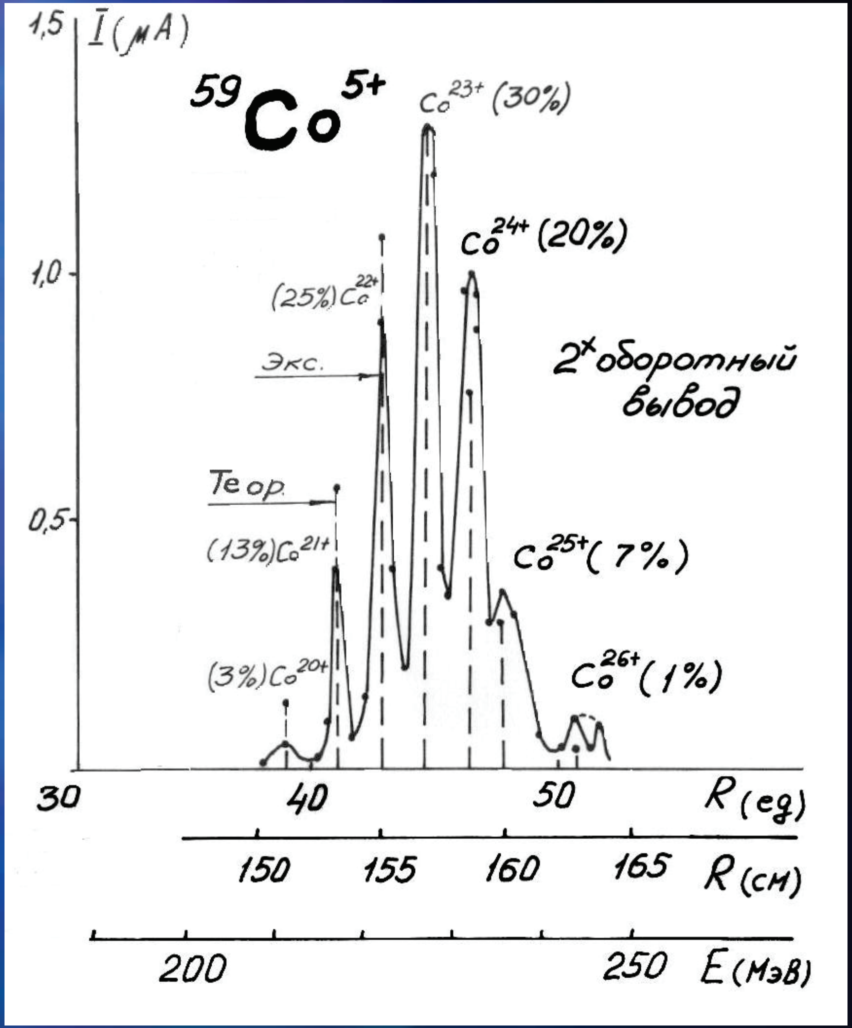
ECR4M (14 GHz)
made by GANIL 1995,
upgraded by FLNR 2013

$^{48}Ca^{5+}$ - 100 eμA
$^{132}Xe^{12+}$ - 50 eμA
$^{209}Bi^{19+}$ - 20 eμA



Heavy Ion Beam Extraction by Stripping Foil





Thickness of stripping foil – 20 -200 μg/cm²

Efficiency of transporting a $^{48}Ca^{5+}$ beam from the ECR source to a physical target

<table>
<tr><th>Measuring point</th><th colspan="2">Beam intensity</th><th>Ion</th><th colspan="5">Transmission factor</th></tr>
<tr><td>ECR source, after separation</td><td>$1 \cdot 10^{14}$ pps</td><td>84 µAe</td><td>$^{48}Ca^{5+}$</td><td rowspan="2">32%</td><td></td><td></td><td></td><td rowspan="5">8.5%</td></tr>
<tr><td>Cyclotron centre</td><td>$3.5 \cdot 10^{13}$ pps</td><td>27 µAe</td><td>$^{48}Ca^{5+}$</td><td rowspan="2">81%</td><td></td><td></td></tr>
<tr><td>Extraction radius</td><td>$2.8 \cdot 10^{13}$ pps</td><td>22 µAe</td><td>$^{48}Ca^{5+}$</td><td></td><td rowspan="2">40%</td><td></td></tr>
<tr><td>Extracted beam (by charge exchange)</td><td>$9.7 \cdot 10^{12}$ pps</td><td>28 µAe</td><td>$^{48}Ca^{18+}$</td><td></td><td></td><td rowspan="2">82%</td></tr>
<tr><td>Target</td><td>$8 \cdot 10^{12}$ pps</td><td>23 µAe</td><td>$^{48}Ca^{18+}$</td><td></td><td></td><td></td></tr>
</table>

- Ionization efficiency of ^{48}Ca (neutral) to $^{48}Ca^{5+}$ - about 10%
- Transformation of ^{48}Ca as working substance into the ^{48}Ca beam on target is about 1% in routine operation.

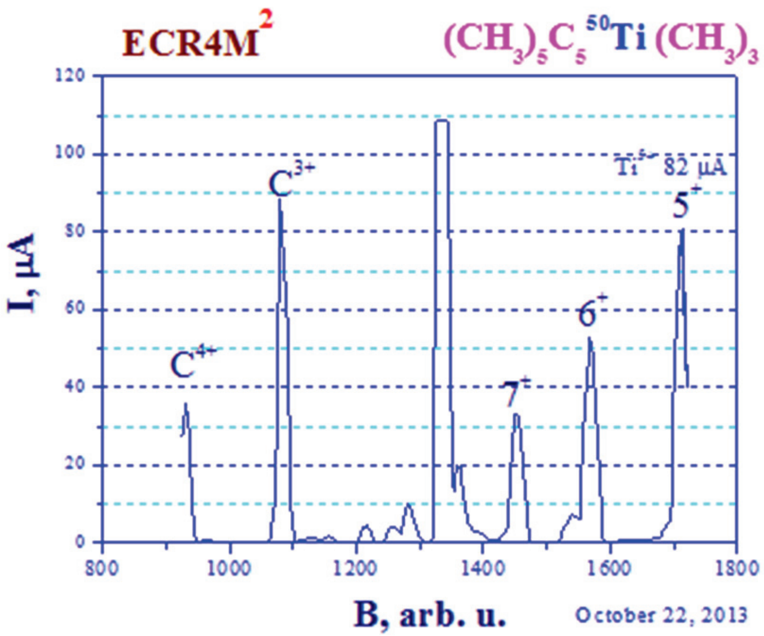
Development of ^{50}Ti beam using MIVOC method

(Collaboration between IPHC (Strasbourg, France) and FLNR JINR.)

Synthesis of compound (two steps)

$^{50}TiCl_4 + (CH_3)_5C_5Si(CH_3)_3 \rightarrow Cp{*}TiCl_3 + 3CH_3Li \rightarrow Cp{*}Ti(CH_3)_3$

where $Cp{*}$ - $(CH_3)_5C_5$



The spectrum of Ti ions, the source settings are optimized for $^{50}Ti^{5+}$ (82 eμA).

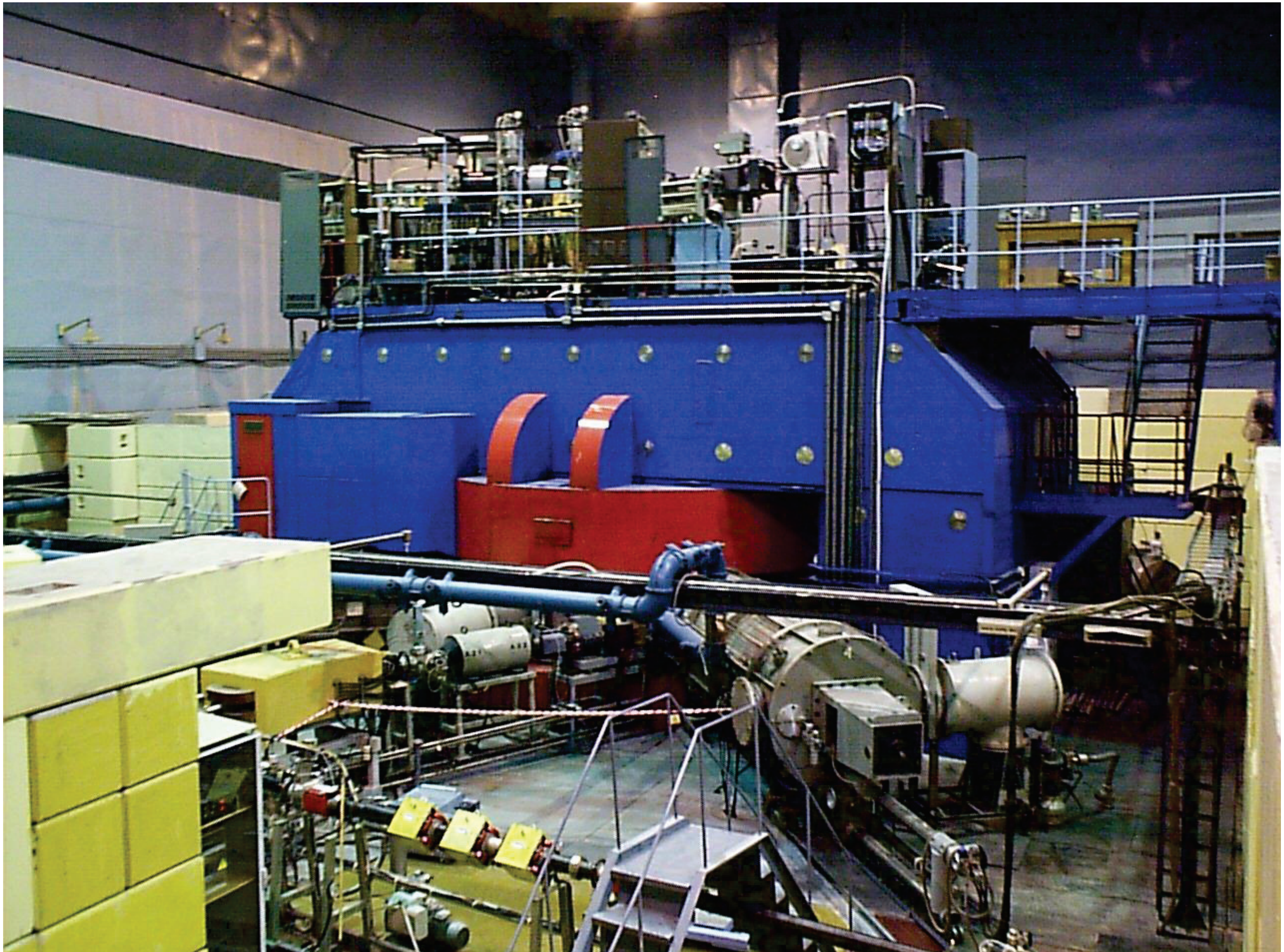
Acceleration at the U-400 cyclotron

The intensity of the injected beam of $^{50}Ti^{5+} \geq 50$ eμA

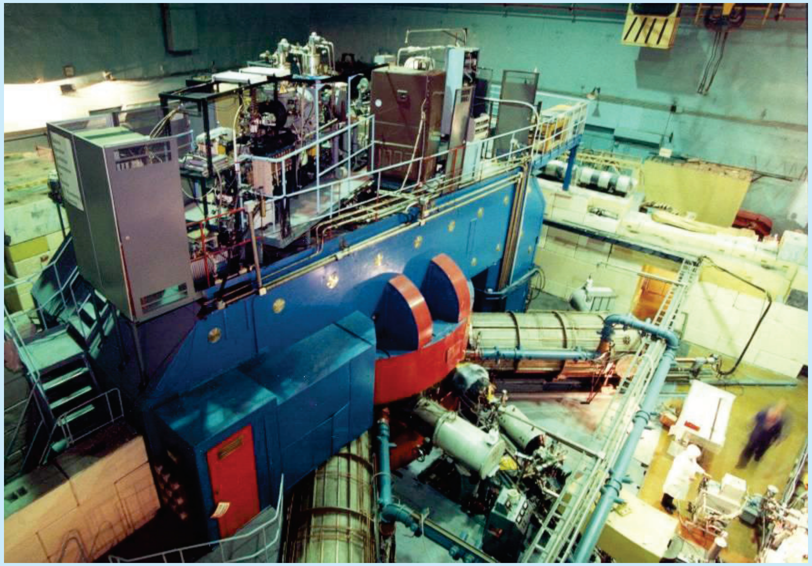
The beam intensity at the target ~ 10 eμA (~ 0.5 pμA)

The compound consumption rate of 2.4 mg/h (^{50}Ti consumption of 0.52 mg/h)

The U-400M heavy ion cyclotron (1991)



U400M CYCLOTRON
stand-alone & driving accelerator



U400M E=30 ÷ 50 MeV/A E=4.5 ÷ 9 MeV/A		
Ion	Ion energy [MeV/A]	Output intensity
^{7}Li	35	6×10^{13}
^{18}O	33	1×10^{13}
^{40}Ar	40	1×10^{12}
^{48}Ca	5	6×10^{12}
^{54}Cr	5	3×10^{12}
^{58}Fe	5	3×10^{12}
^{124}Sn	5	2×10^{11}
^{136}Xe	5	4×10^{11}
^{238}U	7	2×10^{10}

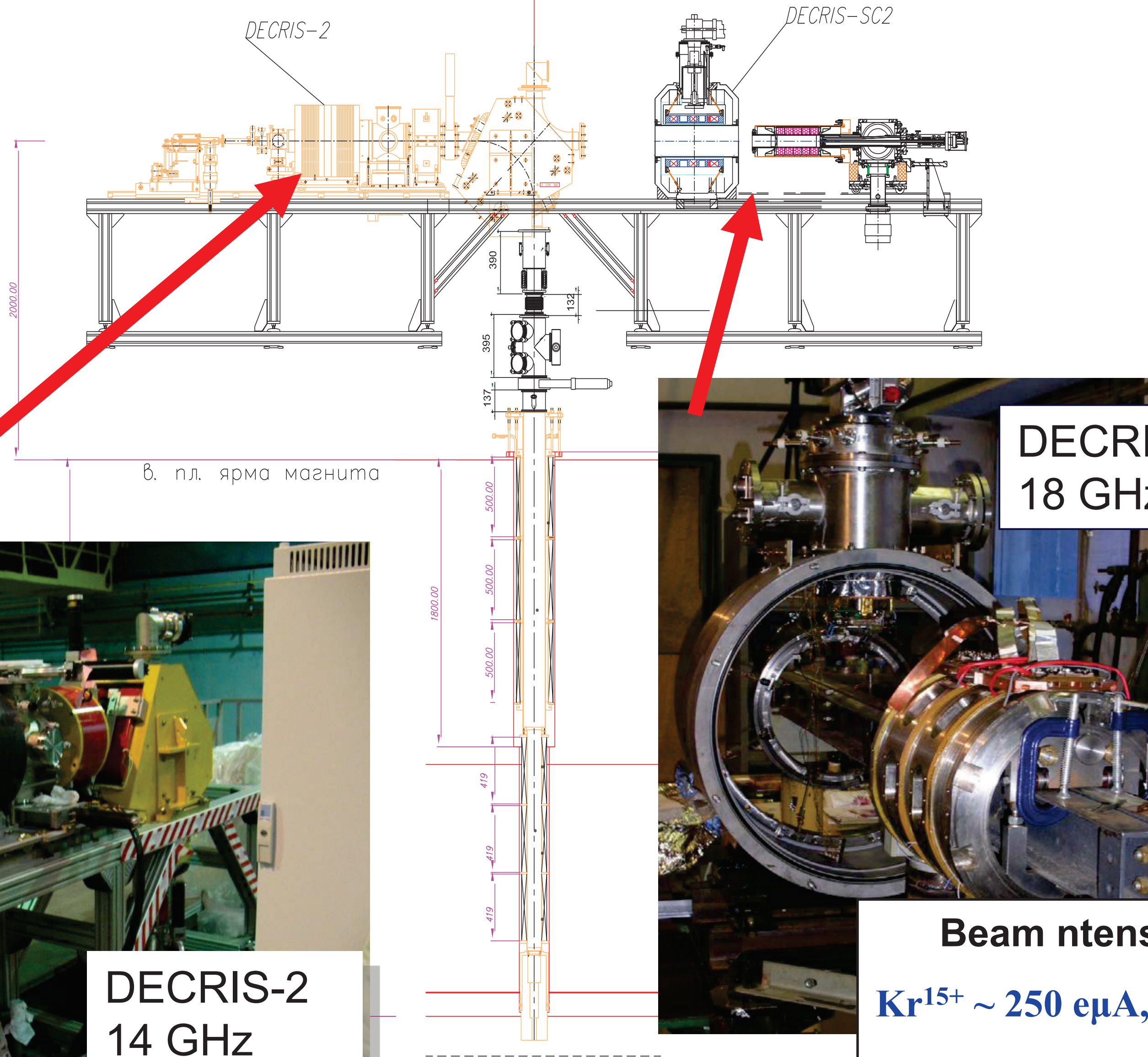
Main setup:

Fragment separator ACCULINNA-2

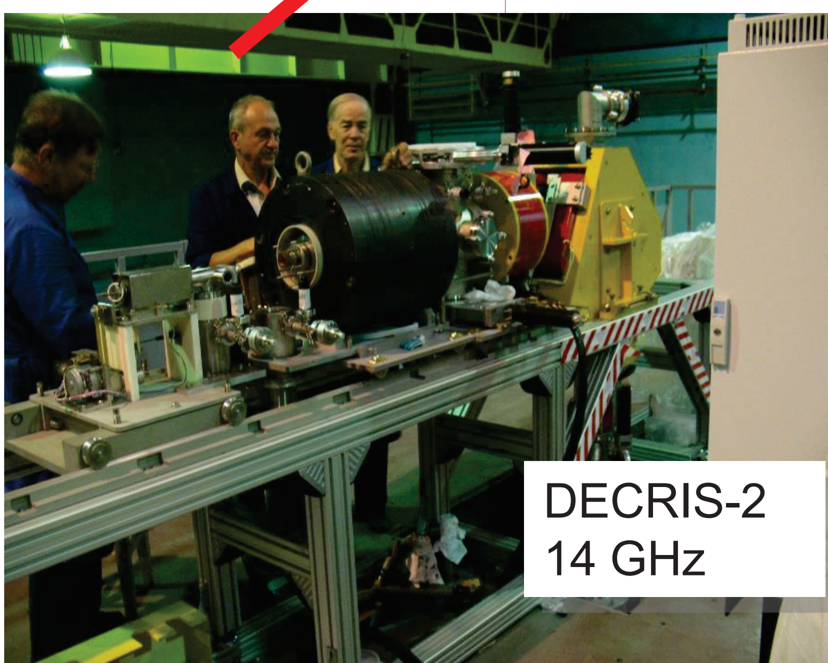
Main tasks:

- *Producing of RIBs.*
- *Reactions with exotic nuclei;*
- *Properties and structure of light exotic nuclei;*

U-400M. New ion sources and axial injection system



Median plane



DECRIS-2
14 GHz

DECRIS-SC2
18 GHz

Beam ntensity:

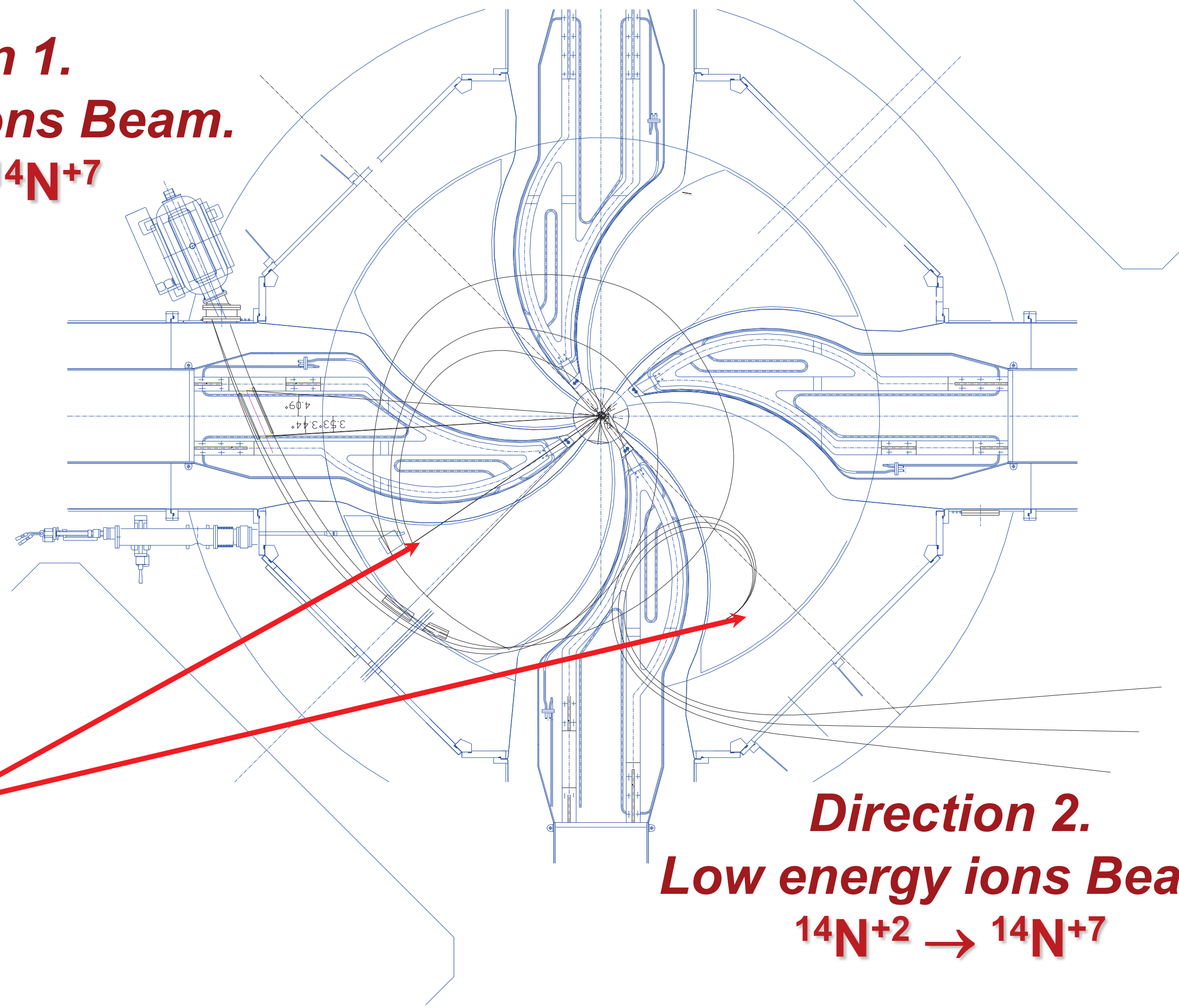
Kr^{15+} ~ 250 eμA,

Kr^{17+} ~ 150 eμA,

Xe^{30+} ~ 1 eμA

U-400M. Ion beam extraction by charge exchange method

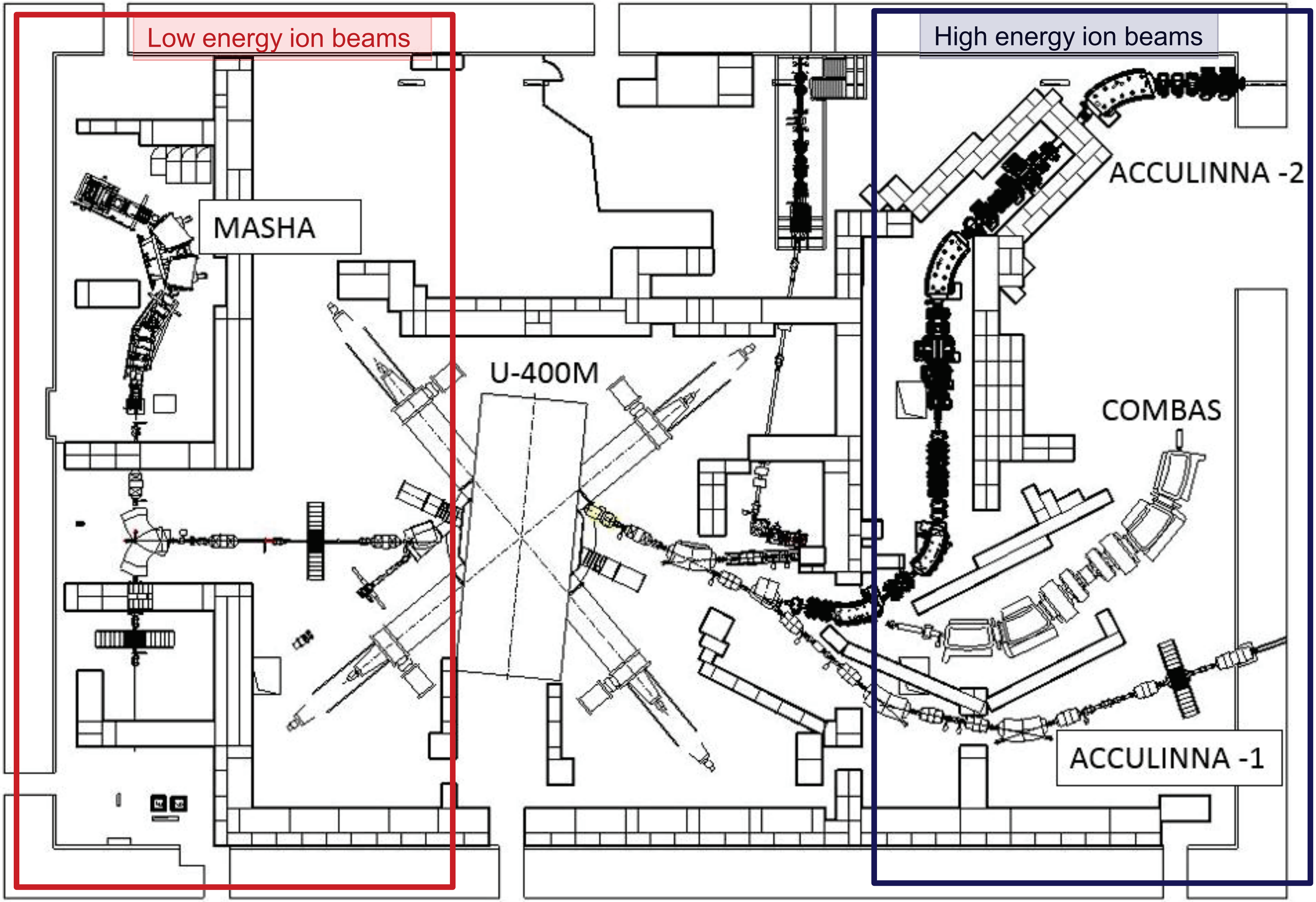
Direction 1.
High energy ions Beam.
$^{14}N^{+5} \rightarrow {}^{14}N^{+7}$



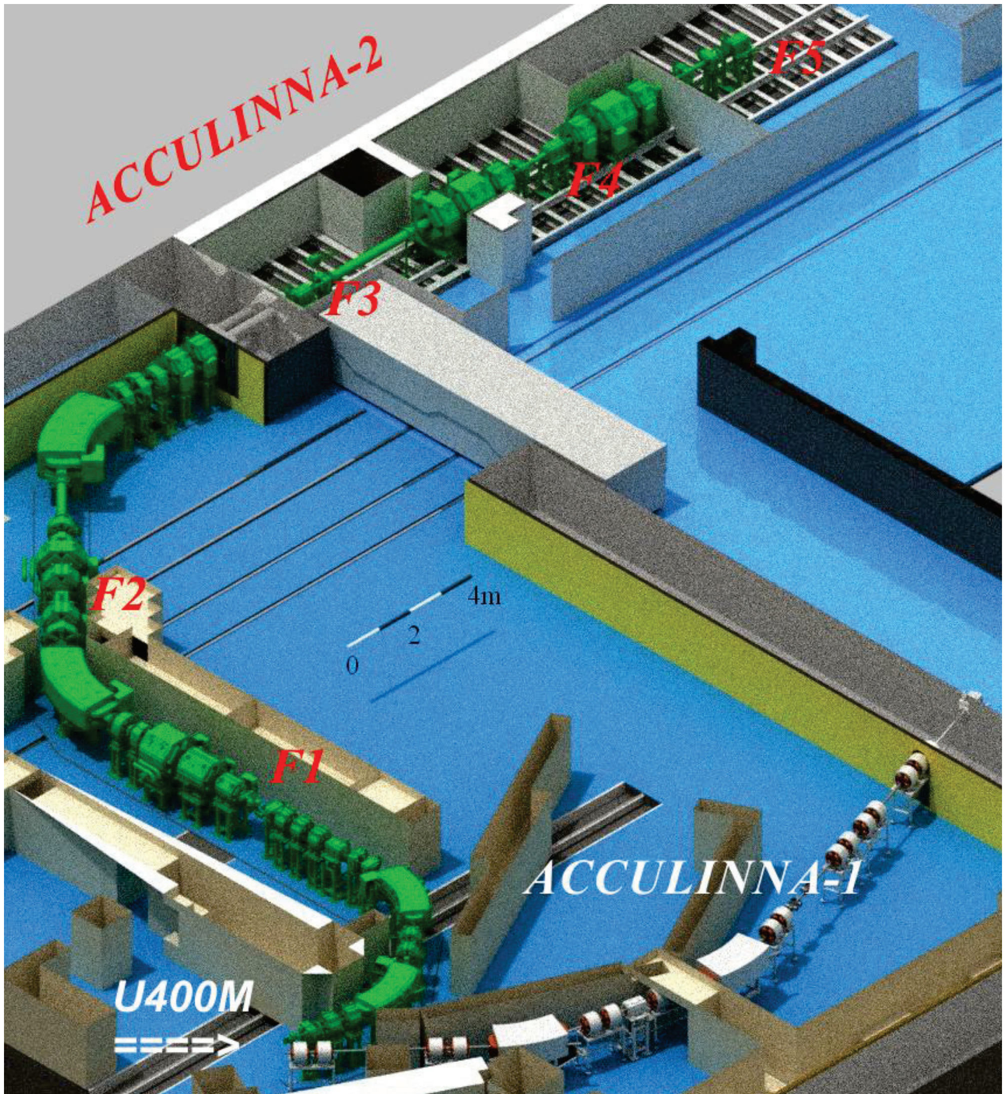
Direction 2.
Low energy ions Beam.
$^{14}N^{+2} \rightarrow {}^{14}N^{+7}$

Thickness of stripping foil
– 20 -200 $\mu g/cm^2$

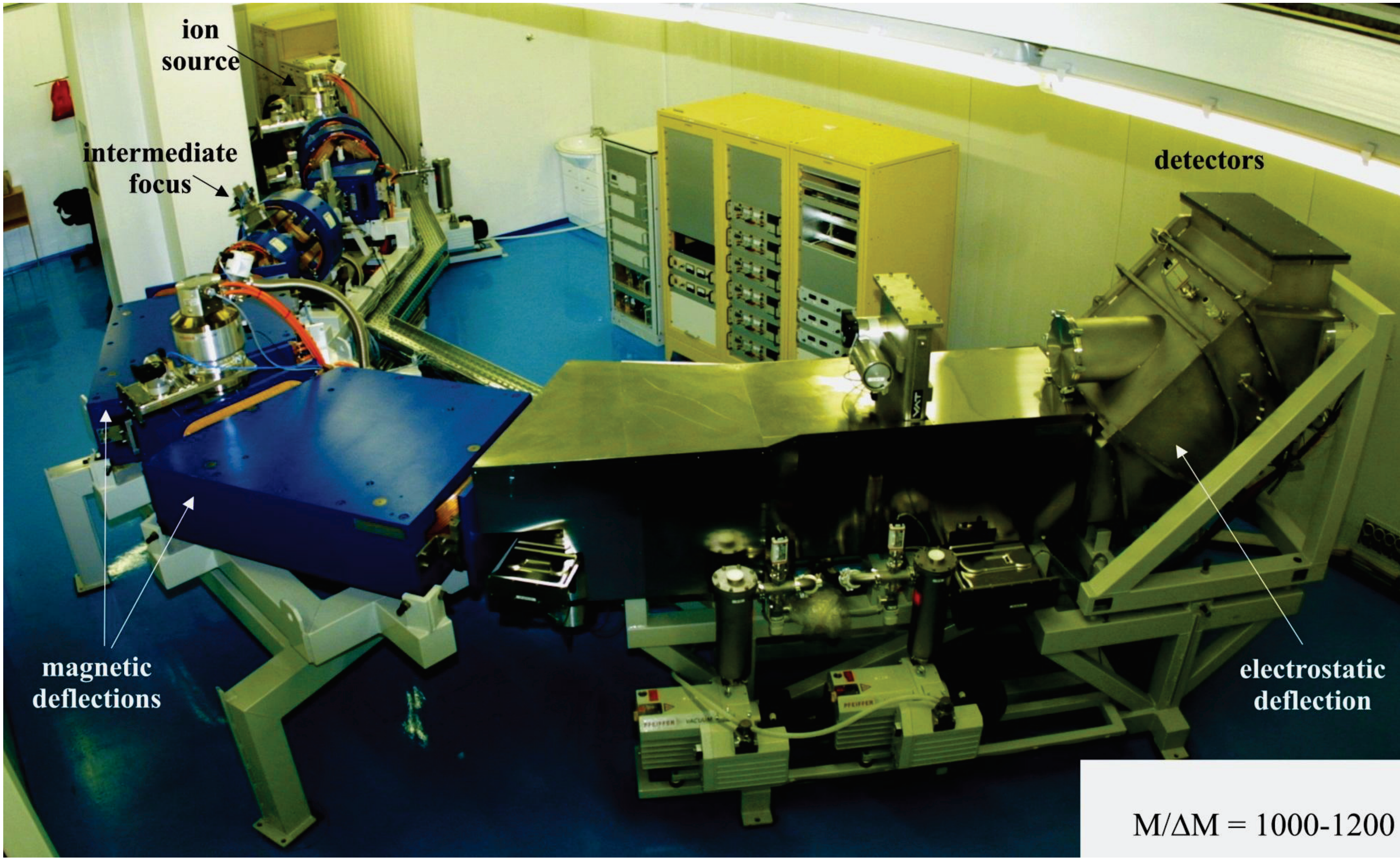
New experimental set-ups at U400M



Scheme of the full ACCULINNA-2 setup (left) and the main part of magnets inside of the cyclotron hall (right). Manufactured by SIGMAPHI, http://www.sigmaphi.fr/



Mass-spectrometer MASHA



The main task of the FLNR Seven-Year Plan for 2017–2023 is the full implementation of the DRIBs-III Project, namely:

1. Commissioning and development of "**SHE Factory" based on the DC-280** cyclotron (design parameters of beams with smoothly variable energy; attaining maximum beam intensity (up to 10 pμA) for nuclei with A≤100; development of infrastructure for accommodation and use of experimental set-ups of other research centers);

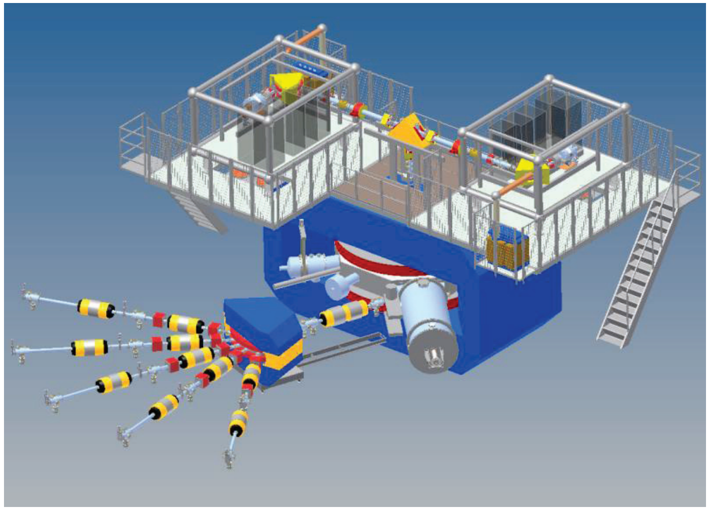
2. **Reconstruction of the U-400** cyclotron and building of a new experimental hall (extension of the range of accelerated ions from helium to uranium with energies smoothly varying within a wide range 0.8–25 MeV·A);

3. **Reconstruction of the U-400M** cyclotron (production of intensive beams of radioactive ions, advancing toward the boundaries of proton and neutron stability of nuclei; conduct of research of nuclear interactions with maximum proton and neutron excess, employing the new powerful ACCULINNA-II separator);

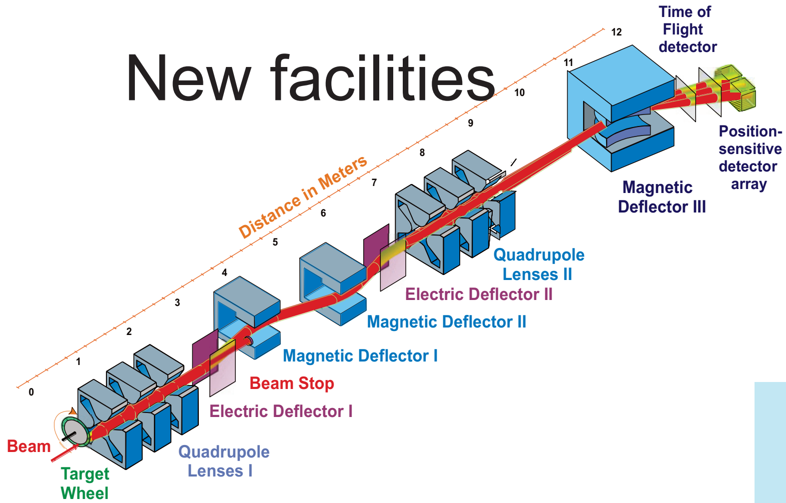
4. Development of long-running experimental set-ups.

SHE factory:

High-current cyclotron DC-280

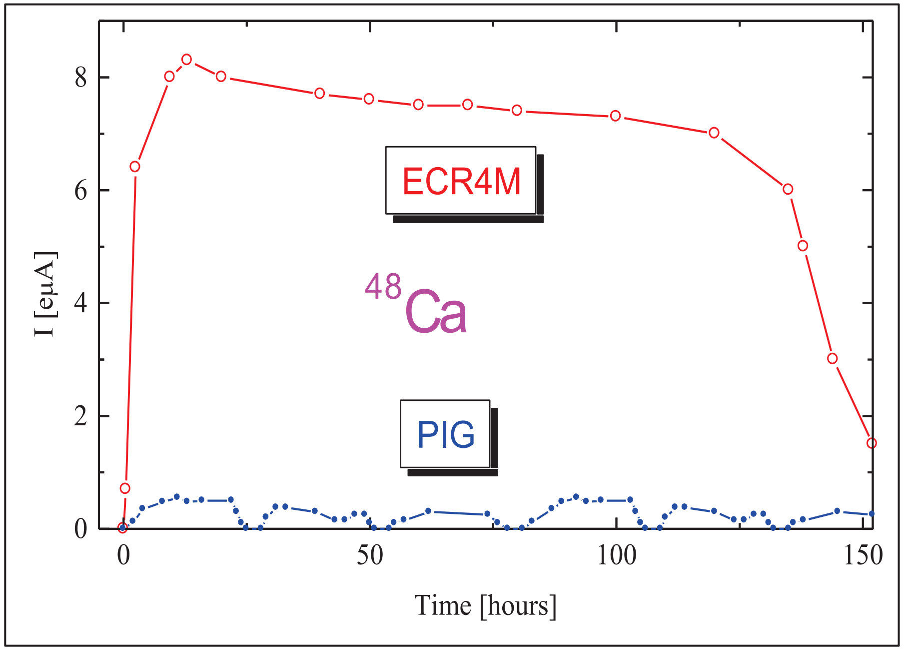


New facilities



New experimental hall

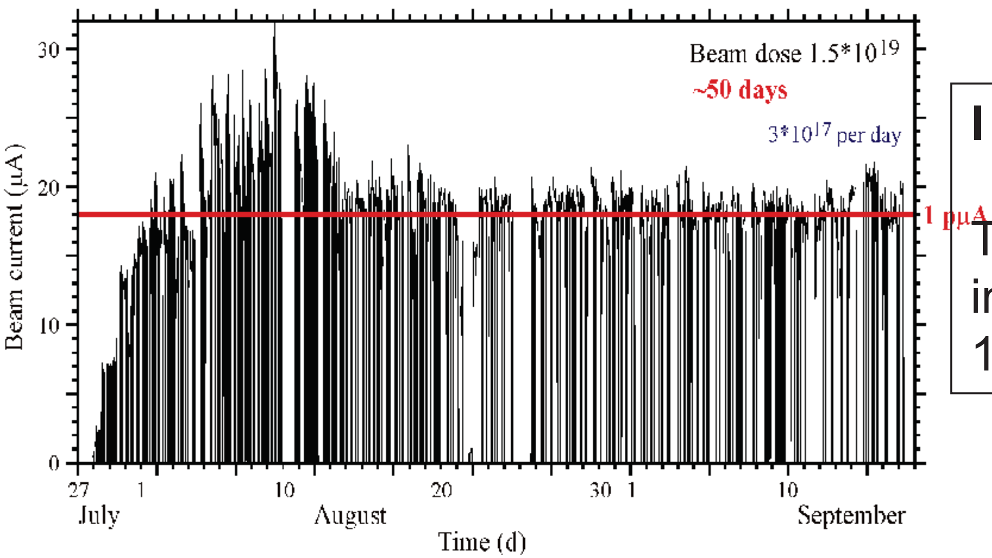
Cyclotron U-400. $^{48}Ca^{5+}$



1996

PIG: I ~ 0.4 μA,
48Ca consumption: 4 ÷ 15 mg/h

ECR: I ~ 8 μA,
48Ca consumption 0.4 ÷ 0.5 mg/h



2010

I ~ 18 μA (1pμA)

Transformation of 48Ca working substance into the 48Ca beam on the target is about 1% in the routine operation.

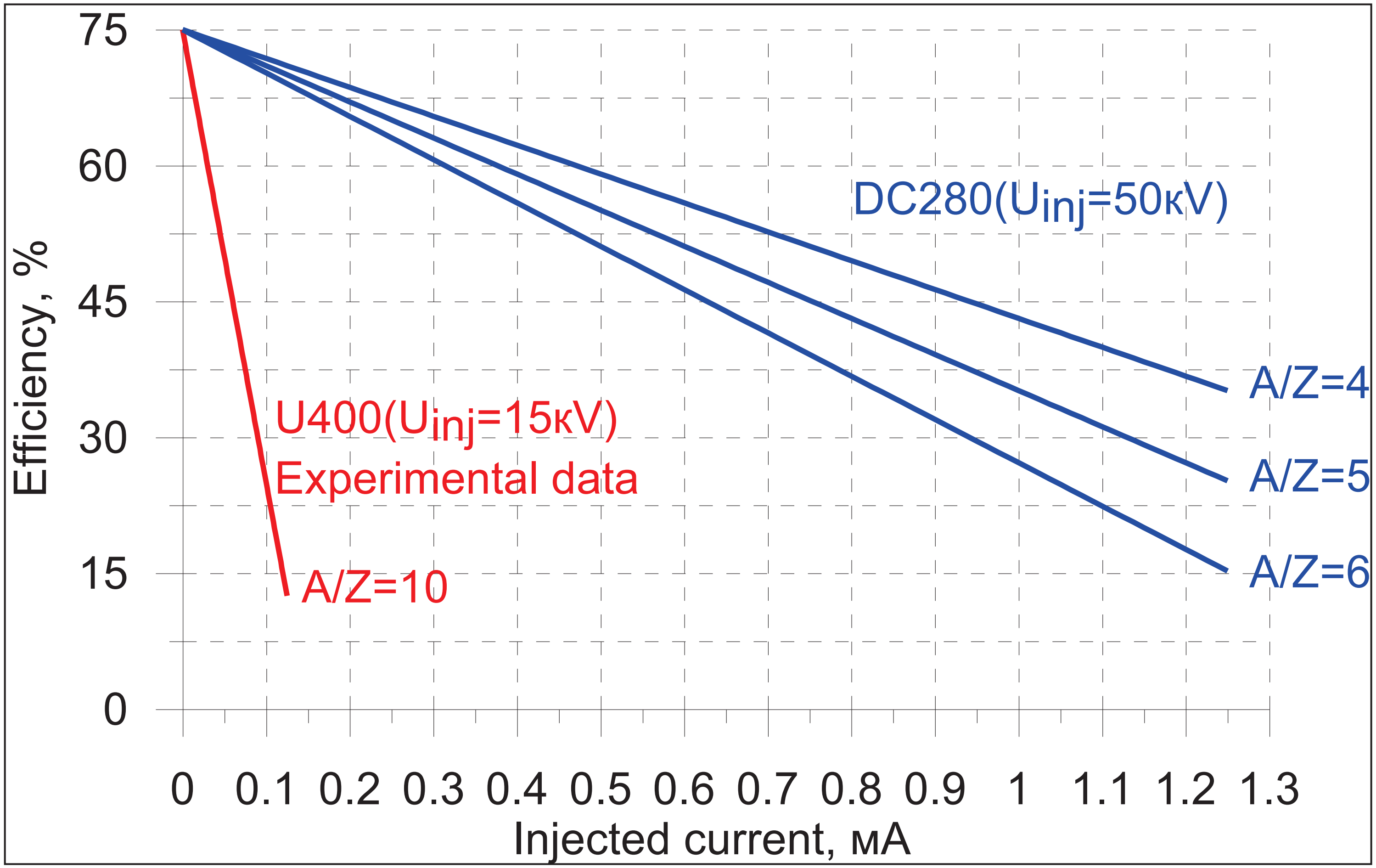
2017

DC-280

Intensity 48Ca 1 pμA → 10 pμA

<u>DC-280</u>

Overall (ion source → extraction radius) beam current transfer efficiency



SHE-factory: High-current cyclotron DC280

Main setups:

GFS (synthesis), GFS (chemistry), SHELS

Main tasks:

- *Synthesis of SHE.*
- *Properties and Spectroscopy of SHE;*
- *Chemistry of SHE;*
- *Searching for new reactions leading to SHE*

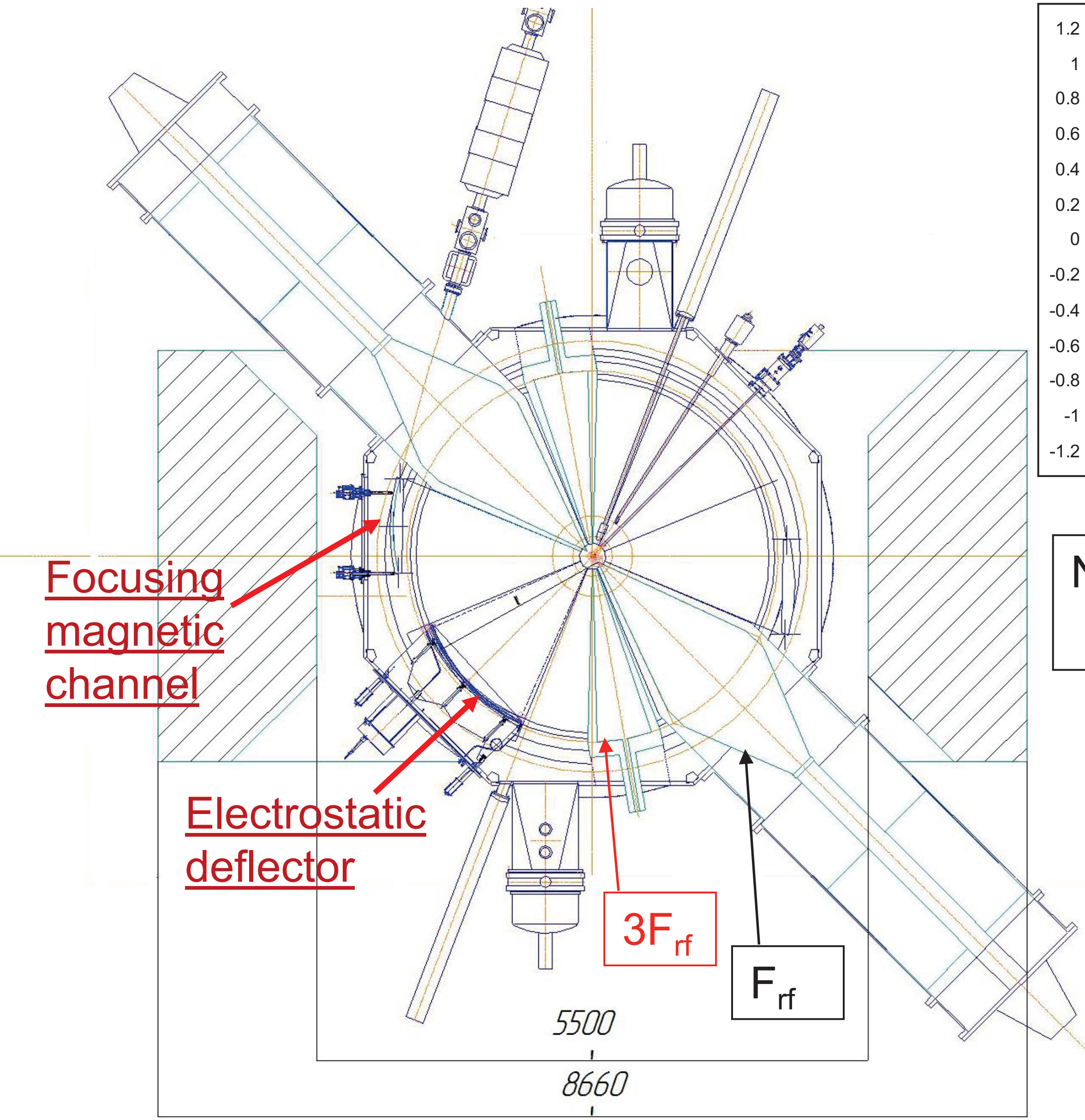
DC280 (expected) E=4÷8 MeV/A		
Ion	Ion energy [MeV/A]	Output intensity
^{7}Li	4	1×10^{14}
^{18}O	8	1×10^{14}
^{40}Ar	5	6×10^{13}
^{48}Ca	5	$0{,}6\text{-}1{,}2\times10^{14}$
^{54}Cr	5	2×10^{13}
^{58}Fe	5	1×10^{13}
^{124}Sn	5	2×10^{12}
^{136}Xe	5	1×10^{14}
^{238}U	7	5×10^{10}

DC-280

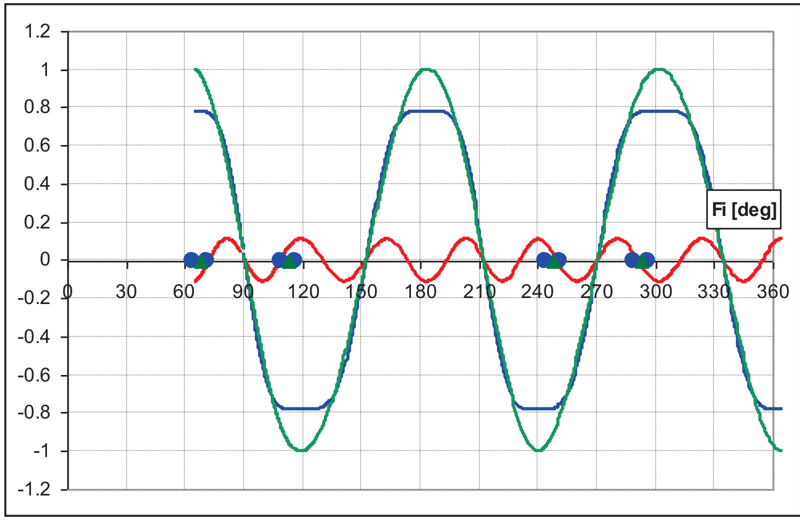
Main Parameters

Ion source	DECRIS-4 - 14 GHz DECRIS-SC3 - 18 GHz
Injecting beam potential	Up to 100 kV
A/Z range	4÷7
Energy	4÷8 MeV/n
Magnetic field level	0.6÷1.35 T
K factor	280
Gap between plugs	400 mm
Valley/hill gap	500/208 mm/mm
Magnet weight	1000 t
Magnet power	300 kW
Dee voltage	2x130 kV
RF power consumption	2x30 kW
Flat-top dee voltage	2x14 kV

Beam extraction system



Flat-Top system



Net effect $A_1 Sin(\omega_{rf}\ t) + A_2 Sin(3\omega_{rf}\ t)$

$A_2 \approx 0.1 \cdot A_1$

The magnet of DC-280 cyclotron

The DC-280 cyclotron magnet has been manufactured at Novokramatorsky machine-building plant (Ukraine) and delivered to Dubna.

The start of the assembling magnet at the FLNR - 2016 August 15.

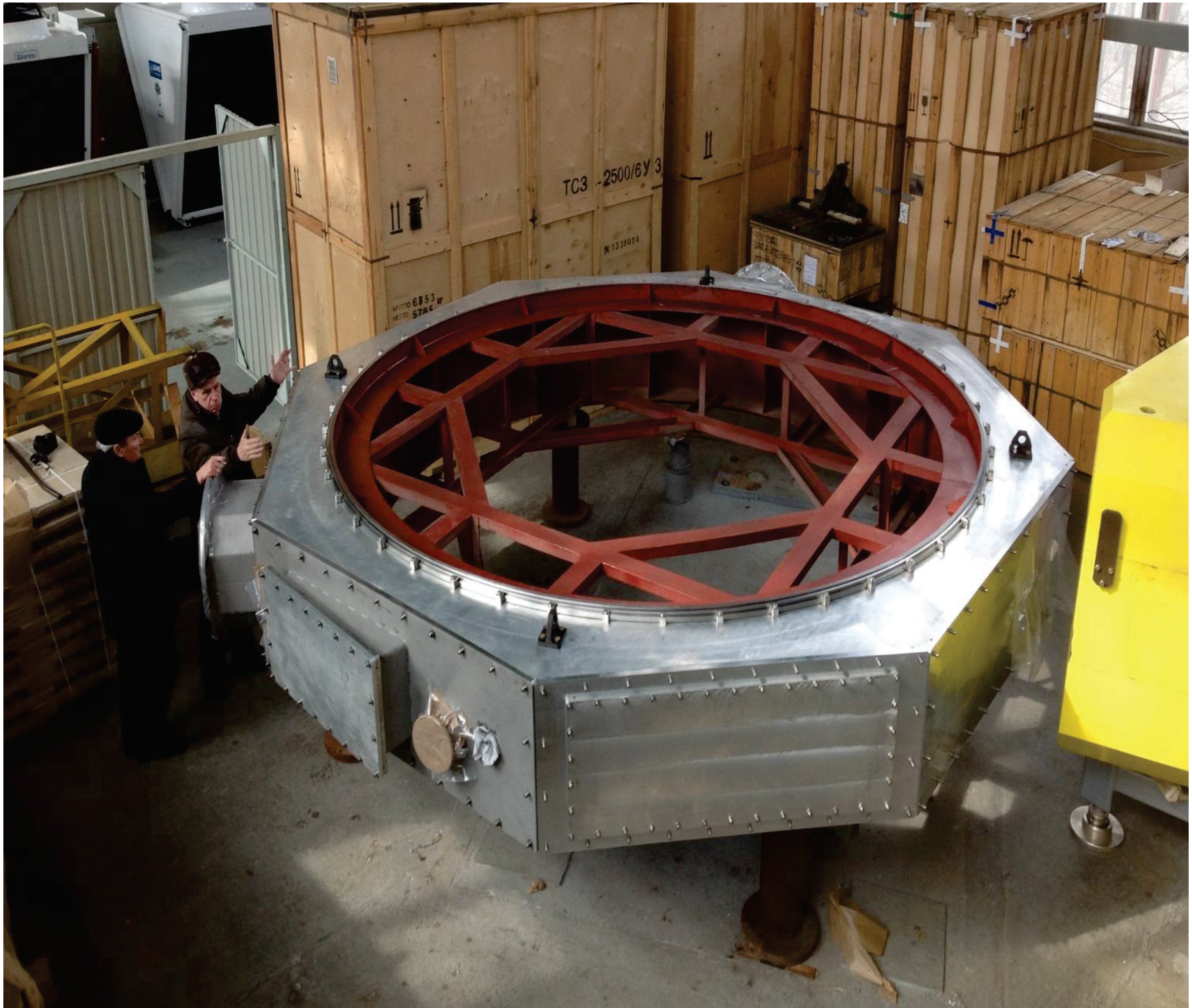
Correction coils
(azimuthal and radial)

3-10 October 2016 -
installation of the correcting coils at the cyclotron magnet in new FLNR accelerator hall

Cooling lines

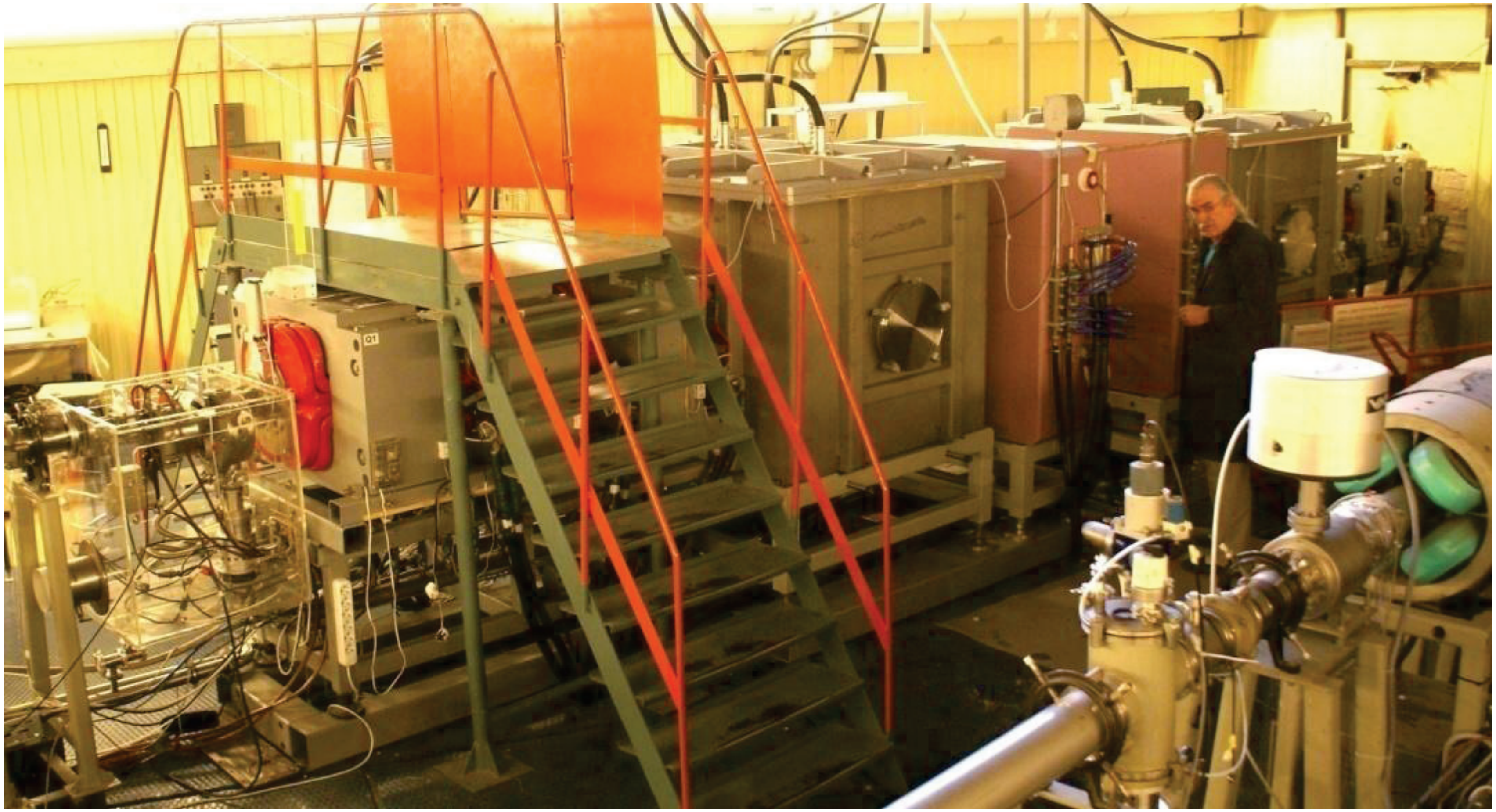



DC-280. Vacuum chamber



DC-280. Water cooling system

New experimental set up - SHELS velocity filter (Separator for Heavy ELement Spectroscopy)



Experimental Hall of the SHE-Factory (August 2016)

Modernization of the U400 cyclotron (Project U-400R)

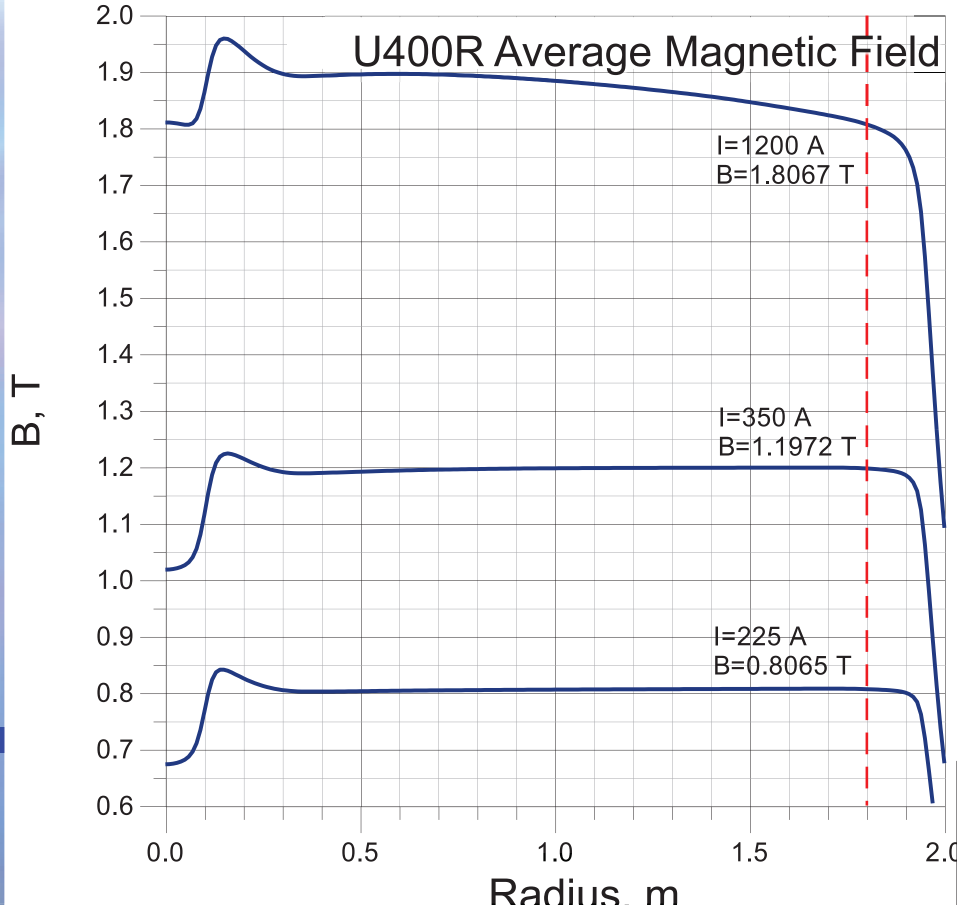
The U-400 cyclotron has been operating since 1978.
The project of the U-400 cyclotron modernization is developed.
The upgrade will be performed after the completion of the DC-280 cyclotron construction

MAIN PURPOSE

- Improvement of the quality and intensity of stable and radioactive beams (^{48}Ca – 2.5÷3 pμA)
- **Providing a smooth variation of ion energy in the range of 0.8 – 27 MeV/A,**
- Decrease the consumption of rare isotopes
- Decrease the power consumption of the magnet from 1 to 0.25 MW

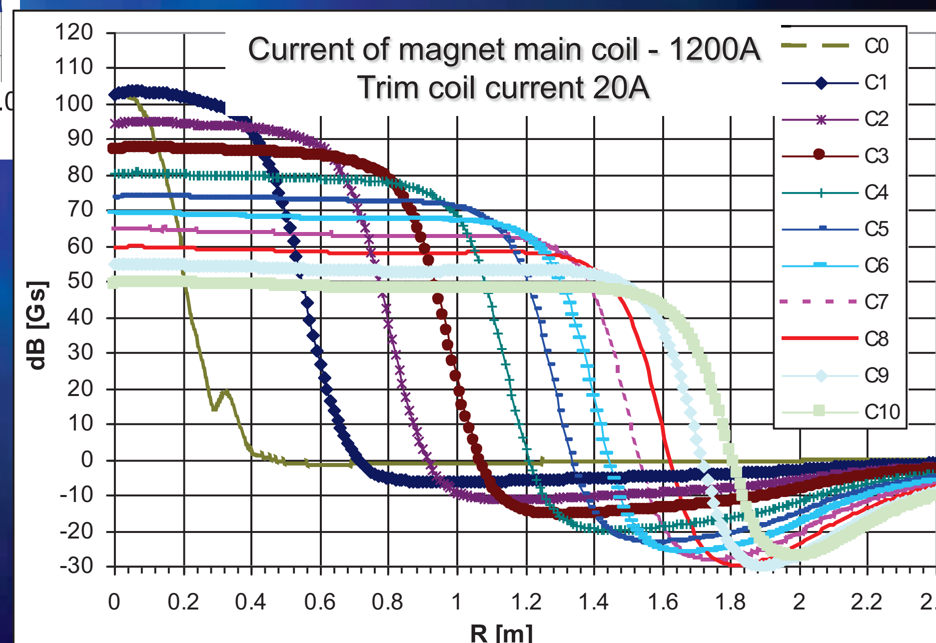
Cyclotron U400
has been operating since 1979

U400 → U400R

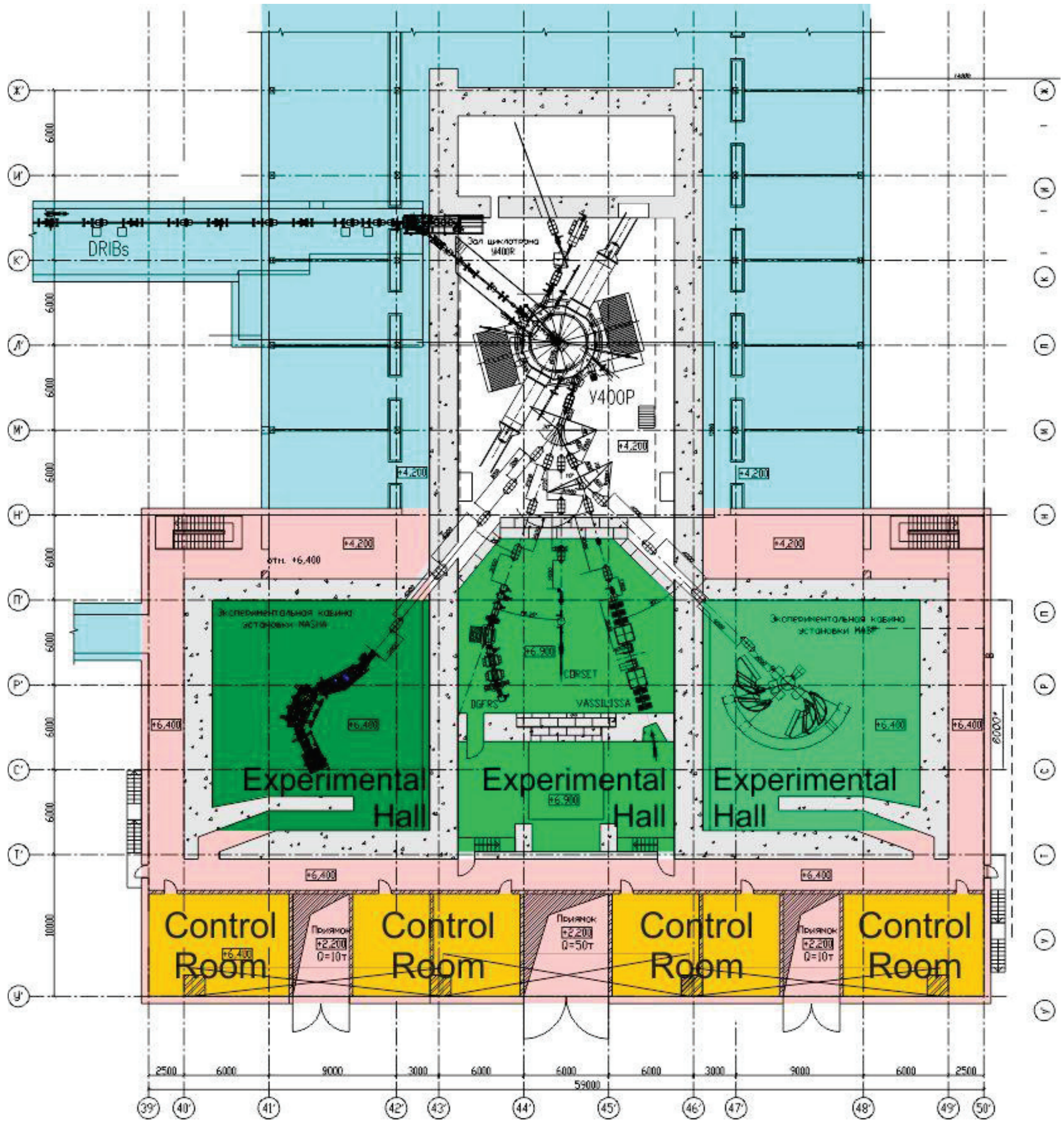


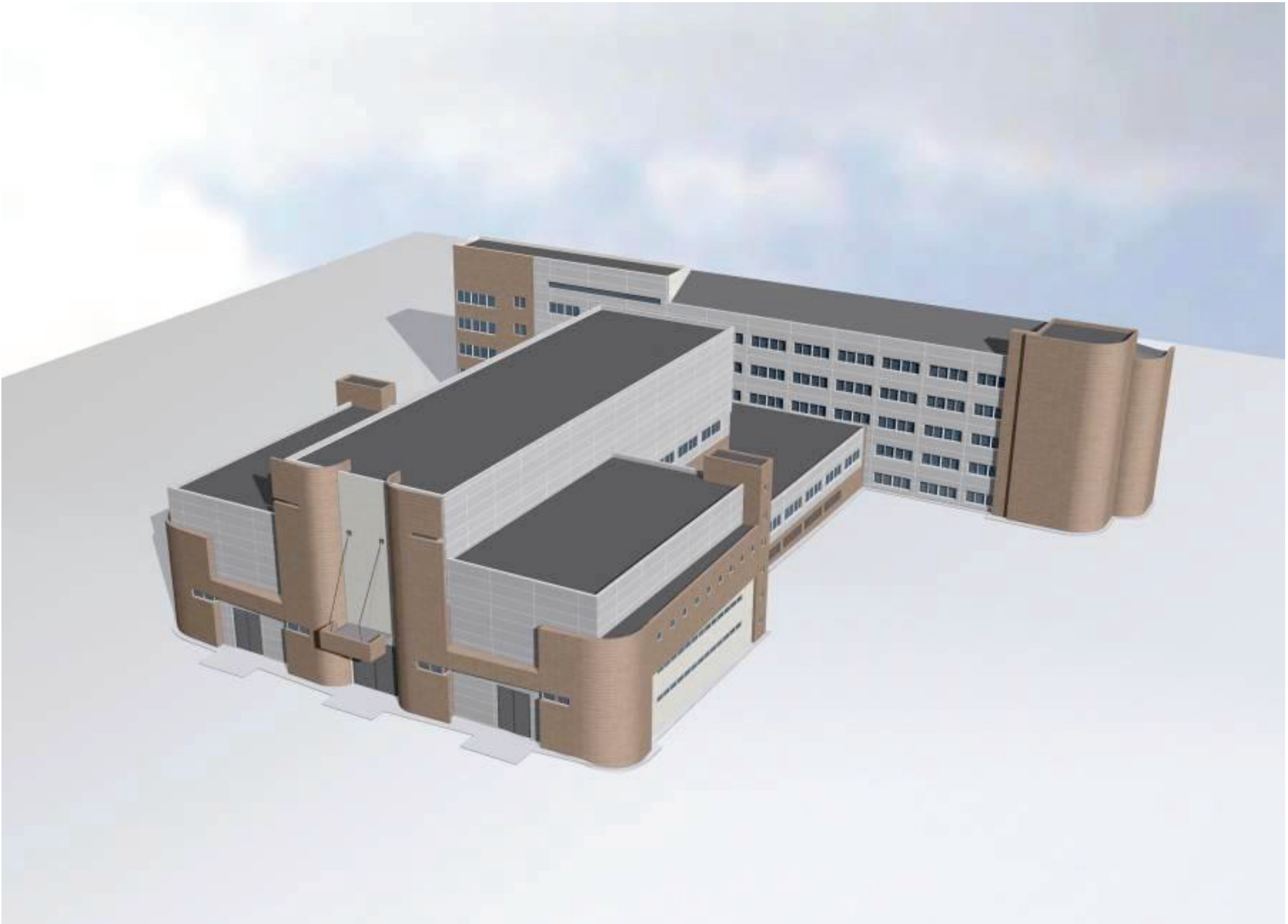
Radial Distribution of Average Magnetic Field without Trim Coil's Shimming

Radial Distribution of Magnetic Field of Trim Coils



U-400R. Median plane level. Second floor.





Parameters of U400 and U400R typical ions

U400		
Ion	Ion energy [MeV/u]	Output intensity
$^{4}He^{1+}$	-	-
$^{6}He^{1+}$	11	$3\cdot10^{7}$ pps
$^{8}He^{1+}$	7.9	-
$^{16}O^{2+}$	5.7; 7.9	5 pμA
$^{18}O^{3+}$	7.8; 10.5; 15.8	4.4 pμA
$^{40}Ar^{4+}$	3.8; 5.1 *	1.7 pμA
$^{48}Ca^{5+}$	3.7; 5.3 *	1.2 pμA
$^{48}Ca^{9+}$	8.9; 11; 17.7 *	1 pμA
$^{50}Ti^{5+}$	3.6; 5.1 *	0.4 pμA
$^{58}Fe^{6+}$	3.8; 5.4 *	0.7 pμA
$^{84}Kr^{8+}$	3.1; 4.4 *	0.3 pμA
$^{136}Xe^{14+}$	3.3; 4.6; 6.9 *	0.08 pμA

U400R (expected)		
Ion	Ion energy [MeV/u]	Output intensity
$^{4}He^{1+}$	6.4 ÷ 27	23 pμA **
$^{6}He^{1+}$	2.8 ÷ 14.4	10^{8} pps
$^{8}He^{1+}$	1.6 ÷ 8	10^{5} pps
$^{16}O^{2+}$	1.6 ÷ 8	19.5 pμA **
$^{16}O^{4+}$	6.4 ÷ 27	5.8 pμA **
$^{40}Ar^{4+}$	1 ÷ 5.1	10 pμA
$^{48}Ca^{6+}$	1.6 ÷ 8	2.5 pμA
$^{48}Ca^{7+}$	2.1 ÷ 11	2.1 pμA
$^{50}Ti^{10+}$	4.1 ÷ 21	1 pμA
$^{58}Fe^{7+}$	1.2 ÷ 7.5	1 pμA
$^{84}Kr^{7+}$	0.8 ÷ 3.5	1.4 pμA
$^{132}Xe^{11+}$	0.8 ÷ 3.5	0.9 pμA

Increasing of accelerated ion energy at the U-400M cyclotron

U-400M cyclotron

At the U-400M cyclotron 3 acceleration modes are provided	Ion	Energy [MeV/u]	Intensity of extracted beam, pps
Acceleration mode of low energy ions			
E=4.5 ÷ 11 MeV/u (mass to charge ratio accelerated ions) A/Z=6-10 Harmonic of acceleration - 4 Extraction by charge exchange method: Z_{acc}/Z_{ext}= 2,0-4,0	$^{12}C^{2+}$	11	3×10^{12}
	$^{48}Ca^{6+}$	6.6	3×10^{12}
	$^{136}Xe^{17+}$	6.3	2×10^{10}
	$^{238}U^{30+}$	5	
Acceleration mode of high energy ions (main mode)			
E=30 ÷ 55 MeV/u (mass to charge ratio accelerated ions) A/Z=2,8-5 Harmonic of acceleration - 2 Extraction by charge exchange method: Z_{acc}/Z_{ext}= 1,4-1,7	$^{7}Li^{2+}$	35	6×10^{13}
	$^{18}O^{5+}$	33	1×10^{13}
	$^{40}Ar^{12+}$	40	1×10^{12}
Acceleration mode of high energy ions (additional)			
E=55 ÷ 100 MeV/u (mass to charge ratio accelerated ions) A/Z=2,0-2,8 Harmonic of acceleration - 2 **In this mode the accelerator did't operate** **(The existing extraction method by stripping foil does not allow to extract accelerated beam from the cyclotron. It is necessary to use an electrostatic deflector)**	$^{11}B^{5+}$	86	
	$^{32}S^{14+}$	80	
	$^{22}Ne^{9+}$	70	
	$^{48}Ca^{18+}$	59	

2016÷2024 years FLNR accelerators running, creation and modernization schedule (2016)

Year / Accelerator	2016	2017	2018	2019	2020	2021	2022	2023	2024
DC280	Assembling	Assembling; Beam tuning	5000	5000	5000	5000	5000	5000	5000
U400M-U400MR	5000	5000	5000	Reconstruction	5000	5000	5000	5000	5000
U400-U400R	5000	5000	5000	5000	2000; Reassembling	Building	Assembling	2000; Beam tuning	5000
Beam time on the targets	10 000	10 000	15 000	10 000	12 000	10 000	10 000	12 000	15 000

Hour - annual beam time on the targets.


THANK YOU
FOR YOUR
ATTENTION !
Flerov Laboratory of Nuclear Reactions , JINR