THE JINR FLNR HEAVY ION CYCLOTRON COMPLEX
– PRESENT STATUS AND FUTURE

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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)

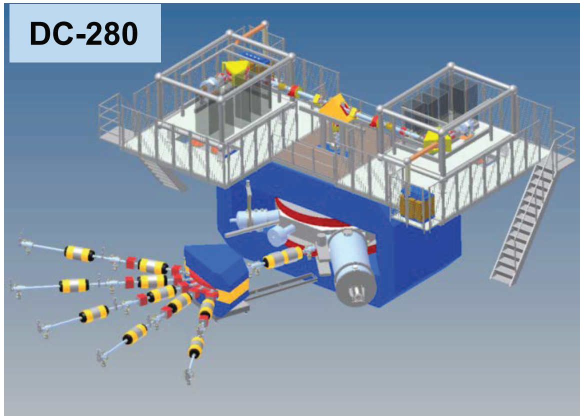
- Light exotic nuclei:

- 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


DC-280


U-400

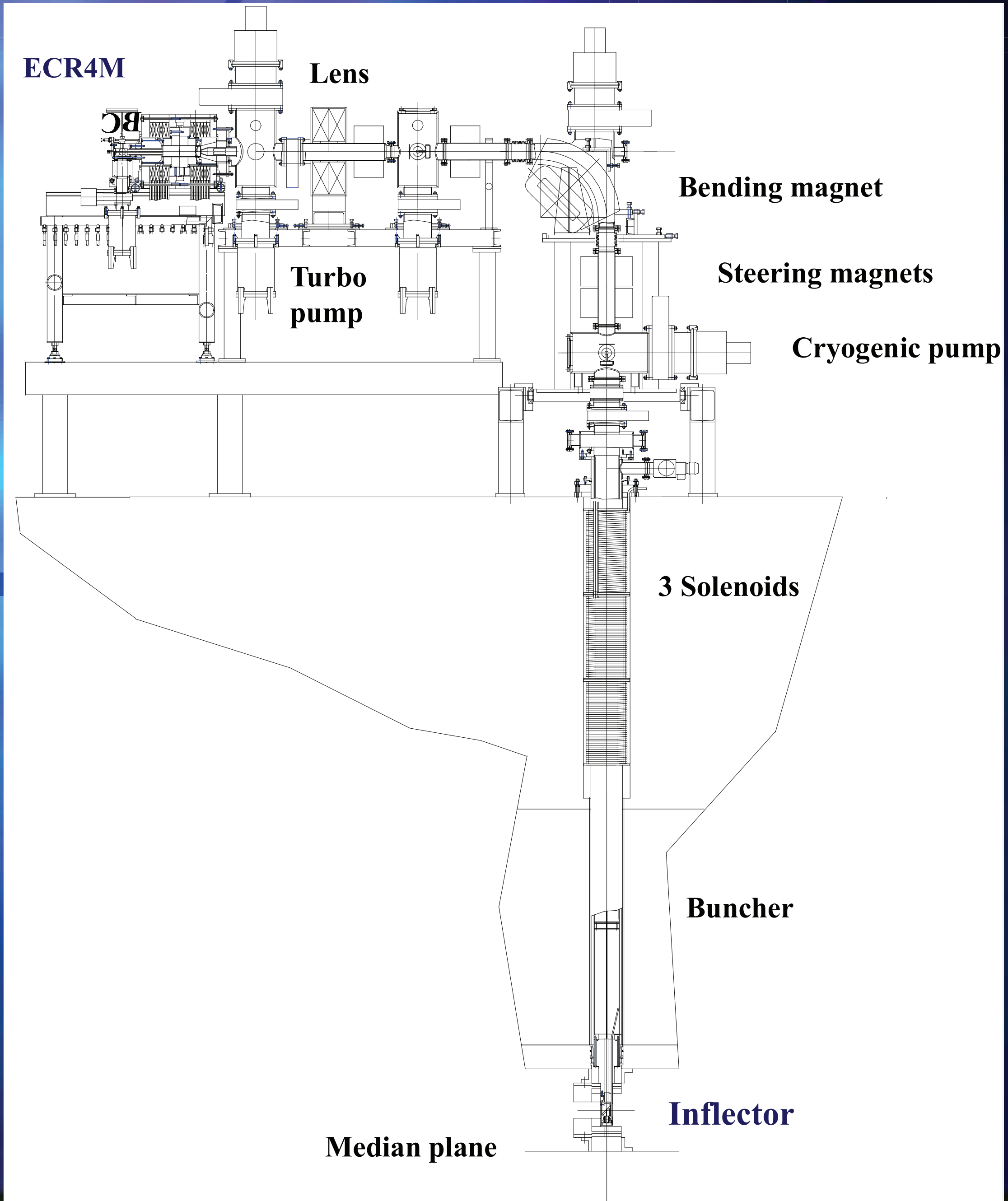

U-400M

U400 Cyclotron (1978)

Axial injection system of U-400 Cyclotron

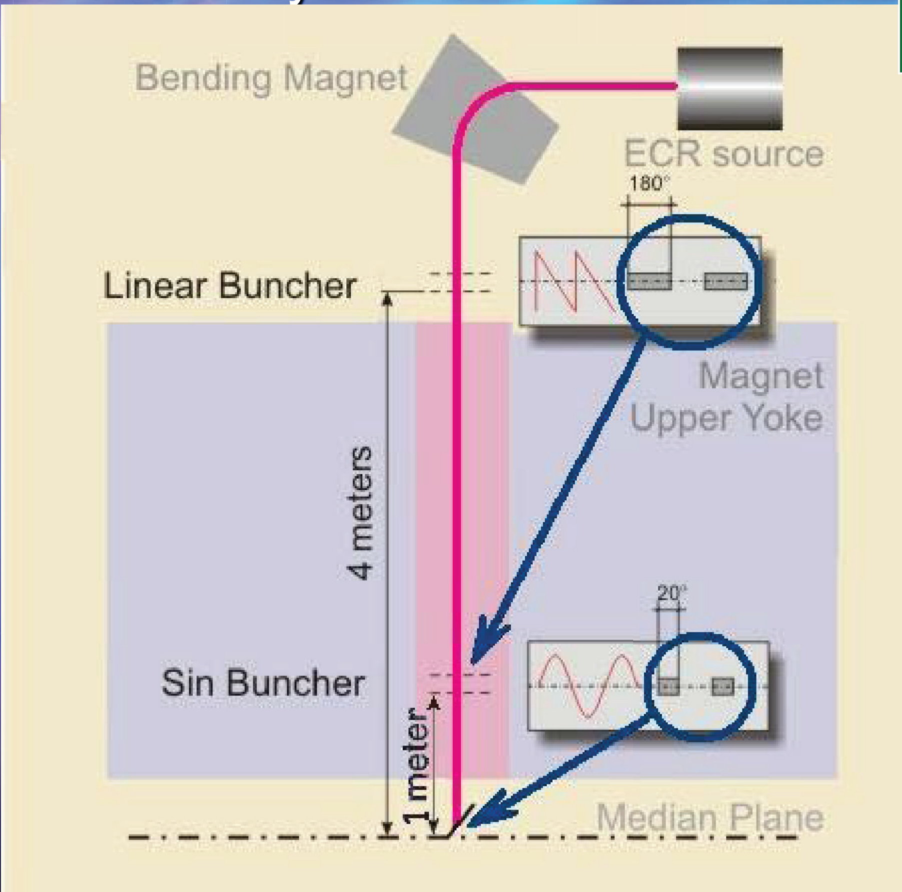
ECR4M
made by GANIL 1995,
upgraded by FLNR 2013

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



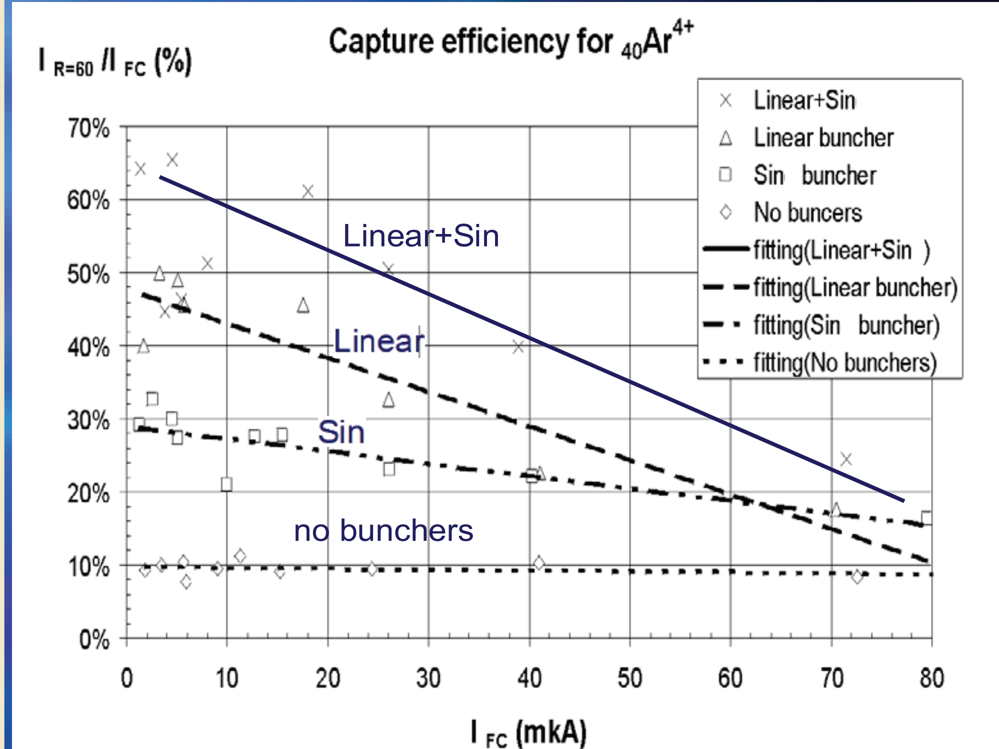
Axial injection system of U-400 Cyclotron

Buncher system of U-400



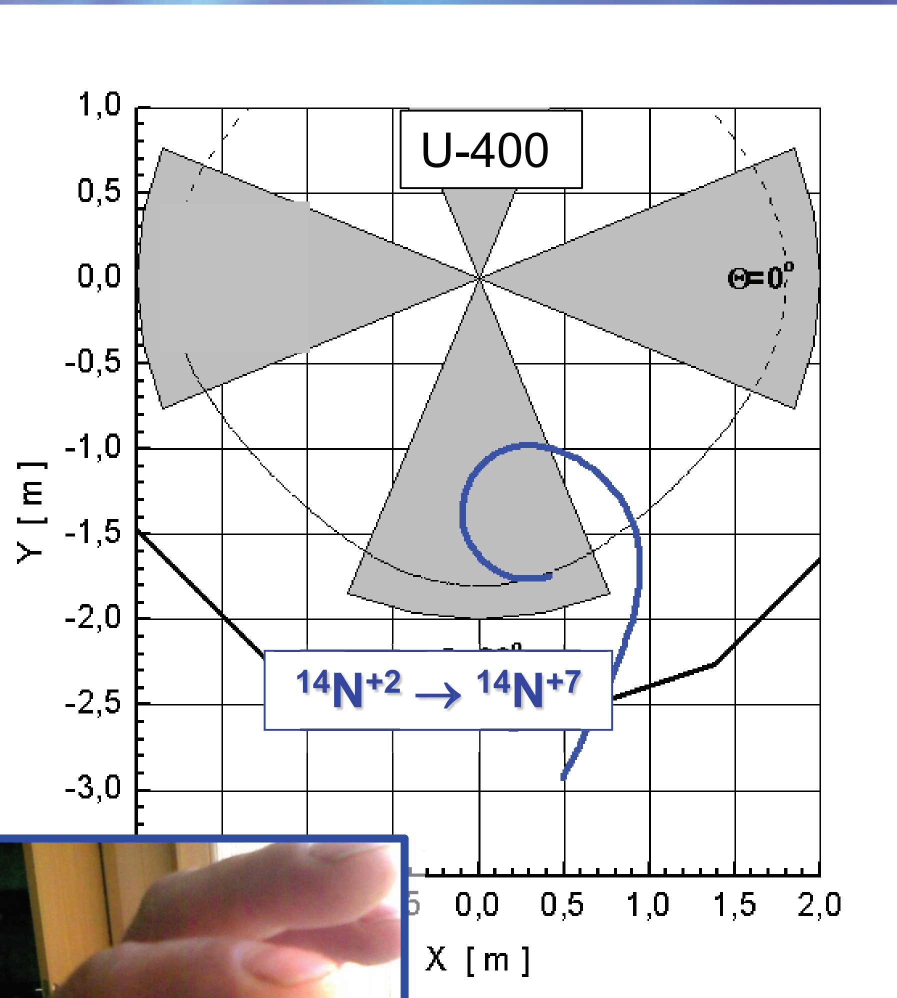
Phase length of bunch, which is captured in the acceleration – 20-40° from 360°.

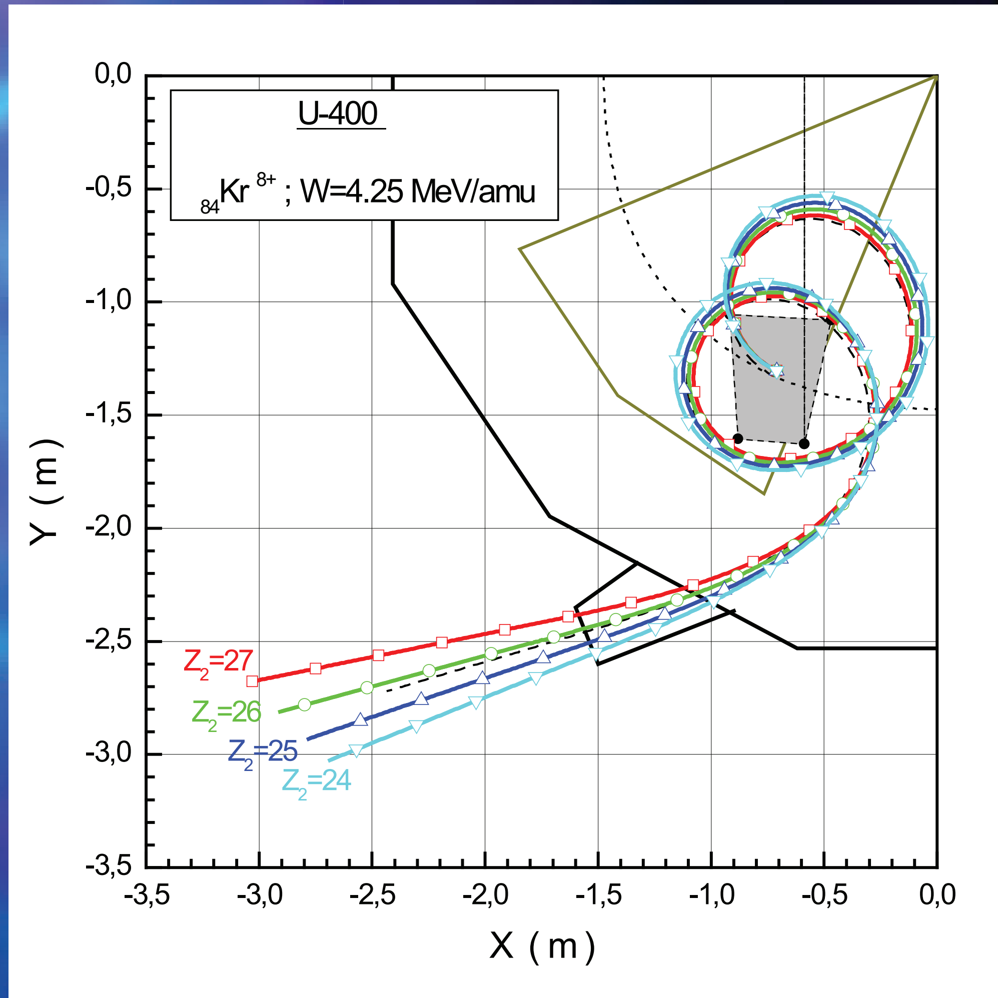
Influence of space charge



Accelerated beam $^{48}Ca^{5+}$ U inj =14,7 kV; I inj = 52 μA	Sin – off Lin – off	Sin – on Lin – off	Sin – off Lin – on	Sin – on Lin – on
The beam intensity on the target	2,3 μA	11 μA	4,9 μA	20 μA
The magnification ratio of the intensity		K = 4,8	K = 2,1	K = 8,7

Heavy Ion Beam Extraction by Stripping Foil

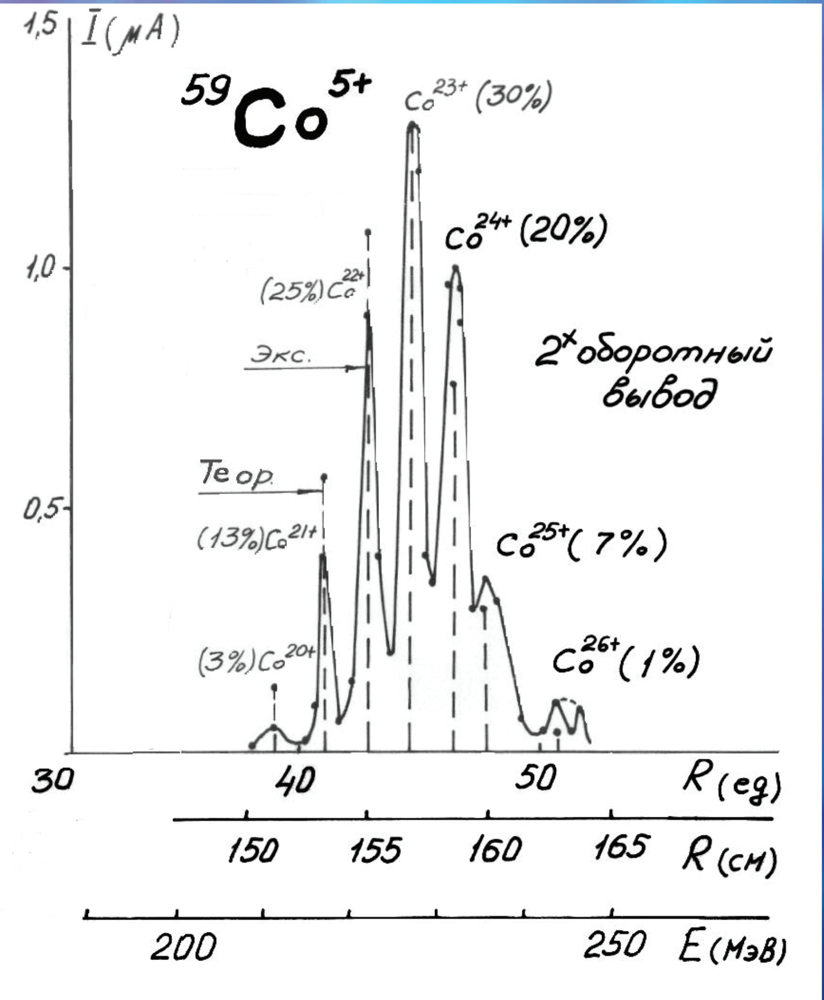


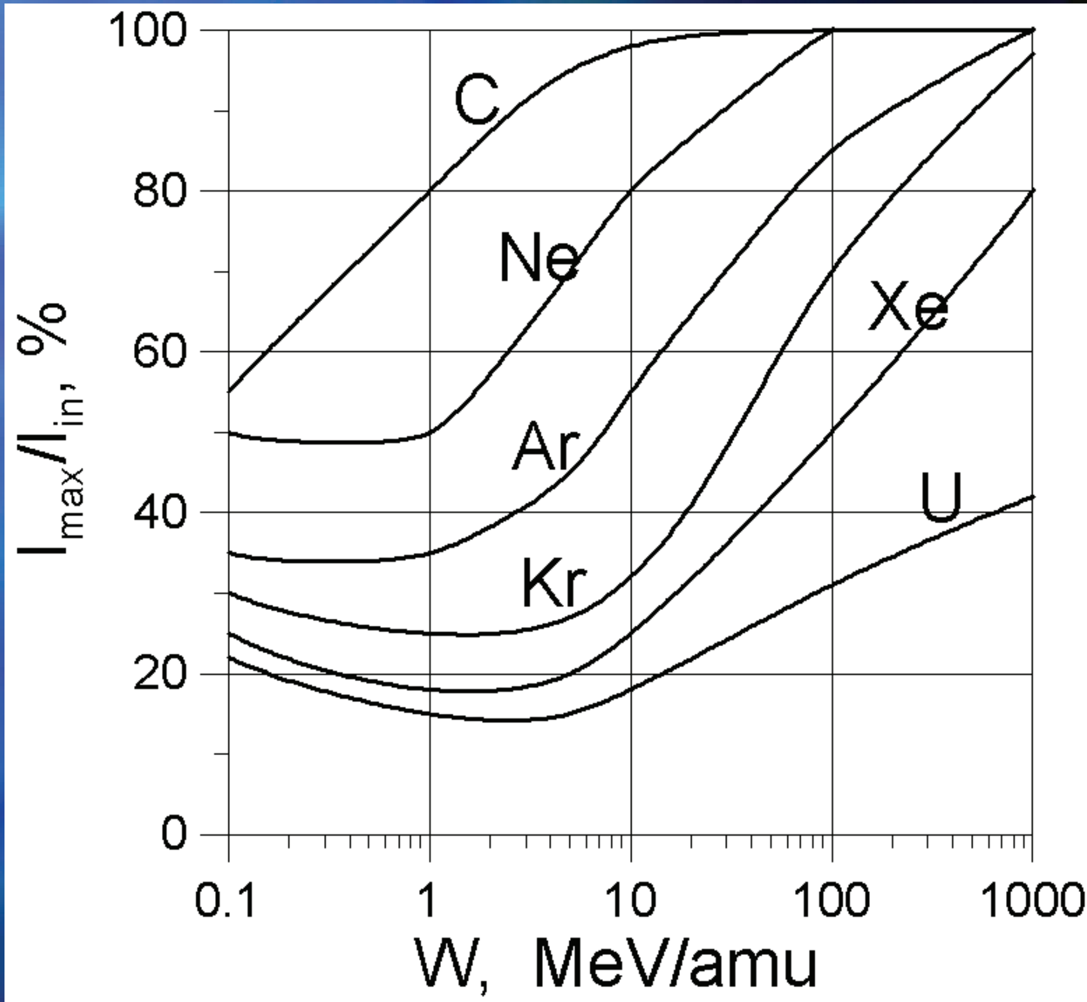


Thickness of stripping foil – 20 -200 μg/cm²

Heavy Ion Beam Extraction by Stripping Foil

Charge spread





Dependence of the maximum efficiency of a single charge extraction by stripping versus the ion energy

U400 CYCLOTRON stand-alone & post-accelerator

Ion	Ion energy [MeV/A]	Output intensity
$^{4}He^{1+}$	-	-
$^{6}He^{1+}$	11	$3 \cdot 10^{7}$ 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
$^{160}Gd^{19+}$	5.5	0.01 pμA
$^{209}Bi^{19+}$	3.4	0.01 pμA

- **New heavy isotopes**
- **Fusion-fission**
- **Nuclear spectroscopy**
- **SHE chemistry**
- **Multi nucleon transfer reactions;**
- **Reactions with exotic nuclei**
- **Structure of light exotic nuclei;**

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>$1\cdot10^{14}$ 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>$3.5\cdot10^{13}$ 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>$2.8\cdot10^{13}$ 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>$9.7\cdot10^{12}$ 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>$8\cdot10^{12}$ 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.

DUBNA Gas Filled Recoil Separator

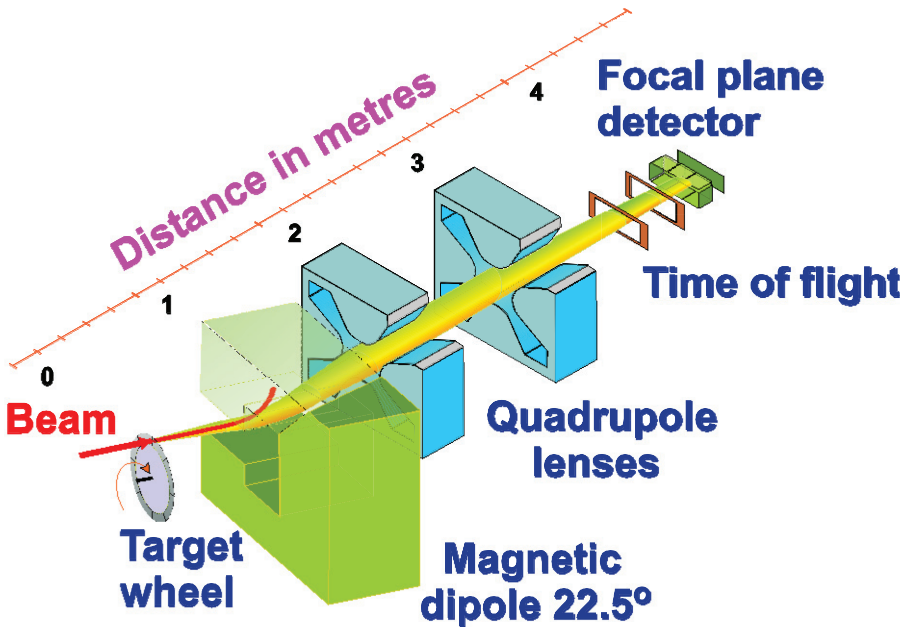
Target		Beam		Isotopes
^{238}U, $^{242,244}Pu$, ^{243}Am, $^{246,248}Cm$, ^{249}Cf	+	^{48}Ca	→	112 – 118

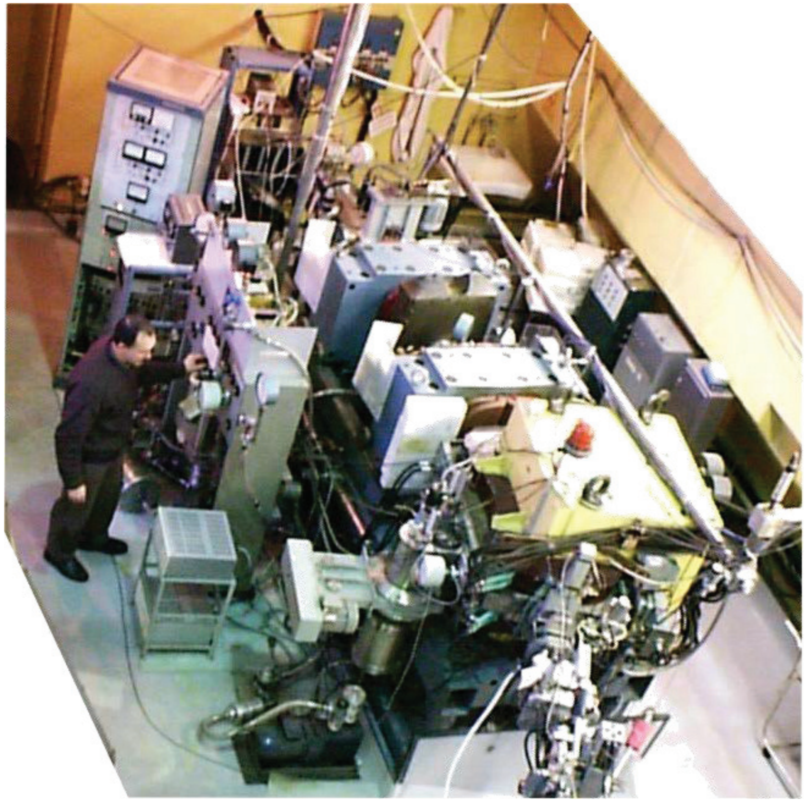
Ion beam energy: 5.00 – 5.75 MeV/A

Beam intensity: 6 - 8·10^{12} pps

Consumption of ^{48} Ca < 0.5 mg/h

Beam time: 2000 – 4000 hours per year





International Union of Pure and Applied Chemistry

May 2011:

Approval of the discovery of new elements *114* and *116*

May 2012:

Official approval of the name *Flerovium* for element *114* and the name *Livermorium* for element *116*

30th December 2015:

Approval of the discovery of new elements *113, 115, 117, and 118*

Priority for the discovery is assigned to:

- element *113*: RIKEN (Japan)
- elements *115* and *117:* JINR (Dubna) - LLNL (USA) – ORNL (USA) collaboration
- element *118:* JINR (Dubna) – LLNL collaboration

8th June 2016:

Provisional recommendations for naming elements *113, 115, 117, 118*

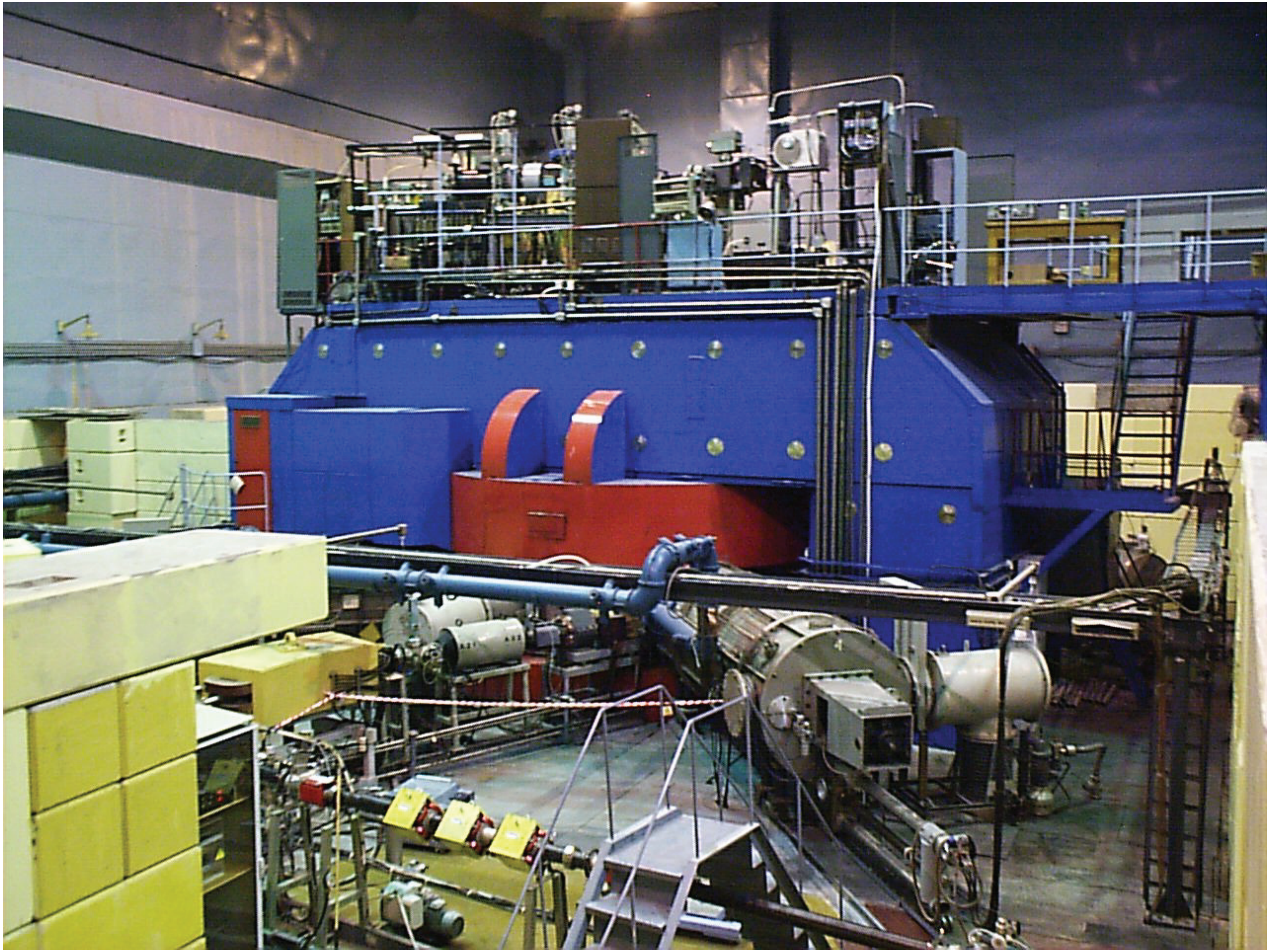
8th November 2016:

A five-month public review expires.

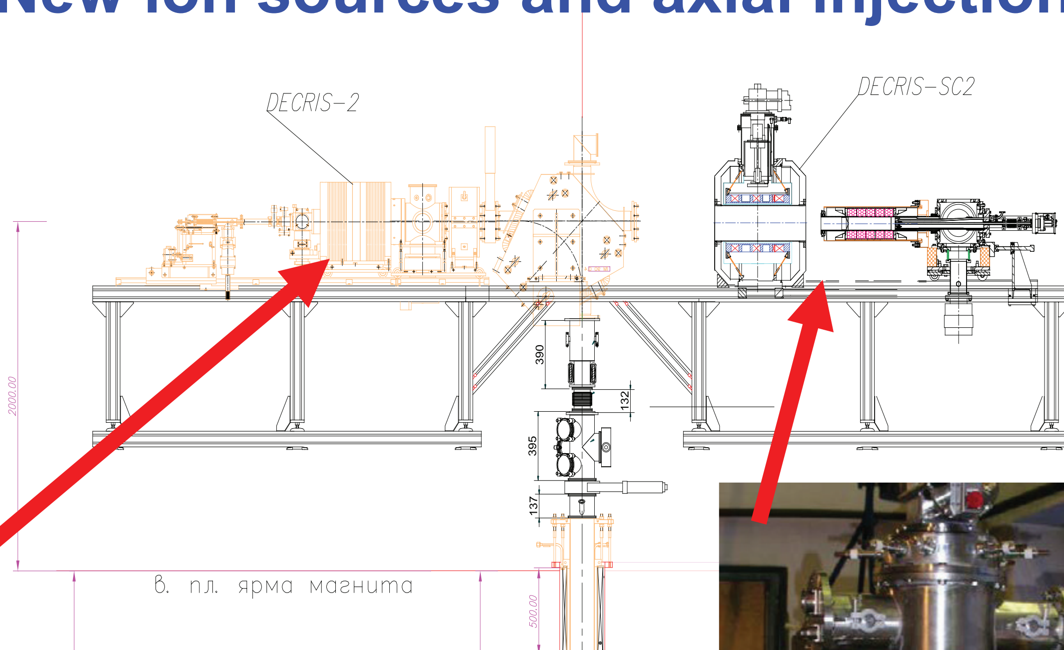
The formal approval by the IUPAC Bureau is expected thereafter

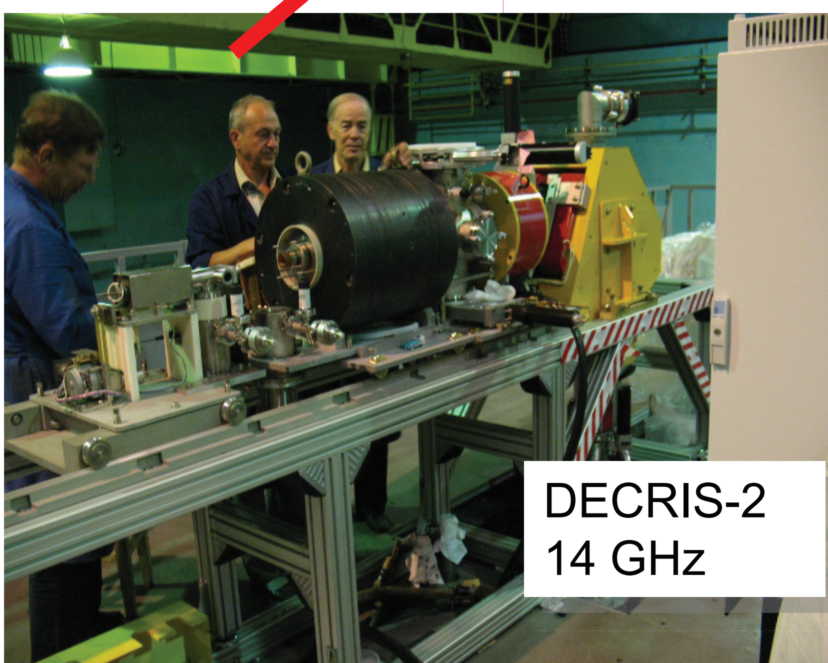
(Нихоний) 113	Флеровий 114	(Московий) 115	Ливерморий 116	(Теннессин) 117	(Оганесон) 118
(Nh)	Fl	(Mc)	Lv	(Ts)	(Og)
(Nihonium)	Flerovium	(Moscovium)	Livermorium	(Tennessine)	(Oganesson)

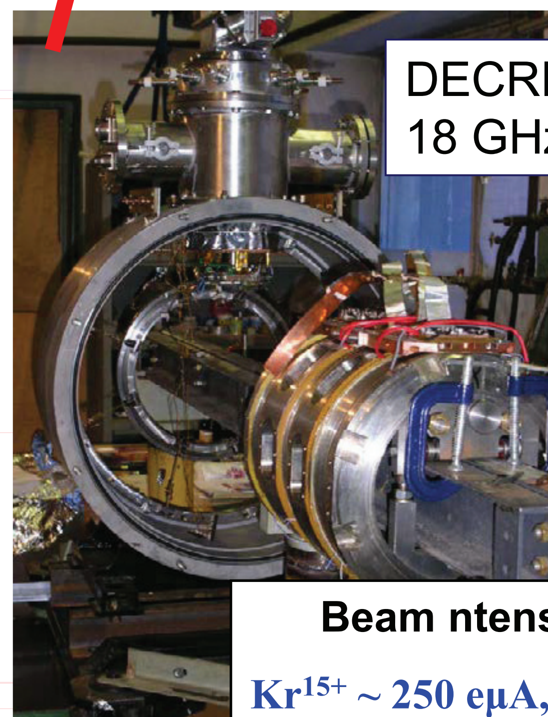
The U-400M heavy ion cyclotron (1991)



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







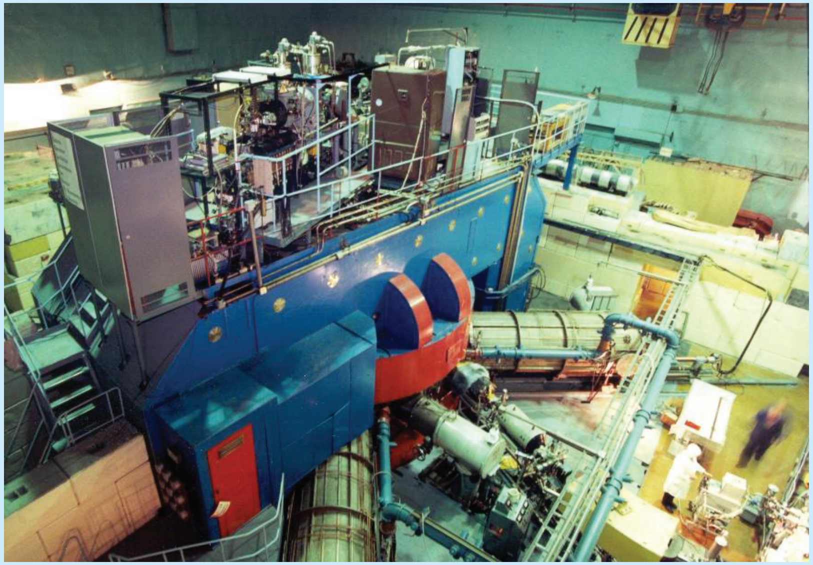
Beam ntensity:

Kr^{15+} ~ 250 eμA,

Kr^{17+} ~ 150 eμA,

Xe^{30+} ~ 1 eμA

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:

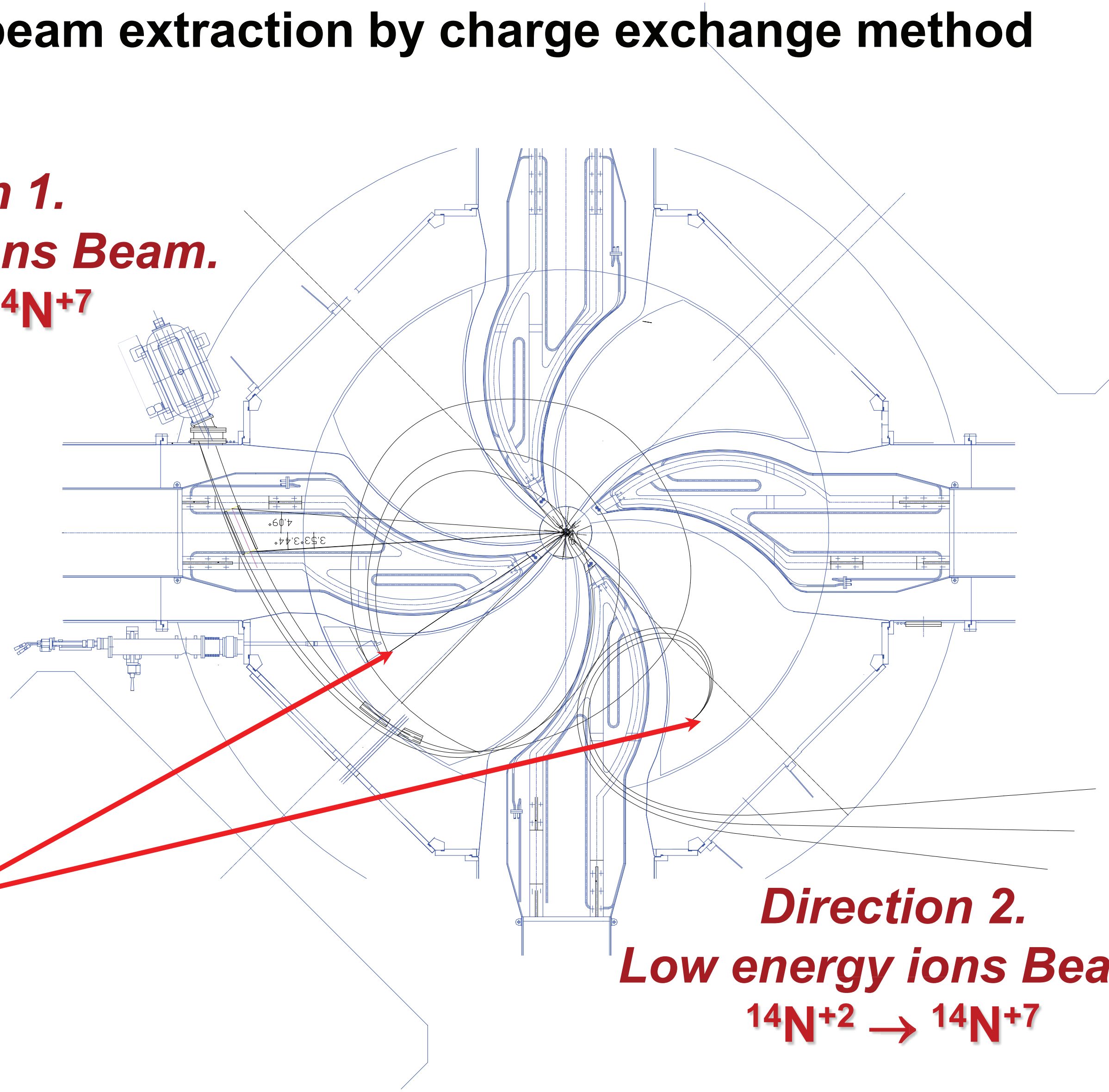
Fragment separator ACCULINNA-2

Main tasks:

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

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

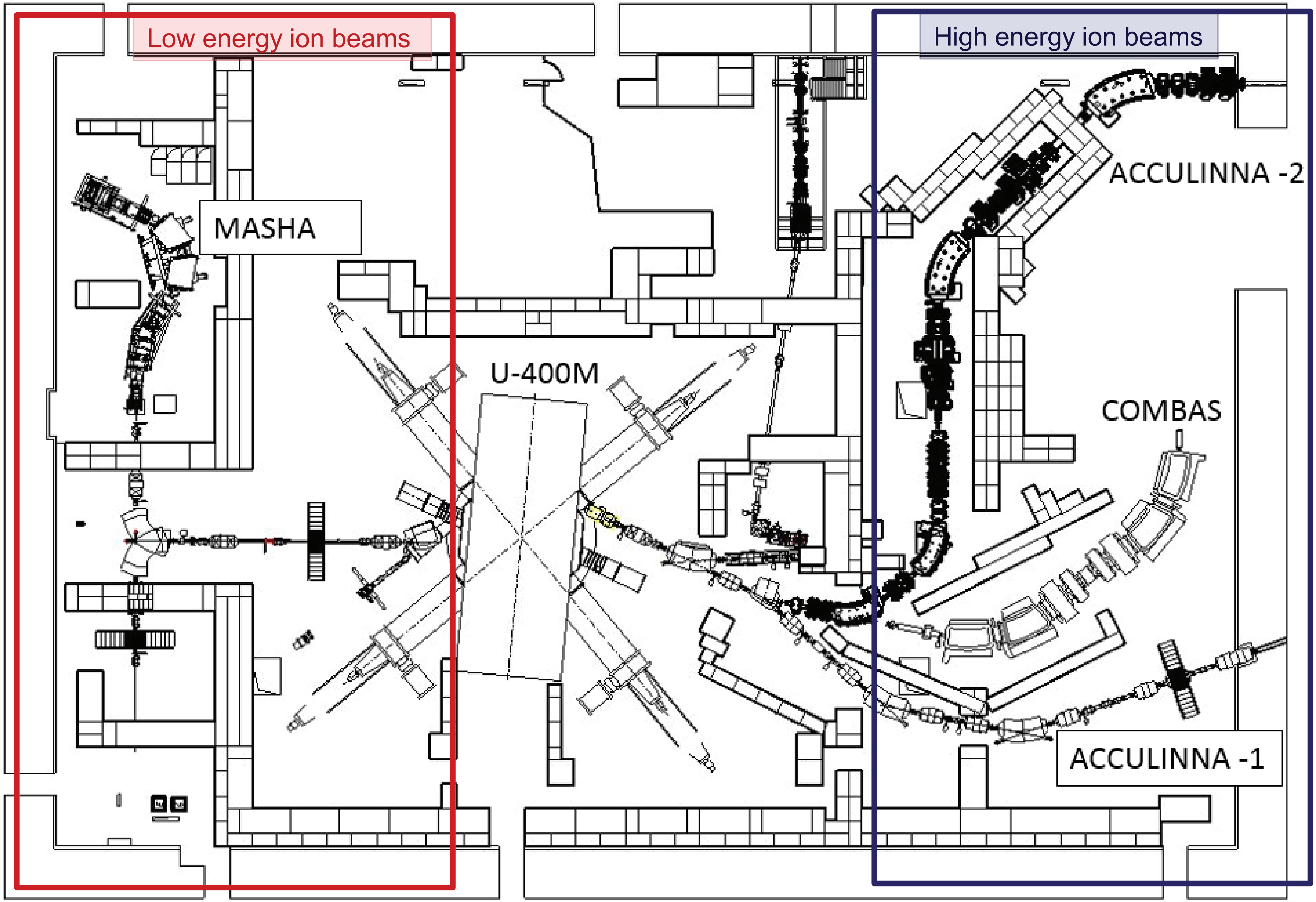
Direction 1.
High energy ions Beam.
$^{14}N^{+5} \rightarrow {}^{14}N^{+7}$



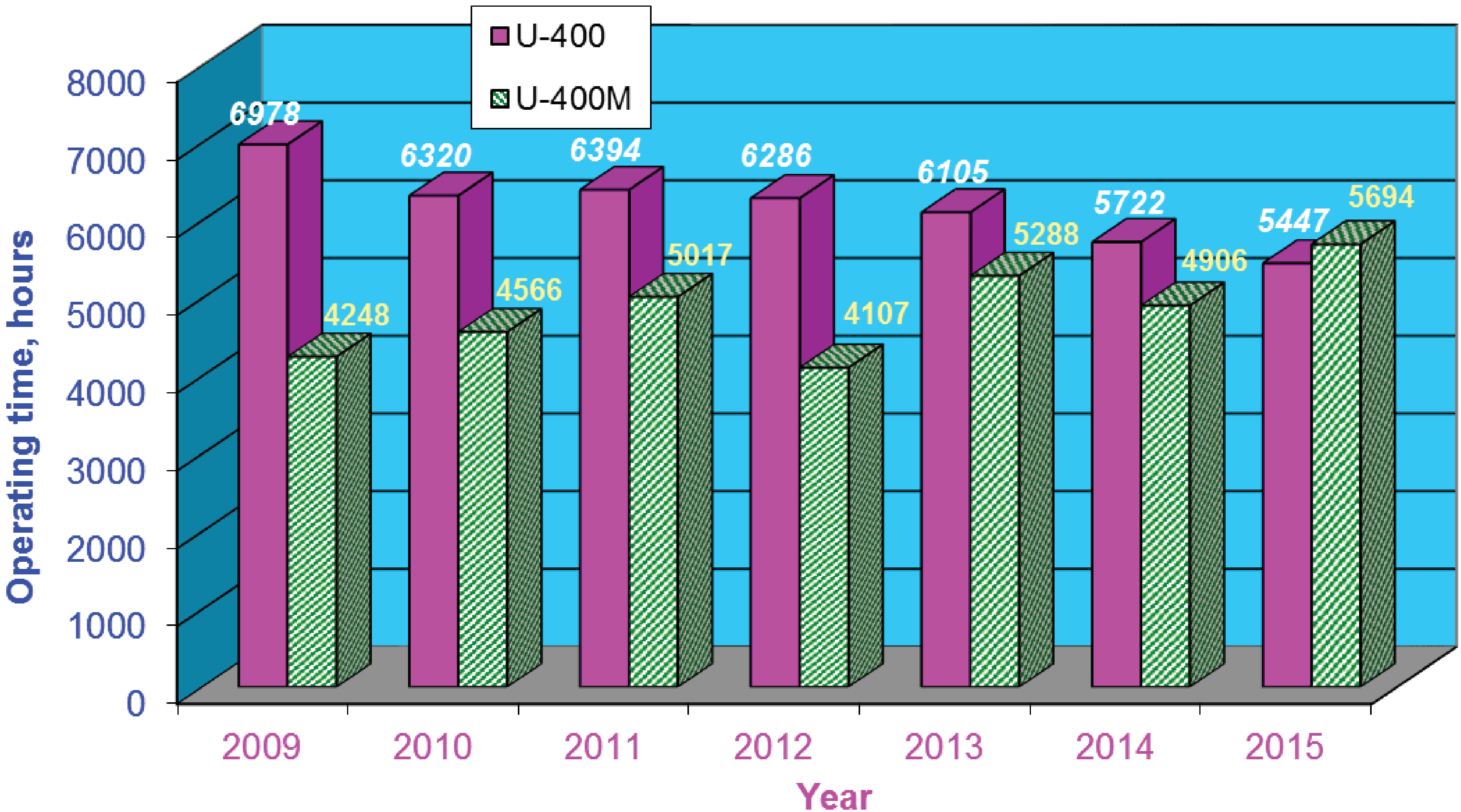
Direction 2.
Low energy ions Beam.
$^{14}N^{+2} \rightarrow {}^{14}N^{+7}$

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

New experimental set-ups at U400M



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



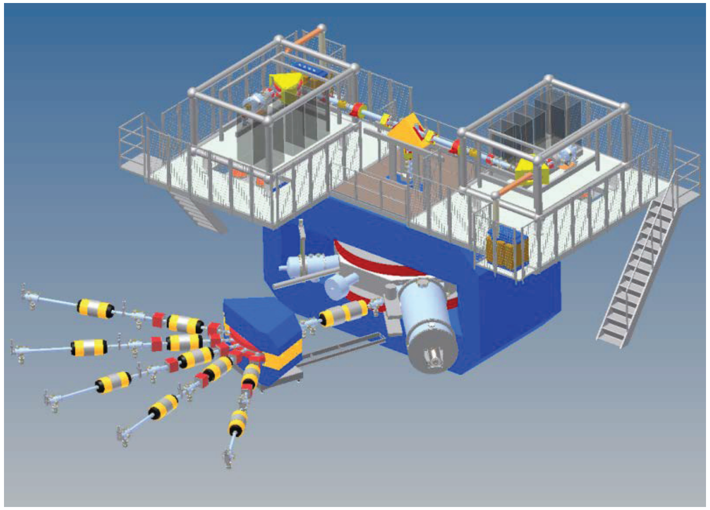
The main task of the FLNR Seven-Year Plan for 2017–2023 is the full implementation of the DRIBs-III Project, namely:

1. Commissioning and development of "**Superheavy Elements (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.

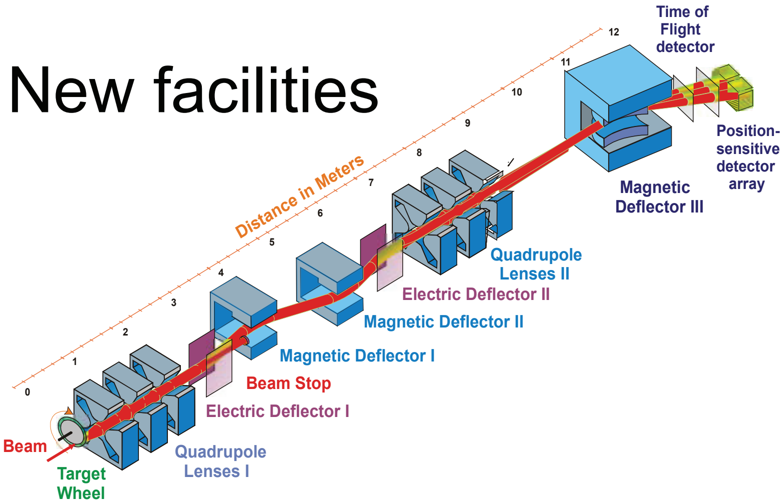
SHE factory:

Superheavy Elements (SHE) Factory

High-current cyclotron DC-280



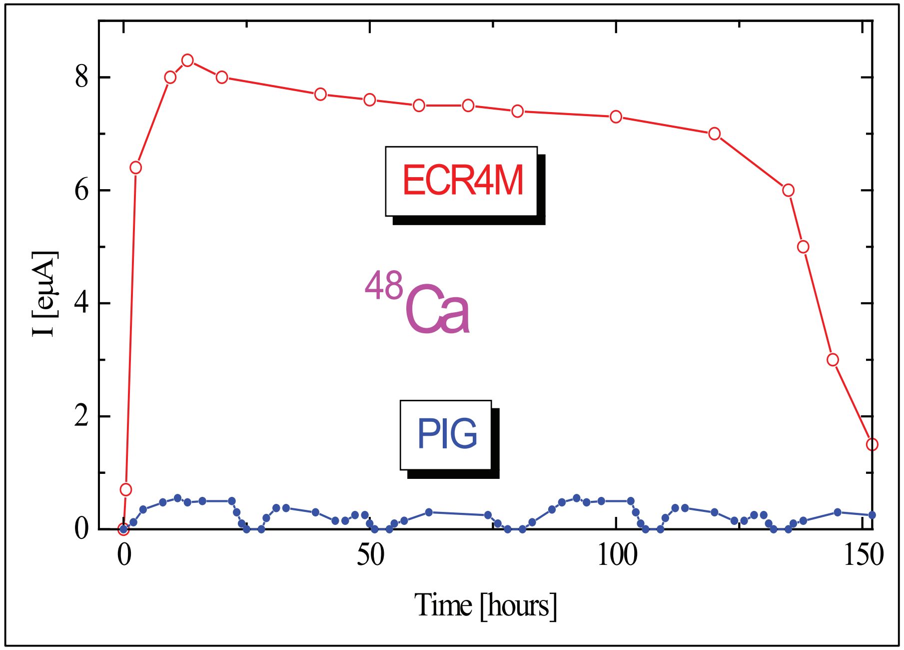
New facilities



New experimental hall

- **Why new cyclotron ?**

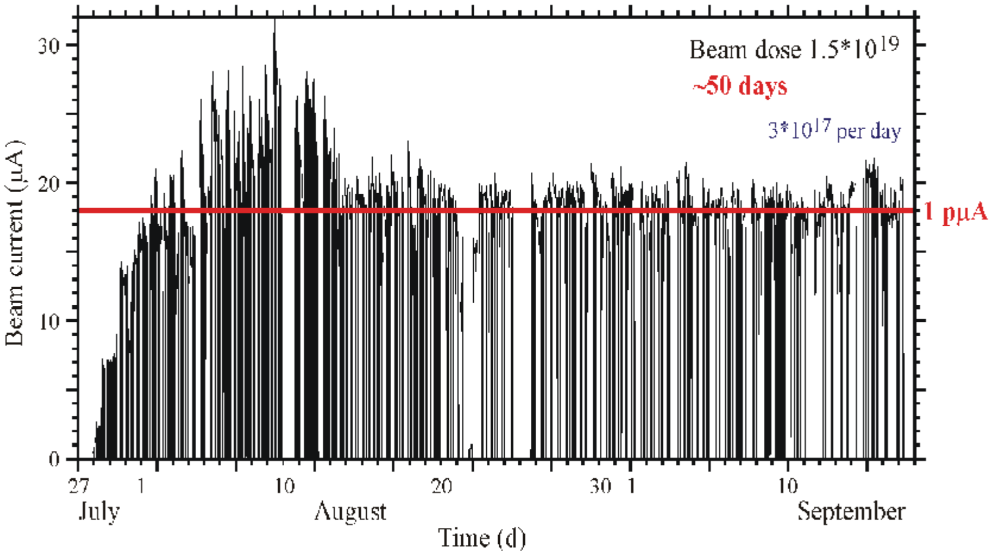
Cyclotron U-400. $^{48}Ca^{5+}$



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.

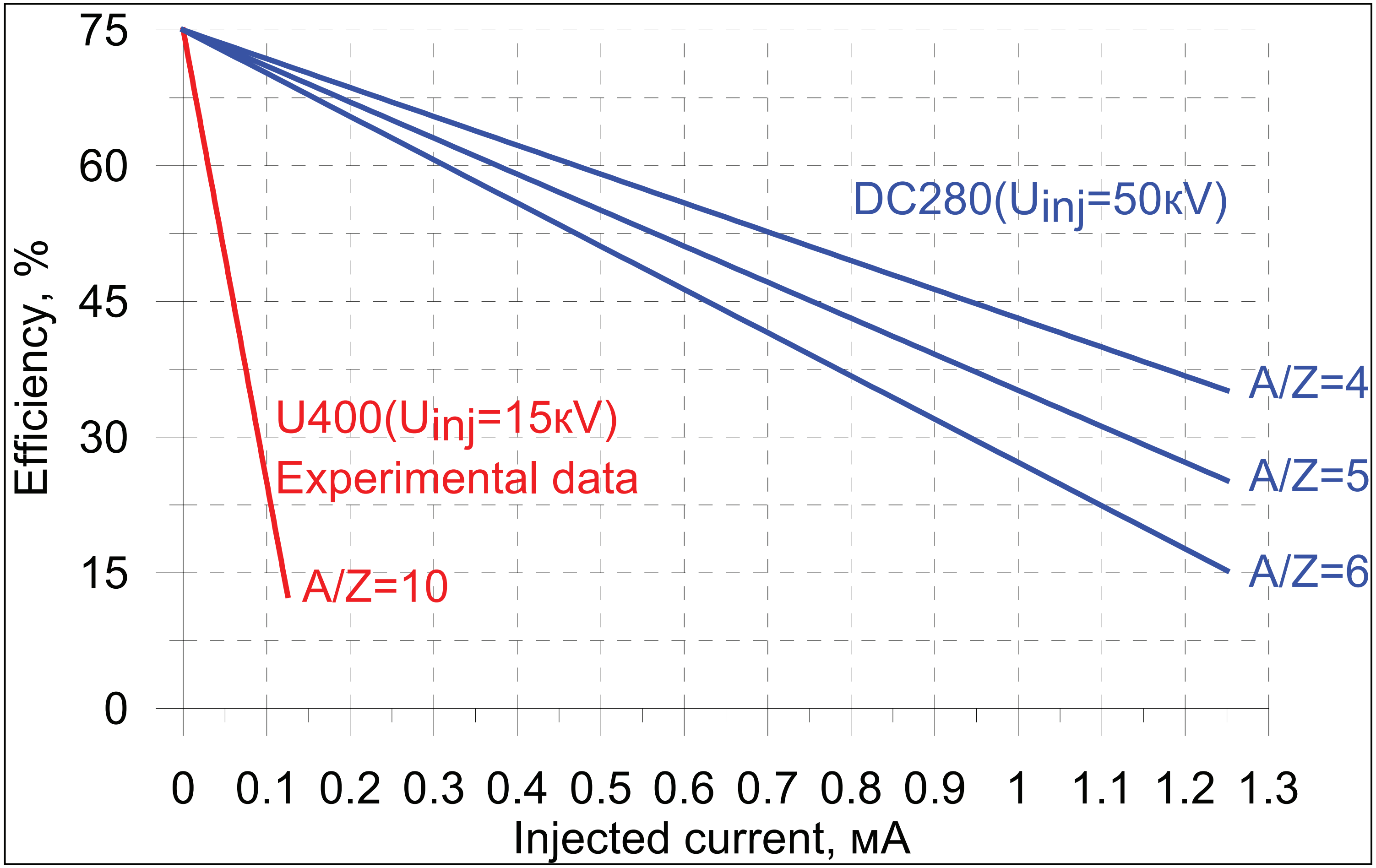
2017

Intensity 48Ca 1 pµA → 10 pµA

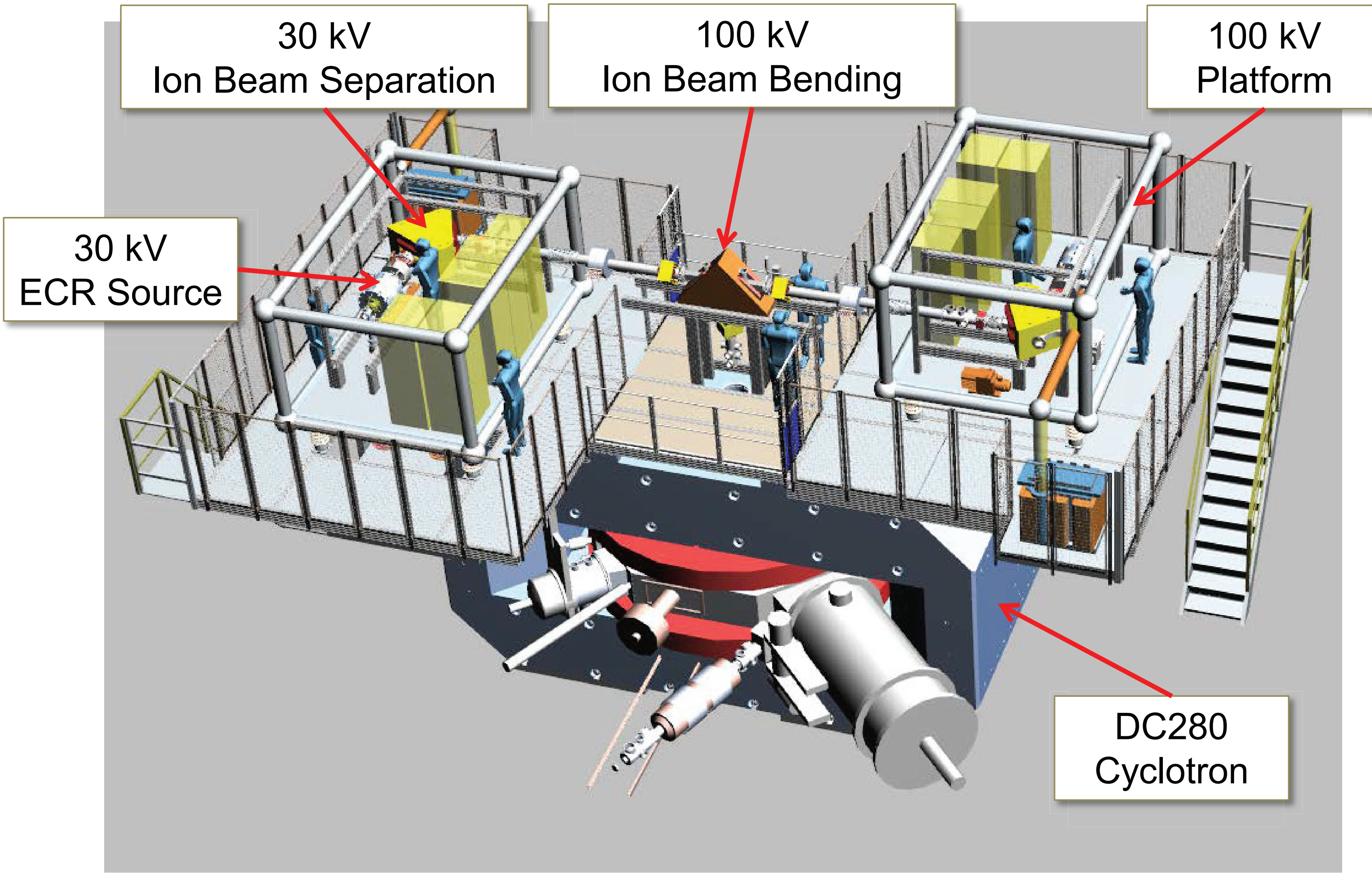
DC-280

<u>DC-280</u>

Overall (ion source $\rightarrow$ extraction radius) beam current transfer efficiency

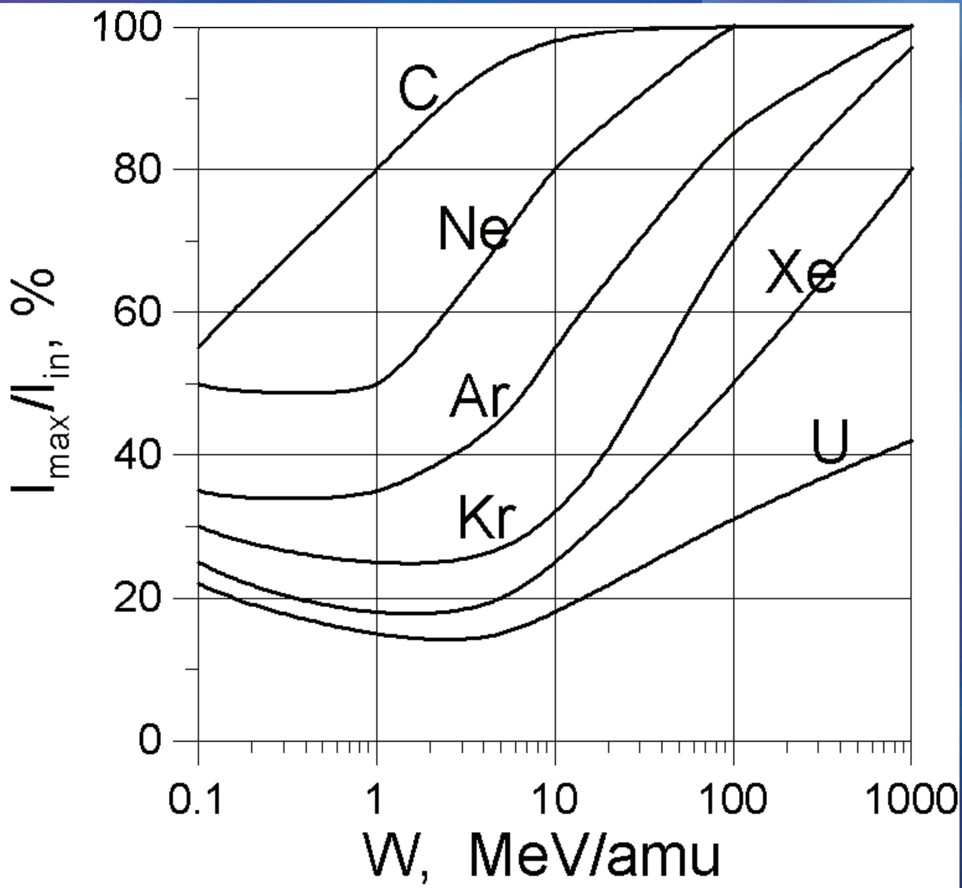


DC-280 Cyclotron



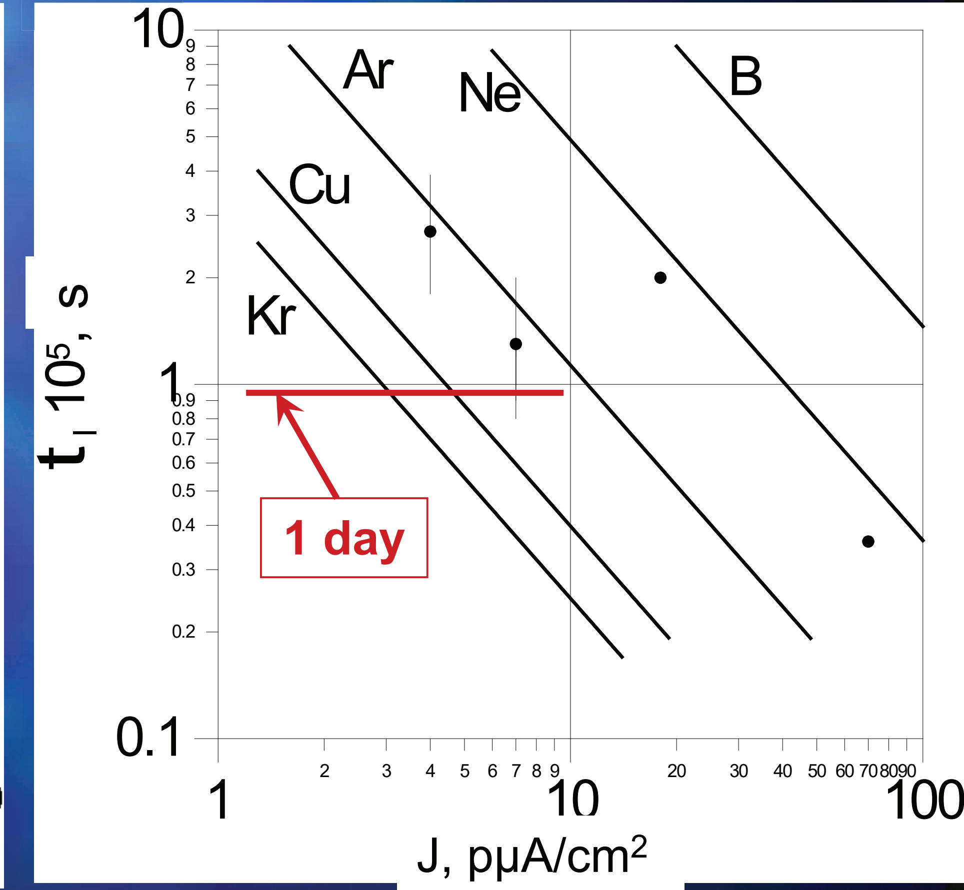
Heavy Ion Beam Extraction by Stripping Foil

1. Charge spread



Dependence of the maximum efficiency of a single charge extraction by stripping versus the ion energy

2. Life time of stripping foil



Dependence of life time of carbon stripping foil versus beam current density

$1\ p\mu A = 1\ e\mu A / Z_{ion} \cong 6 \cdot 10^{12}$ pps

SHE-factory: High-current cyclotron DC-280

DC280 (expected) E=4÷8 MeV/A		
Ion	Ion energy [MeV/A]	Output intensity [pps]
^{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}

Main setups:

GFS (synthesis), GFS (chemistry), SHELS

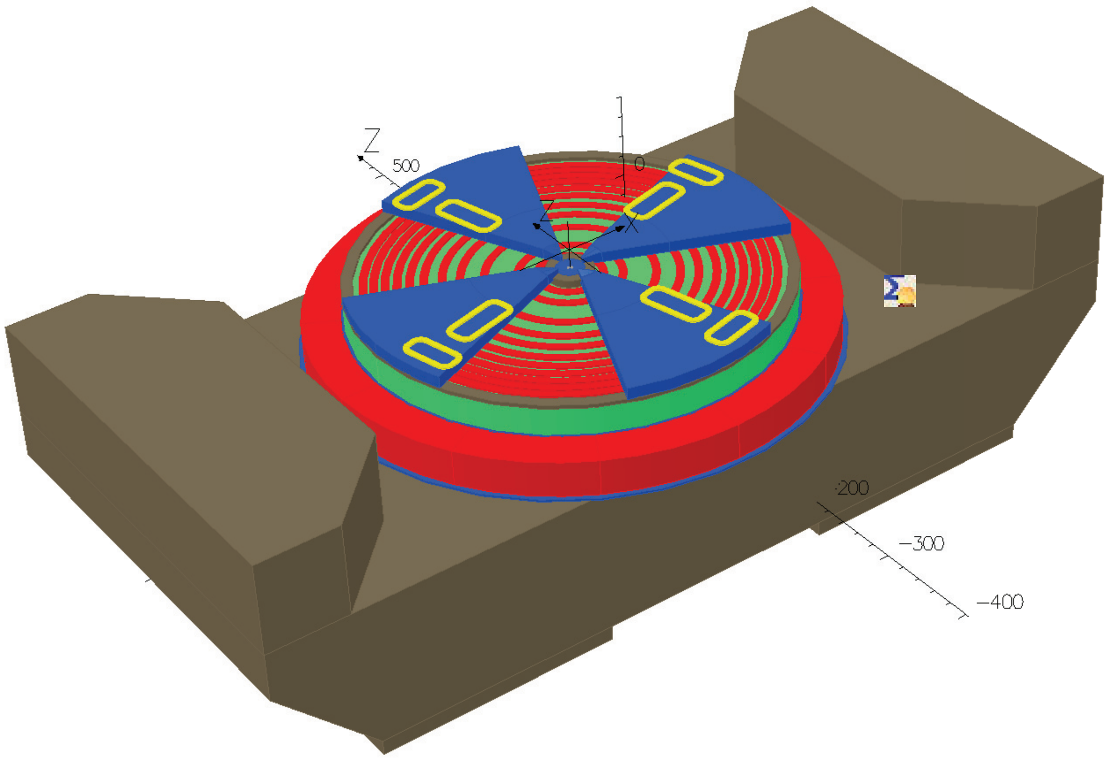
Main tasks:

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

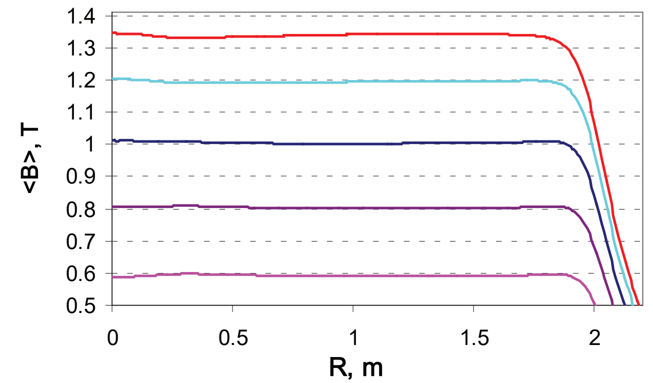
Main Parameters of DC-280 cyclotron

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
Magnet pole diameter	4 m
Magnetic field level	0.6÷1.35 T
K factor	280
Valley/hill gap	500/208 mm/mm
Gap between plugs	400 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	electrostatic deflector

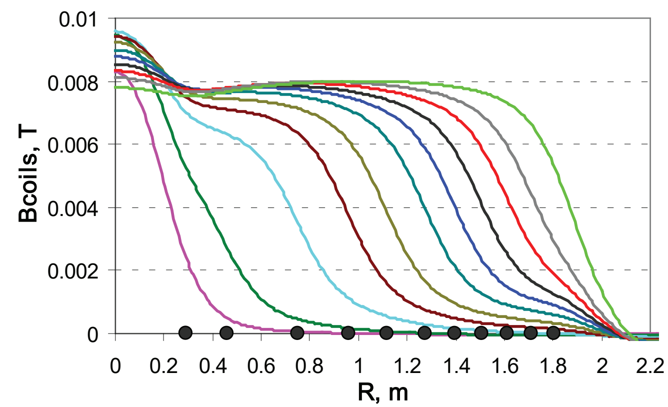
3D calculation of DC-280 cyclotron magnetic field



Model of DC-280 cyclotron magnet system

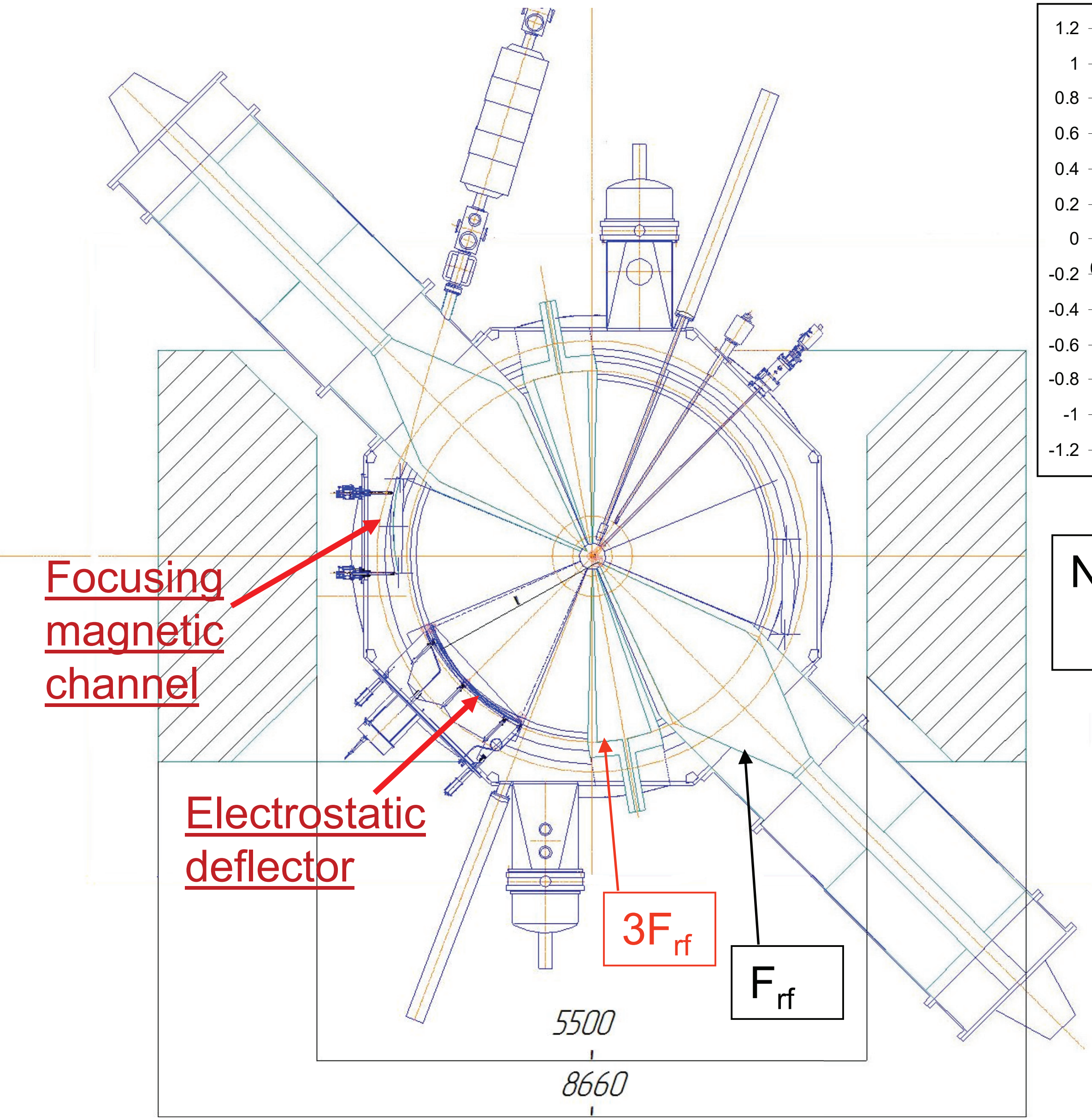


Calculated average magnetic fields

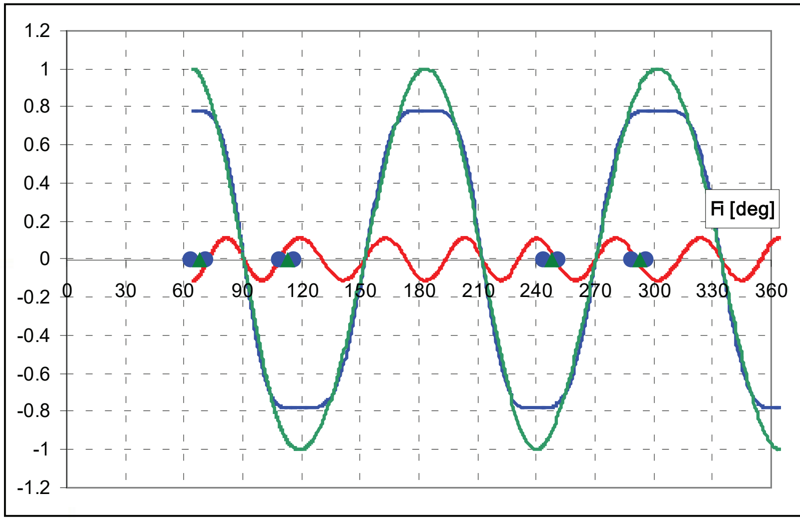


Magnetic field of the radial coils

Beam extraction system



Flat-Top system



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

$A_2 \approx 0.1 \cdot A_1$

Experimental Hall of the SHE-Factory (August 2016)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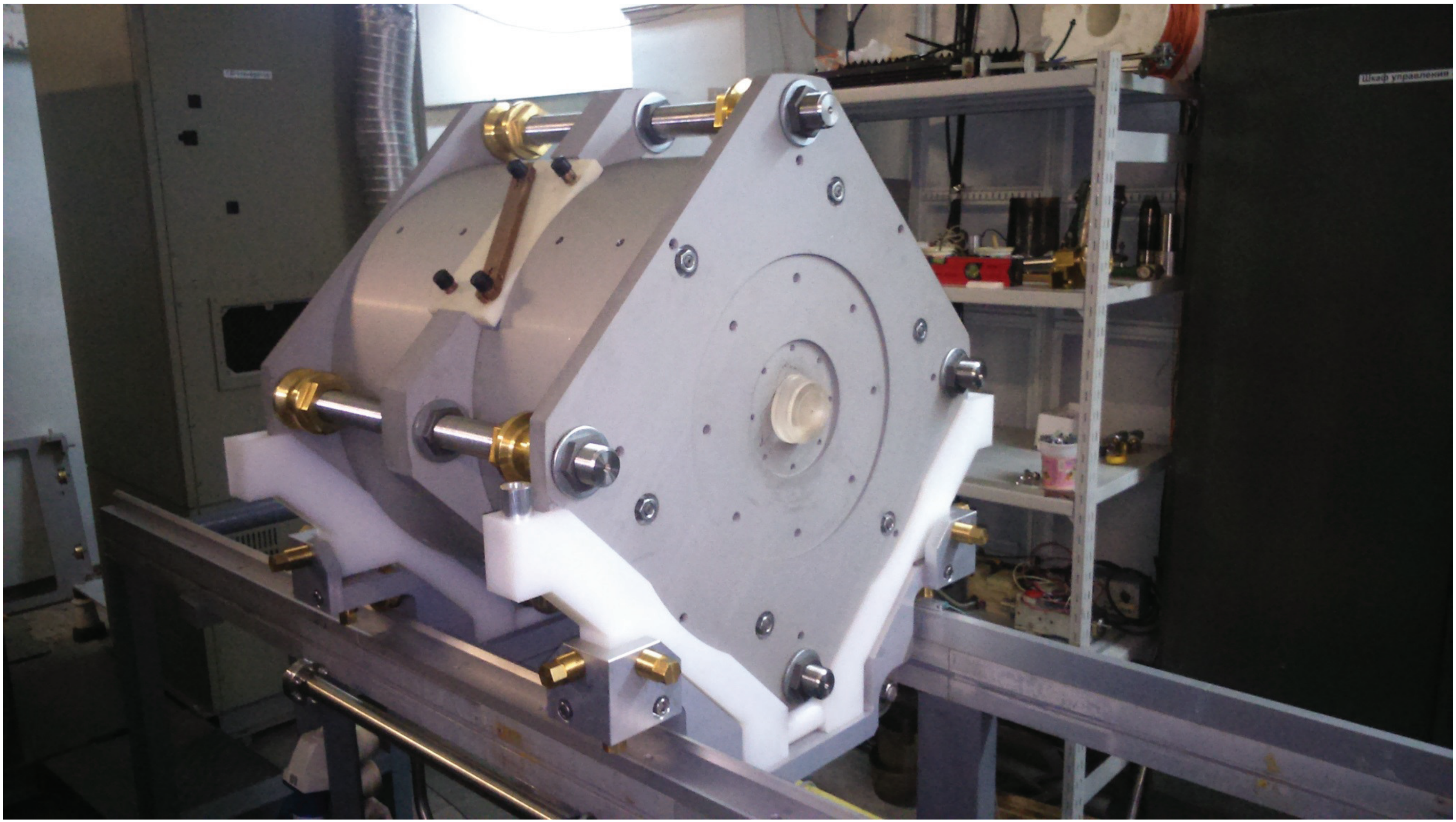
Correction coils
(azimuthal and radial)

Cooling lines

DC-280. Vacuum chamber

Permanent magnet ECR ion source at the test bench



Time-schedule of installation of the DC-280 accelerator complex

№	The content of the work	2016 (months)												2017 (months)											
		1	2	3	4	5	6	7	8	9	10	11	12	1	2	3	4	5	6	7	8	9	10	11	12
1	Preparing hall of the cyclotron and driveways for installation of the DC-280.		■	■	■	■	■	■	■	■															
2	Assembling of the DC-280 cyclotron magnet.									■	■	■													
3	Installation of power supply and cooling module of the main winding of the DC-280 for carrying out magnetic measurements.									■	■	■													
4	Installation and commissioning of magnetic measurement system. Measurements of a magnetic field of the DC-280 cyclotron.											■	■	■	■										
5	Installation of the vacuum chamber and components of the vacuum chamber. Test pumping.															■	■	■							
6	Assembling high-voltage platform and axial injection channel of the beam.																			■	■	■	■		
7	Installation of ECR ion source.																				■	■	■		
8	Assembling of the RF accelerating system.																		■	■	■	■			
9	Installation of the high energy ion beam channels.																		■	■					
10	Installation of the equipment of the vacuum system.											■	■						■	■	■				
11	Installation of the cooling system and pneumatic system.											■	■	■	■				■	■	■				
12	The installation and commissioning of power supply system and control system.									■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
13	Installation of the dosimetry control system.													■	■	■	■	■	■	■	■				
14	Creation of the test benches for commissioning of the cyclotron equipment:											■	■	■	■	■	■	■	■						
15	Commissioning of the accelerator systems. Obtaining accelerated ion beam.																								■

Modernization of the U-400 cyclotron (U-400R project)

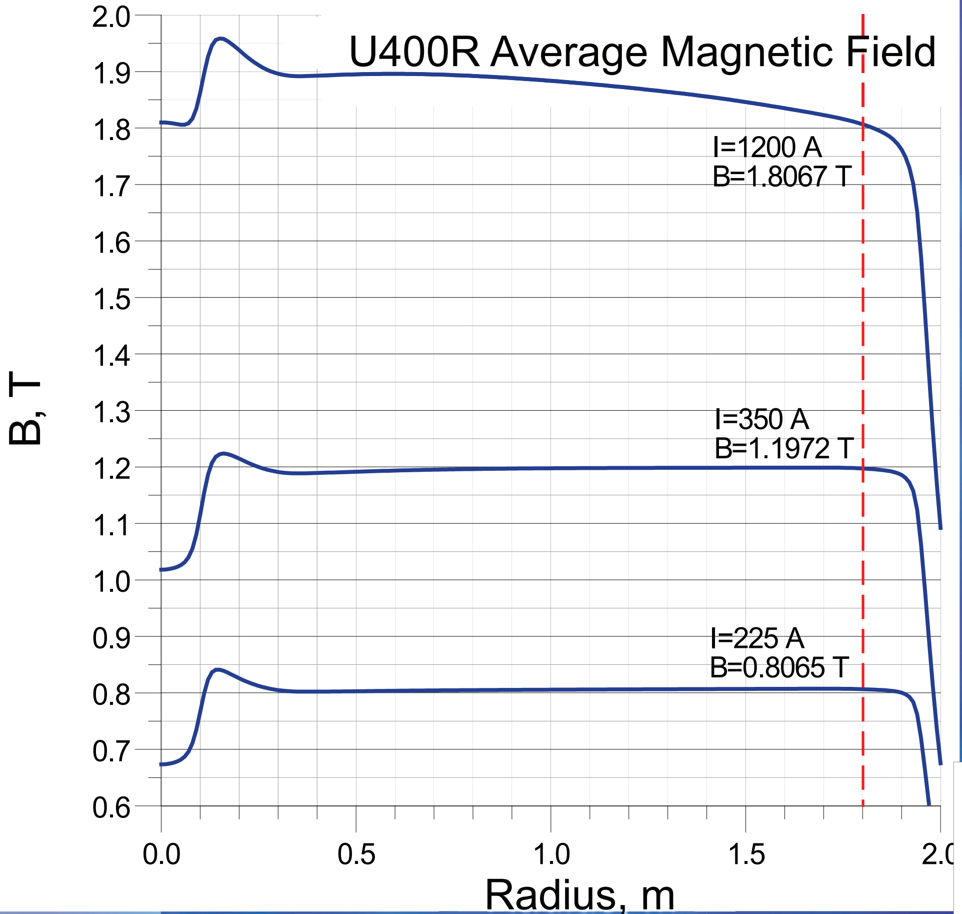
The U-400 cyclotron has been operating since 1978.
The project of the U-400 cyclotron modernization is developed.
The upgrade will be performed after the completion of the DC-280 cyclotron construction

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 from 1 to 0.25 MW.

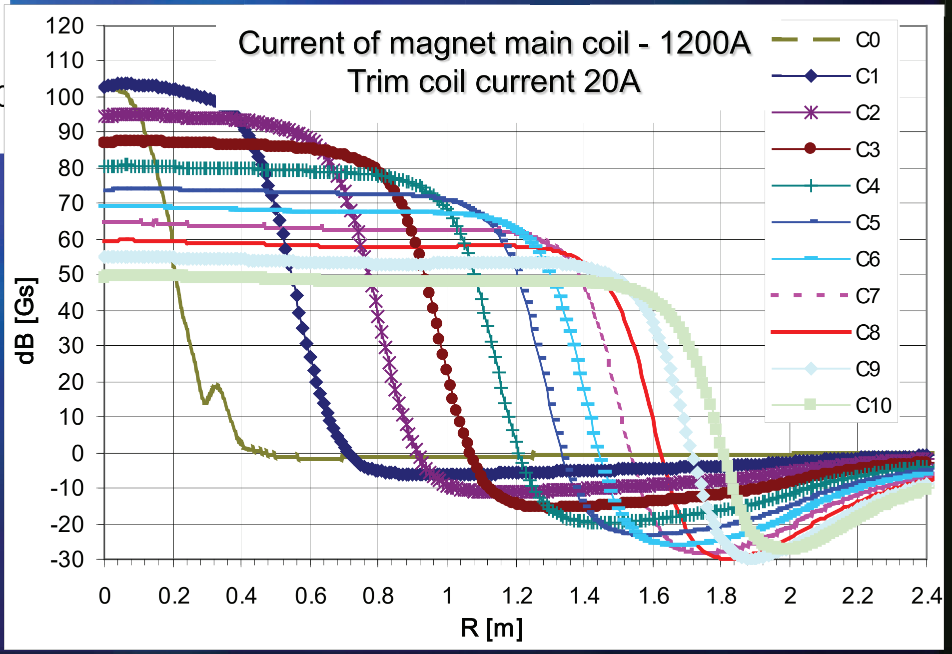
Cyclotron U400
has been operating since 1979

U400 → U400R



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

Radial Distribution of Magnetic Field of Trim Coils



U400		
Ion	Ion energy [MeV/u]	Output intensity
$^{4}He^{1+}$	-	-
$^{6}He^{1+}$	11	$3 \cdot 10^{7}$ 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

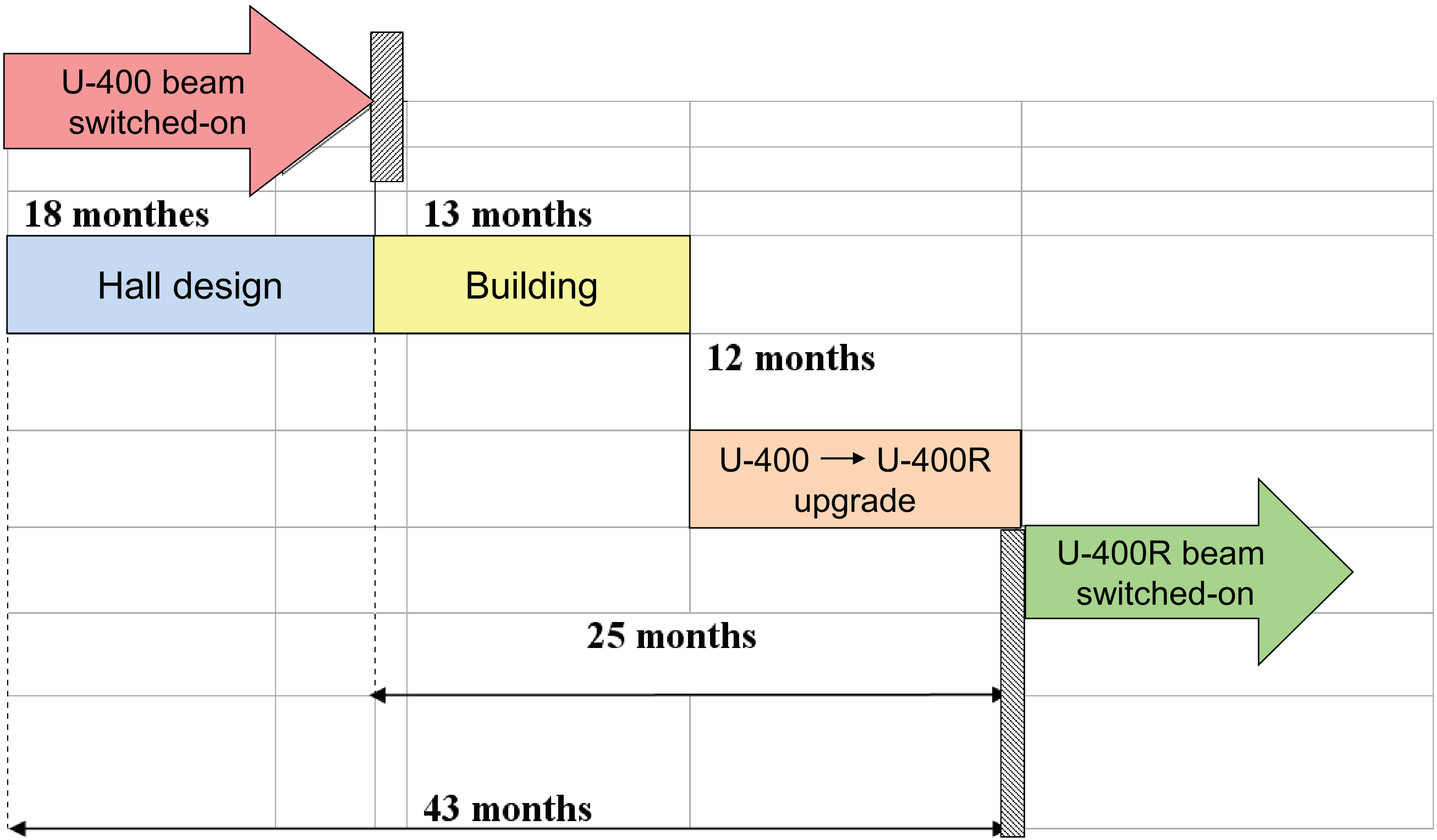
U400R (expected)		
Ion	Ion energy [MeV/u]	Output intensity
$^{4}He^{1+}$	6.4 ÷ 27	23 pμA **
$^{6}He^{1+}$	2.8 ÷ 14.4	10^{8} pps
$^{8}He^{1+}$	1.6 ÷ 8	10^{5} pps
$^{16}O^{2+}$	1.6 ÷ 8	19.5 pμA **
$^{16}O^{4+}$	6.4 ÷ 27	5.8 pμA **
$^{40}Ar^{4+}$	1 ÷ 5.1	10 pμA
$^{48}Ca^{6+}$	1.6 ÷ 8	2.5 pμA
$^{48}Ca^{7+}$	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

Parameters of U-400 and U-400R 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

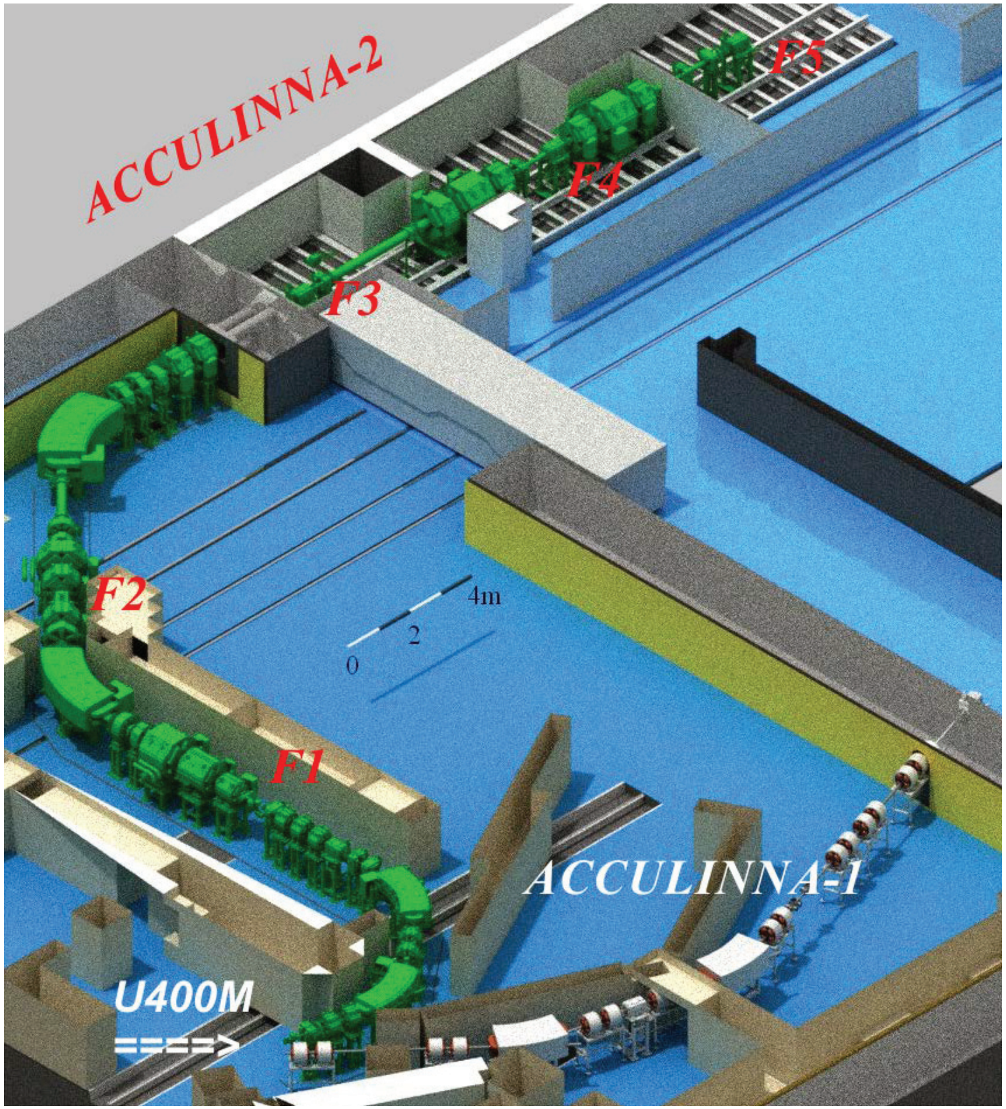
U-400 → U-400R Time-schedule



The development project of the cyclotron U-400M

Increase of the energy of accelerated ions at the cyclotron U-400M

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/



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)

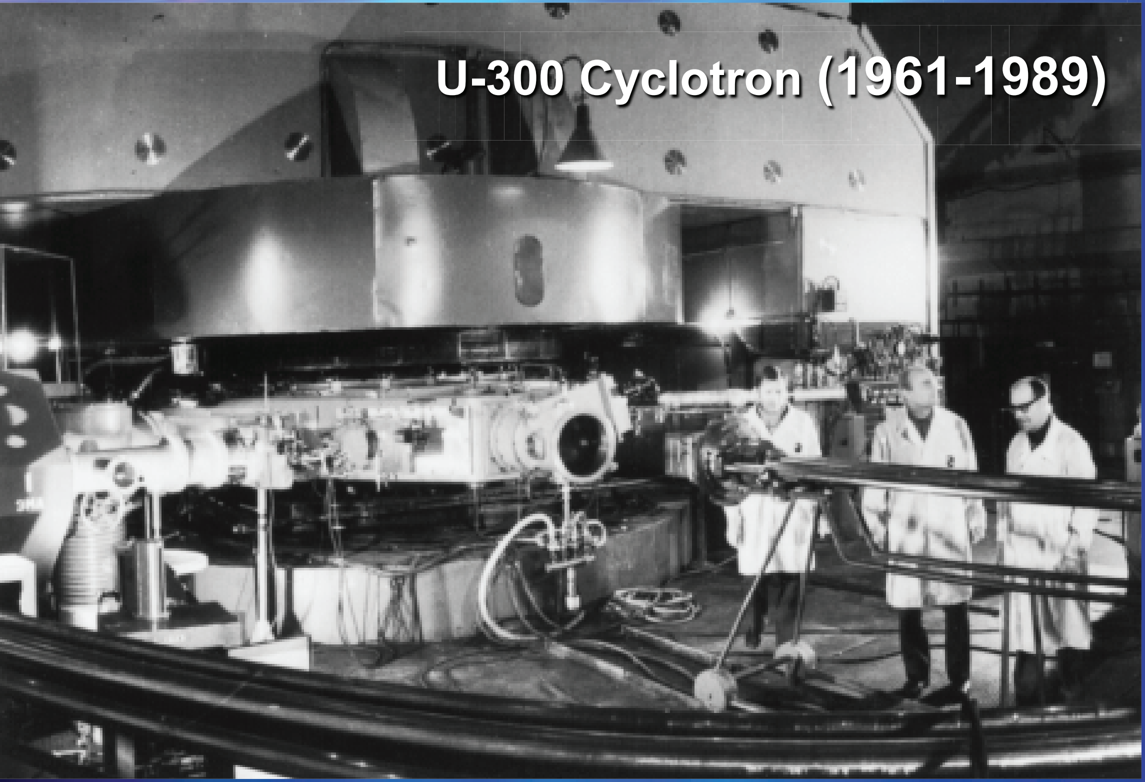
Year / Accelerator	2016	2017	2018	2019	2020	2021	2022	2023	2024
DC280	Assembling	Beam tuning	5000	5000	5000	5000	5000	5000	5000
U400M-U400MR	5000	5000	5000	Reconstruction	5000	5000	5000	5000	5000
U400-U400R	5000	5000	5000	5000	2000 Reassembling	Building	Assembling	2000 Beam tuning	5000
Beam time on the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

FLNR HEAVY ION CYCLOTRONS for APPLIED RESEARCH and INDUSTRIAL APPLICATION

HEAVY ION ACCELERATORS FOR TRACK MEMBRANE PRODUCTION AND POLYMER MODIFICATION

U-300 Cyclotron



- U-300 was created in D.V. Efremov Institute
- U-300 was in operation at FLNR JINR from 1961 to 1989.

❖ A specialized accelerator channel for polymer film irradiation has been created in the middle of 70ies.

❖ Xe ion beams of 1MeV/nucleon energy were used for manufacture of track membranes and for research tasks.

The track membrane technology has been developed on the basis of heavy particles registration by plastic detectors.

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HEAVY ION ACCELERATORS FOR TRACK MEMBRANE PRODUCTION AND POLYMER MODIFICATION

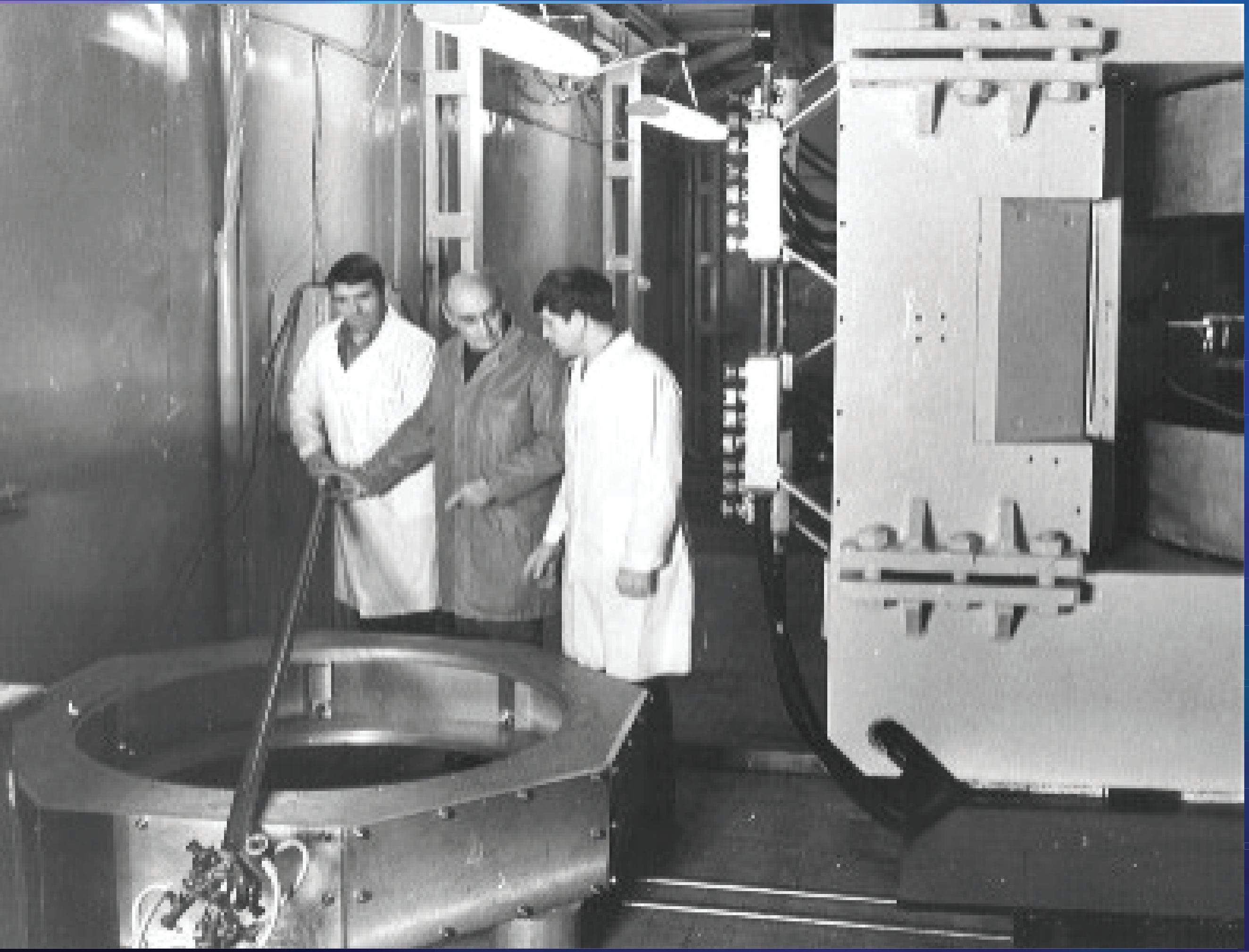
FLNR JINR

Cyclotron U-400 (1978)

- Beams of Kr, Xe, Bi ions with an energy of 2.5-5 MeV/n are used for track membrane production.
- The irradiation chamber provides an opportunity of processing polymer films with a width of up to 60 cm

- **power consumption - 1500 kW**

IMPLANTING CYCLOTRON IC-100
History pages 1985



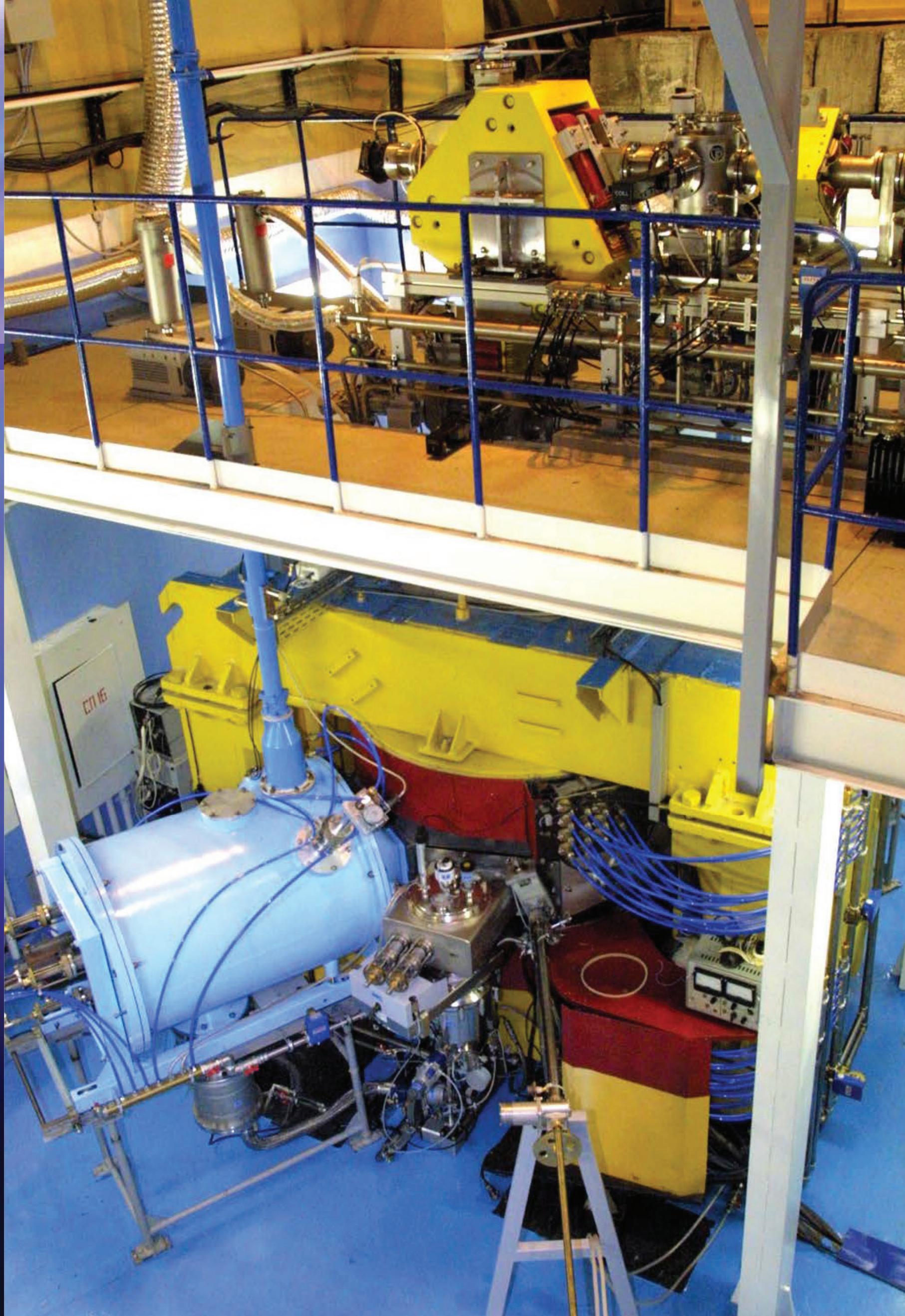
The first dedicated cyclotron for production of track membranes (nuclear filters)

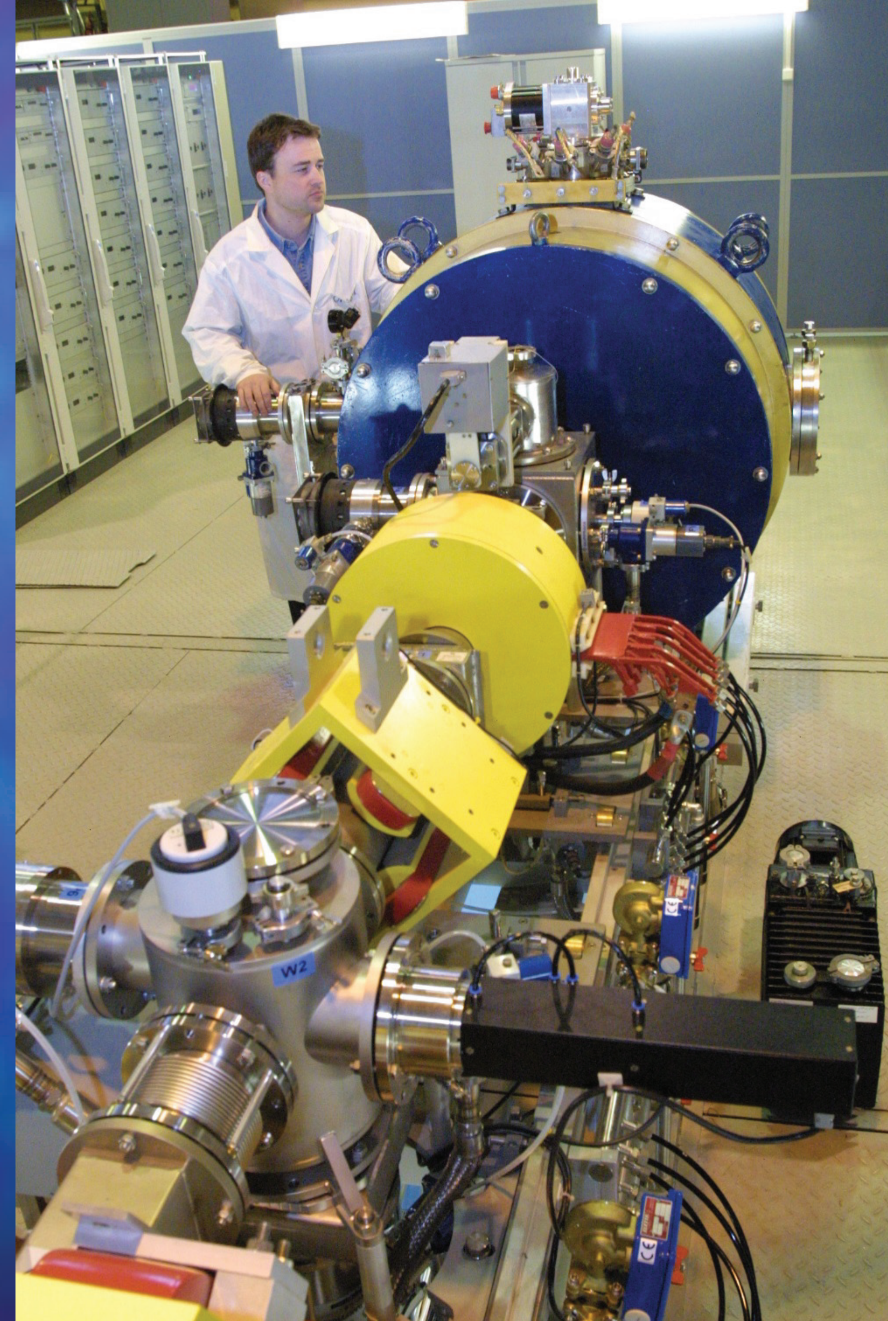
Energy of ions: ~ 1.2 MeV/nucleon.

Internal source of ions – PIG-type

Accelerated ions:
C - Ar (A/Z = 5.7-6)

Beam intensity of Ar - 1 μA





Reconstruction of IC-100 cyclotron (2001-2002)

Parameters of the IC-100 cyclotron

	Parameters	Project	Operation
1	Accelerated ions	Ar, Kr, Xe	$^{22}Ne^{+4}$ $^{40}Ar^{+7}$ $^{56}Fe^{+10}$ $^{86}Kr^{+15}$ $^{127}I^{+22}$ $^{132}Xe^{+23}$ $^{132}Xe^{+24}$ $^{182}W^{+32}$ $^{184}W^{+31}$ $^{184}W^{+32}$
2	Mass-to-charge ratio of accelerated ions	A/Z = 5.3 – 6.0	A/Z = 5.5 – 5.95
3	Ion energy	1-1,25 MeV/A	0,9-1,2 MeV/A
4	Diameter of the magnet pole	1 m	1 m
5	Average magnetic field	1.88 – 2.01 T	1.78 -1.93 T
6	Frequency of the RF system	20.4 - 20.9 MHz	19.8 - 20.6 MHz
7	Injection energy	12.5 kV	14-15 kV
8	Vacuum in injection channel	$5 \cdot 10^{-7}$ Torr	$1.5 \cdot 10^{-7}$ Topp
9	Working vacuum in cyclotron	$5 \cdot 10^{-7}$ Torr	$5 \cdot 10^{-8}$ Torr
10	Voltage on the dees	50 kV	45-55 kV
11	Intensity of the accelerated and extracted beam of $^{86}Kr^{15+}$	$\sim 10^{12}$ pps (2.5 μA)	$1.4 \cdot 10^{12}$ pps (3.5 μA)
12	Intensity of the accelerated and extracted beam of $^{132}Xe^{23+}$	$\sim 2.6 \cdot 10^{11}$ pps (1 μA)	$\sim 10^{12}$ pps (3.7 μA)

DC-60 CYCLOTRON

DC-60 is developed and created at FLNR JINR for Research Center of L.N.Gumilev Euroasia State University in Astana, Kazakhstan

DC-60 CYCLOTRON

MAIN PARAMETERS

Ion beam injector	ECR ion source (14 GHz) + axial injection system
Magnet pole diameter	1.62 m
Cyclotron magnetic field Power consumption	1.45 T - main mode 1.25 -1.65 T - magnetic field variation 12 - 45 kW
Correction coils: - radial coils - azimuth coils Total power of correction coils	5 couples 2 couples ~ 1 kW
RF system: - frequency - harmonic number - dee voltage - RF power	11.00 - 17.5 MHz 4 and 6 50 kV One amplifier of 20 kW (two coaxial resonators connected in the cyclotron centre)
Pressure in cyclotron vacuum chamber	(1-2)·10^{-7} Torr

DC-60 CYCLOTRON

PARAMETERS OF ACCELERATED ION BEAMS

Ions	**Li - Xe**
Mass to charge ratio A/Z	**6 - 12**
Energy of accelerated ions	**0.35 - 1.77 MeV/nucleon**
Energy spread	**2 %**
Discrete change of ion energy	**Due to A/Z ratio**
Smooth energy variation with respect to nominal energy	**-25 % / +25%** **Due to magnetic field variation**

LOW ENERGY ION BEAM PARAMETERS (from ECR)

Ions	**He - Xe**
Mass to charge ratio (A/Z)	**2 - 20**
Ion energy from ECR source	**10 - 20 keV/charge**
Energy spread	**0.1 %**
Discrete ion energy change	**Due to change of A/Z**
Smooth ion energy variation	**Due to extracted potential variation in ECR source**

Table 1: Current characteristics of accelerated ion beams

Ion	A/Z	Energy, MeV/nucl.	Beam current ECR, μA	Extracted beam current, μA
$^{7}Li^{1+}$	7	1.32	110	2.2
$^{12}C^{1+}$	12	0.40	63	0.6
$^{12}C^{2+}$	6	1.00	147	1.7
$^{12}C^{2+}$	6	1.25	150	1.5
$^{12}C^{2+}$	6	1.50	170	2.1
$^{12}C^{2+}$	6	1.75	140	1.7
$^{13}C^{2+}$	6.5	1.25	18.1	0.7
$^{13}C^{2+}$	6.5	1.50	19.9	0.6
$^{13}C^{3+}$	4.3	1.75	16.3	0.5
$^{14}N^{2+}$	7	0.4	84	0.9
$^{14}N^{2+}$	7	1.0	134	1.5
$^{14}N^{3+}$	4.6	1.4	325	2.0
$^{14}N^{3+}$	4.6	1.5	320	2.7
$^{14}N^{3+}$	4.6	1.75	120	1.9
$^{16}O^{2+}$	8	1.0	90	1.08
$^{16}O^{3+}$	5.3	1.25	85	1.1
$^{16}O^{3+}$	5.3	1.4	112	0.9
$^{16}O^{3+}$	5.3	1.5	95	0.8
$^{16}O^{3+}$	5.3	1.75	86	1.1
$^{20}Ne^{3+}$	6.67	1.08	106.0	1.03
$^{20}Ne^{3+}$	6.67	1.4	95.8	1.56
$^{20}Ne^{4+}$	5	1.75	76.4	2.0
$^{32}Se^{6+}$	5.33	1.75	61.1	0.8
$^{40}Ar^{4+}$	10	0.48	44.6	0.67
$^{40}Ar^{4+}$	10	0.64	37.2	0.84
$^{40}Ar^{5+}$	8	0.58	24.2	0.4
$^{40}Ar^{7+}$	5.7	1.1	42.7	1.2
$^{40}Ar^{7+}$	5.7	1.75	45.1	1.0
$^{84}Kr^{9+}$	9.3	0.4	47.6	0.25
$^{84}Kr^{10+}$	8.4	0.7	49.8	0.4
$^{84}Kr^{12+}$	7	1	34.3	1.7
$^{84}Kr^{15+}$	5.6	1.4	26.2	1.9
$^{84}Kr^{15+}$	5.6	1.75	28.6	2.1
$^{132}Xe^{14+}$	9.42	0.6	11.8	0.14
$^{132}Xe^{15+}$	8.8	0.4	10.7	0.25
$^{132}Xe^{17+}$	7.7	1	21.2	0.40
$^{132}Xe^{20+}$	6.6	1.5	22.6	0.46
$^{132}Xe^{22+}$	6	1.75	16.5	0.32

Proceedings of RuPAC2014, Obninsk, Kaluga Region, Russia THCA01

ACCELERATOR COMPLEX BASED ON DC-60 CYCLOTRON

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DC-110 dedicated heavy ion cyclotron developed and created at the Flerov Laboratory of Nuclear Reactions of the Joint Institute for Nuclear Research for the BETA research and industrial complex in Dubna (Russia)

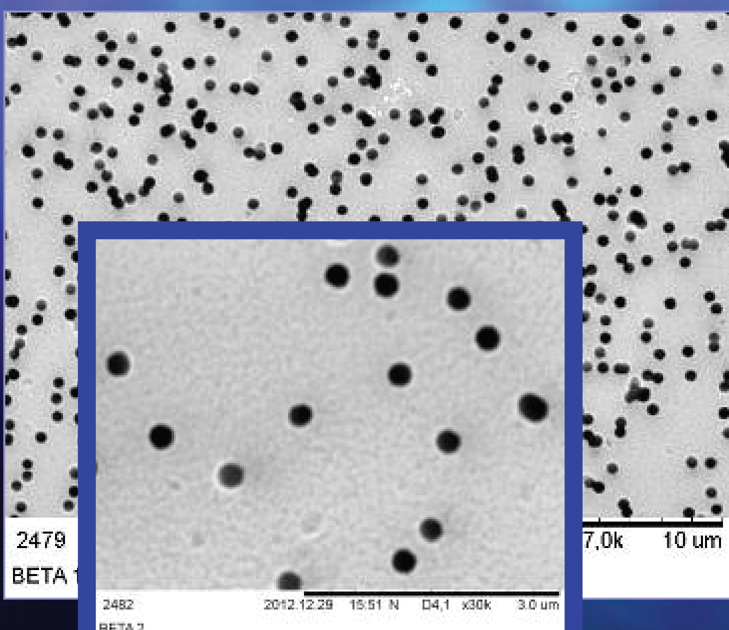
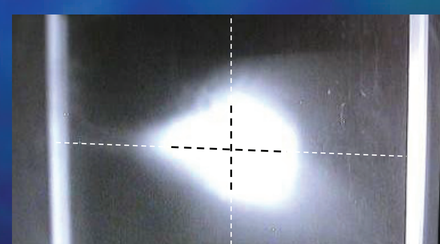


Photo of membrane on the electron microscope.
Pore density - $1.32 \cdot 10^8$ pores/cm2.
Magnification of 30,000 times

<u>December 29, 2012</u>
first samples of track membranes were received



Spot of $^{132}Xe^{20+}$ beam on luminophor

Facility for polymer film irradiation

Main parameters of DC-110 cyclotron.

ACCELERATED IONS	$^{86}Kr^{13+}$	$^{132}Xe^{20+}$	$^{40}Ar^{6+}$
Mass to charge ratio of ions A/Z	6.615	6.60	6.667
Ion energy	2.5	2.5	2.5
Beam intensity, pps	$6{\cdot}10^{12}$	$3{\cdot}10^{12}$	$6{\cdot}10^{12}$ (*)
MAGNETIC SYSTEM			
Pole diameter, m	2		
Average magnetic field B_o, [T]	1.670	1.666	1.6830
Increasing average magnetic field at final radius ΔB,[Gs]	45	45	45
RF SYSTEM			
Ion revolution frequency, F_{ion}, [MHz]	3.877	3.877	3.877
Acceleration harmonic number	2	2	2
Frequency of RF system, F_{RF} , [MHz]	7.754	7.754	7.754
ION SOURCE	ECR, 18 GHz		
EXTRACTION SYSTEM	Electrostatic deflector		

Ion beam parameters of the DC-110 cyclotron

Optimal frequency values of the RF system and the magnetic field during acceleration of $^{40}Ar^{6+}$, $^{86}Kr^{13+}$ and $^{132}Xe^{20+}$ ions.

Ion	Mass to charge ratio (A/Z)	Cyclotron magnetic field, T	Acceleration harmonic	RF generator frequency, MHz	Frequency difference, ΔF,
$^{40}Ar^{6+}$	6.6667	1.6612	2	7.653	23 kHz
$^{86}Kr^{13+}$	6.6154	1.6612	2	7.712	-18 kHz
$^{132}Xe^{20+}$	6.6000	1.6612	2	7.730	0 kHz

Experimental beam parameters of the DC-110 cyclotron obtained after completion of start-up works

Ion	Beam intensity from ECR source, μA	Accelerated and extracted beam intensity, μA		Ion energy, MeV/nucleon
		design	result obtained	
$^{40}Ar^{6+}$	94	6	13	2.5
$^{86}Kr^{13+}$	150	13	14.5	2.5
$^{132}Xe^{20+}$	190	10	10.9	2.5

Testing of electronic devices at FLNR cyclotron beams

The Russian Space Agency (**Roscosmos**) carries out investigations of single-event effects (SEE) in electronic devices using ion beams of U-400 and U400M.

- U400 cyclotron delivers beams of ions with atomic masses of 4÷209 at energies of **3÷20 MeV/nucleon**.
- U400M cyclotron was intended for acceleration of ion beams in two modes:

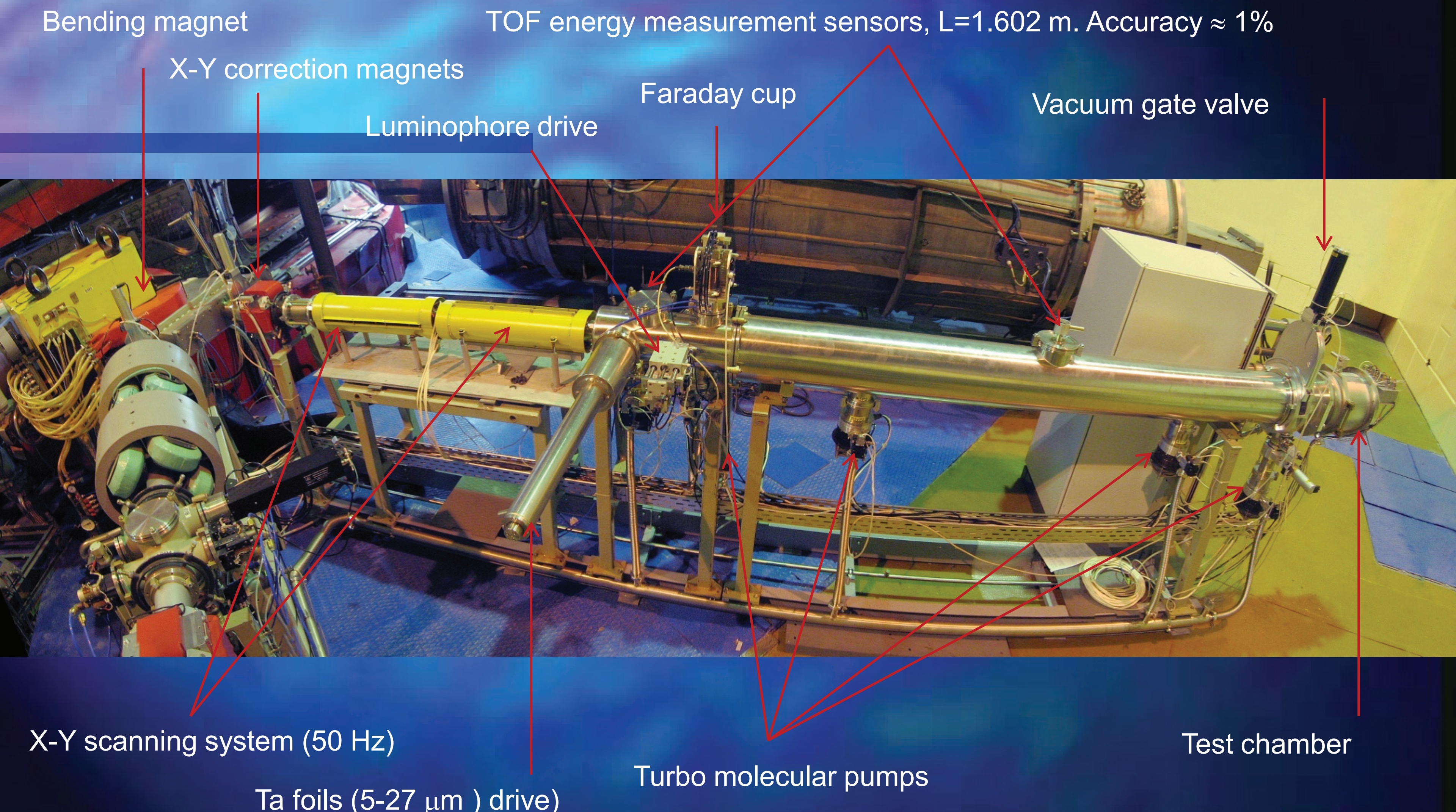
\- high energy ion acceleration mode - **19–53 MeV/nucleon** (mass to charge ratio of accelerated ions A/Z = 2.8 – 5),
\- low energy ion acceleration mode - **5–10 MeV/nucleon** (mass to charge ratio of accelerated ions A/Z = 7– 10).

- Now, ions of **O, Ne, Ar, Fe, Kr, Xe, Bi** with an energy of **3÷6 MeV/nucleon** and ions from **C up to Xe** with energies from **25 to 53 MeV/nucleon** are available for experiments of testing the electronic devices at **4 beam channels of U-400 and U-400M**.

U-400M

U-400

Ion Beam Line for SEE Testing



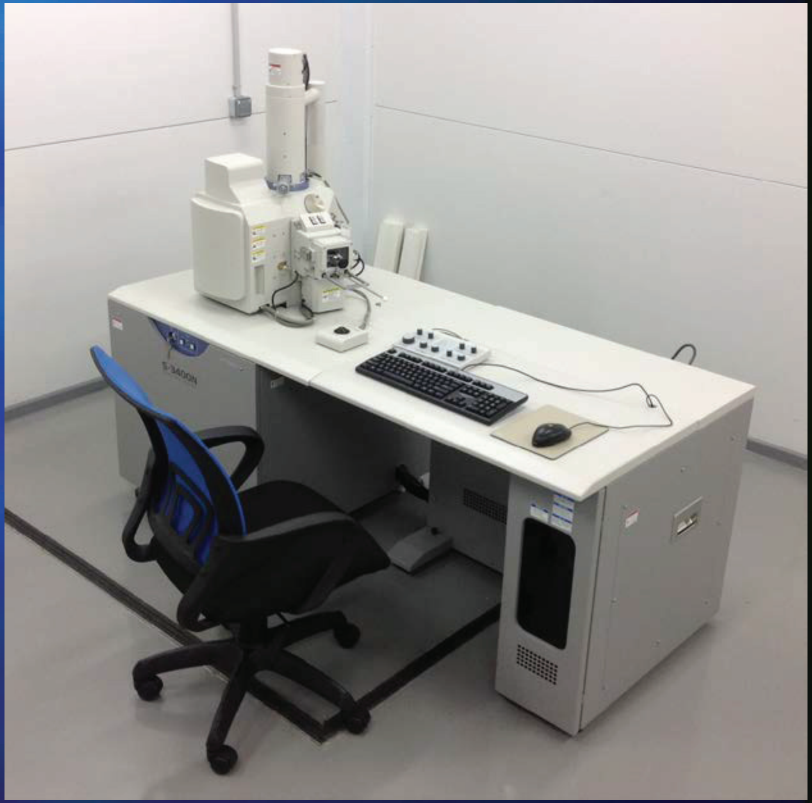
New building of the nanotechnology Center

The equipment in the new building of the nanotechnology Center

The equipment of the nanotechnology Center

Scanning electron Microscope
(resolution 1.3 nm)

Scanning electron Microscope
(resolution 6 nm)




THANK YOU
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