Heavy ion cyclotrons of FLNR JINR – status and plans

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The FLNR scientific program on heavy ion physics :

- Synthesis of new nuclei and study of nuclear properties and heavy ion reaction mechanisms;
- Investigation of reactions with light radioactive nuclei, investigation of proton halos in neutron pure nuclides, investigation of resonance states in ^{5}H, ^{7}H, ^{7}He, ^{9}He and ^{10}He
- Radiation effects and modification of materials, radioanalytical and radioisotopic investigations using the FLNR accelerators;
- Development of the FLNR cyclotron complex for producing intense beams of accelerated ions of stable and radioactive isotopes;
- Development of the U400+U400M cyclotron complex for the production of radioactive ion beams (the DRIBs project).

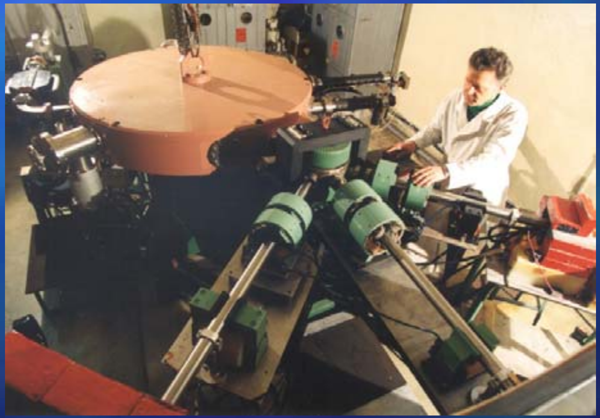
FLEROVLAB ACCELERATORS views of set-ups

U-400M **(6 - 100 MeV/n)**

U-400 **(2.5 - 20 MeV/n)**

U-200 **(α - 9 MeV/n)**

IC-100 **(1 - 1.3 MeV/n)**



MT-25 **(e - 25 MeV)**

DRIBs in Gallery

Running time of the FLNR U400 and U400M cyclotrons in 2003-2008

Accelerator	Running time in hours					2008 (expected)
	2003	2004	2005	2006	2007	
U400	6500	6500	5500	5500	5600	4400 (2900 Sep.)
U400M	3300	2500	3500	3500	1700	2700 (1400 Sep.)
Total	9800	9000	9000	9000	7300	7100

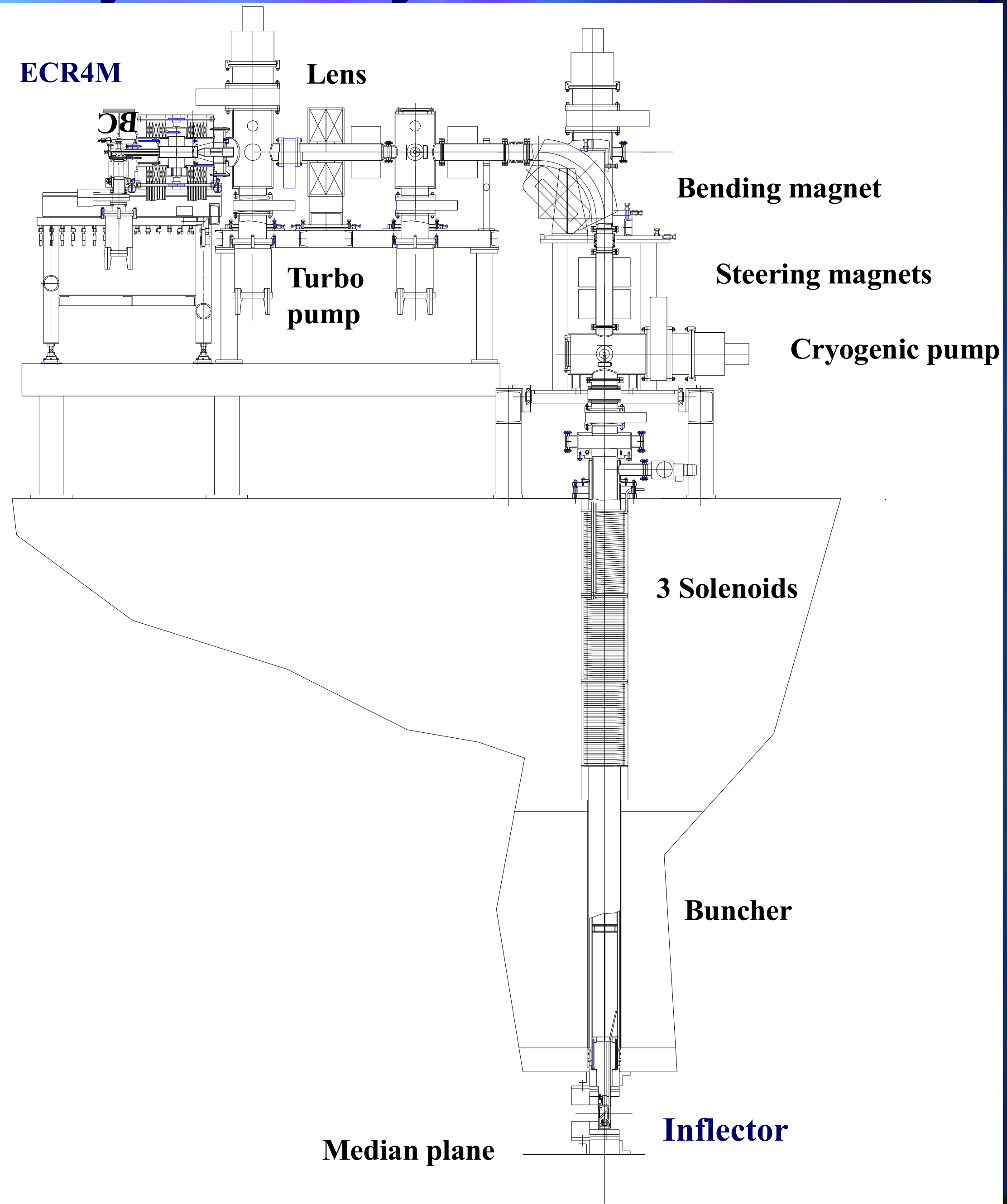
* - Rest of the time is used for accelerators development of and installation of new equipment

U400 Cyclotron (1978)

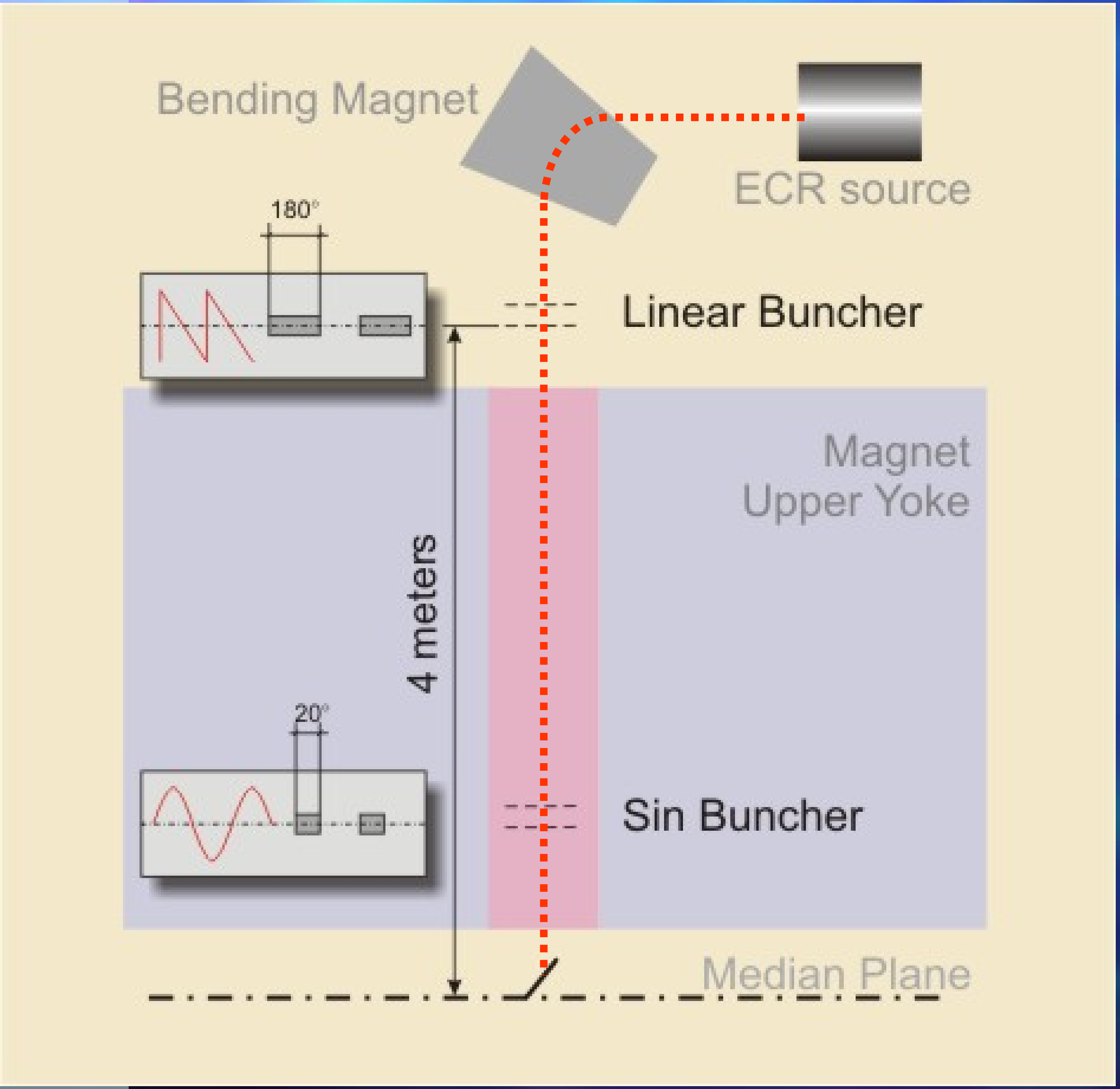
TECHNICAL PARAMETERS of the FLNR CYCLOTRONS

Technical parameters	IC-100 *1985*	U-200 *1968*	U-400 *1978*	U-400M *1992*
Pole diameter [m]	1.05	2.0	4.0	4.0
Magnetic field [T]	1.94	1.93 ÷2.0	1.95÷ 2.15	1.5 ÷1.95
Energy factor	40	145	550÷ 625	400 ÷550
Weight of magnet [tons]	50	200	2000	2300
N sectors / Sect. Angle	4/56°	4/42°	4/42°	4/42°
Sectors Spiral	0°	0°	0°	43°
Number of trim coils	-	12	14	14
Number of dees	2	2	2	4
Dee voltage [kV]	50	70	100	170
RF frequency [MHz]	20.5	14÷ 22	5.5÷ 12	11.5÷ 24
RF harmonics	4	2; 3	2; 6	2; 3; 4
Vacuum [Tor]	$2 \cdot 10^{-7}$	$1 \cdot 10^{-6}$	$3 \cdot 10^{-7}$	$2 \cdot 10^{-7}$
Ion Source	ECR	PIG	ECR	ECR
Extraction	El. deflector	Z_2/Z_1	Z_2/Z_1	Z_2/Z_1
A/Z	5.7	2.7 – 5.5	5 -12	2 -10
Ion Energy	1.2; 0.5	3÷ 15	0.5 ÷20	6 ÷100

Axial injection system of U-400 Cyclotron



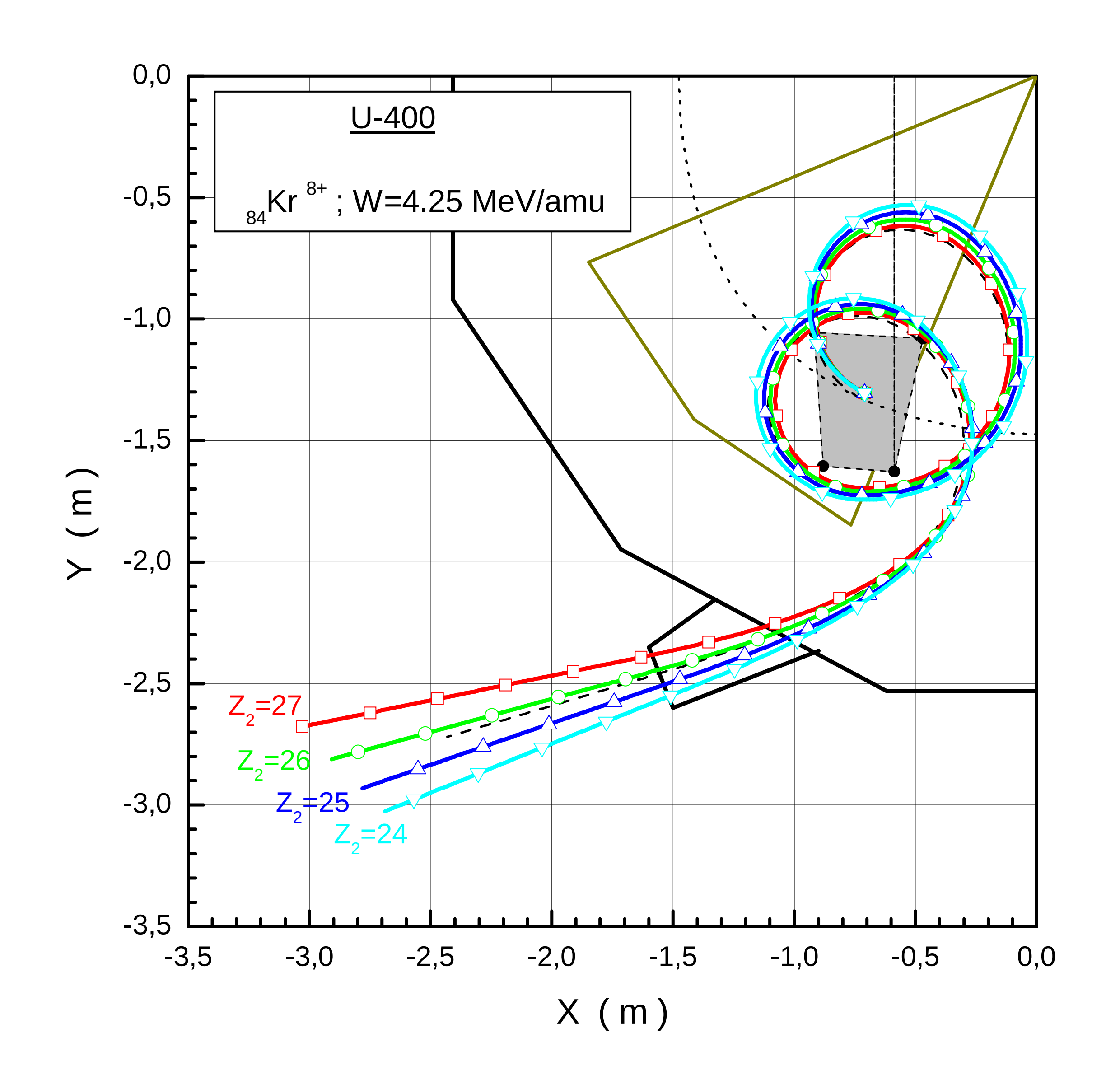
U400 Cyclotron
Buncher System



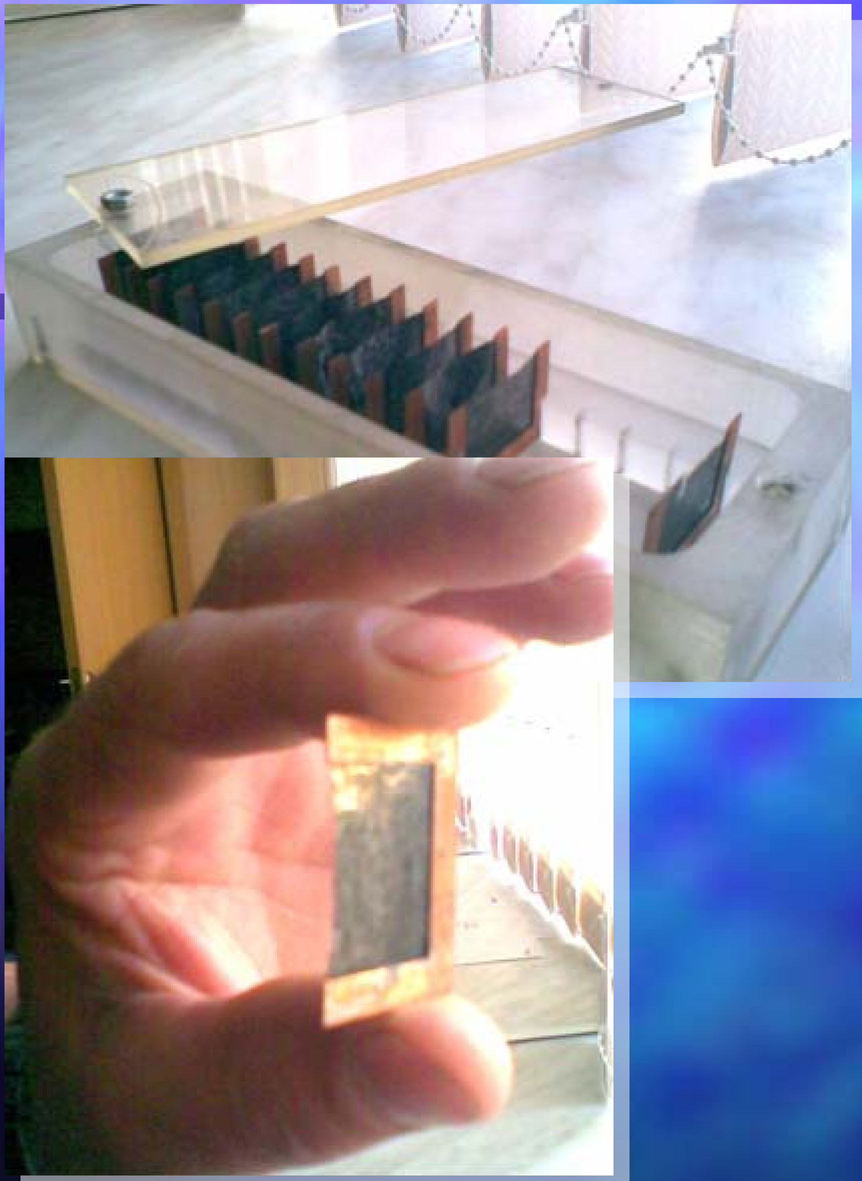
Efficiency of Buncher System (I_{inj} / I_{acc})

for 1 μA - 70%

for 100 μA - 30%



Two-turn extraction from U400



The stripping foil before using

Probe head of U400 cyclotron with the stripping foil

U400 Beam parameters

Ion	E, MeV/n	I, ECR	I, extracted	I, extracted
$^{7}Li^{1+}$	16.6	100μA	30μA	$6*10^{13}$ pps
$^{6}Li^{1+}$	12.6	100μA	30μA	$6*10^{13}$ pps
$^{11}B^{2+}$	17.8	90μA	33μA	$4*10^{13}$ pps
$^{12}C^{2+}$	16.6	100μA	35μA	$4*10^{13}$ pps
$^{13}C^{2+}$	14.4	100μA	35μA	$3*10^{13}$ pps
$^{14}N^{2+}$	9.4	100μA	35μA	$3*10^{13}$ pps
$^{14}N^{3+}$	20.3	100μA	35μA	$3*10^{13}$ pps
$^{18}O^{3+}$	19.3	100μA	35μA	$2.5*10^{13}$ pps
$^{20}Ne^{4+}$	20.9	100μA	35μA	$2*10^{13}$ pps
$^{22}Ne^{4+}$	17.8	100μA	35μA	$2*10^{13}$ pps
$^{36}S^{6+}$	15	60μA	25μA	$9*10^{12}$ pps
$^{40}Ar^{8+}$	19.9	100μA	35μA	$1*10^{13}$ pps
$^{48}Ca^{5+}$	5.3	60μA	22μA	$7*10^{12}$ pps
$^{48}Ca^{9+}$	19	30μA	10μA	$3*10^{12}$ pps
$^{86}Kr^{9+}$	5.1	60μA	10μA	$2*10^{12}$ pps
$^{136}Xe^{14+}$	4.4	5μA	0.2μA	$3*10^{10}$ pps

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

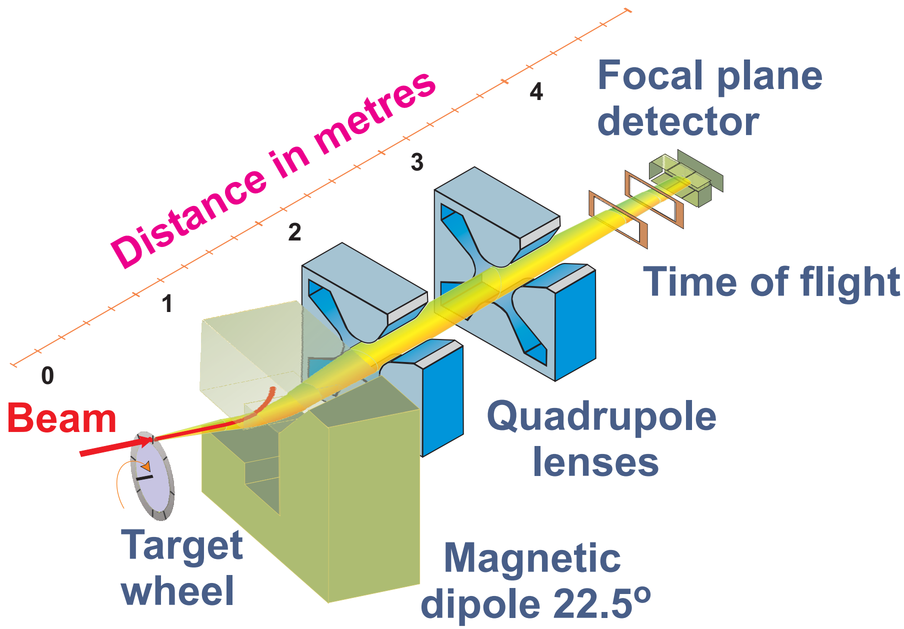
Target	+	Beam	→	Isotopes
^{238}U, $^{242,244}Pu$, ^{243}Am, $^{246,248}Cm$, ^{249}Cf	+	^{48}Ca	→	112 – 118

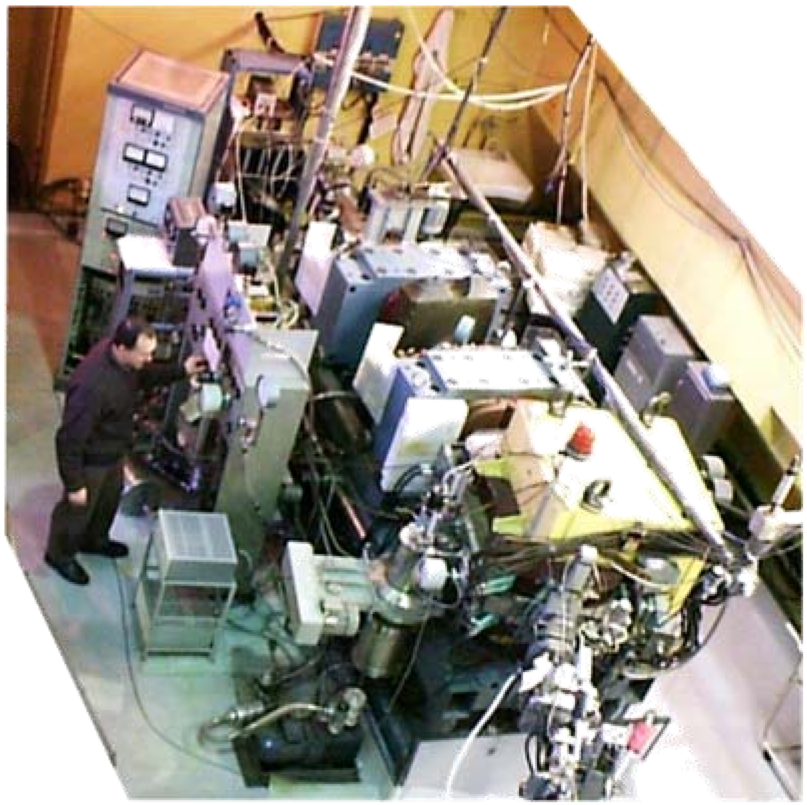
Ion beam energy: 5.00 – 5.75 MeV/A

Beam intensity: 6 - 8·10^{12} pps

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

Beam time: 2000 – 4000 hours per year





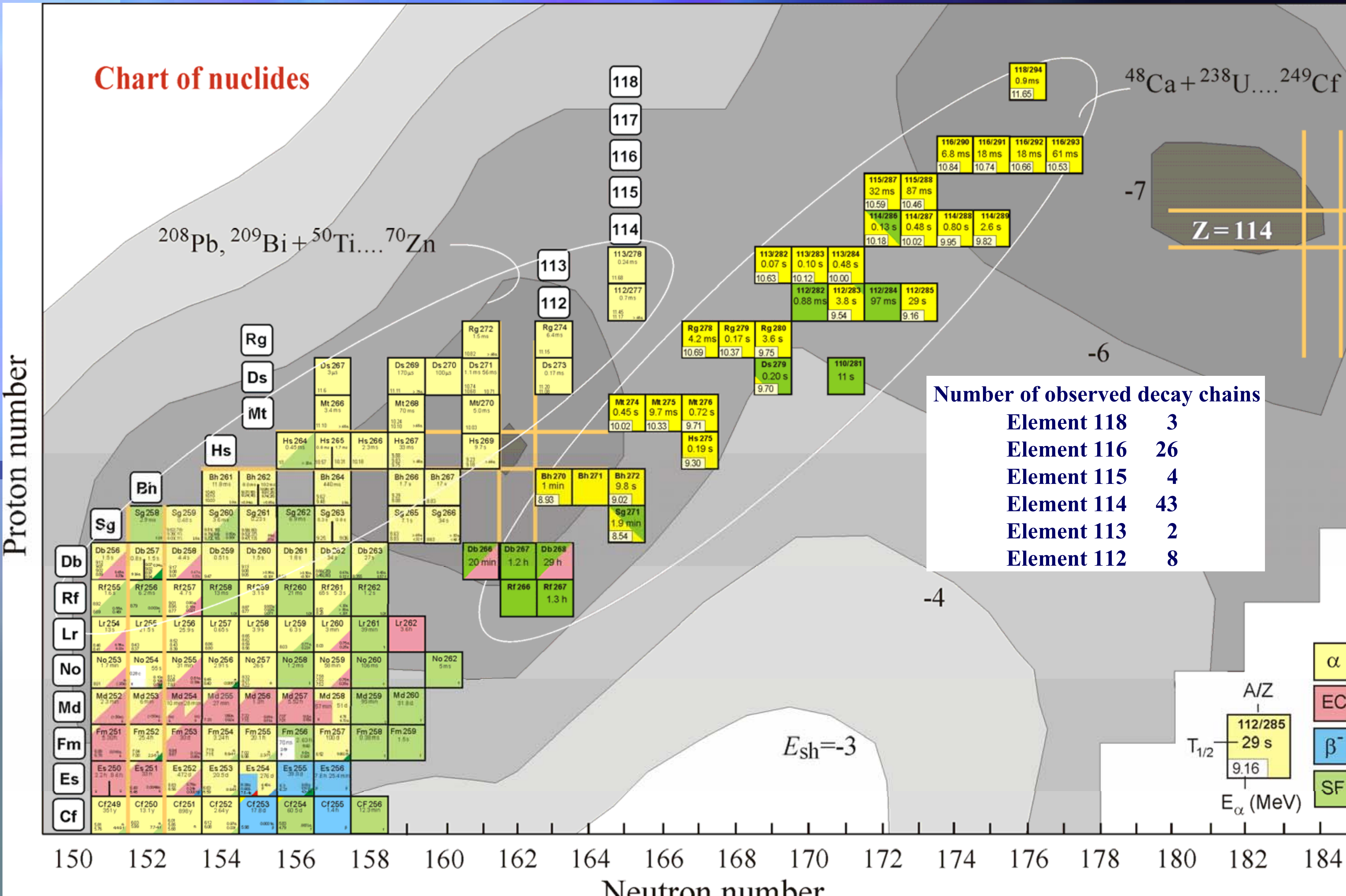
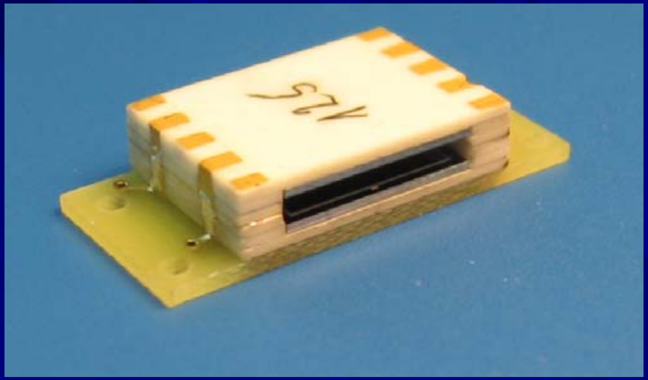
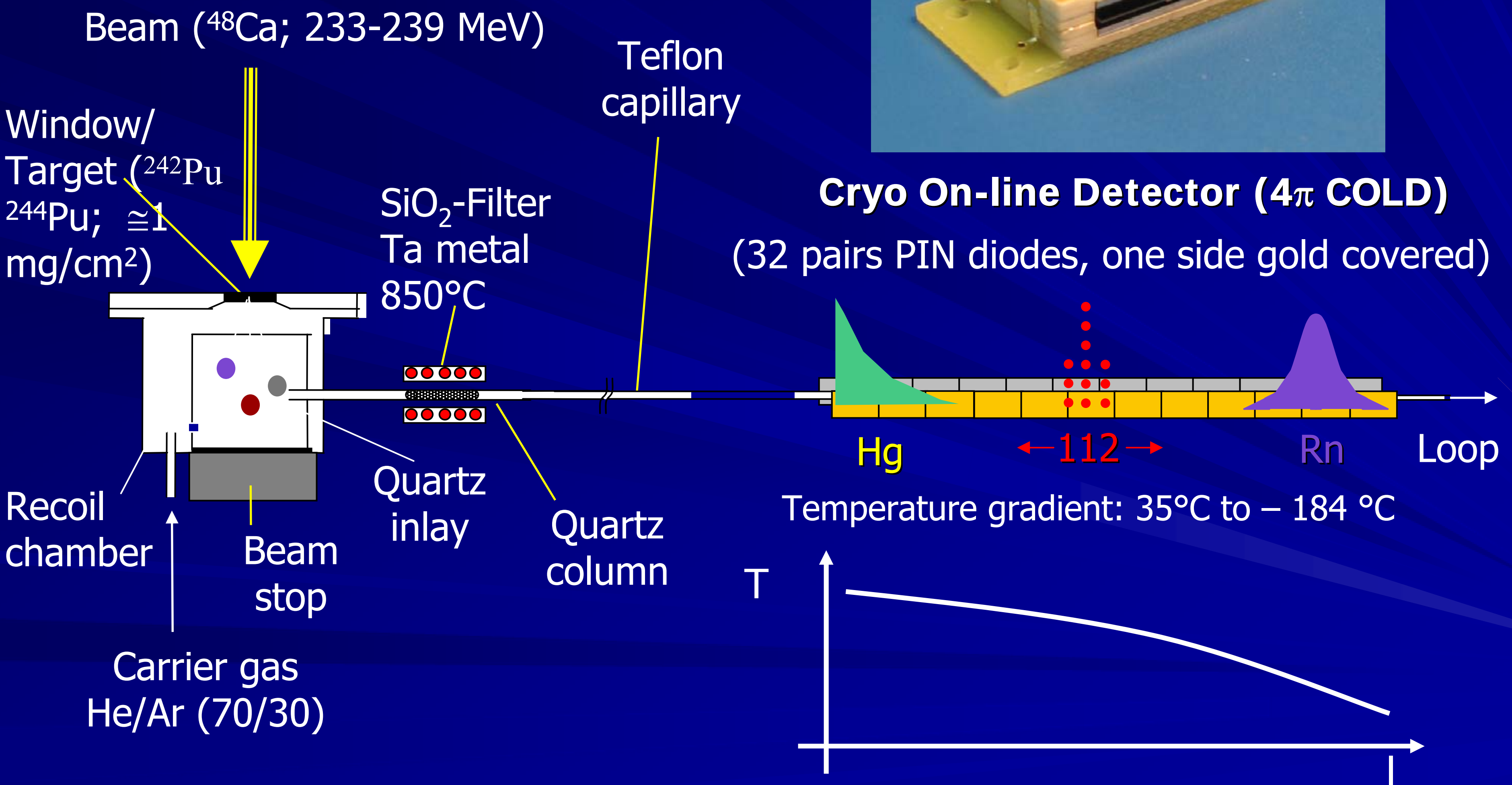


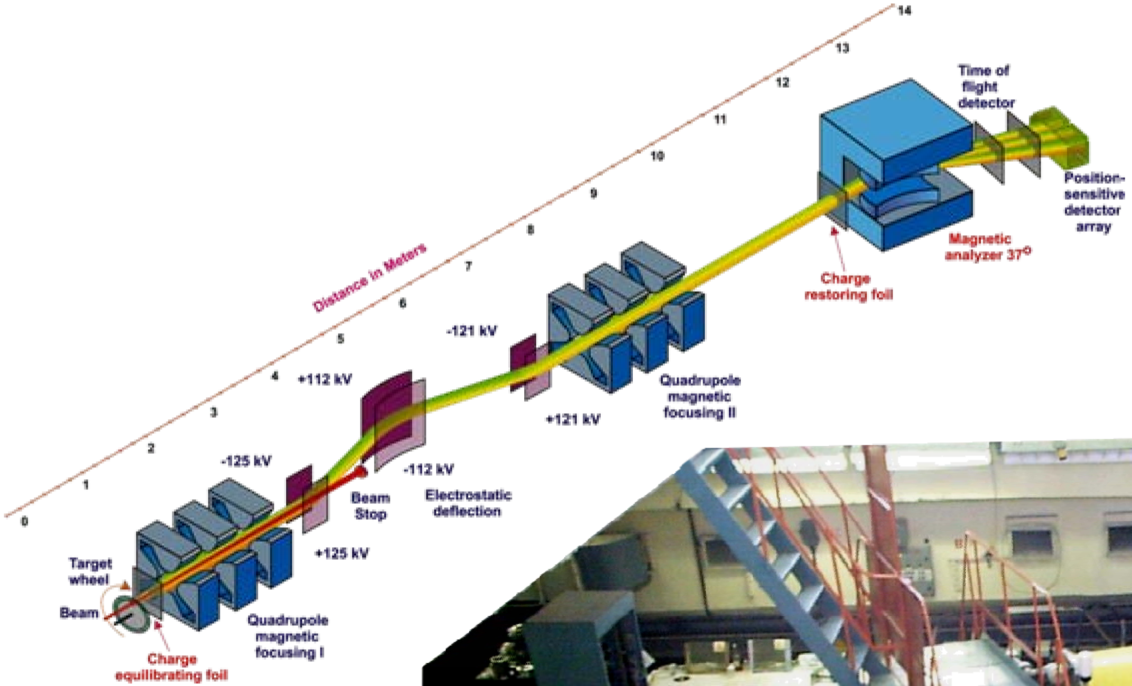
Chart of nuclides
208Pb, 209Bi + 50Ti....70Zn
48Ca + 238U....249Cf
118
117
116
115
114
113
112
Rg
Ds
Mt
Hs
Bh
Sg
Db
Rf
Lr
No
Md
Fm
Es
Cf
118/294 0.9 ms 11.65
116/290 6.8 ms 10.84
116/291 18 ms 10.74
116/292 18 ms 10.66
116/293 61 ms 10.53
115/287 32 ms 10.59
115/288 87 ms 10.46
114/286 0.13 s 10.18
114/287 0.48 s 10.02
114/288 0.80 s 9.95
114/289 2.6 s 9.82
113/282 0.07 s 10.63
113/283 0.10 s 10.12
113/284 0.48 s 10.00
112/282 0.88 ms
112/283 3.8 s 9.54
112/284 97 ms
112/285 29 s 9.16
Rg 278 4.2 ms 10.69
Rg 279 0.17 s 10.37
Rg 280 3.6 s 9.75
Ds 279 0.20 s 9.70
110/281 11 s
Mt 274 0.45 s 10.02
Mt 275 9.7 ms 10.33
Mt 276 0.72 s 9.71
Hs 275 0.19 s 9.30
Bh 270 1 min 8.93
Bh 271
Bh 272 9.8 s 9.02
Sg 271 1.9 min 8.54
Db 266 20 min
Db 267 1.2 h
Db 268 29 h
Rf 266
Rf 267 1.3 h
-7
-6
-4
Esh=-3
Z=114
Number of observed decay chains
Element 118 3
Element 116 26
Element 115 4
Element 114 43
Element 113 2
Element 112 8
A/Z
112/285
29 s
9.16
T1/2
Eα (MeV)
α
EC
β-
SF
Proton number
Neutron number
150
152
154
156
158
160
162
164
166
168
170
172
174
176
178
180
182
184

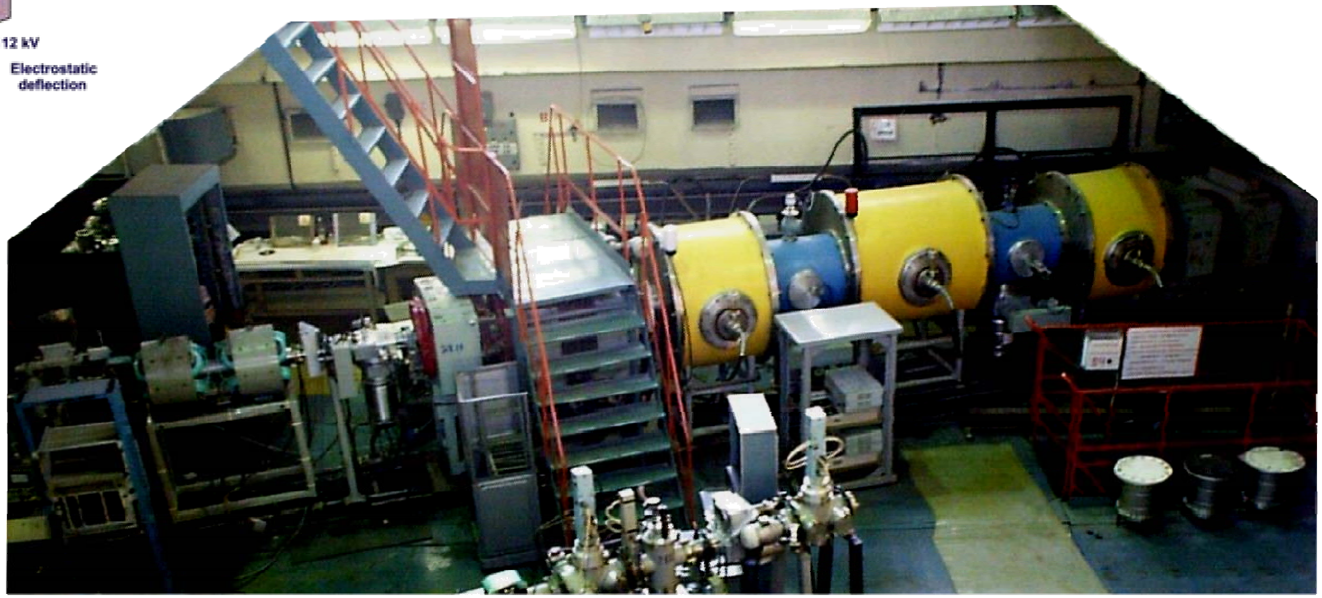
The element 112 experiment





Electrostatic separator VASSILLISA





U-400 → U-400R

1. Beam intensity of masses A ≈ 50 with energy ≈ 6 MeV/n up to 4 ρμa.

2. Smooth ion energy variation on the target

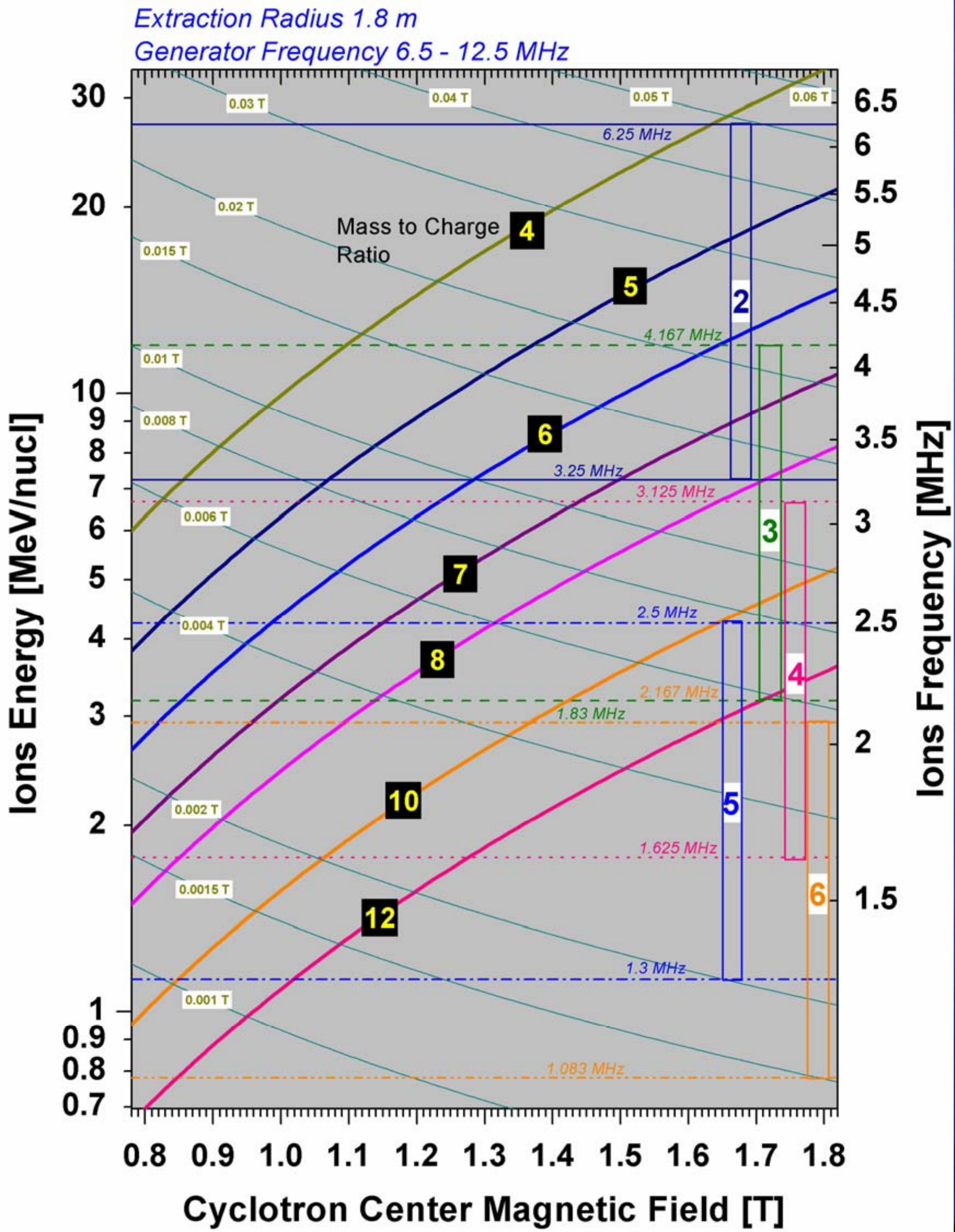
3. Variation of cyclotron average magnetic field from 0,8 up to 1,8 T.

4. Energy spread on the target up to 10^{-3}.

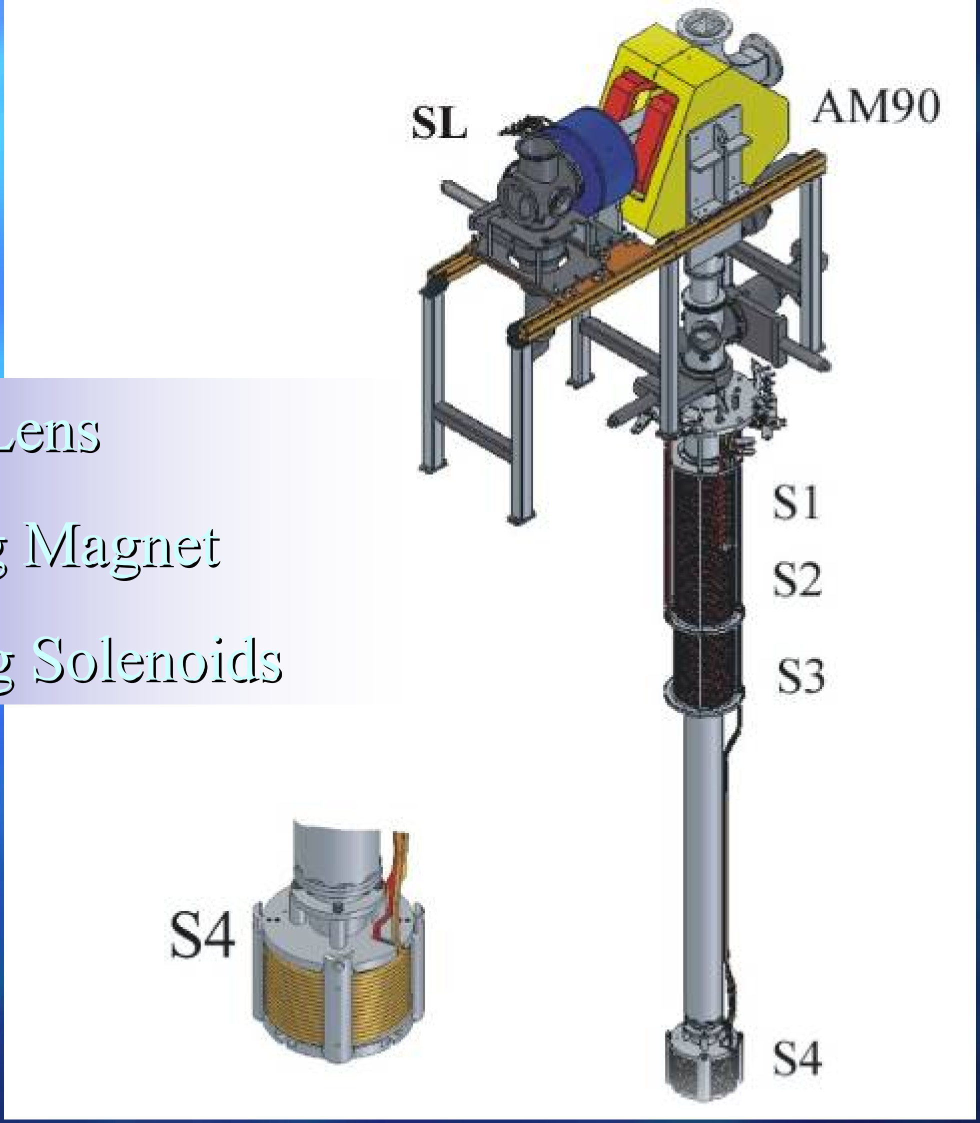
5. Beam emittance on the target – 10 π mm · mrad

6. New equipment.

Working diagram U-400R cyclotron



U400 → U400R



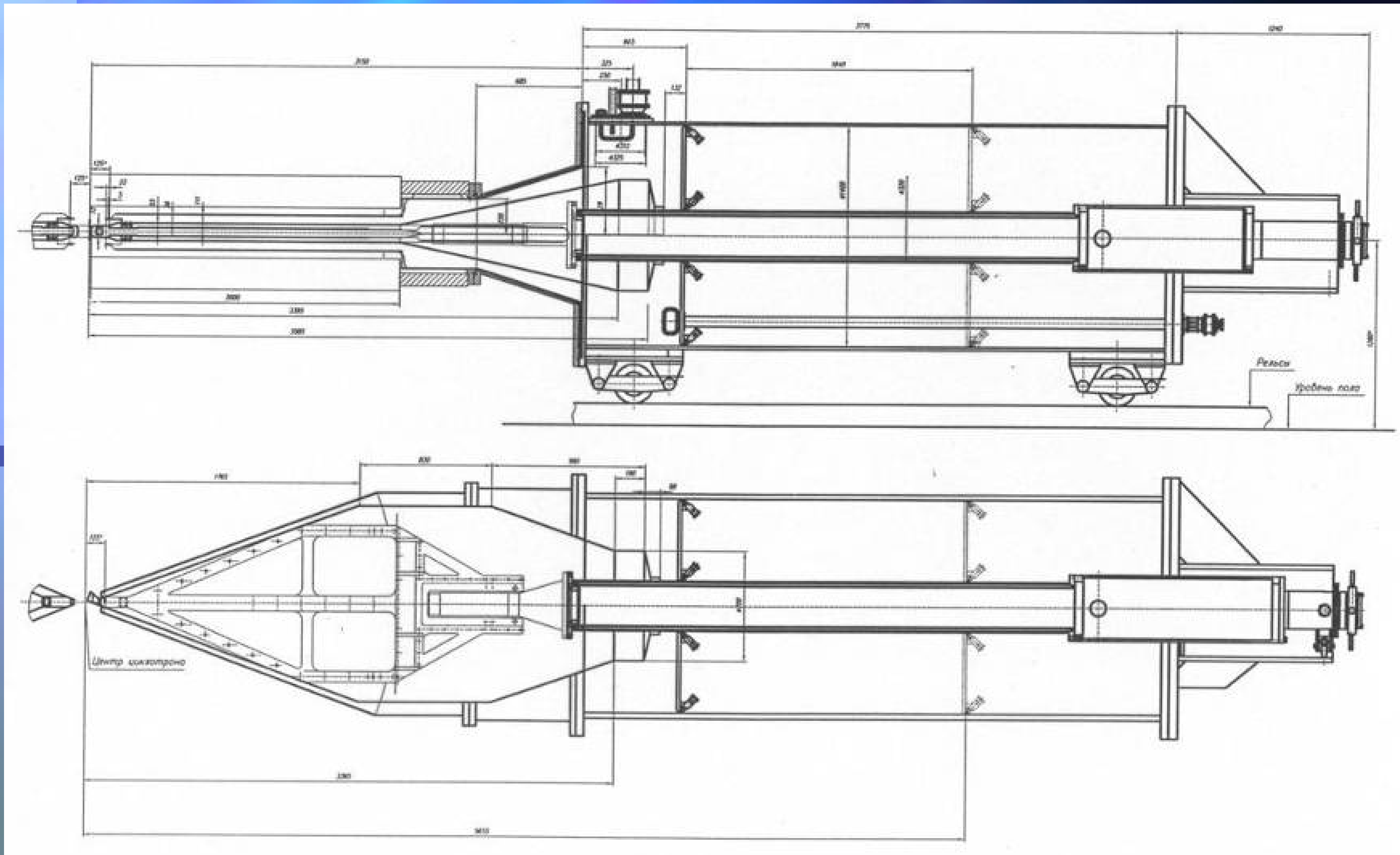
SL - Solenoidal Lens

AM90 – Bending Magnet

S1-S4 – Focusing Solenoids

Axial Injection System

U400 → U400R



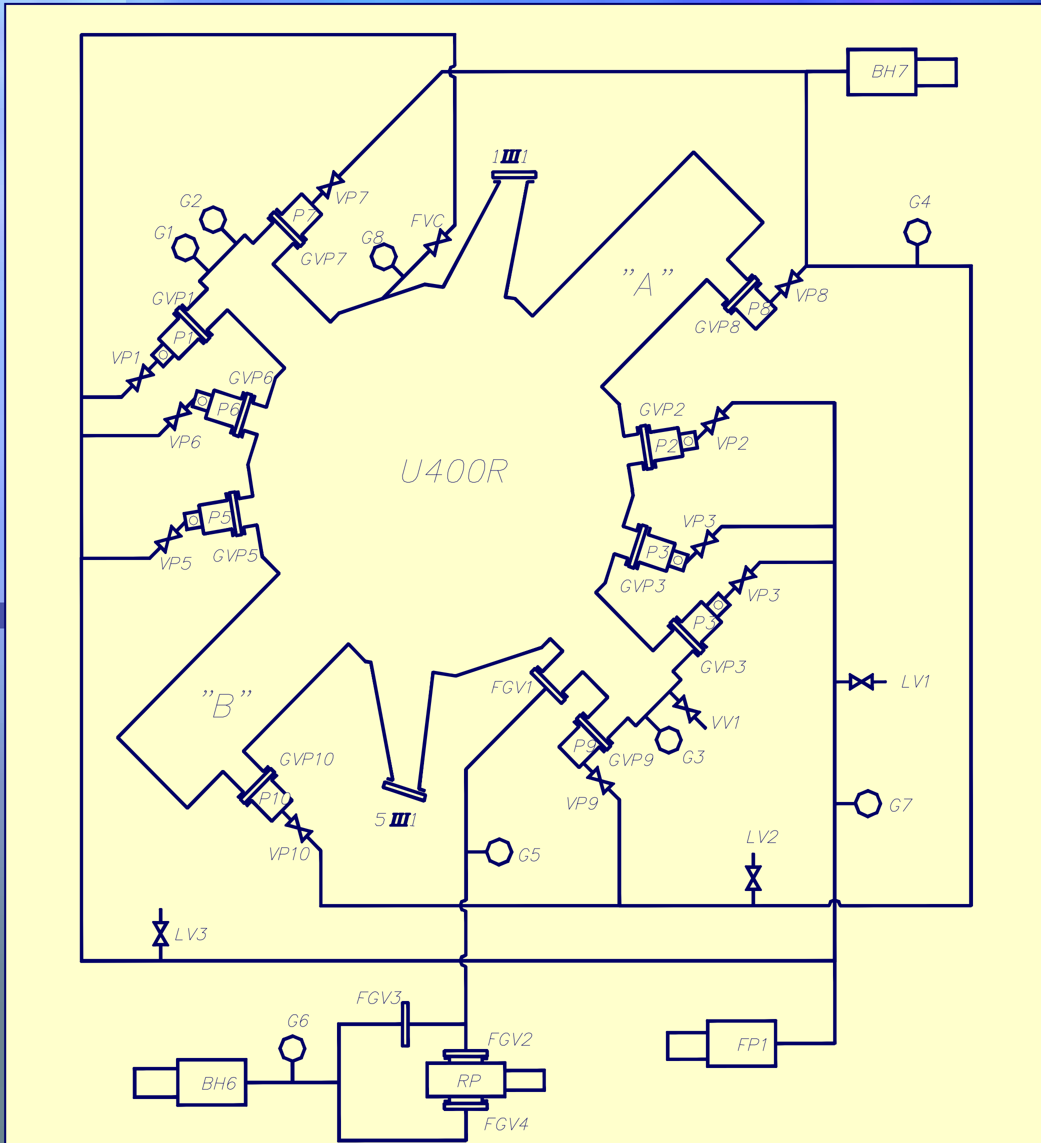
RF System

As an example - RF system of DC-60 cyclotron

- Bimetallic resonators – copper plated stainless steel

- Copper balls used as contacts on shorting plate

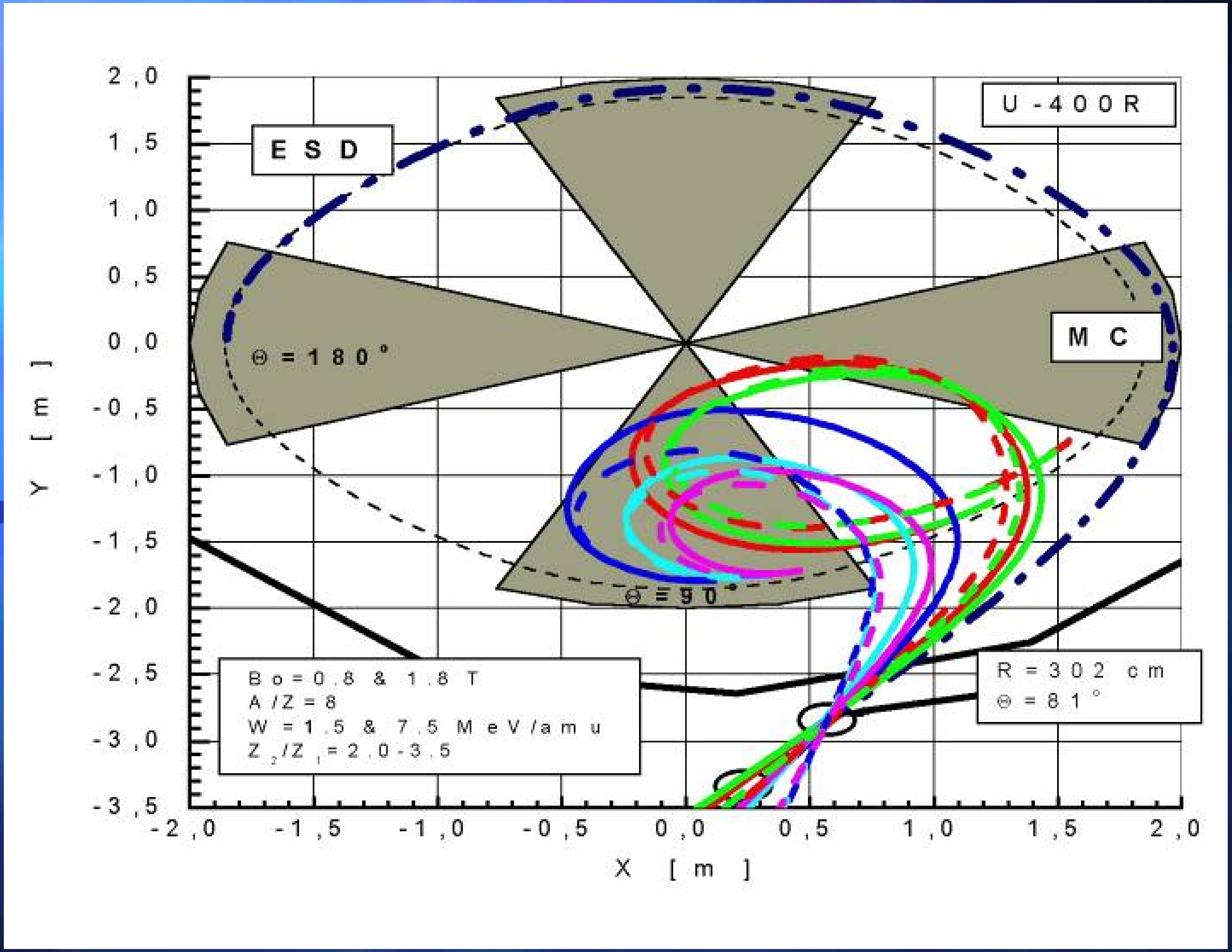
U400 → U400R



- Cryogenic pumps
  6 units - 5000 l/s
- Turbomolecular pumps
  4 units - 500 l/s

Vacuum System Scheme

U-400 → U-400R



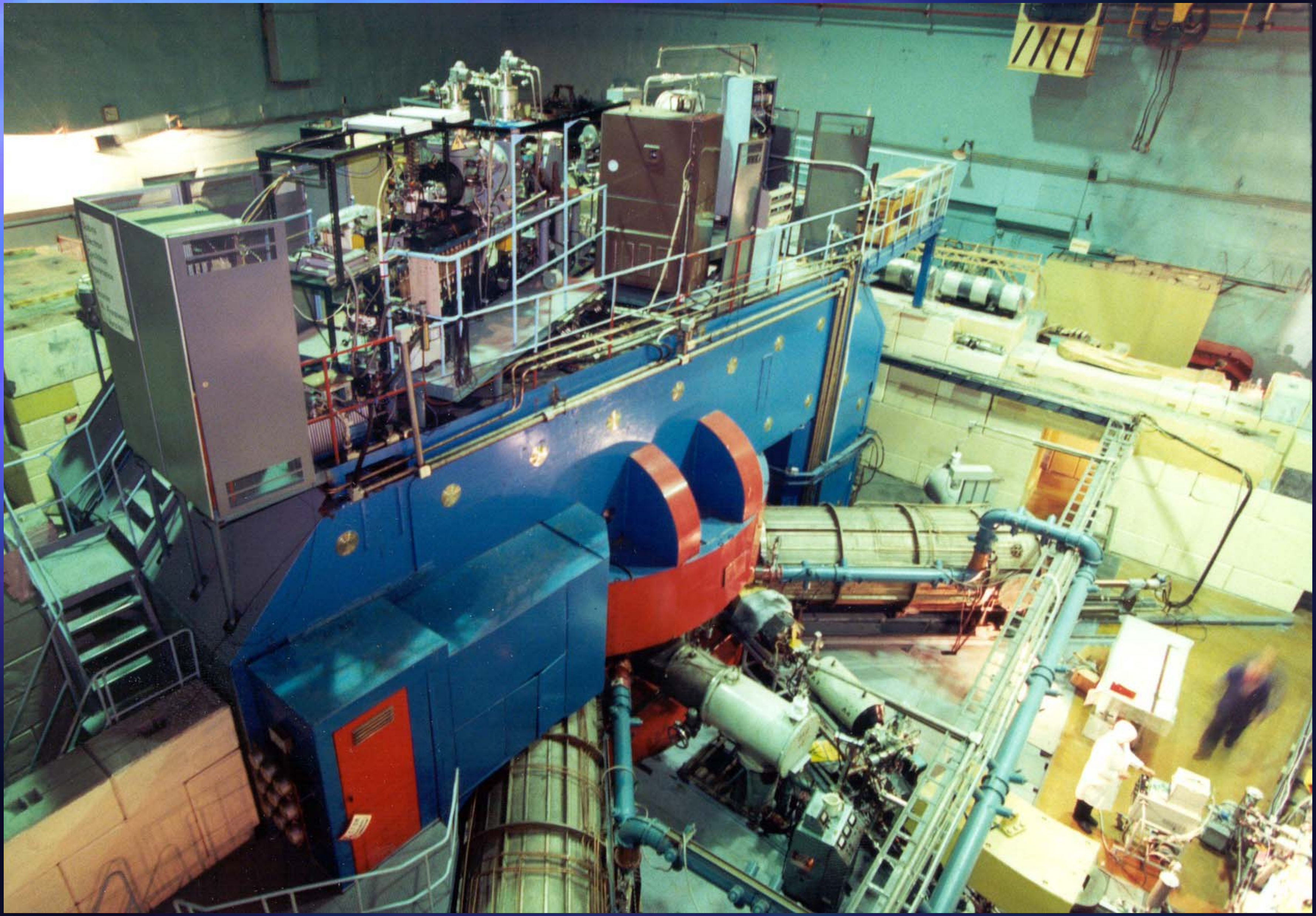
Beam Extraction by Electrostatic Deflector and by Stripping

Modernization of the U400 cyclotron (2008 – 2009)

- to improve the quality and intensity of beams of stable and radioactive nuclei ions,
- to improve the overall experiment efficiency,
- to decrease the power consumption from 1 to 0.25 MWt.

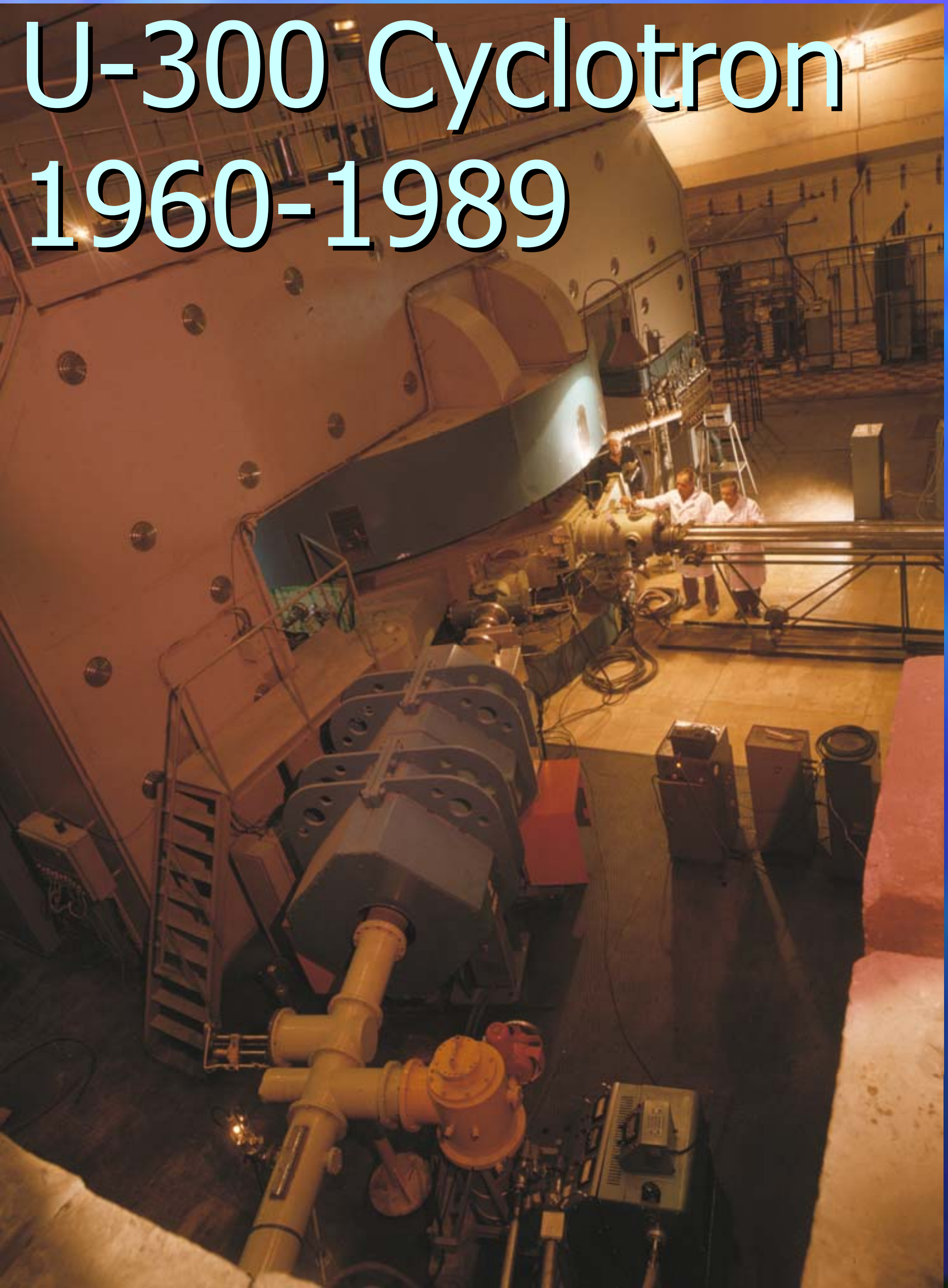
Cyclotron U400
has been operating since 1979

U-400M Cyclotron (1991)



FLEROVLAB

U-300 Cyclotron 1960-1989



1957	FOUNDATION *of* the LABORATORY
1960	CLASSICAL CYCLOTRON U300 START-UP
1963	DISCOVERY *of* **102** ELEMENT
1964	DISCOVERY *of* **104** ELEMENT
1965	DISCOVERY *of* **103** ELEMENT
1968	ISOCHRONOUS CYCLOTRON U200 START-UP
1970	DISCOVERY *of* **105** ELEMENT - DUBNIUM
1971	CYCLOTRON U300 + U200 TANDEM START-UP

1989- 1991: Reconstruction

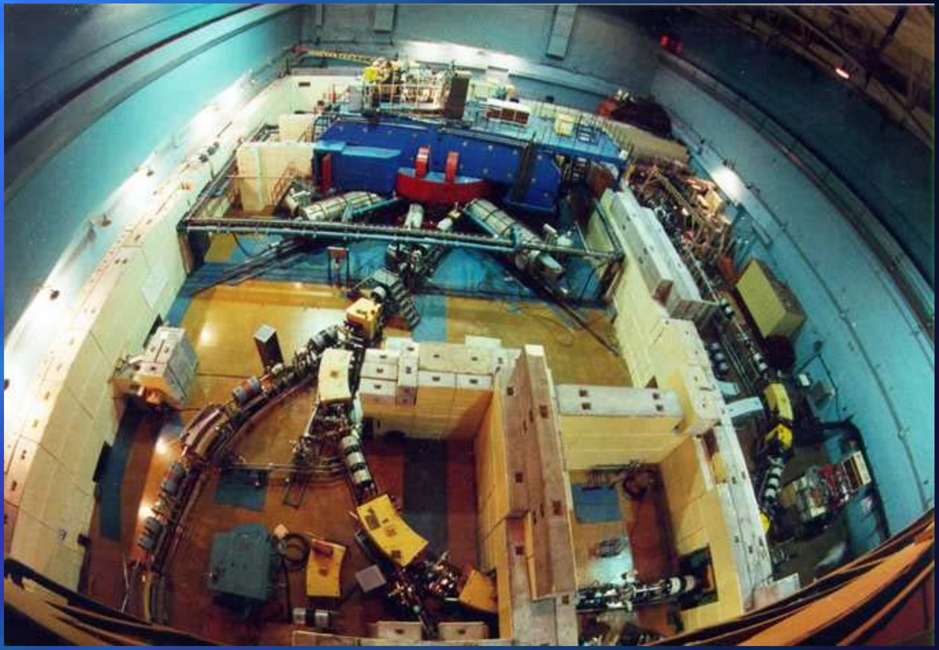
U-300→U-400M

U400M Beam parameters

Ion	E, MeV/n	I, ECR	I, extracted	I, extracted
$^{7}Li^{2+}$	35	100μA	30μA	$6*10^{13}$ pps
$^{11}B^{3+}$	32	90μA	30μA	$4*10^{13}$ pps
$^{12}C^{4+}$	47	100μA	35μA	$4*10^{13}$ pps
$^{14}N^{4+}$	35	100μA	35μA	$3*10^{13}$ pps
$^{14}N^{5+}$	54	50μA	15μA	$1.5*10^{13}$ pps
$^{18}O^{5+}$	33	100μA	30μA	$2.5*10^{13}$ pps
$^{22}Ne^{6+}$	32	50μA	15μA	$1*10^{13}$ pps
$^{22}Ne^{7+}$	43	50μA	15μA	$1*10^{13}$ pps
$^{36}S^{10+}$	33	10μA	1.7μA	$6*10^{11}$ pps
$^{40}Ar^{12+}$	40	12μA	2μA	$7*10^{11}$ pps
$^{48}Ca^{10+}$	20	10μA	1.7μA	$5*10^{11}$ pps

Modernization of the U400M cyclotron (2007-2008)

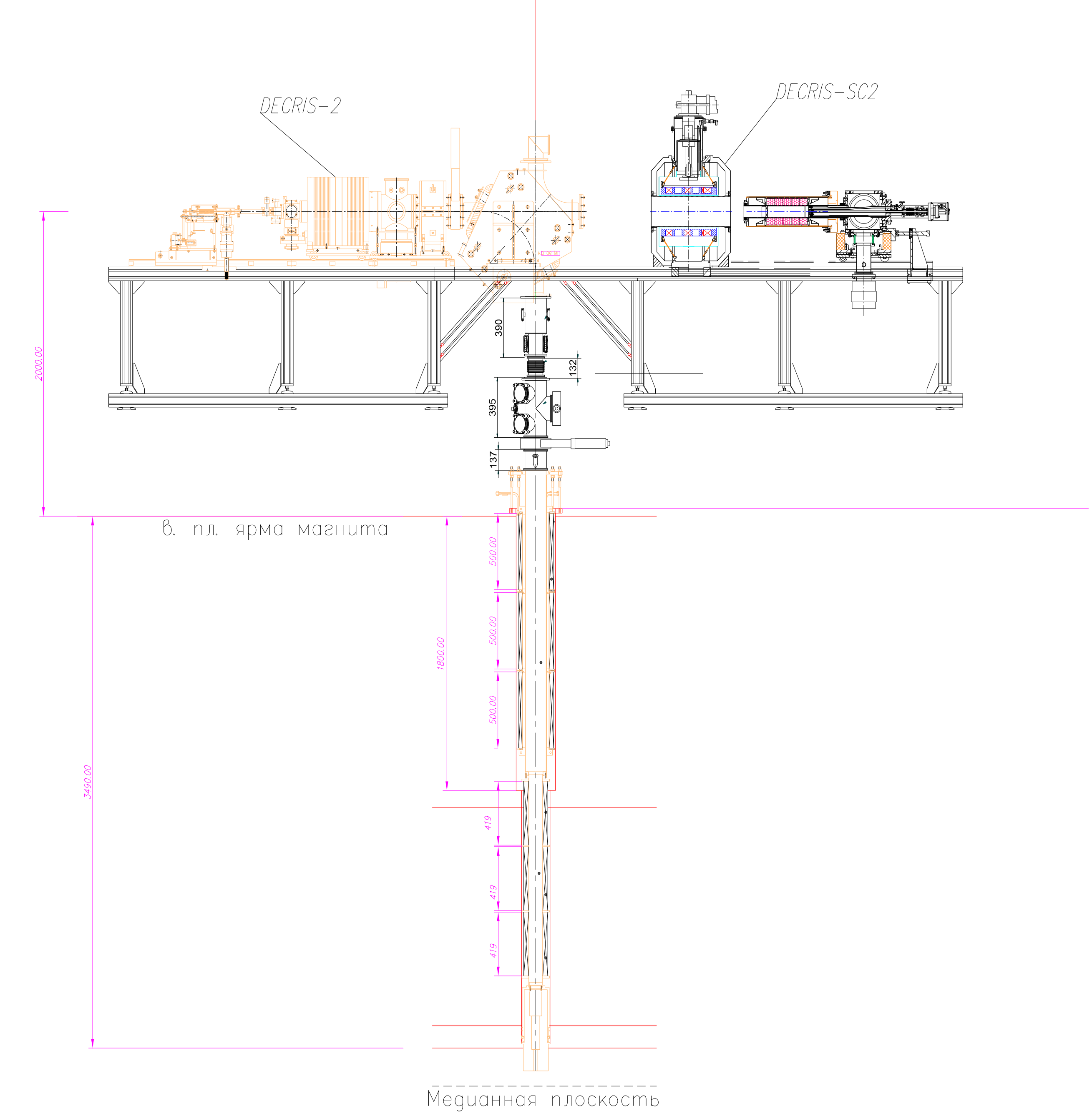
- to install new axial injection system with two ECR ion sources
- to accelerate "low" (6÷15 MeV/A) energy ions,
- to extract the beams to the second direction.



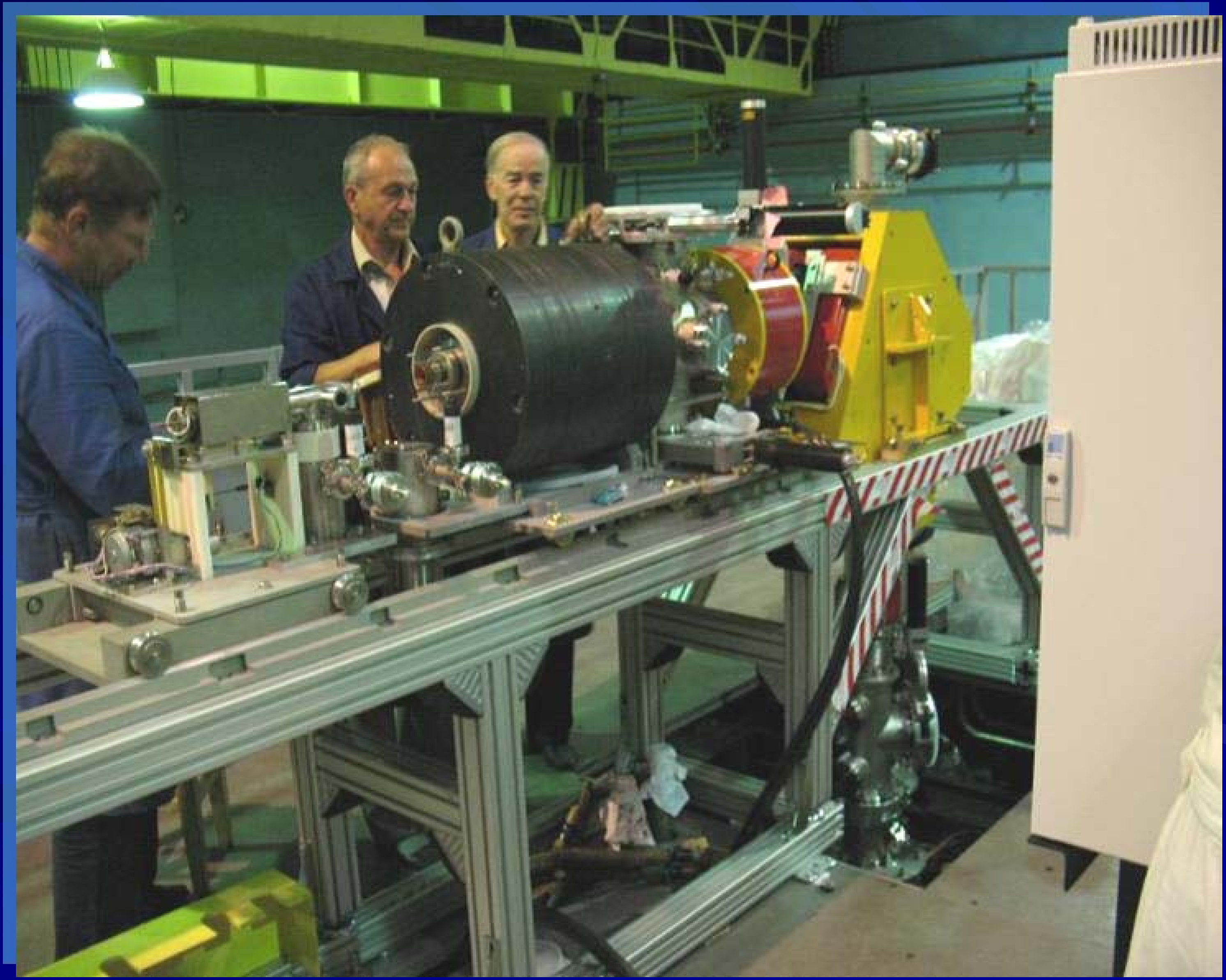
Cyclotron U400M
has been operating since 1993

U400M (2007)

Ion sources and axial injection

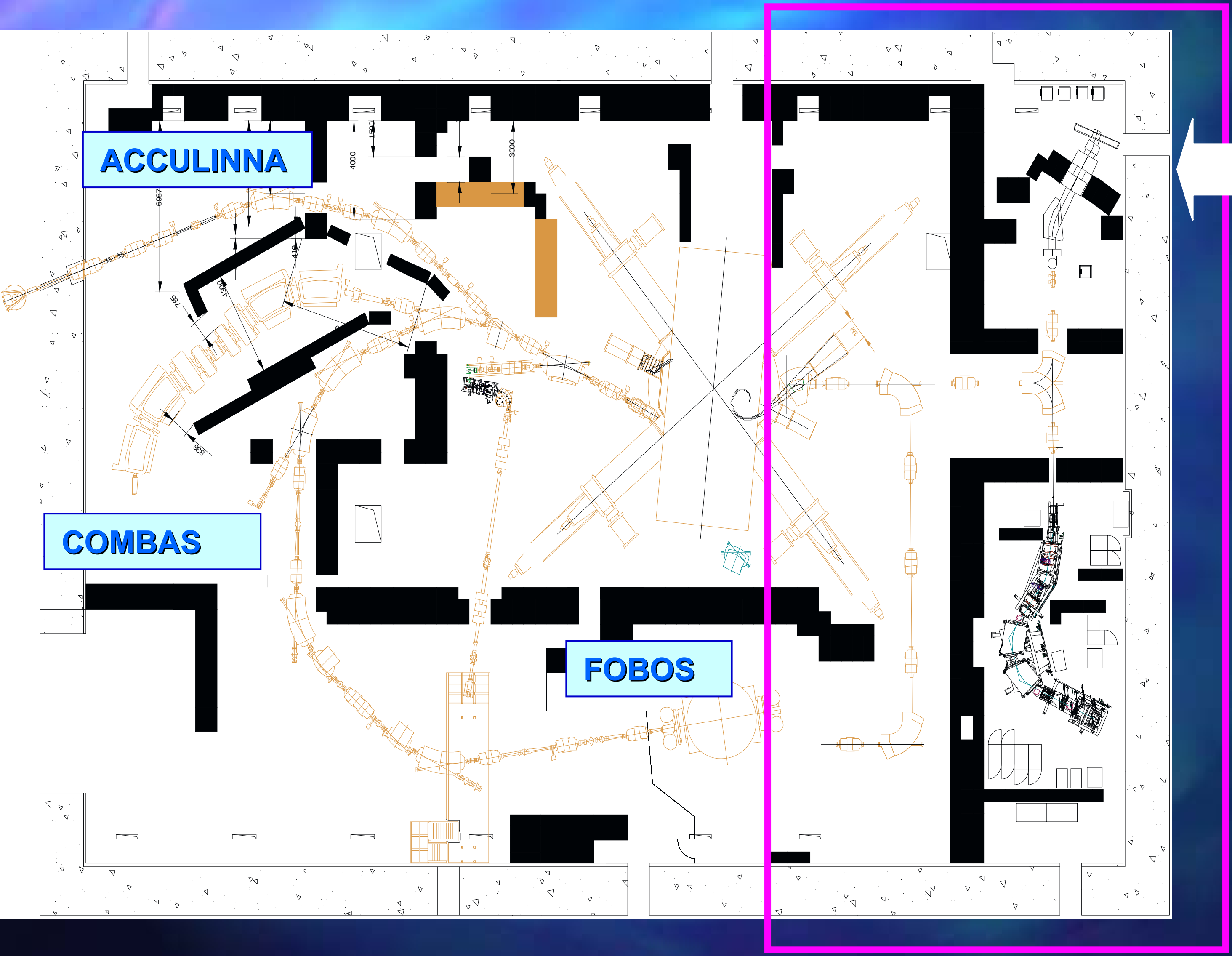


Mounting of new axial injection system of U400M cyclotron



DECRIS-SC2 on test bench

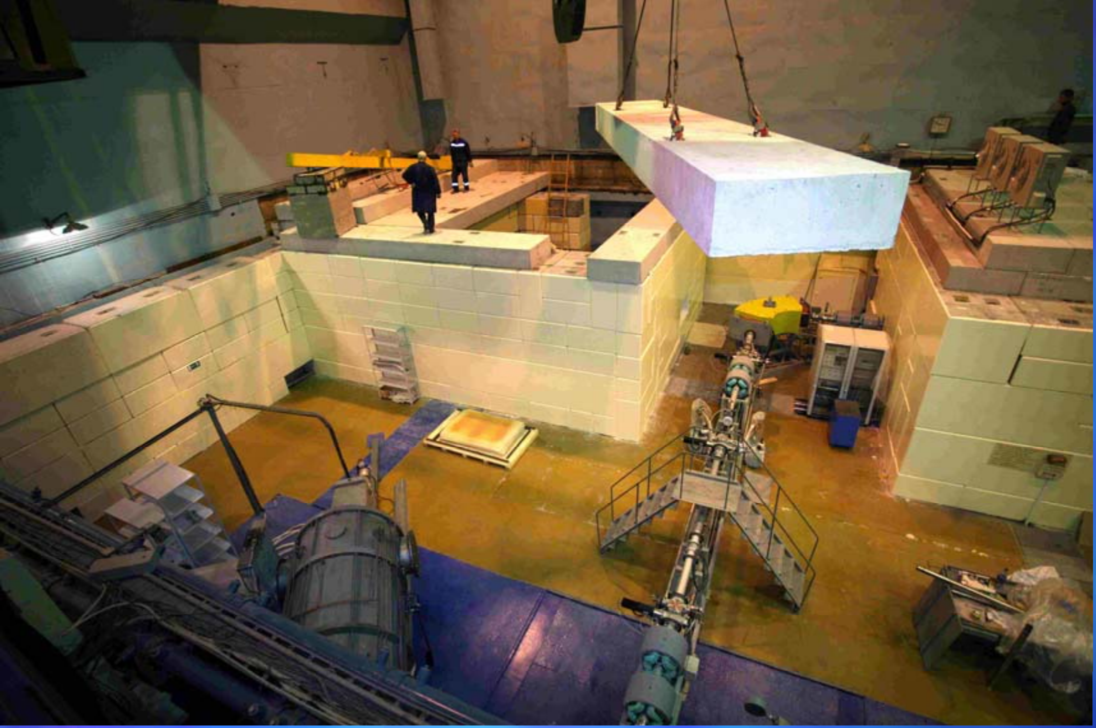
New experimental set-ups at U400MR

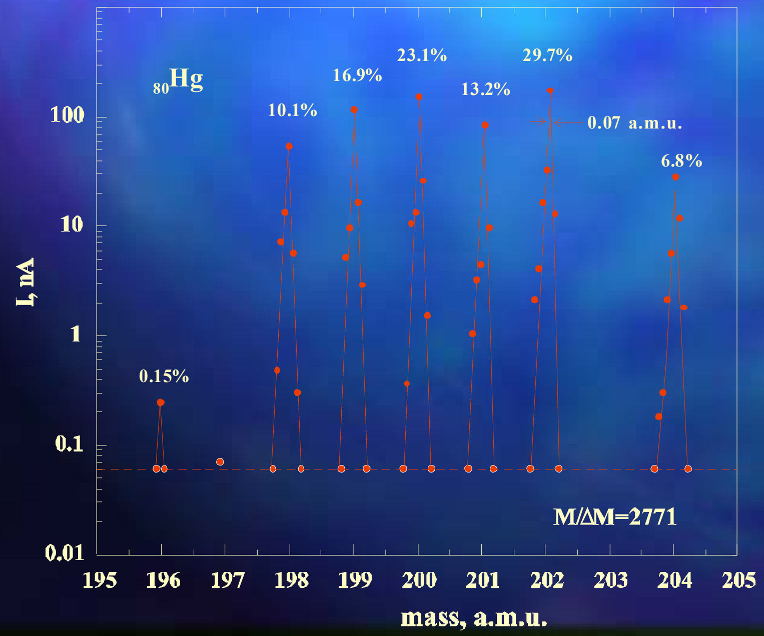


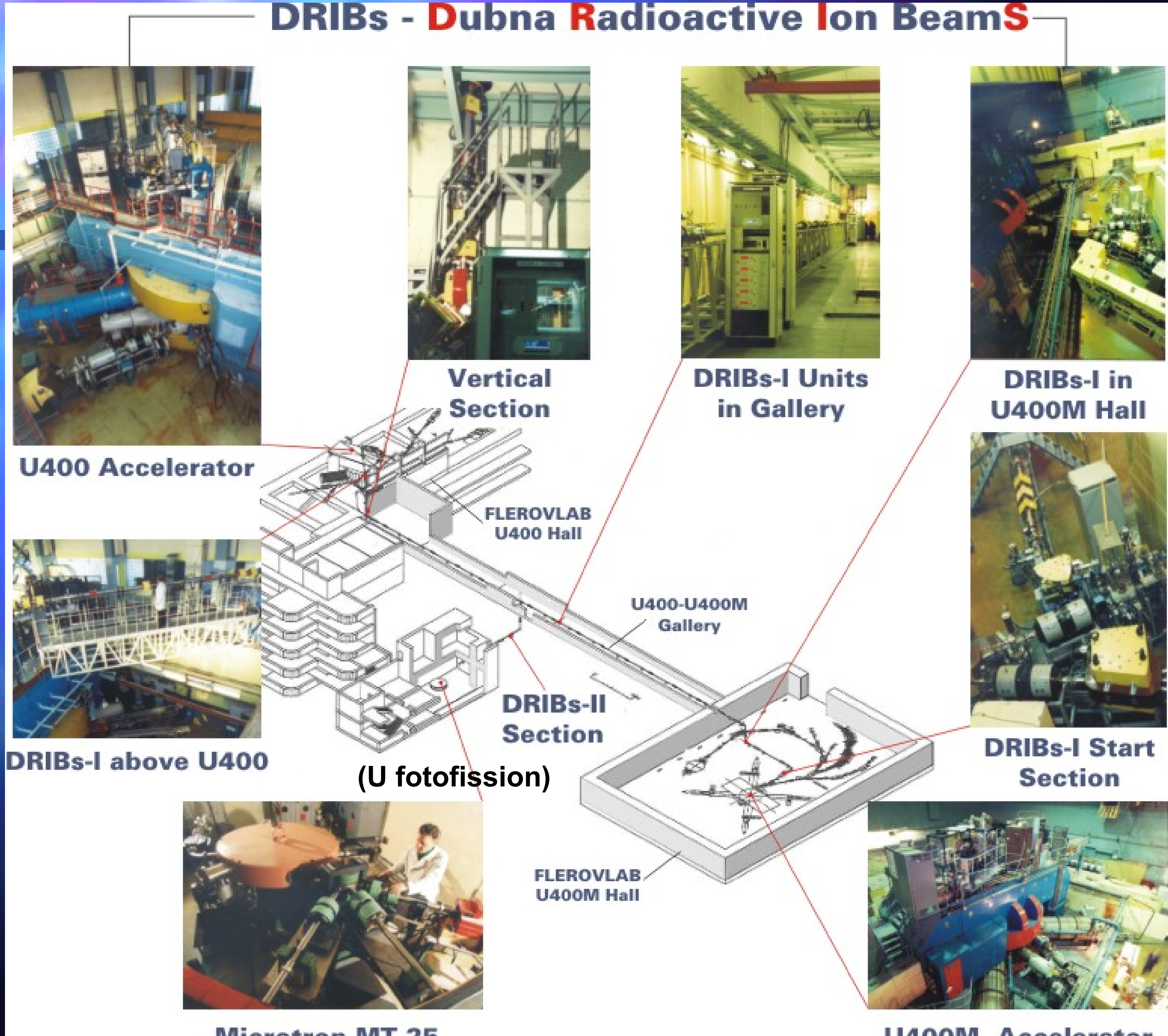
Installation for chemical identification and study of properties of superheavy elements

MASHA

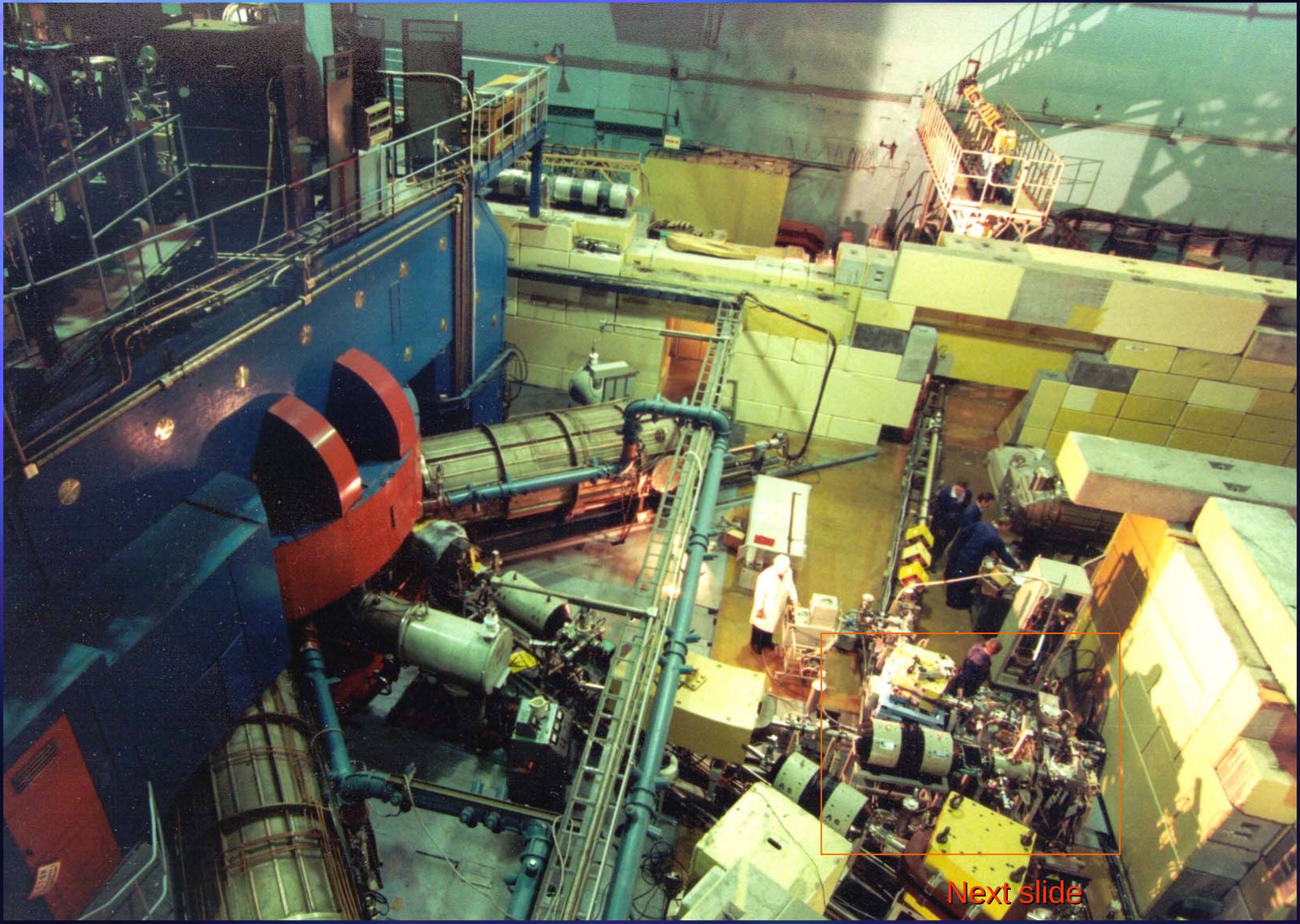
Launching of MASHA as on-line separator at the beams of U400MR (2007 – 2008);





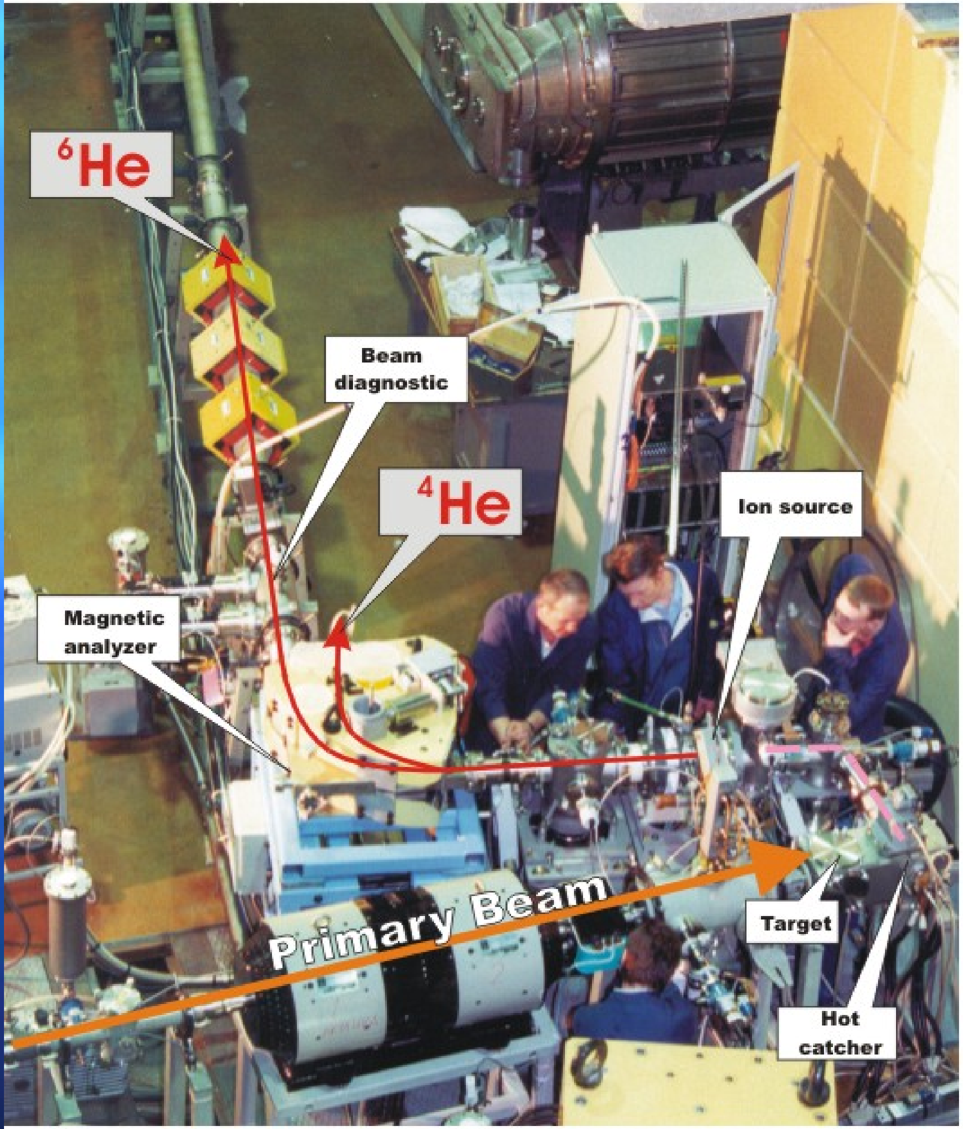

DRIBs - Dubna Radioactive Ion BeamS
Vertical Section
DRIBs-I Units in Gallery
DRIBs-I in U400M Hall
U400 Accelerator
FLEROVLAB U400 Hall
U400-U400M Gallery
DRIBs-II Section
DRIBs-I above U400
(U fotofission)
DRIBs-I Start Section
FLEROVLAB U400M Hall
Microtron MT-25
U400M Accelerator

U400M Cyclotron with DRIBs Complex



DRIBs - Project

Transformation of the primary beam into a low energy radioactive ion beam



FLNR (JINR) Feb. 2001

DRIBs Accelerated Complex

RIB facilities: ^{6}He, ^{8}He beam intensities

		DRIBS
^{6}He 808 ms	RIB	~ 10^{8} pps 11 MeV/n
	Primary beam Target	7Li; 10 μA 32 MeV/n Be
^{8}He 119 ms	RIB	~ 10^{5} pps (expected) 6÷8 MeV/n
	Primary beam Target	11B; 10 μA 34 MeV/n Be

DRIBs Accelerated Complex

Generation on U400M and acceleration on U400 ^{6}He $t_{1/2}$=800 msec

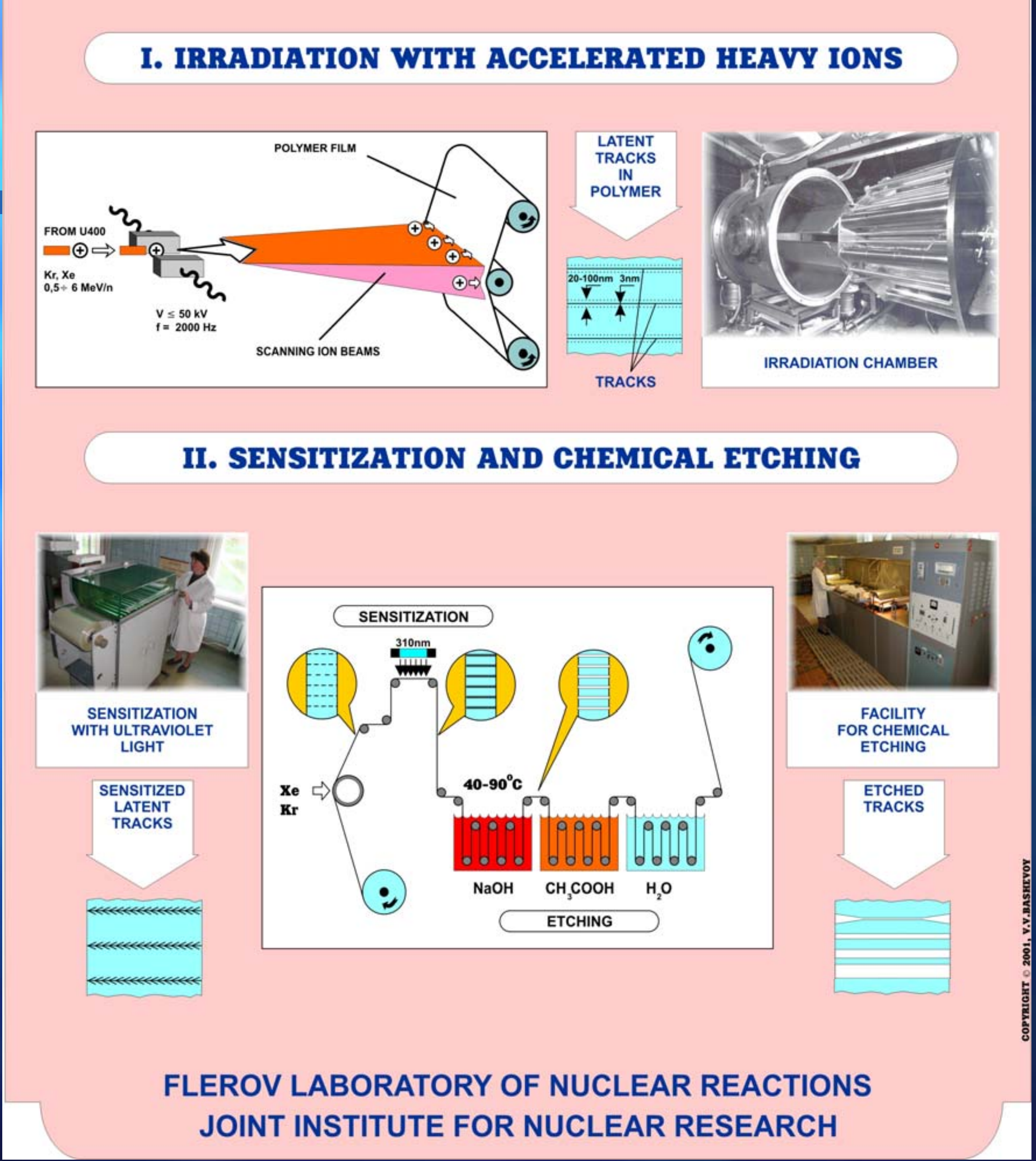
Process	Time, sec		Efficiency	
	Project	Test	Project	Test
Σ_1-difussion from carbon catcher (1μ)	50×10^{-3}	50×10^{-3}	1	1
Σ_2-transport to ion source (1 m x Ø 0,1 m)	20×10^{-3}	20×10^{-3}	1	1
Σ_3-ionization 1+ and separation	1×10^{-3}	$(50 \div 130) \times 10^{-3}$	0,5	0,1
Σ_4-transport ^{6}He 1+ (120 m length)	2×10^{-4}	2×10^{-4}	0,8	0,23
Σ_5-acceleration capture	0	0	0,5	0,4
Σ_6-acceleration	50×10^{-6}	50×10^{-6}	1	0,8
Σ_Σ	70×10^{-3}	$(120 \div 200) \times 10^{-3}$	15×10^{-2}	$0,736 \times 10^{-2}$

$$\frac{\sum \Sigma\, project}{\sum \Sigma\, test} = 20$$

Track membranes and applied research

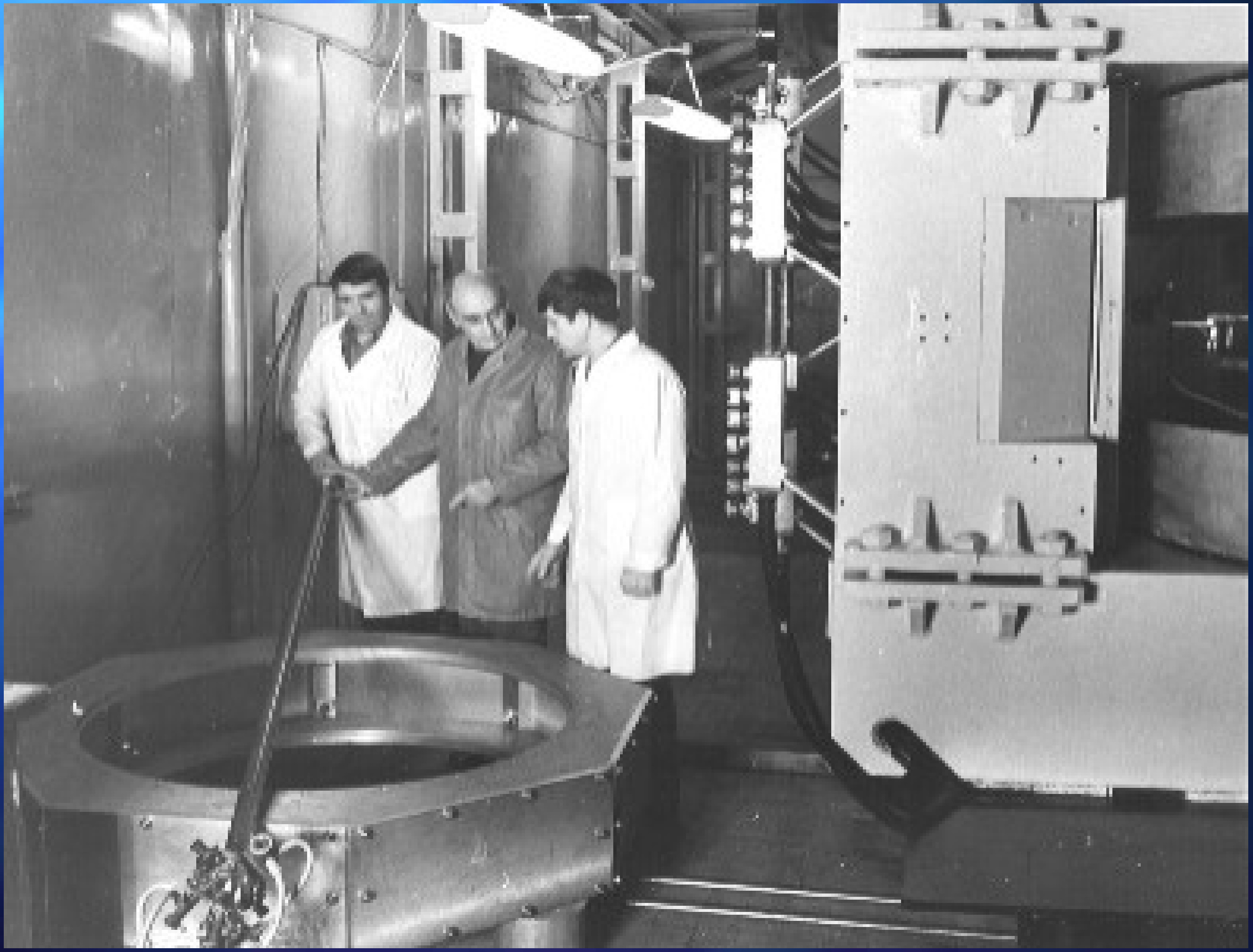
Flerov Laboratory of Nuclear Reactions

Track membrane production technology

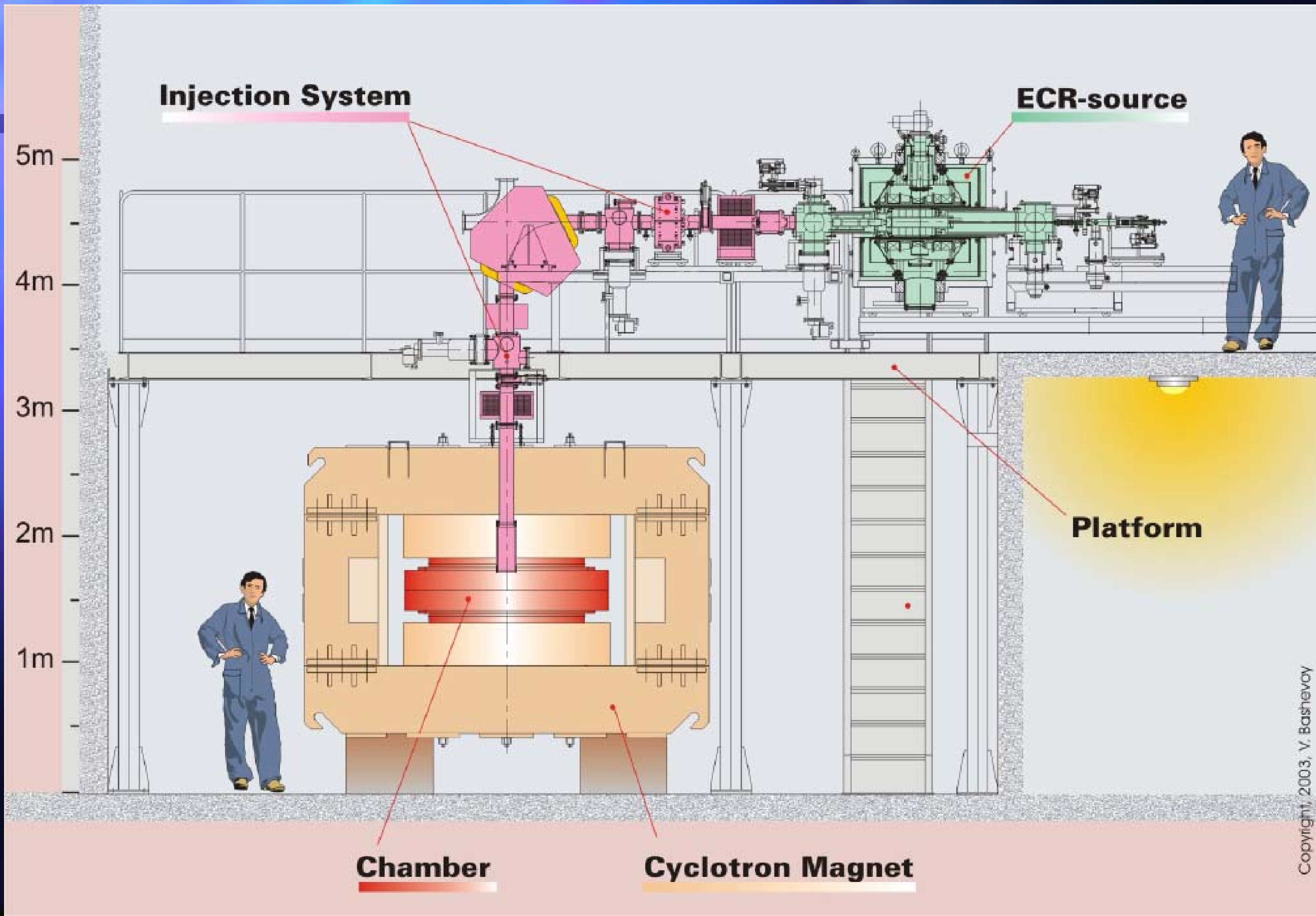


Track membrane production technology

IMPLANTING CYCLOTRON IC-100
History pages 1985

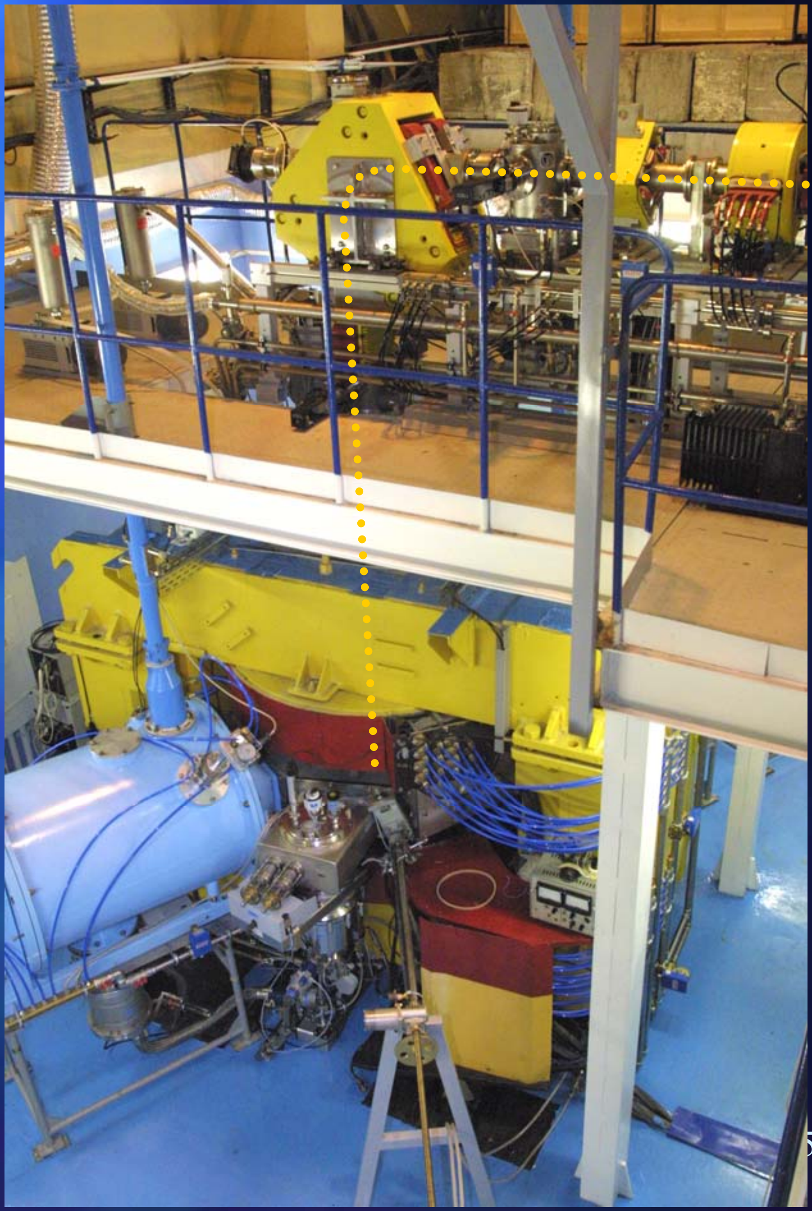


IC-100 Cyclotron (2002-2003)



IC-100 CYCLOTRON

Axial Injection System



Intensity of the accelerated and extracted ion beams (IC-100 cyclotron, February 2007).

Element	Ion	A/Z	F_{HF} MHz	Target beam current in the experiments	Maximum beam current
Neon	$^{22}Ne^{+4}$	5.5	20.160	0.7 μA	
Argon	$^{40}Ar^{+7}$	5.714	20.200	2.5 μA	
Iron	$^{56}Fe^{+10}$	5.6	20.240	0.5 μA	
Krypton	$^{86}Kr^{+15}$	5.733	20.200	3.5 μA	3.5 μA
Iodine	$^{127}I^{+22}$	5.773	20.200	0.25 μA	
Xenon	$^{132}Xe^{+23}$	5.739	20.180	3.7 μA	3.7 μA
Xenon	$^{132}Xe^{+24}$	5.5	20.180	0.6 μA	
Tungsten	$^{182}W^{+32}$	5.6875	20.142	0.015 μA	0.015 μA
Tungsten	$^{184}W^{+31}$	5.9355	20.142	0.035 μA	0.035 μA
Tungsten	$^{184}W^{+32}$	5.75	20.142	0.017 μA	0.017 μA

NEW ACCELERATOR PROJECTS

DC-72 CYCLOTRON

multi-purpose cyclotron for Cyclotron Centre of Slovak Repablic (CC SR) in Bratislava (Slovakia) (delivery stage)

The main field of DC-72 cyclotron application:

- Nuclear medicine:
  - Production of short lived radioisotopes for PET and SPECT diagnostic - ^{123}I, ^{81}Rb, ^{201}Tl in (p, xn) reactions
  - Production α-emitters (^{211}At in (α, xn) reactions) for radiotherapy
  - Development of Borum Neutron Capture Therapy (BNCT).
  - Neutron therapy.
  - Eyes proton therapy by 72 Mev proton beam.
- Investigation at the heavy ion beams
  - Production of polymer track membranes
  - Surface modification of standard materials
  - Nuclear, atomic and solid state research

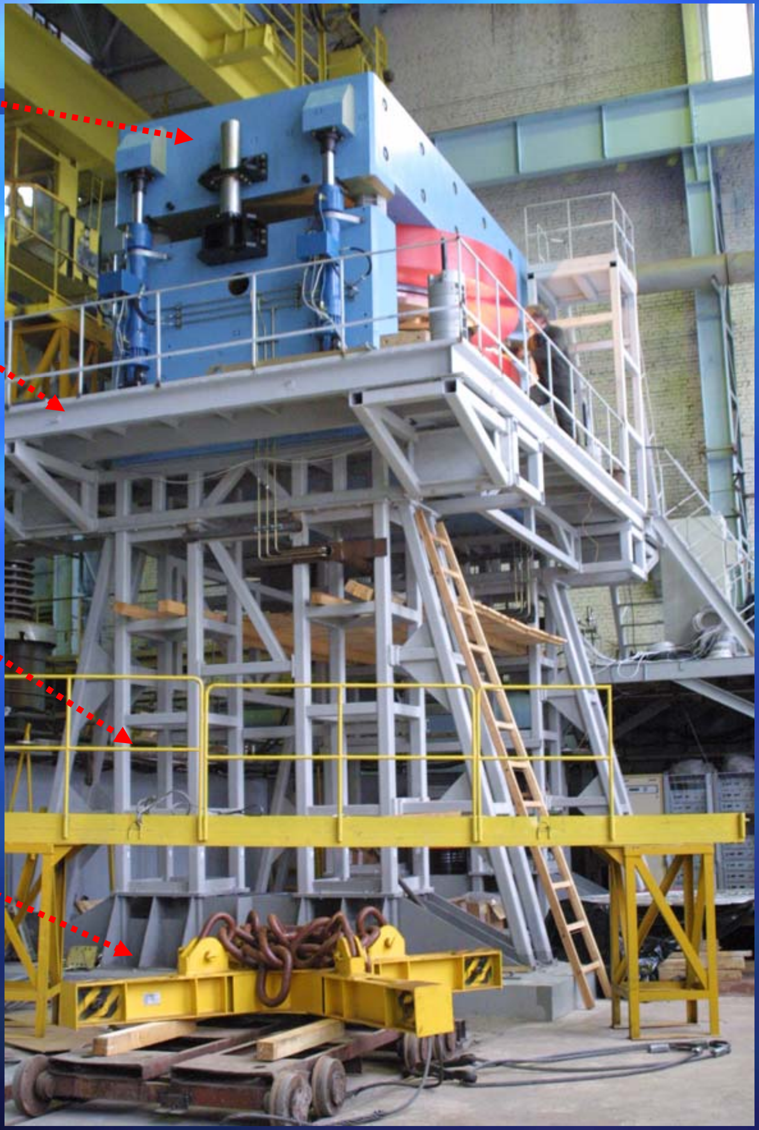
DC-72 CYCLOTRON

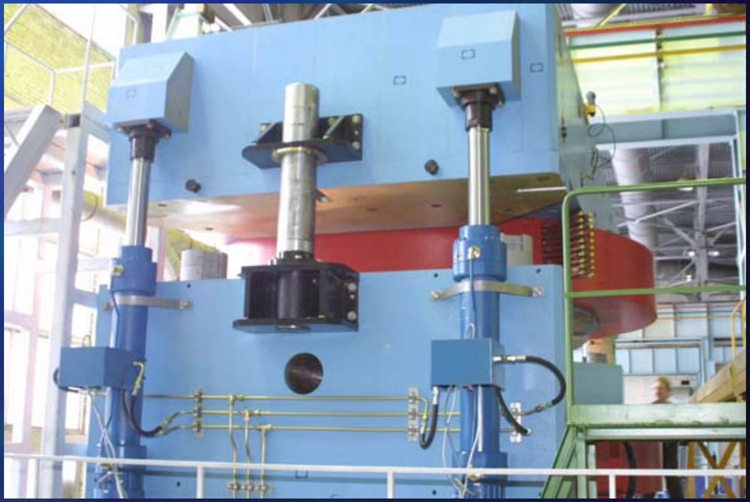
Parameters of Accelerated Ion Beams

Accelerated Ion	Energy, MeV/nucl	Maximal intensity of the extracted beams (eμA)	(pps)
H^-	72 - 36	50	$3 \cdot 10^{14}$
$^{2}H^{1+}$	30 - 15	100	$6 \cdot 10^{14}$
D^-	30 - 15	50	$3 \cdot 10^{14}$
$^{3}He^{1+}$	14 - 7	50	$1{,}5 \cdot 10^{14}$
$^{4}He^{1+}$	8,6 - 4,3	50	$1{,}5 \cdot 10^{14}$
$^{7}Li^{1+}$	2,8 - <2	3	$6 \cdot 10^{12}$
$^{12}C^{3+}$	8,6-4,3	20	$2 \cdot 10^{13}$
$^{14}N^{3+}$	6,2 - 3,1	20	$1{,}7 \cdot 10^{13}$
$^{16}O^{4+}$	8,6 - 4,3	20	$1{,}5 \cdot 10^{13}$
$^{20}Ne^{5+}$	8,6 - 4,3	20	$1{,}2 \cdot 10^{13}$
$^{40}Ar^{8+}$	5,6 - <2	10	$3 \cdot 10^{12}$
$^{84}Kr^{12+}$	2,8 - <2	3	$7 \cdot 10^{11}$
$^{129}Xe^{18+}$	2,7 - <2	1	$1{,}6 \cdot 10^{11}$

DC-72 CYCLOTRON

Underside View of Magnet





DC-60 CYCLOTRON

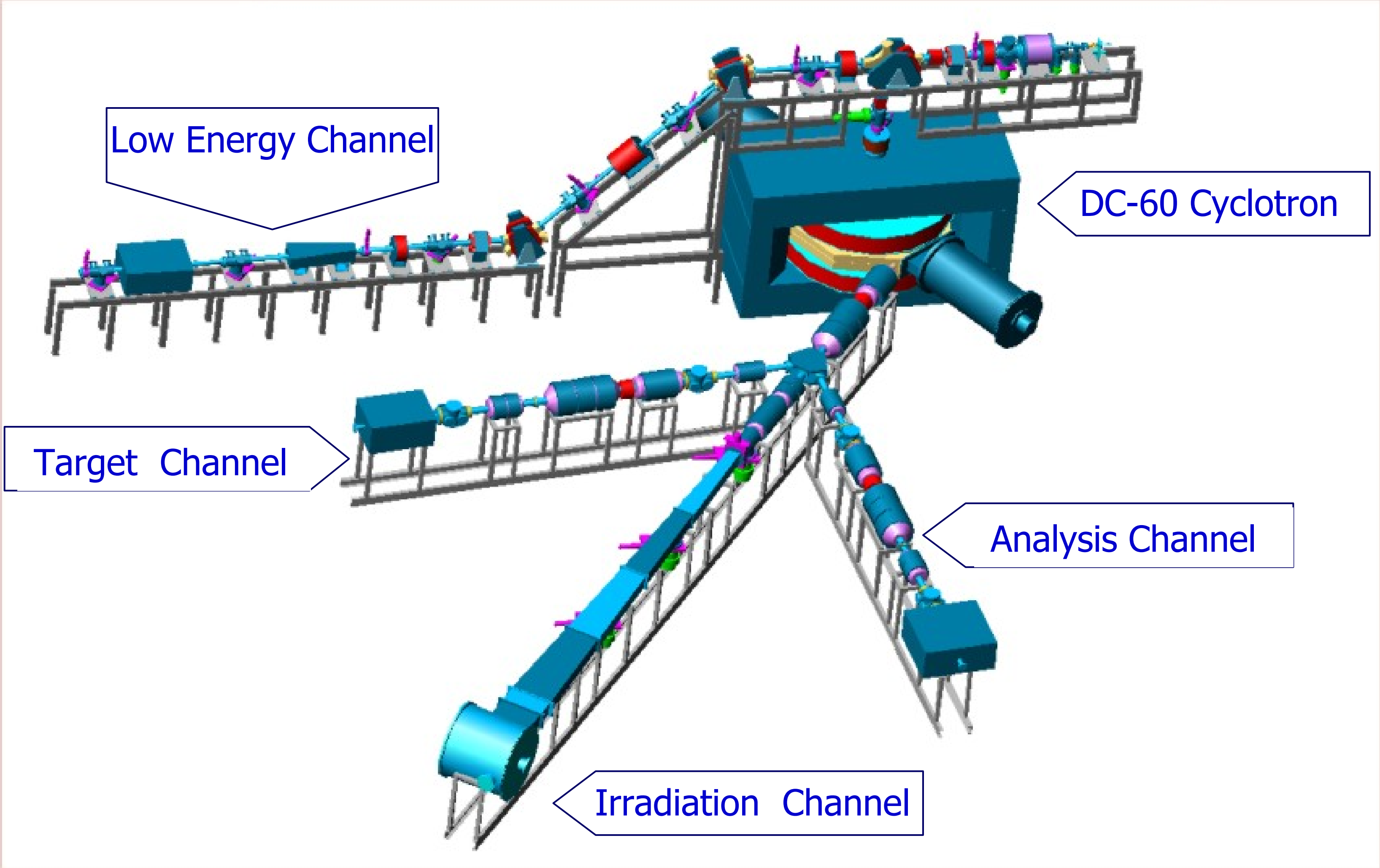
created by FLNR for Research Center of State University in Astana, Kazakhstan

MAIN OBJECTIFS

- PRODUCTION OF TRACK MEMBRANS WITH SPECIAL PROPERTIES
- CREATION OF MICRO- AND NANOSRUCTURES
- SURFACE MODIFICATION OF STANDARD MATERIALS, CREATION OF NEW MATERIAL WITH REQUIRED PROPERTIES
- EDUCATION OF STUDENTS

DC-60 CYCLOTRON: MAIN VIEW

Flerov laboratory of nuclear reactions



DC-60 CYCLOTRON

MAIN ACCELERATED ION BEAM PARAMETERS

Ions	Li ÷ Xe
Mass to charge ratio A/Z	6 ÷ 12
Accelerated ion energy	0.35 ÷ 1.7 MeV/nucleon
Energy spread	2 %
Discrete ion energy change	Due to A/Z ratio
Smooth energy variation with respect to nominal one	-25 % / +25% Due to magnetic field variation

DC-60 CYCLOTRON

LOW ENERGY ION BEAM PARAMETERS

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

DC-60 CYCLOTRON

DC-60 CYCLOTRON

CYCLOTRON CENTRE BUILDING

DC-350 CYCLOTRON

project designed for scientific centre in Almaty, Kazakhstan

MAIN FIELDS OF PHYSICAL RESEARCHES AT DC-350 ION BEAMS

Fundamental investigations

- Synthesis and study properties of superheavy elements
- Radiochemistry laboratory for identification and study of chemical properties of the synthesized elements

Applied researches

- Track membranes and their application
- Modification of materials surface
- Ion-implantation nanotechnology

DC-350 CYCLOTRON

ACCELERATED ION BEAMS PARAMETRS

Ions	Li ÷ U
Mass to charge ratio (A/Z)	3 ÷ 6
Ion energy	3 ÷ 12 MeV/nucl
Energy spread	$\pm (1 \div 5) \cdot 10^{-3}$
Discrete ion energy change	due to ion charge change (A/Z)
Smooth ion energy variation from nominal	40% due to magnetic field variation
Beam emittance	20 π mm mrad
Maximum beam intensity	3×10^{13} pps
Maximum beam power	~ 2 кW

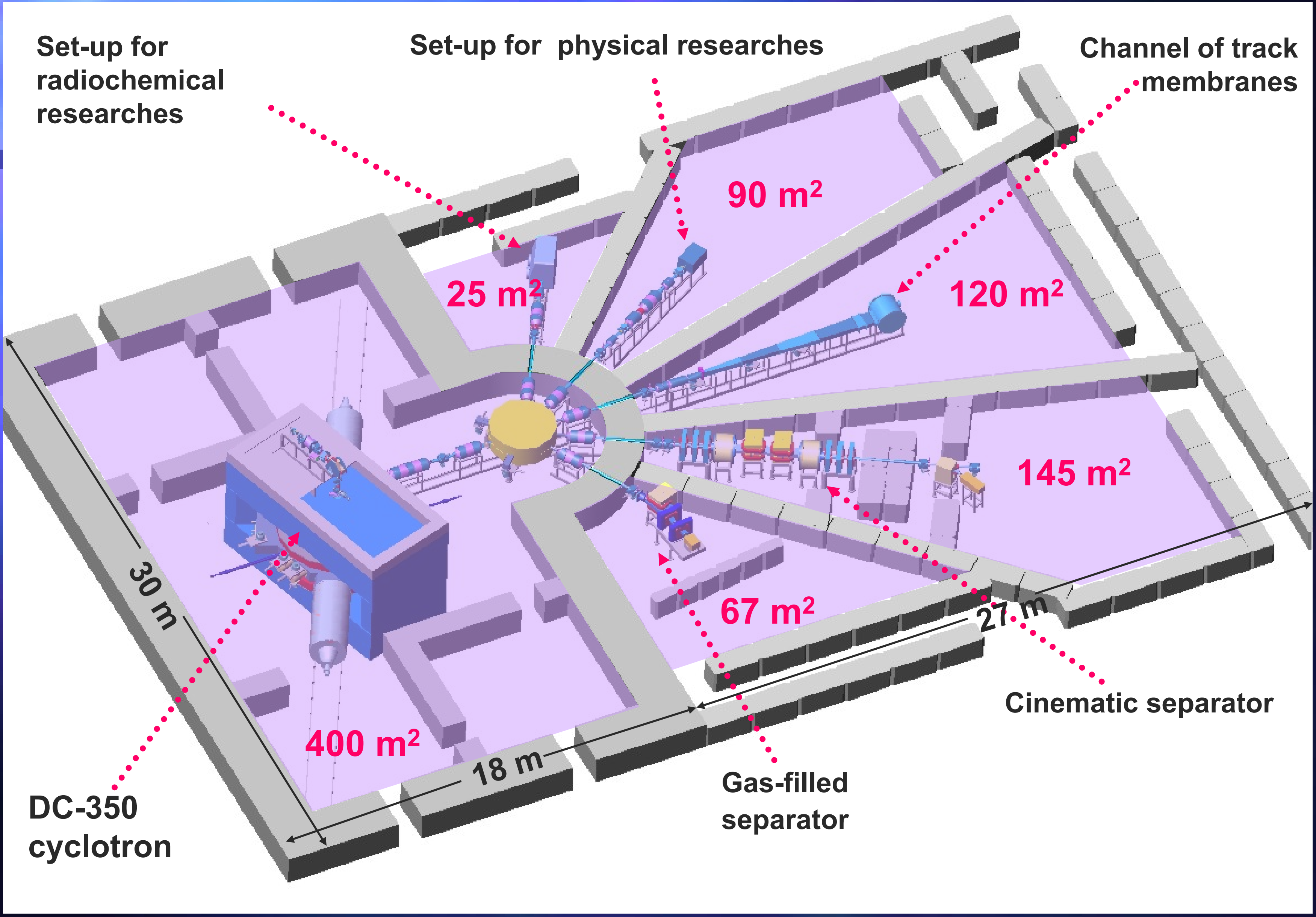
DC-350 CYCLOTRON

Maximal beam intensity of rare isotopes

at present (U-400)	DC-350 accelerator complex ★
48Ca – from 1,0 to 1,5 pμA	48Ca – from 2 to 5 pμA
50Ti – from 0,8 to 1,6 pμA	50Ti – from 2 to 3 pμA
54Cr – from 1,0 to 1,25 pμA	54Cr – from 2 to 3 pμA
58Fe – from 0,8 to 1,0 pμA	58Fe – from 2 to 3 pμA
64Ni – from 0,6 to 0,8 pμA	64Ni – from 2 to 3 pμA

★ Ion energy of accelerated beams - 4,5÷5,5 MeV/nucleon

DC-350 CYCLOTRON



FLEROV LABORATORY of NUCLEAR REACTIONS

ACCELERATOR COMPLEXES OF THE LABORATORY

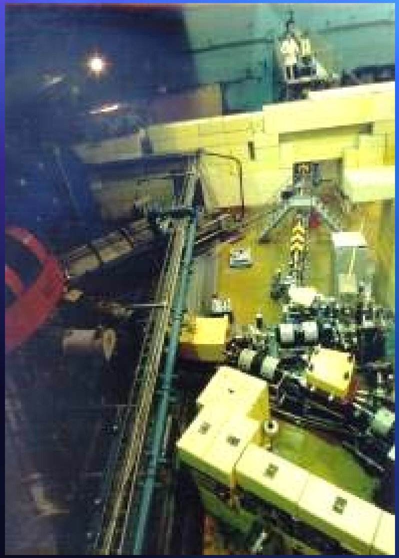

U400


U400M


U200


Microtron MT-25

NEW ACCELERATOR COMPLEXES


DRIBs


DC-40


DC-72


DC-60