FLNR Heavy Ion Cyclotrons for Investigation In the Field of Condensed Matter Physics and Industrial Applications

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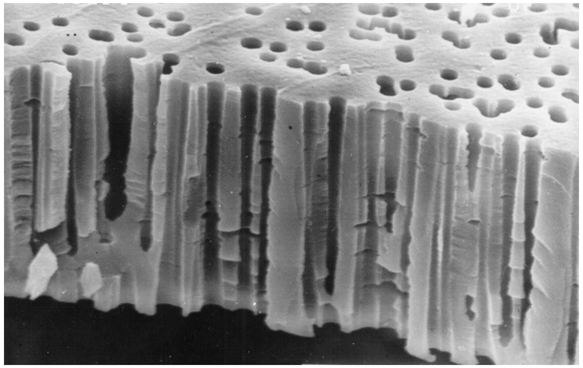
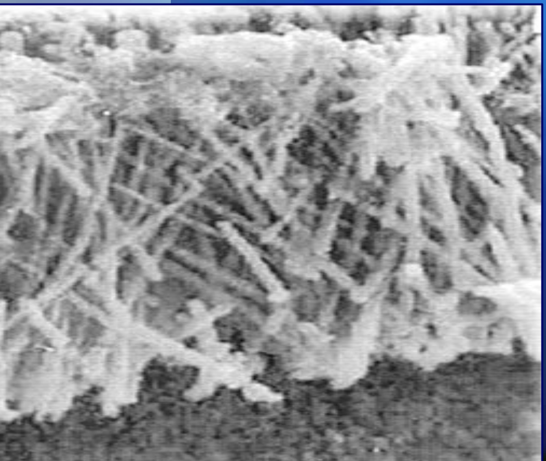
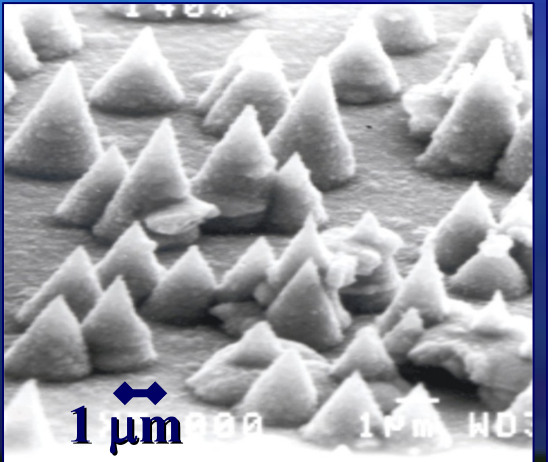
Interaction of heavy ions with matter

- Scientific aspects of radiation damage and formation of ion tracks in solid materials.
- Ion implantation.
- Use of nuclear track technology:
  - track membrane production

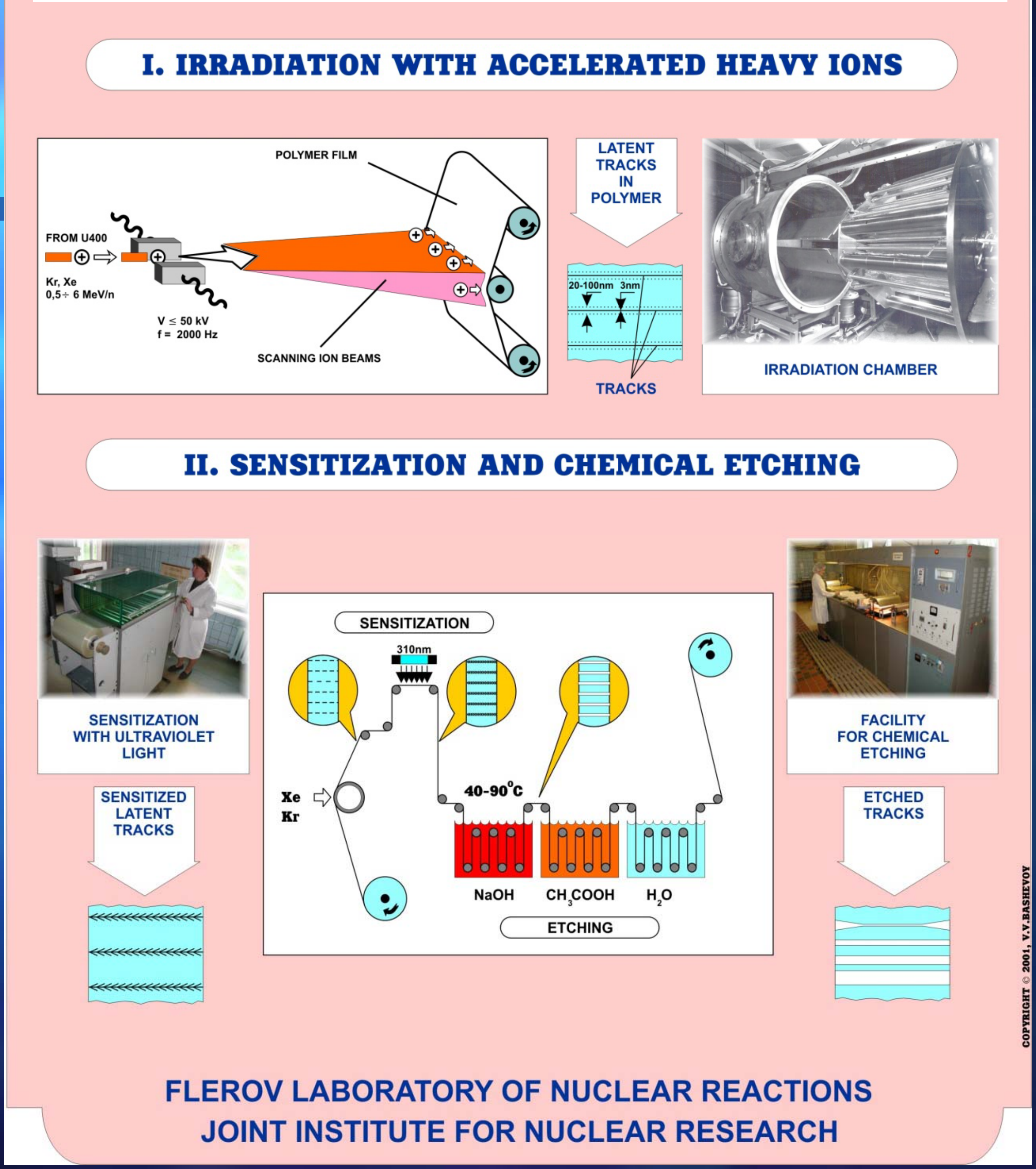


  - Synthesis of three-dimensional structures in solid materials



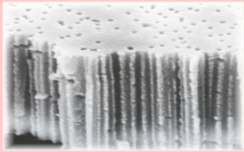


Track membrane production technology

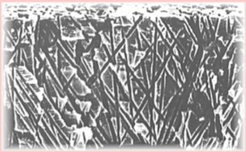


Track membrane production technology

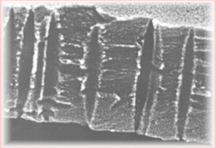
I. TRACK MEMBRANES WITH VARIOUS PORE SHAPES



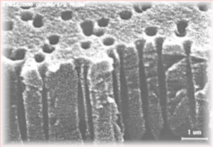
PARALLEL CYLINDRICAL PORES



NON-PARALLEL CYLINDRICAL PORES



CIGAR-LIKE PORES

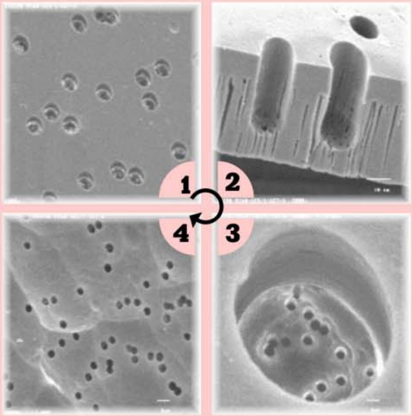


BOW-TIE PORES

ASYMMETRICAL POROUS SUBSTRATES

ARRAY OF MICROWELLS

CROSS-SECTION OF MICROWELL:
- 12 μm IN DIAMETER
- 35 μm IN DEPTH

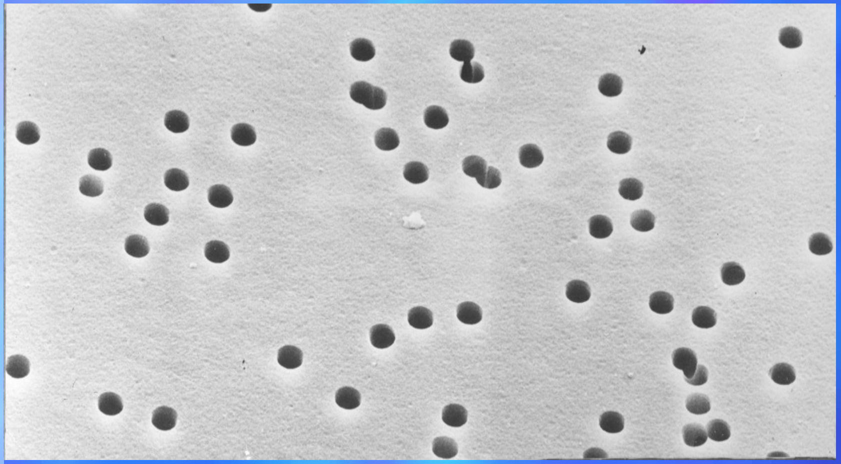


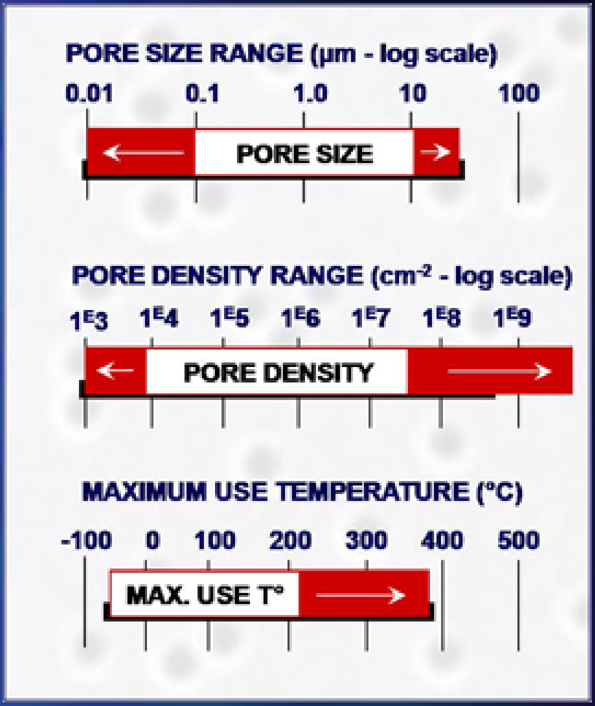
BOTTOM OF THE MICROWELL: PORE DIAMETER IS 0,8 μm

MICROWELL: TOP VIEW

FLEROV LABORATORY OF NUCLEAR REACTIONS
JOINT INSTITUTE FOR NUCLEAR RESEARCH

TRACK MEMBRANES





PROPERTIES:

- Pore density - (10^5 – $1.4x10^{10}$) pores/cm^2
- Pore diameter   0.01 - 20 microns

Membrane material:

Polycarbonate and polyethylene terephthalate - the most widespread.

Polypropylene and polyvinylidene fluoride - for filtration of aggressive technological substances.

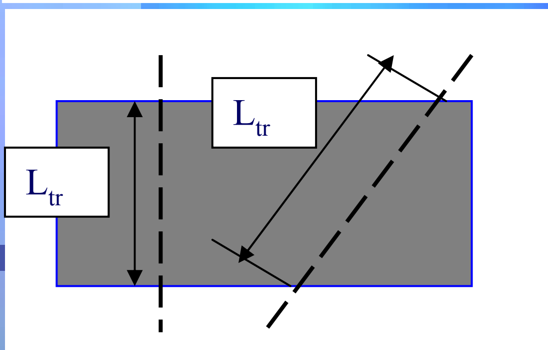
Polyimide - unique thermal and radiation resistance.

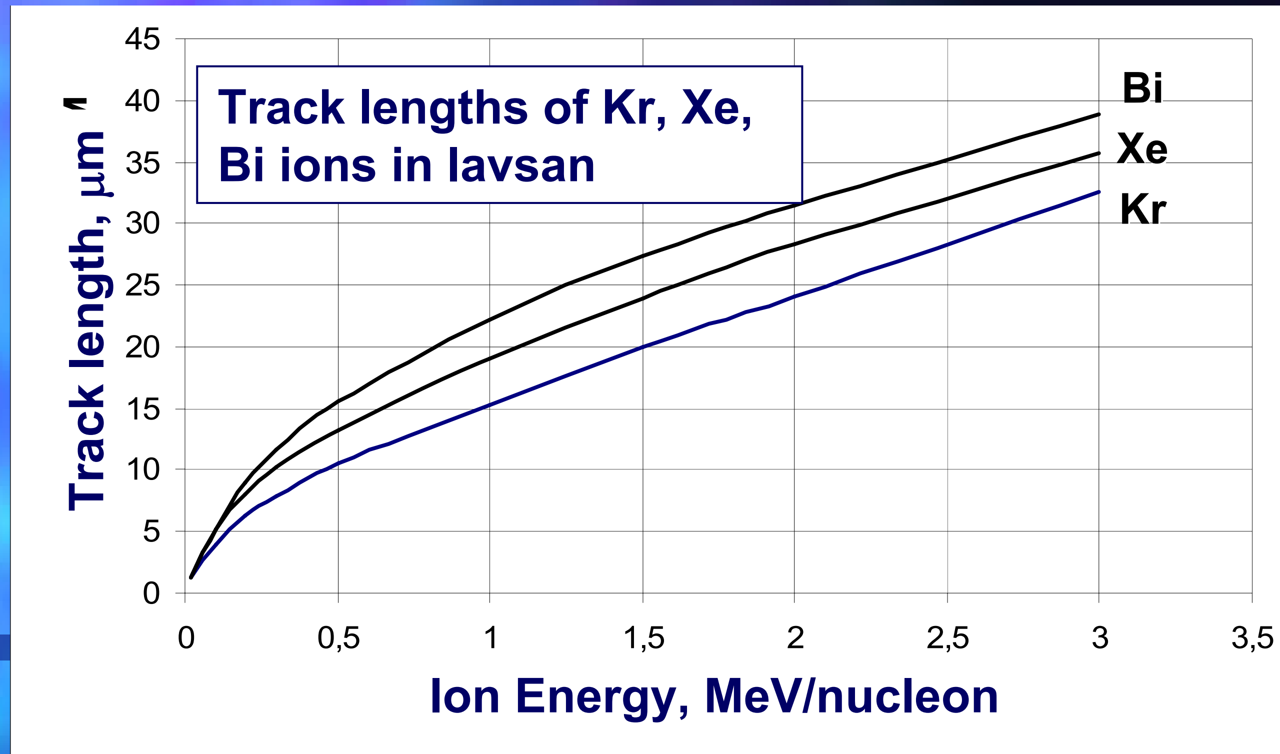
APPLICATION:

Medicine
Biology
Industry

Track membrane production technology

Choice of ion energy for polymer film irradiation





Film thickness		**12 µm**	**19 µm**	**21 µm**	**30 µm**
Energy of ions at perpendicular irradiation	Kr (MeV/n)	0.7	1.4	1.6	2.7
	Xe (MeV/n)	0.4	1.0	1.2	2.2
Energy of ions at irradiation at 15 °	Kr (MeV/n)	0.75	1.45	1.66	2.8
	Xe (MeV/n)	0.45	1.05	1.25	2.3
Energy of ions at irradiation at 30 °	Kr (MeV/n)	1.0	1.8	2.0	3.2
	Xe (MeV/n)	0.6	1.25	1.5	2.7

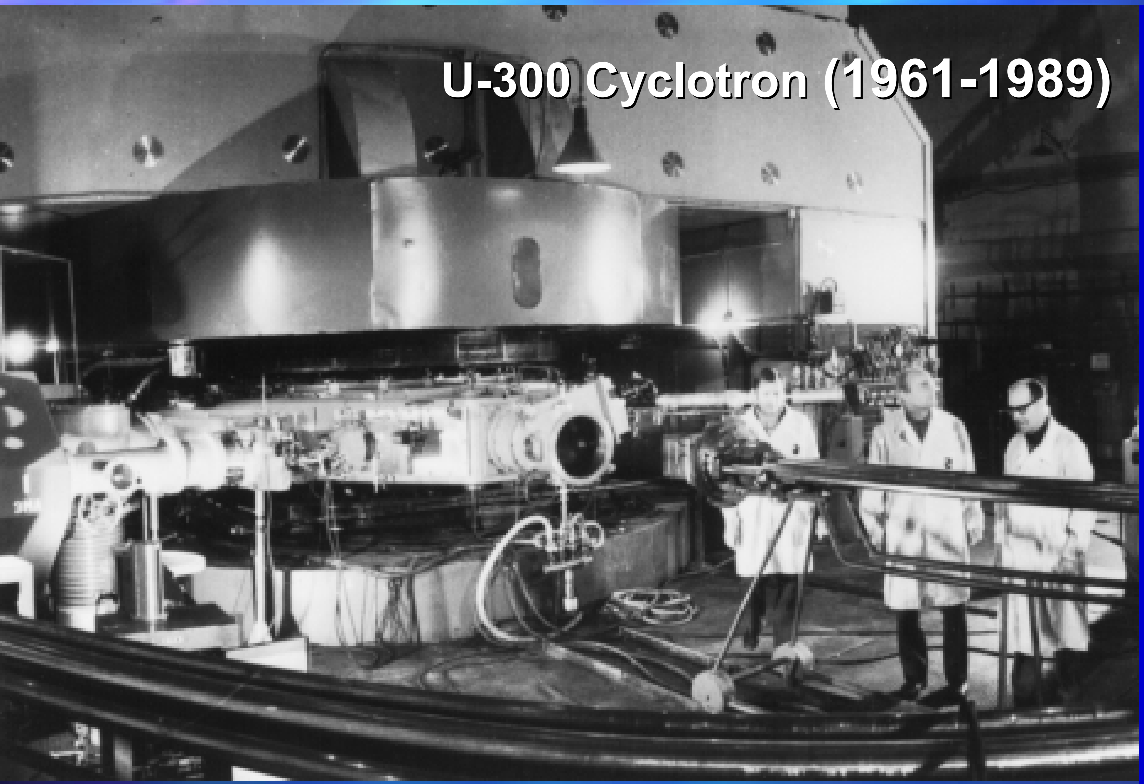
HEAVY ION ACCELERATORS FOR TRACK MEMBRANE PRODUCTION AND POLYMER MODIFICATION

Applied research on heavy ion beams are carried out in many scientific centres of the world. Some of the developed technologies are successfully used in industry, for example, a well-known method of track membrane production using heavy ion beams, which as a rule have an energy from 1 to 3.5 MeV/nucleon.

- USA, Brookhaven National Laboratory
- France, GANIL,
- Belgium, (CYCLONE) Cyclotron of L'Ouvain la Neuve
- Germany, GSI
- Japan, Takasaki, JAERI, AVF cyclotron
- many other scientific centers

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.**

❖ The specialized channel for an irradiation polymer films at the accelerator has been created in the middle of 70th years.

❖ Beams of Xe ions with 1MeV/nucl energy were used for manufacture of track membranes and research task.

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

1. Флеров Г.Н., Барашенков В.С. Практическое применение пучков тяжелых ионов. УФН, 1974, 114, №2, 351

2. Агапьев Г.Н., Барашенков В.С., Самойлова Л.И., Третьякова С.П., Щеголев В.А. К методике изготовления ядерных фильтров. Деп. Публикация ОИЯИ, Дубна,1074, Б1-14-8214.

HEAVY ION ACCELERATORS FOR TRACK MEMBRANE PRODUCTION AND POLYMER MODIFICATION

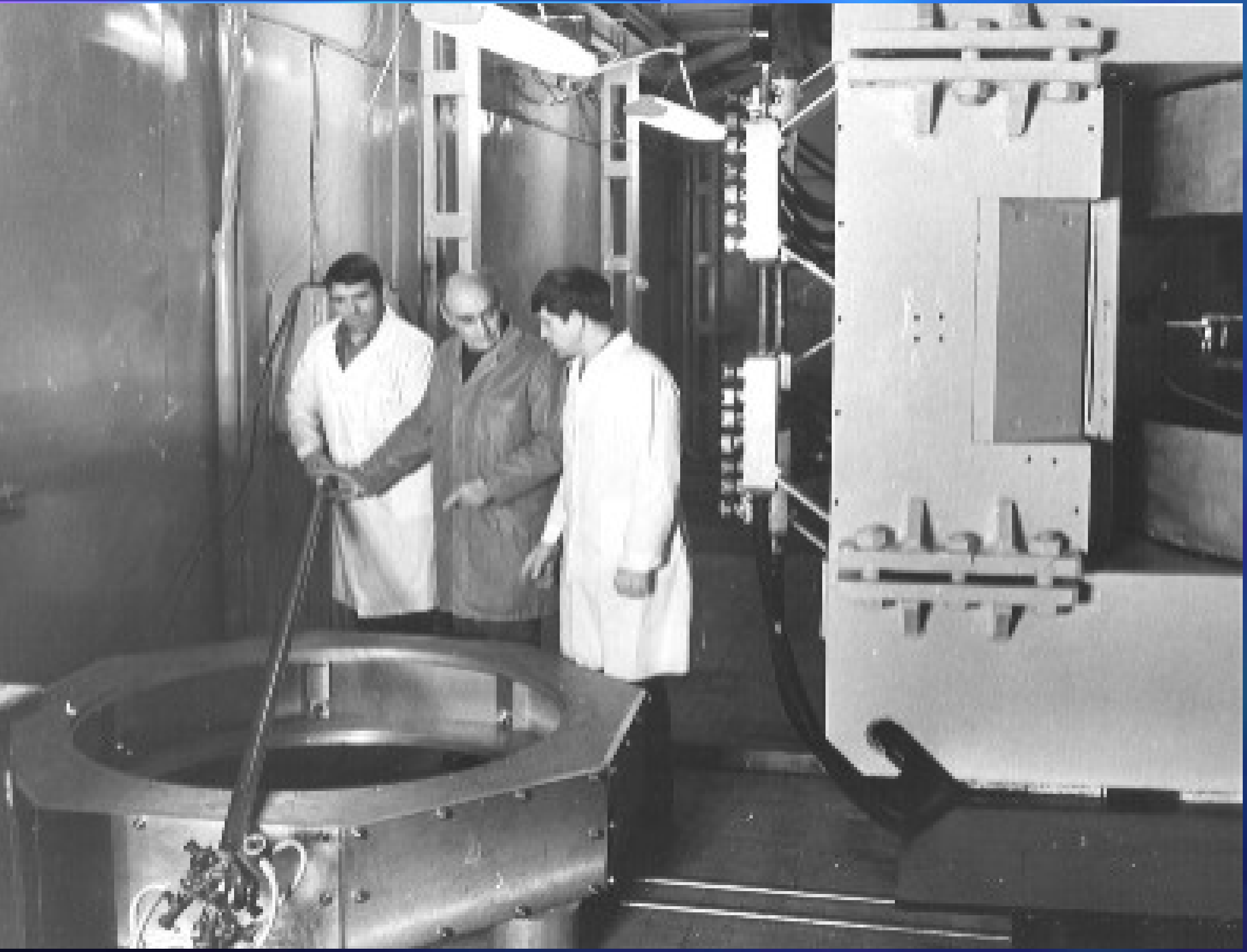
FLNR JINR

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
- **1500 kW - power consumption**

SPECIALIZED HEAVY ION CYCLOTRONS
for production of track membranes and industrial use in the field of nanotechnologies

IMPLANTING CYCLOTRON IC-100
History pages 1985



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

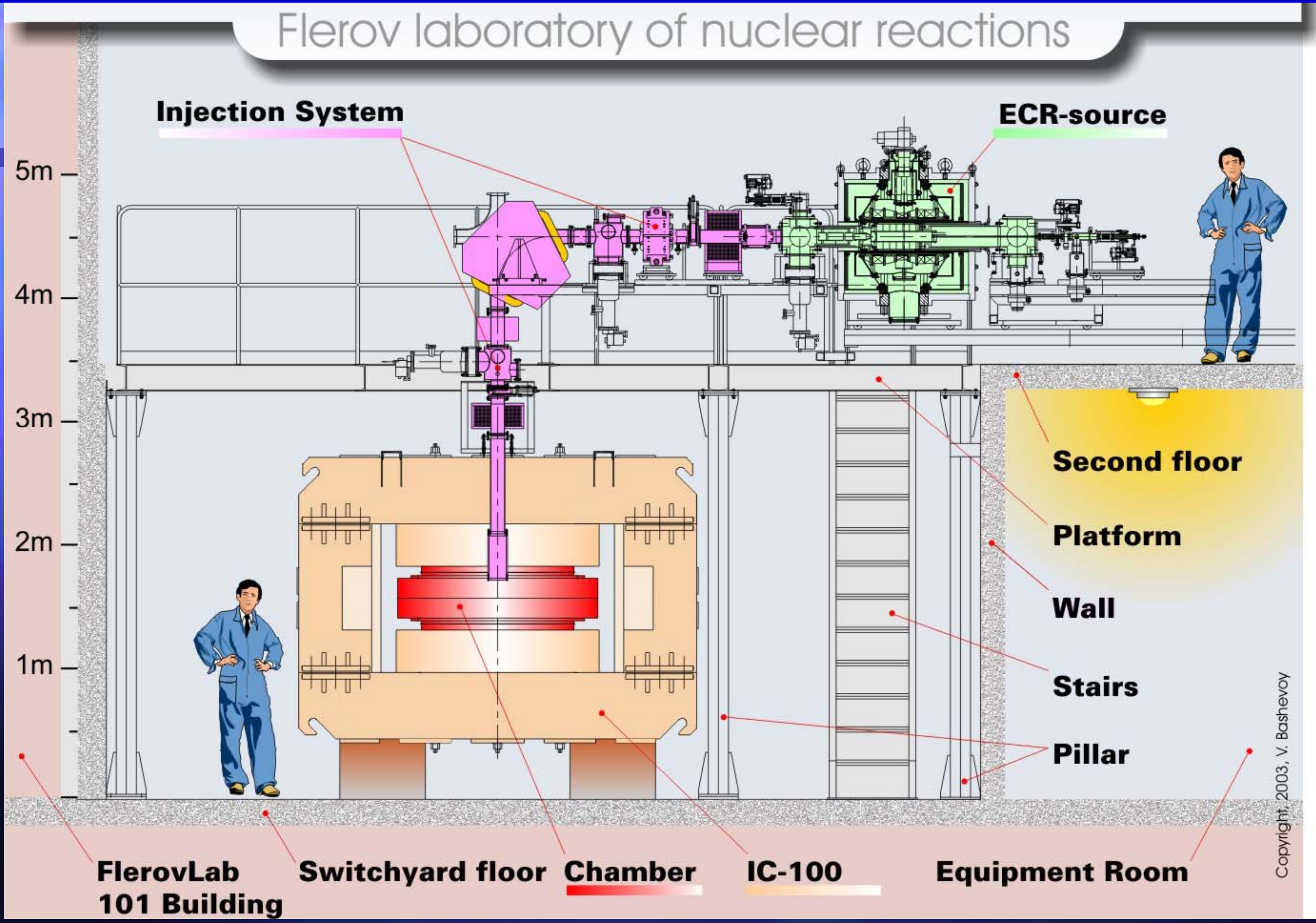
Energy of ions: ~ 1.2 MeV/nucleon.

Internal ion source - PIG

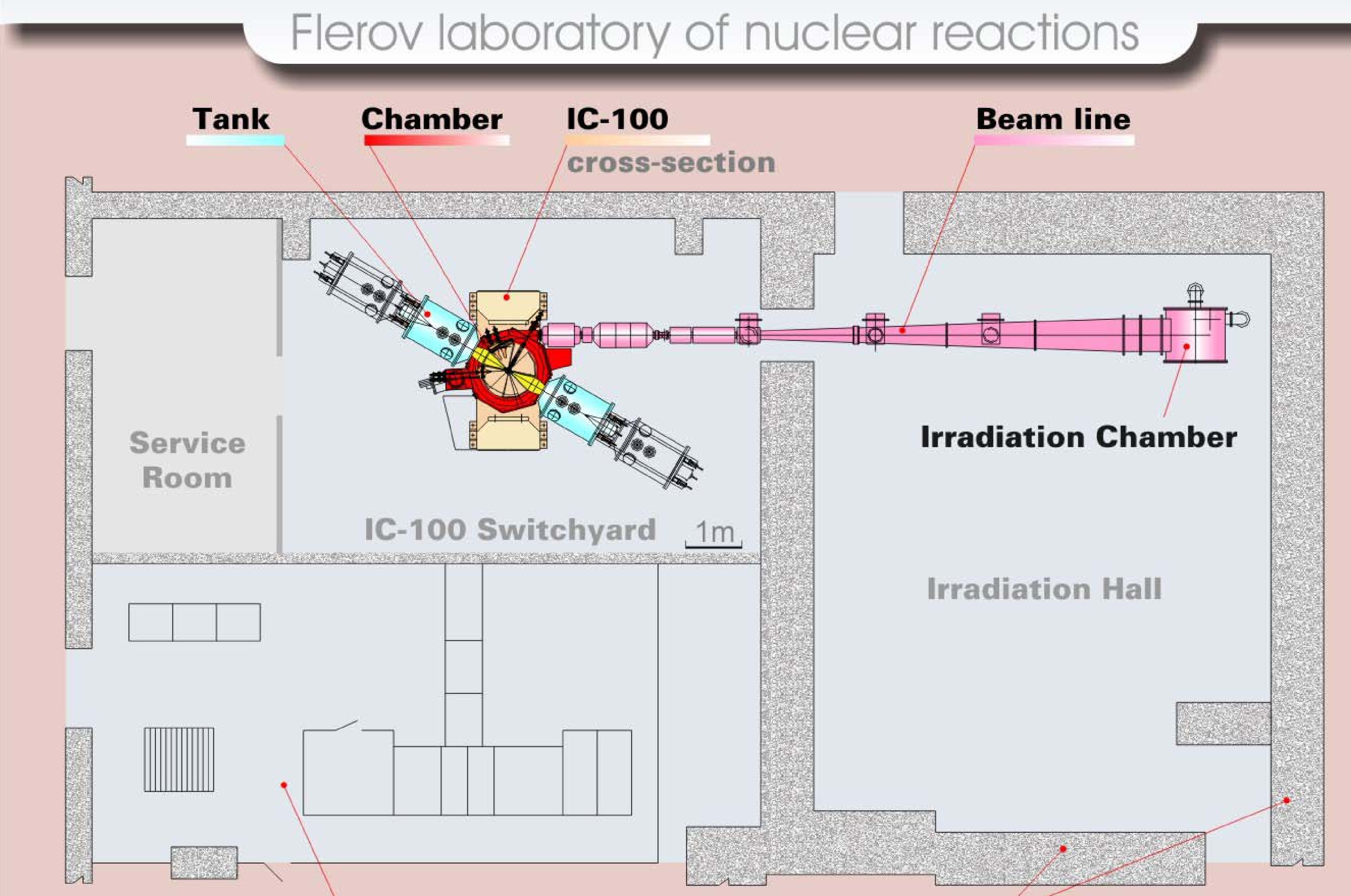
Accelerated ions:
C - Ar (A/Z = 5.7-6)

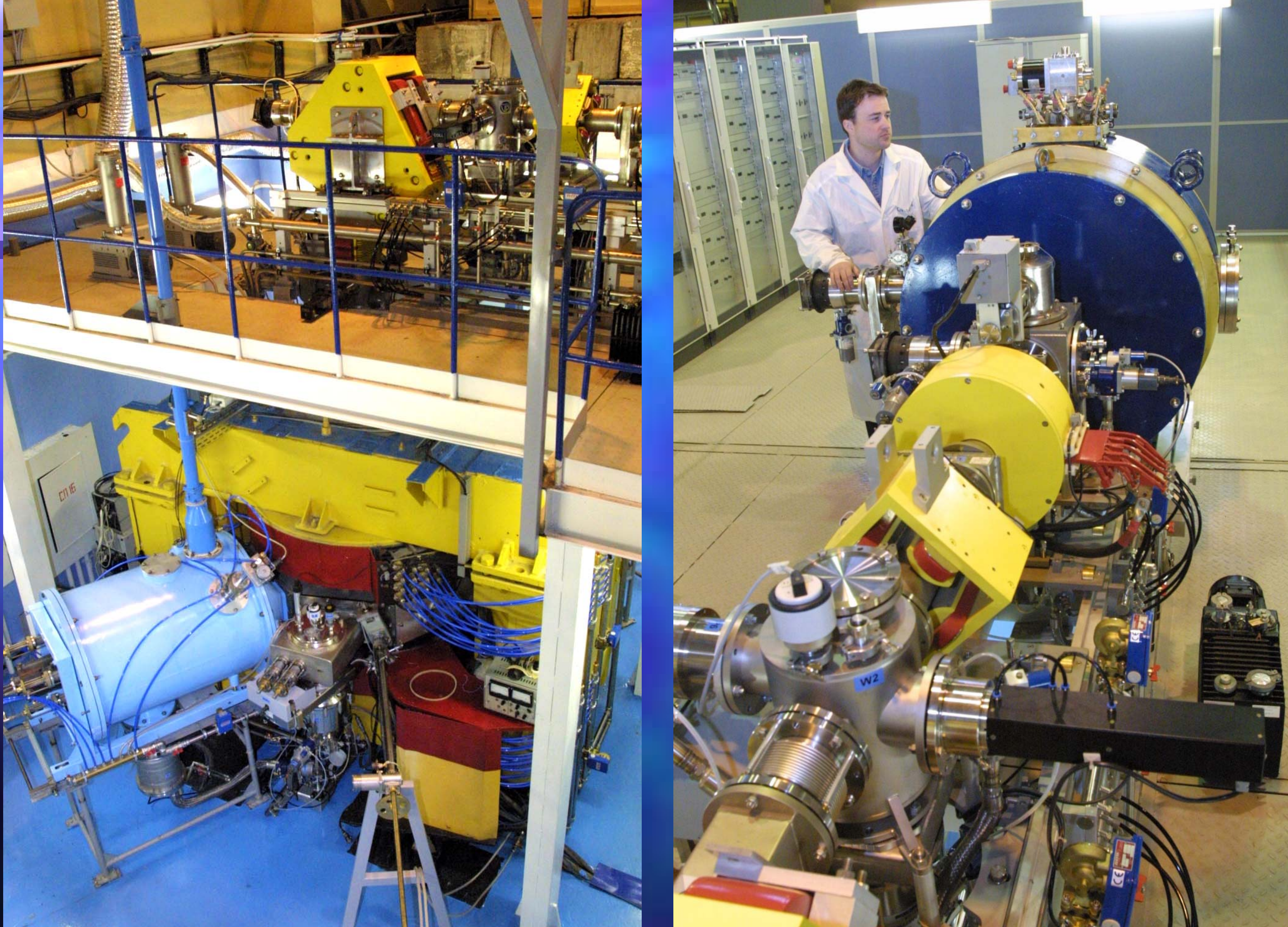
Beam intensity of Ar - 1 μA

Reconstruction of IC-100 cyclotron (2001-2002)



Reconstruction of IC-100 cyclotron (2001-2002)





Reconstruction of IC-100 cyclotron (2001-2002)

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

Element	Ion	A/Z	F_{RF} 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

DC-60 CYCLOTRON

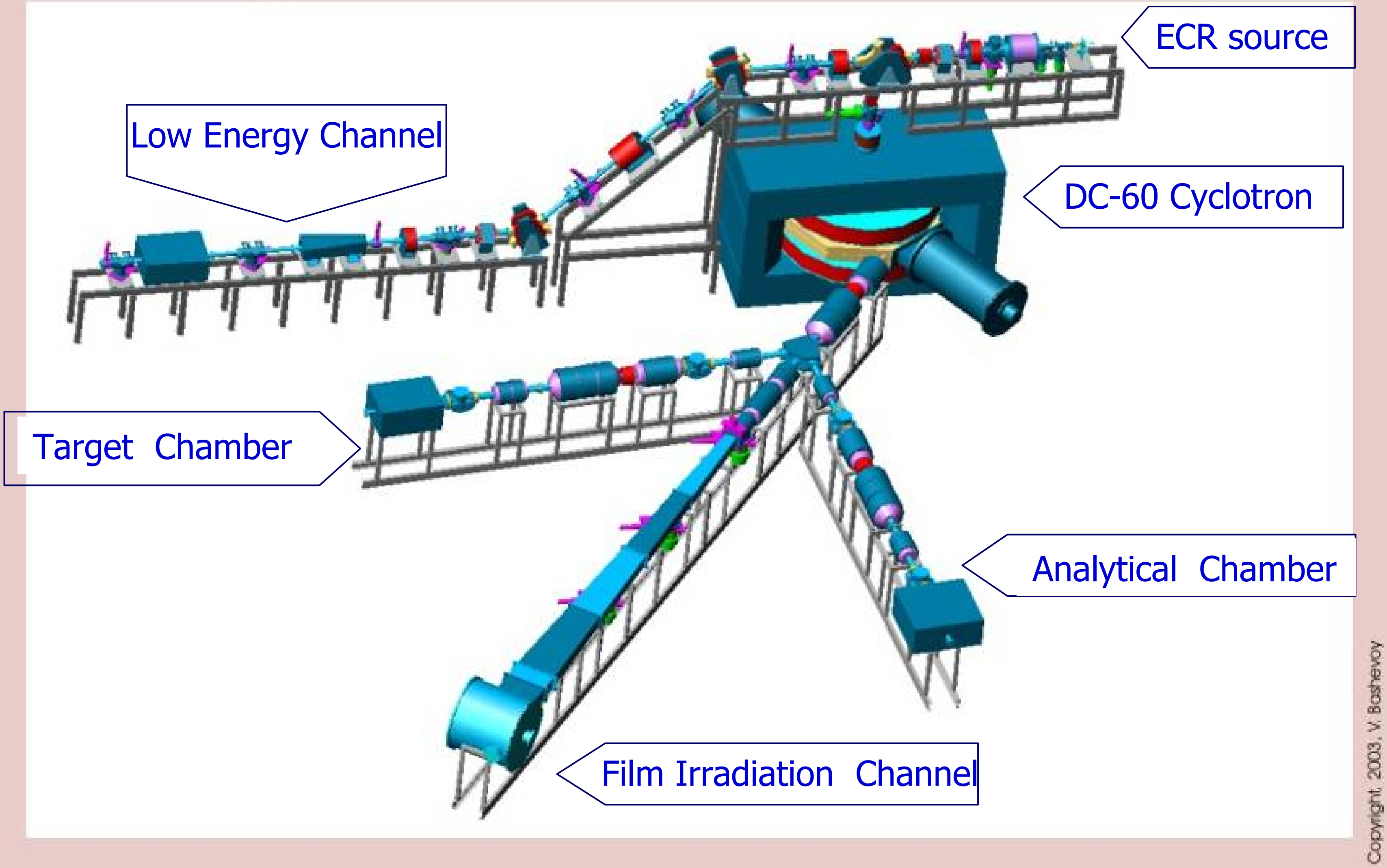
DC-60 has been developed and created at FLNR JINR (2004 - 2006) for Research Center in L.N. Gumilev Euroasian State University in Astana, Kazakhstan

MAIN OBJECTIVES:

- Scientific research
- Education of students

- Production of track membranes with special properties
- Creation of micro- and nano-sructures
- Surface modification of standard materials, creation of new materials with required properties

DC-60 CYCLOTRON: GENERAL VIEW



DC-60 CYCLOTRON

MAIN PARAMETERS

Ion beam injector	ECR ion source + axial injection system
Magnet pole diameter	1.62 m
Cyclotron magnetic field	1.45 T - main mode 1.25÷1.65 T - magnetic field variation
RF system: - frequency - harmonic number - dee voltage	11.00 ÷ 17.5 MHz 4 and 6 50 kV
Pressure in cyclotron vacuum chamber	$1 \div 2 \cdot 10^{-7}$ Torr

DC-60 CYCLOTRON

MAIN 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

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 extraction potential variation in ECR source

DC-60 CYCLOTRON

RF system of DC-60 cyclotron

- **Bimetallic resonators – copper plated stainless steel**

- **Copper balls used as contacts on shorting plate**

VACUUM SYSTEM

Pumping units	Turbomolecular pumps	Cryogenic pumps
Axial injection channel and low energy beam channel	5 units - 150 l/s	4 units - 800 l/s
Cyclotron chamber	2 units - 150 l/s 4 units - 500 l/s	2 units - 5000 l/s
Extracted beam channels	7 units - 100 l/s	-
Dedicated channel for irradiation of polymer films	4 units - 500 l/s	-

Vacuum	Design	Received
Axial injection channel and low energy beam channel	$1 \cdot 10^{-7}$ Torr	$(6\text{-}9) \cdot 10^{-8}$ Torr
Cyclotron chamber	$(1\text{-}2) \cdot 10^{-7}$ Torr	$5 \cdot 10^{-8}$ Torr
Extracted beam channels	$5 \cdot 10^{-6}$ Torr	$5 \cdot 10^{-7}$ Torr

Pumping of cyclotron chamber

1 stage - for-vacuum pumps - $\sim 10^{-3}$ Torr

2 stage – turbo-molecular pumps - $(1 \div 2) \cdot 10^{-6}$ Torr

3 stage - cryogenic pumps - $(5) \cdot 10^{-8}$ Torr

DC-60 CYCLOTRON EXPERIMENTAL RESULTS

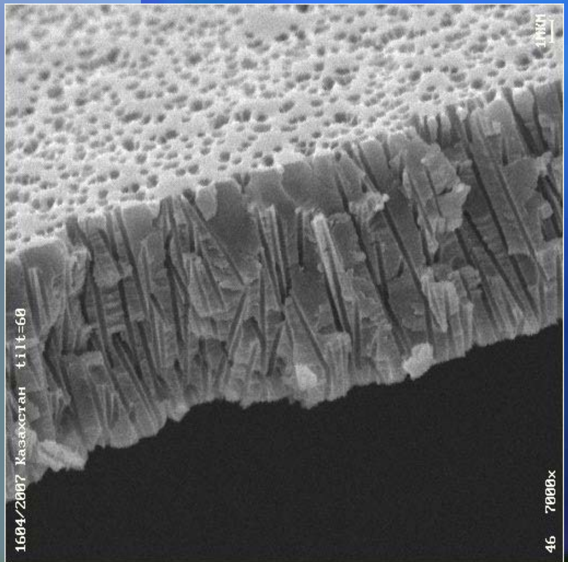
Accelerated Ion Beams (December 2006)

Ion	A/Z	Ion energy MeV/nucleon	Magnetic field, T	Beam current, μA, at internal radius R=120mm	Beam current, μA, at extraction radius R=680mm
$^{14}N^{2+}$	7	1	1.42	10.5	10
$^{14}N^{2+}$	7	1.05	1.47	1.86	1.7
$^{14}N^{2+}$	7	1.32	1.64	1.62	1.46
$^{20}Ne^{3+}$	6.67	1.03	1.4	2.2	2
$^{22}Ne^{2+}$	11	0.38	1.4	1.85	1.77
$^{40}Ar^{4+}$	10	0.65	1.64	1.5	1.4
$^{40}Ar^{5+}$	8	0.58	1.25	0.98	0.64
$^{40}Ar^{5+}$	8	0.98	1.63	0.61	0.52
$^{40}Ar^{6+}$	6.67	1.06	1.4	2	1.85
$^{40}Ar^{7+}$	5.71	1.14	1.25	1.92	1.83
$^{84}Kr^{+12}$	7	1	1.42	2.72	2.48

Track membranes produced at DC-60

- Irradiation by ^{84}Kr ion beam

- Energy of ions 1.0 MeV/nucleon.
- Full current of the beam – 0.1 μA
- Speed of film transport - 5 cm/sec
- The size of the beam on the target:
  Vertical 100 mm
  Horizontal 30 mm
- Beam scanning frequency- 100 Hz



PARAMETERS OF A TRACK MEMBRANE

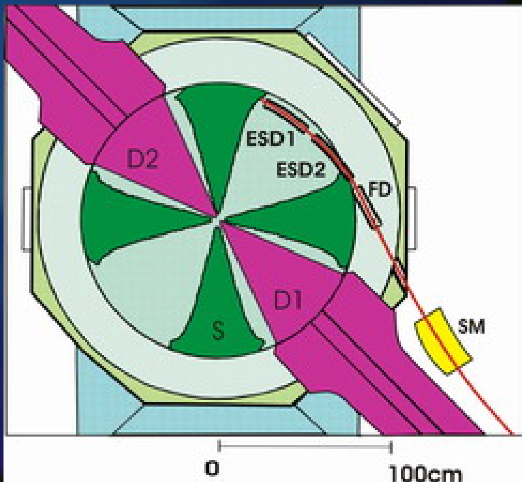
- Film thickness	12 microns
- Pore diameter	0.38 - 0.4 microns
- Pore density	$2 \cdot 10^8$ pores/cm^2
- Non-uniformity of pore density across the width and length of the film	±5 %
- Pore axis angle to surface normal	0±15º

"Alpha" Film Irradiation Complex on the basis of CYTREC cyclotron

The ALPHA industrial complex constructed for industrial track membrane production.

❖ Base installation - cyclotron CYTREC (start August 2002) is developed at the Laboratory of Nuclear Problems, JINR.

❖ Accelerated ions - Ar with a fixed energy – 2.4 MeV/nucleon



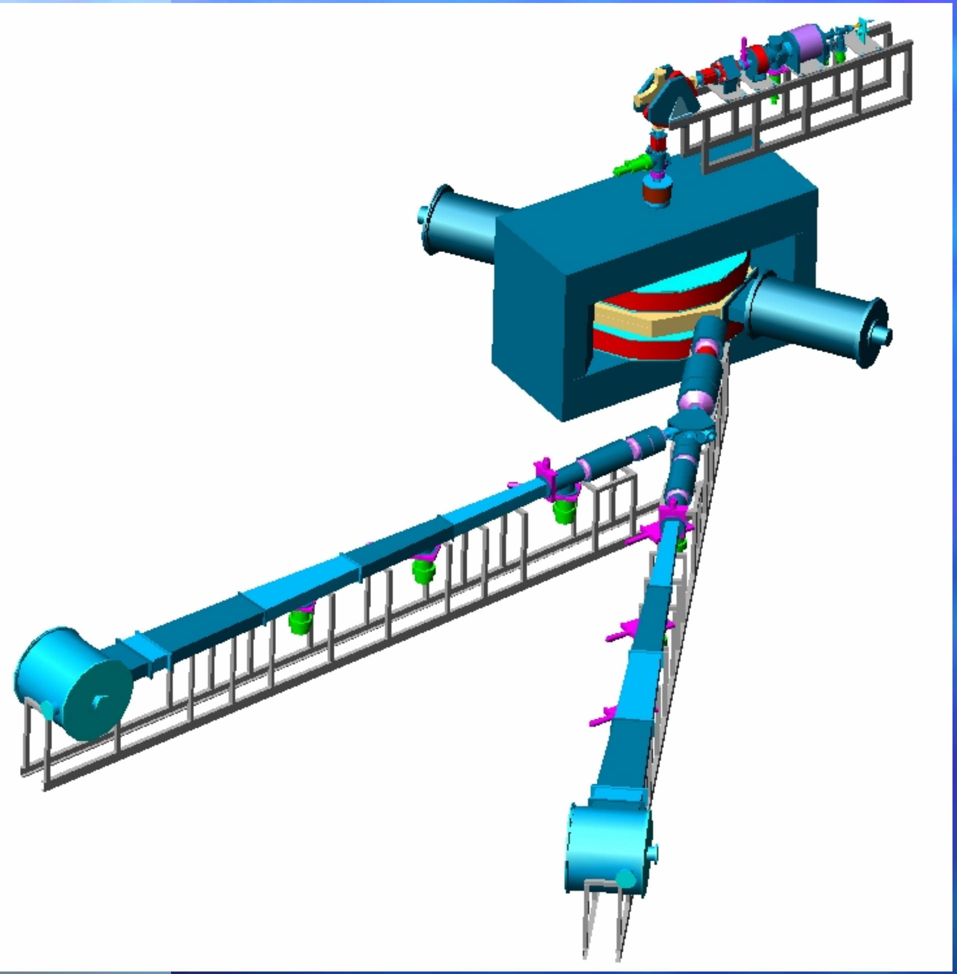
DC-110 Heavy Ion Cyclotron for track membranes production for "BETA" industrial complex

Flerov Laboratory of Nuclear Reactions,
Joint Institute for Nuclear Research, Dubna, Russia

REQUIREMENTS TO CYCLOTRON

- Manufacture of track membranes on the basis of polymer films with thickness up to 30 microns.
- The cyclotron should accelerate beams of ions *Ar*, *Kr*, *Xe* with the fixed energy 2,5 МэВ/нукл., beam intensity ~ 1 pμA ($6 \cdot 10^{12}$ particles / sec)
- The equipment should be simple and reliable.
- Operating time in a mode of an film irradiation - 7000 hours/year.
- The beginning of the project August 2009.

DC-110 Cyclotron Complex



- DC-110 Cyclotron
- ECR type external ion source.
- Beam axial injection system
- 2 channels for accelerated ion beams
- Technological equipment
  - vacuum system
  - power supply and control systems
  - cooling system
  - RF system

DC-110 Cyclotron has been developed on the basis of the DC-60 cyclotron design, created at the FLNR and successfully commissioned in Astana in 2006.

ION SOURCE

(comparison of characteristics)

Accelerated ions	$^{40}Ar^{6+}$	$^{86}Kr^{13+}$	$^{132}Xe^{20+}$	
Mass to charge ratio of ions A/Z	6.667	6.615	6.60	
Injection voltage	20 keV	20 keV	20 keV	
Intensity of injected ion beam in a routine operation	20 pμA (max 40 pμA)	5 pμA (max 10 pμA)	1 pμA (max 2 pμA)	«room temperature» ECR 14 GHz 60 kW - power consumption
Intensity of extracted ion beam at full efficiency of 10 %	2 pμA *12 μA*	0.5 pμA *6,5 μA*	0.1 pμA *2 μA*	
Intensity of injected ion beam in a routine operation	25 pμA (max 50 pμA)	15 pμA (max 30 pμA)	5 pμA (max 10 pμA)	«room temperature» ECR 18 GHz 150 kW -power consumption
Intensity of extracted ion beam at full efficiency of 10 %	2,5 pμA *15 μA*	1.5 pμA *20 μA*	0.5 pμA *10 μA*	
Intensity of injected ion beam in a routine operation	25 pμA (max 50 pμA)	15 pμA (max 30 pμA)	10 pμA (max 15 pμA)	Superconducting ECR 18 GHz 60 kW - power consumption
Intensity of extracted ion beam at full efficiency of 10 %	2.5 pμA *15 μA*	1.5 pμA *20 μA*	1.0 pμA *20 μA*	

Main parameters of DC-110 cyclotron.

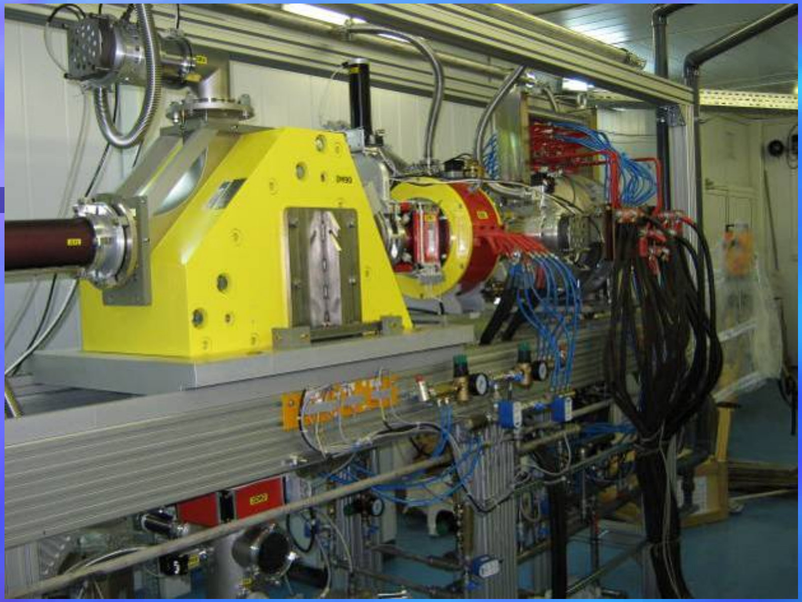
Accelerated ions	$^{40}Ar^{6+}$	$^{86}Kr^{13+}$	$^{132}Xe^{20+}$
Mass to charge ratio of ions A/Z	6.667	6.615	6.60
Ion energy – 2.4 MeV/nucleon	2.5	2.5	2.5
Beam intensity, pps	$6 \cdot 10^{12}$ (*)	$6 \cdot 10^{12}$	$3 \cdot 10^{12}$
MAGNETIC SYSTEM			
Pole diameter, m	2		
Average magnetic field B_o, [T]	1.683	1.670	1.666
Increasing average magnetic field at final radius ΔB,[Gs]	45	45	45
RF SYSTEM			
Revolution of ions, F_{ion}, [MHz]	3.877	3.877	3.877
Harmonic number	2	2	2
Frequency of RF system F_{RF}, [MHz]	7.754	7.754	7.754
Ion source	SC ECR, 18 GHz		
Extraction system	Electrostatic deflector		

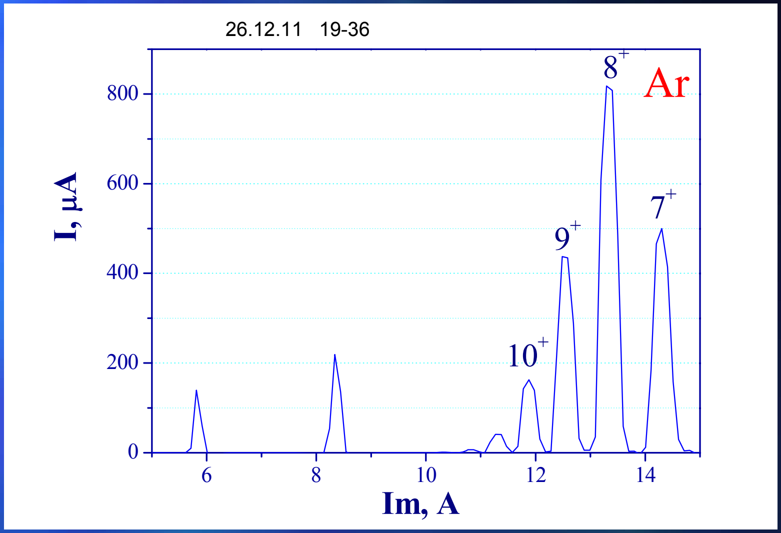
DC-110 cyclotron

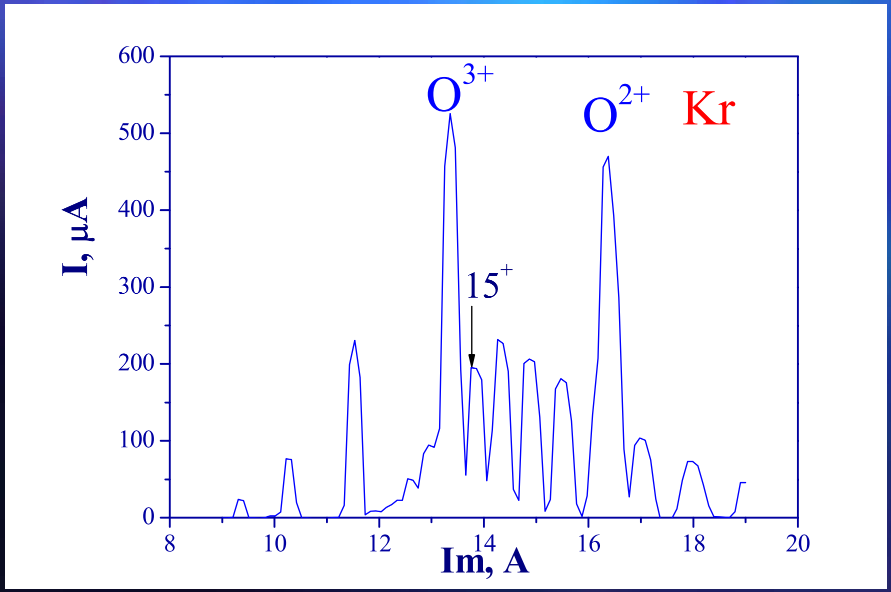
(Commissioning stage September 2012)

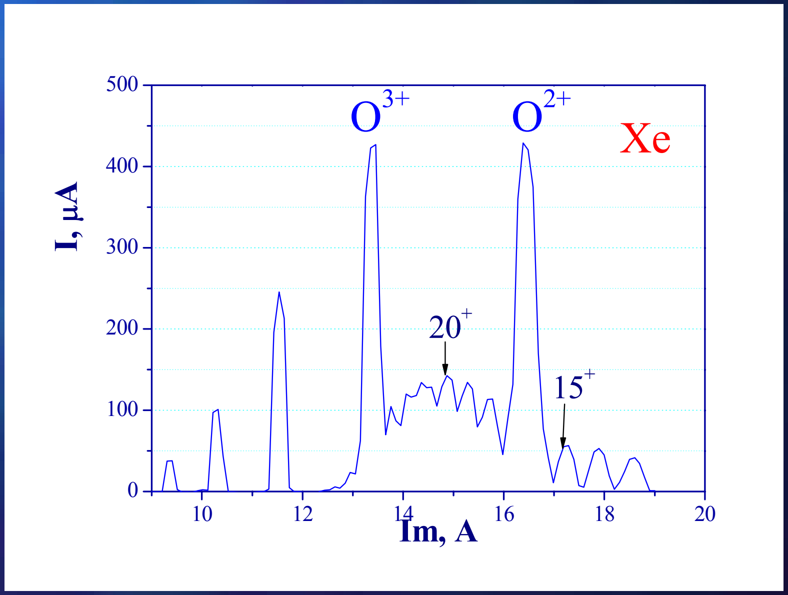
ECR ion source of DC-110

Ions	$^{40}Ar^{6+}$	$^{86}Kr^{13+}$	$^{132}Xe^{20+}$
Project intensity	190 eμA	210 eμA	150 eμA









Efficiency of $^{84}Kr^{12+}$ beam acceleration at DC-60 cyclotron

<table>
<tr><th rowspan="2">ION</th><th rowspan="2">Injection beam current, eμA</th><th colspan="2">Accelerated beam current, eμA
(With buncher system)</th><th rowspan="2">Extracted beam current, eμA</th><th rowspan="2">Beam current at target, eμA</th></tr>
<tr><th>R= 120 mm</th><th>R= 680 mm</th></tr>
<tr><td>^{84}Kr $^{12+}$</td><td>11.4</td><td>2.7</td><td>2.5</td><td>1.65</td><td>1.65</td></tr>
<tr><td></td><td colspan="2">22% (30-40% DC-110)</td><td></td><td></td><td></td></tr>
<tr><td></td><td></td><td colspan="2">92%</td><td></td><td></td></tr>
<tr><td></td><td></td><td></td><td colspan="2">66%</td><td></td></tr>
<tr><td></td><td></td><td></td><td></td><td colspan="2">100%</td></tr>
<tr><td></td><td colspan="5">14.5% (20-25% DC-110)</td></tr>
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SPECIALIZED HEAVY ION CYCLOTRONS (JINR)

for production of track membranes and industrial use in the field of nanotechnologies

HEAVY ION CYCLOTRONS	Accelerated ions	Ion energy	Intensity of extracted beam
IC-100 (1986) **FLNR JINR** *(developed at the Laboratory of Nuclear Reactions, JINR)*	Ar, Kr, Xe, I, W	1,2 MeV/nucl	0,4 pμA 0,2 pμA 0,05 pμA
DC-60 (2006) in Astana, Kazakhstan *(developed at the Laboratory of Nuclear Reactions, JINR)*	C - Xe	0,35 – 1,7 MeV/nucl	10 – 0,1 pμA
CYTREC (2002) **"Alpha", Dubna, Russia** *(developed at the Laboratory of Nuclear Problems, JINR)*	Ar	2,4 MeV/nucl	0,03 pμA
DC-110 (commissioning–2012) **"BETA", Dubna, Russia** *(developed at the Laboratory of Nuclear Reactions, JINR)*	Ar, Kr, Xe,	2,5 MeV/nucl	1 pμA 1 pμA 0,5 pμA

Single-Event Effects (SEE) Testing at FLNR Cyclotrons

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

- U400 cyclotron delivers beams of ions with atomic masses of 4÷209 at energies of **3÷29 MeV/nucleon**.
- U400M cyclotron was intended for acceleration of ion beams in two modes:

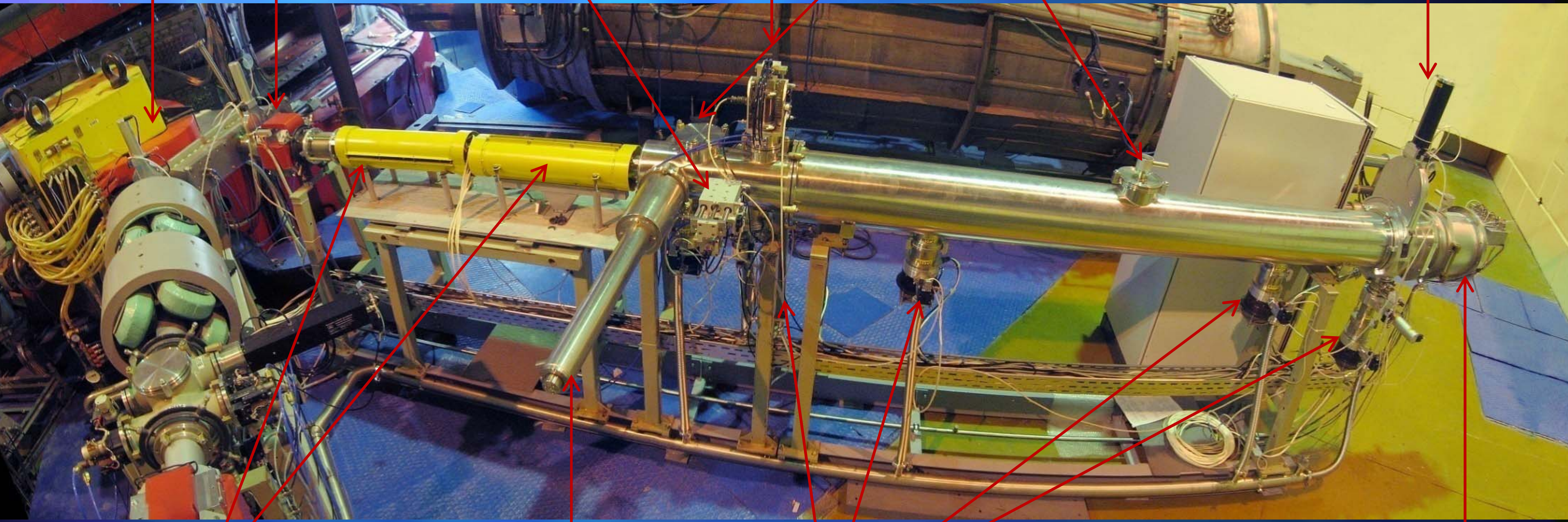
  - acceleration mode of high energy ions - **19–53 MeV/nucleon** (mass to charge ratio of accelerated ions A/Z = 2.8 – 5),
  - acceleration mode of low energy ions - **5–10 MeV/nucleon** (mass to charge ratio of accelerated ions A/Z = 7– 10).

- Now Ions of **O, Ne, Ar, Fe, Kr, Xe, Bi** with an energy of **3÷6 MeV/nucleon** are available to users.
- At the end of 2012 the installation of the channel will be finished for testing at high energy ion beams.
- Beams of ions from **C up to Xe** with energies from **25 to 53 MeV/nucleon** will be available for carrying out experiments.

U-400M

U-400

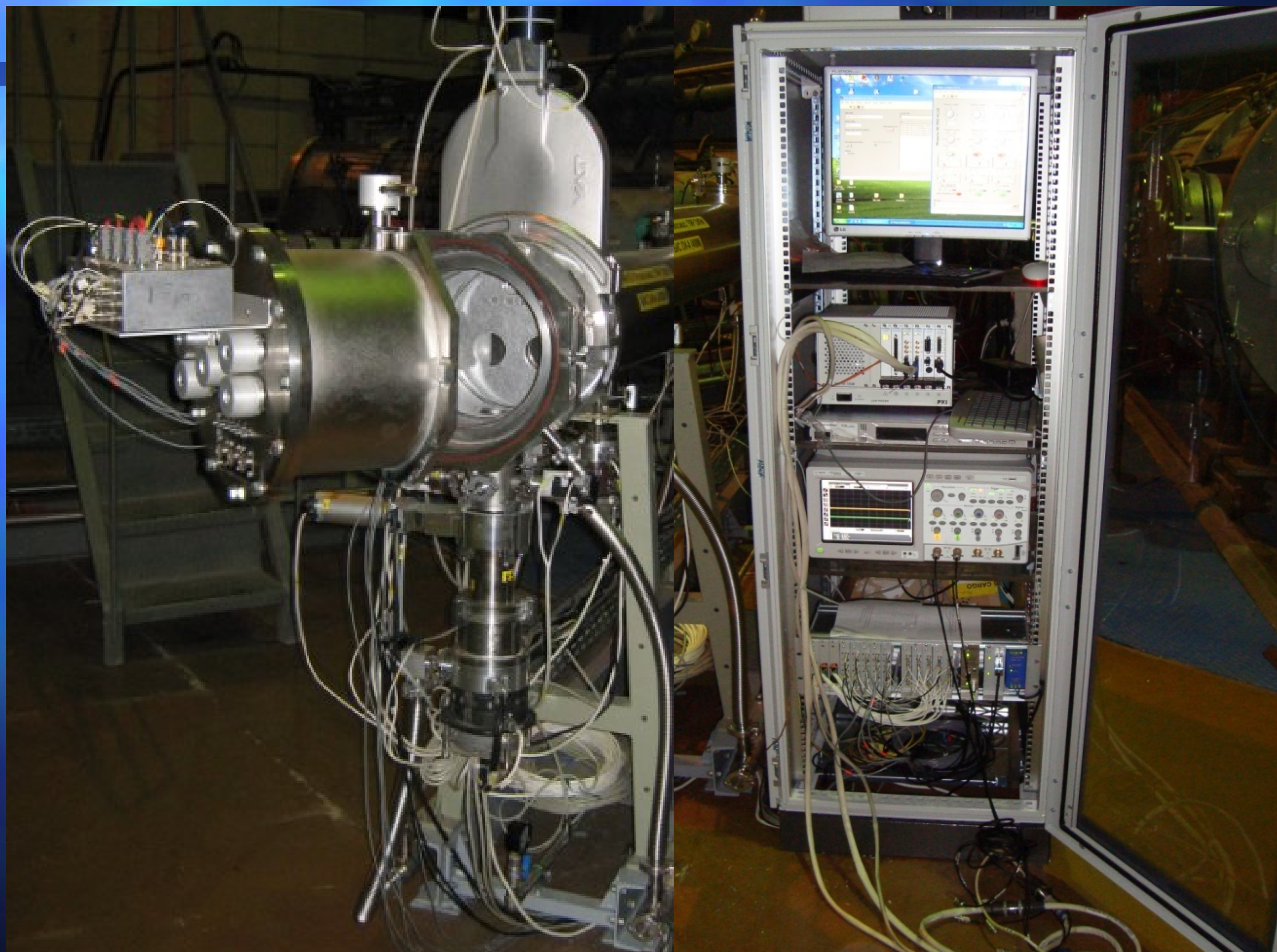
Ion Beam Line for SEE Testing



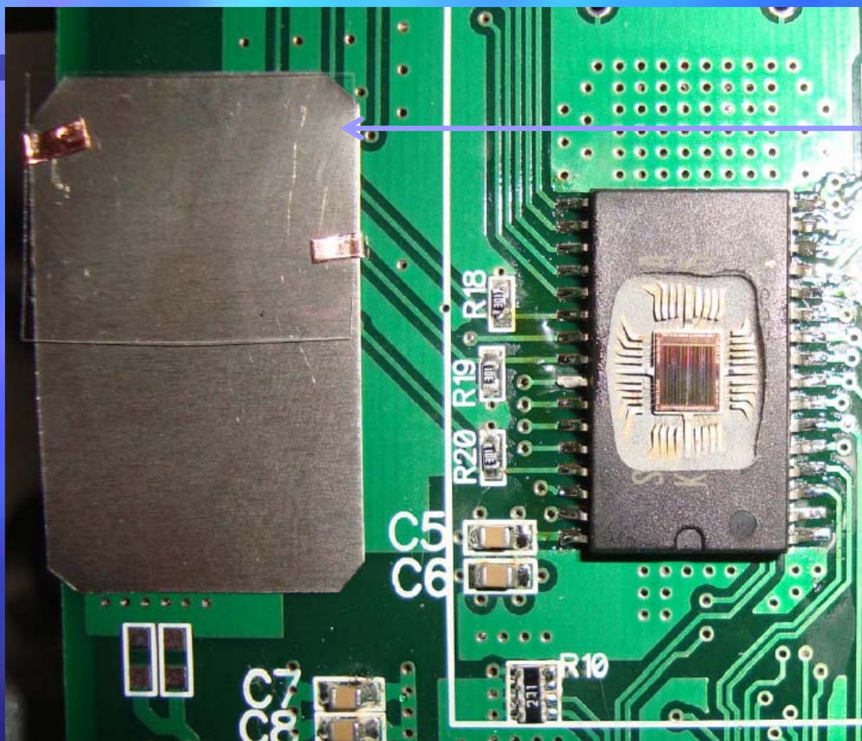
ION BEAM PARAMETERS USED FOR SEE TESTING

Ion type	Energy, MEV	LET, MeV/(mg/cm^2)	Ion flux, cm^{-2}s^{-1}
^{16}O	56±3	4.5	1 ÷ 10^5
^{22}Ne	65±3	7	
^{40}Ar	122±7	16	
^{56}Fe	213±3	28	
^{84}Kr	240±10	41	
^{136}Xe	305±12	67	
^{209}Bi	490±10 (820±20)	95 (100)	

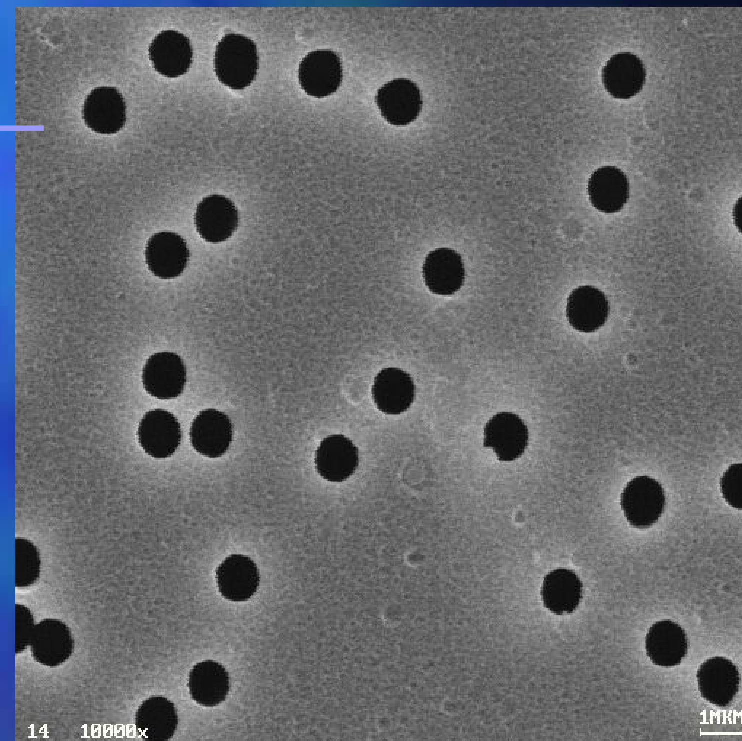
Test chamber and diagnostic equipment



ION BEAM DIAGNOSTIC



Polymer track detector and the DUT



SEM micrograph of polymer track detector