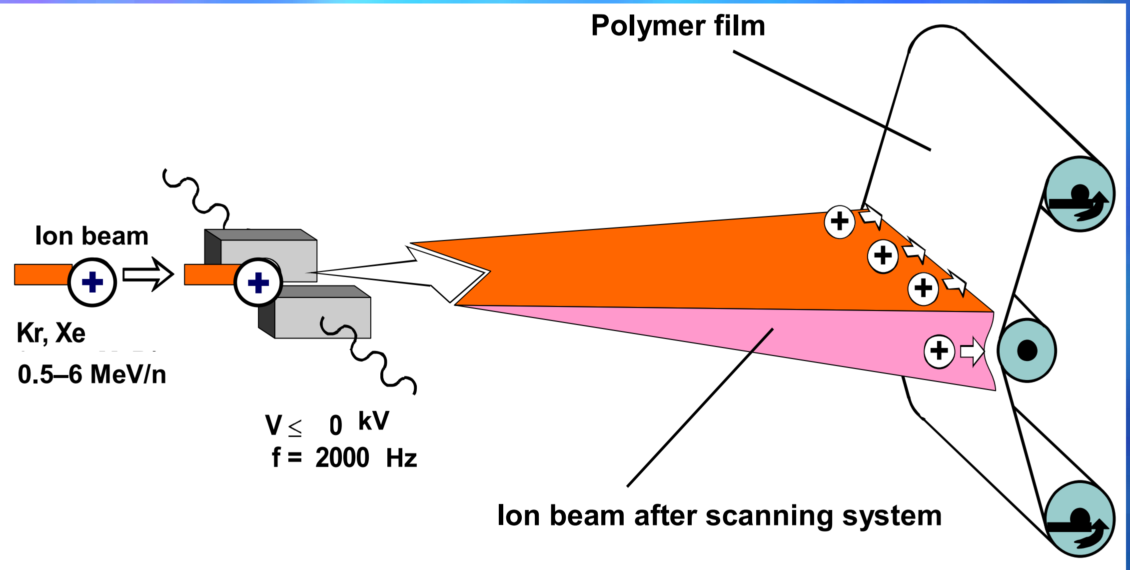
DC-110 dedicated heavy ion cyclotron for industrial production of track membranes

B.N.Gikal, S.N.Dmitriev, G.G.Gulbekian, P.Yu.Apel, S.L.Bogomolov, O.N.Borisov, V.A.Buzmakov, A.A.Efremov, I.A.Ivanenko, N.Yu.Kazarinov, V.I.Kazacha, I.V. Kalagin, V.N.Melnikov, V.I.Mironov, S.V.Pashchenko, O.V.Semchenkova, V.A.Sokolov, N.F.Osipov, A.V.Tikhomirov, A.A.Fateev, M.V.Khabarov

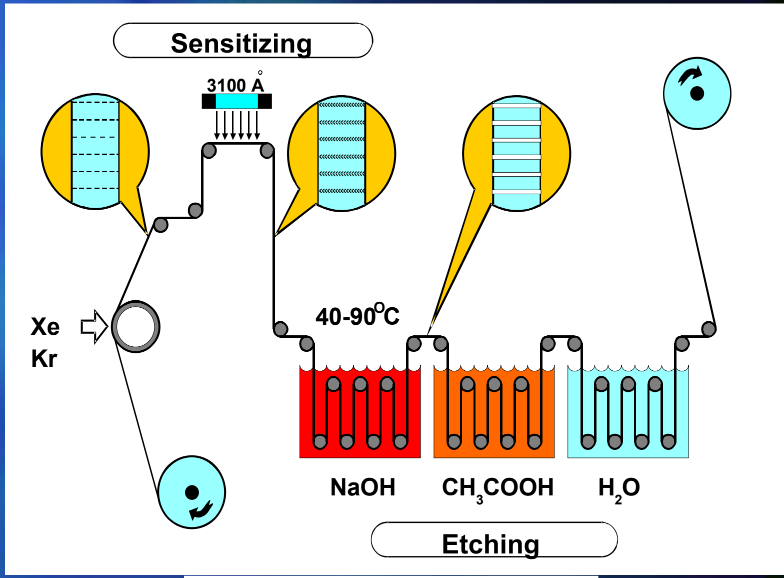
Joint Institute for Nuclear Research
Flerov Laboratory of Nuclear Reactions

TRACK MEMBRANES

Production of track membranes using heavy ion accelerators is one of the most important areas of nuclear technology application.

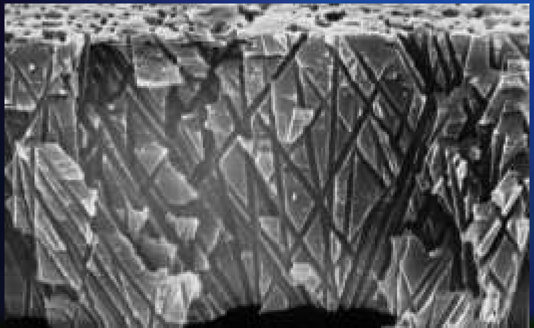


1-st stage

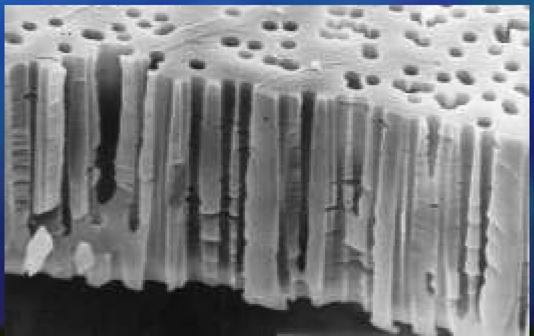


2-nd stage

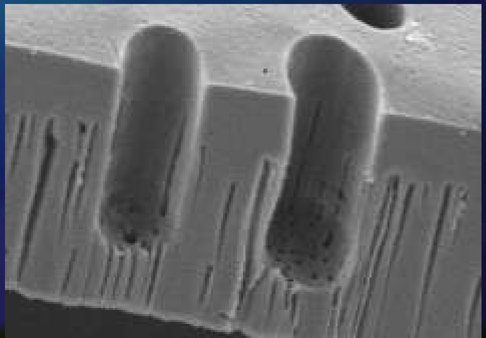
Polycarbonate track membranes



10 µm



20 µm



60 µm

DC-110 dedicated heavy ion cyclotron for industrial production of track membranes

The aim of the project:

Industrial production of track membranes based on polymer films with a thickness of 30 μm .

Requirements to the accelerator:

- accelerated ions: Ar ,Kr ,Xe
- ion energy : 2.5 MeV/nucleon (fixed),
- intensity: ~ 1 pμA ($6 \cdot 10^{12}$ particles/s)

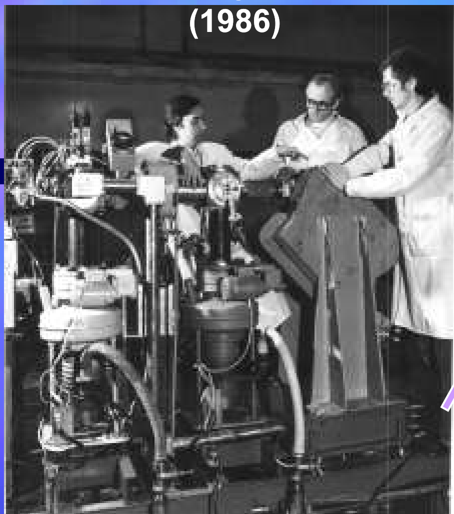
The equipment must be simple and reliable.

Operating time in the mode of film irradiation - 7000 hours/year

Project start: August 2009.
Commissioning: 2012.

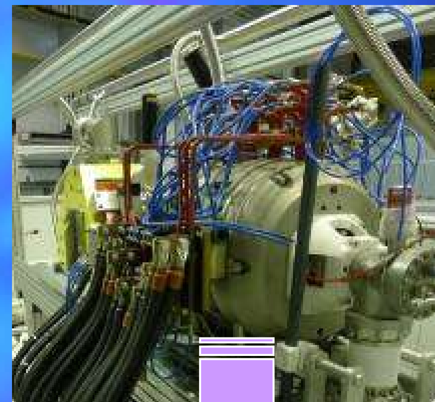
Technical solutions underlying the DC-110 project

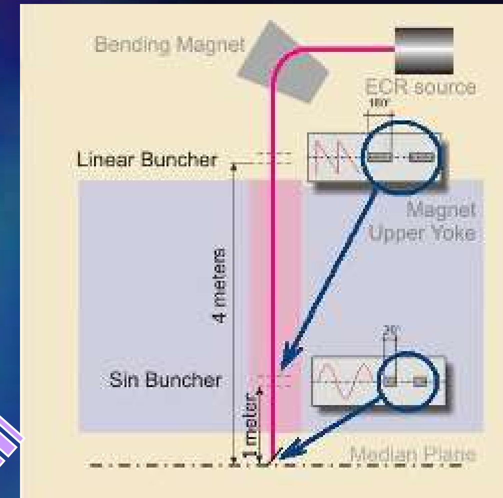
The first axial injection system at the U-200 cyclotron JINR (1986)

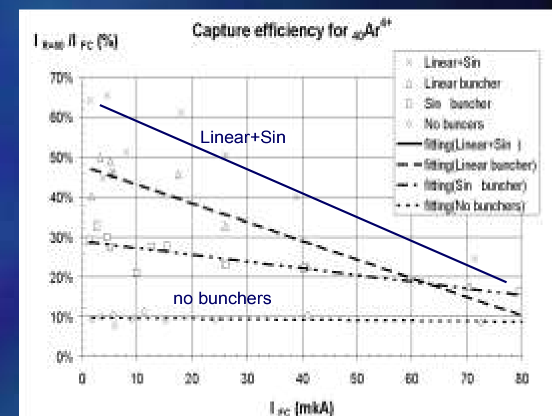


The DECRIS ion sources.

Since 1994 11 sources were created at FLNR





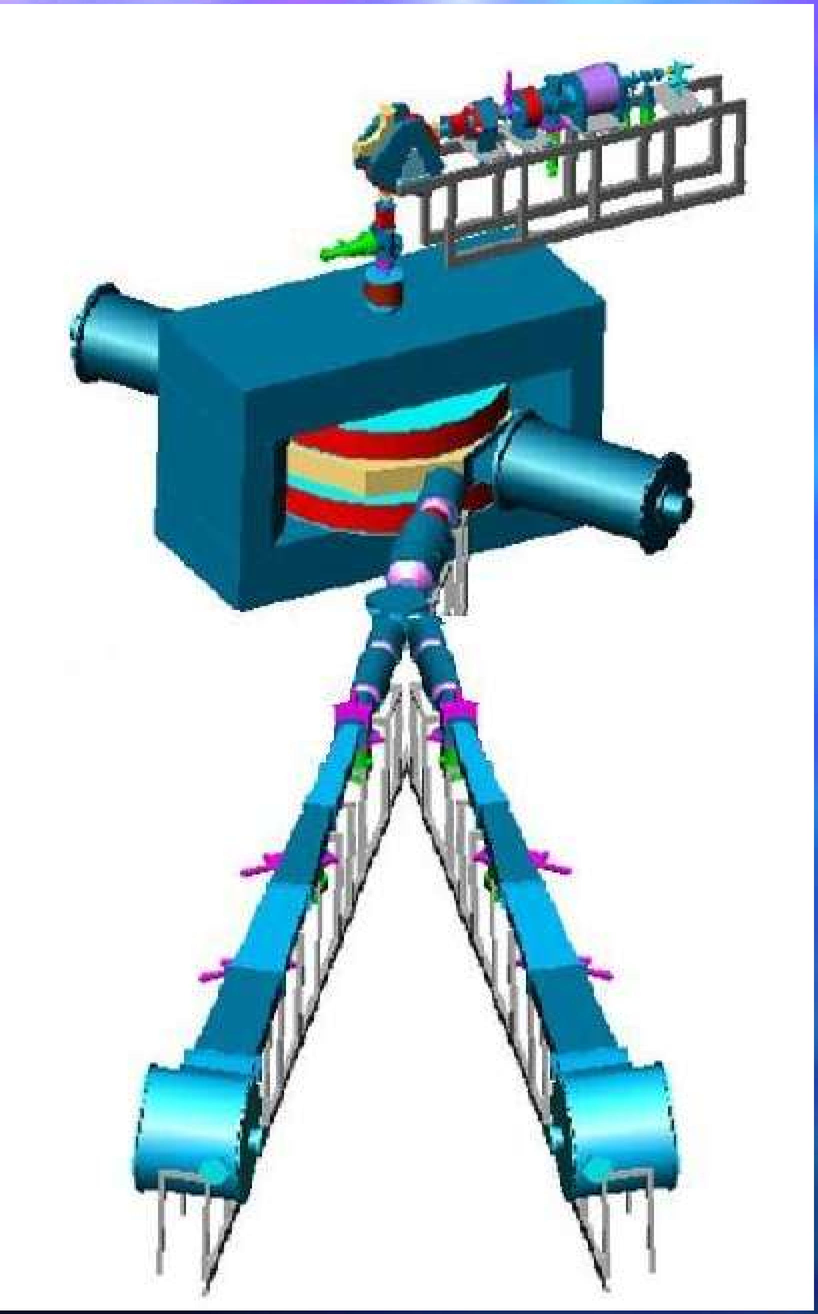


U-400. Axial injection line with double-bunching system (Lin+ Sin) (1995)

DC-110

The IC-100 cyclotron (commissioning in 1985, reconstruction 2001-2002).

The DC-60 cyclotron (2006)



DC-110 cyclotron complex (2009-2012)

- The DC-110 cyclotron
- External ECR ion source
- Beam axial injection system
- 2 beam channels of accelerated ions
- Technological equipment:
  - vacuum system
  - power and control
  - cooling system
  - RF system

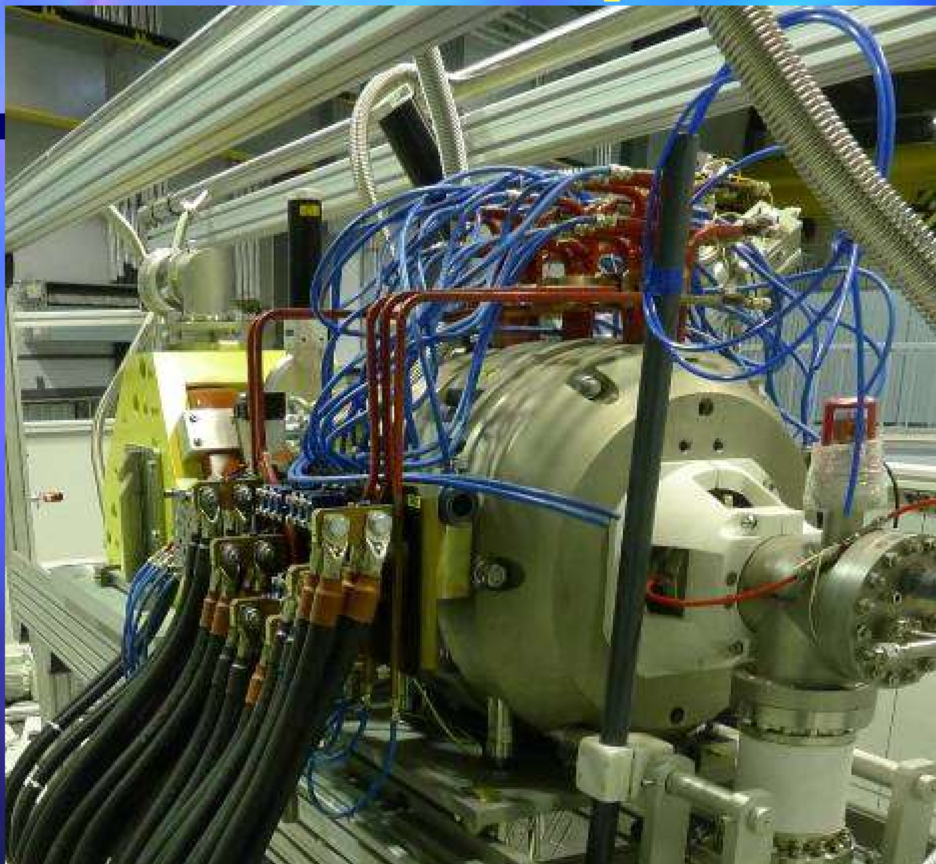
The main beam parameters of the DC-110 cyclotron (project)

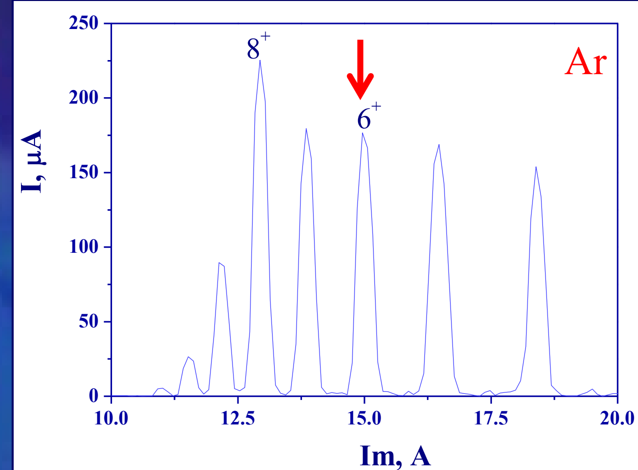
Ion source	ECR, 18 GHz		
Accelerated ions	$^{40}Ar^{6+}$	$^{86}Kr^{13+}$	$^{132}Xe^{20+}$
Mass-to-charge ratio (A/Z)	6,6667	6,6154	6,6000
Ion energy	2.5 MeV/nucleon		

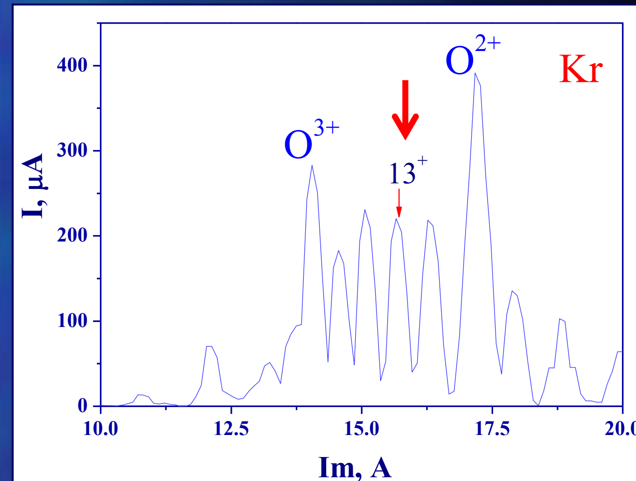
Beam intensity in routine operation (1 pμA ≈ $6 \cdot 10^{12}$ pps)	ECR	On the target
Ar	10 * pμA *(60 μA)*	1* pμA *(6* μA)*
Kr	10 pμA *(130 μA)*	1 pμA *(13 μA)*
Xe	5 pμA *(100 μA)*	0,5 pμA *(10 μA)*

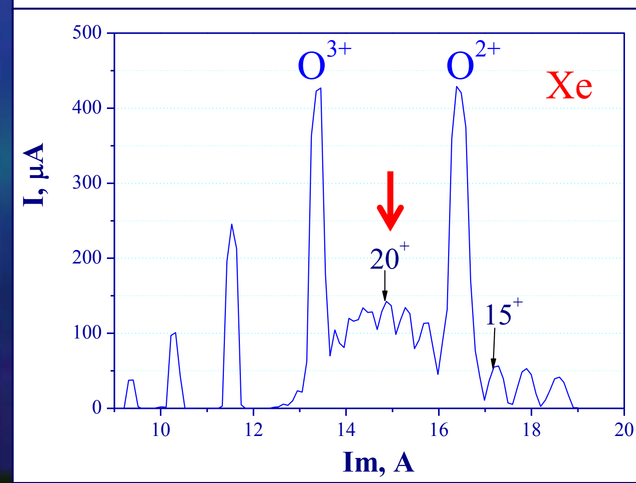
*) - the beam intensity can be higher than the one indicated in the table

DECRIS-5 - ECR ion source of the DC-110 cyclotron







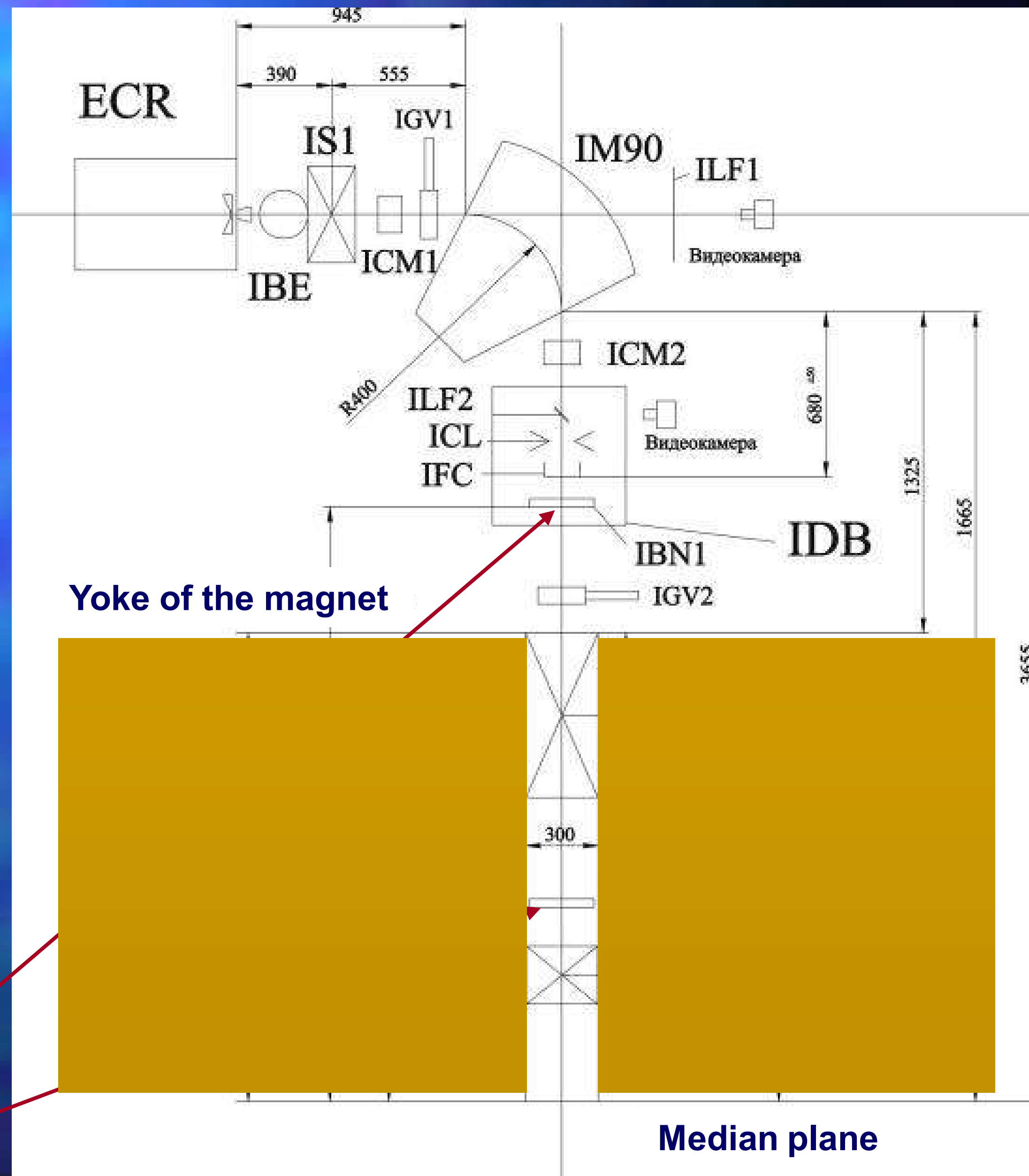


The maximum intensity of ion beams

Charge	8+	9+	11+	15+	18+	19+	20+
Ar	1200	750	300				
Kr				325	182	120	70
Xe							220

DC-110 cyclotron

Scheme of beam axial injection line at the cyclotron

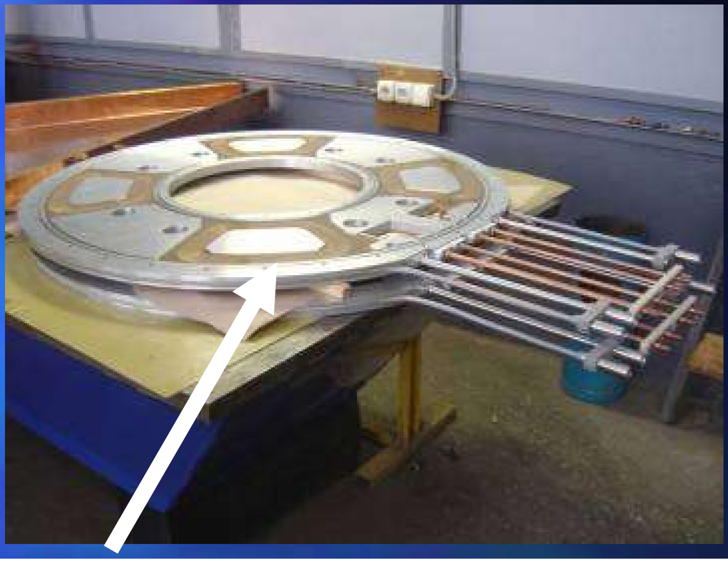


Injection voltage - 20 kV

Designation	Type of element	Maximum field
IS1	Solenoid	6.0 kG
IM90	Analyzing magnet	1.9 kG
IS2	Solenoid	2.0 kG
IS3	Solenoid	5.0 kG

Designation	Type of element	Voltage amplitude
IBN1	Linear buncher	700-750 V
IBN2	Sinusoidal buncher	300-350 V

Magnetic structure of the DC-110 cyclotron

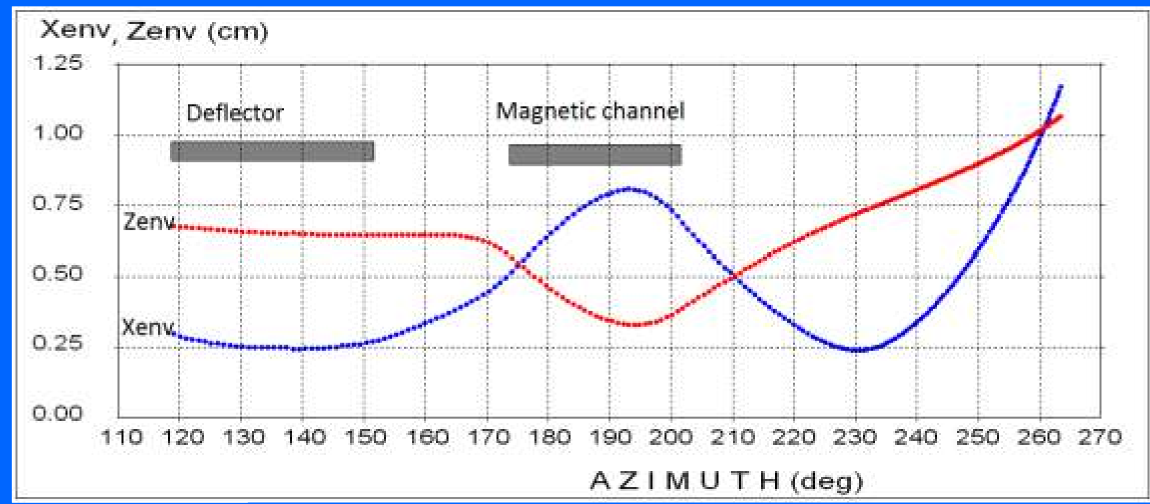


Azimuthal correction coils unit

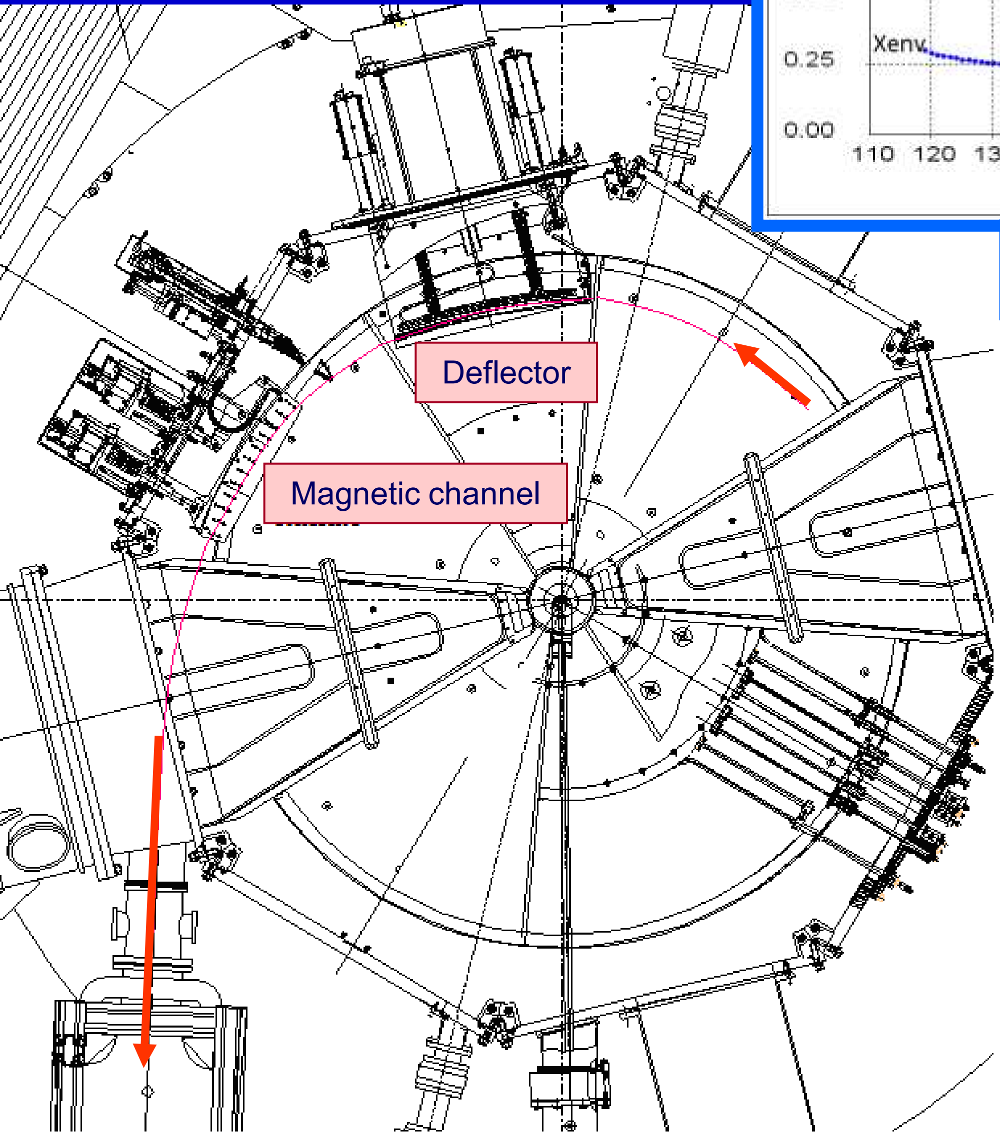
Main parameters of DC-110 cyclotron electromagnet

Size of magnet, L × W × H, [mm]	4940×2075×2840
Pole diameter	**2000 mm**
Interpole gap, [mm]	218
Number of sector pairs	4
Angular length of sector (helicity)	52° (0°)
Sector height, [mm]	65.5
Gap between sectors, [mm]	**42**
Gap between sector and pole, [mm]	24.5
Gap between central plugs, [mm]	112
Number of radial correction coils	0
Number of sets of azimuthal correction coils	2
Electromagnet weight	**250 tons**
Power consumption of main coil	**51 kW**
Maximal power consumption of correction coils	**0.4 kW**
Isochronous magnetic field at center, Tl	**1.67**
Flutter	0.117
Betatron oscillation frequency - ν_r - ν_z	0.34 1.015

Beam extraction system of DC-110 cyclotron

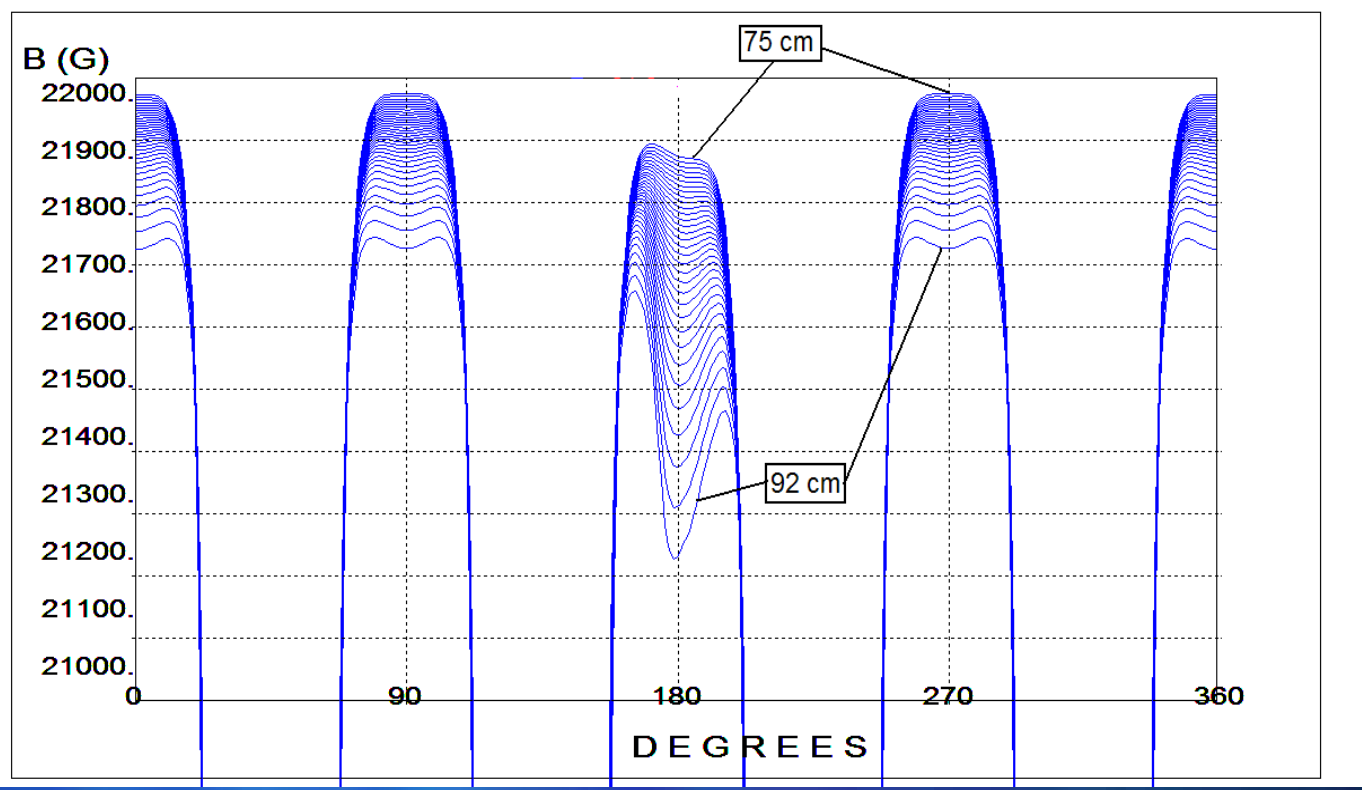


Ion beam envelope in extraction system



Magnetic structure of DC-110 cyclotron

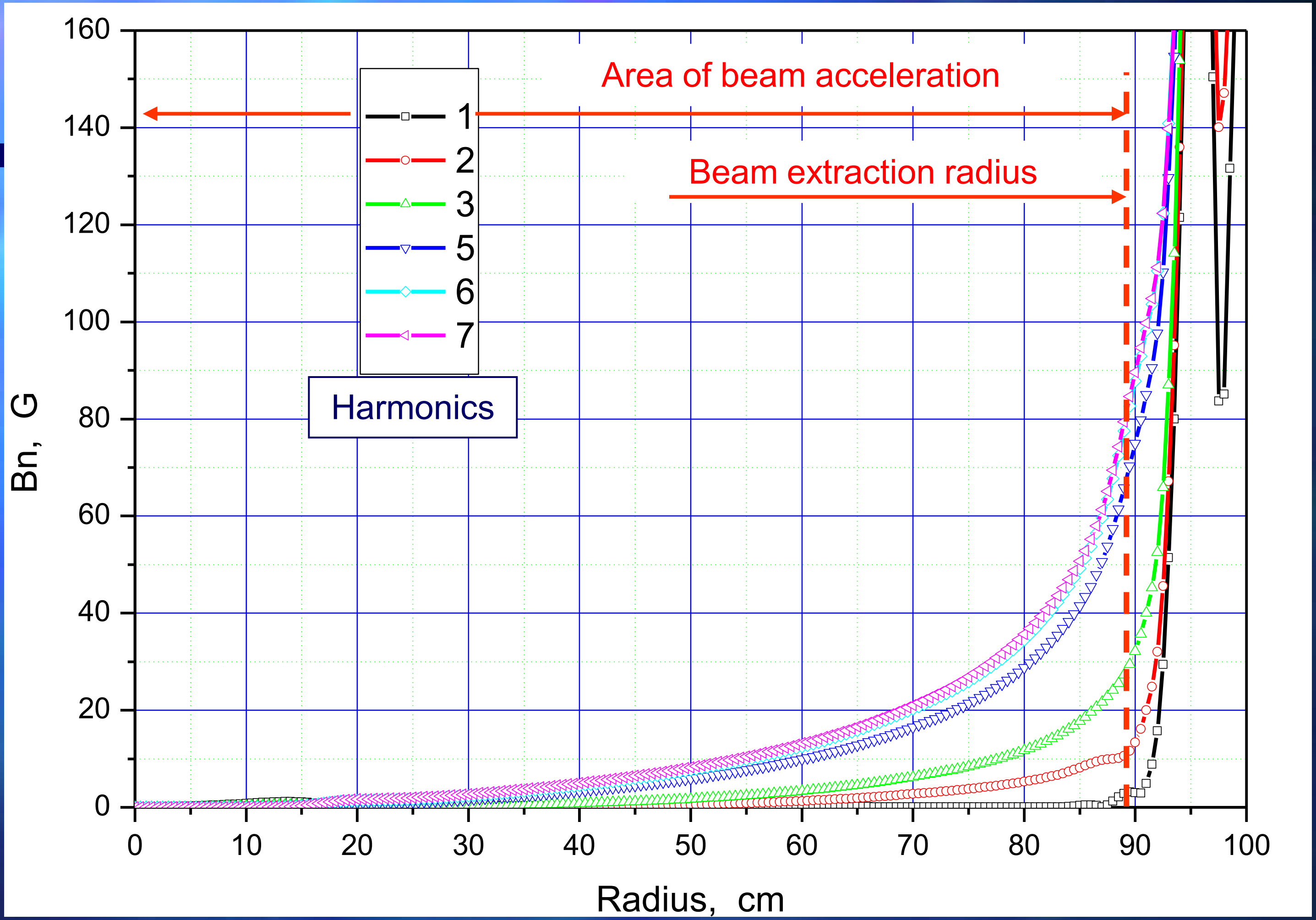
Influence of the magnetic channel on cyclotron magnetic field



Calculated distribution of the magnetic field at the radius of 75-92 cm

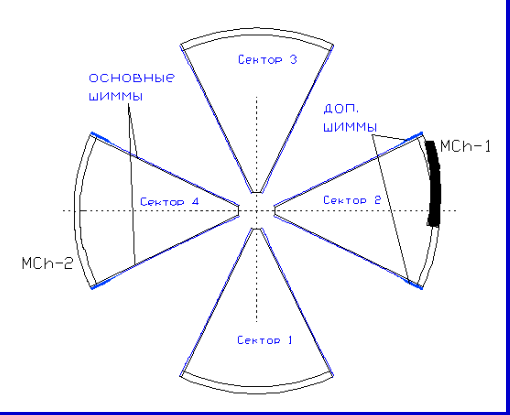
- The influence of the magnetic channel on the cyclotron magnetic field is compensated by means of iron shims on sectors.
- 1st harmonic of the magnetic field caused by the magnetic channel is compensated by means of iron shims on sectors.

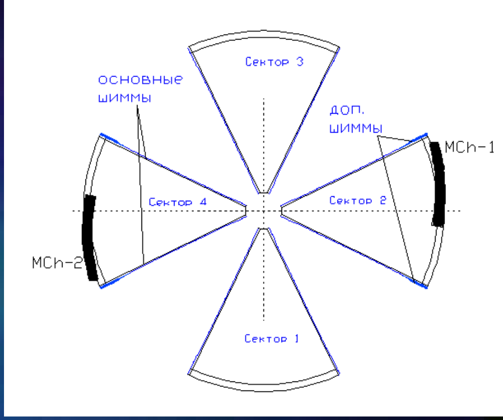
Magnetic structure of DC-110 cyclotron



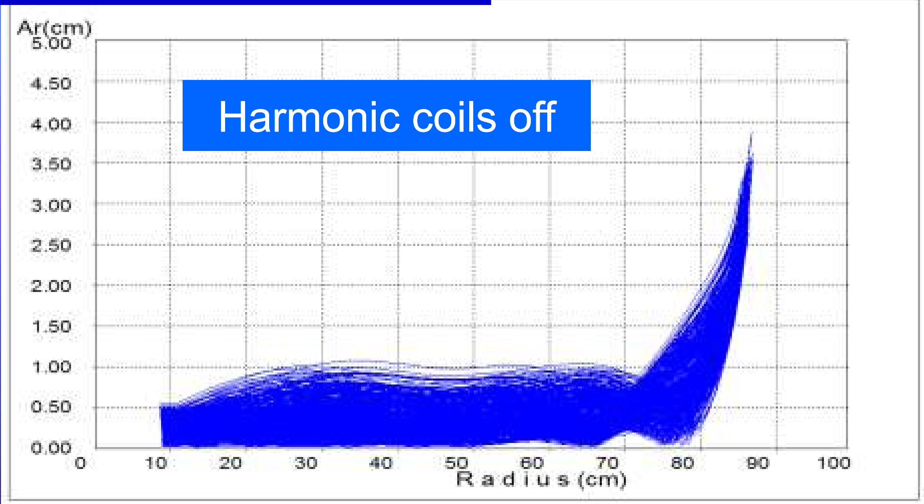
The amplitude of the magnetic field harmonics in the case of installation of the magnetic channel and the compensation of average magnetic field and 1st harmonic by means of iron shims.

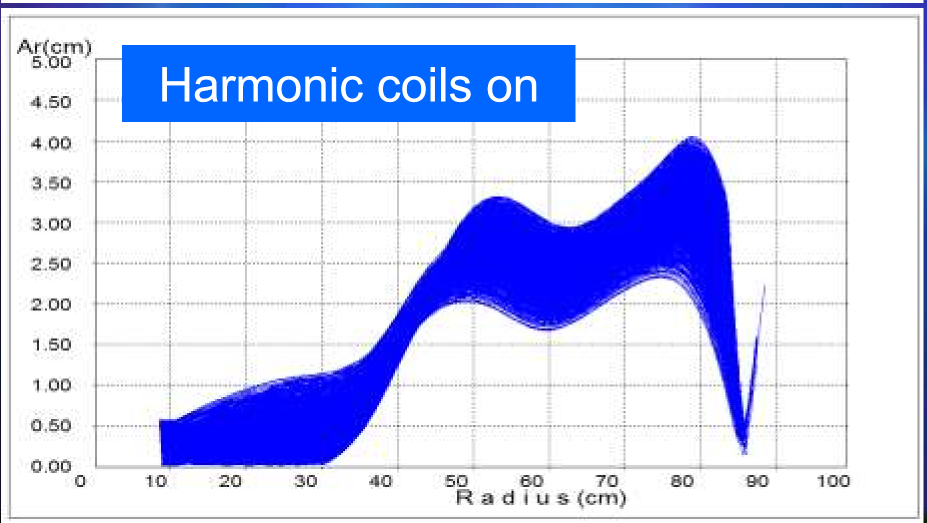
Magnetic structure of DC-110 cyclotron



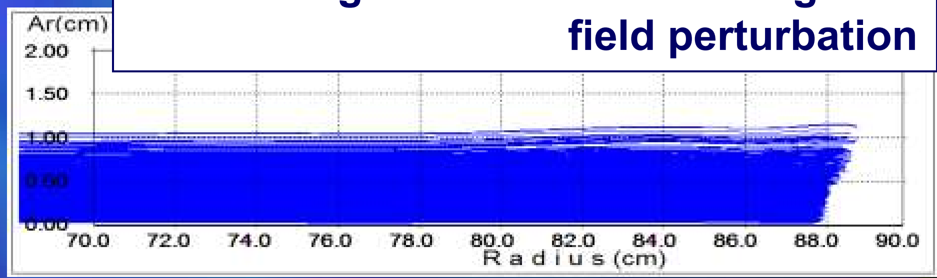


The amplitude of beam radial oscillation in the cyclotron depending on the orbit radius.

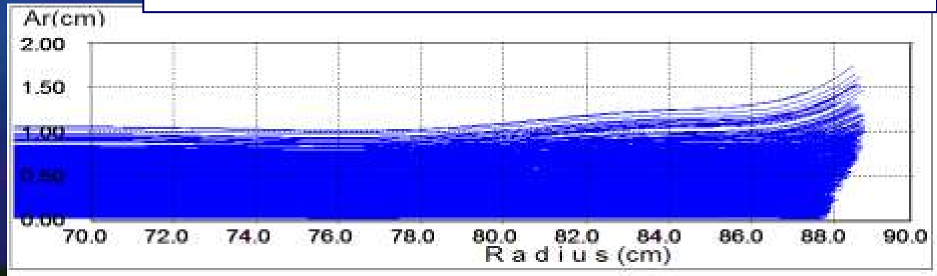




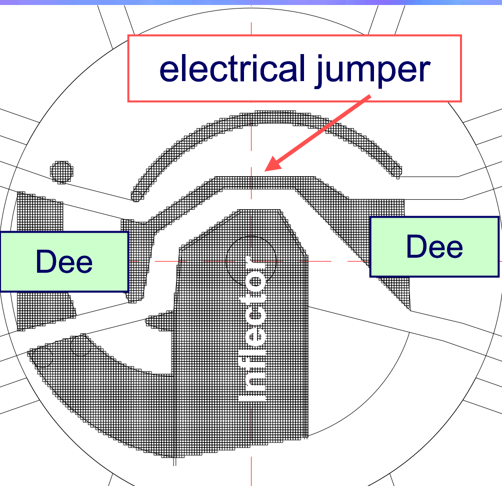
Excluding harmonics of the magnetic field perturbation

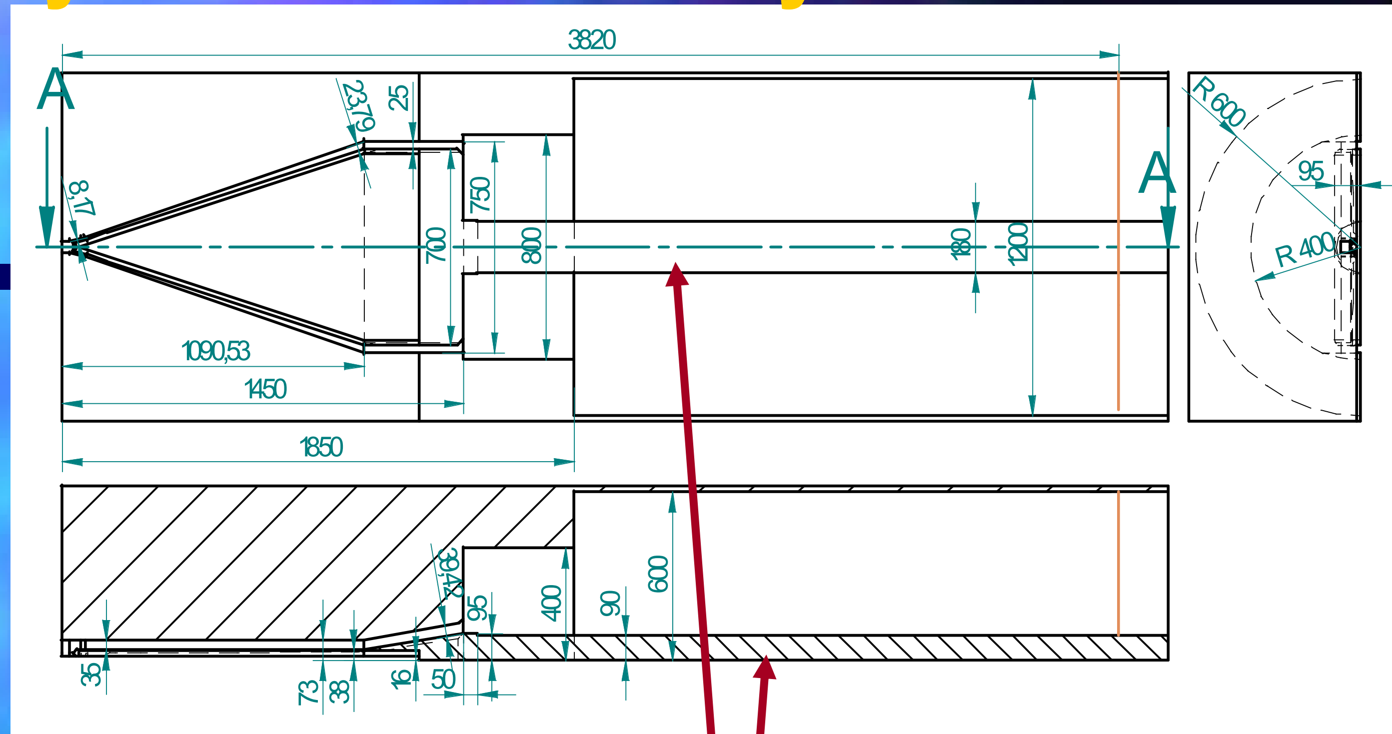


With account of the 2nd harmonic of magnetic field perturbation



RF system of DC-110 cyclotron





1. Two dees have an electrical jumper in the center of the cyclotron.
2. One RF-generator.
3. One trimmer of automatic resonance frequency tuning

Resonance frequency of resonators	7.494 - 7.806 MHz
Acceleration harmonic	2
Nominal position of shorting plate from cyclotron center	3760 mm
Dee voltage	55 kV
Calculated RF power consumption of one resonator	4.3 kW
Maximum current density on stem surface	32 A/cm
Frequency tuning range by AFC trimmer	100 kHz (0.1%)
Maximum power of RF generator	20 kW

Element RF system	Distance from the center, mm	Power dissipation, W
Dee	0 - 1050	76
Stem	1450 - 3660	2825
Anti-dee	0-1063	68
Outer cylindrical part of the cavity	1063 - 1450	996
Shorting plate	3660	266
	Σ	***4231***

Vaccum system of DC-110 cyclotron

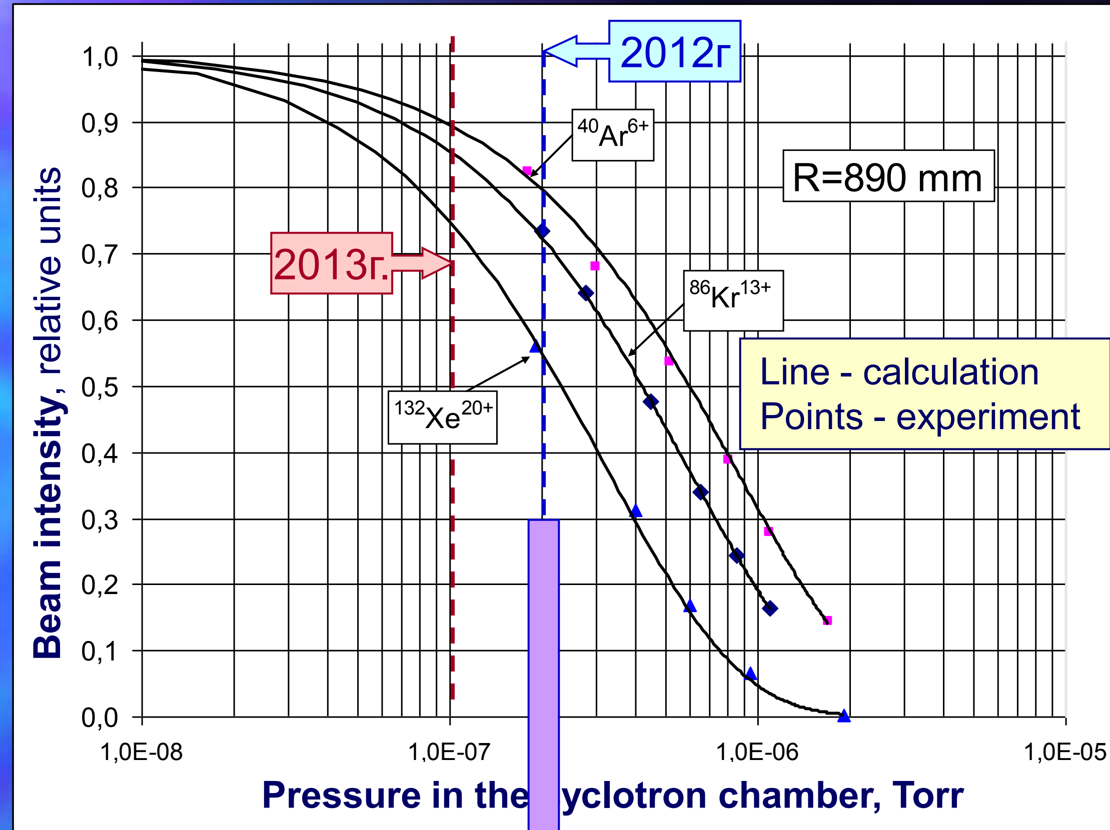
Design and obtained vacuum in DC-110 cyclotron

	Required	Obtained
Injection channel	$1 \cdot 10^{-7}$ Torr	$1{,}1 \cdot 10^{-7}$ Torr
Cyclotron chamber	$(1\text{-}2) \cdot 10^{-7}$ Torr	$1{,}7 \cdot 10^{-7}$ Torr (in static regime) $2{,}7 \cdot 10^{-7}$ Torr (in working regime, with beam)
High energy ion channel	$5 \cdot 10^{-6}$ Torr	$2 \cdot 10^{-7}$ Torr

Vacuum pumping

1-st stage – forepump -	~ $5 \cdot 10^{-2}$ Torr
2-nd stage – turbomolecular pumps -	~ $1 \cdot 10^{-6}$ Torr
3-rd stage – cryogenic pumps -	~ $1 \cdot 10^{-7}$ Torr

Beam losses during acceleration in the DC-110 cyclotron



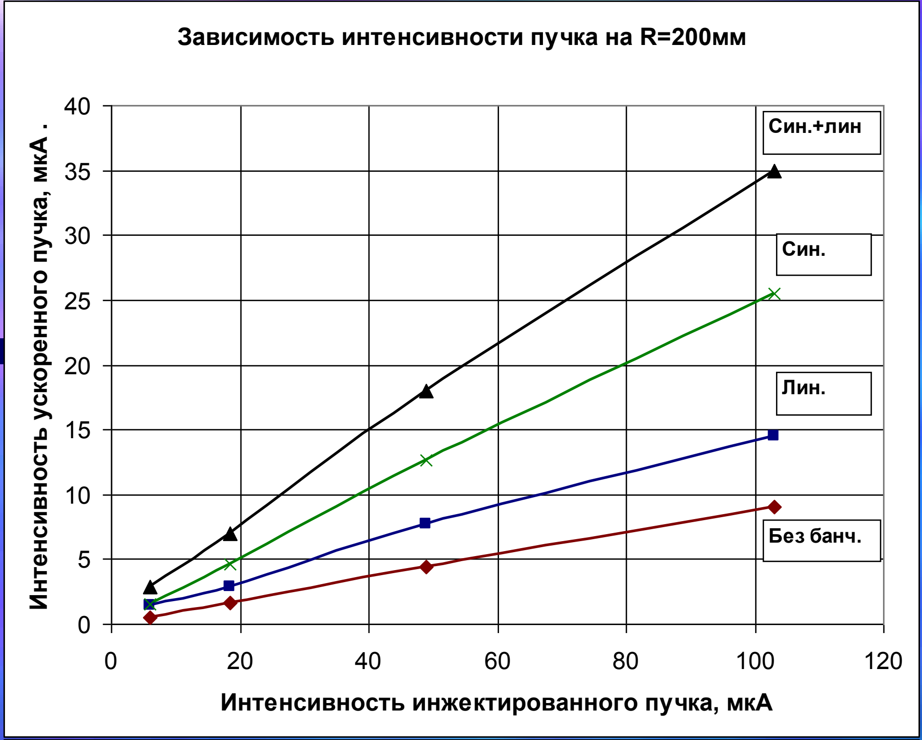
Beam losses during acceleration from the center to the final radius - 890 mm at a pressure in the cyclotron ~ $2 \cdot 10^{-7}$ Torr (2012)

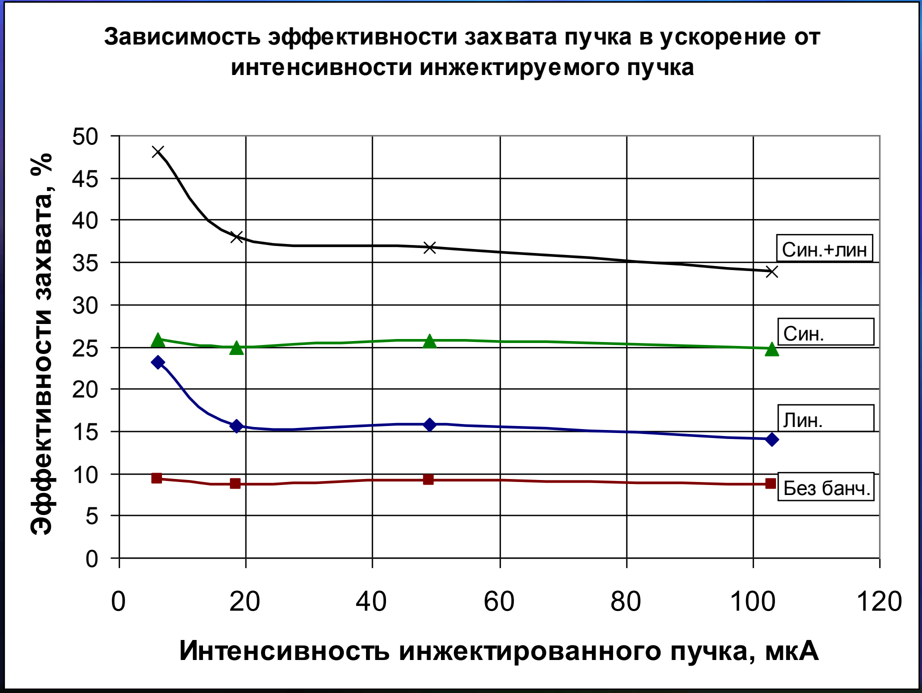
Ion beam	Phase and aperture beam losses	Vacuum beam losses	Total beam losses
$^{40}Ar^{6+}$	9 %	18%	27 %
$^{86}Kr^{13+}$	9 %	25 %	34 %
$^{132}Xe^{20+}$	9 %	44%	53 %

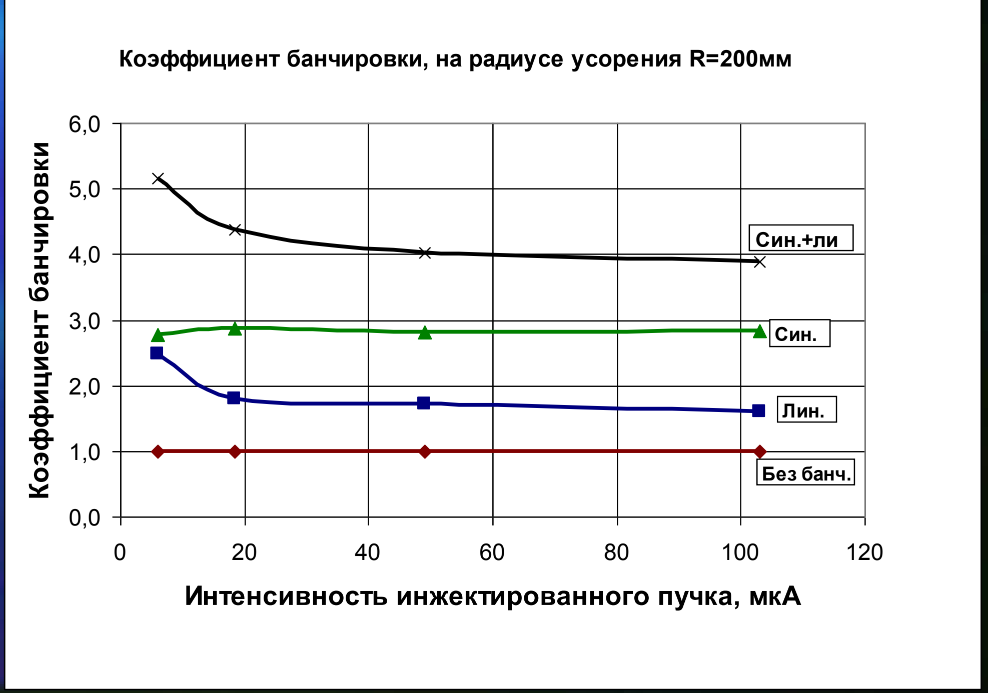
DC-110 cyclotron Experimental results

$^{40}Ar^{6+}$ beam capture into acceleration.

I inj, μA	Capture coefficient of injected beam into acceleration			
	Bunchers switched off	Lin - on	Sin - on	Sin+Lin - on
6	9,3 %	23,2 %	25,8 %	48,2 %
18,4	8,7 %	15,6 %	25,0 %	38,0 %
49	9,1 %	15,7 %	25,7 %	36,7 %
103	8,7 %	14,1 %	24,8 %	34,0 %







Transmission of beam from ion source to film irradiation device with disconnected bunching system.

Ion	Injected beam current, μA	Accelerated beam current, μA (beam bunching system switched off)		Extracted beam current, μA	Beam current on the target, μA
		R= 140 mm	R= 908 mm		
$^{84}Kr^{13+}$	150	13	5.8	3.9	3.9
	8.7% (8%)				
		45% (75%)			
			67% (60%)		
				100% (90%)	
	2.6% (3.2%)				

Transmission of beam from ion source to film irradiation device with connected sinusoidal and linear bunchers

Ion	Injected beam current, μA	Accelerated beam current, μA (beam bunching system switched on)		Extracted beam current, μA	Beam current on the target, μA
		R= 140 mm	R= 908 mm		
$^{84}Kr^{13+}$	150	44	20.7	14.5	14.5
	29% (30%)				
		47% (75%)			
			70% (60%)		
				100% (90%)	
	9.7% (10 -12%)				

* Design values are indicated in parentheses

Ion beam parameters of the DC-110 cyclotron

Optimal frequency values of RF system and 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

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)

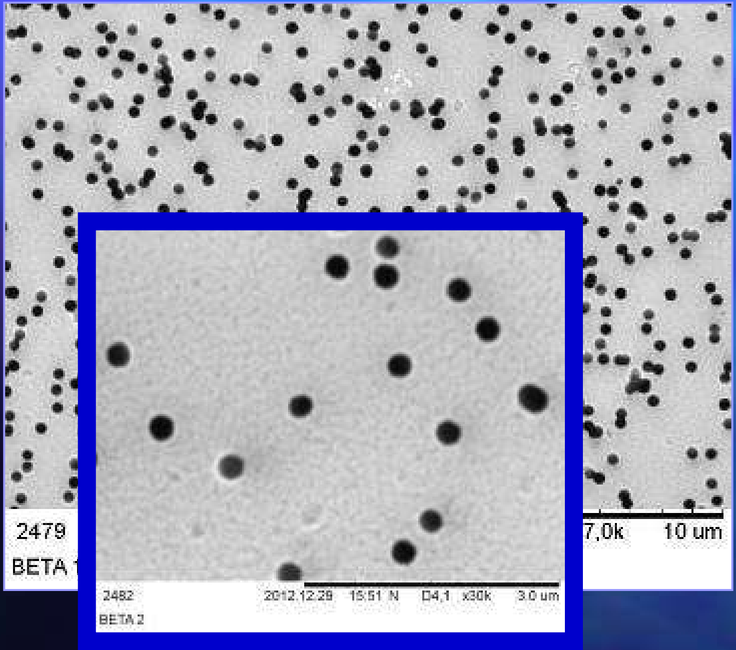
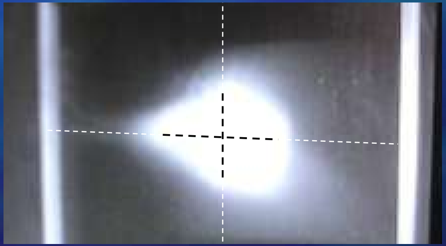


Photo of membrane on the electron microscope.
Pore density - $1.32 \cdot 10^{8}$ pores/cm2.
Magnification of 30,000 times

<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

Parameters of specialized heavy ion cyclotrons for industrial applications

Heavy ion accelerators		Accelerated ions	Ion energy	Beam intensity
IC-100 **FLNR JINR** (cyclotron project – FLNR JINR)	**(1986)**	C-Ar	**1.2** MeV/nucleon	0.1 pμA
	(2002)	Ar Kr, Xe I, W	**1.2** MeV/nucleon	0.4 pμA 0.2 pμA 0.05 pμA
DC-60 **Interdisciplinary Research Center of the Gumilev Eurasian National University (Astana, Kazakhstan)** (cyclotron project – FLNR JINR)	**(2006)**	C - Xe	**0.35 – 1.7** MeV/nucleon	10 – 0.1 pμA
CYTREC **ALFA research and industrial complex in Dubna (Russia)** (cyclotron project – DLNP JINR)	**(2002)**	Ar	**2.4** MeV/nucleon	0.03 pμA
DC-110 **BETA research and industrial complex in Dubna (Russia)** (cyclotron project – FLNR JINR)	**(2012)**	Ar Kr Xe	**2.5** MeV/nucleon	1 pμA 1 pμA 0.5 pμA