Accelerator Hadron Therapy Technique Developed at JINR

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On behalf of following teams :

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Project of demonstration center of proton therapy

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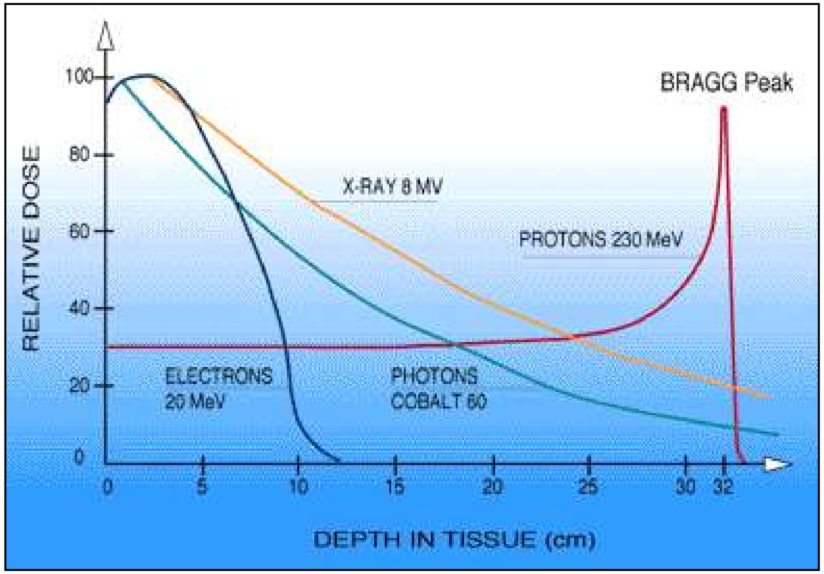
Medical superconducting synchrotron team: E.Syresin, V. Mihailov, A. Tuzikov, N.Agapov, A.Eliseev, E.D. Donets, E.E. Donets, G. Hodshibagijan, V.Karpinskij, A. Kovalenko, A.Malahov, I.Meshkov, A.G. Olshevsky, G. Shirkov, S. Shirkov, G. Trubnikov

HADRON THERAPY IN WORLD AND IN RUSSIA



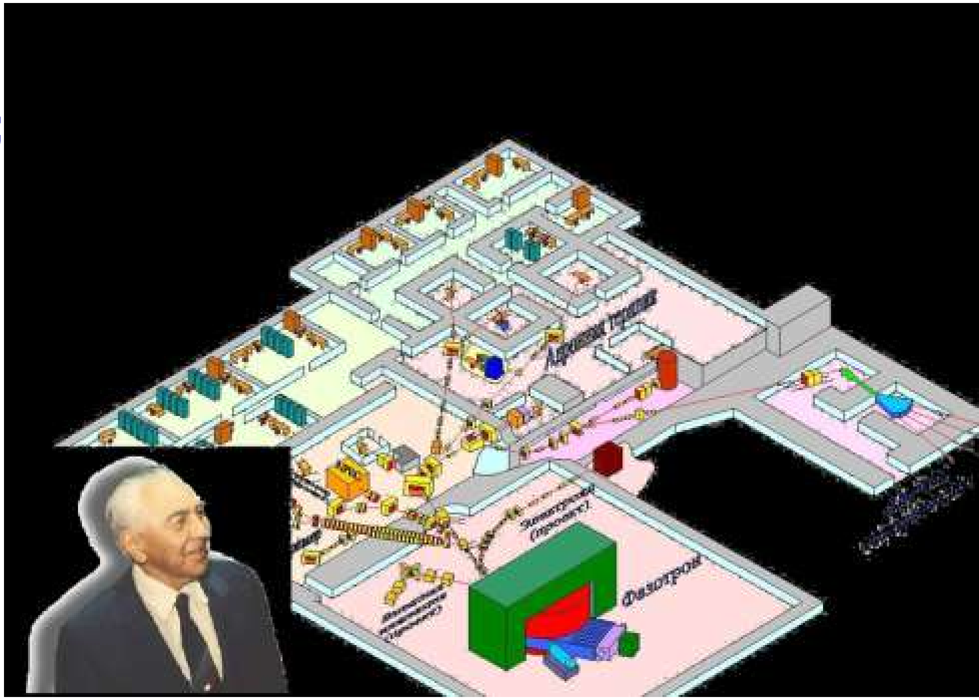
There are about 30 centers of the proton therapy and 5 centers of carbon therapy at the world now. About 100 thousand patients were treated with application of hadron therapy during last 50 years, 60 % of them were treated over last 10 years and 90% of total patients now treated in the hospital based facilities.

2.3 million of tumor patients there are in Russia 450 thousands of new patients are appeared per year.

The proton therapy is recommended 50 thousands of patients per year in Russia.

JINR Medical-Technical Complex on proton beams of synchrocyclotron

<u>1967</u> – First investigations at cancer treatment;
1<u>968 –1974</u> –84 patients was irradiated by proton beams on synchrocyclotron;
<u>1975 –1986</u> – Upgrade of synchrocyclotron, creation of Medic-Technical Complex (MTC) of hadron therapy in JINR;
<u>1987– 1996</u> –40 patients were radiated by proton beams;
<u>1999,</u> – Creation of radiological department in Dubna hospital;
<u>2000 – 2014,</u> –1040 patients were radiated by proton beam.



During last years around 100 patients per year were radiated by proton beam in JINR Medical-Technical Complex in frame of research program of Medical Radiological Research Center.

More than 1000 patients were treated by the JINR proton beams

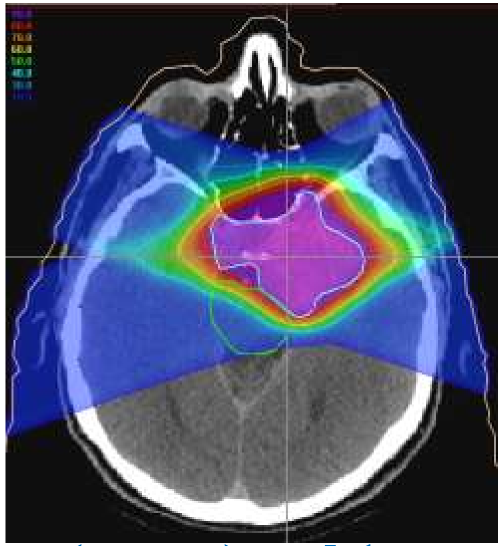
JINR PHASOTRON MEDICAL PROTON BEAMS

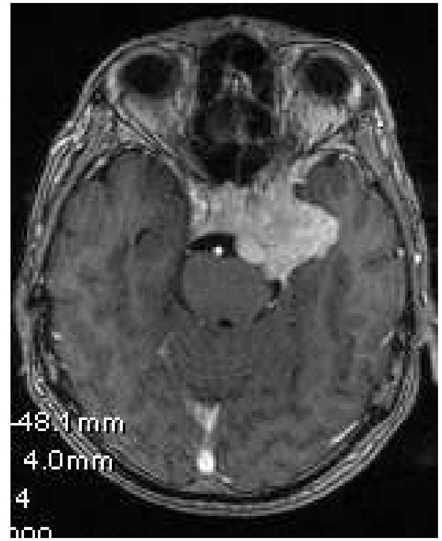
Cancer treatment in cabin №1

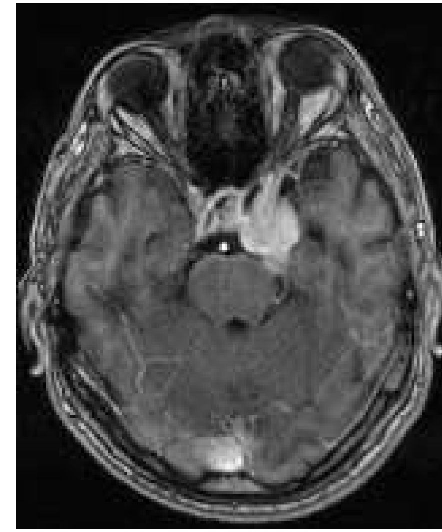
3D conformal proton beam treatment were realized in Russia only in JINR.

3D conformal proton therapy in JINR

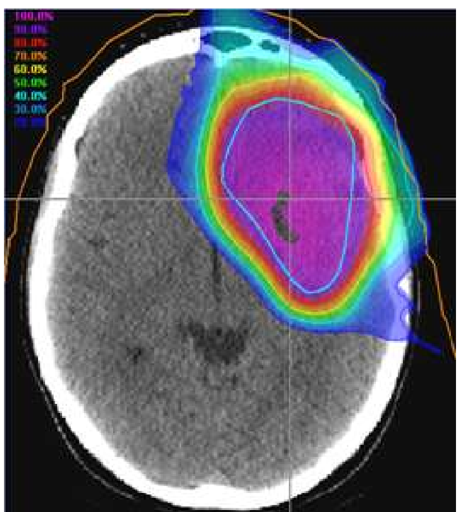
Plan of proton treatment of meningiomas







MRI before treatment(center) and 1 year later after treatment (right)large reduction of meningiomas volume

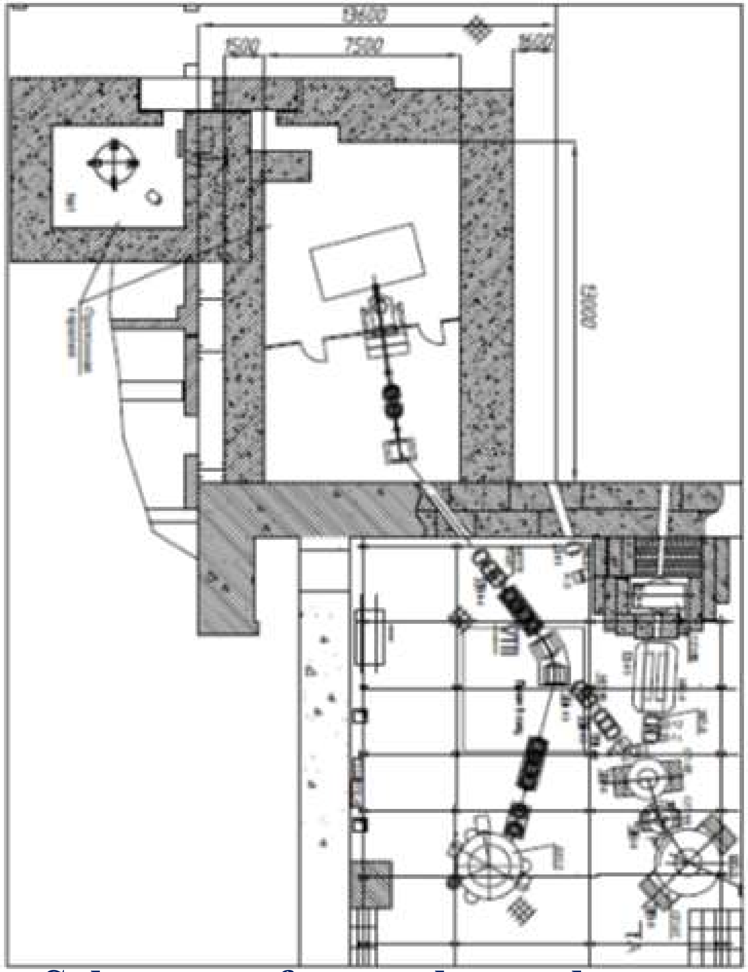


Treatment of brain astrocytomas by proton beams

Diseases treated by proton beams in JINR

Meningiomas	179
Chordomas, chordosarkomas	37
Gliomas	65
Lymphoma	1
Acoustic Neurinomas	20
Astrocytomas	48
Paragangliomas	6
Pituitary Adenomas	26
AVMs	78
Brain and other metastasis	77
Other head and neck tumors	286
Melanomas	19
Skin diseases	69
Carcinoma metastasis of the lung	8
Breast cancer	52
Brain cancer	11
Prostate Adenomas	1
Sarcomas	17
Other	41
Total	1041

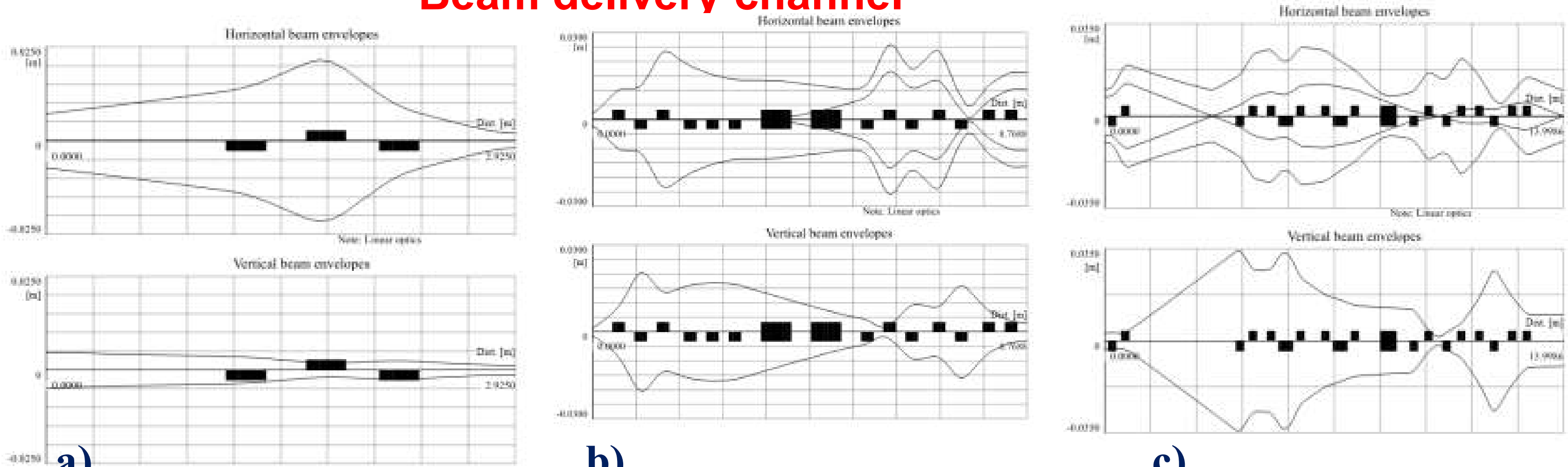
Demonstration center of proton therapy



Scheme of synchrocyclotron with beam delivery channel and modernized medical cabin in demonstration center of proton therapy.

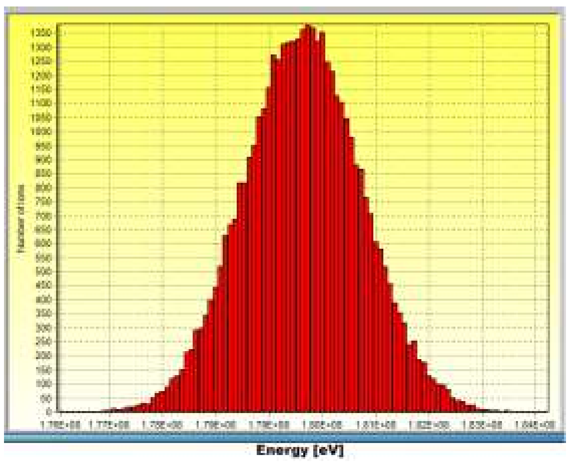
Irradiation	Active
Diameter, m	2,3
Weight, t	50
Magnet	Superconducting
Average field, center/extract., T	5,64/5.24
Voltage of dee-electrodes, kV	14
RF–frequency, MHz	90-61.5
Frequency of beam pulses, kHz	1
Average current, nA	20
Proton energy, MeV	230
Energy spread, 2σ, MeV	2,5

Beam delivery channel



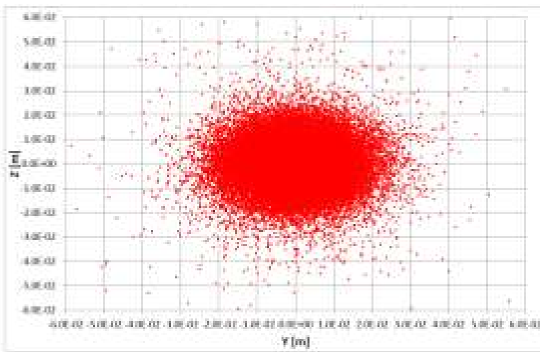
a) b) c)

a) Beam transportation from cyclotron to degrader. b)Beam transportation from degrader to momentum slit. c) Beam delivery from momentum slit to entrance of treatment room.



Energy distribution after collimator with 10 mm gap is decreased from 2.37% to 1.58%.

Two wobbling magnets will be installed to form the uniform dose distribution with transverse size of 15×15 cm in double scattering scheme. The efficiency of beam formation in double scattering scheme is about 30%. As result the average current on tumor target is about 2.4 nA at proton energy of 180 MeV.



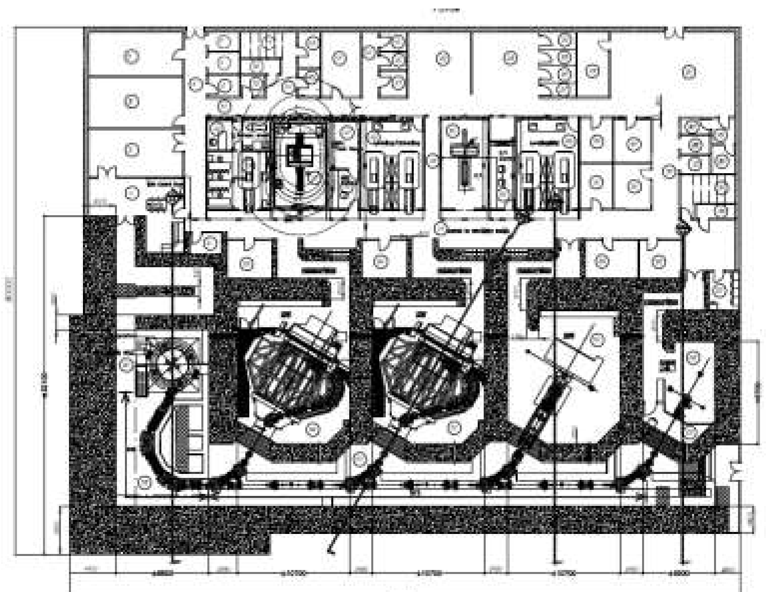
Beam spot size at the entrance of treatment room is 9.6/9.7 mm

Federal High Technology Center of Medical Radiology (Dimitrovgrad, Ulyanovsk reg.)

E.Syresin et al, IPAC11, p.2706.

The Federal high technology center of medical radiology involves:
Center of Proton therapy
PET Center

The Project of the Center of proton therapy was developed by Federal Medico-Biological Agency in collaboration with JINR



The center consists of two gantry systems, a medical treatment room with a fixed beam, an eye treatment room and a PATLOG system of preliminary patient positioning.

The JINR-IBA collaboration has developed and constructed the C 235-V3 proton cyclotron for this center.

Equipment of Dimitrovgrad proton center for proton therapy was certificated first time in RF.

Planed Centers of Proton Therapy, realized in frame of Russian Federal program:

- Dimitrovgrad
- Obninsk
- Tomsk

Production of medical proton cyclotron in JINR

E.Syresin et al, Physics of Particle and Nuclear Letters,2011, v. 8 p.379

JINR-Ion Beam Application (IBA, Belgium) collaboration since 2007 starts development of essentially modified version of IBA serial cyclotron C235 so called cyclotron C235-V3 applied for hospital centers of proton therapy.

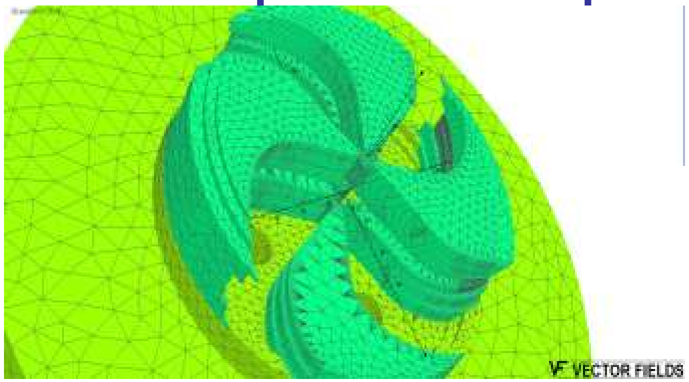
C235-V3 cyclotron is superior in its parameters to the IBA C235 serial medical proton cyclotron of previous generations installed in 12 hospital centers in the world.

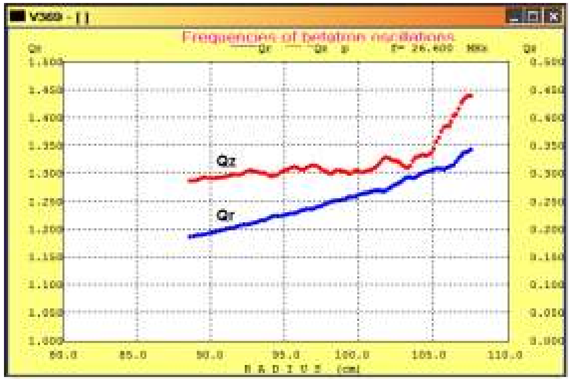
The further improvement of cyclotron C235-V3 parameters is expected also in frame of JINR-IBA research works proposed by JINR

2010–C235-V3 construction was completed

June 2011 г. – Start of assembling and tests of cyclotron in Dubna

September 2012 - Delivery of cyclotron in Dimitrovgrad hospital center of proton therapy





Cyclotron C235-V3 produced by JINR-IBA collaboration

P.V. Galkin et al, JTPh, 2014, V.59 N.6, p.917

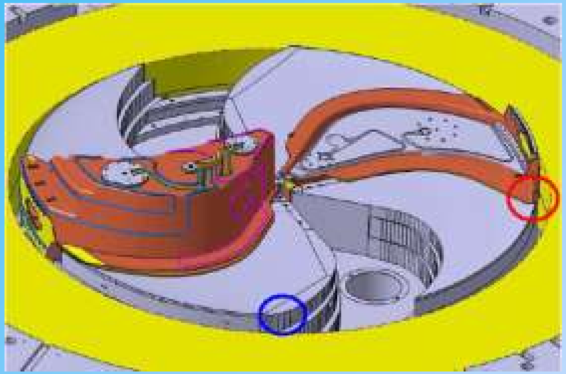
General parameters	Value
Proton energy, MeV	235
Internal current, uA	1
Beam emittances, π·mm·mrad	12/11
Magnetic field (min/max) T	0.9/2.9
Number of sectors	4
Magnet diameter, m	4.3
Radius of beam extraction, m	1,08
Elliptical hill gap, cm	9,6/0,9
Duant aperture, cm	2
RF frequency, MHz	106.1 (4 harmonic)
Dee voltage, (min/max) kV	60/130
Ion source	PIG, internal
Electrostatic deflector field, kV/cm	170
Extraction efficiency, %	60
Power, kW	446
Weight, t	220

JINR engineering center for assembling and tests of medical accelerators.
FLNR JINR Cyclotron for filter production applied for blood plasmoferese (forward plan).
DLNP JINR cyclotron for proton therapy (behind plan)

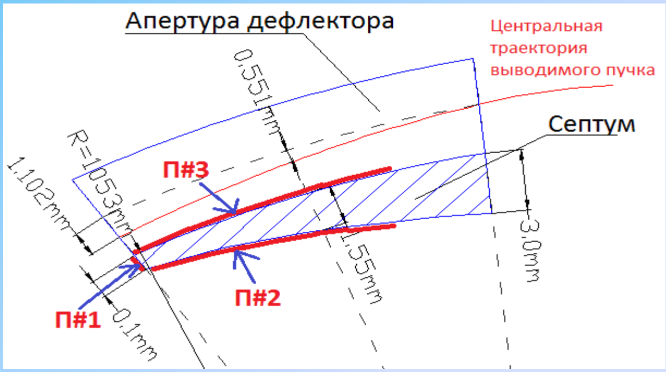
Medical proton cyclotron C235-V3 in JINR

Peculiarities of cyclotron C235-V3 in comparison with serial IBA cyclotrons C235

The structure of the magnetic field was modified in area of the minimum axial betatron frequency, increase axial focusing and reduce radial component of magnetic field, axial beam size was reduced by two times, acceleration efficiency was obtained 72% without cutting diaphragm

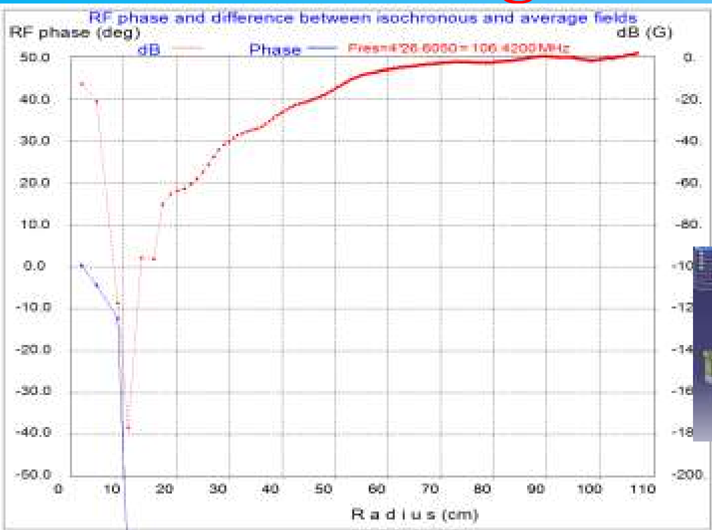


Modified geometry of RF cavity at large radius, optimized axial magnetic field for this geometry

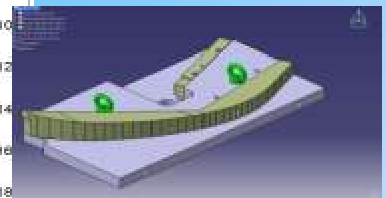


Modified construction of extraction system. Improve extraction efficiency from 50% up 75% with new JINR extraction system

Shimming of C235-V3 magnetic field in JINR



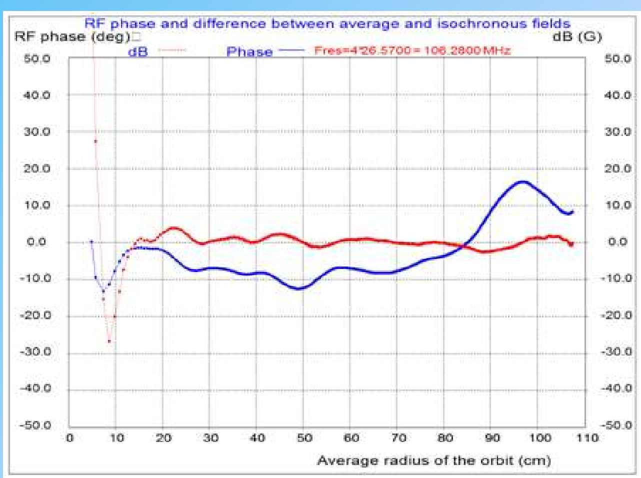
New technologies realized in JINR at magnetic shimming of C235-V3



Special platform for mechanical fabrication with diameter of 1 m was constructed instead IBA platform diameter of 1.5 m

Special 3D Carl Zeiss machine provided sector edge surface measurements with um accuracy was incorporate in shimming technology

Errors of magnetic fields after cyclotron construction in plant is of 180 Gs.



Errors after shimming in JINR is 2-3 Gs.

New calibration dipole magnet on field 2.9 T instead 2.5 T IBA magnet

**The new system for measurement of the average radial component
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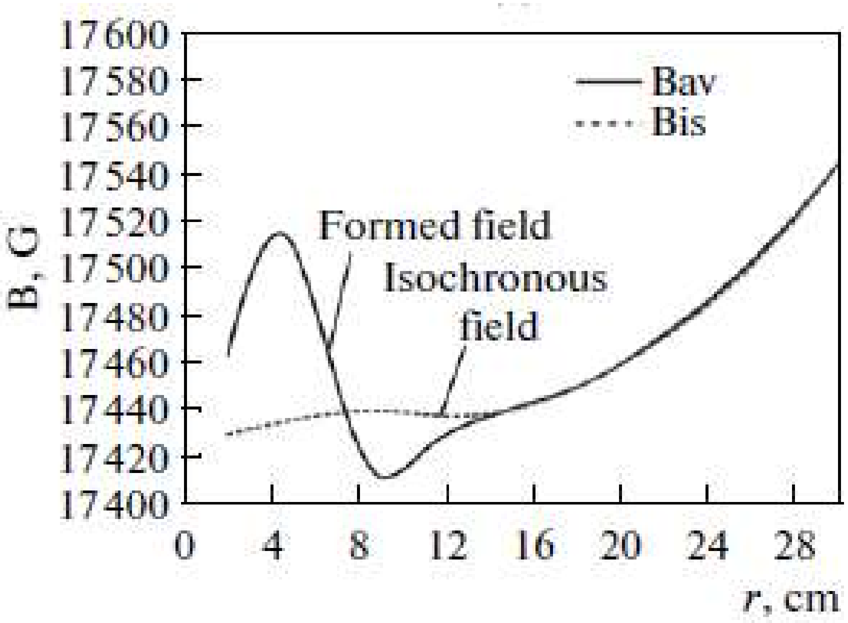
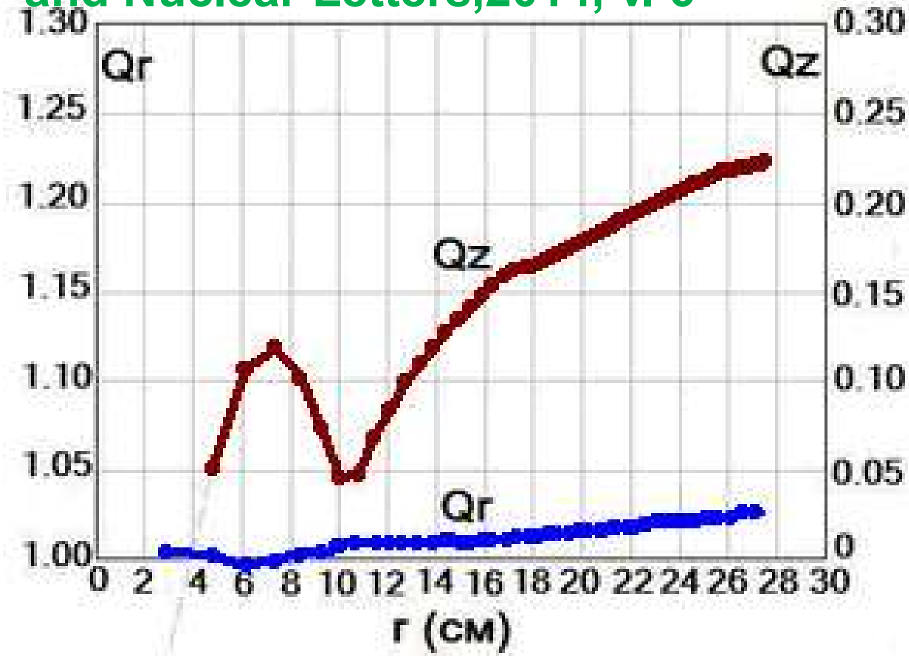
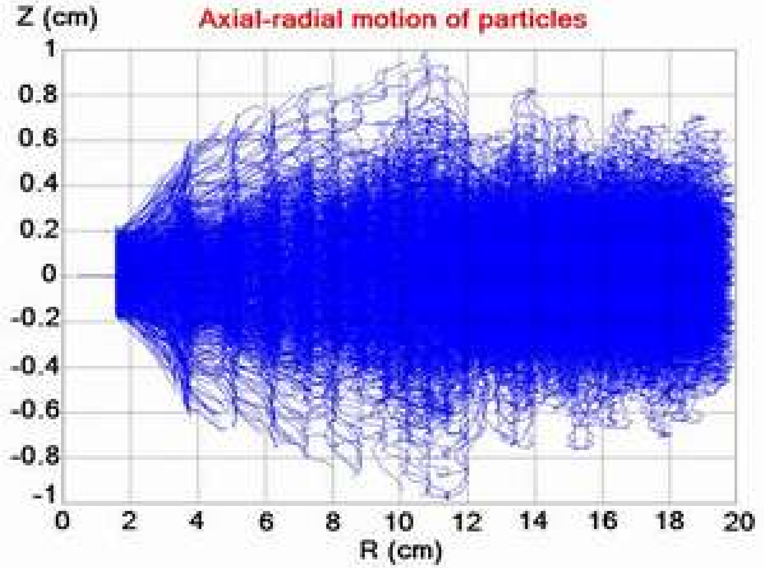
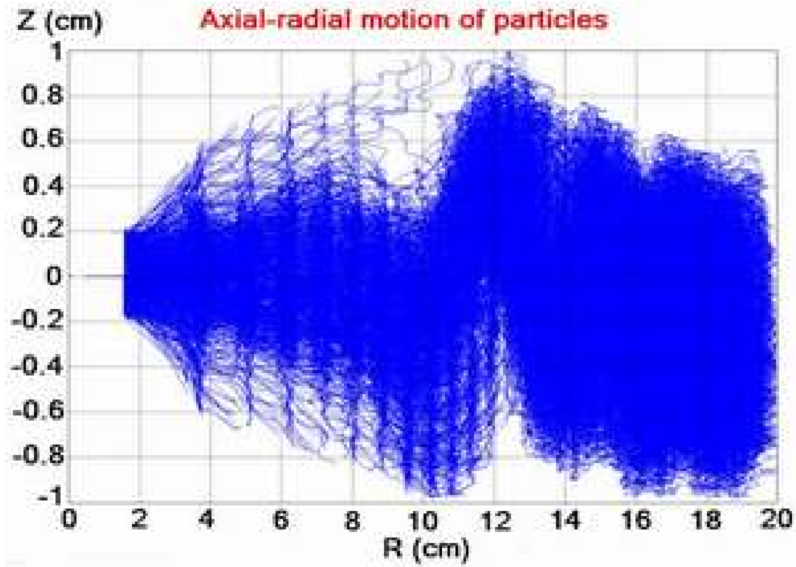
Beam dynamic at imperfection of magnetic field radial component in median plane and bump of axial magnetic field

G.Karamysheva et al, Physics of Particle and Nuclear Letters,2014, v. 6

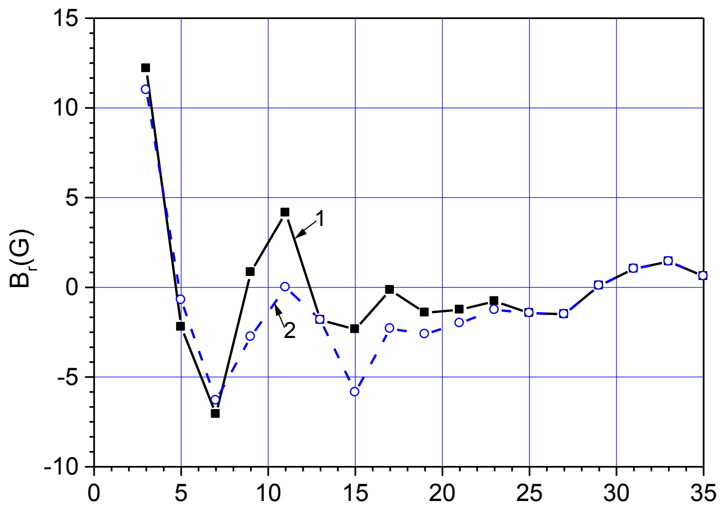


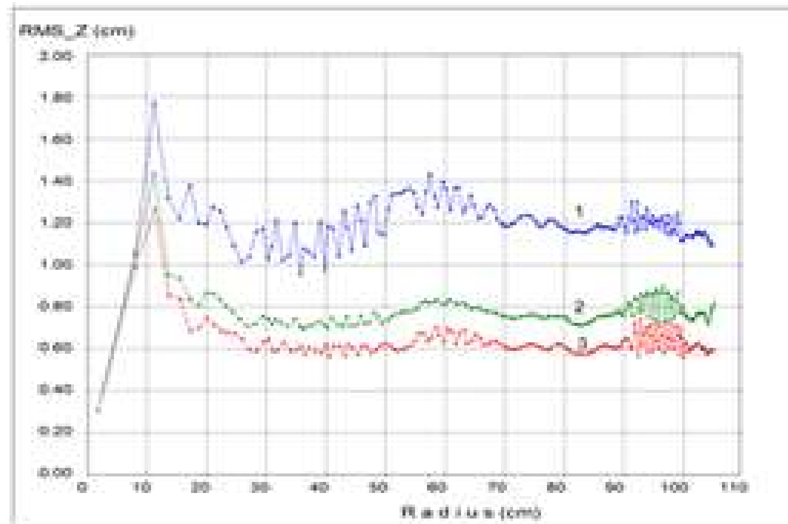






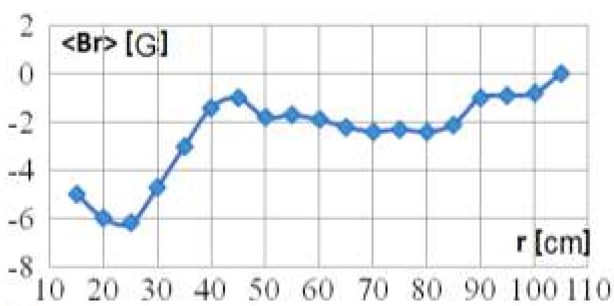
Beam dynamic simulation at imperfection of radial components of magnetic field





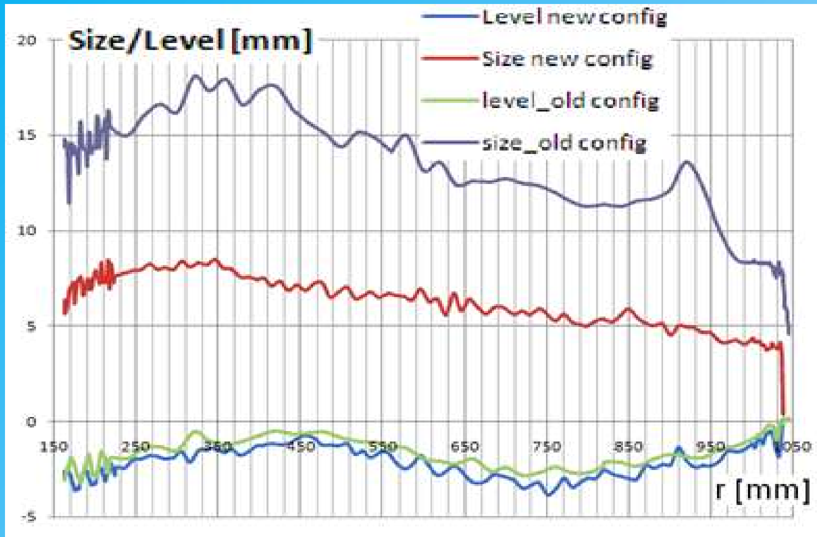
Distribution of average radial component in cyclotron median plane at shim thickness 2 mm (curve 1) and shim thickness 1.7 mm (curve 2).

Simulated dependence of axial r.m.s. size on radius: curve 1 at Br (curve 1 in Fig.1), curve 2 at Br (curve 2 in Fig.1), curve 3 at Br=0.



Radial losses	Axial losses	Captured in acceleration	
18%	21%	61%	0
18%	42%	40%	Br

BEAM TESTS OF CYCLOTRON C235-V3 IN JINR



Axial beam size is reduced by 2 times, acceleration efficiency was increased from 50% up 72%

P.V. Galkin et al, JTPh, 2014, V.59 N.6, p.917, S.Kostromin, E.Syresin, 2014, Physics of Particle and Nuclear Letters, 2013, v.10, p.1346

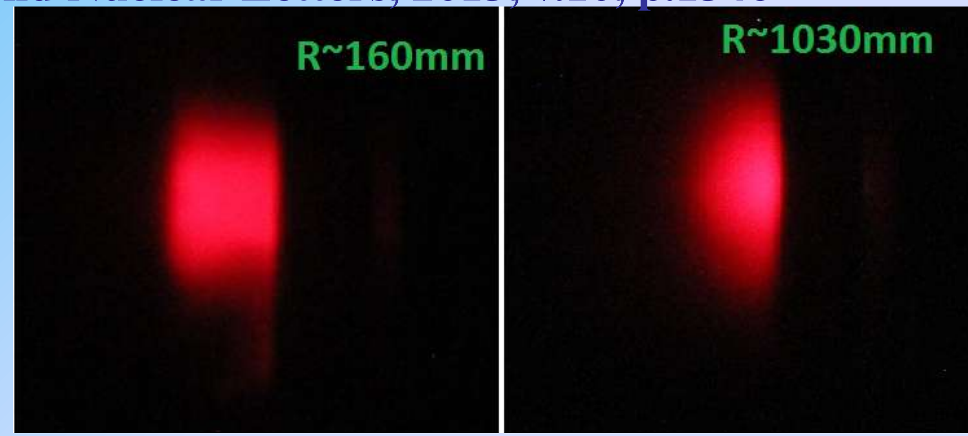
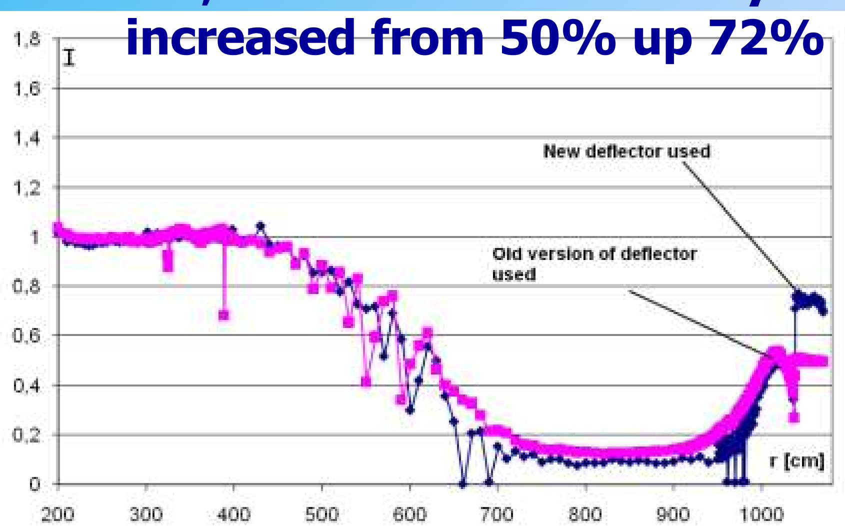


Photo of accelerated beam size in C235-V3



Improve extraction efficiency from 50% up 75% with new JINR extraction system

Picture of extracted beam size from cyclotron C235-V3

Intensity of extracted beam was increased by 3 times

MODIFIED CYCLOTRON C235-V3

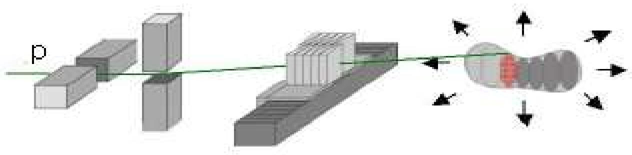
Advantages of C235-V3 with high intensity of proton beam are important:

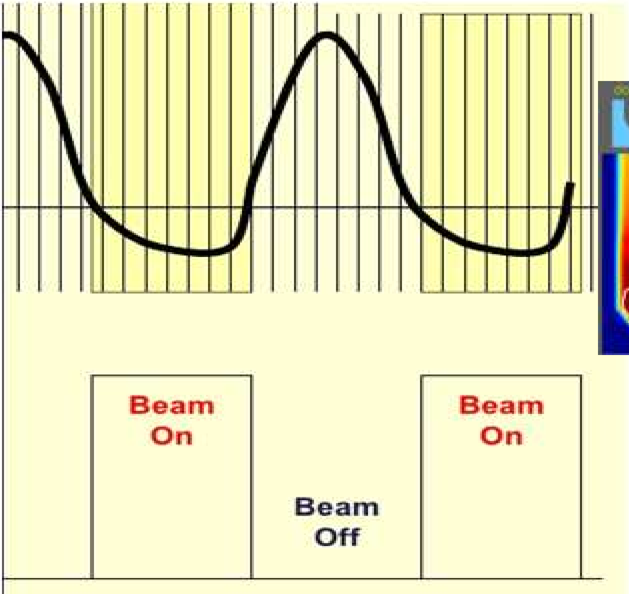
- at synchronisation of irradiation and organ motion
- at realisation of irradiation by intensity modulated proton beams
- at treatment of large volume tumors with application of pencil beam scanning system;
- at treatment technology with large dose per irradiation fraction and small number of fractions;

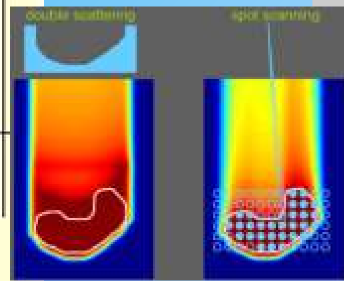
Parameter	C235	C235-V3
Optimization of magnetic field at modification of sector	no	Modification of sector azimuthal angle at R>80
Vertical betatron frequency at R>80	Qz=0,25	Qz=0,45
Axial beam size at radius 20 cm	16mm	8 mm
Beam losses at proton acceleration with out installed diaphragm	50%	25%
Beam losses at extraction	50%	25%
Extracted beam current, uA	0.3	1
Br-component measurements, reduction of median plane effects	no	yes

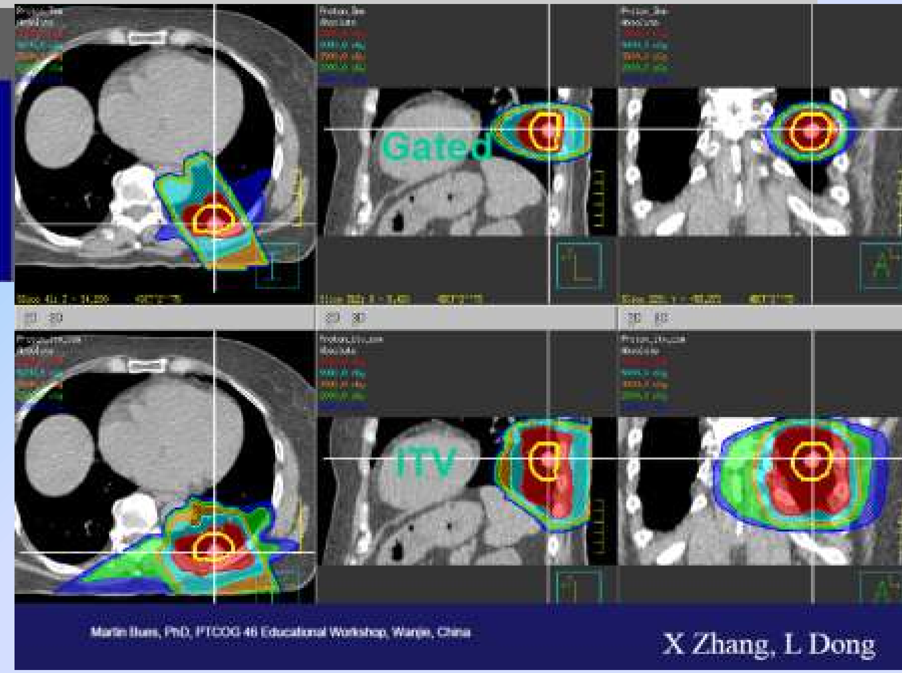
Synchronisation of irradiation and organ motion

a)Active scanning system with pencil proton beam
б)Raster scanning-Passive irradiation system at using of wobbling magnetst









d=5 mm –motion amplitude of irradiated organ
h=1 mm –space accuracy of dose distribution

T =3s – period of moving organ
t=0.8s- irradiation time during period

$$I_c/I=\pi(d/2h)^{1/2}\cong 4\text{-}5.$$

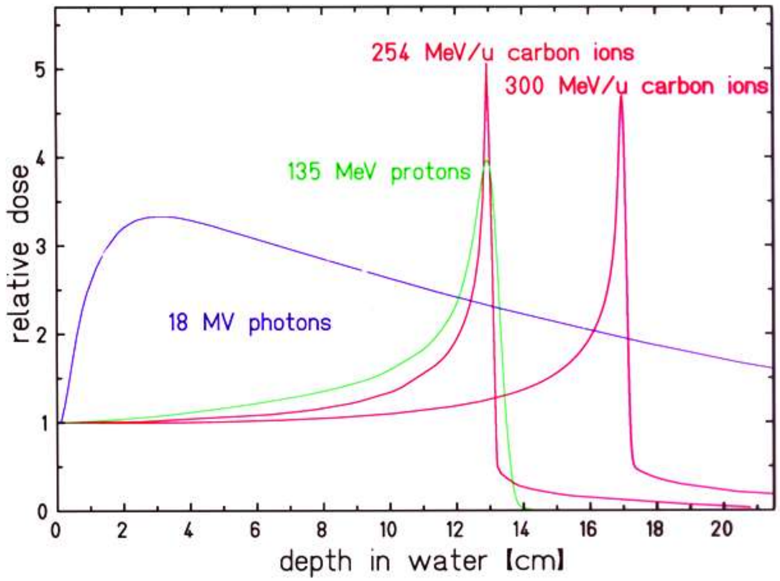
Ic- beam current at synchronization of irradiation and organ motion
I- beam current at irradiation without synchronization

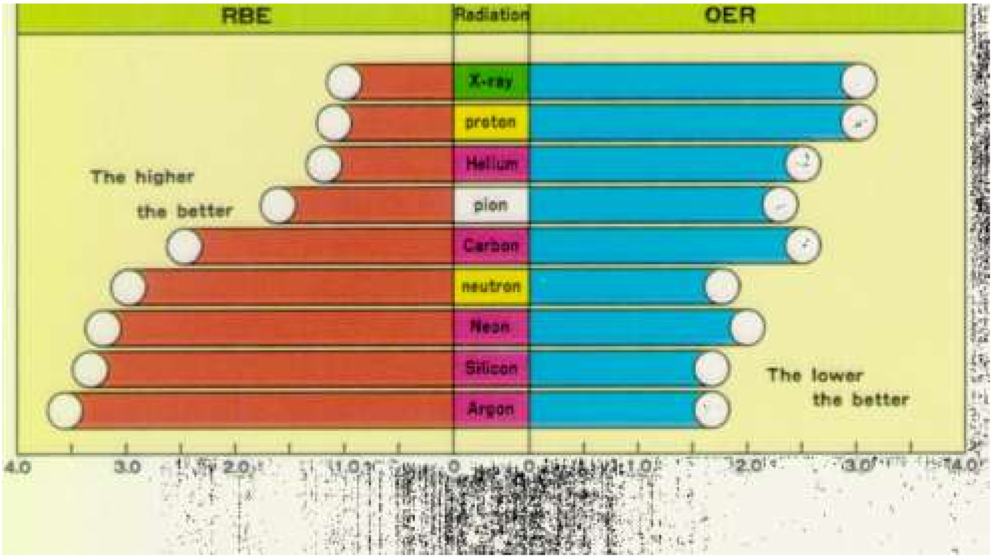
Proton –ion therapeutic complex applied for carbon ion therapy

Adventures of ion carbon therapy:

- Carbon ions are especially efficient for radio resistant tumors
- Carbon ions produces by 4 times less dose irradiation of normal tissues comparing with X-ray radiation, at same irradiation dose in tumor.

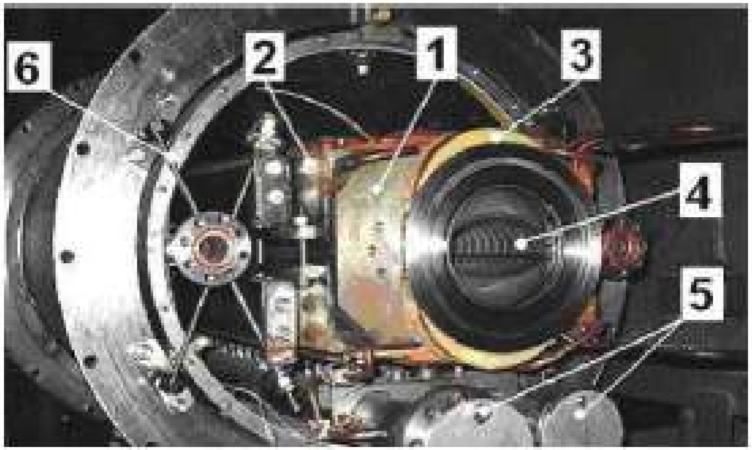
• Carbon ions produces by 2 times less dose irradiation of normal tissues comparing with protons.





Nuclotron technologies as basis of superconducting medical synchrotron for hadron therapy

Nuclotron –JINR superconducting synchrotron



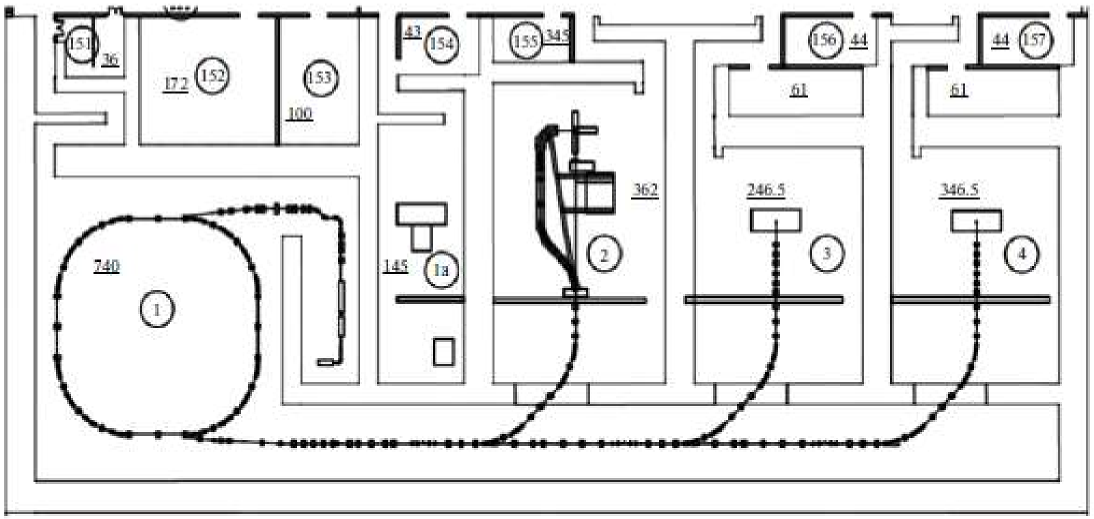
Nuclotron superconducting dipole magnet

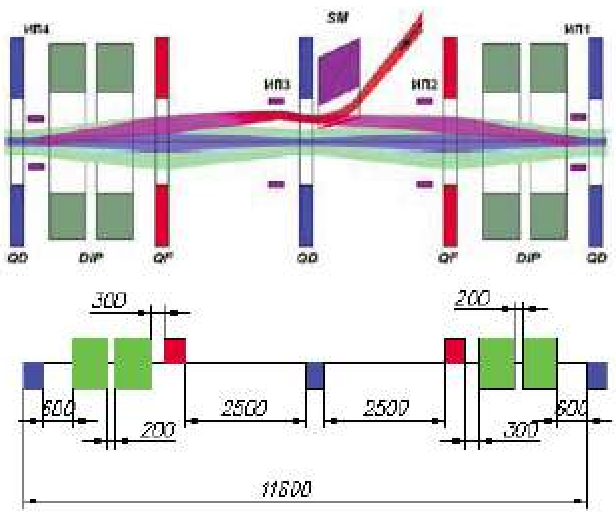
Parameters of medical synchrotron	
Ion source	*«Krion»*
Linear accelerator	*RFQ &IH*
Circumference	*69.6 m*
Injection energy	*4 MeV/n*
Max. ion energy at A/Z=0.5	*400 MeV/n*
Max. magnetic field n	*1,8 T*
Magnetic field rate dB/dt	*3.6 T/s*
Repetition frequency	*1 Hz*

Complex of ion therapy on the basis of superconducting synchrotron

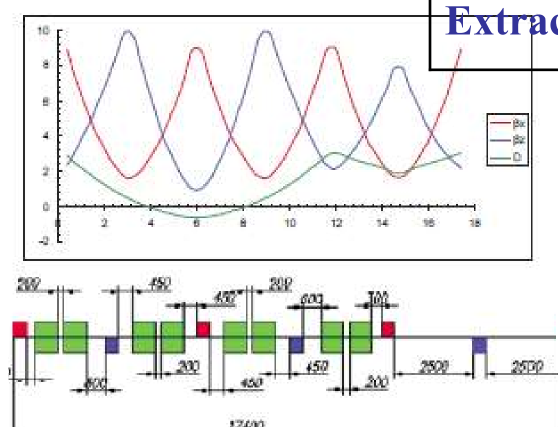
E. Syresin et al, Physics of Particle and Nuclear Letters, 2012, v.9, p.328

Injection/maximal energy	4,2/400 MeV/u
Maximal/ injection magnetic rigidity	6,36/0.59 T·m
Circumference	69,6 м
Column limit of intensity at injection	$6 \cdot 10^9$ p/cycle
Betatron tune shift	0,02
Number of turns at injection	20
Injection efficiency	50 %
Time of synchrotron acceleration	0.5 s
Slow extraction time	(0,5 -10) s
Extraction efficiency	96%

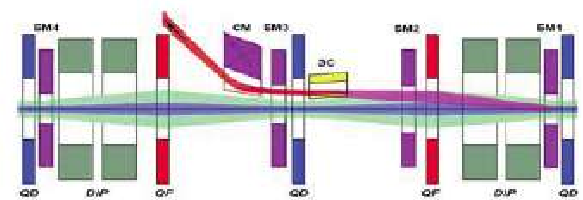




Multiturn injection in synchrotron



Superperiod of synchrotron



Extraction from synchrotron

Betatron tunes	3,25
Chromaticity $DQ_x/(Dp/p)$	-3,1
$DQ_z/(Dp/p)$	-3,2
Parameter of orbit compaction	0,053
COD, mm	3
Horizontal/Vertical acceptance, π·mm·mrad	180/70
Emittance of injected beam, π·mm·mrad	10
Emittances of accelerated beam $\varepsilon_x/\varepsilon_z$, π·mm·mrad	20/1,5
Emittance of extracted beam $\varepsilon_x/\varepsilon_z$, π·mm·mrad	0.5/1,5
Relative momentum spread	10^{-3}
Relative maximal momentum spread	$2\ 10^{-3}$

Parameters of medical ion synchrotron

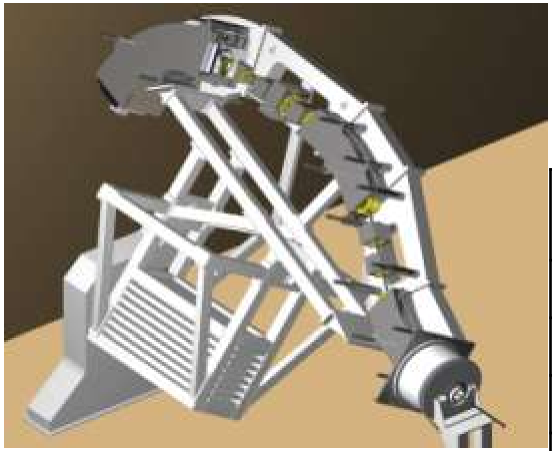
Number of superperiods/FODO periods	4/12
Number of dipole magnets/ quadrupole lenses	32/24
Magnetic field at injection/maximal field	0,17/1,8 T
Rate of magnetic field	3,26 T/s
Maximal/injection gradients in F lenses	8,5/0.8 T/m
Maximal/injection gradients in D lenses	–7,5/–0,7 T/m
Curvature radius in dipole magnets	3,53 m
Sagitta in dipole magnets	8,7 mm

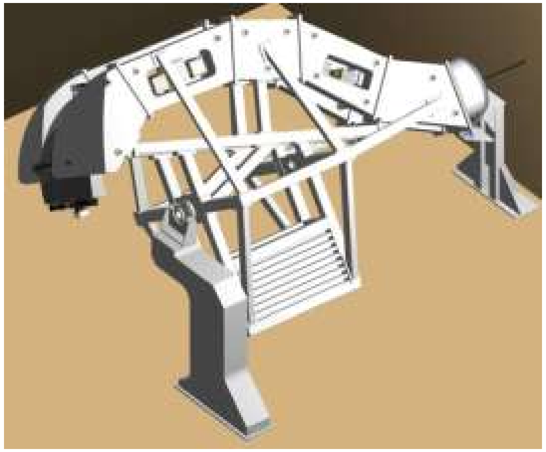
Beam delivery system

The beam delivery system consists of following sections:
the extraction section;
the foil section provided equal beam emittances in both transverse planes;
the accommodation section;
the section for beam delivery in the cabin;
the section of beam transportation between the medical cabins;
the isocentric gantry;
the channel with fixed beam position cabin.

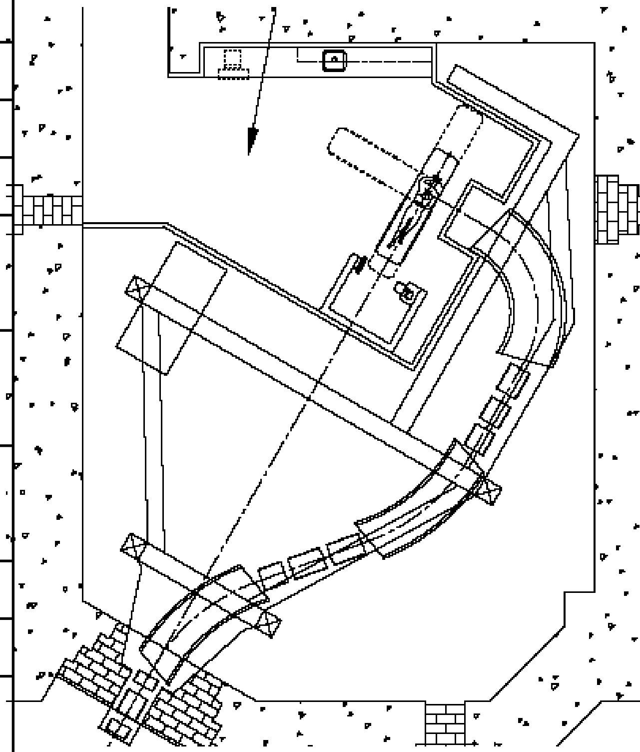
The compact carbon gantry

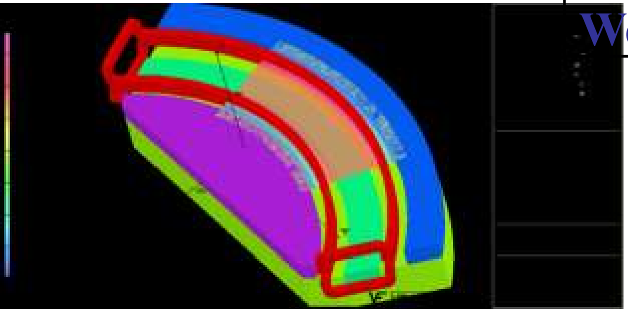
JINR-IBA collaboration





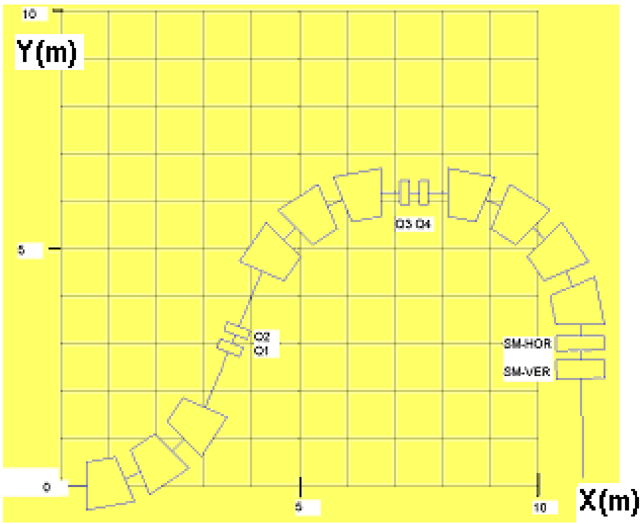
Gantry	
Weight, t	156
Diameter, m	9.2
Length, m	12,7
Scanning area in isocenter, cm	20×20
Gantry rotation angle, degree	180
Positioner rotation angle, degree	180
Main dipole magnet	
Magnetic field, T	3.2
Magnetic field rate, T/min	1
Bending radius, m	2
Weight, t	28

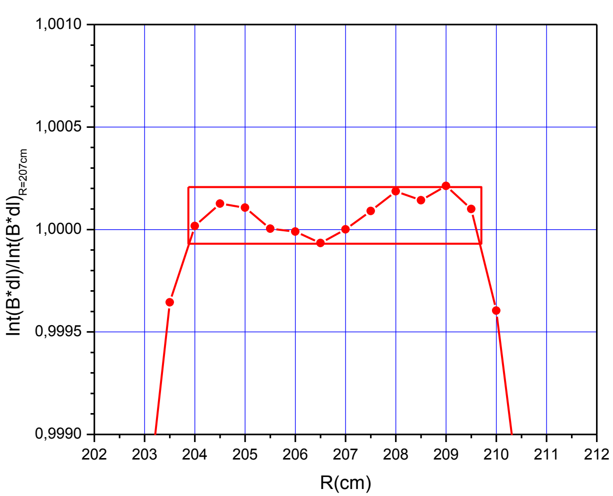




The application of superconducting gantry permits to increase number of recommended for carbon treatment cases from 7% up 30%

The carbon gantry with small aperture magnets





Uniformity of magnetic field integral in the dipole magnet.

Number of dipole magnets	**8**
Magnet type, current distribution	**cosψ**
Number of winding sectors	**10**
Total number of turns (per pole)	**2841**
Operating current, A	**220**
Magnetic field, T	**3.2**
Magnetic field rigidity, T m	**6.63**
Turning radius, m	**2.07**
Turning angle, °	**22.5**
Rms beam sizes (1σ), σ*y*/σ*x*, mm	**6/3**
Horizontal homogeneity of magnetic field, mm	**16**
Homogeneity of magnetic field	**2.2×10^{-4}**
Homogeneities of field integral	**10^{-3}**
Internal and external radii of winding, mm	**61/72**
Internal and external radii of yoke, mm	**78/178**

THANKS FOR YOU ATTENTION

Injection system in medical superconducting synchrotron

ESIS –Superconducting JINR ion source, applied for carbon ion injection

Linear accelerator of carbon ions, NIRS (Japan)

Parameters of carbon IH linac

Parameters	RFQ	IH-DTL
Injection energy, MeV/u	0.01	0.61
Extraction energy, MeV/u	0.61	4
Operation frequency, MHz	200	200
Charge-mass ratio	1/3	1/3
Cavity length, m	2.5	3.4
Cavity outer diameter, m	0.42	0.44
Power, kW	120	360
Normalized 90% emittance, $\pi \cdot$mm$\cdot$mrad	0.85	1.1
Normalized 90% longitudinal emittance, $\pi \cdot$ns$\cdot$keV/n	1	1.2
Energy spread,%		±0.4
Maximal beam current, eμA	392	390