JOINT INSTITUTE FOR NUCLEAR RESEARCH
Flerov Laboratory of Nuclear Reactions

FINAL REPORT ON THE
SUMMER STUDENT PROGRAM

Design of the coaxial resonator for ECR ion source

Supervisor:
Ph. D.Sergey Leopoldovich Bogomolov

Student:
Riyaz Fatkullin, Russia
MEPHI

Participation period:
July 01 – July 17
August 15 - August 31

Dubna, 2016

Contents

Introduction

Ion source is a significant part of the ion accelerator. Many types of ion sources were created for different purposes and uses. Objective of this work - to design a coaxial resonator that will be used in a ECR ion source. The obtained results will be used in creation of real ECR ion source.

Flerov Laboratory of Nuclear Reactions

Flerov Laboratory of Nuclear Reactions (FLNR) was founded in 1957 by soviet physicist Academician G. N. Flerov. Since then, FLNR has achieved many major discoveries:

1966 - element 102 (Nobelium)
1968 - element 105 (Dubnium)
1999-2005 – elements 113 (Ununtrium), 114 (Flerovium), 115 (Ununpentium), 116 (Livermorium), and 118 (Ununoctium)
2006 – chemical identification of element 112 (Copernicium)
2010 – successful synthesis of element 117 (Ununseptium)

Now the Flerov Laboratory is one of the world's leading scientific centers in the field of nuclear physics. Among about 450 members of the FLNR staff there are more than 150 research scientists (among them 18 Doctors of Science and 65 Candidates of Science (PhD)). To realize Laboratory’s program and original ideas its accelerators and experimental setups are being developed intensively. Four heavy ion accelerators, one electron accelerator and more than ten major multifunctional experimental setups are in effect or under development in the Laboratory [1].

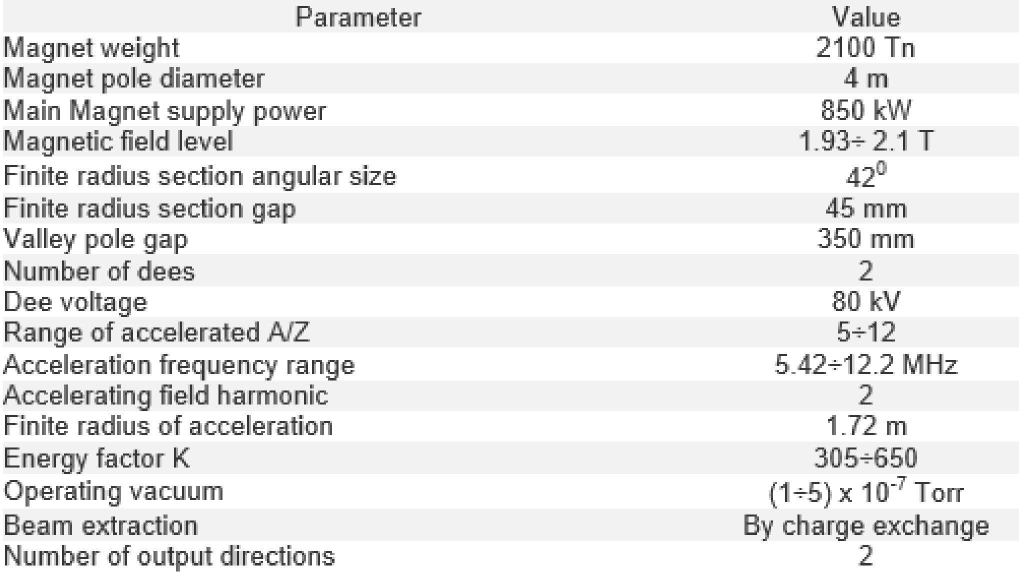
Accelerator complex of the laboratory

The laboratory’s accelerator complex consist of 4 isochronous cyclotrons and 1 microtron.

U400 *(Fig.1)* is an isochronous cyclotron designed for production of accelerated ion beams of atomic mass in the range A=4 ÷ 209 and energy 3 ÷ 29 MeV/nucleon. Cyclotron was first launched in 1978. The diameter of accelerator’s magnet pole is 4m. The ion source, which is used in present day operations is electron cyclotron resonance ion source ECR-4M. Other specifications are mentioned in Table 1.

Fig. 1. U400 isochronous cyclotron.

Table 1. U400 specifications.



Parameter	Value
Magnet weight	2100 Tn
Magnet pole diameter	4 m
Main Magnet supply power	850 kW
Magnetic field level	1.93÷ 2.1 T
Finite radius section angular size	42^0
Finite radius section gap	45 mm
Valley pole gap	350 mm
Number of dees	2
Dee voltage	80 kV
Range of accelerated A/Z	5÷12
Acceleration frequency range	5.42÷12.2 MHz
Accelerating field harmonic	2
Finite radius of acceleration	1.72 m
Energy factor K	305÷650
Operating vacuum	(1÷5) x 10^{-7} Torr
Beam extraction	By charge exchange
Number of output directions	2

U400M (Fig. 2) is an isochronous cyclotron that has been put into operation since 1993. The energy of ions, accelerated by U400M is 20 - 120 MeV/n, the diameter of magnet pole is 4m. Accelerator uses DECRIS-14-2 and DECRIS-SC2 [2] ion sources for its operations. Other specifications are mentioned in Table 2.

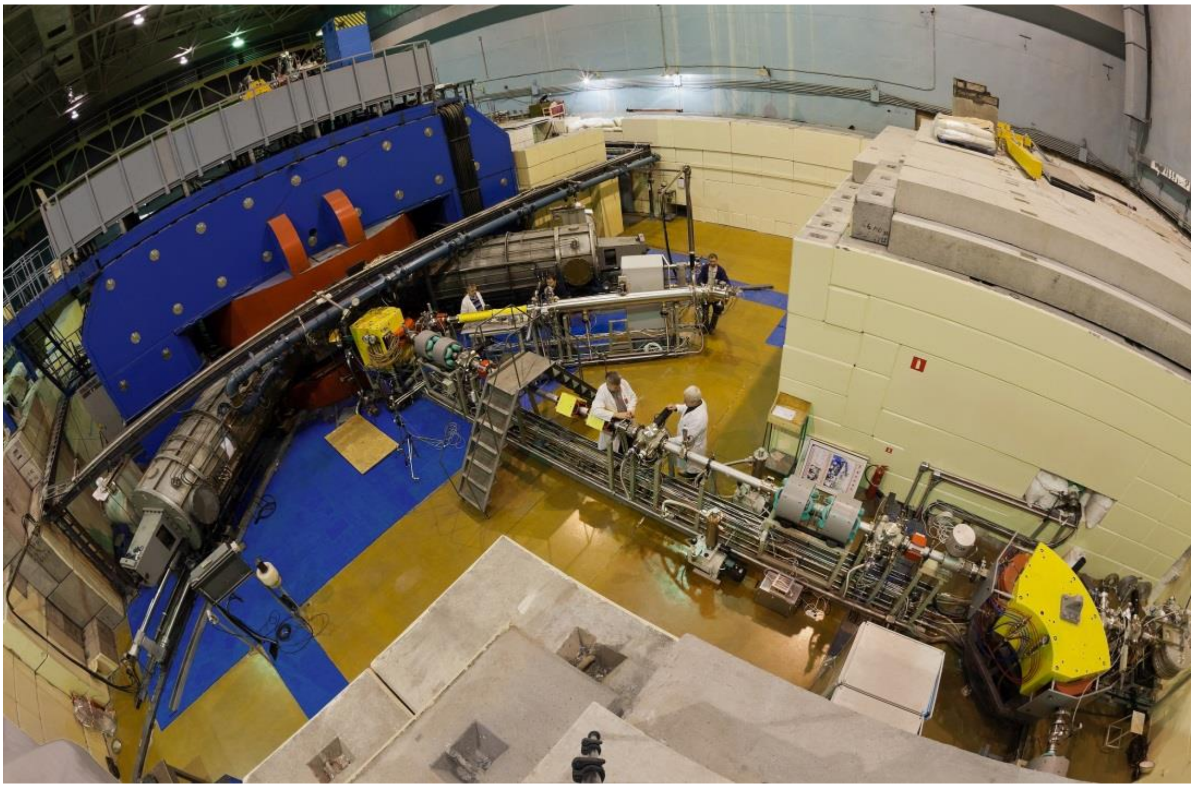
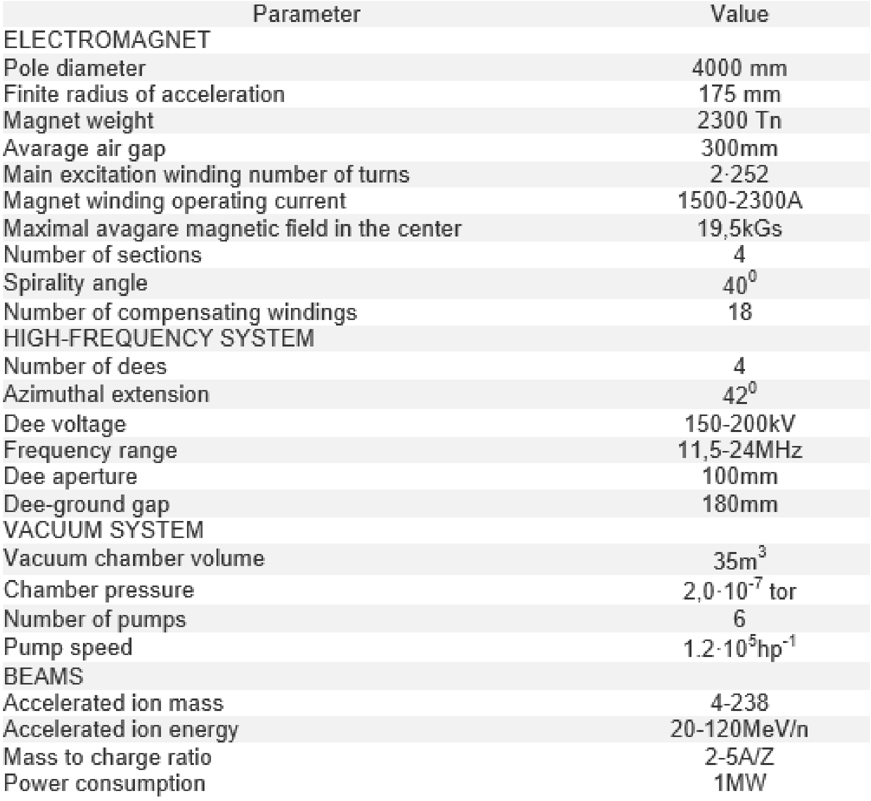


Fig. 2. U400M isochronous cyclotron.

Table 2. U400M specifications.



Parameter	Value
ELECTROMAGNET	
Pole diameter	4000 mm
Finite radius of acceleration	175 mm
Magnet weight	2300 Tn
Avarage air gap	300mm
Main excitation winding number of turns	2·252
Magnet winding operating current	1500-2300A
Maximal avagare magnetic field in the center	19,5kGs
Number of sections	4
Spirality angle	40^0
Number of compensating windings	18
HIGH-FREQUENCY SYSTEM	
Number of dees	4
Azimuthal extension	42^0
Dee voltage	150-200kV
Frequency range	11,5-24MHz
Dee aperture	100mm
Dee-ground gap	180mm
VACUUM SYSTEM	
Vacuum chamber volume	$35m^3$
Chamber pressure	$2{,}0\cdot10^{-7}$ tor
Number of pumps	6
Pump speed	$1.2\cdot10^5 hp^{-1}$
BEAMS	
Accelerated ion mass	4-238
Accelerated ion energy	20-120MeV/n
Mass to charge ratio	2-5A/Z
Power consumption	1MW

MT-25 (Fig. 3) is a cyclic accelerator which is used for production of electron beams (microtron). MT-25 was created in 1986. It is an upgraded version of MT-22 (1980) which itself is an upgraded version of MT-17 (1973). This microtron is used for study and production of ultraclean radioisotopes.

Fig. 3. Microtron MT-25.

DRIBs (**D**ubna **R**adioactive **I**on **B**eams) (Fig. 4) is an accelerator complex created for the production of radioactive ion beams. It is based on U400, U400M isochronous cyclotrons and MT-25 microtron. The construction of complex is divided into three phases (DRIBs I, II, III), the last one is now in progress.

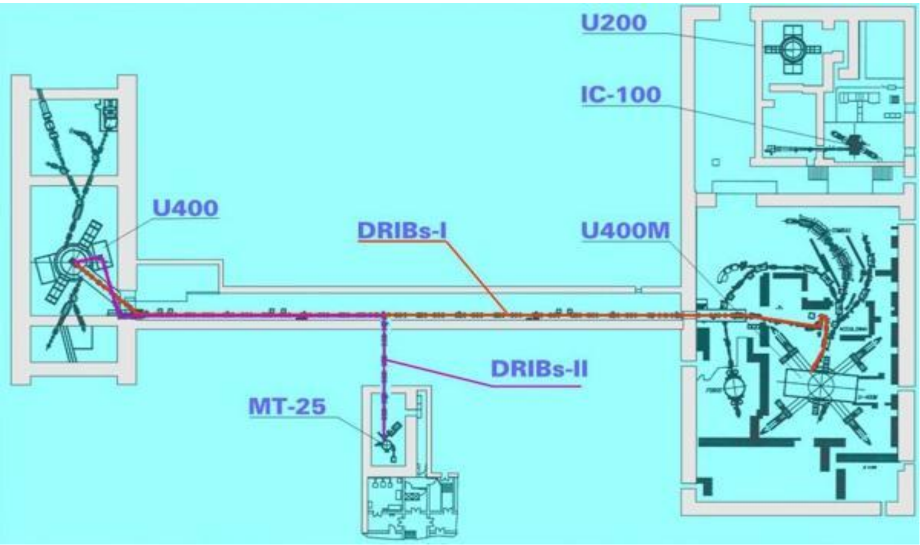


Fig. 4. Accelerator complex DRIBs.

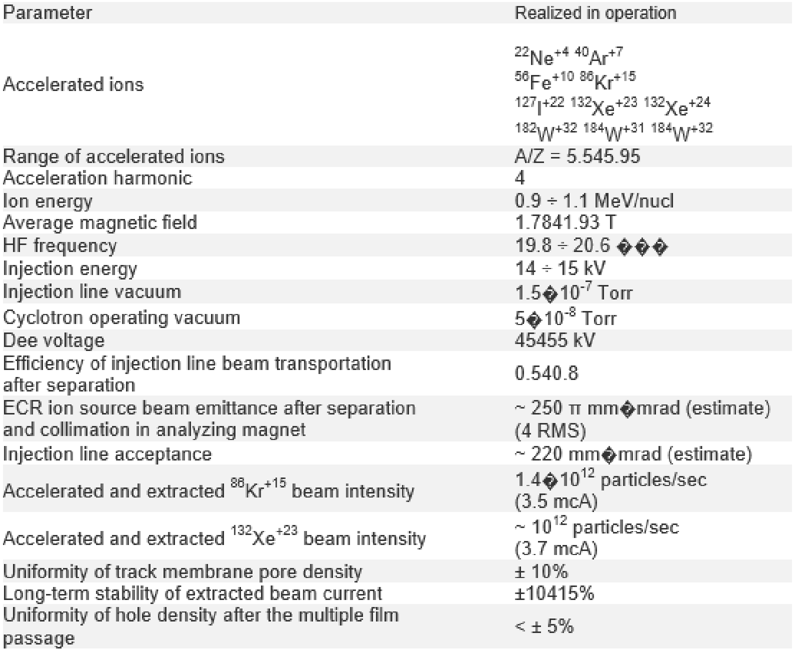
U200 (Fig. 5) is an accelerator which was used for production of ion beams of A/Z=2.8 ÷ 5 from D to Ne accelerated up to the energy of 145 x Z^2/A MeV (A- atomic weight of the accelerated ion; Z - ion charge). It is an isochronous cyclotron. The ion source for U200 is an internal PIG ion source. In present time, the operation of the U200 is stopped and the accelerator is prepared for future upgrade.

Fig. 5. U200 isochronous cyclotron.

DC-40 *(IC-100)* (Fig. 6) heavy ion cyclic implanter was designed at the FLNR JINR in 1985. In 2003-2005 its internal PIG ion source was replaced with superconducting ECR ion source DECRIS-SC which allowed to produce intensive beams of highly charged ions of xenon, iodine, krypton, argon and other heavy elements of the Periodic Table. This accelerator is currently used for ion implantation and polymer film irradiation. Specifications of DC-40 are mentioned in Table 3.

Fig. 6. DC-40 isochronous cyclotron.

Table 3. DC-40 specifications.



Parameter	Realized in operation
Accelerated ions	$^{22}Ne^{+4}$ $^{40}Ar^{+7}$ $^{56}Fe^{+10}$ $^{86}Kr^{+15}$ $^{127}I^{+22}$ $^{132}Xe^{+23}$ $^{132}Xe^{+24}$ $^{182}W^{+32}$ $^{184}W^{+31}$ $^{184}W^{+32}$
Range of accelerated ions	A/Z = 5.545.95
Acceleration harmonic	4
Ion energy	0.9 ÷ 1.1 MeV/nucl
Average magnetic field	1.7841.93 T
HF frequency	19.8 ÷ 20.6 ���
Injection energy	14 ÷ 15 kV
Injection line vacuum	1.5�10^{-7} Torr
Cyclotron operating vacuum	5�10^{-8} Torr
Dee voltage	45455 kV
Efficiency of injection line beam transportation after separation	0.540.8
ECR ion source beam emittance after separation and collimation in analyzing magnet	~ 250 π mm�mrad (estimate) (4 RMS)
Injection line acceptance	~ 220 mm�mrad (estimate)
Accelerated and extracted $^{88}Kr^{+15}$ beam intensity	1.4�10^{12} particles/sec (3.5 mcA)
Accelerated and extracted $^{132}Xe^{+23}$ beam intensity	~ 10^{12} particles/sec (3.7 mcA)
Uniformity of track membrane pore density	± 10%
Long-term stability of extracted beam current	±10415%
Uniformity of hole density after the multiple film passage	< ± 5%

ECR ion sources

Almost all of the accelerators in FLNR are equipped with ECR (**E**lectron **C**yclotron **R**esonance) ion sources. This type of source makes use of the electron cyclotron resonance to ionize atoms [3]. When a particle is baking in a magnetic field and a transverse time varying electric field, a resonant transfer of energy from the electric field to the particle can occur, provided the particle cyclotron frequency equals the electric field frequency. An electron in a static and uniform magnetic field will move in a circle due to the Lorentz force. The circular motion may be superimposed with a uniform axial motion, resulting in a helix, or with a uniform motion perpendicular to the field, e.g., in the presence of an electrical or gravitational field, resulting in a cycloid. The angular frequency ($\omega = 2\pi f$) of this *cyclotron* motion for a given magnetic field strength *B* is given (in SI units) by:

$$\omega_{ce} = \frac{eB}{m}, \tag{1}$$

ECR resonance condition (for a given H-field frequency ω_{HF}):

$$\omega_{HF} = \omega_{ce} = \frac{eB}{m}, \tag{2}$$

Figure 7 shows a schematic drawing of an ECR ion source. Its main components are:

- Plasma chamber and vacuum system
- Solenoid and hexapole magnets for axial and radial confinement of the plasma, respectively
- Injection of neutral atoms or molecules (by oven, gas inlet, etc.) to be ionized
- RF power input with appropriate frequency which is the source of energy for the electrons, so that high charge state ions can be created via successive ionization
- Ion extraction system for the ion beam formation

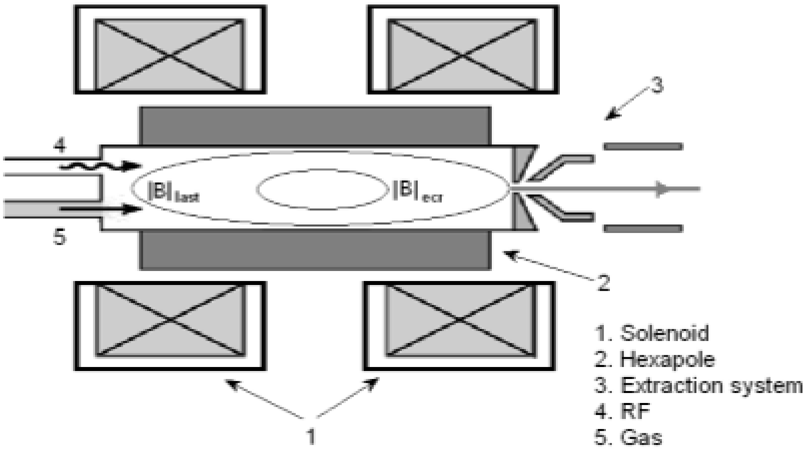


Fig. 7. Schematic drawing of ECR ion source.

Plasma confinement is very important part of ECR ion source: it keeps ionized particles away from the vacuum chamber's walls. There are two types of confinement in ECR: radial and axial. Radial confinement is provided by magnetic field (Fig. 8, a) which is created by hexapole magnet. Axial confinement is provided by magnetic field which is created by solenoids (Fig. 8, b). Summary distribution of magnetic field «Minimum-B» in the structure is presented in Fig. 9.

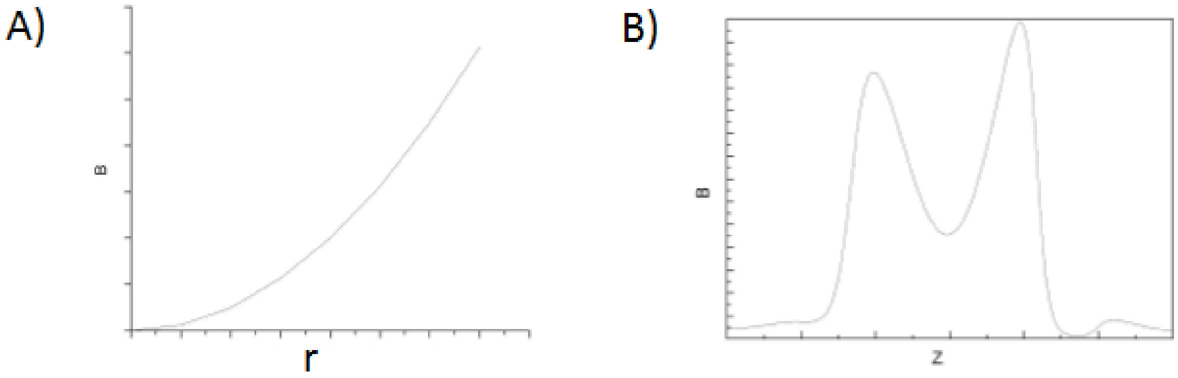


Fig. 8. Radial (a) and axial (b) magnetic field.

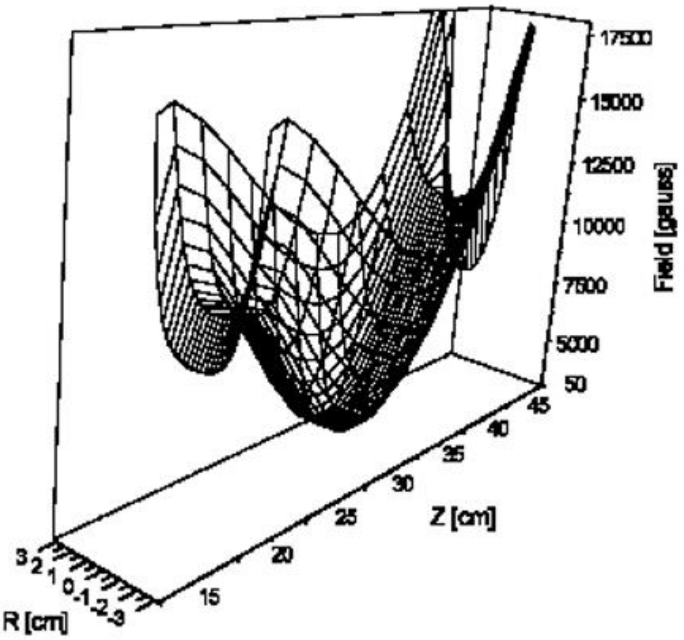


Fig. 9. Summary distribution of magnetic field.

One of ECR sources that are used in DRIBs and MASHA [4] (**M**ass **A**nalyzer of **S**uper **H**eavy **A**toms) projects is ECR-2.45 [5] (Fig. 10.). It is an ECR ion source which axial and radial field is created by permanent magnets. ECR-2.45 uses 2.45 GHz electric field, which is considered low for the ECR sources. The diameter of its plasma chamber is 9 cm, the length of the plasma chamber is 10 cm. ECR-2.45 is used for creation of principally singly charged ions ($^{6}He^{1+}$for example). The distribution of axial magnetic field and magnetic field contour plot are presented in Figure 11.

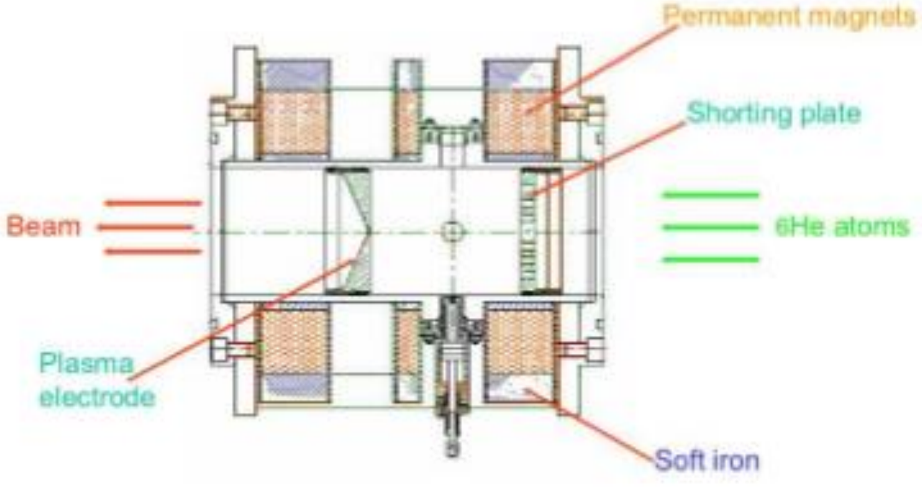


Fig. 10. Schematic view of ECR-2.45 (DRIBs).

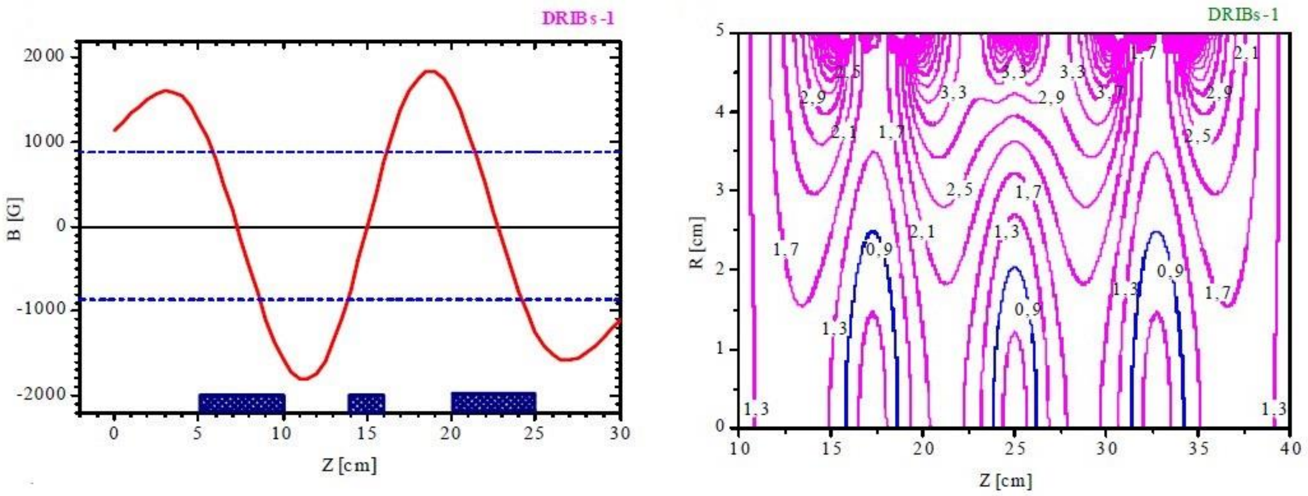


Fig.11. Distribution of axial magnetic field (left) and magnetic field contour plot (right) of ECR-2.45.

Design of the coaxial resonator

One of the projects that is currently under development in FLNR is the new ECR ion source for mass-separator MASHA. It has to be small, work on 2.45 GHz frequency and provide singly charged ions with high efficiency. One of the way to do that is creation of a permanent magnet 2.45 GHz ion source based on coaxial resonator.

Magnetic field of the source is created by a radially magnetized permanent magnet ring. The magnetic field contour map is shown in the Fig. 12. The closed surfaces of the magnetic field should be placed in the gap between resonator electrodes.

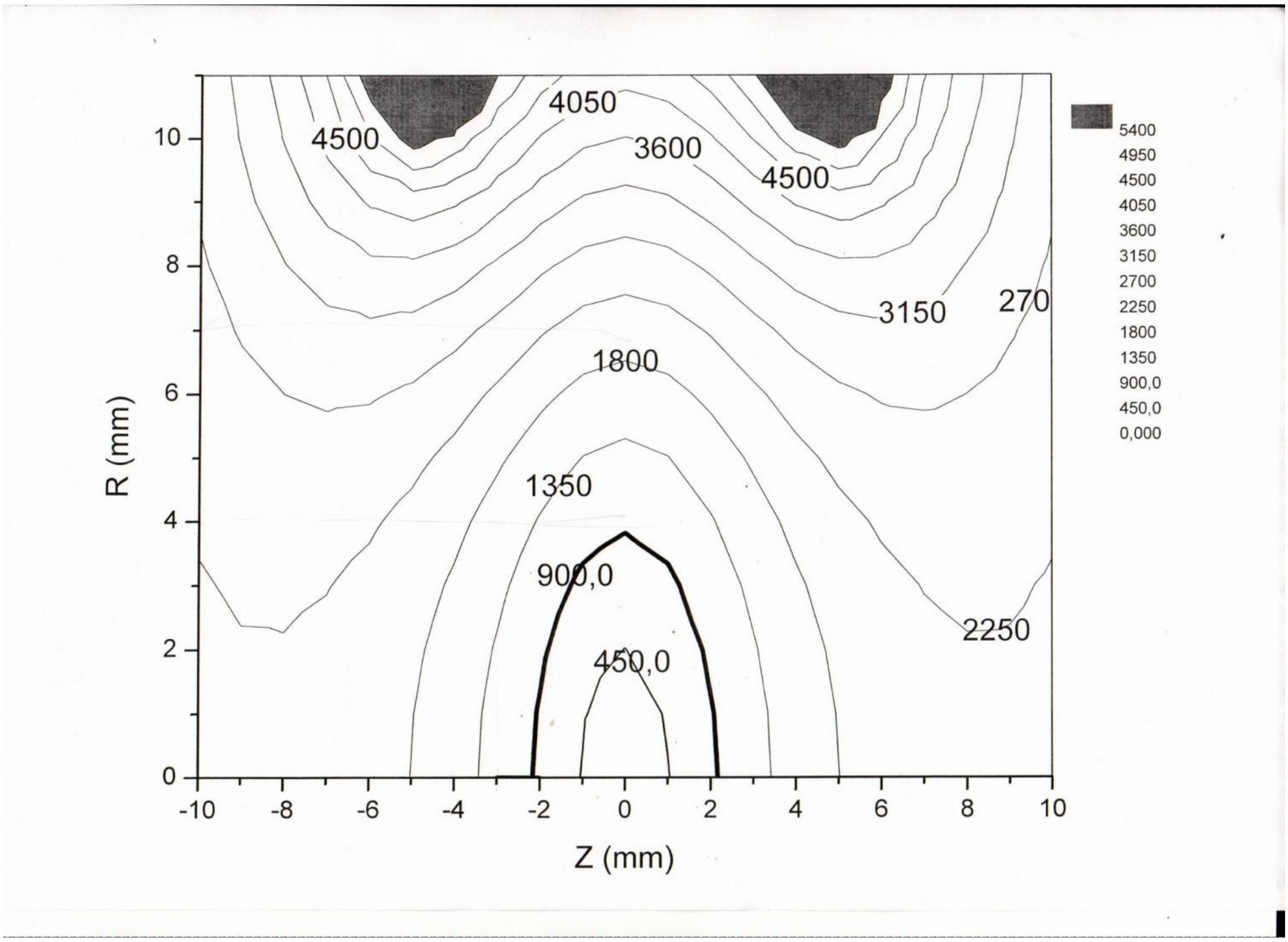


Fig.12. Magnetic field contour map (the solid line 900 Gs represents the resonance zone for 2.45 GHz frequency).

Two types of coaxial resonator were designed using CST Studio Suite [6]: cylindrical coaxial resonator (Fig. 13, a) and cylindrical coaxial resonator with cone transition (Fig. 13, b). Schematic drawing of ion source (using both resonators) is presented in Figure 14.

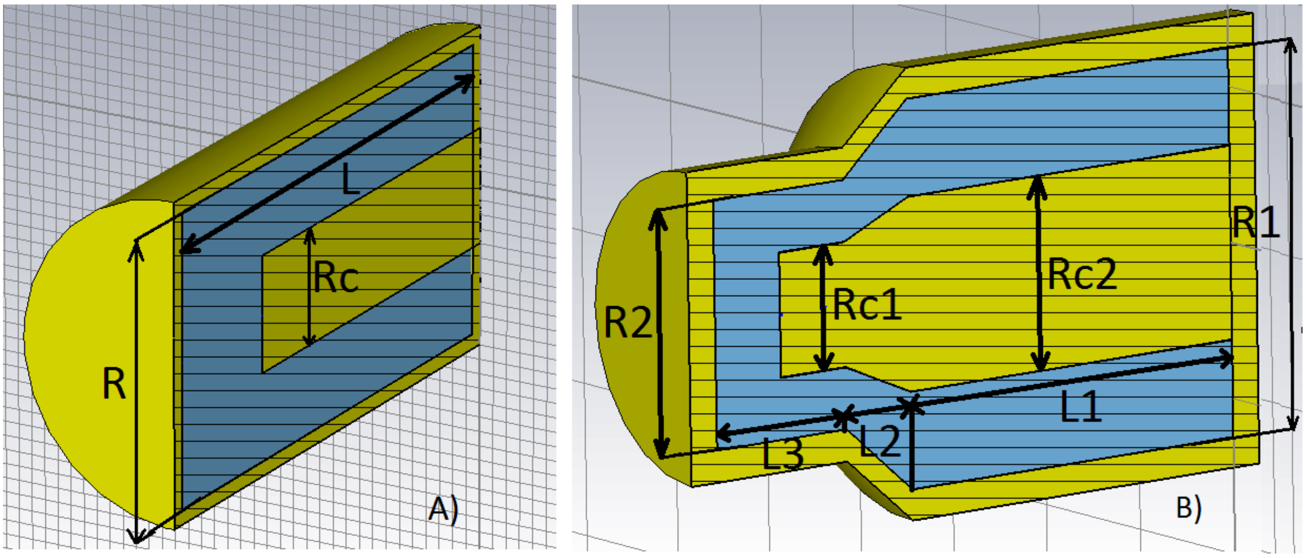


Fig. 13. Coaxial resonators.

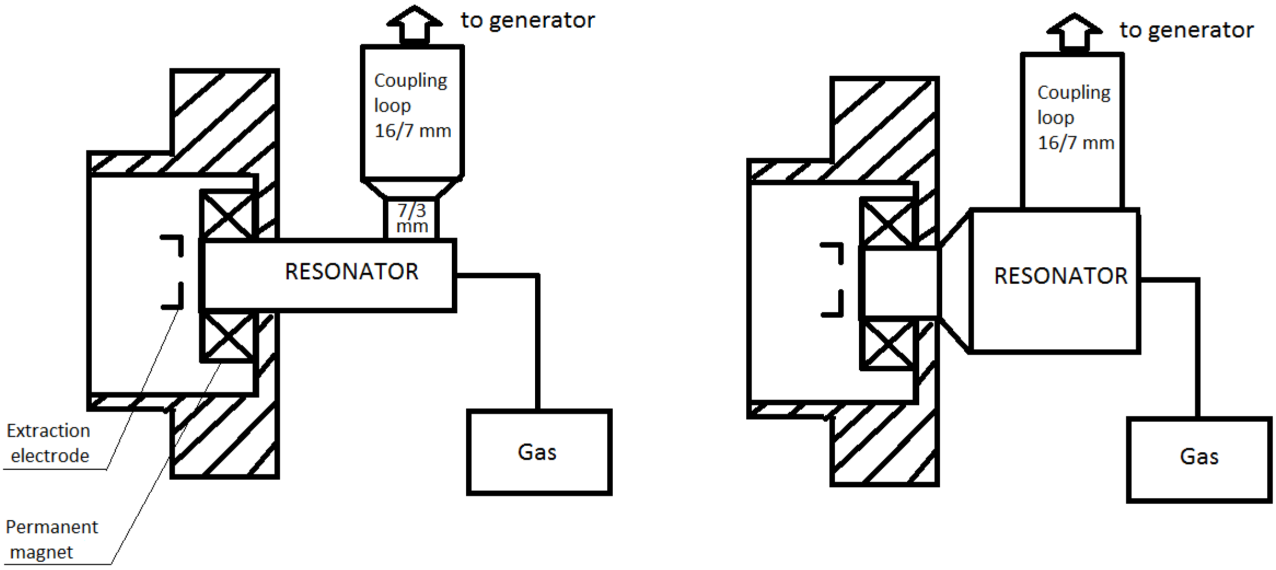


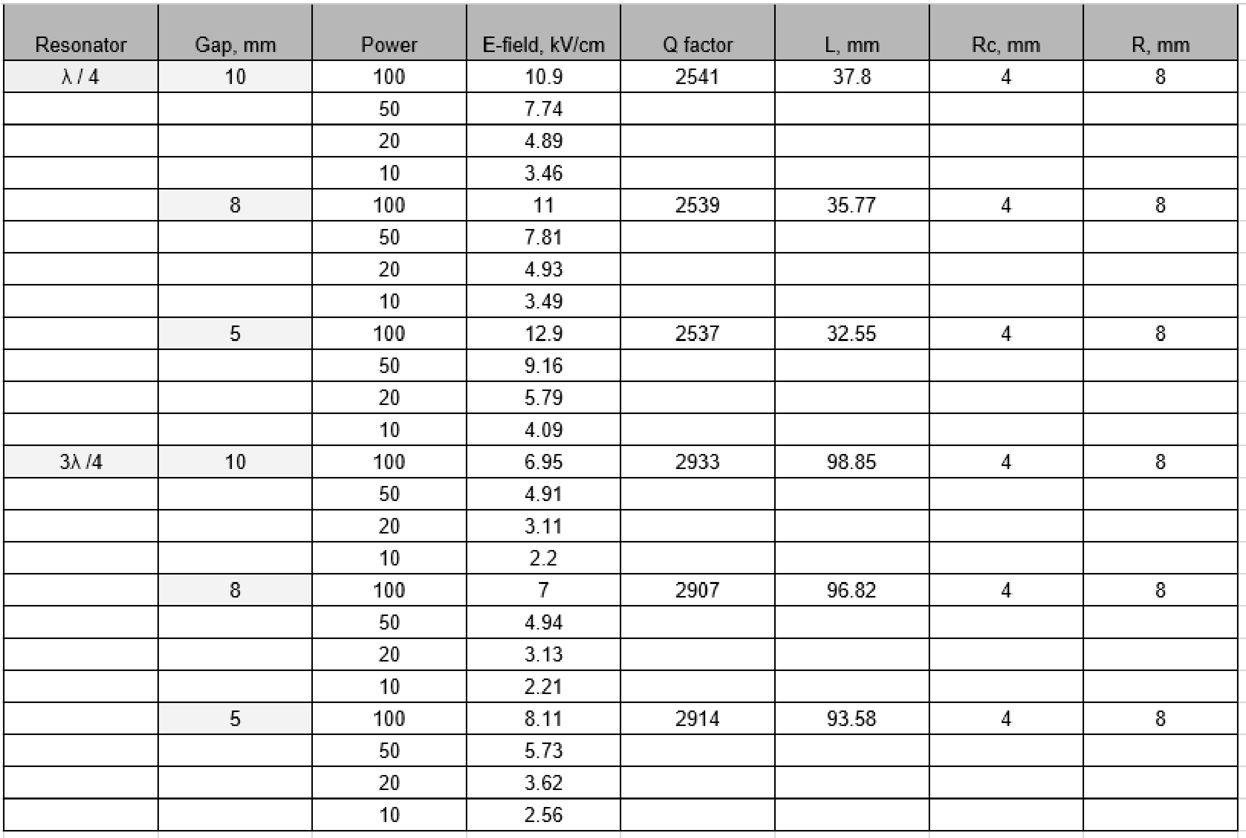
Fig. 14. Schematic drawing of ion source using cylindrical resonator (left) and cylindrical resonator with cone transition (right).

Generator with coupling loop creates a distribution of electric and magnetic fields in resonator's cavity. Electric field will be located near the edge of coaxial electrode (in gap between electrode and the shell of resonator). The certain amplitude of electric field will create an avalanche breakdown. The electrons will gain energy from RF field by ECR effect. The electrons will cause impact ionization of neutral molecules of gas, which are fed into the gap of resonator. A magnetic field created by permanent magnet ring is used for confinement of plasma before positive charged ions will be extracted from resonator using extraction electrode.

Electric fields

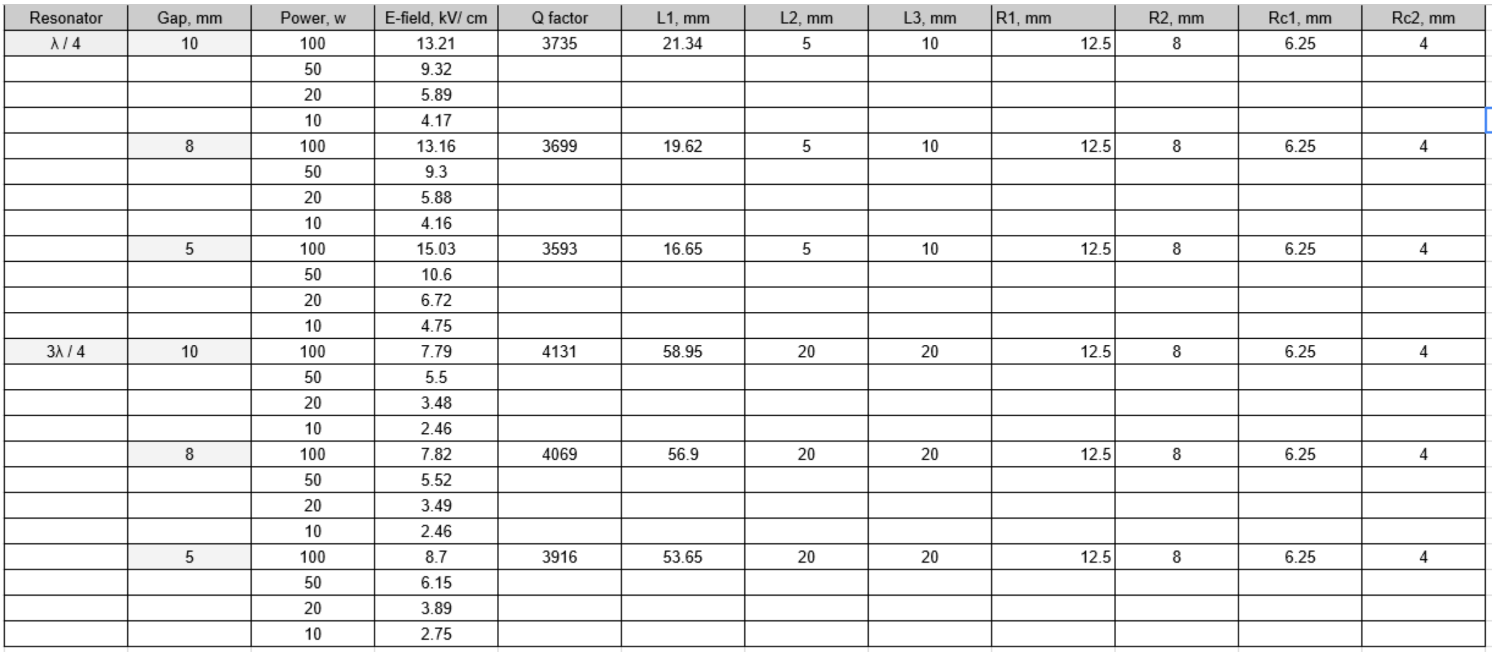
To create an avalanche breakdown, the amplitude of electric field and the distance between electrodes must correspond to the Paschen's Law. It was decided to simulate in CST Studio what amplitude of electric field in the gap between electrodes we can achieve by powering up both resonators up to 10, 20, 50 and 100 W. The results for $\frac{\lambda}{4}\ and\ \frac{3\lambda}{4}$ cylindrical coaxial resonators are presented in Table 4. Results for $\frac{\lambda}{4}\ and\ \frac{3\lambda}{4}$ cylindrical coaxial resonators with cone transition are presented in Table 5. The gaps between electrodes were varied according to magnetic contour map of permanent magnet ring (Fig. 12), as they must contain closed contours inside (1800, 1350, 900).

Table 4. Amplitude of electric field for cylindrical resonator.



Resonator	Gap, mm	Power	E-field, kV/cm	Q factor	L, mm	Rc, mm	R, mm
λ / 4	10	100	10.9	2541	37.8	4	8
		50	7.74				
		20	4.89				
		10	3.46				
	8	100	11	2539	35.77	4	8
		50	7.81				
		20	4.93				
		10	3.49				
	5	100	12.9	2537	32.55	4	8
		50	9.16				
		20	5.79				
		10	4.09				
3λ /4	10	100	6.95	2933	98.85	4	8
		50	4.91				
		20	3.11				
		10	2.2				
	8	100	7	2907	96.82	4	8
		50	4.94				
		20	3.13				
		10	2.21				
	5	100	8.11	2914	93.58	4	8
		50	5.73				
		20	3.62				
		10	2.56				

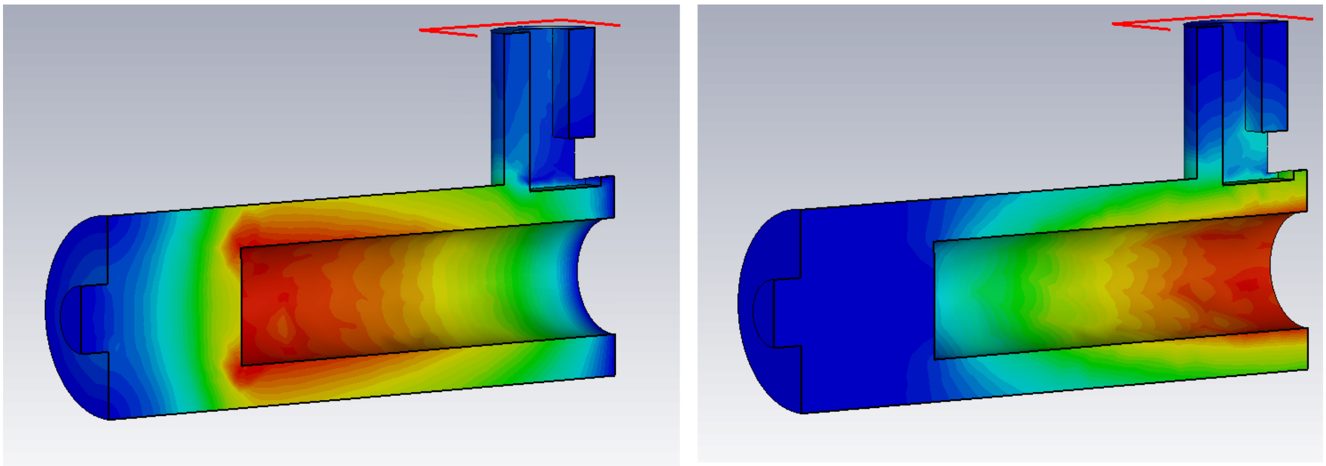
Table 5. Amplitude of electric field for cylindrical resonator with cone transition.



Resonator	Gap, mm	Power, w	E-field, kV/ cm	Q factor	L1, mm	L2, mm	L3, mm	R1, mm	R2, mm	Rc1, mm	Rc2, mm
λ / 4	10	100	13.21	3735	21.34	5	10	12.5	8	6.25	4
		50	9.32								
		20	5.89								
		10	4.17								
	8	100	13.16	3699	19.62	5	10	12.5	8	6.25	4
		50	9.3								
		20	5.88								
		10	4.16								
	5	100	15.03	3593	16.65	5	10	12.5	8	6.25	4
		50	10.6								
		20	6.72								
		10	4.75								
3λ / 4	10	100	7.79	4131	58.95	20	20	12.5	8	6.25	4
		50	5.5								
		20	3.48								
		10	2.46								
	8	100	7.82	4069	56.9	20	20	12.5	8	6.25	4
		50	5.52								
		20	3.49								
		10	2.46								
	5	100	8.7	3916	53.65	20	20	12.5	8	6.25	4
		50	6.15								
		20	3.89								
		10	2.75								

From the results it is clear that cylindrical resonator with cone transition has slightly higher amplitude of electric field in the gap than ordinary cylindrical resonator with equal power level. Still, amplitudes that are created in both resonator's cavities is high enough to create an avalanche breakdown.

The distributions of electric and magnetic fields in resonator’s cavities (with coupling devices on) are shown on Figure 15 and Figure 16.



E-Field

H-Field

Fig. 15. Distribution of fields in cylindrical resonator.

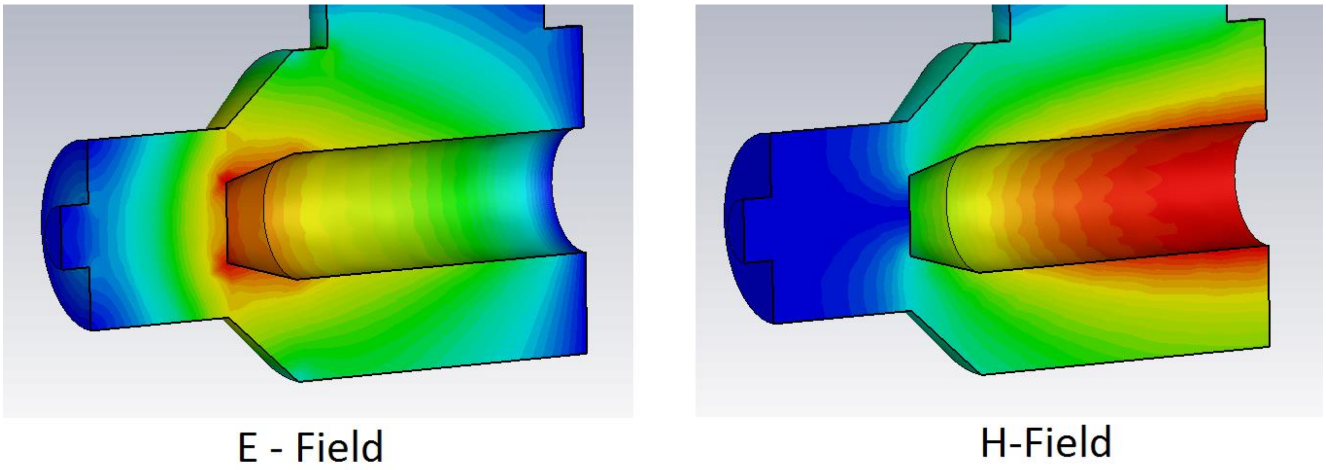


Fig. 16. Distribution of fields in cylindrical resonator with cone transition.

Inductive loop coupler

A coupling device is used to power up resonator. There are two types of coupling devices: capacitive rods and inductive loops. Capacitive rods must be installed near the area where electric field prevails. The presented construction of ion source (Fig. 14) wouldn't allow that. Therefore it was decided to use an inductive loop coupler, which will be installed in area where magnetic field prevails.

A very important part of design a coupling device is impedance matching between the generator and the load. When the impedance of load is equal to the impedance of source the amount of power transfer will be at its maximum and there will be no power reflection. This condition can be satisfied if external Q factor (Q_{ex}) will be equal to the intrinsic Q factor (Q_{in}):

$$Q_{ex} = Q_{in} \tag{3}$$

External Q factor depends on inductive loop dimensions and location. Intrinsic Q factor depends only on resonator properties. So, design of the loop coupler must be done according to the rule (3).

The couplers which were designed for different resonators (all $\frac{\lambda}{4}$) in CST Studio Suite are shown in Figure 17. Loops are made of copper. Schematic drawing of loops are presented in Fig. 18.

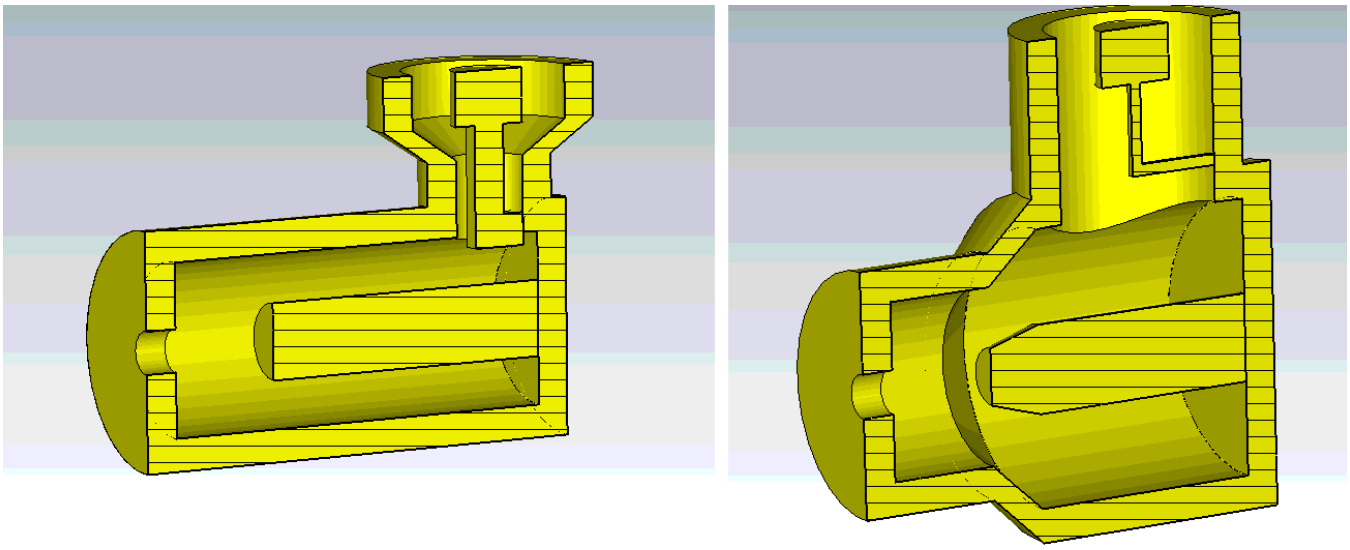


Fig. 17. Inductive loop couplers for two types of resonator.

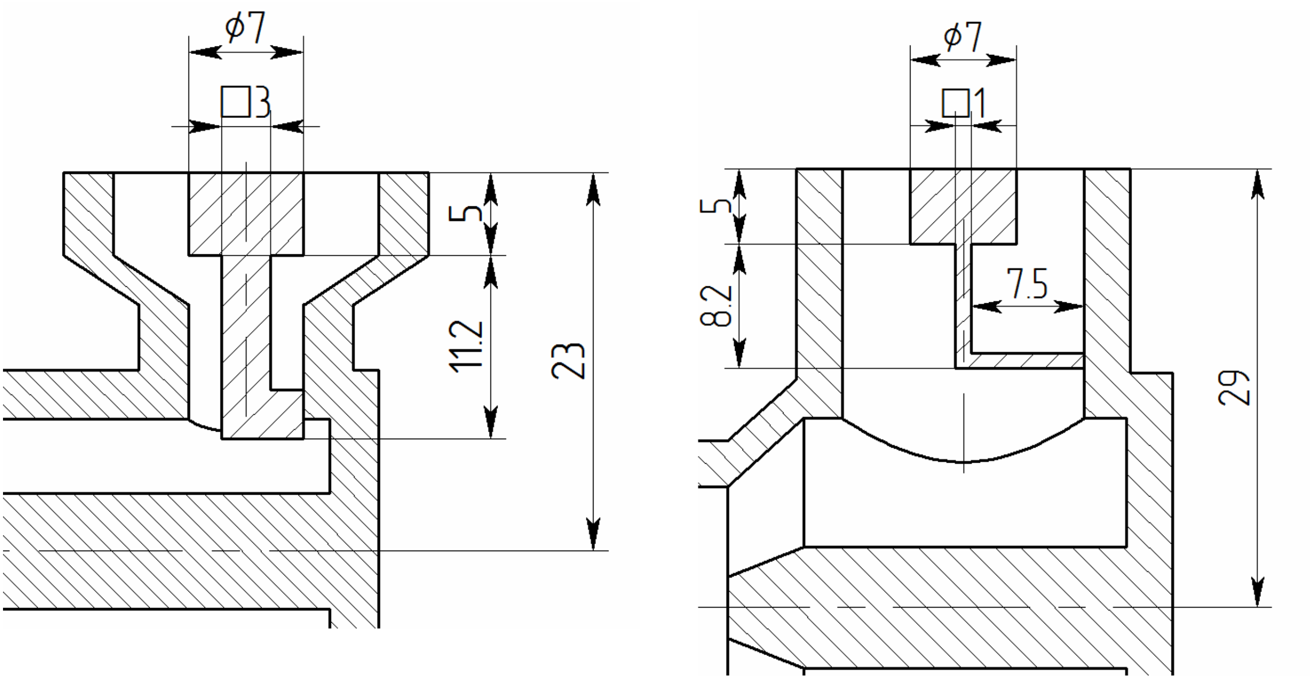


Fig. 18. Dimensions of coupling loops for cylindrical resonator (left) and for resonator with cone transition (right).

Schematic drawings of final versions of resonators are presented in Fig. 19 and Fig. 20.

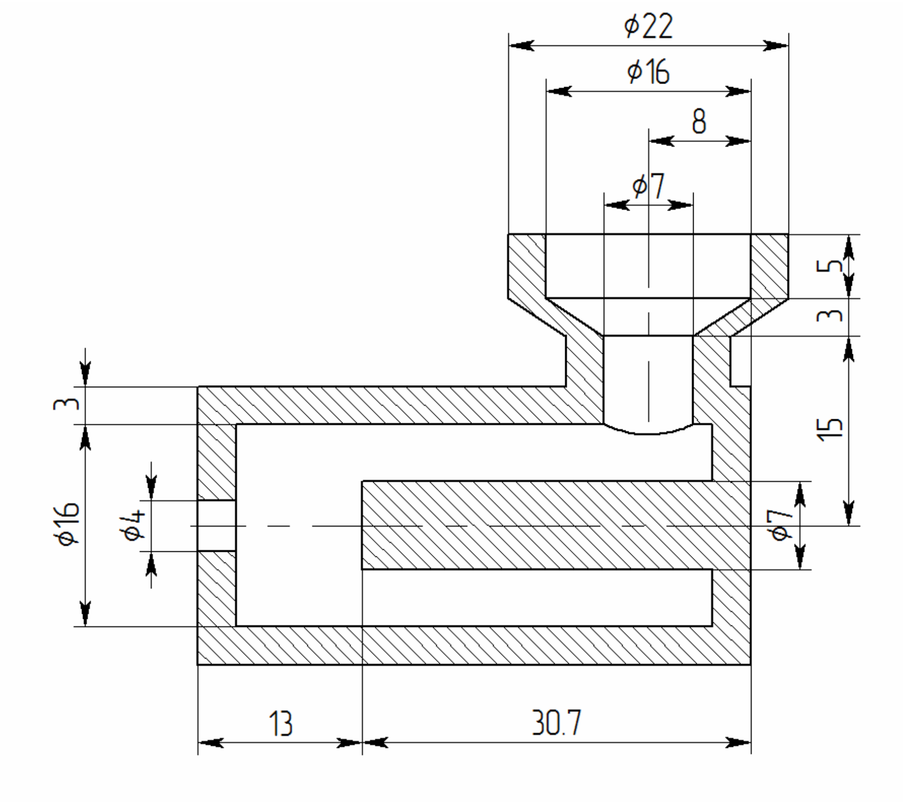


Fig. 19. Final version of cylindrical resonator ($\frac{\lambda}{4}$).

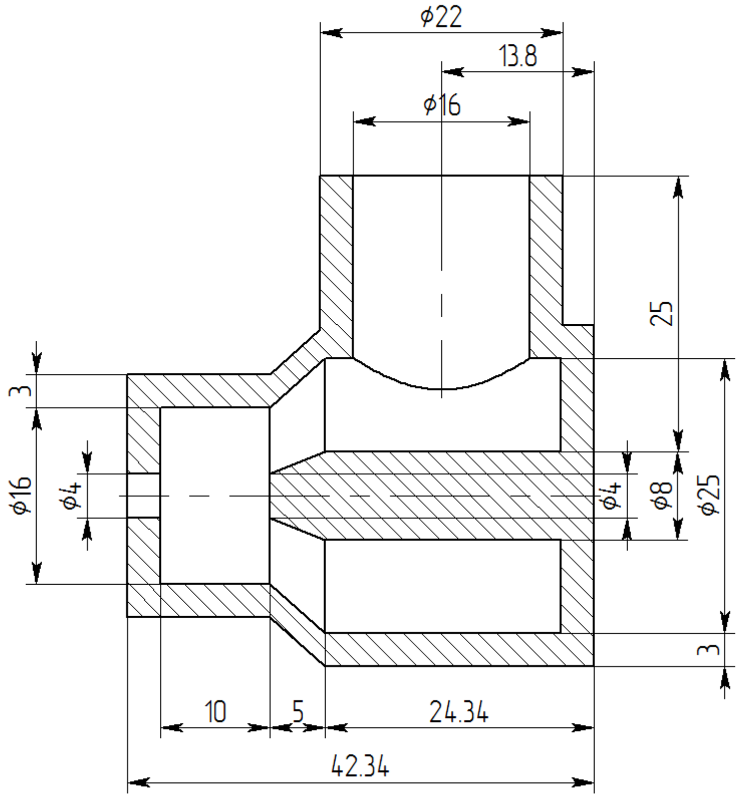


Fig. 20. Final version of cylindrical resonator with cone transition ($\frac{\lambda}{4}$).

Conclusions

The main goal of this work was to design a resonator that will be used in development of new ECR ion source. Two types of coaxial resonator were designed: coaxial (Fig. 13, a) and coaxial with cone transition (Fig. 13, b).

With the help of CST Studio Suite, the distributions of electric and magnetic field were simulated (Fig. 15, 16). The dependence of electric field's amplitude by power is presented in Tables 4 and 5.

According to the rule (3) two loop couplers for the resonators were designed (Fig. 17). Parameters of coupling loops are presented in Fig. 18.

Schematic drawing of final versions of resonators are presented in Fig. 19 and 20.

Obtained results of this work will be used in design of the ECR source for FLNR's mass-separator MASHA.

Acknowledgement

I would like to express my appreciation to PhD Sergey Leopoldovich Bogomolov, my practice supervisor and Head of the Ion Source Sector in Flerov Laboratory of Nuclear Reactions.

I also wish to thanks Karpova Elena Gennadyevna and all committee of JINR Summer Student Program for giving me opportunity to participate.

References

1. http://flerovlab.jinr.ru/

2. «PRESENT STATUS OF FLNR (JINR) ECR ION SOURCES», S.Bogomolov, A.Efremov, V.Loginov, et. al., Proceedings of ECRIS2010, Grenoble, France http://accelconf.web.cern.ch/AccelConf/ECRIS2010/papers/mocobk02.pdf

3. «The Physics and Technology of Ion Sources», Ian G. Brown, 2004 WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim, ISBN: 3-527-40410-4

4. «The project of the mass separator of atomic nuclei produced in heavy ion induced reactions», Yu.Ts. Oganessian, V.A. Shchepunov, S.N. Dmitriev, et. al., Nuclear Instruments and Methods in Physics Research B 204 (2003) 606–613

5. «ION SOURCES FOR THE FIRST STAGE OF THE DRIBS PROJECT»,
A.Efremov, S.L.Bogomolov, A.N.Lebedev, et. al., CP600, Cyclotrons and Their Applications 2001, Sixteenth International Conference, edited by F. Marti © 2001 American Institute of Physics
http://accelconf.web.cern.ch/AccelConf/c01/cyc2001/paper/P3-08.pdf

6. https://www.cst.com/