THE STUDY OF THE HELICAL RF RESONATOR FOR THE 300 keV NITROGEN ION CW IMPLANTER

N.V. Avreline, TRIUMF, Vancouver, B.C., Canada
S.M. Polozov, A.G. Ponomarenko, National Research Nuclear University -Moscow Engineering Physics Institute, Moscow, Russia

Abstract

The helical RF resonator for the single charged 300 keV nitrogen ion CW implanter was designed, simulated in CST Microwave Studio and the results were experimentally verified. The current setup of the implanter is described as well as possible modifications to accelerate ions of other types. The results of the field distribution's RF measurements and the results of the high-power test are also presented.

INTRODUCTION

The implanter RF system consists of the helical type accelerating resonator that is loaded by the channel of drift tubes, the Duoplasmatron source of nitrogen single charged ions with 25 keV of energy, the mechanical backing pump, the turbomolecular vacuum pump TMN-500, the ion pump Nord-250, 3 kW CW RF amplifier, the control cabinet with power supplies and the turning magnet that is used to analyze the resulting beam (Fig. 1). This implanter was primarily designed to accelerate CW beam up to 100 μA. It could accelerate ions with other charge-to-mass ratio after changing the helical inductor.

Figure 1: The 300 keV Implanter of single charged nitrogen ions.

THE DESIGN OF THE RF RESONATOR

Given a rather low operating frequency of 13.56 MHz, in the efforts to reduce the size of an accelerating structure, the resonator of a helical type loaded by an accelerating channel was selected in the design. The accelerating channel is composed of 10 drift tubes and is operating in π mode. These tubes are connected to the two longitudinal bars that are connected respectively to the ends of the half-wave length helical elements of the resonator. The main advantage of using this accelerating resonator in this implanter is that just the accelerating channel is in the vacuum chamber, but not helical inductor. This kind of a design allows to change the inductance by just replacing the helical part without opening the vacuum chamber. Specifically, the frequency of the resonator could be modified and the implanter could be used to accelerate different kinds of ions. The photo of the open resonator is presented in Fig. 2. To tune the resonance frequency of this resonator, two plates were used to shorten the windings.

Figure 2: The opened resonator with the replaceable helical part that is connected to the accelerating channel via a feedthrough.

Copyright © 2017 CC-BY-3.0 and by the respective authors

ISBN 978-3-95450-181-6

The helical element was built out of two 12 mm diameter copper pipes that were soldered together. These pipes are water cooled. They are connected through the feedthrough insulators with the two bars that support the drift tubes. The helical element could be easily disconnected and replaced by another one as these connections are located outside of the vacuum chamber. Moreover, those connectors are of the flange type, which provide good RF connection and prevent water leaks. Indium gaskets were used to seal these connections.

The accelerating channel consists of 10 drift tubes with outer and inner diameters of 30 mm and 18 mm. The accelerating channel was designed to be inside a cradle (see Fig. 3) which allowed assembly of this channel outside of the vacuum chamber. Two longitudinal bars were supported by four insulators attached to this cradle. Drift tubes were connected to the two longitudinal bars via the supports of 5 mm in diameter. During assembly, to ensure channel's alignment, the first and the last half tubes that were soldered onto the bars first and then a stainless shaft was inserted through these tubes to provide support for the intermediate tubes. To ensure specific distance between drift tubes, washers have been used.

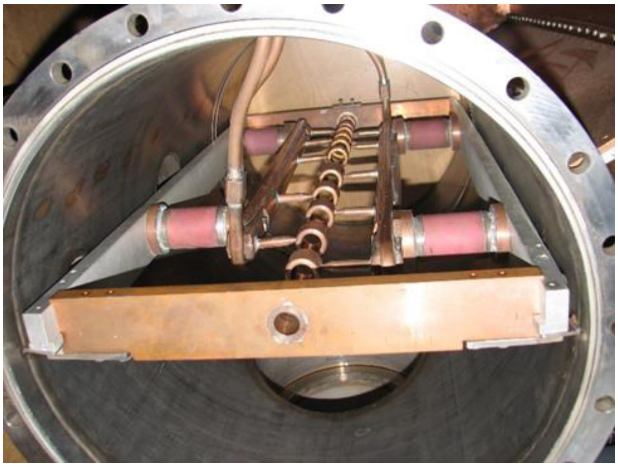

Figure 3: The accelerating channel of the implanter.

CALCULATION AND SIMULATION OF THE ACCELERATING STRUCTURE

The design and optimization of the accelerating structure were done in in the following steps: the analytical model, the study of the scalable mock-up of the resonator, simulations of the structure in the CST Microwave Studio and the experimental measurements and tests.

The analytic model was created to estimate the dimensions of the accelerating structure and to optimize its electrodynamic characteristics. The structure was represented as a resonator that consists of piece of a transmission line with a helical element instead of the inner conductor, shorted on the one end and connected to a capacitor and an inductor in series on the other end. The capacitor and the inductor represent the capacitance of the accelerating channel and the inductance of the two leads of the helical element. In the first approach this transmission line was running in the TEM mode. For the simulation, this half wavelength resonator was represented as two quarter wavelength resonators. The equivalent circuit of the quarter wavelength resonator is represented on Fig. 4.

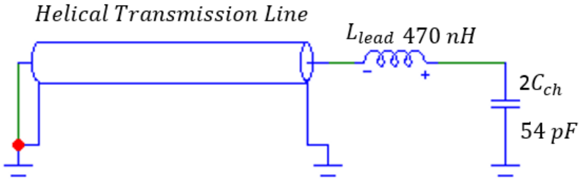

Figure 4: The model of the transmission line and the equivalent circuit of the resonator.

The helical element allows to significantly reduce the dimensions of the accelerating structure. To simulate a resonator that is based on a transmission line with the helical inner conductor, we have calculated its characteristic impedance Z_0, propagation constant γ and losses α_{loss}. In the model, an unwrapped ribbon helix was used for an equivalent representation of the transmission line geometry [1, 2] (Fig. 5).

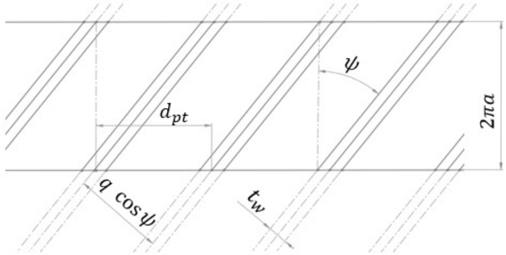

Figure 5: The model of the helical transmission line.

The model allows to find the characteristic impedance Z_0 and to minimize losses in the transmission line for different pitches and cross-sections of its helical conductor. The formula to determine α_{loss} is given by:

$$\alpha_{loss} = \frac{4}{\pi\ \sin\theta} \frac{F\left(\frac{\pi}{2}, \cos\theta\right)}{P_{-q}(\cos\theta) P_{-q}(\cos\theta')} \frac{R_0}{2Z_0} \quad (1)$$

where

$$Z_0 = \frac{1}{4}\sqrt{\frac{\mu_0}{\varepsilon_0}} \frac{1}{\sin(q\pi)} \frac{P_{-q}\left(cos(\theta')\right)}{P_{-q}\left(cos(\theta)\right)}$$

$F\left(\frac{\pi}{2}, cos\theta\right)$ is the elliptical Integral of the first kind,

$$P_q(cos\theta) = \frac{\sin(q\pi)}{\pi} \sum_{m=0}^{\infty} (-1)^m \left(\frac{1}{q-m} - \frac{1}{q+m+1}\right) P_m(\cos\theta),$$

$P_m(\cos\theta)$ are the Legendre polynomials,

$$\theta = \pi - \theta', \qquad \theta = \frac{\pi t_w}{d_{pt}}, \qquad q = k\,a\,cos(\psi), \qquad k = \frac{2\pi f_0}{c},$$

f_0 - operating frequency, $R_0 = \frac{\sqrt{4\pi f_0 \frac{\mu_0}{\sigma_{cu}} ctg^2(\psi)}}{2\pi a\ cos^2(\psi)}$,

a - radius of helical element, σ_{cu} - conductance of copper, ψ - angle of helical turns.

The plot of α_{loss} is presented in (Fig. 6). The minimal losses correspond to the ratio of conductor width and the helical pitch of 0.54. The conductor width was selected

Copyright © 2017 CC-BY-3.0 and by the respective authors

ISBN 978-3-95450-181-6

based on a compromise between the losses and the dimension of the whole accelerating structure.

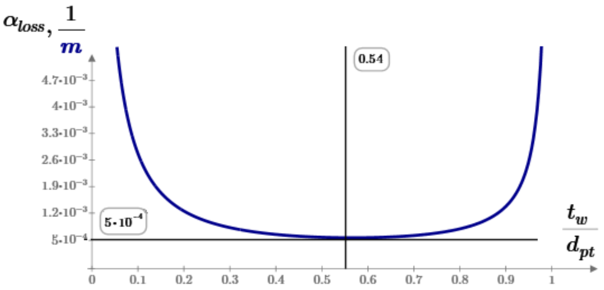

Figure 6: Losses of Helical Transmission Line.

The accelerating channel capacitance was calculated based on the formulas from [3, 4] and based on the simulation of equivalent circuit in Micro-Cap and Comsol 5.2. The equivalent circuit representing the accelerating channel is shown in (Fig. 7).

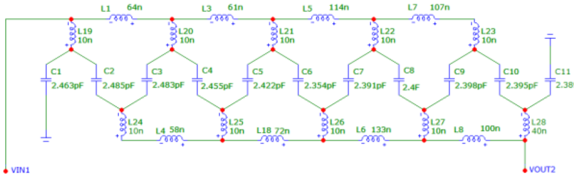

Figure 7: Equivalent Circuit of Accelerating Channel.

As a result of this calculation, the capacitance between terminals “VIN1” and “OUT2” was found to be $C_{ch} = 27\ pF$. As per the equivalent circuit presented on Fig. 4, the calculated length of the whole helical element was 239 mm and the optimal helical pitch was 43 mm.

INVESTIGATION OF THE MOCK-UP ACCELERATING STRUCTURE

Before the operational accelerating structure was manufactured, a mock-up version with a scale factor of two was designed, manufactured and investigated. The experimental investigation of this resonator determined the resonance frequency of 29.12 MHz, $Q_l = 1135$. The field distribution was measured using a complex PLC device [5] that allowed to calculate Q_l factor and shunt impedance. The measurements of the electric component distribution of the electromagnetic field, E_z along the Z axis is presented on Fig. 8.

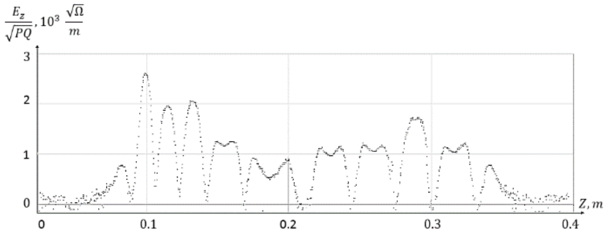

Figure 8: The distribution of E_z along of accelerating axis in the mock-up resonator.

The post processing calculation gave $R_{sh} = 163\,\frac{M\Omega}{m}$ and $R_{eff\ sh} = 123\,\frac{M\Omega}{m}$.

EXPERIMENTAL STUDY OF THE ACCELERATING STRUCTURE

Following the experimental investigation of the mock-up accelerating structure, the full scale accelerating resonator was manufactured and studied. The frequency of this resonator was adjusted to 13.56 MHz using the shortening plates (Fig 2.). The Q_l factor was measured using the method of resonator phase shift and the resulting value was $Q_l = 1100$. The experimental investigation and the CST Microwave Studio simulation results of the accelerating field distribution are presented on Fig.9.

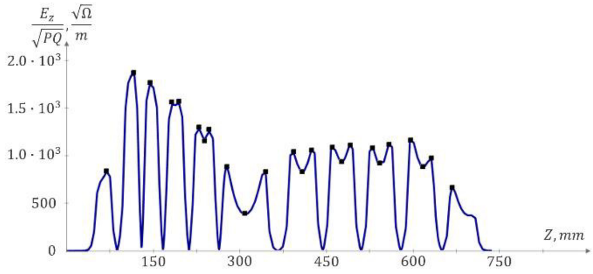

Figure 9: The distribution of E_z in the accelerating channel and the experimental extremal points (marked as “■”) before the hot test.

Post processing calculations gave $R_{sh} = 167\,\frac{M\Omega}{m}$ and $R_{eff\ sh} = 132\,\frac{M\Omega}{m}$.

CONCLUSION

The experimental study of the accelerating resonator in the implanter showed that it has high $R_{sh\ eff}$ and Q_l factor. The implanted could be used to accelerate ions of a different type by changing helical element and could be run using a CW RF amplifier with power less than 3 kW.

REFERENCES

[1] R.A Silin, V.P. Sazonov, Moderating Systems, Sov. Radio, 1966

[2] Chiao-Min Chu, Propagation of wave in helical guides, Journal of Applied Physics, vol.29, number 1, January, 1958, pp. 88-99

[3] N.V. Avrelin et al., Calculation of Electrodynamic Characteristics of H-Resonator Based Accelerator Systems Using the Approximation Methods. Preprint 078-88, MEPhi, 1988.

[4] N.P. Sobenin, B.V. Zverev, Electrodynamic Characteristics of Accelerating Cavities, London – Moscow, 1993

[5] N.V. Avrelin, I.N. Demidov, A.G. Ponomarenko, S.V. Popov, A.E. Rodionov, Autonomous Microprocessor-based Complex for Measuring Electrodynamic Characteristics of Accelerators. Accelerator-Based Radiation Equipment, Energoatomizdat, 1987, p.31.

Copyright © 2017 CC-BY-3.0 and by the respective authors