

CURRENT DEVELOPMENTS OF THE VENUS ION SOURCE IN RESEARCH AND OPERATIONS *

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Abstract

The VENUS ion source functions as a research and development tool in the ECR community as well as an injector for LBNL’s 88-Inch cyclotron. In order to meet the needs of both the ECR community and users at the 88-Inch cyclotron, technology such as ovens and a sputter probe have been developed for introducing metals into the plasma. Using a modified high temperature oven, VENUS has produced 450µA of 238U³³⁺ and 400µA of 238U³⁴⁺, twice the required Uranium beam current needed for FRIB. In addition, after upgrading its high voltage capabilities VENUS produced 11mA of 4He²⁺, a capability that remains unparalleled by other ECR ion sources. In addition to its recent record high intensities VENUS is also being developed to deliver low intensity, ultra high charge state ions for the cocktails beams, where many species are produced simultaneously for use by the BASE Facility. 124Xe⁴³⁺ is now in regular production for the 16MeV/u cocktail, and development of 209Bi⁵⁶⁺ for the 10MeV/u cocktail is in progress and has been accelerated through the 88-Inch cyclotron. This paper presents the latest work towards integrating the VENUS ion source into our research and operational goals.

INTRODUCTION

During the last two years a lot of effort has gone into the integration of VENUS into the operation of the 88-Inch cyclotron as well as a continued effort to use it to push the limits of ECR’s. To meet the needs of the 88-Inch cyclotron users VENUS should provide intense medium charge state beams for studies involving low-cross section reactions as well as several low intensity medium and high charge state ions simultaneously for the cocktails. A low temperature oven has been developed and work with the high temperature oven continues for the production of intense metal ion beams. To produce a variety of low intensity beams development of a sputter probe has begun and initial results are presented. In order to continue to explore the limits of ECR ion production capability we continue to work to make improvements. In this paper we discuss improvements in the VENUS high voltage capability as well as potential improvements to be made in the VENUS plasma chamber. The mechanical layout and specifics of the VENUS ECR ion source have been discussed at length previously and as such will not be done so here [1,2]. Table 1 provides key specifics.

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Table 1: Key Parameters of the VENUS ECR Ion Source

VENUS Key Parameters	Values
Maximum 18GHz/28GHz Power	2,000W/10,000W
Maximum INJ/ /EXT Fields	4.0T/3.0T
Maximum RADIAL Field at wall	2.2T
Superconductor	NbTi
Coil Structure	Sextupole in Solenoid
Plasma Chamber Volume	9L
Plasma Chamber Diameter/Length	14.4cm/50cm

SPUTTER PROBE DEVELOPMENT

A sputter probe being developed for use in VENUS is intended to be used to produce metal beams for the cocktails used by the chip testers at the BASE Facility [1]. Cocktail beams consist of ions from up to 14 different elements with similar mass-to-charge, M/Q, ratio which are all extracted from the ion source and delivered to the cyclotron simultaneously. The 88-Inch cyclotron then selects the ion to deliver to the user. Each ion has a different range or penetration depth and will deliver a different amount of energy to the tested part.

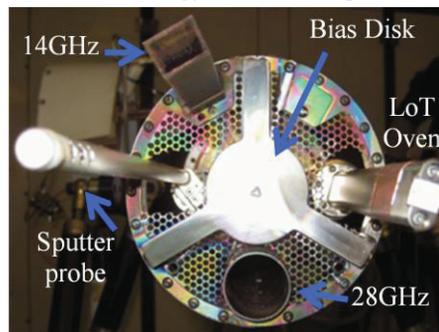


Figure 1: The VENUS injection is shown with the sputter probe and low temperature oven.

The sputter probe, shown in Figure 1, is inserted axially on a water-cooled support tube and a moveable bellows. The intention is to get the sputter probe, made to hold three metal samples, as close as possible to the plasma in order to take advantage of the high ion density regions since it is biased negatively from 0 to -3000V. Because it is inserted axially, placing the sputter probe at the maximum radial position closest to the wall will allow us to insert it further along the chamber in between the plasma flutes. Figure 2 shows the initial results when sputtering ¹⁸¹Ta. At -2000V, 16µA of 29+ was obtained.

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However, at its current radial position of 5.6cm, compared to the plasma chamber radius is 7.2cm, the sputter probe is too close to the plasma to operate without melting. Although positive results have been obtained, modifications are planned to place it at the maximum radius inside the plasma chamber.

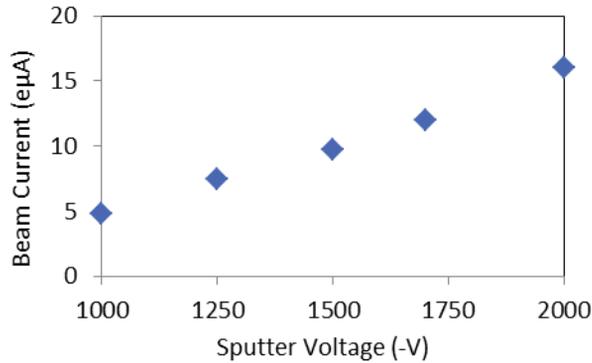


Figure 2: Initial sputter probe results producing 181Ta^{29+} .

LOW TEMPERATURE OVEN DEVELOPMENTS

Calcium Development

With the development of the low temperature oven [4], shown in Figure 1, several long term performance tests have been done. Because 48Ca is of particular importance to the 88-Inch cyclotron users, consumption measurements have been performed using 40Ca . During one test with the low temperature oven 40Ca was run for 94 hours with a consumption rate of 0.67mg/h , a 2% efficiency into the 40Ca^{11+} charge state, and a total efficiency of 9% into all charge states. The 40Ca was run using 18GHz heating only at a typical 18GHz axial field configuration of 2.2T at injection, 1.5T at extraction, 0.3T at the center, and 1.3T radially at the wall.

Hot Liner Test

In an effort to further decrease the calcium consumption rate a test was performed using a hot tantalum liner as done by the Dubna group who showed the use of the hot liner covering the plasma chamber walls increases the ion source efficiency [5]. In the 14GHz AECR-U the use of the Ta liner decreases the consumption rate by a factor of 3. The VENUS liner test lasted 46 hours with a consumption rate of 0.73mg/hr and a 2.11% efficiency into the 40Ca^{11+} charge state. The liner did not decrease the consumption rate as expected. As with the previous run only 18GHz was used with the same magnetic field configuration. The run started with an equivalent radial field of 1.3T at the wall but soon after the run commenced, Ta peaks began to appear in the spectra, disrupting the 40Ca charge state distribution, and it was necessary to turn up the radial field to 2.2T which is usually used only for 28GHz operation. Figure 4 shows how quickly the Ta^{20+} peak corresponded with the radial field.

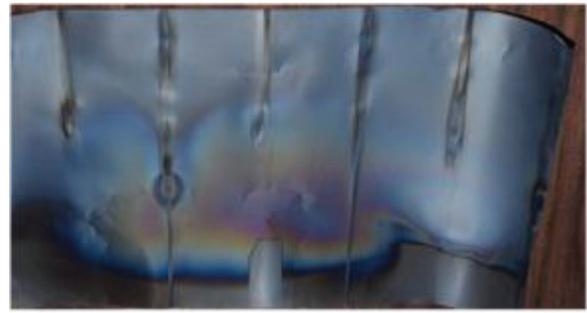


Figure 3: Innermost layer of the tantalum liner.

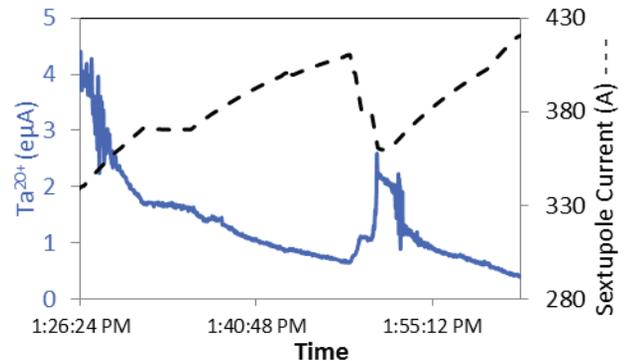


Figure 4: The graph shows the response of the Ta^{20+} peak, coming from the Ta liner, to the sextupole field.

The liner consisted of three individual Ta layers each 0.003" thick and was 12 inches long. Figure 3 shows the innermost layer of the liner after the test as well as the markings made by the plasma flutes. The plasma chamber length is about 20 inches long but the liner was placed at the injection side where the oven is located. When the liner was removed no layers were burned through but the innermost layer was dimpled at the locations where it saw the most hot electrons. It is interesting to note that little to no CaO was found on the liner when removed. This suggests that either little calcium makes it onto the wall or that it is efficiently re-circulated back to the plasma.

Bismuth Development

The VENUS low temperature oven allows for the development of new ions in the cocktail beams. Development has begun to add 209Bi^{56+} or 209Bi^{57+} to the 10MeV/u cocktail. The ion 209Bi^{56+} would extend the Linear Energy Transfer in the 10MeV cocktail from 78 to 91 MeV/(mg/cm²) for silicon. In May of 2012, Bi^{56+} , Bi^{57+} , and Bi^{58+} were accelerated and extracted from the cyclotron. The maximum 209Bi^{56+} measured at cyclotron extraction on a Faraday cup was 0.08enA. 209Bi^{57+} and 209Bi^{58+} were only seen in trace amounts. Table 1 lists the important parameters of the VENUS tune when producing these high charge states of Bismuth. More cyclotron development time is needed to allow for tuning the VENUS ion source in conjunction with the cyclotron. With VENUS tuned for very high charge states, it produced $5.3\text{e}\mu\text{A}$ of Bi^{50+} .

Table 1: Summary of Parameters used in High Charge State Production of Bismuth

VENUS Bismuth parameters	values
Extraction Voltage	12.5kV
Bi ⁵⁶⁺ at cyclotron extraction	0.08 enA
Bi ⁵⁰⁺ at source extraction	5.3 eμA
Bi Oven Temperature	605°C
18GHz/28GHz Power	2000W/4700W
INJ/MID/EXT Fields	3.4T/0.55T/2.2T
RADIAL Field at wall	2.2T
INJ/EXT Pressure	1.3x10 ⁻⁷ /1.9x10 ⁻⁸ mbar

URANIUM RESULTS

Recently the high temperature oven used to produce uranium beams was modified to improve the water cooling of the current carrying leads, which allowed us to reach higher oven power [4]. This modification led to the successful production of high intensity uranium beams. To reach a vapor pressure of UO₂ between 1x10⁻² and 1x10⁻¹mbar requires temperatures from 2000-2300°C [7]. UO₂ has a melting point at about 2820°C. Two tests were done to produce uranium beams from UO₂, one using a tungsten oven and one using a rhenium oven.

The first test, which was done using the tungsten oven, was unsuccessful in producing a stable and intense uranium beam. Figure 5 shows the resulting condition of the oven after the test and removal from VENUS. The tungsten oven's lower stem, in the presence of the strong axial magnetic field and resulting Lorentz force, traveled sideways in the soft copper housing. Poor contact between the lower stem and the copper housing may have resulted in a higher local temperature which allowed the stem to move in the then soft copper. The resulting contact between the oven body and the copper housing caused the oven to be electrically and thermally shorted. This was apparent during the run when the resistance of the oven became unstable.

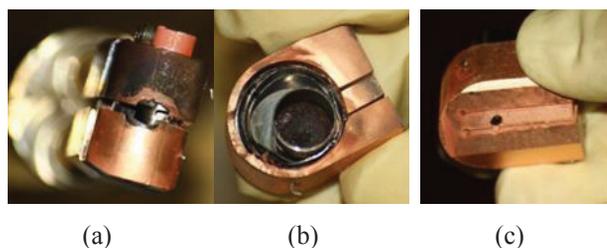


Figure 5: High temperature oven with the tungsten oven used in the first and unsuccessful uranium production test. (a) and (b) show that the tungsten oven moved off center within the copper housing. (c) shows the underside of the copper housing and the tungsten stem moved off from the center.

The second test, using the rhenium oven shown in Figure 6, successfully produced 450eμA of 238U³³⁺ and 400eμA of 238U³⁴⁺. Figure 7 shows the uranium spectrum. The source parameters for the high intensity tune are shown in Table 2. With this oven, tuning for high charge states of uranium was also done. We reached 13eμA of 238U⁵⁰⁺ which required both a lower injection pressure of 1.8x10⁻⁷mbar and a lower oven power of 340W than the values used to produce the high intensity results. The high charge states were very sensitive to the oven power and, hence, the amount of uranium vapour introduced.

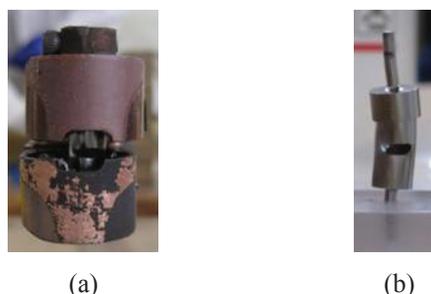


Figure 6: (a) High temperature oven with the rhenium oven used in the second and successful uranium production test. (b) rhenium oven after the run shows a deformed body.

One factor contributing to the success of the rhenium oven is that the rhenium oven requires less current to reach the temperature at which UO₂ vaporizes due to its higher resistance than the tungsten oven. This is shown in Figure 8, which compares the oven power versus temperature for the tungsten, tantalum and rhenium axial ovens currently in use to produce various metal vapours. When the rhenium oven was removed from VENUS it was seen that the oven walls had slightly buckled but there was no damage to the stems and no indication of instabilities during the test. Approximately 179 mg of UO₂ was used over the course of about 29 hours, giving a consumption rate between 6-7mg/hr. The emittance of the uranium beams produced with the rhenium oven is discussed in reference [6].

Table 2: Summary of Parameters used in High Intensity Production of Uranium Beam with a Rhenium Oven

VENUS Uranium parameters	Values
Extraction Voltage	12.5kV
Bi ⁵⁶⁺ at cyclotron extraction	0.08 enA
Bi ⁵⁰⁺ at source extraction	5.3 eμA
Bi Oven Temperature	605°C
18GHz/28GHz Power	2000W/4700W
INJ/MID/EXT Fields	3.4T/0.55T/2.2T
RADIAL Field at wall	2.2T
INJ/EXT Pressure	1.3x10 ⁻⁷ /1.9x10 ⁻⁸ mbar

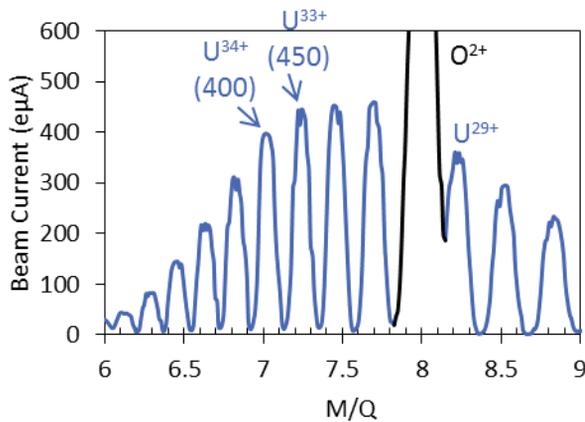


Figure 7: A high intensity Uranium spectrum produced using a rhenium high temperature oven.

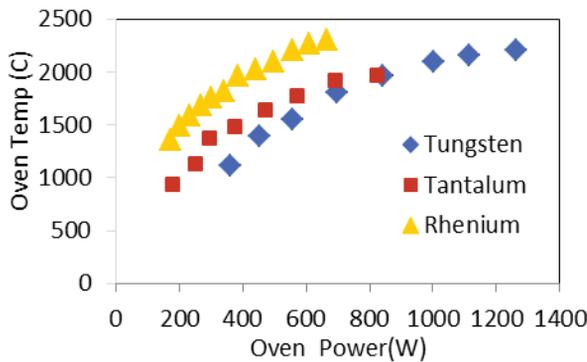


Figure 8: A comparison of the oven power required to reach a certain temperature for the axial ovens available for use in VENUS.

HIGH VOLTAGE UPGRADE

In an effort to increase the maximum high voltage capability of VENUS, and increase transmission efficiency, several improvements were made to the source. One change was in the region after beam extraction. It was known to us that during operation there was sparking in the extraction region that prevented VENUS from holding more than 22kV.

An investigation of the extraction region revealed burn marks between the last high voltage surface and the ground shield that protects the 40kV insulator, as shown in Figure 9. Figure 10 is a mechanical layout of the extraction region and shows the region where the sparking occurred. In addition water damage to the surfaces, from an incident that occurred in 2004, was seen on the ground shield. The surfaces were cleaned and the ground shield was replaced. The distance between the high voltage surface and the ground shield was increased by 0.32" to a new distance of 0.75" with the installation of the new ground shield. This improvement has allowed VENUS to reach 30kV during operation and is currently limited by the 28GHz high voltage break.



Figure 9: Damage caused by sparking between ground shield, that protects the 40kV insulator, and the high voltage surface. The ground shield is removed here, exposing the 40kV insulator.

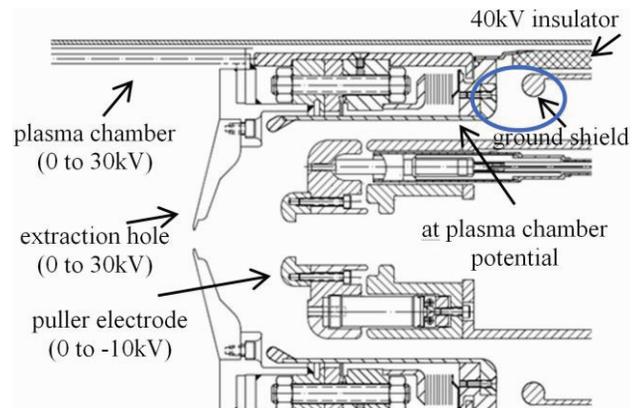


Figure 10: Drawing showing the extraction region of VENUS. The distance between the ground shield and the high voltage surface was increased and the surfaces cleaned, allowing VENUS to reach higher voltage.

High Intensity Helium

With the improvements to the VENUS extraction system a new record intensity for the production of helium was achieved. A total extracted current of 25.4mA was obtained with 9.3mA of He¹⁺ and 11mA of He²⁺. This was the upper limit of the power supply current capability and no saturation in extracted current was noted. With a higher voltage, higher current power supply we anticipate that VENUS can extract much more beam intensity. It is worth pointing out that the amount of current on the aluminium bias disk at the injection end was 57.5 mA, twice that of the total extracted current.

Table 3 lists the source settings used in the intense production of helium.

VENUS PLASMA CHAMBER

VENUS' large superconducting magnet structure allows for a large plasma chamber with a 9L volume. The increased plasma volume allows the absorption of larger amounts of microwave power. Most of the power heats the electrons, which are lost to the walls. Because of this

it is important that there be adequate cooling of the chamber walls where the magnetic confinement field is weakest. These weak points are located where the solenoid field's radial component partially cancels out the radial field produced by the sextupole. In total, there are 18 water cooling channels, with the six wide supply channels oriented to the six plasma flutes, or loss lines. A CAD drawing of the plasma chamber is shown in Figure 11. The plasma chamber is aluminum and designed to have a wall thickness of 1.85 mm (0.073") at the water supply channels, with this being the thinnest region, and 3.50 mm (0.138") where there is no water channel. The inner diameter is 14.4 cm and the total length is approximately 103 cm, however the total length of the plasma chamber is 50cm.

Table 3: Summary of Parameters used in High Intensity Production of Helium Beam

VENUS Helium parameters	Values
Extraction Voltage	25kV
Total Extracted Current	25.4mA
He ¹⁺	9.3mA
He ²⁺	11mA
18GHz/28GHz Power	1745W/1000W
INJ/MID/EXT Fields	3.4T/0.41T/2.1T
RADIAL Field at wall	2.2T
Bias Disk V/I	335V/57.5mA
INJ/EXT Pressure	1.1x10 ⁻⁶ /8.7x10 ⁻⁷ mbar

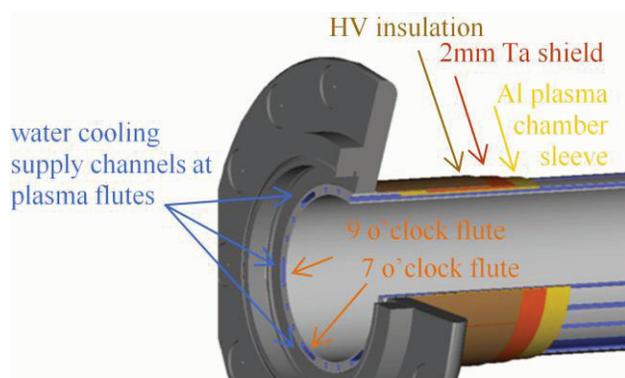


Figure 11: A CAD drawing of the VENUS plasma chamber. The water cooling supply channels are aligned with the plasma flutes. Towards the injection the flutes are located at 3, 7 and 11 o'clock.

Recently the VENUS plasma chamber developed a hole in the wall along one of the flutes. Figure 12 shows the hole which is located at the 7 o'clock position when looking from the injection towards extraction, along an injection flute line. The position of the hole has proved to

be an exact point of localized heating of the plasma chamber in the past. Figure 12 shows the hole. After the hole occurred, the wall was inspected carefully. The thickness of the wall along this supply channel was only 0.053", 0.020" thinner than called for in the drawings. This is attributed to the complexity in machining and assembling the plasma chamber. It is also interesting to point out that the hole is located in approximately the same location as the first chamber failure in 2004. Figure 13 shows a side-by-side comparison of the holes when viewed with the outer layer cut away to expose the water channel and hole. Despite the location being the same, there is a significant difference in the heating pattern. The accident in 2004 was instantaneous and caused by a failure in the 28GHz gyrotron power control circuit where the power went to a full 10kW. The 2012 hole appears to be the result of long term heating.

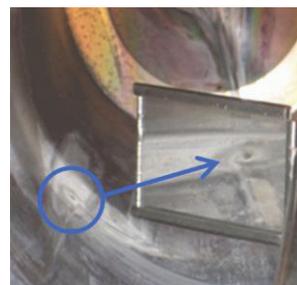


Figure 12: Location of the water leak along an injection flute line.

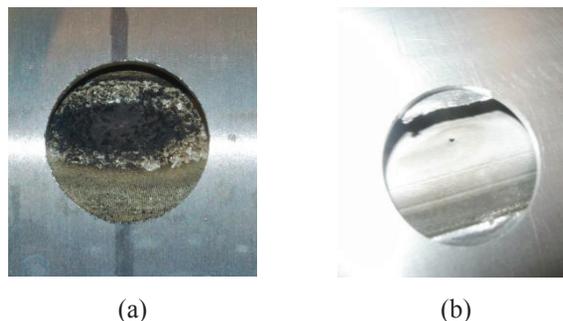


Figure 13: The outer sleeve of the plasma chamber was cut to expose the water channel at the position of the hole in both pictures. (a) 2012 hole (b) 2005 hole.

The plasma chamber failure led us to study the magnetic fields in VENUS in detail. A magnetic field survey along each pole, at the plasma chamber wall, was done using the sextupole at 460A, with the solenoid field off. Figure 14 shows the magnitude of the maximum radial field for each pole, as indicated by the clockwise position of the pole, at r=7.2cm (at the wall) and at the location of the plasma chamber hole. It appears that there is a misalignment between the plasma chamber and the position of the sextupole magnets, which would increase

the local heating at the location of the 2012 hole. Plans to improve the alignment of the plasma chamber and the magnetic field are under way.

SUMMARY

VENUS operated without any quenches or other cryogenic issues for 22 months. This was the longest period of cold operation and no degradation of the cooling capacity of the Gifford McMahan cryocoolers was observed. During this time it produced a number of new beams, summarized in Table 4.

Improvements in the VENUS high temperature oven and the high voltage capability have allowed for new records. Development of the sputter probe continues as well as an investigation of improvements in the plasma chamber and alignment to the magnets.

Table 4: Summary of Recent High Intensity Beam Production Milestones for VENUS

Ion	Charge State	Intensity (eμA)
⁴ He	2+	11,000
¹⁶ O	6+	3,000
⁴⁰ Ar	11+	860
²⁰⁹ Bi	31+	300
²⁰⁹ Bi	50+	5.3
²³⁸ U	33+	450
²³⁸ U	50+	13
⁴⁰ Ca	11+	400

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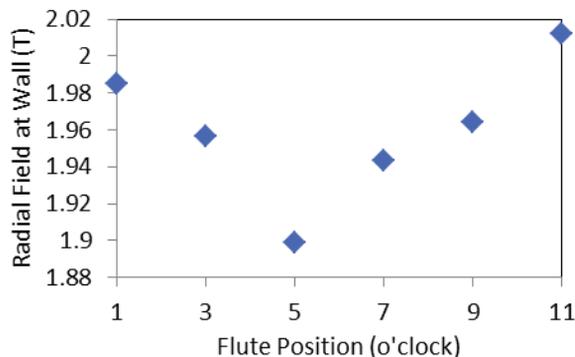


Figure 14: The maximum radial magnet field due to the sextupoles at each pole at the position where the plasma chamber was damaged.