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NEW RESULTS WITH THE SUPERCONDUCTING ECR ION SOURCE VENUS

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Abstract

During the last year, the VENUS ECR ion source was commissioned at 18 GHz and preparations for 28 GHz operation, which is set to begin early in 2004, are now underway. The goal of the VENUS ECR ion source project as the RIA R&D injector is the production of 240eμA of U^{30+}, a high current medium charge state beam. On the other hand, as an injector ion source for the 88-Inch Cyclotron the design objective is the production of 5eμA of U^{48+}, a low current, very high charge state beam. During the commissioning phase with 18 GHz, tests with various gases and recently metals have been performed with up to 2000 W RF power and the performance is very promising. For example, 1100 eμA of O^{6+}, 180 eμA of Ar^{12+}, 150 eμA of Xe^{20+} and 100 eμA of Bi^{24+} were produced in the early commissioning phase, ranking VENUS among the currently highest performance 18 GHz ECR ion sources. The emittance of the beams produced at 18 GHz was measured with a two axis emittance scanner. In FY04 a 10 kW, 28 GHz gyrotron system will be added, which will enable VENUS to reach full performance.

The performance of the VENUS ion source, low energy beam transport (LEBT) and its closed loop cryogenic system are described in the paper.

Recently, a new high temperature axial oven has been installed in the source and the first results on metal beams such as bismuth are given. The design of the 28 GHz, 10 kW gyrotron system is also be described.

I. Introduction

The 3rd generation superconducting ECR ion source, now called VENUS, (Versatile ECR ion source for Nuclear Science), evolved from a concept for a gyrotron driven superconducting ECR that was proposed in 1989, but not further pursued [1]. 1995 an updated concept of a high field superconducting ECR ion source was proposed [2]. In 1997, a prototype magnetic structure was tested and it demonstrated that the required magnet fields were feasible. Improved sets of superconducting magnets were built that incorporated the lessons learned during the construction and testing of the prototype magnet. The new magnets were designed to produce axial fields of 4 T, 3 T and a radial field 2 T at the plasma wall and they reached their design fields during the summer of 1999 [3]. The same year, a conceptual design for the superconducting driver linac was developed for the proposed Rare Isotope Accelerator, RIA. This design called for an increase in U^{30+} by a factor of 8 beyond the performance of the Berkeley AECR-U [4]. Since the field strengths of the new magnets were suitable for 28 GHz operation and frequency scaling was experimentally demonstrated, VENUS was identified as ideal RIA R&D source. Consequently, a mechanical design for optimum operation at 28 GHz gyrotron was developed between 1999 and 2001 and the ion source project was named VENUS. The cryostat and the superconducting magnets were delivered in September 2001 and the first plasma was ignited in June 2002.

II. Design of VENUS

Figure 1 shows the main components of the ECR ion source. The mechanical design has been optimized for maximum ion source performance as well as easy serviceability for operational use. The plasma chamber has been designed to be able to handle 15 kW of CW RF power. It is made out of aluminum with 18 gun-drilled water-cooling channels. Six of the channels were further opened up with an EDM wire cut at the magnetic poles of the sextupole. The plasma chamber has six cutouts at the magnetic poles in order to match the plasma shape. Therefore, the chamber geometry provides for additional volume where the ECR plasma is protruding outward. In addition, this shape allows maximum utilization of the magnetic sextupole field. In between the plasma flutes, where the plasma radius is significantly smaller, the chamber is thicker in order to provide structural rigidity. Aluminum was chosen because of its favorable secondary electron emission properties and its resistance to plasma etching.

Only metal vacuum seals were used in the ion source and beam line to ensure the cleanest vacuum condition. Up to three off-axis microwave guides and two high temperature ovens can be installed from the injection tank. A water-cooled aluminum biased disk terminates the plasma in the axial direction at the injection end. Its shape has been optimized to allow maximum pumping through the injection end. The complete injection assembly can be rolled out conveniently for service on a rigid support system, which provides precise alignment of the more than 1 m long injection assembly with the plasma chamber. [5].

The design and development of the superconducting magnets has previously described in detail[3]. The sextupole coils are wound around a pole with iron in the center, which enhances the peak field about 10%. The superconducting sextupole coils experience strong forces in the axial field of the solenoids. Therefore, a new clamping scheme utilizing liquid metal filled bladders was developed to prevent any movement of the energized coils. During commissioning of the superconducting magnets, the sextupole reached 110% of its design field after a few training quenches (2.4T) with the solenoids operating at their design fields of 4T at injection and 3T at extraction.

The cryogenic system for VENUS was designed to operate at 4.2° K with two cryocoolers each providing up to 45 W of cooling power at 50° K and 1.5 W at 4.2° K in a closed loop mode without further helium transfers. During the acceptance tests in September 2001, the cryostat failed to meet its design specifications. It had a heat leak of 3 W, which exceeded the design goal of 1.5 W by a factor of 2. The pair of cryocoolers can remove 3 W, if they are efficiently coupled to the helium bath. However the original heat exchanger, which coupled the LHe reservoir to the cryocoolers, functioned very inefficiently and this made it necessary to frequently transfer liquid He. A thorough analysis of the original heat exchanger showed that the thermal resistance of the flexible copper link was too high to efficiently transfer heat from the He reservoir to the cryocoolers. Therefore, a new design approach was developed. Sets of fins machined from blocks of high conductivity copper are mounted directly on each cryocooler head and act as helium vapor condensers. A tube was installed to transfer He vapor from the reservoir to the condensers. There the vapor condenses, and the liquid He returns to the reservoir through a second tube[6],[7].

The two cryocoolers can now provide sufficient cooling power to maintain a helium bath temperature below 4.5 K for 18 GHz operation. In addition to the static heat load and the heat generated by the current leads, some of the bremsstrahlung produced by the hot electrons colliding with the plasma chamber penetrates through the wall and is adsorbed into the liquid helium temperature portion of the cryostat. VENUS currently operates with 2000 W of 18 GHz RF power and much of that power goes into heating the electrons in the plasma, some of which reach one or more MeV in energy. The amount of heat deposited in the helium temperature portion of the cryostat depends on the source tuning. With the source carefully tuned for stable plasma conditions, the additional heat load is on the order of 300 mW for 2000 W of 18 GHz RF.

Beam Transport System

The low energy ion beam transport system shown in Fig. 2 consists of an accel-decel extraction system (operating at voltages up to 30 kV), a solenoid lens, and a large gap, 90 degree double focusing analyzing magnet [6, 8]. The beam transport system was designed for high current, high charge state extraction. Therefore, to minimize beam blow up due to space charge, the extracted ion beam is directly matched into the analyzing magnet. In this kind of arrangement, a single solenoid lens is used to adjust the divergence of the beam going into the magnet. The beam diameter cannot be adjusted independently at the same time with only a single solenoid lens. Consequently, a large gap (18 cm) magnet was chosen to accommodate the ion beam size at high intensities [5].

After the mass analyzing section, a two-axis emittance scanner has been installed. In order to measure the actual ion source emittance instead of the magnet acceptance, 100% ion beam transmission with minimal aberrations through the analyzing section is essential.

In the early commissioning phase, during which total currents between 1 and 5 emA have been extracted, ion beam transmissions of 80 to 100% have been measured. Systematic emittance measurements are being carefully compared to the beam transport simulations. These studies will improve the theoretical understanding of the multi-ion species beam transport and will provide guidance for the design of future high current ECR injector systems.

III. Commissioning Results at 18 GHz

During the commissioning period, a number of improvements were made to the cryostat system, the 18 GHz microwave system, and the magnet power supply control system. The new heat exchangers for the two cryocooler described above have now operated for more than 11 months without the addition of liquid helium. A new waveguide high voltage break was designed and installed, which uses a thin quartz plate sandwiched between to water-cooled and matched copper waveguide sections. This new design provides reliable operation with minimum reflected power at 2 kW and up to 25 kV isolation. The 18 GHz injection waveguide in VENUS was modified to provide additional pumping, which enables operation at full power without waveguide arcing. The RF screen at the injection side of the plasma chamber was improved to reduce the microwave leaks and to eliminate long-term temperature shifts that affected operation of the bias probe. A digital control system for the ion source operation and interlock system was developed using process logic controller (PLC). A digital regulation loop was developed so that the PLC could regulate the superconducting magnet power supplies. was a particular important step. This eliminated initial power supply instabilities related to the low resistance and high inductance load presented by the superconducting coils and it simplified the operation of the source. Following this change, the magnets were successfully operated without quenching at currents required for optimum operation at 28 GHz.

VENUS is now operating at the full capacity of the 2 kW, 18 GHz klystron. The operation experience has been excellent. The UHV vacuum system is designed for good plasma chamber pumping and this enables the ion source to recover very rapidly after being exposed to air. Its performance in terms of charge state production, beam intensity, stability, and emittance is very promising and is still improving as we gain more tuning experience. Its performance has already surpassed the performance of the AECR-U even though the microwave power density in VENUS is about 1/10th of the density achieved in the AECR-U[9]. The AECR-U uses 10 and 14 GHz heating to achieve a microwave power density of 1700 W/liter while VENUS with its much larger plasma volume of 9 liters only reaches about 220 W/liter at 2000 W. Once the 10 kW gyrotron is in operation, the microwave density in VENUS will increase by a factor of 5. Figure 3 shows the analyzed O^{6+} current in eμA as a function of 18 GHz microwave power. The current increases almost linearly with power, demonstrating that more rf power is needed to reach optimum performance.

The initial performance for gases at 18 GHz is summarized in Table 1. The argon data was taken in the spring, before it was possible to operate at full power. So far, the source has been tuned to optimize the intermediate charge states, since those are critical for RIA. We plan to explore its performance for very high charge states that are important for the 88-Inch Cyclotron in the near future.

Recently a high temperature oven has been installed in VENUS. A prototype of this oven has been developed and successfully tested previously with LBNL ECR ion source for temperatures up to 2000 degree C. Therefore it should be well suited for the production of uranium beams, which need to operate at about 1700 degree C. Figure 4 shows initial results (first day of tuning) for VENUS at 18 GHz with a high temperature oven for ^{209}Bi charge state distribution. Table II summarizes the early results for bismuth.

The first emittance measurements with argon were performed in the spring of 2003 prior to reaching full power operation and results are presented in Fig. 5. The 1-rms normalized emittance values for different argon charge states are plotted. Several charge states have been measured for various ion source and tuning conditions (rf power, plasma stability, extraction matching and ion optics). The different values are graphed to show the spread in measured emittance values. The theoretical minimum emittance caused by the axial magnetic field of the ion source at the extraction is also plotted in this graph. The strong axial ion source magnetic field at the extraction induces a beam rotation that leads to emittance growth as described in [10],[8]. There is a good agreement between the measured data and the predicted values. This suggests that the extraction system is well matched to the extracted ion beam current. On the other hand, these measurements differ from previously measured emittance values at the AECR-U ion source [10], in which the emittance decreases for the higher charge states. It may be that the VENUS source tuning is not yet optimized for very high charge state production, in which higher charge states are extracted closer to the beam axis. [8]. With the source is now running at full power, systematic emittance measurements for various charge state distributions and source conditions will be done during the fall of 2003.

IV. Plans for the next year

During the next year, the VENUS development will focus on the commissioning of the source at 28 GHz. The 28 GHz gyrotron is scheduled for delivery in December 2003. Prior to that, the cryostat service tower will be enlarged so that a third 1.5 W cryocooler can be installed. This will provide additional cooling capacity to remove the added bremsstrahlung heating expected with the higher power operation at 28 GHz. The revised system will also enable the use of the 50 K stage of one or two of the cryocoolers to eliminate the need for liquid nitrogen cooling in the future.

The layout of the 28 GHz waveguide is shown in Fig. 6. The 28 GHz high voltage break, which is currently under construction at the Berkeley Lab, is based on an earlier design from the institute for plasma physics, Stuttgart University [11]. To make it more robust, the insulating rings are made from alumina rather than Teflon. The new gyrotron and wave guide components will be tested at CPI in mid September and then integrated with the power supplies and control system prior to delivery.

After the installation of the gyrotron at Berkeley, we plan to begin commissioning VENUS at 28 GHz, first with gases and then with metals. Tests with uranium will follow with the goal of meeting the RIA beam requirement of 240 eμA of U^{29+}. The two axis emittance scanner will be used to measure the beam emittances, which will provide important input data for beam tracking studies for the RIA driver linac.

Table 1. Initial intensities for gases with VENUS operating at 18 GHz. Intensities in eμA.

O^{6+}	O^{7+}	Ar^{11+}	Ar^{12+}	Xe^{20+}	Xe^{27+}	Xe^{30+}	Xe^{31+}	Xe^{32+}	Xe^{33+}
1100	324	290	180	164	84	28	15	9	3

Table 2. Performance of VENUS for bismuth. Intensities in eμA.

Bi^{24+}	Bi^{25+}	Bi^{26+}	Bi^{27+}	Bi^{28+}	Bi^{29+}	Bi^{31+}	Bi^{32+}	Bi^{34+}	Bi^{35+}
97	90	80	71	73	68	57	43	34	12

Figure Captions:

Fig. 1. An elevation view of the VENUS ECR ion source. The source is mounted on a six strut suspension system, which allows easy alignment. The magnet and the cryostat are surrounded by a thick iron yoke to keep the magnetic field contained within the source.

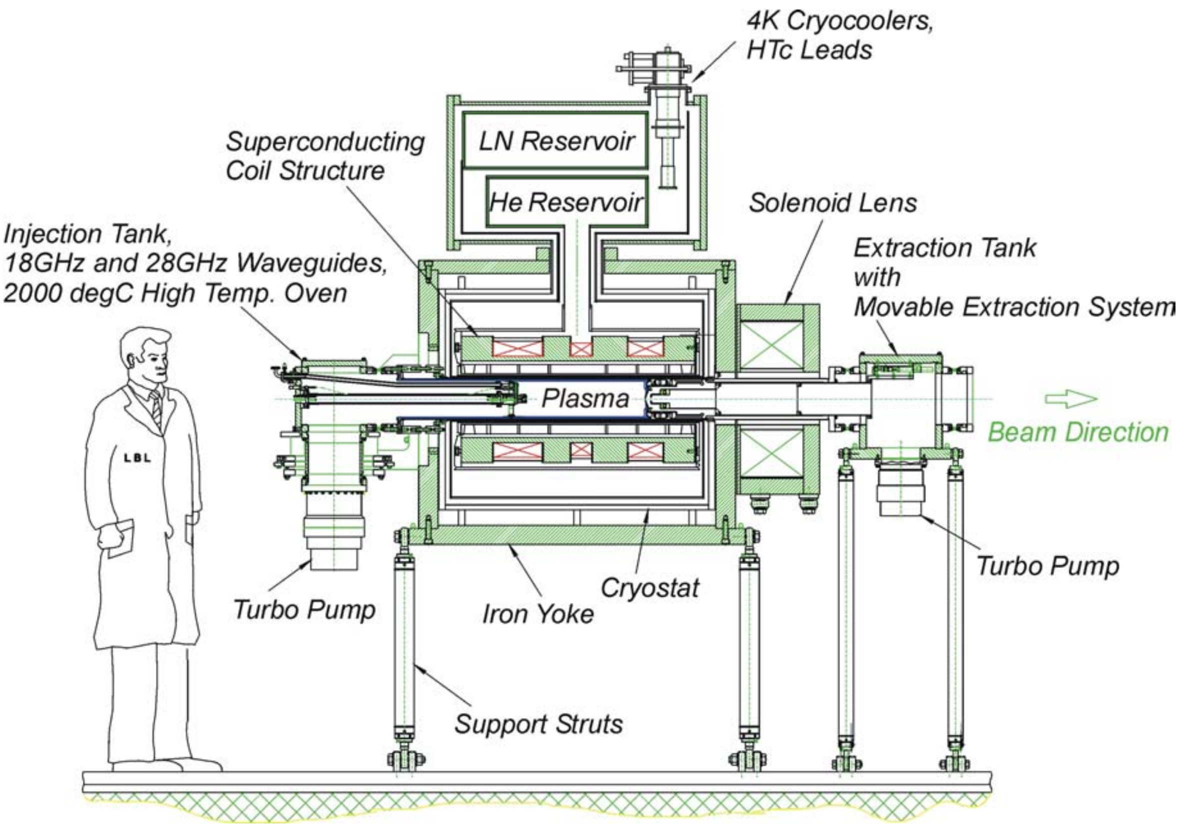
Fig. 2: Mechanical layout of the beam transport system for VENUS.

Fig. 3. The dependence of O^{6+} intensities from VENUS on incident microwave power.

Fig. 4. Charge state distribution for bismuth from VENUS. For this measurement the source was tuned to maximize Bi^{25+}.

Fig. 5. Emittances for various argon charge states. The solid line indicates the theoretical emittance due to the magnetic field.

Fig. 6. Schematic drawing showing the layout of the 28 GHz waveguide system for VENUS.



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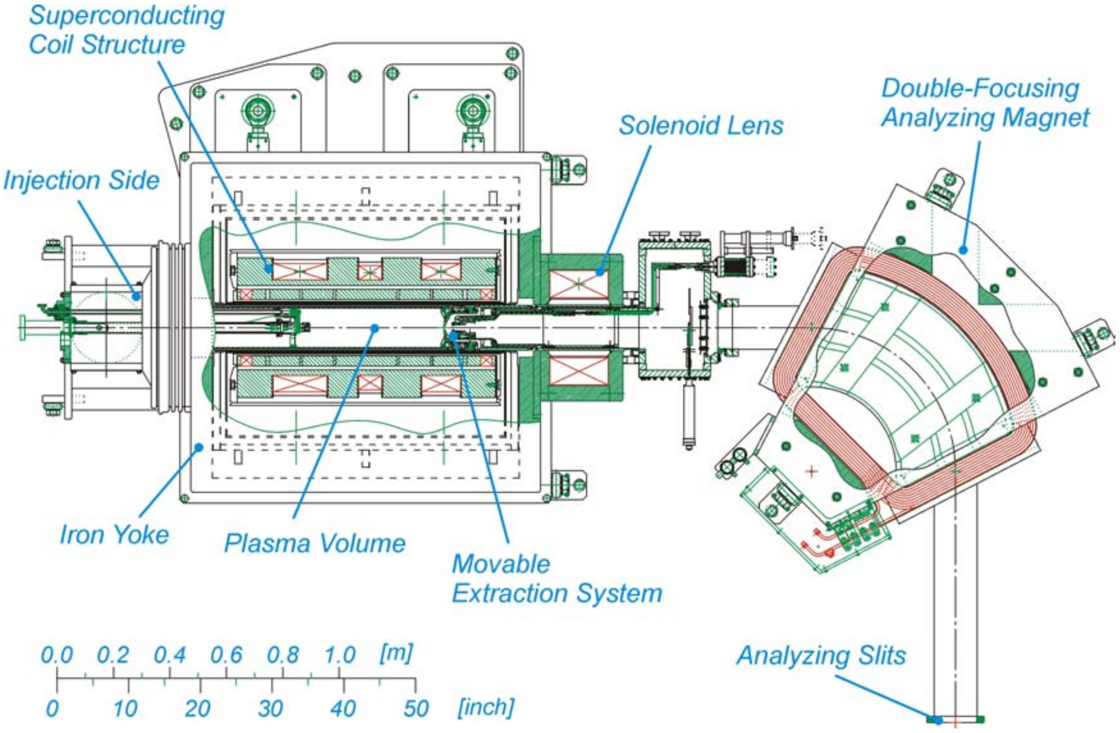

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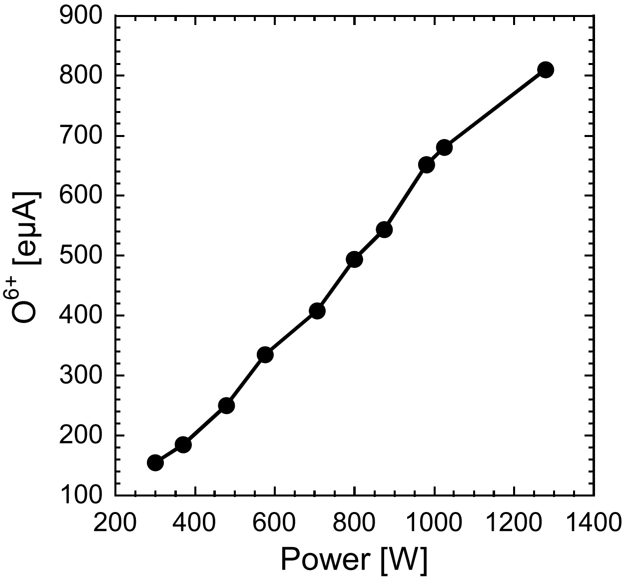

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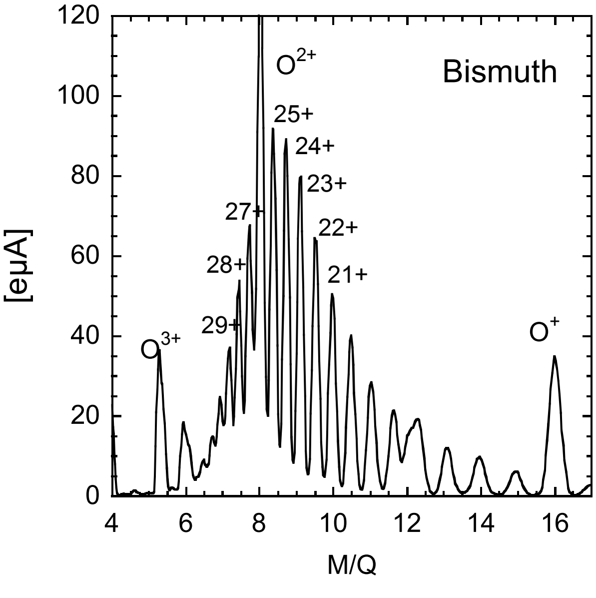

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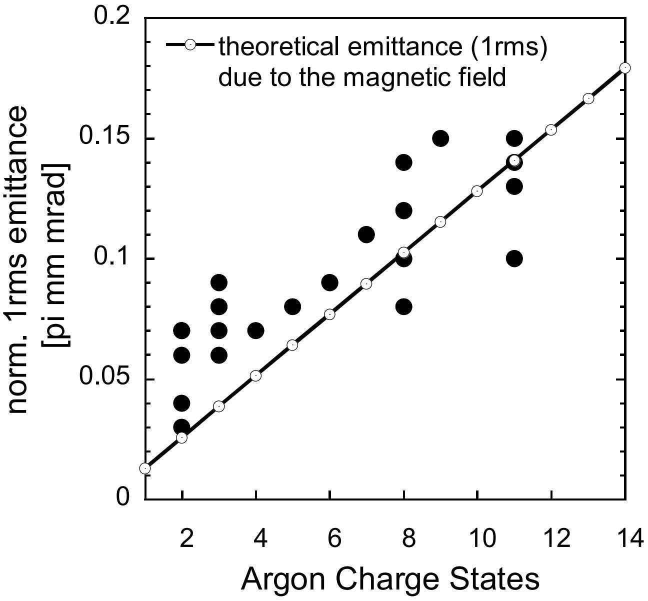

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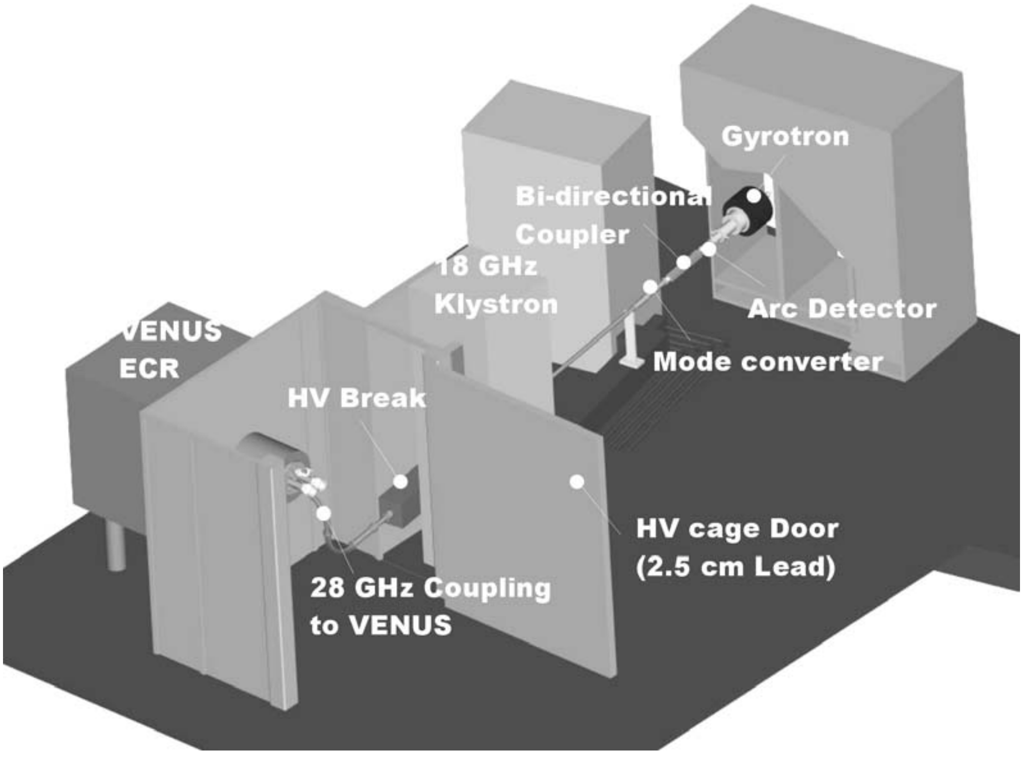

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