FIBER-OPTICAL DEE POSITION MEASUREMENT SYSTEM FOR THE VINCY CYCLOTRON

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A fiber-optical dee position measurement system is developed for the VINCY Cyclotron, the main part of the TESLA Accelerator Installation. The system includes a sensor head, a coherent optical fiber bundle, and a light detector with the control electronics. The sensor head is placed within the dee, and all the electronic components are placed outside the main chamber of the machine, while the information on the position of the dee is carried by the optical fibers. Each dee contains two such systems (two sensor heads), enabling the measurements of movements of the dee-tip in three directions and the twist of the dee with the resolution better than 50 μm. The possible improvements of the operation of the machine based on the information obtained from the dee position measurement systems are discussed

1 Introduction

The effects of misalignment in the central region of cyclotrons have been studied in the early works on AVF cyclotrons [1,2]. The misalignments in horizontal plane cause coherent radial oscillations and increase the phase width of the beam, decreasing the extraction efficiency. Perturbations of the median plane excite the axial oscillations. For a good beam quality, the central region must be carefully aligned axially as well as radially [1]. In modern variable energy multiparticle machines, RF gaps in central region can be as small as 1 cm (for widely used dee-in-valley construction) and vertical beam apertures 2-3 cm (because of the need for high flutter and high magnet efficiency). This makes the alignment in the central region more difficult task than before. The small RF gaps increase also the possibility of sparking in the central region.

The usual sources of misalignment in the central region are fabrication imperfections, and, in case of cantilever stem - dee construction, vertical sag of the dee. These misalignments can be detected and corrected during the assembly of the machine. Other possible sources of imperfections, like the magnetic field, or changes in the dee geometry due to RF heating, can cause misalignments that are detected only by their influence on the beam.

VINCY cyclotron [3] is an isochronous machine with 2m pole diameter, four sectors and two RF cavities of $\lambda/4$ type. The RF system parameters contribute to the possibility of misalignments: the frequency range is 17-31 MHz and the frequency is varied by a sliding short with a 125 cm excursion, leading to dee and stem length of more than 3.7 m. Beam aperture is 22 mm and minimal RF gap in the central region is 10 mm in horizontal and 30 mm in vertical direction. The maximal RF voltage of 100 kV and the minimal edge radius on the dee tip of 6 mm contribute to high sparking probability.

In order to resolve the problems of possible misalignment, we have developed a system for on line measurement of the dee position. It is a laser based distance measuring system, using a coherent optical fiber bundle to carry the diagnostic information out of the cyclotron where all the electronic components of the system are placed. The system measures the dee position in 4 degrees of freedom with a resolution better than 50 μm.

The arguments for a precise dee positioning are more important if a cyclotron works as an injector, when the beam has to be matched precisely [4], or in case of new projects with high beam currents of 1 to 2 mA [5]; at these intensities the axial dimension of the beam in the accelerating region becomes critical due to axial space charge effect [6], and induced radioactivity due to beam loss can become significant. Also, in high beam power RF systems cavity losses can be very high, causing strong temperature gradients in cavity walls, making temperature stability of the cavity very delicate [7].

2 RF cavity misalignments

There are two principal consequences of errors in dee positioning that motivated us to develop the dee position measuring system: the increase in sparking probability due to decrease of RF gaps in central region, and the influences on the beam quality due to errors in central region and accelerating region geometry. The cantilever dee-stem construction of VINCY RF cavities more than 3.7 m long is prone to misalignments expected to be comparable to the gaps in central region. In order to establish the measuring system configuration, we studied the possible sources of errors in dee centering in case of VINCY RF cavities. They are following:

Fabrication errors

All the fabrication errors that could be envisaged do not seem to be out of range of the tuning mechanism.

Thermal stress

When the RF power is dissipated in the walls of the cavity, the differential thermal expansion of the parts of the dee and the stem can cause the elongation of the cantilever structure as well as bending in different directions. The estimated temperature distribution on the dee surface has a maximal difference of $\Delta T=12°C$. The maximal elongation compared to the cold dee is 1.2 mm. The calculations were done with up to date codes (PHOENICS [8] for temperature distribution and CAEDS [9] for stress and strain analysis). However, because of the rather complicated geometry of the problem, the composite bending due to possible asymmetric temperature distribution can not be estimated. There are four possible directions of dee centering errors due to thermal expansion: translation movement of the dee tip in three directions and twisting of the dee around the axis of the stem.

Vibrations

The possible source of dee vibrations is the turbulence in the cooling water of the dee. The maximal estimated temperature difference of $\Delta T=12°C$ corresponds to the nominal cooling water velocity of 1.2 m/s. This gives the Reynolds number of 12000 corresponding to a fully developed turbulent flow. However, the eigenfrequencies of the dee - stem construction are not in the same range as possible induced frequencies, giving the estimation of possible vibrations amplitudes of few μm.

Magnetic forces

Forces induced by the magnetic field can cause vertical displacement of the pole plates thus perturbing the vertical beam aperture and dee-to-antidee alignment. This displacement can be as large as 2.5 mm [10]

The overall misalignment can be hardly calculated, but we estimate them to be comparable to the gaps in central region. While the fabrication errors can be detected during the mounting of the machine, other sources of misalignment could be detected much easier and corrected with use of an on line measuring system. According to four possible directions of dee centering errors due to thermal expansion, the dee support system of the VINCY RF cavities is equipped with a tuning mechanism that can compensate the misalignment of the dee in all three directions as well as the rotation around the the stem axis - the "twist" of the dee. The same reason made us try to develop a measuring system sensitive to the same four degrees of freedom.

3 Measuring system

In a cyclotron, influence of magnetic field, high RF field, high levels of ionizing radiation and high vacuum are limiting factors on use of electronic equipment inside the machine, and impose strong restraints on the materials that can be employed. Photons behave quite differently from electrons because they are not influenced by magnetic and electric fields and they do not require electrically insulated conductive materials for their transport. That makes them ideal for carrying the diagnostic information from inside the cyclotron to any desired distance outside.

It would be very convenient to do the measurement with laser light propagating through free space, but it is very difficult to provide mechanical and directional stability of such a system for high resolution measurement. Therefore it is necessary to carry the optical signal to the place of measurement and the information about the target position back to the optical detector via optical fibers.

Various fiber-optical methods have been evaluated for use in dee position measurement, like optical frequency domain reflectometry, or low-coherence ineterferometry, and the modified optical triangulation method was chosen [11].

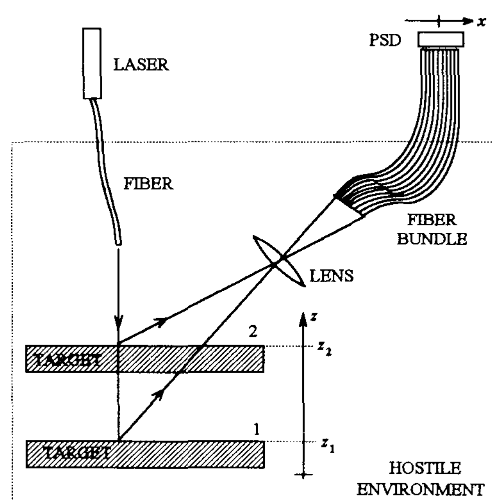

Fig. 1. The modified optical triangulation method.

Basic principle of the modified optical triangulation with diffusely reflecting target is shown in Fig. 1. The light from the laser diode is delivered to the target by a single fiber. With the lens, the image of the light spot on the target is reflected on the input surface of coherent optical fiber bundle. The coherent optical fiber bundle is employed for faithful transmission of the light distribution from the image plane of the lens to the one-dimensional position sensitive detector PSD outside the hostile environment. The change of the target position along the z direction causes the movement of the light spot on the PSD along the x direction.

The PSD output signal can be made independent on the optical flux falling on the PSD and directly proportional to the position of the light spot. The general layout of the position measuring system is presented on Fig. 2. The light beam from the diode laser (LD) is carried to the place of measurement via one optical fiber. The position information is carried to the optical detector (PSD) via a coherent fiber bundle. The electrical signal from the PSD is, after analog to digital conversion (A/D), analyzed by a computer (PC). The laser diode is driven by a power supply in pulse regime to maximize the signal to noise ratio (the signal from the PSD is analyzed synchronically with the laser pulses).

The fiber-optical displacement sensor consists of the optical sensor head, coherent optical bundle, and electronic equipment. The laser diode, PSD detector and all the other electronic components are placed out of the cyclotron and thus not disturbed by electromagnetic field or high radiation. Only the sensor head (with optical fiber bundle) consisting completely of dielectric components is positioned inside the cyclotron. Two sensor heads are incorporated in the surface of each of two dees (Fig. 3).

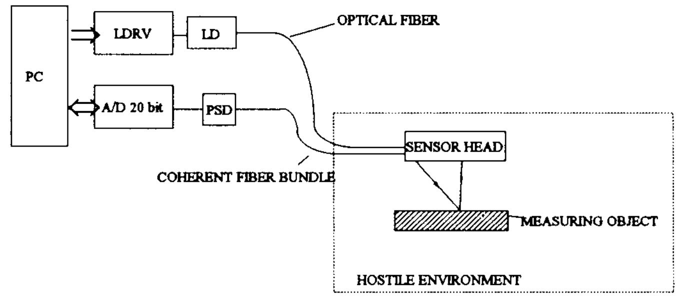

Fig. 2. General arrangement of the two coordinates fiber-optical displacement sensor. (PC - personal computer, LDRV - laser driver, LD - laser diode, PSD - position sensitive detector, A/D 20 bit - converter.)

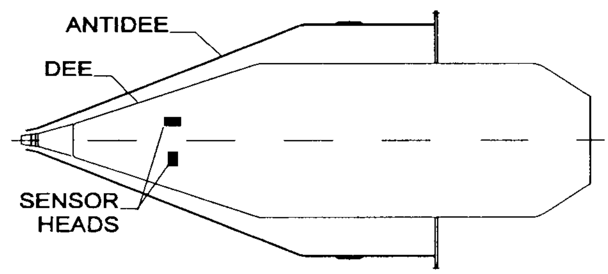

Fig. 3. Sensor heads disposition on the upper surface of the dee.

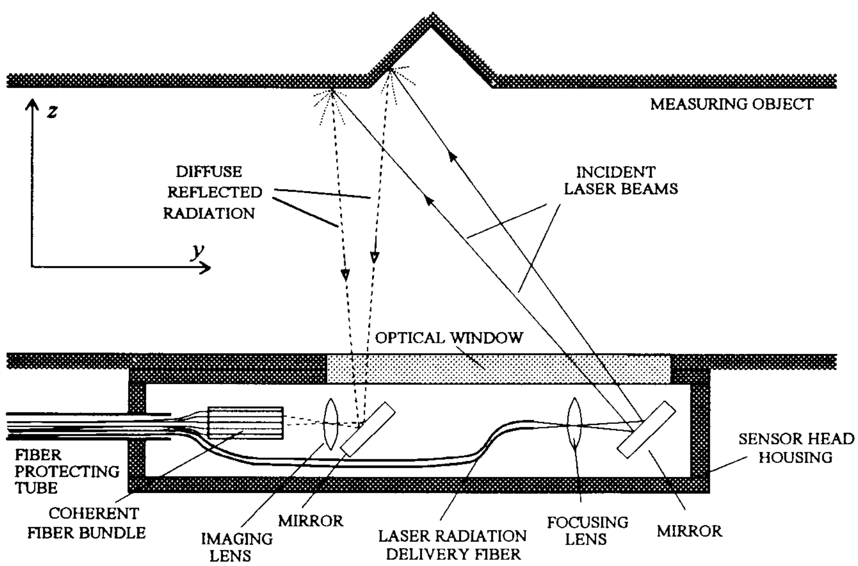

Fig. 4. Optical head design for measuring two orthogonal coordinates z and y.

The sensor head cross section is given on the Fig. 4. The laser beam from incoming fiber is directed to the target, making light spot on its surface. A lens is used to transfer the image of the light spot to the input surface of the optical bundle. One sensor head is used for measuring in two directions, using two fibers for two incoming beams, and only one fiber bundle for the reflected beam (Fig. 4). Both heads measure the dee-to-antidee distance, and the twist of the dee is calculated by combining these two measurements. The positions in two horizontal directions are measured by using the reflection from the sloped surfaces of the channels cut in the antidee surfaces (Fig. 4.). The coherent fiber bundle consists of 35×6 fibers with 100 μm core diameter. Incident laser beam and the scattered light are redirected (between horizontal and vertical direction) using two mirrors to reduce the head thickness to only 10 mm so that it could fit in the space available inside the dee. The range of the measurement is 20 mm.

A sensor head prototype was installed on a model dee plate, and testing of the measuring system on an optical test bench demonstrated a resolution of 10 μm. No construction changes need to be done in fabrication of final four sensor heads. However, the choice of optical components resistive to high radiation doses is only carried out to some extent and needs to be reconsidered. Considering possible deviations due to temperature changes in optical components, we expect, after the final calibration of the measuring system on the cyclotron, to have the measurement repeatability better than 50 μm.

4 Effects on RF system performance

In order to analyze the benefits of the precise dee centering on beam quality, we analyzed the consequences of an off centered dee. The misalignments of the dee can influence the beam both in central and accelerating region. We payed attention to the acceleration region for two reasons: first, sensitivity of the beam to misalignments in central region is already studied in details [1,2]; second, while the beam lost in the central region is at low energy, and decreases only the overall efficiency of the machine, the beam lost closer to the extraction region induces significant radioactivity in cyclotron components.

The effects of dee misalignments were included in a general study of beam dynamics in the acceleration region of the VINCY cyclotron [12]. We studied two principal kinds of dee misalignments in the acceleration region (from radius R=10 cm to extraction): vertical movement of the dee out of the median plane of the machine, the "shift", and rotation of the dee around the stem axis, the "twist". The H^- beam was studied, because it makes a large number of turns in the machine, and because of high level of induced radioactivity in case of beam loss on high energies. Calculations showed that for radii larger than 10 cm, shift of 0.5 mm and twist of 0.5° of the dee could be allowed without essential change of the beam size. If one dee undergoes a 3 mm vertical shift, or a 2° twist, the axial beam envelope increases from 2.5 mm to 8 mm. Both effects contribute to significant increase in beam axial dimension and decrease the beam quality.

Another problem in connection with dee misalignment is the RF sparking. Precise dee positioning can enable the minimization of sparking probability for a given central region. In design of a cyclotron RF cavity, one generally tries to keep the gaps in the central region above the value defined by the Kilpatrick criterion. It determines a threshold below which no sparking should be observed. However, with widely used four sectors and dee in valley construction, horizontal gaps tend to be rather narrow. It often means that one is forced to work with a surface field above the Kilpatrick threshold. This is the case of VINCY cyclotron cavities, where the highest used RF voltage is 100 kV, with the minimal horizontal gap of 10 mm. It is obvious that the sparking rate will be highly dependent on precise dee positioning.

Very few experimental data on sparking exist at all. The sparking rate depends on electrode geometry, RF frequency, vacuum properties, electrode material and surface condition. Still, no formula exists that could, at least roughly, predict the sparking rate for a given case. The VINCY cyclotron cavities with four directions movement of the dee tip and the precise position measurement can be used as a tool for a study of sparking phenomena.

5 Conclusion

The misalignments of the dee can influence the overall efficiency of modern cyclotrons by various mechanisms such as median plane perturbations, beam off centering, irradiation of components by partial beam loss, beam time loss due to sparking, etc. The problems due to misalignment can be avoided using an on line dee position measuring device. Most of the constraints on use of electronic measuring equipment inside the cyclotron, like magnetic field, high RF field, ionizing radiation and high vacuum can be overcome by using a fiber-optical measurement. The fiber-optical dee position measuring system based on modified optical triangulation method for VINCY cyclotron shows to be a good solution for such a measurement. Generally, the fact that electromagnetic fields and other specific conditions inside accelerators do not disturb fiber-optical measuring methods, implies consideration of their use for various measurements in accelerators.

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