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論文内容の要旨

KEKB, B-Factory at KEK, is a double ring collider of 3.5 GeV positrons and 8 GeV electrons. The two rings were named LER (Low Energy Ring) and HER (High Energy Ring) after their energies. They were constructed in the tunnel that was used for TRISTAN. One of the main physics objectives of this facility is the detection of so-called CP-violation, which may give an answer to the question why the amount of matter and anti-matter is not the same.

With regard to the accelerator, KEKB is a very challenging accelerator in the sense that it has to deal with ampere-class current (2.6 A for LER and 1.1 A for HER), which is about two orders of magnitude higher than that of TRISTAN and has never been realized with any machine before. To achieve high current without suffering from single bunch instabilities, the beam will consist of some 5000 bunches, i.e., every RF bucket will be filled with a bunch of several 10^{10} positrons/electrons. In this case, HOM (Higher Order Mode) fields that are excited by a bunch at accelerator components such as RF cavities are likely to affect the following bunches because the decay times of the fields sometimes get longer than the bunch interval, e.g., 2 ns for KEKB.

This situation makes the beams susceptible to coupled bunch instabilities, i.e. intolerable growth of the oscillatory coupled-bunch motions. For the success of KEKB, it is essential to lower HOM impedances so that the threshold currents are higher than the designed currents or they are manageable with bunch-by-bunch feedback system. The most effective way to achieve this is to lower Q's (quality factors) and R/Q's (effective shunt impedances) of most HOM's in RF cavities since RF cavities are normally the main source of HOM's. This can be embodied by so-called HOM-damped structures. At KEK, we use two types of such structures, one is called ARES (Accelerator REsonantly coupled Structure) and the other is SCC (Superconducting Cavity).

ARES is an invention of creative people at KEK. Using a three-cell structure with a big energy-storing cell, it can lower R/Q to 15. Whereas, SCC is inherently suited for high intensity machines such as KEKB since the aperture of the beam pipe can be larger with enough accelerating gradient, i.e., reduced interaction with beam, and by virtue of the high gradient, the number of total cavities can be small and thus total impedance can be reduced as well as the saving of capital costs. Furthermore, at KEK, we can use the refrigerator that was used for TRISTAN, a substantial cost saving. The damped structure for SCC has large beam pipes through which most HOM's go out from the cavity and are absorbed at an absorbing material on the beam pipes. This scheme, however, which puts a microwave absorbing material such as ferrite in the same SCC structure and vacuum, was a new thing and its feasibility had to be proved. Therefore, one of the key components for the success of this scheme was the HOM absorber, which is the subject of this thesis.

The HOM absorber for SCC requires sufficient HOM damping, power handling capability (>5 W/cm^2), UHV (Ultra High Vacuum) compatibility (< ~1×10^{-9} Torr), free of particulates that enter and degrade the cavity, some surface electric conductivity to prevent charge-up and sparks.

Due to good results of preliminary tests on HOM damping, outgassing rate, high availability and short delivery time, we chose to use a microwave-absorbing ferrite IB-004 of TDK, Inc. However, the most difficult part of the development was to bond this material with high integrity to meet above-mentioned requirements. Neither brazing nor soldering of commercial tiles (60 x 60 x 4 mm^3) were successful due to cracking during cooling down from brazing/soldering temperature. Also, we thought of making a cylindrical-shape ferrite, but experts at TDK said that making a thin (~4 mm) cylinder of large diameter (220/300 mm) ferrite would be very difficult and would probably crack. Forming a thin layer with, for example, plasma spraying, would probably result in a very porous surface and incompatible with UHV and free-of-particulate conditions.

The idea, that we demonstrated its usefulness and high potential for more applications, is sinter-bonding of pre-sintered ferrite powder directly onto the inner surface of a copper beam pipe with HIP (Hot Isostatic Press). Having developed proper tooling and optimized the conditions, we succeeded in establishing a technique to make full-size absorbers that meet all the requirements. SEM (Secondary Electron Microscopy) and EDX (Energy Dispersive X-ray) analyses showed high integrity of the bonding, namely, a 90 μm-wide transition region is formed, which consists of a mixture of ferrite and copper. This firm bonding appears to be accomplished by a combination of interlocking and diffusion of copper and ferrite. In addition, acoustic tomography showed highuniformity of the bonding through the entire area.

A 1/3-size (109 mm in ferrite outer diameter) model was first manufactured for various evaluation tests using TM01 mode of 2.45 GHz 5 kW power source. A maximum absorbed power of 3.95 kW (average power density of 8.3 W/cm^2 with a maximum density being 29 W/cm^2) was reached without any problem. In addition, at this experiment, effectiveness of having tapers at the edges to avoid excess heating was confirmed, thereafter 25-mm-long tapers have been machined on both ends.

Then, two sizes of full-size absorbers, 220/300 mm in outer diameter of ferrite, 120/150 mm in length and 4 mm in thickness, were manufactured. A mile-stone experiment, the first beam test, was performed at TRISTAN MR (Main Ring) in 1995. We installed a full-size (300-mm in diameter) absorber at Nikko section of the ring with tapers on both sides and tested its performance. There was no spark, discharge, damage or degradation up to available maximum single bunch current of 4.4 mA or 2.8 x 10^{11} electrons per bunch, which is 20 times that of KEKB-HER.

The second important test was carried out at TRISTAN AR (Accumulation Ring) in 1996. A fully equipped superconducting cavity of KEKB shape was assembled with HOM absorbers attached on upstream and downstream sides, installed in the east tunnel and tested for three periods of time. SCC could store 0.57 A, about half of the design current at KEKB-HER, without any instability due to cavity HOM's, no degradation of cavity performances were observed, and up to a total power of 4.2

kW was absorbed at the absorbers without any problem, which is about 80 % of the power expected at KEKB-HER. After these tests, micro-cracks (<10 μ m, invisible with bare eyes) were accidentally found in the ferrite, but the following intense investigation showed that these cracks were present before these tests and caused by baking. In other words, these tests demonstrated that these cracks do not affect the necessary performance of superconducting cavities.

Finally, total of 8 absorbers were assembled with four KEKB-HER superconducting cavity modules and installed in Nikko D11 tunnel in the summer of 1998. These modules have shown gap voltages of 2.5-3 MV without beams, which is much higher than the design value of 1.5 MV, assuring significant margin for stable operation. Since the commissioning started in December of 1998, the system has been operated very smoothly. As of January 31, 2000, the maximum current achieved so far is 0.51 A, about half of the designed value. All HOM absorbers have been showing similar behavior and the maximum power absorbed so far is about 2.5 kW per module, which is consistent with calculation.

論文の審査結果の要旨

田島　健氏の博士論文の内容は、高エネルギー加速器研究機構（KEK）の B ファクトリー電子加速器用超伝導加速空洞のための高次モード減衰器の開発に関するものである。

B ファクトリーのような大ビーム電流強度のリング型電子加速器開発における大きな問題の一つは、荷電粒子ビームとビームが真空チェンバー内に作るウェーク
フィールドとの相互作用により、ビーム不安定性が発生することである。最大のウェークフィールド源は高周波加速空洞の高次モード電磁場である。このため大ビーム電流用加速空洞にはいわゆる高次モード減衰型空洞が採用され、ビームによって励起された高次モード電力を空洞外に取り出して、ビームへの影響を極力小さくする方策が講じられる。超伝導空洞の場合には、空洞の性能の劣化およびクライオスタットの構造の複雑化を避けるために、高次モードを空洞側面から取り出すことができず、ビームダクト側へ取り出さざるを得ない。このため高次モード減衰器には、真空中でビームに曝される環境下で大きな電力を吸収し、かつ発生した熱を速やかに外部に逃がす機能が要求される。また超伝導空洞の性能を損なわないような低ガス放出特性も要求される。したがって、このような高次モード減衰器を実現することが、超伝導空洞の大強度ビーム電流下での使用を可能にするための必要条件となる。

高次モード減衰器開発における最重点課題は電磁波吸収体中に発生した熱を、いかに効率良く外部に取り出すかである。超伝導空洞から取り出される高次モード電磁波の周波数帯は 0.6 ～ 2.5GHz であり、電力は減衰器 1 台当たり最大 5kW、ビームダクト内径は 300mm である。先ず吸収体としてはマイクロ波領域の電磁波吸収体として実績のあるフェライトに着目し、誘電率・透磁率の周波数特性、電気伝導度、熱伝導度、熱膨張率等の基本的特性の測定に加えて、使用周波数領域での大電力電磁波吸収特性およびガス放出特性を測定し、超伝導空洞の高次モード吸収体としての使用に適することを確かめた。次の段階はフェライトを熱伝導の良い銅円筒ビームダクトの内側にどのようにして接合させるかであるが、この問題が高次モード減衰器開発における最大の難関であった。

鑞付け等による接合実験を行っていた時に、申請者は熱間静水圧プレス（Hot Isostatic Press, HIP）法を用いて、仮焼成した粉末状フェライトから高密度焼結体フェライトを作製する過程の中でフェライトを銅円筒内面に拡散接合するという着想を得た。この方法による高次モード減衰器の開発段階で、カプセルの真空漏れ、フェライトの割れ、層状裂け、空隙の発生等の様々な問題に遭遇した。これらの問題を HIP 条件（温度、圧力とその時間変化）の最適化、製作工程の改良、治具の改良等により一つ一つ解決していき、内径 300mm の銅円筒の内面に厚さ 4mm、長さ 150mm の高密度のフェライト焼結体を拡散接合することに成功した。出来上がった高次モード減衰器について電磁波吸収率の周波数特性、大電力電磁波吸収特性、ガス放出特性等の測定を行い、超伝導空洞用高次モード減衰器として十分な性能を有していることを確認した。その後、減衰器単体のビームテスト、超伝導空洞と組み合わせたビームテストを経て、現在 KEKB ファクトリーの 8GeV 電子リングに計 8 台の高次モード減衰器が使用され、期待通りの性能を発揮し安定に動作している。

以上のように本研究は、大電力高次モード減衰器で従来困難とされていた電磁波吸収体と銅円筒との接合の問題を、既に焼結されたフェライトと銅を接合する方法ではなく、熱

間静水圧プレスによるフェライトの焼結過程の中でフェライトと銅との接合をも同時に完了させてしまうという極めて巧妙な方法により見事解決したものであり、今後の加速器用高次モード減衰器の大電力化への道を拓いたものと高く評価できる。また、この方法は加速器以外にも応用が可能であり、セラミックと金属との接合体作製の分野に新たな知見を加えたものと評価できる。よって本審査委員会は、本論文が博士学位論文として十分な水準にあり、また本専攻に相応しい内容を持つものであると判定した。