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论文内容の要旨

Higher-Order-Mode (HOM) damped accelerating cavity structures play a significant role in high-luminosity electron-positron colliders such as the B-meson factories of KEKB and PEP-II operated with beam currents over 1 A. The coupled-bunch beam instabilities driven by long-lived higher order modes trapped in cavity structures should be suppressed first in order to raise the stored current limit. Various types of HOM-damped cavity structures have been proposed so far to boost the collider performance toward the luminosity frontier.

This thesis describes a series of studies on a HOM damping scheme with "grooved beam pipe" structures, from its original concept started with breaking the cylindrical symmetry of "single mode cavity" well known as the oldest HOM damping scheme in 1980's, through computer-aided analysis on its RF properties followed by benchmark experiments, finally to its application to the normal-conducting RF cavity system developed and successfully operated for KEKB. The essence of the grooved beam pipe scheme is to selectively lower the cutoff frequency of the TE11 mode propagating through the circular beam pipe below the lowest TM110-like dipole mode of the accelerating cavity by grooving the inner wall of the beam pipe. Moreover, this scheme could be more suitably applied to super-conducting (SC) cavities because waveguide apertures or ports dedicated to HOM damping are not allowed usually in the SC accelerating cell to avoid quenching under high accelerating gradients.

The contents of the thesis are as follows:

Chapter 2 starts with a cylindrically symmetric "single mode cavity", briefly reviewed with a problem related to the lowest dipole mode still trapped in the cavity. Then, the idea of "grooved beam pipe" of non-cylindrical symmetry is introduced in order to damp the last HOM by selectively lowering the cutoff frequency of the TE11 mode propagating in the original circular beam pipe. Next, the HOM damping with a grooved beam pipe structure are analyzed with use of a three-dimensional (3D) electromagnetic simulation code. The analysis procedure is generally based on Slater's "tuning curve method" for waveguide-loaded cavities. Also, the effect of the grooved beam pipe on the accelerating mode is investigated. That is because HOM damping is usually accompanied with some degradation in the Q value of the accelerating mode. The latter part of Chapter 2 describes the experiments with 20%-scale model cavities, as the benchmark for further R&D, and compares those results with the above 3D simulation results.

Chapter 3 describes the application of the "grooved beam pipe" method to the normal conducting (NC) RF cavity system developed for KEKB, which is a high-luminosity electron-positron collider with unequal beam energies, consisting of the High Energy Ring (HER) for the 8-GeV electron beam and the Low Energy Ring (LER) for the3.5-GeV positron beam. The luminosity goal for KEKB is set at $1\times10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$, which is very challenging, in order to produce very large sample of B mesons for an exhaustive study of CP violation in the B meson system. In addition to the HOM-related instability problems mentioned before, the operation of NC cavities under heavy beam loading conditions would give rise to another serious problem. That is the longitudinal coupled instabilities driven by the accelerating mode itself, whose resonant frequency is usually detuned toward the lower side from the RF frequency in order to compensate for the reactive component of the beam-induced cavity voltage. When this detuning becomes comparable to the beam revolution frequency or larger, violent longitudinal coupled-bunch instabilities would be unavoidable. Needless to say, we are not allowed to damp the accelerating mode like the HOMs. In order to solve this problem, a three-cavity system operated in the $\pi/2$ mode has been developed for KEKB, in which an accelerating cavity is resonantly coupled with an energy storage cavity via a coupling cavity between. The storage cavity is used in order to reduce the detuning by increasing the ratio of the electromagnetic stored energy of the accelerating mode to the beam loading. Moreover, the coupling cavity is equipped with a parasitic mode damper against the 0 and π modes emerging at both side of the $\pi/2$ mode. This coupled cavity system was later named ARES, which is the acronym for Accelerator Resonantly coupled with Energy Storage. Needless to say, the accelerating cavity itself of this ARES system must be a HOM-damped cavity, too. Furthermore, the HOM-damped structure needs to be fairly compatible with the ARES scheme. That is an inevitable structural boundary condition, i.e. two coupling apertures at both sides of the accelerating cavity: one toward the coupling cavity, and the other toward a half-cell coupling cavity for the $\pi/2$ mode termination keeping the accelerating field symmetrical with respect to the vertical mid plane including the beam axis. In a similar way in case of SC cavities mentioned before, the grooved beam pipe scheme could be applied to HOM damping of the ARES system to meet this boundary condition. The HOM-damped structure actually developed for the ARES system is as follows. Four straight rectangular waveguides are brazed directly to the upper and lower sides of the accelerating cell for damping the monopole HOMs, and the dipole HOMs deflecting the beam in the vertical direction. The HOM power extracted from the cavity is guided through each straight waveguide in the vertical direction, and through an E-bend waveguide in the horizontal direction, finally to the end with two bullet-shape sintered SiC ceramic absorbers. Moreover, for damping the dipole HOMs deflecting the beam in the horizontal direction, two grooved beam pipes are attached to both end plates of the accelerating cell. This grooved beam pipe structure is of twofold symmetry, where two grooves at the upper and lower sides of the original circular pipe with an inside diameter of 150 mm. In each groove, eight SiC ceramic tiles are arranged in a line, where the extracted HOM power is dissipated.

Chapter 4 describes the performance of the ARES cavity, focusing on its HOM damping properties and comparing the HOM power dissipation data with theoretical predictions. In December 1998, the commissioning of the HER of KEKB was first started with 6 ARES cavities and 4 superconducting cavities, and followed by the commissioning of the LER with 12 ARES cavities in January 1999. In the summer shutdown of 1999, the number of ARES cavities in the LER was increased from 12 to 16, and in the HER from 6 to 10. The beam currents of both rings were increased stepwise: overcoming many difficulties, for example, with movable mask devices; and improving the machine performance, for example, with solenoid windings in the LER in order to suppress photo-electron clouds causing a blowup of the beam size. As a whole, the ARES cavities armed with the "grooved beam pipe" structures have performed well as expected, stably supporting the beam currents up to 1400mA in the LER and up to 900mA n the HER. Troubles and accidents, which we have encountered so far, could be roughly categorized into two groups: infancy problems especially with accessory devices emerging in a long term operation, and cavity problems attributed to quality control issues usually incompatible with the stringent cost goals in the production phase. Focusing on the HOM damping performance, we have not encountered any troubles or coupled-bunch instabilities so far. In addition, fortunately, the HOM loads currently used for the ARES cavity have ample margins for higher beam currents. These facts lead us to conclude that the ARES cavity system armed with the grooved beam pipes has been successfully demonstrated, and is expected, with its growth potential, to boost KEKB toward the high luminosity frontier beyond $1 \times 10^{34} cm^{-2}s^{-1}$.

In the last chapter, other "grooved beam pipe" applications are discussed, together with an example of HOM-damped SC cavity with a grooved beam pipe of fourfold symmetry developed for the Cornell B-Factory. In addition, a conceptual design of upgrading the grooved beam pipe structure, including HOM absorbers, for a future project following KEKB is discussed.

論文の審査結果の要旨

影山達也氏の博士論文は、高エネルギー加速器研究機構のBファクトリー電子・陽電子非対称衝突リングのための常伝導加速空洞(ARES空洞)の設計、開発、実用化研究についてまとめたものである。研究の主題は、Bファクトリーのような大電流を貯蔵する高エネルギーリングの加速空洞において加速モード以外の、ビーム不安定性をもたらす全ての高調波モードの新しい減衰法についてでである。

この研究において申請者の独創になる業績の中心は、溝つきビームパイプ(grooved beam pipe:以下ではGBPと略称)による空洞高調波モードの有効な減衰法の提案と、それをBファクトリーのARES空洞に応用し、所期の成果を収めた点である。 その結果、高エネルギー加速器研究機構のBファクトリーリングは1アンペアから1.5アンペアの高エネルギービームを安定に貯蔵し、世界最高のルミノシティを達成している。

大電流貯蔵リングではビーム不安定性を引起す高調波モードの減衰が重要な課題で、20年来さまざまな提案がなされてきたが、なかでも1983年のT. Weilandの単モード空洞が有名である。これは空洞両側のビームパイプを拡幅することで減衰を達成しようとすものであるが、加速モード自身のQ値劣化も避けられないという欠点があった。申請者はGBPを利用すれば、加速モードと高調波モードの対称性の違いからWeilandの単モード空洞の欠点が解決されることを見いだし、精密な電磁場シミュレーションとテスト空洞実験によってそれを実証した。なおこの過程では極めて低いQ値の正確な同定が極めて重要な課題であるが、Slaterの同調曲線理論を応用し見事に成功したことも申請者の特筆すべき業績の一つである。さらにGBP法ではSiC吸収体がバンチのウェーク場から良く遮へいされているという利点を持っていることも申請者は見通している。これは大電流リングに広く応用されうる可能性を有し、今後の発展が期待される技術である。

さてKEKB空洞へのGBPの応用は単純、容易ではなく、申請者による様々な高周波工学的工夫のうえに完成されたものである。その要因の一つは、加速モードへの大電流ビーム・ローディングによる不安定性を抑止するために、エネルギー貯蔵空洞と結合空洞を含む3セル90度進相モード構造が必要条件となったことである。その結果、GBPは水平偏向モードの減衰に、垂直偏向モードと単極HOMの減衰には導波管という複合減衰構造を採用せざるを得なかった。また結合空洞による加速モードの円筒対称生の破れによる双極子成分発生を防ぐ工夫も行わなければならなかった。 HOM電力の吸収体としてSiCロッドを使うが、時間位相面でのシミュレーションによるHOM電力吸収率の正確な評価、その高周波整合性、あるいはその金属基盤への良好な接合と冷却という困難な工学上の問題も解決しなければならなかった。

このような設計に基づいて製作された最初の予備空洞をトリスタンARリングに設置し、ビーム試験をおこなった。そこでは(1)複合減衰構造型3セル空洞で、大電流ビーム・ローディングのもとでも加速モードが高周波シミュレーションどおり十分に安定できているか、 (2)可動チューナー、入力カプラー、 SiC吸収体など実用空洞に不可欠な付属装置が高周波的に問題がないか、 (3)単バンチビームによるHOMスペクトル及び電力の測定、などの基本的問題のチェックを行った。その結果、ほぼ予想通りの性能が達成されていることを確認した。特に重要なのは、バンチ長に依存した損失係数を空洞自身、GBP

に分けて MAFIA-3T や ABCI 等の先進的な電磁界コードで評価し実測との整合性を確かめたことである。このような周到な準備研究をへて、計36台に及ぶ ARES 空洞量産に順調に移ることができた。

Bファクトリーリングに設置されたそれらの空洞は、極めて安定な運転性能を示しているが、申請者の主導のもとに精密な動作特性が数年にわたり測定されている。特に、各空洞間の HOM 電力のばらつきが少なく、電流値が800 mAから 1300 mA の範囲でシミュレーションを良く再現していることは申請者の優れた総合設計によるものと確言できる。

申請者が完成したこれらの ARES 減衰空洞は、LEP 用エネルギー貯蔵空洞の発明者で高周波空洞技術の世界的権威者である CERN のW. Schnell博士に毎年の評価委員会で高く評価されており、KEKが産出した加速器科学への世界に誇れる貢献の一つと云える。審査委員会では、申請者の独創的かつ世界最高性能の空洞を完成させた仕事をまとめた本論文について、全員一致で学位授与に相応しいと判定した。