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論文内容の要旨

Summary of thesis contents

Introduction

Many new projects dealing with new light sources are dedicated to Energy Recovery Linac (ERL) scheme. Research teams dealing with this technology are based in United States at Cornell University, Jefferson Laboratory and Brookhaven Laboratory, in Europe at Helmholtz Center in Berlin (BERLinPro) and in Japan at KEK.

At KEK, the project is divided in two phases:

- the first phase is the development of a prototype type device, relatively small (around 300 m circumference) and being a compact version of the ERL (c-ERL) to prove, develop and test the technology required for this kind of particle accelerator,
- the second phase is the building of the actual device that will be larger (around 3 km circumference) and will allow many user front ends in order to exploit the unique properties of the light produced by the this machine.

In order to prove, understand and develop the technology needed for such particle accelerators, a compact model (c-ERL) was designed. The c-ERL is composed of different parts and thus, all the particle accelerator components can be tested and improved. In the c-ERL, the main linac is equipped with two L-band superconducting cavities. The design of the cavities took into account all the ERL machine requirements. Thus, during the optimization of an L-band cavity, the shape was modified to allow a CW operation with 100mA current and strong higher order modes (HOMs) damping avoiding beam break-up (BBU).

Motivation

Due to the cavity design requirements and CW operation field emission can be a severe limiting factor for ERL cavity performance.

In order to address this problem a research program is ongoing, it can be divided in three broad areas:

1. Detection: in order to measure the field emission effects during cavity operation (x-ray production, Q-E curve slope, quenches and bursts)
2. Simulation and calculation: Is carried out by means of simulation codes and algorithm to achieve a deeper understanding of the phenomena related to field emission process, in order to explain the experimental results
3. Possible solutions: once the experimental and analytical tools have proved their reliability they can be used to investigate different cavity shapes in order to find the optimum solution with respect to field emission phenomena

One of the main concerns while designing the cavity was the ratio between the Electric Field on the surface and the Accelerating Field. Indeed, while in the original TESLA-type cavity the maximum of this ratio (Epeak/Eacc) reaches 1.98, in the ERL type the Epeak/Eacc reaches 3.0.

In a broader frame field emission can be a limiting factor not only for CW operating machine, but also for high gradient ones operating in pulsed mode, like the International Linear Collider (ILC). Due to the wide spreading of this issue there is strong motivation to achieve a better knowledge about field emission effect inside superconductive cavities, in order to understand the complex relation between cavity geometry, operating conditions and field emission effect.

Field emission can be one of the major limiting factor in the cavity performance. In fact, the emitted electrons can increase the cavity loss and cryogenic load and also generate dark current, increasing the radiation dose suffered by components up-stream and down-stream with respect to the cavity.

Trying to summarize in one list the issues connected to field emission they can be:

- Quenches
- Q drop
- Cryogenic losses increase
- Dark current
- Radiation dose increase

Since the development of first single cell cavity, a large effort has been put to detect field emitted electrons moving inside the cavity. Thus, a special system was designed in order to detect x-ray produced by electrons impacting on the cavity surface. This system consists of a set of PIN diodes that are placed around the cavity surface and that can turn around it. This setup gives a detailed image (0.5° resolution) of the x-ray profile.

The same principle was used to design a detection system for the 9-cell structures, capable to detect x-ray during vertical tests operation (rotating mapping system). The images obtained from the sensors are like a map showing x-ray “hot spot”, allowing online and offline data analysis in order to provide valuable information on field emission events.

<u>State of the art</u>

Field emission effect is well known since the beginning of the last century and it was well explained by quantum mechanics theory in 1928 by Fowler and Nordheim. Field emission was recognized as one of the limiting factor along with multipacting and quenches in the path towards high gradient in RF cavities.

Mainly all the studies performed about field emission in RF cavities dealt with the heat effect produced by the emitter because a typical vertical test set up was equipped with temperature sensor in order to spot quenches location. With recent improvement in cavity preparation surface defects that generate quenches will become less and less common, field emission effect could be the next challenge to overcome.

Among these studies few analyze field emission in multi-cell RF cavities and none of them investigate the x-ray produced by emitted electrons incident to the cavity surface, neither gives a systematic approach to understand the complex relation between field emission, cavity geometry and operating condition.

Findings and Conclusions

Through the combination of a rotating mapping system and x-ray detector it is possible to collect precious information about field emitted electrons, and such detailed x-ray data are the valuable tool for understanding the field emission behavior in superconducting cavities.

Aside the greater resolution and sensitivity of x-ray detection, in comparison to a conventional temperature mapping, x-ray detection is able to gather information from cavity region usually not accessible for temperature sensors like cavity iris. The iris, as is shown in the dissertation, have a pivotal role for field emission in RF cavities, their geometry and local surface electric field can strongly influence the cavity performance with respect to field emission phenomena.

Data analysis coming from vertical tests and high power test allow to shed light on the complex relation between cavity geometry, their operating condition and field emission effect. Through a comparison between experimental data and simulation it was possible to determine a possible emitter location for each test. The x-ray detection system installed on the c-ERL main linac cryomodule will allow to observe continuously the radiation pattern produced by field emitted electrons and detect changes in the emitter location.

Through a systematic study it was possible to derive some general aspect about field emission with respect to different cavity geometry in order to achieve a deeper understanding and possibly do some step towards its reduction or elimination. In particular it was developed a method to analyze different cavity geometry with respect to field emission process, this method can be used to evaluate new geometry performance and their behaviour under field emitted electrons loading.

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博士論文の審査結果の要旨

Summary of the results of the doctoral thesis screening

Enrico CENNI 氏の論文には、超伝導空洞内の電界電子放出の振る舞いについて、空洞内電子軌道のシミュレーションから解析が行なわれ、空洞縦測定での PIN ダイオードを用いた X 線マッピング装置から得られた実験結果を対応させることによって、電界放出電子の放出源の場所を特定できることが示されている。さらに、モジュールに組み込まれた空洞の大電力試験においても、PIN ダイオードおよび X 線計測器を駆使した測定結果と放射線シミュレーションから電界放出電子の軌道を解析することによって、空洞性能の劣化を引き起こした電界放出電子の放出源の場所を推定することが可能であることが示されている。したがって、本論文は、X 線計測の実験結果とシミュレーションの両面から空洞内の電界放出電子の運動を説明できる手法の確立として、要約される。

エネルギー回収型リニアック（ERL）などの高周波加速には高電界の連続波（CW）運転が必要であり、そのために超伝導空洞が用いられる。一方、超伝導空洞の高電界運転では空洞表面の電界放出電子が空洞内の電界により加速され内壁に衝突することによって、付加的な電力損失や強い放射線の発生、暗電流などの現象が発生し、特に CW 運転では性能を著しく制限することが知られている。本論文において Enrico CENNI 氏は、高ネルギー加速器研究機構で開発が進められている ERL の実証器(コンパクト ERL)に設置される 9 連型 1.3GHz の超伝導高周波空洞について、まず低温性能試験において空洞外面で検出される X 線を観測した。次いで、電界放出電子の空洞内の運動を詳細に計算し、観測結果と突き合わせることによって、電子の動きだけでなくその放出源の位置や飛び出る時の高周波位相と、加速された電子の到達点やその時のエネルギーなどに相関があることを突き止めた。さらに、放出電子密度を導入して、空洞性能に大きく影響する危険な放出源領域がアイリス部分に存在することを示した。クライオスタットへ装着後の大電力性能試験においては、空洞に PIN ダイオードを取付け、発生する X 線分布を観測し、空洞単体での性能試験とは異なる X 線分布や放出源の位置を示す測定結果によって、電子放出源の原因が組立工程に起因することを示唆した。また、同時に NaI(Tl)結晶を用いてクライオスタット外部から加速電界をパラメーターとした電界放出電子のエネルギー分布を計測し、EGS5 を用いた放射線シミュレーションと対応させて電子放出源の位置を推定できることを示した。本論文で示された一連の新しい解析手法は、超伝導空洞の性能向上に向けた電界放出電子に関する信頼できる診断方法として、今後有効に用いられることが大いに期待される。

以上のことにより、本審査委員会は全員一致で、Enrico CENNI 氏の論文は博士論文として十分な内容であり、合格と判断する。