Article ID: 1007-4627(2014) 03-0385-06

Study on Thermal Shock Damage to Injector II of China ADS Project

HE Shoubo[1,2], HE Yuan[1], WANG Zhijun[1], YANG Yangyang[1], ZHANG Shenghu[1], ZHAO Hongwei[1]

(*1. Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou 730000, China;*
2. University of Chinese Academy of Sciences, Beijing 100049, China)

Abstract: Because of injecting an out-of-control beam pulse, thermal shock damage to the accelerator may well cause a failure of focusing and steering elements. In order to prevent RFQ accelerator, superconducting cavities and other accelerator components from thermal damage, it is essential to conduct a quantitative evaluation of the thermal stresses induced in the material during the thermal shock. The present study in this paper proposed a novel method to evaluate the thermal stresses quantitatively, which can clarify the characteristics of thermal shock of several materials, such as OFHC, SUS304 and Niobium. Transitional thermal stress is investigated by three dimensional finite element method (FEM) to obtain the temperature distribution for three materials at the beam incident angle of 90°. Finally the simulation results prove that the machine protect system response time meets the requirement when the allowable injection time is defined as 20 μs.

Key words: thermal shock damage; allowable injection time; thermal stress; finite element method

CLC number: TL53; TL503.1 **Document code:** A **DOI:** 10.11804/NuclPhysRev.31.03.385

1 Introduction

The China Accelerator Driven Subcritical System (C-ADS) project is being developed by Chinese Academy of Sciences (CAS). Recently the injector II of C-ADS is being designed and built in Institute of Modern Physics (IMP), CAS[1]. The accelerator of injector II will be operating at the frequency of 162.5 MHz with continuous wave (CW) mode. Because the beam intensity is quite high, the out-of-control beam will lead to considerably permanent damage to the accelerator due to the thermal shock damage. To protect the linac against beam trips, a machine protect system (MPS) has been developed in several projects. For instance, it is used to shut down the beam pulse before the permanent damage in the Japan Proton Accelerator Research Complex (J-PARC) project[2]. In Spallation Neutron Source (SNS) project of Oak Ridge National Laboratory (ORNL), which is operating at pulsed wave mode, the time to reach thermal shock damage for a copper accelerating structure was evaluated[3−4].

Thermal shock is a transient process that a potentially catastrophic stress in a material from sudden extreme changes in temperature[5]. Thermal shock damage caused by the particle beam is an important issue in a high intensity linac. It is fairly significant to evaluate the allowing injection time to determine the MPS specifications. As an conventional method, quench tests[6−7] were used to evaluate the thermal shock resistance of materials. The quench test has the advantage of being easily conducted everywhere but the disadvantage of an absence of physical meaning in the parameter: critical temperature δT. Using three dimensional finite element method(FEM), it is convenient to clarify the

Received date: 18 Sep. 2013; **Revised date:** 9 Nov. 2013
Foundation item: National Natural Science Foundation of China (11221064, 91026001)
Biography: He Shoubo (1985–), male, Qingdao, Shandong, Ph.D, engaged in multi-physics analysis for CADS project; E-mail: heshb@impcas.ac.cn

characteristics of thermal shock of several materials. In this paper, the simulation results of thermal shock damage analysis for each section in Injector II are presented. During the thermal shock damage simulations, allowable injection time is obtained when the maximum thermal stress attains the material yield stress[8]. The yield stress is also a strict limitation which prevents the accelerator element from permanent damage.

2 Brief introduction to Injector II

With the long-term planning lasting until 2032, the ADS driver linac is defined to be 1.5 GeV in energy, 10 mA in current and in CW operation mode. For the first phase, the project goal is to build a CW proton linac of 50 MeV and 10 mA by about 2015, including an injector II of 10 MeV in energy[9]. Injector II is composed of an ECR ion source, Low Energy Beam Transport (LEBT), Radio Frequency Quadruple (RFQ) and superconducting accelerating section. In the RFQ section it will deliver the proton beam from 35 keV to 2.1 MeV. As following MEBT will match beam from output of RFQ to the injection of superconducting accelerating section. Finally in superconducting accelerating section, there are two cryomodules, in which eight superconducting (SC) half-wave resonator (HWR) cavities and nine SC solenoids are involved. The proton beam will be accelerated from 2.1 to 10 MeV. The layout of the Injector II is shown in Fig. 1. The major material and beam parameters in each section of Injector II are listed in Table 1.

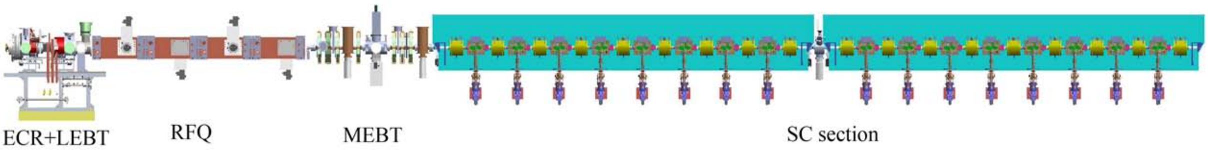

Fig. 1 (color online) The layout of the CC-ADS Injector-II.

Table 1 The major beam parameters and material in Injector II*.

Section	Particle	Input energy /MeV	Output energy /MeV	Operation mode	Beam current /mA	$R_{\min}$/mm[1)]	Major material
LEBT	proton	0.035	0.035	CW	15.0	2.5	SUS304[2)]
RFQ	proton	0.035	2.1	CW	10.0	0.25	OFHC[3)]
MEBT	proton	2.1	2.1	CW	10.0	1.3	SUS304
SC section	proton	2.1	10.0	CW	10.0	1.7	Niobium

* 1) $R_{\min}$ is the minimum root mean square (rms) beam radius in every part. 2) SUS304 stands for the austenitic stainless steel with AISI type 304. 3) Oxygen-Free High Conductivity Copper (OFHC) is an alloy containing a minimum of 99.99% copper.

3 Analysis process of thermal shock damage

In traditional method, the allowable injection time was fixed to prevent the temperature rise from going above the melting point of material. However, when the thermal stress is larger than the yield stress, it also will result in the permanent damage to the material. All what is discussed above means a more rigorous evaluation should be needed, which is presented in the following section.

3.1 Physics model

When the proton beam energy is absorbed in the material, the thermal expansion of material is confined to a very small volume. And if the proton incident energy is extremely high, the proton range in material is much larger than the beam radius. A simple evaluation method mentioned in the application to J-PARC project[2] can be used to estimate the allowable injection time. In terms of lower than 10 MeV for proton beam incident energy, the proton range in main material, which are given in Fig. 2, is much smaller than the beam radius. It is worth pointing out that the method used in calculation before[2] is not suitable for the diffusion and then the thermal stress cannot be disregarded in beam direction. So it is necessary to analyze thermal shock damage using 3-D FEM.

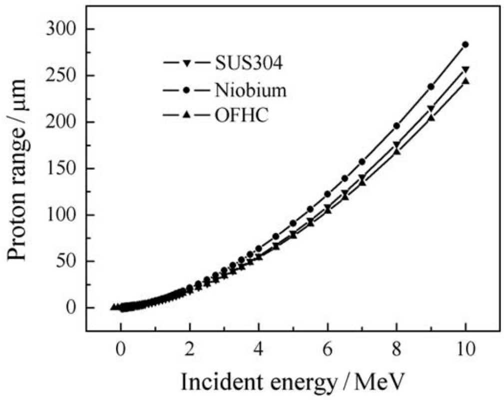

Fig. 2 Proton range as a function of the incident energy E_0 in different materials.

First there are some assumptions as follows for the injection proton beam:

(1) The proton beam is injected into the materials perpendicularly. It could be rare for a beam hit a surface at 90°, unless intentionally on a target. However, if the scattering and reflecting of particles are ignored when beam hits a surface at a large grazing angle, so the relationship between incident angle and damage time is weak. So the assumption of perpendicular to materials for the beam is appropriate when the safest allowable injection time is calculated rigorously.

(2) The current density distribution of beam is approximated by a Gaussian distribution:

$$\rho(x,y) = \frac{I_0}{2\pi\sigma_x\sigma_y}\exp(-\frac{x^2}{2\sigma_x^2} - \frac{y^2}{2\sigma_y^2}) \ . \qquad (1)$$

In the above equation, I_0 means peck current, σ_x is the beam rms size in x direction and σ_y represents beam rms size in y direction. The allowable injection time δt is the time when the thermal stress from beam heating exceeded the yield stress. The heat generation is shown in Eq. (2):

$$q = \frac{I_0 \times R_{\max}(E_0)}{2\pi\sigma_x\sigma_y}\rho \ , \qquad (2)$$

where $R_{\max}(E_0)$ is the maximum stopping power at certain incident energy, ρ means the mass density of material. The stopping power of the incident energy for proton beam, which is calculated by Monte-Carlo algorithm, is simulated with the code Stopping and Range of Ions in the Matter (SRIM)[10]. The maximum stopping power as a function of the incident energy for proton beam in different material is plotted in Fig. 3. And in accordance, the stopping power at different incident energy is easily available for three kinds of materials respectively.

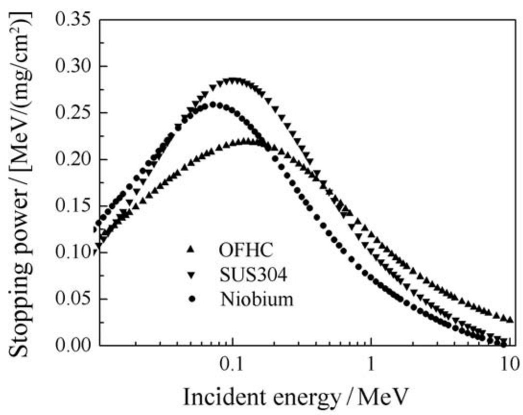

Fig. 3 The relationship between stopping power and incident energy E_0 for three materials.

3.2 Thermal-mechanical coupled analysis

Considering thermal diffusion and thermal stress in beam injection direction, transient thermal analysis and thermal-mechanical coupled analysis in finite element software ANSYS have been applied. The properties of these materials used in the thermal shock analysis in the following are listed in Table 2.

Table 2 The properties of material in Injector II.

Materials	Density /(g/cm^3)	Tensile strength /MPa	Young's modulus /GPa	Thermal expansion /(10^{-6}/K)	Specific heat /(J/g/K)	Thermal conductivity /(W/m·k)
OFHC	8.9	210	115	17.0	0.39	393
SUS304	8.0	290	193	17.3	0.50	59.5
Niobium	8.6	400	103	5.1	0.28	45

The material properties for Niobium at 4 K are depicted in Table 2 and the two other materials properties are at room temperature (300 K). In the thermal shock study, taken the analysis of OFHC as an example, the procedure is listed below.

(1) The RFQ accelerator is made of OFHC and

the energy of proton beam for this section is from 35 KeV to 2.1 MeV. As illustrated in Fig. 2 and Fig. 3, the proton rang is about 0.05 mm and the maximum stopping power for OFHC at this energy range is about 0.218 MeV·cm^2/mg. Then according to Eq. (2), the heat generation is obtained of 1.4×10^{13} W/m^3.

(2) Transient thermal analysis is applied to calculate heat load distribution firstly. The number of finite element mesh grid is 124 618, which can guarantee the accuracy of analysis results. There is one assumption that thermal properties of OFHC do not vary with temperature rise during the simulation.

(3) The thermal distribution on each node will be transferred to the mechanical analysis at the end of transient thermal solution. The area opposite to beam incident plane is fixed in every direction as the boundary conditions. Then the thermal stress will be calculated via the mechanical study.

(4) Finally comparing the max thermal stress with tensile strength, when the max thermal stress is equal to yield strength, the allowable injection time can be solved in principle.

3.3 Results and discussions

The results of thermal shock analysis for OFHC are illustrated in this section. The temperature distribution and maximum mises equivalent stress at different time are listed in Table 3.

Table 3 The results of thermal shock analysis for OFHC.

δt/μs	δT/K	$\varepsilon_{\max}$/MPa
20	71	198
25	89	248
50	175	490

In the Table 3 δt implies the time at end of load step, δt is the temperature rise, $\varepsilon_{\max}$ means the maximum stress. If the time at end of load step is shorter than 20 μs, the maximum thermal stress does not exceed the yield strength. So the allowable injection time of out-of-control proton beam for OFHC in RFQ should be defined as 20 μs.

The temperature distribution in beam injection view at time at end of load step of 20 μs is shown in left picture of Fig. 4. The maximum temperature is located at half of the beam radius because of no thermal conductivity existing between OFHC and

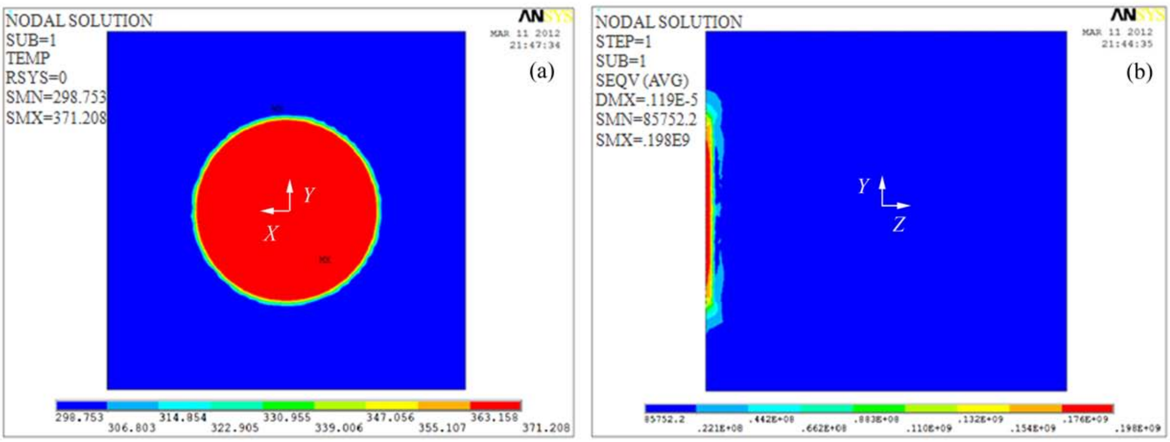

Fig. 4 (color online) The temperature distribution (a) and thermal stress distribution (b) at time of 20 μs.

vacuum. Therefore the heat conduction is much faster in beam injection direction than the horizontal direction.

In the right of Fig. 4, the thermal stress distribution corresponding to the temperature calculation is shown. The thermal stress distribution from side view is consistent with the temperature distribution. The maximum stress is 198 MPa, which is below the yield strength of OFHC. For the other two kinds of materials SUS304 and Niobium, the stopping power corresponding to energy scope is in the same order of magnitude. The allowable injection time for SUS304 and Niobium is about 50 μs and 100 μs separately from the parallel analysis. For superconducting section, the temperature rise and the change of thermal stress with growth of time are shown in Fig. 5.

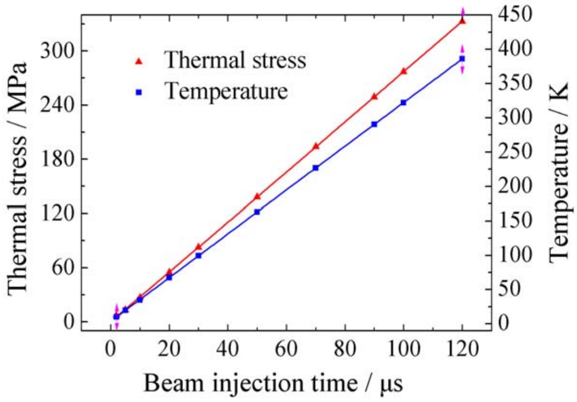

Fig. 5 (color online) The results of thermal shock analysis in SC section.

Thermal shock damage is a big challenge especially in superconducting section. From Fig. 5, when the beam injection time reaches more than 2 μs, the temperature on the cavity surface will beyond the superconductor critical temperature 9.5 K. But the thermal stress is still below the yield stress, so the process will not be defined as the allowable injection time for superconducting section. The final limitation of maximum stress is set to 60% of yield stress of niobium, which will prevent the SC cavity from thermal shock damage more safely. However, due to the high loaded quality factor of the superconducting cavity, it is very sensitive to detuning and easy to damage in the thermal shock. This also will decrease the accelerating voltage and bring about beam loss. If the situation is serious, it will lead to a quench for the superconducting cavity. Therefore, RF system needs to supply a surplus RF power to compensate the cavity frequency shift for keeping the cavity voltage in a superconducting cavity during the allowable injection time. At the same time, beam injection must be stopped immediately. Once a fault is observed, the MPS can then stop or reduce beam intensity during the allowable injection time. For example, the MPS response time requirement for FRIB project is defined to be a maximum of 35 μs for faults occurring in linac segment 2[11]. Table 4 lists the allowable injection time for MPS in some high power accelerators in the world.

Table 4 Allowable injection time of several high power linacs.

Projects	Beam	Mode	t/μs
TTF[12]	e	pulse	50
CEBAF	e	CW	40
SNS[3]	p	pulse	20
FRIB	ion	CW	20～40
Injector-II (C-ADS)	p	CW	20～100

4 Conclusion

Unexpected beam loss from a beam element failure at the C-ADS driven linac may cause accelerator component damage in a very short time. For the purpose of building the MPS to prevent permanent damage to the accelerator element in Injector II, the thermal shock analysis with finite element analysis code ANSYS has been applied to main materials. Traditionally, quench tests in the former method were used to evaluate the thermal shock resistance of materials. The study discussed in this paper proposes a new method that enables the quantitative evaluation of thermal stresses and overcomes the problem of critical temperature difference for former methods.

The simulation results demonstrate the allowable injection time is between 20 and 100 μs. The most remarkable point is that the beam in RFQ accelerator could be most easily lost and therefore the allowable injection time of OFHC is the shortest. Taking the results from the thermal shock study into account, the allowable injection time for MPS of Injector II is considered as 20 μs. Due to the narrow bandwidth of superconducting cavity, although the beam injection time in superconducting section is longer than others, more consideration should be taken into. In addition, there are some reasonable assumptions for thermal shock simulation in this paper. For more detailed results, it is necessary to adopt probable grazing injection beam and complete structure of accelerator component.

References:

[1] WANG Zhijun, HE Yuan, LIU Yong, *et al.* Chinese Physics C, 2012, **36**(3): 256.

[2] TAKEI H, KOBAYASHI H. J Nucl Sci Technol, 2005, **42**(12): 1032.

[3] SIBLEY C. Machine protection strategies for high power accelerators[C]//Terry Anderson ed. Proc 2003 Particle Accelerator Conf. USA: Stanford Linear Accelerator Center, 2003: 607.

[4] SHAFER R E. Internal documentation: Spallation Neutron Source , 2001, April 20.

[5] POMPE W E. NATO ASI Series, 1993, **241**: 3.

[6] ISHIHARA S, GOSHIMA T, MIYAO K, *et al.* Trans Japan Soc Mech Engrs, 2002, **25**: 647.

[7] NISHIKAWA T, GAO T, TAKATSU M. J Soc Mat Sci Japan, 1994, **47**(476): 213.

[8] LU T J, FLECK N A. Acta mater, 1998, **46**(13): 4755.

[9] LI Zhihui, CHENG Peng, GENG Huiping, *et al.* Phys Rev ST Accel Beams, 2013, **16**(080101): 1.

[10] ZIEGLER J F. The Stopping and Range of Ions in Matter. [2013-04-15]. http://www.srim.org/SRIM/SRIMINTRO.html.

[11] KIUPEL G, ASSADI S, BROWN T, *et al.* Fast and critical devices planned for the machine protection system at the Facility for Rare Isotope beams. [C]// Norbert Wentowski ed. Proc DIPAC2011. Hamburg, Germany: Deutsches Elektronen Synchrotron. 2011: 533.

[12] SCHLARB H. Design and Performance of the TESLA Test Facility Collimation System[C]//Leonid Rivkin ed. Proc. 2002 EPAC. France: European Physical Society Interdivisional Group on Accelerator. 2002: 2706.

ADS 注入器 II 热冲击损伤研究

贺守波[1,2,1)]，何 源[1]，王志军[1]，杨阳阳[1]，张生虎[1]，赵红卫[1]

(1. 中国科学院近代物理研究所，兰州 730000;
2. 中国科学院大学，北京 100049)

摘要: 由于束流脉冲无法控制而引起直线加速器的热冲击损伤是造成加速器无法完成聚束及偏转的主要因素，而对热冲击进行定量的热应力评估可以有效地避免 RFQ、超导腔以及其他加速元件等加速器设备的损伤，这在研制强流直线加速器的过程中至关重要。本研究引用一种新颖的计算方法定量分析整个注入器的热冲击损伤并明确了三种不同材料高纯铌、无氧铜和不锈钢对应的加速器件的热冲击的特征。基于有限元方法对瞬态热应力进行分析，得出三种不同材料对应的加速器件在入射角度为 90 度时的温度分析结果。对于所研制的注入能量低于 10 MeV 的强流直线加速器来讲，得到可允许的入射时间为 20 µs。

关键词: 热冲击损伤; 可允许入射时间; 热应力; 有限元方法

收稿日期: 2013-09-18; **修改日期:** 2013-11-09

基金项目: 国家自然科学基金(11221064, 91026001)

1) E-mail: heshb@impcas.ac.cn。