T.1 : Successful development of a novel technique for SCRF cavity fabrication for particle accelerators

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On behalf of team for laser welding of SCRF cavity

Introduction

A novel technique has been indigenously developed for fabrication of SCRF cavities with the help of laser welding process at Raja Ramanna Centre for Advanced Technology (RRCAT), Indore. The technique uses an Nd:YAG laser for welding of components of SCRF cavity made of niobium. The welding is carried out in a specially designed welding rig in inert gas environment. Conventional fabrication technique for SCRF cavities prevalent all over the world is based on electron beam welding (EBW) of niobium components in high vacuum. This innovative fabrication technique based on laser welding developed at Cryomodule Engineering Lab of CCDS, RRCAT in collaboration with Solid State Laser Division of RRCAT has a very promising future because of several inherent advantages.

This technique has advantages such as, very significantly reduced capital and operating cost, small heat affected zone, no necessity to weld in vacuum and an enhanced rate of production. High production rates are possible, since multiple joints can be made in a single setting as laser energy can be delivered through flexible optical fiber and less evacuation time is required as compared to EBW based process.

It is pertinent to mention here that laser welding (LBW) is a well known technology which finds application in many areas of industry. The crux of this new technique is the use of flexibilities provided by laser welding, so as to facilitate an easier fabrication process at reduced cost, without compromising on performance. An example of achieving such a simplification is the use of inert gas environment instead of high vacuum, as is prevalent in the case of EBW based cavity fabrication process.

This idea was conceptualized at RRCAT in 2008 and after conducting feasibility experiments a patent application through PCT route was filed[1]. After receiving a favourable search report from international search authority, patent applications were filed in different patent offices of the world. More than 150 experiments were conducted to optimize the weld parameters and determine the process of fabrication. Finally, a 1.3 GHz single cell cavity was fabricated to evaluate the technique.

The very first prototype 1.3 GHz single cell SCRF cavity, fabricated at RRCAT with this new technique, which was processed and tested at Fermilab (USA), has achieved a quench field of 31.6 MV/m with a Q_0 of 1.0 x10^{10}. This is a standard result for any SCRF cavity. The fact that this novel technique uses comparatively less expensive LBW process and inert atmosphere, instead of high cost EBW in high vacuum environment, has been hailed all over the world by experts in the field.

RRCAT has taken up a programme for development of SCRF technology. This programme is aimed at setting up a high intensity superconducting proton linac, which is a major project being planned at the centre. The necessary infrastructure required for this project, is in an advanced stage of commissioning [2]. Technology development has been taken up in different fields related to SCRF technology. This effort for developing an alternate technique for fabrication of SCRF cavities is a part of this exercise.

Fig.T.1.1: First laser welded 1.3 GHz SCRF cavity.

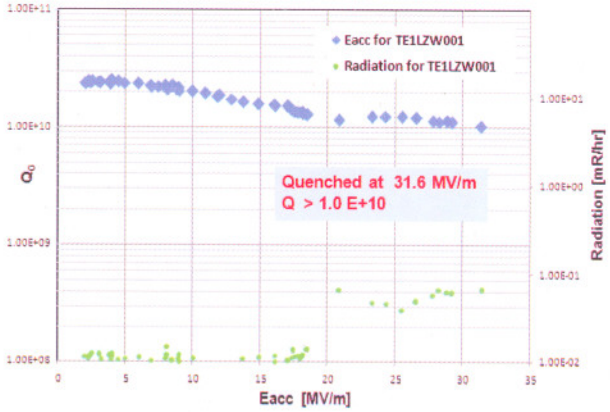

Fig.T.1.2: Q_0 v/s E_{acc} for laser welded single-cell 1.3 GHz SCRF cavity

FABRICATION TECHNIQUE CHALLENGES

Establishing a fabrication technique for SCRF cavities is a challenging task. The superconducting properties of niobium have to be kept intact. The heat affected zone (HAZ) has to be kept at a minimum. The distortion due to welding has to be minimized. During the whole process, it is imperative that no foreign material inclusion should be there. Apart from these, the weld joint should be mechanically sound with no defects like cracks, incomplete fusion, etc.

A. Optimization of welding parameters on coupons

Laser welding experiments were carried out on niobium (Nb) samples using Nd:YAG (1.064 μm) laser system. The first challenge was to obtain full depth penetration. It is difficult since absorption at this wavelength is just ~10% for Nb and the melting point of niobium is ~2500 °C. After a number of experiments, parameters could be ascertained for full depth penetration. Welding parameters were optimized for full penetration in Nb samples with different thicknesses (1.7 mm, 2.1mm, and 3 mm). These parameters were fine tuned for reliability in depth of penetration and vacuum leak tightness. Parameters were further optimized, so as to get full depth penetration with minimum possible energy input rate, to keep heat affected zone (HAZ) to a minimum.

It is desirable that inner surface of the weld bead is smooth. As it is possible to transport energy through optical fiber, it was tried that the inner part of the bead is smoothened with an inclined beam and this is also a unique feature of this technique. The required parameters were also optimized for smoothening of weld bead by laser beam. The angle of inclination was optimized by performing few experiments on flat samples. Experimental trials were carried out for optimizing weld smoothening parameters on number of circular rings of niobium sheet (see *Fig.T.1.6*). Other parameters were similarly optimized on flat samples.

Metallographic Analysis of coupons

Metallographic analysis was done for most of the samples. Laser welded specimen exhibited ~2.5 mm wide weld bead with smooth ripple pattern (see *Fig.T.1.4*)

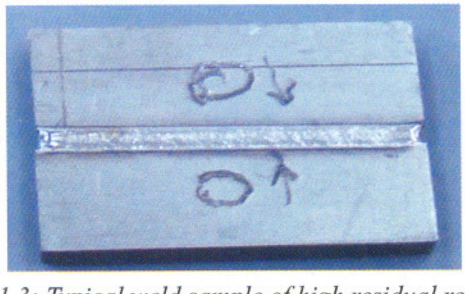

Fig.T.1.3: Typical weld sample of high residual resistivity ratio (RRR) niobium.

A cross-sectional metallographic examination of laser welded niobium specimen with finalized parameters did not reveal any defect. The laser welded metal displayed coarse columnar grains, growing from the two sides of the melt pool to meet axial grains at the weld center line as shown in *Fig.T.1.5*. Due to the low heat input associated with the laser welding process, the laser welded joints develop a very narrow HAZ of about 500 μm, on both the sides of the weld bead. None of the weld samples made with final parameters showed any micro crack or voids.

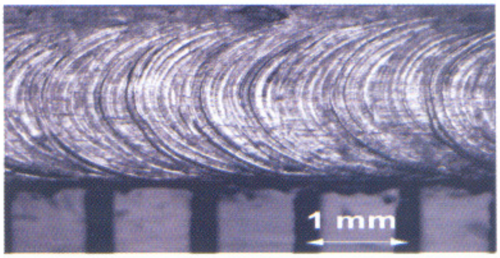

Fig.T.1.4: Weld bead with smooth ripple pattern.

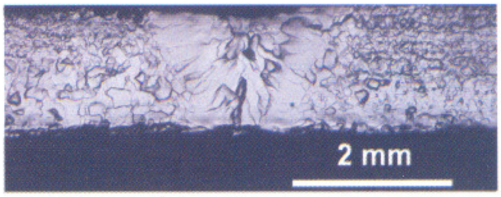

Fig.T.1.5: Cross-sectional view of Nb specimen

Coupons made with finalized parameters were tested for tensile strength & vacuum leak tightness.

Tensile Test

The results of tensile strength tests (Table 1) were found satisfactory.

Table 1: Tensile test results of Nb samples

LBW sample	UTS 170 MPa
	YS 100 MPa
Original substrate	UTS 180 MPa
	YS 100 MPa

Vacuum Leak Tightness

To qualify the weld joint, vacuum leak tightness was checked for laser welded Nb sample using a mass spectrometer leak detector having minimum detectable leak rate of $< 1x10^{-11}$ mbar.ltr./sec of helium. The sample was a Nb disk welded along diameter. The observed leak rate was of the order of $1x10^{-10}$ mbar.ltr./sec.

B. Optimization of Welding Environment

These experiments were followed by experiments to optimize the welding environment. As laser can travel through gases (unlike an electron beam), a recipe was established, which could ensure high RRR of the welded samples, subsequent to welding, even in the environment comprised of inert gas instead of high vacuum.

Experiments were conducted with helium and argon gas of different purity. It was found that high purity argon gas with 99.9999% purity level, could be used for this technique. Argon gas jet was used to assist the laser welding process, to drive away, the evaporated material and weld spatter, from the sensitive region. Gas jet parameters (flow rate, orifice diameter, incident angle, etc.) were optimized, so that any evaporated material and spatters are not allowed to deposit on the cavity surface, while keeping the weld pool undisturbed. Subsequent to parameter finalization, RRR measurement was carried out. The RRR value for the pristine Nb sample was 314 and for the welded sample, it was 296, which shows a reduction of just 6%, which is acceptable. Literature survey suggests that 10% degradation after welding is acceptable.

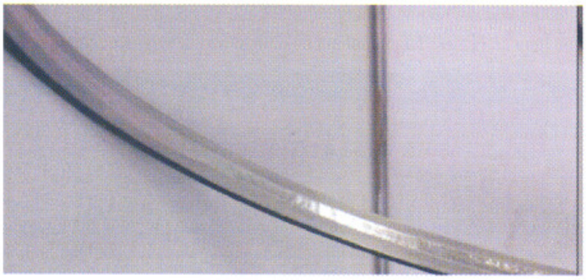

Fig.T.1. 6: Equatorial cut out of smoothened Nb ring.

C. Fabrication of Prototype 3.9 GHz Cavity

After proving the technique on flat samples, a 3.9 GHz SCRF cavity (*Fig.T.1.7*) made of low RRR Nb was fabricated with optimized parameters, in an argon environment, for testing the functioning of all subsystems as a single unit. Fabrication was carried out in a small welding rig developed with a local industry.

This exercise provided two important inputs. The first was about weld shrinkage and the second was about gas flow regulation through nozzle, for assisting in muck removal, when a circumferential joint is welded. This trial also showed how much weld overlap has to be there for smooth surface finish.

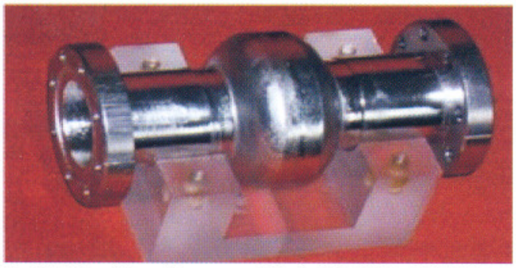

Fig.T.1.7: First laser welded 3.9 GHz SCRF cavity.

This cavity was also used to check fixturing of half cells and smoothening of weld bead from inside of the cavity.

INFRASTRUCTURE DEVELOPMENT FOR SCRF CAVITY FABRICATION

WELDING RIG

A special SCRF cavity welding rig was designed and fabricated for 1.3 GHz SCRF cavity (see *Fig.T.1.8*). The vacuum vessel of the rig can achieve vacuum level of the order 10^{-6} mbar. Although the welding is done in inert gas environment, but the chamber was designed and fabricated for high vacuum level, to perform welding in high vacuum environment as an alternate option, for comparing the results. The rig comprised of motion feed through, optical fiber feed through, and gas feed through to carry out welding in an inert gas atmosphere. Special teflon sealed feed through has been developed for optical fiber cable, which carries laser beam inside the weld chamber.

TARGET MANOEUVRING SYSTEM

A stepper motor based target manoeuvring system was developed specially for this project. The system imparts motion to the job at desired speed and direction. The system is based on Philips 89C51VRD2 microcontroller. It drives two stepper motors. Special features of the system are:

- Interactive user interface
- Programmable speed and distance for linear and rotational movement stages.

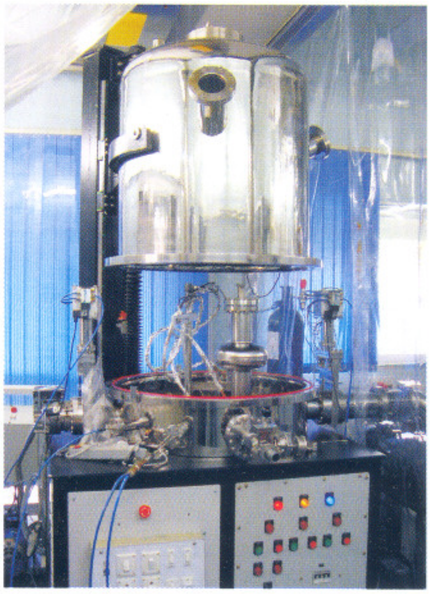

Fig.T.1.8: Photograph of laser welding rig.

- Movement in both the directions, in continuous as well as with fixed distance mode.
- Stopping the motion of job at any instance and precise display of distance moved.
- Facility to provide tagging locations at diametrically opposite points for initial weld tagging purpose.
- Online display of set parameters.

This system consists of 20X4 LCD and 4X4 keyboard to provide user interface. A software was developed for this task, which facilitates all application specific functions, through a user friendly interface.

SPECIALLY DEVELOPED LASER SYSTEM

The parameters required for fabrication were assessed during experimentation on flat coupons and then a tailor-made, Nd:YAG laser was developed for the task with an average output power of 500 W and a peak power of 10 kW (Fig.T.1.9). The laser system provides maximum pulse energy of 300 J. Laser can operate with variable pulse repetition rate of 1-100 Hz. Laser output pulse shape can be varied in time domain with pre-determined heating and cooling rates. Nd:YAG laser systems with such high energy, variable pulse energy and pulse duration are hardly available. Laser beam is delivered to weld joints by means of an optical fiber and lens arrangement, passing via an optical feed through, into the vessel.

In the laser resonator, there are two efficient identical pump chambers. Each pump chamber has an Nd:YAG rod, a flash lamp, and two halves of gold plated elliptical reflector. In each of the pump chambers, a 10% samarium oxide doped glass plate is inserted between the lamp and rod to absorb the UV radiation from the lamp and convert the UV radiation into the useful visible light, thus contributing to laser output power. A water cooling unit with an optimized flow rate, to reduce thermal problems, has been used to achieve good efficiency and good beam quality. The laser system provides an electrical to laser conversion efficiency of about 5%, which is on higher side as compared to commercially available laser systems. Laser system is driven by two 5kW average power high energy charging capacitor pulsed power supplies. A touch screen controller drives both the power supplies synchronously, to generate high average output power and high laser pulse energy. This controller is used to select flash lamp current, pulse duration, pulse frequency and number of laser pulses. Laser resonator has been carefully designed in such a way that it remains stable for the whole range of pump power from 0-10 kW and also for single shot operation. The laser system has been designed to provide a good beam quality, which is better than 20 mm.mrad for the whole range of operation. Hence, it was possible to deliver the laser beam efficiently and reliably through a 400 μm core diameter and 0.22 numerical aperture silica-silica optical fiber with a transmission efficiency of 90% over the entire range of operation. It has been equipped with two fiber optic time shared ports, for selection of full depth and smoothening nozzles quickly.

Fig.T.1. 9: A photograph of Nd:YAG laser system.

1.3 GHz SCRF CAVITY FABRICATION

After establishing the infrastructure for fabrication of SCRF cavity and getting the experience of fabricating the 3.9 GHz SCRF cavity, it was planned to fabricate a 1.3 GHz SCRF cavity with high RRR niobium material. This was the logical next step, after the welding samples were qualified on all accounts, including RRR measurement.

The weld sequence for cavity components, weld overlap, and other such aspects were ascertained and thus the process was finalized. Suitable fixtures were developed for welding of Nb components of a single cell 1.3 GHz Tesla-shape cavity. The first cavity was fabricated at RRCAT and initial tests like vacuum leak test, and vacuum integrity tests subsequent to cold shock at 80K, were performed at RRCAT. Resonant frequency measurement was also done at PHPMS Section of RRCAT, which showed that the estimations of weld shrinkages were very accurate. The results are summarized as below in Table 2 :-

Table 2: Test results of 1.3 GHz SCRF cavity at 22°C

Test	Result
Vacuum leak tightness	1 x 10^{-10} mbar. litre./sec.
Room temp. frequency	1.2962GHz
Quality factor	9542
Overall length	393 mm
Vacuum. leak tightness (after cold shock)	2 x 10^{-10} mbar. litre/sec

PROCESSING AND TESTING OF 1.3 GHz LASER WELDED SCRF CAVITY

Laser-welded 1.3 GHz cavity was shipped to FNAL for surface processing and RF testing at 2K in the Vertical Test Stand (VTS). On its arrival at FNAL, vacuum leak tightness at room temperature was re-checked and was optically inspected (see Fig. T.1.10).

It was observed that a very narrow weld bead (~2.5 mm) and HAZ was visible in optical inspection. A standard approach was taken to process the cavity, as reported in references [4], [5]. As a first step, buffer chemical polishing (BCP) was done to remove 120 µm of material. A solution comprising of 1:1:2 HF (48%), HNO_3 (65%), and H_3PO_4 (85%) was used, and the bath temperature was kept around 12°C.

BCP was followed by a bake at 800°C for 2 hrs. at 10^{-6} mbar of vacuum. A second optical inspection was performed which showed a small HAZ and weld bead. After second optical inspection, a light EP for 40 µm material removal was carried out. The temperature was around 24°C near equator while average cavity temperature was kept below 30°C.
As a next step, ultrasonic cleaning and high pressure rinsing (HPR) of cavity was carried out. The cavity was assembled in Class 10 clean room. First testing was then carried out at 2 K in Vertical Test Stand (VTS).

The cavity reached an acceleration gradient (E_{acc}) of 17 MV/m with a quality factor (Q_0) of $1.4x10^{10}$ at 2 K in its maiden test (see Fig.T.1.10). At 17 MV/m, there was a hard quench. No field emission was observed.

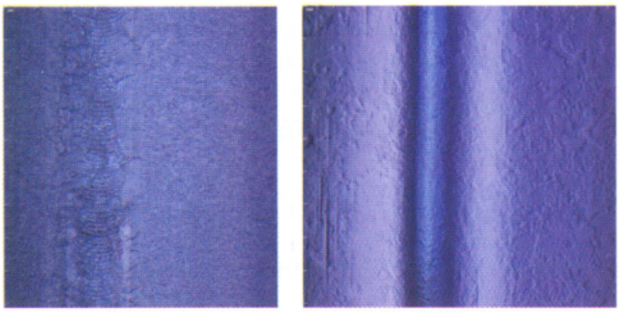

Fig.T.1.10: Images of inner surface of SCRF cavity

Small weld defect was likely the cause of the early quench in the first test. A repair process was implemented that included removal of a layer > 100 m by centrifugal barrel polishing (CBP), to remove any surface morphological defects. The CBP process was continued through the mirror finish stage prior to light EP and high temperature bake [3]. *Fig.T.1.10* shows inner surface of cavity after CBP. The cavity received a 15 µm EP prior to the 800°C, 3-hour plateau hydrogen degasification bake.

The cavity was again tested in VTS at FNAL. The cavity reached an accelerating gradient (E_{acc}) of 31.6 MV/m with a quality factor (Q_0) of $1 x10^{10}$ at 2 K.

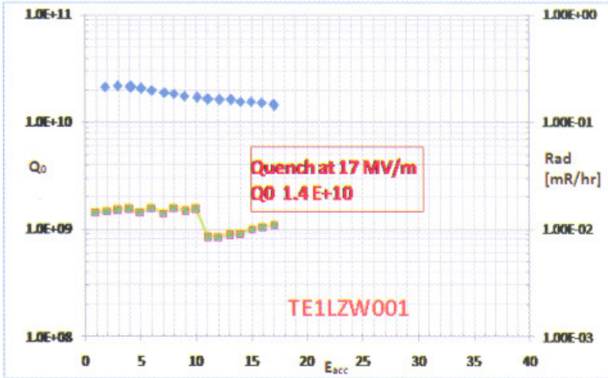

Fig.T.1.11: Q_0 v/s E_{acc} plot of first test.

ADVANTAGEOUS FEATURES

This new technique based on laser welding has many advantageous features compared to the conventional EBW based technique. These are :

- Low capital cost, as laser system along with welding rig and other auxiliary systems are ~25 times cheaper than EBW set up.
- This technique imparts flexibility for new cavity designs (low, medium or high beta) as laser beam can be manoeuvred to any location and it can travel through optical fibers.
- High vacuum environment is not needed.
- Evaporated material, spatter etc. are blown away with the help of a gas jet.
- Operating cost is also cheaper by 4-5 times for laser system as compared to electron beam welding system.

- Better control on energy deposition (frequency, pulse shape, duration etc.).
- Energy deposited has been optimized to obtain
  - Lower HAZ (~500 µm on both sides)
  - Narrower bead (2-2.5 mm wide)
  - Less shrinkage and distortion (5-6 times compared to EBW)
- Higher production rate is possible as
  - Multiple joints are possible in a single setting.
  - One laser can operate many welding rigs with time shared multi-port fibre optic beam delivery (Fig.T.1.12)
  - More predictable shrinkage reduces machining time

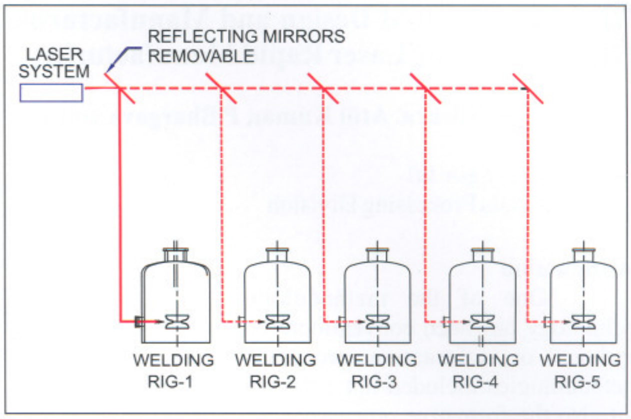

Fig.T.1.12: A schematic diagram showing multi-port fiber optic beam delivery by same laser.

SUMMARY

A new LBW based technique has been developed for fabricating SCRF cavities for the first time. This technique uses laser beam welding to join Nb components in inert gas environment. There are significant advantages which are foreseen from this technique. The process and infrastructure have been developed. The very first 1.3 GHz Tesla-shape SCRF cavity fabricated at RRCAT, using this new technique, reached an acceleration gradient (E_{acc}) of 31.6 MV/m with a quality factor (Q_0) of $1.0x10^{10}$ at 2K. This is a very encouraging result, as the cavity has been welded with LBW, which is significantly economical process compared to EBW. Furthermore, the process is carried out without vacuum, thereby mitigating complications associated with it. These advantages make the new technique of SCRF cavity fabrication an attractive choice for future accelerator projects. To the best of our knowledge, these are the first high quality test results of an SCRF cavity, which has both, RF sensitive and non RF sensitive joints, made with laser beam welding process. Efforts are being made at our centre to further improve the performance of cavities and make the process simpler and economical by using other flexibilities, which have become available due to laser welding process. Efforts are now being made to develop a couple of multi-cell cavities with repeatable performance.

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