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А.М. Медведев[1,3], А.М. Семенов[1,2], Ю.И. Семенов[1], М.М. Сизов[1,3], А.А. Старостенко[1,3], А.С. Цыганов[1]

[1] Институт ядерной физики им. Г.И. Будкера СО РАН, Новосибирск, Россия
[2] Новосибирский государственный технический университет, Новосибирск, Россия
[3] Новосибирский государственный университет, Новосибирск, Россия

ПРОЦЕСС ИЗГОТОВЛЕНИЯ ВАКУУМНЫХ КАМЕР ДЛЯ ПРОЕКТА FAIR С ИСПОЛЬЗОВАНИЕМ ЭЛЕКТРОННО-ЛУЧЕВОЙ СВАРКИ

Институт ядерной физики Сибирского отделения Российской академии наук, Новосибирск, Россия, успешно использовал электронно-лучевую сварку при производстве вакуумных камер в течение длительного времени. Установка электронно-лучевой сварки оборудована системой перемещения свариваемого образца, обеспечивающей максимальную длину швов до 2 м, свариваемых в два этапа. Электронная пушка разработана в институте, ускоряющее напряжение составляет 60 кВ, мощность достигает 60 кВт. В настоящее время институт производит дипольные вакуумные камеры для проекта HEBT, FAIR (Германия). Камеры для дипольных магнитов этого проекта предназначены либо «для поворота пучка», либо «для разветвления пучка». Первые состоят из двух продольно сваренных *U*-образных профилей из нержавеющей стали 316 LN различной длины, с толщиной стенки 4 мм. После сварки камера загибается на требуемый угол. Камеры для разветвления пучка состоят из трех частей: двух небольших прямых выходов пучка, сваренных также из двух *U*-образных профилей, и одного разветвляющего участка с переменной площадью сечения, с толщиной стенки 6 мм. Три заготовки свариваются между собой с использованием аргонно-дуговой сварки. После сварки изделия дополняются фланцами для стыковки с другими вакуумными камерами. Для исключения «виртуальных» течей сварка выполняется с полным проваром. Установка электронно-лучевой сварки модернизируется для обеспечения выполнения шва длиной 2 м за один цикл работы установки. В настоящее время прототипы вакуумных камер прошли вакуумные тесты в Институте ядерной физики Сибирского отделения Российской академии наук и в FAIR.

Ключевые слова: электронно-лучевая сварка, газоотделение, вакуумная камера, FAIR, HEBT, полный провар, спектр остаточных газов, проверка на герметичность, вакуумные испытания, процедура очистки.

A.M. Medvedev[1,3], A.M. Semenov[1,2], Yu.I. Semenov[1], M.M. Sizov[1,3], A.A. Starostenko[1,3], A.S. Tsyganov[1]

[1] Budker Institute of Nuclear Physics, Siberian Branch of Russian Academy of Sciences, Novosibirsk, Russian Federation
[2] Novosibirsk State Technical University, Novosibirsk, Russian Federation
[3] Novosibirsk State University, Novosibirsk, Russian Federation

EBW ASSUMED MANUFACTURING PROCESS OF VACUUM CHAMBERS FOR THE FAIR PROJECT

Budker Institute of Nuclear Physics, Novosibirsk, Russia, have successfully used the electron beam welding for manufacturing of vacuum chambers for a long time. The electron beam welding facility has the moving system that helps to weld seams up to 2 meters long (by using several independent launches). The electron gun has developed in the institute, the acceleration voltage is 60 kV, and the power of beam is up to 60 kW. Currently Budker Institute manufactures the dipole vacuum chambers for HEBT, FAIR (Germany). There are two types of dipole vacuum chambers for this project: or bended chambers or branching chambers. The bended vacuum chambers consist of two longitudinally EBW U-shaped stainless steel 316 LN profiles different length with the wall thickness 4 mm. After welding, the chamber bends to the required angle. The branching chamber includes three parts: two small direct parts for beam evacuation, which welded of two U-shaped stainless steel 316 LN too, and one branching segment with variable aperture area, with the wall thickness 6 mm. Three parts have welded with each other with using TIG welding. After that, there are flanges and fastening elements have been welded to the chambers. To eliminate the virtual leak, the welds will have the full penetration. The electron beam welding facility is being updated so that the maximum seam of 2 meters would be achieved with one single launch. At present time, vacuum tests were carried out for vacuum chamber prototypes in Budker Institute of Nuclear Physics and FAIR.

Keywords: electron beam welding, outgassing rate, vacuum chamber, FAIR, HEBT, full penetration, residual gas spectrum, leak test, vacuum tests, cleaning.

Introduction

Facility for Antiproton and Ion Research (FAIR) is an unique international accelerator complex which will use antiprotons and ions to perform research in different fields of particle physics [1, 2]. The FAIR accelerator complex consists of two superconducting synchrotrons, a high energy beam transport system (HEBT) with a total length of about 2.4 km and four storage rings [3, 4]. For each of the subsystems different vacuum requirements have to be fulfilled. The vacuum system for HEBT consist of a combination of cryogenic and room temperature sections, a vacuum pressure of 10^{-8} mbar is sufficient, and they need no additional bakeout.

On January of 2013 year BINP got a contract with FAIR to make dipole vacuum chambers for HEBT line Batch 1. These chambers must fit specific criteria (e.g. have rectangular aperture) so they need a custom manufacturing. The dipole chamber is made of U-shape profiles with longitudinal seam. Since chambers will be placed between magnets, its magnetic permeability must be less than 1.005. TIG welding influences on magnetic permeability of material so it is not acceptable. Electron beam welding (EBW) doesn't have this disadvantage.

Description of vacuum chambers

HEBT line Batch 1 have two variants of dipole chambers: bended and branching chambers.

Bended HEBT chambers consist of two or four 4mm U-shaped stainless steel 1.4429 profiles and two CF160 flanges which are welded longitudinally by EBW. Long variant of the chamber (with four U-shaped profiles) is welded transversally. The aperture of chambers is a rectangle with size 120×60 mm or 110×67 mm. The radius of bended chambers varies in range from 3,33° to 15°. Bending is being performed on chambers with water inside (under pressure of 40-60 bar) to prevent chamber deformation. After bending procedure the hall probe groove is milled. The bended chamber with fixation to magnet is shown on Figure 1.

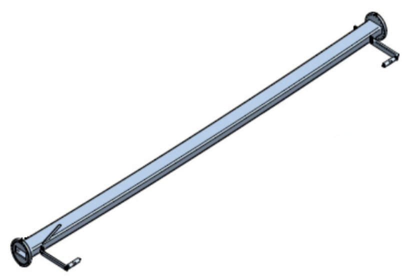

Fig. 1. The bended chamber with fixation to magnet

Branching chambers consist of branching parts made of U-shaped stainless steel (quality 1.4429 or 1.4435 or 1.4404) profiles welded longitudinally with EBW; one part with variable cross-section made of 6 mm stainless steel (quality 1.4429) profiles; one transition flange, and three CF160 flanges. Part with variable cross-section consists of two symmetrical parts welded longitudinally with EBW. Transition flange is made of 50 mm stainless steel 1.4429 quality. The hall probe groove is milled. The aperture of branching parts is a rectangle of 110×67 mm. The branching chamber with holders for fixation to magnet is presented on Figure 2.

All chambers are undergone the following cleaning for removal of mechanical and chemical contaminations and outgassing rate reduction [5]:

1. Ultrasonic cleaning in alkaline detergent (pH = 9.7) at 60 °C for 15-20 minutes.

2. Immediate rinsing with technical water jet.

3. Immediate rinsing in demineralised water by immersion during 1-2 minutes (with ultrasonic agitation).

4. Immediate rinsing in demineralised water jet.

5. Drying with clean (oil and moisture free) compressed air or nitrogen.

6. Covering of CF flanges with aluminium foil and sealing with cleaned PE cap.

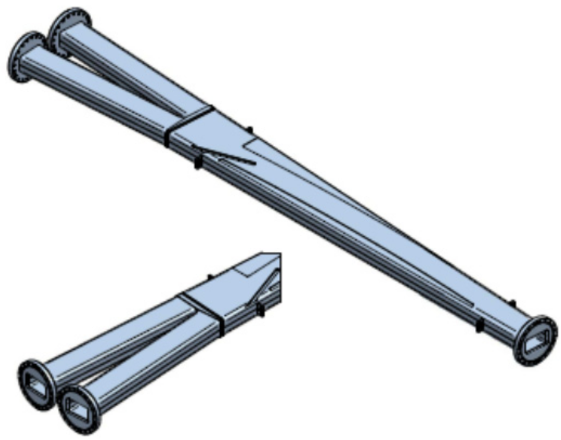

Fig. 2. The branching chamber with holders for fixation to magnet

Electron beam welding facility

Budker Institute has an electron beam welding facility [6]. Its primary goal is to weld various constructions for customers as well it is used in fundamental studies of charged particle physics [7–10]. The facility consist of cylindrical vacuum chamber 3.5 m length and 0.98 m diameter, vacuum system, electron gun and coordinate table.

Vacuum system contains of two-stage forevacuum pump (Pfeiffer Vacuum, “DUO 65”) and two turbomolecular pumps (Pfeiffer Vacuum, “HiPace 1500U”). Electron gun has additional turbomolecular pump (Pfeiffer Vacuum, “HiPace 80”). The time of pumping is about 20 minutes. Duration of chamber open procedure after the welding is approximately 5 minutes.

The electron gun generates an electron beam and transmits it to welding sample. The emitter of electrons is directly heated tantalum cathode. The acceleration voltage is adjustable. Maximum voltage is 60 kV. The beam current (at 60 kV) may reach 750 mA. The electron gun was developed in BINP [11].

The gun is fixedly mounted on the facility. The details moving system contains two linear moving modules forming Cartesian coordinate system. The size of the achievable area is 1970×300 mm.

Pre-welding settings proceed with visual control and system of reflected electrons [12]. The welding process is running in automatic mode.

Setup for vacuum tests

Figure 3 shows a setup for measurement of thermal outgassing rate. The pumping down exists series of turbomolecular pump (TMP) and turbomolecular station. The turbomolecular station consists of turbomolecular pump and oil-free scroll pump (MP). The total pumping speed of pumps through all-metal angle valve DN40 is about 10 l/s in nitrogen equivalent. The bypass is required for two tasks: reduction of total speed down to 0.5 l/s (in nitrogen equivalent) and pump down of residual gas analyzer (RGA) during dry nitrogen venting.

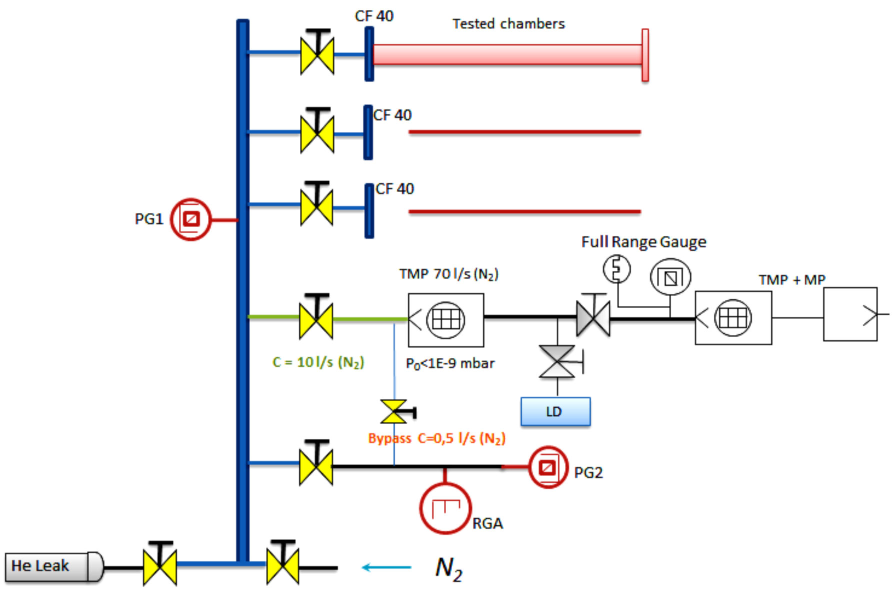

Fig. 3. The setup for vacuum tests: (PG1, PG2 – penning gauges, RGA – residual gas analyzer, TMP – turbo-molecular pump, MP – mechanical oil-free pump, LD – leak detector (sensitivity better than 1E-10 l*mbar/s), He leak – stable, known He leak

The combination gauge (Pirani + cold cathode gauges) measures fore-vacuum. The penning gauges (PG1 or PG2) are used for the measurement of pressure in vacuum system and outgassing rate. Residual gas analyzer receives and records the spectrums of vacuum system.

The chambers are joining to vacuum system through all-metal angle valve DN40. Leak detector and turbomolecular station are connected through viton angle valves DN25. The nitrogen venting and external helium leak are connected through all-metal angle valves DN16.

Vacuum tests

The vacuum tests are carried out after 24 hours of continuous pumping down. The pressure is less than 10^{-6} mbar measured by combination gauge.

A) Leak test

The leak test is fulfilled with using a standard leak detector with internal or external calibration leaks. Before leak test, need to calibrate the leak detector.

Minimum detectable leak of leak detector (mbar · l/s)

$$L = 2 \cdot \frac{\text{Max.background} - \text{Min.background}}{\text{Sensitivity}}, \qquad (1)$$

where Max.background and Min.background are maximum and minimum of leak detector background, correspondingly, mbar·l/s;

$$\text{Sensitivity} = \frac{X_2 - \text{Aver.background}}{Q_c}, \qquad (2)$$

Q_c – known leak value, mbar·l/s; X_2 – measurement of known helium leak-by-leak detector, mbar·l/s; Aver.background – mean value between Max.background and Min.background, mbar · l/s.

After calibration of leak detector the chamber to be tested is be enclosed with a PE pocked and filled with He for 10 minutes. The leak level (mbar · l/s) is defined as

$$Q_m = \frac{X_p - \text{Aver.background}}{\text{Sensitivity}}, \qquad (3)$$

where X_p – measuring maximum of leak detector signal during leak test, mbar · l/s.

B) Spectrum of residual gases and measurement of outgassing rate

Measurements have to be done after pressure stabilization (from 10 to 30 minutes after a valve opening/closing). Measurements of outgassing rate ((mbar · l/(s · cm^2)) is defined as

$$q = \frac{\left(P(PG1)_{on} - P(PG1)_{off}\right)}{A} \cdot C, \tag{4}$$

where $P(PG1)_{on}$ & $P(PG1)_{off}$ – measured pressure by penning gauge at opened and closed correspondent tested chamber, mbar; C – molecular conductivity to TMP, l/s; A – internal surface area of tested chamber, cm^2.

The outgassing rate was measured from $5 \cdot 10^{-11}$ to $8 \cdot 10^{-11}$ mbar · l/(s · cm^2) for different HEBT chamber prototypes.

For residual gases spectrum exist the following criteria [13]:

– all mass peaks between 18 amu and 46 amu (except peak 28, 32 and 44) shall be 100 times less than the sum of all peaks;

– all mass peaks higher than 46 amu shall be 1000 times less than sum of peaks of masses 2, 18, 28 and 44 amu.

Fig. 4 and 5 show spectrums of test vacuum system with and without a testing chamber, correspondingly.

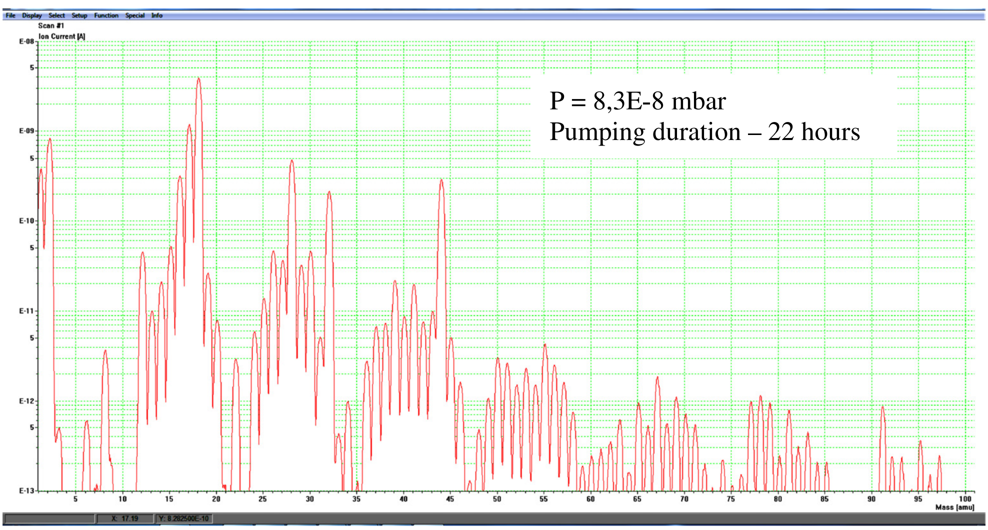

Fig. 4. Spectrum of test vacuum system with a testing chamber

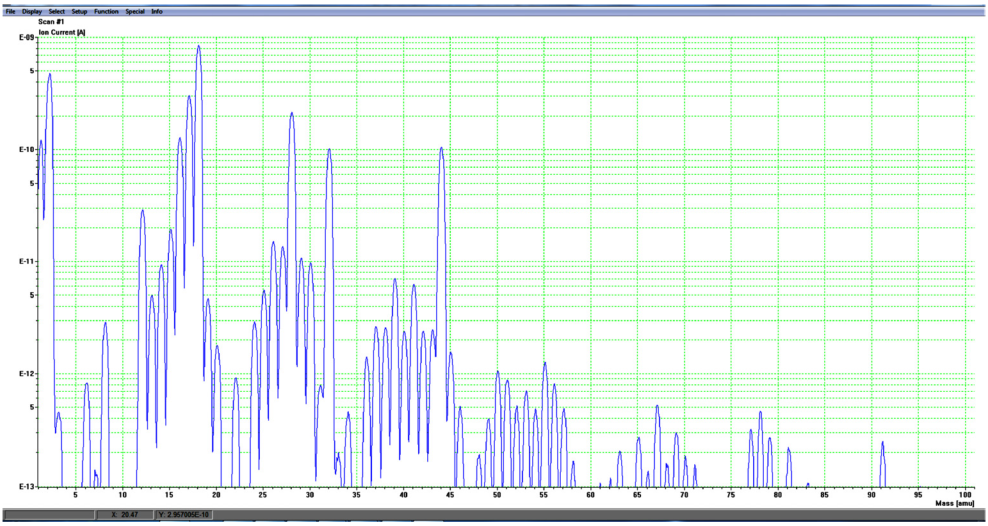

Fig. 5. Spectrum of test vacuum system without a testing chamber

Conclusion

For all longitudinal seams was fulfilled X-ray analysis according to ISO 5817 (class B). The results of vacuum tests and X-ray analyses confirm qualitative of longitudinal seams performed at Budker Institute using EBW [14]. The first prototype of branching chamber was delivered at FAIR and placed into dipole magnet. Two prototypes are waited for one's turn. 3D models and 2D drawings approval for serial chambers are completed.

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Об авторах

Алексей Михайлович Медведев – лаборант Института ядерной физики им. Г.И. Будкера Сибирского отделения Российской академии наук; e-mail: alexey.m.medvedev@gmail.com.

Алексей Михайлович Семенов – кандидат технических наук, научный сотрудник Института ядерной физики им. Г.И. Будкера Сибирского отделения Российской академии наук; e-mail: A.M.Semenov@inp.nsk.su.

Юрий Игнатьевич Семенов – научный сотрудник Института ядерной физики им. Г.И. Будкера Сибирского отделения Российской академии наук; e-mail: Yu.I.Semenov@inp.nsk.su.

Александр Анатольевич Старостенко – кандидат физико-математических наук, старший научный сотрудник Института ядерной физики им. Г.И. Будкера Сибирского отделения Российской академии наук; e-mail: astar@inp.nsk.su.

Михаил Михайлович Сизов – лаборант Института ядерной физики им. Г.И. Будкера Сибирского отделения Российской академии наук; e-mail: sizov.m.m@gmail.com.

Александр Сергеевич Цыганов – научный сотрудник Института ядерной физики им. Г.И. Будкера Сибирского отделения Российской академии наук; e-mail: a.s.tsygunov@inp.nsk.su.

About the authors

Aleksei M. Medvedev (Novosibirsk, Russian Federation) – Technician, Budker Institute of Nuclear Physics, Siberian Branch of Russian Academy of Science; e-mail: alexey.m.medvedev@gmail.com.

Alexei M. Semenov (Novosibirsk, Russian Federation) – Ph. D. in Technical Sciences, Researcher, Budker Institute of Nuclear Physics, Siberian Branch of Russian Academy of Sciences; e-mail: A.M.Semenov@inp.nsk.su.

Yuri I. Semenov – Researcher, Budker Institute of Nuclear Physics, Siberian Branch of Russian Academy of Sciences; e-mail: Yu.I.Semenov@inp.nsk.su.

Aleksandr A. Starostenko – Ph. D. in Physical and Mathematical Sciences, Senior Researcher, Budker Institute of Nuclear Physics, Siberian Branch of Russian Academy of Sciences; e-mail: astar@inp.nsk.su.

Mikhail M. Sizov – Technician, Budker Institute of Nuclear Physics, Siberian Branch of Russian Academy of Sciences; e-mail: sizov.m.m@gmail.com.

Aleksandr S. Tsyganov – Researcher, Budker Institute of Nuclear Physics, Siberian Branch of Russian Academy of Sciences; e-mail: a.s.tsygunov@inp.nsk.su.