POWER BEAM WELDING: LASER AND ELECTRON BEAM

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ENGINEERING DEPARTMENT

Outline

1. Introduction and physical principles of beam welding.
2. Description of equipment.
3. Beam welded assemblies – joint design and preparation.
4. Weldability of materials by beam welding.
5. Welding qualifications.
6. Safety.
7. Conclusions.

1 – Introduction and physical principles of beam welding

And adventure which started 40 years ago.

Team of 8 people belonging to the FW section:

- Laser beam welding (LBW) and cutting
- Electron beam welding (EBW)

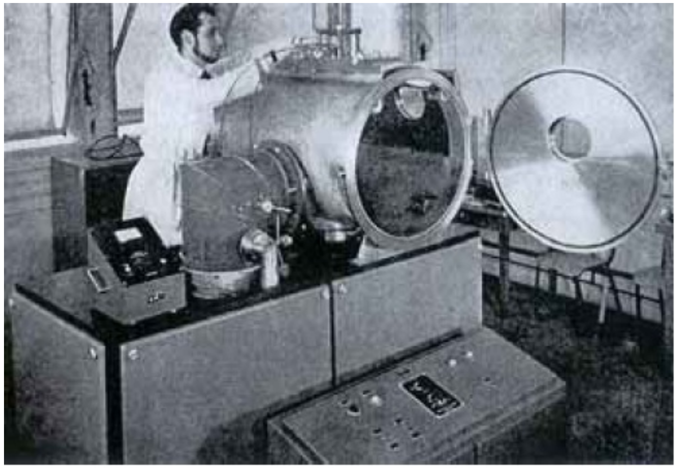
HISTORY OF EBW

- 1930s: EB developed for electron microscopes.
- 1949: Dr Steigerwald obtained the first welds when manipulating electron microscopes.
- 1950s: First EBW machines.

First EBW machine (Germany -1952)

Dr Steigerwald

Dr J. A. Stohr



First EBW machine in France (1956)

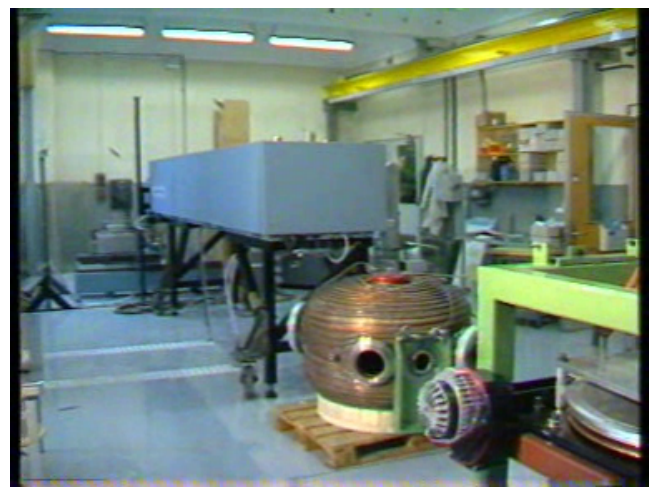
An international history of electron beam welding – Dietrich v. Dobeneck

HISTORY OF LASER WELDING AND CUTTING

- 1960s: Development of ruby and CO_2 lasers.
- 1967: First CO_2 laser cut and The Welding Institute (Cambridge, England).
- 1970s: First commercially available laser cutting machines.
- 2000s: Development of fibre laser sources.

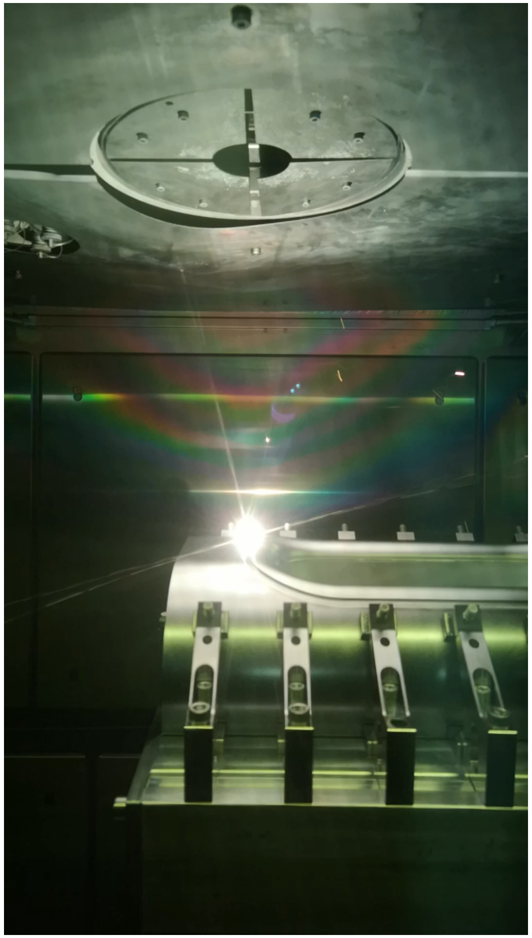
First 2 axis laser cutting machine (1975, Laser - Work AG, Switzerland)

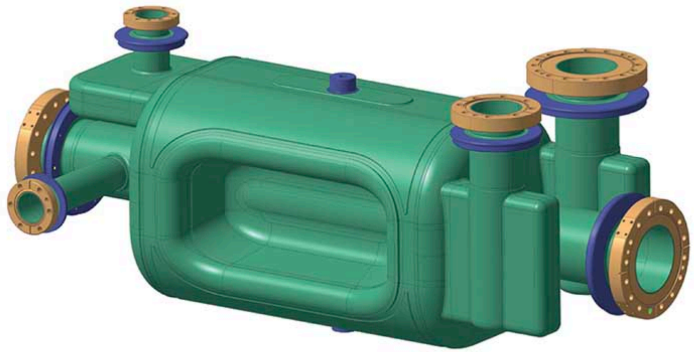
The History of laser cutting – P. A. Hilton, TWI.

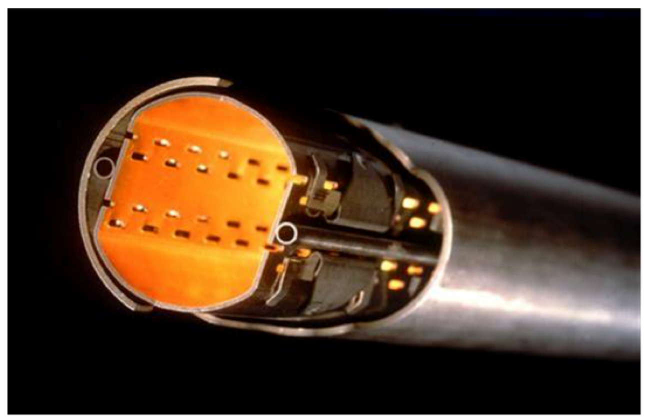


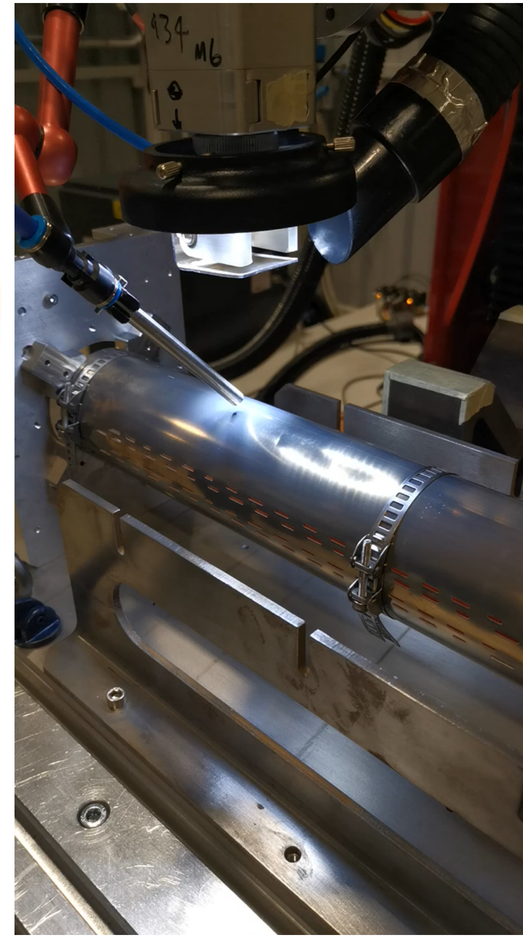
First CO laser machine at CERN (1980s)

1 – Introduction and physical principles of beam welding









Courtesy of T. Demazière

Courtesy of T. Gjelvik

1 – Introduction and physical principles of beam welding

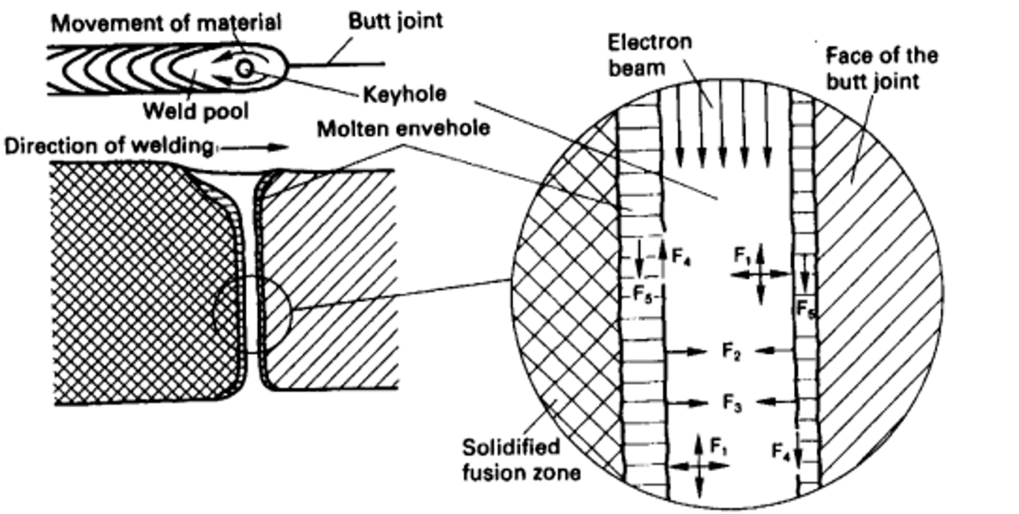
EBW

- Mainly performed under high vacuum (< 1 x 10^{-3} mbar).
- Only metallic materials, but all which can be welded by fusion under vacuum.
- Thickness range from 0.1 to 300 mm in steel (even more if needed).
- Not used for cutting. Drilling of thin plates is possible with dedicated machines.

LBW

- Both gas protection and vacuum welding possible, but gas shielding is much more common.
- Welding and cutting of non metallic materials.
- Thickness range from 0.1 to several tens of mm in steel (not easy to say because power of new fibre laser sources increases rapidly).
- Problems with reflection for some metals, such as copper.

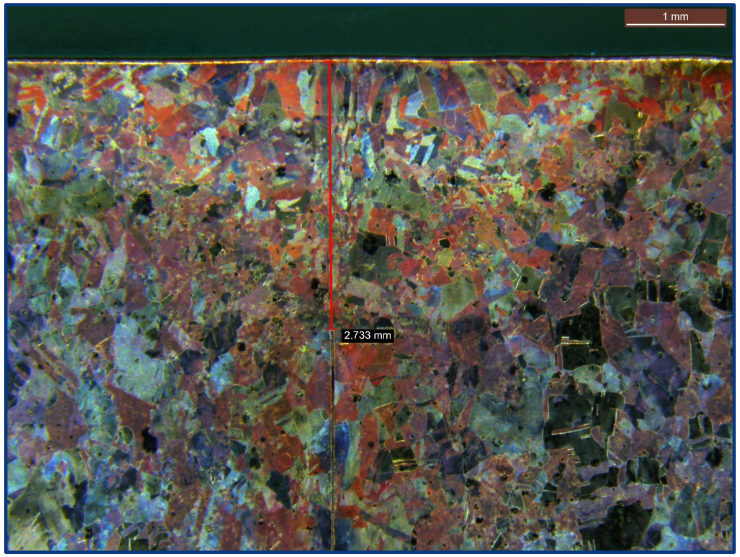
Keyhole / Conduction welding



F_1 = Vapour pressure; F_2 = Force resulting from surface tension; F_3 = Hydrostatic pressure; F_4 = Frictional force from the escaping metal vapour; F_5 = Weight of the molten mantle.

Fig. 36 The major forces acting within the keyhole and molten envelope in deep penetration welding.

Electron beam welding, by Dipl.-Ing. H. Schultz – Woodhead Publishing Ltd, 1993



HIE Isolde cavity test piece
- Courtesy of I. Avilés.

LBW → laser radiation absobed by the material

- Focalisation of the beam on the piece.
- Part of the laser radiation is absorbed by the material. Absorption increases with temperature.
- If energy density is high enough, a cavity will be formed.
- Coupling of laser beam increases by the formation of the hole (higher absorption).
- When moving the beam along the welding joint, the tail of the welding pool closes the hole behind the beam.

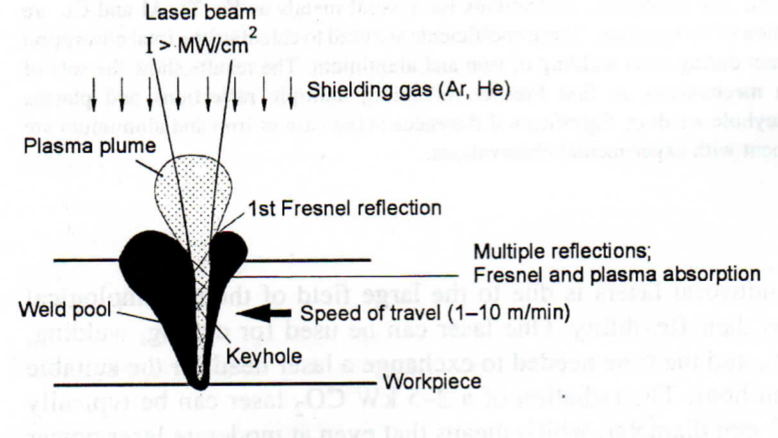
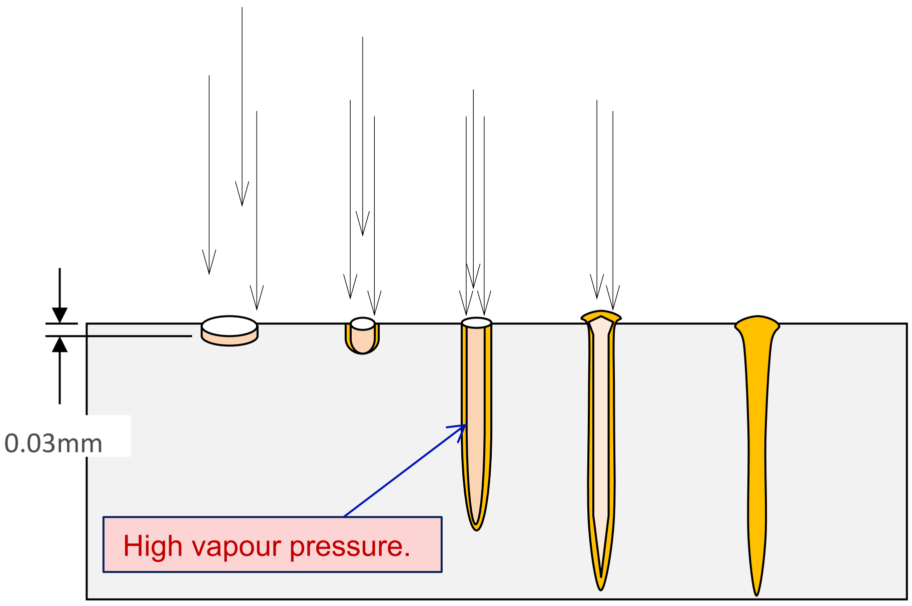


Fig. 1. Mechanism of keyhole welding.

Jacek Hoffman, Zygmunt Szymanski, Absorption of the laser beam during welding with CO_2 laser, 2002

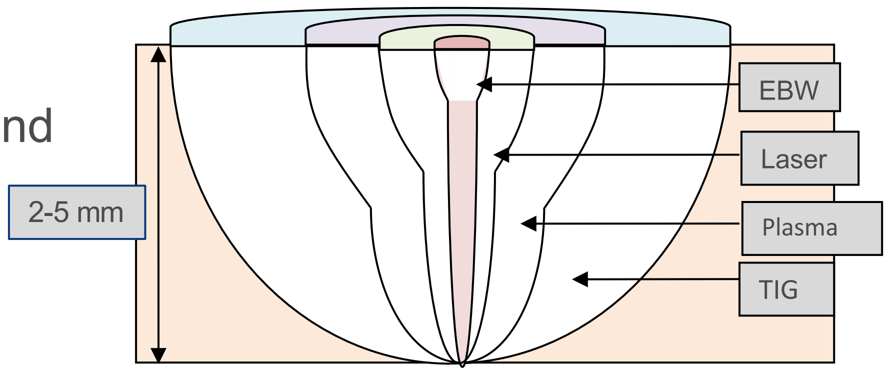
EBW → Kinetic energy of electrons transferred to the metal

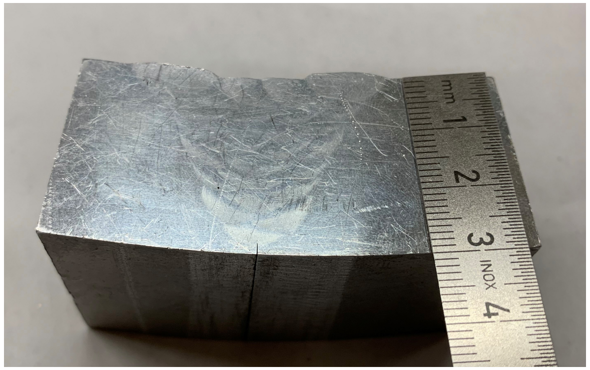
- Focalisation of the beam on the piece
- Kinetic energy of electrons is transferred to the piece. Electrons penetrate a few tens of microns (depending of material and speed of electrons).
- Sublimation of a thin layer of material.
- Beam continues to penetrate into the material.
- Formation of a hole.
- Liquid metal around the wall of the hole.
- When moving the beam along the welding joint, the tail of the welding pool closes the hole behind the beam.



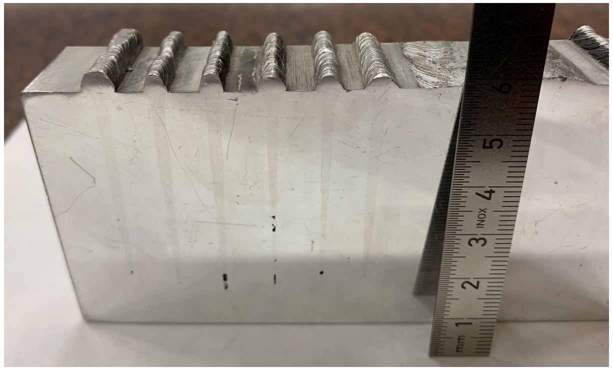
1 – Introduction and physical principles of beam welding

- Fusion welding processes with high power density (up to 10^8 W/cm^2 compared to 10^5-10^6 W/cm^2 for arc welding processes) → low heat input and distortion.
- Automatic processes with high repeatability.
- Fast welding speed (several m/min).

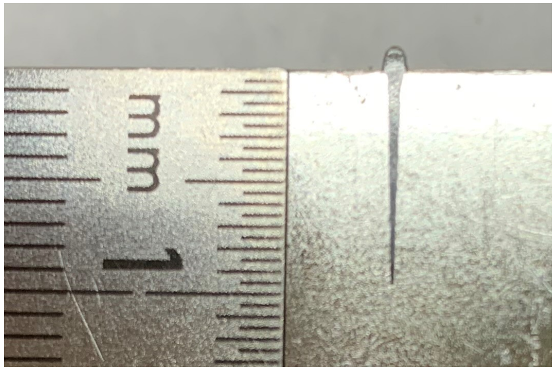




Arc welding aluminium.

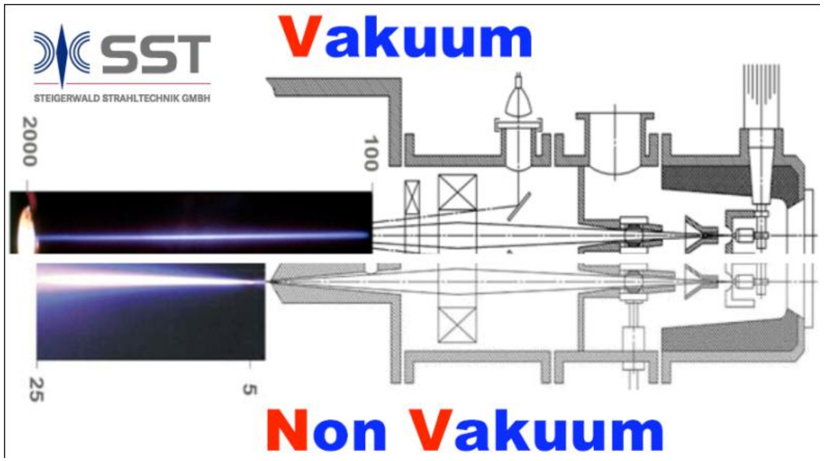


EBW aluminium.



EBW stainless steel.

The importance of vacuum for welding



High vacuum → $P<10^{-3}$ mbar
Medium vacuum → $10^{-3} < P < 10^{-2}$ mbar
Non vacuum

See also → CAS course on "Mechanical & Materials Engineering", P. Chiggiato, Vacuum

- Protects the material against oxidation. Very important for reactive metals (Nb, Ti).
- Provides a more stable keyhole.
- Used in laser welding to obtain sharper welds. Pressures ranging from 10^{-1} mbar up to several kPa (partial pressure of inert gas).
- Problems to weld alloys with low boiling point elements such as Zn (brass, Al alloys series 7000).
- Not good for casting materials (internal voids) and low purity metals (steels with high S and P).
- It will decrease the content in some alloy elements in the molten zone (N for the 316LN, Mg for the Al series 5000).

The importance of vacuum for welding

- Globe box→ 2 to 5 ppm O_2 at atmospheric pressure.
- Vacuum chamber with P=5x10^{-3} mbar → equivalent to around 1 ppm O_2 at atmospheric pressure.
- For high RRR Nb, P<5x10^{-5} mbar → equivalent to around 0.01 ppm O_2 at atmospheric pressure.

Glove box – EN / MME / FW workshop

EBW machine– EN / MME / FW workshop

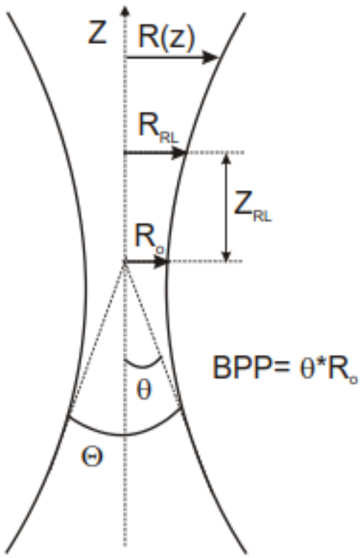
2 – Description of equipment

Types of laser sources for welding and cutting purposes:

- Solid state → Nd-YAG – wavelength 1064 nm – typical power range up to 5 kW.
- Gas lasers→ CO_2 – wavelength 10.6 µm – typical power range up to 25 kW.
- Fibre lasers→ solid state lasers, the active gain medium is an optical fibre doped with low levels of a rare earth element – typical wavelengths from 1000 to 2000 nm – typical power range up to 50 kW.

2 – Description of equipment

BPP (beam parameter product)



	CO_2	Diode-pumped Nd:YAG	Yb-fibre (multi-mode)	Thin disc Yb-YAG
Lasing medium	Gas mixture	Crystal-line rod	Doped fibre	Crystal-line disk
Wavelength, micron	10.6	1.06	1.07	1.03
Output powers [a], kW	Up to 15kW	Up to6kW	Up to20kW	Up to 4kW
Typical beam quality [b], mm.mrad	3.7	12	12	7
	3.7	<12	1.8	4

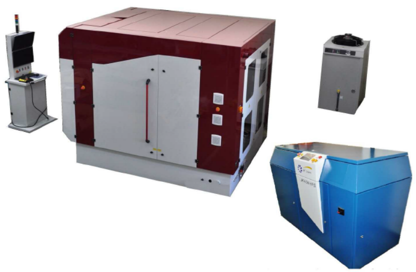
G Verhaeghe, published in Welding Journal August 2005

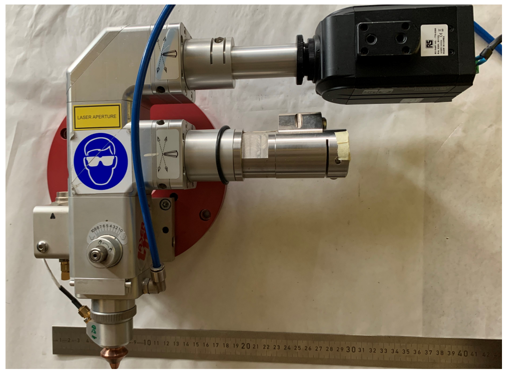
R_o Minimum beam radius

θ Divergence

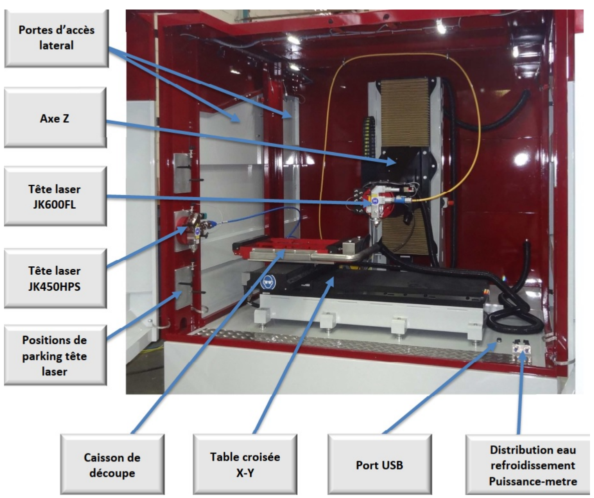
2 – Description of equipment

Main components in a LBW installation





- Laser source.
- Delivery system: rigid lens and mirrors (CO_2) or optic fibre cable.
- Cooling installation.
- Laser head.
- Gas supply.
- CNC machine / robot.



CERN's LBW machine HC 1000

CERN's LBW machine HC 1000 F

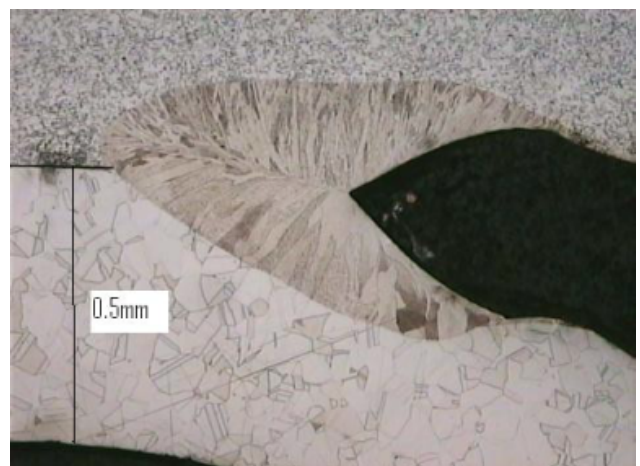
2 – Description of equipment

Spot welding LHC beam screens

Main parameters LBW

- Spot diameter (laser characteristic).
- Focalisation.
- Beam peak power.
- Pulse – percentage and frequency.
- Welding speed.
- Shielding and purging gases.
- Angle of incidence.

Cross-section of cooling tube



Cross-section of capillary and beam screen weld

2 – Description of equipment

Types of EBW guns

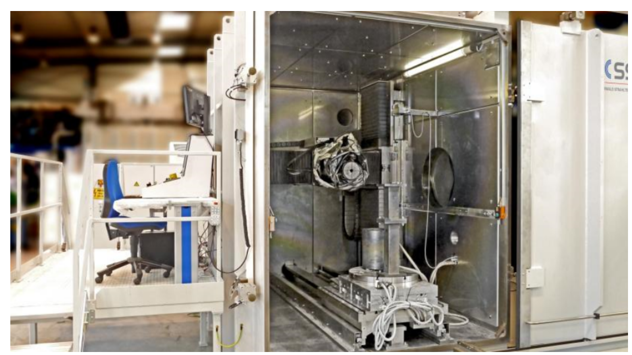
- Low voltage (0 < HV ≤ 60 kV)
- High voltage (60 < HV ≤ 150 kV)

External guns (vertical / horizontal)

- Fix

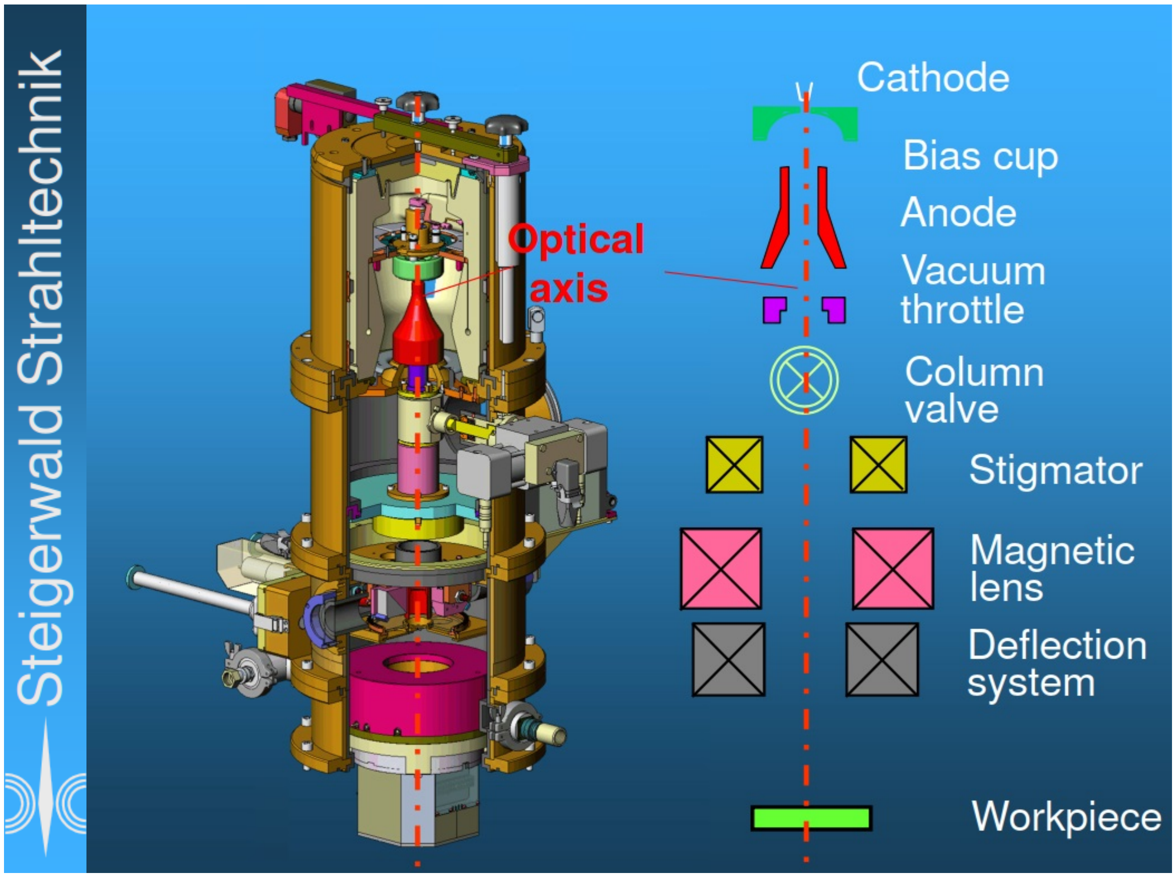
- Mobile

Internal guns

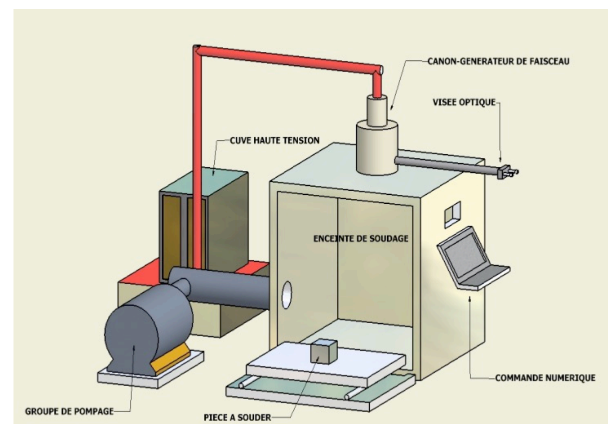


2 – Description of equipment

Main components in a EBW installation

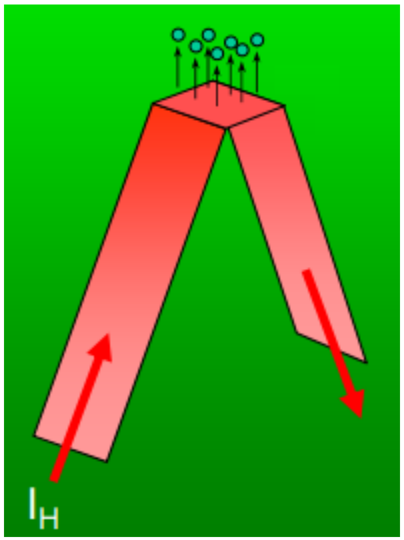


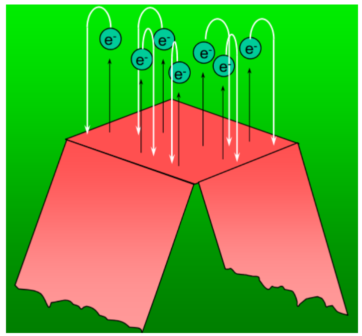
- Vacuum chamber.
- Vacuum pumps.
- HV power supply.
- EB gun.
- Cooling system.
- CNC machine.



2 – Description of equipment

EBW – The cathode





Current density j

$$j = R \cdot T^2 \cdot e^{-\frac{\varnothing}{k \cdot T}}$$

R Richardson constant

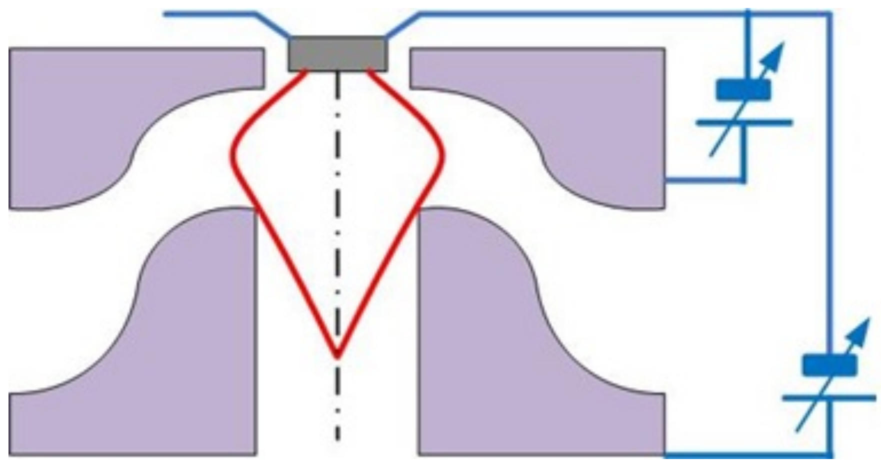
T Absolute temperature

$\varnothing$ Work function

k Boltzmann constant

$k = 1.38 \cdot 10^{-23}\ J \cdot K^{-1}$

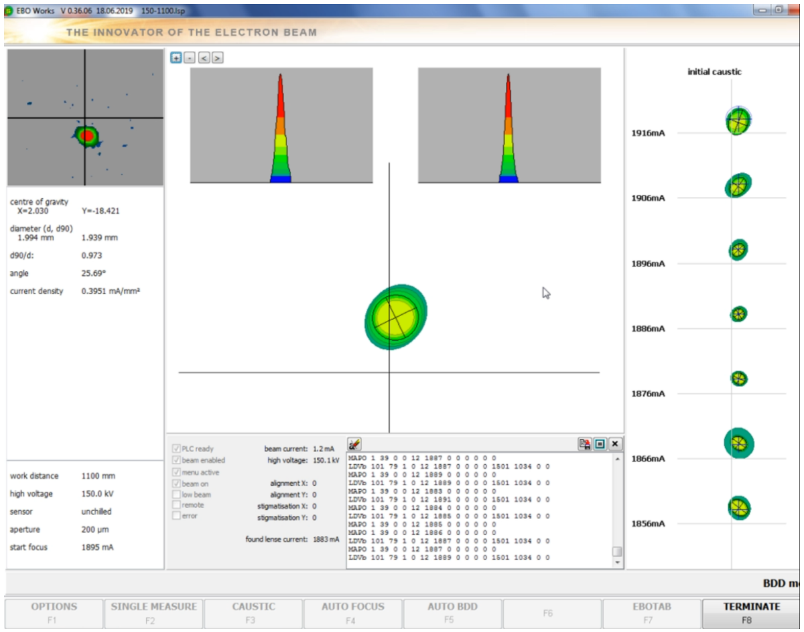
$R_W = 60 - 100\ A \cdot cm^{-2} \cdot K^{-2}$



BIAS voltage
0 – 4000 V

HV
60 – 150 kV

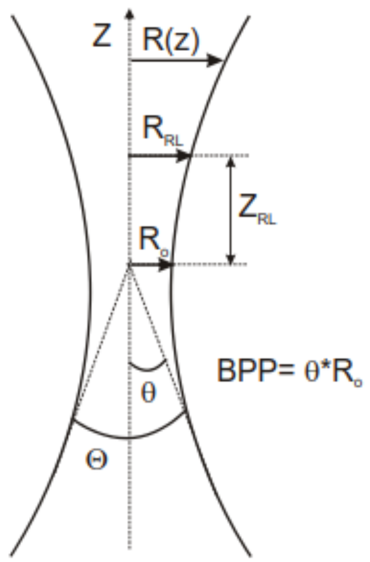
2 – Description of equipment



Main parameters EBW

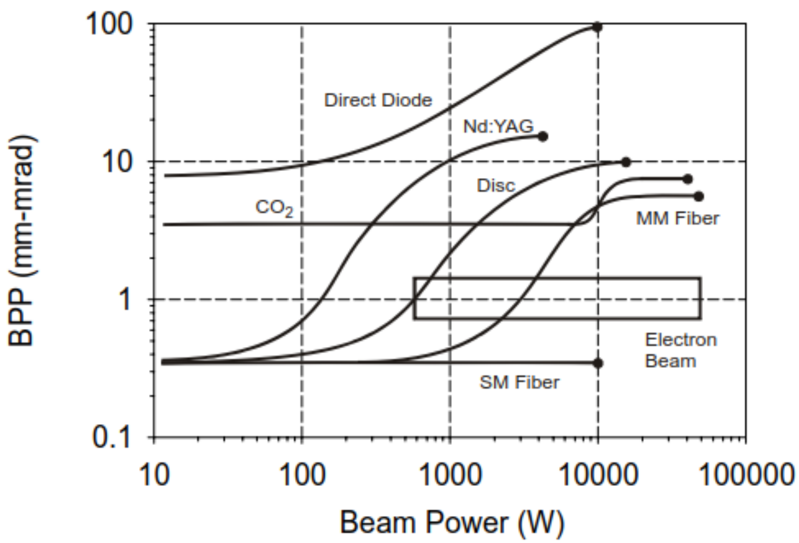
- Working distance
- Focus current
- High Voltage
- Beam Current
- Welding speed
- Vacuum pressure
- AC deflection
- Beam pulse

2 – Description of equipment



Short working distance → θ ↑ R_o ↓

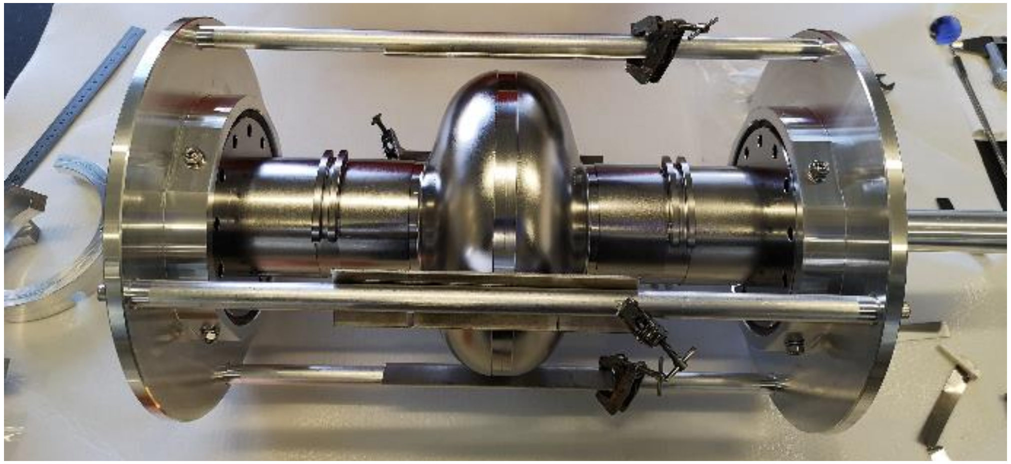
Long working distance → θ ↓ R_o ↑

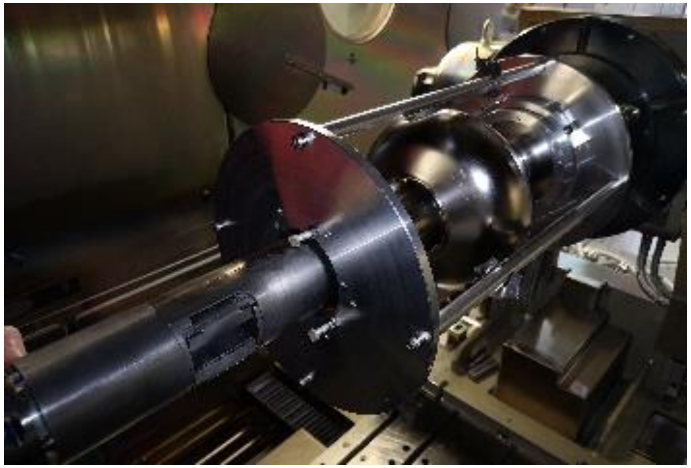


Source: LLNL-BOOK-417590 (2009)

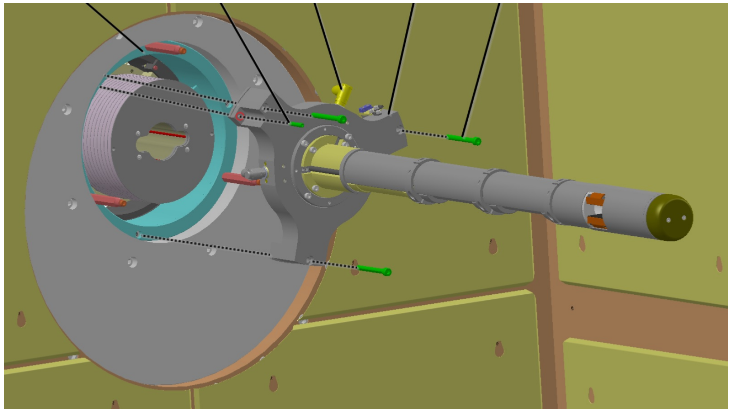
2 – Description of equipment

EB DEFLECTOR FOR INNER WELDING

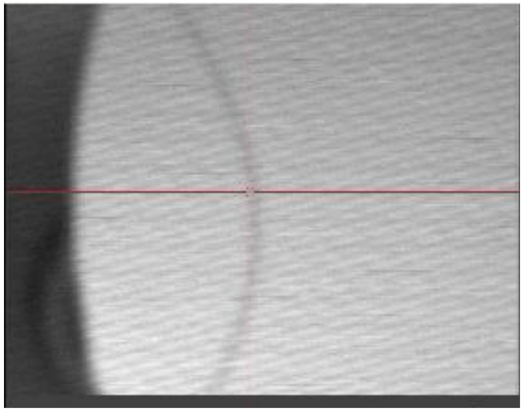




1.3 GHz KEK niobium cavity



EB deflector

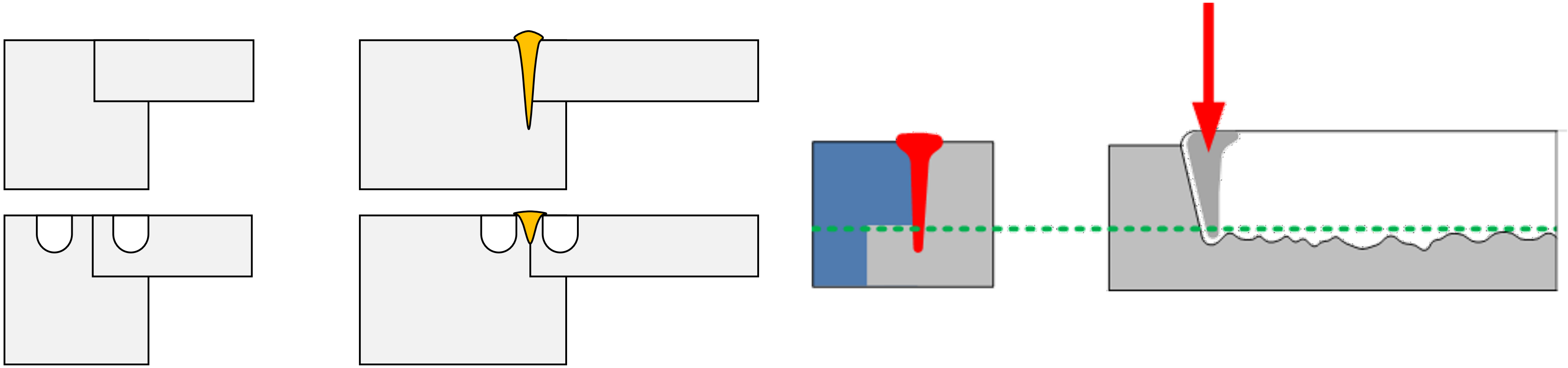


EO view equator joint

3 – Beam welded assemblies – joint design and preparation

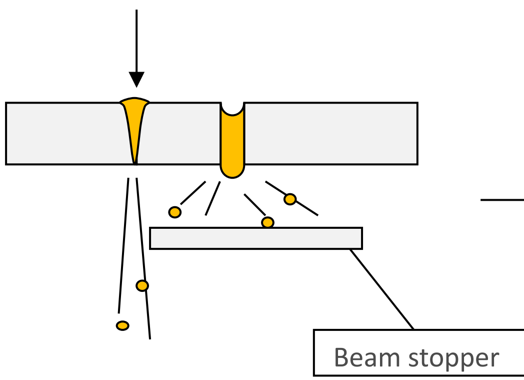
Partial penetration welds

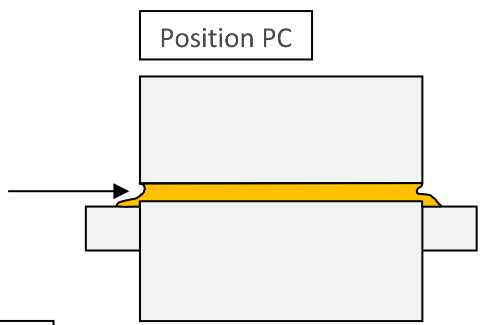
- Frequently used since the weld bead tends to have good visual aspect.
- Root defects called «spikes» are intrinsic to this type of welds when using sharp focus.
- Degassing of weld pool occurs only from one side, which can lead to a greater porosity rate.
- For thick plates (limit approximately around 60 mm) the horizontal position is recommended.



Full penetration welds

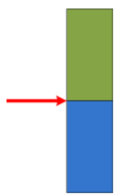
- Degassing from both sides which limits porosity.
- No spikes.
- When welding in vertical position, depths of penetration higher than 30mm become difficult. Geometrical imperfections appear, such as undercuts and shrinkage grooves, leading to re-machining operations to meets quality requirements.
- When welding in keyhole mode spattering is unavoidable in the root side. Severity of this phenomena increases with the thickness of the material. Beam stoppers are used to minimise this issue and protect the inner side of the piece from the beam. The beam stopper is often melted down by the beam, so pollution may occur in case it's not clean or material is inadequate.



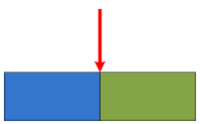


3 – Beam welded assemblies – joint design and preparation

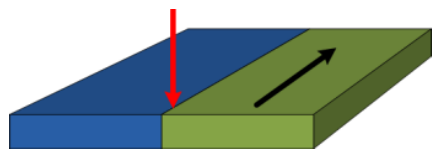
Types of welds



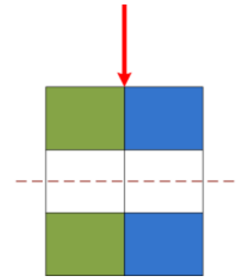
Horizontal (PC)



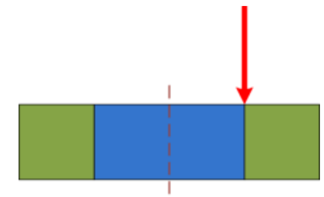
Vertical (PA)



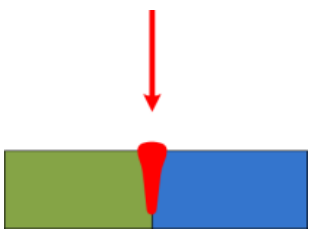
Linear weld



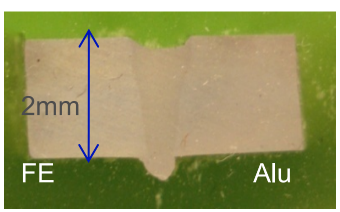
Radial weld

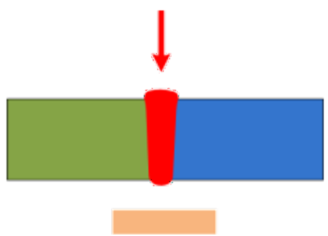


Axial weld

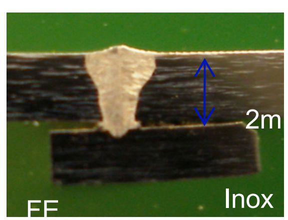


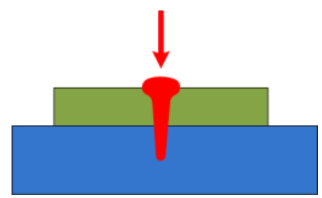
Partial penetration



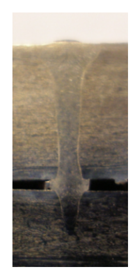


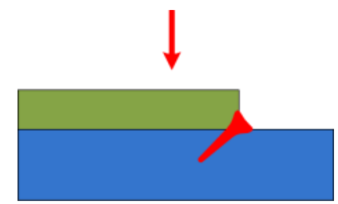
Full penetration



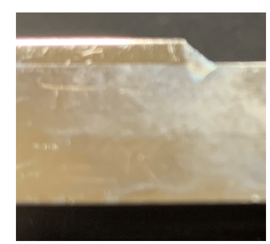


Stake weld





Fillet weld

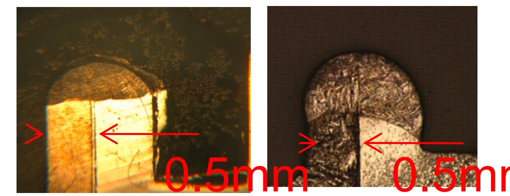


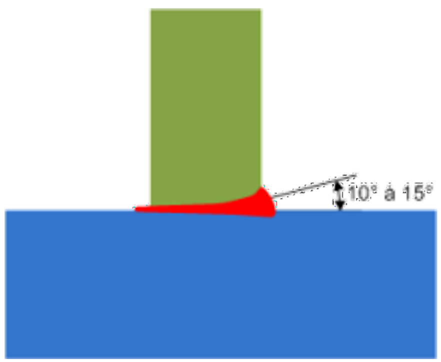
3 – Beam welded assemblies – joint design and preparation

Types of welds

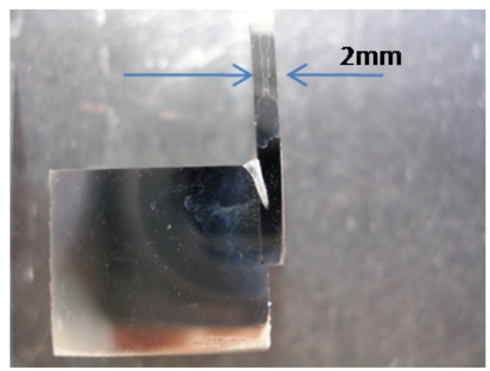
Step or key joint
(not allowed for some UHV applications)

Backing strip or ring





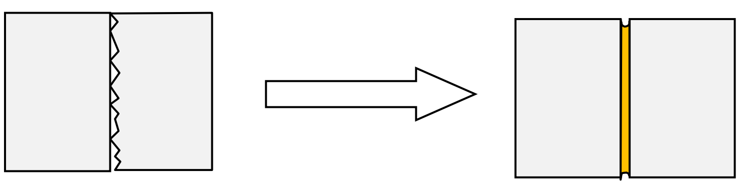
T joint



Edge joint

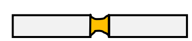
Machining

- Ra 1.6 / 3.2 (N7 / N8) is the required quality for the joint surface.
- Ideally, all the surfaces in the vicinity of the weld bead must be machined, except for thin cold rolled products (thicknesses below 5mm approximately).
- If beam welding is performed near a brazed joint and after the brazing operation, attention must be paid to the absence of brazing filler in the weld joint.



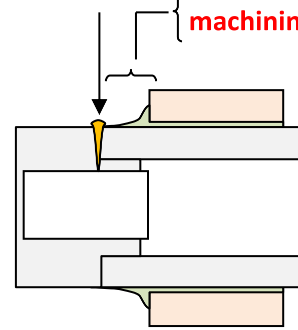
Rough machining

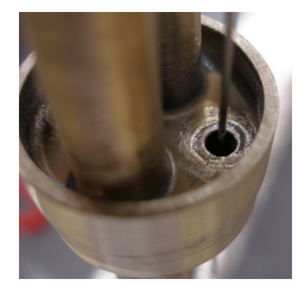
Lack of thickness at the weld bead



Consequences
Shrinkage
Porosity rate
Residual stresses

Brazing filler – to be removed by machining before beam welding

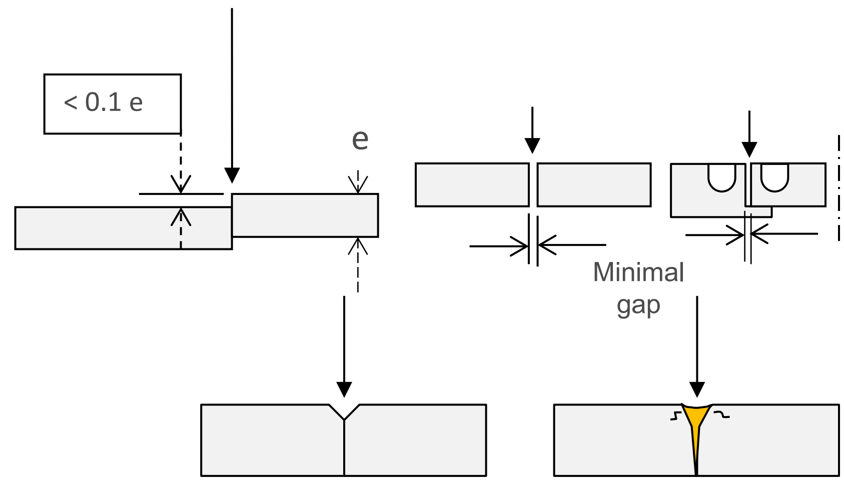


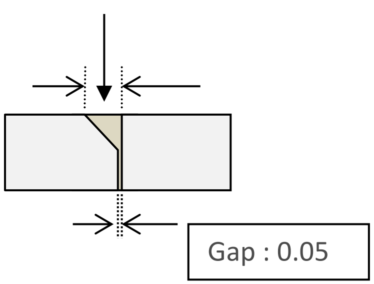


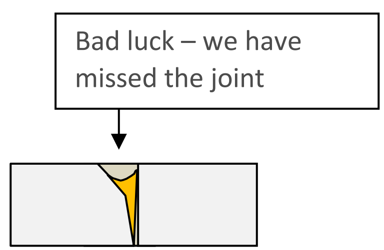
3 – Beam welded assemblies – joint design and preparation

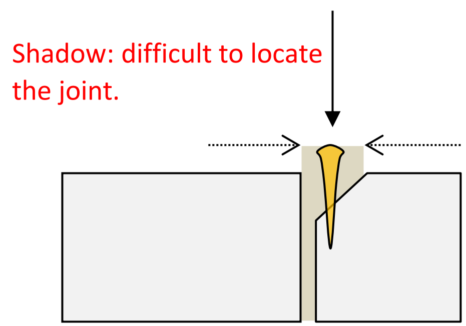
- Tolerances will depend on the type of weld an accuracy of the assembly. The gap shall be the minimum possible and maximum misalignment is 10% of the thickness (usually much less than this value).

- Chamfers are not allowed. They create high stresses in the head of the weld (more critical for small depths of penetration). In addition, they produce a shadow which impedes the accurate positioning of the beam on the joint.



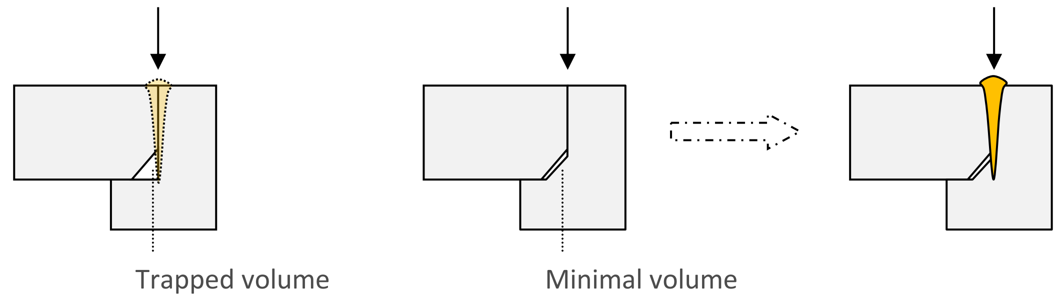


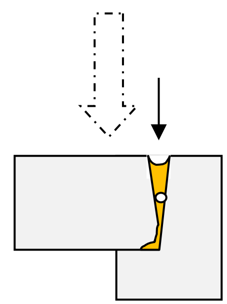




3 – Beam welded assemblies – joint design and preparation

- Trapped volumes must be minimised.
- Pressure differences in the vicinity of the weld might produce critical defects. The pressure of the trapped gas increases greatly due to the high temperature and create important instabilities in the molten pool (i.e. violent spattering, big pores).

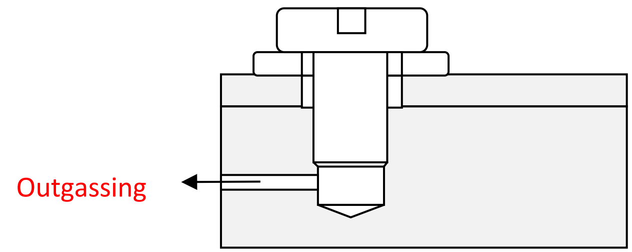




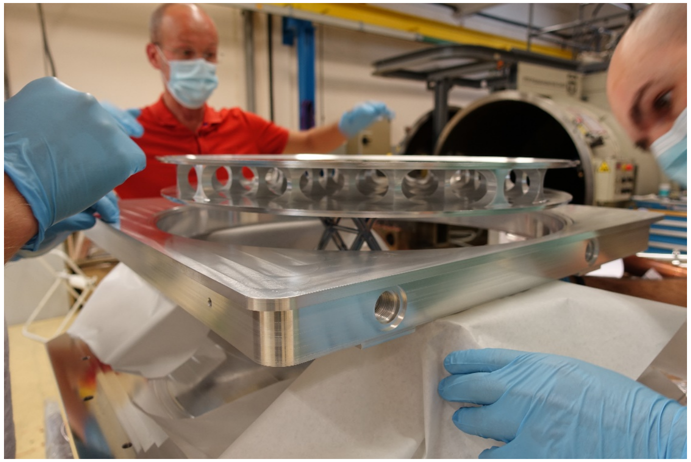
Laser is less sensible to this problem since it usually works at atmospheric pressure

3 – Beam welded assemblies – joint design and preparation

- For EBW, tooling must not be ferromagnetic in order to prevent beam deviations. Trapped volumes shall also be avoided to minimise pumping time.



- For tight adjustments, orientation of the pieces is some times not possible once fitted, specially when they are degreased (high risk of galling). Heating up the external piece makes the task easier, but it allows for one single trial. Not fun when we assemble high added value components.

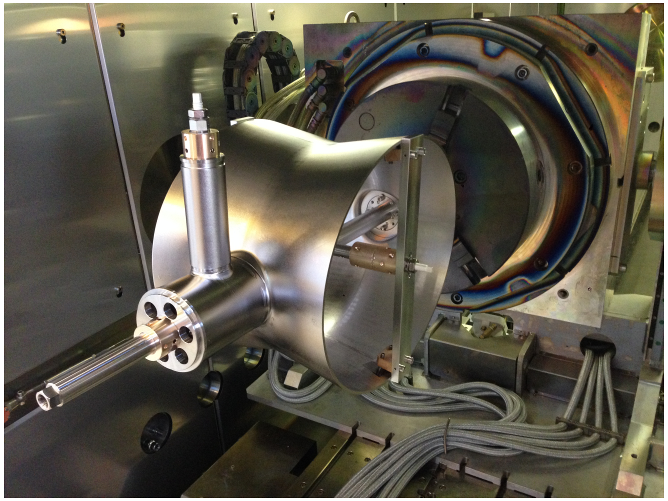


- Tooling design has to take into account the thermal loads and fusion temperatures of the material to avoid bonding or melting. In particular, aluminium tooling are not recommended in the vicinity of the joint when welding cooper of niobium due to high risk of pollution for the base material.

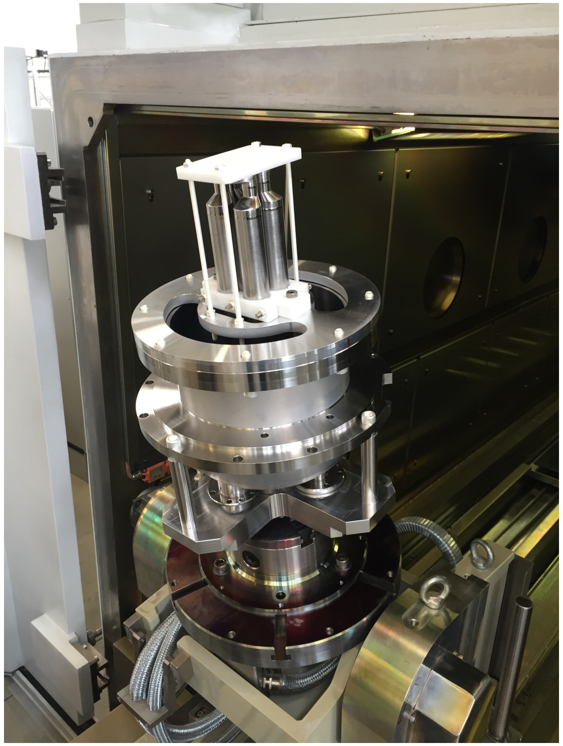
3 – Beam welded assemblies – joint design and preparation

- Tooling design and quality is of crucial importance for the success of the weld. Ideally it should be taken into account already at an early stage of the design phase, otherwise complexity and cost might be increased.

- Tooling represents often an important part of the welding costs, specially for prototypes and short series of components.



DQW cavity body

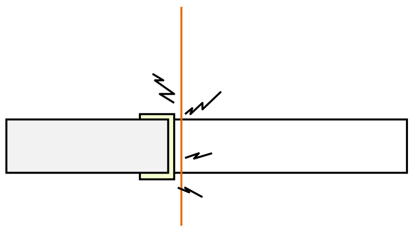


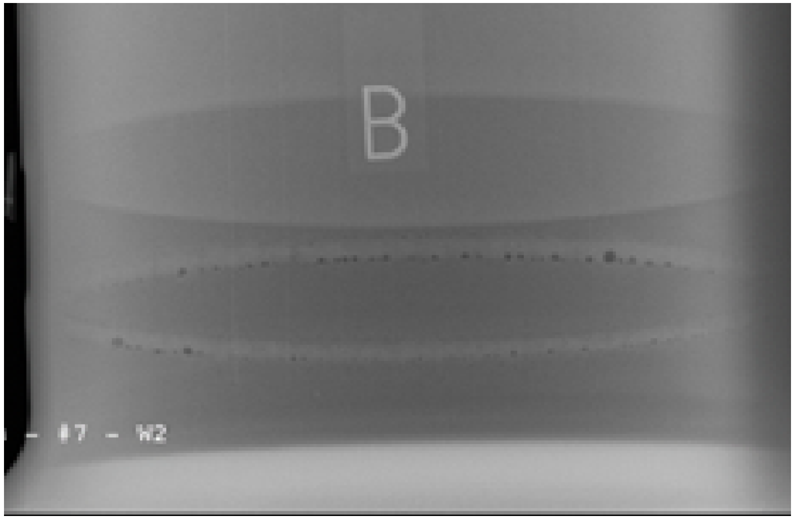
QPR Resonator

3 – Beam welded assemblies – joint design and preparation

Surface treatment

- Degreasing and chemical etching are commonly employed. The choice depends on the material and its application.
- Electrical Discharge Machining produce an important oxidation. This oxides layer has to be compulsory removed before welding. Machining is the preferred method, removing at least 200 µm.
- The same applies for water jet cutting. Inclusions of abrasives have to be removed by machining.





1.3 GHz copper cavity – iris weld (Courtesy of A. Porret)

4 – Weldability of materials by BW

Steels and other ferrous alloys

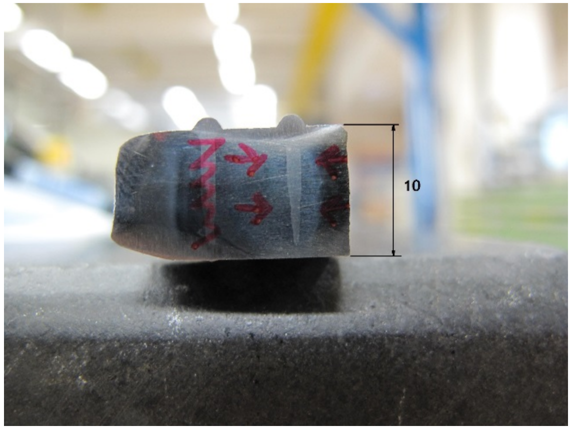
See also → CAS course on "Mechanical & Materials Engineering", S. Sgobba, Steels & Stainless Steels

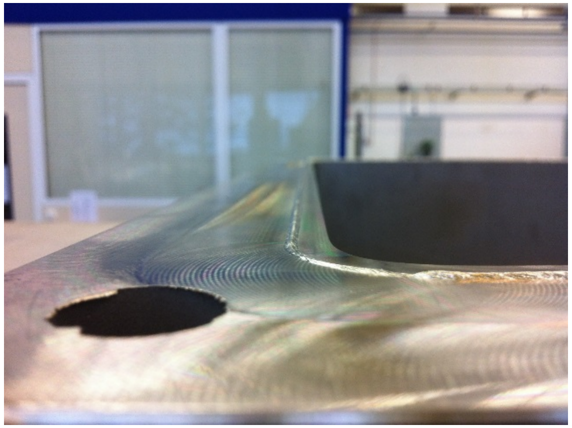
- In general, steels and ferrous alloys which are weldable by arc techniques can also be welded by LB and EB.
- Austenitic stainless steel: good weldability. Attention to degassing for grades with high nitrogen content (304LN, 316LN), specially when welding under vacuum.
- Duplex: nitrogen degassing favours ferrite formation → decrease of corrosion resistance.

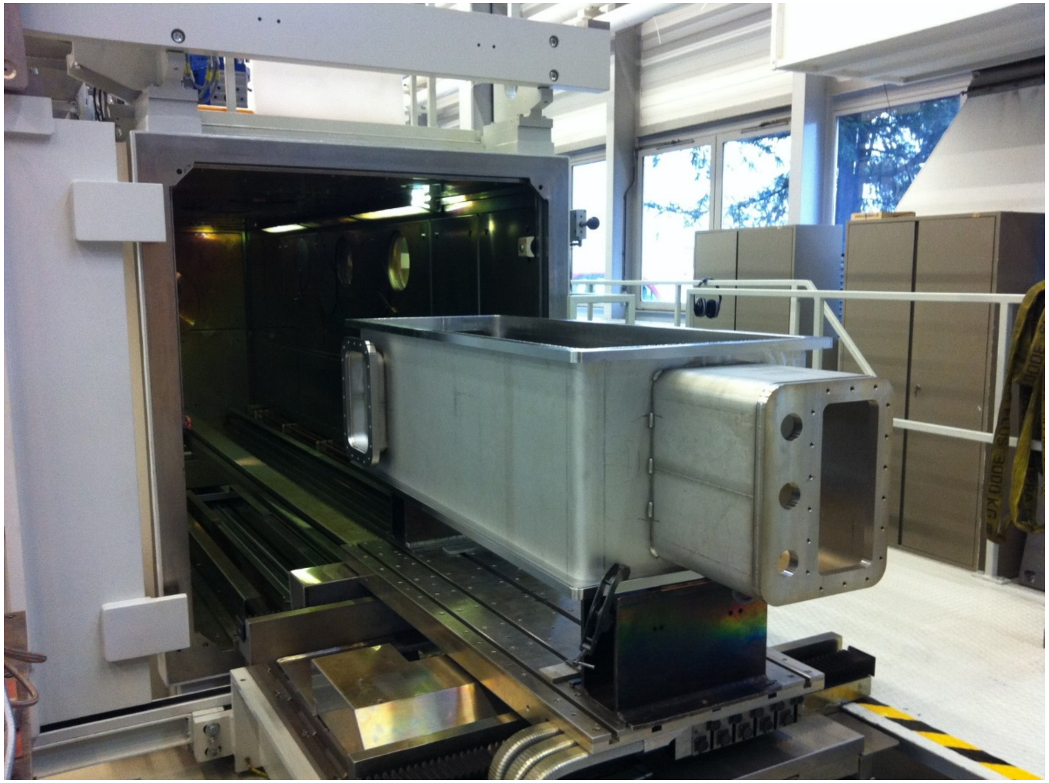
Ni alloys

- Pure Ni and most of Ni-Fe alloys can be welded by both LB and EB.
- Ni-Cu alloys are weldable by EB (also LB but with greater difficulties).

4 – Weldability of materials by BW







HiRadMat vacuum tank

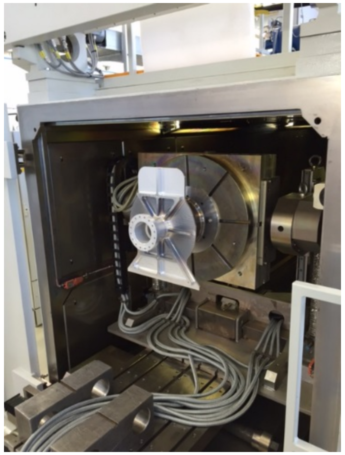
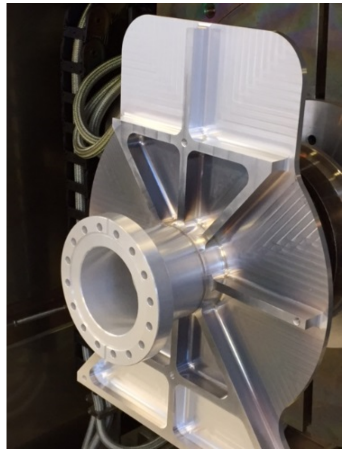
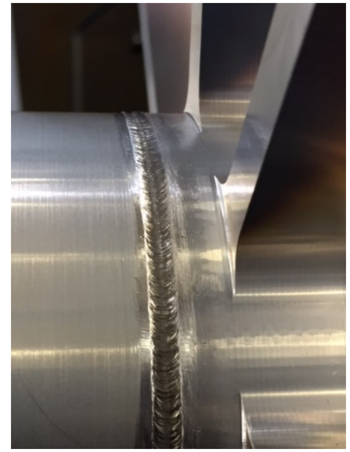
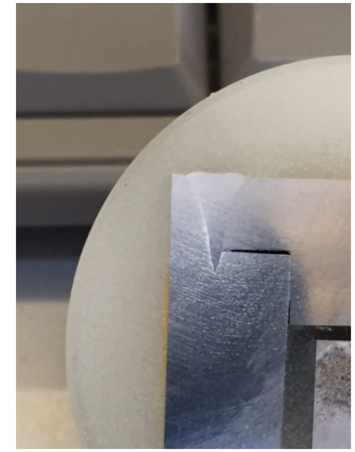
4 – Weldability of materials by BW

Aluminium and its alloys

See also → CAS course on "Mechanical & Materials Engineering", I. Avilés, Non – ferrous materials.

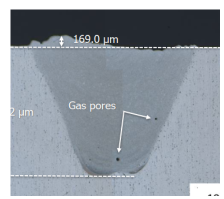
- Electrons destroy the alumina layer easily. Depths of penetration up to 200 mm with a good aspect ratio are obtained with EBW.
- Despite high surface reflectivity to infrared and near infrared laser radiation, good results are also obtained with laser for low thicknesses. CO_2 and powerful fibre laser can achieve penetrations in the range of 20-30 mm.
- Series 5000 (AlMg): good weldability (risk of porosity due to Mg degassing under vacuum).
- Series 2000 (AlCu), Series 4000 (AlSi) and series 6000 (AlMgSi): attention must be paid to the risk of hot cracking.
- For castings, porosity rate is very high (high H_2 content). Welding under vacuum not recommended.

4 – Weldability of materials by BW

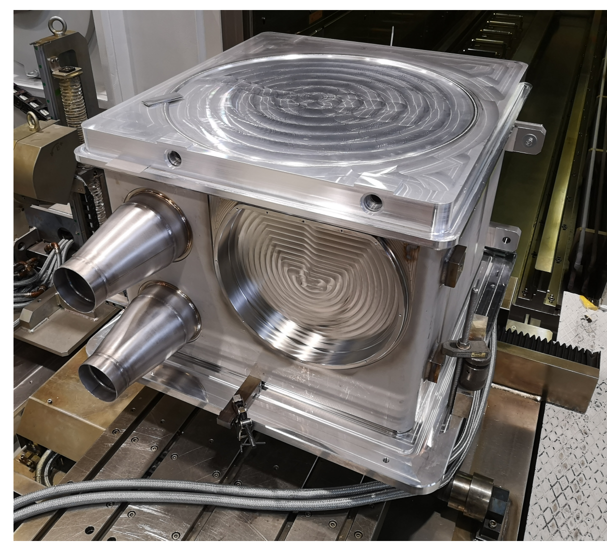





CLIC sub-harmonic buncher





n_TOF target #3



4 – Weldability of materials by BW

See also → CAS course on “Mechanical & Materials Engineering”, I. Avilés, Non – ferrous materials.

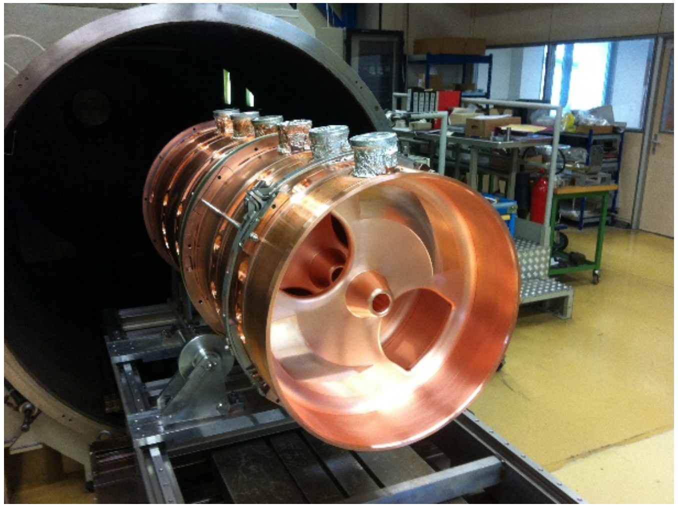
Copper and copper alloys

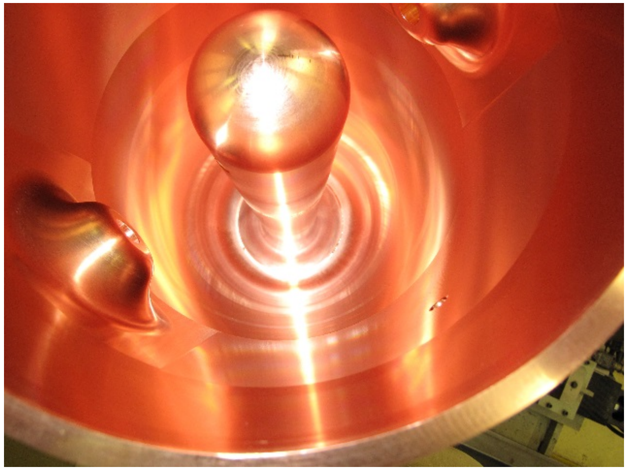
- Most of cooper alloys (except for brass, Zn boiling point 910°C) are weldable by EBW. Welding by laser is very difficult due to reflection. Green lasers (wavelength around 500 nm) improve the absorption coefficient.

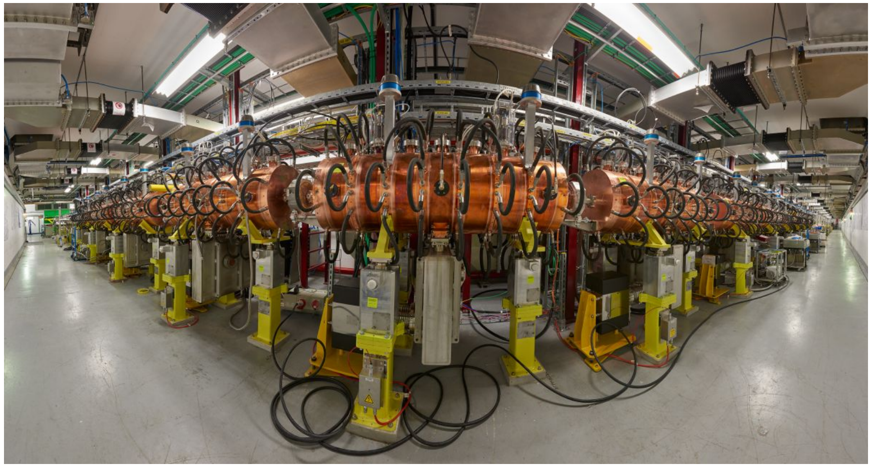
- For OF and OFE copper (Oxygen 0.001% max) weldability is good. The physical properties of cooper limit the depth of penetration.

- High thermal conductivity and thermal expansion coefficient lead sometimes to important welding shrinkage depending on the heat input. Fitting needs to be tight to homogenize heat distribution (depth of penetration is very sensible to this).

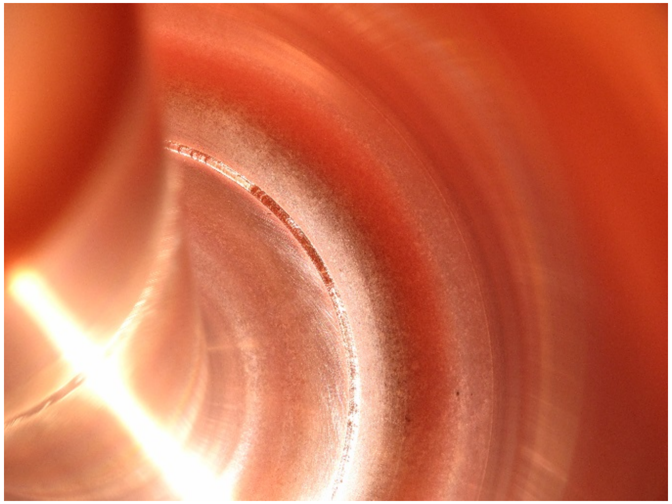
4 – Weldability of materials by BW





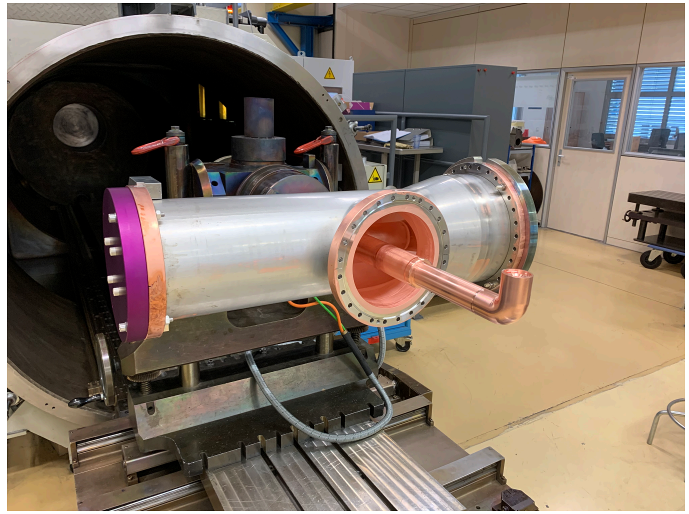


PIMS (Pi-Mode Structures) for LINAC 4

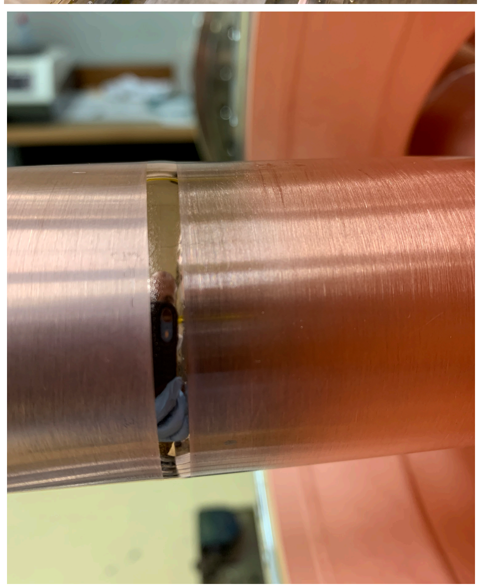


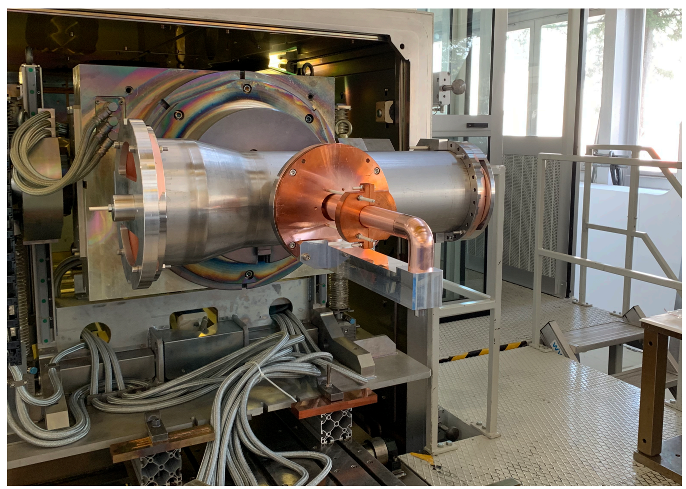
HIE (High Intensity and Energy) ISOLDE cavity

5 – Weldability of materials by BW



SPS 200 MHz antenna



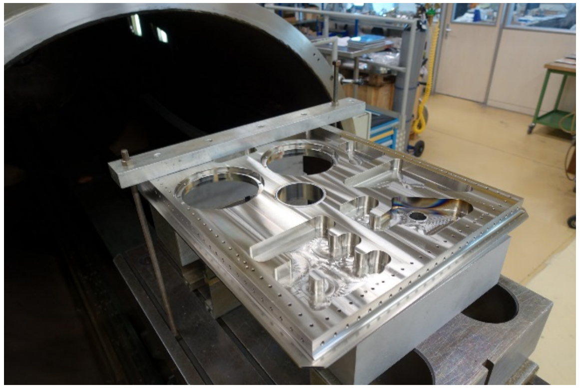


4 – Weldability of materials by BW

Refractory and reactive metals

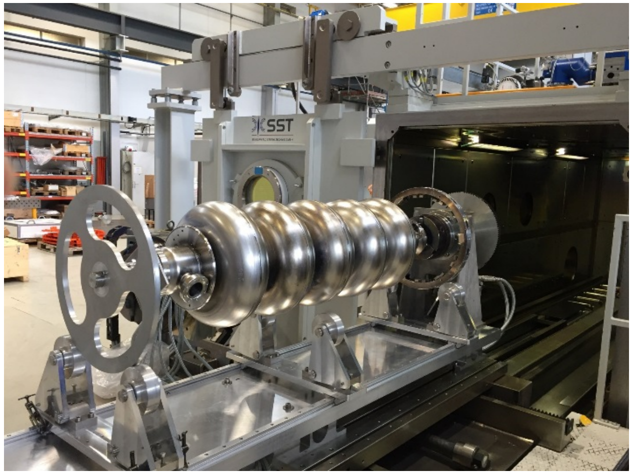
See also → CAS course on "Mechanical & Materials Engineering", I. Avilés, Non – ferrous materials.

- Ti and its alloys have a good weldability by EB and LB. Welding under vacuum is preferred.
- Nb has a very good weldability, with special attention to the quality of vacuum. Welded by EB (P < 5 x 10^{-5} mbar).
- W, Mo and its alloys are also weldable, but with very low ductility of the joint.

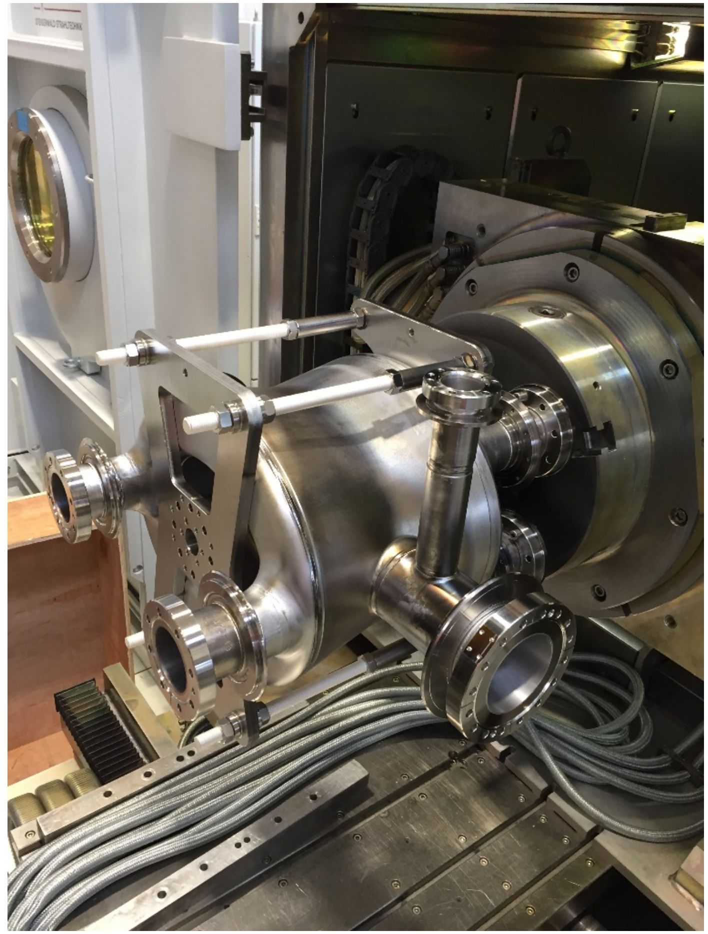


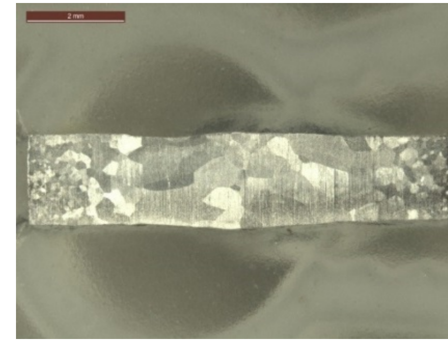
DQW (Double-Quarter Wave) crab cavity He tank

4 – Weldability of materials by BW



SPL (Superconducting Proton Linac) 704 MHz cavity





DQW crab cavity and HOM (High-Order-Modes) coupler

5 – Welding qualifications

- ISO 15614-11

Specification and qualification of welding procedures for metallic materials – Welding procedure test. / Part 11: Electron and laser beam welding.

- ISO 13919

Electron and laser beam welded joints – Guidance on quality levels for imperfections.

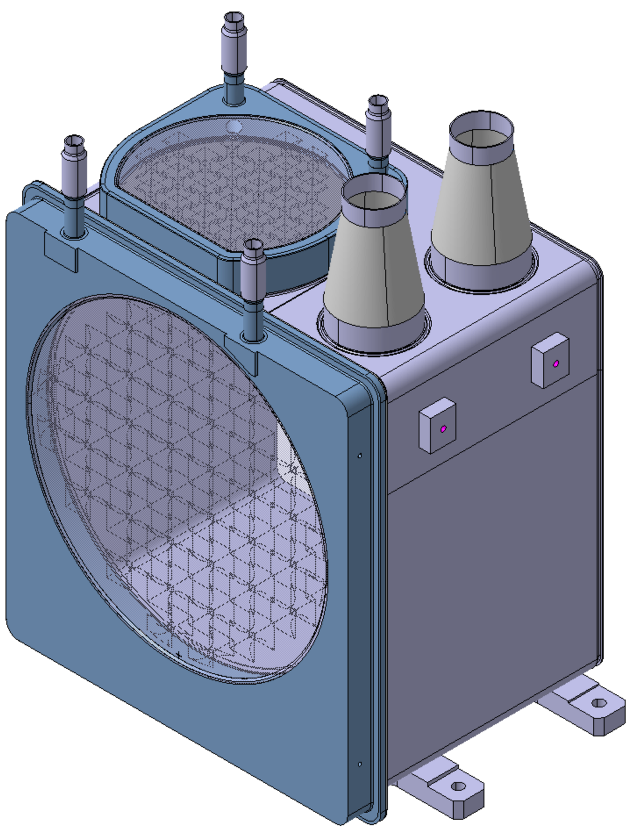
Part 1: Steel

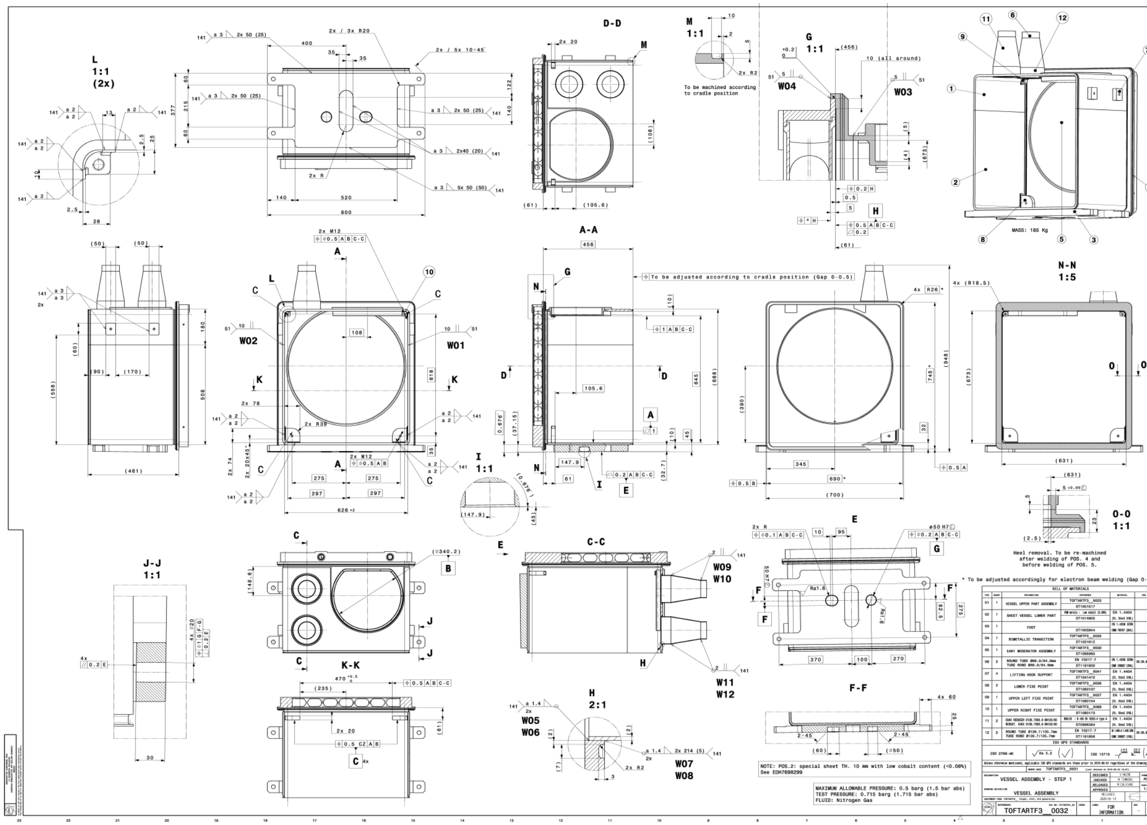
Part 2: Aluminium, magnesium and their alloys and pure copper.

Moderate → D / Intermediate → C / Stringent → B

5 – Welding qualifications

nTOF target # 3





5 – Welding qualifications

WELDING BOOK / CAHIER DE SOUDAGE :												nTOF Target #3			REV. 3 / DATE: 29-Jul-20	EDMS: 2166338 / JOB: J3054531	Issued/Réalise: Julien DEBEUX (I.W.E)
Weld N. / N° soudure	Dwg's reference / Références plans de détail	Joint Type / Type de joint	Dimension: Øext [mm]	Dimension: Thickness [mm]	Dimension: Throat Pentration [mm]	Dimension: Materials	Process / Procédé	WPS / DMOS Descriptif de Mode Opératoire de Soudage	PQR / QMOS Qualification de Mode Opératoire de Soudage	Filler metal / Metal d'apport: Ø & Heta N. / Ø et N° Coulee	Id N° / N° Soudeur: Signature & date	VT (Visual testing): Acceptance Criteria / Niveau d'acceptation: ISO 5817 B	PT (Penetrant testing): Acceptance Criteria / Niveau d'acceptation: ISO 23277, level 2X	RT (Radiographic testing): Acceptance Criteria / Niveau d'acceptation: ISO 17636-2 B	Leak Test / Test d'étanchéité: Report N. / N°Rapport, Signature & date	Pressure Test / Test de pression: Report N. / N°Rapport, Signature & date	Observations
FINAL TARGET - INLET NITROGEN TUBE DN80 EXTENSION																	
W01 to W04	TOFTARTF3__0084	FW	88.9	3 2	z2	EN 1.4306 (304L) EN 1.4306 (304L)	141	2020-39-FW	EN-SE-17-0280	Ø 1.6 N°Coulee: 101954	N°: 1488 Date: 30/07/20	Ref.: J.DEBEUX Date: 06.08.20	Ref.: Date:	Ref.: Date:	Ref.: Date:	Ref.: Date:	
W05	TOFTARTF3__0084	BW	88.9	2	2	EN 1.4306 (304L) EN 1.4404 (316L)	141	2020-34-FW	EN-SE-17-0280	Ø 1.6 N°Coulee: 101954	N°: 1488 Date: 30/07/20	Ref.: J.DEBEUX Date: 06.08.20	Ref.: Date:	Ref.: Date:	Ref.: Date:	Ref.: Date:	
FINAL TARGET - OUTLET NITROGEN TUBE DN80 EXTENSION																	
W01 to W08	TOFTARTF3__0086	FW	88.9	3 2	z2	EN 1.4306 (304L) EN 1.4306 (304L)	141	2020-39-FW	EN-SE-17-0280	Ø 1.6 N°Coulee: 101954	N°: 1488 Date: 6/08/20	Ref.: J.DEBEUX Date: 06.08.20	Ref.: Date:	Ref.: Date:	Ref.: Date:	Ref.: Date:	
W09	TOFTARTF3__0086	BW	88.9	2	2	EN 1.4306 (304L) EN 1.4404 (316L)	141	2020-34-FW	EN-SE-17-0280	Ø 1.6 N°Coulee: 101954	N°: 1488 Date: 6/08/20	Ref.: J.DEBEUX Date: 06.08.20	Ref.: Date:	Ref.: Date:	Ref.: Date:	Ref.: Date:	
FINAL TARGET - OUTLET WATER TUBE DN20 EXTENSION																	
W01	TOFTARTF3__0088	BW	26.9	2	2	EN 1.4404 (316L) EN 1.4404 (316L)	141	2020-32-FW	EN-SE-17-0279	Ø 1.6 N°Coulee: 101954	N°: 1488 Date: 6/08/20	Ref.: J.DEBEUX Date: 06/08/20	Ref.: Date:	Ref.: Date:	Ref.: Date:	Ref.: Date:	
FINAL TARGET - EXTERNAL INLET WATER TUBE DN20																	
W01	TOFTARTF3__0089	BW	26.9	2	2	EN 1.4404 (316L) EN 1.4404 (316L)	141	2020-32-FW	EN-SE-17-0279	Ø 1.6 N°Coulee: 101954	N°: 1488 Date: 6/08/20	Ref.: J.DEBEUX Date: 06/08/20	Ref.: Date:	Ref.: Date:	Ref.: Date:	Ref.: Date:	
FINAL TARGET - CENTRAL INLET WATER TUBE DN20 EXTENSION																	
W01	TOFTARTF3__0090	BW	26.9	2	2	EN 1.4404 (316L) EN 1.4404 (316L)	141	2020-32-FW	EN-SE-17-0279	Ø 1.6 N°Coulee: 101954	N°: 1488 Date: 6/08/20	Ref.: J.DEBEUX Date: 06/08/20	Ref.: Date:	Ref.: Date:	Ref.: Date:	Ref.: Date:	
FINAL TARGET - OUTLET NITROGEN LINE																	
W01 to W04	TOFTARTF3__0104	BW	88.9	2	2	EN 1.4306 (304L) EN 1.4404 (316L)	141	2020-34-FW	EN-SE-17-0280	Ø 1.6 N°Coulee: 101954	N°: 1488 Date: 29/07/20	Ref.: J.DEBEUX Date: 30/07/20	Ref.: Date:	Ref.: Date:	Ref.: Date:	Ref.: Date:	
W05	TOFTARTF3__0104	BW - Piquage	88.9	2	2	EN 1.4306 (304L) EN 1.4306 (304L)	141	2020-22-FW	EN-SE-17-0280	Ø 1.6 N°Coulee: 101954	N°: 1488 Date: 28/07/20	Ref.: J.DEBEUX Date: 30.07.20	Ref.: Date:	Ref.: Date:	Ref.: Date:	Ref.: Date:	
W06 to W07	TOFTARTF3__0104	BW - Piquage	88.9	2	2	EN 1.4306 (304L) EN 1.4306 (304L)	141	2020-23-FW	EN-SE-17-0280	Ø 1.6 N°Coulee: 101954	N°: 1488 Date: 28/07/20	Ref.: J.DEBEUX Date: 30.07.20	Ref.: Date:	Ref.: Date:	Ref.: Date:	Ref.: Date:	
W08 to W09	TOFTARTF3__0104	BW	88.9	2	2	EN 1.4306 (304L) EN 1.4404 (316L)	141	2020-34-FW	EN-SE-17-0280	Ø 1.6 N°Coulee: 101954	N°: 1488 Date: 29/07/20	Ref.: J.DEBEUX Date: 30.07.20	Ref.: Date:	Ref.: Date:	Ref.: Date:	Ref.: Date:	
FINAL TARGET - NITROGEN INLET LINE																	
W01 to W03	TOFTARTF3__0094	BW	88.9	2	2	EN 1.4306 (304L) EN 1.4404 (316L)	141	2020-34-FW	EN-SE-17-0280	Ø 1.6 N°Coulee: 101954	N°: 1488 Date: 30/07/20	Ref.: J.DEBEUX Date: 30.07.20	Ref.: Date:	Ref.: Date:	Ref.: Date:	Ref.: Date:	
FINAL TARGET - BORATED WATER INLET TUBE ASSY																	
W01 to W02	TOFTARTF3__0107	BW	26.9	2	2	EN 1.4404 (316L) EN 1.4404 (316L)	141	2020-32-FW	EN-SE-17-0279	Ø 1.6 N°Coulee: 101954	N°: 1488 Date: 5/08/20	Ref.: J.DEBEUX Date: 06.08.20	Ref.: Date:	Ref.: Date:	Ref.: Date:	Ref.: Date:	
FINAL TARGET - BORATED WATER OUTLET TUBE ASSY																	
W01 to W02	TOFTARTF3__0109	BW	26.9	2	2	EN 1.4404 (316L) EN 1.4404 (316L)	141	2020-32-FW	EN-SE-17-0279	Ø 1.6 N°Coulee: 101954	N°: 1488 Date: 5/08/20	Ref.: J.DEBEUX Date: 06.08.20	Ref.: Date:	Ref.: Date:	Ref.: Date:	Ref.: Date:	
FINAL TARGET - DEMINERALIZED WATER INLET TUBE ASSY																	
W01	TOFTARTF3__0111	BW	26.9	2	2	EN 1.4404 (316L) EN 1.4404 (316L)	141	2020-32-FW	EN-SE-17-0279	Ø 1.6 N°Coulee: 101954	N°: 1488 Date: 5/08/20	Ref.: J.DEBEUX Date: 06.08.20	Ref.: Date:	Ref.: Date:	Ref.: Date:	Ref.: Date:	
FINAL TARGET - DEMINERALIZED WATER OUTLET TUBE ASSY																	
W01 to W02	TOFTARTF3__0117	BW	26.9	2	2	EN 1.4404 (316L) EN 1.4404 (316L)	141	2020-32-FW	EN-SE-17-0279	Ø 1.6 N°Coulee: 101954	N°: 1488 Date: 5/08/20	Ref.: J.DEBEUX Date: 06.08.20	Ref.: Date:	Ref.: Date:	Ref.: Date:	Ref.: Date:	

REVIEWED & APPROVED / RÉVISÉ ET APPROUVÉ
WELDING ENGINEER /
INGÉNIEUR SOUDAGE

DATE

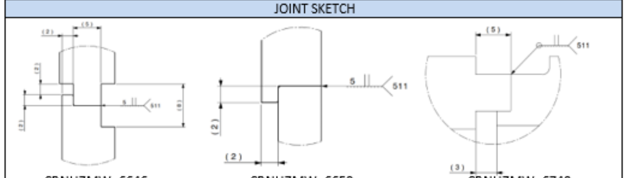
5 – Welding qualifications

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH 1211 Geneva 23 - Switzerland	**PRELIMINARY WELDING PROCEDURE SPECIFICATION**	pWPS No.: pWPS_EBW_PTR_19961 Rev.: 0 Date: 09-06-2020
Operator: MANUEL REDONDAS	*Welding Process: Electron Beam Welding (№ 511 acc. ISO 4063)*	*Location: Building 100*
Ref. WPQR:	*Ref. standard:*	*Job No.: J3054531*
Client: MARCO CALVIANI	*Project: nTOF*	

PREPARATION

Joint configuration: BW	*Joint type:* Horizontal butt weld with step	*Single/Double:* Single
Cleaning: Alc. degreasing	*Welding position:* PA	*Backing:* (Base Metal)

JOINT SKETCH



CRNHZMW_6646 CRNHZMW_6659 CRNHZMW_6740

EQUIPMENT IDENTIFICATION

Welding Machine	PTR 0-30-70 CNC
Gun Type	

PARENT METAL(S)

	Name / Grade	Standard	Group	Delivery cond.	Thickness (mm)	Diameter (mm)
I	*316 L*	*EN 10088-4*	*8.1*	*Plate*	*10*	
II	*316 L*	*EN 10088-4*	*8.1*	*Plate*	*10*	

FILLER METAL

	Trade name	Classification	Group
I			

WELDING PARAMETERS

	First pass	Second pass	Third pass
Vacuum (mbar)			
Pressure in the Gun (mbar)	*<5xE-5*		
High Voltage (kV)	*60*		
Working distance (mm)	*400*		
Prim. Focus (mA) / Focus (mA)	*1000 / 425*		
I_{BEAM} (mA)	*37*		
Adv speed (mm/s)	*12*		
Energy (kJ/mm)	*185*		
Up slope (mm)	*25*		
Overlap (mm)	*15*		
Down slope (mm)	*25*		
Slope Profile	*Linear*		
Travel Direction			

Deflection	*Function*	*7*		
	Frequency (Hz)	*100*		
	Amplitude X	*1*		
	Amplitude Y	*1*		
Pulsation	*Frequency (Hz)*			
	Pulse Interval			

TACK WELDING PARAMETERS

Mask		*High Voltage (kV)*	*60*	
Working distance (mm)	*400*	*Primary Focus (mA) / Focus (mA)*	*1000*	*425*
I_{BEAM} (mA)	*9*	*Adv (mm/s)*	*12*	
Up slope (mm)	*10*	*Tack distance / F2 (mm)*	*20*	
Down slope (mm)	*6*	*Beam On (%):*		
Repartition		*Segments length (mm)*		
Deflection	*Function* 7	*Amplitude X*	*1*	
	Frequency (Hz) 100	*Amplitude Y*	*1*	
Pulsation	*Frequency (Hz):*	*Pulse interval (%):*		

CATHODE

Sectioning (mm) :	*Current control (A) :*
Range	*Ring (mm)*
Heating current (A)	*Type* BK3
Current calibration (mA) 50	

HEAT TREATMENT

Preheat temp.(°C): N.A.	*Interpass temp.(°C):* N.A.	*PWHT procedure:* N.A.

ADDITIONAL COMMENTS

The weld is full penetration (7mm). Backing (2mm) to be removed by machining after EBW.
SW = 54

Test pieces for longitudinal welds CRNHZMW_6646 and CRNHZMW_6659.

Test pieces for corners: CRNHZMW_6738 --> Programs for corners (IB=37 mA / Foc 1000-425 / v = 12 mm/s / N°7 XY1 100 Hz):

- program J3054531_NTOF_COR_OUT_1 (test piece A) - talon à 0°
- program J3054531_NTOF_COR_IN_2 (test piece A) - talon à 30° aprox (voir photos)
- program J3054531_NTOF_COR_IN_1 (test piece B) - talon à 0°
- program J3054531_NTOF_COR_OUT_2 (test piece B) - talon à 30° aprox (voir photos)

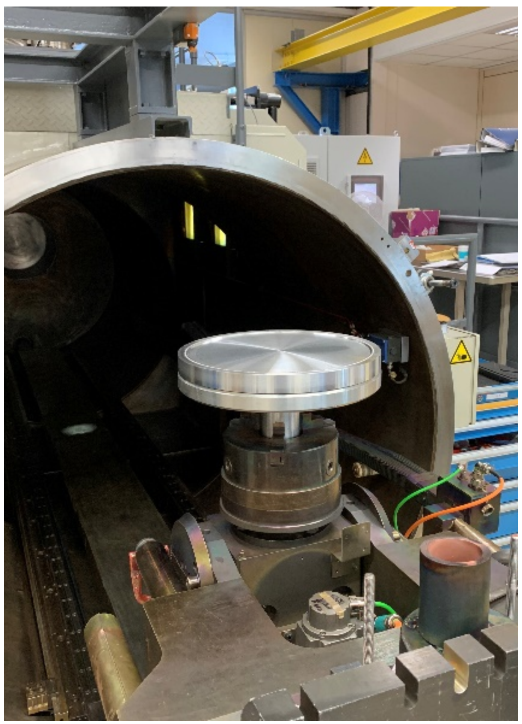
ADDITIONAL INFO ENCLOSED

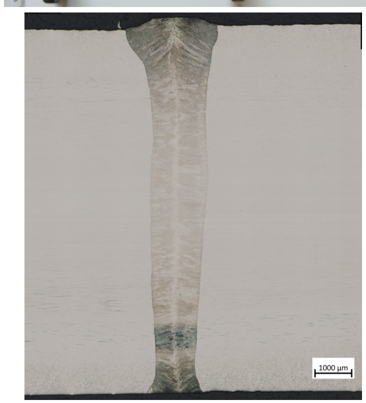
Drawing of the welding configurations for corners.

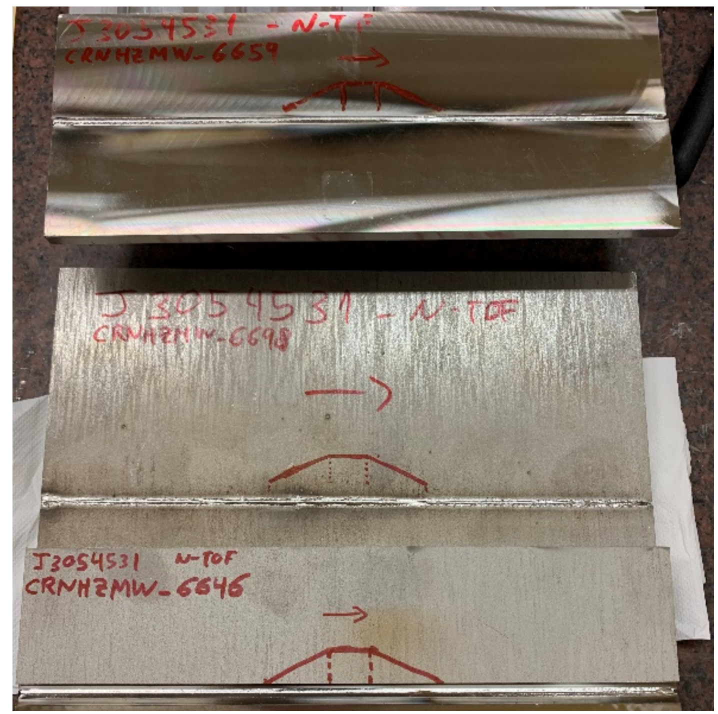
Approved by	Date	Signature
Julien DEBEUX	09/06/2020	International Welding Engineer DEBEUX Julien FR IWE 01436 Association Française du Soudage

5 – Welding qualifications

For a project like nTOF target #3, more time is dedicated to the development of welding parameters and realization of WPQRs than to the welding of the component.



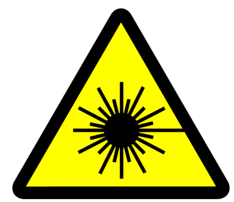




6 – Safety

Potential hazards:

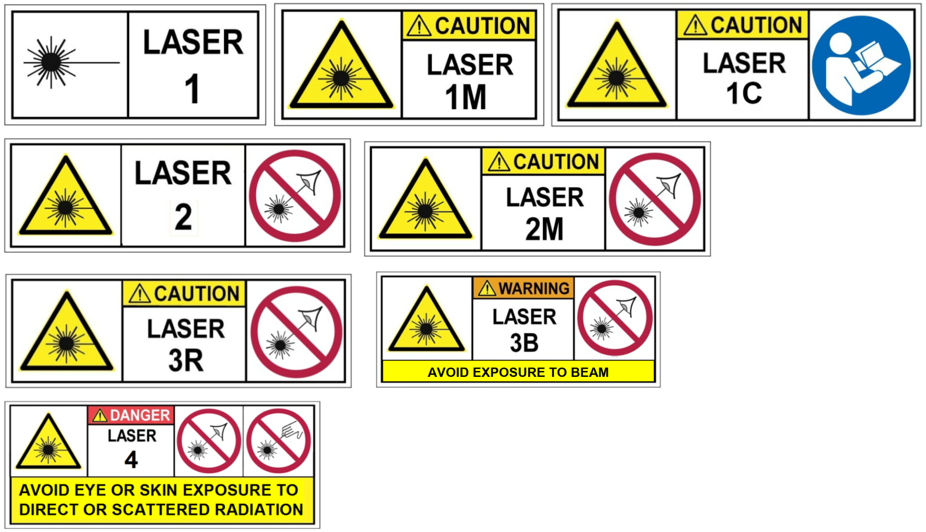
- Electrical shock
- Welding fumes / dust
- X-rays
- Laser radiation
- Vacuum
- Hot surfaces
- Mechanical danger

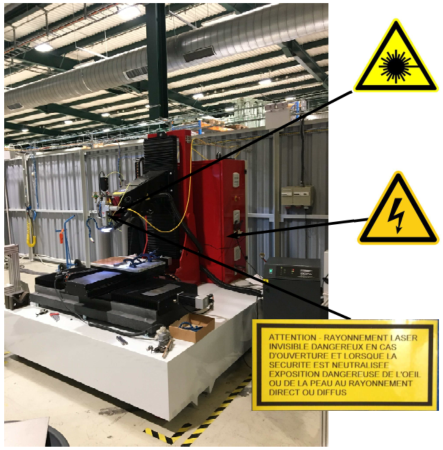


6 – Safety

Laser classification according to IEC 60825-1:2014:

- Class 1 / 1M / 1C
- Class 2 / 2M
- Class 3R / 3B
- Class 4

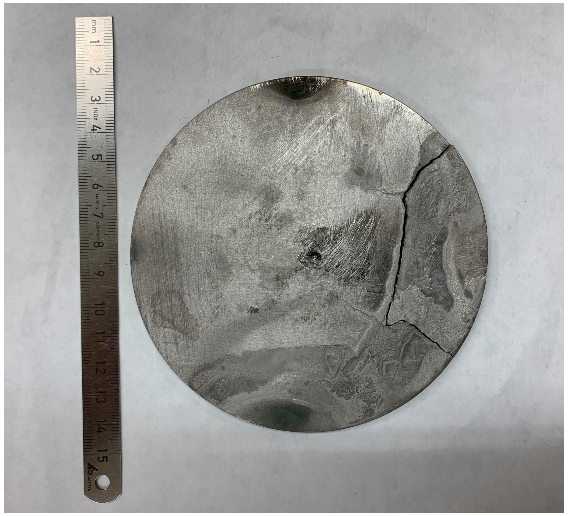




6 – Safety

X-rays at EBW machines

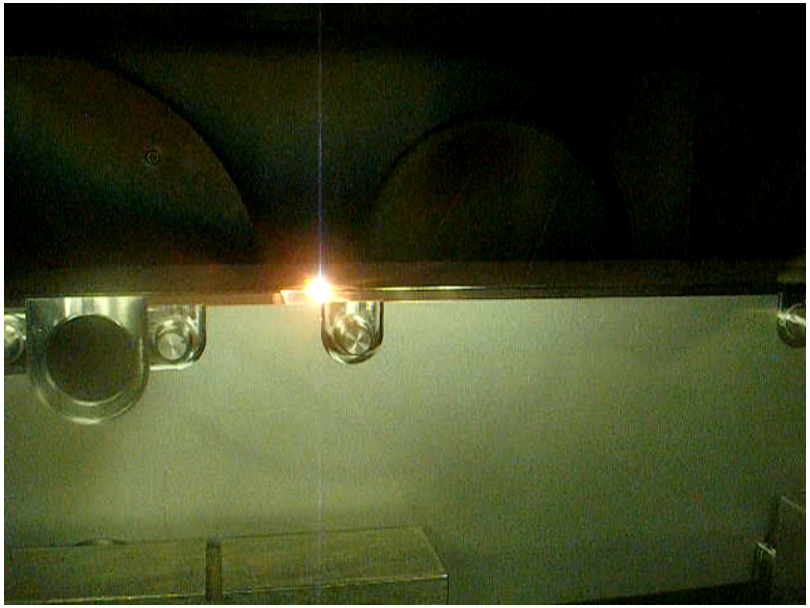
- X-rays intensity increases with beam power (HV, I_B) and with the atomic mass of the material.
- Lead shielding for most of EBW machines, specially HV (150 kV).
- Machines are tested at full power, usually with W.



7 - Conclusions

When to choose beam welding over other fusion welding techniques ?

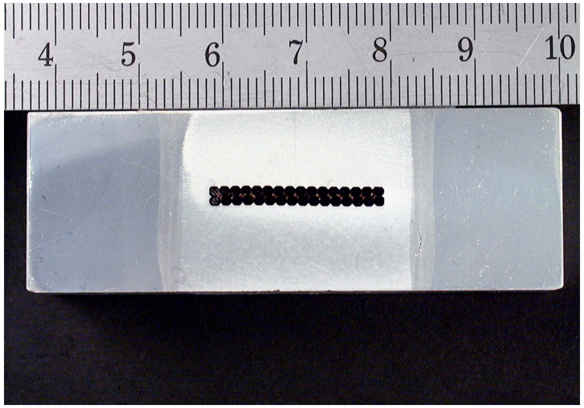
- Minimising distortion – High accuracy.
- Minimising heat input (welding close to brazed joints).
- Dissimilar joints (Ti – Nb, Cu – Nb…).
- Welding refractory metals (low ductility, welding is not possible in many cases).
- Welding under vacuum.



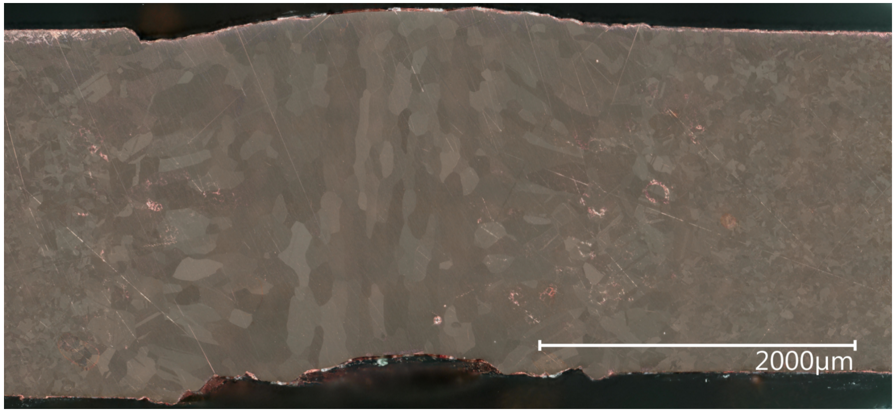
7 - Conclusions

When to choose beam welding over other fusion welding techniques ?

CMS conductor
Al 6082 / Al 99.998%



Heat Exchanger Tubes
OFE Copper



7 - Conclusions

When to choose laser over EB welding ?

- In general, laser is more suitable for low thicknesses (approximately less than 4 / 5 mm) and its faster than EB since vacuum is not needed.

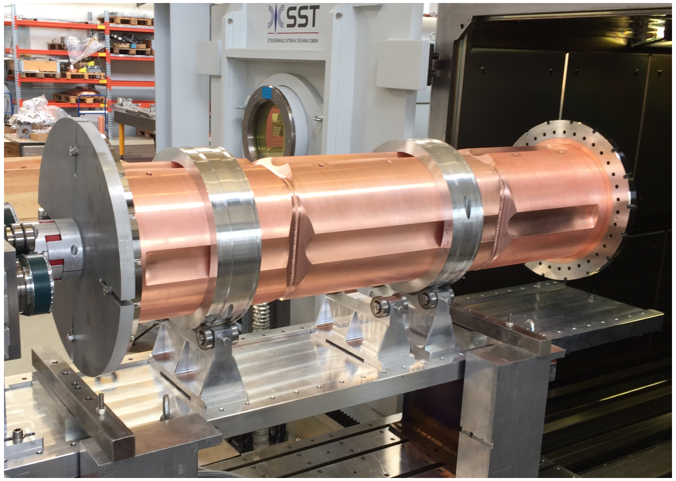
- Big assemblies that don’t fit inside a vacuum chamber.

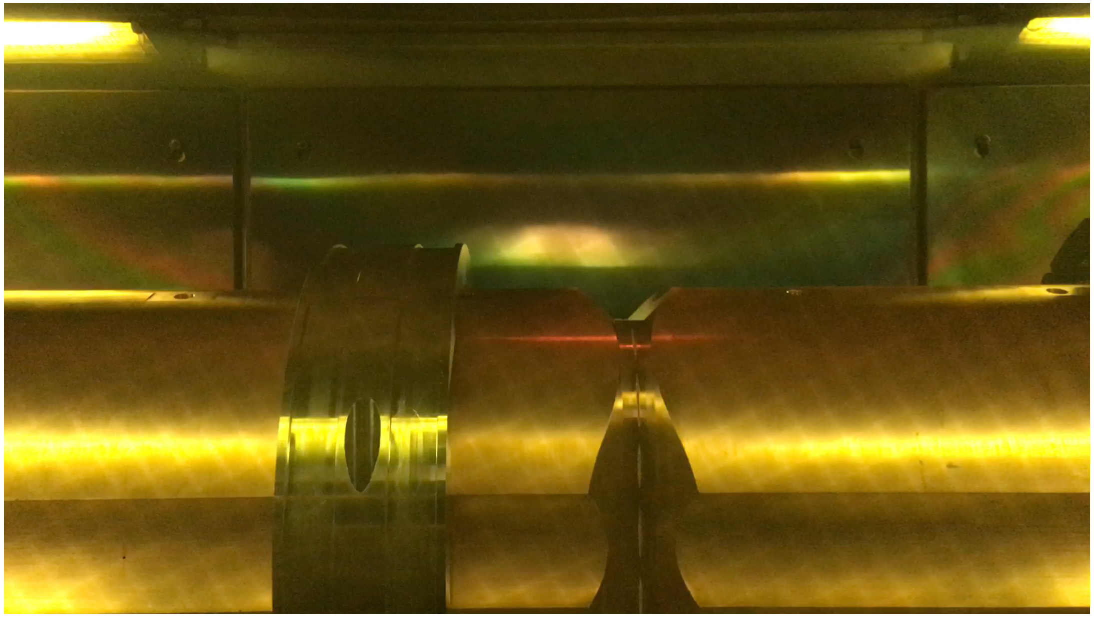
- Robot welding.

7 - Conclusions

When to choose EB over laser welding ?

- Materials for which welding under vacuum is compulsory such as Nb.
- Welding of copper.
- Welding of thick walls.





7 - Conclusions

Basic rules

- No material certificate → no weld.
- Check the design and feasibility of the joints with the welders before manufacturing.
- Surface preparation is of paramount importance.
- Success of the weld depends mainly on the following factors:

  - Base material.

  - Preparation of the joint (machining / surface treatment).

  - Welding tooling.

  - Welding procedure and welder.

Thank you for your attention!

CERN

ENGINEERING DEPARTMENT

6 – Main international standards related to BW

- ISO 15609 parts 3 and 4

Specification and qualification of welding procedures for metallic materials — Welding procedure specification — Part 3: Electron beam welding — Part 4: Laser beam welding

- ISO 14732

Welding personnel: qualification testing of welding operators and weld setters for mechanized and automatic welding of metallic materials.

6 – Main international standards related to BW

- ISO 14744 – Acceptance inspection of electron beam welding machines

Part 1: Principles and acceptance conditions
Part 2: Measurement of accelerating voltage characteristics
Part 3: Measurement of beam current characteristics
Part 4: Measurement of welding speed
Part 5: Measurement of run-out accuracy
Part 6: Measurement of stability of spot position

6 – Main international standards related to BW

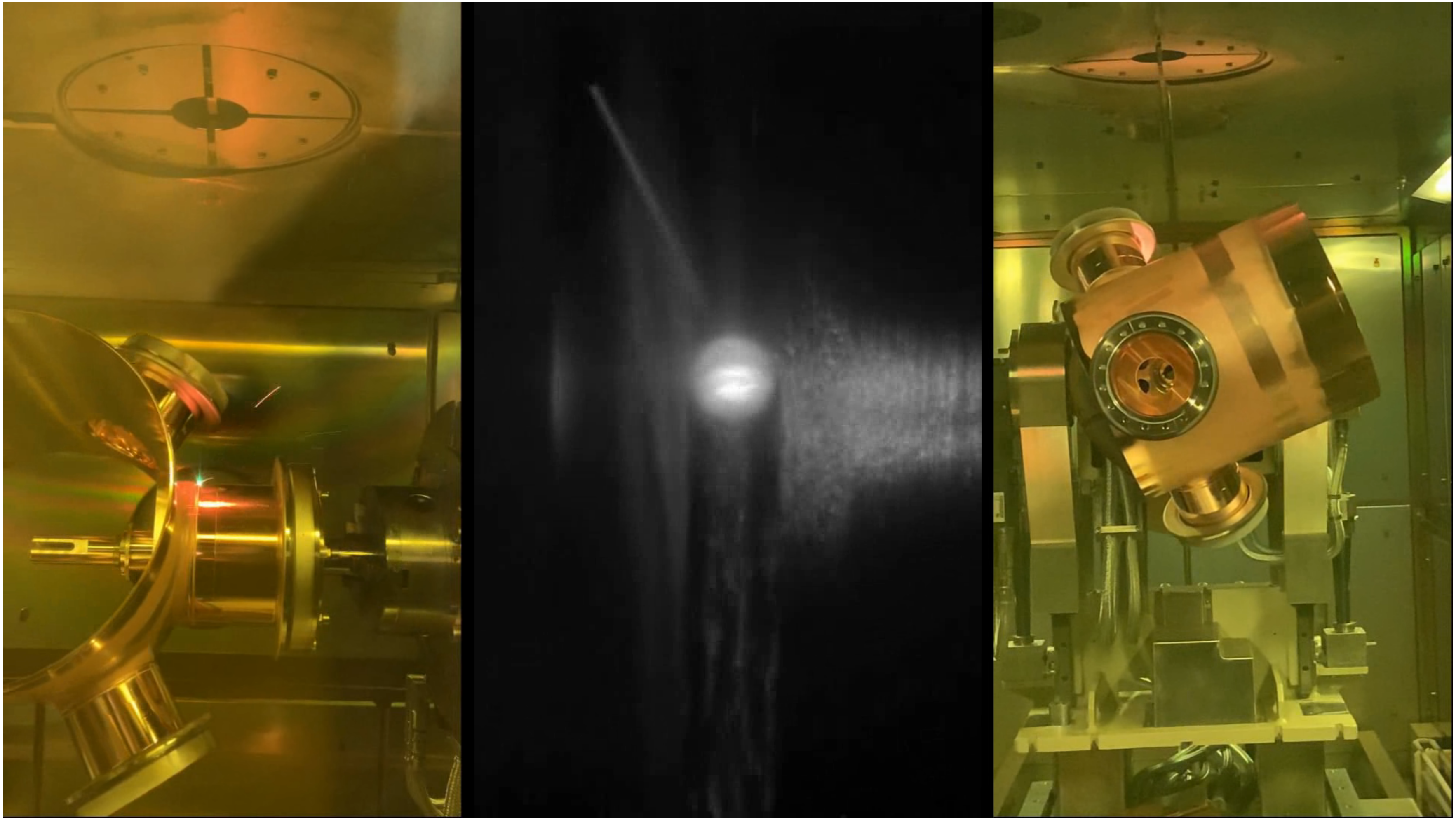
- ISO 22827 - Acceptance tests for Nd:YAG laser beam welding machines — Machines with optical fibre delivery

  Part 1: Laser assembly
  Part 2: Moving mechanism

- ISO 15616 - Acceptance tests for CO2-laser beam machines for high quality welding and cutting

  Part 1: General principles, acceptance conditions
  Part 2: Measurement of static and dynamic accuracy
  Part 3: Calibration of instruments for measurement of gas flow and pressure

4 – Weldability of materials by BW



LHC cavity extremity – EBW of main coupler port (Courtesy of T. Demazière)