Courtesy of NAC and IPG Photonics Japan

Welding II

High Energy Density Laser and Electron Beam Welding

CERN Accelerator School: Mechanical & Materials Engineering for Particle Accelerators and Detectors

Romain Gerard - CERN EN-MME

https://indico.cern.ch/event/1326947/

2024-06-10

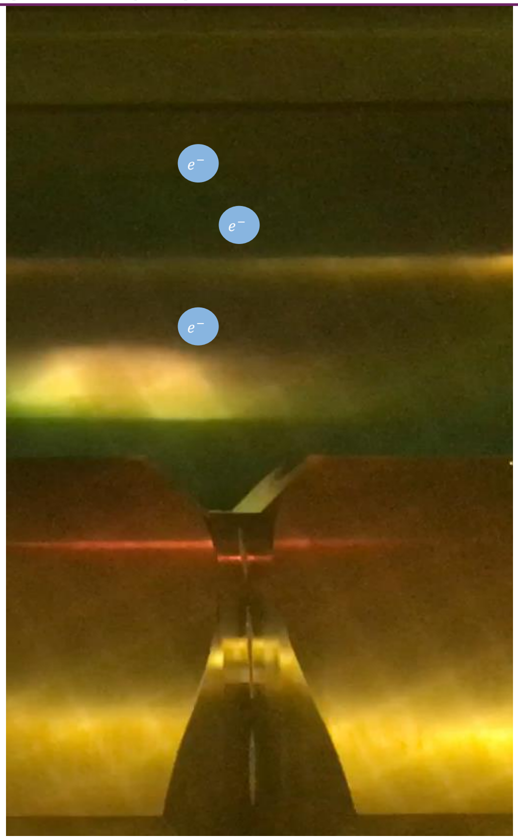
Outline

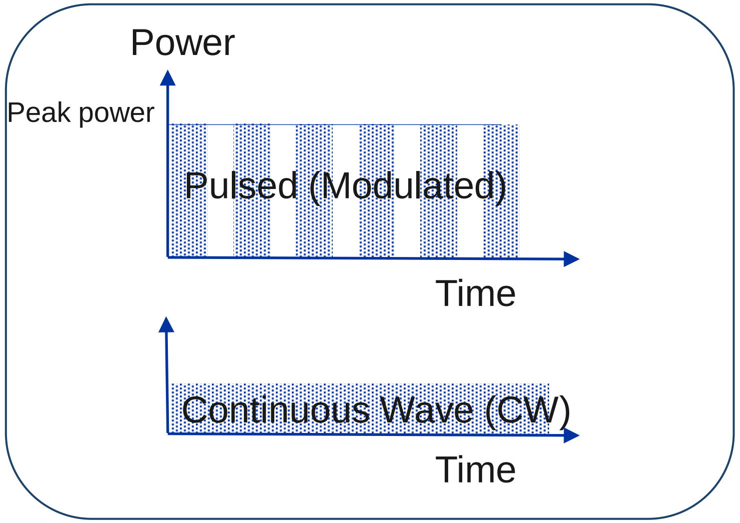
- Motivations to go to high density energy beam
- History of Electron Beam Welding and Laser Beam Welding
- Main principle on beam-matter interaction
- Technologies
- Welded Joint design
- Weldability of materials and illustrations with HEP examples
- Normative and safety hot topics

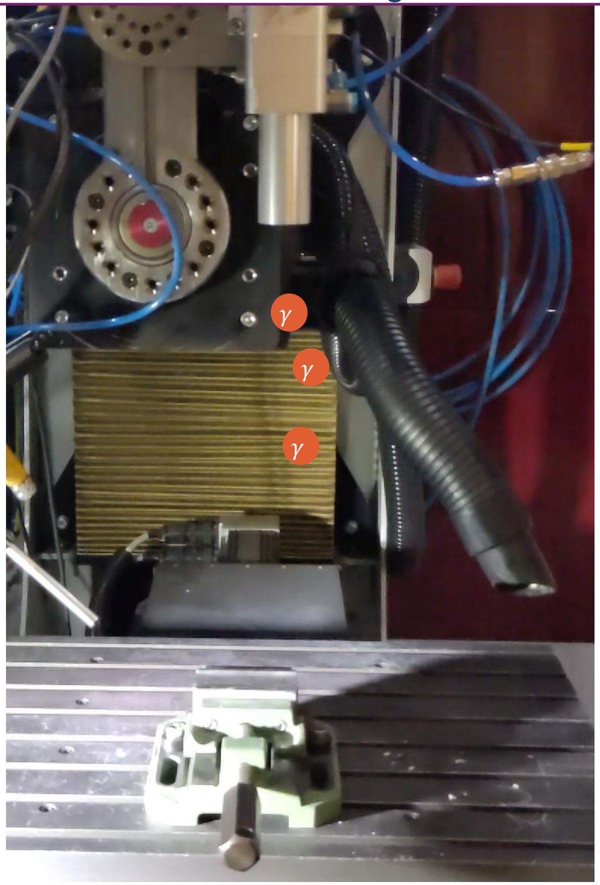
Electron and laser beams

Electrons e^-
Rest mass: $9.1 \cdot 10^{-31}\ kg$
Speed: at 10kV => 30% c
at 270kV => 70% c
Their **kinetic energy** is used for welding
Wavelength (de Broglie) λ 0.01 nm down to 0.002nm

Photons
Transparent through air and inert gases
Specific wavelength:
CO2 laser : λ= 10 000 nm
IR laser: λ= 1070nm => energies of 1.16 eV



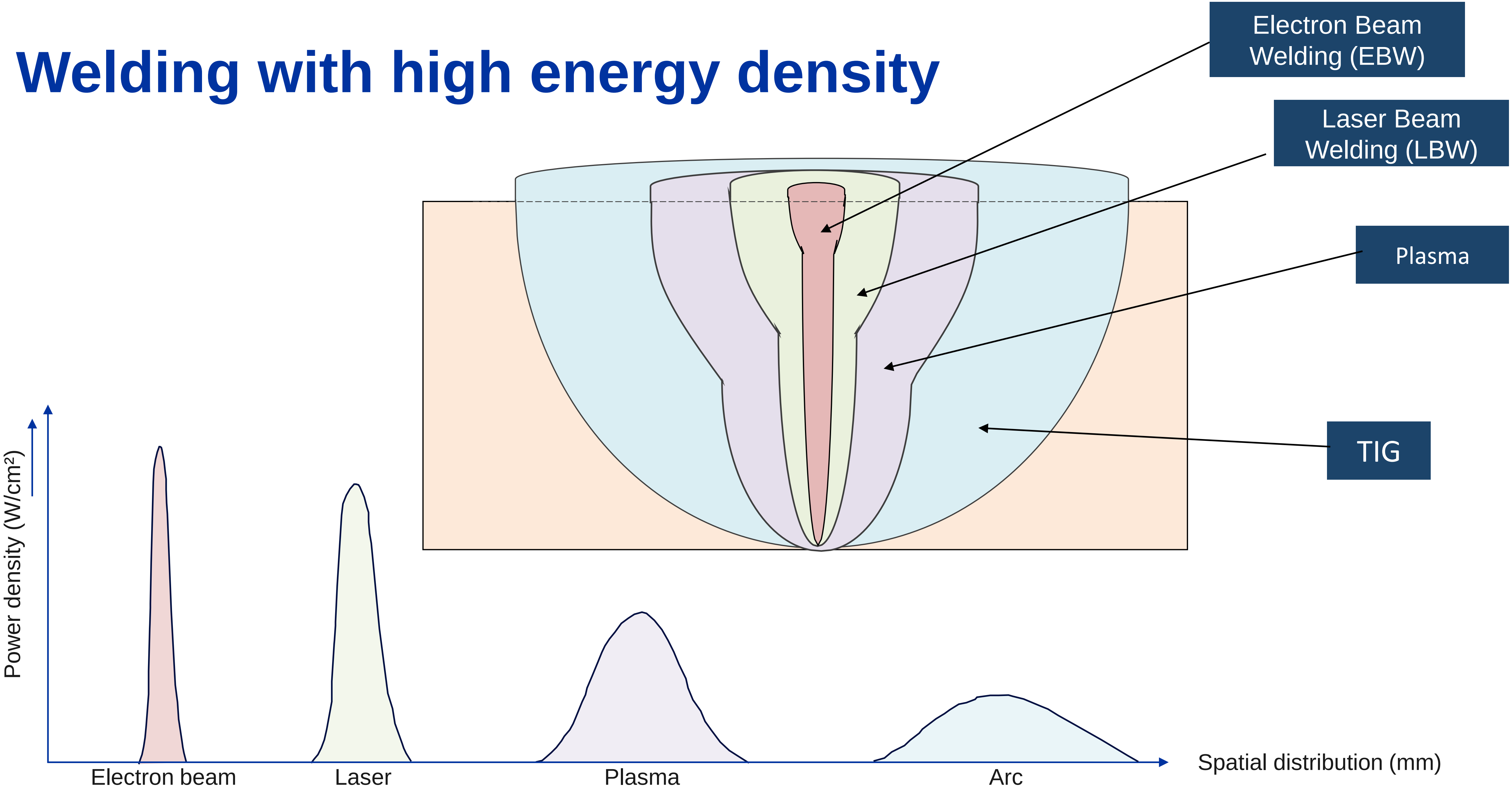




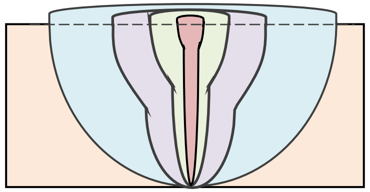
Different wavelengths
Different particle energies:

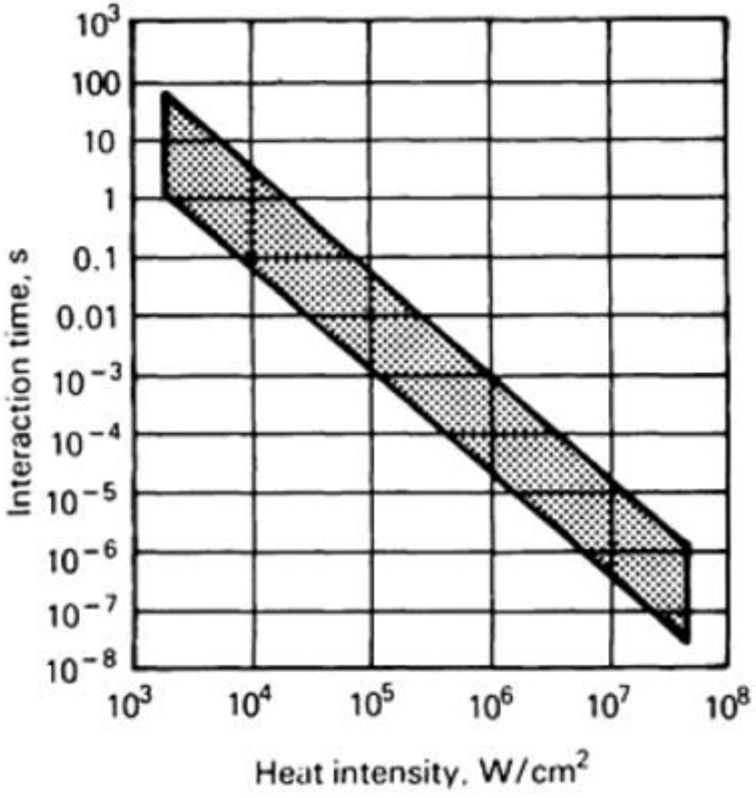
Very different material interaction mechanisms
EBW is more efficient.

Welding with high energy density



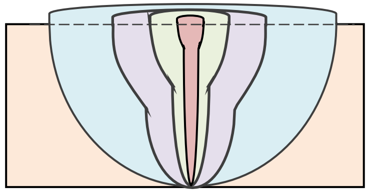
Benefits of Increased energy density

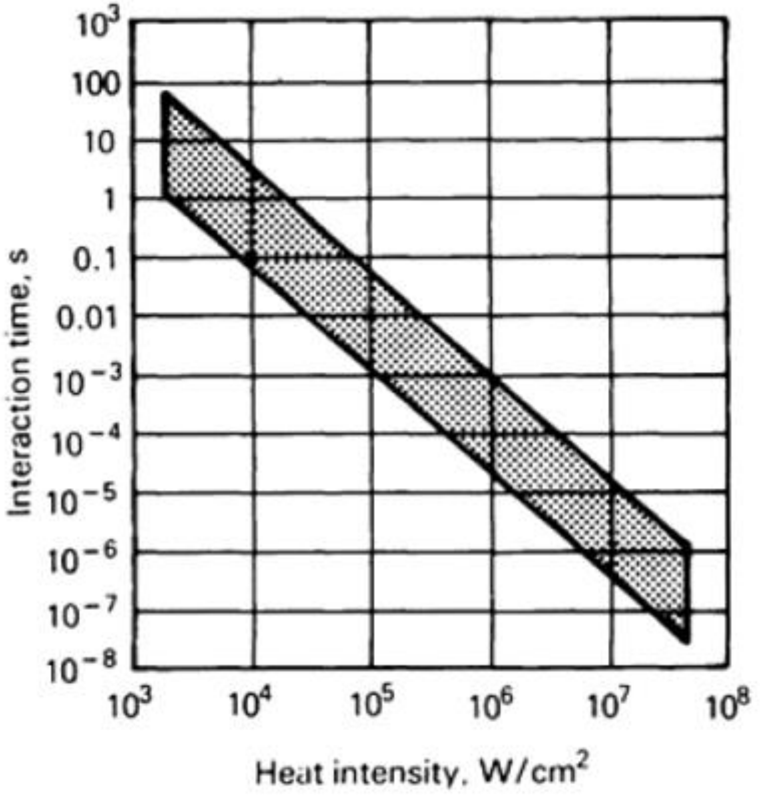


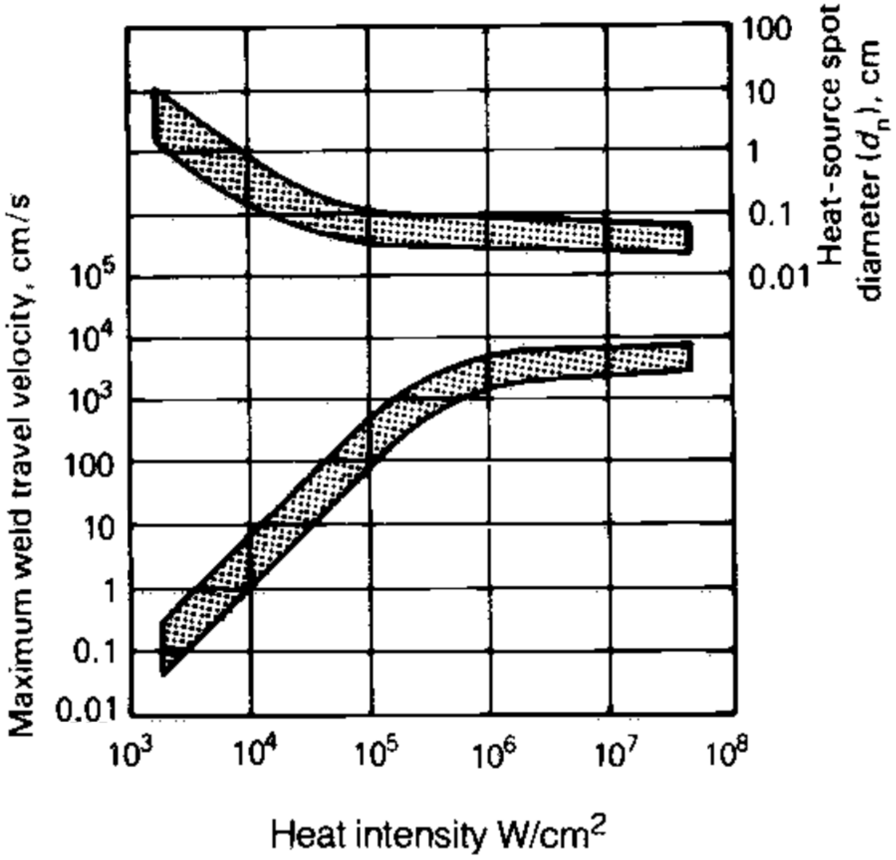


↓ Time required for melting

Benefits of Increased energy density



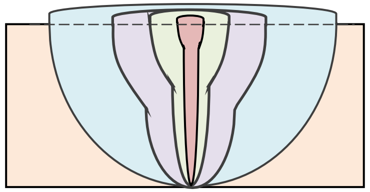


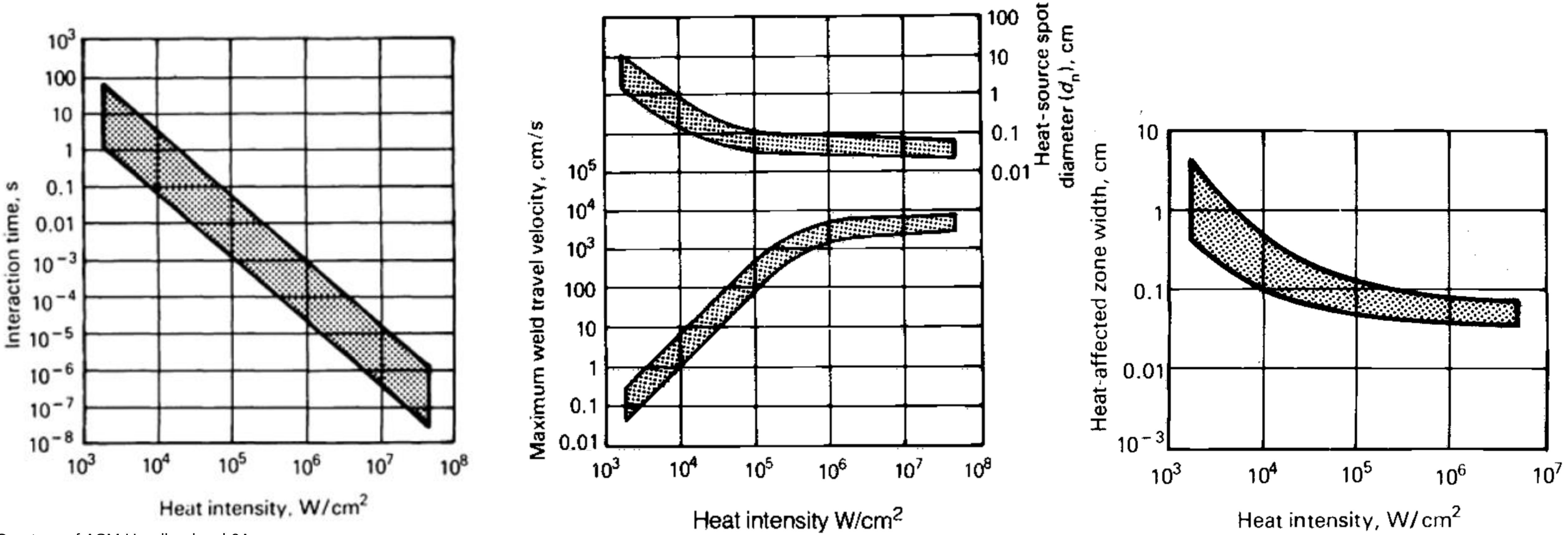


↓ Time required for melting

↑ Welding speed

Benefits of Increased energy density





Courtesy of ASM Handbook vol 6A

↓ Time required for melting → ↑ Welding speed → ↓ Heat affected zone and deformations

History

How and when was it invented ?

History of electron beam welding

Early 1950s: Dr Steigerwald obtained the first welds when manipulating electron microscopes.

At the same time, Dr Jacques-Andre Stohr, looking to weld reactive materials with X-ray tubes began to develop EBW at CEA.

1950s: First EBW machines thanks to well understood science behind production, acceleration and focusing of EB.

1960s: High voltage (125 – 150 kV) EBW systems sold by Carl Zeiss.

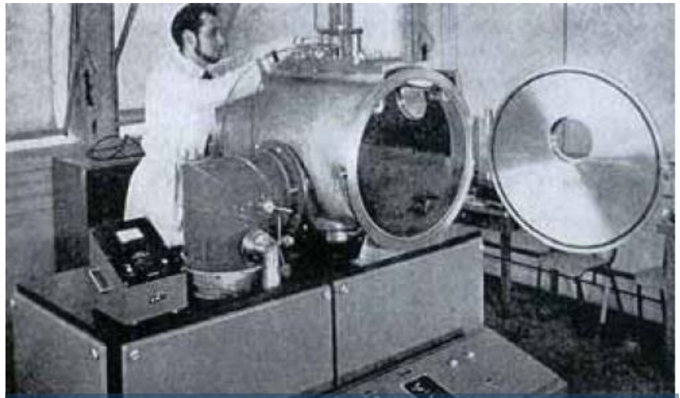
1970s: EB welding became the technology of choice for high precision weld (driven by the nuclear and aerospace industries).

The largest and more powerful EB welder to date (from Japan) 300kW at 600kV, it was able to penetrate 305 mm of steel.


Dr Steigerwald


First EBW machine (Germany - 1952)

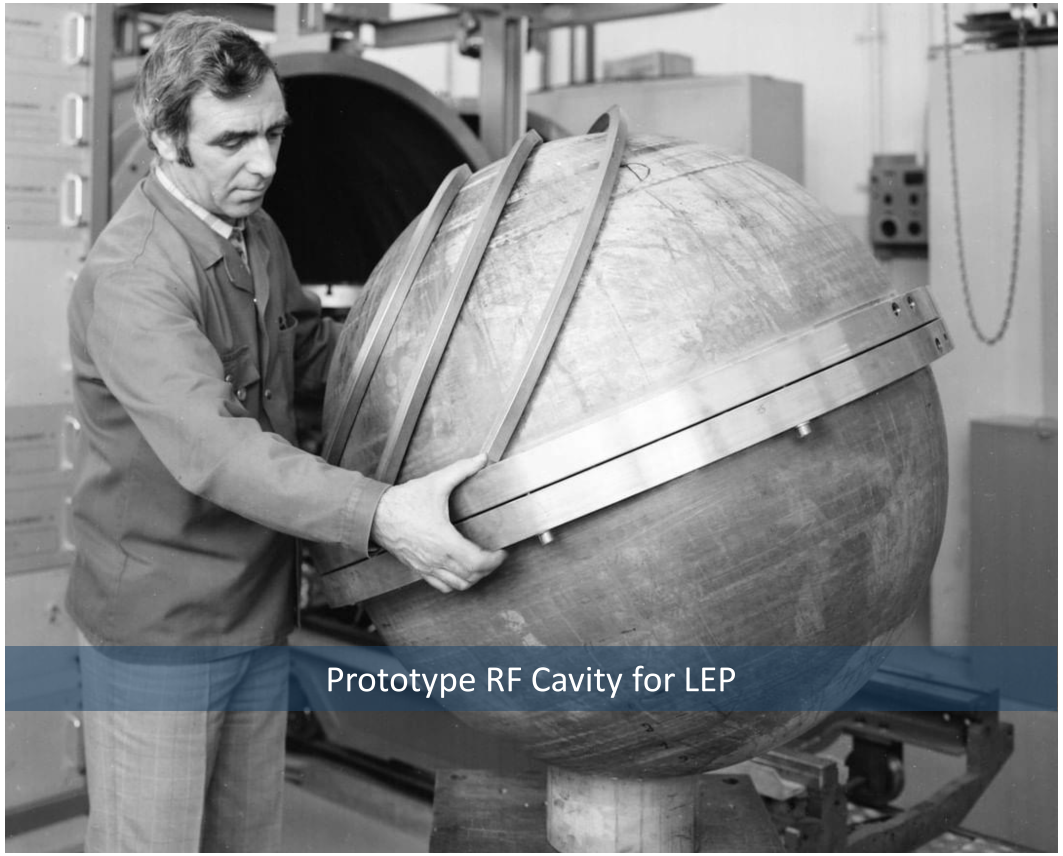

Dr J. A. Stohr


First EBW machine in France (1956)

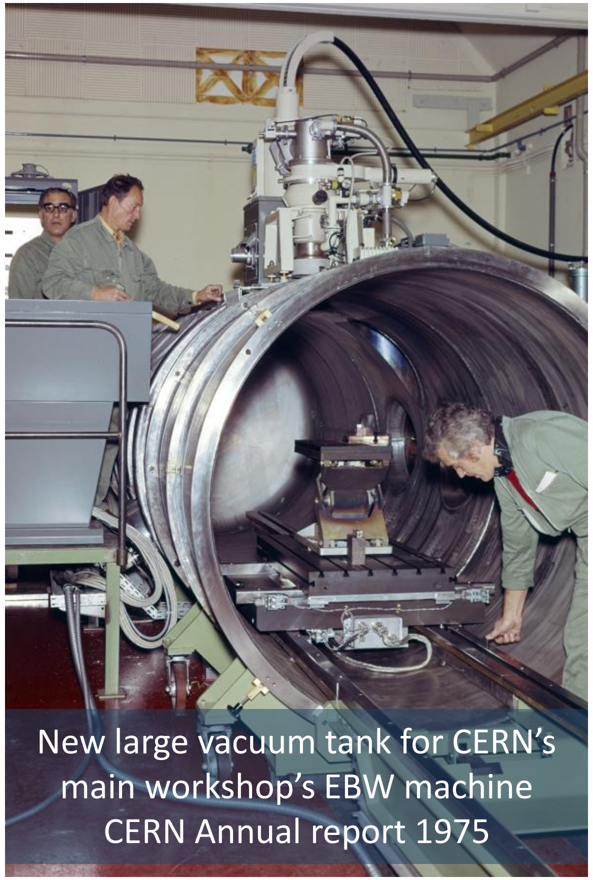
Source: An international history of electron beam welding – Dietrich v. Dobeneck

History of electron beams at CERN

Long tradition driven by the need to weld reactive materials (niobium, titanium, tantalum and many others)



Prototype RF Cavity for LEP



New large vacuum tank for CERN’s main workshop’s EBW machine
CERN Annual report 1975

CARL ZEISS

Postanschrift: CARL ZEISS – 7082 Oberkochen – Postfach 35/36

C.E.R.N.
à l'attention de M. BERTHET

CARL ZEISS
Oberkochen/Württemberg
Allemagne

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Angebot

Unsere Zeichen	Hausruf	Oberkochen,
Koe/Swa	606	29/10/1965

Ihre Anfrage	freibleibender Liefertermin
conformément aux entretiens à Genève du 28/10/1965	env. sept. 1966

Gegenstand	Bestellnummer	Stück	Einzelpreis sfr	Gesamtpreis sfr	Empfängervermerke
Soudeuse électronique		1		506.000,-	+)
Modèle SES 1013 (de dimensions spéciales) suivant les indications complémentaires figurant dans la description technique jointe et les photos déjà en votre possession, diamètre de la chambre à l'intérieur 1500 mm longueur de la chambre à l'intérieur 1700 mm avec microscope spécial d'observation (distances focales variables pour différentes distances frontales) sans équipement d'évacuation					
Le prix s'entend, frais de douane non compris, par ailleurs aux conditions de notre lettre du 25/10/1965. En ce qui concerne les conditions de paiement des accords spéciaux pourront être pris.		Moins subvention au CERN		50'000	
				456'000 F.	

+) La contribution n'est pas encore déduite

SOUDEUSE ELECTRONIQUE
Specification

E. Koehncke

X/62

Lieferung erfolgt gemäß unseren umseitigen Lieferungs- und Zahlungsbedingungen.

Drahtwort: Zeisswerk Oberkochen / Fernschreiber: 7-13 213 / Fernsprecher: Oberkochen (0 73 64) 3 81
Bankkonto: Deutsche Bank Heidenheim / Postscheck: Stuttgart 2015 / Bahnstation: Oberkochen (Württ.)

EB Welding machine 1965

Electron beam welding machine for the superconducting cavity LEP

History of Laser welding

Light
Amplification by
Stimulated
Emission of
Radiation.

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

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

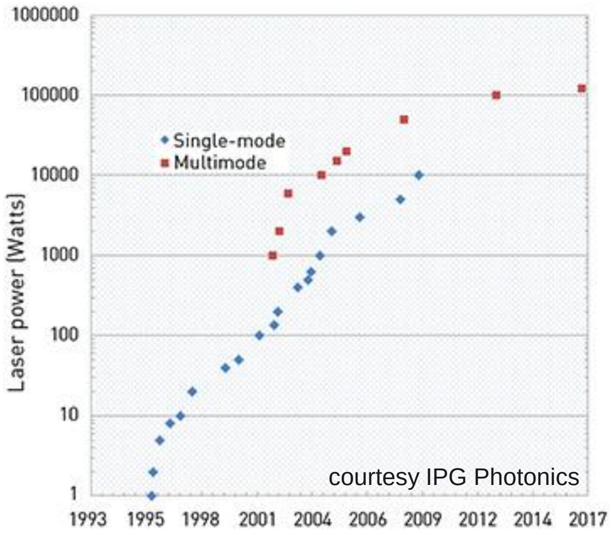
First CO2 laser machine at CERN (1980s)

First development from Pioneering work by Schawlow and Townes at Bell Labs (Infrared MASERS)

1960: The first working laser, the Ruby laser, was developed by Theodore Maiman

1960s: Gas laser (He/Ne, then CO2): Power scaling thanks to heat management.

2000s: Boom of fibre laser sources, providing high efficiency. Widespread adoption of fiber-delivered laser systems in industrial applications.



Growth in power of IPG fiber-laser in the past 25 years

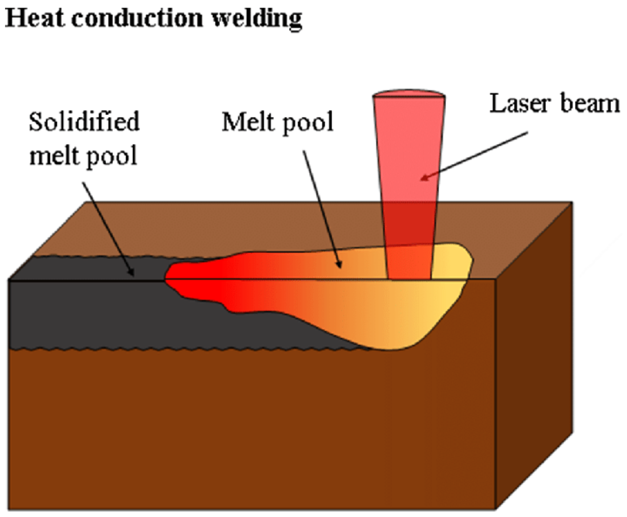
Main principle

Of the beam – material interaction

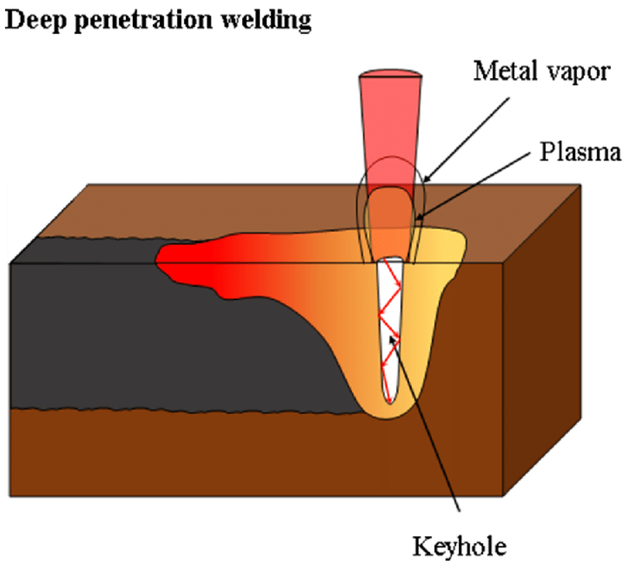
Welding with a powerful beam

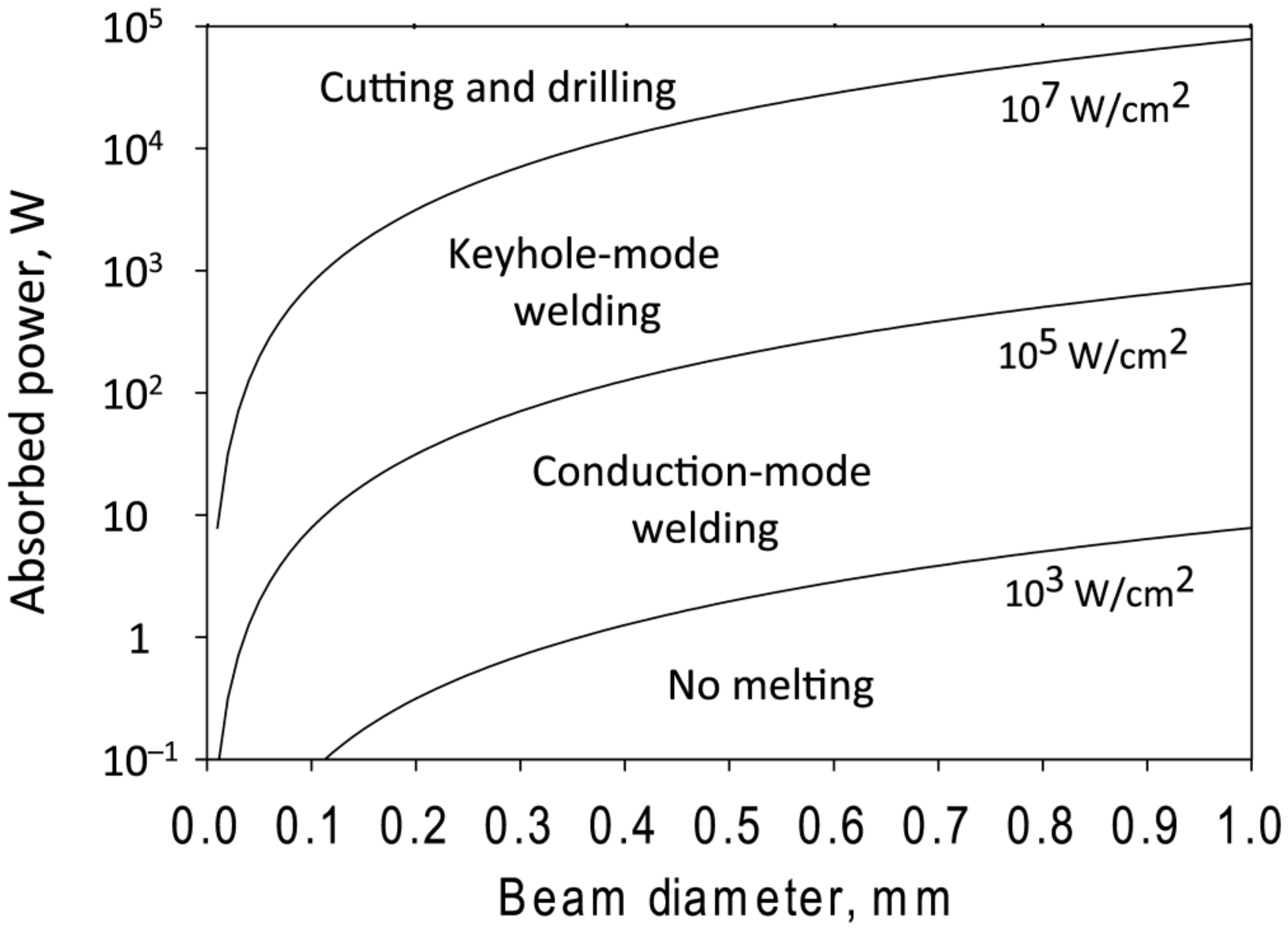
Aspect ratio: $\frac{Width}{depth} < 1$

Typ. 1/2



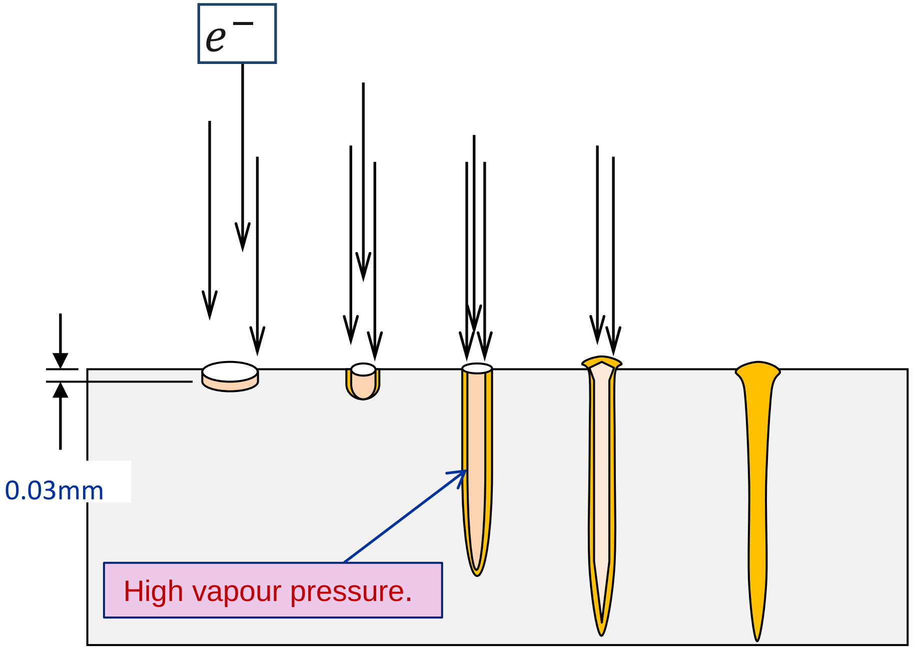
Aspect ratio: $\frac{Width}{depth} > 1$

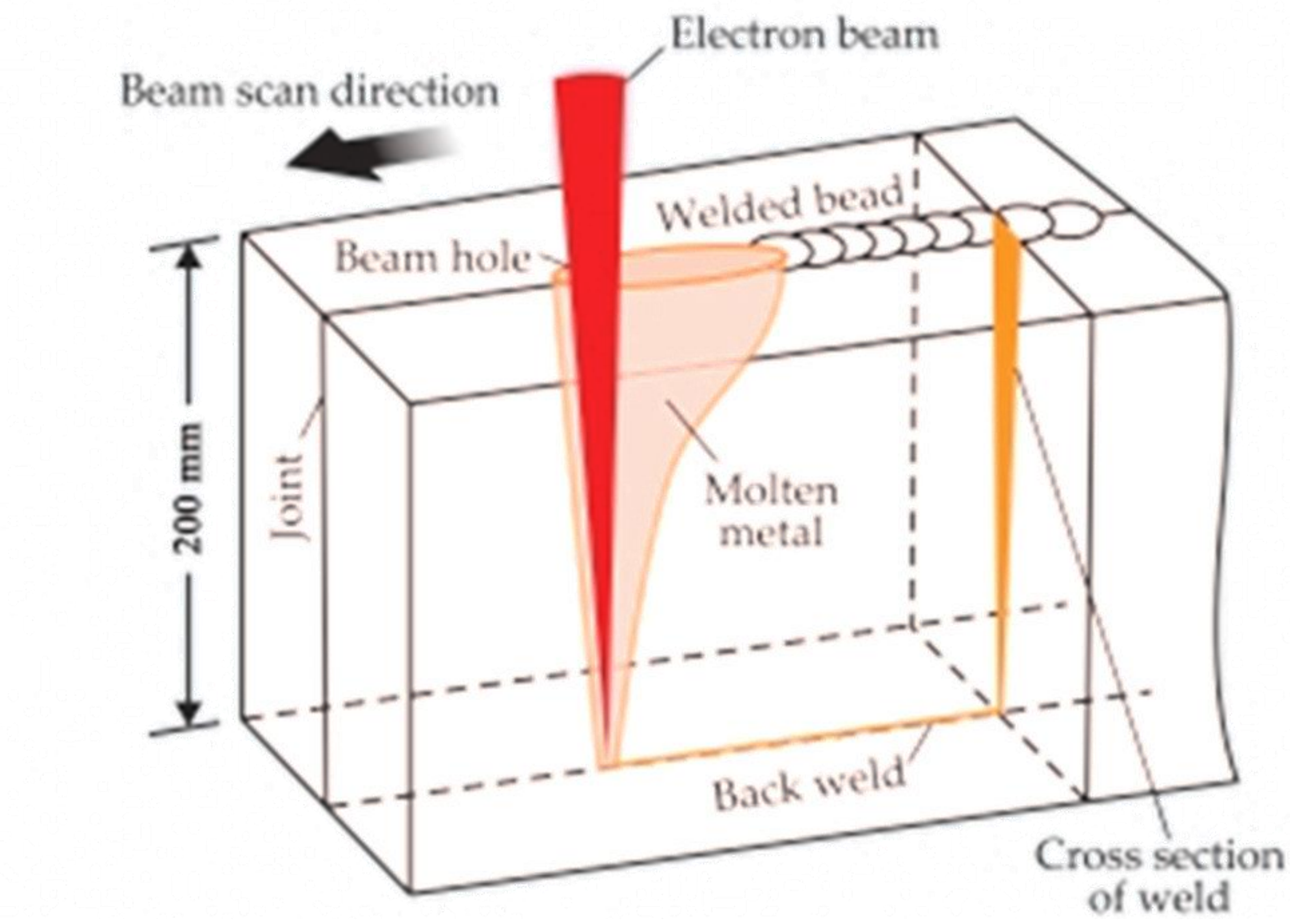




Courtesy of J. Helm et al. & Elmer et al.

The Keyhole welding regime with EBW

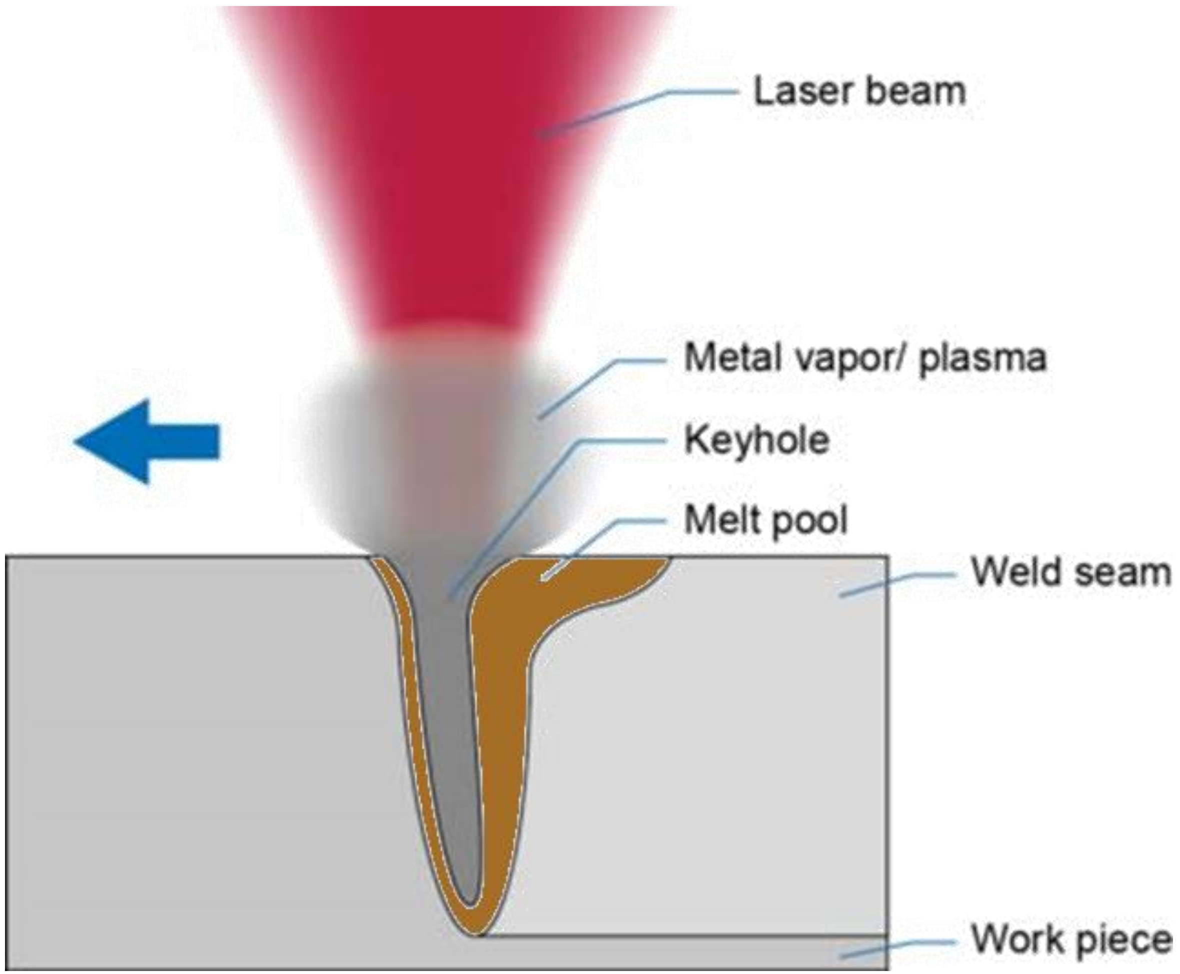




Courtesy Laserline

Keyhole welding

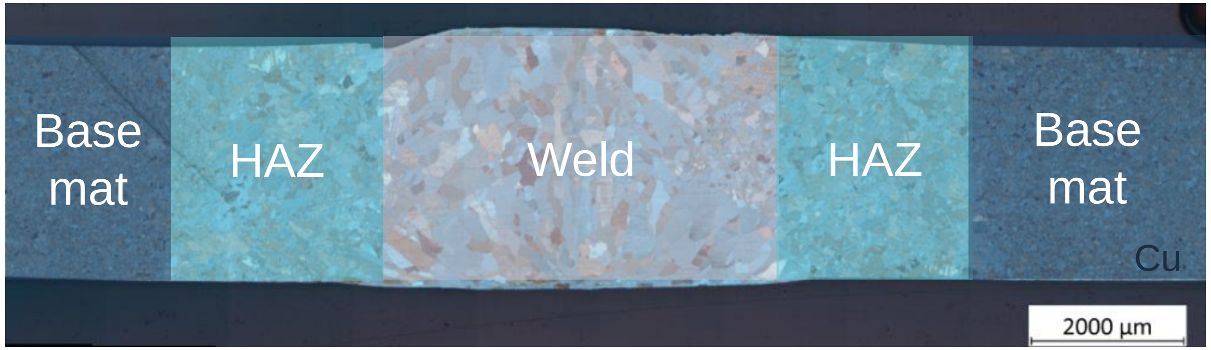
Courtesy of Photron

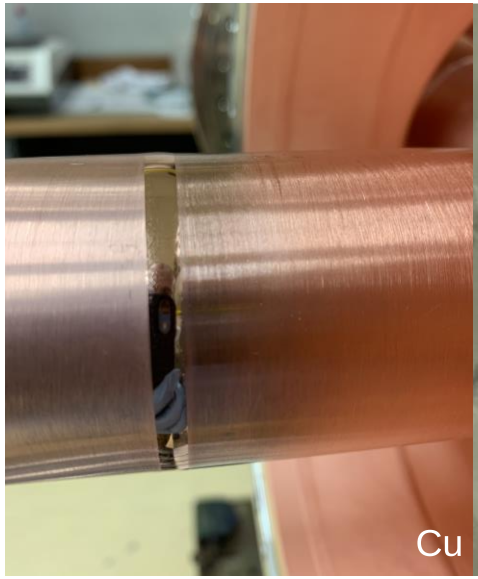


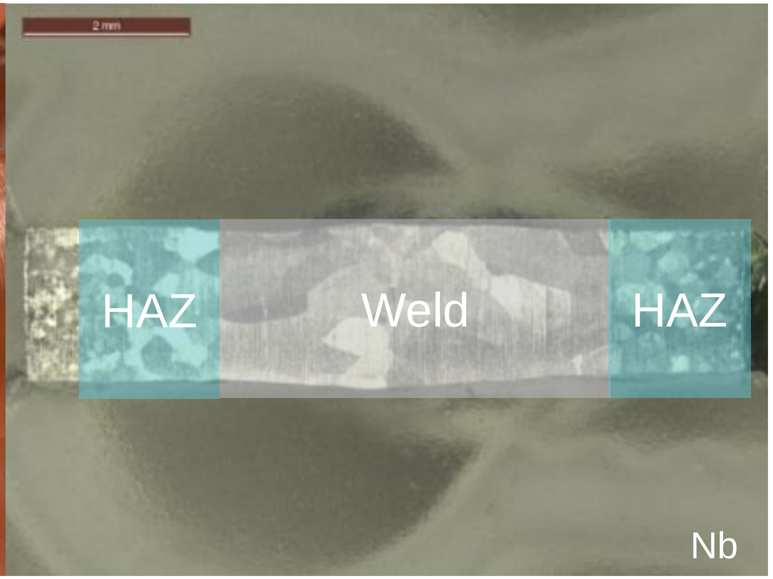
Courtesy of Laserline

Examples of Keyhole and condution welds

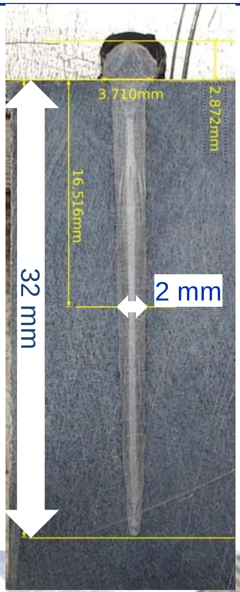
Conduction

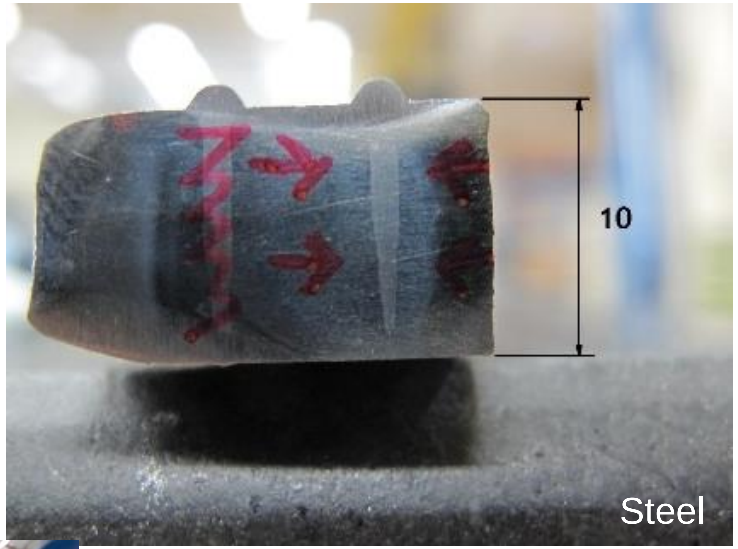


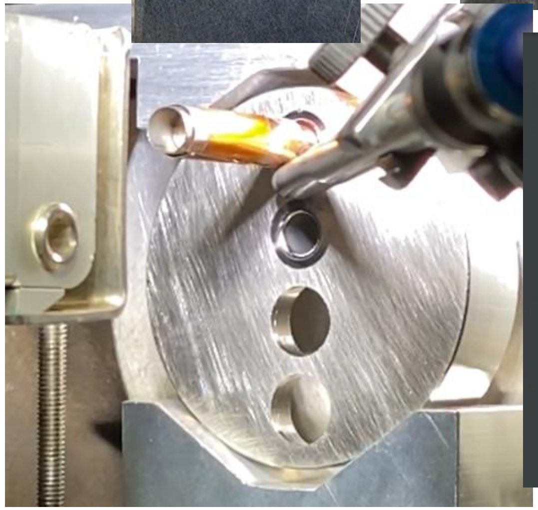


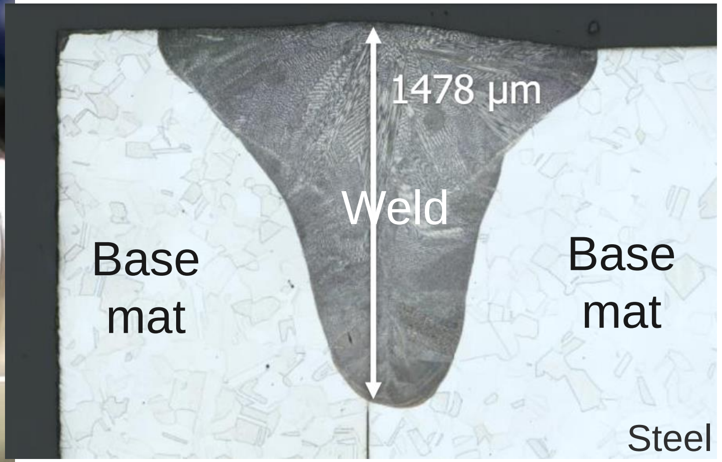


Keyhole





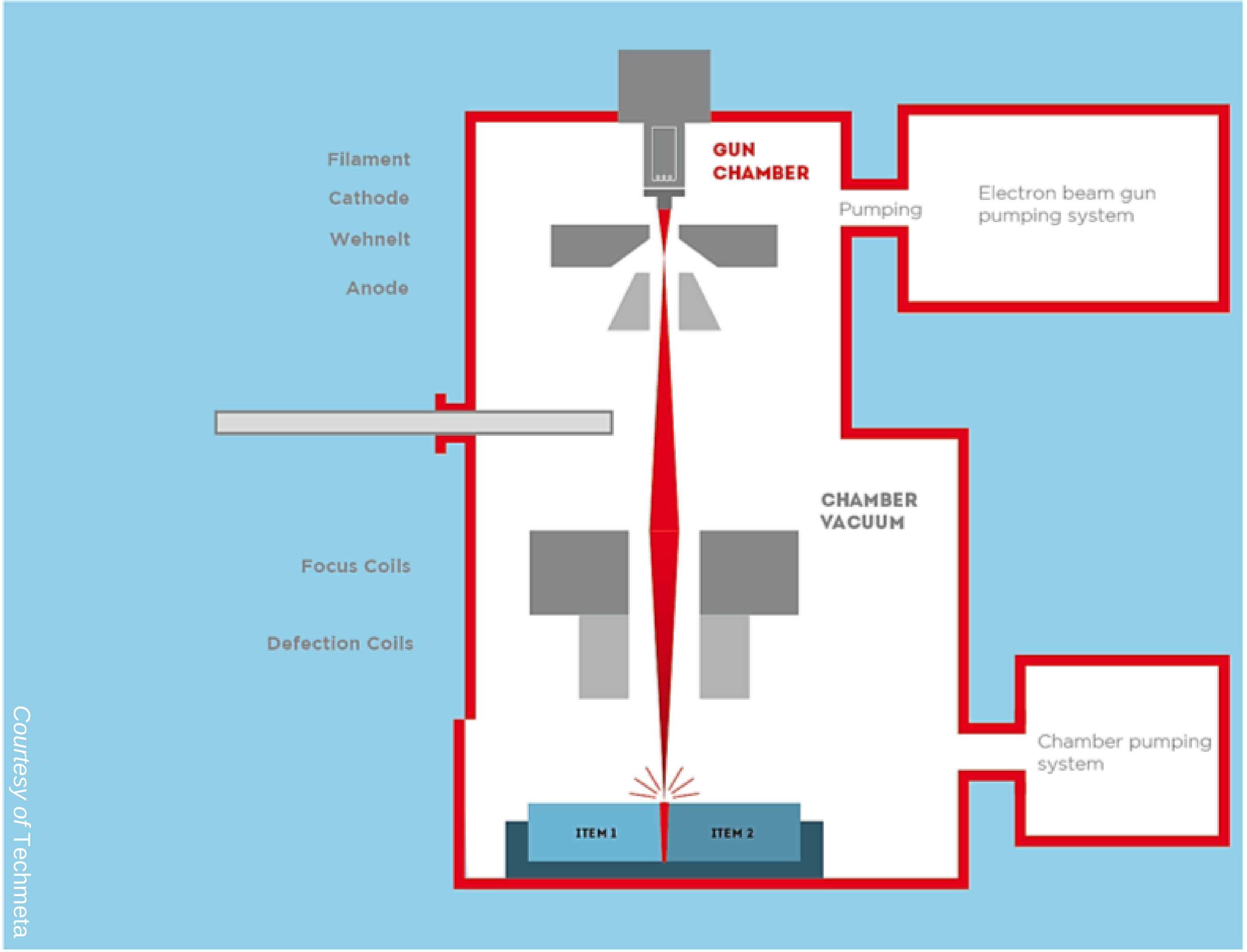




Technologies

To generate electron and laser beams

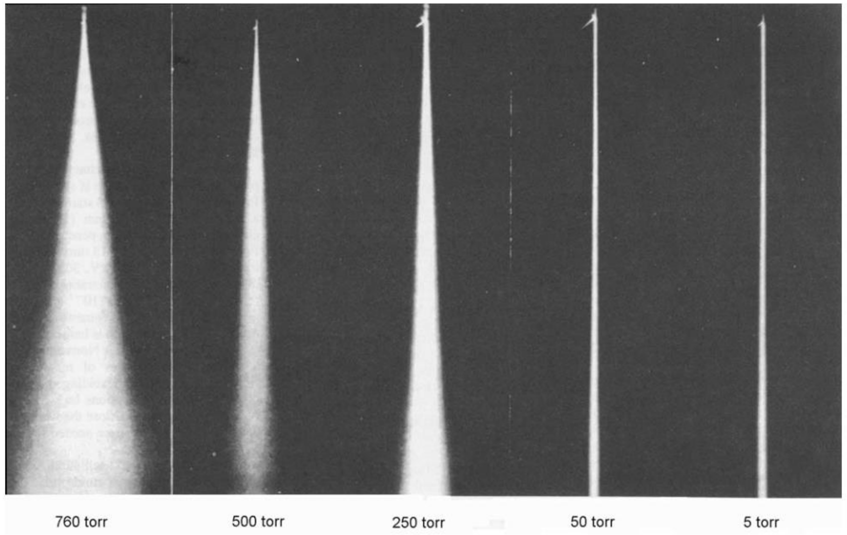
The Electron Beam Welding Machine



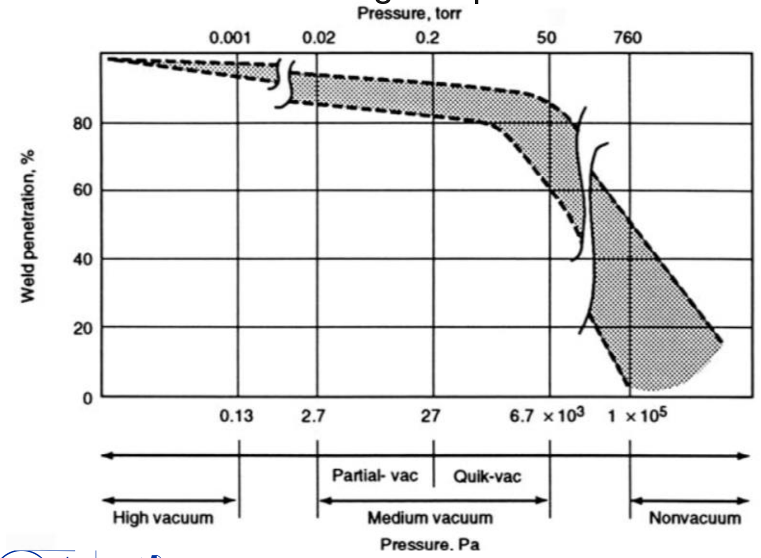
Courtesy of Techmeta

Courtesy of Steigerwald Strahltechnik GmbH

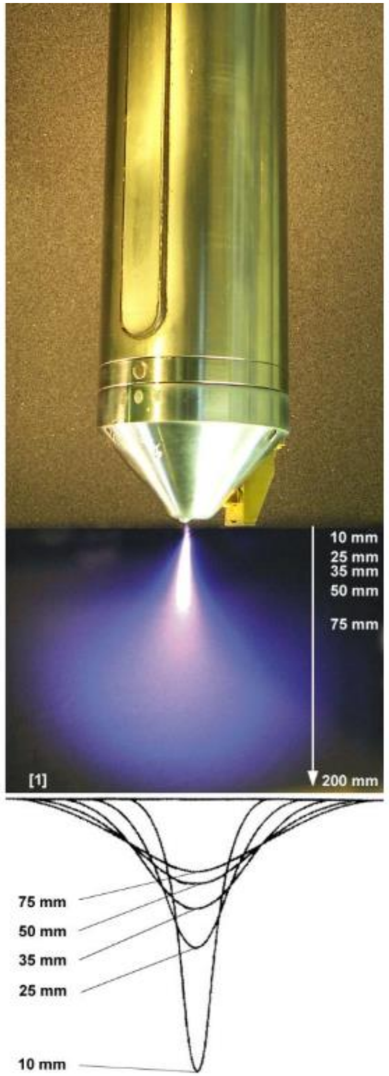
Importance of the vacuum for EBW



A low vacuum induced a large dispersion of the electron beam



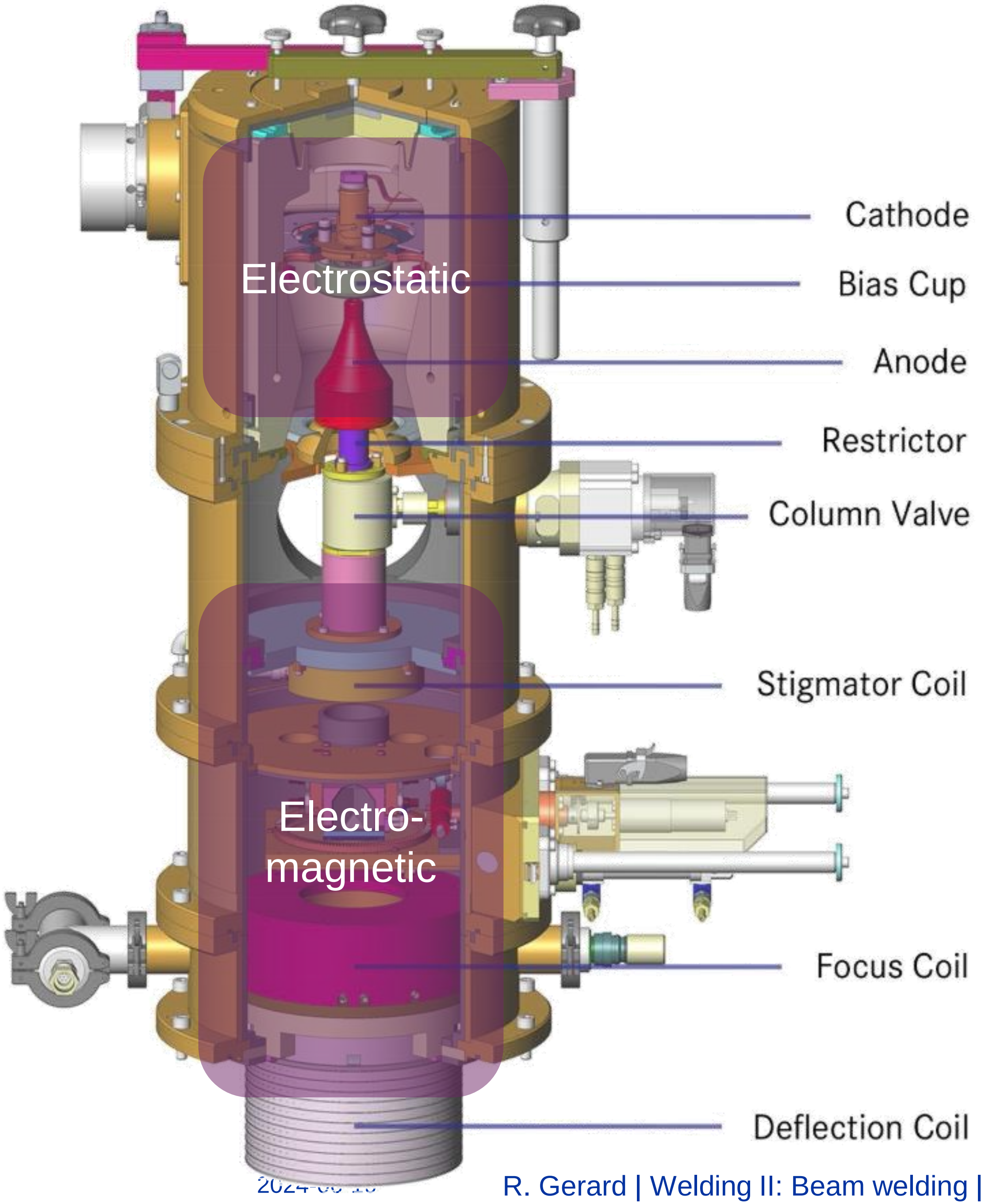
Courtesy of ASM Handbook vol 6A



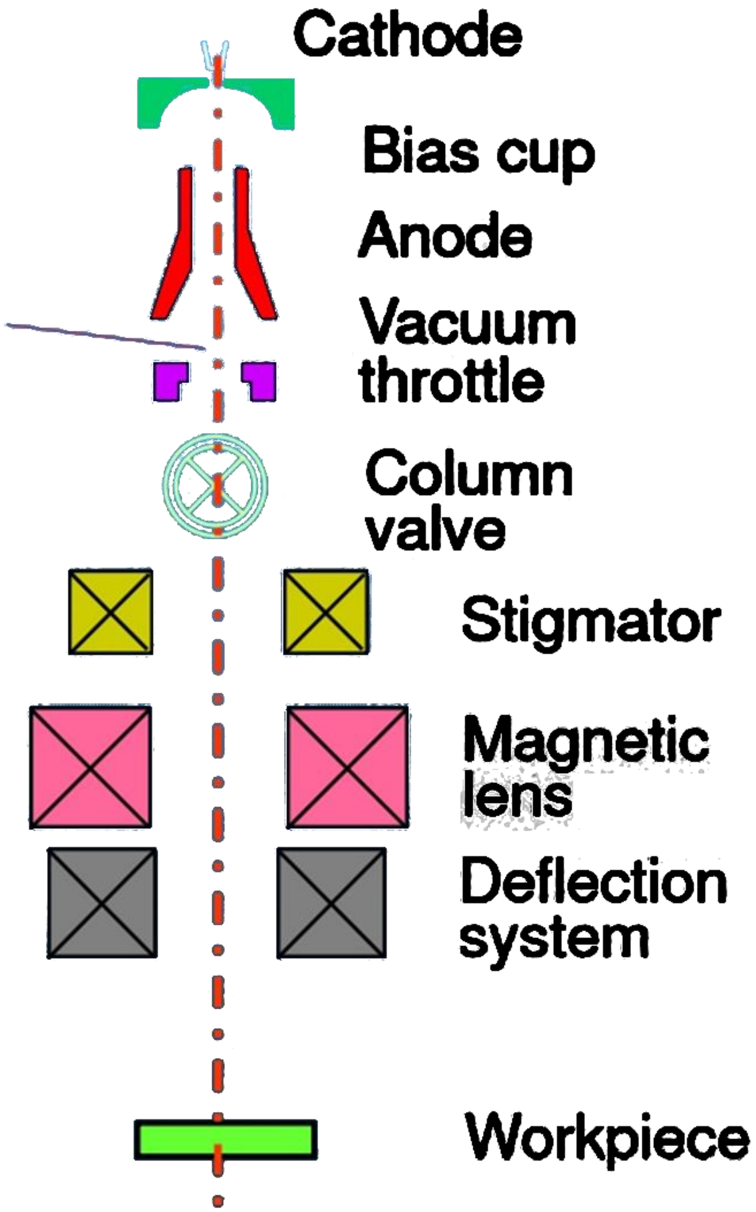
A Non-Vacuum EBW machine

Courtesy PTR EB

The EB Gun

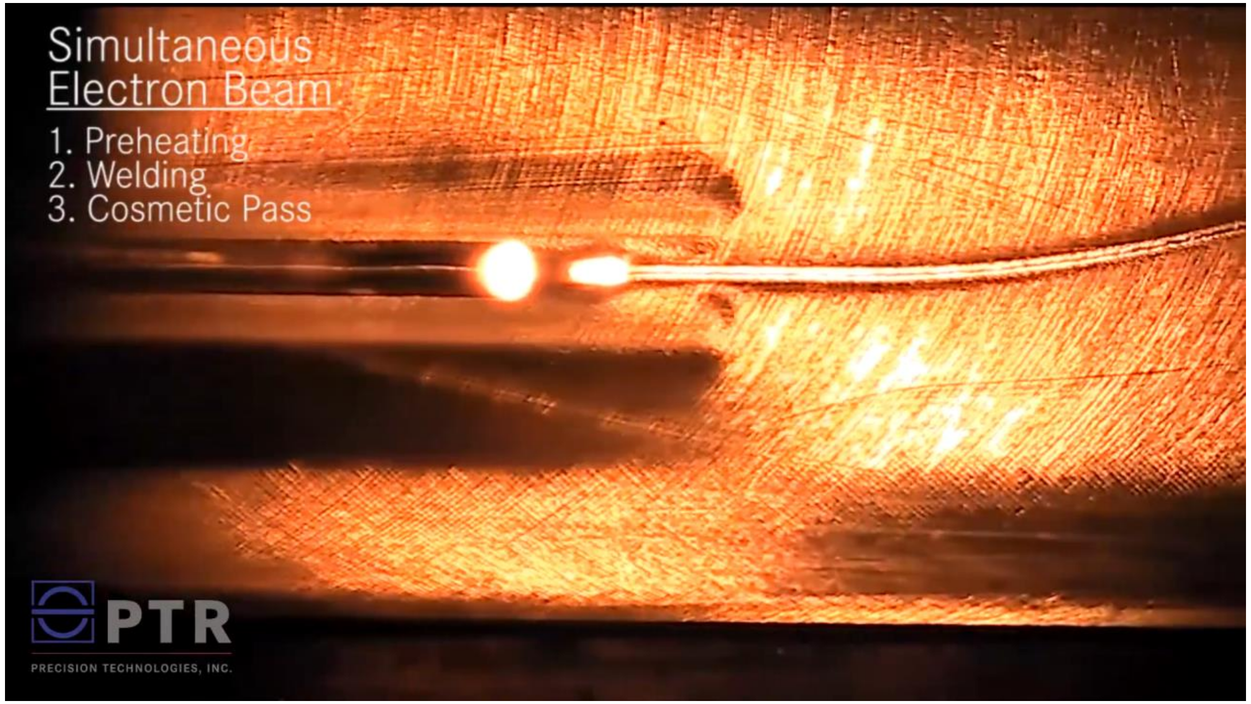


Electrostatic
Electro-
magnetic
Cathode
Bias Cup
Anode
Restrictor
Column Valve
Stigmator Coil
Focus Coil
Deflection Coil



Cathode
Bias cup
Anode
Vacuum throttle
Column valve
Stigmator
Magnetic lens
Deflection system
Workpiece

Deflecting system

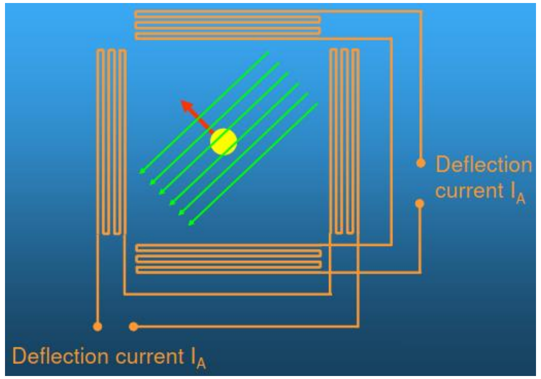


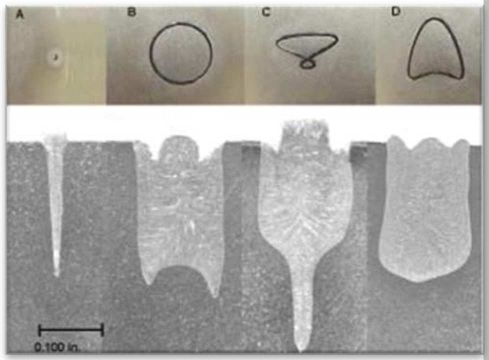
Static deflection

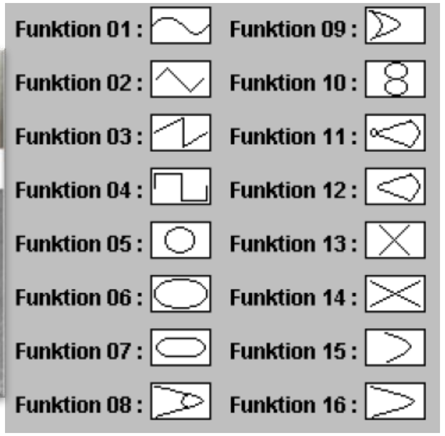
- Simple translation of the beam
- Alignment with optical reference
- Manual alignment from the operator during welding

Dynamic deflection

- Fast movement of the beam
- Allows to sustain several meltpools at the same time
- Allows rapid beam deflection

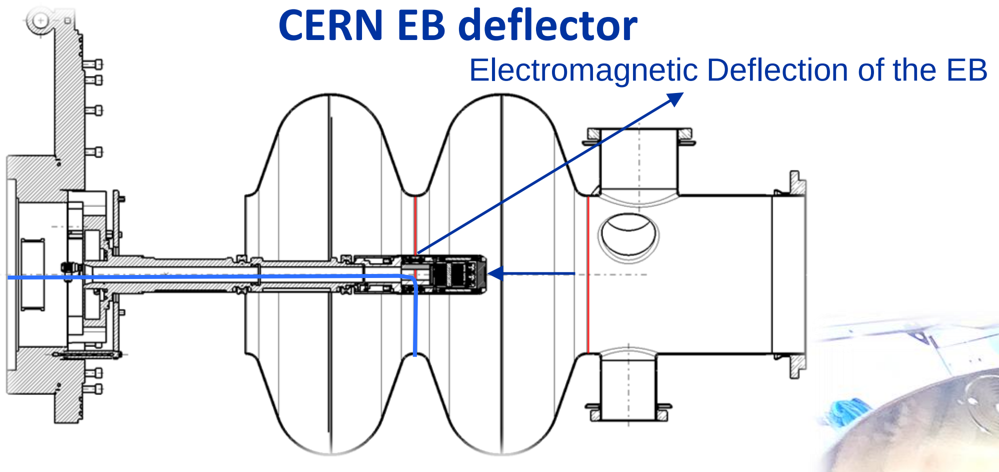


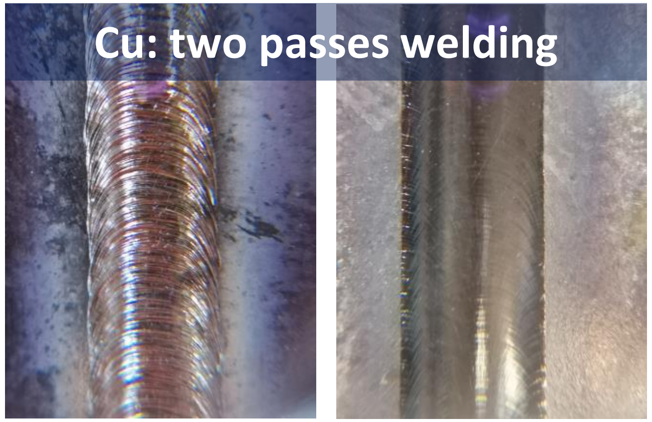




Courtesy PTR EB

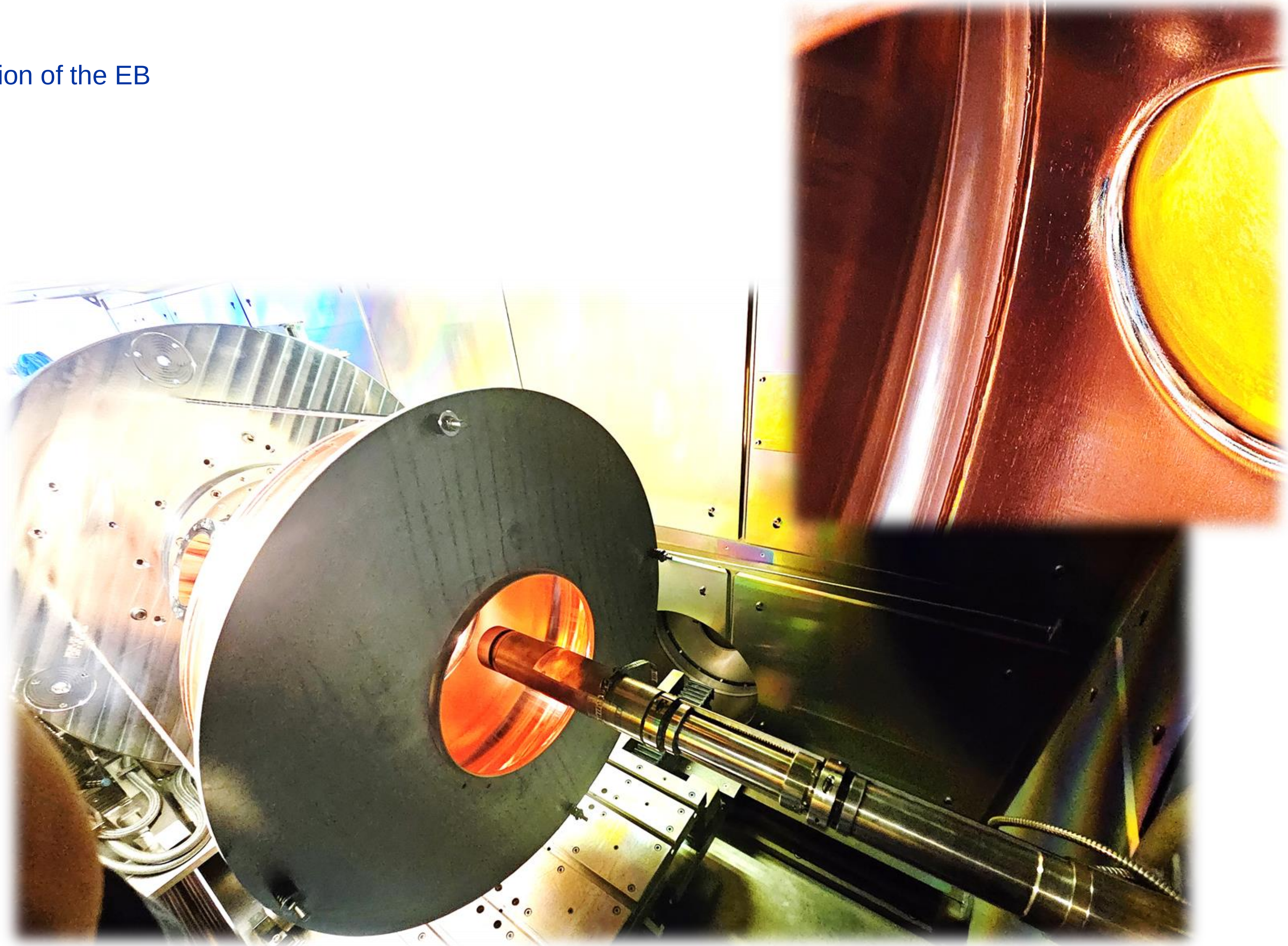
Internal welding with additional beam deflector





Keyhole 1st pass

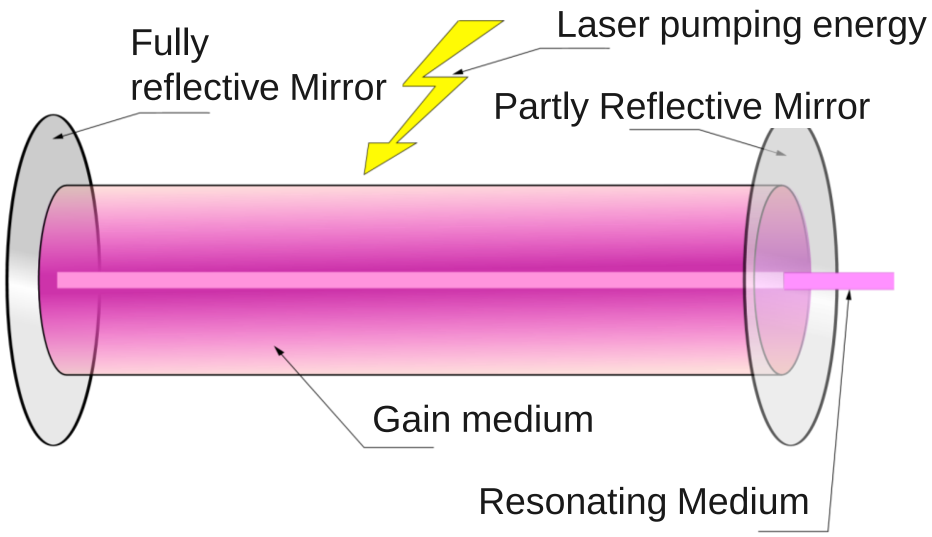
Conduction pass

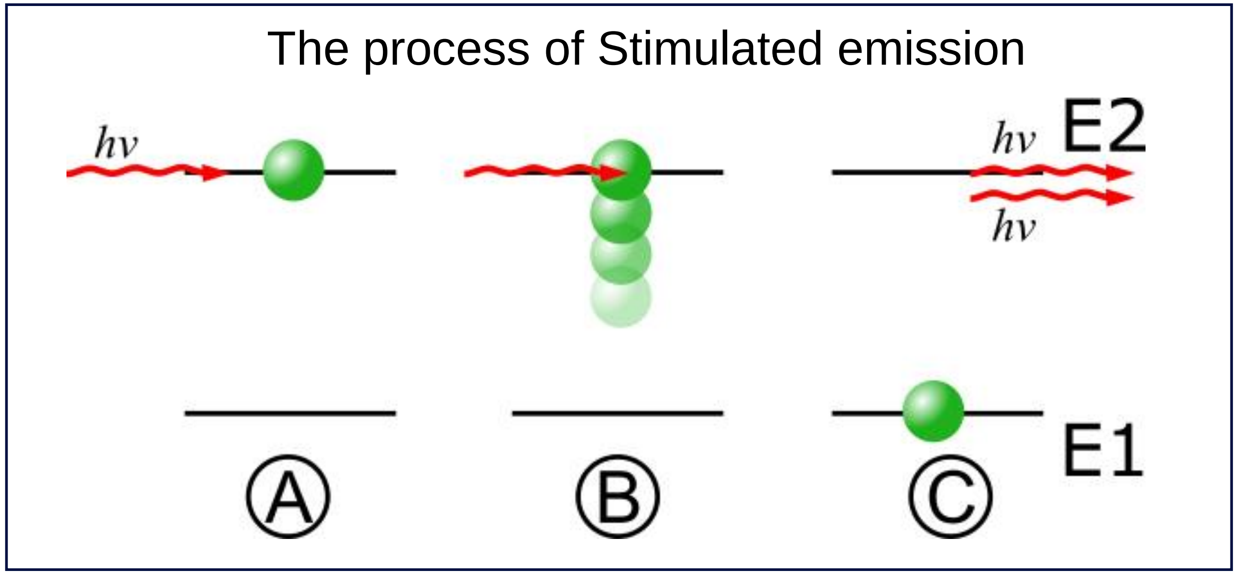


The LASER light

The laser radiation is:

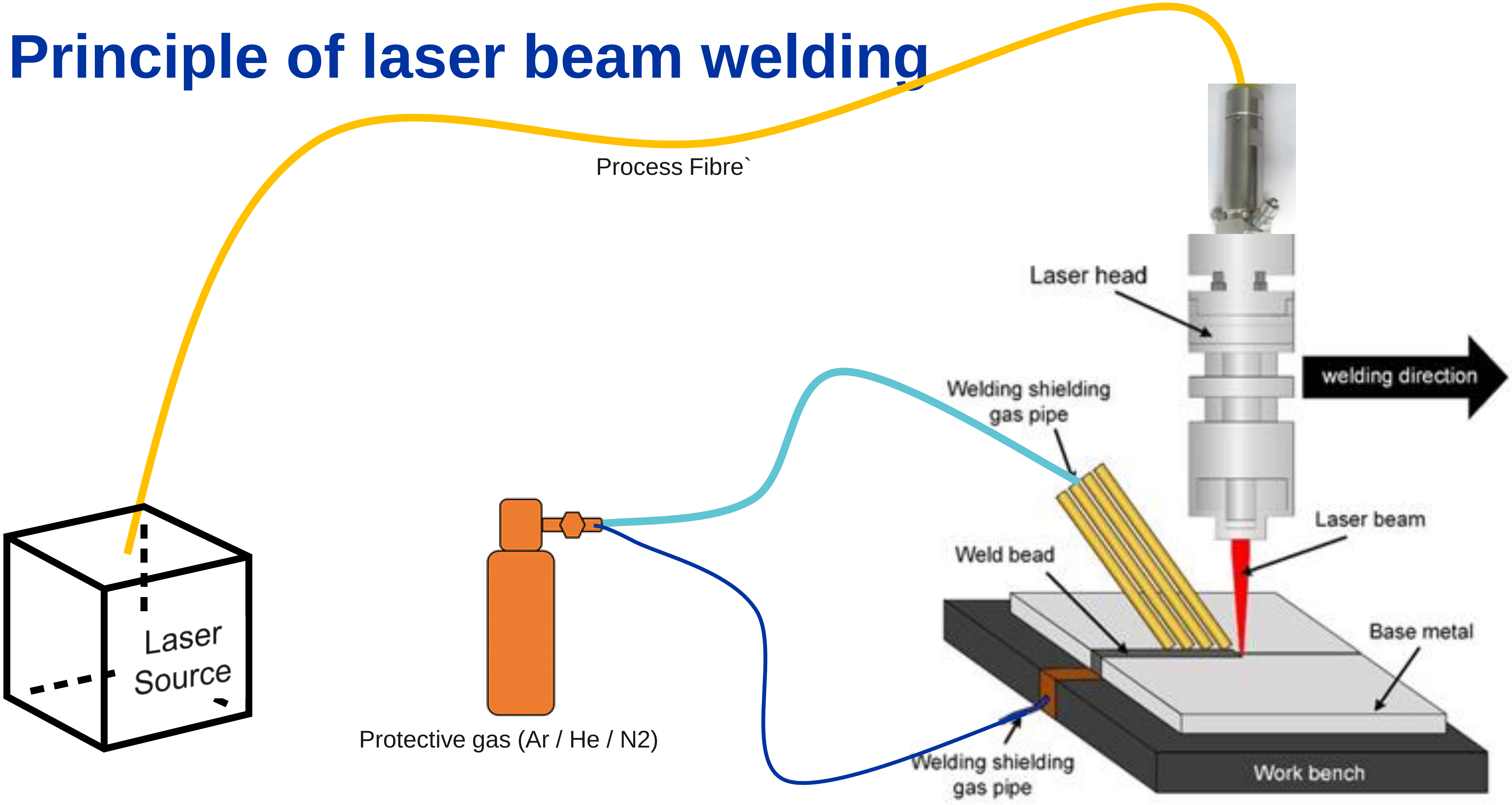
- Monochromatic
- Unidirectionnal (Low divergence)
- Coherent in time and space



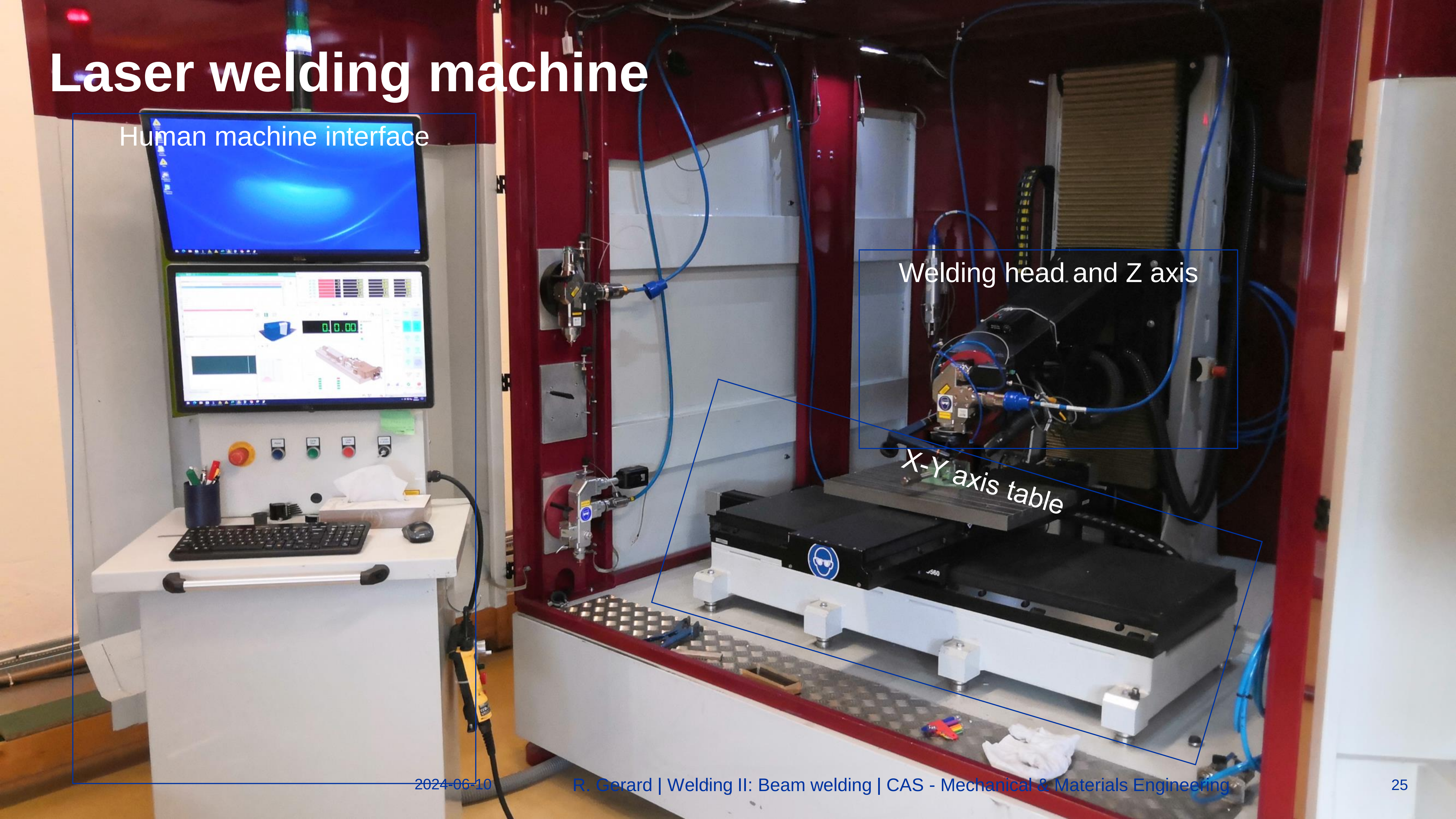


Credit: Kimbar adapted from Masur [CC BY-SA 3.0]

Principle of laser beam welding

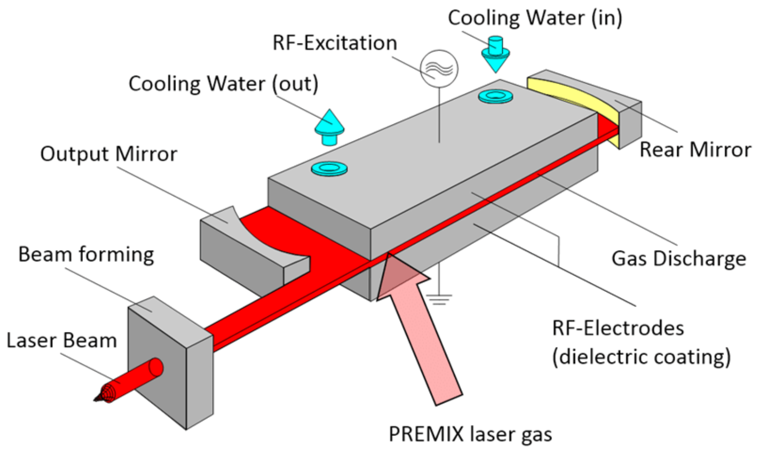


Laser welding machine

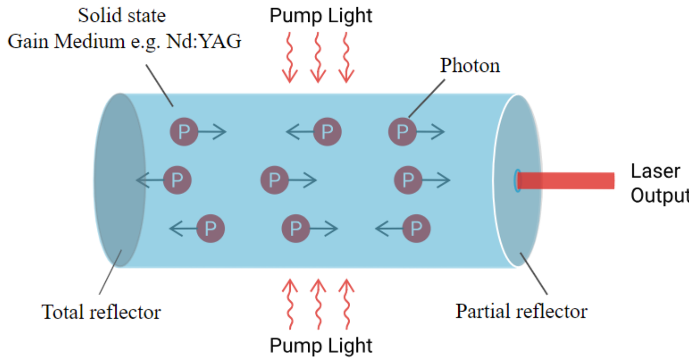


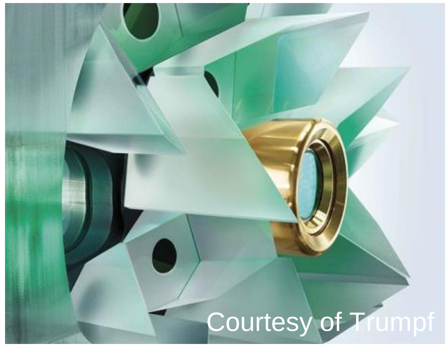
Laser sources for material processing

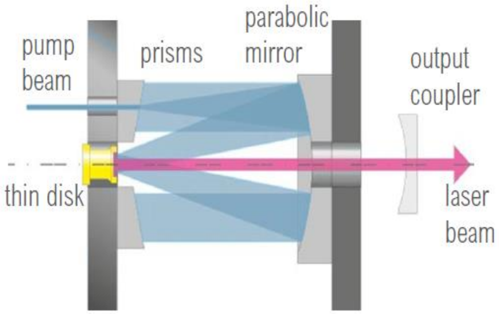
CO2 SLAB Laser (gas)



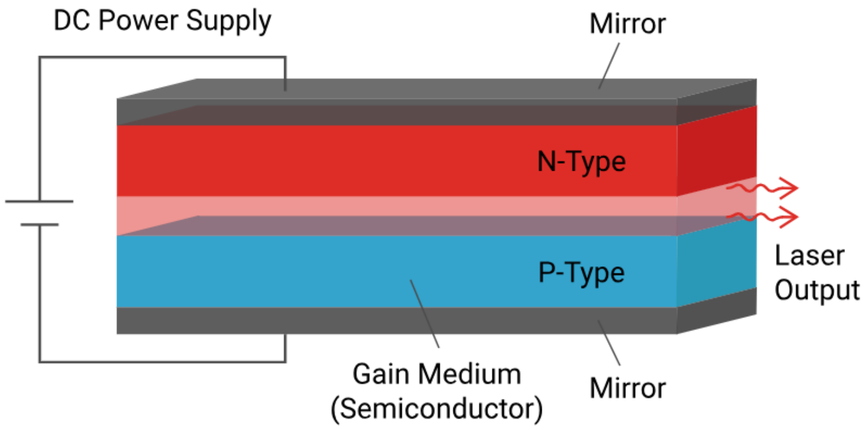
YAG and Disk laser (solid)



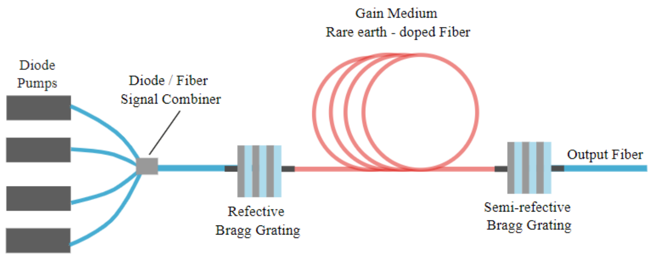


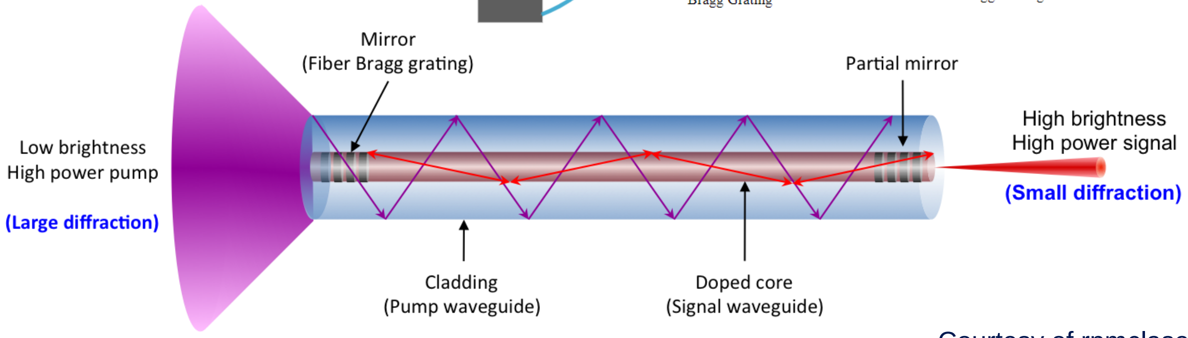


Direct Diode laser (electronic)



Fibre laser (Solid)

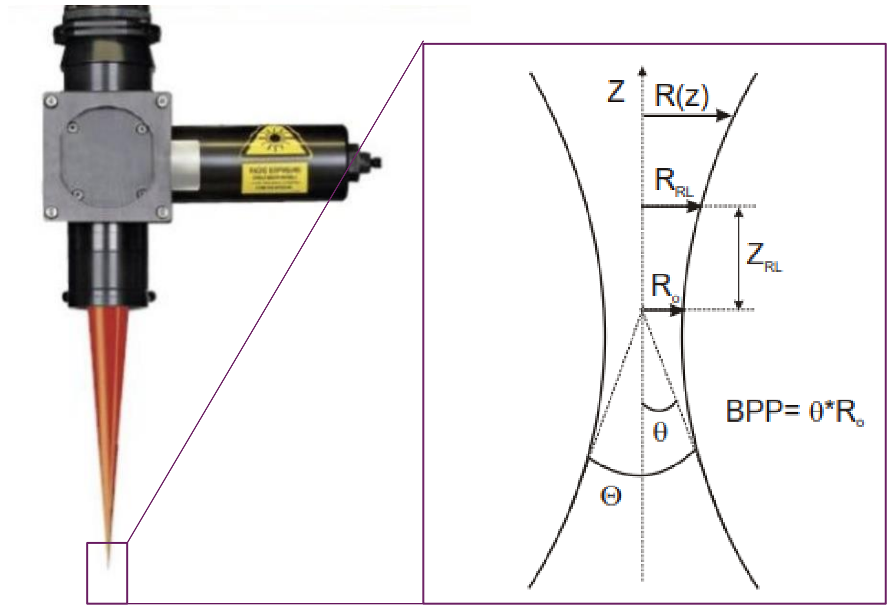


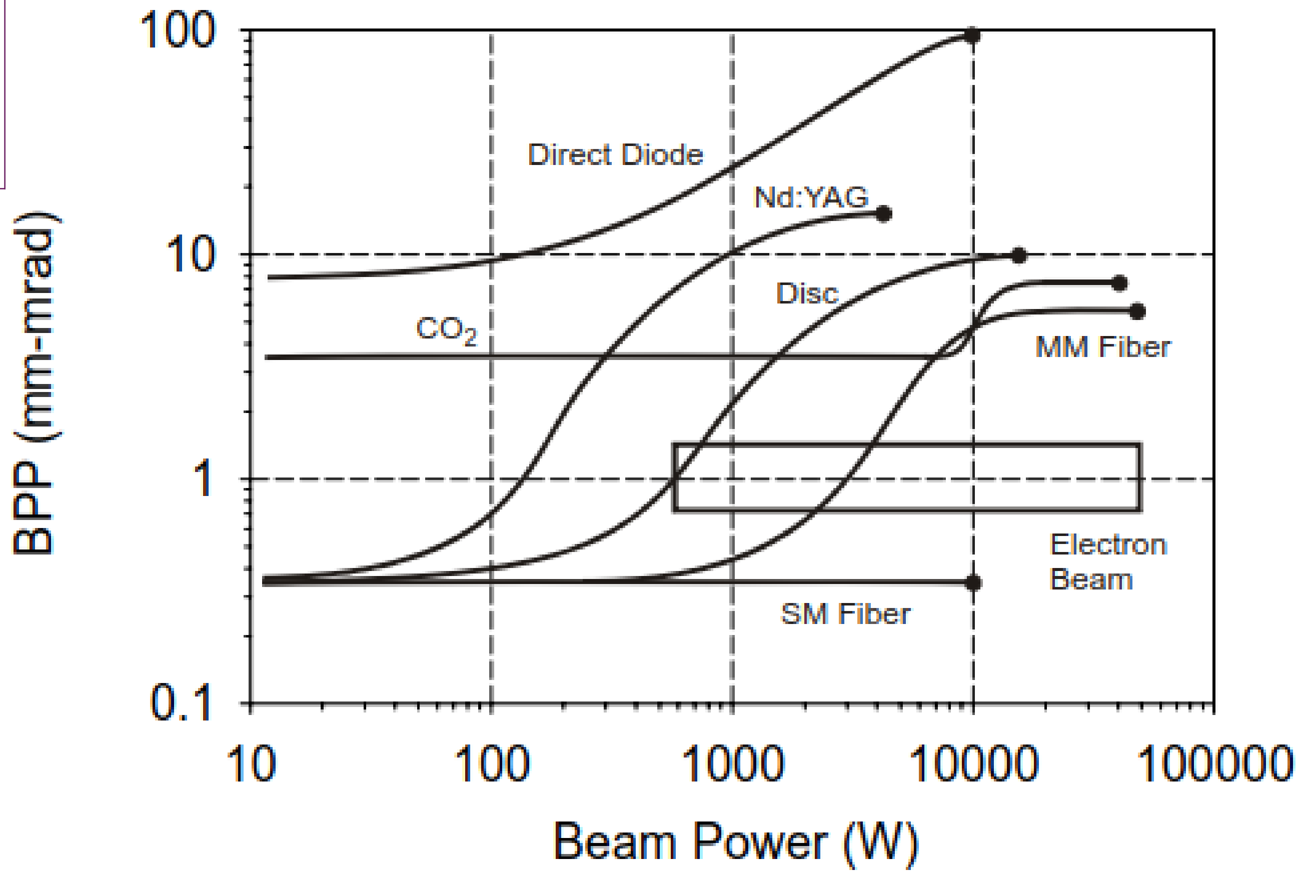


Courtesy of rpmclasers

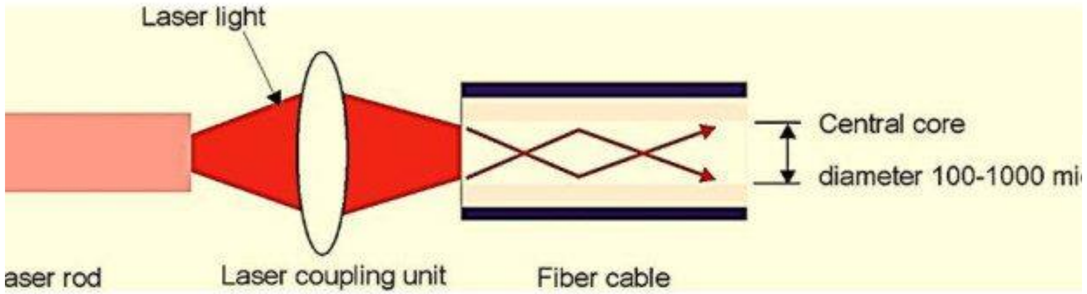
Comparison of the laser sources (and EB)

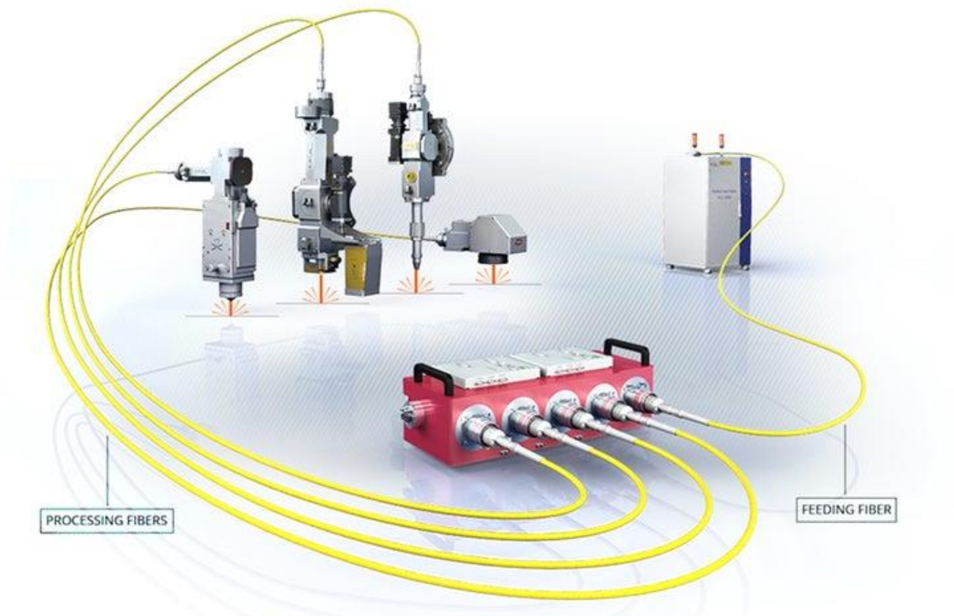
Source	Power	Efficiency
CO2	45 kW	20%
Nd:YAG	4 kW	6-10%
Fibre	50 kW	Up to 40%
Disk	16 kW	15%



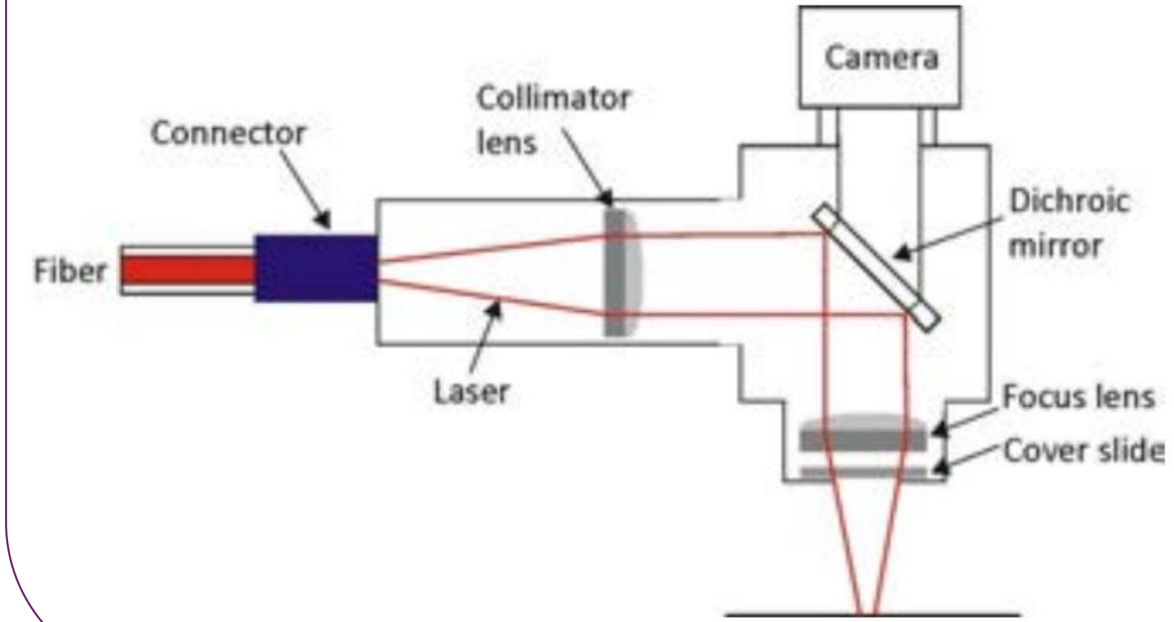


Laser beam delivery and processing head





Laser Welding Head



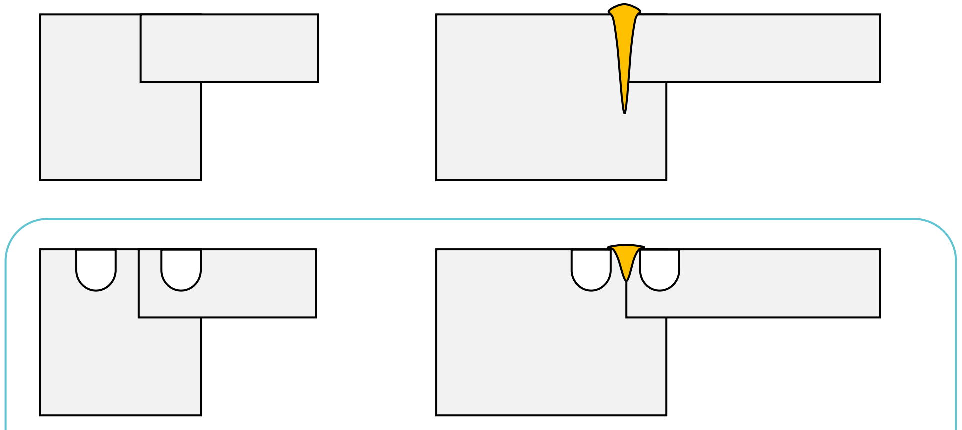
Courtesy IPG Photonics and fabricatingandmetalworking

Joint design

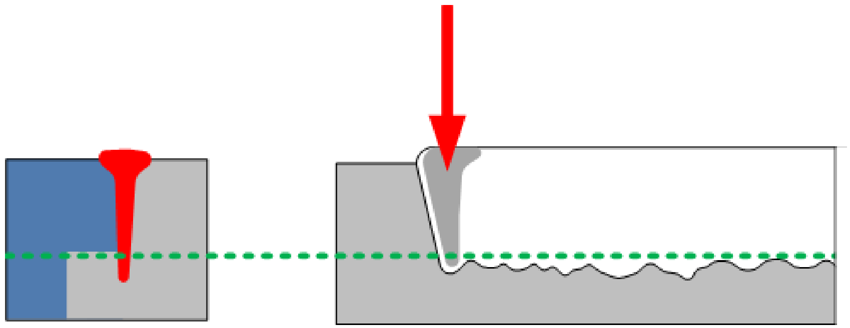
Important considerations for Beam Welding

Partial penetration welds

- Frequently used since the weld bead tends to have good geometries.
- 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.

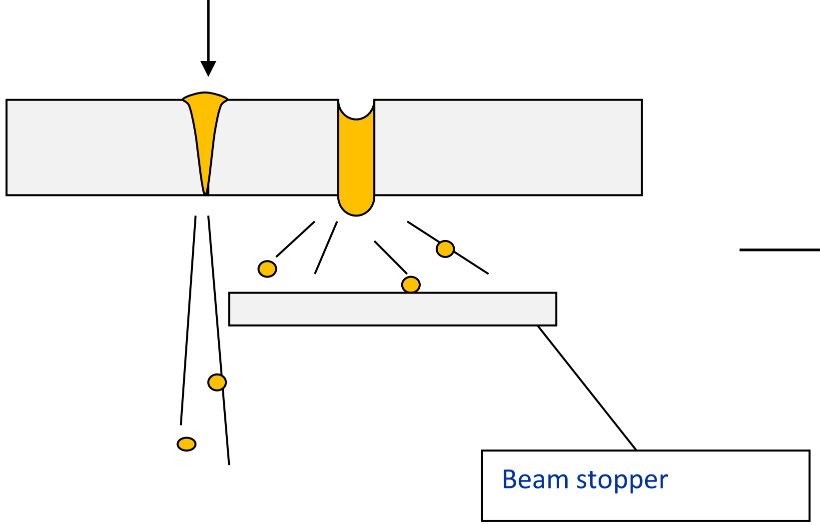


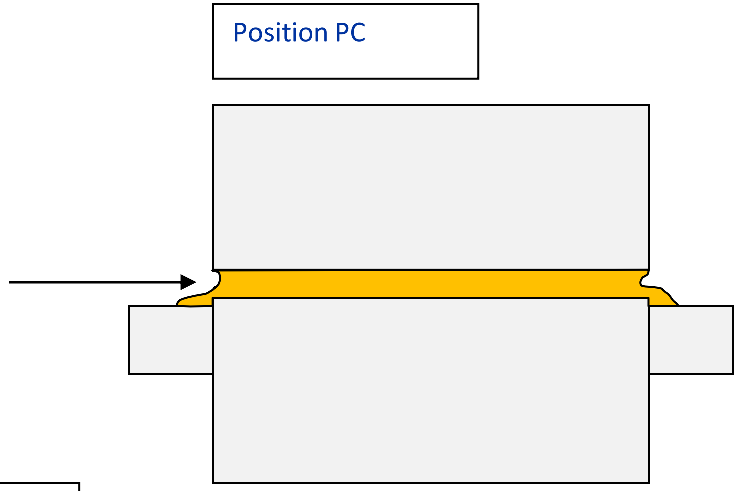
Good practice for circular welds (reduces stresses)



Full penetration welds

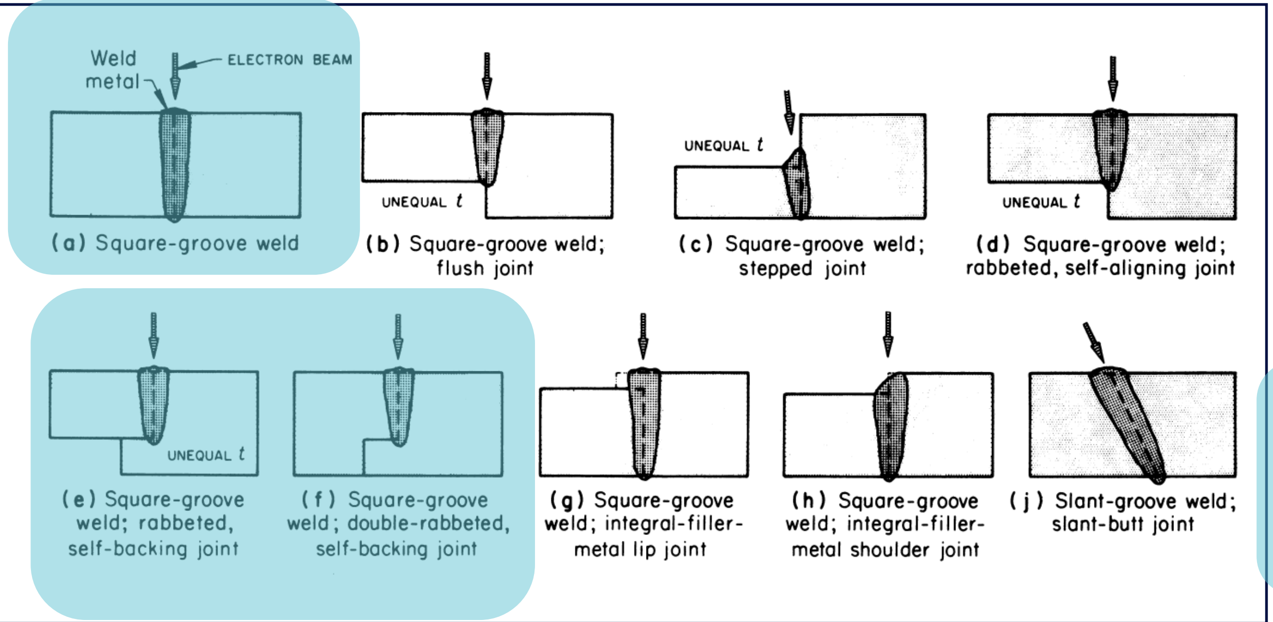
- Degassing from both sides which limits porosity
- No spikes
- Weld positions
  - Vertical position (PA), Penetrations >30mm become difficult.→ Geometrical imperfections: undercuts and shrinkage grooves
  - Horizontal position (PC) is recommended for thick plates
- Beam stopper: in keyhole mode spattering 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.



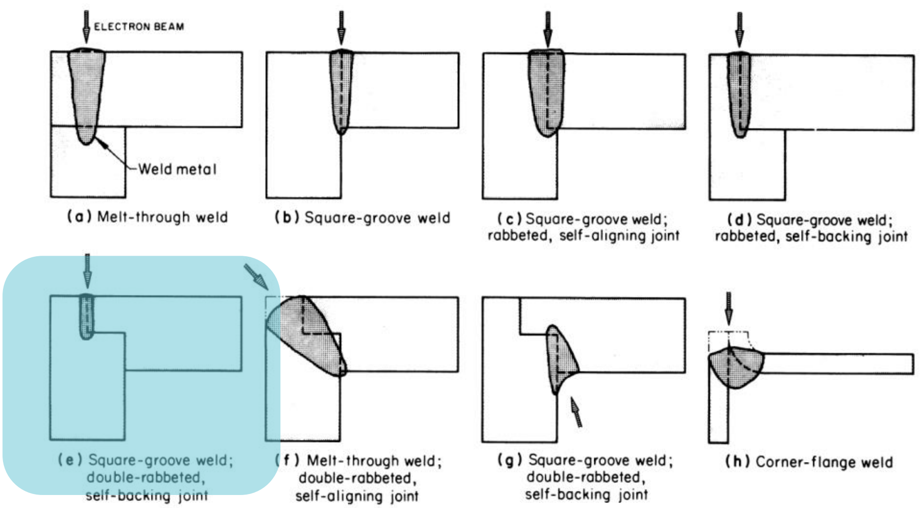


Beam welded assemblies – joint design and preparation

Butt joints

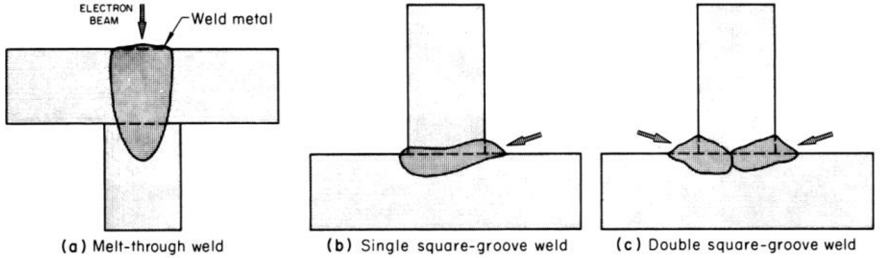


Corner joints

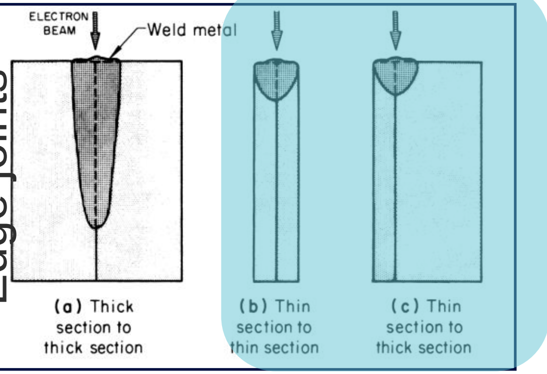


Most common configurations For HEP

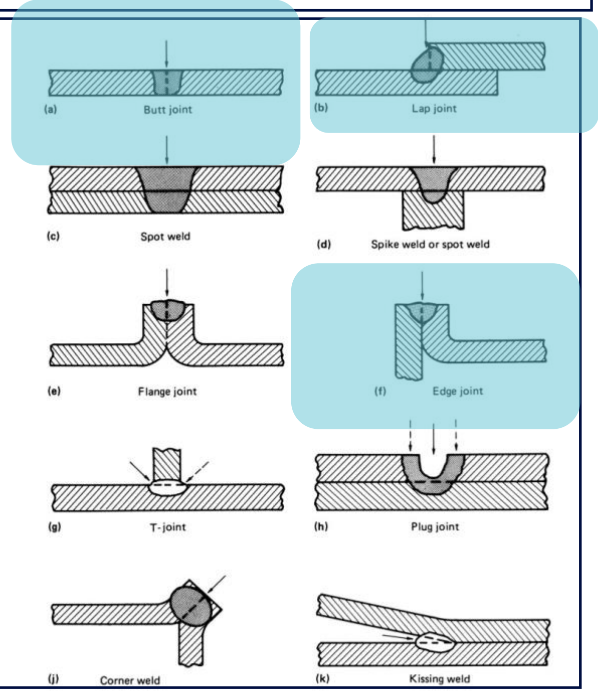
Fillet joints



Edge joints



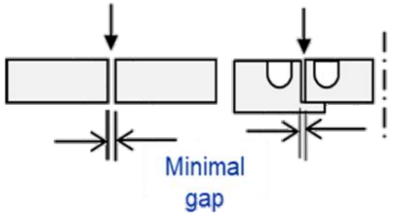
Joints on metal sheets



Courtesy of ASM Handbook vol 6A

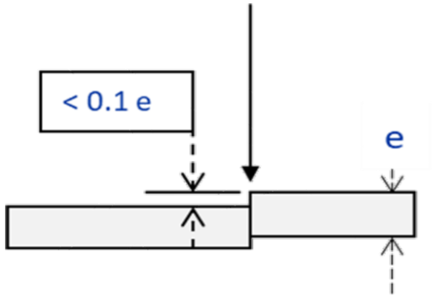
Preparation for High energy beam weld Geometrical considerations

Gaps



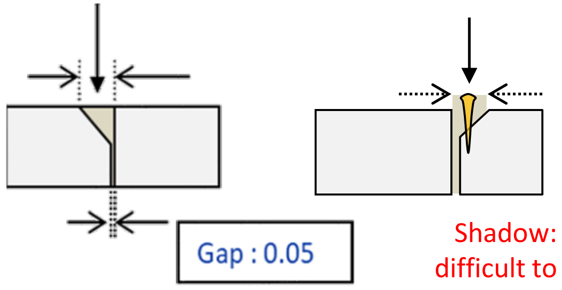
- **<5% of the material thickness**
- Strategies for bridging larger gaps exists
- Leads to concave welds!

Misalignment



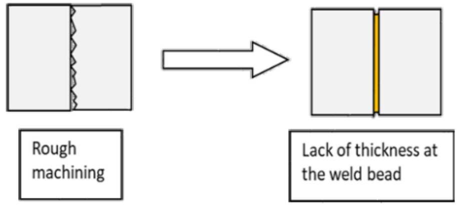
<10% of sheet thickness (depending on quality level ISO13919)

Chamfers



- **Sharp angles pref.**
- High stresses in the head of the weld
- Concave weld geometry
- Shadow which makes it difficult to locate the joint

Roughness

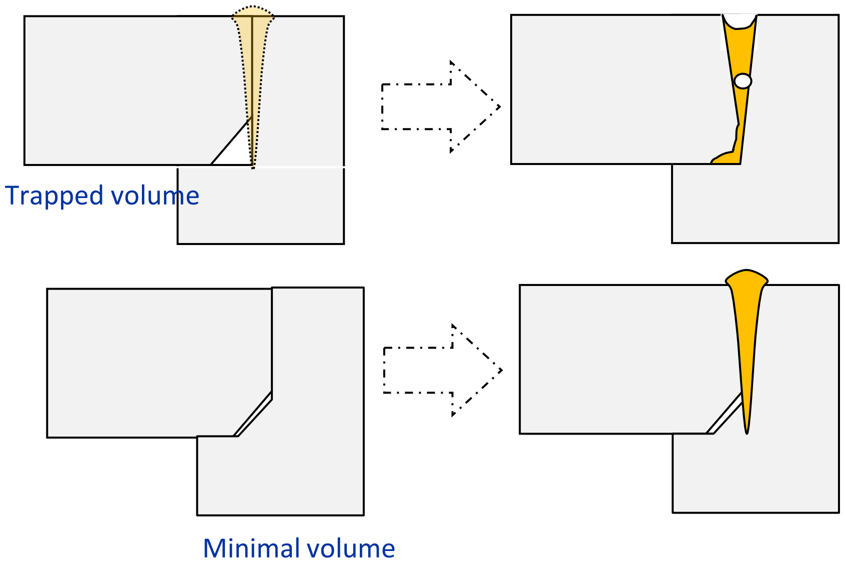


Ra 1.6 / 3.2 µm is the required quality for the joint surface. Consequences:

- Shrinkage
- Porosity rate
- Residual stresses

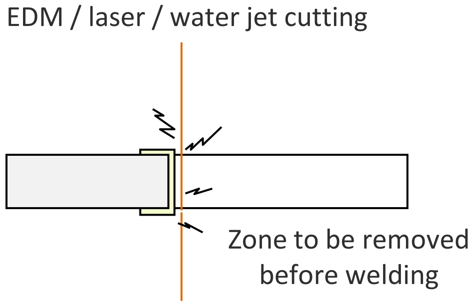
Preparation for High energy beam weld
Other considerations

Trapped volumes

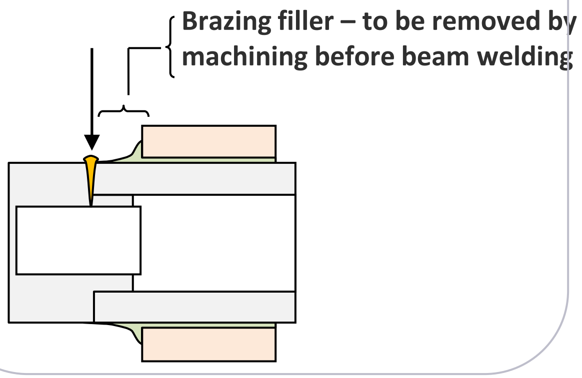


Laser is less sensible to this problem since it usually works at atmospheric pressure

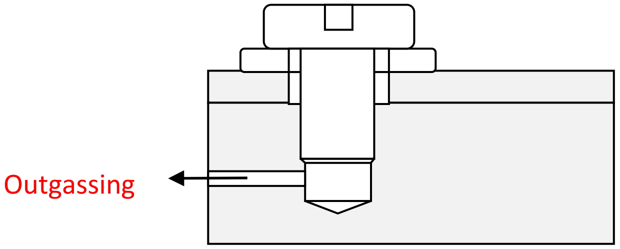
Edge oxidation removal

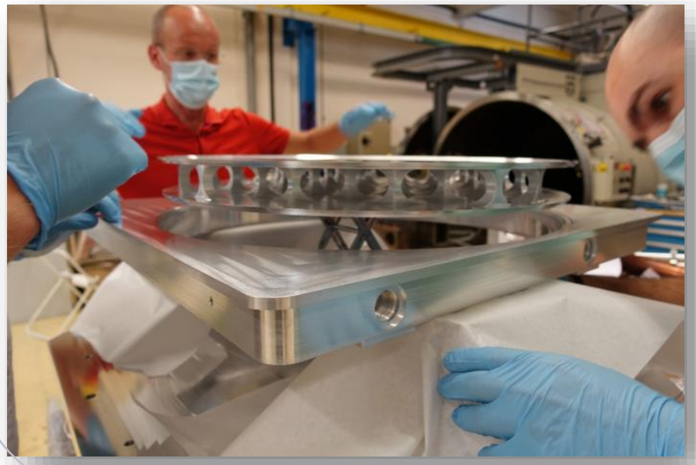


Foreign materials

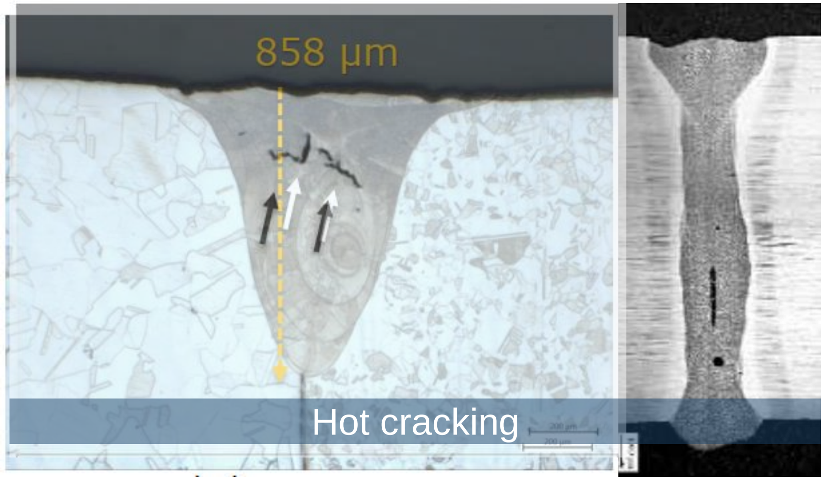


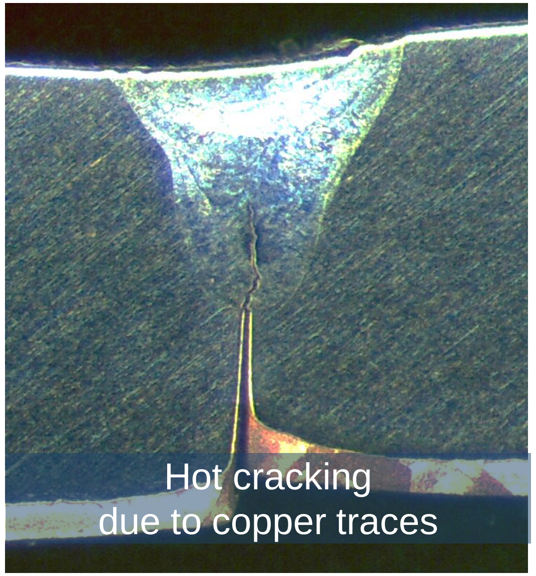
Tooling outgassing

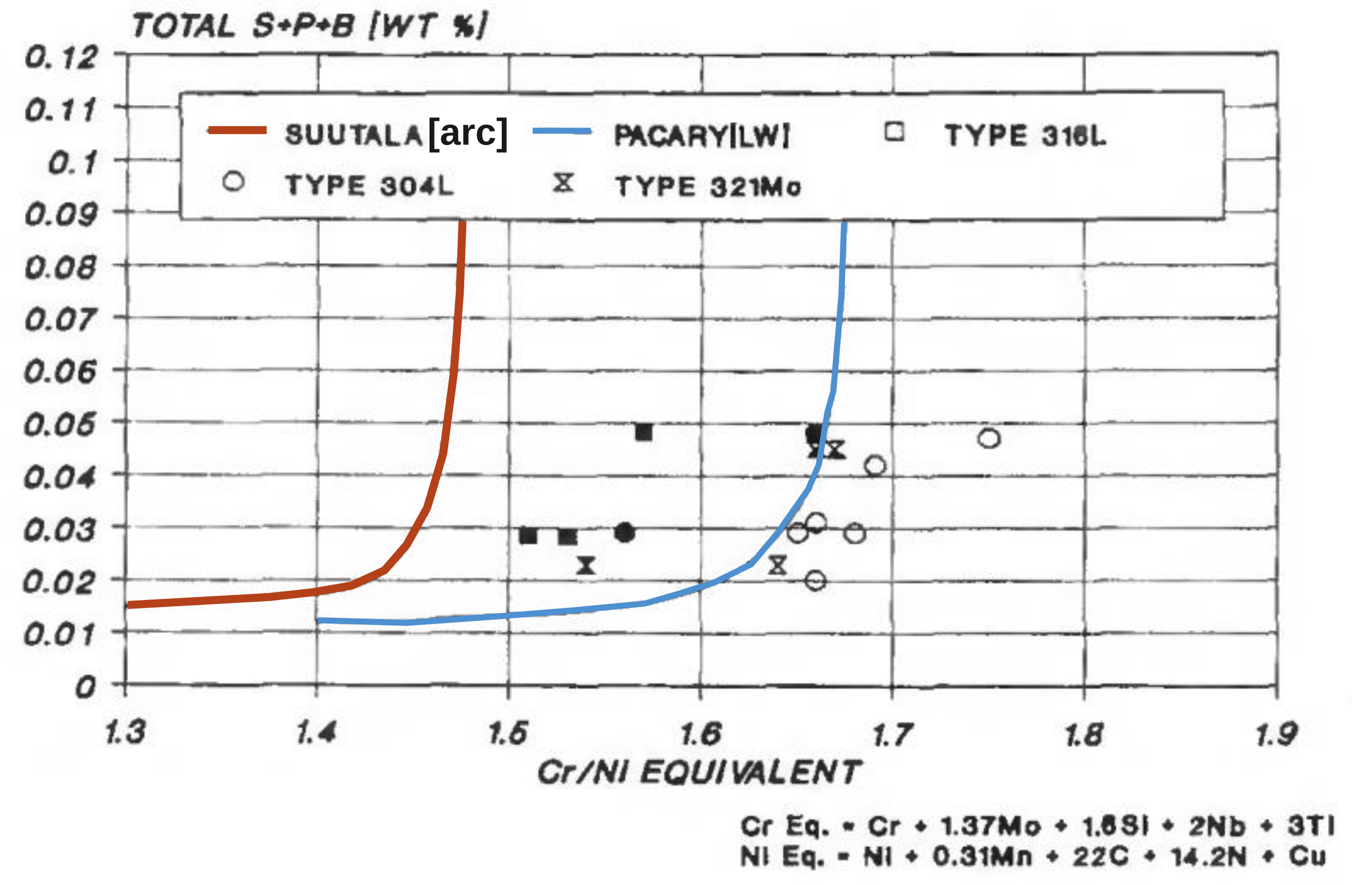




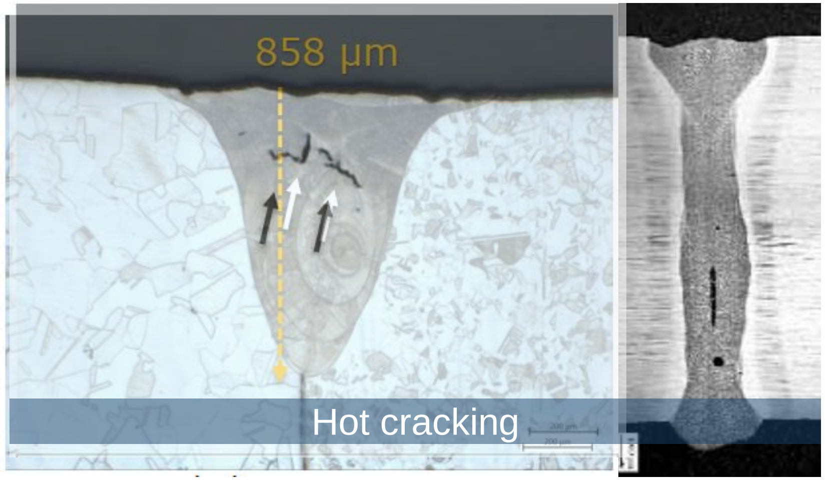
Beam welding defects



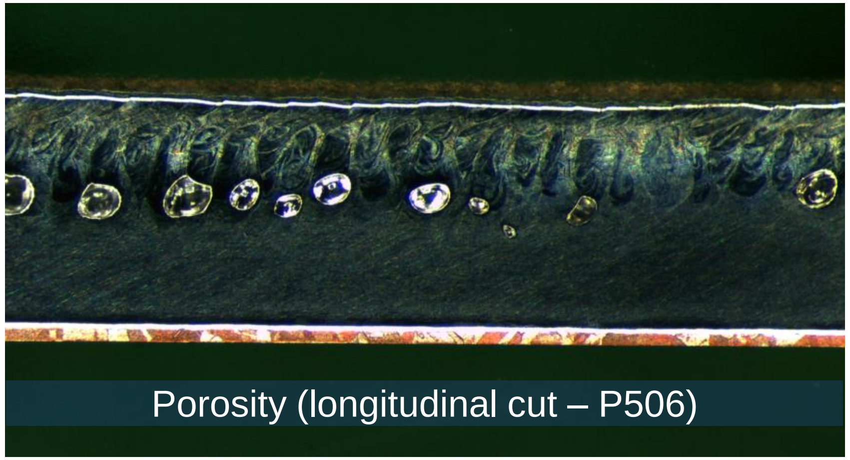




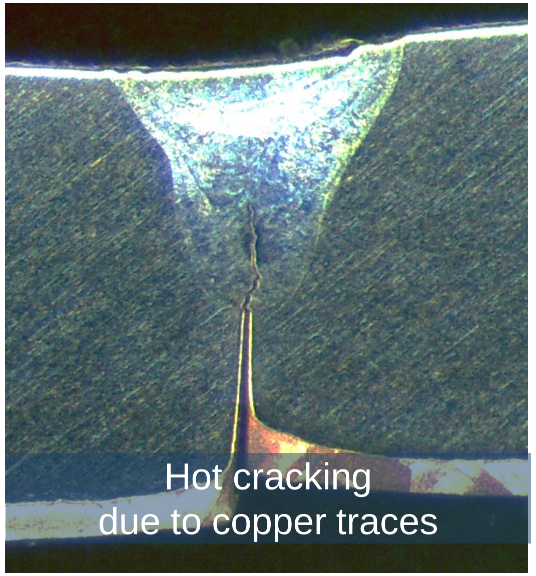
Beam welding defects



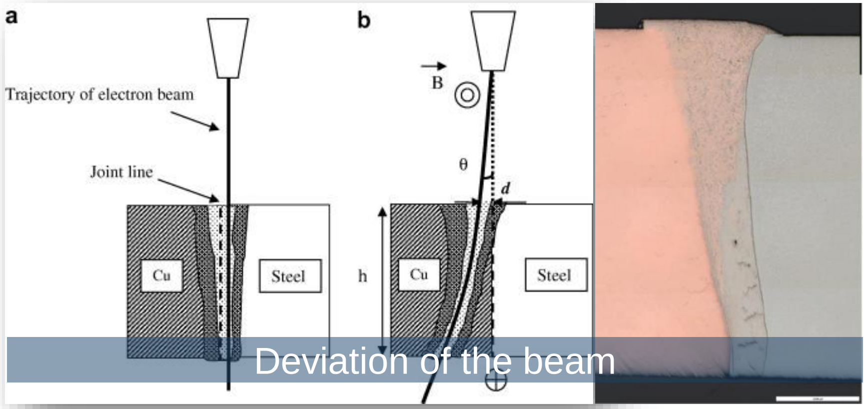
Hot cracking



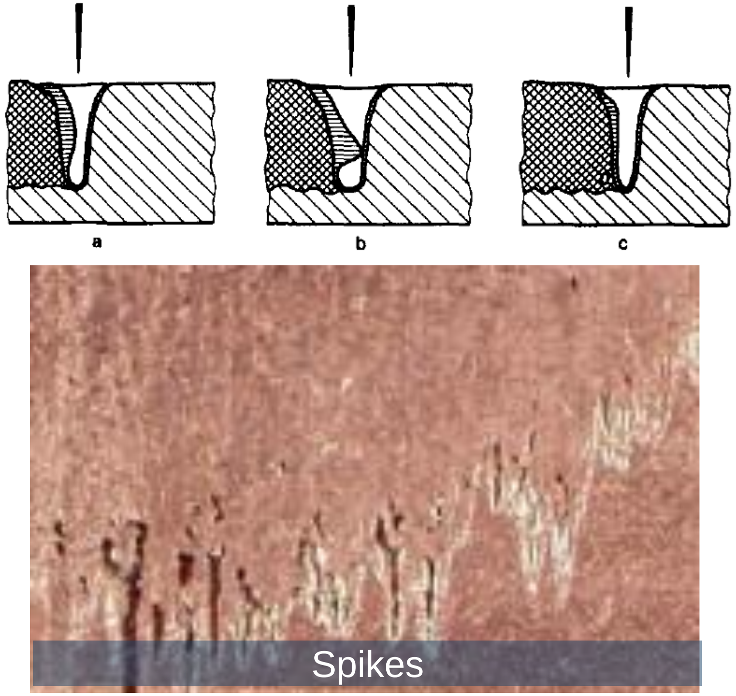
Porosity (longitudinal cut – P506)



Hot cracking
due to copper traces



Deviation of the beam



Spikes

Weldability of materials

And their applications in High Energy Physics

Steel and Nickel alloy

Stainless steel is the most common material for beam welding in High Energy Physics

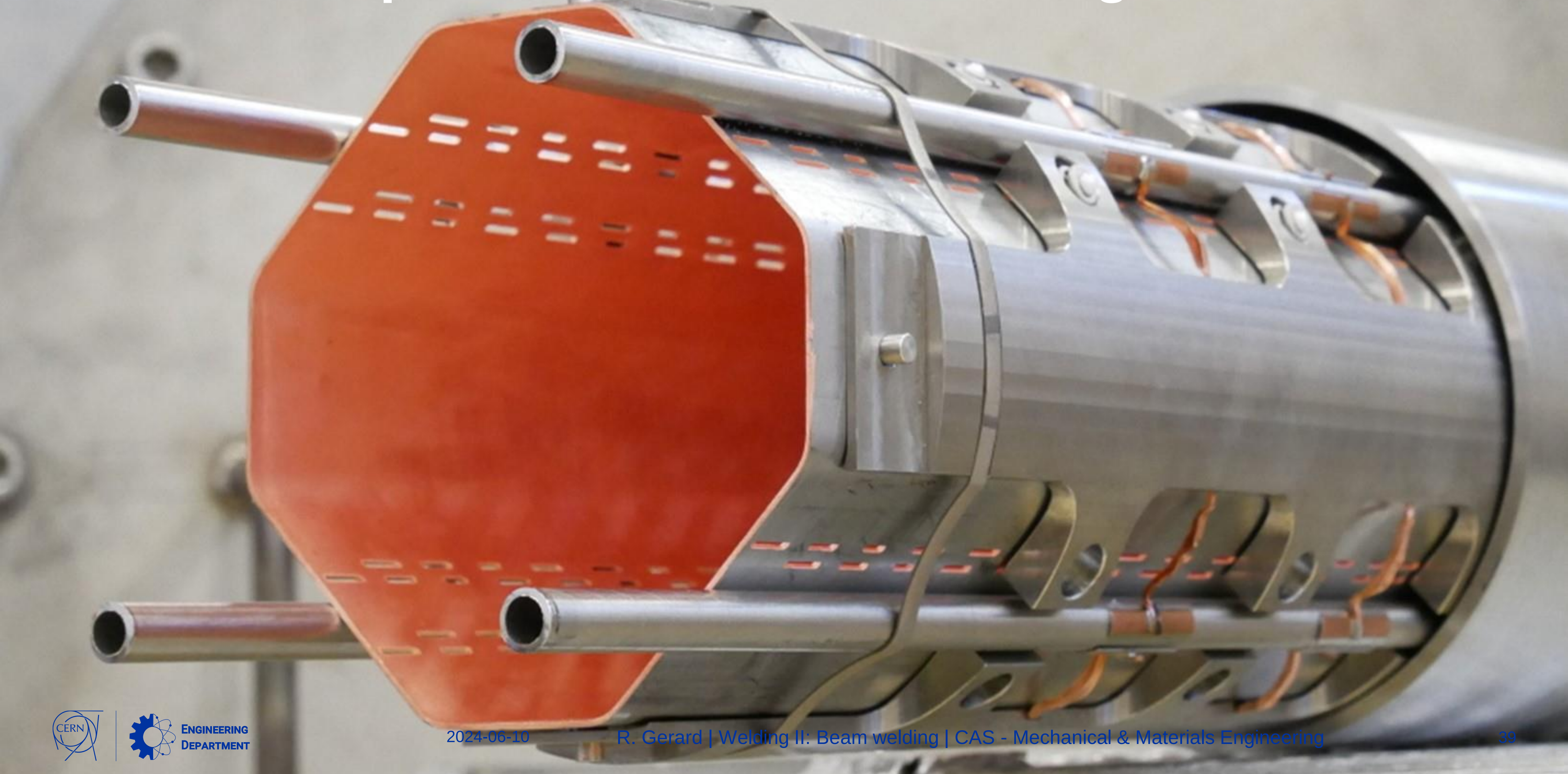
Austenitic Stainless steels have a good general weldability. Care should be taken for hot cracking (due to impurities (S,P,B)).

EBW: strong degassing of Nitrogen in vacuum (316LN) can lead to more eruptive process

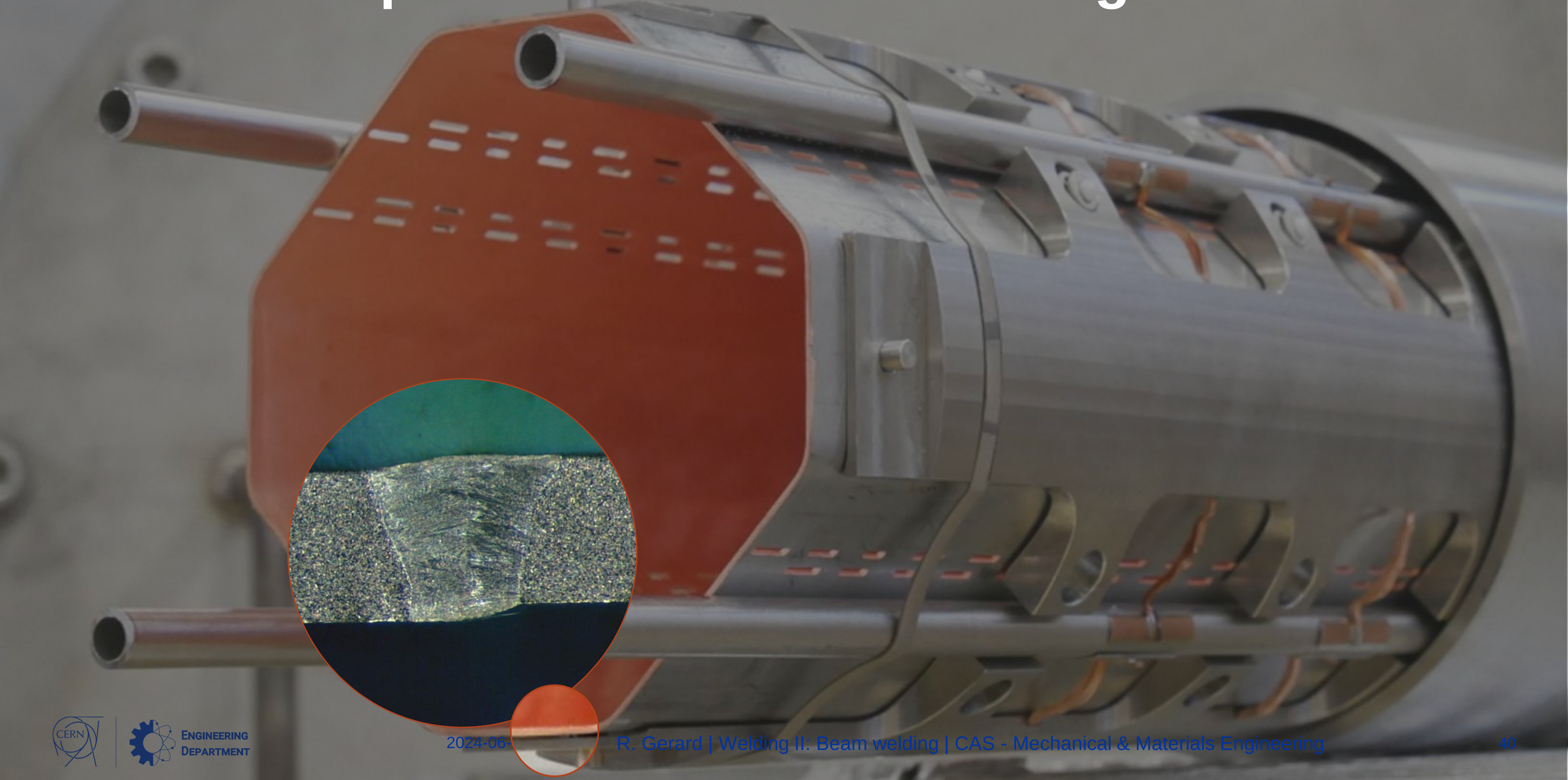
Duplex steel (austenitic-ferritic): outgassing of N and Cr may reduce corrosion resistance

Pur Ni, Ni-Cu and Ni-Fe alloys can be advantageously welded by beam welding. In most cases without difficulty.

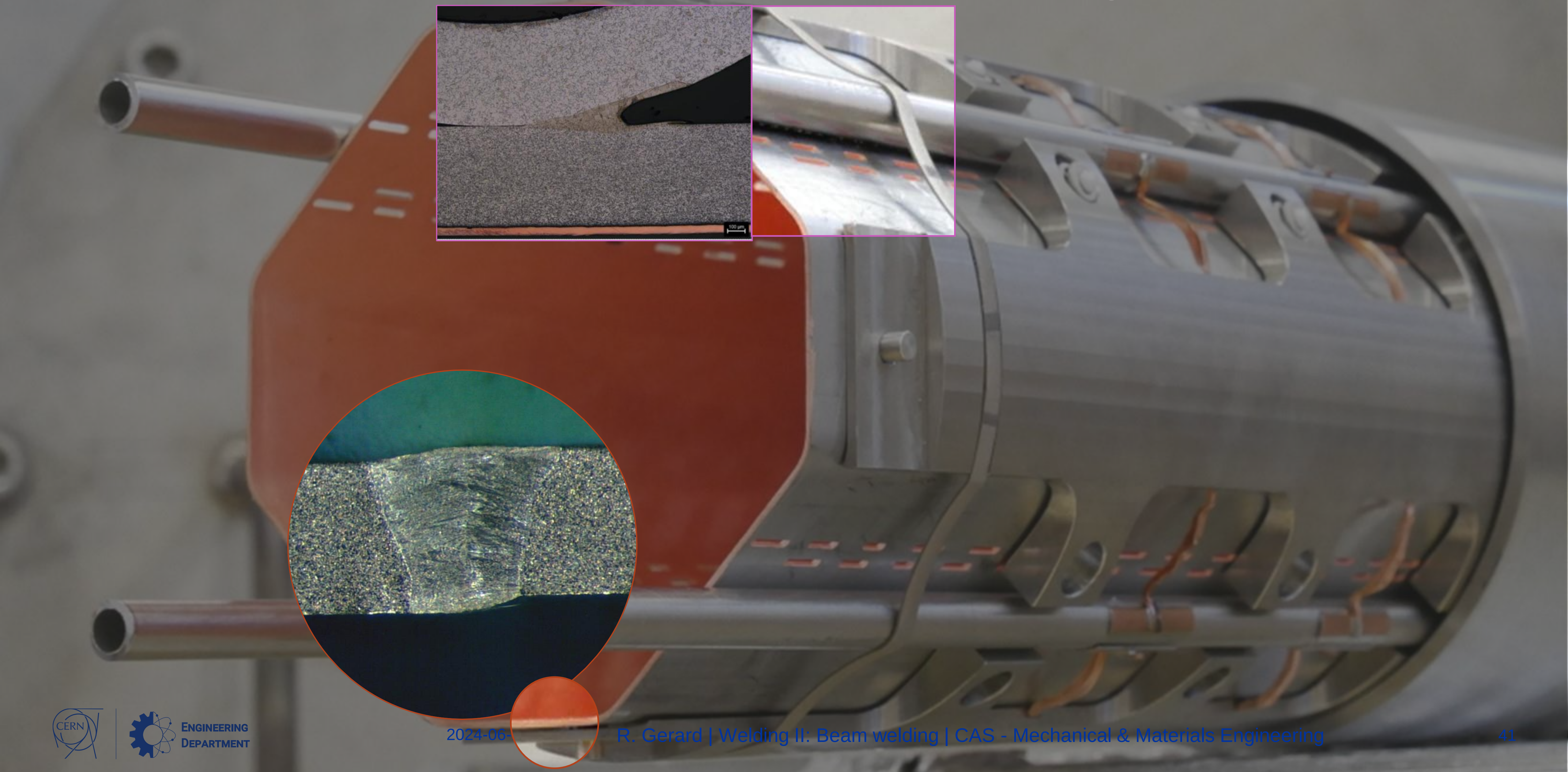
Some examples of Steel beam welding in HEP



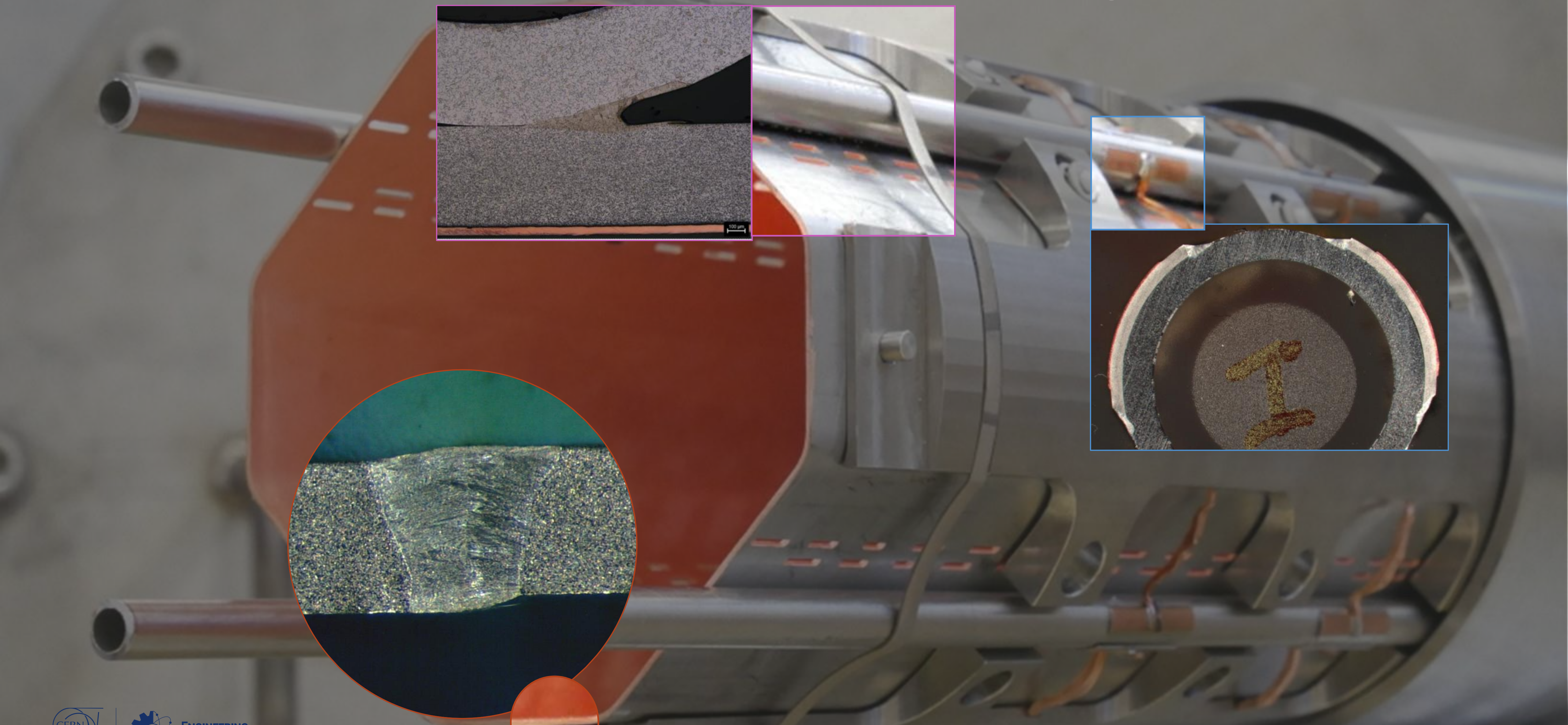
Some examples of Steel beam welding in HEP



Some examples of Steel beam welding in HEP



Some examples of Steel beam welding in HEP



Some examples of Steel beam welding in HEP

Aluminium and its alloys

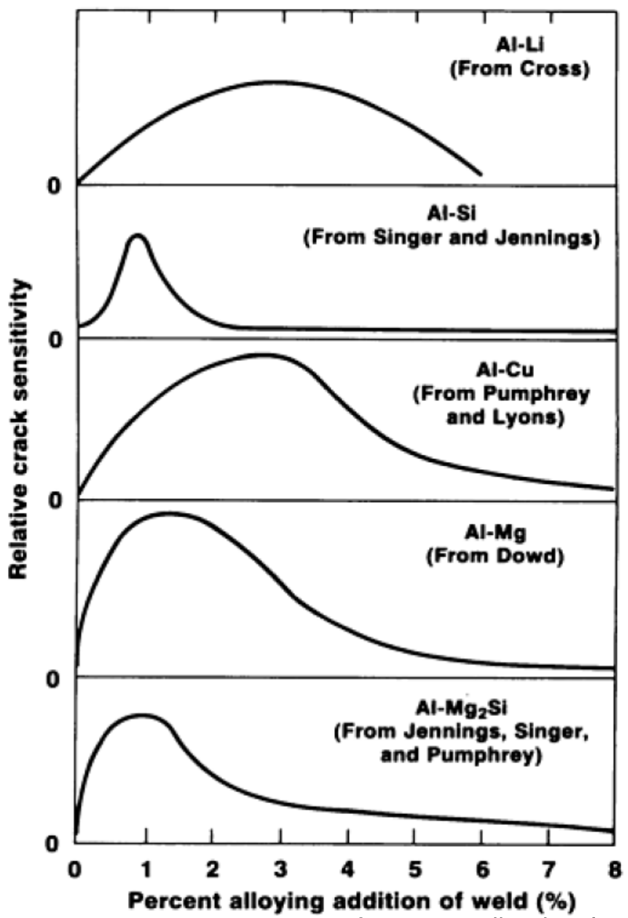
Electrons destroy the alumina layer easily (compared to arc processes). Depths of penetration up to 200 mm with a good aspect ratio are obtained with EBW.

Despite high surface reflectivity to infrared laser radiation, good results are also obtained with laser. CO_2 and powerful fibre laser can achieve penetrations in the range of 20-30 mm.

Series 5000 (Al-Mg): good weldability (risk of porosity in EBW due to Mg degassing under vacuum).

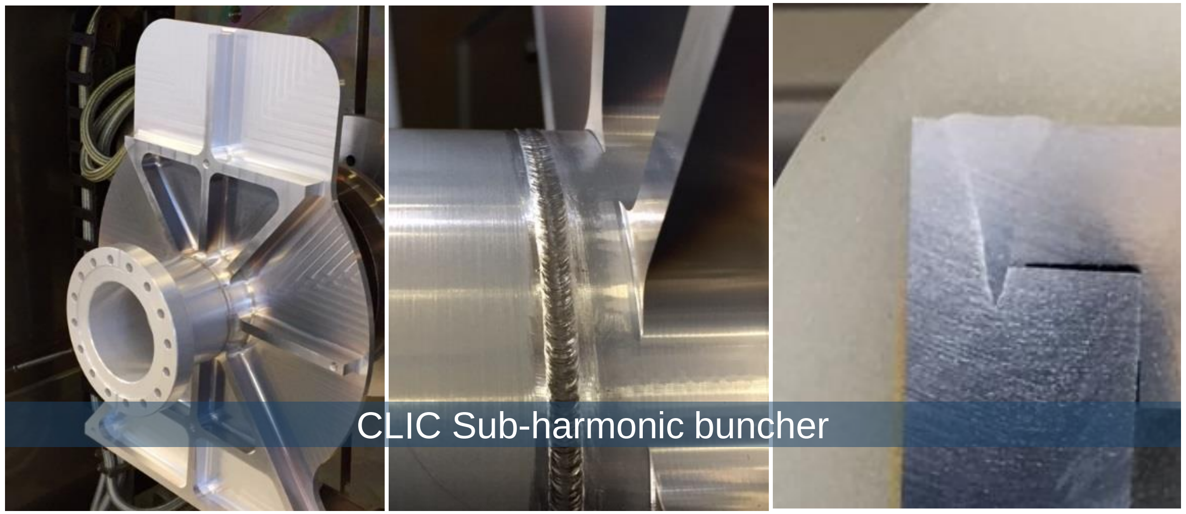
Series 2000 (Al-Cu), Series 4000 (Al-Si) and series 6000 (Al-Mg-Si): attention must be paid to the risk of hot cracking.

For castings, porosity rate is very high (high H_2 content). Welding under vacuum not recommended.

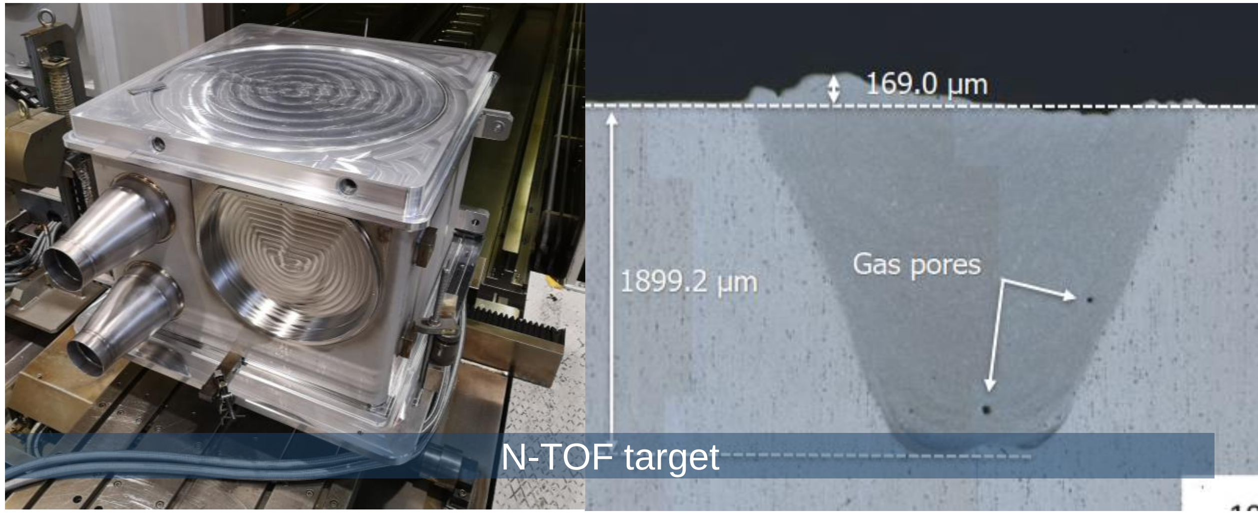


Courtesy of ASM Handbook vol 6

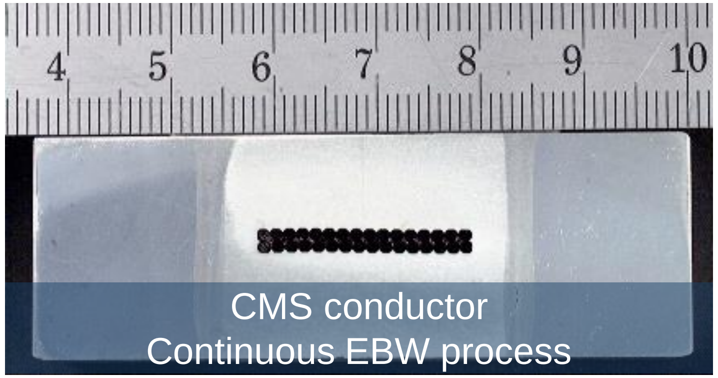
Aluminium and its alloys



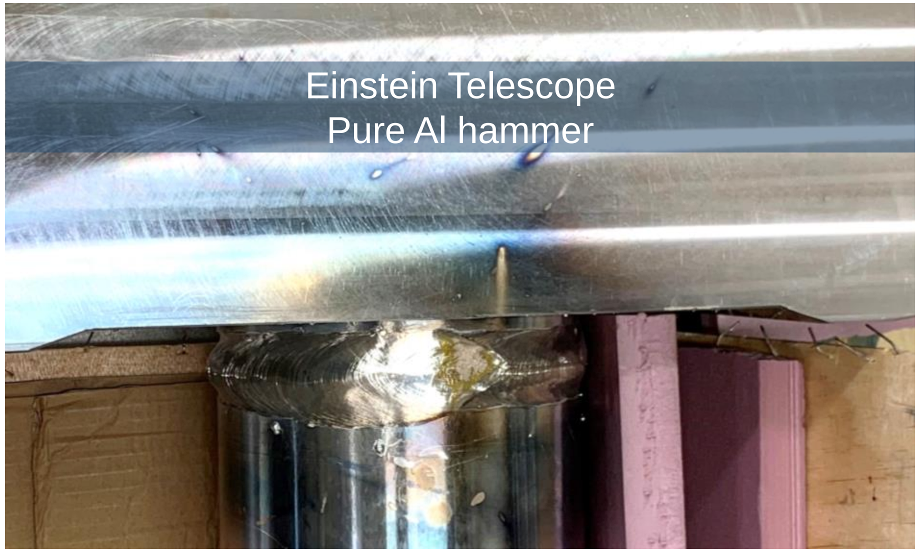
CLIC Sub-harmonic buncher



N-TOF target



CMS conductor
Continuous EBW process



Einstein Telescope
Pure Al hammer

Copper and copper alloys

Most of cooper alloys are weldable by EBW.

Except for brass, Zn boiling point 910°C

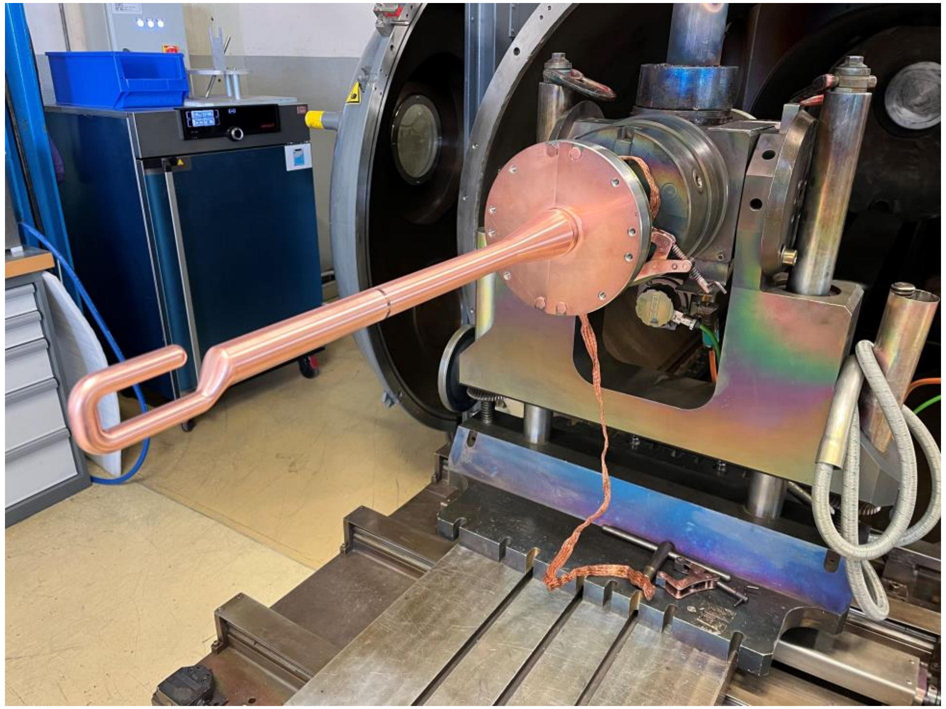
Welding by laser is very difficult due to reflection.
Bright Infrared, Green and blue lasers improve the absorption coefficient.

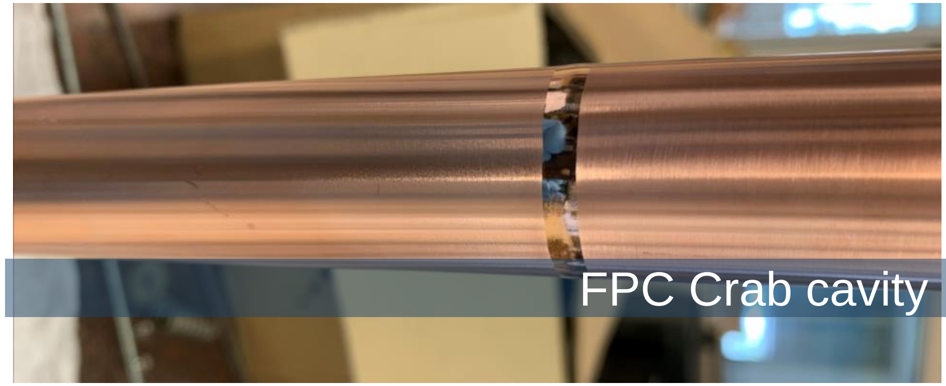
For OF and OFE copper (Oxygen 0.001% max) weldability is good. The physical properties of cooper limit the depth of penetration.

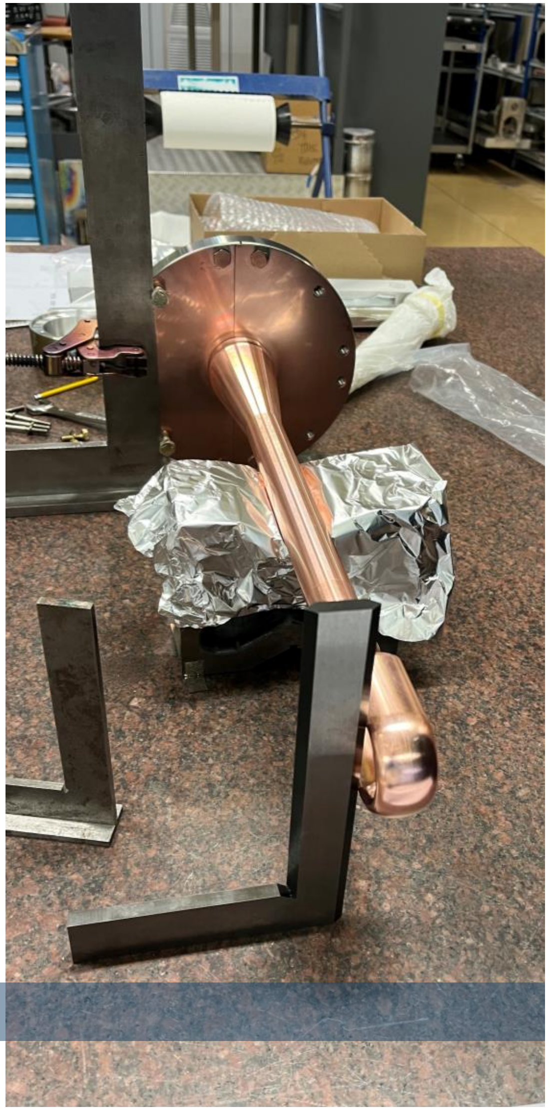
High thermal conductivity and thermal expansion coefficient lead sometimes **to important welding shrinkage** depending on the heat input. Fitting needs to be tight to homogenize heat distribution.

The depth of penetration is very sensible to this heat pumping effect.

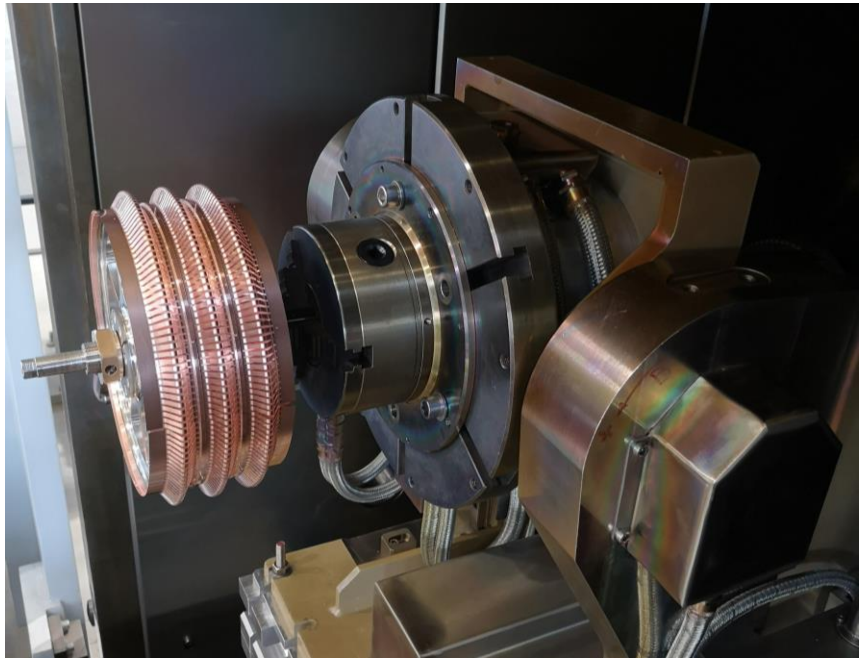
Copper and copper alloys

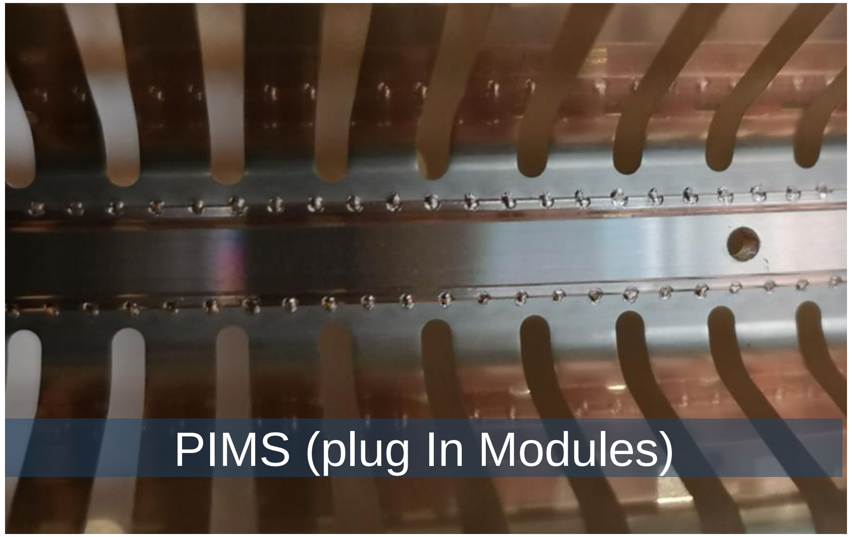






FPC Crab cavity





PIMS (plug In Modules)

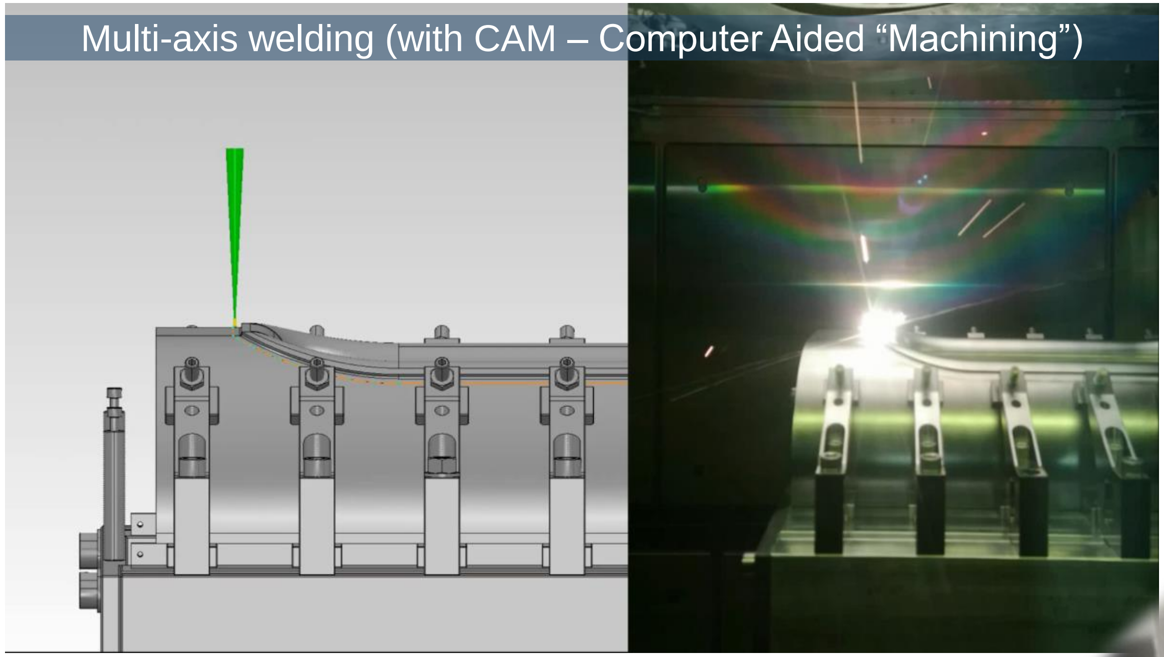
Refractory and reactive metals

Ti and its alloys have a good weldability by EB and LB. Welding under vacuum is preferred.

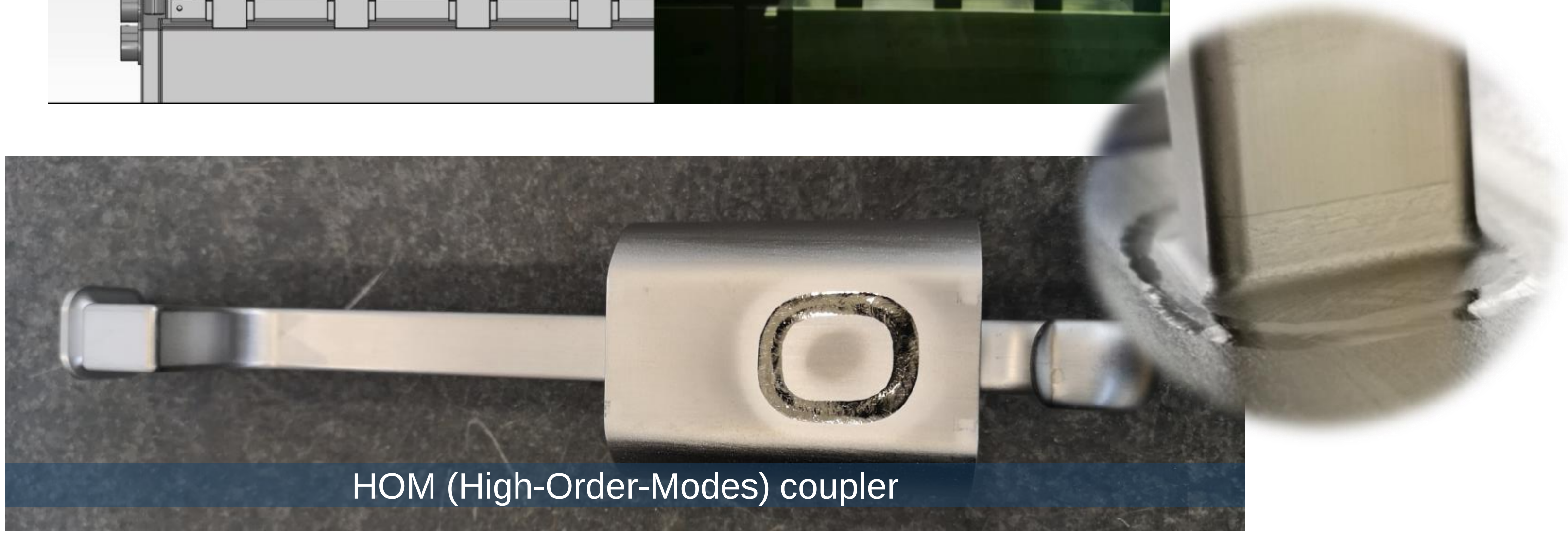
Nb has a very good weldability, with special attention to the quality of vacuum. Welded by EB ($P < 5 \times 10^{-5}$ mbar).

W, Mo and its alloys are also weldable, but with very low ductility of the joint.

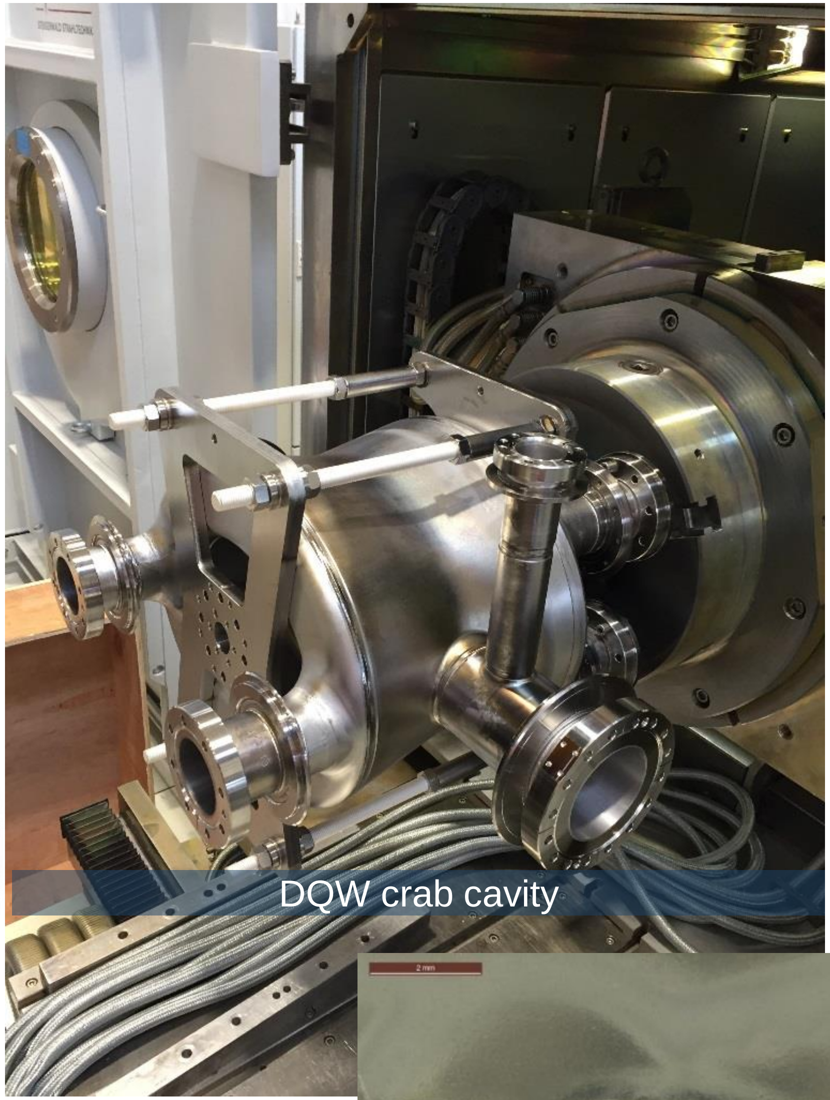
Refractory and reactive metals



Multi-axis welding (with CAM – Computer Aided “Machining”)



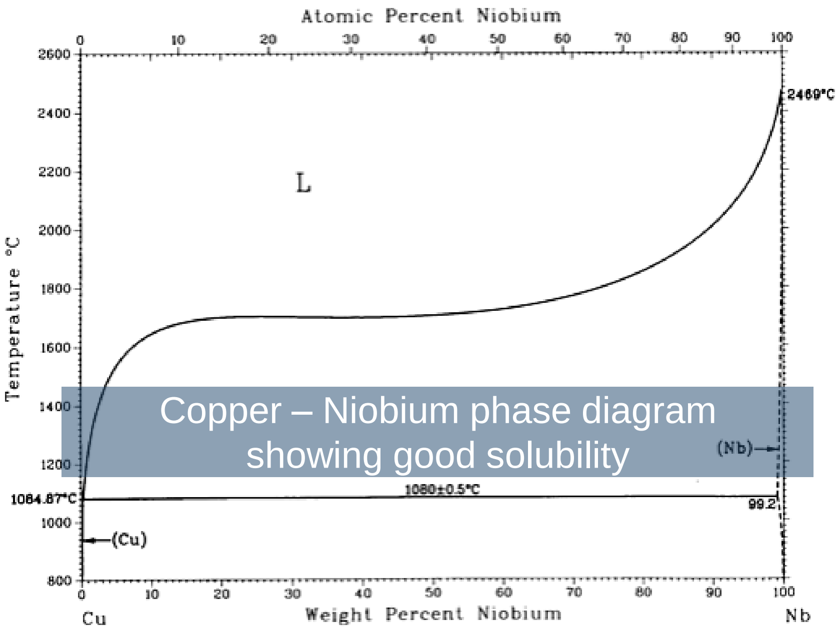
HOM (High-Order-Modes) coupler



DQW crab cavity

Dissimilar joint

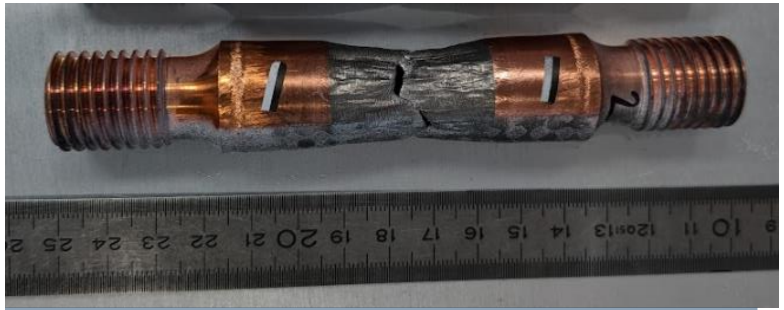
- Many combinaison possible
  With or without the use of filler material (often in the form of a foil at the interface)
- Pro's of beam welding: **high intensity** and **precise position** of the beam



Copper – Niobium phase diagram showing good solubility

Stainless steel and copper

Nb and Cu

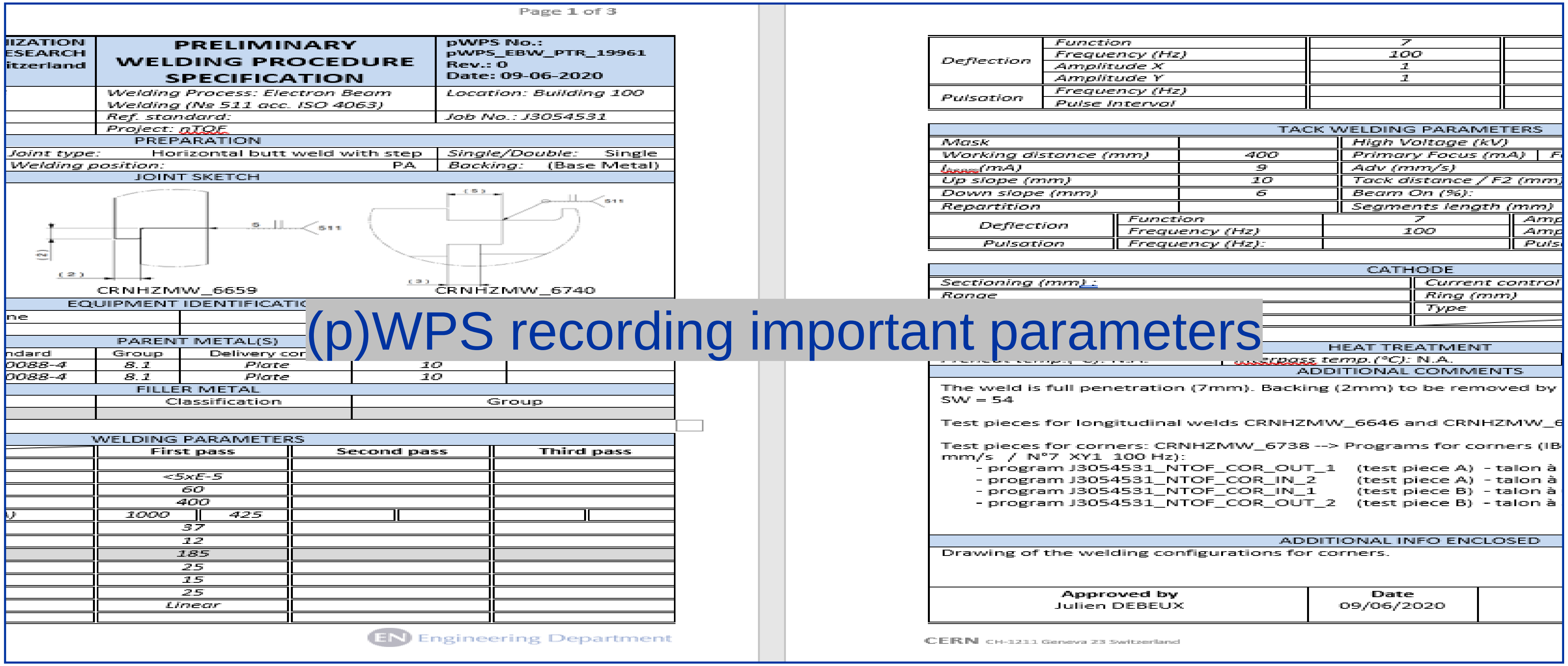

Nb and Cu tensile test showing advantageous rupture in the niobium base material

Normative and safety aspects

The specificities of High energy Beam Welding

Weld qualification according to int. standards !

Definition of a Welding procedureISO 15609-3 (EB) & -4 (Laser)



Page 1 of 3

IIZATION ESEARCH itzerland	PRELIMINARY WELDING PROCEDURE SPECIFICATION	pWPS No.: pWPS_EBW_PTR_19961 Rev.: 0 Date: 09-06-2020
	Welding Process: Electron Beam Welding (Nr 511 acc. ISO 4063)	Location: Building 100
	Ref. standard:	Job No.: J3054531
	Project: nTOF	

PREPARATION

Joint type:	Horizontal butt weld with step	Single/Double:	Single
Welding position:	PA	Backing:	(Base Metal)

JOINT SKETCH

CRNHZMW_6659 CRNHZMW_6740

EQUIPMENT IDENTIFICATIO

PARENT METAL(S)

ndard	Group	Delivery cor	
0088-4	8.1	Plate	10
0088-4	8.1	Plate	10

FILLER METAL

	Classification	Group

WELDING PARAMETERS

	First pass	Second pass	Third pass
	<5xE-5		
	60		
	400		
)	1000 425		
	37		
	12		
	185		
	25		
	15		
	25		
	Linear		

EN Engineering Department

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

TACK WELDING PARAMETERS

Mask		High Voltage (kV)
Working distance (mm)	400	Primary Focus (mA)
I_{beam}(mA)	9	Adv (mm/s)
Up slope (mm)	10	Tack distance / F2 (mm)
Down slope (mm)	6	Beam On (%):
Repartition		Segments length (mm)

Deflection	Function	7	Amp
	Frequency (Hz)	100	Amp
Pulsation	Frequency (Hz):		Puls

CATHODE

Sectioning (mm):	Current control
Range	Ring (mm)
	Type

HEAT TREATMENT

Interpass temp.(°C): N.A.

ADDITIONAL COMMENTS

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

Test pieces for longitudinal welds CRNHZMW_6646 and CRNHZMW_6

Test pieces for corners: CRNHZMW_6738 --> Programs for corners (IB mm/s / N°7 XY1 100 Hz):
- program J3054531_NTOF_COR_OUT_1 (test piece A) - talon à
- program J3054531_NTOF_COR_IN_2 (test piece A) - talon à
- program J3054531_NTOF_COR_IN_1 (test piece B) - talon à
- program J3054531_NTOF_COR_OUT_2 (test piece B) - talon à

ADDITIONAL INFO ENCLOSED

Drawing of the welding configurations for corners.

Approved by	Date
Julien DEBEUX	09/06/2020

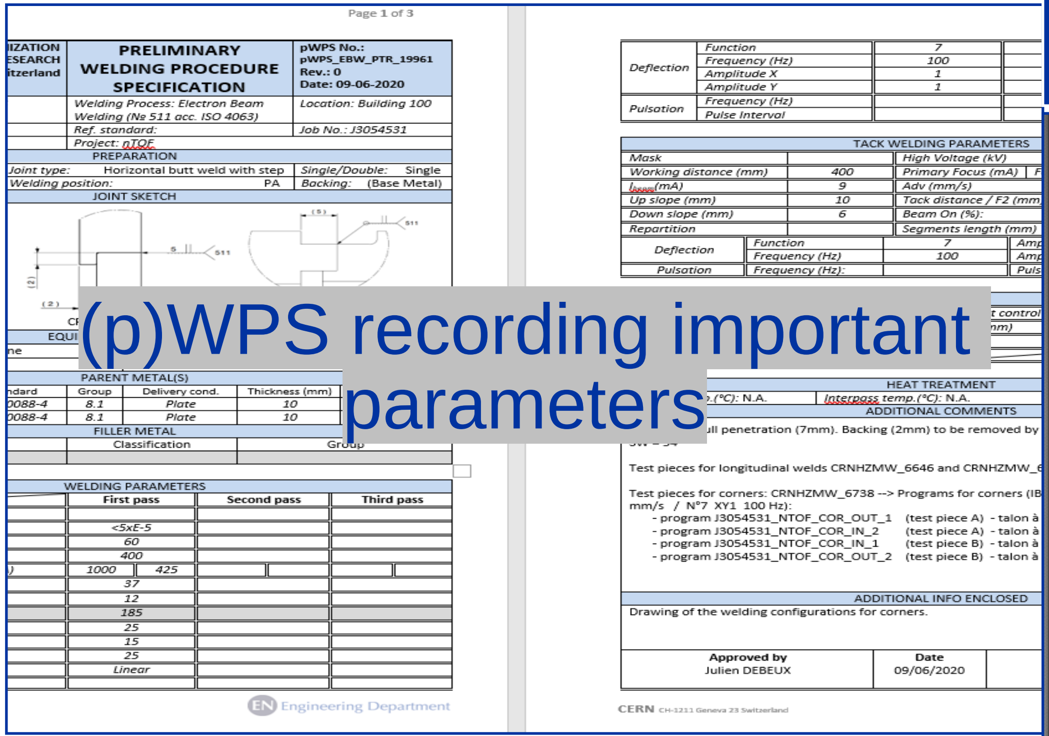
CERN CH-1211 Geneva 23 Switzerland

(p)WPS recording important parameters

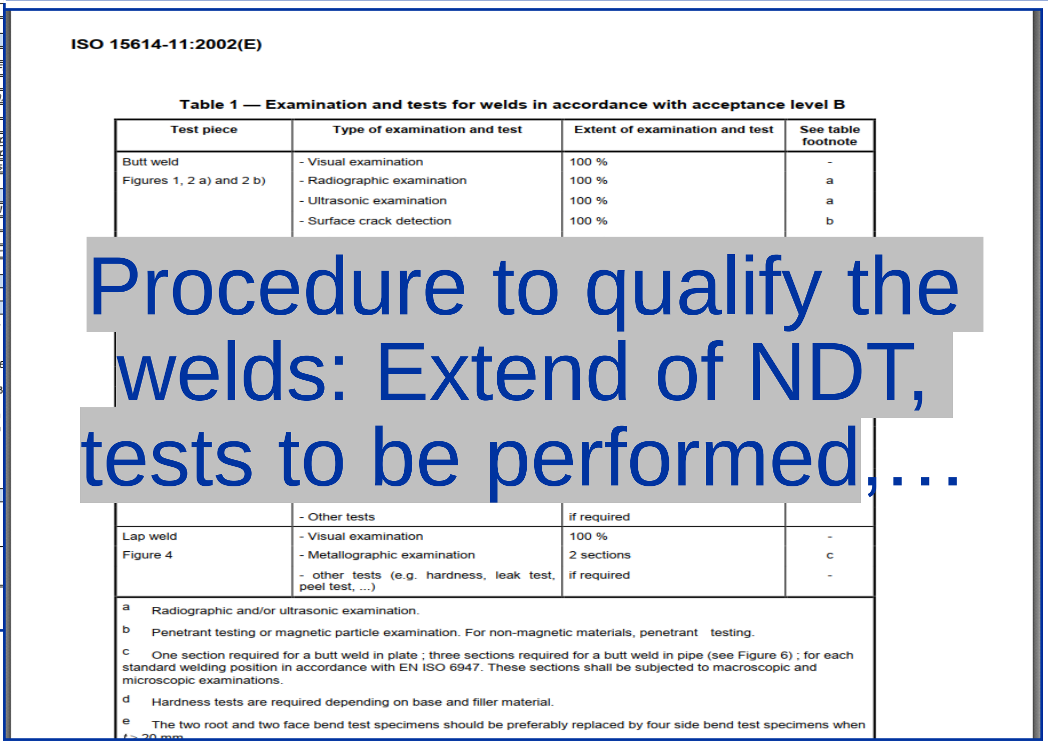
Weld qualification according to int. standards !

Definition of a Welding procedure ISO 15609-3 (EB) & -4 (Laser)

Qualification (ISO 15614-11)



(p)WPS recording important parameters



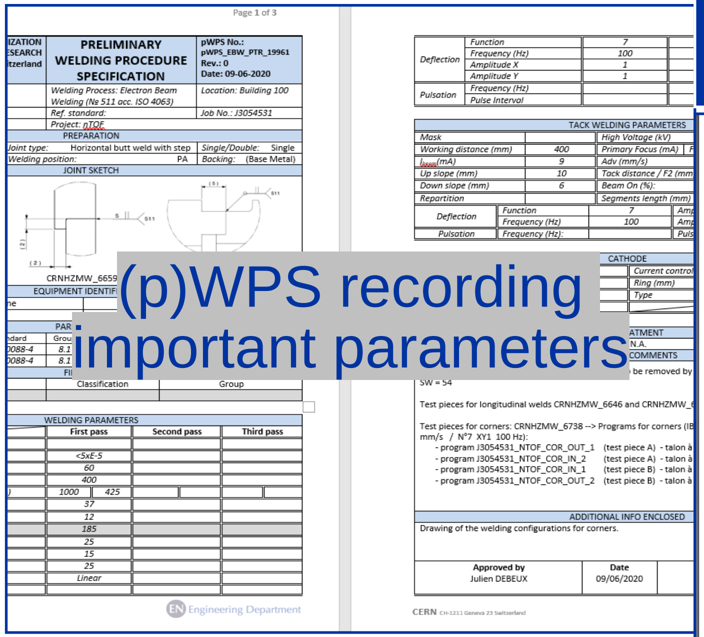
Procedure to qualify the welds: Extend of NDT, tests to be performed,…

Weld qualification according to int. standards !

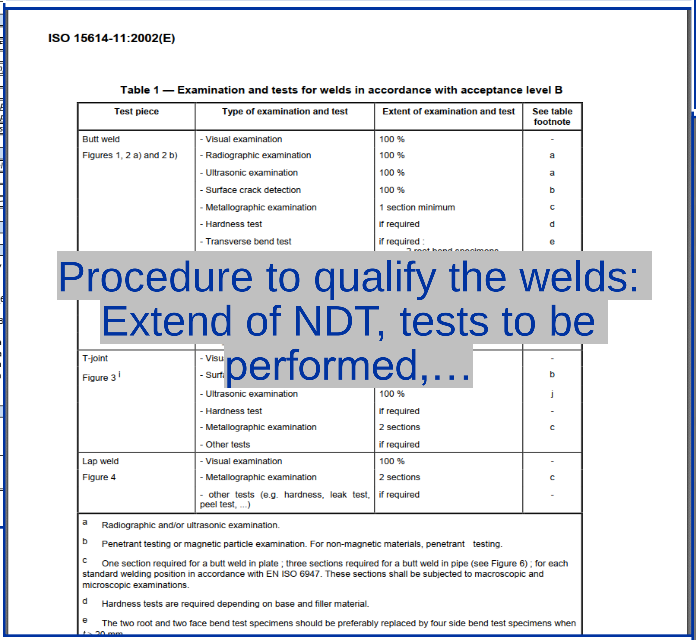
Definition of a Welding procedure ISO 15609-3 (EB) & -4 (Laser)

Qualification (ISO 15614-11)

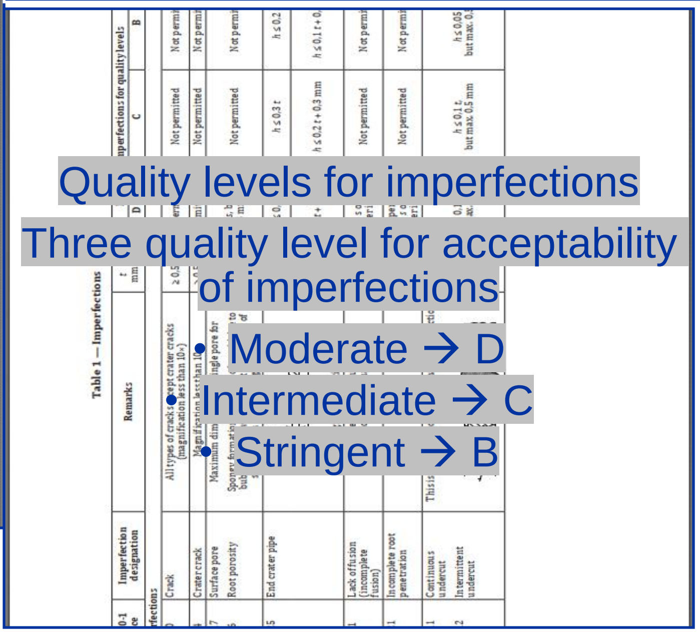
Imperfections (ISO 13919)



(p)WPS recording important parameters



Procedure to qualify the welds: Extend of NDT, tests to be performed,…



Quality levels for imperfections

Three quality level for acceptability of imperfections

- Moderate → D
- Intermediate → C
- Stringent → B

Weld qualification according to int. standards !

Definition of a Welding procedure ISO 15609-3 (EB) & -4 (Laser)

(p)WPS recording important parameters

Qualification (ISO 15614-11)

Procedure to qualify the welds: Extend of NDT, tests to be performed,…

Imperfections (ISO 13919)

Quality levels for imperfections

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- Stringent → B

Welding books

Weld qualification according to int. standards !

Definition of a Welding procedure ISO 15609-3 (EB) & -4 (Laser)

(p)WPS recording important parameters

Qualification (ISO 15614-11)

Procedure to qualify the welds: Extend of NDT, tests to be performed,…

Imperfections (ISO 13919)

Quality levels for imperfections

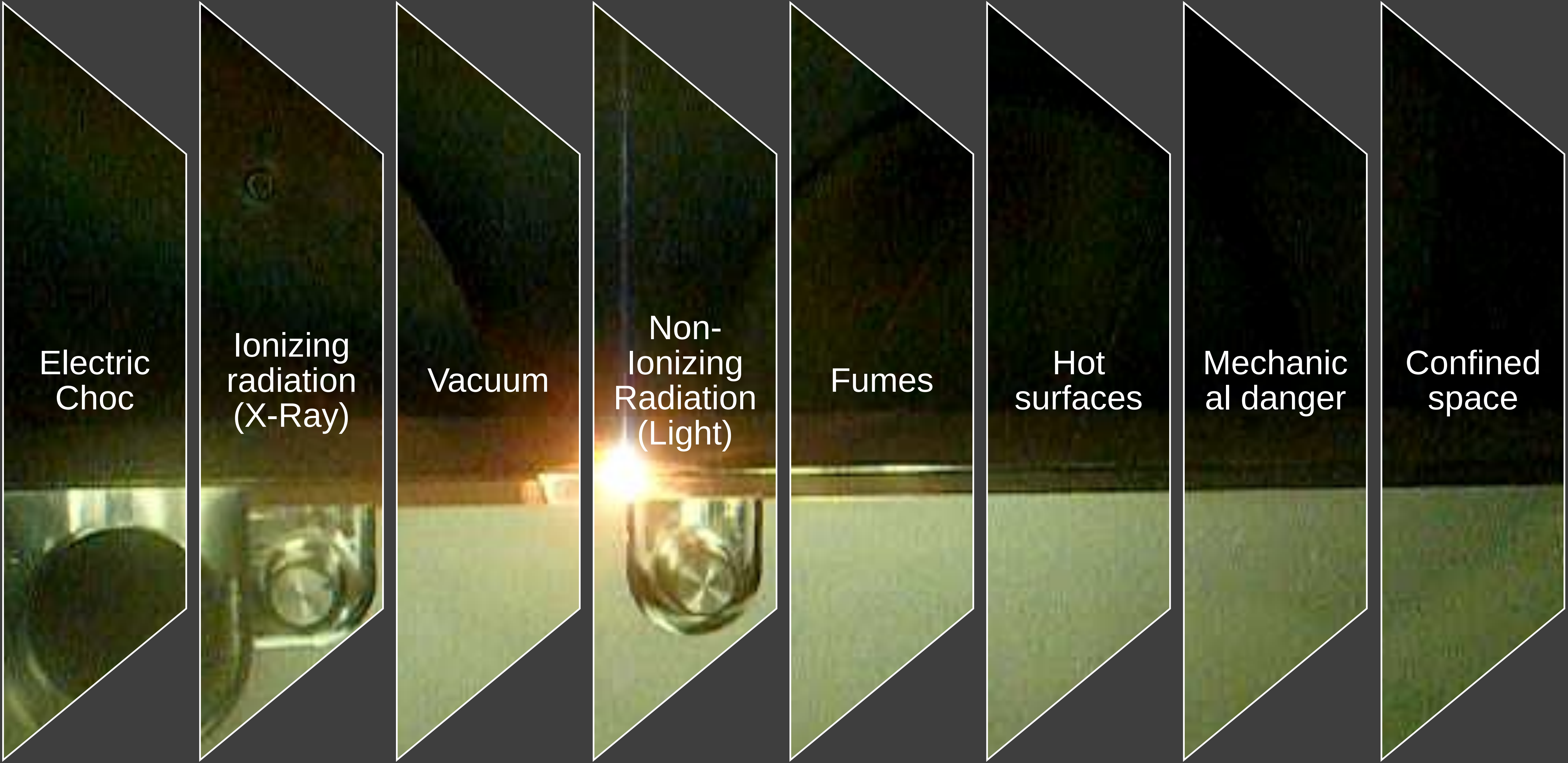
Three quality level for acceptability of imperfections

- Moderate → D
- Intermediate → C

Welding books

Welding operators EN ISO 14732

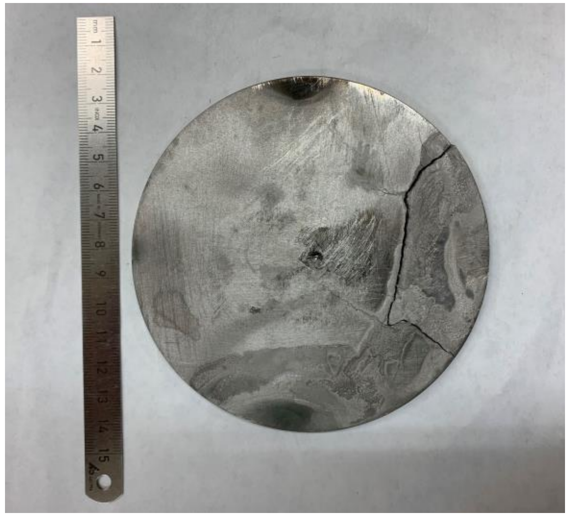
Hazard inventory



X-ray for EBW

X-rays at EBW machines

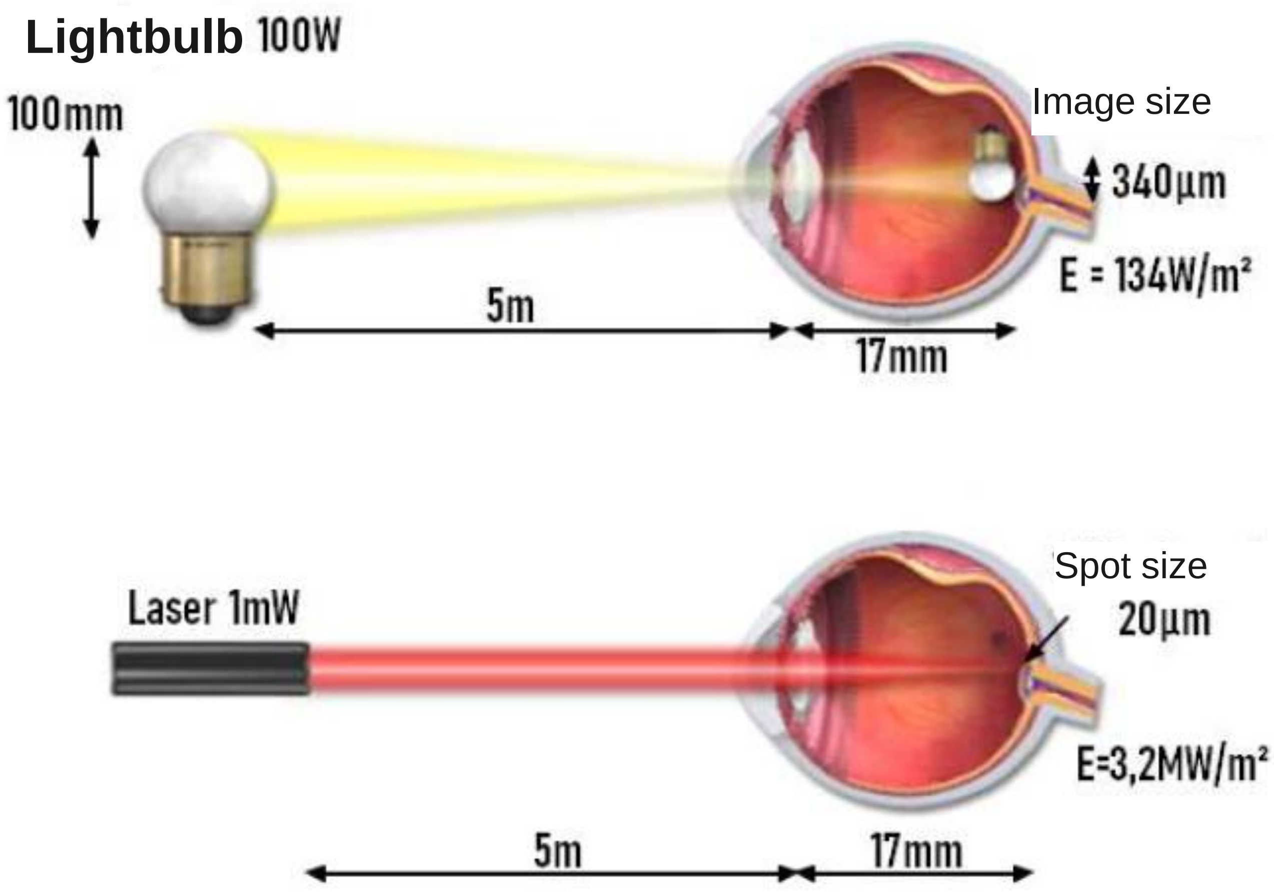
- X-rays intensity increases with beam power (**HV**, I_B) and with the atomic number of the material.
- **Lead shielding** for most of EBW machines, specially HV (150 kV) and Non-Vacuum.
- Machines are tested at full power, usually with W
    - Not qualified for higher density than W



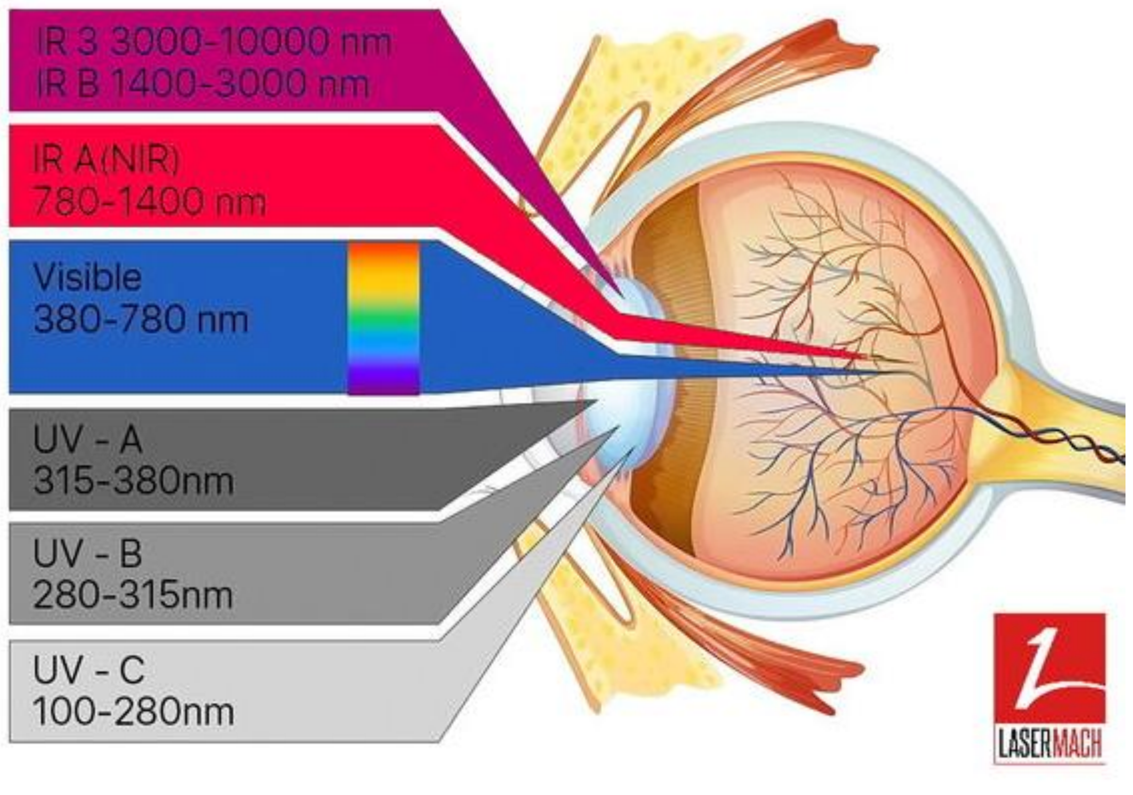
Tungsten bloc for X-Ray exposure test
With defocalised beam

Laser radiation hazard

Function of the nature of the light source



Dangerous Infra-red Laser light



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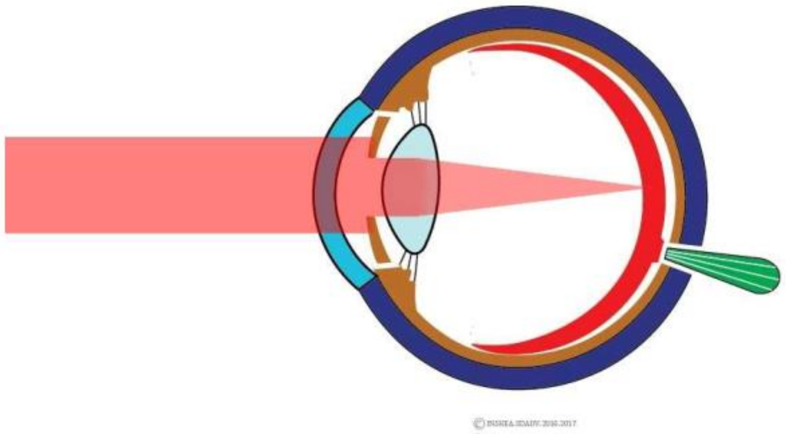
Laser radiation hazard: serious danger !

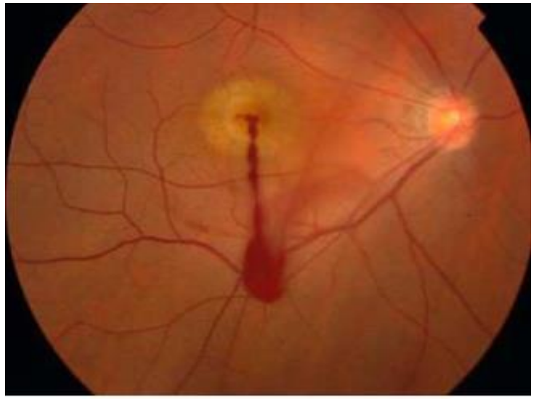
In the visible and near-Infrared spectrum:

A hole in the retina !
Variable effects
In the **macula**, peripheral: black spotdamage depending on the area:

- Outside of the macula (main vision area) – No major
- In the center area (Fovea): Almost complete loss of vision



Accident from a technician after alignment operation



Retinian hole with active bleeding

Laser parameters:
Pulse energy: 500 mJ, duration 8ns, repetition 10Hz.
Visual acquity reduced to 20/200

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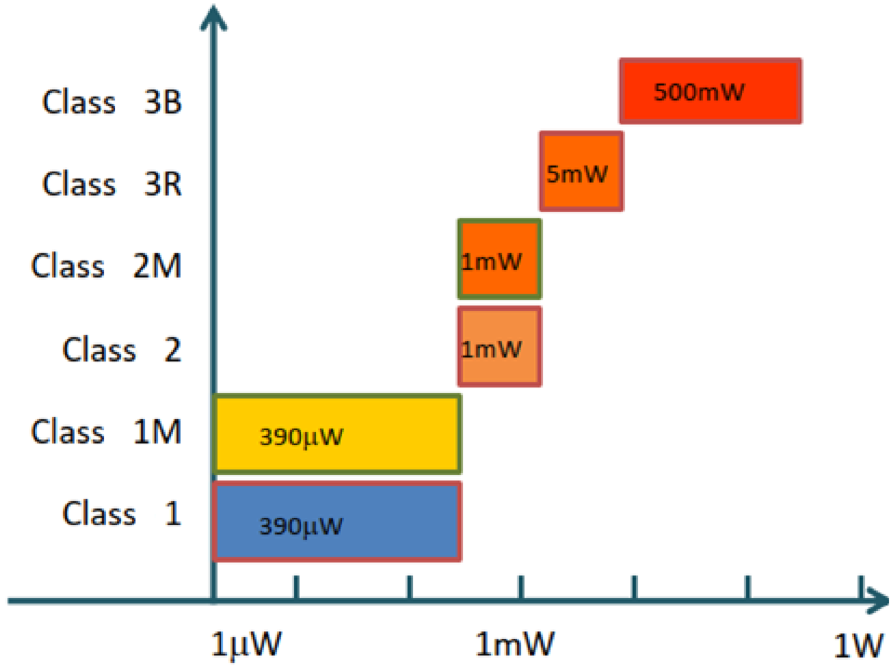
Laser classification (in the visible spectrum)

Risks / Classes	Eye: Direct viewing	Eye: Optics aided	Extended source	Skin	Fire
1					
1M		⚠⚠			
2	⚠	⚠			
2M	⚠	⚠⚠			
3R	⚠⚠	⚠⚠⚠			
3B	⚠⚠⚠	⚠⚠⚠	⚠⚠	⚠⚠	
4	⚠⚠⚠	⚠⚠⚠	⚠⚠⚠	⚠⚠⚠	⚠⚠⚠



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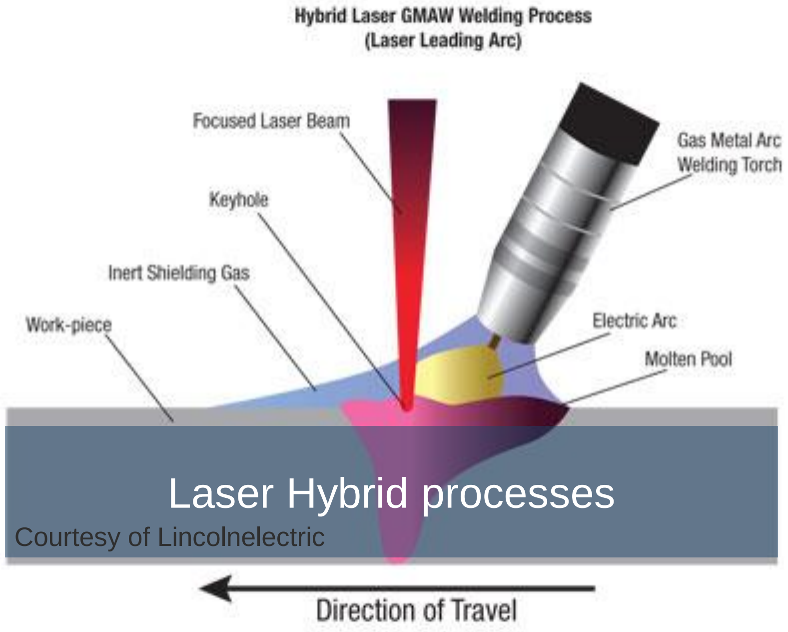
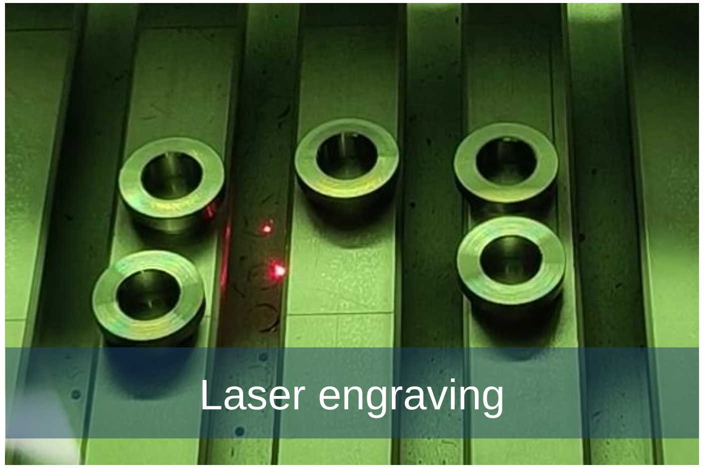
Alternative applications in material processing

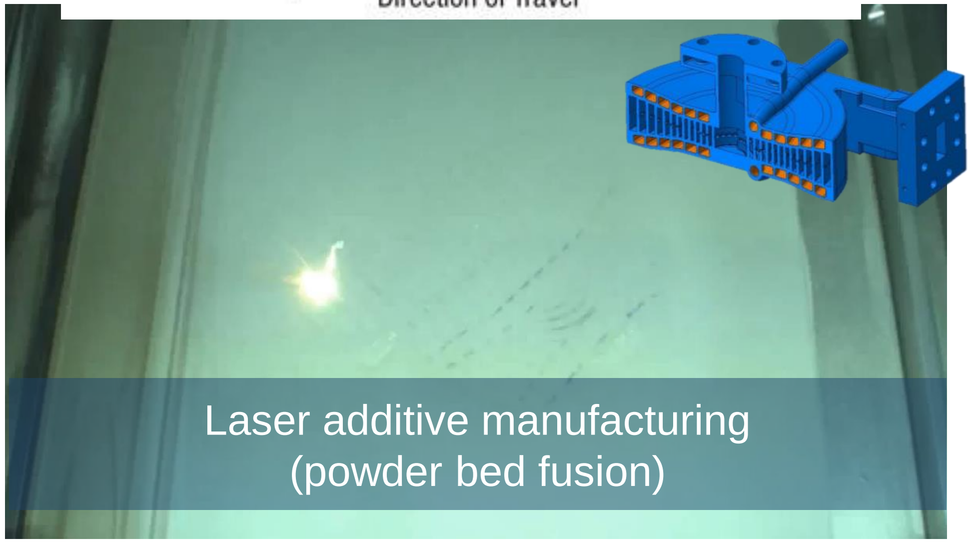


Laser Hybrid processes

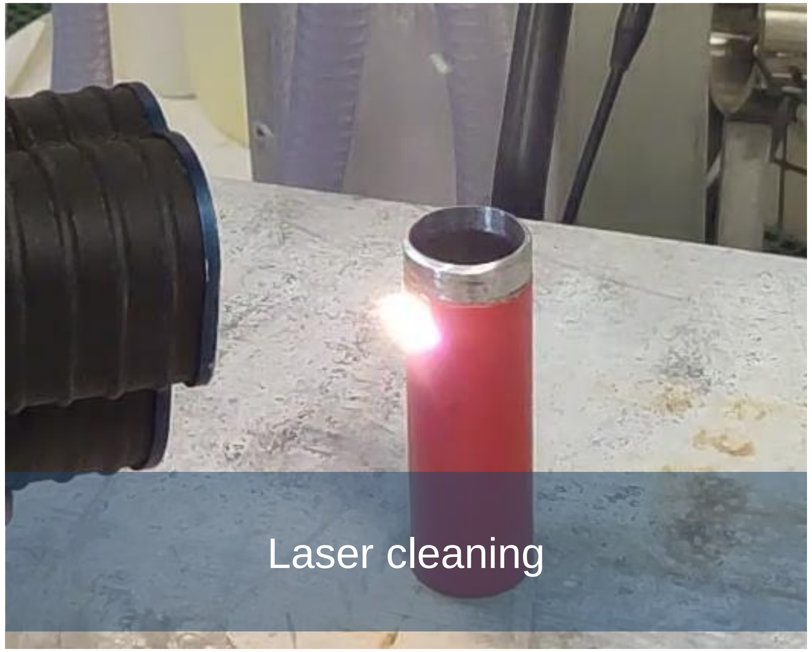
Courtesy of Lincolnelectric



Laser engraving



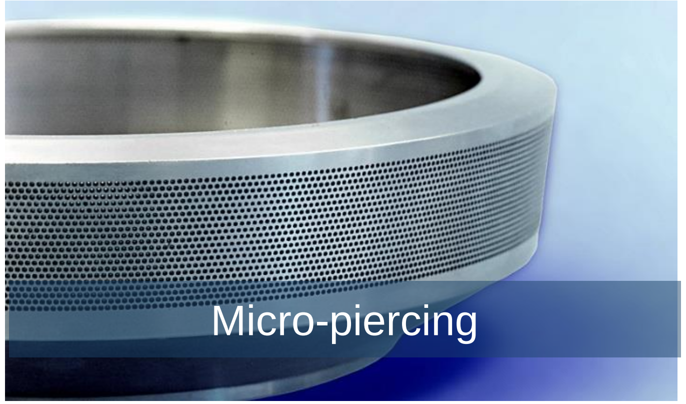
Laser additive manufacturing (powder bed fusion)

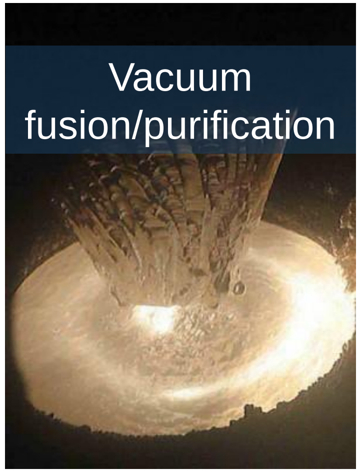


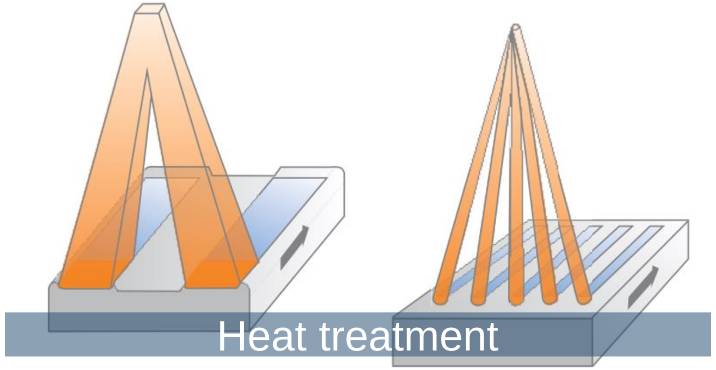
Laser cleaning

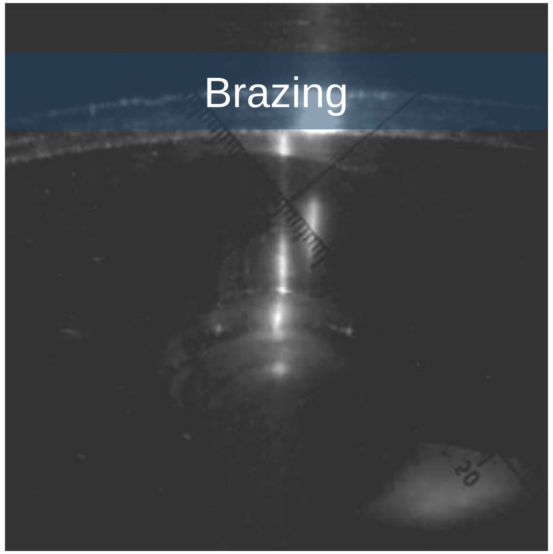
Laser cutting

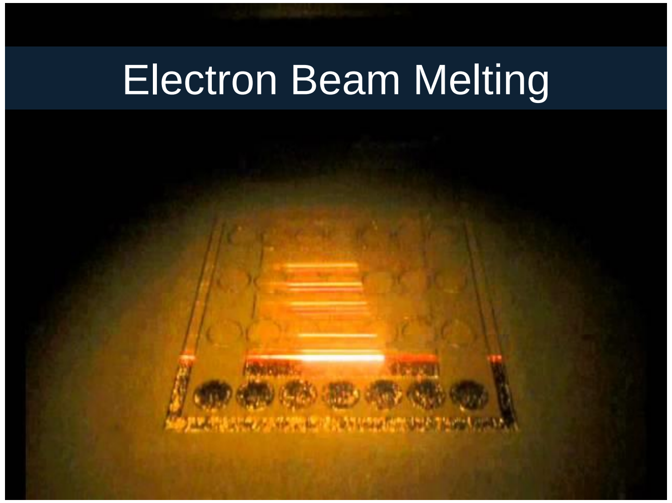
Alternative applications in material processing
Electron Beam











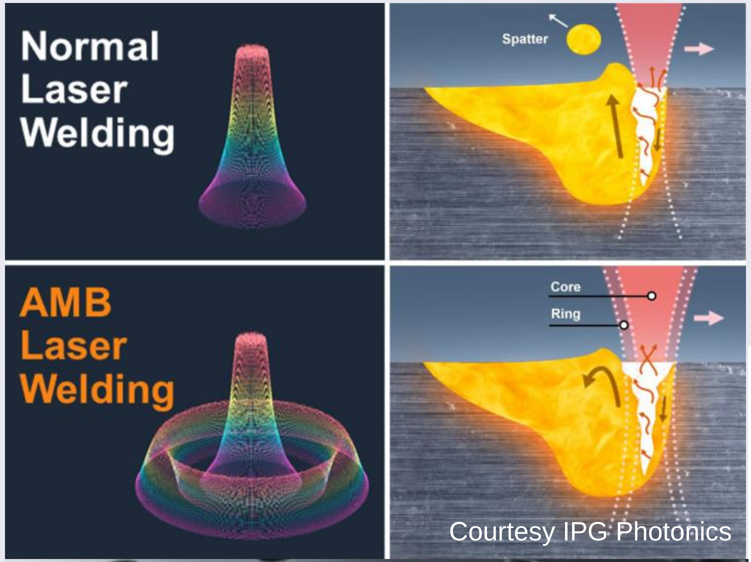
Current trends in Laser beam welding

Manual processes	Laser Beam Shapping	Process control

Manual processes

Courtesy IPG Photonics

Laser Beam Shapping



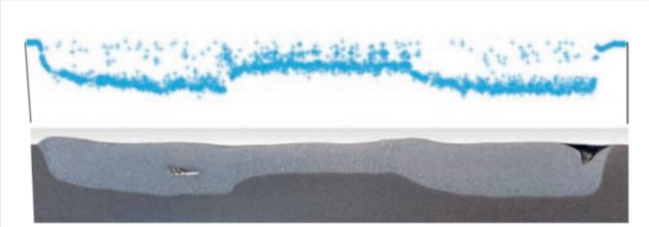
Courtesy IPG Photonics

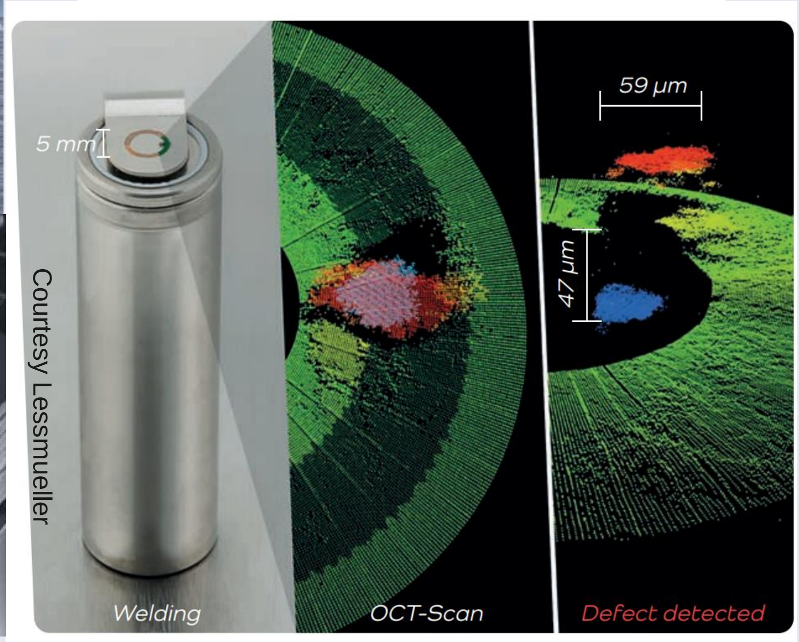
Courtesy Trumpf

Process control

Optical Coherence Tomography

Weld depth measurement





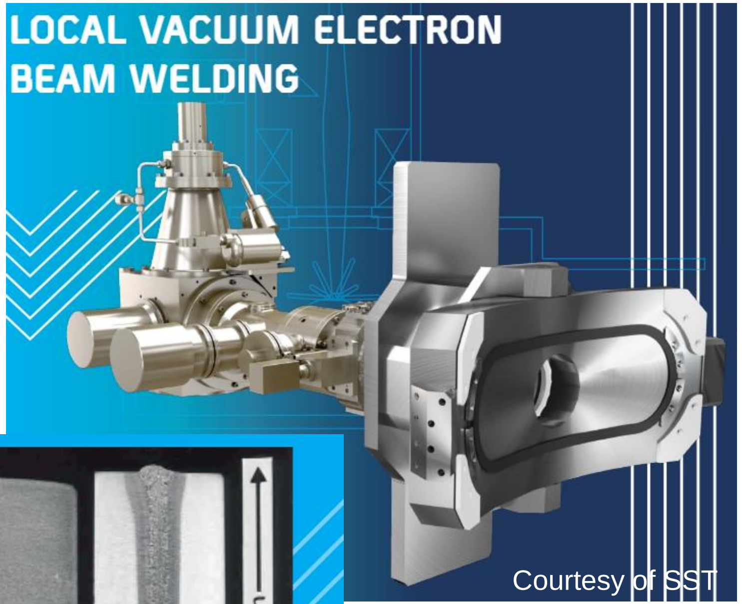
Courtesy Lessmueller

Current trends in Electron Beam Welding

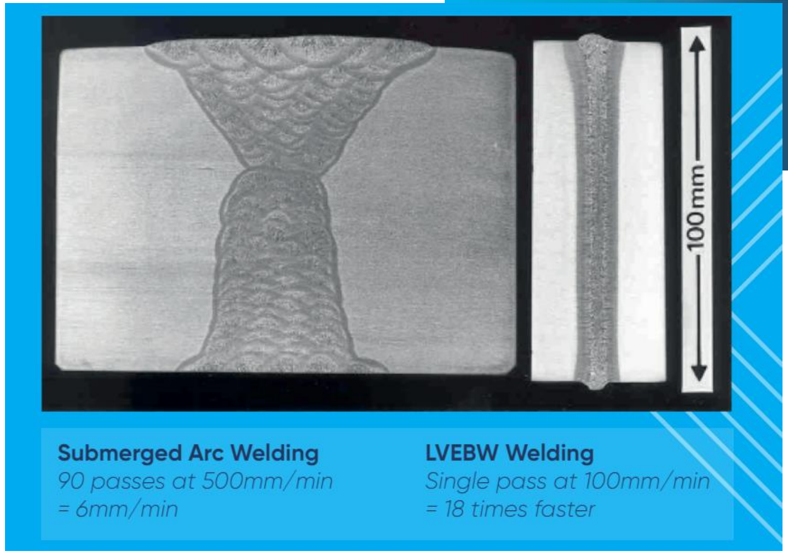
Additive Manufacturing	Local vacuum EBW

Courtesy of PTR

Courtesy of Sciaky



Courtesy of SST



ELECTRON BEAM WELDING	VS	LASER BEAM WELDING
High Vacuum	Atmosphere	Inert gas
Up to 200 mm in stainless steel Down to 100 µm	Penetration	Up to 50 mm in stainless steel Down to a few 10's µm
Metallic materials great for reactive materials and copper.	Materials	Metallic and polymer. Complications for reactive materials and Cu
~ 1 MCHF	Cost	~ 500 kCHF

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