e- BEAM WELDING & MACHINING

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PHY 554, Dec. 2016

Outline

- **Introduction**
- Components
- Principles
- Advantages
- Applications

Applied Fusion Inc. EBW machine

Introduction

- First electron beam welding (**EBW**) machine developed in 1958 by Dr. K. H. Steigerwald, rapidly used in nuclear industries

- **Electro-thermal** advanced manufacturing method

- EBW is a fusion welding process

fuse welding: join two metal parts together by melting them temporarily & locally in vicinity of contact

“heat source” concentrated beam of high-energy **e-** applied to the materials to be joined

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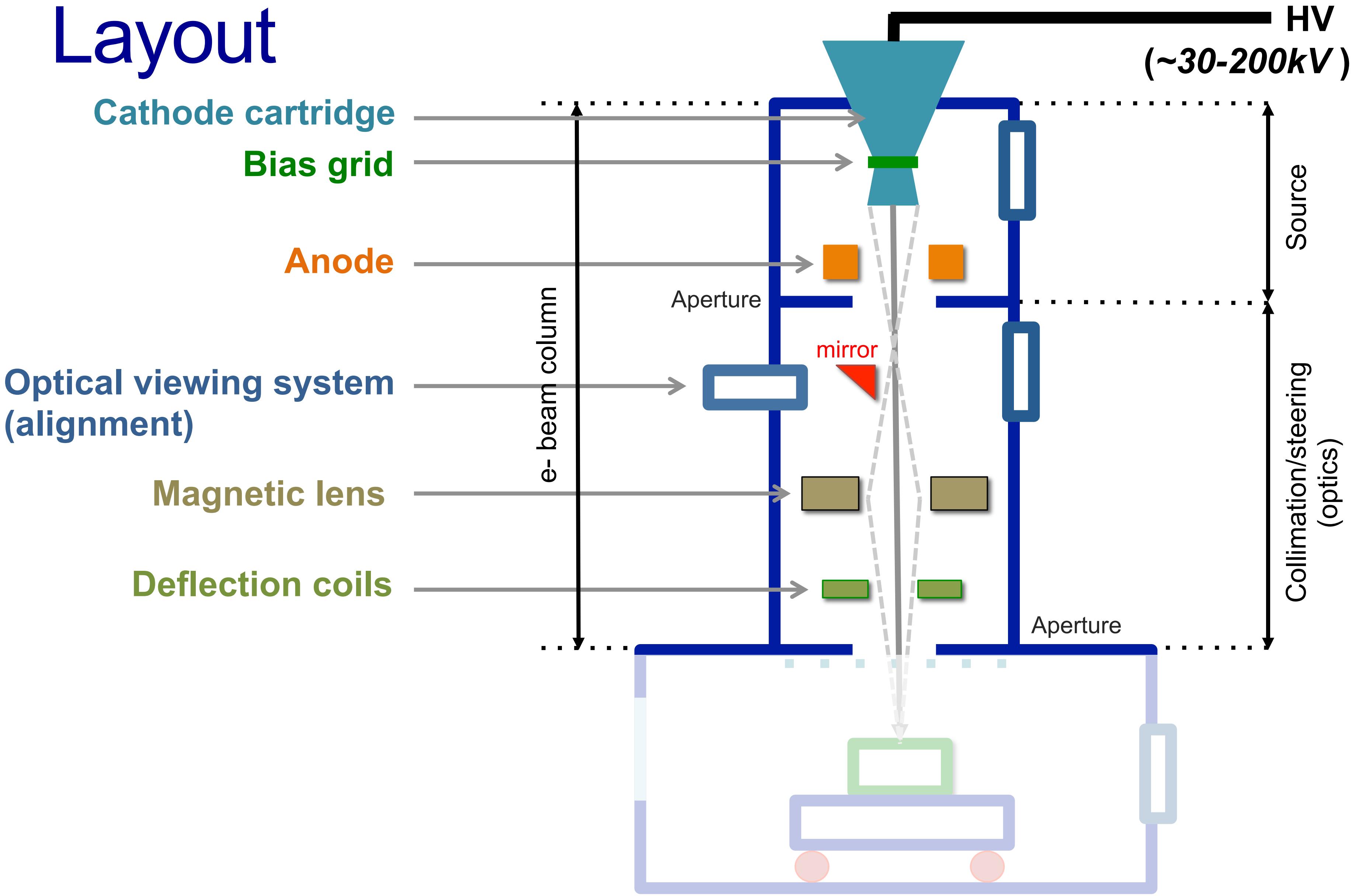
Layout



Schematic diagram of EBM/EBW

Components: gun

- Production of free **e-** at the cathode by thermo-ionic emission

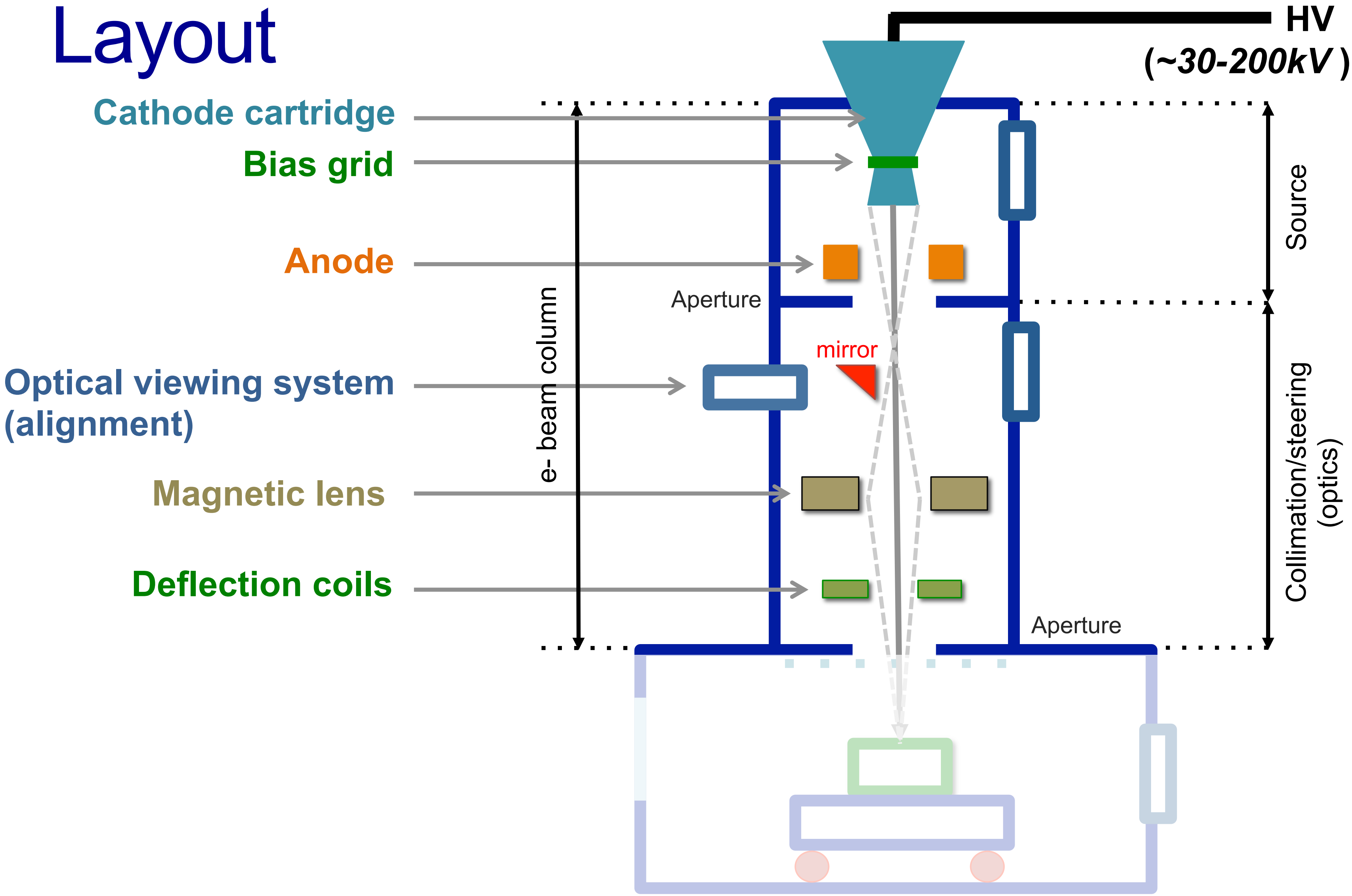
  Source: incandescent (~2500C) tungsten/tantalum filament

- Cathode cartridge: negatively biased so that **e-** are strongly repelled away from the cathode

- Due to pattern of **E** field produced by bias grid cup, **e-** flow as converging beam towards anode; biasing nature controls flow (biased grid used as switch to operate gun in pulsed mode)

- Accelerated: high-voltage potential between a negatively charged cathode and positively charged anode $\approx \frac{1}{2} - \frac{2}{3}c$

Layout



Schematic diagram of EBM/EBW

Components: focusing/steering

- **e-** beam passes through series of lenses and apertures:

➔ the lenses shape the beam and reduce it's divergence

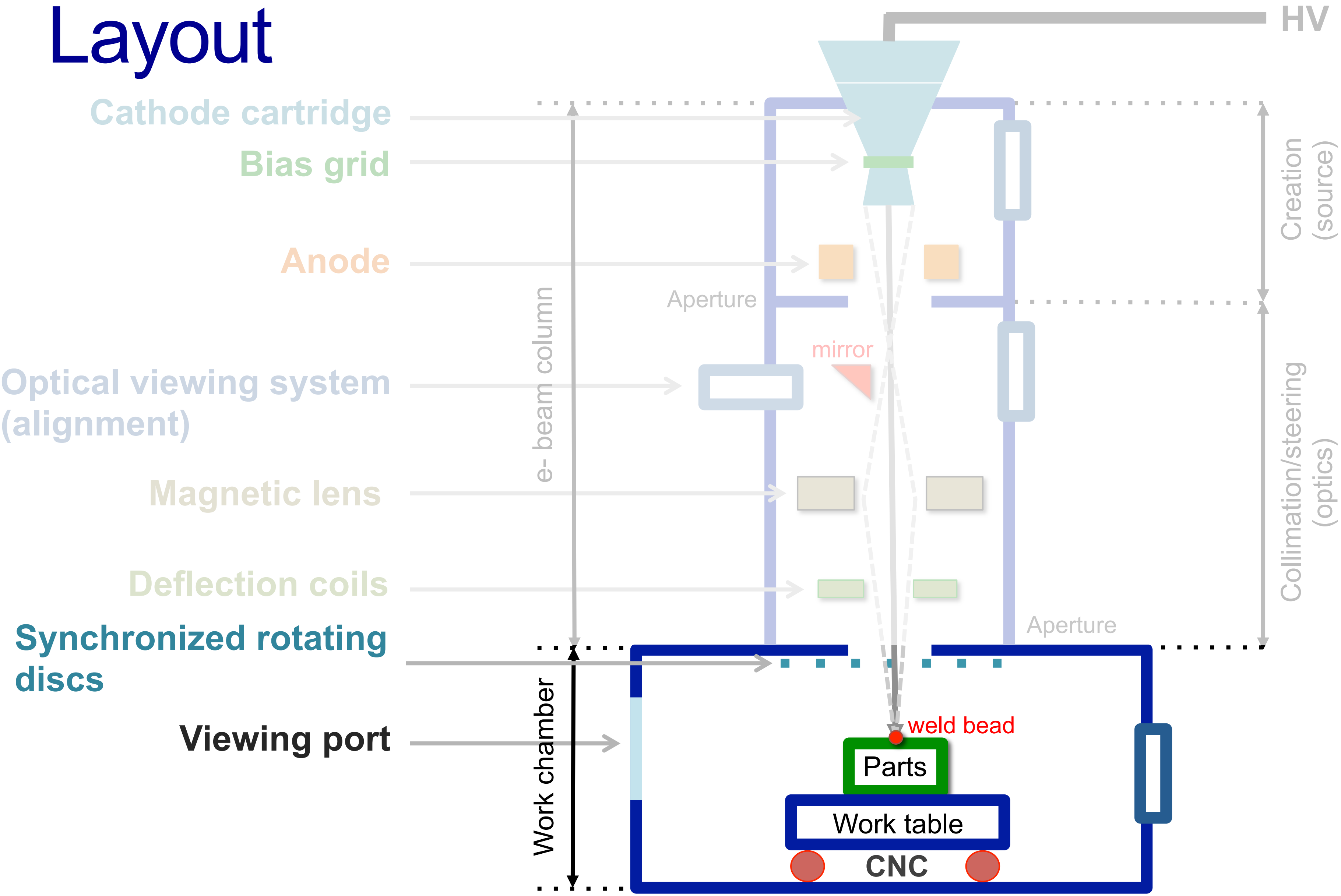
➔ apertures allow only the convergent electrons to pass and captures the stray **e-**

- After leaving anode, the divergent **e-** don't have a power density sufficient for welding metals: has to be focused

➔ accomplished by a magnetic field produced by a coil, focuses **e-** beam to desired spot size (localized heating: ~10^3-10^6 W/mm^2)

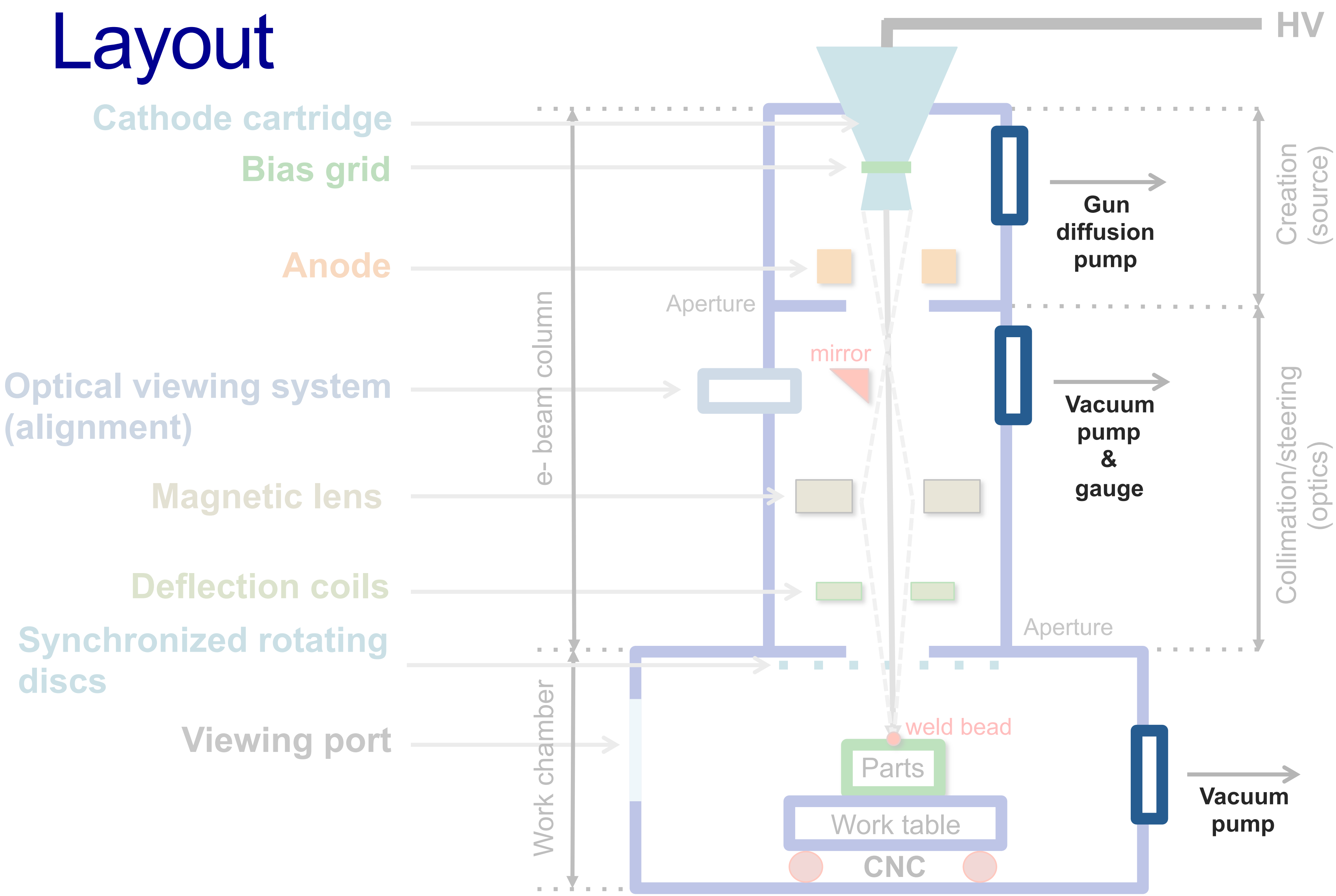
- Deflection coil maneuver the **e-** beam, by a small amount, to improve the shape of the machined holes

Layout



Schematic diagram of EBM/EBW

Layout



Schematic diagram of EBM/EBW

∀ in vacuum

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Parameters

- Accelerating voltage (*V*)

~30-200kV

- Beam current (*I*)

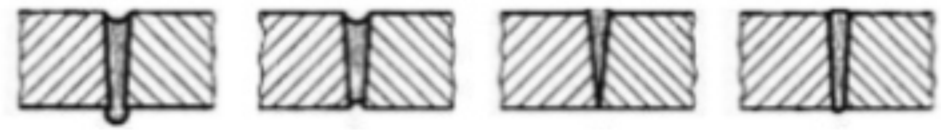
~50uA-1A

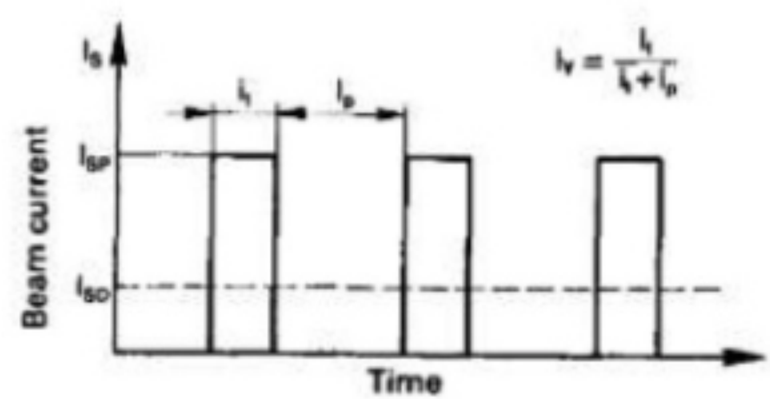
- Pulse duration (*t_on*)

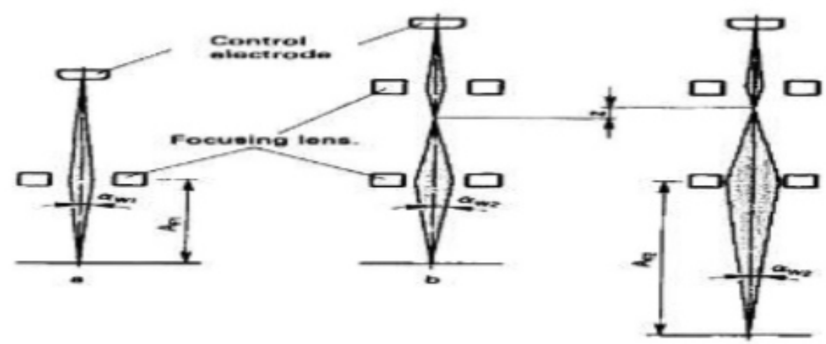
~50us-continuous

- Energy per pulse
- Welding speed
- Power per pulse (*I.V*)
- Table positioning
- Focusing current (spot size)

~10um-500um







Source: A. H. Maleka, *EBW Principles and Practice*

Principles

- Beam directed out of the gun column ➔ strikes the work-piece
- **e-** will travel only a few *cm* in air: **entire** chamber needs to be at vacuum
- Fast charged particles moving through matter interact with **e-**/atoms in material. Energy loss of beam is dominated by excitation and ionization effects and Bremsstrahlung losses (X-rays):

$$\left(\frac{dE}{dx}\right)_{tot} = \left(\frac{dE}{dx}\right)_{exc} + \left(\frac{dE}{dx}\right)_{rad}$$

- **e-** impact work-piece at high velocity, most of the kinetic energy lost to thermal energy; "stopping power":

$$\left(\frac{dE}{dx}\right)_{exc} = \frac{2\pi e^4 N \cdot Z}{m_0 \cdot v^2}\left(ln\frac{m_0 \cdot v^2}{2I^2(1-\beta^2)} - ln\ 2(2\sqrt{1-\beta^2} - 1 + \beta^2) + \frac{(1-\sqrt{1-\beta^2})^2}{8}\right) \boxed{\approx \frac{2\pi e^4}{m_0 v^2} NB}$$

where *N* is number density of absorber atoms, *B* stopping number (αZ)

(Bethe-Bloch formula)

Principles

- Higher *E* less loss per *dx:* beam current & accelerating voltage change penetration depth (*um-mm*)

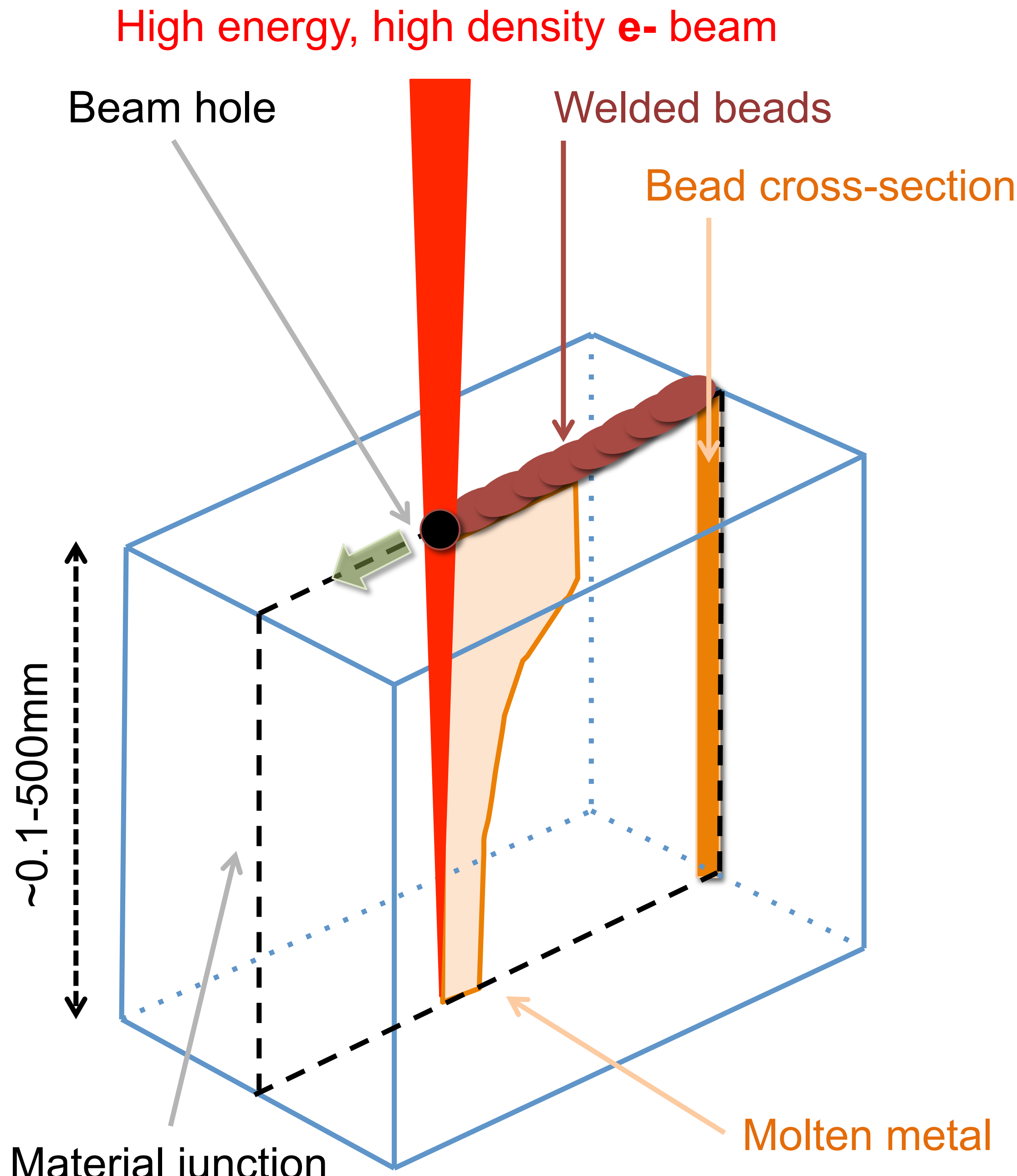
- The lens current determines the spot size, determining the power density:

$$P_d = \frac{KE}{Spot_{Size}} = \frac{\frac{1}{2}m_e v_e^2}{\frac{\pi}{4}d_s^2} \rightarrow \boxed{\frac{V \times I \times t_{on}}{\frac{\pi}{4}d_s^2}}$$

- *P_d* most important parameter: i.e up to *200kW* power of that density ➔ enough to melt/vaporize any material regardless of it's thermal conductivity or melting point

Welding

- Work-pieces melt as the kinetic energy of **e-** transformed into heat upon impact
- Fusion of base metals: eliminates need for filler metals



Process EBW

- The **e-** beam melts the parent metal to form the weld pool
- Heating of the joint to **melting** temperature is **quickly** generated (10^8K/s) at or below the material surface followed by thermal conductance throughout the joint for complete or partial penetration

Forms a hole at the weld joint, molten metal fills in behind the beam, creates a deep finished weld

- Resulting weld is very narrow for two reasons:

➔ produced by a focused beam spot with energy concentrated into a *10um* to *50um* localized area

➔ high-energy density allows for quick travel speeds allowing the weld to occur so fast that the adjacent metal doesn't absorb excess heat

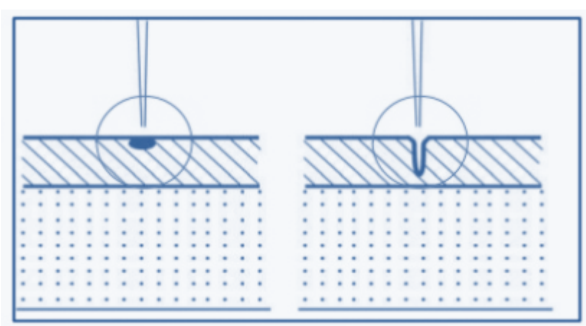
Process EBM

- Mechanism of **material removal due to very high-power density**

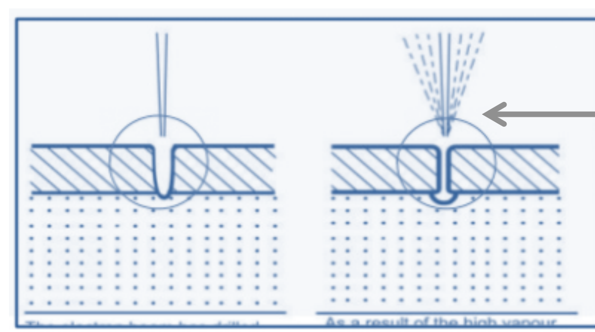
- Pulsed gun mode (>10^4 W/mm^2): **e-** beam sub-surface penetration, causing rapid **vaporization** of the material and hole to be drilled through the material:

➔ in cavity rapid vaporization causes a pressure to develop thereby suspending the liquid material against the cavity walls

➔ finally molten material left is expelled by the high vapor pressure of base-plate



Gradual formation of hole



Ejection due to high vapor pressure

Penetration till the auxiliary support

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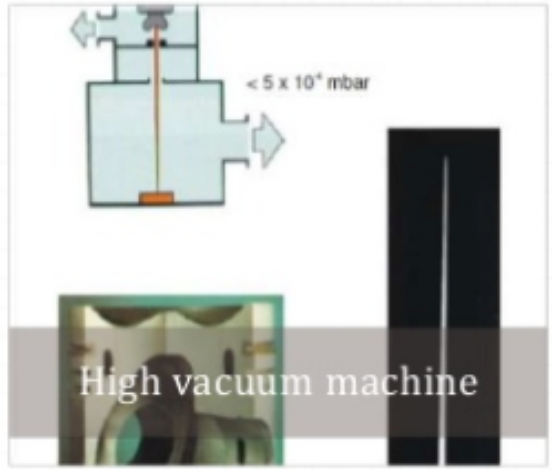
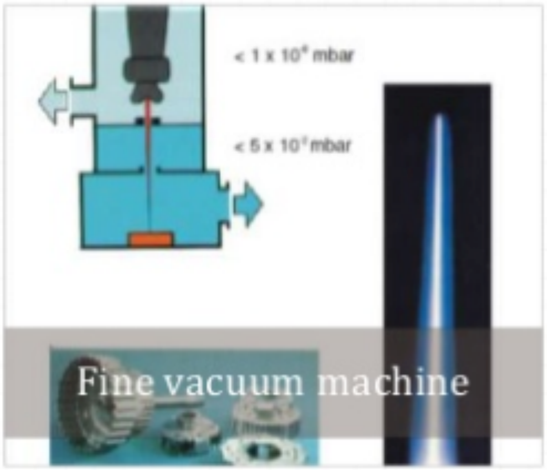
- **Principles** > **Plasma window**
- Advantages
- Applications

Components: environment

- Level of vacuum within the gun is on the order of ~*10^-5* Torr, work area ~*10^-4* Torr

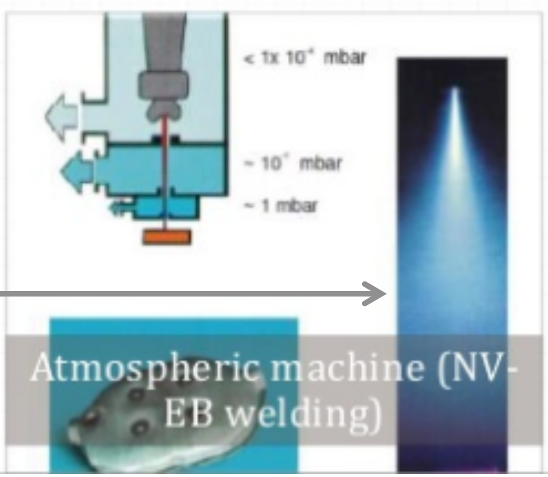




- Vacuum is essential, interaction with air molecules:

➔ **e-** lose their energy

➔ ineffective for cutting/melting



large dispersion of **e-** beam, practically nullifies all the advantages of EBW

scatter & diffuse

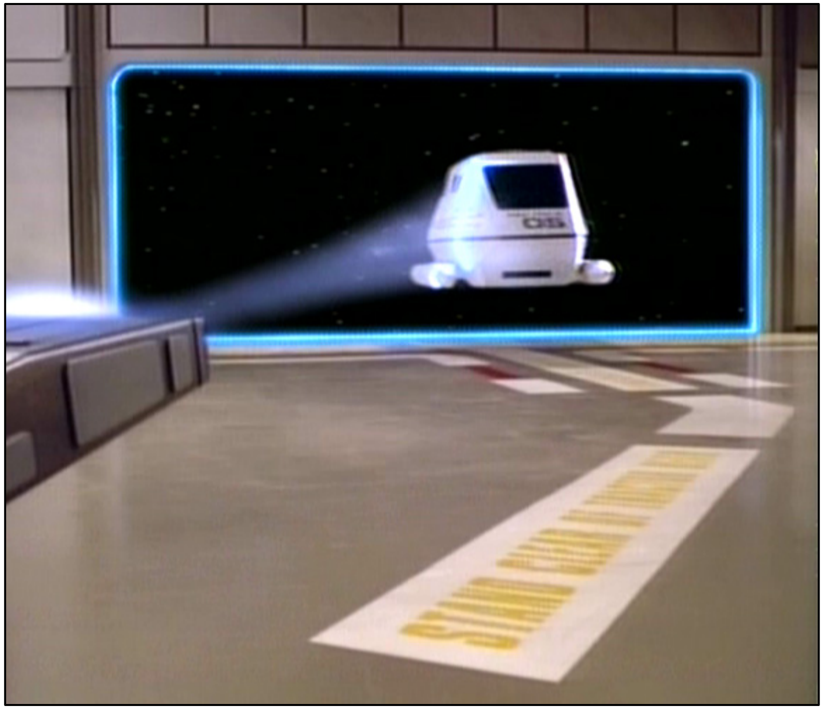
Plasma window

- *Force-fields (Sci-Fi) are exaggerated… would vaporize spaceship if used*

- Plasma window: an apparatus that utilizes a stabilized/confined plasma arc (hot ionized gas) as interface between vacuum and atmosphere (pressurized target) **without solid material**

- In 1995 Dr. A. Hershcovitch (Senior Physicist at Brookhaven National Laboratory) invented the plasma window

- Useful in Non-Vacuum Electron Beam Welding! (2005)



Star Trek shuttle bay “door”

Principles

- In plasma, like any gas, particles exert pressure, which prevents air from rushing into the vacuum chamber

- Pressure P: $P \propto nT$

Where *n* is gas/plasma density and *T* is temperature of the thermal plasma. Latter fills a channel tube of diameter *d*, length *l*, gas/plasma viscosity η:

- Gas flow-rate (throughput) *Q*: $\boxed{Q \propto \frac{d^2}{\eta l}(P_1 - P_2)}$
- Plasma viscosity η: $\boxed{\eta \propto T^x}$ *(for ions & e- x=5/2)*

➔ Increased viscosity and decreased number density results in decreased flow-rate *Q* through the opening

Principles

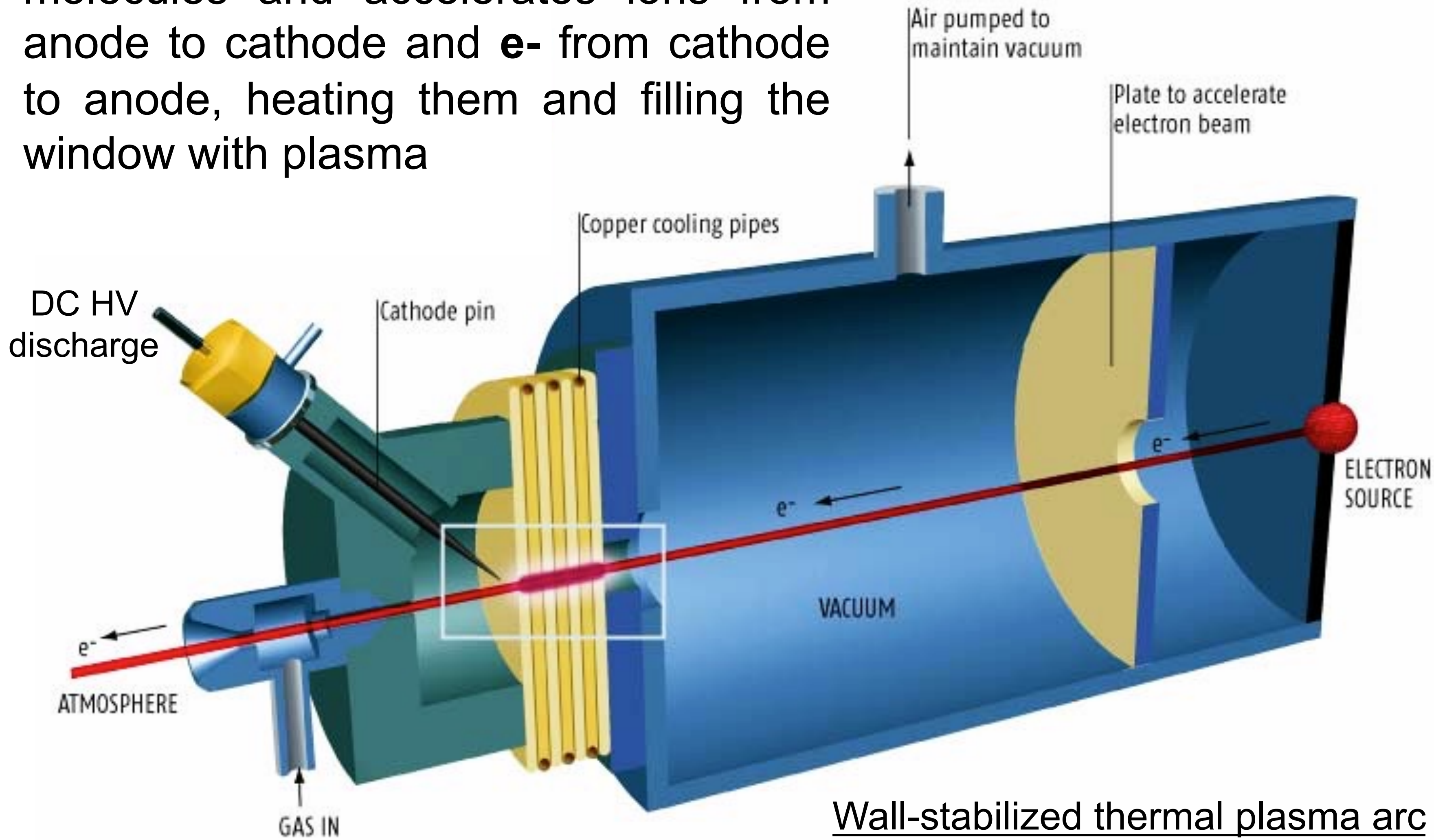
- Results in plug formation: vacuum separation or maintain **pressure differential**

- Balance *atm* pressure at ~*1/50th* density. Lower density means fewer electron collisions so the beam passes through the window essentially unimpeded, making it a viable "window"

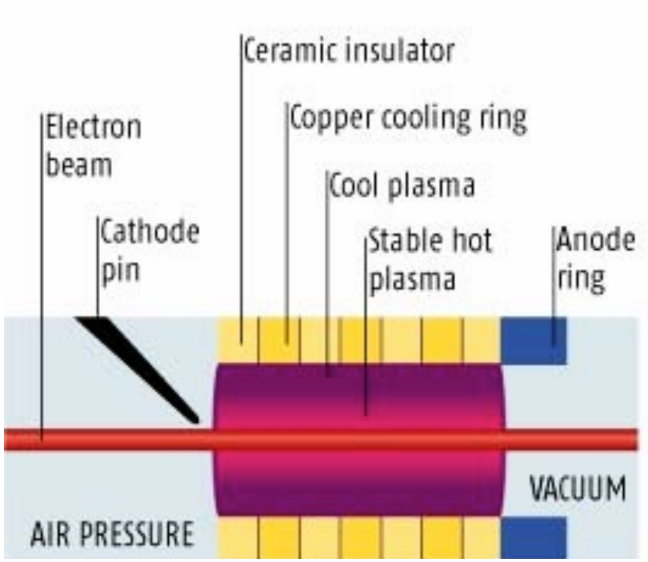
- In EBW also prevents back streaming of vapor and metal chips

- Compared w/ foil window (successive PD), plasma window can sustain high-current e- beam with almost no energy loss (+invulnerable)

Inert gas feeds into cavity containing a cathode and anode w/ HV potential applied, strips **e-** from the gas molecules and accelerates ions from anode to cathode and **e-** from cathode to anode, heating them and filling the window with plasma



Wall-stabilized thermal plasma arc



Keeping plasma stable is tricky because ionization process that creates it becomes more energetic and difficult to confine with increasing temperature; cooling the plasma makes it less energetic and electrically conductive.

Plasma window takes advantage of this:

➔ surrounds the cavity walls with a system of water-cooled copper tubes

➔ tubes pull heat from the plasma to maintain a low-temperature outer ring while core remains hot (*T~12-15000K)*.

e- beam passes from a vacuum to atm through hot plasma core

Example: argon at 1bar

At BNL (2005): plasma window (w/ argon) separated a vacuum of 8x10^-6 Torr from atmosphere

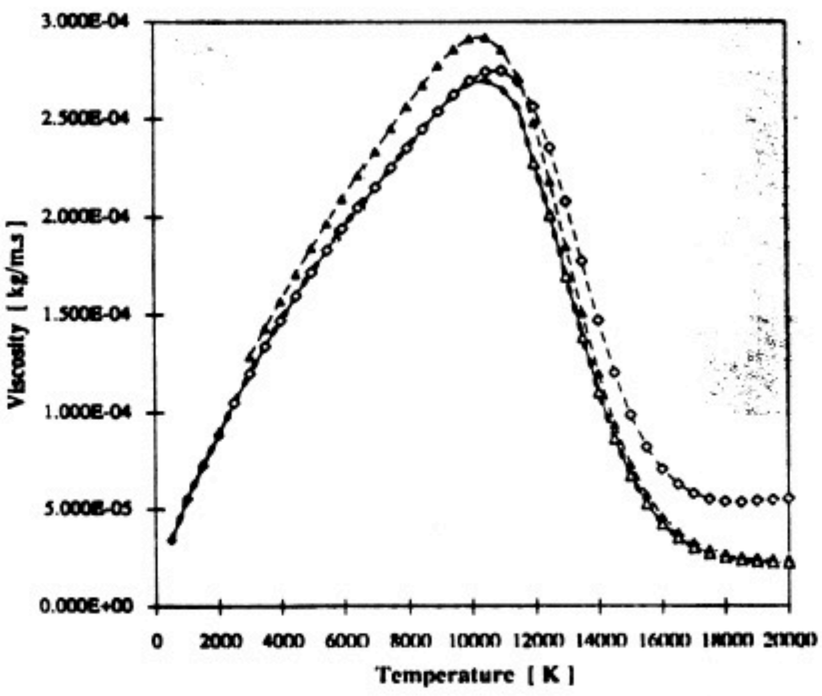


Fig: Viscosity vs Temperature for argon plasma; high temperatures increases viscosity to the point where matter has trouble passing through: separating gas at atm pressure from vacuum

[Plasma emits a bright glow with the color dependent on the gas used: Startrek got it right w/ argon!]

Features

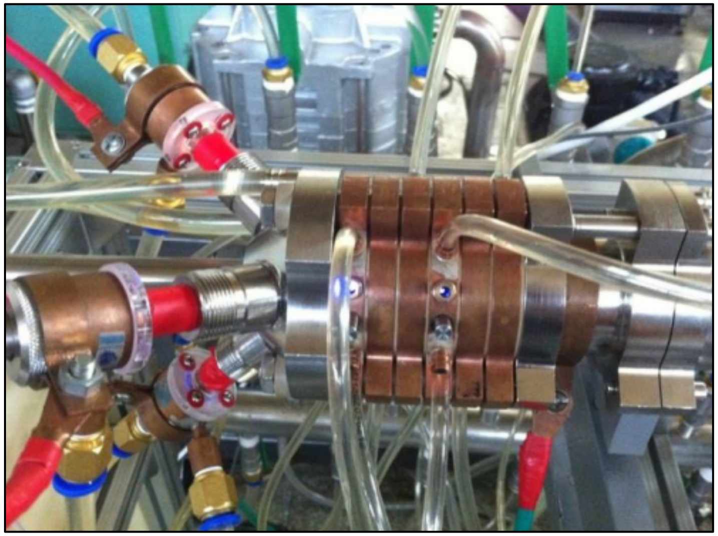
- *22,000x* more effective at maintaining a vacuum than current differential pumping methods

- As **e-** beam passes through the plasma window it's performance improves due to ionization and further heating of the arc plasma:

➔ the plasma arc voltage and the pressure both drop when the electron beam is fired

RIBF, Japan

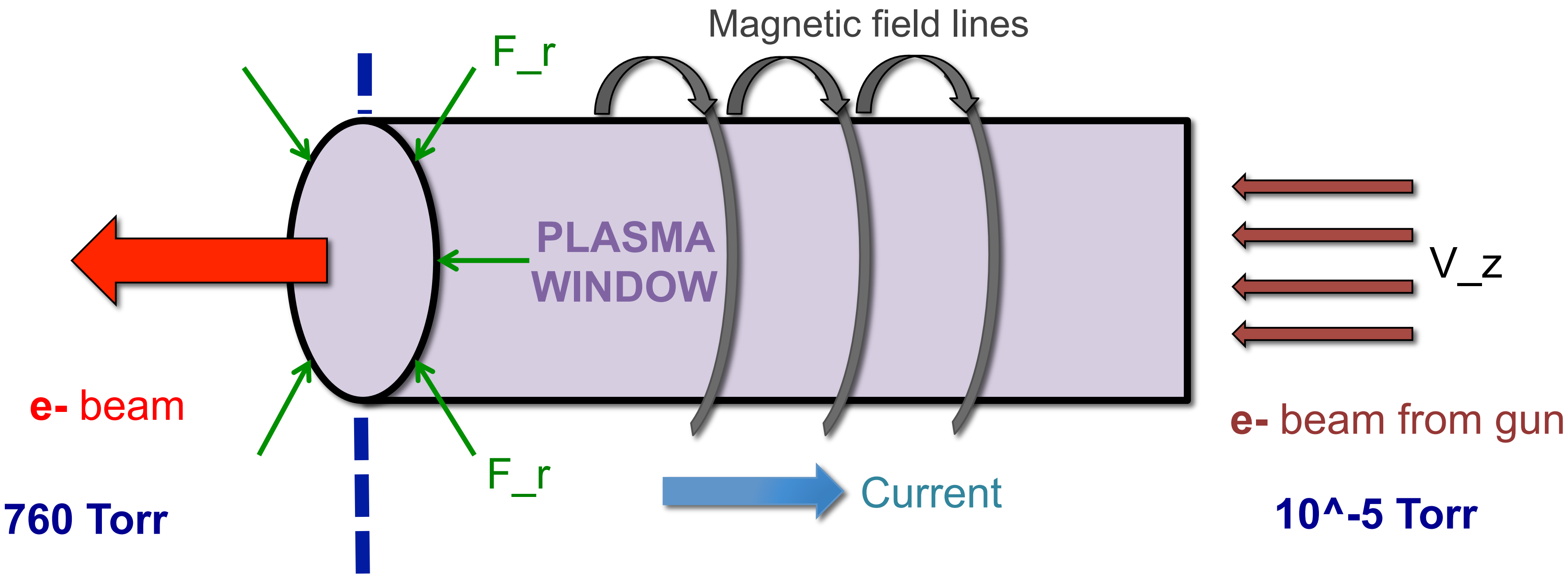
Electron beam current	Gauge reading (Ar-He ?)	PS Voltage (arc current 45 A; R = 1Ω)
No Current	2000 mTorr	148 V
15 mA	750 mTorr	135 V
20 mA	500 mTorr	129 V



Features: lensing effect

- Plasma current generates an azimuthal magnetic field, which exerts a radial Lorentz force on charged particles moving parallel to the current channel: $F_r = qV_z \times B_\theta$

- Force is radially inward, **focusing the beam to** very small spot sizes overcoming beam dispersion due to scattering by atmospheric atoms and molecules



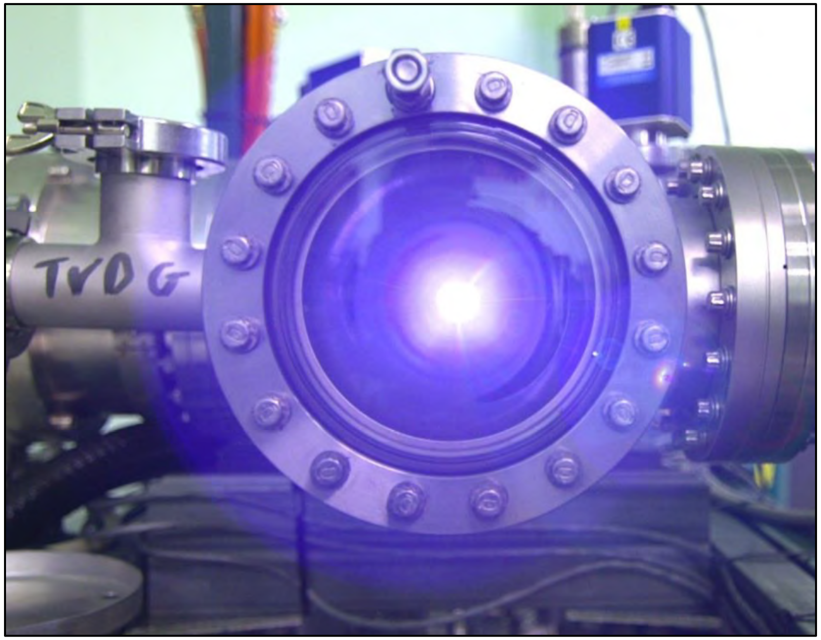
Status

What has been achieved (at BNL): plasma window & plasma valve

- Vacuum separation: atmospheric pressure (~1bar) up to 9 bar (gas cell) separated from vacuum

- Transmission of charged particle beams & radiation from vacuum through the plasma window:

- electron beam transmission
- radiation X-ray transmission
- ion beam transmission



Plasma window at BNL

Commercialization

BNL: *"Acceleron Electron Beam LLC, wins grant from the U.S. Department of Energy to commercialize new welding technique developed at Brookhaven Lab."*

Acceleron: *" Electron beam welding is the highest quality welding that can be performed. But it's done in vacuum, resulting in low production rates and limits on object size. Double hull ships can't fit in a vacuum system."*

↓

No limitation on work-piece size!

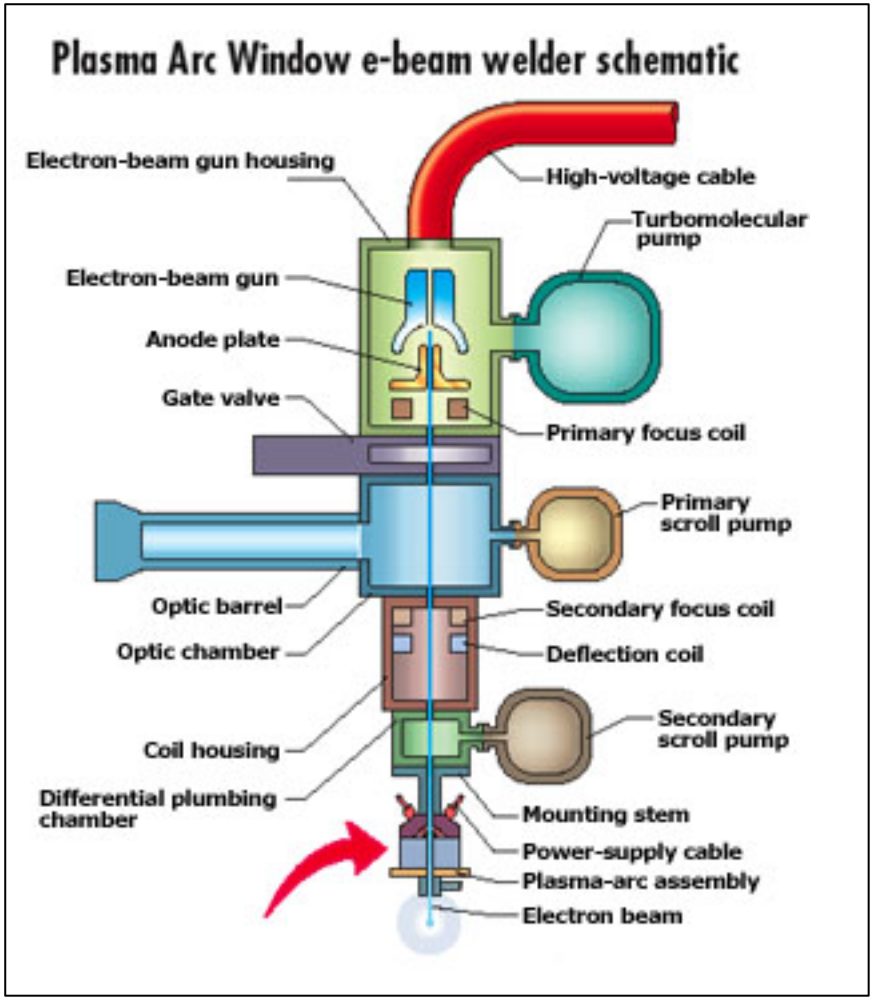


Diagram of electron beam welder, to which a **plasma window** was mated (source: Acceleron)

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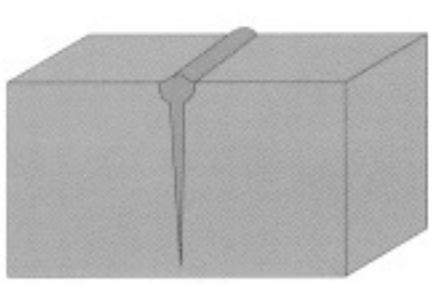
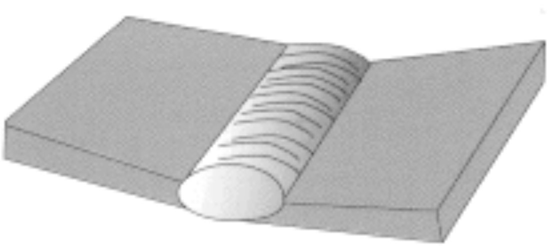
Applied Fusion Inc. EBW machine

Advantages: high quality welding

- Due to intense and concentrated generated heat, total heat input is low: minimizes heat affected zone size (~10-50um) and part distortion

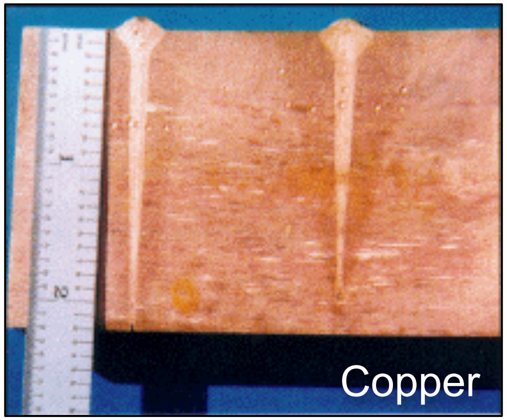


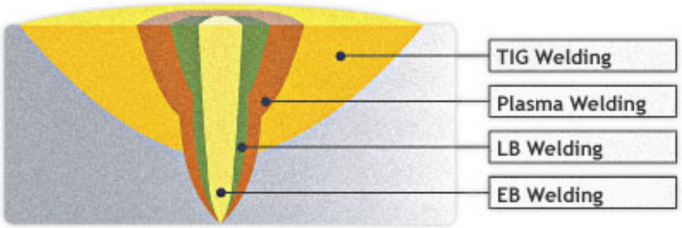
Fast & clean with no distortion!



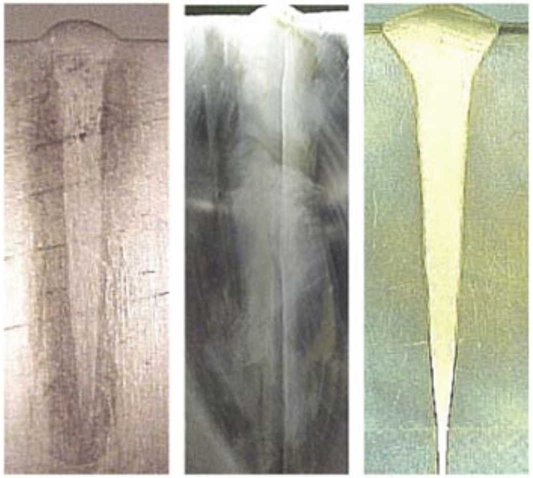
Time consuming stick welding creates distortion.

- Deep penetration narrow knife-like shape welds:





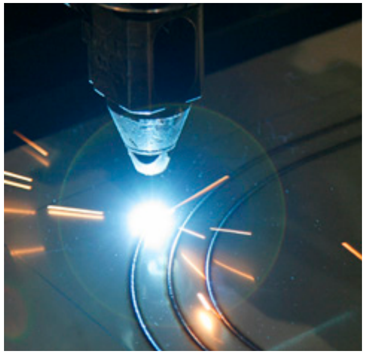
Comparison



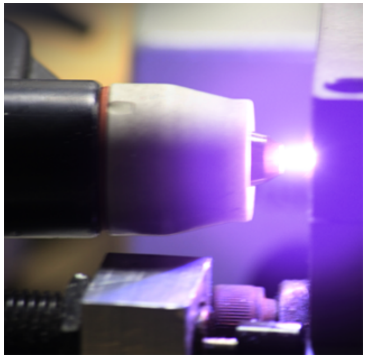
Advantages: high quality welding

- High drilling rates and very small sizes (2um; good process for micro machining: grattings)
- **Welding of materials that other methods can't** (i.e easily joining dissimilar metals) & without requiring any additional filler material
- No mechanical cutting force (i.e holding/fixtures not complex/ expensive like CNC) & allows to process **fragile and brittle materials**
- **Control of weld penetration and high depth-to-width ratio**
- & so on… exceptional weld strength, good surface finish, no cutting tool wear, high precision and repeatability, 0% scrap, and fast!

Comparison



Laser



Plasma

TIG

PARAMETER	TIG	PLASMA	LASER	EB
Power input to W-P	2kW	4kW	4kW	5kW
Total power used	3kW	6kW	50kW	6kW
Traverse speed	2mm/s	5.7mm/s	16mm/s	40mm/s
Positional welding	Good penetration	Good penetration	Yes Require optics to move the beam	Requires mechanism to move the beam
Distortion shrinkage	Nominal significant in V-shaped weld	Nominal significant in V-shaped weld	Small Minimum	Minimum Minimum
Special process requirement	Normal light screening	Normal light screening	Safety interlock against misplaced beam reflection	Vacuum chamber-ray screen
Surface geometry	Underside protrusion	Underside protrusion	Very fine ripples	Ruffled swarf on back face

Disadvantages

- High capital costs of necessary equipment and regular maintenance (i.e vacuum system…)

- Maintaining perfect vacuum is difficult, and large non-productive time due to pump down periods (PW!)

- Vacuum chamber limits the size of the work piece (PW!)

- **Production of X-rays ➔** cannot be handheld or within reach of an operator, machining process can't be seen directly by operator

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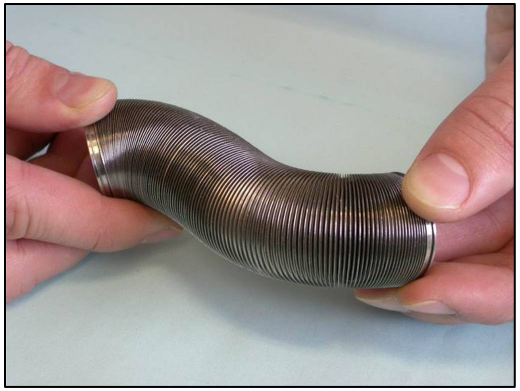

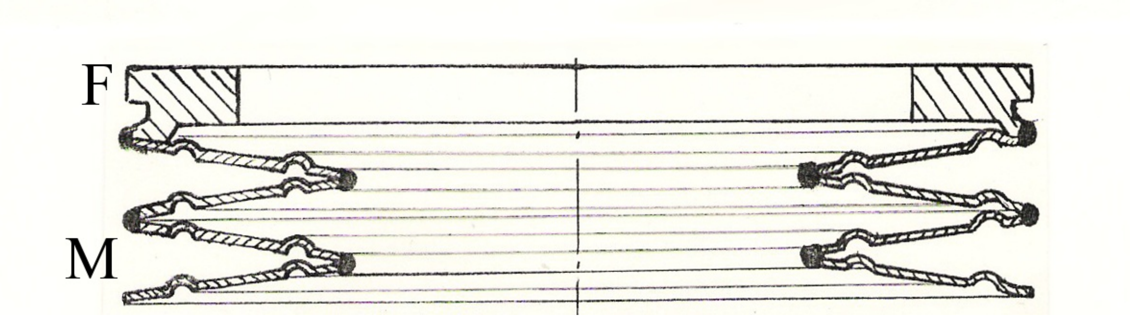

Manufacturing and welding of thin-walled parts (i.e flanges & bellows in vacuum): no distortion, but full depth penetration of weld ➔ EBW

Source: ISI Brno; http://ebt.isibrno.cz/

Applications

Other example applications:

- Drilling of 10^x holes in fine gas orifices and pressure differential devices: nuclear reactors, aircraft engines, diesel injection nozzles…

- Welding of sealed detectors and instruments containing vacuum (i.e X-ray tube)

- RF/SRF cavities ➔

Conclusion

- Electro-thermal process for welding and machining using an accelerated electron beam. Wide range of applications: parts ranging in sizes from delicate miniature components using a few watts of power, to welding steel up to thickness of *20in* and even dissimilar metals

- **Established application of industrial accelerator physics, continually evolving (i.e plasma window). Next: plasma vortex / shielding to prevent oxidation and EB-FDM (3DP)**

- Highly used in nuclear, aerospace, automotive industries, and experimental physics

References

- A. H. Maleka, *Electron-beam Welding, Principles and Practice*, McGraw-Hill, New York, 1971
- A. Hershcovitch, Non-vacuum electron beam welding through a plasma window, *Nuclear Instruments and Methods in Physics Research, Beam Interactions with Materials and Atoms*, V. 241, 2005
- A. Hershcovitch, *Journal of Applied Physics*, 1995