HIGH POWER DENSITY SYSTEMS USED IN ADVANCED METALLURGICAL APPLICATIONS & SAFETY ASPECTS

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Out line

- High power density systems
- Electron Beam as a High Power Density System
- Applications of Electron Beam technology
- Electron in motion and generation of photons/ X -rays.
- Electron Beam Melting & Refining – EBMF & Principles
- Safety aspects in EBM equipment.
- Types of Electron Beam Melting and applications
- Experience of NFC in operation & Maintenance of EB units
- Aspects in Indigenous development of 300kW EBMF

High Energy Sources

- **Electron beam (collimated electrons)**
- **Laser beam (coherent electro magnetic radiation)**
- **Plasma (directed unbound positive & negative particles)**
- **Proton beam (collimated protons)**
- **Neutron beam (collimated neutrons)**
- **X Rays and Gamma rays**

They will be High Energy (Power Density) Sources

- When focused / directed appropriately they can be used as **High Power Density** sources

Electron beam as High Power Density Source

and

Safety issues in EB machines are topic of this presentation

Electron beam as a High Power Density Source

- **Using magnetic lenses electron beam can be shaped into a narrow cone and focused to a very small diameter. This allows very high surface power density on the surface(i.e feed charge/molten pool).**

- **Values of power density in the focus of the beam can be as high as 100 W/mm^2.**

- **Shallow penetration allows for very high volumetric power density, which can reach values of the order 100 W/mm^3.**

- **Consequently, the temp in this volume increases extremely rapidly up to 1000 K/s & melting/ refining .**

Applications of Electron Beam technology :

- **EB melting, refining and casting processes e.g** ***Nb, Ta, Zr, Hf***
- **EB Evaporation – Titanium /Zr carbide and borides- Use of transversal EB gun**
- **EB machining and Drilling , Micro Applns,** High Power density of 10^7-10^9 W/cm2
- **EB Thin film coating -** ***Turbine Blade Coating***
- **EB Welding/ brazing -** ***Steel / Aluminium***
- ***Electron beam accelerators – plastic modifications- cross linking-polymer***
- **EB Non thermal Processing , Carburising , Hardening process**
- **EB Lithography , Nanofabrication**
- ***EB*** **irradiation (*eBeam*) , food items, EB pasteurization / dairy products,**
- **Electron Microscopy, Thin film & metallurgical coating e.g. Turbine blade coating,**
- **Micro & Nano Electromechanical systems , VLSI , carbon nanotubes**
- **EB radiation in medication, Electron therapy**
- **EB accelerators – e.g. plastic modifications- cross linking-polymer,**
- **Industrial environmental applns in waste processing, Wastewater, toxic chemicals**

Basic principles of electrons Generation , Focusing & Acceleration

- In these machines, electrons are generated by thermionic emission, accelerated by using high dc voltage, harnessed to a specific point by using magnetic lenses, which are further maneuvered in the required directions .

- The electrons accelerated thus, attain tremendous kinetic energy (at 25 kV it is 1/3rd of velocity of light) which is lost on collision with the charge in the form of energy transformation in the form of heat. Using magnetic lenses Electron Beam can be shaped into a narrow cone & focused to very small diameter.

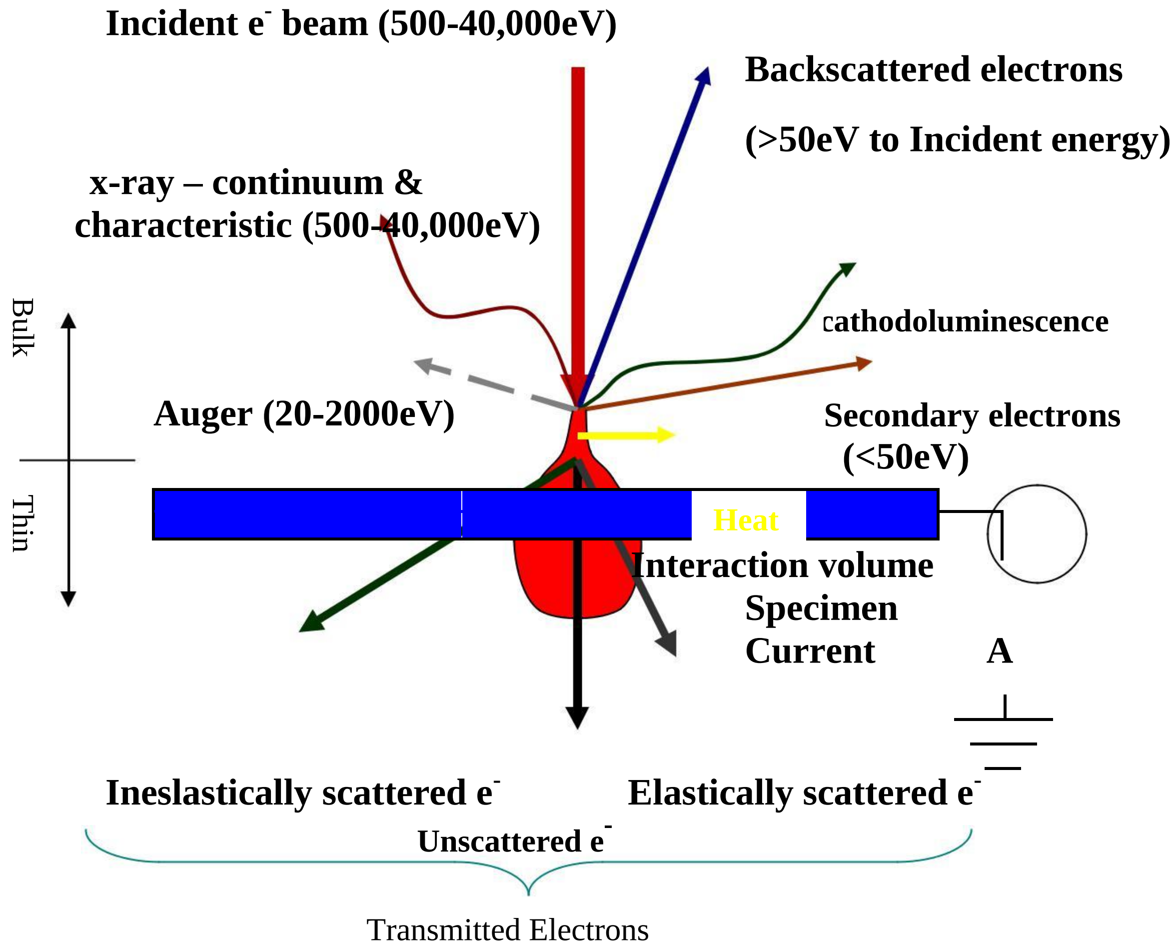
- This allows very high surface power density on the surface, penetration extremely rapid rise of temp.

- At NFC 6 Nos of EB machines are used for welding and purification of refractory metals and their alloys.

Electron Beam – Specimen Interaction

The interaction of a high energy electron beam with the specimen will produce various effects resulting in a range of signals being emitted. The incident electrons interact with specimen atoms and are significantly scattered by them (rather than penetrating sample in a linear fashion).

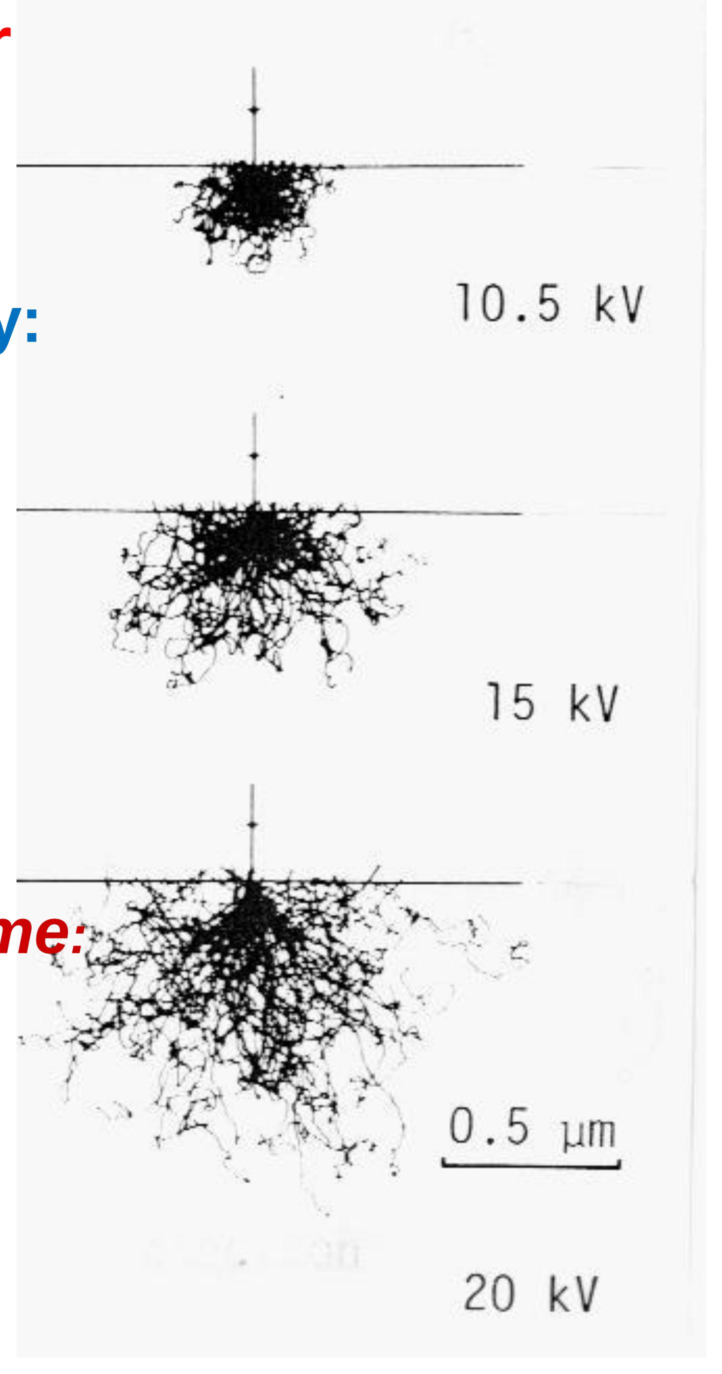
Most of the energy of an electron beam will eventually end up heating the sample (phonon excitation of the atomic lattice); however, before the electrons come to rest, they undergo two types of scattering: ***elastic and inelastic.***



Copper

The interaction volume is influenced by:

- ➢ The beam energy;
- ➢ The atomic number of the solid;
- ➢ Surface tilt and
- ➢ Density of the solid.



Influence of beam energy on interaction volume:

- **As the beam energy is increased, the electron beam can penetrate to greater depths.**

- **There is no a significant change in the shape of the interaction volume with beam energy**

Decrease in KE of electrons & Rise of temperature in material

Significant amounts of heat are produced with a sample because electron excitation of X-rays is not very efficient.

Many low energy continuum photons and low-energy inelastically scattered electrons do not escape the sample and their energy is transformed into higher vibrational energies of the bonds (heat).

The maximum temperature rise for a material can be expressed as

$$\Delta T = \frac{4.8\, E_0\, b_i}{C_t\, d_0}$$

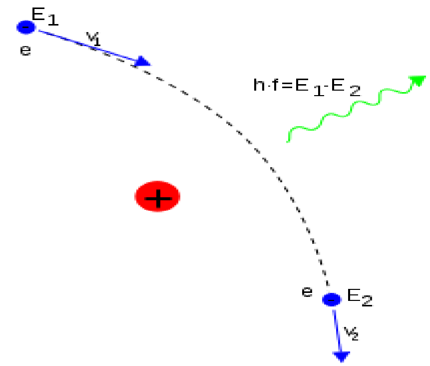
where,

E_0 = accelerating voltage (keV)
b_i = beam current (μA)
C_t = thermal conductivity (W/cm·K
d_0 =beam diameter (μm)

		1 μm diameter spot			5 μm diameter spot		
Material	C_t	5 nA	10 nA	25 nA	5 nA	10 nA	25 nA
Epoxy	0.002	180	360	900	36	72	180
Mica	0.005	72	144	360	14	29	72
Obsidian	0.014	26	51	128	5	10	26
Zircon	0.042	9	17	43	2	3	9
Calcite	0.05	7	14	36	1	3	7
Quartz	0.10	4	7	18	0.7	1	4
Kyanite	0.17	2	4	11	0.4	0.8	2
Periclase	0.46	0.8	2	4	0.2	0.3	0.8

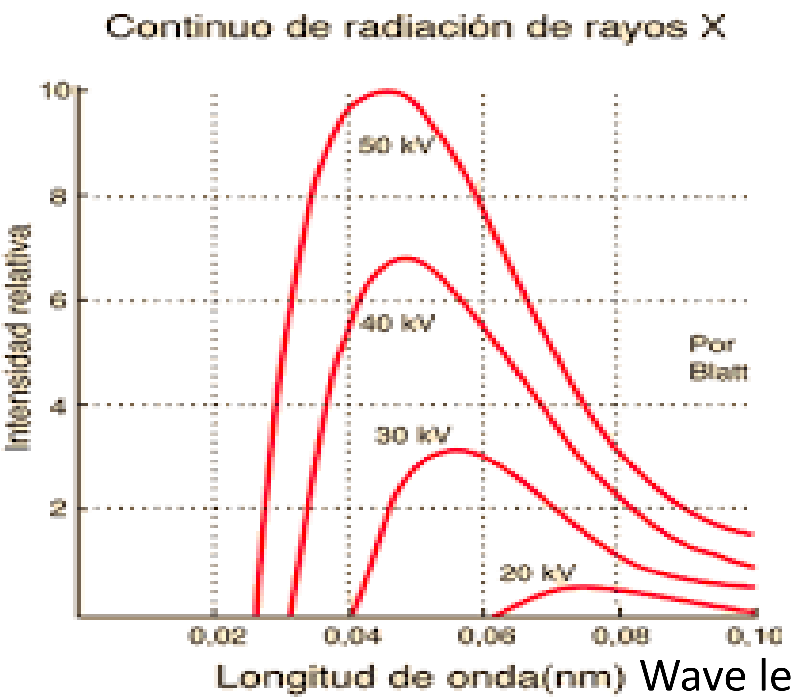
The moving charged particle **loses kinetic energy**, which is converted into a **photon**, thus satisfying the law of conservation of energy.

i.e the process of **producing the radiation.**

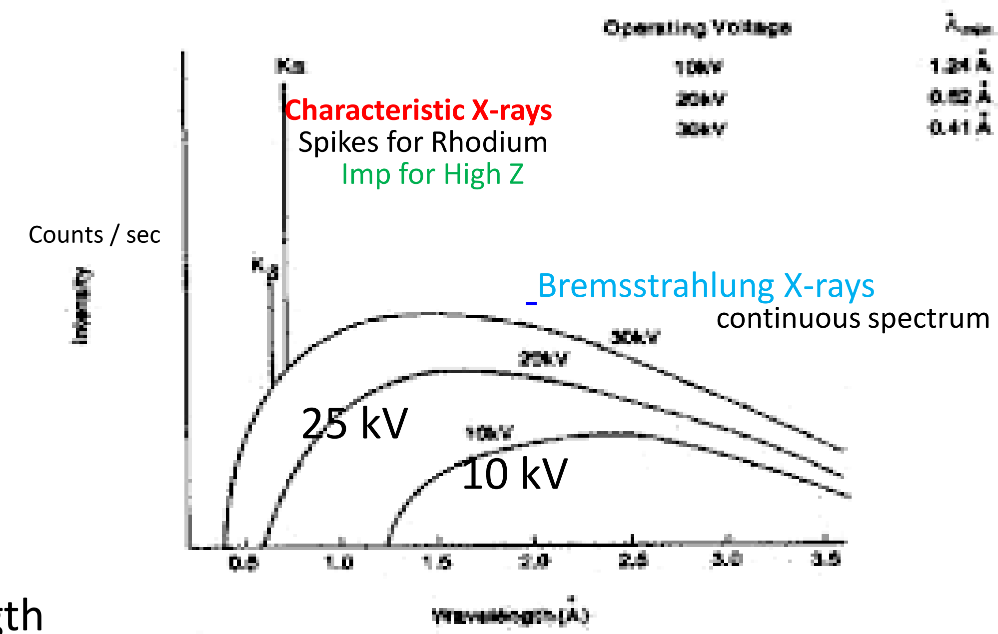


Bremsstrahlung has a continuous spectrum which becomes more intense and whose peak intensity shifts toward higher frequencies as the change of the energy of the decelerated

Bremsstrahlung produced by a high-energy **electron** deflected in the electric field of an atomic nucleus



Wave length

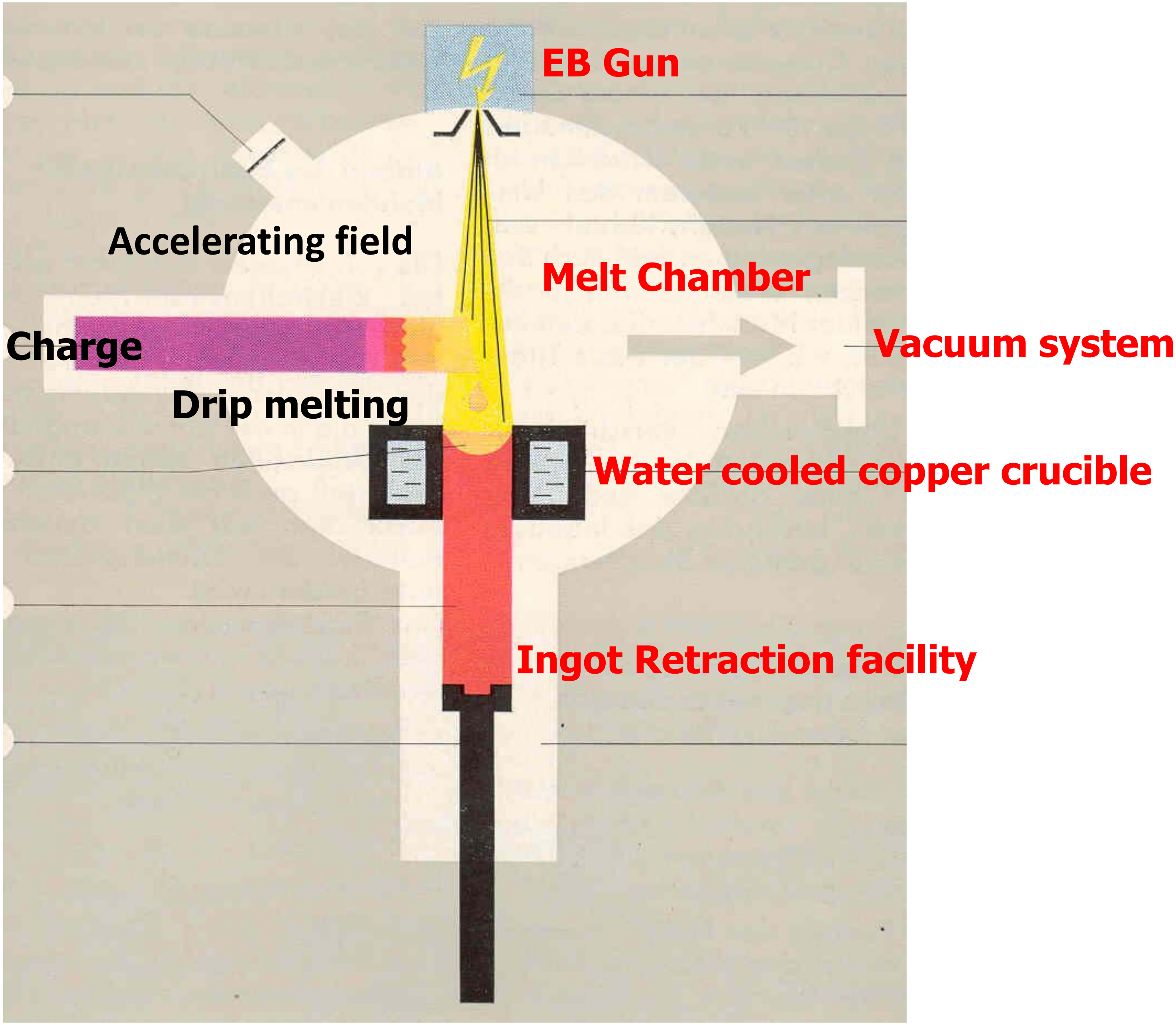


Metallurgical EB machines operate at lower voltages . Hence x ray is not a very serious issue

Basics of Electron Beam Melting

The Architecture of the System at NFC

Basic parts of an EB Melting furnace

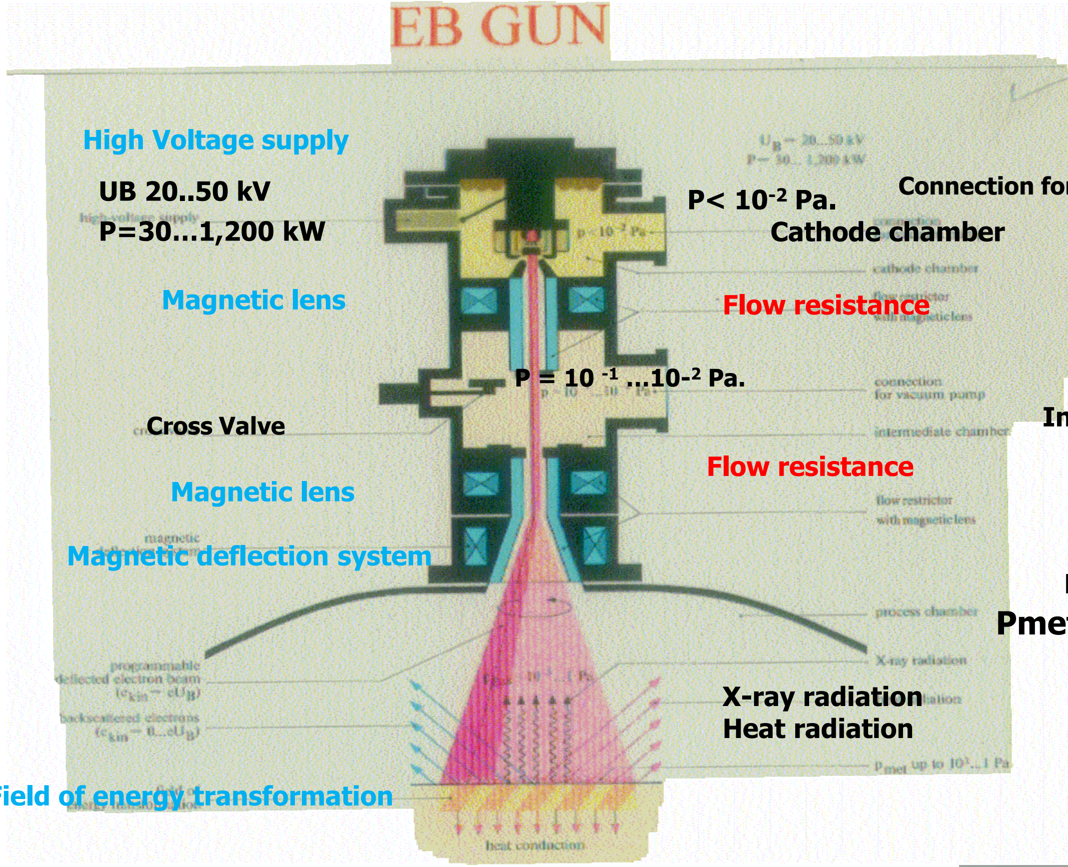


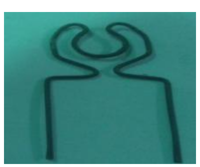
EB Gun is the heart of the EB technology

10 $^{-6}$ mm

10 $^{-4}$ mm
Air admittance –Needle valve
Self focusing effect

1- 10 $^{-5}$mm



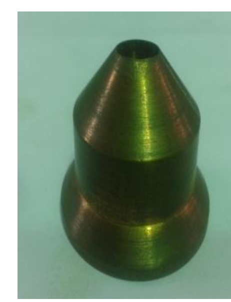


W Filament

Cathode Assembly used in EMO 60

W Cathode

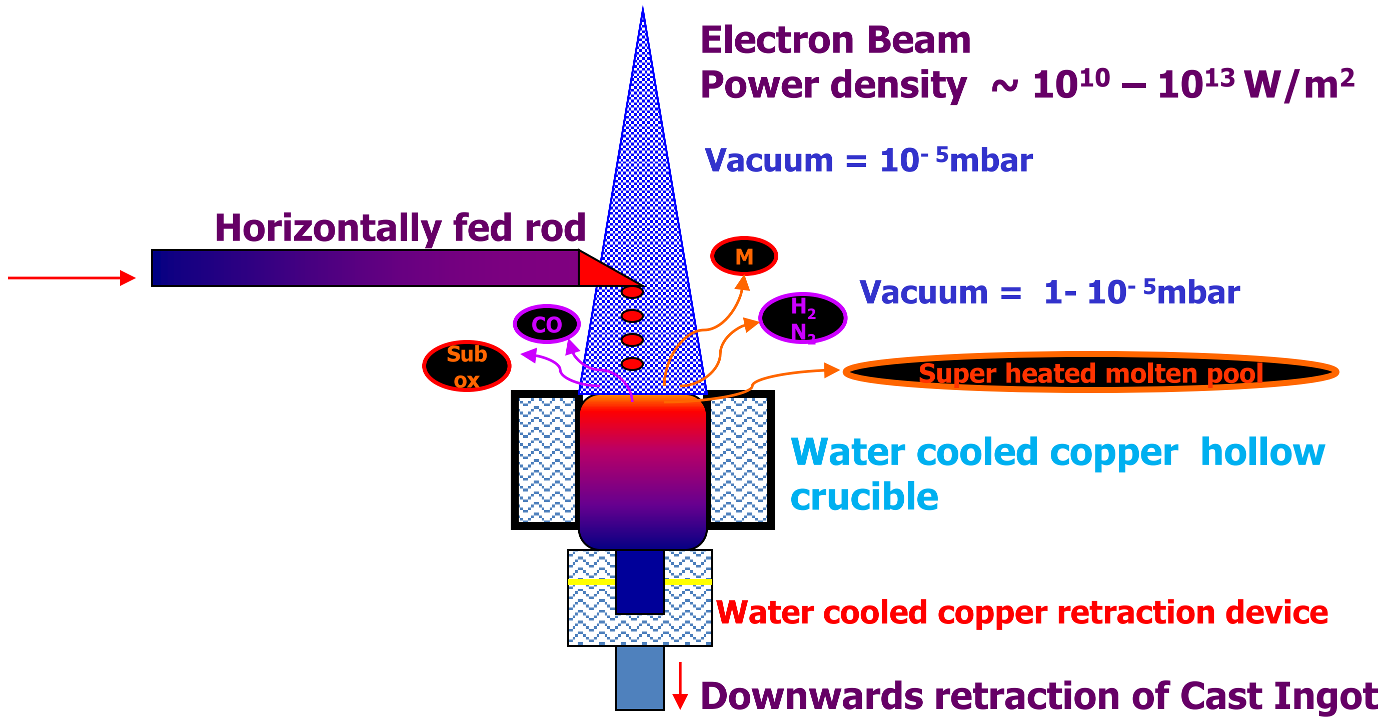
W Filament for EBW



Cu anode

Electron Beam Drip Melting Process

(Purification Principles)



Note: Molten pool can be super heated and exposed to very high vacuum for any desired dwell time , to reduce the impurities level to near equilibrium concentrations. Hence leading to ultra purification .

Major Safety Issues

in Electron Beam Machines

Safety in High Voltage Direct Current System

- Generation of HV DC i.e EB transformer and rectifier .
- Transport of HV DC to the EB machine, i.e., HV cables, terminals, insulators, etc.
- Cathode assembly used for electrons generation and the earthed anode
- Acceleration voltage in kV (upto 50 kV)
- Electrical and electronic earthing
- Qualification and maintaining of HV transformer oil w.r.t break down voltage.

Safety issues in operation of high vacuum system & refining of metals in EBMF

- Proper interlocks & automatic operation valves of Rotary, Roots & DP.
- Accidental impingement of EB on anode, flow resistors, water cooled copper crucible, chamber etc.
- Electric discharge due to abrupt degassing from the feed charge
- Accidental leakage of water from melting crucible, chamber, feed charger, EB gun, flow resistors or increase of temp or stoppage of cooling water / compressed air.
- Coating of metallic vapors on viewing ports.
- Simultaneous control of charge feeding, ingot casting, acceleration voltage and beam focusing, deflection and oscillation
- Adjustment of cathode plug holder /W filament, W solid cathode, W rods, support rods & plates, focusing electrode, insulators, ion collector, critical control of gap between filament to cathode, focusing electrode & Cu anode.
- Utmost care in opening of gun top and discharge of static electricity by built-in self earthing mechanism and external earthing stick.
- Appropriate conditioning of the melt chamber containing the atomized metallic deposition on the walls prior to opening the chamber.

Safety issues in maintenance of EBMF

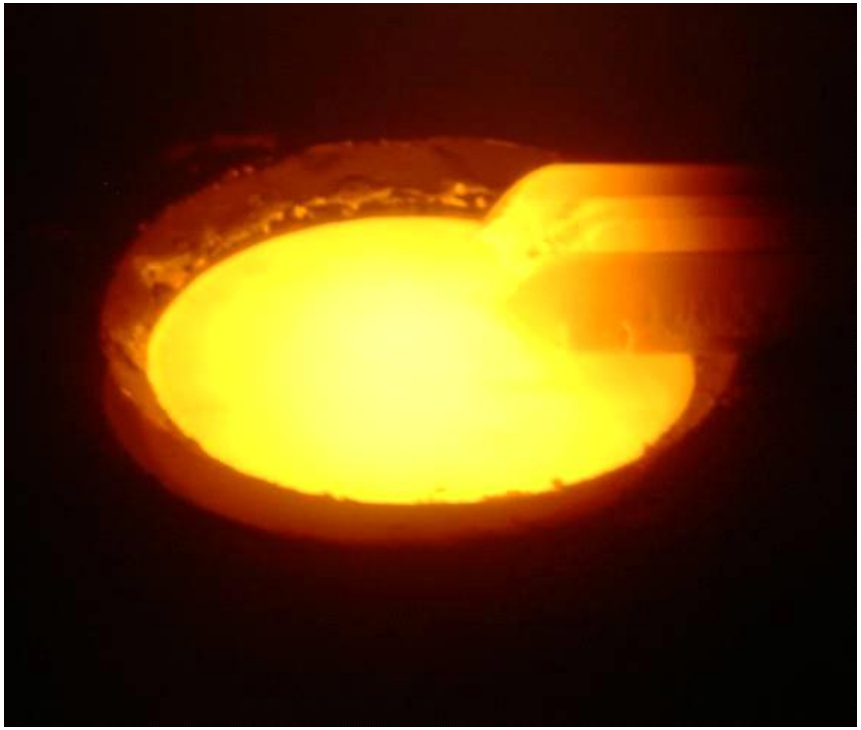
- Testing of transformer oil, integrity of HV cables/ terminals & insulators.
- Regular testing of electrical and electronic earth resistance.
- Careful removal of the atomized metallic deposition on the walls of the chamber to avoid metallic fire due to friction during cleaning.
- Periodic checking & qualification of interlocks to ensure safety in controls.
- Both preventive & corrective maintenance are important to avoid failures, unnecessary production loss and safety violations.
- Regular greasing of rotating parts.
- De-scaling of cooling water lines and periodic checking of flow switches & alarms to ensure cooling water supply regularly.
- Proper disposal of used vacuum pump oil & dust collected in vacuum pumps

Safety aspects in Development of EBMF

- Proper design and accurate application of electron optics & assessment of quality of the electron beam.
- Strict quality control in fabrication & surface finish of EB gun parts, charge feeder, ingot casting parts etc.
- Automation of process parameters for majority of the operations through PLC & interlocks with appropriate alarms.
- Observation & control of the operation using camera in addition to stroboscopic viewing port.
- Built-in safety features to attenuate soft / hard x-rays generated & emergency cooling water supply.
- Development of step wise diagnostic that is easy to handle and operator friendly.

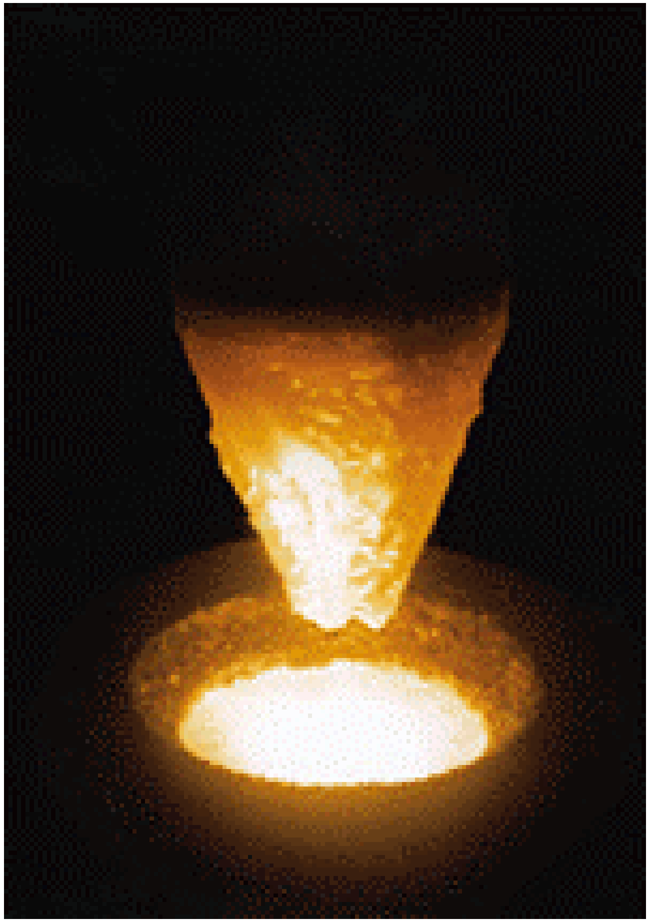
Types of EB Melting Equipment

Horizontal drip E.B melting



Used for melting/purification of granules/pellets/odd shapes

Vertical drip EB melt



Used for melting/purification of rods/electrodes shapes

If Multi gun system is used then – one gun on electrode, other one on molten pool

Cold hearth EB refining furnaces

Used for melting/purification of impure granules/pellets/odd shapes

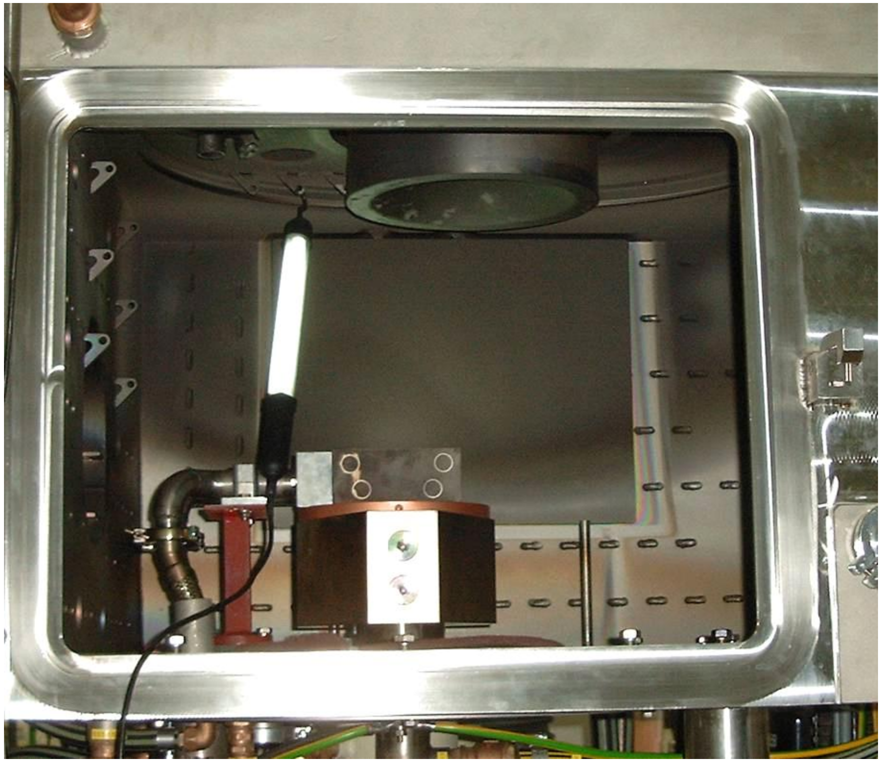
Separation of high density/low density can be achieved

Highly energy consuming process

Cold hearth refining furnaces for melting of titanium

Cold cathode glow discharge Electron guns of high power are used in Ti scrap recycling in Ukraine

Laboratory Installations for Button Melting and Small Ingot Production



Used for development of metal/alloy in pure form

Experience of NFC in Operation & Maintenance of EBMF

EB Refining of Refractory & Reactive Metals & Alloys

All the process parameters have been standardized for EB refining of various refractory & reactive metals & alloys at SMP, NFC

Off grade Materials	High Pure Materials	Alloys	Applications
Tantalum powder Off grade tantalum	EB grade Ta	TaW	Electronics , Chemical industries & high temperature
Niobium thermit	RG niobium	NbZrC, NbW, NbZrW, NbMoZrC , bulk metallic glass etc.	Nuclear , defence & high temperature applications
Niobium metal scrap	RRR grade niobium	NbTi	Super conducting applications
Off grade zirconium	Special grade zirconium	ZrNb master alloy, Zr2.5Nb, ZrNbB,	Nuclear power reactor components
C-103 turnings etc		C-103	Space applications
Electrolytic Cu	Pure Copper		Defence applications

* - In case of Ta & Nb, SMP produces these metals starting from the minerals by hydrometallurgical processing followed by EB melting / refining.

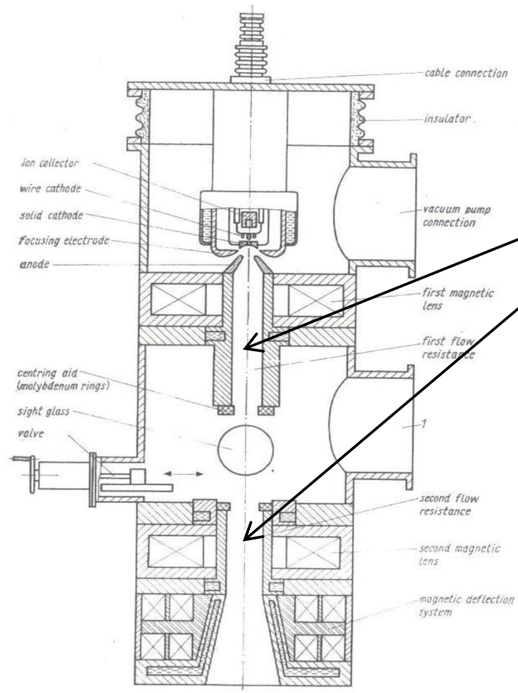
Experience of NFC in operation & Maintenance of EB units

Make	Power	Remarks
BARC, EBM	15 kW	Complete unit built by BARC ,
Leybold make, EBW	36 kW	Complete unit Purchased in 1970s. Two Chamber system
Leybold make, EBW	36 kW	Only gun & power supply purchased. Chamber & other parts built by NFC
LEW make, EBM	80 kW	Complete unit procured
LEW make, EBM gun being used for EBW	80 kW	Only gun & power supply purchased. Chamber & other parts built by NFC
Techmeta make, EBW (Precision welding)	6 kW	Complete unit procured
Techmeta make, EBW (EBM gun used for EBW)	60 kW	Complete unit procured Three chambered

MIDHANI & DMRL have procured 300 & 100 kW EBMF from ***Retech Systems LLC, USA*** in which I was member in the procurement committee and also in training

- **Complete vacuum systems for various other high vacuum furnaces have been built by NFC**
- **NFC has gained sufficient experience in O&M of EBM & EBW units**
- **These things gave confidence for taking up of indigenization**

Concept of "Differential vacuum " and "Use of flow resistors"



Flow Resistor

- By controlled dia to length ratio – max resistance to flow of fluid
- Axial guns have high reliability in operation , long continuous service life and easy pressure Decoupling. The extent of pressure de-coupling lies in the range of 10-100.
- This concept is more important in purification of off grade materials like Nb thermit containing 4-5% of Al
- This concept is useful in preparation of alloys containing wide variation in vapor pressures like Nb & Ti

Indigenisation of EBM components
&
300 kW EBM Furnace

Indigenisation of EB components for EMO 60 (Supplied by LEW, East Germany, 1984)

- Cathode Assembly
  - Tunsgten Solid Cathode
  - Tungsten Filament
  - Molybdenum Focusing Electrode
  - Guiding Rods
  - Insulators etc
- Double walled Melt Chamber (SS 304 L)
- Copper Anodes
- Flow Resistors
- Copper crucibles (40 mm to 120mm dia)
- High vacuum valves (electro pneumatic)
- High voltage Transformer with rectifier
- Control Panels

Note : Indigenisation of the above components had become compulsion after unification of East & West Germany .

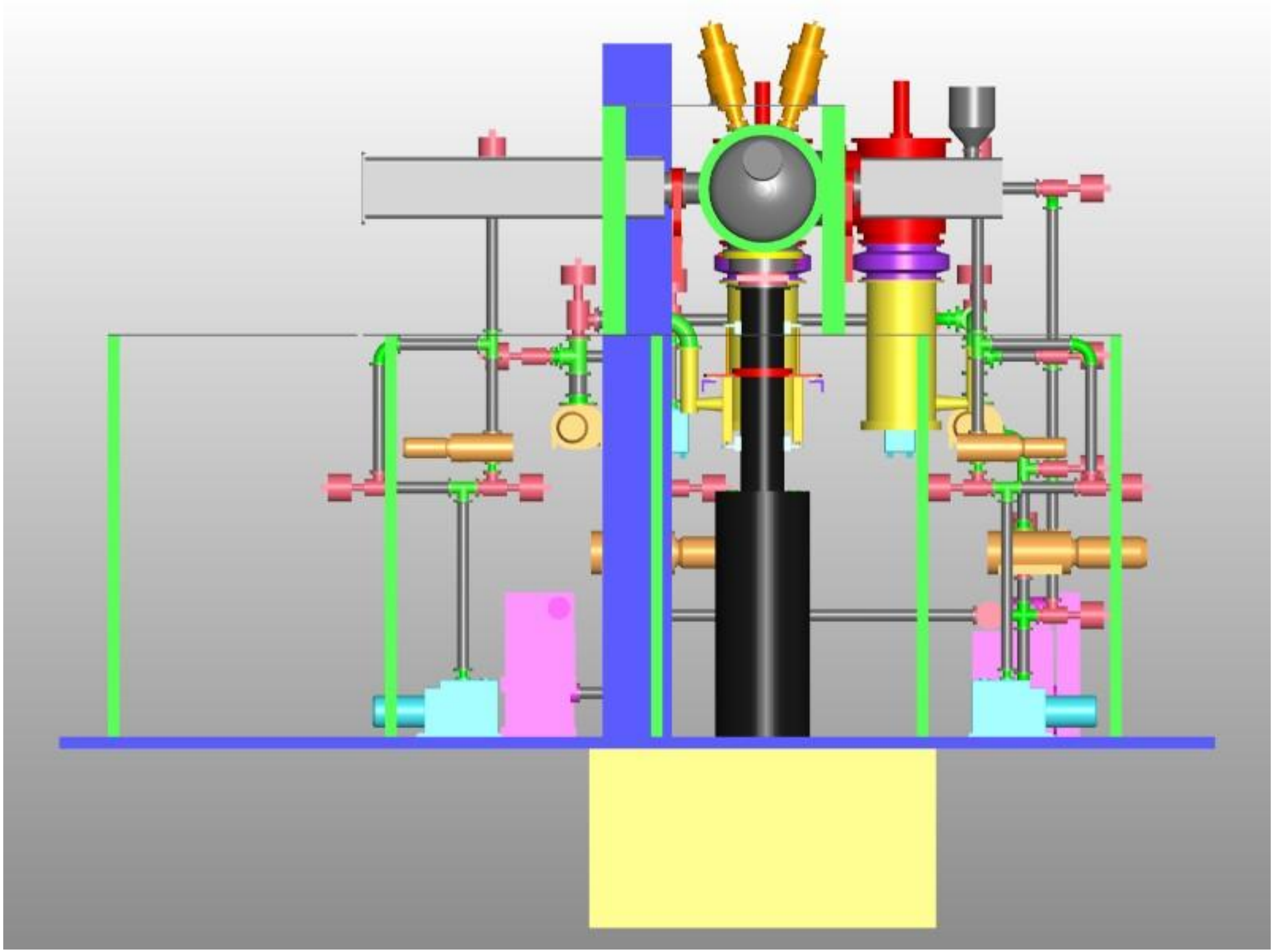
Indigenous (seventies) & Imported EBMF (eighties) operated at SMP , NFC

15 kW indigenous EBMF

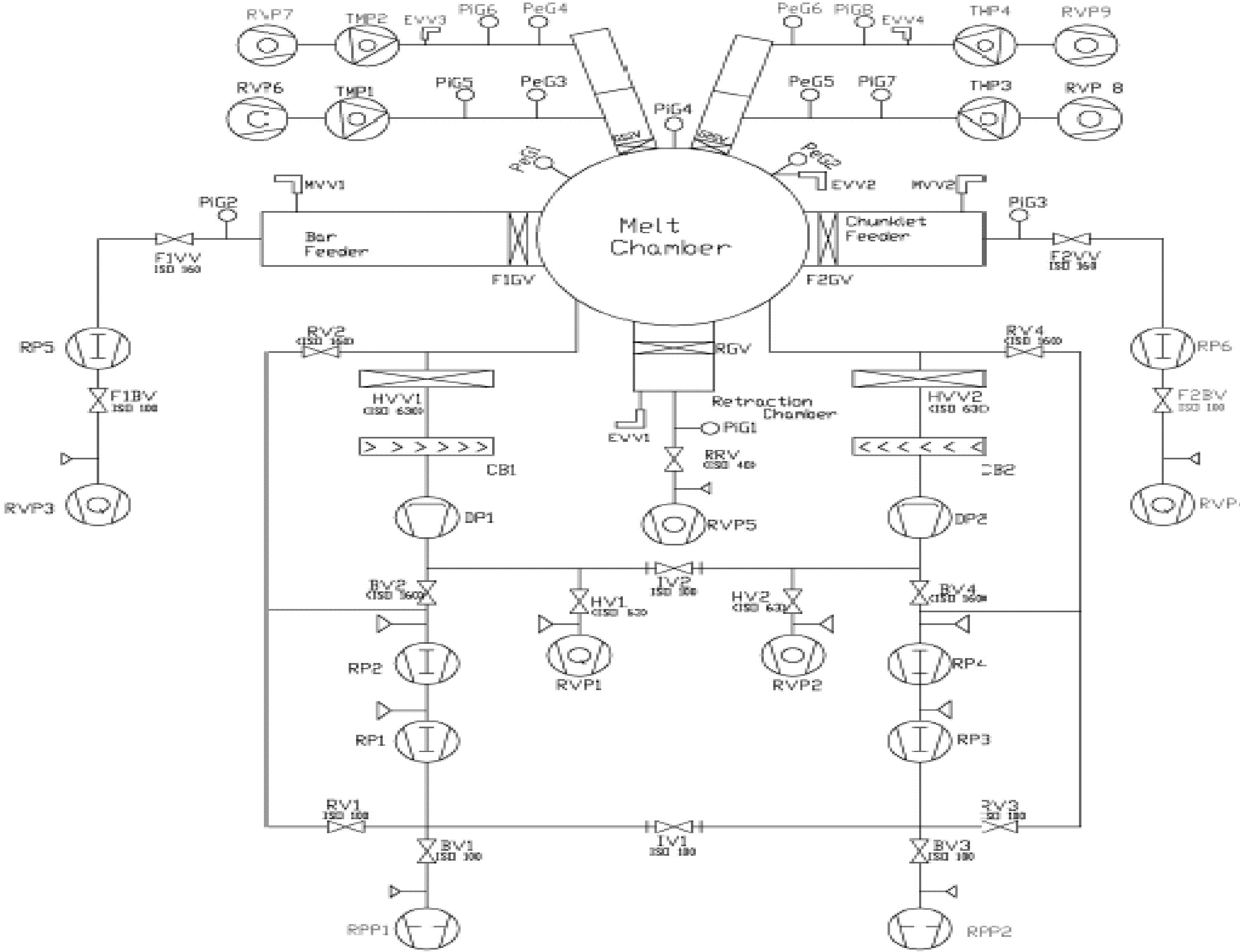
- No continuous casting
- Used mainly for Ta powder
- Few hundred kg per annum

LEW, German make EMO 60 (60 kW)

- Continuous casting
- Used for Ta, Nb, their Alloys
- Few tonnes per annum



Indigenous 300 kW EBMF (Being built by BARC & NFC) at M/s I Design and M/s Ador Pune



300 kW EBMF

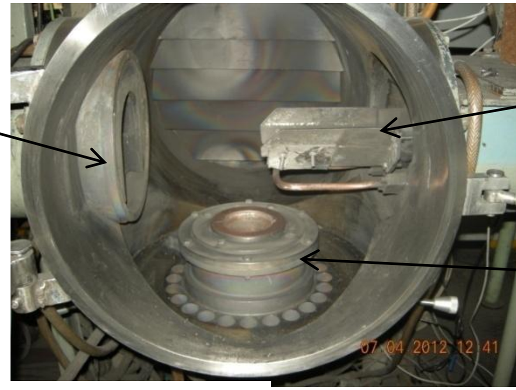
Parallel Vacuum Pumping System for continuous round the clock operations

Feeding device (Horizontal feed , Diameter ratio of 1: 1.4)

Melting of Rods produced by pressing, sintering, casting or joint metal chunks

Rod Feeder

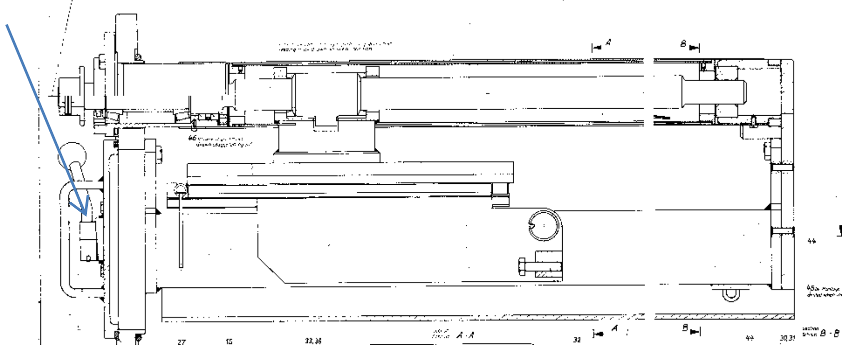
Granule Feeder

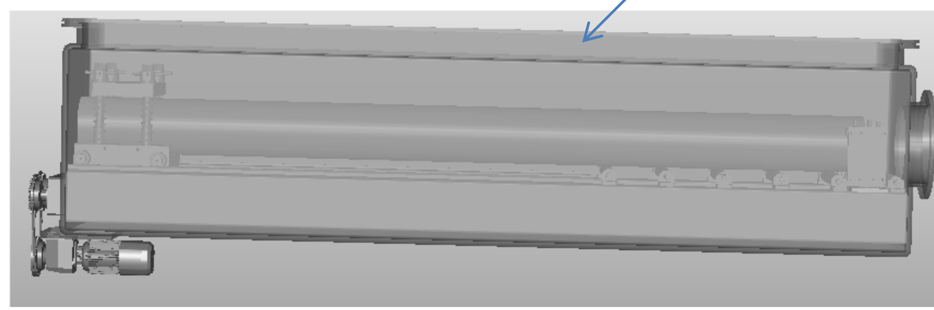


Crucible

Cover on back end

Top cover





EMO 60

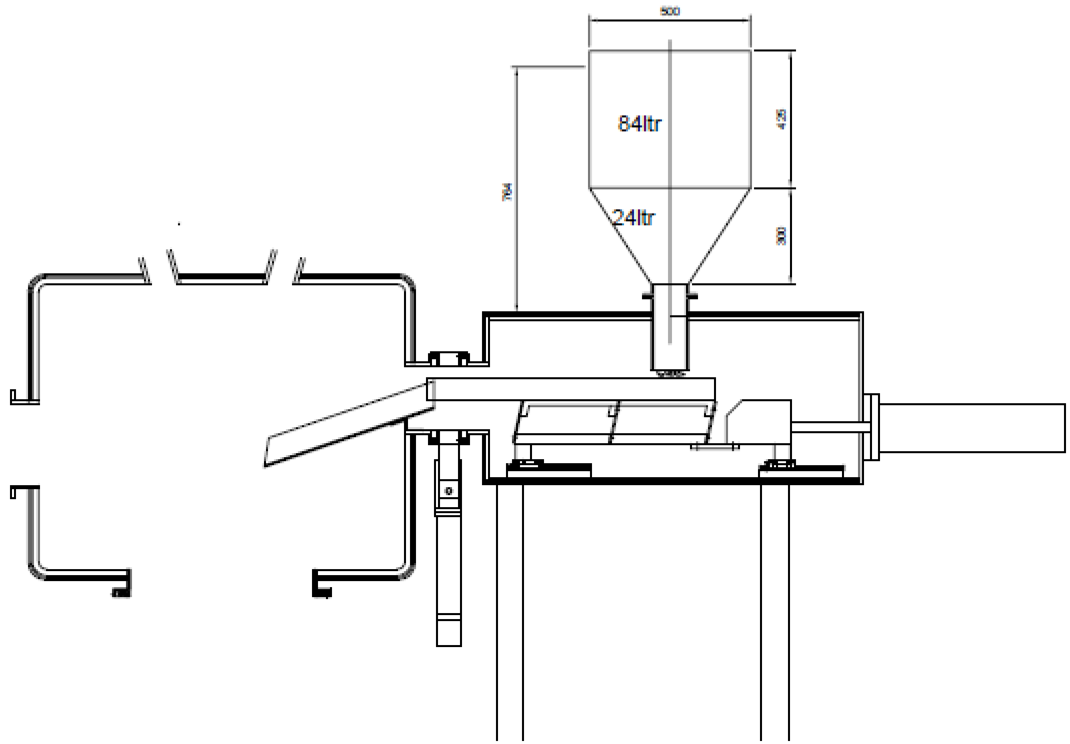
- Axial Feeding
- Requires additional length equal to the size of the feeder
- Manual feeding of charge int o feeder
- Max. length of charge – 1m
- Granule feeder can be replaced with additional rod feeder (feeding from 2 sides)

300 kW EBM

- Top Feeding
- No additional space required
- Charge can be fed by hoist
- Max. length of charge -

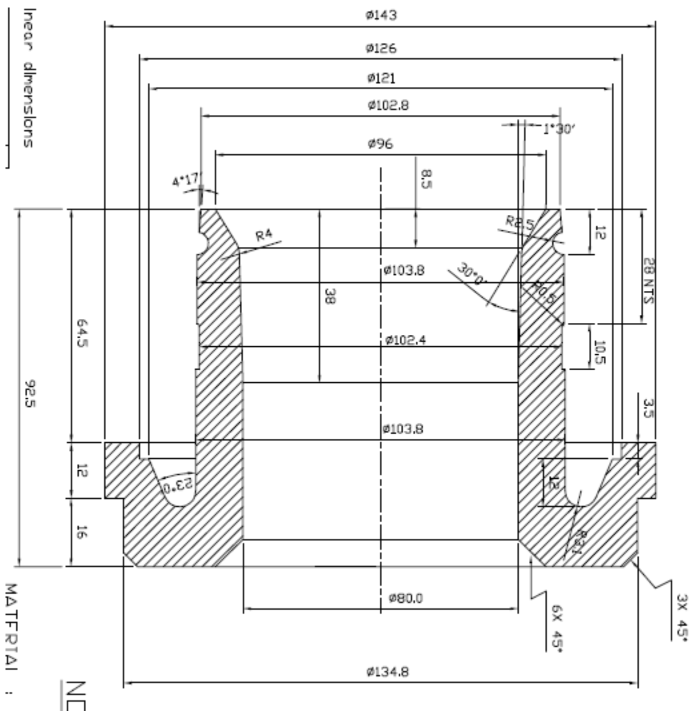
Feeding device (Feeding of pellets or granules or bulk or chunklets)

EMO 60
Vibratory feeder



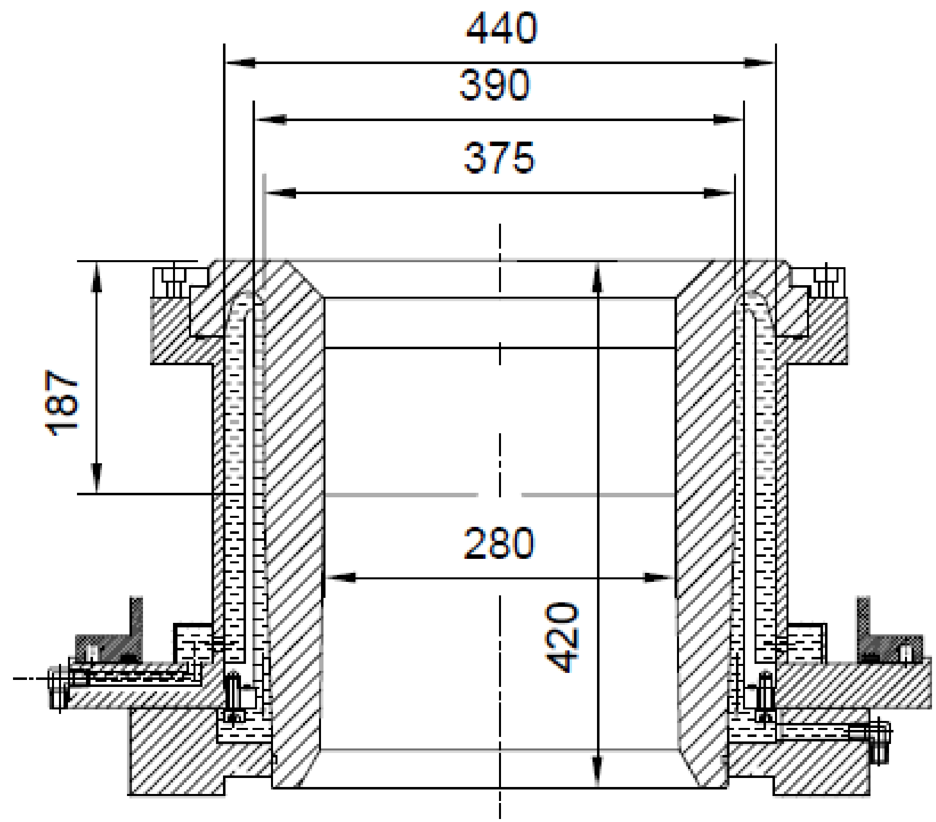
300 kW EBMF
Auger feeder

Water Cooled Copper Crucible Assembly (Crystallizers)



EMO 60

Ø280 crucible assy



300 kW EBMF

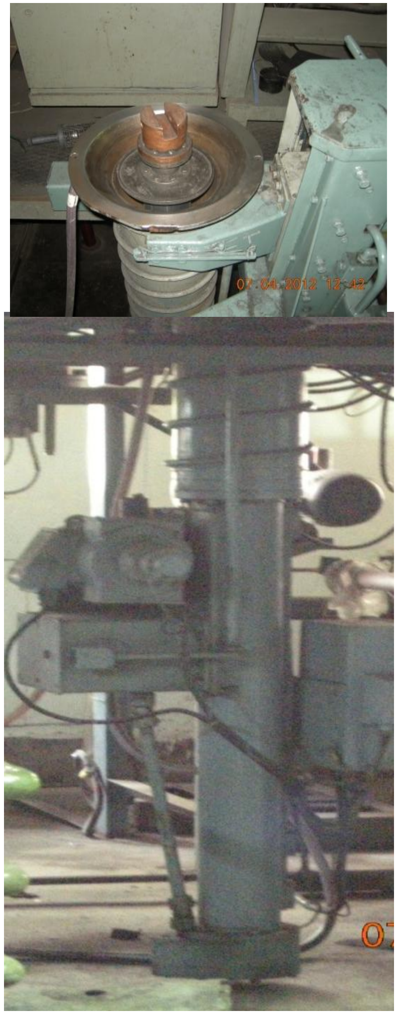
- For each Crucible diameter a separate housing assembly is required.
- Assembling/Disassembling of crucible assembly is done within the melt chamber

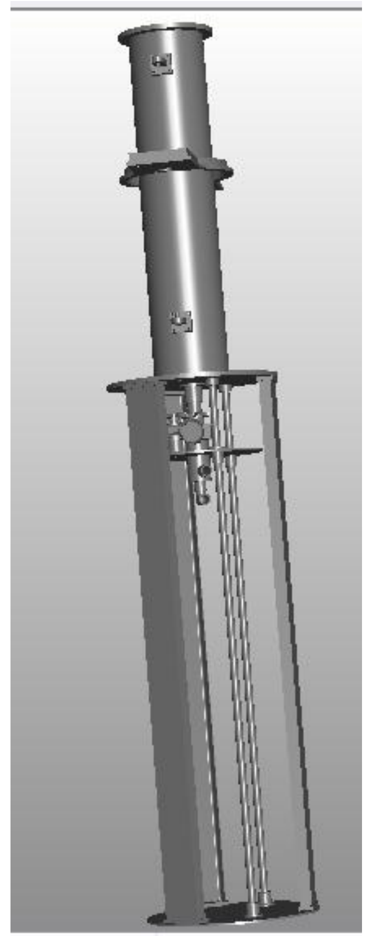
Max Dia: 125 mm

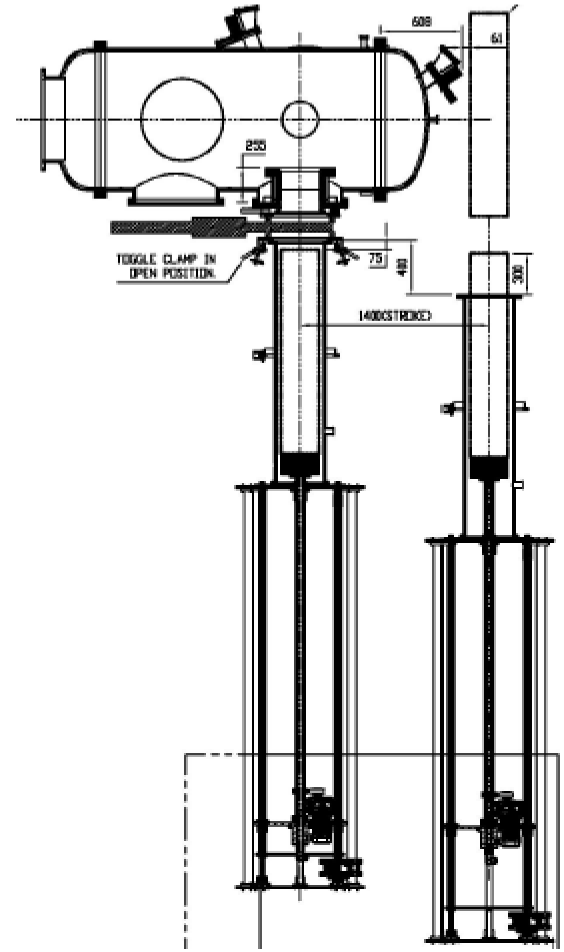
- For each Crucible diameter a separate housing assembly is not required. A common Assembly is designed.
- Assembling/Disassembling of crucible assembly is done outside the melt chamber by sliding down , then moving forward.

Max Dia: 280mm

Retraction Assembly (Ingot Pullers) – Lower able bottom







LEW make EMO 60

Retraction assembly moves inside guide cylinder . The whole system is above ground.

Max Dia: 125mm Max. Length: 1m

300 kW EBMF

Retraction assembly moves inside guide rods

Required a pit for housing the assembly.

Max Dia: 280mm Max. Length: 1.5m

Summary

- NFC has developed expertise in operation of various Electron Beam melting & welding units .
- Process parameters have been optimized for refining of refractory & reactive metals and in preparation of alloys by EBM
- Safety systems have been improved over the period. There has been no major incidence in operation of the melting furnace.
- Tonnage quantities of various EB refined materials have been produced and supplied for strategic applications.
- Indigenisation of components for EMO – 60 melting & other welding units at NFC has been achieved.
- Based on the O & M experience and understanding developed during indigenisation of components, indigenisation of complete EB melting furnace has been carried out BARC & NFC .
- The indigenously built 300 kW EBMF is being commissioned at NFC.


THANK YOU