Hypervapotrons for High-Power Accelerator Targets

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TSD Topical Meeting - August

10 August 2023

Overview

- High Performance Cooling

  -Industry Tour of Cooling Solutions

- Hypervapotrons

  -History & how it works

  -Applications

  -Targetry

- Integration

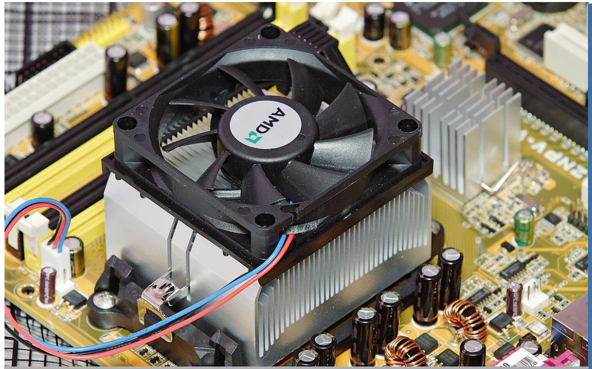
  -Target Packaging

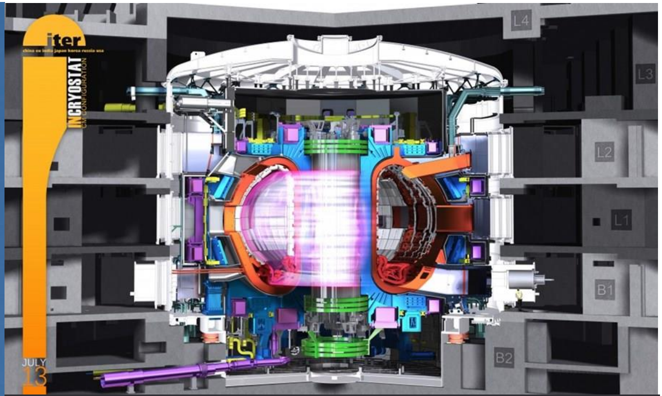
  -Likely issues

High-Performance Cooling
-
An Industry Tour

High-Performance Cooling

- How to keep things from melting/deforming/exploding?
- Heat fluxes from 1 MW/m^2… … to 30+ MW/m^2





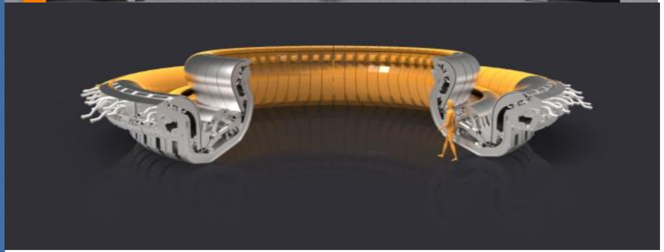


Image Sources: Wikipedia, ITER

Convective Heat Transfer

For large heat flow, need some combination of:

- High heat transfer coefficient – cheat with flow parameters, phase change
- Large temperature difference – cheat with materials science and metallurgy
- Large area - cheat with thermal conduction to a larger area
- Large mass flow – cheat with very high mass flow (flow velocity is part of HTC, also consider outlet temp)

$$\dot{Q} = hA(T_2 - T_1)$$

$$h = \frac{q}{\Delta T}$$

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Air/Water Cooling – Computer Chips

- Heat spreaders, fans, fins…
  - Physically reduce heat flux, spread out hot spots
- Water-cooling
  - Microchannels, jet impingement
- 100 W in 1 cm^2 = 1 MW/m^2
  - Dies around 1-2 cm^2 are typical of modern processors
  - Smaller transistors, more in same area, more heat

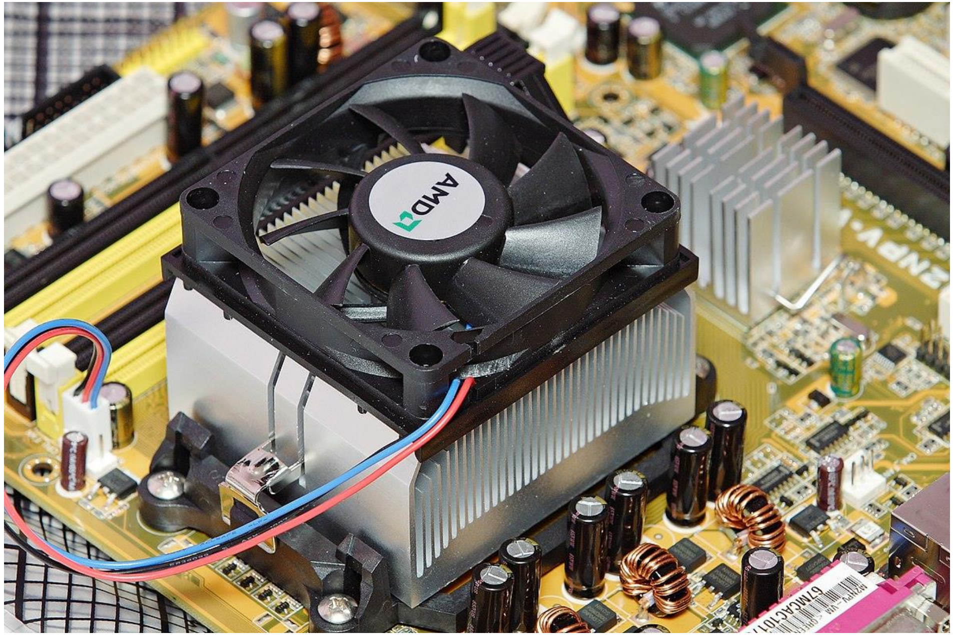

Image Source: Wikipedia

Air/Water Cooling – Computer Chips

- Example: My work laptop…
  - Intel i9-12950HX
- TDP of 55W, short-term boost to 157W
  - 2.15 cm^2 die area
- 157 W in 2.15 cm^2 = 0.73 MW/m^2 heat flux out of the die
  - Heat spreaders/heat sinks
  - A very overworked fan…

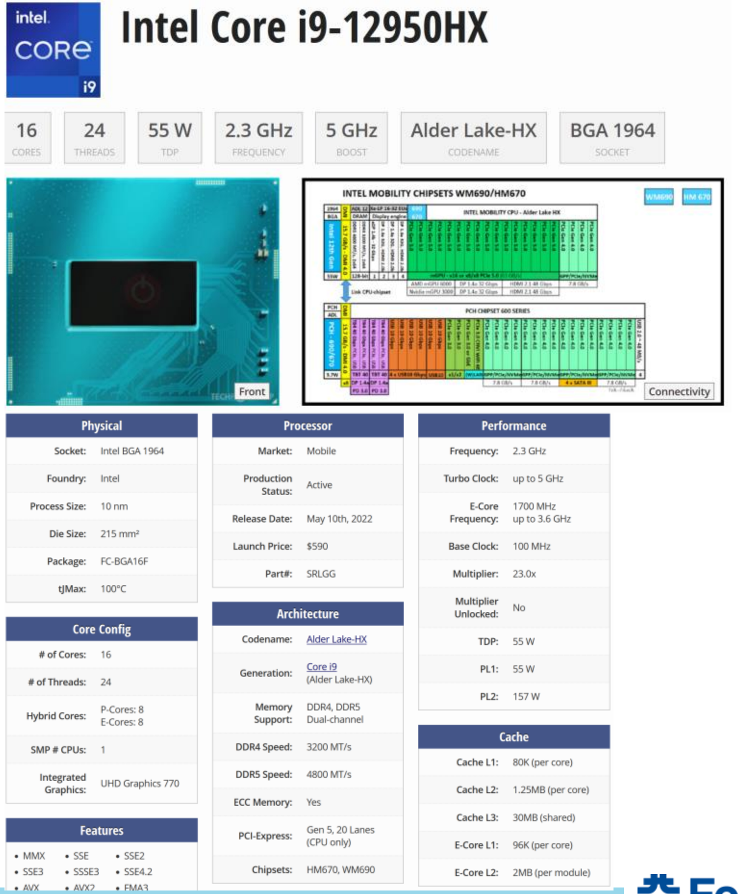

Image Source: TechPowerUp

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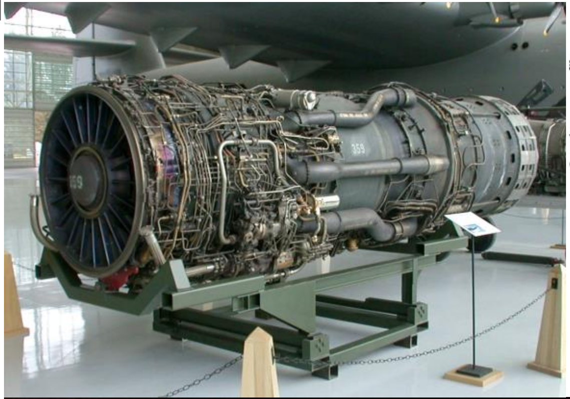
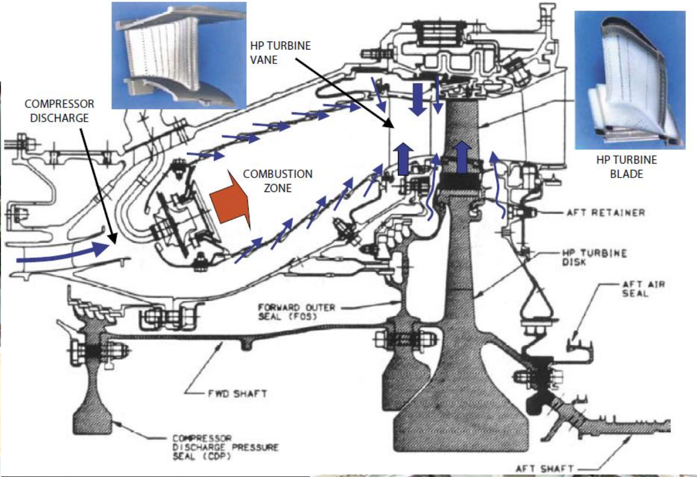
Gas Cooling – Jet Engines

- Avoid needing high heat transfer – insulate or use high-temp materials
- High mass flow, lower HTC
- Film cooling, metallurgy (directional and single-crystal materials)





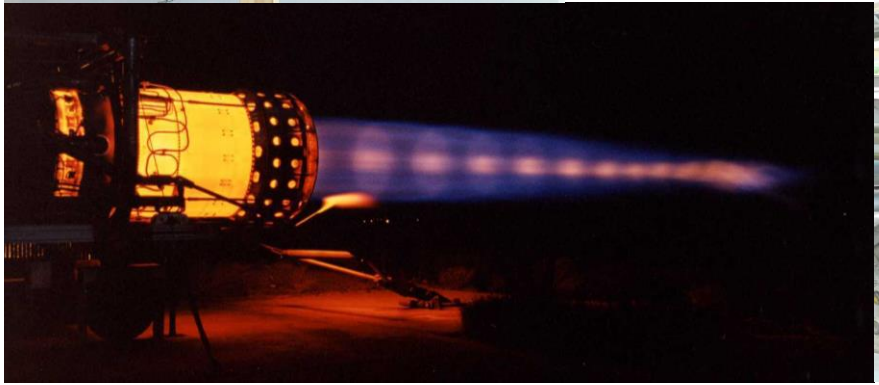


Image Source: SoftInWay, Wikipedia

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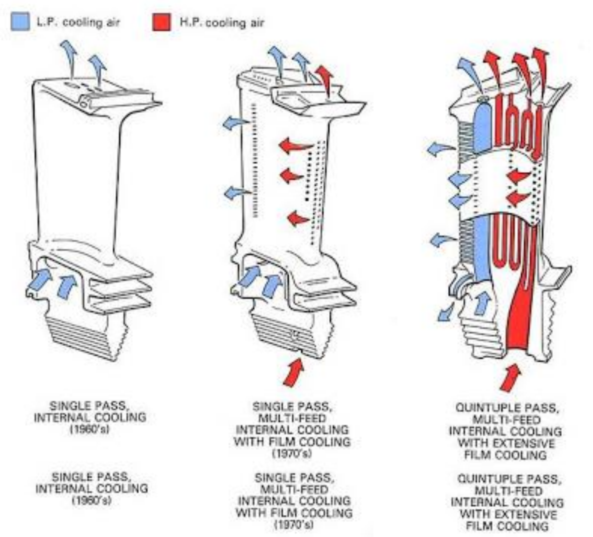
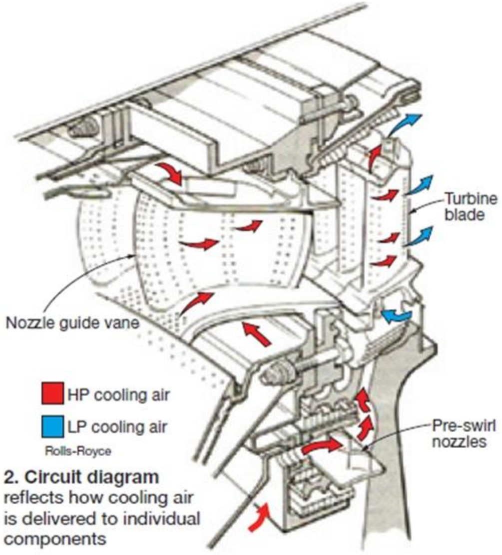
Gas Cooling – Jet Engines

- Forced convection – turbulators, impingement liners, film cooling…
- High-pressure air from compressor – use for cooling





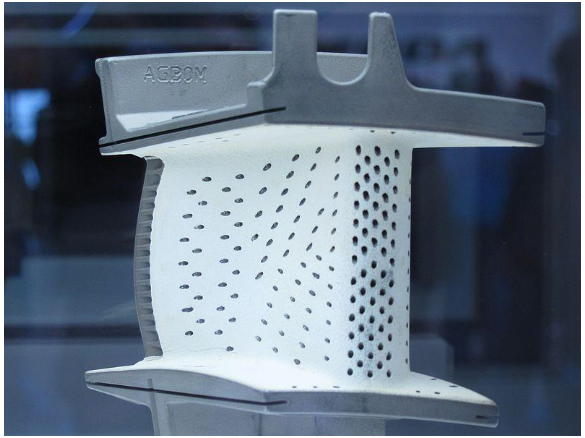
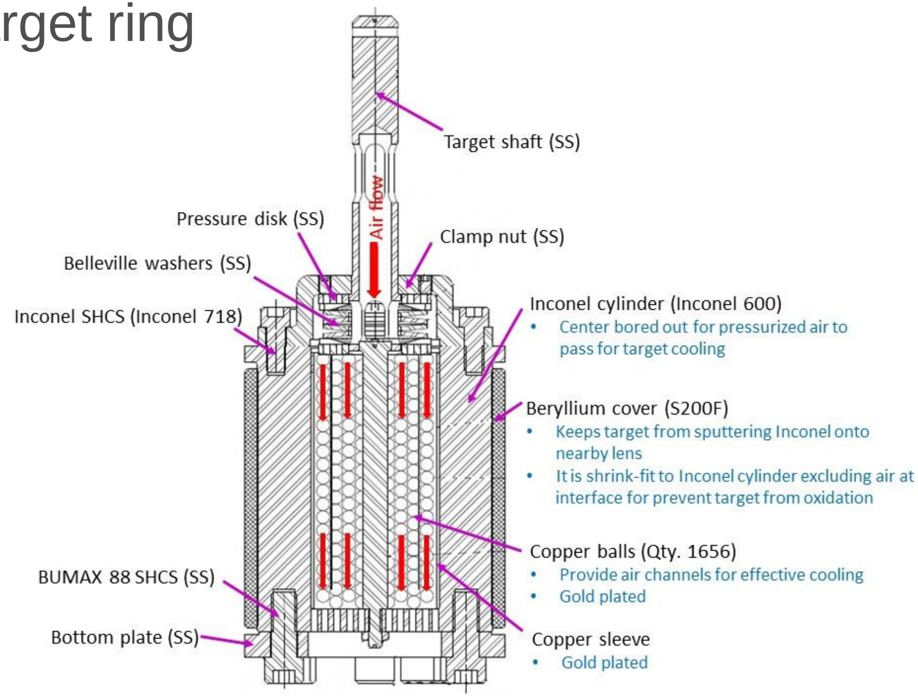


Image Source: Concepts NREC, Combined Cycle Journal, SoftInWay

Gas Cooling – AP0 Target

- Forced convection – Air
- Au-plated copper balls, Inconel target ring



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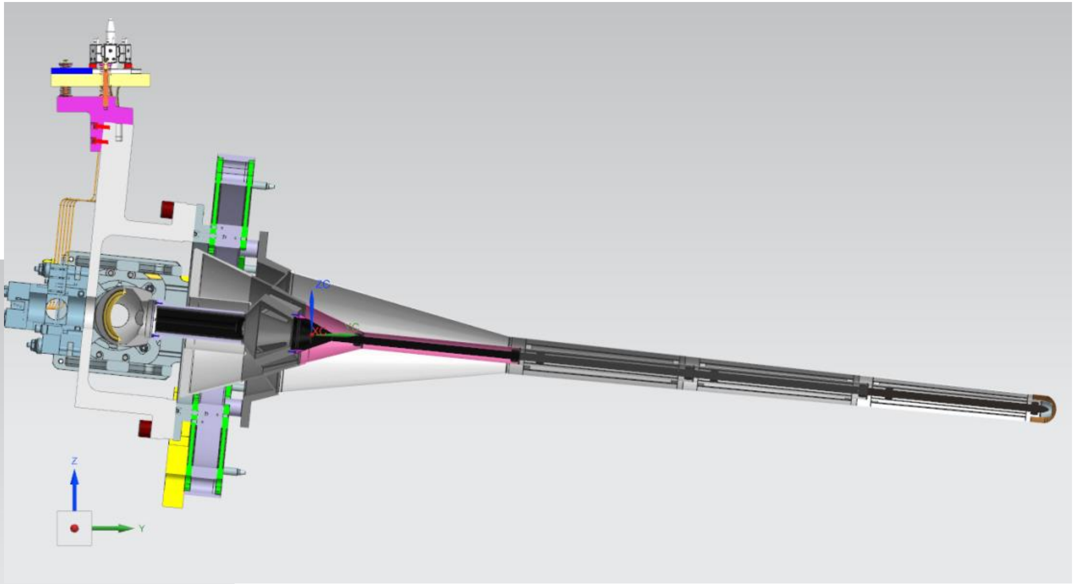
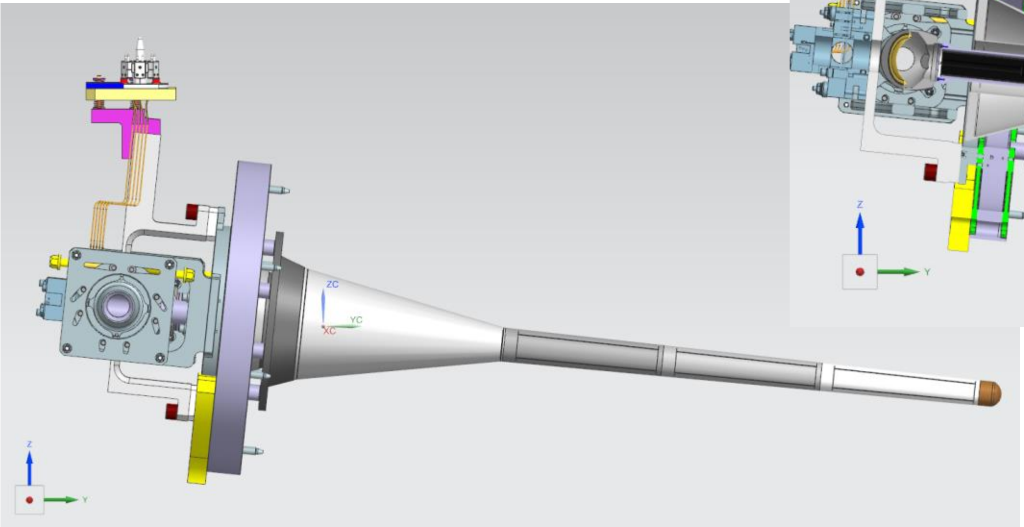
Gas Cooling – LBNF Target

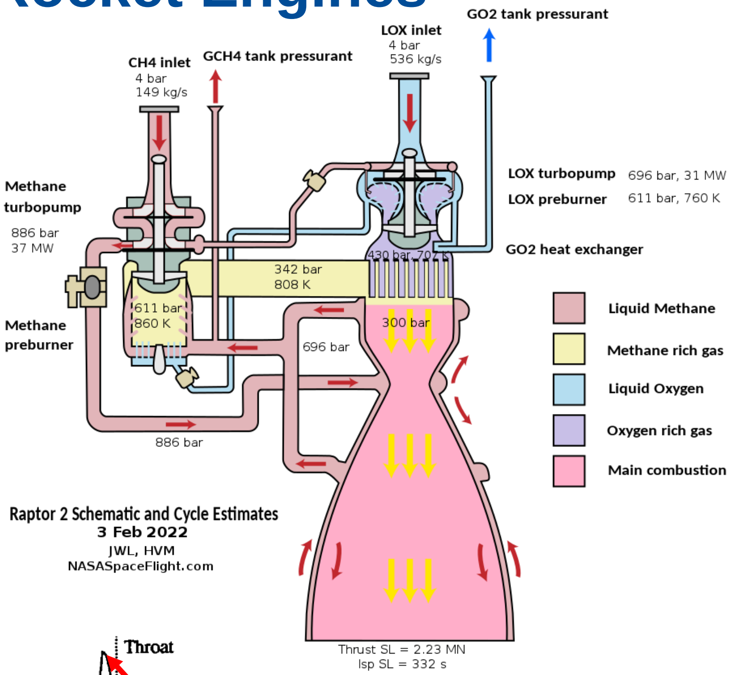
- Forced convection – Helium
- Long, thin graphite target





Liquid Cooling – Rocket Engines

- Regenerative cooling, cryogens, phase change, film cooling…
- 1-30+ MW/m^2
- Worst near nozzle throat



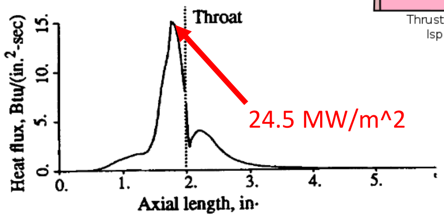


Fig. 17. Wall heat fluxes predicted for the film-cooled nozzle using the stratified core assumption.

Source: NasaSpaceflight.com, NASA, NASA-TM-106617

Aerojet Rocketdyne (L3 Harris) RL-10 Altitude Cell Hot Fire Test, Injector face inset

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Liquid Cooling - Fusion Research

- Very high power densities
- Heat extraction from a cryostat
- Large radiative fluxes
- Material compatibility, radiation resistance
- Often liquid-cooled, very space constrained

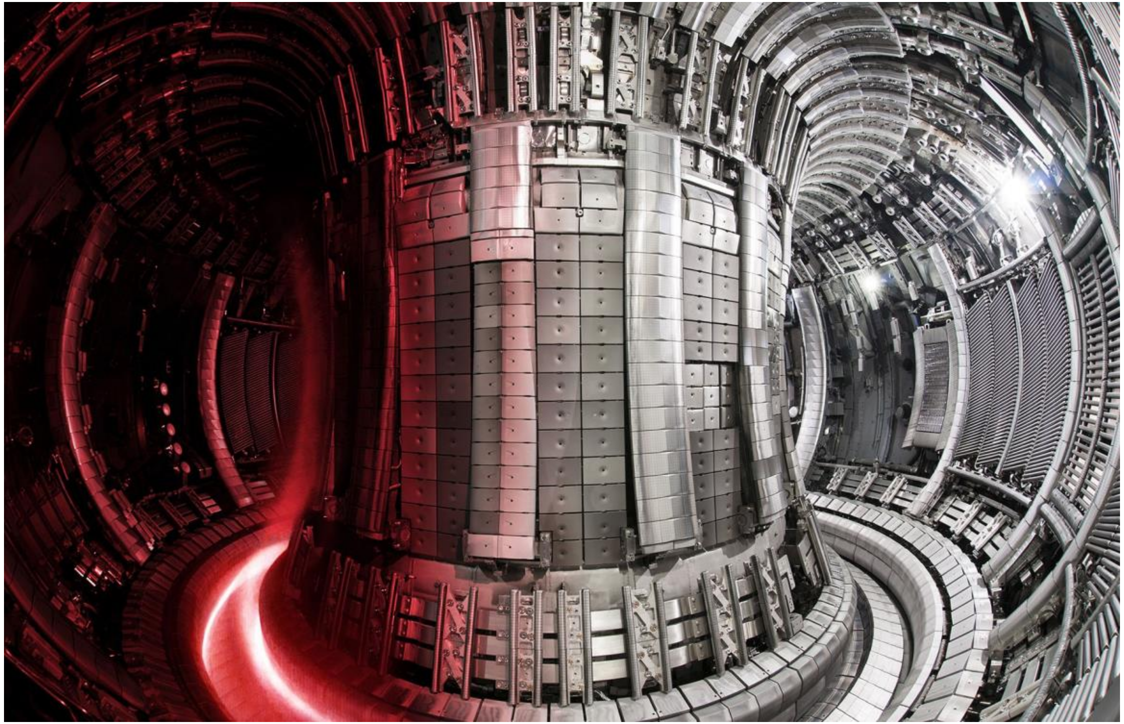

Image Source: https://www.iter.org/newsline/-/3722

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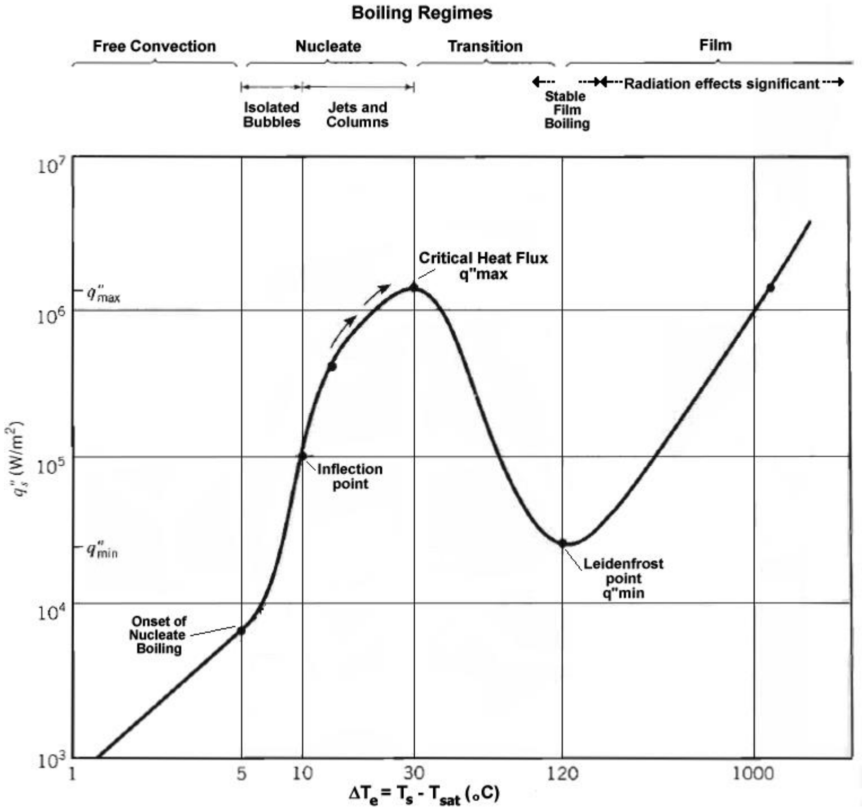
Takeaways

- Forced convection gas cooling is widely applicable
    - Heat spreaders/fin stacks can help, but run into heat transfer limits
- Space-constrained applications lean towards liquid cooling (sometimes with phase-change)
    - Very application-specific, e.g., rocket nozzles, laptop heat pipes
    - High pumping power
    - Boiling vs. risk of burnout



Boiling Curve for water at 1 atm.
Surface heat flux q" as a function of excess temperature $\Delta T_e = T_s - T_{sat}$

Image Source: Wikipedia

Hypervapotron Cooling-
History & Theory

Hypervapotron Cooling - History

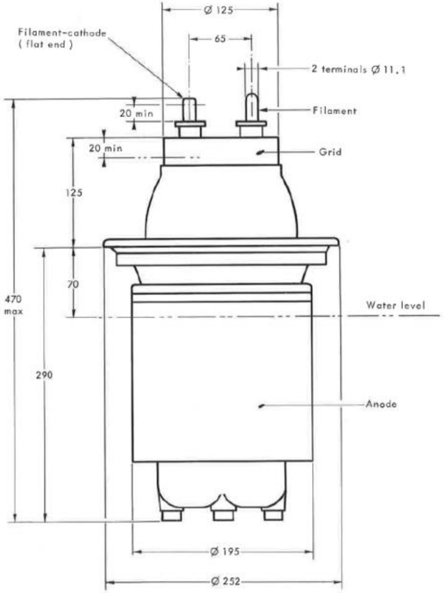
- Hyper… what?
  - Cooling technology pioneered by Thompson CSF (now part of Thales-Alenia Group) in the 1950's
  - "Vapotron effect"– steady-state, high heat flux cooling, >1MW in some triode tubes

TH480 TRIODE
VAPOTRON

The TH 480 is a transmitting vapor cooled triode used as an oscillator or AF or RF amplifier.

The anode cooler of special design (Thomson patents) can dissipate 70 kW. The corresponding energy can be transferred to a secondary circuit at a temperature of about 100 °C.

Source: Datasheet TH 480, May 1972, Thompson-CSF



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History

- SuperVapotron
  - Water flow parallel to many thin channels (into page) – little/no forced flow within channels
  - Steam fills channels, then ejects into bulk flow
  - Channels refills behind the steam jet from along the channel – pulsing operation

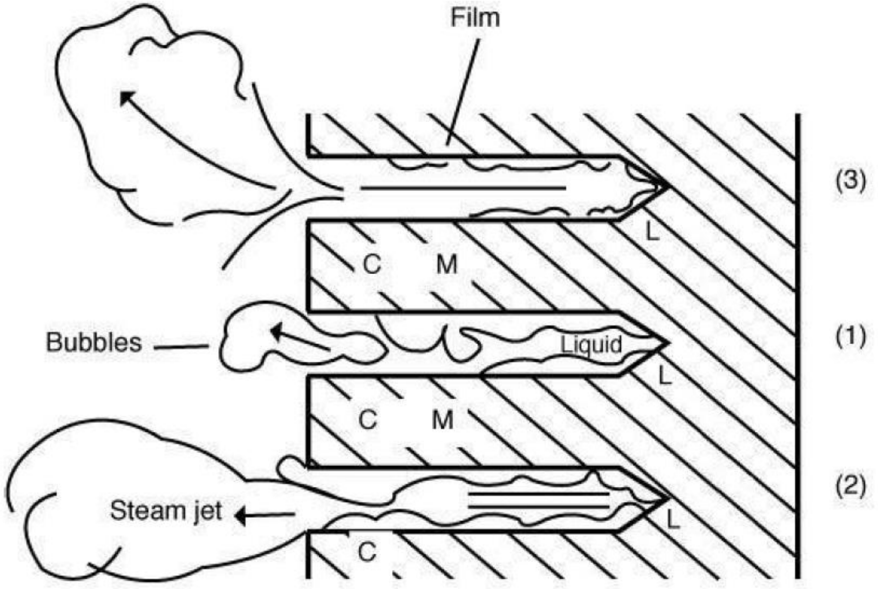


Image source: Computational Modelling of the HyperVapotron Cooling Technique for Nuclear Fusion Applications, Joseph Milnes, PH.D. Thesis, 2010, Cranfiled University, UK

History

- HyperVapotron (HVT)
  - Flow transverse to the fins
  - Induced recirculation in each groove moves in more water as it boils
  - Steam condenses in bulk channel flow
- Current designs follow this layout

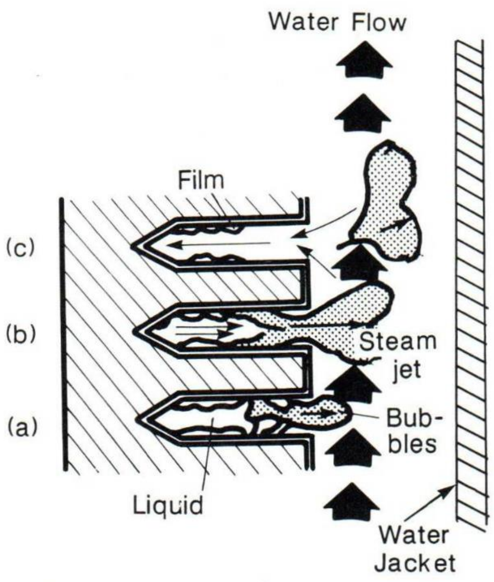
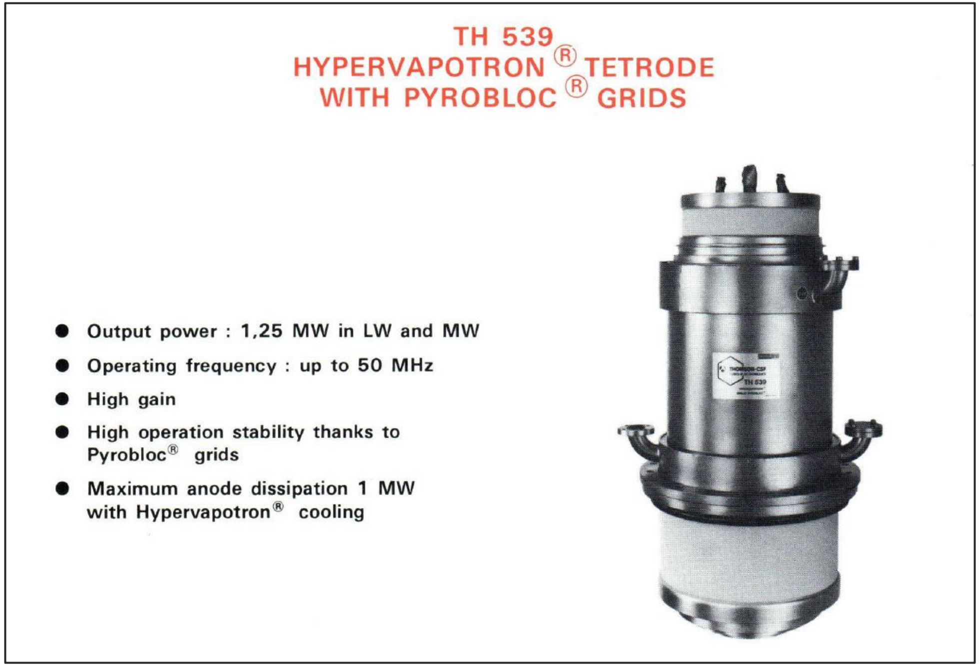


Figure 12 - Hypervapotron® anode cross-section, showing operation

Source: "Power Grid Tubes for Radio Broadcasting," Thomson-CSF Publication #DTE-115, Thomson-CSF, Dover, NJ, 1986.

Hypervapotron Cooling - History



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Performance

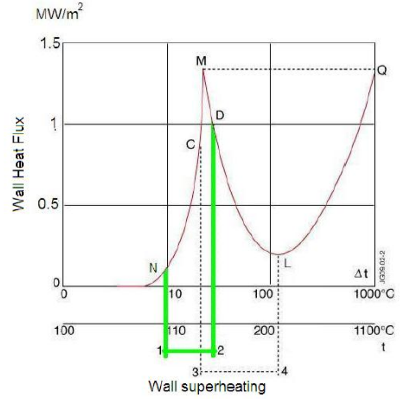
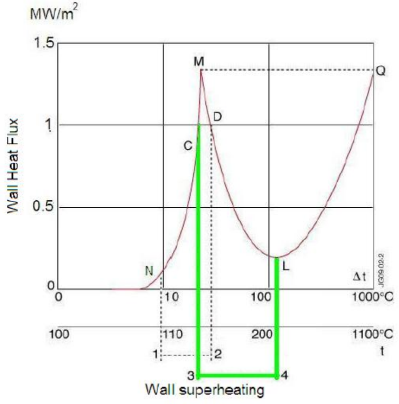
Vapotron	Super-Vapotron	Super-Vapotron with narrow slot effect	HyperVapotron
< 1.5 MW/m^2	< 3 MW/m^2	< 5 MW/m^2	< 20 MW/m^2
Means for cooling fins not specified.	Assumed forced flow parallel to fins	As for the Super-Vapotron but also benefits from steam jet ejection due to narrow slots.	Forced flow perpendicular to fins to avoid upsetting the vapour producing processes in the slots.
			

Figure 10: Vapotron to HyperVapotron, Key differences

Image source: Milnes, Computational Modeling of the Hypervapotron Cooling Technique for Nuclear Fusion Applications (Thesis, Cranfield Univ., UK)

Fins and Channels

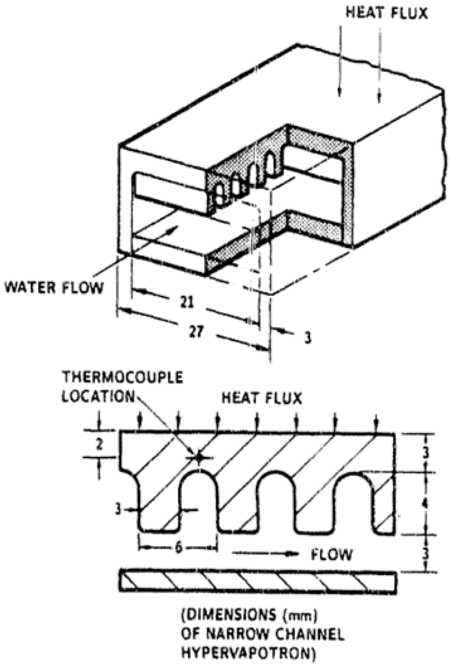


Fig. 1. Hypervapotron geometry. Dimensions are in millimeters (typical fin height = 3–6 mm, thickness = 3 mm, pitch = 6 mm).

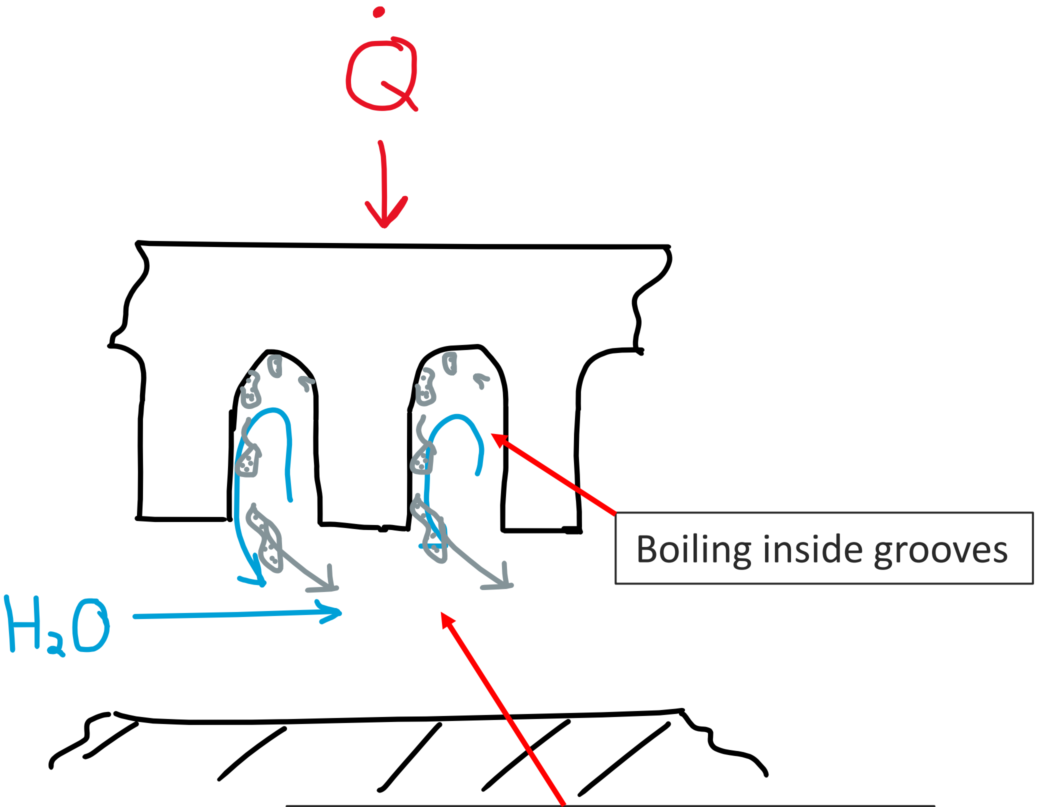


Image source: C.B. Baxi, H. Falter. "A Model for Analytical Performance Prediction of Hypervapotron," General Atomics Project 3467, 1992

Fins and Channels

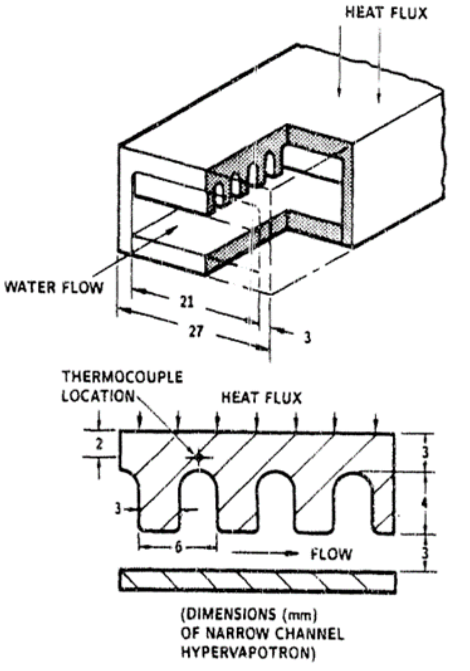


Fig. 1. Hypervapotron geometry. Dimensions are in millimeters (typical fin height = 3–6 mm, thickness = 3 mm, pitch = 6 mm).

Number	Fin shape	Configuration	Number	Fin shape	Configuration
1	Sin curve		4	Triangle to the flow direction	
2	Rectangle with fillet		5	Triangle against the flow direction	
3	Rectangle		6	Right -angle triangle	

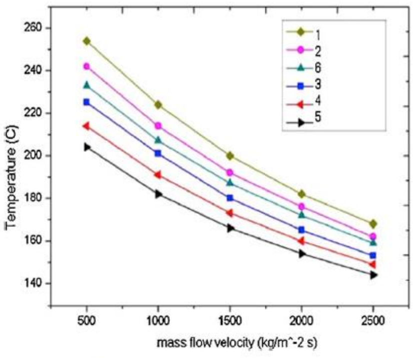


Fig. 7. Peak temperature vs. mass flow velocity.

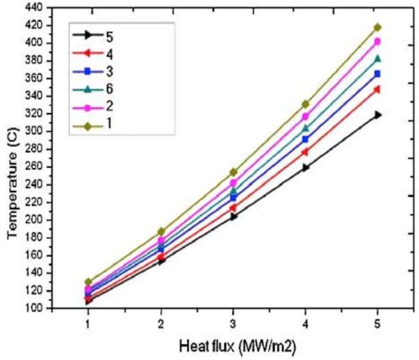


Fig. 8. Peak temperature vs. heat load.

Image source: C.B. Baxi, H. Falter. "A Model for Analytical Performance Prediction of Hypervapotron," General Atomics Project 3467, 1992

Image source: Fusion Engineering and Design 87 (2012) 868–871

Flow Behavior

- Some dispute in literature over exact steam behavior
  - May be due to different flow regimes?

> The hypervapotron technique is suitable for the removal of high heat fluxes (up to about 30 MW/m^2) wherever high values of fluid velocity and subcooling are not practical. In fact, it is typically employed at low values of liquid velocity and subcooling that in turn directly affect enhancement of the CHF in subcooled flow boiling.

- "High… fluid velocity and subcooling"
  - High pressure drop/losses
  - High pumping and refrigeration power
  - e.g., rocket engines

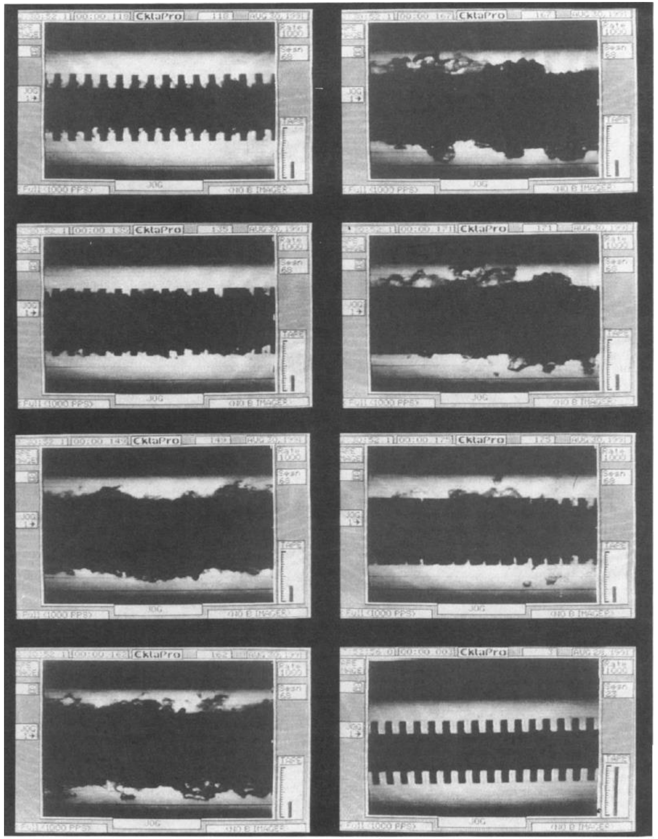


Figure 10. A typical hypervapotron effect occurrence: the sequence of boiling and condensation stages.

Source: Cattadori, G. https://doi.org/10.1016/0894-1777(93)90006-5

Heat Transfer Coefficient vs. Heat Flux

- Rating for a given HVT generally given as a heat flux in MW/m^2
- Heat transfer coefficient has less physical relevance – at least for basic layout
  - Wide range of coefficients over a single fin, plus boiling heat transfer variation
  - Bulk properties of the integrated cooler matter – thermal conductivity prevents burnout
  - Critical heat flux limits any individual point
  - From the perspective of the incoming heat flux, may be operating above the projected-flat-plate CHF

*Screenshot of a pdf of a microfiche of a conference paper… in a PowerPoint!

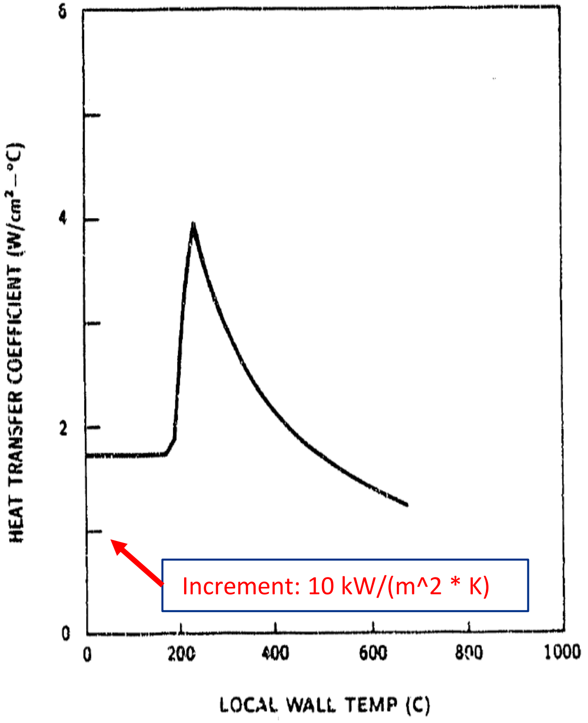


Fig. 2. Heat transfer coefficient for 6 mm channel (V = 4.0 m/s, P = 6.4 bar, TB = 37.0 C).

Image source: C.B. Baxi, H. Falter. "A Model for Analytical Performance Prediction of Hypervapotron," General Atomics Project 3467, 1992

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Thermal Conductivity

- Copper lets us cheat the system
- A part of the cooler already at CHF isn't doomed – heat can dissipate along the fin to bring more area to its respective CHF
- Conduction up the fin ultimately limits – can't add more area forever, even if it's all at CHF
  - Diminishing returns from longer fins
    - Fluid dynamics into the fin cavity
    - Decreasing temp along the fin

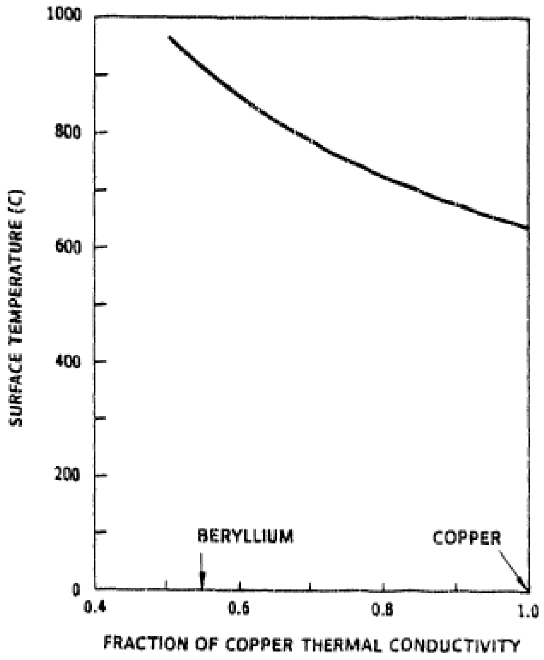


Fig. 9. Effect of thermal conductivity on surface temperature ($q'' = 25$ MW/m^2).

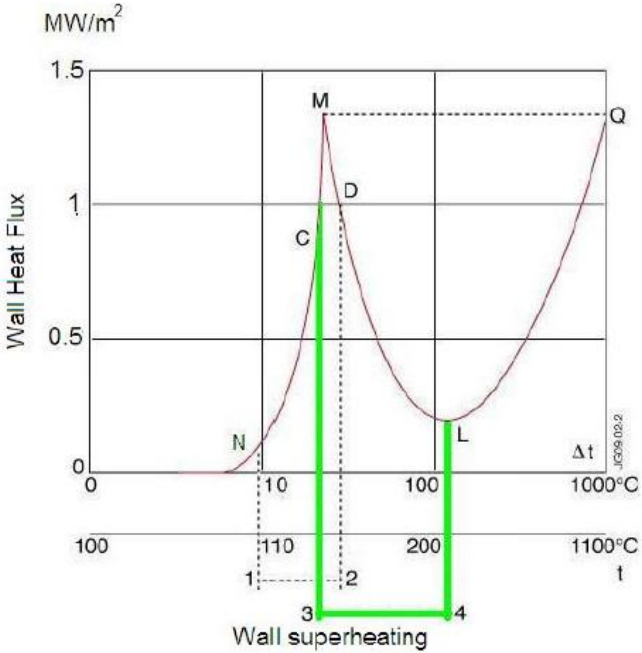
Image source: C.B. Baxi, H. Falter. "A Model for Analytical Performance Prediction of Hypervapotron," General Atomics Project 3467, 1992

Performance

- Three flow regimes
  - 1. Forced convection
  - 2. Nucleate Boiling
  - 3. Critical heat flux (over increasingly large parts of surface)

$$\dot{Q} = hA(T_2 - T_1)$$

$$h = \frac{q}{\Delta T}$$



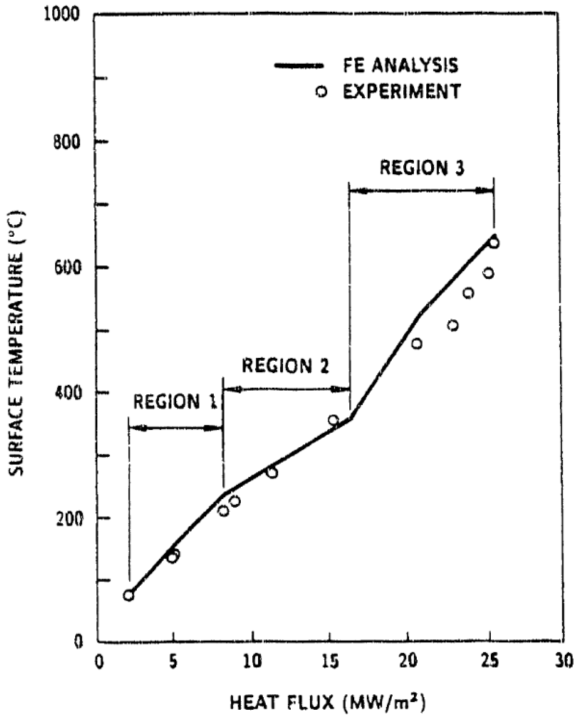


Fig. 4. Comparison of analysis and experiment for narrow channel vapotron, V = 11.5 m/s, P = 5.7 bar (inlet coolant temperature = 20° C).

Image sources: Milnes (thesis), &
C.B. Baxi, H. Falter. "A Model for Analytical Performance Prediction of Hypervapotron," General Atomics Project 3467, 1992

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Regime 1: Forced Convection

- Flowing water, recirculation in channels
- Nothing too special
- I = 73 C
- F = 63 C
- A = 46 C

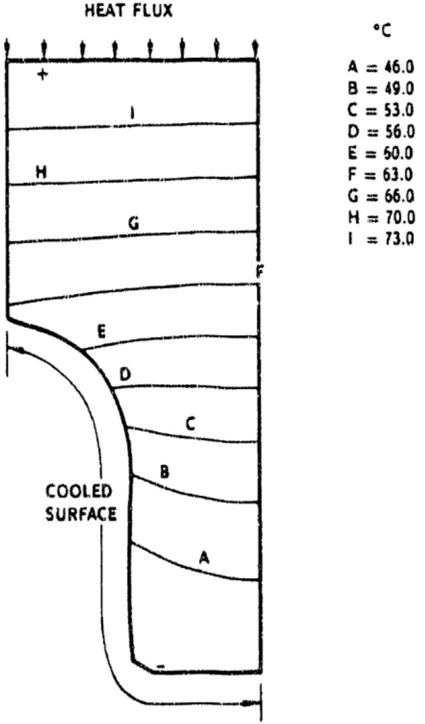

Fig. 6. Isotherms for forced convection regime (heat flux = 2 MW/m^2).

Image source: C.B. Baxi, H. Falter. "A Model for Analytical Performance Prediction of Hypervapotron," General Atomics Project 3467, 1992

Regime 2: Nucleate Boiling

- Water starts boiling
- Wall is starting to superheat significantly
- I = 240 C
- F = 200 C
- A = 130 C

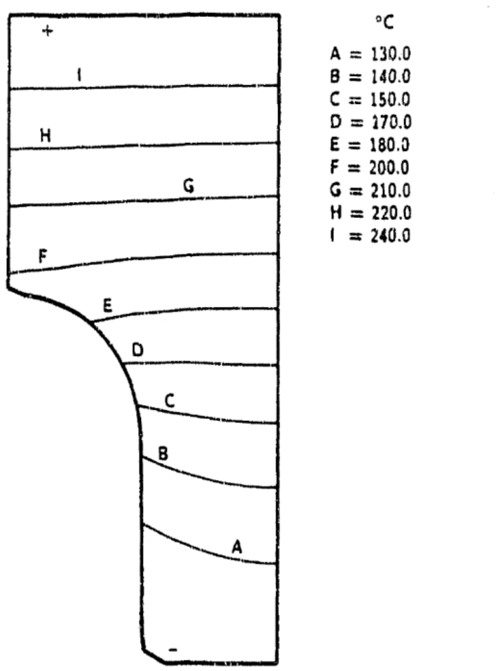

Fig. 7. Nucleate boiling regime (heat flux = 8 MW/m²).

Image source: C.B. Baxi, H. Falter. "A Model for Analytical Performance Prediction of Hypervapotron," General Atomics Project 3467, 1992

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Regime 3: Critical Heat Flux

- Aggressive boiling, stabilized by recirculating flow and/or steam ejection
- I = 620 C
- F = 500 C
- A = 290 C

The term HyperVapotron therefore has a fairly strict definition. Specifically, it is a water cooled device with internal fins orientated perpendicular to the flow with a fin temperature profile bounded by the Leidenfrost temperature at the root and allowed to exceed incipient boiling temperature at the fin tip. For the purposes of this study,

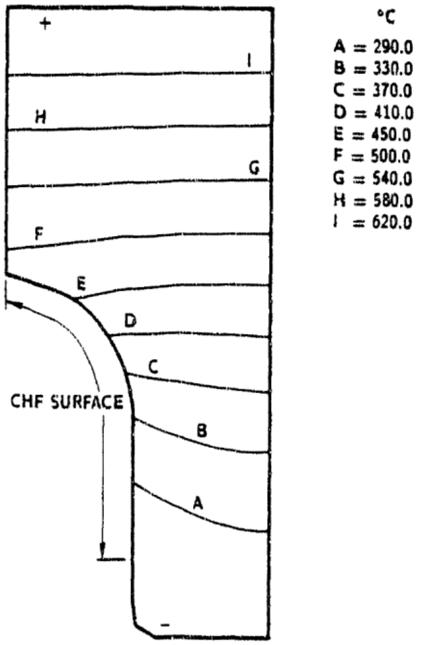


Fig. 8. Critical heat flux on large part of the heat transfer surface (heat flux = 25 MW/m^2).

Sources: Milnes (thesis). & C.B. Baxi, H. Falter. “A Model for Analytical Performance Prediction of Hypervapotron,” General Atomics Project 3467, 1992

HVTs in Fusion

Current Designs

- Fusion and high-heat flux applications
    - JET divertor
    - JET neutral beam injector –beam dumps, scrapers, and calorimeters
        - (3 m/s flow, 15 MW/m^2 rating, 10MW/m^2 design point, see image)
    - ITER High Heat Flux first wall panels
    - ITER divertor targets (considered, using swirl tubes)

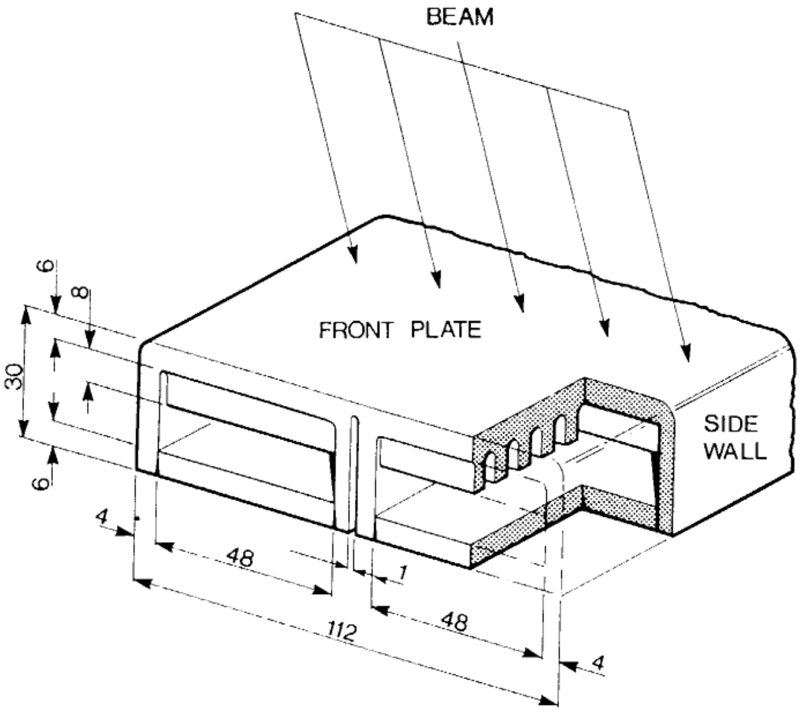
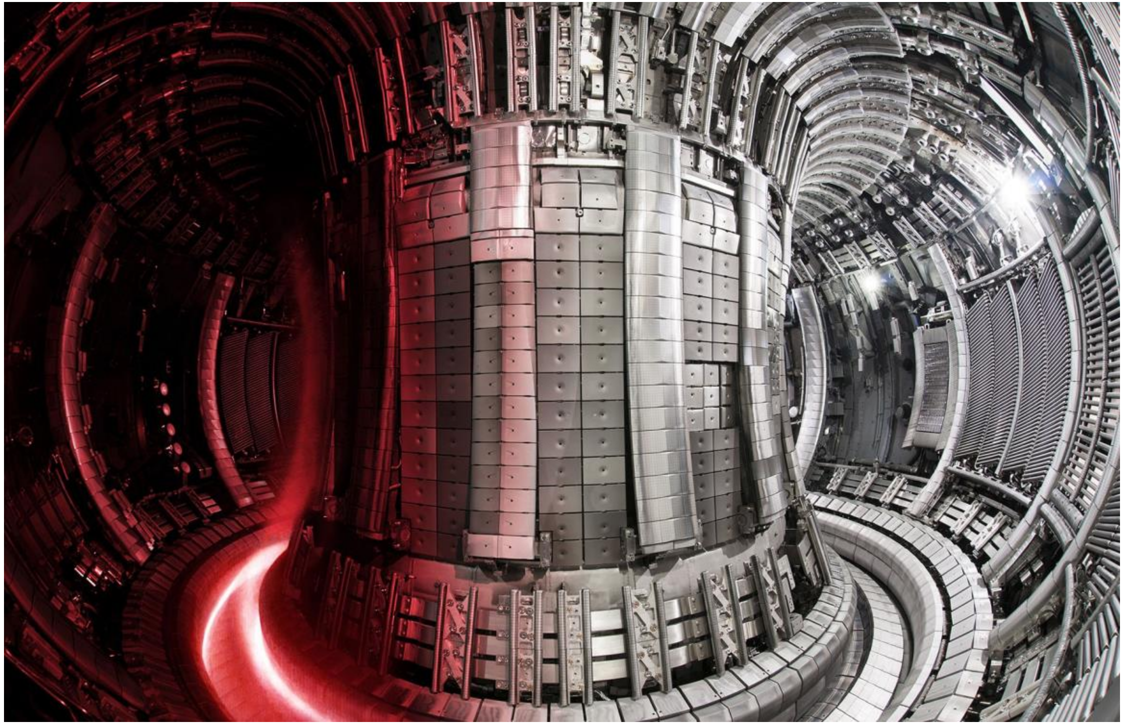


Fig.1: Dimensions of the standard JET flat Hypervapotron.

Image source: Falter & Thompson, "Performance of Hypervapotron Beam Stopping Elements at JET", Report # JET-P(95)13.

Joint European Torus (JET) Divertor



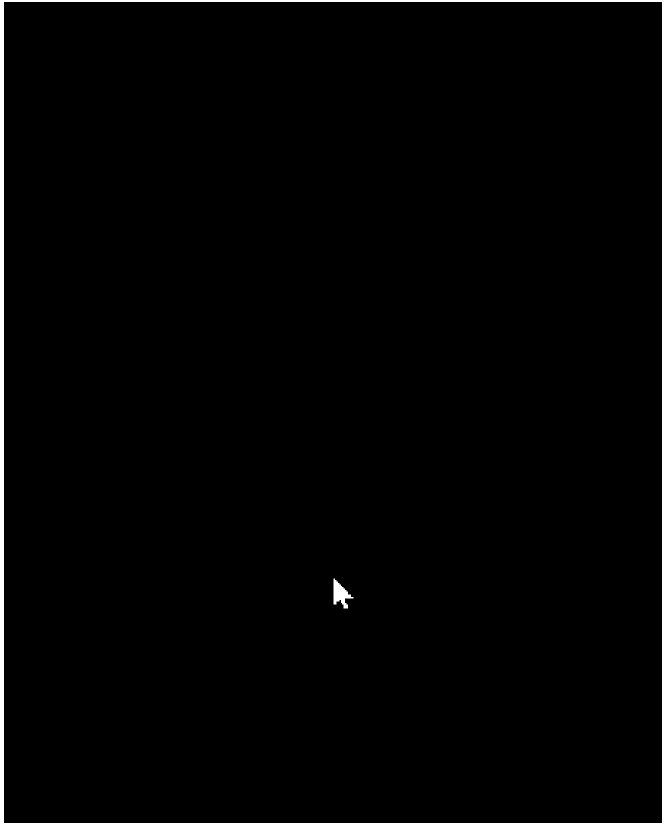


Image Source: https://www.iter.org/newsline/-/3722

JET Neutral Beam Injector

- Inject neutral particles (D_0) – plasma heating and online refueling
- HVTs in dumps, calorimeter, and scrapers
- 34 MW total beam power
- 130 kV – 8 injectors, up to 60A each (on upgraded injectors)

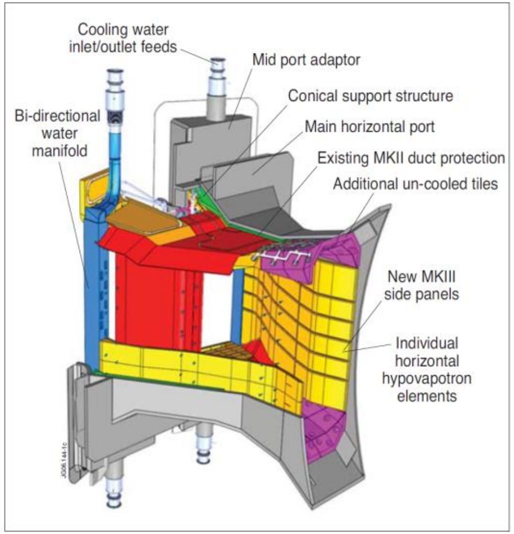


Figure 3: Section through MHP showing internal duct protection orientation

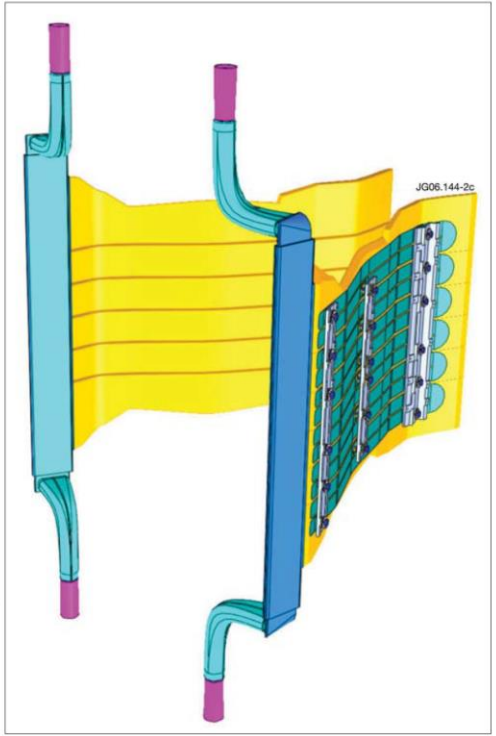
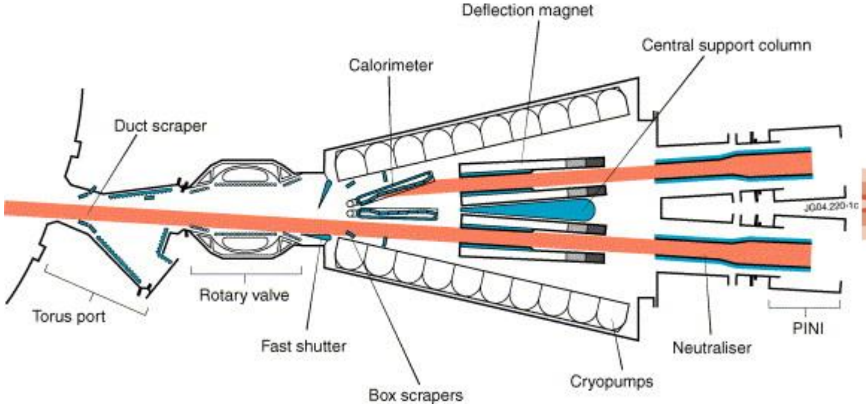


Figure 4: Scheme Design of the new MkIII actively cooled Duct Scraper left and right hand side panels

Image source: Fusion Eng. Des. 82 (2007) 845–852.

JET Neutral Beam Injector



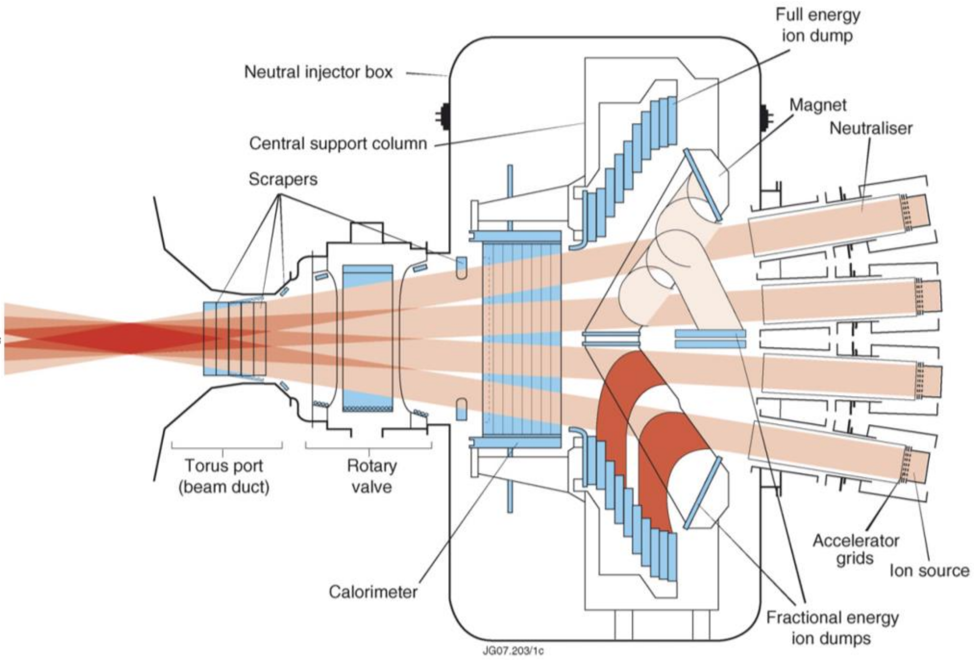


Fig. 1. Elevation view of the JET neutral injector box.

Image source: https://doi.org/10.1016/j.fusengdes.2005.06.348

Image source: Fusion Engineering and Design 82 (2007) 610–618

ITER Blanket/First Wall

- 440 blanket modules - ~610 m^2
  - Approx. 1 m x 1.5 m each
  - Cooling water supply, 4 MPa @ 70C
  - 776 MW total thermal rejection
- 215 “normal heat flux” panels (cooling pipes) @ 2 MW/m^2
- 225 “enhanced heat flux” panels (HVTs) @ 4.7 MW/m^2

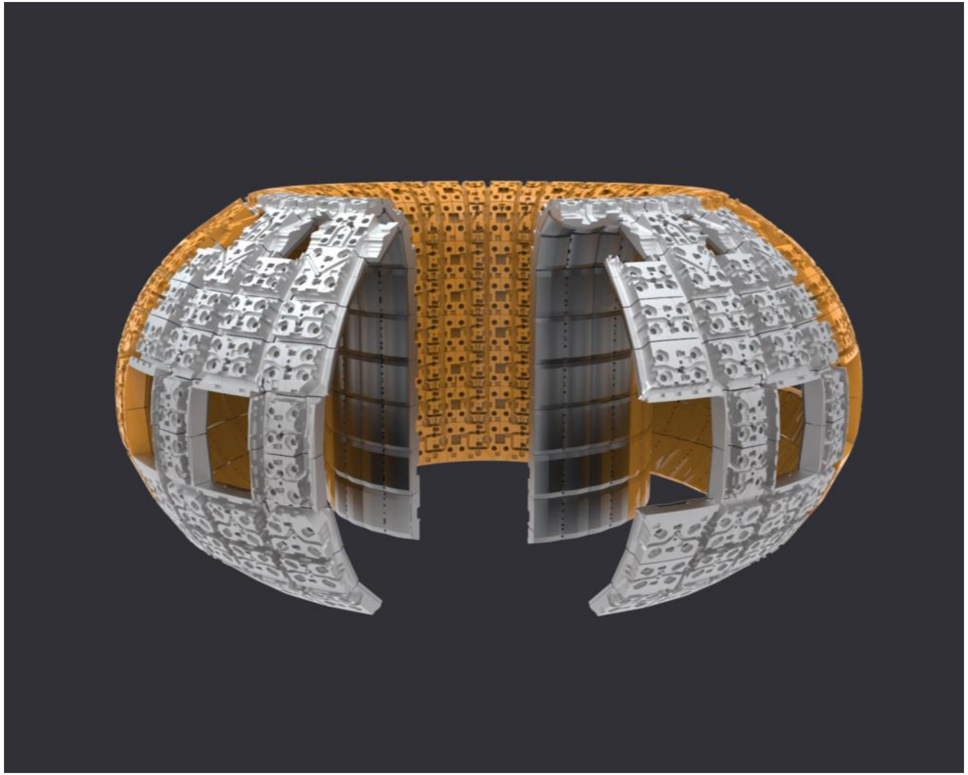
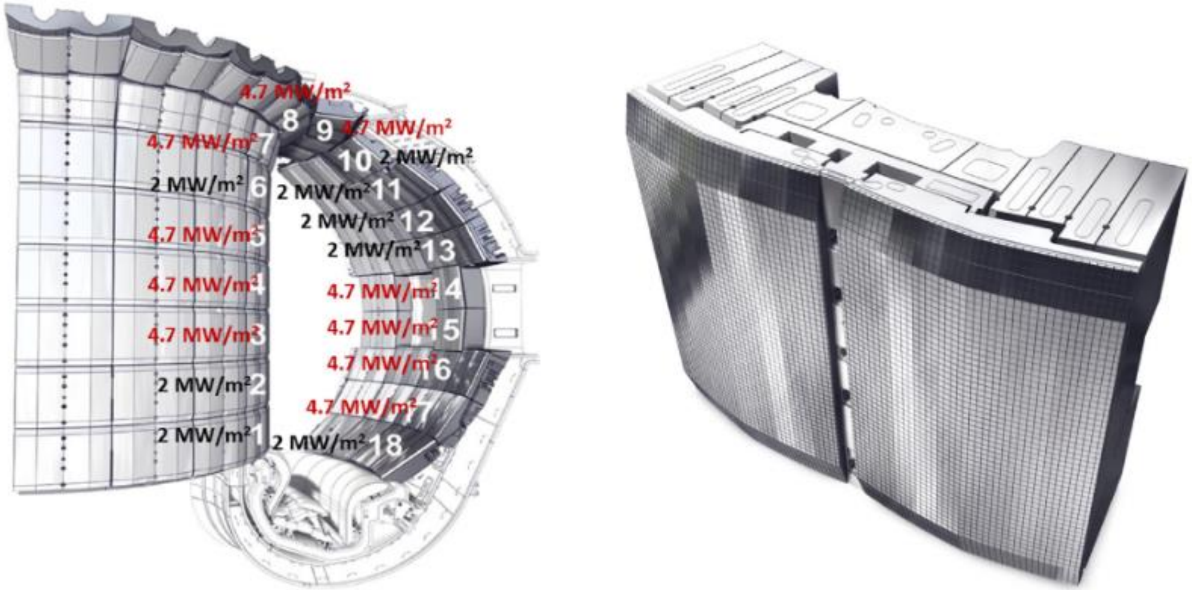


Image source: https://www.iter.org/mach/Blanket

ITER Blanket/First Wall



(a) Portion of the ITER first wall with the FWP poloidal row reference numbers used in the text and heat flux design limits [20]

(b) ITER inner wall FWP (poloidal row 4) mounted on its shield block[21].

Fig. 2. (a) Portion of the ITER first wall with the FWP poloidal row reference numbers used in the text and heat flux design limits [20]. (b) ITER inner wall FWP (poloidal row 4) mounted on its shield block [21].

Image source: Fusion Engineering and Design 137 (2018) 143–151

ITER Blanket/First Wall

- Stainless steel support structure, CuCrZr heat sink, Be (or W) tiles
- Multiple HVT "fingers"
- Braze, expl. bond, HIP, laser welds…

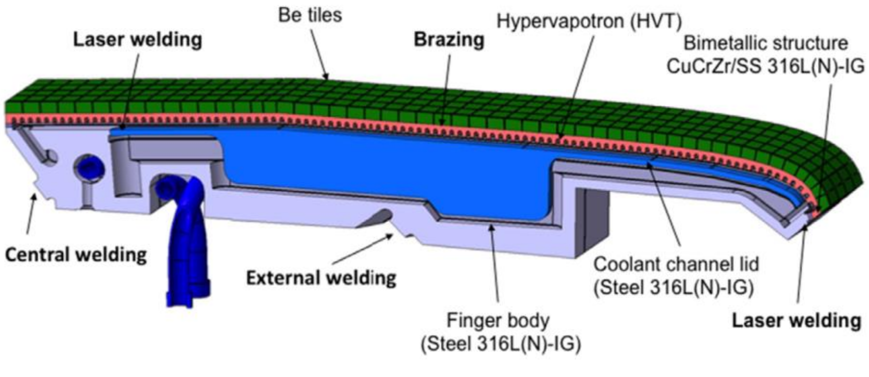


Figure 10. Details of EHF FW 14 showing the hypervapotron configuration in the finger.

Image source: A.R. Raffray et al 2014 Nucl. Fusion 54 033004

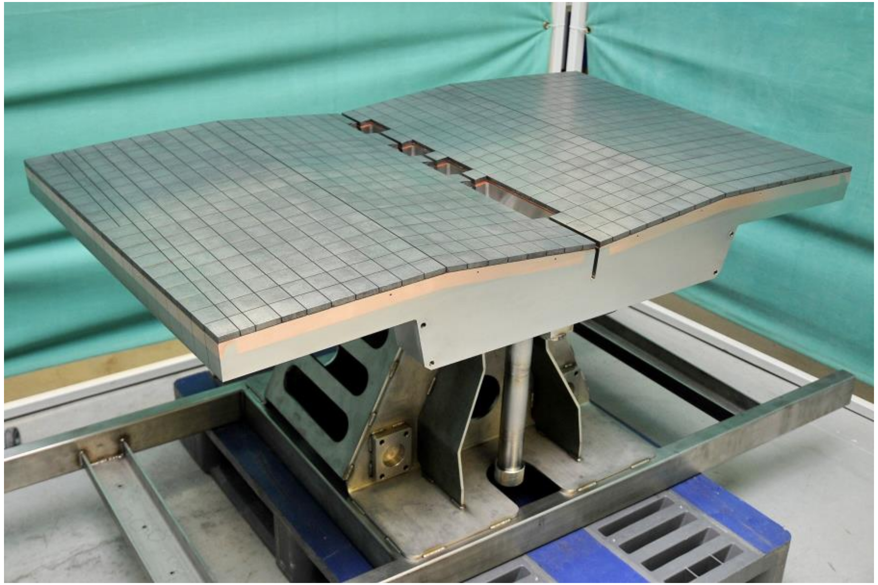


Image source: https://www.iter.org/newsline/-/3568 "Blanket first wall - Manufacturing kicks off in Europe

Downsides?

ITER Divertor – Why Not a Hypervapotron?

- Reference design is tungsten monoblocks with swirl tubes
- HVTs were strongly considered
    - Difficult to guarantee bond to some materials (e.g., carbon fiber composites)
    - Higher mass flow and pressure drop per unit heat flux rejected – would need redesign of pumping system

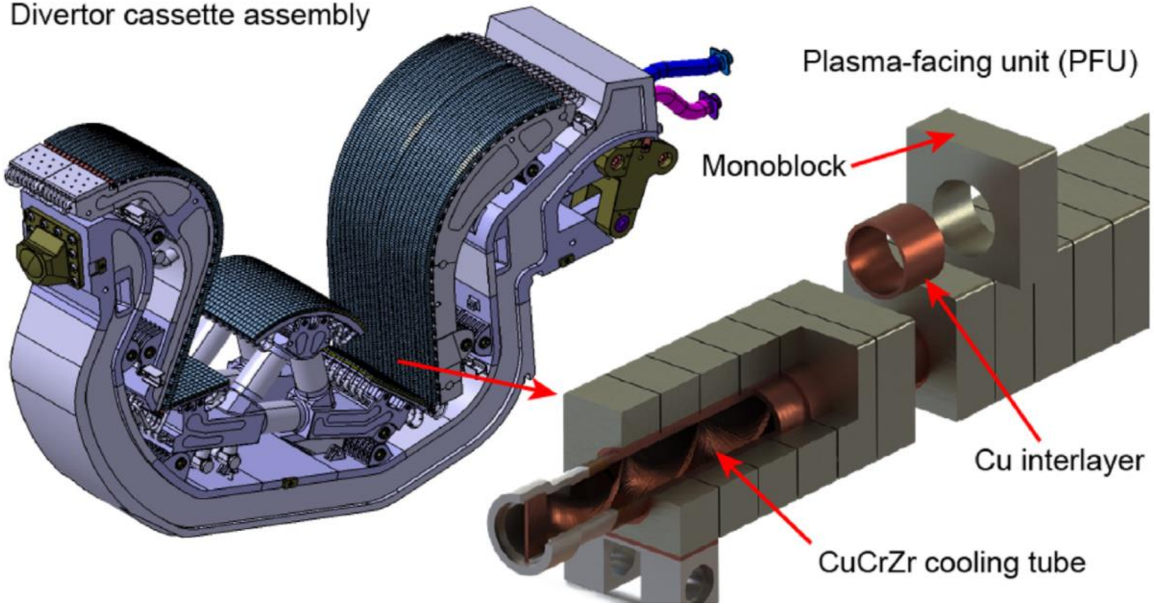
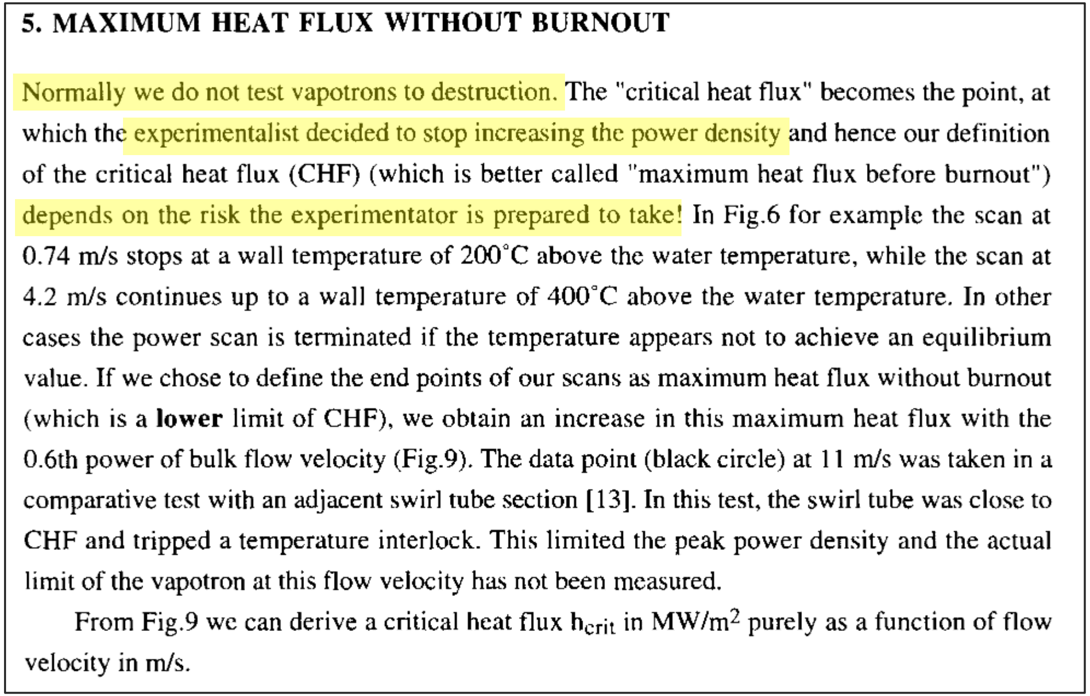


Image source: R.A. Pitts et al. / Nuclear Materials and Energy 12 (2017) 60–74

Failure Modes

- Direct burnout
  - Rather difficult…
- Delamination of components
  - Weld/braze failure
  - Material compatibility, fatigue
- JET: 300 HVTs installed in 1984 lasted over 10 years with zero failures
  - Total: 100 MW of heat rejection



5. MAXIMUM HEAT FLUX WITHOUT BURNOUT

Normally we do not test vapotrons to destruction. The "critical heat flux" becomes the point, at which the experimentalist decided to stop increasing the power density and hence our definition of the critical heat flux (CHF) (which is better called "maximum heat flux before burnout") depends on the risk the experimentator is prepared to take! In Fig.6 for example the scan at 0.74 m/s stops at a wall temperature of 200˚C above the water temperature, while the scan at 4.2 m/s continues up to a wall temperature of 400˚C above the water temperature. In other cases the power scan is terminated if the temperature appears not to achieve an equilibrium value. If we chose to define the end points of our scans as maximum heat flux without burnout (which is a **lower** limit of CHF), we obtain an increase in this maximum heat flux with the 0.6th power of bulk flow velocity (Fig.9). The data point (black circle) at 11 m/s was taken in a comparative test with an adjacent swirl tube section [13]. In this test, the swirl tube was close to CHF and tripped a temperature interlock. This limited the peak power density and the actual limit of the vapotron at this flow velocity has not been measured.

From Fig.9 we can derive a critical heat flux h_{crit} in MW/m^2 purely as a function of flow velocity in m/s.

Source: Falter & Thompson, "Performance of Hypervapotron Beam Stopping Elements at JET", Report # JET-P(95)13.

Failure Modes

- When they do burn out, fail at center
  - Edges are more robust
  - Conduction up sides
  - More thermal capacity/inertia et edge
- Limits on width of channel, ~75 mm
  - Pressure stress, flow effects, manufacturability

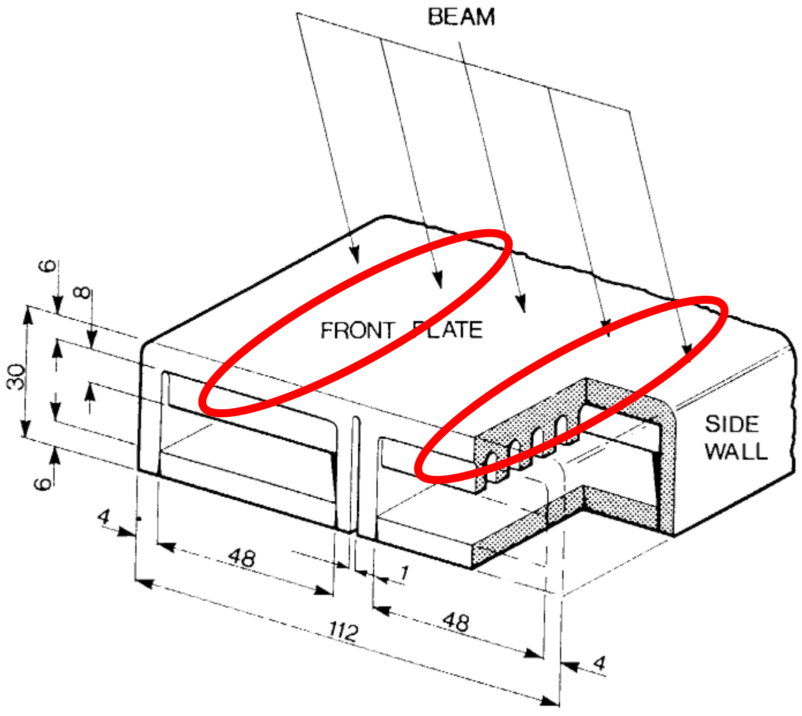


Fig.1: Dimensions of the standard JET flat Hypervapotron.

Source: Falter & Thompson, “Performance of Hypervapotron Beam Stopping Elements at JET”, Report # JET-P(95)13.

Other Considerations

- Accelerator beams are thin – mm scale, even thinner
  - Rotating targets can distribute heat
- NBIs make fairly wide beams – 10+ cm @ keV-scale energy (ITER NBI = 1 MeV)
  - Energy is already distributed spatially
  - Angled coolers further reduce heat flux
- 6.1 MW dump for ITER NBI testbed →
  - Not a monolithic unit – individual HVT strips mounted together

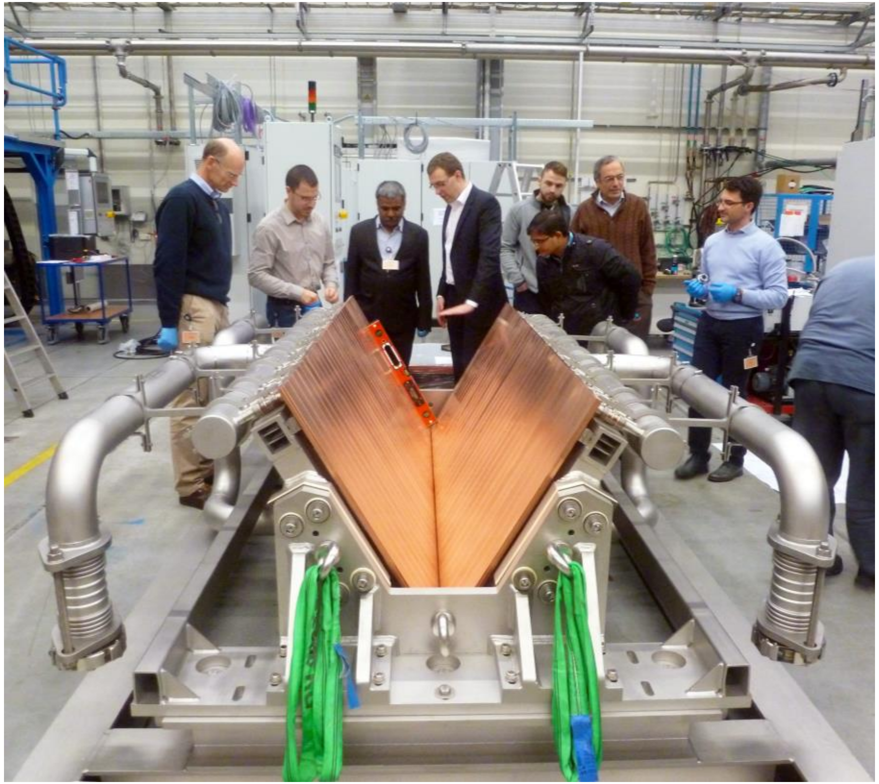


Image source: https://www.iter.org/newsline/-/2097

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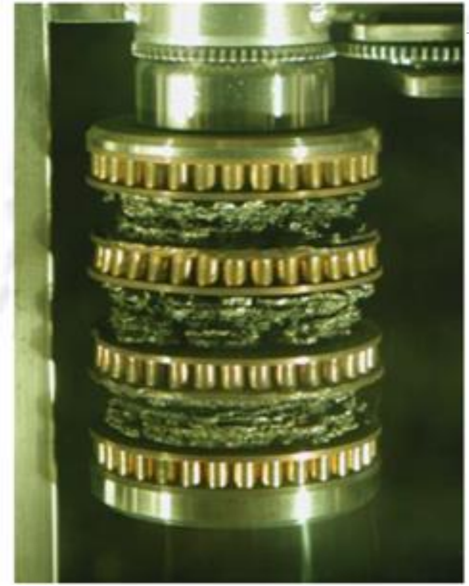
Radiation Damage

- HVTs don't solve radiation damage – thermals only!
  - Indirectly, could run at higher temp and anneal out flaws
  - CuCrZr , Glidcop, OFHC copper
- High beam power, not much target material => limited life
  - Rotating targets provide more material
- HVT grooves could be warped by radiation damage
  - Reduced effectiveness?



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Tradeoffs

The Good

-HVTs give better performance for same thickness

-Tunable – channel depth, fin profiles, water pressure and flow

-Good for wrapping curved surfaces

-Can bond target materials to hot side surface

Main advantage is compactness combined with stable high performance

The Bad

-Swirl tubes outperform for a given pumping power (less pressure drop)

-Conceptually simple but complex manufacturing – tolerance sensitive grooves, closeout

-Computationally difficult– phase-change

-Outer material bond can be fatigue-limiting, if not unreliable

Main disadvantage is opaque operation – plenty of correlations, but usually bespoke design for application

The Ugly: Copper-SS bond reliability

Target Packaging Concepts

HVT Packaging – Static HVT

- Bond a strip of target material to HVT hot side (or use the cooler itself)
- Cylindrical option (flow visualization from earlier) →
- High heat deposition is a big problem for targets…
- HVts a re a compact option to handle higher heat loads

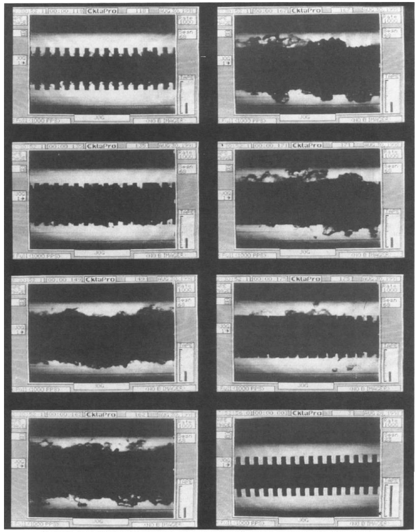
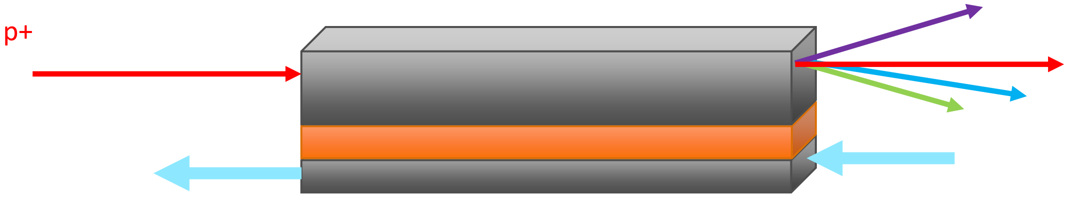


Figure 10. A typical hypervapotron effect occurrence: the sequence of boiling and condensation stages.



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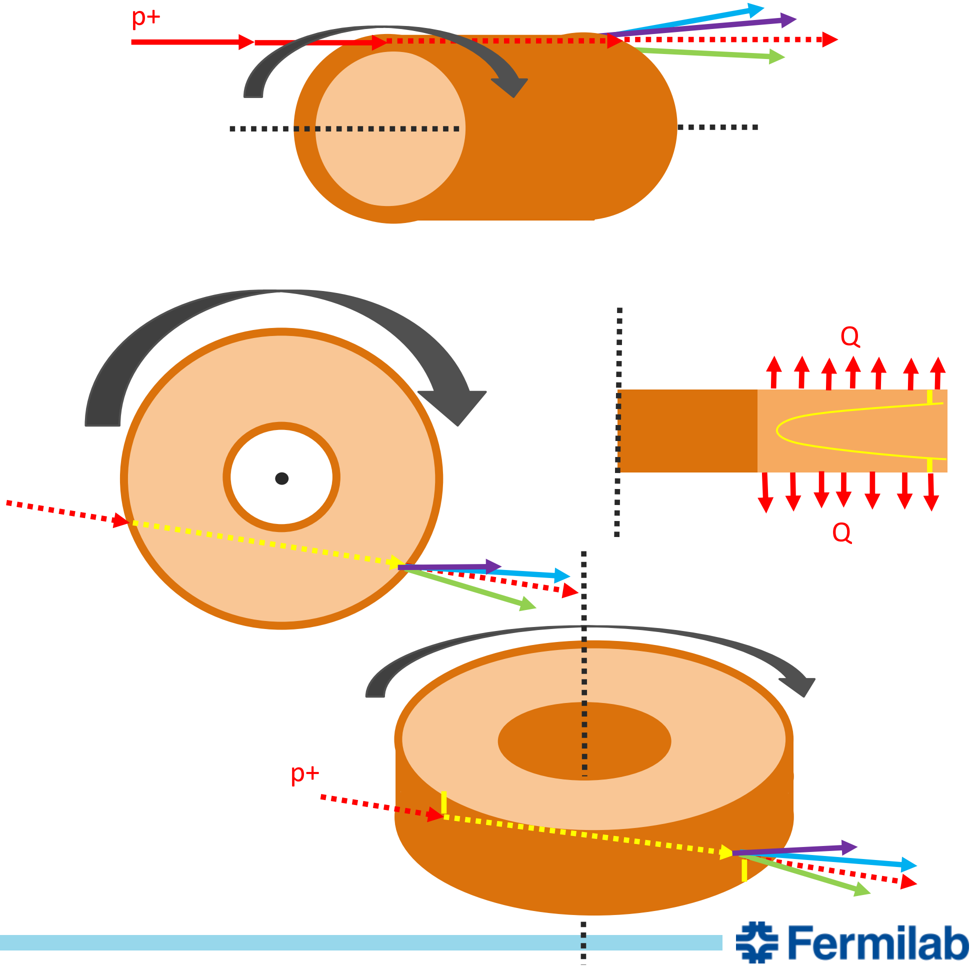
Beam/HVT Orientation

- Static HVTs could surround a volume of target material, or cool a block from one or more sides
- For rotating targets, beam can approach from parallel or perpendicular to rotation axis – and angles between
- Cylindrical shell
- End-cooled "puck"
    - Through-flow ring target, similar to AP-0 Inconel ring
- Angled ring



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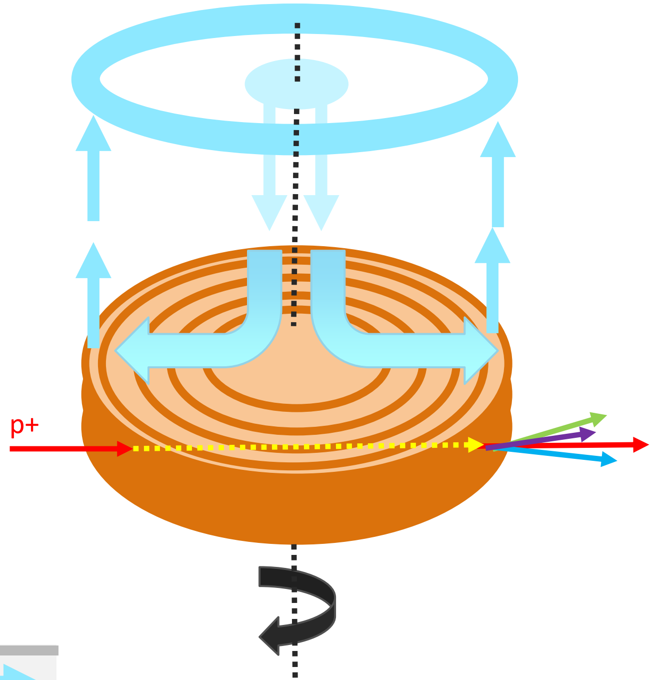
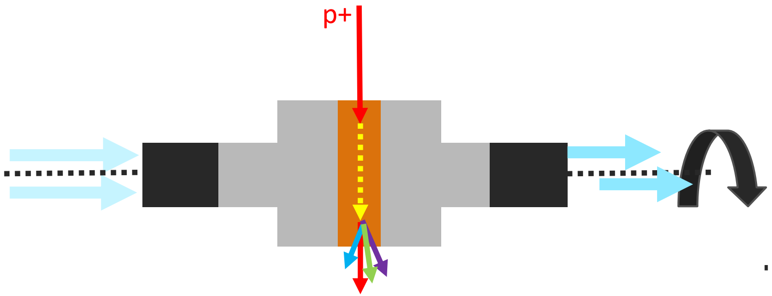
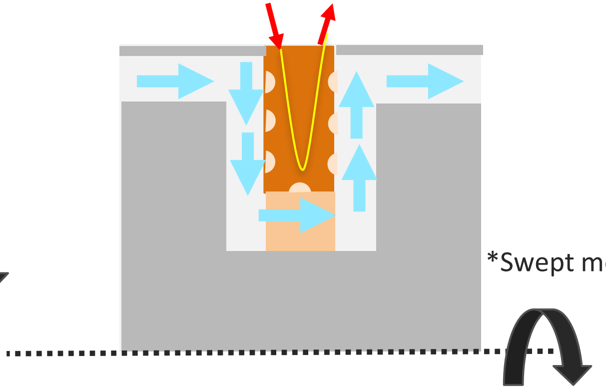
HVT Packaging – AP0-like

- Rotation axis perpendicular to beam – AP0-like puck
  - Coolant flow radially inward/outward from rotation axis
  - Radial-flow HVT has no prior art – possible flow issues
- Through-flow ring
  - Inlet on one side, outlet on other, target ring in center



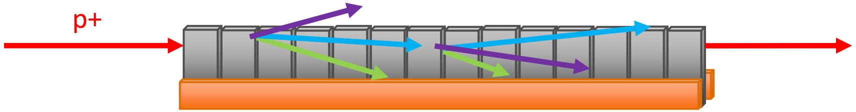




*Swept meridional view of beam

HVT Packaging – Neutrinos?

- LBNF layout (long target surrounded by coolant) does not suit HVTs well
  - Lots of material to interact with secondaries – less yield
  - Cylindrical HVTs have been tested…
- NuMI fins might be a better fit?
  - "Cold rail" with HVTs on the sides/bottom
  - ITER divertor tests - fatigue issues bonding carbon fiber composites to HVT copper alloy – graphite may have issues
  - Conduction down the fin would probably limit
    - Graphite sandwich – HVT on 2 sides? Can beam power be increased enough to compensate for reduced yield?



Issues to Consider

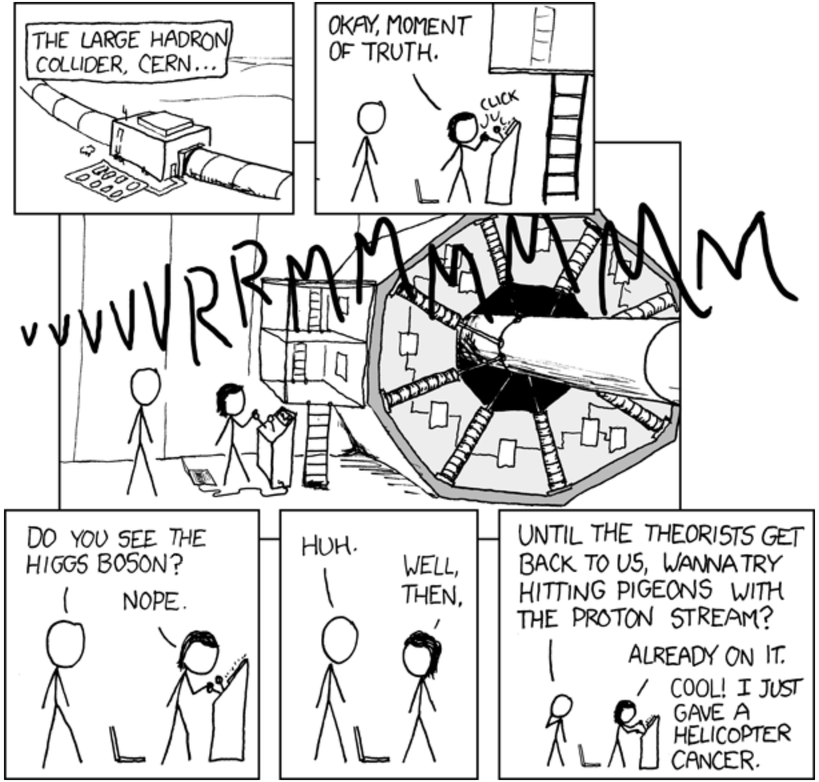
- Tritium mitigation in real systems – water close to beam
- Seals in rotating flow joints – few options without O-rings (radiation concerns)
  - Mechanical seals – industry has solutions (dry gas seals)
  - Labyrinth seals – costly and delicate, controlled leakage
- Radial-flow HVTs unproven
  - CFD
- Best for shorter targets – perhaps not ideal for neutrinos

Applications

- "Normal" Applications:
- Targets – muon & positron sources?
- Beam dumps (esp. high current, low* energy)
- Other targets?

- "Mad Science" Applications:
- μ-CF production targets?
- Bulk antimatter targets?
  - "Antiproton Annihilation Propulsion", R. L. Forward, 1985, report for AFRPL; https://apps.dtic.mil/sti/tr/pdf/ADA160734.pdf

Questions?



If XKCD was in charge of LBNF…

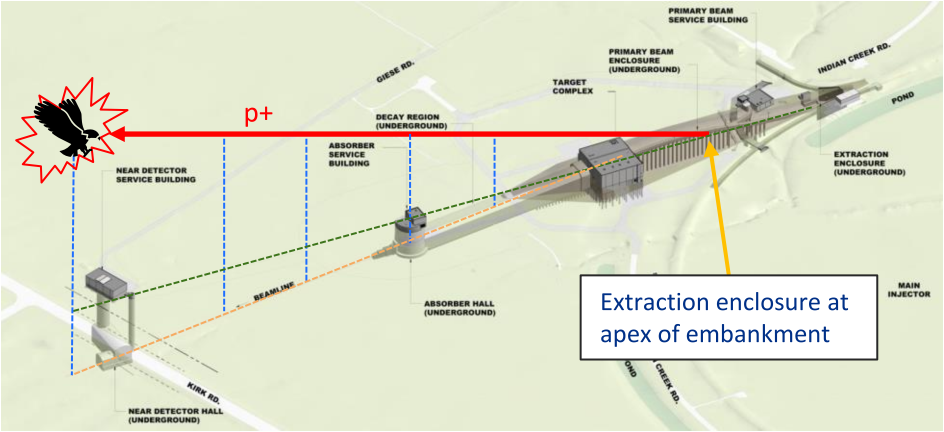
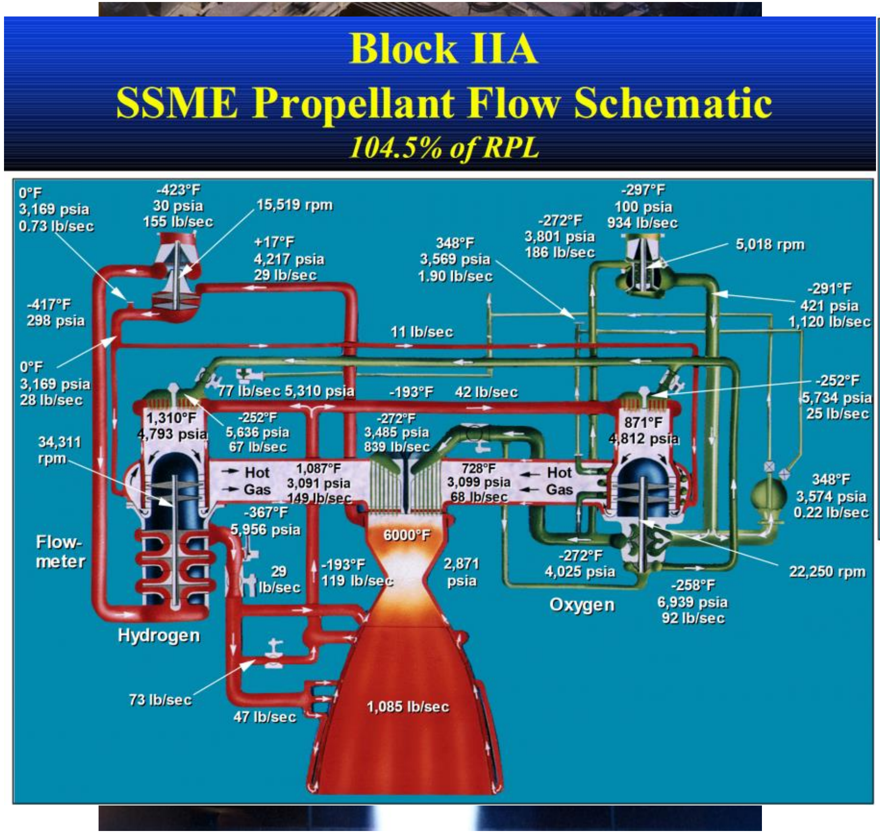
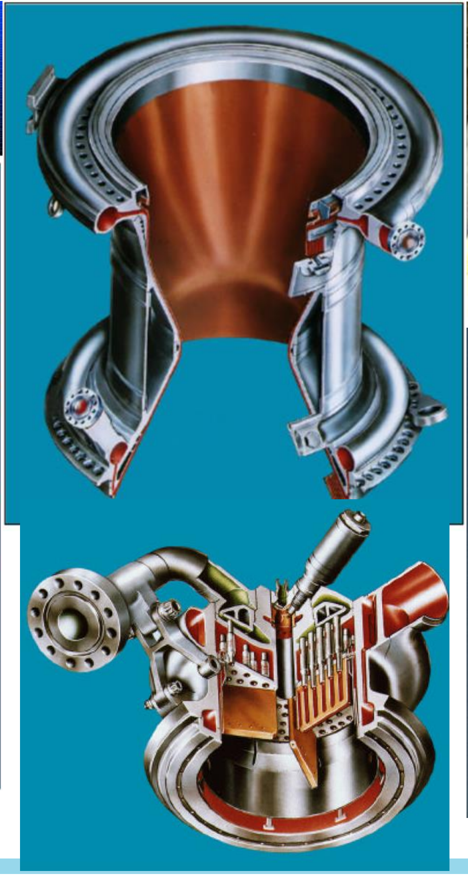


Image sources: https://xkcd.com/401/ , https://lbnf-dune.fnal.gov/how-it-works/excavations-and-structures/

Backup

Liquid Cooling – Rocket Engines





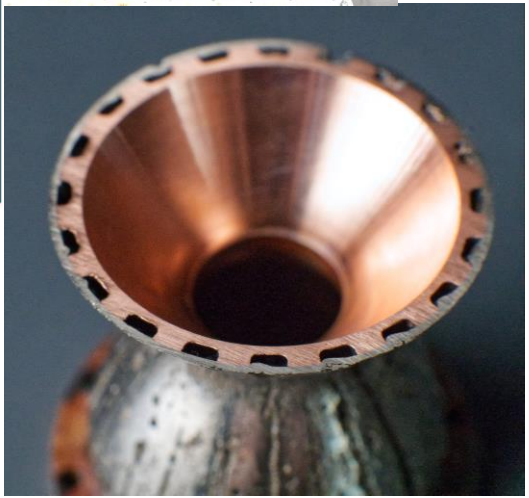


Image Source: NASA, Boeing, Breaking Taps

Fermilab

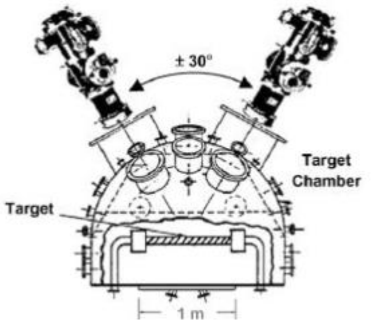
Liquid Cooling – Rocket Engines

Image Source: Boston University Rocket Propulsion Group, SpaceX

High Heat Flux Testing

- Electron beam heating
  - High demand, limited test space/availability
- Induction heating - volumetric effect
  - Cheaper, still useful
- Cooling – active (water) or inertial
  - Inertial system needs a large mass to absorb heat without fluid, e.g., large copper heat sink
  - CFS SPARC using passive cooling and strike point sweep to mitigate heat flux

EB1200 has two 600 kW e-guns mounted horizontally at 30° from center.



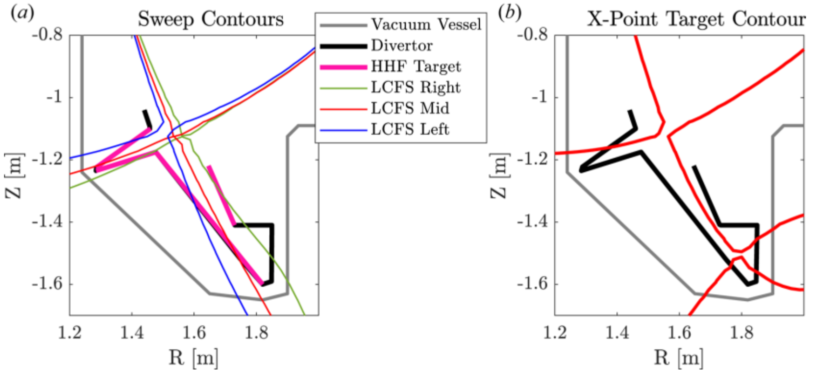


Image sources: https://www.osti.gov/servlets/purl/1377729, https://www.osti.gov/servlets/purl/1647785 https://doi.org/10.1017/S0022377820001117

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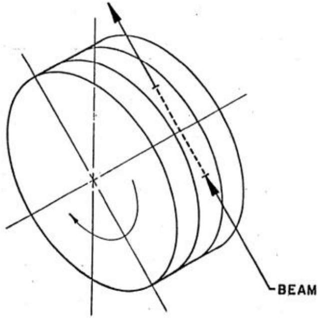
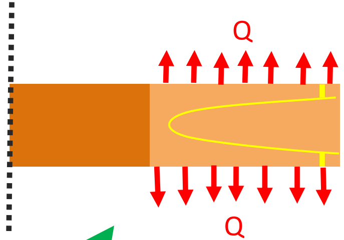
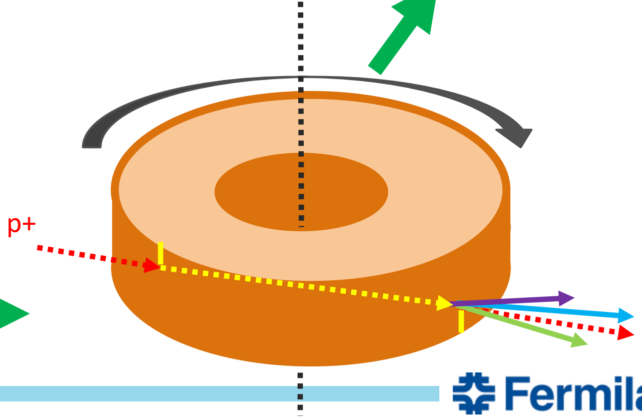
Angled Ring

- Tilt rotation axis of target ring w.r.t. beam
- Illuminated material is hyperboloid of revolution – think flattened Tractricious
- Moves some of the illuminated volume closer to the edges -> better cooling
- Potentially integrates well with a HVT
  - Through-flow ring target, similar to AP-0 Inconel rings

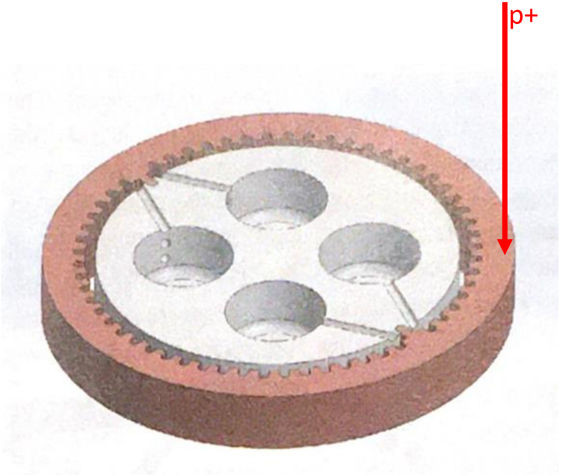


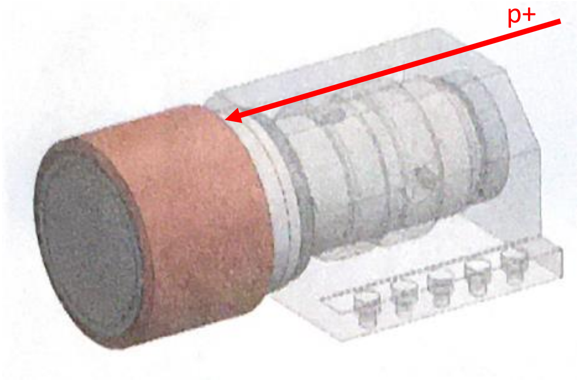


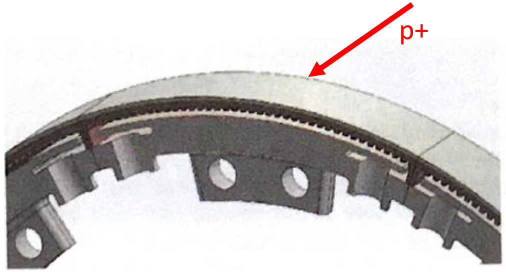


HVT Packaging – Cylindrical Shell

- Rotating cylindrical shell with HVT fins on inside
  - Axial flow – dividers on hub to keep channel width
  - Circumferential flow – hard to manifold
  - Helical flow? Coriolis effects?







LDRD ^Pre- Proposal

LDRD Proposal

- Examine whether hypervapotrons are useful for high-power targetry
  - Static, rotating arrangements – what works for different physics requirements?
  - CFD model of HVT – analytical prediction is crucial, especially for nonstandard geometry
  - Design prototypes – weld layouts, manufacturing, etc.
  - Design/build test bench – induction heater, pressurized water supply
  - Test prototypes – different heat loads, calorimetry of coolant, post-test inspections
  - Report results
- 2 year project, (~1.1 FTE-year total, $340k M&S) – pre-proposal rough estimate