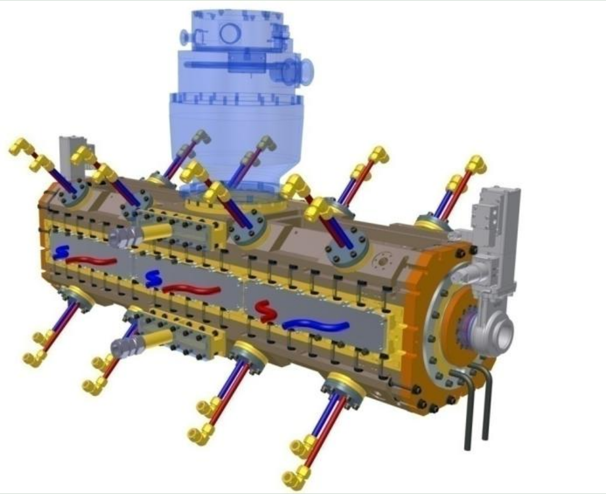
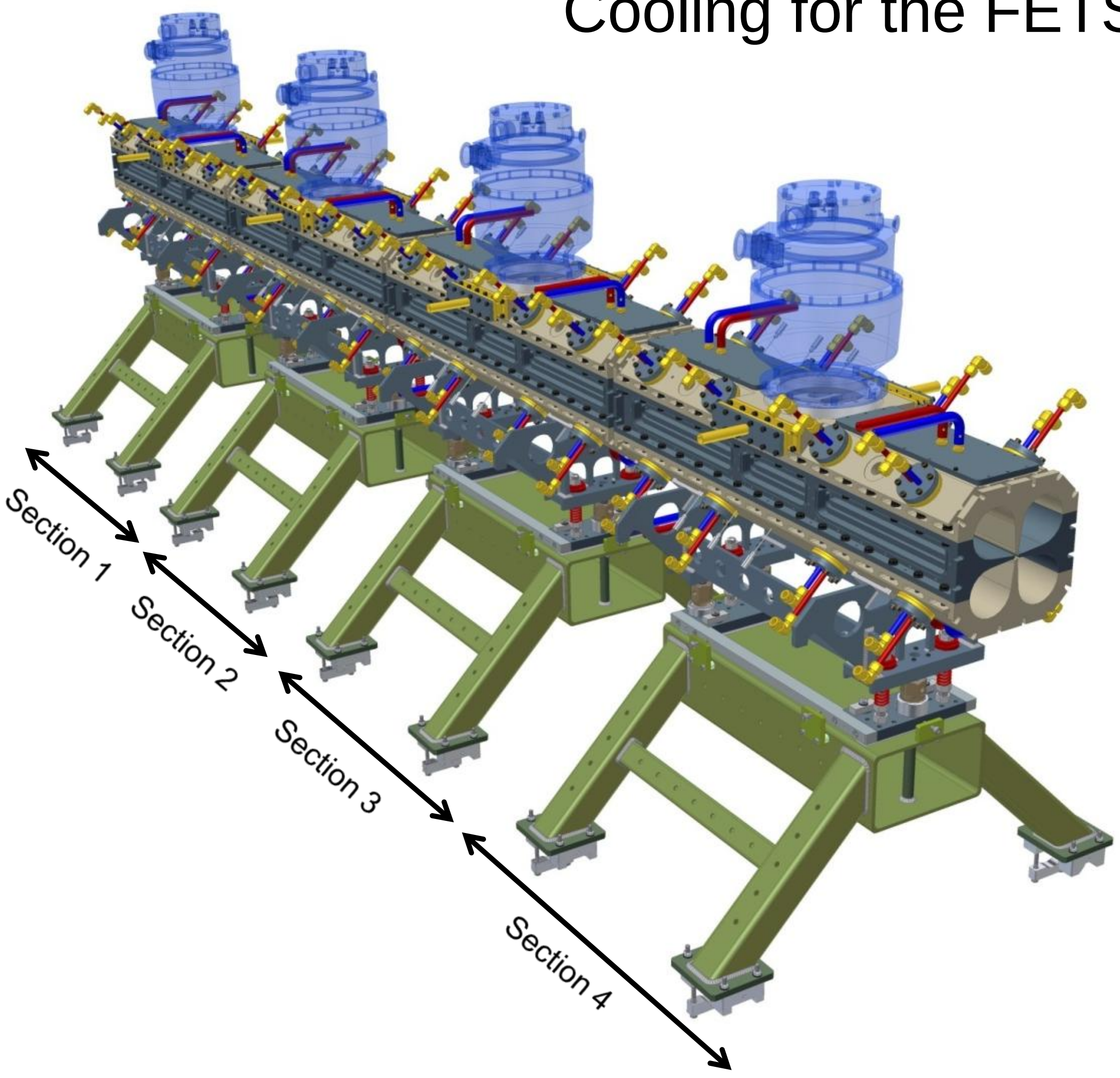
FETS RFQ + MEBT Cooling

21st February 2012



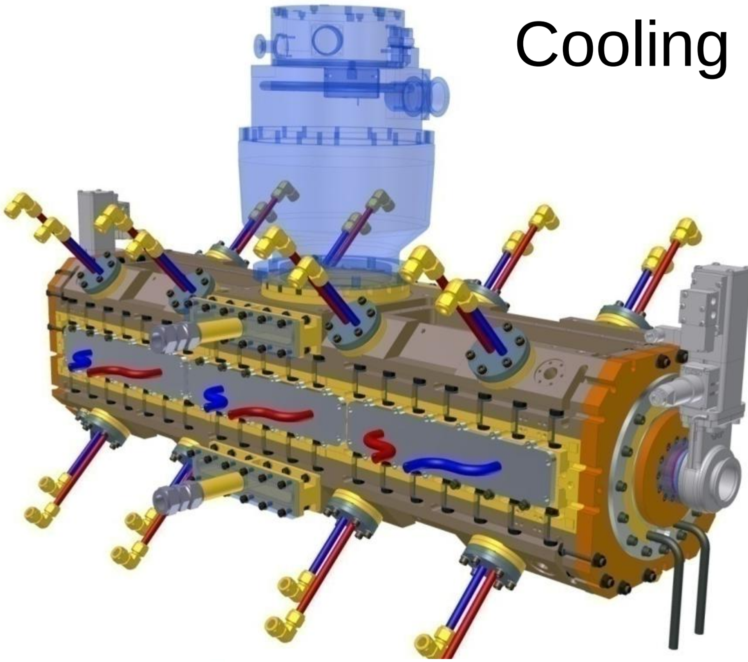
Cooling for the FETS RFQ

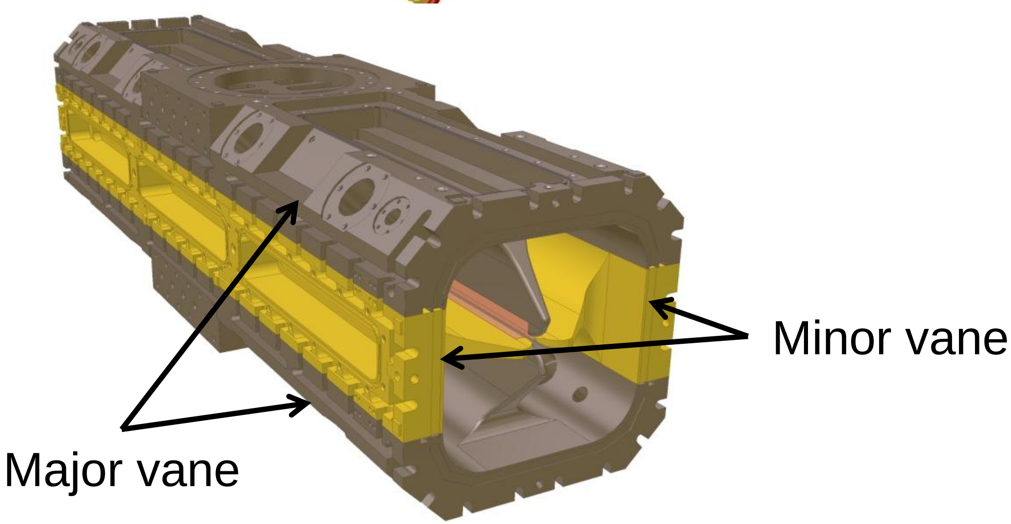


The RFQ is made up from 4 x 1m long sections that for the purposes of cooling can be considered to be identical.

Therefore, let's consider the cooling of just one RFQ section......

Cooling for one RFQ section





A one metre RFQ section is made from 2 major vanes (shown in brown) and 2 minor vanes (shown in yellow).

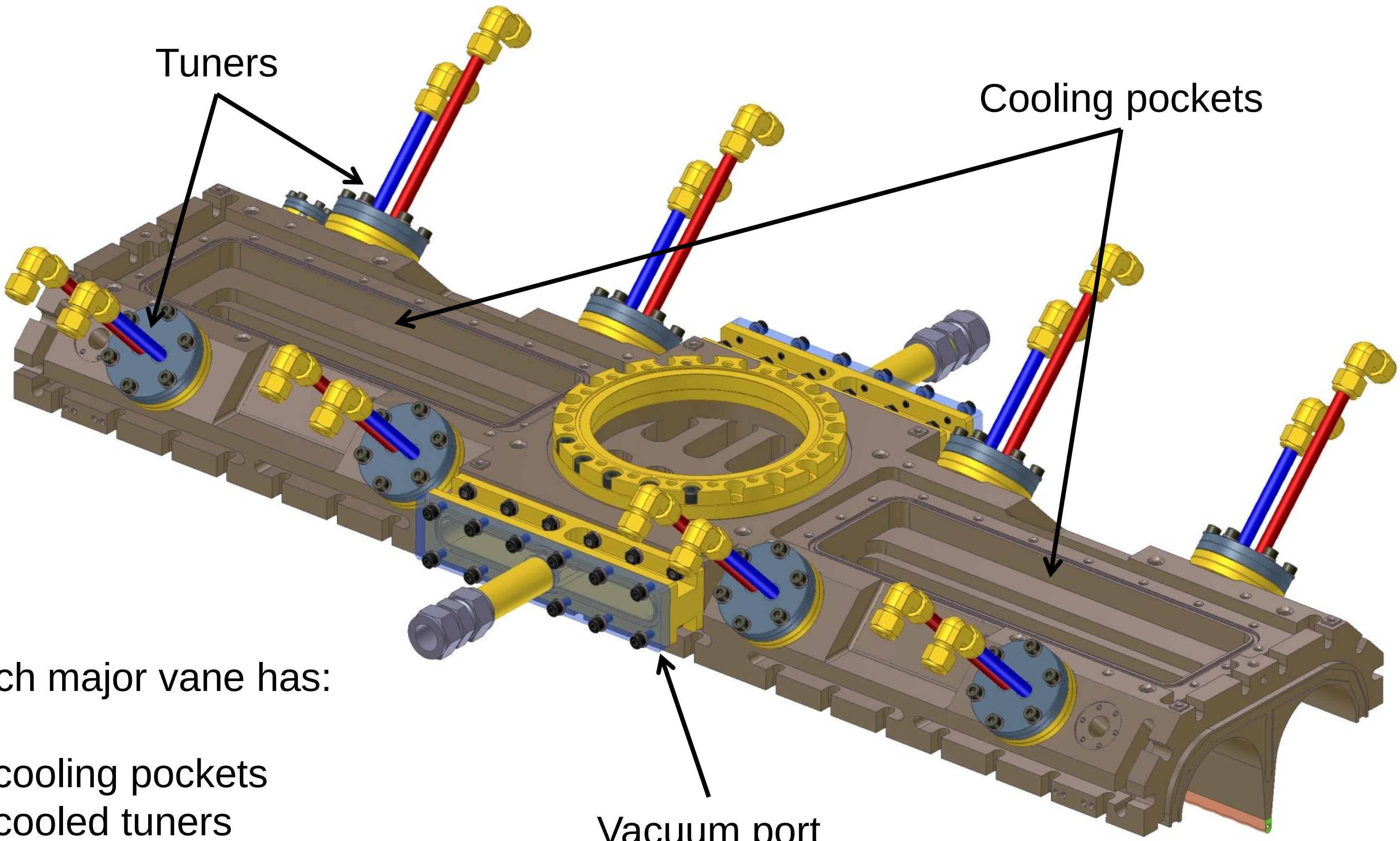
Each major vane is identical and each minor vane is identical. So now we can just consider the cooling requirements of:

- A major vane
- A minor vane

Both major and minor vanes are made from C10100 oxygen free copper.

Cooling a FETS RFQ major vane

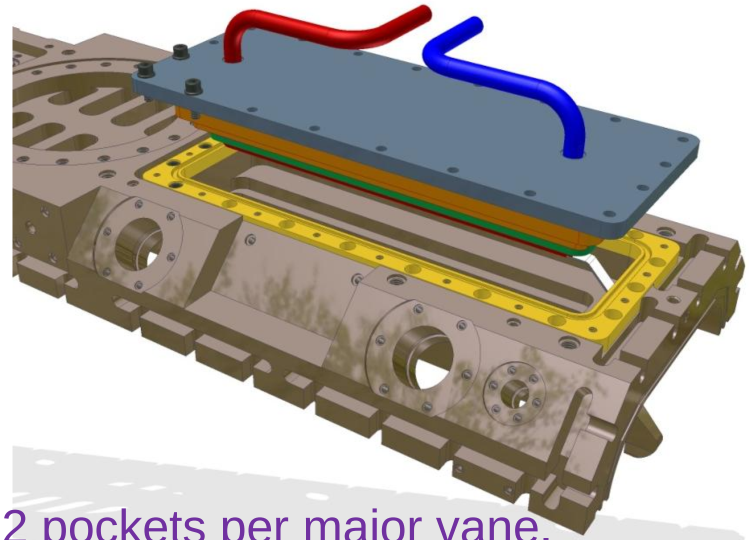
Cooling for one major vane

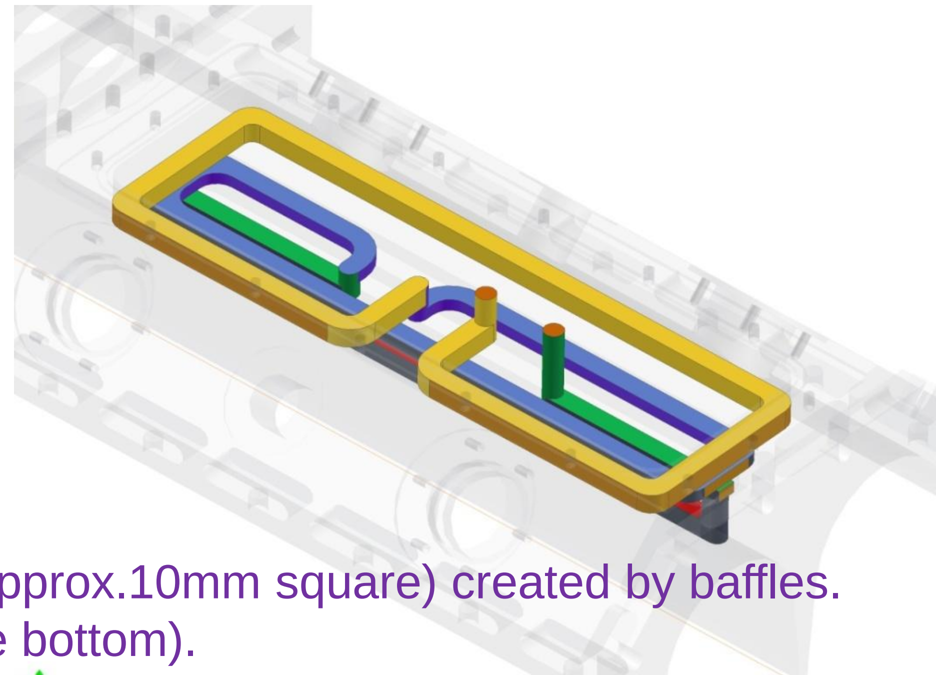


Each major vane has:

- 2 cooling pockets
- 8 cooled tuners
- 1 cooled vacuum port

A major vane cooling pocket

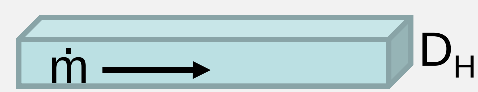




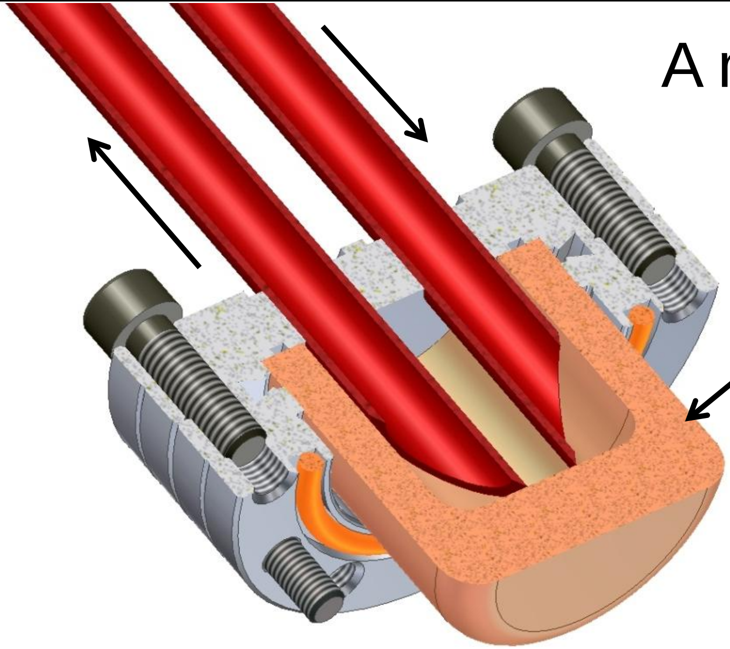
2 pockets per major vane.
Water flows along square channel (of approx.10mm square) created by baffles.
(not 5mm as shown in calculation at the bottom).
Inlet and outlet: OD = 12mm, wall = 1mm, ID = 10mm

Sample calculation from Scott

Square Cross-Section Milled Main Flow Channel:
Hydraulic diameter of 5 mm square pipe is same as circular pipe ∴ D_H = 5 mm.
For constant mass flow rate in all sections, → expected flow velocity ≈ 2.4 m/s.
For total milled length = 0.5 m, this gives:
$\Delta p \approx 0.09$ Bar $R_e \approx 13{,}000$ HTC ~ 11,500 W m^{-2} K^{-1}

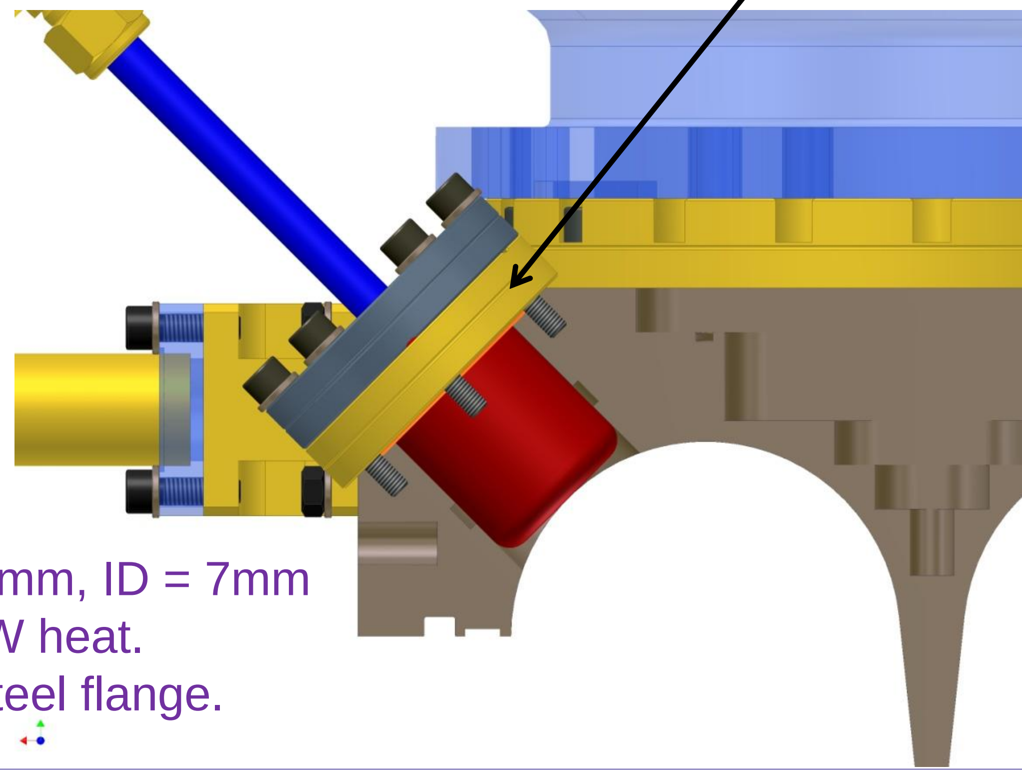


A major vane tuner



Section view of assembled tuner

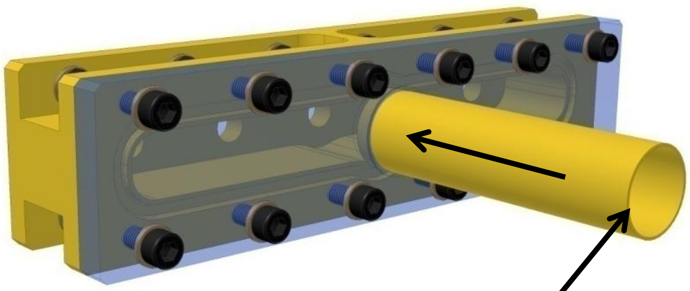
Section view of major vane showing tuner in-place.

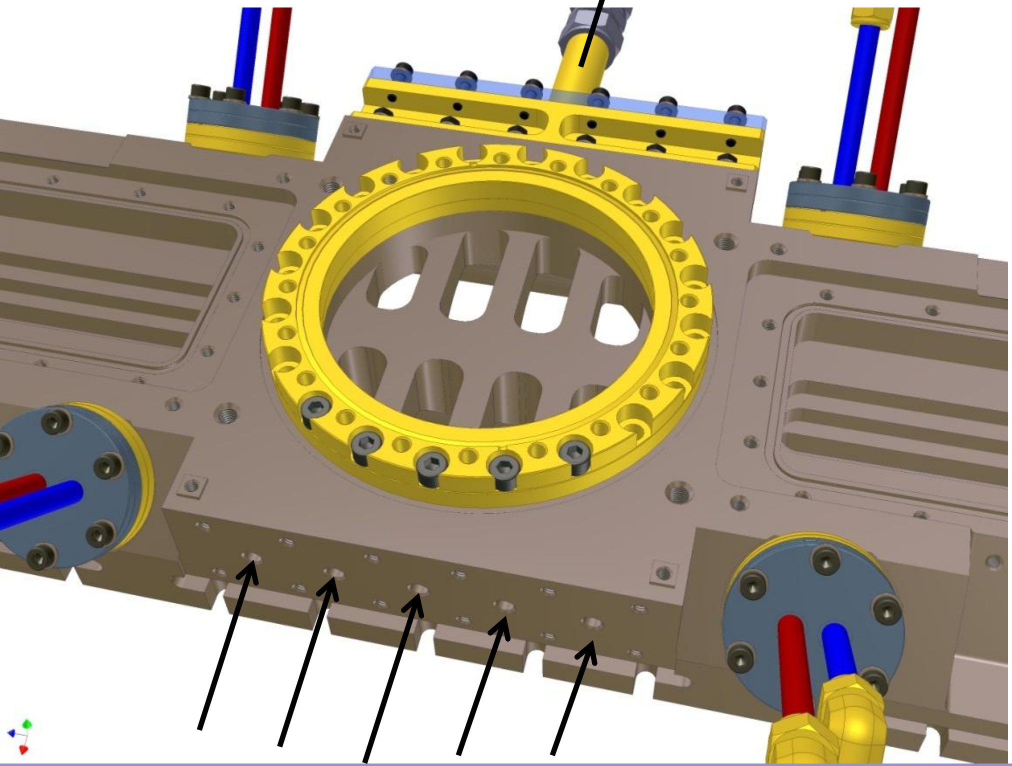


8 tuners per major vane.
Inlet and outlet: OD = 10mm, wall = 1.5mm, ID = 7mm
Each tuner required to cool 100 to 200W heat.
Copper plug brazed into a DN40CF s/steel flange.

The major vane vacuum port

1 vacuum port per major vane.
Flow enters by 21mm ID inlet of manifold.
Flow divided into 5 x 8mm ID x 260mm long.
Flow exits via identical manifold on opposite side.



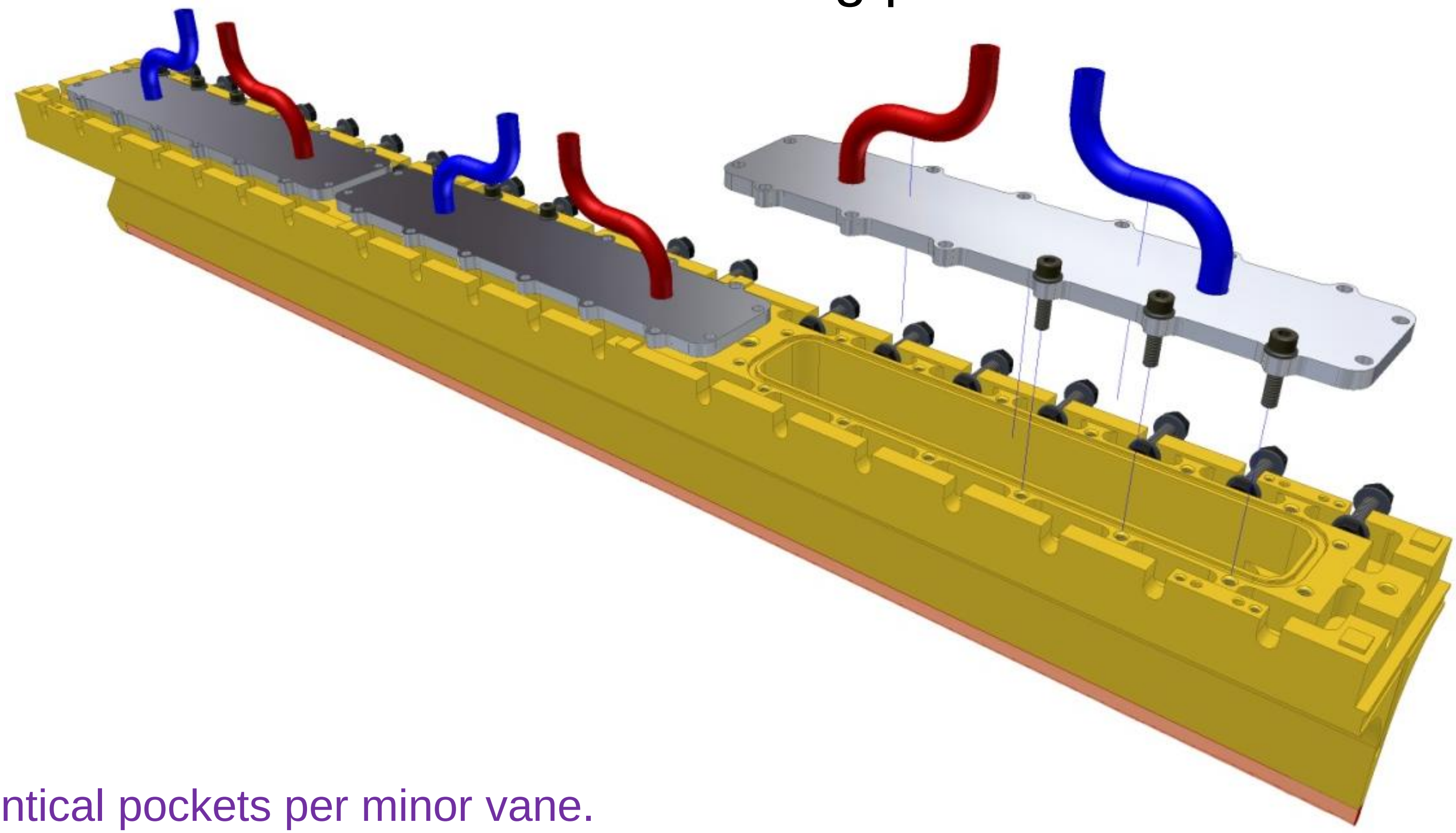


Inlet and outlet:
OD = 25mm
Wall = 2mm
ID = 21mm

Manifold is made from stainless steel.

Cooling a FETS RFQ minor vane

Minor vane cooling pockets



3 identical pockets per minor vane.
Water flows along square channel (of approx.10mm square) created by baffles.
Flow length shorter than for major vane (perhaps 350mm versus 500mm – TBC)
Inlet and outlet: OD = 12mm, wall = 1mm, ID = 10mm

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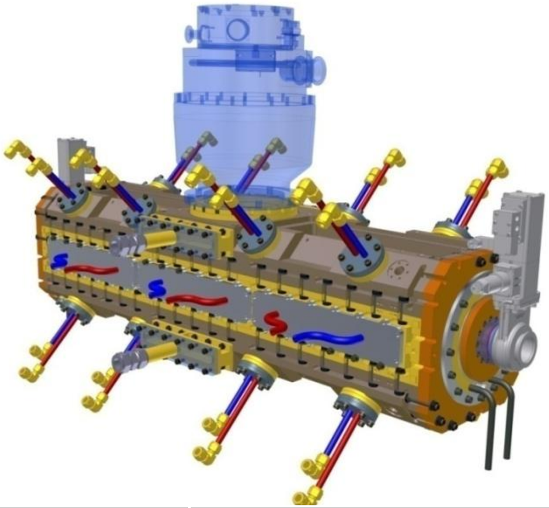
Cooling zones

Each 1m RFQ section should be divided into separate cooling zones that can be flow / temperature controlled.

A typical division of zones might be:

1. Major vane - upper
2. Major vane - lower
3. Minor vane - left
4. Minor vane – right
5. Major vane upper – tuners
6. Major vane lower – tuners



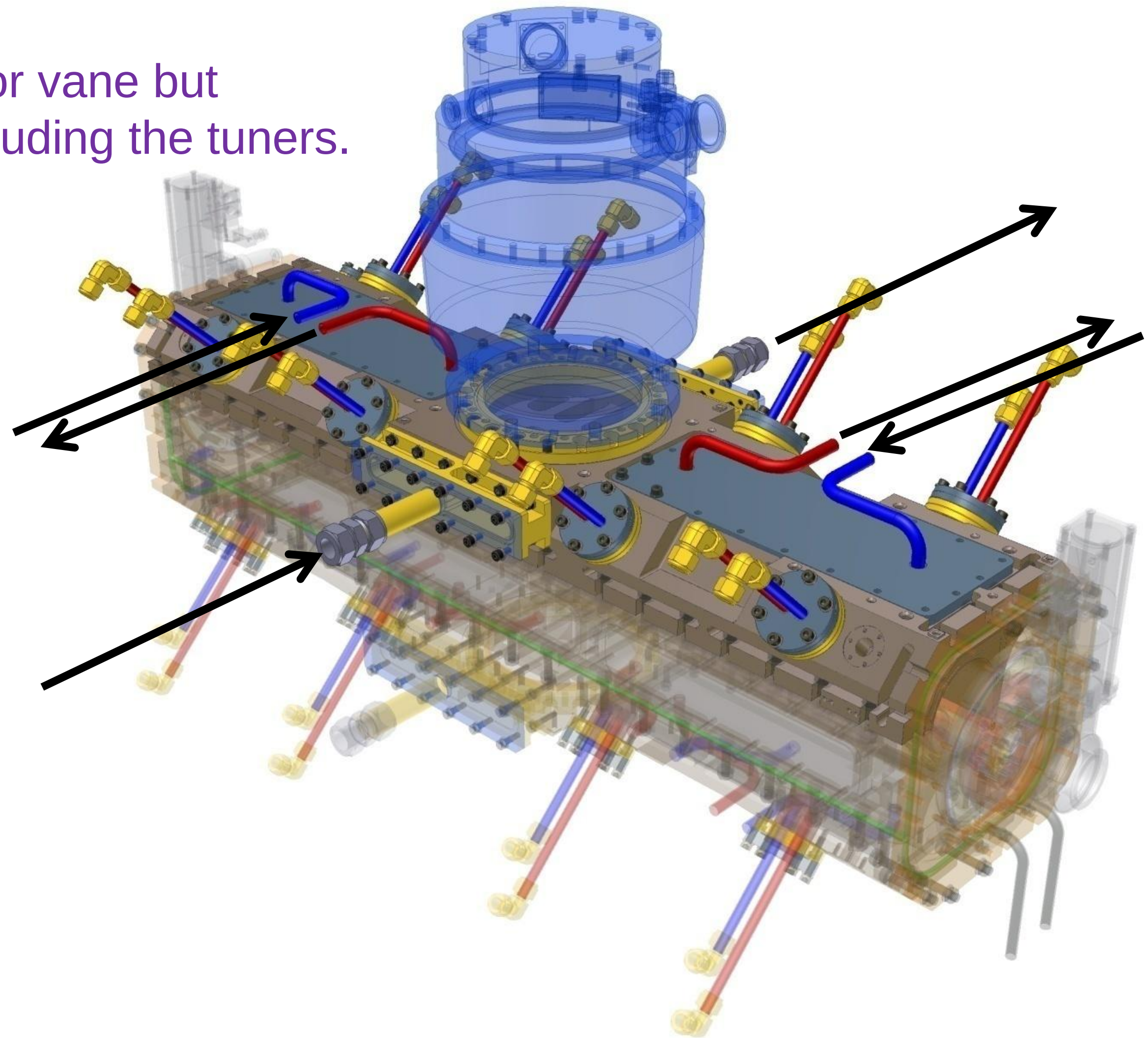
Zone	Features	Inlets	Outlets
1	2 pockets 1 vac port	2 x 12mm OD, wall 1mm 1 x 25mm OD, wall 2mm	2 x 12mm OD, wall 1mm 1 x 25mm OD, wall 2mm
2	2 pockets 1 vac port	2 x 12mm OD, wall 1mm 1 x 25mm OD, wall 2mm	2 x 12mm OD, wall 1mm 1 x 25mm OD, wall 2mm
3	3 pockets	3 x 12mm OD, wall 1mm	3 x 12mm OD, wall 1mm
4	3 pockets	3 x 12mm OD, wall 1mm	3 x 12mm OD, wall 1mm
5	8 tuners	8 x 10mm OD, wall 1.5mm	8 x 10mm OD, wall 1.5mm
6	8 tuners	8 x 10mm OD, wall 1.5mm	8 x 10mm OD, wall 1.5mm

Cooling zone 1

Top major vane but
NOT including the tuners.

3 inlets
3 outlets

For tube sizes see
table on slide 11

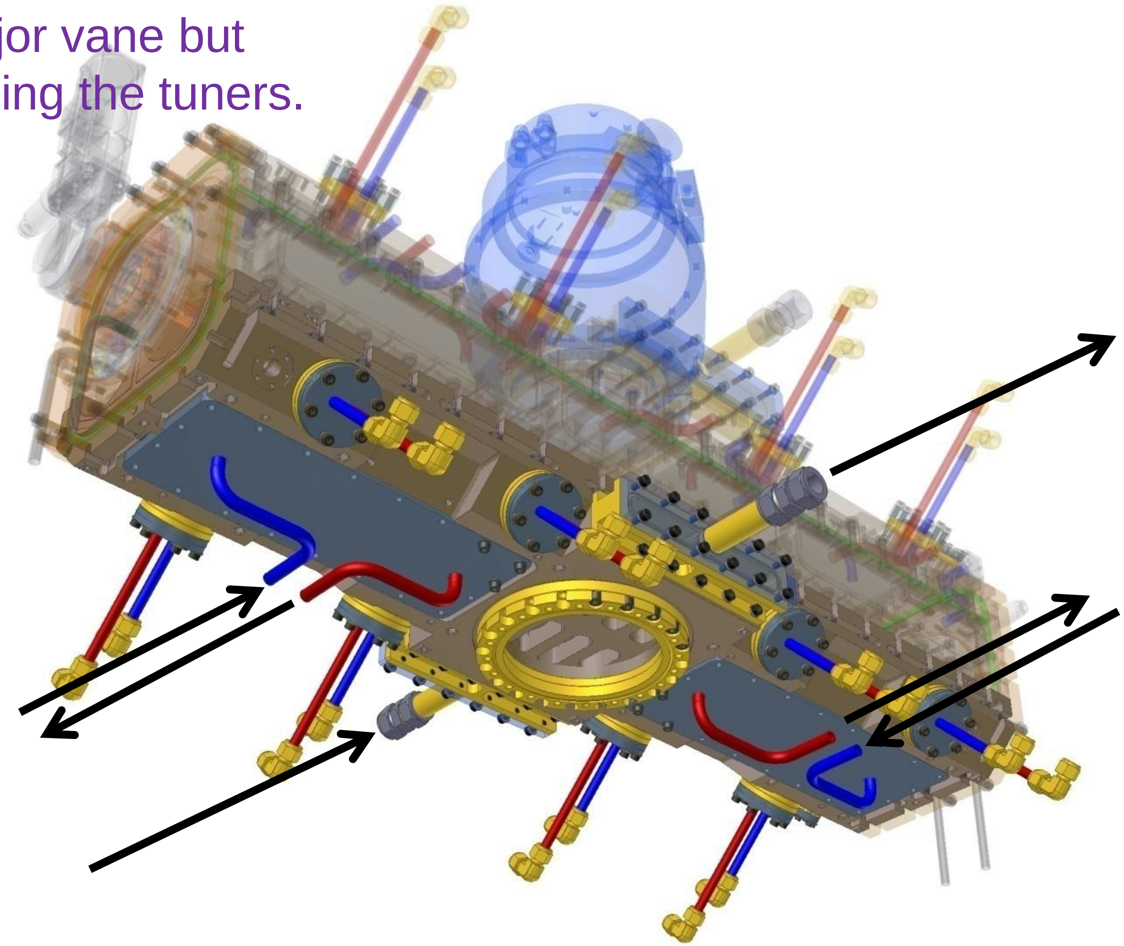


Cooling zone 2

Bottom major vane but NOT including the tuners.

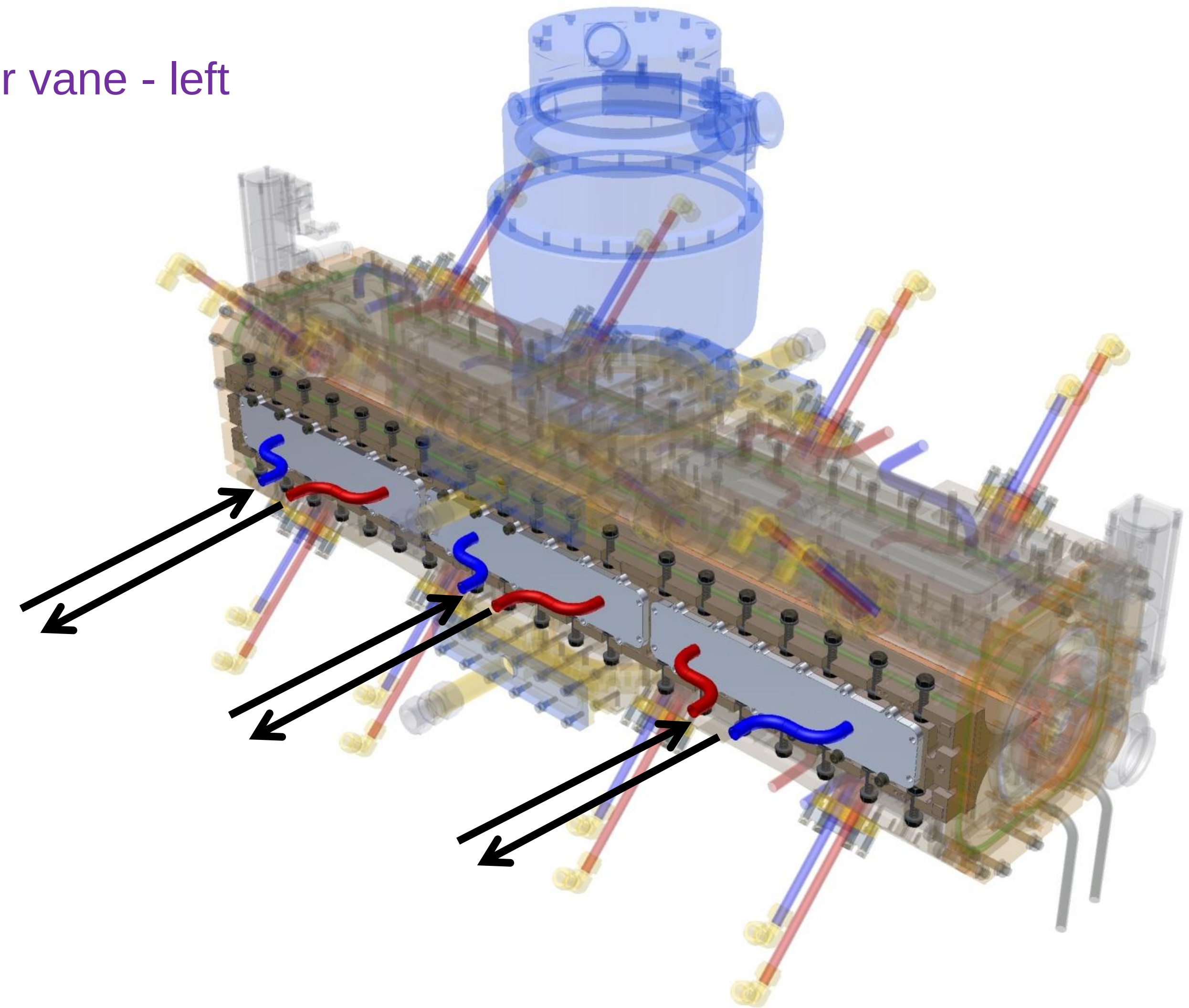
3 inlets
3 outlets

For tube sizes see table on slide 11



Cooling zone 3

Minor vane - left



3 inlets
3 outlets

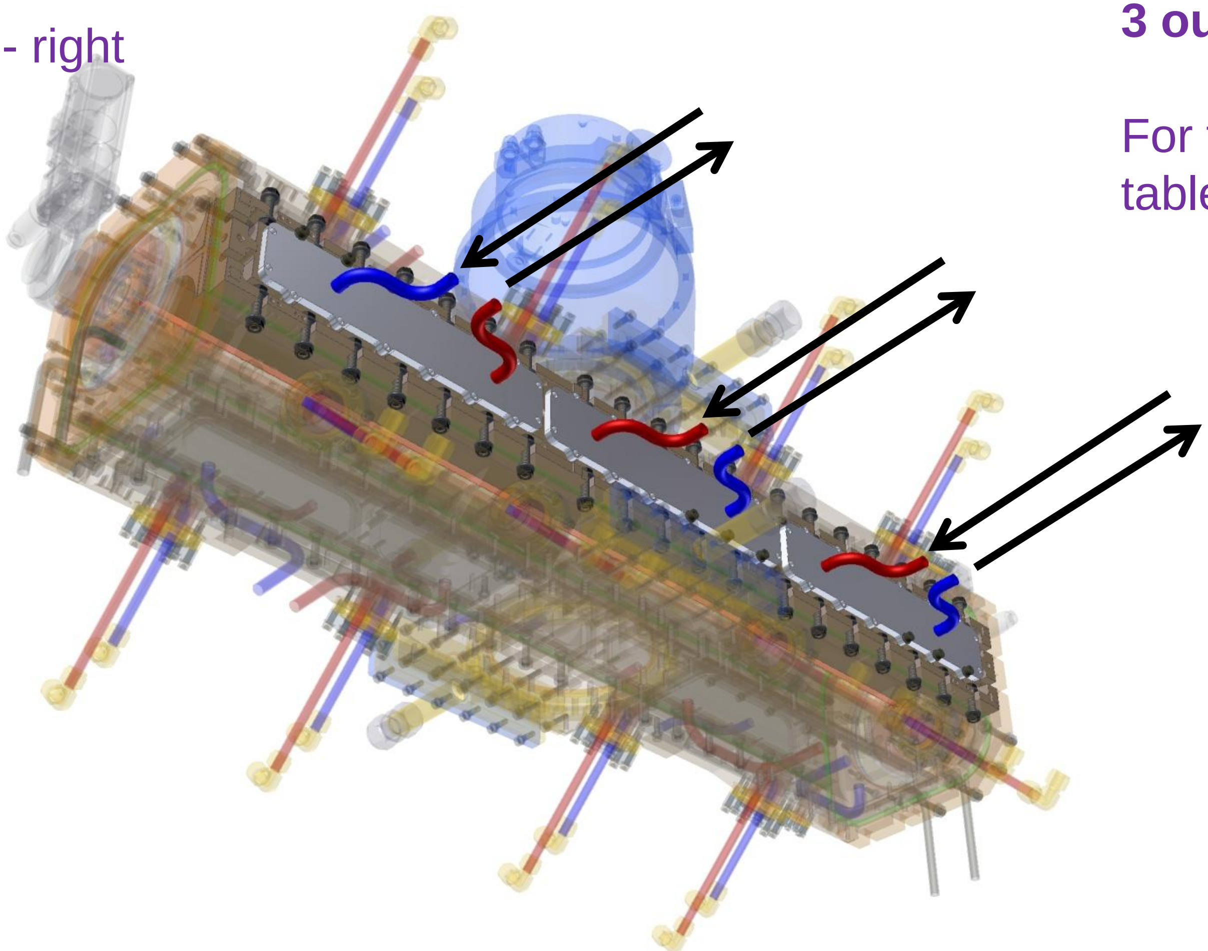
For tube sizes see table on slide 11

Cooling zone 4

Minor vane - right

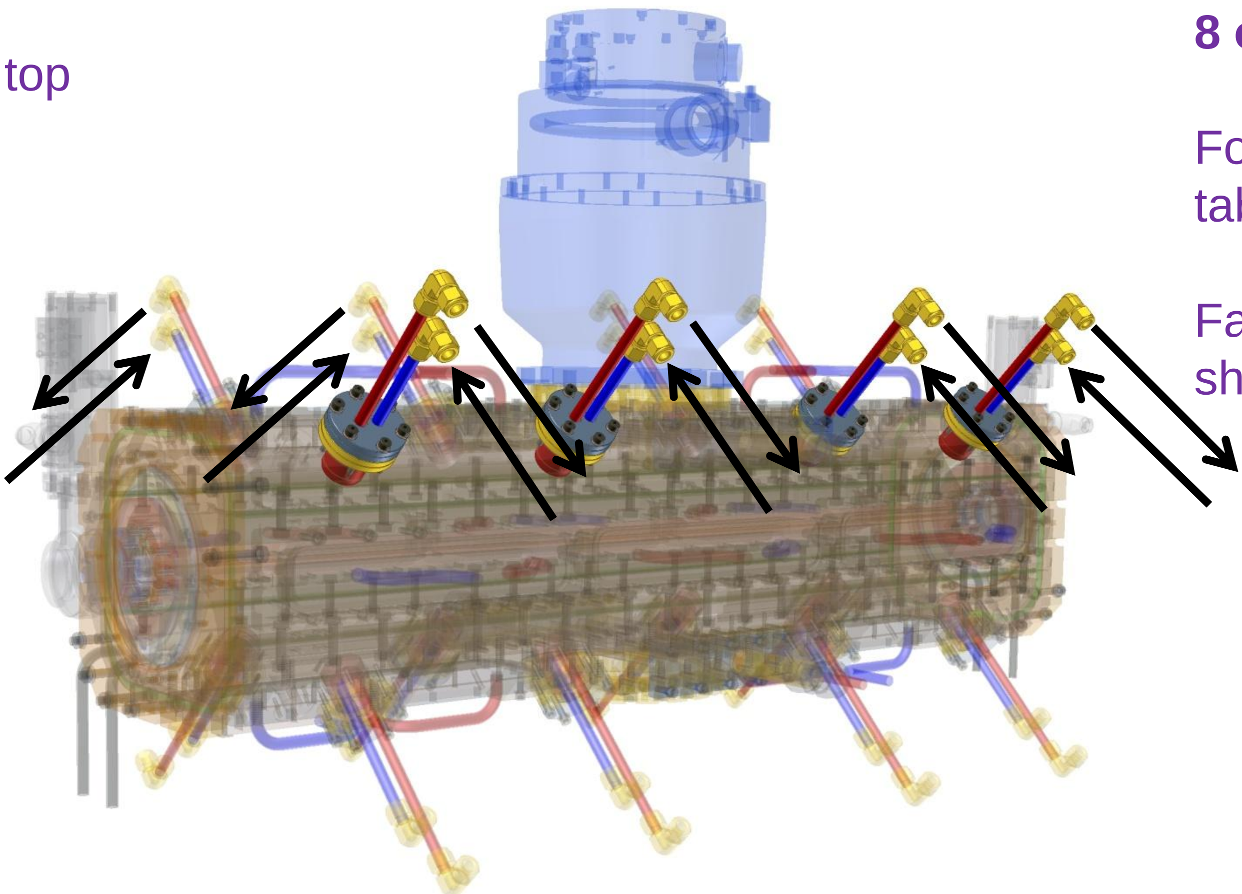
3 inlets
3 outlets

For tube sizes see table on slide 11



Cooling zone 5

Tuners – top
8 off



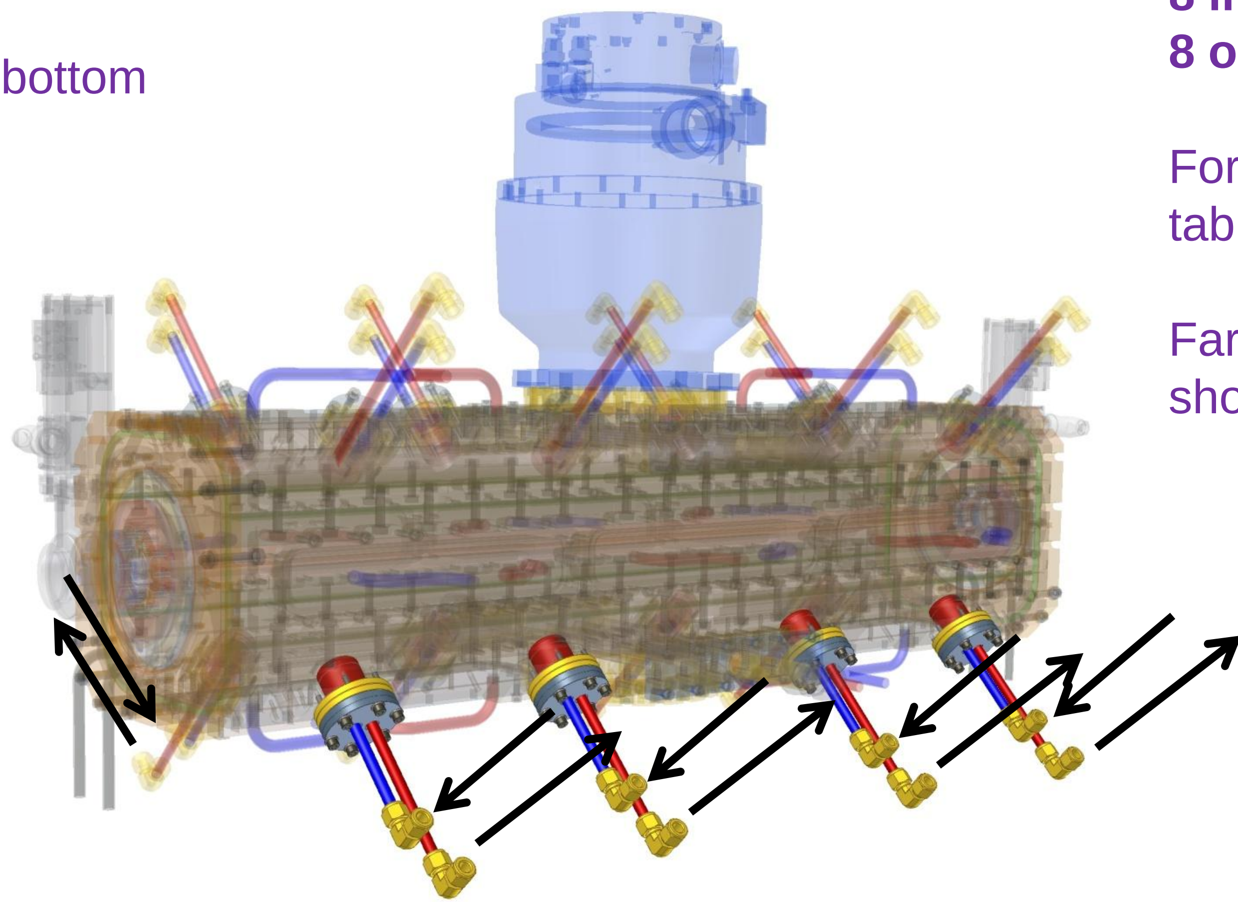
8 inlets
8 outlets

For tube sizes see table on slide 11

Far side tuners not shown for clarity.

Cooling zone 6

Tuners – bottom
8 off



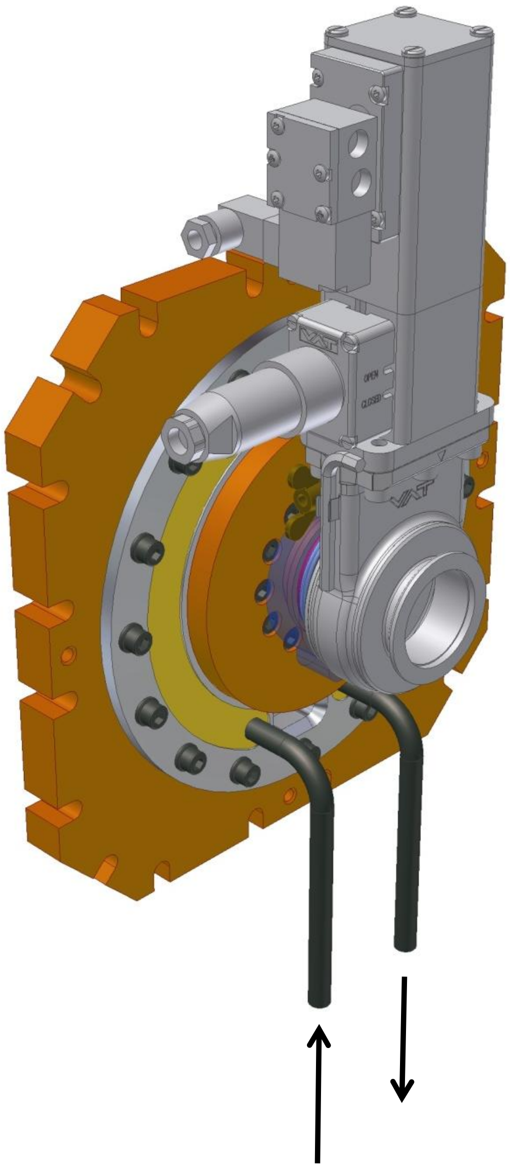
8 inlets
8 outlets

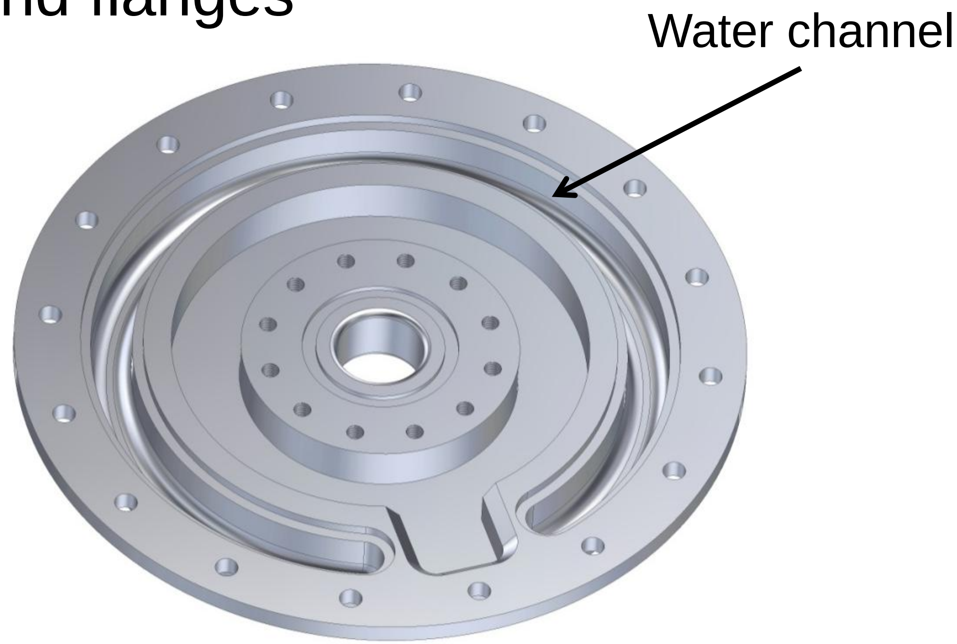
For tube sizes see table on slide 11

Far side tuners not shown for clarity.

Some additional cooled RFQ features

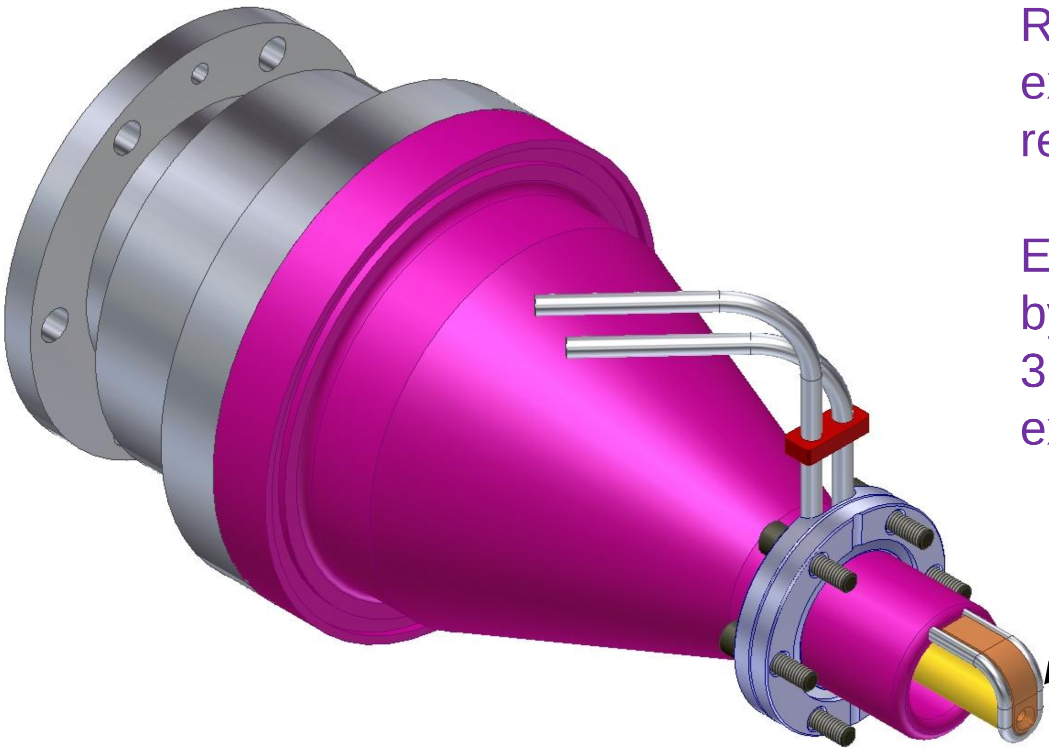
RFQ end flanges





At either end of the RFQ is an end flange assembly. It is cooled via water flowing into a circular channel that can be considered to be 10mm square with a length of 450mm. The assembly is made from copper with diameter 10mm OD, wall 1.5mm, 7mm ID stainless steel input and output tubes.

RFQ couplers



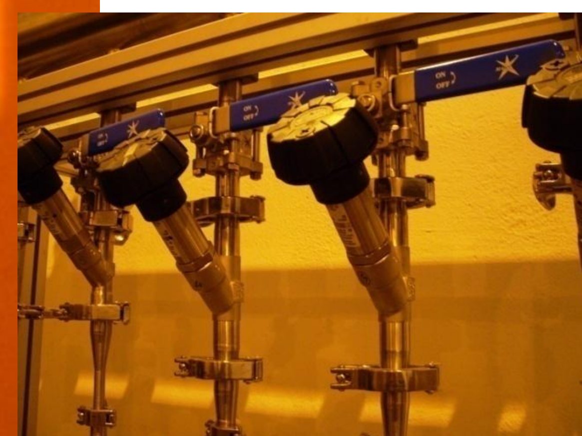
The reference design is to have 2 couplers for the 4m long RFQ. There is an option to extend this to 4 couplers if required.

Each coupler is cooled at its tip by a 4mm OD, 0.5mm wall, 3mm ID copper pipe (if that exists).

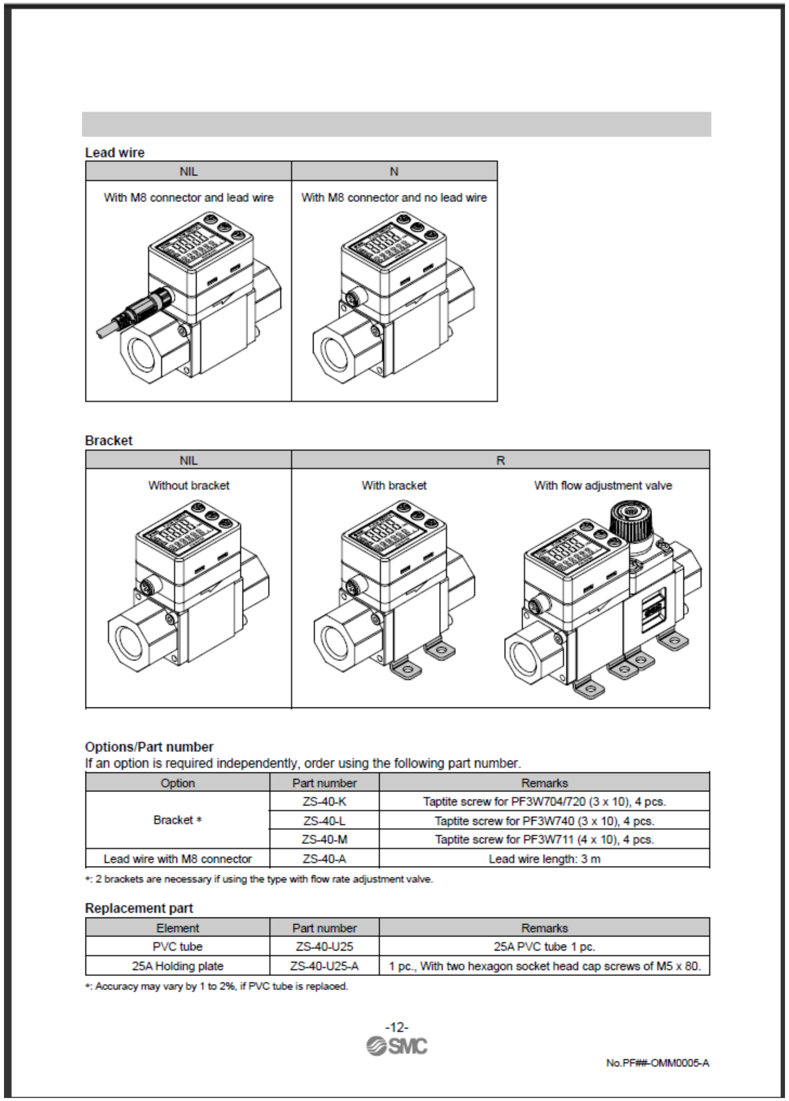
Possible flow control items

Flow control test panel in R6

SMC flow switch



Cooling for one RFQ section



Lead wire

NIL	N
With M8 connector and lead wire	With M8 connector and no lead wire

Bracket

NIL	R	
Without bracket	With bracket	With flow adjustment valve

Options/Part number

If an option is required independently, order using the following part number.

Option	Part number	Remarks
Bracket *	ZS-40-K	Taptite screw for PF3W704/720 (3 x 10), 4 pcs.
	ZS-40-L	Taptite screw for PF3W740 (3 x 10), 4 pcs.
	ZS-40-M	Taptite screw for PF3W711 (4 x 10), 4 pcs.
Lead wire with M8 connector	ZS-40-A	Lead wire length: 3 m

*: 2 brackets are necessary if using the type with flow rate adjustment valve.

Replacement part

Element	Part number	Remarks
PVC tube	ZS-40-U25	25A PVC tube 1 pc.
25A Holding plate	ZS-40-U25-A	1 pc., With two hexagon socket head cap screws of M5 x 80.

*: Accuracy may vary by 1 to 2%, if PVC tube is replaced.

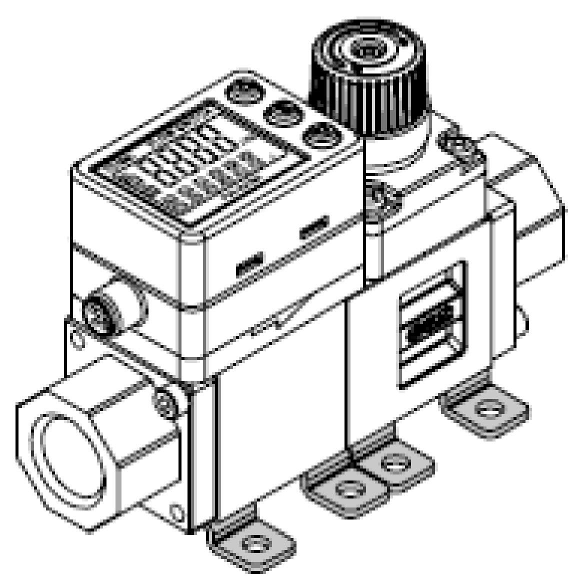
-12-

SMC

No.PF##-OMM0005-A

Duncan has supplied me with a copy of the SMC manual – note flow switch option with built in control valve for neat close packaging.

With flow adjustment valve



Flow rates (l / m)
0.5 - 4
2 - 16
5 -40

Calculating flow rates........

Flow rates are easy to calculate, if you know how much heat you need to remove and the maximum allowable temperature rise........

$$Q = MC_p\Delta T$$

Where Q = heat load in kW
M = mass flow rate (can be taken as volume flow rate in l/s)
C_p = specific heat capacity of water 4.18 kJ/kg/K *
ΔT = temperature rise

So for the entire RFQ with a heat load to remove of 75kW and a maximum temperature rise of 1K we get a flow rate of 18 l/s or 4.5 l/s for each 1m long RFQ section.

Duncan Couchman, RAL

** This means it takes 4.18 joules of energy to raise 1 gram of water by 1 degree Celsius*

HOW EFFECTIVE IS THE COOLING FLOW AROUND ONE MINOR VANE POCKET?

We have a flow rate m of 4.5 l/s per 1m RFQ section.
Assume that each RFQ section is divided into 6 equal zones, giving 4.5/6 = 0.77 l/s per zone
Consider, as an example, the minor vane with 3 identical pockets, each pocket has a flow of 0.77/3 = 0.26 l/s per pocket

Calculating the flow velocity C per minor vane pocket:

using, $m = \rho A C$ $C = m / \rho A$ $C = 0.26 / (1000) \times (1\times10^{-4})$

where, m = mass flow rate (kg/s or l/s for water)
ρ = density of water = 1000 kg / m^3
A = cross-sectional area of flow (m^2)

Flow velocity per minor vane pocket = 2.6 m/s

What is the Reynolds number (or, how effective is that flow velocity at cooling)?

Assume water channel created by baffles is 10mm x 10mm

Using, $Re = \rho v d / \mu$

where, ρ = density of water = 1000 kg / m^3
v = 2.6 m/s
d = 10mm = 0.01 m
μ = dynamic viscosity = 1×10^{-3} N.s/m^2 (for water at 20^0C) (think honey kept in fridge versus room temp.)

Re = 26,000 too high if flow rate isn't reduced.

1. The Reynolds number should be greater than 4,000 for lines actively involved in cooling to ensure that there is turbulent flow within the circuits and hence efficient cooling.
2. The ideal Reynolds number to achieve is 10,000.
3. Do not aim for a Reynolds number that is greater than 10,000

Therefore, lets see the result of reducing the flow rate from 0.26 l/s to 0.1 l/s

Now, C = 1 m/s
Re = 10,000 Spot on!

What is the Heat Transfer Coefficient of this pocket?

We have the **Reynold's** number so we first need the **Prandtl** number to calculate the **Nusselt** number:

The Prandtl Number is a dimensionless parameter of a convecting system that characterises the regime of convection. It approximates the ratio of momentum diffusivity and thermal diffusivity:

$P_R = v / a$ or $P_R = C_p\, \mu/k$

where: μ = *absolute or dynamic viscosity (kg/m s)* = $1\text{x } 10^{-3}$
c_p = *specific heat capacity (J/kg K) = 4.18* x 10^3
k = thermal conductivity (W/m K) = 0.6 for water

$P_R = (4.18 \text{ x } 10^3) \text{ x } (1\text{x } 10^{-3}) / 0.6 = 7$

$$R_e = \frac{\rho v D_H}{\mu} \Rightarrow N_u = 0.023 R_e^{0.8} P_R^{0.4} \Leftarrow P_R = \frac{c_p \mu}{k}$$

$$\Downarrow$$

$$HTC = \frac{N_u k}{D_H}$$

Nusselt Number: Dittus-Boelter equation
The Dittus-Boelter equation (for turbulent flow) is an explicit function for calculating the Nusselt number. It is easy to solve but is less accurate when there is a large temperature difference across the fluid. It is tailored to smooth tubes, so use for rough tubes (most commercial applications) is cautioned. The Dittus-Boelter equation is:

$$N_D = 0.023\, R_e^{0.8}\, P_R^{n}$$

where:
n = 0.4 for heating of the fluid and *n* = 0.3 for cooling of the fluid. The Dittus-Boelter equation is valid for:

$0.6 < P_R < 160$ **YES**
$R_e \sim 10{,}000$ **YES**
$L/D > 10$ **YES**

Nusselt number:
Given two parallel plates at different temperatures, the Nusselt number gives the ratio of actual heat transferred between the plates by a moving fluid to the heat transfer that would occur by conduction.

now: **$Nu = 0.023\, (10000)^{0.8}\, (7)^{0.4} = 80$**

Finally we can calculate the heat transfer coefficient:

$h = 80 \text{ x } 0.6 / 0.010$
$= 4800 \text{ W/m}^2 \text{ K}$
$h = 0.0048 \text{ W/mm}^2$

(a practical maximum is 0.6 W/mm²)

Extra.......

Circuits:
•De-min circuit in place.
•New low delta T circuit to follow existing – needs to be insulated.
•Low delta T circuit for accelerating structures only - RFQ and MEBT Cavities.
•Remainder of FETS line can be on existing de-min circuit.
•Chiller needs connecting.
•John to check / confirm power of chiller unit.
•Alan to send Pete original cooling power document for comparison.
•Duncan to get quote for running flow and return along same route as de-min circuit in both plastic and stainless steel with crimped fittings.
•Duncan can start after this shutdown – end of next week.
•John to assign new chap to this work after Duncans start.
•Current R8 infrastructure work will be in the way of new pipework installation.

Flow meters:
•John currently trialling new flow meters with no moving parts in R6 – Cost ~£500 each.
•Flow meters on return line only.
•Ideally flow meters should measure vertical flow upwards – will impact on manifold layout.
•Avoid rotameters.

Valves:
•Need separate flow control valves and on/off valves.
•Ability to isolate whole manifold.
•Don't use ball valves as on ISIS RFQ manifold – not fine enough flow control.
•John to forward pics of recommended flow control valve to Pete for sizing / spacing of manifold lines.

Manifolds:
•FETS team need to define cooling zones and produce manifold layout.
•Alberto to look at manifold layout options? (after existing job is out to manufacture).
•Extra lines in manifolds and at ends for future extensions.
•Manifolds can be made in-house (RAL) – John knows a man.

What could be bought?
•Pipework for new circuit
•Fittings + brackets etc.
•Lagging
•Some flow meters and valves plus some small fittings for manifolds (Swagelok or cheaper alternative).

General:
•David Findlay requested overhaul and improvement of ISIS cooling – no particular need for FETS to comply but may help.
•David Findlay likes to see water flowing – can we have windows somewhere in line?
•Problem with pump on existing de-min circuit – suspect control system. John / Duncan to advise.
•Pete to estimate pressure drop and conductivity through various circuits.
•Pete had wrong end date for MEBT build - to be confirmed.
•Cooling to be complete before end of 2013 – BIG shutdown coming.
•While we are at it – are any more air supplies needed along the FETS?
•At a later date – talk to John about waveguide support framework job.

Summary from first cooling meeting on Monday 6th Feb 2012

John Govans
Trevor Pike
Alberto
Me
Alan
Duncan Couchman

Comparison of Results

Property	Hand estimate	ANSYS CFD Result
Mass flow rate	0.157 kgs^{-1} (9.42 Lmin^{-1})	0.1545 kgs^{-1} (9.27 Lmin^{-1})
Average water flow	2 ms^{-1}	1.914 ms^{-1}
Maximum water flow	5 ms^{-1} (desired upper limit)	4.227 ms^{-1}
Total Pressure	0.12 Bar	0.375 Bar
Average HTC	8650 Wm^{-2}K^{-1}	9000 Wm^{-2}K^{-1}
Water temperature rise	3 ˚C	3 ˚C

Simulation matches back-of-the-envelope calculations (again… well done ANSYS!)

Copper temperature similar to previous simulations with different flow → <u>Good</u>

To do now: try a more accurate model and put in a squirt nozzle

Metals compatible with demineralised water

IMPACTS ON THE DESIGN

Metals choice

Due to distinctive chemical aggressiveness of demineralised water and to the galvanic effect anyhow present with low conductivity media, the choice of metals to be used into the different parts of the cooling closed loop shall be compliant with the following non exhaustive list of instructions:

- Metals **compatible** with demineralised water:
  - Stainless steel
  - Copper
  - Aluminium
  - Zinc free bronze
- Metals **non compatible** with demineralised water:
  - Brass
  - Bronze
  - Carbon steel
  - Galvanised steel
  - Chromate steel
- **Allowed metals mixture** in the same circuit
  - Aluminium and stainless steel
  - Copper and stainless steel
- **Mixture of metals** to be avoided in the same circuit
  - Aluminium and copper / copper alloys

Paolo Guglielmini - TS / CV **JCOV - 11/05/2006**

Estimate of services required for FETS in R8

	Electricity	Amps	Isolation	Phase	Water (demin)			
					Temp. controlled	Non temp. controlled	Flow rate for 1C H_20 temp rise (l/m)	Flow rate for 10C H_20 temp rise (l/m)
	kVA				kW*	kW**		
Ion source	16	20	}Yes, isolate	1				
Ion source	10	20	}Yes	3				
Ion source HT	5	6	} together	3				
LEBT solenoid PSUs	30	39	Yes	3		5		7
LEBT solenoids	0					25		36
Klystron	300	390	Yes	3		175		250
Load						75		107
RFQ					75		1071	
Chopper	10	13	}Yes, isolate	1	10		143	
MEBT magnet PSUs	20	26	} together	1				
MEBT magnets						20		29
MEBT RF	50	65	Yes	3	25		357	
Beam dump						20		29
Vacuum system	20	26	}Yes, isolate	1				
Other†	50	65	} together	1	10	10	143	14
Chillers*	50	65	Yes	3		170		243
Total	561	719			120	500	1714	714
				Water velocity in 3" pipe (m/2)			6.3	2.6
				Water velocity in 4" pipe (m/2)			3.5	1.5

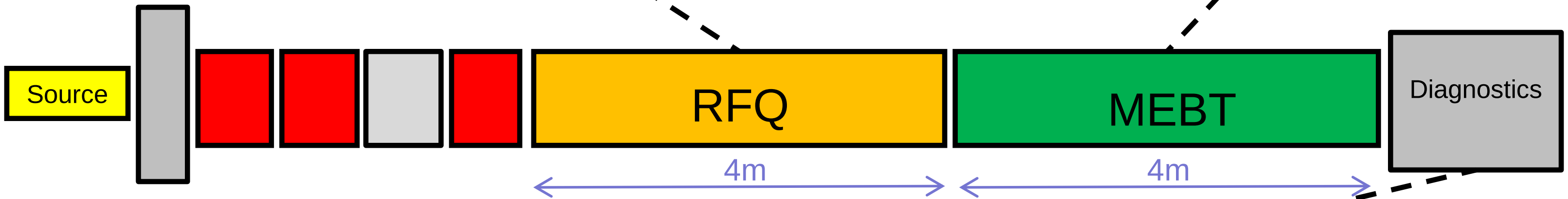
* assumes temp. controlled water comes from chillers cooled by tower water
** demin water cooled by tower water via heat exchanger
†diagnostics, controls, low power stuff

Original calculations from Alan

How much power are we trying to cool?

RFQ: ~ 50-60 kW average or 15 kW/m

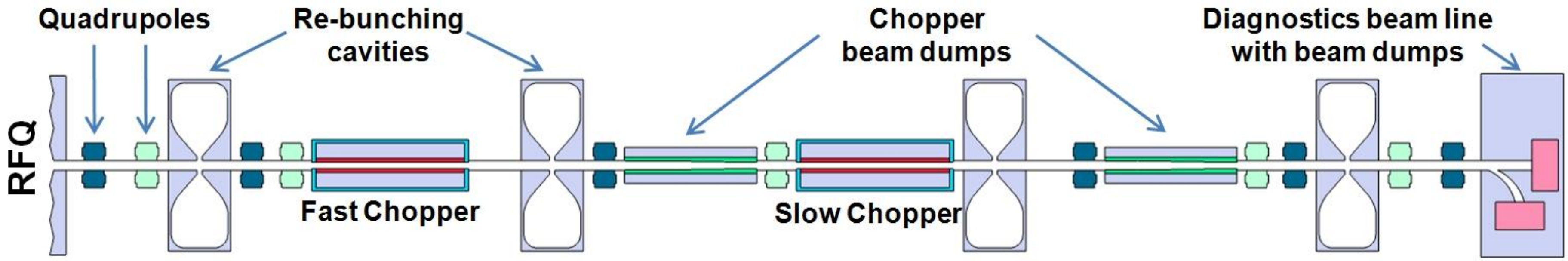
MEBT:
Cavities, ~3kW each, 12kW total
Quads, ~500W each, 5.5kW total
Allow 20kW total or 5 kW/m

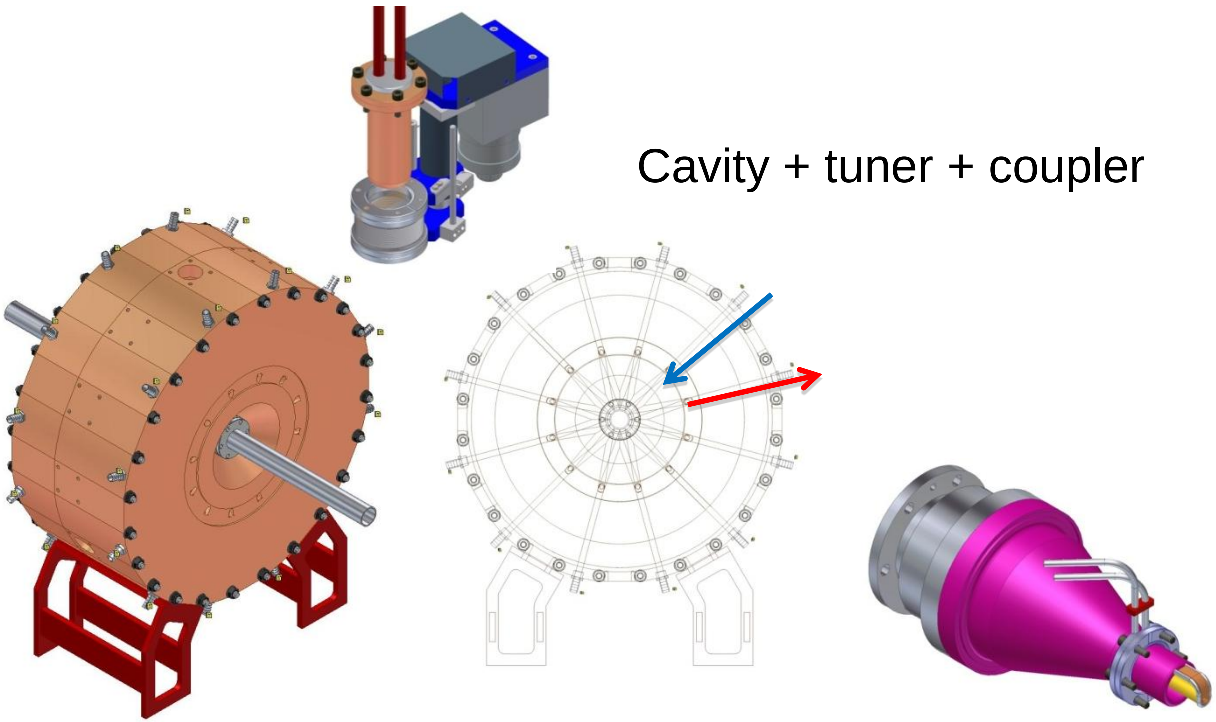


Diagnostics:
Dipole magnet, ~2kW
Beam dump, ~3MV * 0.060A * 0.1 (DF) = 18kW

In total we require something like 100kW of cooling. Note that the distribution of cooling power will not be evenly spread along the length of the FETS.

MEBT cooling





Cavity + tuner + coupler