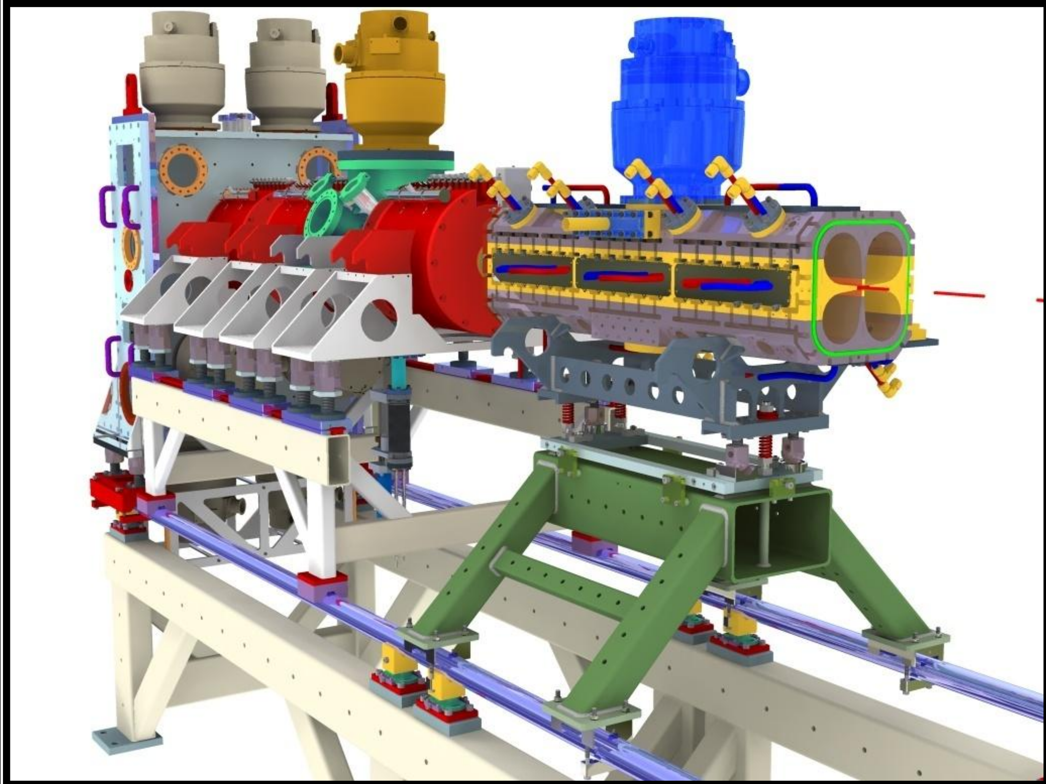
2011

FETS RFQ Design Review



Peter Savage

Imperial College

10/12/2011

Present:

Amanda Brummitt	*Rutherford Appleton Laboratory*
Alberto Garbayo	*Rutherford Appleton Laboratory*
Scott Lawrie	*Rutherford Appleton Laboratory*
Alan Letchford	*Rutherford Appleton Laboratory*
Juergen Pozimski	*Imperial College London*
Peter Savage	*Imperial College London*

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Overview

A Radio Frequency Quadrupole (RFQ) can be used to accelerate an ion beam. In our case this RFQ will be used to accelerate H- ions from 65keV to 3 MeV. It is part of the Front End Test Stand (FETS) accelerator line being built in R8 at the Rutherford Laboratories.

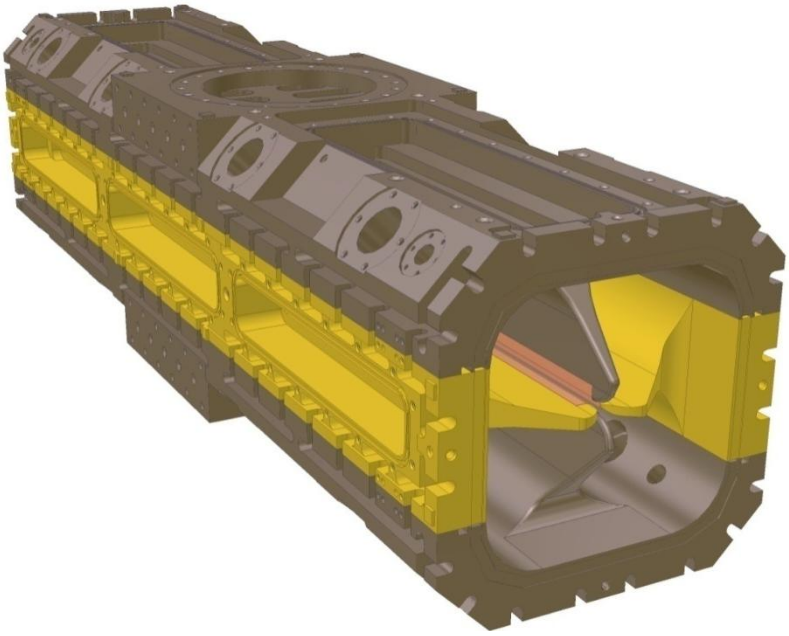


Figure 1: One metre long RFQ – an assembly of two pairs of parts

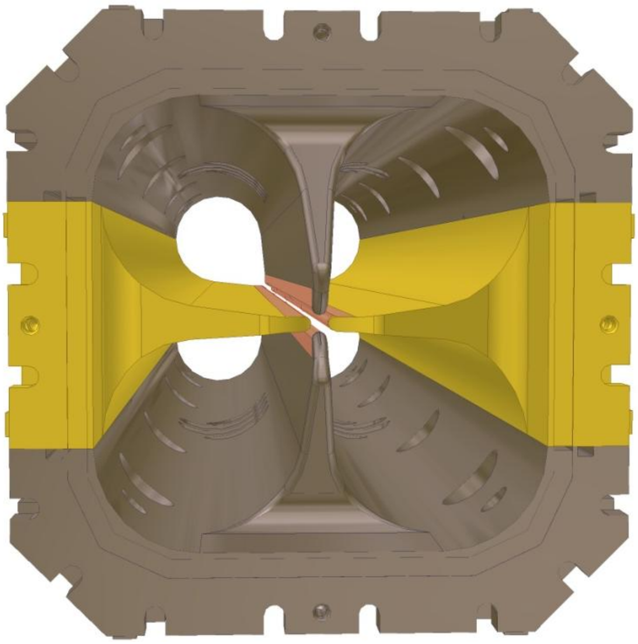


Figure 2: Looking along the RFQ beam axis

The RFQ is an assembly of two major vanes (shown in brown) and two minor vanes (shown in yellow).

Design Philosophy

Many RFQs have been built to date with varying degrees of success. The tried and tested method is to manufacture the RFQ as an assembly of parts. The complex internal geometry makes a build from solid impractical with today's machining technology.

The default method for joining the parts is vacuum brazing. This technique offers a number of advantages including:

1. Results in one solid part.
2. Good vacuum seal.
3. Good RF seal.
4. High Q value.
5. Many joints made in one operation.

Some of the disadvantages include:

1. The RFQ cannot be dismantled if required.
2. Distortion of material due to high temperatures used during brazing.
3. Annealing of material due to high temperatures used.
4. Precise stress relieving cycles required during manufacture.

The most experienced RFQ builders in the world cannot guarantee successful vacuum brazing and, even when successful sometimes RFQs do not perform to the designed specification. For these reasons the FETS team decided to pursue an RFQ design that allowed the assembled parts to be dismantled. Reasons for dismantling could include:

1. Realignment
2. Cleaning
3. Removing surface irregularities caused by sparking
4. Re-machining to change operating frequency

The price to pay for this flexibility of design includes:

1. Challenging vacuum seal.
2. Potentially lower Q value

Transverse Profile

Both the major and minor vanes use one 2D sketch to define their shape. The sketch is fully constrained to the centre origin that represents the beam axis. The result is that if one parameter is changed in the spreadsheet the assembly grows or shrinks transversally around the beam axis.

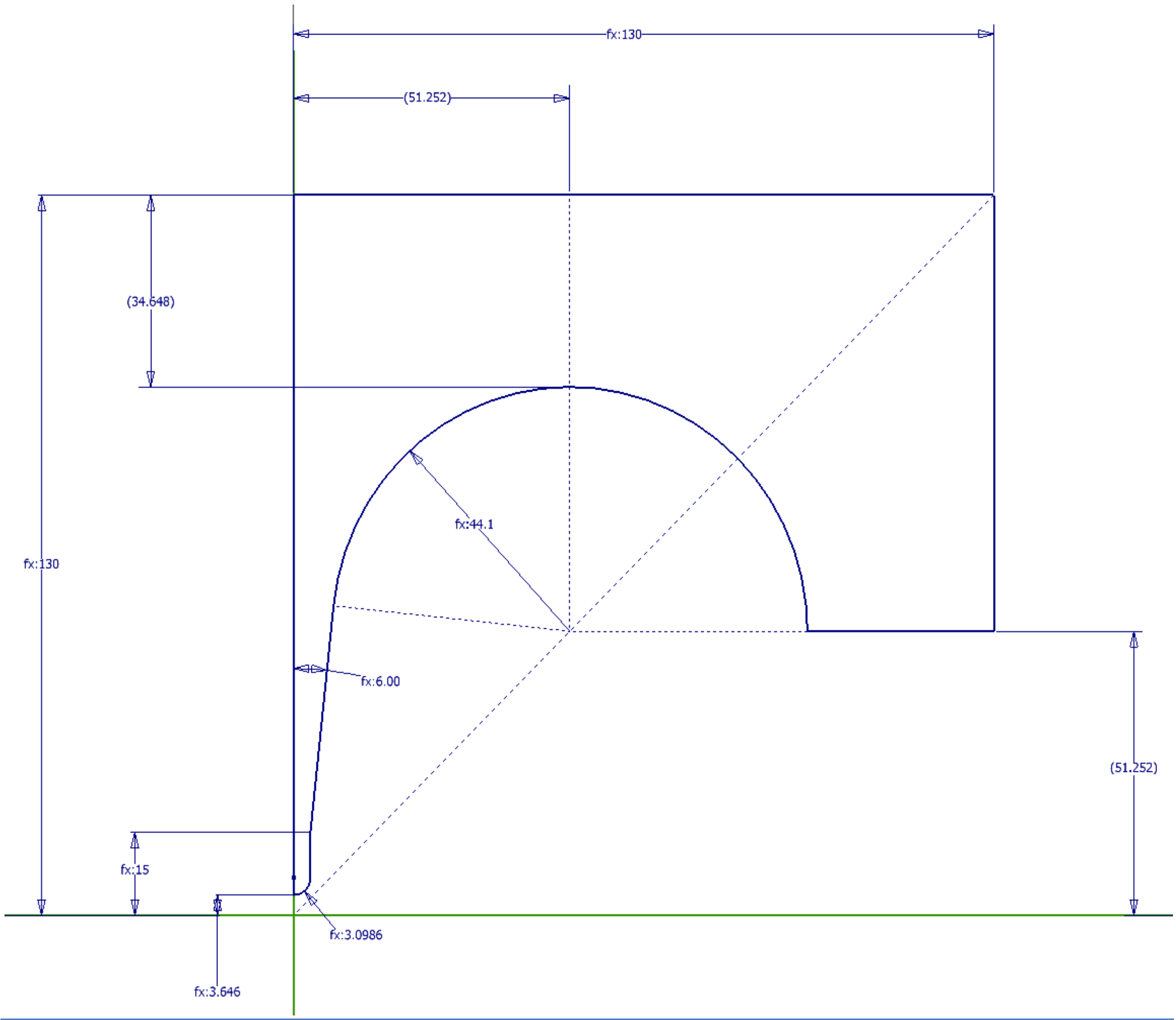


Figure 3: 2D sketch that controls the geometry of the major and minor vanes

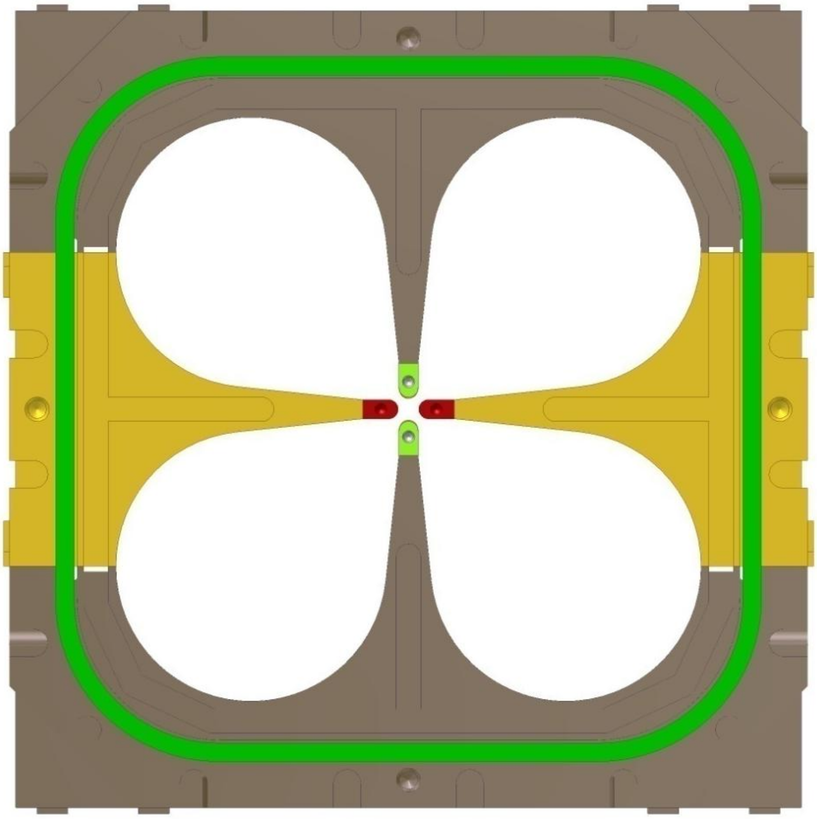


Figure 4: End view of RFQ section 1

Why is the RFQ this shape transversally?

Radiofrequency currents flow radially in the four quadrants producing two opposing vane tips of positive voltage and two opposing vane tips of negative voltage at any one time. This produces a quadrupole focusing or defocusing effect on the beam. One half cycle later the voltages change sign, reversing the focusing. The overall focusing effect keeps the beam within the small volume between the vane tips.

The importance of size and alignment

To keep the RFQ running at the designed frequency (324MHz) the size of the transverse profile and the alignment of the major and minor vanes must be tightly controlled. If the size deviates too far from the designed specification then we risk exciting dipole modes (with frequencies close to 324MHz) in addition to the desired quadrupole mode. Similarly if the alignment isn't within specification then the asymmetry will encourage the excitation of dipole modes.

Longitudinal Profile

Looking along the length of the RFQ the transverse profile remains largely the same. The changes are at the vane tips (ignoring external features).

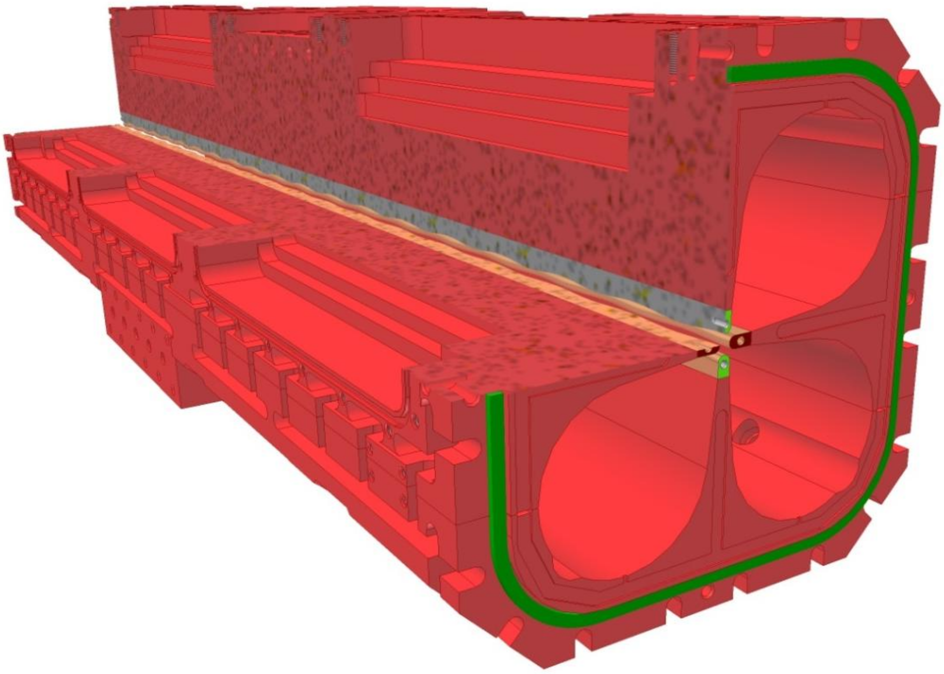


Figure 5: Three-quarter view of RFQ section 3

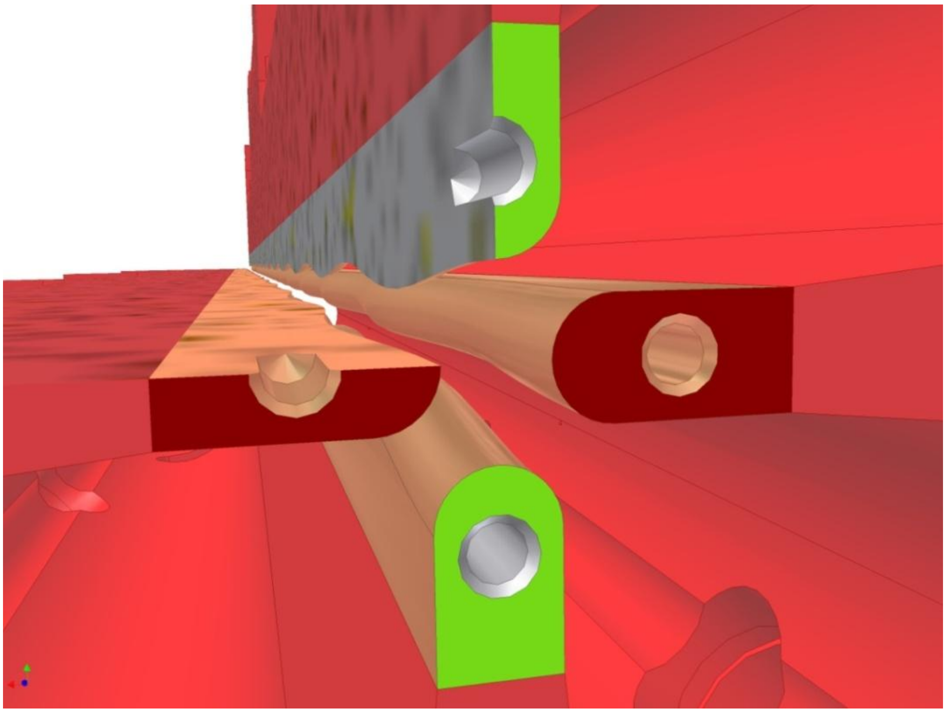


Figure 6: Close-up view showing the vane tip modulations that produce the longitudinal electric field.

Figure n: Close-up view showing the vane tip modulations that produce the longitudinal electric field.

What do the vane modulations do?

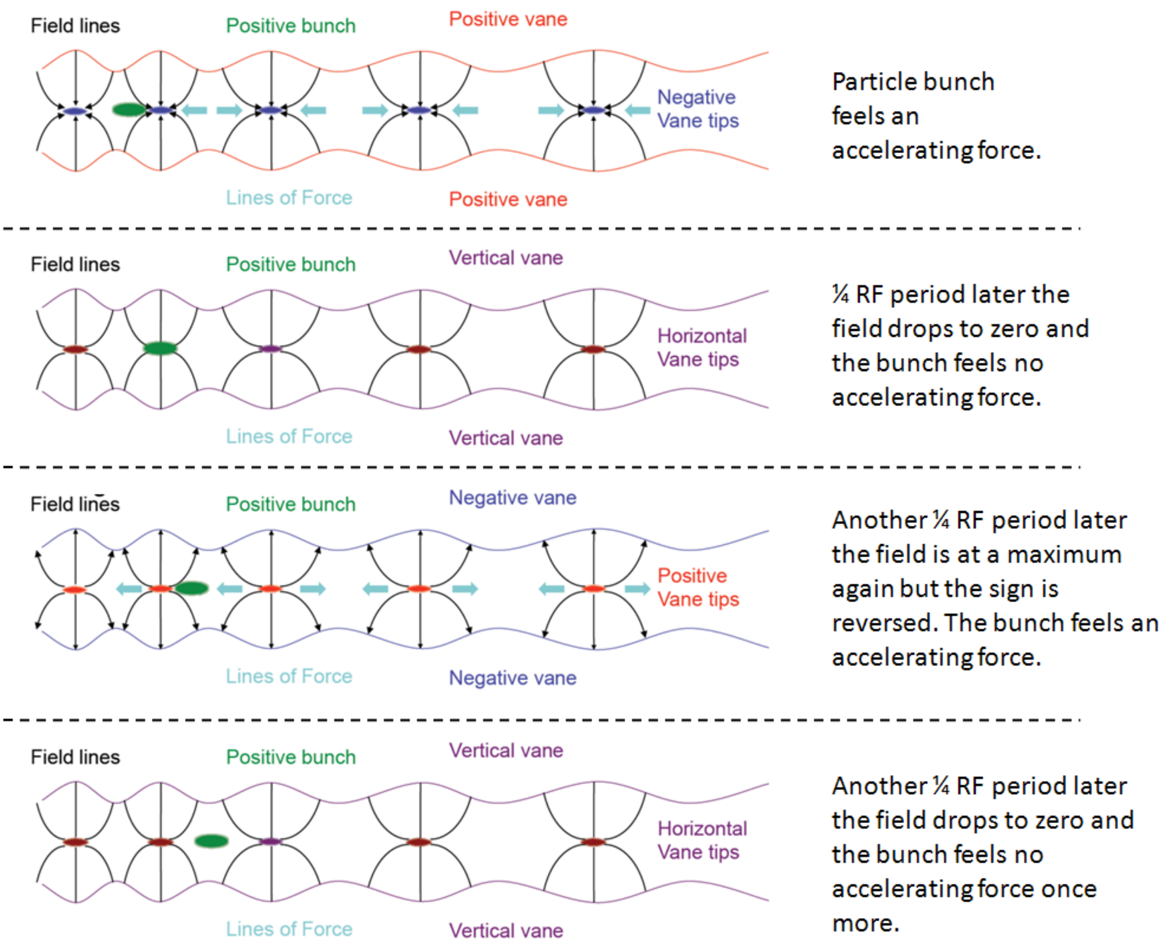


Figure 7: Sequence to show how the vane modulations accelerate a particle bunch – Simon Jolly

How were they generated?

Alan Letchford used his RFQSIM code to generate the parameters a, ma, r0 and rho. These parameters control the shape of the RFQ modulations and hence they control the acceleration performance.

Simon Jolly wrote a Visual Basic script for Autodesk Inventor that takes the parameters from a spreadsheet (RFQVaneParamsMaster.xls) and generates a 2D spline. The spline is then revolved to create a 3D rod (much like that used for a rod type RFQ). Some further manipulations are then performed to generate a vane tip, see figure 8.

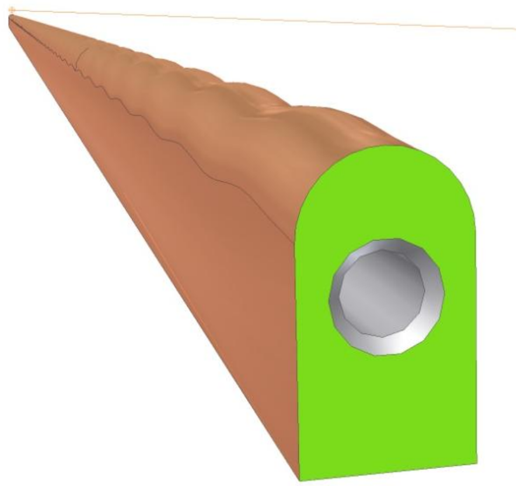


Figure 8: A vane tip with modulations

Simon then imported these vane modulation models into GPT and then later into COMSOL finite element software to perform particle tracking simulations.

This modelling procedure allowed Simon Jolly to work on the particle tracking in parallel to Peter Savage working on the mechanical design.

Major Vane

Major Vane	Stock	Finished part
Length (mm)	1050	1010,67
Width (mm)	270	260
Height (mm)	137	128,63
Mass (kg)	357	77
Material	Copper C10100	

Table 1: RFQ major vane sizes and weights

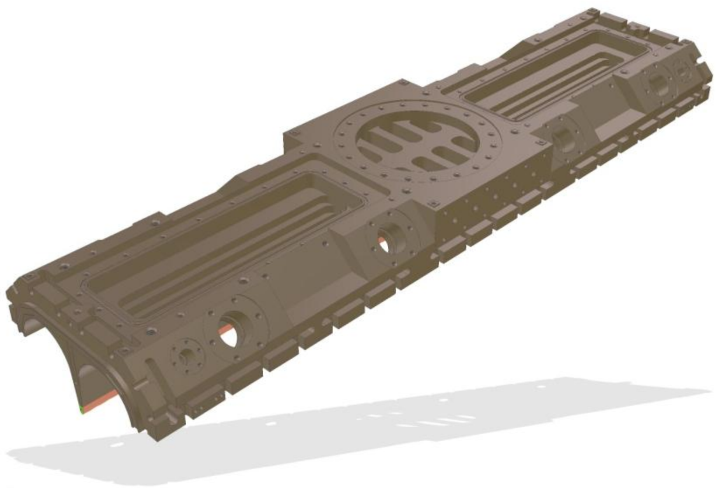


Figure 9: RFQ major vane – showing external features

Figure 10: RFQ major vane – showing internal features

Minor Vane

Minor Vane	Stock	Finished part
Length (mm)	1050	1010,67
Width (mm)	113	102,50
Height (mm)	137	128,63
Mass (kg)	148	29
Material	Copper C10100	

Table 2: RFQ minor vane sizes and weights

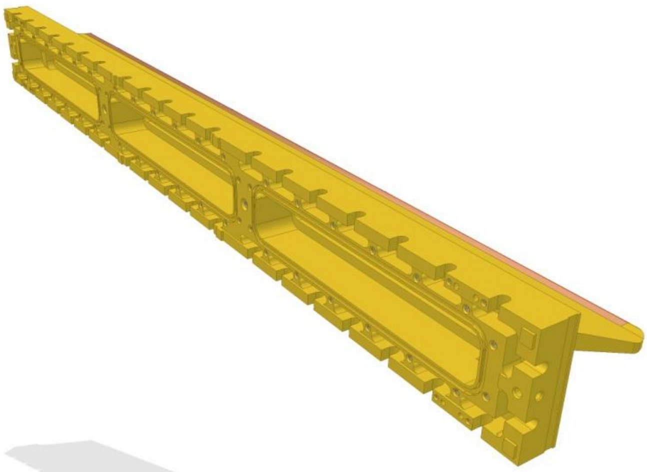


Figure 11: RFQ minor vane – showing external features

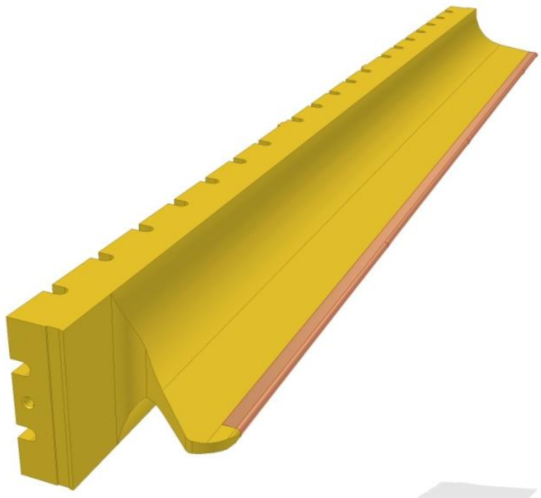


Figure 12: RFQ minor vane – showing internal vane

Datum System

Major Vane

Datum	Location	Function
A	Main face	Primary machining reference
B	Side face	Secondary machining reference
C	End face	Tertiary machining reference

With three datum planes the part is full constrained, i.e. there are no remaining degrees of freedom. What we need now is to refine the datum system to allow accurate positioning of the internal profile. By using external datum features as references for the position of the internal profile we have provided features that can be used during manufacture and assembly.

D	Interface planes (common zone)	Control alignment of vanes during assembly
E	1st dowel hole on A	External longitudinal vane modulation reference
F	2nd dowel hole on A	
G	Line linking E and F (derived feature)	Controls inner profile longitudinal alignment

The manufacturer can mount the major vane onto a simple plate with two dowels at the correct spacing for datum holes E and F and that are aligned to the machine axis – see figure n. The position of one of the dowels can be clocked and recorded. Now the vane alignment and the start position of the vane modulations can be defined by the position of the first dowel centre and the derived axis between the two dowels centres. These external references can be used both for vane to vane alignment during assembly and for alignment of the assembled RFQ section onto the FETS.

H	Vacuum port centre
J	45^0 faces
K	Probe port axis
L	Tuner port axis

The remaining datums control the locations of external features.

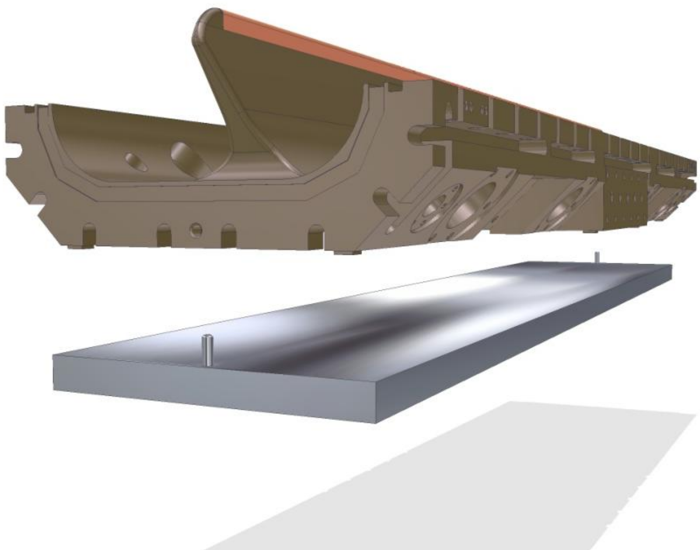


Figure 13: Major vane with machining mounting plate

MINOR VANE

Datum	Location	Function
A	Main face	Primary machining reference
B	Side face	Secondary machining reference
C	End face	Tertiary machining reference

The interface planes for the minor vane have a high degree of accuracy for separation and parallelism. They do not define the relative height of the vane and therefore a dowel hole is introduced onto the end face for this purpose.

D	Dowel hole on face C	External reference for vane profile (eq to D above)
E	1st dowel hole on A	External longitudinal vane modulation reference
F	2nd dowel hole on A	
G	Line linking E and F (derived feature)	Controls inner profile longitudinal alignment

The remaining datums control the locations of external features.

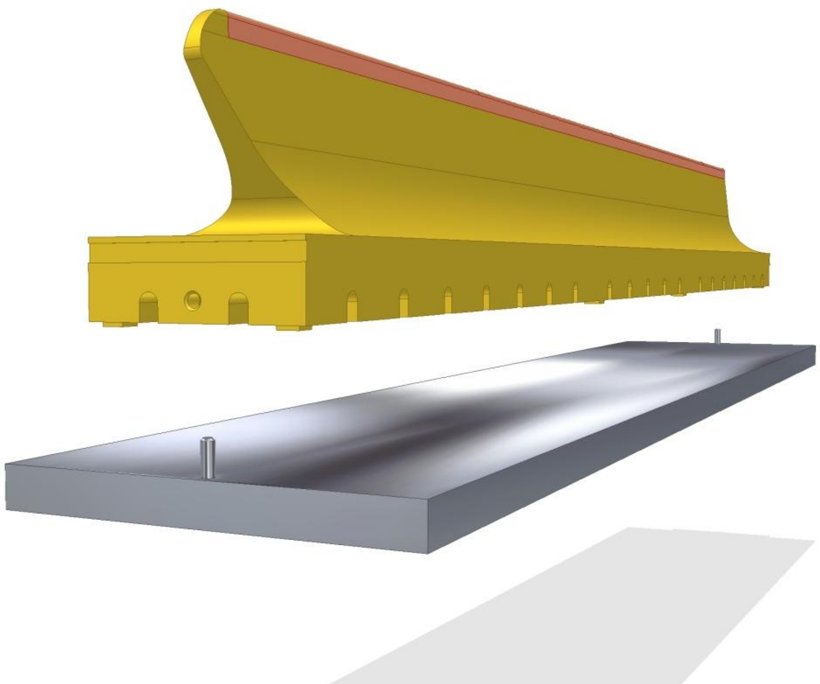


Figure 14: Minor vane with machining mounting plate

Frequency Modelling

Scott Lawrie (RAL) and Saad Alsari (Imperial College) performed extensive modelling simulations to study the effects of features that impacted on the RFQ internal volume and hence the RFQ frequency.

The features studied include:

- Quadrant radius
- Model length
- Influence of ports
- Influence of tuner depth

Autodesk Inventor CAD software was used to create the 3D solid models representing the RFQ internal volume – see figure n. This 3D CAD file was then passed to Saad and Scott who performed FEA modelling using COMSOL and ANSYS respectively.

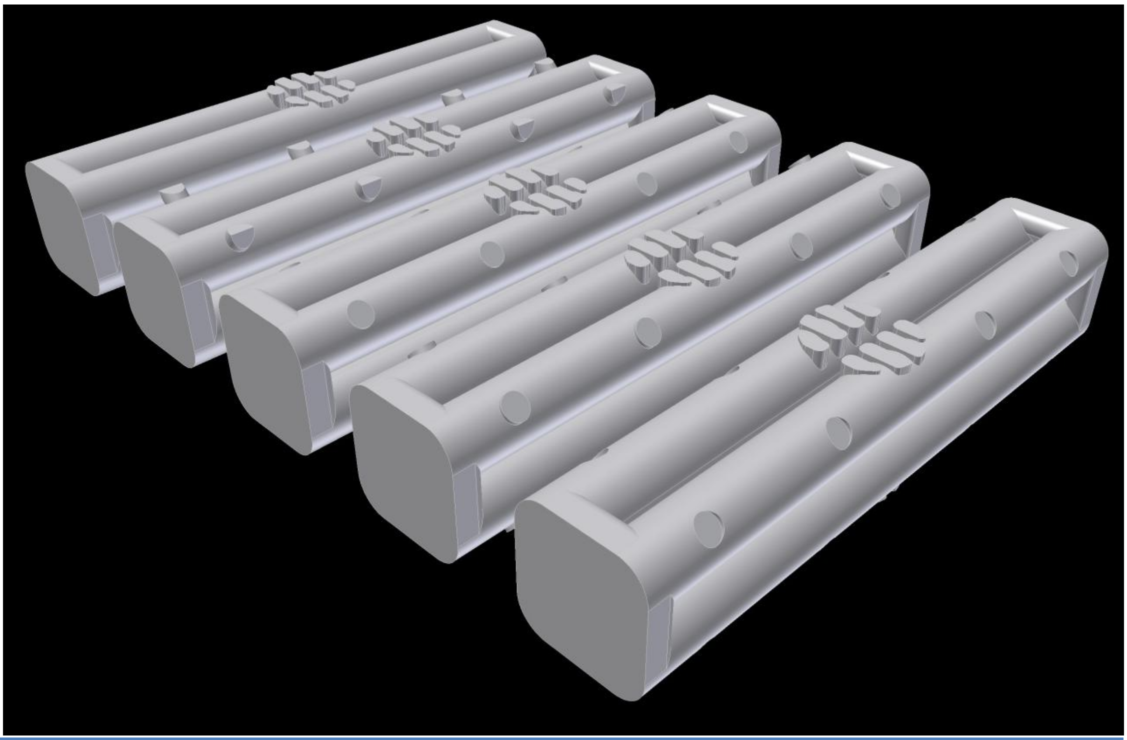


Figure 15: 3D CAD data in SAT format used to study the effect of tuner depth on frequency

As a rule of thumb the quadrant radius to frequency relationship can be taken as:

0,1mm quadrant radius change = 800kHz frequency change

Hence the use of a profile tolerance of 0,05mm which incorporates size, location, orientation and form to produce a structure with a potential deviation of 400kHz from the designed frequency. This is within the range of the tuners.

Vacuum Port

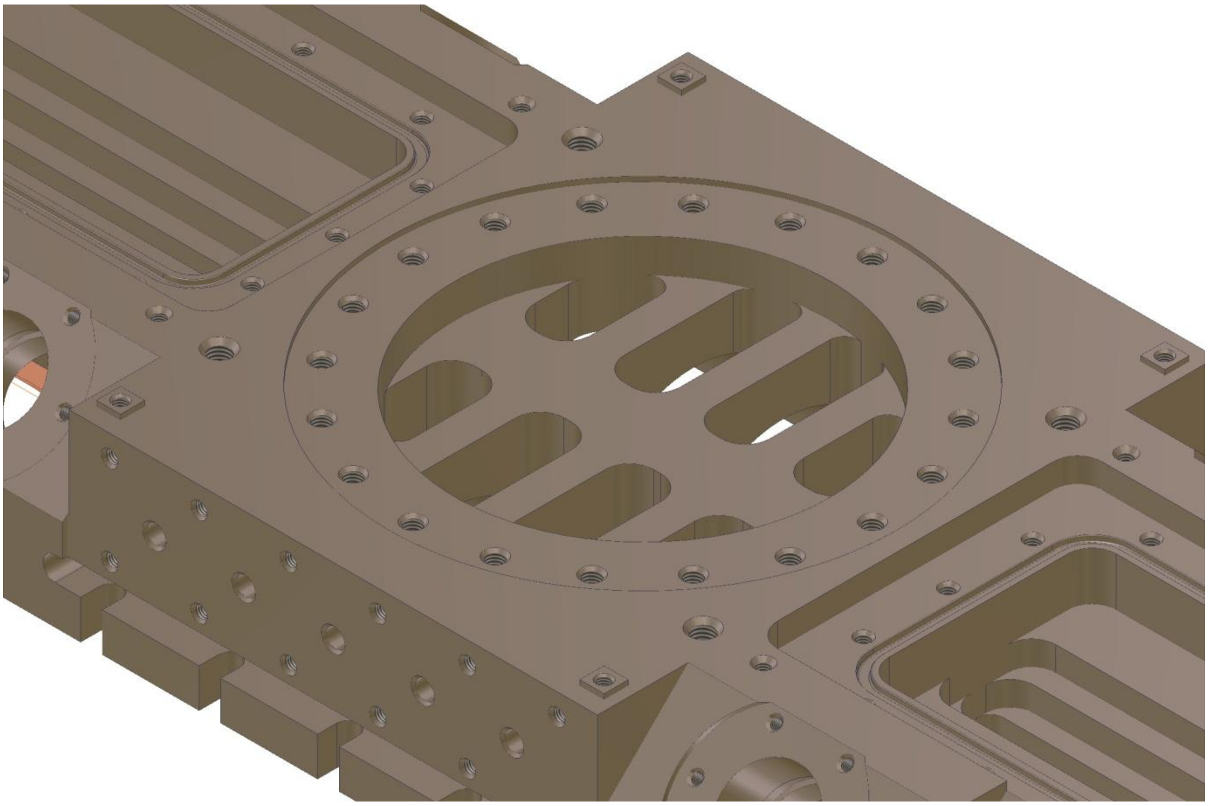


Figure 16: RFQ major vane vacuum port

Features:

Recessed to protect vacuum sealing face from scratches.

Stainless steel interface flange used to prevent excessive use of tapped holes in copper.

Standard CF? Used

Keep short distance from pump to RFQ body to maximise pumping efficiency.

Large diameter as possible to maximise pumping efficiency.

Water cooled through webs.

Central to the (varying) length RFQ sections

Webs optimised for maximum pumping efficiency with sufficient width for cooling channels.

leybold

TURBOVAC MAG W 830
DN 160 CF

Part no. 400100V0041

Pumping speed:	900 l / s (Nitrogen)
Ultimate pressure:	< 1 x 10^{-10} mbar
Connecting flange high-vacuum:	DN 160 CF Connecting flange fore-vacuum: DN 40 ISO-KF water-cooled

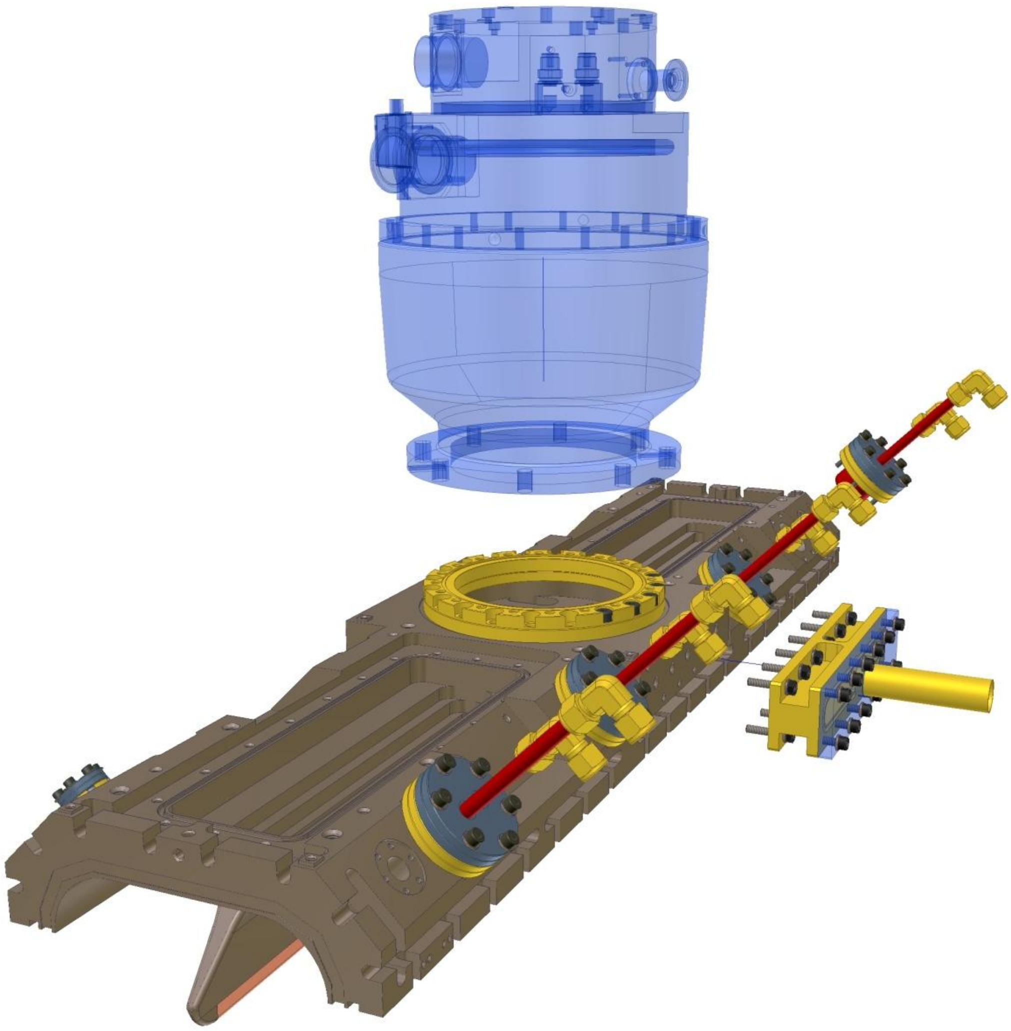


Figure 17: Exploded view of major vane showing vacuum pump mounting

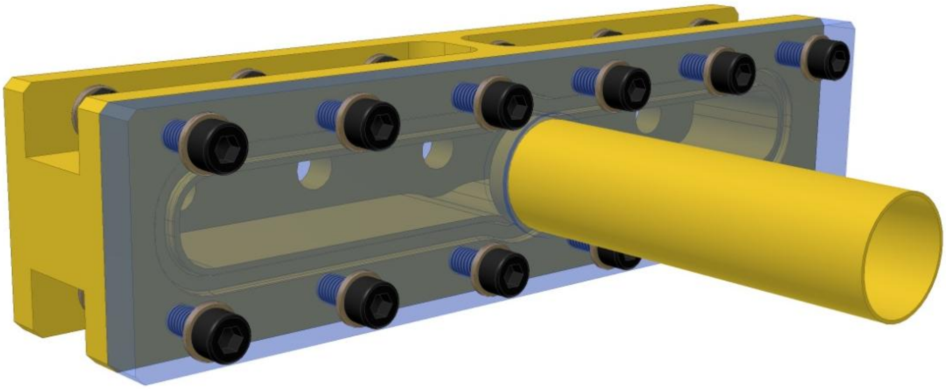


Figure 18: Vacuum port cooling manifold

Vacuum seal

The internal volume of the RFQ is required to be under a vacuum pressure in the low 10^{-6} mbar region.

Many techniques for joining the RFQ assembly (to achieve a good vacuum seal) have been investigated including:

1. Vacuum brazing
2. Laser welding
3. Friction stir welding
4. Using Indium wire as a gasket
5. Using a 3D bonded rubber O ring

Our FETS RFQ cold model was assembled using vacuum brazing with some success. The remaining welding techniques have been investigated but not exhaustively. Laser welding could offer several advantages to the RQF builder. Insufficient resources prevented a complete evaluation of the various joining techniques.

A desire to be able to disassemble the FETS RFQ led to investigations of gaskets to provide the vacuum seal. A vacuum seal was achieved using Indium wire but the assembly process was found to be very sensitive and regarded to be impractical at full scale. A bonded rubber gasket was found to maintain a good vacuum seal at elevated temperatures and could be produced at low cost with basic fixtures. For these reasons the bonded rubber gasket is the sealing method used for the FETS RFQ.

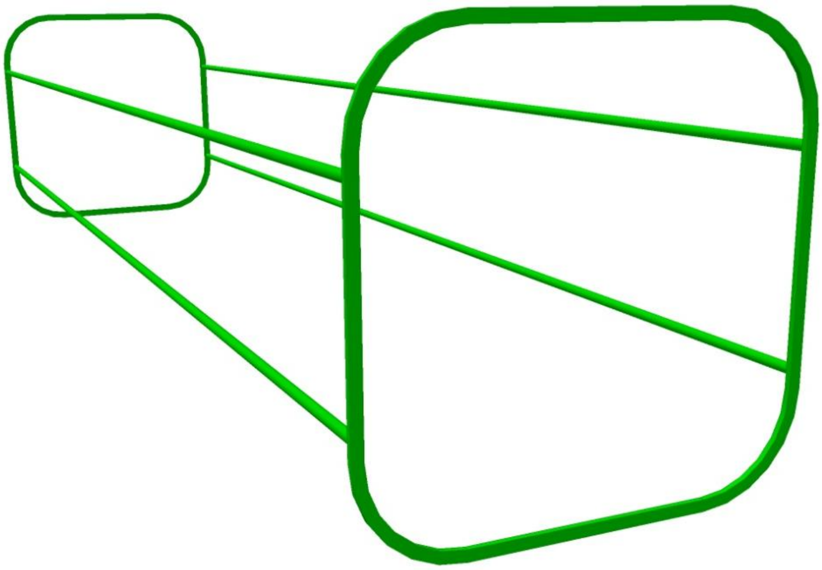


Figure 19: 3D Viton O ring

One weld test model assembly was used to vacuum test the rubber O ring design.

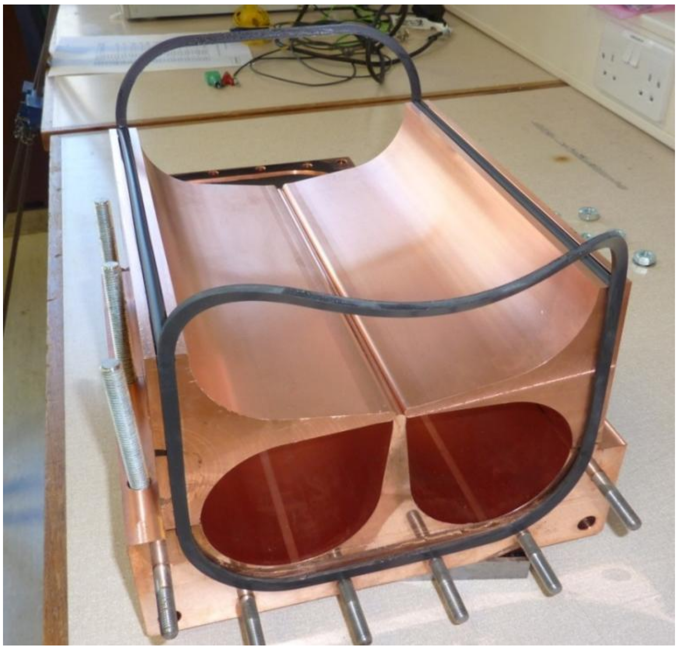


Figure 20: Weld test model with 3D rubber seal in place

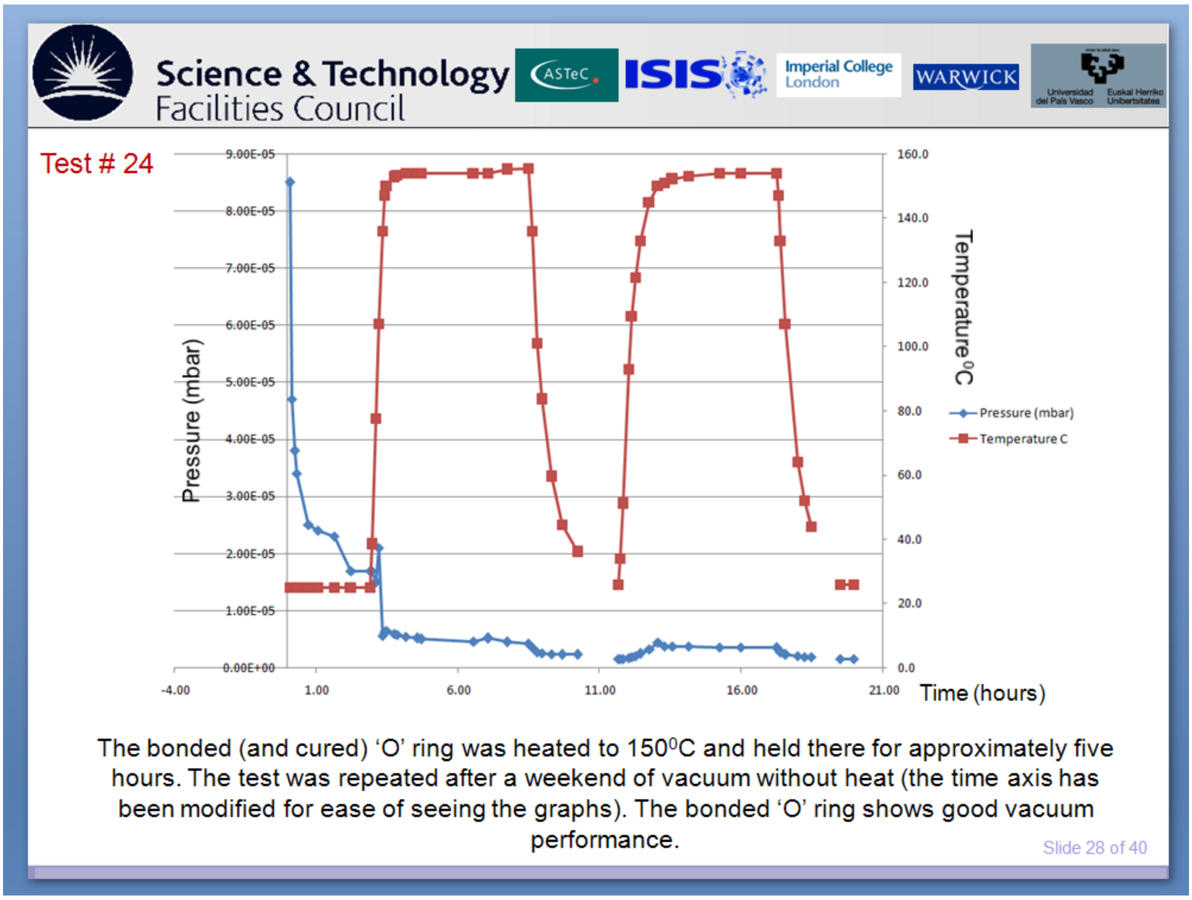
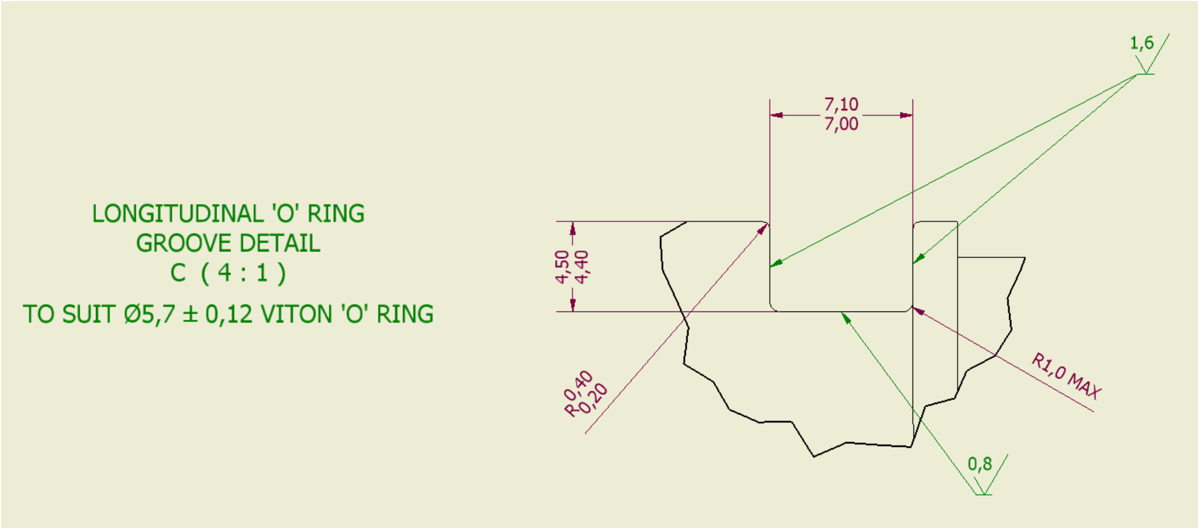


Figure 21: Vacuum performance of 3D O ring at elevated temperatures (talk # 64)


LONGITUDINAL 'O' RING
GROOVE DETAIL
C (4 : 1)
TO SUIT Ø5,7 ± 0,12 VITON 'O' RING
1,6
7,10
7,00
4,50
4,40
R0,40
R0,20
R1,0 MAX
0,8

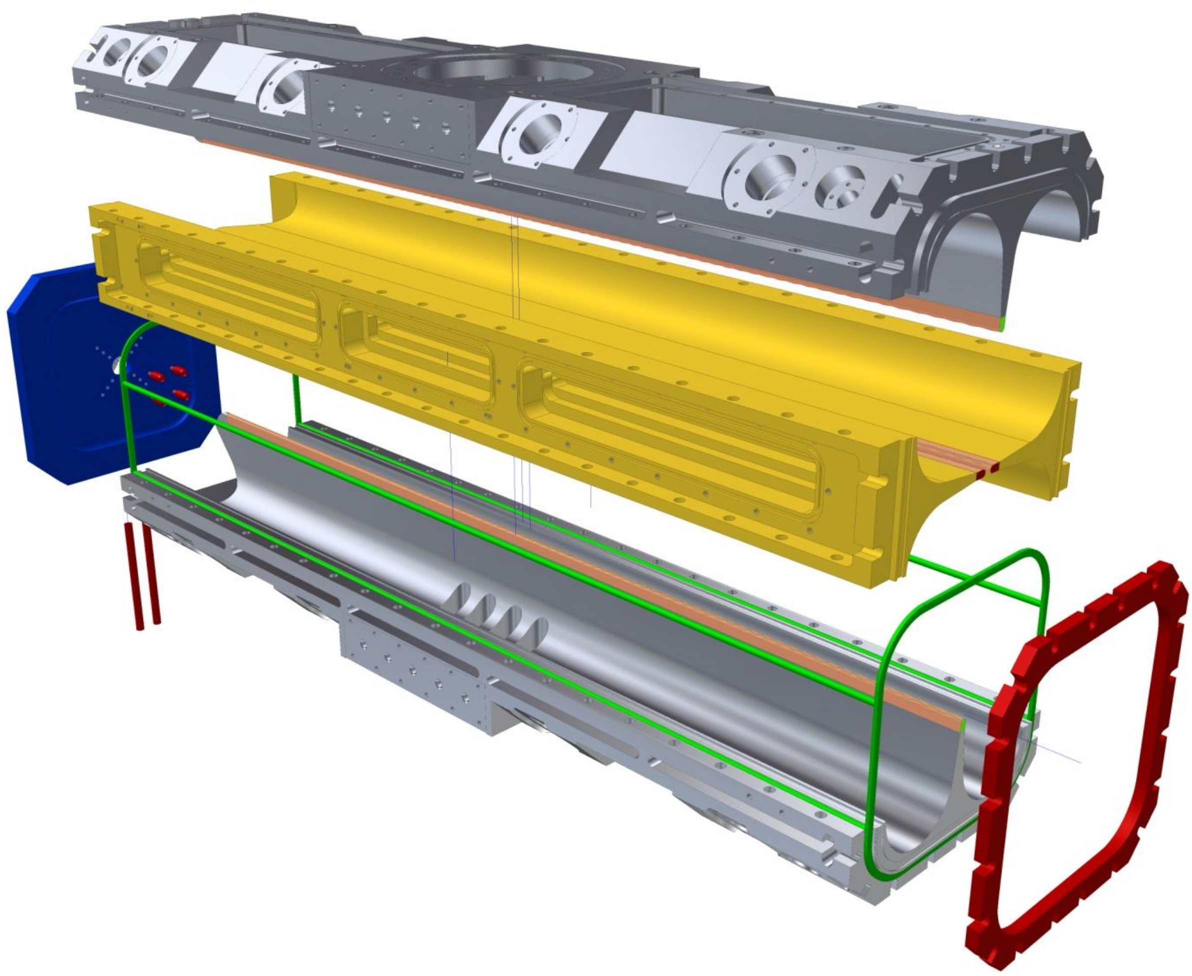


Figure 22: Exploded view showing 3D O ring vacuum seal

Probe Port

Name: Probe Port

Function: Provide CF16 port for vacuum measurement and/or analysis

Quantity: 4 per major vane

Technical Data C15

DN	CF	16	40	63	100	160	200	250
~~Outside diameter o. D.~~	~~inch~~	~~1.33"~~	~~2.75"~~	~~4.50"~~	~~6.00"~~	~~8.00"~~	~~10.00"~~	~~12.00"~~
Outside diameter o. D.	mm	34.0	69.5	113.5	152.0	202.5	253.0	305.0
~~Inside diameter i. D.~~	~~inch~~	~~0.33"~~	~~1.375"~~	~~2.50"~~	~~4.00"~~	~~6.00"~~	~~8"~~	~~10.00"~~
Inside diameter i. D.	mm	16.0	36.8	66.0	104.0	155.0	200.0	250.0
Bolt circle diameter k	mm	27.0	58.7	92.2	130.3	181.0	231.8	284.0
High h	mm	7.5	13.0	17.5	20.0	22.0	24.5	24.5
Number of holes		6	6	8	16	20	24	32
Hole diameter	mm	4.3	6.6	8.4	8.4	8.4	8.4	8.4

Conversion Factors

1. Magnetizing field H, unit:	$A \times m^{-1}$
Previously used unit: Oerstedt (Oe)	$1\ Oe = 79{,}577\ (A \times m^{-1})$
2. Strength of the magnetic field B, unit:	$Vs \times m^2$ = Tesla (T)
Previously used unit: Gauß (G)	$1\ G = 10^{-4}\ Vs \times m^2 = 10^{-4}\ T$

Leybold Vacuum Full Line Catalog 2005 — 3 | C15

Table 3: CF flange dimensions, source Leybold 2005

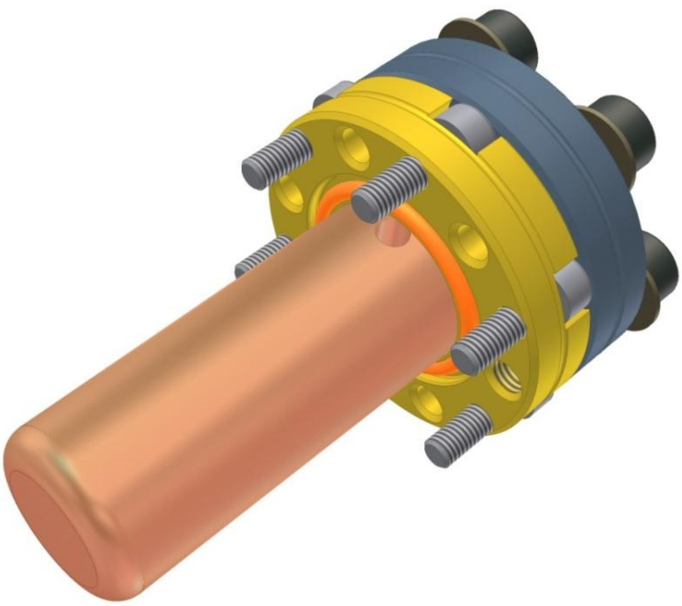


Figure 23: Probe Port plug assembly

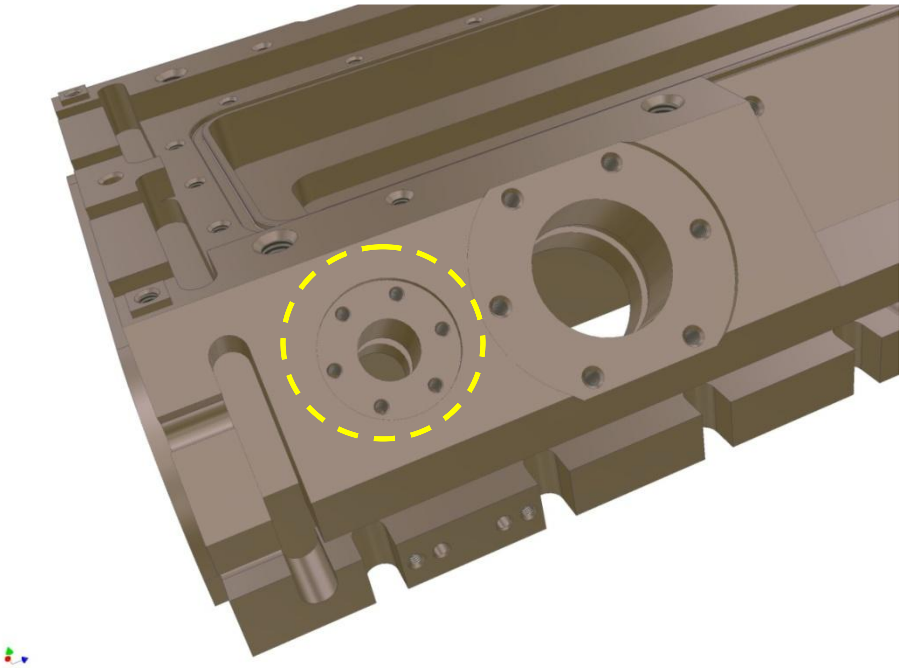


Figure 24: Probe Port location on RFQ major vane

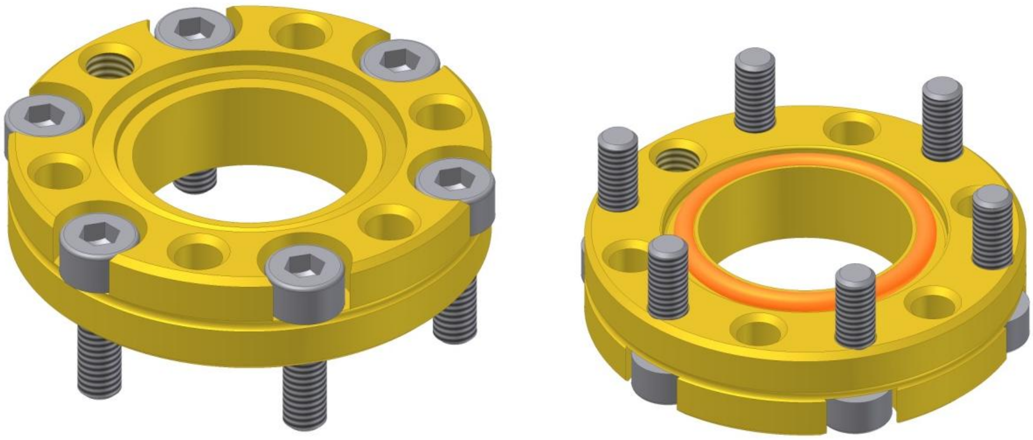


Figure 25: Probe port modified CF16 bored flange

Flange:	Modified Kurt Lesker CF flange F0133X000NM
Vacuum seal:	Viton O ring 0181-16
Screws:	M3 x 12 Stainless Steel Caphead

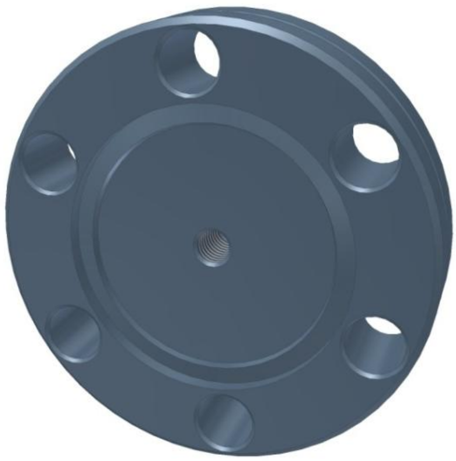


Figure 26: Probe port modified CF16 blank flange

Flange:	Modified Kurt Lesker CF flange F0133X000N
Vacuum seal:	Viton or copper standard CF gasket
Screws:	M4 x 12 Stainless Steel Caphead

Tuners

The tuners are simple cylinders that fit into ports that are equi-spaced transversally in the RFQ. There are 8 tuner ports per major vane giving a total of 16 tuner ports per 1m length of RFQ. Each tuner will be water cooled and mounts to the RFQ via a stainless steel interim flange. This will protect the copper threads from stripping.

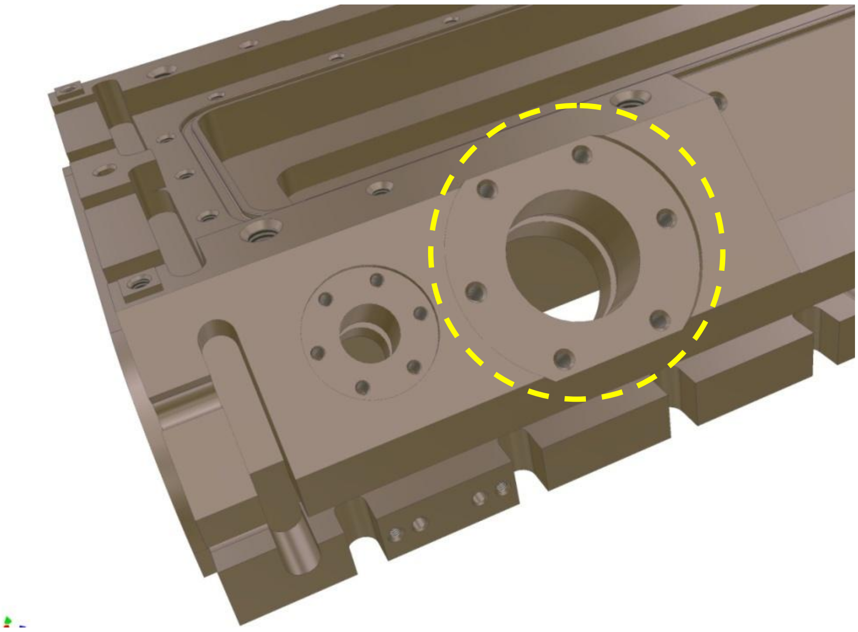


Figure 27: Tuner port location on RFQ major vane

The RFQ frequency has been modelled to be correct when the tuner faces are sitting flush with the inner surface of the quadrant radius. Once the RFQ has been assembled a bead pull test will determine whether the longitudinal fields are sufficiently flat. If required the tuners will be skimmed to make them protrude less, increasing the internal volume and driving the frequency down. Alternatively the interim flange will be skimmed making the tuner protrude into the cavity, reducing the internal volume and driving the frequency up.

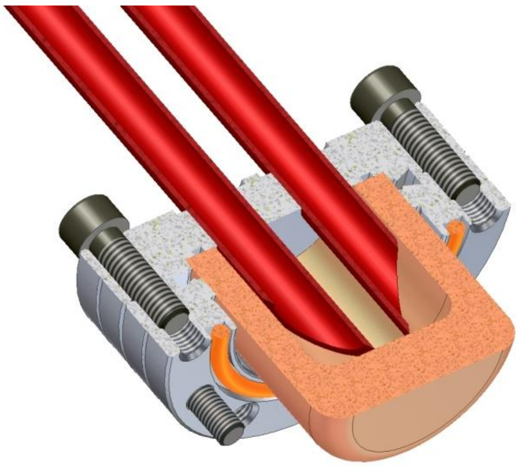


Figure 28: Section view of static tuner

In addition one tuner port per 1m RFQ section will be fitted with a moveable tuner. The aim of the moveable tuner is to constantly move into and out of the RFQ in response to a signal from the feedback system. A loop protruding inside the RFQ will send a signal to the feedback system. The frequency will change due to volume changes caused by fluctuations in temperature. The movement is provided by a ZLTM50M (stepper motor) linear shift mechanism from VG Scienta.

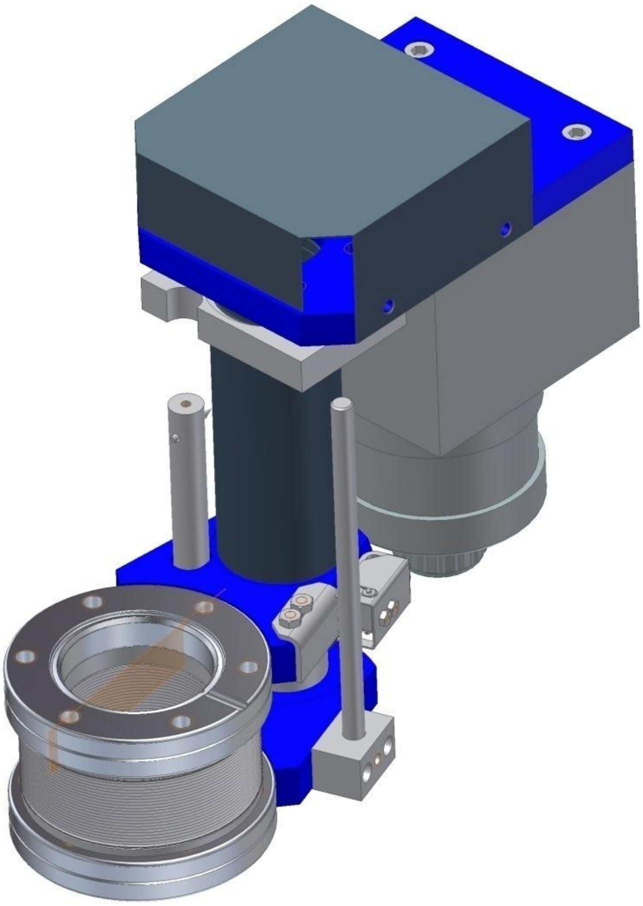


Figure 29: ZLTM50M linear shift from VG Scienta

Linear Transfer Mechanism - LTM Series

Linear Transfer Mechanism LTM

- Range of travel 25 to 100 mm
- Easy adjustment
- Graduated scale in 1mm increments
- Fully bakeable to 250 °C
- Operating temperature range -20 °C to +200 °C
- Fitted with tapped flanges at both ends
- Positive stops at extremes of movement
- Motorised resolution is 0.25 µm per half step

VG SCIENTA
a gammadata company

Specifications	
Clear bore through bellows	38.0 mm
Parallelism of flange faces	Within 0.04 mm/cm
Concentricity of flange bores	Within 0.5 mm
Approximate torque required to elevate	1.2 Nm
Maximum applied axial load	200 N
Maximum applied radial load (to small pillar)	50 N
Operating pressure range	1 bar to 10^{-11} mbar

Linear Transfer Mechanism - LTM Series

Flange OD mm[1]	Flange OD inch[1]	Travel	Operation	A Extended	A Compressed	B Extended	B Compressed	Bake Temp °C	Shipping weight kg	Order Code
70T	2.75	25	Manual	63	38	159	134	250	3.2	ZLTM25
70T	2.75	50	Manual	92	42	215	165	250	3.4	ZLTM50
70T	2.75	75	Manual	125	50	258	183	250	3.8	ZLTM75
70T	2.75	100	Manual	163	63	310	210	250	4.2	ZLTM100
70T	2.75	150	Manual	215	65	434	284	250	4.6	ZLTM150
70T	2.75	25	Motorised[2]	63	38	162	137	250[3]	4.4	ZLTM25M
70T	2.75	50	Motorised[2]	92	42	218	168	250[3]	4.6	ZLTM50M
70T	2.75	75	Motorised[2]	125	50	261	186	250[3]	5.0	ZLTM75M
70T	2.75	100	Motorised[2]	163	63	313	213	250[3]	4.4	ZLTM100M
70T	2.75	150	Motorised[2]	215	65	437	287	250[3]	5.8	ZLTM150M
70T	2.75	25	DC Motor[4]	63	38	162	137	250[3]	4.4	ZLTM25D
70T	2.75	50	DC Motor[4]	92	42	218	168	250[3]	4.6	ZLTM50D
70T	2.75	75	DC Motor[4]	125	50	261	186	250[3]	5.0	ZLTM75D
70T	2.75	100	DC Motor[4]	163	63	313	213	250[3]	4.4	ZLTM10DC
70T	2.75	150	DC Motor[4]	215	65	437	287	250[3]	5.8	ZLMT15DC

All dimensions in mm unless otherwise stated.

Notes

(1) 70T mounting flanges have M6 tapped bolt holes.

(2) Drive is assembled to stepper motor and is supplied with a wired connector to suit VG Scienta's stepper motor control system. A separate mating connector is available (Details).

(3) Motor must be removed for bakeout.

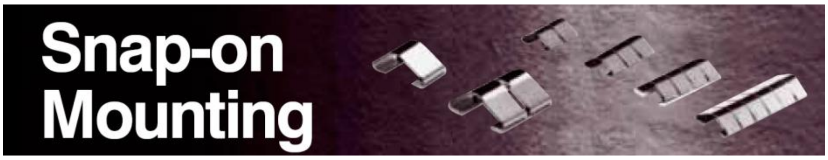
(4) DC motor supplied complete with power supply (Details)

LTM Series - Accessories

Figure 30: Linear Transfer Mechanisms by VG Scienta

Finger Strip RF Seal

LONGITUDINAL AND TRANSVERSE JOINTS



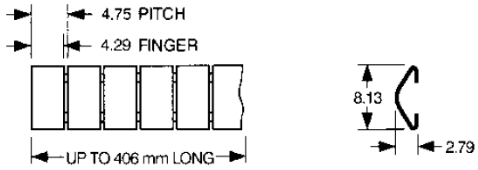
ECP 0612

SYMMETRICAL

Performance Range

	25% Compression		50% Compression
Standard 0.089 Thk.	43 kg/m	to	109 kg/m
"LC" Style 0.05 Thk.	13 kg/m	to	42 kg/m

Material: beryllium copper – .09 mm thick (LC style– .05 mm thick)



Groove depth: 25% to 50% compression.

Thickness = 2.79mm ~ 2.80mm

25% of 2.80mm = 0.70mm. Therefore groove depth = 2.10mm.

50% of 2.80mm = 1.40mm. Therefore groove depth = 1.40mm.

37.5% depth longitudinal (Groove on one side only) = 1.75mm +/- 0.2mm

37.5% depth transverse (Groove on both sides) = 0.88mm +/- 0.1mm

Load at 37.5% compression = 76 kg/m

Groove width: 8.00mm +/- 0.1mm

Supplier: TBA Electro Conductive Products Ltd.

Quantity: 6m per 1m RFQ assembly

Order quantity = 30m

TUNER AND PROBE PORTS

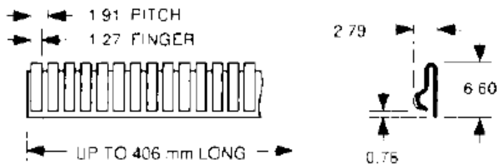
ECP 0694

REVERSE BEND SPHERICAL

Performance Range

	25% Compression		50% Compression
Standard 0.15 Thk.	13 kg/m	to	25 kg/m

Material: beryllium copper – .16 mm thick



Groove depth: 25% to 50% compression.

Thickness = 2.79mm ~ 2.80mm

25% of 2.80mm = 0.70mm. Therefore groove depth = 2.10mm.

50% of 2.80mm = 1.40mm. Therefore groove depth = 1.40mm.

37.5% depth (Groove on one side only) = 1.75mm +/- 0.2mm

Load at 37.5% compression = 19 kg/m

Groove width: 6.60mm +/- 0.1mm

Supplier: TBA Electro Conductive Products Ltd.

Quantity: 3m per 1m RFQ assembly

Order quantity = 15m

How much current will the finger strip need to withstand?

“Assuming 500 kW of RF power in the copper I get an rms current averaged over the structure of 10.4 kA based on the surface resistance. However this current flows through all the four fingerstrip joints simultaneously giving 26 A/cm rms peak for a 4m RFQ or 2.6 A/cm rms averaged for the duty factor.” – Alan, 27th Sep 2011

Cooling Pockets

The RF power fed into the RFQ will make it hot. If it gets hot it will grow and go off-tune. We therefore need to maintain a stable temperature and this will be achieved with cooling water circuits. Conventionally RFQs have gun drilled channels running the full length that are blanked off at the end faces using vacuum brazed copper plugs. Access to the drilled holes is via holes drilled into the outer faces. Our design philosophy of avoiding vacuum brazing meant that this option would have required a novel end face plug seal. In addition, to avoid having a water seal inside the vacuum and to avoid the problems caused by deep drilling holes in copper we opted to mill channels into the RFQ from the outer faces.

The advantages of this concept include:

1. No water seal inside the vacuum
2. No need to consider drift from long gun drilled holes
3. Accessible for cleaning
4. The coolant run can be modified by modifying the baffles.

The disadvantages of this concept include:

1. Large volume of material needs to be removed to get close to the vane tip
2. Getting coolant close to the vane cutback is challenging

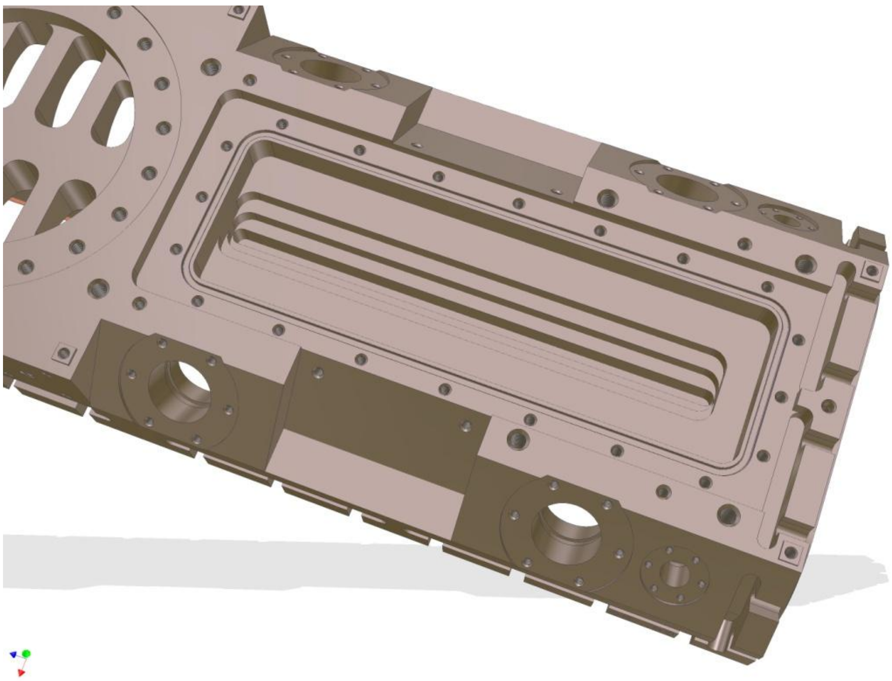


Figure 31: Major vane cooling pockets

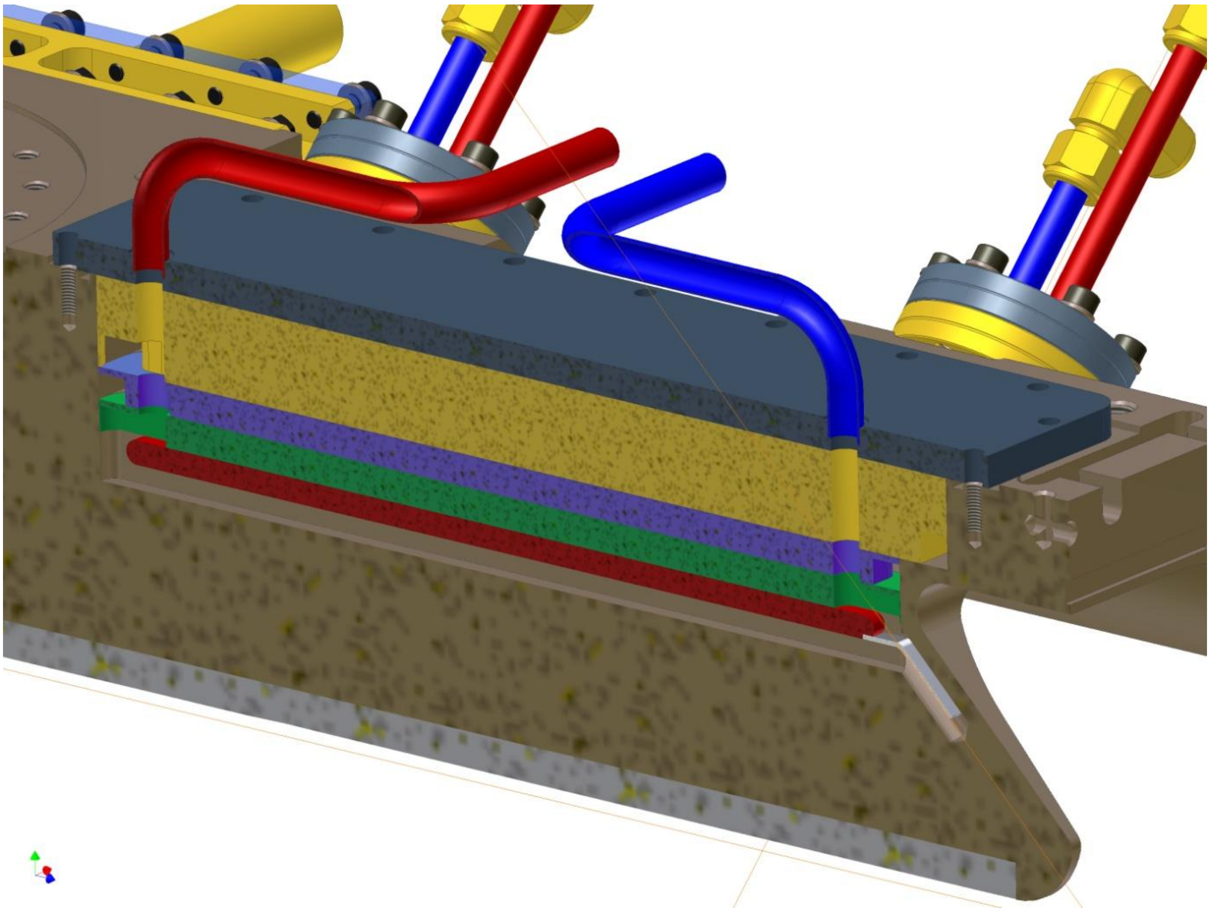


Figure 32: Section view showing major vane fitted with cooling baffles

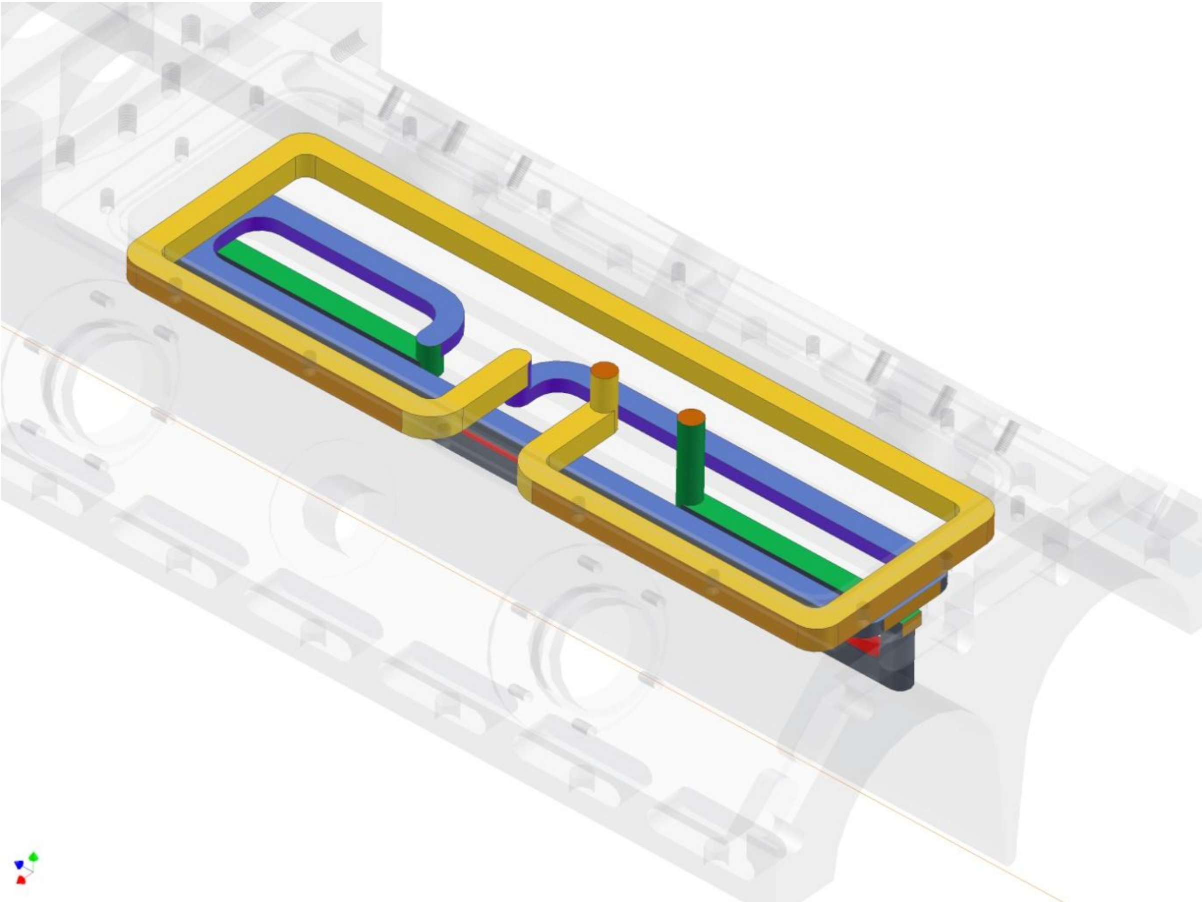


Figure 33: Coolant path around baffles in major vane

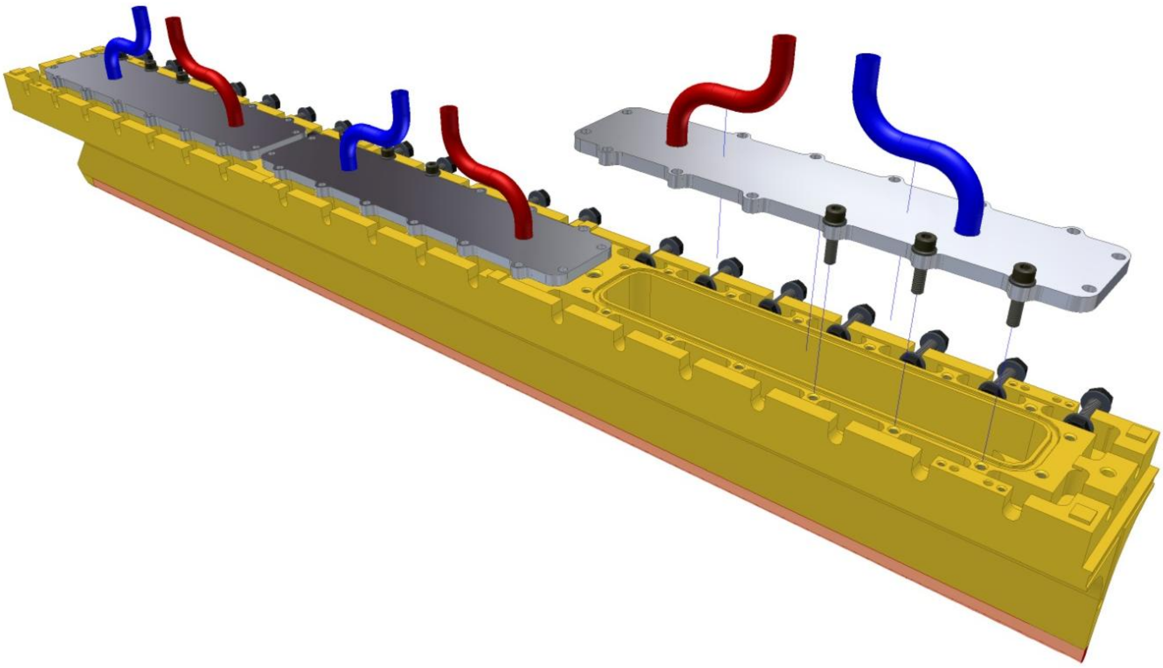


Figure 34: Minor vane cooling channel lids – baffles not shown

Support System

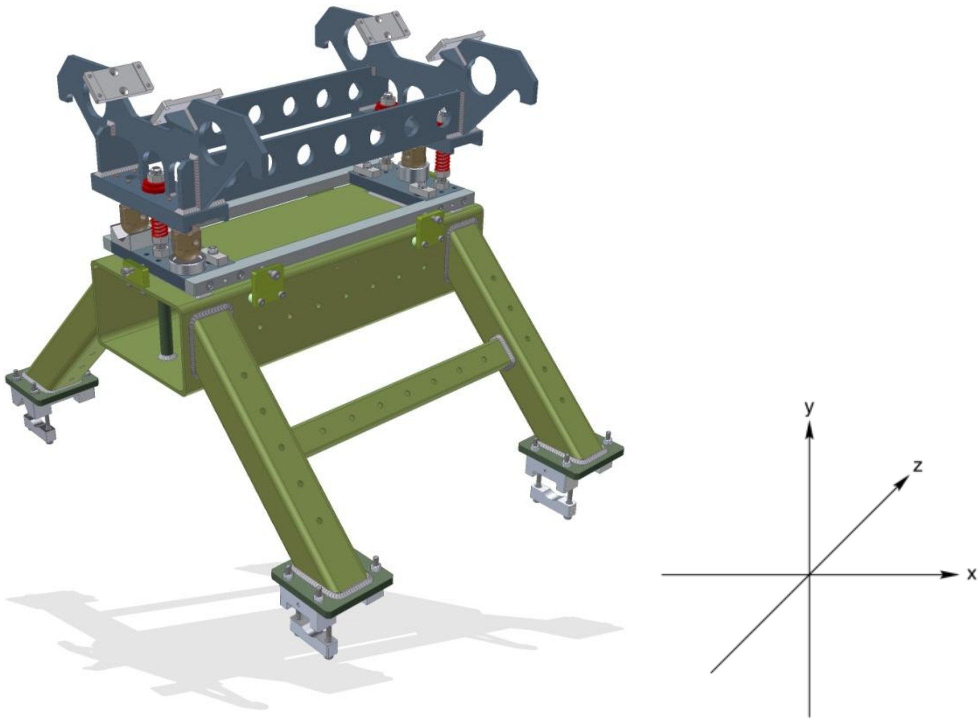


Figure 35: RFQ 1m section support system

Each (nominally) 1m long RFQ section is mounted into a cradle which in turn mounts to a support frame via a kinematic system. The entire support system can be moved in Z along the FETS rail system.

The centre of the FETS rail system is at 800mm above the hall floor. The FETS beam axis is 800mm above the rail system centre (the plane that passes through the axes of both rails).

Figure 36: Four RFQ support frames on the FETS

RFQ Alignment

The procedure for aligning each RFQ section relative to the beam axis will be discussed and approved by the RAL alignment team.

The main alignment steps can be envisaged as:

1. Levelling
2. Setting the height
3. Setting the transverse alignment

Levelling:

Adjust the three screw jacks until the datum pads that create datum face A on a major vane are level to within 50 microns. This will ensure that the vanes have a rotation of less than $0{,}011^0$ - see figure n. Each screw jack uses a standard M20 x 2,5 thread which provides 50 microns translation for a 7.2^0 turn.

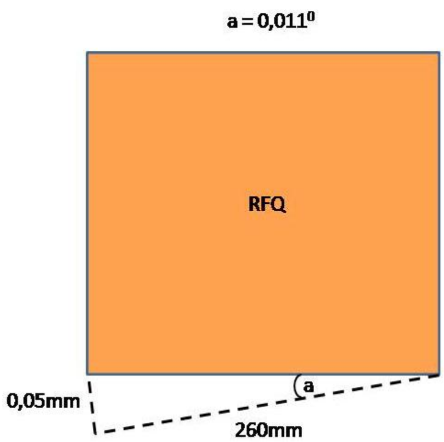


Figure 37: RFQ transverse rotation

Setting the height:

Rotate the three screw jacks by the same amount to achieve the desired height. If required dowel holes on the end faces of the RFQ can be used as a reference to the position of the vane tips.

Setting the transverse alignment:

Undo the bolts on the base of the kinematic system and use the jacking screws to position the frame transversally. Longitudinal positioning will be made when the RFQ sections are bolted together.

Bulk Copper

Based on LME price on afternoon of 10th February 2011 of £6147 - **ORDERED**					
Size	**Quantity**	**Unit price**	**Amount**	**Unit weight**	**Weight**
		£	£	kg	kg
137 x 270 x 1050	6	£3,708.26	£22,249.56	357	2140
137 x 113 x 1050	6	£1,542.22	£9,253.32	148	890
137 x 270 x 1100	2	£3,898.88	£7,797.76	375	750
137 x 113 x 1100	2	£1,611.54	£3,223.08	155	310
			£42,523.72		**4090**
Test certificate	4	£35.00	£140.00		
Delivery			£180.00		
Grand total			**£42,843.72**		

Table 4: Copper prices and weights

METELEC

Component Engineering Division
Unit L7
Cherrycourt Way
Leighton Buzzard
Bedfordshire
LU7 8UH
Tel: (01525) 381010
Fax: (01525) 244308

Head Office
Vulcan Industrial Estate
Leamore Lane
Walsall
West Midlands
WS2 7BZ
Tel: (01922) 712665
Fax: (01922) 710919

Email: sales@metelec.co.uk

Company Registration Number 4416364

Contact: Bob Richards

.d.

METELEC

Vulcan Ind. Est.,Leamore Lane,Walsall,West Midlands,WS2 7BZ.
Tel: O1922 712665 Fax: 01922 710919

TEST CERTIFICATE

	25742
IMPERIAL COLLEGE LONDON PH/2590105	
Description: PLATE HOT C10100 137X 270 X 1050	
Metelec Product Ref: QY 698 137X 270 X 1050	

Date :	06.04.2011
Metelec Reference :	QY 698
Customer Order No :	PH/2590105
LOT NO	71629/56901
NO OF PIECES	6
MATERIAL	C10100ASTMB152/ 2009
TEMPER	M20ASTMB152/2009
TEST	ASME SA-578 OK

Chemical Analysis
CU >99.99% O2 0.0001% SB 0.0001%AS 0.0001%
BI 0.0001% CD 0.0001% FE 0.0001%PB 0.0001%
MN 0.00005% P 0.0001%SE0.0001%AG 0.0013%
S0.0003%TE 0.0001%SN0.0001% ZN0.0001%

	ACTUAL	RANGE
Mechanical Tests	BATCH 40	BATCH40
HRF	44.8	MAX 75.0
RM N/MM2	217.0%	205-260
RP0.2 N/MM2	200	
RT 0.5 N/MM2	201	
A 50 %	78	
ELECTRICAL CONDUCTIVITY IACS %	101	

We hereby certify that all materials and supplies listed above have been manufactured, tested and inspected in accordance with all conditions defined by the applicable drawings, specifications, standards and customer order, except where duly stated

Signed :

Position: Quality Manager

Figure 38: Bulk copper test certificate (3 of 4)

Low Energy End

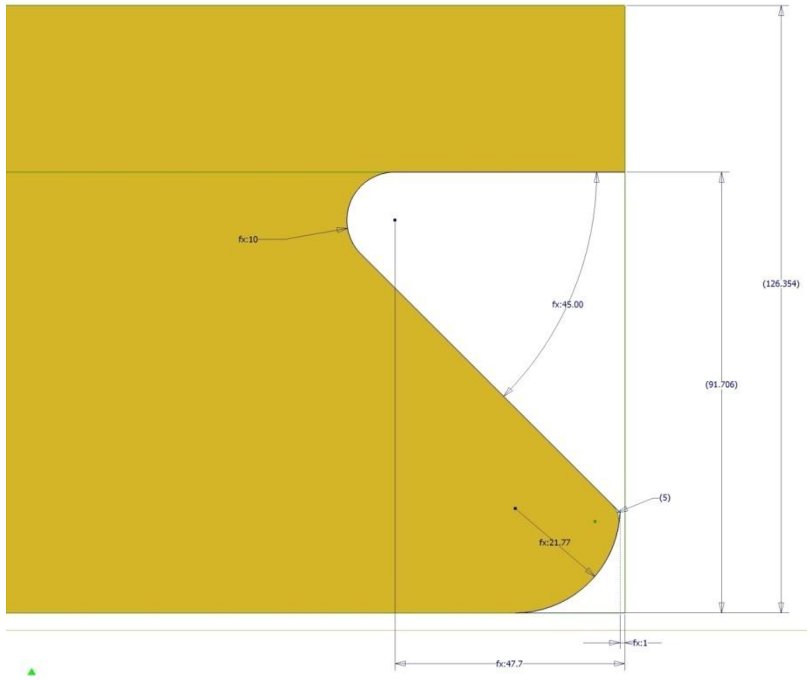


Figure 39: RFQ Low energy end profile

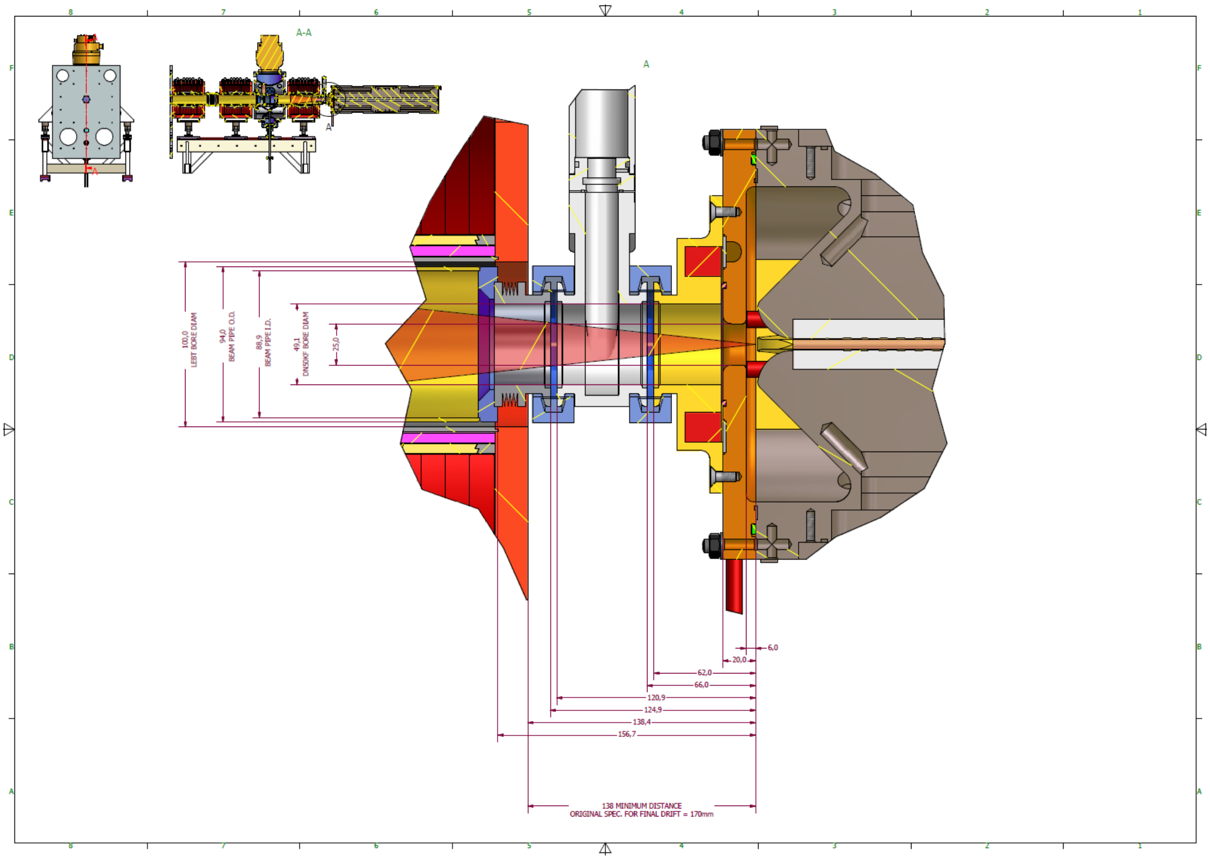


Figure 40: LEBT to RFQ interface

High Energy End

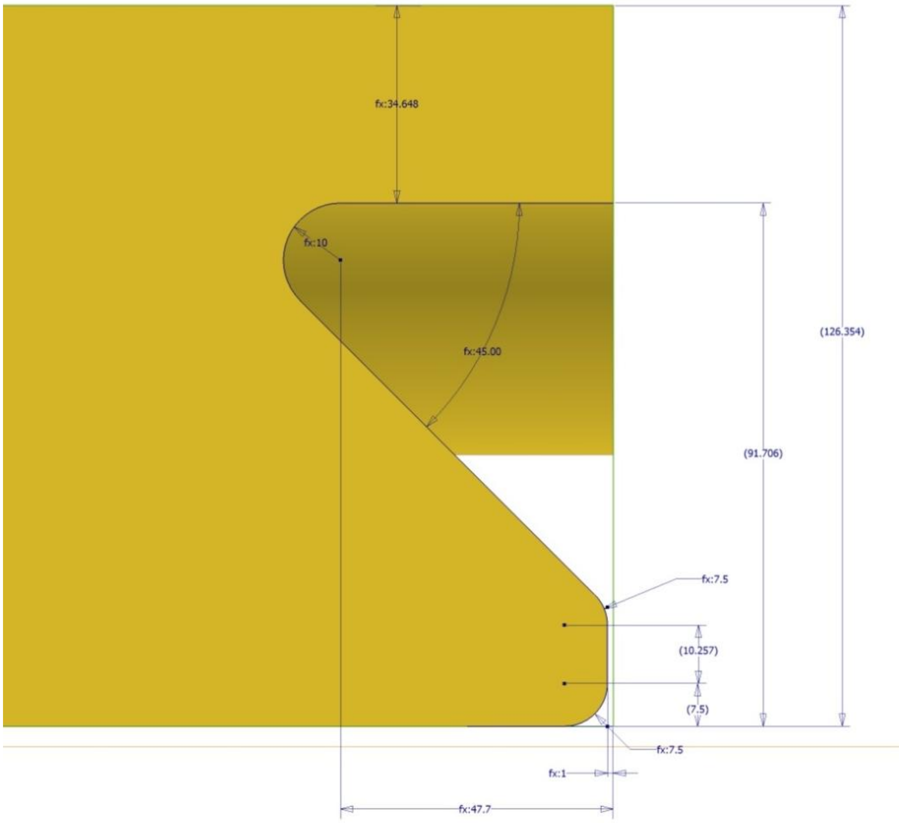


Figure 41: RFQ High energy end profile

Modulation Compensation

Any internal features that change the internal volume will alter the frequency. The last features to be modelled were the vane modulations. The effect of the vane modulations on frequency can be seen in figure 42.

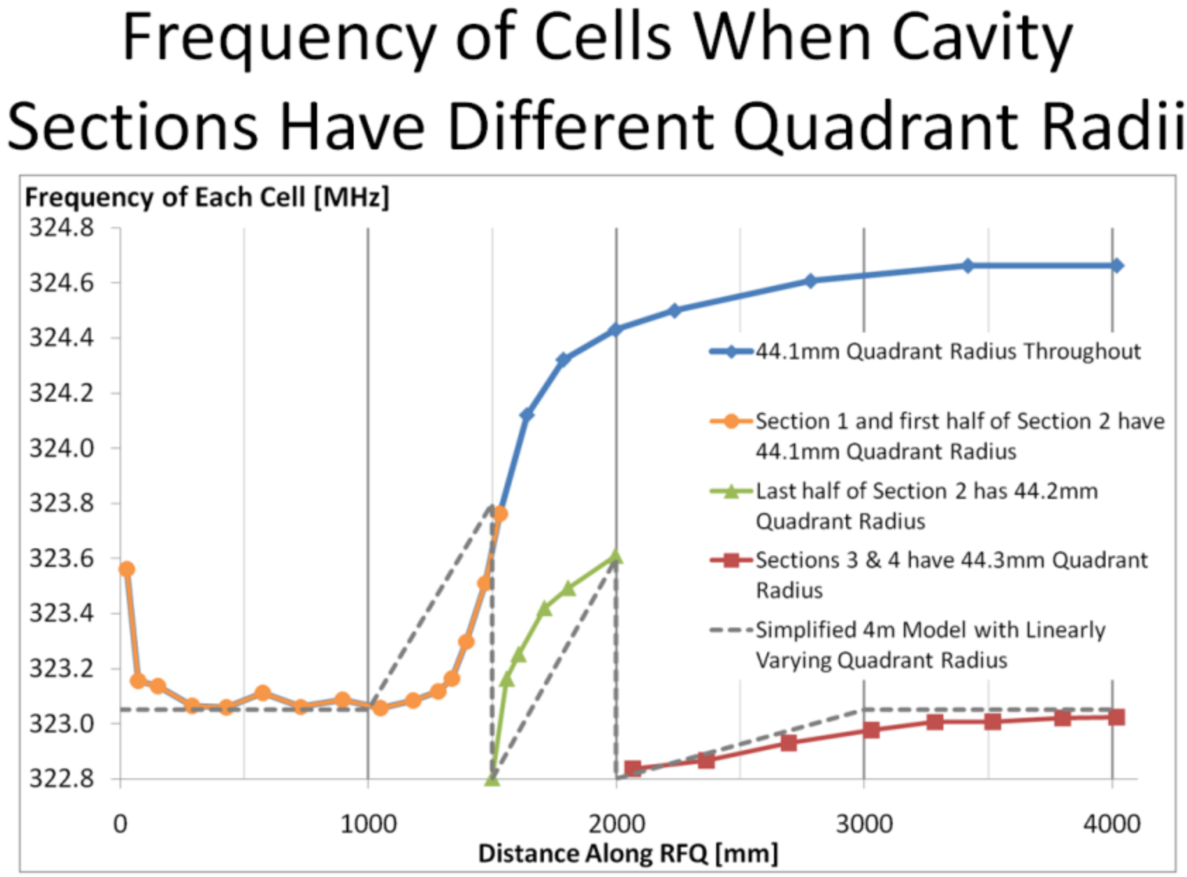
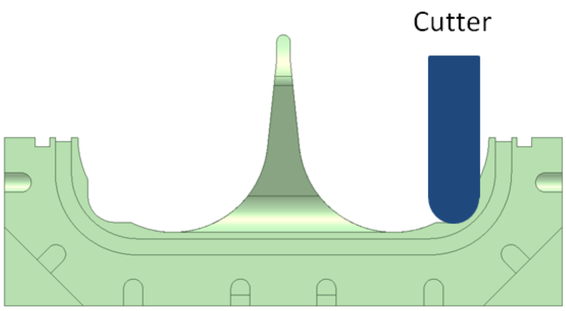


Figure 42: RFQ frequency versus quadrant radii - Scott Lawrie, RAL

One idea to offset the changing frequency with length was to have different quadrant radii for different RFQ sections. However this would present too many engineering challenges with custom designs required for each section and mating problems at the section to section interfaces.

The chosen concept was to maintain constant quadrant radius along the entire 4m RFQ length and introduce grooves where required to alter the internal volume, see figure 43.



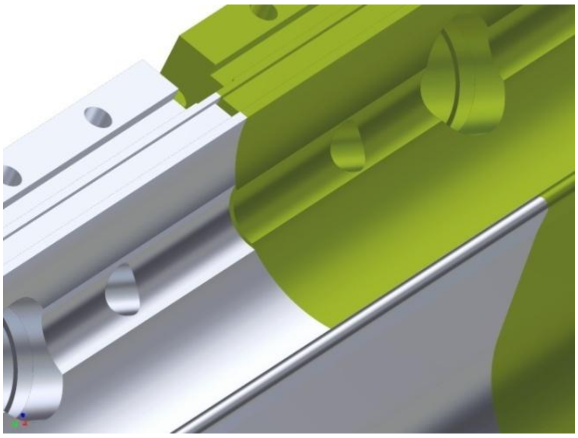


Figure 43: Diameter 25mm ball nosed cutter used to create modulation compensation grooves

Scott's ANSYS modelling showed that a constant frequency over the 4m RFQ length can be achieved with the following groove specification:

Section	Portion	Groove depth
1	All	None
2	First 0,5m	None
2	Last 0,5m	2,55 mm
3	All	4,10 mm
4	All	4,10 mm

Table 5: Groove depths required in RFQ sections

For more information refer to "RFQ Eigenmode Overview" by Scott Lawrie

Inspection

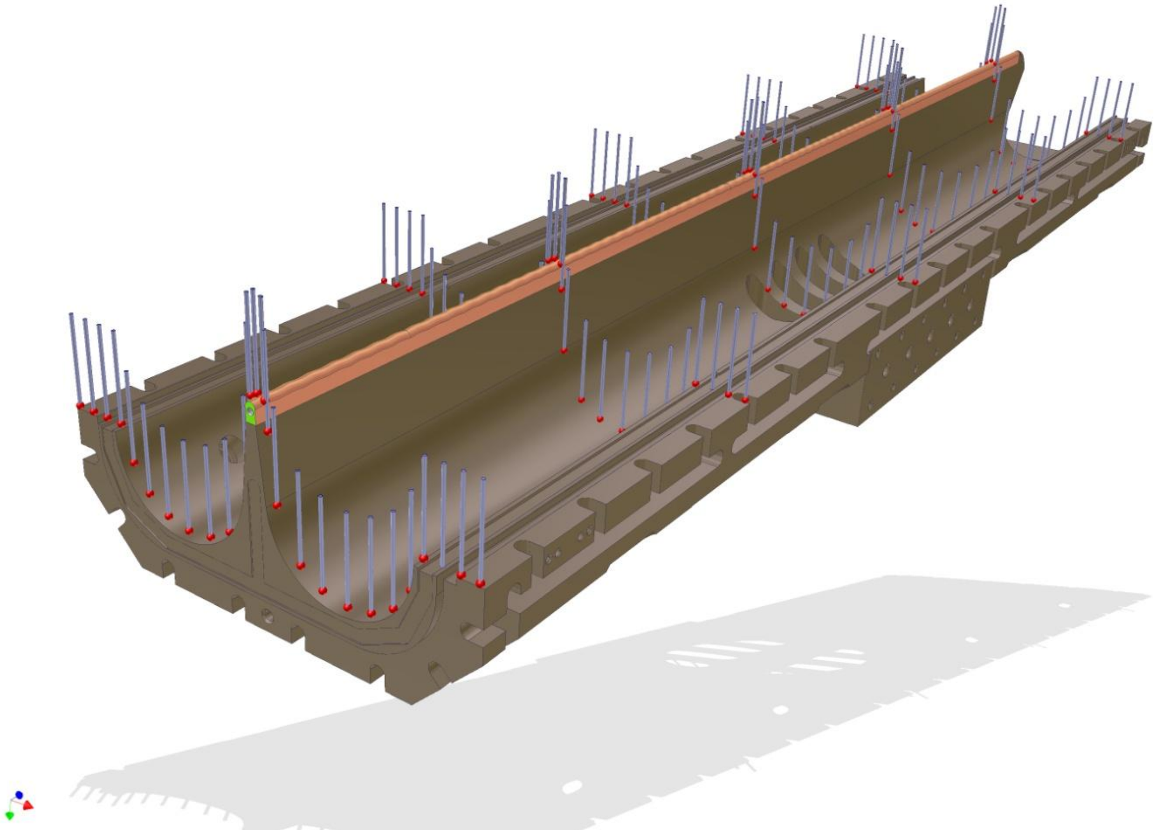


Figure 44: Inspecting the major vane internal profile and interface surfaces.

Inspection to take place and approved before delivery to the customer.

Measurements (w.r.t. datum dowel holes) to prove part is within tolerance for:

1. Internal profile at discrete intervals along the length.
2. Interface surfaces (datum D)
3. End faces

Visual inspection of external features.

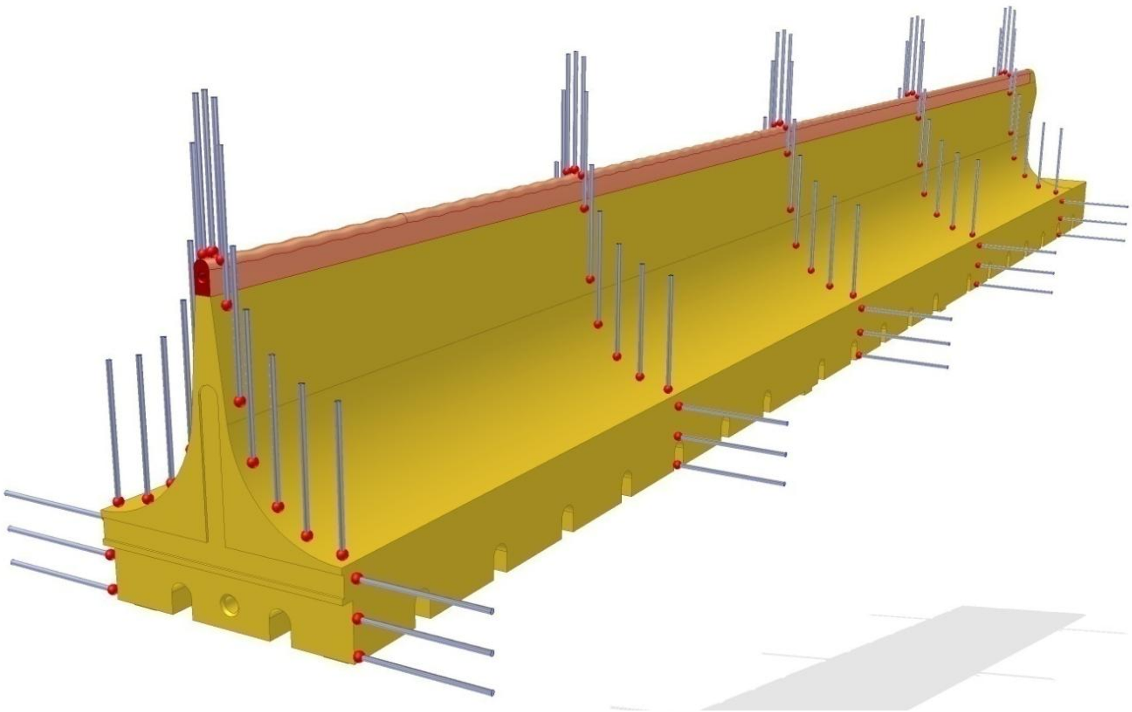


Figure 45: Inspecting the minor vane internal profile and interface surfaces.