S. Myers : head of office for medical applications at CERN

The "750MHz" team (layout and beam dynamics, radio-frequeuncy and mechanics) : A. Dallocchio, V. A. Dimov, M. Garlasché, A. Grudiev, A. M. Lombardi, S. Mathot, E. Montesinos, M. Timmins and M. Vretenar.

BEAM DYNAMICS IN A HIGH FREQUENCY RFQ

Alessandra M Lombardi

Office for CERN medical applications

- Lead by Steve Myers with the aim for CERN to become established as an important facilitator of medical physics in Europe

- It will work to develop
  - a CERN biomedical facility using the LEIR storage ring, suitably adapted with external funding.
  - It will increase the use of ISOLDE in developing isotopes for clinical trials, and
  - work to develop on-going accelerator, detector and information technologies in ways that will benefit medicine.

LINAC-based hadron-therapy facility

- Around 20 m long system of accelerators to deliver protons around 250 MeV
- Based on high frequency RF cavities adapted to non-relativistic beta (3 GHz)
- Successful acceleration demonstrated from 10 MeV onwards, it is likely to work from 5 MeV
- Issue is the energy range from tens of kev to 5 MeV, where the use of 3 GHz is excluded.

3GHz SDTL structure

Courtesy ENEA Frascati

50keV to 5 MeV : missing link

Recapture at 5 MeV

- Free choice of a off-the-shelf accelerator : Cyclotron or a linac
- Free choice of frequency
- Drawbacks :
  - Extremely long or bulky system
  - Losses at 5MeV

Bunch-to-bucket injection

- Frequency must be a sub-harmonic of 3GHz (600,750 or 1000Mhz)
- Unexplored frequencies for a pre-injector :
  - Short wave-lenght/rfq length and tunability can be an issue
  - Small dimension and machining tolerances

An unconventional RF Quadrupole

- Standard design are not applicable
- Both the longitudinal and the transverse acceptance at 5 MeV are extremely tight
- Need to balance the challenges between the source and the RFQ

Source and RFQ parameters	
RF Frequency	Subhar of 3GHz
Input energy	>30keV
Output Energy	5 MeV
Output Pulse Current	30 μA
Repetition frequency	200 Hz
Pulse duration	20 μsec
Transverse Emittance (100%,normalized)	0.4 (π mm-mrad)
Bunch length	±20 deg at 3 GHz
Energy spread	±35 keV
Length	Less than 2.5m

Choice of the frequency

LUMPED-CIRCUIT MODEL OF FOUR-VANE RFQ RESONATOR*

Thomas P. Wangler, AT-1, MS-H817
Los Alamos National Laboratory, Los Alamos, NM 87545 USA

Proceedings of the 1984 Linear Accelerator Conference,

$$P_\ell = \left[\frac{4+3\pi}{32\sigma}\right]^{1/2} (\omega C_\ell)^{3/2} V^2 \quad ,$$

σ=conductivity
C= capacitance weak function of the frequency
f=frequency, V=vane voltage L=length

$$P \div f^{3/2} V^2 \; L$$

Higher frequency needs higher power for the same vane voltage and length 750 vs 600MHz power factor would be 1.4

fix voltage =80 kV

750 MHz , 170 cm (=4.25 lambda)

600 MHz , 260 cm (=5.2 lambda)

- Length $*f^{3/2}$ is about constant, power is the same

fix the length = 5lambda

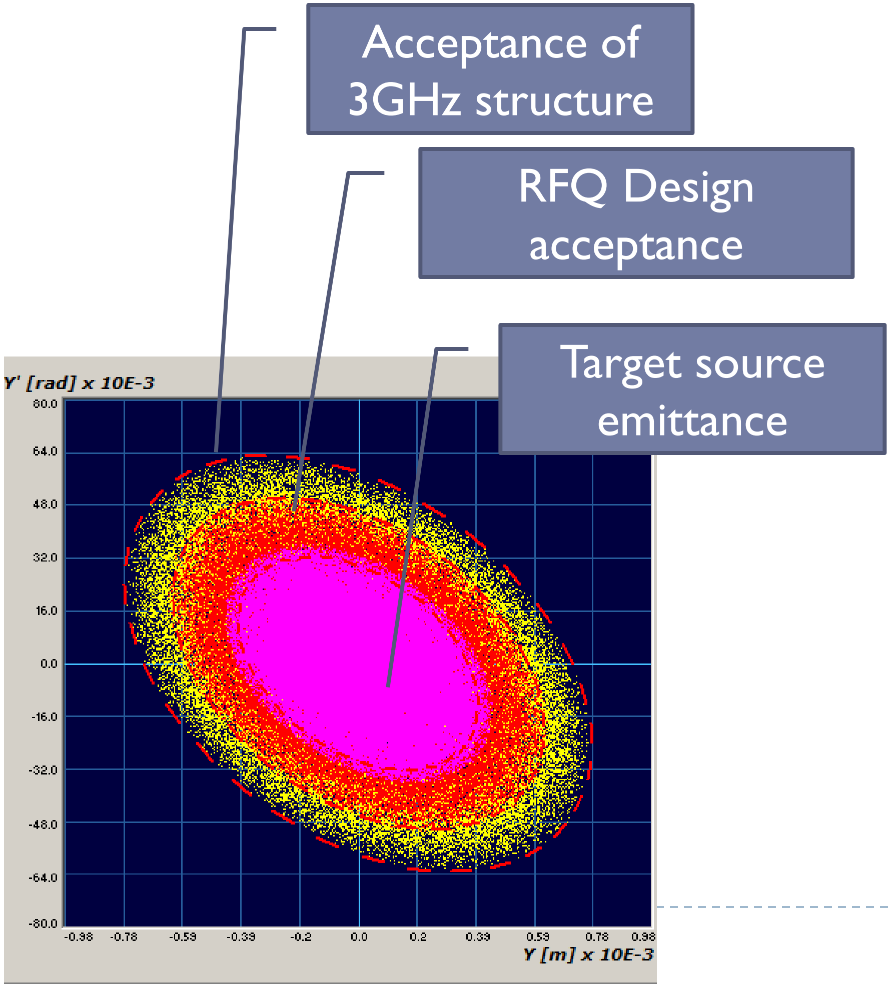
750 MHz , 200 cm (=5 lambda) V=65 kV

600 MHz , 260 cm (=5.2 lambda) V=80 kV

- For the same length in units of lambda the 750 MHz version would require 70% of the power of the 600 MHz version

Initial choices - transverse

30μA in 0.4 pi mm mrad

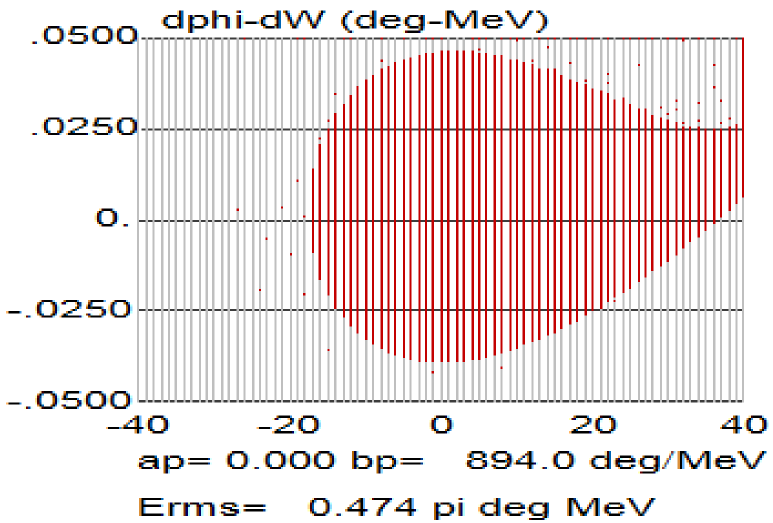


Emittance budget (norm total mm mrad)	
0.4	acceptance at 5MeV 3GHz
0.3	RFQ acceptance, allowing for 20% emittance increase
0.15	Target source emittance
Intensity budget (μA)	
30	Into SDTL
40	Out of RFQ
100-50	Into the RFQ
Current in emittance for existing sources	
600	LINAC4 (60mA at 45keV in 1.5 mm mard)
4500	LINAC2 (200mA at 90keV in 1 mm mrad)

Initial choices – longitudinal

Acceptance at 3GHz , 5MeV

- from "SPECIFICATIONS FOR A RFQ TO BE USED AS INJECTOR FOR LIGHT ACCELERATOR" by J. Nardulli, C. Ronsivalle



Backwards Design philosophy

- Accelerate to 5 MeV only what can be captured.
- Special bunching system in the RFQ : size the stable bucket around the longitudinal acceptance at 3GHz and make sure that the particle outside the acceptance have energies below few hundreds keV

Initial choices – longitudinal

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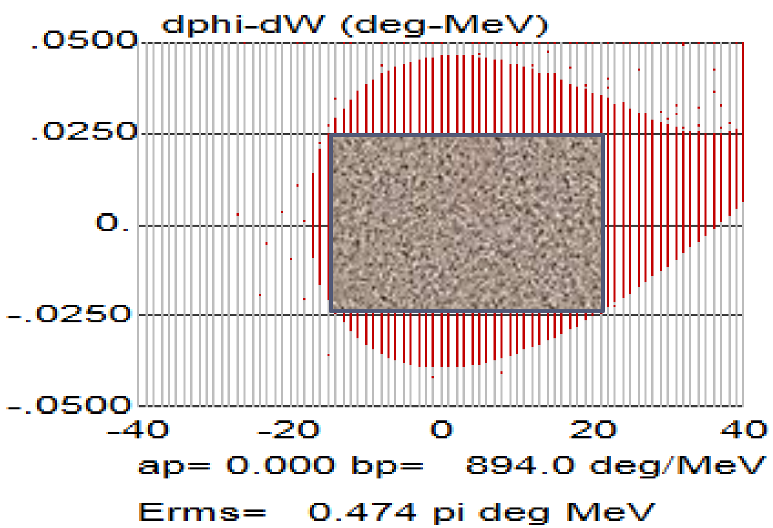


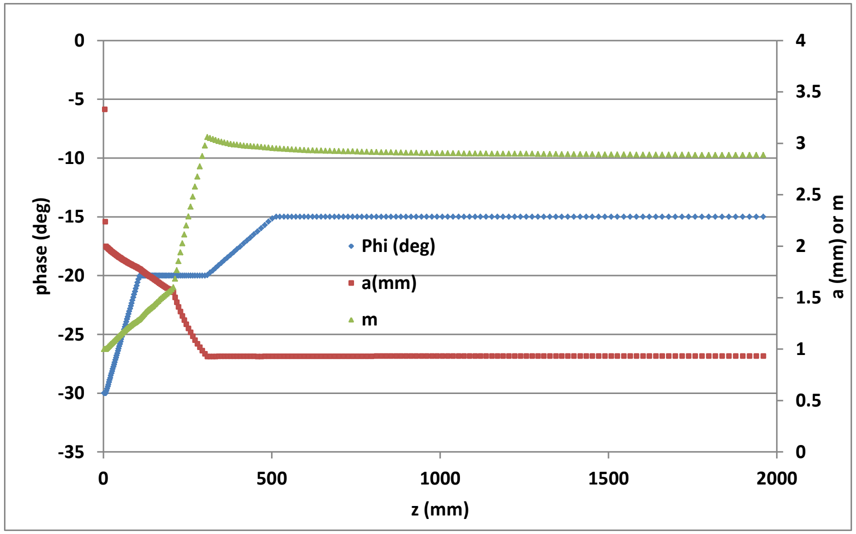
Backwards Design philosophy

- Accelerate to 5 MeV only what can be captured.
- Special bunching system in the RFQ : size the stable bucket around the longitudinal acceptance at 3GHz and make sure that the particle outside the acceptance have energies below few hundreds keV

Acceptance = 0.3 pi mm mrad, V_source=40 kV, V_vane=80KV , 750 MHz

Short **180 cm** **30% trans.**	
Medium 240 cm 40% trans.	2 independent RF cavities (120cm/5cm/120cm)
Long 360 cm 90% trans.	3 independent RF cavities (120cm/5cm/120cm/5cm/120cm)

Short it is ….



- maximum RF peak power of 400kW;
- maximum electric field on the vane tip of 50 MV/m corresponding to 2 Kilpatrik limit;
- a two-term potential vane profile, a constant average aperture radius and a constant transverse radius of curvature for an easier tuning and the possibility of machining with a 2D cutter;
- Cooling for a higher dc than needed

Source and RFQ parameters	
RF Frequency	750 MHz
Input/output Energy	40 keV/5MeV
Length	2m
Vane voltage	65kV
Peak RF power	400kW
Duty cycle / max	0.4% /(5%max)
Input/Output Pulse Current in 3GHz acceptance	100/30 μA
Transv. emittance 90%	0.1 pi mm mrad
Average aperture (r0)	2mm
Transverse radius (ρ)	1.5 mm
Maximum modulation	3

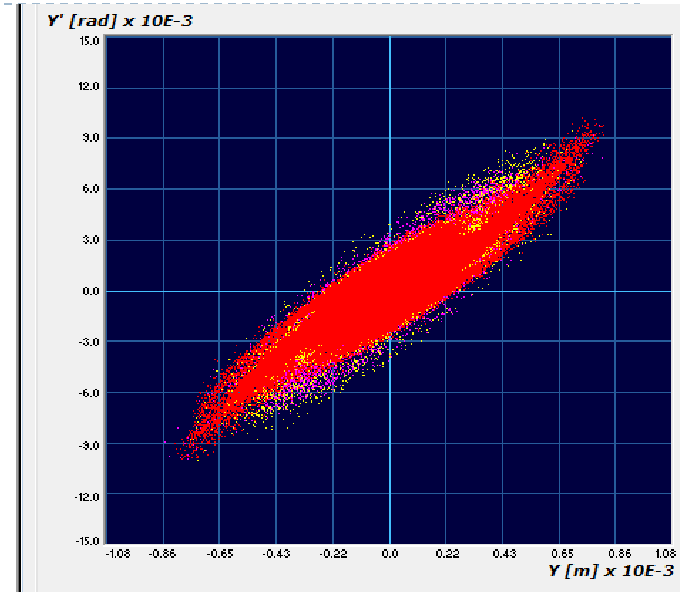
Beam dynamics

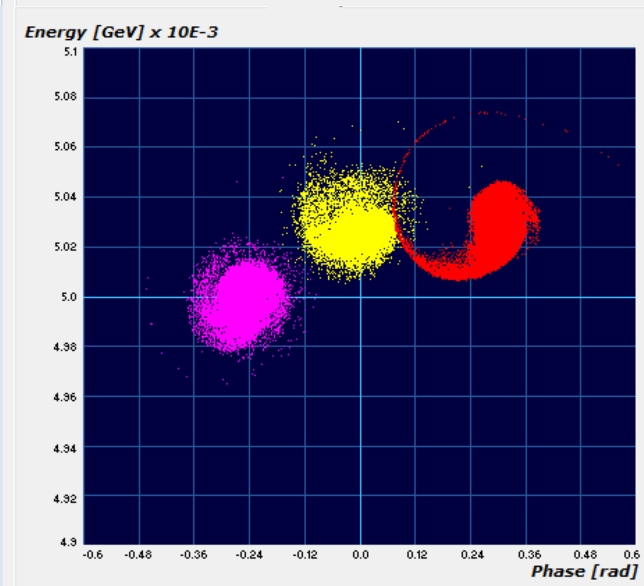
<u>3 independent codes</u>

PARMTEQ (LANL) : field from 3D static calculation, described with 8 m-pole components.

TOUTATIS (CEA-Saclay): 3d field solver.

PATH/TWin + HFSS : full 3d field map.





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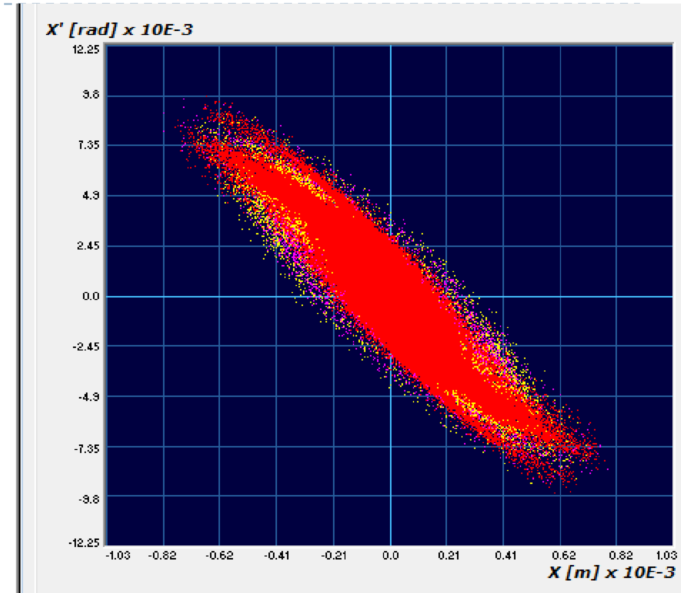
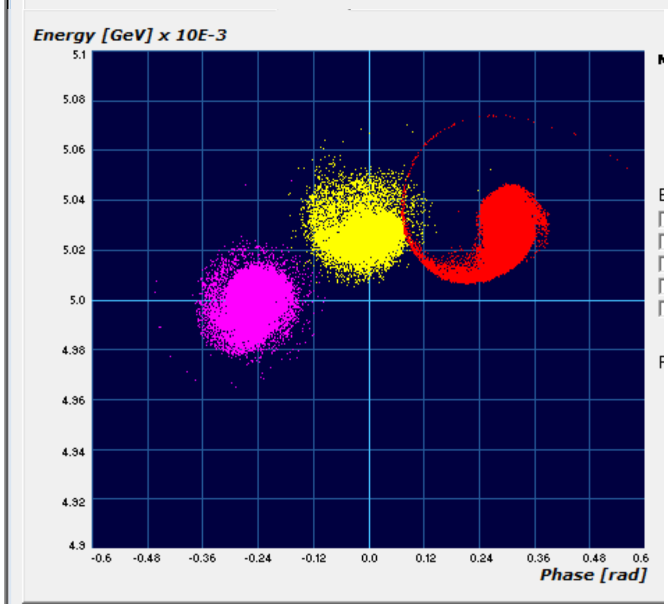
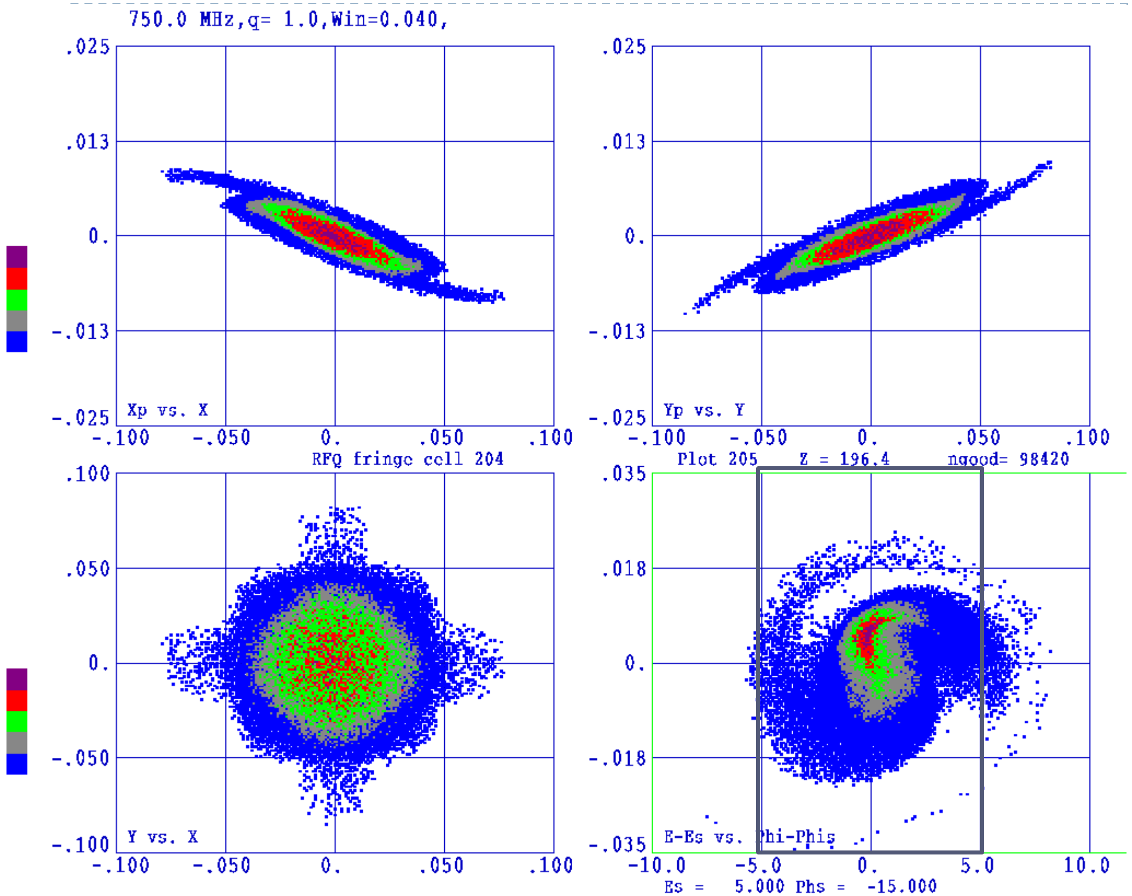
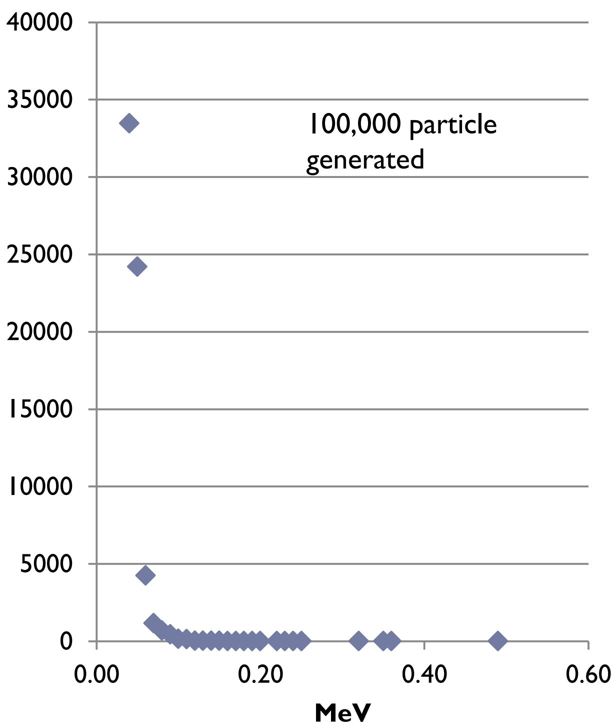




Beam at 5 MeV and losses

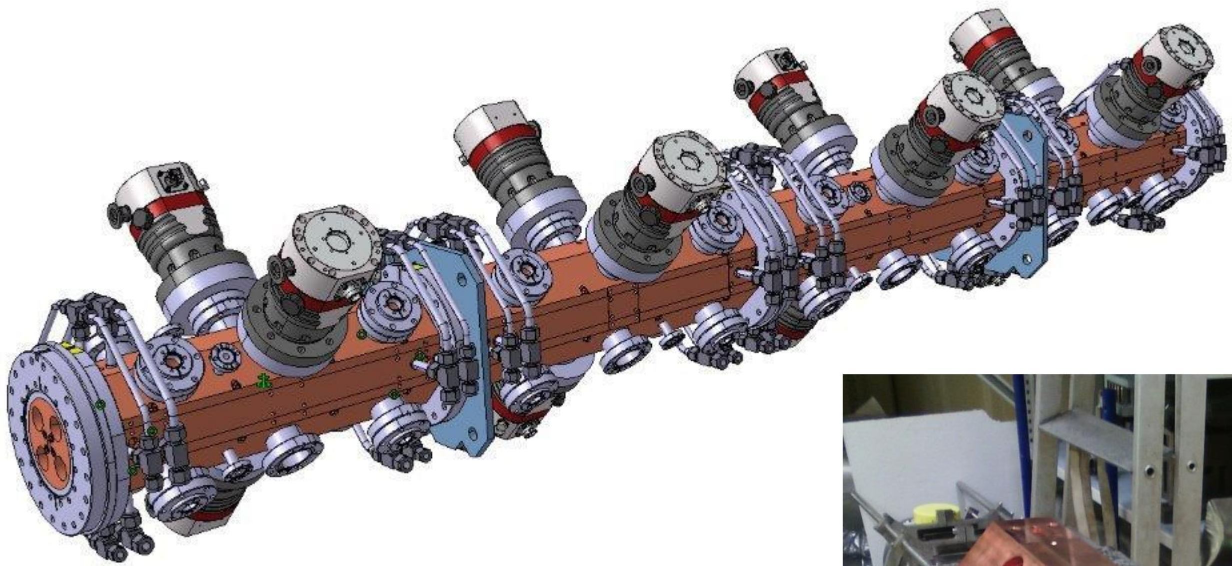


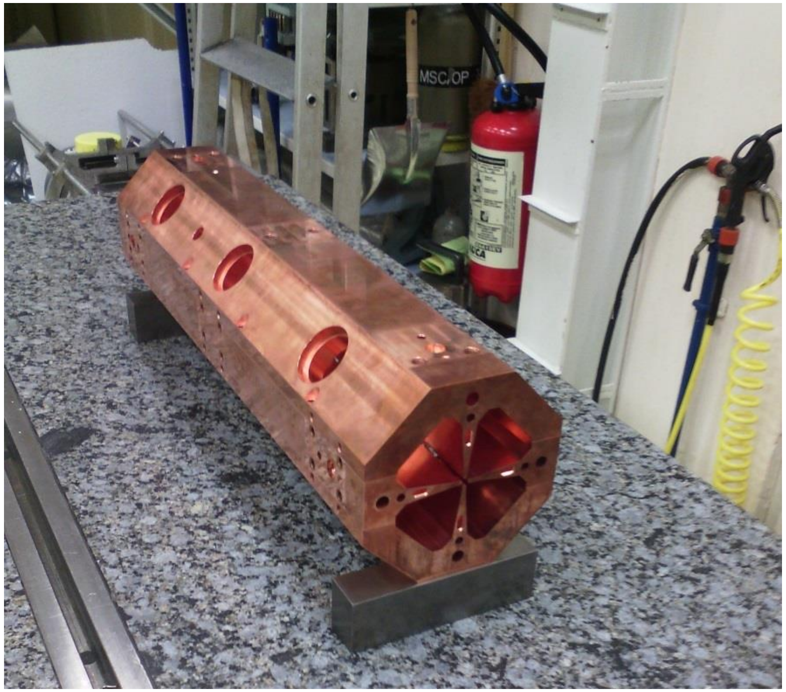


Transverse phase spaces (cm and rad) : top
Transverse profile (cm) : bottom left
Longitudinal phase space(deg and MeV) : bottom right

The highest energy particle lost carries 500 keV ; 99.5% of the lost particles have an energy below 100keV.

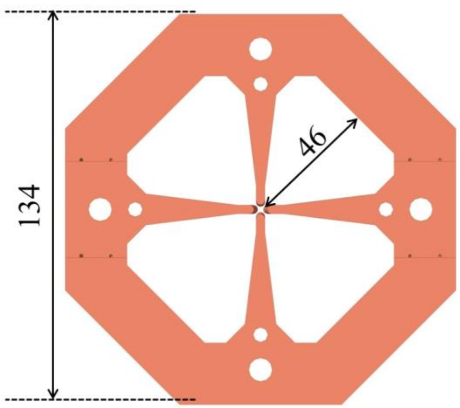
.....towards realising

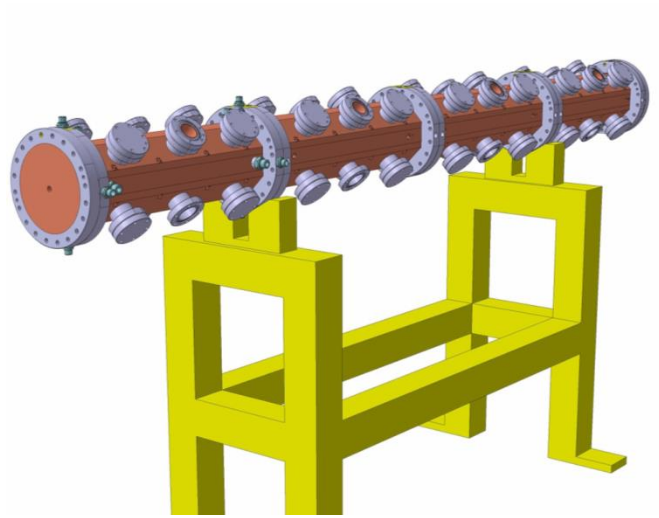


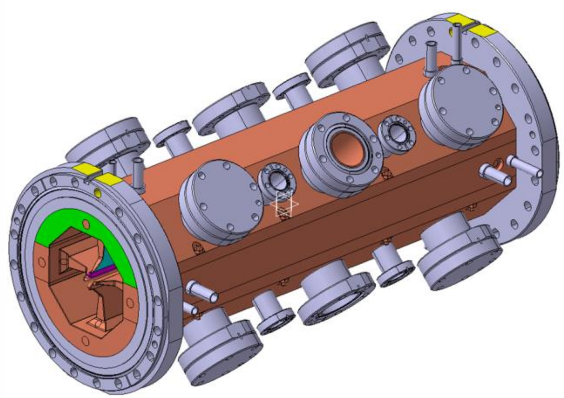


Mechanical design

Mechanical design and construction procedure based on the Linac4 RFQ:
4-vane structure with 2 brazing steps. Inner radius 46 mm; total weight 220 kg.



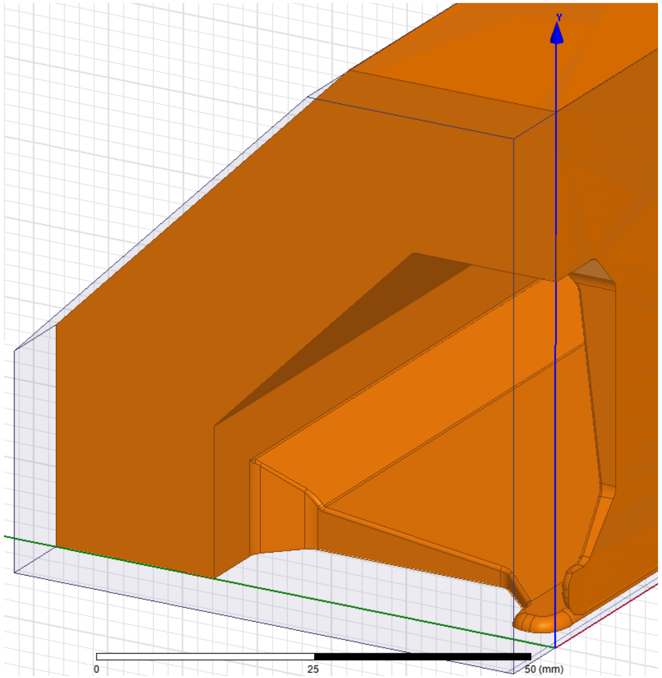




Modular design: assembly of 0.5 m long modules, each with 8 tuning ports and 4 combined tuner/power coupler ports. The modules differ only by the vane modulation (and for the end cells at both ends).

RF design

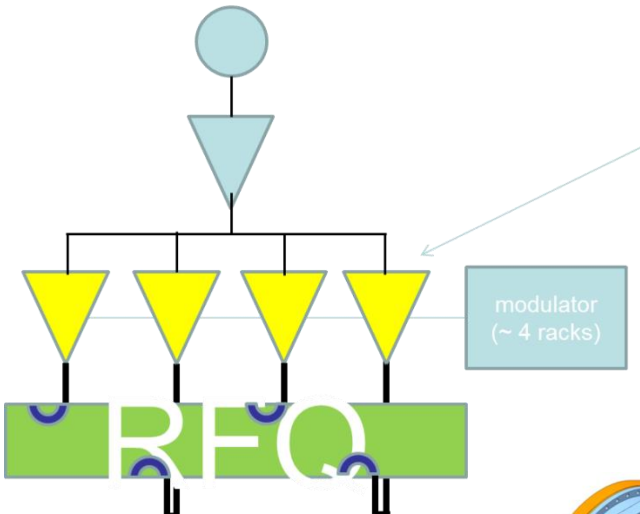
- Challenge : length is 5 times the wave-length, limit for tuning the RFQ with simple tuners. 2 tuners/section with provision of a third one.
- Minimisation of RF power losses
  - Cavity geometry
  - Number and shape of tuners
  - 3D simulations to keep into account all the effects

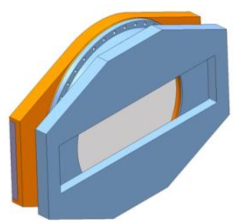


Input vane tip – 3d detail

Including all margins we need 0.043 kW/m (kV)2

RF system





Basic concept:
Combine several small RF amplifiers into the RFQ (that acts like a combiner).

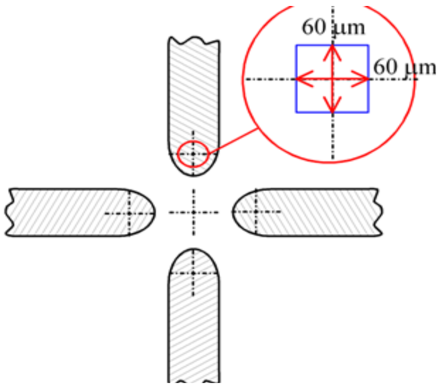
Testing of the prototype RFQ: arrangement of 4 IOT-based amplifiers on a common modulator, each connected to an RF coupler. Most economic and easier to procure option.

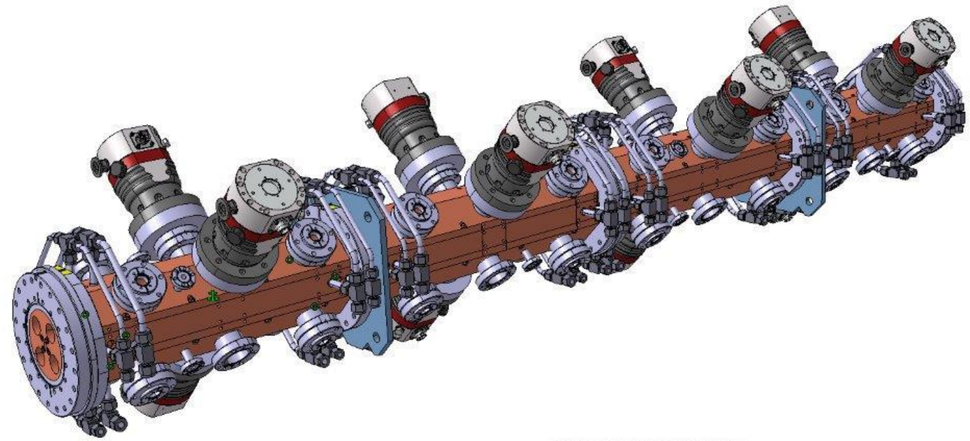
Work on reducing the cost of the RF system:

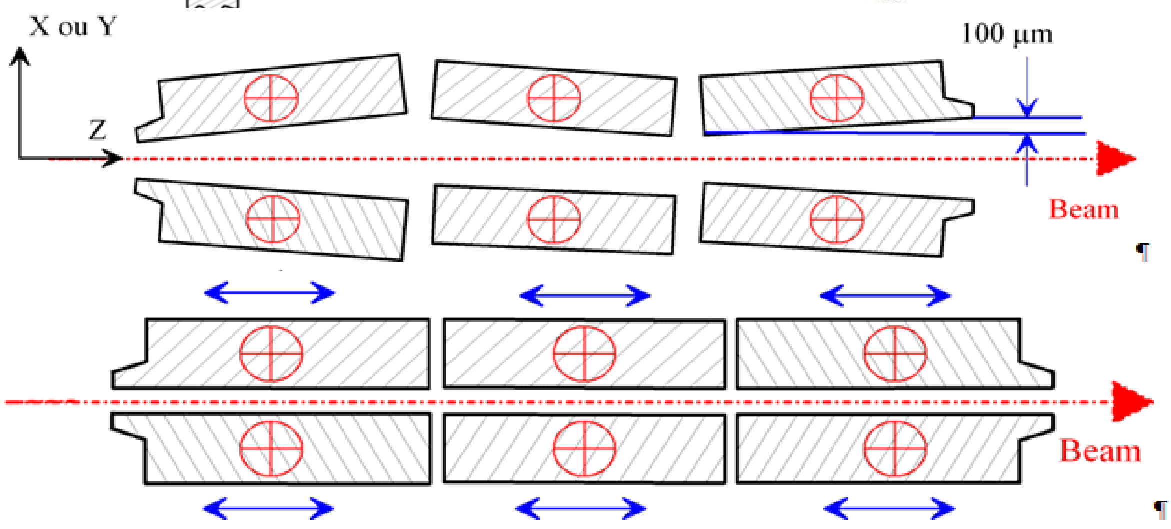
- Use of solid-state amplifiers
- «Stripped-down» units with minimum control and LLRF (RFQ does not need phase control and requires only a limited voltage control).

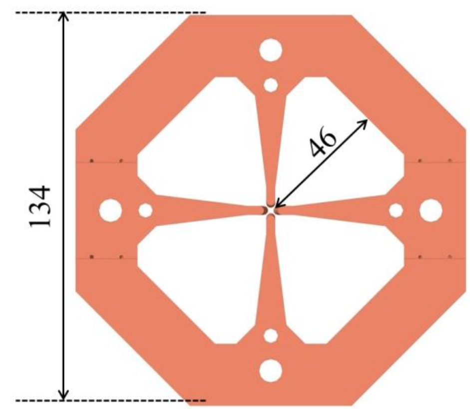
Error studies and alignment tolerances

Alignment errors :









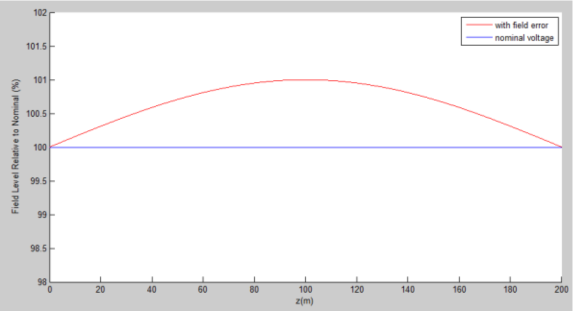
Error studies and tuning errors

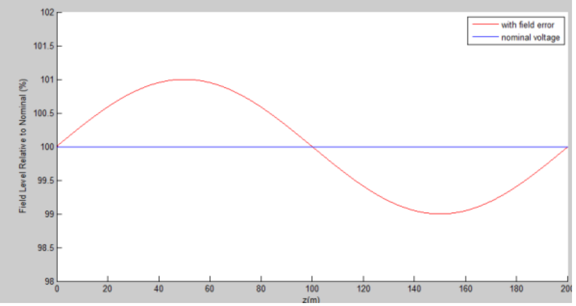
- Error distribution

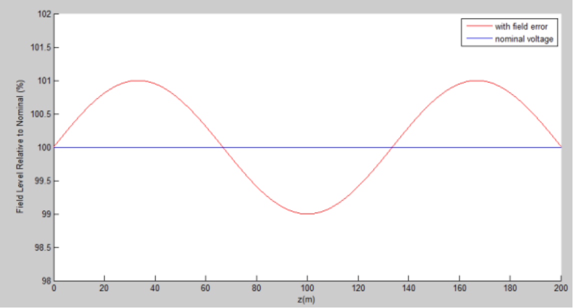
$$V = V_{nominal}[1 \pm \varepsilon * cos(\frac{z}{l} n\pi)]$$

$$V = V_{nominal}[1 \pm \varepsilon * \sin(\frac{z}{l} n\pi)]$$

- ε is the max error (in %) along the RFQ
- ± (multiplication factor) defines if the voltage is higher or lover at z→0+
- Function (cos or sin) defines where the maximum error occurs along the RFQ
- n defines how many peaks we will see in the error profile.
- l is the length of the RFQ, z is the distance from the beginning of the RFQ.







Tolerances

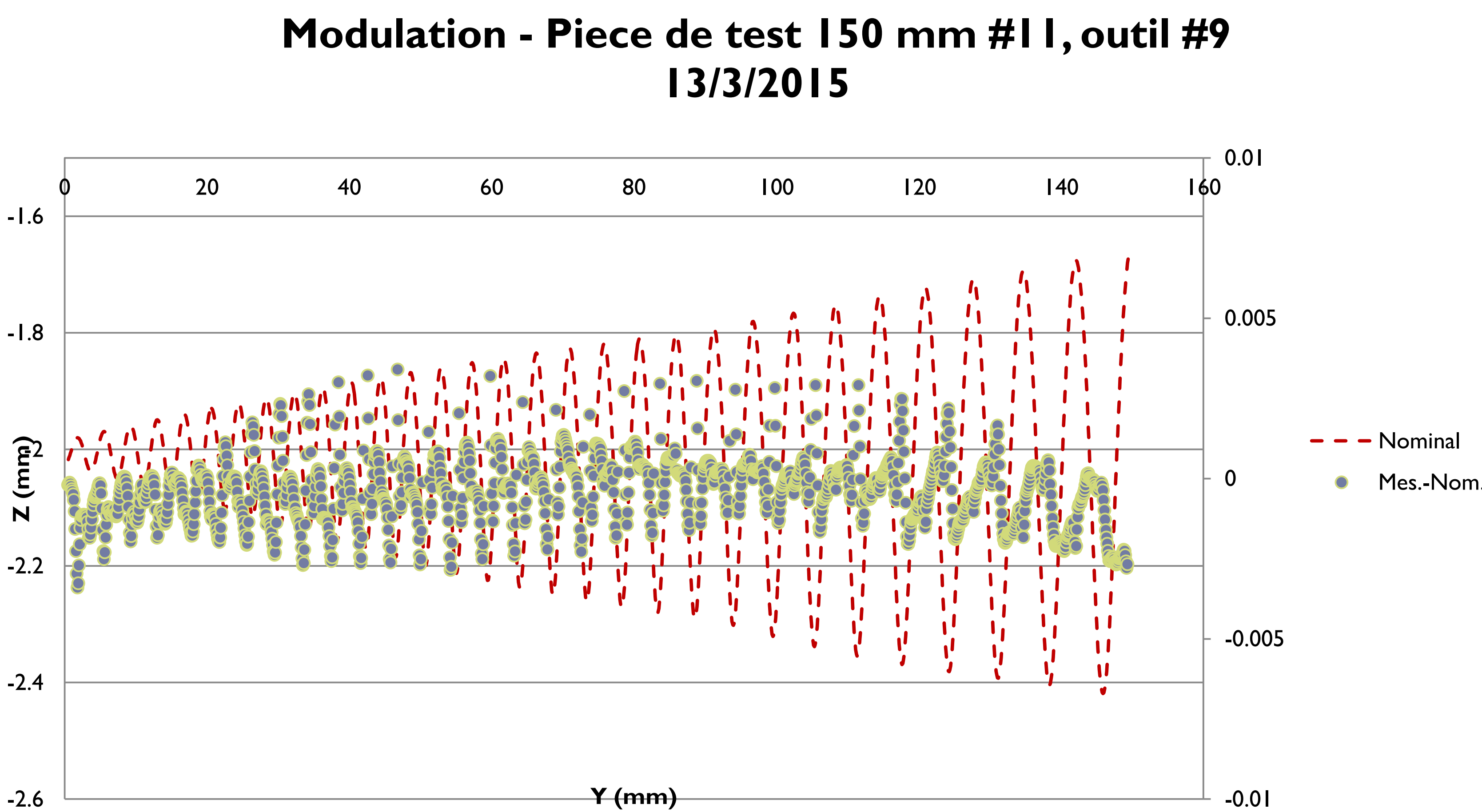
Error	Tolerance	Part concerned
Field error	±1% to ±2	Tuning
Transverse radius of curvature	±10 μm	Cutting tool
longitudinal profile	±10 μm	Machining
X and y pole displacement	±30 μm	Assembly before brazing and brazing process
Longitudinal pole displacement	±40 μm	
X and y pole tilt	±30 μm	
X and y segment tilt	±60 μm	Assembly of sections
X and y segment displacement	±20 μm	

Cutting metal….

Choice of constant transverse radius of curvature allows for a 2d machining with a relatively cheap and simple tool

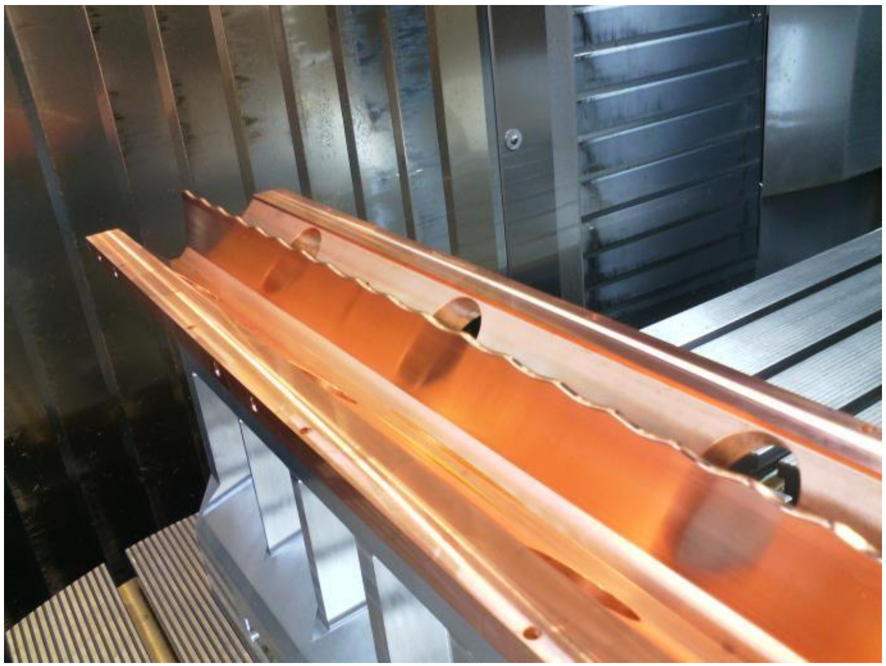
Shape tools made by the company BOUDON-FAVRE, Feillens (France).
Precision machining obtained with a CNC grinding machine ANCA type mx7 with camera control Iview

Well within the tolerances



Shape tool #9 – 150 mm Test piece #11 (13.3.2015)

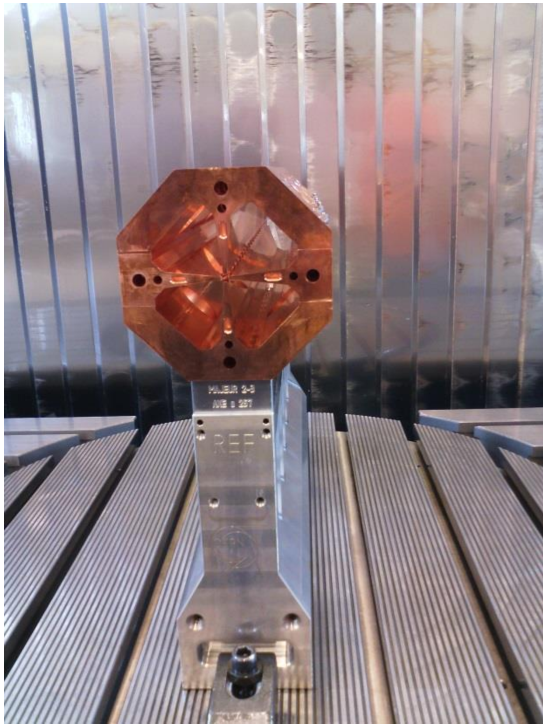
Error on the modulation vs nominal value well within ± 5 µm.

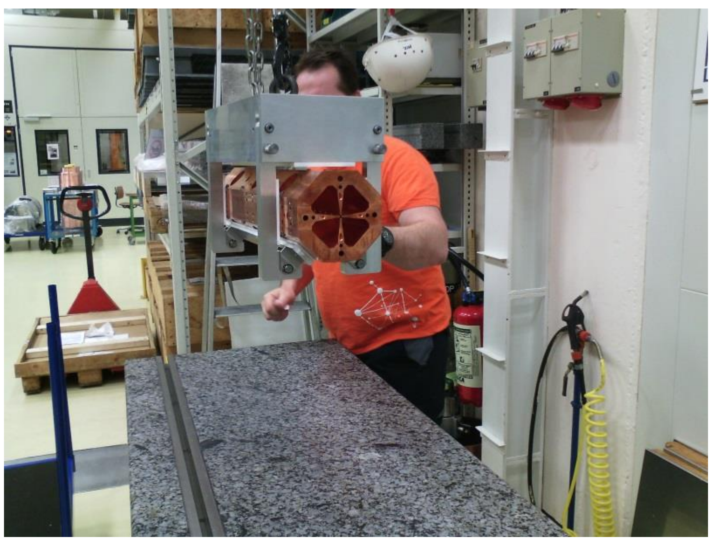


Module 2 – Major vane – Final machining (16.3.2015)

Module 2 – Minor vane

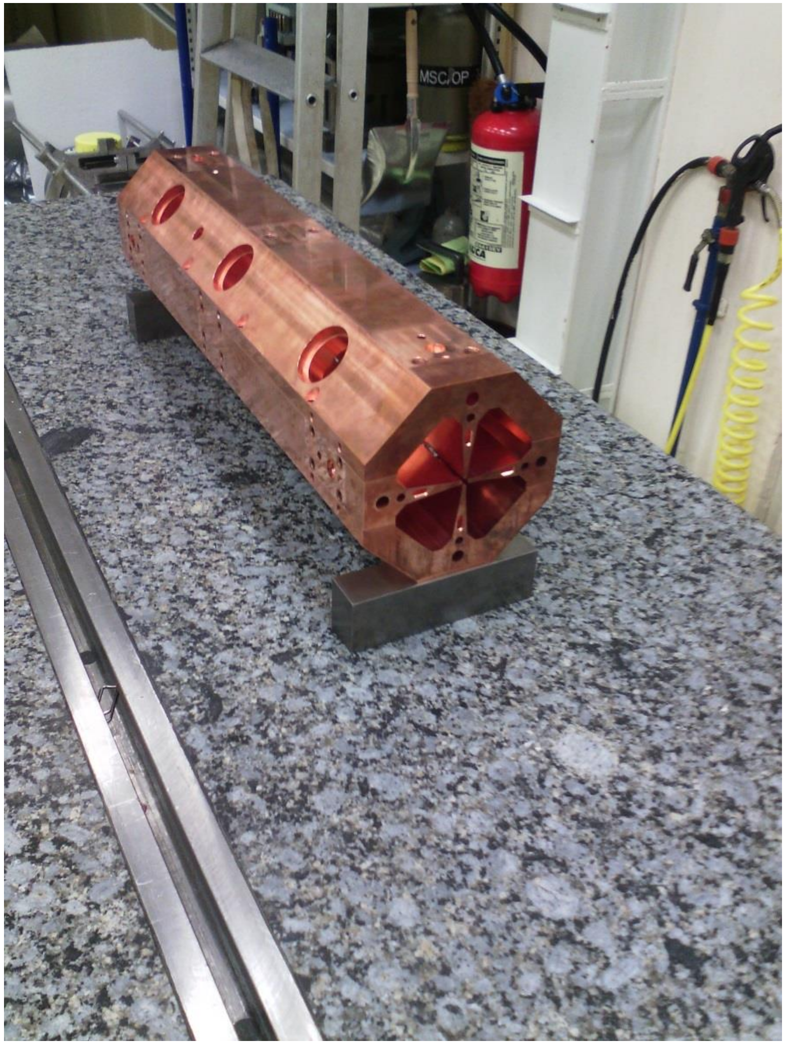
Rough to Final Machining





One/four section assembled, 50 cm long 13 cm across. Getting ready for brazing

May 2015 – first section assembled



What next?

- Completing machining, brazing assembling
- RF measurements and tuning
  - Learn about scaling factor for power
  - Learn about max electric field on vane-tip
- Test with beam at the ADAM test facility at CERN during 2016
  - Validate the layout approach
  - Learn about beam quality and source optimisation

By 2016 we should have all the information necessary to further optimise the design of the next RFQ, with higher duty cycle, higher current or a combination of both!

Further developments , among others

- Energy of 10MeV for isotope production in hospitals

2 RFQs
Source W = 40 KeV
L = 4 m
Output W = 8-10 MeV
Average current = 50 mA
Duty cycle = 5 % or 1%
Peak current = 1 mA or 5 mA

Conclusions and outlook

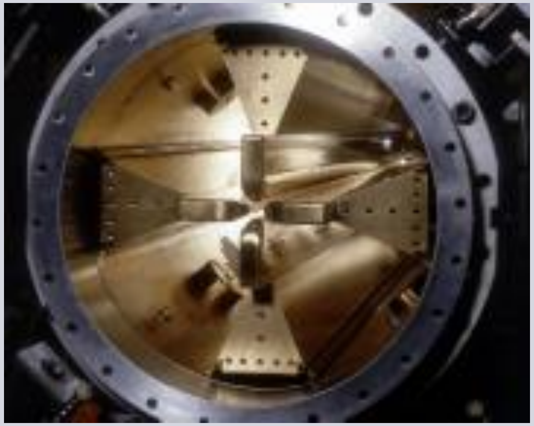
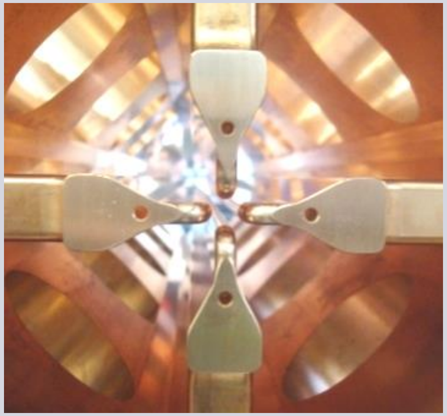
- We have established a new beam dynamics design for RFQ which allows the use of higher frequencies
- This opens up the road for compact RFQ for use in medical facilities
- The results of the test in the ADAM test facility at CERN will (hopefully) confirm our design choices and enhance our knowledge of high frequency RFQ issues.
- The next step is to attempt a design at 1Ghz and/or a design for q/m =1/2 able to accelerate C6+ (or Alpha particles)

Mario Weiss Ken Crandall

if I saw further
is by standing on their shoulders

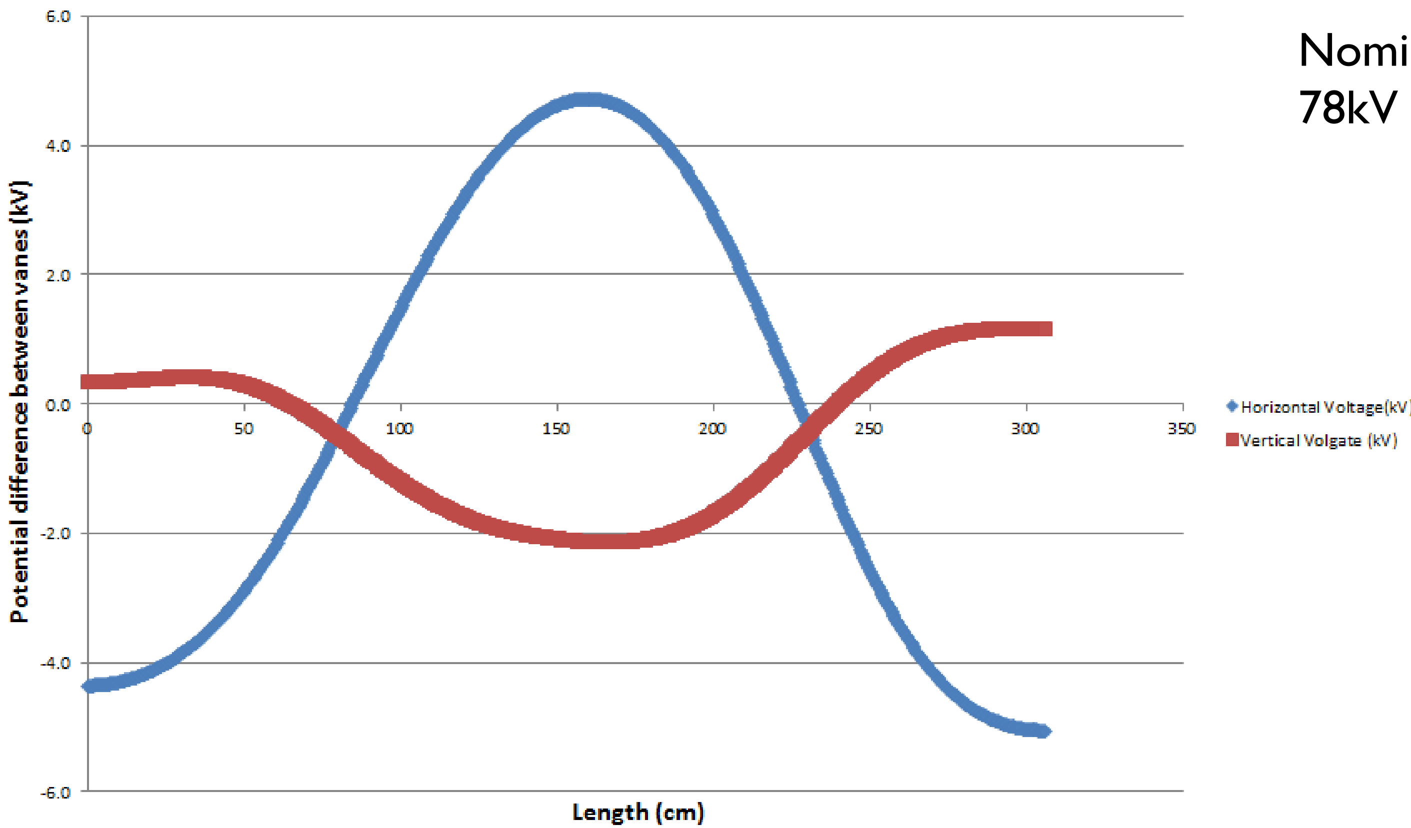
Extra slides

The higher the frequency..

1990 RFQ2 200 MHz 0.5 MeV /m Weight : Ext. diametre : ~45 cm	2007 LINAC4 RFQ 352 MHz 1MeV/m Weight : 400kg/m Ext. diametre : 29 cm	2014 HF RFQ 750MHz 2.5MeV/m Weight : 100 kg/m Ext. diametre : 13 cm
		

Example from Linac4

- Dipole voltage error



Nominal vane voltage 78kV