RF Design of a High-Frequency RFQ Linac for PIXE Analysis

H. W. Pommerenke[†,1,2], A. Bilton[1], A. Grudiev[1], A. M. Lombardi[1], S. Mathot[1], E. Montesinos[1], M. Timmins[1], M. Vretenar[1], U. van Rienen[2]

[1] *CERN, Geneva, Switzerland*
[2] *University of Rostock, Germany*

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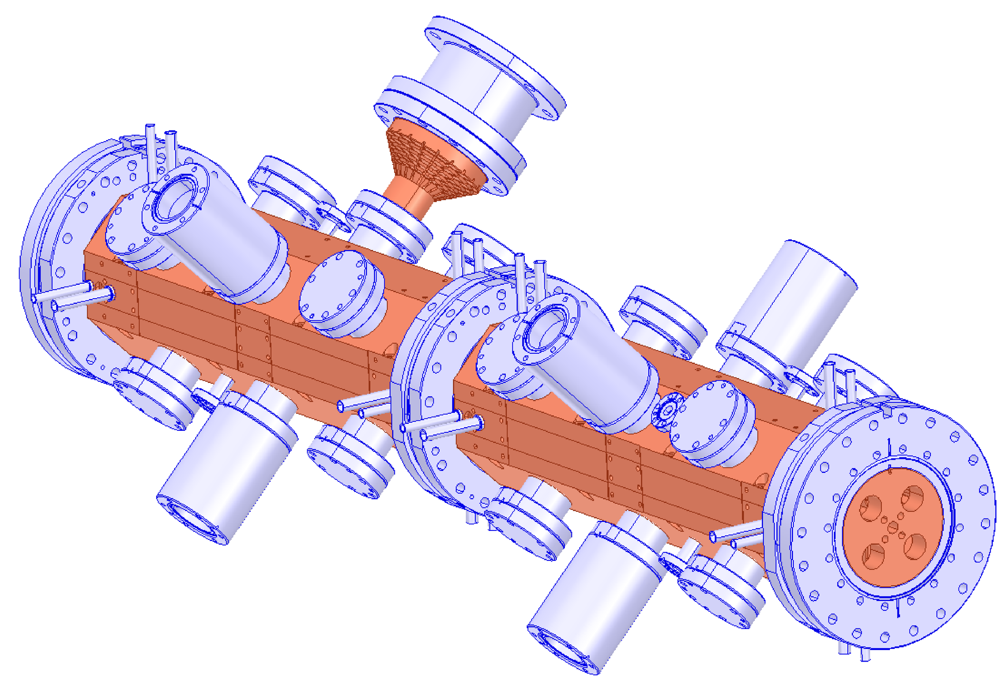
Abstract

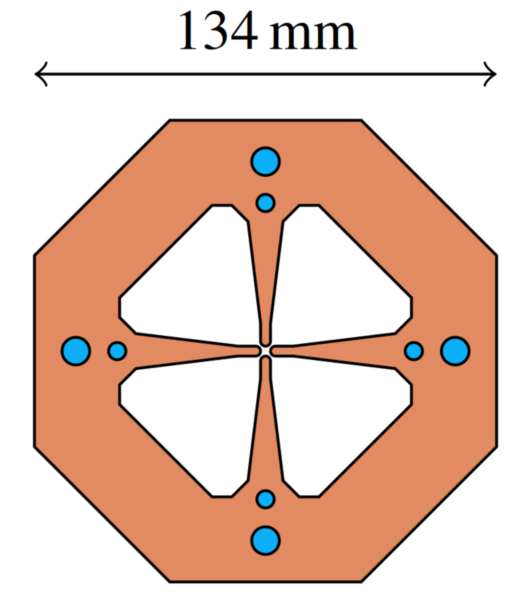
Protons with an energy of few MeV are commonly used for Ion Beam Analysis of materials, in particular with the Proton Induced X-ray Emission technique (PIXE). Because of its non-damaging character, PIXE is used in a variety of fields, in particular for the diagnosis of cultural heritage artwork. A compact accelerator based on a high-frequency RFQ (Radio Frequency Quadrupole) linac has been designed and is being built at CERN. The length of the RFQ is only one meter and it allows the acceleration of a proton beam up to an energy of 2 MeV. The complete system is conceived to be transportable, allowing PIXE analysis almost anywhere. This paper covers the RF design of the compact RFQ operating at 750 MHz. We present general accelerator parameters and the current state of the RF design, which includes RFQ geometry and coupler design, thermal simulation and first particle tracking results.

The PIXE RFQ Linac

PIXE = particle/proton-induced X-ray emission [1]

- ion beam excites X-ray in specimen atoms, spectrum allows for quantitative, highly sensitive, non-destructive analysis
- applied in analysis of environment, atmosphere; tissue, cells, proteins; **artefacts, cultural heritage**
- 750 MHz RFQ can provide 2 MeV protons over length of only one meter [2]
- RFQ developed within MACHINA project [3]: first **transportable** system for *in situ* ion beam analysis
- based on HF RFQ for medical applications [2,4,5]



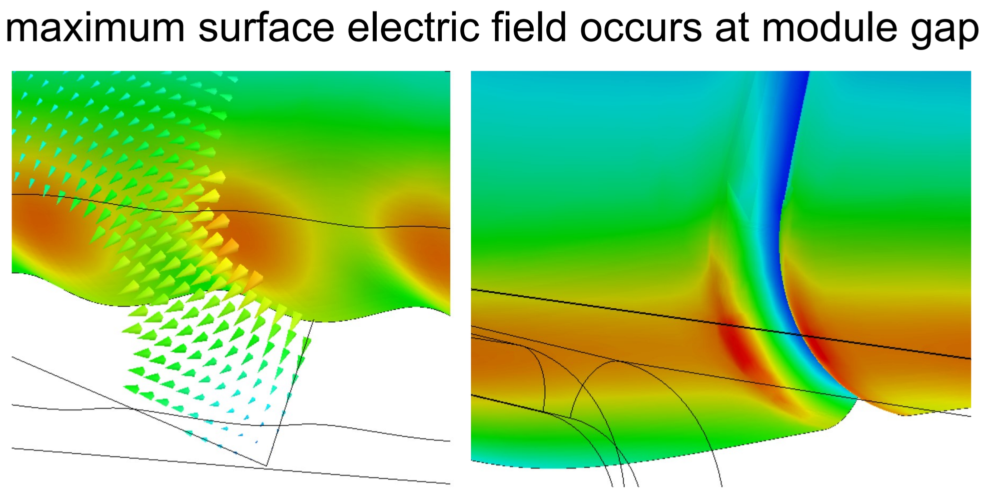


PIXE RFQ design parameters

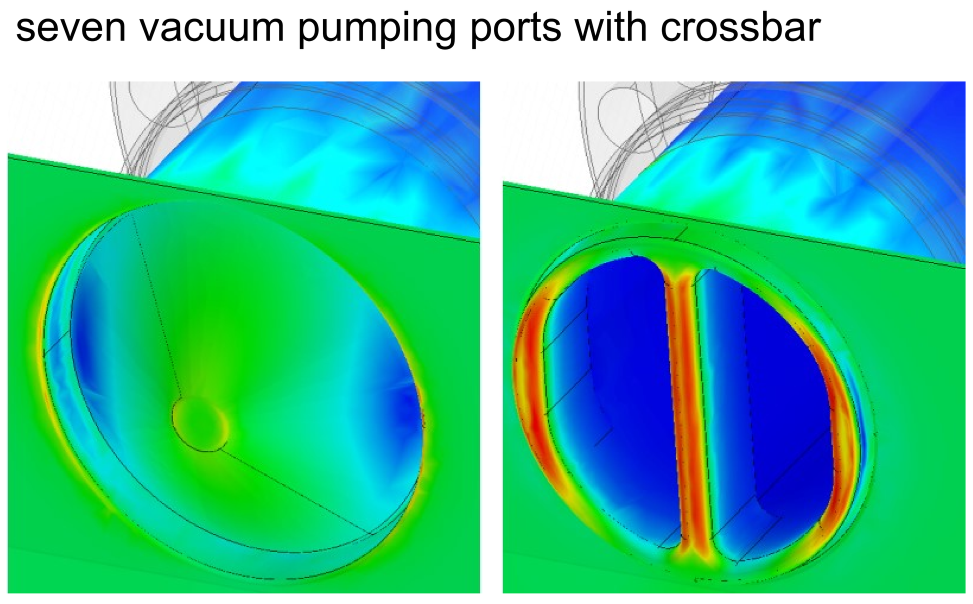
Input Energy	E_{in}	20	keV
Output Energy	E_{out}	2	MeV
RF frequency	f_0	749.48	MHz
RFQ length		1072.938	mm
Vane voltage	V	35	kV
Min. aperture		0.7	mm
Vane tip radius		1.439	mm
Peak current		200	nA
Transmission	T	30	%
Max. duty cycle	d_{max}	2.5	%

RF Design

- optimisation of geometries to 749.48 MHz resonant frequency and minimum surface losses
- end plates with bead pull holes in each quadrant
- dipole stabilization rods (+/- 12 MHz spectral margin)
- maximum surface electric field occurs at module gap



- sixteen copper slug tuners with conic tip
- seven vacuum pumping ports with crossbar



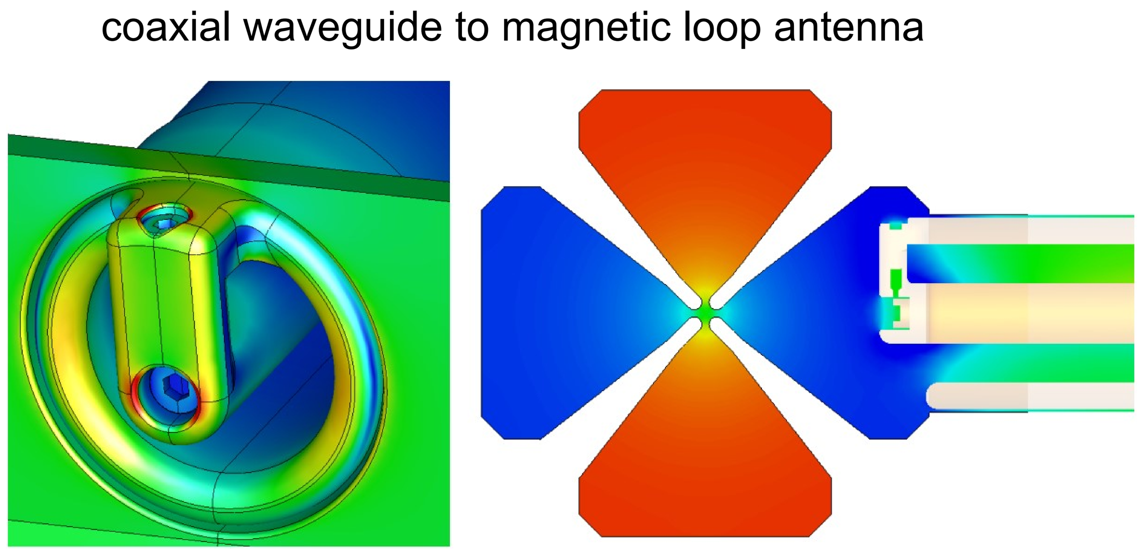
- total RF power can be calculated by decomposing RFQ into segments assuming constant energy over length, which avoids simulation the full model

$$P_0 = \frac{\omega_0 V^2}{2} \sum_s \frac{1}{Q_{0,s}} \int_{\mathrm{Seg.}\,s} C'(z)dz$$

Computed RF quantities for V = 35 kV

Loss factor	Q_0	6000	
Capacitance	C'	125	pF/m
Stored energy	W	82	mJ
RF power loss	P_0	64.5	kW
Max. surface field	E_s	39.1	MV/m

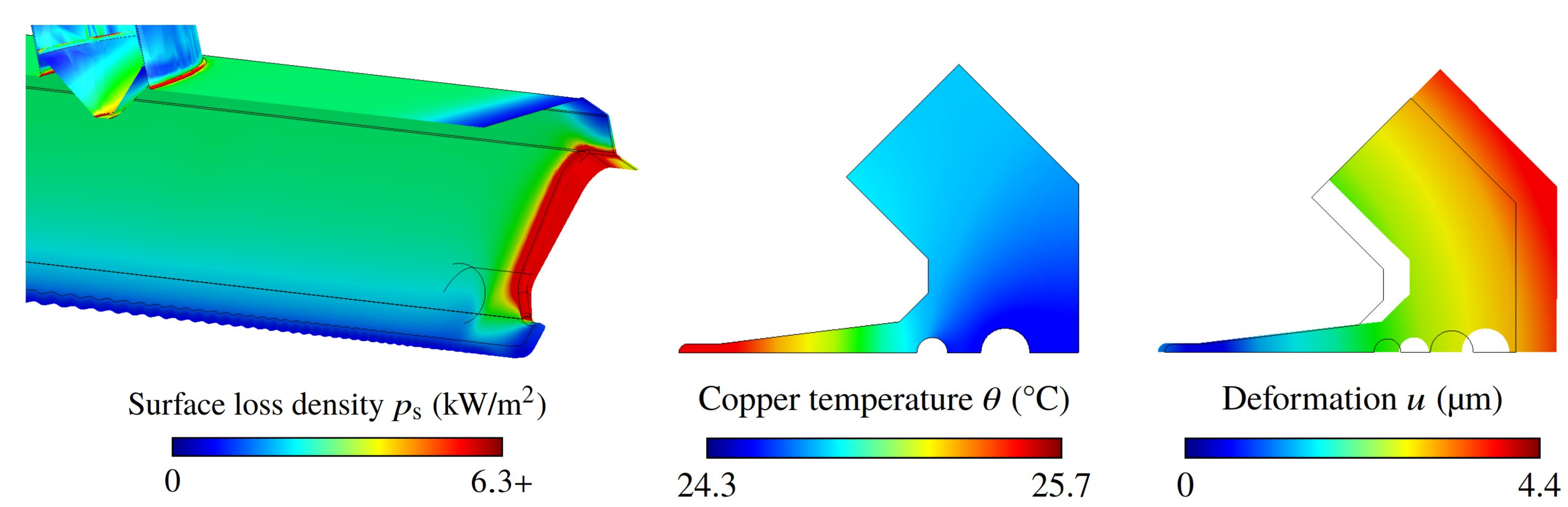
- one input power coupler: coaxial waveguide to magnetic loop antenna



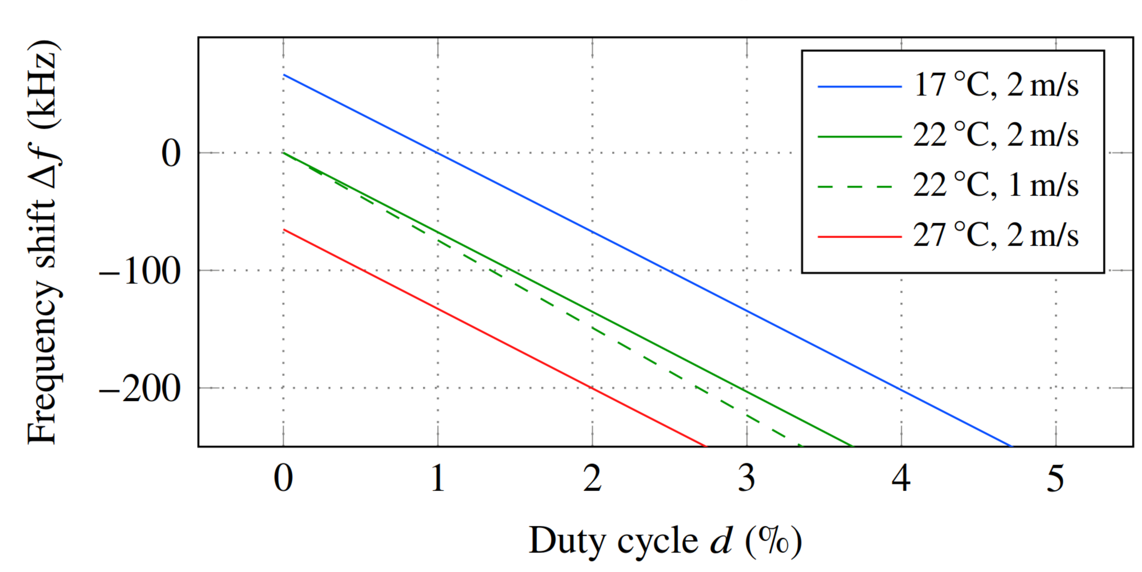
Thermal Simulation

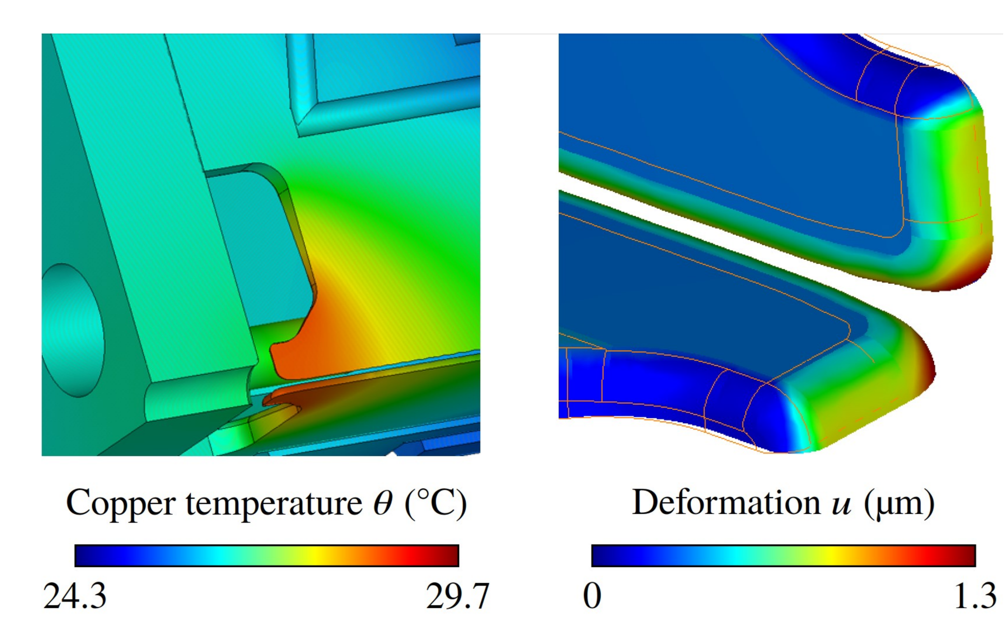
- due to RF power loss, RFQ temperature increases and it is deformed by thermal expansion, leading to change in resonant frequency depending on duty cycle, cooling water temperature and average water speed
- combination of effects:
  - tank size and thus inductance L increases
  - vane tips move closer together due to temperature gradient, capacitance C increases

  both reduce resonant frequency $\omega = 1/\sqrt{LC}$



- decided on 22°C and 1 m/s cooling water

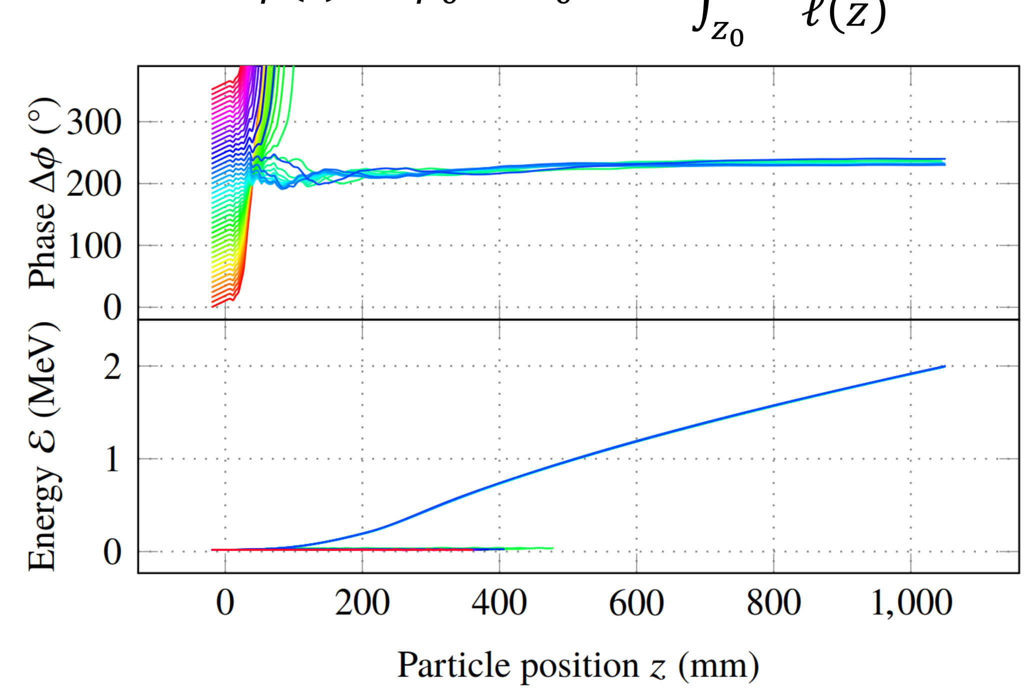




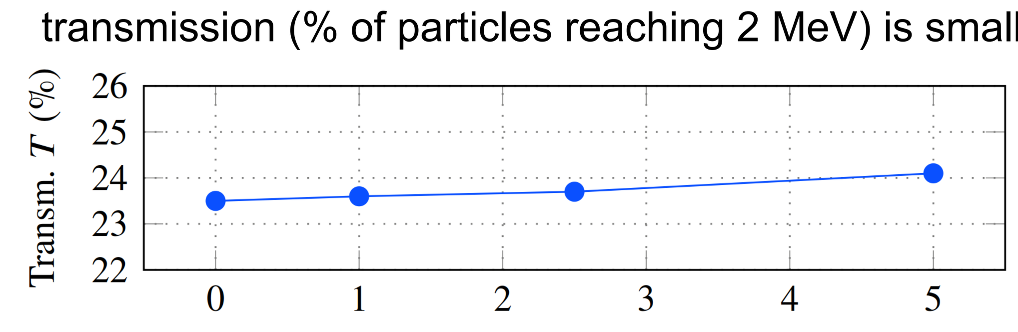
1D Particle Tracking

- simple 1D tracking simulation for RF field validation: $x = y = 0$, initial phase 0..2π, initial energy 20 keV
- reference phase defined by RFQ vane modulation

$$\Delta\phi(t) = \phi_0 + \omega_0 t - \pi \int_{z_0}^{z(t)} \frac{dz}{\ell(z)}$$



- effect of changing RF frequency due to heating on transmission (% of particles reaching 2 MeV) is small



Conclusion

The RF design of the PIXE RFQ linac has been conducted including cavity geometry, tuners, pumping ports, and power coupler. The thermal expansion and resulting resonant frequency shift due to RF power dissipation has been studied to yield the requirements on the cooling circuit. Further, first results of particle tracking through the RF field have been presented. It has been shown, that the frequency shift due to thermal expansion has little effect on the beam dynamics.

References

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