Design of a high-frequency RFQ for Carbon ion therapy

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Traditio et Innovatio

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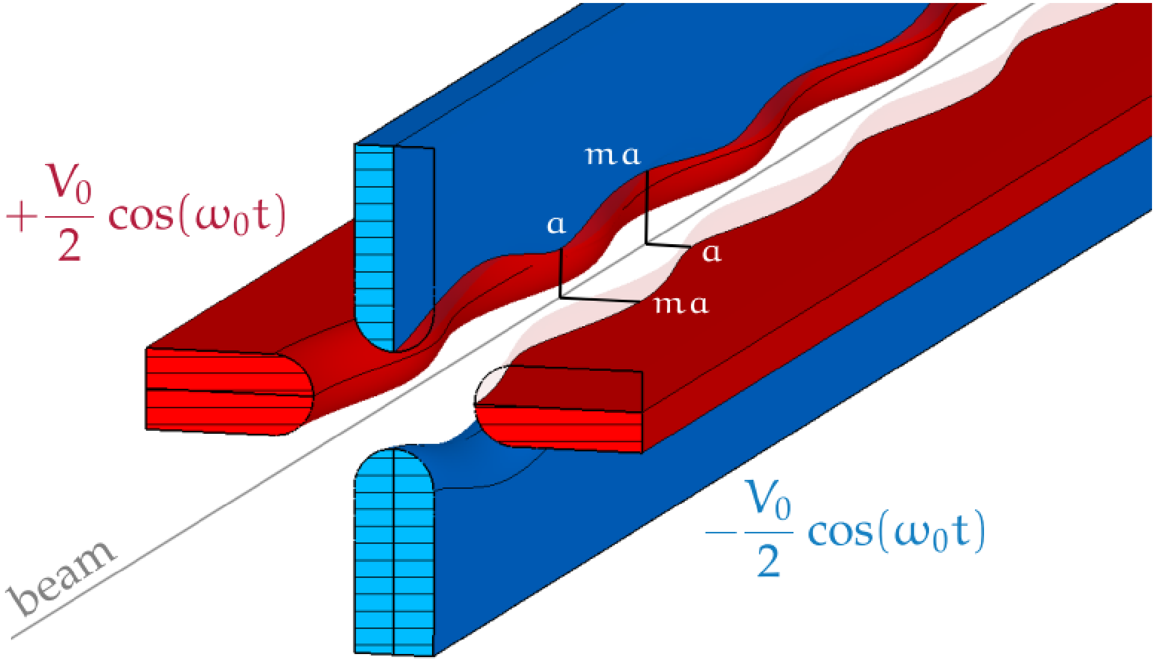
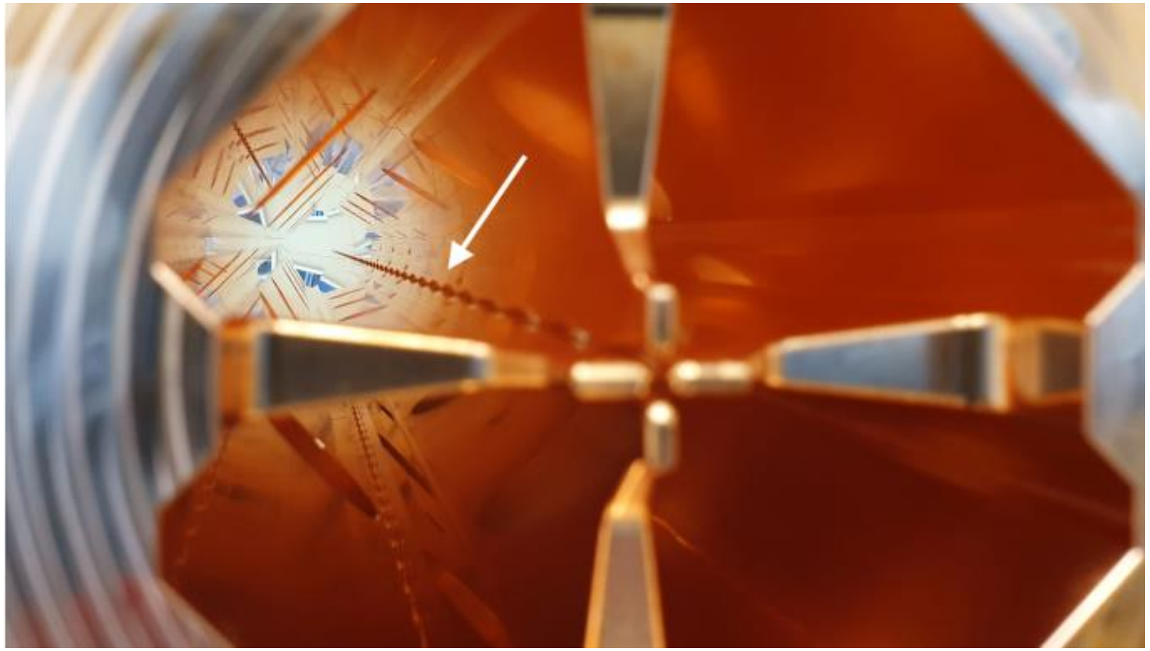
Very briefly: what is an RFQ?

- accelerator of choice for low-energy hadrons up to few MeV/u
- strong electric quadrupole focusing field
- modulation on quadrupole electrodes produces Ez field
- accepts continuous input beam from LEBT, performs adiabatic bunching





Recent RFQs developed at CERN

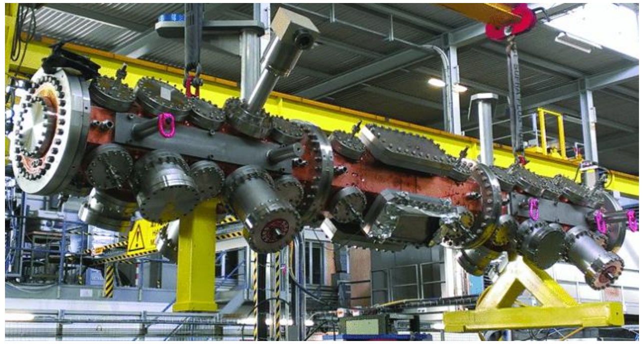
older RFQs…

Linac4-RFQ
352 MHz
3 m

HF-RFQ
750 MHz
2 m

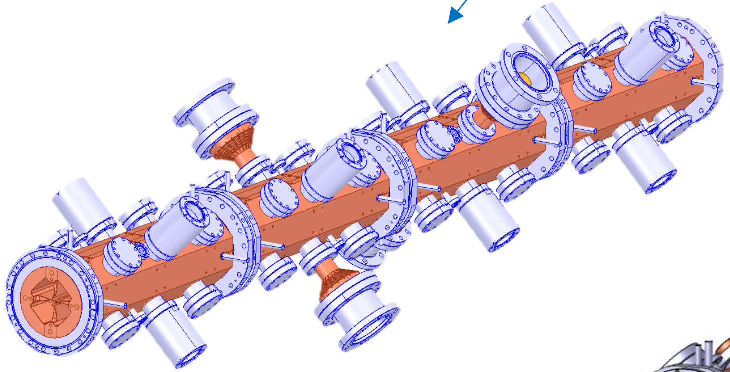
PIXE-RFQ
750 MHz
1 m

Carbon-RFQ
750MHz
4.8 m

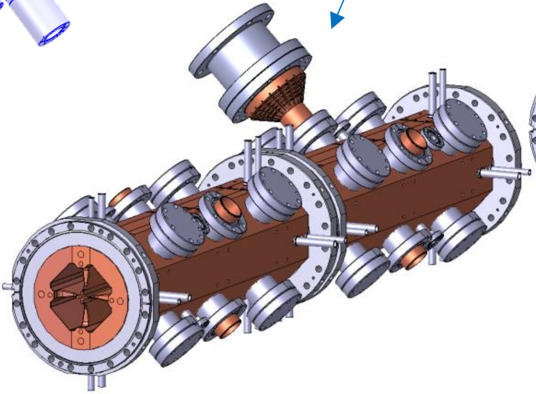


C. Rossi et al., „Commissioning and operational experience gained with the Linac4-RFQ at CERN", Proc. Linac14, 2014

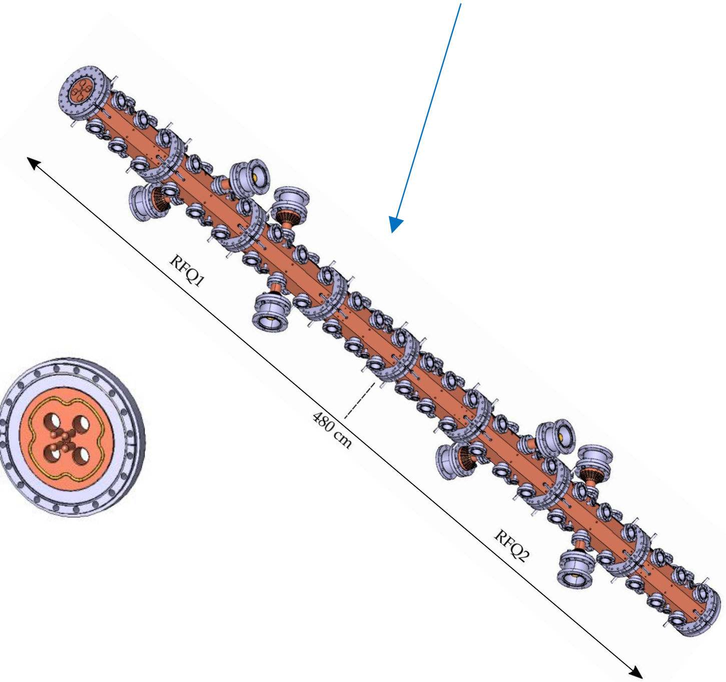
operational,
work in progress on
spare and upgrade



commissioned 2018
(now with AVO ADAM)



RF measurements &
tuning in progress
(Bat. 112)

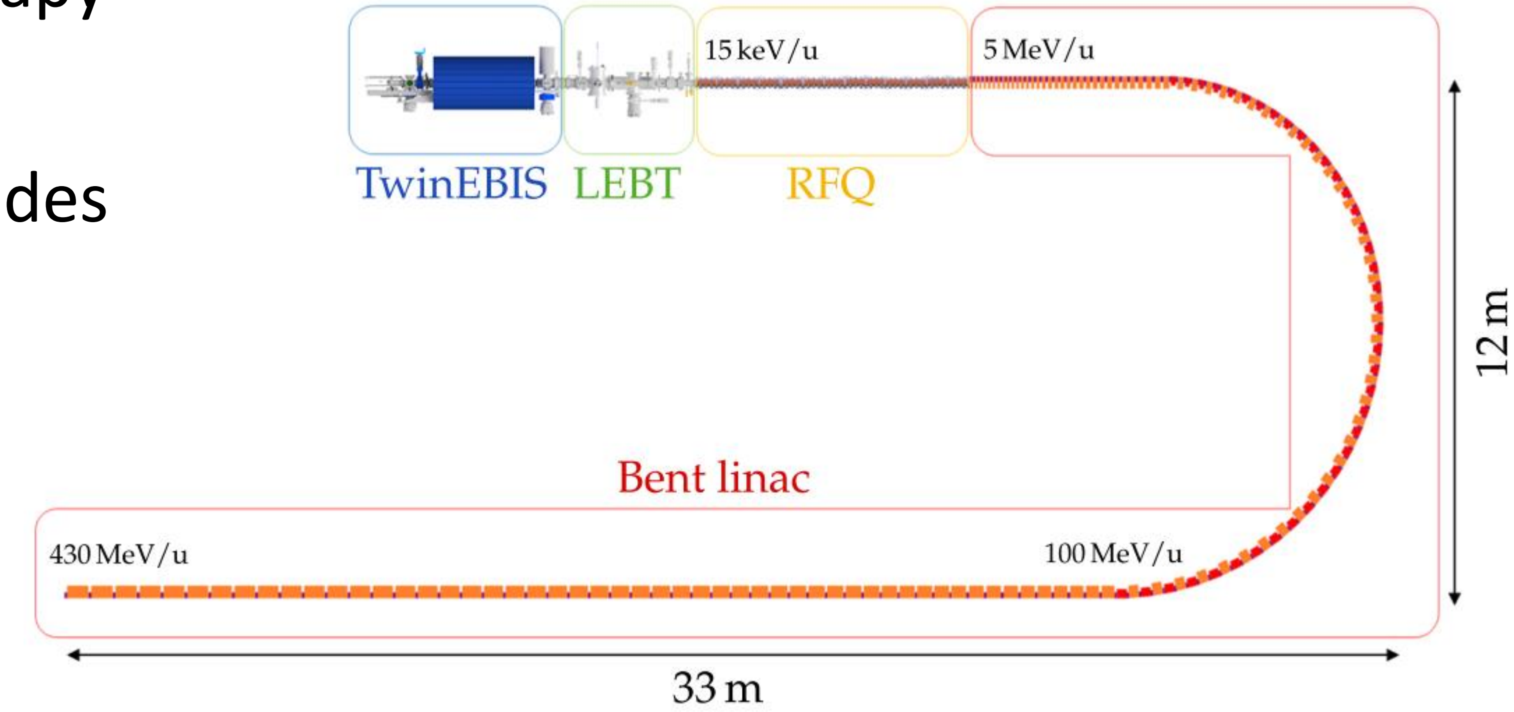


Beam dynamics & RF design
completed early 2020,
now mechanical design by
CIEMAT

Part I: Carbon-RFQ Beam Dynamics Design

Context & initial Carbon-RFQ design

- conceived by V. Bencini (BE-ABP) as first RF structure of „bent linac“ for carbon ion cancer therapy

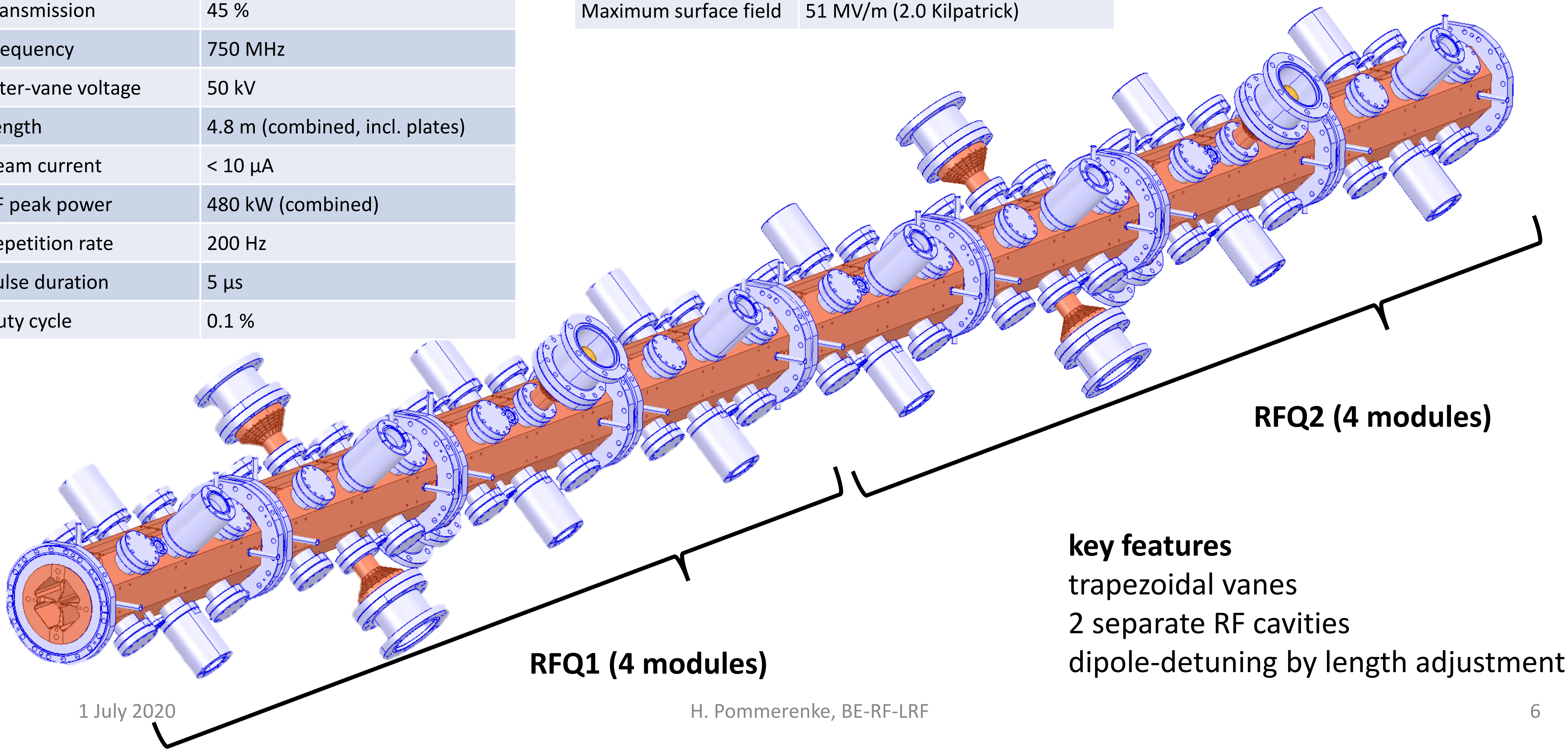


- initial design with LANL codes (PARMTEQ):
  - low beam current
  - ~ 50 % transmission
  - up to 5 MeV/u (60 MeV)

Carbon-RFQ design parameters

Species (q/A)	fully stripped carbon-ion (1/2)
Input energy	15 keV/u
Output energy	5.06 MeV/u
Transmission	45 %
Frequency	750 MHz
Inter-vane voltage	50 kV
Length	4.8 m (combined, incl. plates)
Beam current	< 10 µA
RF peak power	480 kW (combined)
Repetition rate	200 Hz
Pulse duration	5 µs
Duty cycle	0.1 %

Mid-cell aperture	1.411 mm
Minimum aperture	0.672 mm
Number of cells	726
Maximum surface field	51 MV/m (2.0 Kilpatrick)



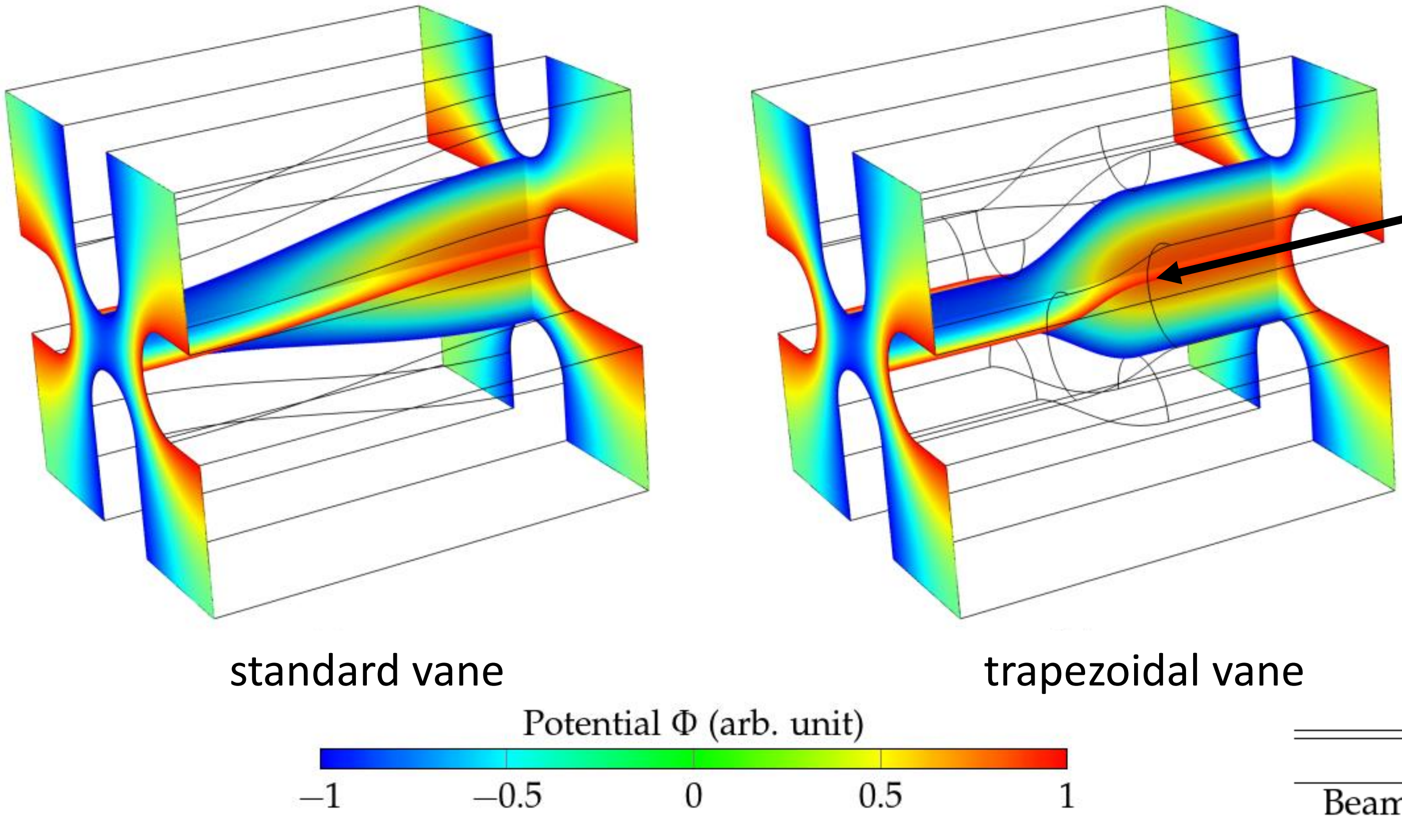
key features

trapezoidal vanes

2 separate RF cavities

dipole-detuning by length adjustment

From standard to trapezoidal vanes

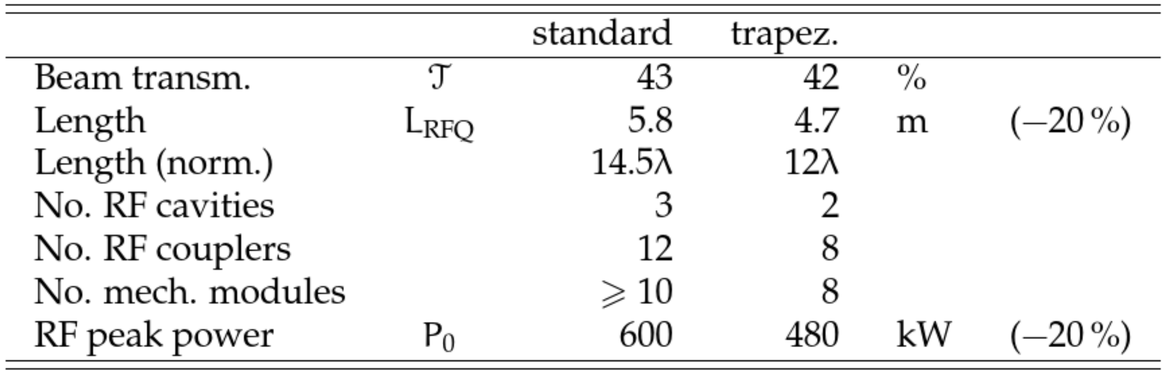


standard vane

trapezoidal vane

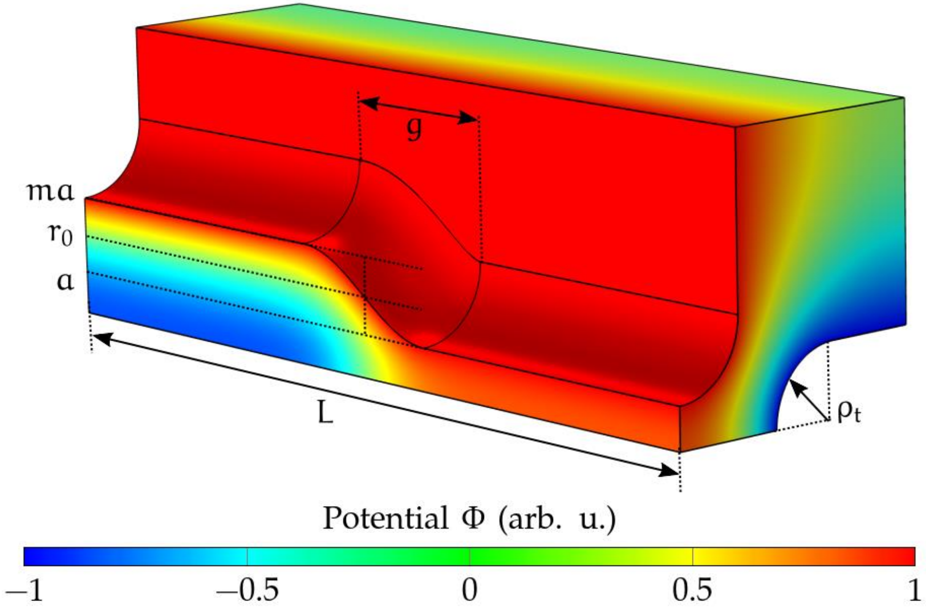
concentrate more electric field in the gap (equivalent to reducing gap length in DTL)

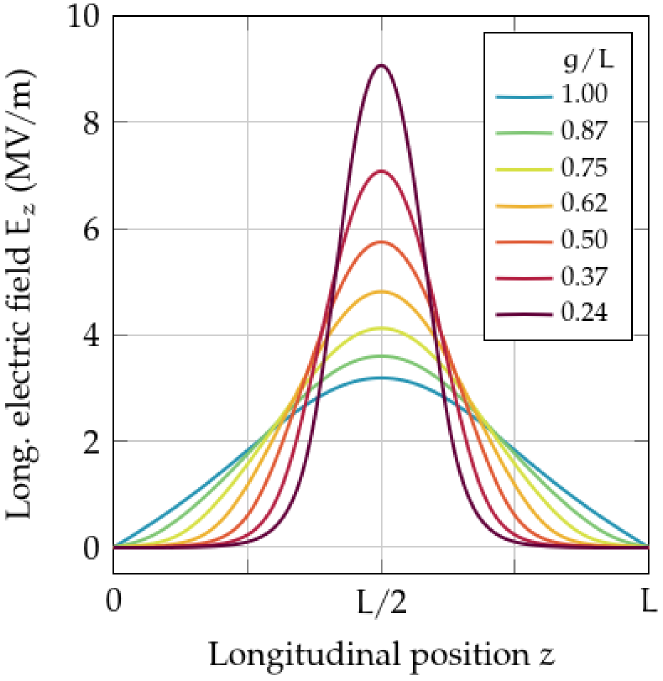
what do we gain?

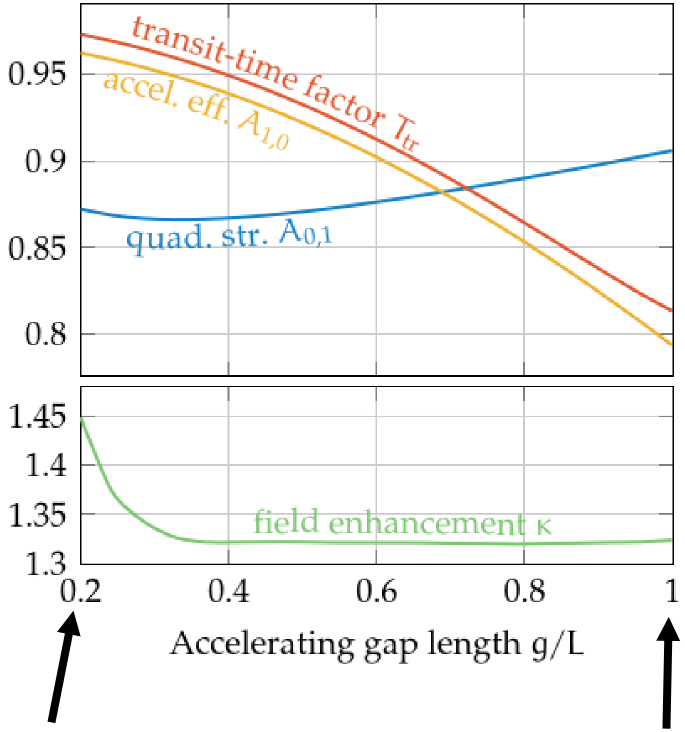


		standard	trapez.		
Beam transm.	$\mathcal{T}$	43	42	%	
Length	L_{RFQ}	5.8	4.7	m	(−20 %)
Length (norm.)		14.5λ	12λ		
No. RF cavities		3	2		
No. RF couplers		12	8		
No. mech. modules		$\geqslant 10$	8		
RF peak power	P_0	600	480	kW	(−20 %)

The trapezoidal vane - details







maximum steepness

purely sinusoidal

in Carbon-RFQ: 3 degrees of freedom

m : modulation

L : length

g : accelerating gap length [not in standard vanes]

[$\rho_t = 0.9r_0$ = const. in this RFQ]

Sixteen-term potential function

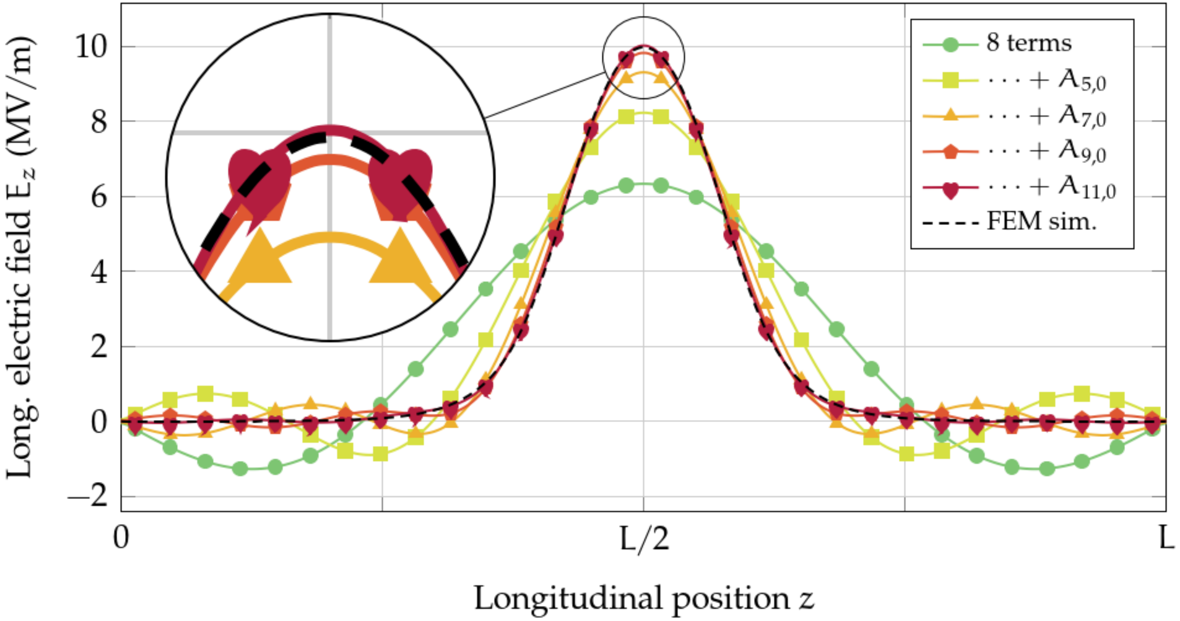
- RFQ electric fields commonly described by multipole expansion
  - two-term potential function (focusing + acceleration terms)
  - eight terms for beam dynamics purposes (PARMTEQ and others)
- for trapezoidal vanes we need more terms!
- precomputed in lookup tables

quadrupole

$$
\begin{aligned}
\frac{\Phi(r,\vartheta,z)}{V_0/2} = \; & A_{0,1}\left(\frac{r}{r_0}\right)^2 \cos(2\vartheta) && + A_{0,3}\left(\frac{r}{r_0}\right)^6 \cos(6\vartheta) \\
& + A_{1,0} I_0(kr)\cos(kz) && + A_{3,0} I_0(3kr)\cos(3kz) \\
& + A_{5,0} I_0(5kr)\cos(5kz) && + A_{7,0} I_0(7kr)\cos(7kz) \\
& + A_{9,0} I_0(9kr)\cos(9kz) && + A_{11,0} I_0(11kr)\cos(11kz) \\
& + A_{1,2} I_4(kr)\cos(4\vartheta)\cos(kz) && + A_{3,2} I_4(3kr)\cos(4\vartheta)\cos(3kz) \\
& + A_{2,1} I_2(2kr)\cos(2\vartheta)\cos(2kz) && + A_{2,3} I_6(2kr)\cos(6\vartheta)\cos(2kz) \\
& + A_{4,1} I_2(4kr)\cos(2\vartheta)\cos(4kz) && + A_{4,3} I_6(4kr)\cos(6\vartheta)\cos(4kz) \\
& + A_{6,1} I_2(6kr)\cos(2\vartheta)\cos(6kz) && + A_{6,3} I_6(6kr)\cos(6\vartheta)\cos(6kz)
\end{aligned}
$$

acceleration

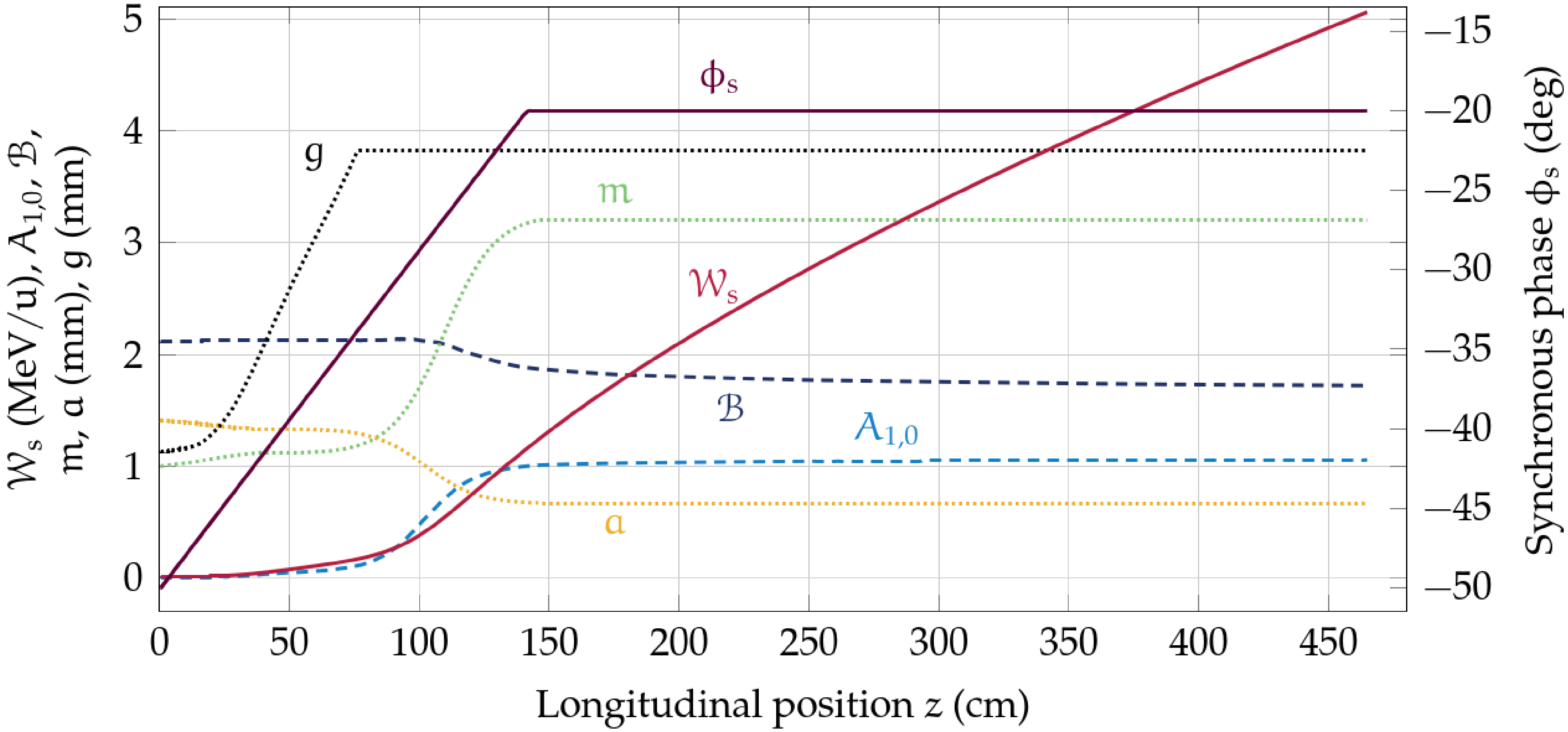
approximation of Ez by adding more terms



Carbon-RFQ channel parameters

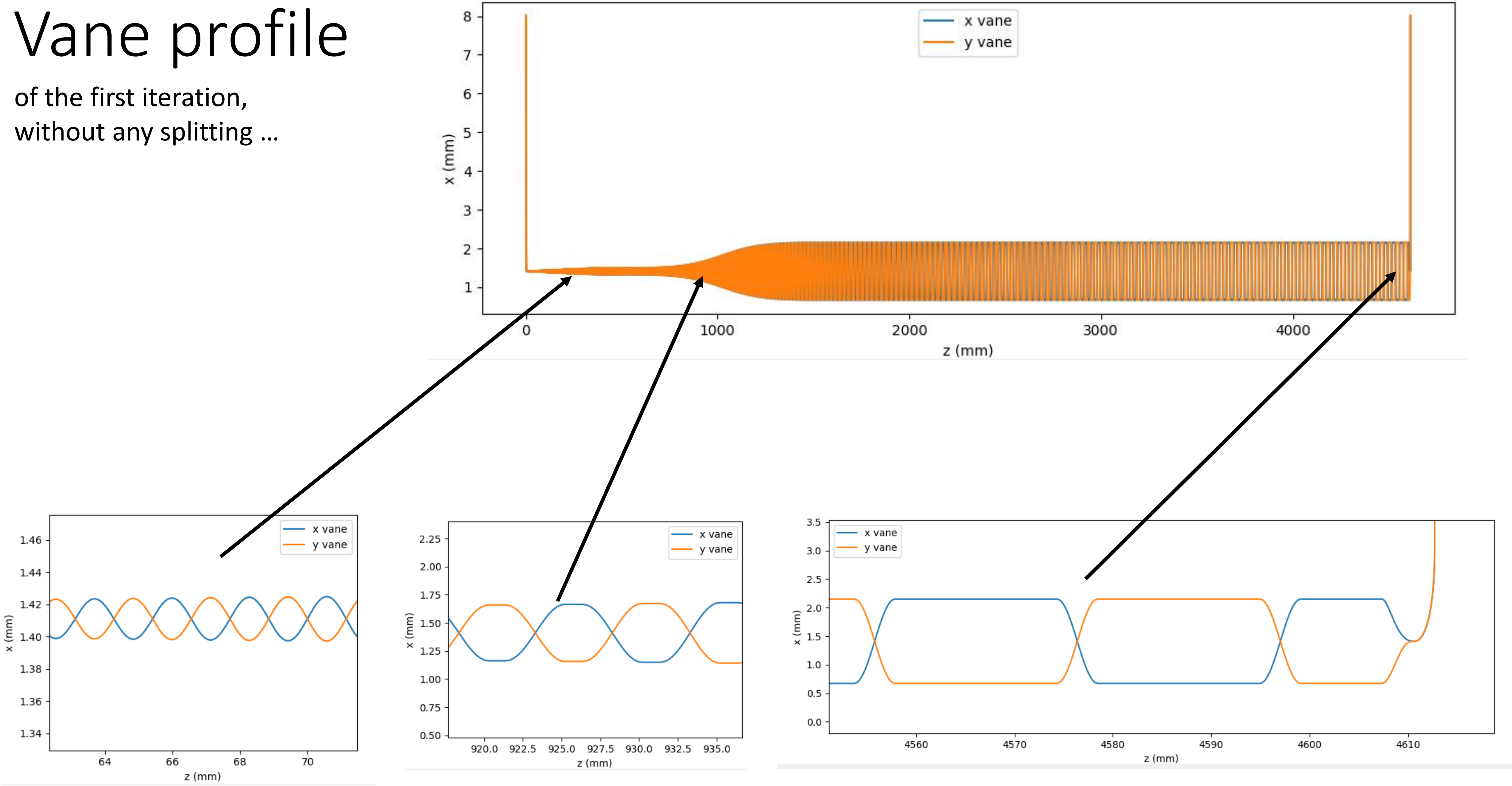
- initial beam dynamics by V. Bencini with conventional vanes designed in PARMTEQ
- use same sync phase ϕ(z) and aperture a(z) for the trapezoidal vane

m : modulation
a : min. aperture
g : accelerating gap length
Ws : sync. energy
ϕs : sync. phase
B : eff. focusing
A10: eff. acceleration (~TTF)

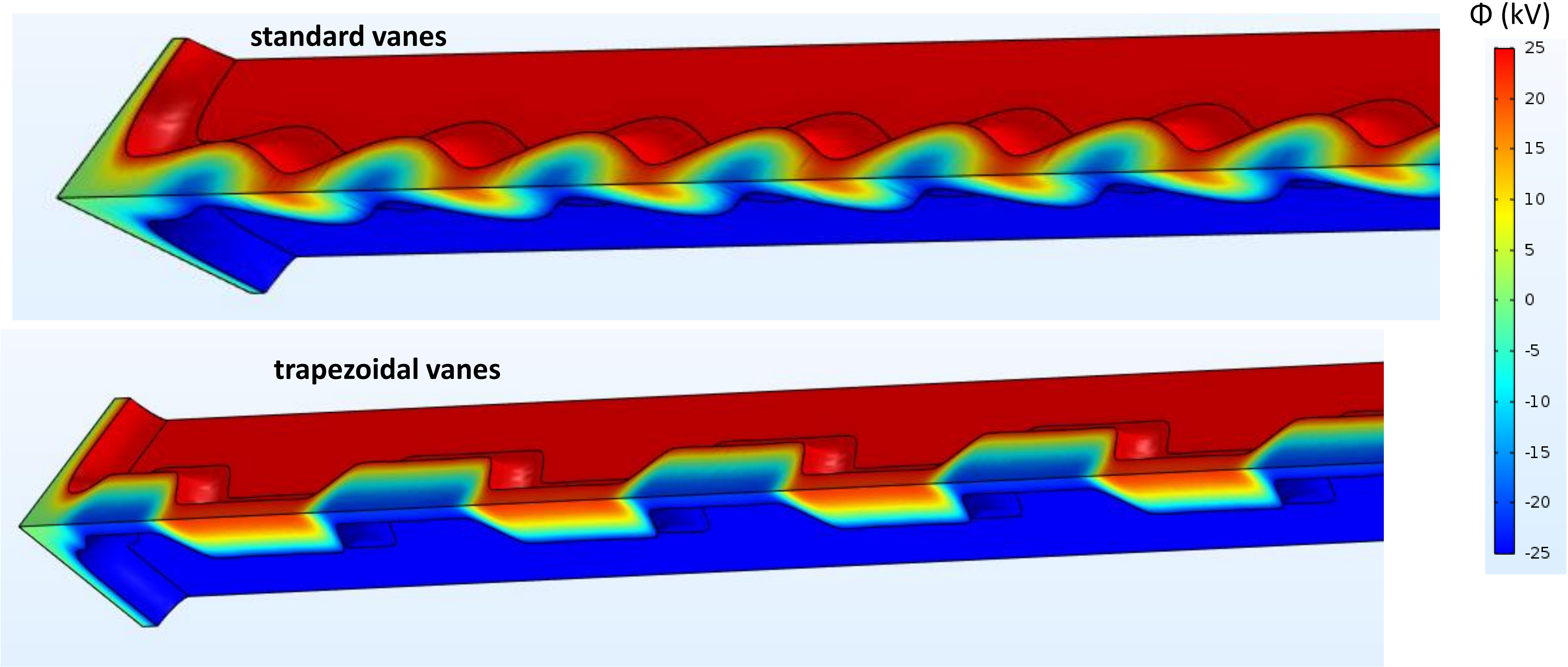


Vane profile

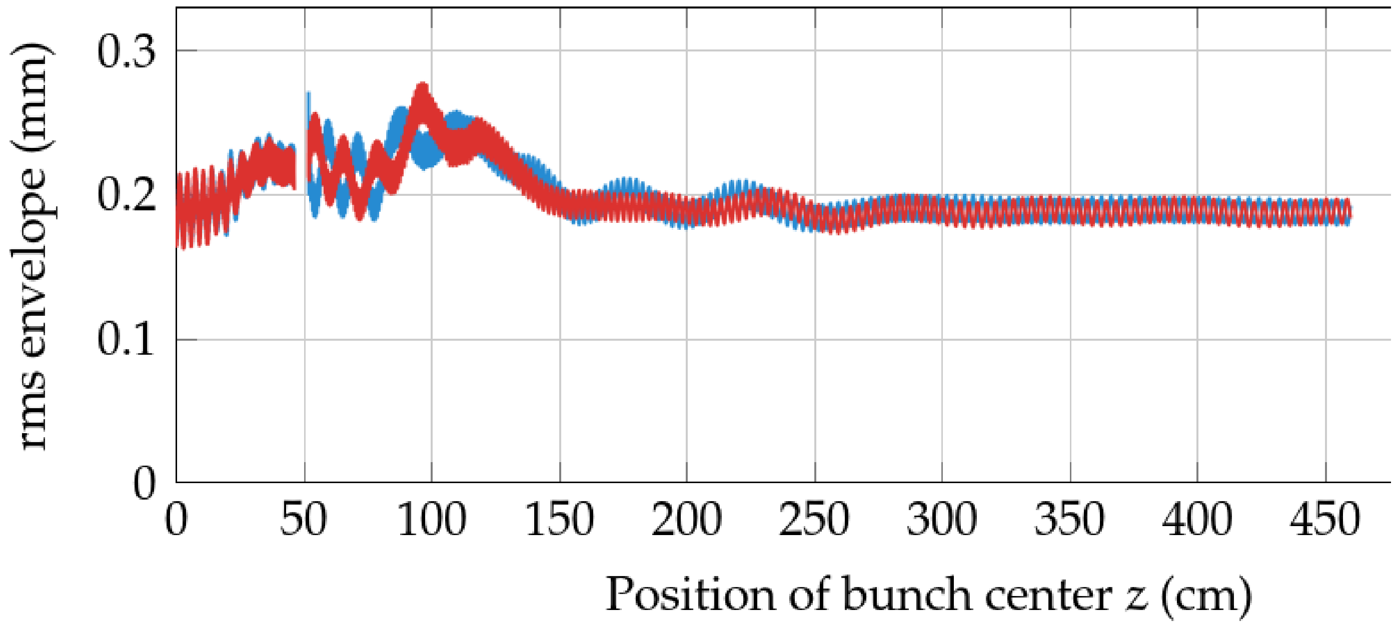
of the first iteration,
without any splitting …

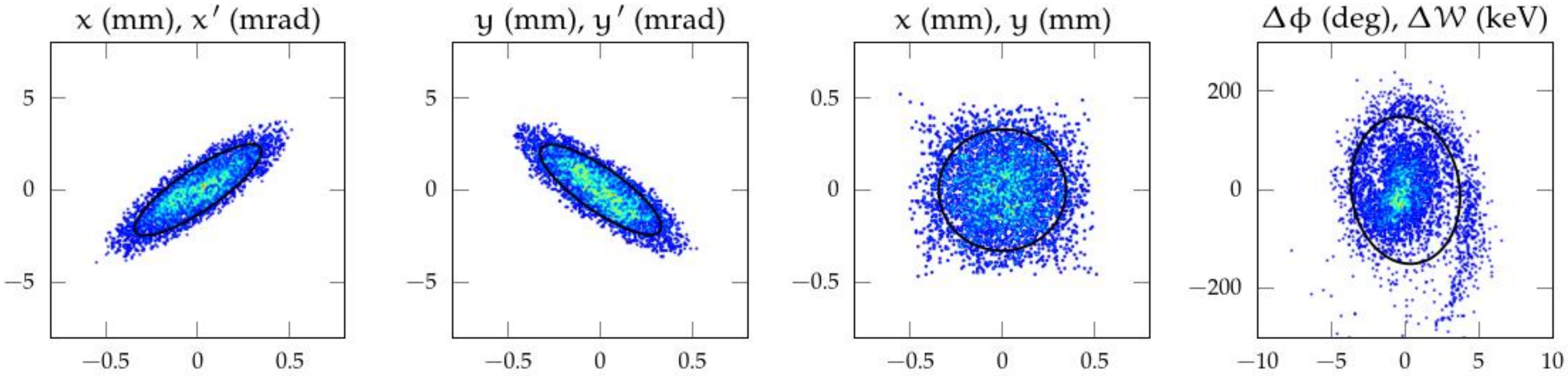


Vane CAD models / Potential



Beam envelope and output phase space

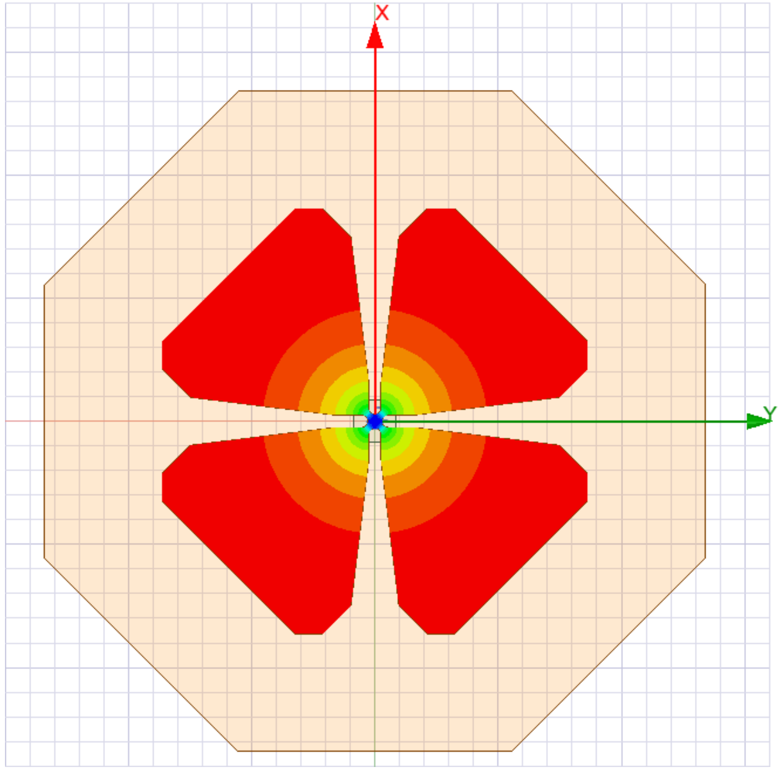




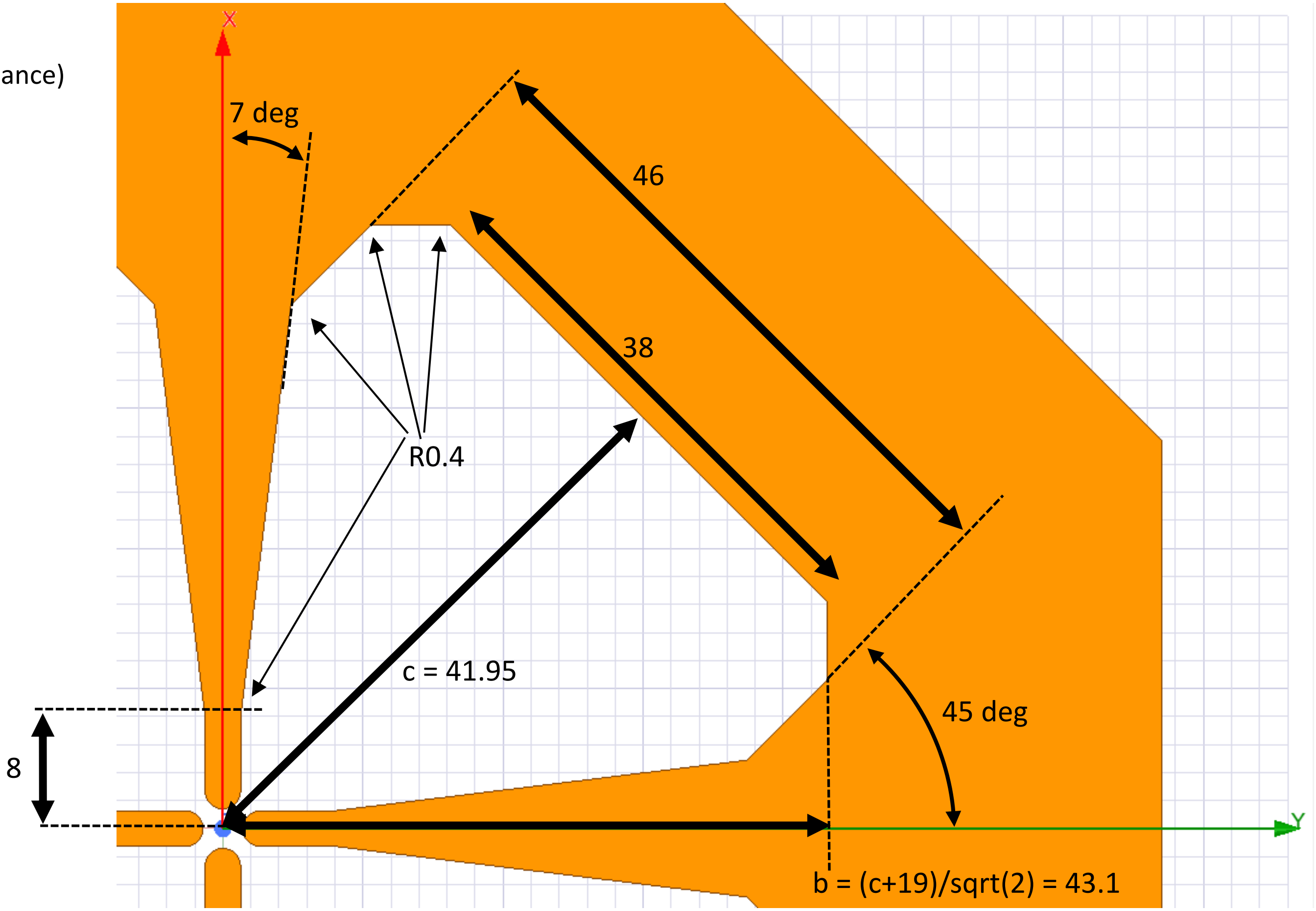
Part II: Carbon-RFQ RF Design

2D cross section

- adapted from HF-RFQ / PIXE-RFQ
- restrictions: planar back wall for flange aperture, cooling channels
- 2D Q0*: 7540, 2D power: 93 kW/m
  (*7830, 85 kW/m for trapezoidal vanes at high energies, due to lower capacitance)

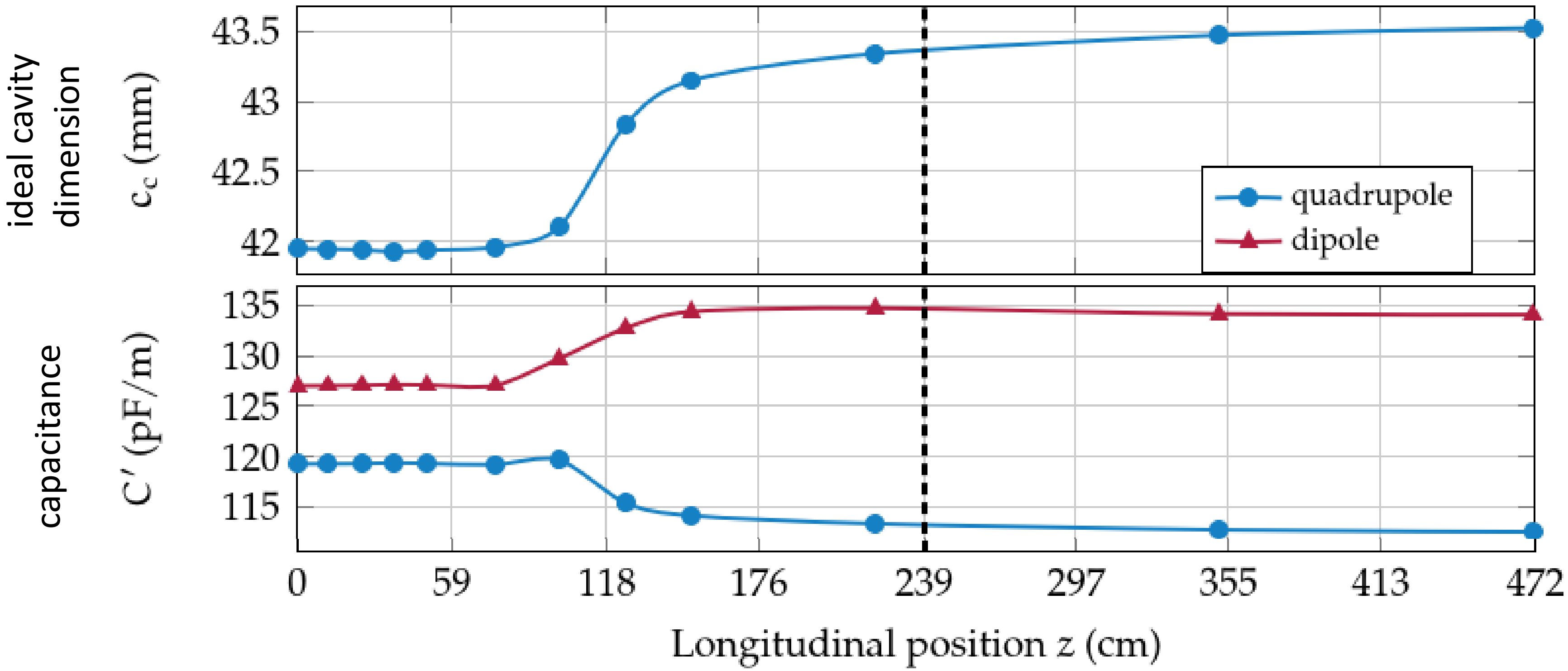


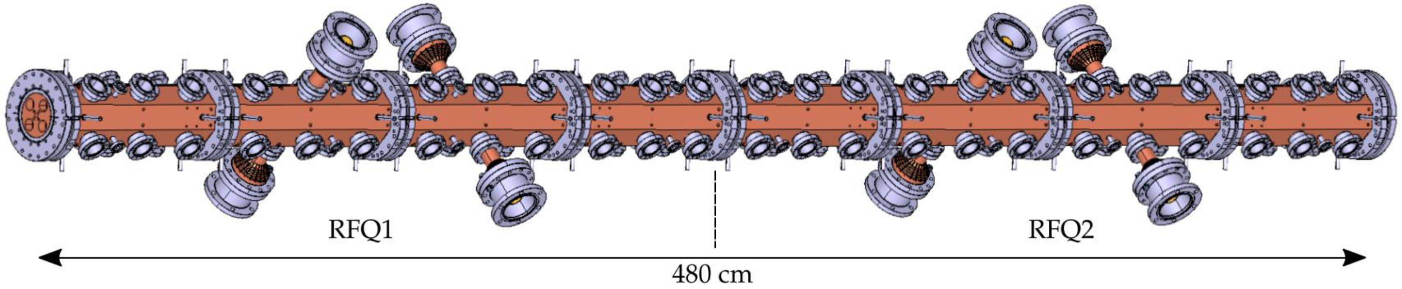
plot: magnetic field magnitude

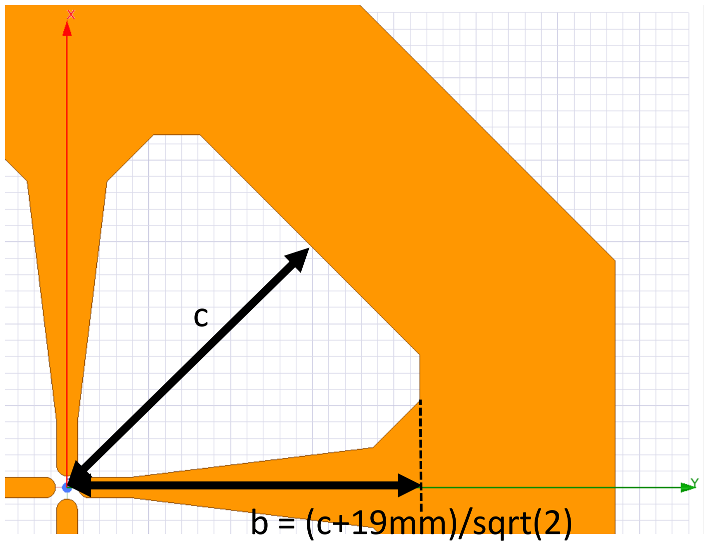


c is shown for the 2D cavity. they will be different for each module

RFQ is a tapered structure





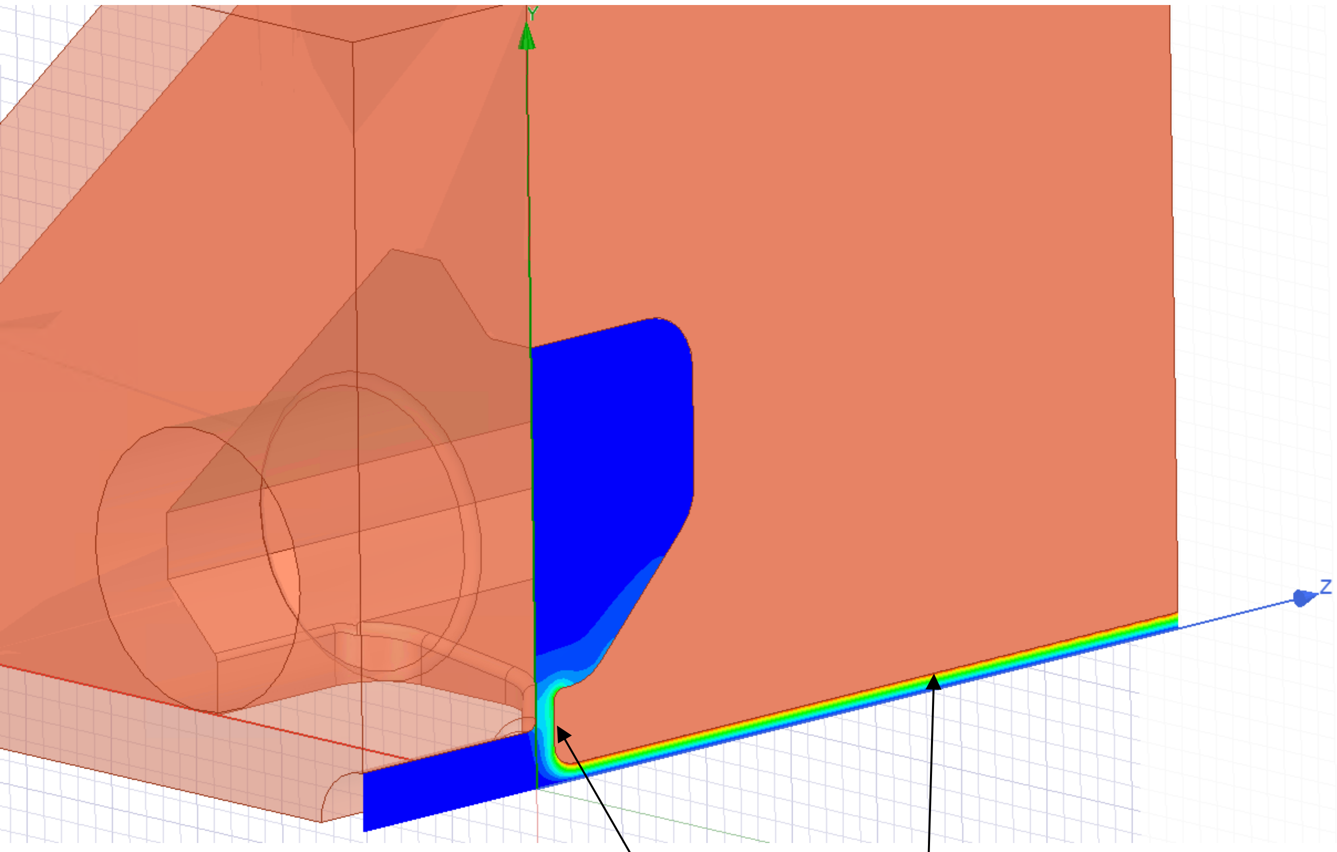


each cell requires a slightly different value for c to tune the LC circuit of vane capacitance and cavity inductance

→ we average over each module for only planar surfaces

maximum fields in 3D

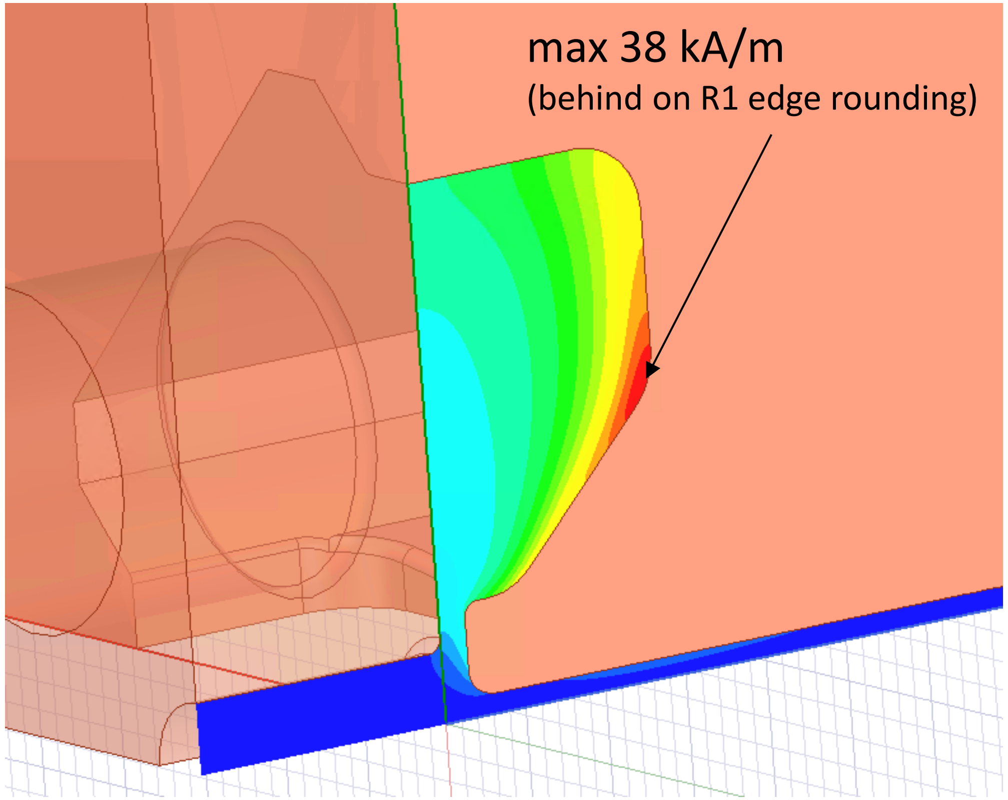
E-field



26 MV/m

max 51 MV/m
vane surface field
(= 2.0 Kilpatrick @ 750 MHz)

H-field



max 38 kA/m
(behind on R1 edge rounding)

The 750 MHz HF-RFQ has been successfully commissioned with 50 MV/m and similar pulse length.

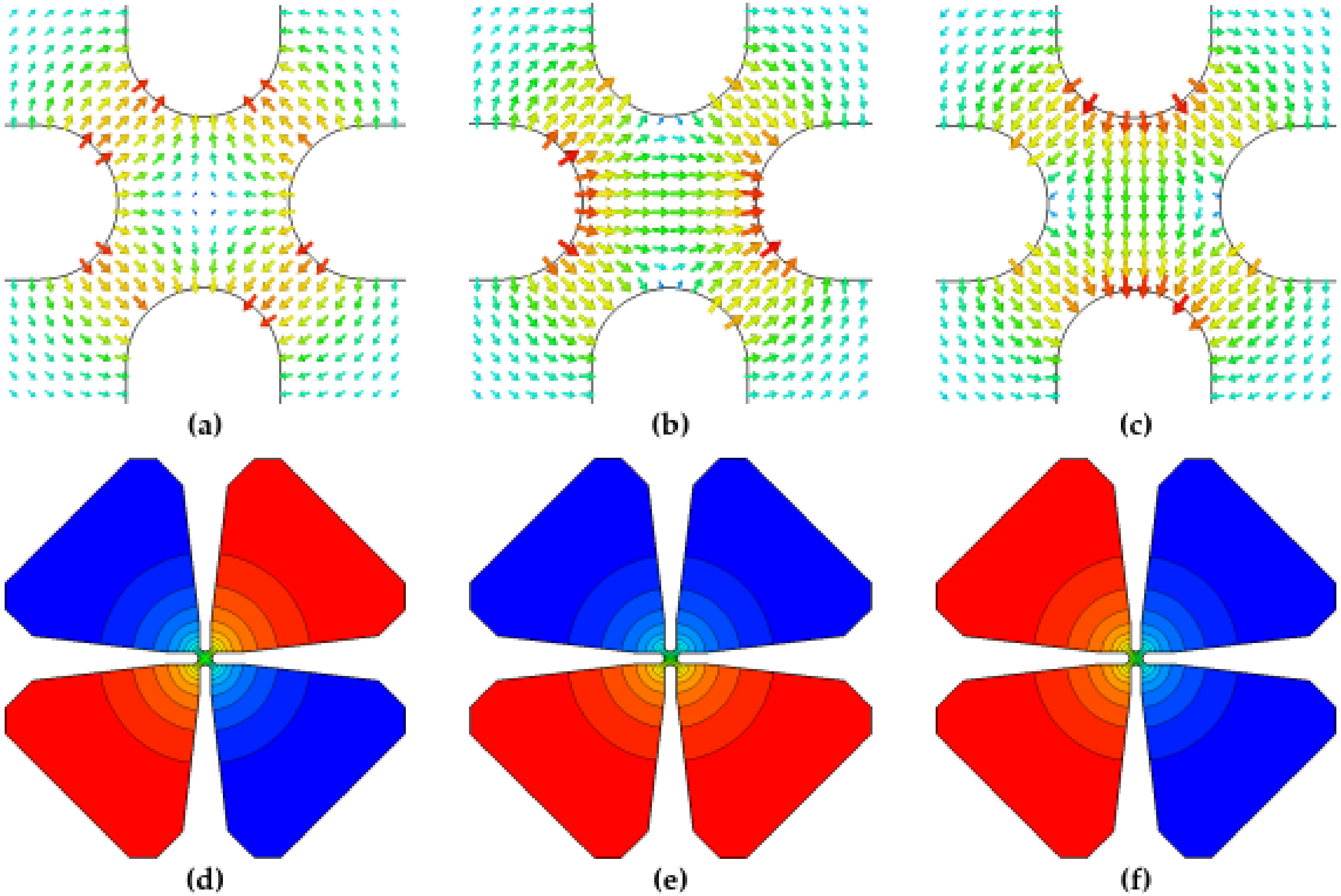
Four-vane RFQ eigenmodes

Quadrupole (TE21n)

Dipoles (TE11n), 2 polarizations

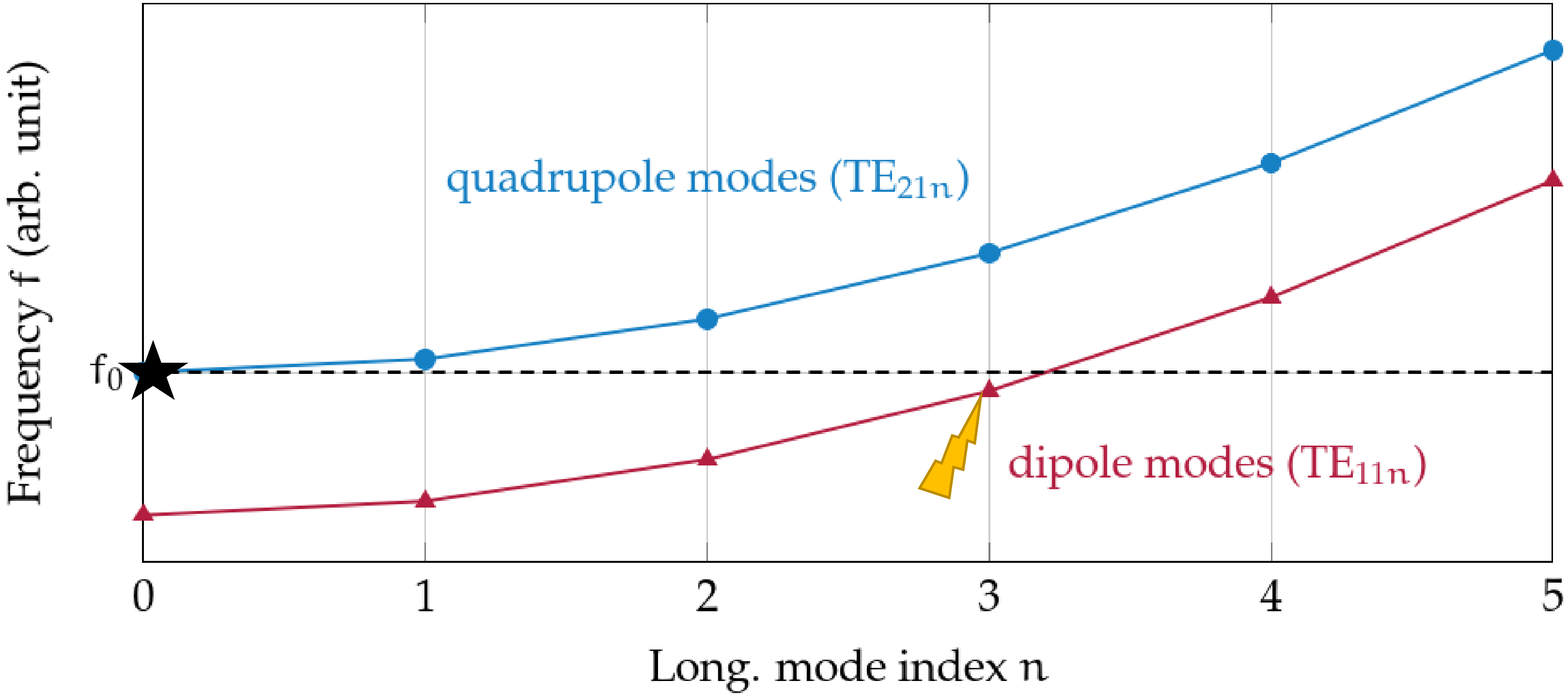
E-field
between vane tips

H-field
in cavity



RFQ spectrum

- RFQ sensitivity to tuning errors goes with $(L/\lambda)^2$ as more modes appear



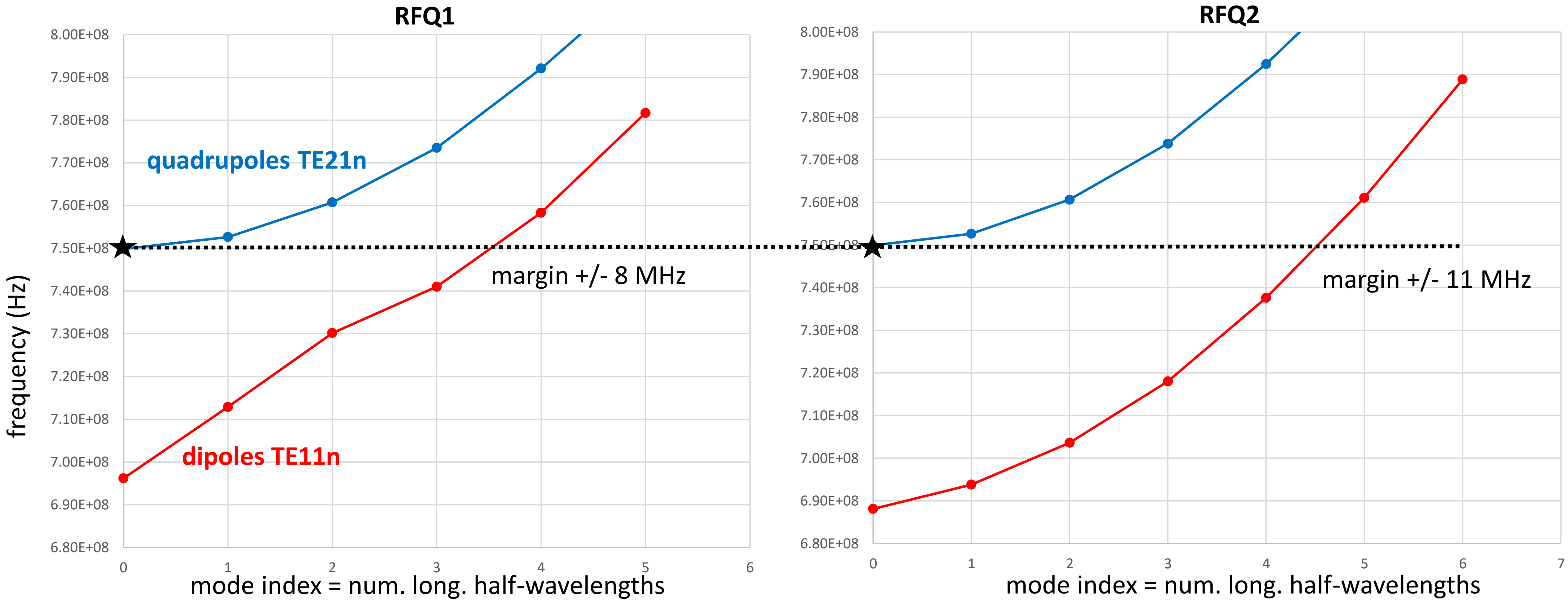
example of ideal RFQ

hyperbolas known from any waveguide with constant cross section

- length limit generally 4…6λ
- Carbon-RFQ with trapezoidal vanes: L = 12λ, far too long

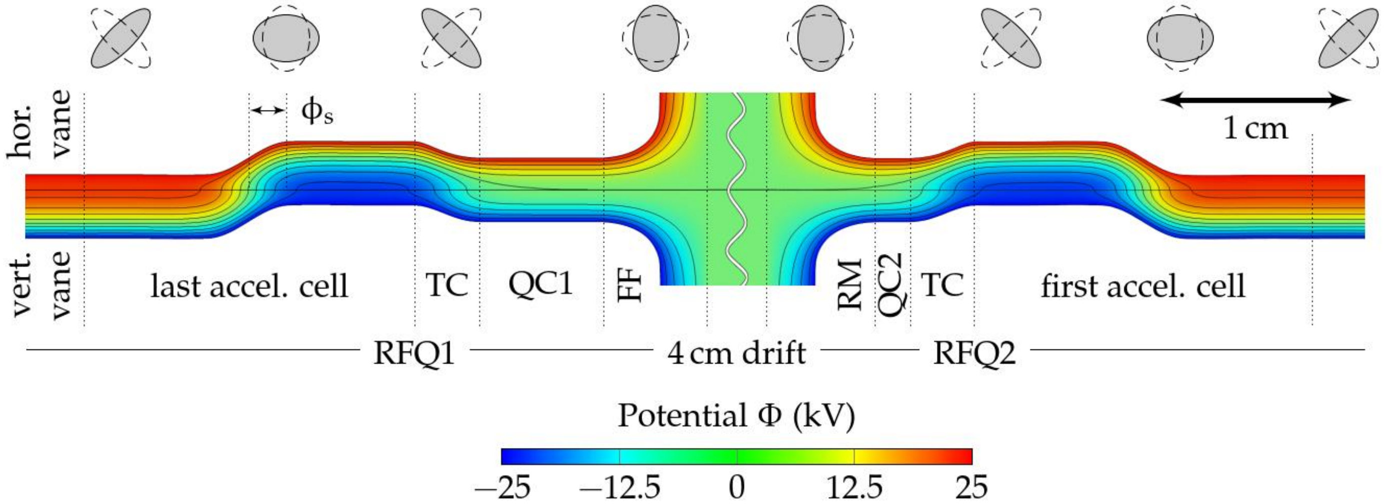
Splitting the RFQ - spectrum

- split RFQ into two fully decoupled cavities, share only vacuum
- spectrum of each cavity tuned solely by length adjustment
  (novel technique that needs no dipole rods, coupling rings etc…)

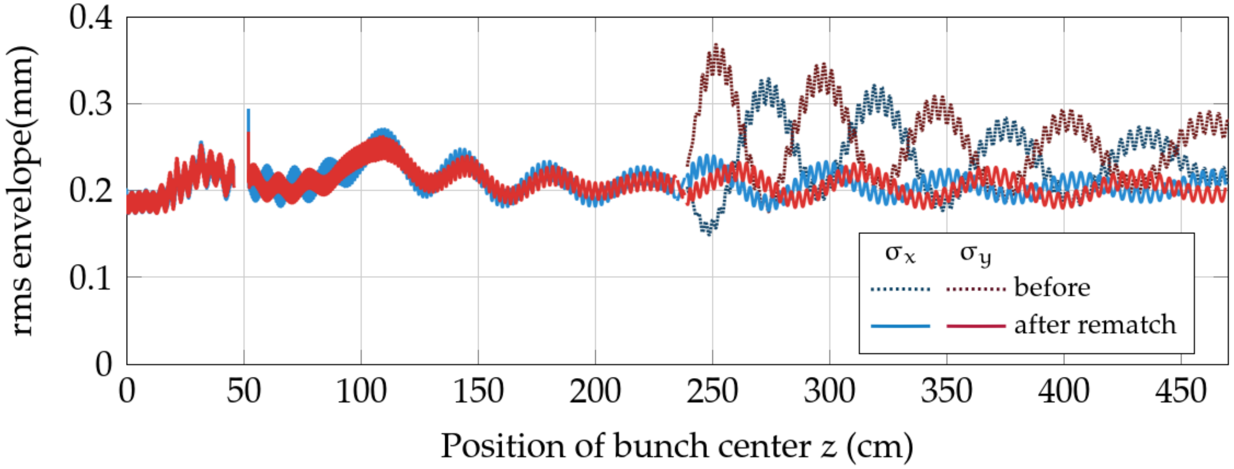


Splitting the RFQ – beam rematching

- beam needs to traverse 4cm drift space, which break focusing periodicity
- rematching by modifying vane shape at RFQ1 exit / RFQ2 entrance

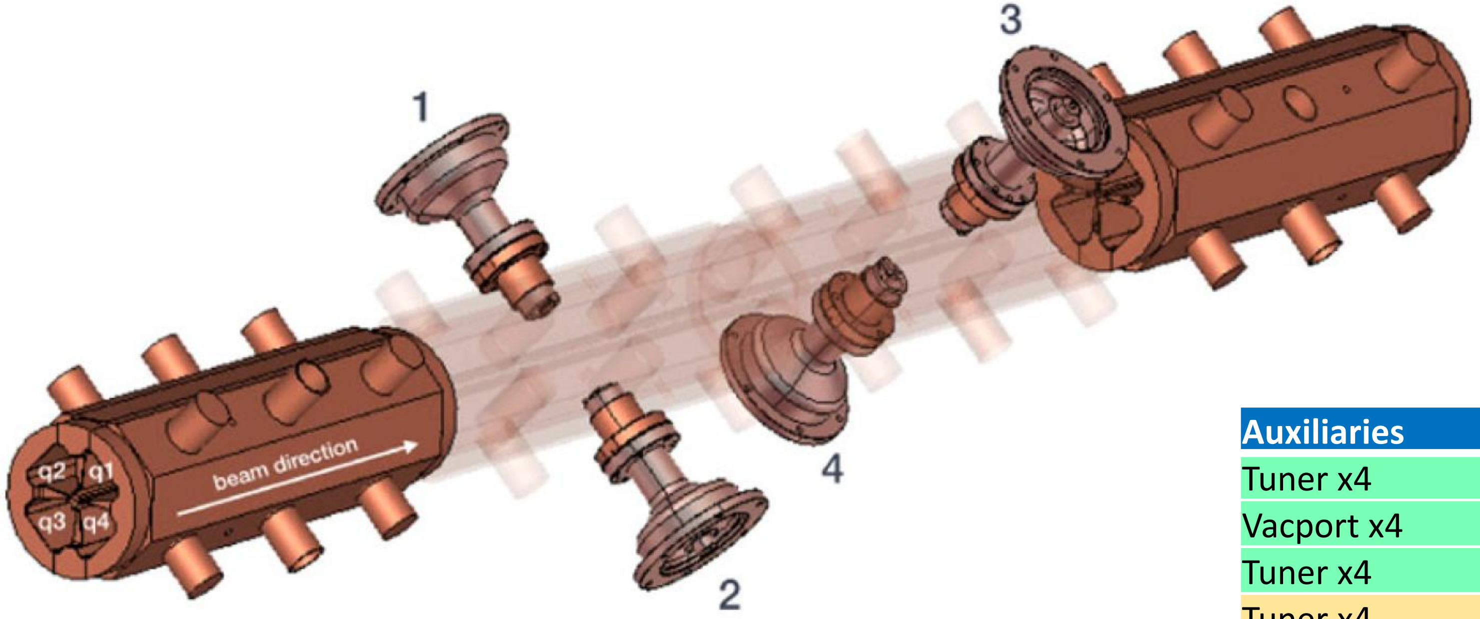


- after re-match, slight beating remains, but well within RFQ aperture



RFQ auxiliaries

- configuration (of both RFQ1 and RFQ2) identical to HF-RFQ



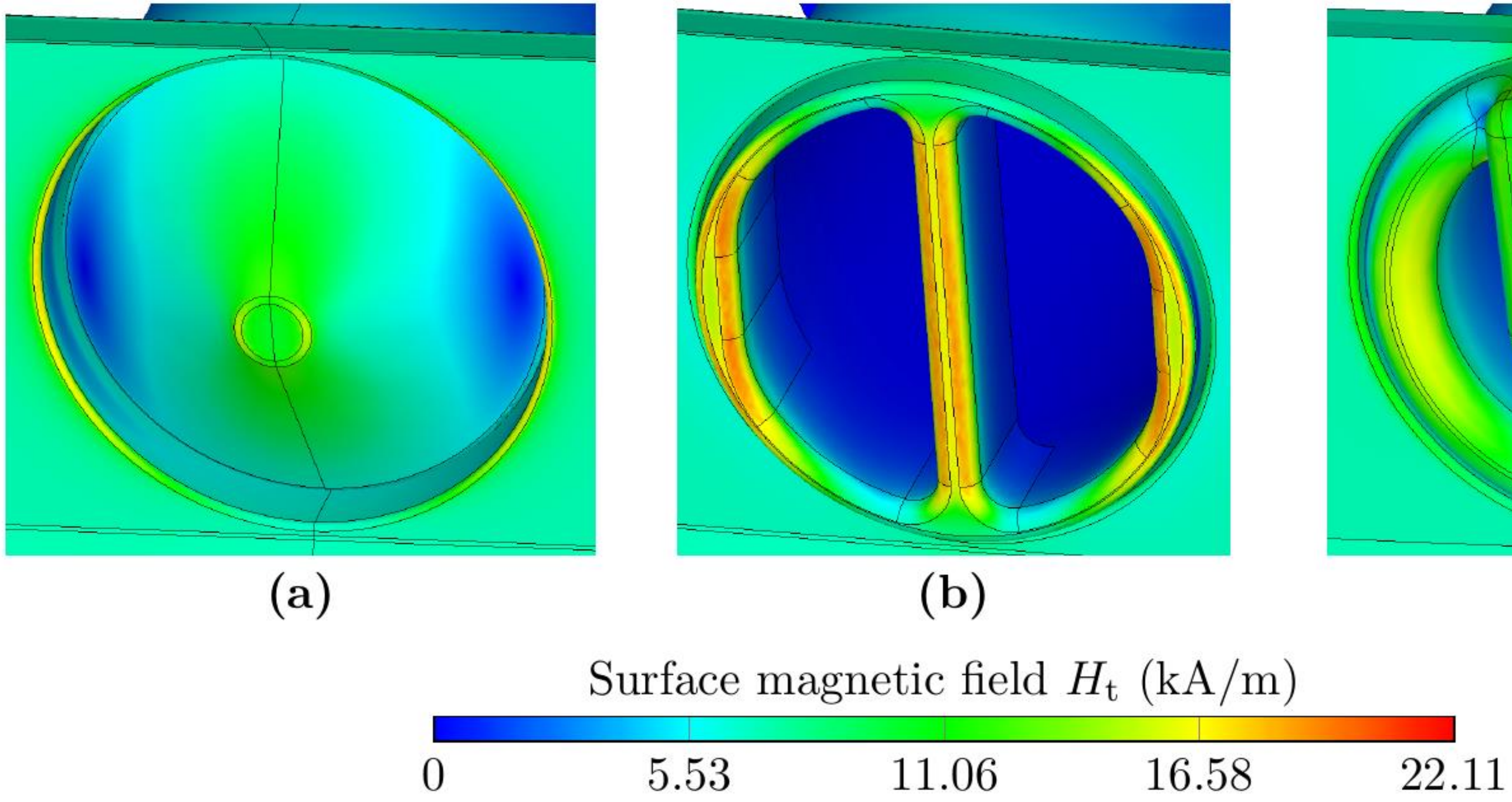
B. Koubek, A. Grudiev, and M. Timmins, "RF measurements and tuning of the 750 MHz radio frequency quadrupole," Physical Review Accelerators and Beams 20(8), 2017.

Auxiliaries	Number per RFQ
Tuners	32 (1.3/λ)
Vacuum pumping ports	12
Couplers	4
RF diagnostic antennas	8 or 16 (?)

Auxiliaries	RFQ1 : Z of center (mm)	RFQ2 : Z of center (mm)
Tuner x4	146.820	2536.022
Vacport x4	293.640	2682.015
Tuner x4	440.460	2828.008
Tuner x4	734.860	3118.155
Vacport x2 / Coupler x2	882.340	3262.210
Tuner x4	1029.820	3406.265
Tuner x4	1323.457	3696.967
Vacport x2 / Coupler x2	1469.515	3843.515
Tuner x4	1615.572	3990.062
Tuner x4	1908.803	4282.465
Vacport x4	2055.875	4428.220
Tuner x4	2202.948	4573.975

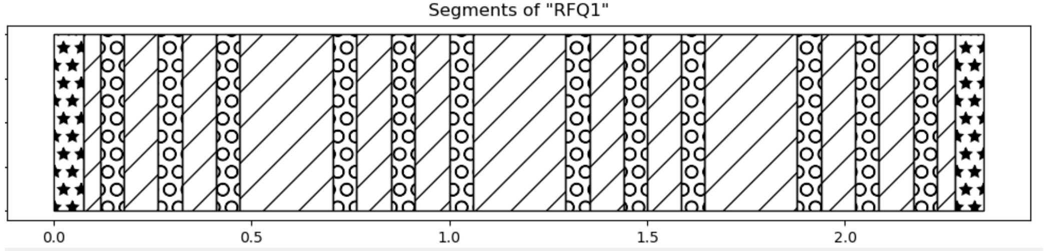
RFQ auxiliaries

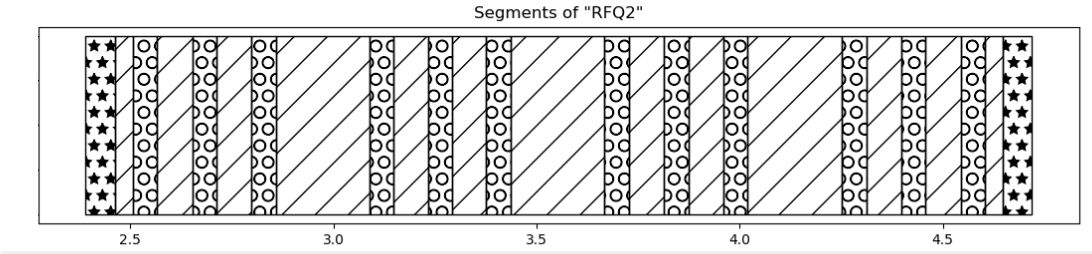
Tuner **Pumping port** **Coupler**



(a) (b) (c)

RF power loss





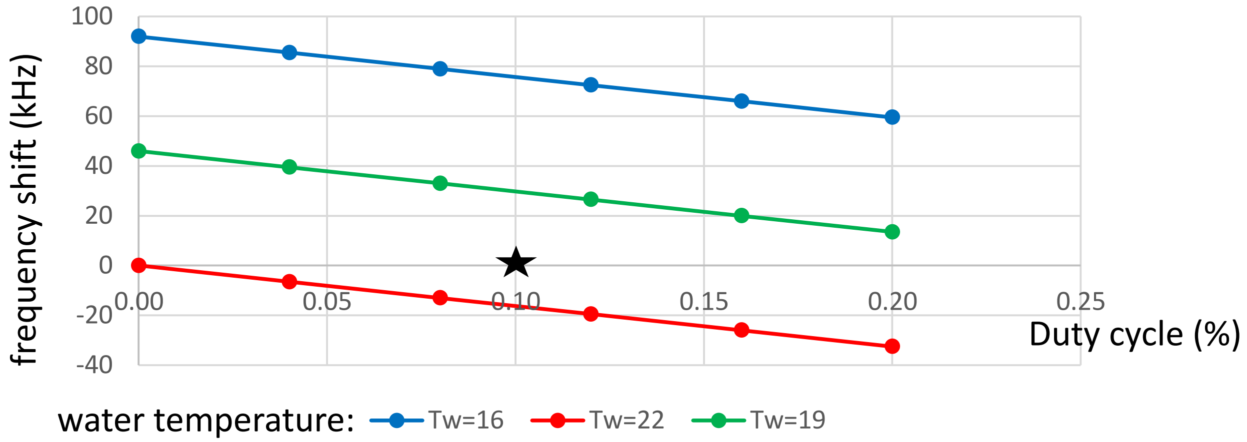
Quantity	Carbon-RFQ1	Carbon-RFQ2	HF-RFQ	
Inter-vane voltage	50	50	67.6	kV
Length	235	230	200	cm
Surface losses	244	230	350	kW
Stored energy	343	329	480	mJ
<C'>	117	113	100	pF/m
Q0	6620	6750	6440	
Coupling	1.32 (+32 %)	1.35 (+35 %)	1.18 (+18 %)	
Qex (total)	5000	5000	5475	
# couplers	4	4	4	
Qex (per coupler)	20000	20000	21900	
Power per coupler	< 80	< 80	< 100	kW

Segment legend

★ ends
○ ports
▨ plain

Thermal study

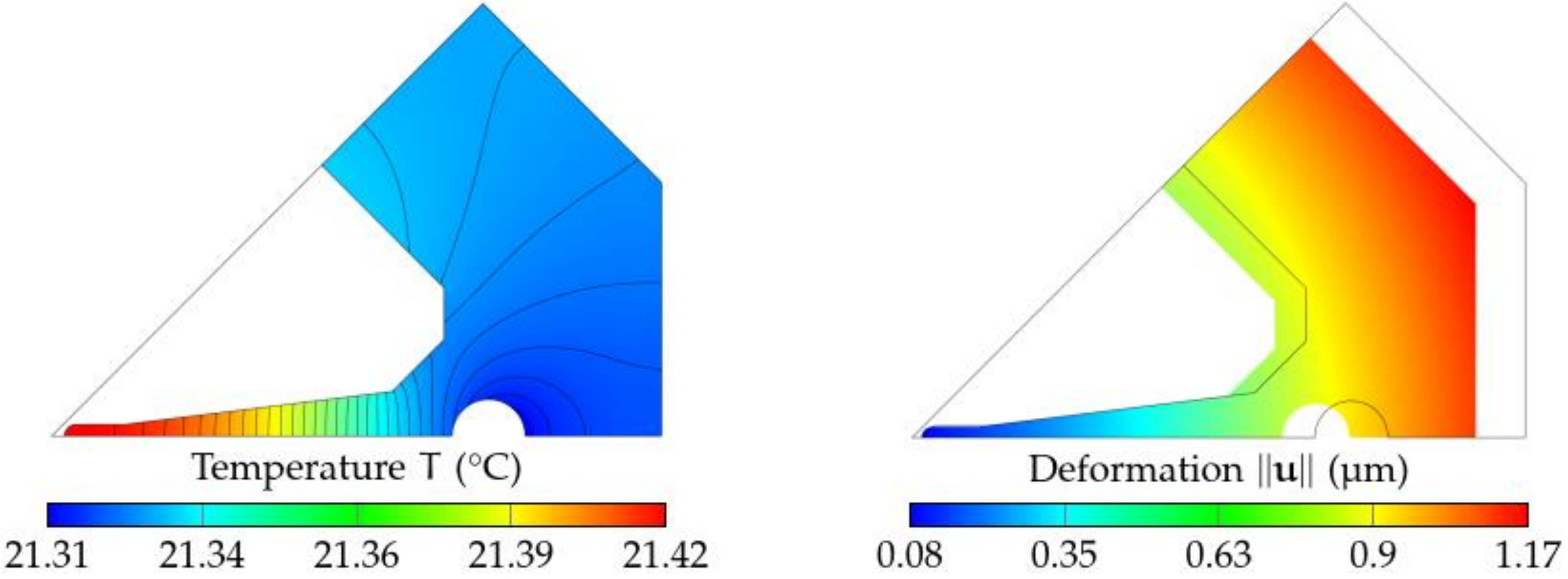
proposal for cooling system:
a single cooling channel per vane with
Ø = 8 mm, <vWater> = 1 m/s
(= 12 L/min per module)



★ likely operating point, DC = 200 Hz * 5 µs = 0.1 %

effect of RF losses on frequency can be compensated by reducing cooling water temperature by ca. 1K

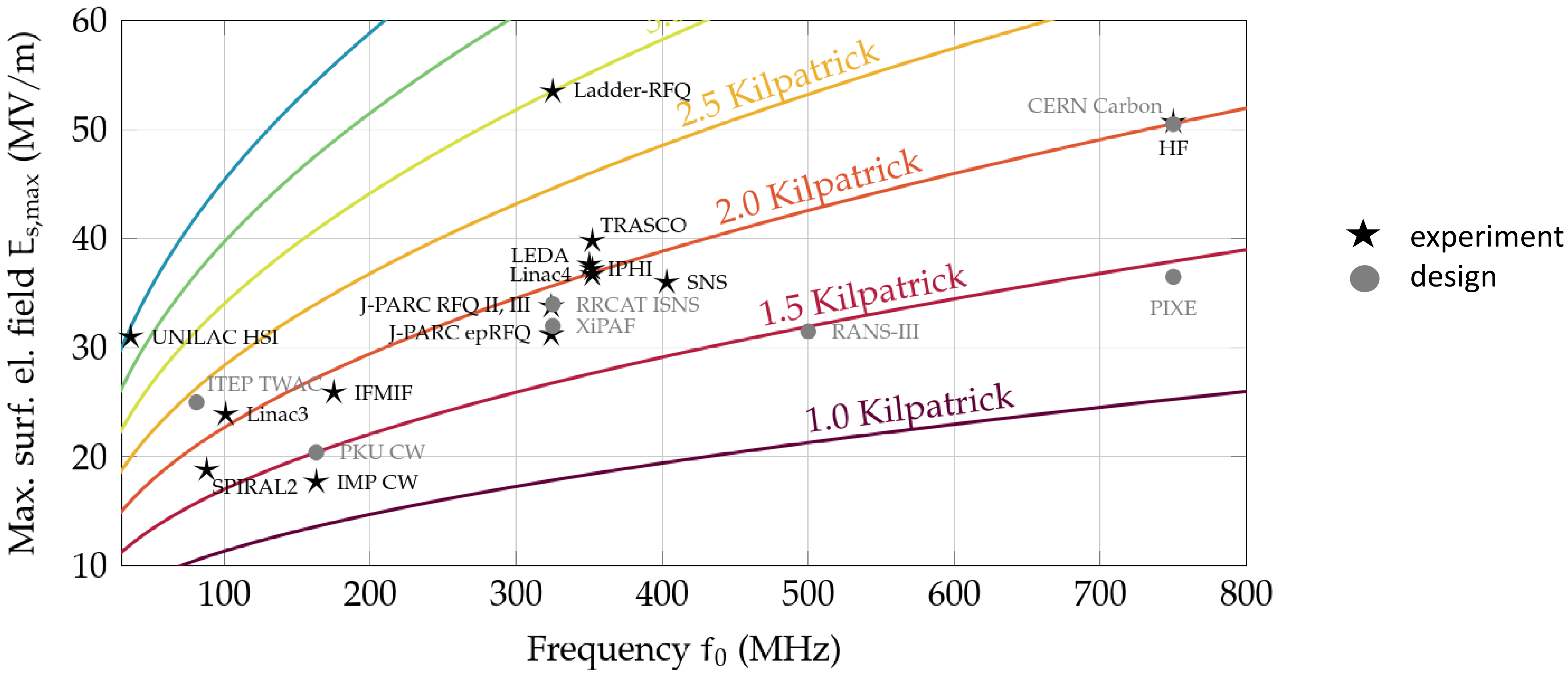
plots for the likely operating point



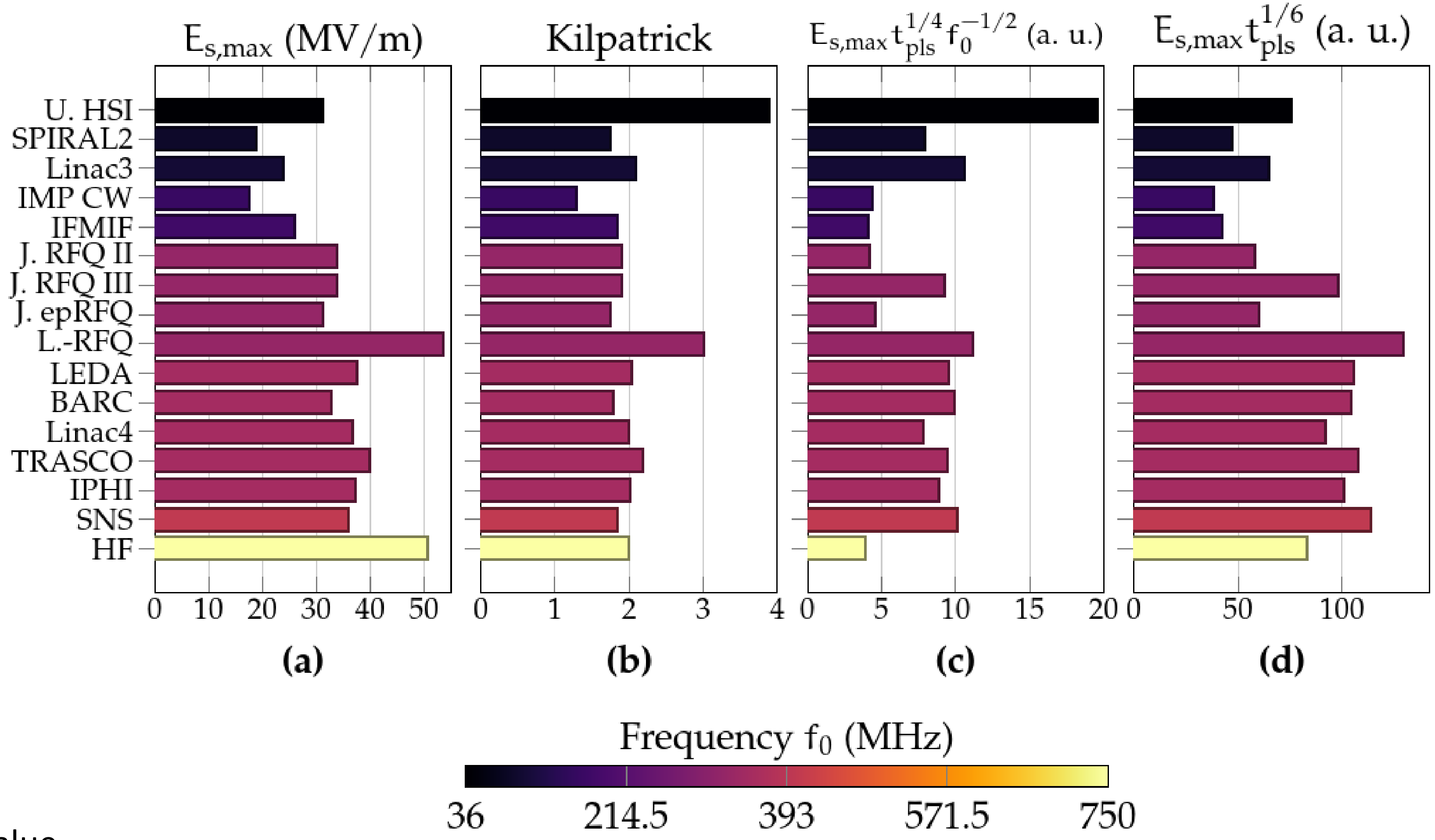
Part III: Maximum surface fields in RFQs

RFQs worldwide – Kilpatrick criterion

- Kilpatrick criterion is used for most RFQ developments
  (common design choices CW-RFQ: <=1.8 Kp, pulsed RFQ: <=2.0 Kp)
- but: during commissioning: more can often be achieved:



Are other E-field-related quantities more suitable?



(a) raw E-field

(b) Kilpatrick value

(c) proportionality from high-gradient structures
(Palmer, R. B., "Prospects for High Energy e^+e^- Linear Colliders“, Ann. Rev. Nuc. Part. Science 40(1), 1990.)

(d) proportionality from X-band/30GHz structures, also used for Sc
(Grudiev, A., Calatroni, S. and Wuensch, W, "New local field quantity describing the high gradient limit of accelerating structures". Phys. Rev. Accel. Beams 12(10) 2009.)

What about Sc and RF pulsed heating?

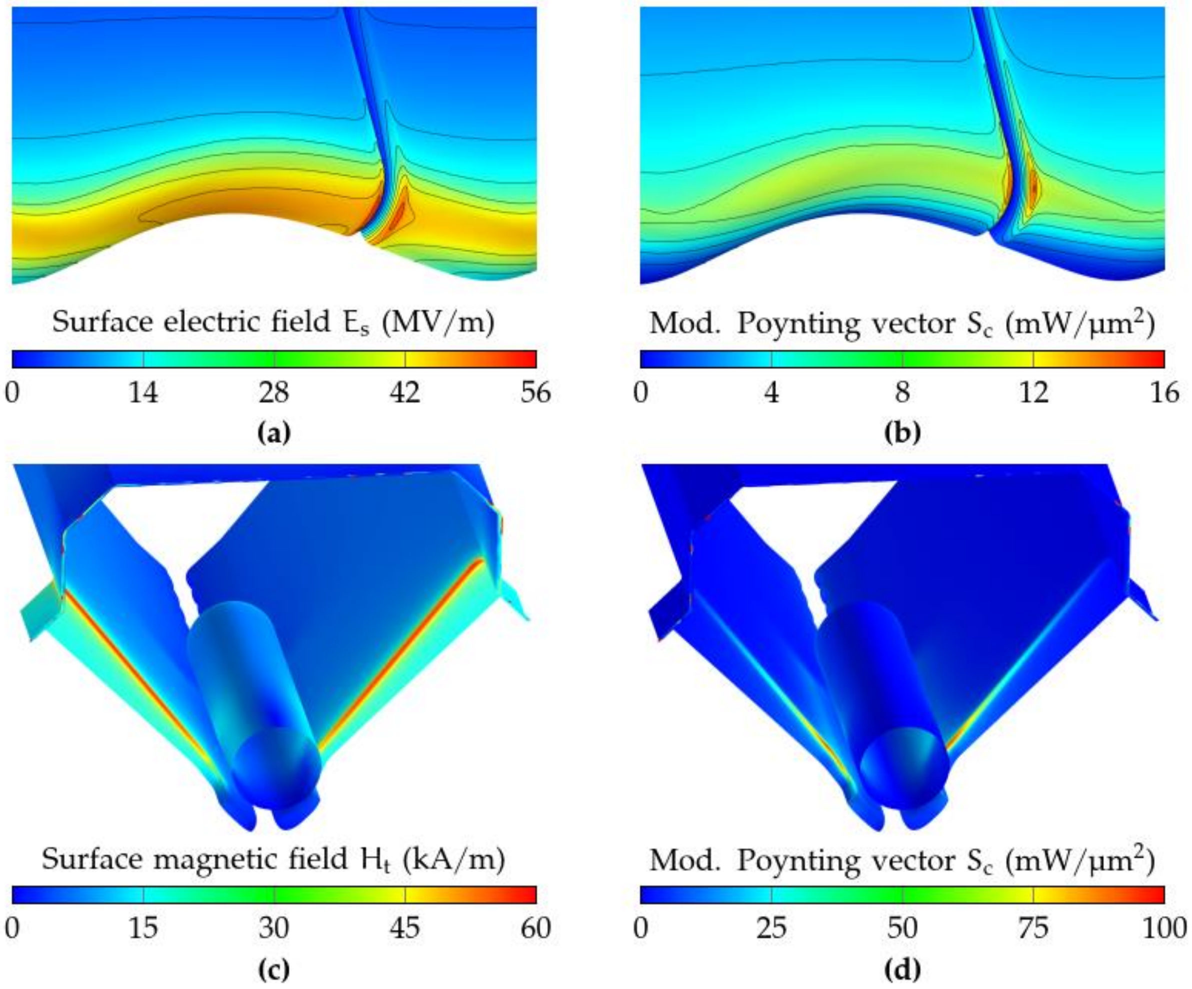
- Example: proton HF-RFQ: t_{pls} = 20 us, f_0 = 750 MHz

Emax on vane tip (2.0 Kilpatrick)

small hotspot on inter-module gap (2.2 Kilpatrick)

Hmax on vane undercut edge

resulting pulsed heating:
ΔT = 1.8 K (critical: 40…100 K)



Sc maximum is not on vane, i.e. not in location of breakdowns

E & H are well-separated in RFQ

Sc maximum is located on undercut edge next to dipole rod

not critical either, scaled threshold at 20 us: 860 mW/um²

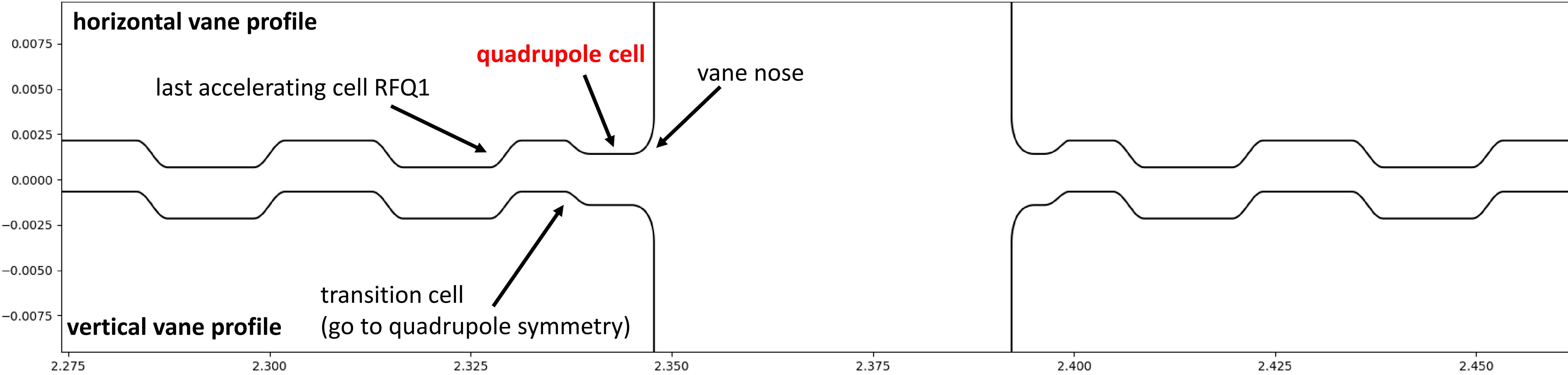
Conclusions

- for RFQs, Kilpatrick is the most consistent quantity with smallest fluctuation, however there are exceptions
- Kilpatrick consistency might just be a consequence of design choice, since it is used for development (1.8 … 2.0 Kp depending on pulse length!)
- promising quantity is $E_{max}t_{pls}^{1/6}$, but „to the best knowledge of the author“ nobody has designed RFQs with this quantity
- RF pulsed heating not relevant at pulse lengths < few milliseconds
- Sc maximum does not coincide with breakdown locations
- Sc on dipole rod in HF-RFQ relevant at ~10 milliseconds pulse length

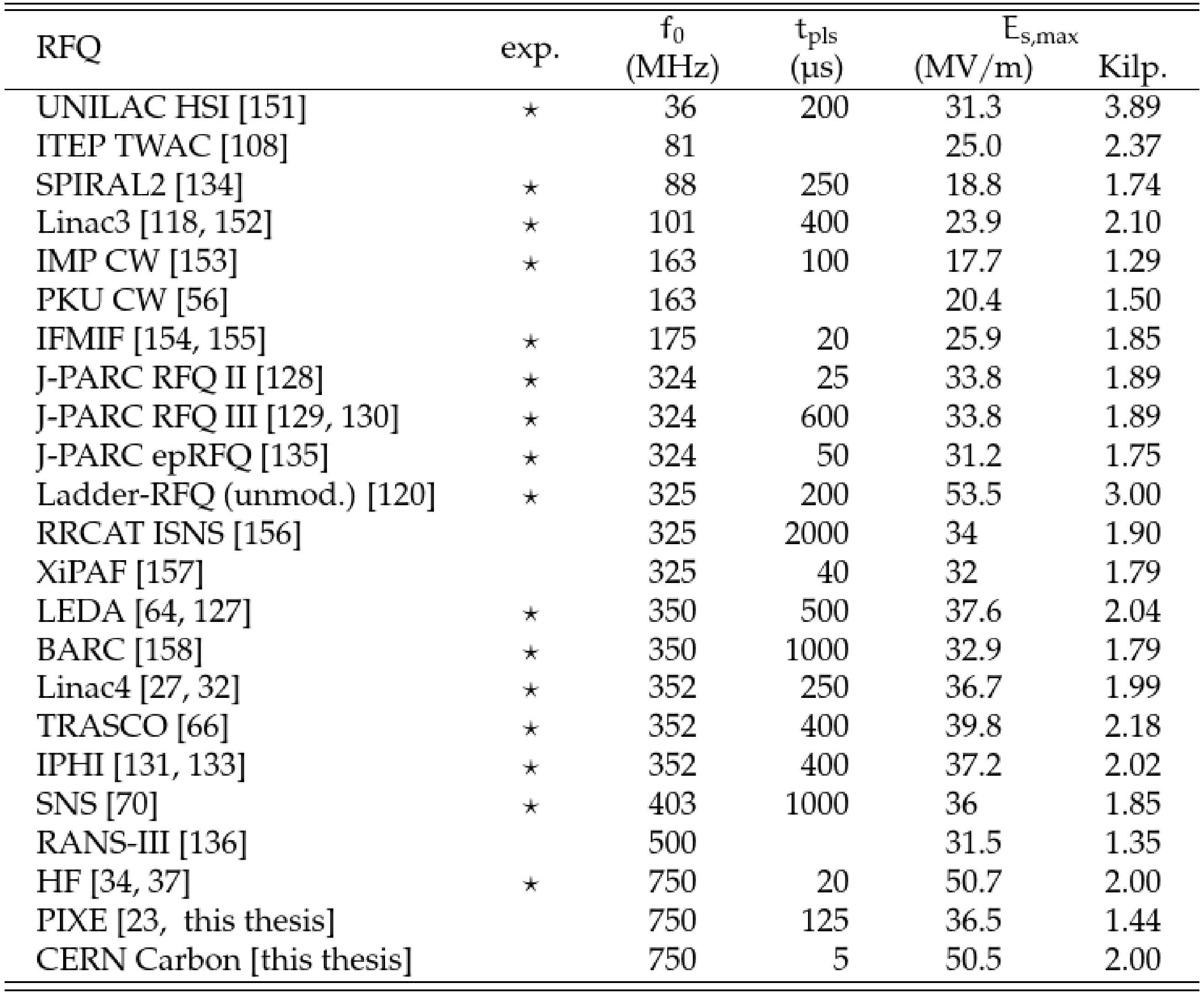
Thank you!

Splitting the RFQ

- for reasonable RF field stability, cavity split into 2 sections; length of each section ~ 6λ
- specific position of split is chosen w.r.t. to dipole mode separation
- beam needs to traverse a 4 cm drift, requires dedicated quadrupole cells (m = 1) to re-match
- length of quadrupole cells chosen to minimize beam envelope in RFQ2



Data collected on RFQ Emax



RFQ	exp.	f_0 (MHz)	t_{pls} (μs)	$E_{s,max}$ (MV/m)	Kilp.
UNILAC HSI [151]	⋆	36	200	31.3	3.89
ITEP TWAC [108]		81		25.0	2.37
SPIRAL2 [134]	⋆	88	250	18.8	1.74
Linac3 [118, 152]	⋆	101	400	23.9	2.10
IMP CW [153]	⋆	163	100	17.7	1.29
PKU CW [56]		163		20.4	1.50
IFMIF [154, 155]	⋆	175	20	25.9	1.85
J-PARC RFQ II [128]	⋆	324	25	33.8	1.89
J-PARC RFQ III [129, 130]	⋆	324	600	33.8	1.89
J-PARC epRFQ [135]	⋆	324	50	31.2	1.75
Ladder-RFQ (unmod.) [120]	⋆	325	200	53.5	3.00
RRCAT ISNS [156]		325	2000	34	1.90
XiPAF [157]		325	40	32	1.79
LEDA [64, 127]	⋆	350	500	37.6	2.04
BARC [158]	⋆	350	1000	32.9	1.79
Linac4 [27, 32]	⋆	352	250	36.7	1.99
TRASCO [66]	⋆	352	400	39.8	2.18
IPHI [131, 133]	⋆	352	400	37.2	2.02
SNS [70]	⋆	403	1000	36	1.85
RANS-III [136]		500		31.5	1.35
HF [34, 37]	⋆	750	20	50.7	2.00
PIXE [23, this thesis]		750	125	36.5	1.44
CERN Carbon [this thesis]		750	5	50.5	2.00

*Table shamelessly screenshotted from thesis

Precomputed multipoles