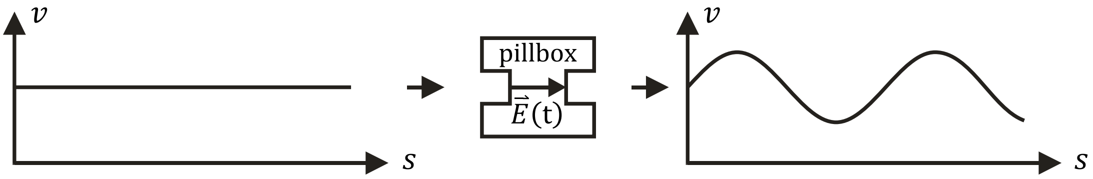
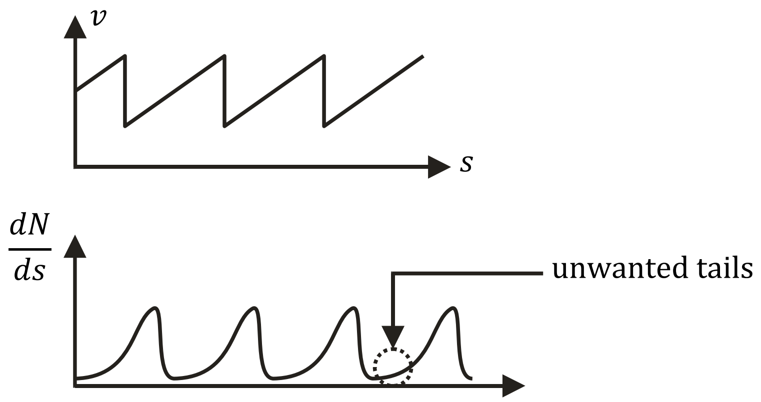
Radio Frequency Quadrupole

- Acceleration with static E-field: maximum beam energy limited by maximum dc-voltage that can be realized within reasonable dimensions. Limit is at some 10 MV.
- Dimensions can be decreased by using fields that oscillate in time $E(t) = E_0 cos(\omega t)$
- Disadvantage of $E(t)$:
  - just particles that arrive within periodically occurring "good time slots" are accelerated
  - particles arriving outside a slot are decelerated, not accelerated, too weakly accelerated, ….
  - duration of "good slot" ΔT depends on frequency ω: $\Delta T \cdot \omega \approx 60°$
  - beam durations from source/LEBT are much longer w.r.t. slot duration
  - particles outside slots will be lost
- Accelerate all particles, i.e. no losses:
  - need to arrange particles inside slots. This process is called "bunching"
  - particles within a "good slot" form the "bunch"
- Beam arranged into slots is "bunched beam"
- Bunched beam will de-bunch, i.e. exceed slot-border, if bunches are not kept together. This is due to tiny differences within individual particle velocities

velocity modulation with pillboxes leaves "tails"



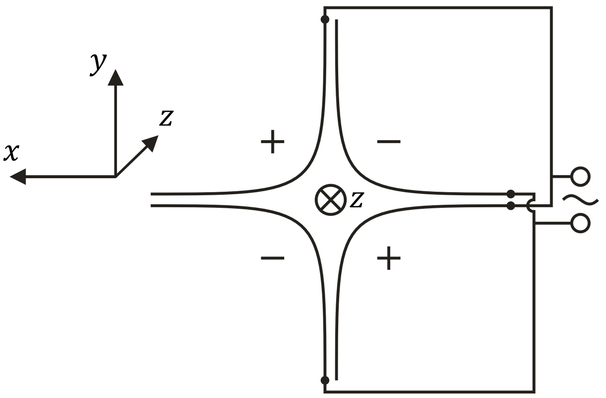
after some drift:



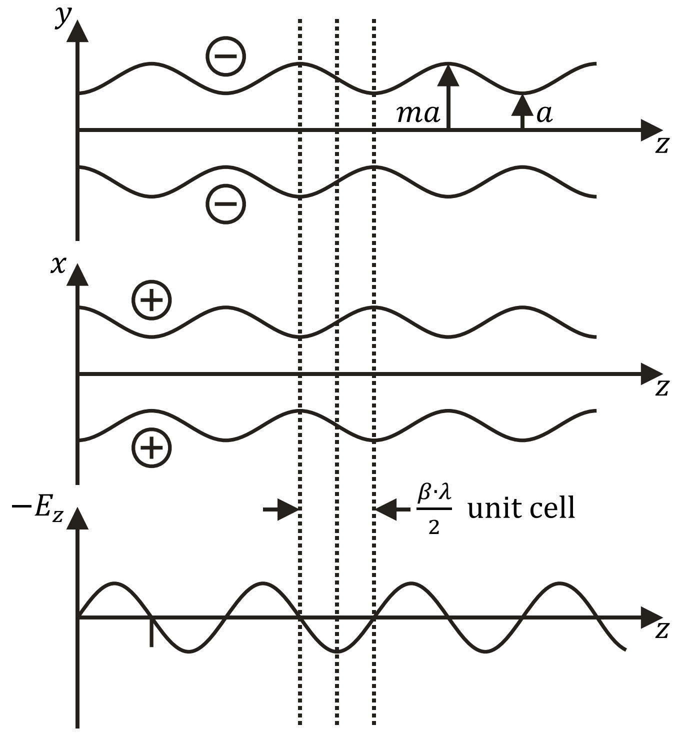
Radio Frequency Quadrupole

Bunching is done most efficiently (hadrons !) with **R**adio **F**requency **Q**uadrupole (RFQ):

bunching + focusing device:



4 Poles, rf-driven → RFQ



- focusing in each plane changes with time
- particles move along z
- focusing varies along z

→ net focussing like F0D0

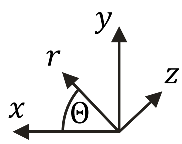
description of fields:

$\vec{B}$ close to beam axis ≈ 0

$\vec{E}(r,\Theta,z,t) = -\vec{\nabla}\cdot\Psi(r,\Theta,z)\cdot\sin(\omega t+\Phi_0)$

at beam $\Delta\Psi = 0$

$$\frac{\partial^2\Psi}{\partial r^2}+\frac{1}{r}\frac{\partial\Psi}{\partial r}+\frac{1}{r^2}\frac{\partial^2\Psi}{\partial\Theta^2}+\frac{\partial^2\Psi}{\partial z^2}=0$$



general solution:

$$\Psi(r,\Theta,z) = \sum_{s=0}^{\infty} A_s r^{2(2s+1)}\cdot\cos[2(2s+1)\Theta] + \sum_{n=1}^{\infty}\sum_{s=0}^{\infty} A_{ns} I_{2s}(knr)\cdot\cos(2\Theta s)\cdot\sin(knz)$$

I_1: mod. Bessel-function

simplification/trick:

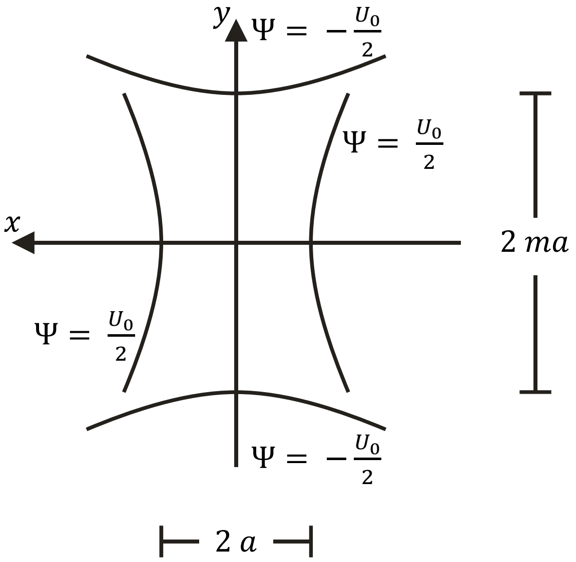
- use just terms with $s=0$ & $n=1$
- shape electrodes such that ($\Psi = \text{const}$) - surface = electrode-surface
  "two term potential function"

→ $\Psi(r,\Theta,z) = A_0\cdot r^2\cdot\cos 2\Theta + A_{10}\cdot\cos kz\,;\quad k=\frac{2\pi}{\beta_s\cdot\lambda}$ (∗)

Radio Frequency Quadrupole

<u>A_0 & A_{10} from evaluation at pole-tips:</u>

$z = 0$:



$$\Longrightarrow A_0 = \frac{U_0}{2a^2} \cdot \frac{I_0(ka)+I_0(kma)}{m^2 I_0(ka)+I_0(kma)}; \qquad A_{10} = \frac{U_0}{2} \cdot \frac{m^2-1}{m^2 I_0(ka)+I_0(kma)}$$

$$A_0 = \frac{U_0}{2a^2} \cdot X(a, m, \beta_s, \lambda); \qquad A_{10} = \frac{U_0}{2} \cdot A(a, m, \beta_s, \lambda) \qquad (**)$$

$(**)$ into $(*)$ $\rightarrow$ (Ψ = const) - surface = electrode-surface

$\vec{E} = -\vec{\nabla} \cdot \Psi$:

$$E_x = -\frac{XU_0}{a^2} \cdot x \; - \frac{k \cdot A \cdot U_0}{2} \cdot I_1(kr) \cdot \frac{x}{r} \cdot \cos kz$$

$$E_y = \frac{XU_0}{a^2} \cdot y \; - \frac{k \cdot A \cdot U_0}{2} \cdot I_1(kr) \cdot \frac{y}{r} \cdot \cos kz$$

transv. quad.   transv. rf – defocusing

$$E_z = \frac{AU_0}{2} \cdot k \cdot I_0(kr) \cdot \sin kz$$

X ≙ focusing efficiency

A ≙ acc.eff. (= 0 for $m = 1$)

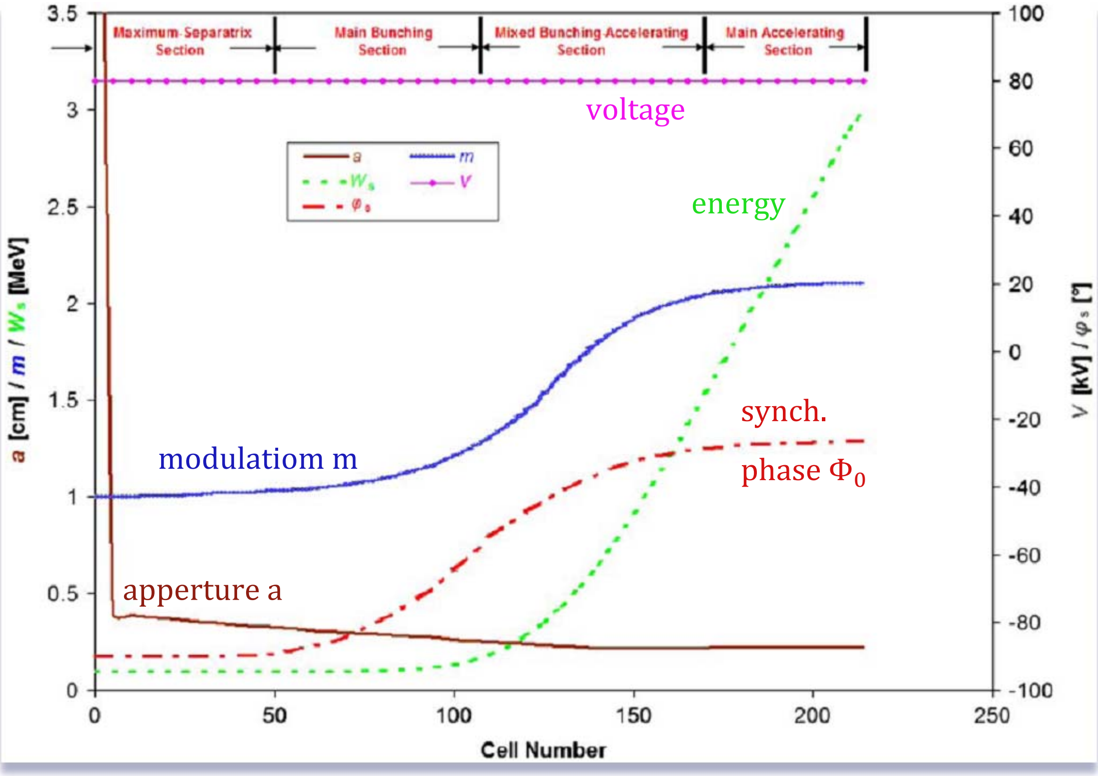
in RFQ transverse & longitudinal dynamics are coupled!

RFQ has only one knob: U_0

a, m, Φ_0 are frozen by geometry!

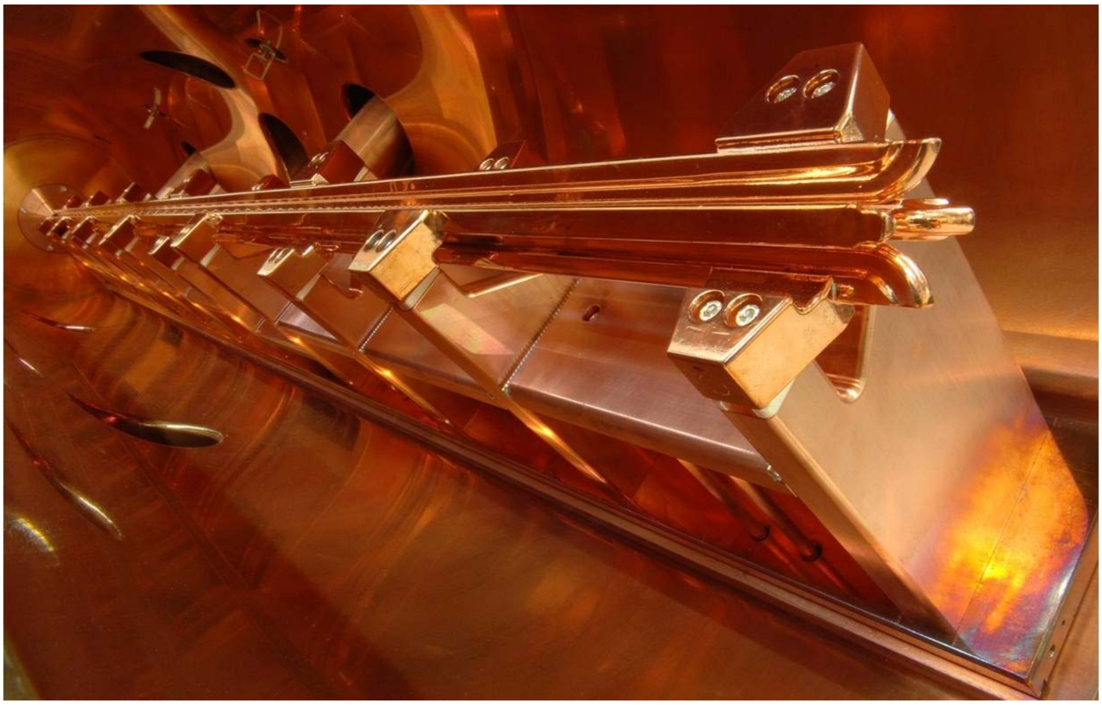
Radio Frequency Quadrupole

RFQ Parameters vs Length



protons, length = 3.2 m, $\beta_{\text{in}} = 0.014$, $\beta_{\text{out}} = 0.08$, resonance frequency: 325 MHz

HLI 4-rod RFQ, GSI/Germany



Deuterium – Uranium, length: 2.055 m, $\beta_{\text{in}} = 0.0023$, $\beta_{\text{out}} = 0.025$, res. frequency: 108.408 MHz

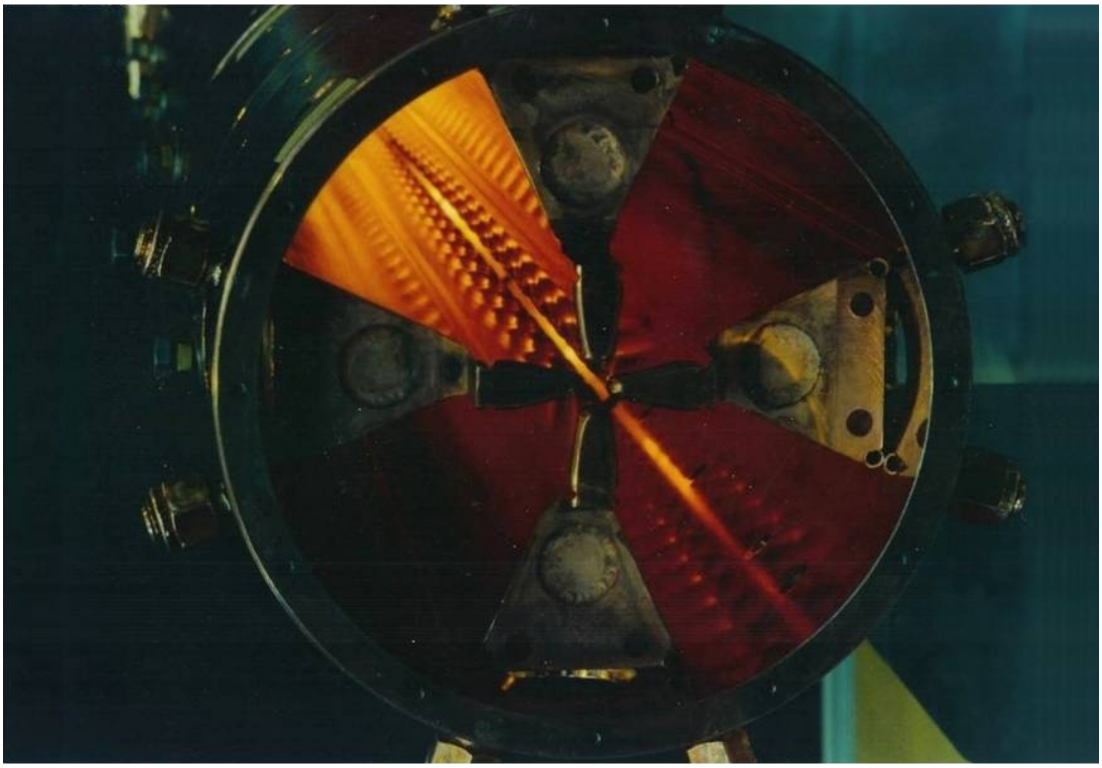
Radio Frequency Quadrupole

4-rod RFQ at SARAF/Israel

SARAF-RFQ: 3 MeV D+, res. frequency: 175 MHz, 250 kW CW

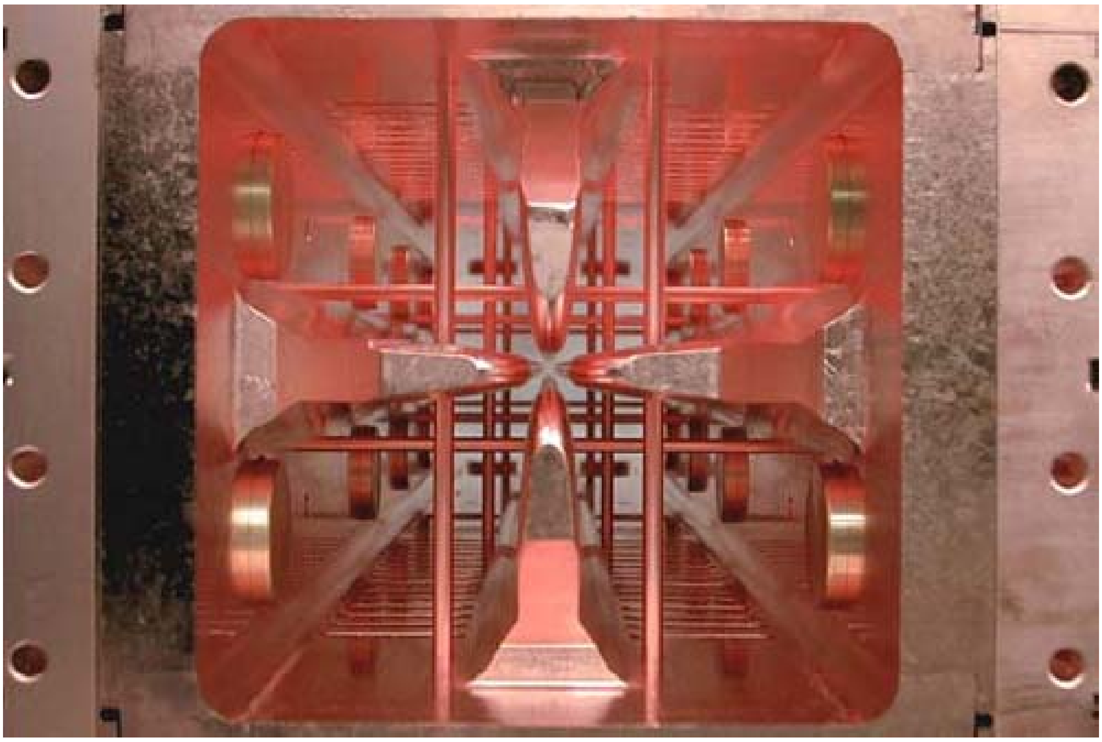
Radio Frequency Quadrupole

ATS 4-vane RFQ



Protons, length: 2.89 m, $\beta_{\text{in}} = 0.015$, $\beta_{\text{out}} = 0.065$, res. frequency: 425 MHz

4-vane RFQ at SNS/Oak Ridge/USA



H^-, length: 3.7 m, $\beta_{\text{in}} = 0.012$, $\beta_{\text{out}} = 0.073$, res. frequency: 402.5 MHz