Lecture 17

Linacs - protons & ions

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Lecture 17 - Proton & Ion Linacs **Feb 16, 2021**

MW-class linacs

Time structure
- 1) short pulses
- 2) long pulses
- 3) continuous waveform

Multi-cell operation & synchronism

Longitudinal motion
- Radial de-focusing
- Transverse focusing

Radio Focusing Quadrupoles (RFQ)

Beam loss & haloes

BROOKHAVEN NATIONAL LABORATORY

"High-frequency power generators, developed for radar applications, became available after World War II. A .. new and more efficient high frequency proton-accelerating structure .. was proposed by Luis Alvarez and co-workers at the University of California. .. A 1-m diameter, 12-m drift-tube linac with a resonant frequency of 200 MHZ .. accelerated protons from 4 to 32 MeV."

T. Wangler, "RF Linear Accelerators".

State of the art proton linacs are MW-class & superconducting

Table 13.1

Q: What are they (FRIB, PIP-II, SNS, ESS)?

Q: What does H^- mean? 1p + 2e Why? see below

Protons @ 1 GeV : $\beta < 1$

Electrons @ >10 MeV : $\beta \approx 1$ Fig 13.1

⇒ RF technology "zoo" is VERY different, p cf e

⇒ Proton linacs use many RF structures

⇒ NOTE: Revolutionary RFQ structures !!

study in detail below ...

Table 13.1 *Parameters of representative MW-class hadron linacs.*

Linac	Ion	Kinetic energy [GeV]	Beam power [MW]	Pulse current [mA]	Pulse length [ms]	Repetition rate [Hz]	Max RF freq. [MHz]
ESS	p	2.0	5.0	62	2.86	14	704
FRIB	p	0.61	0.4	0.66	–	–	322
	U	0.20[a]	0.4	0.0084	–	–	
PIP-II	H^-	0.8	1.2[b]	2	0.55[c]	20	650
SNS	H^-	0.94	1.4	27	0.97	60	805

[a] Kinetic energy for each of 238 nucleons.
[b] After accumulation and acceleration of half the beam to 120 GeV.
[c] Compatible with continuous waveform operation.

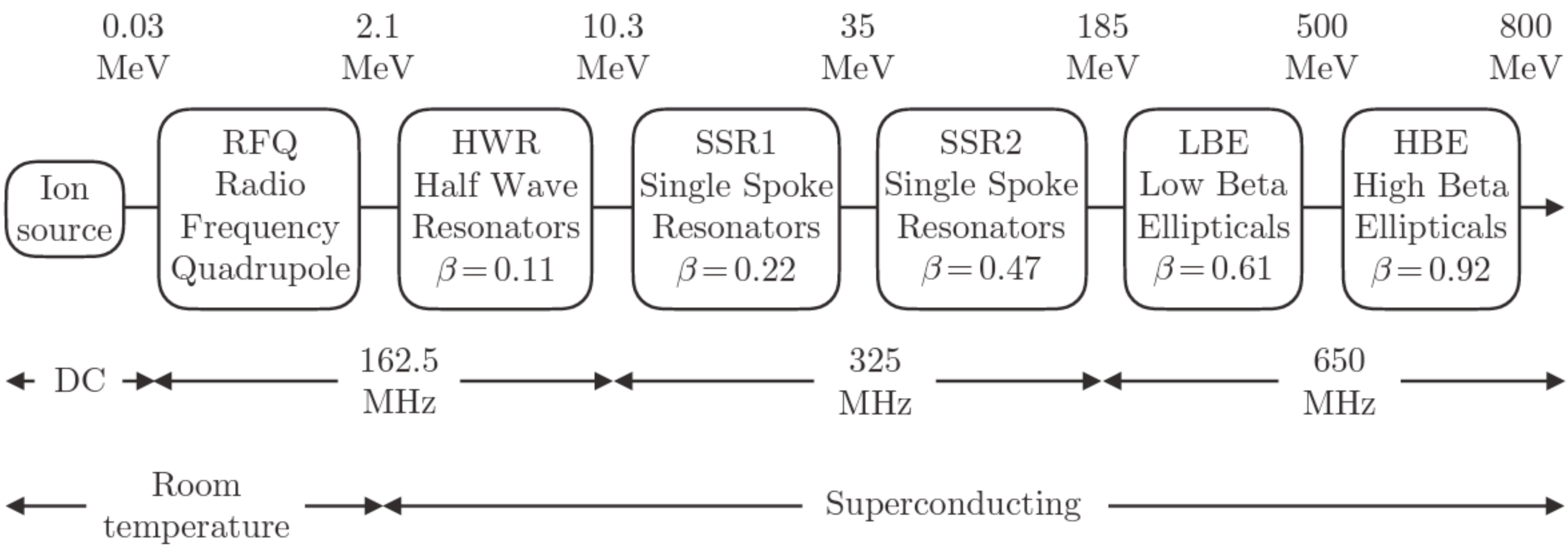
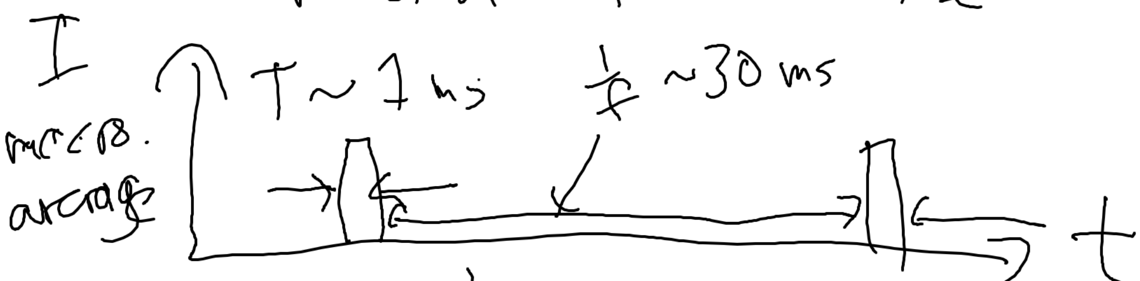


Figure 13.1 A typical technology map, for the PIP-II proton linac. Six technologies (RFQ, HWR, SSR1, SSR2, LBE and HBE) are constructed and tuned for different optimum values of β, the relativistic speed. Except for the single RFQ, each technology is repeated in many identical superconducting resonators of the same frequency, assembled into cryomodules. Elliptical RF cavities are also used in electron linacs (with $\beta = 1$).

TIME STRUCTURES

- Beam from ion source is continuous (ON or OFF) then bunched by RFQ at its frequency : $f_{RFQ} \lesssim 1$ GHz
- Typically $\sim 10^6$ bunches form a MACROPULSE repeated at ~ 30 Hz



- Average beam power

$$P = I V f T$$

power $\sim 10^6$ W

V: 10^9 V

T: 10^{-3} s

f: 10^2 Hz

I: 10^{-2} A

Kinetic energy

$$V = \frac{m_p c^2}{e}(\gamma - 1)$$

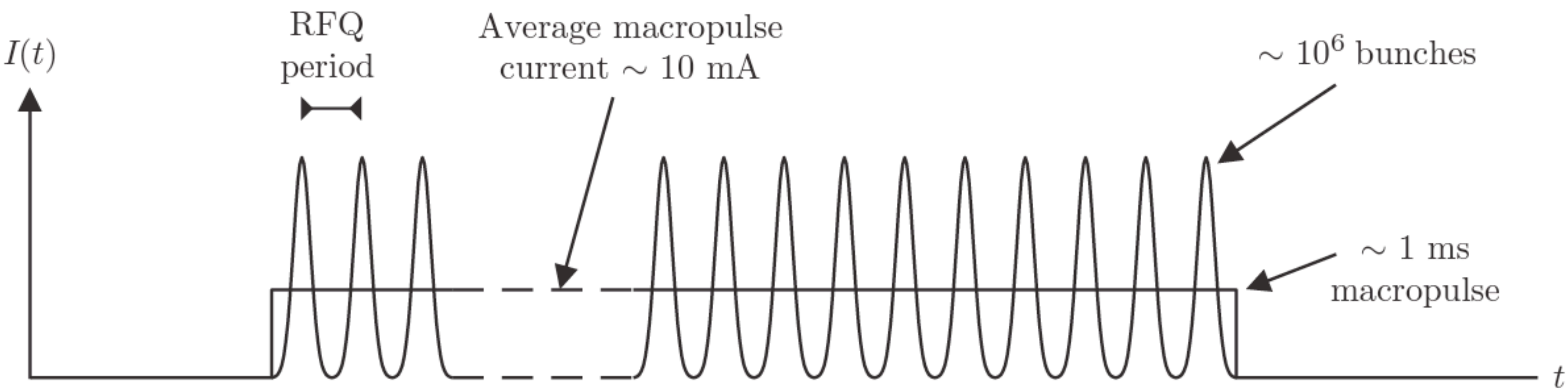


Figure 13.2 The bunches accelerated in a proton linac are typically separated by a few nanoseconds, forming a single macropulse that is of order a millisecond long. This structure is usually imposed by a Radio Frequency Quadrupole that creates of order a million bunches from a DC beam.

1. SHORT PULSE: e.g. SNS ~1 μs, H^-

- Notch the 1 ms macro pulse into 1 μs segments
  - SEGMENT period matches the accumulator
  - SEGMENT are accumulated ...
    - ON TOP each other longitudinally
    - SIDE-BY-SIDE transversely:
    - (H^- stripped to $H^+ = p$)

- After accumulating 10^3 turns, extract in a single turn

⇒ Short pulse with 10^3 times the intensity

....but very large in transverse space. Who cares?


H⁻
DIPOLE
p
stripping foil

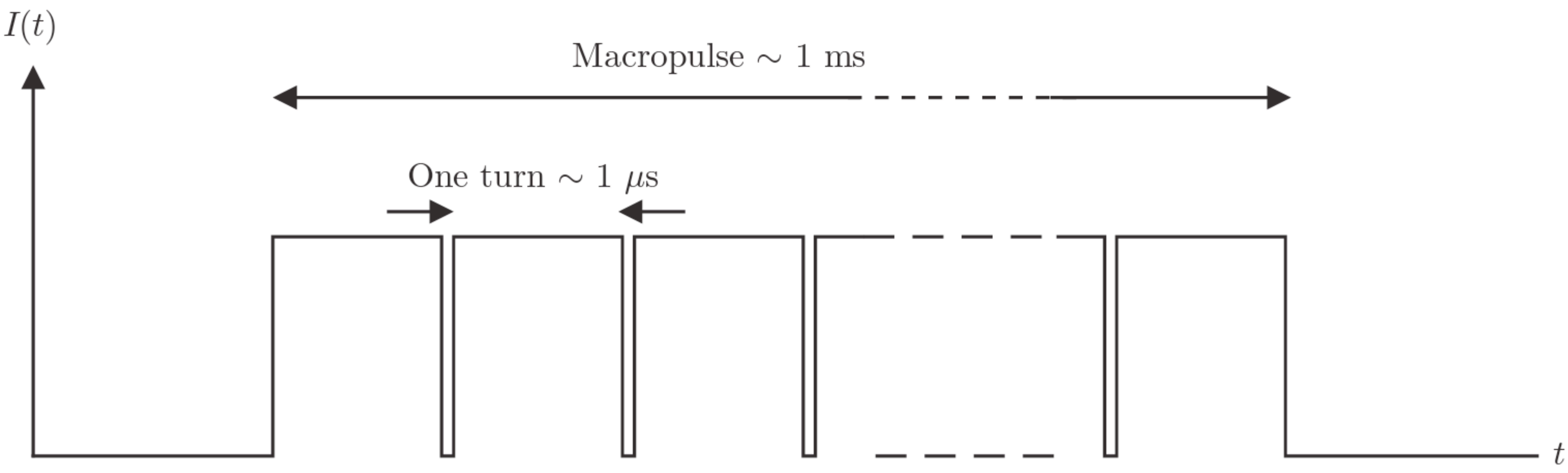


Figure 13.4 In an H^- macropulse, short gaps chop the macropulse into segments that can be accumulated and compressed in a storage ring, as shown in Figure 13.3.

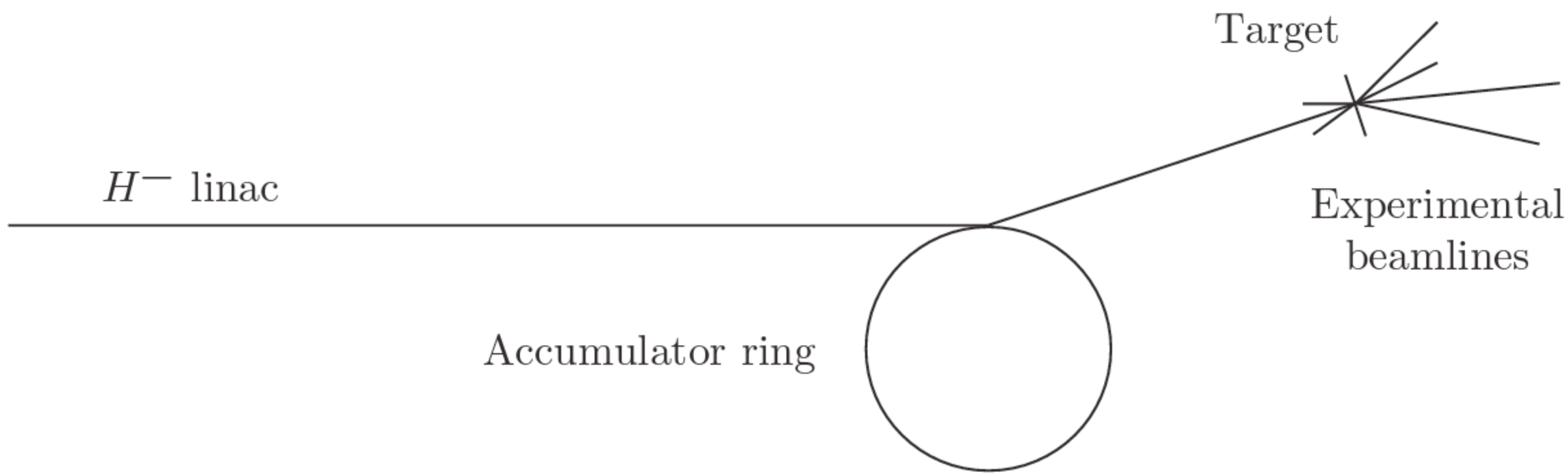


Figure 13.3 An H^- linac feeding an accumulator ring, in order to compress the beam in time. The single pulse of accumulated beam that is extracted from the ring is much shorter in time than the macropulse length (compressed into microseconds rather than milliseconds), but has much larger transverse emittances. The accumulator ring is not necessary in long pulse or continuous waveform operation, in which case protons are preferred.

② LONG PULSES e.g. ESS, p, ~1 ms

Simply put beam on target !!

- Some neutron physicists want LONG, some SHORT....
- No accumulation ring !!

② CONTINUOUS WAVE FORM 1 bunch every $\frac{1}{f_{RFQ}}$ secs.

- At fixed power, fewer protons/bunch

$$N = 6.3\times10^{6}\ \frac{I\,[mA]}{f_{RFQ}\,[GHz]}$$

- Eliminates: microphonics, Lorentz force detuning, ...
- BUT: RF power delivery is different.

PIP-II can upgrade from "LONG" to CW eventually)

FREQUENCY DOUBLING

- BUNCHES SHORTEN during acceleration: $\sigma_s \sim \frac{1}{\gamma}$

Q: How big is an RF cavity? $\lambda f = c$

NEED $\lambda \ll \sigma_s \sim \frac{1}{\gamma} \Rightarrow f_{STRUCT} \sim \gamma$

- ENERGY FILLING a RF structure

$U \sim \text{Volume} \sim \frac{1}{f^3}$

So double frequency to shrink cavity

$\Rightarrow$ saves money, both capital and operational

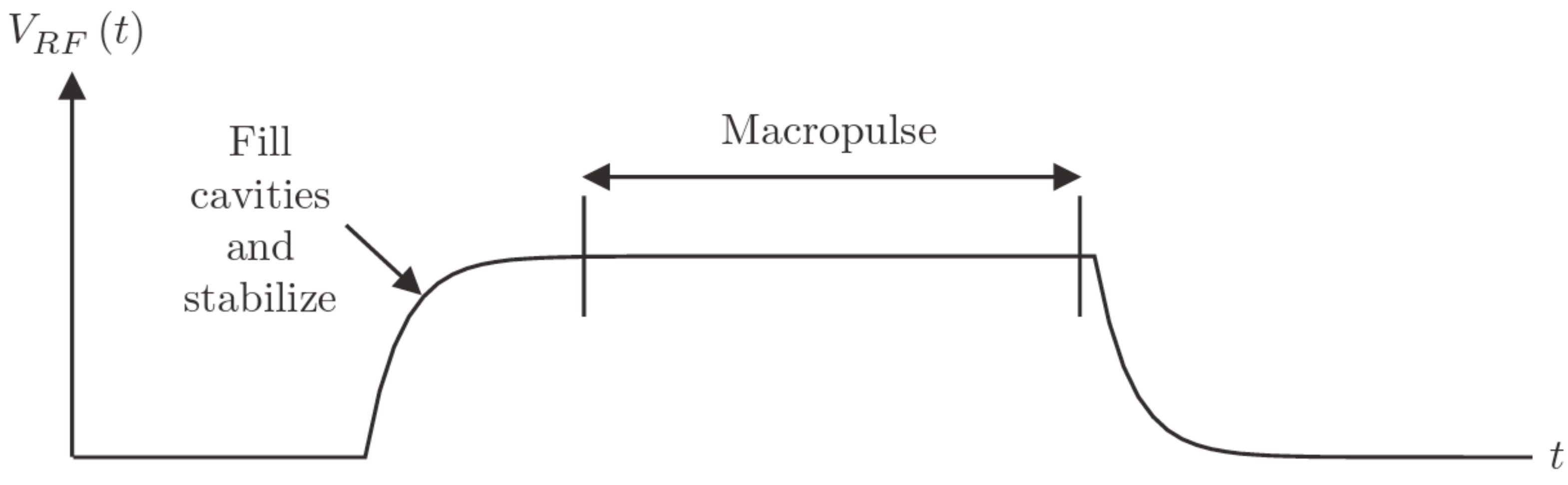


Figure 13.5 The RF voltage ramps up for around a millisecond before the beam arrives, to settle transients and to stabilise the low level RF controls.

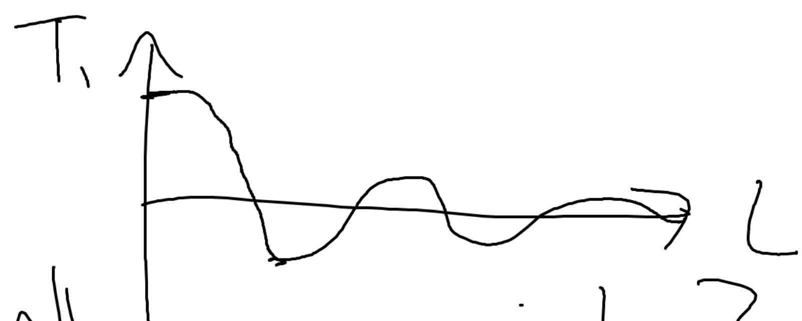
MULTI-CELL SYNCHRONISM

In L7 we discussed optimum length L of a single-cell cavity

$$V_A = E_0 L \cdot T_1(L)$$

TRANSIT TIME FACTOR

$$T_1 = \frac{\sin(\omega L / 2\beta c)}{(\omega L / 2\beta c)}$$



Q: WHAT is optimum # of cells per cavity? N

$$V_A = N E_0 L \cdot T_1 S$$

Accelerating voltage

cells

Max. gradient

$S(N, \beta/\beta_G)$ — β_G: geometric β

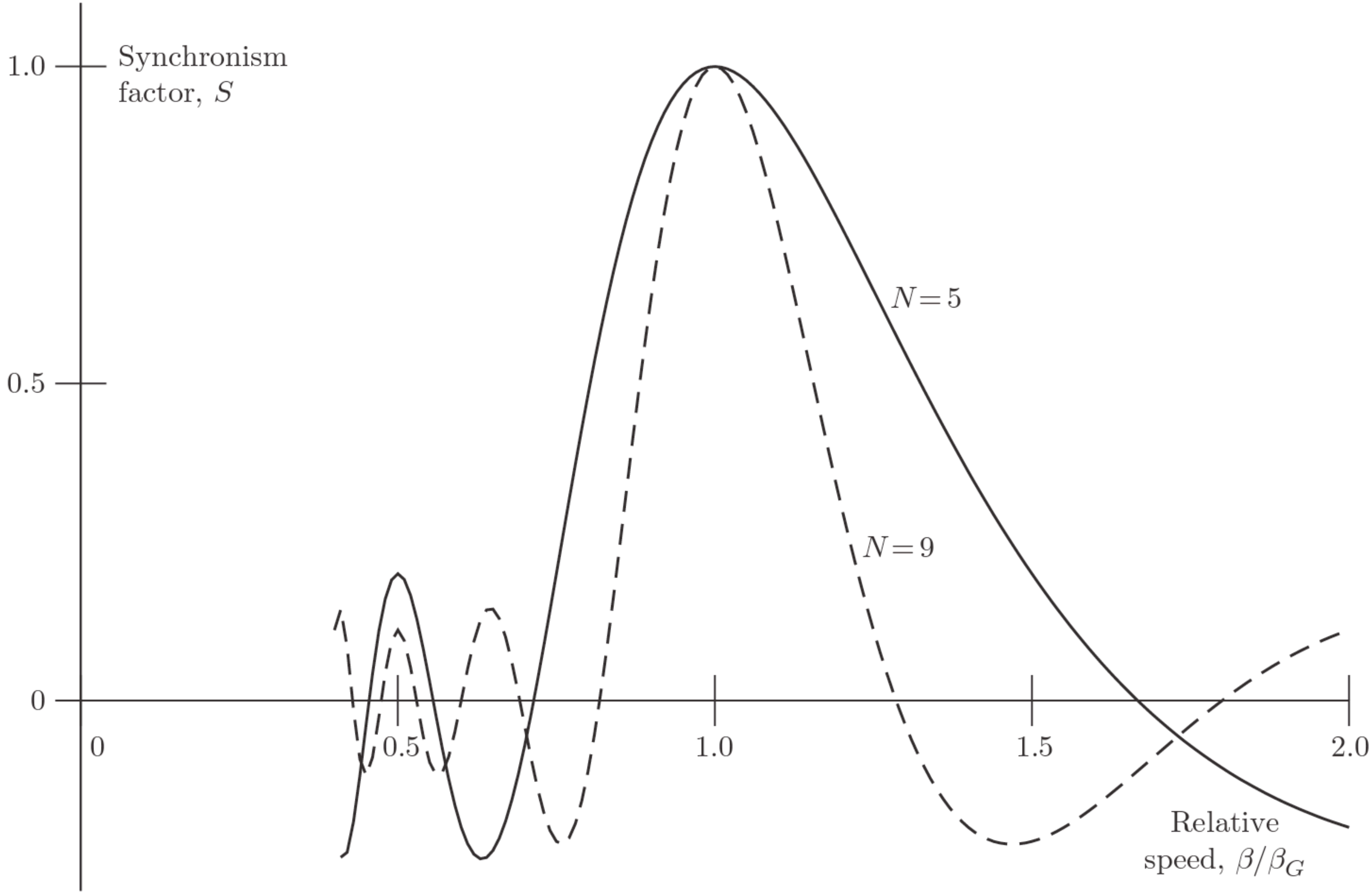


Figure 13.6 The multi-cell synchronism factor, $S(N, \beta/\beta_G)$. The useful dynamic range of $|\beta - \beta_G|$ scales like $1/N$, so proton linacs usually have fewer cells per cavity (e.g. $N = 5$) than electron linacs (e.g. $N = 9$).

- Assume β = constant in one cavity ...

NEED $|\beta - \beta_G| < \frac{1}{N}$

RADIAL DEFOCUSSING

RF cavities DEFOCUS transversely while FOCUSING longitudinally

- "It can be shown" that beampipe transitions (in an axially symmetric cavity) RADIALLY DEFOCUS at entry, FOCUS at exit

$\Rightarrow$ NET DEFOCUSING, because exit beam is more rigid

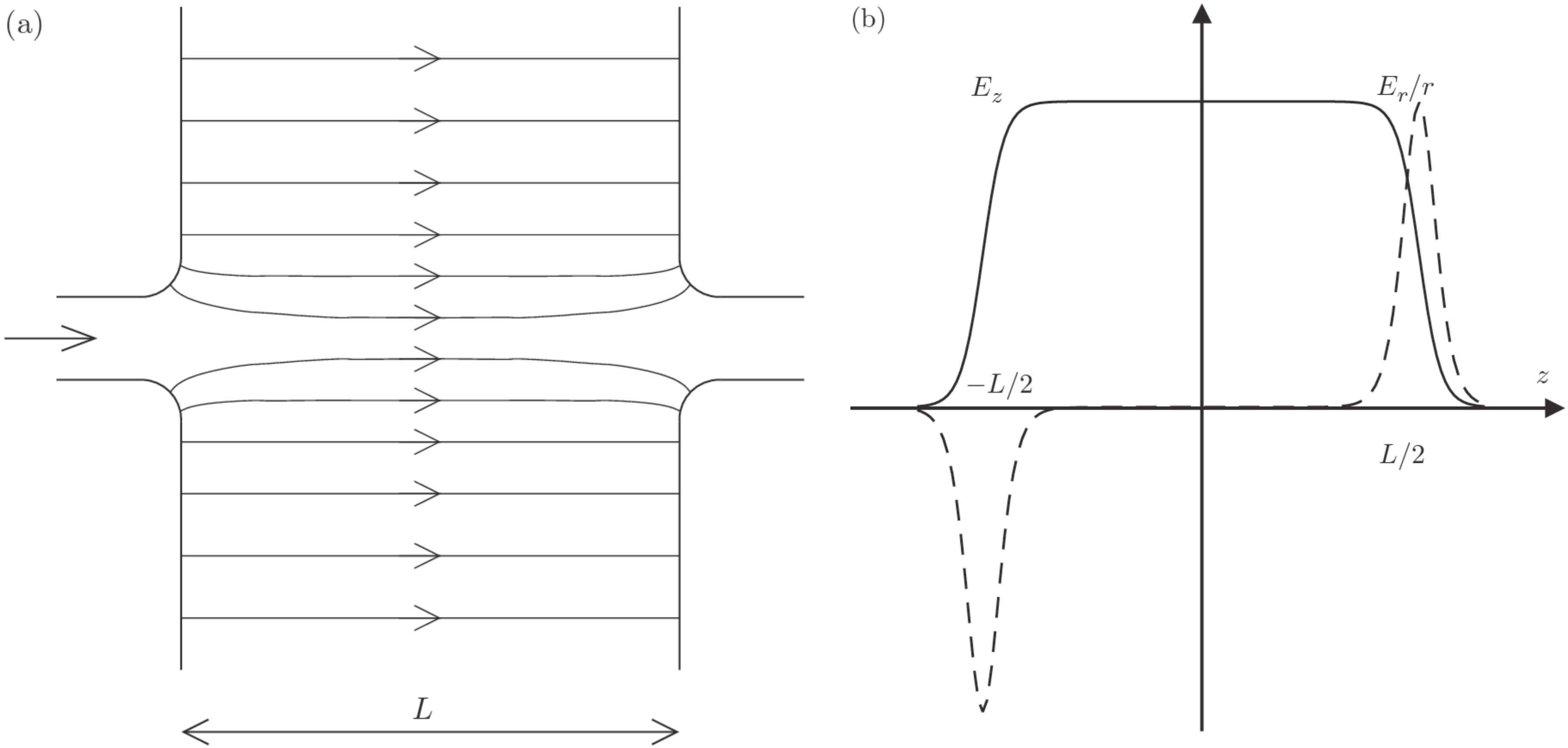


Figure 13.8 Unbalanced radial impulses at the ends of a rotationally symmetric cavity. Radial electric fields inevitably occur where the beampipes intrude at the cavity ends in (a). They are linear in r for small r, defocusing and focusing at entry and exit respectively, as shown in (b). The defocusing effect dominates, because the exiting beam is more rigid.

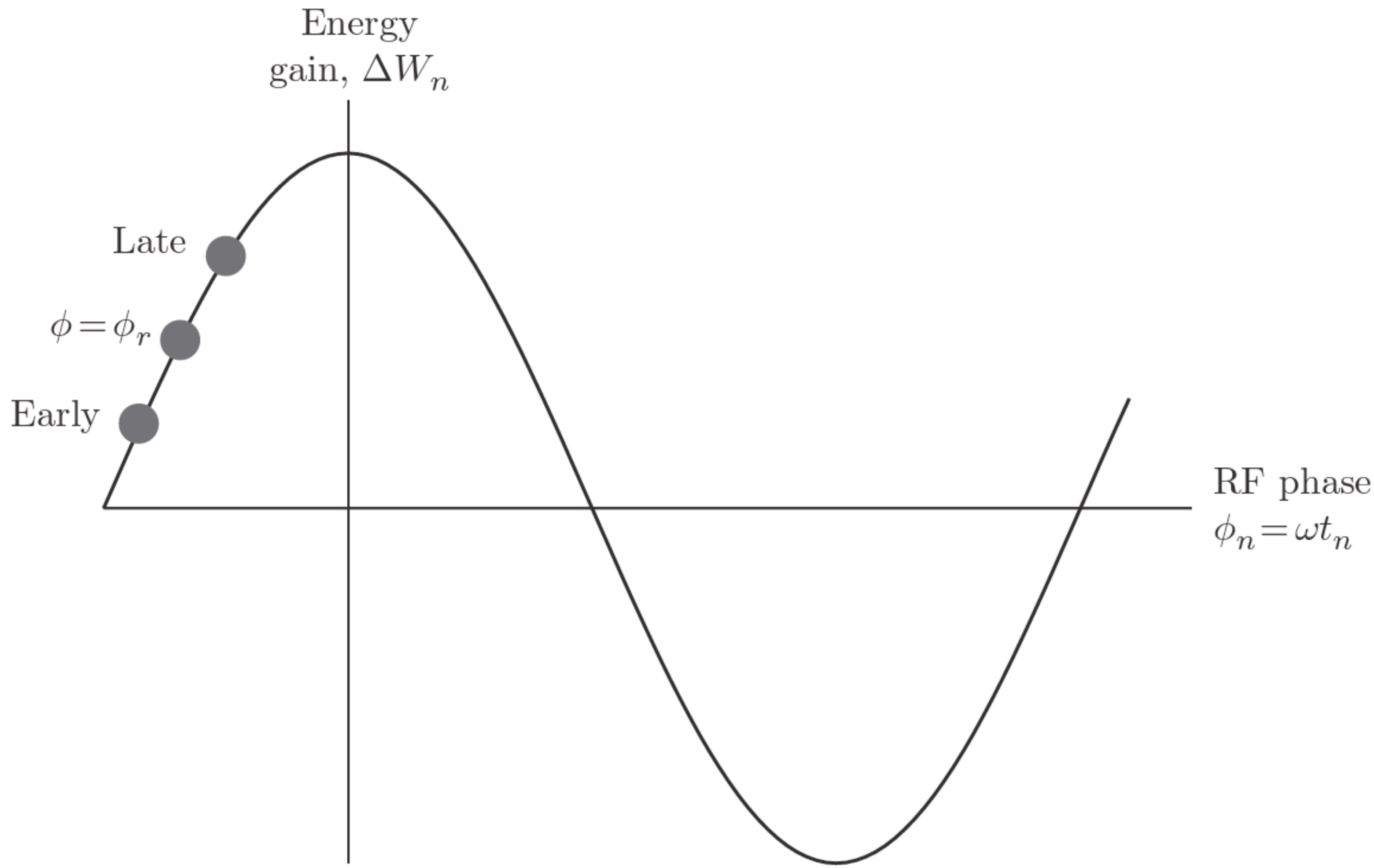


Figure 13.7 Energy gain and reference phase ϕ_r at the electrical centre of a thin cavity. Early and late particles receive a relative restoring force that keeps them bunched with the reference particle. See Figure 11.4 for a comparison with the synchronous particle in a circular accelerator.

$$\Delta r' = -\frac{\pi q E_0 T_1 L}{mc^2 (\beta\gamma)^3 \lambda} \cdot \sin(\phi_R)$$

radial angle

Strong dependence!
(no problem for electrons)

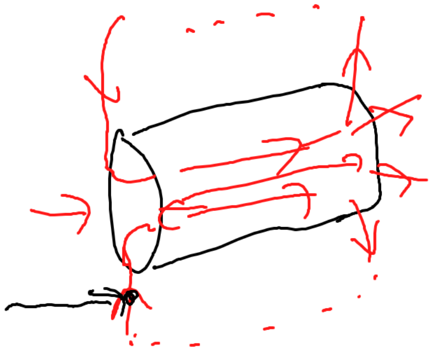
$\sin(\phi_R) < 0$

TRANSVERSE FOCUSING (except for RFQs)

< 50 MeV   SOLENOIDS

A proton entering a solenoid with

$$\begin{pmatrix} x \\ x' \\ y \\ y' \end{pmatrix} = \begin{pmatrix} r \\ 0 \\ 0 \\ 0 \end{pmatrix}$$



$$\begin{pmatrix} x(s) \\ y(s) \end{pmatrix} = \frac{r}{2} \begin{pmatrix} 1 + \cos(2Ks) \\ -\sin(2Ks) \end{pmatrix}$$

$$\left[K = \mathrm{sgn}(q) \frac{B_{soln}}{(B\rho)} \right]$$

So for a thin solenoid $KL_{soln} \ll 1$

$$\Delta r' \simeq - \left(\frac{B}{2(B\rho)} \right)^2 L \cdot r$$

Focuses, but weakens quadratically with rigidity

$\Rightarrow$ NO GOOD at higher energy

$\geq$ 50 MeV Quadrupoles

- Weaken LINEARLY with rigidity
- Place SINGLET or DOUBLET (usually) between SEGMENTED cryomodules

A doublet with equal strength F + D quads L apart focuses like

$$\frac{1}{f_{NET}} \approx -\frac{L}{f^2}$$

in BOTH PLANES!

- Doublet focusing delivers rounder beams
- Periodicity is halved - good for space charge ....
- SEGMENTED cryomodules p : NON-SEGMENTED for e^-

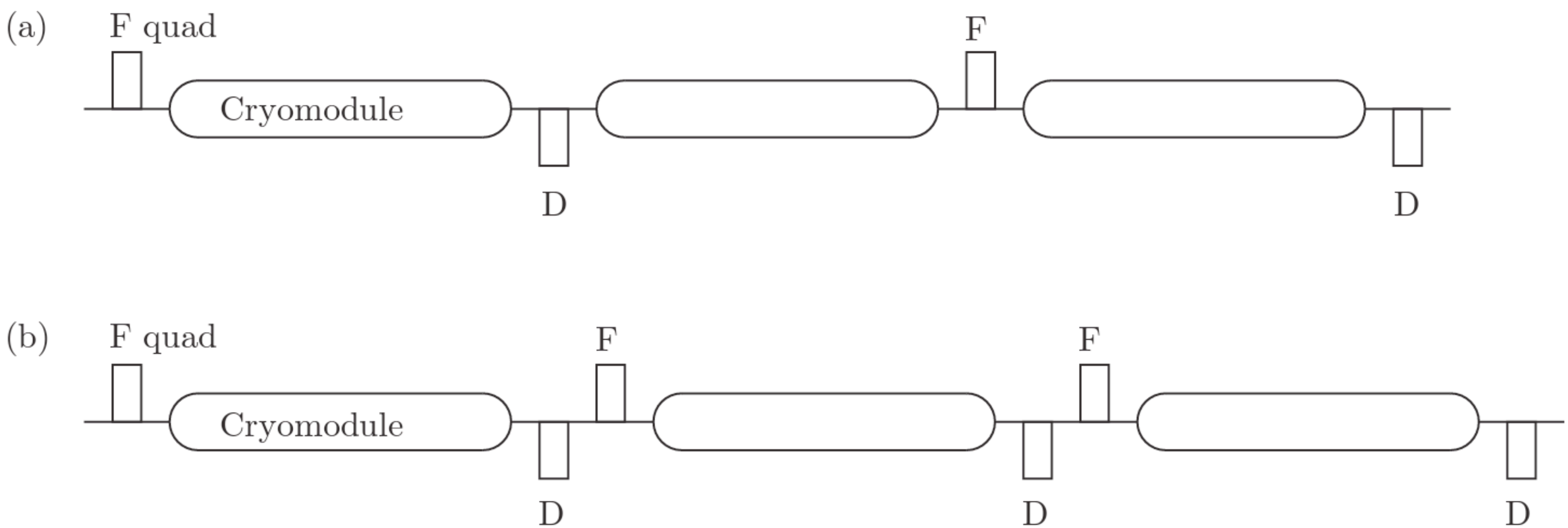


Figure 13.9 Singlet (a) and doublet (b) focusing, with normal-conducting quadrupoles placed between superconducting cryomodules. Doublet focusing increases the linac length slightly, but approximately halves the length of the optical period, and delivers rounder beams.

RADIO FREQUENCY QUADRUPOLES (RFQ)

$0.01 < \beta < 0.06$

- Revolutionary invention in 1969 still reverberating
- Essentially electrostatic, since low speed ⇒ weak magnetic response
- Bunch, focus & accelerate!! HOW? see below

3 CONTROL PARAMETERS
- a : inner radius of vanes
- m : modulation parameter
- L : longitudinal period of vane oscillation

- (a, m, L) evolve SLOWLY along the RFQ
- Excite vanes pair-wise :

$$V = \pm\frac{V_0}{2}\cos(\omega t)$$

+ : horizontal
− : vertical

CONSIDER $t=0$

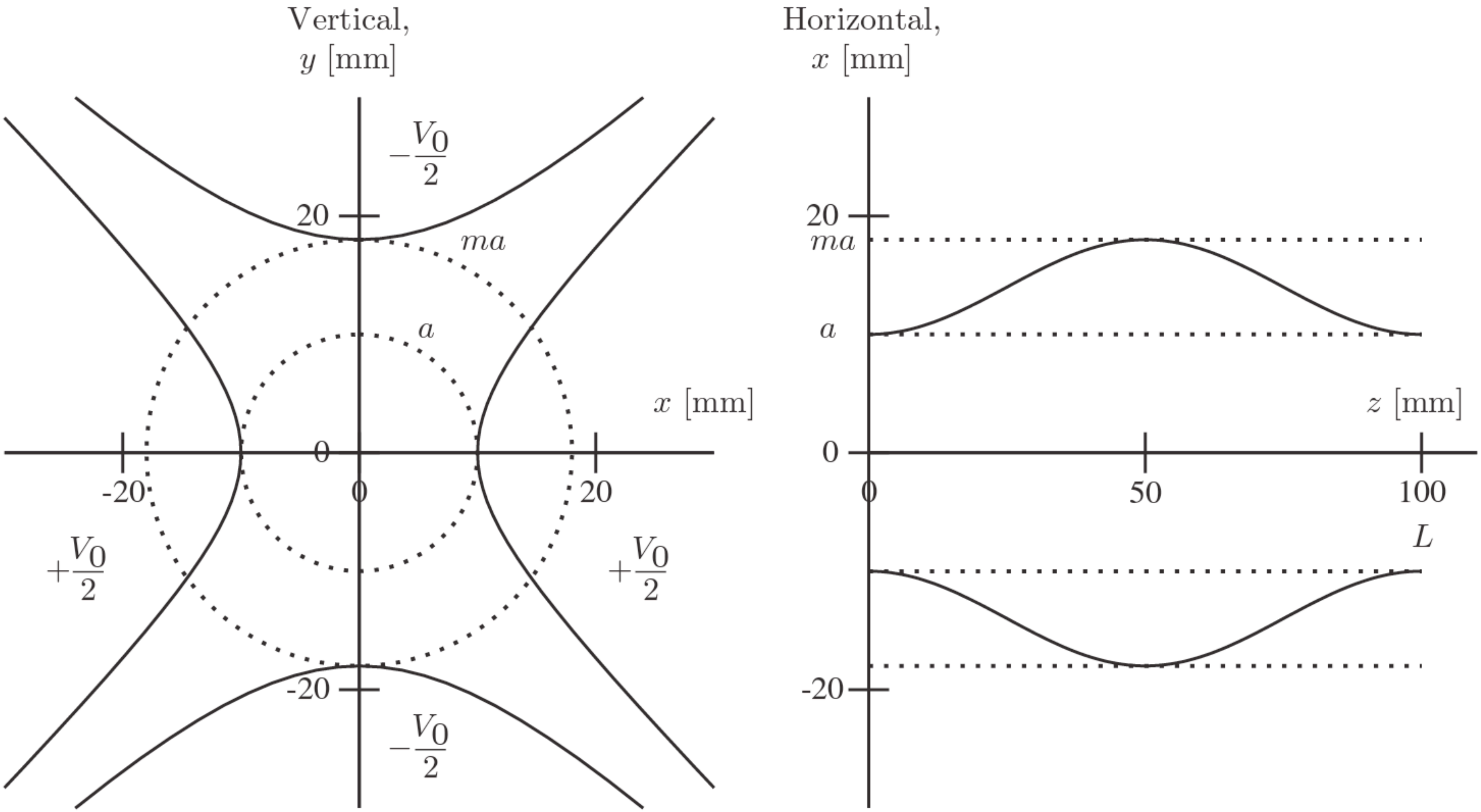


Figure 13.10 Cross-sectional and top views of a typical RFQ vane geometry, with minimum vane radius $a = 10$ mm, $m = 1.8$ and $L = 100$ mm. The vertical vane separation also oscillates with longitude z, between radii of a and ma, but out of phase with the horizontal.

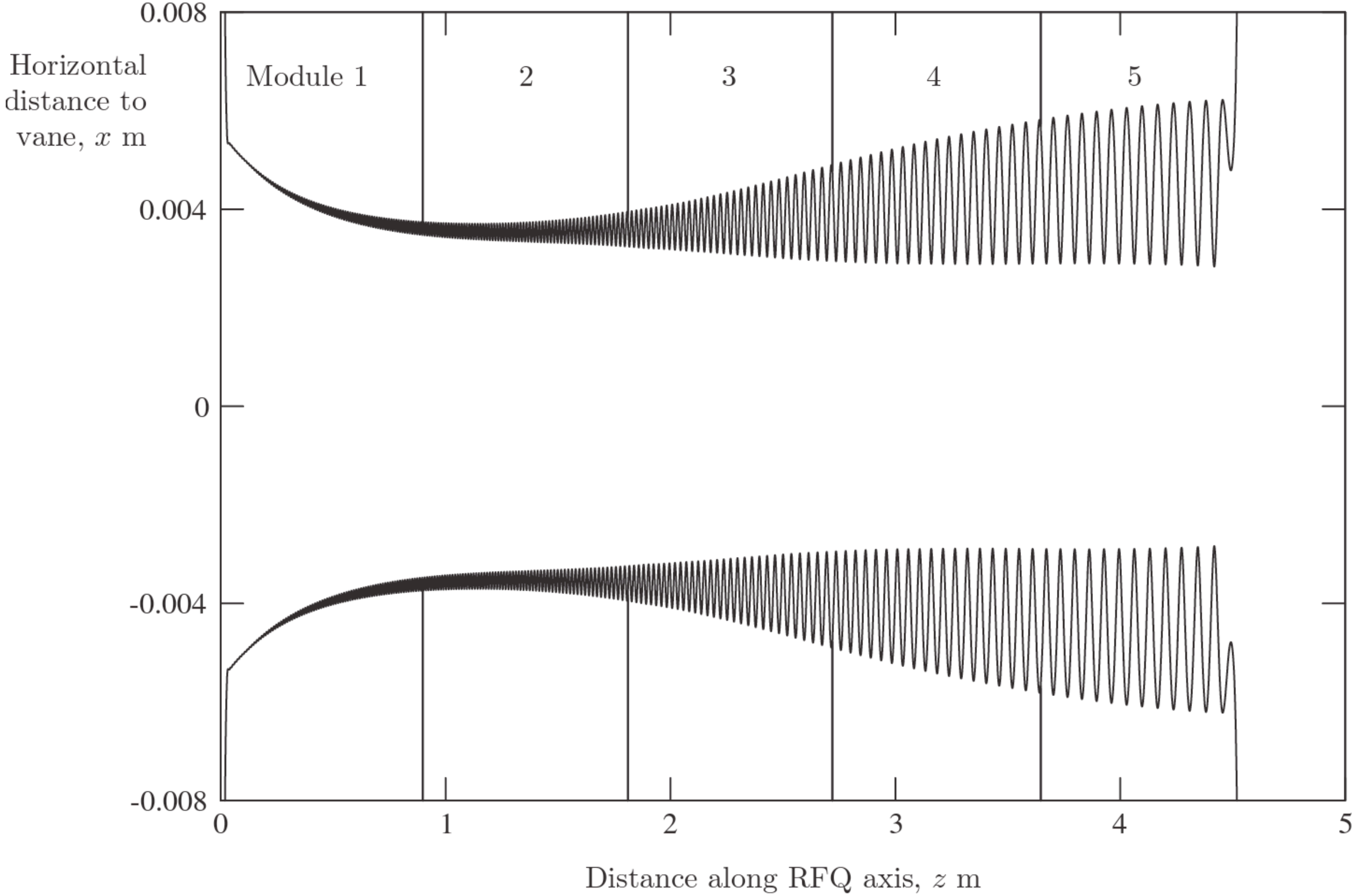


Figure 13.12 Longitudinal profile of the vanes in the ESS RFQ, showing the adiabatic evolution of the control parameters L, a and m. The RFQ is assembled from five modules to form a single resonant cavity that is excited at 352 MHz. (Courtesy of A. Ponton.)

POTENTIALS ON-AXIS — Potential is +ve @ z = 0

$\Rightarrow E_z$ gradient ACCELERATES $0 < z < \frac{L}{2}$

DECELERATES $\frac{L}{2} < z < L$

$\Rightarrow E_x$ FOCUSES everywhere

E_y DEFOCUSES "

By carefully shaping the vanes (not just hyperbolae)

$k = 2\pi/L$

"A" Accelerate

"X" X-roads

Almost constant

Bessel fns.

$$E_z = A \cdot \left(\frac{k V_0 I_0(kr)}{2}\right) \cdot \sin(kz)$$

$$E_x = -X \cdot \left(\frac{V_0}{a^2}\right) x - A \cdot \left(\frac{k V_0 I_1(kr)}{2r}\right) \cdot \cos(kz) \cdot x$$

$$E_y = X \cdot \left(\frac{V_0}{a^2}\right) y - A \cdot \left(\quad \right) \cdot \cos(kz) \cdot y$$

ACCELERATION & FOCUSING EFFICIENCES

$$(A, X) = \frac{\left(m^2 - 1\ ,\ I_0(ka) + I_0(kma)\right)}{m^2 I_0(ka) + I_0(kma)}$$

For $kma \lesssim 1$ then $A + X \simeq 1$

so can trade off acceleration with focussing

RFQ entrance : $m \simeq 0$ ⇒ focus, little bunching

exit : m max ⇒ Mostly accelerating

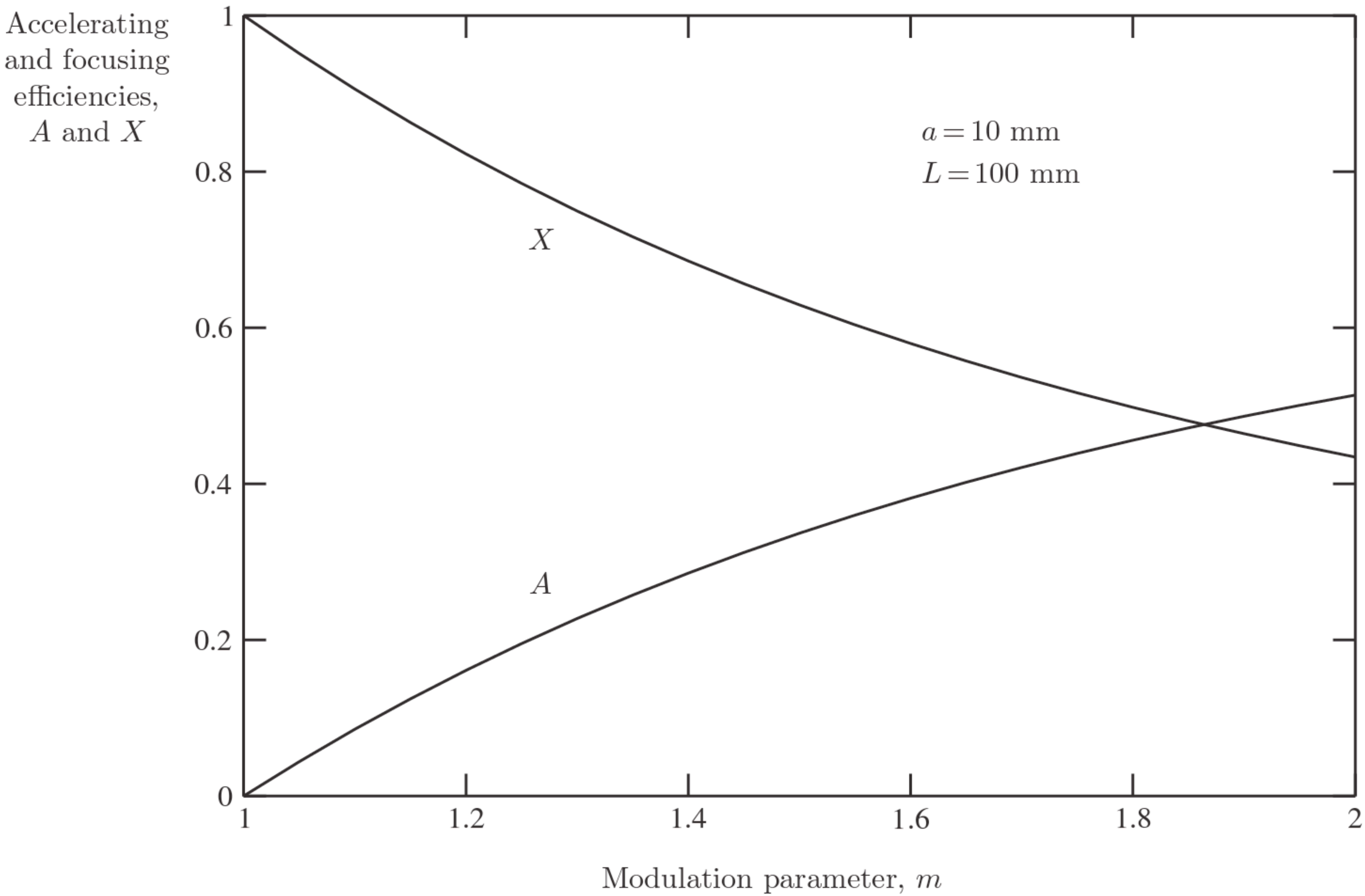


Figure 13.11 RFQ acceleration and focusing efficiencies, A and X, versus modulation parameter m, for the typical vane geometry in Figure 13.10.

ADVANTAGE High currents !! eg ≲ 100 mA

DISADVANTAGES

- Very tight (+ complex) machining tolerances
- Thermal-mechanical stability can be challenging
- Only one charge-to-mass ratio
- Expensive !

But how did we ever live without them !!

FORWARD to 10 MW, ADSR, et cetera ...

BEAM LOSS + HALOES

- Keep beam losses to < 1 W/m to allow hands-on maintance immediately ...
  - ⇒ ~ 10^{-4} total loss of a 10 MW beam
  - ⇒ Very weak halos in 3-D are important !!
- THEORETICAL + EXPERIMENTAL understanding is LIMITED !!
  - ⇒ intrabeam stripping is important for H^- (not H^+) beams
  - ⇒ protons escaping RF bucket can "overfocus" transversely

ELEPHANT IN THE ROOM – SPACE CHARGE !!