# Lecture 13:

# Linacs – protons & ions

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January 30, 2024

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"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".

A) Time structures

B) Multi-cell synchronism

C) Linear motion

D) Radio Frequency Quadrupoles

E) Beam losses & haloes

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 |

- State of the art proton linacs are MW-class

Q: What are they used for? e.g. SNS, ESS make neutrons

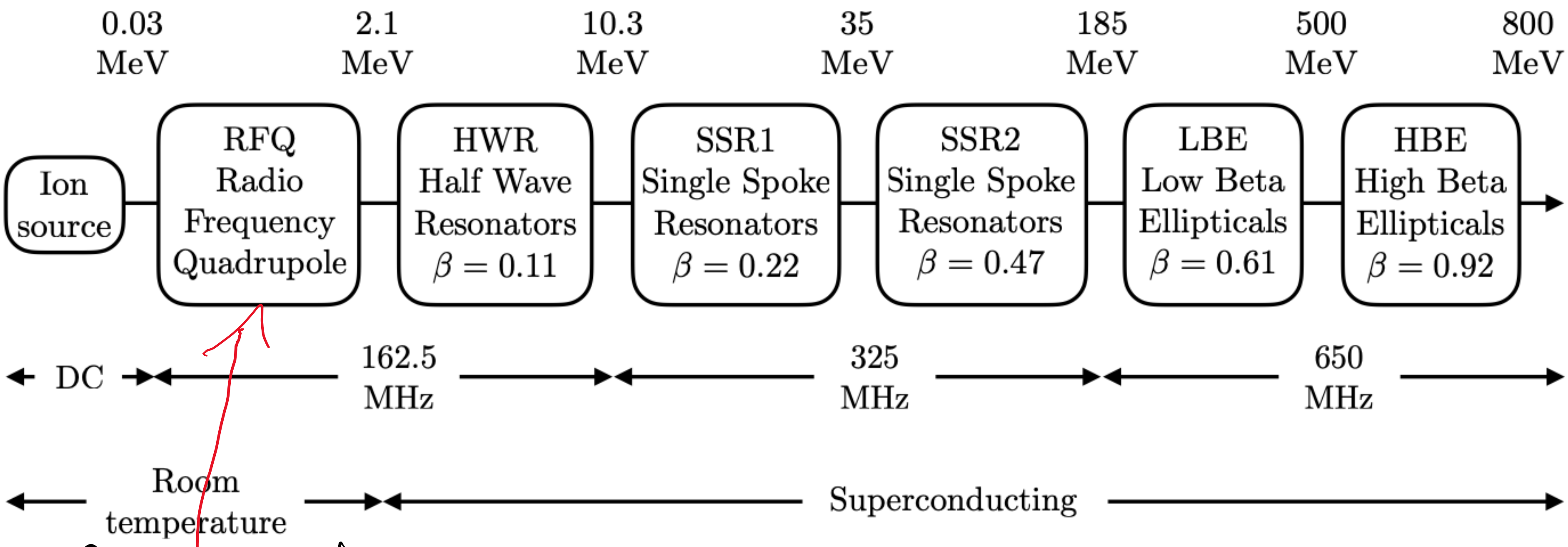
ADSR ??

Q: What does $H^-$ mean? Why?

$\beta < 1$ - protons, even at 1 GeV

$\beta \approx 1$ - electrons, even at 10 MeV

# 13.1 Typical technology map (PIP-II)



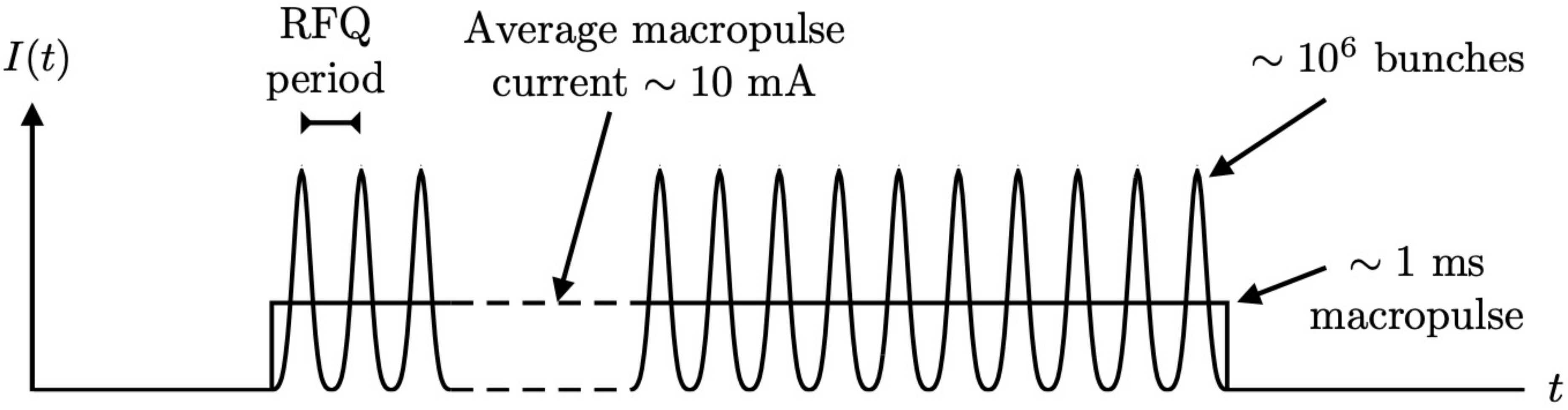
- RF technology "zoo" is v. different, $p$ are $e^-$

  ⇒ protons use many structures which we will not EXCEPT for revolutionary RFQ

- But first . . .

# A)  Time structures

# 13.2 Macropulse time structure



- Take "continuous" beam from source (ON or OFF) & bunch with the RFQ at $f_{RFQ} \lesssim 1$ GHz
- Typically ~$10^6$ bunches in each macropulse repeated @ ~30 Hz

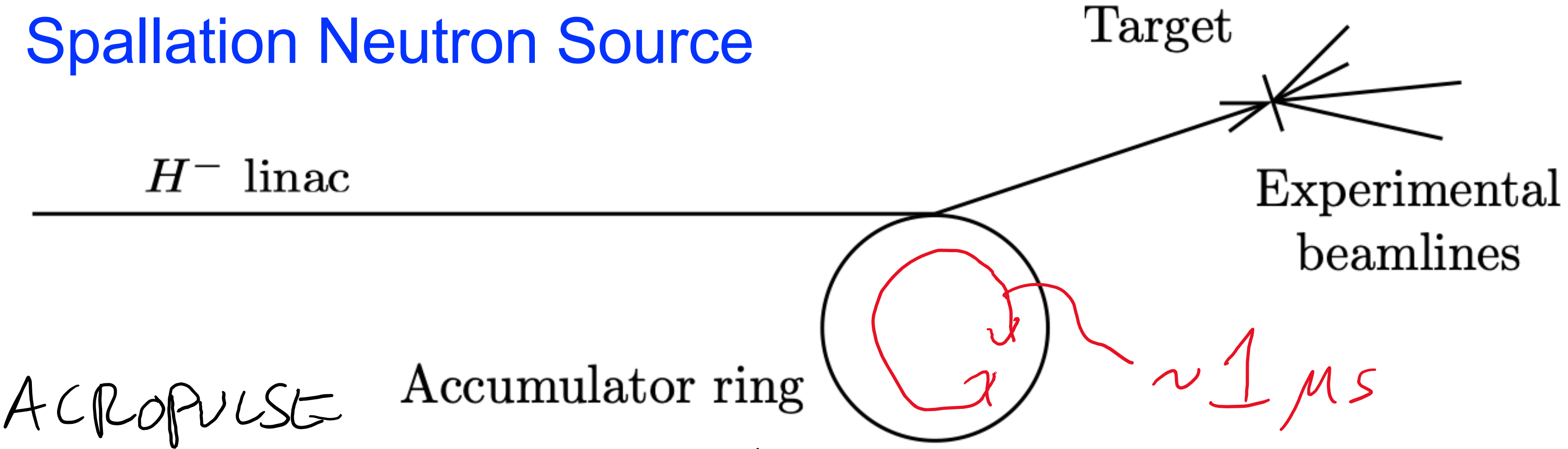
- Average beam power is

$$\boxed{\underset{\sim 10^{6}\,W}{P} = \underset{\sim 10^{-2}A}{I}\,\underset{10^{9}V}{V}\,\underset{10^{2}Hz}{f}\,\underset{10^{-3}s}{T}}$$

where "kinetic" "energy" is $V = \frac{m_p c^2}{e}(\gamma - 1)$ in Volts

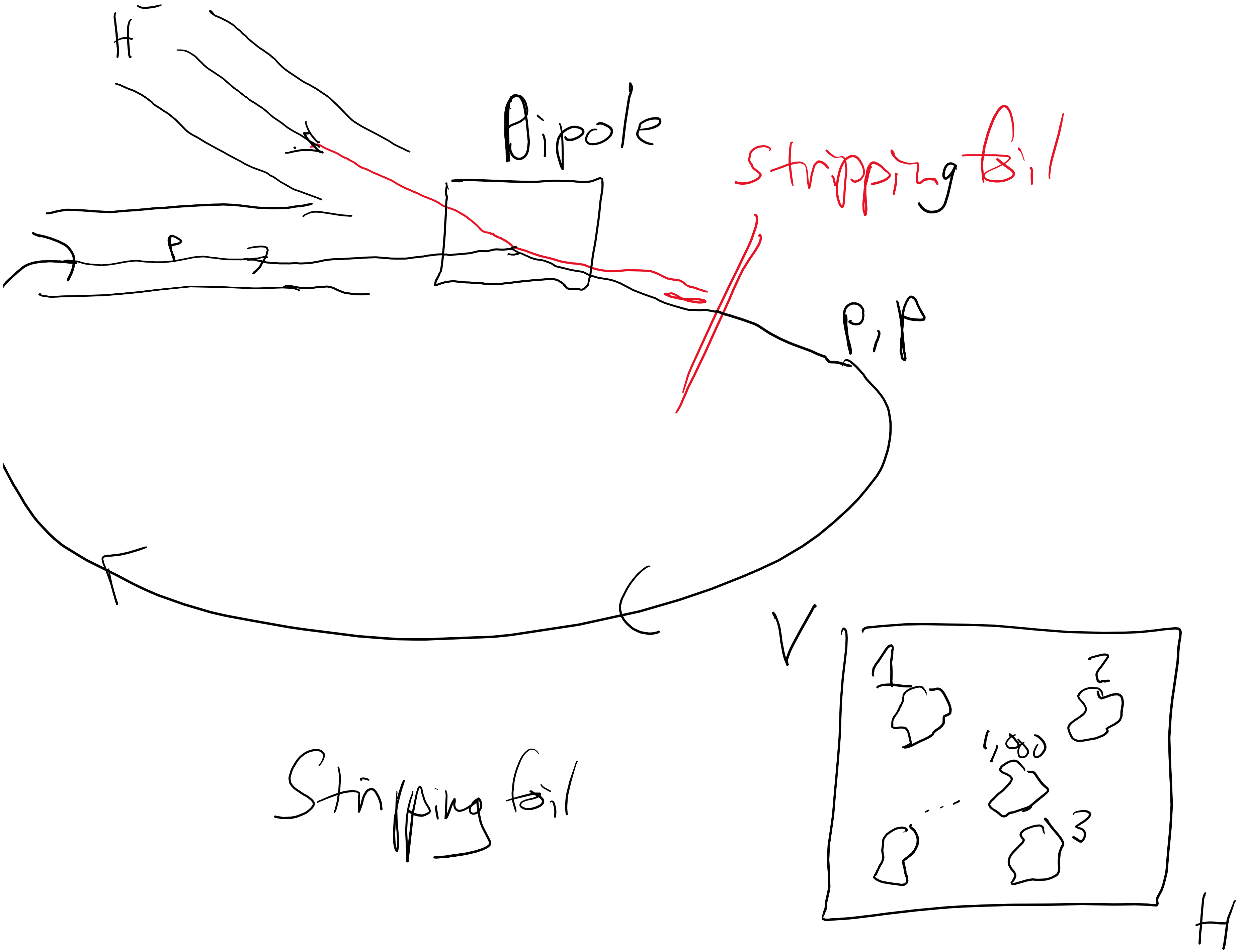
$\boxed{\text{EG SHORT PULSES}}$ MAKE a long macropulse into a SHORT beam pulse on Target

# 13.3 Spallation Neutron Source

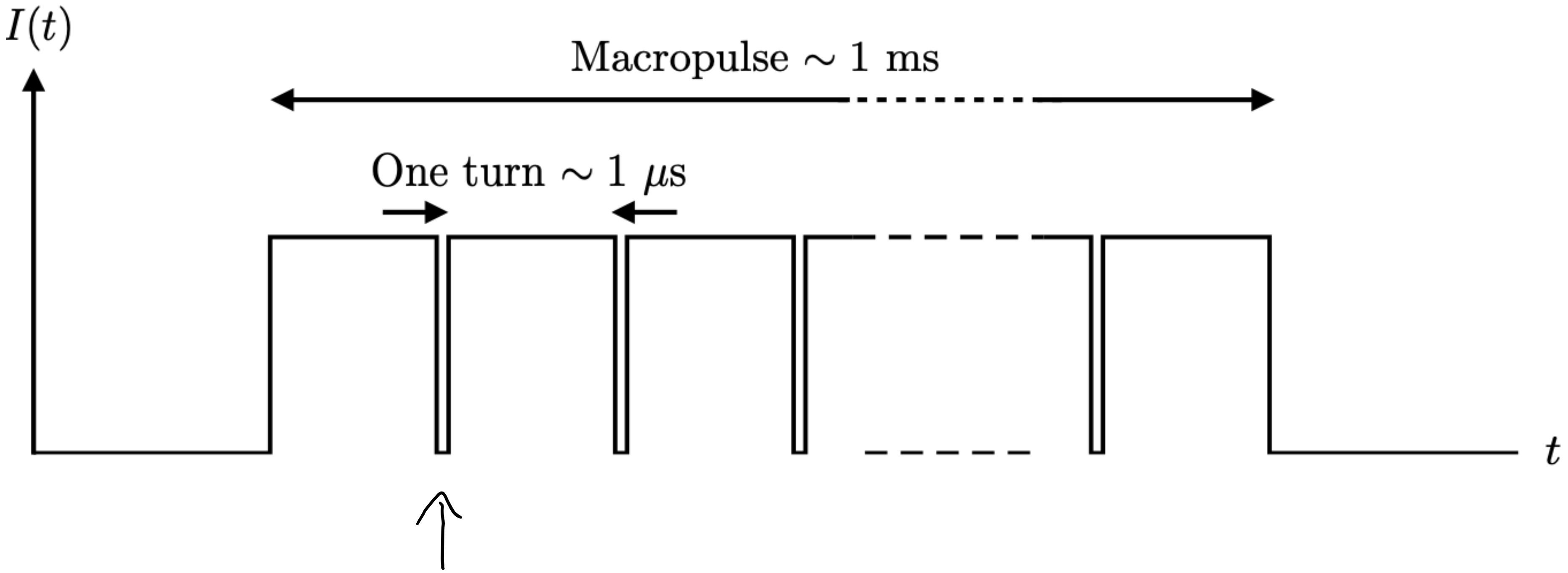


MACROPULSE

- SEGMENT : period of the accumulator
- ACCUMULATE segments
  → ON-TOP of each other (LONGITUDINALLY)
  → SIDE-BY-SIDE transversely
- After accumulating $\sim 10^3$ segments, extract beam onto target! $10^3$ times the intensity!!


H⁻
Dipole
stripping foil
p
p, P
V
1
2
1,000
3
H
Stripping foil

# 13.4 SNS *H-* chopping & stacking



Turn ion source on & off to CHOP the micropulse to avoid beam losses when kickers are turning on or off!!

EG 2 **LONG PULSES** ESS ~1 ms, p ($H^+$)

- Simply put macropulses on target
- No need for an accumulator
- No need for $H^-$ beams
- BUT some experimenters need SHORT pulses.

EG 3 **CONTINUOUS WAVEFORM** 1 bunch every $\frac{1}{f_{RFQ}}$

- Fewer protons per bunch (at fixed power)

$$\boxed{N = 6.3 \times 10^6 \, \frac{I\,[\mathrm{mA}]}{f_{RFQ}\,[\mathrm{GHz}]}}$$

- CW eliminates transients: microphonics, Lorentz force detuning
- BUT RF power system is different ..
- PIP-II could be upgraded from LONG PULSE to CW

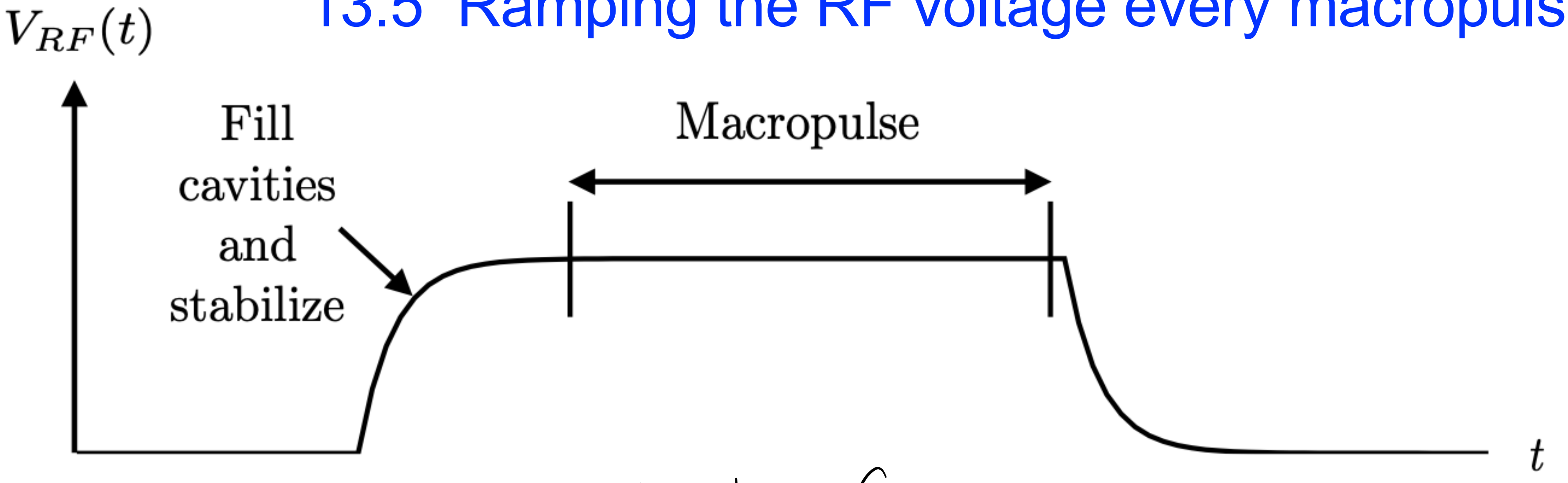
## $\boxed{\text{SAVE MONEY 1}}$ FREQUENCY DOUBLING

- BUNCHES shorten in acceleration $\sigma_s \ll \lambda_{RF}$
- Double the frequency

  $\Rightarrow$ ENERGY in cavity $\sim \frac{1}{f^3} - \frac{1}{8}$
- ~~E~~ Saves money: capital & operational

SAVE MONEY 2 | LOWER the RF DUTY FACTOR

# 13.5 Ramping the RF voltage every macropulse



– Must wait while filling & stabilizing

$$\boxed{D_{RF} > D_{MACROPULSE} = fT}$$

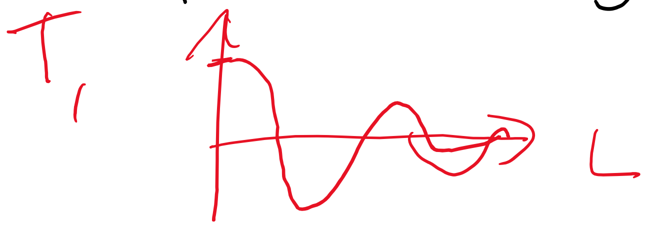
$D_{MACROPULSE}$ ← 0.06

$f$: 60Hz (SNS)

$T$: $10^{-3}$ s

# B)  Multi-cell synchronism

PREVIOUSLY we discussed the optimum length of a cavity

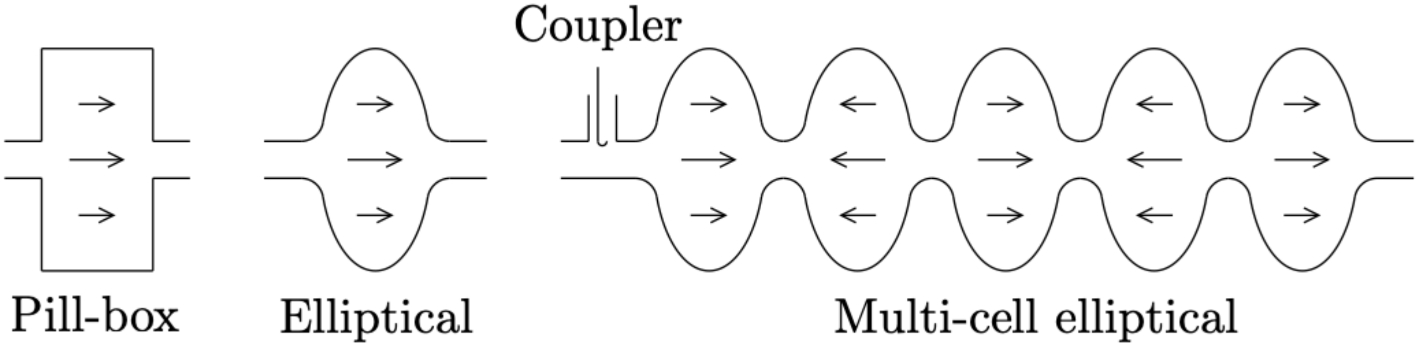


$$V_A = E_0 L . T_1$$

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

Q: What is the best number of cells per cavity??

(Adjust $T_1$ for elliptical cavities??)



## 7.5 Multi-cell cavities

# 13.6 Multi-cell synchronism factor

Ⓐ $\boxed{V_A = N E_0 L \cdot T_1 S}$

cells/cavity

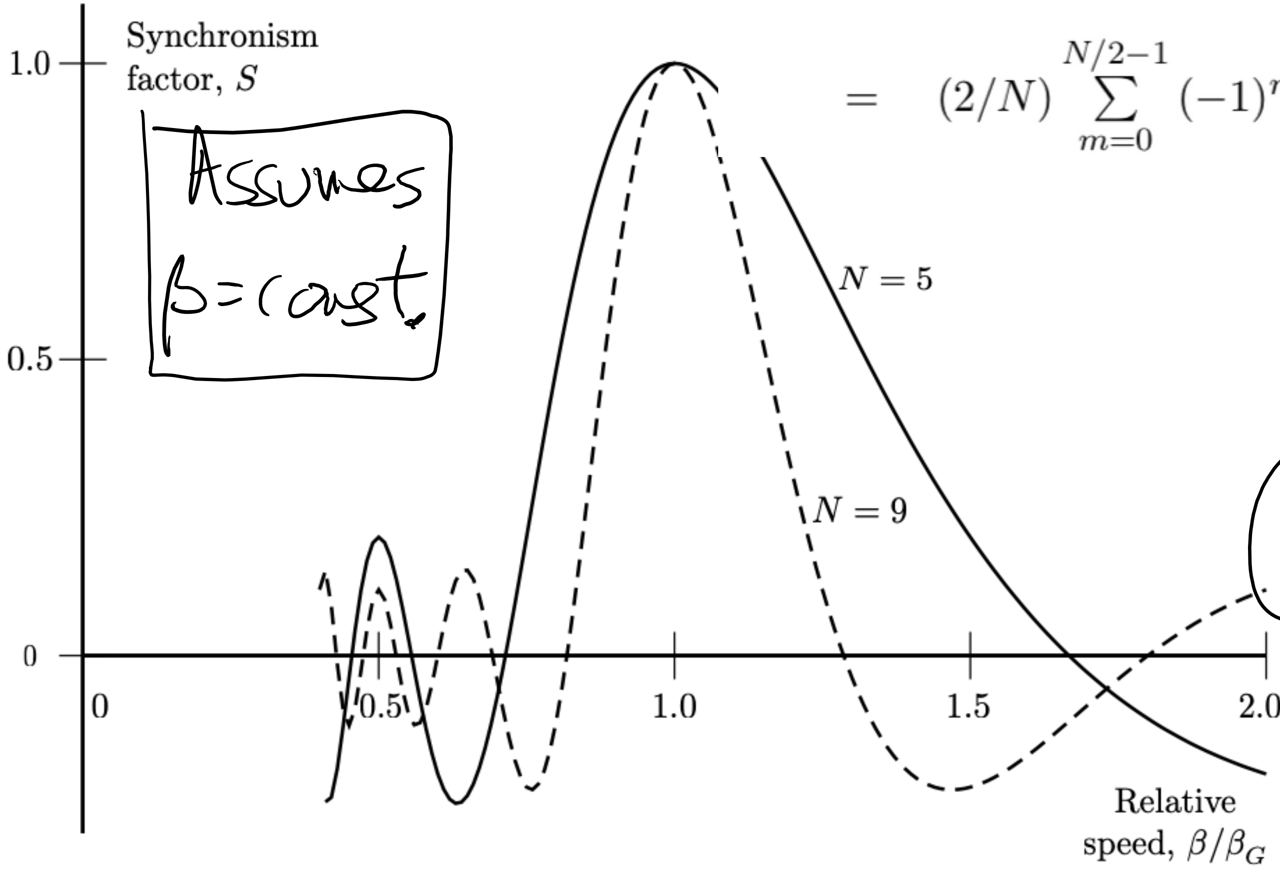
max gradient

SYNCHRONISM FACTOR $S(N, \beta/\beta_G)$

$$S(\beta) = (1/N)\left[1 + \sum_{m=1}^{(N-1)/2} (-1)^m \, 2\cos(m\pi\beta_G/\beta)\right] \qquad N \text{ odd}$$

$$= (2/N) \sum_{m=0}^{N/2-1} (-1)^m \sin\left((m+\tfrac{1}{2})\pi\beta_G/\beta\right) \qquad N \text{ even}$$

$S$



Assumes $\beta$=const.

$\beta_{\text{GEOMETRY}}$

$\beta/\beta_G$

A : Need $\boxed{|\beta - \beta_G| < \frac{1}{N}}$

ELECTRONS : NOT a problem, since $\beta \simeq 1$

→ typically $N = 9$ (elliptical) cells per cavity

PROTONS : each cavity style handles a limited $\beta$ range

→ at higher $\beta$ use elliptical cavities

→ typically $N = 5$

# C) Linear motion

# LONGITUDINAL MOTION

- How do kinetic energy & RF phase $(W_n, \phi_n)$ vary from THIN cavity $n$ to cavity $n+1$?

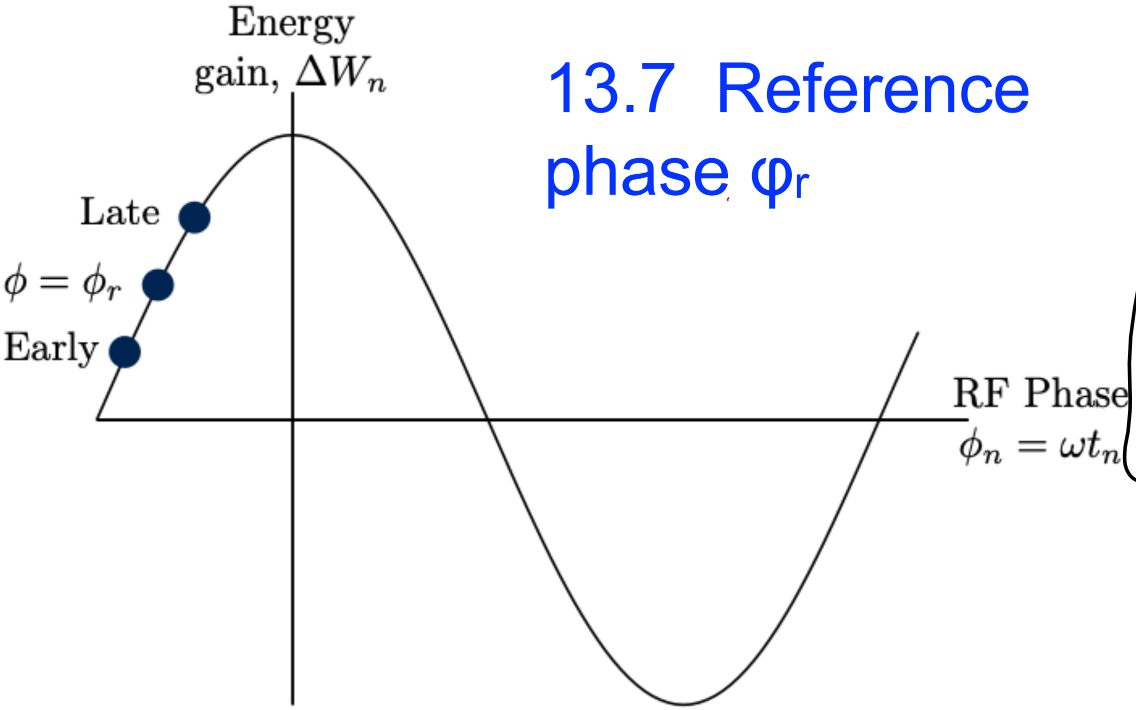
$$\Delta W_n = q V_{A,n}(\beta_n) \cdot \cos(\phi_n)$$

where max. voltage gain $V_{A,n}$ depends on $W_n$ (& $\beta_n$) through equation Ⓐ

- cf EQN 13-18 !
- Exercise 13.2 ("Prove Eqn 13-18") IS DECEPTIVELY DIFFICULT !!

- There is NO natural SYNCHRONOUS PHASE in a linac, so use a REFERENCE PHASE $\phi_R$
- Early (late) arrivals need smaller (larger) $\Delta W_n$ to keep bunch together

## 13.7 Reference phase $\varphi_r$



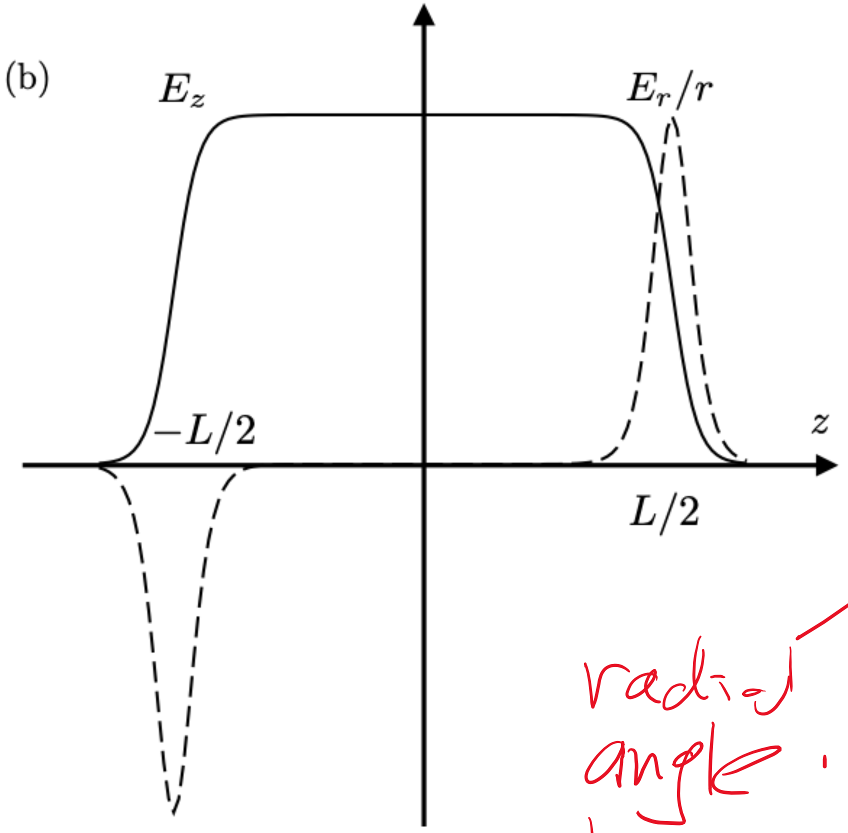
$\boxed{\phi_R \text{ IS NEGATIVE}}$

# RADIAL DEFOCUSING A LOW ENERY EFFECT!

"It can be shown" that beampipe transitions in a rotationally symmetric cell RADIALLY defocus at entry, FOCUS at exit.

⇒ NET DEFOCUSSING, because exiting beam is mor rigid

## 13.8b Unbalanced radial impulses at cavity ends



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

radial angle kick

strong dependence!!

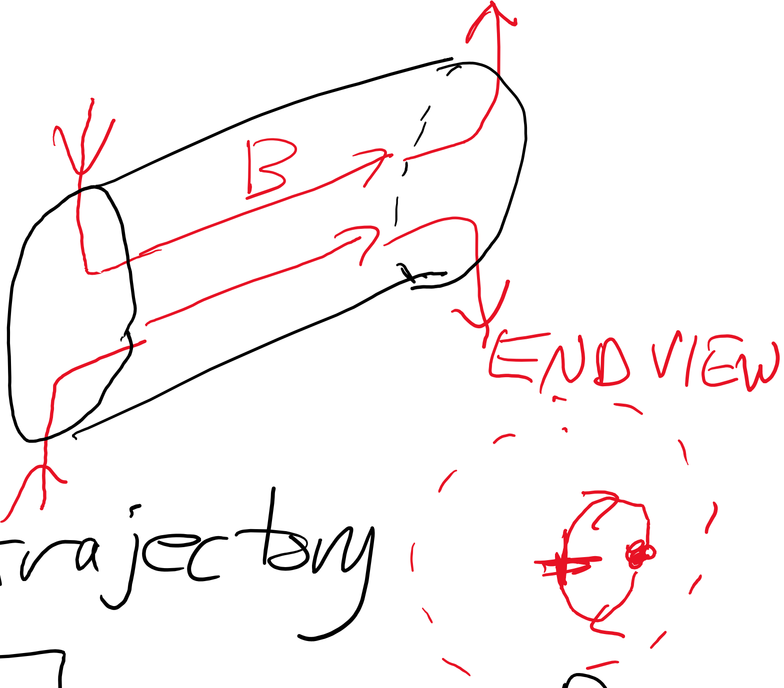
$\sin(\phi_R) < 0$

# TRANSVERSE FOCUSSING

$\boxed{\lesssim 3\ \text{MeV}}$ RFQs provide transverse focussing while bunching & accelerating. (See below)

$\boxed{\lesssim 50\ \text{MeV}}$ SOLENOIDS

(See Equ A-22)



A proton entering with

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

follows a trajectory

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

$$k = \text{sgn}(q) \frac{B}{2(B\rho)}$$

- So for a THIN solenoid with $KL \ll 1$

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

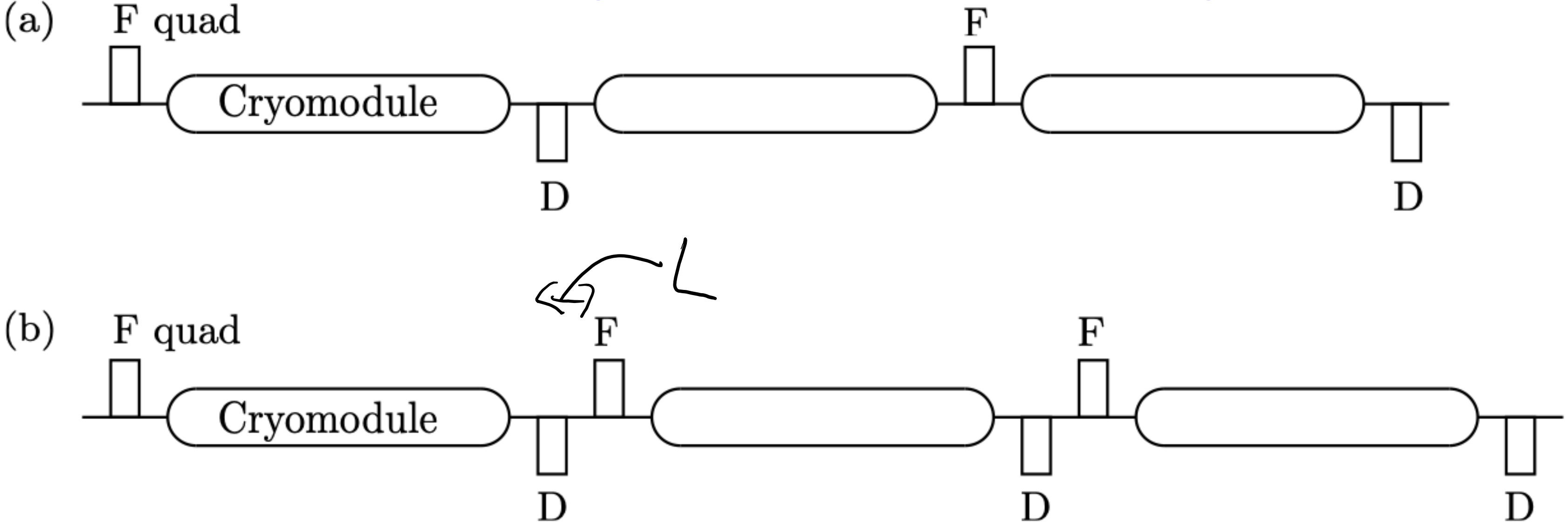
focuses, but solenoid effect weakens quadratically with rigidity & momentum

$\Rightarrow$ NO GOOD at higher energies

$\boxed{\geq 50 \text{ MeV}}$ QUADRUPOLES

- Weaken LINEARLY with rigidity
- Permanent quadrupoles can be placed, e.g. in DTL poles!
- Place singlets or (usually) doublets between SEGMENTED cryomodules

# 13.9 Singlet & doublet focusing



- A doublet with equal strength F & D quads $\frac{1}{f}$ L apart focuses like $\boxed{\frac{1}{f_{NET}} \approx \frac{L}{f^2}}$ in BOTH planes !!

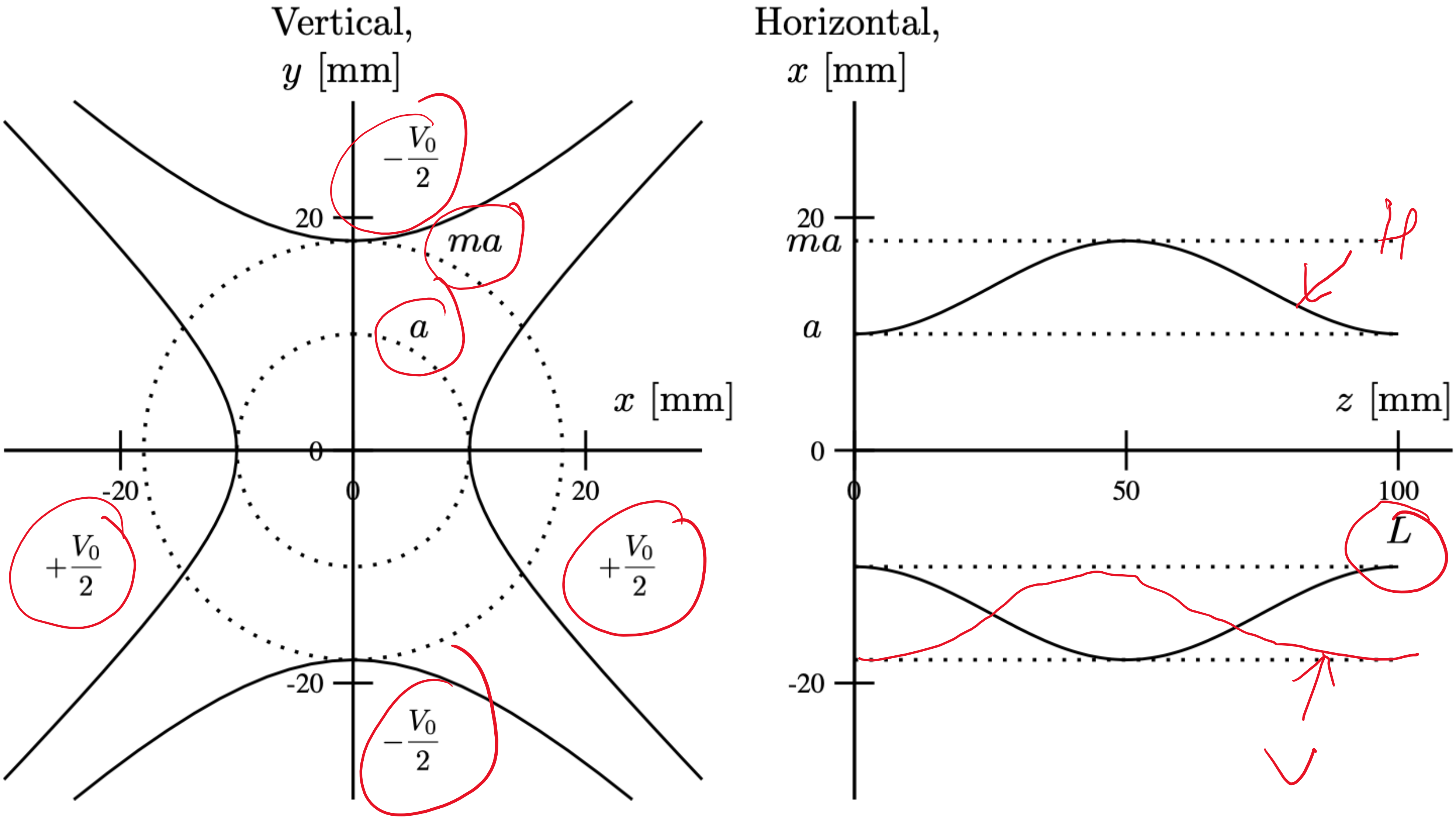
- Larger β-functions (& sizes) than singlet focusing, but rounder beams.

SEGMENTED cryomodules have more heat load (more ends), & are longer, but are more convenient

NON-SEGMENTED cryomodules are used in high energy ELECTRON linacs, with SC quads.

# D)  Radio Frequency Quadrupoles

# 13.10 RFQ vane structure: cross-section & top views



# RFQ $0.01 < \beta < 0.06$

- 1969 Russian invention enables acceleration of currents as high as 100 mA!
- Essentially electrostatic: low speeds weaken magnetic effects
- Bunch, focus & accelerate! How?

CONTROL PARAMETERS

- $a$ : inner vane radius
- $m$ : modulation parameter
- $L$ : longitudinal period of vane size oscillations
- $V_0$ : Voltage amplitude

- $(a, m, L)$ evolve SLOWLY along RFQ length

- Excite vanes (pairwise) with time

$$\boxed{V \pm \frac{V_0}{2}\cos(\omega t)} \quad + : \text{horizontal}$$

- Consider $t=0$ : H vanes +ve

V −ve

POTENTIAL ON-AXIS

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is +ve at $z=0$, −ve at $z=L/2$

$\Rightarrow$ GRADIENT ACCELERATS $0<z<L/2$

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

$\Rightarrow E_x$ FOCUSES everywhere

DEFOCUSES "

- EXACT (for carefully shaped vanes) not hyperbolae

$$\begin{aligned} E_x &= -X\,(V_0/a^2)\,x - A\left(\frac{kV_0 I_1(kr)}{2r}\right)\cos(kz)\,x \\ E_y &= X\,(V_0/a^2)\,y - A\left(\frac{kV_0 I_1(kr)}{2r}\right)\cos(kz)\,y \\ E_z &= A\left(\frac{kV_0 I_0(kr)}{2}\right)\sin(kz) \end{aligned}$$

modified

$I_0, I_1$ Bessel functions

$k = 2\pi/L$

"A"ccelerate

"X"verse

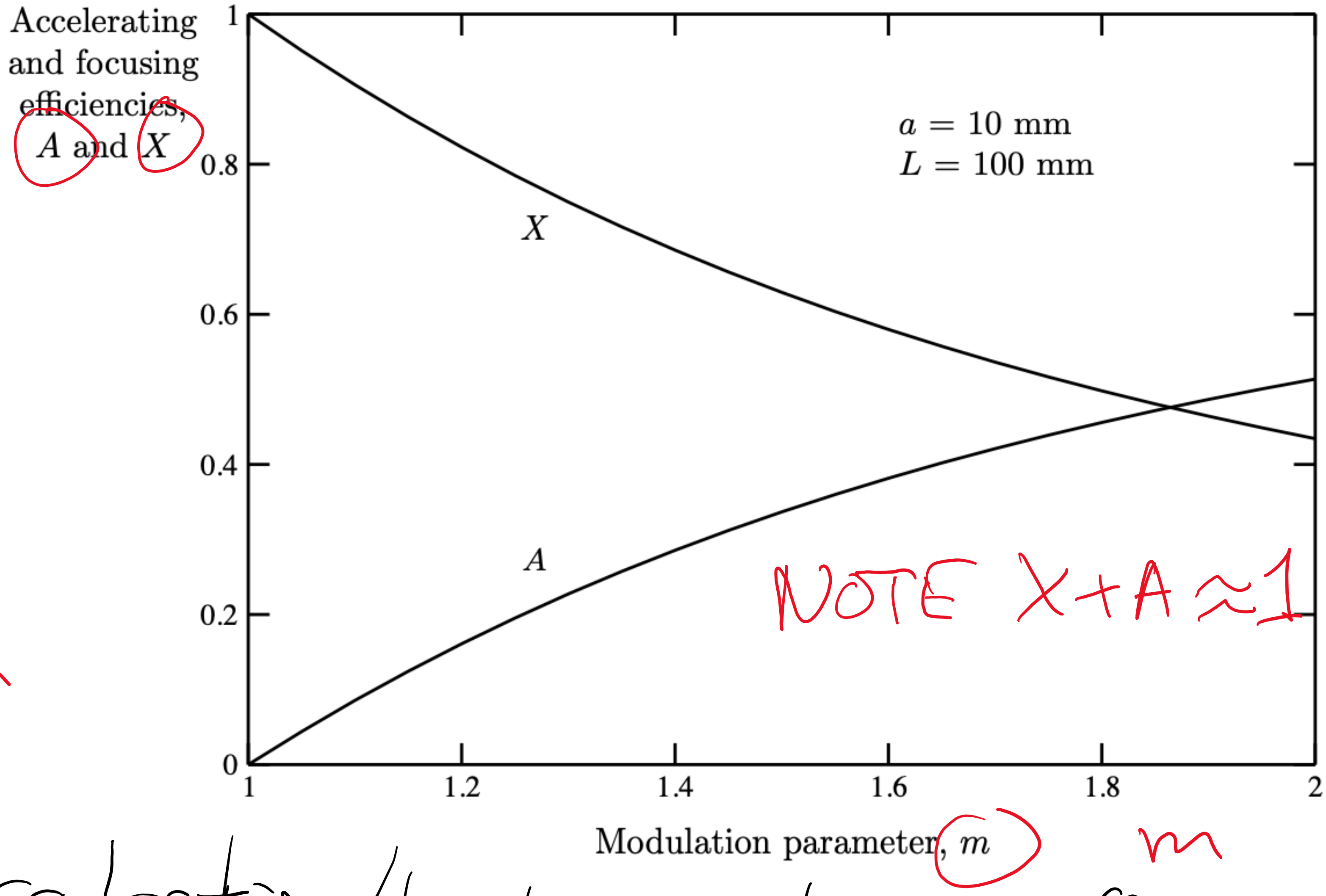
LINEARIZE

$$\begin{aligned} E_x &\approx V_0\left(-\frac{X}{a^2} - \frac{\pi^2 A}{L^2}\cos(kz)\right)x \\ E_y &\approx V_0\left(\frac{X}{a^2} - \frac{\pi^2 A}{L^2}\cos(kz)\right)y \\ E_z &\approx V_0\,\frac{\pi A}{L}\,\sin(kz) \end{aligned}$$

X + A ?? as functions of (m, k, a)

$2\pi/L$

# 13.11 Accelerating & focusing efficiencies, *A* & *X*

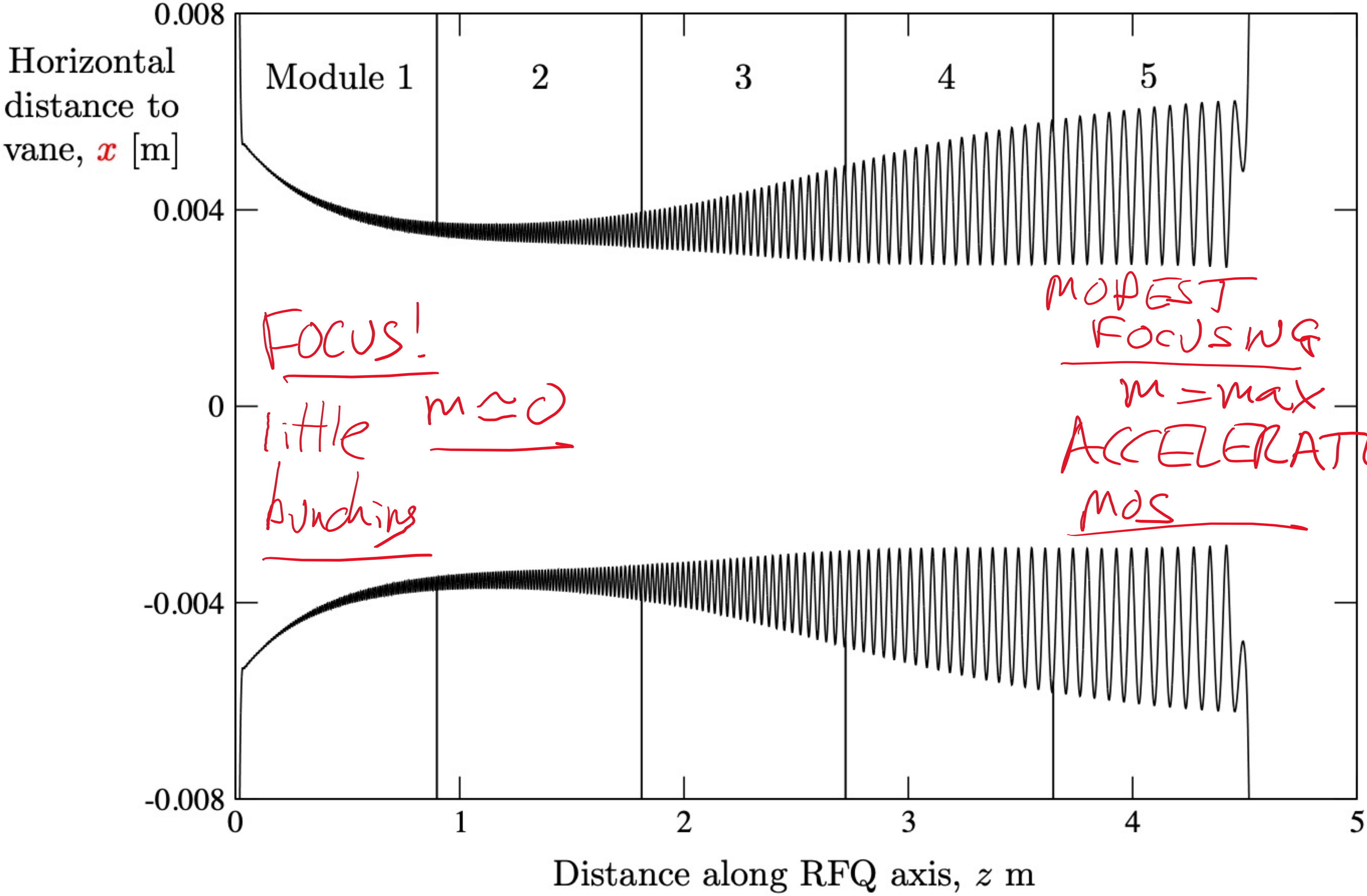


NOTE $X+A \approx 1$

$m$

- Acceleration/bunching are traded off against transverse focusing!

# 13.12  Profile of the 4.5 m ESS RFQ vanes



FOCUS!

little bunching

$m \simeq 0$

MODEST FOCUSNG

$m = max$

ACCELERATE MOS

# DISADVANTAGES

- Very tight & complex machining tolerances
- Thermo-mechanical stability can be challenging
- Only one charge-to-mass ratio ????
- Expensive
- (used to be 50% failure rate, in the past)

But how did we ever live without them?

# E)  Beam losses & haloes

- Must keep beam losses to $< 1$ W/m to allow hands on maintenance
  - $\Rightarrow \sim 10^{-4}$ total loss in a 10 MW beam !!
  - $\Rightarrow$ very weak halos in 3-D tails are important
- THEORETICAL & EXPERIMENTAL understanding is limited
  - $\Rightarrow$ intrabeam stripping is important for $H^-$ linacs not p linacs
  - $\Rightarrow$ protons escaping RF bucket can "overfocus"

BUT 2 elephants in room

① Power sources, high especially

② SPACE CHARGE !!