#13: LINACS – PROTONS & IONS

1/30/19

State-of-art protons are GeV- & MW-class

Q: What are they used for?

Q: What does H^- mean? Why?

$\beta < 1$ PROTONS even @ 1 GeV

$\beta \simeq 1$ ELECTRONS even @ 10 MeV

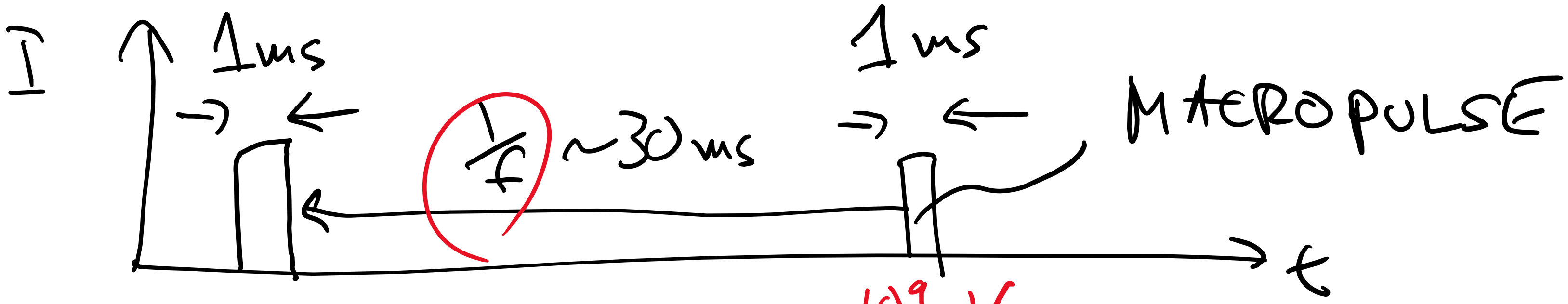
⇒ RF technology "zoo" is very different, e vs p

⇒ Proton linacs use many RF structures.

⇒ NOTE: Revolutionary RFQ technology

TIME STRUCTURES

- "Continuous" beam from the ion source (ON or OFF) is bunched by RFQ at <u>its</u> frequency: $f_{RFQ} \lesssim 1\,\text{GHz}$
- Typically $\sim 10^6$ bunches in a MACROPULSE repeated at ~ 30 Hz



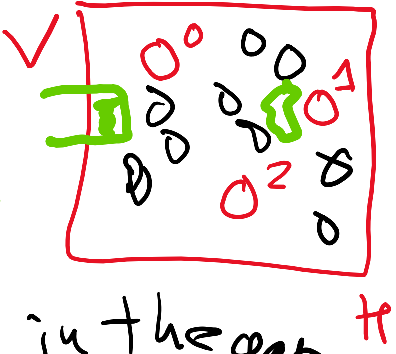
- So average beam power:

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

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

① SHORT PULSE EG SNS ~1 μS , H^-

- Notch the macropulse into ~10^3 sub-pulses
- SEGMENT period is the circulation time of Accumulato
- ACCUMULATE SEGMENTS
  - LONGITUDINALLY on-top of each other
  - TRANSVERSELY (H&V) side-by-side
  - (H^- is stripped to H^+ on injection)
- AFTER accumulation, extract in 1-turn using a kicker that turns on in the gap



⇒ SHORT PULSE ~1 μs long made from 1,000 sub-pulses in a 1 ms macro-pulse

10^3 times intensity!! (but very large transverse emittance)

② LONG PULSE : ESS ~1 ms, H^+

- Simply put beam on target
- Avoids H^- beam generation, eliminates accumulator ring
- *Some* neutron physics *NEEDS* short pulses

③ CONTINUOUS WAVEFORM 1 bunch *EVERY* $1/f_{RFQ}$

- At constant power, fewer protons per bunch

$$N = 6.3 \times 10^{-6} \frac{I\,[mA]}{f_{RFQ}\,[GHz]} \sim 10^7, 10^8$$

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

DOUBLE THE FREQUENCY ?

Bunches shorten during acceleration : $\sigma_s \sim \frac{1}{\gamma}$

Q: How big is an RF structure (cavity?)

- Energy filling a cavity

  $U \sim$ Volume $\sim 1/f^3$

So doubling the frequency (always with $\lambda \gg \sigma_s$) whenever possible SAVES MONEY (capital + operational)

MULTI-CELL SYNCHRONISM

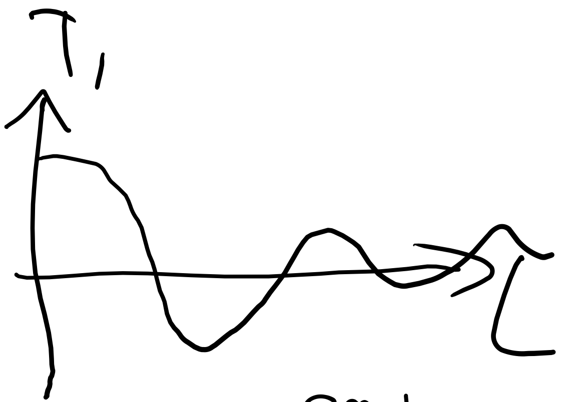
L

In lecture 7 we discussed optimum length of a single cell cavity

$$\boxed{V_A = E_0 L \cdot T_1(L)}$$

where Transit Time Factor

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



[T_1 needs modest adjustment for geometry, e.g. elliptical]

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

Ⓐ $$\boxed{V_A = N E_0 L \cdot T_1 S(\beta)}$$

Accelerating VOLTAGE

\# of CELLS

Max GRADIENT

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

- Assume β is ~constant in ONE cavity

How well matched to β_G must it be?

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

ELECTRONS: No problem, $\beta \approx 1$, $\beta_G = 1$

- typically $N = 9$

PROTONS: Each cavity style handles a limited β range

- at higher β use elliptical cavities
- typically $N = 5$

LONGITUDINAL MOTION

How do kinetic energy W_n and RF phase ϕ_n vary from THIN cavity n to n+1 to n+2 ...

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

where max. voltage gain $V_{A,n}$ depends on W_n (through β) through Ⓐ

THERE IS NO SYNCHRONOUS PHASE to use a REFERENCE PHASE ϕ_R

$$\rightarrow \boxed{\phi_R \text{ is NEGATIVE}} \quad !\,!$$

RADIAL DEFOCUSING

RF cavities DEFOCUS transversely while focusing longitudinally:

- "It can be shown" (Maxwell) that beam pipe transitions in an axially symmetric cavity DEFOCUS at ENTRY, FOCUS at exit

⇒ Net defocusing, because ① exit rigidity is larger
② ϕ_R is $-$ve !

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

radial angle

strong dependenc

$\sin(\phi_R) < 0$

⇒ ELECTRONS: No problem

TRANSVERSE FOCUSING

$\boxed{\lesssim 3\,\text{MeV}}$ RFQ focus transversely AND accelerate AND bunch longitudinally! (later...)

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

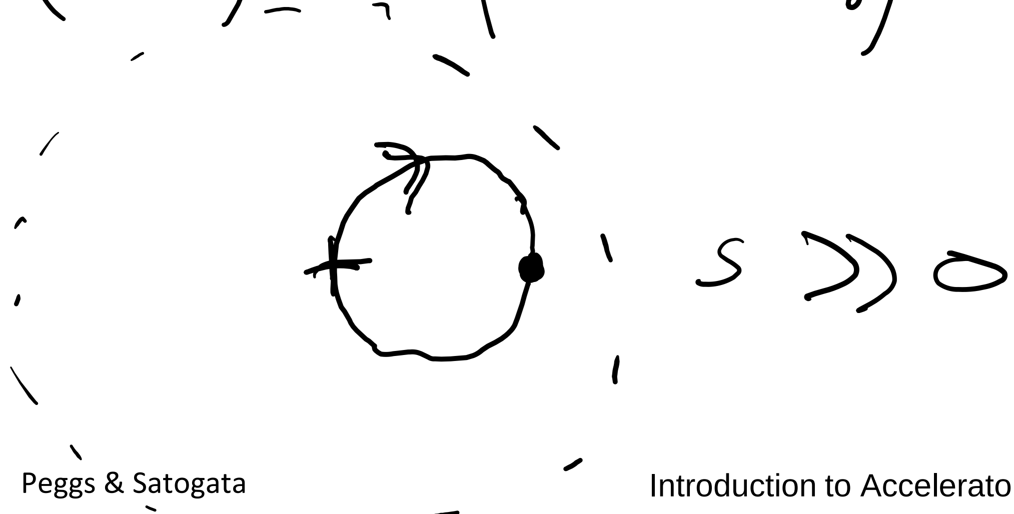
SOLENOIDS

A proton enters a solenoid with

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

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

$$\left[k = \text{sgn}[q] \, \frac{B_{sol}}{(B\rho)} \right]$$



For a THIN solenoid with $kL \ll 1$

$$\Delta r' \approx -\left(\frac{B}{2(B\rho_0)}\right)^2 L \cdot r$$

Weakens QUADRATICALLY with $\beta\gamma$

$\Rightarrow$ No good at higher momenta $\gtrsim 50$ MeV

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

- Weakin LINEARLY with rigidity
- Permanent magnet quadrupoles can be placed inside DTL poles!
- Place singlets or doublets (usually) between SEGMENTED cryomodules

DOUBLET QUADS

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

$$\frac{1}{f_{NET}} \approx -\frac{L}{f^2}$$ in both planes!!

Larger β-functions (+ beam sizes) than singlet, but rounder beams

SEGMENTED cryomodules have more heat leaks, + are longer.

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

RADIO FREQUENCY QUADS. $.01 \lesssim \beta \lesssim .06$

- 1969 invention enables currents of ~ 100 mA
- Essentially electrostatic : low speeds → weak magnetics
- Bunch, focus + accelerate

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

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

- CONSIDER $t=0$: H vanes +ve, V -ve

POTENTIALS ON-AXIS $(t=0)$

Potential is +ve at $z=0$, −ve at $z=L/2$

$\Rightarrow$ Gradient ACCELERATES $0<z<L/2$

DECELERATES $L/2<z<L$

$\Rightarrow$ E_x FOCUSES everywhere

E_y DEFOCUSES everywhere

By carefully shaping the vanes (NOT hyperbolae!)

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

$k=\frac{2\pi}{L}$, I_0 + I_1 modified Bessel functions, and .....

…. ACCELERATING + FOCUSING EFFICIENCIES are

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

For $kma \lesssim 1$

Then $\boxed{A + X \simeq 1}$

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

exit : m max ⇒ least focus, most acceleration.

DISADVANTAGES

- Expensive
- Very tight & complex machining tolerances.
- Thermo-mechanical stability can be challenging
- Only one charge-to-mass ratio

But how did we ever live without RFQ's

Forward to 10 MW...

BEAM LOSS & HALOES

- Keep losses to < 1 W/m limit for hands-on maintenance
  - ⇒ ~ 10^{-4} total loss of 10 MW beam?
  - ⇒ Very weak "halo" particles in 3-D tails are important
- THEORETICAL & EXPERIMENTAL understanding is LIMITED
  - ⇒ intrabeam stripping is important for H^- (not H^+) beams
  - ⇒ protons escaping RF bucket can "overfocus" transverseley

But the elephant in the high power room is SPACE CHARGE!