Presentation of the LINAC2010 invited talk on Design of Proton Drivers. (Draft as of September 9, 2010)

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APC Seminar

September 9, 2010

Multi-GeV Proton and F Linacs

The 1 VV/n beam loss limit

Consideration
Zero-Current
Design

Beam Losses

Jitters
H- Stripping
Correction

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Multi-GeV Proton and H-Linacs

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Multi-GeV Proton and H- Linacs Overview

| Project | E [GeV] | I _{av} [mA] | Power [MW] | Application | Status |
|-------------------|------------|-------------------------|---------------|----------------|--------------|
| | [GeV] | [۱۱۱۲] | [IVIVV] | | |
| FNAL 8-GeV Pulsed | 8 | 25 | 2 | neutrinos | proposed |
| FNAL 3-GeV CW | 3 | 1 | 3 | neutrinos | proposed |
| | | | | kaons, muons | |
| CERN LP-SPL | 4 | 0.05 | 0.2 | LHC upgrade | proposed |
| CERN HP-SPL | 5 | 8.0 | >4 | neutrinos, RIB | proposed |
| ESS1 (EU) | 1.334 | 3.75 | 5 | neutrons | proposed |
| ESS2 (EU) | 1.334 | 7.5 | 10 | neutrons | proposed |
| ORNL SNS1 | 1 | 26 | 1.4 | neutrons | in operation |
| ORNL SNS2 | 1.3 | 42 | 3 | neutrons | proposed |

Multi-GeV Proton and H-Linacs

The 1 W/m beam loss limit

Design Consideration

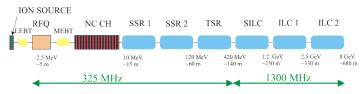
Zero-Curren Design High-Curren

Beam Losses

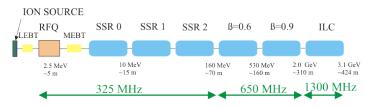
Jitters
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FNAL 8-GeV Pulsed / 3-GeV CW Linacs Layout

FNAL 8-GeV Pulsed Linac



FNAL 3-GeV CW Linac



Multi-GeV Proton and H-Linacs

The 1 W/n beam loss limit

Design Consideration

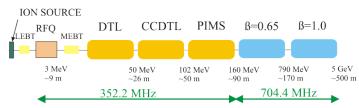
Zero-Current Design High-Current Design

Beam Losses

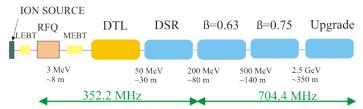
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CERN SPL / ESS Linacs Layout

CERN SPL Linac



ESS Linac

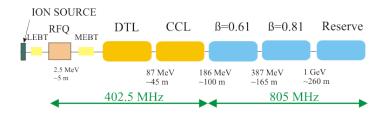


Multi-GeV Proton and H-Linacs

Zero-Current

Correction

ORNL SNS Linac



Multi-GeV Proton and I Linacs

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Tolerable Beam Loss in High-Intensity Linacs: 1W/m

- Beam loss in accelerators lead to beamline component activation
- Maintenance Restriction (for example LANSCE, Los Alamos Guidelines)
 - Limited access time: 100 $\mu {\rm Sv/h}$ to 1 mSv/h, 30 cm from the component surface
 - Very limited controlled: 1 mSv/h to 100 mSv/h
 - Remote maintenance required: >100 mSv/h
- Experience from Asia, Europe and US on high-energy accelerators <u>AND</u> calculation results from three different codes (LAHET (Los Alamos), HETC/MCNP/ORIHET (ORNL) and MARS (FNAL)) lead to the basic result:

$$1 \text{ mSv/h} \Longleftrightarrow \sim 1 \text{W/m}$$
 (1)

Multi-GeV Proton and Linacs

The 1 W/m beam loss limit

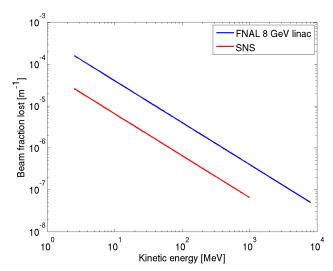
Design

Zero-Currer Design High-Currer

Beam Losse

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H- Stripping Correction Permissible Beam Loss Fraction to achieve $1~\mathrm{W/m}$



Design Considerations

Zero-Current Design

Considerations

- The zero current phase advance of transverse and longitudinal oscillations should be kept below 90° per focusing period to avoid parametrically-excited instabilities at high-current.
- The transverse and longitudinal wavenumbers k_{T0} and k_{I0} must change adiabatically along the linac to minimize the potential for mismatch and assure a current independent lattice

$$k_{T0} = \frac{\sigma_{T0}}{L_f}, \qquad k_{L0} = \frac{\sigma_{L0}}{L_f} \tag{2}$$

where σ_{T0} and σ_{L0} are the zero current transverse and longitudinal phase advances per focusing period L_f

• Avoid the n=1 parametric resonance between the transverse and longitudinal motion.



Multi-GeV Proton and F Linacs

The 1 W/n beam loss limit

Design Considerations

Zero-Current Design High-Current Design

Beam Losses

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High-Current Design

 Avoid energy exchange between the transverse and longitudinal planes via space-charge resonances by:

- providing beam equipartitioning. Emittance ratio close to one
- avoiding instable areas in Hofmann's stability charts
- Provide Longitudinal-to-transverse emittance ratios close to one (0.5 $< \epsilon_I/\epsilon_t < 2$) and a tune depression > 0.5 provide larger stable areas in the stability charts
- Provide proper matching in the lattice transitions to void appreciable halo formation
- ullet Keep a ratio aperture-to-rms-beam-size > 10, if possible

Multi-GeV Proton and H Linacs

The 1 W/n beam loss limit

Design Consideration

Zero-Current Design High-Current

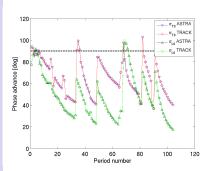
High-Curren Design

Beam Losses

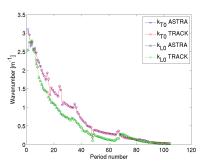
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Zero-Current design

Phase advance



Wavenumber



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The 1 W/r beam loss limit

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Zero-Current Design

Design High-Currer Design

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Zero-Current design

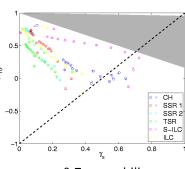
 the condition of occurence of an n-th order transverse motion parametric resonance is

$$\sigma_{T0} = \frac{n}{2}\sigma_{L0}$$

- the strongest resonance occur if for n = 1 (grey area)
- the defocusing factor γ_s is defined as

$$\gamma_s = \frac{\pi}{2} \frac{1}{(\beta \gamma)^3} \frac{L_f^2}{\lambda} \frac{e E_m sin(\phi_s)}{m_0 c^2}$$

Kapchinskiy Stability Chart



 $\gamma_s <$ 0.7 \Leftrightarrow stability

Multi-GeV Proton and H Linacs

The 1 W/n beam loss

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Zero-Curre Design

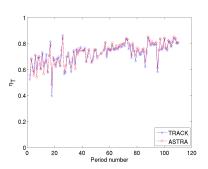
High-Current Design

Beam Losse

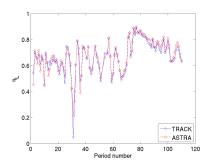
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High-Current design

Transverse Tune Depression



Longitudinal Tune Depression



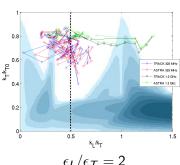
High-Current

Design

High-Current design FNAL 8-GeV Pulsed Linac

- core-core resonance
- the shadded area indicate regions where non-equipartioned beams are subject to space-charge coupling resonances that are expected to cause emittance transfer between transverse and longitudinal planes
- the vertical dash line show the condition for equipartition

Hofmann Stability Chart



$$\epsilon_L/\epsilon_T = 2$$

Multi-GeV Proton and H Linacs

The 1 W/n beam loss limit

Design Considerations

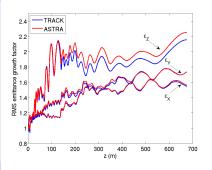
Zero-Current Design High-Current Design

Beam Losses

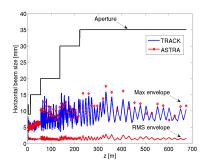
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High-Current design

RMS Emittance Growth



Max. and RMS Hor. Beam Size



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The 1 W/r beam loss limit

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Zero-Current Design High-Current Design

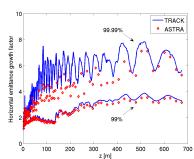
Beam Losses

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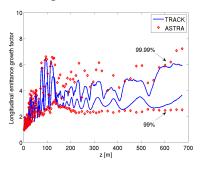
High-Current design

FNAL 8-GeV Pulsed Linac

99% & 99.99% Hor. Emittance Growth



99% & 99.99% Long. Emittance Growth



Multi-GeV Proton and H Linacs

The 1 W/n beam loss limit

Design Consideration

Zero-Current Design High-Current Design

Beam Lo

Errors and Jitters

H- Stripping Correction Algorithm

Beam Losses Errors in the FNAL 8-GeV Linac

| Beam Parameter | | Error Value | Distribution |
|-----------------------------------|--------|-------------|--------------|
| Solenoid Displacement (x and y) | [mm] | 0.5 | Uniform |
| Solenoid Rotation (x and y) | [mrad] | 2 | Uniform |
| Solenoid Field Jitter | [%] | 0.5 | Gaussian |
| Quadrupole Displacement (x and y) | [mm] | 0.5 | Uniform |
| Quadrupole Rotation (x and y) | [mrad] | 2 | Uniform |
| Qaudrupole Field Jitter | [%] | 0.5 | Gaussian |
| Cavity Displacement (x and y) | [mm] | 0.5 | Uniform |
| Cavity Rotation (x and y) | [mrad] | 2 | Uniform |
| Cavity Field Jitter | [%] | 1.0 | Gaussian |
| Cavity Phase Jitter | [%] | 1.0 | Gausssian |

Multi-GeV Proton and H Linacs

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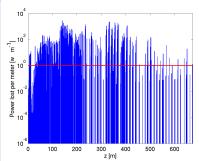
Zero-Current Design High-Current Design

Errors and

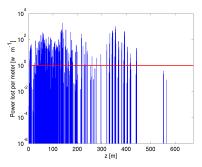
Jitters H- Stripping Correction

Beam Losses Errors FNAL 8-GeV Pulsed Linac

Loss Pattern from TRACK



Loss Pattern from ASTRA



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Multi-GeV Proton and H Linacs

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Beam Losses

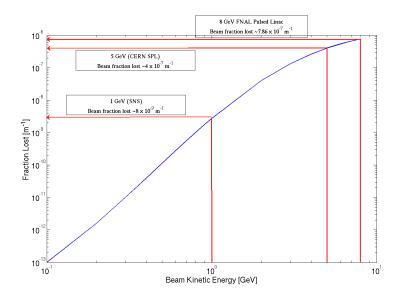
Errors and

H- Stripping

Correction

Beam Losses

Blackbody Radiation

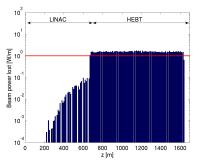


H- Stripping

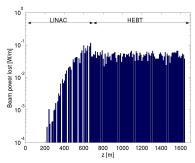
Algorithm

Blackbody Stripping FNAL 8-GeV Pulsed Linac

HEBT at 300 K



HEBT at 150 K



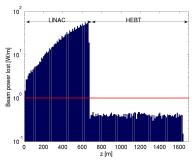
H- Stripping

Algorithm

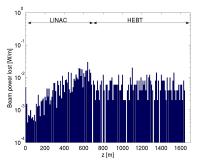
Residual Gas Stripping

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HEBT at 300 K



HEBT at 150 K



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Multi-GeV Proton and H Linacs

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Zero-Current Design High-Current Design

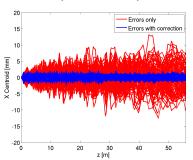
Beam Losses

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One-to-one correction algorithm

Errors + Correction FNAL 8-GeV Linac

Hor. Beam Centroid Motion (from TRACK)



Loss Pattern (from TRACK)

