Beam dynamics studies for Multi-GeV Proton and H-Minus Linacs

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Multi-GeV Proton and H- Linacs

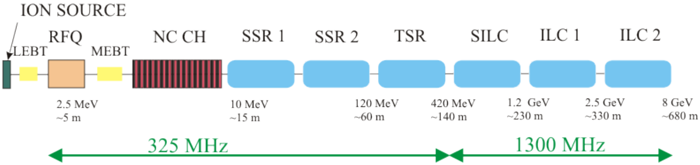
Overview

Project	E [GeV]	I_{av} [mA]	Power [MW]	Application	Status
FNAL 8-GeV Pulsed	8	25	2	neutrinos	proposed
FNAL 3-GeV CW	3	1	3	neutrinos kaons, muons	proposed
CERN HP-SPL	5	40	>4	neutrinos, RIB	proposed
ESS1 (EU)	2.5	75	5	neutrons	proposed
ORNL SNS1	1	26	1.4	neutrons	in operation
ORNL SNS2	1.3	42	3	neutrons	proposed

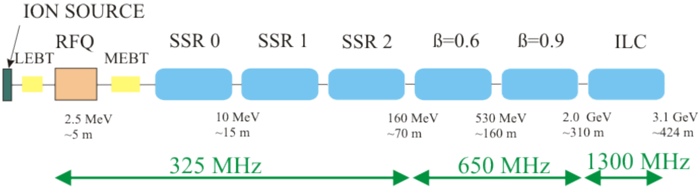
FNAL 8-GeV & 3-GeV Linacs

Layout

- FNAL 8-GeV Pulsed Linac



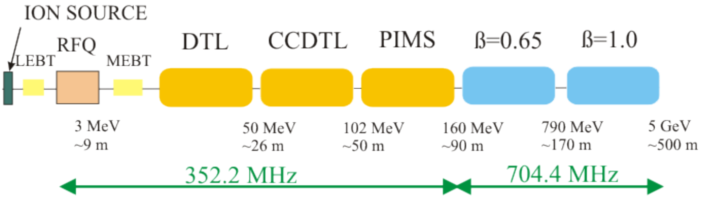
- FNAL 3-GeV CW Linac



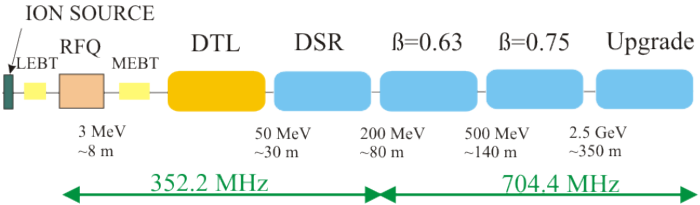
CERN SPL & ESS Linacs

Layout

- CERN SPL Linac

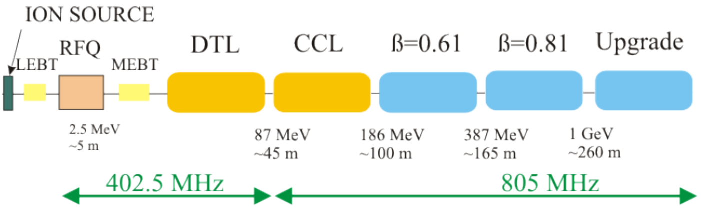


- ESS Linac



ORNL SNS Linac

Layout



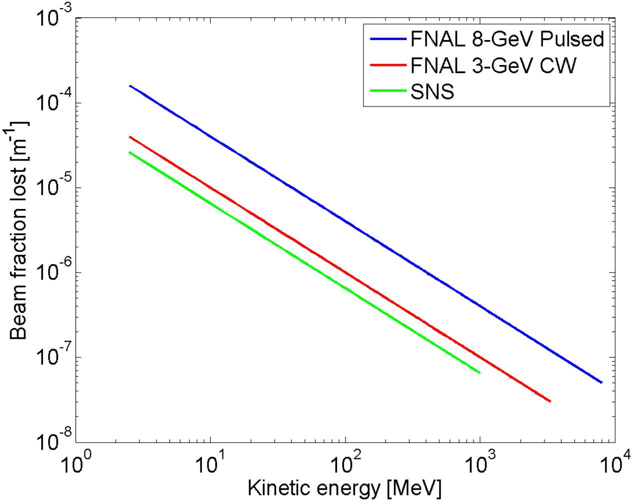
The 1W/m Beam Loss Limit

- Beam loss in accelerators lead to beamline component activation
- Maintenance Restriction (for example LANSCE, Los Alamos Guidelines)
  - Limited access time: 100 μSv/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 AND calculation results from three different codes (`LAHET` (Los Alamos), `HETC/MCNP/ORIHET` (ORNL) and `MARS` (FNAL)) lead to the basic result:

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

Permissible Beam Loss

- Permissible Beam Loss Fraction to achieve 0.1 W/m



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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_{L0} must change adiabatically along the linac to minimize the potential for mismatch and assure a current independent lattice

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

  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.

High-Current Design

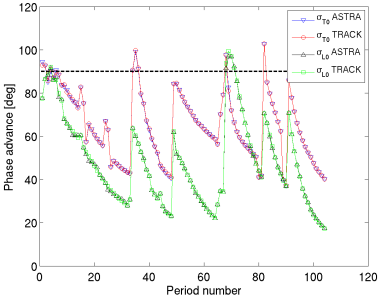
Considerations

- Avoid energy exchange between the transverse and longitudinal planes via space-charge resonances by:
  - providing beam equipartitioning
  - avoiding instable areas in Hofmann's stability charts
- Provide longitudinal-to-transverse emittance ratios close to one $(0.5 < \epsilon_l/\epsilon_t < 2)$
- Provide a tune depression $\eta = k/\ k_0 > 0.5$
- Provide proper matching in the lattice transitions to avoid appreciable halo formation
- Keep a ratio aperture-to-rms-beam-size > 10

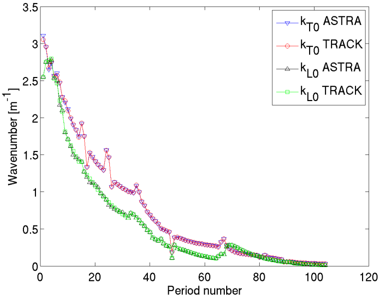
Zero-Current design

FNAL 8-GeV Pulsed Linac

Phase advance



Wavenumber



Zero-Current design

FNAL 8-GeV Pulsed Linac

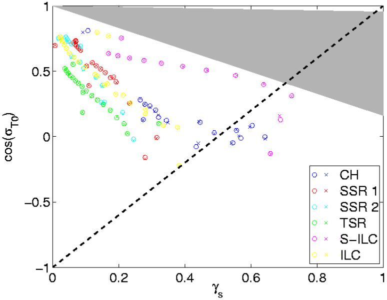
- The condition of occurence of an n-th order transverse motion parametric resonance is:

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

- The strongest resonance occurs for $n = 1$ (grey area)
- The defocusing factor γ_s is defined as:

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

Kapchinskiy Stability Chart

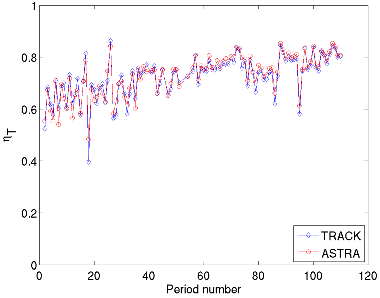


$\gamma_s < 0.7 \Leftrightarrow$ stability

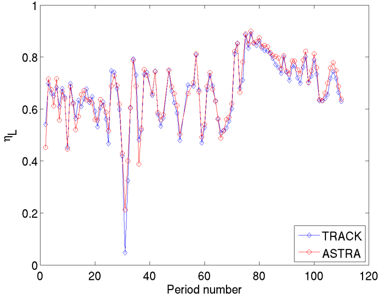
High-Current design

FNAL 8-GeV Pulsed Linac

Transverse Tune Depression



Longitudinal Tune Depression

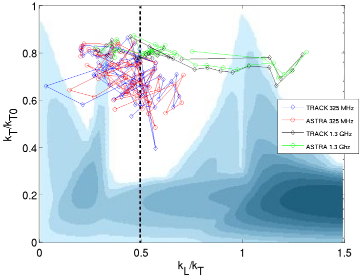


High-Current design

FNAL 8-GeV Pulsed Linac

- The shadded areas 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

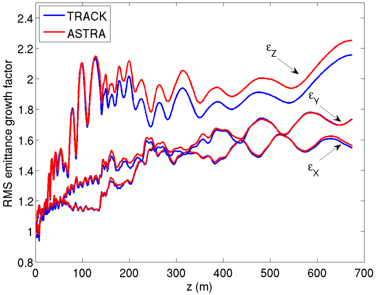


$$\epsilon_L/\epsilon_T = 2$$

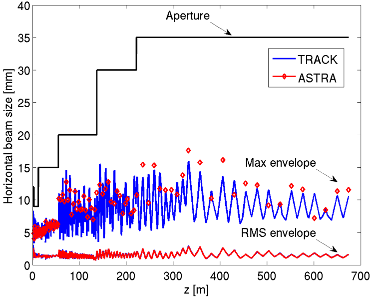
High-Current design

FNAL 8-GeV Pulsed Linac

RMS Emittance Growth



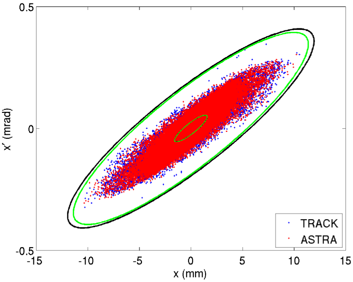
Max. and RMS Hor. Beam Size



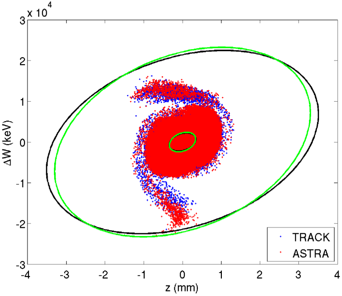
High-Current design

FNAL 8-GeV Pulsed Linac

Hor. Phase Space at $\sim$ 674 m



Long. Phase Space at $\sim$ 674 m



Beam Losses

Beam Losses

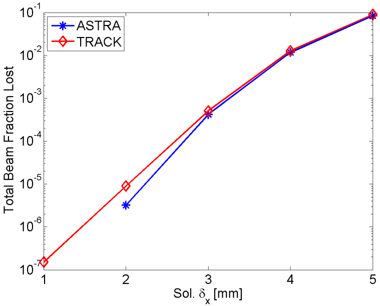
Error Generation

$$\text{Main Contributor} = \begin{cases} \text{Solenoid Trans. Rotation} & (\phi_x, \phi_y) \\ \text{Solenoid Trans. Displacement} & (\delta_x, \delta_y) \\ \text{Quadrupole Trans. Displacement} & (\delta_x, \delta_y) \\ \text{Cavity Phase \& Field Jitter} & (\delta_\phi, \delta_E) \end{cases}$$

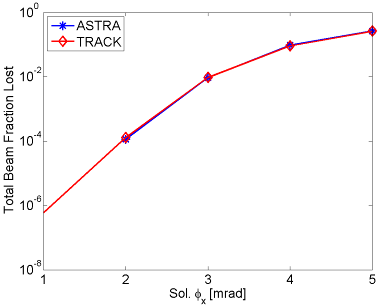
Beam Losses

Error Generation

Total beam lost at ∼138 m
Displacement Hor. Solenoids



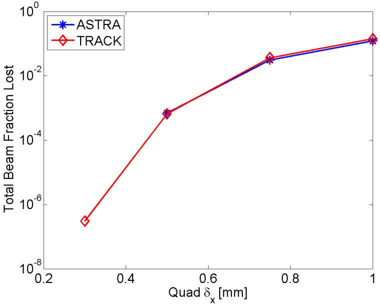
Total beam lost at ∼138 m
Rotation Hor. Solenoids



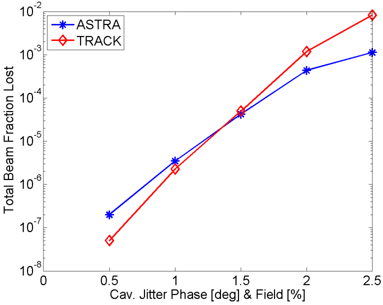
Beam Losses

Error Generation

Total beam lost at ∼138 m
Displacement Hor. Quads



Total beam lost at ∼138 m
Cavity Phase and Field Jitter



Beam Losses

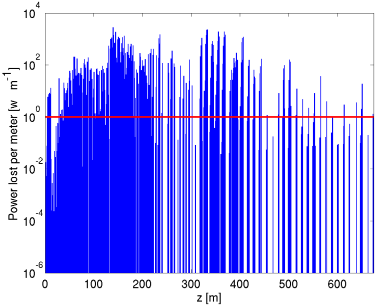
Typical errors in the FNAL 8-GeV Pulsed Linac

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

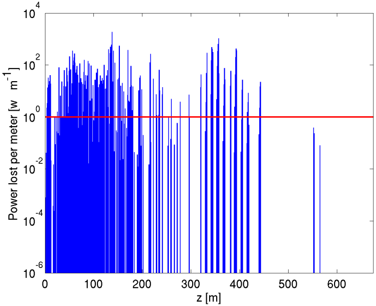
Beam Losses

Typical errors in the FNAL 8-GeV Pulsed Linac

Loss Pattern from TRACK



Loss Pattern from ASTRA



Correction algorithm in TRACK

One-to-one steering procedure

- The steering algorithm implemented in TRACK steers the beam so that to minimize the transverse displacements measured at the BPM's.
- The response function of monitors to correctors is determined for a given accelerator section

$$M = A * C + B$$

with: M the array of monitors readings, A the response function matrix, C the array of correctors strenghts and B the monitors readings for $C = 0$

Correction algorithm in TRACK

One-to-one steering procedure (cont.)

- TRACK performs a least square minimization of the equivalent function

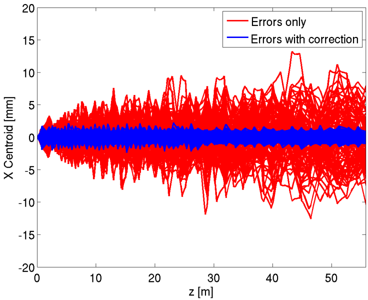
$$f(C_{i_c}, i_c = 1 : N_c) = \sum_{i_m=1}^{N_m} \frac{(A_{i_c,i_m} \times C_{i_c} + B_{i_m})^2}{\sigma^2_{res_m} + \sigma^2_{pos_m}};$$

for $C_{i_c} \leq C_{max}$, with σ_{res} the resolution of the monitors and σ_{pos} the error in the position of the monitors.

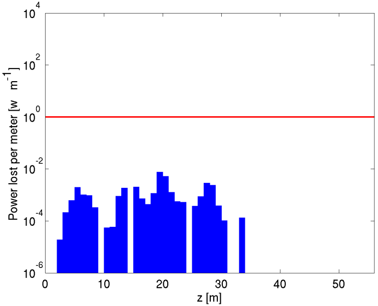
One-to-one correction algorithm

Errors + Correction FNAL 8-GeV Linac

Hor. Beam Centroid Motion (from TRACK)



Loss Pattern (from TRACK)



H^- Stripping

Blackbody Radiation

- The spectral density S of thermal photons per unit volume emitted by a beam pipe at a temperature T is given by the Planck formula:

$$S(\omega; T)d\omega = \frac{\hbar}{\pi^2 c^3} \frac{\omega^3}{\exp(\hbar\omega/kT - 1)} d\omega$$

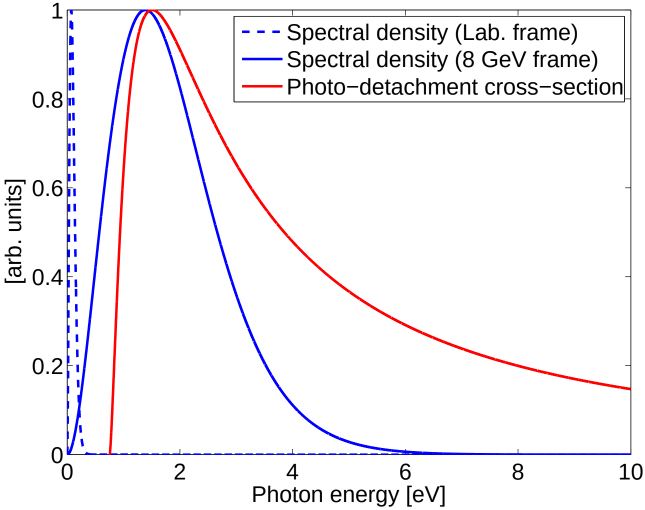
- Photodetachement of H^- ions by thermal photons given by:

$$\sigma(E) = 8\sigma_{max} \frac{E_0^{3/2}(E - E_0)^{3/2}}{E^3}$$

where $E = \hbar\omega$ is the photon energy, $\sigma_{max} = 4.2 \times 10^{-21}$ m^2 and $E_0 = 0.7543$ eV, the lowest electron binding energy for H^-.

H^- Stripping

Blackbody Radiation



H^- Stripping
Blackbody Radiation

- Beam fraction lost due to blackbody radiation is defined by[1]:

$$\frac{1}{L} = \int_0^\infty d\epsilon \int_0^\pi d\alpha \frac{d^3 r}{d\epsilon d\alpha dl}$$

where $\epsilon = E/E_0$ and α is the angle between the thermal photon and the H^- beam.

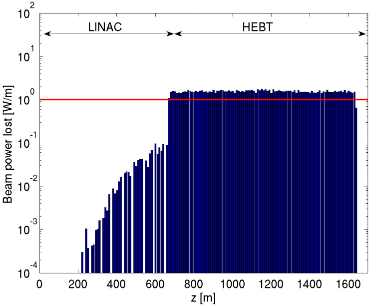
$$\text{Beam fraction lost } [m^{-1}] = \begin{cases} 300\text{ K, 8 GeV} & \Leftrightarrow & \sim 7.8 \times 10^{-7} \\ 300\text{ K, 5 GeV} & \Leftrightarrow & \sim 4.0 \times 10^{-7} \\ 300\text{ K, 1 GeV} & \Leftrightarrow & \sim 5.0 \times 10^{-9} \\ 150\text{ K, 8 GeV} & \Leftrightarrow & \sim 2.5 \times 10^{-8} \end{cases}$$

[1] H.C. Bryant and G.H. Herling, Journal of Modern Optics (2006)

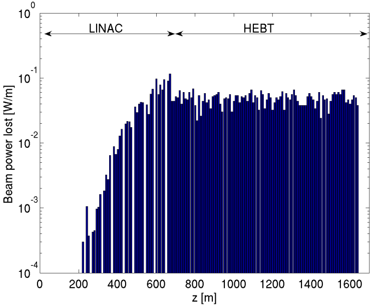
H^- Stripping

Blackbody Radiation

HEBT at 300 K



HEBT at 150 K



H^- Stripping

Residual Gas

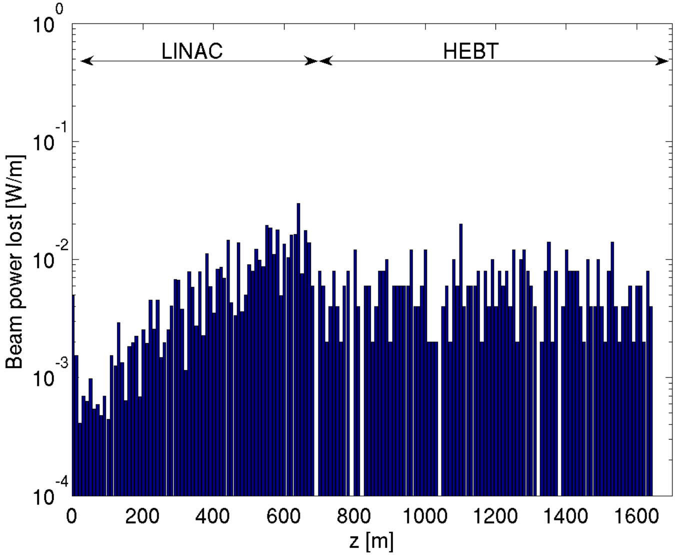
- H^- beam can be stripped by interaction with the residual gas in the beampipe
- Residual gas stripping has been implemented into `TRACK`
- `TRACK` allows the user to set the temperature, pressure and composition of the residual gas (H_2 & He & N_2 & O_2 & Ar & Xe & H_2O & CO_2 & CO)

Simulations for the FNAL 8-GeV linac and HEBT

- 1×10^{-7} torr in RT sections, 1×10^{-10} torr in cryomodules and 5×10^{-9} torr in HEBT
- Warm sections: 70% H_2, 10% H_2O, 10% CO_2 and 10% CO at 300 K
- SC sections: 100% H_2 at 2.1 K

H^- Stripping

Residual Gas Stripping at the FNAL 8-GeV Linac + HEBT



H^- Stripping

Magnetic field

- Magnetic field stripping has been implemented into `TRACK`
- SNS HEBT: $\sim$ 2088 G at 1 GeV $\Leftrightarrow \sim 1.4 \times 10^{-13}$ m^{-1}
- FNAL HEBT: $\sim$ 480 G at 8 GeV $\Leftrightarrow \sim 1.25 \times 10^{-10}$ m^{-1}

Summary

- General design considerations for high-intensity proton drivers have been discussed and the overall picture for the FNAL 8-GeV linac looks fine

<u>BUT</u>

Summary

- General design considerations for high-intensity proton drivers have been discussed and the overall picture for the FNAL 8-GeV linac looks fine

BUT

- We should try to simulate (with `TRACK`, `ASTRA`, `TRACEWIN`, `IMPACT`, `PARMILA`, etc...) the experimental observations made at SNS (loss pattern, contributor to the beam losses)

Thank you for your attention