Characterizing and Controlling Beam Losses at the LANSCE Facility

Presented at HB2012, September 17-21, 2012

Beijing, China

Lawrence Rybarcyk, AOT-ABS

Los Alamos National Laboratory

Abstract

The Los Alamos Neutron Science Center (LANSCE) currently provides 100-MeV H^+ and 800-MeV H^- beams to several user facilities that have distinct beam requirements, e.g. intensity, micropulse pattern, duty factor, etc. Minimizing beam loss is critical to achieving good performance and reliable operation, but can be challenging in the context of simultaneous multi-beam delivery. This presentation will discuss various aspects related to the observation, characterization and minimization of beam loss associated with normal production beam operations in the linac

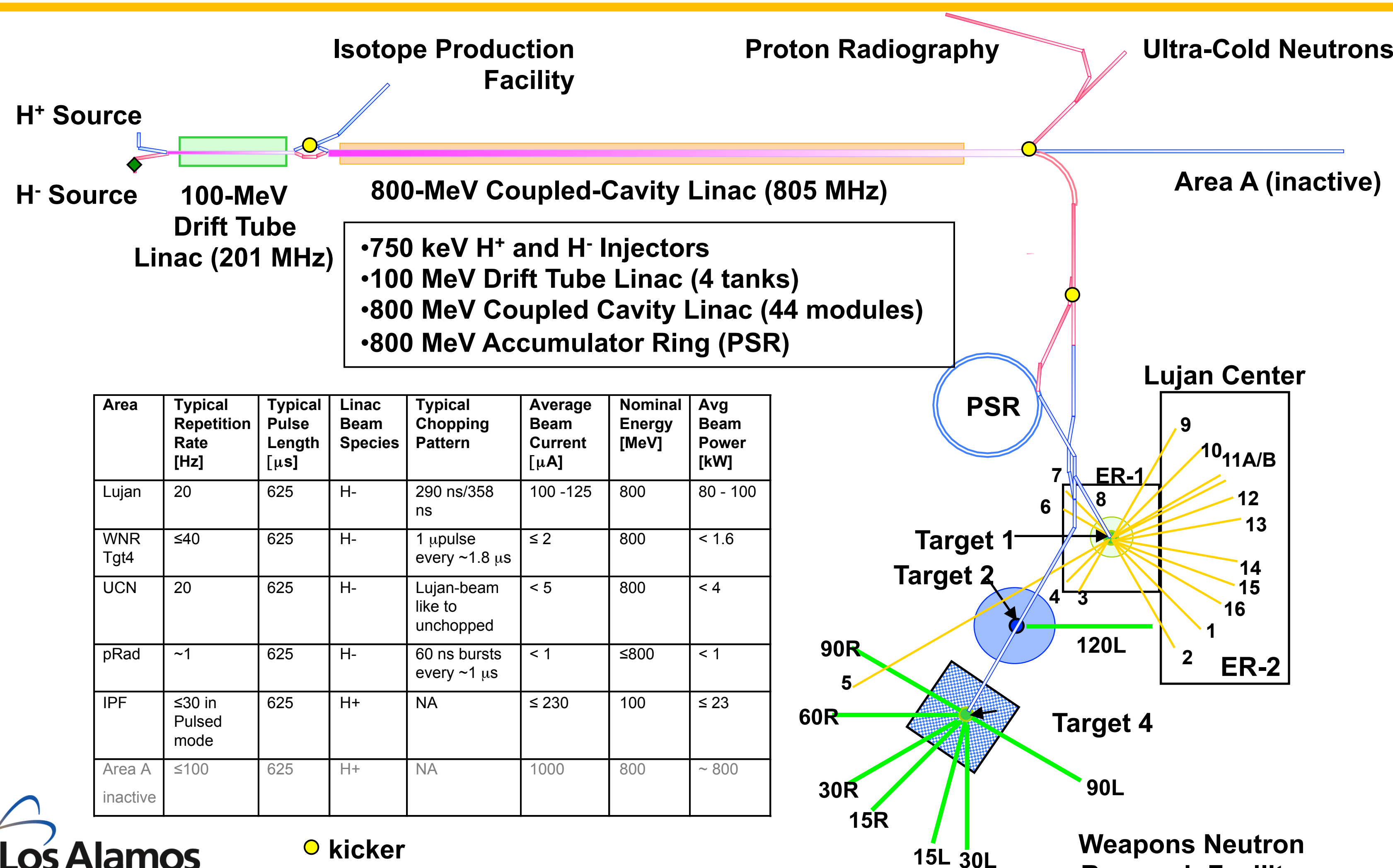
Outline

- **LANSCE facility overview**
  - Layout
  - Operating parameters
- **Beam loss observations, characterization**
  - Measurement devices
  - Observations, modeling and simulations of H^+ and H^- along linac
- **Loss Control**
  - Operational settings
  - Virtual diagnostic

Los Alamos Neutron Science Center

- **LANSCE is a multi-user, multi-beam facility that produces intense sources of pulsed, spallation neutrons and proton beams in support of national security and civilian research.**
- **LANSCE is comprised of a high-power 800 MeV proton linear accelerator (linac) and a proton storage ring and has been in operation for over 37 years.**
  - Formerly known as LAMPF, designed to provided 800 kW beam for meson physics program
- **The LANSCE Experimental User Facilities includes**
  - The Manuel Lujan Jr. Neutron Scattering Center (Lujan Center), which uses an intense time-compressed proton bunch from the proton storage ring (PSR) to create a short pulse of moderated neutrons (meV to keV range)
  - The Proton Radiography (pRad) Facility, which provides time-sequenced radiographs of dynamic phenomena with billionths-of-a-second time resolution
  - The Weapons Neutron Research (WNR) Facility that provides a source of unmoderated neutrons in the keV to multiple MeV range
  - The Isotope Production Facility (IPF) is a source of research and medical radioisotopes for the US
  - The Ultra Cold Neutrons (UCN) which is a source of sub-μeV neutrons for fundamental physics research

Present Day LANSCE Facility Overview

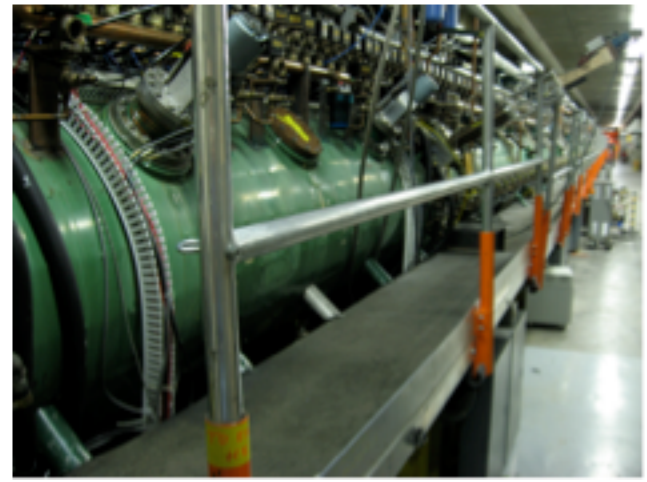


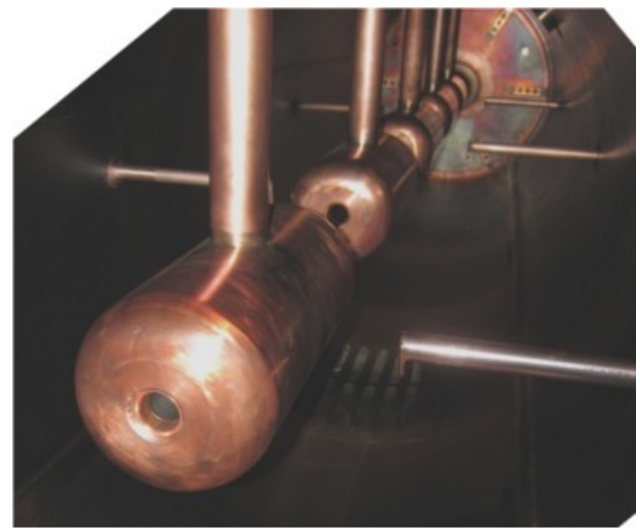
- •750 keV H^+ and H^- Injectors
- •100 MeV Drift Tube Linac (4 tanks)
- •800 MeV Coupled Cavity Linac (44 modules)
- •800 MeV Accumulator Ring (PSR)

Area	Typical Repetition Rate [Hz]	Typical Pulse Length [µs]	Linac Beam Species	Typical Chopping Pattern	Average Beam Current [µA]	Nominal Energy [MeV]	Avg Beam Power [kW]
Lujan	20	625	H-	290 ns/358 ns	100 -125	800	80 - 100
WNR Tgt4	≤40	625	H-	1 µpulse every ~1.8 µs	≤ 2	800	< 1.6
UCN	20	625	H-	Lujan-beam like to unchopped	< 5	800	< 4
pRad	~1	625	H-	60 ns bursts every ~1 µs	< 1	≤800	< 1
IPF	≤30 in Pulsed mode	625	H+	NA	≤ 230	100	≤ 23
Area A inactive	≤100	625	H+	NA	1000	800	~ 800

LANSCE 100 MeV Drift Tube Linac (DTL)

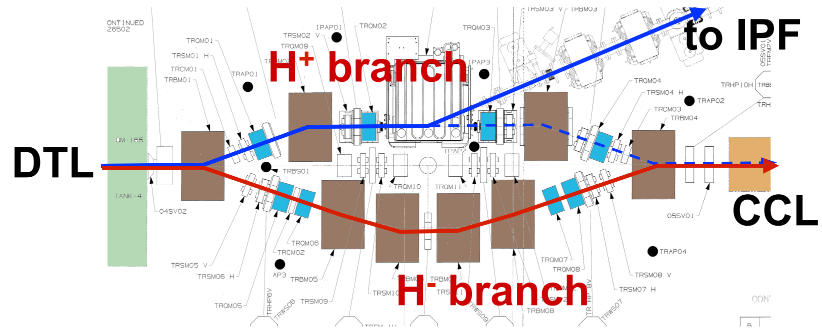
- **Design**
  - Alvarez type
  - 4 Tanks – Total Length: 61.7 m
  - 0.75 to 100 MeV
  - Frequency: 201.25 MHz
  - DT bore radii: 0.75 to 1.5 cm
  - Design phase: -26 degree
  - E0:
    - T1: ramped 1.6 to 2.3 MV/m
    - T2-4: 2.4 MV/m
  - Quad lattice
    - T1-2: Singlet FODO
    - T3-4: Singlet FODO (every other drift tube)



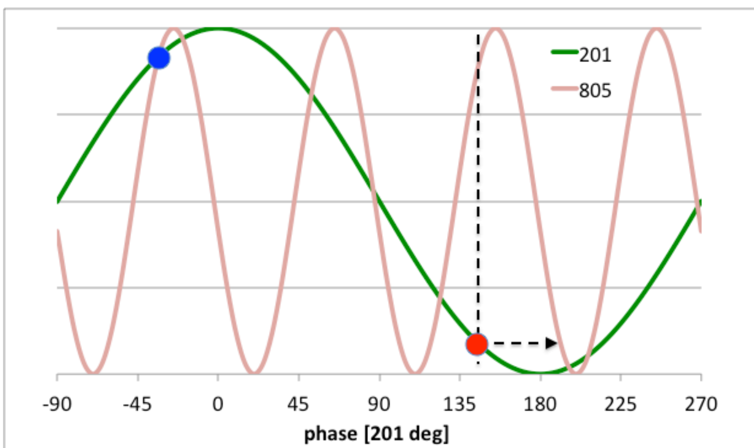


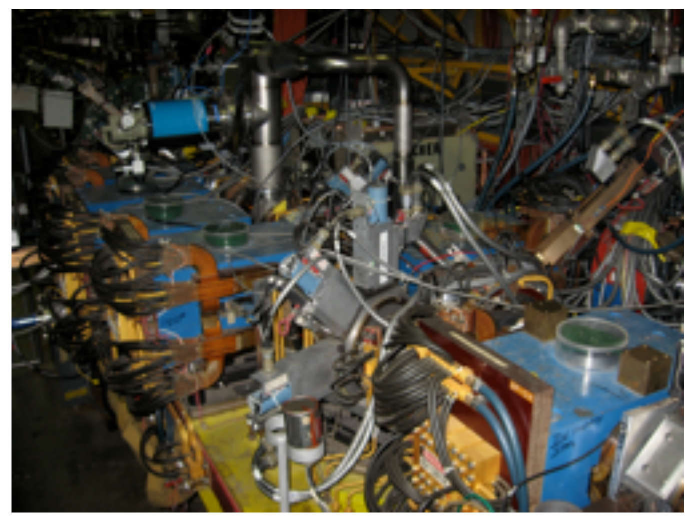
100 MeV Beam Transport (Transition Region - TR)

- **Purpose**
  - Independently match, steer and phase H^+ and H^- beams into CCL
  - Extraction point for 100 MeV IPF(H^+) beam
  - Independent phasing necessary for dual species operation with frequency jump from 201 to 805 MHz



Top View of 100 MEV TR transport

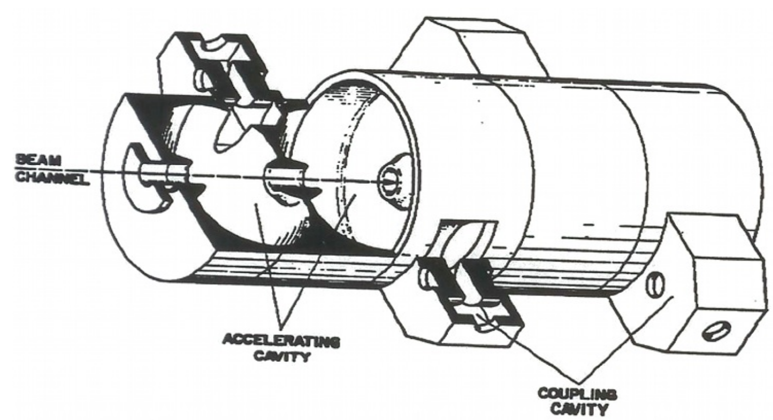




LANSCE 800 MeV Coupled Cavity Linac (CCL)

- **Design**
  - Side coupled structures
  - 44 Modules – Length: 727 m
    - M5-12: 4 tanks per module
    - M13-48: 2 tanks per module
  - 100 – 800 MeV (or lower)
  - Frequency: 805 MHz
  - Bore Radii: 1.59 to 1.91 cm
  - E0T: ≈1.4 – 1.2 MV/m
  - Design phase: -36 to -30 deg
  - Quad lattice (2” dia.)
    - M5-12 FDO, 4 doublets per module (gradient profile: ramped)
    - M13-48: FDO, 2 doublets per module (gradient profile: constant)


View of CCL near upstream end

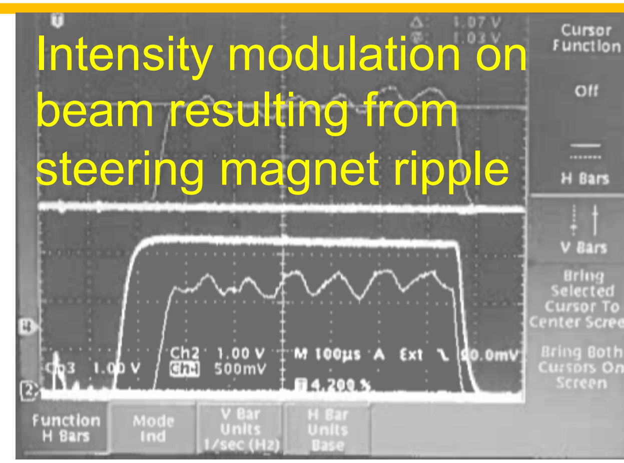


Presentation will Focus on Lujan Center (SPSS) Beam

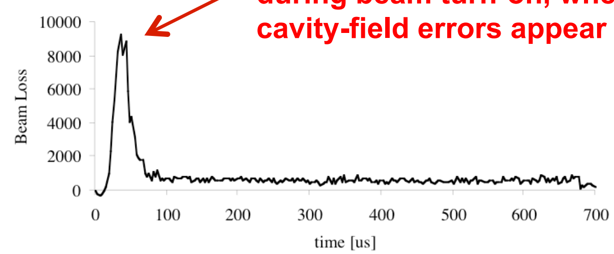
- **Highest power beam (H^-) currently in operation at LANSCE**
- **Data shown are representative of typical high-power operation**
  - For comparison include: H^+ (800 kW and IPF) and H^- WNR beam data
- **LANSCE does not employ dedicated collimators in the LINAC or PSR**
  - Collimation used in 750-keV LEBT to
    - Minimize likelihood of beam damage on buncher cavities and slow-wave chopper structure
    - Fixed and adjustable chopping apertures
    - Reduce peak beam intensity, trim distribution, when needed
- **LANSCE does not employ steering magnets in DTL or CCL**
  - Steering performed in separated and common LEBT's and 100 MeV transports
  - Rely on reasonable alignment of structures, elements

Beam Loss Measurement Devices at LANSCE

- **Beam Current Monitors (Hardware Transmission Monitor System)**
  - Large to moderate losses between devices
  - Time structure
  - Resolution to 0.1 µA for 1000 µA beam
- **Scintillator & PMT (everywhere)**
  - Small losses
  - Time structure
- **Ion Chambers (HE beamlines & PSR)**
  - Small to large loss
  - Slow response time
  - Don’t sag/saturate like PMT
  - Appropriate for high intensity/short pulses bunches in PSR



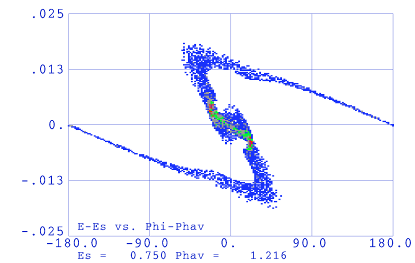
Additional linac spill produced during beam turn-on, when cavity-field errors appear



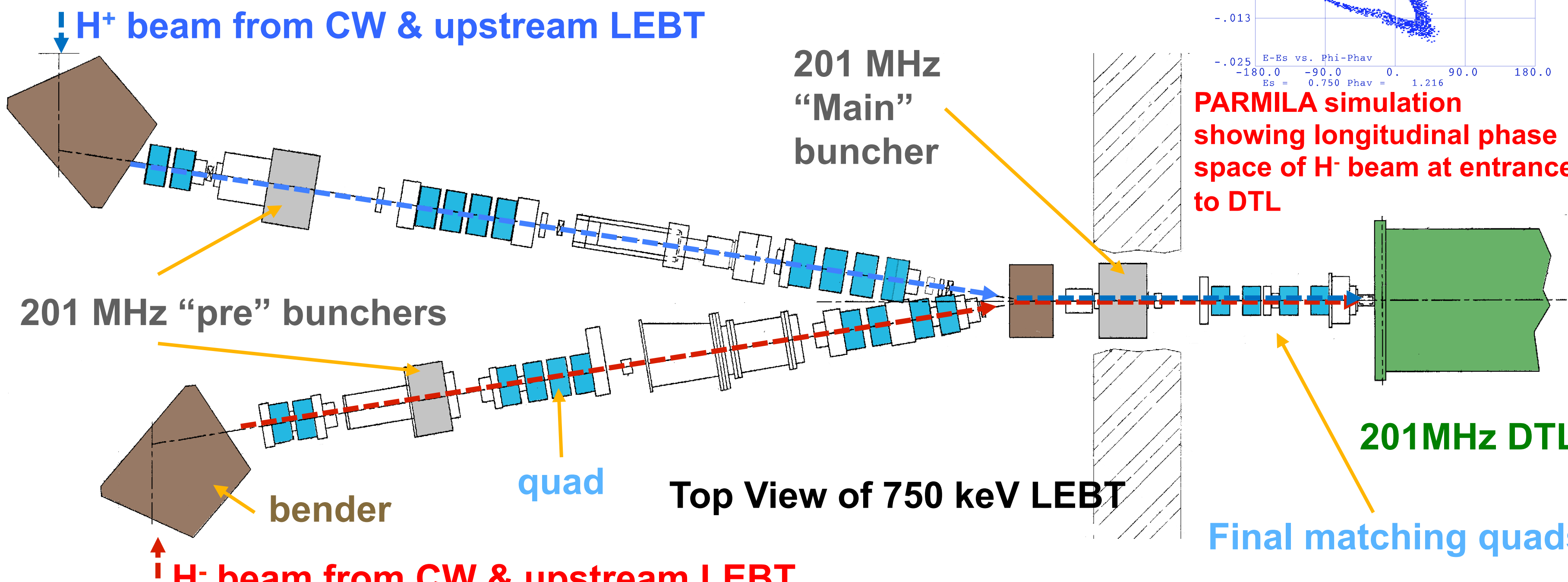
Summed CCL LM signal for high peak H^+ beam

Beam Formation Plays Key Role in Linac Beam Losses

- **Both H^+ and H^- species utilize dual-buncher scheme for transforming DC into partially bunched beam**
- **Incomplete bunch has significant longitudinal tails!**



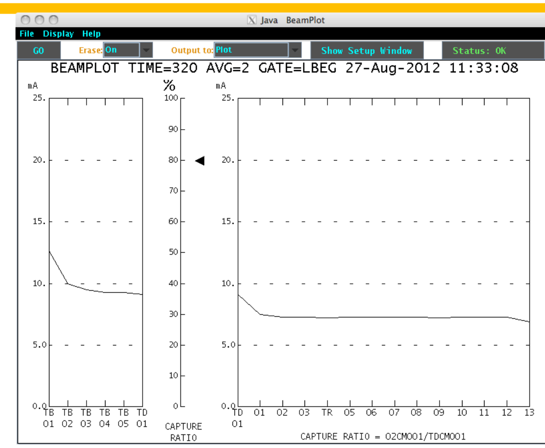
PARMILA simulation showing longitudinal phase space of H^- beam at entrance to DTL



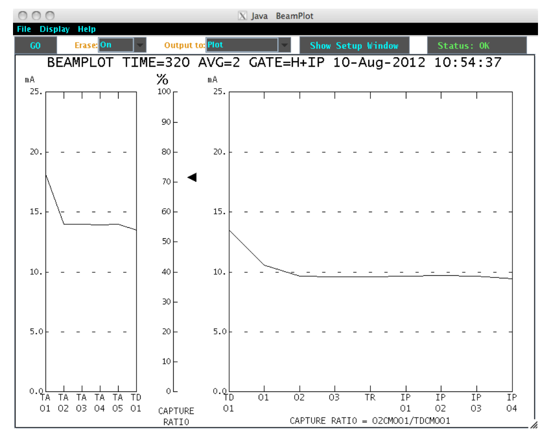
Top View of 750 keV LEBT

DTL Beam Losses Dominated by Capture Issue

- **Typically 18-20% of injected beam is lost in Tank 1(2)**
  - Incomplete capture of partially bunched beam
  - Power deposited at low beam energy (few 10's W for the Lujan beam)
- **Some radio-activation in DTL Tanks 3 & 4 indicate small amount (~<0.2%) of higher energy beam loss**
  - Transition in FODO lattice
- **Larger capture losses sustained during simultaneous H^+/H^- operation**
  - Compromise setting for common buncher
  - Higher capture (approx. 30 to 40%) for few μA H^- (WNR high-charged micropulse) at the expense of 230 μA H^+(IPF)



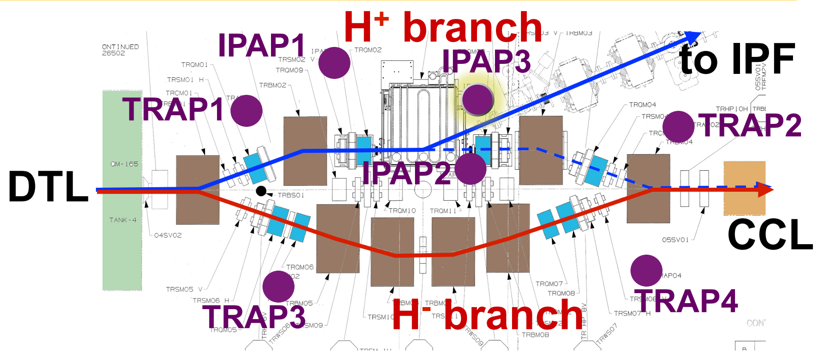
Current Monitors along H^- LEBT, DTL and portion of CCL showing capture losses in DTL



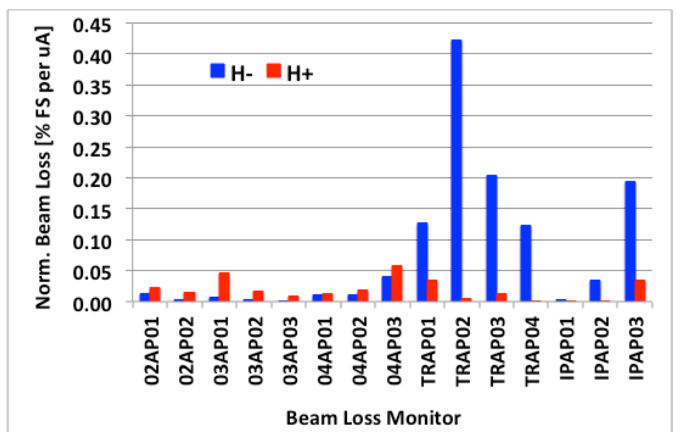
Current Monitors along H^+ LEBT, DTL and IPF beam transports showing capture losses in DTL

TR Beam Losses Reveal Differences

- **Beam loss sources**
  - Low energy tails
  - Transverse tails lost in matching from DTL FODO to CCL FDO lattices
- **Comparison of Normalized H^+ and H^- Beam Spill Monitor Signals**
  - TR losses significantly different
    - H^+ spill near two major bends
    - H^- spill is LARGER and everywhere
  - Spill in IPF beamline (IPAP3) during H^- beam pulse can only come from stripped H^- !
    - Specific mechanisms and source?
    - Magnitude: <0.2% from Mods 3-12 loss



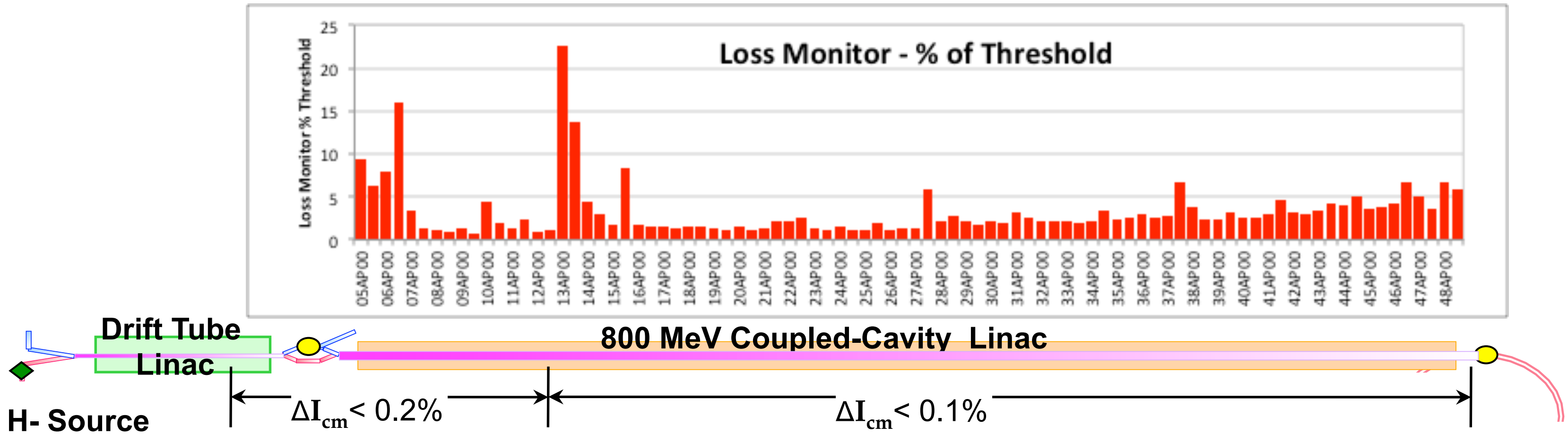
Top view of 100 MeV TR Transport



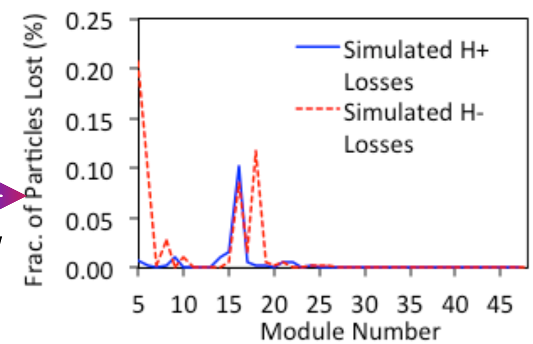
Comparison of H^+ and H^- beam loss normalized to current in the vicinity of the TR.

Typical CCL Beam Loss Profile has Distinct Features

Typical H^- Lujan beam operation, I_{avg}=110 μA, I_{pk}=10 mA, DF=1.25%, chopping pattern=290ns/358ns



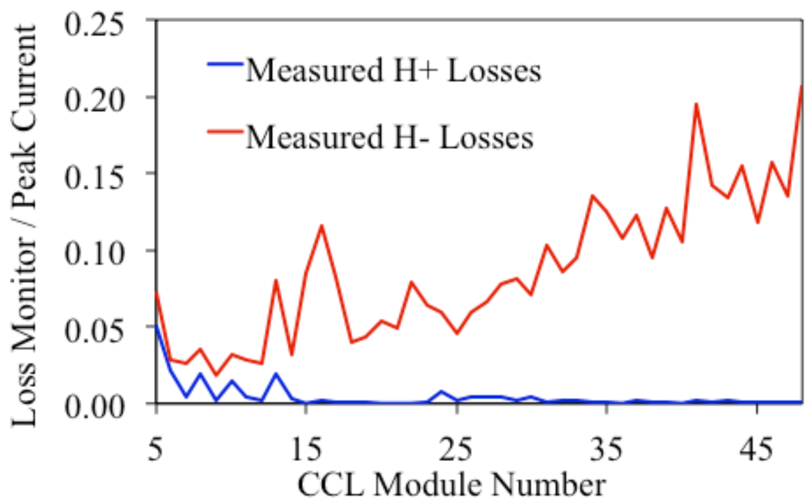
- **Both H^+ and H^- beams spill at transitions in the lattice**
  - Transverse mismatch at entrance to CCL
  - Off-energy beam spills nears Module 13-14 where quad FDO period doubles
  - Qualitatively reproduced with multiparticle simulations[1]
  - Fractional losses ~<0.2%, assuming ≈100 MeV -> ≈10's W



[1] F. Merrill and L. Rybarcyk, "Beam Dynamics Simulations of the LANSCE Linac," proceedings of Linac98, pp. 839-841.

However, One Feature Not Present for Both Beams

- **Comparison of measurements made with both 800 MeV H^+ and H^- beams revealed dramatically different loss profile**[2]
  - Increasing loss signature for high intensity H^-, not seen with H^+
  - Significantly higher loss per mA_p for H^- than for H^+
- **H^- stripping responsible for slowly increasing Loss Monitor signal along CCL**
  - Residual gas?
  - Intra-beam?
  - Lorentz field?



Measured H^+ and H^- beam loss profiles along CCL during typical high power beam operation.

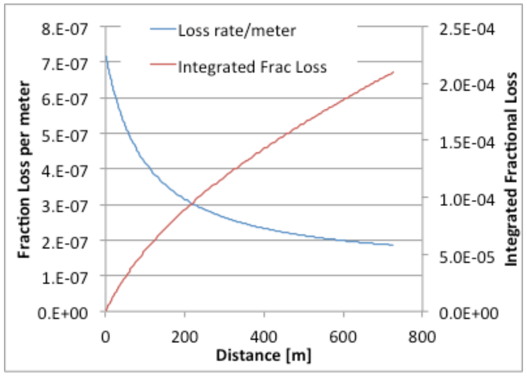
Beam	H^+	H^-
I_{peak} [mA]	16.5	9.5
I_{avg} [μA]	1000	76

[2] ibid.

Residual Gas and Intra-beam Stripping Important Contributors to H^- Beam Loss in CCL

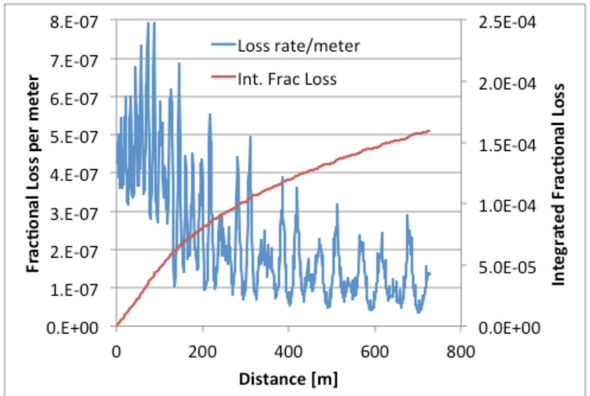
- **Residual Gas (RG) stripping**
  - Loss of one or both electrons
  - Fractional loss proportional to
    - Cross-section[3], which scales as $1/\beta^2$
    - Residual gas density
  - Assume constant pressure along linac (~$1x10^{-7}$ T)
    - Limited measurements
    - RGA: H_2, H_2O, N_2/CO

Integrated Fraction Loss ~$2.1x10^{-4}$



- **Intra-beam (IB) stripping**
  - Loss of electron from binary collisions between H^- ions within the same bunch
  - Utilize work of V. Lebedev *et al*.[4] for estimating fractional loss rate
    - Fraction loss rate proportional to bunch density
    - Beam envelope model and profile measurements used for estimating beam size/divergence along linac

Integrated Fraction Loss ~$1.6x10^{-4}$



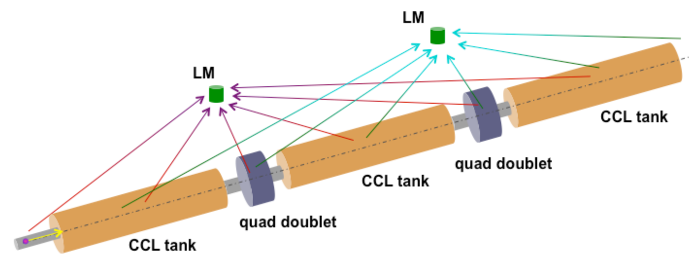
Lorentz stripping is a relativistic and quantum mechanical effect that can be ignored at these low energies – Int.Frac.Loss<10^{-8}

[3] G. Gillespie, Phys. Rev. A 15 (1977) 563, Phys. Rev. A 16 (1977) 943.

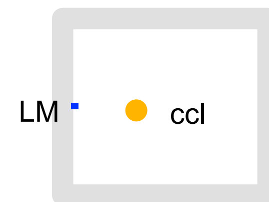
[4] V. Lebedev *et al*., "Intrabeam Stripping in H- Linacs," Proceedings of the LINAC2010, pp. 929-931.

Radiation Transport Model Critical to Characterizing Stripped Beam Losses

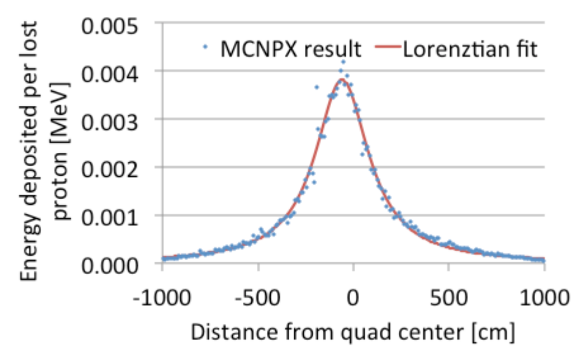
- **MCNPX[5] code used to estimate energy deposited in each LM versus location & energy of lost proton**
  - CCL represented as a copper cylinder with radius chosen to conserve copper mass per unit length
  - Concrete walls included (30 cm adequate for scattered contribution)
  - Proton started on axis at design energy for z location
  - For each detector, a distribution of charged-particle energy deposited vs. location of lost proton along linac was generated
- **MCNPX results fitted with 3 parameter Lorentzian line-shape**
- **Lorentzian folded with previously estimated fractional loss distributions within ±20m of each LM to produce loss-profiles, i.e. LM signal vs. location**



LM's wrt CCL in tunnel



MCNPX representation of CCL in tunnel

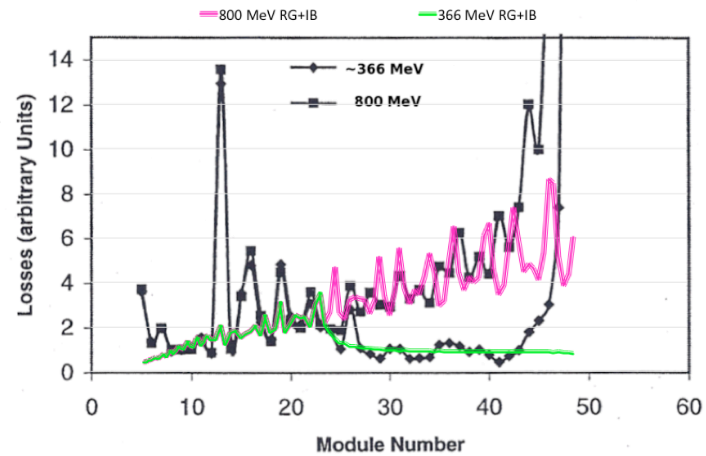


MCNPX results including fit for one LM

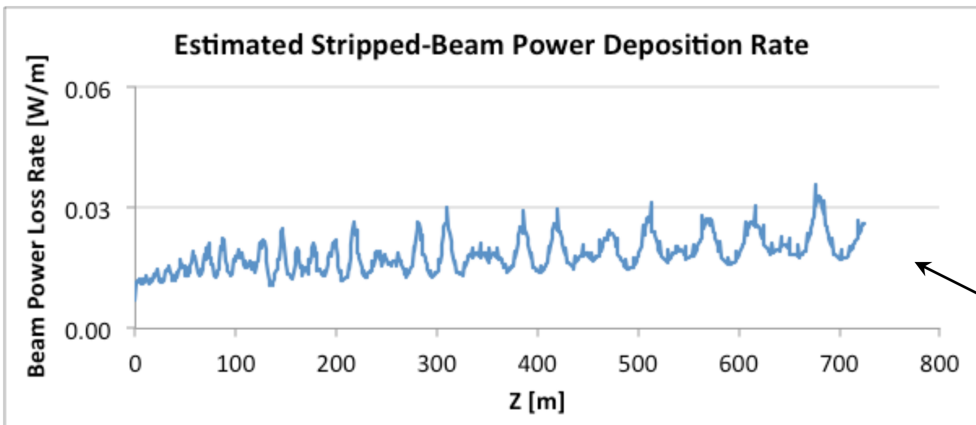
[5] D. B. Pelowitz, editor, "MCNPX User's Manual Version 2.6.0," Manual LA-CP-07-1473, Los Alamos National Laboratory, April 2008.

Loss Profiles for Different Final-Energy Beams Reveal Contributions from RG & IB Stripping

- **RG & IB loss rates similar for 800 MeV**
- **RG & IB stripping rates diverge immediately following last accelerating module for 366 MeV**
  - RG rate remains constant for fixed energy
  - IB rate drops rapidly as bunch length increases



Comparison of measured and simulated beam loss profiles for 366 and 800 MeV H^- beam. [6] **Relative contribution: IB≈75%, RG≈25%**



Estimated beam power deposition from stripping losses along CCL for 100 µA, 800 MeV H^- beam.

Few 10's mW/m of stripped beam power loss in CCL

[6] L. Rybarcyk *et al.*, "H- Beam Loss and Evidence for Intrabeam Stripping in the LANSCE Linac," proceedings of IPAC2012, pp. 3892-3895.

High Energy H^+ Seen Originating from H^- Beam

- **Experiment performed[7] where sensitive image plate detector introduced into post-linac 800-MeV H^+ chicane**
- **115 µA H^- accelerated through linac**
- **Two loss-fraction measurements**
  - CCL only contribution
  - 750 keV LEBT to end of CCL
    - But LEBT vacuum ~10x worse than normal
- **Under normal vacuum conditions loss fraction expected to be about 0.4×10^{-6}**

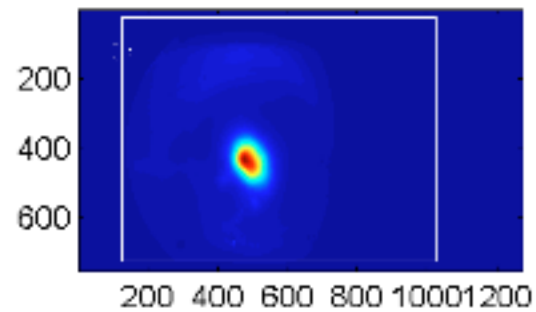


Image plate exposed to CCL-only source of high-energy H^+. Color indicates intensity.

Meas. results	CCL-only	All
Fraction of H- beam stripped	0.38×10^{-6}	9.2×10^{-6}
Likely source	RG & IB	RG, RG & IB

[7] R. McCrady *et al.*, "Stripping of H- Beams by Residual Gas in the LINAC at the Los Alamos Neutron Science Center," proceedings of LINAC2010, pp. 908-910.

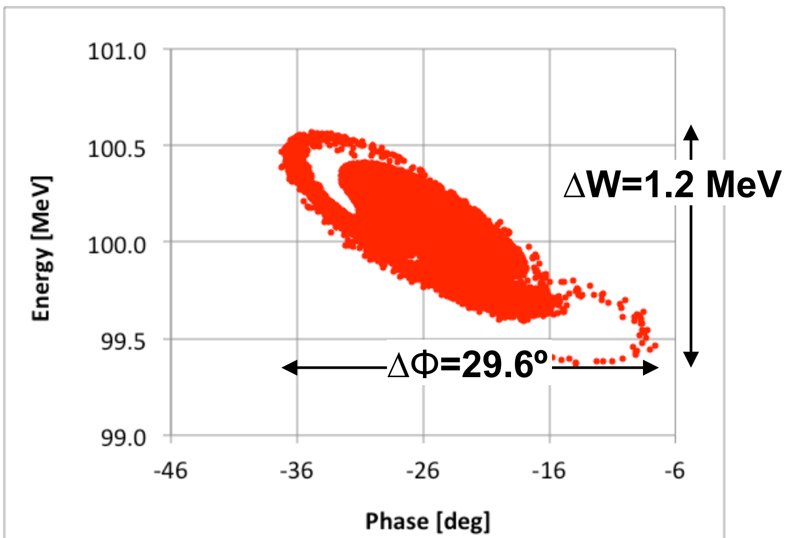
LINAC Beam Quality (Losses) Controlled Primarily through DTL RF Field Settings

- **During LAMPF era, it was recognized that operating the DTL at design settings would not result in low-loss, high power beam operation**
- **Operators found it necessary to undo the DTL "physics design" tune to achieve acceptable, low-loss operating conditions**
- **Subsequent analysis with the multiparticle beam dynamics model (PARMILA) of DTL phase scan data from low-loss operations showed markedly lower DTL cavity fields**
  - Approx. cavity field amplitudes wrt design: T1=98%, T2=96%, T3=94%, T4=98%
  - Tune-up procedure modified to incorporate more realistic cavity amplitudes
- **"Unacceptable" losses driven by desire to preserve low activation levels along CCL (< few mR/hr everywhere except few hot spots < 100 mR/hr) and allow for easy access and hands on maintenance**
- **Transverse lattice operated at design values, except for last few quads in T4, which aid downstream match**

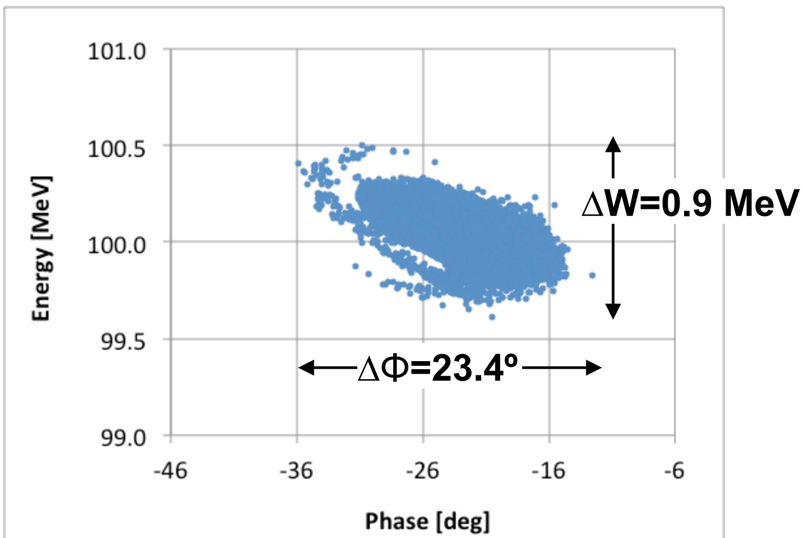
Simulations Provide Insight into the Reasons Why Lower DTL Amplitudes are Better

- **PARMILA simulations indicate lowering DTL tank amplitudes results in better 100 MeV beam**
  - Smaller longitudinal core: rms emittance reduced by 23%
  - Tighter buncher, smaller tails: ΔW reduced by 25%, ΔΦ reduced by 21%
  - Slight reduction (4%) in low energy (< 99 MeV) particles
  - Minimal increase in capture/transmission

DTL @ Design Cavity Amplitudes



DTL @ Production-like Cavity Amplitudes



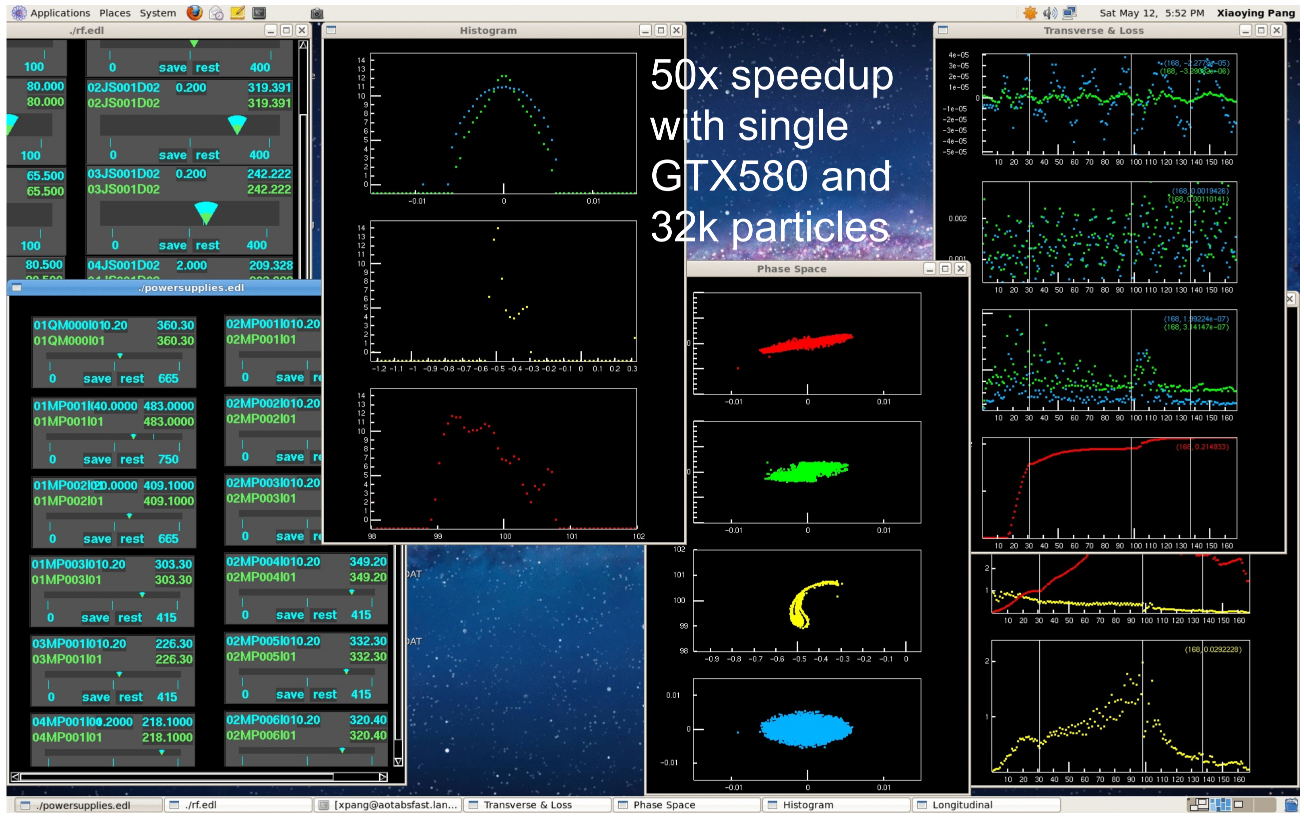
Simulated H^- longitudinal phase space at entrance to CCL

Better Control of Losses Requires Deeper Understanding of Beam Evolution in LINAC

- **Present day situation**
  - Limited beam diagnostics – tuning based mostly on spill
  - Injected beam not fully bunched – envelope model insufficient
  - Gap between “Physics” tune and Production operations bridged by poorly understood changes to machine parameters
- **Possible paths toward improvement**
  - Add more diagnostics – always helpful but expensive; may be incompatible with high current beam, provide limited information, etc.
  - Offline analysis with multiparticle beam dynamics simulations – helpful but limited due to slow response time
  - Online analysis with multiparticle beam dynamics simulations (includes space charge and emittance growth)
    - Employ GPU’s for speed (~$1k/card; can be 20-100 times faster than CPU alone)
    - Tie model to actual machine parameters for realistic online simulation
    - ***A virtual beam diagnostic***

High Performance Simulator will Provide Insight into Impact of Operational Changes on Beam

- **Multi-particle simulator running continuously on GPU provides rapid(secs) updates**
- **EPICS connection allows simulation to track machine parameter changes on the fly**
- **Currently under development[8]**



Screen image of High Performance Simulator generated beam profiles and phase-space distributions(center) at end of DTL. Also shown are EPICS DTL RF and magnet controls (left) and beam centroid, size, loss and emittance profiles (right).

[8] X. Pang *et al.*, “High-performance Beam Simulator for the LANSCE Linac,” proceedings of IPAC2012, pp. 103-105.

Summary

- **LANSCE provides pulsed proton and neutron beams to several user facilities whose missions include defense applications, isotope production and research in basic and applied science.**
- **Beam losses along the linac arise from a number of sources.**
  - DTL capture losses arise from injection of an incomplete bunch.
  - Losses are observed near all transitions in the quadrupole lattice of the linac.
  - H^- stripping losses are observed in the TR, CCL and SY areas.
- **Most significant reduction in beam losses resulted from operating the DTL cavity fields away from the design values.**
- **A virtual beam diagnostic in the form of a pseudo real time, high-performance tracking simulator could prove invaluable in understanding and controlling beam losses in high power linacs.**

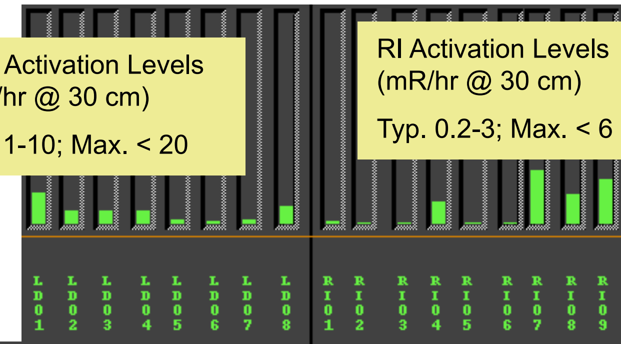
THANK YOU

Thanks to the AOT and LANL staff, who contributed to this work, especially Frank Merrill, Charles Kelsey IV, Rodney McCrady, Xiaoying Pang and Scott Bailey.

Supplemental Slides

Lujan Beam Losses and Residual Activation – 800 MeV

- Line-D, PSR and 1L loss monitors - N_2-filled ion chambers

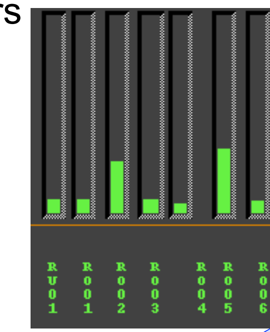


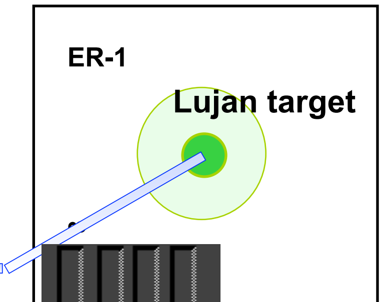
LDN Activation Levels (mR/hr @ 30 cm)

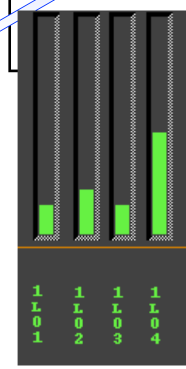
Typ. 1-10; Max. < 20

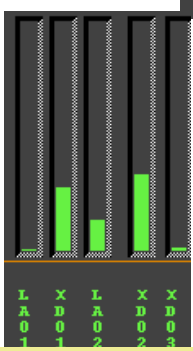
RI Activation Levels (mR/hr @ 30 cm)

Typ. 0.2-3; Max. < 6



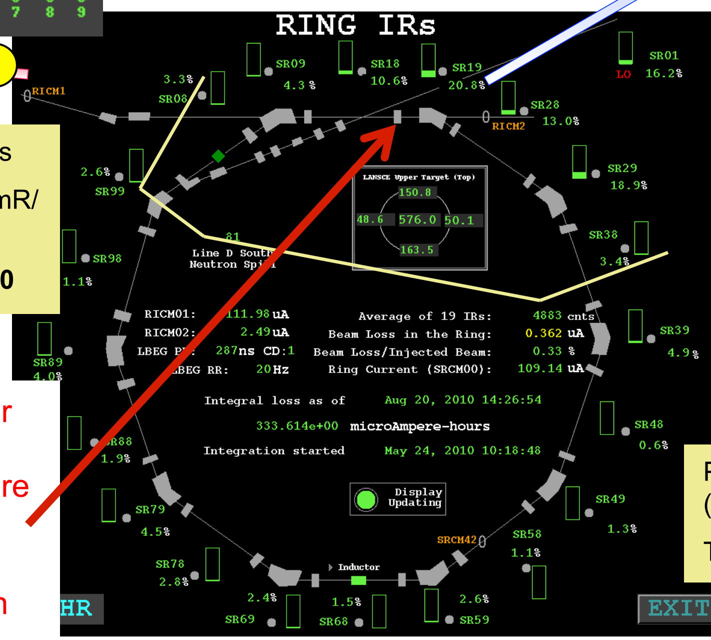






SY Activation Levels (mR/hr @ 30 cm)

Typ. 0.1-3; Max. < 30



PSR (2) Activation Levels

(Inj, Foil Area) (mR/hr @ 30 cm)

Typ. **20-300**; Max. < **1500**

kicker

Higher integrated spill over recent operations likely resulted in premature failure of water hose on SRQU01 during recent accelerator development, Cancellation of 2 experiments & ~0.5 man-Rem of dose to repair

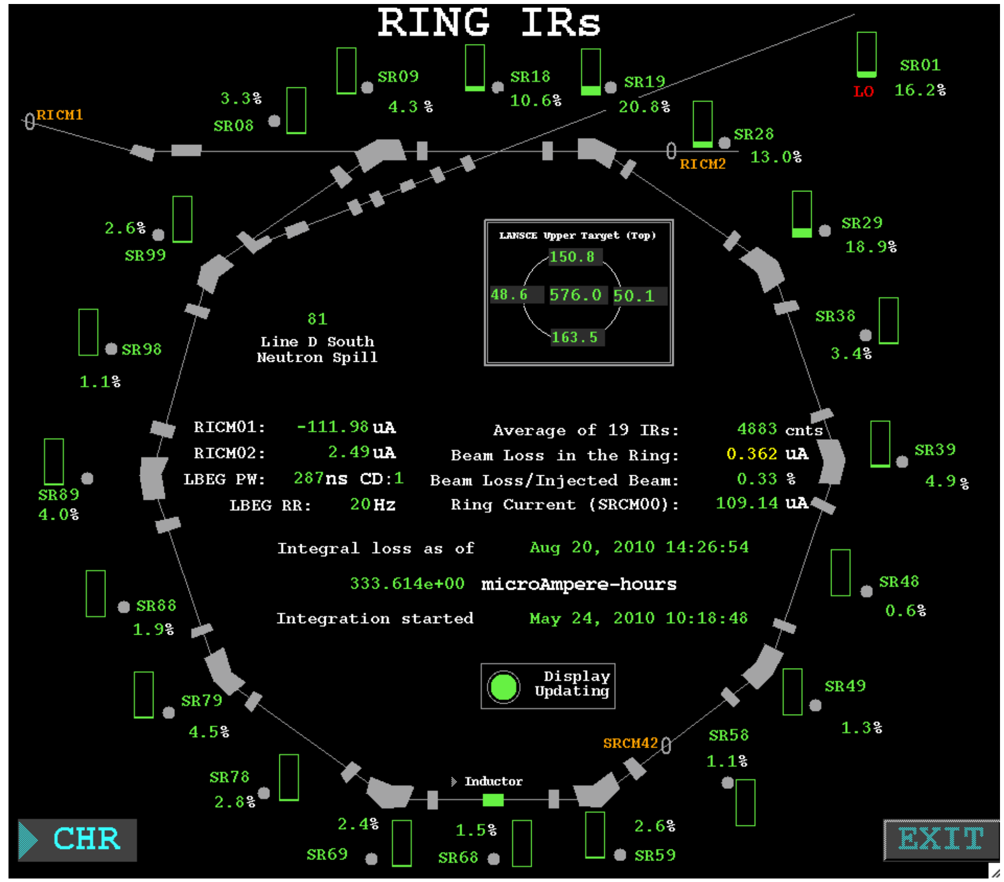
PSR (1) Activation Levels (mR/hr @ 30 cm)

Typ. **10-100**; Max. < **200**

1 mR/hr = 10μSv/hr

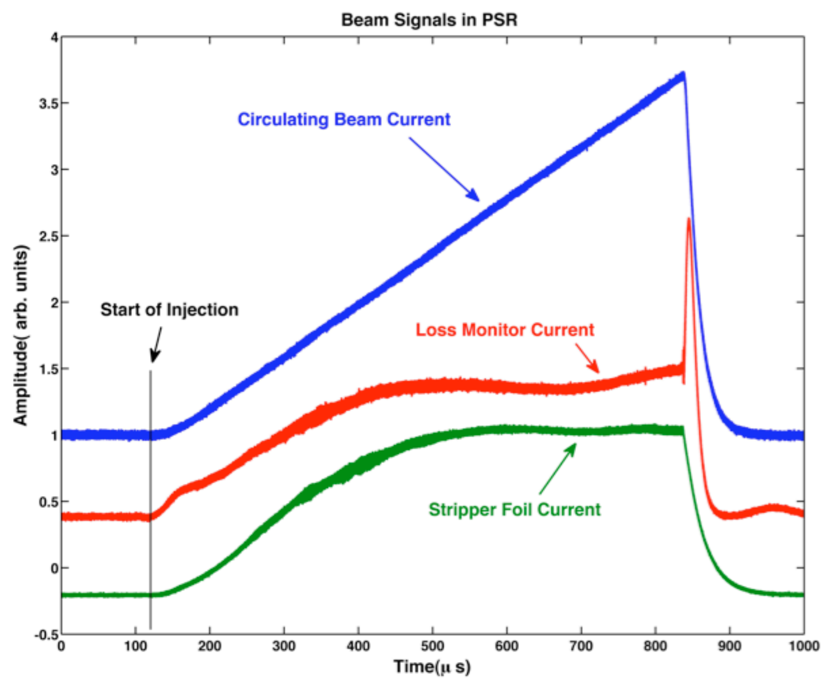
PSR Beam Losses – Spatial Distribution

- **800 MeV beam loss**
  - 0.2(typical) - 0.4%
  - E.g. 0.36 μA out of 112 μA or 290 W
- **Injection loss**
  - First turn – excited state H^0's lost in first quadrant of ring (~20% of total)
  - Foil scattering
    - Nuclear(Inj. region)
    - Coulomb(whole ring)
- **Circulating Beam loss**
  - Foil scattering
  - Scraping
- **Extraction loss** (extraction area)
  - Protons in the gap
  - Kicker – bunch issues



PSR Beam Losses – Temporal Distribution

- **Injection occurs over 625 μs**
  - Linear increase in circulating current vs time
- **First turn losses present only during injection**
- **Injection painting (V-only) reduces circulating beam losses below linear vs. time**
- **Extraction spike**



Operational Changes for Mitigating PSR Beam Losses

- **Physics tune results in fractional loss typically <0.3%**
- **Empirical tweaking required for further reduction (0.2 - 0.25%)**
  - Bumps to reduce scraping
    - H – bender shunts
    - V – steerers
  - Closed Orbit
  - Injection energy
    - Linac tweaks
  - Tune (Quads)
  - Beam size (Injection offset)
  - Extraction timing
  - Buncher phase & amplitude