High Power Operational Experience with the LANSCE Linac

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Nashville, TN

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AOT-ABS

Los Alamos National Laboratory

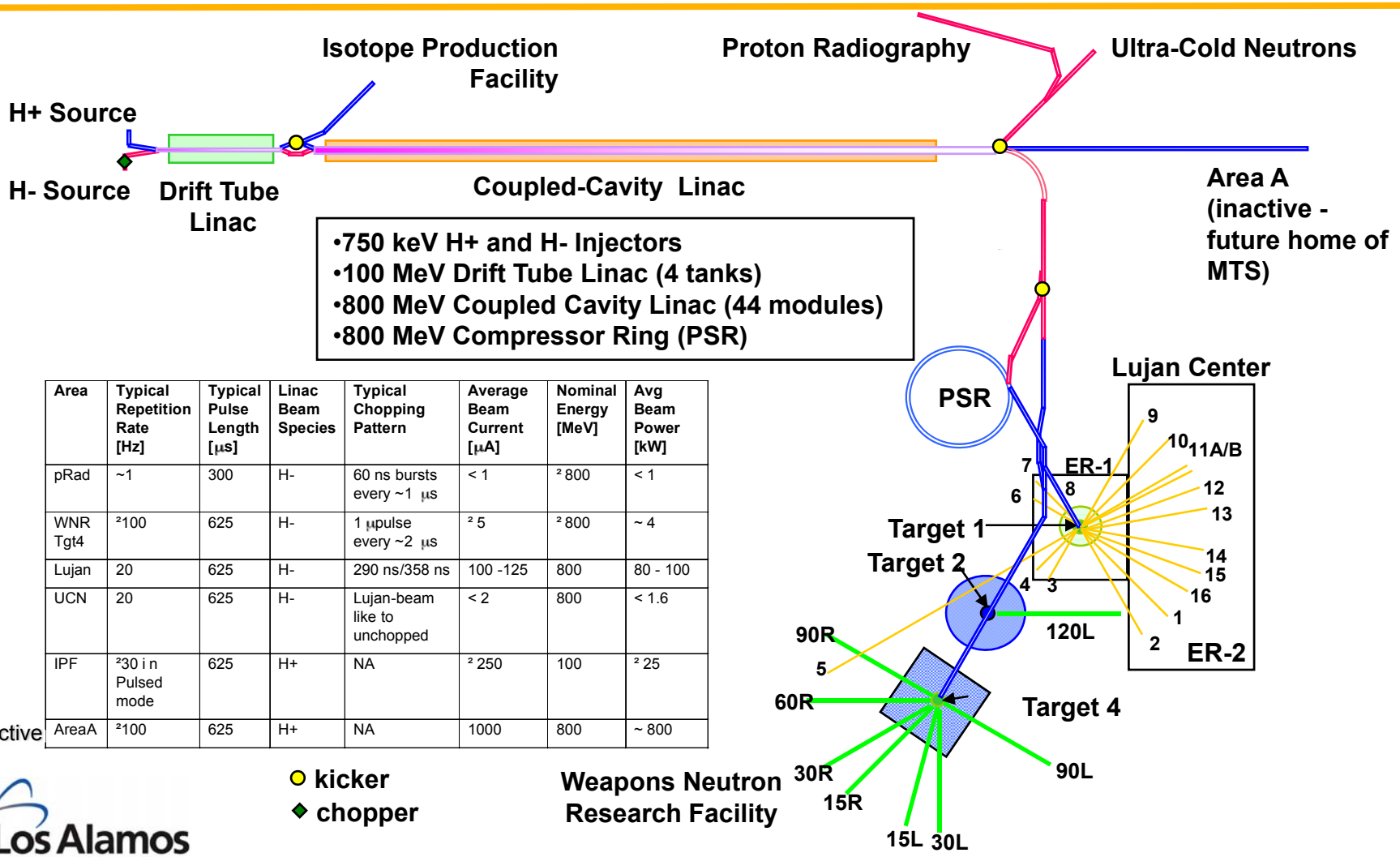
Outline

- Introduction to LANSCE
- Performance, Schedule & Reliability
- Startup, Tune-up
- Beam Losses - Activation - Protection
- Summary

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 30 years.**
  - Formerly known as LAMPF, designed to provided 800 kW of beam for meson physics program
- **The LANSCE Experimental User Facilities includes**
  - 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 Manuel Lujan Jr. Neutron Scattering Center (Lujan Center), which uses a time-compressed proton beam to make a moderated neutron source (meV to keV range)
  - The Isotope Production Facility (IPF) is a source of research and medical radioisotopes for the nation
  - The Ultra Cold Neutrons (UCN) which is a source of sub-μeV neutrons for fundamental physics research

LANSCE Facility Overview



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]
pRad	~1	300	H-	60 ns bursts every ~1 μs	< 1	² 800	< 1
WNR Tgt4	²100	625	H-	1 μpulse every ~2 μs	² 5	² 800	~ 4
Lujan	20	625	H-	290 ns/358 ns	100 -125	800	80 - 100
UCN	20	625	H-	Lujan-beam like to unchopped	< 2	800	< 1.6
IPF	²30 i n Pulsed mode	625	H+	NA	² 250	100	² 25
inactive AreaA	²100	625	H+	NA	1000	800	~ 800

kicker
chopper

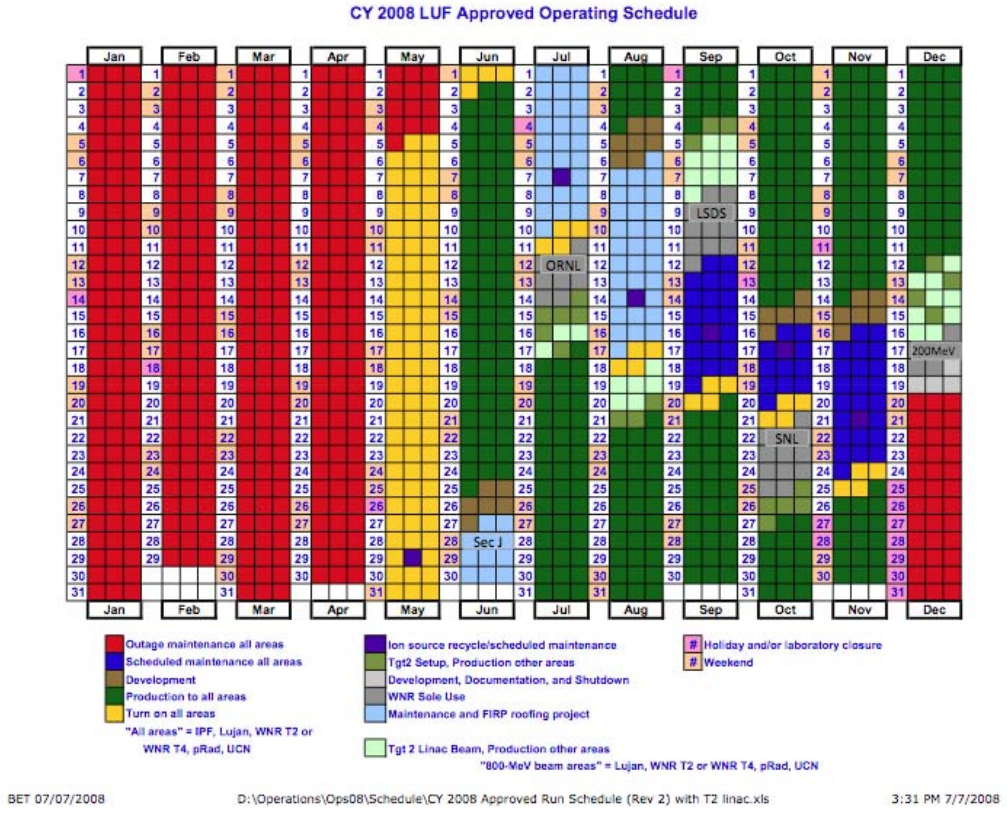
Weapons Neutron Research Facility

Linac Performance - Historical, Present & Demonstrated

- **Historical Performance**
  - 120 Hz x 625 μs beam gates -> 7.5% duty factor
  - Combined and simultaneous H+ & H- operation (limited by peak RF power)
  - Typical maximum peak beam current: 16.5 mA
  - RF duty factor: ~ 10%
- **Present Performance**
  - 60 Hz Operation (limited by 7835 in DTL 201 MHz RF System)
  - Peak beam current: ~13 mA (H- ion source limit)
- **Demonstrated Performance (non-coincident)**
  - RF duty factor: ~12%
  - Beam gates: 1225 μs
  - Peak beam current: 21 mA (800 MeV with I_{avg}= 320 μA)
  - 1 MW beam operation

2008 Operating Schedule is Typical of Recent Years

- **Extended Maintenance January 1 thru May 5**
- **Start-up ~ 1 month**
- **Six blocks of "production beam" over a 6 1/2 months**
  - ~ 24 day of user beam per cycle, including sole use
  - Machine development
  - Separated by maintenance activities and H- source recycle
- **Extended Maintenance begins Dec 20**

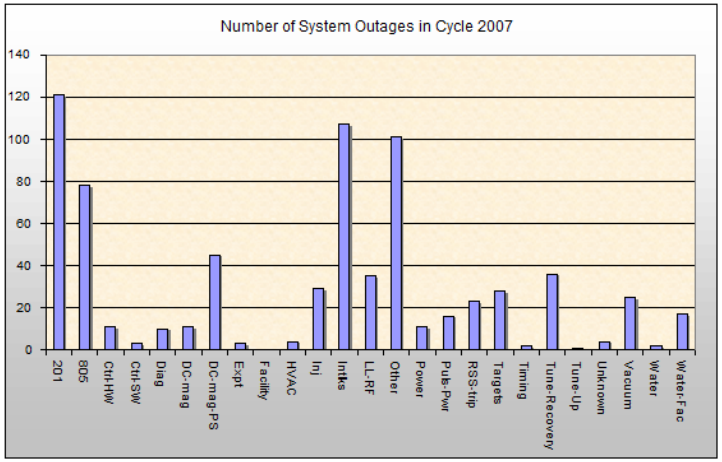


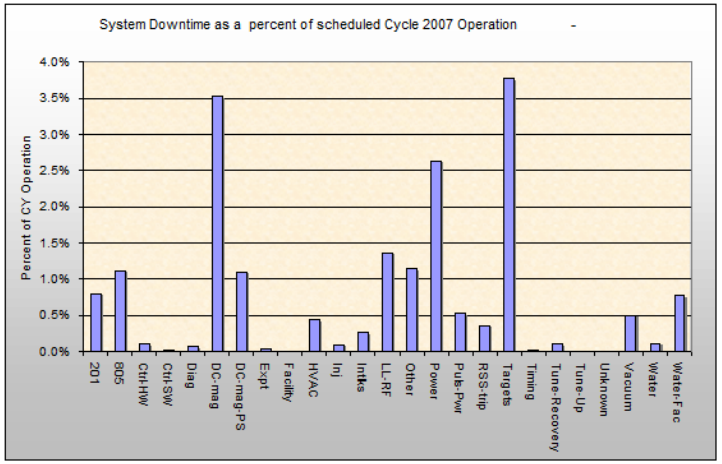
Beam Reliability - Accelerator Systems Performance

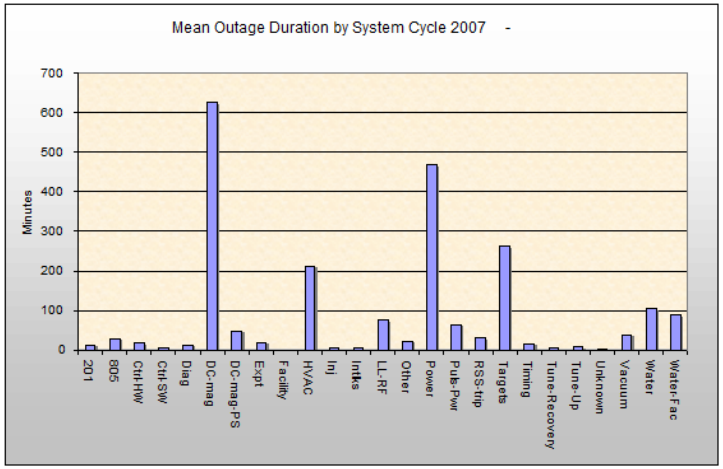
Lujan Center - CY2007 - 3255 hrs scheduled - 81.2 % reliability

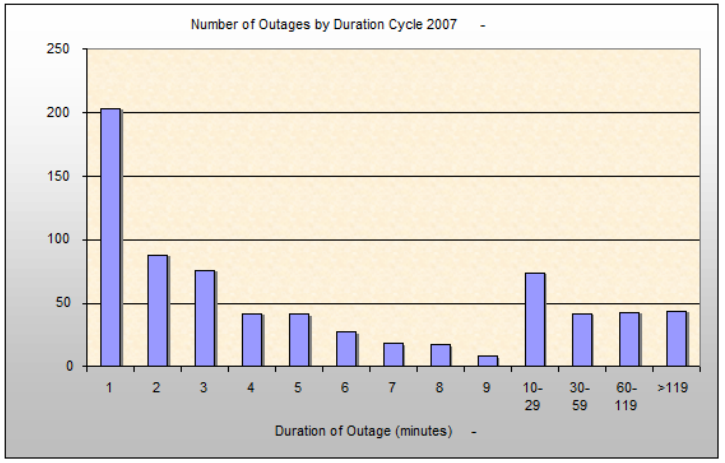
Linac reliability: 93.4%

Average number of trips per day for Lujan beam in CY2007	
With beam-off time ≥ 1 min	5.3
With beam-off time > 1 hour	0.64
With beam-off time > 3 hour	0.2









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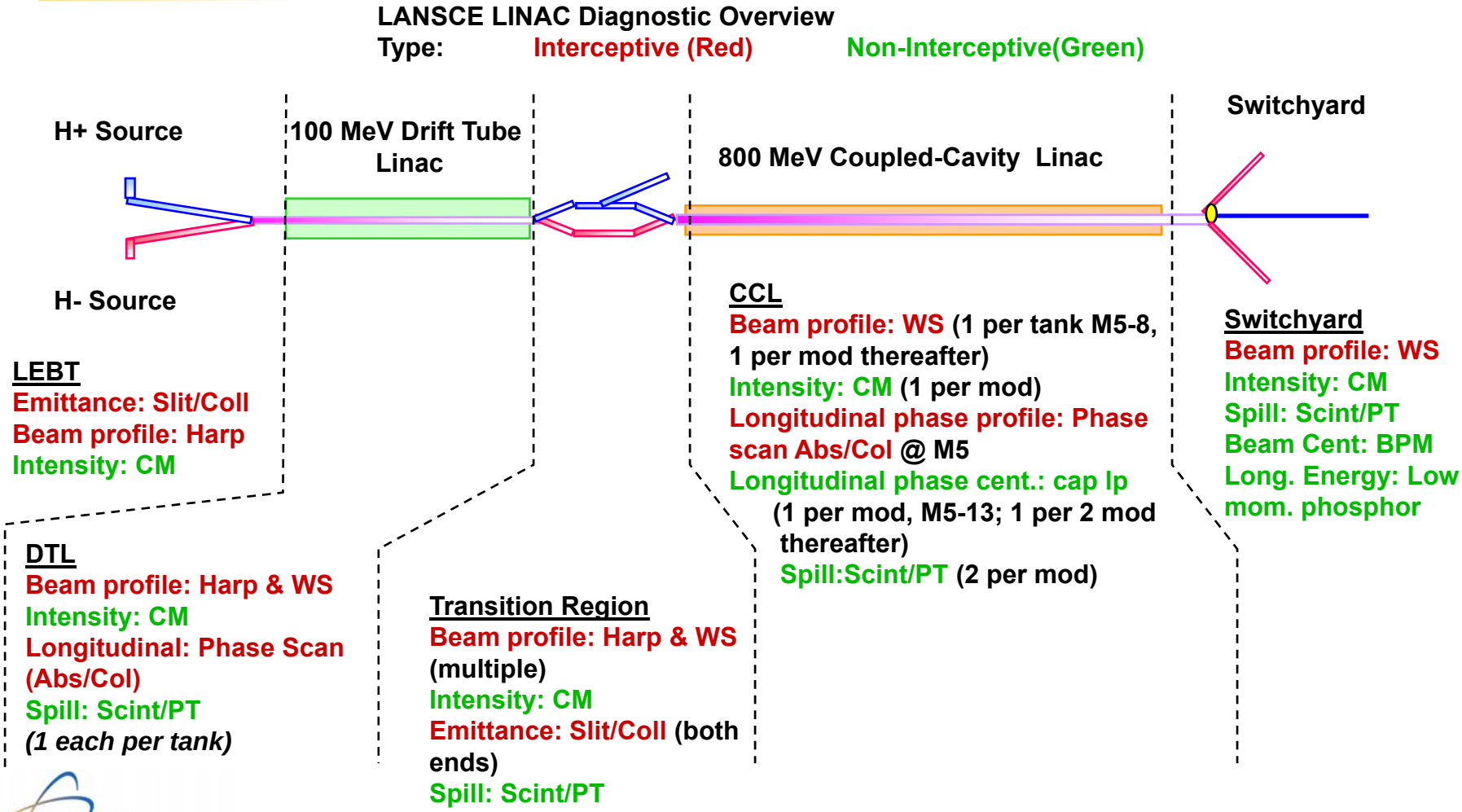
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Annual Facility Startup/Tuneup has Two Goals

- **Goals**
  - Achieve low-loss, stable, beam operation to all experimental areas
    - Establish physics tune starting with last years set points as initial values
    - Finish with empirical tweaking to reduce losses while raising average current
  - Recertify Safety (RSS) and Protection Systems (RP, FP)
    - Radiation Safety System (RSS) certification has 6 month lifetime
      - 80 checks performed bi-annually (few hours/check)
      - moving toward rolling process to reduce peak load
    - Machine protection certification performed annually
      - Over 49 Run Permit (RP) (+ 40 Albatross Neutron Detectors) checks
      - Over 24 Fast Protect (FP) checks
- **Perform in timely fashion and conserve energy ($$$'s)!**
    - Interlock checks and accelerator tune up are interleaved
    - Approximately 1 month allocated to take facility from cold state to full production-level beams
    - Most tuneup performed with CCL RF at 10 Hz to save on cost of $1M/mo for 60Hz ops

Tune-up Relies Heavily on All Available Beam Diagnostics



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Linac Physics Tune-Up is a Multi-Step Process

- **Basic strategy developed over many years of high-power, multi-beam operation**
  - Use “zero” current beam measurements combined with previous predictions from single- and multi-particle beam dynamics models to to establish RF set points
    - Models use ideal accelerating structures
    - Mitigates complications from beam space charge
  - Use slit & collector (S&C), harp and wirescanner measurements to establish (and verify) matched beam conditions at entrance to DTL and CCL structures
  - Use very low duty factor beam, i.e. 4 Hz x 150 μs to limit spill during manipulation of machine parameters and damage to interceptive diagnostics
    - Pulse length chosen to allow beam to reach steady state conditions for measurements
- **Step 1: Establish full peak-current operation of Injectors and LEBTs**
  - Transverse tuning with multiple slit/collector emittance measurements & envelope code
  - Peak currents set by source performance, experimental beam requirements and available duty factor

Linac Physics Tune-Up is a Multi-Step Process (cont.)

- **Step 2: Establish Longitudinal Tune of Linac at "zero" current**
  - LEBT 4-jaws used to reduce peak to ~1 mA (unchopped) and perform tune-up of linac (DTL & CCL) from 0.75 to 800 MeV
  - Linac quadrupole lattice set to nominal design with some tweaks derived from "low-loss, high-power" operation
  - Transverse matching to target values derived from models
  - Longitudinal tune
    - DTL - phase scan of beam above energy threshold (target values derived from multi-particle simulations
    - CCL - ΔT procedure (parameters derived from single-particle model calculations, optimized for either H+ or H-)
- **Step 3: Restore full peak beam and complete tune-up**
  - High-peak transverse match at injection to DTL and CCL
  - Adjust beam energy out of DTL and CCL RF phase

Space Charge Compensation is a Factor in 750 keV LEBT

- **Cockcroft Walton Injectors produce unbunched beams a during macropulse**
  - Microbunching begins ~1/3 way through LEBT
  - Significant bunched beam structure only appears within the last 1.8 m of LEBT
- **LEBT pressure typically mid-10^{-7} T**
- **SC compensation depends upon location and species**
  - H+ : max compensation about 10-20%
  - H- : almost fully compensated over most of LEBT,
- **Accurate estimate of effective peak beam current required for efficient tune-up process**
  - Derived from a comparison of measure beam profile and envelope prediction over for beam through drift space with I_{eff} as a free parameter

Beam Matching into the DTL has Issues

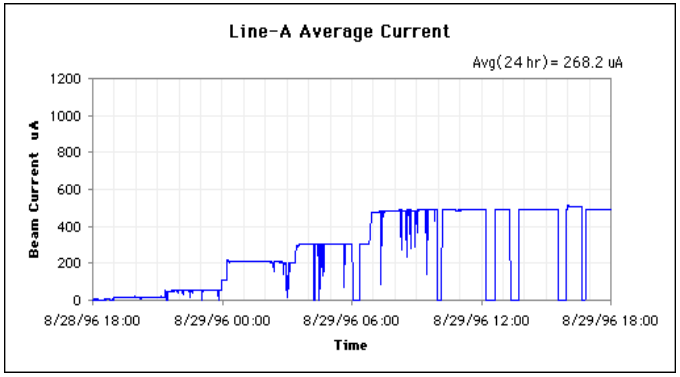
- **Two single-gap bunchers in LEBT produce an incomplete bunch**
  - Rapidly evolving longitudinal emittance as beam approaches the DTL
- **Non-constant space charge neutralization in LEBT affects beam evolution**
  - Degree of neutralization depends on location and pulse format
- **2D TRACE model with scaled-up current works ok**
  - Higher effective current accounts for bunching
  - Does not require knowledge of longitudinal emittance

“Optimal” DTL RF Set Points are not the Design Values

- **Original physics tune-up would not produce low-loss, high-power tune**
  - Phase-scan procedure placed DTL tank fields at design values, which produced a high-quality 1 mA beam for additional tuning activities (CCL ΔT)
  - However, operating DTL at “design” resulted in unacceptably high losses in CCL for high peak current beam, i.e. 16.5 mA
  - Significant changes in phase and amplitude required to run high power
- **Low-loss tune required significant reduction in amplitude set points**
  - New set points were determined empirically during transition from low to high power operation
  - One example of high-power DTL tank amplitudes T1@98%, T2@96%, T3@94%, T4@98% wrt design, (estimates based upon analysis of phase scan data using modified PARMILA code)
  - Effect of lowering tank amplitudes is to reduce longitudinal acceptance in DTL and removes “tails” early in the acceleration process, i.e. spill at lower rather than higher energy

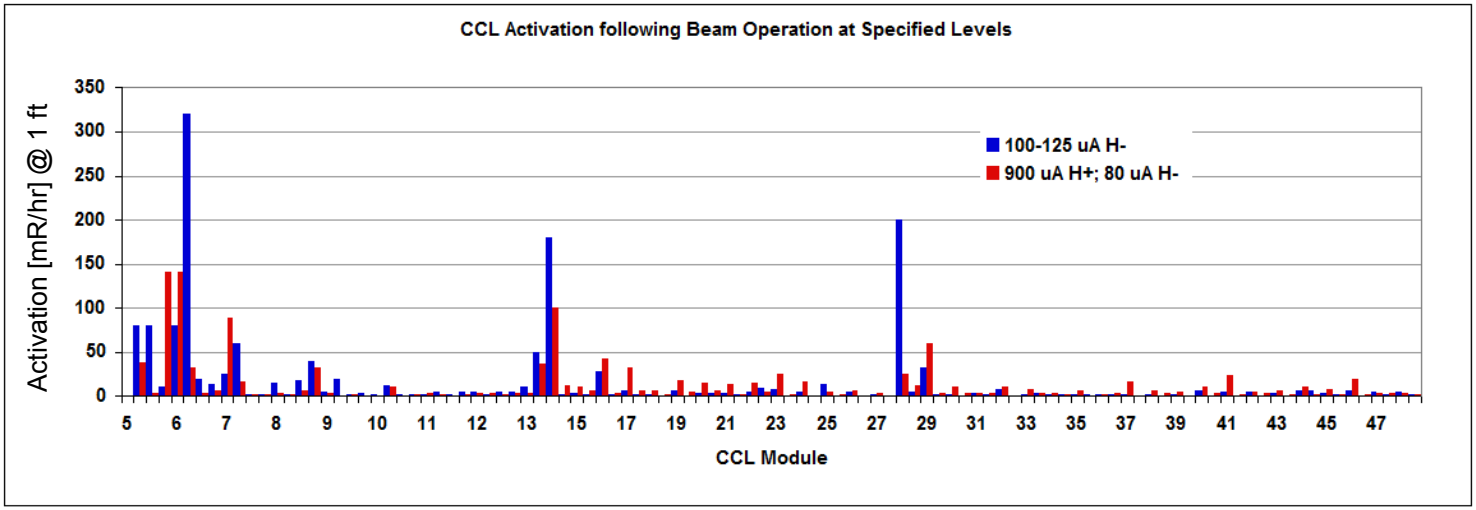
Transition from Physics Tune to High Power

- **Following physics tune-up, linac is ready to deliver high-peak, low-power beam**
  - Everything done to produce good quality beam with desired average properties
  - Tuning now driven by off-energy components and transverse tails
- **Beam duty factor slowly increased while "machine" is tweaked to reduce losses**
  - Beam losses would limit initial maximum H+ current to ~ few hundred μA
  - Combination of longitudinal and transverse issues associated with beam losses in TR, along CCL and in beam Switchyard
- **Tuning to reduce losses aided by**
  - Dispersion in Switchyard transports which reveal off-momentum components in beam
  - Moderate density of beam loss monitors along CCL
- **Reaching full power would take a few days**



Beam Losses and Activation

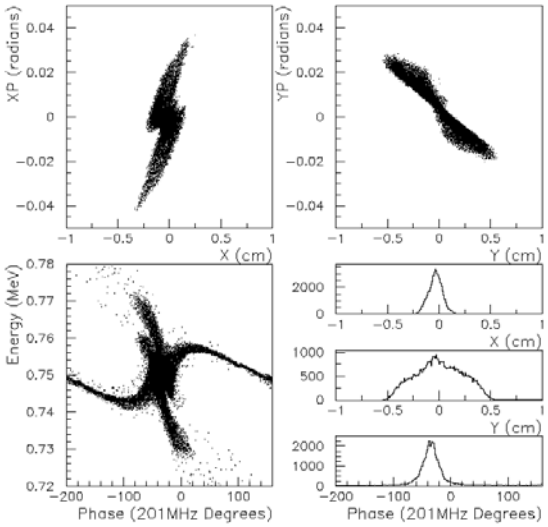
- **Largest losses (~20%) are longitudinal in nature and occur in DTL due to incomplete bunch formation prior to beam entering Tank 1**
- **Next area in the TR where off-energy and transverse tails spill (~0.1%)**
- **CCL losses are a combination of longitudinal and transverse components (<0.1%)**
  - Transverse mismatch at 100 MeV contributes to higher losses at CCL front end
  - Longitudinal tails and a smaller RF bucket contribute to higher losses near module 13 where transverse lattice period doubles



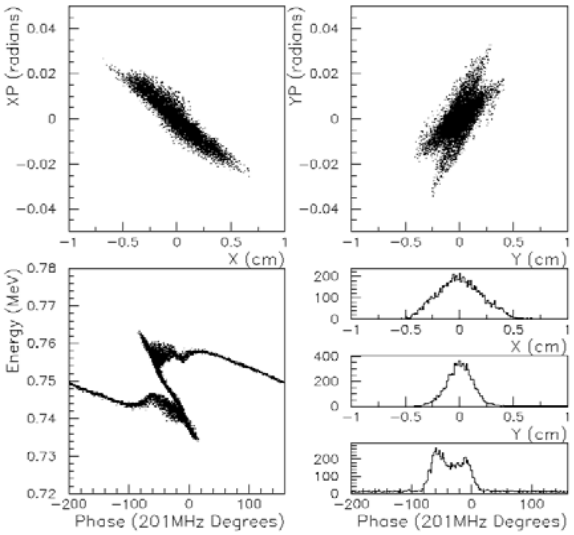
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LINAC Beam Loss Simulations (steady state)

- **Multiparticle simulations were performed to compare to measured and simulated beam emittance and losses in linac**
  - Equivalent operation: 1 mA H^+, 75 μA H^-
- **Simulation began in 750 keV LEBT where input beam was constructed from measured transverse and simulated longitudinal distributions**
  - Space charge neutralization was included



The simulated transverse and longitudinal H^+ beam distributions at injection to the DTL.



The simulated transverse and longitudinal H^- beam distributions at injection to the DTL.

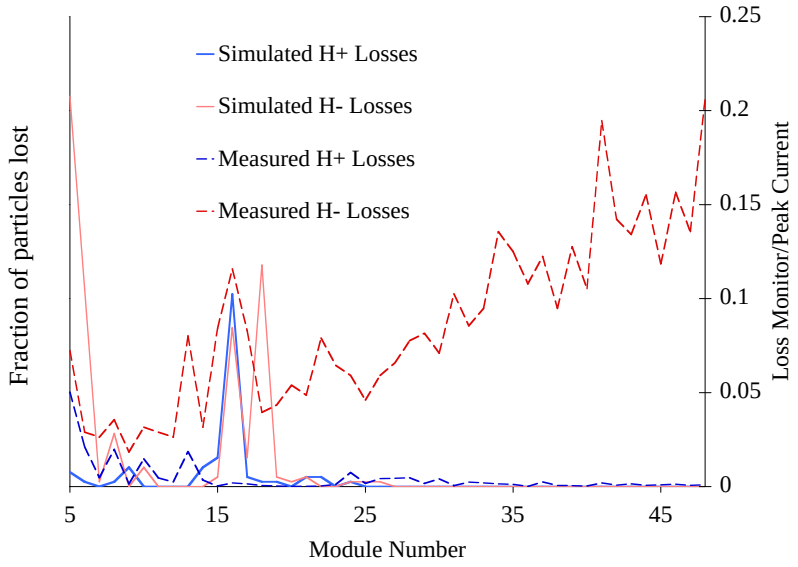
LINAC Beam Loss Simulations in Agreement with Data

- **Magnet focusing lattice at operational set points in LEBT, DTL, TR & CCL**
- **RF fields**
  - DTL simulated at operational set points extracted from a comparison of PARMILA simulations of phase-scan measurements.
  - CCL at design settings installed by ΔT

	H- Sim.	H- Meas.	H+ Sim.	H+ Meas.
Capture	**80%**	**81±1%**	**80%**	**82±1%**

	Emittance Station		H^+ RMS Emittance (π cm-mrad) Sim.	H^+ RMS Emittance (π cm-mrad) Meas.	H^- RMS Emittance (π cm-mrad) Sim.	H^- RMS Emittance (π cm-mrad) Meas.
0.75 MeV	TDEM1	H	$.93\times10^{-2}$	$.93\times10^{-2}$	1.9×10^{-2}	1.9×10^{-2}
		V	$.92\times10^{-2}$	$.92\times10^{-2}$	2.5×10^{-2}	2.5×10^{-2}
100 MeV	TREM1	H	5.2×10^{-2}	3.1×10^{-2}	3.2×10^{-2}	2.8×10^{-2}
		V	2.7×10^{-2}	2.8×10^{-2}	5.1×10^{-2}	3.4×10^{-2}

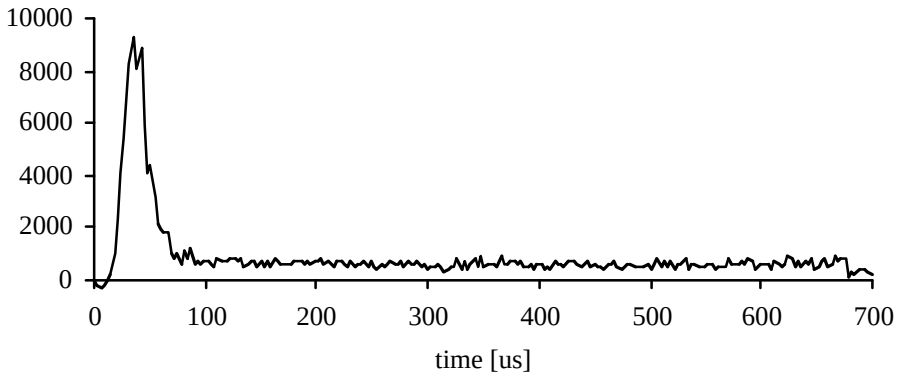
Between Modules	H^+ Losses		H^- Losses	
	Sim.	**Meas.**	**Sim.**	**Meas.**
3-12	0.04%	0.1%	0.15%	<0.1%
12-48	0.28%	<0.1%	0.24%	<0.1%



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Higher Transient Losses Related to Cavity Field Errors

- **Time dependence of beam loss in linac shows higher losses during beam turn-on transient**
- **All field errors acceptable, i.e. below the "fast protect" threshold of 1° & 1% phase and amplitude error, respectively**
- **Present feed-forward signal (scaled version of beam current macropulse) not adequate to mitigate error**



Typical CCL Loss Monitor signal for high peak H+ beam

Fast Protect - Machine Protection on a “Fast” Time Scale

- **Mitigates beam damage to accelerator structure and transports that could occur from errant beam that results in excessive spill**
- **Primary inputs**
  - RF field errors: trips levels at ± 1°, ± 1%
  - beam loss monitors: initial setup based upon ~100 nA of beam spill
  - beam current transmission monitors: adjustable set points/tolerances
- **Faults are transmitted to chassis which inhibits gating of either LEBT deflectors or ion sources**
- **Beam gates are truncated and remain off until fault clears**
- **System response time ~ 10 μs**
- **Fault indications provided via hardware status panels and software displays allow for quick analysis of fault type and location**

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
- The linac has a long history of delivering high power beam (800 kW) while today's operation provides more modest levels (130 kW)
- Present day operations include ~3000 hours/CY of scheduled beam to user programs with typical reliability of 80%
- Tuning the linac for high-power beam operation begins with physics/model based tuning to get the "rms" performance correct, but then requires empirical tuning to address "tails" and minimize spill
- Good agreement has been observed between H^+ and H^- beam emittance and loss measurements and the corresponding results from beam dynamics simulations which included realistic estimates of LEBT space-charge neutralization, RF field levels, magnet strengths and more accurate initial beam distributions

References

- F.E. Merrill and L.J. Rybarcyk, “Tranverse Match of High Peak-Current Beam into the LANSCE DTL Using PARMILA”, Proceedings of the XVIII International Linac Conference, August 26-30, 1996, Geneva, Switzerland, pp. 231-233
- F.E. Merrill and L.J. Rybarcyk, “Beam Dynamics Simulations of the LANSCE Linac”, Proceedings for the XIX International Linac Conference, August 23-28, Chicago, IL, pp. 839-841

Additional LANSCE Information for HB2008 WG-D

- **Measured Performance - Maximum Operating Beam Power**
  - LANSCE Linac: 1 MW
  - PSR-Lujan: 100 kW
- **Typical residual activation observed on accelerator and beam transports**
  - Areas not designed for controlled for beam loss: 1-2 mSv/hr @ 1ft (PSR & linac)
  - Areas controlled for beam loss: 10-30 mSv/hr @ 1ft (PSR) 4 hrs after beam off
- **Average Annual dose for Rad workers**
  - In 2007, 108 mSv over 116 persons
- **ALARA principle practiced to minimize dose to workers**
- **Future activitation levels predictable to ~2x based upon historical performance**
- **PSR entries typically require minimum of 4 hours beam off before entries**