SNS Diagnostics:
Accelerator Physics Perspective

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For the SNS Accelerator Physics Team

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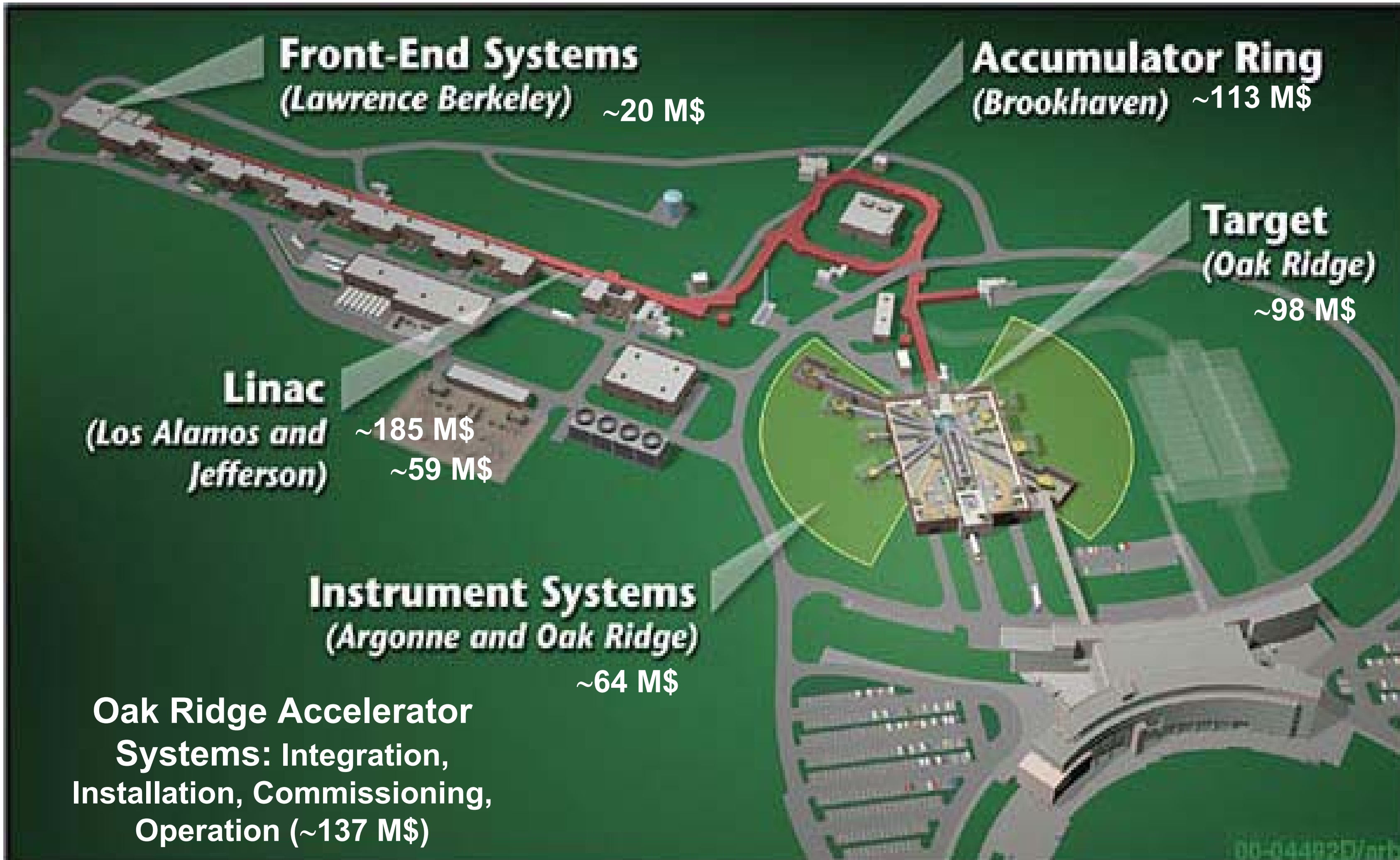
SNS Organization: Partnership of 6 DOE National Laboratories



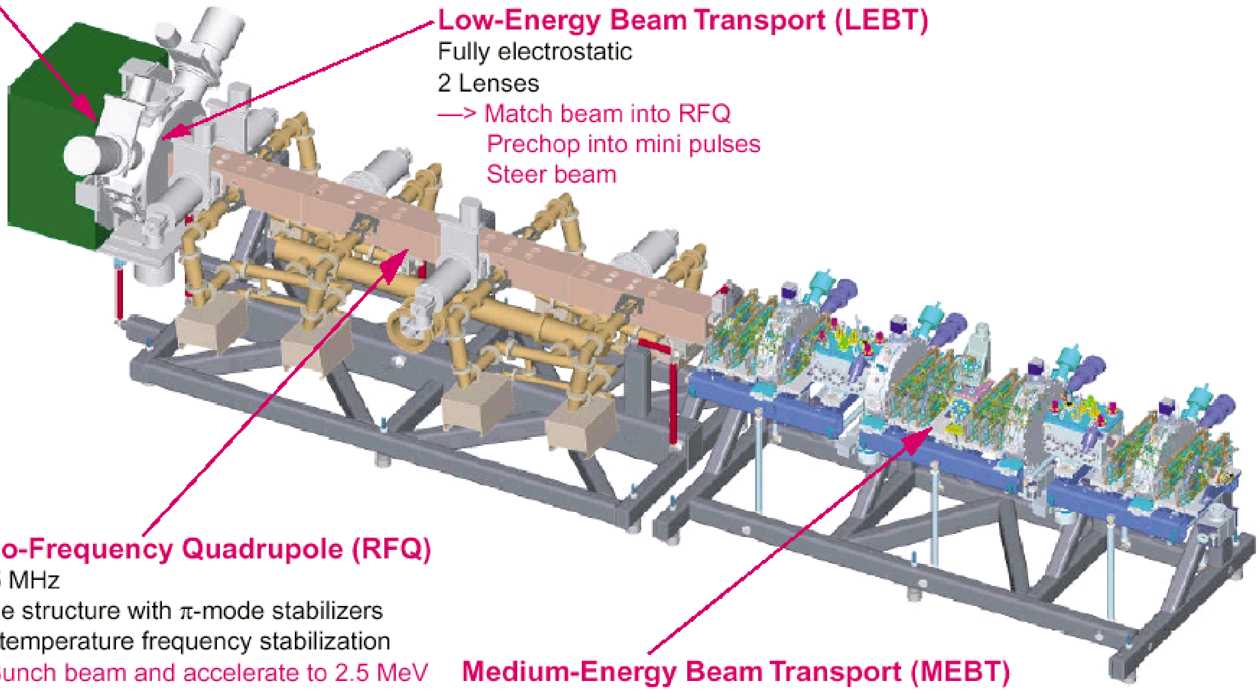
Front-End Systems Overview

SNS Front End (Linac Injector)

Built and commissioned at LBNL Berkeley

Ion Source
Multicusp, rf driven, cesium-enhanced
—> Create beam of about 50 mA, 65 keV
Dump extracted electrons at 5 keV

Low-Energy Beam Transport (LEBT)
Fully electrostatic
2 Lenses
—> Match beam into RFQ
Prechop into mini pulses
Steer beam



Radio-Frequency Quadrupole (RFQ)
402.5 MHz
4-vane structure with π-mode stabilizers
Dual-temperature frequency stabilization
—> Bunch beam and accelerate to 2.5 MeV

Medium-Energy Beam Transport (MEBT)
14 quadrupoles
4 rebunchers
Diagnostics
—> Match 38-mA beam to chopper target and into Drift-Tube Linac
Provide 10-ns chopping flanks
Diagnose beam

Design Parameters

Ion Source/LEBT:

48-mA peak H-minus

65 keV

0.20 pi mm-mrad (rms,norm)

Chopper: 50 nsec rise

RFQ

402.5 MHz

2.5 MeV

38-mA peak

MEBT

14 quads for matching

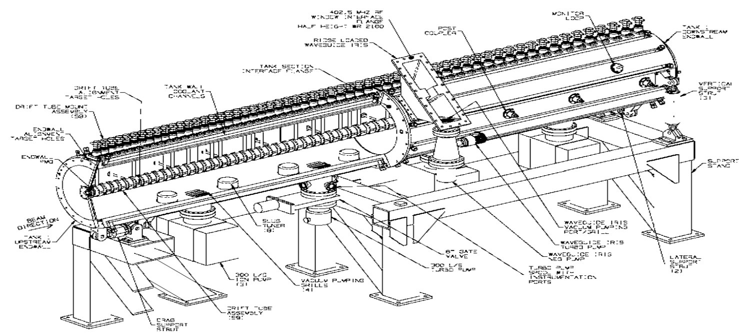
Chopper: 10 nsec rise, 68% beam-on duty

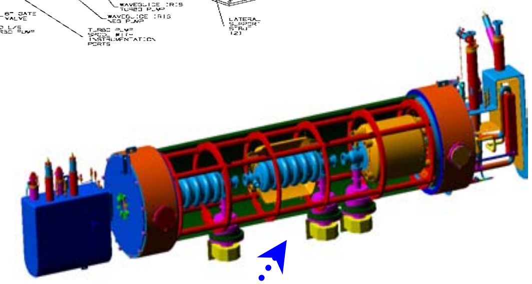
4 Rebunchers

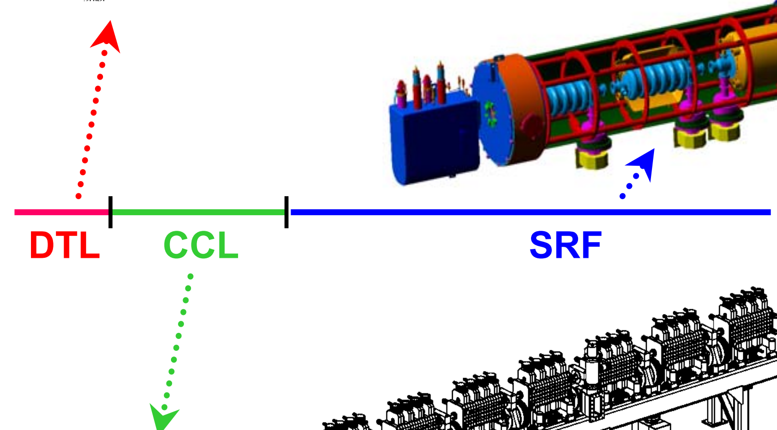
0.27 pi mm-mrad output emit (rms, norm)

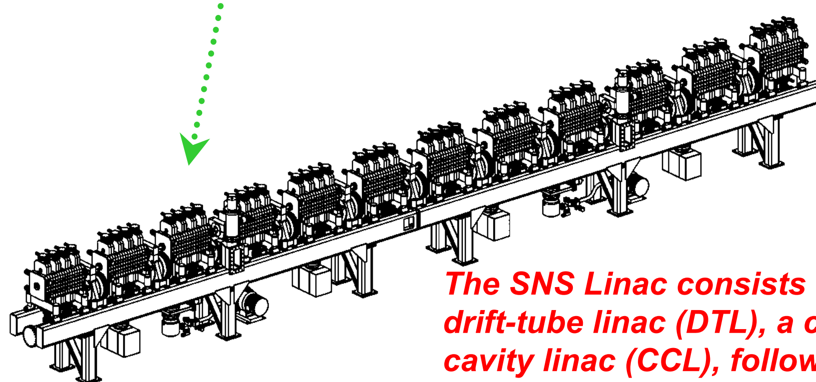
SNS Linac Systems Overview

Input Beam Energy	2.5 MeV
DTL Energy	87 MeV
CCL Energy	186 MeV
SRF β_1 Energy	387 MeV
SRF β_2 Energy	1.0 GeV
DTL/CCL/SCL Length	37/55/157m
DTL Frequency	402.5 MHz
CCL/SCL Frequency	805 MHz
SCL Geometric Beta	0.61/0.81
SCL Peak Surface Field	27/35 MV/m
SCL Accelerating	10/16 MV/m
SCL External Q	$7.3/7.0 \times 10^5$
SCL Bandwidth	1100/1150 Hz





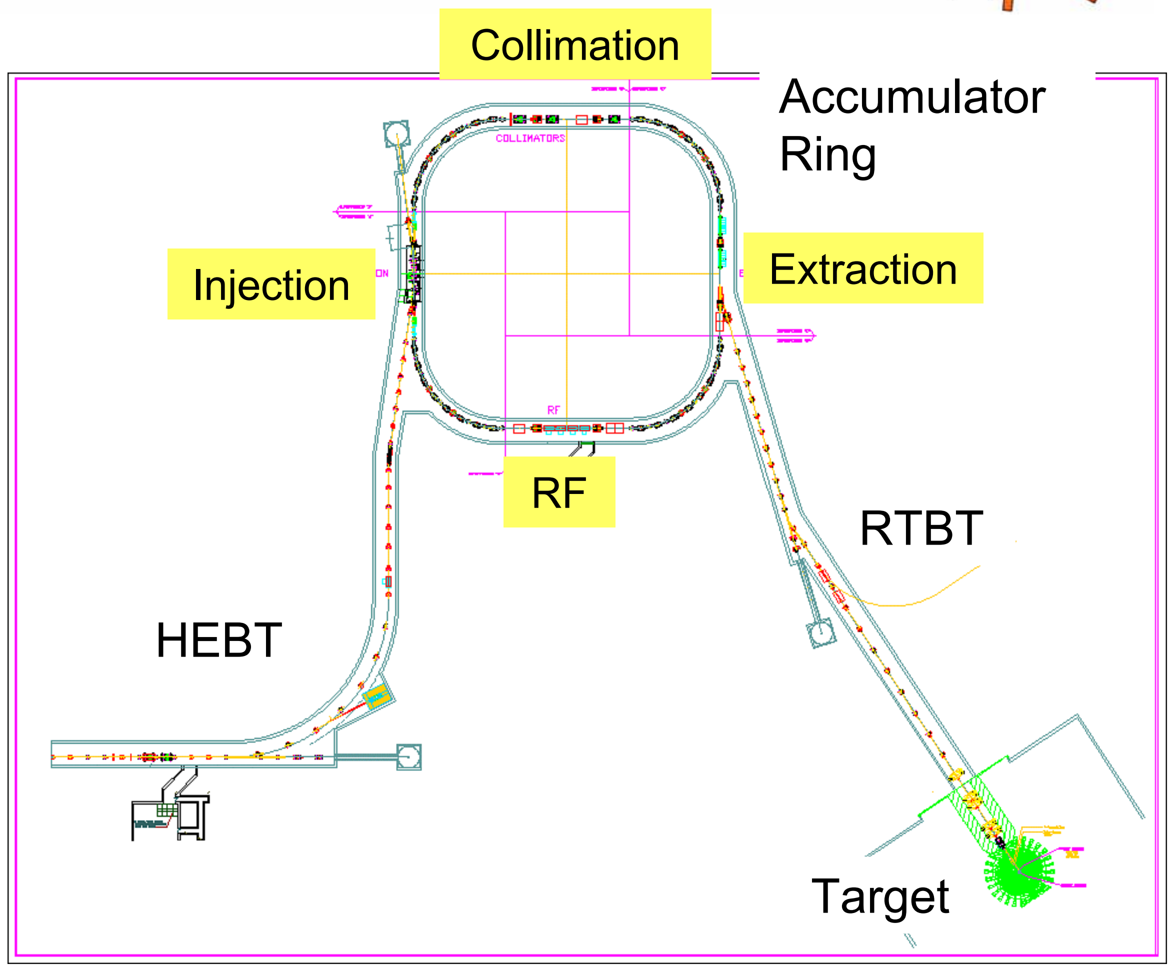




The SNS Linac consists of a drift-tube linac (DTL), a coupled-cavity linac (CCL), followed by a superconducting rf (SRF) linac

Ring and Transport Lines Overview

Circum	248 m
Energy	1 GeV
f_{rev}	1 MHz
Q_x, Q_y	6.23, 6.20
ξ_x, ξ_y	-7.9, -6.9
Accum turns	1060
Final Intensity	1.5×10^{14}
Peak Current	52 A
RF Volts (h=1)	40 kV
(h=2)	20 kV
Injected $\Delta p/p$	$\pm0.27\%$
Extracted $\Delta p/p$	$\pm0.67\%$

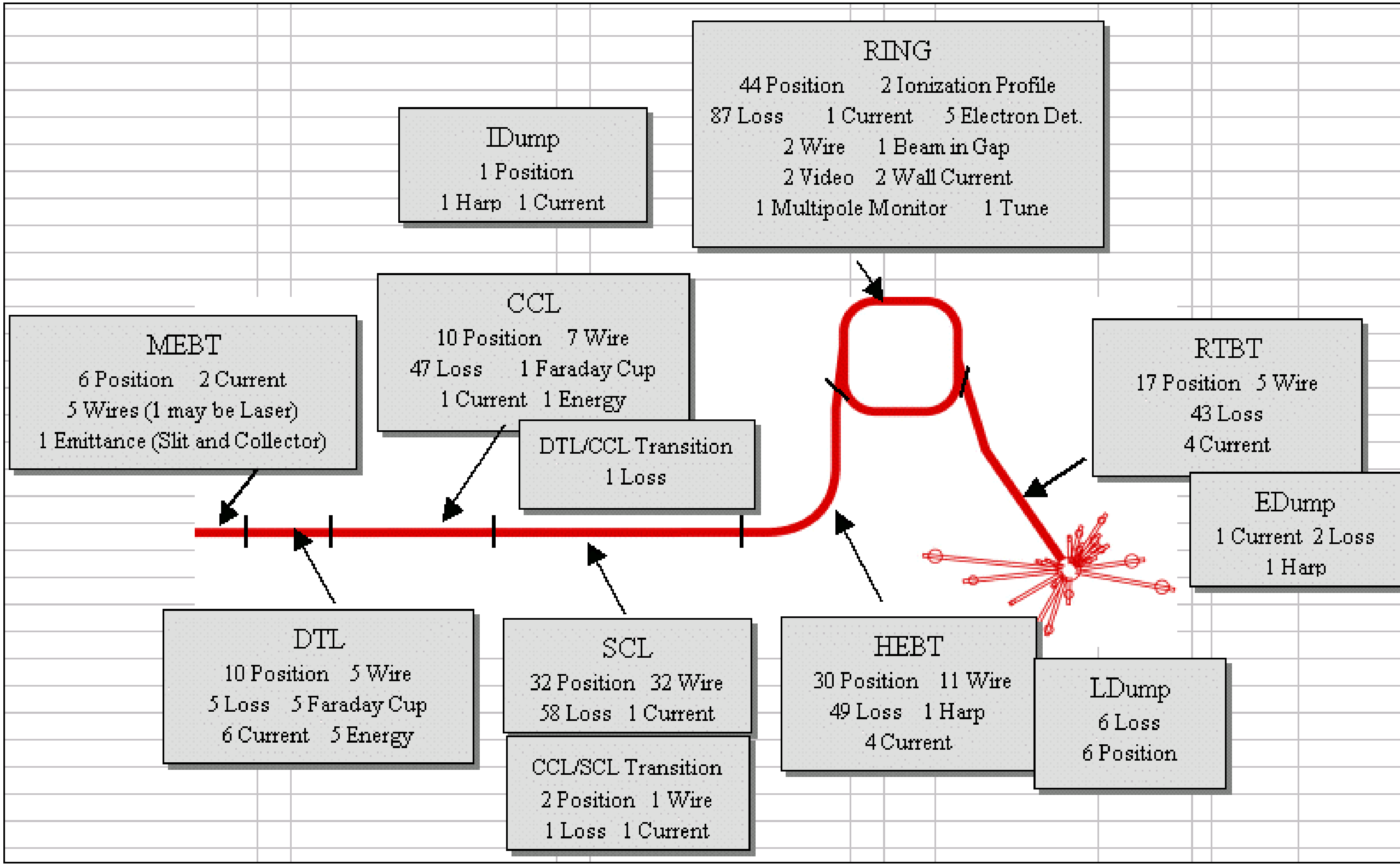


SNS High-Level Baseline Parameters

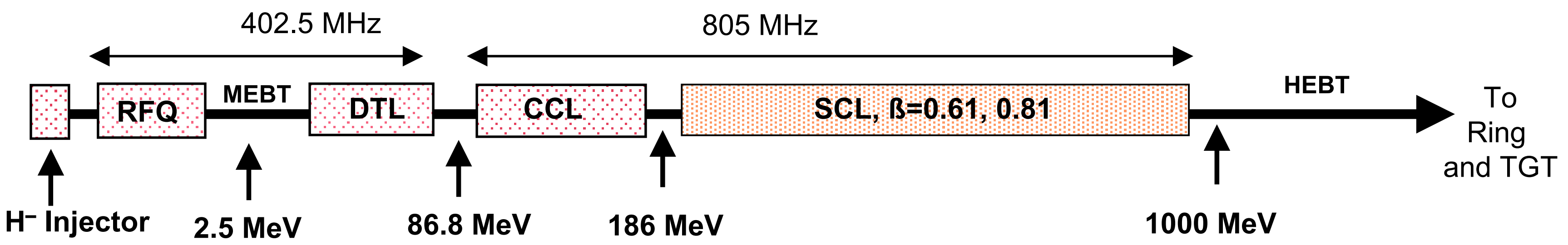
	Baseline
Kinetic energy, E_k [MeV]	**1000**
Uncertainty, ΔE_k (95% probability) [MeV]	+/- 15
SRF cryo-module number	11+**12**
SRF cavity number	33+48
Peak gradient, E_p (β=0.61 cavity) [MV/m]	27.5 (+/- 2.5)
Peak gradient, E_p (β=0.81 cavity) [MV/m]	**35 (+2.5/-7.5)**
Beam power on target, P_{max} [MW]	**1.4**
Pulse length on target [ns]	695
Chopper beam-on duty factor [%]	68
Linac beam macro pulse duty factor [%]	6.0
Average macropulse H- current, [mA]	**26**
Linac average beam current [mA]	**1.6**
Ring rf frequency [MHz]	1.058
Ring injection time [ms] / turns	1.0 / 1060
Ring bunch intensity [10^{14}]	**1.6**
Ring space-charge tune spread, ΔQ_{sc}	0.15

assuming 4% injection loss to dump; 4% target window loss; linac max. -20^o phase

SNS Diagnostics



SNS linac diagnostics



MEBT
- 5 WS elec
- 5 WS act.
- 6 BPM elec
- 6 BPM p/u
- 2 CM p/u
- 2 CM elec
- 2 SI&Col

DTL
- 5 WS
- 10 BPM
- 6 CM p/u
- 6 CM elec.
- 5 ED/FC
- 6 BLM

D-plate (7.5 MeV)
- 1 WS
- 3 BPM
- 1 CM p/u
- 1 CM elec
- 1 ED/FC
- 2 SI&Coll emit
- 1 Phosphor screen
- 1 8 seg. halo scraper
- 1 Beam stop / F-Cup
- 3 ND

CCL
- 8 WS
- 12 BPM
- 2 CM p/u
- 2 CM elec
- 1 ED/FC
- 24 BLM
- 3 BSM

SCL
- 8 laser profile monitors
- 32 BPM
- 58 BLM

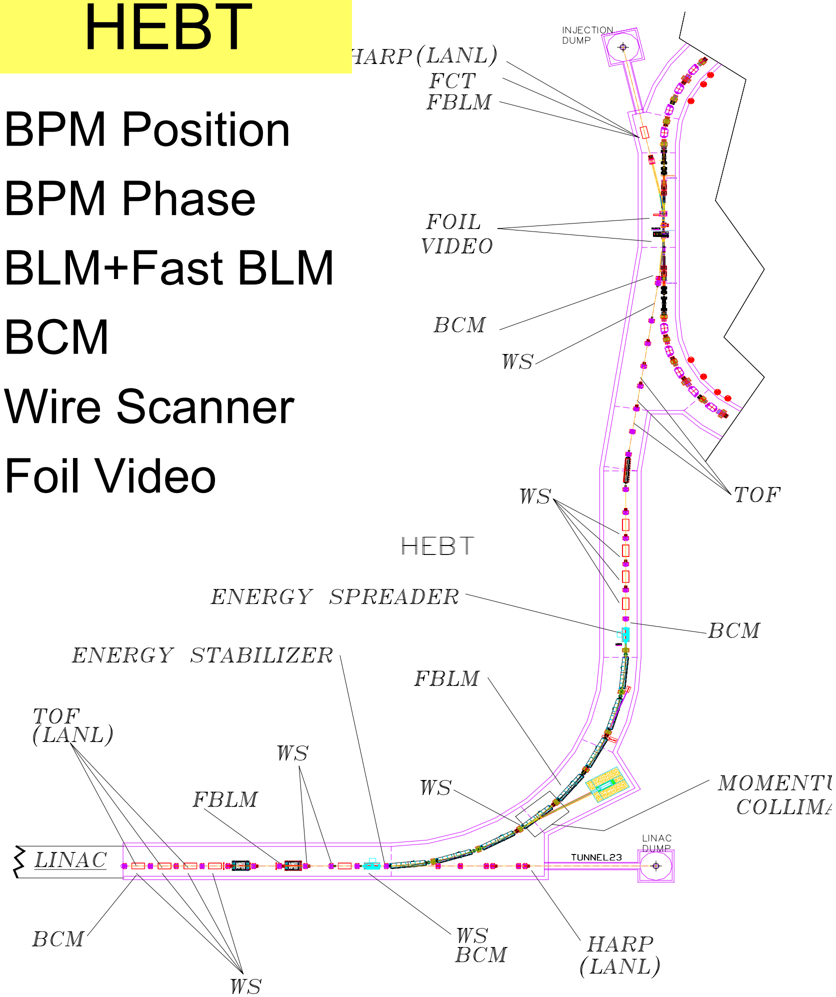
Responsible lab
- LANL
- BNL
- LBNL
- ORNL

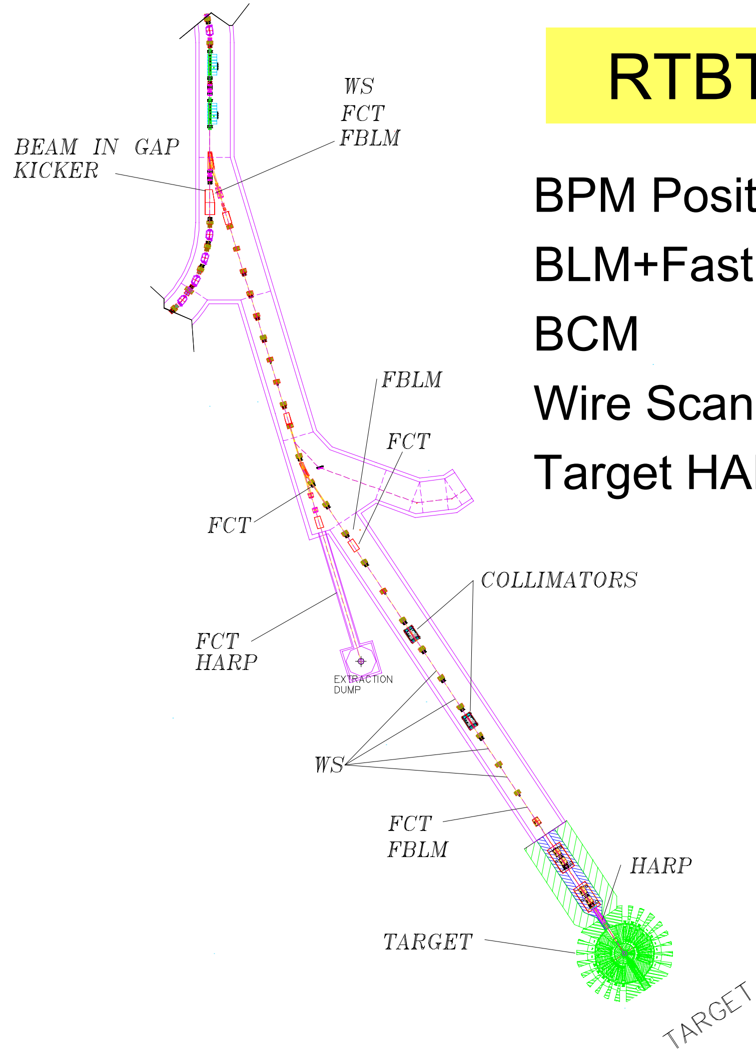
Key
- WS = wire scanner
- BPM = beam position monitor
- SI&Col = slit and collector emittance station
- CM = current monitor
- ED/FC = energy degrader & Faraday Cup
- BLM = loss monitor
- ND = neutron detector
- BSM = bunch shape monitor

HEBT and RTBT Diagnostic Systems

HEBT

- BPM Position
- BPM Phase
- BLM+Fast BLM
- BCM
- Wire Scanner
- Foil Video



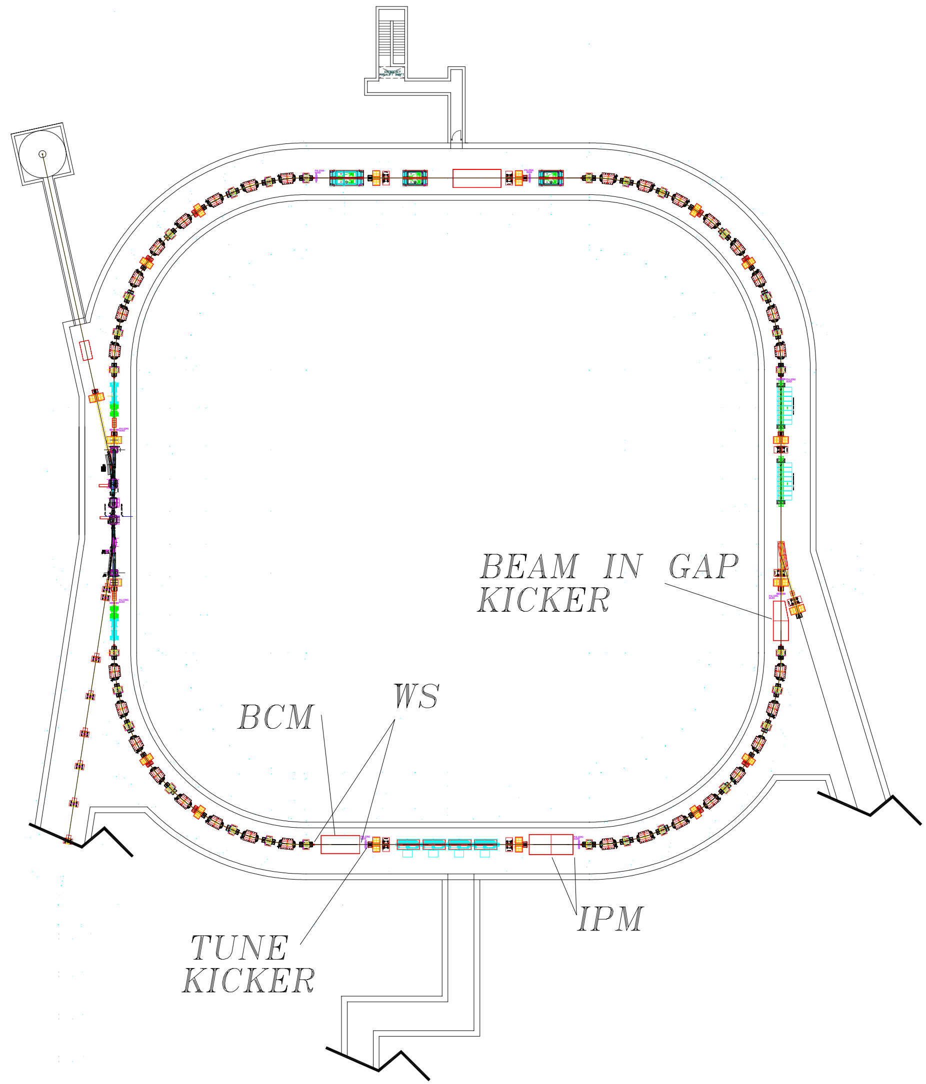


RTBT

- BPM Position
- BLM+Fast BLM
- BCM
- Wire Scanner
- Target HARP

Ring Diagnostic Systems

- BPM
- BLM+Fast BLM
- Beam-in-Gap
- Ionization Profile Monitor
- Wire Scanner
- Coherent Tune
- Incoherent Tune
- BCM
- Wall Current
- Electron Detectors
- Quad/Oct Moment Monitor

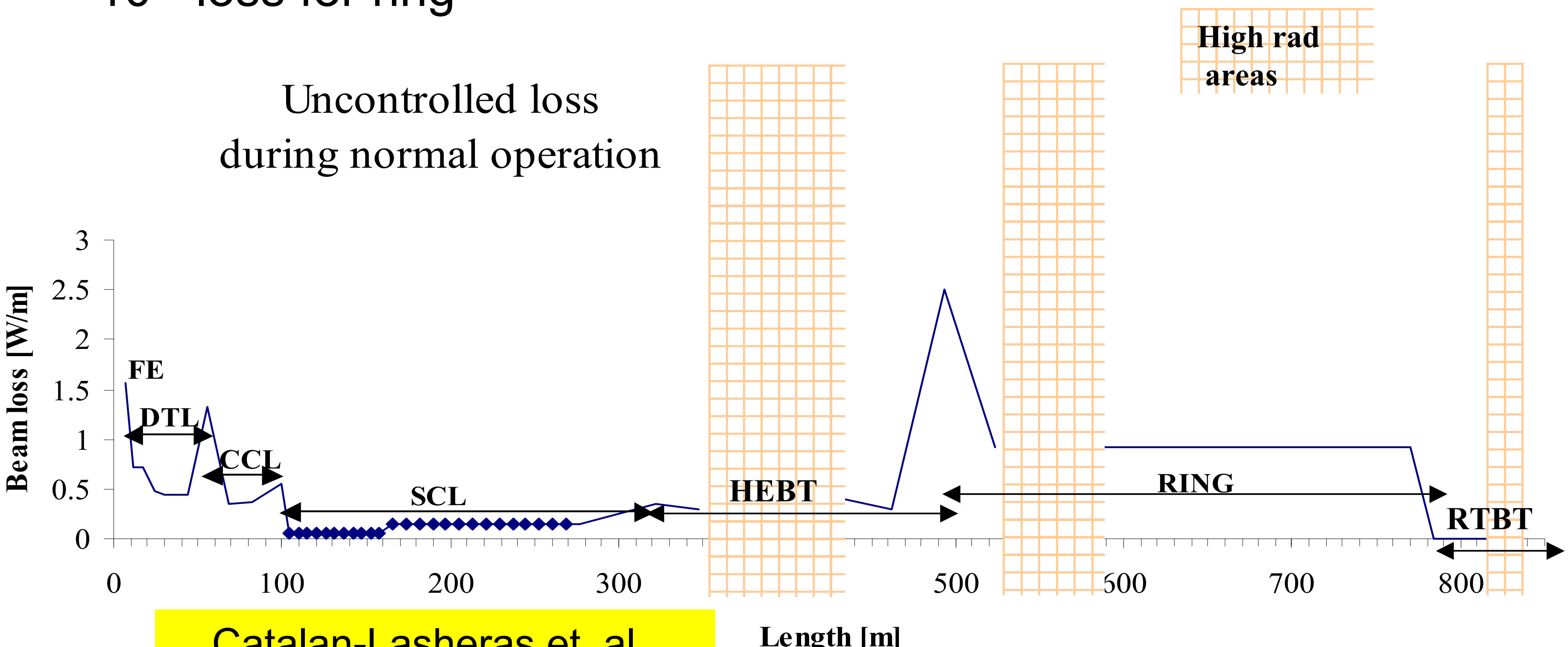


Accelerator Physics Requirements for Diagnostics

Device	Location	Intensity [ppp]	Pulse length [μ sec]	Range	Accuracy	Resolution	Data structure	Comments
BPM	MEBT	5e10 - 2e14	.3 - 1000	+/- 0.5*apert	+/-.5mm	.05mm	inside mini pulse	6, dual plane
(position)	DTL	2e10 - 2e14	.3 - 1000		+/- 1% of a	0.1% of a		?, dual plane
	CCL-SCL	2e10 - 2e14	.3 - 1000		+/- 1% of a	0.1% of a		
	HEBT	5e10 - 2e14	.3 - 1000	+/- 20mm	+/-1%	1%		20/38 each quad, dual plane, 402.5M
	Ring-RTBT	5e10 - 2e14		+/- 100 mm	+/-1 %	0.5%	turn-by-turn	each quad/doublet, dual plane,402.
BPM	MEBT	5e10 - 2e14	.3 - 1000	+/- 180 deg	+/-2 deg	0.1 deg		6, 805MHz
(phase)	DTL	2e10 - 2e14	.3 - 1000	+/- 180 deg	+/-2 deg	0.2 deg		?, 805MHz
	CCL-SCL	2e10 - 2e14	.3 - 1000	+/- 180 deg	+/-2 deg	0.2 deg		?, 402.5MHz
	HEBT	5e10 - 2e14	.3 - 1000	+/- 180 deg	+/-2 deg	0.1 deg		2?, 402.5MHz
IPM	Ring	5e10 - 2e14		+/- 64 mm	2 mm	2 mm	few per turn	three planes (H, V, 45 deg.)
Wire	MEBT		.3 - 100	+/- 15mm		0.2mm		three planes
	DTL							
	CCL-SCL		.3 - 100	+/- 15mm		0.2mm		three planes; each cryo.
	HEBT	5e10 - 2e11	.3 - 1000	+/- 50mm	10% rms	5% rms	40 kHz	SEM; three planes
	Ring	5e10 - 2e14		+/- 100mm	10% rms	5% rms	40 kHz	SEM+FBLM; three planes
	RTBT	2e12 - 2e14		+/- 100mm	10% rms	5% rms	40 kHz	SEM+FBLM; three planes
Harp	DTL		.3 - 50	+/- 10 mm		1mm		after tank #3,#6; comissioning
	HEBT,RTBT	3e11-2e14		+/- aperture	1mm p.	.5mm	single shot	
Misc. profile	D-plate		.3 - 1000					video fluorescence
	Foi Video Ring	5e10 - 2e14			+/-1mm	1 mm		foil video 2 systems
BLM(10 Hz)	Linac-Ring	1e7 - 2e14	.3 - 1000	1-1000 rem/h	1%	0.6%, .5r/h	average at 10Hz	of 1W/m
BLM(35 kHz)	Linac-Ring	6e8 - 2e14	.3 - 1000	30-2.5e5 rem/h		30r/h	once /10 turns	
FBLM	DTL-to-CCL		.3 - 1000	1-1000 rem/h			inside mini pulse	fast; not calibrated
	SCL-to-HEBT		.3 - 1000	1-1000 rem/h			inside mini pulse	fast; not calibrated
	Ring			1-1000 rem/h			intra turn	fast; not calibrated
Current	MEBT-to-HEBT		.3 - 1000	15mA - 52 mA	+/- 1%	.1%	inside mini pulse	
	Ring-RTBT	5e10 - 2e14		15mA-100A	+/- 1%	.5%	turn-by-turn	
Tune	Ring - Coherent				+/- 0.001	+/- 0.0005	req. averaging	tune kicker/pick-up
	Ring -Incoherent				+/- 0.005	+/- 0.001	req. averaging	BTF and QM
Beam-in-gap	Ring			0 - 0.1 A	20%		TBT	BIG kicker/monitor
Emitance	MEBT		.3 - 10		10%			H & V
	D-plate		.3 - 50		10%			H & V
e - detectors	Ring			2e8 - 2e11 (e-)	5%	1e8 (e-)	turn-by-turn	conspicuous locations
WB BPM	Ring			+/- 1-60 mm?	+/-1 mm	0.5 mm	turn-by-turn	100MHz BW
Laser wire	SCL		.3 - 1000	+/- 15mm		.5mm ?		dual, three plane ?
HM monitor	Ring							"High moments" of transverse distr.

Most Critical Design and Operational Issue: Uncontrolled Beam Loss

- Hands-on maintenance: no more than 100 mrem/hour residual activation (4 h cool down, 30 cm from surface)
- 1 Watt/m uncontrolled beam loss for linac & ring
- Less than 10^{-6} fractional beam loss per tunnel meter at 1 GeV; 10^{-4} loss for ring



Catalan-Lasheras et. al., EPAC 2002

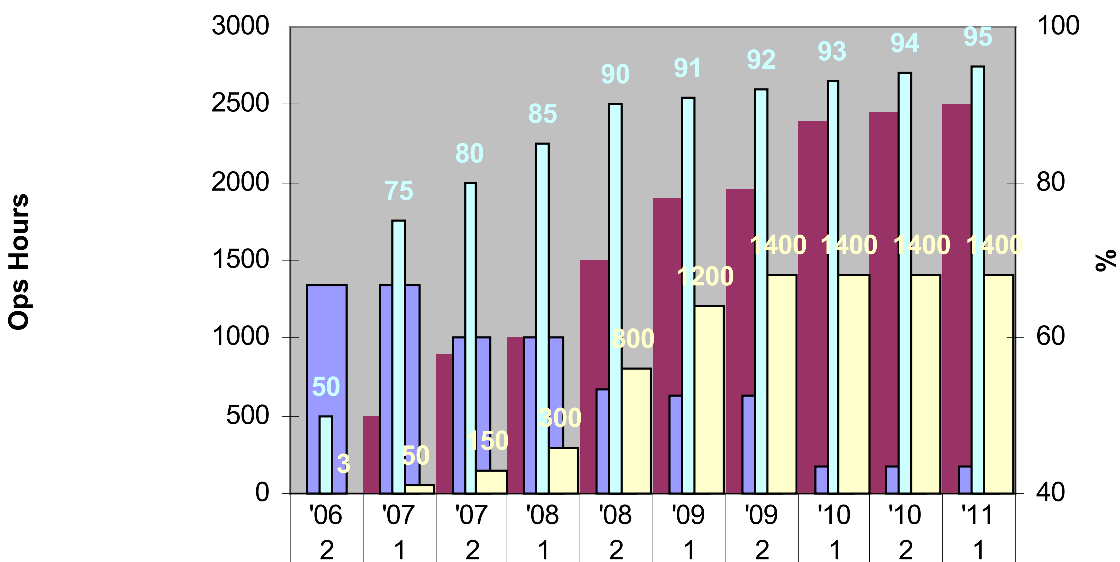
Sources of Uncontrolled Beam Loss

- Linac:
  - Optical and Steering Errors and aperture restrictions
  - Mismatch at structure interfaces (MEBT/DTL, DTL/CCL, CCL/SCL)
  - Partially chopped beam (partial deflection in chopper system)
  - Halo generation in front-end where space-charge is doing most damage
  - Space-charge driven Halo and Emittance growth: RMS mismatch, Coherent SC resonances, parametric resonances driven by mismatch oscillations, equipartitioning, …
- Ring:
  - Optical and Steering Errors and aperture restrictions
  - Injection losses (H- stripping losses, foil hits, injection errors, etc.)
  - Space-charge induced halo and emittance growth
  - Beam-in-gap during ring extraction kicker risetime
  - Collective instabilities: resistive wall, microwave, electron cloud

SNS Reliability is Expected to Reach 95% (!!)

- Diagnostics are on the Front-Lines of Operational Problems: Rapid diagnosis, diagnostics systems accumulating info all the time, etc……

Accelerator Availibility and Operation



	'06 2	'07 1	'07 2	'08 1	'08 2	'09 1	'09 2	'10 1	'10 2	'11 1
User Ops hours	0	500	900	1000	1500	1900	1950	2400	2450	2500
Accel. Phyics	1344	1344	1008	1008	672	624	624	168	168	168
Beam Power/kW	3	50	150	300	800	1200	1400	1400	1400	1400
Reliability (%)	50	75	80	85	90	91	92	93	94	95

Years

User Ops hours · Accel. Phyics · Beam Power/kW · Reliability (%)

Diagnostic Uses and Timeline

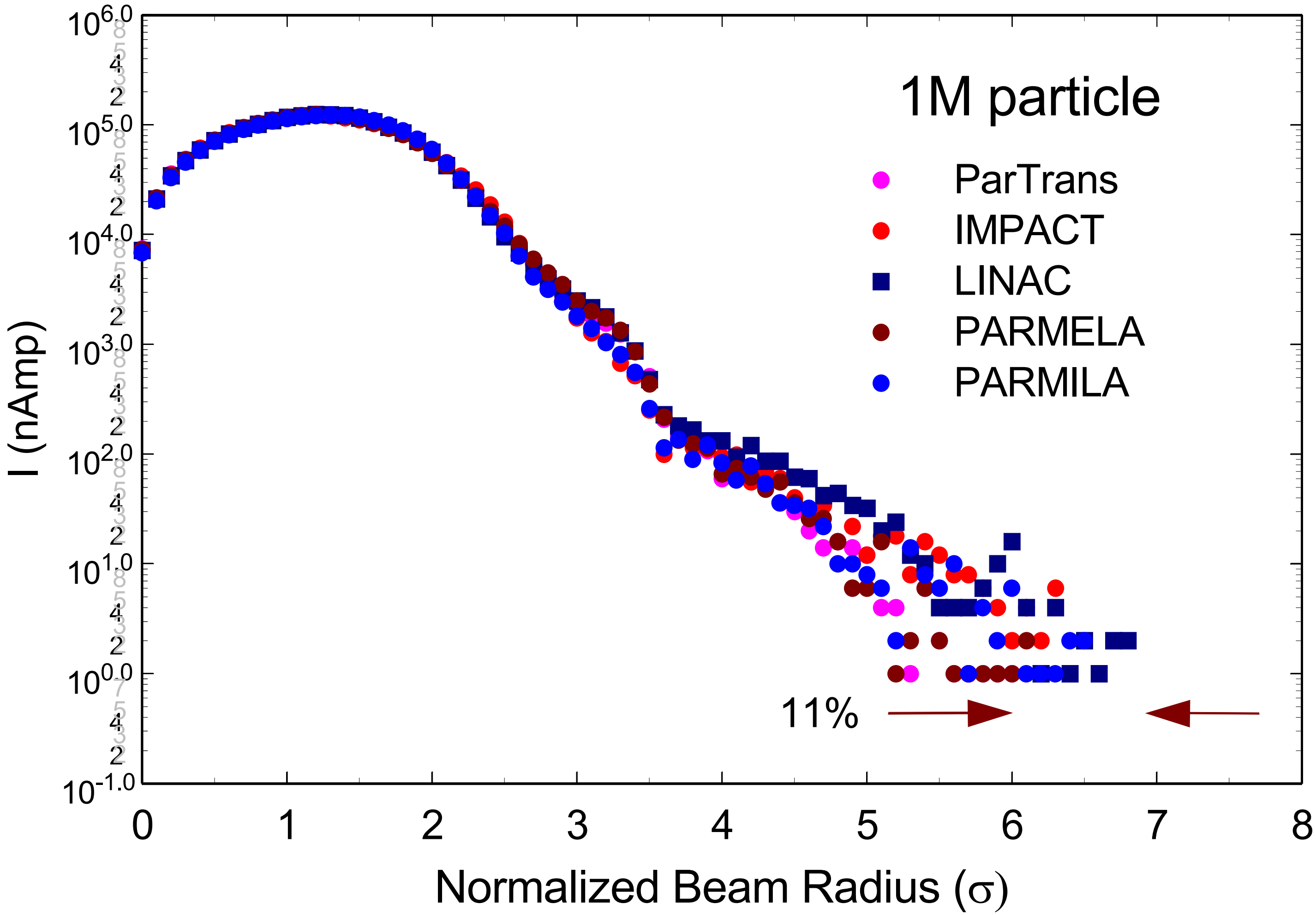
- Commissioning Linac and Ring at low intensity (BPM pos+phase, BLM, BCM, profile, tune)
  - Identify and correct gross errors
  - Trajectory and Orbit Control
  - Linear Optics Measurement and Correction
  - Establish proper RF setpoints
  - Establish injection conditions (first-turn measurement capability in ring)
- Transition to Full Intensity in Linac (BLM, profile)
  - Various mechanisms of emittance/halo growth: with appropriate diagnostics, opportunity to unravel high-intensity physics!
  - Needs: profile measurements capable of resolving halo
  - Would be useful to have single-shot profile measurements on single linac bunch through acceleration rather than averaged quantities (HARP vs. WS; Laser Harp??)
- Transition to Full Intensity in Ring (BLM, tune, profile, WB BPM, WCM)
  - Lots of high-intensity Ring Physics encountered: Space-charge effects, collective instabilities, electron-cloud, RF system beam-loading
  - With appropriate diagnostics, opportunity to unravel high-intensity physics and limitations
  - Needs: track many parameters through accumulation and along bunch length (tunes, profiles, tune vs. bunch length, tune footprint)

Diagnostic Uses and Timeline

- Transition to Full Power in Linac and Ring
  - High-intensity physics + effects related to longer pulse and high-power delivered through RF structures
    - RF controls
    - Thermal effects
    - Sensitivity to losses
    - Machine “stability” and “reproducibility”
    - Machine Protection
  - Needs: diagnostics capable of full pulse length, rep-rate, etc!
  - Needs: beam observables vs. time in pulse in linac!
  - Laser Wire will give info but ultimately need more and better
- Operations:
  - Diagnose machine problems quickly and routinely to achieve high reliability. (What is different from yesterday when the machine worked?)
  - Needs: correlate many diagnostic signals with other variables (RF parameters, temperatures) to analyze post-mortem events to diagnose complicated system of many interdependent-variables.

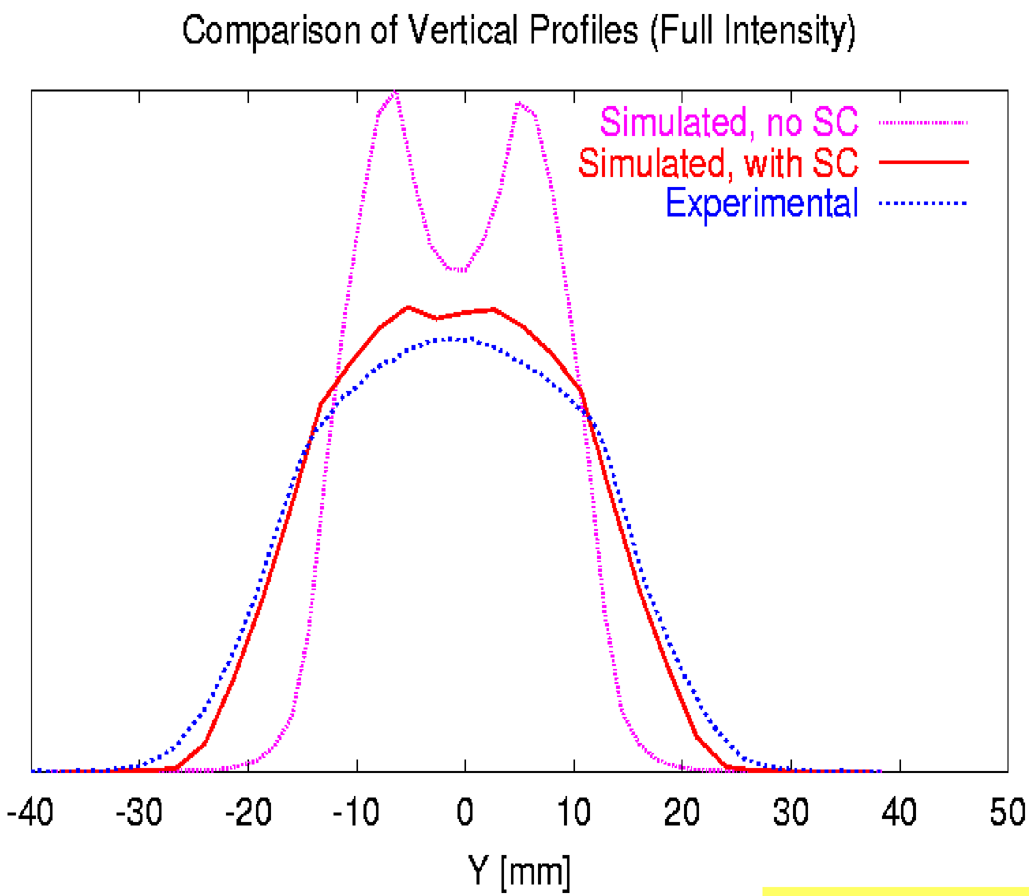
Halo Development and Prediction: Code Comparison of Radial Distribution at Tank 1 Exit

- Need measurement sensitivity to 10^{-4} in beam tails to understand and diagnose halo



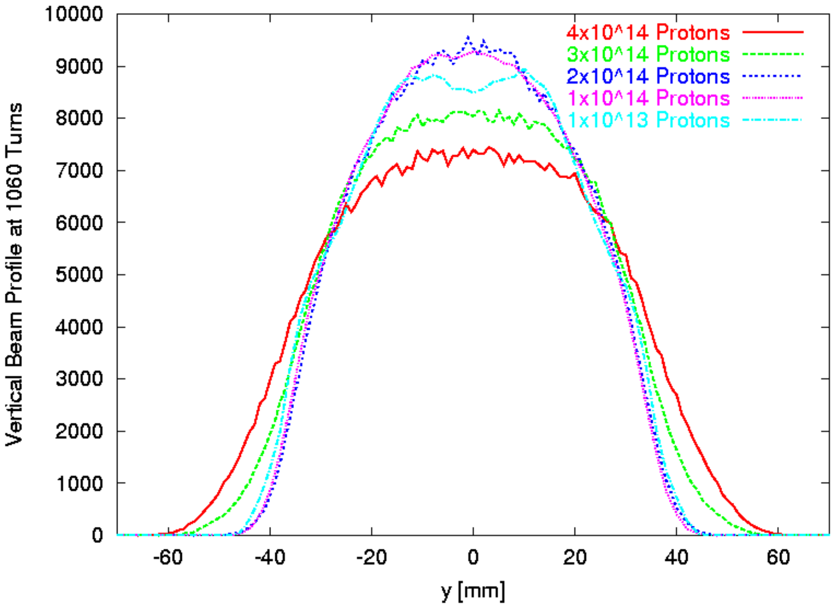
Space-charge Induced Broadening in the PSR Ring

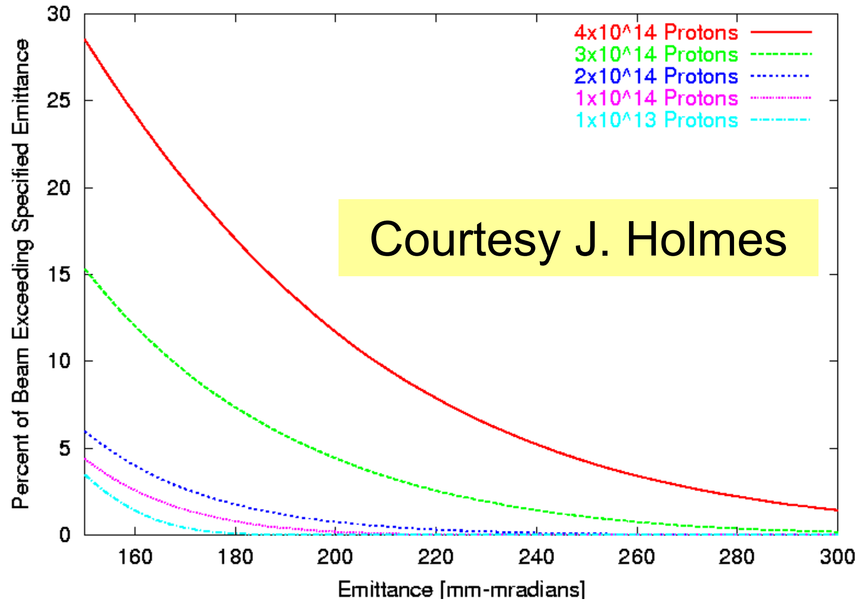
- Need to understand, accurately measure, predict and control RMS beam properties!



Courtesy S. Cousineau

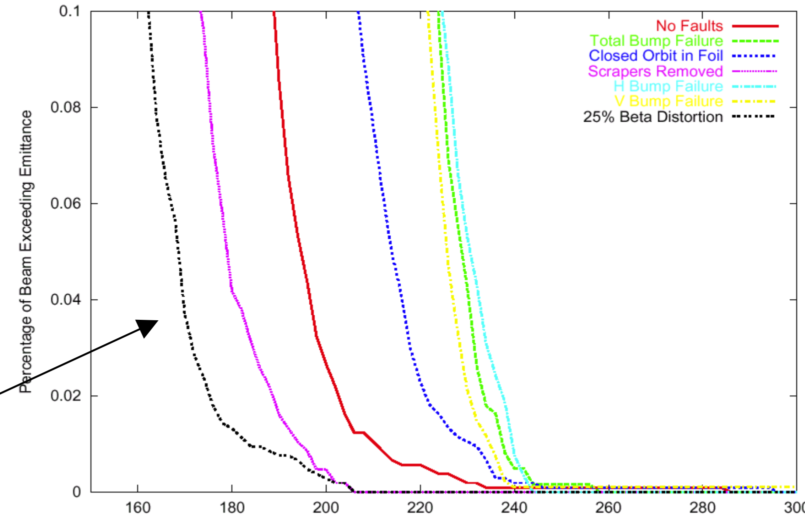
Intensity Study for SNS Accumulator Ring





- Need to measure down to 10^{-3}-10^{-4} levels to unravel halo growth mechanisms

Ring Painting Fault Scenarios

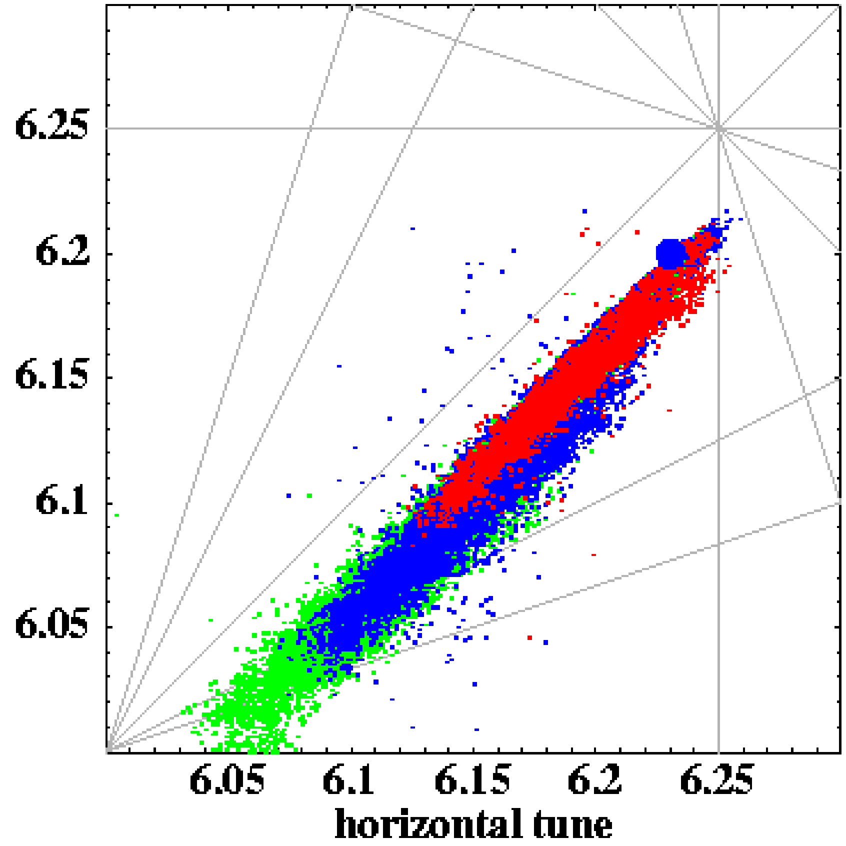


Space Charge Tune Spread Evolution During SNS Ring Accumulation (6.23, 6.20)

N=0.5*10^{14} – 263 turns

N=1.0*10^{14} – 526 turns

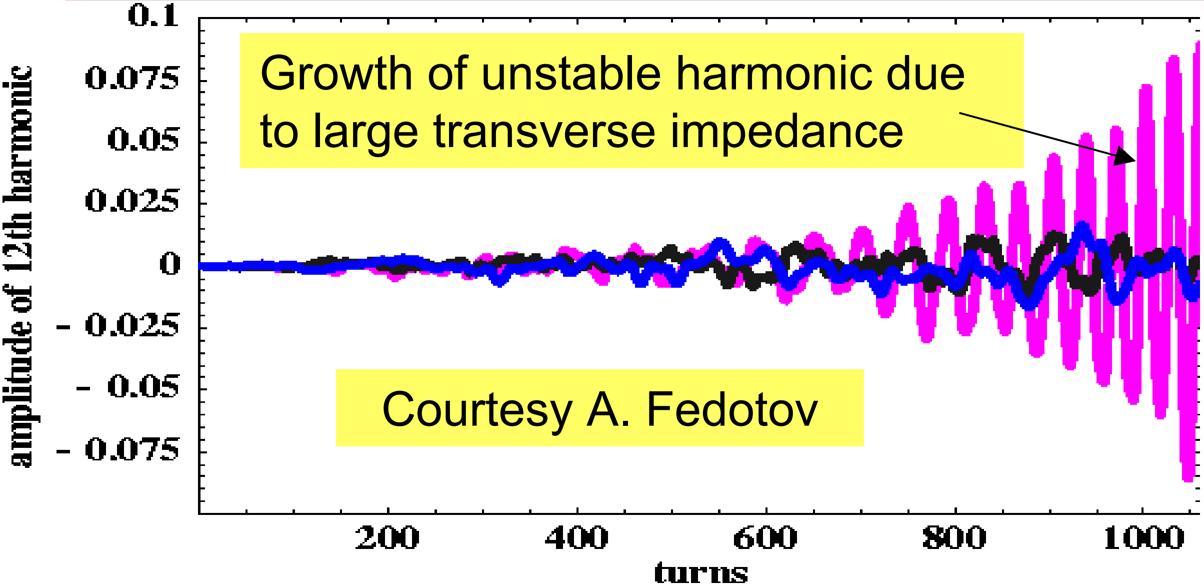
N=2.0*10^{14} – 1052 turns

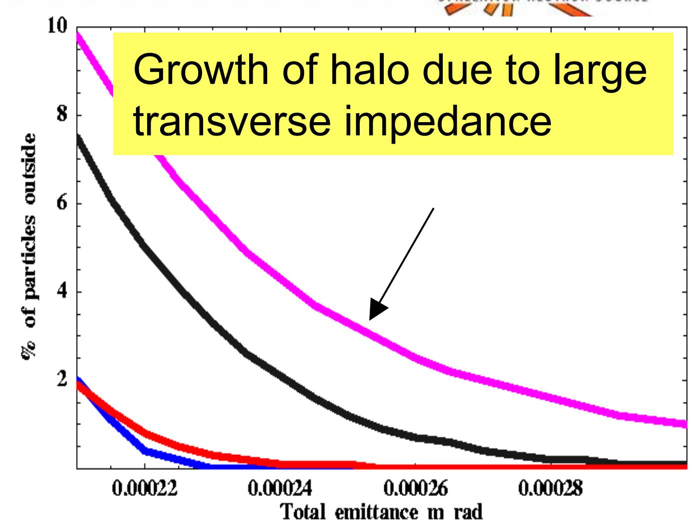


Need to measure, predict and control tune footprint!

Courtesy A. Fedotov

Collective Instabilities in the Ring

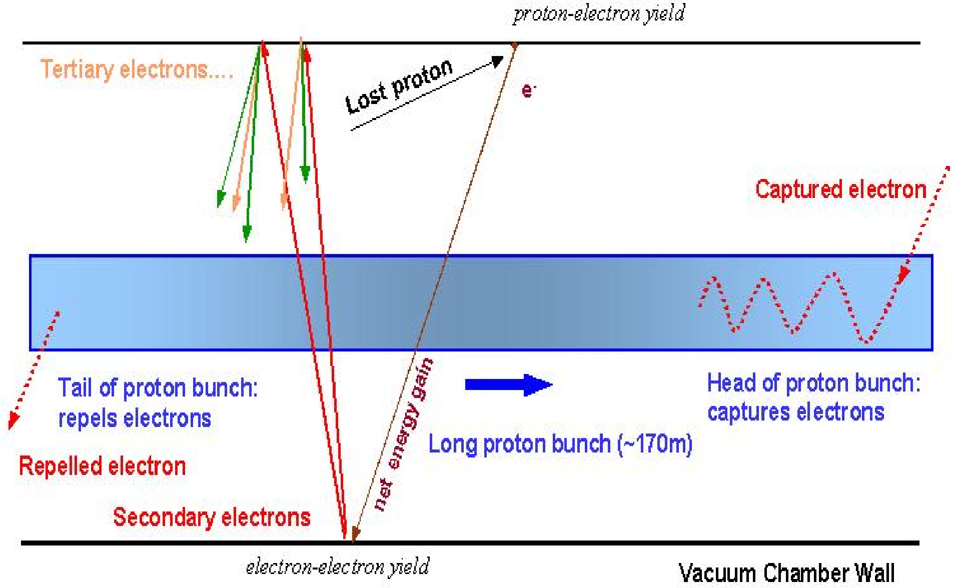




- Eventually, all machines hit a limit from collective instabilities
- Need diagnostics up to the task of diagnosing instabilities:
  - Which plane?
  - Which frequencies?
  - Which modes (dipole, quad, etc.)
  - Growth rates and thresholds
- Needs:
  - Wideband BPMs
  - Tunes vs. bunch length
  - Tune trajectory during accumulation
  - Moment monitors
  - Transducers for feedback:
    - Dipole, quadrupole, higher-moment

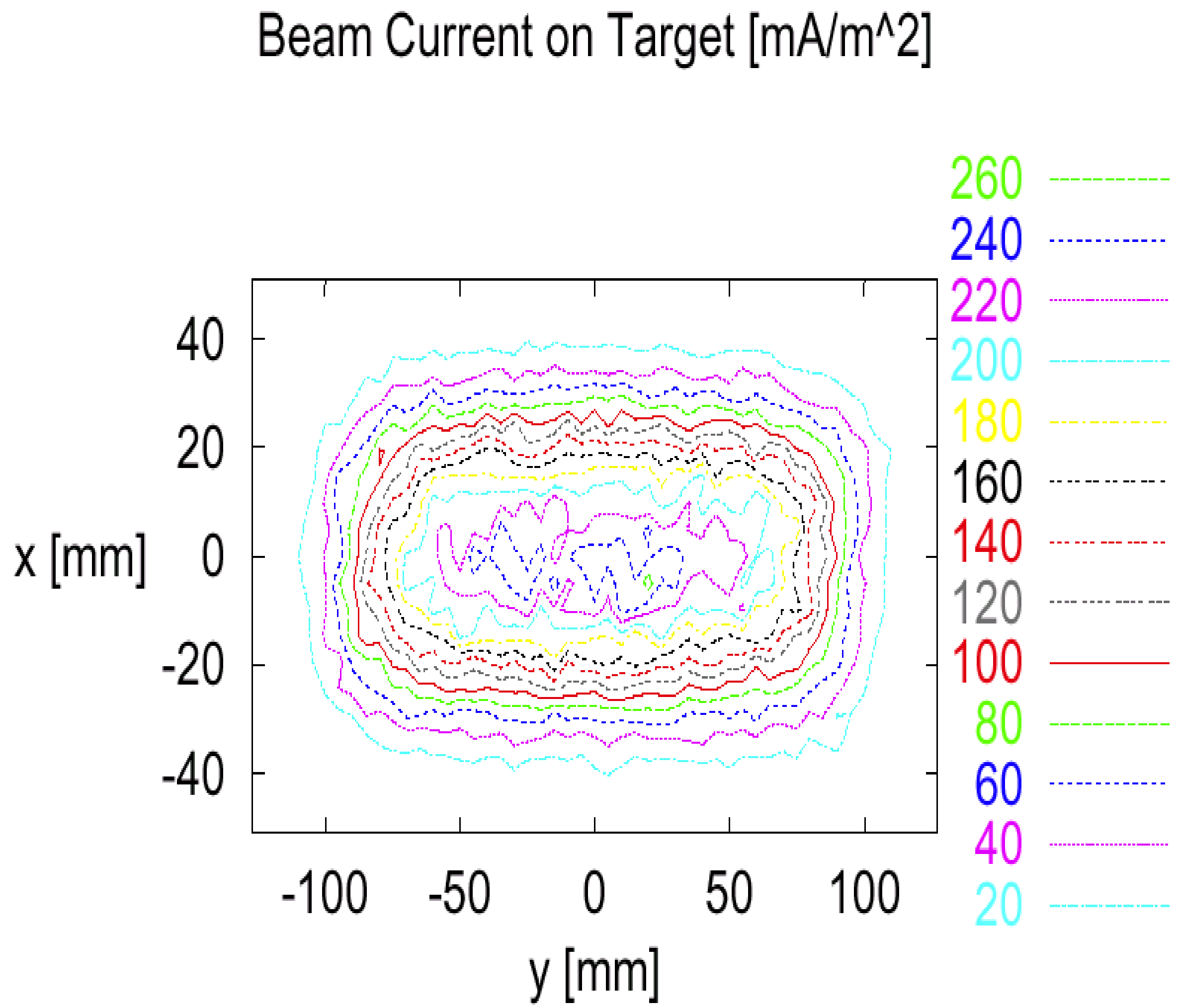
Electron Cloud Effects

- Many uncertainties ….complicated physics problem which must be unraveled with careful experimentation:
- Quantities that need measurement/control:
  - Surface properties (In-situ SEY monitor)
  - Electron densities across chamber aperture (in beam vs. at wall) vs. time
  - Neutralization (Tune shift vs. bunch length)
- Wideband Feedback



Measurement and Control of Beam Profile on Target is Critical!

- Is there an easy diagnostic which makes use of interaction of 1.4 MW beam with a thick window, or with 20cm Hg?



Wish List, Crazy Ideas, Random Thoughts

- Single linac bunch profile diagnostics – not averaged!
- Laser-based HARP ??
- Beam observables vs. time in linac pulse
- Diagnostics capable of handling full pulse length and rep-rate
- Halo/beam tail measurement capability to 10^{-4} level
- Incoherent tune (tune footprint)
- In-situ Secondary Electron Yield Monitor
- Electron Cloud Monitor (across chamber aperture)
- Beam profile on target measurement
- As long as we're at it, how 'bout 6-d phase space tomography?
- Apply "Learning" methods (neural networks, etc.) for complicated tuning problems (losses, luminosity) rather than simple single variable optimization x N variables