ACCELERATOR PHYSICS ISSUES

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SNS/ORNL Accelerator Physics

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Primary concern: *radio-activation*

- Linac hand-on maintenance achieved at LANSCE
  - 0.13 nA/m loss for 1 mA, 800 MeV proton beam
- High ring radio-activation at injection, extraction,collection
  - AGS: up to 1 rem / hour at localized area
- High ring beam loss
  - FNAL Booster (25 - 40%): ramp tracking, debunching-recapturing, transition, aperture!
  - AGS/Booster (20 – 30%): pushing record intensity
  - ISIS (~15%): injection capture, initial ramp
  - PSR (0.3%! Full energy accumulation): injection loss
- 100 – 200 mrem / h average activation (30 cm, 4h down)
- 1 – 2 W / m maximum average beam power loss

Past activities

- Choice of Accumulator Ring (May 1999)
  - Rapid-cycling-synchrotrons: preferred for upgradeable ring-cluster configuration; preferred for realizing short bunch length
  - Accumulators: preferred for loss minimization
- Choice of Super-conducting RF linac (March 2000)
  - Constructional/operational cost savings: definite choice for CW applications; about even for SNS (6% duty)
  - Lower-loss, higher maintainability: potentially higher energy, higher power at a shorter length; larger bore & lower loss; maintainability & reliability (tolerable to missing cavity, two-type-fit-all)
  - Technology of the future: support from community/industry
- Choice of 1-klystron-per-cavity for SRF linac control (June 2000)
  - $\beta << 1$, requires longitudinal focusing & control
  - Injection jitter, Lorentz detuning, microphonics, beam loading/transient

Linac emittance comparison

Machine	Energy [MeV]	Peak current (in) [mA]	Peak current (out) [mA]	Emittance (in) [p mm mr]	Emittance growth (times)	Species	Comments
IUCF	7	1	1	0.3	3.3	P	RFQ/PMQ
IHEP©	35	250	40	3	2	P	
KEK	40	25	18	0.4	3	P	
DESY	50	60	18	0.6	3.3	H-	RFQ
CERN	50	300	150	0.8	6.3	H-	RFQ
RAL	70	35	25			H-	RFQ
IHEP®	103	300	100	0.2	10	P	
BNL	200	100	40	0.4	5	H-	RFQ
FANL	400	100	50	0.1	15	H-	
INR	423	250	20	0.5	3	P	
LAMPF	800	20	16	0.09	5 -- 8	P	
SNS	1000	56	52	0.2	2.5	H-	RFQ/PMQ

- Key figure of merit for SNS linac performance:
  - Emittance preservation & pulse-to-pulse transverse jitter control
  - Energy spread preservation & pulse-to-pulse energy jitter control
  - Consider measurement conditions & factors (vibration sensitivity …)
  - How well does measurement agrees with simulation?

SC RF linac comparison

	SNS	JJP	ESS	SPL	APT	TRASCO/ASH
Institute	DOE 6 labs.	JAERI/KEK	EU	CERN	LANL	INFN/CEA
frequency [MHz]	805	972	700	352.2	700	704.4
Eergy [MeV]	185 -- 1250	400 --600	70--1334	120 - 2200	212 -- 1030	85--2000
Beam Power [MW]	> 2	0.75	5	4	103	4
Rep. Rate [Hz]/Pulse length [ms]	60/1	60/0.75	50/1	75/2.2	CW	CW
Length [m]	237	110	~300	691	514	506
Real estate acc. Gradient [MV/m]	4.5	1.82	~4.3	3	1.6	3.8
Number of β	2	2	4	4	2	3
Cavity β (geometrical)	0.61, 0.81	0.73, 0.77	0.5, 0.6, 0.75, 0.9	0.52, 0.7, 0.8, 1	0.64, 0.82	0.5, 0.68, 0.86
peak (avg.) current [mA]	52 (2)	50	107 (3.75)	67 (11)	100 (100)	20 (20)
Max. acc. grad. (interial cell) [MV/m]	10.5, 12.8	9.9, 10.5	~10	3.5, 5, 9, 7.5	6.1, 7.1	8.5, 10.2, 12.3
peak surface E_{peak} [MV/m]	27.5	30.2, 29.9	n/a	?	19.0, 19.7	30.4, 26.5, 29.2
peak surface H_{peak} [mT]	57, 59	52.5	n/a	?	42.3, 44.5	50
Inter-cell coupling (%)	1.6	2.9, 2.6	n/a	?	?	1.34, 1.1, 1.28
number of cavities	117 (33+59+25)		~168	230	242	234
lattice	warm doublet	warm doublet	warm doublet	warm doublet	warm doublet	warm doublet
longitudinal phase law	const grad/cont. F	equal phase slip			constant power	
transverse phase law	constant gradient	equipartitioning			const. phase adv	
rf control	invididual	vector sum		invid/vector sum	vector sum	vector sum
cavity / klystron	1	2	?	?	(2,3), 2	2,2,4
cell / cavity	6	7	5	4,4,5,4	5	5,5,6
cavity / cryomodule	3, 4	2	2	3,4,4,4	(2,3), 4	2,2,4
power coupler/cavity	1	1	1 or 2	1	2	1
Applications	Neutron scattering	transmutation	Neutron scattering	neutrino factory	tritium production	transmutaion

Chopper design

- Three-stage chopping
  - LEBT: chops with > 10^2 on/off ratio @ 65 keV; electrostatic plates
  - MEBT: chops with > 10^4 on/off ratio @ 2.5 MeV; traveling wave plates
  - Ring: cleans ~ 10^{-4} residual @ 1 GeV; strip-line kicker
- Partially chopped beam & image charge
  - Rise-time: LEBT 50 ns (20 pulse); MEBT & ring 10 ns (4 pulse)
  - MEBT anti-chopper, identical but 180 degree in phase
  - Image charge effect causes about 1% deflection change
- Chopper & anti-chopper misfire
  - Hardware/controls system protection for more than one-pulse misfire
  - Anti-chopper misfire causes foil miss of less than 1% beam
- Testing
  - LEBT chopper tested at 40 keV test stand with protons
  - Ring chopper principle verified at NSLS and HERA

End-to-end evolution & simulation

	IS/LEBT	RFQ	MEBT	DTL	CCL	SCL (1)	SCL (2)	HEBT	Ring	RTBT	Target	Unit
Energy, W (in)		0.065	2.5	2.5	86.8	185.6	379.2	948.7	948.7	948.7	948.7	MeV
ΔW							(+/-)	(+/-)	(+/-)	(+/-)	(+/-)	
ε (n, rms)	0.09/0.2	0.19-0.21	0.22-0.27	0.27-0.29	0.29-0.33	0.33-0.4	0.34-0.56	0.34-0.59	44+44	44+44		mm mr
ε (un, 99%)									120+120	120+120		mm mr
Trans. jitter							0.3 (+/-)	0.3 (+/-)	0.3 (+/-)	0.3 (+/-)		mm
ΔE (rms)		.005-.01	.007-.015	.09-.092	0.13-0.15	0.19-0.27	0.27-0.51					MeV
ΔE (jitter)							1.6 (+/-)	0.25 (+/-)				MeV
ΔE (full)								4 (+/-)	10 (+/-)	10 (+/-)		MeV
I (out, peak)	65	56	56	56	56	56	56	56	9.e4	9.e4		mA
Length	0.12	3.72	3.66	36.81	57.47	64.229	172.45	169.49	248	150.75		m
Codes used	IGUN	PARMTEQ	PARMILA	PARMILA	PARMILA	PARMILA	PARMILA	PARMILA	UAL/ORBIT	PARMILA		
N (macro)	200	1e4/1e6	1e4/1e6	1e6/1e5	1e6/1e5	1e6/1e5	1e6/1e5	1e6/1e5	4.e4/1.e5	1e5		
random seeds	1	10/100	10/100	1/10	1/10	1/10	1/10	1/10	10	10		
Loss (control)	0.27	0	0.05	0	0	0	0	0-0.001	0.02 - 0.1	0		
Loss (uncont.)	~ 0.1	0.08	< 0.01	0	0	0	0	1.e-5	0.00014	0	0.04	
ε (rms) growth		5%	19%	18-%	12-%	14-%	3-%	0-11%	5%	3%		
ε (99%) growth								0-20%	10%	5%		
Included	sp. ch.	sp. ch.	sp. ch.	space charge		space charge		sp. ch.	painting	sp. ch.	window	
	Initial	align err.	Quad	rf phase/amp. error		rf phase/amp. error		rf error	space charge	rf error	scatt.	
	electrns		mag. err	quad gradient error		quad gradient error		quad err	magnet error	quad err		
	Ion temp			quad roll		Lorentz detuning		misalign	aperture	misalign		
				cavity-to-cavity tilt		quad roll		quad roll	magnet offset	quad roll		
						cavity-to-cavity tilt						
Excluded	Dumping	Fringe errors		quad misalignment		quad misalignment		linac H0	impedance	collimator		
	mag field			multipoles		multipoles		foil/collim	quad roll	scattering		
	misalign			DTL/quad vibration		missing cavities		scatt.	scattering			
	LEBT-RFQ handover					rematching			beam loading			
						HOM analysis			collimation			
						transient analysis			fringe field			
						quad vibration						
Open issues	will use msrd LEBT distrib.s								ext kicker imp			
									electron cloud			
									fast correction			

Loss & activation (expected)

Item	Controlled loss	Uncontrolled loss		Beam-off residual		Beam-on	
	(fractional)	(fractional)		activation [rem/h]	heat load	damage	background
	(integral)	(integral)	(loss/meter)	(4 h down; 30 cm)	[Watt]	[rad/h]	
IS/LEBT charge exchange		~0.1		none			
LEBT chopper	0.277			none			
LEBT beam recombination		< 0.005		none			
RFQ transmission		0.08		none			
MEBT chopper	0.042			none			
MEBT beam recombination		< 0.005		none			
Linac H- gas stripping			< 1.e-7/m		< 0.2 W/m		
Linac (warm)			< 2.5e-6/m	< 0.1	< 1 W/m		
Linac (SRF)			< 5.e-7/m	< 0.1	< 1 W/m		
HEBT collimators	1.e-3	1.e-5			2 kW		
HEBT H- magnetic stripping			< 1.e-8/m		< 0.02 W/m		
HEBT H- stripping			< 1.e-7/m		< 0.2 W/m		
Ring foil miss	0.02 - 0.1				40 - 200 kW		
Ring foil nuclear scattering		3.e-5			60 W		
Ring collimation section	2.e-3	1.4e-4		6.3 - 9.9	4 kW	100 - 1500	
Ring extraction section			< 5.e-7/m	< 0.1	< 1 W/m		
Ring arc section			< 5.e-7/m	< 0.1	< 1 W/m		
Ring rf section			< 5.e-7/m	< 0.1	< 1 W/m		
RTBT collimation region		1.e-6			2 W		
RTBT (non-collimation)							
Target window		0.04			80 kW		
Goal	0.1		5.e-7/m				

AP requirements on 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	5e10 - 2e14	.3 - 1000		+/-.5mm	+/-.05mm		?, dual plane
	CCL-SCL	5e10 - 2e14	.3 - 1000		+/-1mm	+/-.1mm		
	HEBT	5e10 - 2e14	.3 - 1000		+/-1mm	+/-.1mm		20/38 each quad?, dual plane,
	Ring-RTBT	5e10 - 2e14		+/- 1-20 mm	+/-1 mm	0.15 mm	turn-by-turn	each quad/doublet, dual plane
BPM	MEBT	5e10 - 2e14	.3 - 1000	+/- 180 deg	+/-2 deg	0.1 deg		6, 805MHz
(phase)	DTL	5e10 - 2e14	.3 - 1000	+/- 180 deg	+/-2 deg	0.1 deg		?, 805MHz
	CCL-SCL	5e10 - 2e14	.3 - 1000	+/- 180 deg	+/-2 deg	0.1 deg		?, 402.5MHz
	HEBT	5e10 - 2e14	.3 - 1000	+/- 180 deg	+/-2 deg	0.1 deg		2?, 402.5MHz
IPM	Ring	5e10 - 2e14		+/- 1-100 mm		1mm	turn-by-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		.3 - 1000	+/- 50mm		0.2mm		three planes
	Ring-RTBT	5e10 - 2e14		+/- 1-100mm		0.2mm	turn-by-turn steps	three planes
Harp	DTL		.3 - 50	+/-10 mm		1mm		after tank #3,#6; comissioning
	RTBT							
Misc. profile	D-plate		.3 - 1000					video fluorescence
	Ring							foil video
BLM	DTL-to-CCL		.3 - 1000	1-1000 rem/h	10% ?	1rem/h	100 mini pulses?	
	SCL-to-HEBT		.3 - 1000	1-1000 rem/h	10%	1rem/h	100 mini pulses?	
	Ring-RTBT	1e7 - 2e14		1-1000 rem/h	10%	1rem/h	average/turn-by-turn	
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	0 - 52 mA	1%	.1%	inside mini pulse	
	Ring-RTBT	5e10 - 2e14		0.015-100A	1%	.1%	turn-by-turn	
Phase width	HEBT		.3 - 1000	0 - 600ps	15ps (5deg)	15ps (5deg)		??? LANL
Tune	Ring				+/- 0.01			tune kicker/pick-up
Beam-in-gap	HEBT		.3 - 1000	0 - 0.1mA	20%	.5mkA	each midi pulse	laser neutralization
	Ring			0 - 0.1 A	20%			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	MEBT, DTL, ...?		.3 - 1000	+/- 15mm		.5mm ?		dual, three plane ?
HM monitor	Ring ?							"High moments" of transverse dis

Open issues & to-do list (Overall)

– Detailed loss and activation distribution & protection
    - (project office, N. Catalan-Lasheras, instrumentation, …)
– AP diagnostics requirements and measurement procedure
– More coherent end-to-end simulation
– “standard” simulation codes from RFQ to Ring foil
    - (H. Takeda with D. Raparia & J. Staples)
– Impact of ground motion, settlement, misalignment, vibrations
– Target requirements (distribution, margin, protection)?
    - (D. Raparia, J. Beebe-Wang, Target group, …)
– Application software (J. Galambos, N. Malitsky, S. Sathe …)
– Common ring/line software (UAL / ORBIT) (N. Malitsky, A. Fedotov, J. Holmes, S. Danilov, S. Cousineau …)

Open issues & to-do list (Front End)

- Ion source lifetime and reliability at 65 mA? (R. Keller)
- Protection of MEBT chopper from stray beam?
- Possible requirements to extend the MEBT beam steering capabilities to paint the DTL acceptance space?
- Issue of a MEBT beam stop
- Front-End tuning modes with minimum intrusion on linac tunnel occupation, in absence of high-power beam stop?

Open issues & to-do list (Linac)

- Alignment errors & steering/correction (S. Nath, J. Galambos, …)
- Realistic error distribution for simulation & analysis (system noise, cavity, gradient, magnetic field, alignment)
- Missing cavity & re-matching study
- Comparison of different transverse phase (quad) laws (J. Stovall)
- Linac diagnostics instrumentation & SCL cleanness protection
- Commissioning & operation plan (DTL acceptance scan, SCL phase & amplitude setting? ...) (L. Young)

Open issues & to-do list (Ring/transport)

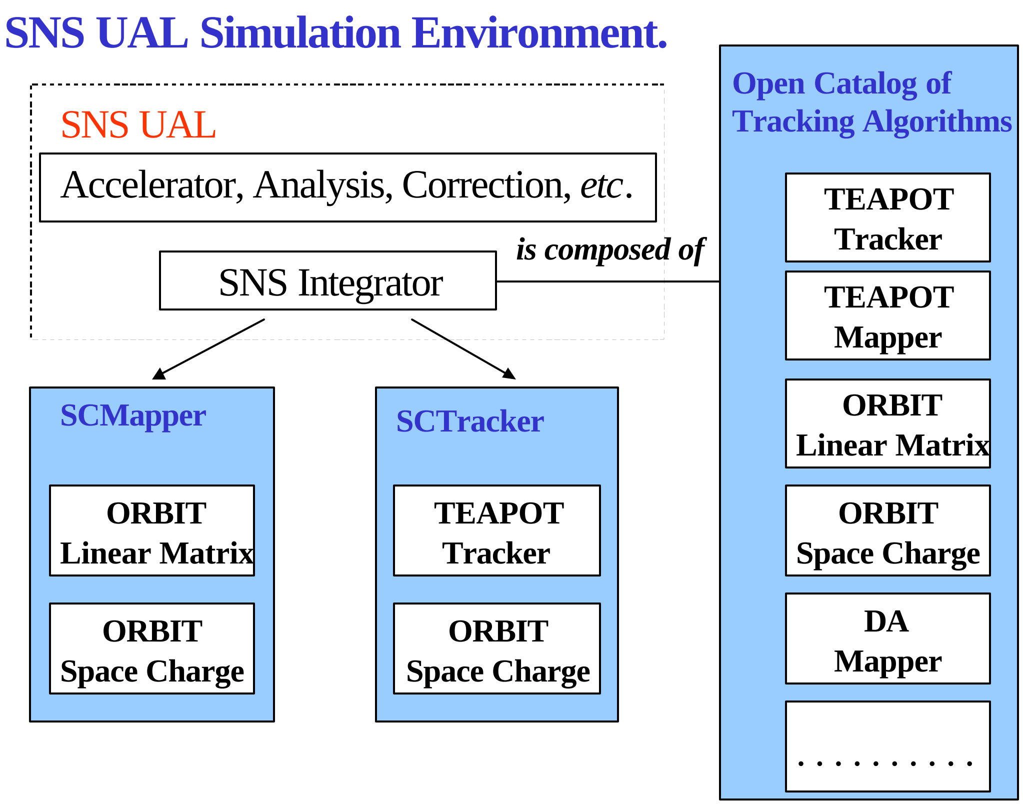
- Chromatic sextupoles (budget issue)? (N. Tsoupas, …)
- Other fast tuning correction? (Y. Papaphilippou)
- Extraction kicker & PFN layout; kicker module impedance minimization? (Y. Lee, S. Zhang)
- Magnet measurement analysis & modeling
- Detailed working point analysis to minimize space charge effect
  - (Y. Papaphilippou, A. Fedotov …)
- Painting optimization & target requirement / collimator heating
- Beam-based correction schemes
- Simulation codes development (impedance, collimator/BIG cleaner, Integrated linac-HEBT-ring-RTBT modeling?)
- Electron-cloud problem? (R. Macek, M. Blaskiewicz, …)
- Chromium oxide coating test (conductivity?) (H. Hsueh …)

Magnet & survey database

- Adopted & developed from RHIC & US-LHC magnet databases

Table name	Content
Magnets	summary, magnet name & parameters
Assembly	combined element assembly information
Integral	integral transfer function & geometric multipoles
LocalHarm	multipoles measured at one position
Hysteresis	magnetization multipoles
FidMagInfo	summary of magnet survey data
FidOpt	fiducial positions from optical survey
CenterMag	magnet center w.r.t. external reference
AngleMag	magnet field angle w.r.t. external reference
Ideal_Built	ideal fiducial position in global coordinates
As_Built	actual surveyed fiducial position in global coordinates
MagRingCheck	check-off list for ring magnets
MagHEBTCheck	check-off list for HEBT magnets
MagRTBTCheck	check-off list for RTBT magnets
MagLinacCheck	check-off list for Linac magnets
MagnetStatus	magnet status and history
MagComment	comment number for magnets
CommentList	contents of comment

Simulation environment (offline/online)



- Tracking (TEAPOT vs MAD)
- Magnetic errors
- Misalignments
- Correction
- DA mapping (vs. MARYLIE)
- Space charge (ORBIT vs SIMPSONS)
- Painting (ACCSIM)
- Aperture
- Beam in gap
- Impedance
- Collimation (K2)

Simulation codes comparison (ring/line)

	UAL	FTPOT	MAD 8	MARYLIE 3.0	ACCSIM	ORBIT	SIMPSONS
Interface	PERL API	FTPOT	MAD	MARYLIE	ACCSIM	SuperCode	SIMPSONS
MAD elements	Yes	Yes	Yes	Yes	Yes (via nodes)	Yes	Yes
Errors	Yes	Yes	Yes	No	No	No	Yes
Dynamic Processes	Yes (via PERL)	No	No	No	Injection	Yes (via SuperCode)	Bρ and RF
Tracking	Thin lenses	Thin lenses	Lie algebra	Lie algebra	Linear matrices + Thin multipole node -lenses	Linear matrices + Thin multipole node-lenses	Thin lenses
Mapping	Any order	Second order	Third order	Third order	Linear order	Linear order	No
Space Charge	2.5D	No	No	No	3D	2.5D	2D and 3D
Analysis(Twiss, …)	Yes	Yes	Yes	Yes	No	No	No
Lattice Optimization	No	No	Yes	Yes	No	No	No
Correction(Orbit, …)	Yes	Yes	Yes	Some	No	No	No
Integration of several lattices	Yes	No	No	No	No	No	No
Support of third party extensions	Yes	No	No	No	No	Yes	No
Painting	Yes	No	No	No	Yes	Yes	Yes
Injection Foil	Yes	No	No	No	Yes	Yes	No
Collimator	Yes	No	No	No	Yes	No	No
3D Fringe Field	Yes (via Map)	No	No	Yes	No	No	No

Consideration of e-p issues for SNS

- Consideration to minimize electron production
  - tapered magnets for electron collection near injection foil
  - TiN coated vacuum chamber to reduce multipacting
  - serrated collimator surface to reduce secondary emission
- Machine design and flexibility
  - high RF voltage to provide momentum acceptance: 40 kV (h=1) + 20 kV (h=2)
  - beam-in-gap kicker to keep a clean beam gap (10^{-4})
  - lattice sextupole families for chromatic adjustments
  - relatively high vacuum (5×10^{-9} Torr)
  - ports screening, step tapering
- Present studies
  - PSR machine study and theoretical understanding (R&D)
  - reserve space for possible wide band damper system
  - coating for extraction kicker ferrite (chromium oxide)

Reliability & design redundancy (overall)

- Controls:
  - Machine protection system limits integral dose
  - 1-pulse emergency shut-down for prevent damage
- Instrumentation
  - Redundant diagnostics (BPMs, wire scanners, harps)
- Vacuum
  - Operational at worse vacuum
- Spares
  - Spare magnets (main dipoles, quads, kickers, correctors) & PS

Reliability & design redundancy (FE)

- Ion Source:
  - 1 hot spare & 1 in rebuild; off-line test & development stand supplied
  - Can operate with 1 (out of 3) missing pumps
  - Regular antenna replacement every 3 weeks
- RFQ
  - 6 pumps; operational with 3
  - 2.5 MW klystron operating at less than 800 kW
  - RFQ kept under vacuum during ion source service
- MEBT
  - Spare dc quad supplies (1 spare of each 2 quad types)
  - 1 spare rebuncher rf PS
  - Wire scanner double as BPM for steering
  - Operational with 1 pump off

Reliability & design redundancy (Linac)

- Linac
  - Linac klystron power supply hot spare
  - Steering windings on all quads
  - Some redundant BPMs
  - Wire scanners double as BPMs
  - Re-phase all cavity/klystron downstream of failed cavity/klystron; operate at lower W_{final}
  - Spare cryogenic module & power coupler
  - Guaranteed defused beam on linac dump

Reliability & design redundancy (Ring)

- Ring
  - Adjustable injection energy (+/- 5%)
  - In-situ injection foil replacement (> 24 foils)
  - No loss against one extraction kicker malfunction
  - Dual-plane BPMs, extra correctors for steering
  - Switchable h=1 and h=2 rf cavities
  - Collimator protection; movable shielding
  - Quick disconnect; cranes; extra free space …
  - Guaranteed defused beam on extraction dump
  - Beam position unchanged upon kicker failure
- Transport
  - Dual-plane BPMs, extra correctors; Collimator protection
  - Restore orbit with long-term 1-kicker failure

Summary

- First-order physics design completed from FE to Target
  - IS / RFQ: first beam & tuning underway / prepared
  - SRF linac: geometry & design settled – physically comfortable
  - Accumulator ring: 1st article measurements & detailed analysis
- End-to-end simulation started
  - First-round parameter evolution & simulation completed
  - Detailed studies performed on individual subjects
  - Open issues identified & actively pursued; codes developed
- Interface issues identified & pursued
- Cold model test & magnet measurement analysis, database & application software development, and commissioning plan
- Greatly improved one-team spirit
  - Shared codes, resources, collaborators, publications

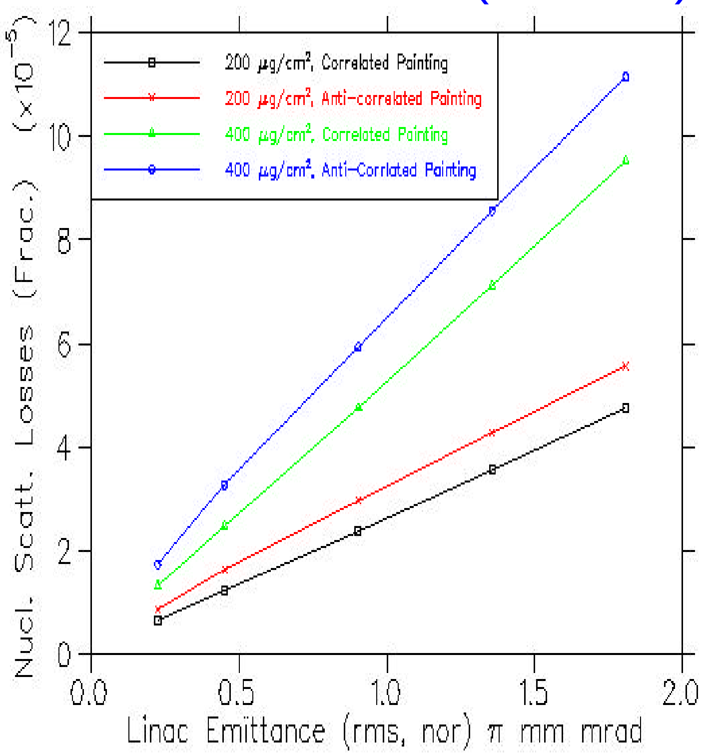
Estimated loss budget for the ring and transfer lines

	Mechanism	Location		Comments
HEBT	Vacuum H- stripping	All line	1.0E-5	~.13nA/m
	Ionization at the LINAC	Linac Dump	1.0E-5	
	Linac Transverse Halo	x-y Collimator	1.0E-5	
	Energy jitter/spread	z Collimator	1.0E-3	
RING	Magnetic H- stripping	INJB2	1.3E-7	Along ~1meter
	Nuclear scattering in the foil	INJB2	3.0E-5	7crossings/p. Depends on Linac beam size
	Excited H_0 at foil	Collimator	1.3E-5	
	Partial ionization and foil miss	Injection dump	1.0E-1	Dump designed for 200kwatt
	Space-charge halo	Collimator	1.9E-3	For 95% cleaning efficiency
	Energy straggling at the foil	Collimator	3.0E-6	Using the BIG system
	Collimator inefficiency	All ring	1.4E-4	Uniform along ~248 meters
RTBT	Kicker missfire	Collimator		Two or three kickers failure

Radiation Due to Nuclear Scattering

(D. Raparia)

Particle Loss (Fraction)



Radiation at Injection Area