The Spallation-Neutron-Source Project

-- physical challenges & technical issues

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For the Spallation Neutron Source Collaboration

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Outline

- Introduction
- Low-loss design philosophy
- Linac and ring design: debates & lessons learned
  - Superconducting RF linac vs. normal-conducting linac
  - Accumulator ring vs. Rapid-cycling synchrotron
  - FODO-doublet lattice vs. all-FODO lattice
- Physical & technical challenges
  - Linac RF control
  - Magnet quality assurance
  - Electron-cloud effects & preventive measures
- Present status
- Summary

Spallation Neutron Source

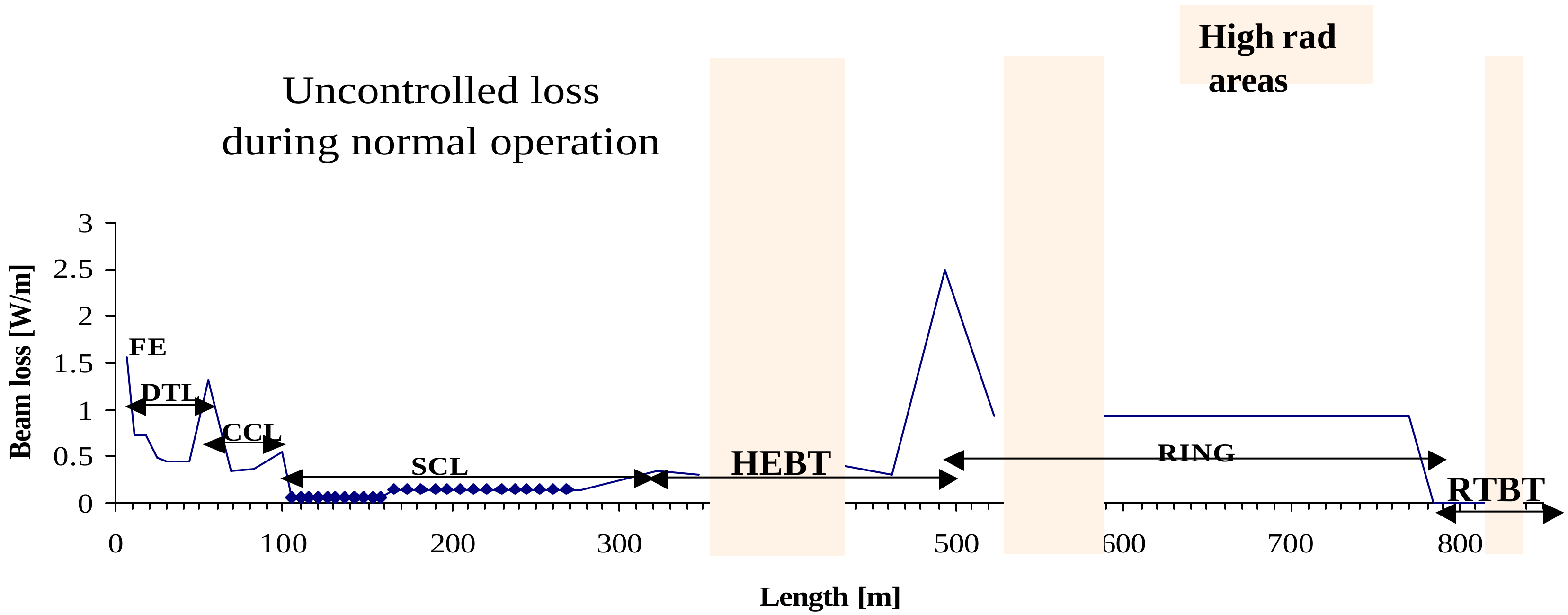
- 60 Hz repetition rate, $2x10^{14}$ per pulse, 2 MW proton facility
- In its 4th year of a 7-year construction cycle
- H^- Source, RFQ, DTL, CCL, SRF linac, Accumulator, Hg-target

Mega Watt Facility Comparison

	Energy [GeV]	Current [mA]	Rep.-rate [Hz]	Ave. power [MW]	Type
SNS	1	2	60	2	LAR
ESS	1.33	1.9	50	2.5x2	LAR
JHF	3	0.33	25	1	RCS
CERN PD	2	2	100	4	LAR
RAL PD	5	0.4	25	2	RCS
FNAL PD	16	0.25	15	2	RCS
EA	1	10 -- 20	CW	10 -- 20	cyclotron
APT	1.03	100	CW	103	linac
TRISPAL	0.6	40	CW	24	linac
ADTW	0.6 – 1.2	20 -- 50	CW	> 20	linac
μ-collider driver	30	0.25	15	7.0	RCS

Primary concern: uncontrolled beam-loss

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



Low-loss design-philosophy

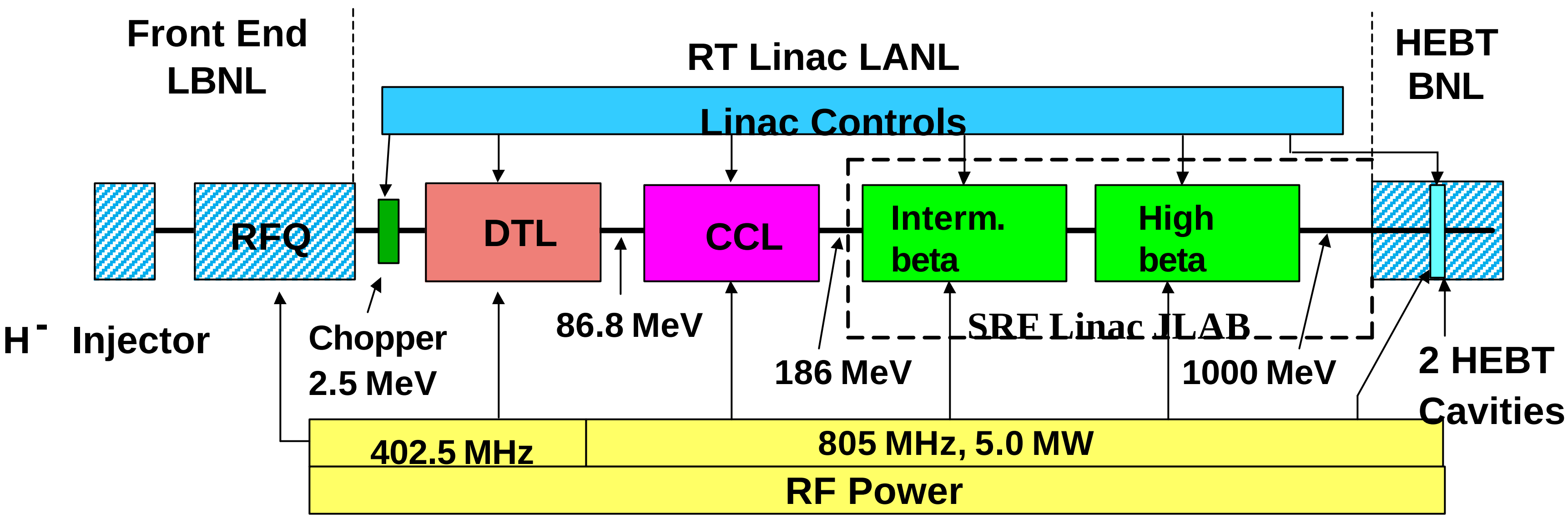
- Localize beam loss to shielded area
  - collimation at low & high energies: MEBT, HEBT, Ring, RTBT
  - 3-step beam-gap chopping/cleaning: LEBT, MEBT, Ring
- A low-loss design: large aperture & long straight-section!
  - Matching between linac structures; space-charge effects
  - Resonance minimization; magnetic-error compensation
  - Lattice design with adequate aperture & straight section
  - Injection optimization, painting & space-charge optimization
  - Impedance (extraction kicker) & electron-cloud control
- Flexibility & redundancy
  - Adjustable energy (+/- 5%), Variable tunes (H 1 unit, V 3 units), flexible 3-D injection painting; adjustable collimation; foil interchange; 1-kicker failure margin; 1 RF-cavity failure margin

Source of uncontrolled beam-loss

- Linac structure & lattice change: mismatches
- Space charge resonances: envelope, parametric halo, non-equipartitioning, tune shift & tune spread
- Physical aperture & momentum aperture limitation: dispersion, injection / extraction channel, chicane perturbation
- Ring injection loss: premature H- and H0 stripping, foil hits
- Ring magnet errors: dipole-quad tracking; eddy-current & saturation, fringe field
- Instabilities: envelope, head-tail, microwave, coupled bunch, electron cloud
- Accidental loss: ion source and linac malfunction, extraction kicker failure

Linac design: superconducting RF linac

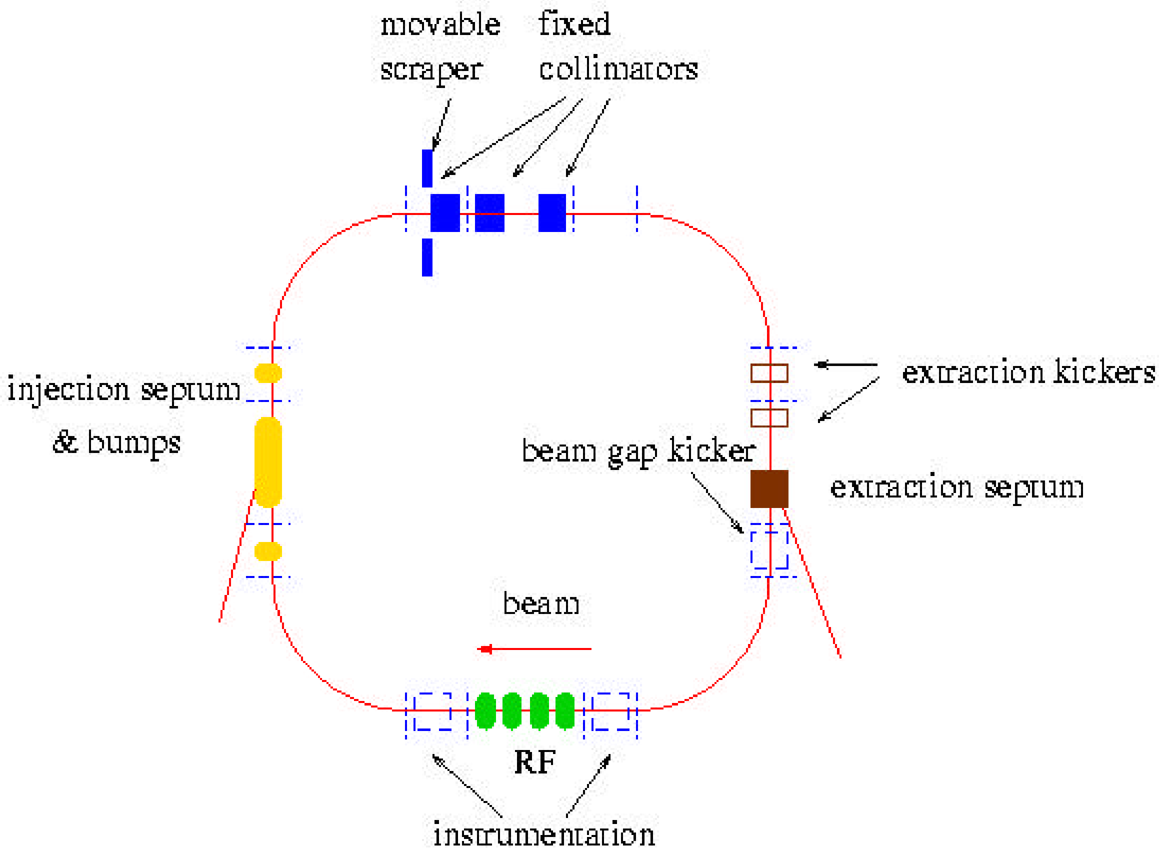
- Adopting superconducting RF technology (186 – 1000 MeV)
- 2 types of cavity (b=0.61 and b=0.81) for economic savings & future energy upgrade
- One-cavity-per-klystron independent RF control of Lorentz detuning, microphonics, beam transients, injection offsets



Linac-design debates

- Warm vs. superconducting RF linac?
  - SRF provides higher gradient (11~16 MV/m); tolerable to cavity/klystron failure; better vacuum & reliability
- Linac RF control: how many cavities per klystron?
  - SRF requires careful RF control on injection energy offset, Lorentz detuning, microphonics, beam loading/transient effects
  - One-klystron-per-cavity individual RF control for SNS linac
- How many types of cold cavity?
  - two cavity beta type: flexible for gradient upgrade, but large phase-slip requires detailed error-sensitivity analysis
  - Constant gradient & continuous focusing: maximizing field strength but compromising equipartition law
- How big should be the warm linac bore size (*)?
  - CCL bore diameter reduced from 4 to 3 cm, now aperture bottle-neck due to CCL-to-SCL lattice (FODO to doublet) matching

Ring: fixed-energy, hybrid lattice

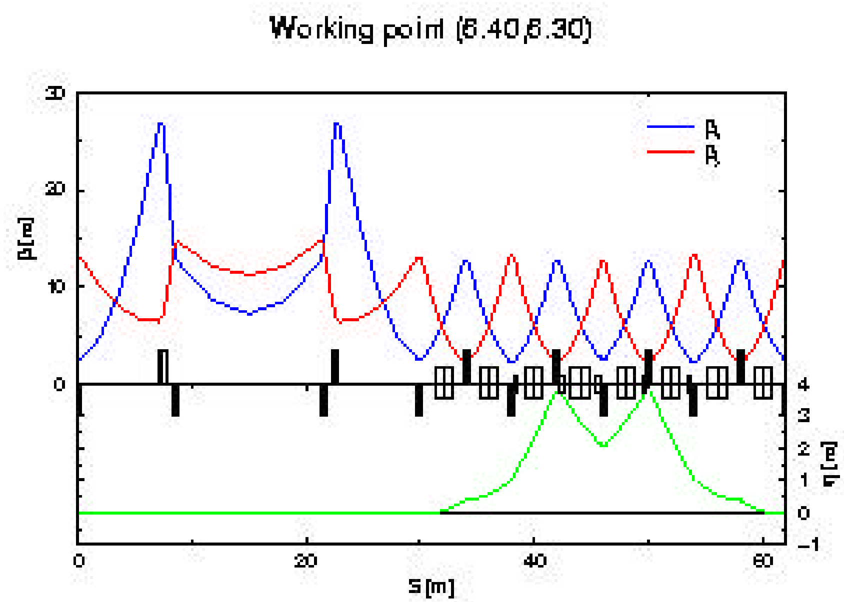


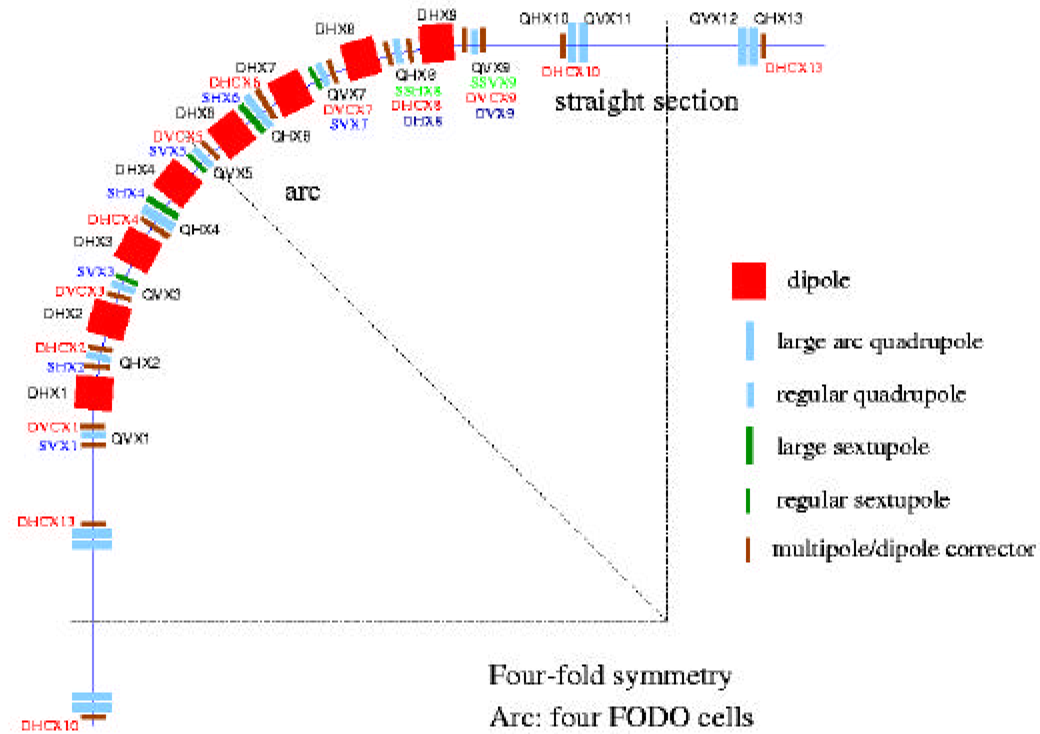
- No energy ramping
- Long straight-section, large aperture
  - Injection flexibility
  - Collimation efficiency
- Four straight-sections for four functions
  - Injection;
  - RF;
  - Collimation;
  - Extraction
  - Diagnostics all-around
- Dispersion-free injection
  - Decoupled H, V, L

Ring-design debates

- Accumulator or rapid-cycling synchrotron?
  - Loss-power comparison: PSR loss 0.3%; usual RCS loss ~10%
  - RF, power supply, beam-pipe shielding, magnetic & track errors
- FODO-doublet lattice or all-FODO lattice?
  - Long, matched straight section: injection independent of tuning; collimation efficiency from ~ 80% to 95%
- Do we need sextupoles? Energy corrector & spreaders?
  - Four-family chromatic sextupole for tune-spread control & match
  - Energy correctors & spreaders for longitudinal painting
- Can we use permanent magnets? Certainly not for a cold linac!
- Should the aperture be reduced? No, aperture is everything!
- Solid-core or laminated-core magnets (*)?
  - Large field variation in a solid-core magnet (although lower cost)

Ring lattice





Four-fold symmetry
Arc: four FODO cells
S.S.: doublets

Linac physical-challenges

- Output energy within +/- 5% window (H^0 stripping loss)
  - SCL gradient? Extra linac tunnel space as a back-pocket plan
- Transverse emittance and jitter
  - Ring foil miss 1-2%; total emittance growth in linac < (2 x); compared with, e.g., 5 –8 times growth at LANSCE), identified transverse jitter as main issue
- Momentum spread and jitter
  - Facilitate longitudinal painting with a narrow "brush" +/- 0.3%
  - Further correct phase-error at corrector with feed-forward
- Beam-loss, cleaning, diagnostics, machine protection
  - Lower than 1 W/m; adjustable scrapers in med.-energy transport
  - Fast loss monitor as part of machine protection
- RF power & overhead for RF control
  - Active Lorentz-force compensation with piezo tuners

Key parameters

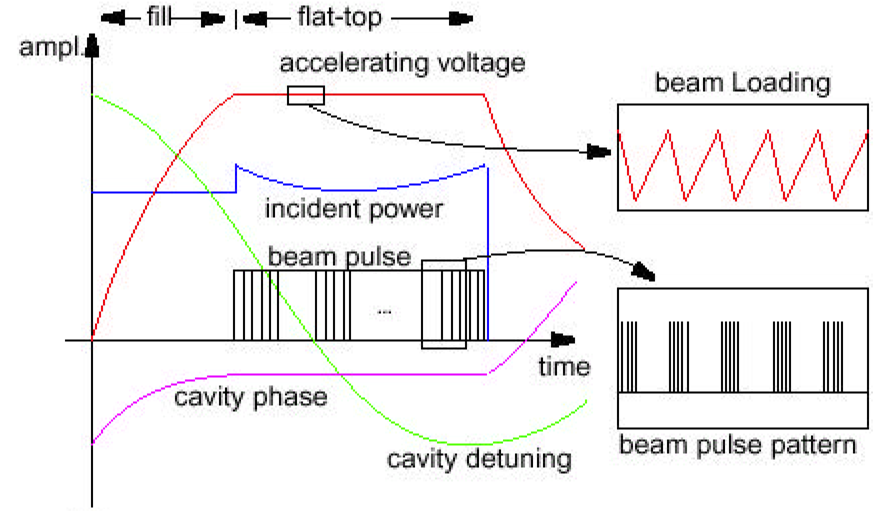
	Baseline	Back-up
Kinetic energy, E_k [MeV]	1000	975
Uncertainty, ΔE_k (95% probability) [MeV]	+ / - 15	+ / - 15
SRF cryo-module number	11+**12**	11+**15**
SRF cavity number	33+48	33+60
Peak gradient, E_p (β=0.61 cavity) [MV / m]	27.5 (+ / - 2.5)	27.5 (+ / - 2.5)
Peak gradient, E_p (β=0.81 cavity) [MV / m]	**35 (+2.5/-7.5)**	**27.5 (+/- 2.5)**
Beam power on target, P_{max} [MW]	1.4	1.7
Pulse length on target [ns]	695	699
Chopper beam-on duty factor [%]	68	68
Linac beam macro pulse duty factor [%]	6.0	6.0
Average macropulse H- current, [mA]	**26**	**32**
Linac average beam current [mA]	1.6	1.9
Ring rf frequency [MHz]	1.058	1.054
Ring injection time [ms] / turns	1.0 / 1060	1.0 / 1054
Ring bunch intensity [10^{14}]	1.6	1.9
Ring space-charge tune spread, ΔQ_{sc}	0.15	0.20

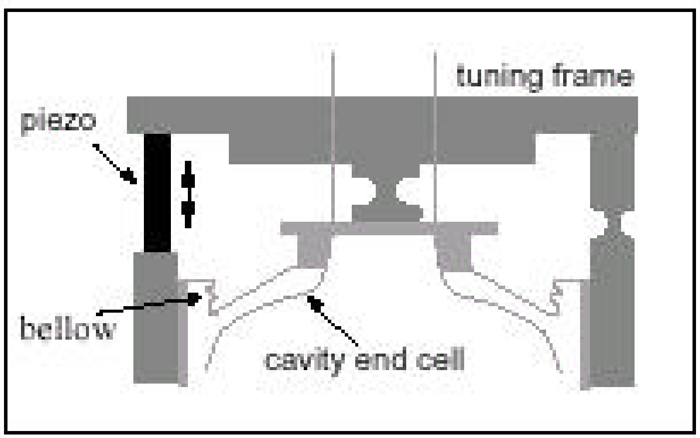
assuming 4% injection loss to dump; 4% target window loss; linac max. -20° phase

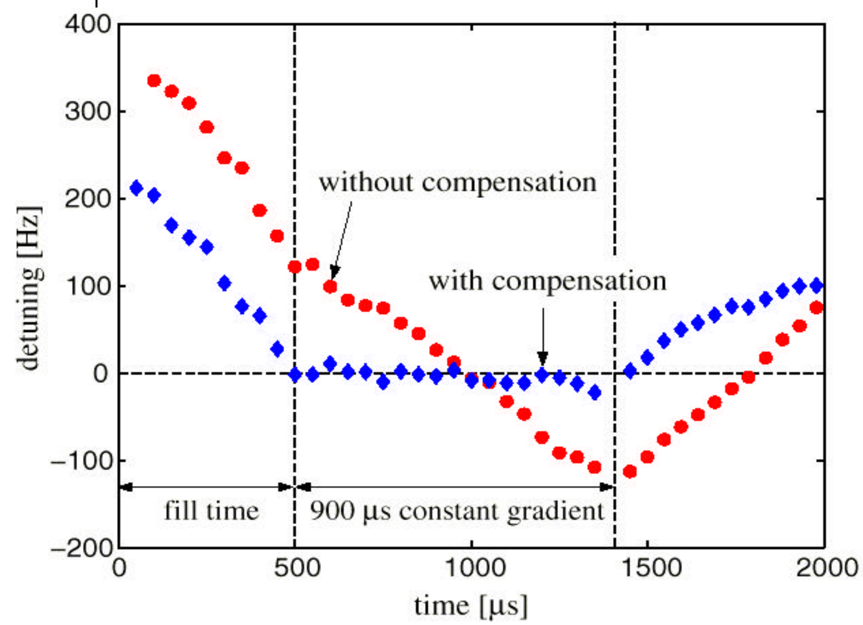
RF overhead & active compensation

- Challenges from pulsed superconducting RF linac
- TTF development of piezo-translator for measurement / feedforward compensation (RF power saving)
- SNS starting R&D program at Jlab
- Workshop planned (Dec. 01)

Courtesy M. Liepe, S. Simrock



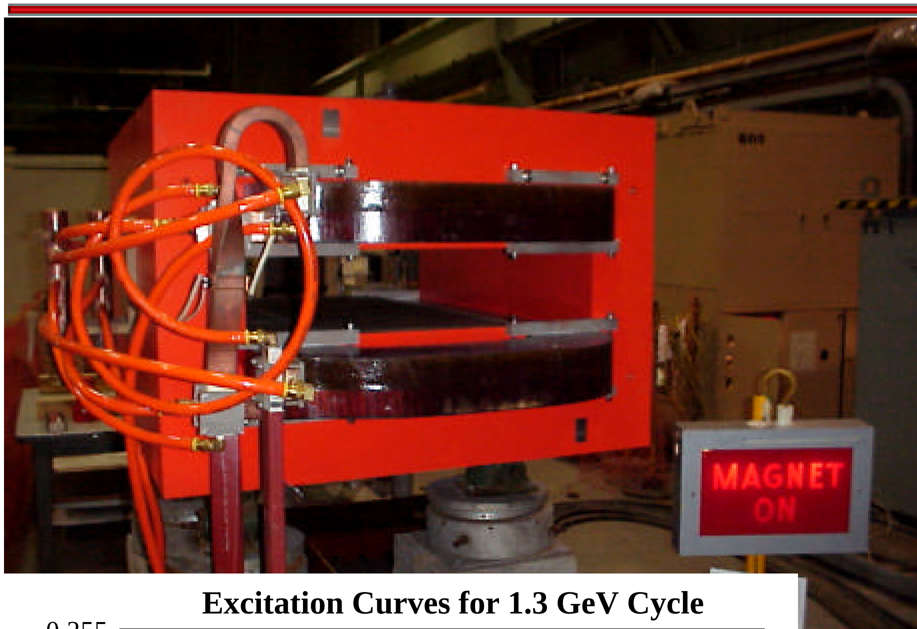


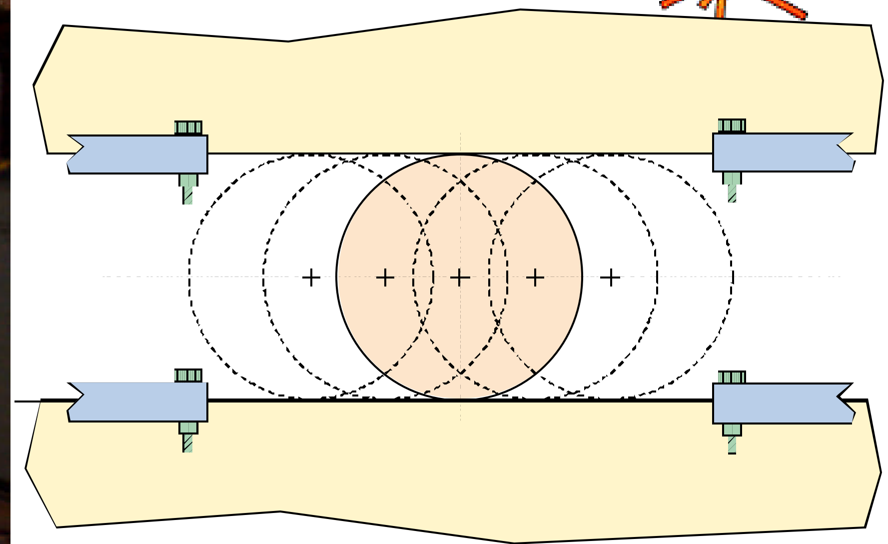


Ring physical-challenges

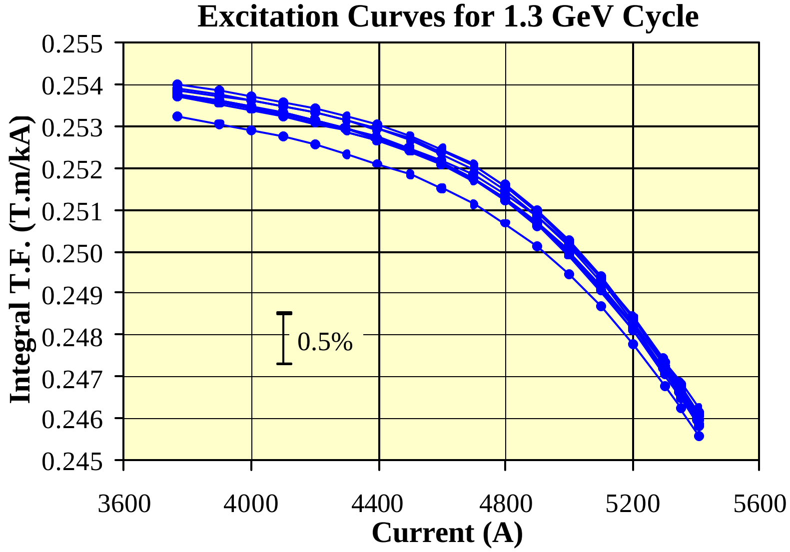
- Guaranteed beam-density on target
  - Immune to kicker misfiring, protected against malfunctions
- Electron cloud & other instabilities
  - Electron collection & control: electron-cloud generated at injection, collimators, and due to multipacting
  - Impedance from kicker ferrite module in the beam pipe
- Magnet field variation, correction, alignment
  - Field uniformity ~ 10^{-4} for main magnets; shimming needed for solid-core magnets
  - Non-trivial design on C-type, septum to reach 10^{-3}
- Loss control
  - Control of injection field to reduce H- and H0 loss
  - Facilitate two-stage collimation and beam-in-gap cleaning
- Diagnostics: e.g., ionization or luminescence profile monitor?

Dipole field variation & shimming





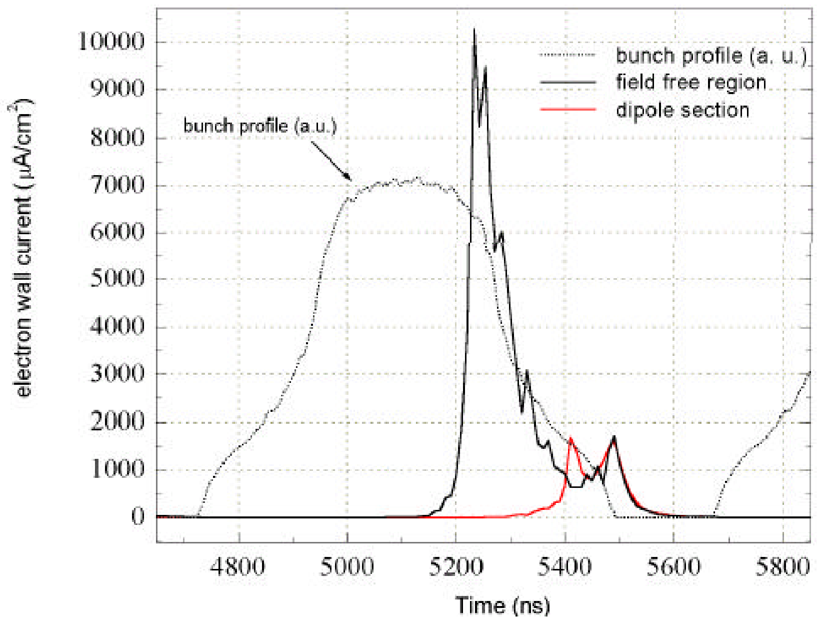
SNS DIPOLE MEASUREMENTS: FIVE HORIZONTAL POSITIONS; 2 INCHES APART

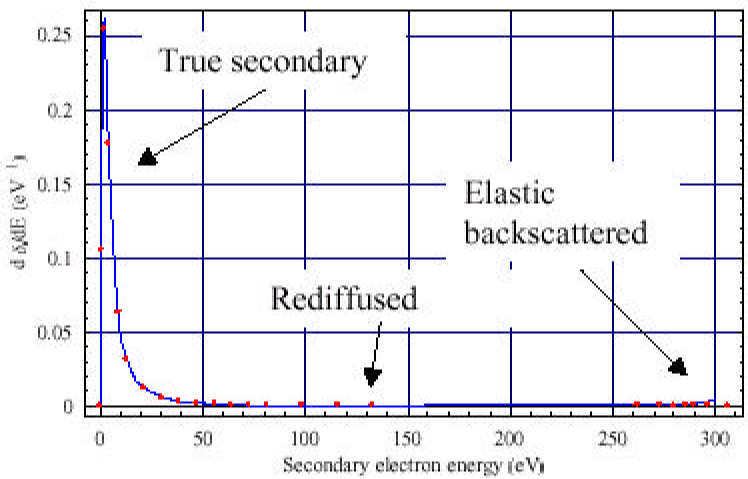


- Multipole field 10^{-4} at 95% gap size
- Initial variation in dipole transfer function up to $2x10^{-3}$
- Combination of mechanical error & material variation (solid core)
- Fixed by shimming gap / side-legs

Electron-cloud effects

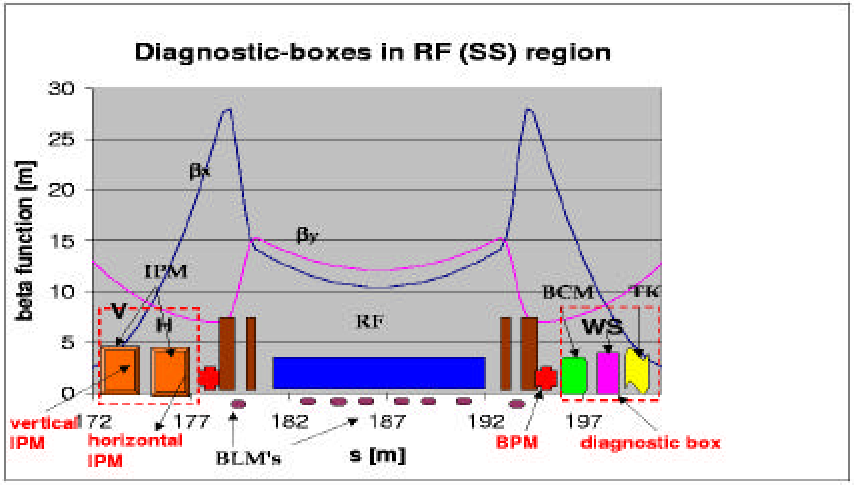
Courtesy M. Pivi, M. Furman





- Minimize electron production
  - Tapered magnets for electron collection near injection foil
  - TiN coated vacuum chamber to reduce multipacting
  - Striped coating of extraction kicker ferrite (TiN)
  - Beam-in-gap kicker (10^{-4})
  - Good vacuum ($5x10^{-9}$ Torr)
  - ports screening, step tapering
  - Electron detectors around ring
  - Clearing electrodes & winding solenoids
- Enhance Landau damping
  - High RF voltage: 60+20 kV
  - Sextupoles for mom. aperture
  - Space for wide band dampers

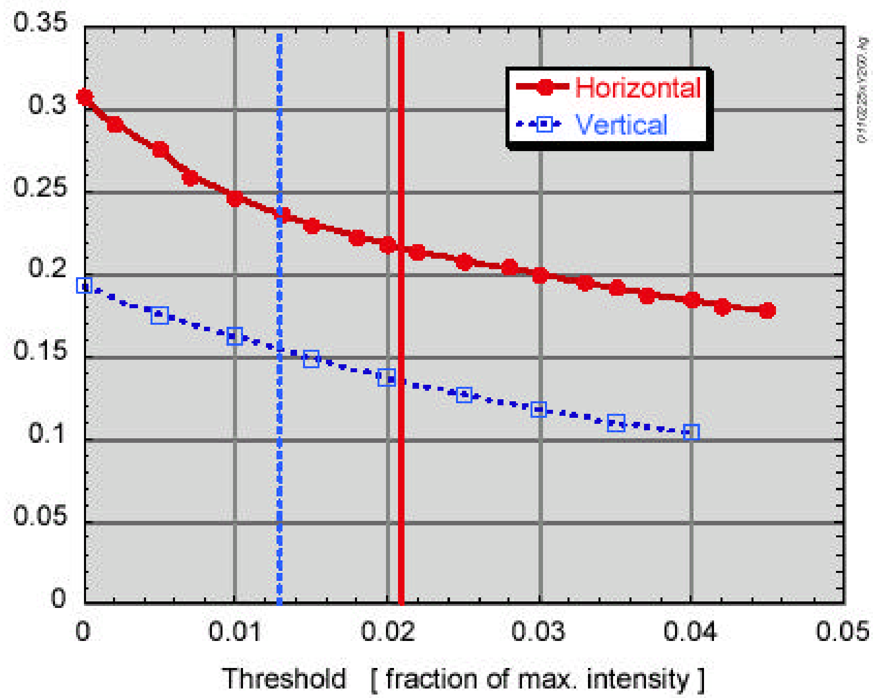
Ring instrumentation demands



- Part of machine protection; fast response
- Wide dynamic range
  - Intensity three order-of-magnitude; amplitude 30 times
- Turn-by-turn capability
- Presence of electron cloud

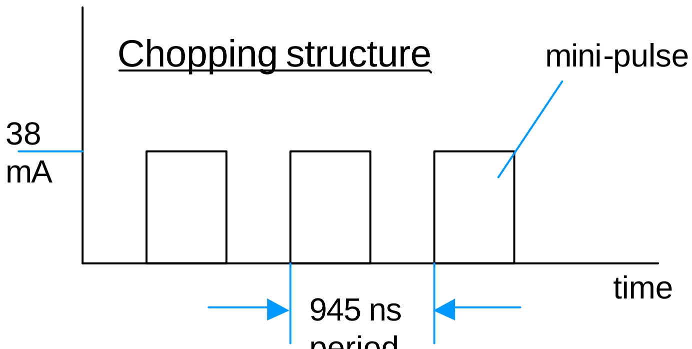
Detectors	BNL	Comments
BPM	44	dual plane
	(includes	2 RF radial loop)
BLM	75	ion chamber
FBLM	12	photomultip.
BIG	1	kicker+PMT
IPM	2	H+V
WS	2	H+V
Coherent Tune	1	kick/PU
Incoherent Tune	2	PLL & QMM
BCM	1	FCT
WCM	2	including RF
E-detector	5	
High Moment	1	
Luminescence profile?		

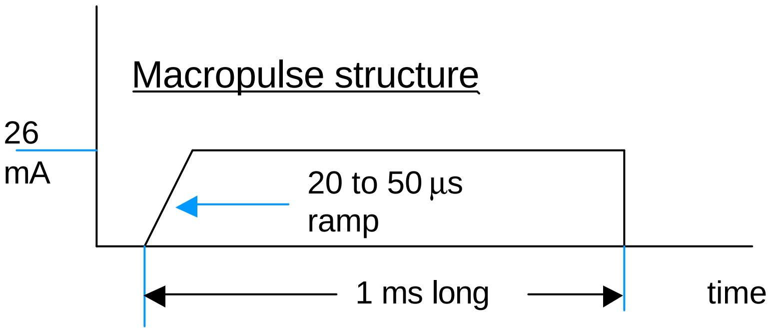
Front-end status (LBNL)

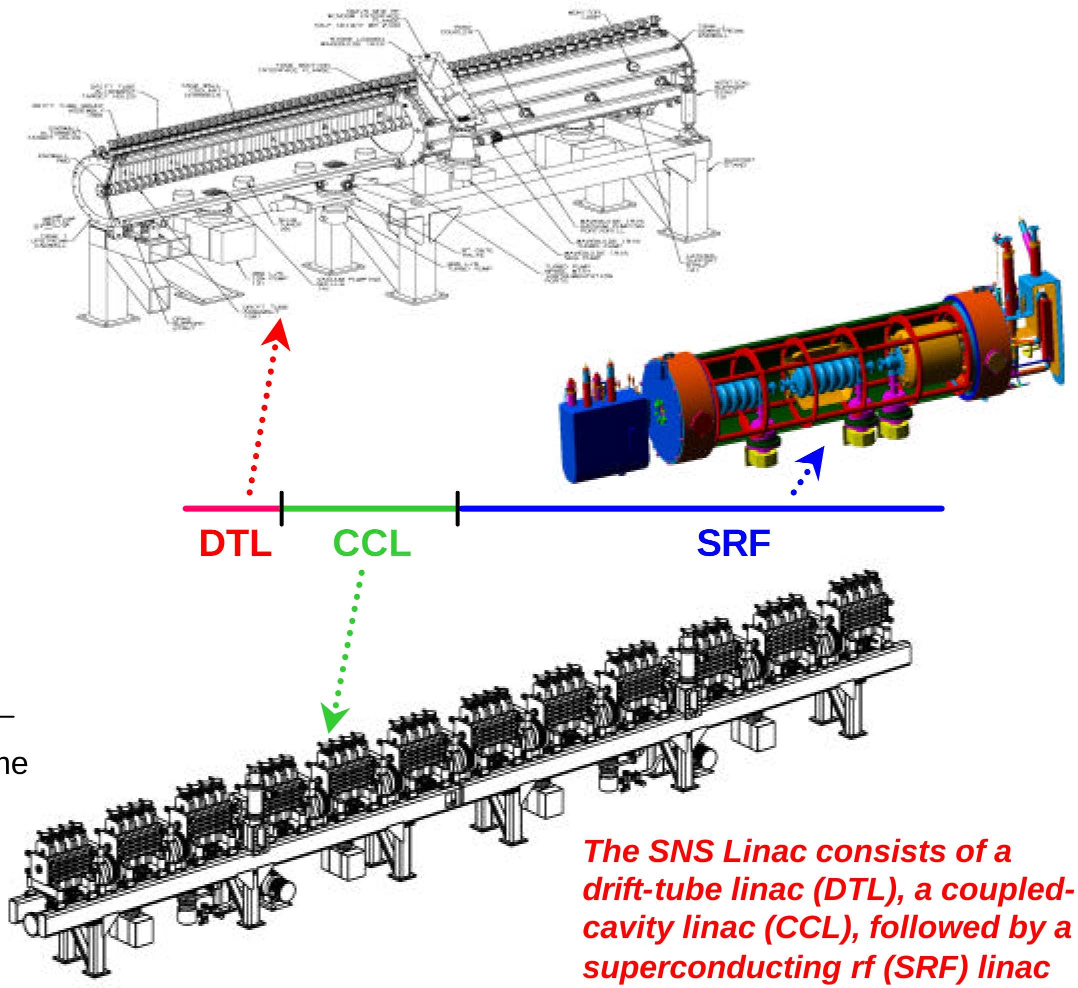


- Ion source & RFQ commissioned at LBL: 33 mA @ 2.5 MeV; 90%
- Emittance meets expectation (LEBT 65 keV)
- Better lifetime (antenna, coating)

Linac structure

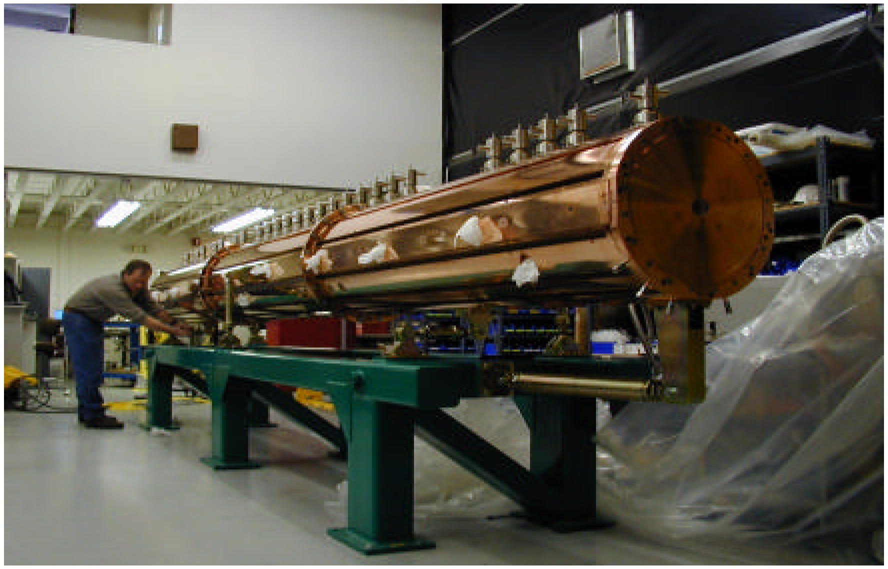


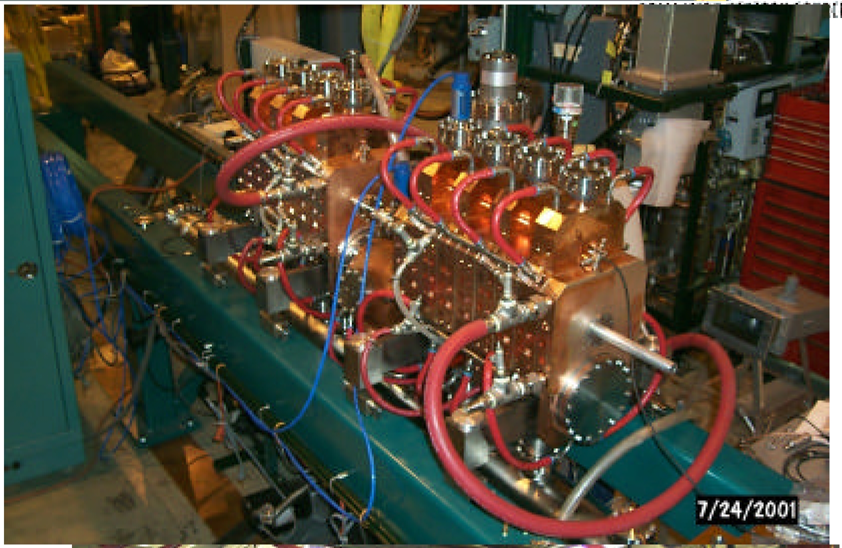


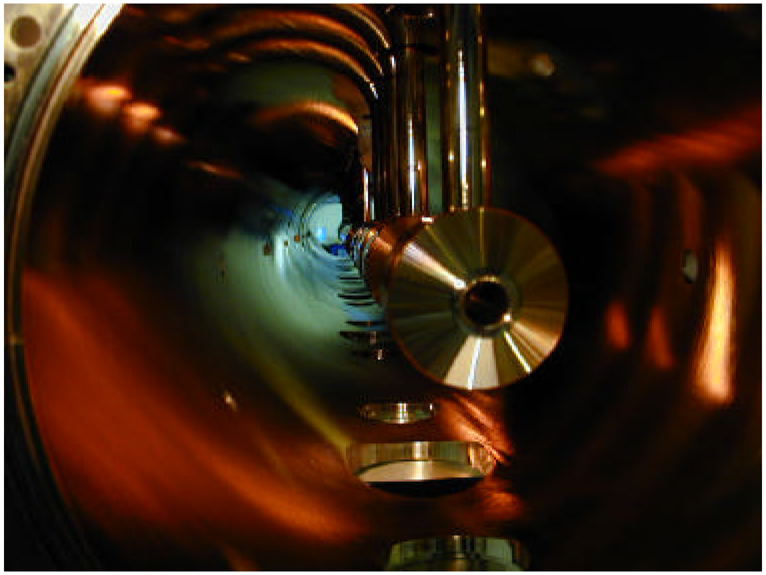


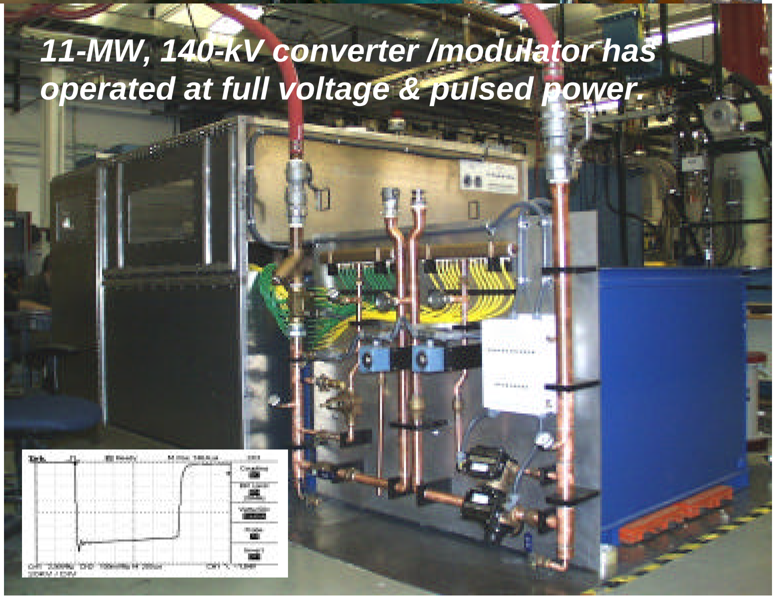
The SNS Linac consists of a drift-tube linac (DTL), a coupled-cavity linac (CCL), followed by a superconducting rf (SRF) linac

Warm-linac status (LANL)



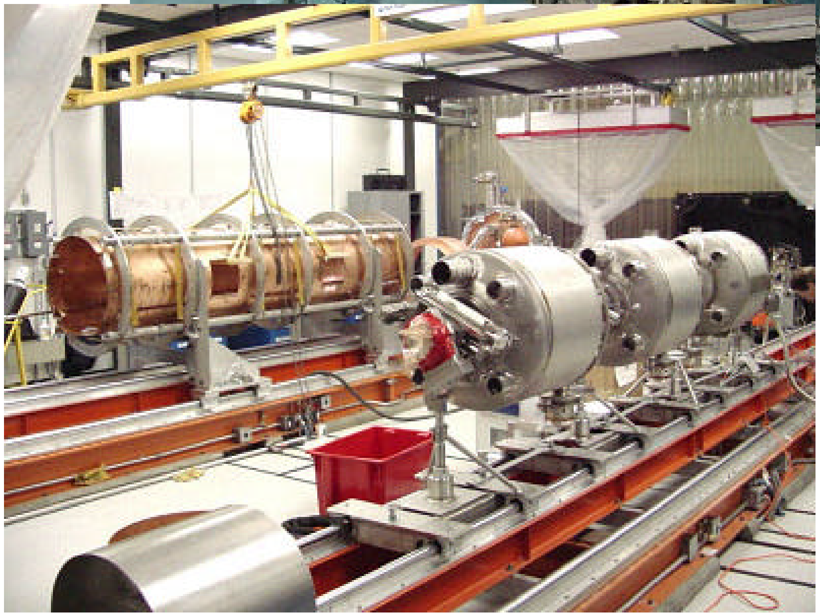




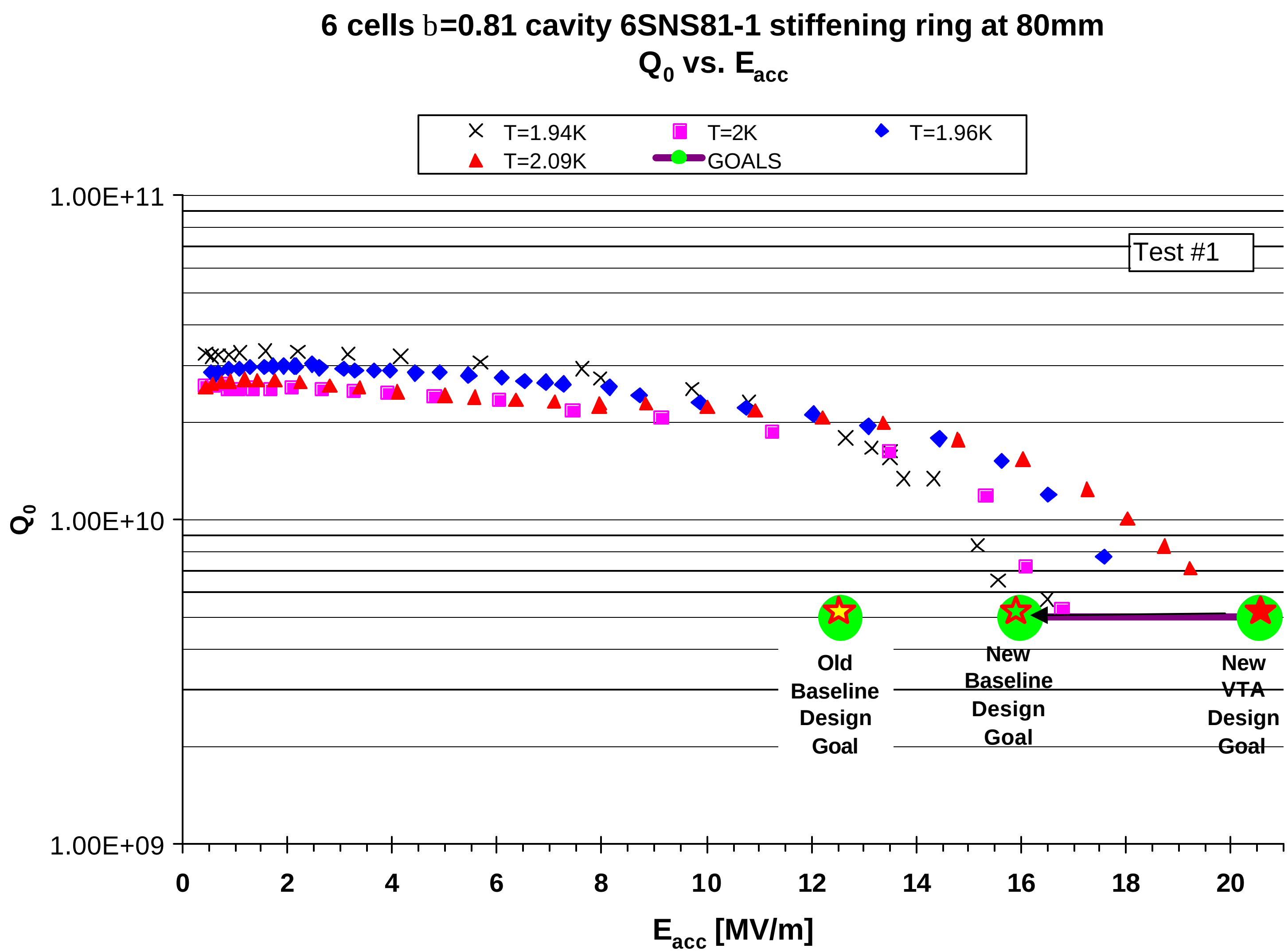


Superconducting linac status (JLAB)

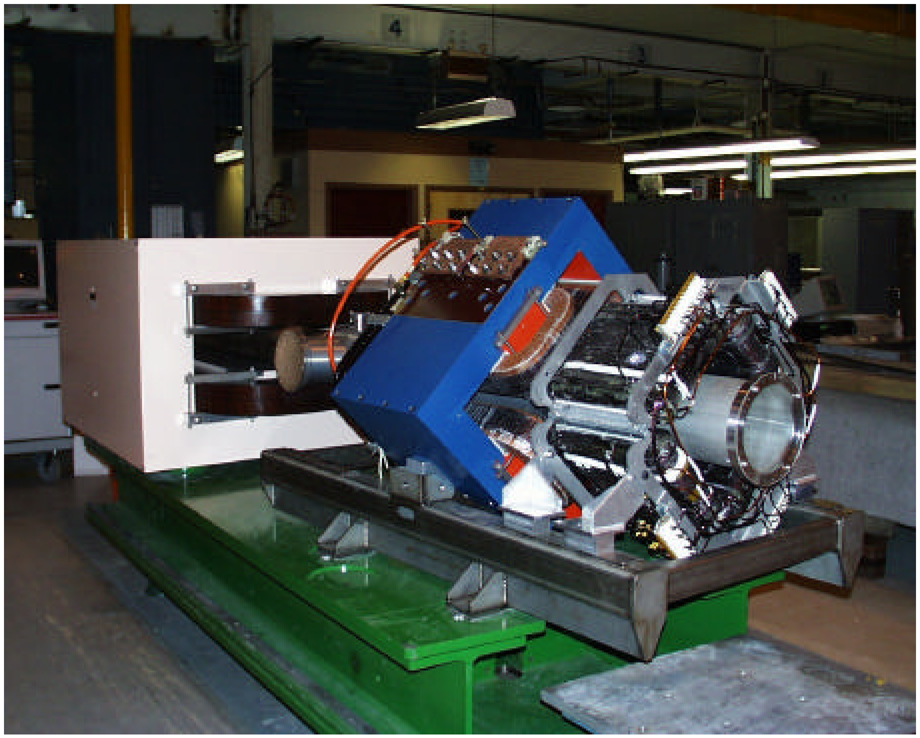
- Three cavities qualified for assembly into prototype cryomodule.
- A 600ºC cavity bakeout has been shown to provide acceptable protection against Q-disease.
- A pair of fundamental power couplers transmitted a peak power of 2MW into a matched load, demonstrating performance that would be acceptable for 500kW into a full mismatch.



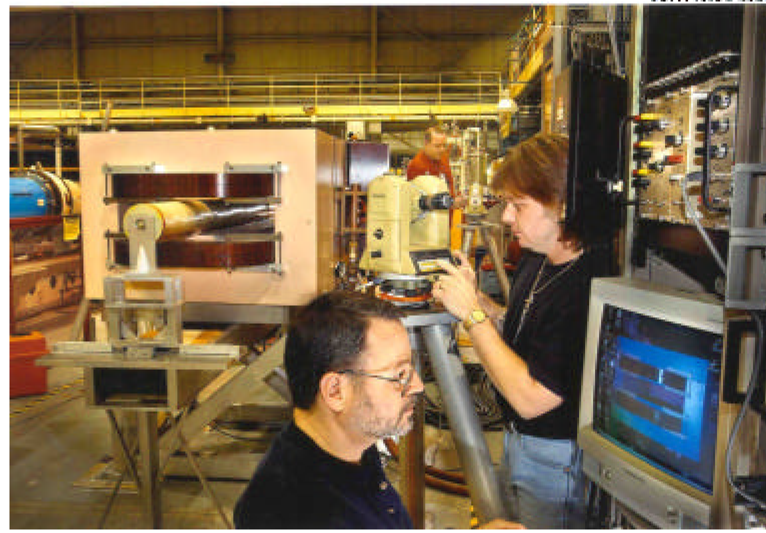
Beta 0.81 Cavity #5 Test Results (JLAB)



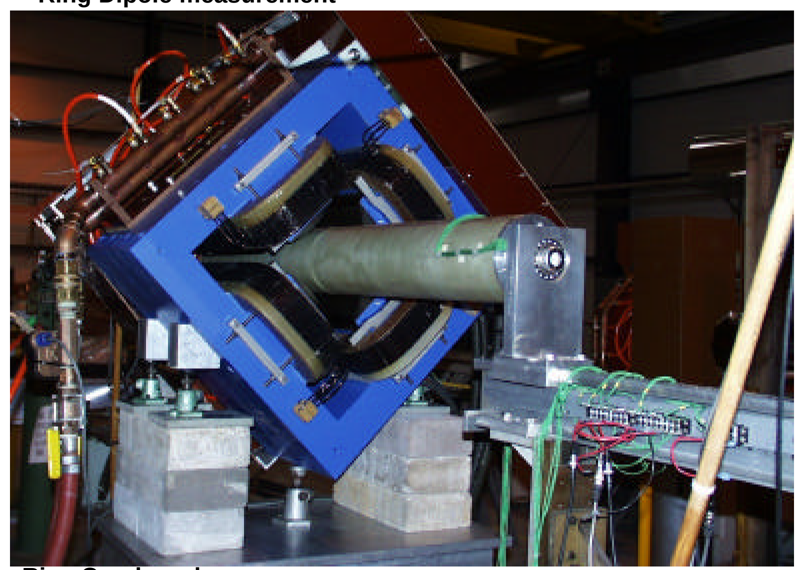
Ring status (BNL)



Ring Arc Half Cell Assembly

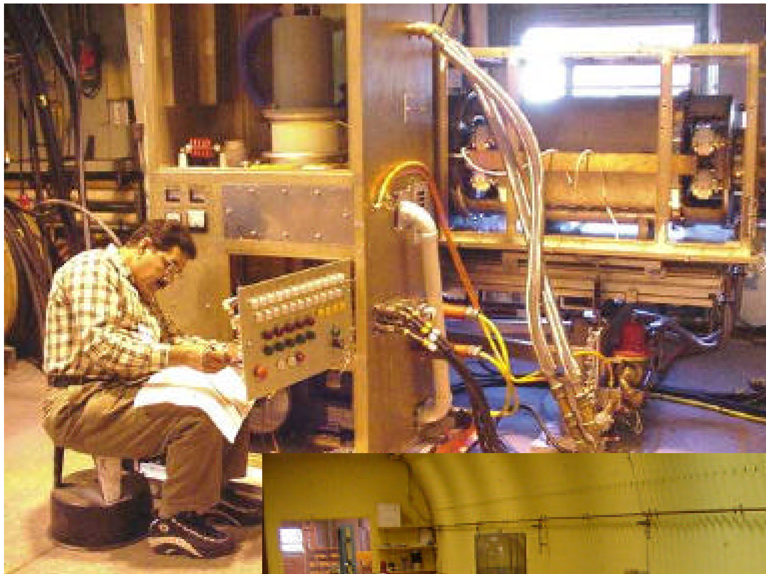


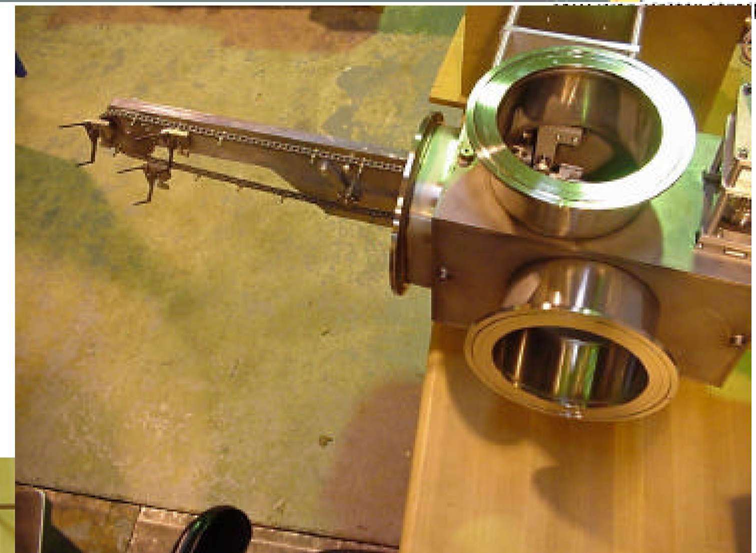
Ring Dipole measurement

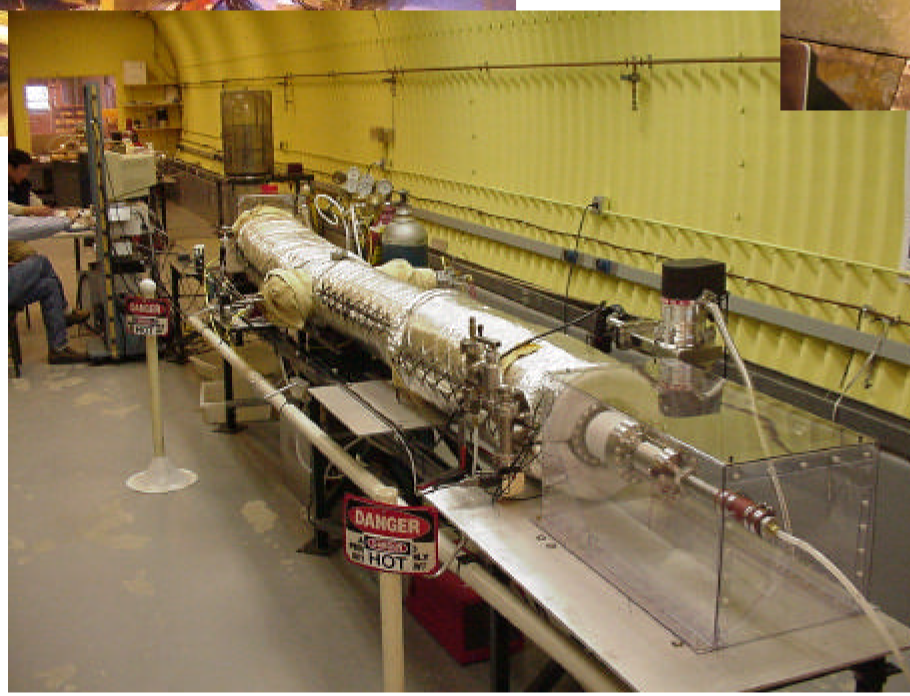


Ring Quadrupole

RF System tests/TiN coating/foil bar





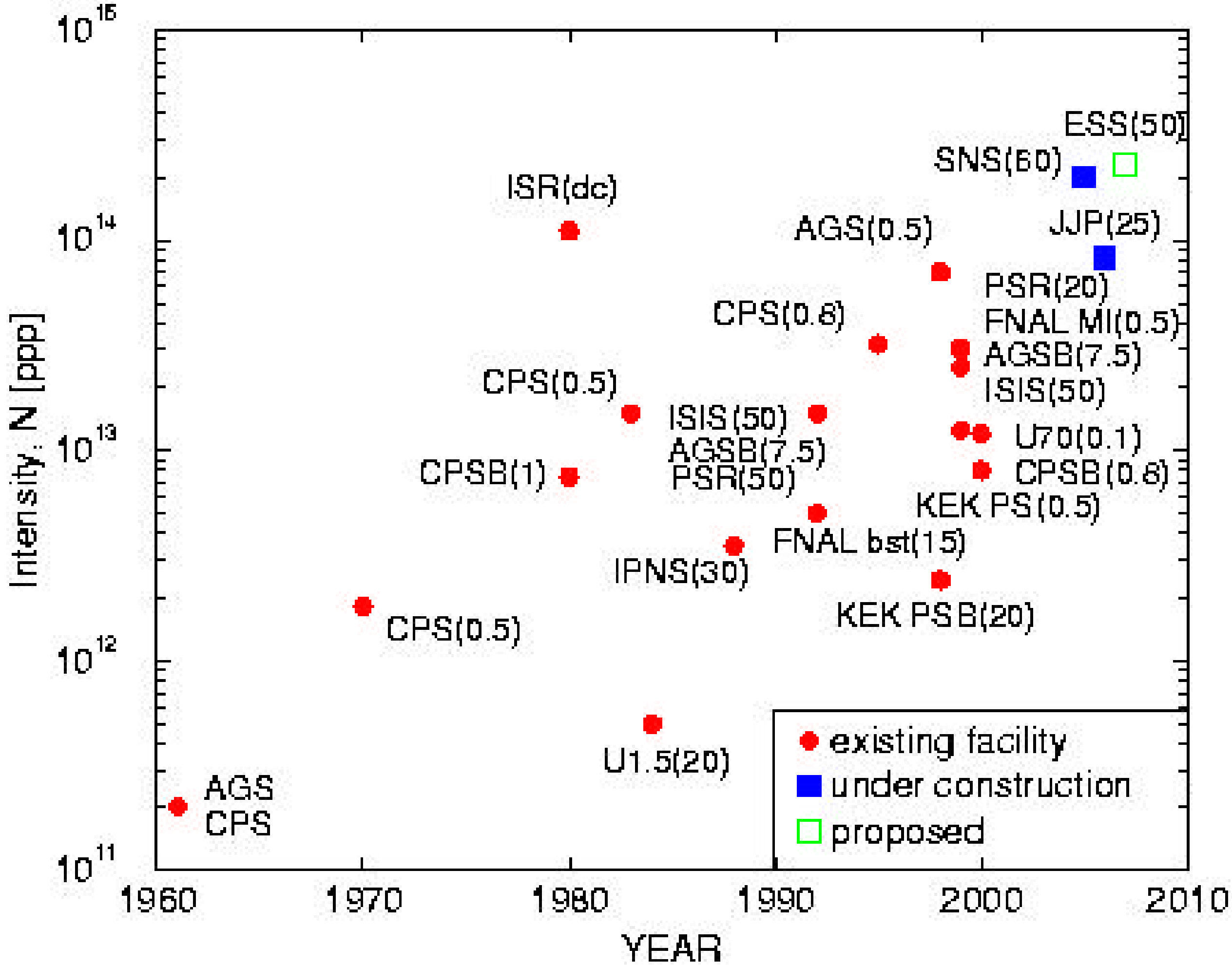


Tunneling & installation (ORNL)

Summary

- SNS is in its 4th year of a 7-year construction cycle, fully funded and marching towards completion upon 2006
- Accelerator systems are making good progress in all fronts: no show stoppers
  - LBNL: ion source & RFQ commissioned;
  - LANL: DTL, CCL tests proceeding
  - JLAB: superconducting cavities reaching goal gradient
  - BNL: magnets being built, measured, assembled
  - ORNL: testing, installation, integration, increasing leadership
- Challenges and uncertainties demands hard work; a close six-laboratory collaboration has been essential
- SNS is paving the path for future high-intensity projects

Marching towards year 2006!



SNS accelerator teams

- LBNL: R. Keller, J. Staples, R. Thomae
- LANL: D. Rej, J. Stovall, S. Nath, H. Takeda, J. Billen, L.Young
- JLAB: C. Rode, J. Delayen, P. Kneisel
- BNL: J. Wei, D. Raparia, M. Blaskiewicz, D. Davino, A.V. Fedotov, Y.Y. Lee, N. Malitsky, W. Meng, Y. Papaphilippou, S. Tepikian, N. Tsoupas
- ORNL: N. Holtkamp, R. Damm, M. White, D. Gurd, J. Galambos, A. Aleksandrov, S. Cousineau, P. Chu, S. Danilov, M. Doleans, S. Henderson, J. Holmes, D. Jeon, S.H. Kim, L. Kravchuk, T. Pelaia, E. Tanke, R. Welton, S. Assadi, A. Shishlo, J. Stovall …
- Collaborators
  - K. Crandall (TechSource), C. Pagani, P. Pierini (INFN), S. Simrock (DESY), K. Bongardt (COSY), R. Ryne, J. Qiang, T. Wangler (LANL), I. Hofmann (GSI), J.M. Lagniel, N. Pichoff, D. Uriot, R. Duperrier (CEA), S. Kurennoy
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