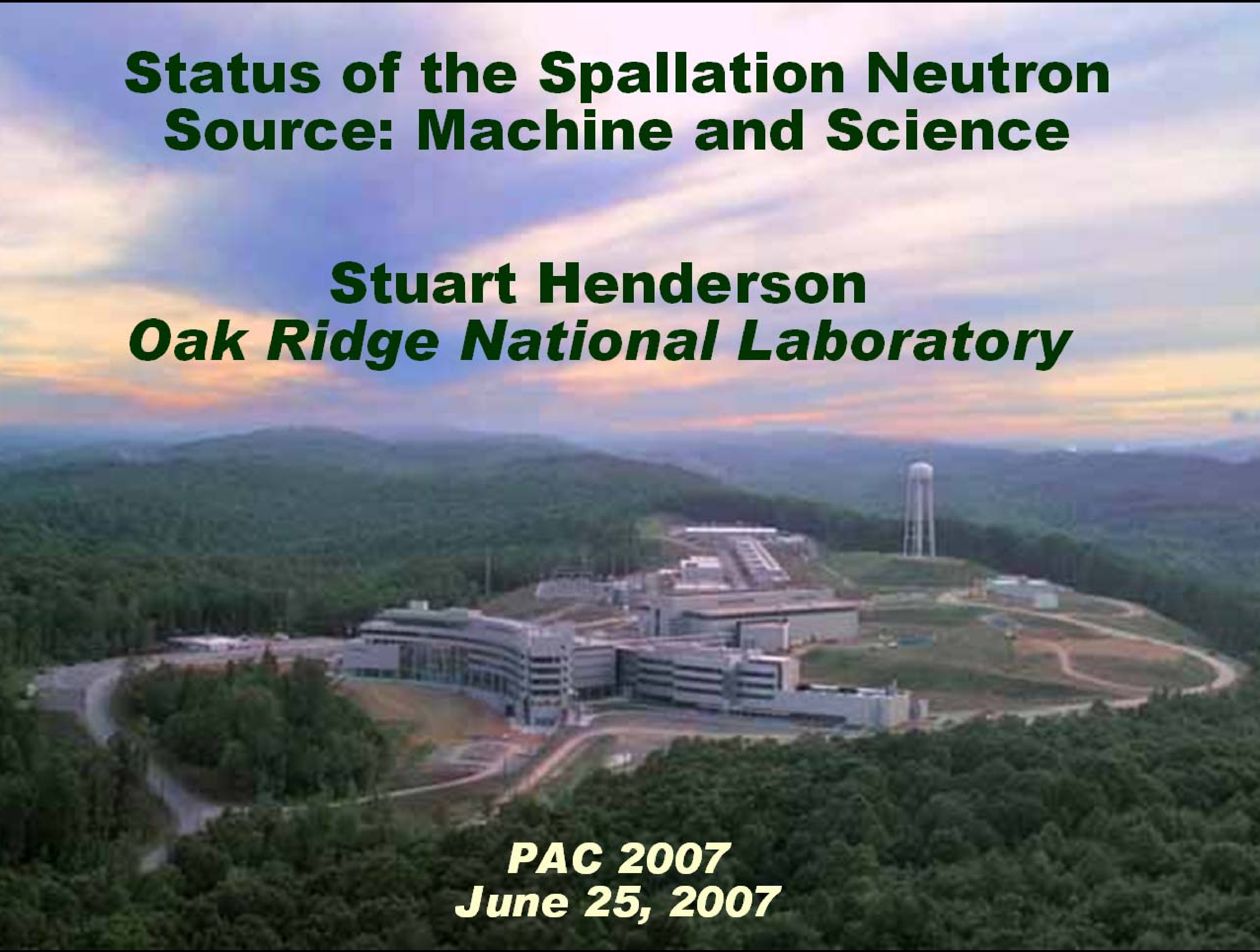
Status of the Spallation Neutron Source: Machine and Science

Stuart Henderson

Oak Ridge National Laboratory

PAC 2007

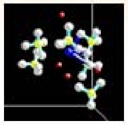
June 25, 2007



The Spallation Neutron Source

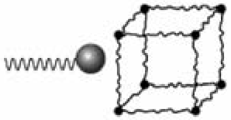
- The SNS at Oak Ridge National Laboratory is a short-pulse neutron source, powered by a 1.4 MW proton accelerator
- At 1.4 MW it will be ~8x ISIS beam power, the world's leading pulsed spallation source
- The SNS construction project, a collaboration of six US DOE labs, began in 1999 and was completed on-time and within budget in June 2006 at a cost of 1.4 B$
- SNS began formal operation in October 2006, and now routinely provides neutron beams to three scattering instruments
- SNS will become the world's leading facility for neutron scattering

Why Neutrons?



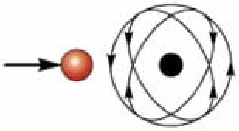
1. Neutrons have the right wavelength

   Neutrons probe a broad range of length scales



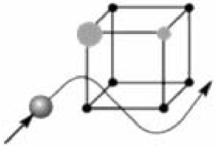
2. Neutrons measure the velocity of atoms

   Neutrons follow catalysts in action; transport through biological membranes



3. Neutrons see the nuclei

   Can offer greater contrast than x-rays (e.g. H); isotopic contrasting

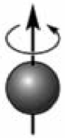


4. Neutrons see light atoms next to heavy ones

   Crucial Oxygen positions in Hi-Tc superconductors; neutrons see H; study H-bonds (chemistry and biology)

5. Neutrons penetrate deep into matter

   Study material properties deep inside materials; characterizing deep welds and their associated stresses

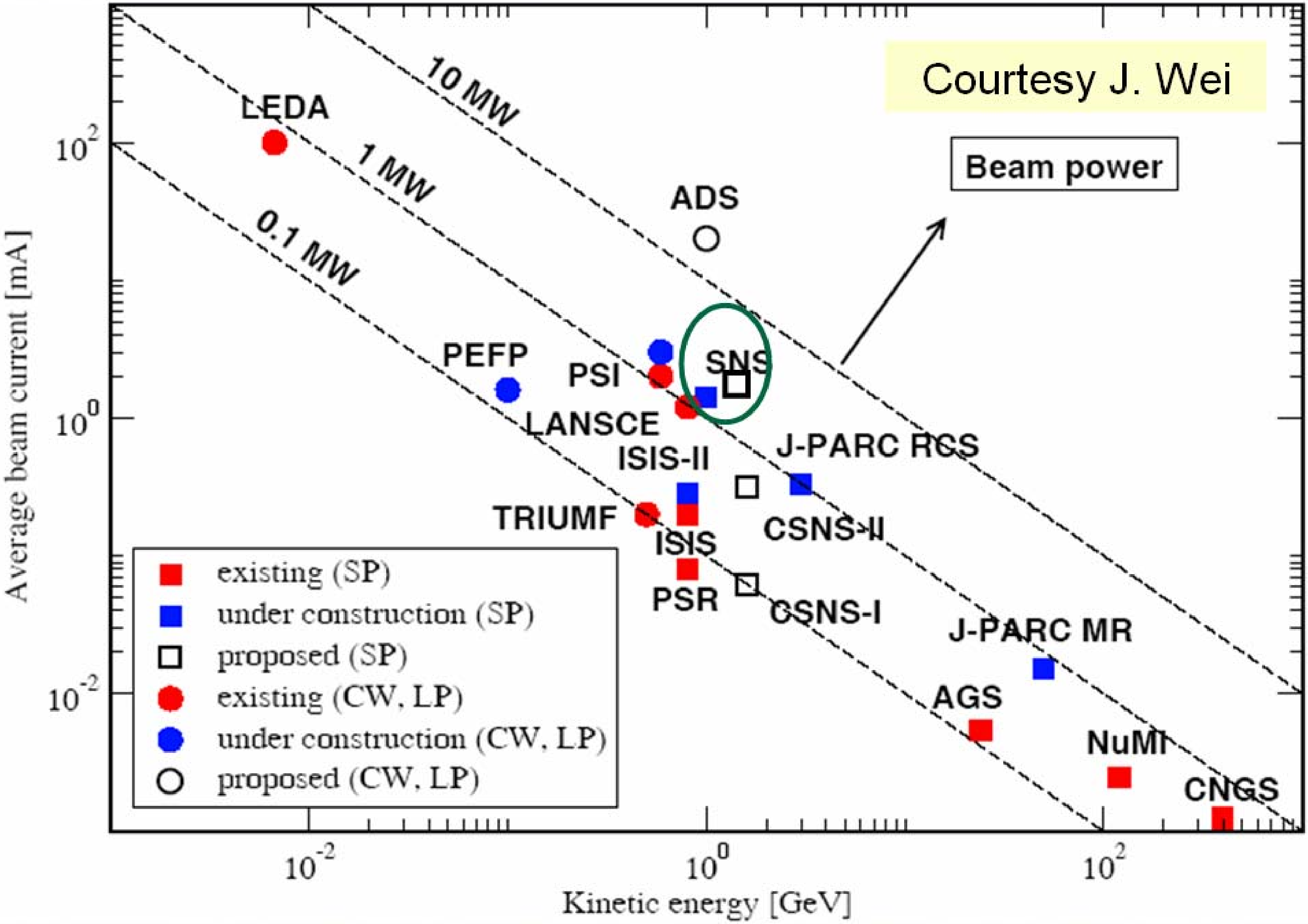


6. Neutrons see elementary magnets

   Study magnetic structure of materials; advanced magnetic materials

The Beam Power Frontier for Protons

- Central challenge at the beam power frontier is controlling beam loss to minimize activation
- 1 nA protons at 1 GeV, a 1 Watt beam, activates stainless steel to 80 mrem/hr at 1 ft after 4 hrs
- Demands careful control of beam injection/ extraction

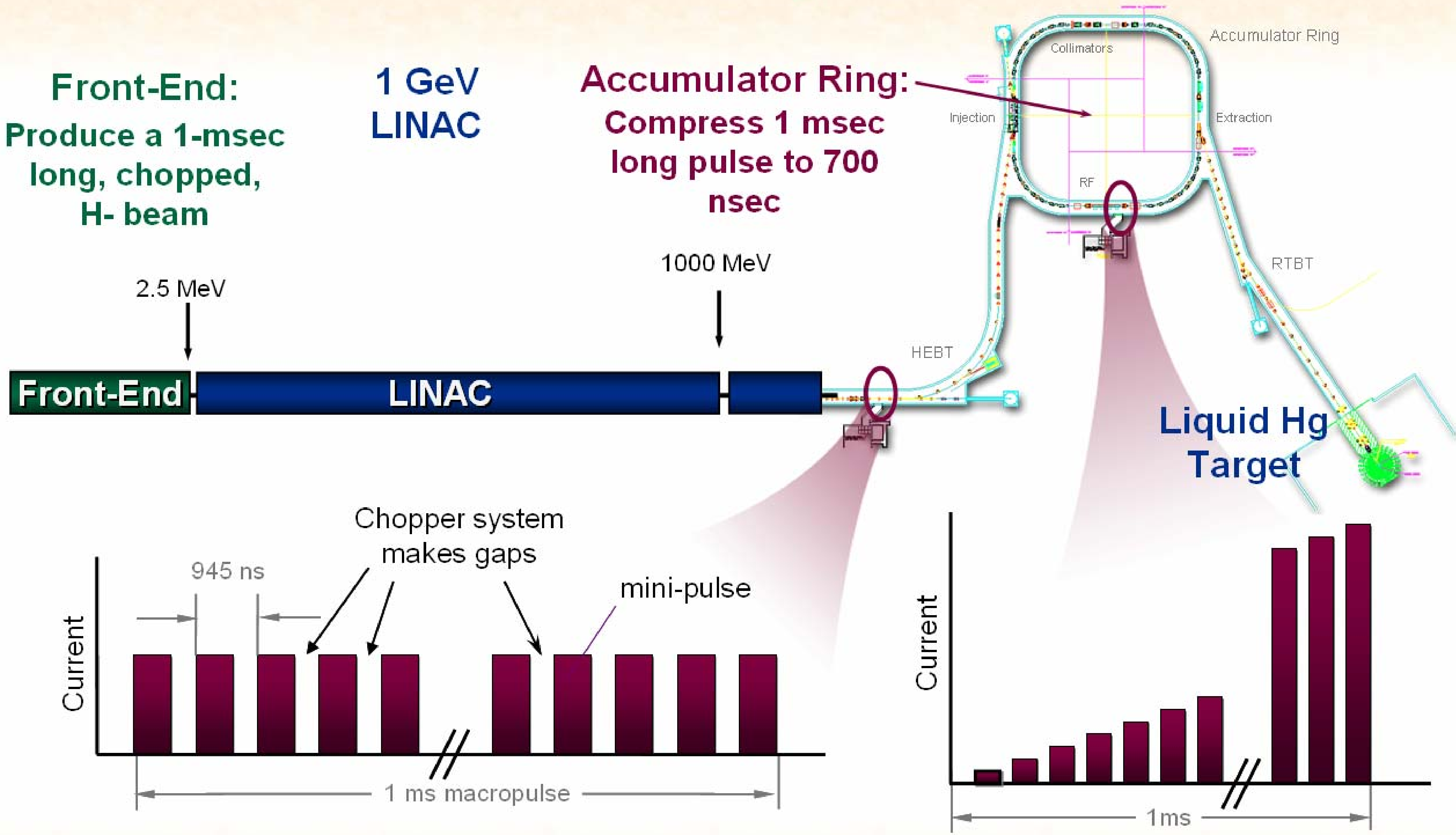


SNS Accelerator Complex

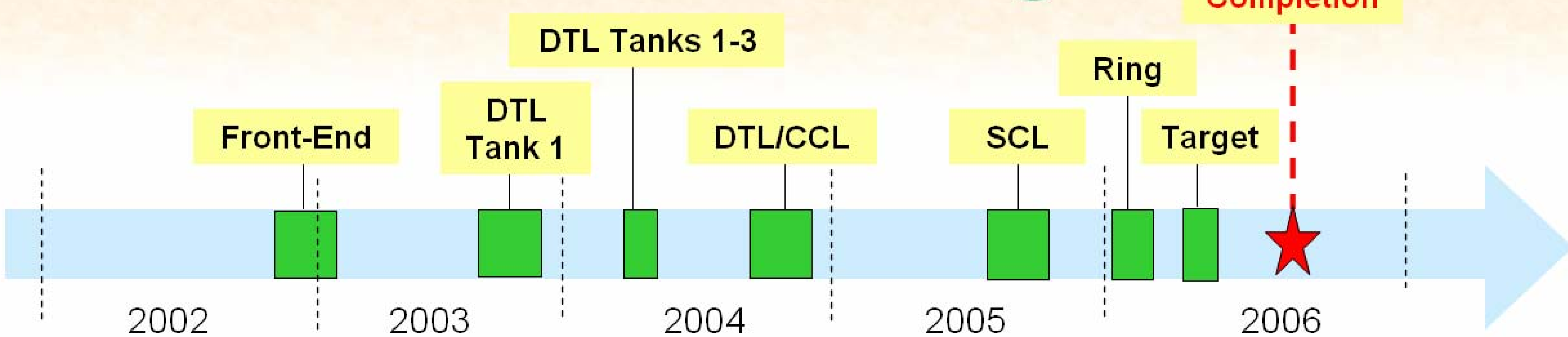
Front-End:
Produce a 1-msec long, chopped, H- beam

1 GeV LINAC

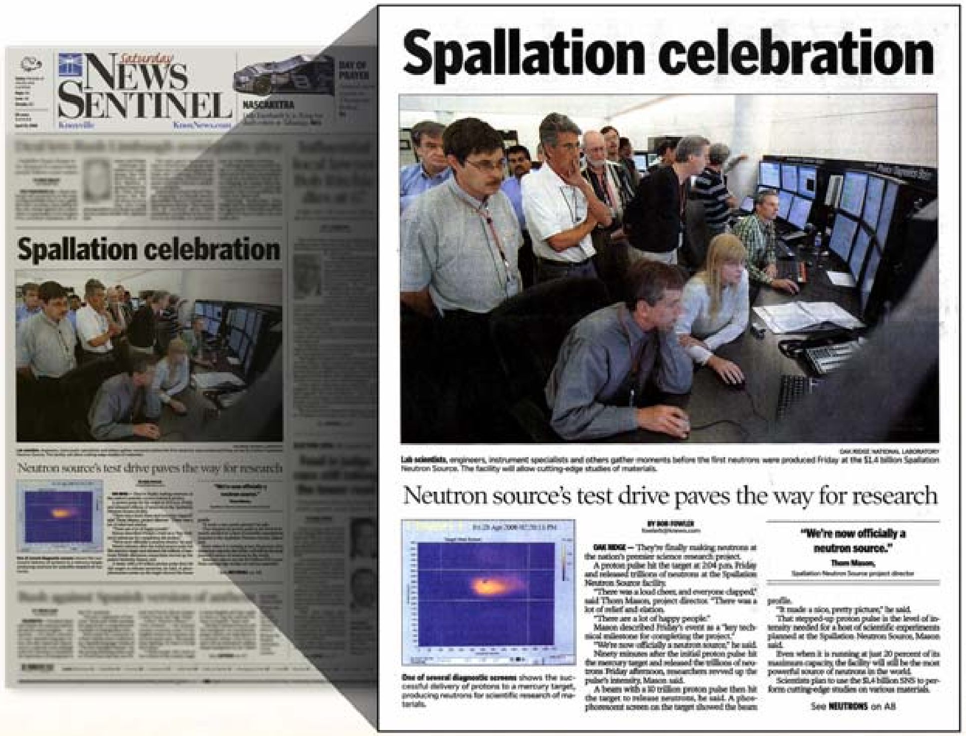
Accumulator Ring:
Compress 1 msec long pulse to 700 nsec



SNS Beam Commissioning



- **First Beam on Target, First Neutrons and Technical Project Completion goals were met April 28, 2006**
  - **10^{13} protons delivered to the target**
  - **Neutron flux goals exceeded**
- **The SNS Construction Project was formally Completed in June 2006**



Saturday News Sentinel

Spallation celebration

Lab scientists, engineers, instrument specialists and others gather moments before the first neutrons were produced Friday at the $1.4 billion Spallation Neutron Source. The facility will allow cutting-edge studies of materials.

OAK RIDGE NATIONAL LABORATORY

Neutron source's test drive paves the way for research

One of several diagnostic screens shows the successful delivery of protons to a mercury target, producing neutrons for scientific research of materials.

BY BOB FOWLER

OAK RIDGE — They're finally making neutrons at the nation's premier science research project.

A proton pulse hit the target at 2:04 p.m. Friday and released trillions of neutrons at the Spallation Neutron Source facility.

"There was a loud cheer, and everyone clapped," said Thom Mason, project director. "There was a lot of relief and elation.

"There are a lot of happy people."

Mason described Friday's event as a "key technical milestone for completing the project."

"We're now officially a neutron source," he said.

Ninety minutes after the initial proton pulse hit the mercury target and released the trillions of neutrons Friday afternoon, researchers revved up the pulse's intensity, Mason said.

A beam with a 10 trillion proton pulse then hit the target to release neutrons, he said. A phosphorescent screen on the target showed the beam profile.

"It made a nice, pretty picture," he said.

That stepped-up proton pulse is the level of intensity needed for a host of scientific experiments planned at the Spallation Neutron Source, Mason said.

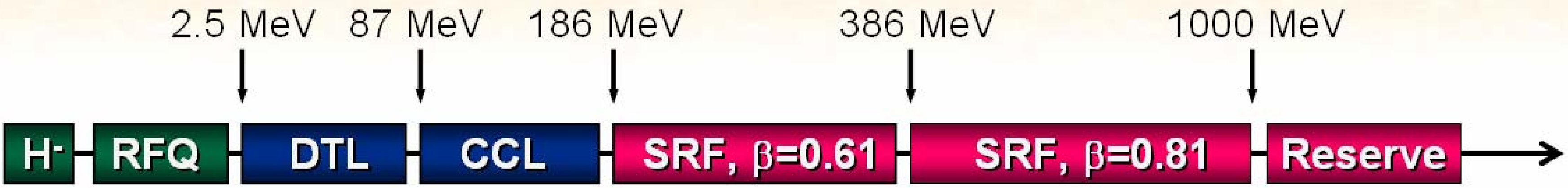
Even when it is running at just 20 percent of its maximum capacity the facility will still be the most powerful source of neutrons in the world.

Scientists plan to use the $1.4 billion SNS to perform cutting-edge studies on various materials.

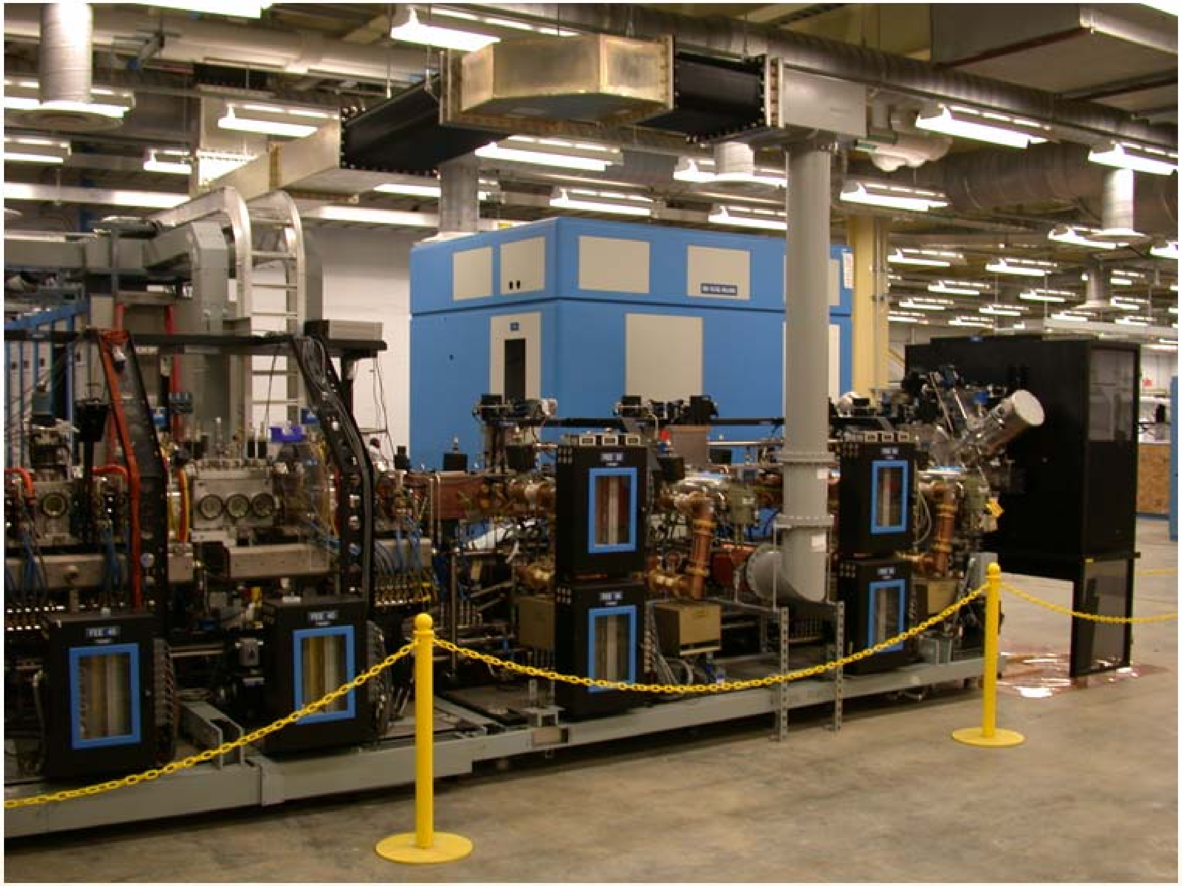
"We're now officially a neutron source."
Thom Mason,
Spallation Neutron Source project director

See NEUTRONS on A8

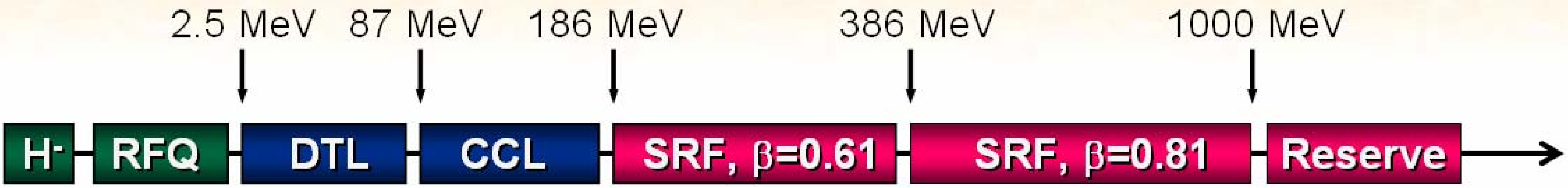
SNS Linear Accelerator



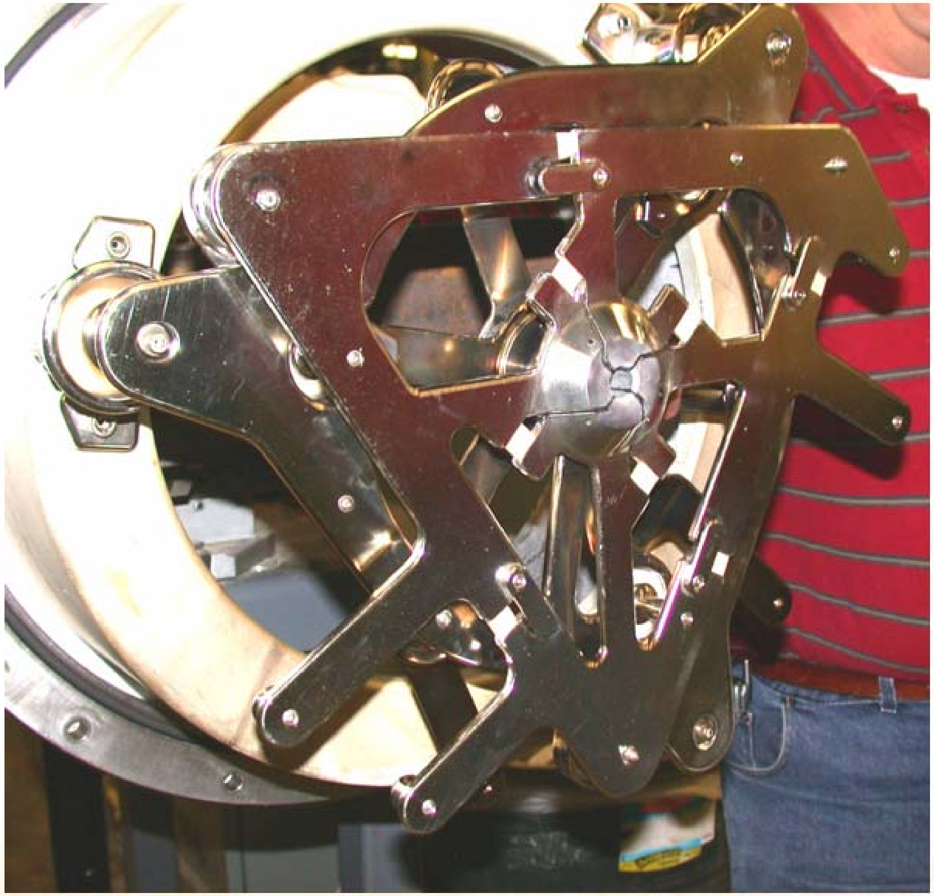
- **Front-end was designed and built by Lawrence Berkeley National Laboratory**
- **Multicusp Cs-enhanced volume production H- ion source**



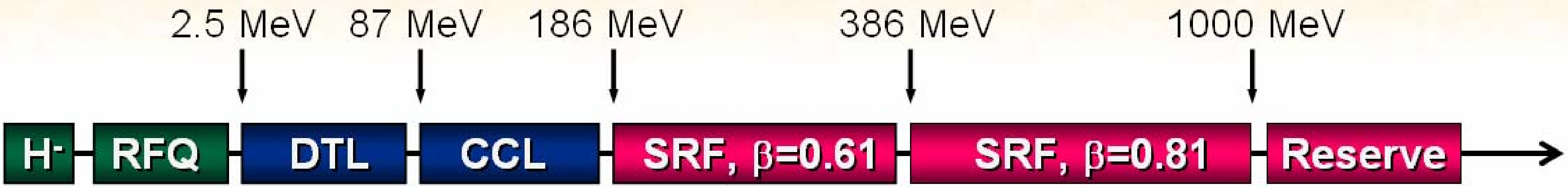
SNS Linear Accelerator



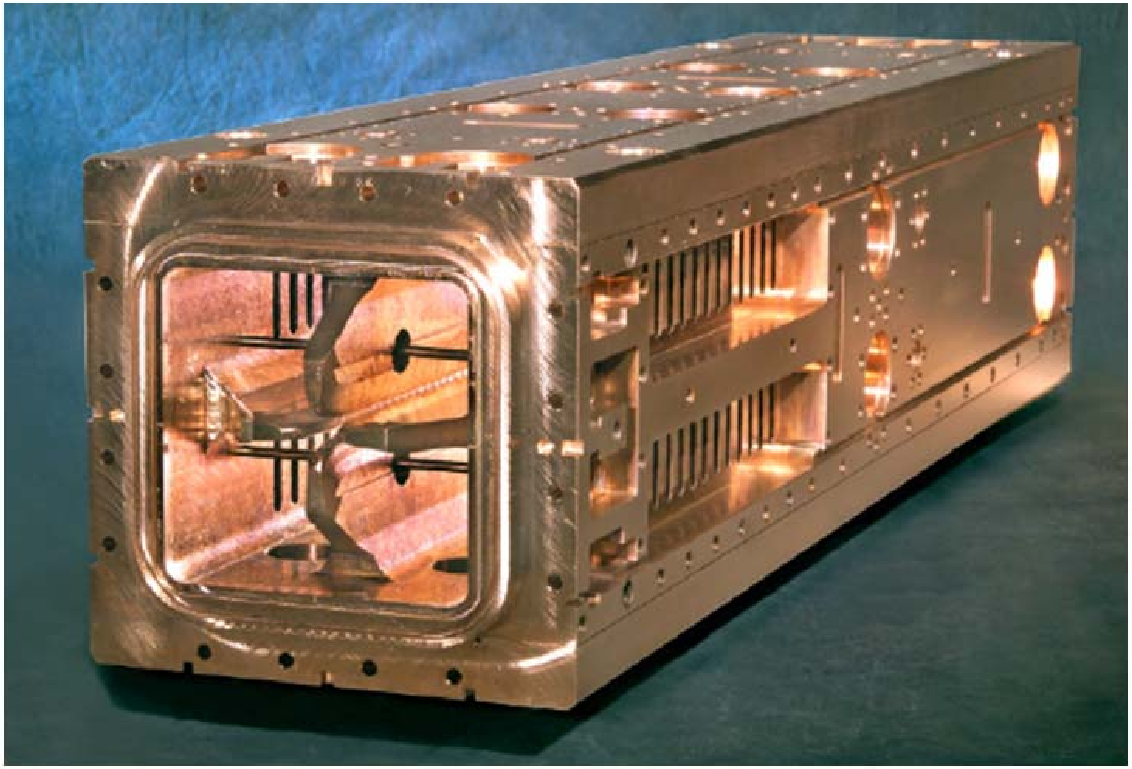
- **Front-end was designed and built by Lawrence Berkeley National Laboratory**
- **Multicusp Cs-enhanced volume production H- ion source**
- **Electrostatic LEBT (Low-energy beam transport)**
- **Chopping of 65 keV beam in LEBT and 2.5 MeV beam in MEBT**



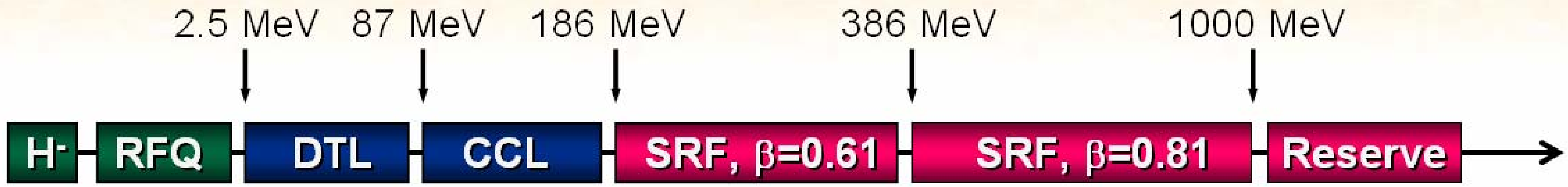
SNS Linear Accelerator



- **Front-end was designed and built by Lawrence Berkeley National Laboratory**
- **Multicusp Cs-enhanced volume production H- ion source**
- **Electrostatic LEBT (Low-energy beam transport)**
- **Chopping of 65 keV beam in LEBT and 2.5 MeV beam in MEBT**
- **402.5 MHz RFQ with 2.5 MeV output energy**
- **Front-end design parameters:**
  - 38 mA peak current
  - 68% beam-on chopping
  - 1.0 msec, 60 Hz, 6% duty
  - 1.6 mA average current



SNS Linear Accelerator



- **SNS linac is the world's highest energy proton/H- linac**
  - Achieved 1.01 GeV in a demonstration run
- **SNS linac architecture consists of**
  - Conventional normal conducting structures to 186 MeV
  - Superconducting structures to 1 GeV

SNS Linear Accelerator

- **SNS linac is the world's highest energy proton/H- linac**
  - Achieved 1.01 GeV in a demonstration run
- **SNS linac architecture consists of**
  - Conventional normal conducting structures to 186 MeV
  - Superconducting structures to 1 GeV
- **Normal conducting linac was designed and built by Los Alamos National Laboratory**
- **DTL system consists of 6-tanks, each powered by 2.5 MW, 402.5 MHz klystron**

SNS Linear Accelerator

- **SNS linac is the world's highest energy proton/H- linac**
  - Achieved 1.01 GeV in a demonstration run
- **SNS linac architecture consists of**
  - Conventional normal conducting structures to 186 MeV
  - Superconducting structures to 1 GeV
- **Normal conducting linac was designed and built by Los Alamos National Laboratory**
- **DTL system consists of 6-tanks, each powered by 2.5 MW, 402.5 MHz klystron**
- **CCL system consists of 4 modules, each powered by a 5 MW, 805 MHz klystron; 12 segments form a module**

SNS Linear Accelerator

- **World's first high-energy superconducting linac for protons**
- **Cryomodules designed and built by Jefferson Laboratory**
- **Two cavities geometries, (β_g=0.61, 0.81) are used to cover broad range in particle velocities**

Medium beta cavity

High beta cavity

SNS Linear Accelerator

- **World's first high-energy superconducting linac for protons**
- **Cryomodules designed and built by Jefferson Laboratory**
- **Two cavities geometries, (β_g=0.61, 0.81) are used to cover broad range in particle velocities**
- **SCL consists of 81 independently-powered 805 MHz cavities, each driven by a 550 kW klystron, in 23 cryomodules**

SNS Linear Accelerator

- **World's first high-energy superconducting linac for protons**
- **Cryomodules designed and built by Jefferson Laboratory**
- **Two cavities geometries, (β_g=0.61, 0.81) are used to cover broad range in particle velocities**
- **SCL consists of 81 independently-powered 805 MHz cavities, each driven by a 550 kW klystron, in 23 cryomodules**
- **Space is reserved for additional cryomodules to give 1.3 GeV**
- **He plant supports operation at 4 or 2 degrees K**

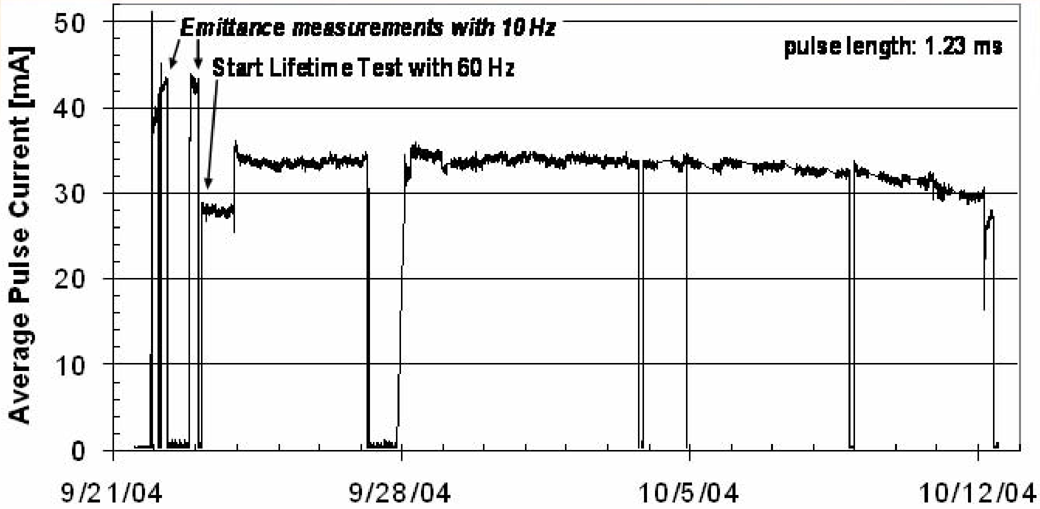
Linac RF Systems
Champion (FRXC01)

- Designed by Los Alamos Nat. Lab
- All systems 8% duty factor: 1.3 ms, 60 Hz
- 7 DTL Klystrons: 2.5 MW 402.5 MHz
- 4 CCL Klystrons: 5 MW 805 MHz
- 81 SCL Klystrons: 550 kW, 805 MHz
- 14 IGBT-based modulators each providing 1 MW average power
- Digital RF controls with feedback and feedforward

- **2nd largest klystron and modulator installation in the world!**

Front-End Commissioning and Performance

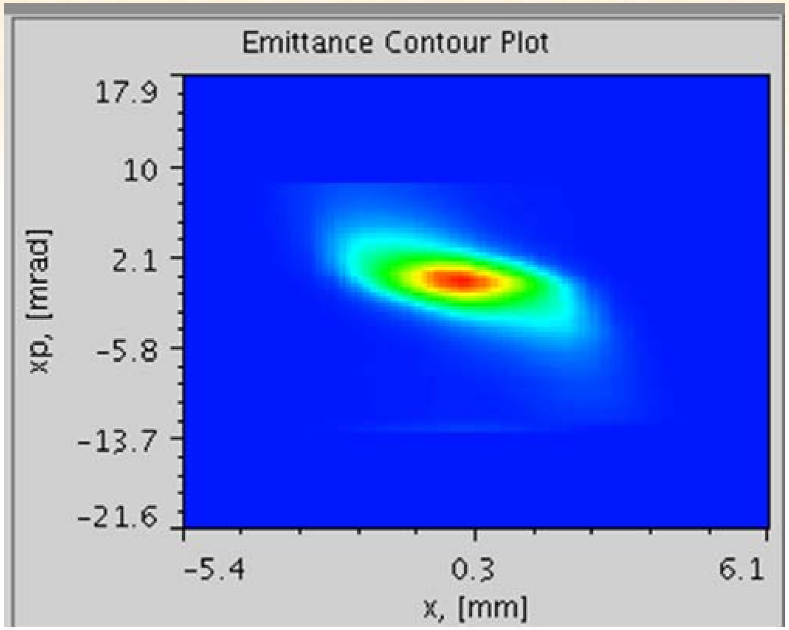
- Challenges:
  - High current (38 mA) and duty factor (6% beam duty)
  - Small emittance
  - Chopping system performance
  - Source lifetime
- Ongoing R&D program to develop long-lived ion sources at design parameters; Welton (FROAAB02)
- Front-end emittance specifications are met at design current
- LEBT and MEBT chopper systems meet risetime and extinction ratio specifications
- Reliability of chopper systems has been a limitation in early operation; Aleksandrov (TUPAS073)



Parameter	Baseline Design (Front-End)	Achieved (Ion Source)	Achieved (Front-End)	Routine Operation
Peak Current	38 mA	60	50	17
Pulse Length	1.0 msec	1.25	1.0	0.3-0.5
Repetition Rate	60 Hz	60	60	30
Average Current	1.6 mA	2.5 mA	1.05 mA	70 uA
Emittance (rms,norm)	<0.3 πmm-mrad	0.22	0.29, 0.26	N/A

Front-End Commissioning and Performance

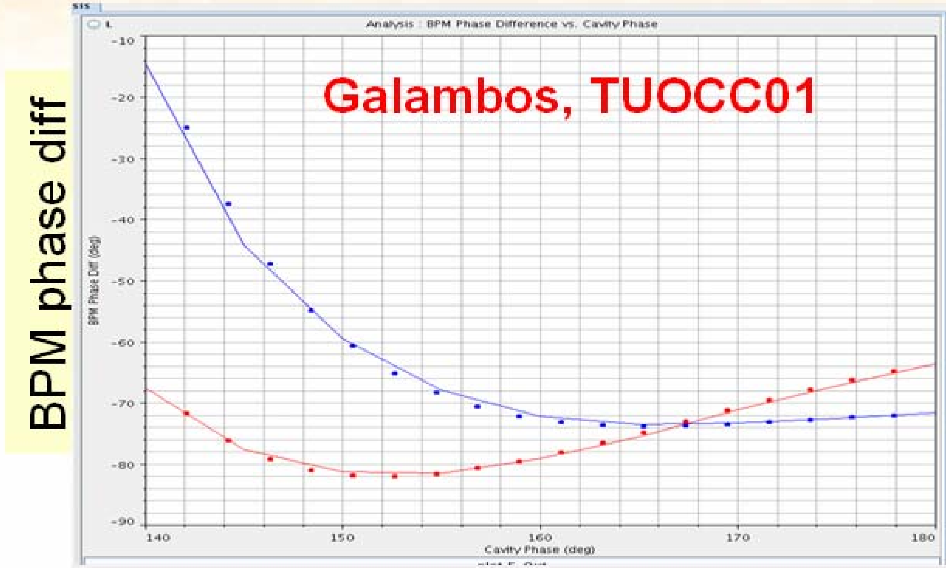
- Challenges:
  - High current (38 mA) and duty factor (6% beam duty)
  - Small emittance
  - Chopping system performance
  - Source lifetime
- Ongoing R&D program to develop long-lived ion sources at design parameters; Welton (FROAAB02)
- Front-end emittance specifications are met at design current
- LEBT and MEBT chopper systems meet risetime and extinction ratio specifications
- Reliability of chopper systems has been a limitation in early operation; Aleksandrov (TUPAS073)

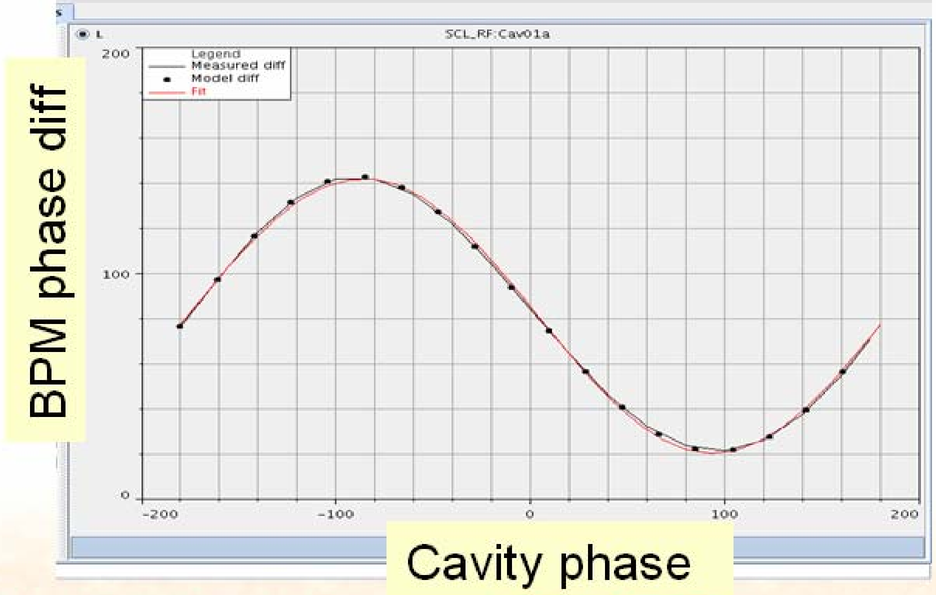


Parameter	Baseline Design (Front-End)	Achieved (Ion Source)	Achieved (Front-End)	Routine Operation
Peak Current	38 mA	60	50	17
Pulse Length	1.0 msec	1.25	1.0	0.3-0.5
Repetition Rate	60 Hz	60	60	30
Average Current	1.6 mA	2.5 mA	1.05 mA	70 uA
Emittance (rms,norm)	<0.3 πmm-mrad	0.22	0.29, 0.26	N/A

SNS Linac Operation and Performance

- Challenges
  - Stringent beam loss constraints of 1 Watt/m
    - Requires accurate RF setpoint determination
    - Careful phase-space matching
  - Output beam quality, particularly emittance growth
    - Requires careful matching
    - Good stability of phase/amplitude
    - Compensation of heavy beam loading with adaptive feedforward methods
  - Evolving SC cavity setpoints
    - Rapid methods to use inherent flexibility of individually powered cavities
- Longitudinal Setpoints determined with “Phase Scan Signature Matching” that uses time-of-flight measurements with a model-based algorithm to determine
  - input energy
  - beam-RF phase and
  - RF amplitude

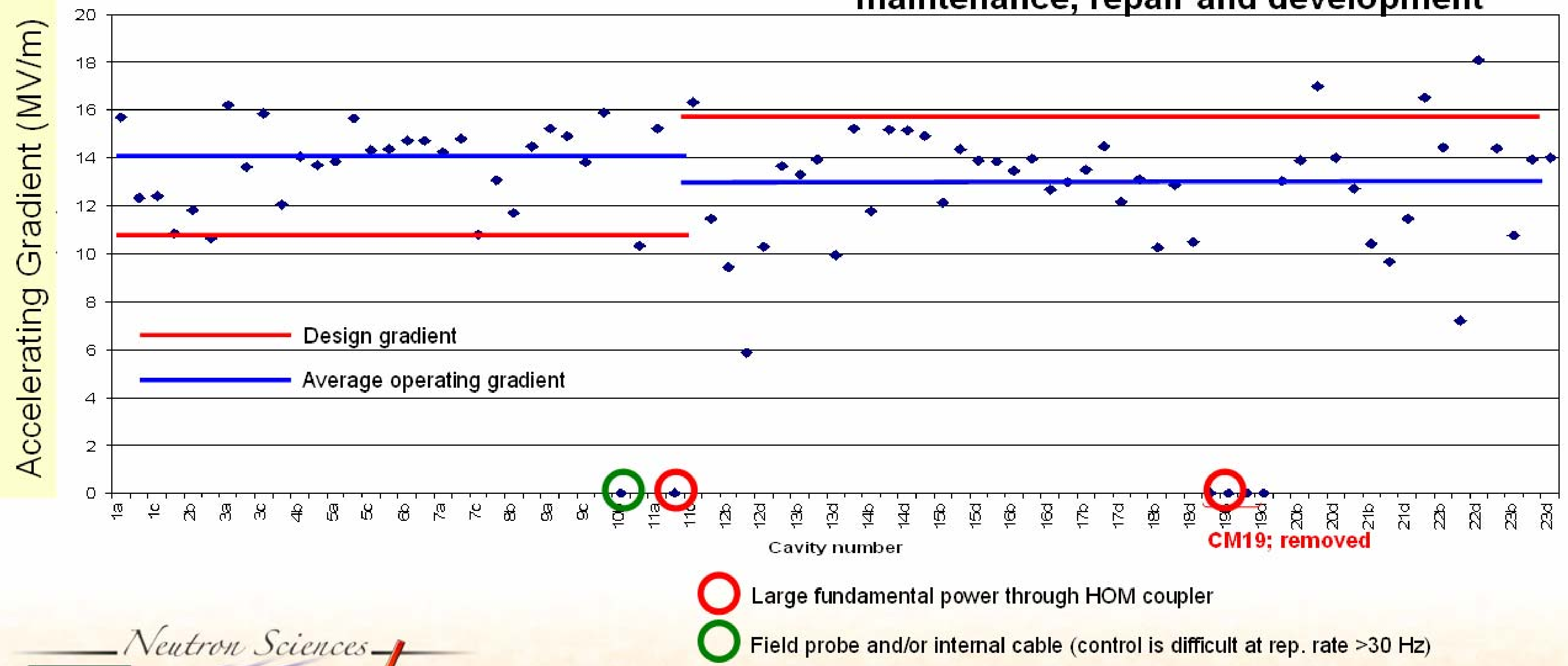




Superconducting Linac Operation

Campisi (WEPMS072), Kim (WEPMS076), Stout (MOPAS082)

- Operating at 30 Hz, 2.1 K, 890 MeV, with 75 cavities online of 77 available (one CM has been removed)
- Operating gradients are shown; individual cavity limits are higher
- We are operating ~6 cavities with unusual HOM signals that indicate electron activity
- The inherent flexibility of individually powered cavities is used to "tune-around" an unpowered cavity.
- A rapid method (1 minute) for "fault recovery" is used to rephase the linac in response to RF setpoint changes
- We are constructing an SRF Facility for maintenance, repair and development



SNS Linac Performance Specifications

Aleksandrov (TUPAS074, THOAAB01)

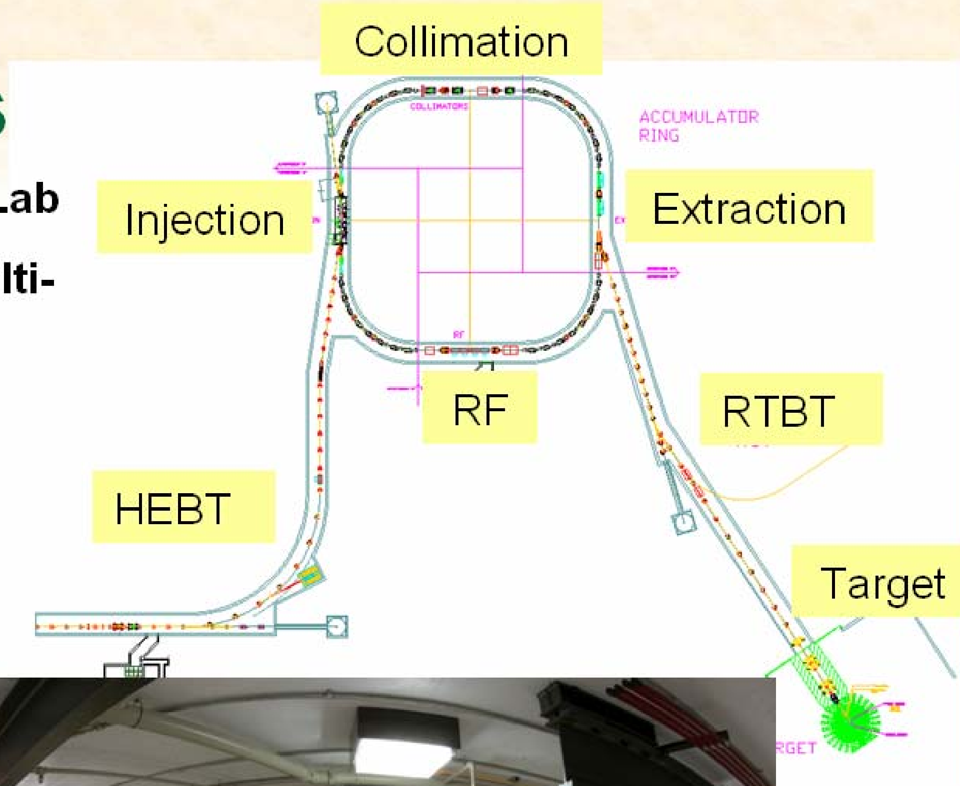
	Baseline Design	Achieved	Routine Operation
Energy	1000	1010 ✓	890
RMS normalized output emittance (π mm-mrad)	<0.4	0.3, 0.3 ✓ (25 mA, 50 μs)	
Pulse to pulse jitter	+/- 1.5 MeV	+/- 1.3 MeV ✓	
Average current	1600 μA	100 μA	70 μA
H-/pulse	1.6×10^{14}	1.0×10^{14}	3×10^{13}
RF phase/amplitude stability	1 deg/1%	0.5 deg/ 0.5% ✓	1 deg/1% ✓

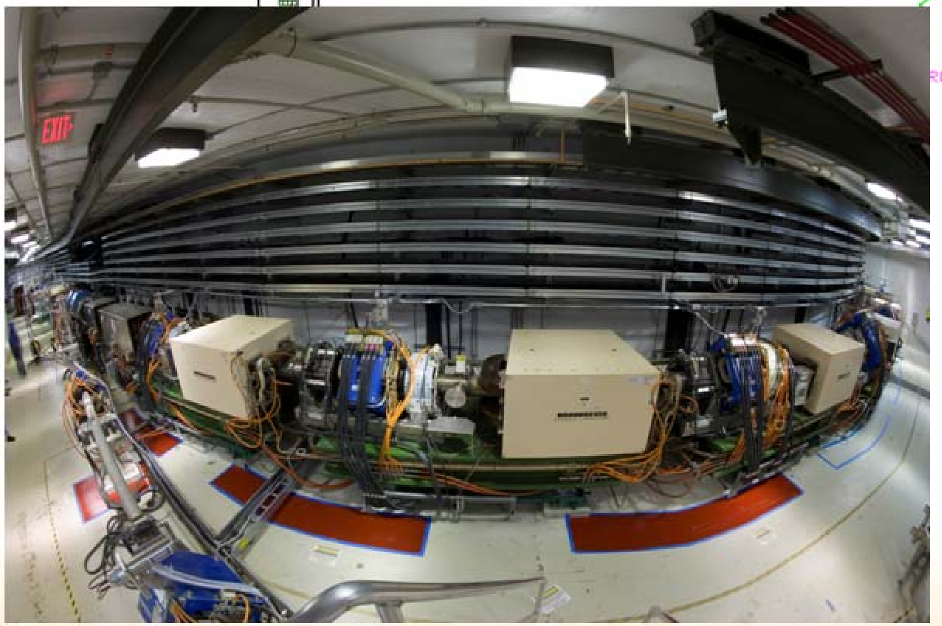
- Emittance growth can be controlled
- SNS linac, with independently powered cavities is extremely flexible
- Linac beam dynamics can accommodate unpowered SC cavities with little or no impact on beam quality

Accumulator Ring and Transport Lines

- **Designed and built by Brookhaven National Lab**
- **Accumulates 1-msec long beam pulse by multi-turn charge exchange injection**

Circum	248 m
Energy	1 GeV
f_{rev}	1 MHz
Q_x, Q_y	6.23, 6.20
Accum turns	1060
Final Intensity	1.5×10^{14}
Current	26 A

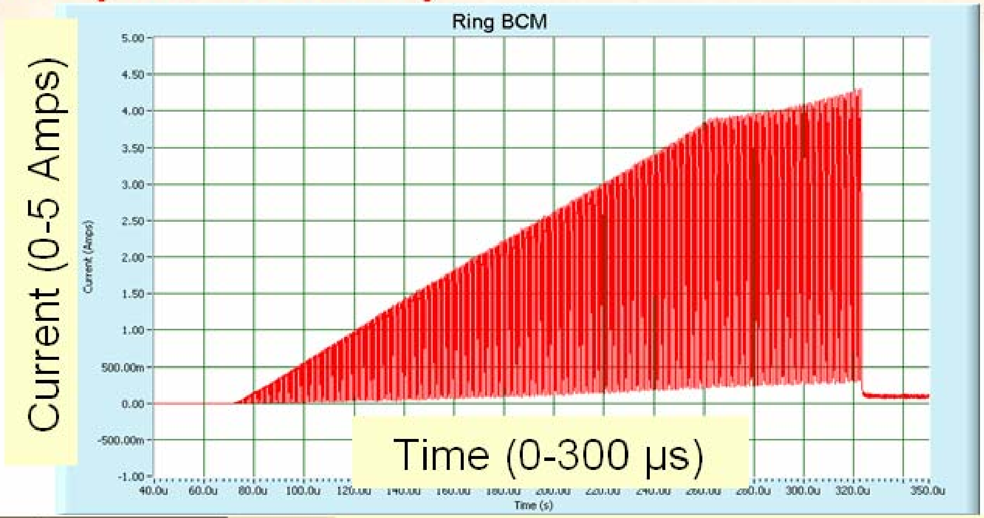


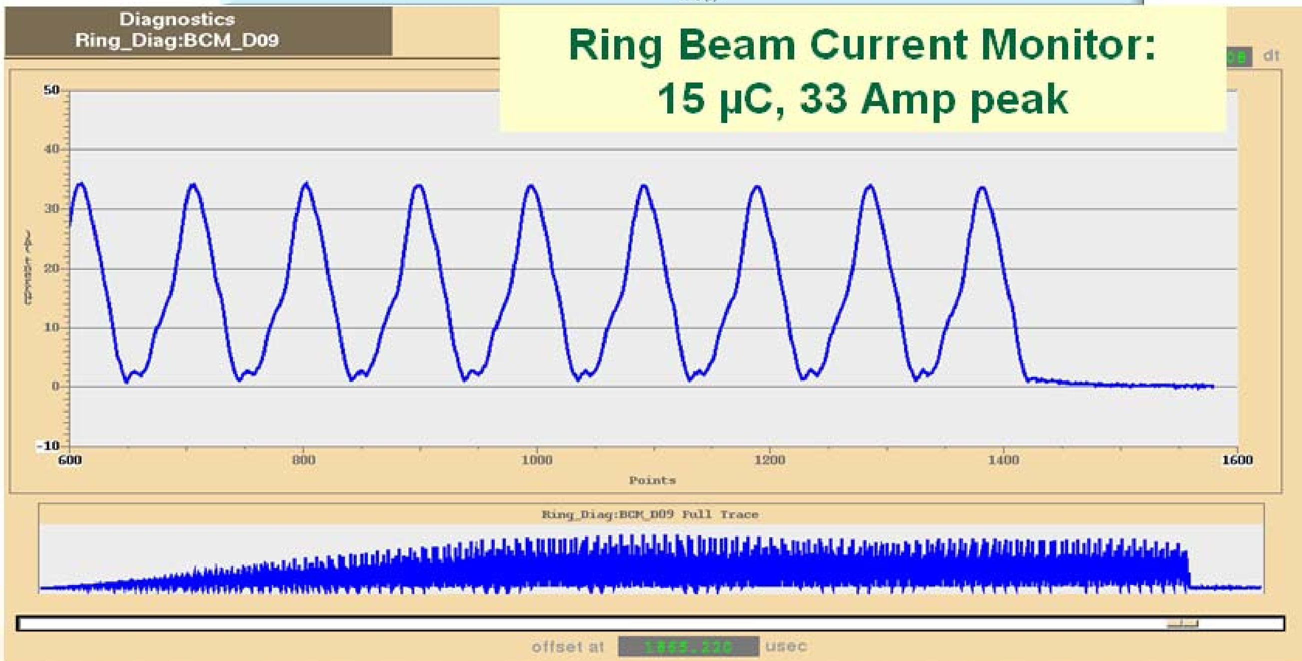


Accumulator Ring Performance

Plum (THXAB03), Cousineau (TUOBKI01)

- Challenges
  - High-intensity
    - Careful consideration and control of collective effects
  - Stringent beam loss constraints < 1 W/m
    - Phase-space painting
    - Dual-harmonic RF
    - 2-stage collimation
  - Beams from H- stripping inefficiency must be cleanly transported
- World Record proton intensity accumulated and extracted from a storage ring: 0.96×10^{14} protons
- No instabilities with 1000 turns storage!



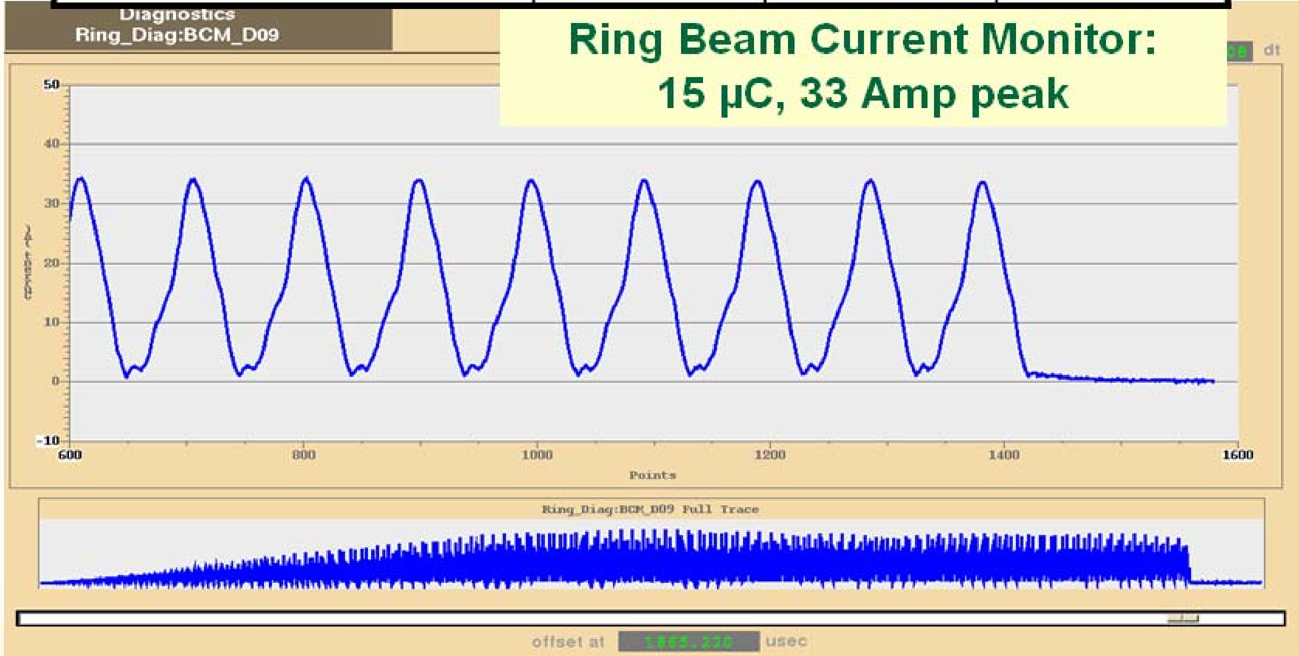


Accumulator Ring Performance

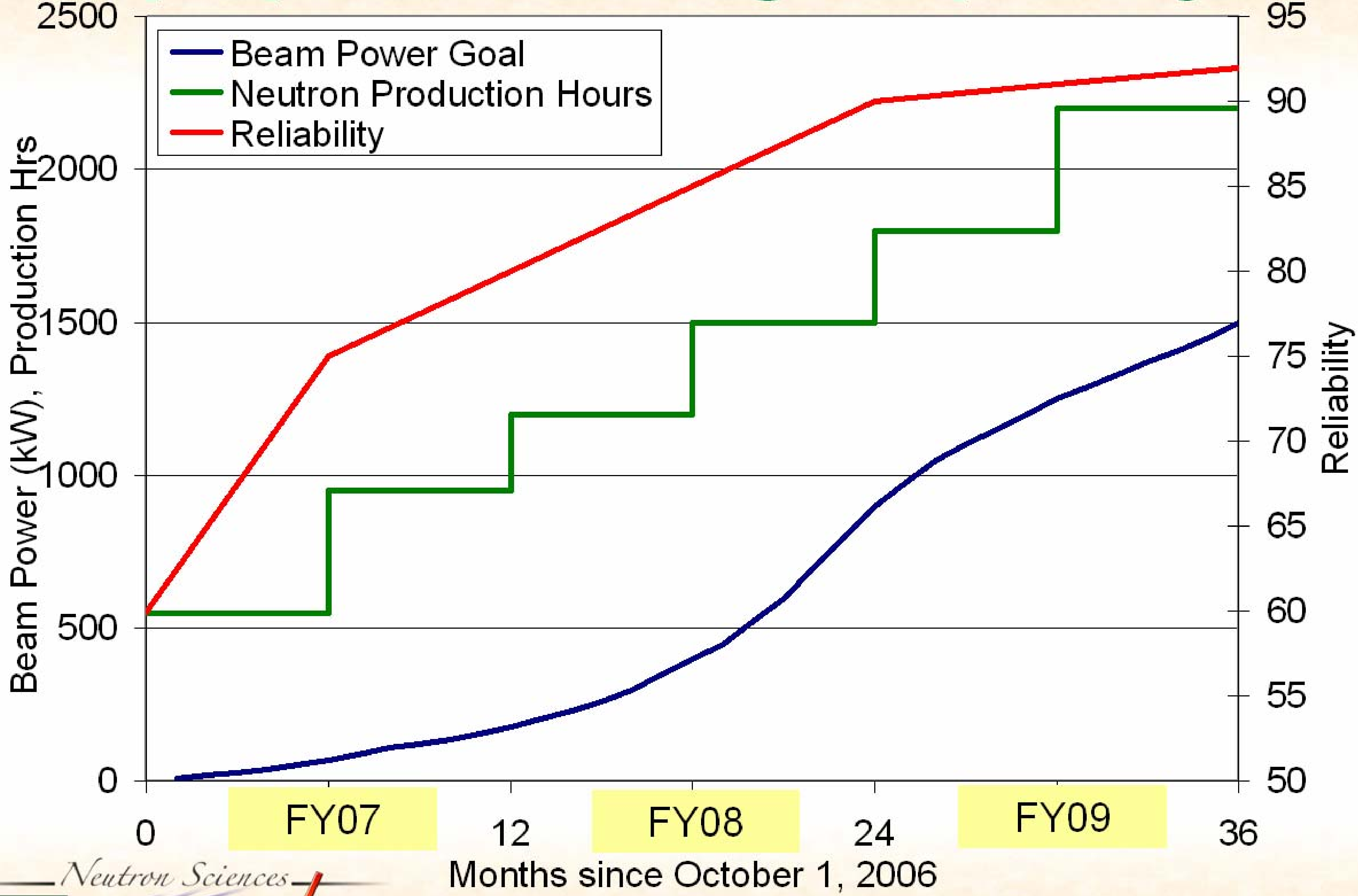
Plum (THXAB03), Cousineau (TUOBKI01)

- Challenges
  - High-intensity
    - Careful consideration and control of collective effects
  - Stringent beam loss constraints < 1 W/m
    - Phase-space painting
    - Dual-harmonic RF
    - 2-stage collimation
  - Beams from H- stripping inefficiency must be cleanly transported
- World Record proton intensity accumulated and extracted from a storage ring: 0.96×10^{14} protons
- No instabilities with 1000 turns storage!

	Baseline Design	Achieved	Routine Operation
Protons/pulse extracted	1.5×10^{14}	0.96×10^{14}	3×10^{13}
Protons/pulse on target	1.5×10^{14}	5.3×10^{13}	3×10^{13}
Current	26 Amps	17 Amps	5
Turns Accumulated	1060	830	500
Space charge tuneshift	0.15	0.10	0.03

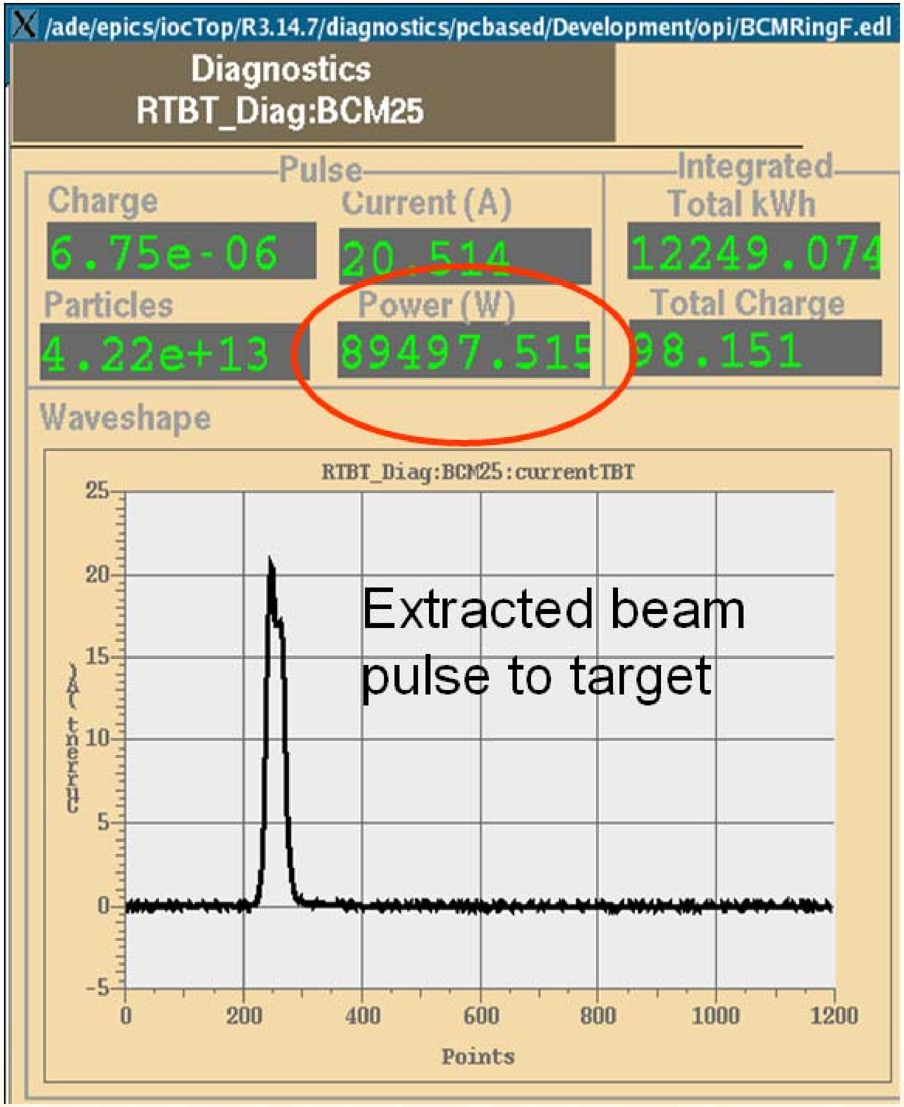


Ramp Up to SNS Design Capability

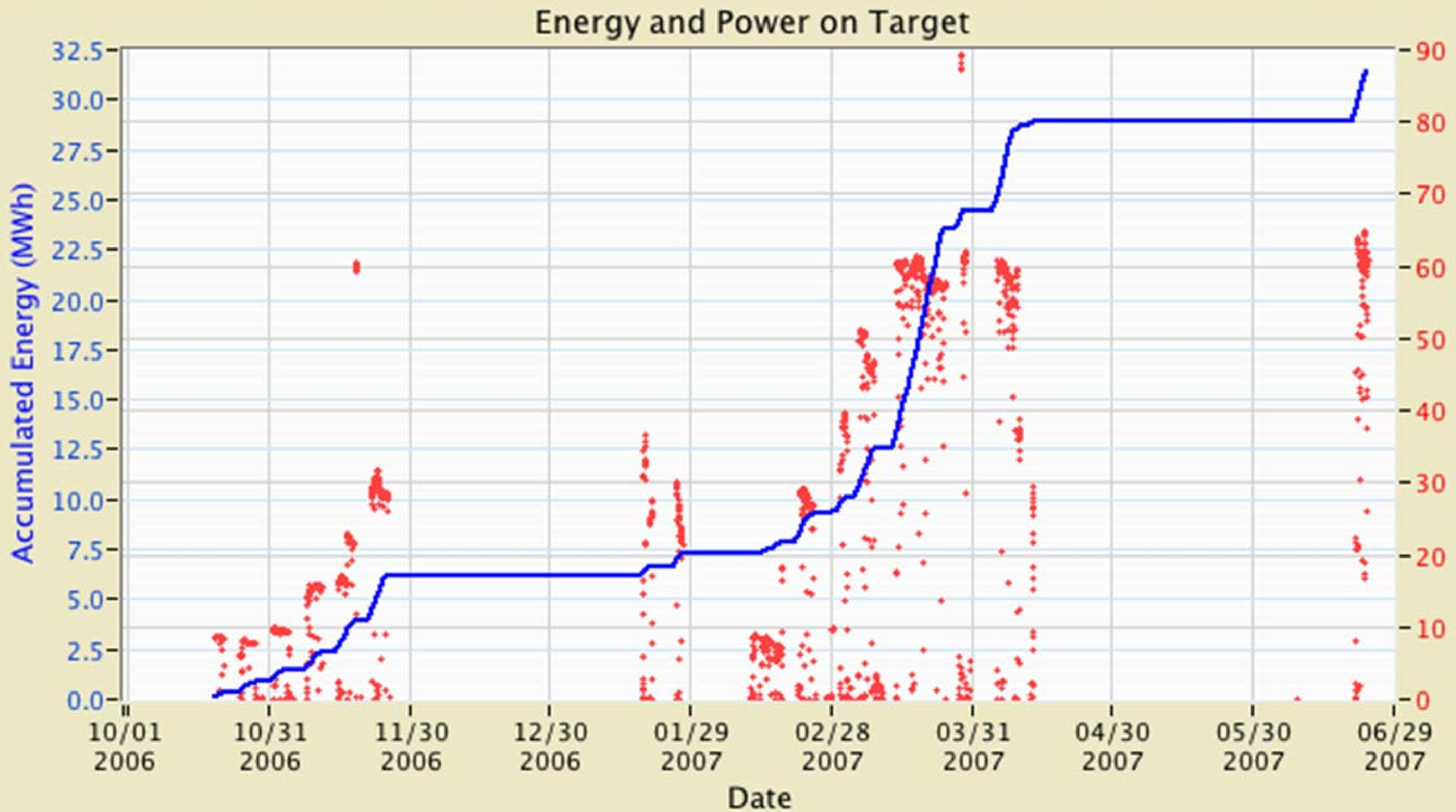


Accelerator Performance Highlights

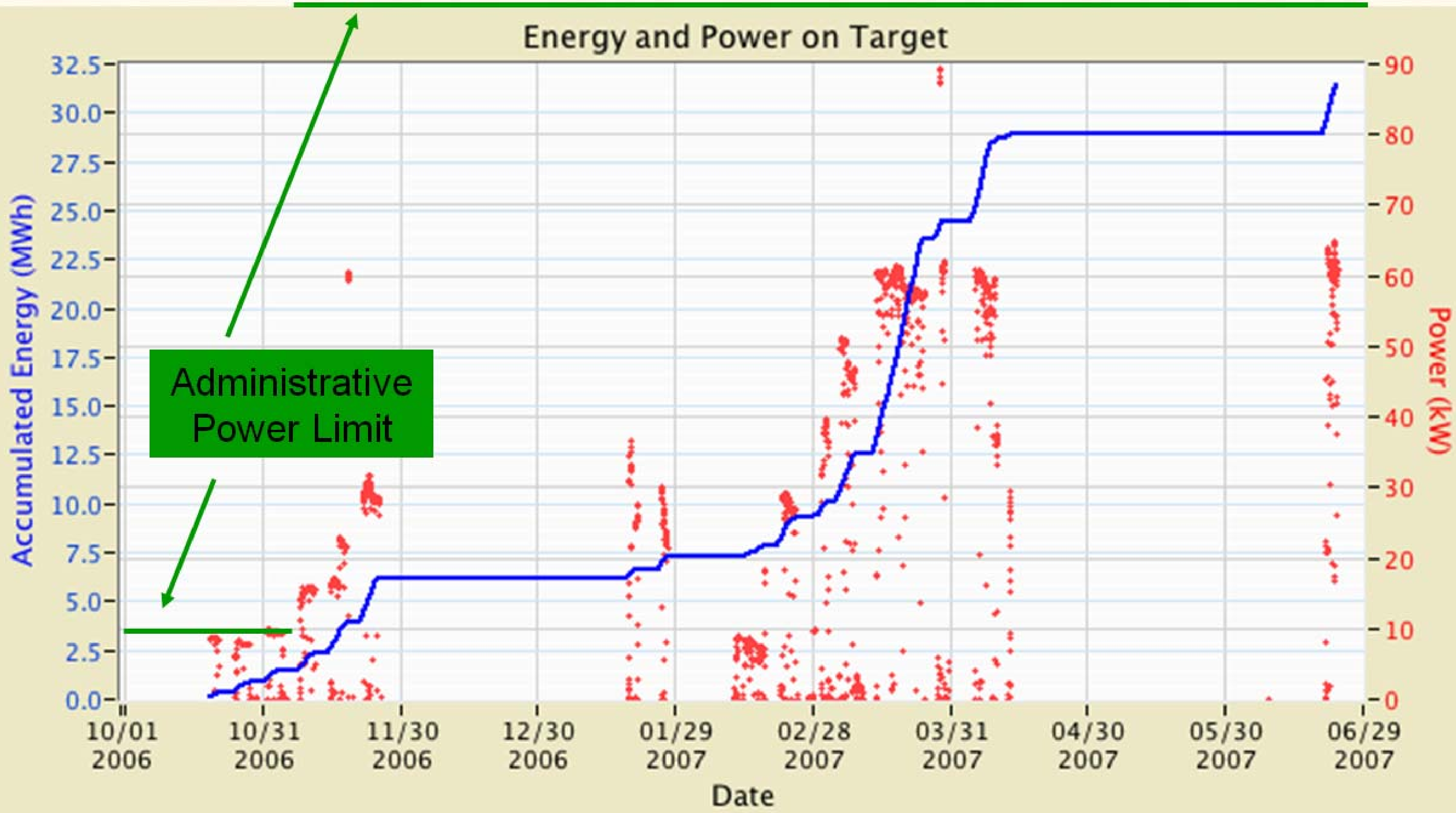
- SNS began formal operations October 1, 2006
- "Brightest" pulsed spallation neutron source: highest single pulse intensity in routine operation, 6 kJ/pulse
  - 30 kW, 5 Hz, 6.7 μC per pulse
- Routine operation at 60 kW for neutron production
  - 15 Hz, 890 MeV, 4.5 μC/pulse
- Achieved 90 kW in demonstration run
  - 15 Hz, 890 MeV, 6.7 μC/pulse
- We recently passed a readiness review to allow operation up to 2 MW beam power



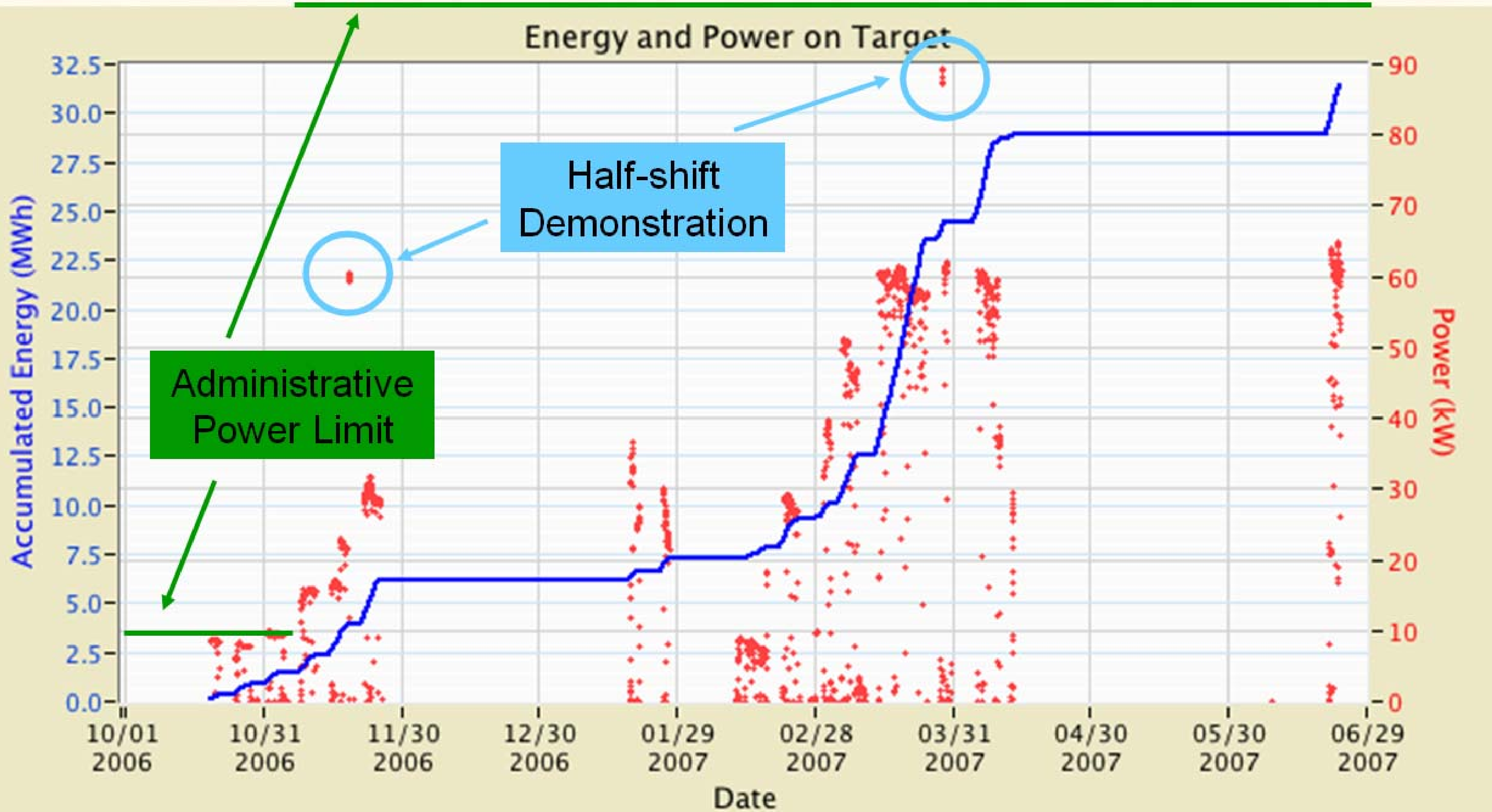
Ramp-Up Progress to Date: Beam Power on Target



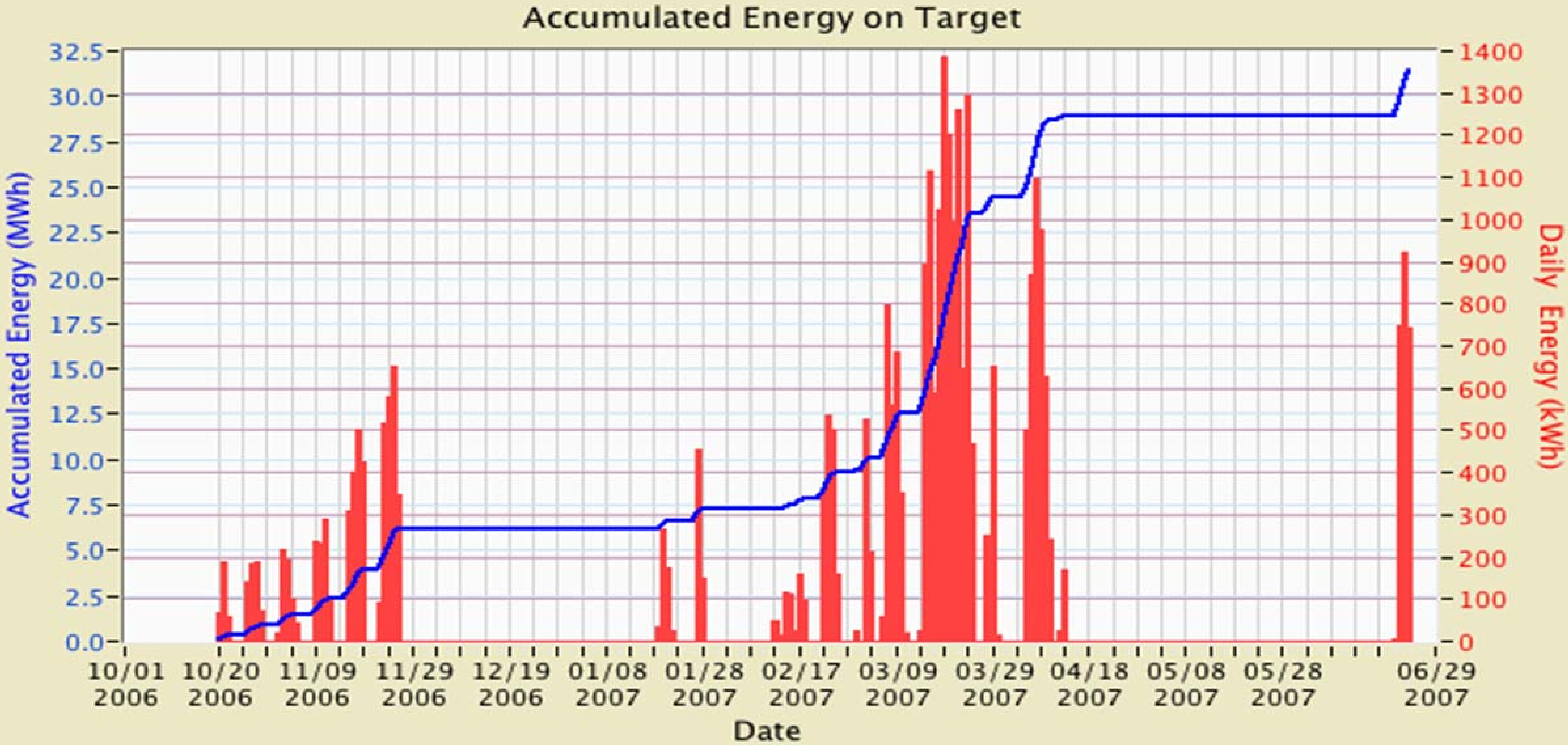
Ramp-Up Progress to Date: Beam Power on Target



Ramp-Up Progress to Date: Beam Power on Target

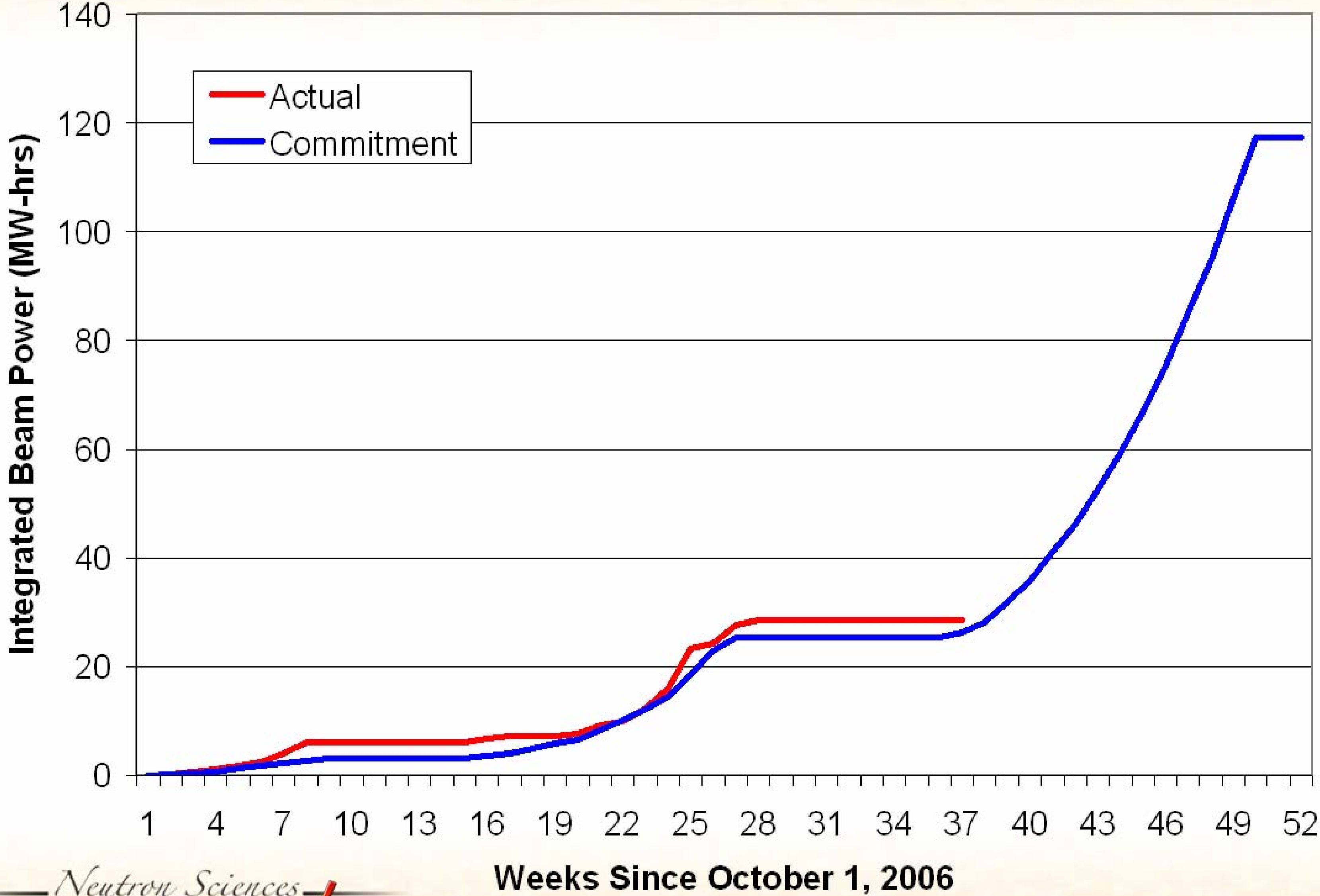


Ramp-Up Progress to Date: Integrated Beam Power



- **Reliability is a performance limitation we are actively addressing:**
  - Beam chopper systems, modulators, ion source, cryogenic moderator refrigerator, accelerator cooling water system

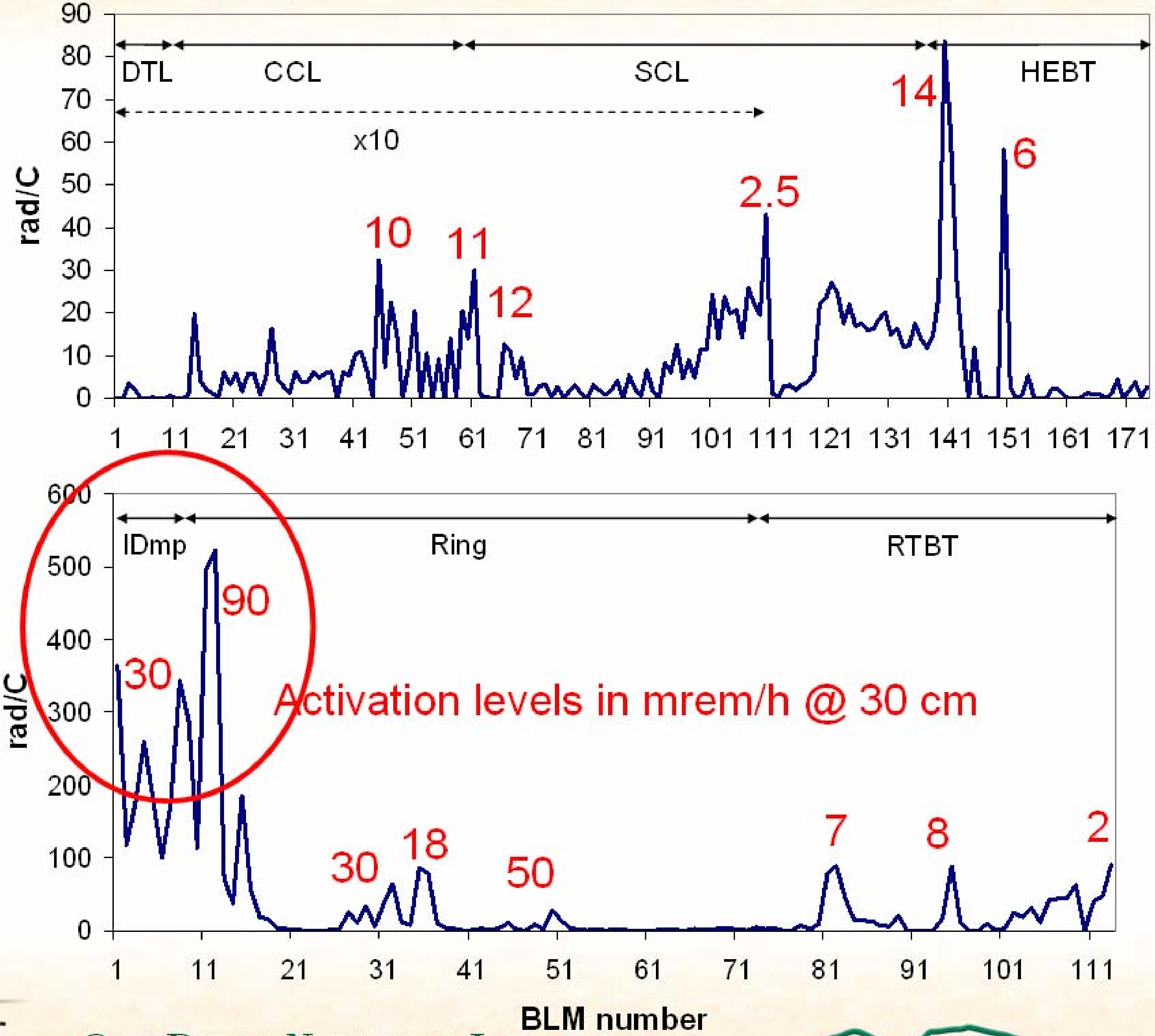
Integrated Beam Power in FY2007: Actual vs. Goal



Beamloss Status at 60 kW Operation

Plum (THXAB03), Zhukov (FRPMN060)

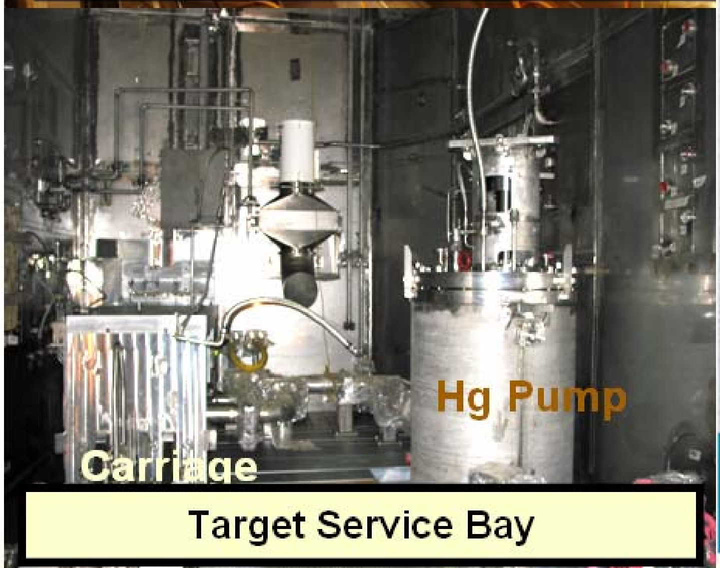
- BLM signals and activation levels (after 30 hr cooldown) from a recent 10 day run at 60 kW (15-25/Mar/07)
- Losses in most of the accelerator are in line with expectations
- We measure higher than desired losses in the Ring Injection region
- We recently re-worked part of the injection dump line to better transport the waste beams from the stripping process; Holmes (THPAS076), Wang (THPAS078)



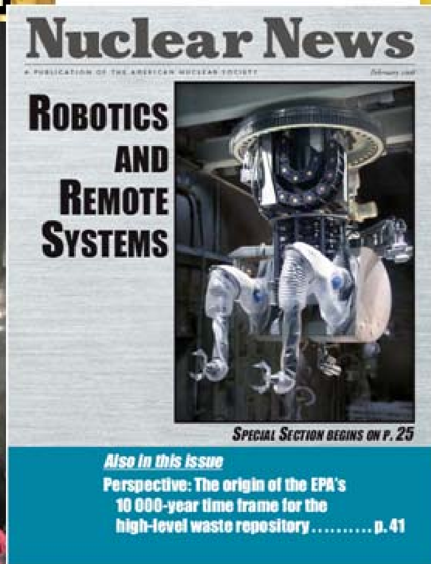
Mercury Target System and Supercritical H_2 Moderator

Target installed on Carriage with phosphor view-screen

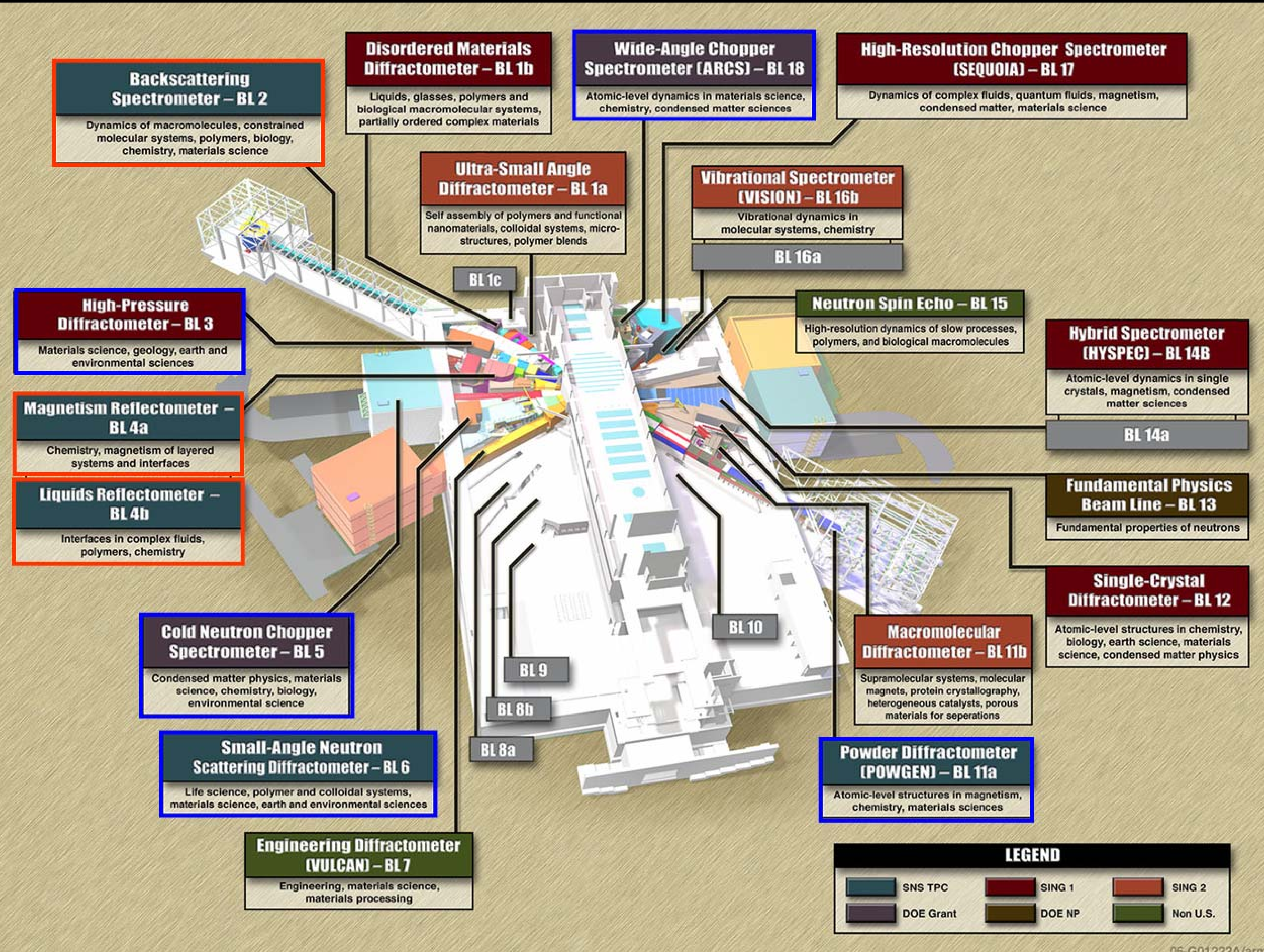
Target Change-out Test performed after mercury testing



Target Service Bay



Remote-handling Control Room

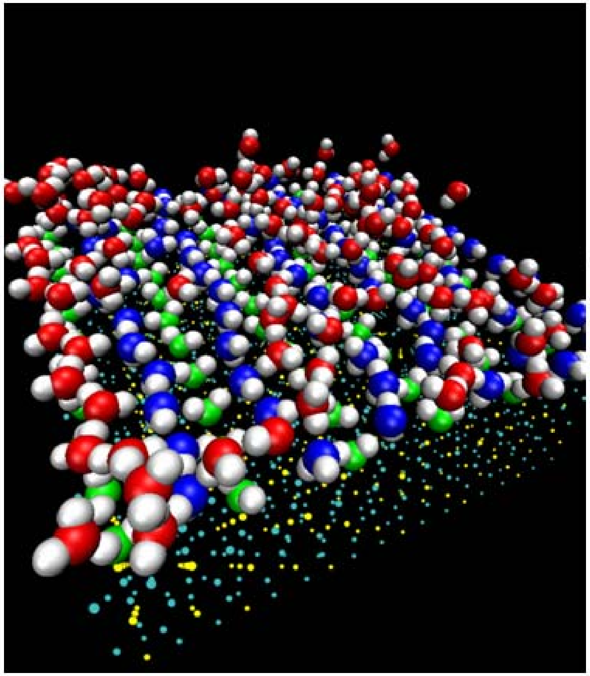

Backscattering Spectrometer – BL 2
Dynamics of macromolecules, constrained molecular systems, polymers, biology, chemistry, materials science
Disordered Materials Diffractometer – BL 1b
Liquids, glasses, polymers and biological macromolecular systems, partially ordered complex materials
Wide-Angle Chopper Spectrometer (ARCS) – BL 18
Atomic-level dynamics in materials science, chemistry, condensed matter sciences
High-Resolution Chopper Spectrometer (SEQUOIA) – BL 17
Dynamics of complex fluids, quantum fluids, magnetism, condensed matter, materials science
Ultra-Small Angle Diffractometer – BL 1a
Self assembly of polymers and functional nanomaterials, colloidal systems, micro-structures, polymer blends
Vibrational Spectrometer (VISION) – BL 16b
Vibrational dynamics in molecular systems, chemistry
BL 16a
BL 1c
High-Pressure Diffractometer – BL 3
Materials science, geology, earth and environmental sciences
Neutron Spin Echo – BL 15
High-resolution dynamics of slow processes, polymers, and biological macromolecules
Hybrid Spectrometer (HYSPEC) – BL 14B
Atomic-level dynamics in single crystals, magnetism, condensed matter sciences
BL 14a
Magnetism Reflectometer – BL 4a
Chemistry, magnetism of layered systems and interfaces
Liquids Reflectometer – BL 4b
Interfaces in complex fluids, polymers, chemistry
Fundamental Physics Beam Line – BL 13
Fundamental properties of neutrons
Single-Crystal Diffractometer – BL 12
Atomic-level structures in chemistry, biology, earth science, materials science, condensed matter physics
Cold Neutron Chopper Spectrometer – BL 5
Condensed matter physics, materials science, chemistry, biology, environmental science
BL 10
BL 9
BL 8b
BL 8a
Macromolecular Diffractometer – BL 11b
Supramolecular systems, molecular magnets, protein crystallography, heterogeneous catalysts, porous materials for seperations
Small-Angle Neutron Scattering Diffractometer – BL 6
Life science, polymer and colloidal systems, materials science, earth and environmental sciences
Powder Diffractometer (POWGEN) – BL 11a
Atomic-level structures in magnetism, chemistry, materials sciences
Engineering Diffractometer (VULCAN) – BL 7
Engineering, materials science, materials processing
LEGEND
SNS TPC
SING 1
SING 2
DOE Grant
DOE NP
Non U.S.

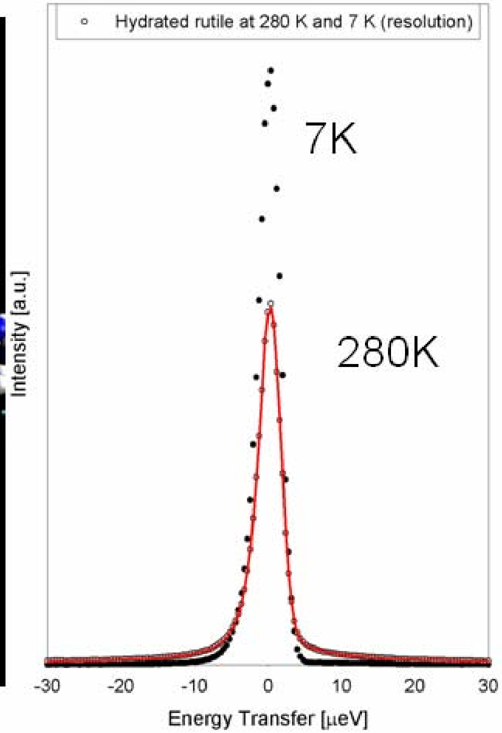
Instrument Commissioning and First Science

Backscattering Spectrometer:

Measures diffusive motion of water on TiO_2 (rutile) nanoparticles

Related to environmental science issues in diffusion and transport of water in minerals



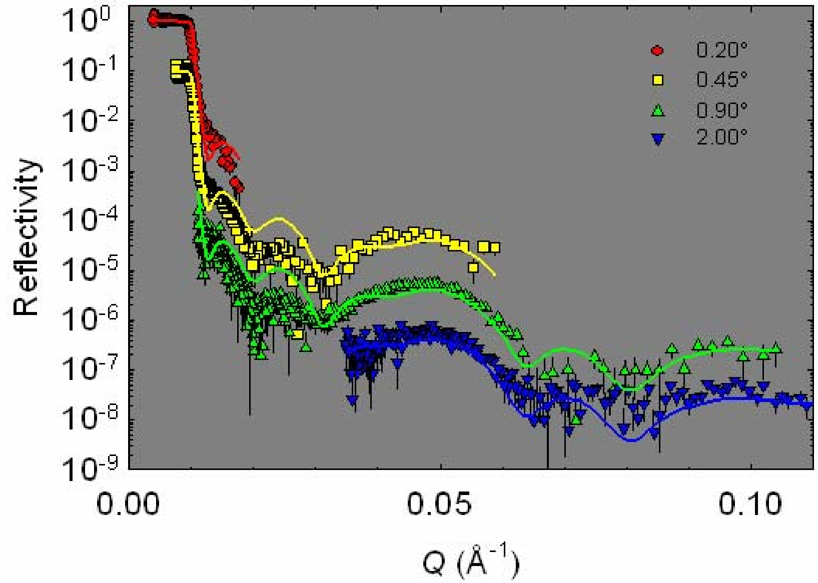


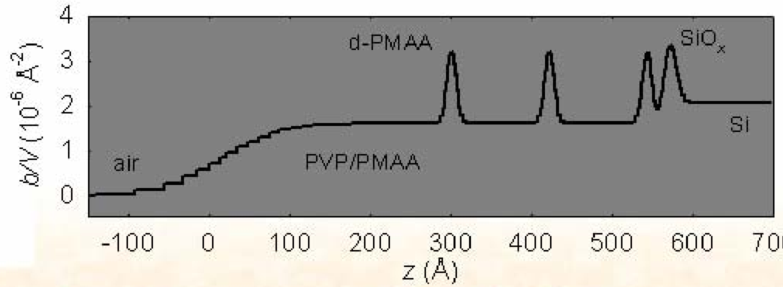
Liquids Reflectometer:

Data from poly-electrolyte multilayer in *in-vivo* conditions

Data shows interference fringes between deuterated markers

Related to biomedical aspects of drug delivery (controlled release)





SNS Upgrade Plans

1. **SNS Power Upgrade Project**
   - Doubles beam power capability to 3 MW
   - DOE 20-year plan, mid-term priority
   - Cost range: $160-183M, project duration 5 years
   - Seeking CD-1 approval now
2. **Second Target Station**
   - Doubles neutron scattering instruments and scientific productivity
   - Lower power and repetition-rate than existing target station
   - In pre-conceptual stage defining science and beam requirements
   - DOE 20-year plan, mid-term priority

Active R&D in many areas:

- Laser-stripping injection: Danilov (THYKI02)
- Stripper foil development: Shaw (MOPAS081)
- E-p active damping: Deibele (WEXC01, MOPAS080)
- Ion Source: Welton (FROAAB02)
- LEBT Design: Han (TUPAS075)

Conclusion

- The SNS is now an operating facility
- We're making rapid progress toward full design capability
- We are 8 months into an expected 3-year performance ramp
- We are on-track with our ramp-up plans
- SNS is open for business: initial user program begins this summer, expect full user program the following year
- Science results from SNS instruments are emerging