The New Generation of Neutron Sources

Presented to the

2009 Particle Accelerator Conference

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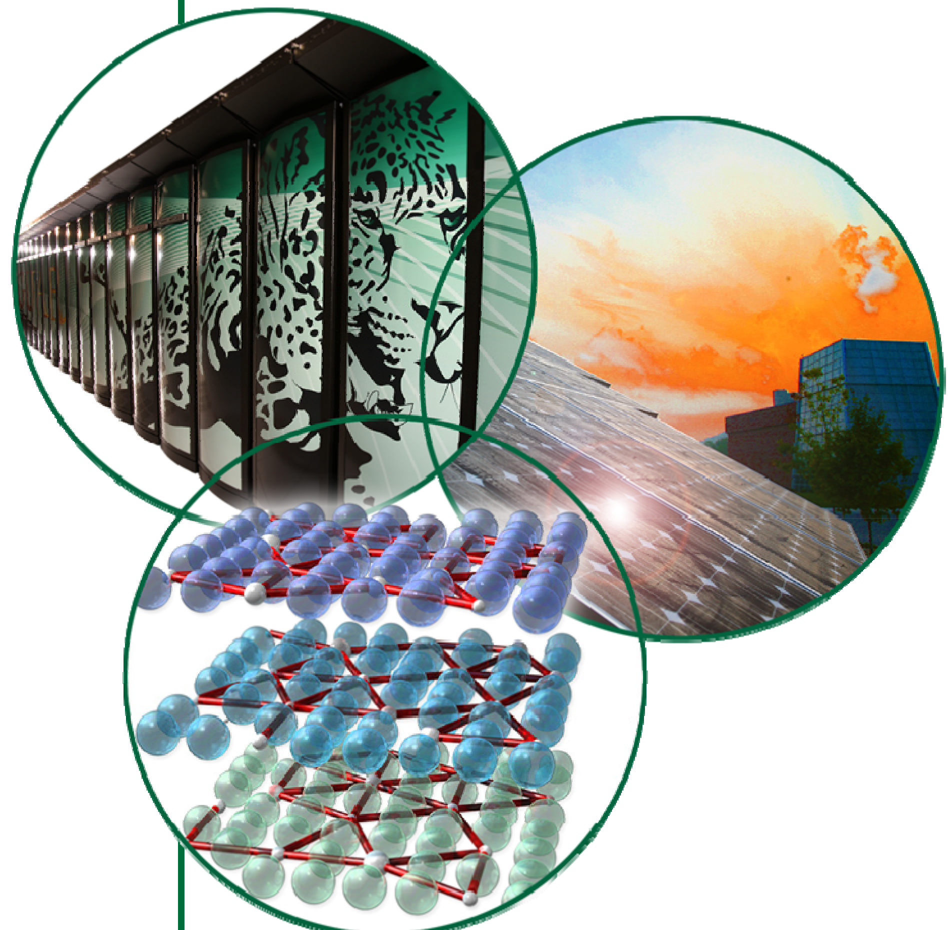

U.S. DEPARTMENT OF ENERGY

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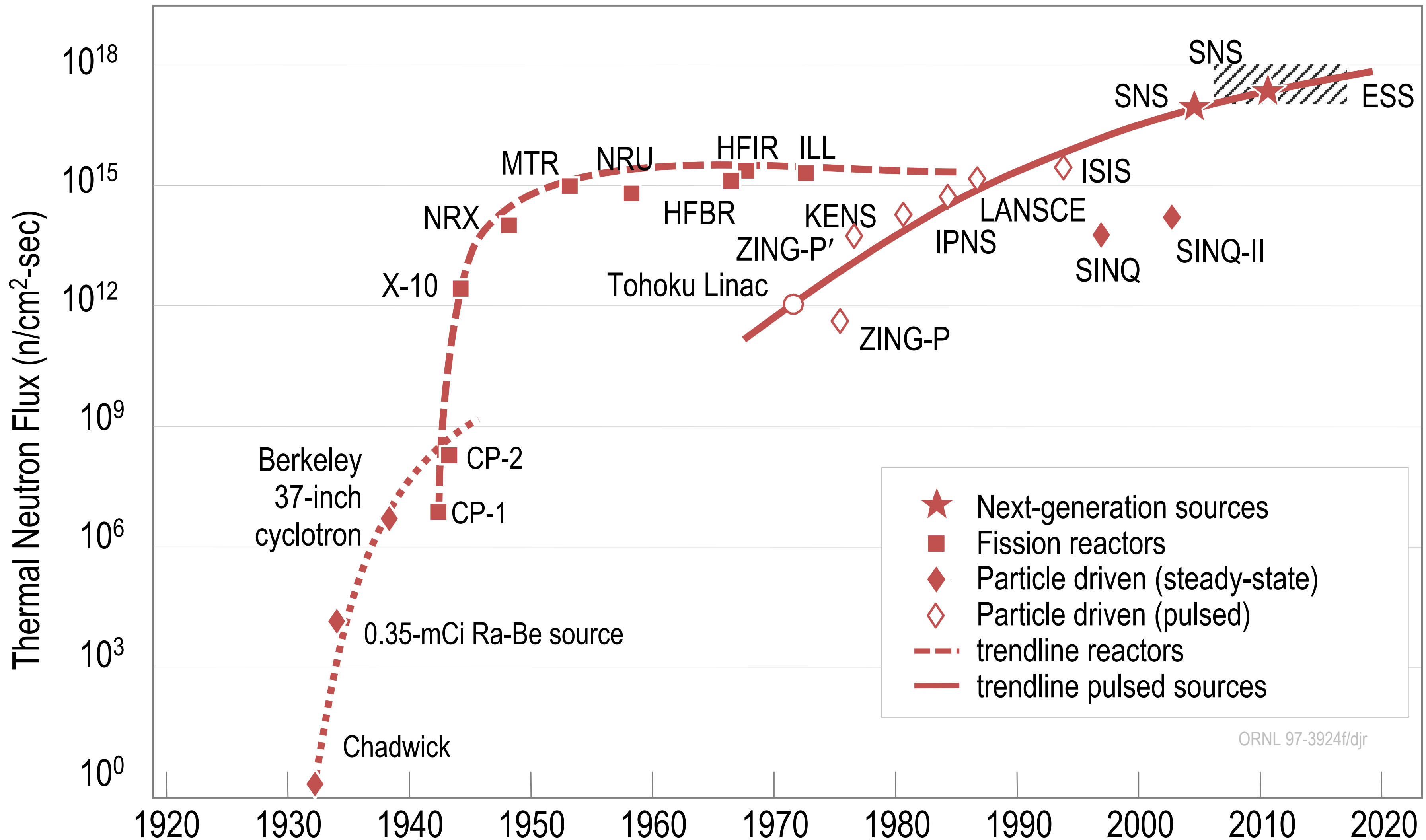
Neutron sources:
How far have we come?



(Updated from *Neutron Scattering,* K. Skold and D. L. Price: eds., Academic Press, 1986)

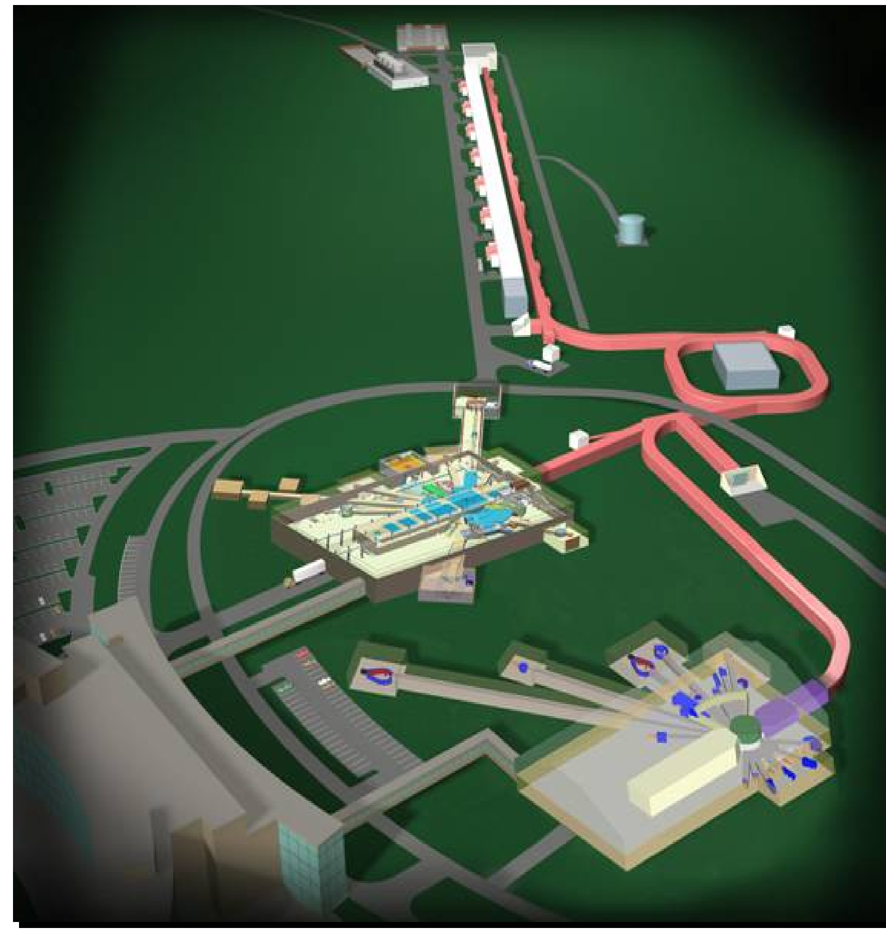
We have consistently managed to squeeze more out of existing sources

- By adding cold sources to existing reactors:
  - NIST, JRR-3M, HFIR, etc., and more coming
- By improving target/moderator optimization:
  - SINQ target, Lujan coupled moderators
- Accelerators also have the potential for increase in beam power
  - Well exploited by high-energy physicists (e.g., AGS)
  - Increases in current at ISIS, Lujan, PSI
- Next-generation sources (J-PARC and SNS) have made provision for power increases in their design

What are the prospects for iterative improvement on the current technology base?

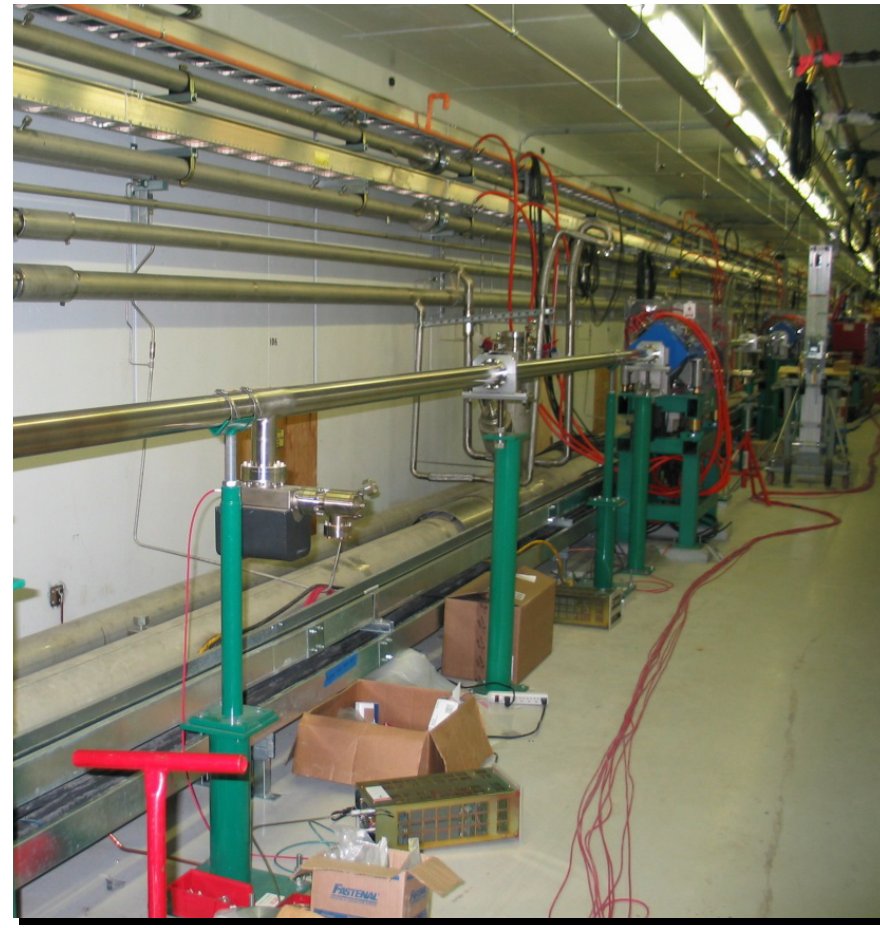
Spallation Neutron Source: 20-year plan

- Evolve along path envisaged in Russell Panel specifications
- In 20 years:
  - Operating ~45 best-in-class instruments
  - 2 differently optimized target stations
  - Beam power of 3–4 MW
- Second target station and power upgrade should follow a sequence that meshes with deployment of initial capability and national needs
- Similar developments likely elsewhere: Japan, China, Europe, . . .

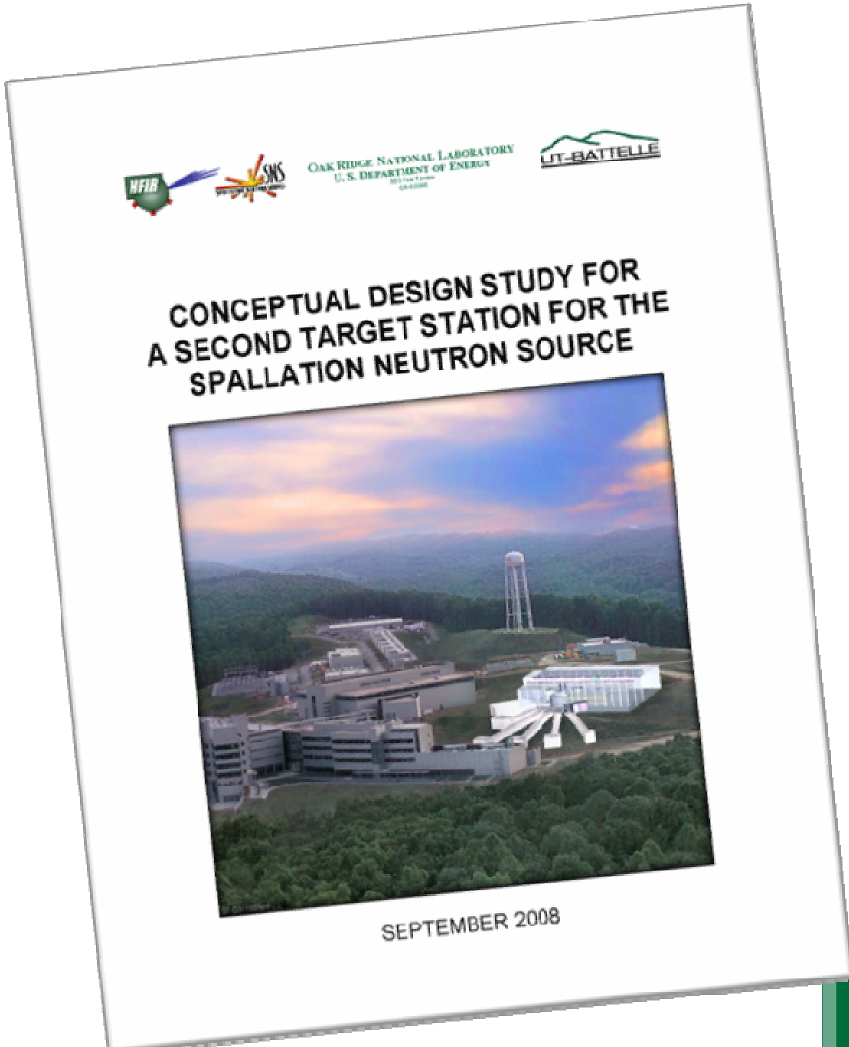


Power Upgrade Project:
Double beam power to 3 MW by 2016

- Increase proton energy to 1.3 GeV (30%)
  - Requires beam current increase (60%) and target improvements
  - Enables second target station
- Minimize impact on user operations
- Conceptual design completed, R&D under way
  - BES review: August 2008
  - Critical Decision 1 (start preliminary design) approved in January 2009



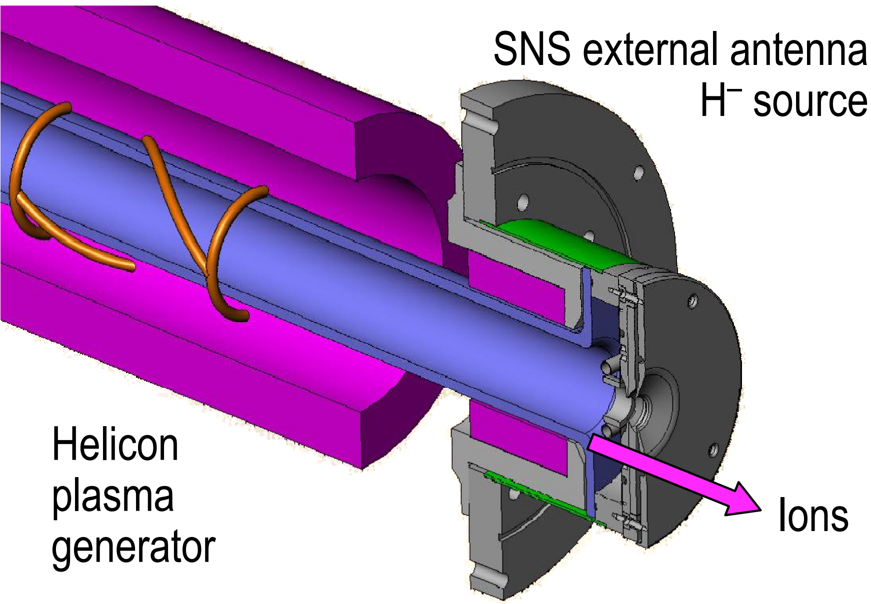
Second Target Station



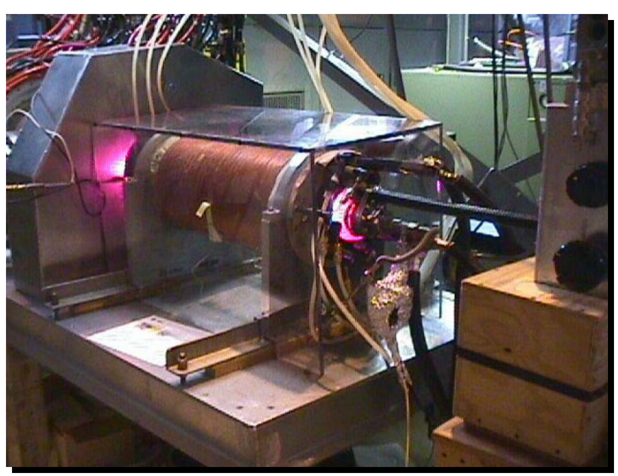
- Design, build, install, test, and commission a second target station optimized for cold neutron beams, yielding an order of magnitude improvement in instrument performance
  - New spallation target and supporting systems
  - Extended accelerator systems
  - Conventional support buildings
  - Initial neutron beam instruments
- Critical Decision 0 (Mission Need) approved in January 2009
  - Cost range $815M to $1150M
  - Start construction in 2012; complete in 2019

Prospects for earlier funding are leading us to consider accelerating this plan by 2 years (CD-1 in early FY 2011)

Meeting the H⁻ needs of the SNS power upgrade:
Next-generation ion source development



Helicon test facility, Building 7625



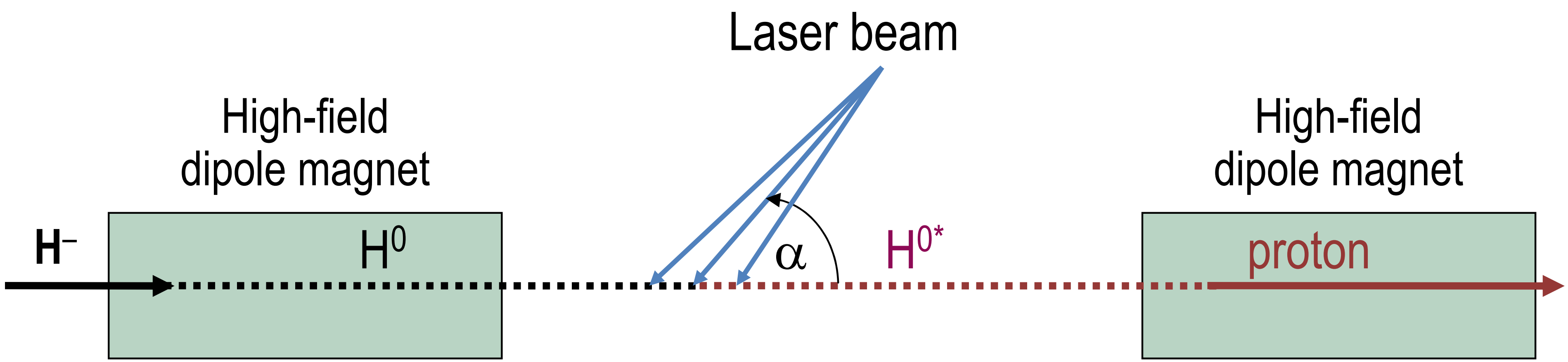
Welton et al., *AIP Conf. Proc.* **1097**, 181–190 (2009)

- Demanding requirements:
  - Beam current: 70–95 mA
  - Pulse length: 1 ms
  - Duty factor: 7.4%
- Solution: RF-driven, inductively coupled H⁻ ion source with AlN ceramic plasma chamber and external antenna
  - Beam currents up to ~100 mA (60 Hz, 1 ms) observed
  - Sustained currents >60 mA (60 Hz, 1 ms) demonstrated on test stand
  - Accelerated beam currents of ~40 mA demonstrated into SNS front end
- Continuing work on high-density plasma production using RF-helicon waves

One potential bottleneck: Stripping H^-

Novel approach to laser stripping:

Use a narrowband laser to convert H^- to protons for high-power operations



Lorentz stripping

$H^- \Rightarrow H^0 + e^-$

Laser excitation

$H^0(n = 1) + \gamma \Rightarrow H^{0*}(n = 3)$

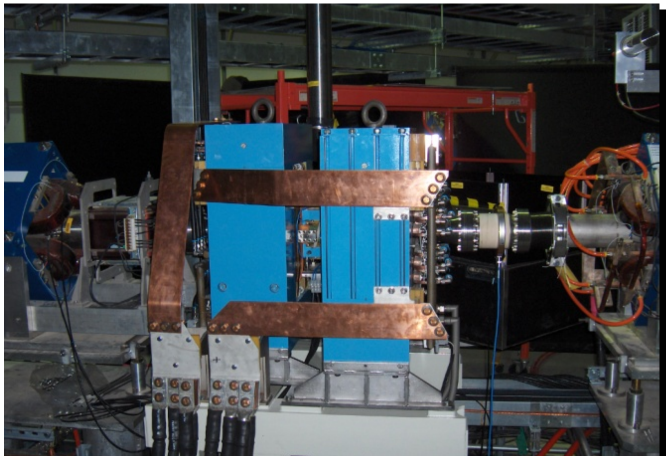
Lorentz stripping

$H^{0*} \Rightarrow p + e^-$

V. Danilov et al., *Phys. Rev. ST Accel. Beams* **10**, 053501 (2007)

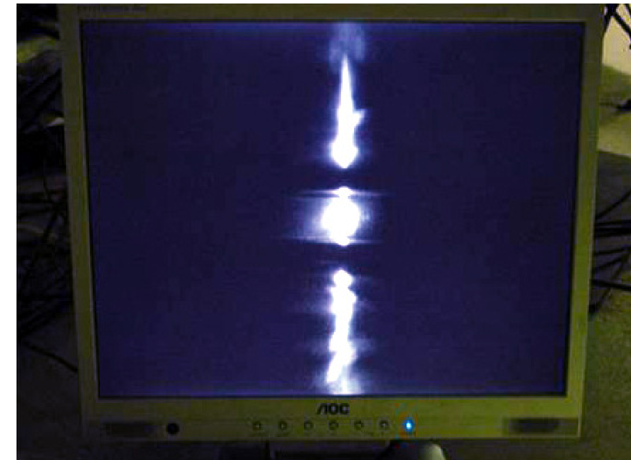
Proof-of-principle experiment at SNS

Magnetic insertions

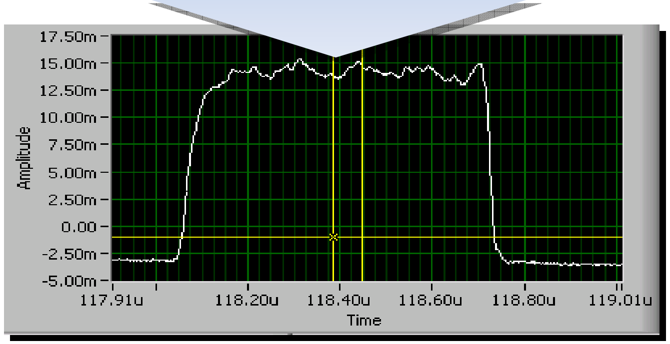


Laser and optics

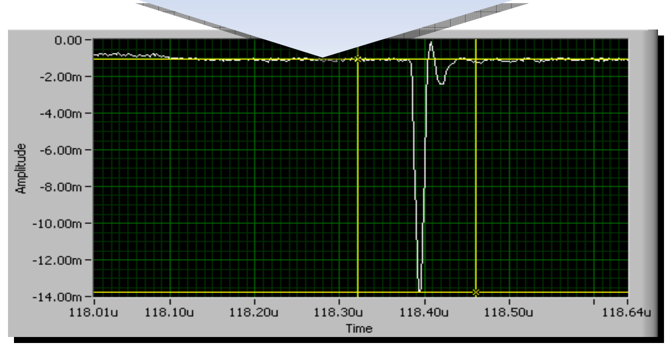
Light in
vacuum chamber



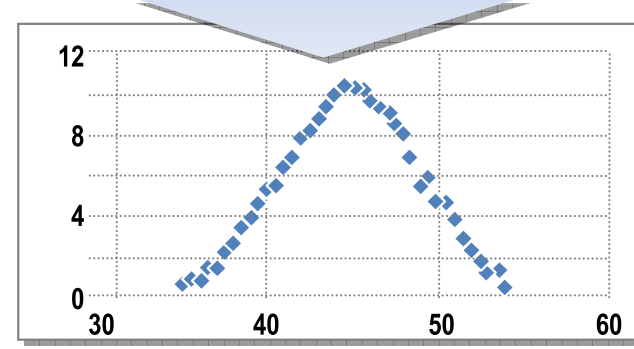
H⁻ beam
current



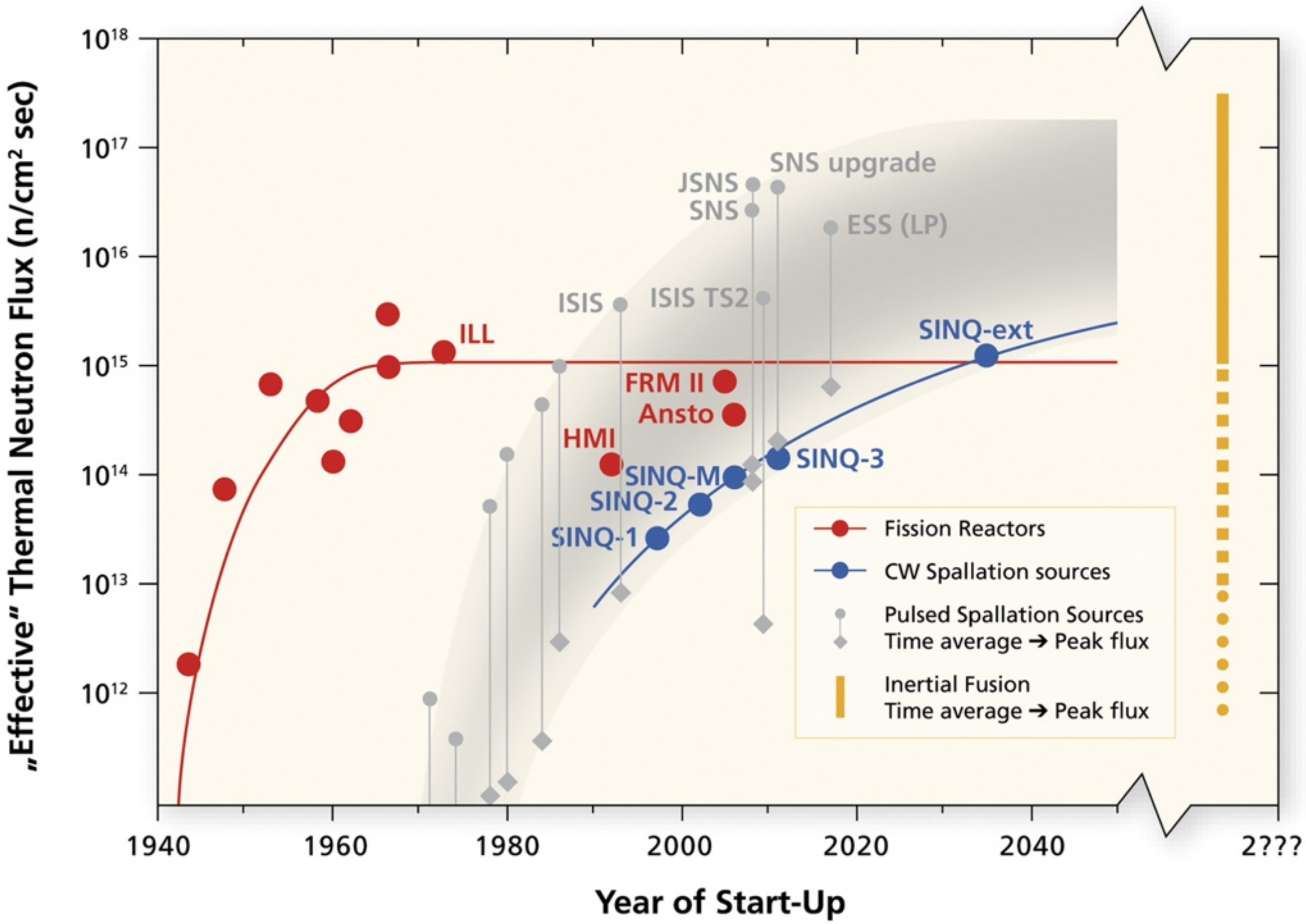
Stripped electrons
by laser light



Stripping efficiency
> 90%



Source development



- No existing or under construction source takes advantage of spallation process efficiency to make more neutrons
- We have taken advantage to make more "useful" neutrons

Figure courtesy K.N. Clausen, PSI

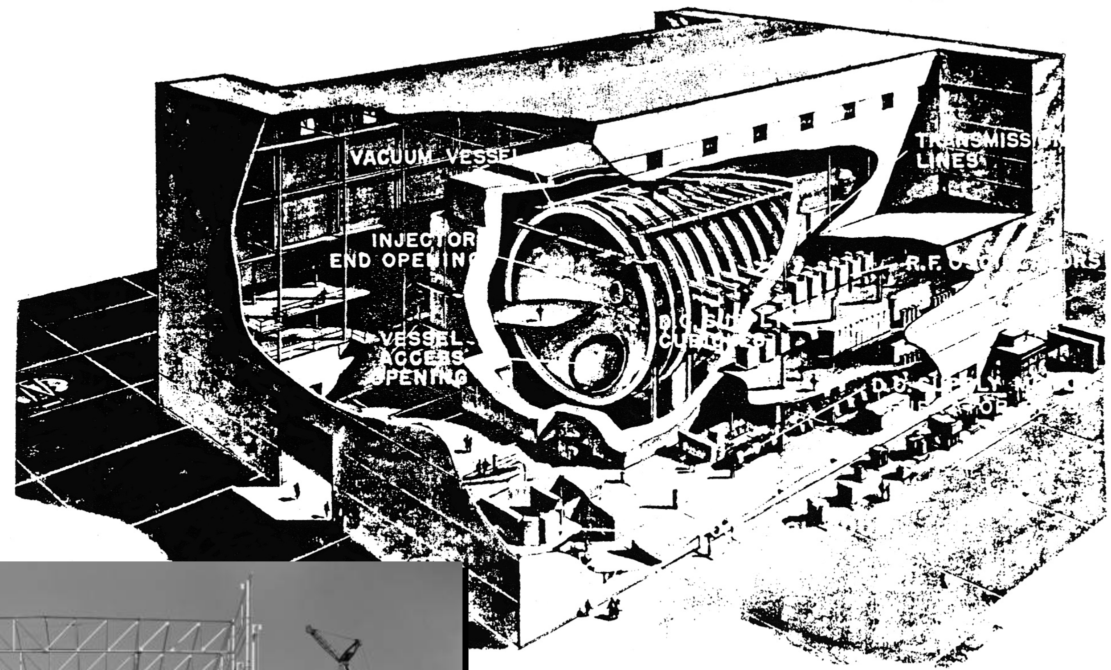
Neutron production

Fission	• 180–200 MeV/neutron • Average kinetic energy ~ 2 MeV
Spallation	• 35–50 MeV/neutron • Average kinetic energy ~ 2–5 MeV
Fusion	• >17.6 MeV/neutron • Average kinetic energy 14 MeV and 3.5 MeV
Other routes (e.g., LENS, bremsstrahlung, . . .)	

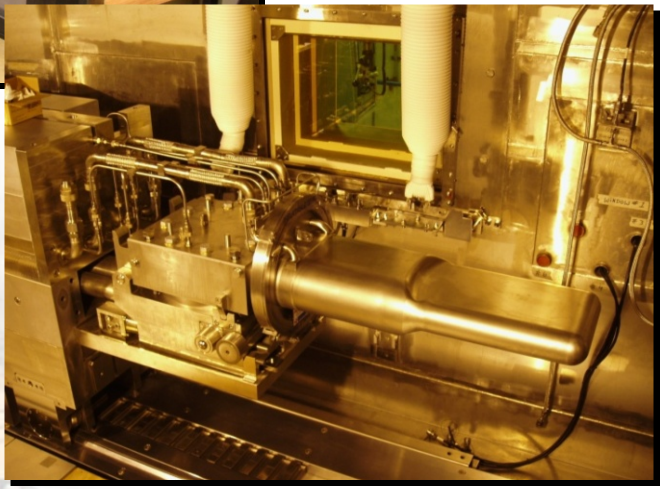
- For power density limit, the ANS reactor design probably represents a practical extreme (~5× ILL)
- CW spallation source not likely to have more than 20× ILL without going to large target volume (lower flux)

Father of all spallation sources:
Lawrence's Materials Testing Accelerator

- Deuteron accelerator
  for production
  of plutonium and tritium
- NaK-cooled Be target
- 500 MeV
- 320 mA
- 160 MW



The neutrons themselves are becoming a problem!



What about the instruments?

- We are bumping up against the limit in terms of steradians (and space)
- We still have lots of room to improve:
  - Optics
  - Sample environment
  - Detector speed, resolution, efficiency, background

Limits to growth

- Intrinsic difficulties of dealing with extremely high neutron flux (radiation/activation, detectors) will ultimately limit us even if we solve the energy density problems through ingenuity or even more efficient production (fusion)
  - Solvable to some extent with money: Remote handling of accelerator/significant parts of instruments, target + higher speed detectors with correspondingly segmented electronics
  - Current “limit” on regional-scale scientific facility is $1–2B (or Euros, Oku Yen, etc.)
  - Global model (ILC/ITER) might provide another order of magnitude, but doesn’t work so well when capacity is as much an issue as performance
- Current (3rd-generation?) spallation source technology will scale to 3–5 MW with reasonable progress in ongoing R&D
- Likely another order of magnitude in a 4th-generation (short pulse, long pulse, or CW: TBD)

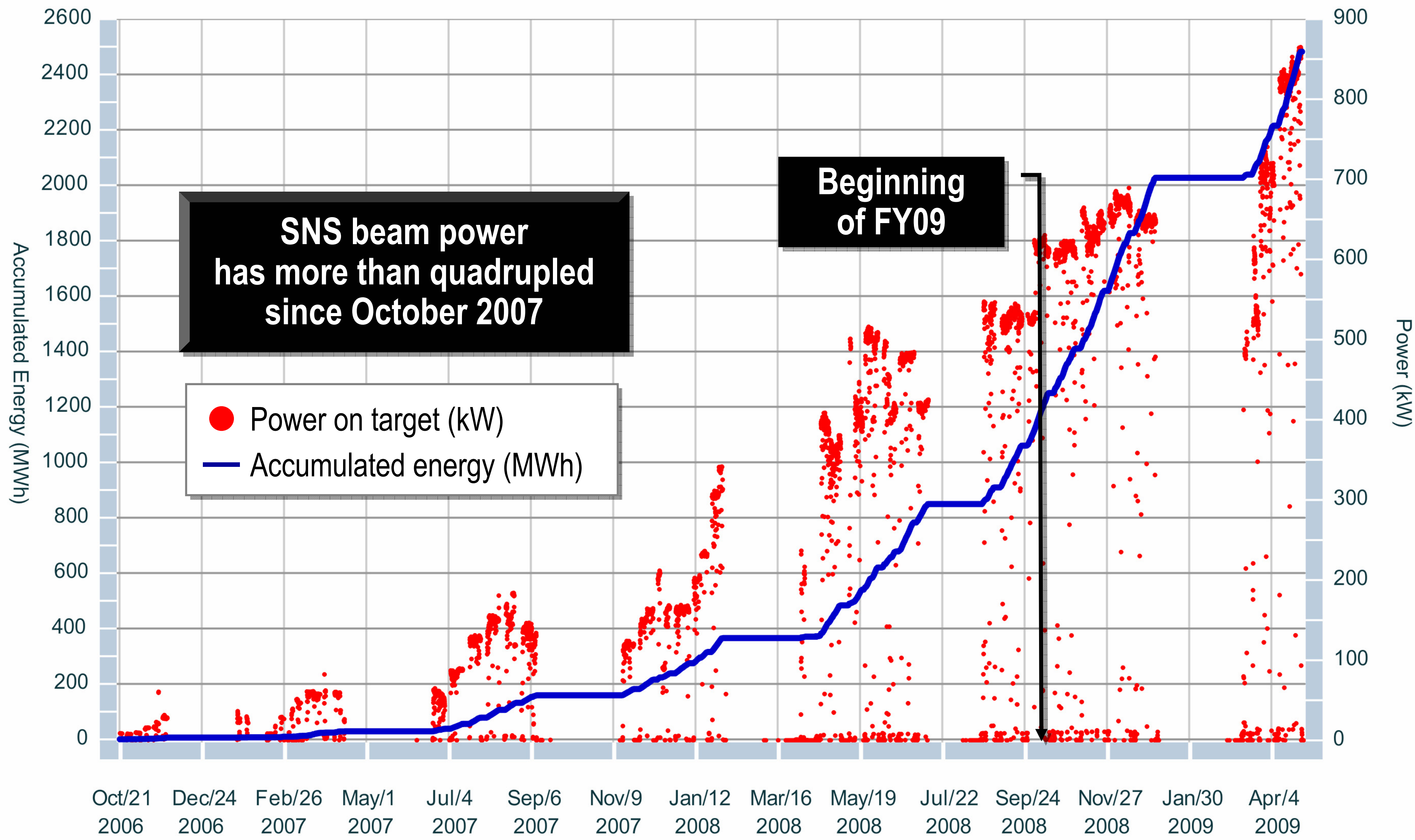
Overcoming the limits

- Beyond a 4th generation of spallation sources (plus continued use of reactors when there is synergy with nuclear energy or isotope interests), things get harder
  - We may be hitting the “neutron limit” with either 100× SNS spallation or a fusion source, unless the economics of science policy undergoes a fundamental shift
- This highlights the importance of continuing to develop ways to make more useful neutrons
  - The X-ray community’s log plot world only applies to useful X rays
- Our success in arranging our neutrons more usefully in time begs a question: What is the optimal time structure for scattering?
  - Current debate is constrained by the accelerators
  - Also: What can we do about spatial distribution?

Update on SNS

- Delivering neutrons to users
- Instruments coming on line
- Meeting or exceeding operational goals
  - Peak beam power: 870 kW
  - Beam pulses: 60 s^{-1}
  - Most losses < 1 W/m at design ion source peak current
  - 80 of 81 SC cavities operable at 60 Hz
  - All modulators operate at 60 Hz
  - Operated at 2 K for 1.5 years
- Moving ahead with upgrade plans

SNS beam power has reached 870 kW

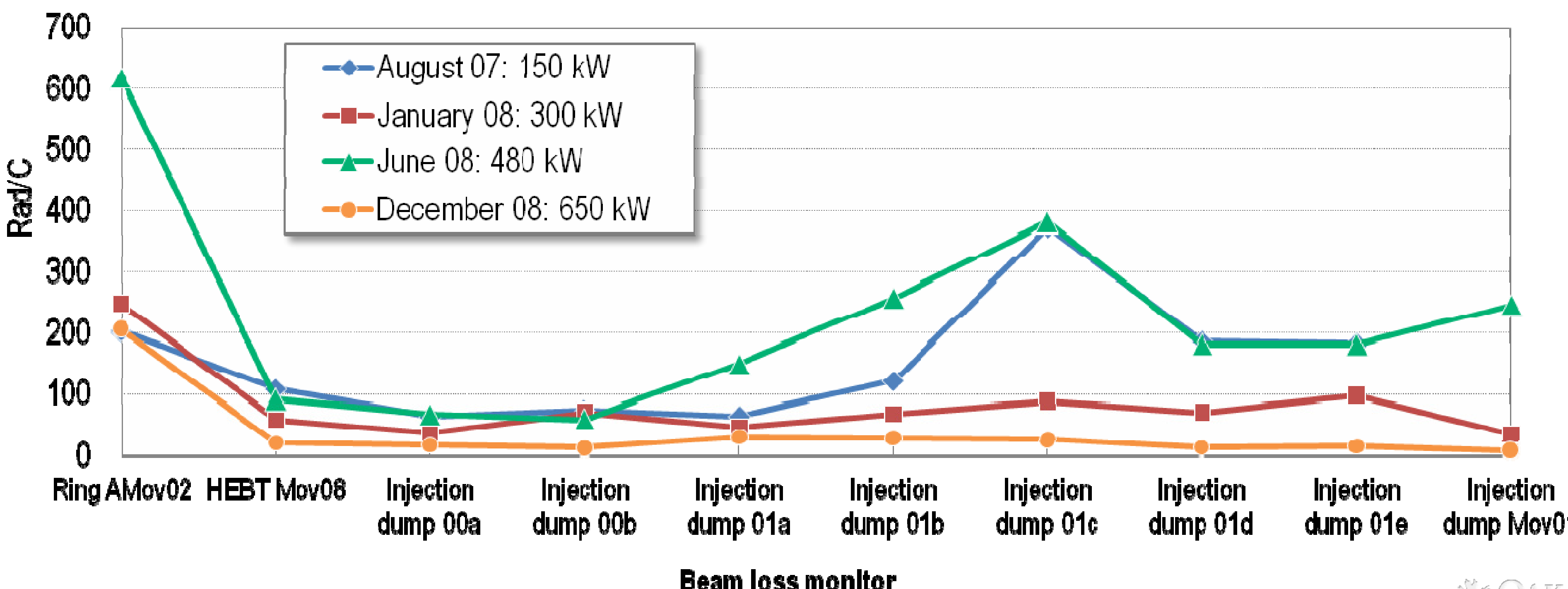


Our ultimate goal: 1.4 MW in FY10

Beam loss is not limiting beam power

- Linac losses are < 1 W/m and therefore not a limit
  - Warm linac loss: Close to expectations
  - Superconducting linac loss: Higher than expected, but not a limit
  - Measured transverse emittances are close to design
  - Longitudinal emittance is ~2× higher

- Ring losses are close to expected levels
  - Injection dump losses: Largely alleviated by improvements in equipment and beam tuning, even with increasing beam power



SNS accelerator: Vigorous improvement and development efforts

High-voltage converter modulators

- 60 Hz capability, fault detection, and diagnostics
- CO_2 fire suppression and fire mitigation features
- Additional modulator for reliable SCL klystron operation

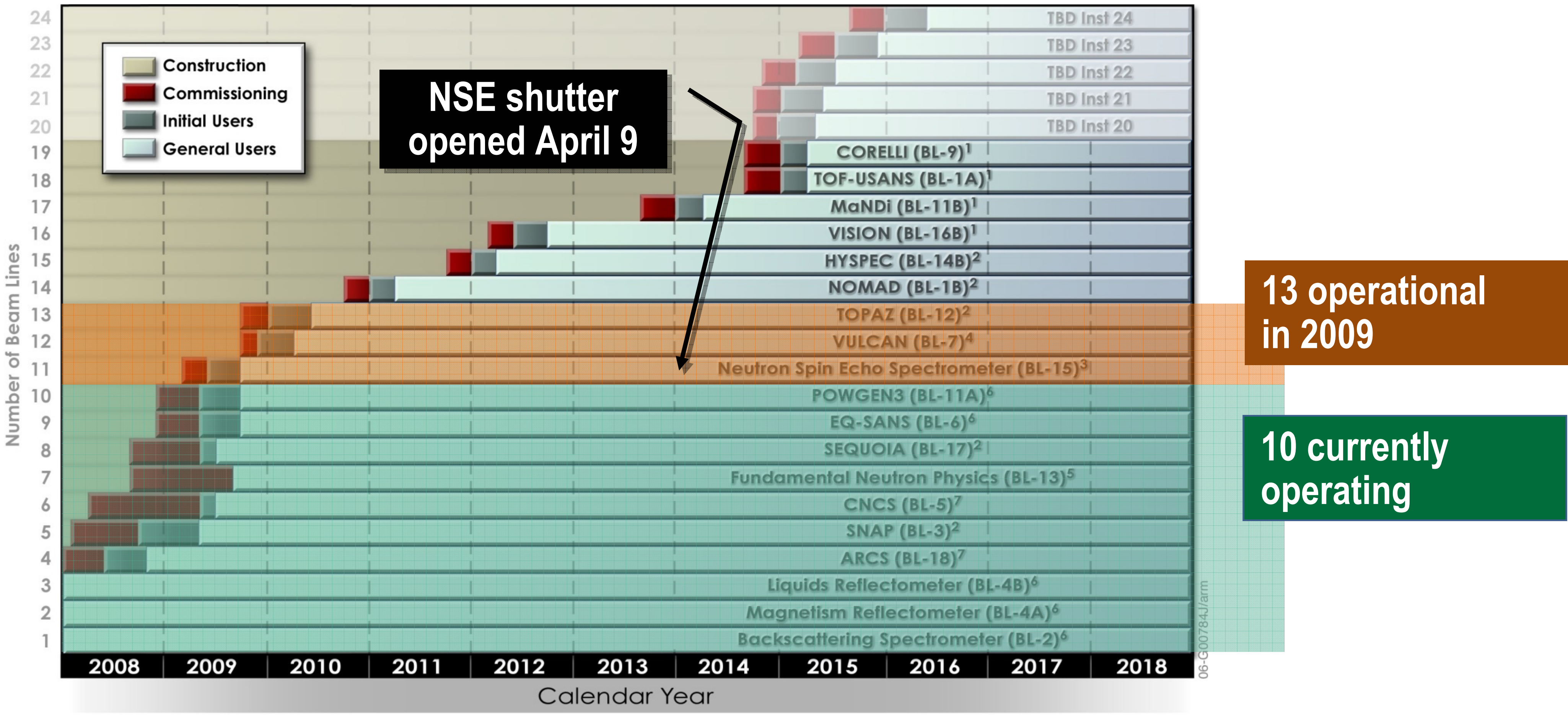
Front-end performance

- Ion source/LEBT delivers design current of 28 mA in production (at 60% of design pulse length)
- Source operates reliably with 3-week replacement time
- RFQ pulse-width feedback system has significantly stabilized RFP and all but eliminated resonance error runaway
- Slow and fast chopper systems reworked

Superconducting linac

- 80 of 81 cavities operating
- Energy ~ 930 MeV

We have reached the halfway point for the initial instrument suite



Funding: [1]SING-II; [2]SING-I; [3]Jülich; [4]Canada Fund for Innovation; [5]DOE-NP; [6]SNS; [7]DOE-BES.