Experience with Recently Commissioned High-Power Proton Accelerators and Prospects for the Future

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Acknowledgments

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- Tadashi Koseki and Yoshi Yamazaki (J-PARC, Japan)
- Israel Mardor (SARAF, Israel)

Applications of High-Power Proton Accelerators

Particle Physics

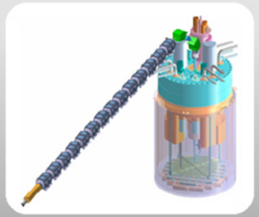
- Existing: FNAL NuMI (US), CNGS (CERN), J-PARC (Japan)
- Under Construction or Upgrade: FNAL MI/RR (US)
- Proposed: Project-X (US), SPL (CERN), MC/NF (US/Eur.)

Nuclear Physics

- Existing: RIKEN (Japan), TRIUMF (Canada),
- Under Construction or Upgrade: FRIB (US), FAIR (Germany), SPIRAL2 (France), SARAF (Israel), PEFP (Korea)
- Proposed: EURISOL (Europe), SPES (Italy),

Materials Science

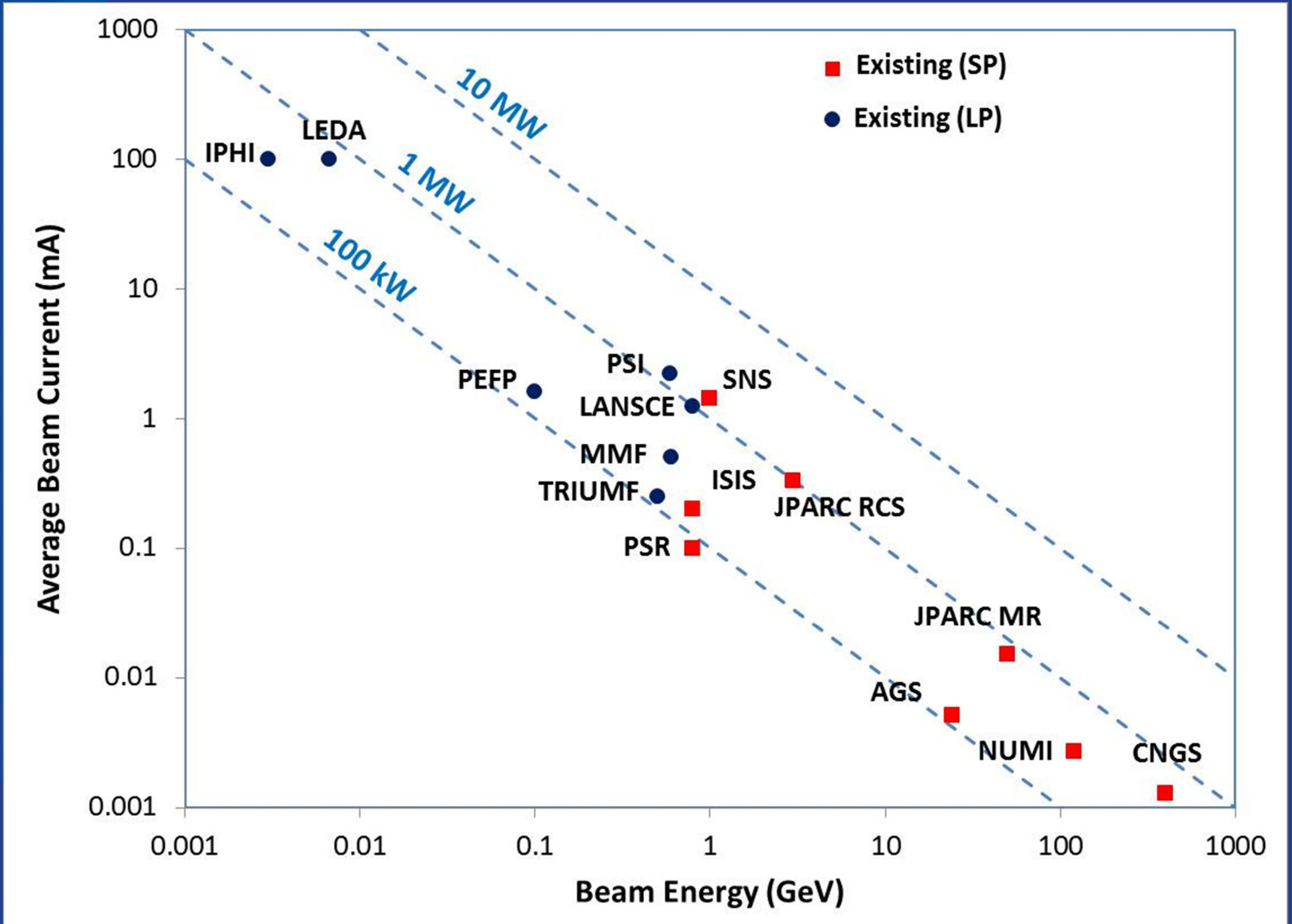
- Existing: SNS (US), SINQ (Switzerland), J-PARC (Japan), ISIS (UK), LANSCE (US)
- Under Construction or Upgrade: CSNS (China)
- Proposed: ESS (Europe), IFMIF (EU&Japan)



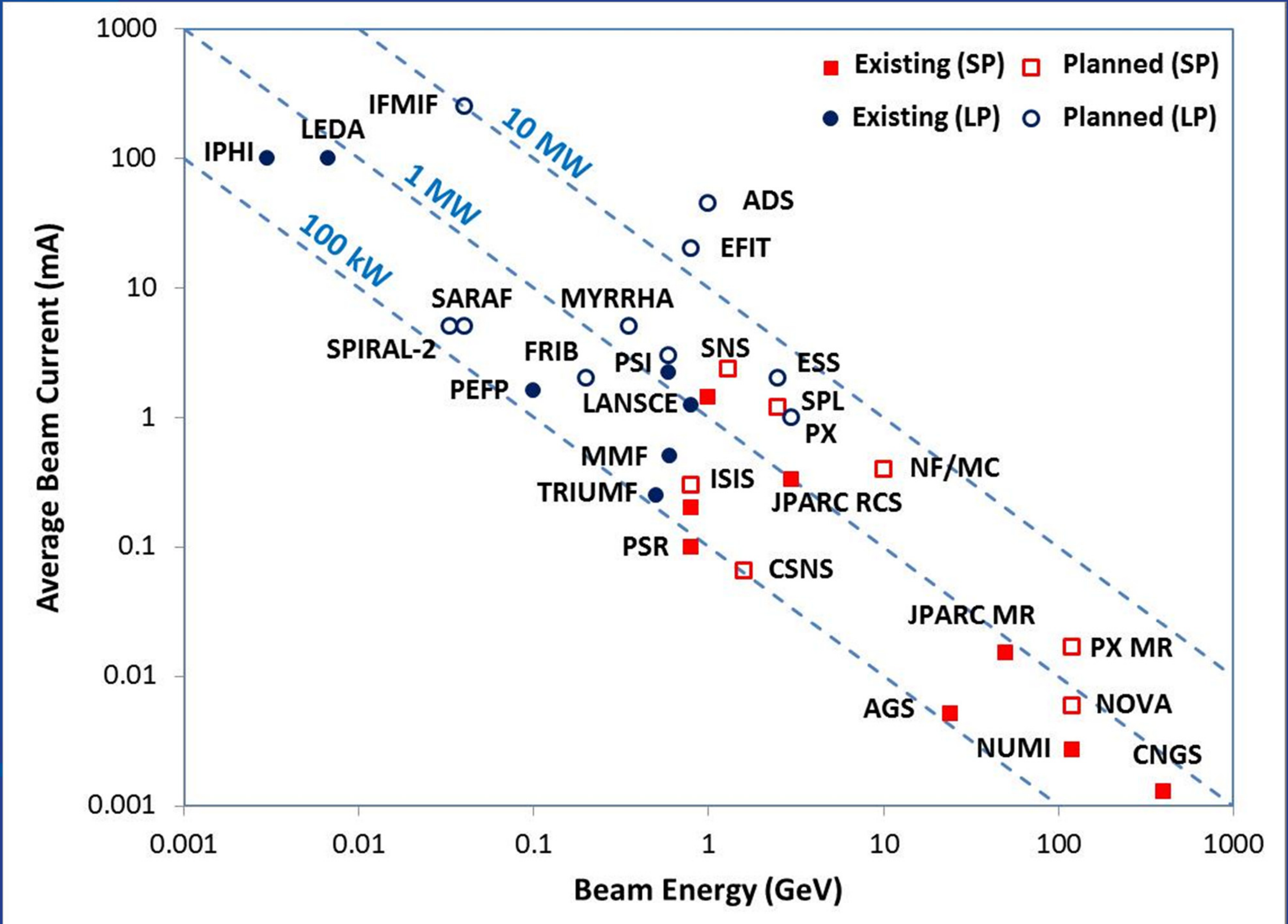
Applications

- Proposed: MYRRHA (Belgium), EUROTRANS (EU), TRASCO (Italy), ADS (China, India, Japan, Korea)

The Beam Power Landscape



The Beam Power Landscape

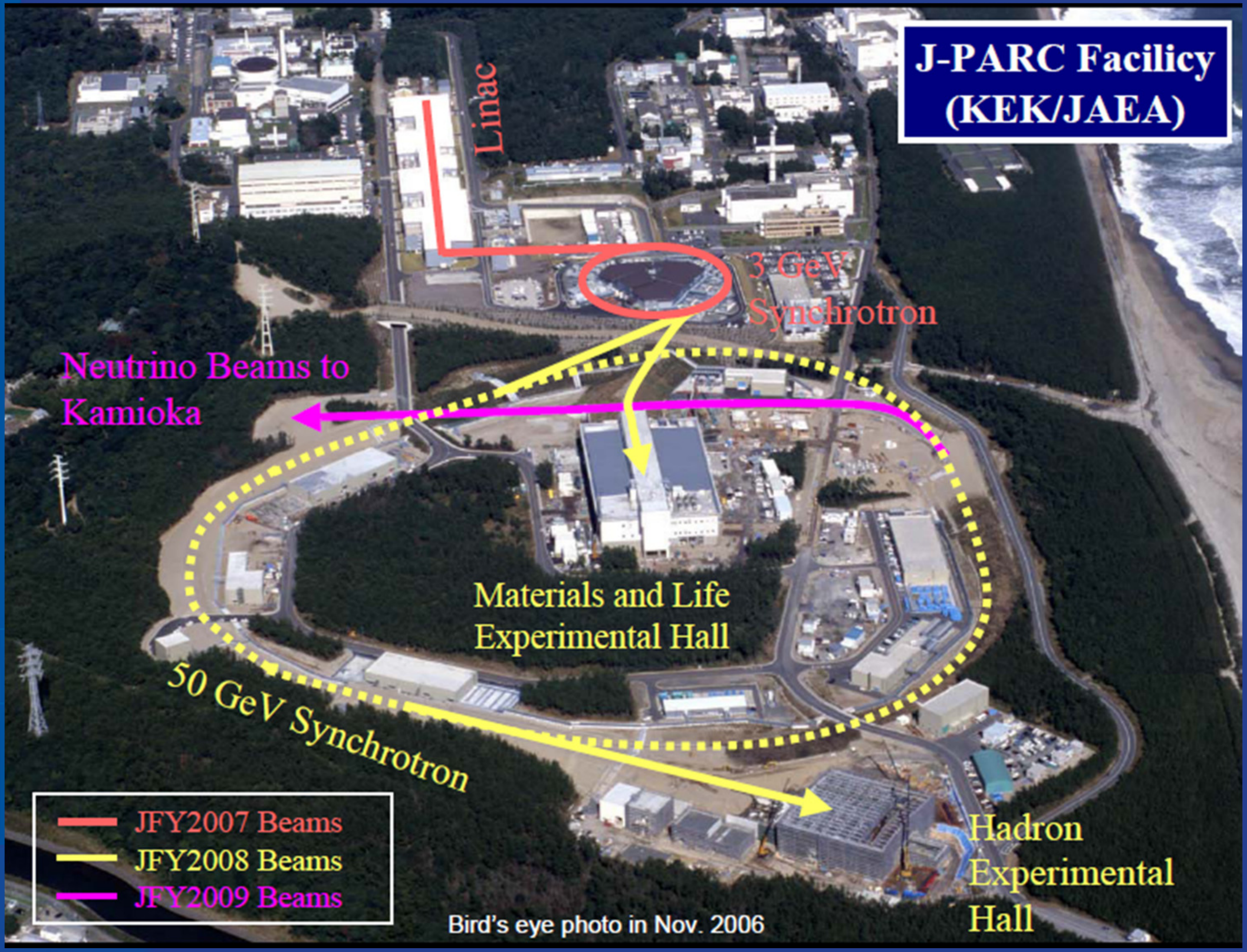


Challenges for High Power Proton Accelerators

- Producing high-quality beams in the injector system (high brightness, low halo) at high duty factor
- Accelerating high beam currents to high energy
  - High-duty factor, high-power RF systems, structures and components; for RF efficiency and practicality, SCRF is the technology of choice
- Transporting high power beams while maintaining beamloss at a level where routine maintenance is possible (<1 Watt/m)
  - Acceleration of beams from keVs to GeVs with little emittance growth, and minimization of halo growth
  - Understanding and control of collective effects that have the potential to generate large-amplitude particles
  - Systems for stripping, collimation, low-loss extraction, machine protection
- Target systems capable of handling extreme power densities and extreme radiation environments (~ 10^5 Rem/hr beam off)

Japan Proton Accelerator Research Complex (J-PARC)

- J-PARC is a multi-purpose proton accelerator facility to support user communities using secondary beams of neutrons, muons, hadrons, neutrinos, with plans for transmutation experiments



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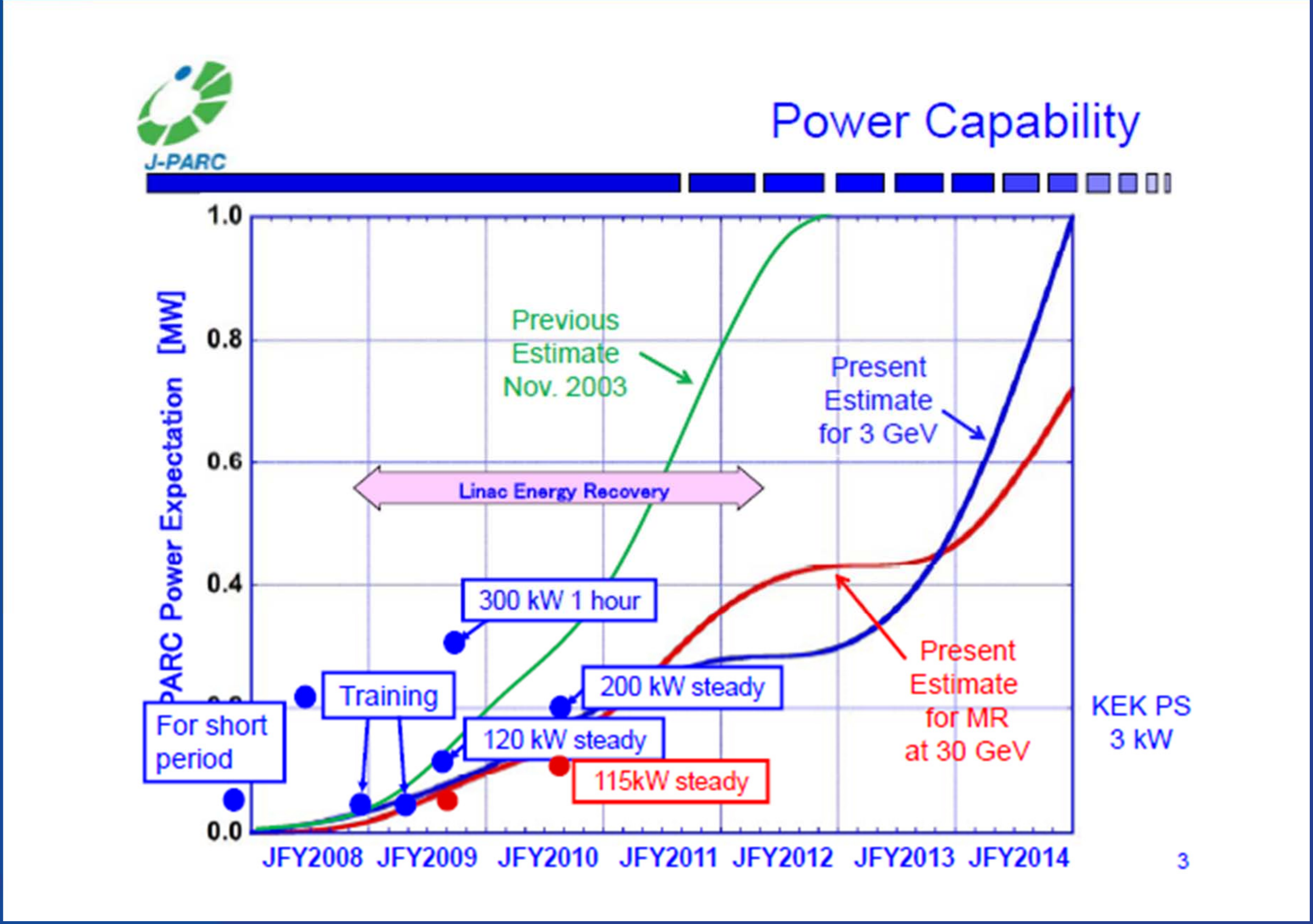
J-PARC Tour

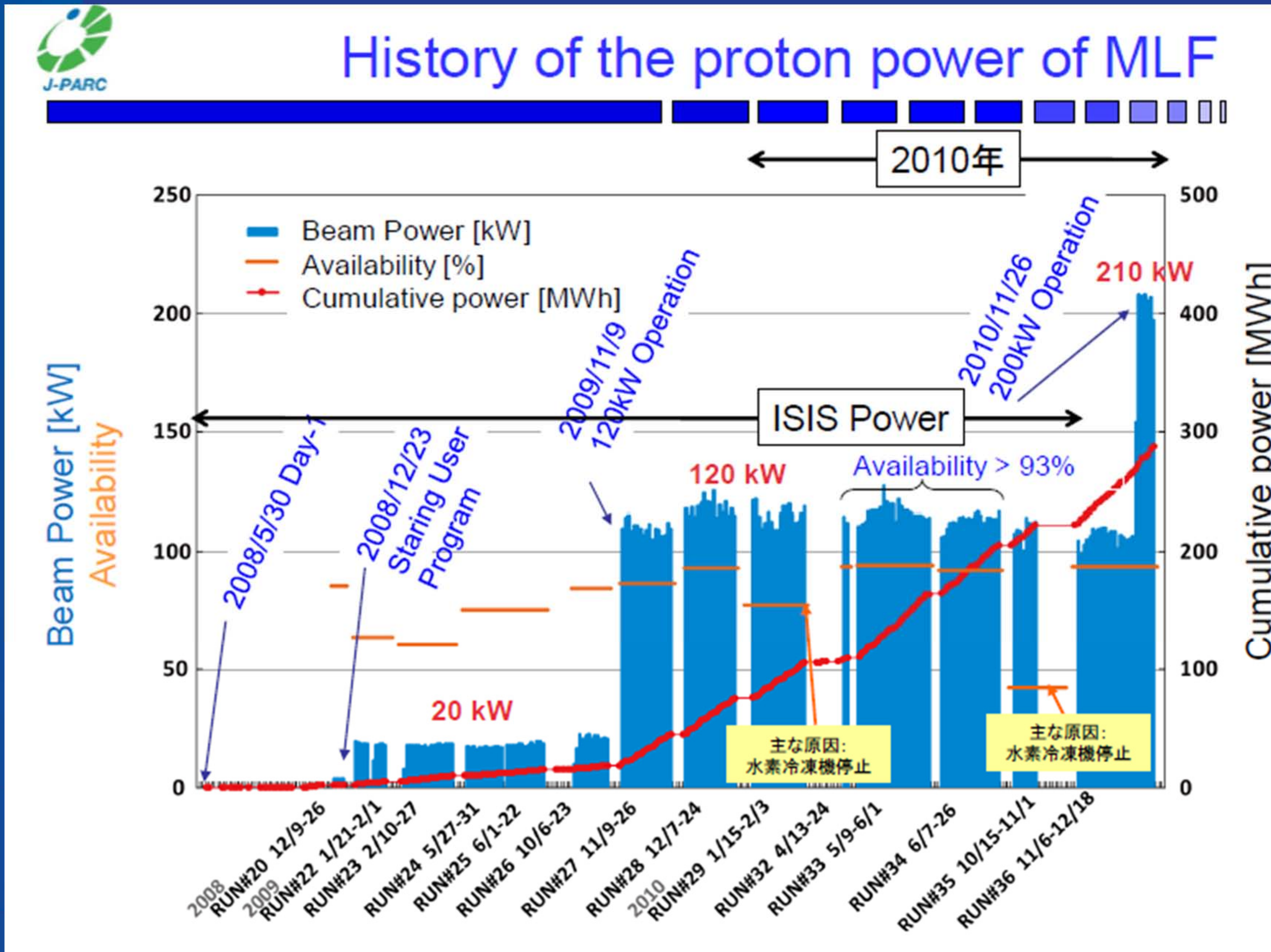
- 181 MeV Linac with 324 MHz RFQ, DTL, SDTL (30 mA, 0.5msec, 25 Hz)
- Space reserved for 400 MeV energy upgrade using 972 MHz Annular Coupled Structure
- 3 GeV Rapid-Cycling Synchrotron
- RCS serves the Materials/Life Sciences Facility
- 50 GeV Main Ring (30 GeV operation)

J-PARC Beam Power Performance and Plans



Courtesy T. Koseki, J-PARC

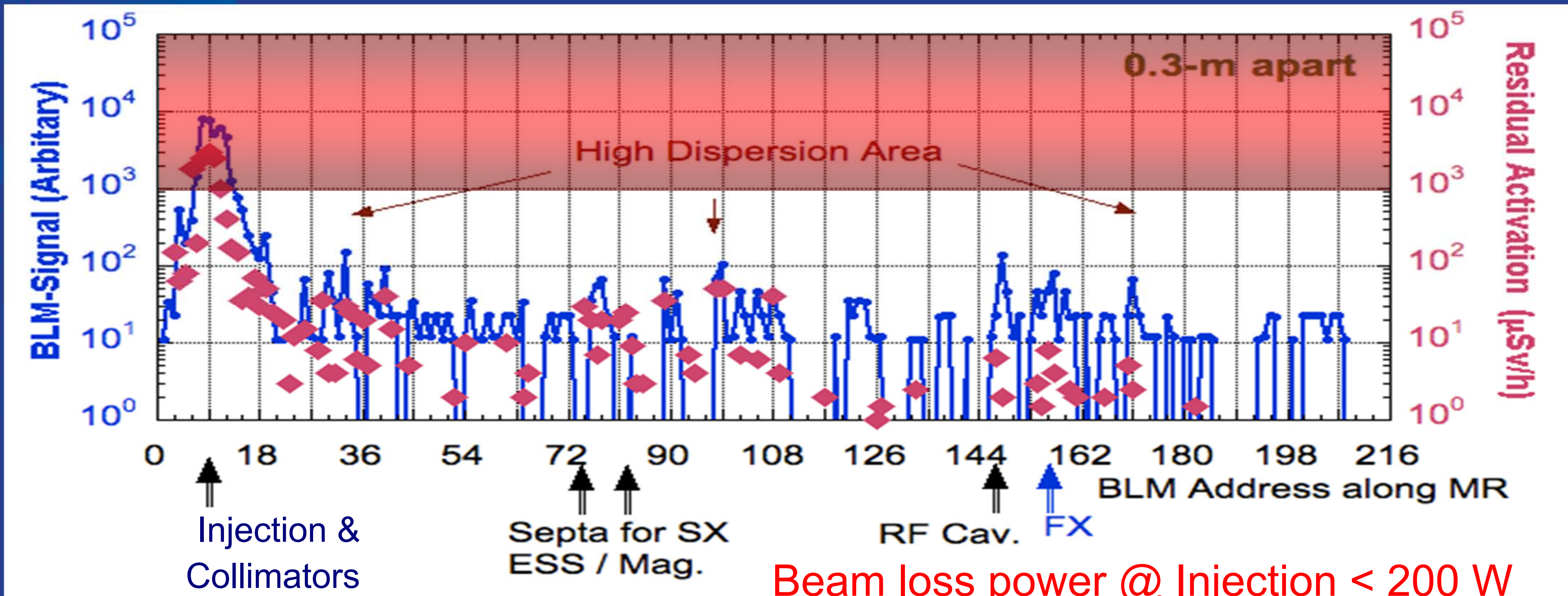
RCS Beam Power Delivered to the Materials and Life Science Facility



Main Ring Performance

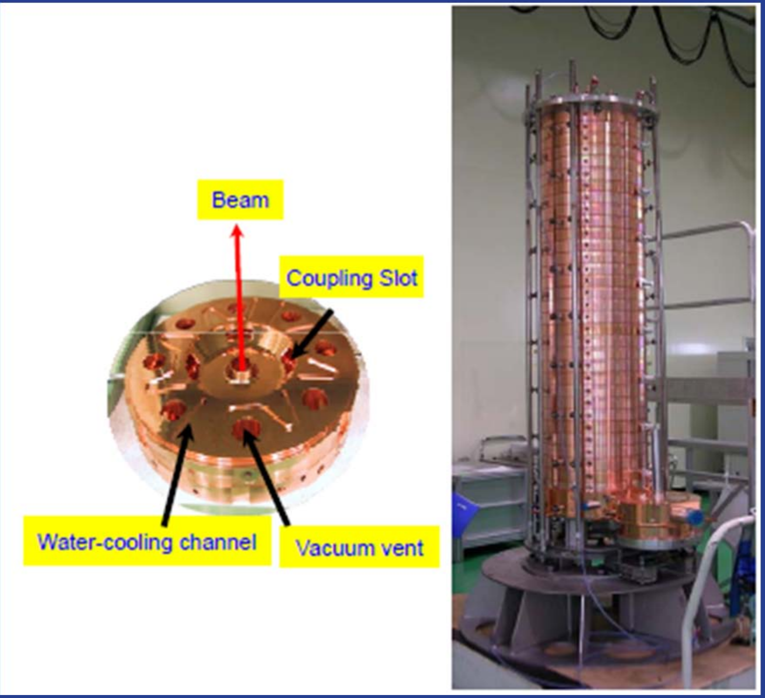
Courtesy T. Koseki, J-PARC

- Fast extraction: 135 kW routine operation at 30 GeV to the neutrino target with 3.2 sec cycle
  - Limited by losses and activation in injection and collimation regions
- Slow extraction: 3.6 kW routine at 30 GeV, extraction efficiency is 99.5% and duty factor is 17%.
  - 10 kW equivalent power demonstrated
  - Limited by extraction losses as intensity increases



J-PARC Performance Issues

- Linac
  - RFQ: conditioning/discharge issues; dramatic improvements recently with better H_2 pumping
  - Beam halo observed at high energy
  - Energy upgrade (recovery of design 400 MeV energy) essential for higher RCS power



- 3 GeV RCS
  - Foil optimization: beamloss at injection and due to multiple foil passages
  - RF magnetic alloy (finemet) cores buckling issues; coating with low-viscosity epoxy mitigates
  - Beam power limited administratively by Hg target concern
- MR
  - Main Ring power supply: ripple limits Slow-Extraction power (100 kW design)
  - Transverse head-tail instability combatted with bunch-by-bunch feedback system

The Situation Following the Earthquake and Tsunami (S. Nagamiya)

- No Tsunami damage due to 10m design basis; damage due to earthquake
- Building generally OK due to many piles; roads and surrounding utilities suffered damage
- 10 cm water in linac tunnel; pumping underway; accelerator looks OK
- RCS: no significant visible damage; tests are needed to validate integrity of ceramic vacuum chamber
- MLF building looks OK due to substantial piles
- 30 cm drop in elevation of adjacent instrument buildings
- MR, hadron hall and neutrino hall OK

The Spallation Neutron Source

- The SNS at Oak Ridge National Laboratory is the world’s most powerful pulsed neutron source
- The SNS construction project, a collaboration of six U.S. DOE laboratories, was completed in 2006, on-time and within budget at a cost of $1.4B

SNS Accelerator Complex

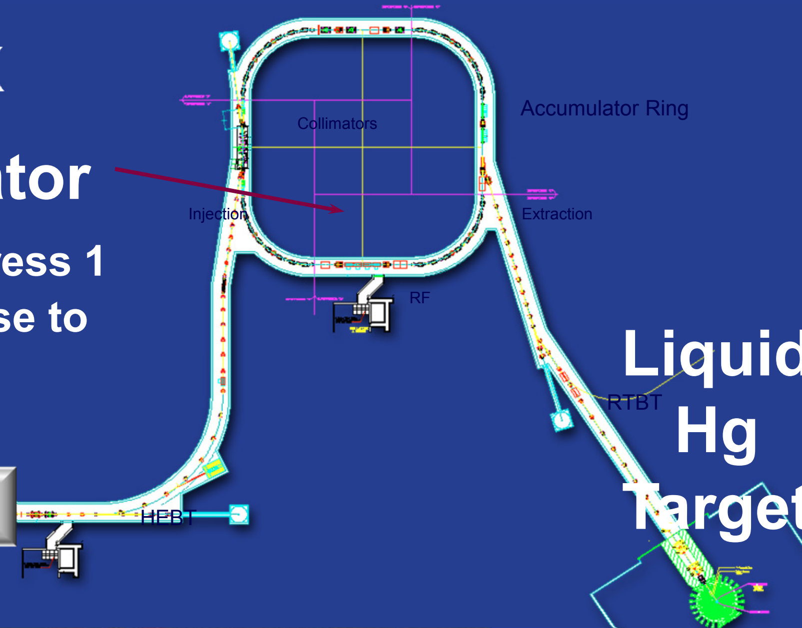
Front-End: Produce a 1-msec long, chopped, H- beam

1 GeV LINAC

Accumulator Ring: Compress 1 msec long pulse to 700 nsec

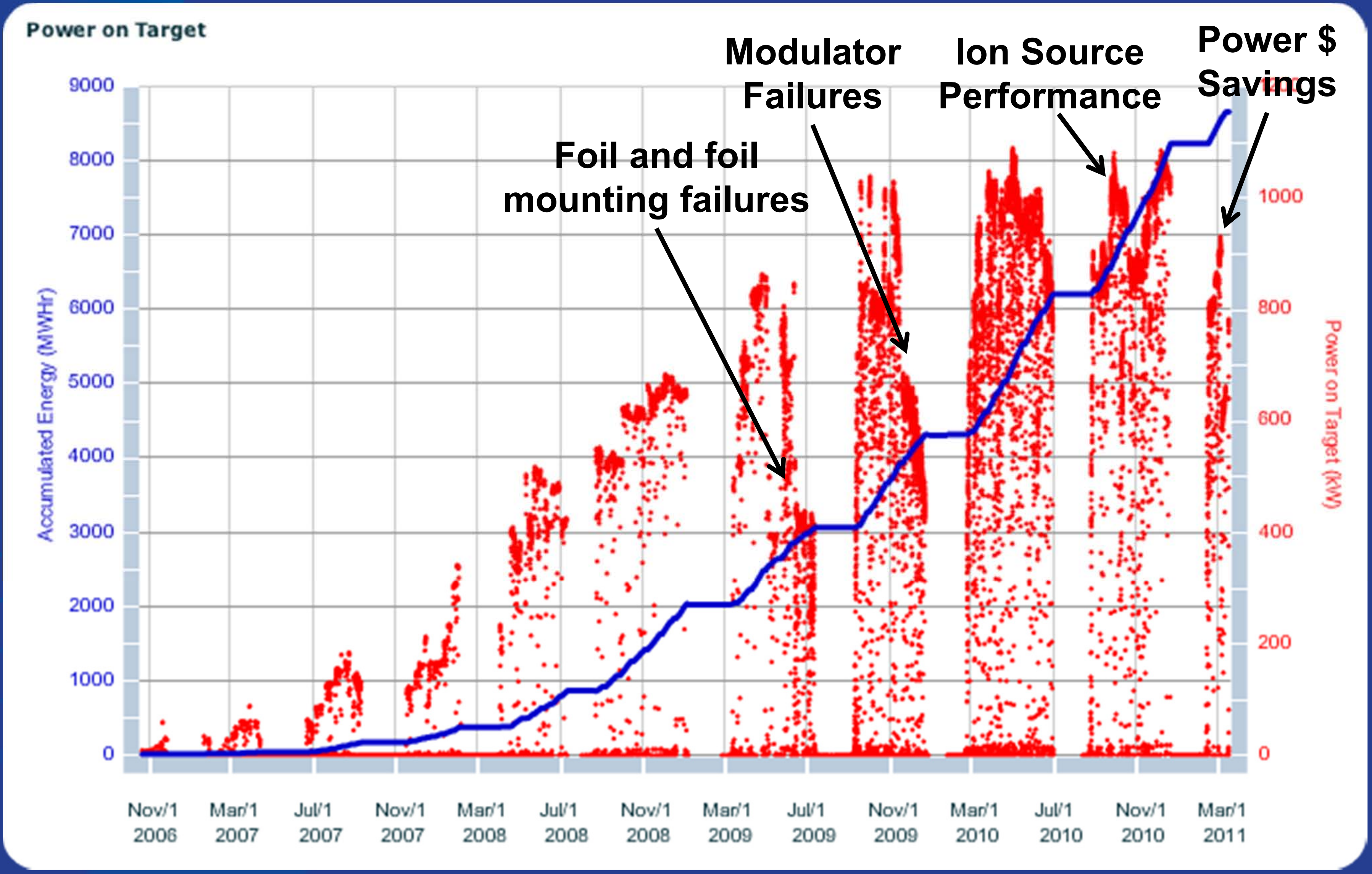
Liquid Hg Target

H$^-$	RFQ	DTL	CCL	SCL



- 402.5 MHz, 6% duty factor RFQ
- 402.5 MHz DTL (87 MeV)
- 805 MHz CCL (186 MeV)
- SC Linac w/ two 805 MHz cavity families
- 1 GeV Accumulator Ring
- Liquid Hg Target

SNS has Ramped-Up to 1 MW Beam Power and ~90% Availability



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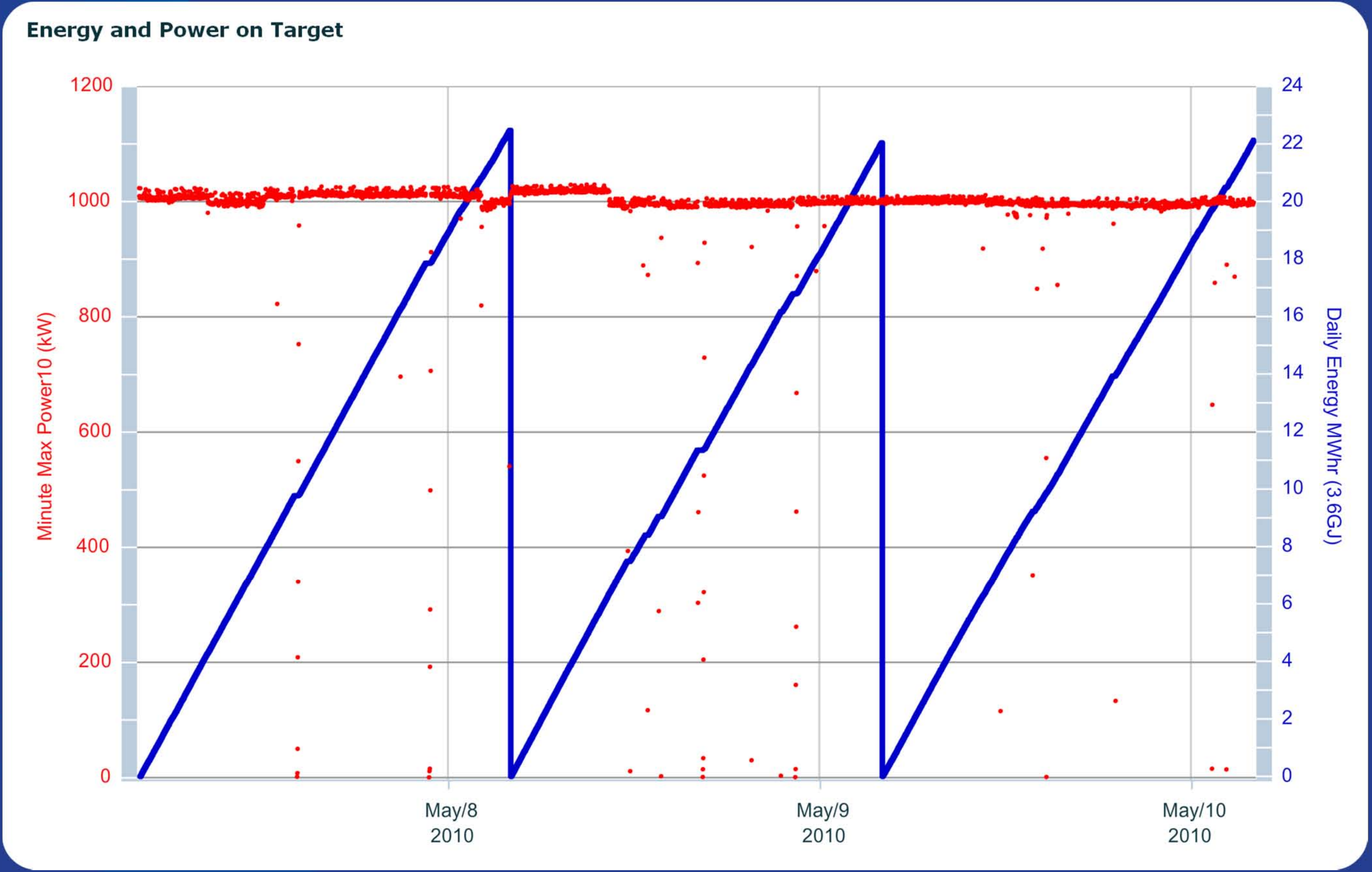
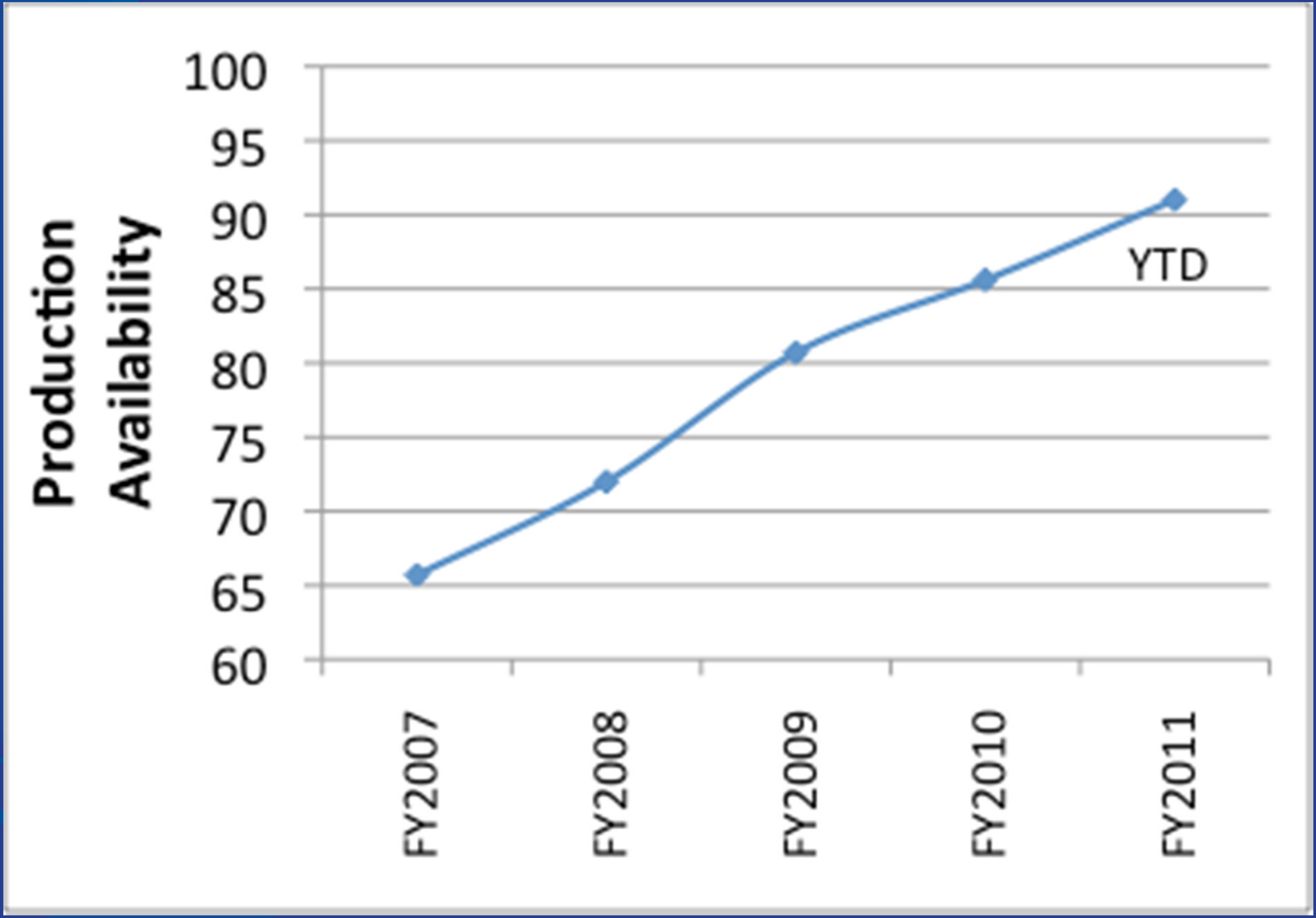
Smooth Running…



Emphasis is on Beam Availability



Major Parameters Achieved vs. Designed

Parameters	Design	Individually achieved	Highest production beam
Beam Power on Target (MW)	1.44	1.1	1.1
Beam Energy (GeV)	1.0	1.01	0.93
Peak Beam current (mA)	38	42	40
Beam Pulse Length (ms)	1000	1000	825
Repetition Rate (Hz)	60	60	60
Linac Beam Duty Factor (%)	6.0	5.0	5.0
Beam intensity on Target (protons per pulse)	1.5×10^{14}	1.6×10^{14}	1.1×10^{14}
SCL Cavities in Service	81	80	80

Technical Issues

Ion Source

- lifetime and reproducibility

RFQ

- resonant frequency shift, resonant-frequency control at high duty factor

SC Cavity/CM Performance

- large variations in operating accelerating gradient; operating at less than design gradients in high-beta
- SC Cavity degradation with severe beamloss observed; recoverable with conditioning

SCL Beamloss

- unanticipated source of beamloss in SCL; doesn't limit performance

Pulsed-power systems

- modulator reliability

Injection region/stripper foil

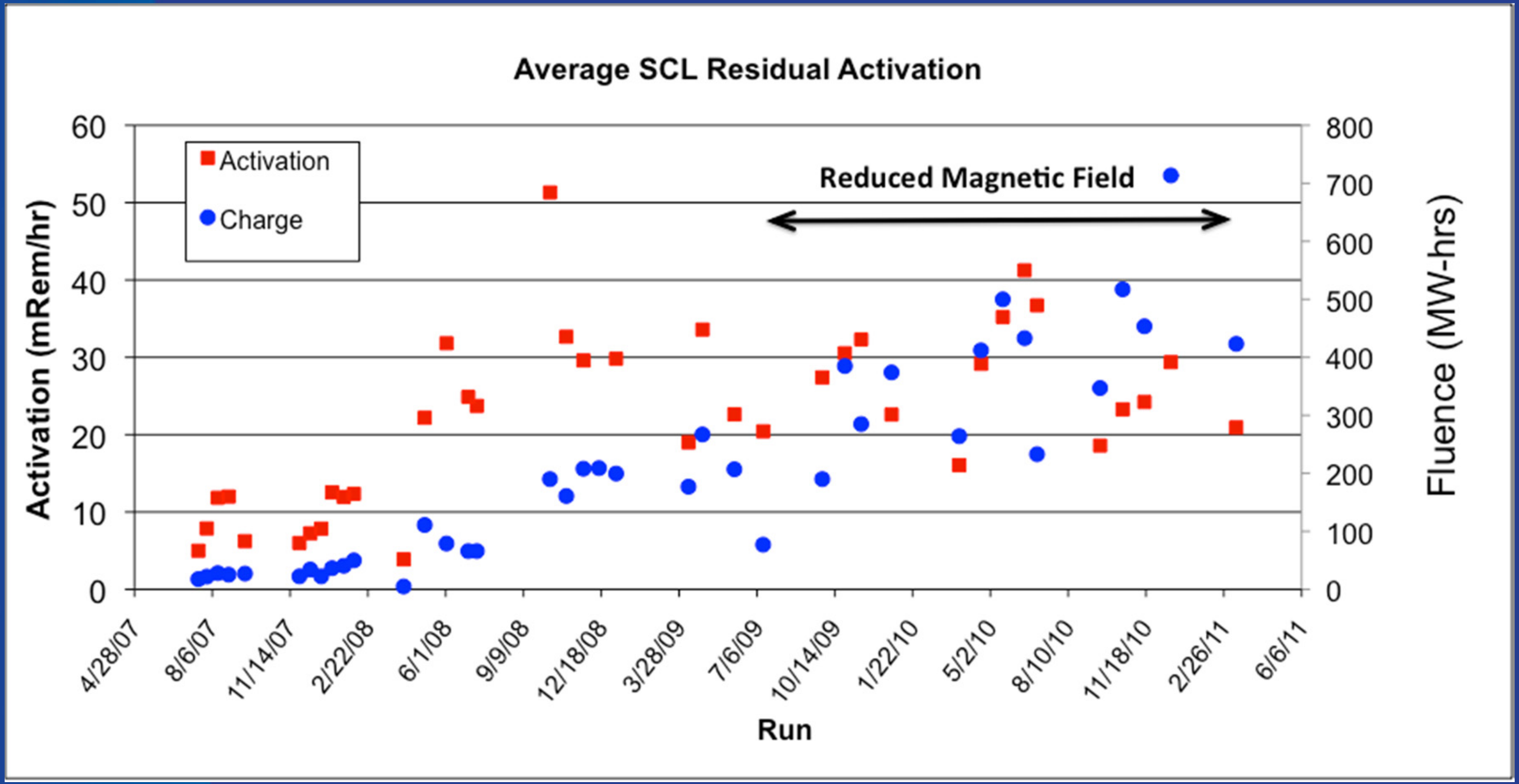
- very sensitive loss location; reworked several aspects of high power injection

Target lifetime

- cavitation induced damage observed; has not limited performance

Linac Activation History

Courtesy J. Galambos, SNS



- Superconducting Linac activation is not increasing, despite significant increase in power and operational hours (A. Shishlo)
- Reduction in quadrupole focusing strength reduced losses
- Beam loss is not a limiting factor in SCL

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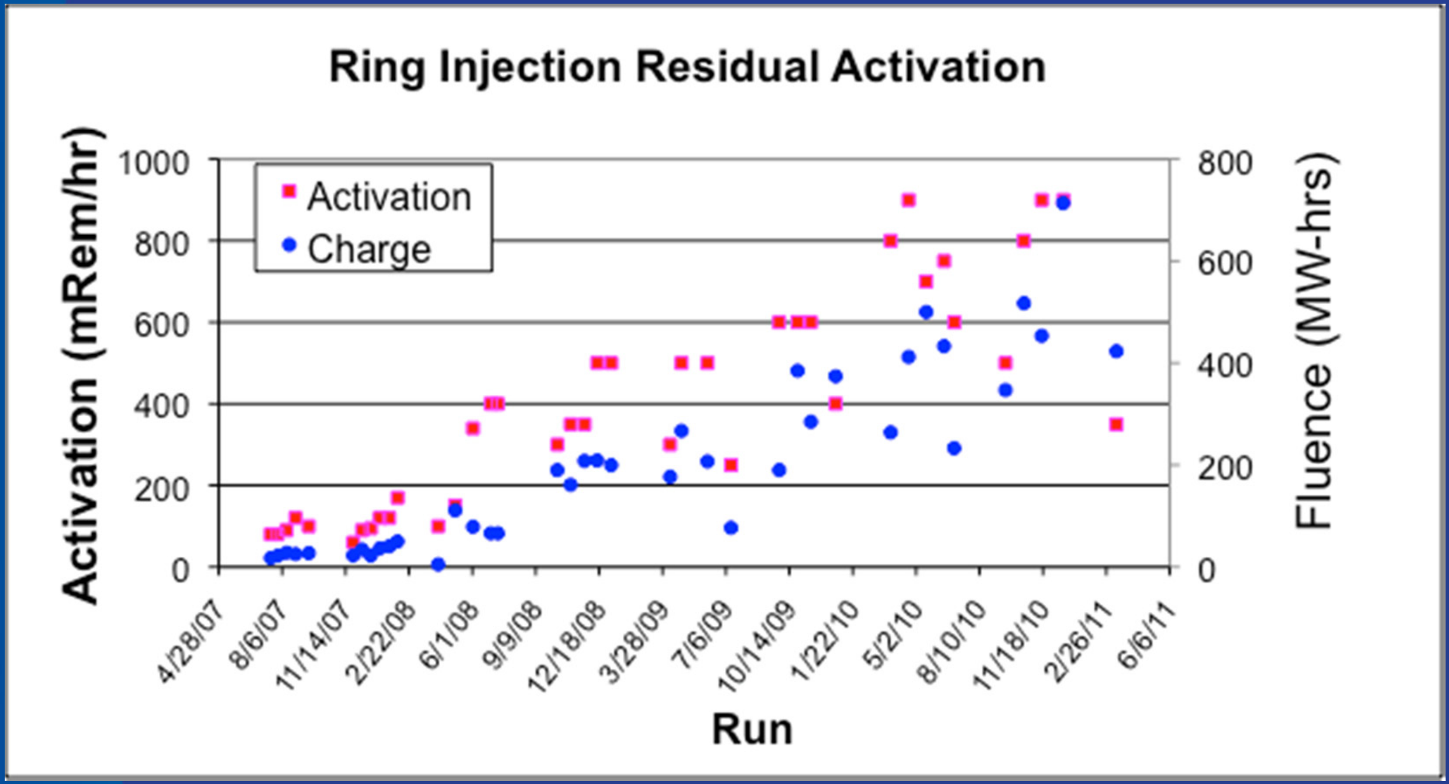
Ring Activation

Courtesy J. Galambos, SNS



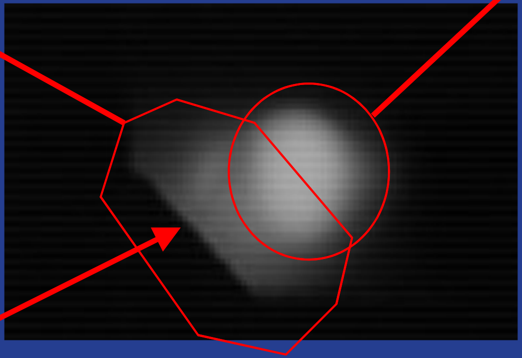
- Ring activation is primarily at the injection point, dominated by scattering losses from the foil
- Activation scales with fluence, close to expectations
- Losses are managed with optimization of injected beam, foil parameters, foil geometry

Ring Injection

Courtesy J. Galambos, SNS

Ring circulating beam heating

Injection spot (linac beam)

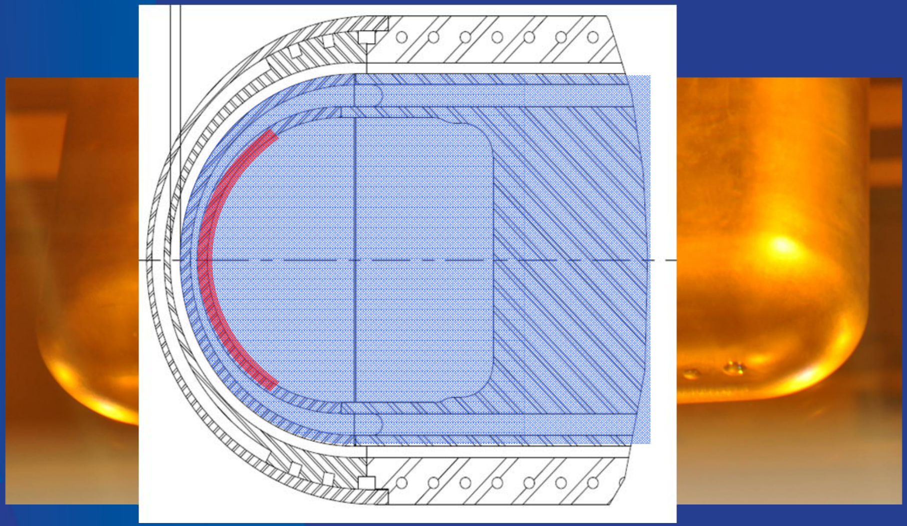


Cut-corner to reduce circulating beam foil interactions

- "Cutting corners" to optimize the foil / linac beam shapes reduces scattering losses ~ 20%

Mercury Spallation Target Experience

- Cavitation induced damage has been a concern since early SNS design
- Two target change-outs have been performed, after ~7 d.p.a. each
- Post-irradiation examination has been performed
- Results reveal cavitation-induced pitting damage on Hg-facing surface
- Expectation is a strong non-linear dependence on pulse intensity
- Observed pitting damage is near stagnant flow region
- Not limiting beam power at present
- Mitigation efforts under study; simple change in Hg flow could mitigate



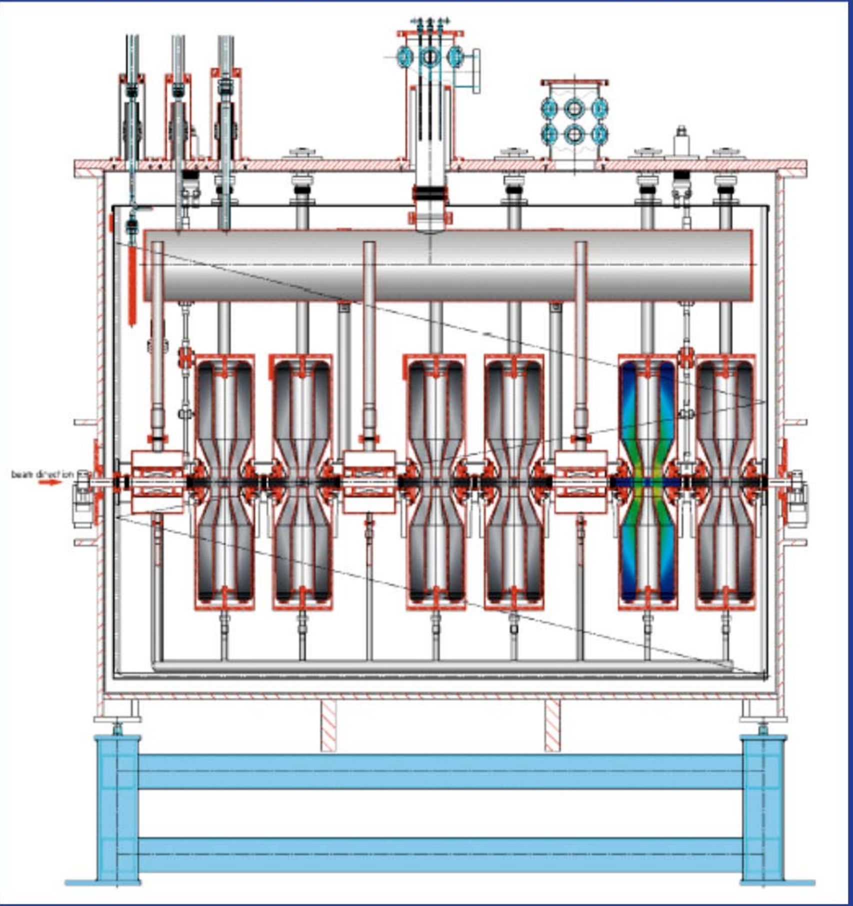
Courtesy B. Riemer, SNS

Progress at Soreq Applied Research Accelerator Facility (SARAF)

Courtesy I. Mardor, SARAF

- The SARAF accelerator will be a 40 MeV, 5mA, CW proton/deuteron superconducting linac
- Phase I, now under commissioning, includes an ECR ion source, a 1.5 MeV/u 4-rod RFQ and a Prototype Superconducting Module (PSM) housing six 176 MHz HWRs and 3 solenoids
- Low duty cycle (10^{-4}) p/d accelerated up to 3.9 and 4.3 MeV
- CW 1 mA proton beams accelerated up to 3.5 MeV
- Duty factor for deuteron operation (which requires higher field and power dissipation) has been limited by a number of RFQ discharge/heating issues

Prototype Superconducting Module (PSM)



Laying the Groundwork for Multi-MW Facilities: What Have We Learned?

1 W/m beamloss in a MW-class pulsed accelerator is achievable

- Space-charge limits in rings can be mitigated by phase-space painting
- Collective phenomena at high intensity are calculable, and results are believable
- Linac emittance growth is calculable and can be minimized in practice

But, …

- Multi-MW facilities need to predict, measure and control beam particle distributions at the part per million level to reach 1Watt/m beamloss requirements
- Prediction of beamloss is not to the point where an accelerator can be "engineered"
- Simulation capability is advanced, but incomplete knowledge of input distributions makes quantitative predictions at the ppm level impossible
- Beam instrumentation tends to focus on beam-core parameters. Lost particles are those that have reached large amplitudes, many-sigma beyond the core.
- Control of beamloss that cannot be predicted or measured demands that flexibility be built into the accelerator design!

Laying the Groundwork for Multi-MW Facilities: What Have We Learned?

- H- sources can provide low-emittance, high beam current at high duty factor
- High-duty factor/CW RFQs are difficult engineering challenges
- Superconducting linac technology works in a proton beam context: high-quality beams are obtained together with flexibility given by independently-powered SC system
  - But CW applications bring new challenges, like pushing quality factor of SC cavities
- Stripping of H- beams of ever-higher power becomes more and more difficult
- Liquid metal targets work at MW beam powers,
  - but extending beam power requires special measures to combat cavitation for short-pulse applications, or use of free-flowing liquid (MERIT experiment)

In Summary…

- The field of high-power proton accelerators has come a long way in the last decade, incorporating and demonstrating new technologies and approaches
- These approaches show that MW-class proton beams can be generated, accelerated, handled and deposited
- The stage is set for the next step in proton beam power by the next-generation Multi-MW accelerators:
    - Project-X (S. Nagaitsev)
    - European Spallation Source (S. Peggs)
    - MYRRHA
    - IFMIF

Thank You