High Intensity Challenges

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Workshop on Optics Measurements, Corrections, and Modeling at High Performance Storage Rings, CERN,
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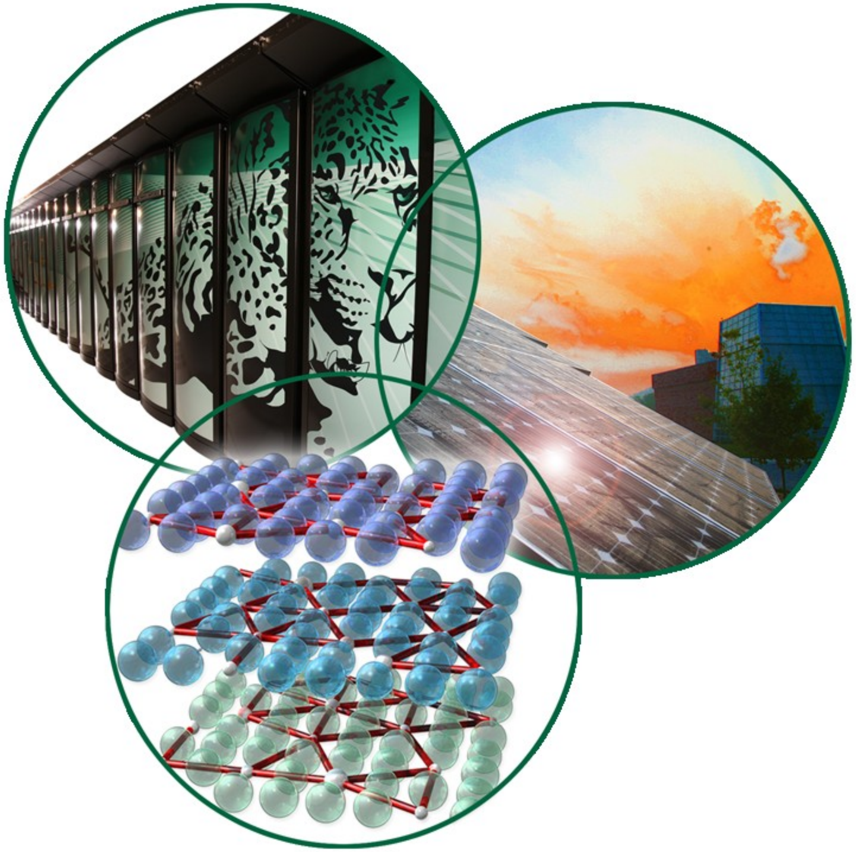

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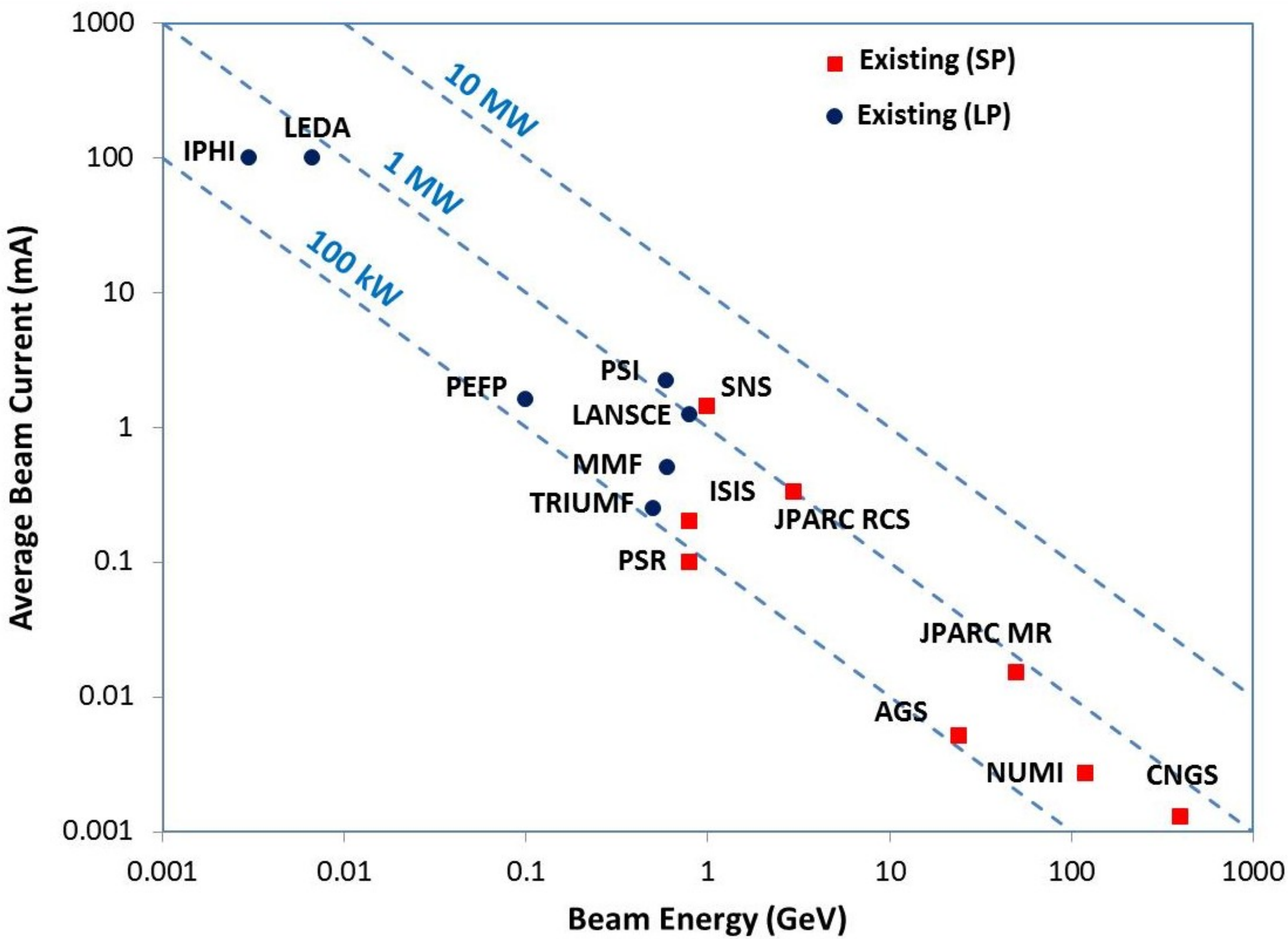
High intensity challenges

This presentation will focus on two high intensity (and high power) rings: The SNS storage ring and the JPARC rapid cycling synchrotron. Previous generation machines (PSR and ISIS) will also be compared. All four are examples of neutron spallation sources.

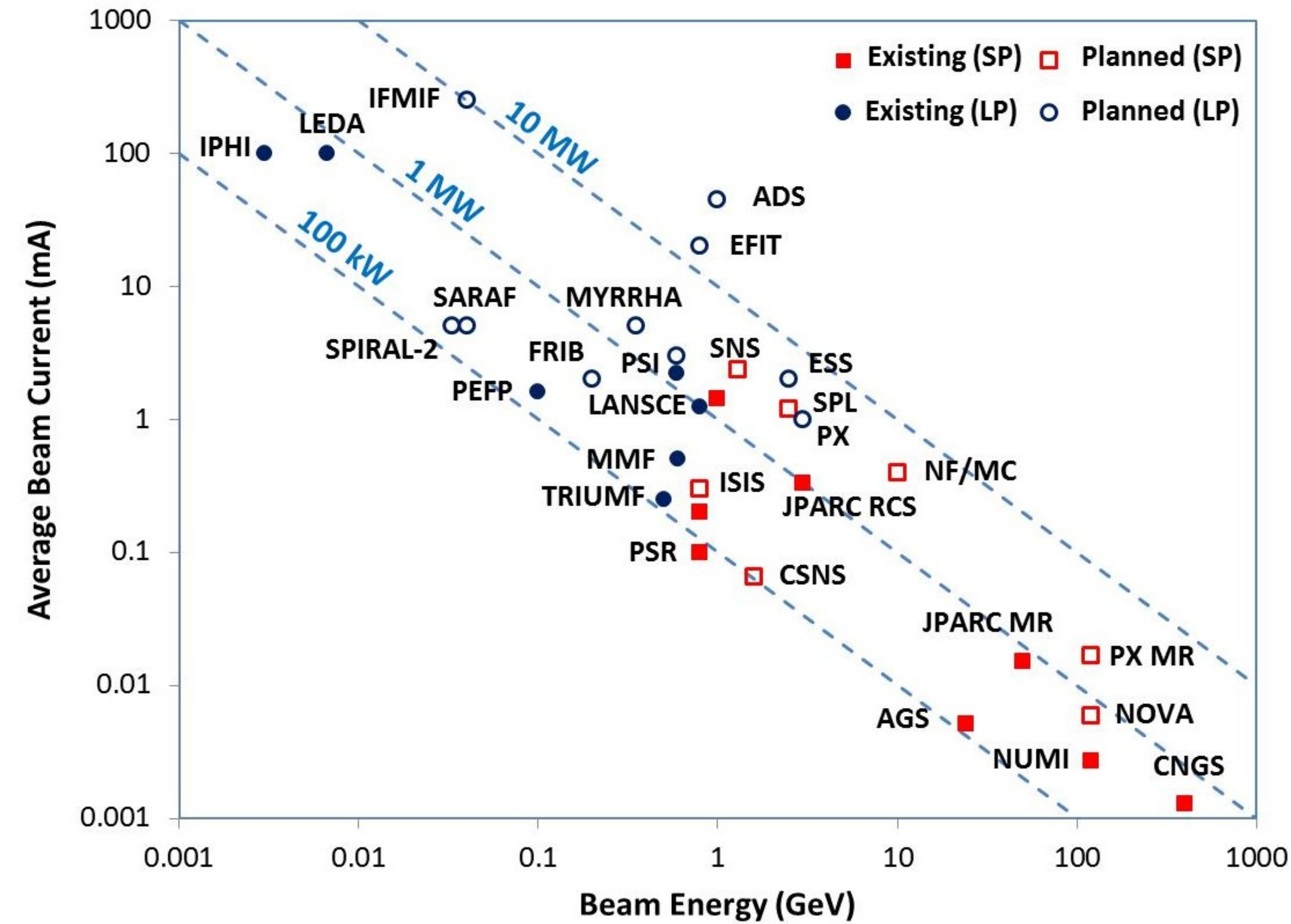
- **Overview of SNS and J-PARC**
- **Some high intensity challenges**
- **Suggestions for future development**

High intensity landscape



Courtesy S. Henderson

High intensity landscape incl. future



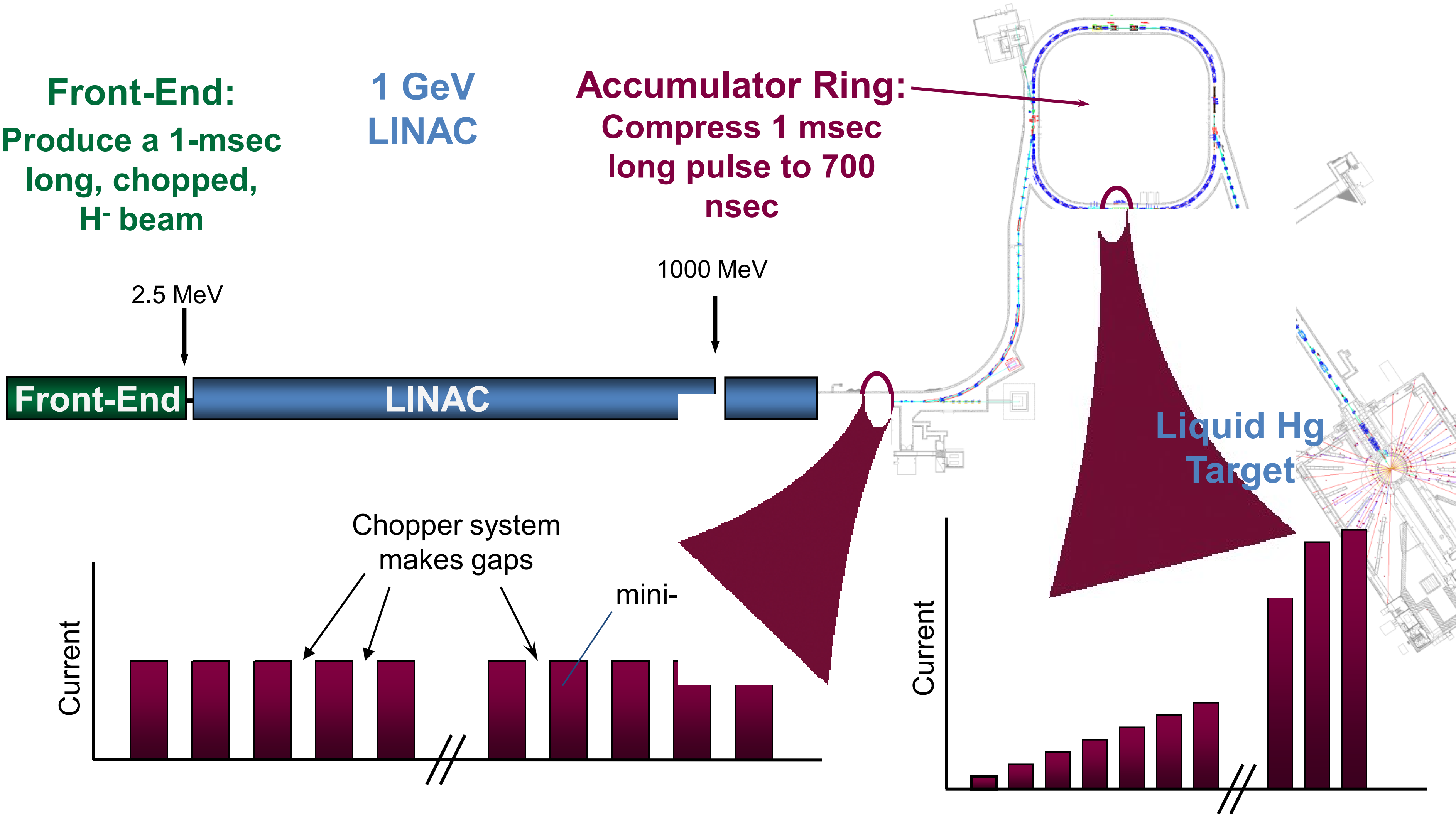
Courtesy S. Henderson

SNS Accelerator Complex

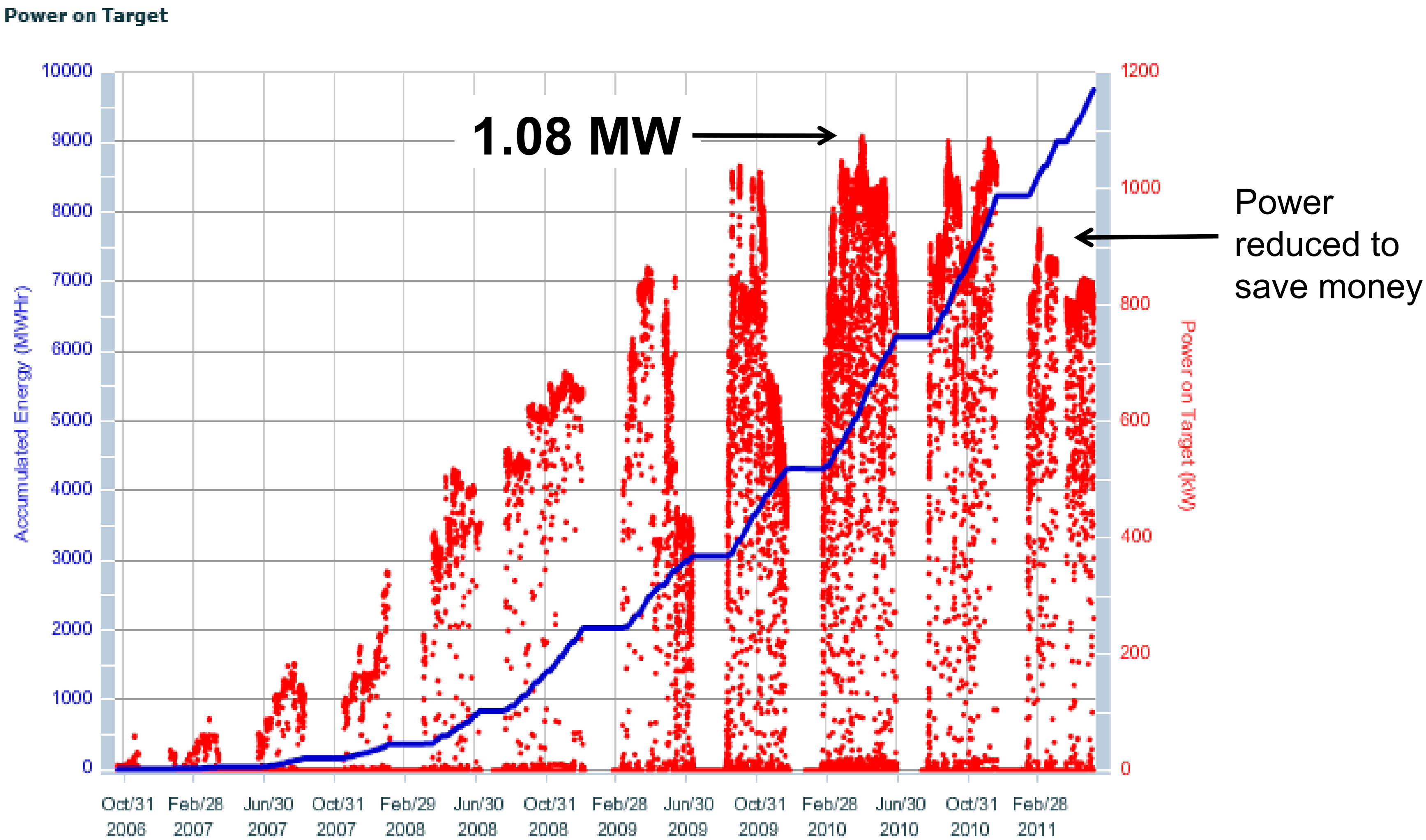
Front-End:
Produce a 1-msec long, chopped, H^- beam

1 GeV LINAC

Accumulator Ring:
Compress 1 msec long pulse to 700 nsec



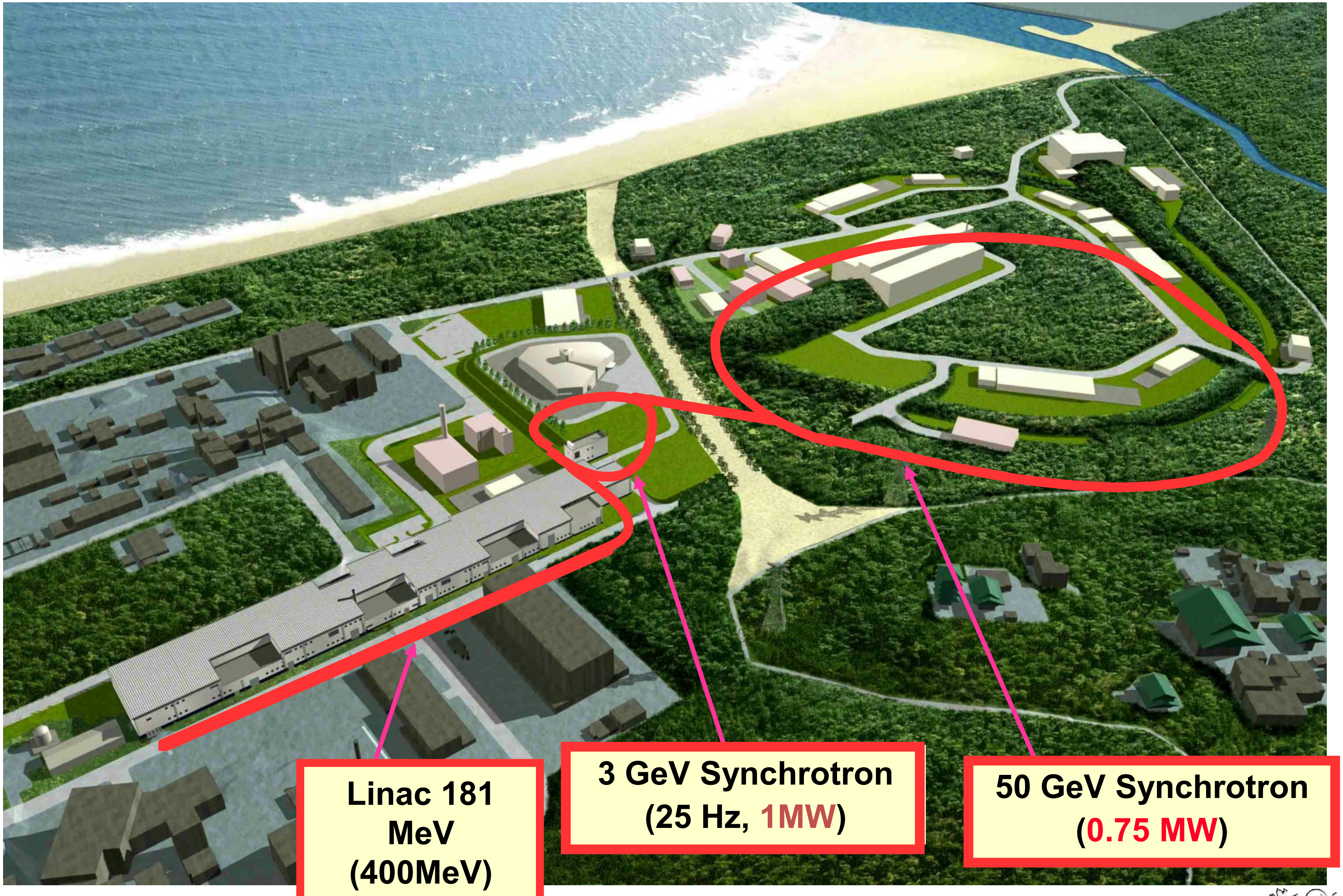
SNS power ramp up to date



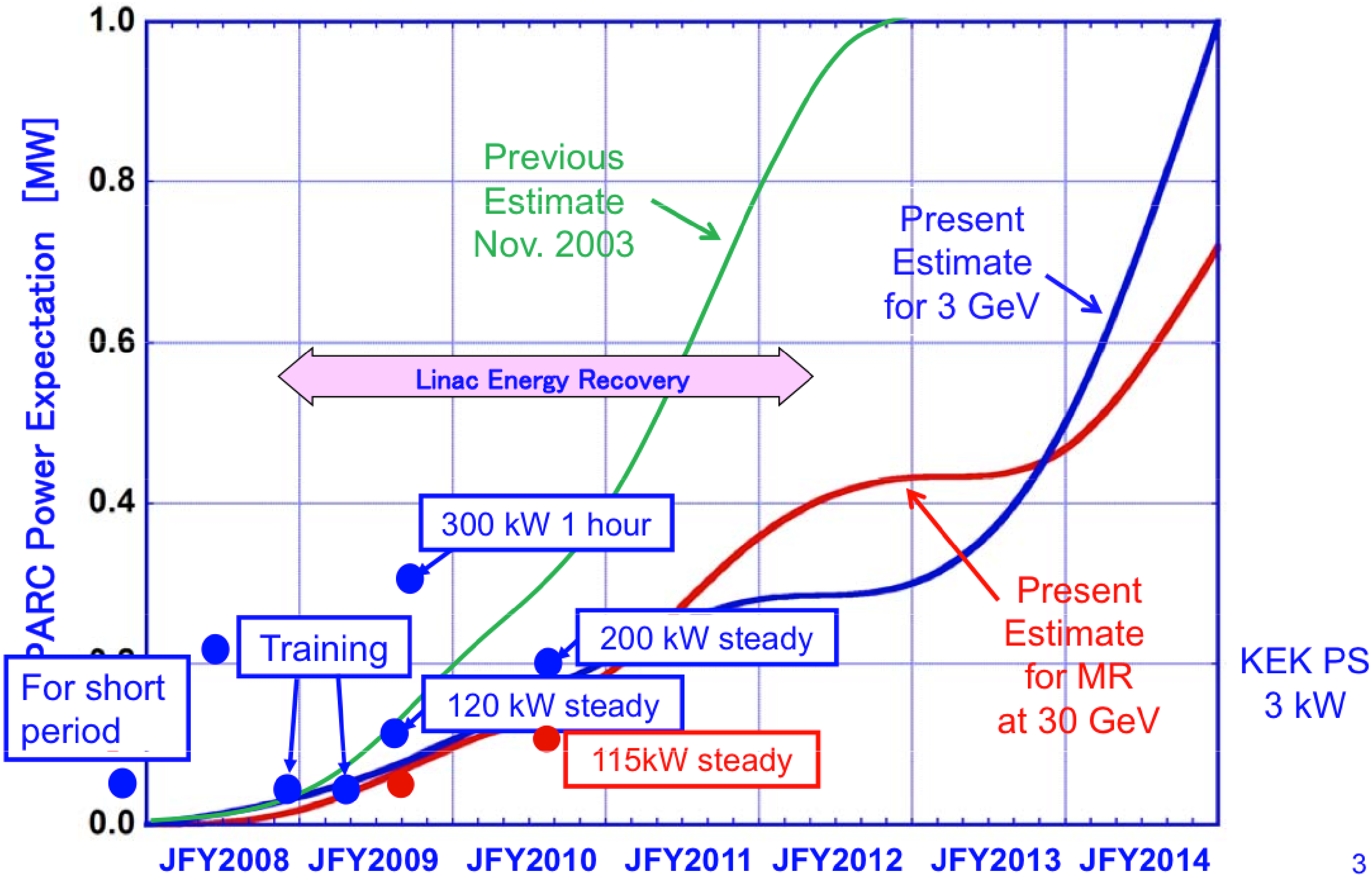
← **October 2006 to present** →

Full design power is 1.4 MW

J-PARC Accelerator Complex



Power Capability



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from S. Nagamiya, Jan. 2011

Some high intensity challenges

- Beam loss
- Charge exchange injection
- Simulations
- Collective effects
- Theory vs. practice
- Beam instrumentation

Beam loss

- **Rule of thumb: limit beam loss to <1 W/m for hands-on maintenance**
  - At high intensity machines such as SNS and J-PARC, this means a fractional loss of $<1\times10^{-6}$ per meter
- **Most beam loss comes from beam halo and beam scattering from stripper foils**
  - This drives the requirement for large apertures (30 cm maximum diameter in the SNS ring, and 41 cm in the JPARC RCS), which leads to other issues…
  - Collimation is also an integral part of today's high intensity machines (e.g. SNS, J-PARC, CSNS) to control beam halo and beam loss. SNS ring has first (?) two-stage collimation system.
  - Stripper foils are as small and as thin as possible

Beam loss at various machines

Relative beam loss

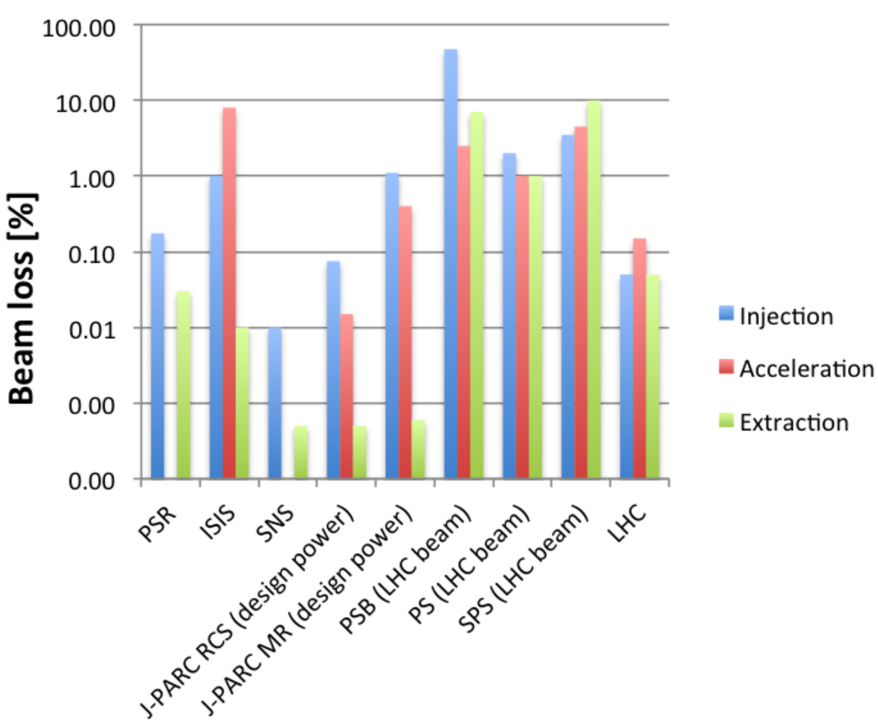
	Injection	Acceleration	Extraction
PSR	0.15 - 0.20%	0	<0.03%
ISIS	1%	8%	0.01%
SNS	0.01%	0	<0.0005%
J-PARC RCS (design power)	0.05 - 0.1%	0.01 - 0.02%	<0.0005%
J-PARC MR (design power)	1.10%	0.40%	<0.0006%
PSB (LHC beam)	45 - 50%	2 - 3%	6-8%
PS (LHC beam)	<2%	<1%	1.0%
SPS (LHC beam)	3 - 4%	4 - 5%	0.1%
LHC	0.01 - 0.1%	0.1 - 0.2%	0.01 - 0.1%

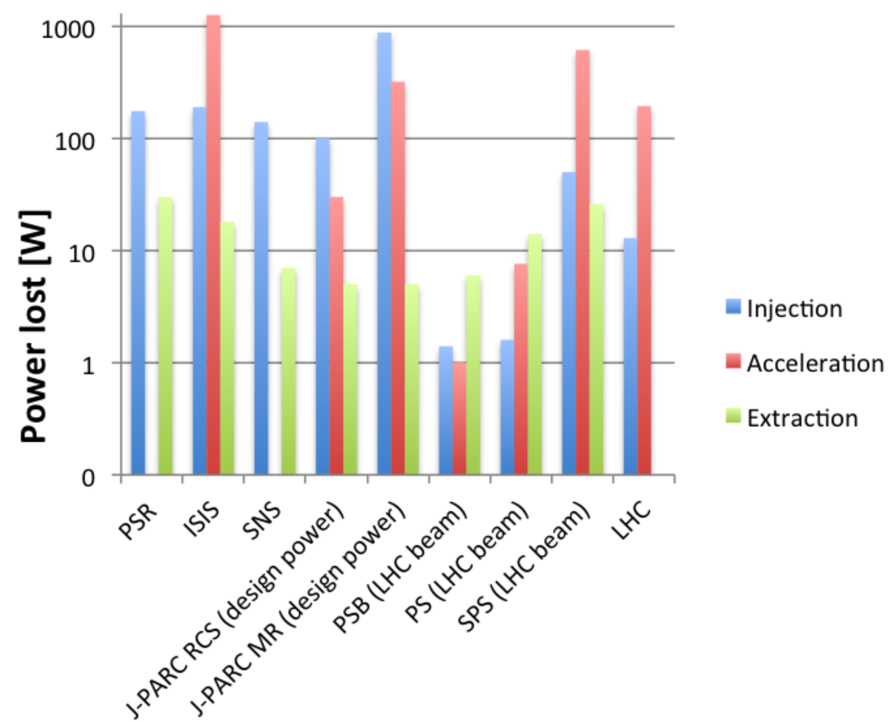
Note: does not include beam loss in beam transport line collimators

Beam power lost at full design power [W]

	Injection	Acceleration	Extraction
PSR	150 - 200	0	<30
ISIS	160 - 320	1260	18
SNS	140	0	<7
J-PARC RCS (design power)	67 - 133	20 - 40	<5
J-PARC MR (design power)	880	320	<5
PSB (LHC beam)	1	1	6
PS (LHC beam)	<1.6	<7.6	14
SPS (LHC beam)	50	614	26
LHC	13	194	

*Assumes 15 minutes to fill LHC

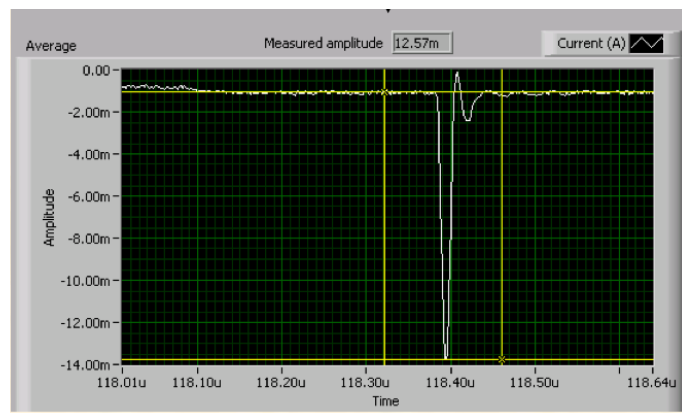




Charge exchange injection

- Charge exchange injection is required for low-loss multi-turn injection
  - And also to utilize phase space painting to control space charge and collective effects
- Best way to do this today is with stripper foils
  - But foil technology is close to its beam power limit due to short lifetimes caused by intense beam heating
  - Laser stripping is the up and coming alternative technology

Blackened, twisted foil from SNS, used for 1 MW production



90% stripping of ~870 MeV H^- beam.
(Danilov, PAC07)

Charge exchange injection today

- Best foils today are HBC and AC-DC foils used at J-PARC and nanocrystalline diamond foils used at SNS
- Laser stripping has been demonstrated in just one series of experiments, at SNS, and only for ~10 ns
- High intensity challenge: Advance the technology for laser stripping to make it practical for the next generation of high intensity machines
  – Laser stripping will eliminate the beam loss caused by foil scattering (which accounts for the majority of the beam loss in high intensity machines) and avoid the thermal foil problems
  – SNS and Project X (FNAL) are collaborating toward this goal
  – A experiment to demonstrate 1 – 10 μs stripping is in progress at SNS, but results are not expected for a few more years. (For SNS, need 1000 μs @ 60 Hz.)

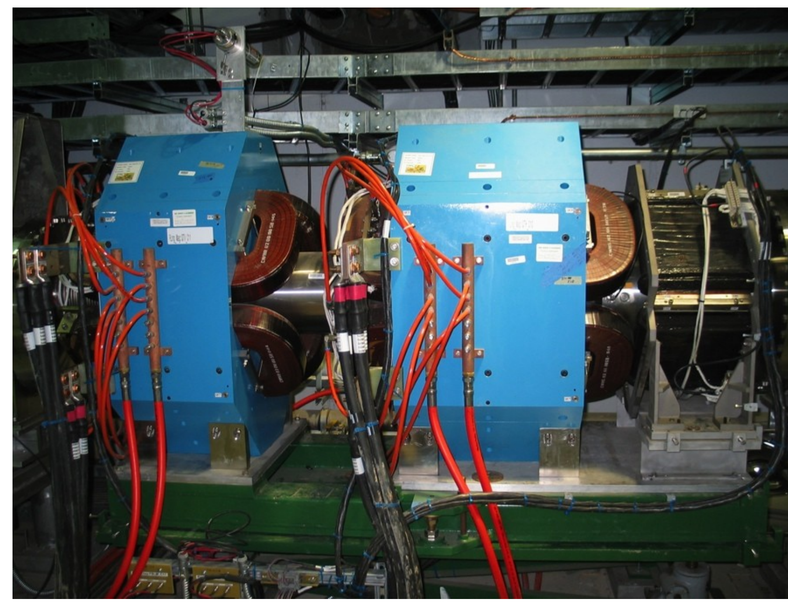
Simulations

- Simulations are needed to design our accelerators and storage rings
  - In general they are better than ever
  - However, they cannot accurately simulate beam loss at the <1x10^{-6} level
  - They rarely include important effects such as magnetic field overlap caused by large aperture / poor-aspect-ratio magnets in close proximity
  - An accurate simulation requires an accurate input 6D phase space beam distribution, but this is not known well enough and is difficult (impractical?) to measure
- **High intensity challenge: improve simulations to accurately predict beam loss at the <1x10^{-6} level**

Consequences of large apertures

- High intensity machines need large beam apertures to reduce the beam loss
  - This often produces problems with fringe fields and magnetic field overlap caused by large aperture / poor-aspect-ratio magnets in close proximity, and these effects are rarely included in simulations

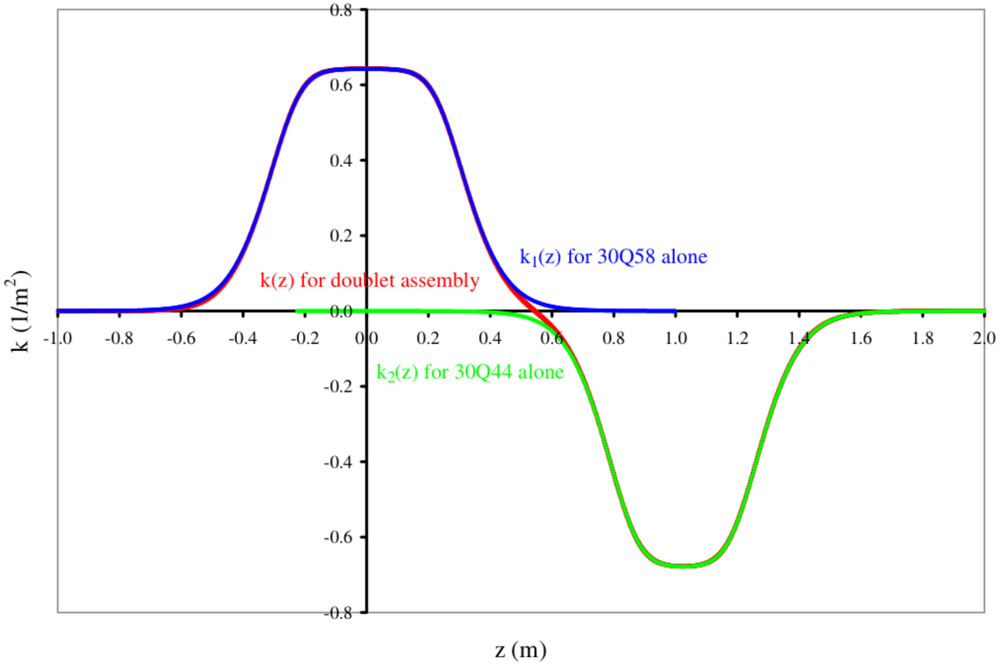
J-PARC injection section



SNS straight section

Effect of magnetic field overlap in the SNS quad doublets

Example focusing perturbation caused by magnetic field overlap



Focal length changes: Δf_x = -4.3%, Δf_y = -6.4%

From J.G. Wang, PRSTAB **9**, 122401 (2006)

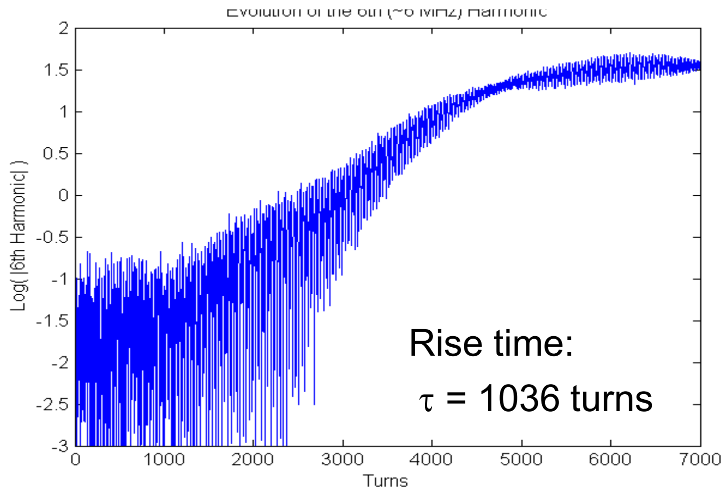
Collective effects

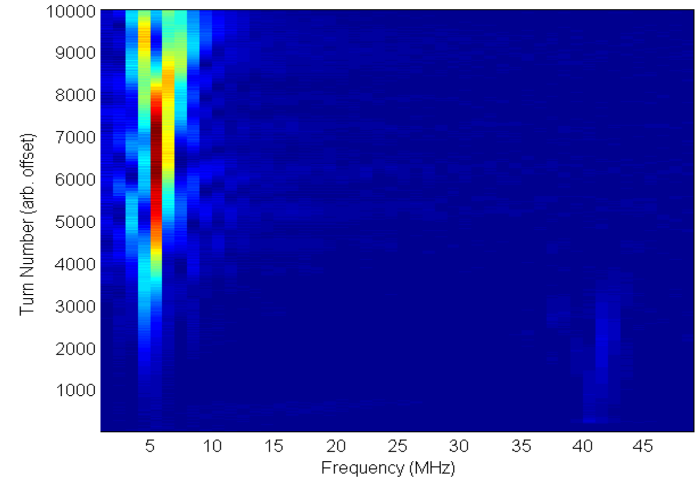
- Space charge effects such as tune spread seem to be well enough understood for today's high intensity rings
- Some beam instabilities are well enough understood, and some are not
  - Example of good understanding: Impedance-driven instability at SNS due to extraction kickers is accurately modeled by ORBIT simulation
  - Examples of poor understanding: e-p instability threshold and behavior at both SNS and J-PARC
- High intensity challenge: improve our understanding of the e-p beam instability

Extraction Kicker Instability Benchmark

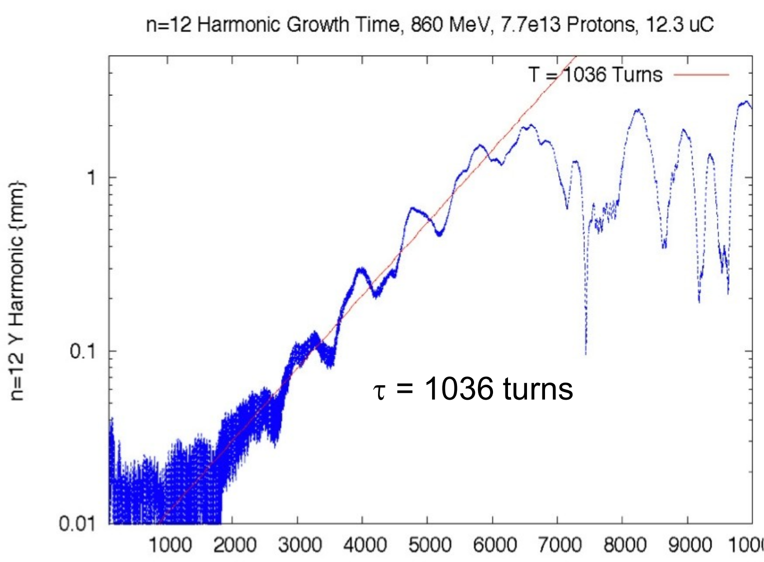
ORBIT's transverse impedance model was successfully used to model the extraction kicker instability. The rise time and the threshold are accurately predicted.

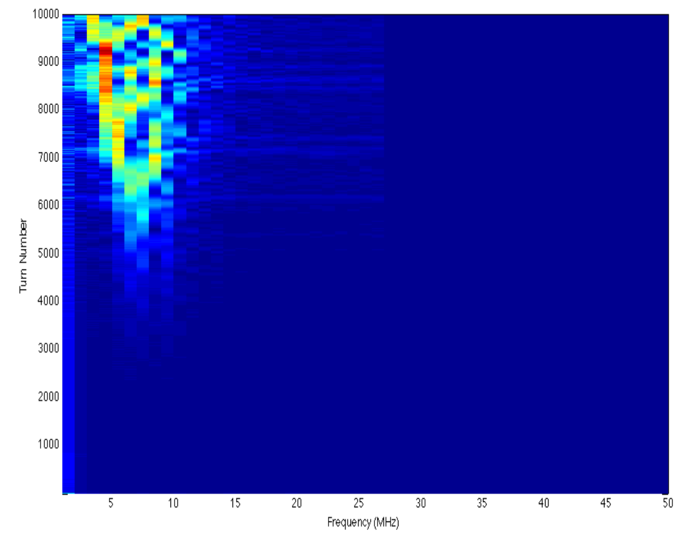
Measured





Simulated





Courtesy J. Holmes

e-p instability

- SNS, J-PARC, ISIS, and PSR have mostly avoided the e-p instability – it does not interfere much with normal operations
  - PSR needs a slightly higher buncher voltage to control it
  - At SNS it is easily controlled with the second harmonic RF buncher voltage
  - It's not seen at the J-PARC RCS or ISIS
- The e-p instability threshold and characteristics cannot be accurately predicted with today's simulations
  - At J-PARC MR the measured e-p oscillation frequency (15-60 MHz) is lower than expected (80 MHz)
  - The characteristics of the e-p instability at SNS and PSR are very different, although they were expected to be very similar

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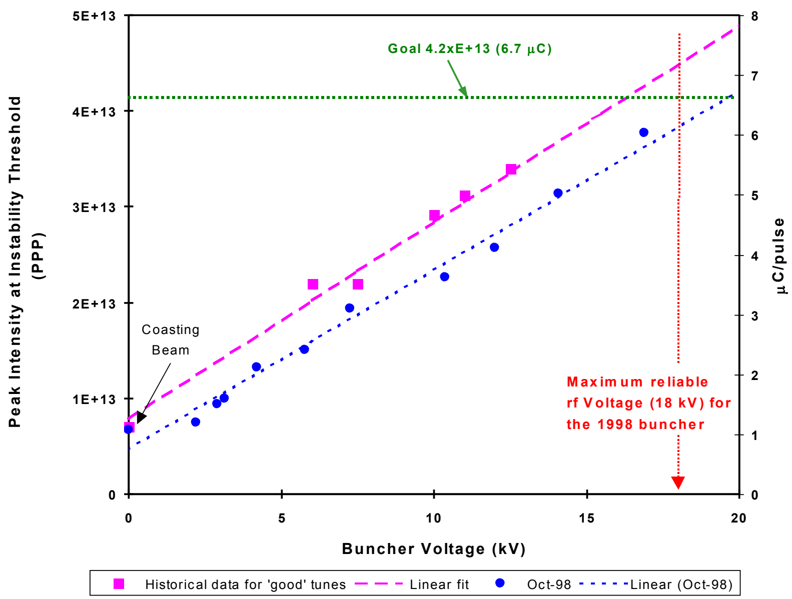
e-p instability at PSR vs SNS

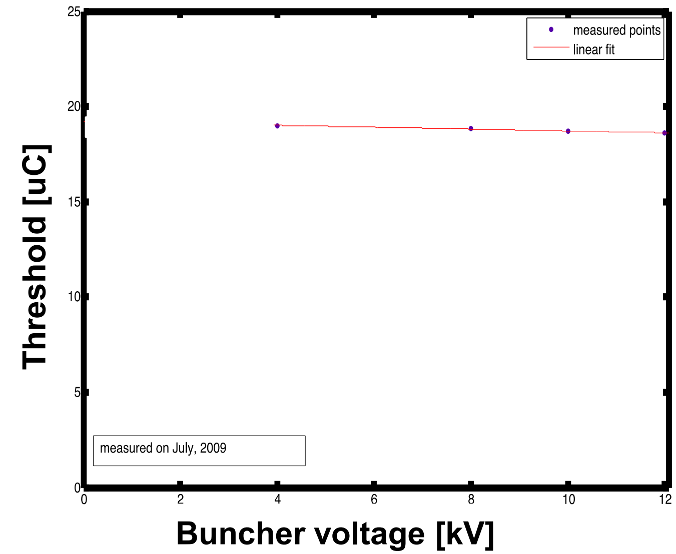
PSR



e-p instability threshold vs. buncher voltage at the Los Alamos PSR

Courtesy R. Macek

SNS



- At SNS, the e-p threshold does not change much with buncher voltage. It is more sensitive to the bunch shape (and thus the second harmonic buncher voltage).
- This result was not predicted by either theory or the simulation codes

Courtesy Z. Liu, PhD thesis

Theory vs practice

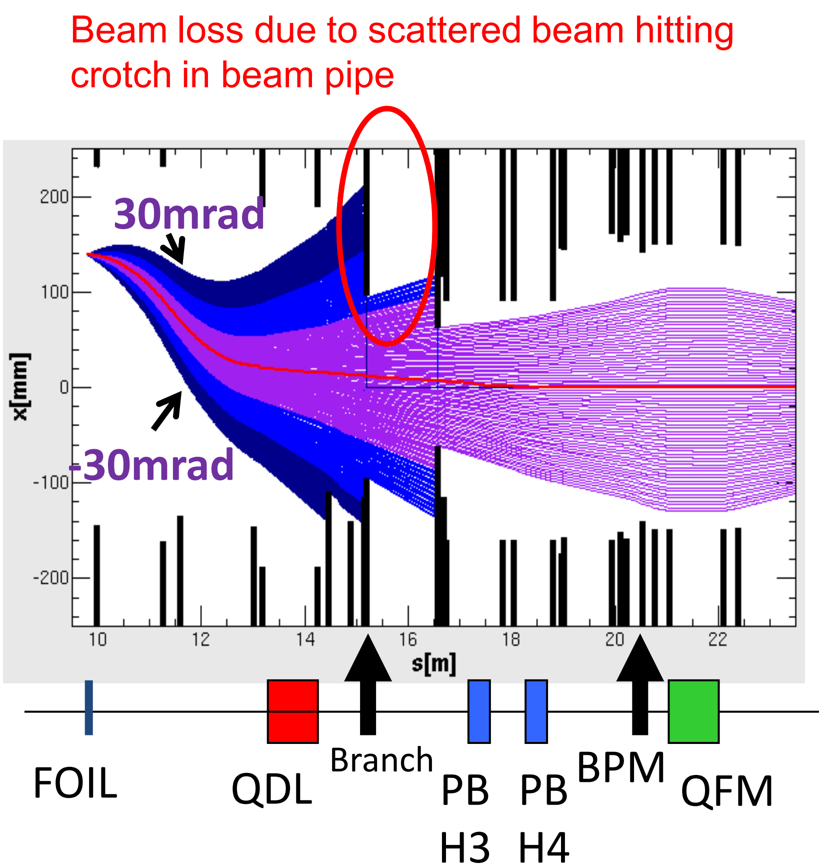
- The low loss tune in practice sometimes does not correspond to the design set points and lattice functions
  – SNS linac quads are ~50% below design values
  – SNS ring RF buncher h=1 phases designed to be the same, but to get the best beam loss they must be separated by 15 - 75 deg
  – J-PARC RCS design tune (6.68, 6.27) ⇒ current tune (6.45, 6.42) due to leakage fields from the extraction beam line magnets and edge focus effect of the injection bump magnets
  – At least in transport lines, beam loss is due to the beam halo, and the magnet set points needed to to efficiently transport this halo can be different from the design and/or different from the settings needed to transport the core of the beam (e.g. SNS HEBT)

Theory vs practice (cont.)

- SNS, J-PARC, and PSR all needed to modify their ring injection sections due to unanticipated problems
  - SNS H^0 and H^- waste beam transport issues due to unintended consequences of a design change in the injection chicane magnets
  - J-PARC RCS high beam loss on the crotch between the ring and injection dump beam lines due to foil scattering
  - PSR high beam loss caused by poor matching and injected beam emittance growth caused by two-step H^- to H^0 to H^+ injection process
- Lesson learned: Particle-tracking simulations using 3-D magnetic fields from magnet simulations were an important tool to address the issues (SNS and J-PARC)
- Lesson learned: For high intensity machines, it is important to have a flexible design that can accommodate a wide range of set points to achieve the empirically-determined low loss tune

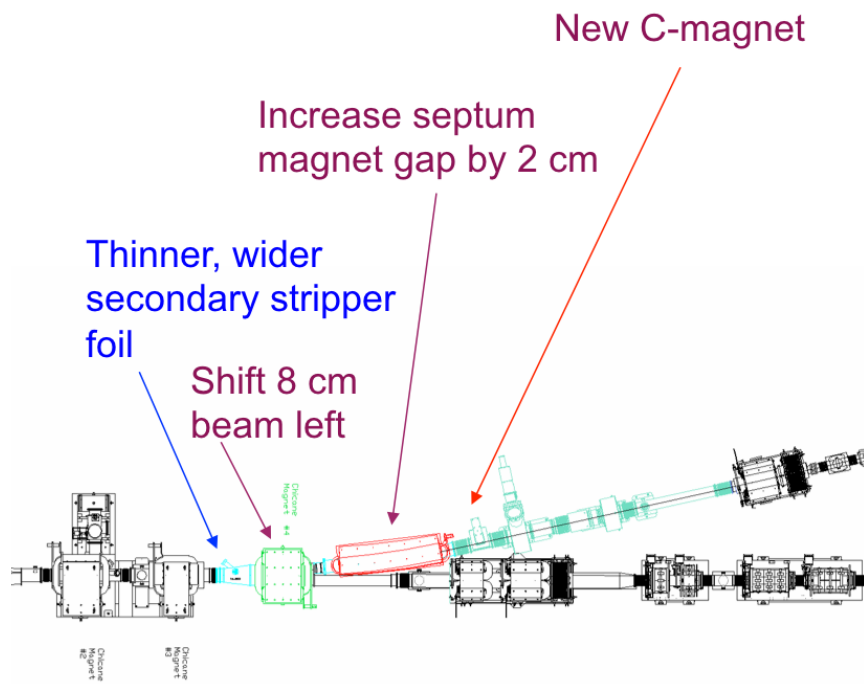
Example injection section modifications

A collimator is being added to the J-PARC RCS to protect the crotch in the H^0 / ring beam line



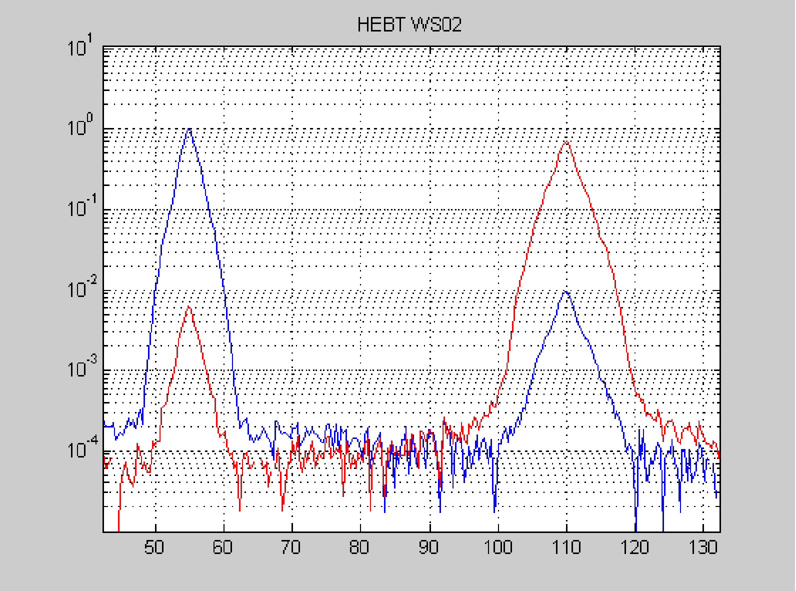
Courtesy: H. Harada

Modifications to the SNS injection section



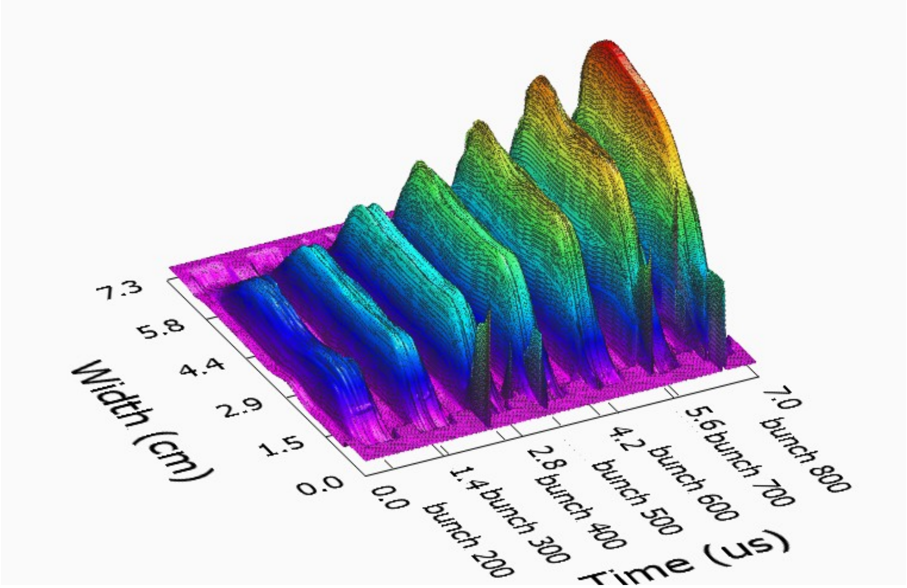
Profile measurements at SNS

Example wire scanner profile measurement in linac-to-ring transport line. Dynamic range is almost 10^4.



Courtesy A. Aleksandrov

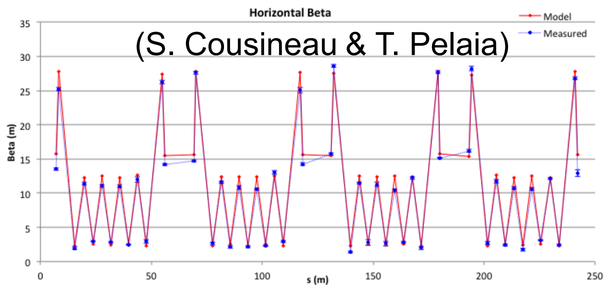
Example non-intercepting electron-beam profile measurement in ring transport line. Dynamic range is 30 - 80.



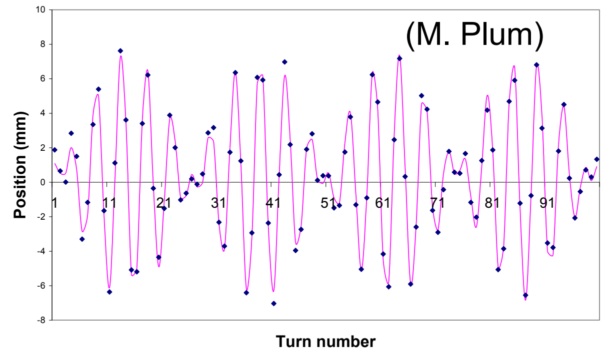
Courtesy W. Blokland

High intensity challenge: develop beam instrumentation that can measure beam distributions with **wide dynamic range**, ideally $>10^6$, preferably **non-intercepting**

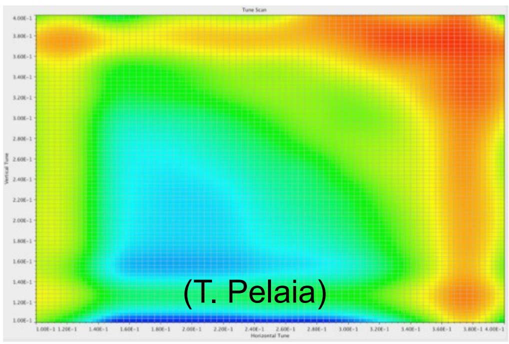
Basic optics measurements at SNS Ring



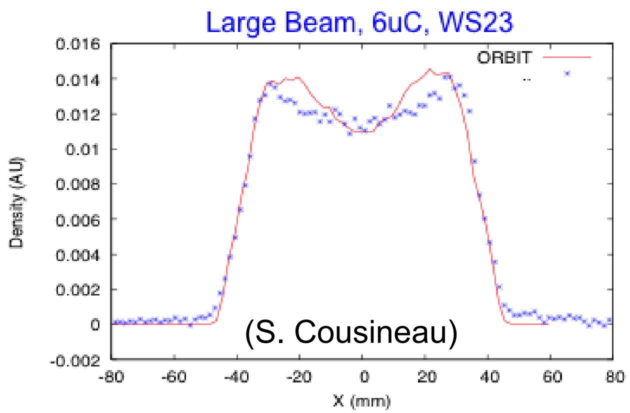
Betatron function measurement by varying quad trims (also used MIA and ORM)



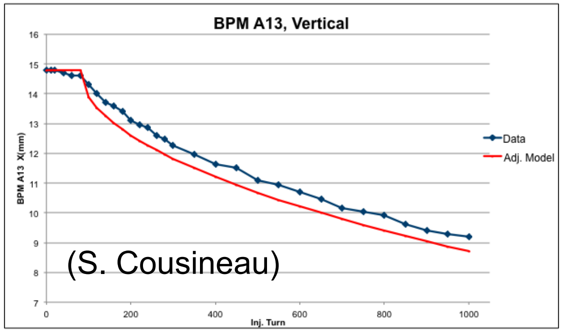
Transverse coupling in the Ring



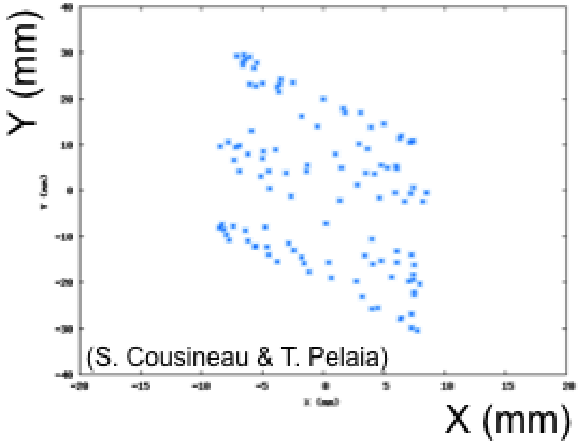
Ring resonance map



Simulation code benchmarking



Phase space painting



2-D beam distribution in extraction line using a BPM and single minipulse reconstruction

Suggestions for future development

- Improve simulations to accurately predict beam loss at the $<1x10^{-6}$ level
- Improve ability to predict and model the e-p beam instability characteristics, especially the threshold
- Advance the technology for laser stripping to make it practical for the next generation of high intensity machines
- Improve beam instrumentation:
  - Measure beam halo, preferably non-intercepting, with dynamic range $> 10^6$
  - Measure input beam distributions (e.g from ion source or RFQ) with greater accuracy, with dynamic range $> 10^6$, full 6D phase space

Acknowledgements

- Thanks to H. Hotchi (J-PARC) and B. Goddard (CERN) for their input into this presentation

The SNS ring is an ideal environment for studying high intensity effects

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