Advanced instrumentation for model-based beam loss control in high intensity hadron linacs

GARD APB Workshop 2, WG1

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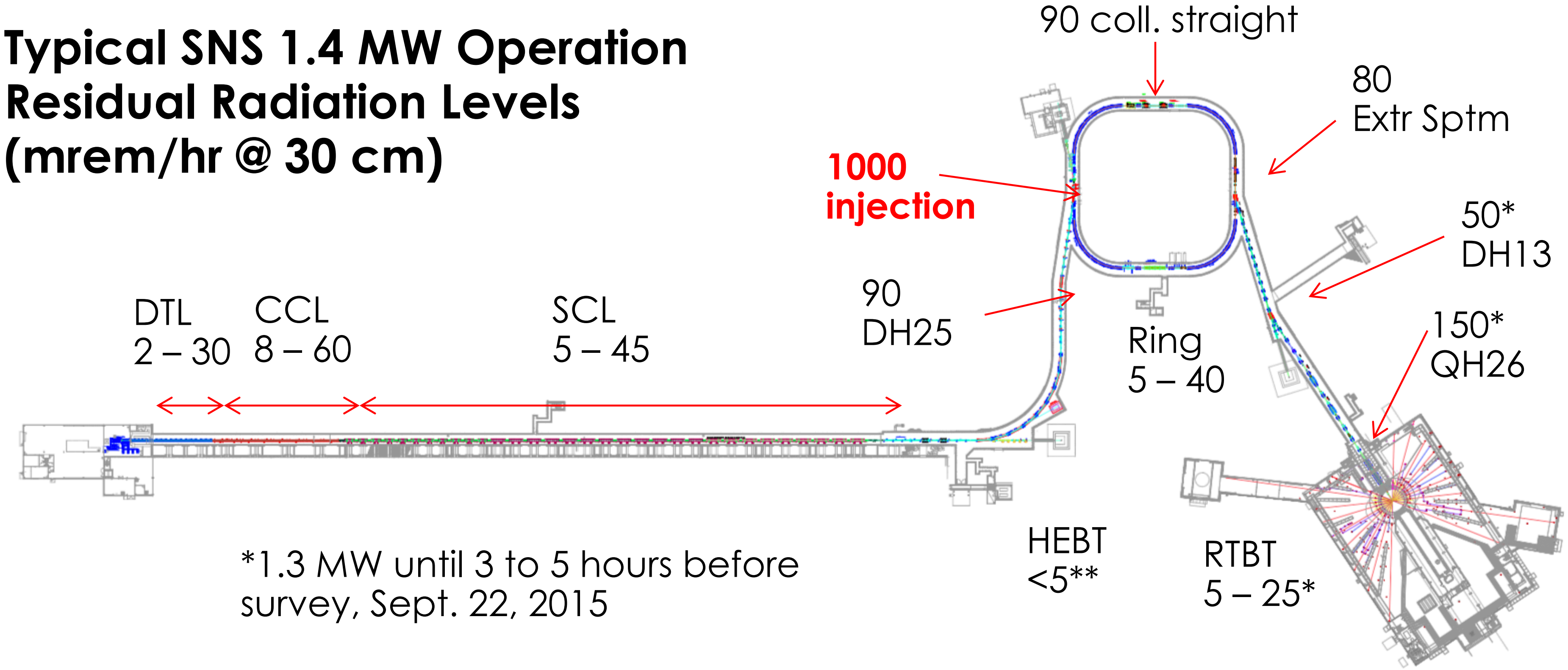
The Science: Controlling Beam Loss at High Intensity

- Beam loss and radiation scales roughly with beam intensity in a proton linac
  - Scaling to 10 MW results in *unserviceable accelerator* in many regions
- **Goal is to achieve 10 MW without 10x radiation**

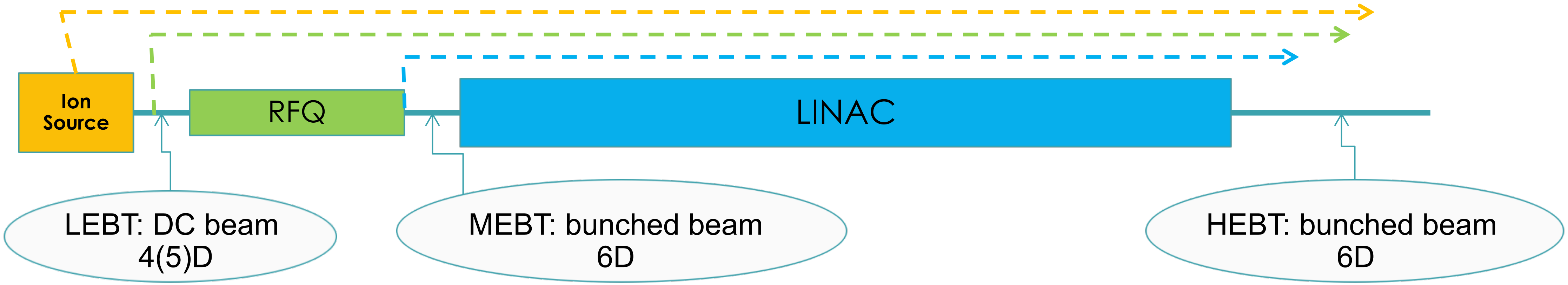
Typical SNS 1.4 MW Operation Residual Radiation Levels (mrem/hr @ 30 cm)



*1.3 MW until 3 to 5 hours before survey, Sept. 22, 2015

OAK RIDGE National Laboratory

The Science: predicting beam loss in a hadron linac using computer simulations

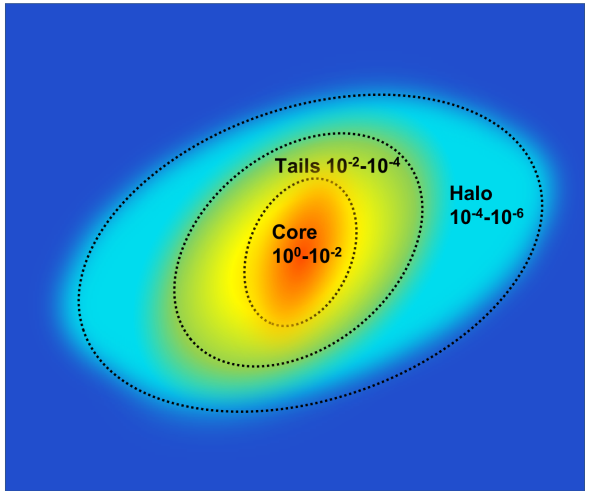


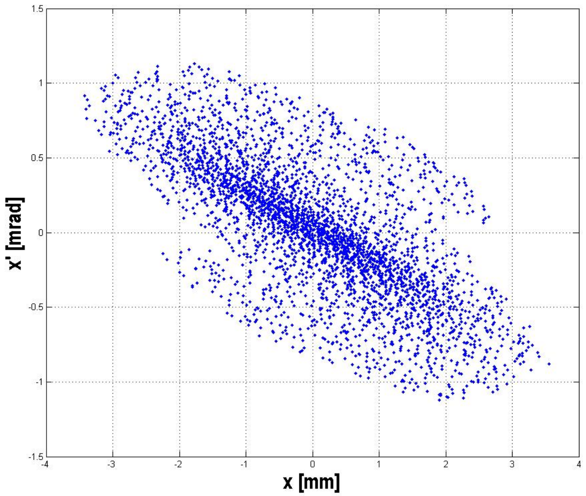
- Required components
  - PIC tracking code /not subject of this talk/
  - Reliable beam line description
  - Initial distribution of particles
  - Verification tools

Provided by beam measurements

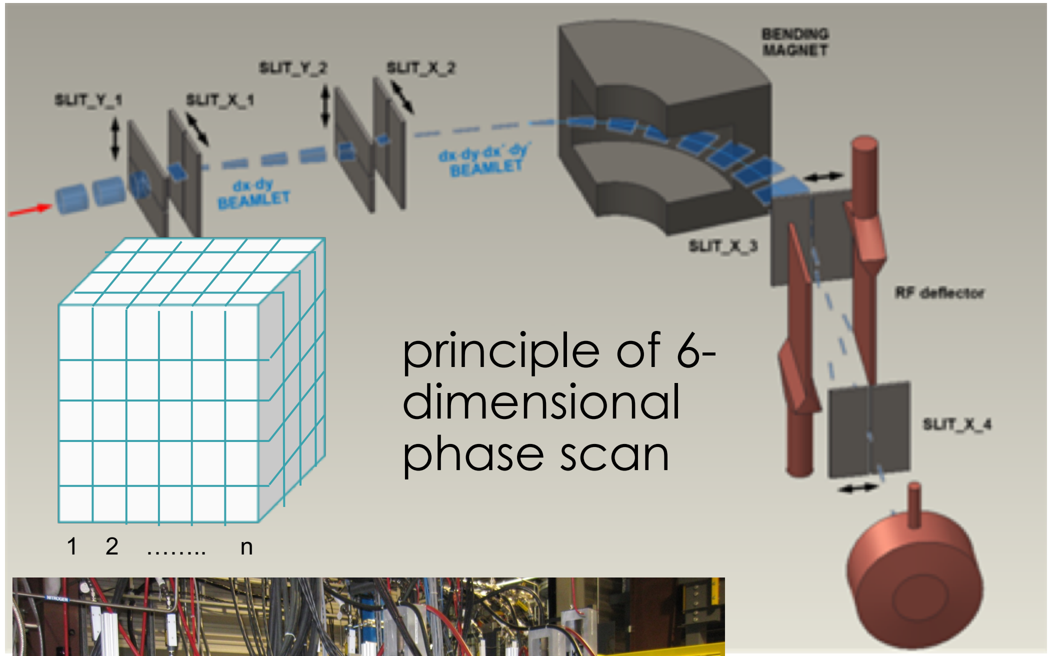
Beam Instrumentation requirements

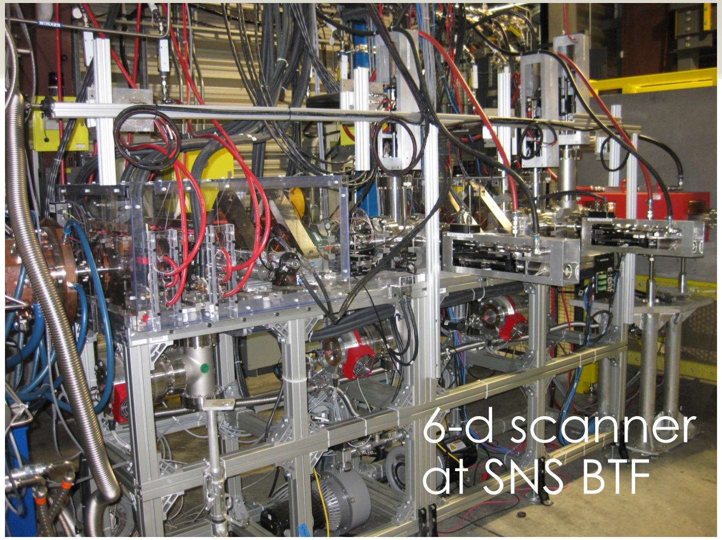
- High dynamic range: $\sim 10^6$
  - To resolve small fraction of ‘halo’ particles in presence of high intensity core
- High dimensionality of phase space measurements: $2,4,6$
  - Data represented in format interchangeable with PIC code
  - (x,x’)(y,y’)(z,z’) or (x,x’,y,y’)(z,z’) or (x,x’,y,y’,z,z’)
- Multiple points of measurement along beam line

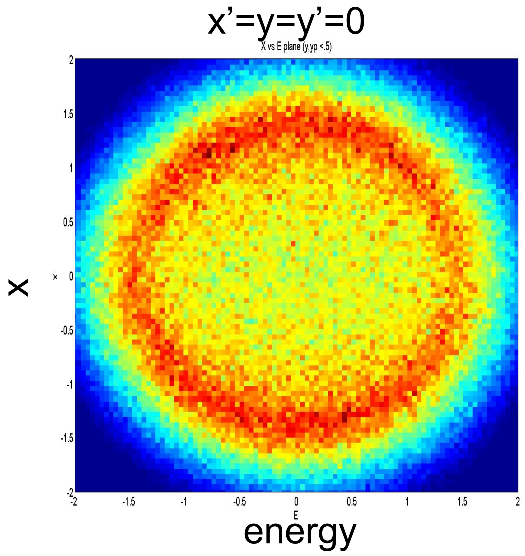


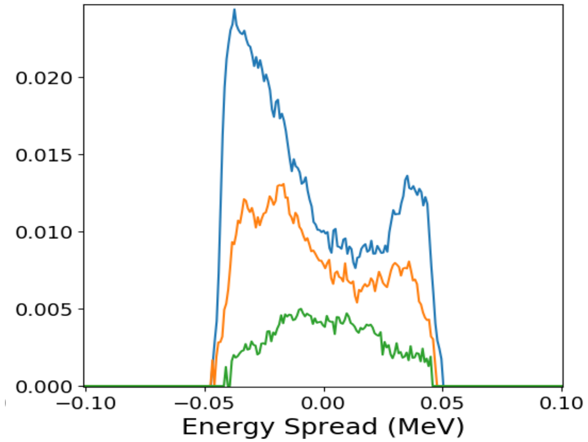


SNS 6-dimensional phase space scanner at 2.5MeV







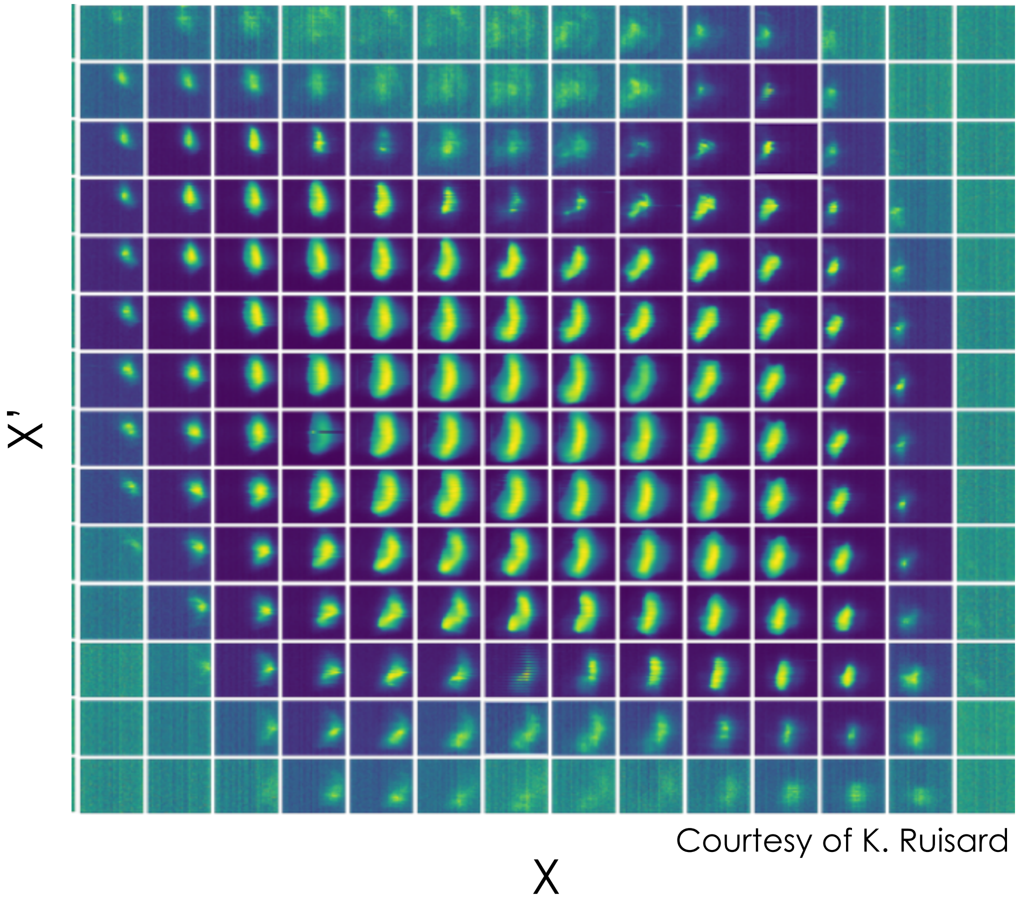


$$f(x', w) \neq f(x') \cdot f(w)$$

The main results so far:

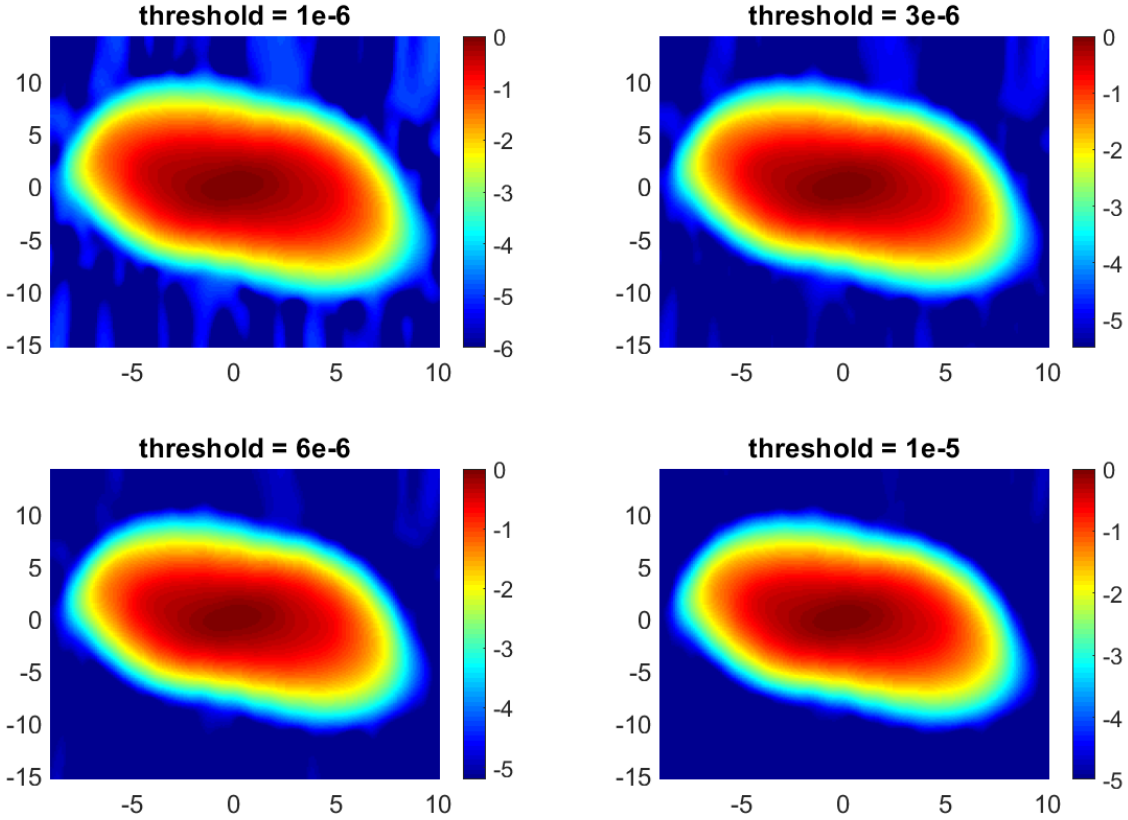
- It is doable
- RFQ output 6-d distribution is much more complex than typical representation in simulations
- There are non-trivial correlations between planes

Multi -dimensional high dynamic range measurements at 2.5MeV



Courtesy of K. Ruisard

An example of a measured 4-d partial projection of the distribution function , plotted on a logarithmic scale.

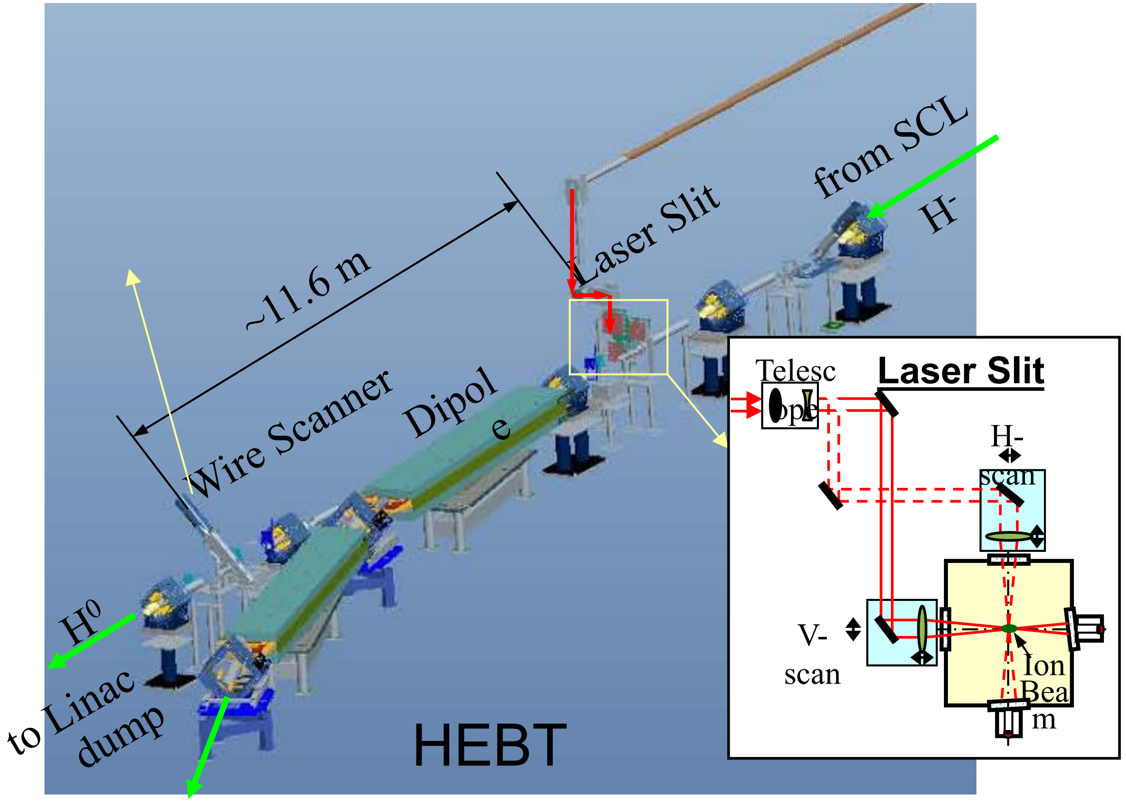


An example of 2-d horizontal emittance measured with $DR = 10^5$ at the SNS Beam Test Facility, plotted on a logarithmic scale.

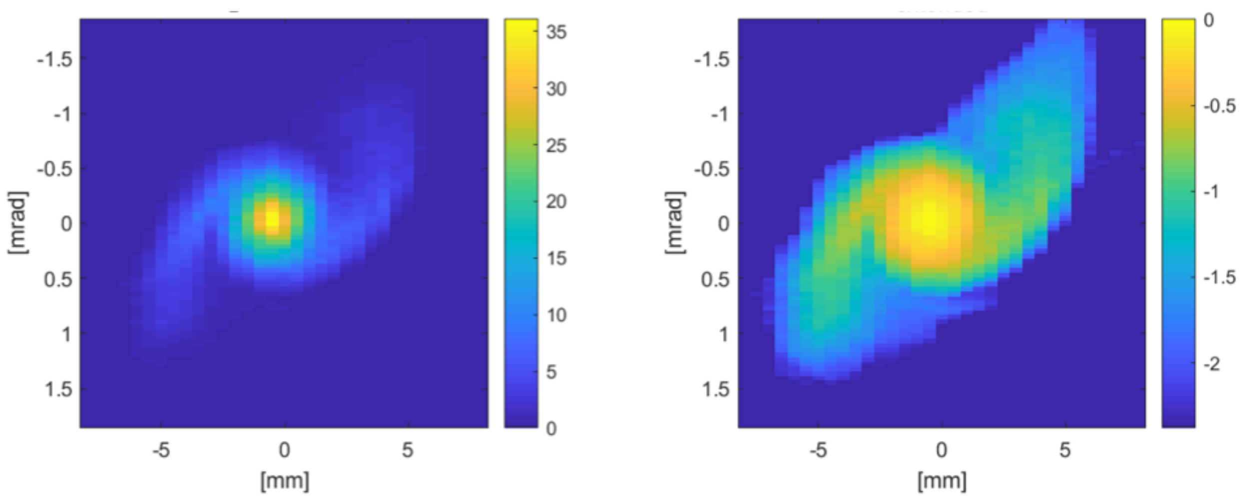
The four panels show the same distribution with different threshold applied for noise suppression.

Laser wire direct emittance measurement at high energy is an option for H- beam

- Slits cannot be used at high energy
- Laser wire is an option for H- beam
- No known option for proton beam



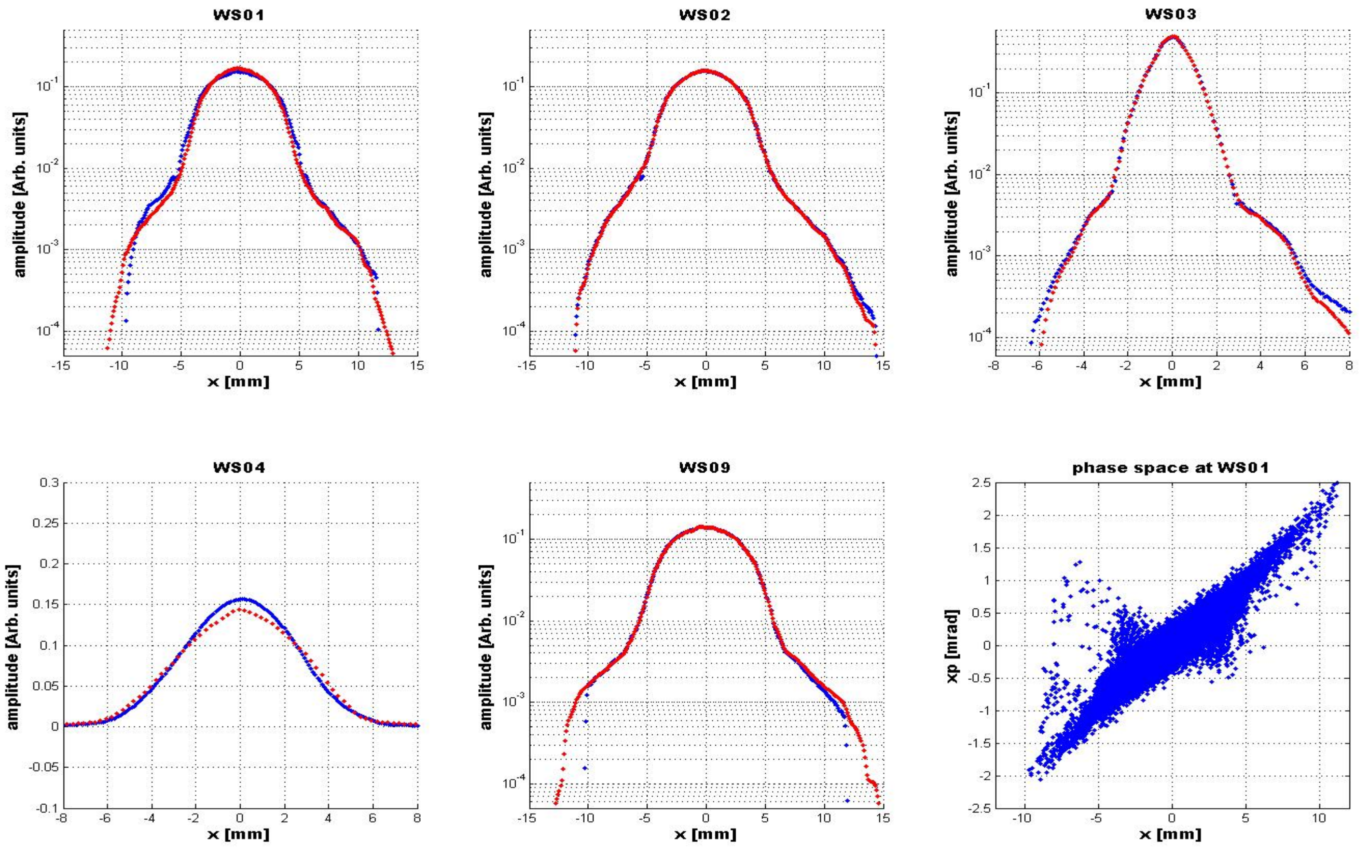
Layout of SNS laser wire emittance scanner



Horizontal emittance of a 1GeV beam measured using the SNS laser emittance scanner. The same data are shown in linear (left) and logarithmic (right) scale.

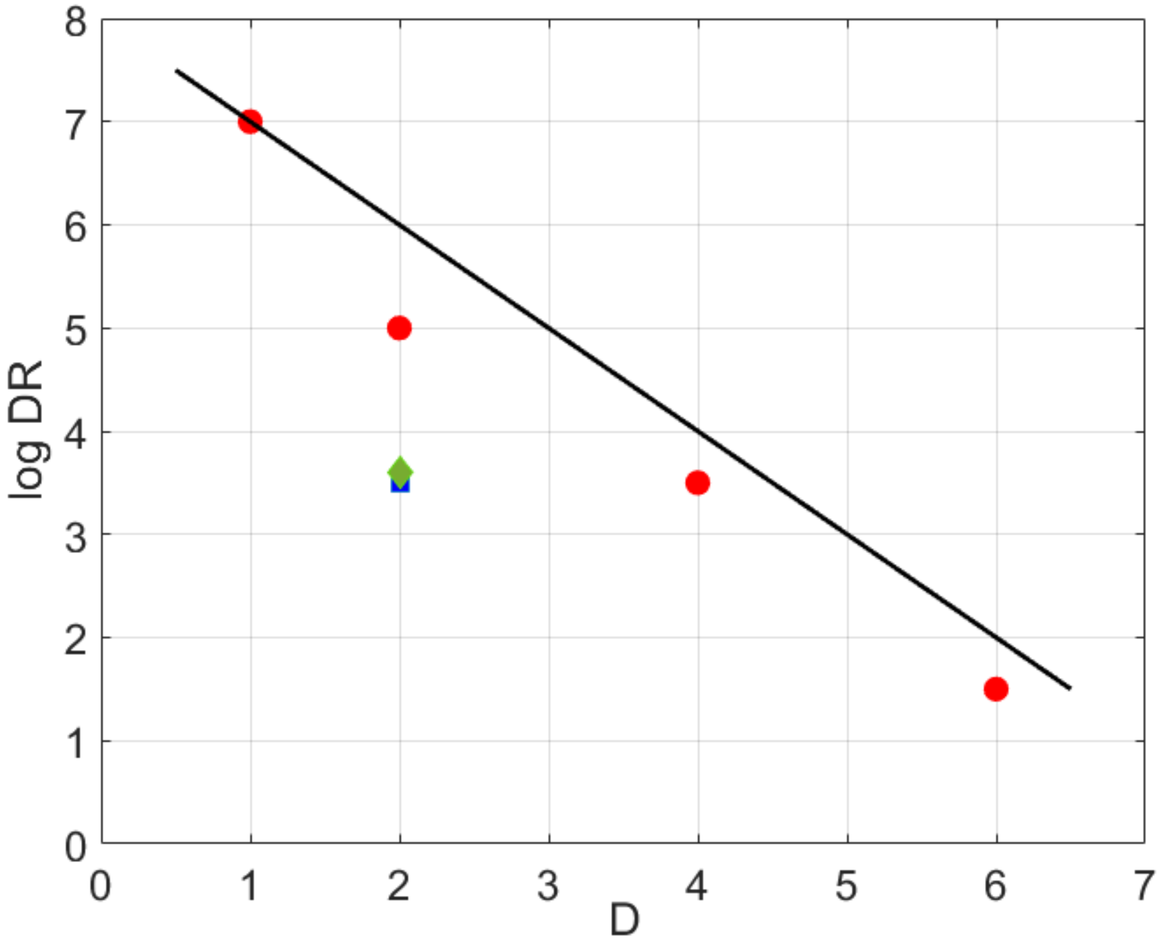
High dynamic range phase-space tomography is an option for high energy proton beam

- Wire scanners can provide high dynamic range 1-d profiles, $> 10^5$
- An algorithm is required to reconstruct 2-d or 4-d distribution with correspondingly high dynamic range
- Iterative application of MENT algorithm showed promising results



An example of high dynamic range phase-space tomography reconstruction.
The measured proton beam profiles at several wire scanners are shown in red.
The corresponding profiles calculated from the reconstructed 2-d distribution are shown in blue.
The reconstructed 2-dimensional distribution is shown in the bottom right panel.

General relation between the measurement dynamic range and dimensionality of the scan.



Examples of what is experimentally demonstrated in today's state-of-the art measurements are shown by the markers:

red circles - the SNS BTF multi-dimensional scanner,

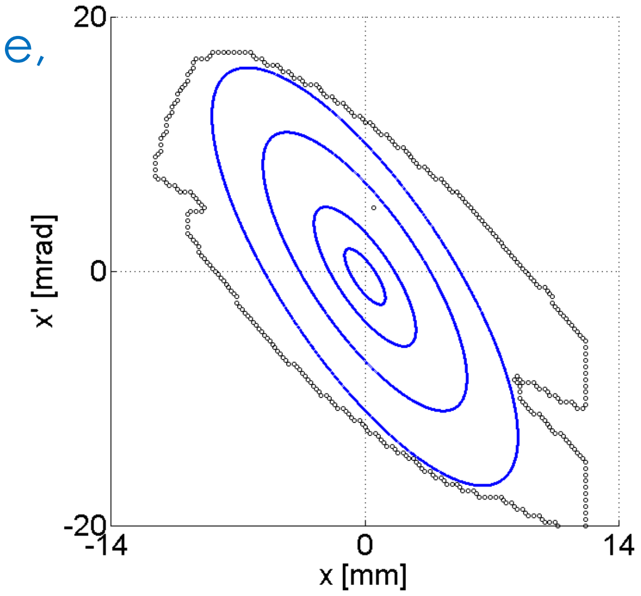
blue square - the SNS 1GeV laser emittance scanner,

green diamond - the phase-space tomography reconstruction from 1D wire scanner profiles

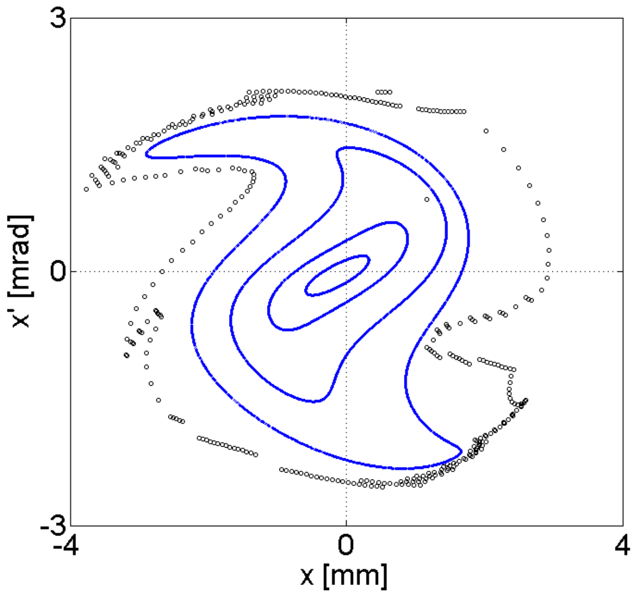
‘A-Z scan’ is a tool to measure non-linear transport map from injector to any point in linac

Layout of A-Z scan

- Transport map is measured in wide range, up to acceptance boundary
- Transport map can be measured to multiple points in a linac simultaneously
- Measurement is essentially non-interceptive
- No special hardware is needed in linac



Phase space at 2.5MeV



Phase space at 1GeV

Timeline

- Multi-dimensional scan at 2.5MeV
  - 10x10x3 plan.
    - Increase dynamic range by x10, decrease scan time by x10 over 3 years
- Laser wire 2-d emittance measurement at 1GeV
  - Achieve 10^4 dynamic range by end of 2020
  - Uncharted territory after that; no reliable timeline
- High dynamic range phase-space tomography
  - On back burner due to lack of manpower; no reliable timeline
- A-Z scan
  - Add measurement point between warm and cold linacs by end of 2020
  - Continue adding measurements points over next few years

Potential Challenges and Delays

- Making sense out of 6-d data can be insurmountable challenge
- Extending laser emittance dynamic range beyond 10^4 is uncharted territory, can be prohibitively difficult

- SNS BTF uses spare SNS RFQ; potentially can have long operation interruptions if RFQ swap is needed

Ties-In with Grand Challenges

Grand challenge #1 (beam intensity): How do we increase beam intensities by orders of magnitude?

To increase intensity by an order of magnitude in a hadron linac, we need to **control losses an order of magnitude better**.

Grand challenge #3 (beam control): How do we control beam distribution down to individual particles?

To control a distribution we need to learn how to measure it down to individual particles

Grand challenge #4 (beam prediction): How do we develop predictive “virtual accelerators”?

Content of previous slides

Relationship to HEP, NP, and BES Missions

Broadly applicable to anyone with a hardon linac, but, specifically:

HEP: Relationship to HEP mission is in the Intensity Frontier

BES: Relationship to BES mission is also intensity frontier for future proton driver applications

NP: Relationship to NP is in intensity frontier for future hadron drivers and heavy ion linacs

Resources for Project

- Who?
  - Right now, SNS team
  - Anyone with a linac or front-end test facility can work on diagnostics R&D
  - Anyone can work on high-dimensional data analysis algorithms and HDR phase space tomography
- Where:
  - Right now, SNS Beam Test Facility and SNS linac
- Facilities Needed:
  - Medium Energy Test Accelerators
    - SNS
    - Fermilab
    - LANL, BNL ?