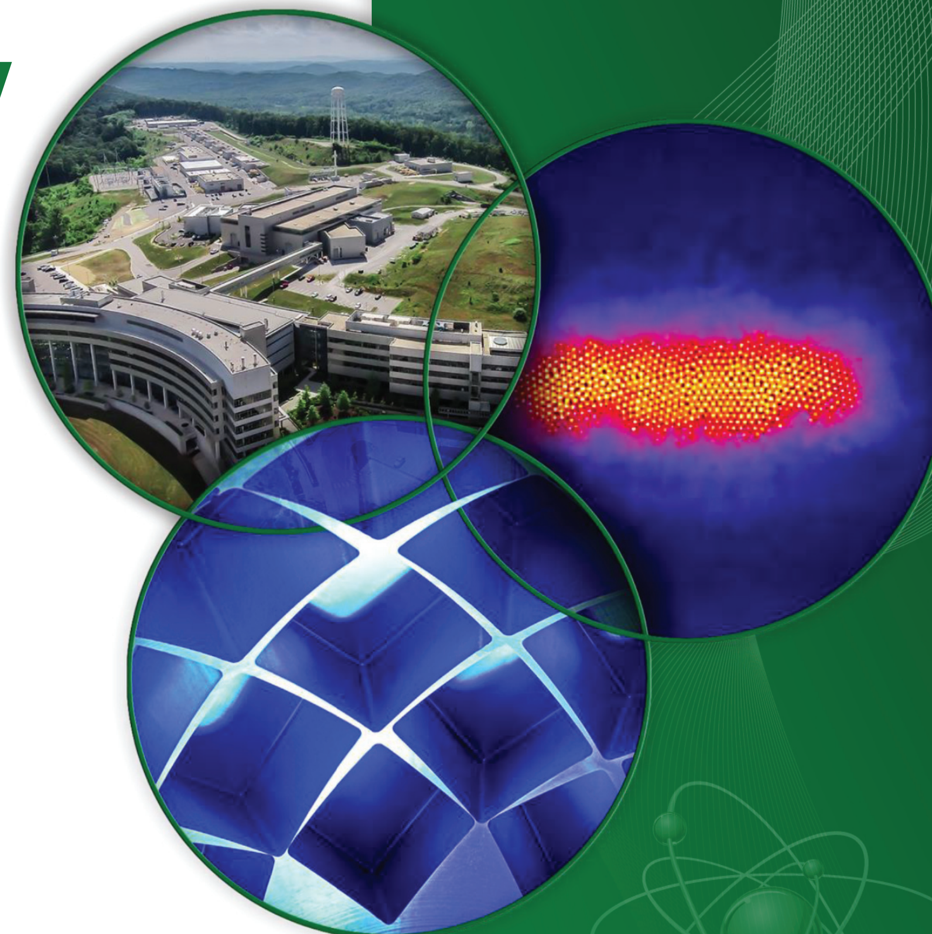
Beam Halo Characterization and Mitigation



Alexander Aleksandrov

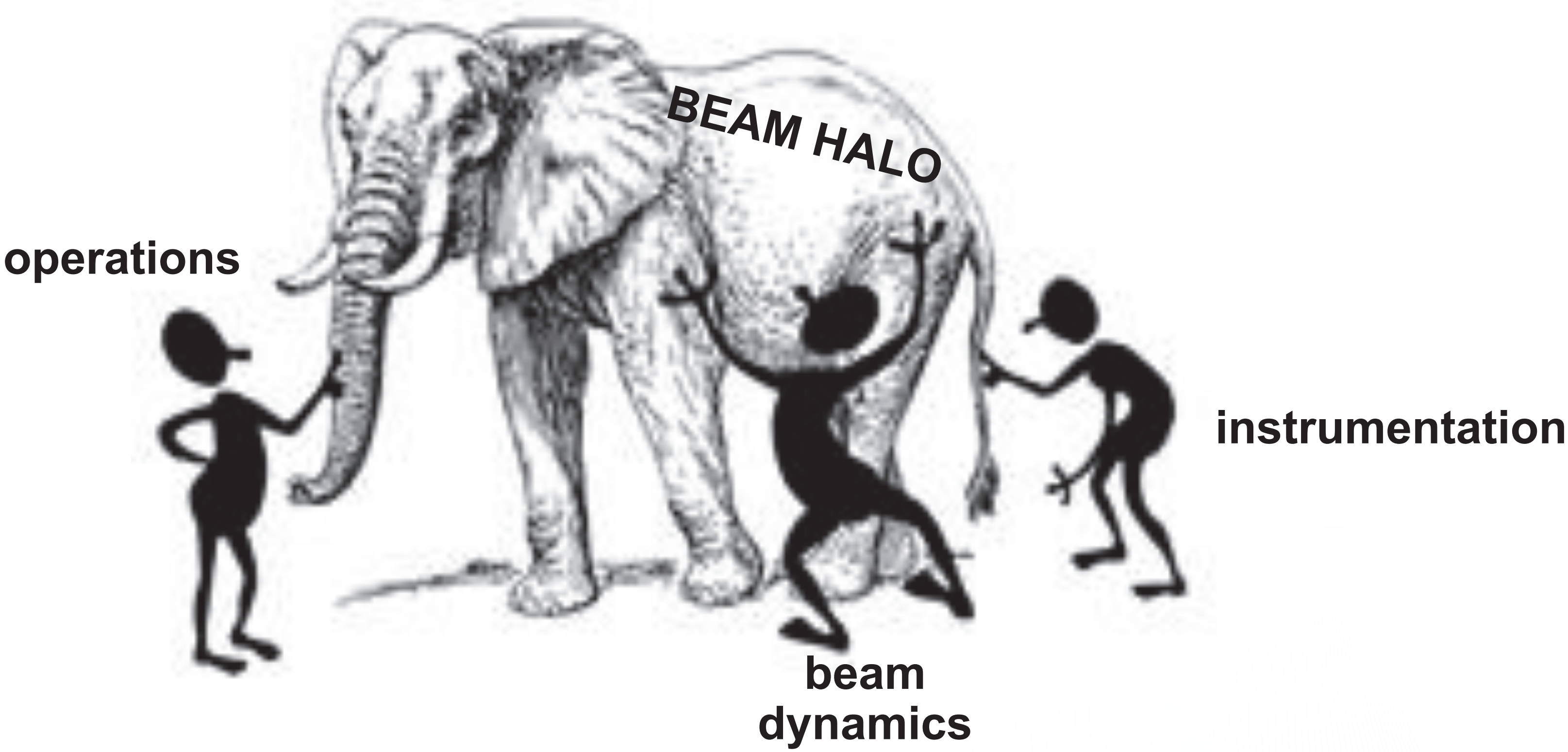
Spallation Neutron Source

Oak Ridge National Laboratory,

USA

ORNL is managed by UT-Battelle
for the US Department of Energy

OAK RIDGE National Laboratory | SPALLATION NEUTRON SOURCE


BEAM HALO
operations
instrumentation
beam
dynamics

Main points of my talk

- Halo measurements

- Halo characterization

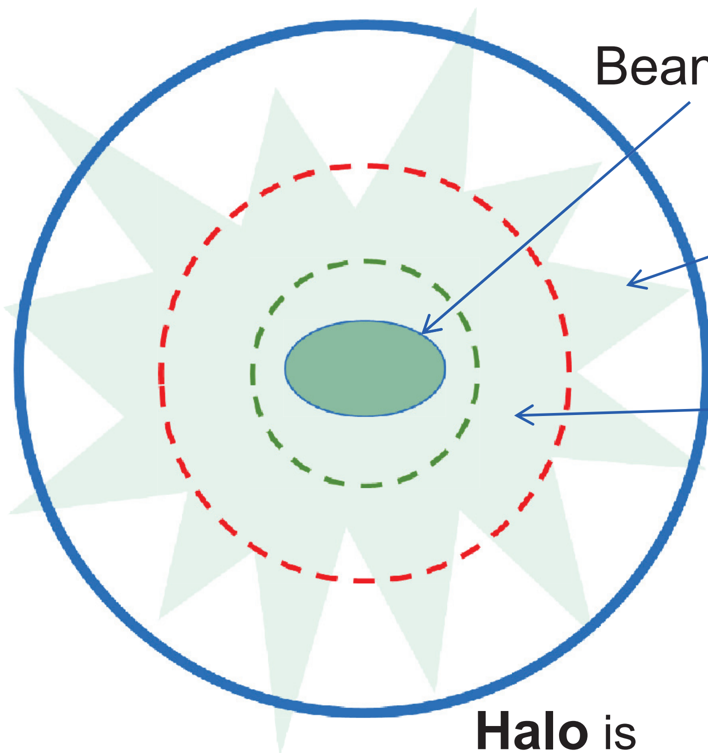
- Halo mitigation

Main points of my talk

- Halo measurements
  - Have been demonstrated since 10-15 years ago at many accelerators by different techniques for different particles
  - Have not become a routine operational diagnostics. Why?
- Halo characterization
  - Is this a missing link between measurement and mitigation?
- Halo mitigation
  - Various techniques are in use, proven by successful operation of high intensity accelerators
  - Typically, do not use halo measurement. Why?

~~Halo definition.~~ What we call 'halo'

- 29th ICFA Workshop on **Beam Halo Dynamics, Diagnostics, and Collimation**, Montauk, New York, 2003
- Workshop on **Beam Halo Monitoring**, at SLAC National Accelerator Laboratory following IBIC 2014



Beam core, $1 \div 10^{-2}$ of the peak density

Beam halo, $10^{-4} \div 10^{-6}$ of the peak density or lower

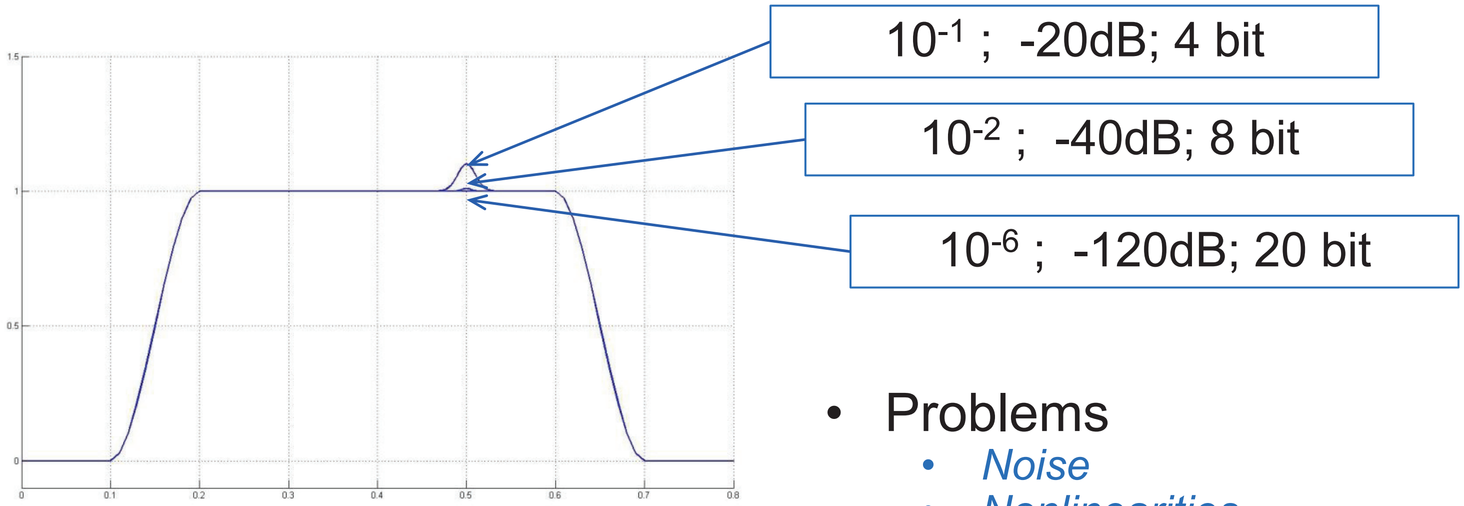
Distribution 'tail', 'shoulders', etc.

Halo is

Low intensity

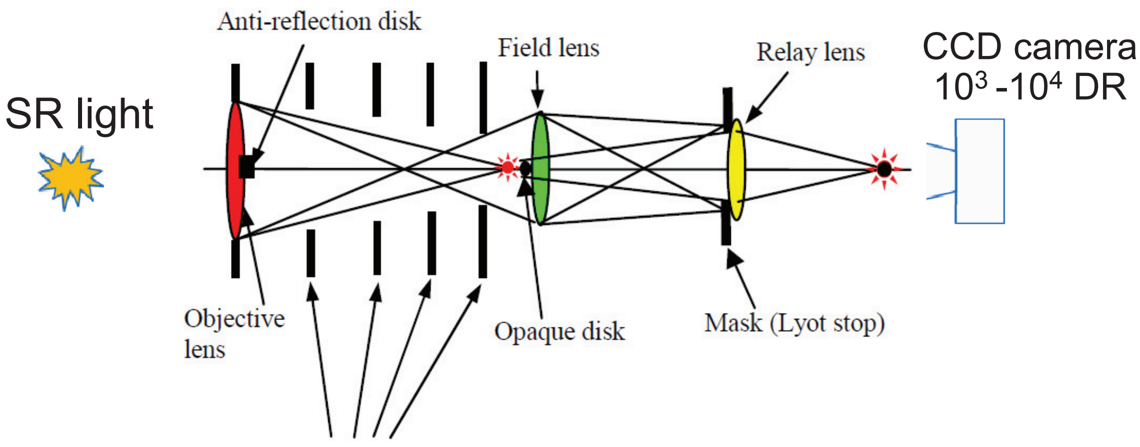
Far from core => creates problems => requires mitigation

Large Dynamic Range Measurement Problem

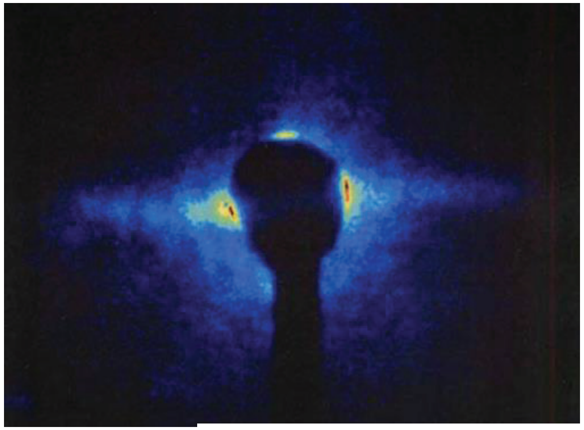


- Problems
  - *Noise*
  - *Nonlinearities*
  - *Reflections*
  - ….
- Mitigation
  - *Reduce all of the above*
  - *Separate high and low level signals*

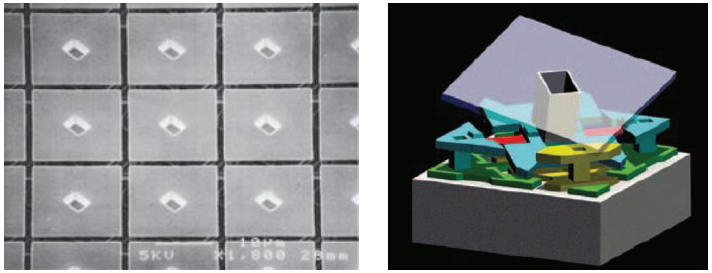
Halo measurement 1. *Beam-emitted light imaging*



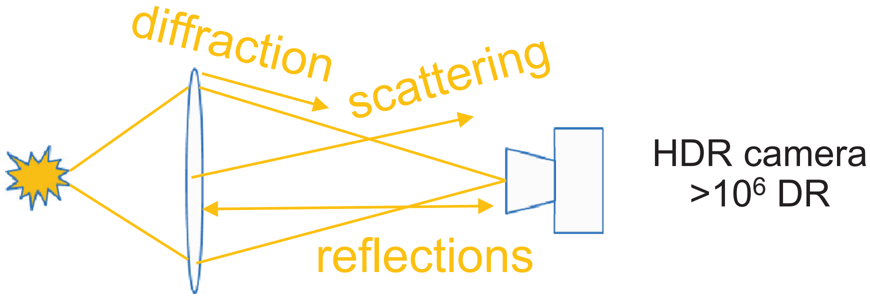
T. Mitsuhashi, Proceedings of DIPAC 2005, Lyon, France

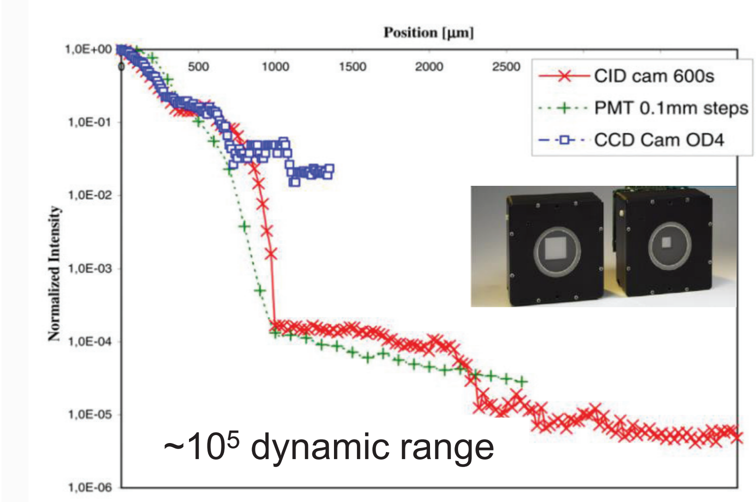


~10^6 dynamic range



DLP mirror array to form adjustable mask

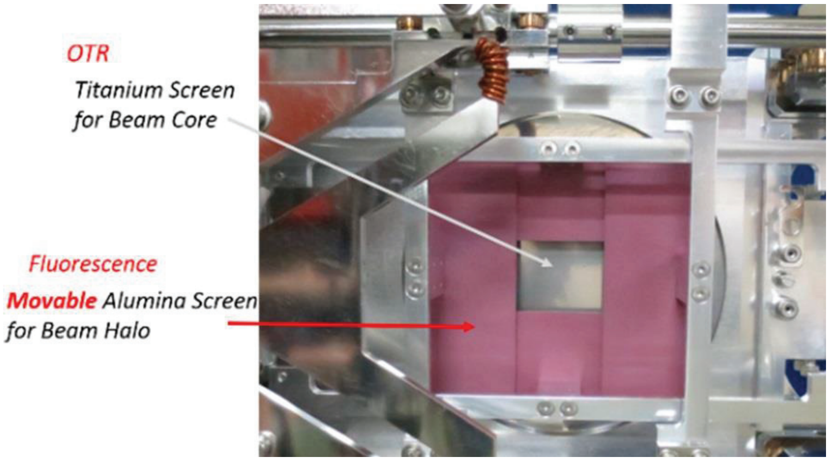


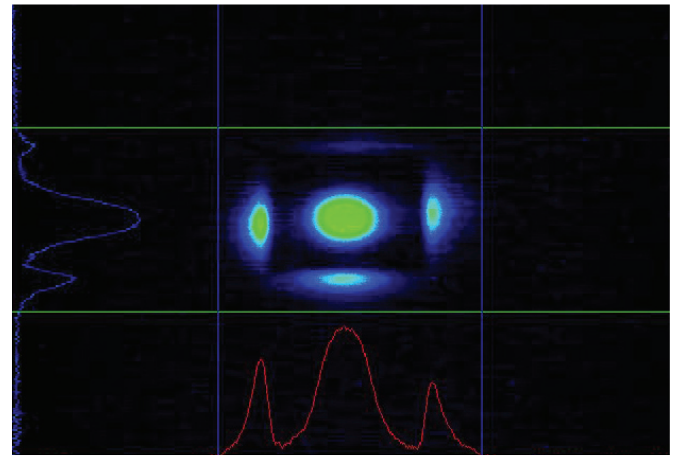


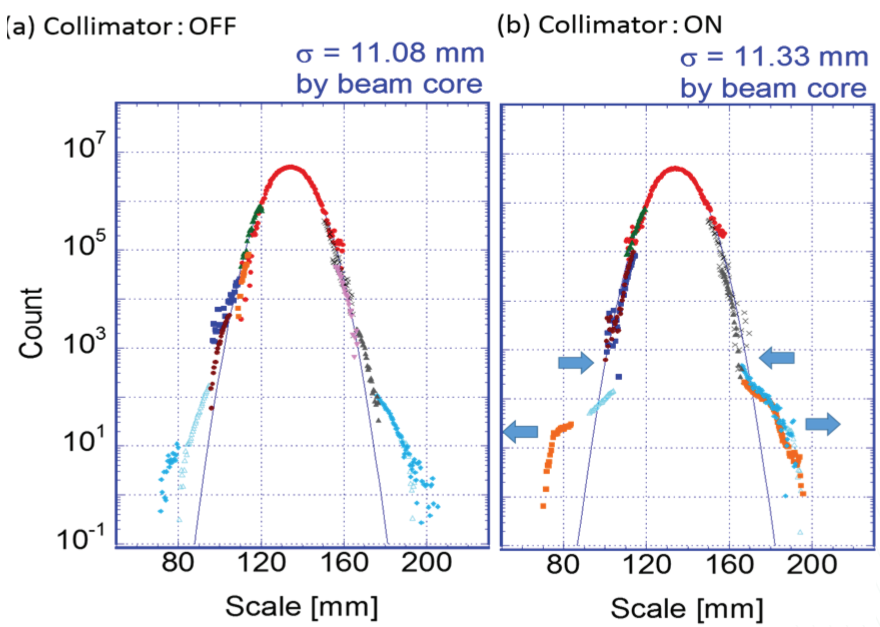
Proceedings of LINAC08, Victoria, BC, Canada

Halo measurement 2. *View screen*

Y. Hashimoto et al, Proceedings of HB2014, East-Lansing, MI, USA

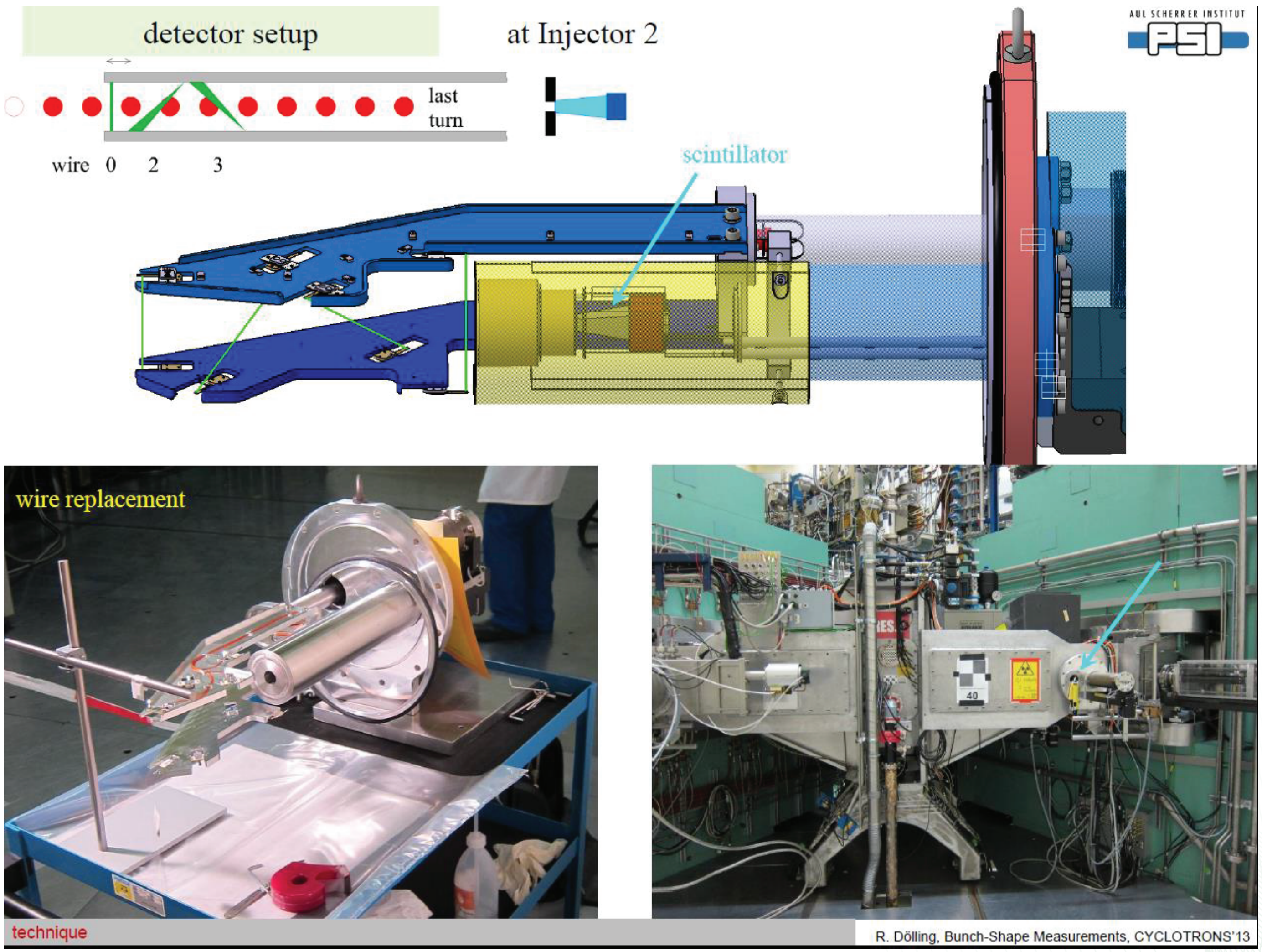






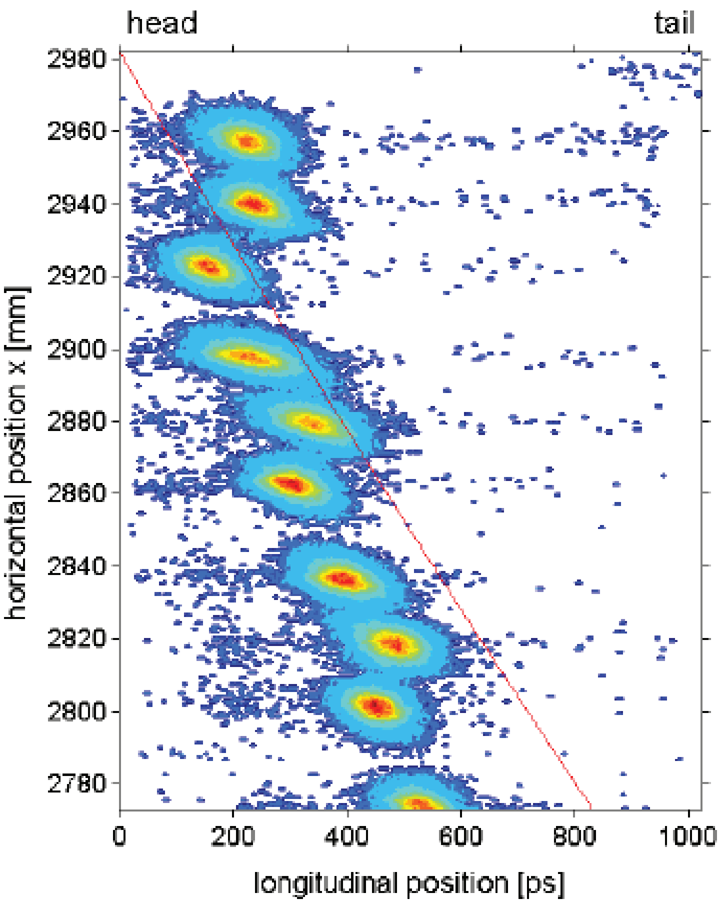
Interceptive diagnostics !

Halo measurement 3a. *Wire scanner + detector of scattered particles*

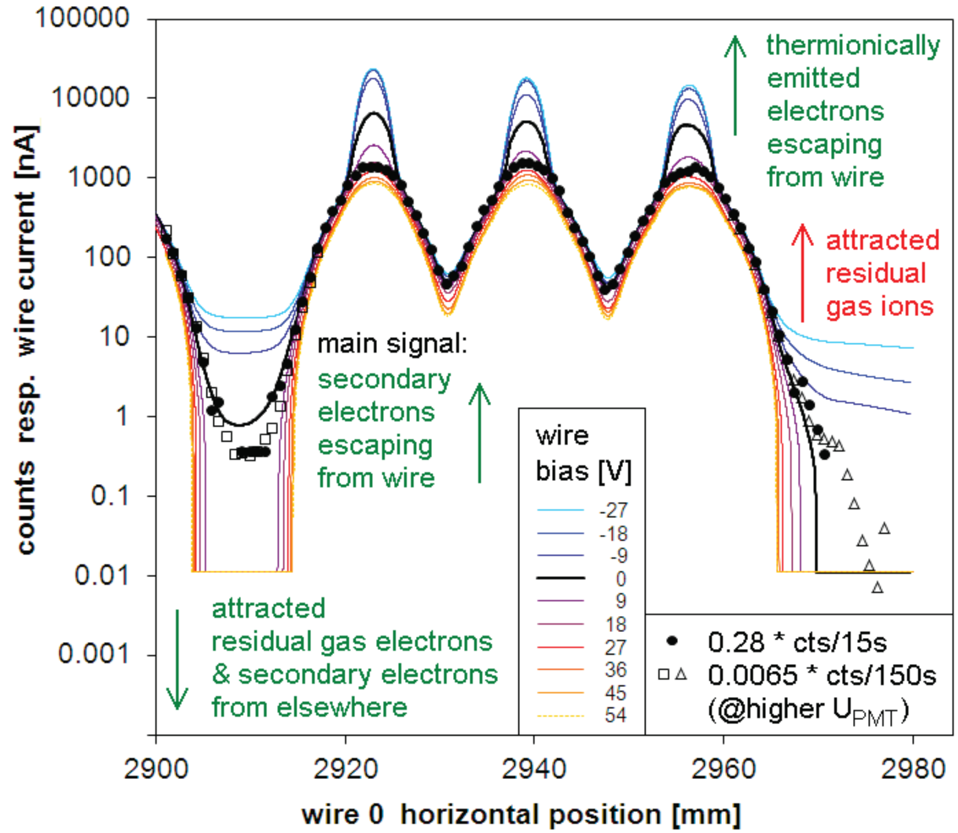


R. Dölling, Bunch-Shape Measurements, CYCLOTRONS'13

Example of large dynamic range and high temporal resolution profile measurements at PSI

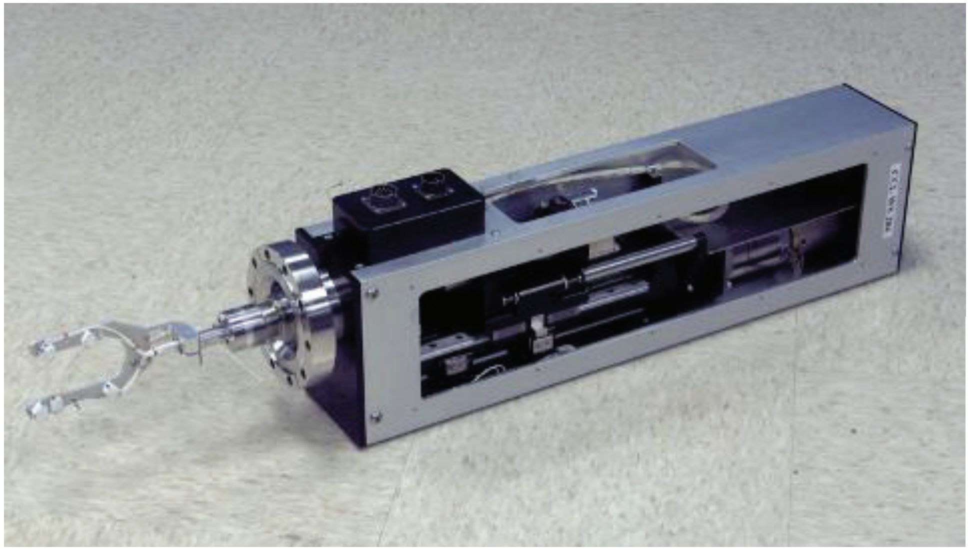


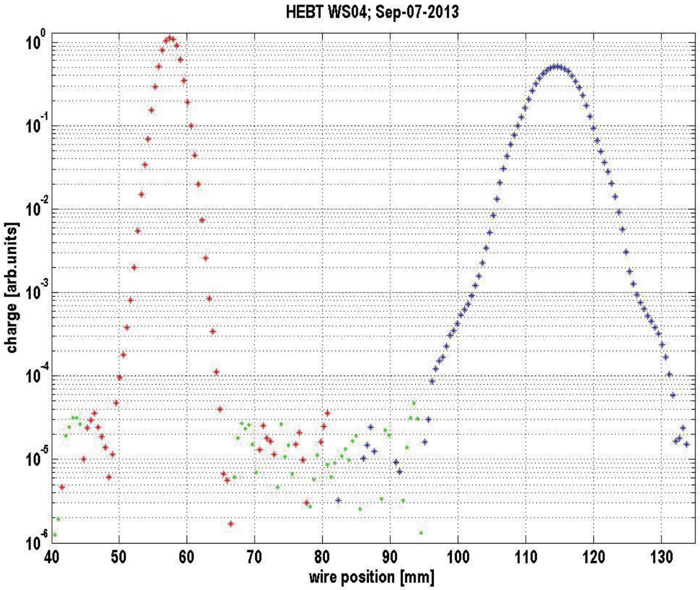
~15ps time resolution



~10^5 dynamic range

Halo measurement 3b. *Wire scanner + charge collection*





Factors limiting dynamic range:

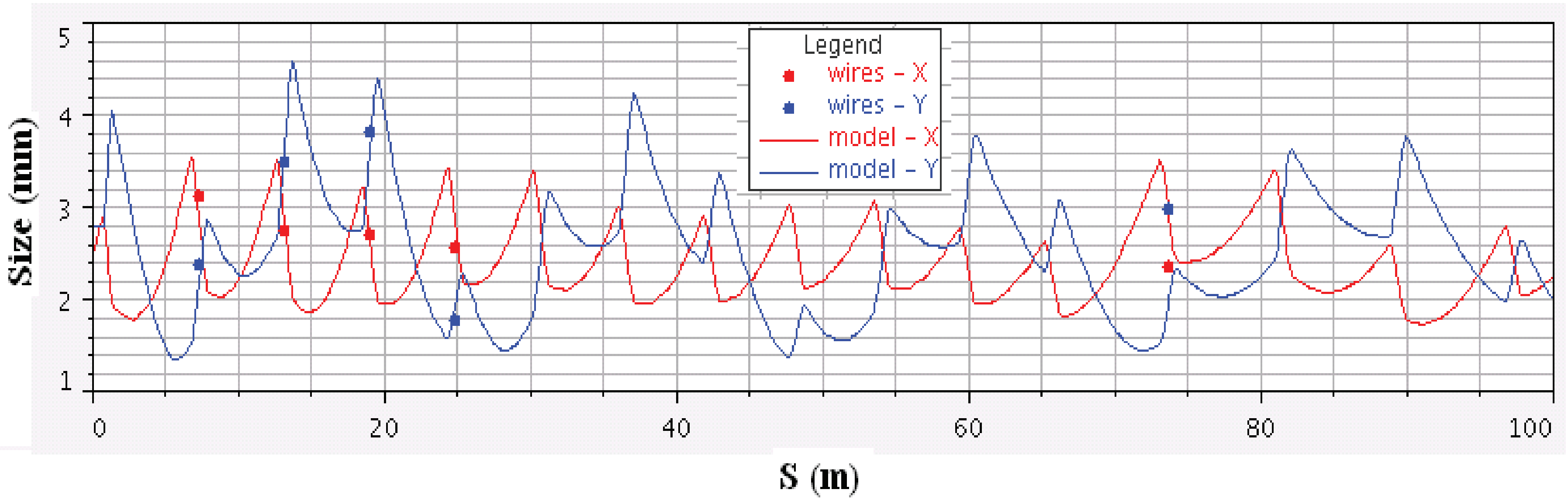
- *Capacitive coupling to beam core*
- *Residual gas ionization*
- *Nearby beam loss*

Dynamic range: ~10^5 BW: ~1kHz

Large dynamic range profile measurements are difficult, intellectually challenging and fun to do

What about usefulness for halo mitigation?

- Is profile right thing to measure?
- How can we use them?



OAK RIDGE National Laboratory | SPALLATION NEUTRON SOURCE

Use of 1D profiles: Root Mean Square (RMS) beam size formalism

$$a'' + K_x(s)\,a - \frac{\varepsilon_x^2}{a^3} - \frac{K_{sc,x2}}{a} = 0$$

RMS envelope equation

$$a = x_{RMS} = < x^2 > = \sigma_{xx}$$

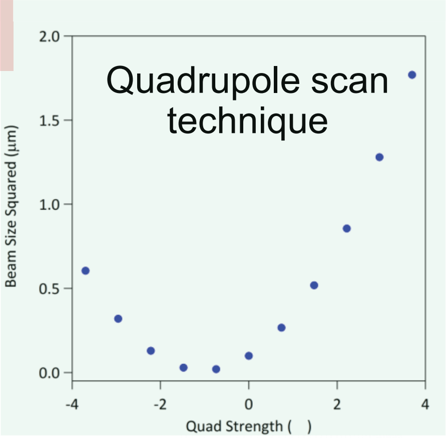
$$\bar{\sigma} = \begin{bmatrix} \sigma_{xx} & \sigma_{x'x} \\ \sigma_{xx'} & \sigma_{x'x'} \end{bmatrix} \qquad \bar{\sigma}_1 = R\bar{\sigma}_0 R^T$$

Beam σ-matrix formalism

$\alpha_{RMS}, \beta_{RMS}$

ε_{RMS}

RMS Twiss parameters



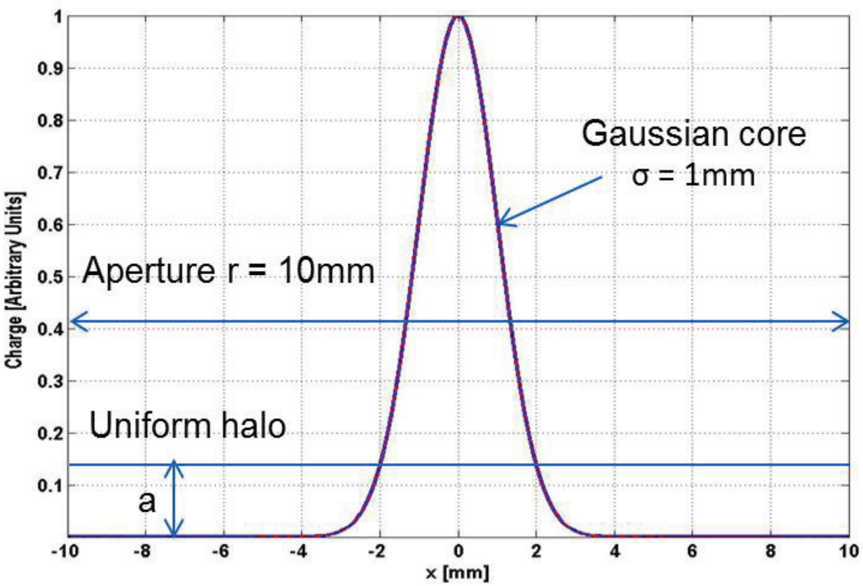
Various techniques e.g. quad scan

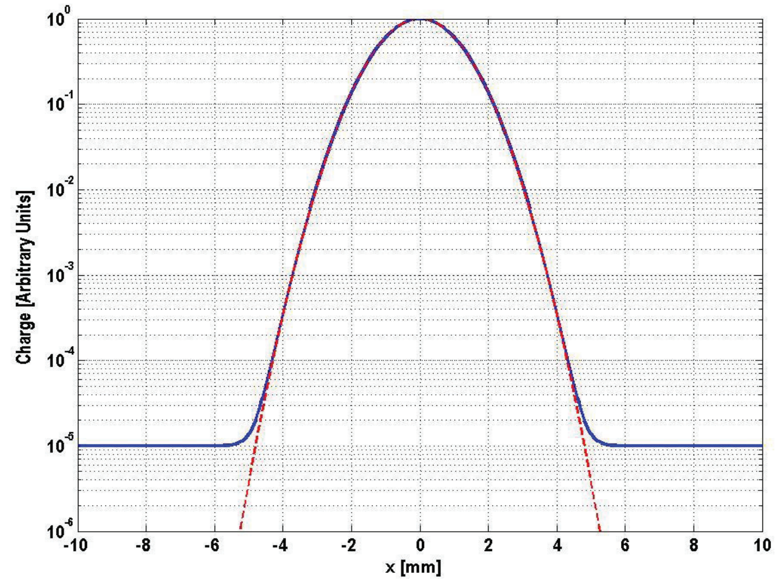
Measure 1D projection (profile) → Calculate RMS Twiss parameters → Calculate RMS envelope size elsewhere

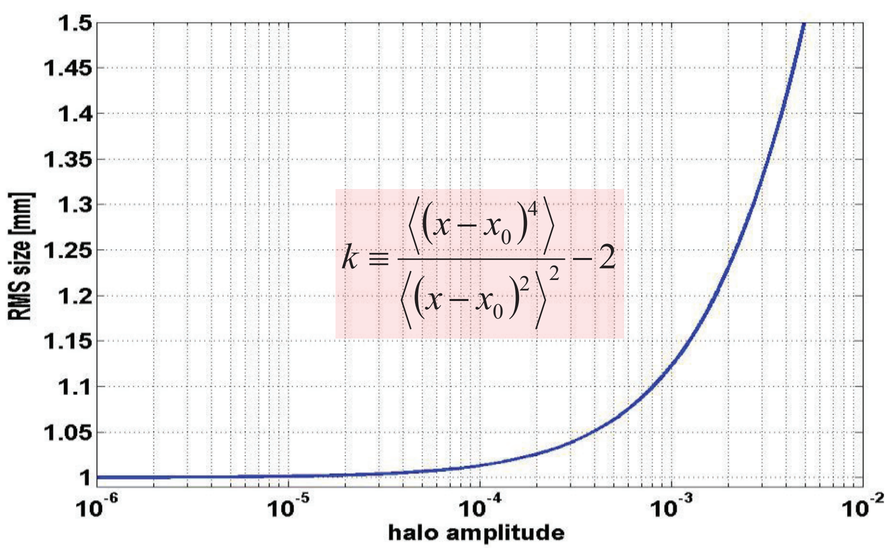
Location independent beam characterization

ε_{RMS}

Can we use RMS formalism for halo?

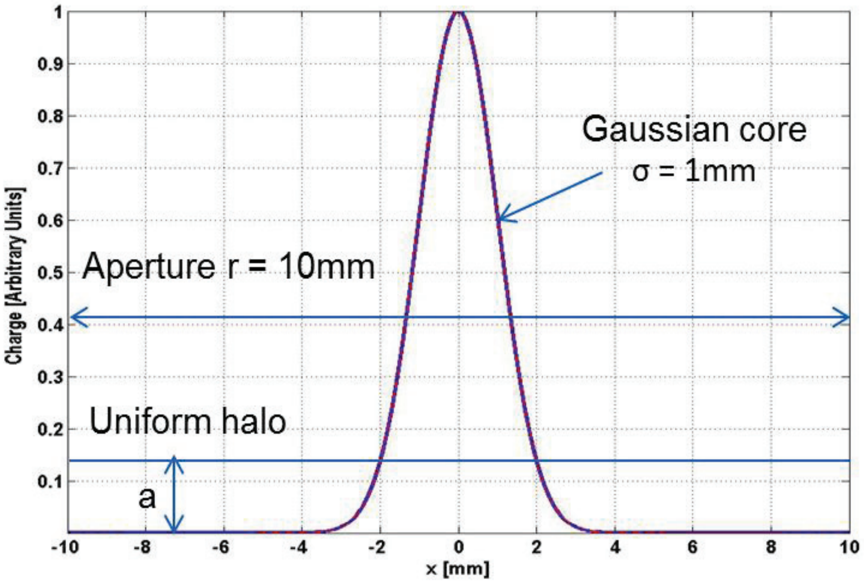


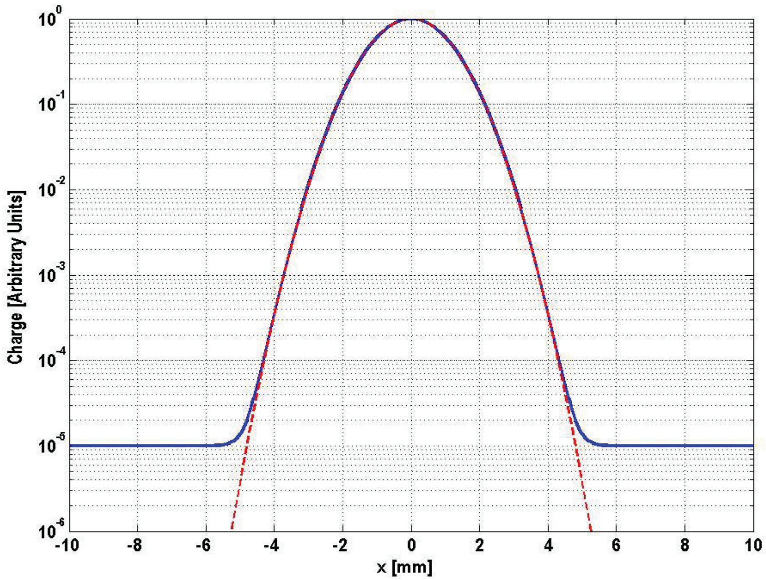


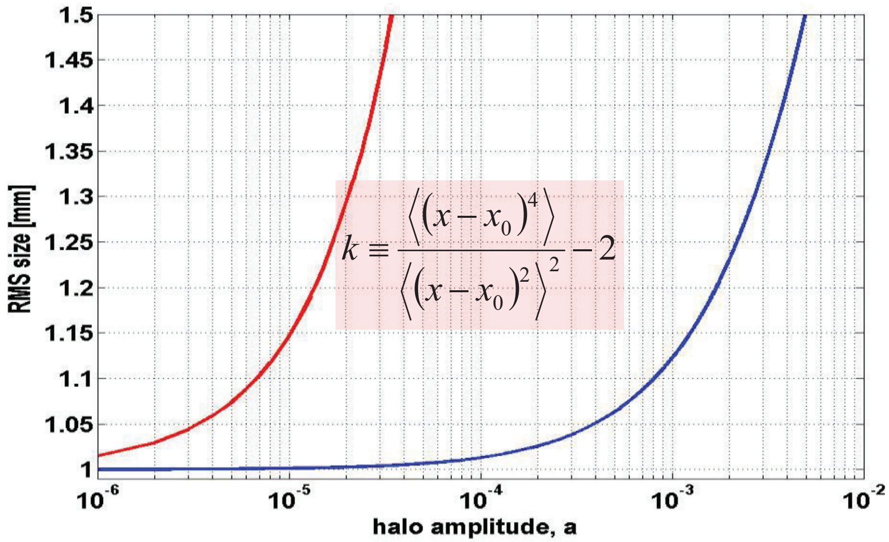


OAK RIDGE National Laboratory | SPALLATION NEUTRON SOURCE

Can we use RMS formalism for halo?

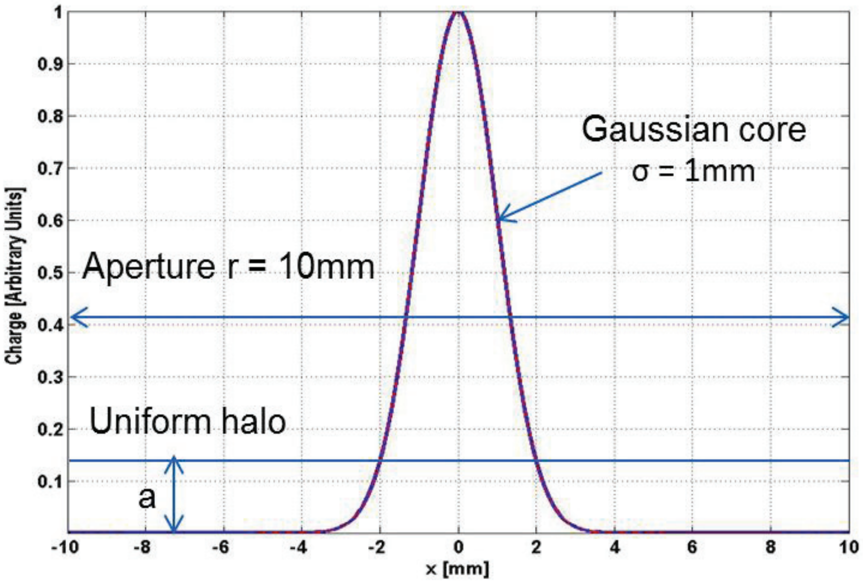


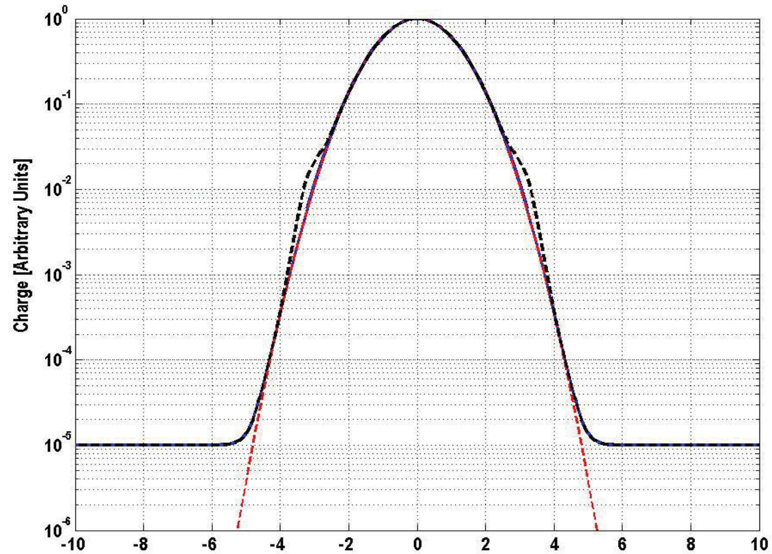


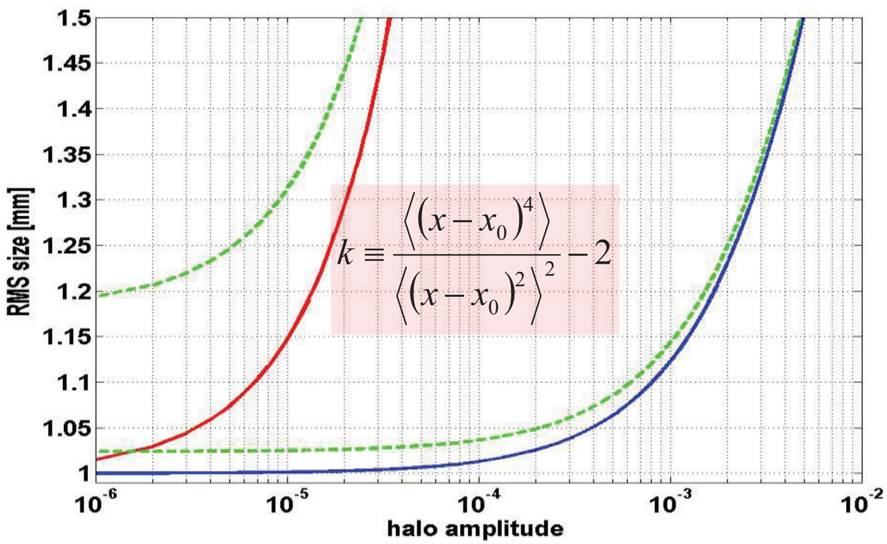


OAK RIDGE National Laboratory | SPALLATION NEUTRON SOURCE

Can we use RMS formalism for halo?



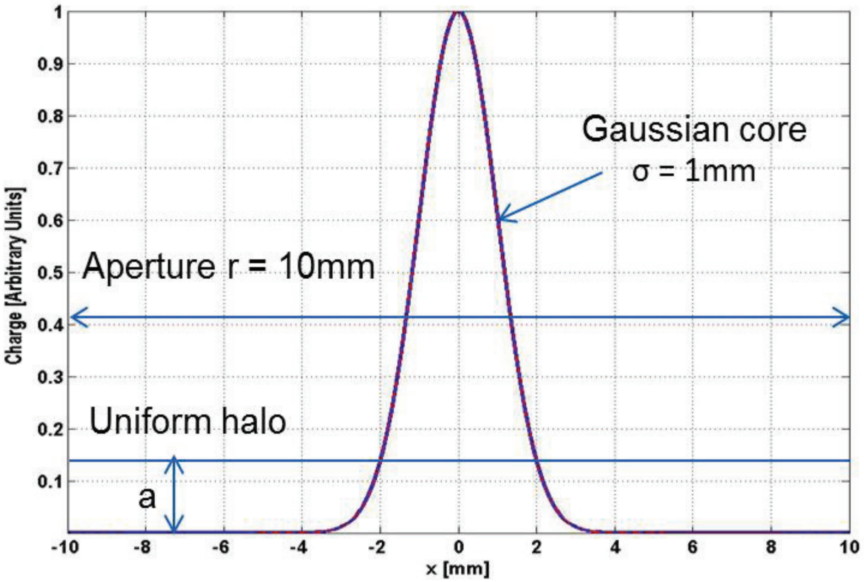


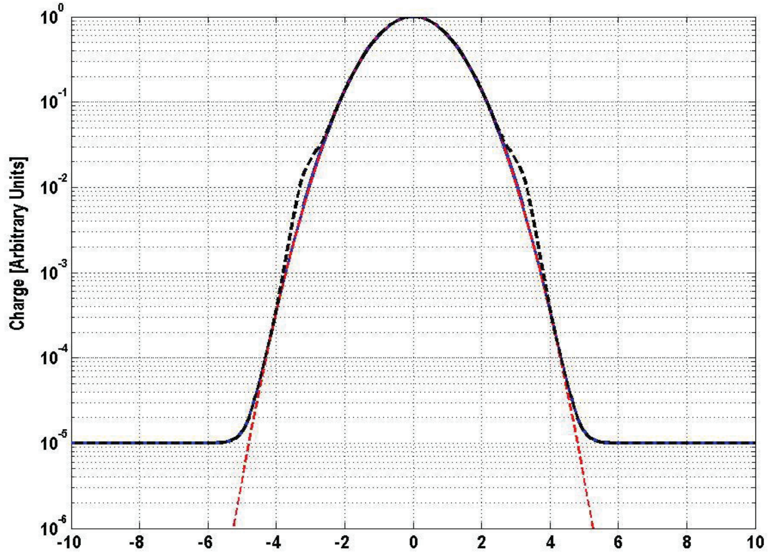


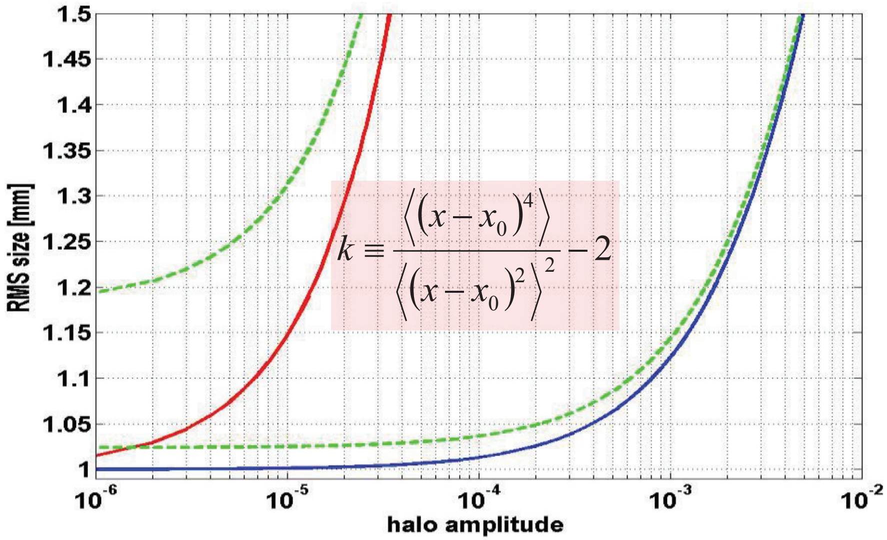
$$k \equiv \frac{\left\langle (x - x_0)^4 \right\rangle}{\left\langle (x - x_0)^2 \right\rangle^2} - 2$$

OAK RIDGE National Laboratory | SPALLATION NEUTRON SOURCE

Can we use RMS formalism for halo?





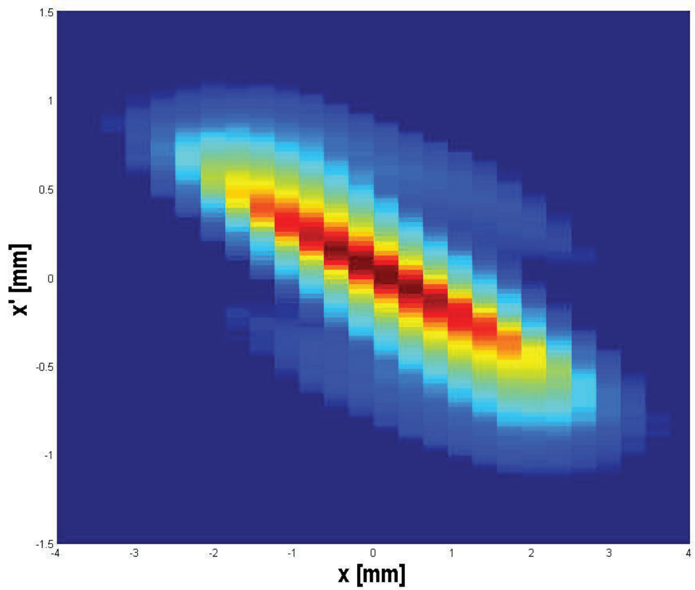


- RMS beam size is **insensitive** to halo
- RMS and higher order moments are very sensitive to profile details at the core boundary
- There is no known equation for propagating higher order moments

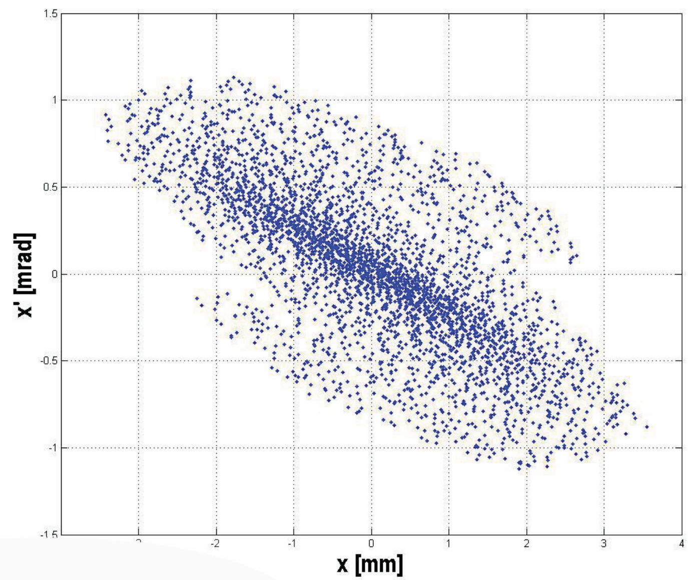
Particle-In-Cell codes instead of RMS envelope

2D phase space projection instead of 1D profile

PIC codes require detailed particle distribution as input,
which can be produced from measured phase space projections

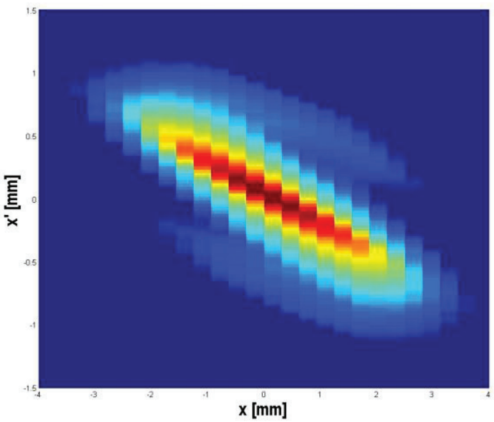


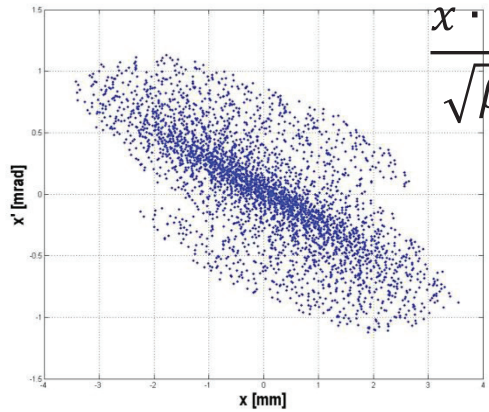
measurement

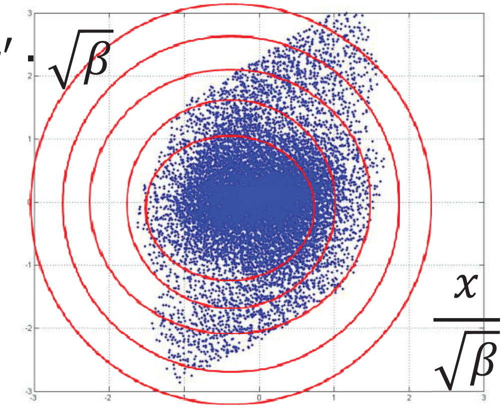


characterization

Example of possible 'global' characterization: phase space density plot instead of RMS emittance







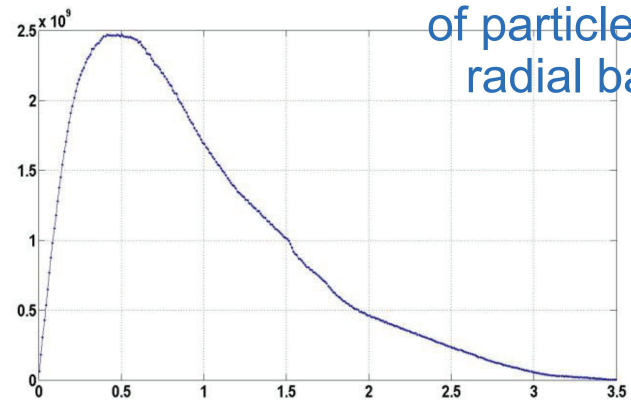
$$\frac{x \cdot \alpha}{\sqrt{\beta}} + x' \cdot \sqrt{\beta}$$

$$\frac{x}{\sqrt{\beta}}$$

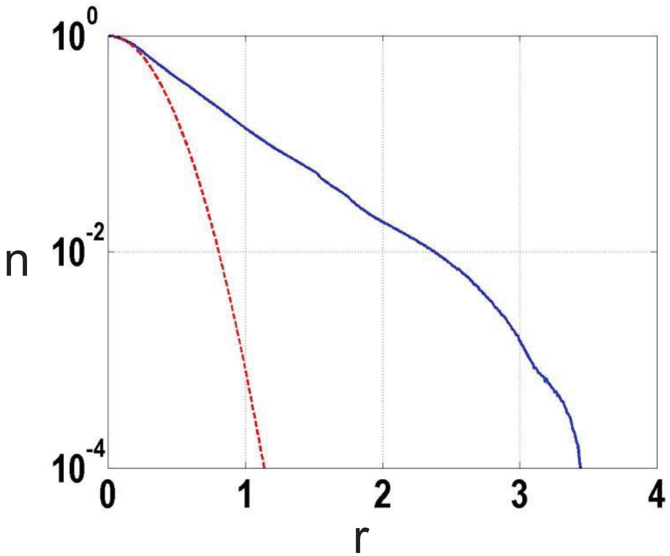
measure → generate particles → Transform to normalized coordinates

↓

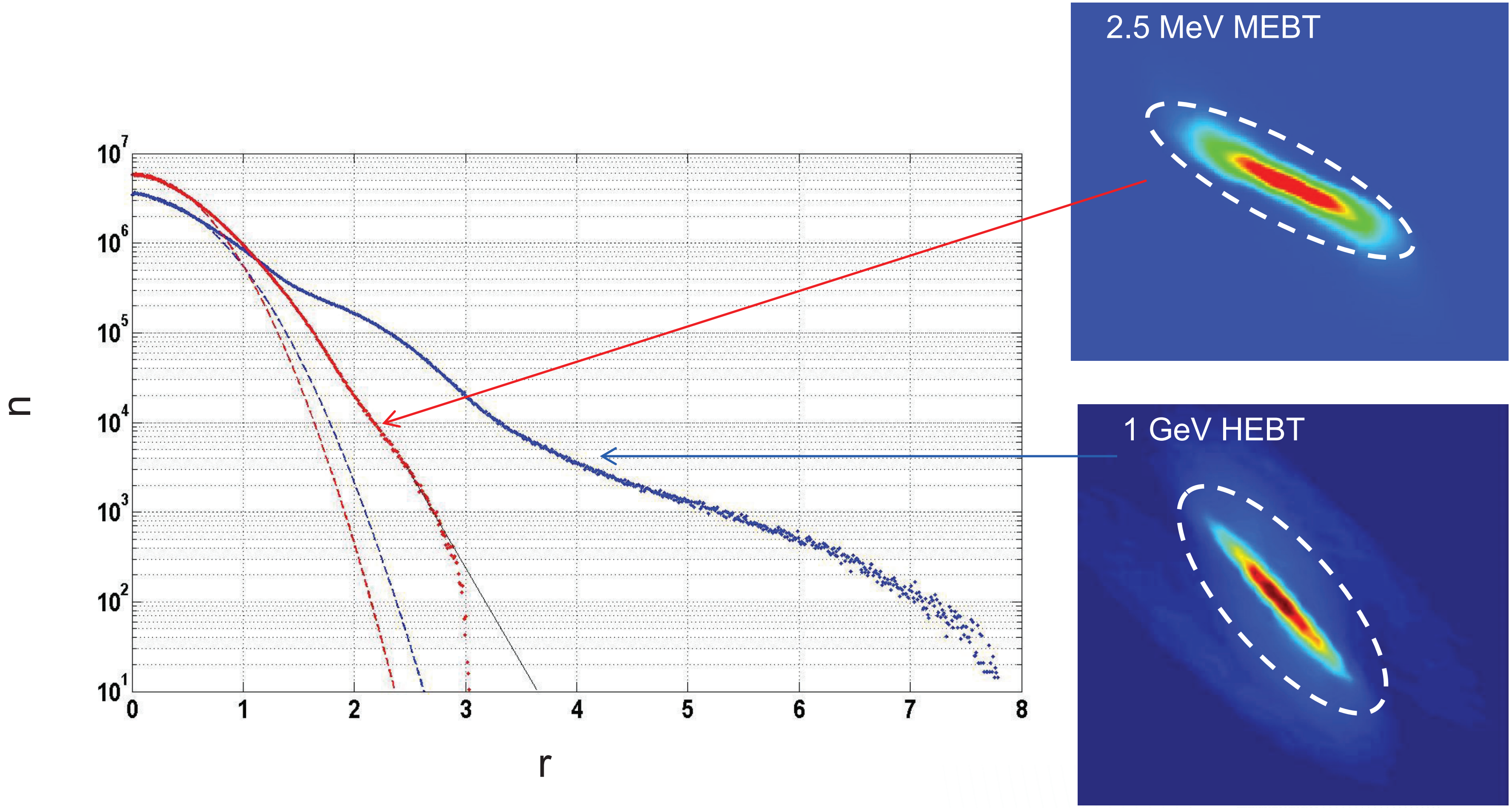
Count number of particles per radial band



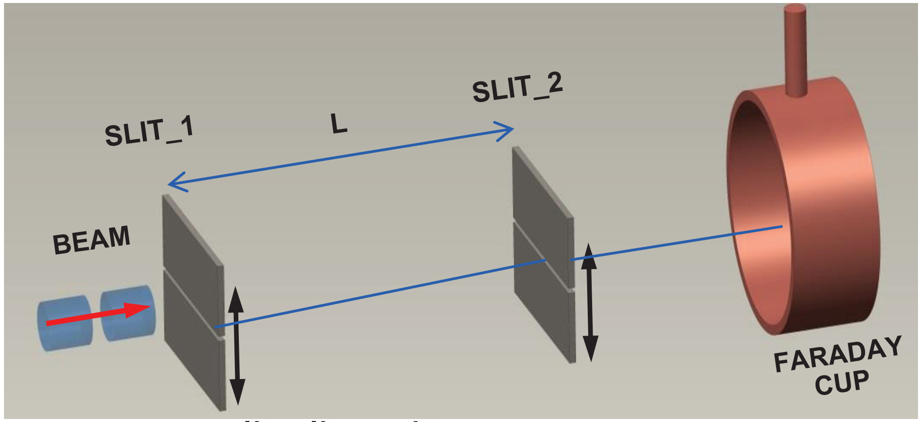
← Normalize by band area



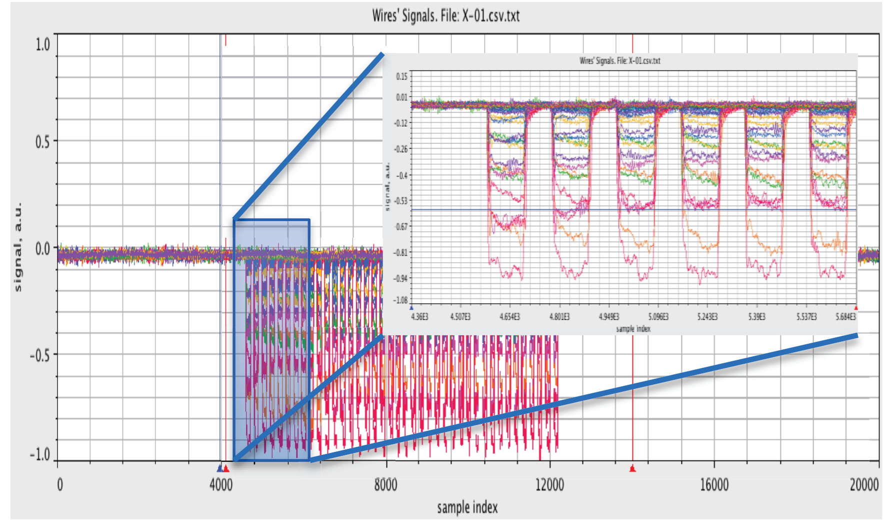
Example: comparison of phase space density measured at SNS MEBT and HEBT

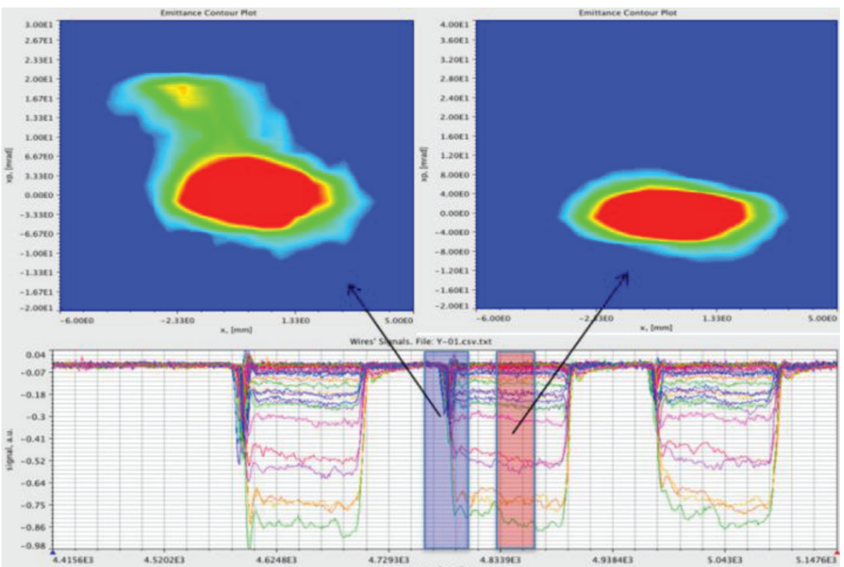


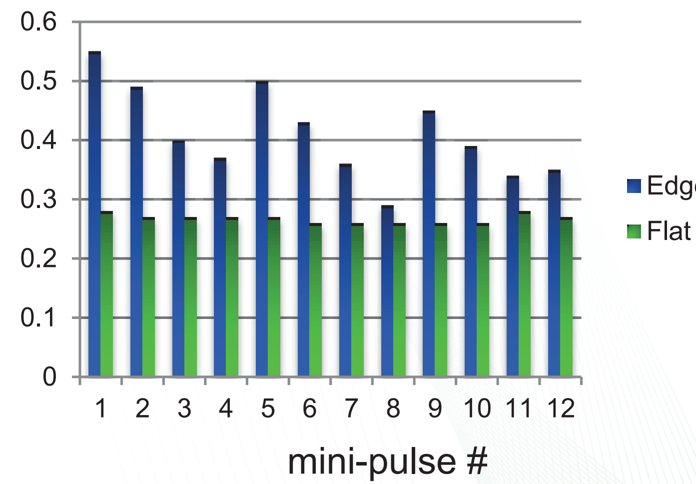
Measuring 2D phase space at low energy



slit-slit emittance scanner





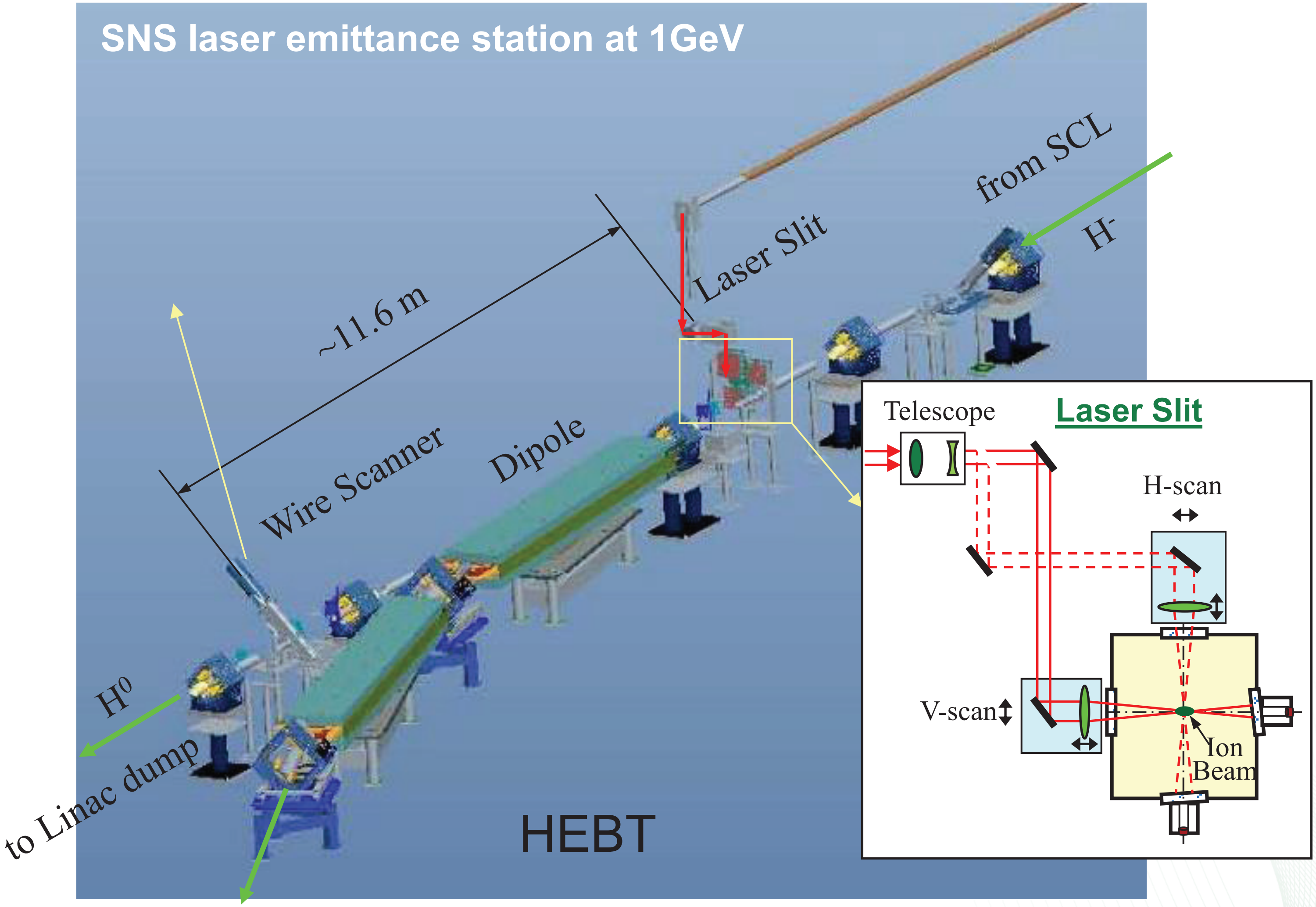


~ 10^5 dynamic range or 20ns temporal resolution

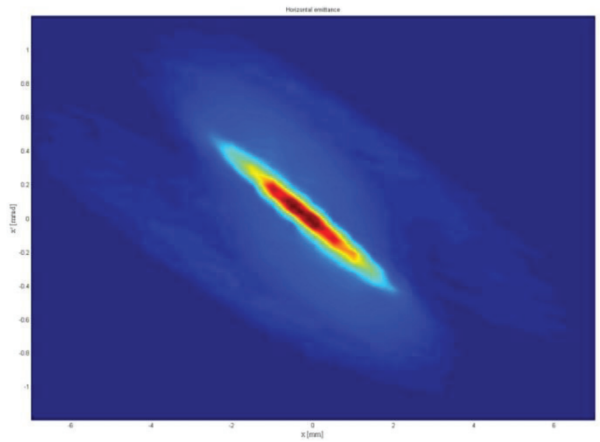
Courtesy of A. Zhukov, SNS

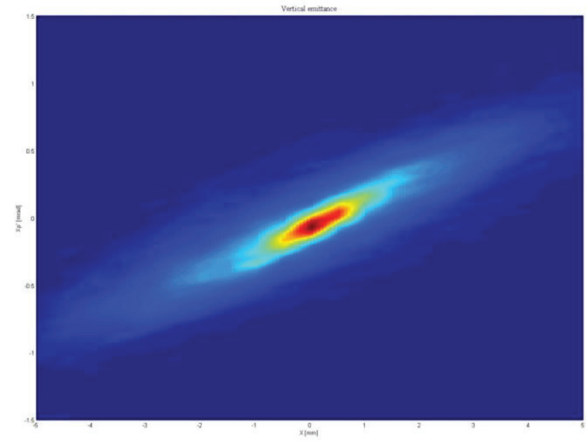
OAK RIDGE National Laboratory | SPALLATION NEUTRON SOURCE

Measuring 2-d at high energy: laser wire emittance measurement for H⁻ beam

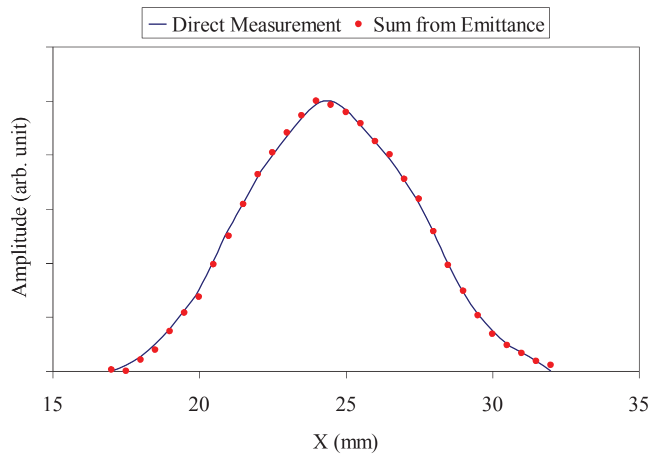


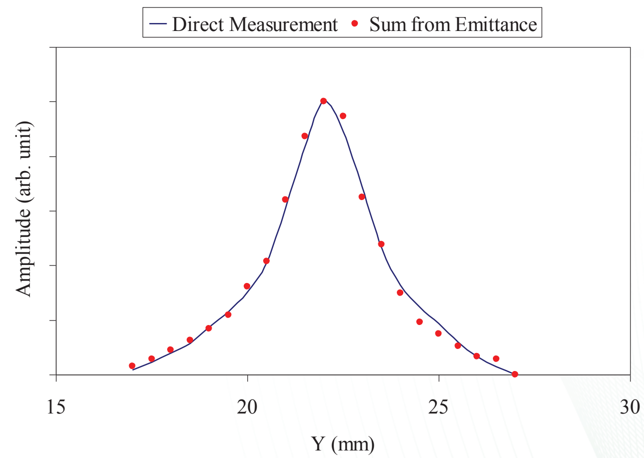
Courtesy of Y. Liu, SNS





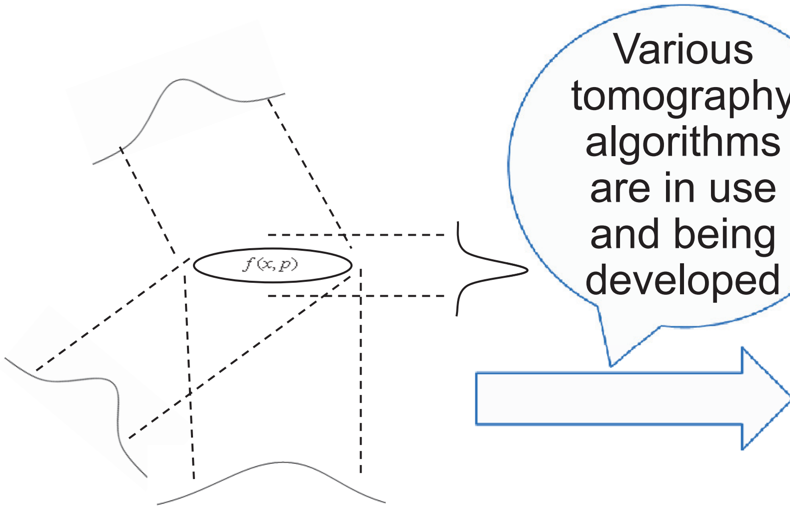
Self-consistency check – comparison between the integration of the emittance (over the angle) with the directly measured profiles

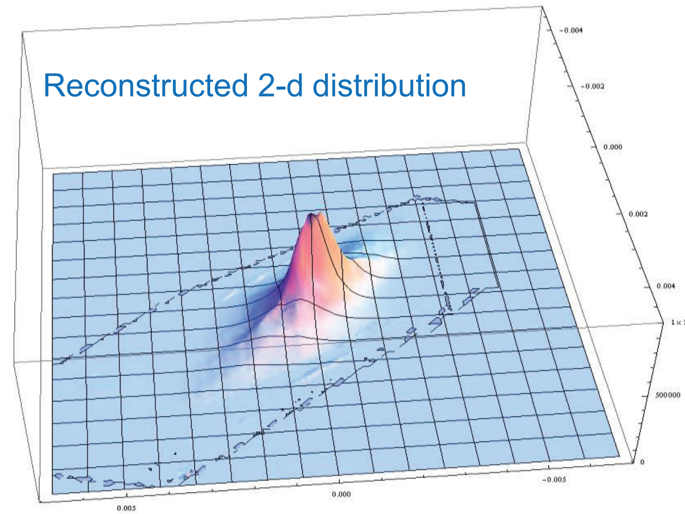




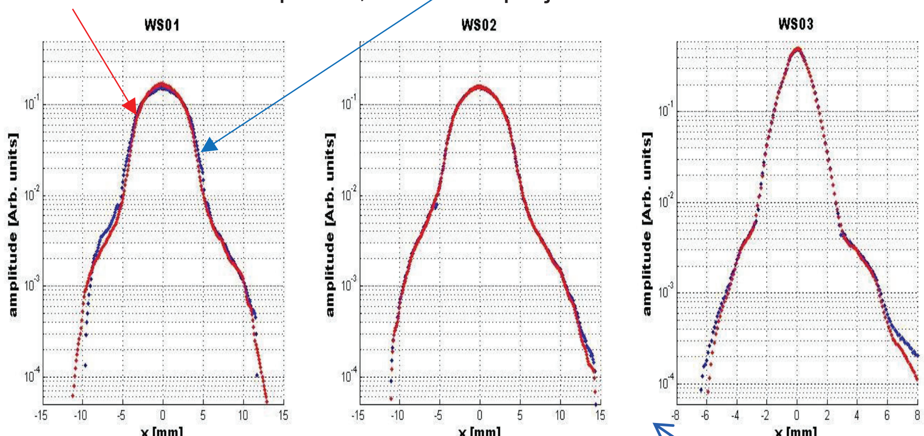
Fitting error: 2.2% ~ 10^3 dynamic range **Fitting error: 5.9%**

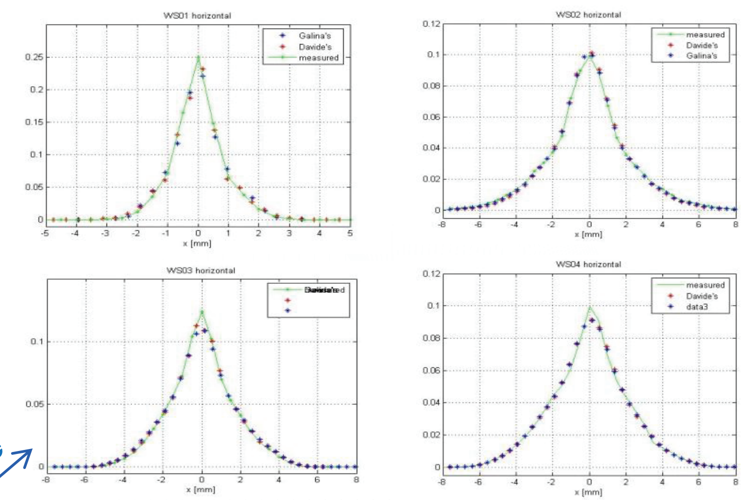
Reconstruction of 2D distributions from 1D profiles





red – measured profile; blue – projection of reconstructed 2D





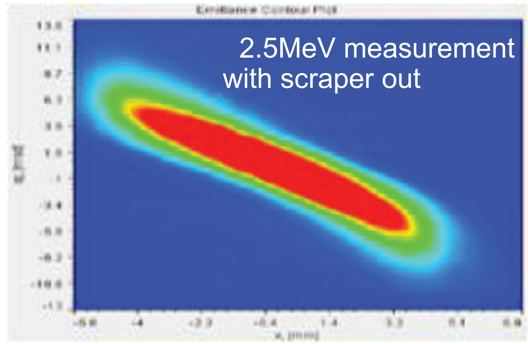
Log scale   Linear scale

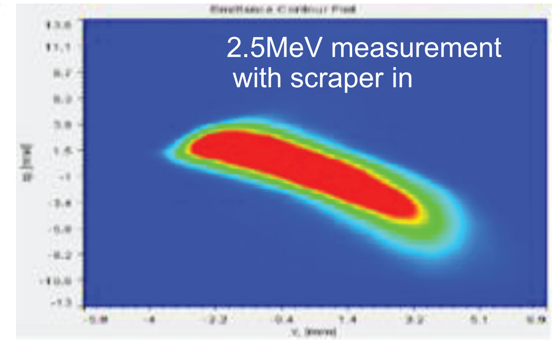
Courtesy of T. Gorlov, SNS

Comparison of measured and reconstructed profiles using modified MENT algorithm

OAK RIDGE National Laboratory | SPALLATION NEUTRON SOURCE

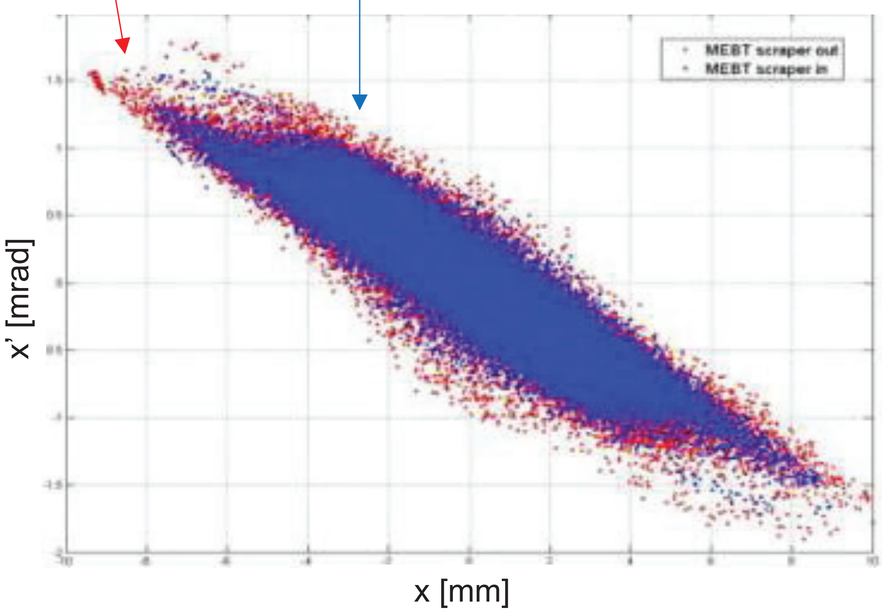
2D reconstruction example: SNS 1GeV HEBT

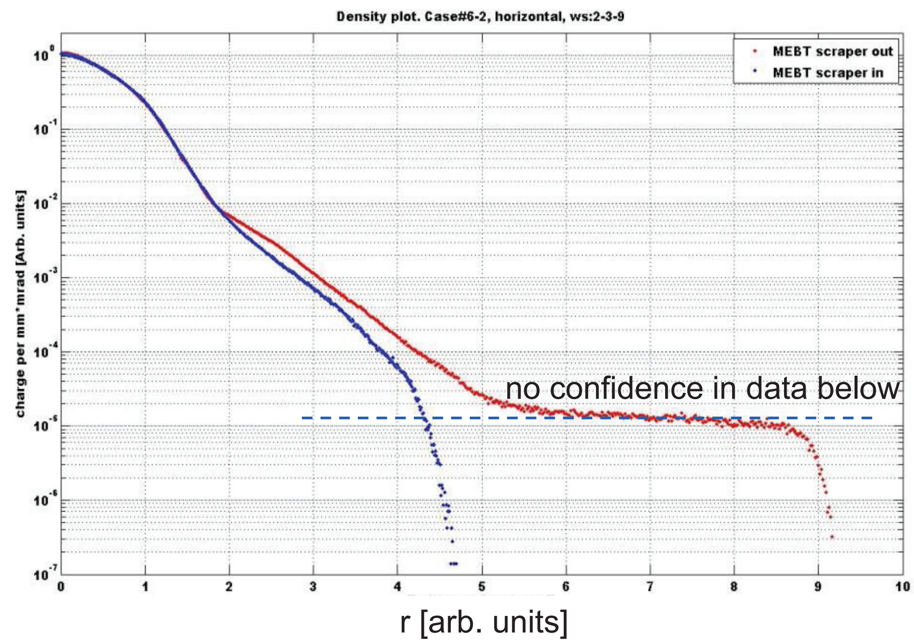




Red - no scrapers inserted

Blue – left scraper inserted in 2.5MeV MEBT



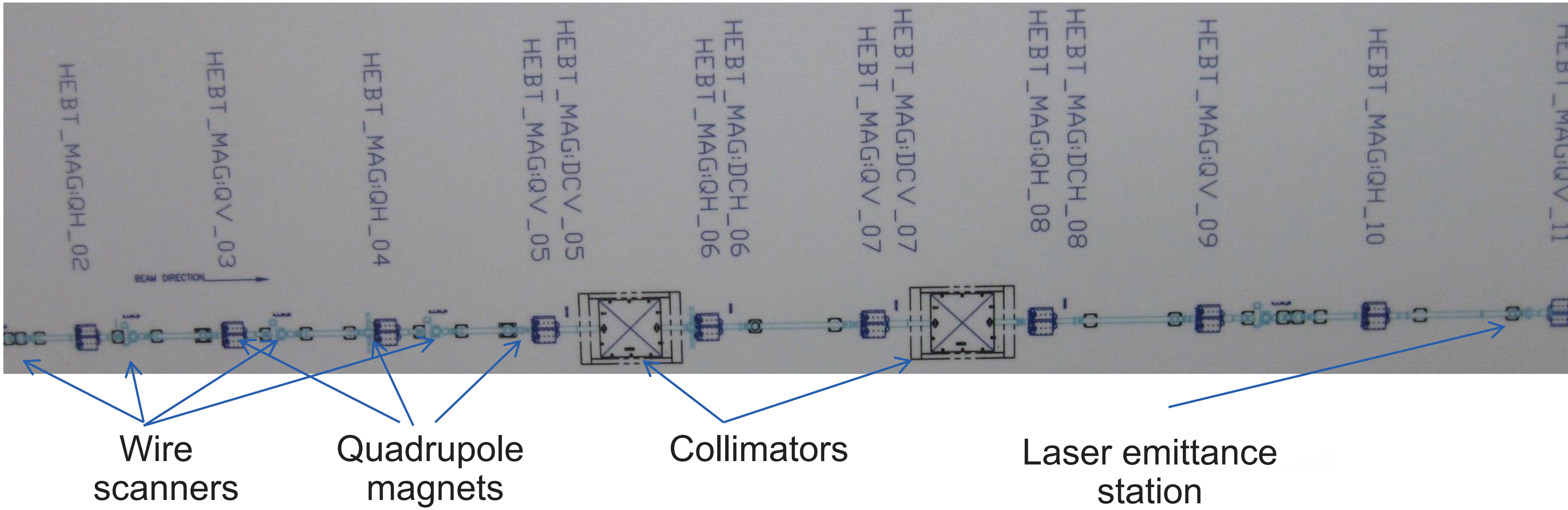


Particles generated from reconstructed 2D distribution.
Modified MENT algorithm with 4 projections

Phase space density plot

OAK RIDGE National Laboratory | SPALLATION NEUTRON SOURCE

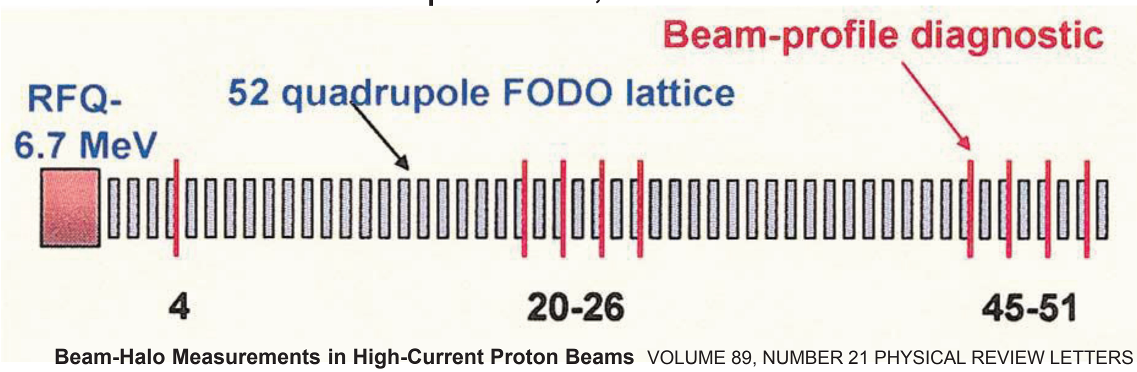
SNS 1 GEV HEBT beam line is well equipped large dynamic range tomography development test bench

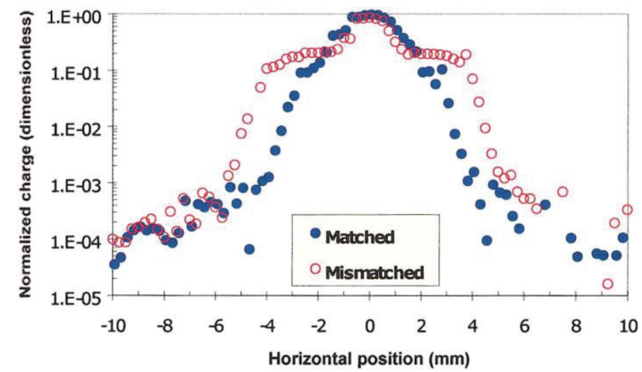


- Five high dynamic range wire scanners
- FODO line with independent magnet controls
- Laser emittance station for direct reconstruction validation
- Two 2-stage collimation sections as application test case

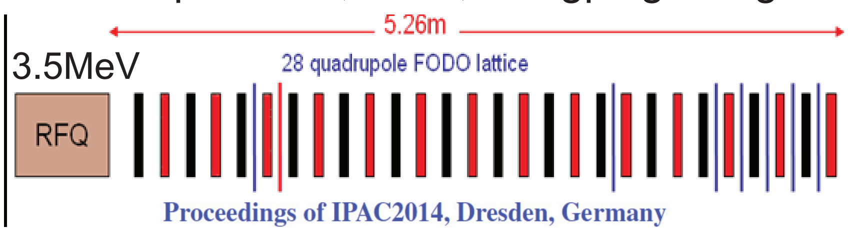
Halo Mitigation 1. *Understanding halo formation*

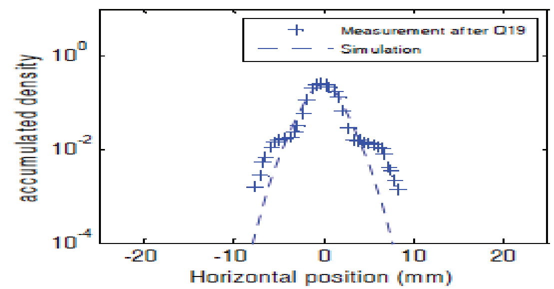
Los Alamos LEDA experiment, 2001



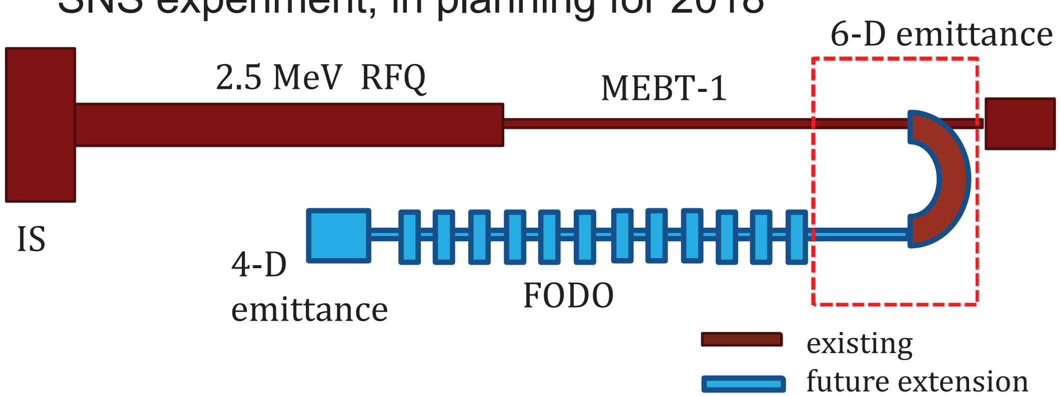


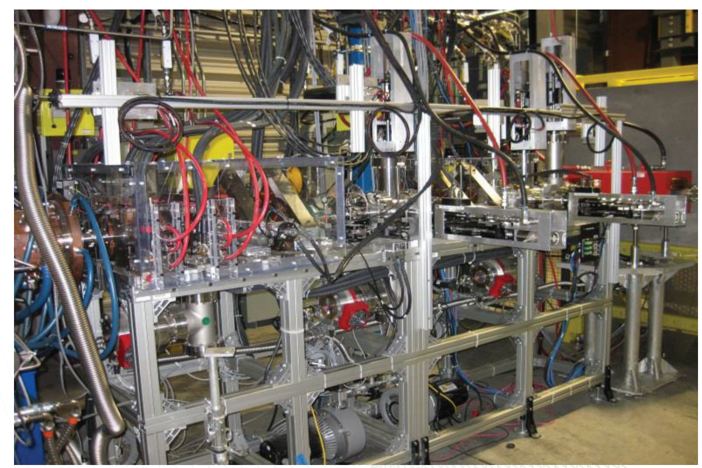
IHEP CAS experiment, 2014, Hongping Jiang et al





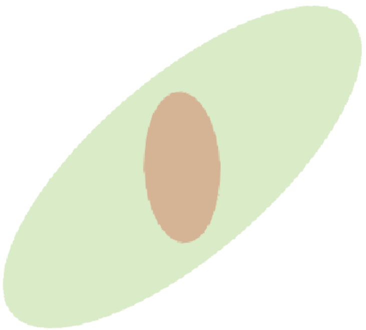
SNS experiment, in planning for 2018

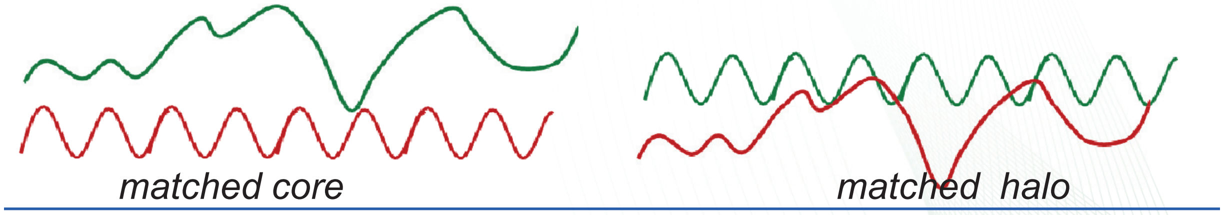




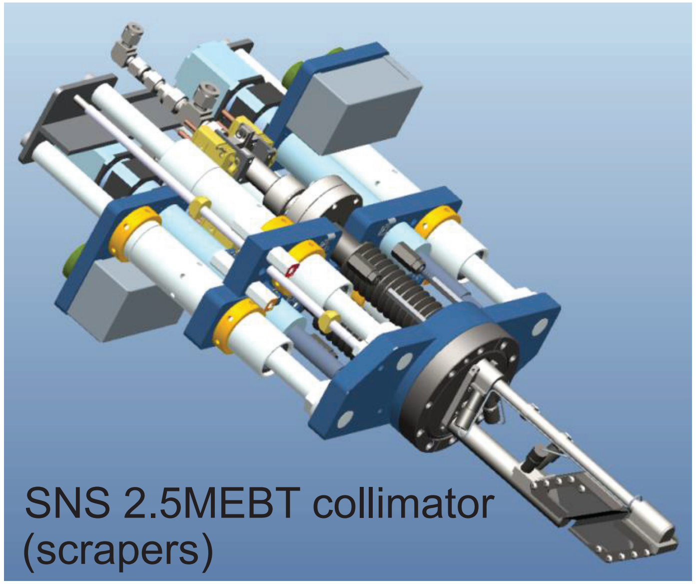
Halo mitigation 2. *Twiss parameters matching*

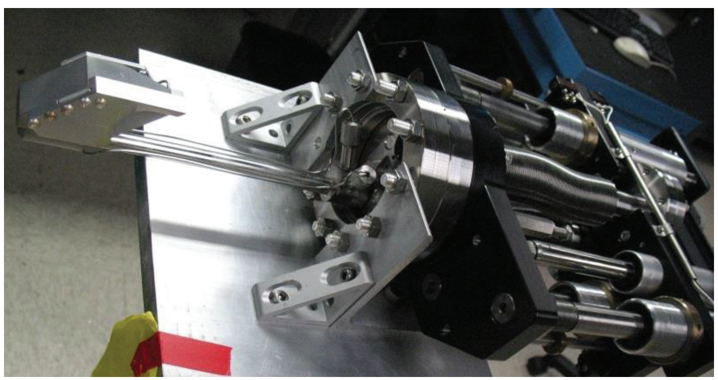
- Matching beam core Twiss parameters at lattice transitions
  - Believed to prevent halo formation in case of strong space charge (no experimental evidence)
  - Minimizes core maximum size and variation
- Matching beam halo Twiss parameters at lattice transitions
  - Minimizes halo maximum size
- Overall effect depends on core and halo Twiss parameters
- Empirical loss reduction in high intensity linacs
  - *Blind matching of halo?*
  - *E.g. minimum loss in SNS linac achieved with mismatched core*

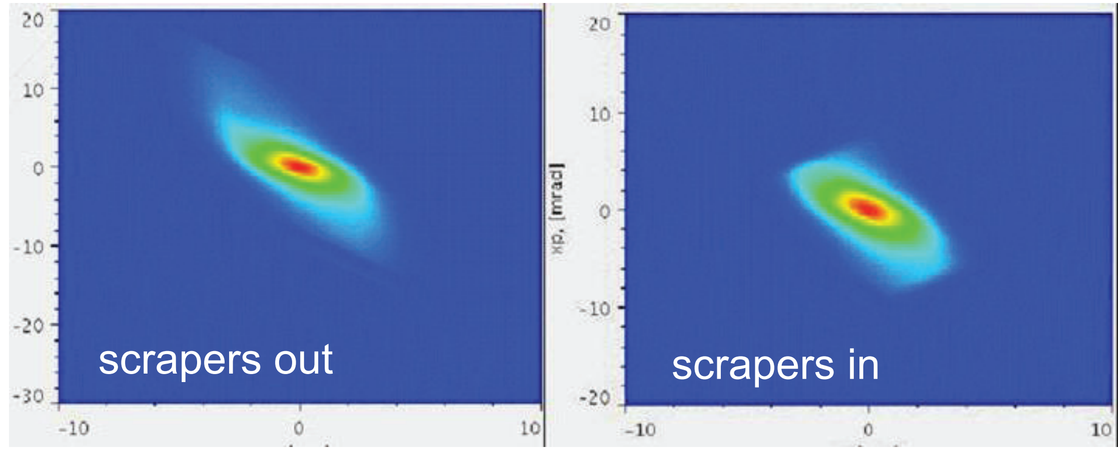


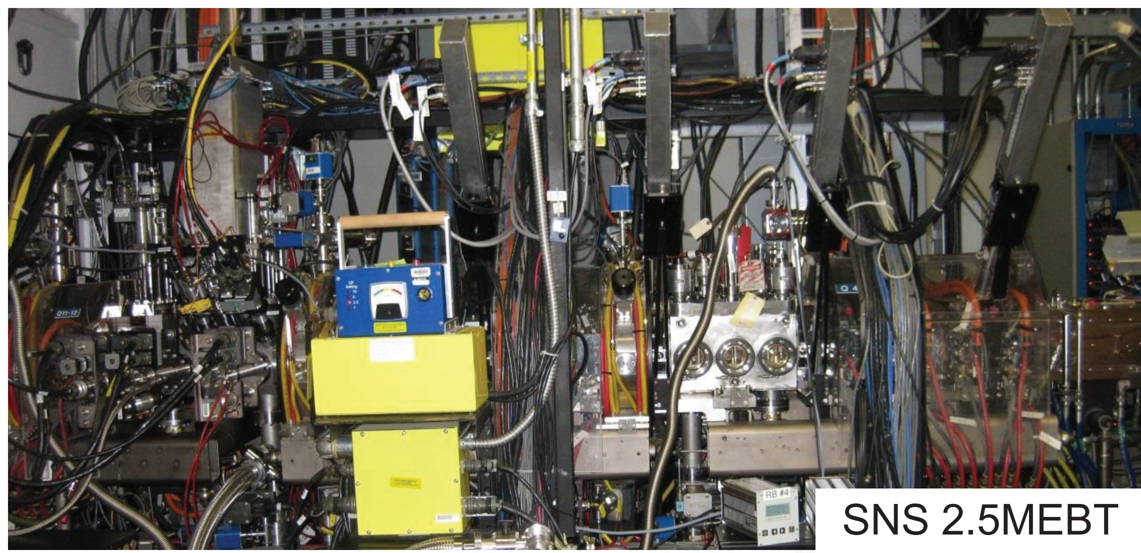


Halo Mitigation 3a. *Collimation at low energy*



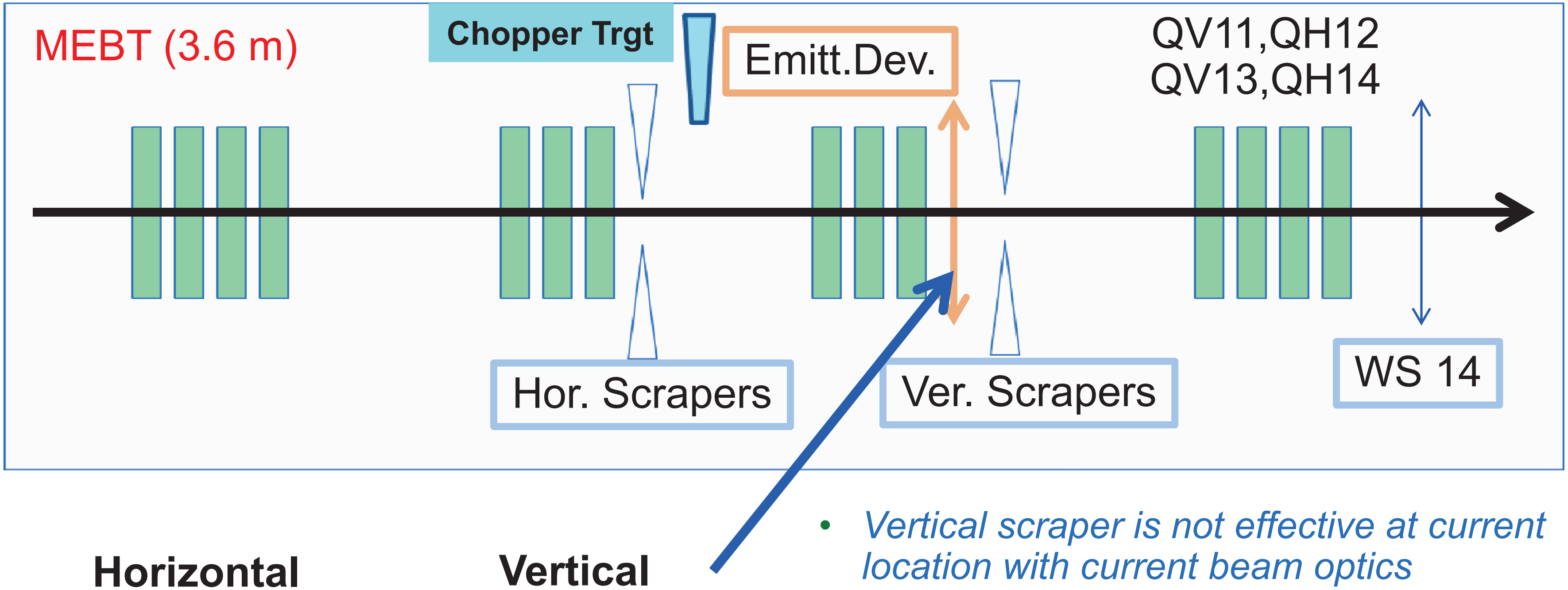




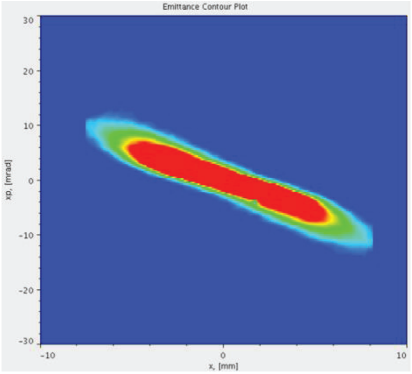


Simple concept and implementation but often hard to find space,
Halo measurement can help to optimize scraper location

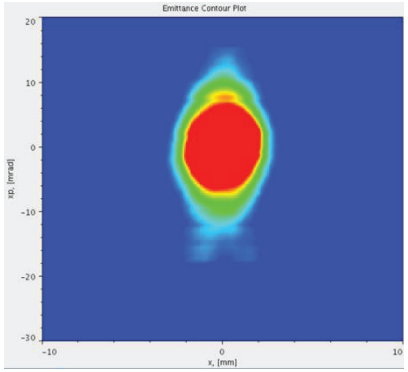
Example: improving collimation in SNS MEBT



Horizontal

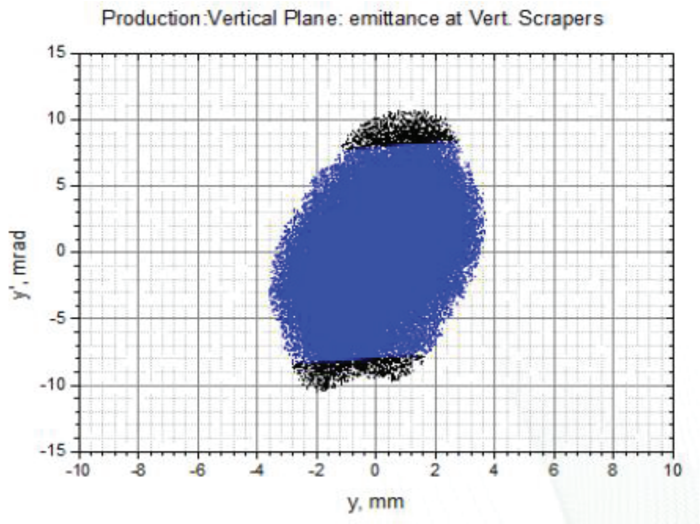


Vertical



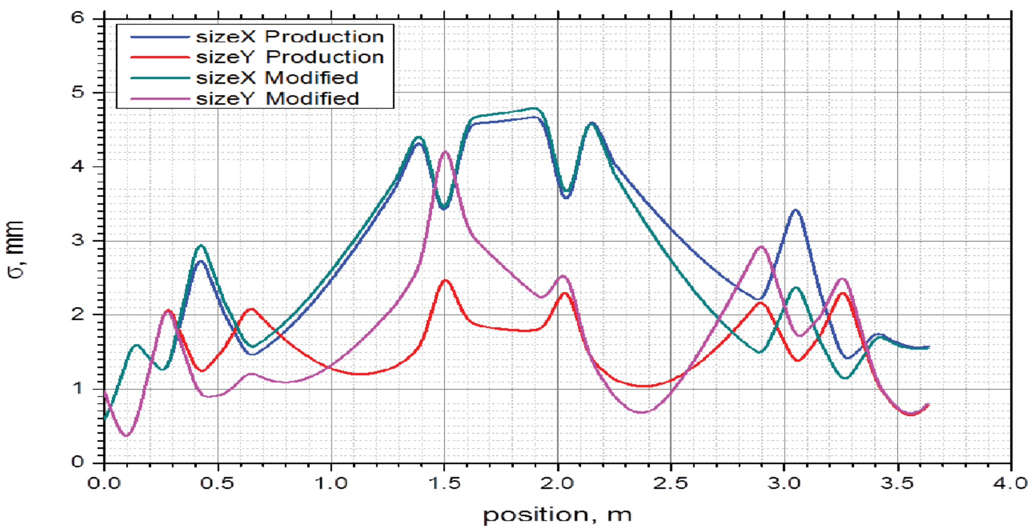
- *Vertical scraper is not effective at current location with current beam optics*
- *Measurements show halo at 90º to scrapers*
- *Modify optics to rotate vertical halo and satisfy other constrains*
  - *Horizontal scraper effectiveness*
  - *RFQ matching*
  - *DTL matching*
- *Virtually impossible without measurements and model*

MEBT optics adjustment to improve collimation

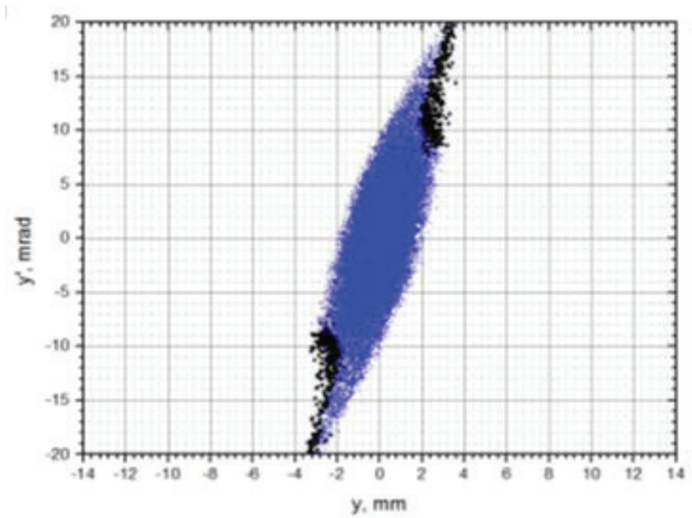


Old

Derived from measurements, 'bad' particles are in black



Old and new transverse beam sizes in MEBT



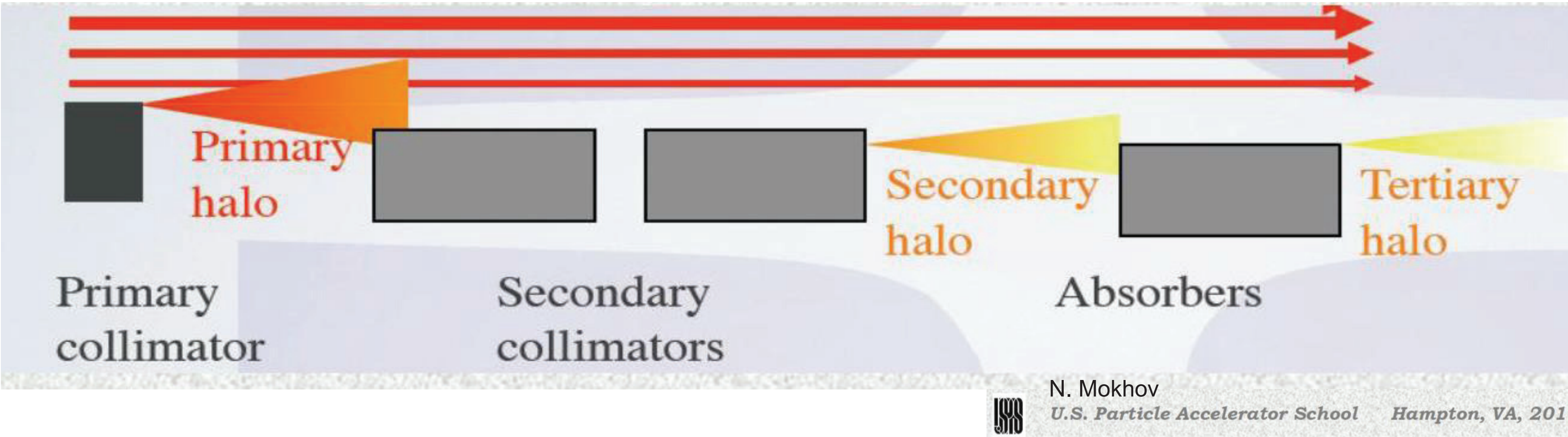
New

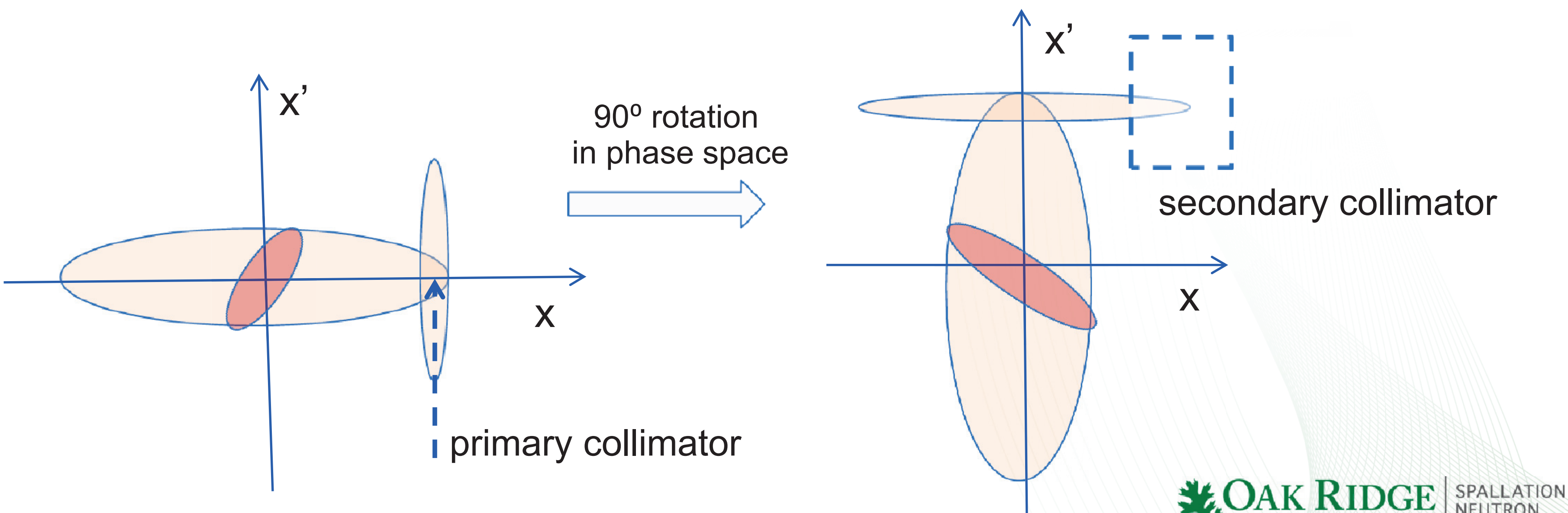
Calculated distribution for modified optics

particle distribution at vertical scrapers location

OAK RIDGE National Laboratory | SPALLATION NEUTRON SOURCE

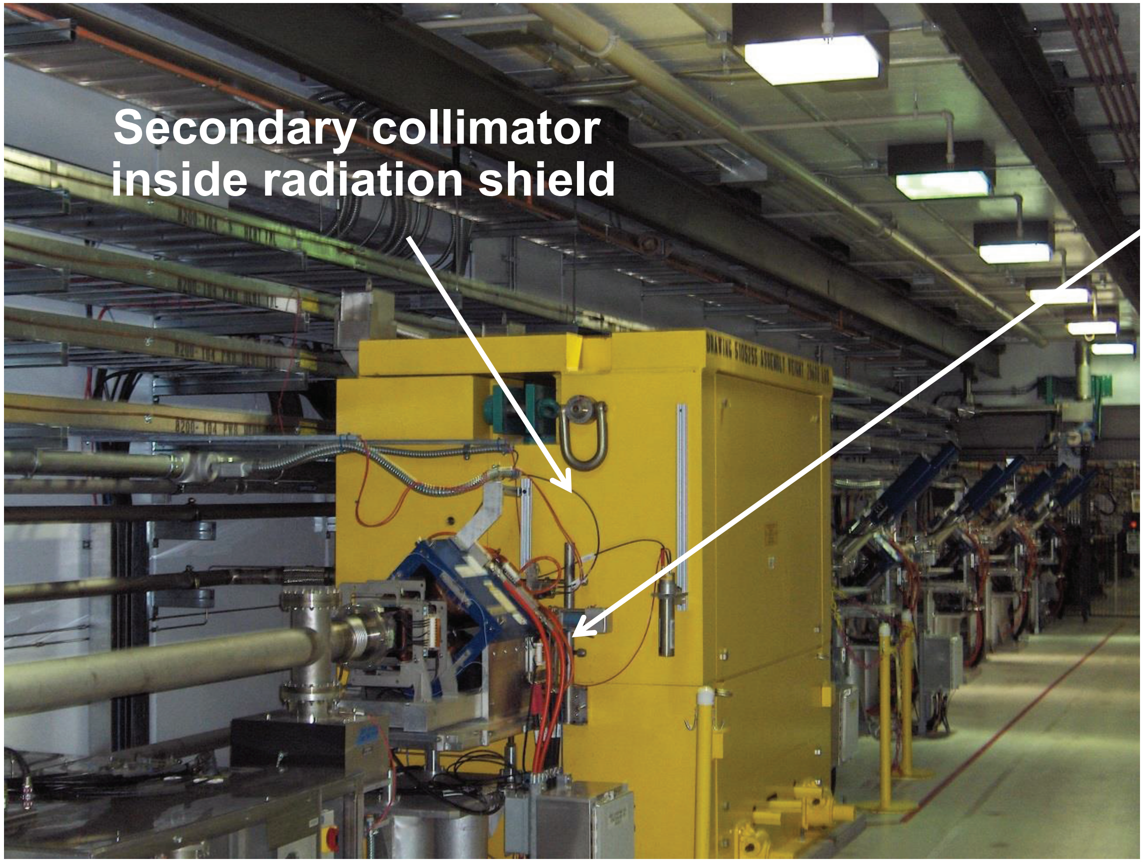
Halo mitigation 3b. *Collimation at high energy*

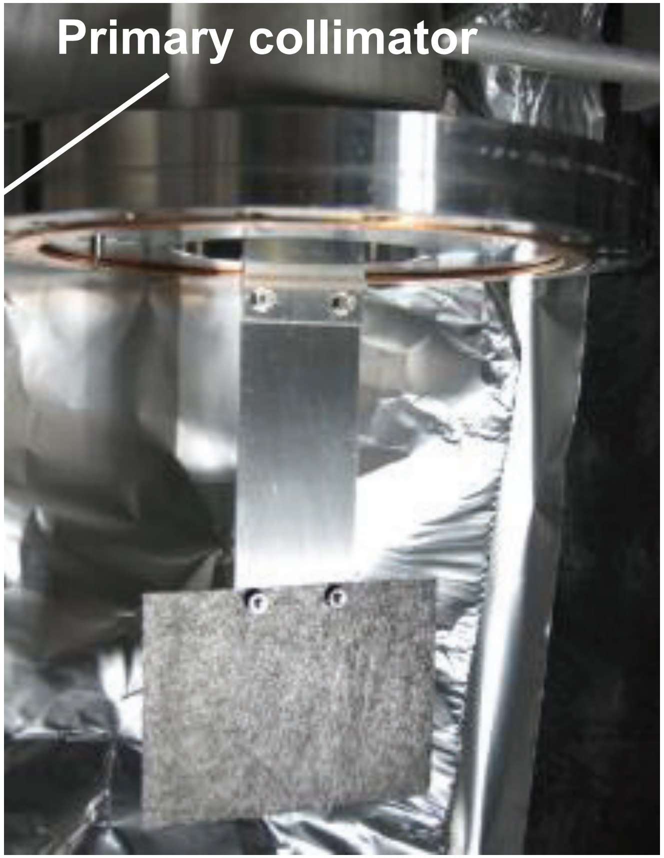




OAK RIDGE National Laboratory | SPALLATION NEUTRON SOURCE

Two stage collimation example. *SNS 1GeV HEBT*





- *SNS HEBT collimator is not effective and is not in use*
- *Good test case for halo measurement, characterization, mitigation study*
- *Similar Accumulator Ring collimator is effective and in use*

Summary

- Halo is defined as low density part of the beam far from the core
- Large dynamic range halo measurements have been demonstrated by several methods in many places
- RMS envelope formalism is not applicable for halo
- Use of PIC codes for propagating halo requires 2D large dynamic range phase space measurement as minimum
- Direct 2D phase space halo measurements are feasible at low energy
- Using 1D profiles for large dynamic range 2D reconstruction is promising but requires development
- Measurements can be useful for halo mitigation if combined with proper simulation code