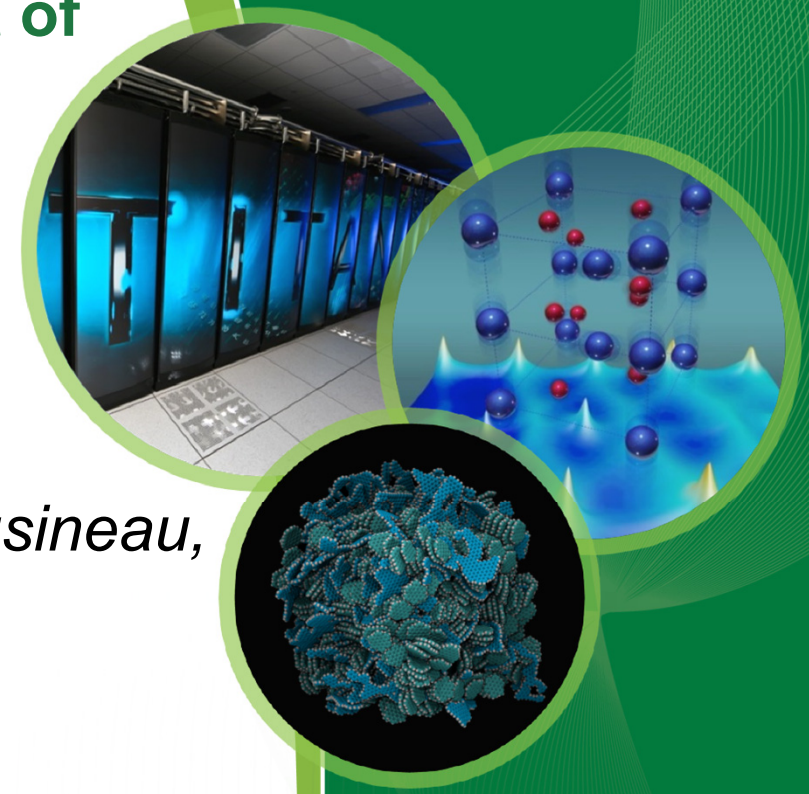
6D Phase Space Measurement of Low Energy, High Intensity Hadron Beam



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Outline

1. Introduction
   a) Simulating beam loss
   b) Measuring phase space
2. Six dimensional scan
   a. Slit based emittance scan
   b. Bunch Shape Monitor
   c. Scan difficulties
   d. Beam Test Facility
3. Early Results
   a. 1D scans
   b. 2D scan
4. Future Plans

Problem with Simulating Beam Loss

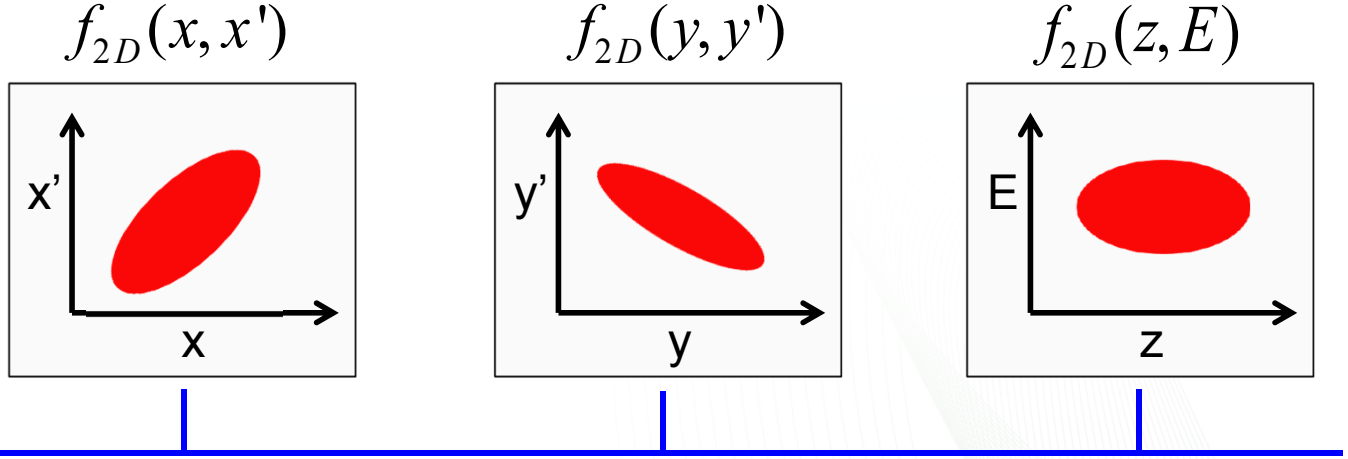
- Simulations prove very accurate at tracking RMS values of beam (such as size).
- Simulations can not accurately predict beam halo formation or beam loss:
  - Simulations should be sophisticated enough to track the formation of beam halo and predict beam loss.
  - LEDA experiment shows problem may lie in an incorrect guess for the initial beam distribution.*
- Our goal is to measure the beam distribution that leads to beam halo formation. (Not to measure the actual halo.)

*J. Qiang, P. L. Colestock, D. Gilpatrick, H. V. Smith, T. P. Wangler, and M. E. Schulze Phys. Rev. ST Accel. Beams **5**, 124201 (2002) – Published 13 December 2002.

Current Phase Space Measurements

- 2D scans measure distributions inside a 2D phase space: (x, x') or (y, y') or (z, E).
- The three two dimension phase spaces are combined for a full six dimensional distribution.
  - This method cannot show any relations between variables in different axis. Ex: no (x, y')

Typically, measure projections:



Combine assuming no other relationships between variables

$$f_{3*2D} = f_{2D}(x,x') * f_{2D}(y,y') * f_{2D}(z,E)$$

True Six Dimensional Scan

- Must fully scan initial distribution over all 6 independent parameters.
  - Only way to find correlations between any variables.
- Correlations could exist due to:
  - Skew magnets
  - Solenoid focusing
  - Space charge

$$f_{2D}(x,x') * f_{2D}(y,y') * f_{2D}(z,E) \neq f_{6D}(x,x',y,y',z,E)$$

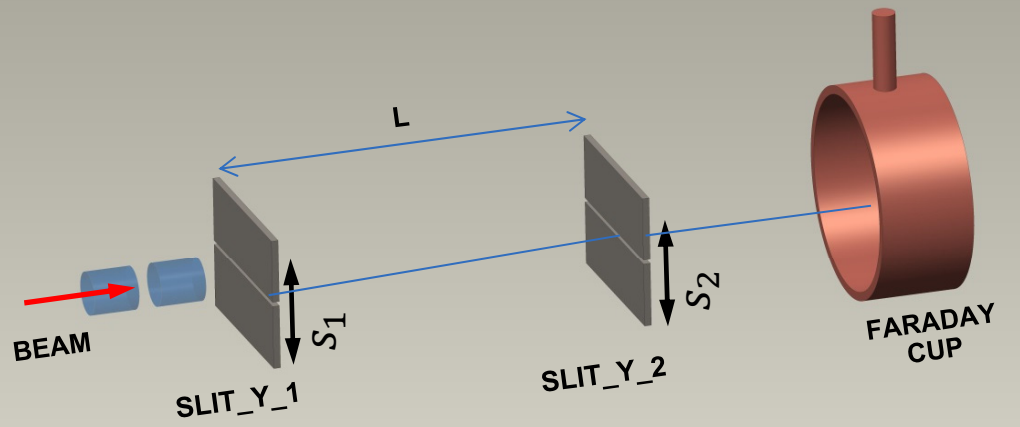
Assumes all cross-terms = 0

Includes cross-terms:

$$[(x,y),(x,y'),(x,z),$$
$$(x,E),(y,x')...]$$

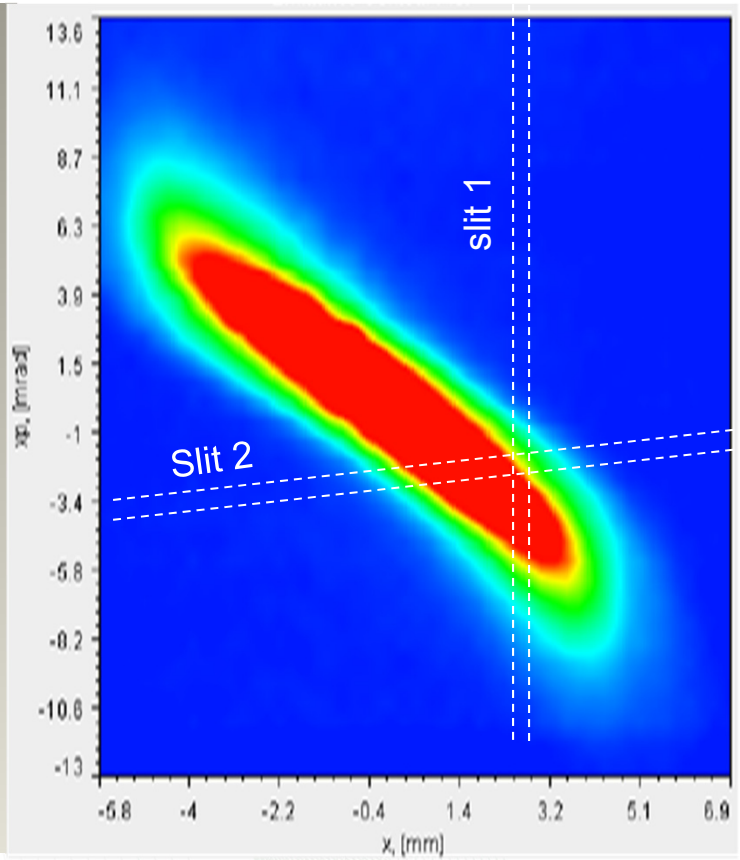
2D emittance using slit-slit technique

$$i_{FC} = f_2(y, y') \frac{\Delta \cdot \Delta}{L}$$

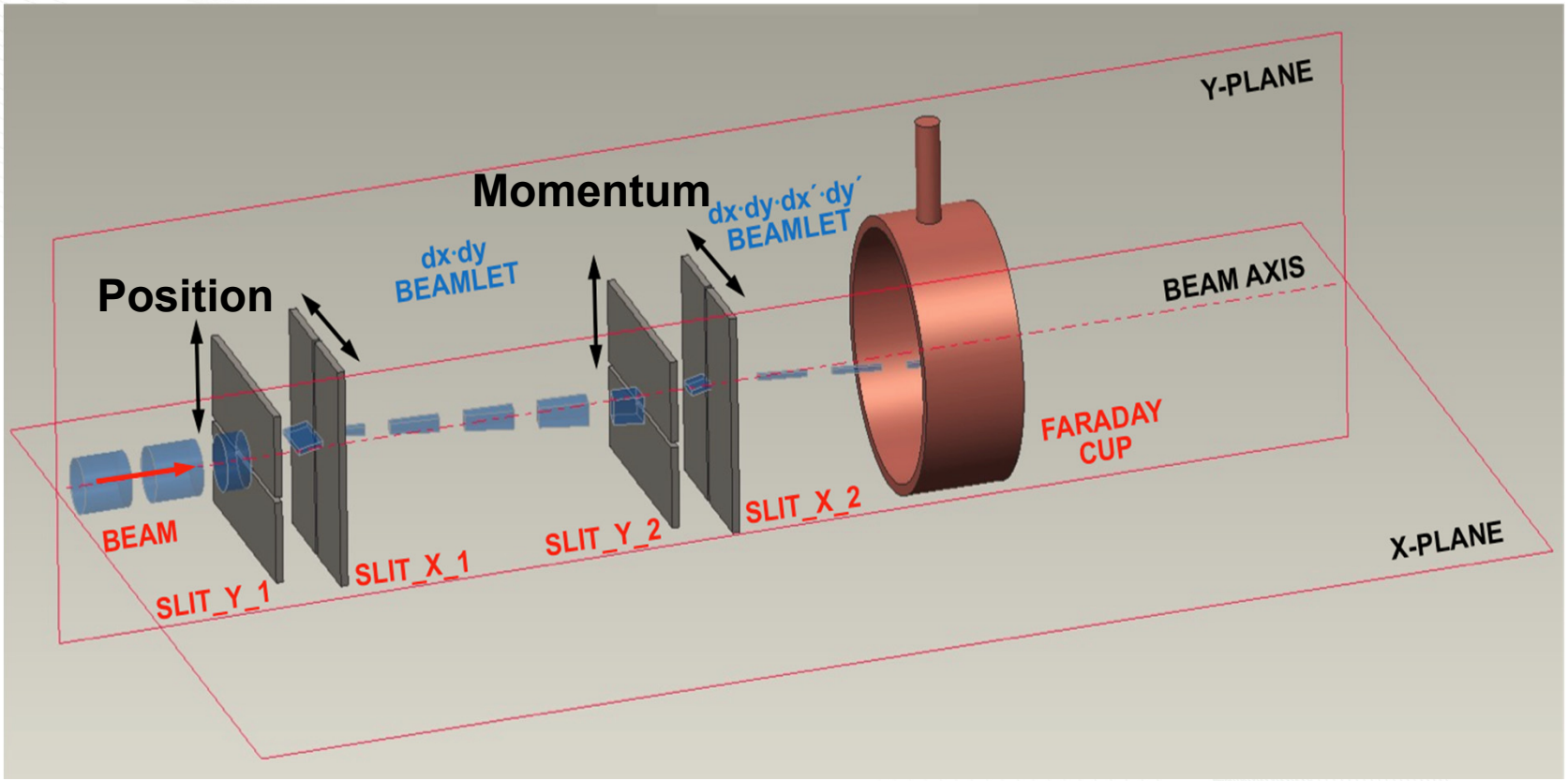


$$y = s_1$$

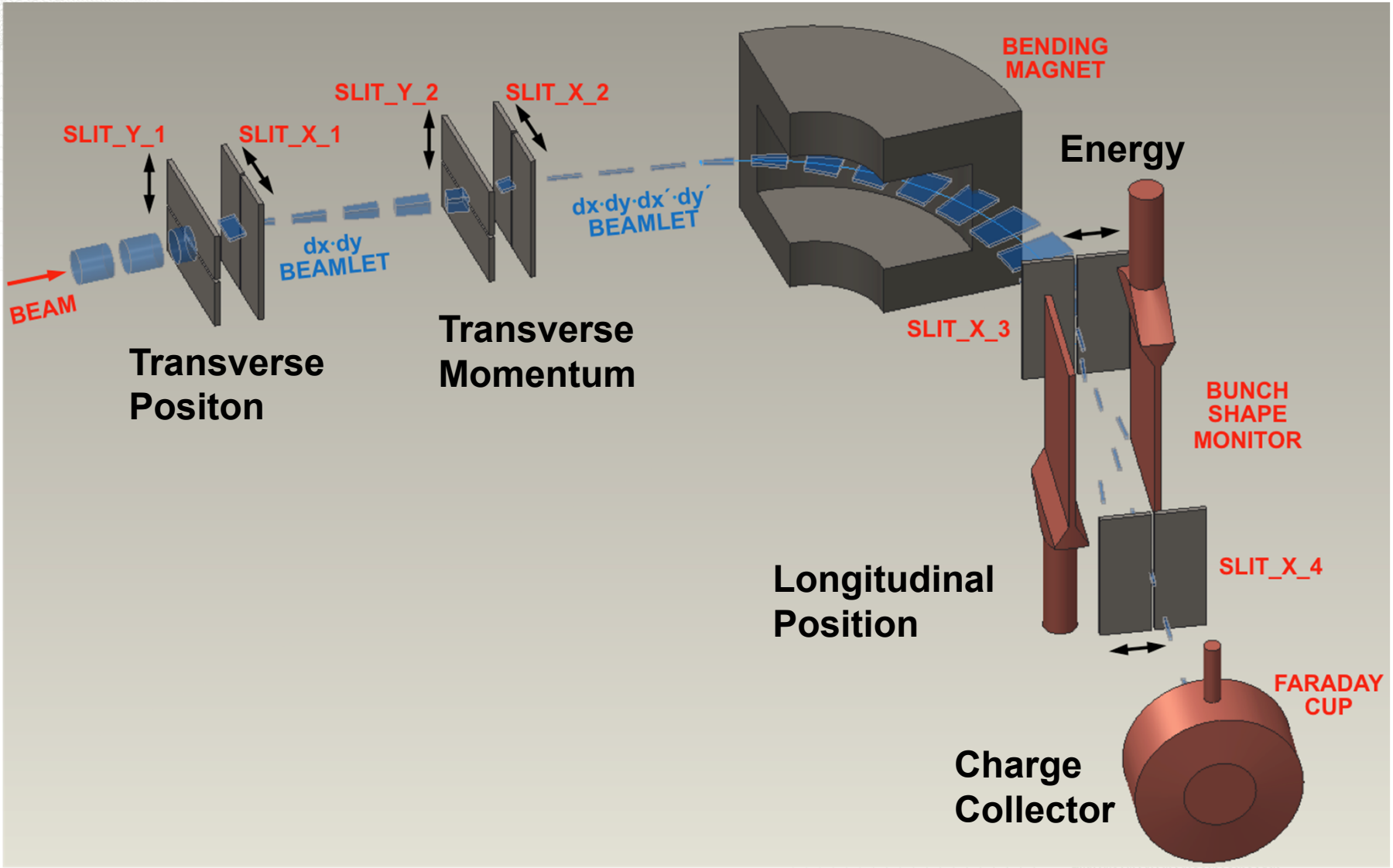
$$y' = \frac{s_2 - s_1}{L}$$



4D emittance measurement

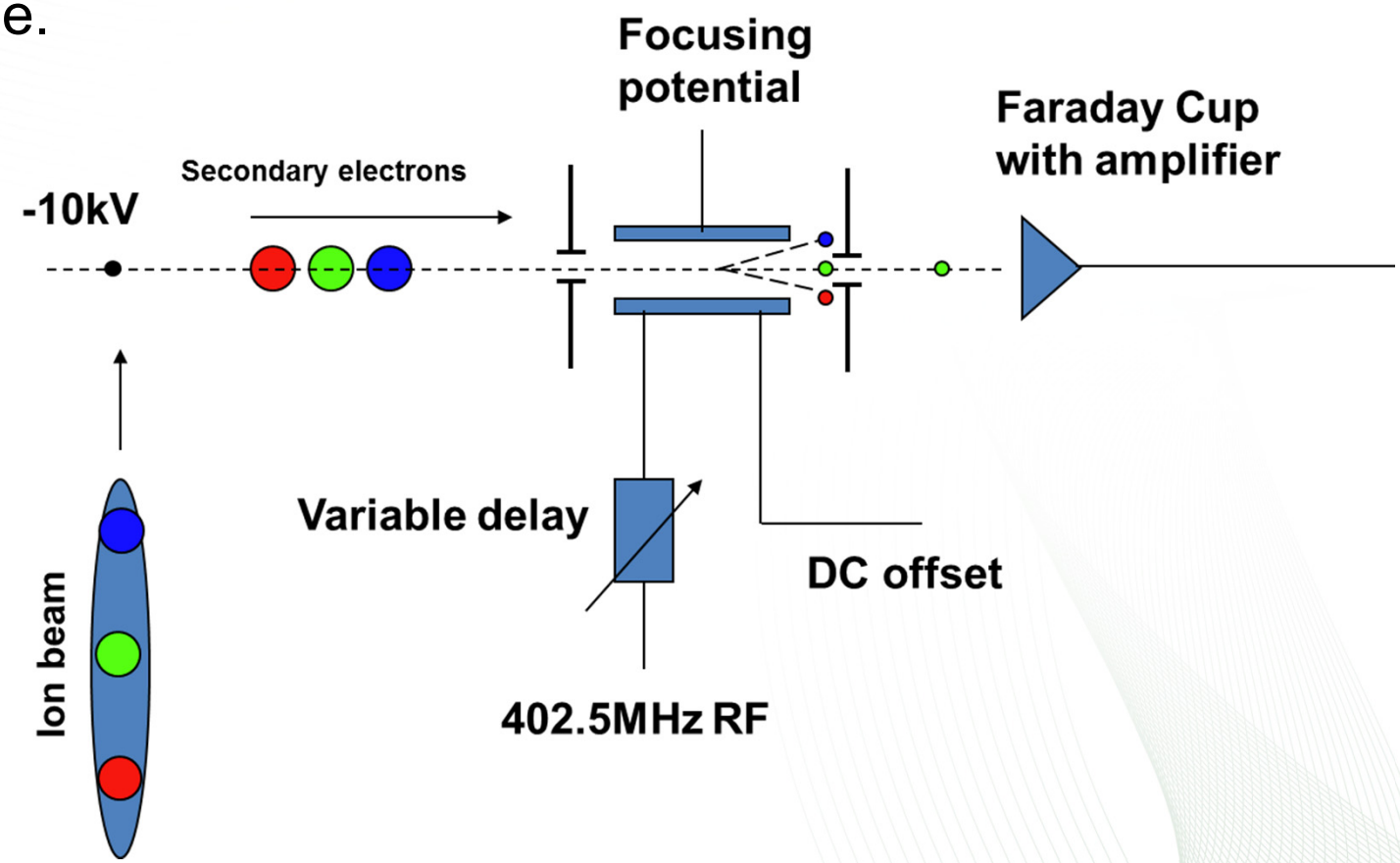


Full 6D Scan



Bunch Shape Monitor principle of operation

- Deflecting a 2.5 MeV proton beam directly with an RF cavity is expensive.
- Used to measure the longitudinal time profile at picosecond scale.



Signal strength estimate

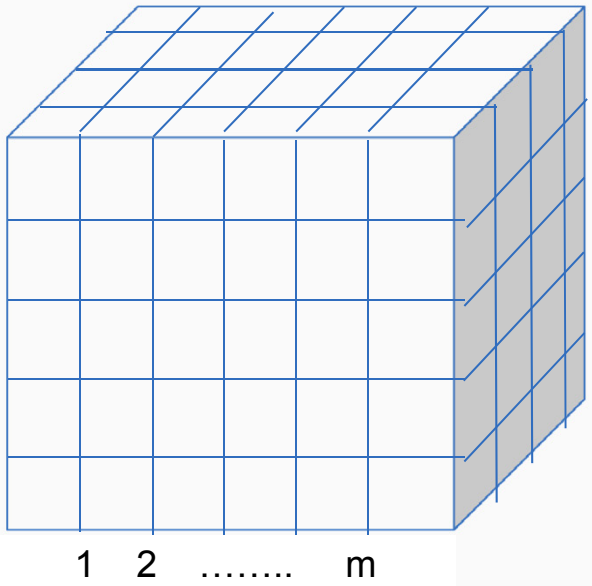
$$I = I_0 \cdot \frac{\exp\left(-\frac{x^2}{2\sigma_x^2}-\frac{x'^2}{2\sigma_{x'}^2}-\frac{y^2}{2\sigma_y^2}-\frac{y'^2}{2\sigma_{y'}^2}-\frac{w^2}{2\sigma_w^2}-\frac{\varphi^2}{2\sigma_\varphi^2}\right)}{8\pi^3}\frac{\Delta_x}{\sigma_x}\frac{\Delta_{x'}}{\sigma_{x'}}\frac{\Delta_y}{\sigma_y}\frac{\Delta_{y'}}{\sigma_{y'}}\frac{\Delta_w}{\sigma_w}\frac{\Delta_\varphi}{\sigma_\varphi}$$

$$I \approx \frac{\exp(\dots)}{8\pi^3}\left(\Delta/\sigma\right)^6$$

- If $\Delta/\sigma \approx 0.2$, after 6 slits, we get $i \approx I_0 \cdot 2.6 \cdot 10^{-7} \cdot \exp(\dots)$.
- For a current of $I_0 \approx 32\ mA$ and beam pulse of $\tau \approx 50\ \mu s$, we get $N_0 \approx 10^{13}$ particles.
- The number of particles after 6 slits is $N_{final} \approx 2.6 \cdot 10^6$ at the distribution center $\mathrm{r} = 0$
  - $N_{final} \approx 1.6 \cdot 10^6$ at $\mathrm{r} = 1\,\sigma$
  - $N_{final} \approx 2.9 \cdot 10^4$ at $\mathrm{r} = 3\,\sigma$ ← Limit to Faraday cup sensitivity
  - $N_{final} \approx 9.7$ at $\mathrm{r} = 5\,\sigma$

6D Scan Mechanics

- Diagnostics exist for each phase space, but time is the constraining factor.
- This is further compounded by the need for averaging.



$$N_{bins} = m^D$$

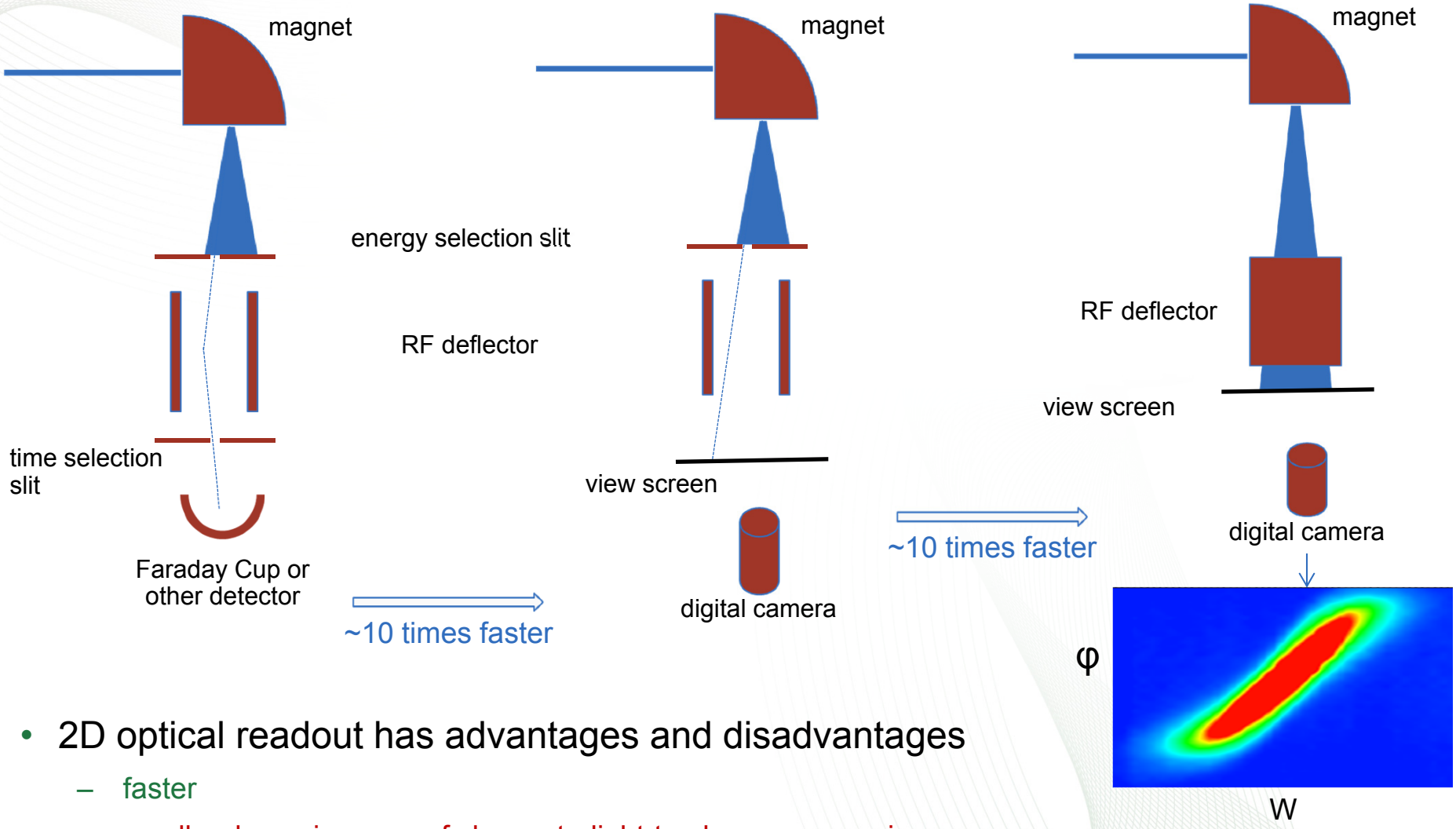
For a course measurement:

$$\left.\begin{array}{l} D = 6 \\ m = 10 \end{array}\right\} \rightarrow N_{bins} = 10^6$$

Scan rate 1 step/sec: 10^6 sec = 280 hrs
Scan rate 10 step/sec: 10^5 sec = 28 hrs

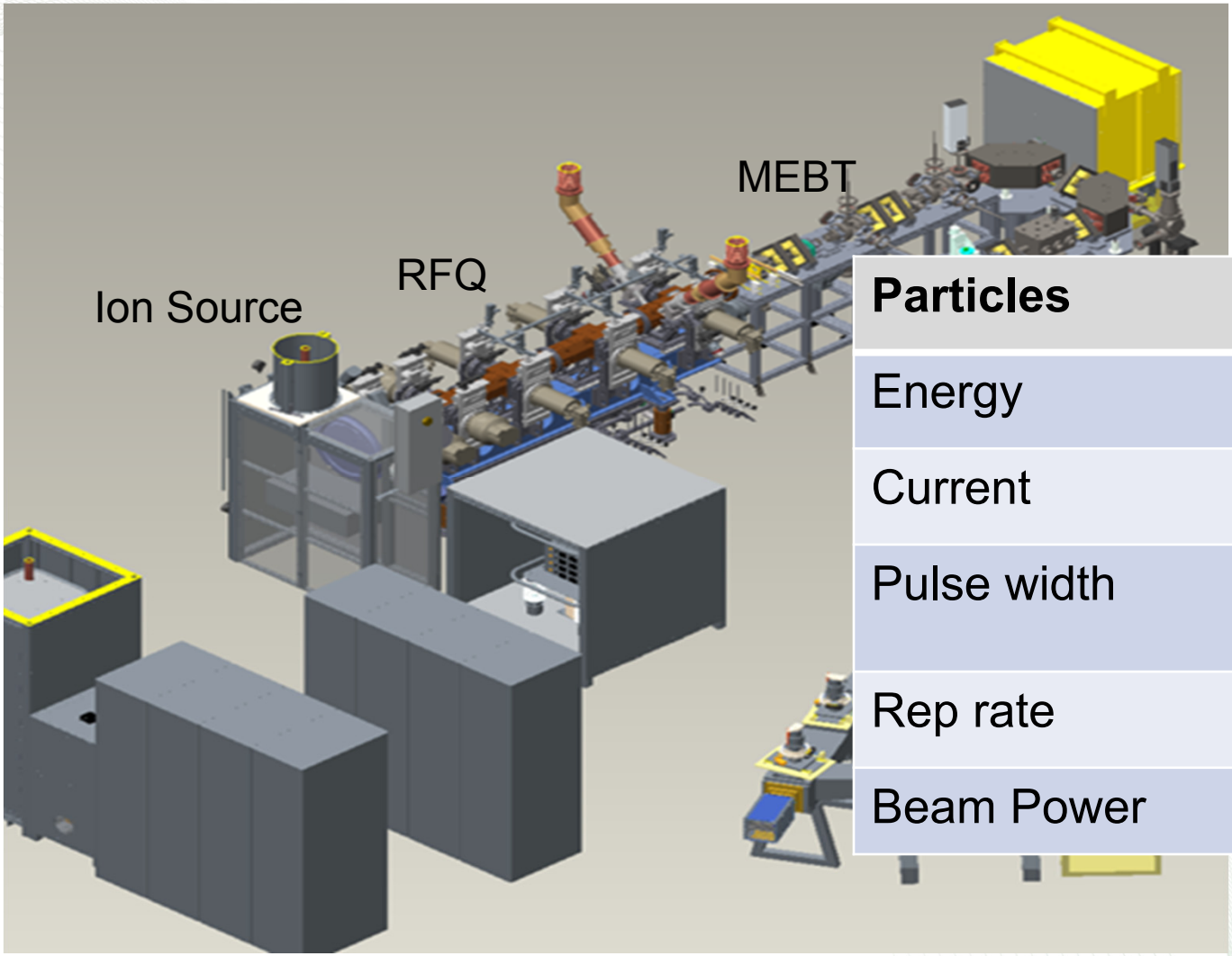
- Because of this, a six dimensional measurement has never been done before.

Speeding up scan in longitudinal phase space



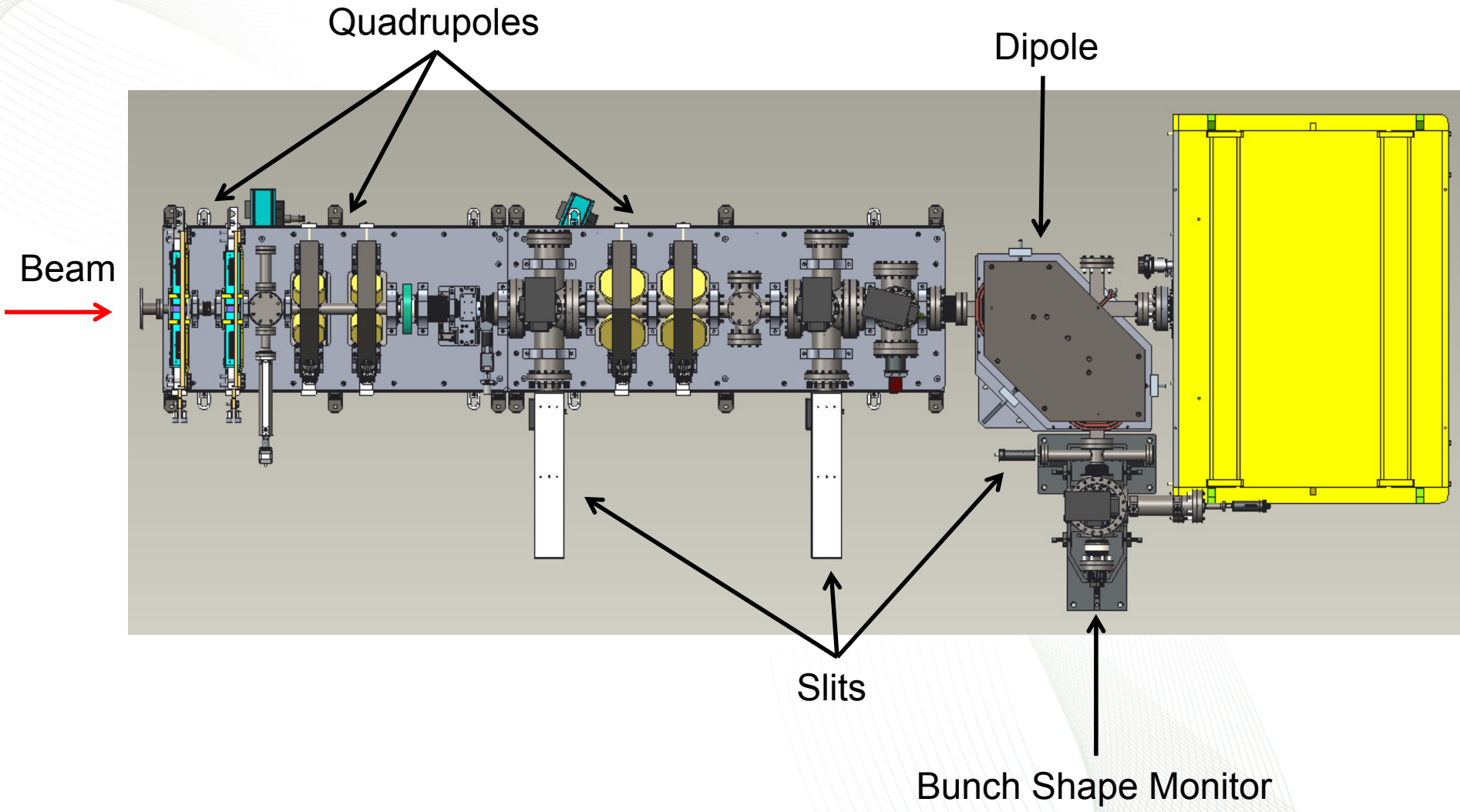
- 2D optical readout has advantages and disadvantages
  - faster
  - smaller dynamic range of charge-to-light-to-charge conversion

SNS Beam Test Facility (BTF)

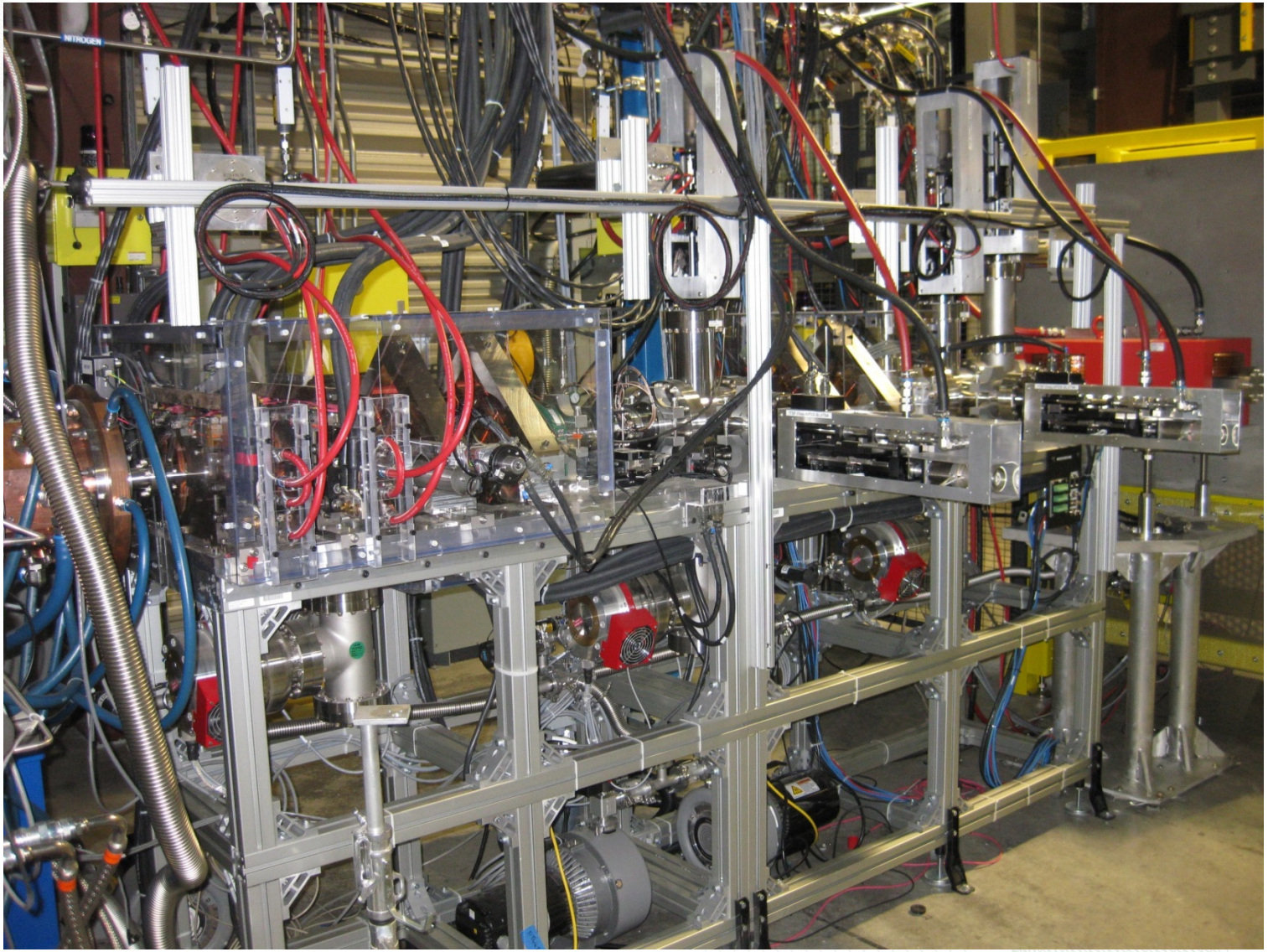


Particles	**H^-**
Energy	2.5 MeV
Current	< 50 mA
Pulse width	< 1 ms
Rep rate	≤ 60 Hz
Beam Power	< 7.5 kW

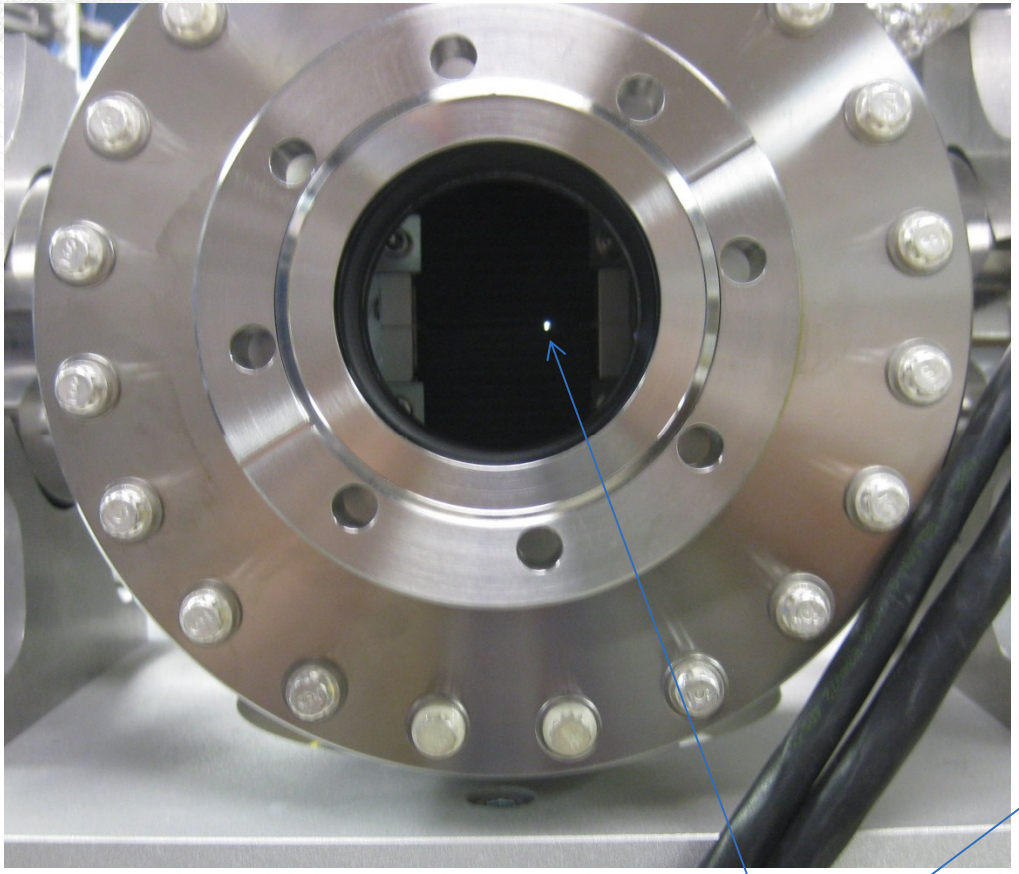
BTF MEBT

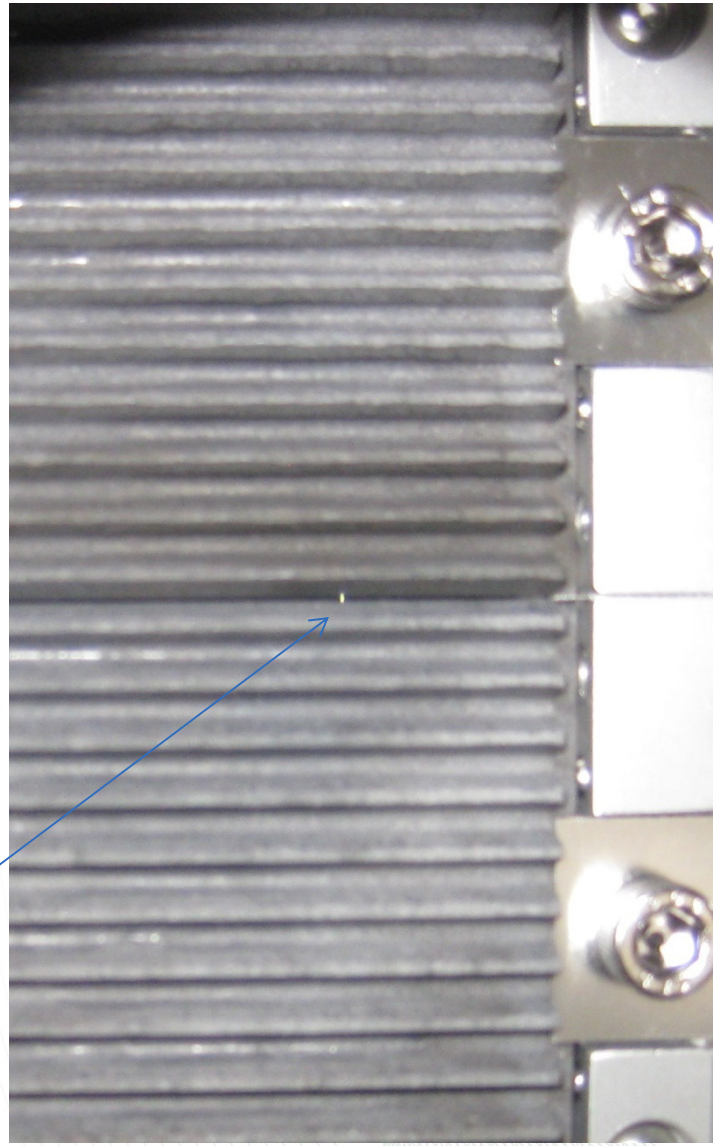


BTF MEBT



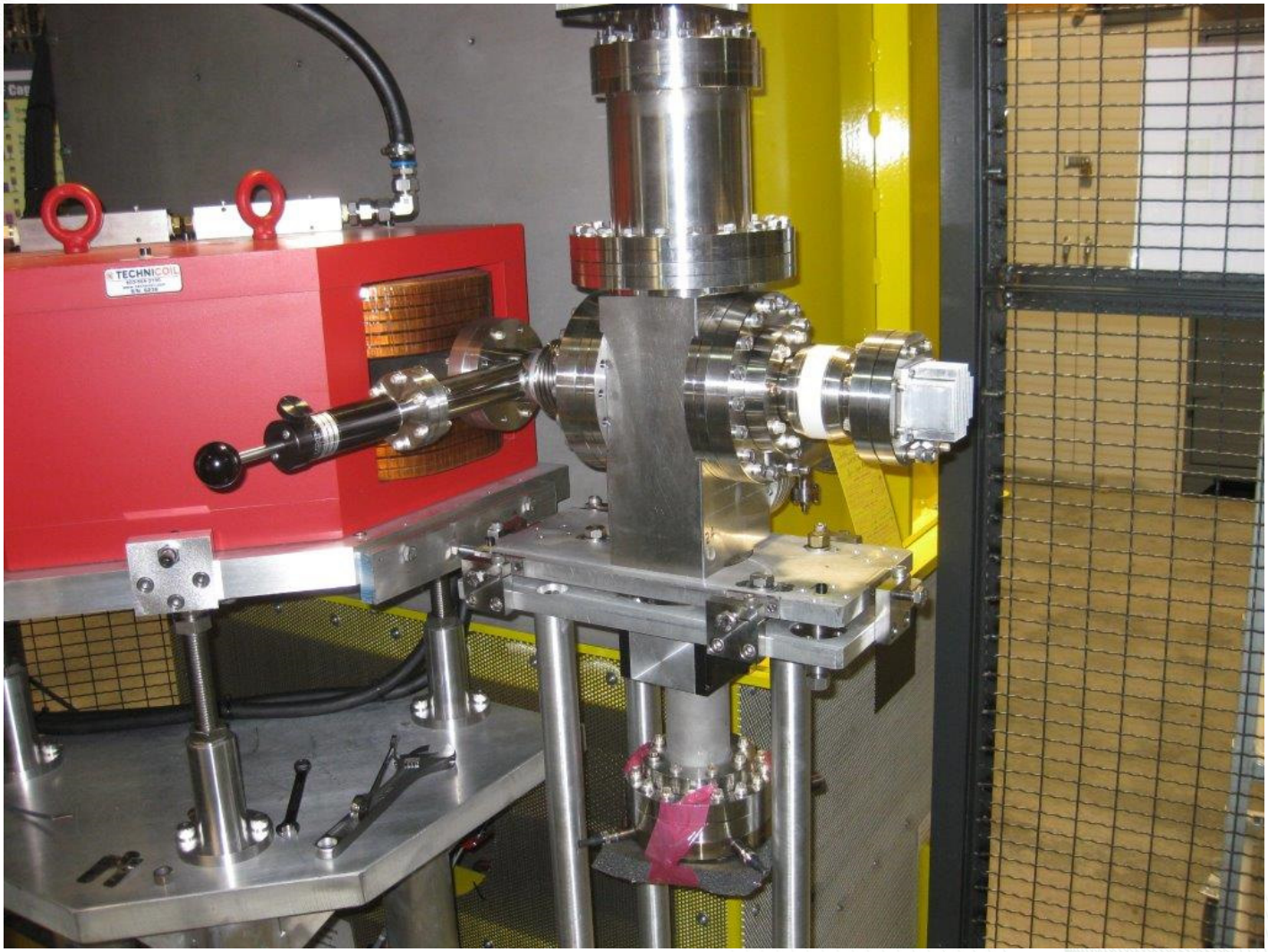
X-Y Slits arrangement



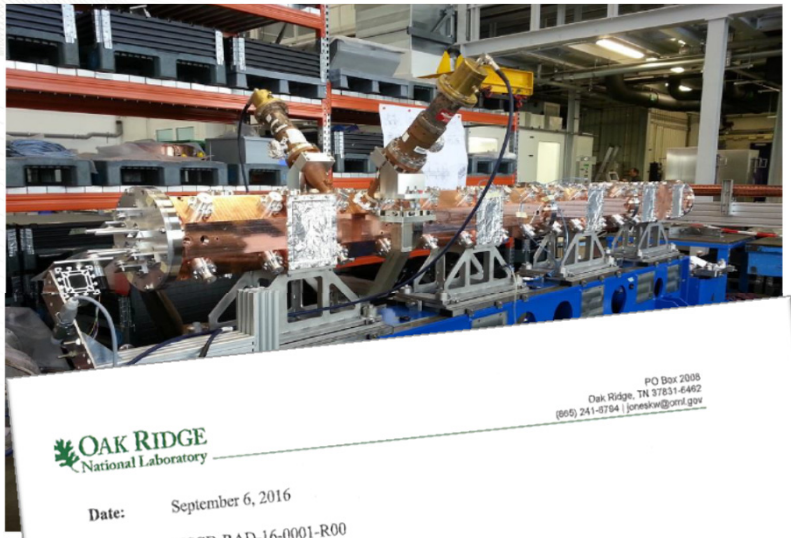


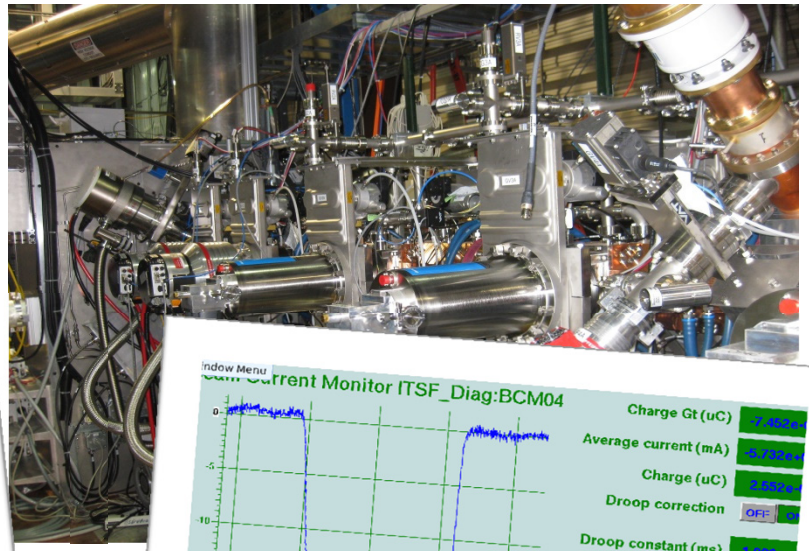
200-by-200 μm aperture

Bunch Shape Monitor



Began operation September 7th





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OAK RIDGE National Laboratory

Date: September 6, 2016

Ref: NSCD-RAD-16-0001-R00

To: A. V. Aleksandrov
M. E. Middendorf
G. D. Johns

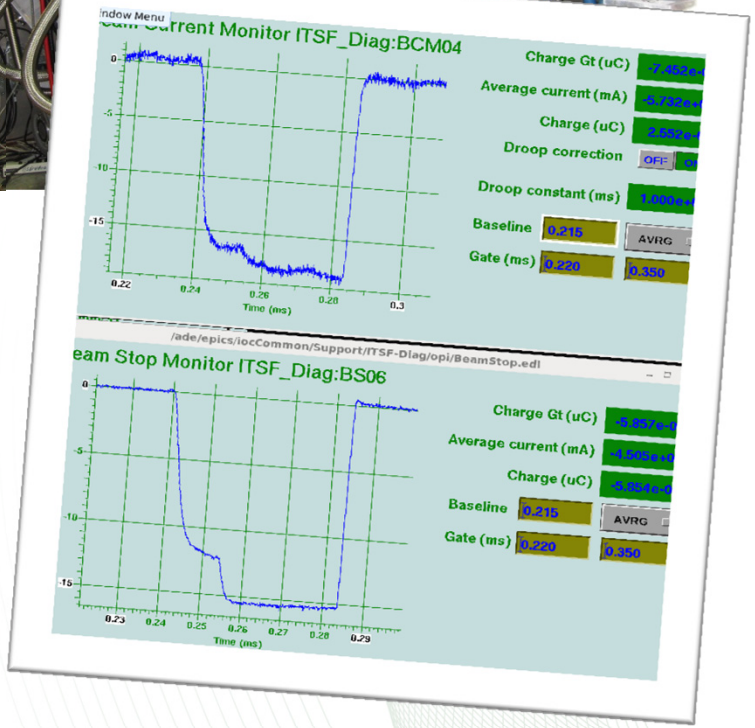
c: G. W. Dodson
S. M. Cousineau
D. E. Paul
M. J. Baumgartner
M. S. Champion
S. Kim
K. S. White
L. A. Longcoy
K. L. Mahoney

From: K. W. Jones

Subject: **Authorization for Integrated Operation of the Beam Test Facility (BTF) for Testing, RFQ Commissioning and Initial Physics Measurements with Bending Magnet Disabled**

References:

1. *"Safety Analysis for SNS Beam Test Facility,"* A. Aleksandrov, G. Dodson, D. Freeman and K. Jones, SNS-102030103-ES0059, July 18, 2016.
2. *"Contract DE-AC05-00OR22725, Request for Exemption from the Provisions of DOE O 420.2C for the Spallation Neutron Source Beam Test Facility,"* Letter from Paul Langan to



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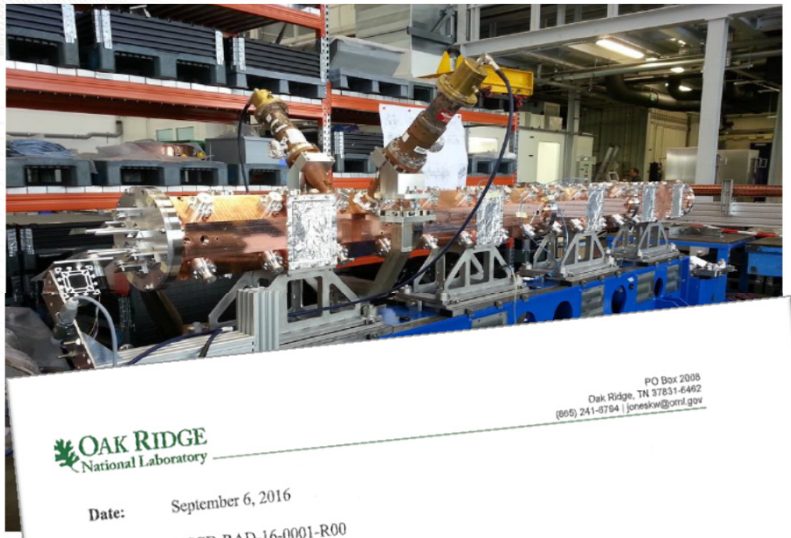
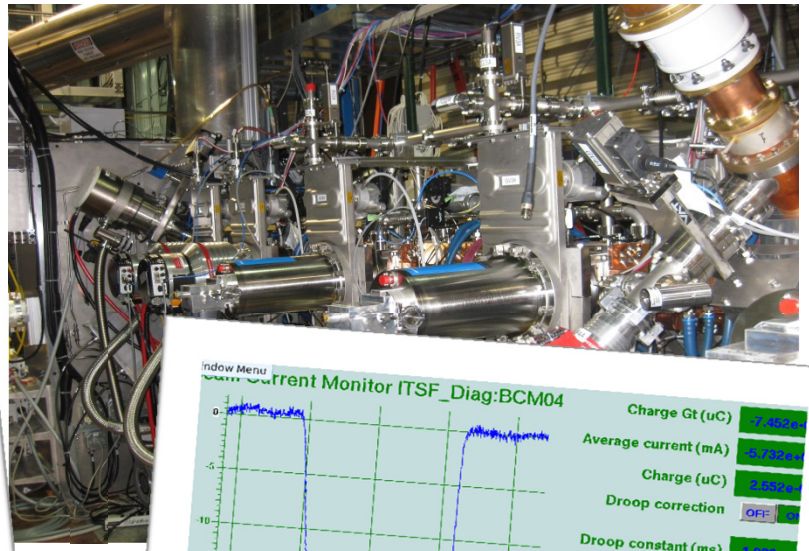
Began operation September 7th





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Testing, RFQ Co
Magnet Disable

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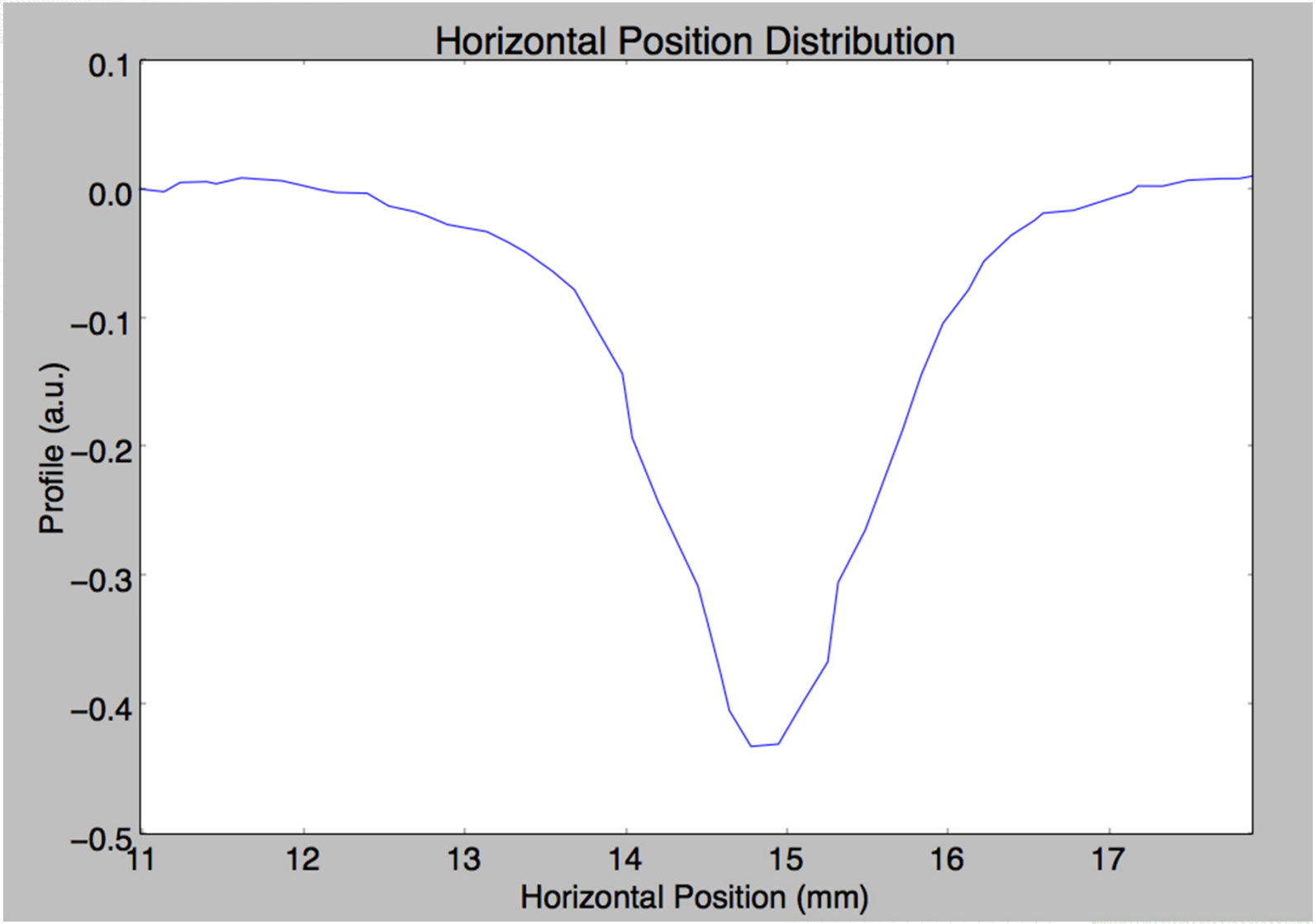
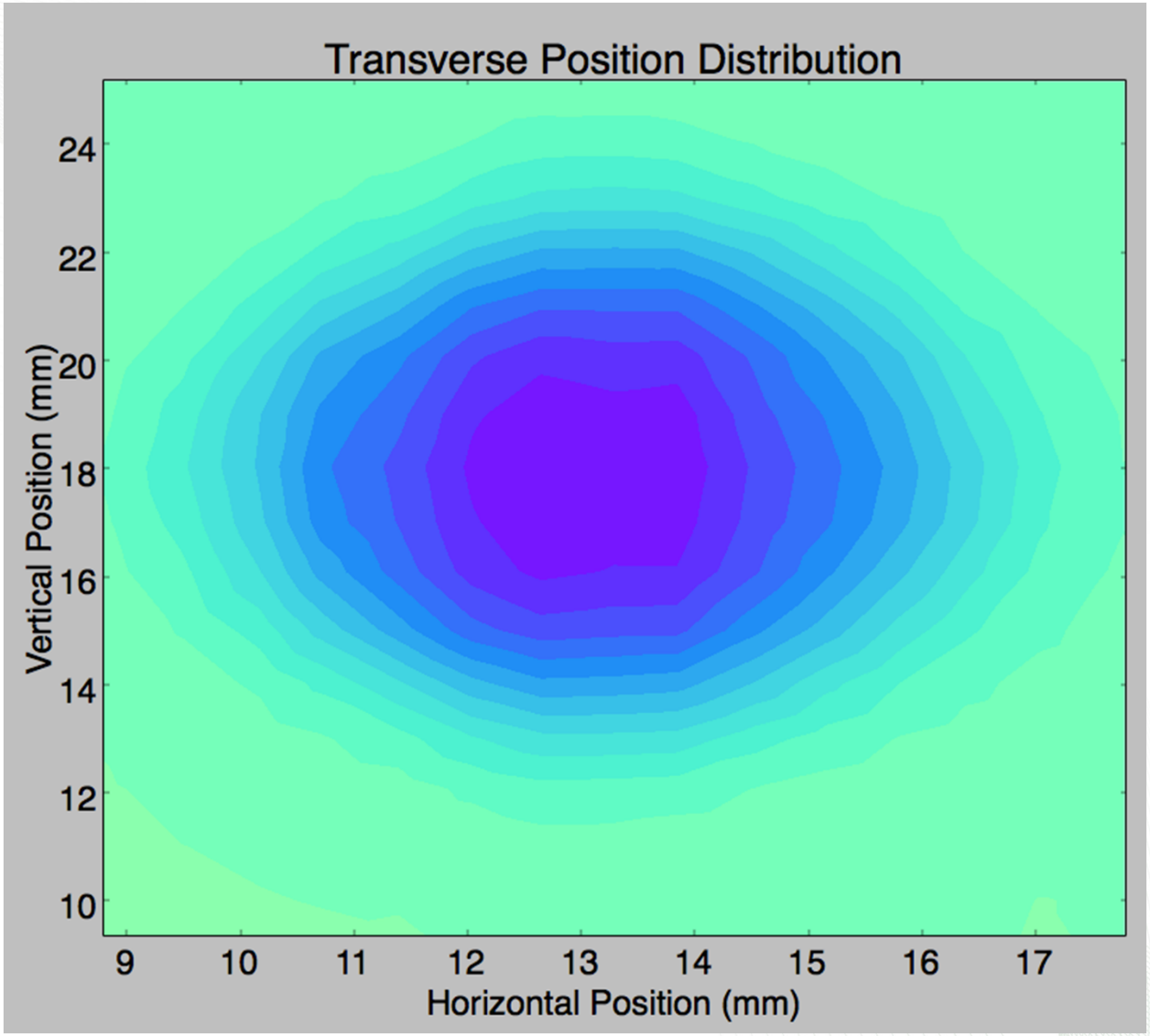
Beam out of RFQ
~18 mA

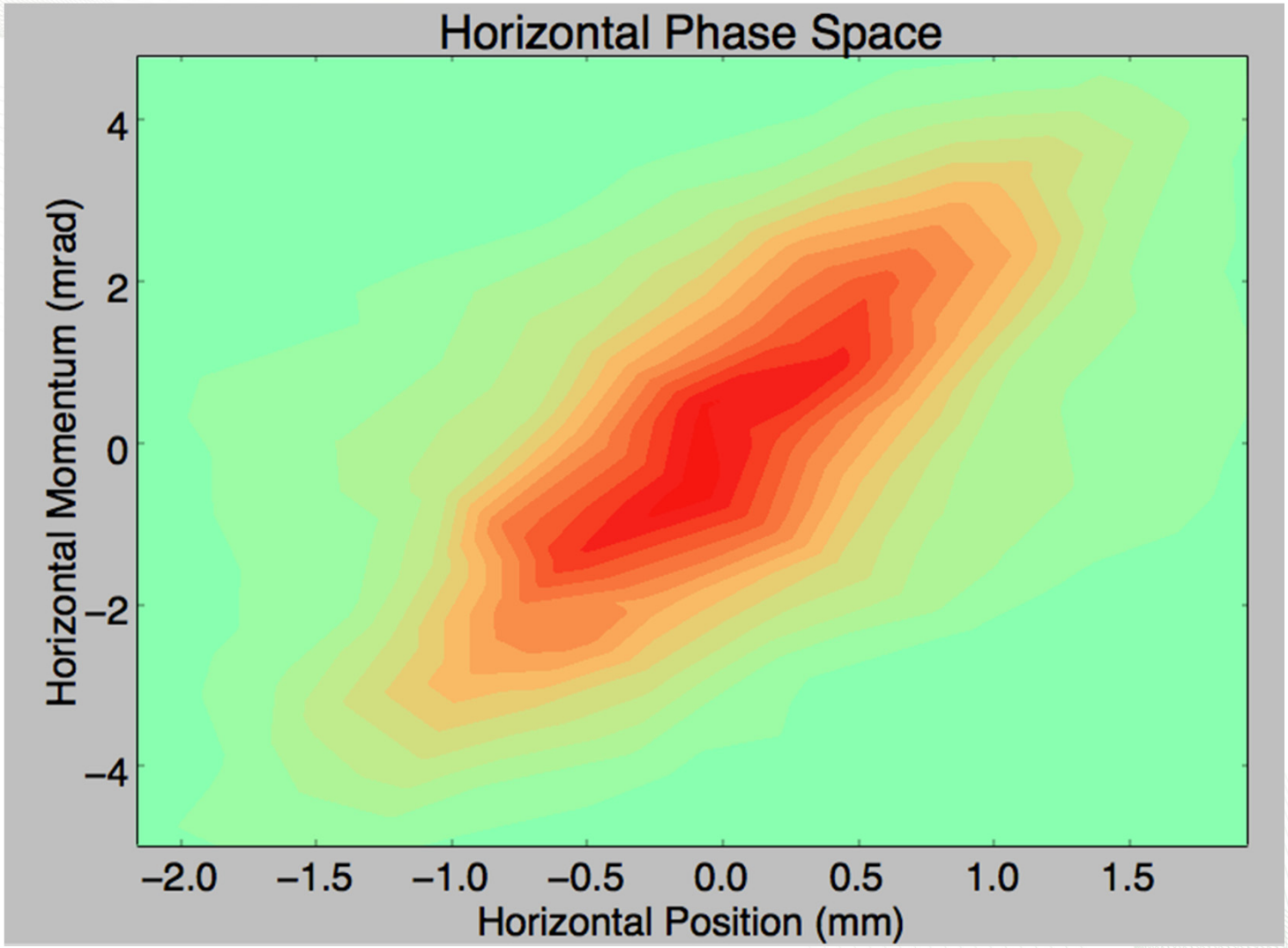
1D Scan Results



2D Scan Results

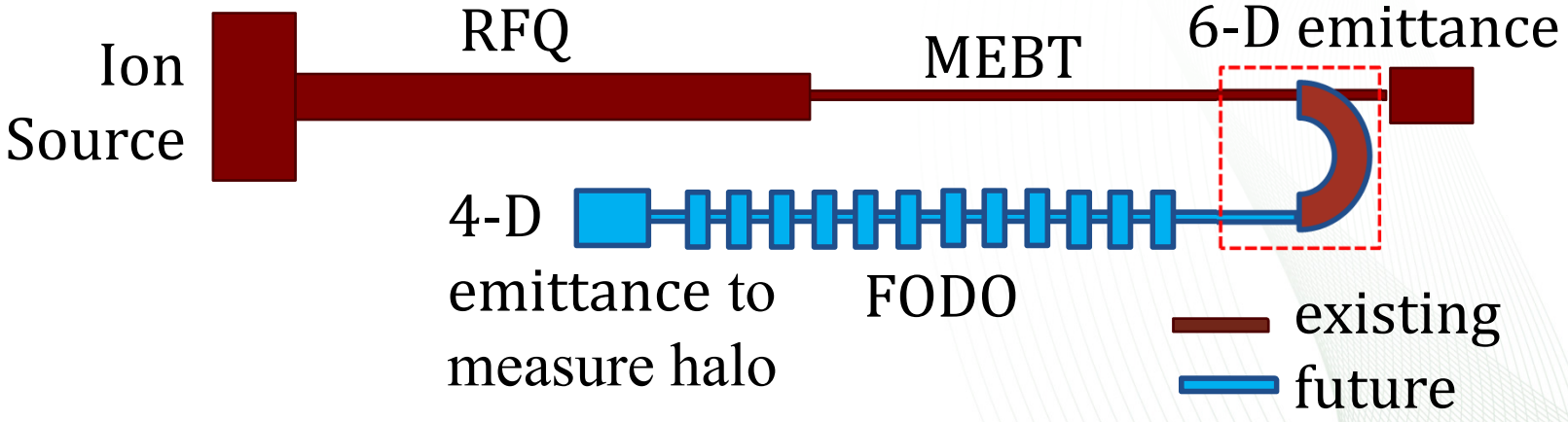


2D Scan Results



Near Term Research Goals

- Perform 4D scan and optimize it for minimal scan time and improved resolution.
- First 6D scan by January 2017.
- Add another dipole followed by FODO line after MEBT on BTF to test halo formation with matched/mismatched settings. Compare results with measured distribution.



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- And thank you for your attention