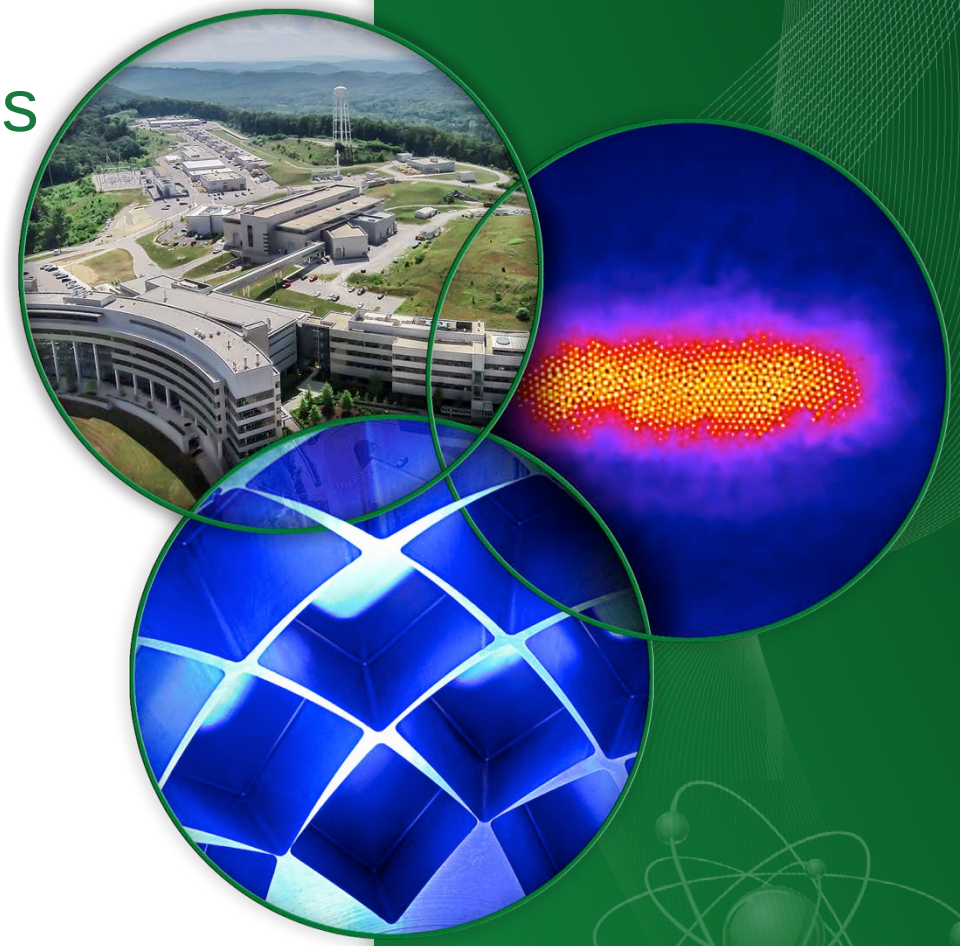
# Measurement of 6D Beam Distributions at Low Beam Energy



*A. Aleksandrov*

Oak Ridge National Laboratory,

USA

ORNL is managed by UT-Battelle
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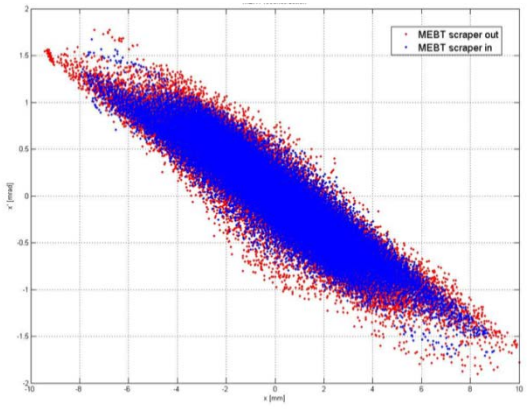
# Outline

- Introduction
  - What
  - Why
  - How
  - Challenges
- Practical Implementation
  - SNS Integrated Test Stand Facility
  - 6D distribution measurement tools
- Status and Plans

# We will measure charge distribution function in 6D beam phase space

$x, x', y, y', w, \varphi$ - coordinates in phase space

$f_2(x, x')$ - 2D distribution function




$f_4(x, x', y, y')$ - 4D distribution function

$f_6(x, x', y, y', w, \varphi)$ - 6D distribution function

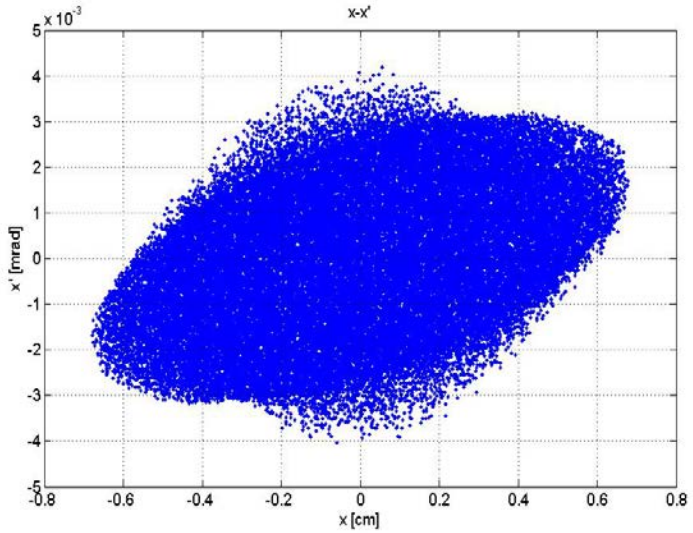
$$f_{3*2}(x, x', y, y', w, \varphi) = f_2(x, x') \cdot f_2(y, y') \cdot f_2(w, \varphi)$$

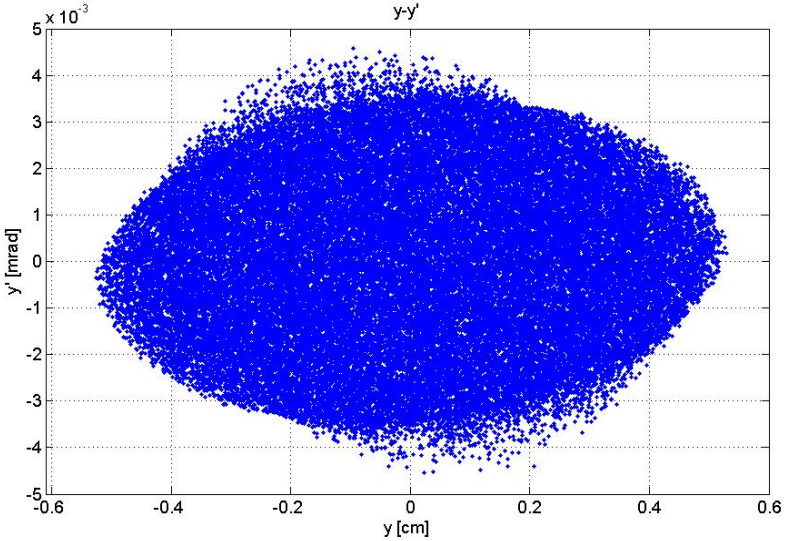
sometimes called 6D but

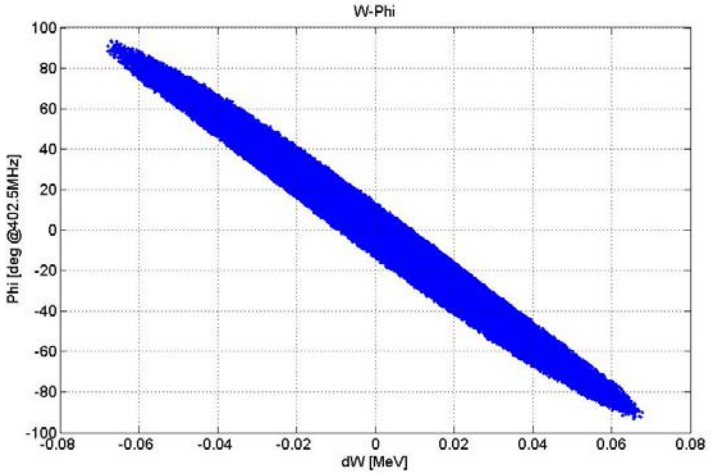
$$f_{3*2}(x, x', y, y', w, \varphi) \neq f_6(x, x', y, y', w, \varphi)$$

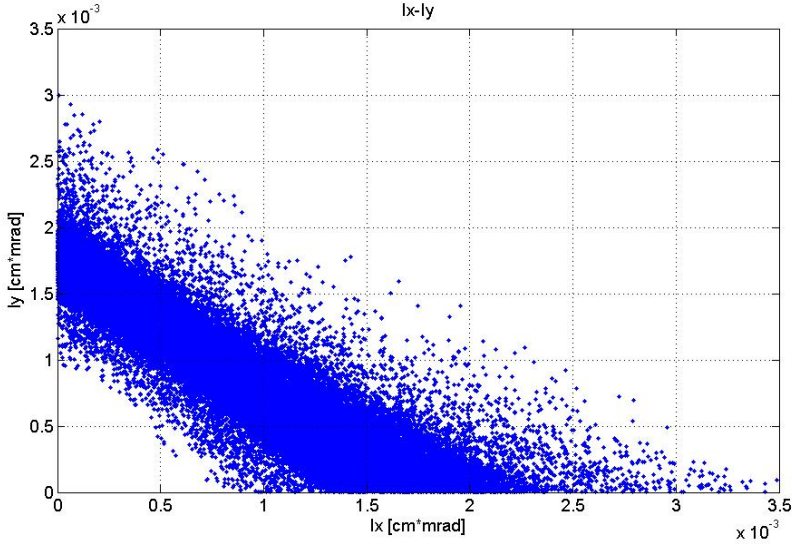
except for special case of no any correlations between degrees of freedom

# Example: ‘K - V like’ distribution



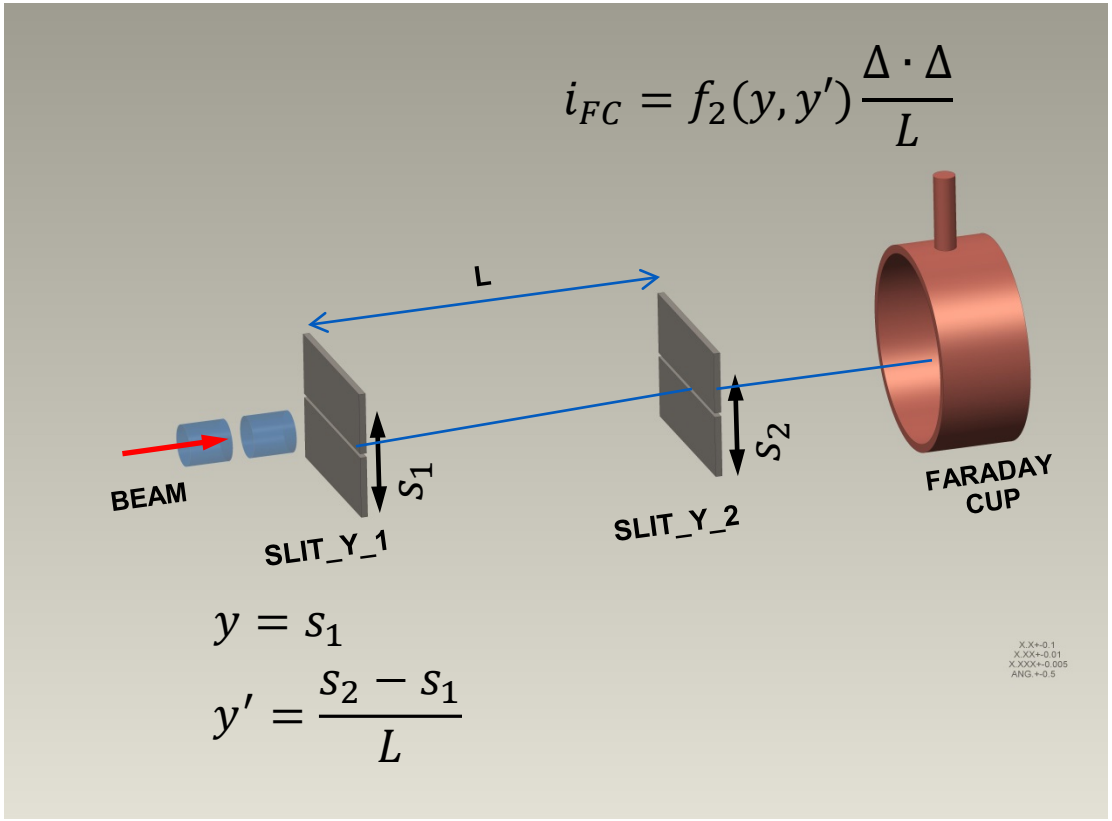



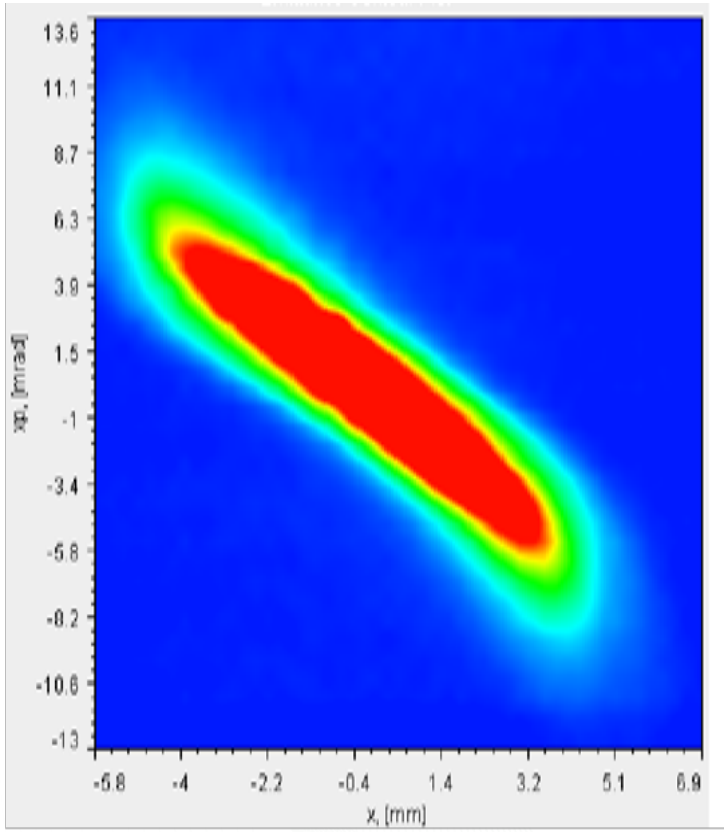



# Realistic initial distribution is needed for PIC simulation of beam dynamics in linac

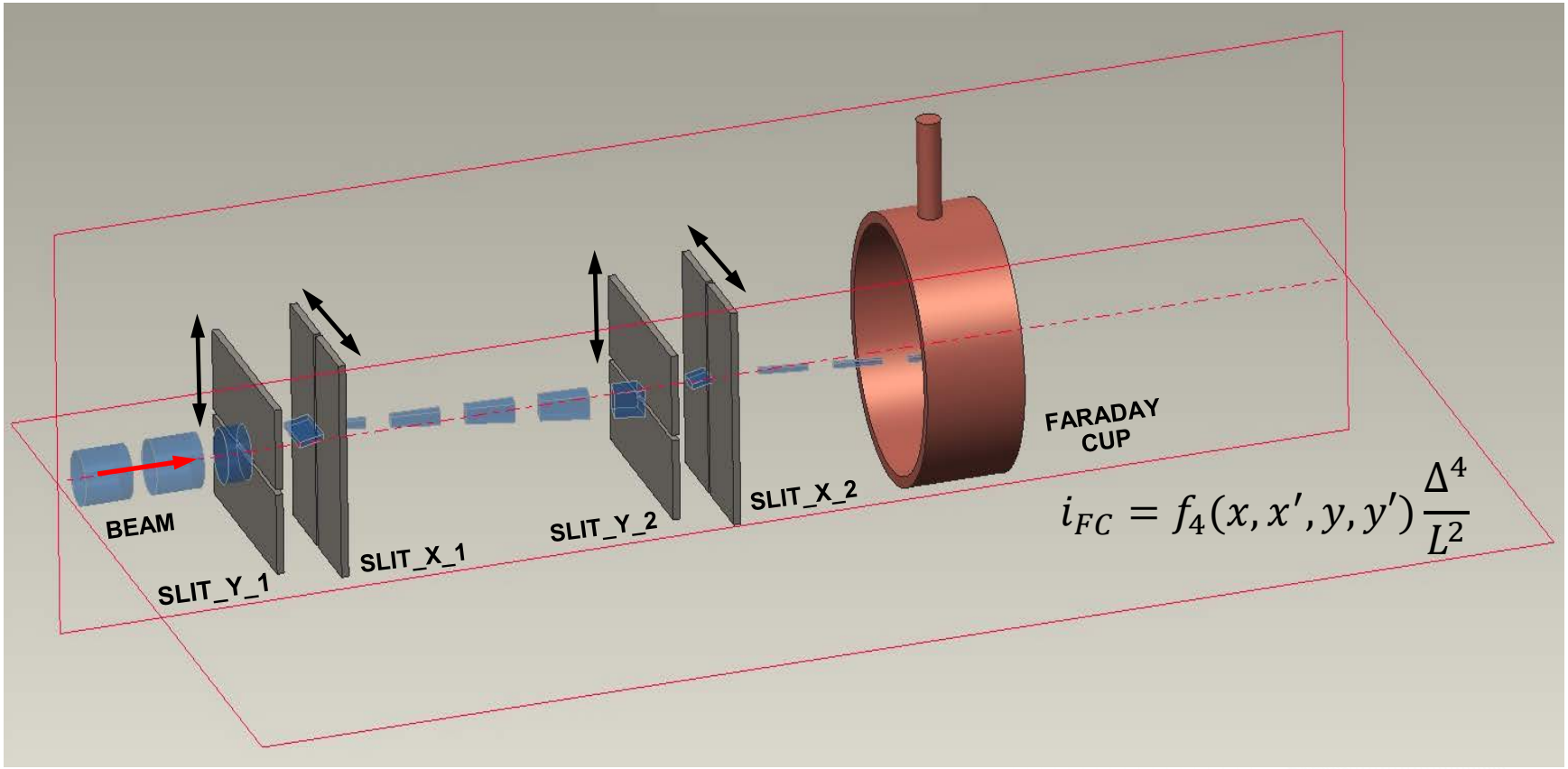
- End-to-end simulation starting from ion source plasma surface
  - No comments
- 4D distribution measurement after ion source + PIC simulation through RFQ
  - Accurate 4D measurement at RFQ entrance is difficult
  - Beam dynamics simulation in RFQ is most challenging part of linac simulation: strong space charge, many cells, no diagnostics
- 6D distribution reconstruction from 1or 2D measurements after RFQ
  - Absence of correlations between degrees of freedom is assumed without experimental validation
  - Dedicated experiment (LEDA) did not support this approach
- Direct measurement of 6D distribution after RFQ

# 2D distribution measurement (emittance) using slit-slit technique



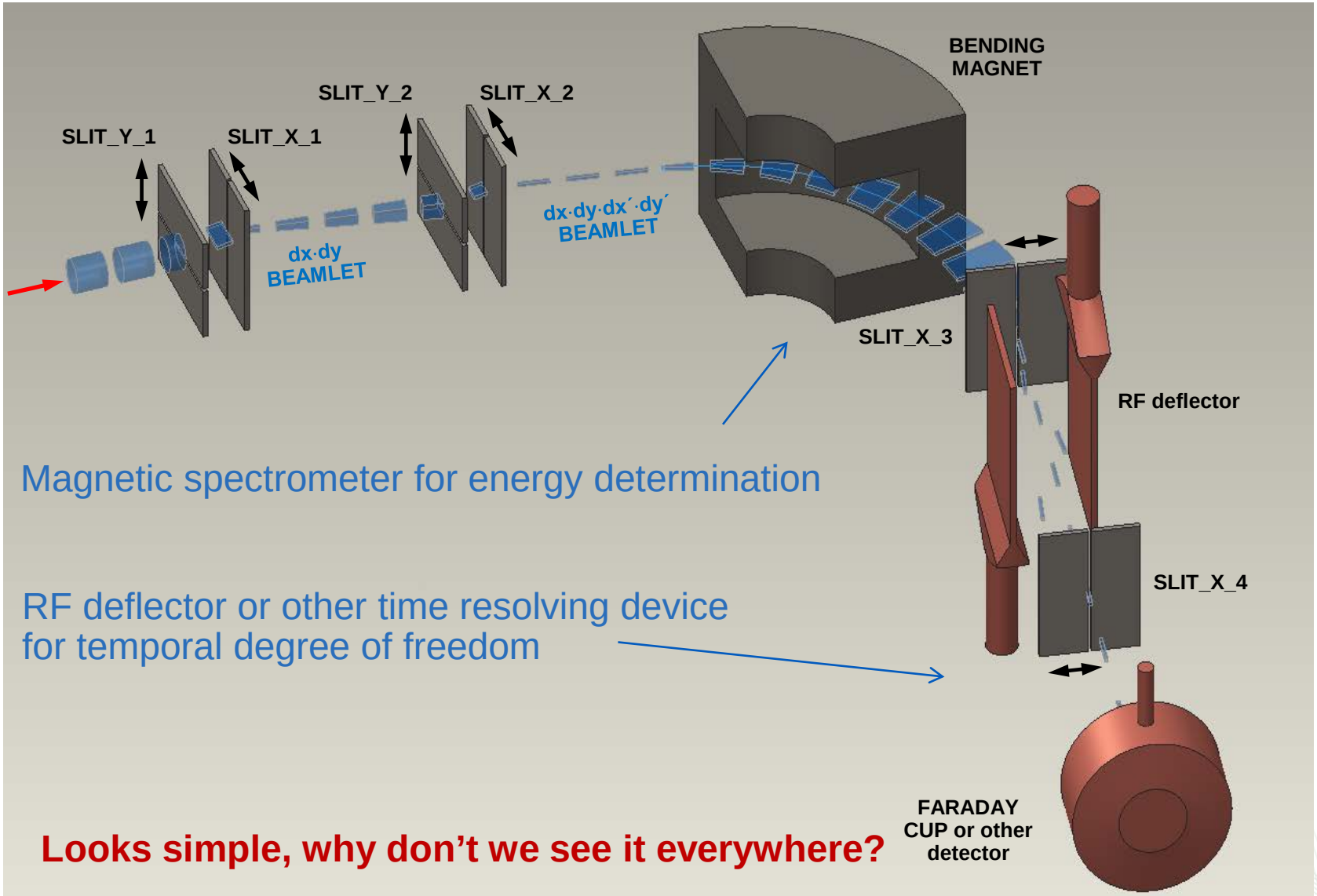
# 4D distribution measurement using four slits arrangement




$$x = s_{x1} \qquad y = s_{y1}$$

$$x' = \frac{s_{x2} - s_{x1}}{L} \qquad y' = \frac{s_{y2} - s_{y1}}{L}$$

# 6D distribution measurement arrangement




Magnetic spectrometer for energy determination

RF deflector or other time resolving device for temporal degree of freedom

**Looks simple, why don't we see it everywhere?**

# “Curse of dimensionality” problem

- High-dimensional spaces have very large volume: $V \sim a^D$
  - Large scan time
  - Low charge density
  - Large data sets

- Same setup can measure all lower dimension projections

  x - x’

  x – y

  x - φ

  x - w

  x’ - y - x

  x’ - φ - x

  x’ - w - x

  ….

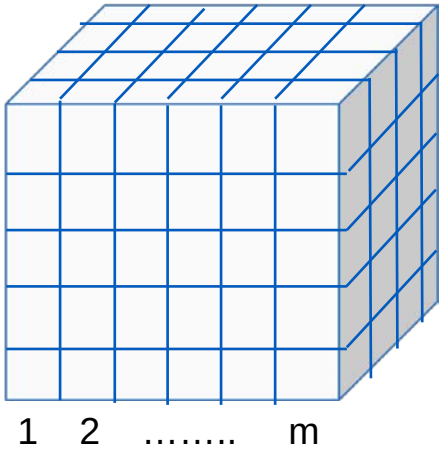
# Scan time estimate

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

$D$: dimensionality

$N_{bins}$: Total number of bins

$m$: Number of steps per degree of freedom

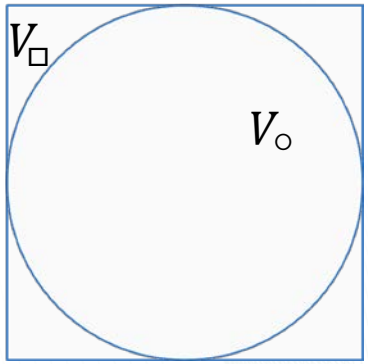



For $m = 10, D = 6$ $\quad N_{bins} = 10^6$

Total scan time at 1 $\frac{step}{sec}$: $T_{total} = 10^6\ sec = 280\ hours$

Total scan time at 10 $\frac{step}{sec}$: $T_{total} = 10^5\ sec = 28\ hours$

$$\frac{V_\circ}{V_\square} = \frac{\pi^{D}/_2}{\Gamma(^{D}/_2 + 1)2^D} = \begin{cases} .79\ ; & D = 2 \\ .52\ ; & D = 3 \\ .081; & D = 6 \end{cases}$$




**Tens of hours total scan time**

# Signal strength estimate

$$\mathrm{i} = I_0 \cdot \frac{\exp\left(-\frac{x^2}{2\sigma^2_x} - \frac{x'^2}{2\sigma^2_{x'}} - \frac{y^2}{2\sigma^2_y} - \frac{y'^2}{2\sigma^2_{y'}} - \frac{w^2}{2\sigma^2_w} - \frac{\varphi^2}{2\sigma^2_\varphi}\right)}{8\pi^3} \frac{\Delta_x}{\sigma_x} \frac{\Delta_{x'}}{\sigma_{x'}} \frac{\Delta_y}{\sigma_y} \frac{\Delta_{y'}}{\sigma_{y'}} \frac{\Delta_w}{\sigma_w} \frac{\Delta_\varphi}{\sigma_\varphi} \approx \frac{\exp(\dots)}{8\pi^3} \left(\Delta/\sigma\right)^6$$

For $\Delta/\sigma \approx .2$ current after all 6 slits $i \approx I_0 \cdot 2.6 \cdot 10^{-7} \cdot \exp(\dots)$

Number of particles in $I_0 \approx 32\, mA,\ \tau \approx 50\, \mu s$ beam pulse is $N_0 \approx 10^{13}$

Number of particles after 6 slits: $N_{FC} \approx 2.6 \cdot 10^6$ at the distribution center $\mathrm{r} = 0$

$N_{FC} \approx 1.3 \cdot 10^5$ at $\bar{X} = 1\,\sigma$

$N_{FC} \approx 16$ at $\bar{X} = 2\,\sigma$

$N_{FC} \approx 4.9 \cdot 10^{-6}$ at $\bar{X} = 3\,\sigma$

$N_{FC} \approx 3.5 \cdot 10^6$ at $\mathrm{r} = 2\,\sigma$

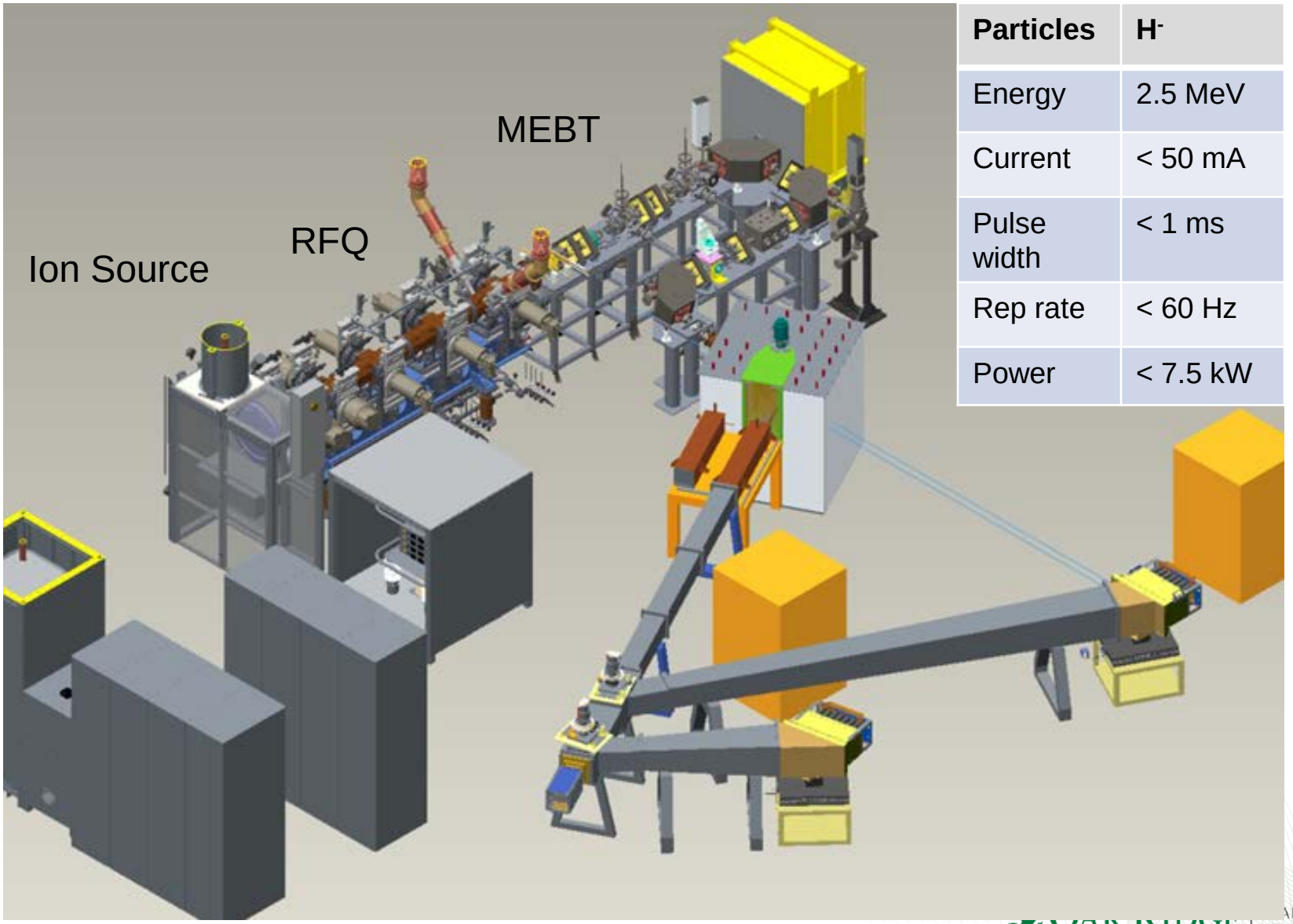
$N_{FC} \approx 2.9 \cdot 10^4$ at $\mathrm{r} = 3\,\sigma$

$N_{FC} \approx 9.7$ at $\mathrm{r} = 5\,\sigma$

Many hours of beam time allocated for single experiment is big challenge for any large scale accelerator facility

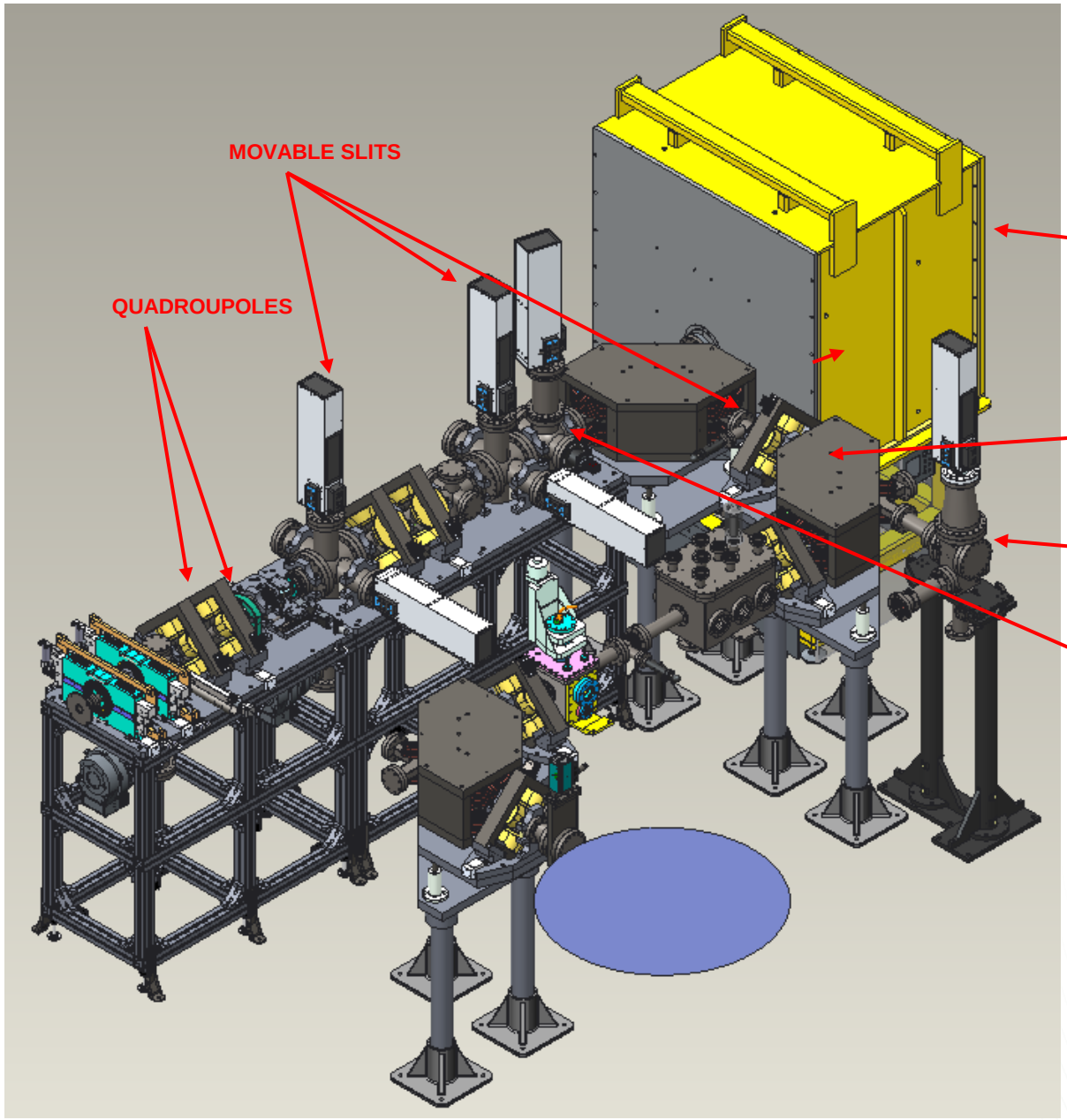
Only feasible at a dedicated facility

# SNS Integrated Test Stand Facility (ITSF)

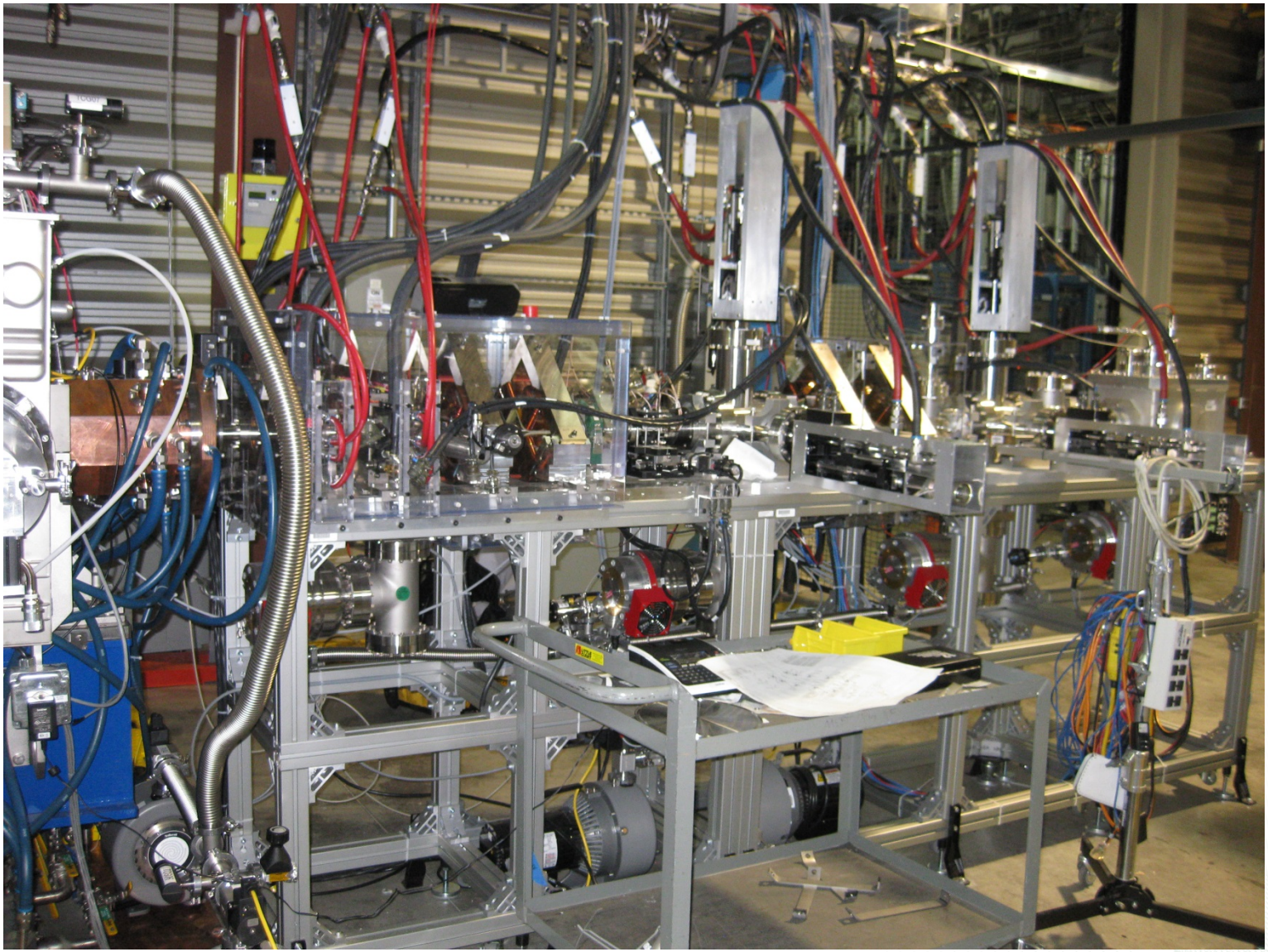



| Particles | $H^-$ |
|---|---|
| Energy | 2.5 MeV |
| Current | < 50 mA |
| Pulse width | < 1 ms |
| Rep rate | < 60 Hz |
| Power | < 7.5 kW |

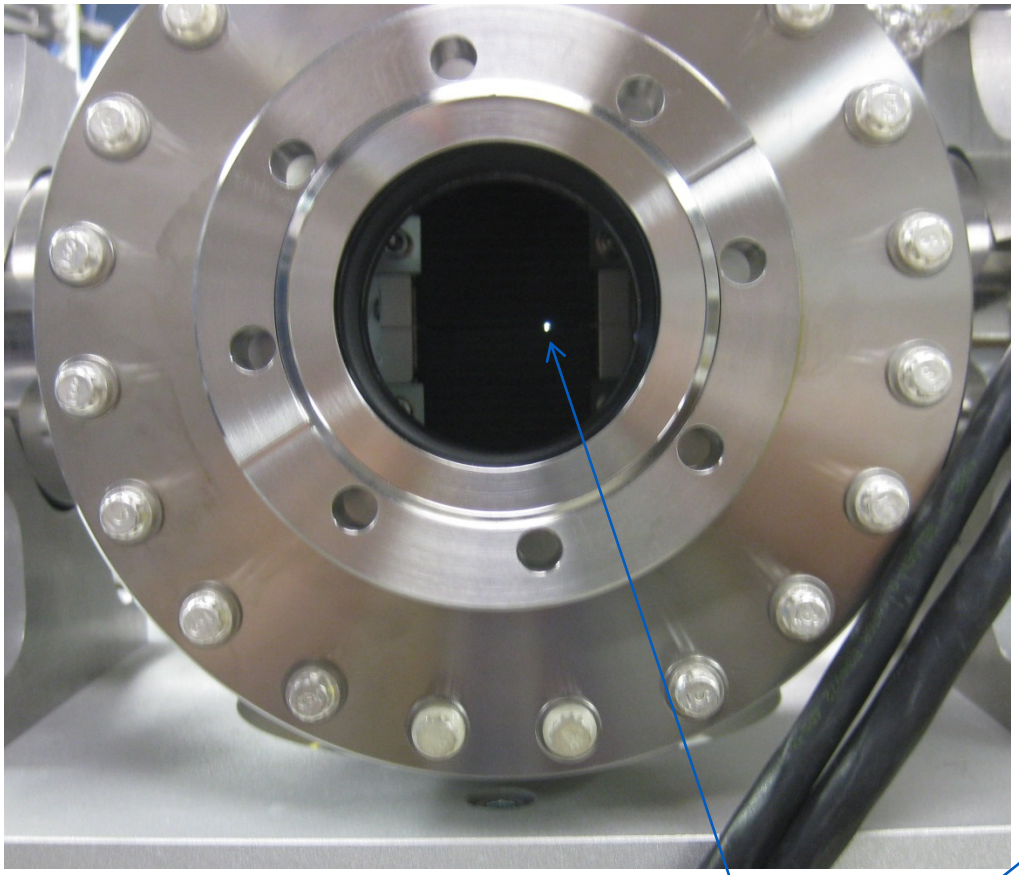
# ITSF Diagnostics Beam Line Layout

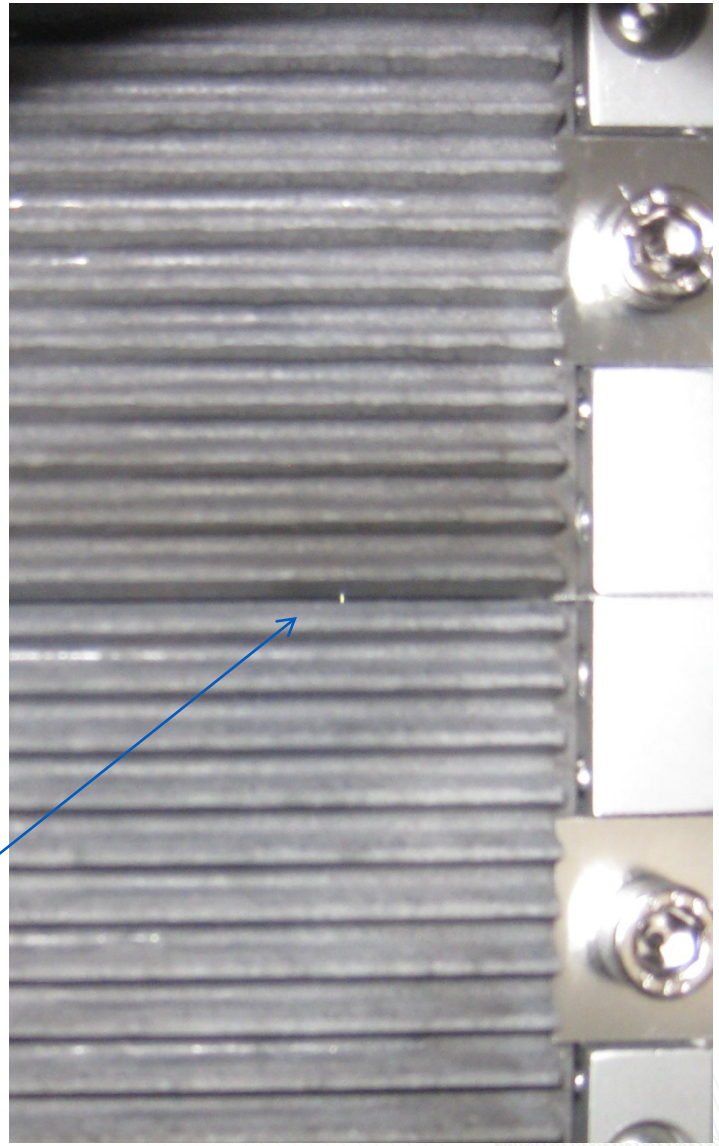


# ITSF MEBT



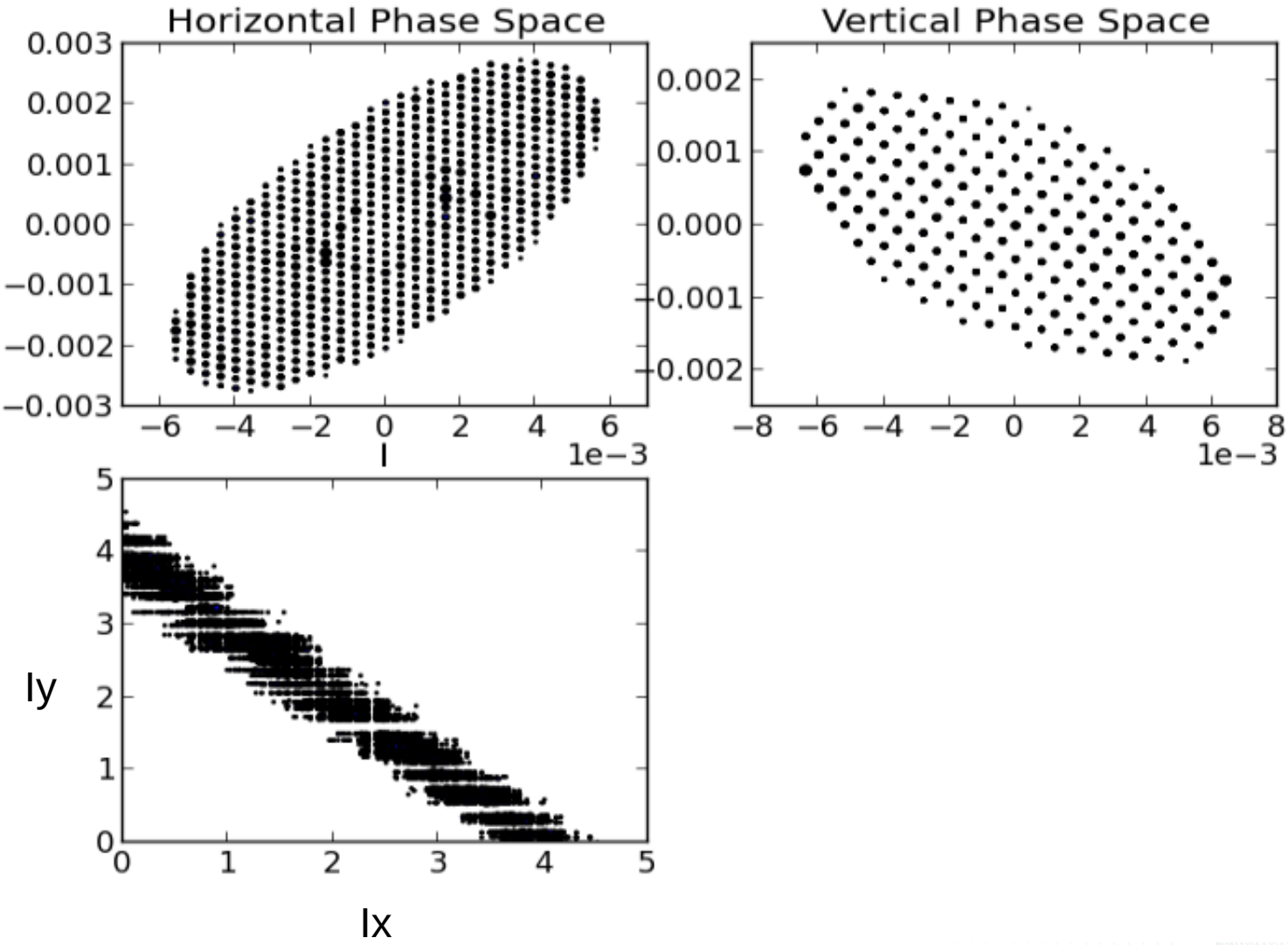
# X-Y Slit arrangement



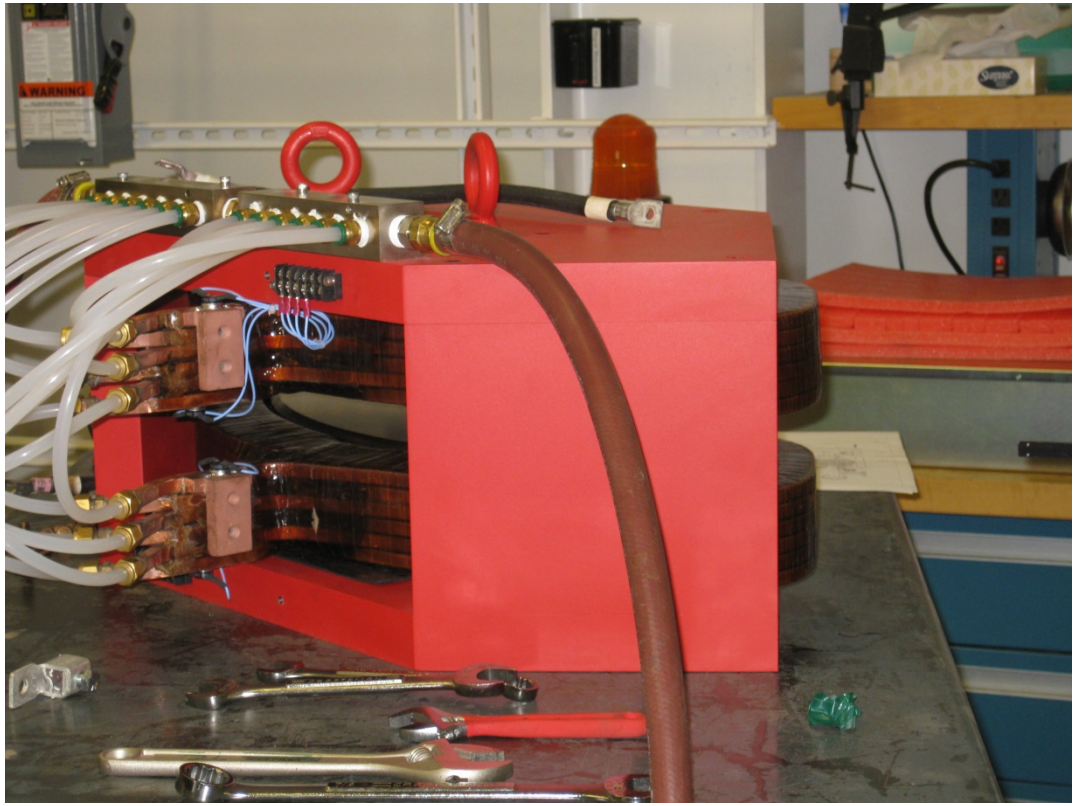


200-by-200 μm aperture

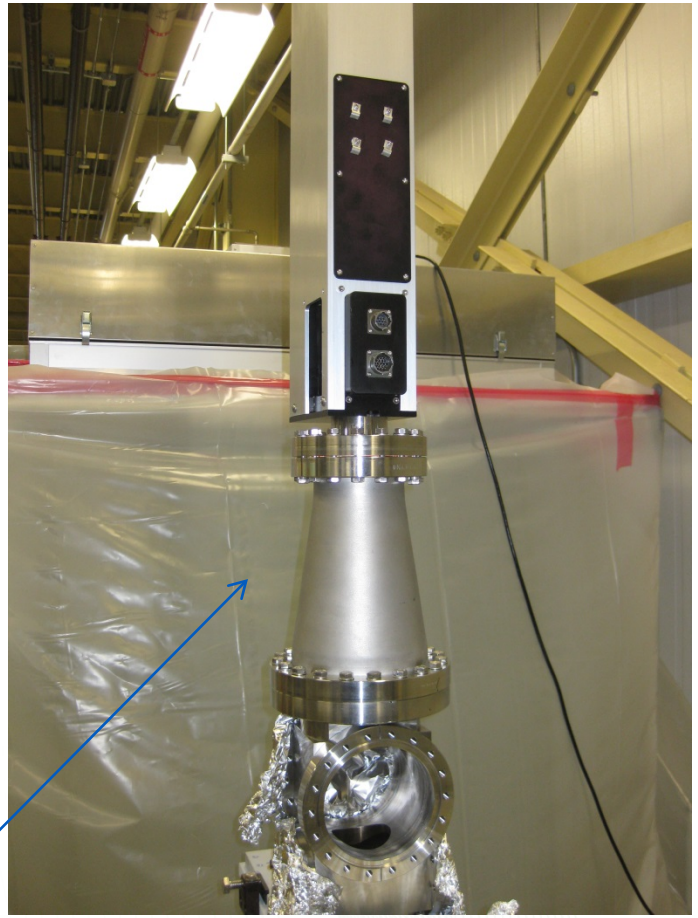
# Simulated scan of ‘K - V like’ distribution



# Equipment for E-φ degrees of freedom measurement to be installed



90º bending magnet

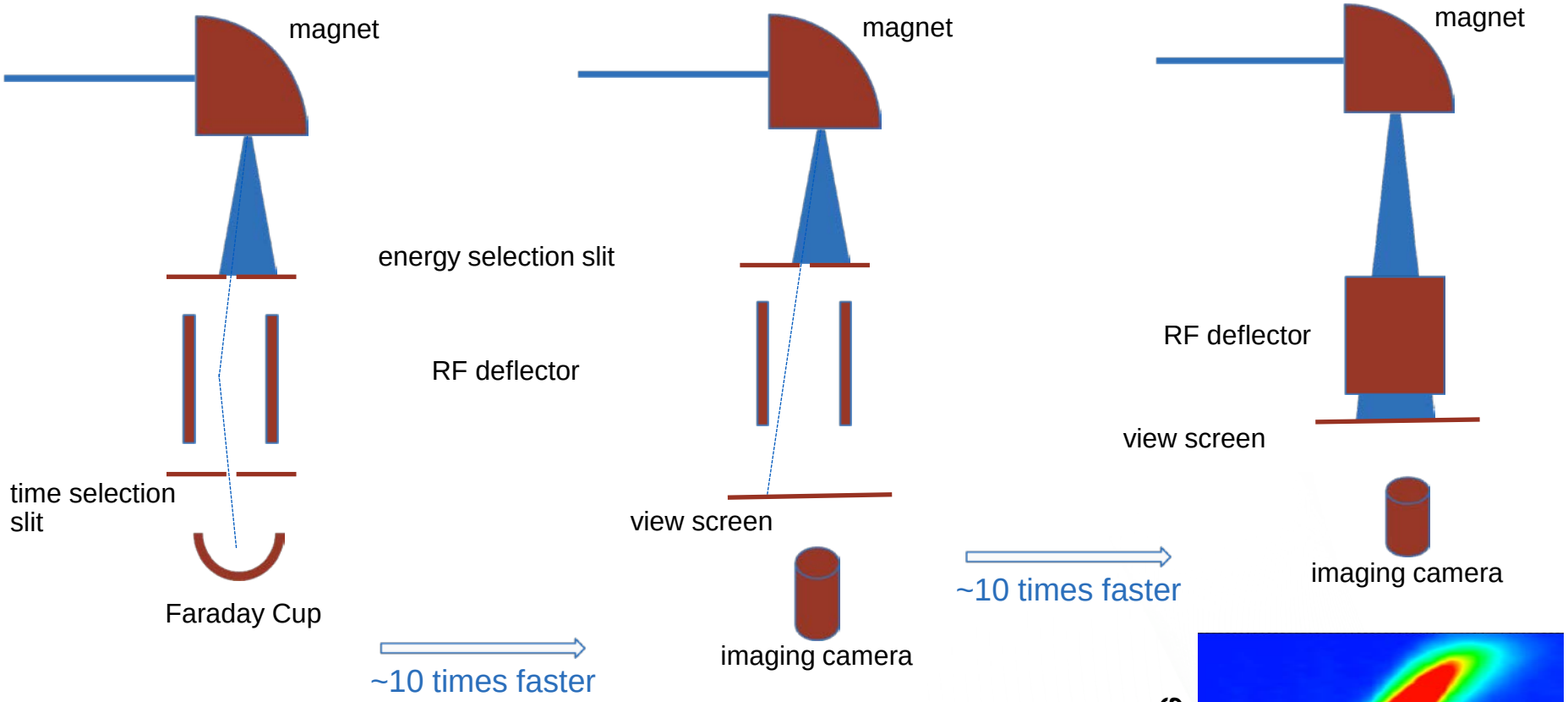


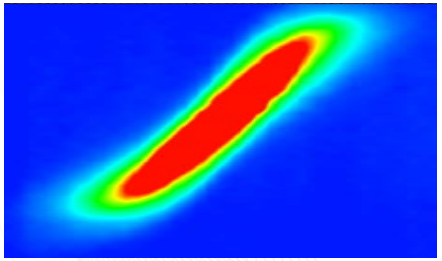
'RF deflector' type longitudinal profile monitor, aka 'Feschenko device'

# Status

| | |
|---|---|
| • Ion Source | operational |
| • RFQ | operational |
| • Straight beam line | operational |
| • Safety systems, documentation | in progress |
| • DOE approval | eventually |
| • 90º bend beam line | spring 2016 |

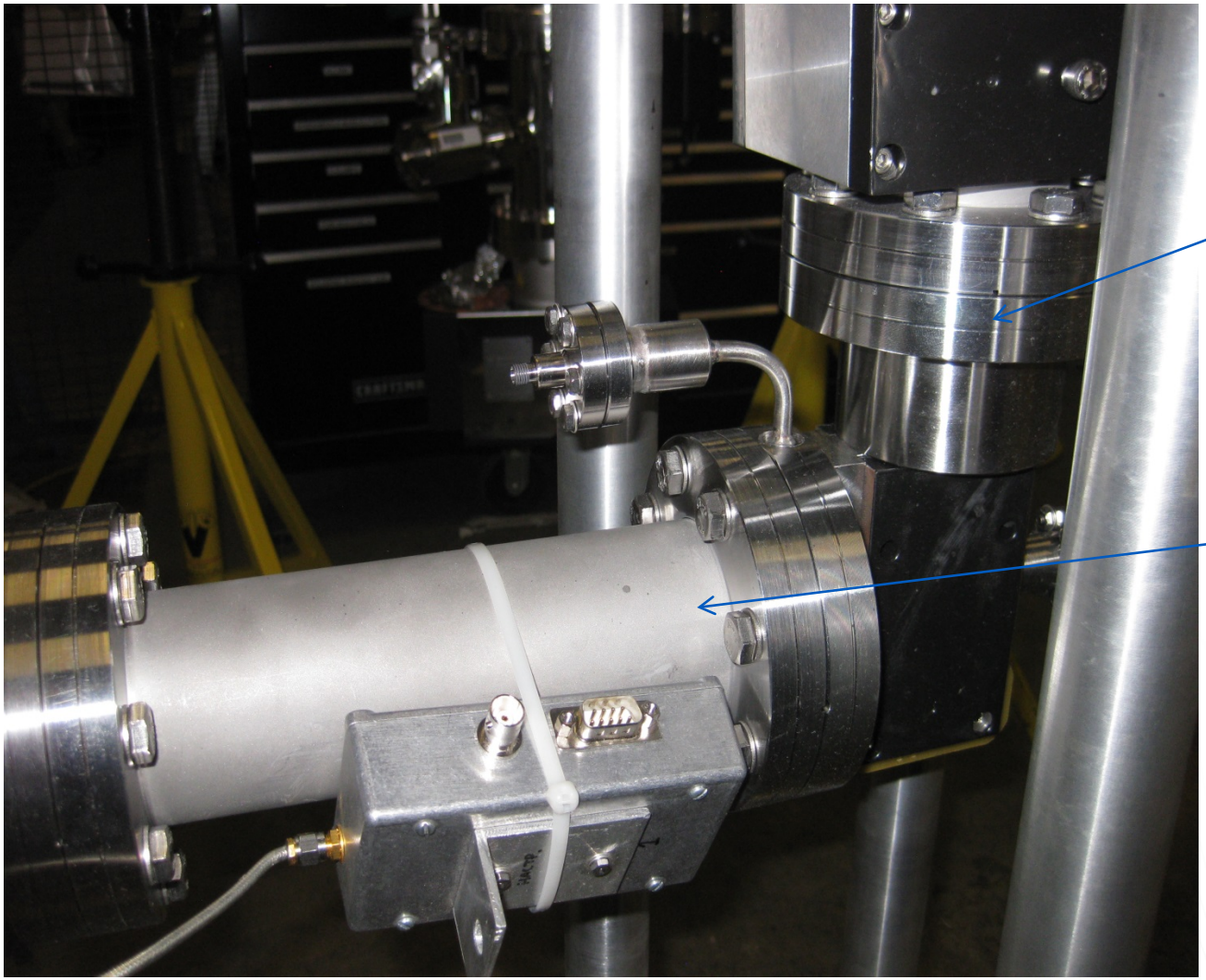
# Speeding up W-φ plane measurement




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

# Detector modification is simple



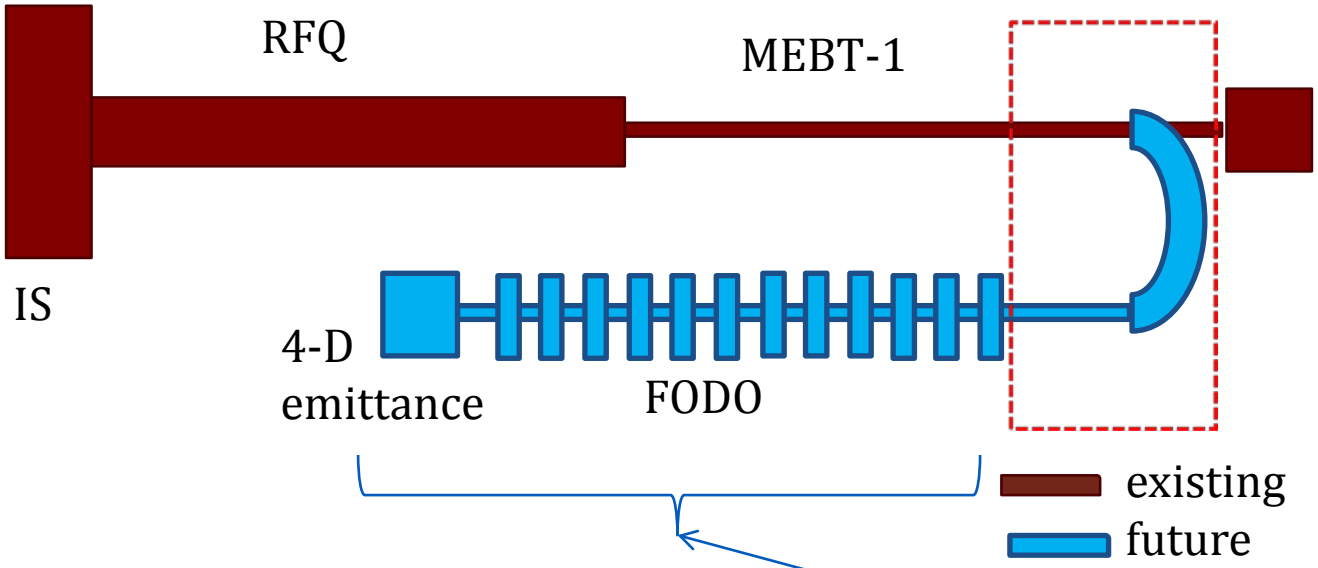
Slit mounted on this flange
to be replaced
with view screen

SEM and Faraday Cup
to be replaced
with digital camera

# Research goals

- Optimize 6D phase space measuring system for maximum resolution and dynamic range
- Develop algorithm for generating particle distributions for loading to PIC codes
- Search for high-dimensional correlations in the measured distribution
- Develop and verify methods of generating 6D distributions from low-dimensional projections
- Repeat LEDA beam dynamics experiment with newly developed diagnostics

# US National Science Foundation Grant with University of Tennessee (Sarah Cousineau is PI)




- Proposal highlights:
  - Direct 6D phase space measurement.
  - Study halo formation in FODO structure.
  - Benchmark codes (community resource), evaluate diagnostics.
  - Funding for 1 postdoc, 1 graduate student, 3 undergraduates for 3 years beginning in September 2015.

LEDA style beam dynamics experiment
To be designed, built and commissioned at ITSF

# Thank you for your attention!