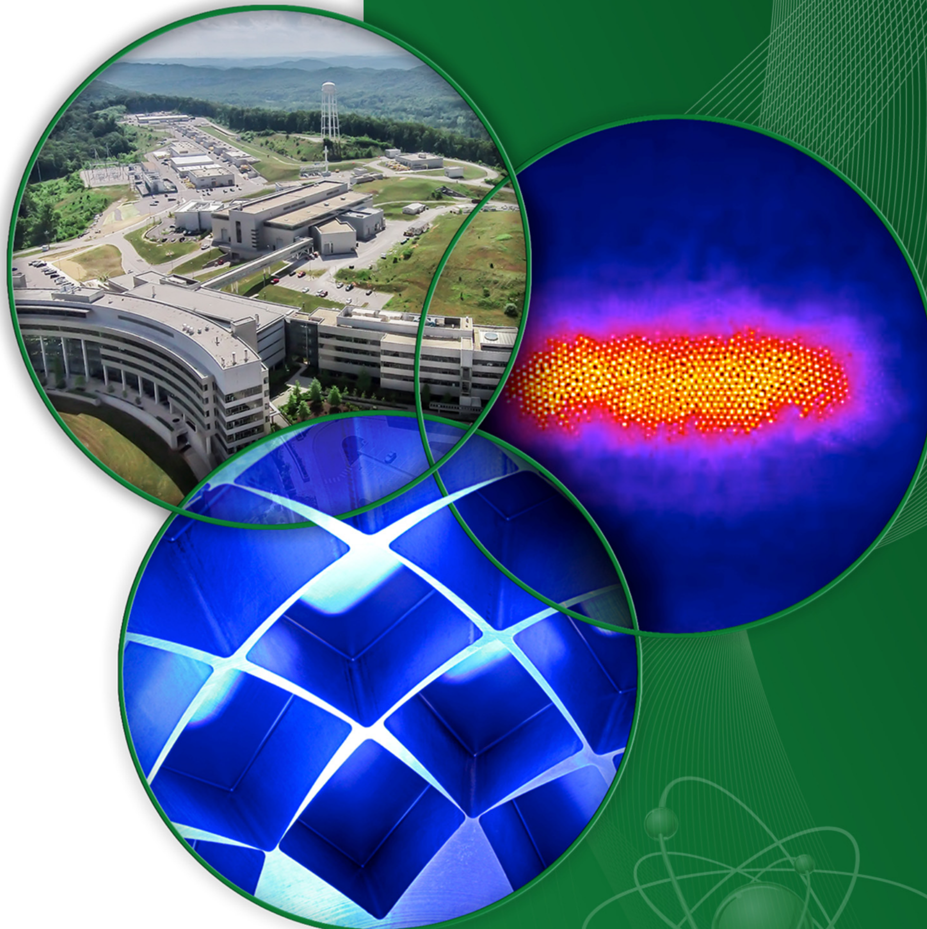
4-D and 6-D Emittance Determination for Hadron LINACs



A. Aleksandrov

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USA

Outline

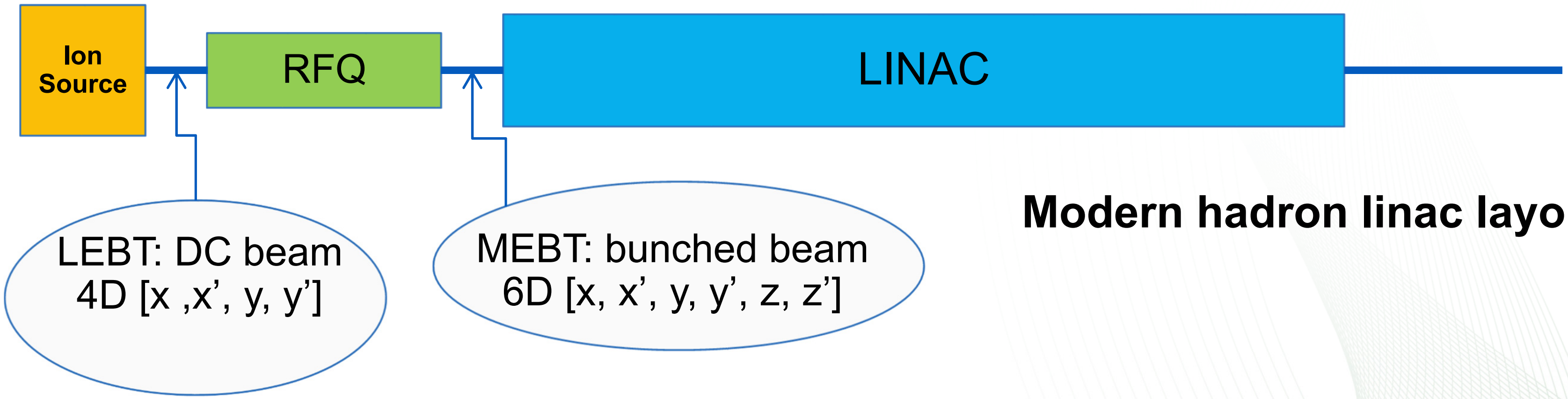
- Introduction
  - Why, what, definitions, etc.
- Example of 4D RMS emittance diagnostics at GSI
- Set up for 6D phase space scan at SNS

Why do we need to know 4D or 6D emittance?

- Generic answer is <u>to provide input data for computer simulation of beam dynamics</u>

What is specific about <u>RF linacs</u>?

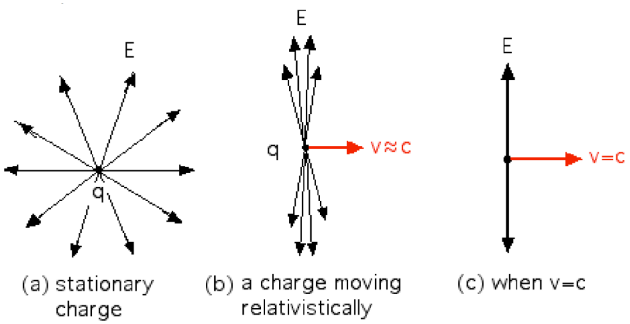
- Linac is single pass system → initial conditions in large degree define particles dynamics
- Beam is bunched and bunch is short → 6D phase space



Modern hadron linac layout

What is specific about hadron RF linacs?

- Non-relativistic energy (γ=1- 2)
  - Large un-normalized emittance (mm range beam size)
  - Significant space charge
  - Weak synchrotron radiation
  - Weak EM field contraction



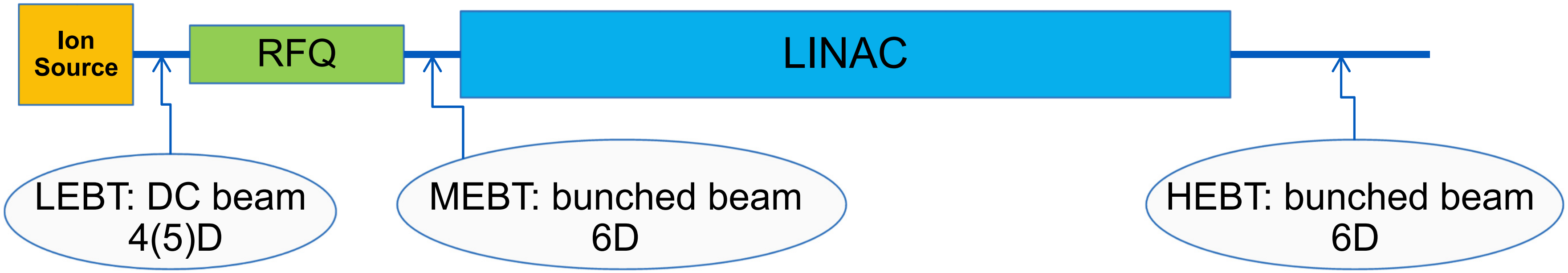
- Particles interaction with materials
  - Large power deposition volume density
  - Material sputtering
  - Neutron production and activation

There is significant difference even within hadrons family:

- Protons
- H-
- Light ions
- Heavy ions

!

Initial parameters for beam dynamics simulation



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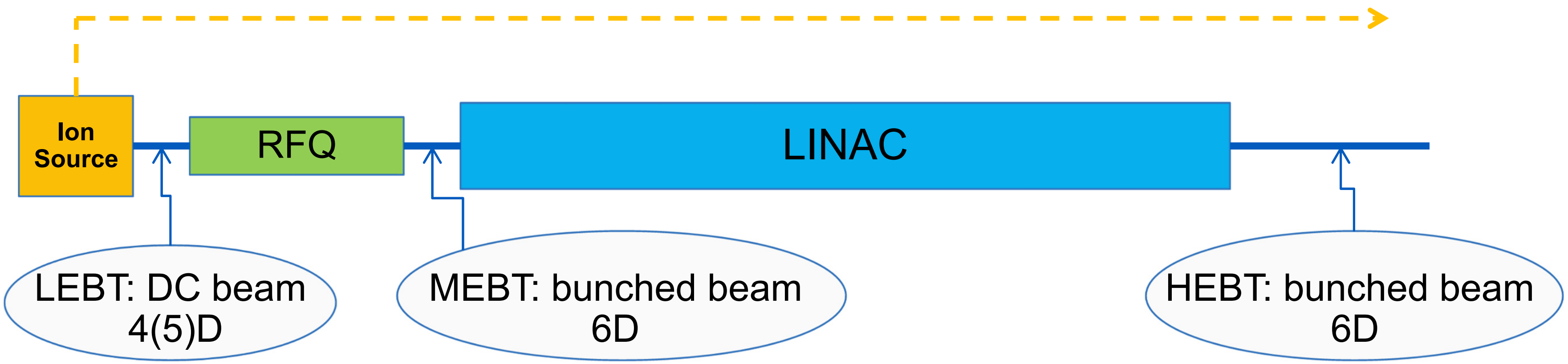
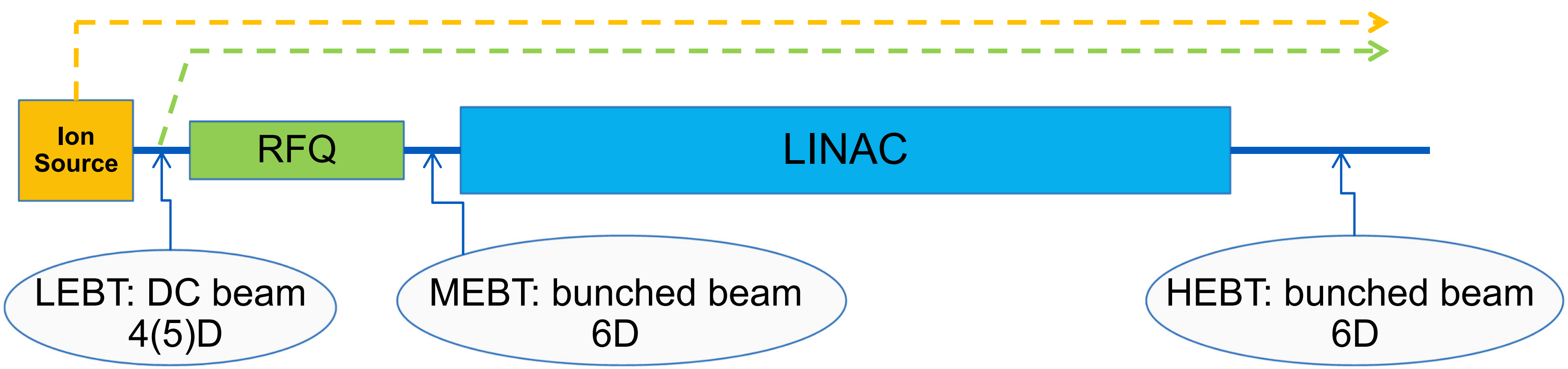


- End-to-end simulation starting from ion source plasma surface
  - No measurements involved. No comments

Initial parameters for beam dynamics simulation



- End-to-end simulation starting from ion source plasma surface
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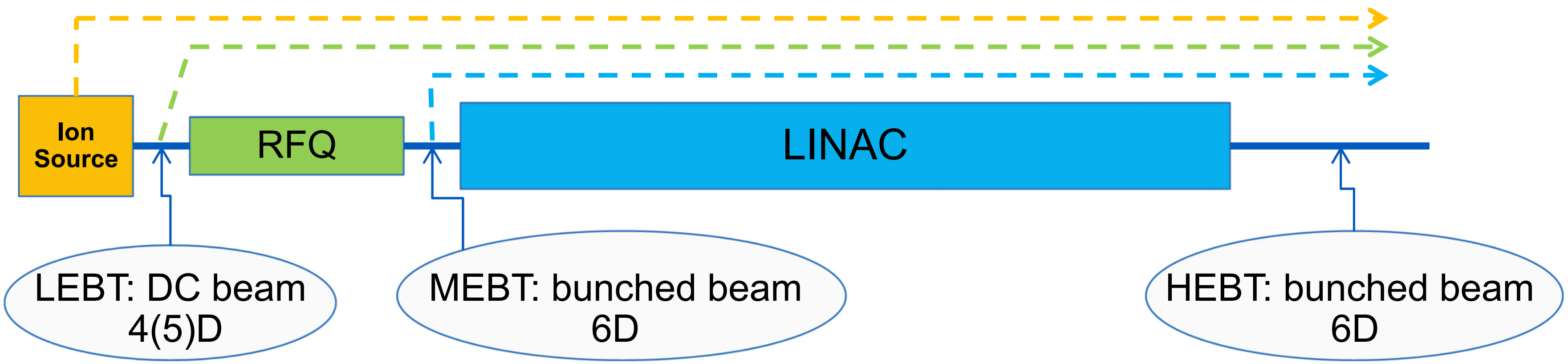
- Measure 4D distribution at ion source exit
  - Beam dynamics in RFQ is the most challenging part of linac simulation: strong space charge, many cells, no diagnostics

Initial parameters for beam dynamics simulation



- End-to-end simulation starting from ion source plasma surface
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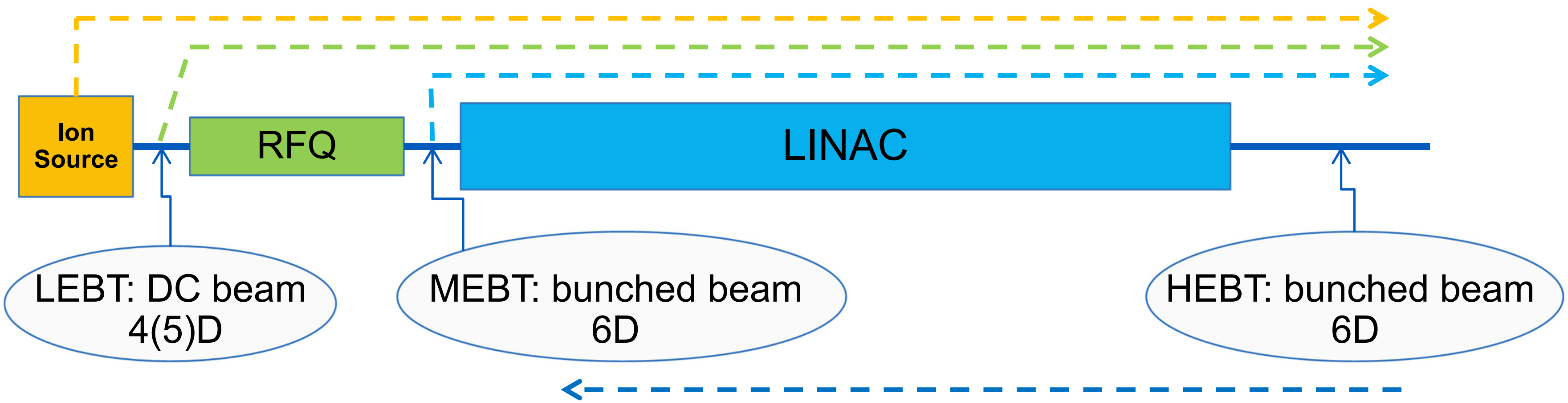
- Measure 4D distribution at ion source exit
  - Beam dynamics in RFQ is the most challenging part of linac simulation: strong space charge, many cells, no diagnostics
- Measure 6D distribution at RFQ exit
  - The most challenging from beam instrumentation point of view

Initial parameters for beam dynamics simulation



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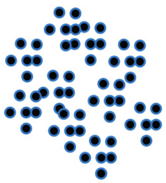
Bunch representation



$N \sim 10^8 \div 10^9$

particle #	coordinates
1	x, x', y, y', z, z'
2	x, x', y, y', z, z'
.	.
.	.
N	x, x', y, y', z, z'

$\Big\}$ $6N$ numbers

impossible to measure individual particles positions
need to simplify representation

σ-matrix formalism

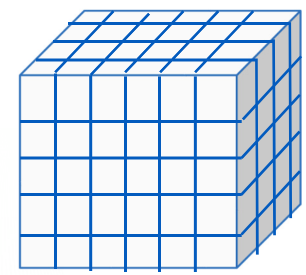
$$
\begin{array}{c}
 \\ x \\ x' \\ y \\ y' \\ z \\ z'
\end{array}
\begin{array}{c}
\begin{array}{cccccc} x & x' & y & y' & z & z' \end{array} \\
\begin{pmatrix}
\langle xx\rangle & \langle xx'\rangle & \langle xy\rangle & \langle xy'\rangle & \langle xz\rangle & \langle xz'\rangle \\
\langle x'x\rangle & \langle x'x'\rangle & \langle x'y\rangle & \langle x'y'\rangle & \langle x'z\rangle & \langle x'z'\rangle \\
\langle yx\rangle & \langle yx'\rangle & \langle yy\rangle & \langle yy'\rangle & \langle yz\rangle & \langle yz'\rangle \\
\langle y'x\rangle & \langle y'x'\rangle & \langle y'y\rangle & \langle y'y'\rangle & \langle y'z\rangle & \langle y'z'\rangle \\
\langle zx\rangle & \langle zx'\rangle & \langle zy\rangle & \langle zy'\rangle & \langle zz\rangle & \langle zz'\rangle \\
\langle z'x\rangle & \langle z'x'\rangle & \langle z'y\rangle & \langle z'y'\rangle & \langle z'z\rangle & \langle z'z'\rangle
\end{pmatrix}
\end{array}
$$

Statistical RMS representation requires

21 numbers for 6D
10 numbers for 4D

distribution function

number of particles per bin in phase space



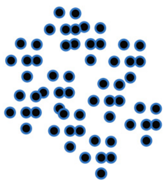
$$f(x, x', y, y', z, z') =$$

$$= \frac{N(x \pm \Delta, x' \pm \Delta, y \pm \Delta, y' \pm \Delta, z \pm \Delta, z' \pm \Delta)}{N_{total}}$$

Distribution function representation requires

n^6 numbers for 6D
n^4 numbers for 4D

Bunch representation



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1	x, x', y, y', z, z'
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.	.
.	.
N	x, x', y, y', z, z'

$6N$ numbers

impossible to measure individual particles positions
need to simplify representation

σ-matrix formalism

$x \quad x' \quad y \quad y'$

x <xx> <xx'> <xy> <

x' <x'x> <x'x'> <x'y>

y <yx> <yx'> <yy>

y' <y'x> <y'x'> <y'y>

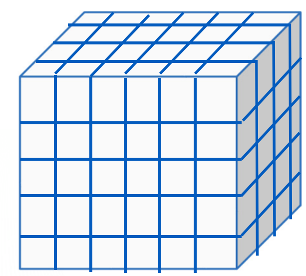
z <zx> <zx'> <zy> <zy

z' <z'x> <z'x'> <z'y> <z'y'> <z'z'

Both representations are measurable and usable to initiate simulation

...ribution function

...rticles per ...pace



$$\frac{\ldots, y \pm \Delta, y' \pm \Delta, z \pm \Delta, z' \pm \Delta)}{N_{total}}$$

Statistical RMS representation requires

21 numbers for 6D
10 numbers for 4D

Distribution function representation requires

n^6 numbers for 6D
n^4 numbers for 4D

σ-matrix vs. distribution function

Measured σ-matrix can be used directly as input for <u>RMS envelope tracking codes</u>:

- Simulate dynamics of beam core only (RMS bunch size)
- Linear motion only
- Cannot predict beam loss

Measured distribution function can be used to generate particles as input for <u>Particle-In-Cell (PIC) tracking codes:</u>

- Simulate dynamics of beam core, tails and halo (track individual particles)
- Non-linear motion in realistic e/m fields
- Should be capable of predicting beam loss

Known distribution function is sufficient for calculating σ matrix

Known σ matrix <u>is not sufficient</u> for calculating distribution function

σ-matrix vs. distribution function

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- Simulate dynamics of beam core only (RMS bunch size)
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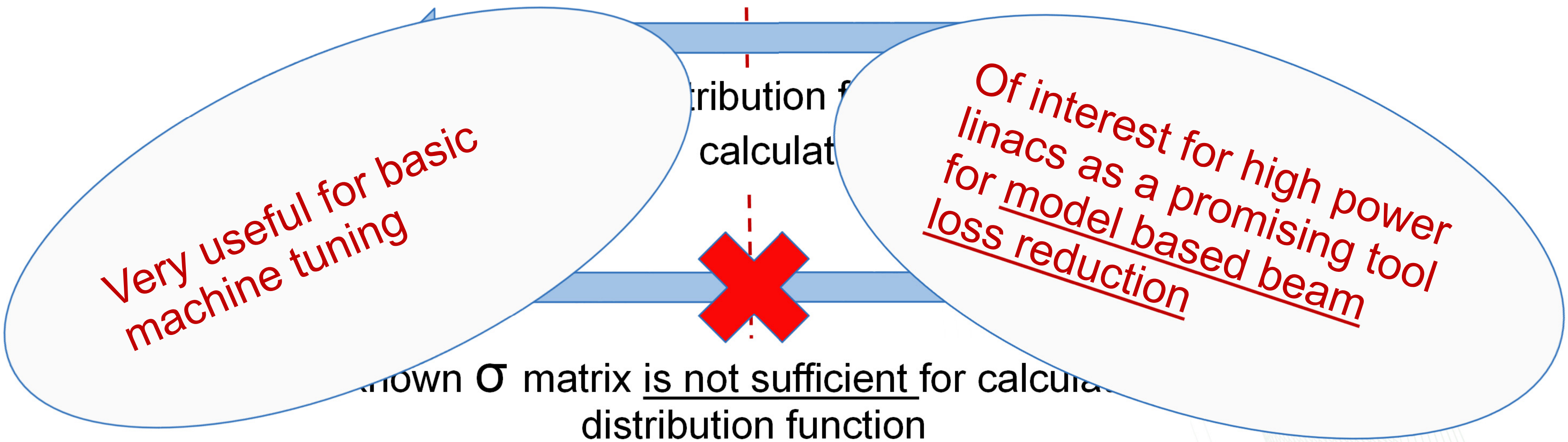
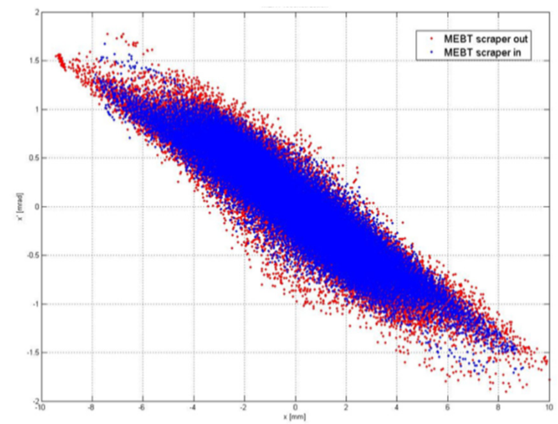


True high dimensional distribution functions

$f_6(x,x',y,y',z,z')$ - true 6D distribution function as defined earlier

$f_2(x,x'); f_2(y,y');\ f_2(z,z')$ → easily measurable 2D projections of f_6 on x, y, z planes



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

↑

Sometimes is called 6D erroneously but

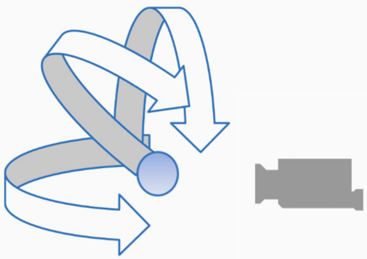
$$f_{3*2}(x,x',y,y',z,z') \neq f_6(x,x',y,y',z,z')$$

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

zero correlation terms in 6D σ-matrix do not guarantee absence of higher order correlations in f_6

How to measure emittance?

Reconstruction from lower dimensional projections



Rotate object
or detector

σ-matrix

exact solution in absence of space charge if number of projections:

- >3 for 2D
- >10 for 4D
- >21 for 6D

well established in 2D
('quad scan' technique)
well established in 4D
(example in next section)

??? for 6D

distribution function

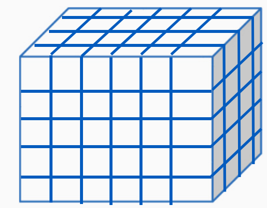
<u>phase space tomography</u> provides approximate solution

well established in 2D

algorithm proposed for 4D

??? for 6D

direct phase space sampling



distribution function

well established in 2D
(slit-slit; slit-grid etc. scan)

well established in 4D
(pepper pot)

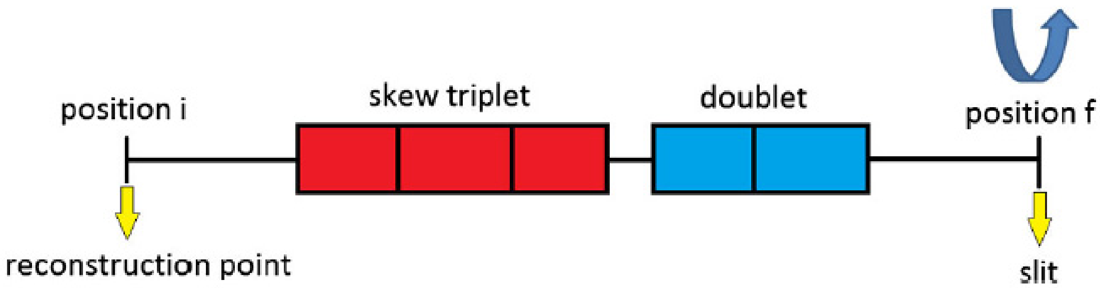
to be demonstrated in 6D
(last part of this talk)

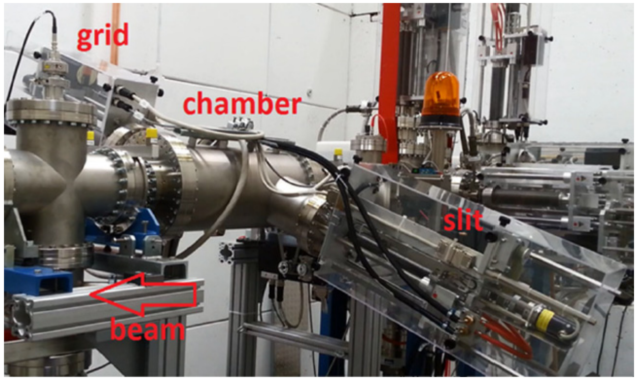
Measuring RMS in 4D example: ROSE at GSI

PHYSICAL REVIEW ACCELERATORS AND BEAMS 19, 072802 (2016)

'Rotating system for four-dimensional transverse rms-emittance measurements'

C. Xiao, M. Maier, X. N. Du, P. Gerhard, L. Groening, S. Mickat, and H. Vormann





$$\langle xy\rangle_f^{a,b} = m_{11}^{a,b} m_{33}^{a,b}\langle xy\rangle_i + m_{11}^{a,b} m_{34}^{a,b}\langle xy'\rangle_i + m_{12}^{a,b} m_{33}^{a,b}\langle x'y\rangle_i + m_{12}^{a,b} m_{34}^{a,b}\langle x'y'\rangle_i,$$

....

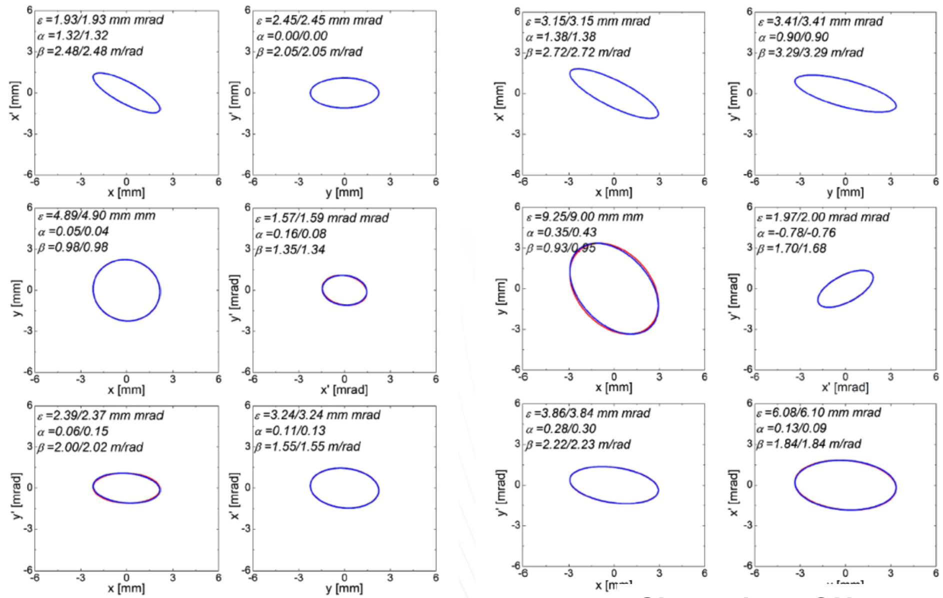
$$\langle xx'\rangle_\theta^{a,b} = \cos^2\theta\langle xx'\rangle_f^{a,b} + \sin\theta\cos\theta\langle xy'\rangle_f^{a,b} + \sin\theta\cos\theta\langle x'y\rangle_f^{a,b} + \sin^2\theta\langle yy'\rangle_f^{a,b},$$

....

$$\begin{bmatrix} \langle xy\rangle_i \\ \langle xy'\rangle_i \\ \langle x'y\rangle_i \\ \langle x'y'\rangle_i \end{bmatrix} = (\Gamma^T\Gamma)^{-1}\Gamma^T\Lambda,$$

Contains known transport matrix elements

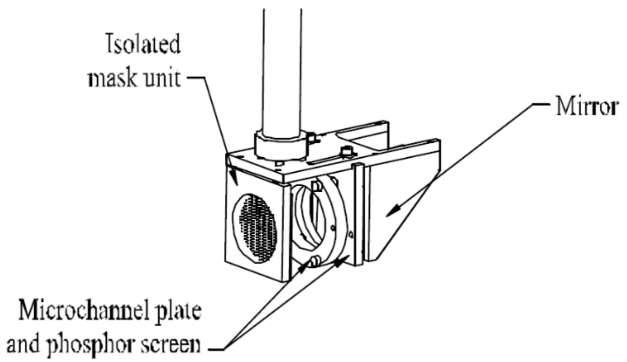
Contains measured 2-nd moments

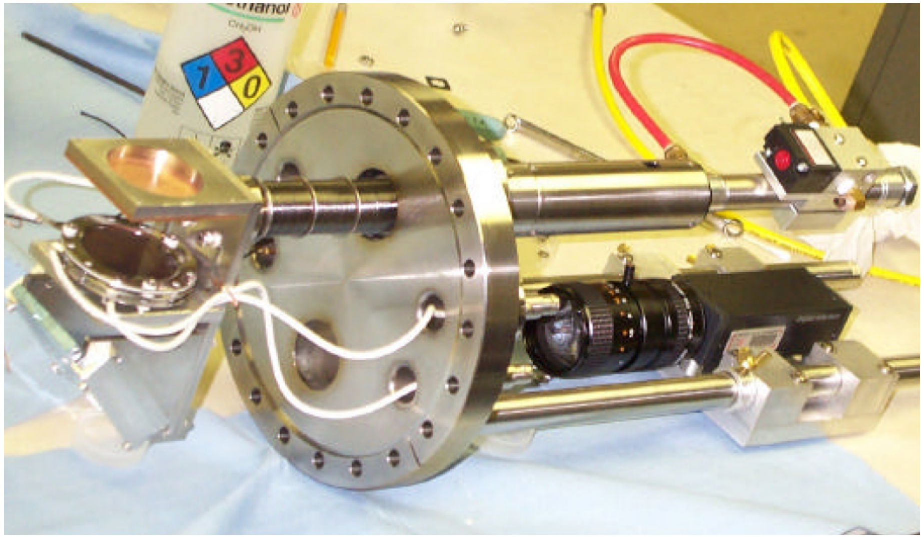


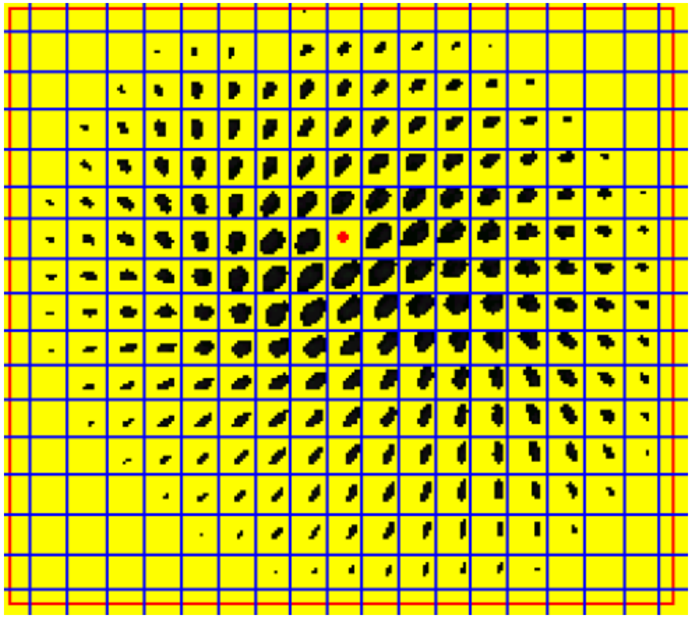
Skew triplet OFF **Skew triplet ON**

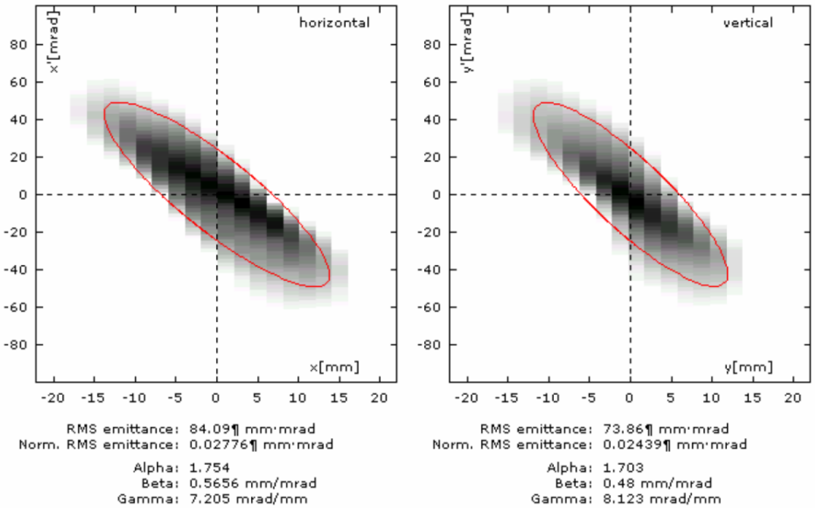
Measuring 4D distribution function. Pepper pot.

BNL C-AD Technote C-A/AP/#244 A. Pikin, A. Kponou, J. Ritter, V. Zajic







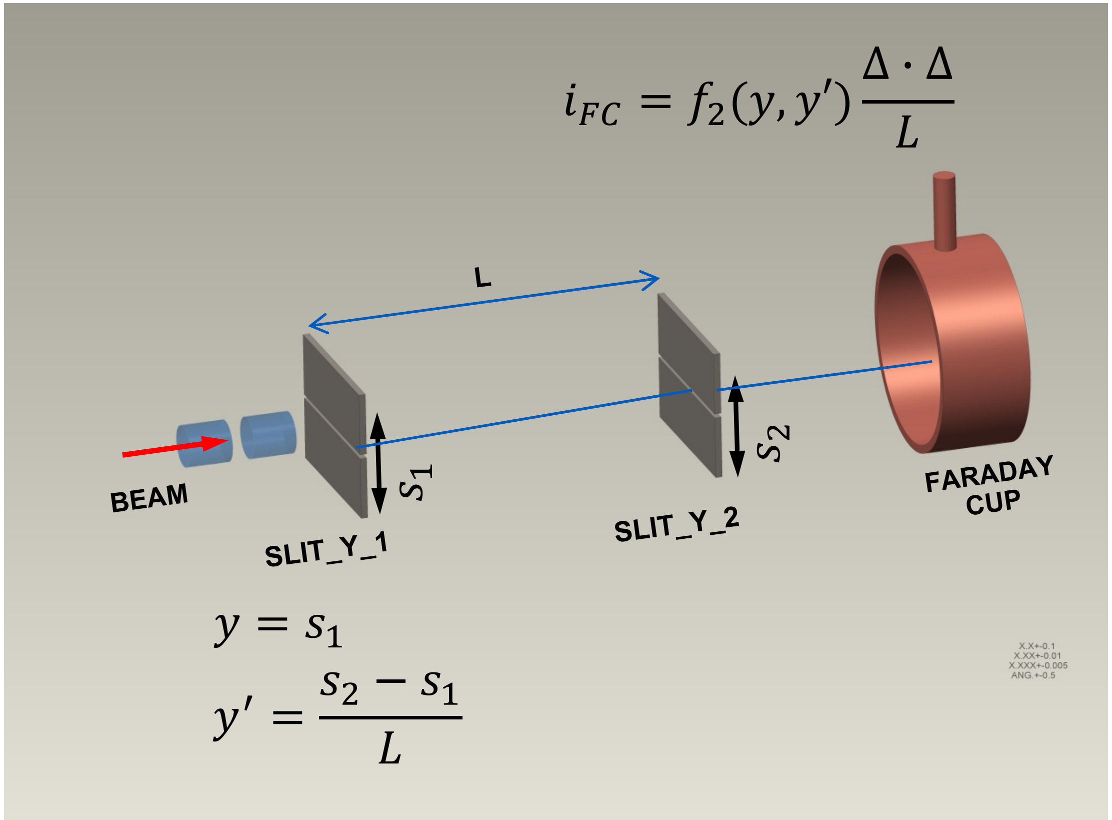


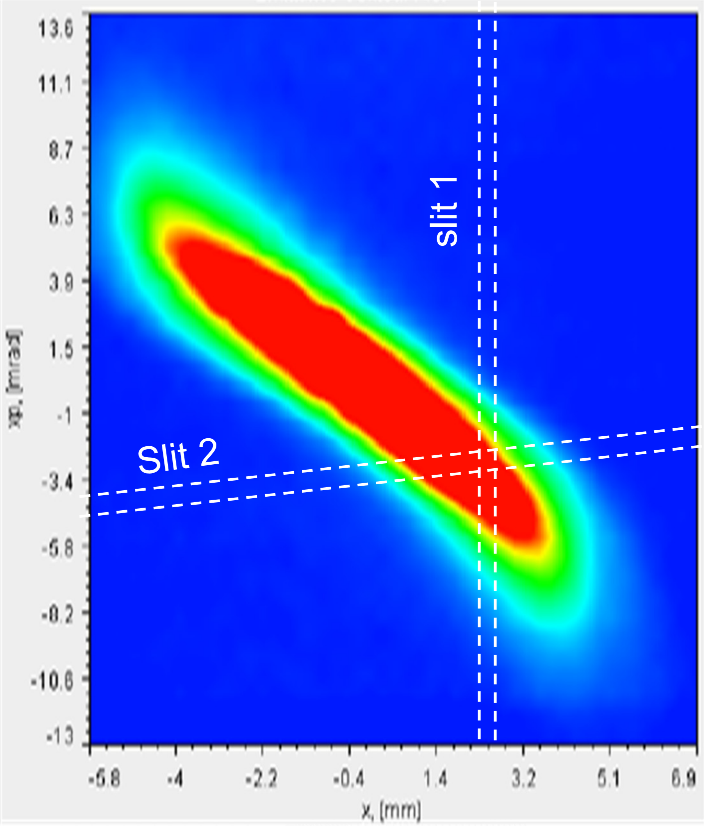
4D emittance measurement techniques are well established

Can we measure 6D emittance?

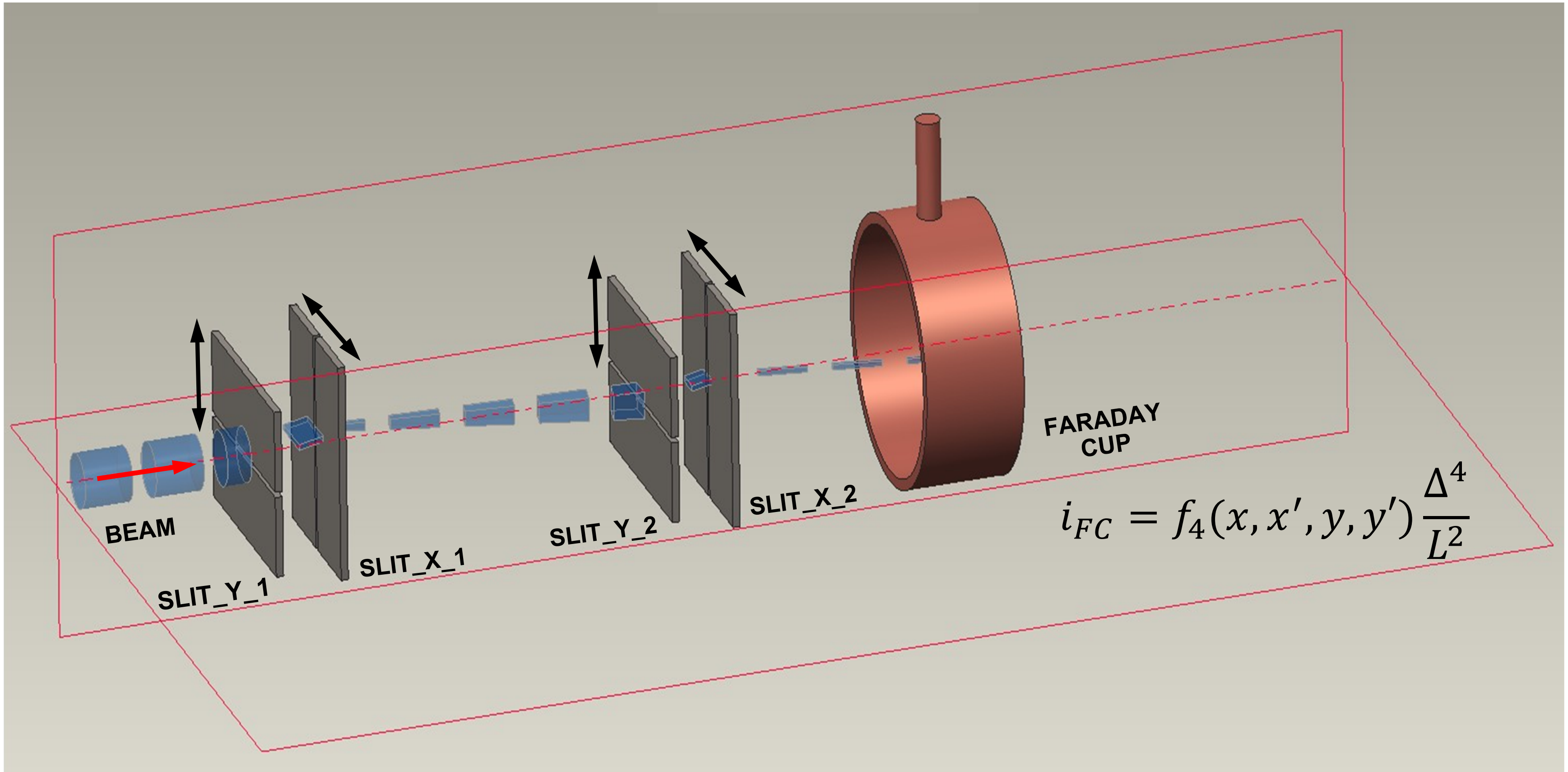
Preferably, the distribution function ?

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





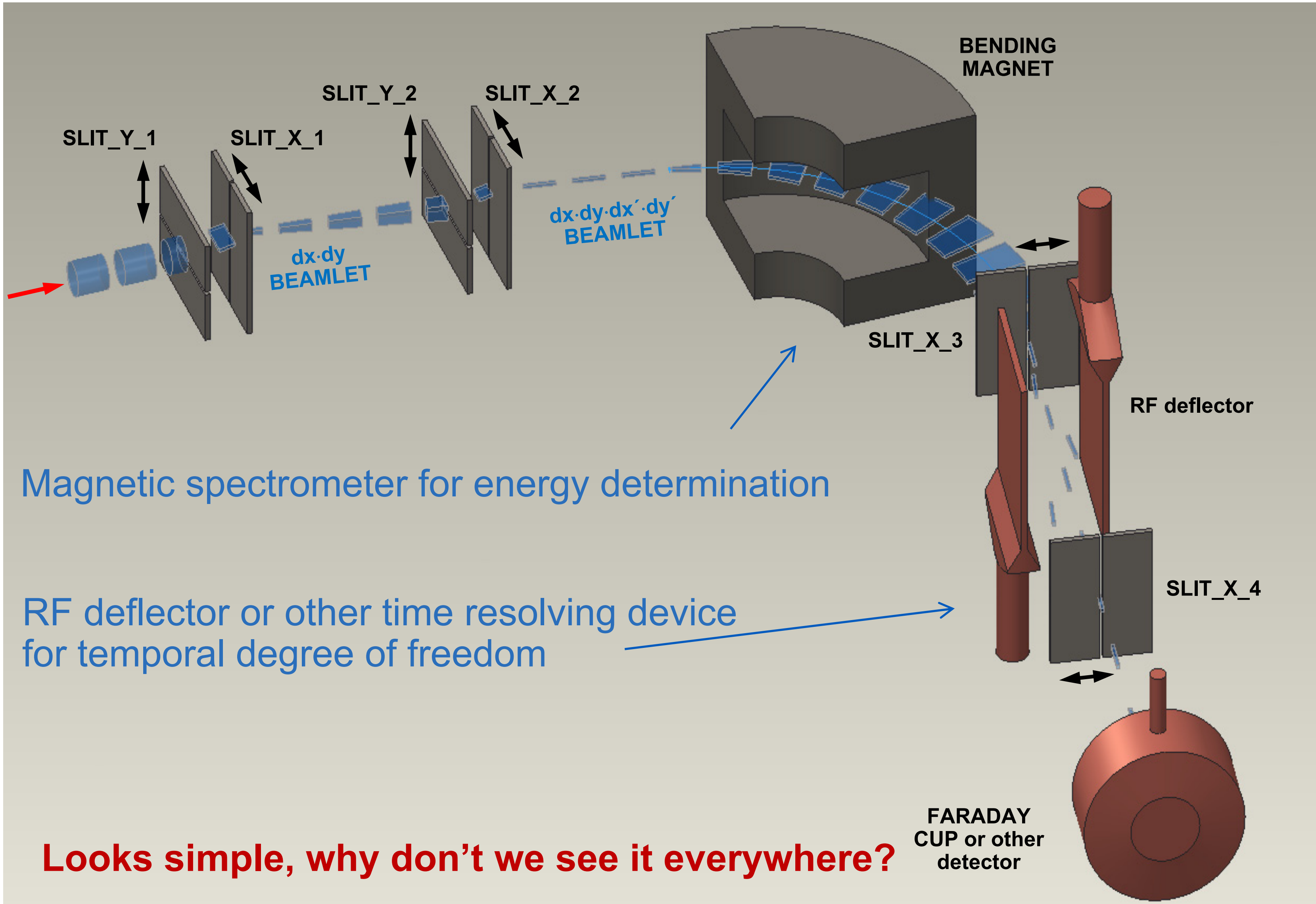
4D distribution measurement using four slits arrangement



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

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

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:

What looks simple in low-dimension problem can become ridiculously difficult in higher dimensions

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

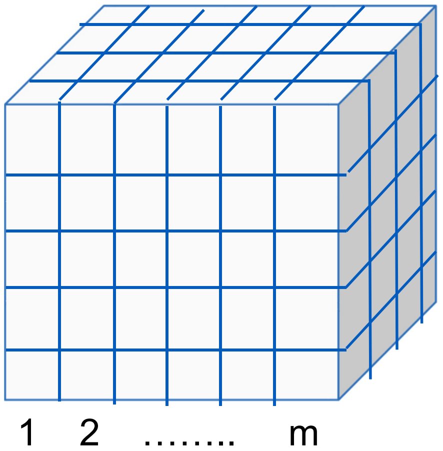
Scan time estimate

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

dimensionality

Total number of bins

Number of steps per degree of freedom

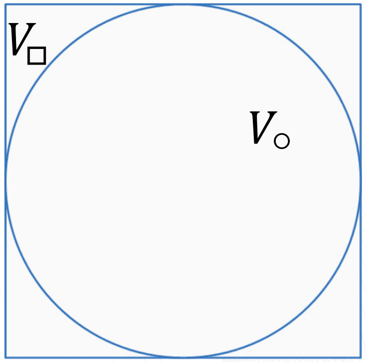


For $m = 10, D = 6$ $\quad N_{bins} = 10^6$

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

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

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



Tens of hours total scan time

Signal strength estimate

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

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: $\boxed{N_{FC} \approx 2.6 \cdot 10^6}$ at the distribution center $\mathrm{r} = 0$

$N_{FC} \approx 1.6 \cdot 10^6$ at $\mathrm{r} = 2\,\sigma$

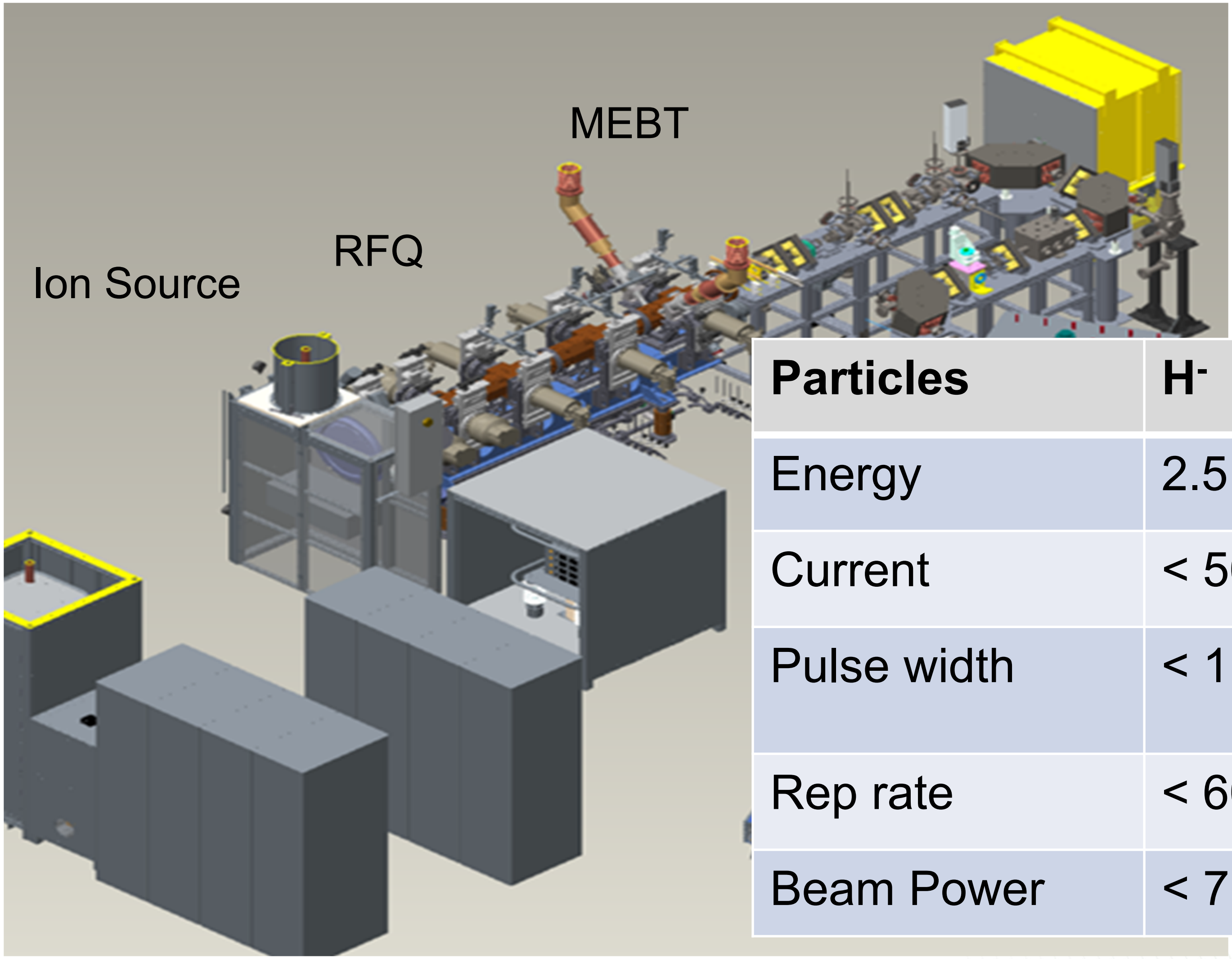
$N_{FC} \approx 2.9 \cdot 10^4$ at $\mathrm{r} = 3\,\sigma$

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

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

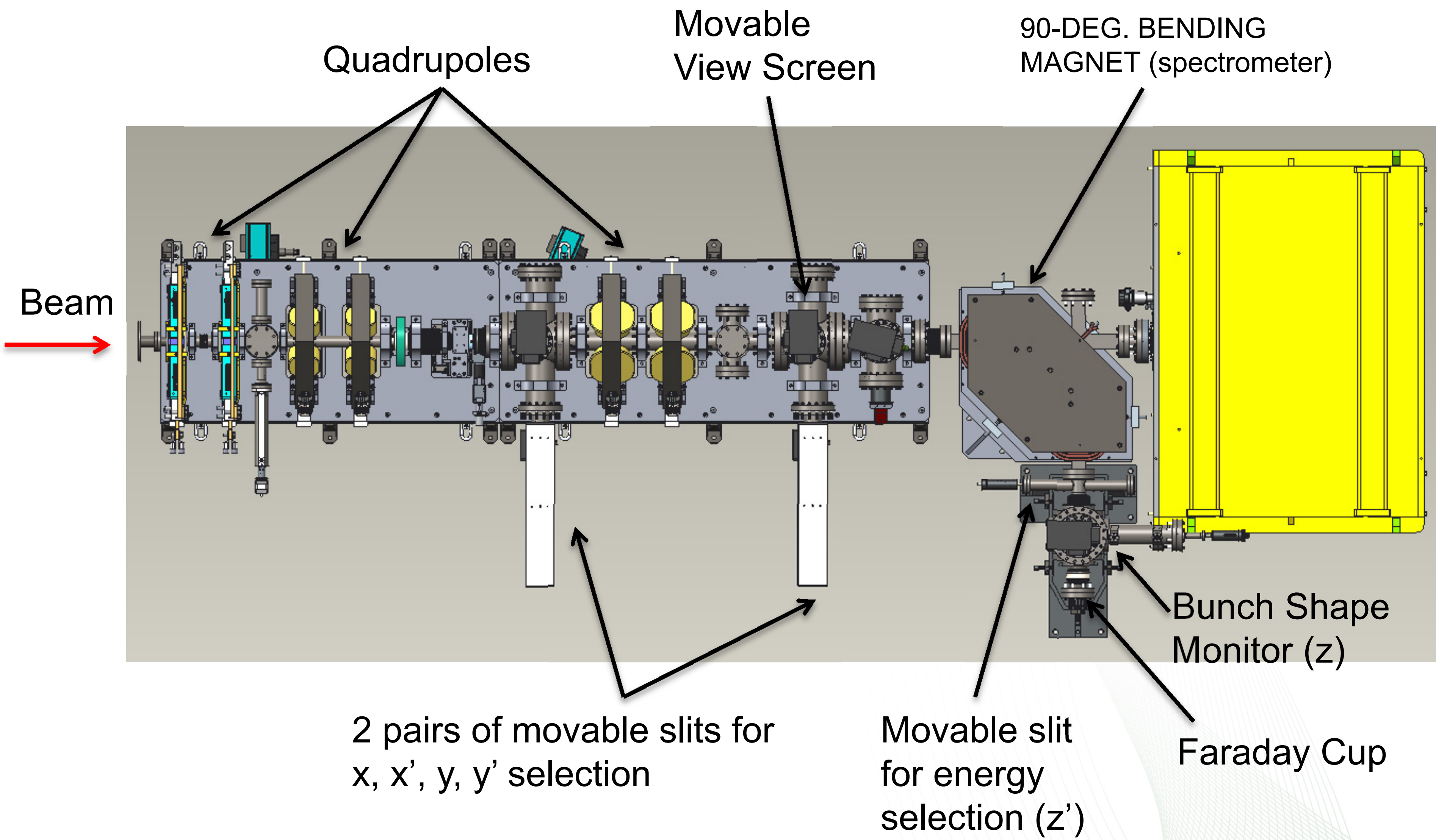
Only feasible at a dedicated facility

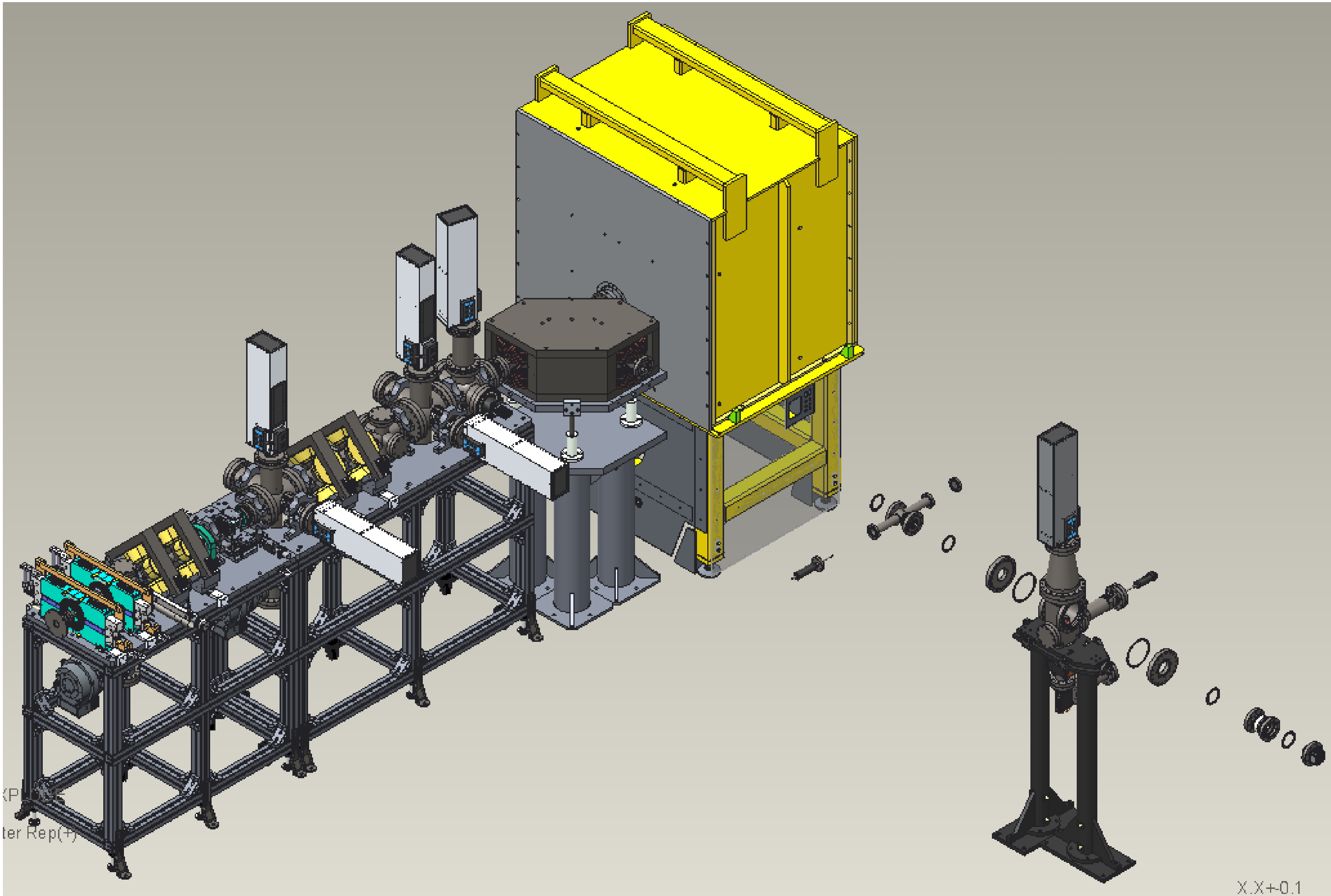
SNS Beam Test Facility (BTF)



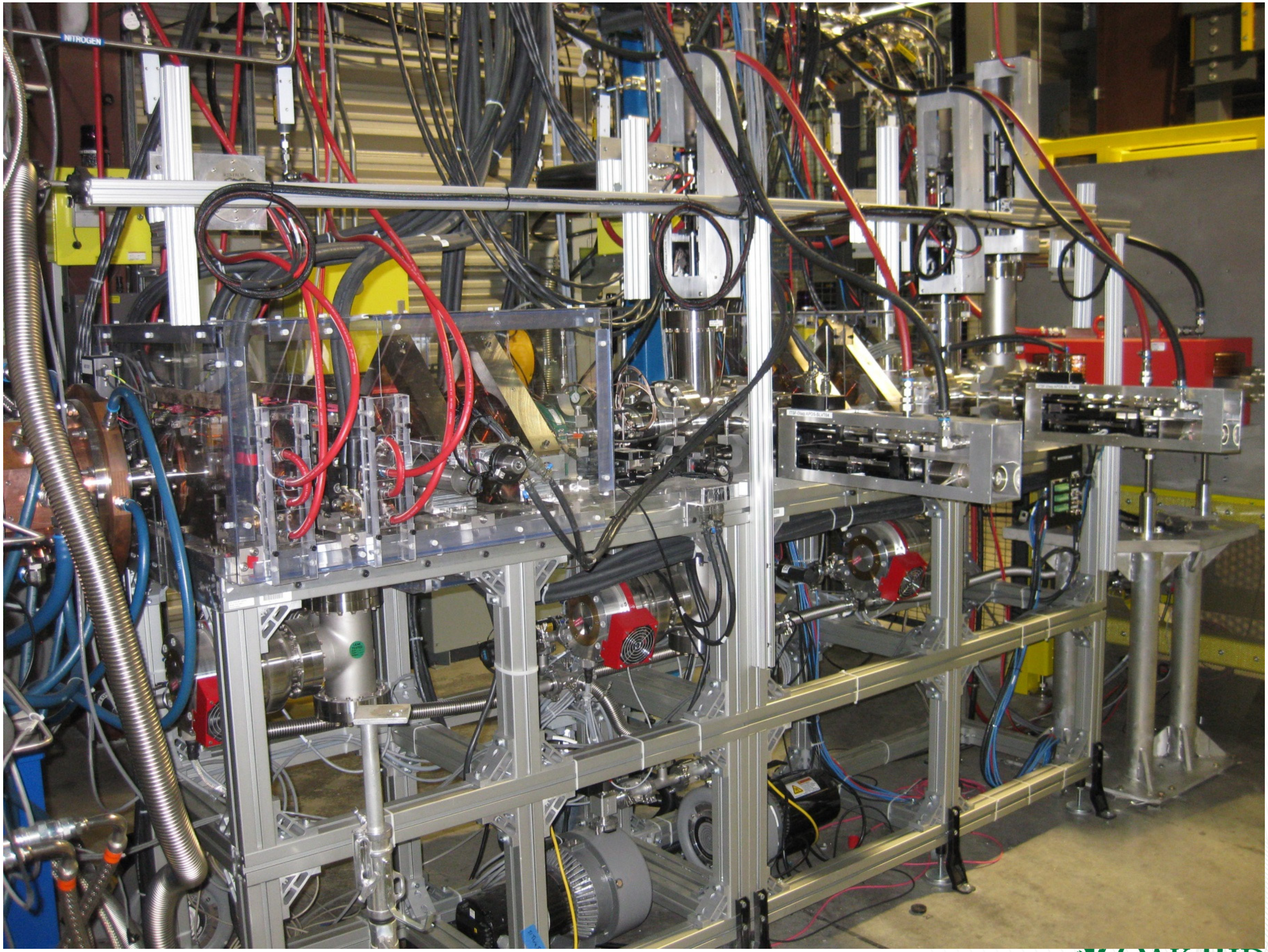
Particles	H^-
Energy	2.5 MeV
Current	< 50 mA
Pulse width	< 1 ms
Rep rate	< 60 Hz
Beam Power	< 7.5 kW

SNS BTF set up for 6D phase space measurement

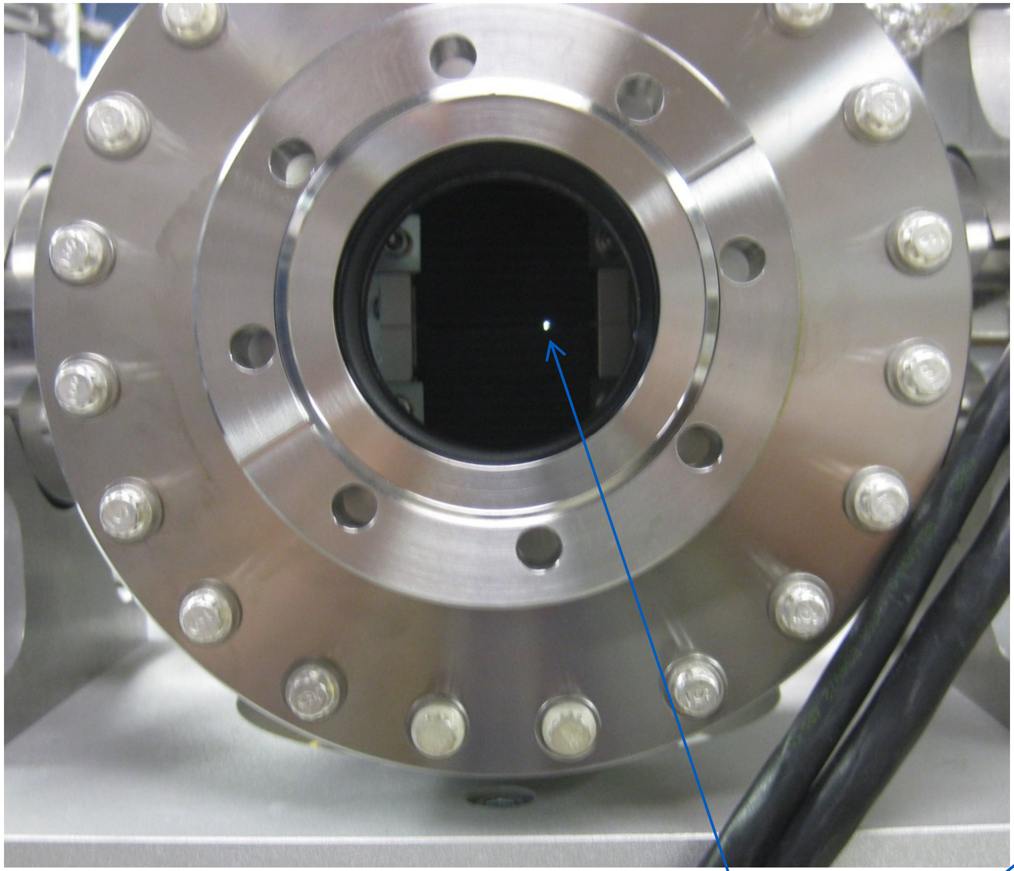


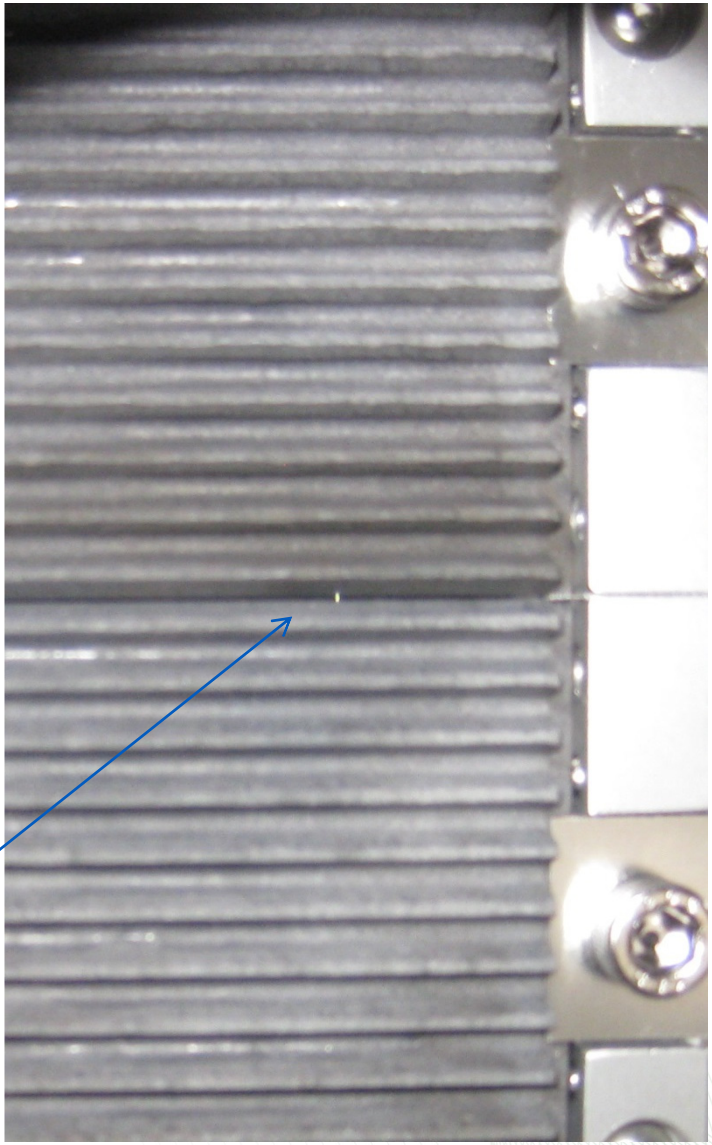

X.X+-0.1

BTF MEBT



X-Y Slits arrangement





200-by-200 μm aperture

~~4D scan~~ First results

OAK RIDGE National Laboratory

Oak Ridg...
(865) 241-6794

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

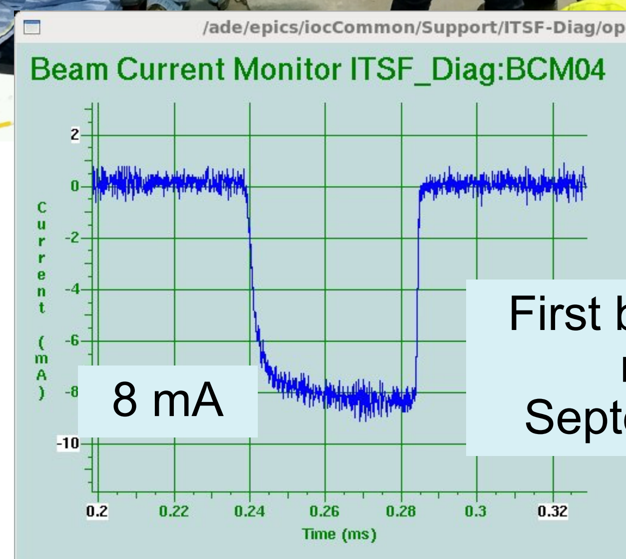
From: K. W. Jones

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

References:

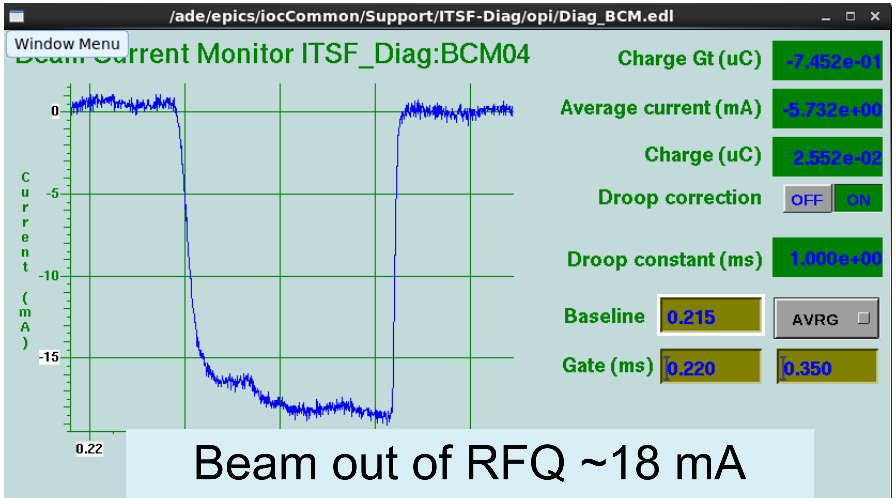
1. *"Safety Analysis for SNS Beam Test Facility,"* A. Aleksandrov, G. Dodson, D. Freeman and K. Jones, SNS-102030103-ES0059, July 18, 2016.
2. *"Contract DE-AC05-00OR22725, Request for Exemption from the Provisions of DOE O 420.2C for the Spallation Neutron Source Beam Test Facility,"* Letter from Paul Langan to Johnny O. Moore, dated July 19, 2016.

Received authorization to run the facility on September 6th 2016

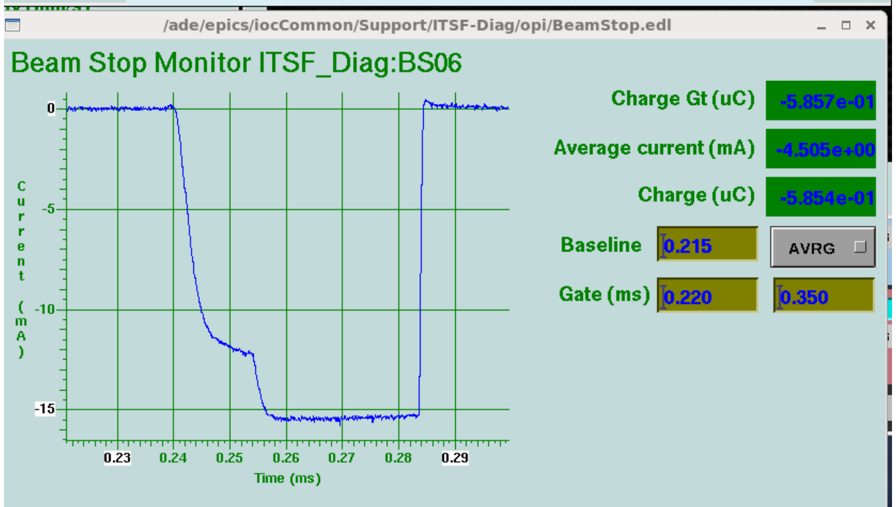


First beam out of the new RFQ!
September 8, 2016

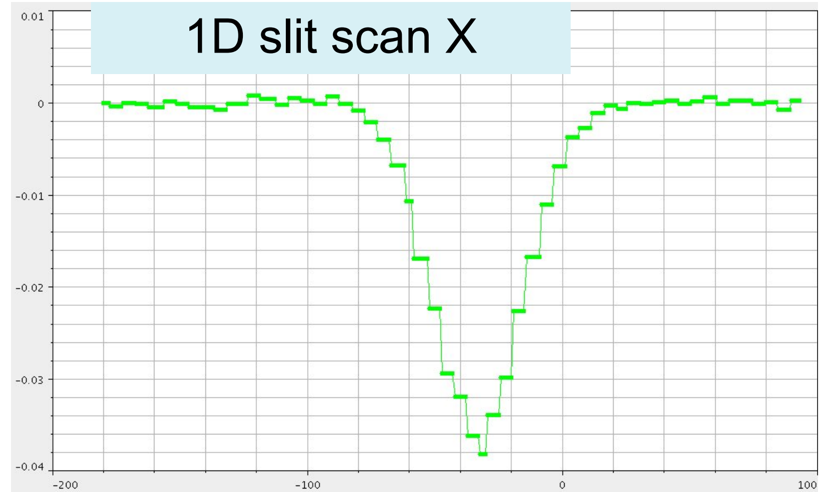
September 9, 2016



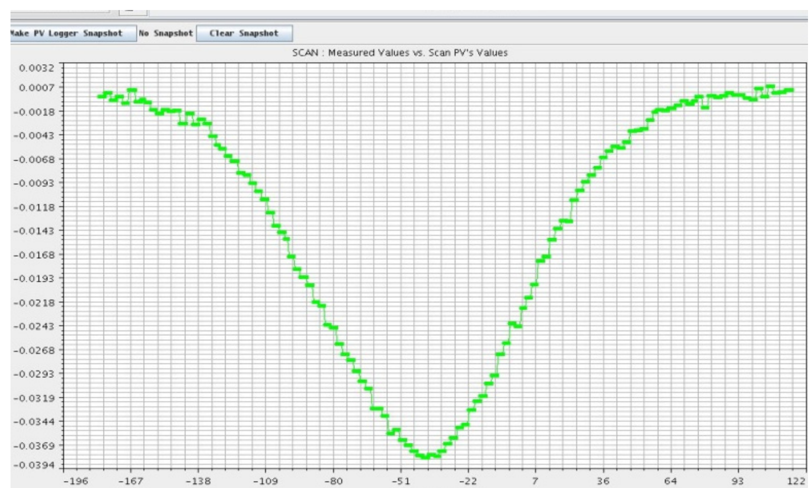
Beam out of RFQ ~18 mA



Beam to beam dump ~17.5 mA



1D slit scan X



1D slit scan Y

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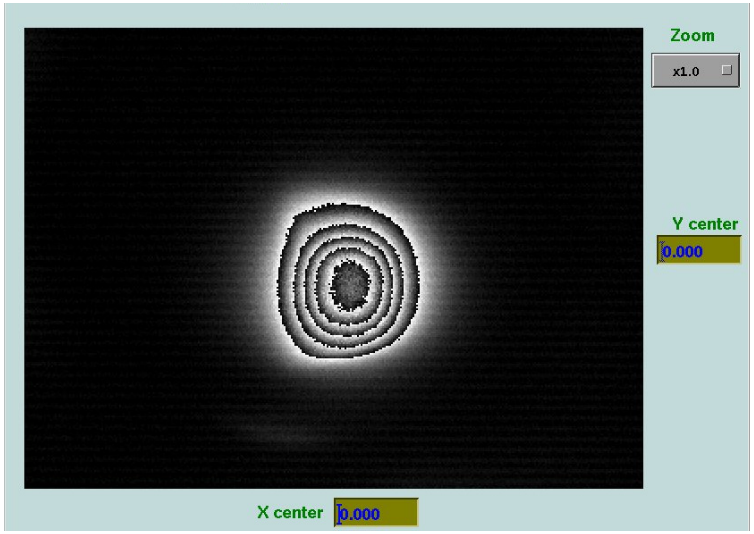
September 9, 2016



View screen image with 2 slits inserted (1 horizontal, 1 vertical)

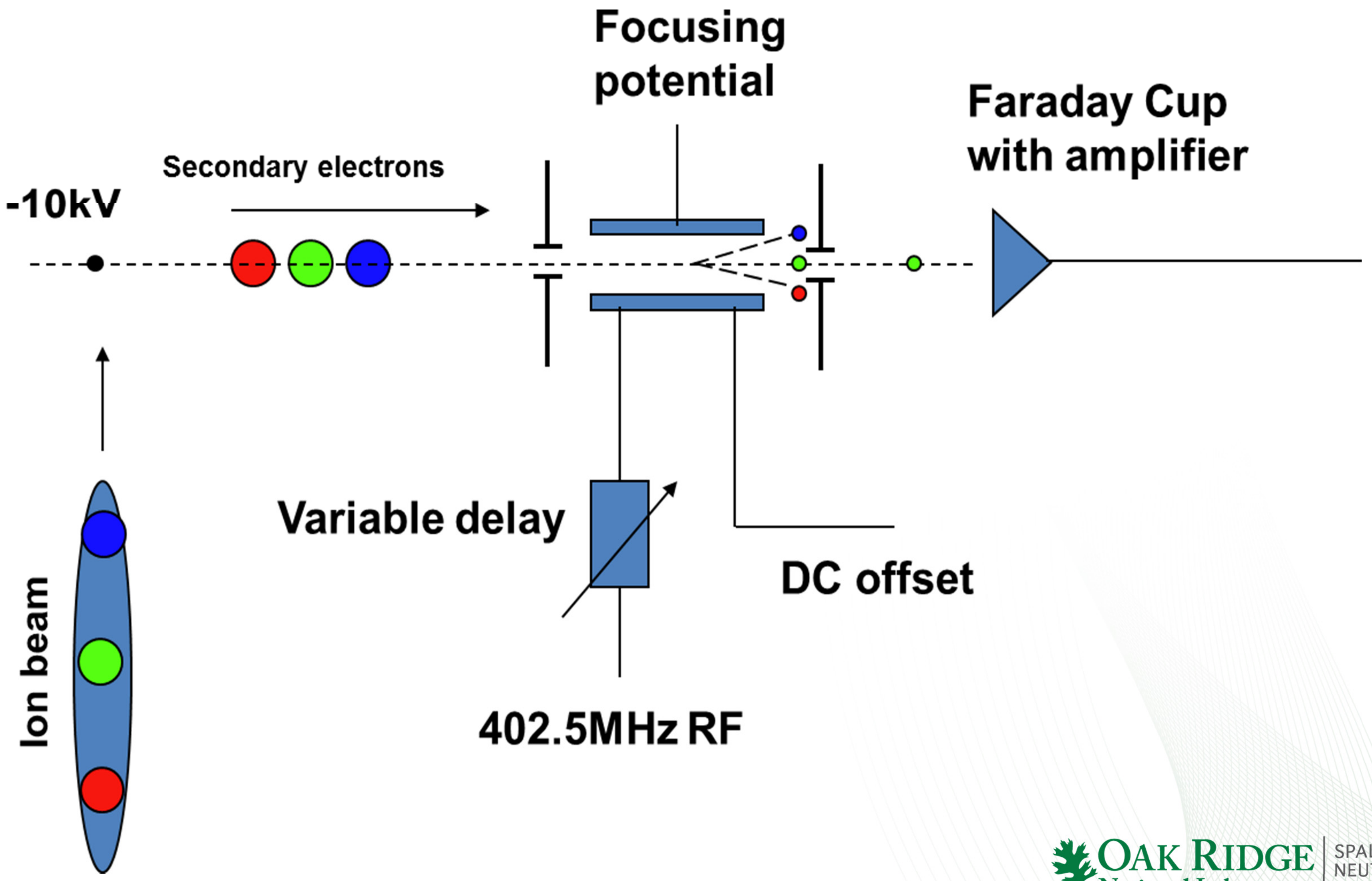
View screen image with 4 slits inserted (2 horizontal, 2 vertical)

Equipment for 4D scan commissioned but we did not have time for full scan

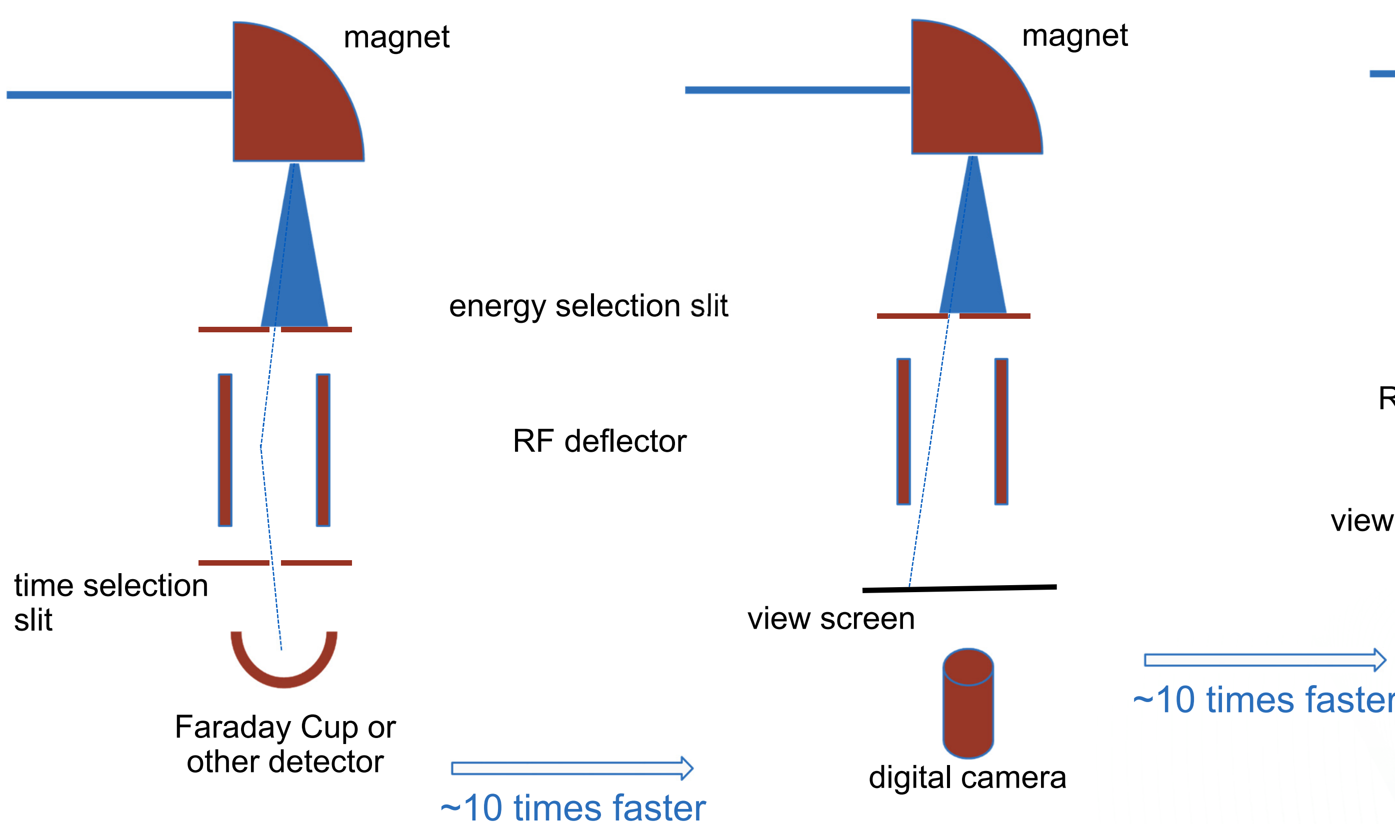
Longitudinal plane is next step

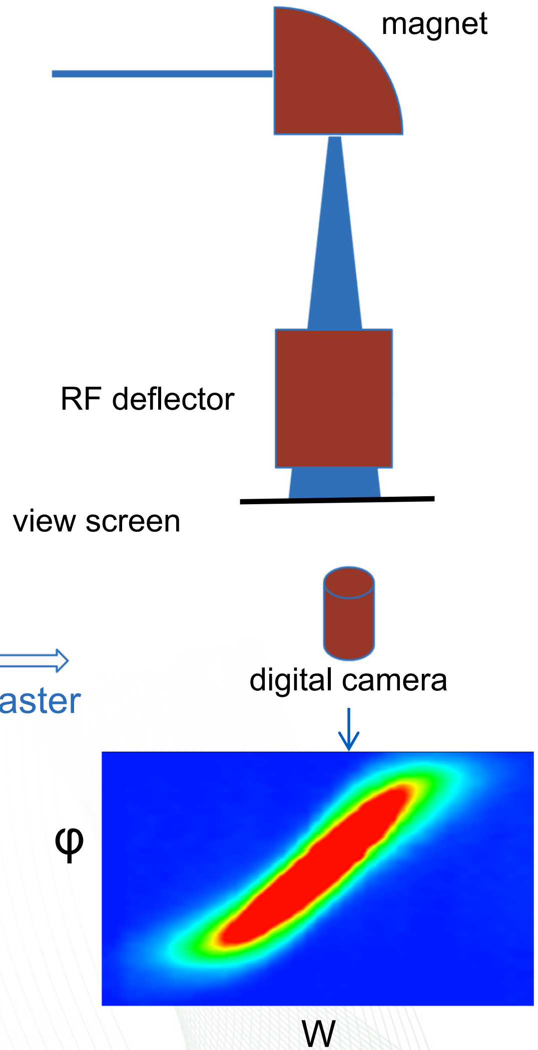
Bunch Shape Monitor principle of operation

Deflecting 2.5MeV proton beam directly with an RF cavity is expensive therefore we use Beam Shape Monitor aka “Feschenko monitor”

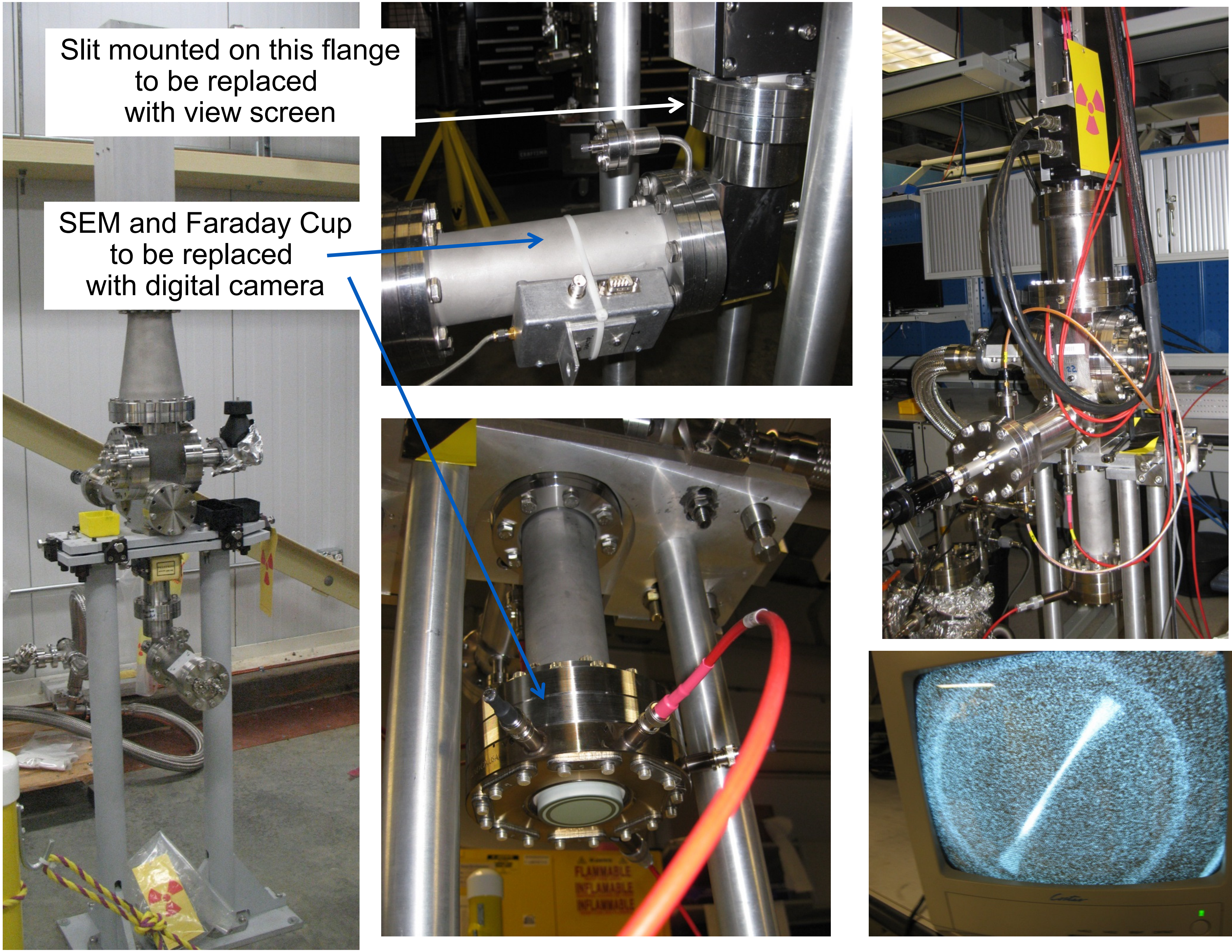


Speeding up scan in z-z' plane





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


Slit mounted on this flange
to be replaced
with view screen
SEM and Faraday Cup
to be replaced
with digital camera
FLAMMABLE

6D scan results

not there yet

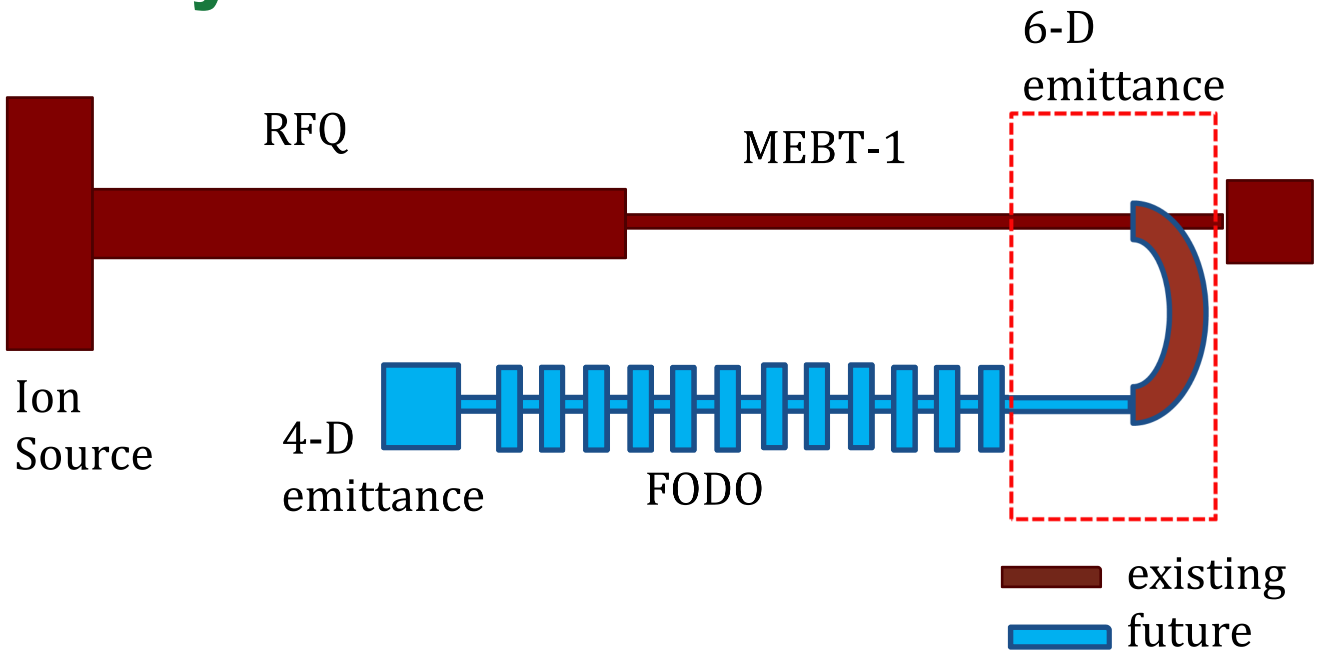
6D scan results

but will be soon

Near Term 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

Experimental study of halo formation in high intensity beam



- Experiment highlights:
  - Direct 6D phase space measurement.
  - Study halo formation in FODO structure.
  - Benchmark simulation codes

Thank you for your attention!