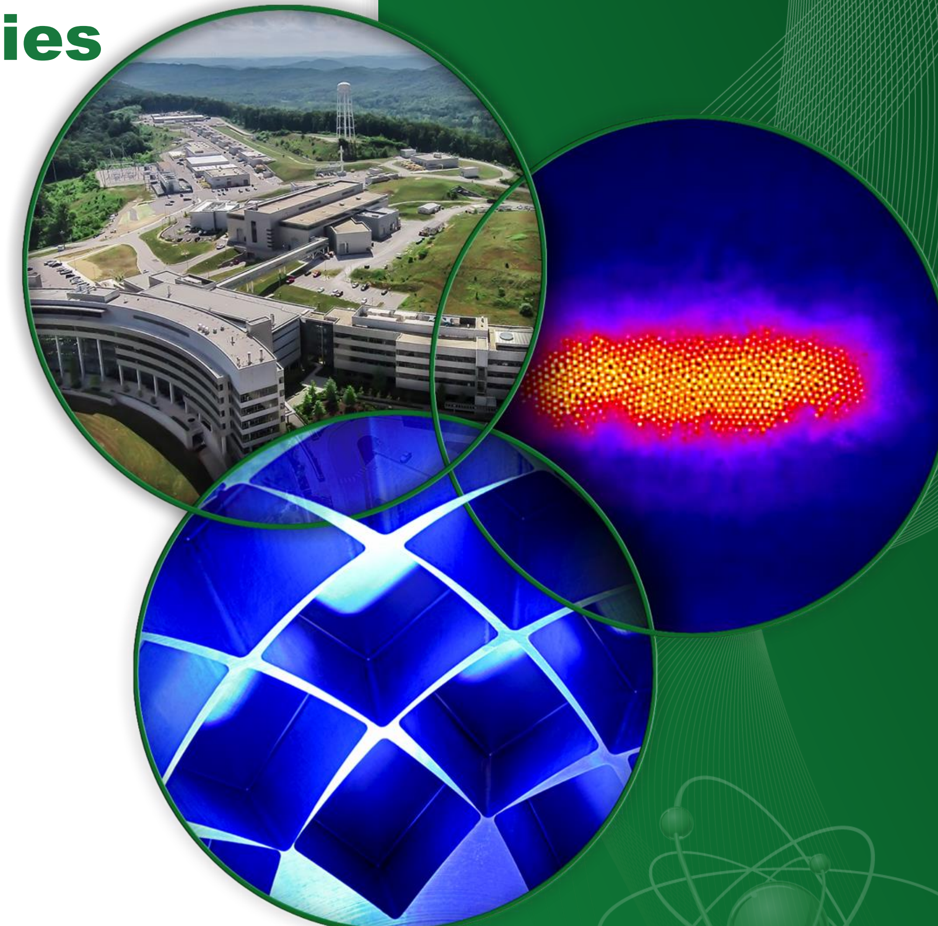
6D Beam Measurement, Challenges and Possibilities



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Credits

- 6-D phase space measurement development team: B. Cathey, S. Cousineau, A. Zhukov, A. Aleksandrov

- Many people in SNS Research Accelerator Division who helped to design, build and operate the SNS Beam Test Facility

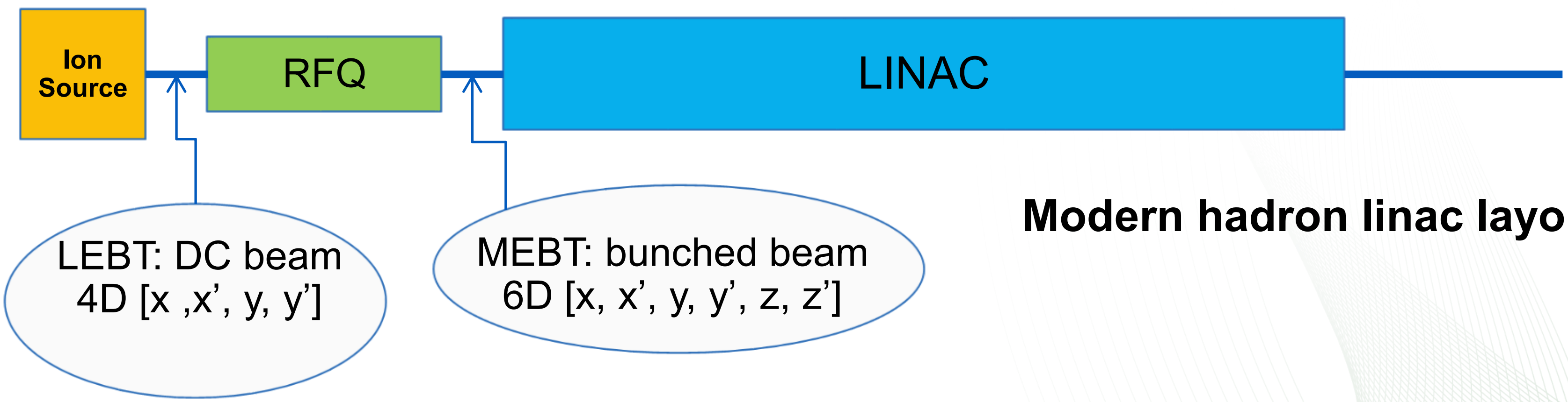
- ORNL is managed by UT-Battelle, LLC, under contract DE-AC05-00OR22725 for the U.S. Department of Energy
- This work has been partially supported by NSF Accelerator Science grant 1535312

Why do we need to know 6D distribution?

- Generic answer is to provide input data for computer simulation of beam dynamics in hadron linacs

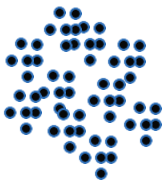
What is specific about RF linacs?

- 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

How to represent bunch of particles



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

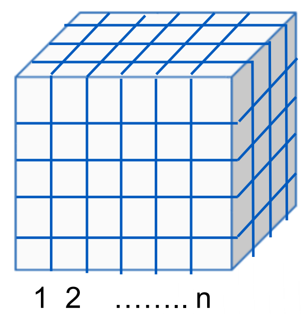
particle #	coordinates
1	x, x', y, y', z, z'
2	x, x', y, y', z, z'
.	.
.	.
N	x, x', y, y', z, z'

$6N$ numbers

impossible to measure individual particles positions
need something different

<u>distribution function</u>

number of particles per bin in phase space



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

$$= \frac{N(x \pm \Delta, x' \pm \Delta, y \pm \Delta, y' \pm \Delta, z \pm \Delta, z' \pm \Delta)}{N_{total} \cdot \Delta^6}$$

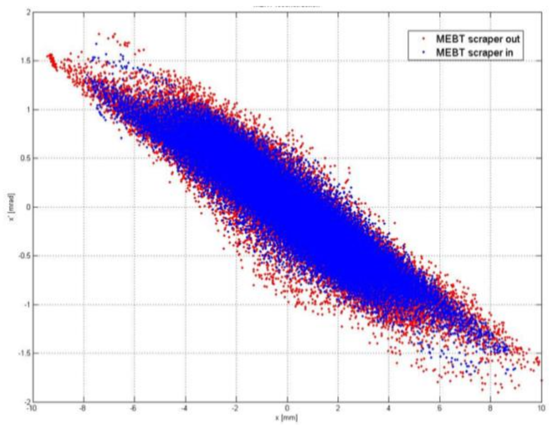
Distribution function representation requires

n^6 numbers for 6D

“True” six-dimensional distribution function

$f_6(x, x', y, y', z, z')$ - 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

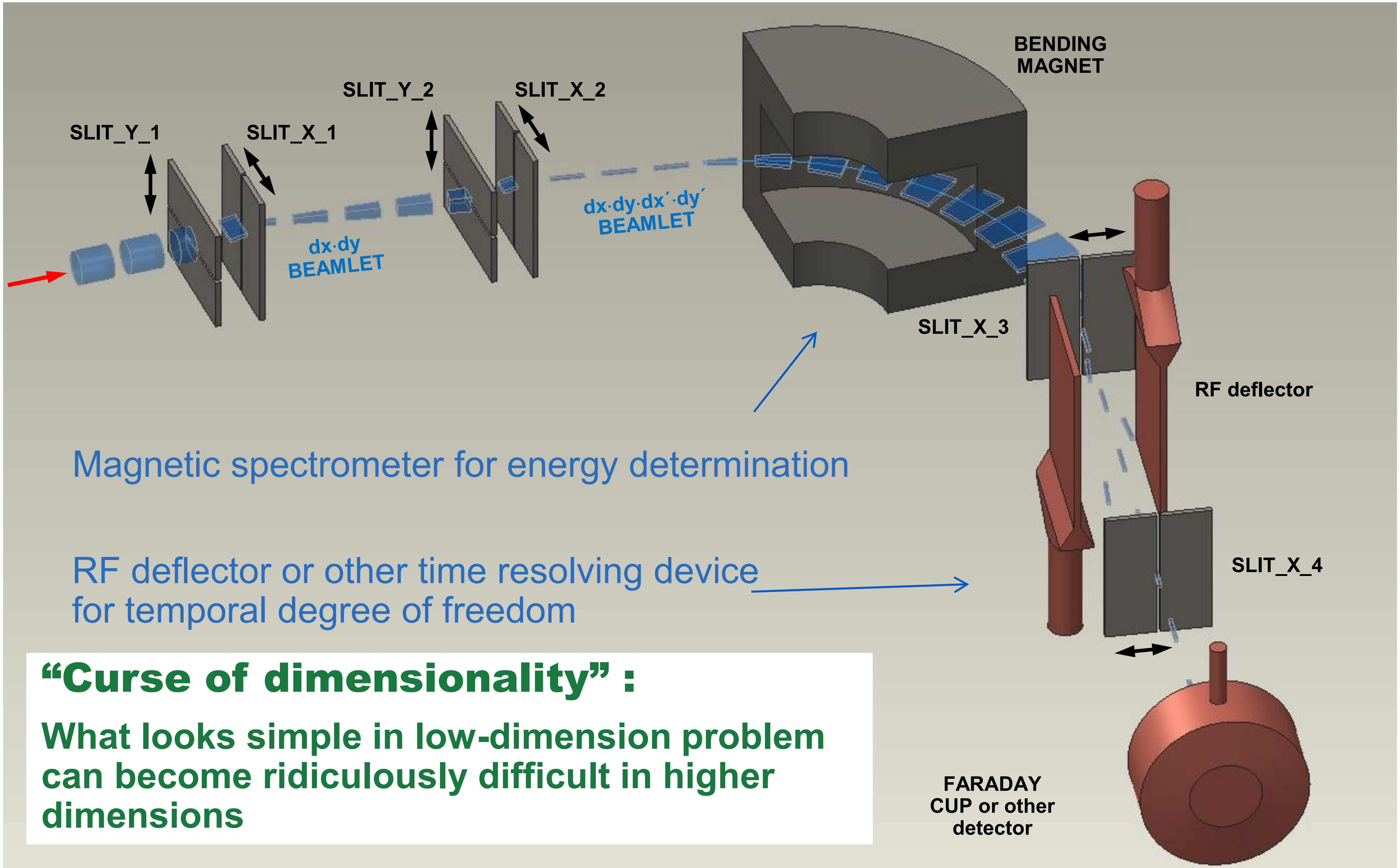
$$f_{3*2}(x, x', y, y', z, z') \neq f_6(x, x', y, y', z, z')$$

except for special case of <u>no correlations</u> between degrees of freedom

$$f_6(x, x', y, y', z, z') = f_x(x, x') \cdot f_y(y, y') \cdot f_z\,(z, z')$$

definition of uncorrelated degrees of freedom

6D measurement arrangement



Magnetic spectrometer for energy determination

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

"Curse of dimensionality" :

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

Signal strength estimate

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

For ${}^{\Delta}/_{\sigma} \approx .1$ current after 6 slits $i \approx I_0 \cdot 4 \cdot 10^{-9} \cdot \exp(\dots)$

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: $N_{FC} \approx 4 \cdot 10^4$ at the distribution center $\mathrm{r} = 0$

$N_{FC} \approx 2.4 \cdot 10^4$ at $\mathrm{r} = 1\,\sigma$

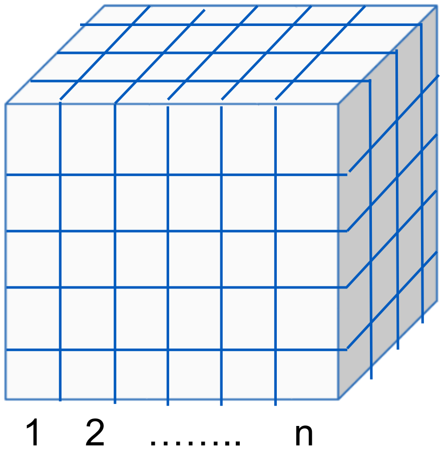
$N_{FC} \approx 5.4 \cdot 10^3$ at $\mathrm{r} = 2\,\sigma$

$N_{FC} \approx 444$ at $\mathrm{r} = 3\,\sigma$

Scan time estimate

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

- N_{bins}: Total number of bins
- n: Number of steps per degree of freedom
- D: dimensionality



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

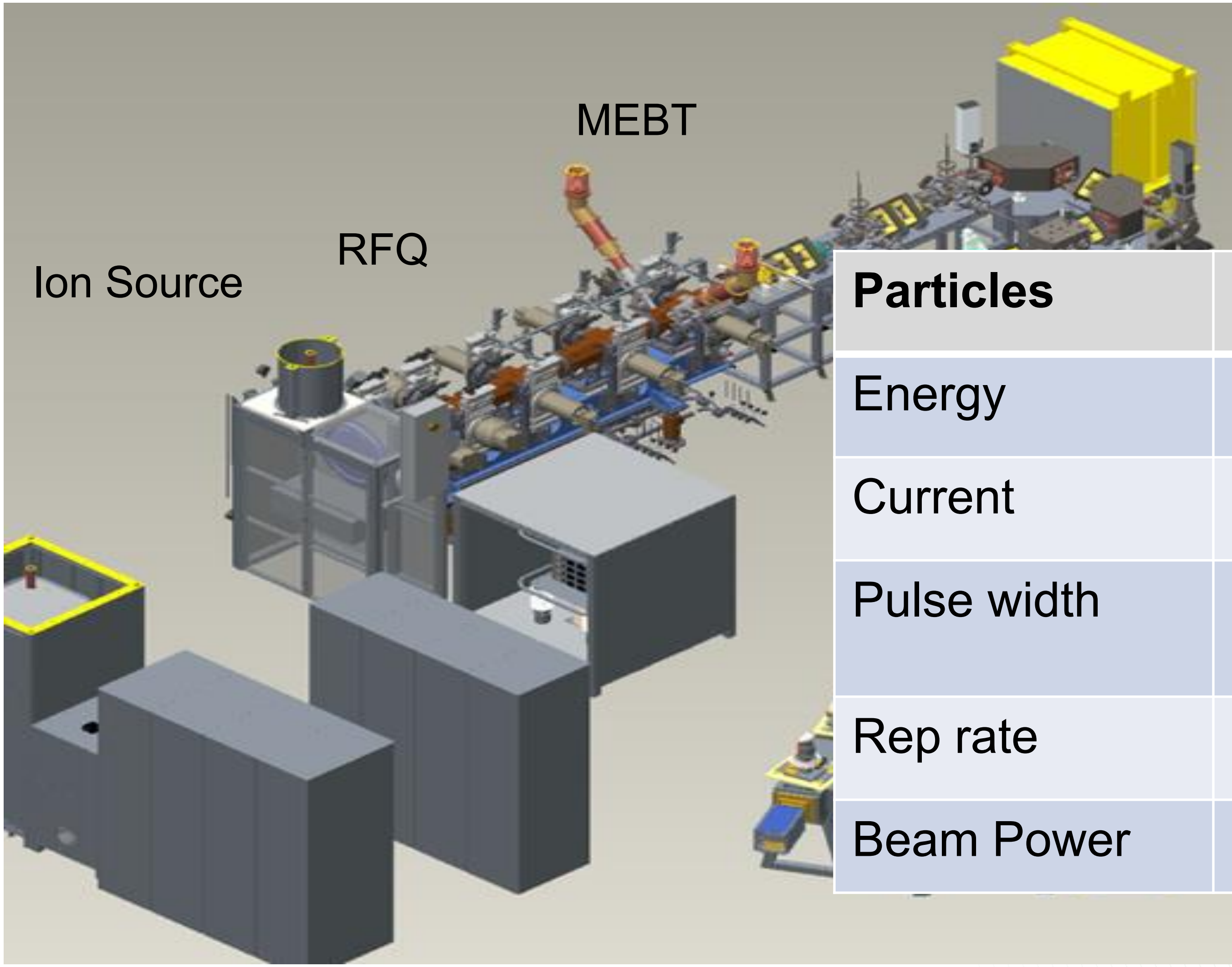
Total scan time at $1\ \frac{step}{sec}$: $T_{total} = 10^6\ sec = 280\ hours\ {\sim}2\ weeks$

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

64 times longer for $\mathrm{n} = 20$

Tens of hours total scan time

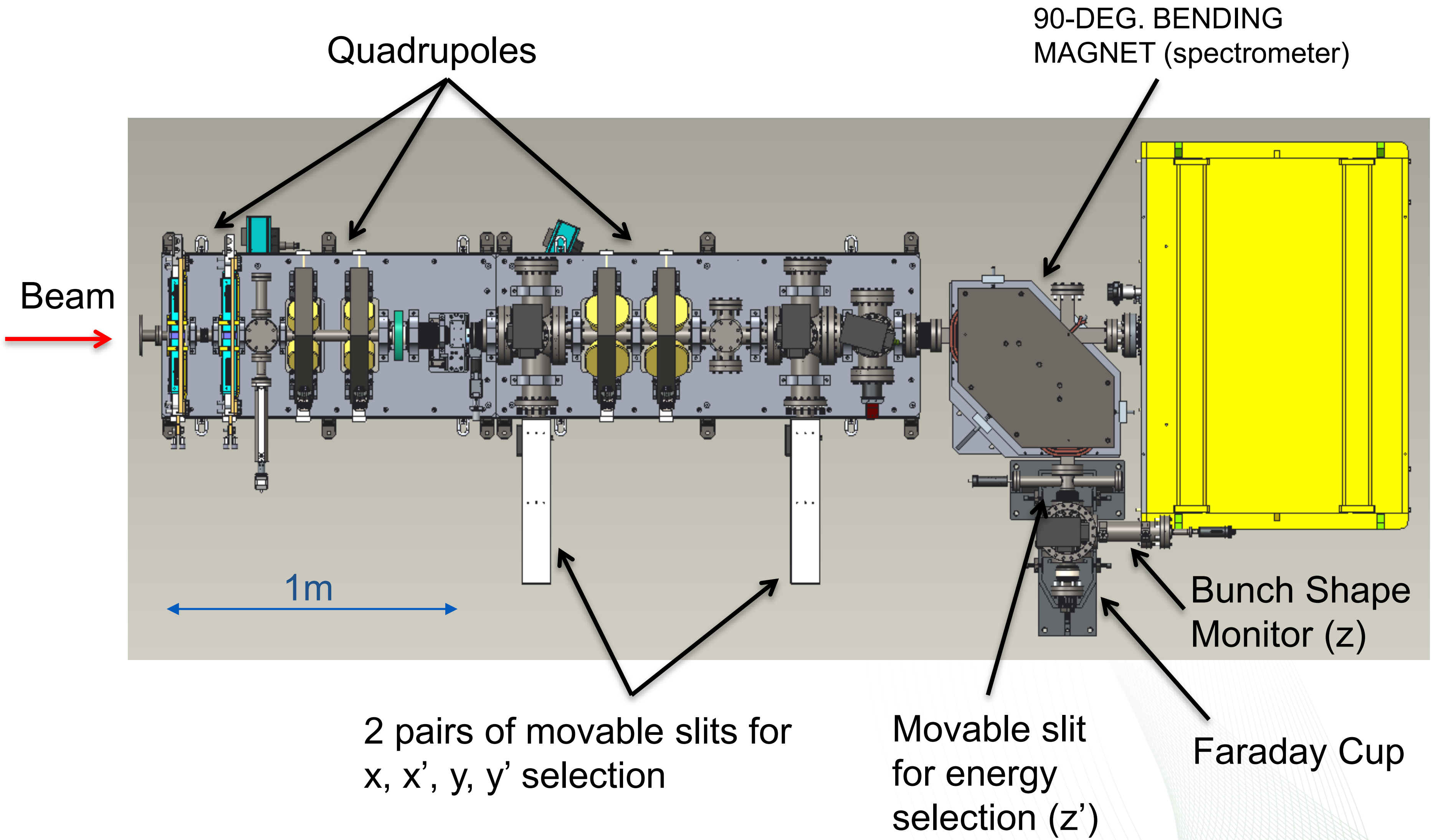
SNS Beam Test Facility (BTF)



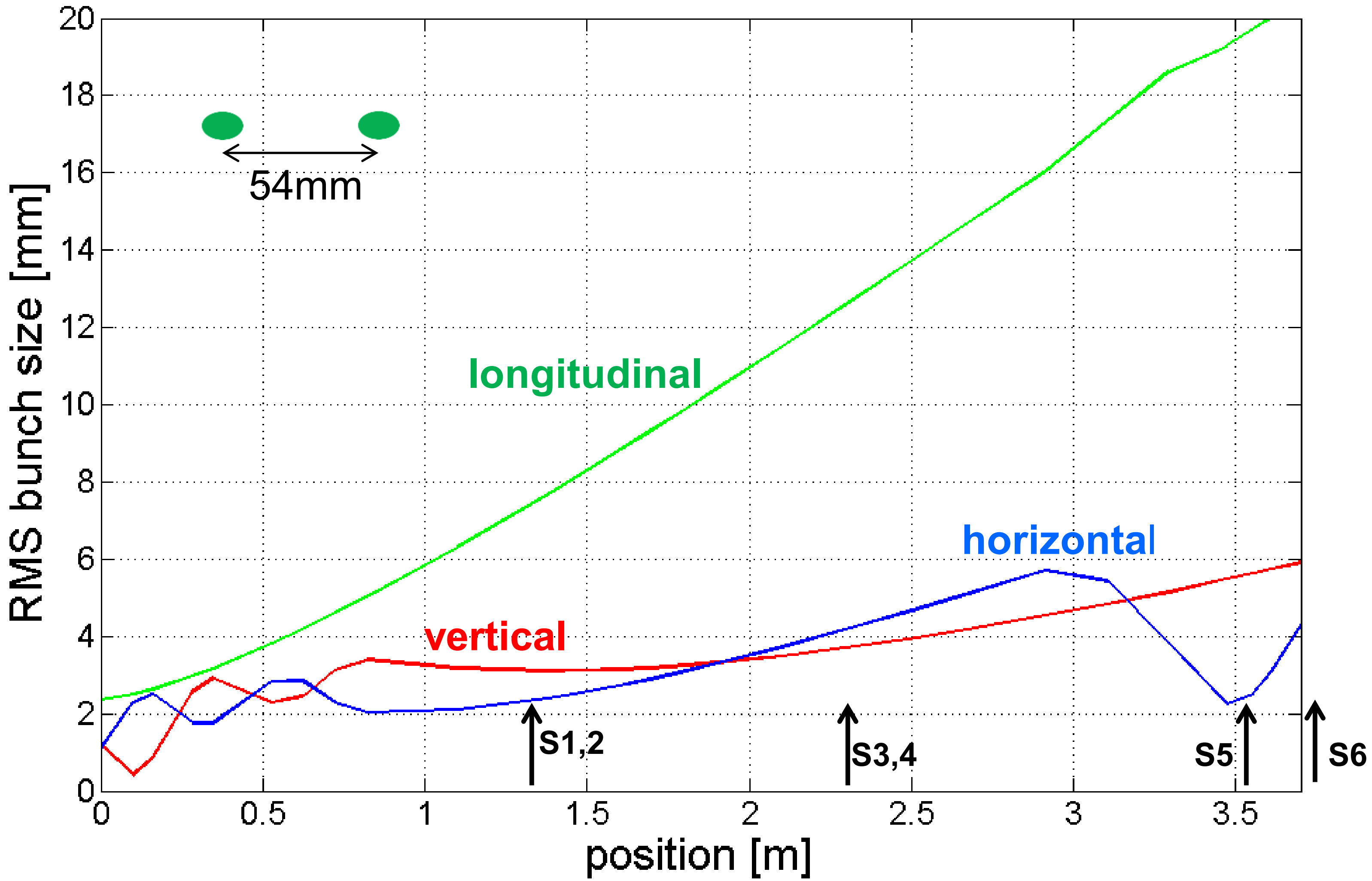
Particles	H^-
Energy	2.5 MeV
Current	< 50 mA
Pulse width	< 1 ms (50μs)
Rep rate	< 60 Hz (10Hz)
Beam Power	< 7.5 kW

A. Aleksandrov

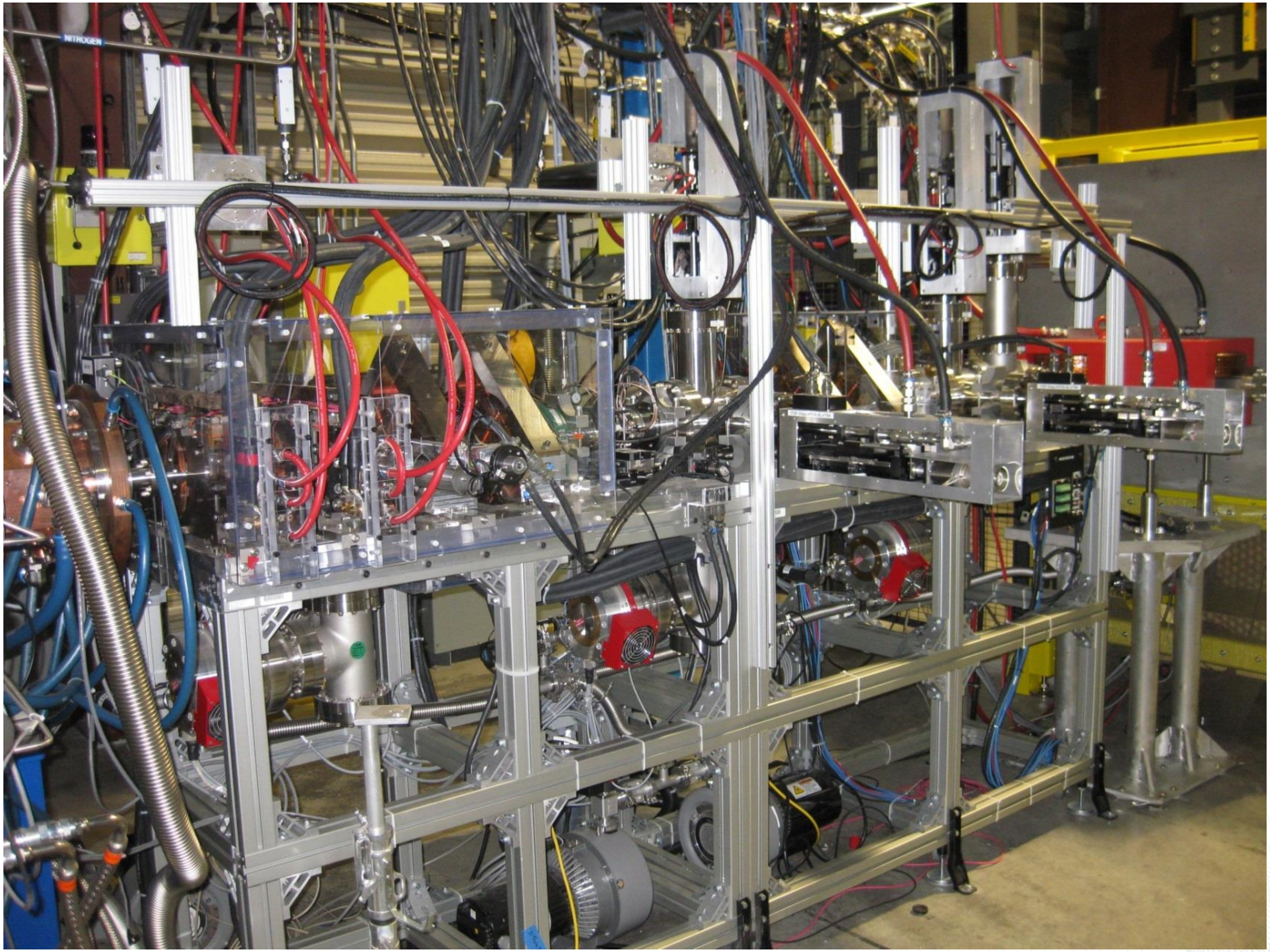
SNS BTF set up for 6D phase space measurement



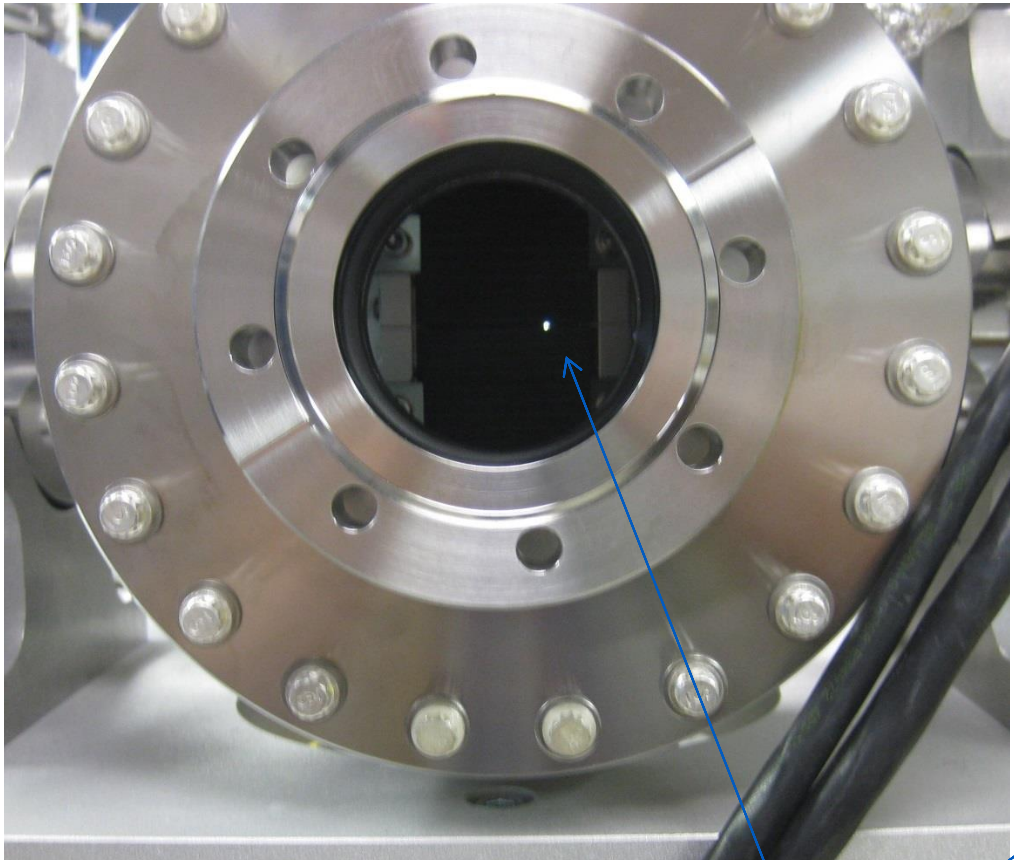
RMS bunch size in BTF beam line

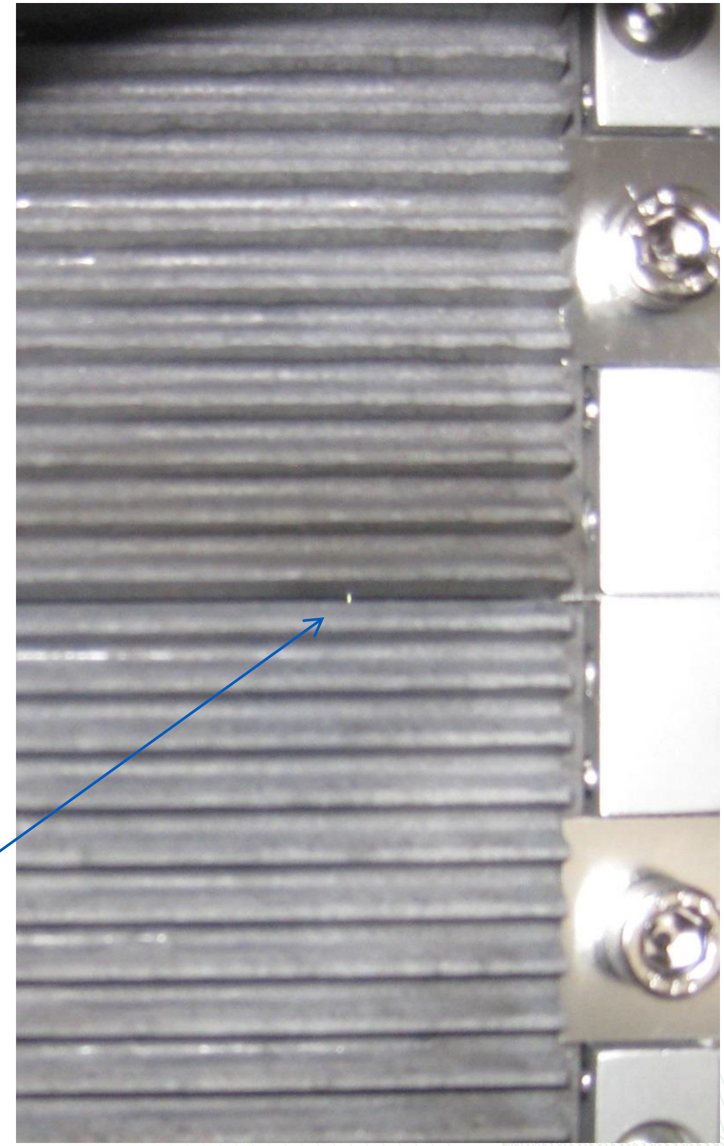


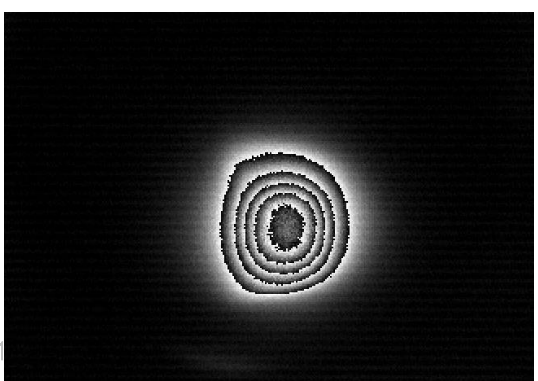
SNS BTF Beam Line



X-Y Slits arrangement



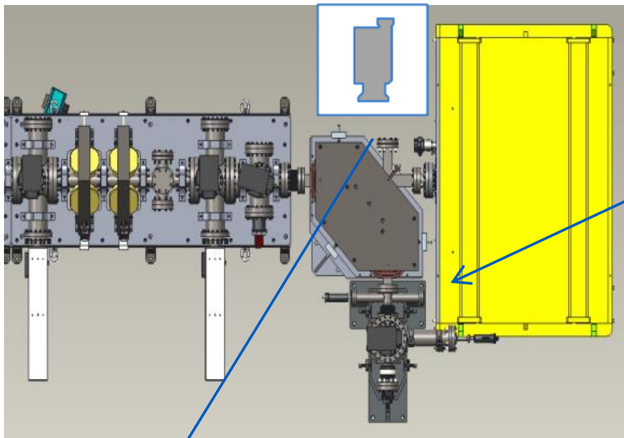


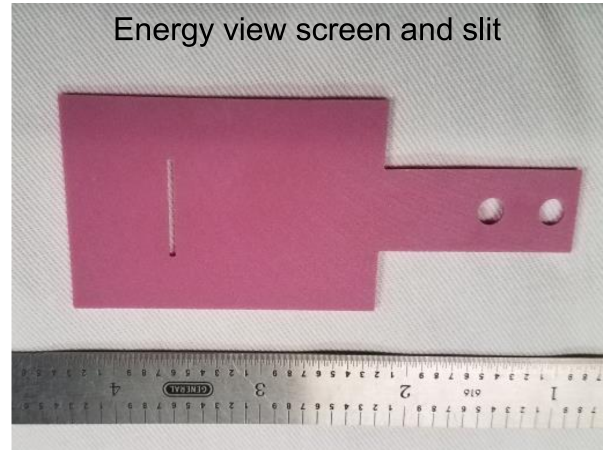


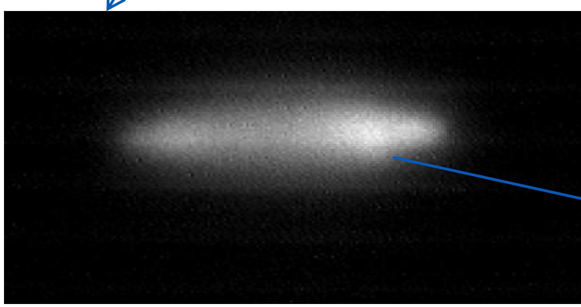
200-by-200 µm
aperture

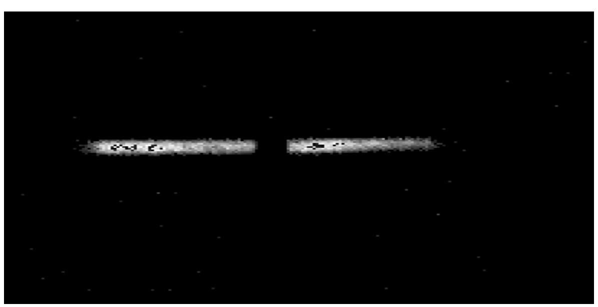
Energy selection and measurement

video camera

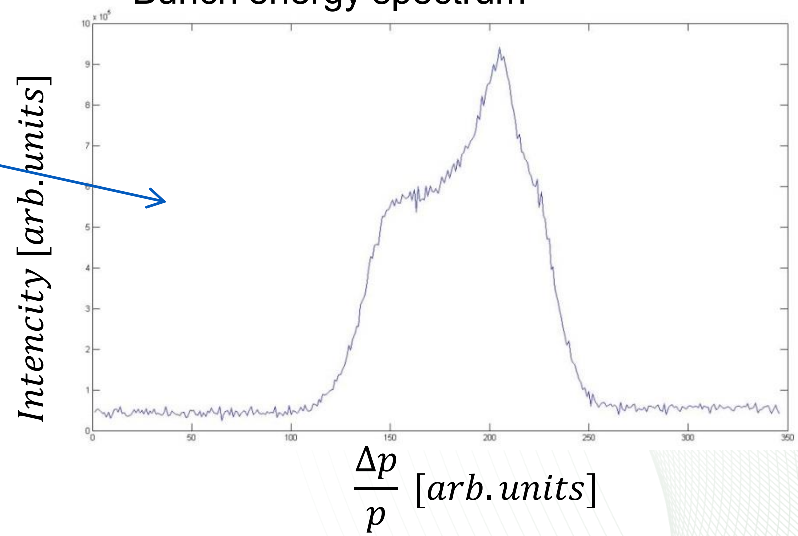






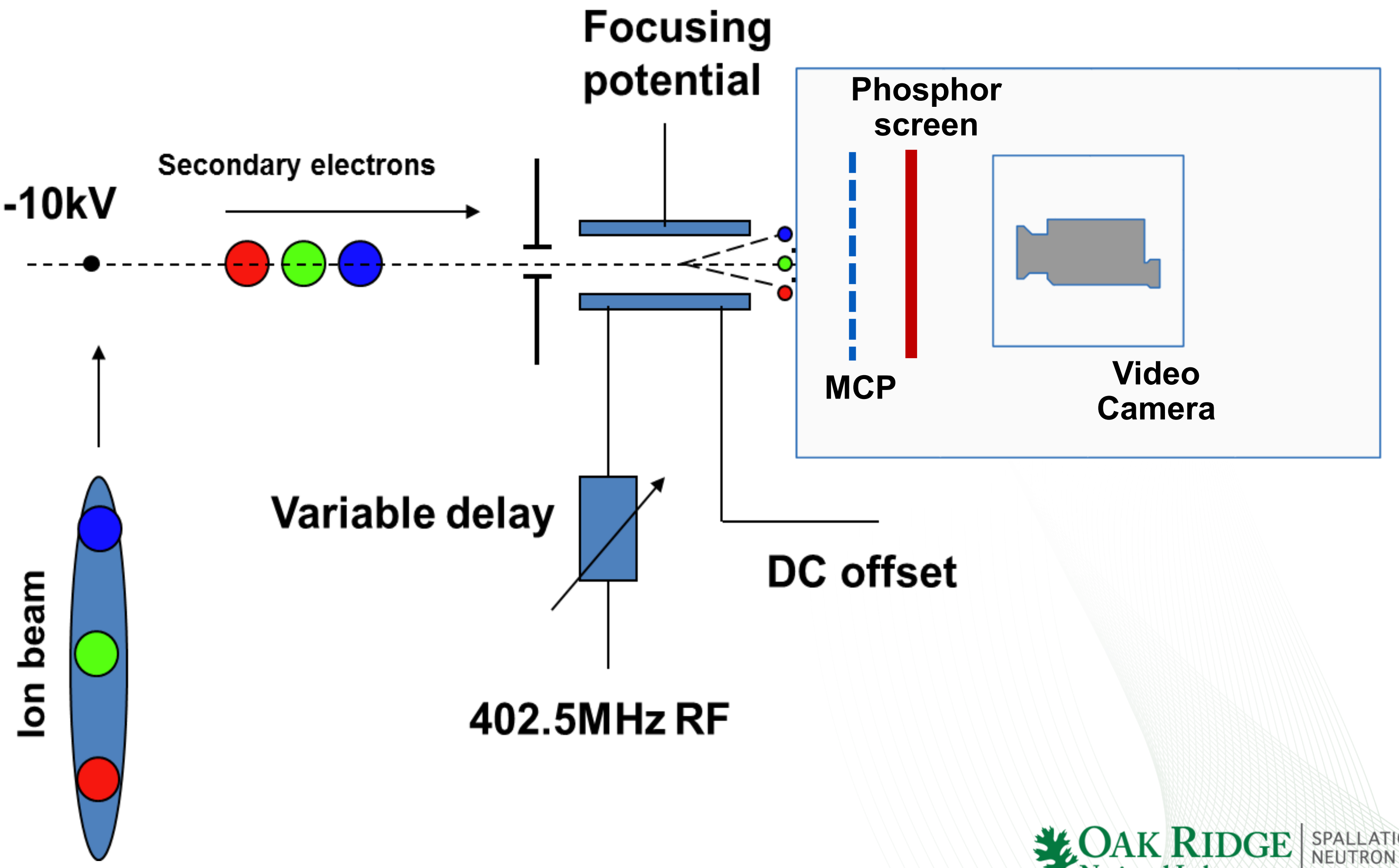


Bunch energy spectrum

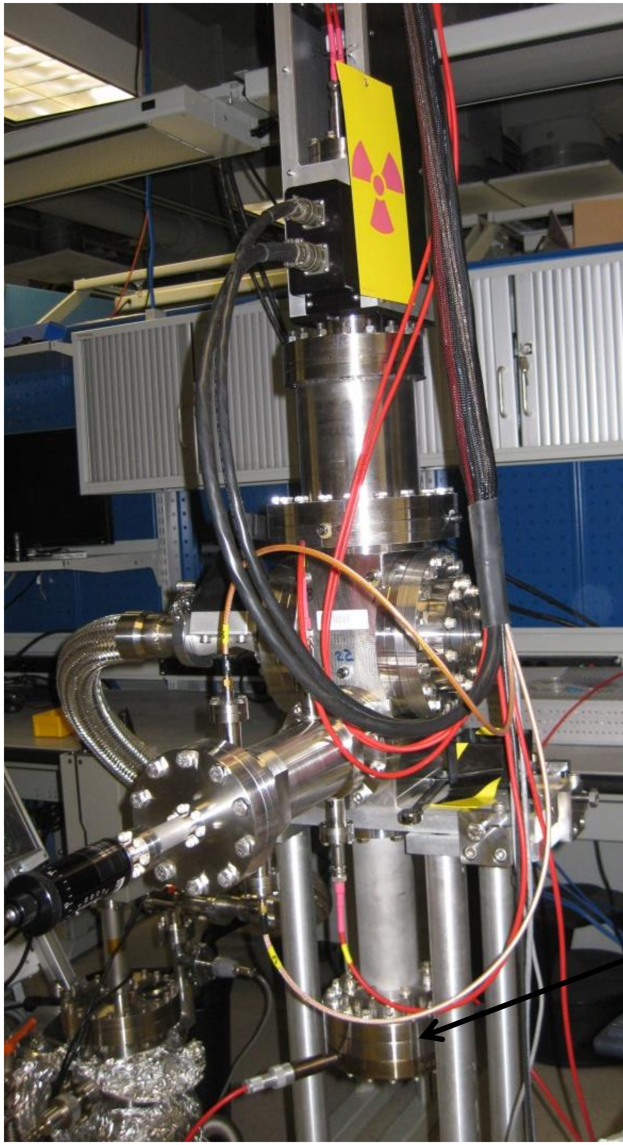


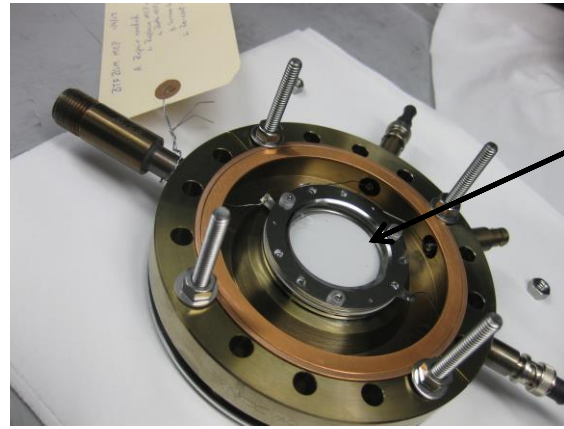
Bunch Shape Monitor principle of operation

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

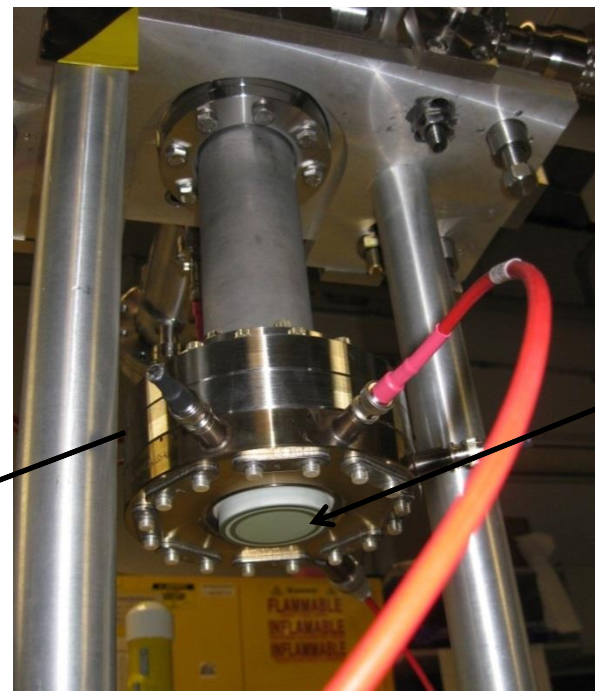


Modified SNS Beam Shape Monitor



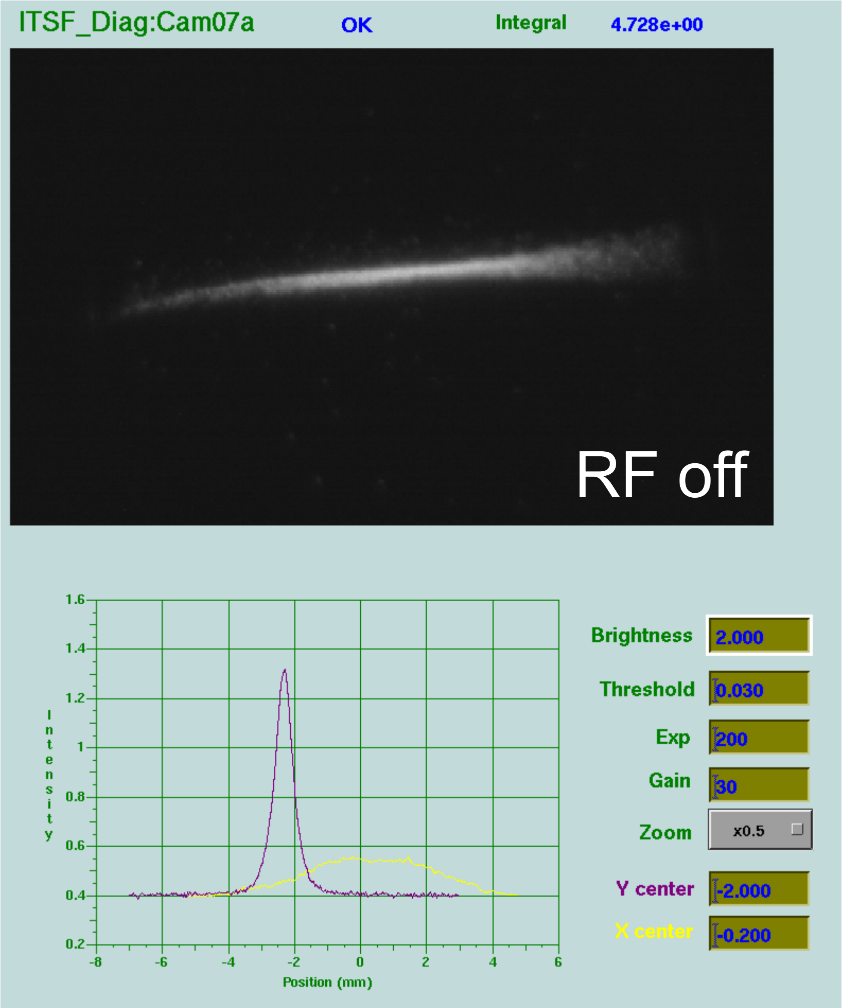


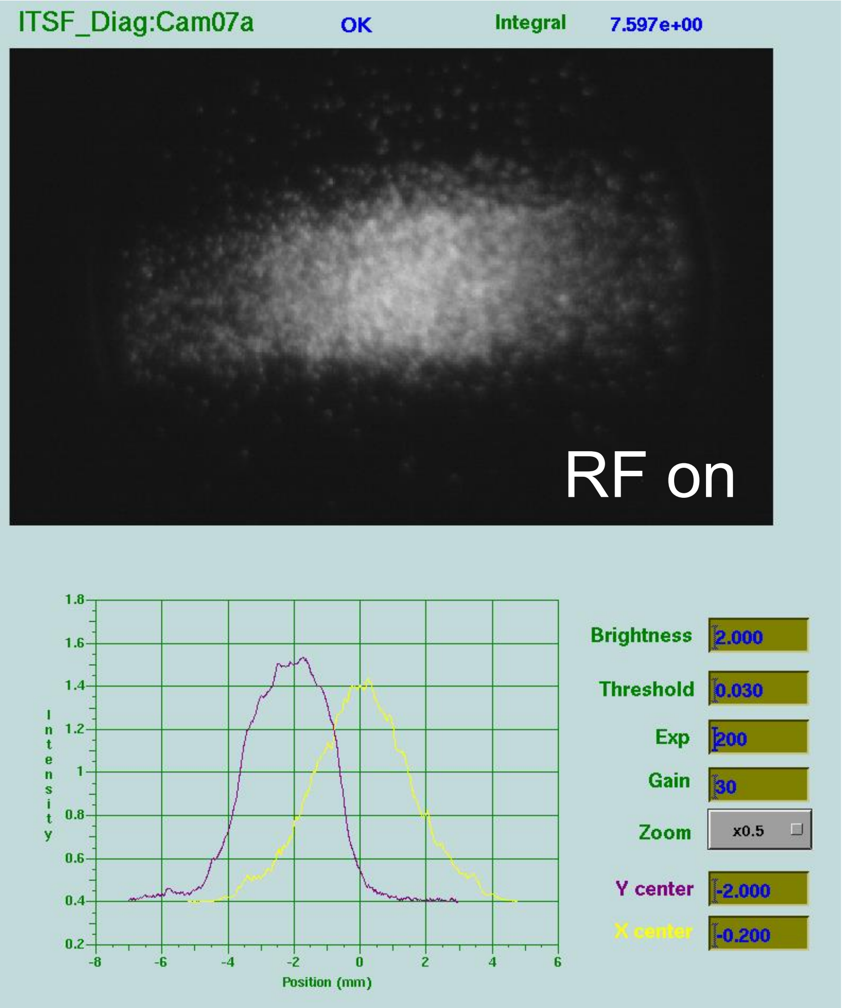
MCP



View screen

BSM view screen images





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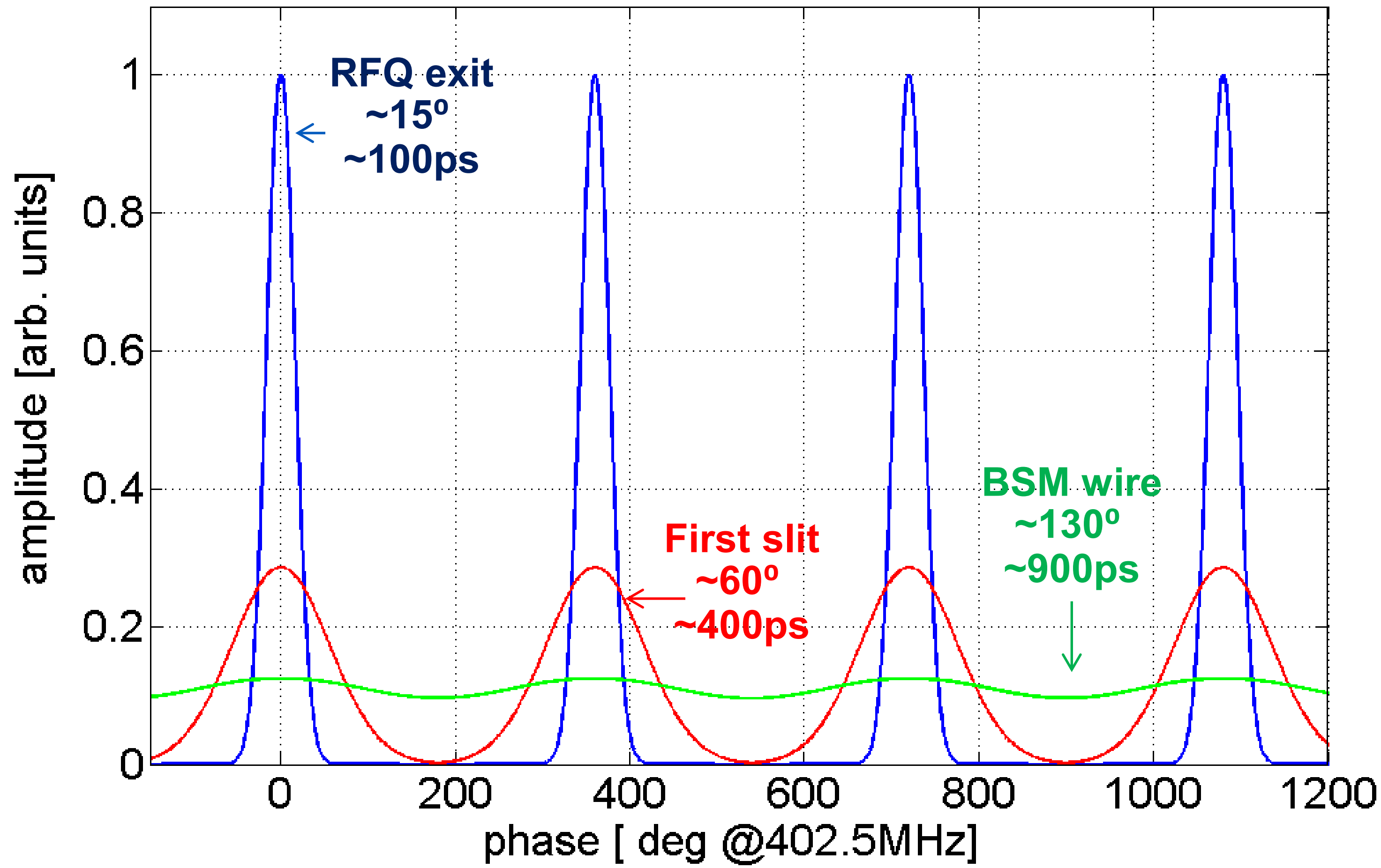
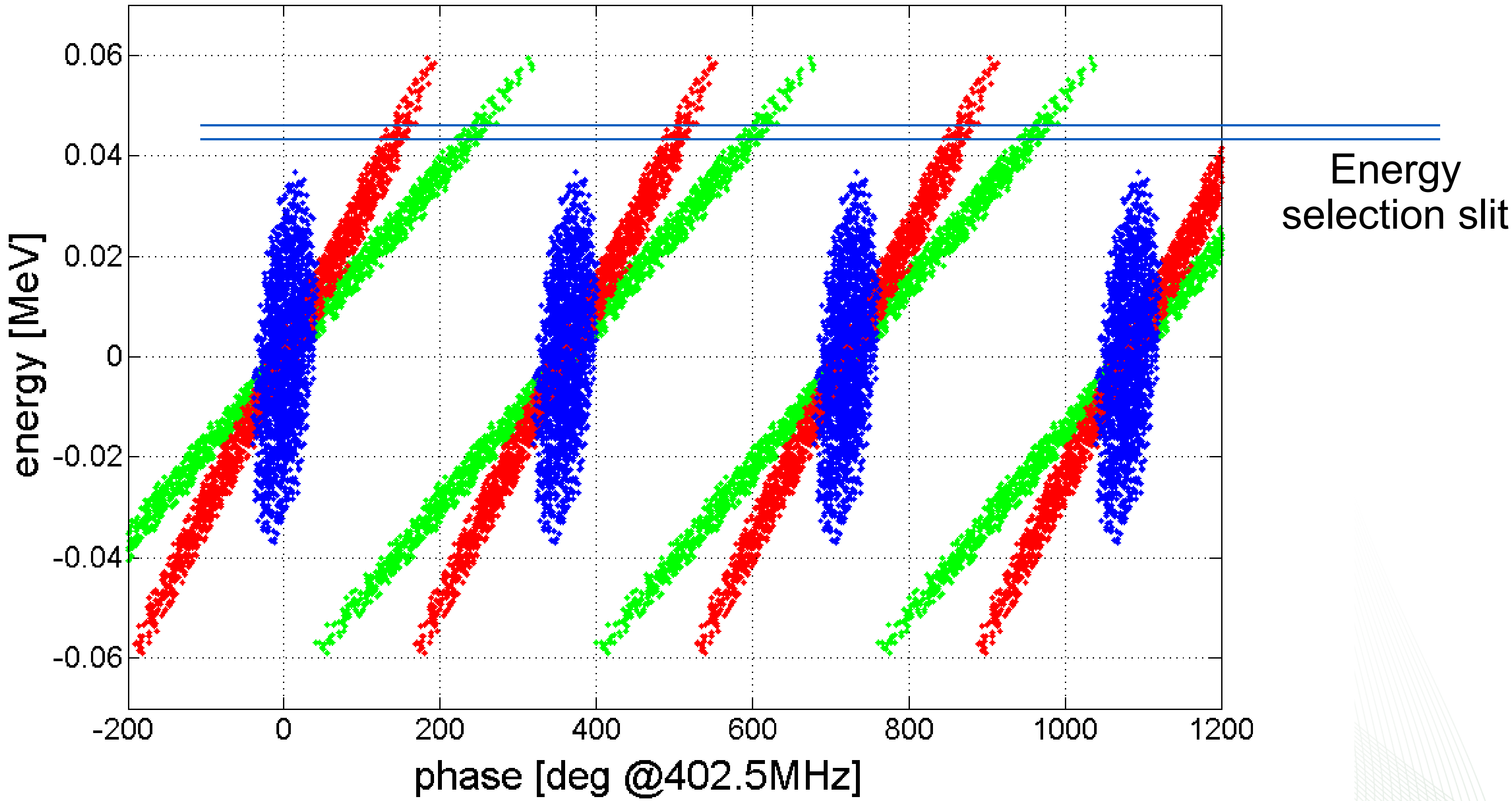
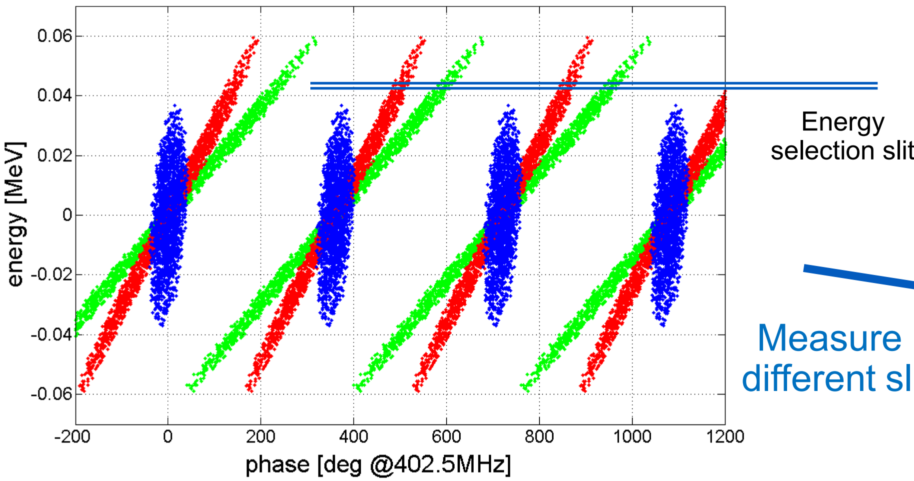
Longitudinal bunch expansion in free space causes overlap of temporal profiles



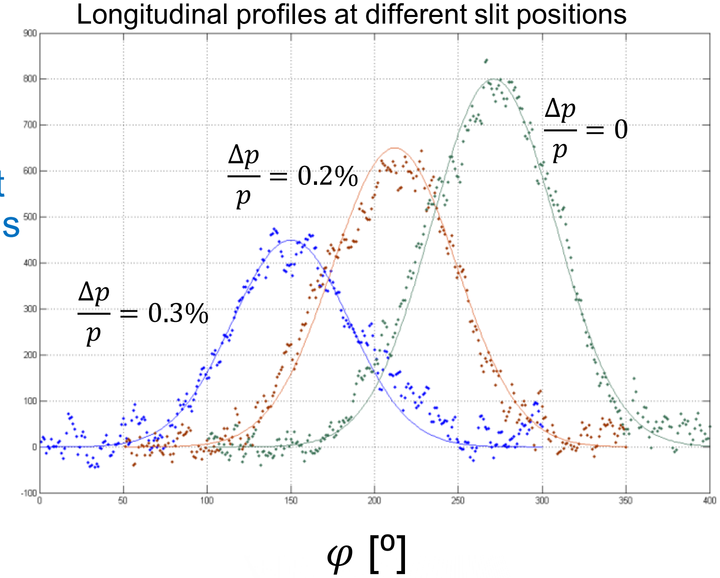
Bunches do not overlap in 2D phase space



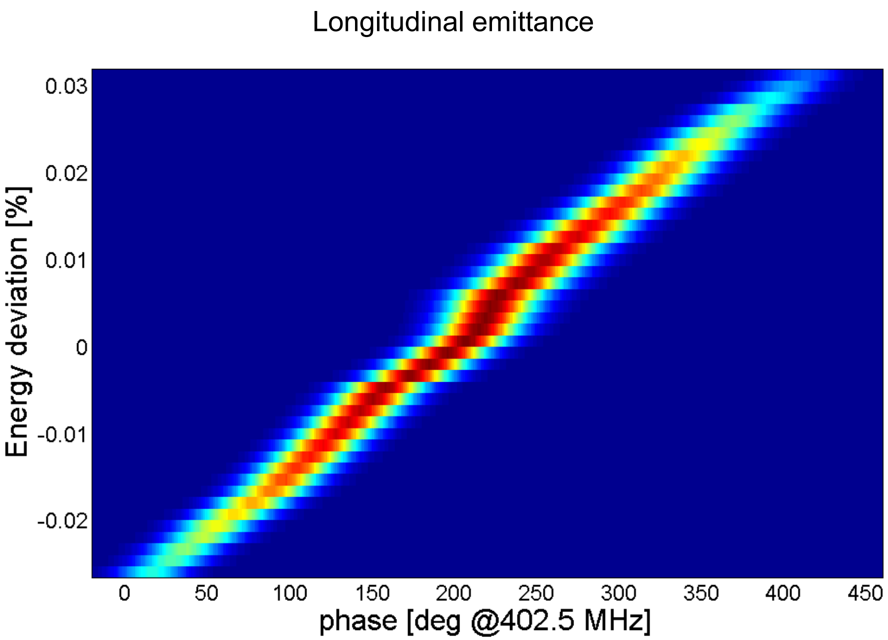
Longitudinal plane 2D scan



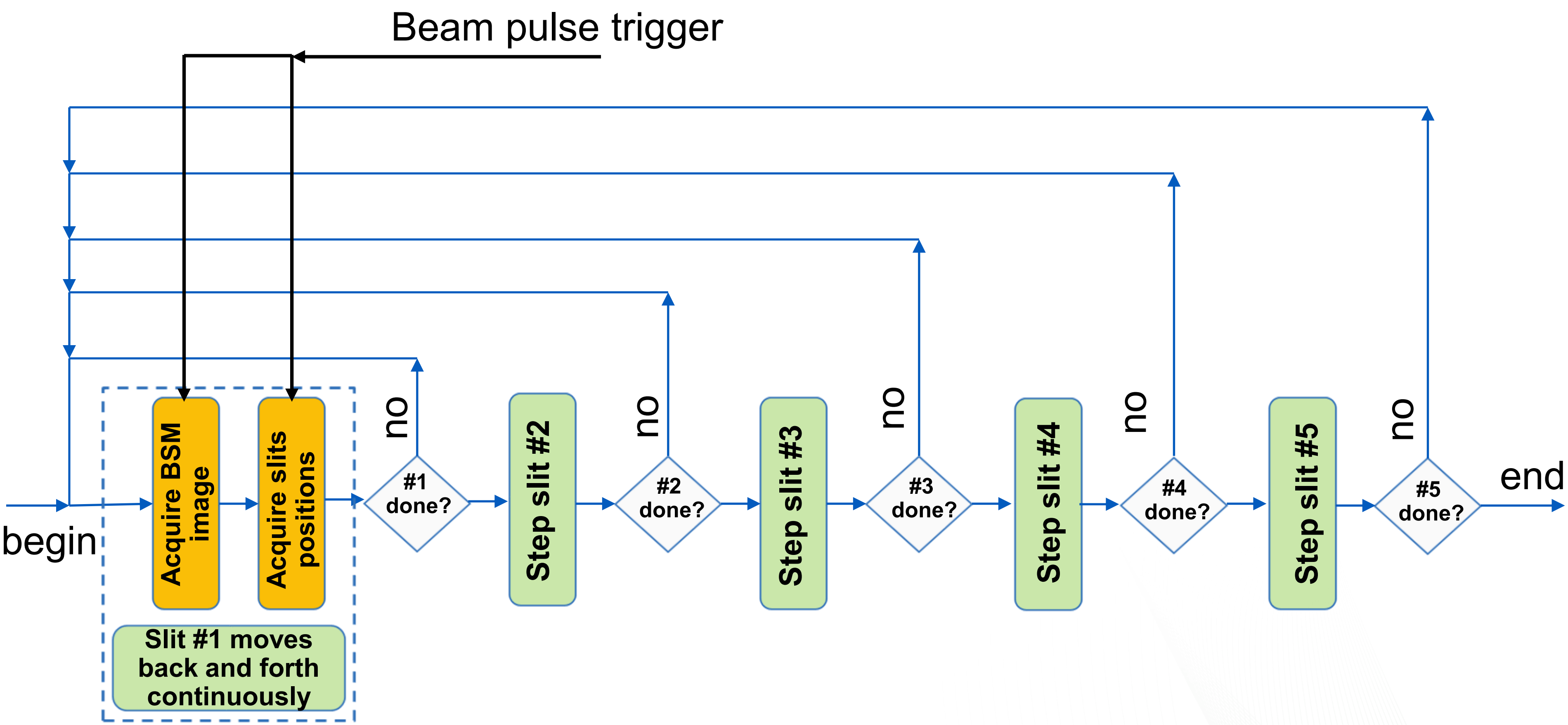
Measure profiles at different slit positions



Combine profiles to obtain full longitudinal emittance



6D scan sequence



Slit number assignment is programmable

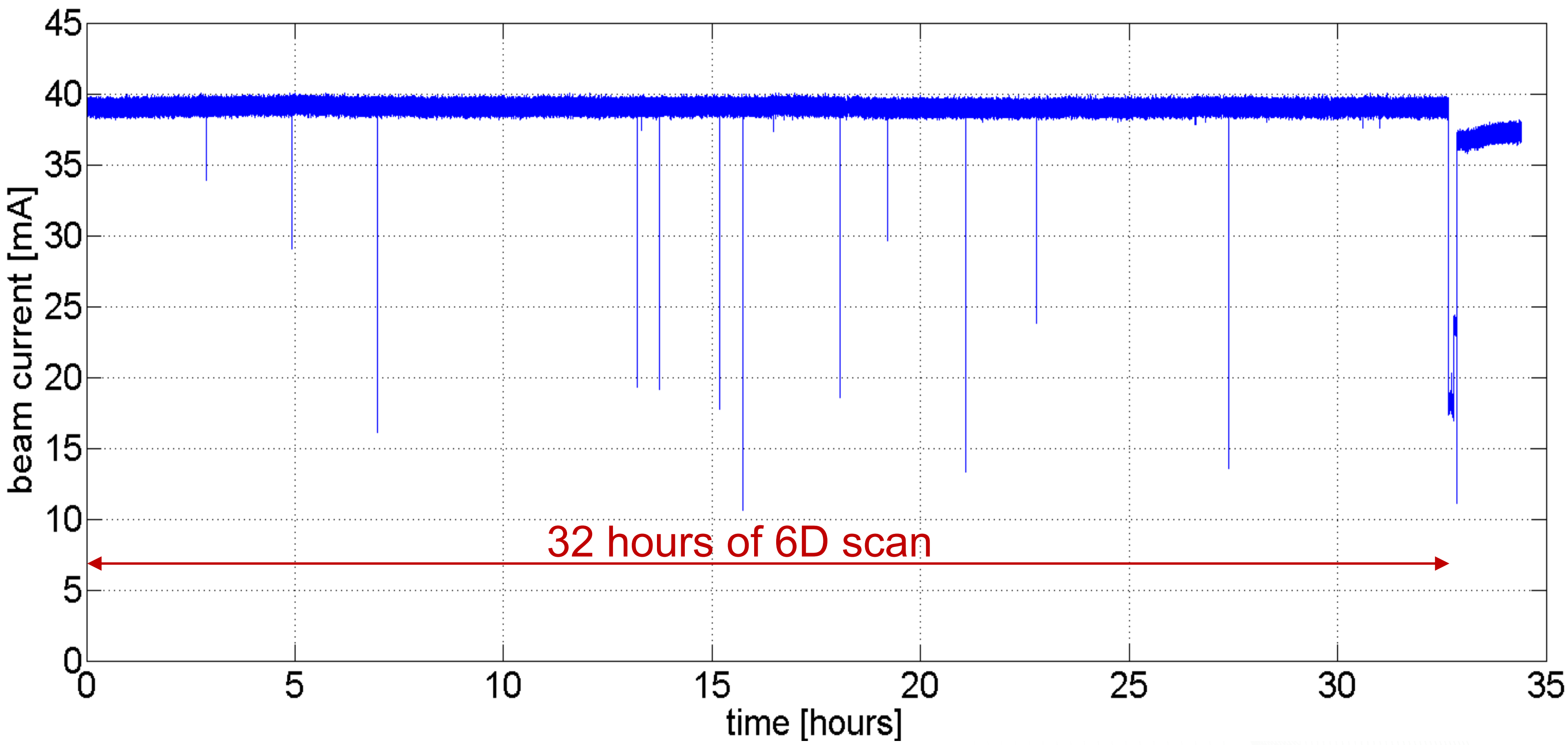
More details in TUPAL044

List of successful D>4 dimensionality scans*

Date	I_{beam}	D	Scan time	Rep. rate	# points	Average # steps / dim
28 Nov 2016	40 mA	5	0h 45min	5 Hz	270,000	~12
28 Nov 2016	40 mA	5	0h 40min	5 Hz	240,000	~12
29 Nov 2016	43 mA	5	3h 55min	5 Hz	1,530,000	~17
30 Nov 2016	41 mA	5	3h 00min	5 Hz	1,080,000	~16
21 Dec 2016	38 mA	5	5h 00min	5 Hz	1,800,000	~18
3 Mar 2017	32 mA	5	2h 50min	5 Hz	1,020,000	~16
5 Mar 2017	30 mA	5	5h 10min	5 Hz	1,860,000	~18
8 May 2017	41 mA	5	20h 05min	5 Hz	7,300,000	~24
10 May 2017	19 mA	5	4h 50min	5 Hz	1,740,000	~18
12 May 2017	30 mA	5	4h 30min	5 Hz	1,620,000	~17
10 Jul 2017	25 mA	5	13h 8min	5 Hz	4,730,000	~22
11 Jul 2017	25 mA	5	15h 25min	5 Hz	5,550,000	~22
12 Jul 2017	26 mA	5	15h 20min	5 Hz	5,520,000	~22
13 Jul 2017	24 mA	5	12h 35min	5 Hz	4,530,000	~21
25 Oct 2017	39 mA	6	32h 06min	2.5 Hz	5,675,740	~13

* Many more of D=1,2,3,4 scans
and some of D=5,6 but not finished successfully are not listed

Beam stability during 6D scan



Data analysis: visual inspection of 1D and 2D partial projections

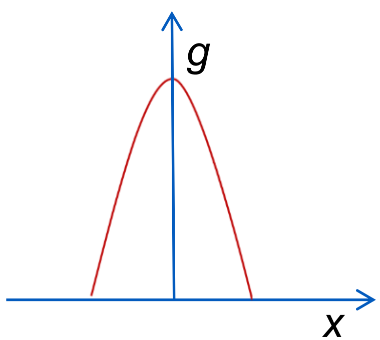
distribution function is Integrated over <u>all</u> non-imaging variables

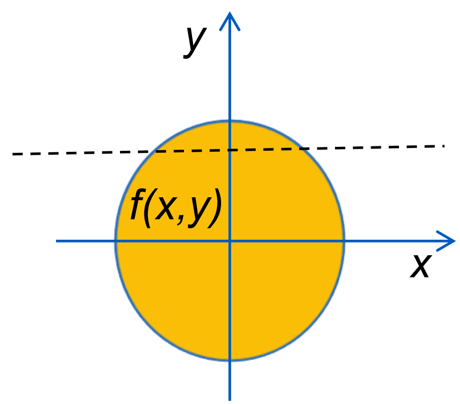
"full projection" ⟵   ⟶ "partial projection"

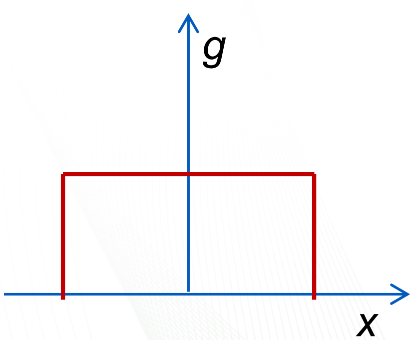
some variables are set to fixed values; distribution function is Integrated over <u>remaining</u> non-imaging variables

$$g(a) = \int_{-\infty}^{\infty} f_6(a,\vec{x})\,d\vec{x}$$

$$g(a) = \int_{-\infty}^{\infty} f_6(a,\vec{v}=\overrightarrow{v_0},\vec{x})\,d\vec{x}$$





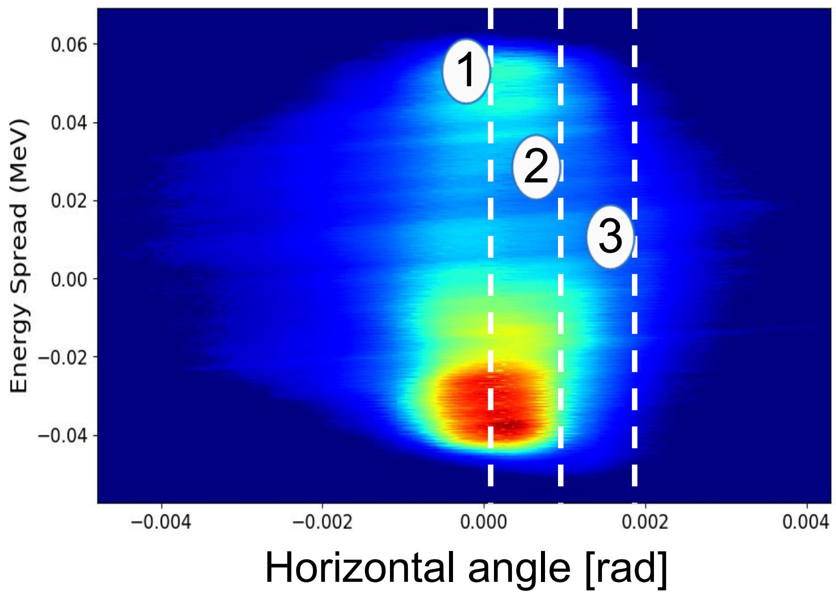


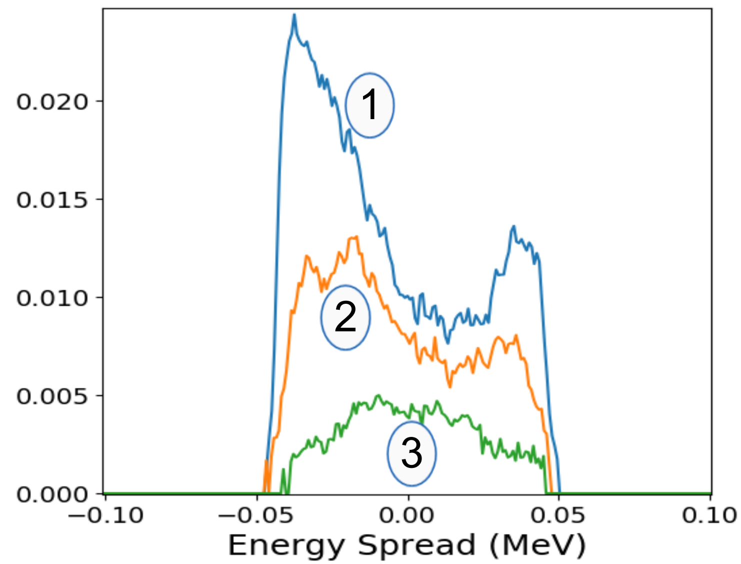
Number of 2D full projections of 6D function = **15**
(x-x', x-y, x-y', x-w, x-ϕ, x'-y, ...)

Number of 2D partial projections of 6D function = **210**

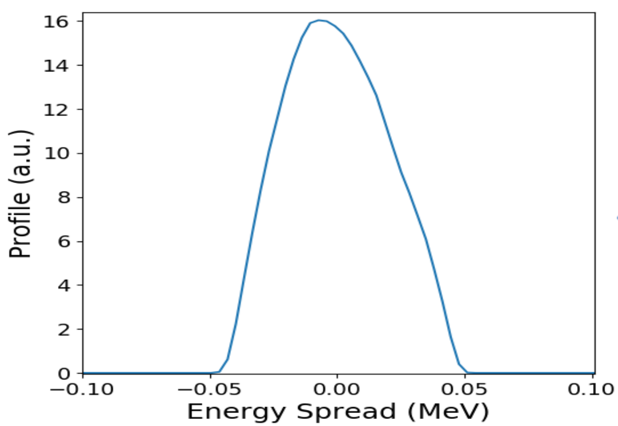
Observed correlation in x'-w partial projection

$$f(x',w) = \int dt \cdot f_6\,(t, x = y = y' = 0)$$





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



full projection (energy spectrum)

$$f(w) = \int dtdxdx'dydy' \cdot f_6\,(x, x', y, y', w, t)$$

looks ordinarily

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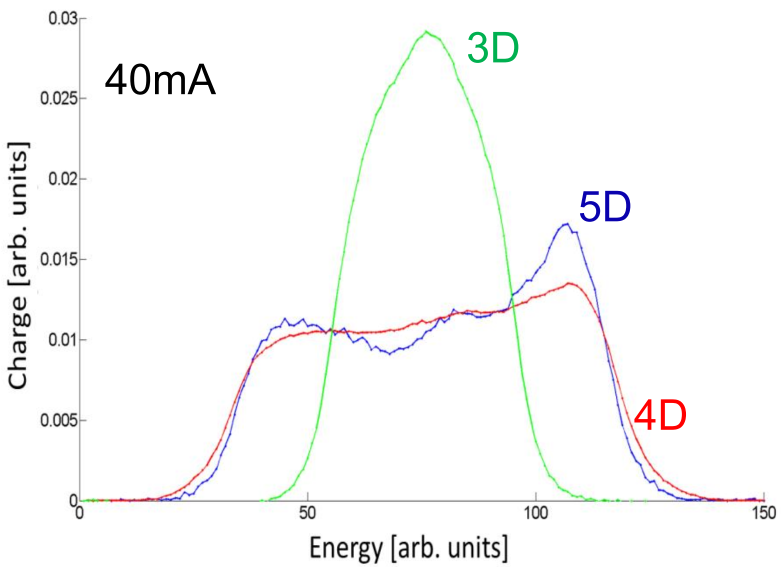
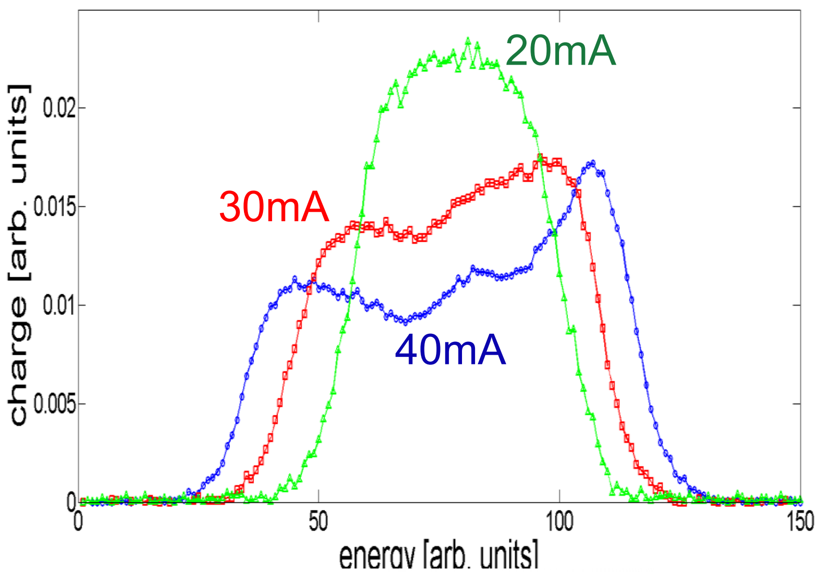
Partial projections of interest can be studied with faster than 6D partial scans



Dependence of partial projection f(w) on dimensionality (number of non-integrated variables)

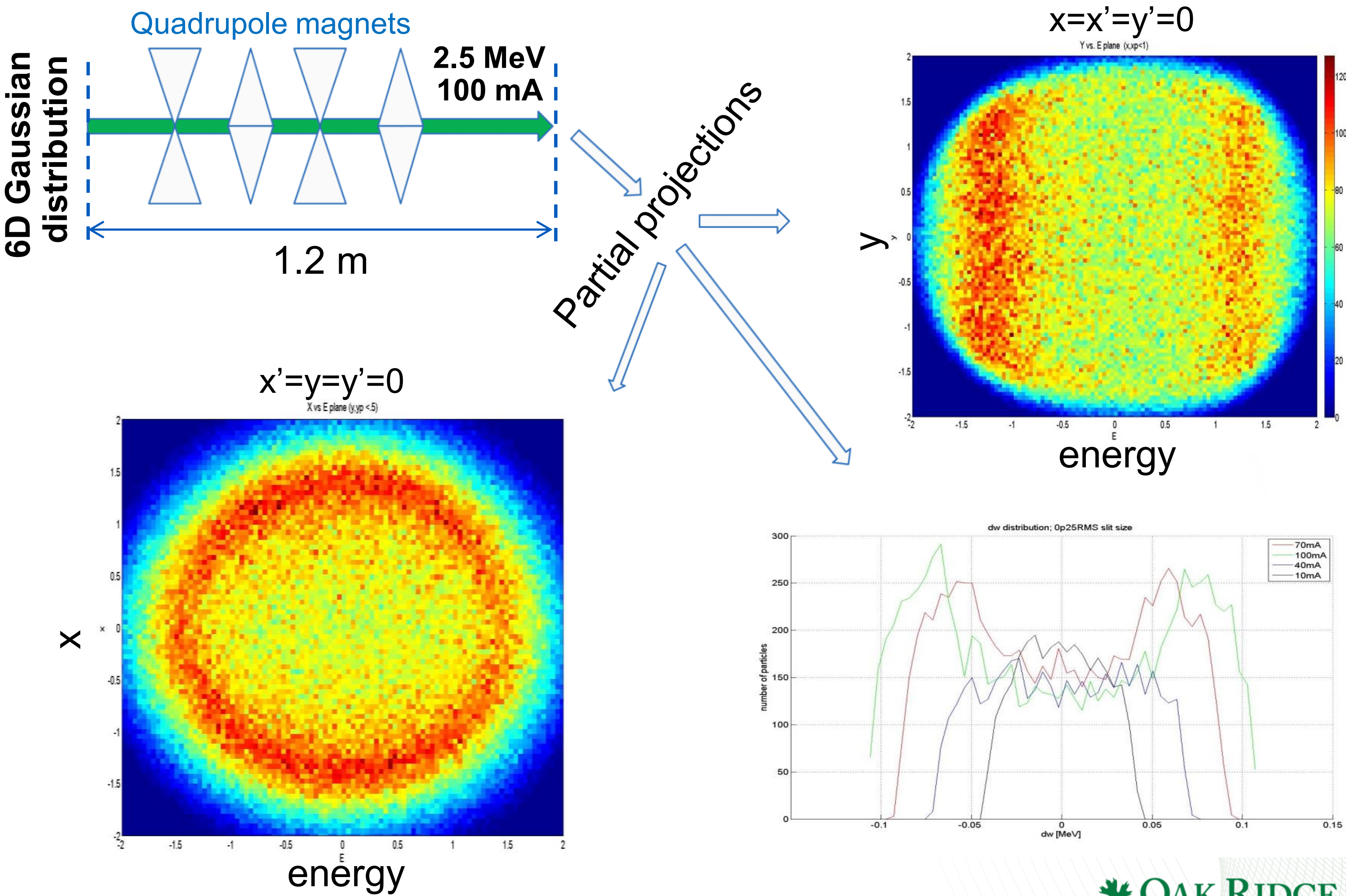


Dependence of partial projection f(w) (x=x'=y=y'=0) on beam current

D>4 measurements are required to observe this correlation

Space charge effect seems to create correlation

Similar patterns are observed in beam simulation with strong space charge



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Developed practical 6D measurement technique

Discovered correlations in high dimensions

What is next?

Can we reduce 6D scan time, increase resolution?

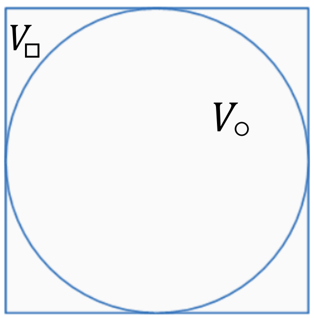
What to do with the data?
Are there other correlations?

Is this fine structure important?

Scan time reduction opportunities

1. Maximize sampling rate to 10 Hz: slit speed, data saving, ~x4

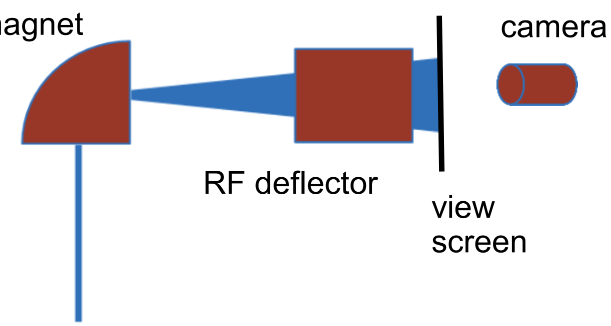
2. Use smarter scanning algorithm, ~x2

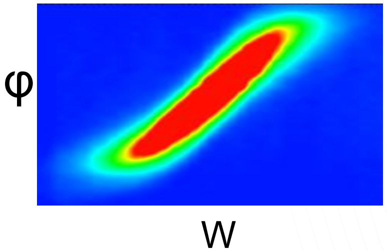


80% of measured points are zero!

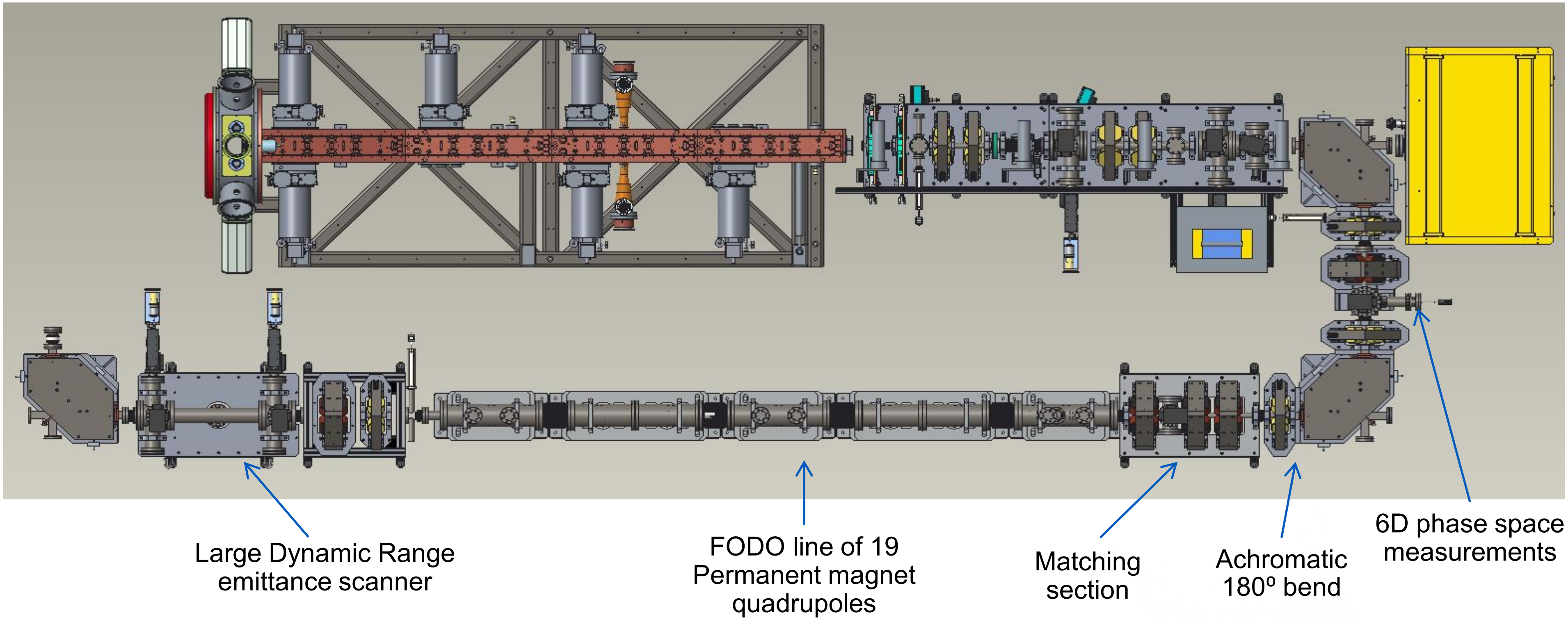
$$\frac{V_{\circ}}{V_{\square}} = \frac{\pi^{D/2}}{\Gamma(D/2 + 1)2^D} = \begin{cases} .79\,; & D = 2 \\ .52\,; & D = 3 \\ .081; & D = 6 \end{cases}$$

3. Redesign BSM for simultaneous W-ϕ measurement, ~x10



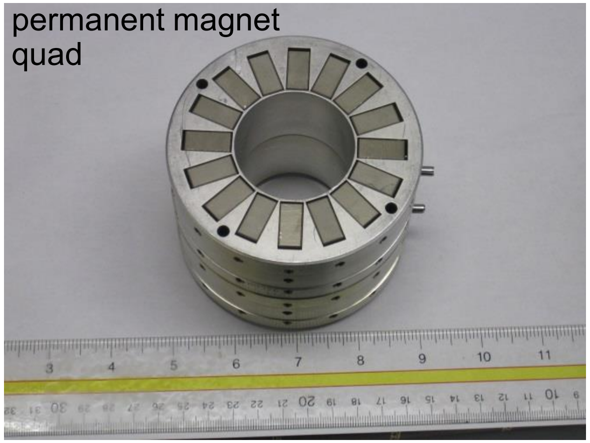


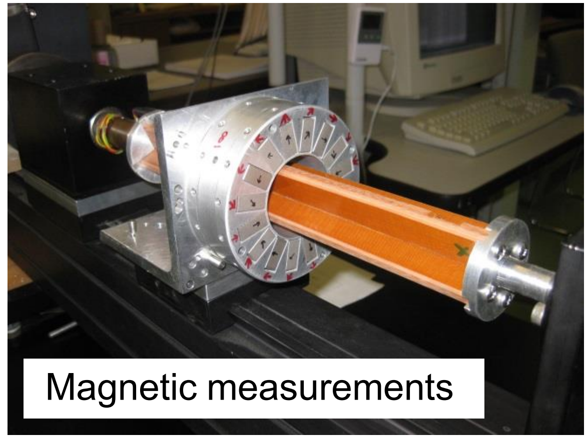
FODO line experiment



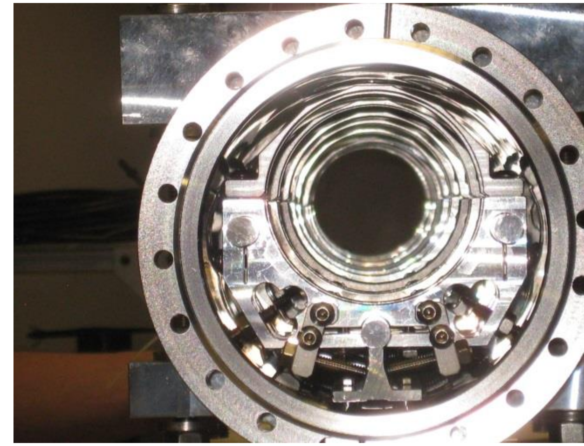
- Beam dynamic simulation benchmark facility :
  - Measured 6D distribution at input
  - FODO transport channel as simulation “benchmark case”
  - Large Dynamic Range emittance measurement at exit

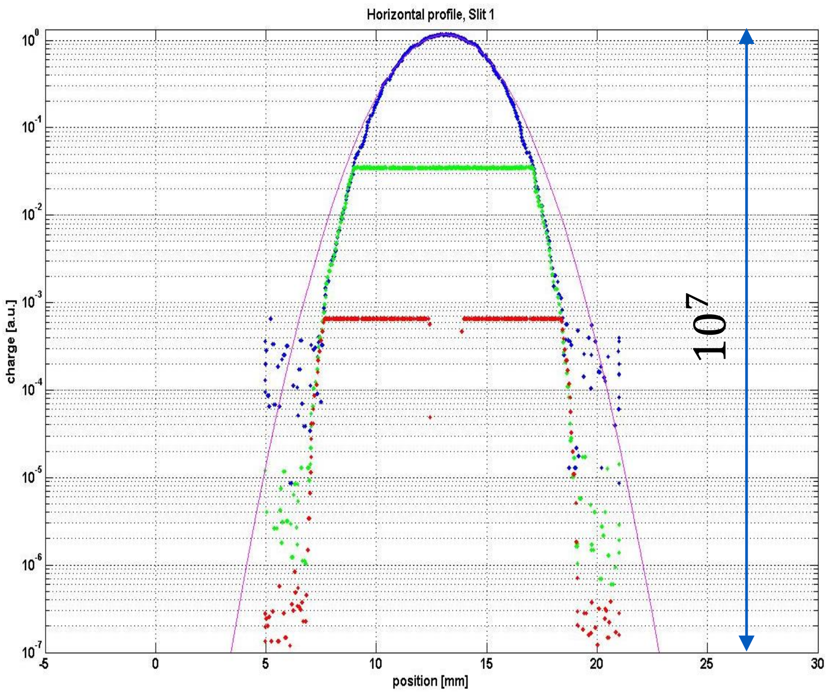
FODO beam line design


permanent magnet quad


Magnetic measurements

permanent magnet quad holding structure





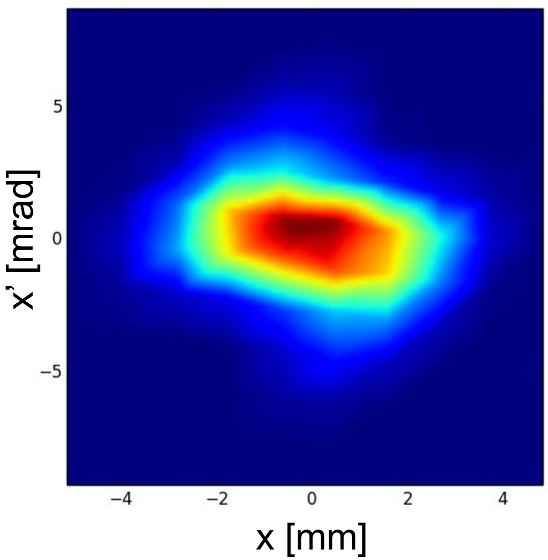
High Dynamic Range 1D scan


Assembled FODO line

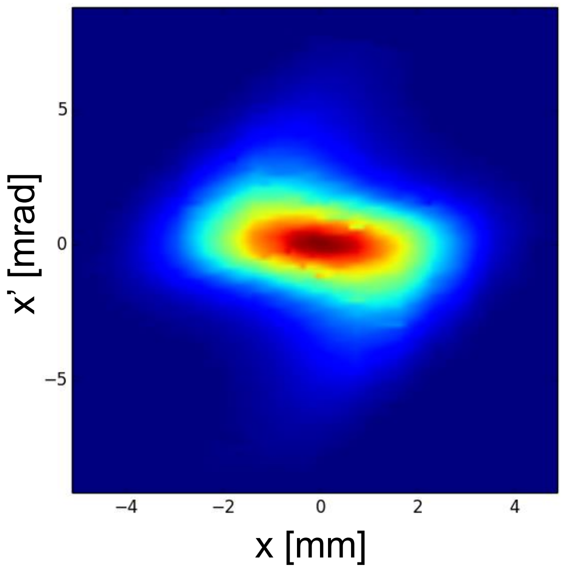
Thank you for your attention!

Cross-checking between different dimensionality scan data

x-x’ projection obtained from measured 4D distribution

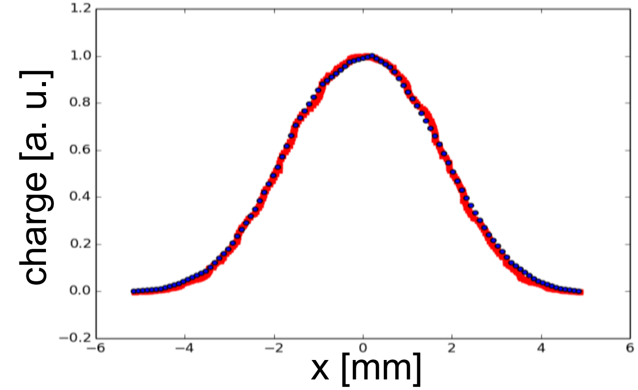


x-x’ emittance from 2D scan

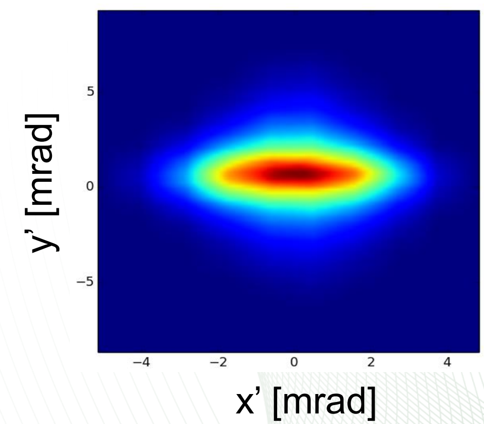


x projection obtained from 4D measured distribution (blue)

x profile from 1D scan (red)



x’-y’ projection obtained from measured 4D distribution



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