6D and High Dynamic Range Measurements of Hadron Beam Phase-Space

12th International Beam Instrumentation Conference

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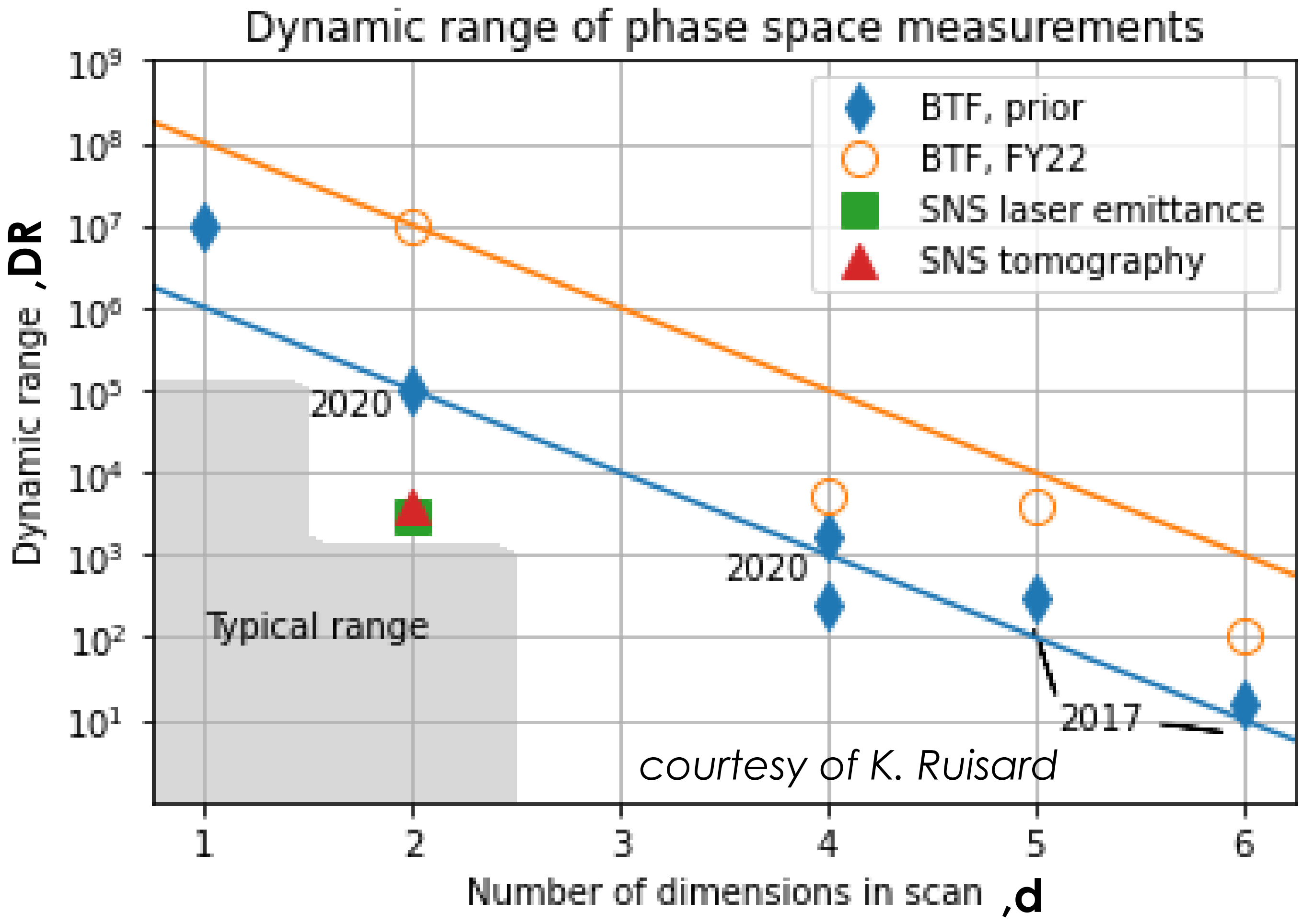
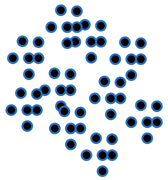
In lieu of outline



$$\log(DR) \approx a - kd$$

Beam dynamics in real 3d space can be represented as evolution of distribution function in 6d phase space



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

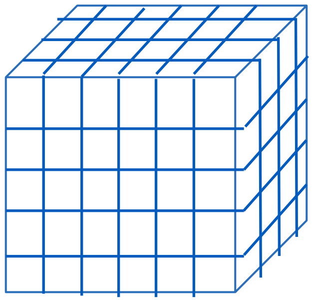
particle #	coordinates
1	x, x', y, y', z, z'
2	x, x', y, y', z, z'
.	.
.	.
N	x, x', y, y', z, z'

$6N$ numbers, e.g. $6 \cdot 10^9$

Cannot measure individual particles positions (yet), need something else

distribution function

number of particles per
bin in phase space



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

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

Distribution function representation requires n^6 numbers in 6D

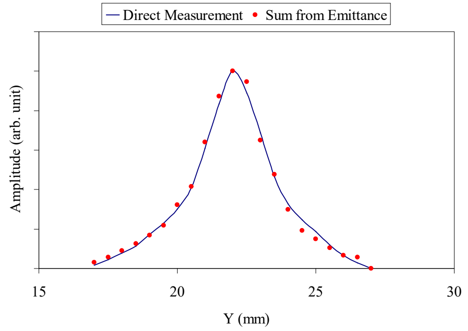
e.g. $6 \cdot 10^7$, for n=20

Next best representation after actual particles coordinates

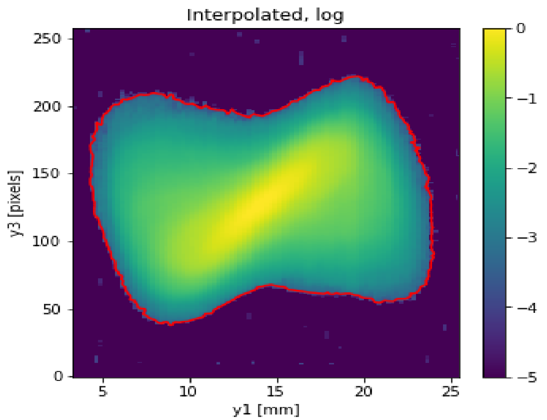
Most important, it's measurable

All commonly used beam parameters can be calculated from 6d distribution function, but not vise versa

1D profiles: $$p(x) = \iiint_{-\infty}^{\infty} f(x, x', y, y, z, z')\, dx' dy dy' dz dz'$$



2D emittances: $$p(x, x') = \iiint_{-\infty}^{\infty} f(x, x', y, y, z, z')\, dy dy' dz dz'$$



σ matrix:

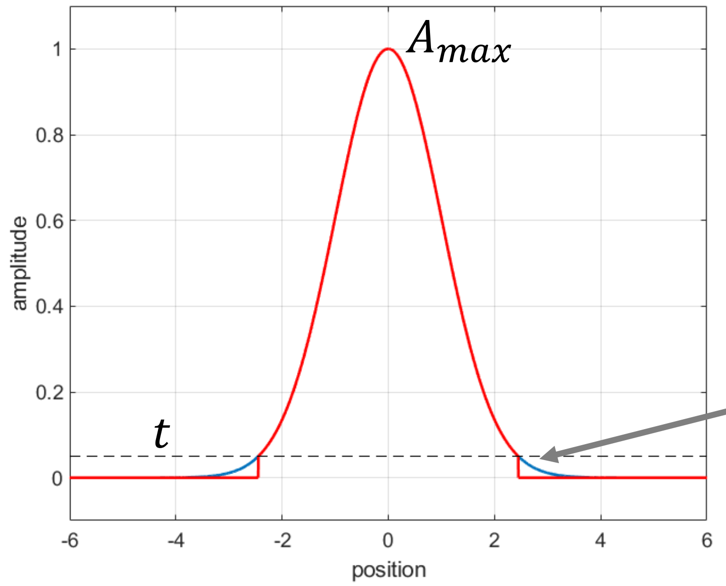
$$\begin{array}{c|cccccc} & x & x' & y & y' & z & z' \\ \hline x & \langle xx\rangle & \langle xx'\rangle & \langle xy\rangle & \langle xy'\rangle & \langle xz\rangle & \langle xz'\rangle \\ x' & \langle x'x\rangle & \langle x'x'\rangle & \langle x'y\rangle & \langle x'y'\rangle & \langle x'z\rangle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

And much more,

including generating particle coordinates

to initialize PIC simulations

Dynamic range is ratio of maximum density at the peak to minimum density resolvable above noise



$$DR = \frac{A_{max}}{t}$$

Maximum amplitude

threshold

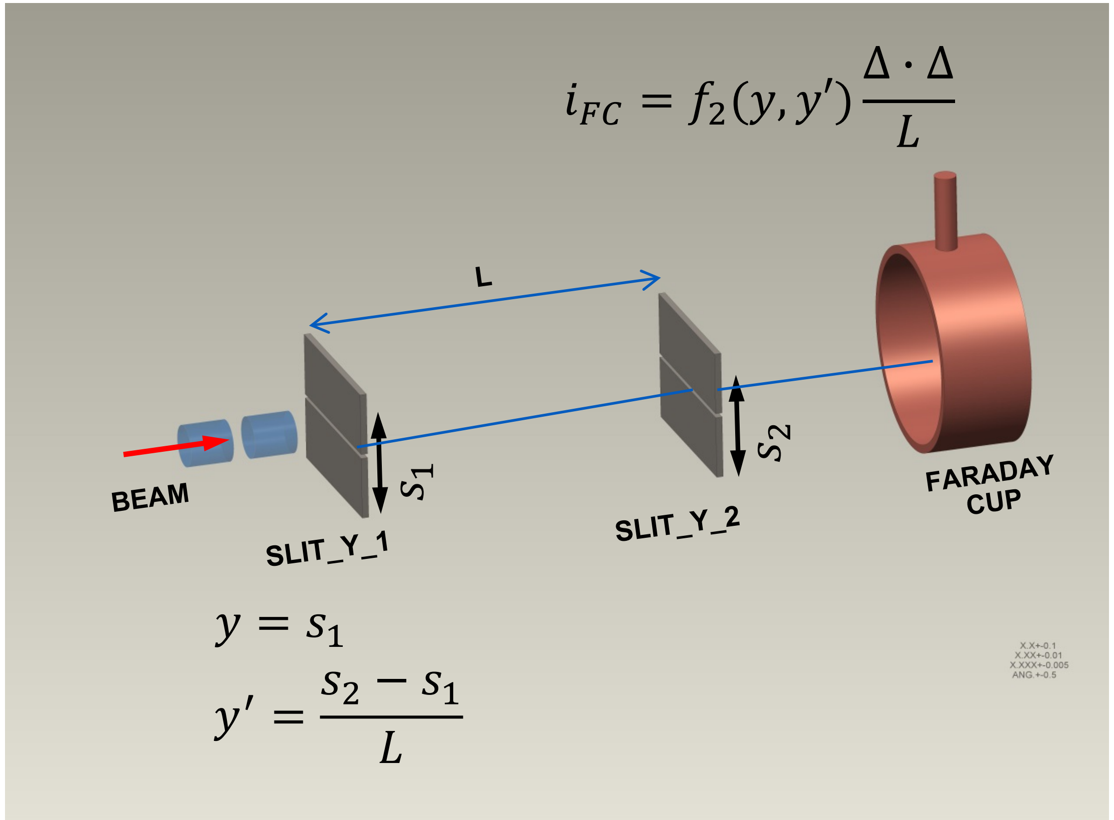
Some fraction **r** is lost due to applying threshold

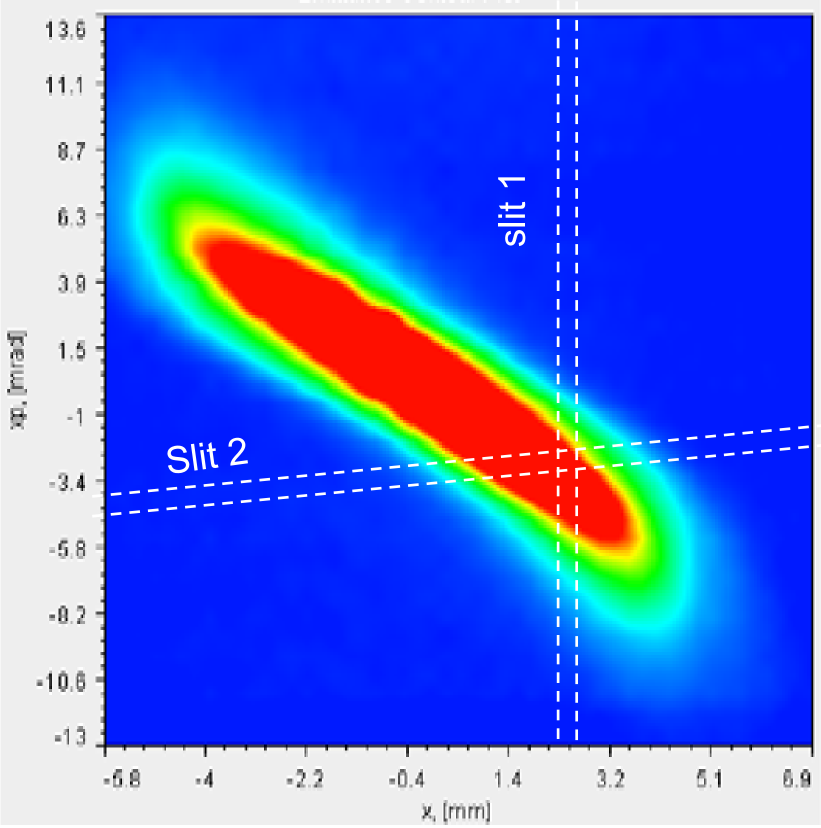
Fraction of particles eliminated by applying threshold depends on threshold, distribution shape, and dimensionality

Example: Gauss distribution, t=10^{-6}

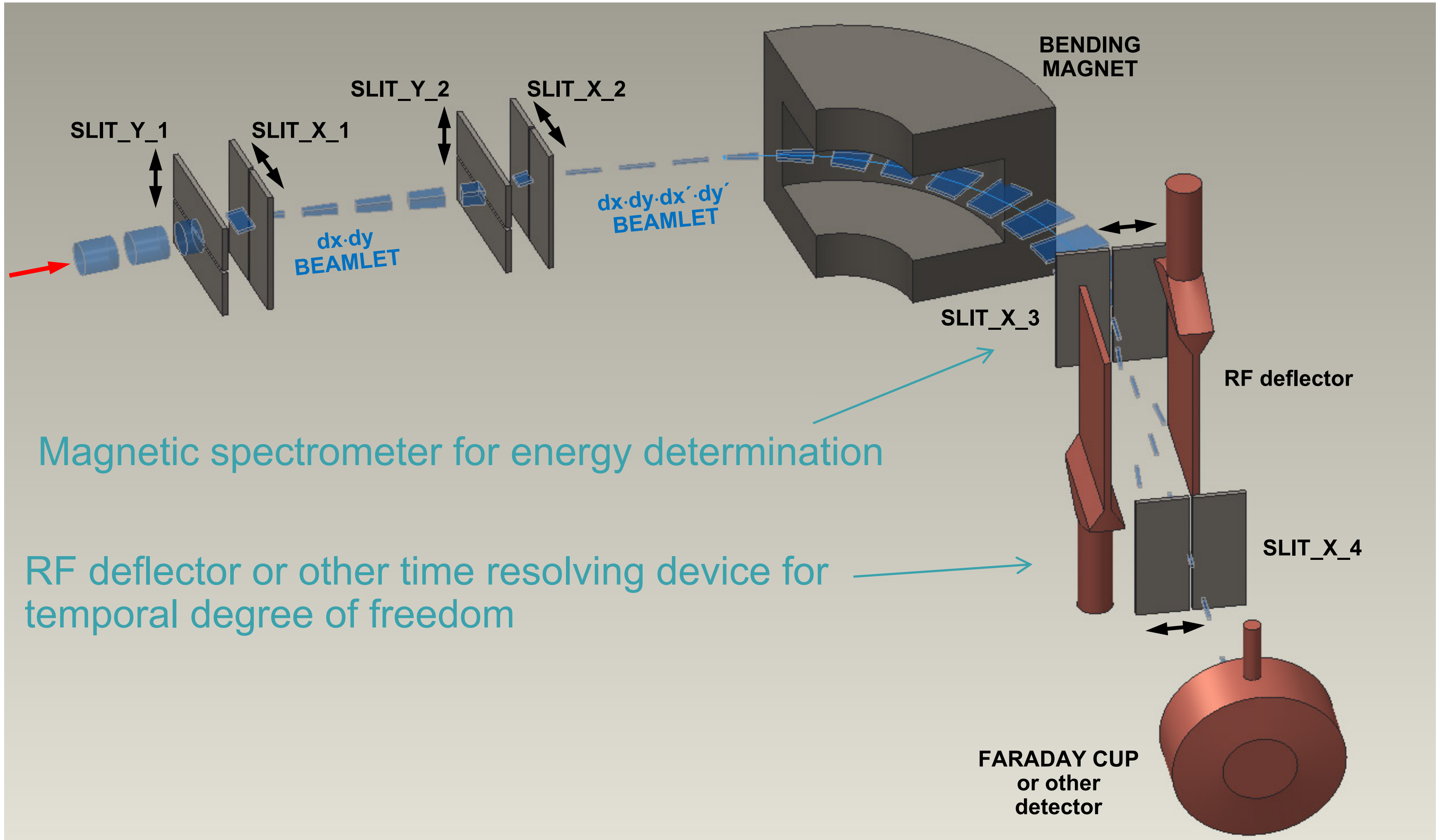
Dimensionality, d	1	2	3	4	5	6
Rejected fraction, r	$2 \cdot 10^{-7}$	$1 \cdot 10^{-6}$	$4 \cdot 10^{-6}$	$2 \cdot 10^{-5}$	$4 \cdot 10^{-5}$	$1 \cdot 10^{-4}$

Slit-slit technique is well suited for measuring charge density in phase space





6d phase scan principle



"Curse of dimensionality" for multi-dimensional scans

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

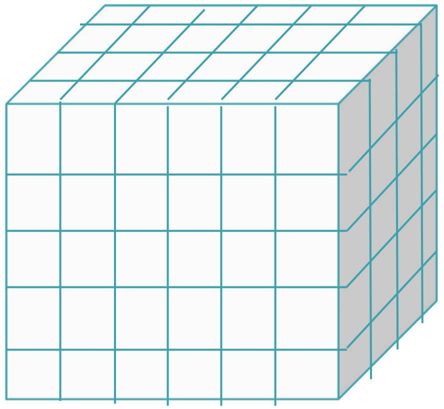
- High-dimensional spaces have very large volume: V$\sim a^d$
  - Large scan time
  - Low charge density
  - Large data sets

$N_{bins} = n^d$

dimensionality

Total number of bins

Number of steps per degree of freedom



Beam current attenuation by 1 slit $\sim \frac{\Delta}{\sigma}$ (Δ: slit width; σ: beam size)

Example: $n = 10,\ d = 6$ $\quad N_{bins} = 10^6$

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

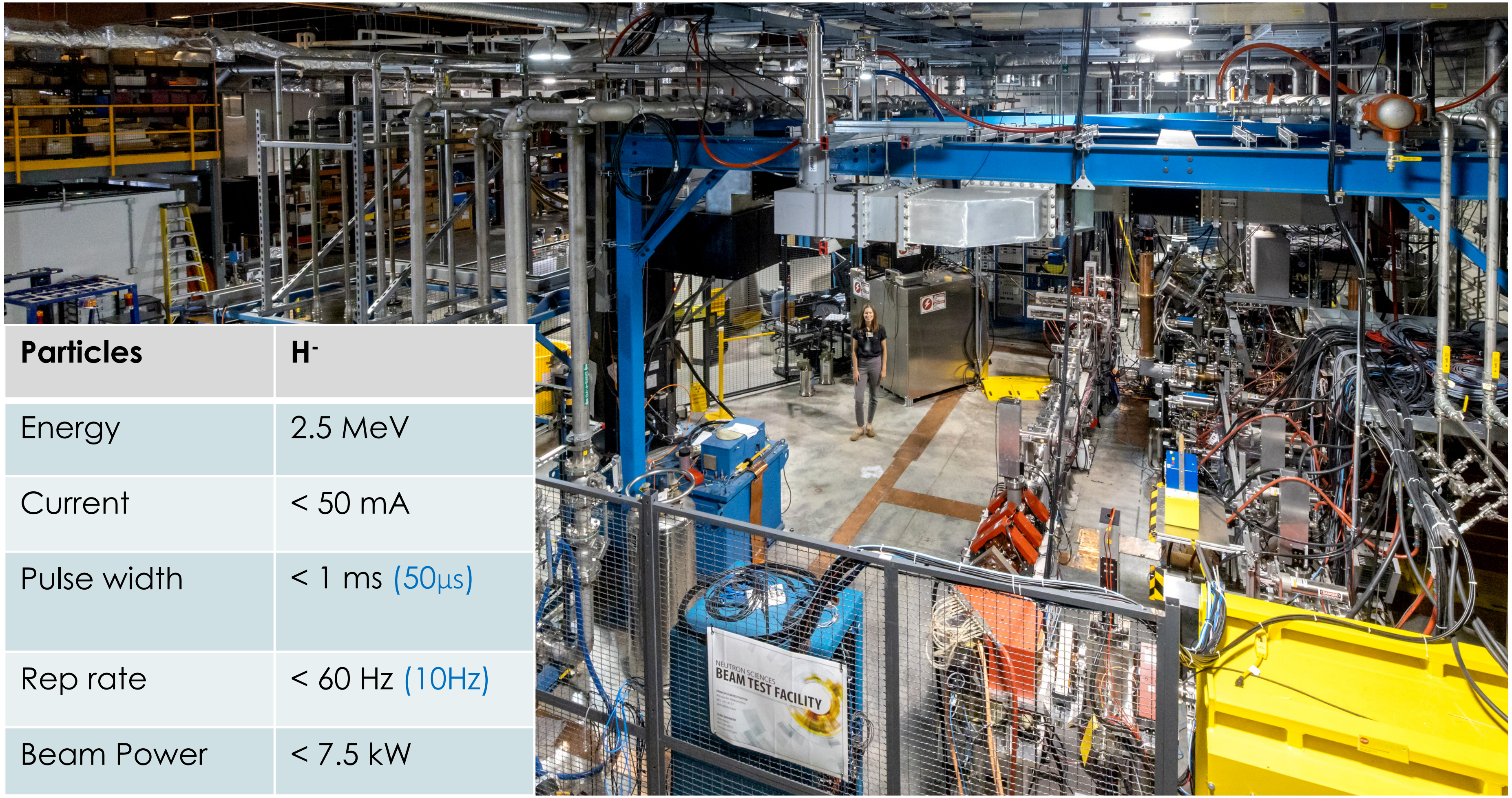
Maximum amplitude after d slits $A_{max} \sim \left(\frac{\Delta}{\sigma}\right)^d$

$$\log(DR) \approx a - kd$$

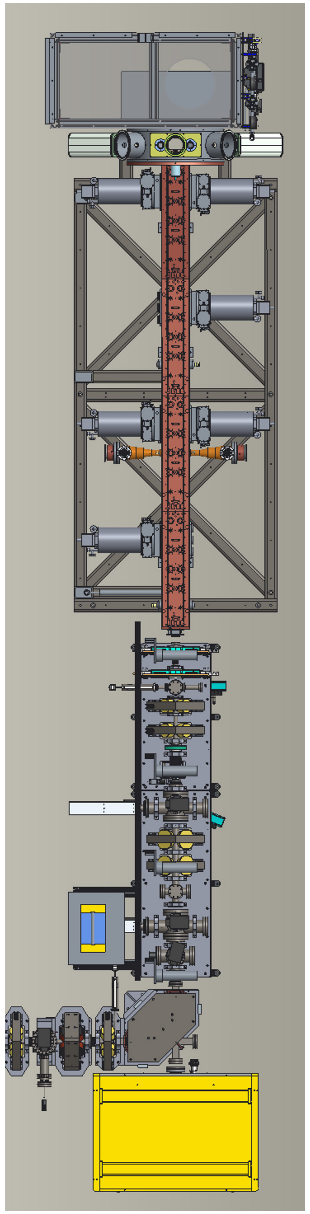
Example: $\Delta/_{\sigma} \approx .2\,,$ $\quad d = 6,$ $\quad I_{beam} = 30mA$

$A_{max} \approx 64\mu A$ $\quad t < 64\ fA$ To achieve DR=10^6

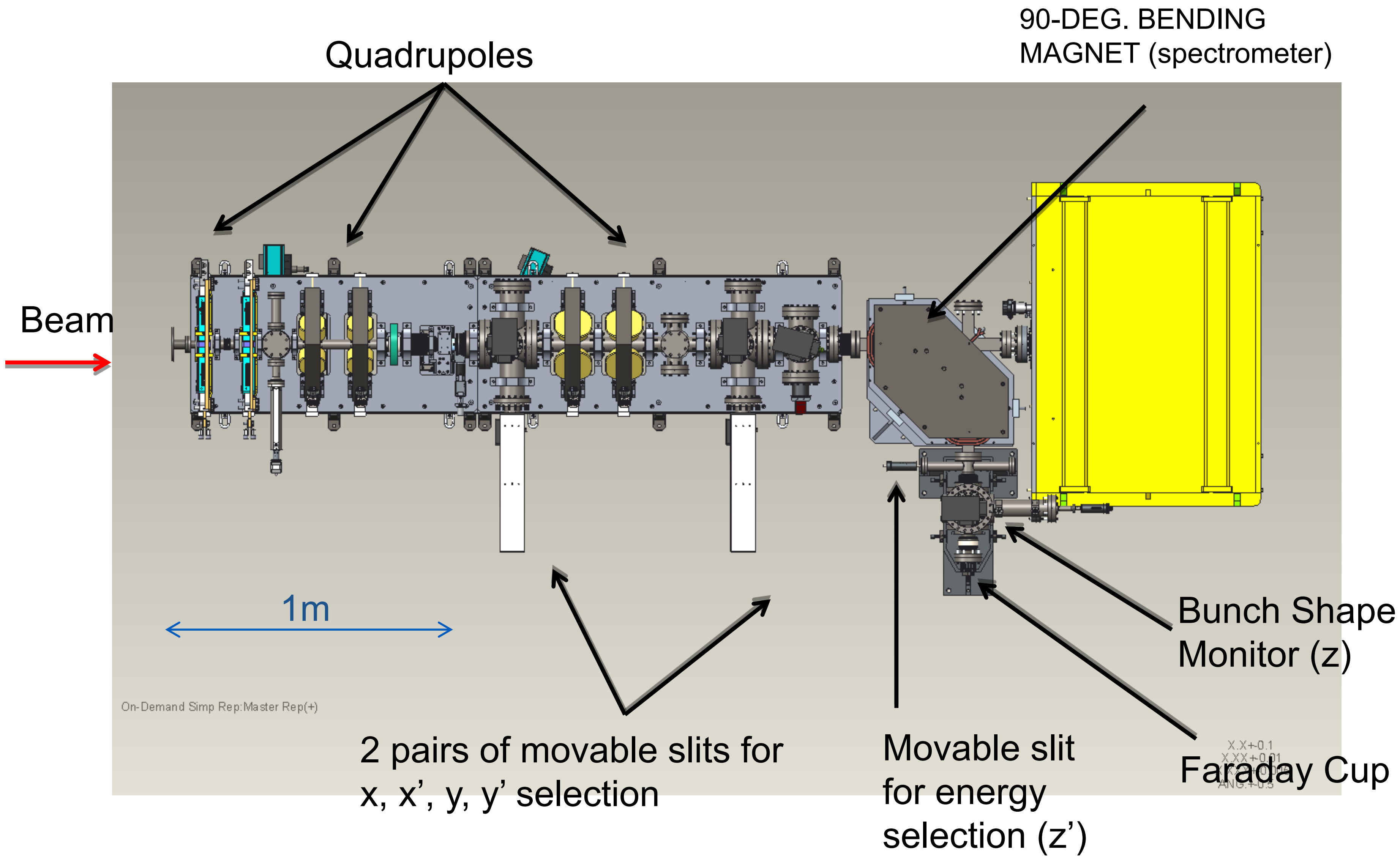
Beam Test Facility at SNS



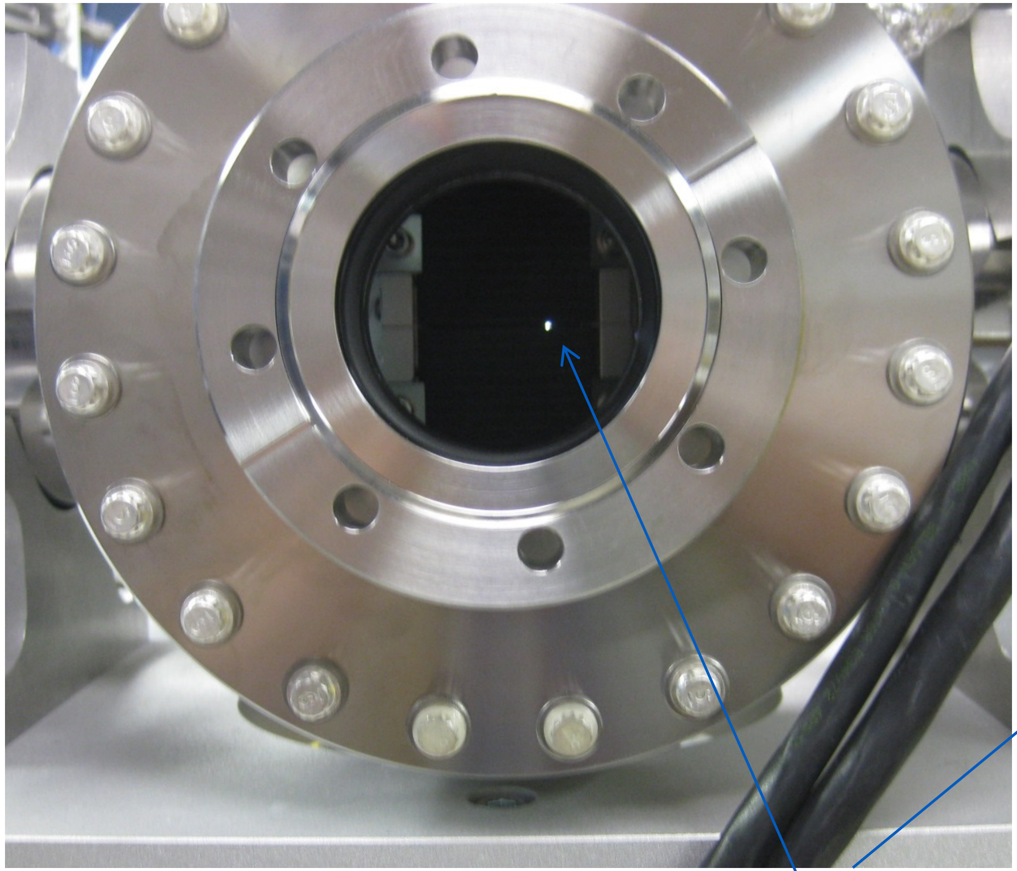
Particles	H^-
Energy	2.5 MeV
Current	< 50 mA
Pulse width	< 1 ms (50µs)
Rep rate	< 60 Hz (10Hz)
Beam Power	< 7.5 kW

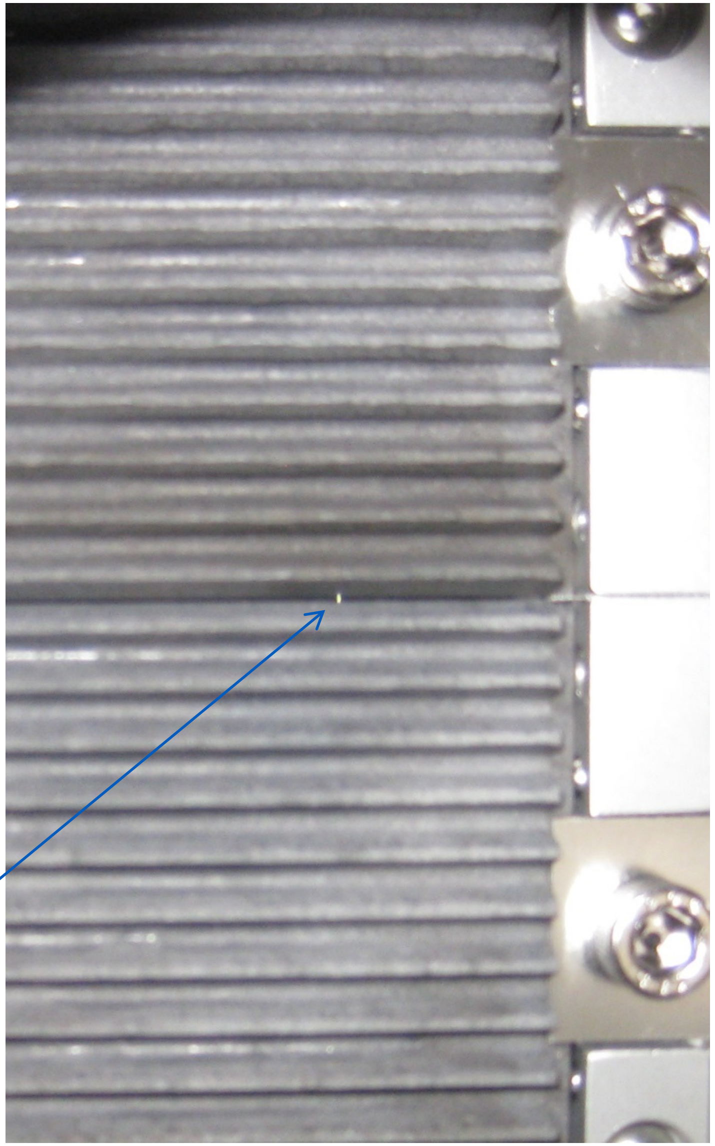


6d phase scan apparatus at SNS Beam Test Facility



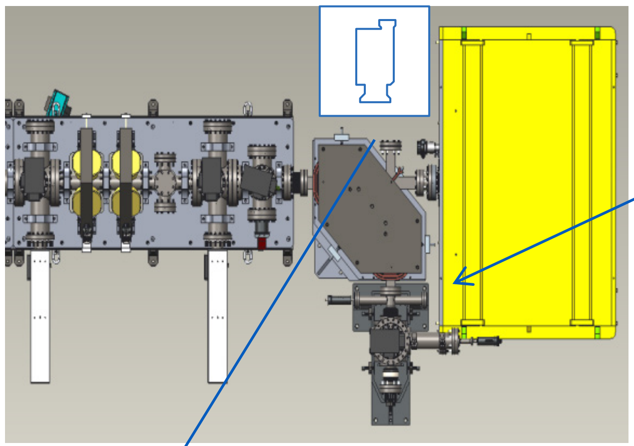
X-Y Slits arrangement

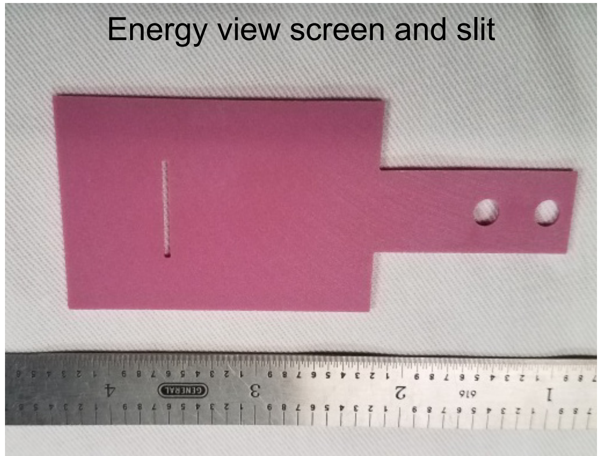


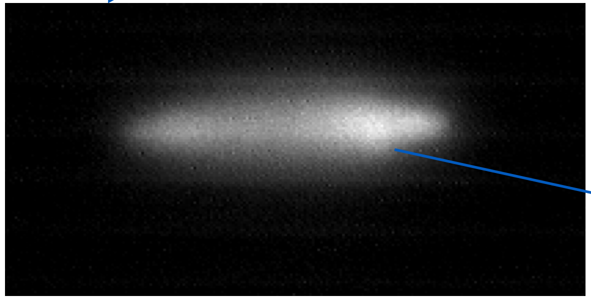


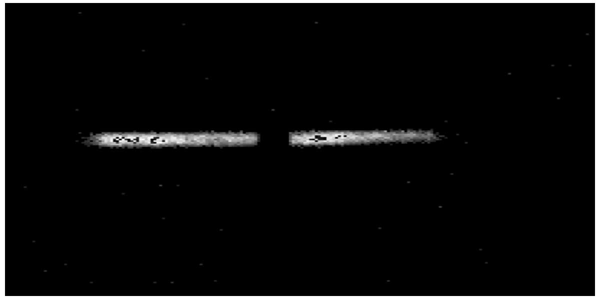
200-by-200 μm aperture

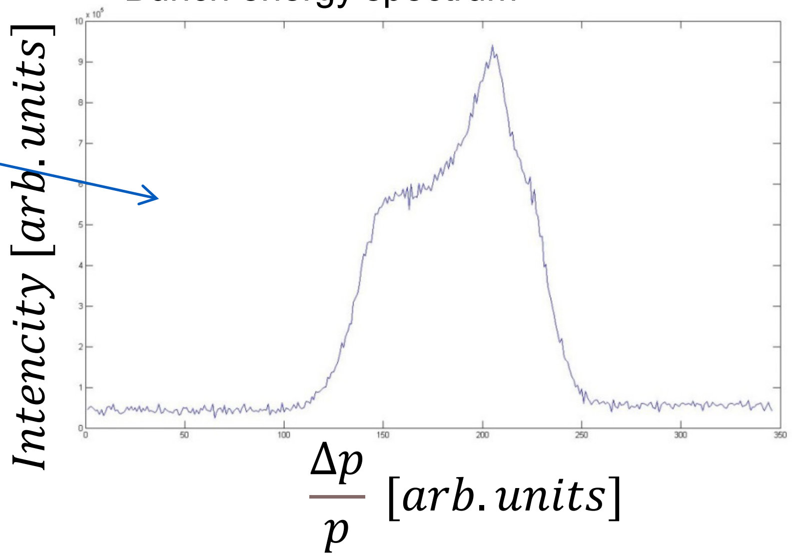
Energy selection and measurement





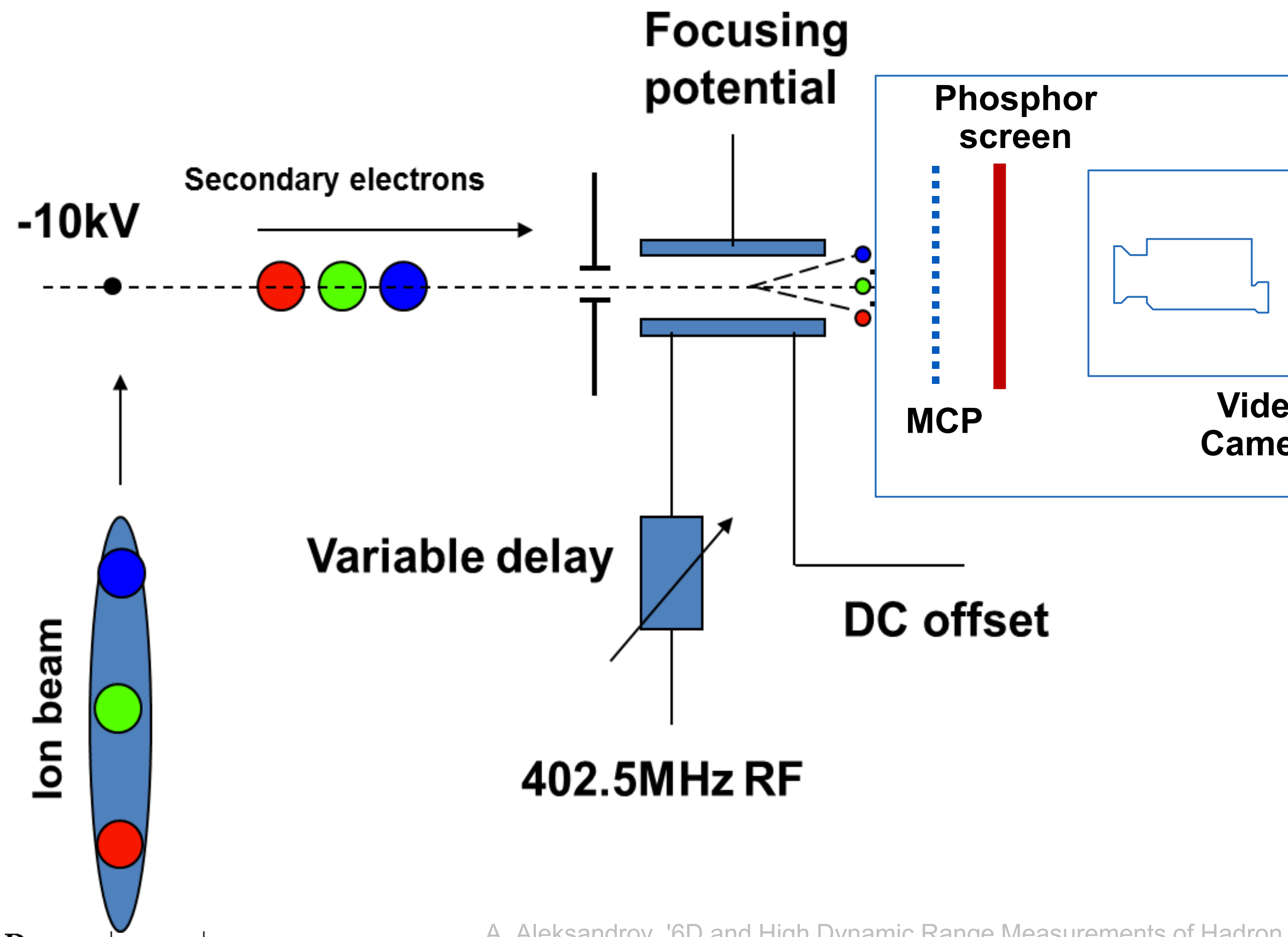


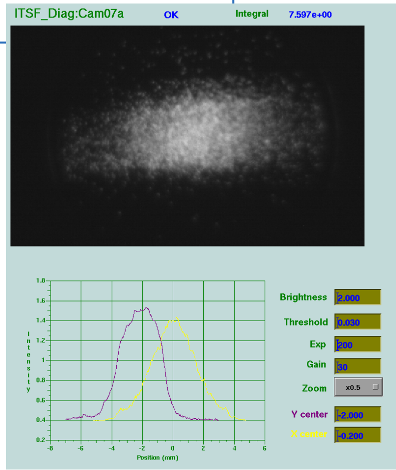


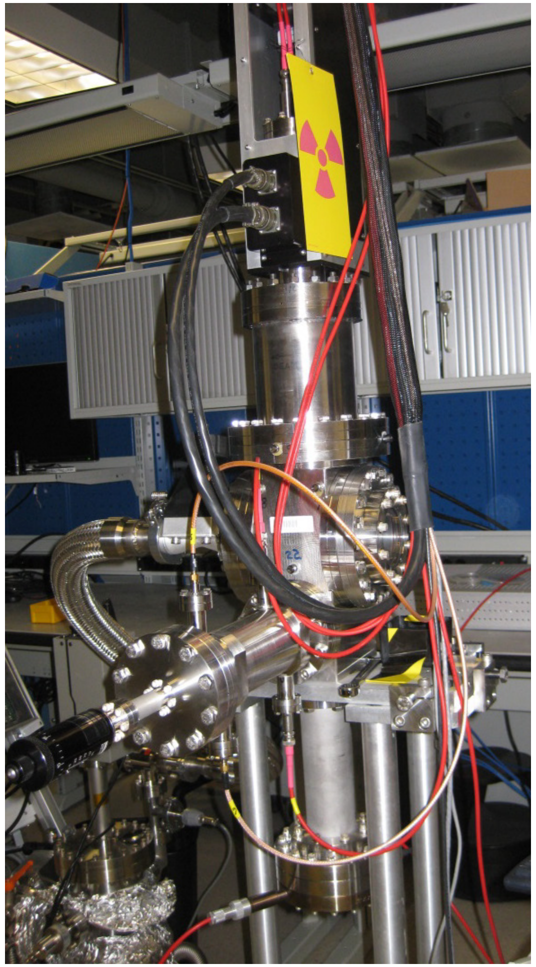


Bunch Shape Monitor principle of operation

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







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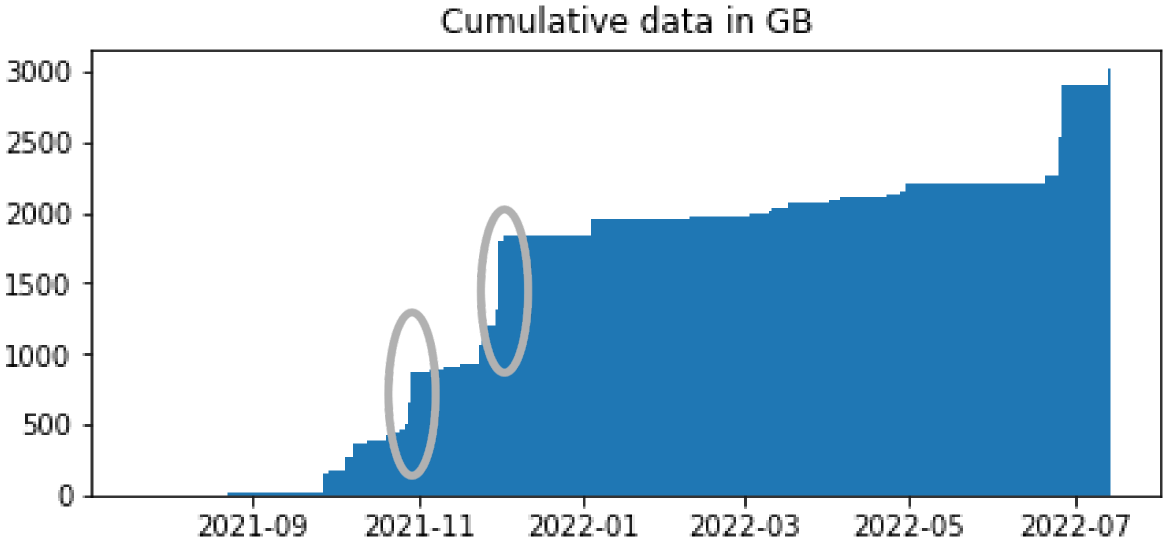
6d scan results

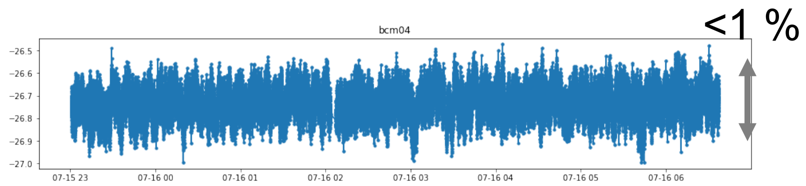
Date	Duration [hr]	#pts	Effective rep. rate	File size	Dynamic range
2018	32	~6M	2.5 Hz		~20
2021	31	~6M	2.8 Hz	370G	~100
2021	27	~6M	3.4 Hz	447G	~100

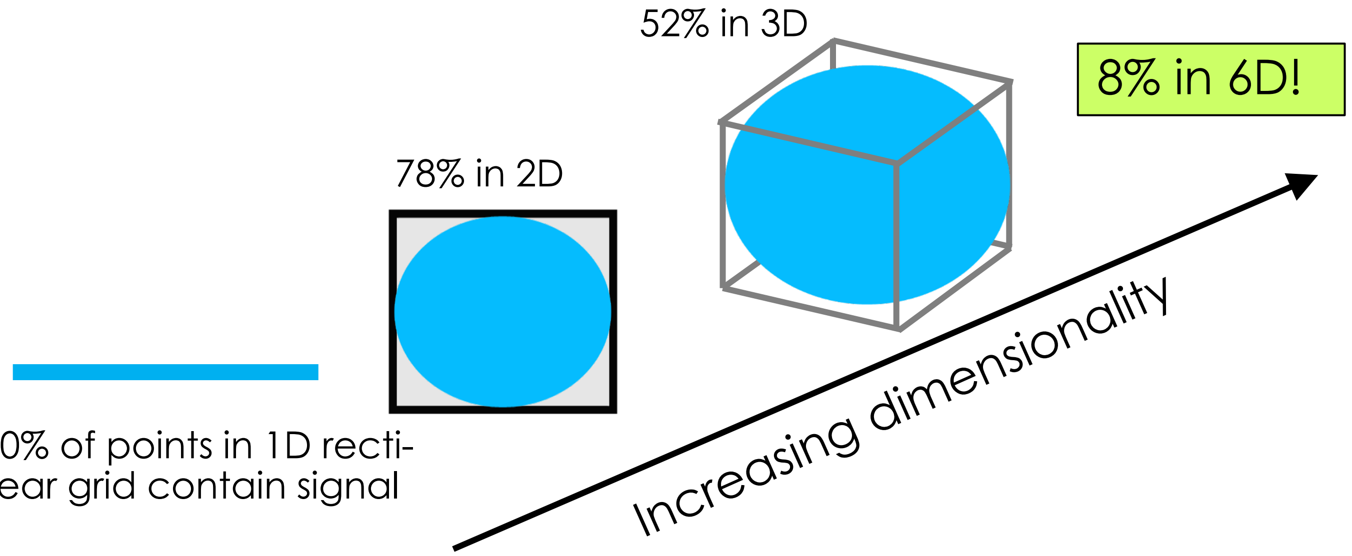


Very large files, but mostly empty

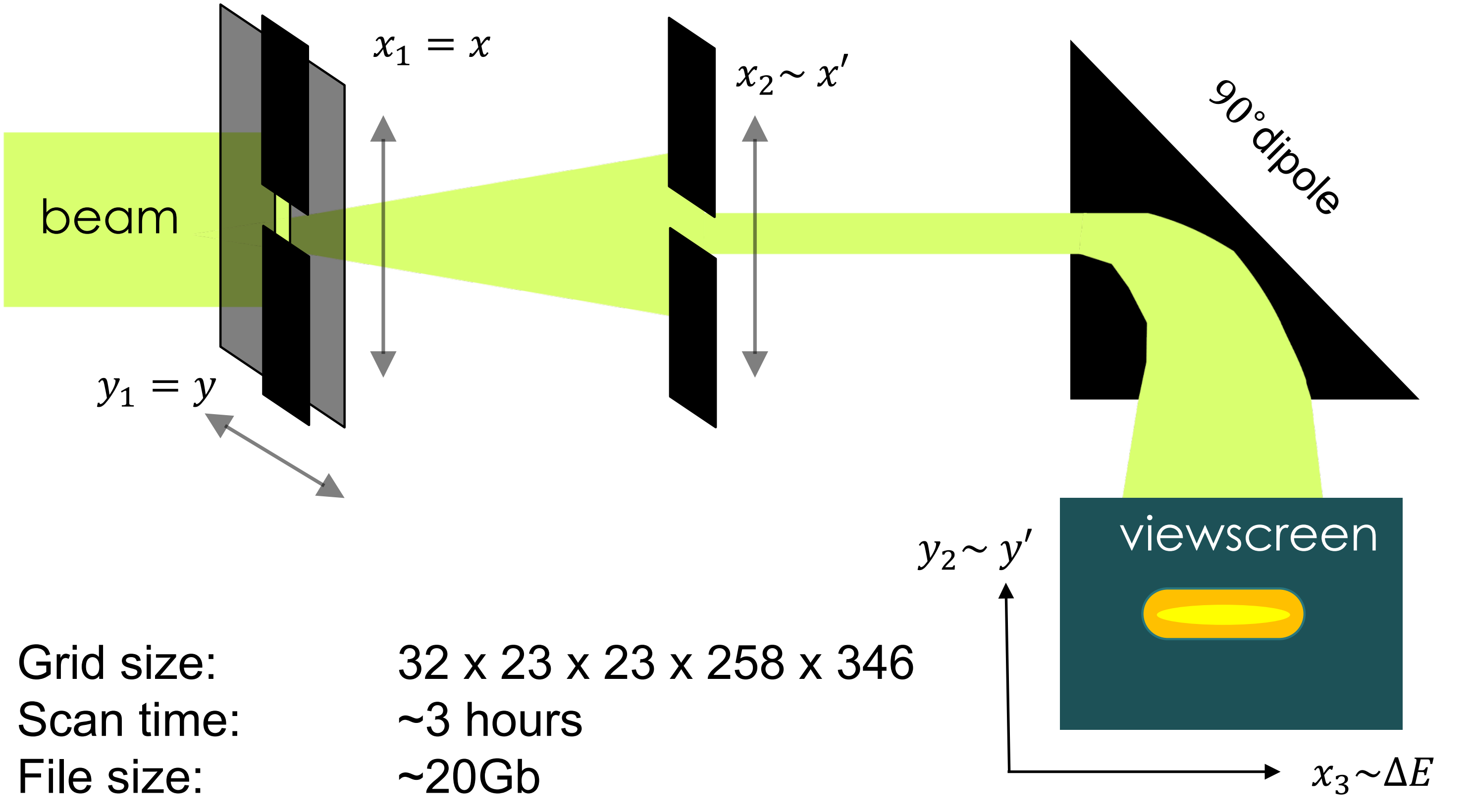
Main outcome:

- It can be done !
- Distribution function is much more complex than we prepared for
- Identified problems to work on
- No useful data for beam dynamics study, in short term

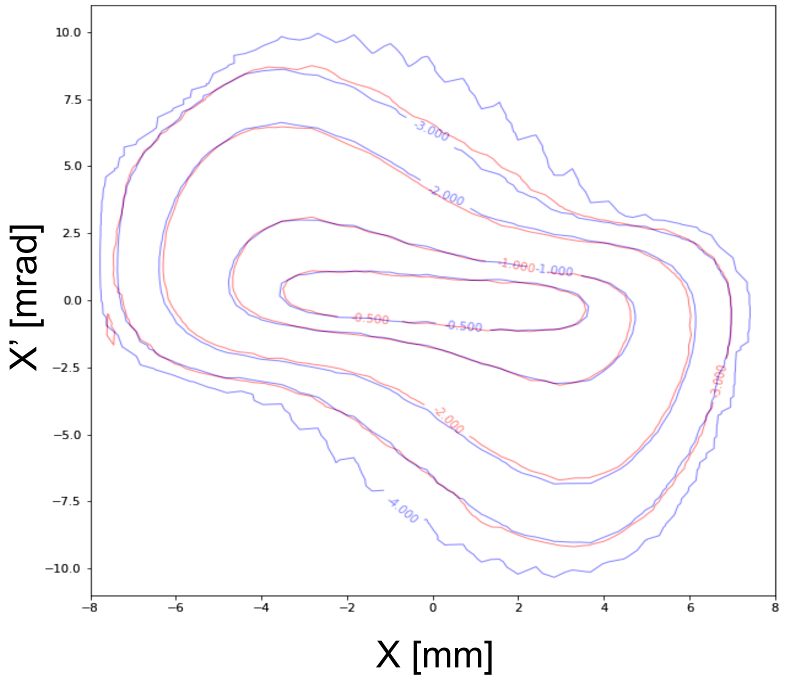




5d scan provides usable dynamic range and resolution in exchange for sacrificing one dimension



courtesy of K. Ruisard



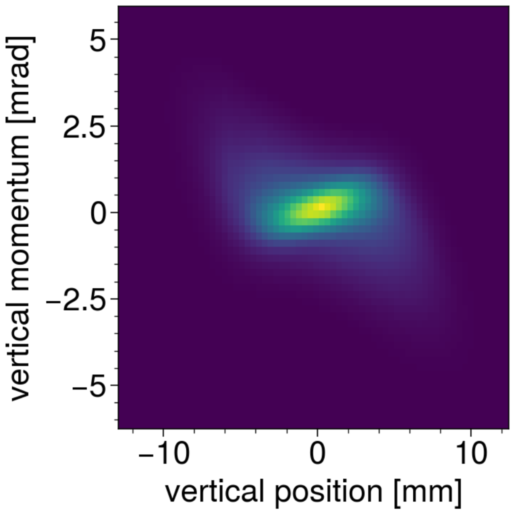
Comparison of 2 datasets taken 2 weeks apart

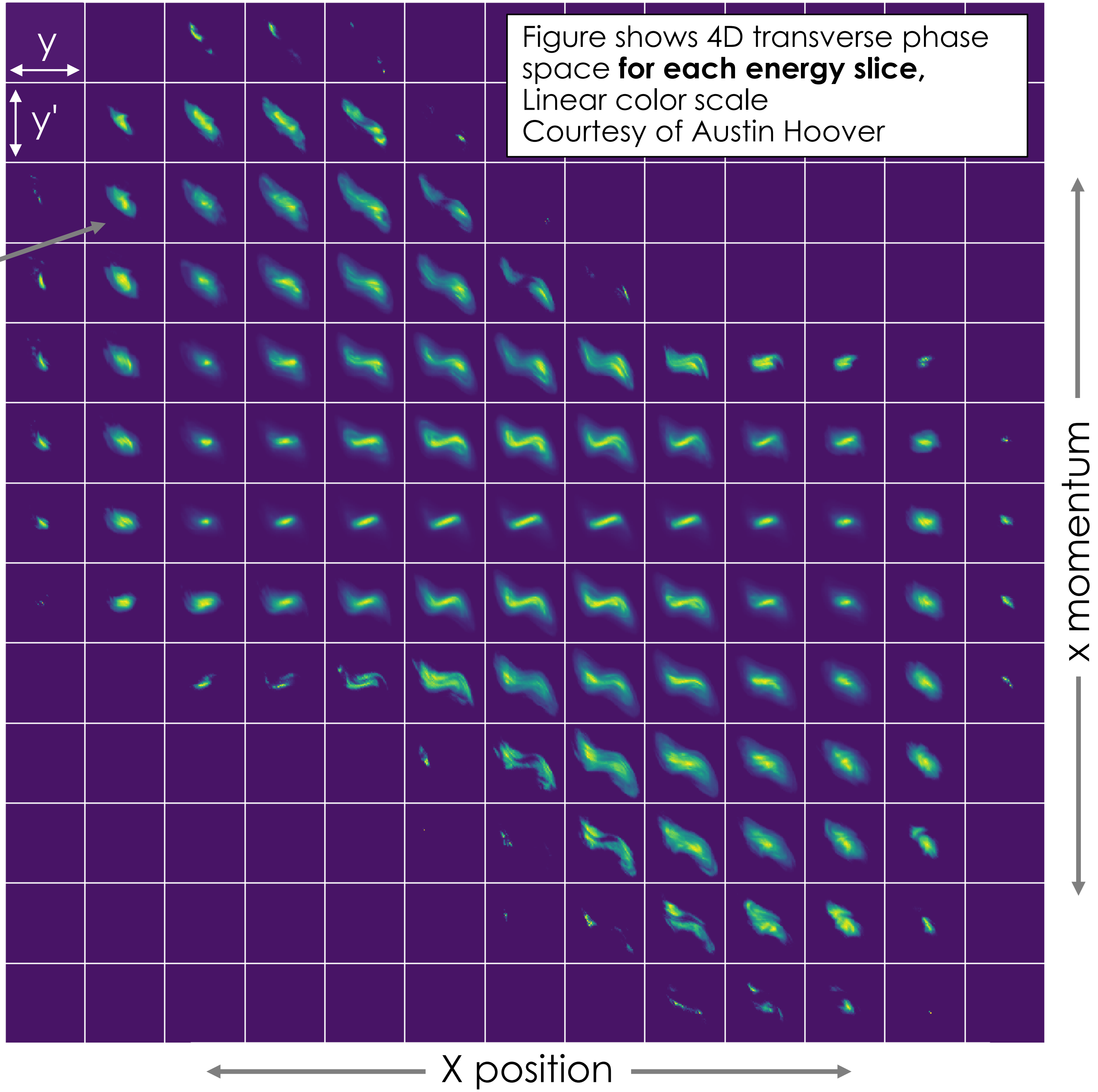
5D scan (integrated along other 3 dimensions)

2D scan

Grid size: 32 x 23 x 23 x 258 x 346
Scan time: ~3 hours
File size: ~20Gb

There is a lot of complexity in high-dimensional beam distribution that is not apparent in “typical” 2D projections



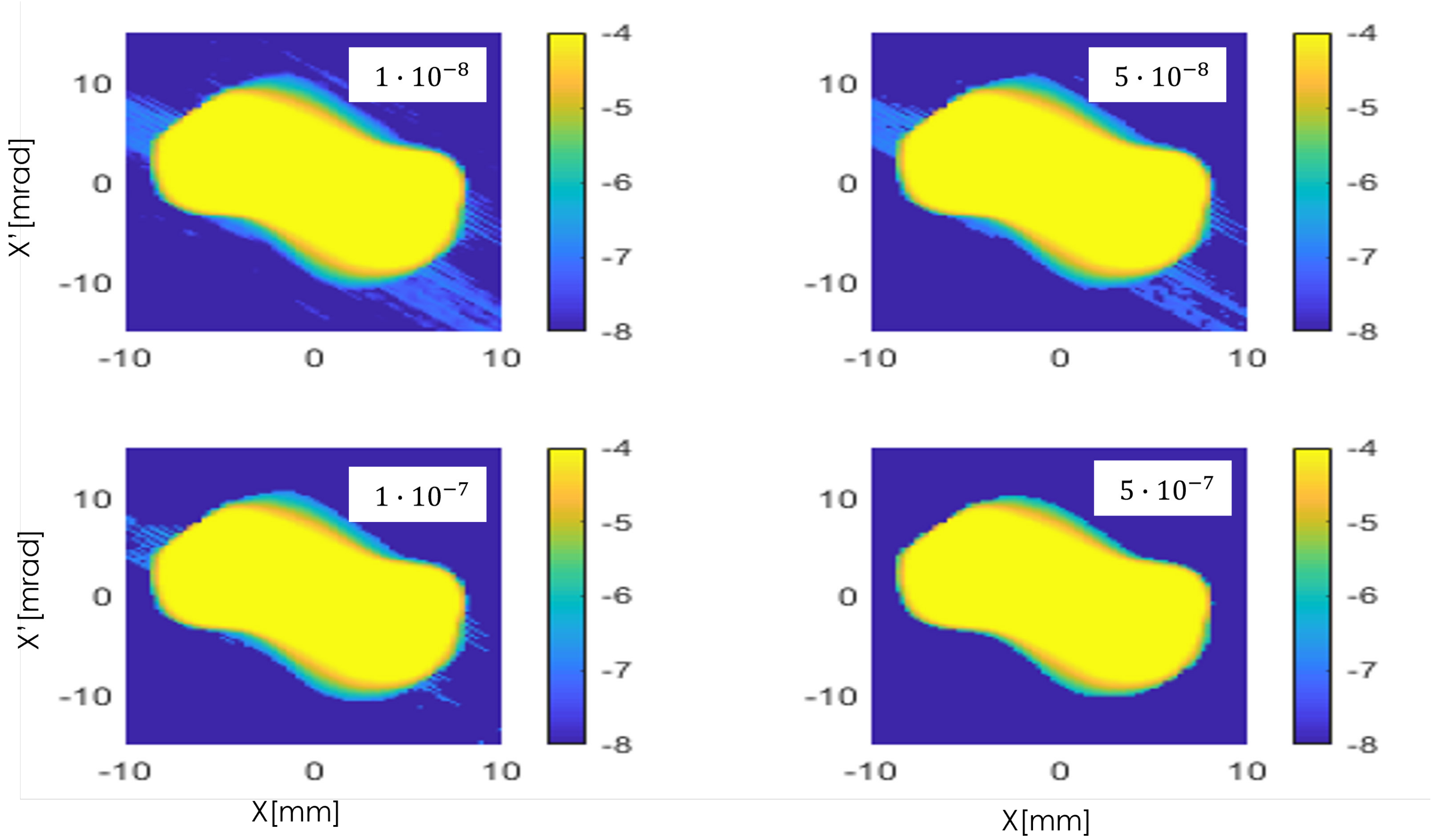


Hoover et al, submitted, https://arxiv.org/abs/2301.04178.

Hoover et al, [Data set]. Zenodo. https://doi.org/10.5281/zenodo.7517479

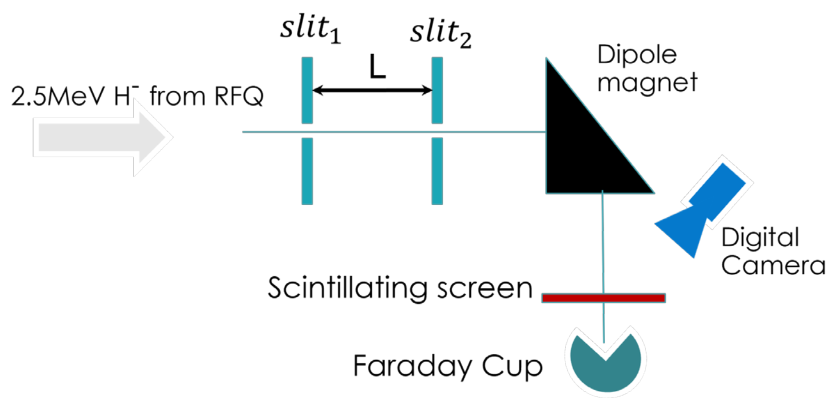
courtesy of K. Ruisard

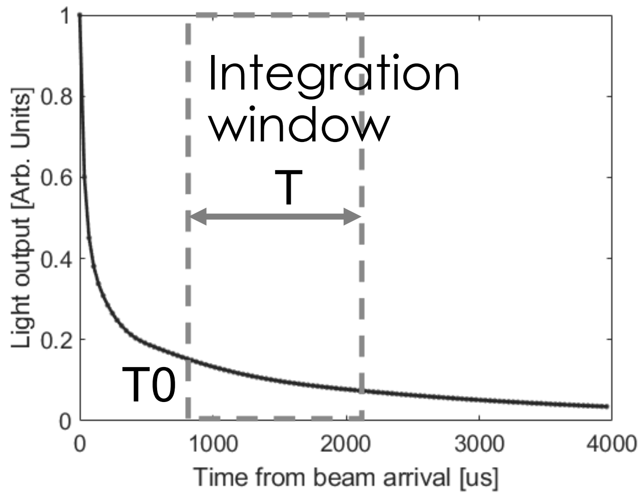
2d scan provides dynamic range usable for halo study

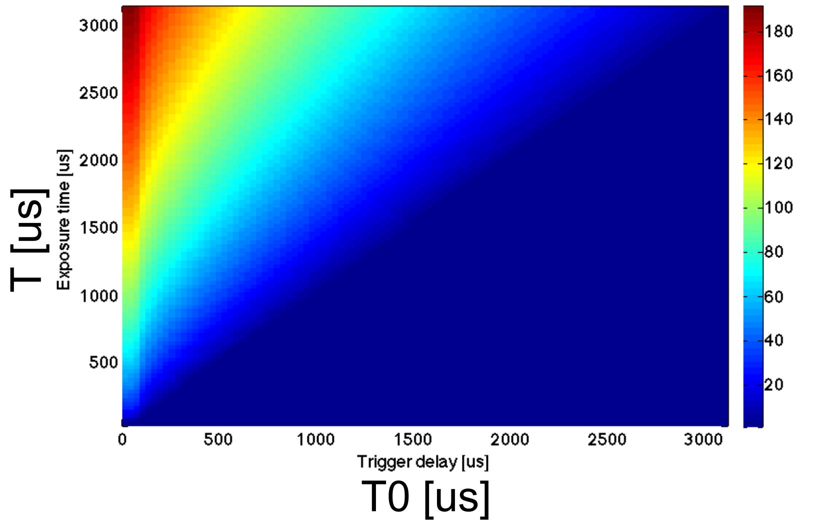


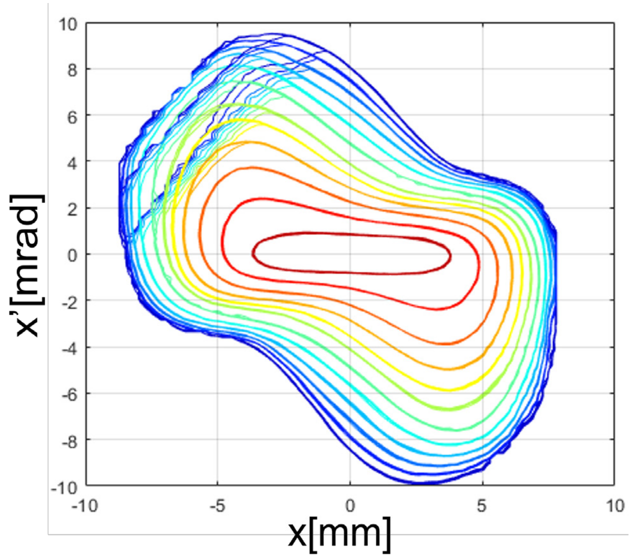
Threshold level is found by visual examination

Synthesized high dynamic range is achieved by charge-to-light conversion and stitching images with variable gain

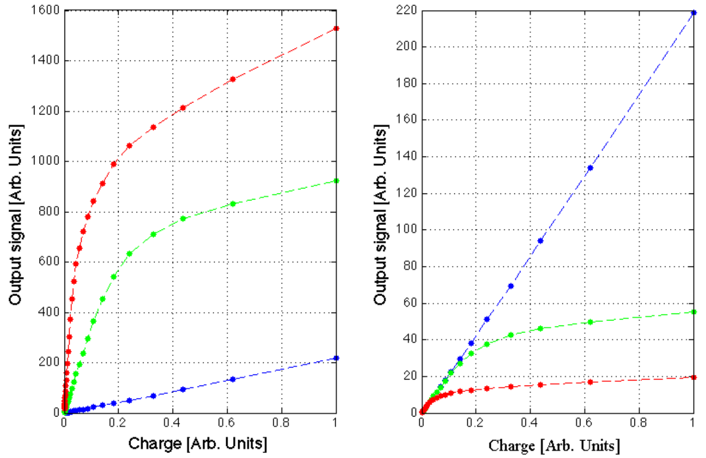




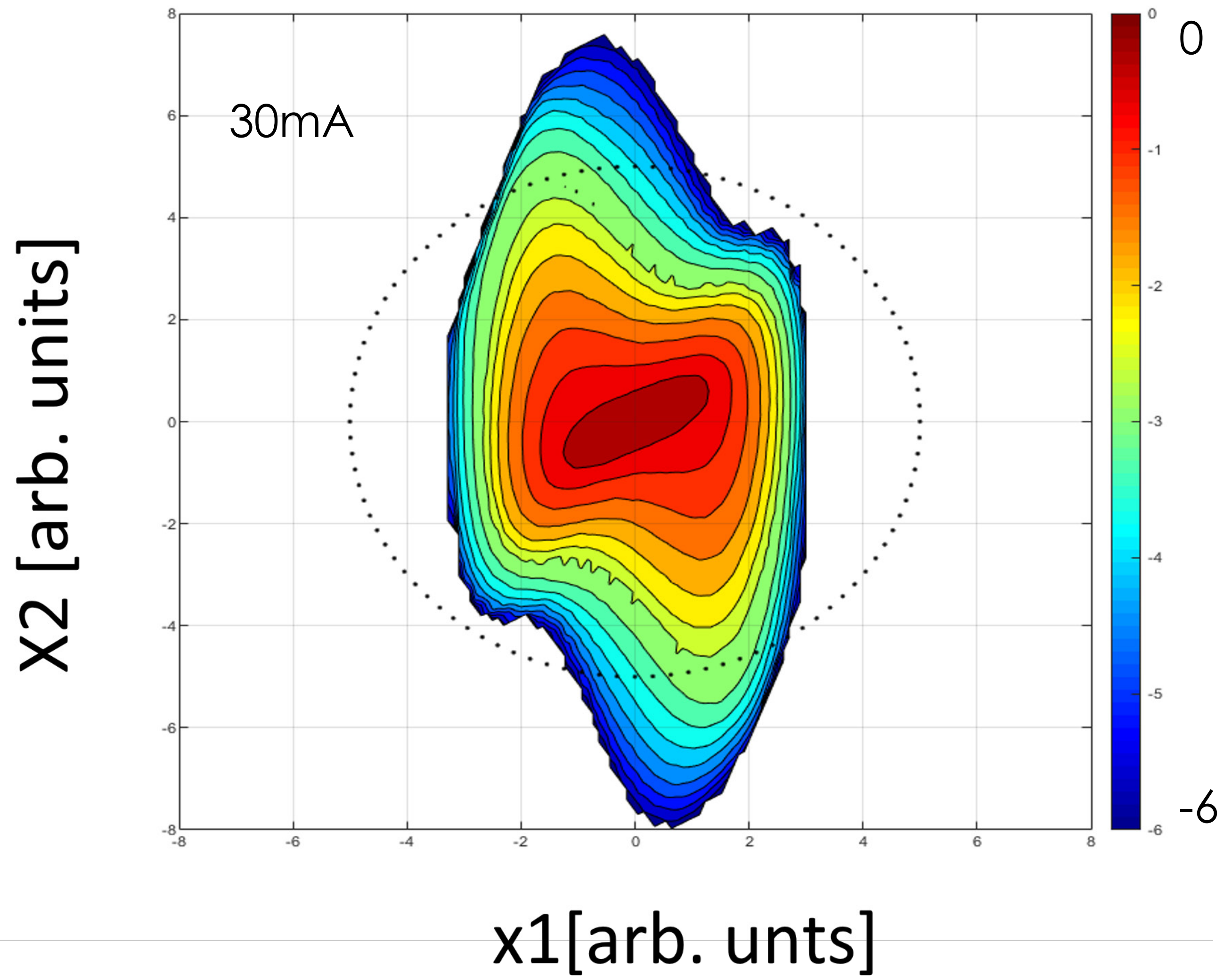


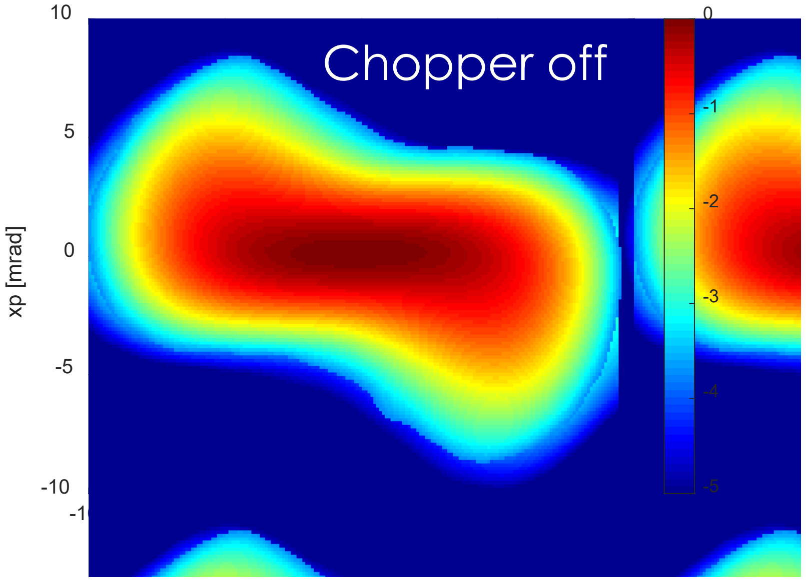


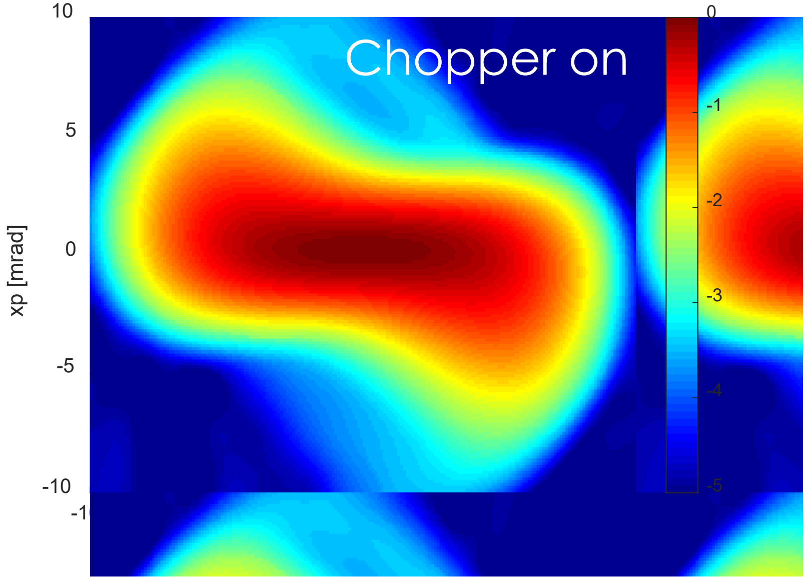
Grid size:	100 x 100
# of averaging	10
# of gains	2
Rep. rate	5Hz
Scan time:	~12 hours



2D high dynamic range scans reveal features at halo level







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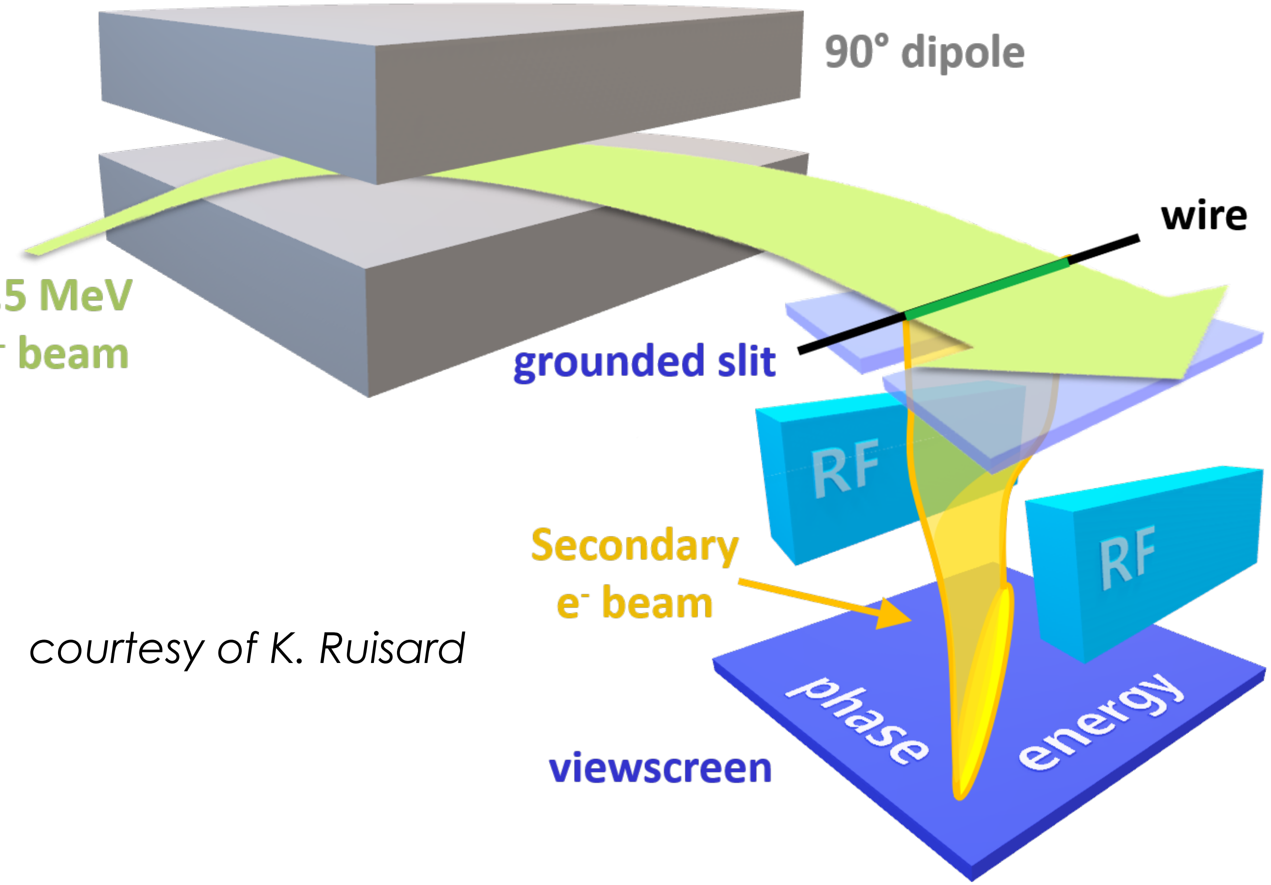
Ways for scan speed and dynamic range improvement

	Scan speed improvement	Dynamic range increase	Comments
Data collection rate ->10Hz	✓	✓	Dedicated camera server
2d BSM	✓		
Dedicated HDR detector	✓	✓	
BSM light collection improvement		✓	Fiber coupled camera?
BSM direct e- image readout		✓	Timex, 200-300k$
Proton RF deflector		✓	>1M$

being implemented

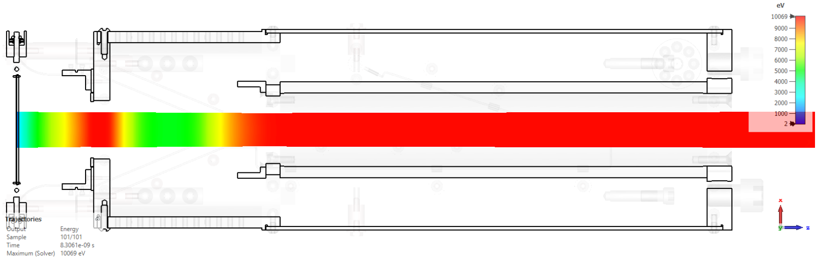
2-dimensional Beam Shape Monitor to reduce time of 6d scan



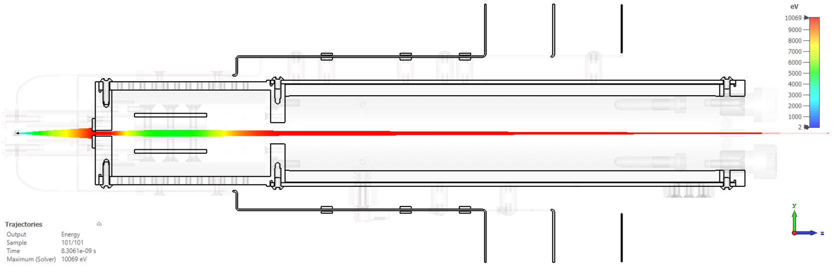
courtesy of K. Ruisard

$E - W$ plane is measured in one shot, reducing number of dimensions to scan to 4

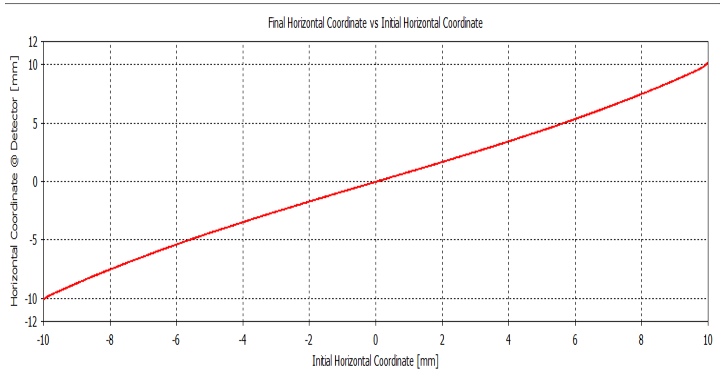
Partnered with industry to develop 2d BSM (Radiabeam)



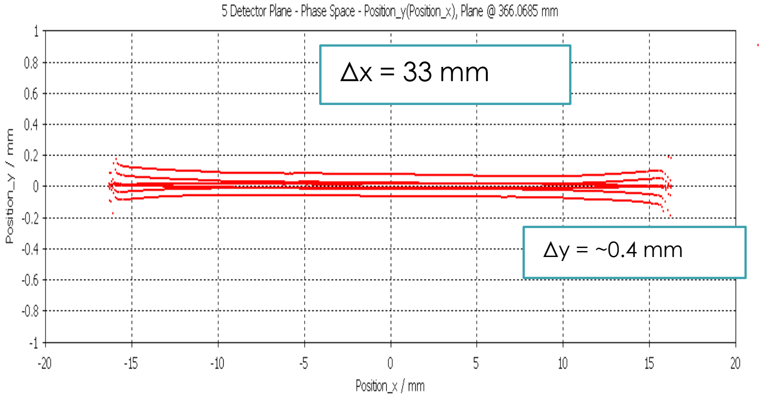
Electron optics simulations, top view



Electron optics simulations, side view



Horizontal position on screen vs. position on wire



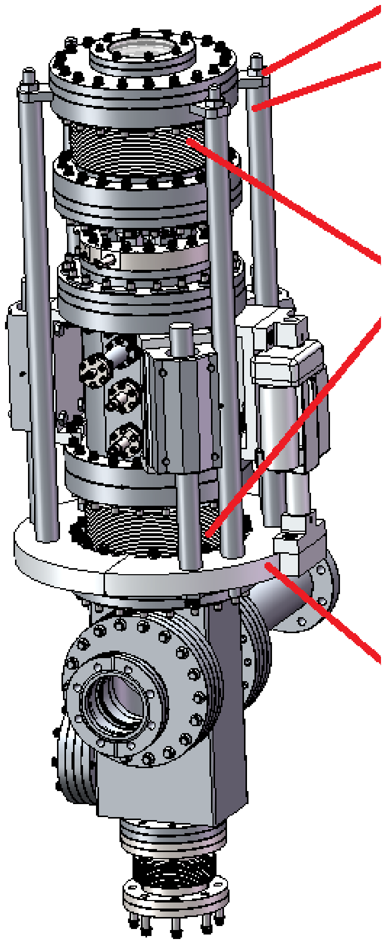
x-y image on screen

courtesy of Aurora Araujo, Radiabeam

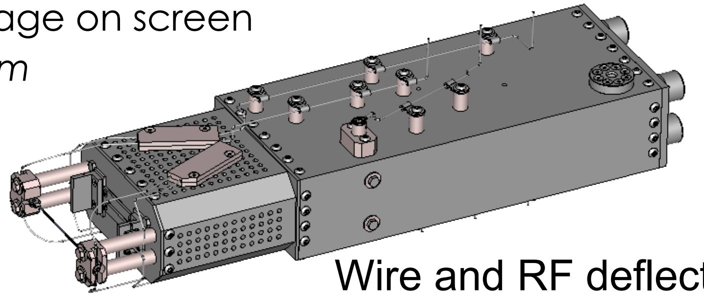
Drop-in compatible with old BSM vacuum chamber, electronics and software

Expect delivery in November 2023

courtesy of Adam Moro, Radiabeam

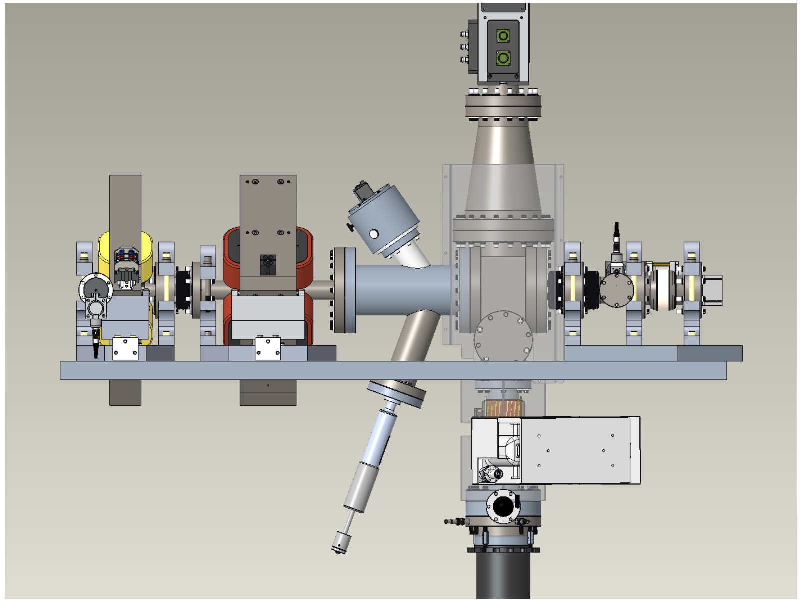


BSM assembly

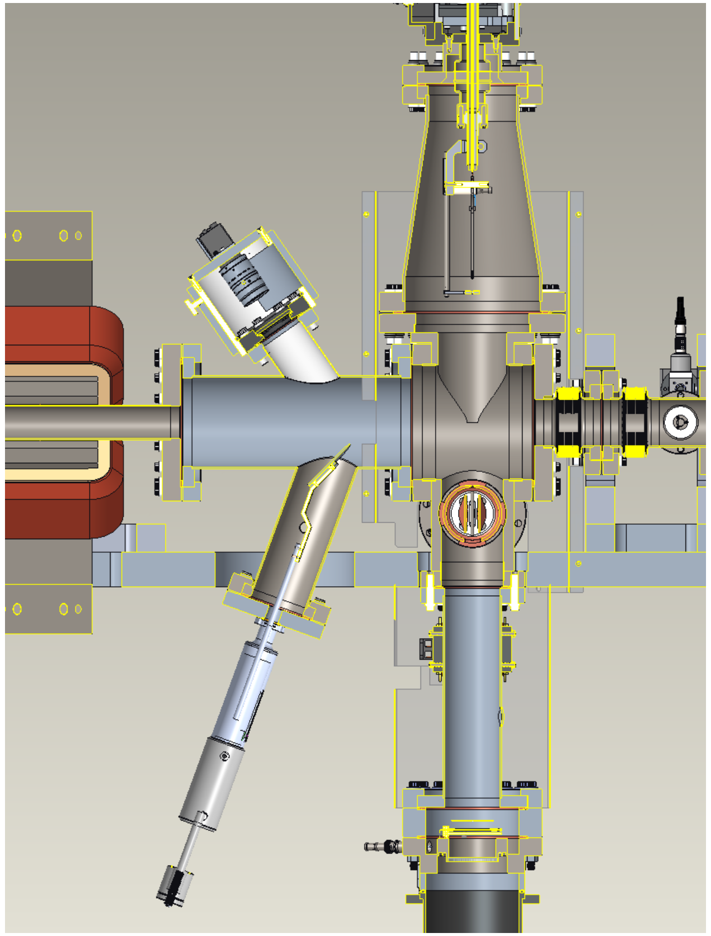


Wire and RF deflector assembly

2-camera synthesized dynamic range light detector to reduce time of 2d scan and improve dynamic range

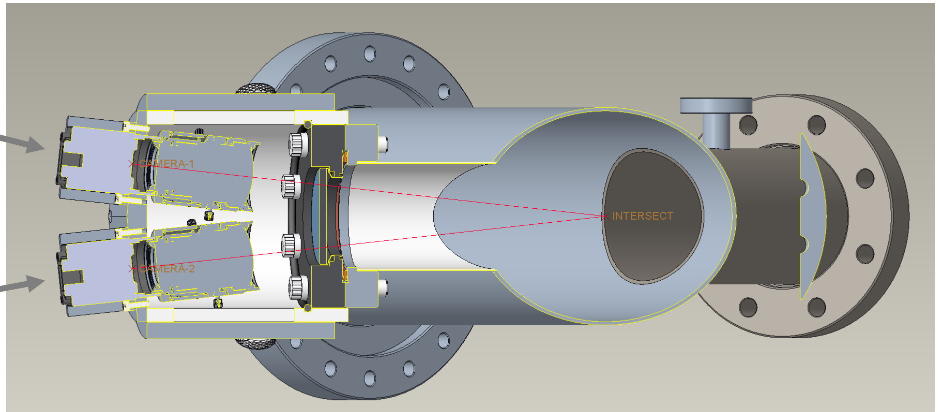


- Shorter camera to screen distance for better light collection
- Two cameras for simultaneous measurements at two gains
- Possibility of using PMT in counting mode
- View screen at 45 degrees to reduce peak density

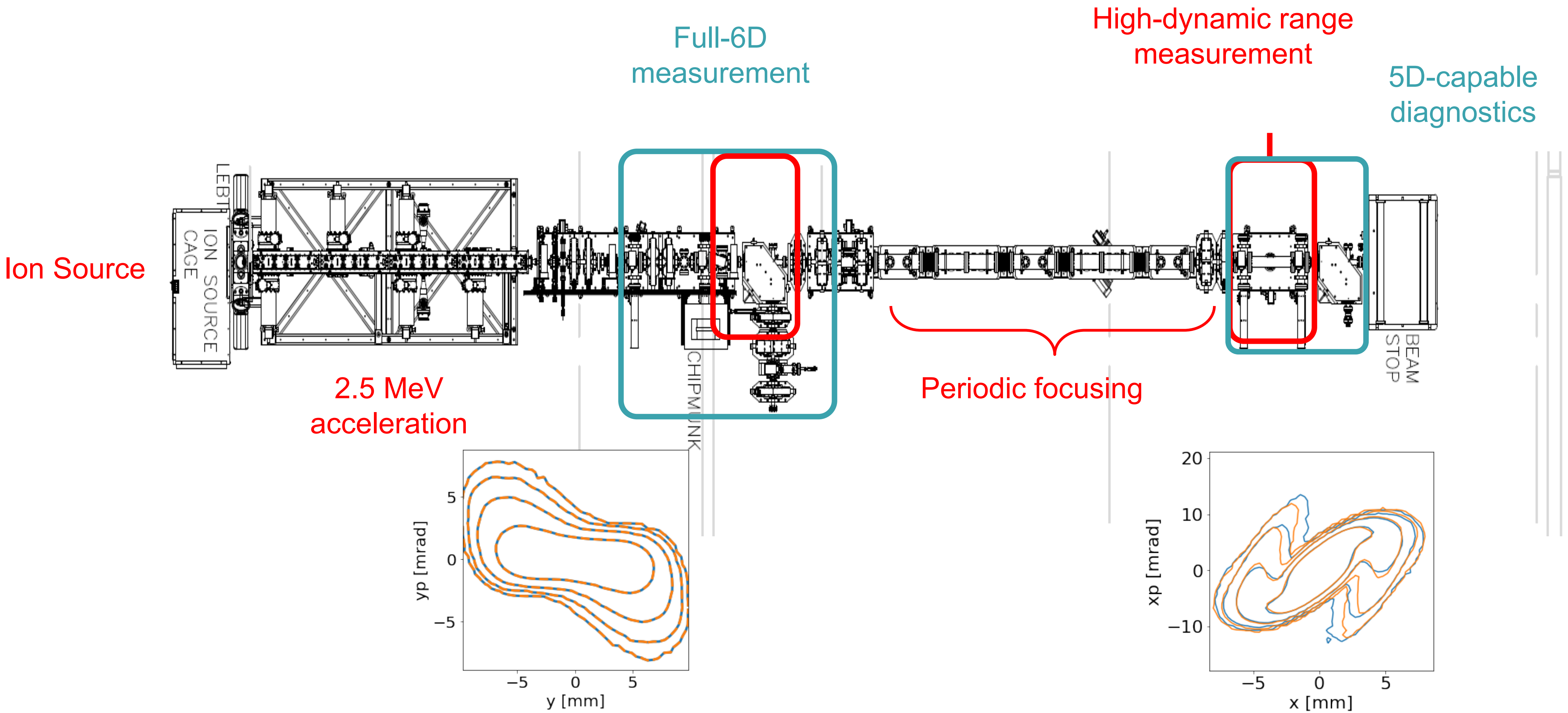


Camera 1, low gain

Camera 2, high gain or PMT



6D and HDR diagnostics is integral part of high intensity beam dynamics experiment at SNS BTF



Plan to resume operation of SNS BTF in November 2023

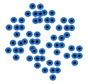
What is beyond?

Reach one-particle-per-bin-per-bunch when $DR \approx 10^9$ in 2d measurement and even earlier for higher dimensionality

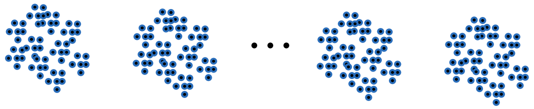
Does it mean ~ infinite DR after that?

Switching to measuring individual particles coordinates instead of distribution function?

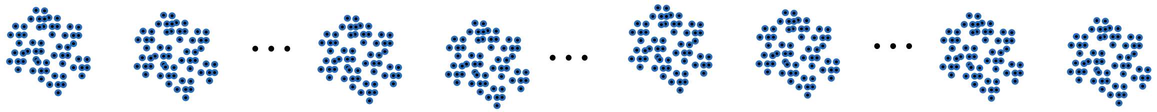
Most advanced simulations are unlikely to reach similar DR anytime soon



1 bunch in simulations



1000s of bunches in measurements



millions of bunches in real linac

In lieu of summary