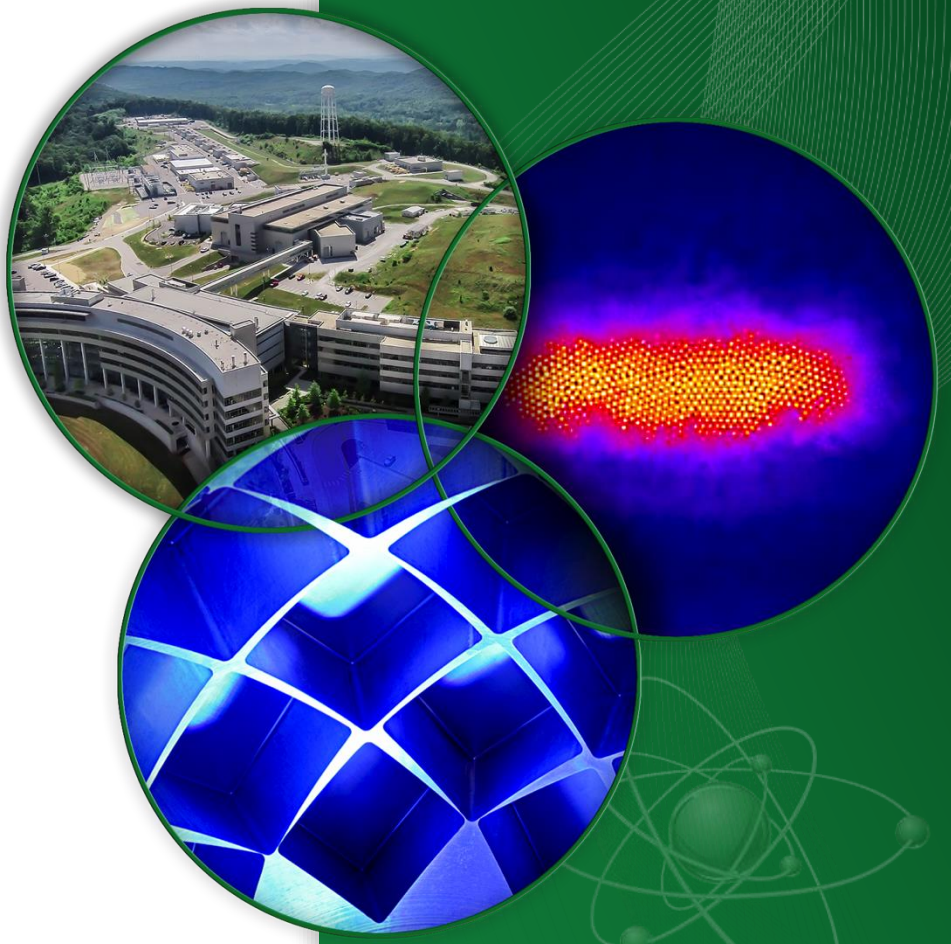
SNS Beam Test Facility for Experimental Benchmarking of High Intensity Beam Dynamics Computer Simulation



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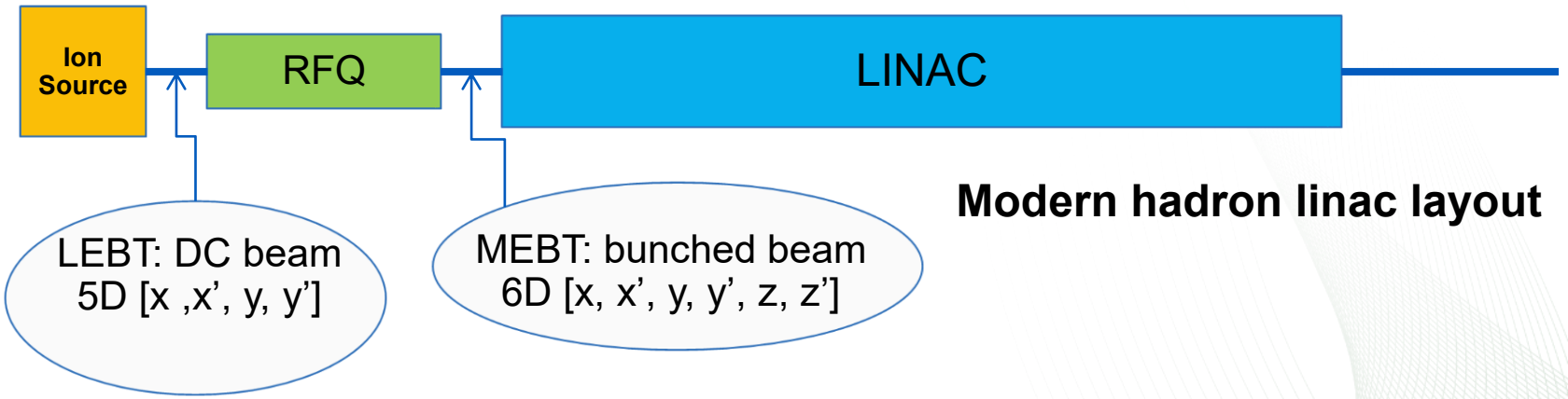
Beam loss control in high power hadron linac demands for accurate tracking of a very small fraction of particles having large oscillation amplitudes

- Less than ~10^{-6} for 1MW beam, even smaller for higher power

Necessary ingredients for realistic beam loss simulation

- Good PIC tracking code: accurate representation of e/m forces, tracking
- Initial particles coordinates
- Good description of linac state: elements positions and parameters
- Verification tools

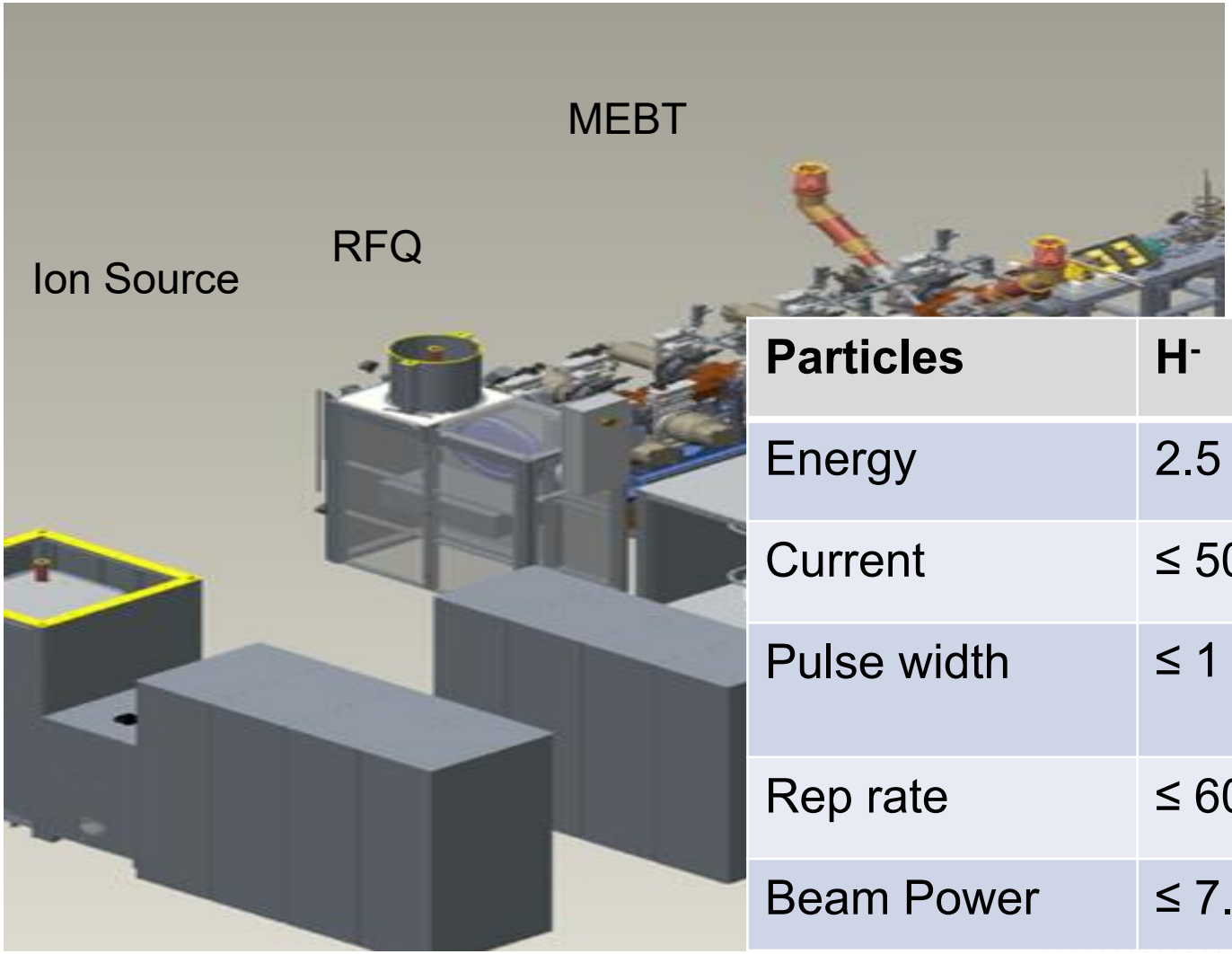
experimental tasks



Modern hadron linac layout

SNS Beam Test Facility (BTF)

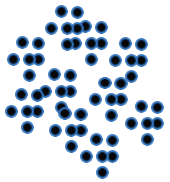
2.5MeV accelerator with beam lines dedicated for beam dynamics experiments



Particles	**H^-**
Energy	2.5 MeV
Current	≤ 50 mA
Pulse width	≤ 1 ms (50μs)
Rep rate	≤ 60 Hz (10Hz)
Beam Power	≤ 7.5 kW (63W)

Problem #1. Initial particles distribution

How to represent bunch of particles



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

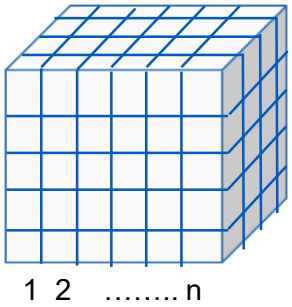
particle #	coordinates
1	x, x', y, y', z, z'
2	x, x', y, y', z, z'
.	.
.	.
N	x, x', y, y', z, z'

$6N$ numbers

impossible to measure individual particles positions
need something different

distribution function

number of particles per bin in phase space



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

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

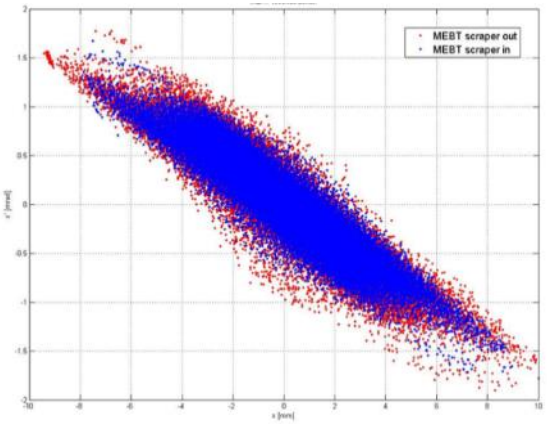
Distribution function representation requires

n^6 numbers 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



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

Often erroneously called “measured 6D distribution”

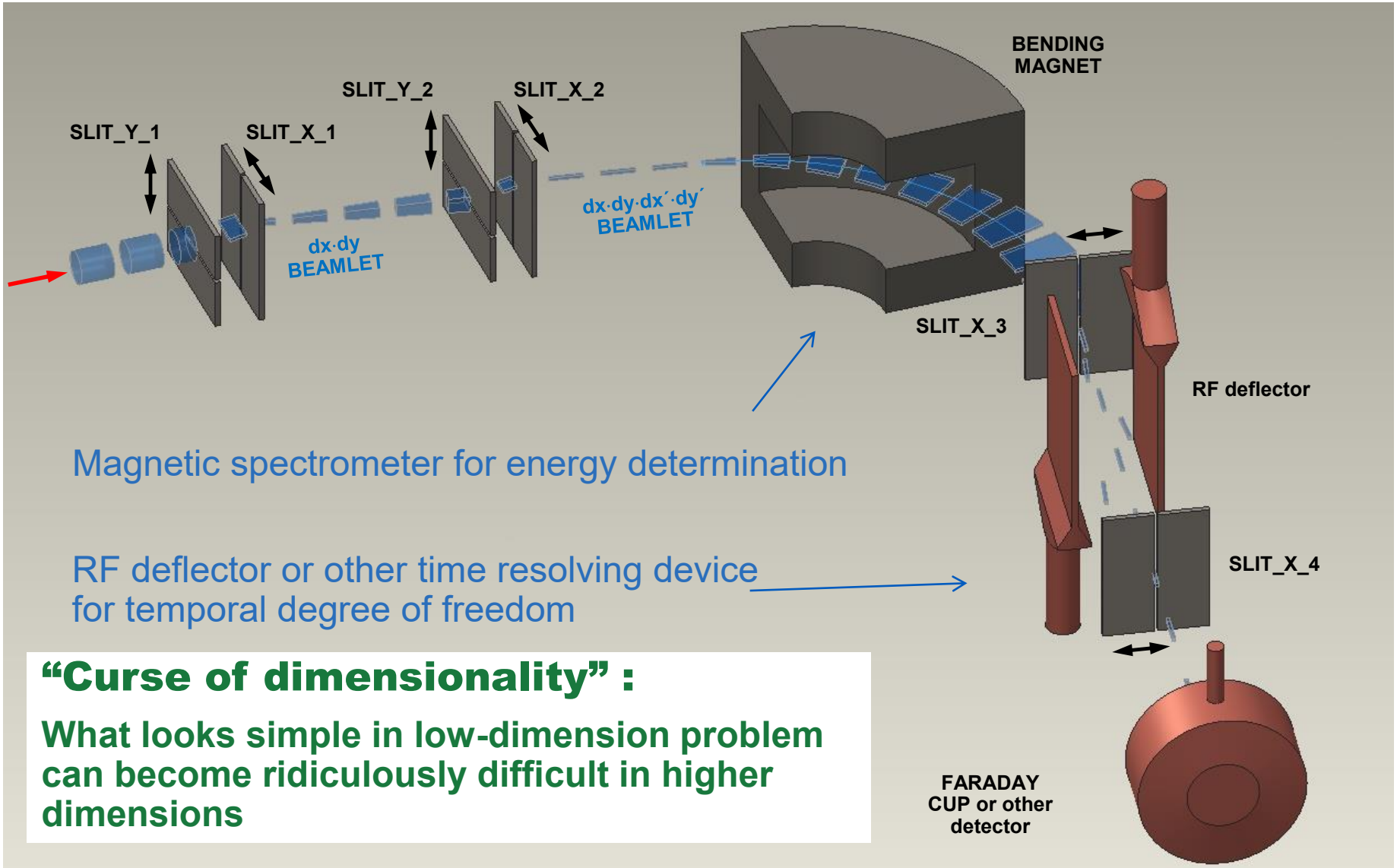
$$f_{3*2}(x, x', y, y', z, z') \neq f_6(x, x', y, y', z, z')$$

except for special case of no correlations 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



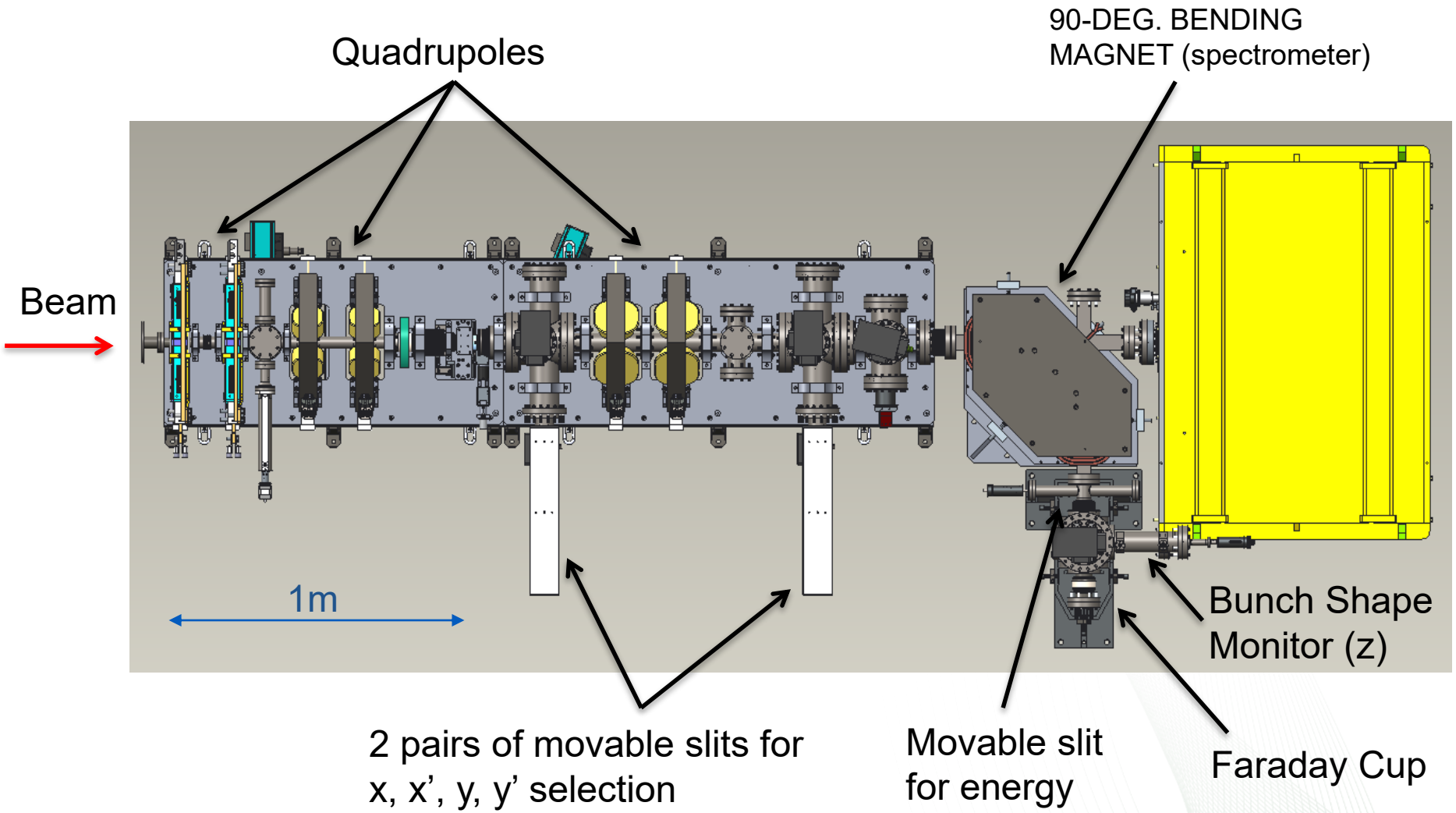
Magnetic spectrometer for energy determination

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

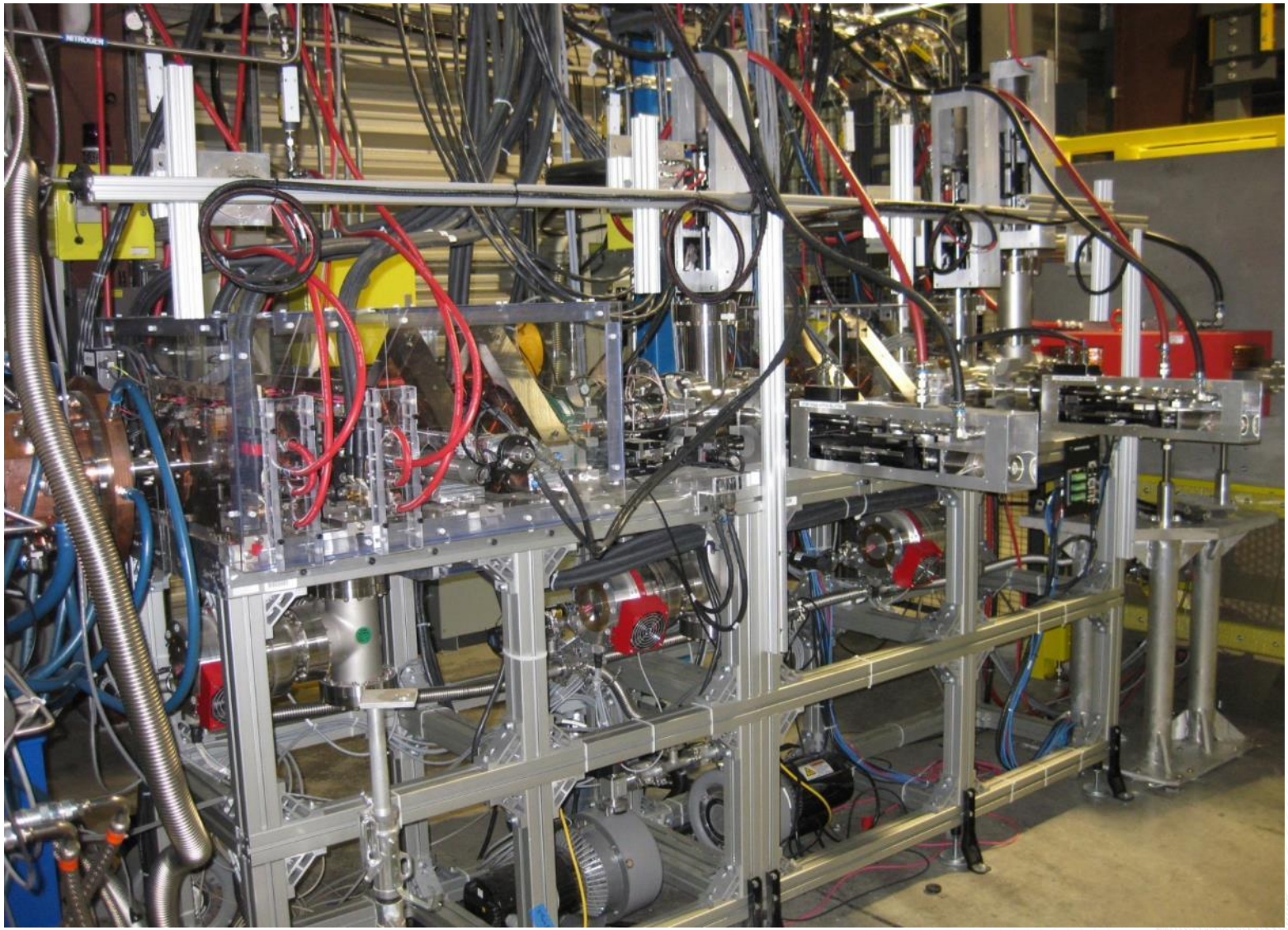
“Curse of dimensionality” :

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

SNS BTF set up for 6D phase space measurement

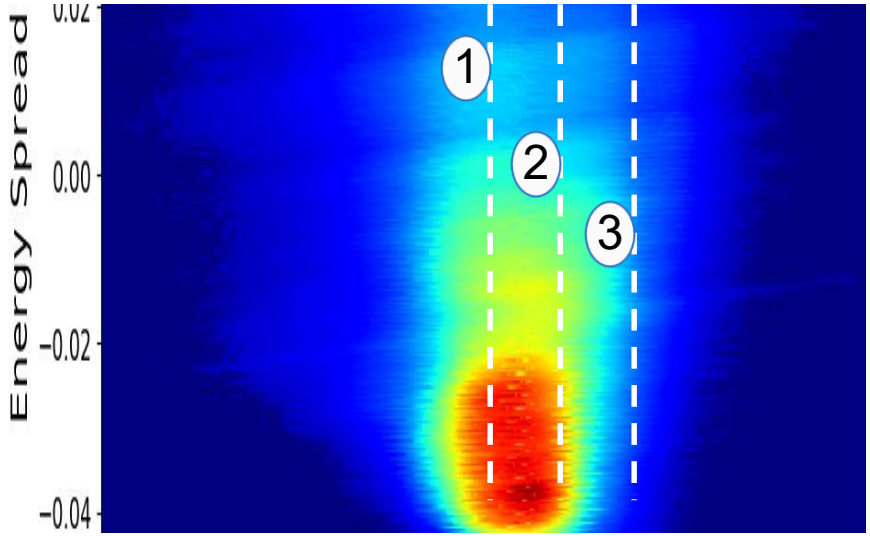


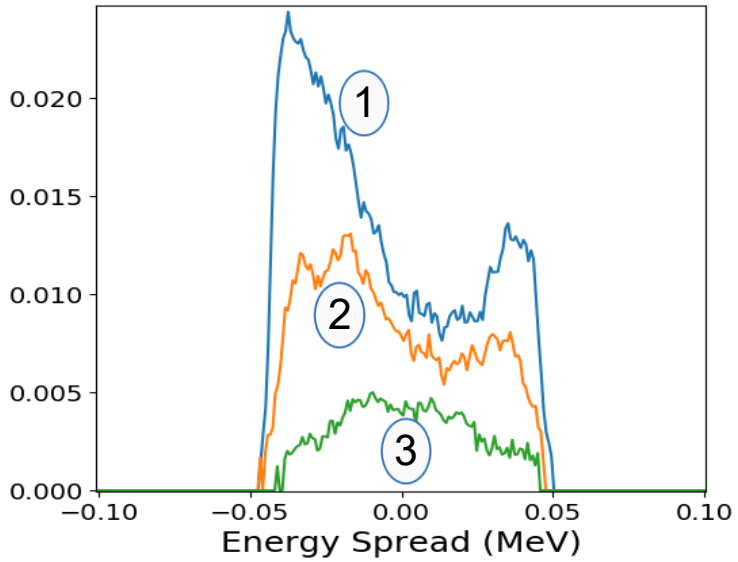
SNS BTF Beam Line for 6D scan



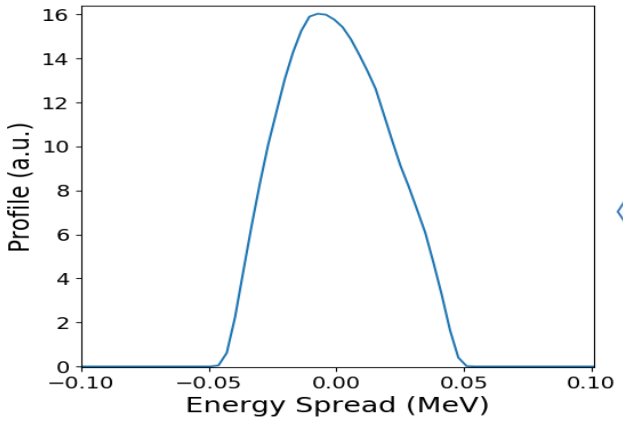
Observed correlation in x'-w partial projection

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





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

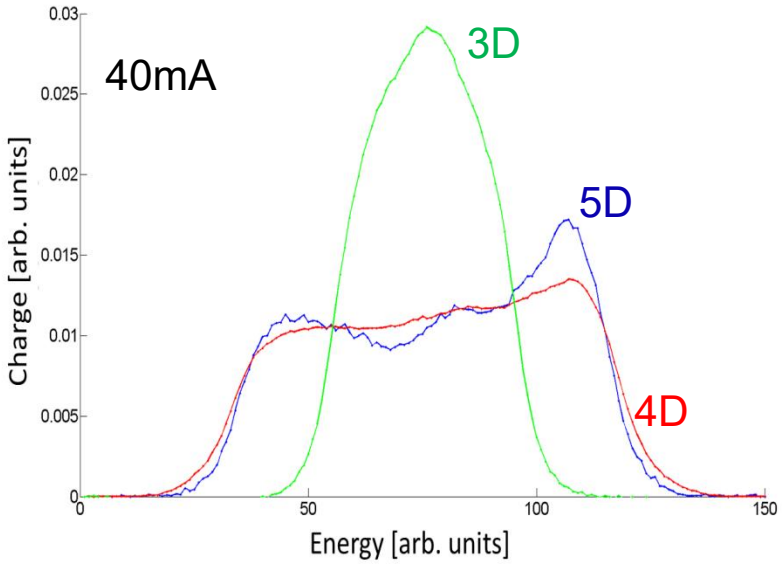


full projection (energy spectrum)

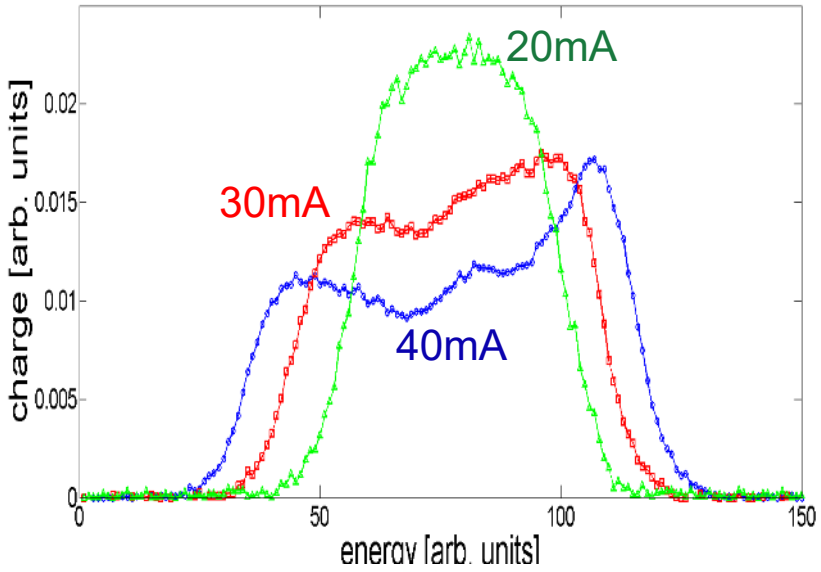
$$f(w) = \int dt dx dx' dy dy' \cdot f_6\,(x, x', y, y', w, t)$$

looks ordinarily

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)

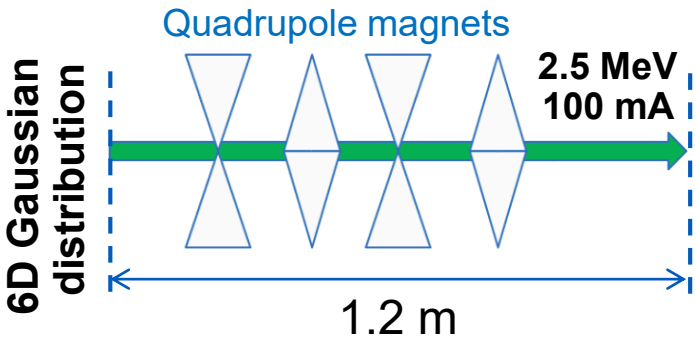


Dependence of partial projection f(w) (x=x'=y=y'=0) on beam current

D>4 measurements are required to observe this correlation

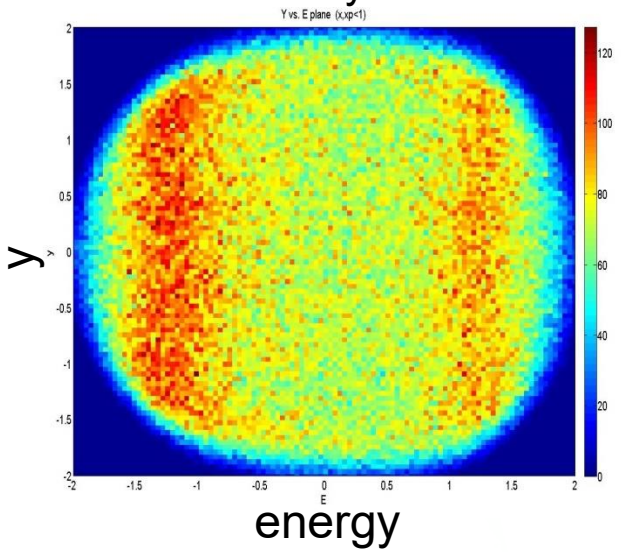
Space charge effect seems to create correlation

Similar patterns are observed in beam simulation with strong space charge

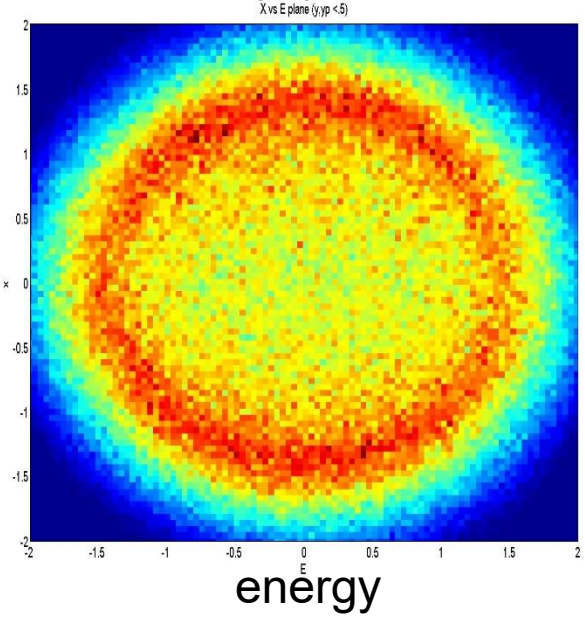


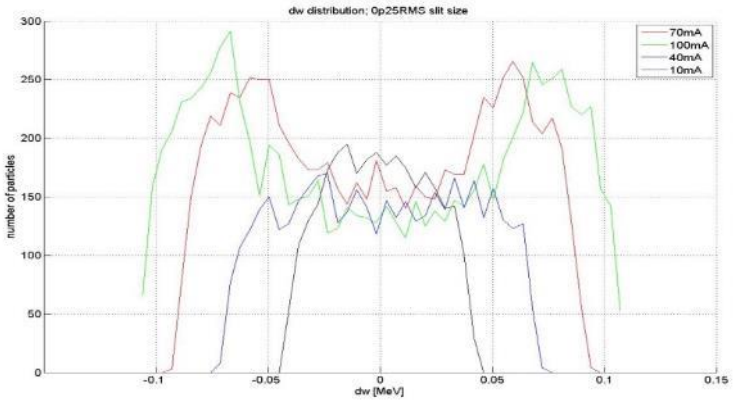
Partial projections

x=x'=y'=0



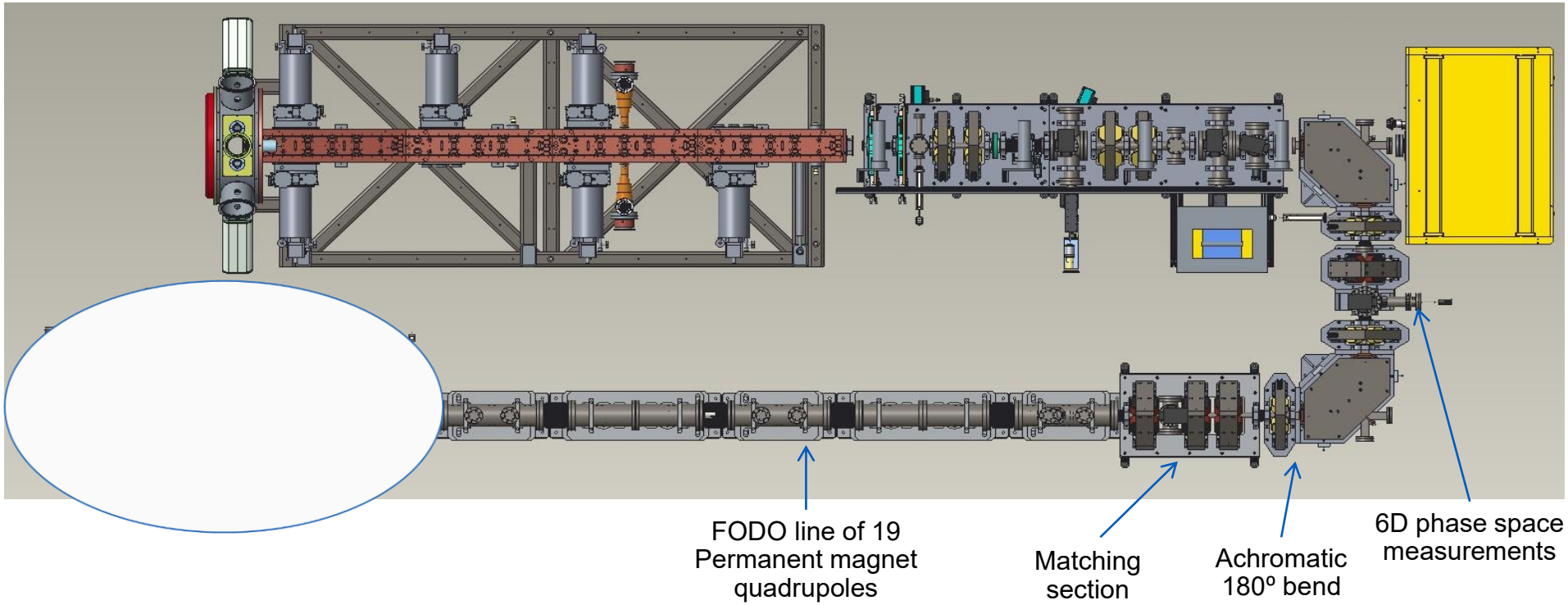
x'=y=y'=0





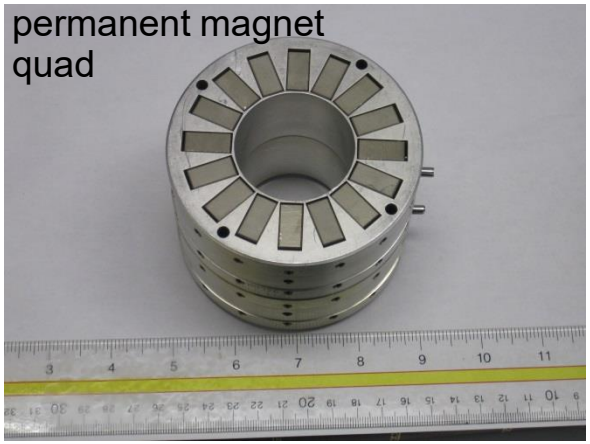
Problem #2. Knowledge of beam line state

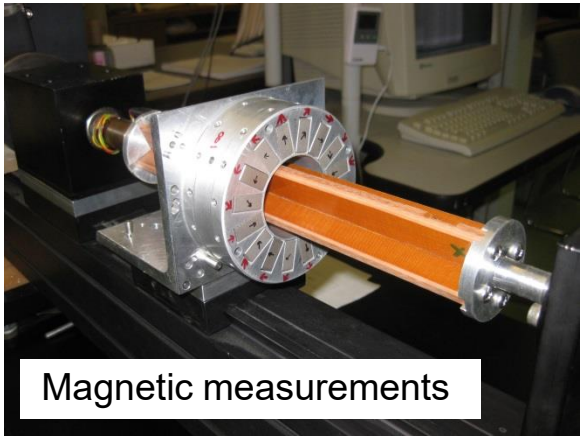
FODO line experiment



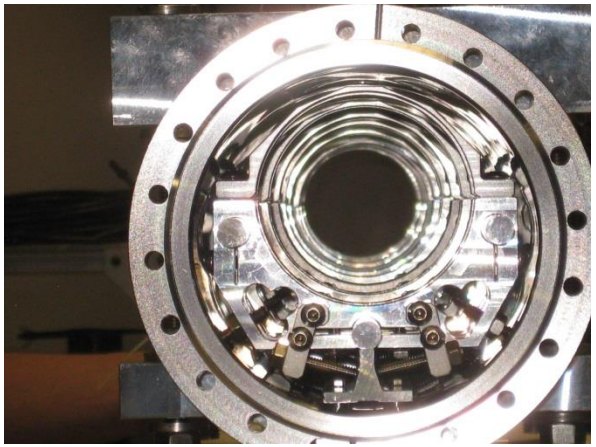
- Beam dynamic simulation benchmark facility :
  - Measured 6D distribution at input
  - Use FODO transport channel as simulation “benchmark case”
    - Made of identical equidistant permanent magnets
    - “Matched” or “mismatched” beam conditions at the FODO entrance

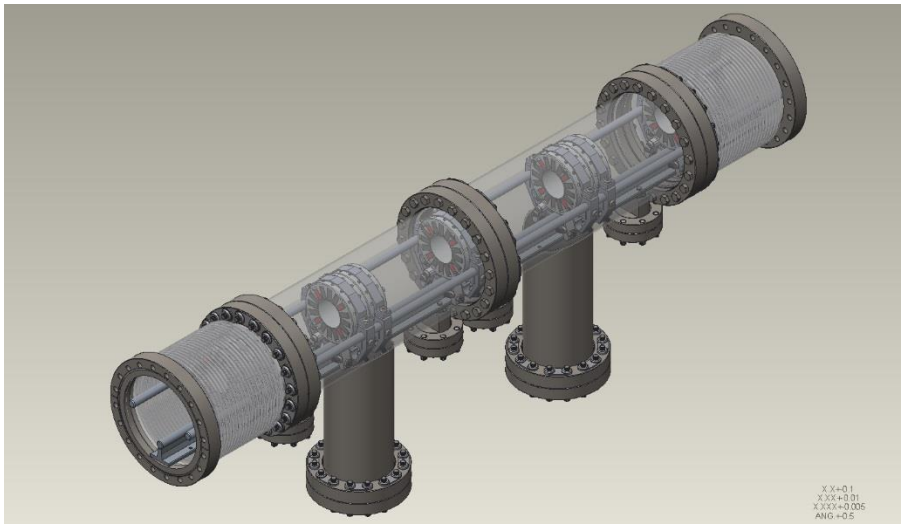
FODO beam line design





permanent magnet quad holding structure





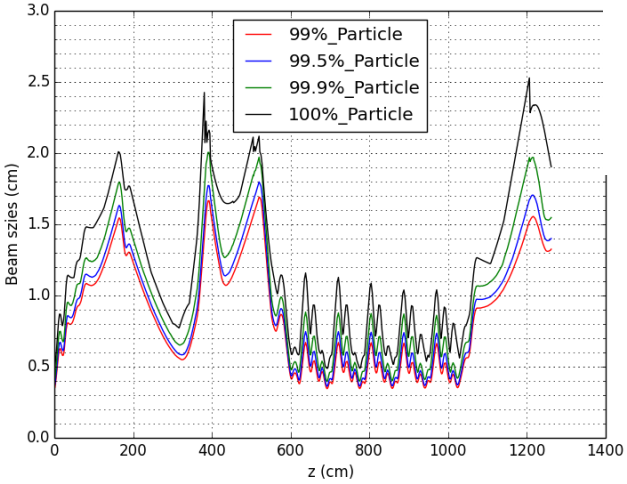
FODO phase advance can be adjusted off-line by changing magnets spacing

Design beam envelope along the beam line

Gradient of the last FODO quadrupole:

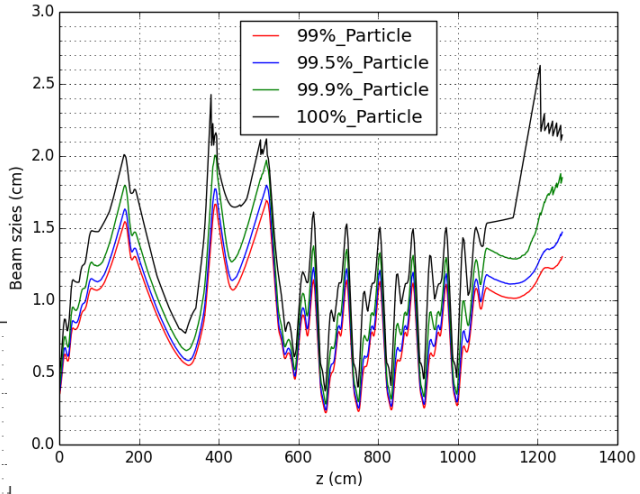
G_{FQ19} = 24 T/m (integrated strength: 1.8T)

Mismatch Factor =1



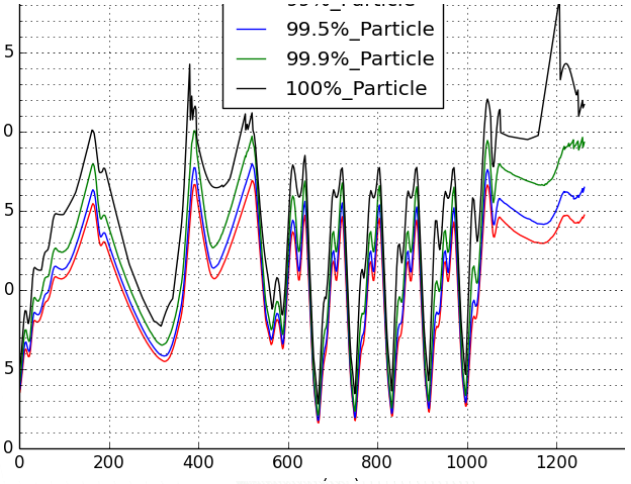
G_{dQ1}= -9.0 T/m, G_{dQ1}= 6.0 T/m

Mismatch Factor =2



G_{dQ1}= -9.0 T/m, G_{dQ1}= 5.5 T/m

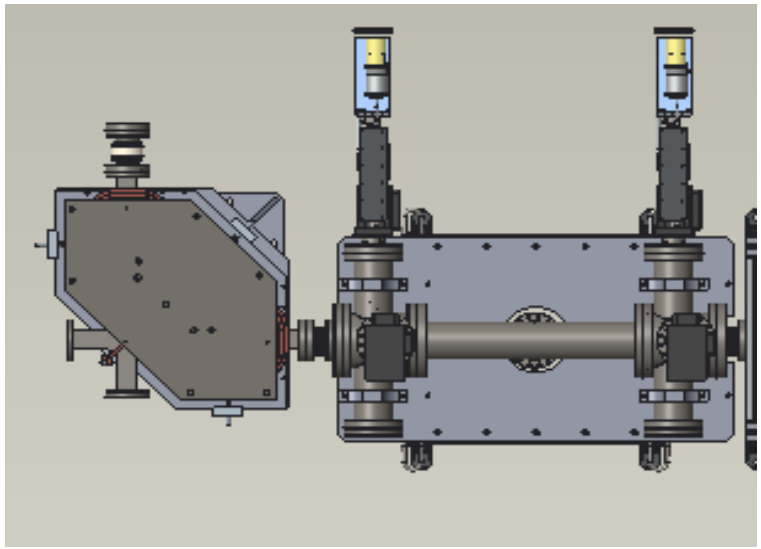
Mismatch Factor =3



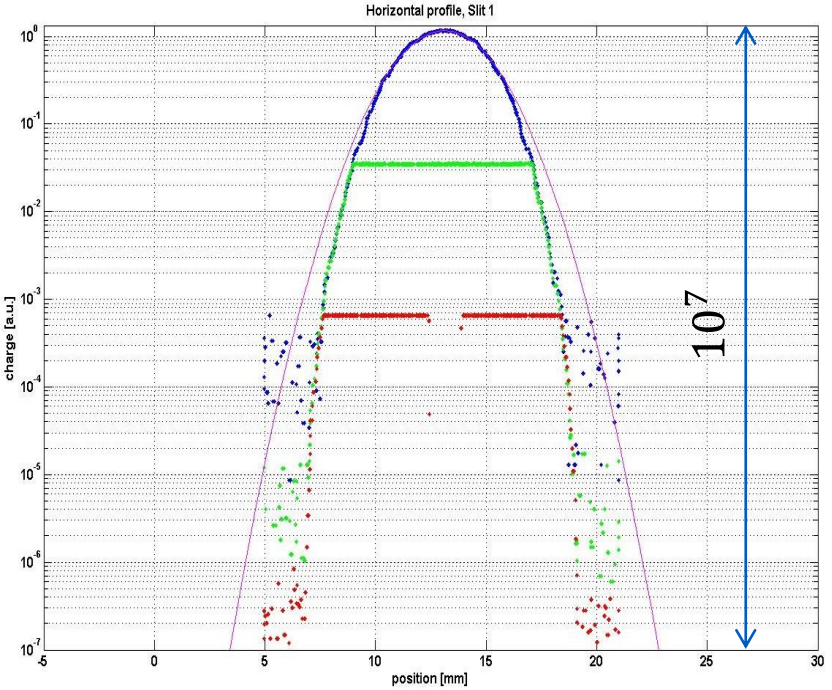
G_{dQ1}= -9.0 T/m, G_{dQ1}= 5.5 T/m

Problem #3. Verification tools = beam diagnostics + representation

High Dynamic Range measurements (halo)



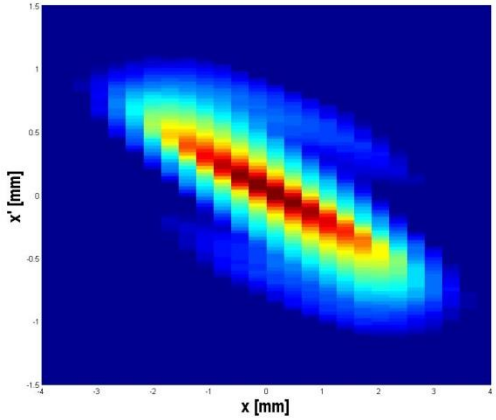
Slit-slit High Dynamic Range emittance scanner

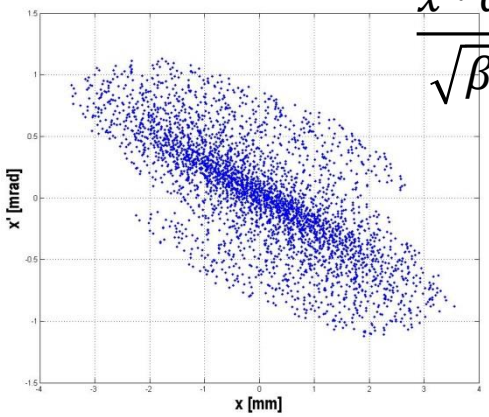


High Dynamic Range 1D scan

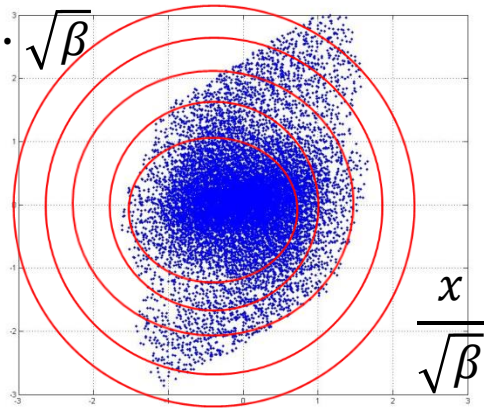
- Measure 1D profiles with ~ 10^7 dynamic range
- Expect $10^5 - 10^6$ dynamic range for 2D emittance scans

Phase space density plot to characterize particles distribution



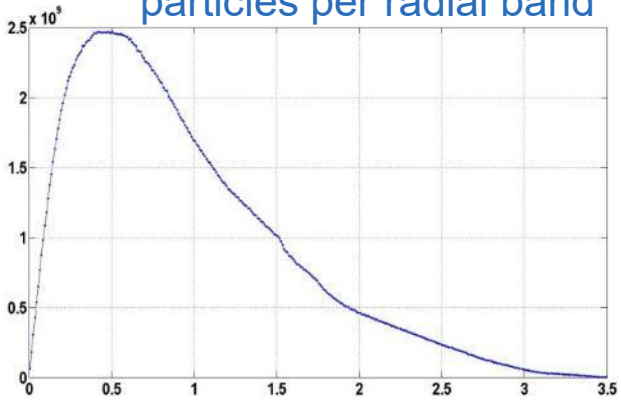


$$\frac{x \cdot \alpha}{\sqrt{\beta}} + x' \cdot \sqrt{\beta}$$

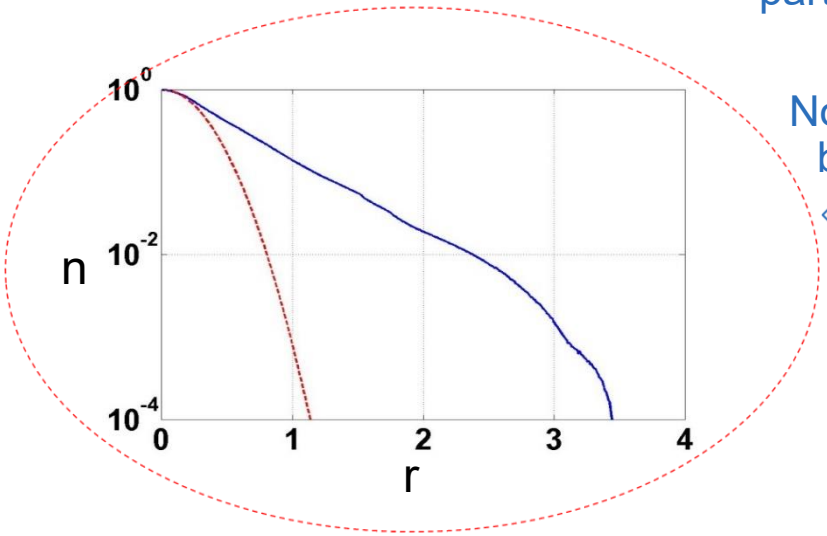


measure → generate particles → Transform to normalized coordinates

Count number of particles per radial band

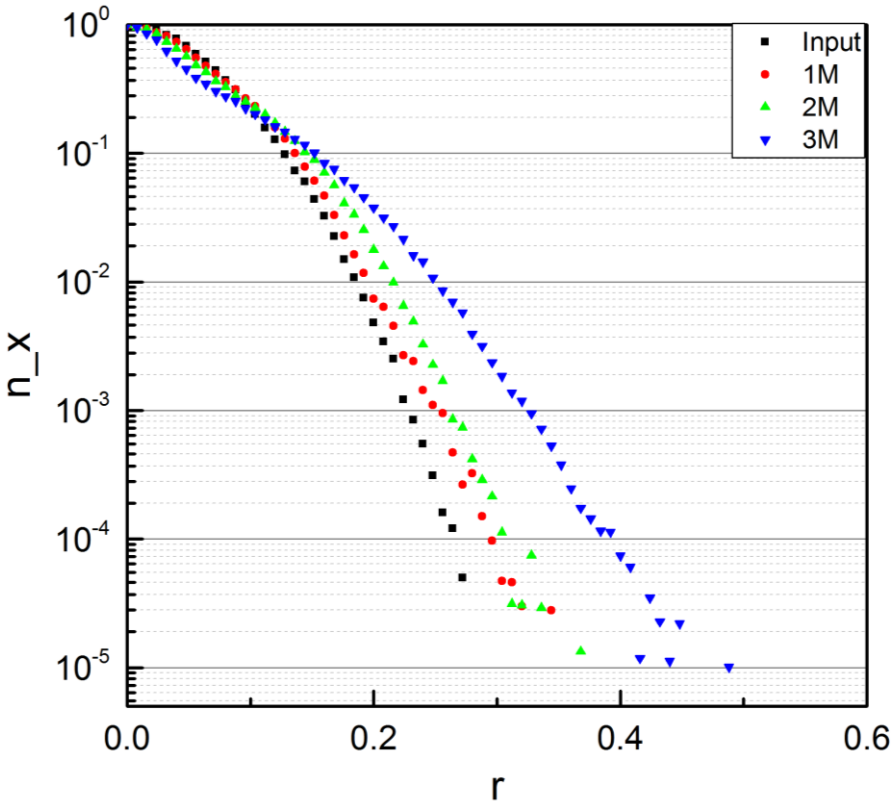


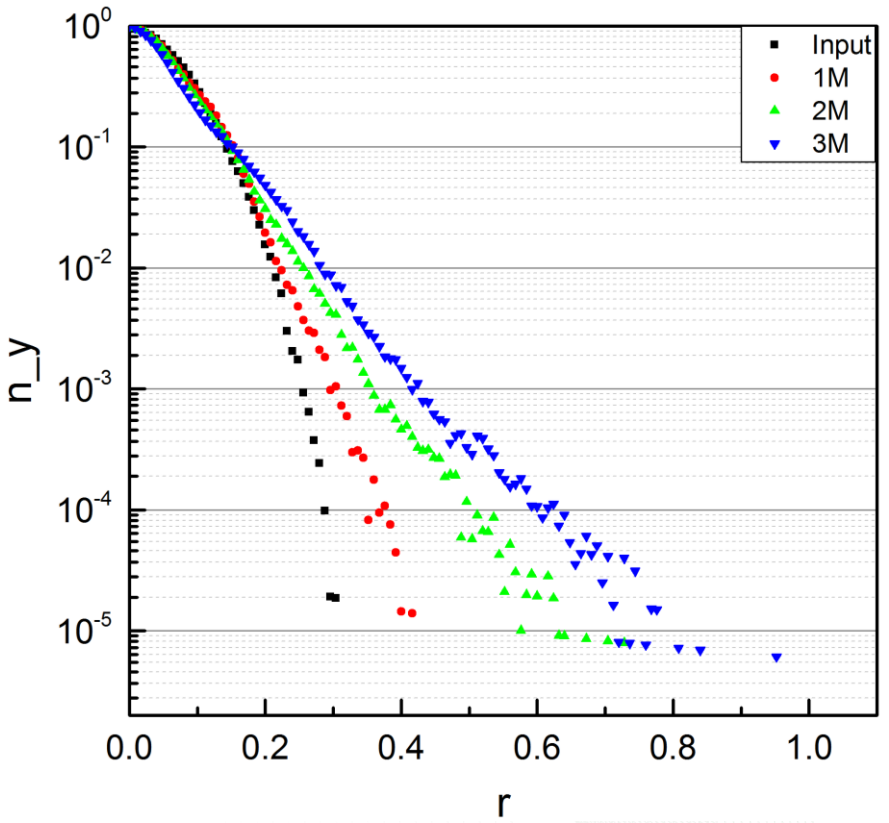
Normalize by band area



- Independent of location along beam line
- Straightforward comparison with simulations

Simulated phase space density plots at end of FODO for different mismatch factors





BTF status as of October 17th 2018

Expect to resume beam operations in December 2018

Thank you for your attention!