PXIE LEBT Emittance Scanner Commissioning

Richard D'Arcy

on behalf of M. Alvarez, B. Hanna, L. Prost, V. Scarpine, A. Shemyakin, D. Slimmer, J. Steimel, mechanical, electrical and other technical support

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Fermilab

Contents

- Specifications and functionality
- Commissioning
- Sanity checks
- Initial measurements
- Analysis techniques and comparison

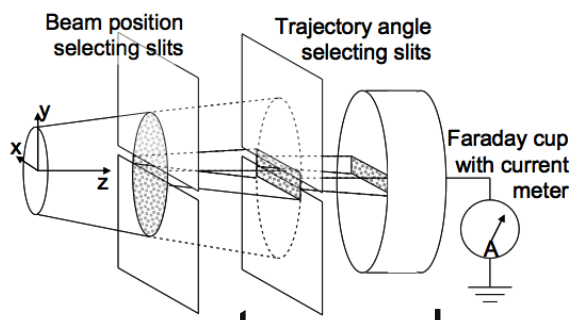
Emittance scanner motivation

- Diagnose the beam properties
- Analyse the 6D phase space
- Calculate accurate and precise emittance values
- Tune the ion source beam parameters
- Optimise transportation into the RFQ

How do we diagnose the emittance?

Emittance scanners:

- All types require a method to measure the spatial and angular divergence of the beam
- A slit-slit scanner operates by moving two identical slits separately, recording a set of *x'* for each *x* position*



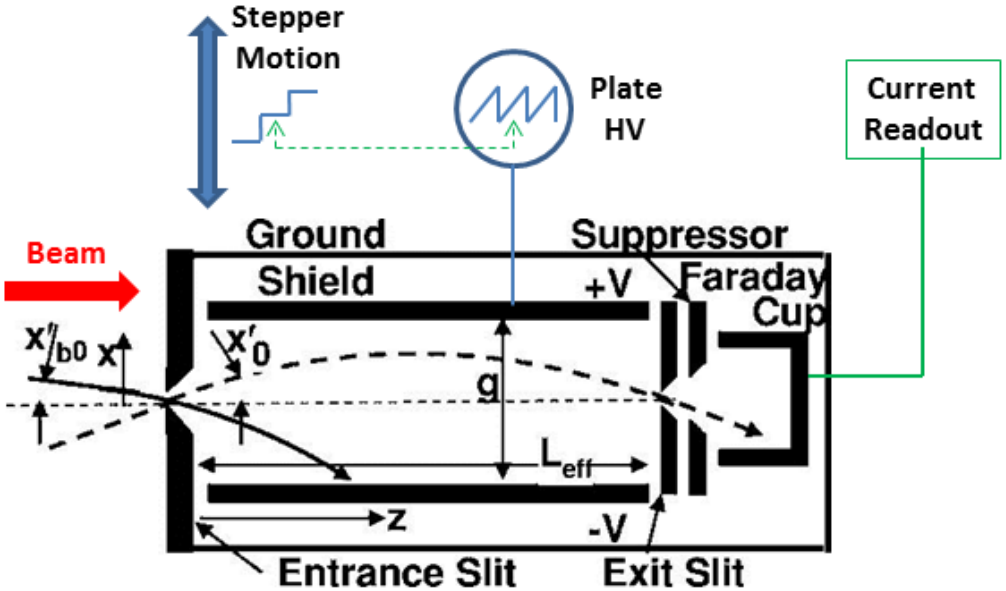
- An Allison Scanner operates under a similar principle but keeps the slits fixed relative to each other, using a pair of electric plates to select a range of angles

*NB – *x/y* and *x'/y'* are used interchangeably throughout this presentation. In the case of the emittance scanner they both refer to the vertical axis.

SNS Allison Emittance Scanner

Key Components:

- Front and back slits
- Electric plates
  - Sawtooth design to eliminate forward scattering
- Faraday cup

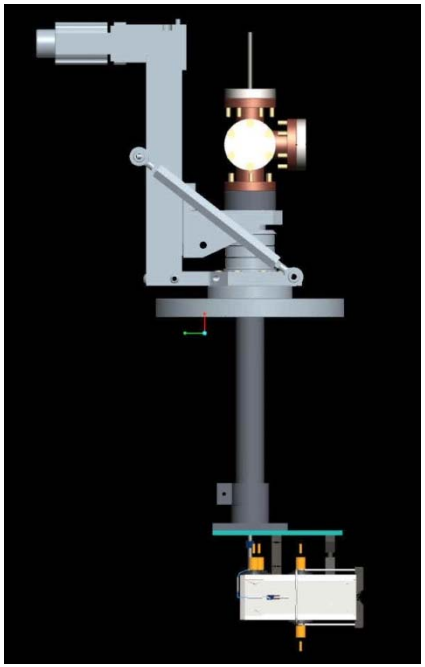


- A voltage sweep across the electric plates provides a range of *x'* values
- Physical movement of the box provides a range of *x* values

Installation

Water Cooled Allison Scanner

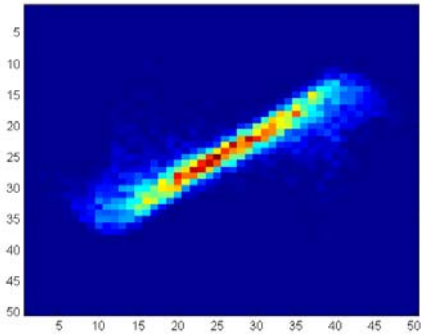
- SNS supplied detector, linear motion stage and vacuum plate
- FNAL-built vacuum chamber and assembled system



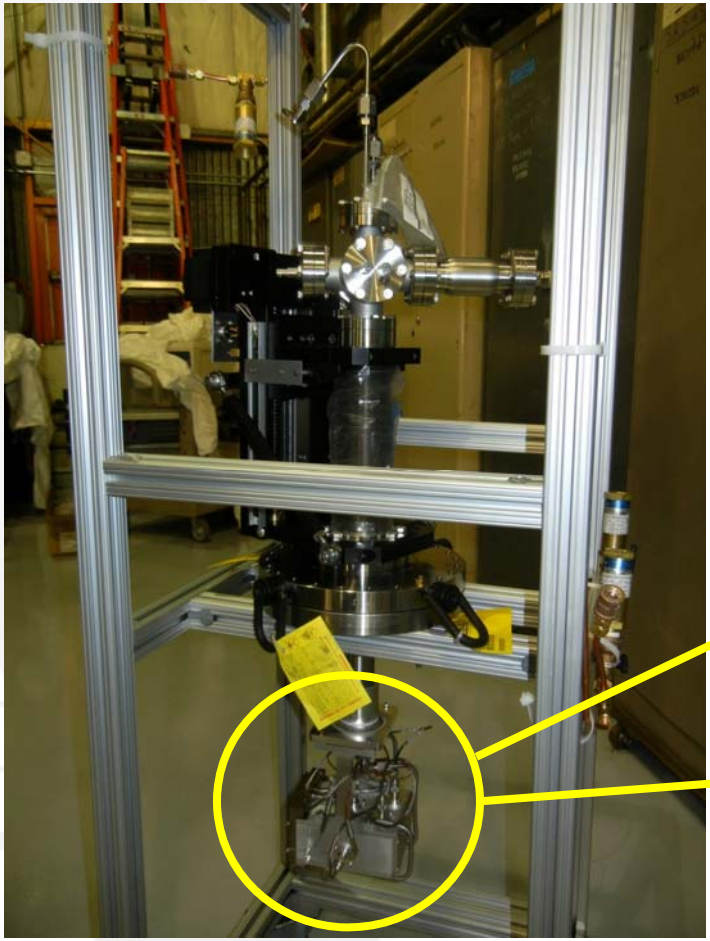
Typical operational Parameters

- *x* range: ± 20 mm
- *x'* range: ± 30 mrad
- Phase map dynamic range: >10^3

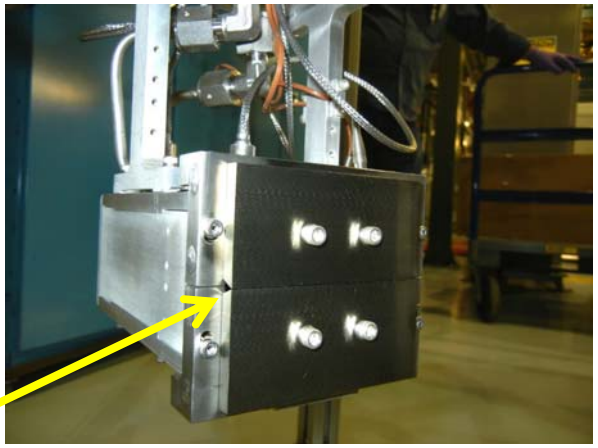
- Algorithm
  - Move to *x*-position
  - Perform a voltage sweep for *x'*
  - Move to next *x*-position, etc.
  - Analyse Phase space



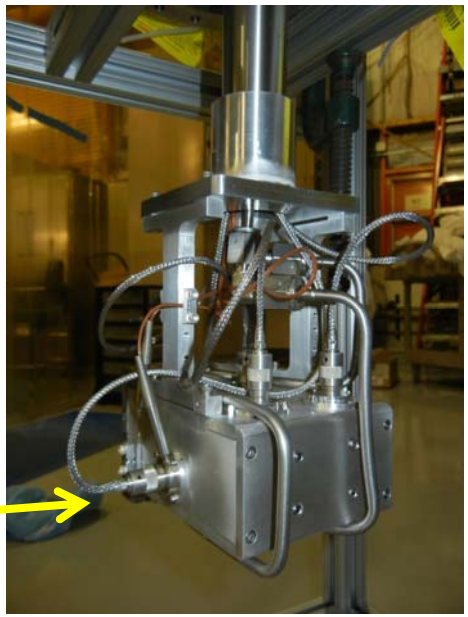
Installation



Scanner fully assembled in the test stand

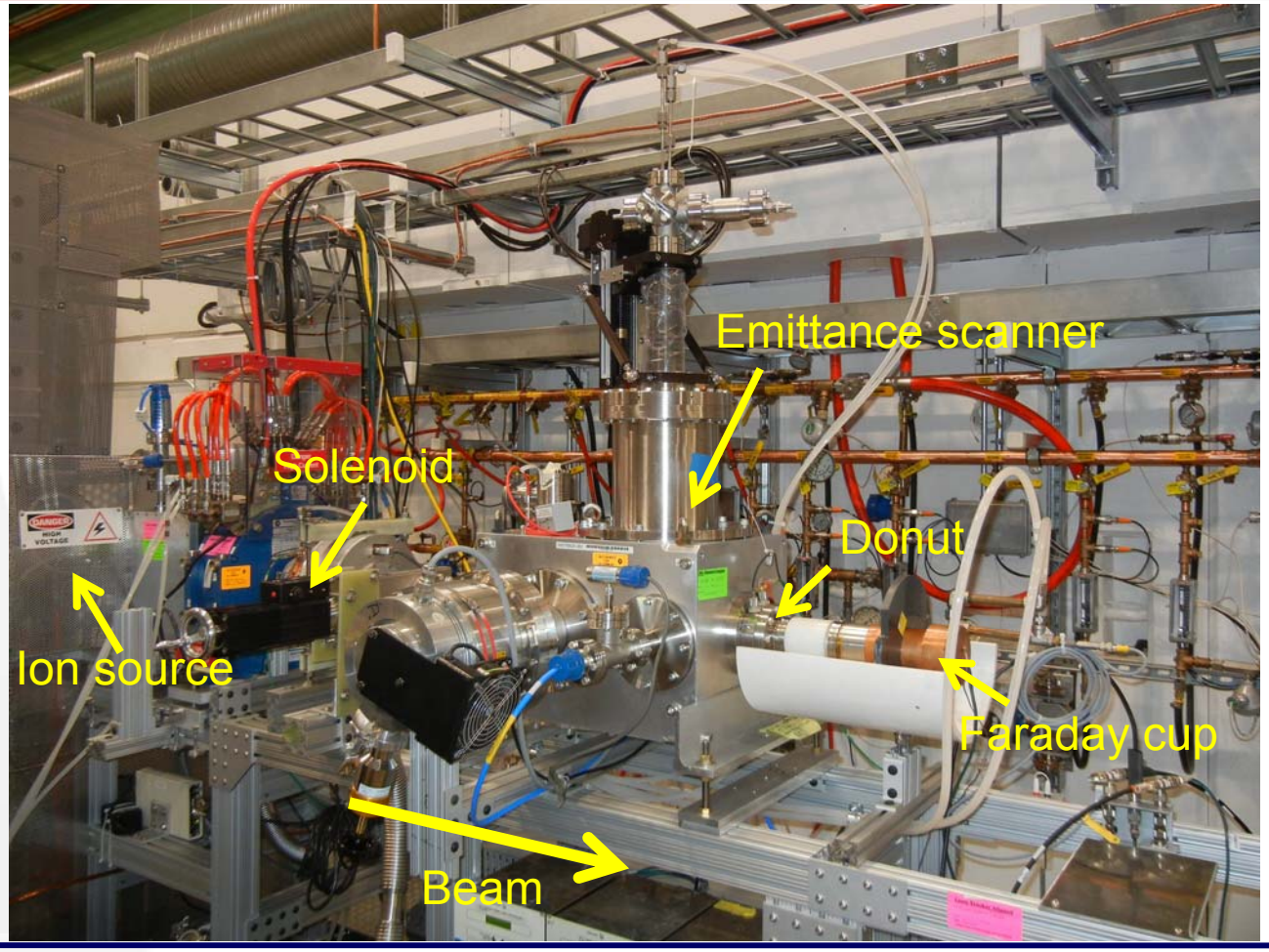


Front slit



Back plate

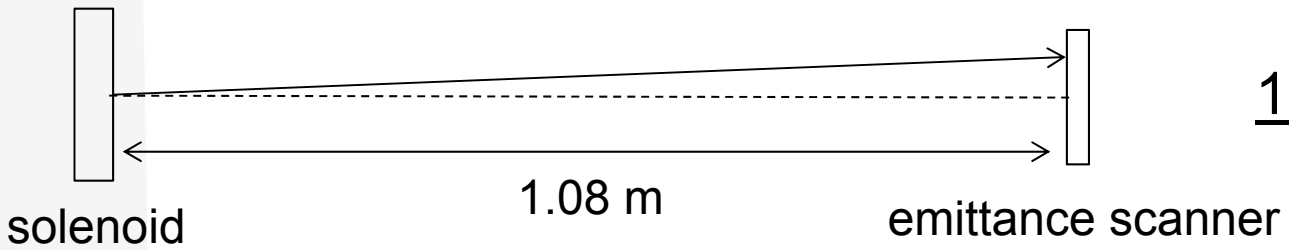
Installation



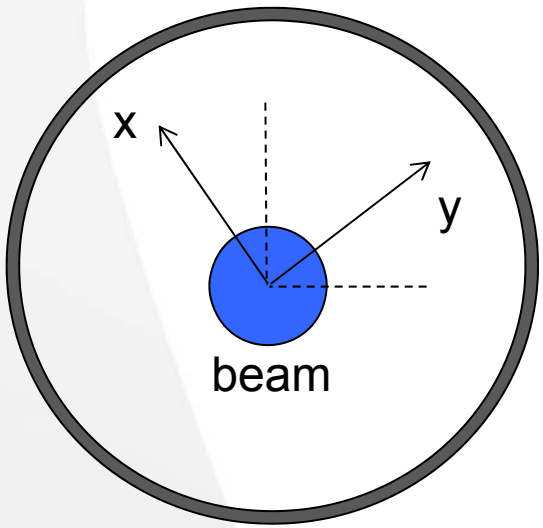
Calibration

- Position, angle, and timing windows require calibration before data-taking can commence
- Movement of the scanner can be confirmed using rulers, spring gauges, etc.
- The read-back given by the Labview position scale is accurate to ± 0.15mm
- The scatter from repeated motor-stops/-starts across a full scan is ± 0.11mm

Calibration - Angle



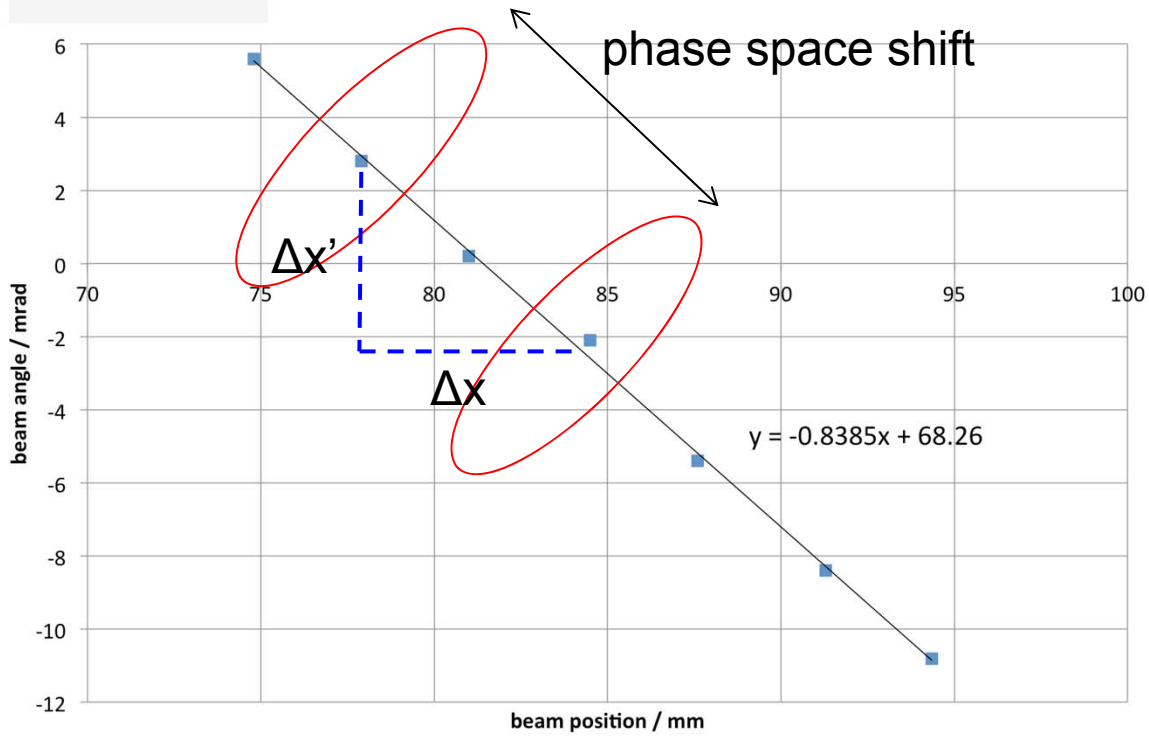
1.75 mm/A



Previous beam size measurements were performed using the donut

The calibration of the correctors was well established

Calibration - Angle



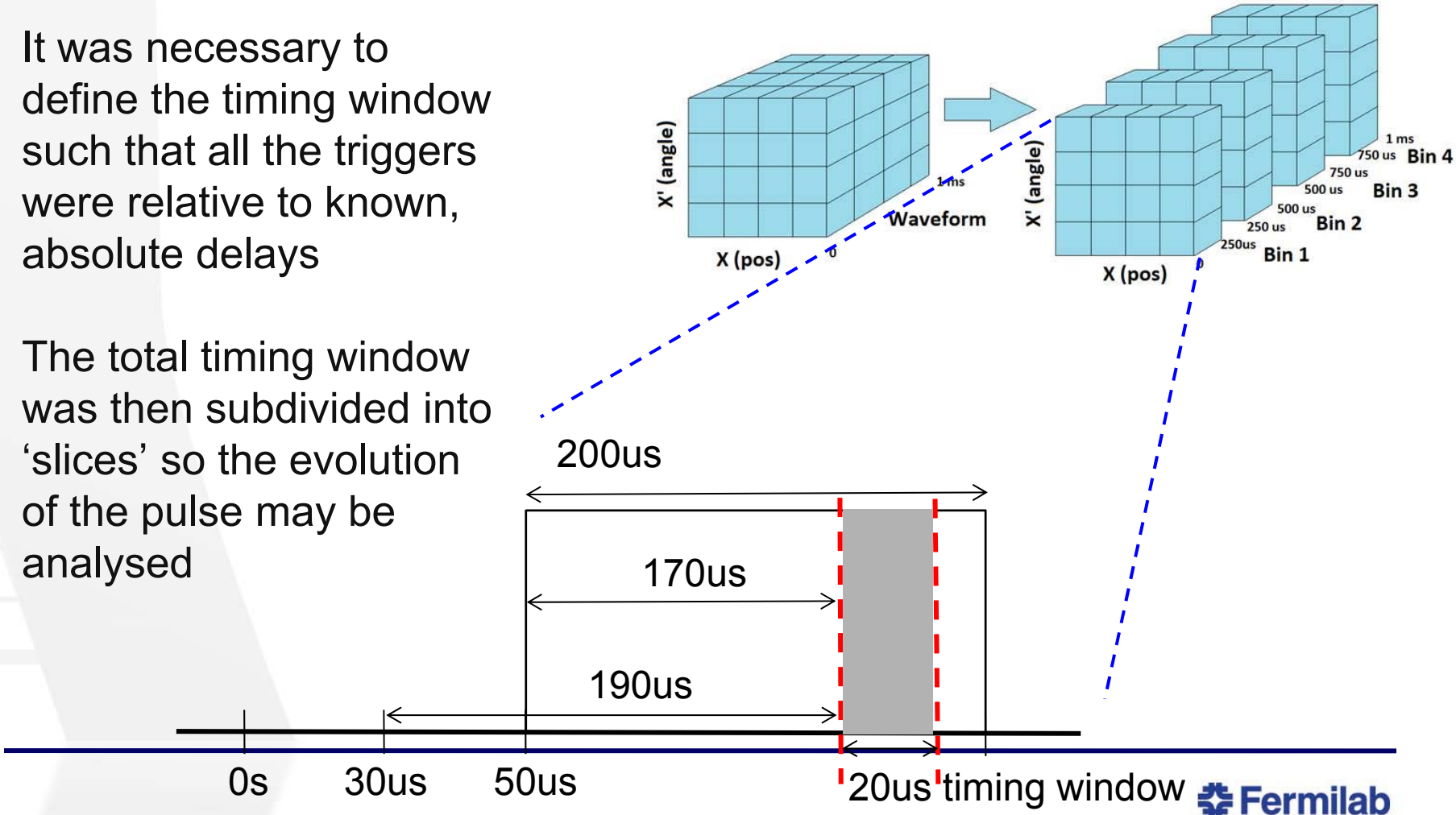
- The centroid values of both *x* and *x'* were taken across a range of corrector values
- d = Δx/Δx' = 1/0.84 = 1.19 ± 0.02 m
- The voltage-to-angle conversion in the emittance scanner configuration file was therefore adjusted by a factor of 1.1 to account for the discrepancy between 1.19 and 1.08

Calibration - Error

- Statistical errors from reproducibility are limited to a few percent
- Error in position is well defined via a number of measurement devices to the order of < 1%
- The main source of error in emittance scanner data will arise from the angle output as the calibration for this was performed via a corrector scan, with an intrinsic error range for the correctors themselves
- At present a < 10% level should be assumed for emittance scanner data presented

Calibration - Timing

- It was necessary to define the timing window such that all the triggers were relative to known, absolute delays
- The total timing window was then subdivided into ‘slices’ so the evolution of the pulse may be analysed



Emittance scanner data sampling

- The emittance scanner takes data across a range of *x* and *x'*, and places them in an array of the form:

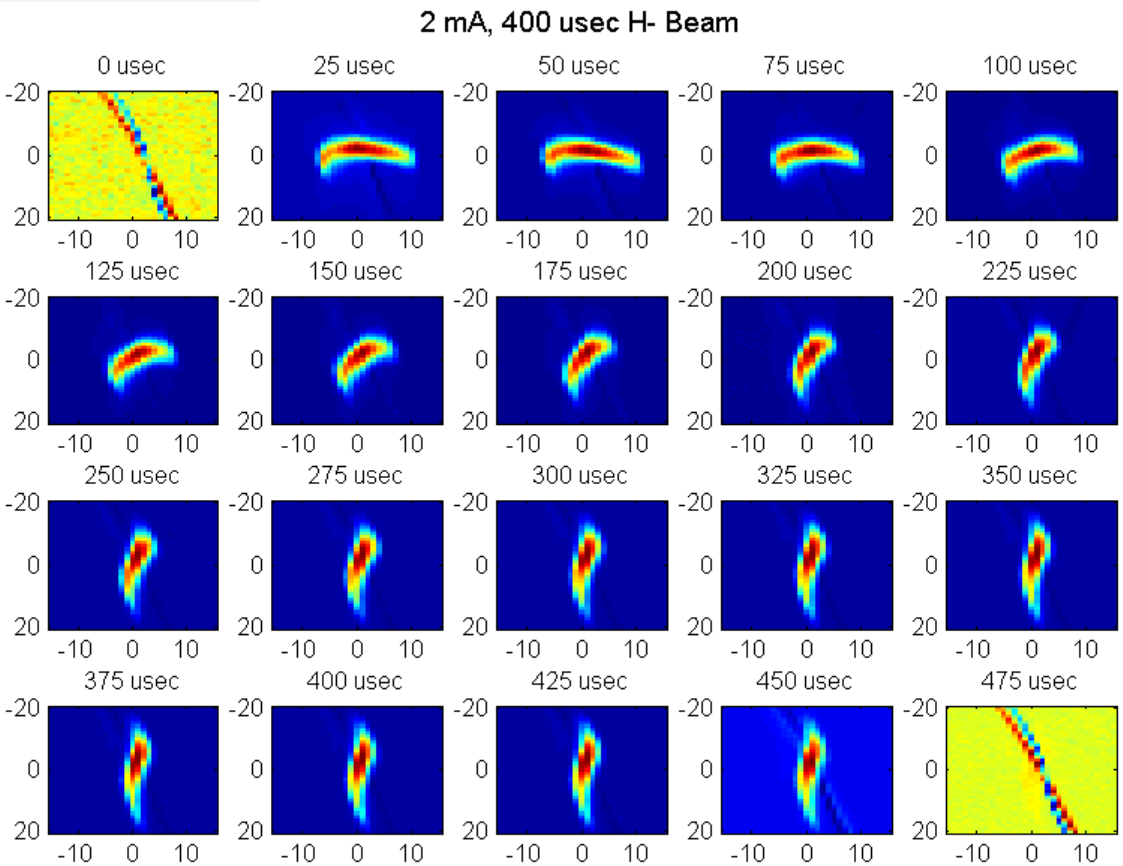
	x_1	x_2	x_3	x_4	…	x_m
x'_1	N_{11}	N_{12}	N_{13}	N_{14}	…	N_{1m}
x'_2	N_{21}	N_{22}	N_{23}	N_{24}	…	N_{2m}
x'_3	N_{31}	N_{32}	N_{33}	N_{34}	…	N_{3m}
x'_4	N_{41}	N_{42}	N_{43}	N_{44}	…	N_{4m}
…	…	…	…	…	…	…
x'_n	N_{n1}	N_{n2}	N_{n3}	N_{n4}	…	N_{nm}

An example data file may run from -30 to 30 mrad and 70 to 100 mm (defined as the insert distance from the home switch at x = 0)

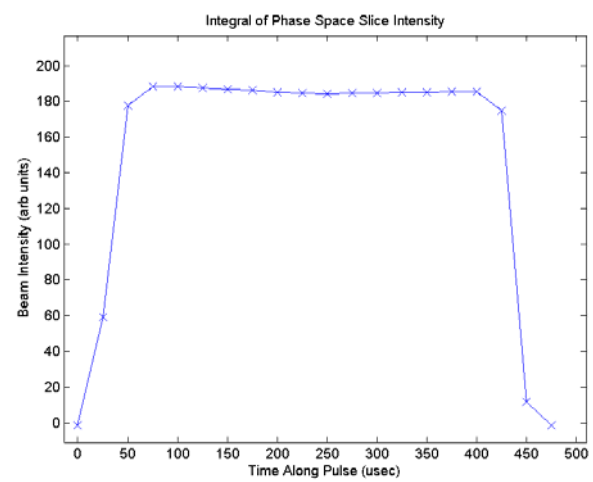
Both dimensions are then centered

Each data file has one 3D array per time-slice

Pulse measurements

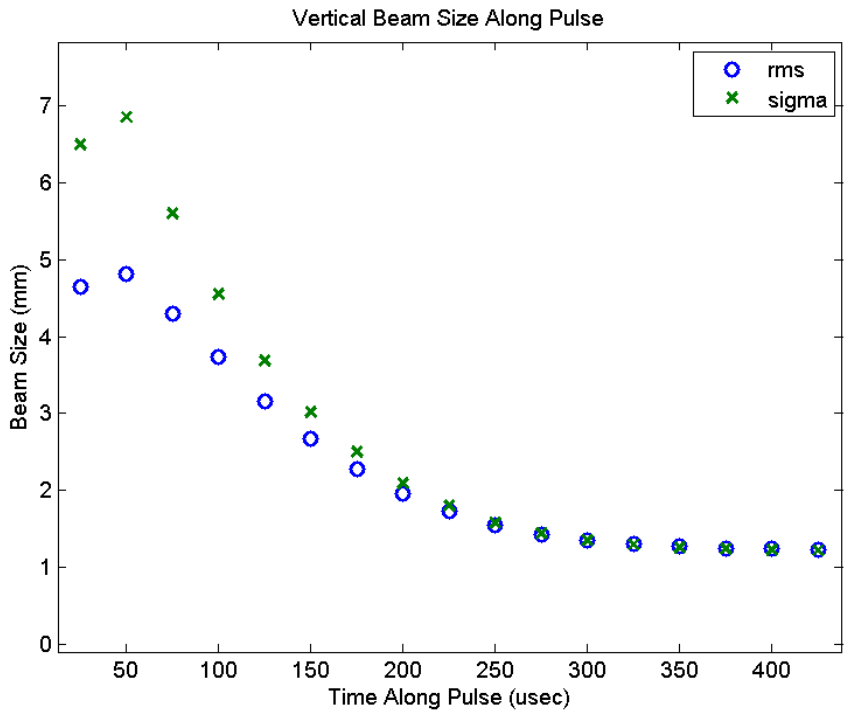


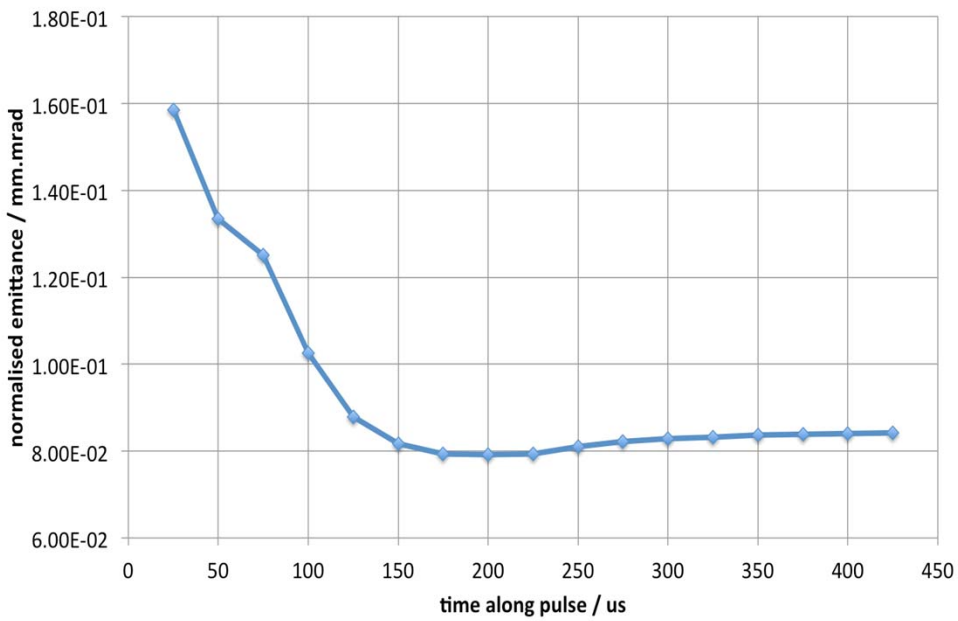
- The evolution of the phase space along the 400us pulse
- The shape settles down after ~300us



*NB – due to a flipped definition of spatial co-ordinates all phase-space plots on this slide should be reflected at *x = 0*

Pulse measurements





- Both the emittance and RMS beam size also level out after approximately 300us suggesting a neutralisation time shorter than this

Definition of emittance

- Numerically it may be defined in different ways: RMS emittance, 95% emittance, etc.
- In this talk it will be defined as a multiplication of moments (unless otherwise stated):

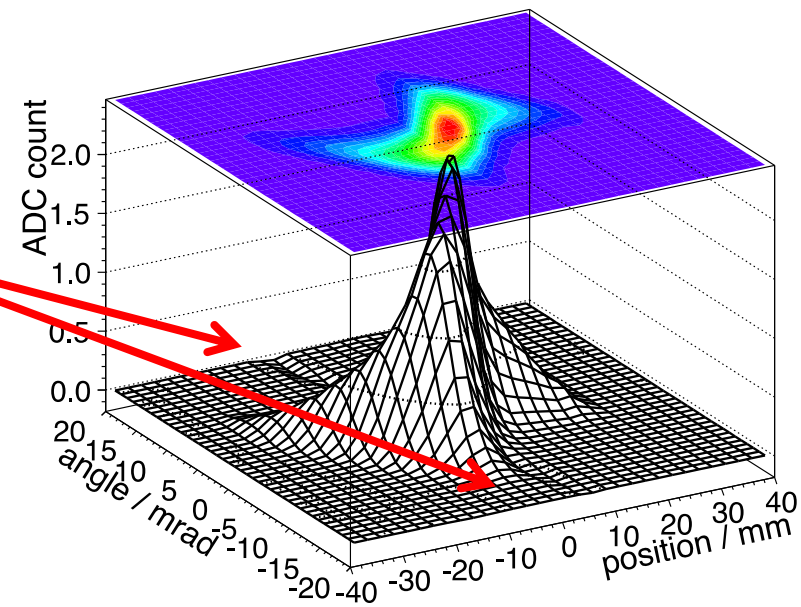
$$\varepsilon = \sqrt{\left(\frac{\sum\limits_{\substack{i=1..N \\ j=1..M}} x_j^2 C_{ij}}{\sum\limits_{\substack{i=1..N \\ j=1..M}} C_{ij}} \right) \cdot \left(\frac{\sum\limits_{\substack{i=1..N \\ j=1..M}} (x_i')^2 C_{ij}}{\sum\limits_{\substack{i=1..N \\ j=1..M}} C_{ij}} \right) - \left(\frac{\sum\limits_{\substack{i=1..N \\ j=1..M}} x_i' x_j C_{ij}}{\sum\limits_{\substack{i=1..N \\ j=1..M}} C_{ij}} \right)^2}$$

where x_j and x'_i are the new arrays after centering

Threshold Cuts

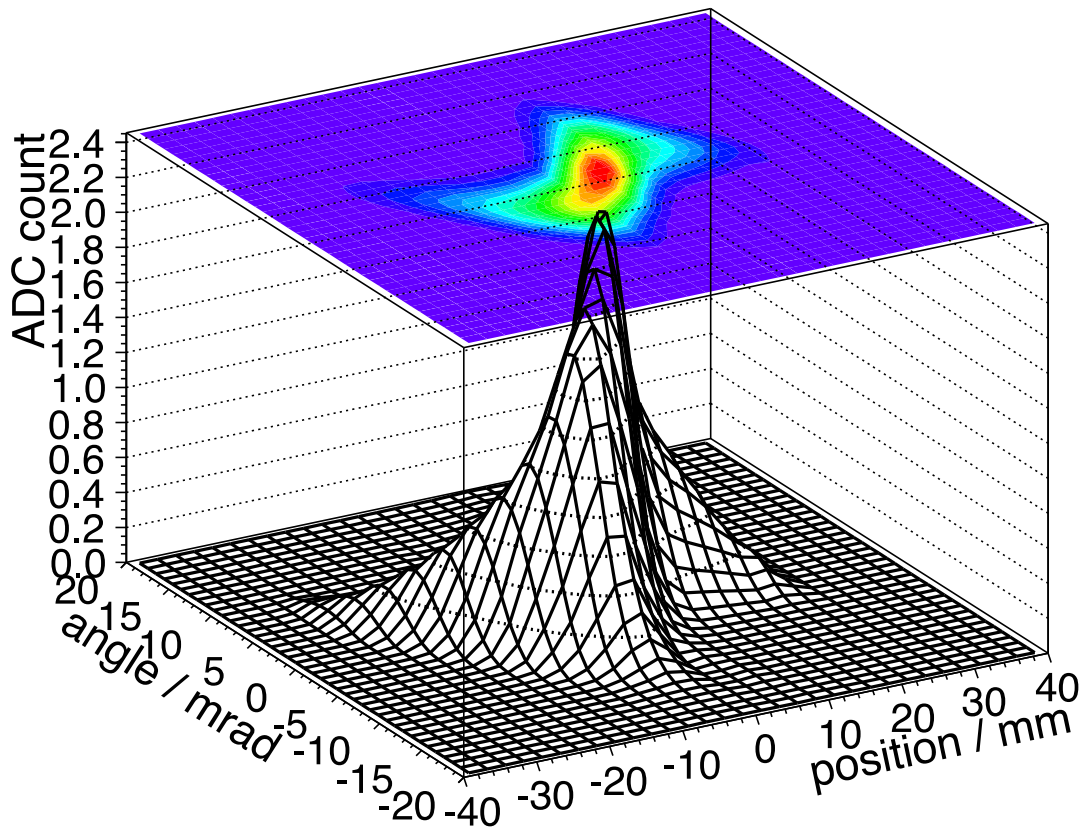
- Before the emittance is calculated it is necessary to consider a threshold choice for potential backgrounds
- All scans will record a certain amount of background:
  - Secondary electrons, protons, neutrons, etc.
- A threshold cut should serve to remove this background, but what value should be chosen?

Negative readings from the Faraday plate



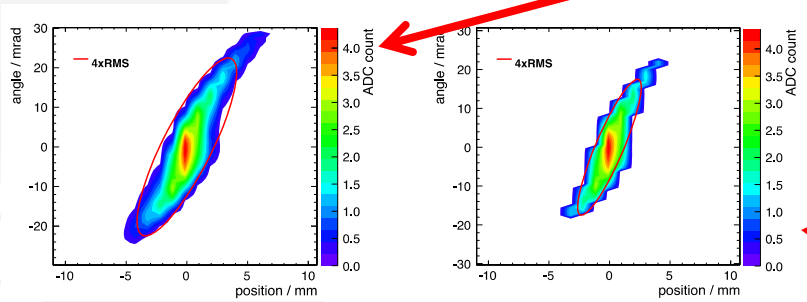
Threshold Cuts

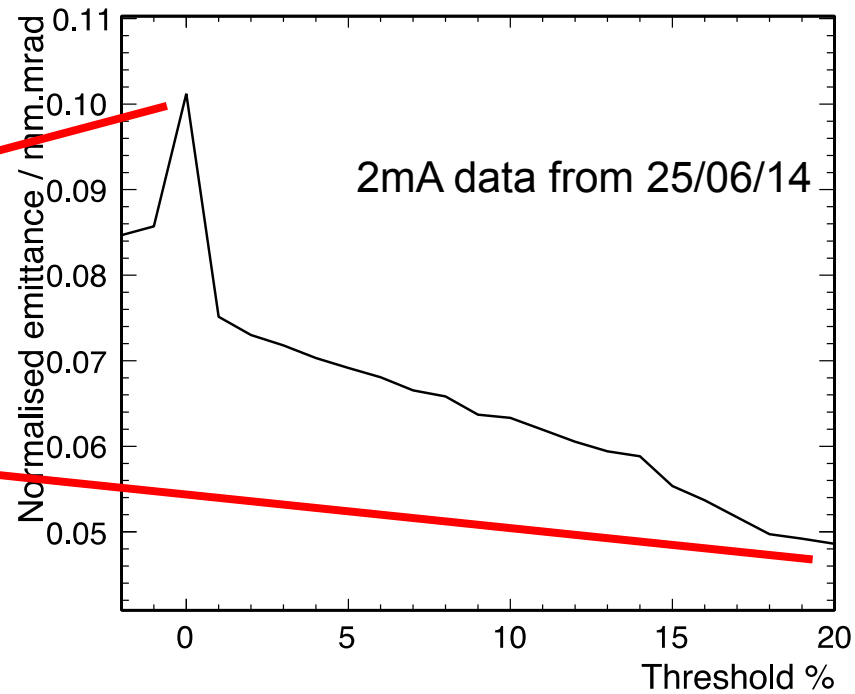
- In the code a threshold cut is defined as a percentage of the peak Faraday plate value in the array
- In this case a 1% cut is made, serving to remove all negative signal



Threshold Cuts

- As can be seen the emittance peaks at a 0% cut i.e. removing only the negative faraday cup array elements
- There is a distinct drop off from 0-1%, then a lower gradient after





- Both 0% and 1% cuts are presented in the next few slides as a guideline to the effects of thresholding

Results - Reproducibility

- All data sets taken across the course of a single afternoon, irrespective of a change in solenoid current, produced an emittance variation of ~3%

date	time	beam current / mA	sol. current / A	norm. emit (0%) / mm.mrad	norm. emit (1%) / mm.mrad
23-Jun	14:53	2	152	0.161	0.151
	15:08	2	154	0.159	0.149
	15:23	2	156	0.159	0.147
	15:31	2	150	0.159	0.149
	15:39	2	148	0.161	0.151
	15:49	2	149	0.159	0.148
	15:56	2	151	0.158	0.147
	16:05	2	153	0.158	0.148
	16:14	2	155	0.158	0.147

2.0%

2.7%

- These were all taken with identical ion source parameters.

Results - Reproducibility

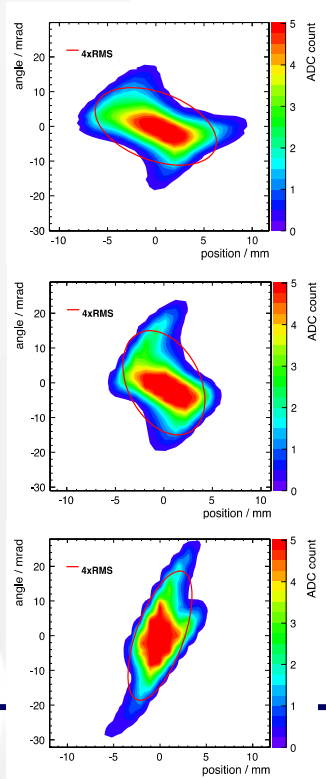
- This is compounded by data taken over night with identical ion source parameters, in this case with a 5mA beam

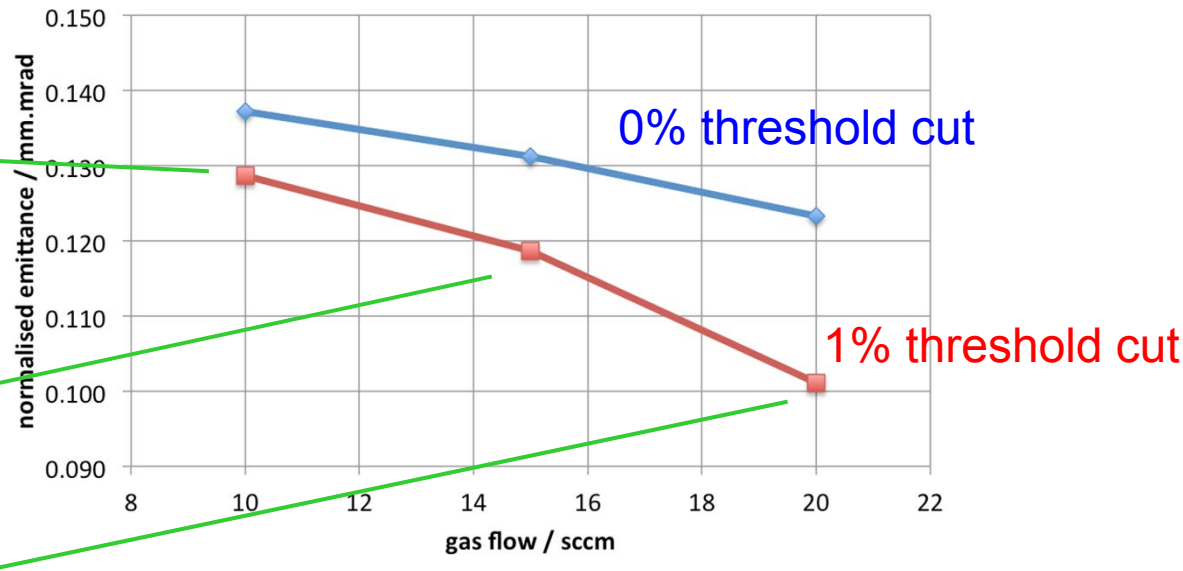
date	time	beam current / mA	sol. current / A	norm. emit (0%) / mm.mrad
24-Jun	16:49	5	152	0.150
25-Jun	10:52	5	152	0.146

2.7%

Results – Gas flow effect

- Changing the gas flow, whilst keeping the beam current constant via small alterations to the extraction electrode voltage, has a 3% per sccm effect on the emittance



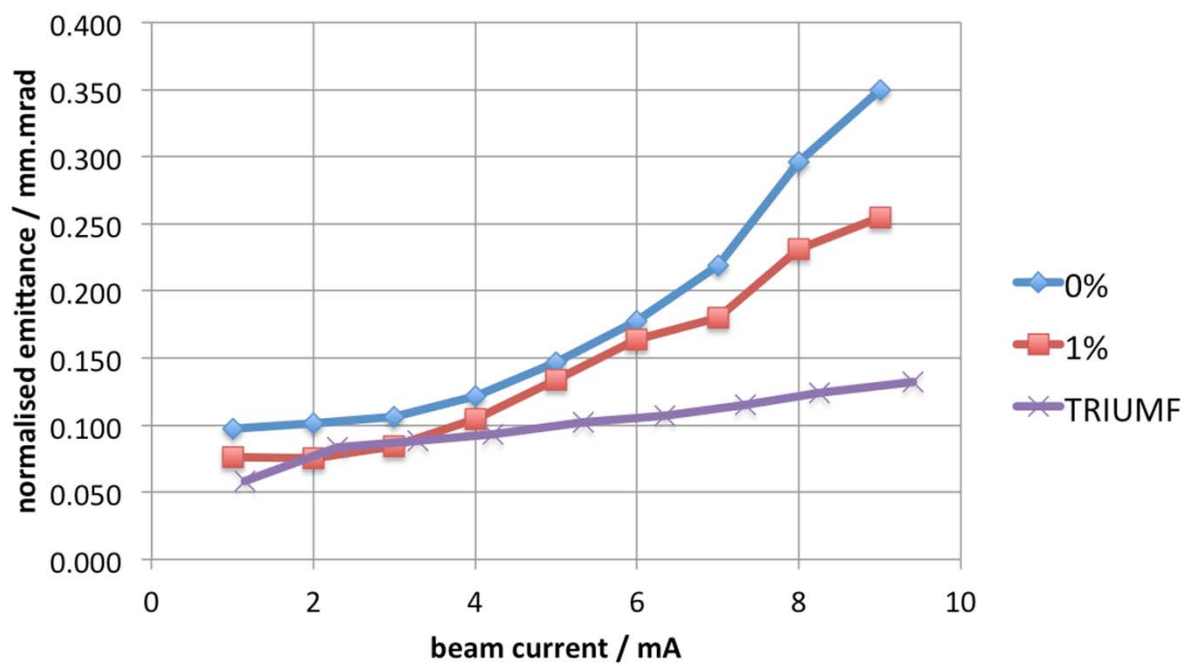


- This requires further investigation once the emittance scanner is reinstalled

Results – Large beam current

- A change in beam current (achieved by varying all ion source parameters, including gas flow) leads to a substantial change in RMS emittance. In this case a factor of 3.6-3.8 across 1-9 mA

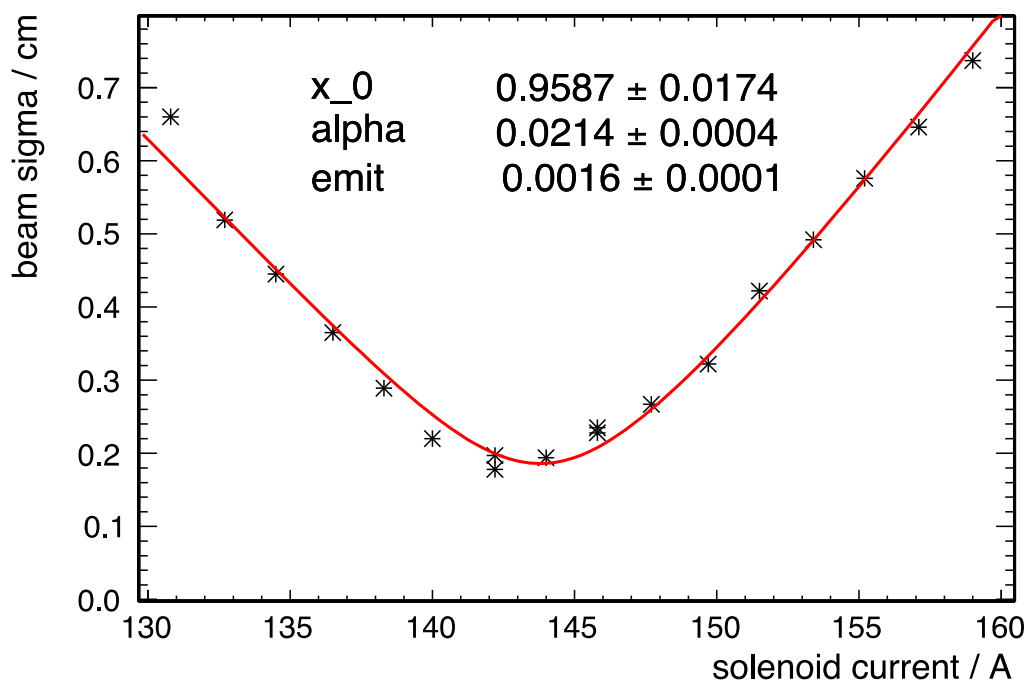
- The TRIUMF data demonstrates the ability of the ion source; we need to investigate whether these results are reproducible with a three-solenoid beam line



Emittance comparison

- Comparison between the emittance scanner results and those of the donut also need to be considered
- The most recent data set for the donut was taken on the 6-Jun-2014 for 2mA with ε= 0.084 ± 0.008 mm.mrad:

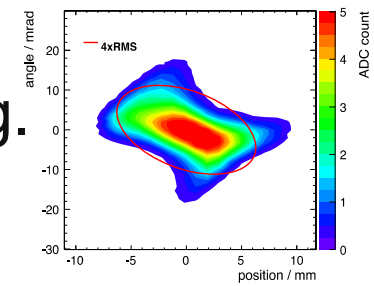
- Statistical errors are of a few percent
- The main source of error for the donut measurements arises from the dependency on the models used for fitting. e.g. is the beam gaussian or flat-top? etc. At present they are understood to the 10% level



Emittance comparison: N(J)

Method

1. The alphas and betas are calculated for all values above 0%
2. The action is calculated for each data point, e.g.



$$J_{11} = \gamma x_1^2 + 2\alpha x_1 x'_1 + \beta x_1'^2$$

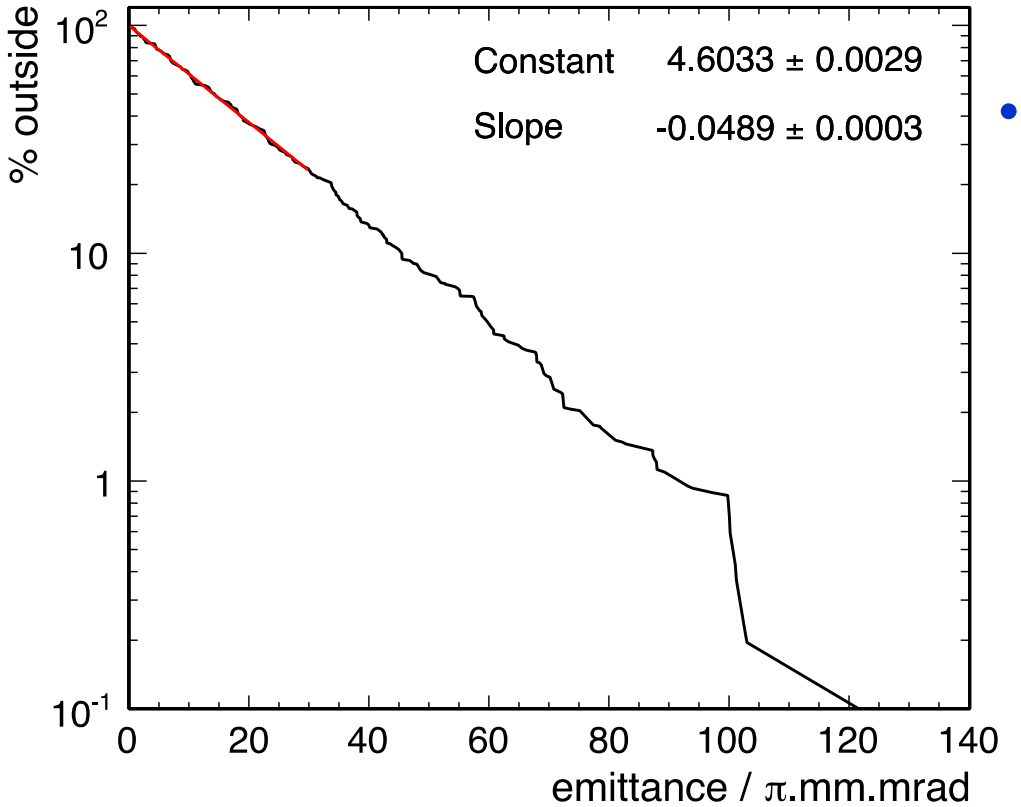
	x_1	x_2	…	x_m
x'_1	N_{11}	N_{12}	…	N_{1m}
x'_2	N_{21}	N_{22}	…	N_{2m}
…	…	…	…	…
x'_n	N_{n1}	N_{n2}	…	N_{nm}

Emittance comparison: N(J)

Method

3. This gives vectors of *J* with their corresponding *N*
4. By ordering the vectors according to the size of *J*, and plotting this against the decreasing sum of all *N* values (for 0%) above a given action, a monotonic plot is given. This is analogous to a plot of % vs. emittance
5. An exponential fit of $N = N_0 e^{(-J/2\varepsilon)}$ to the straight section of the curve should yield the emittance

Emittance comparison: N(J)



- The 25/06/14 2mA data set (with similar ion source settings to the donut data from 06/06/14) gives an emittance value of ε = 0.082 ± 0.008 mm.mrad

Results - Collation

- For a 2 mA beam, created using similar ion source settings, the emittance values for different analysis and methods are the same within the current 10% error range:

	RMS (0.5% cut)	$\varepsilon_{N(J)}$	Donut	TRIUMF
emittance / mm.mrad	0.079	0.082	0.084	0.085

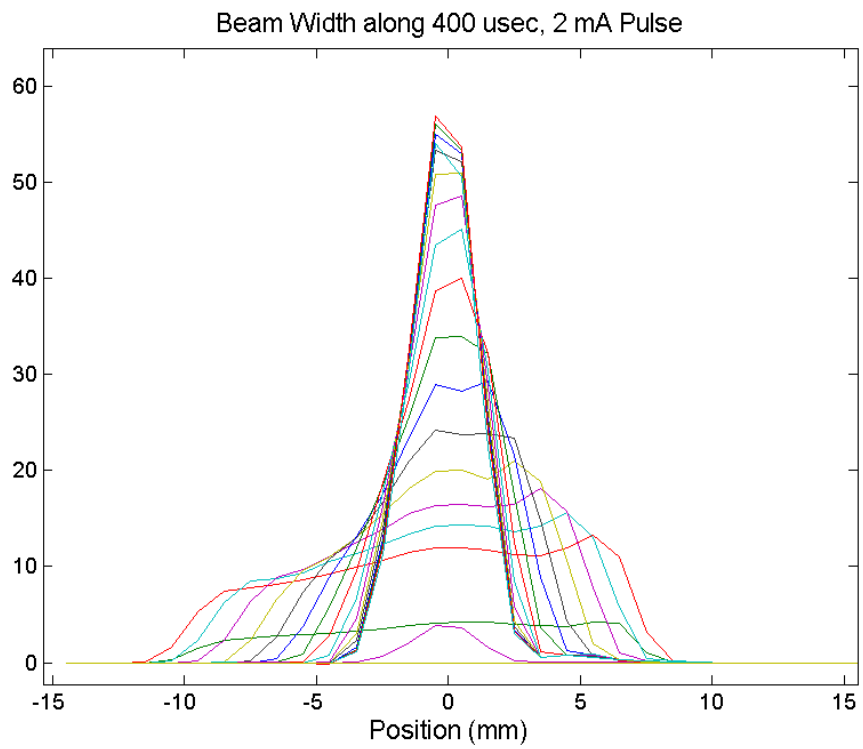
- These results concern themselves primarily with the core of the phase-space ellipse. This is adequate for initial estimates but further understanding of the halo/tails/wings is essential in moving forward

Summary and Conclusions

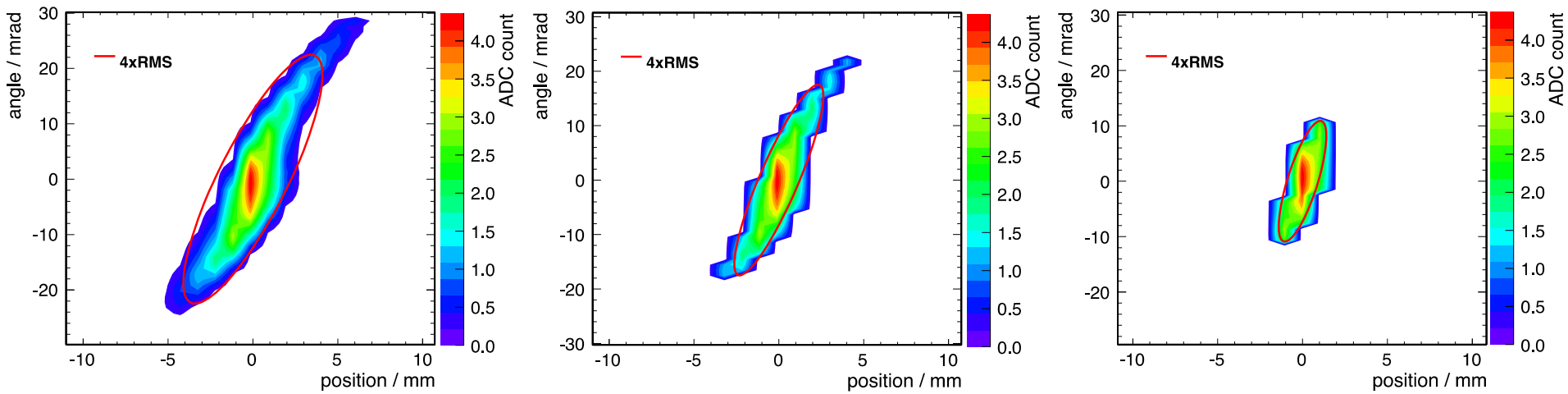
- The emittance scanner has been commissioned and calibrated. It was used primarily in pulse measurements but was tested up to full power, 300W DC
- The absolute error in measuring the RMS core emittance is < 10% and is dictated by the angle calibration
- The emittance scanner measurements with a 2mA beam current agree with the donut result, as well as with the acceptance test at TRIUMF, within the measurement errors
- Capability of the emittance scanner to analyse the phase space evolution during neutralization time in a single set of measurements was demonstrated

BACK UP SLIDES

- Beam profile evolution:



BACK UP SLIDES



0% 25% 50%