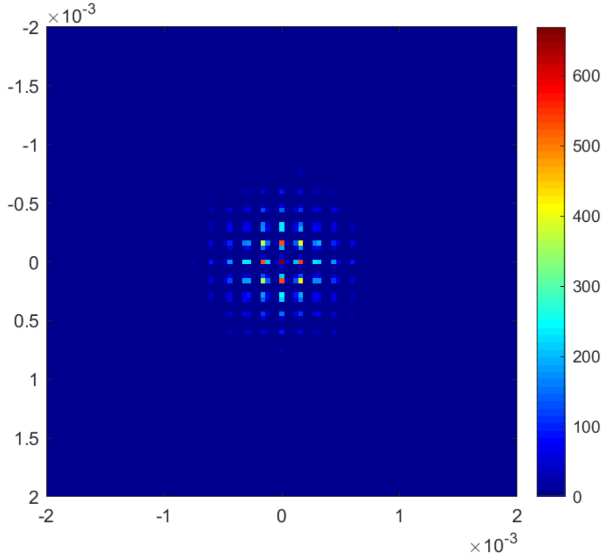
Preliminary studies for emittance measurement with quadrupole scan + pepper pot mask



20.08.2020 @ PPS
H. Qian

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

Outline

- Introduction
- SNR for fastscan and quadscan
- Pepper pot design considerations
- Experiment observation of scattered signal
- Possible diagnostic setup at PITZ
- Summary

Emittance measurement of space charge dominated beam

- RMS envelope equation with linear space charge forces
  - $\sigma_x'' + k^2\sigma_x = \frac{\varepsilon_{nx}^2}{(\gamma\beta)^2\sigma_x^3} + \frac{I/2I_0}{(\gamma\beta)^3\sigma_x}$

External linear focusing

Emittance defocusing

Linear space charge defocusing

Ratio between space charge and emittance term:

$$\rho = \frac{I/2I_0}{\gamma\beta\varepsilon_{nx}^2}\sigma_x^2$$

$\rho \gg 1$, space charge dominated beam

$\rho \ll 1$, emittance dominated beam

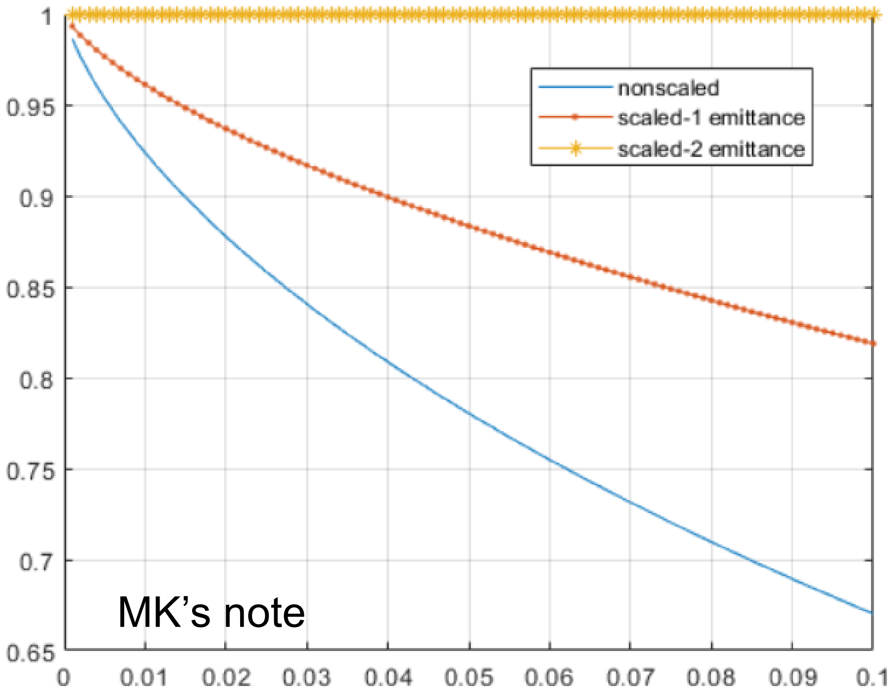
	PITZ		XFEL	
Ek	20	20	130	130
Charge	250	500	250	500
Emit	0.6	1	0.6	1
Peak current	20	30	20	30
Sigx	0.3	0.3	0.2	0.2
rho	**3.66**	**1.98**	**0.26**	**0.14**

- Emittance measurements
  - Slit scan & pepper pot (space charge dominated beam)
    - Pro: direct phase space measurement, not rely on magnet calibration, low energy linac
    - Con: need high SNR & long pulse linac for fast scan
      - Example: 250 pC @0.3 mm rms, 50 um slit
      - Beamlet charge: 17-0.17 pC @center→ 3σ
      - Beamlet SNR variation >100 (if 1% EMSY projection is measured)
  - Quad scan (emittance dominated beam)
    - Pro: full charge, SNR variation 1~4, short pulse linac
    - Con: need reliable magnet calibration, high energy linac
  - Pepper pot + Quad scan (space charge dominated beam)
    - Work with low energy and short pulse linac → good for injector test facility
    - SNR variation 1~4

Emittance vs SNR

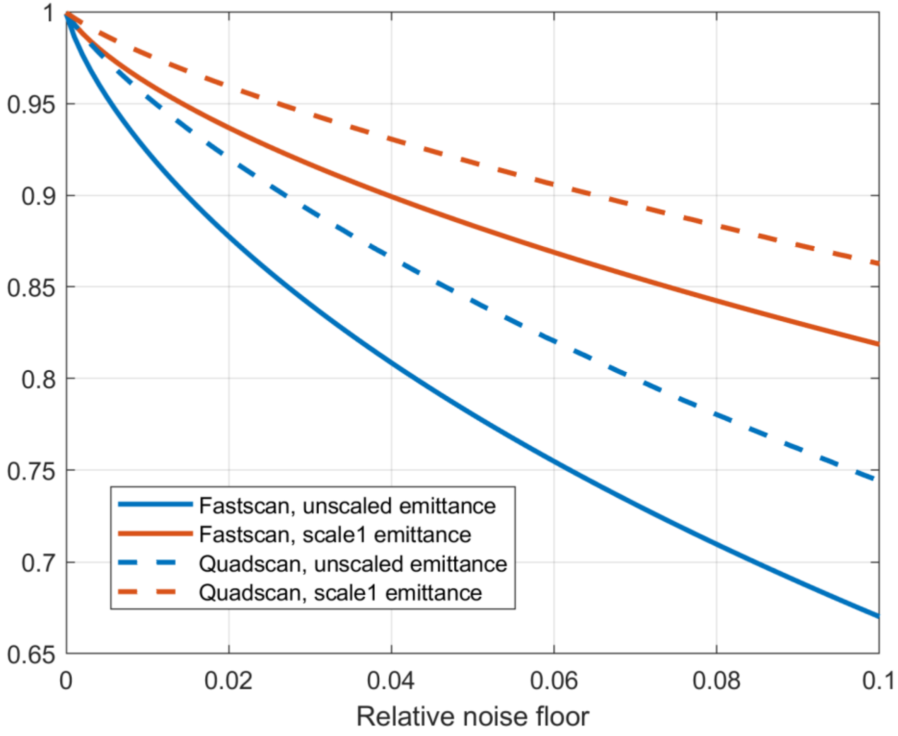
Assuming Gaussian phase space

- Fastscan



Relative noise floor

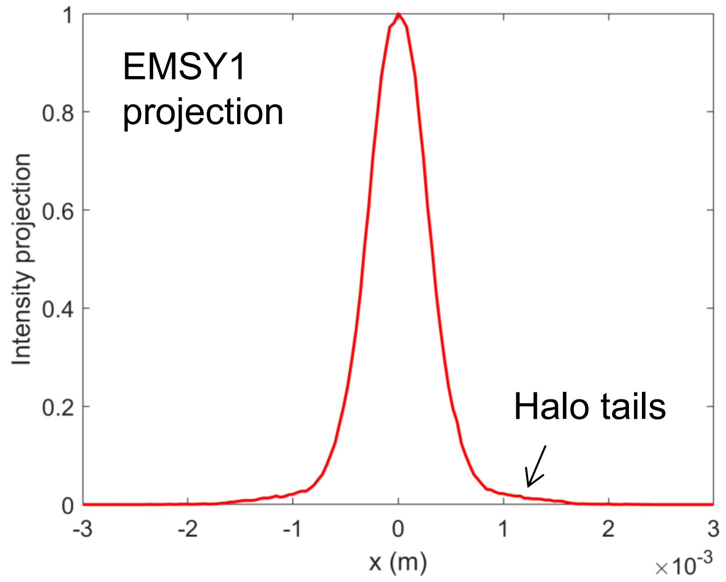
- Quad scan

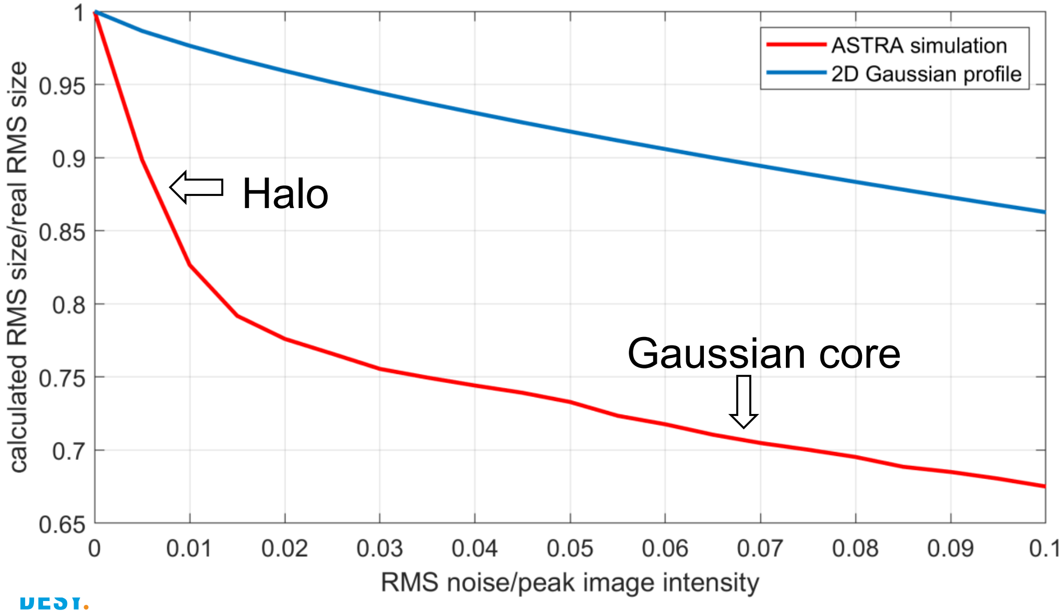


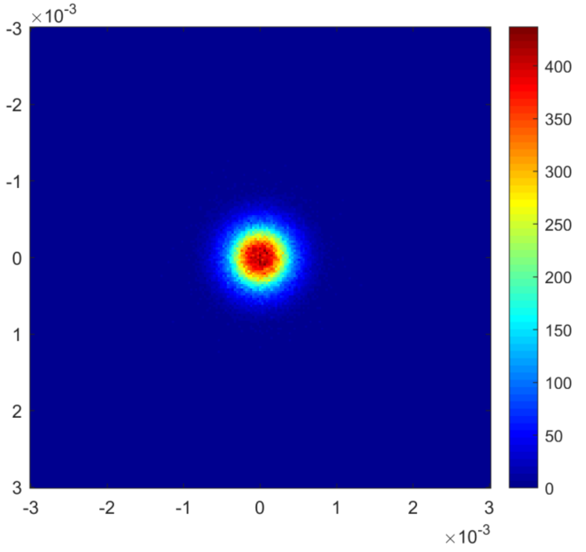
Beam with non-Gaussian phase space

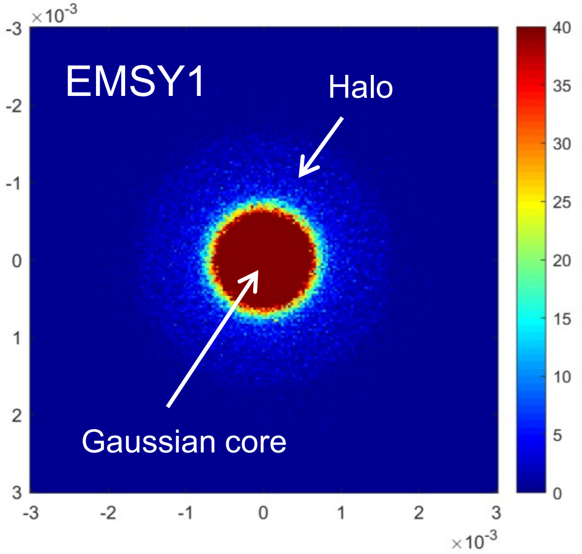
Beam with halos

- 500 pC beam ASTRA simulation
  - BSA1.3mm, uniform VC2, 6 ps Gaussian laser
  - EMSY1 beam size: 0.358 mm rms
  - Emittance ~1 mm.mrad, ~33 A peak current
- Much more sensitive to noise compared to Gaussian beam
  - A 2000 statistics @EMSY1 only reaches 90% of the real rms size





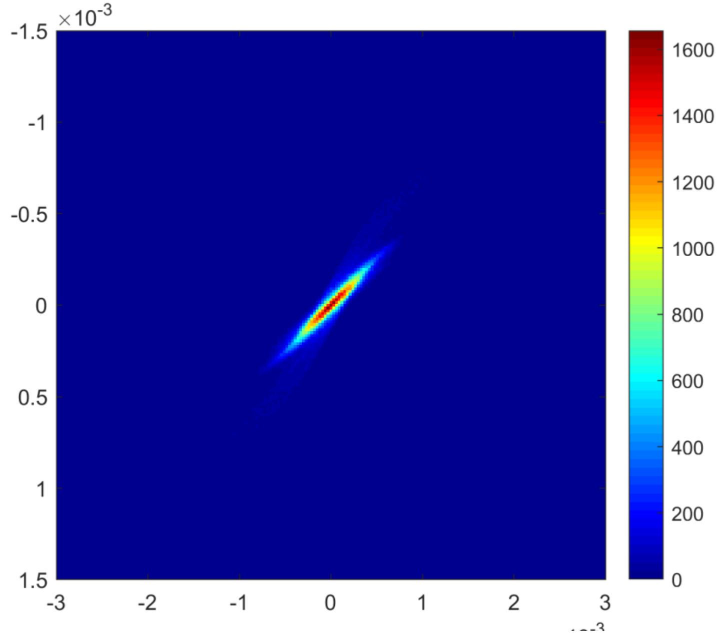


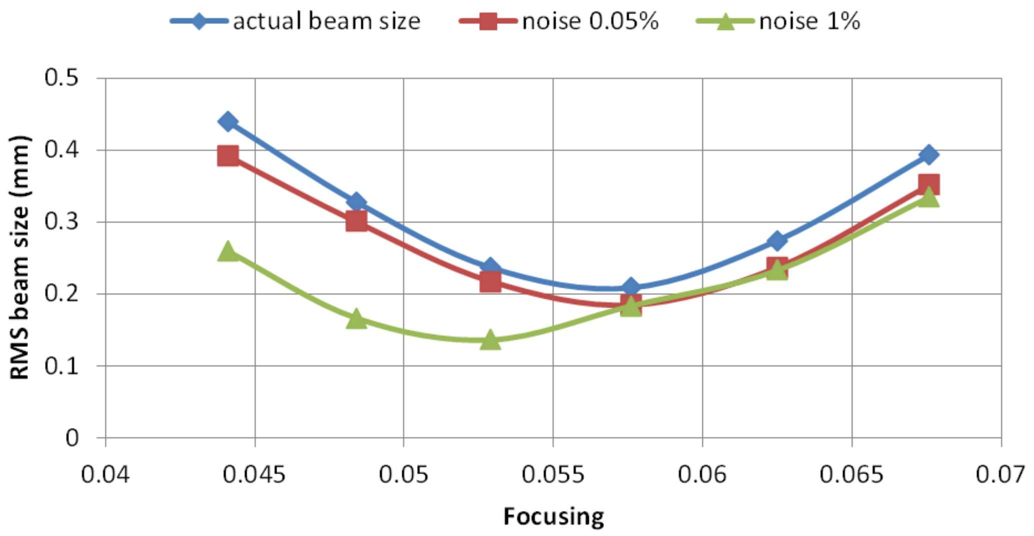


Beam with non-Gaussian phase space

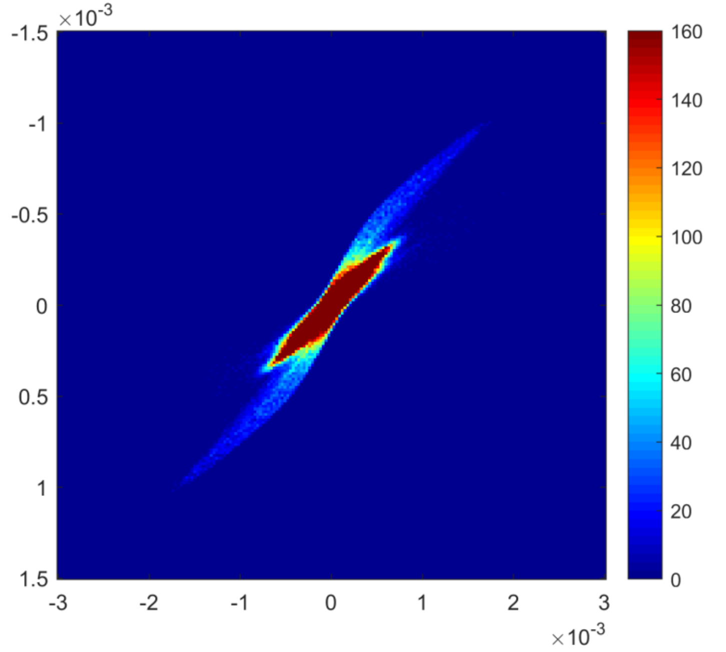
Beam with halos

- 500 pC beam ASTRA simulation
  - BSA1.3mm, uniform VC2, 6 ps Gaussian laser
  - EMSY1 beam size: 0.358 mm rms
  - Emittance ~1 mm.mrad, ~33 A peak current
- A virtual quad scan w/o space charge
  - 2000 statistics (0.5%) → scaling factor ~1.1 → full beam emittance
  - 1000 statistics (1%) → Waist location changed → Gaussian core emittance



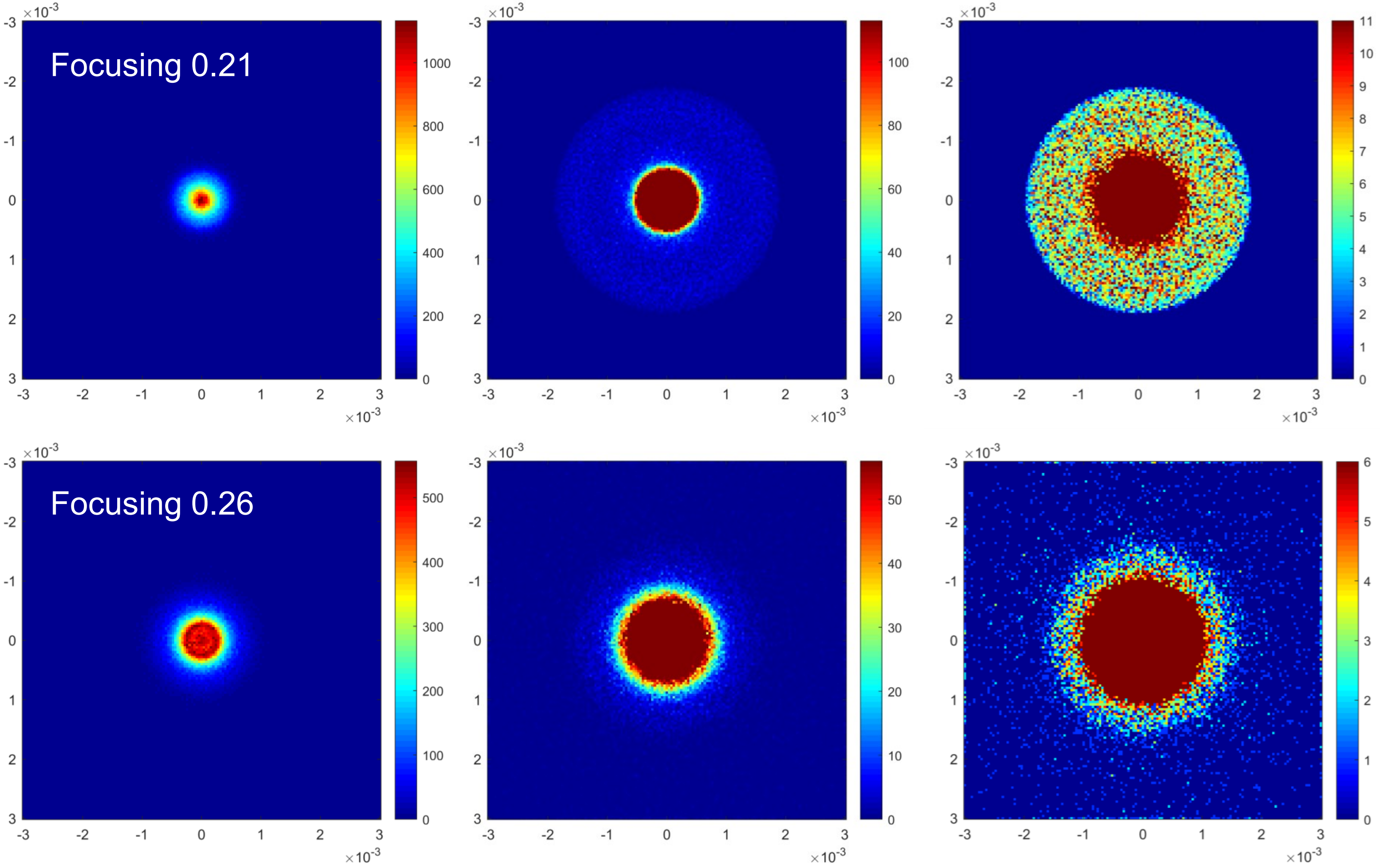


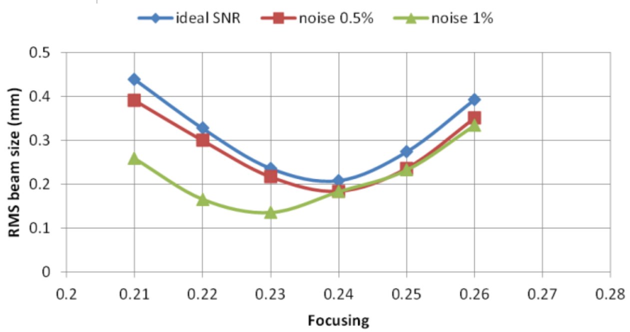
Fastscan for such a beam is expected to be even worse, as seen for Gaussian phase space.



Beam with non-Gaussian phase space

Beam with halos



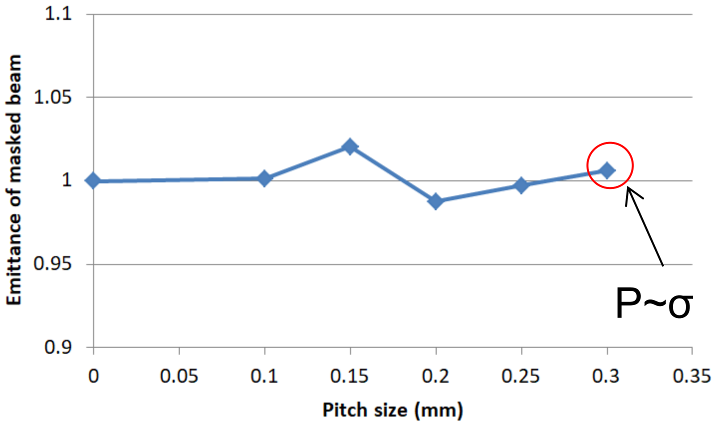


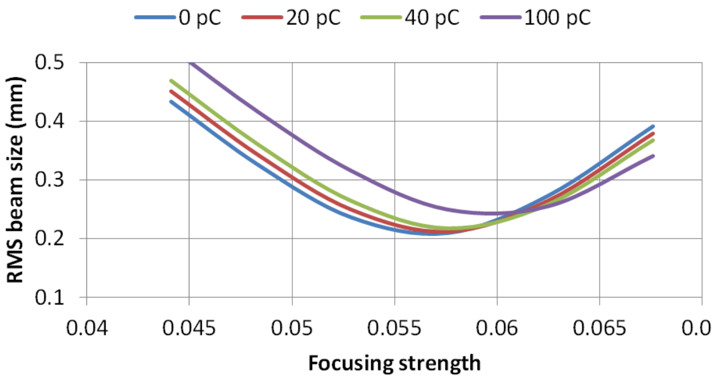
Pepper pot design considerations

- Pepper pot consideratios
  - Charge transmission: $(\frac{\pi D^2}{4P^2})$<10%

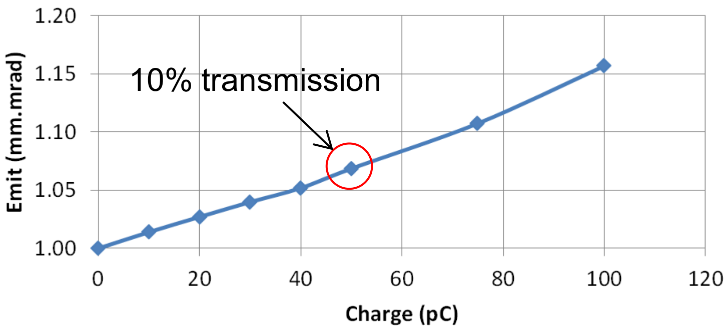
	PITZ		XFEL	
Ek	20	20	130	130
Charge	250	500	250	500
Emit	0.6	1	0.6	1
Peak current	20	30	20	30
Sigx	0.3	0.3	0.2	0.2
rho	**3.66**	**1.98**	**0.26**	**0.14**

  - Pitch dimension (Spatial sampling rate)





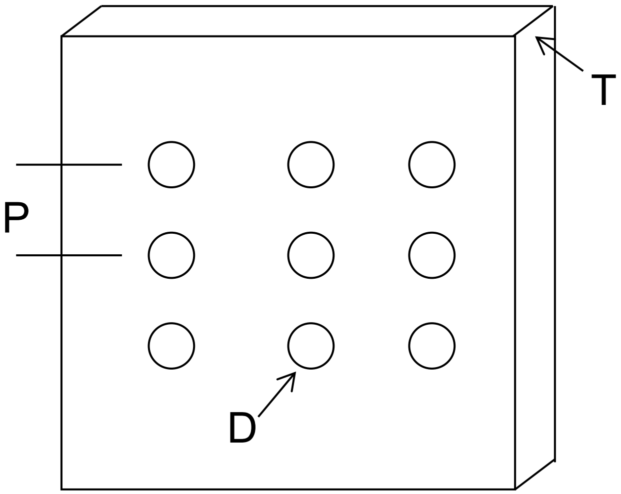
Emittance from quad scan vs charge



XFEL quad scan err ~2%
0.5 nC@130 MV

PITZ 50um slit scan err ~10%
0.25 nC @20 MV

Mask schematics



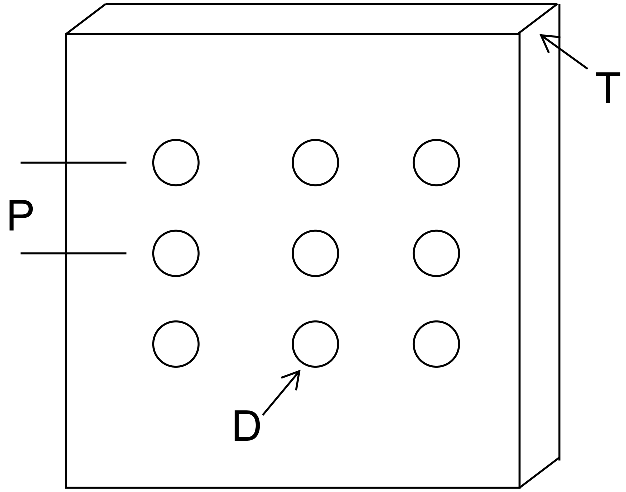
Pepper pot mask examples

	UCLA	PSI	PSI	PSI	PSI	Unit
D	15	20	50	20	50	um
P	85	150	150	250	250	um
Thick	0.025	0.2	0.2	0.2	0.5	mm
Atten	2.45%	1.40%	8.73%	0.50%	3.14%	
angle accpt	600	100	250	100	100	mrad
beam angle	~1	~1	~1	~1	~1	mrad

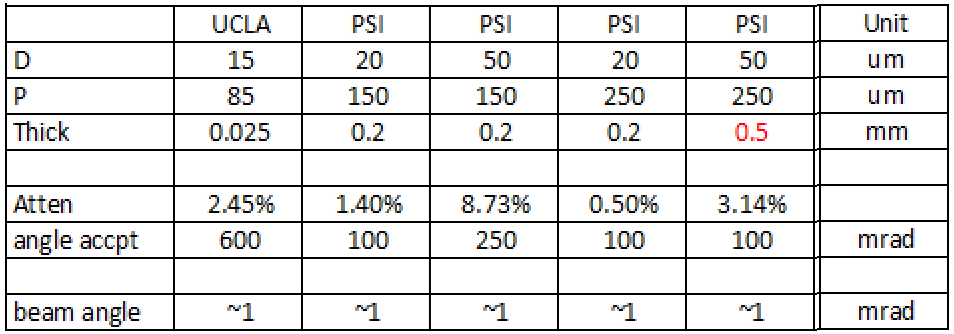
Pepper pot design considerations

- Pepper pot consideratios
  - Mask thickness T
    - CSDA range from NIST database (Continuous slowing down approximation range)
      - ~4 MeV → 3.059 g/cm^2 → 1.6 mm
      - ~20 MeV → 9.594 g/cm^2 → 5.0 mm
    - ~4 MeV mask thickness: 0.025 (1/64 CSDA) ~ 0.5 mm (1/3 CSDA)
    - ~20 MeV: ~0.1 (1/64 CSDA) ~ 1.7 mm (1/3 CSDA)?
  - Angle acceptance $\frac{D}{T}$ >1 mrad

Mask schematics



Pepper pot mask examples



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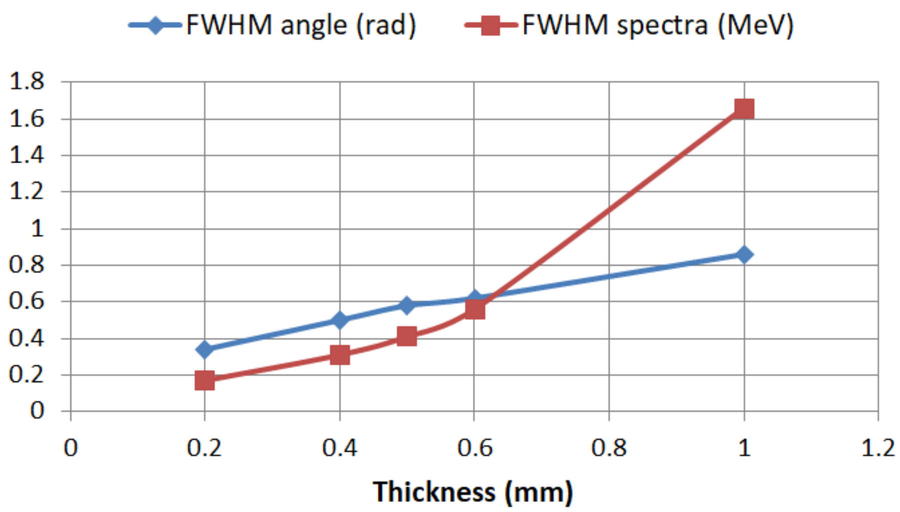
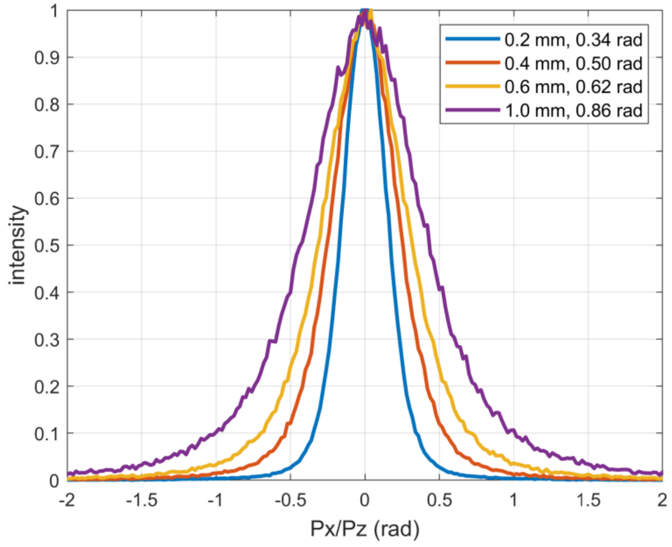
Atten	2.45%	1.40%	8.73%	0.50%	3.14%	
angle accpt	600	100	250	100	100	mrad
beam angle	~1	~1	~1	~1	~1	mrad

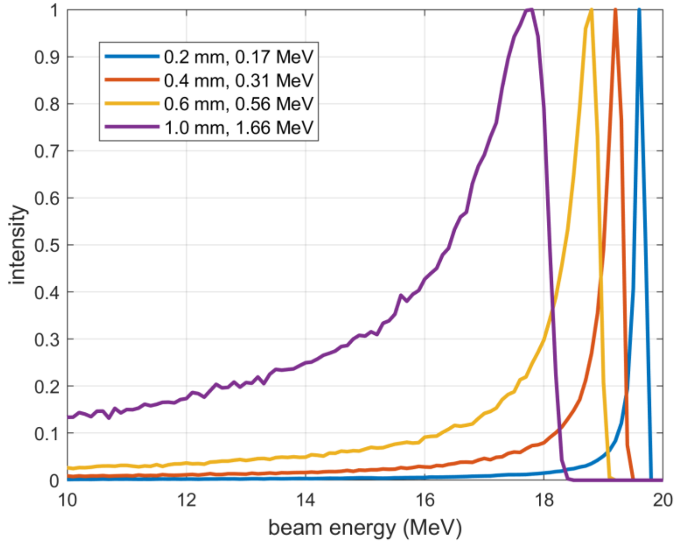
Pepper pot design considerations

FLUKA simulation

- 20 MeV beam scattering with tungsten mask (by Zohrab)
  - 0.2 mm to 1 mm tungsten thickness are simulated
  - Large scattering angle, 0.34 – 0.86 rad (FWHM)
  - Intensity of penetrated electrons almost same as input beam
  - Energy loss quite limited due to thin tungsten mask



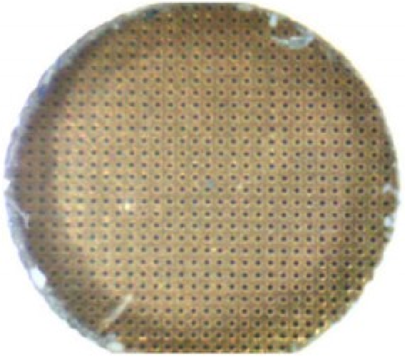




Pepper pot examples

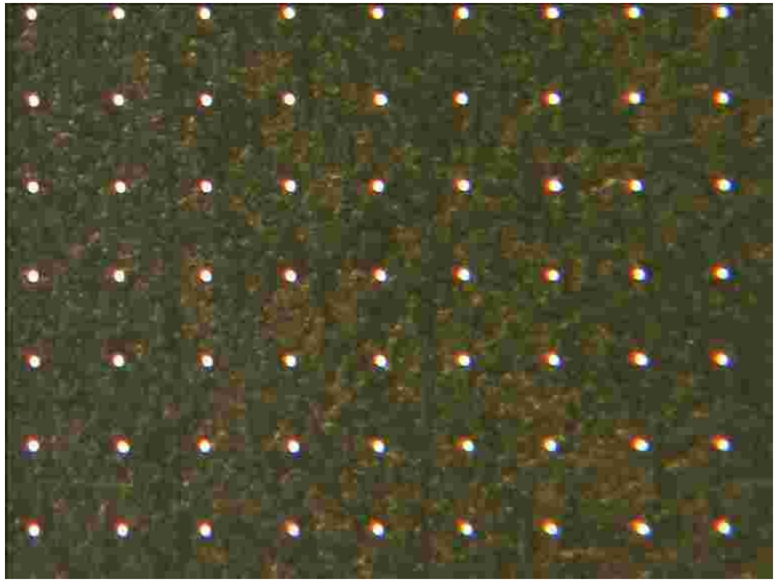
- A few low energy masks

UCLA mask
15 um x 85 um x 0.015 mm

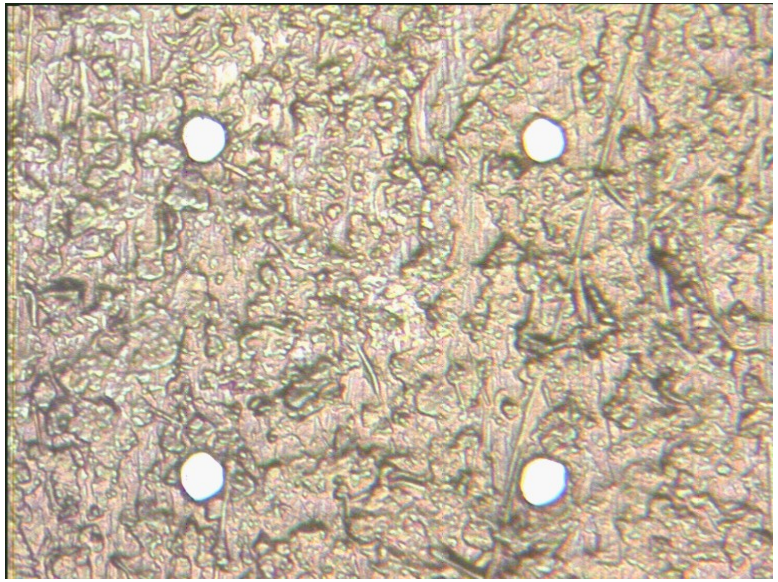


~300 euro per mask, total 4 masks, quote from 2007
Laser Technologie GmbH in Berlin

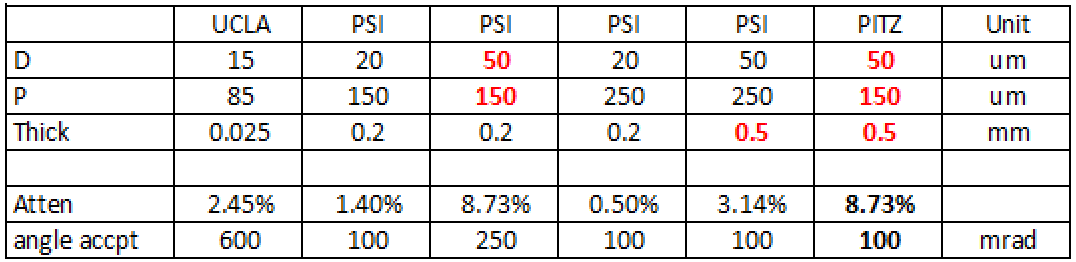
PSI 20 um x 150 um x 0.2 mm



PSI 20 um x 250 um x 0.2 mm



- A mask for 20 MeV beam

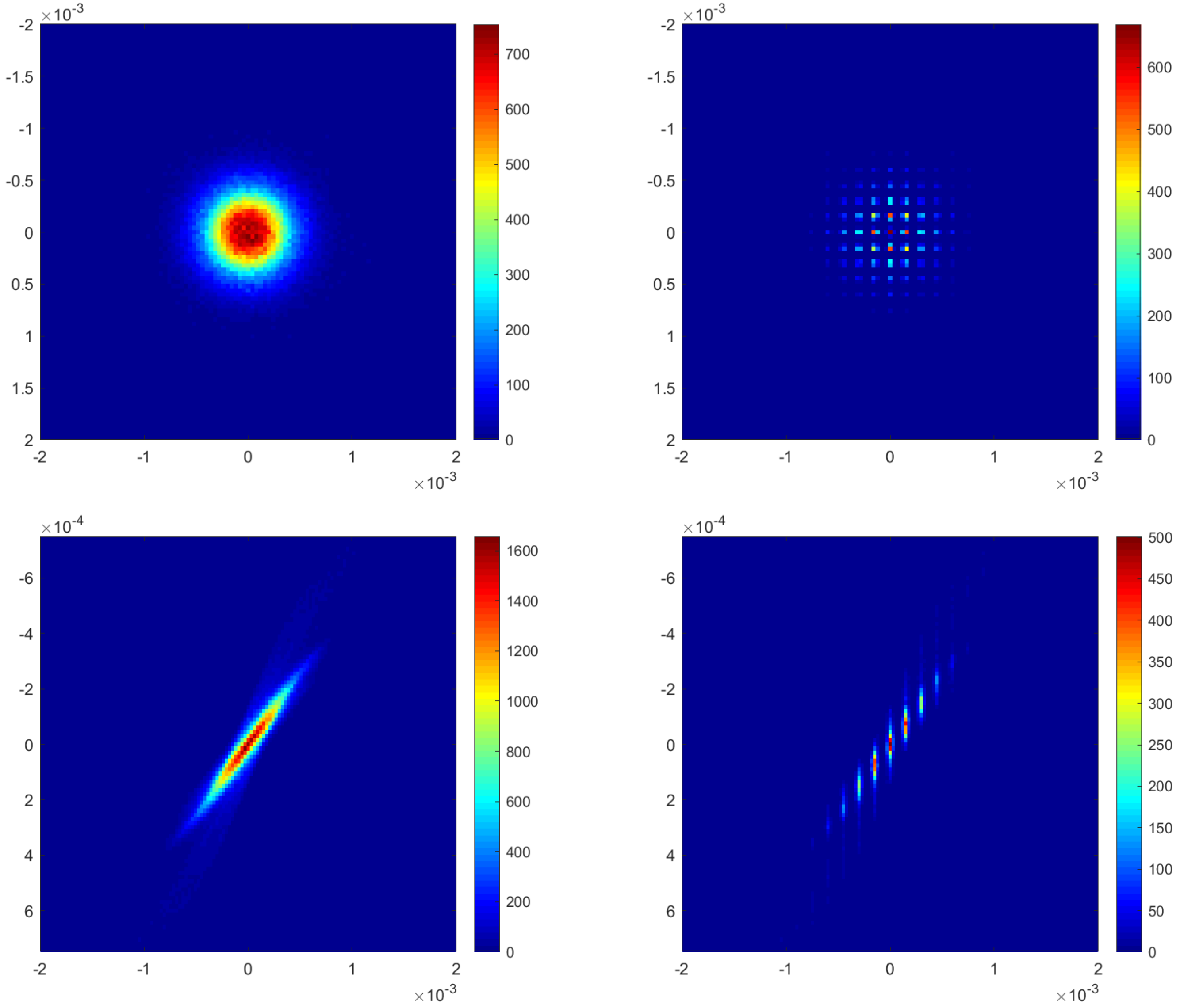


	UCLA	PSI	PSI	PSI	PSI	PITZ	Unit
D	15	20	50	20	50	50	um
P	85	150	150	250	250	150	um
Thick	0.025	0.2	0.2	0.2	0.5	0.5	mm
Atten	2.45%	1.40%	8.73%	0.50%	3.14%	**8.73%**	
angle accpt	600	100	250	100	100	**100**	mrad

D50 um x P150 um → 40 pC @0.5 nC
D35 um x P150 um → 20 pC @0.5 nC

ESMY1 image

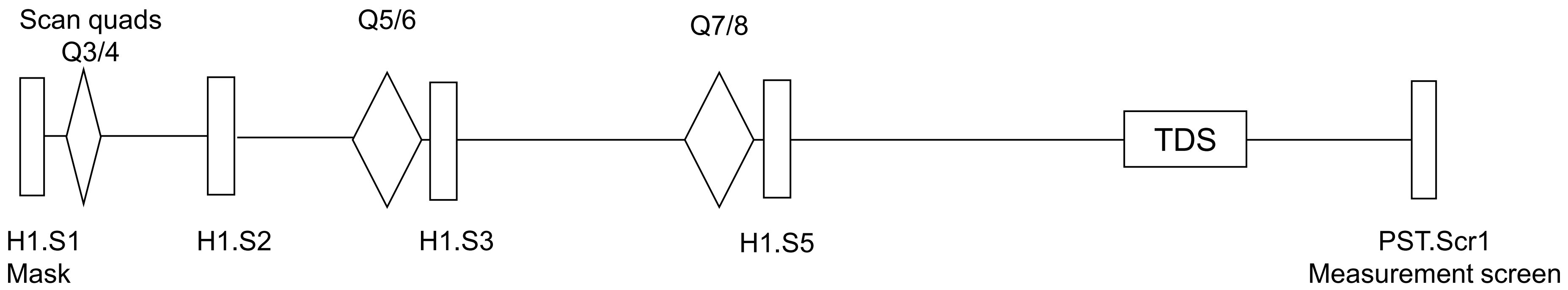
Before and after pepper pot mask



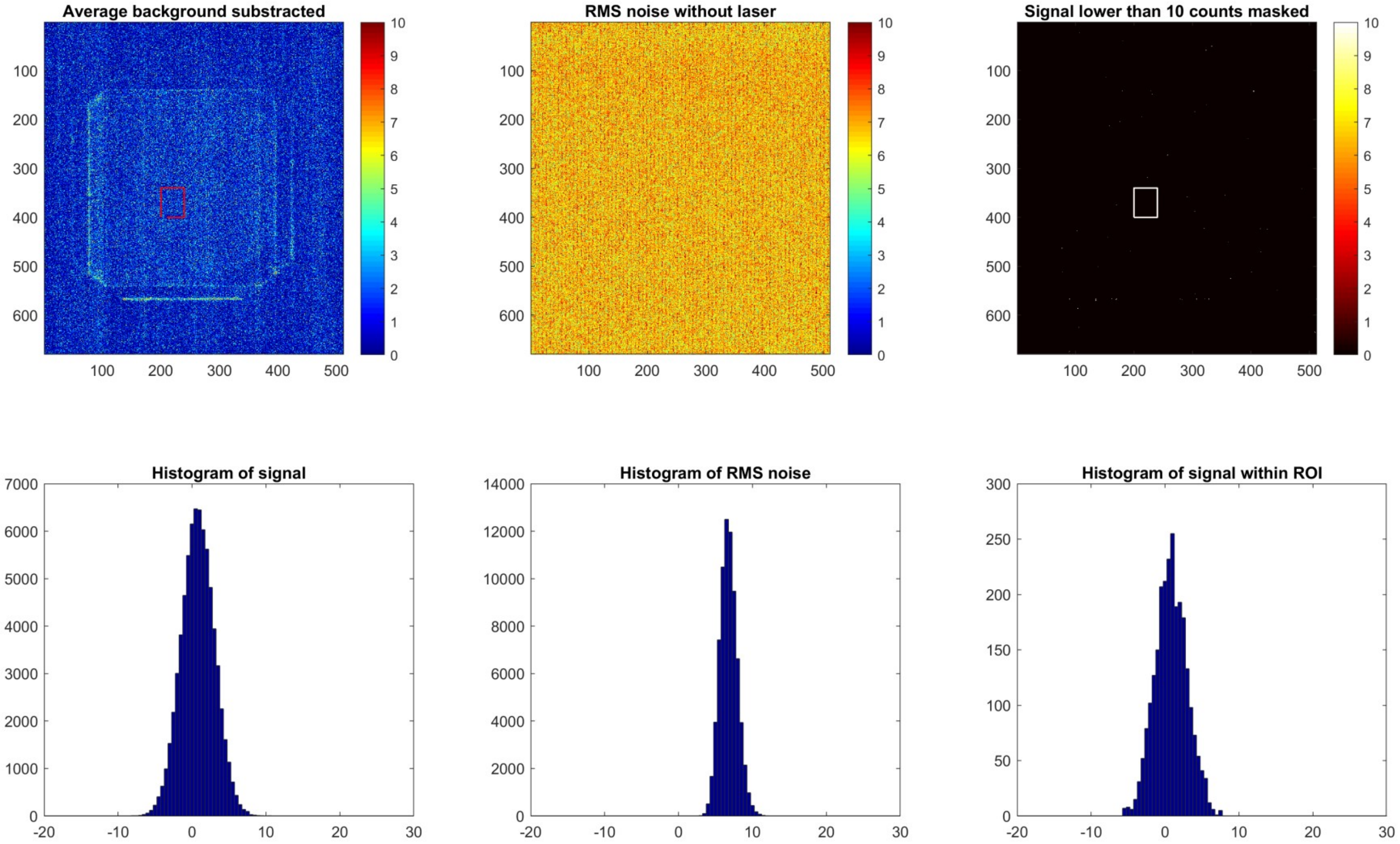
A beam test with 1 mm tungsten plate

20A.08.2019, summer student project

- 500 pC x 20 pulses x 10 Hz, ~20 MeV
- EMSY1 1 mm tungsten plate fully block the beam
- Q3/Q4 doublet scan
- Record 20 images for scattered signal with high1.scr5 LYSO screen, 0 dB gain



No focusing



Average background substracted

RMS noise without laser

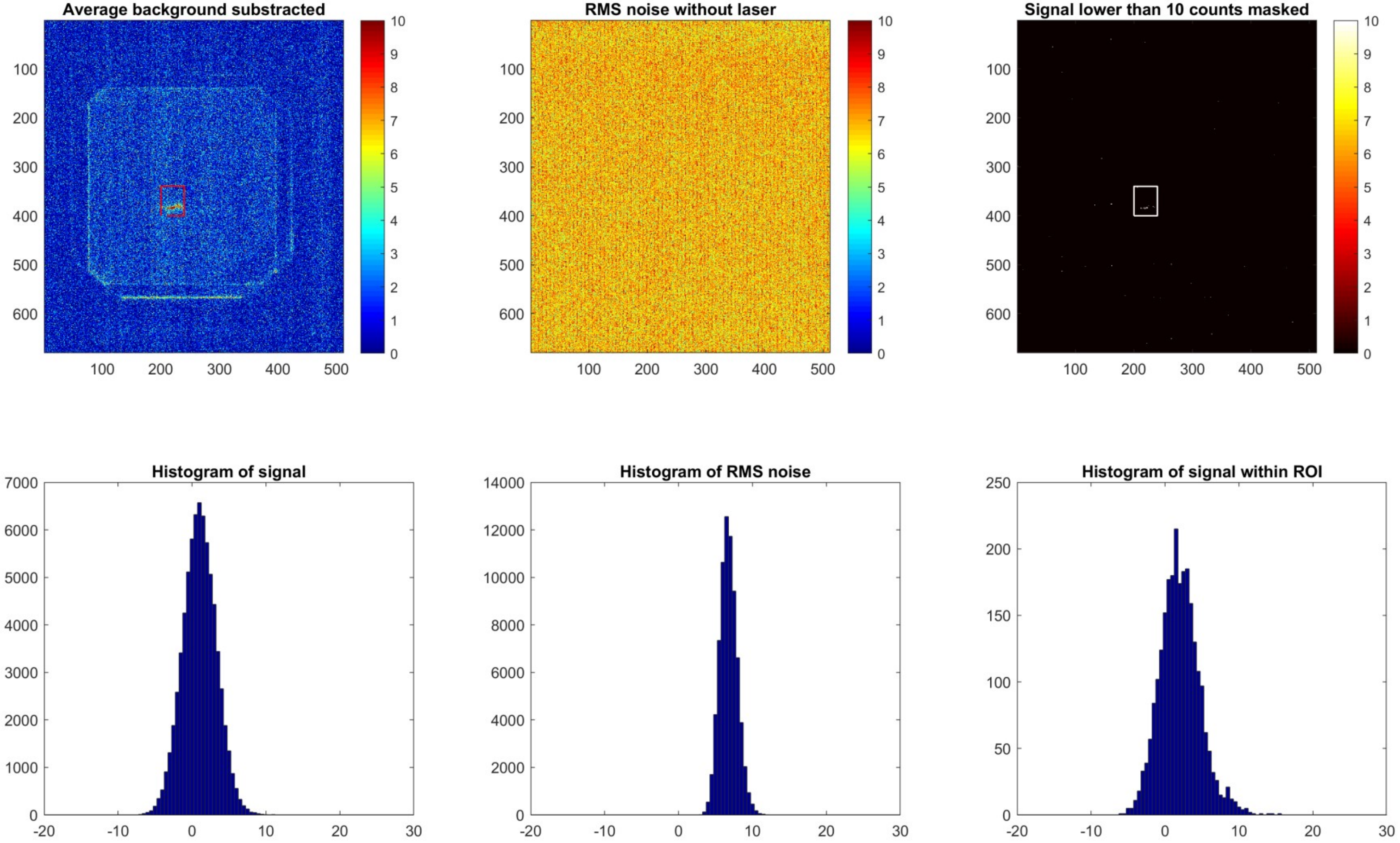
Signal lower than 10 counts masked

Histogram of signal

Histogram of RMS noise

Histogram of signal within ROI

0.05 A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RMS noise without laser
Signal lower than 10 counts masked
Histogram of signal
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Histogram of RMS noise
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Histogram of signal within ROI
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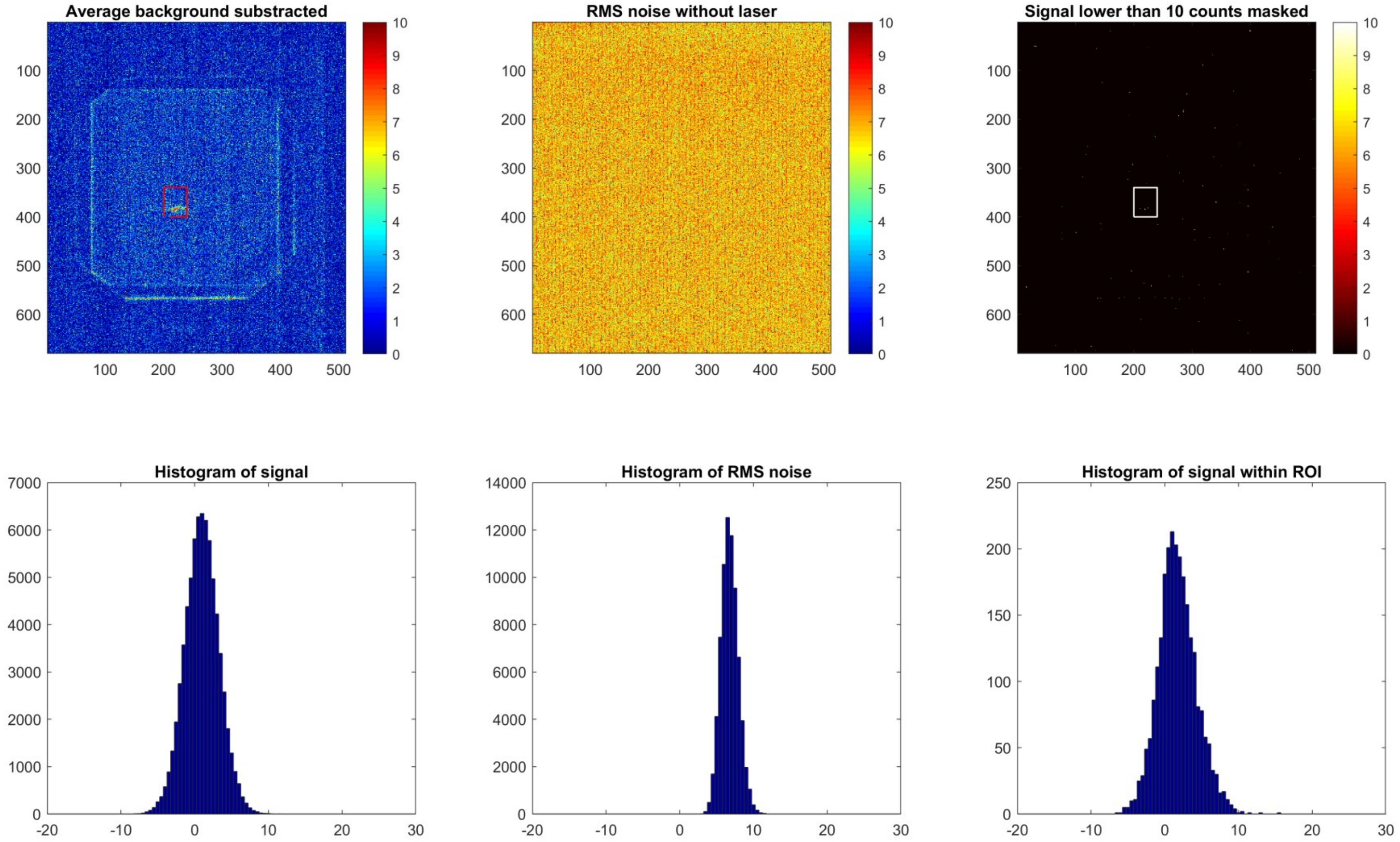
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Histogram of signal
Histogram of RMS noise
Histogram of signal within ROI
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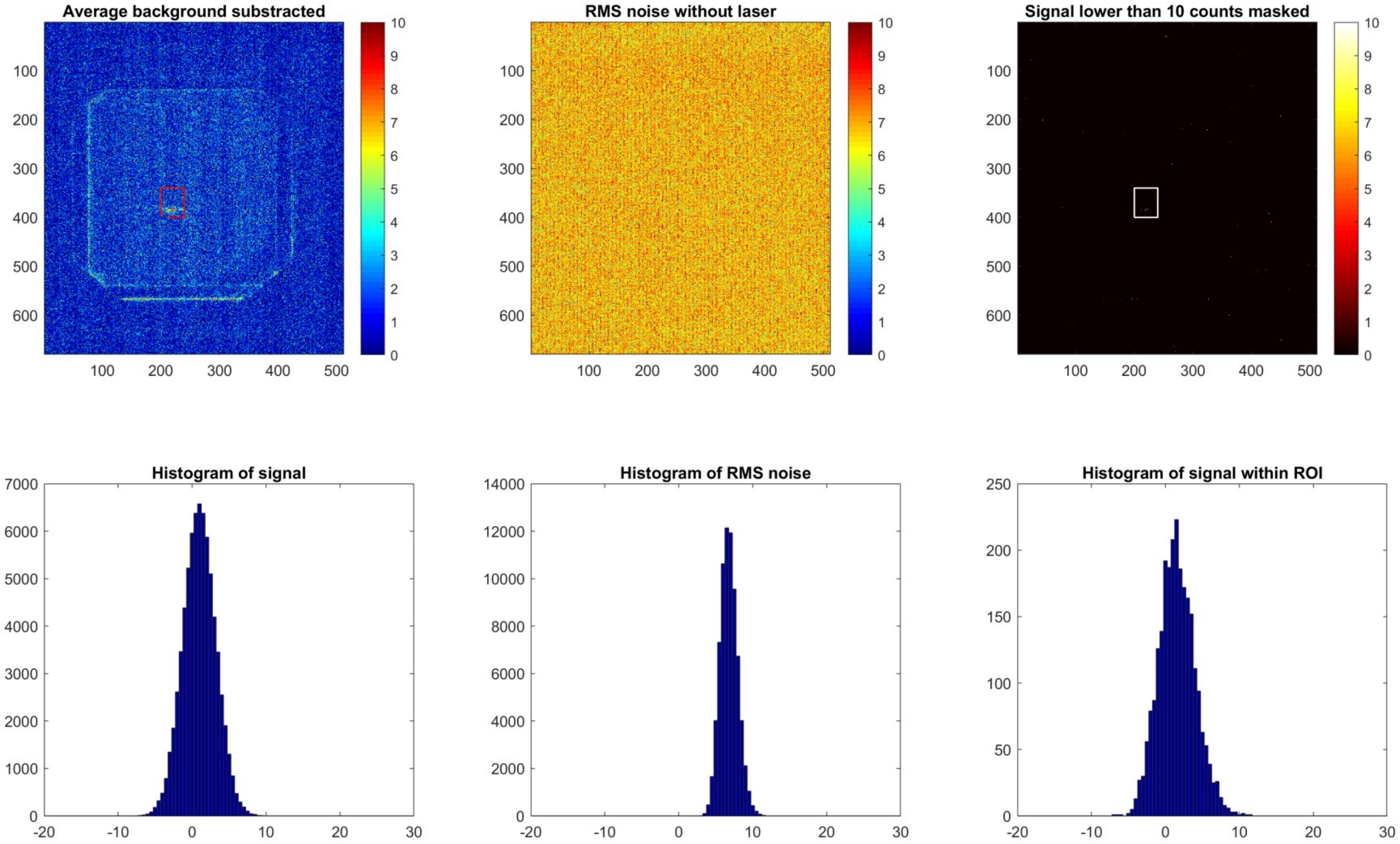
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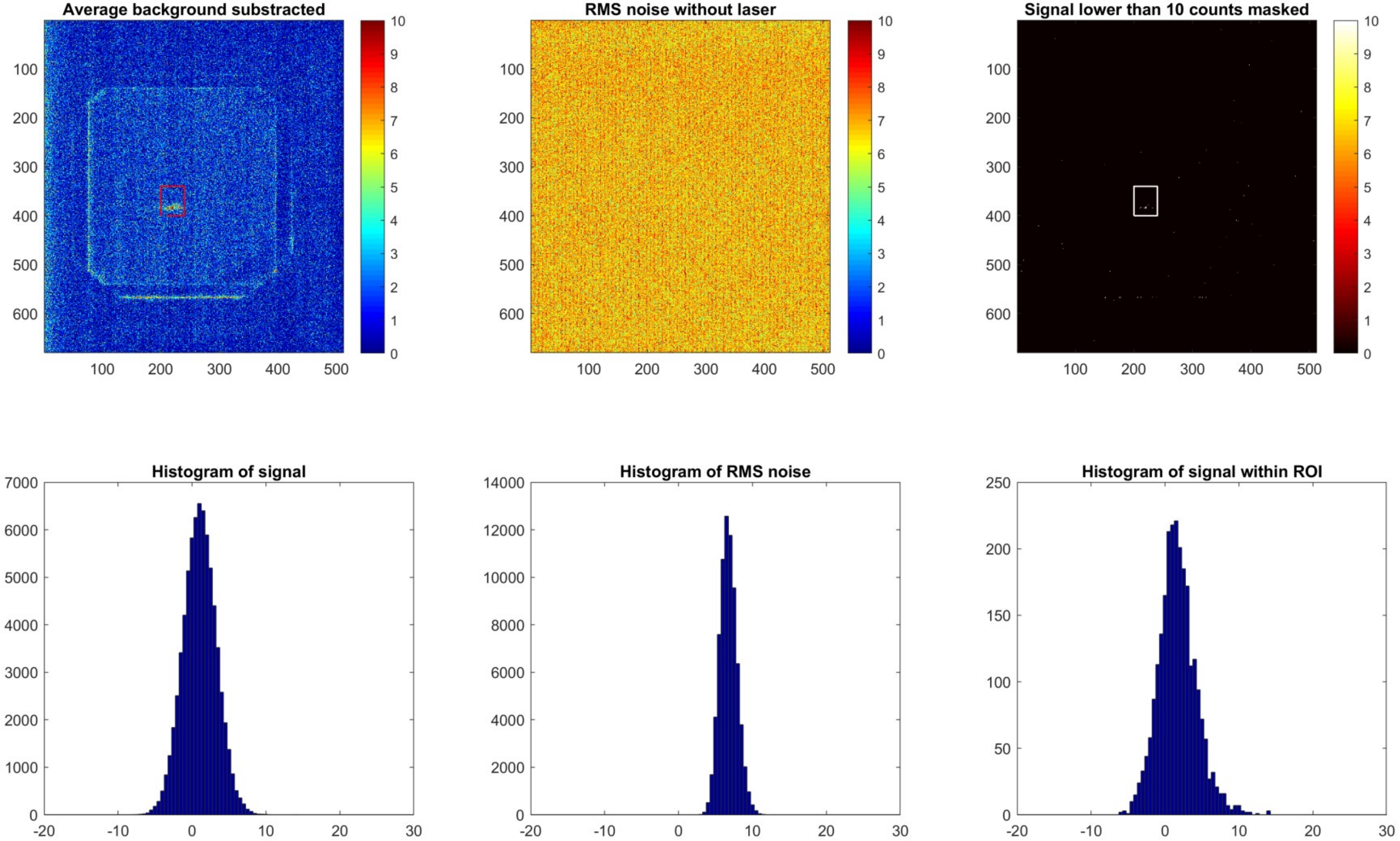
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Histogram of signal within ROI
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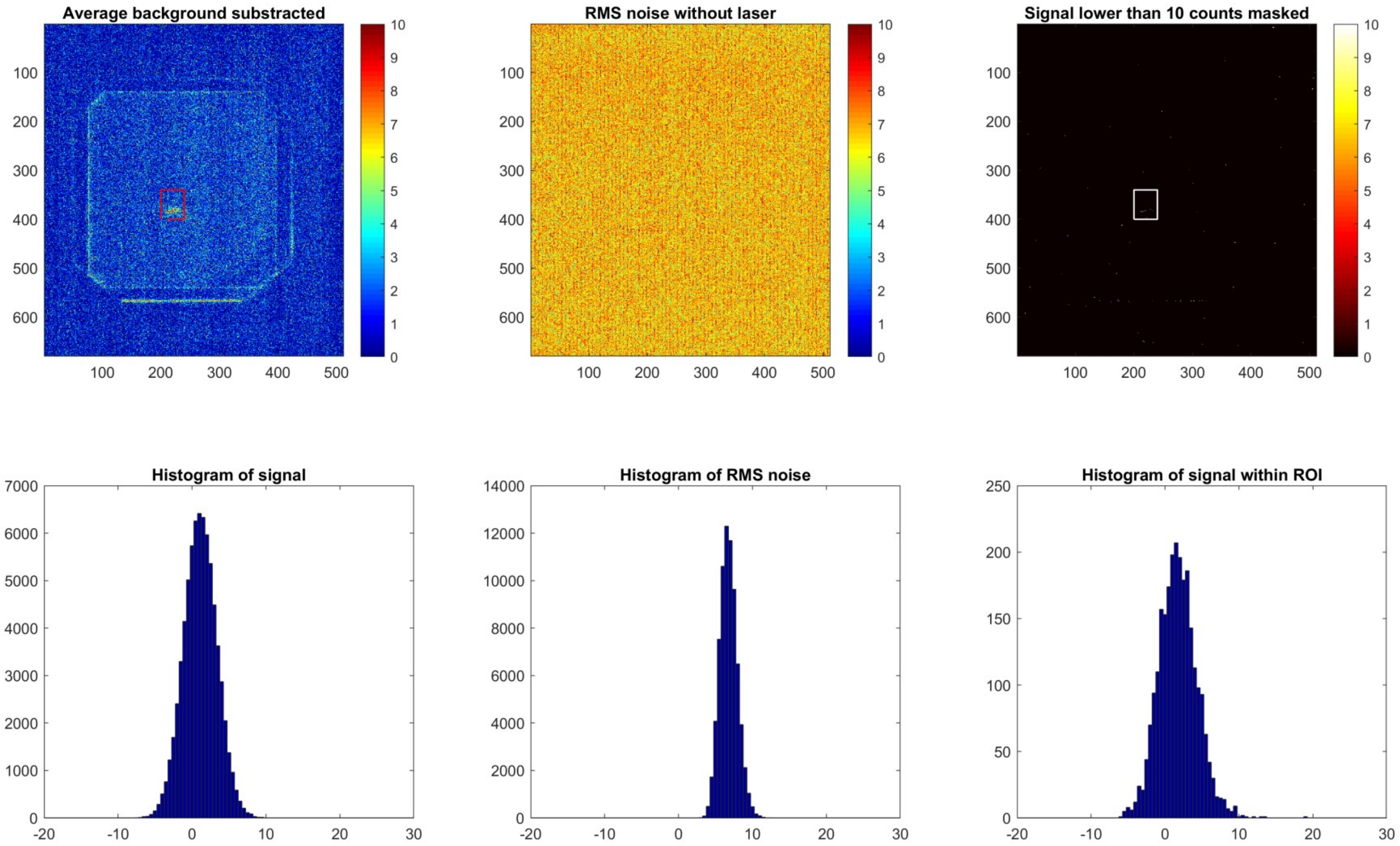


Average background substracted

RMS noise without laser

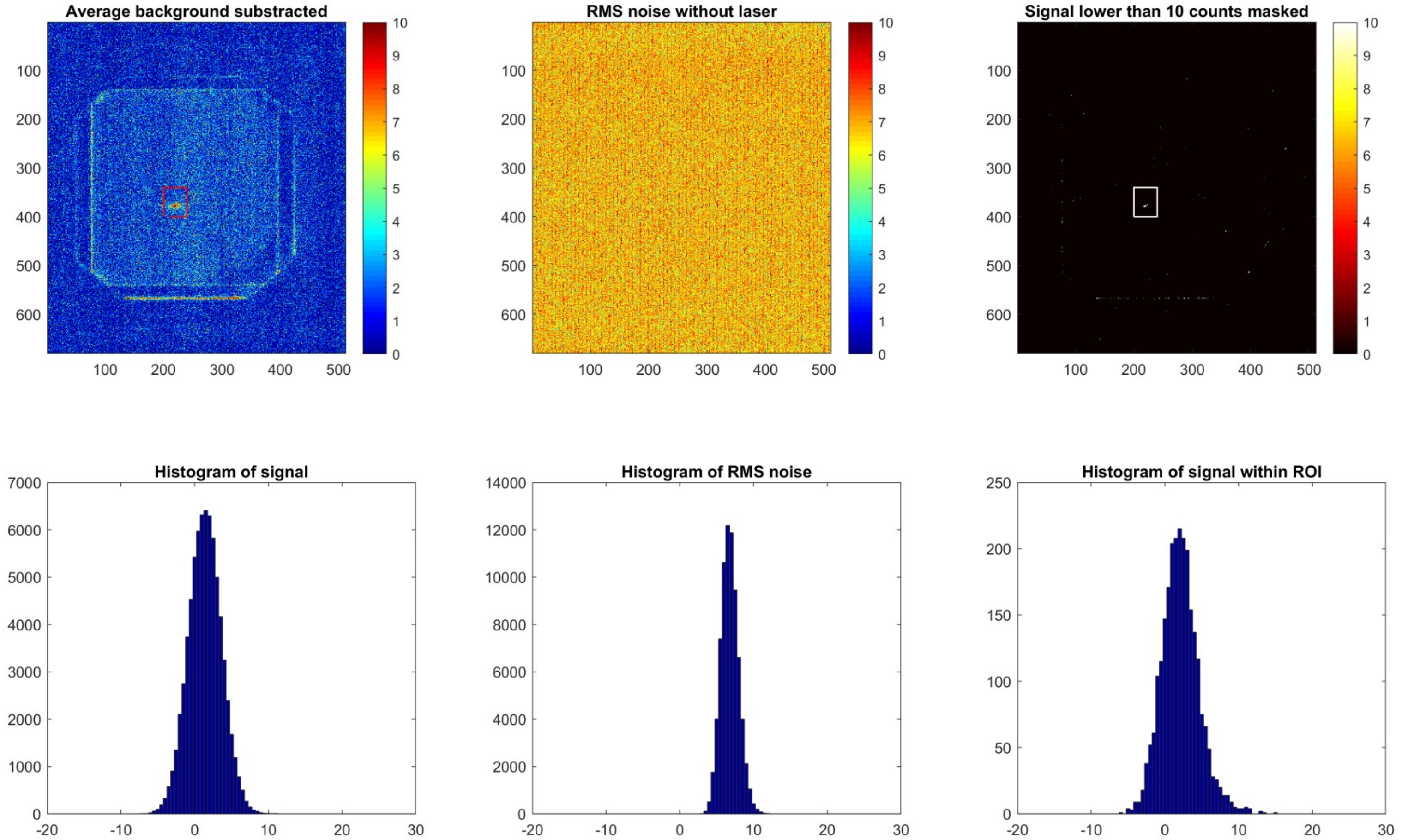
Signal lower than 10 counts masked

Histogram of signal

Histogram of RMS noise

Histogram of signal within ROI

2 A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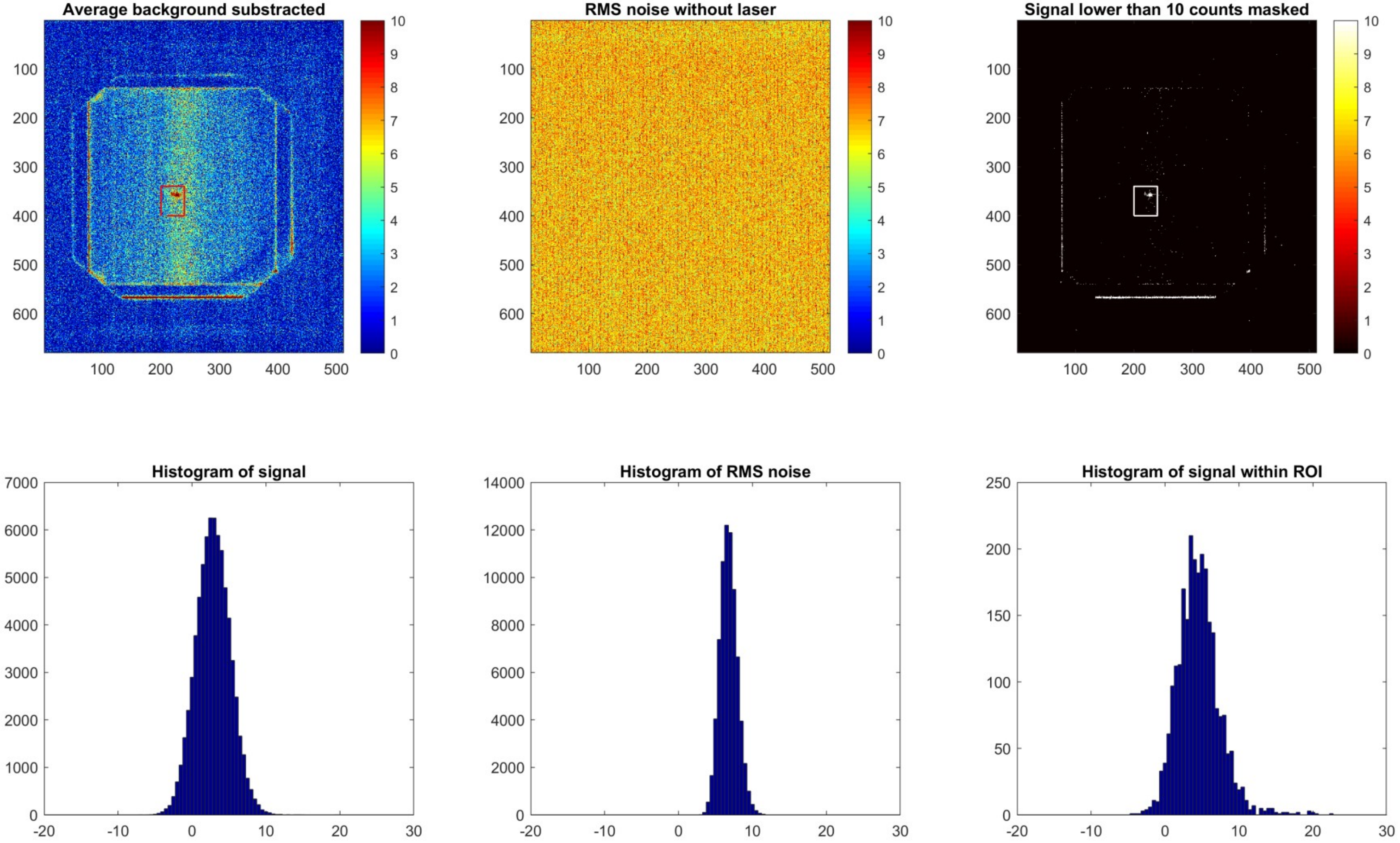
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RMS noise without laser
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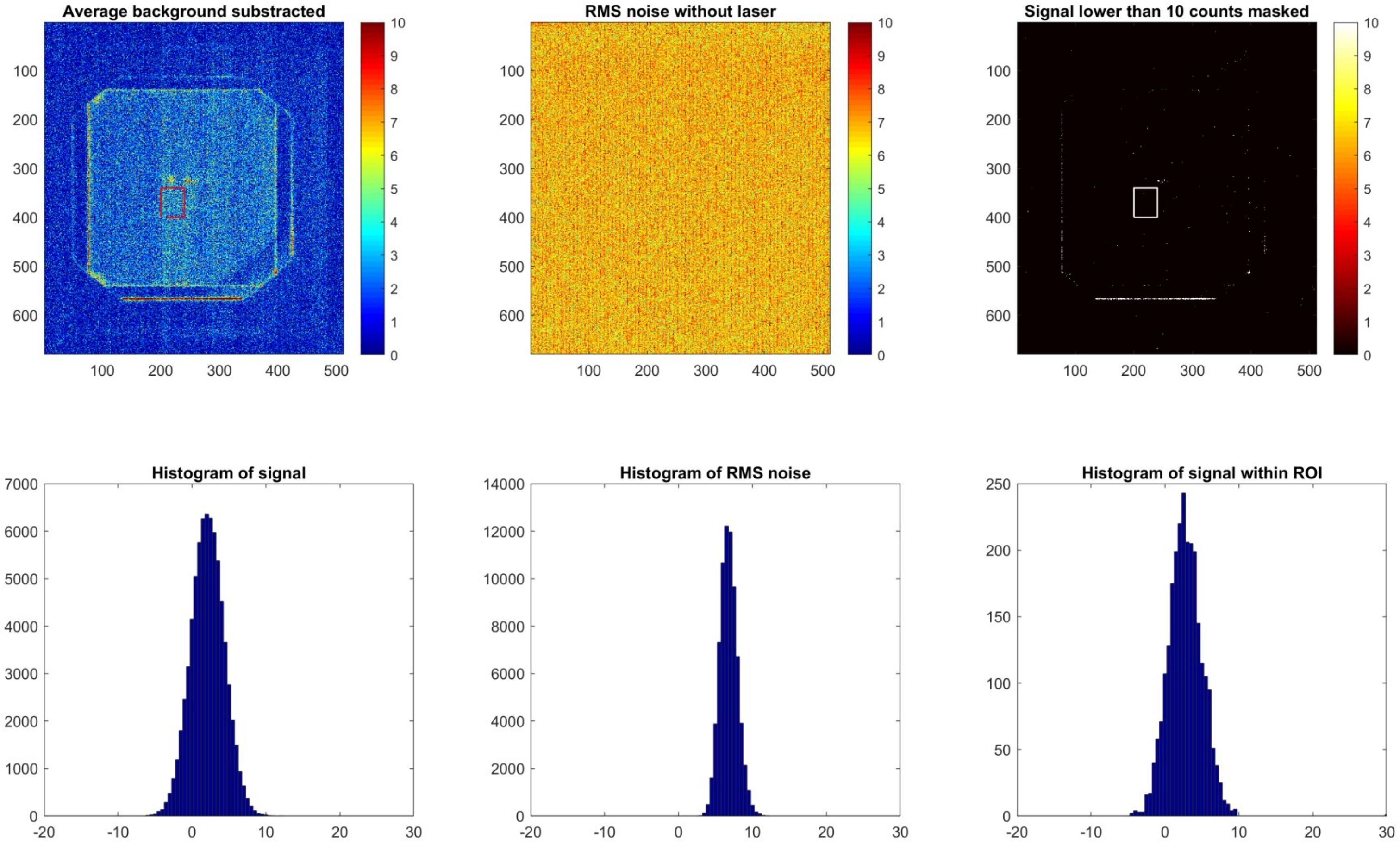
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Histogram of signal within ROI
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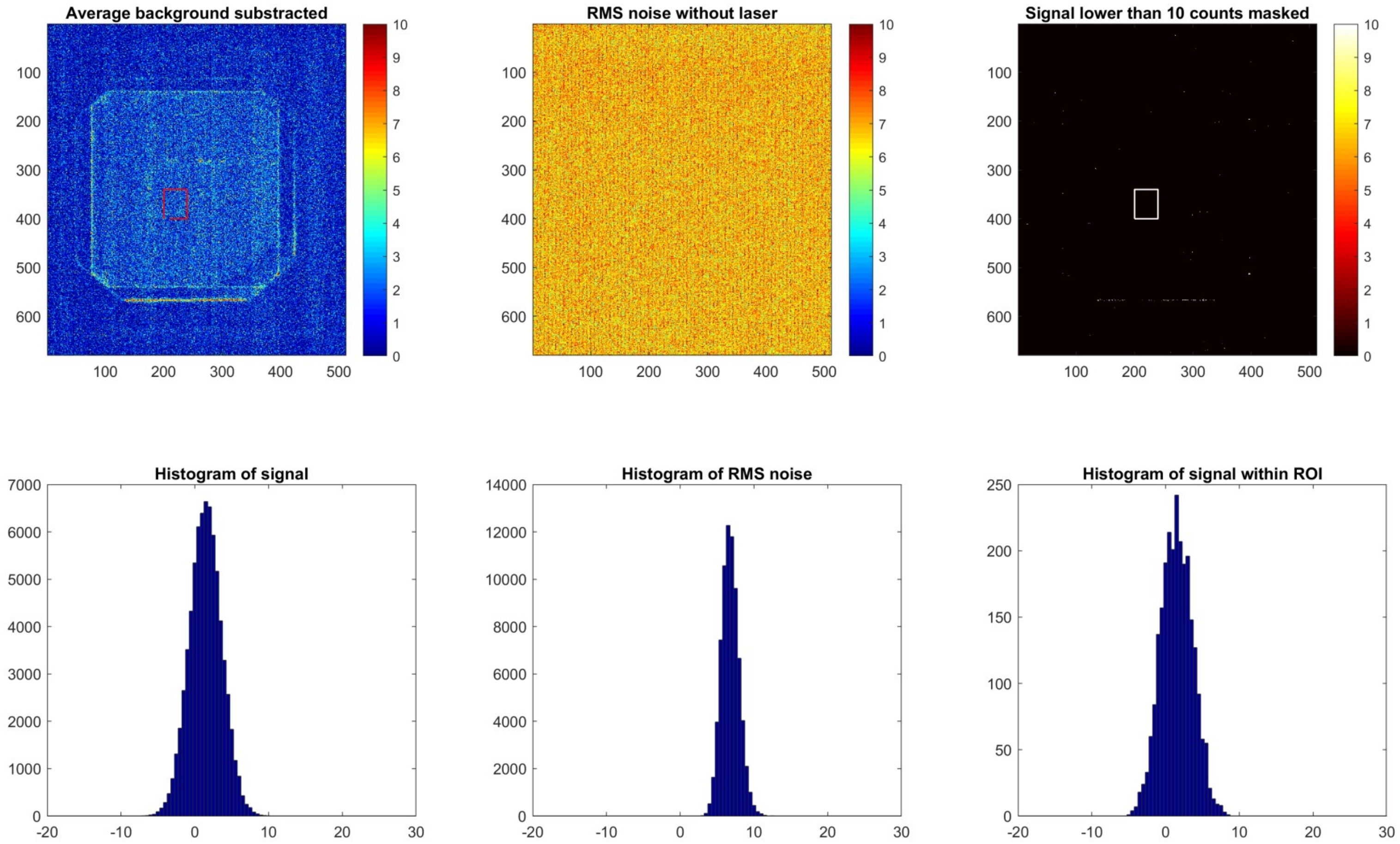
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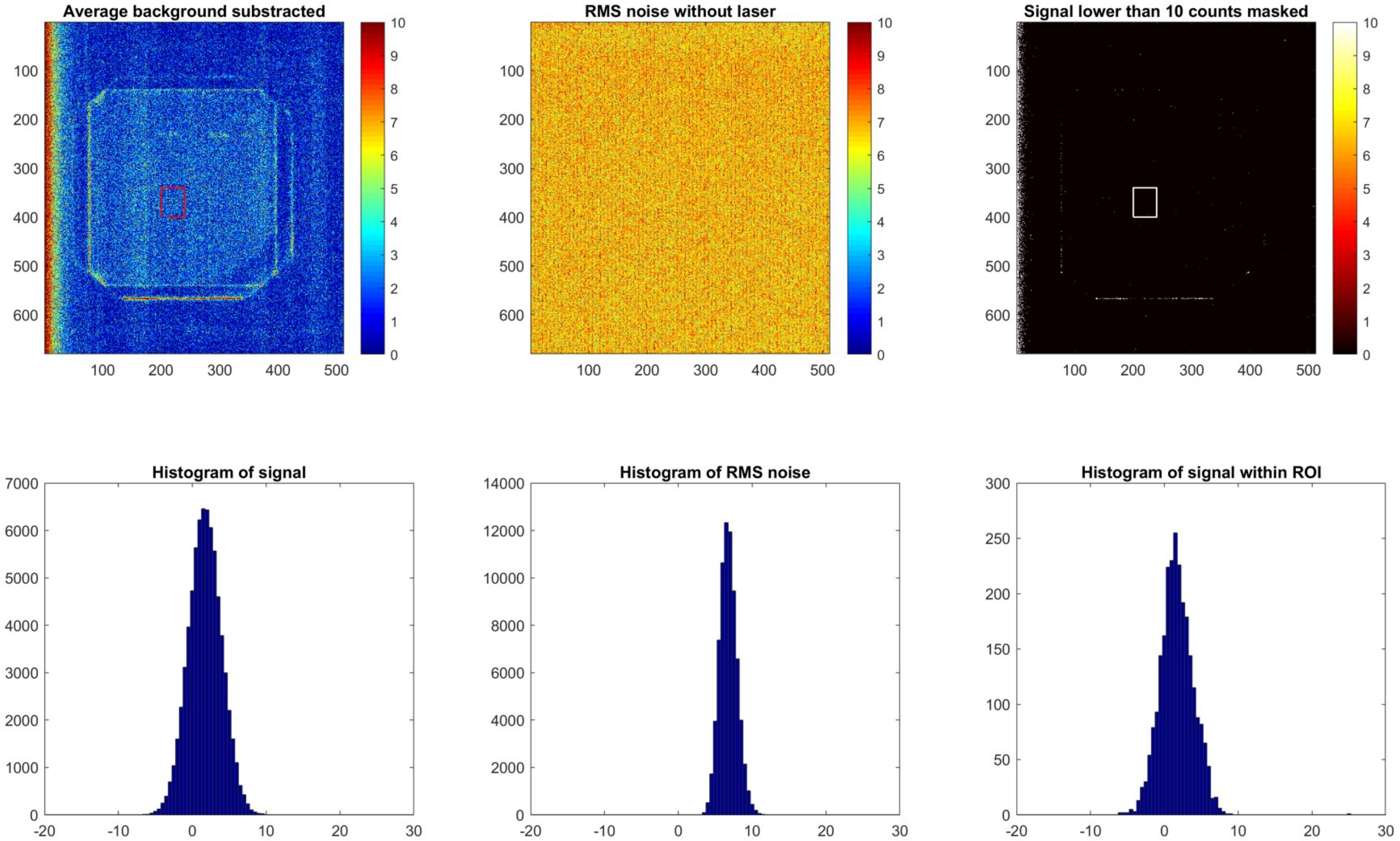


Average background substracted

RMS noise without laser

Signal lower than 10 counts masked

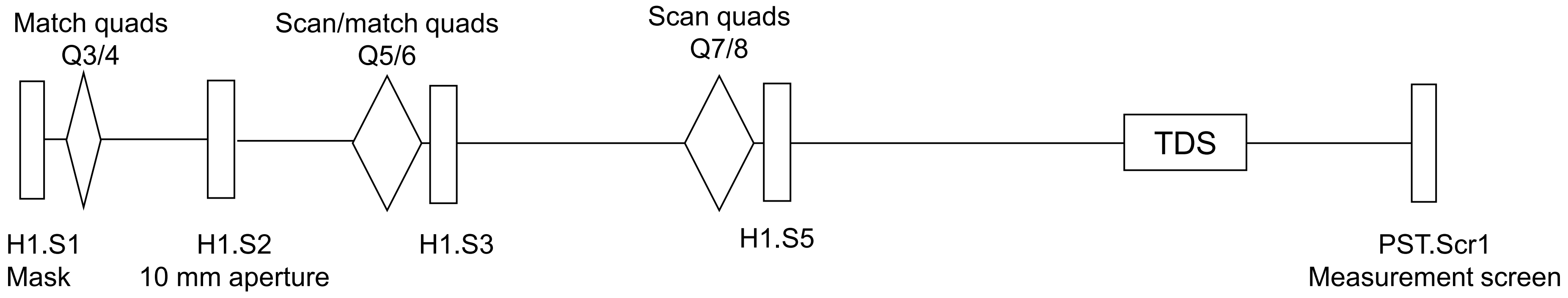
Histogram of signal

Histogram of RMS noise

Histogram of signal within ROI

Possible setup for PITZ emittance

- Possible setup for projected emittance
  - Pepper pot mask @EMSY1, 10 mm aperture @high1.scr2
  - Aperture @high1.scr2, maybe not necessary?
    - 0.5 mm thick plate → <1.6% after 10 mm aperture
    - 1.0 mm thick plate → <1.0% after 10 mm aperture
  - Q3/Q4 to match beam size on H1.scr3, Q5/Q6 for quad scan on PST.scr1 LYSO screen
  - or
  - Q5/Q6 to match beam size on H1.scr5, Q7/Q8 for quad scan on PST.scr1 LYSO screen
- Similar setup for slice emittance with quadrupole scan



Summary and outlook

- Analytical analysis based on Gaussian beam shows an advantage for quad scan over fastscan w.r.t. SNR
- Calculations & FLUKA simulations of a tungsten peperpot mask for 20 MeV beam are done
- Experiments of a 1 mm tungsten mask shows negligible scatter signal after quad focusing
  - Scatter signal should be even lower when reducing pulse number towards single pulse operation
  - If use Q5/Q6 and pst.scr1 for measurements, scatter signal is expected to be lower
- Further tests
  - Test Q5/Q6 and pst.scr1 for scatter signal intensity
  - Install a 0.4 mm tungsten plate at EMSY1 for comparison study, 0.4 x 40 x 50 (mm) tungsten plate exists
- Should we pursue such a diagnostic at PITZ?
  - If works, a diagnostic for gun test facility with a short pulse & low energy linac, e.g. APEX like facility.
  - Direct emittance comparison between slit scan and quad scan, using the same beam.
  - A new tool for slice emittance measurement at PITZ.