Large Dynamic Range Diagnostics for High Current Electron LINACs

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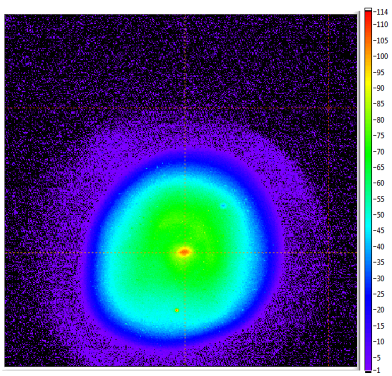
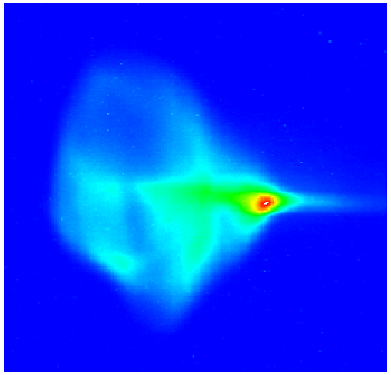
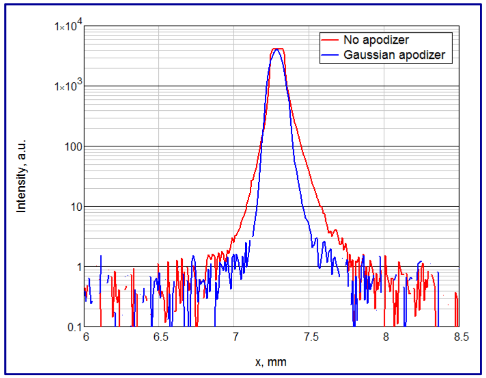






Outline

- Motivation: Why large dynamic range diagnostics?
- Experience with existing high average current FEL driver
- Large dynamic range transverse beam profile measurements
  - Beam imaging
    - imaging sensor dynamic range
    - measurements with 5×10^4 dynamic range
    - imaging optics and diffraction
  - Wire scanner measurements
    - experience so far
    - near term outlook
- Conclusions

Motivation: Why Large Dynamic Range?

- there are several applications of electron LINACs under consideration / design that require average beam power of several **MW**
- these applications also require very high peak beam brightness, comparable to the one at pulse NC LINACs
- similar to low average current (NC, pulses) LINACs, with high average current LINAC a **diagnostic beam mode** must be used
- the **significant difference** is the **ratio** of beam currents in the diagnostic mode and full current mode
- for a high average current LINAC this ration can easily be tens of thousands
- One example of an electron LINAC, which have operated with high average current **9 mA**, while driving FEL (also high average power) **JLab IR/UV Upgrade FEL**. Let's look at some relevant numbers of that machine.

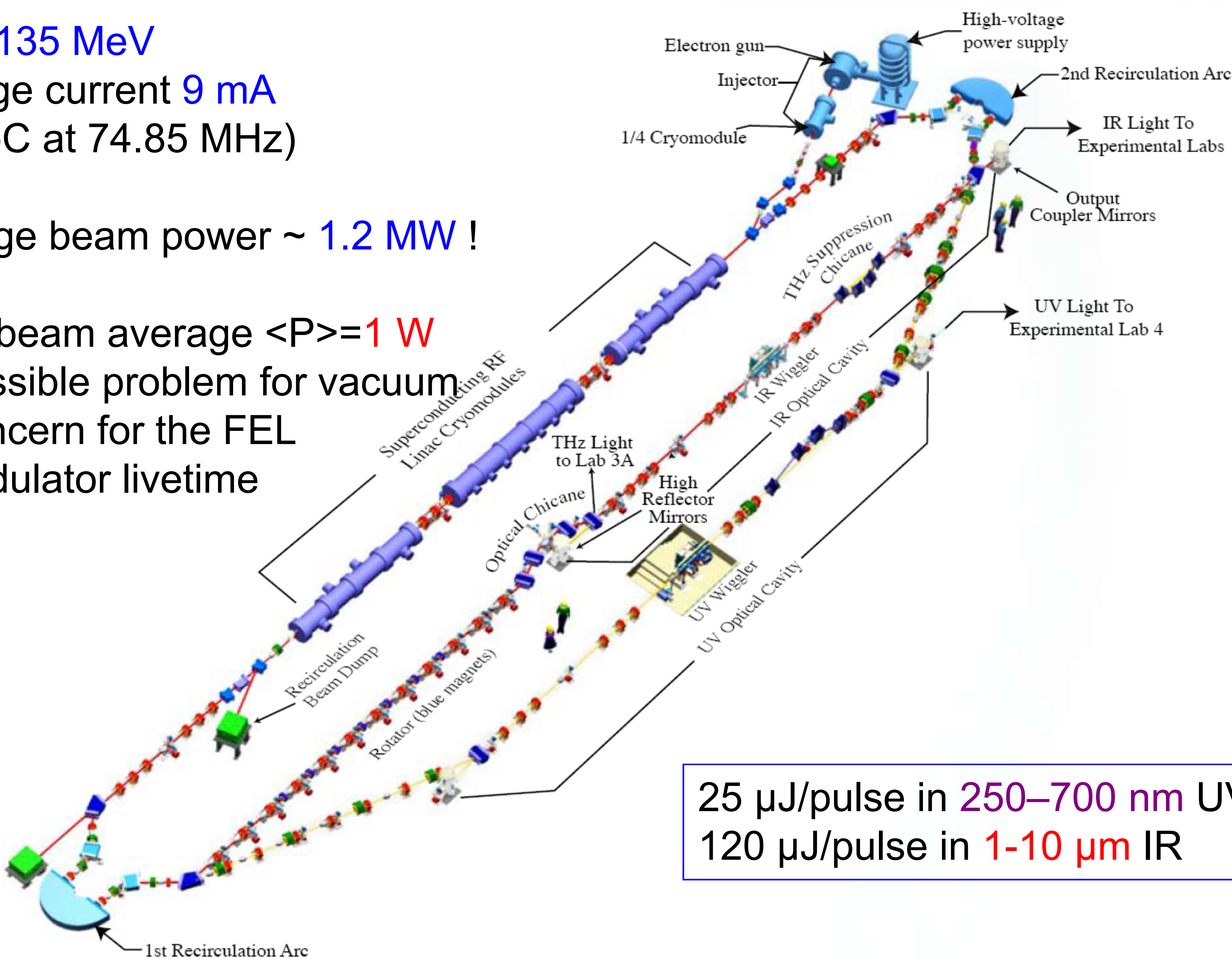
JLab IR/UV Upgrade: 1.2 MW beam power

E_{beam} 135 MeV
average current 9 mA
(135 pC at 74.85 MHz)

Average beam power ~ 1.2 MW !

If lost beam average <P>=1 W

- ✧ possible problem for vacuum
- ✧ concern for the FEL undulator livetime



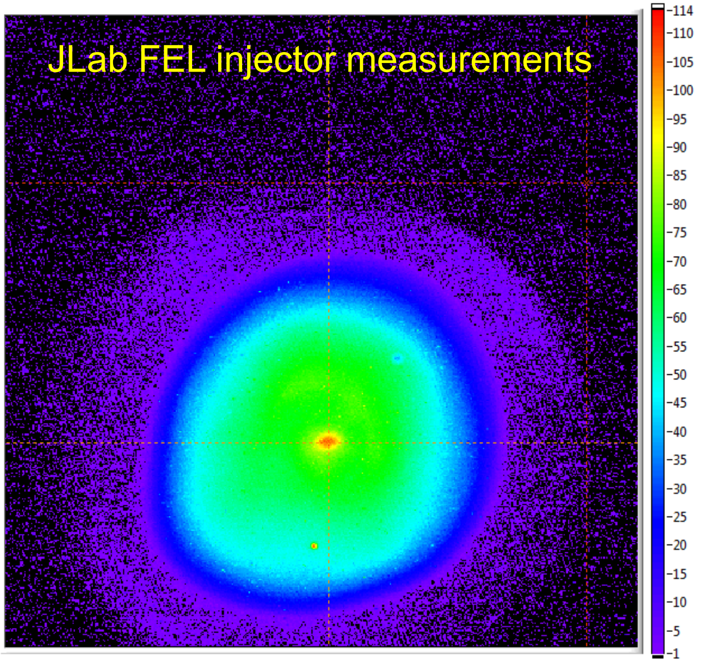
25 μJ/pulse in 250–700 nm UV
120 μJ/pulse in 1-10 μm IR

Lessons from high current FEL operation

- when setting this machine up for high current operation, at fist diagnostic beam mode is used, this gives “best” RMS setup, i.e., the setup which optimizes FEL performance and does not show any measurable beam lose (at that current level)
- then as average beam current is increased we always found that there is a need to alter transverse match to further reduce beam loss to allow higher current operation
- important point is that, such adjustments of the transverse match must be small
- there are very small fractions of the beam, which could prevent high current operation, but are not measured when diagnostic beam mode is used
- it also appears that, such small fractions of the beam have different Twiss parameters than the core of the beam, i.e., transverse phase space is not described well by a single set of Twiss parameters

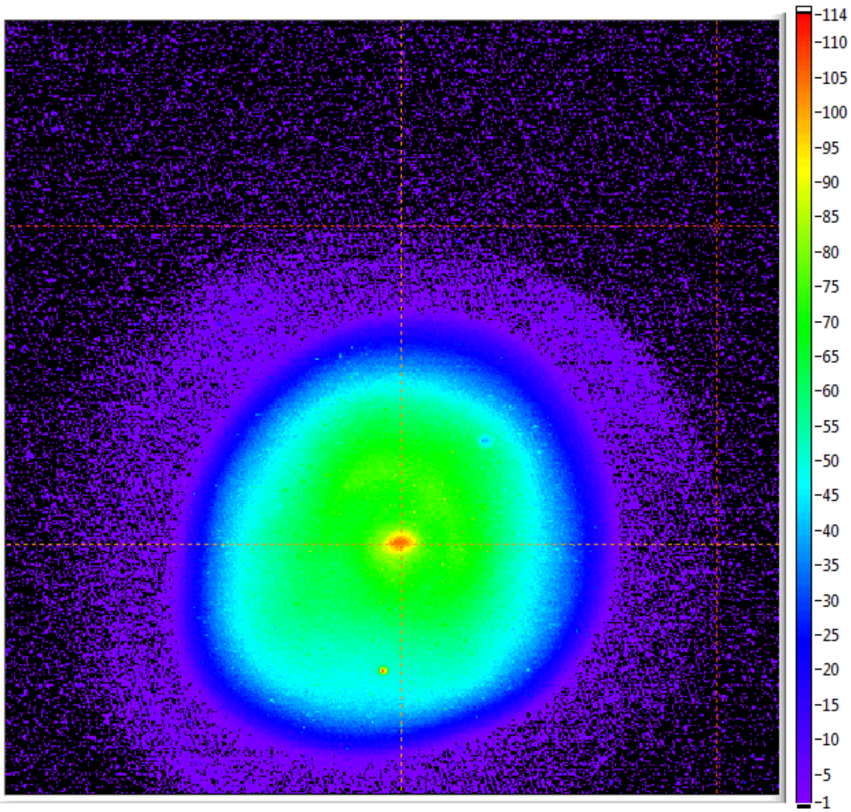
Lessons from high current operation (cont.)

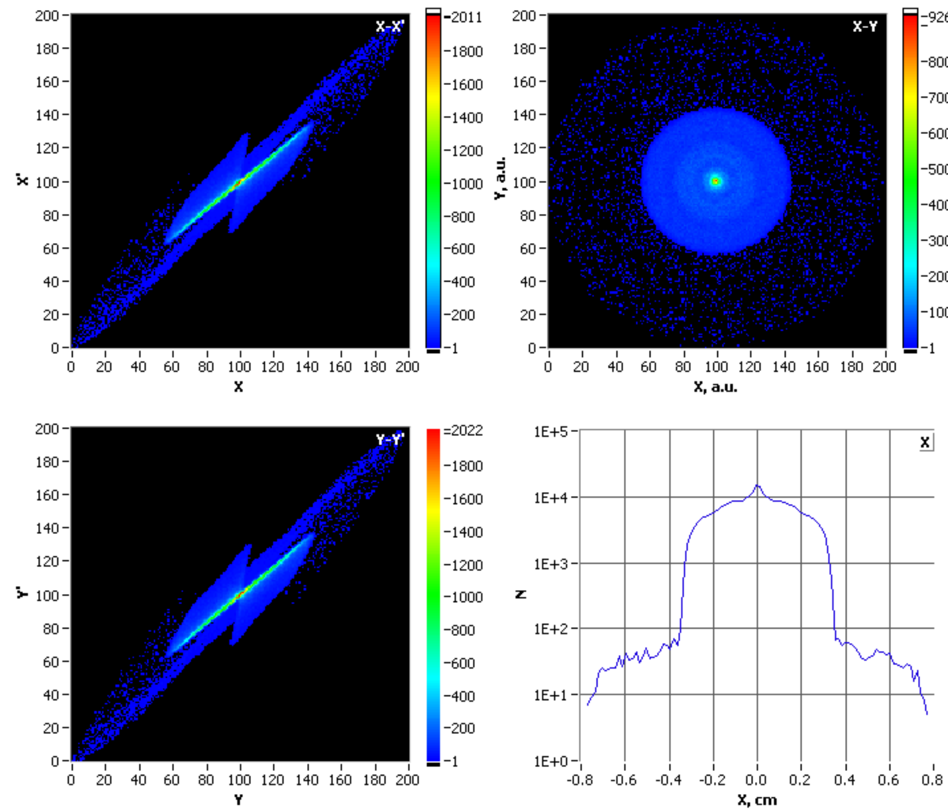
- **The transverse match is difficult, iterative process and never converges easily**
- **High average current operation requires a compromise between high peak beam brightness (required by FEL) and very low beam loss.**
- **Beam halo is one of the limiting factors**
- for match JLab FEL relies completely on beam imaging; large number of beam viewers is used
- LINAC beams have neither the time nor a mechanism to come to equilibrium *(unlike storage rings, which also run high current)*
- With diagnostic beam mode, halo is practically *invisible*; such unmeasured beam fractions become limiting factor with high current



- Increase the dynamic range and sensitivity of transverse beam profile measurements to make the halo measurable already with diagnostic beam mode
- Measure the phase space distribution with the LDR (ultimately topographically)
- Use that information for the match

Beam dynamics driven halo generation





Measured: JLab FEL injector, intensity difference of the peak and “halo” is about 300.
(YAG:Ce, standard CCD - 57 dB SNR 10-bit frame grabber)

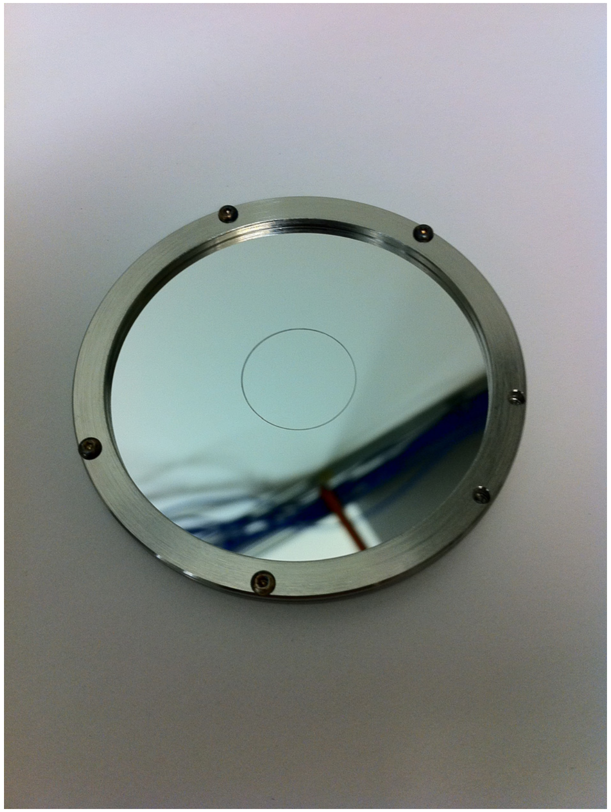
Simulations: PARMELA, 3×10^5 particles; X and Y beam profile and its projection show the halo around the core of about 3×10^{-3}.
Even in idealized system non-linear beam dynamics can lead to formation of halo.

Transverse beam profile measurements

- Dynamic range routinely available now is ~ 500. Analog CCD cameras with SNR of ~ 57 dB are used in a combination with 10-bit frame grabber.

- Although presently the limit is due to hardware, format of the diagnostic beam mode can have an impact as well, since it limits the amount of electrons and therefore photons available for measurements

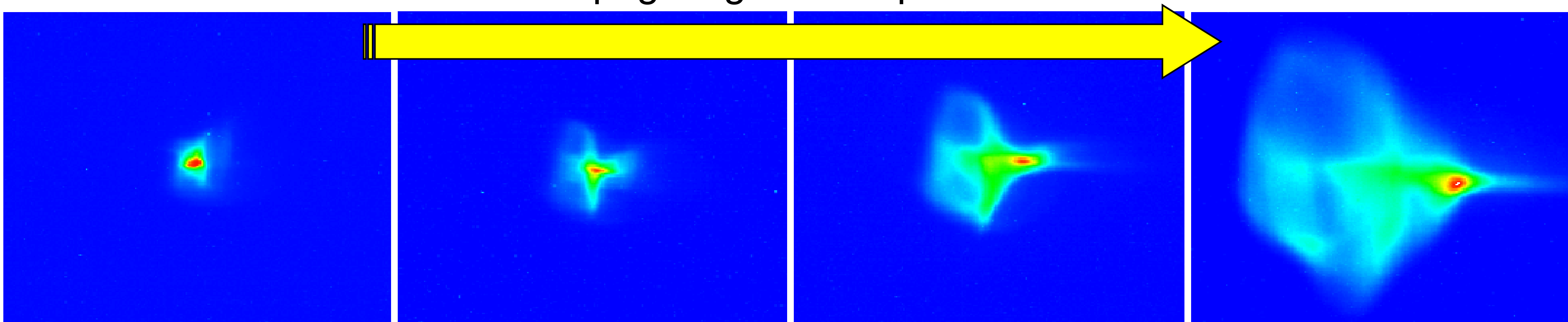
At low beam energies in injector (350 keV, 9MeV) 100 micron thin YAG:Ce

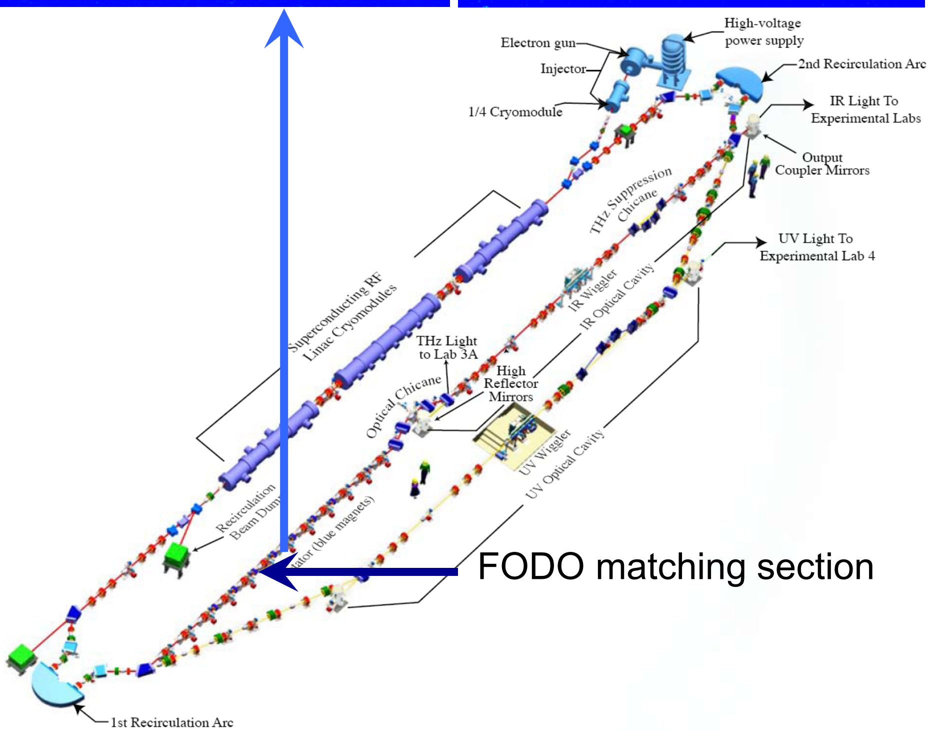


At high beam energies in recirculator OTR from 60 micron thin Si aluminized

LINAC's non equilibrium (non Gaussian) beam

Propagating in drift space …



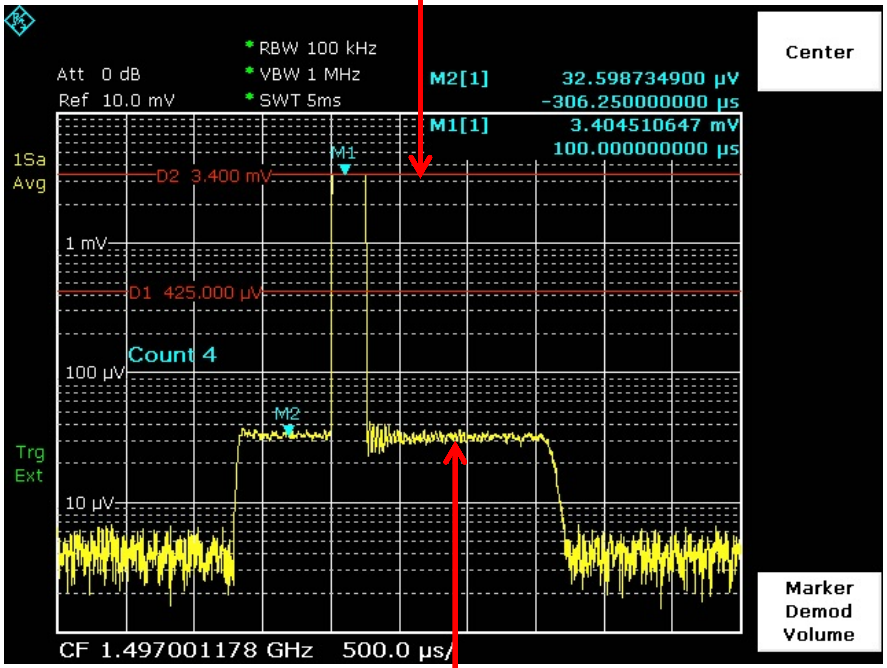


- This are not beam distributions from a nominal setup, but an experiment that shows complexity of the phase space distribution – no single set of Twiss parameters describes the beam
- This is also not a halo. Dynamic range of this measurements is ~ 500, all of this beam later is matched to the FEL's optical cavity and participates in the FEL interaction

Diagnostic beam mode and "ghost" pulses

- For machine setup and beam studies, intercepting diagnostics are needed
- "diagnostic beam mode" with very low average current, but nominal bunch charge is used
- all beam can be lost without
  - damaging the machine and
  - without interruption of the beam operation
- Implementation at JLab FEL
  - max. PRF 74.85 MHz (10 mA at 135 pC)
  - diagnostic: PRF ~4.68 MHz (÷16) - EO cells
  - 250 μs / 2 Hz (÷2000) - done by EO cells and mechanical shutters
  - average current ~300 nA
- The extinction ratio of an EO cell is finite practically about 200 (typical) needs to be very stable, while average power of the Drive Laser may vary a lot

631 uA (100%) 135 pC x 4.678 MHz



5.7 uA (~0.9 %)
74.85 MHz "ghost" pulses

Imaging Sensor(s) Dynamic Range

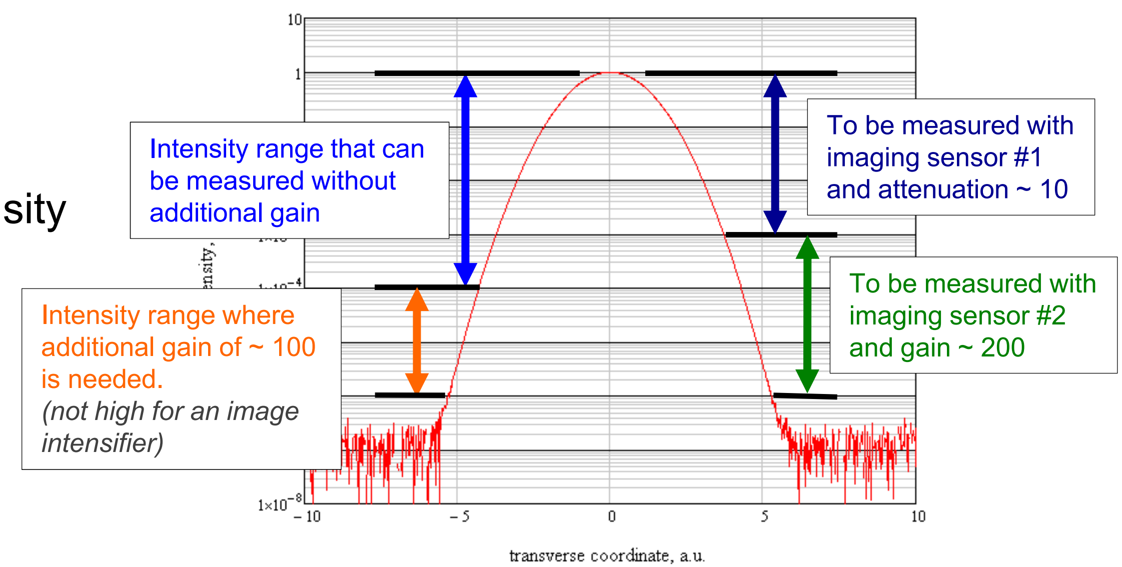
- Required for proper beam imaging:
    1. linear source (conversion of e^- beam density to light intensity)
    2. proper optics (managing Point Spread Function)
    3. linear imaging sensor(s)

- One of the issues to overcome is the Dynamic Range of a single imaging sensor

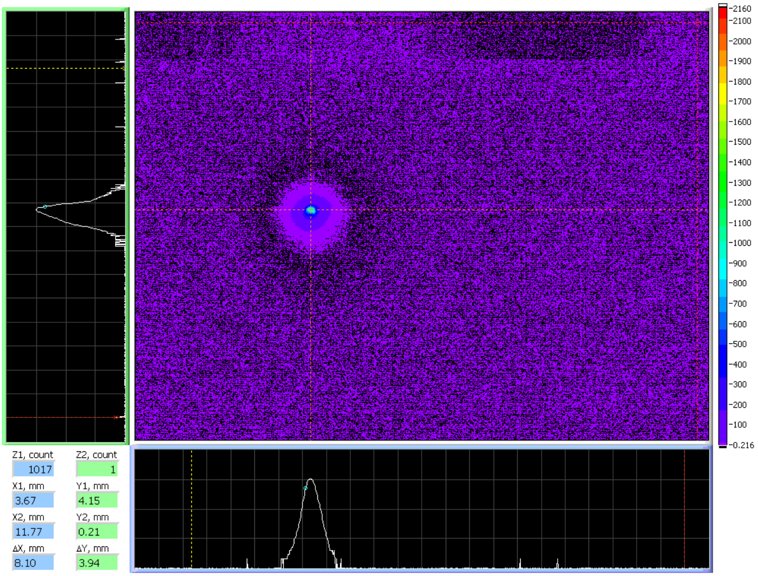
- One of the possible approaches is to use imaging with 2 or 3 sensors with different effective gain simultaneously and to combine data in one LDR image digitally *(single sensor dynamic range 500..1000 if cost is kept reasonable)*

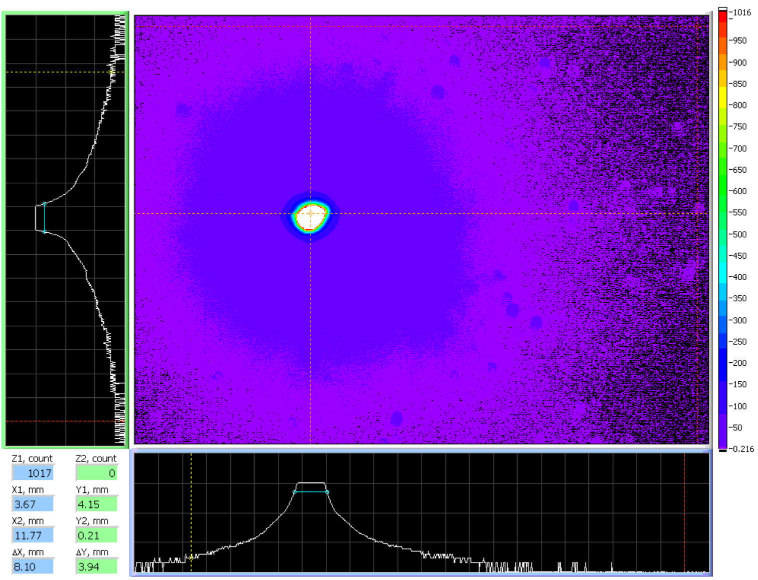
- Diagnostic mode determines number of electrons (photons) available for measurements

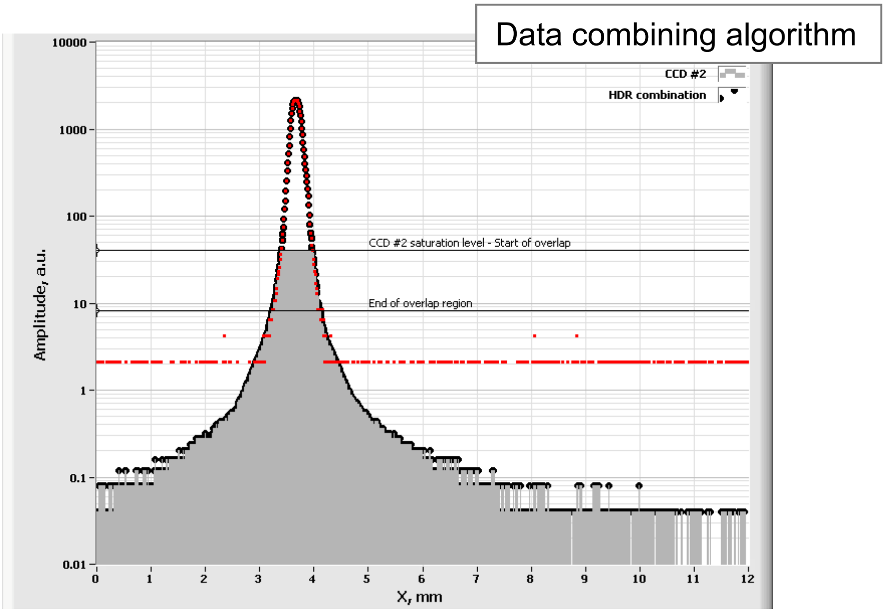
- Using OTR there is enough intensity to measure 4 upper decades; for lower two decades need gain of about 100; with YAG:Ce less gain would be required



Raw images and combining algorithm

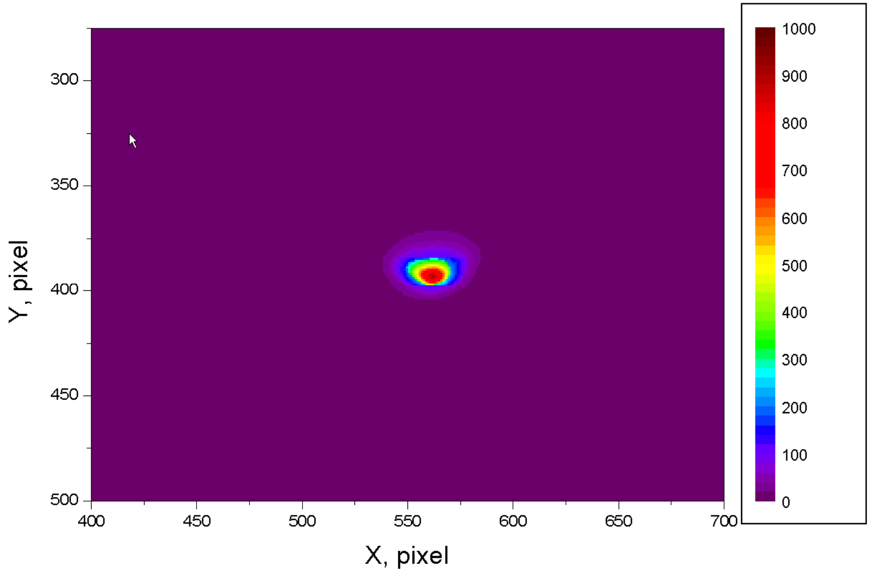


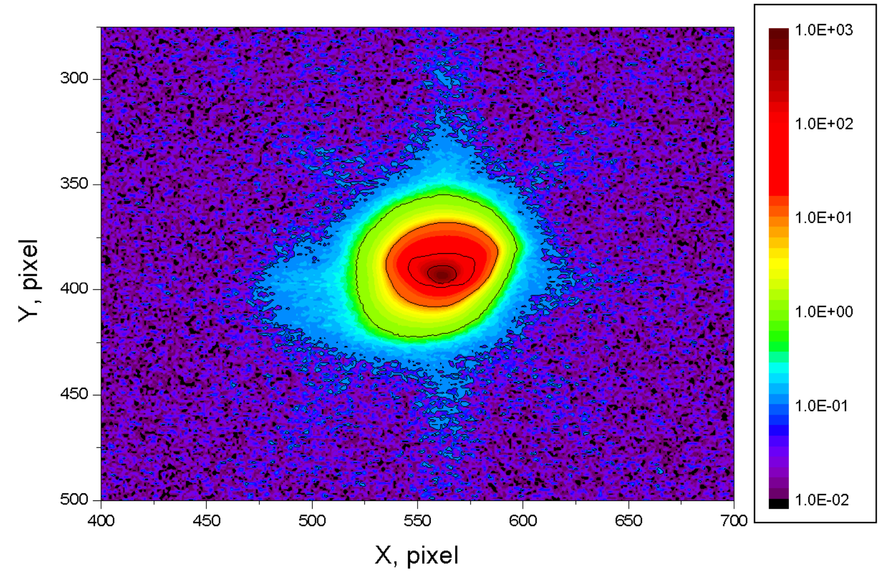




- ❖ Two images (on the left) measured simultaneously with integration times 20 us and 400 us
- ❖ Background measurements and subtraction is crucial! Made separately for two sensors and subtracted on-line.
- ❖ Combining algorithm is efficient enough to provide **5 Hz** repetition rate for **1024x768 images**
- ❖ At the time of measurements was limited by the flexibility of DLPC
- ❖ **Demonstrated dynamic range of ~ 5E+4 (factor of 100 increase)**
- ❖ Integration time is used for normalization and overlap (sufficient)
- ❖ Averaging also improves SNR and therefore DR (beam stability)

linear & log; the "trouble" with the RMS





- The two images show the same data (beam profile - (x,y)) but in linear and log scale
- Next: to use such measurements for beam characterization, emittance and Twiss parameters measurements (add x' and y')
- Ultimately tomographic measurements are planned; but first just quad scan

- **For non-Gaussian beam RMS beam width is a tricky thing!**
  It depends on how much of *tails* of the distribution function f(x) is taken in to account.

$$\boxed{w_{RMS}^{X} = \int x^2 f(x)\,dx}$$

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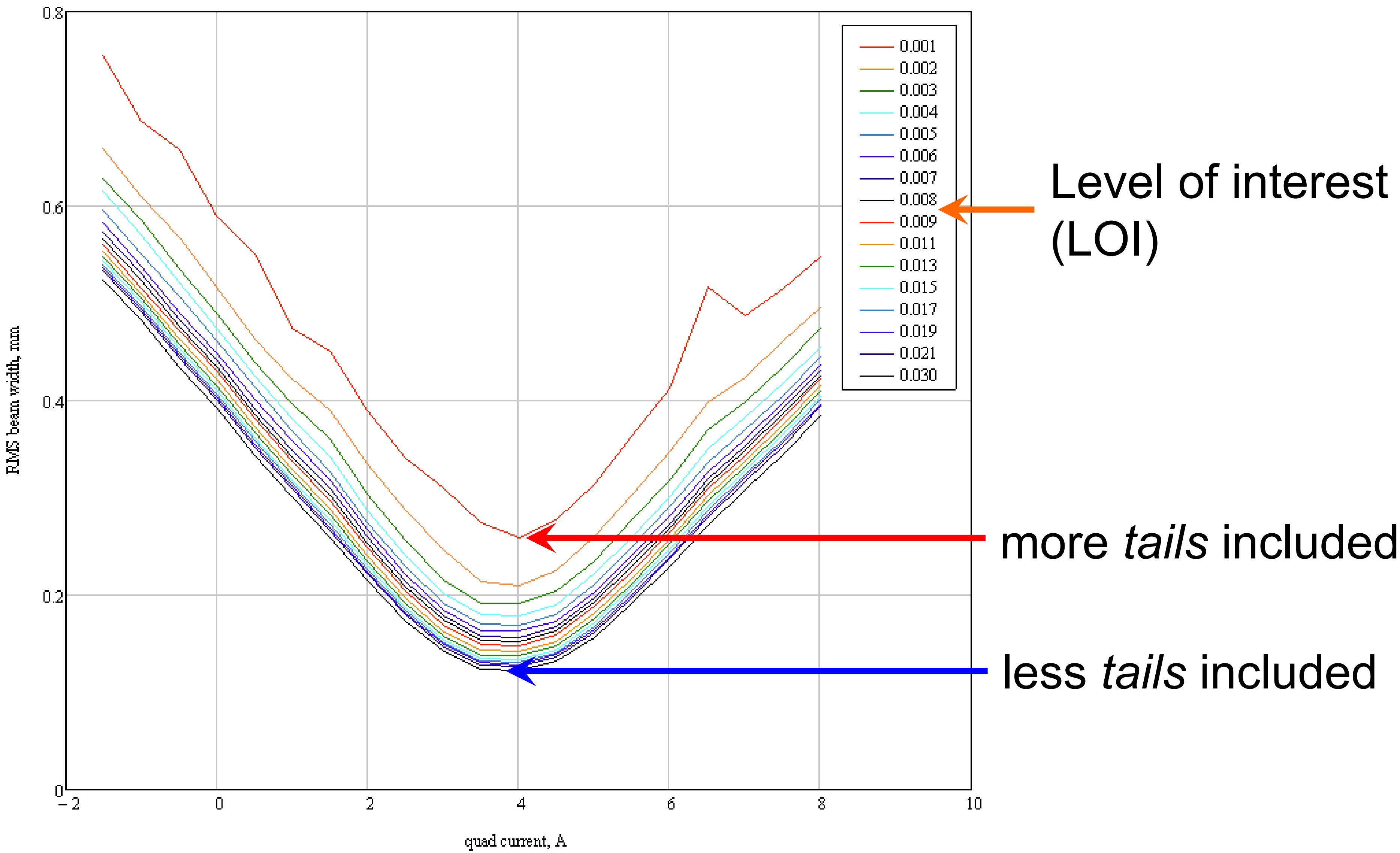
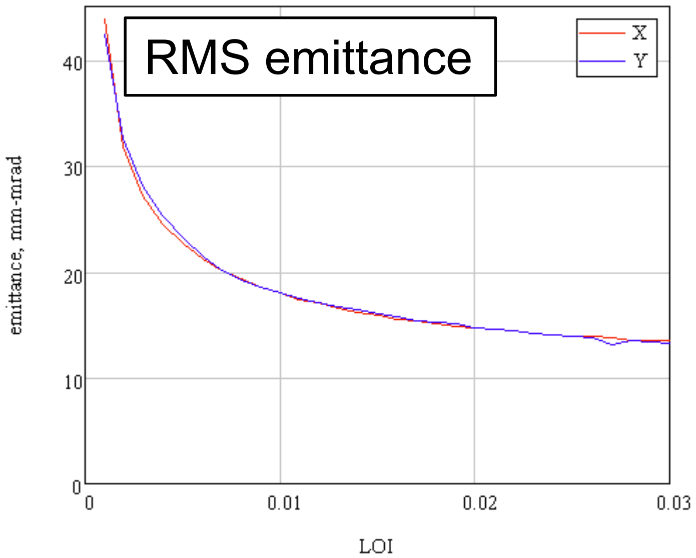
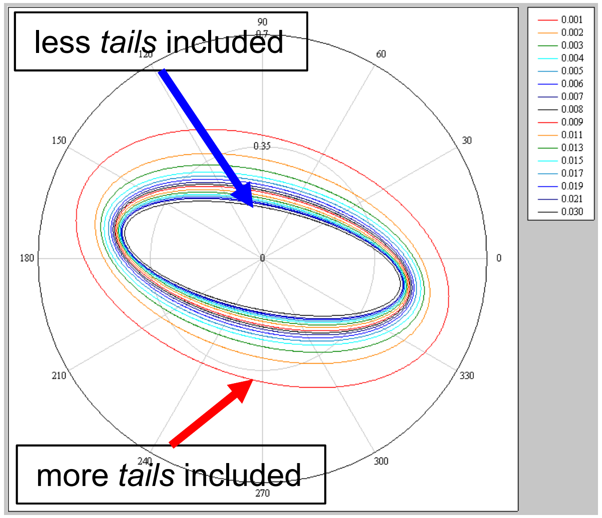
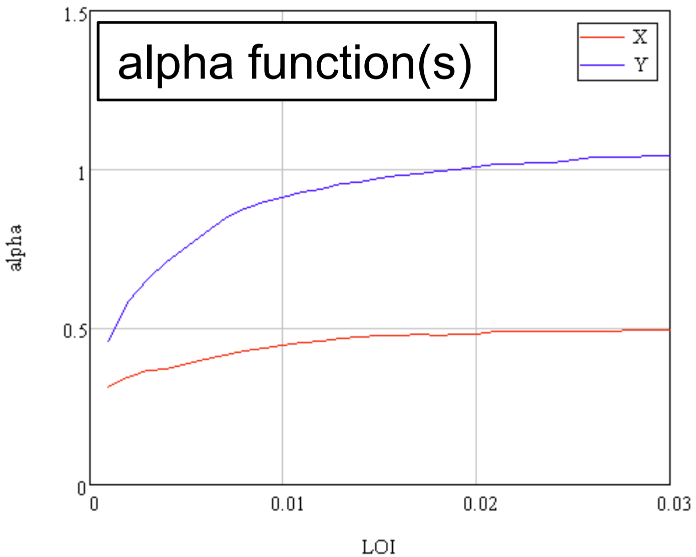
Quadrupole scan raw data

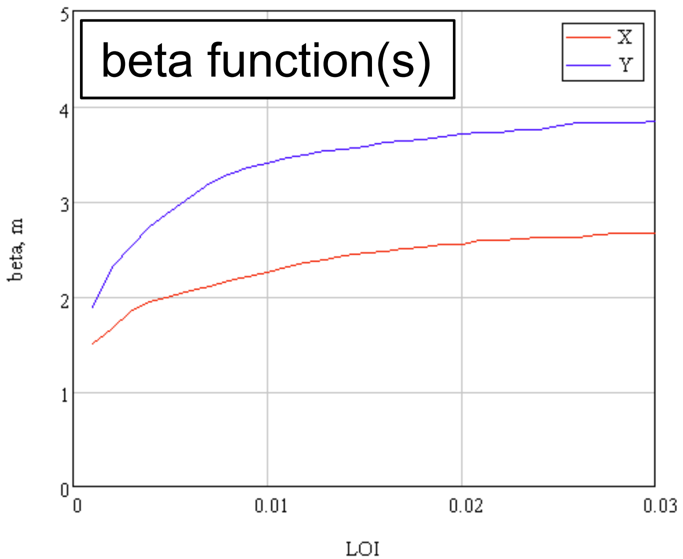


Emittance and Twiss parameters



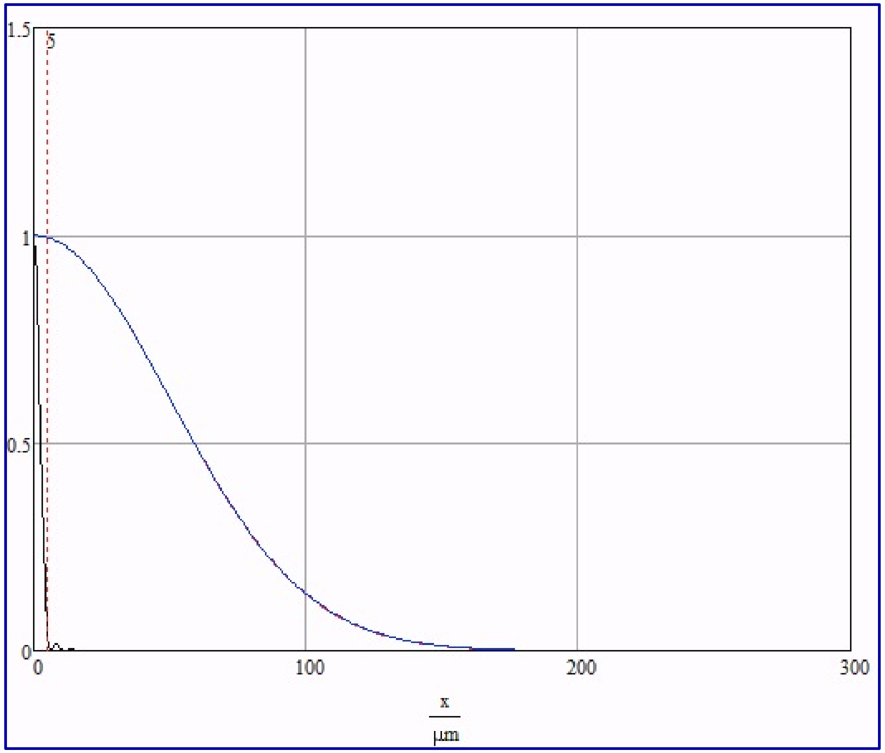


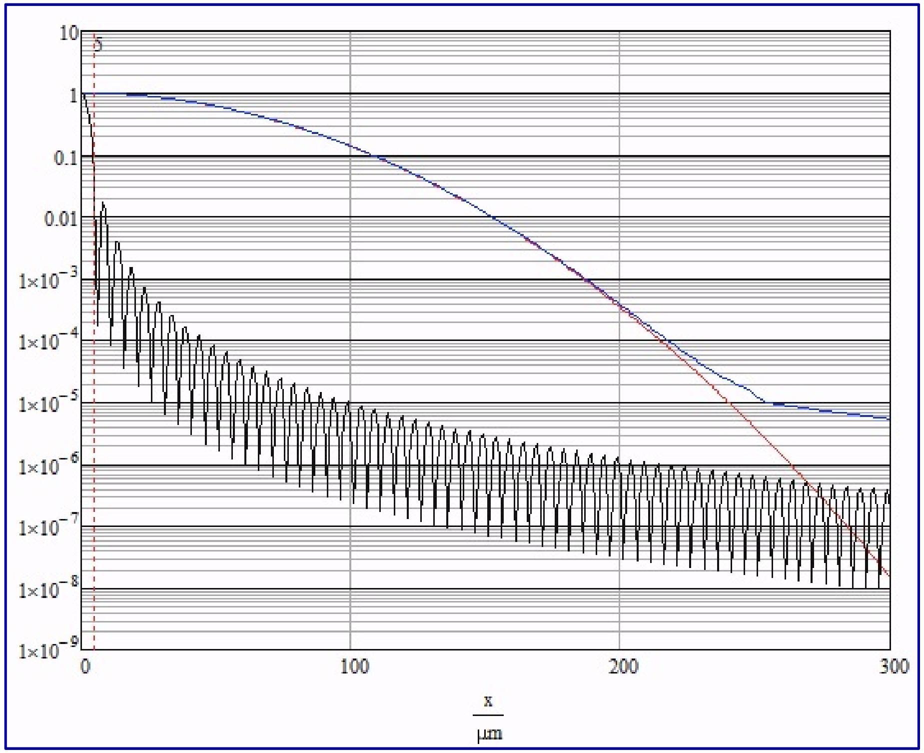




Diffraction limit and PSF

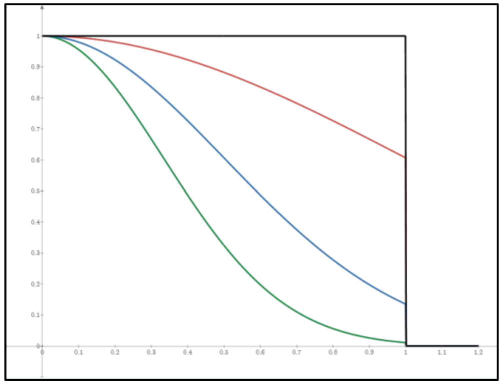
- Imaging: measured distribution is a convolution of source distribution and so-called Point Spread Function (PSF)
- PSF is determined by optical system angular acceptance and by the source angular distribution. (OTR, YAG, synchrotron radiation would have different PSF with identical optical system)
- **Diffraction** imposes rather hard limits to dynamic range of imaging optical system



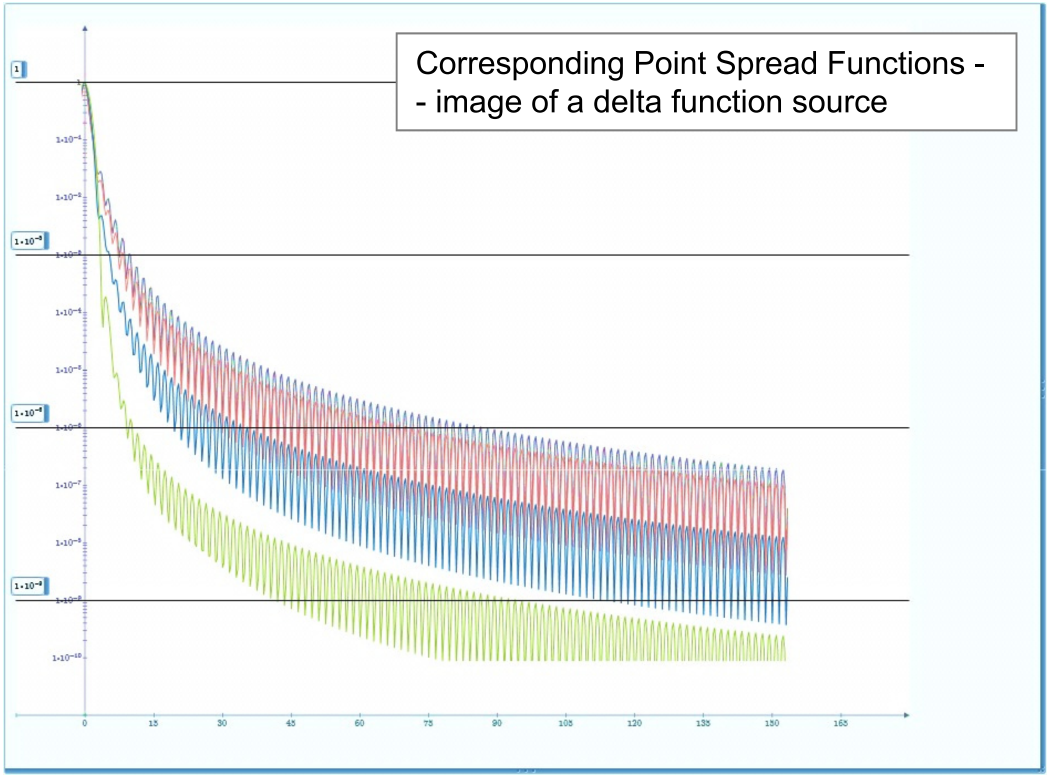


Apodization

- Lyot's coronagraph is a device for solar halo (corona) measurements but it does not allow for simultaneous measurements of the beam core and halo.
- Domain of Fourier optic, always Fresnel approximation - numerical calculations required for most practically interesting cases. This becomes demanding on CPU and memory quickly due to large apertures and optical wavelength (~ 0.5 micron)
- Implemented and used quasi-discrete Hankel transform for optics modeling (allows to do 1D calculations vs. 2D)
- Fourier optics: in image plane intensity distribution - 2D Fourier transform aperture shape with point source (Point Spread Function)
- Then it is easy to see that the uniform pupil function, i.e., the sharp lens edge is the problem *(besides the uncertainty principle)*
- Apodization – modification of the pupil function; First considered Gaussian amplitude apodization



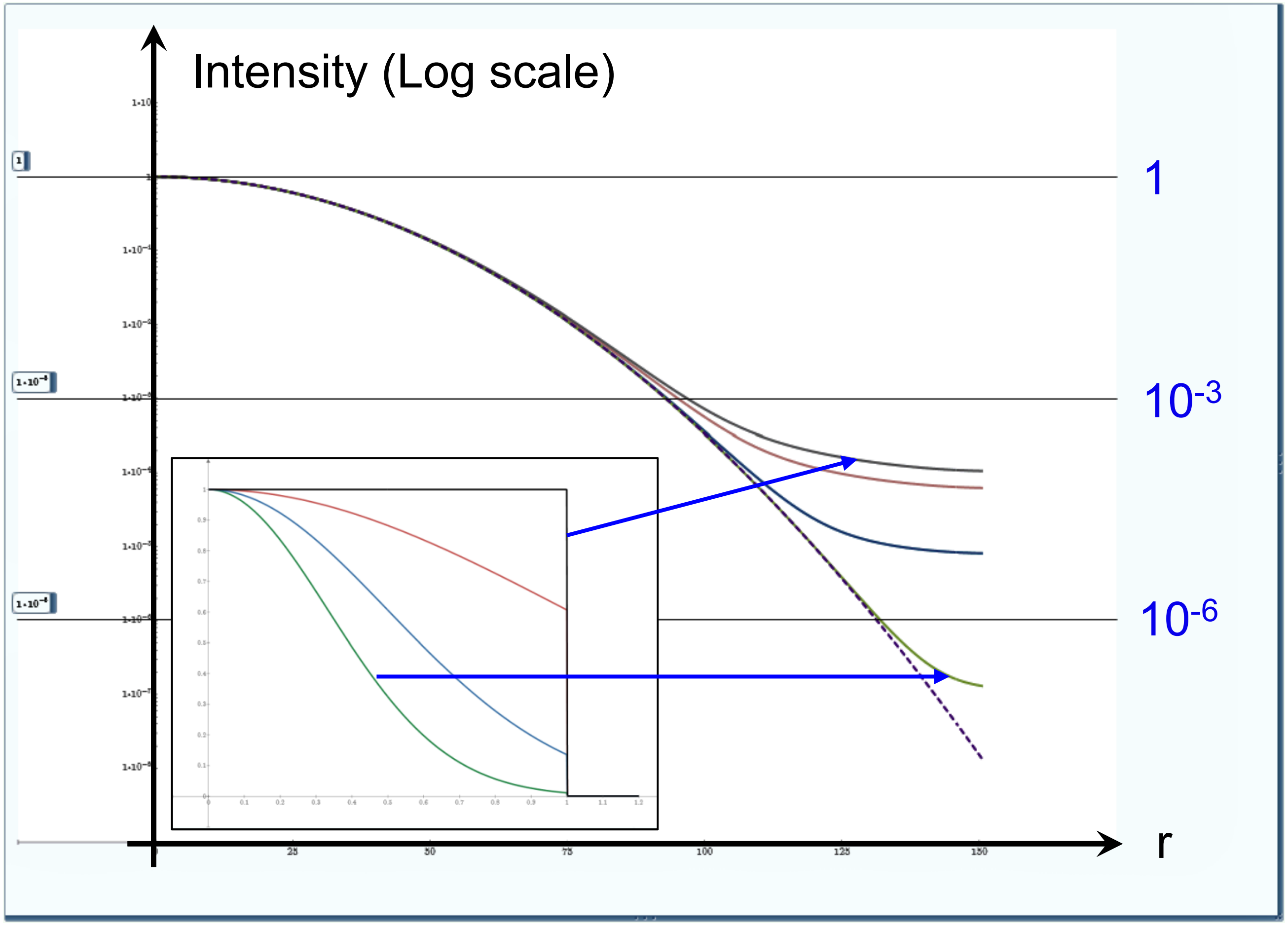
Pupil functions – pupil transparency as a function of radius



Corresponding Point Spread Functions - - image of a delta function source

Convolution - criteria for apodization

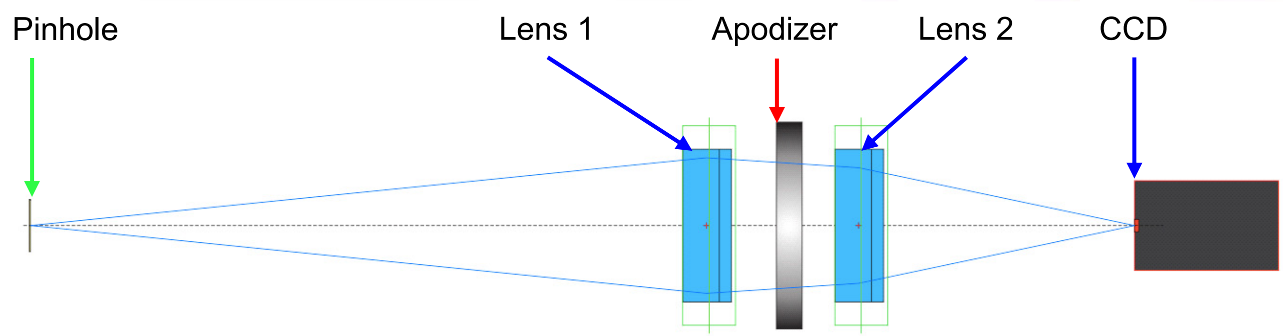
- Convolution of the PSF of Gaussian apodizers with imaginary Gaussian beam
- Criteria – deviations of the original Gaussian distribution and the convolution must be small (few %)



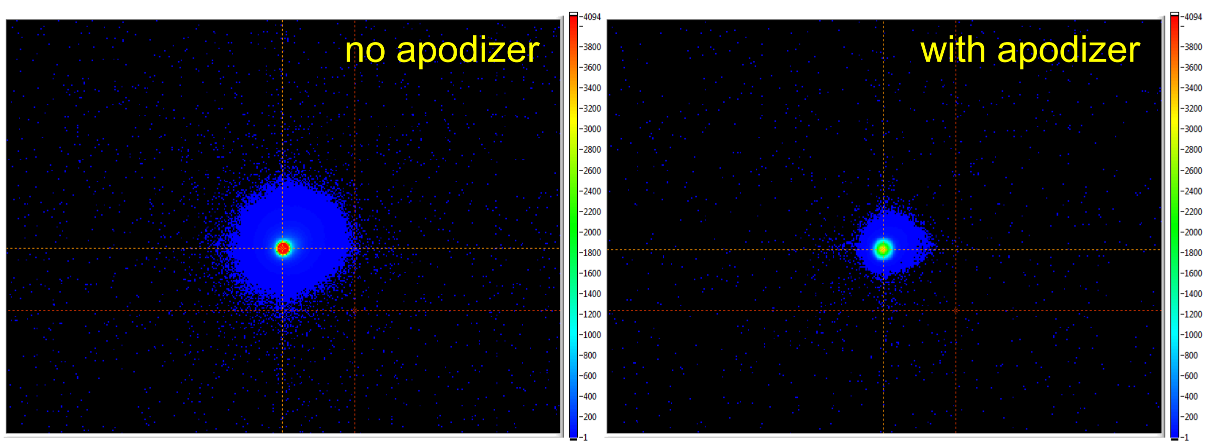
Half-tone dot apodizer

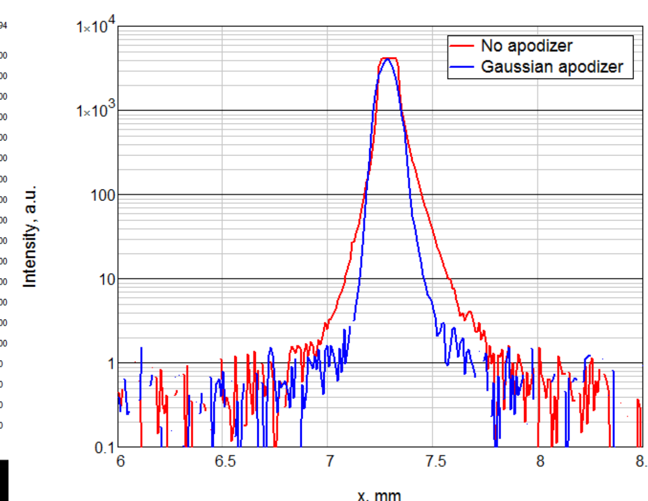
- First two apodizers manufactured using half-tone dot process
- average optical density (OD) adjusted via the average dot density
- 2D binary array of 10 μm pixels with transmission of either 0 or 100 %
- "error diffusion" algorithm used to translate required OD to dot density
- Power spectrum (spatial frequencies) of a pixelated apodizer is different from an ideal continuously variable one
- The claim of the "error diffusion" algorithm is that it adds to an ideal power spectrum only at high spatial frequencies – one of the first things to be tested on a bench
- If pixels are small enough, the high spatial frequency "noise" does not affect image
- **NOTE: the apodizer is placed in the Fourier plane**

Apodizer first bench test (preliminary)



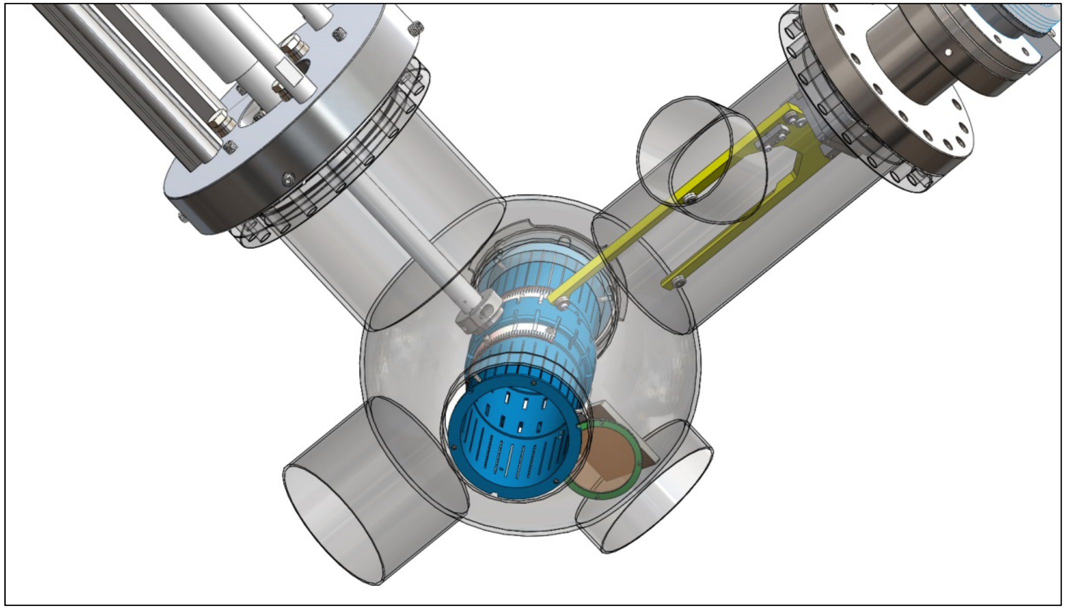
- first simple test to see the apodizer effect (not yet a full characterization)
- imaging with two achromatic doublets, can be thought off as one effective lens – Fourier plane
- apodizer is placed in the Fourier plane
- source: a pinhole with sharp edges (different from Gaussian source) white light illumination
- for the sharp edges it is more difficult to achieve LDR, on the other hand much easier to see the effect of apodizer





Beam viewer wire-scanner combination

- Must have impedance shield, due to high average I
- Two diagnostics at one location
- Can use YAG:Ce or OTR viewer with easy switch
- Shielded, 3 position viewer design for FEL



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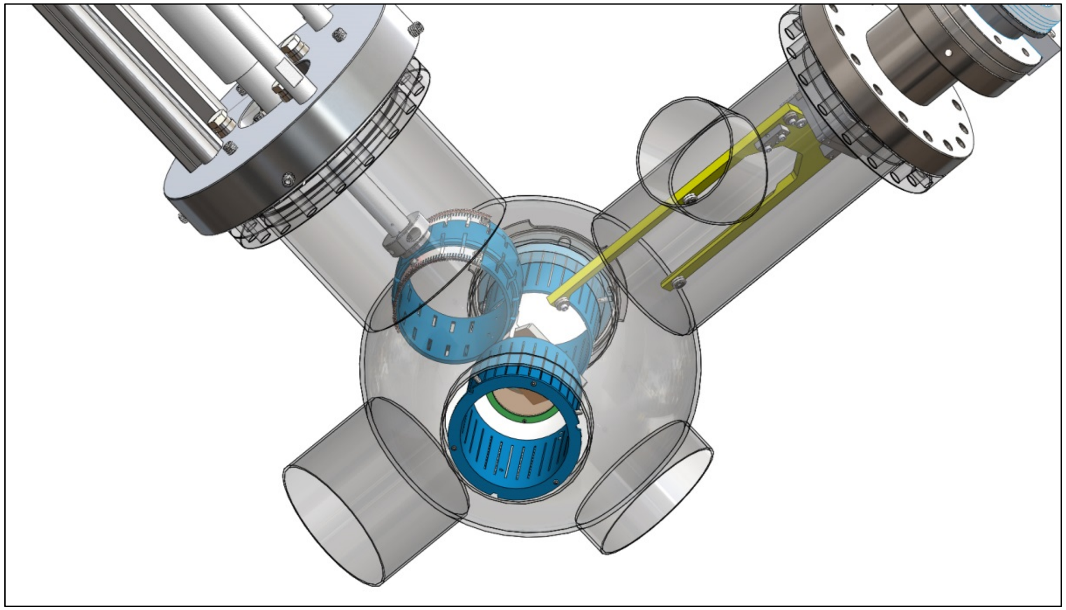

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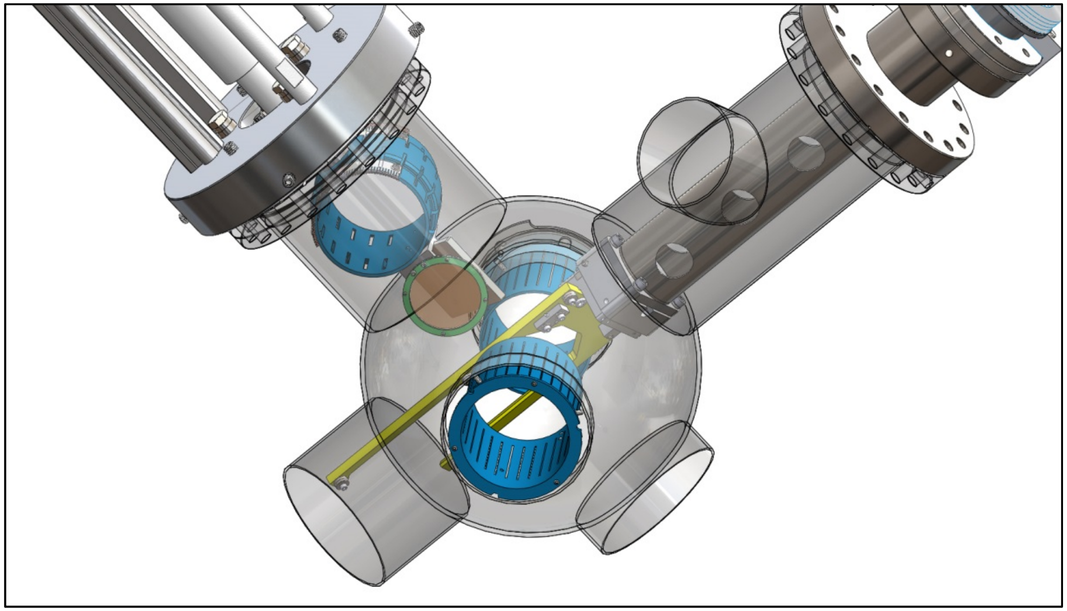
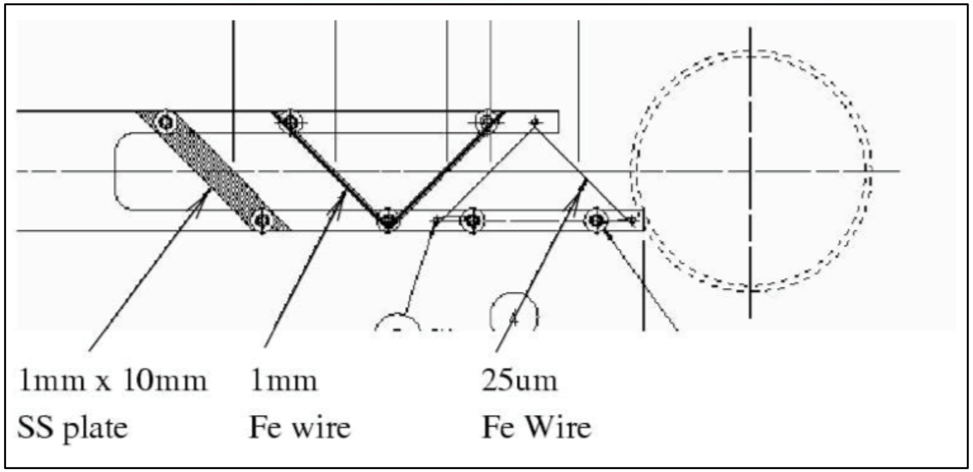
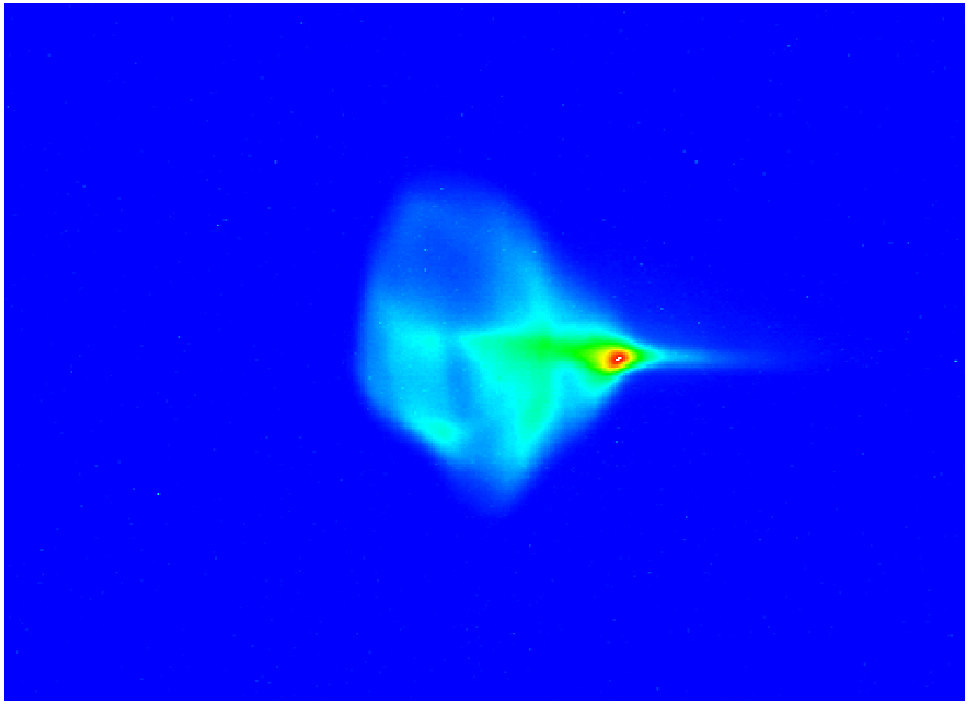


Wire scanner measurements: counting

A. Freyberger, in DIPAC05 proceedings, Measurements made at CEBAF

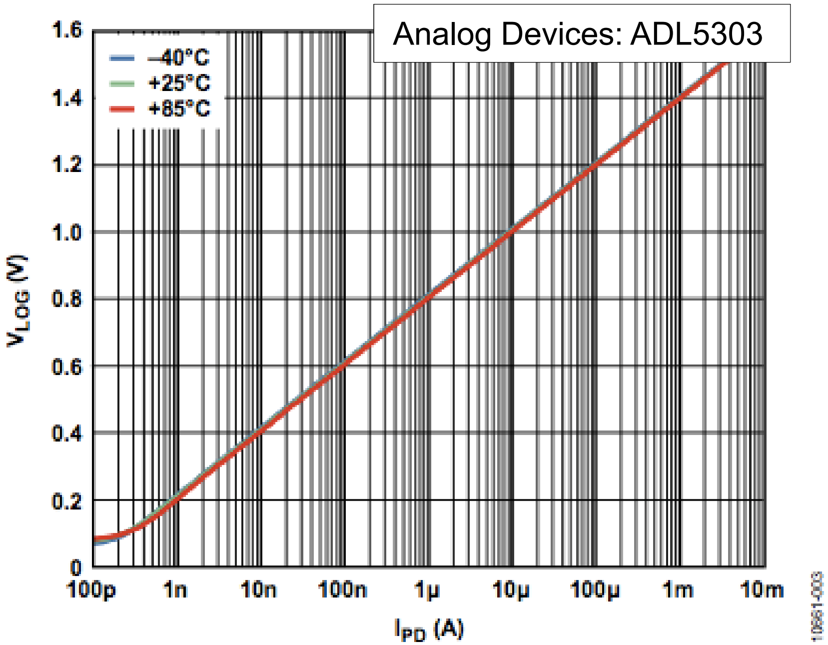
- CEBAF uses wires scanners for transverse beam profile measurements
- 499 MHz repetition – very good for counting
- One of a very few LDR beam profile measurements examples
- Due to very low current (5 nA) made with CW beam
- Max. counting frequency ~ 10 MHz (not a dedicated hardware)
- Coincidence effective to reduce background, but at the expanse of even longer measurements time
- With CW beam measurements time of about 15 min.
- for non-Gaussian beams ☹





Wire Scanner: analog mode

- **To ensure linearity in large dynamic range is the key and challenge at the same time – calibration with LDR sources (current or light) is most essential**
- PMTs with gain of ~ 10^6 provide high sensitivity, but high gain by itself is not enough
  - PMT's dark current - limits DR on the low end (kept low)
  - average current through a PMT is limited (typically to ~ 100 μA)
  - space charge effects in PMT (pulse linearity) usually limits DR on the high end (keep high)
  - with pulsed diagnostic beam: from few nA through 10 mA
- Options for LDR PMT current measurements:
  - Counting-like I-to-f conversion
  - Log-amplifiers for current measurements (160 dB and 200 dB)
  - Gated Integrator: DR of 10^4; combined with 16-bit ADC; x2 overlapping by one decade



In conclusion

1. For electron LINACs with high average current and beam power beam losses needs to be under control at the 10^{-6} level or better
2. Operational experience with high average current, moderate peak beam brightness electron LINACs shows that transverse match is always a compromise between beam brightness and low beam loss
3. Transverse match is a challenge; Non-Gaussian nature of beams has significant impact; Beam halo is one of the limiting factors
4. Based on JLab FEL experience, diagnostics with very large dynamic range 10^6 or higher needed for better measurements and understanding of beam halo distribution, formation and management
5. Beam imaging with LDR would be a preferable techniques, must mitigate diffraction; apodized optics is the key element
6. For ultra bright beams (if imaging dose not work) wire-scanner measurements with LDR can be implemented; easier than imaging but no 2D beam distributions – not optimal for LINAC's beams

Acknowledgement

What is presented in this talk has started from and was motivated by operation of Jefferson Lab FEL – IR/UV Upgrade.

This was a team effort, many colleagues have contributed with their hard work to the operation of this machine, Steve Benson and Dave Douglas specifically!

That’s all, folks! Thank you.