Jefferson Lab Experience with Beam Halo, Beam Loss, etc.

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with a lot of input from many experienced colleagues

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Outline

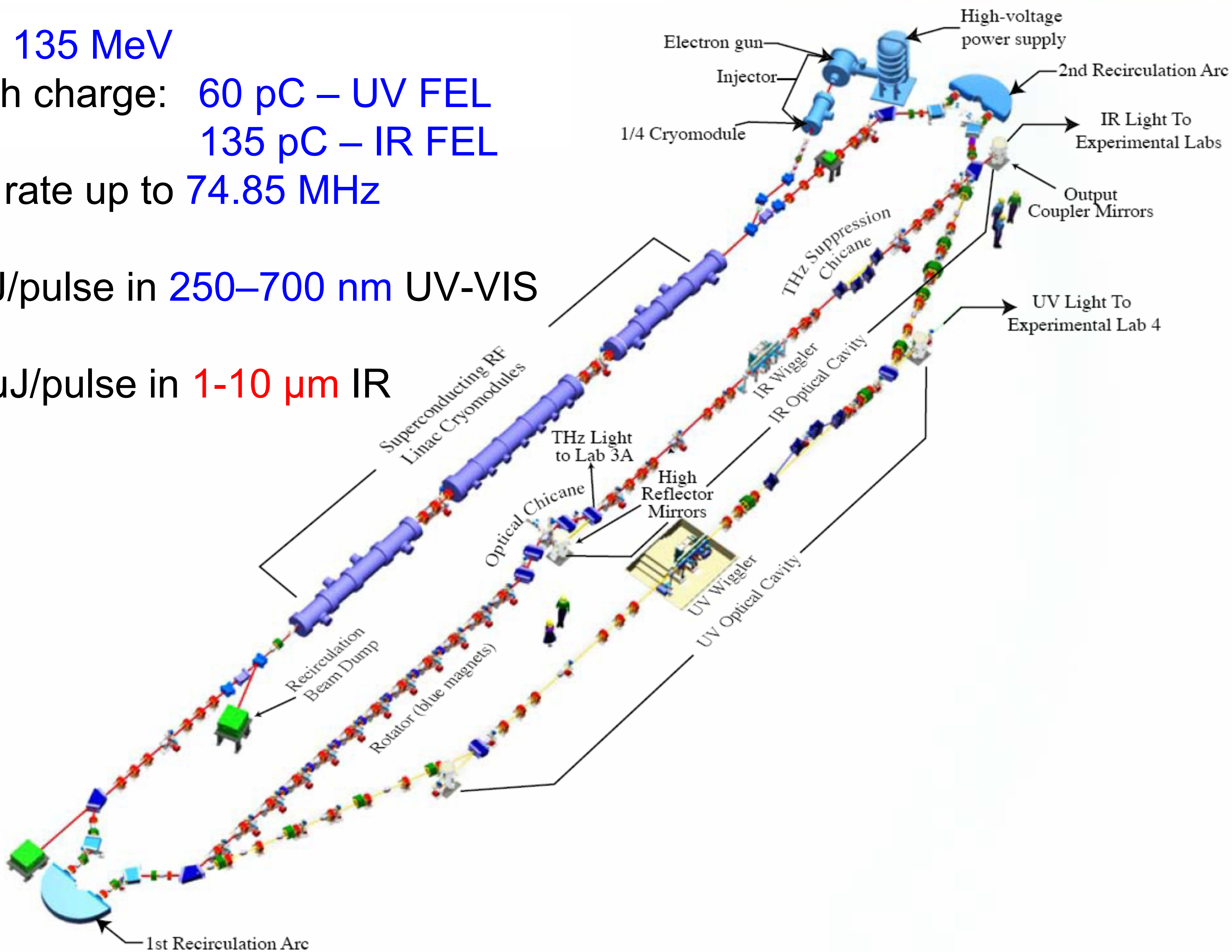
1. IR/UV Upgrade (JLab FEL) overview
2. Different sources of unwanted beam
3. Beam dynamics example
4. Setting up for high current operation
5. Drive Laser related
6. Observations with beam viewers (3 examples)
7. Gun HV processing (FE related)
8. CEBAF overview
9. RF trip rate
10. Direct measurements
11. Vacuum “events”
12. Summary

JLab IR/UV Upgrade

E_{beam} 135 MeV
Bunch charge: 60 pC – UV FEL
135 pC – IR FEL
Rep. rate up to 74.85 MHz

25 μJ/pulse in 250–700 nm UV-VIS

120 μJ/pulse in 1-10 μm IR



Flavors of Unwanted Beam

Four sorts of the unwanted beams

1. Fraction of the phase space distribution that is far away from the core (due to the beam dynamics)

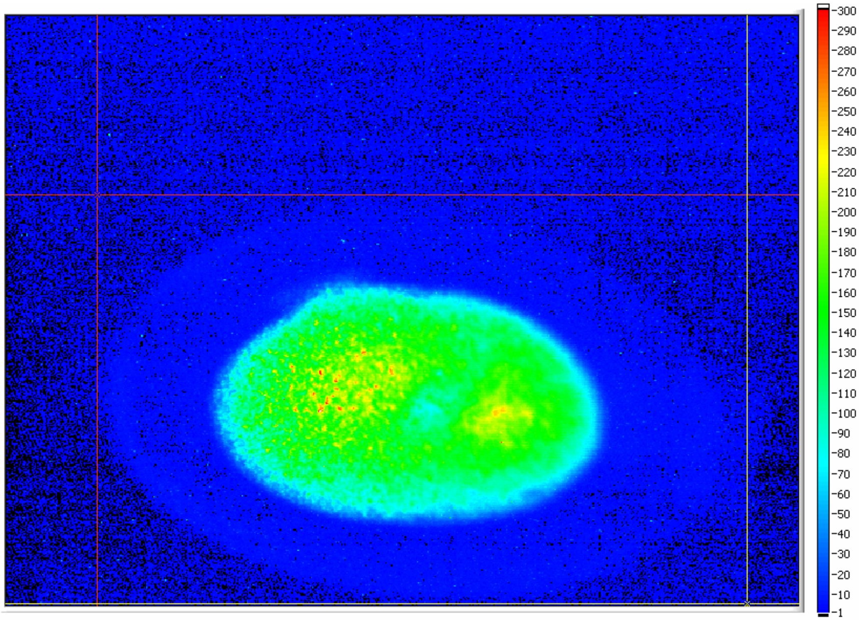
2. <u>Low charge</u> due to not well attenuated Cathode Laser (ERLs) – but real bunches that have <u>proper timing</u> for acceleration

3. Due to the Cathode and Laser but <u>not properly timed</u> (scattered and reflected light on the cathode and in the DL transport)

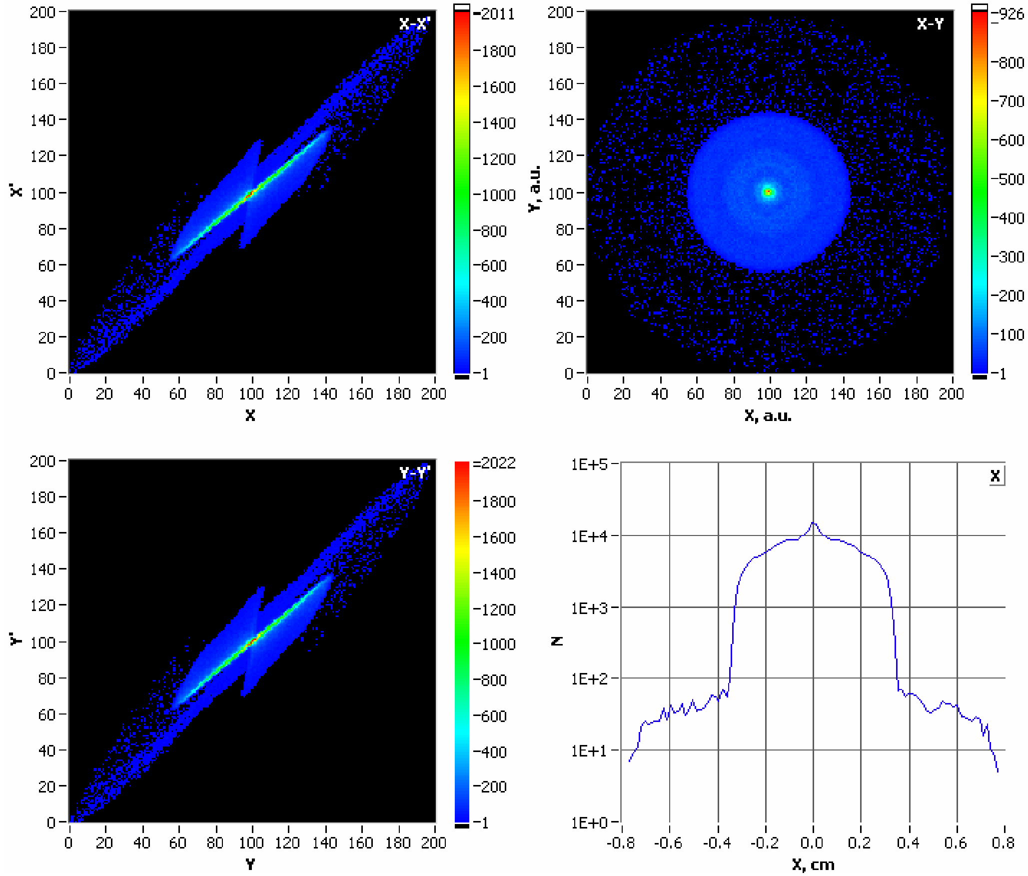
4. Field emission: Gun (can be DC or RF), LINAC itself (is accelerated in both directions)

5. Actually, there is one more – ions that accumulate in are true CW electron beam, travel in both directions with thermal velocities in side the electron beam, reduce Q.E. of the cathode one really does not want this beam.

FEL Injector as an example of #1



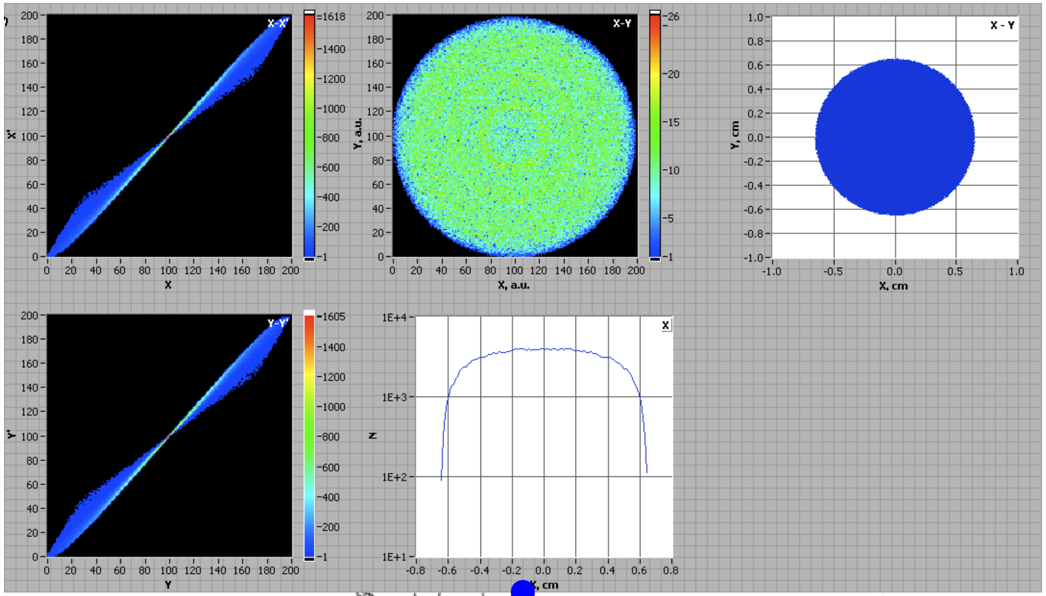
Measured in JLab FEL injector, local intensity difference of the core and “halo” is about 300. (500 would measure as well) 10-bit frame grabber & a CCD with 57 dB dynamic range



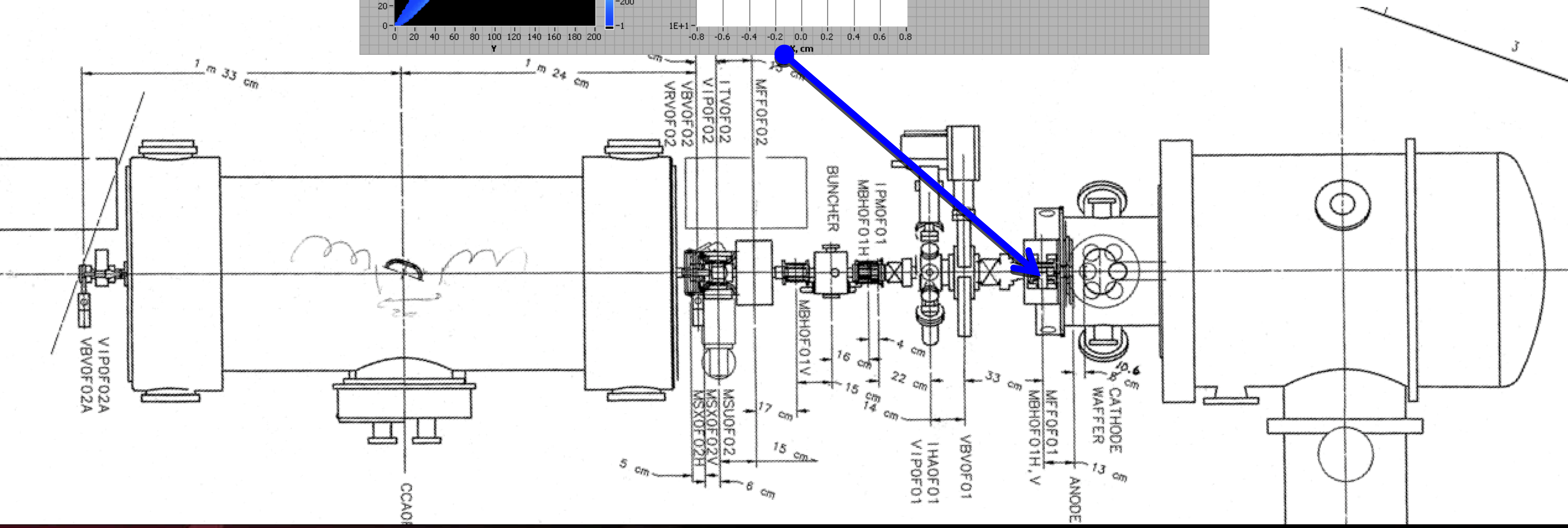
PARMELA simulations of the same setup with 3E5 particles: X and Y phase spaces, beam profile and its projection show the halo around the core of about 3E-3.

Even in idealized system (simulation) non-linear beam dynamics can lead to formation of halo.

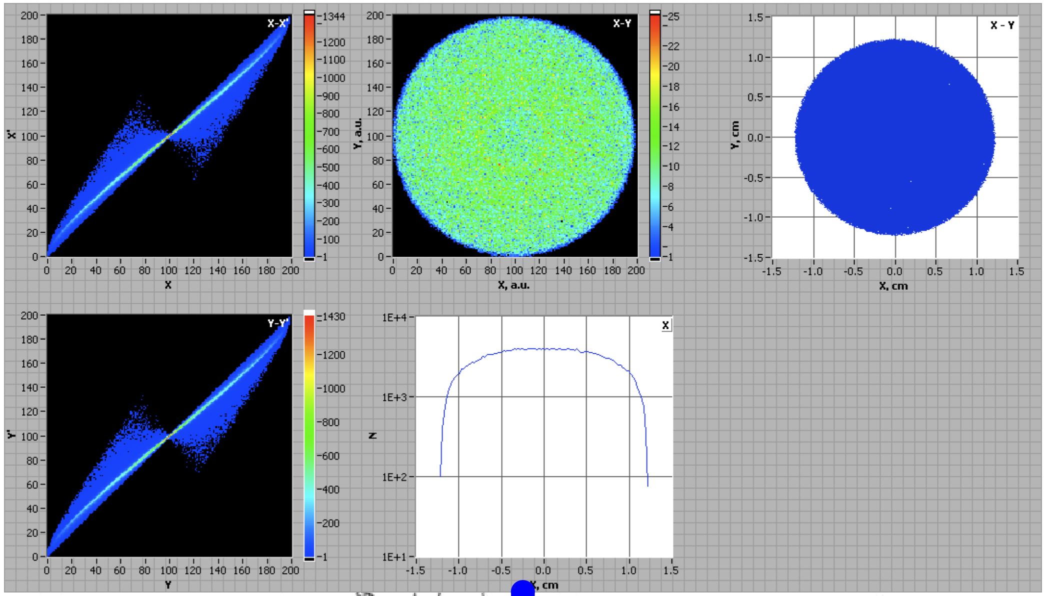
FEL Injector as an example of #1 (1/6)



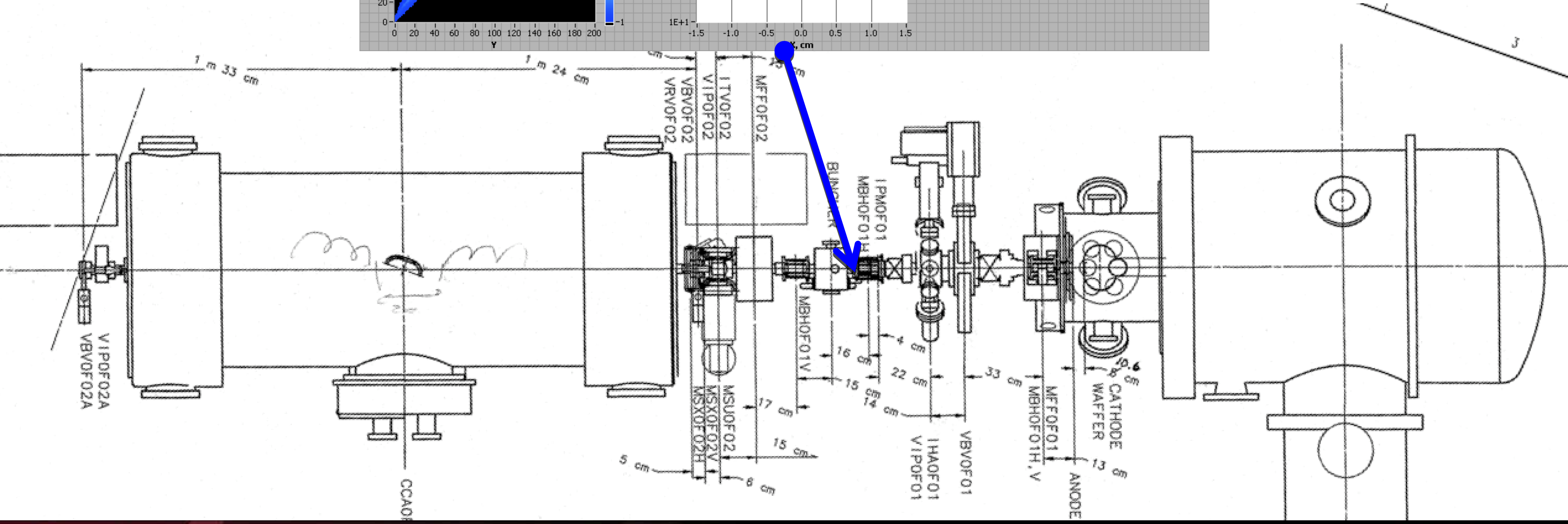
downstream of the gun



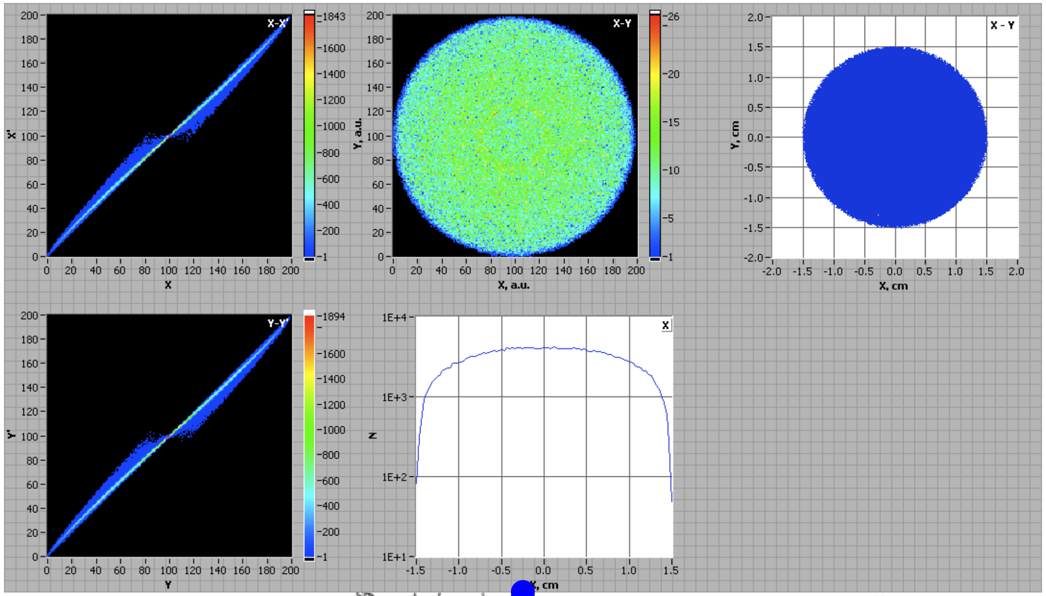
FEL Injector as an example of #1 (2/6)



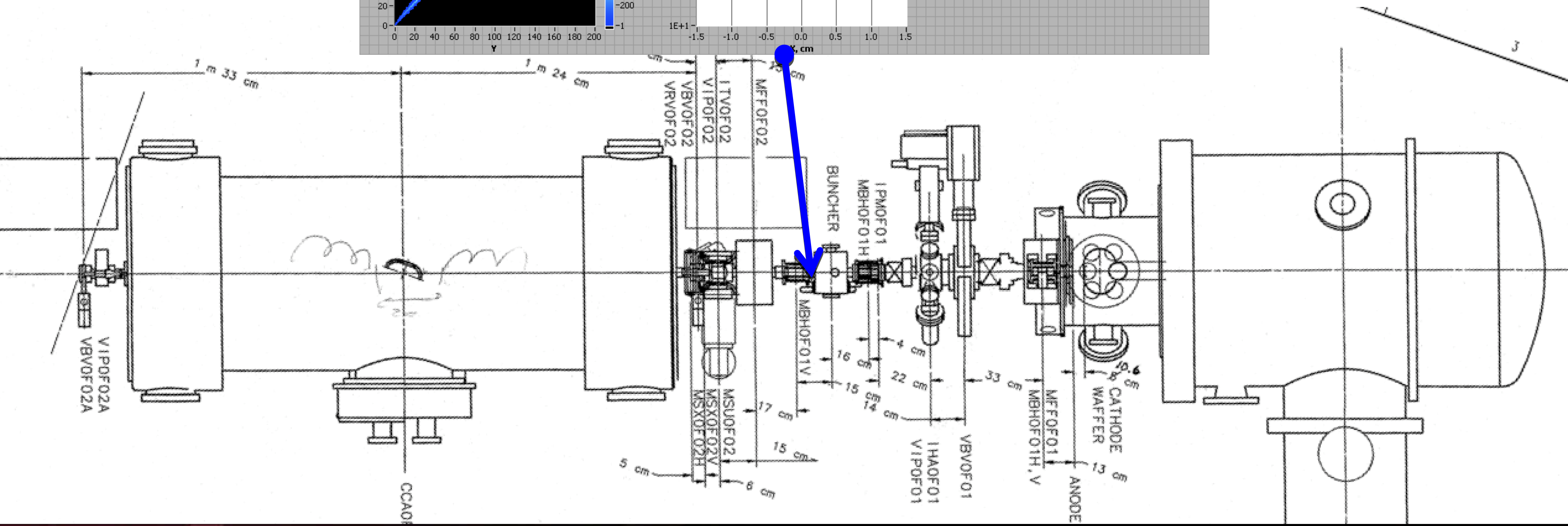
upstream of the buncher cavity



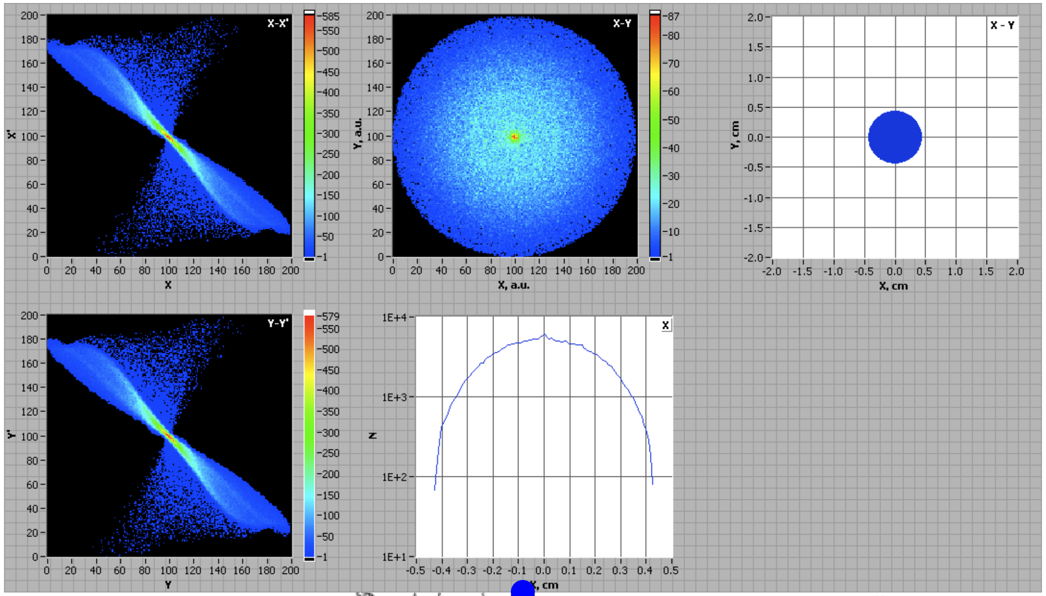
FEL Injector as an example of #1 (3/6)



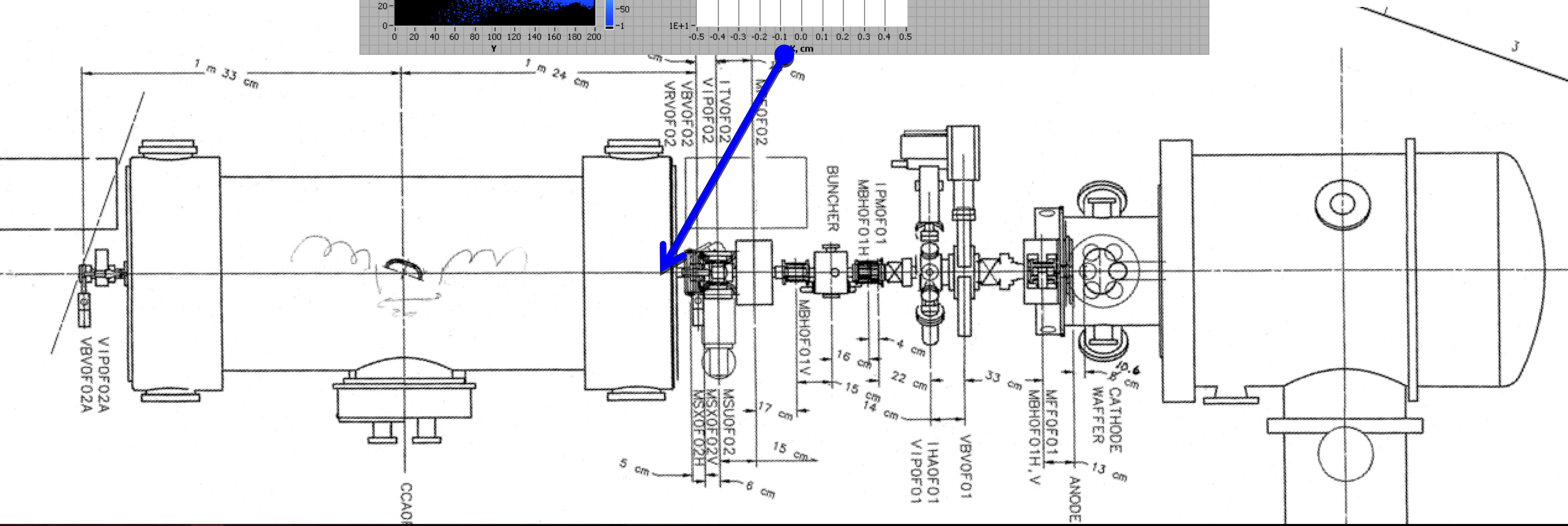
downstream of the buncher cavity



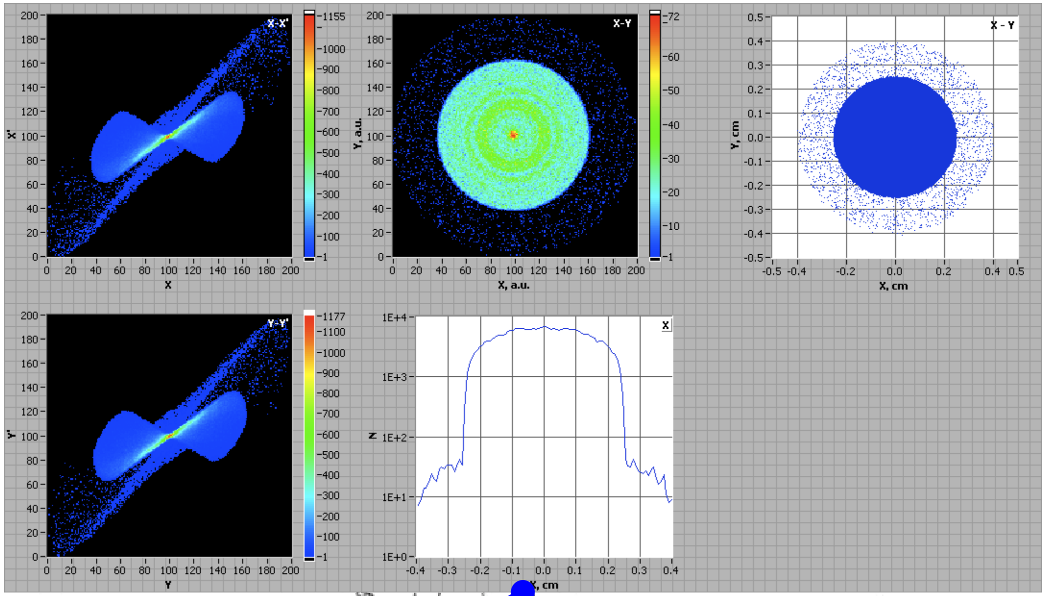
FEL Injector as an example of #1 (4/6)



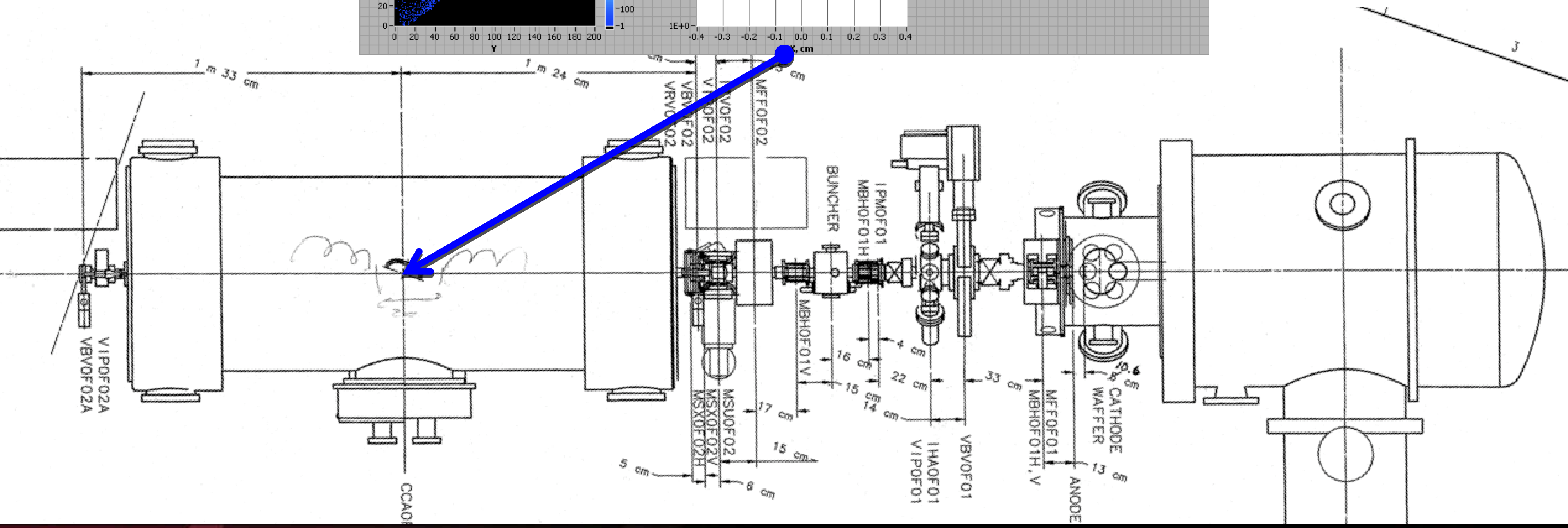
upstream of the SRF cavity 1



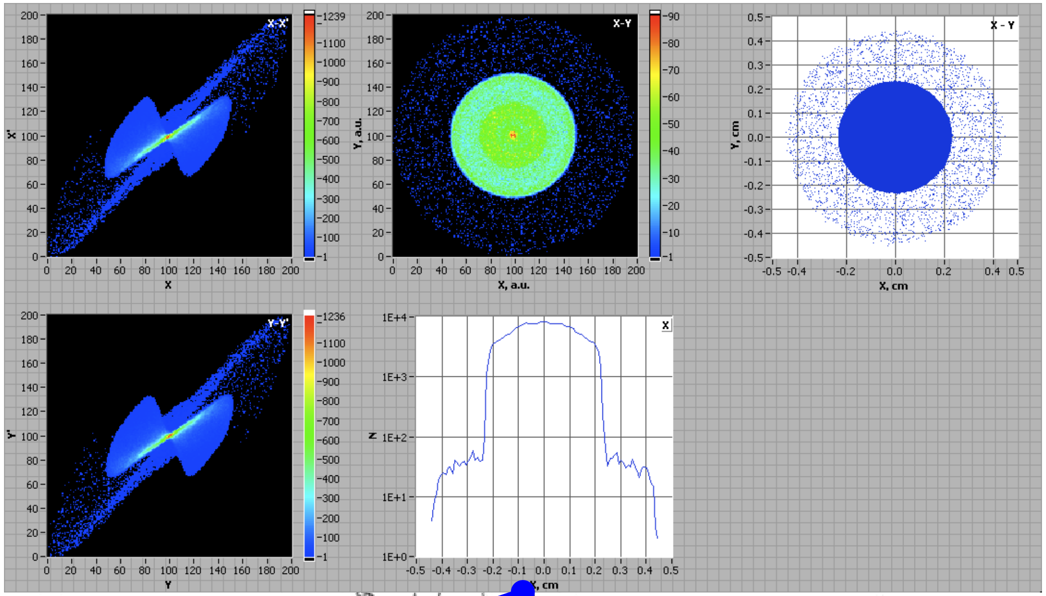
FEL Injector as an example of #1 (5/6)



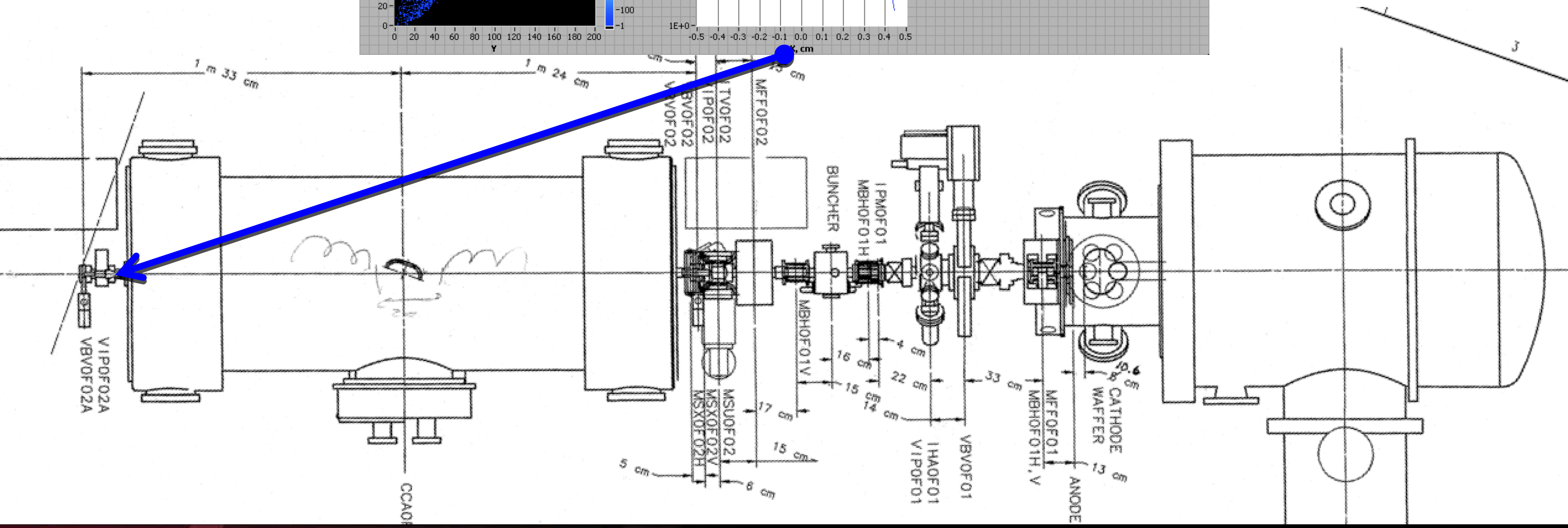
downstream of the
SRF cavity 1



FEL Injector as an example of #1 (6/6)



downstream of the SRF cavity 2

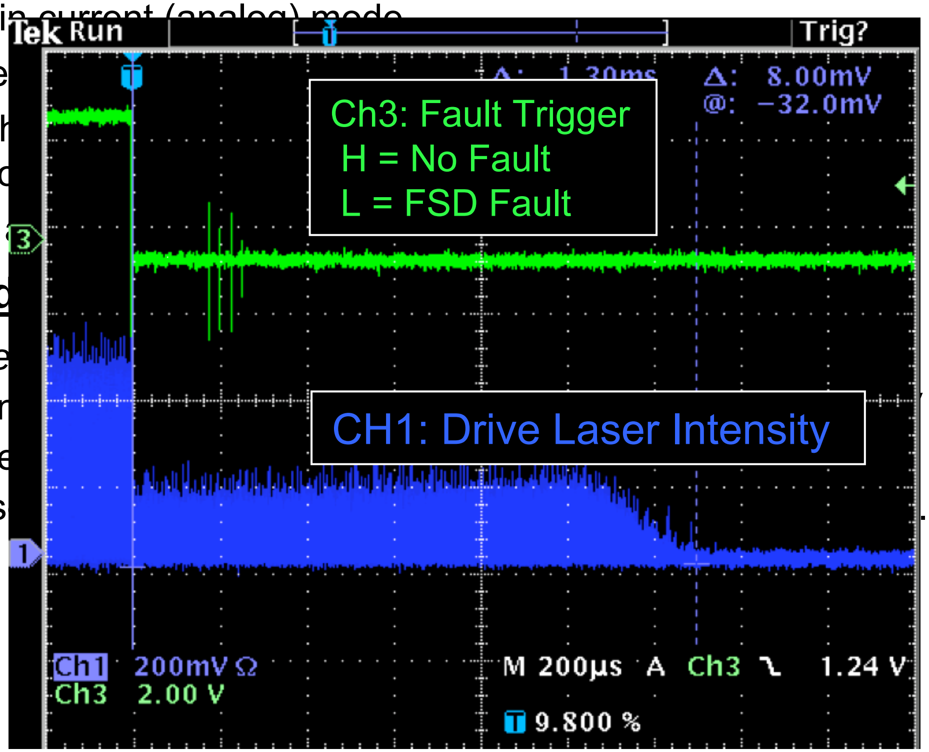


High current operation

- JLab FEL driver is setup for high current operation in three steps/phases
- Most of the measurements are made with low duty cycle beam beam
  (this is **Step 1** that establishes best RMS setup for FEL performance)
  - setting up injector (RF phases and solenoids)
  - transverse match
  - longitudinal match
- **Step 2** is to increase the duty cycle, usually to 6 %, and look at the beam loss, *small* adjustments in transverse and long. match often are required; the adjustments must preserve the high performance of the FEL this is the reason the adjustments have to be small
- When beam loss is small enough high average (9 mA) current can be operated and the long term trends in pressure (vacuum) are used for **Step 3** of machine adjustment, also very small.

Beam Loss Monitors

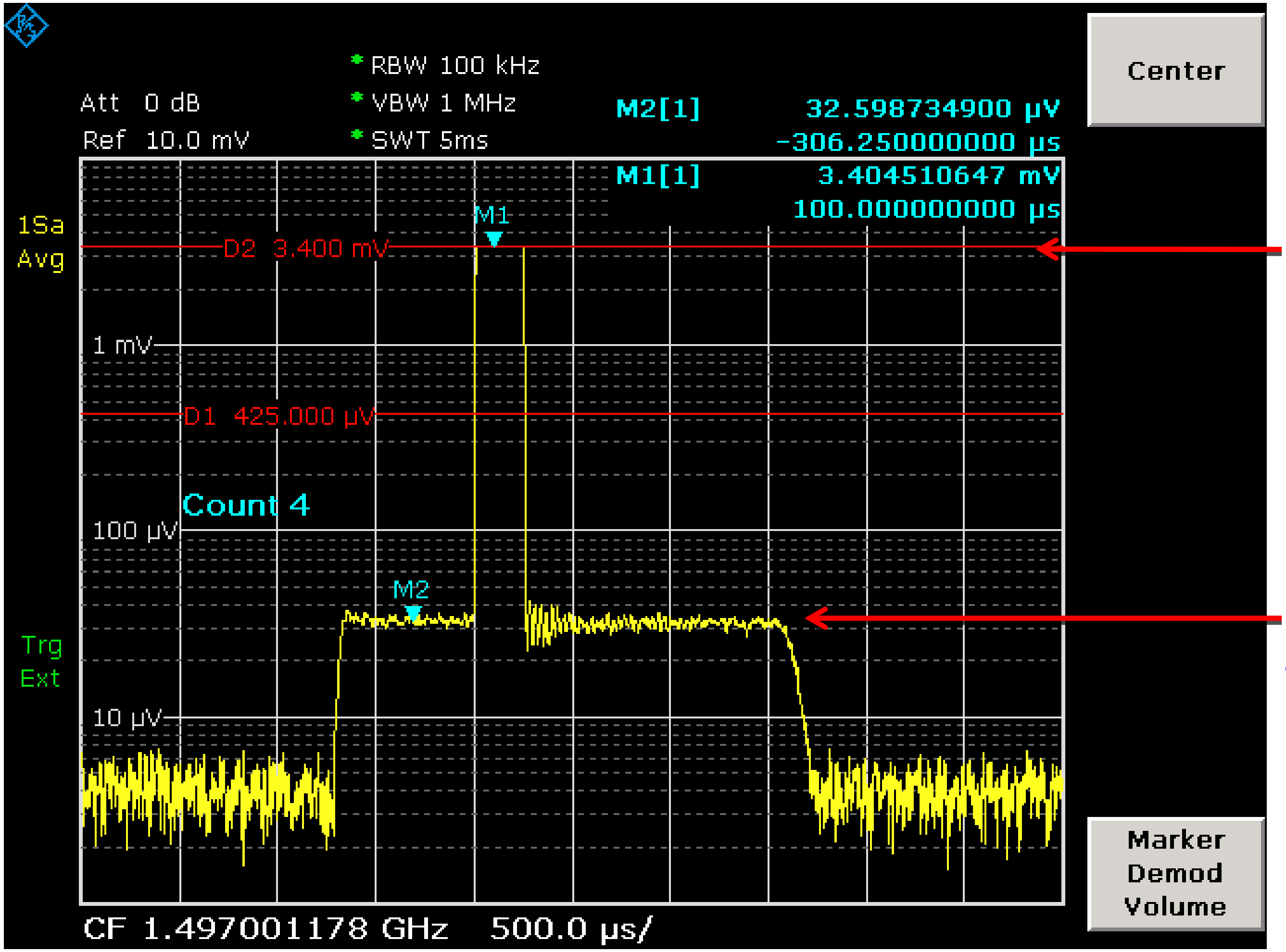
- The primary BLM at the JLab is a 931B Hamamatsu photo-multiplier tube, operated with a fixed integrator and individually variable HV power supply
- The BLM electronics are 12 channel VME boards.
  - ✓ PMTs are used in current (analog) mode
  - ✓ There is a single
  - ✓ All 12 channels h to the Analog Mo
  - ✓ These are used a
- **Calibration proced**
  - ✓ machine is *locke*
  - ✓ beam is driven in
  - ✓ the HV is adjuste
  - ✓ this new "gain" s



Courtesy of K. Jordan, D. Sexton

Drive Laser "ghost" pulses

- Using a Log-amp is an easy way to diagnose presence of the "ghost" pulses
- Log-amps with dynamic range 100 dB are available

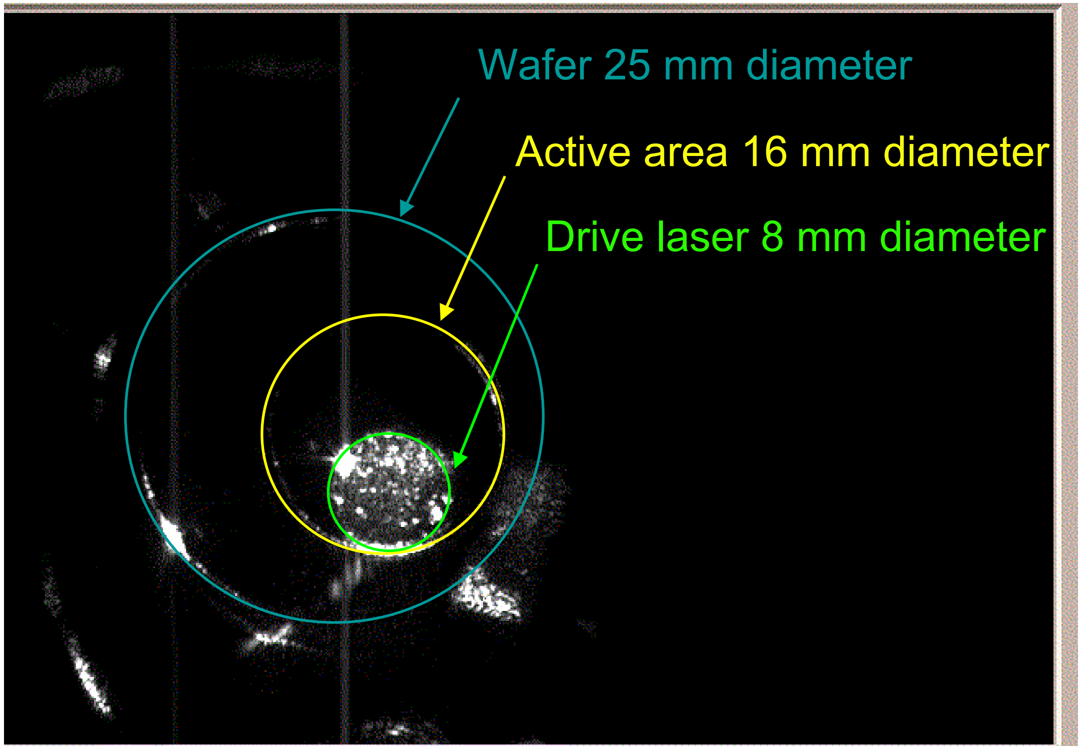


631 uA (100%)
135 pC x 4.678 MHz

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

DL light scattered on photo cathode

- ✓ a view of GaAs photo cathode when running beam (probably 6 % duty cycle or 1.5 %)
- ✓ measured with simple vis. CCD camera
- ✓ locations of the wafer and active area are knows from the same view, HV off and white light on
- ✓ we are looking in to a gap between two non-flat mirrors
- ✓ with a brand new wafer (no heat cleaning) one would not see any light from the DL spot

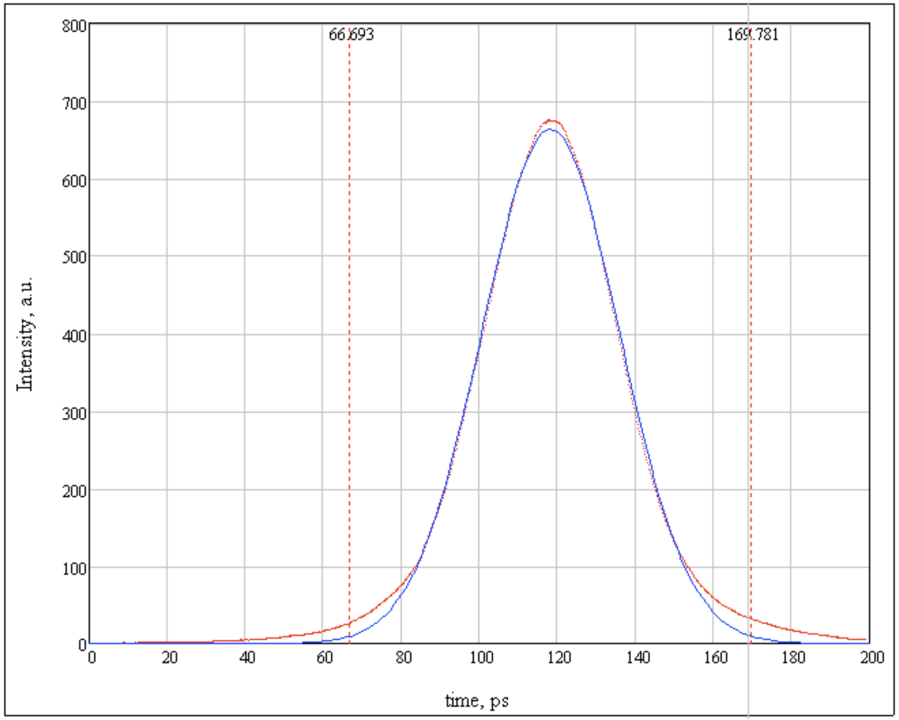


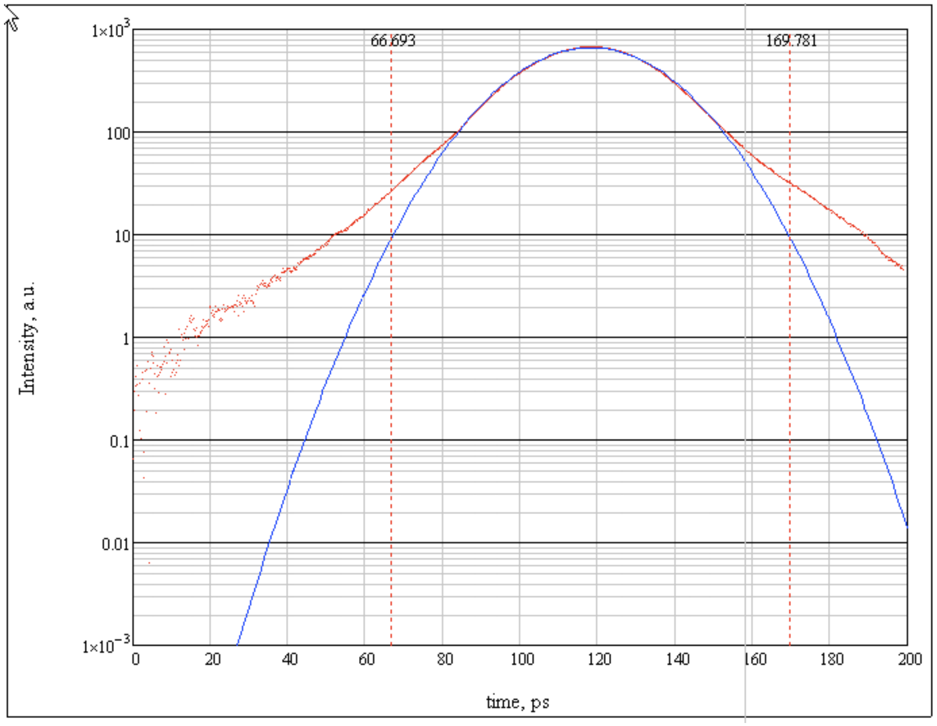
- ✧ At least two processes contribute to the generation of scattering centers
- ✧ Heat cleaning of the cathode (made periodically, every 4-5 re-Cs)
- ✧ HV breakdowns can result in rather large pits – scattering and field emission

- ❖ Visible (green) DL preferable over UV
- ❖ Preserving cathode surface will be very helpful
- ❖ Get rid of heat cleaning for GaAs (H – cleaning)

Courtesy of C. Hernandez-Garcia

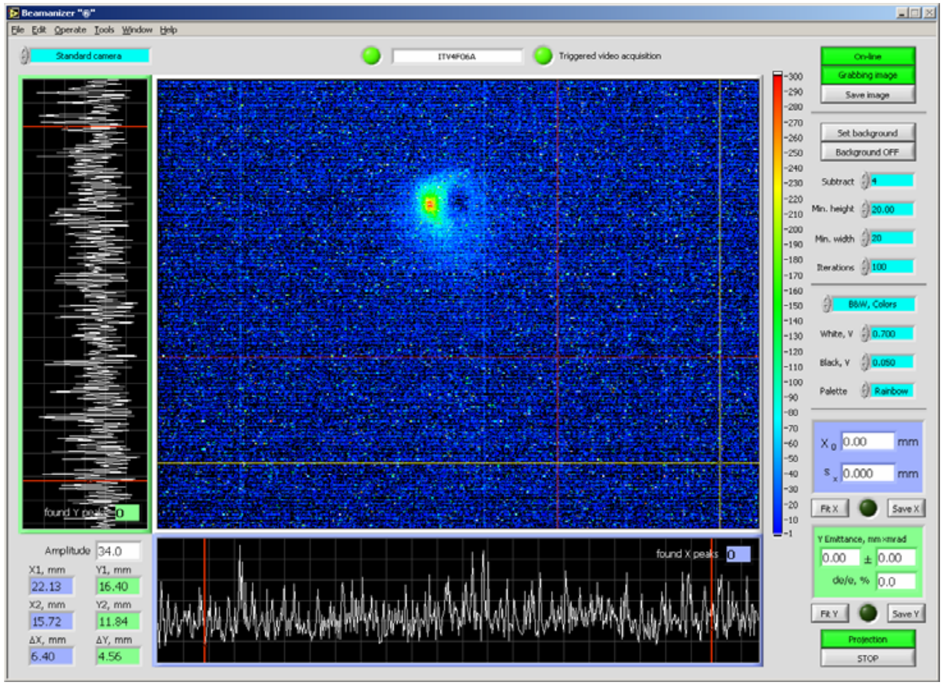
Cathode Laser pulse via streak camera

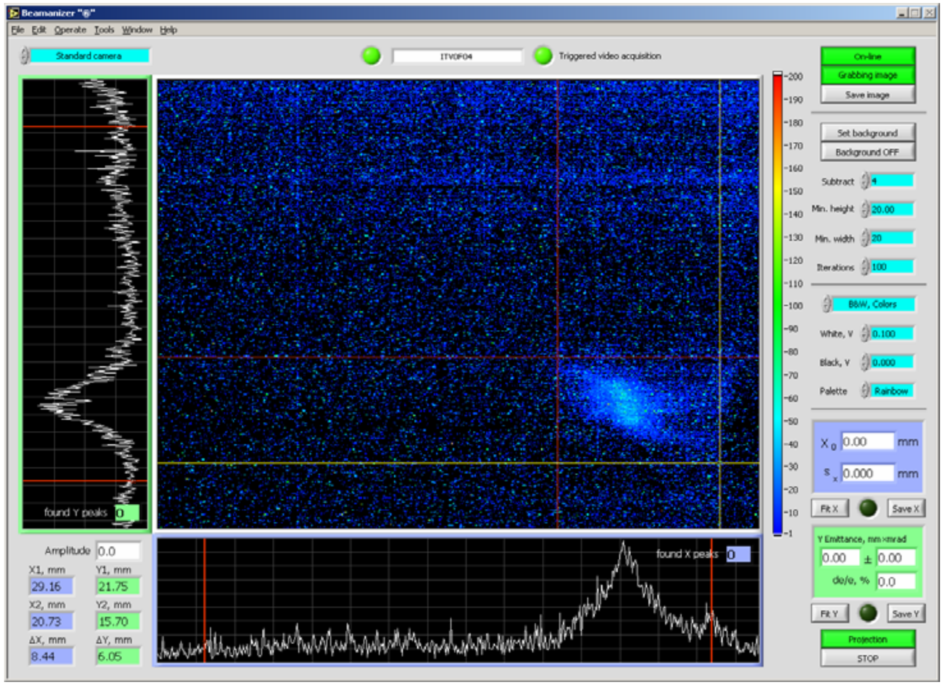




- appears to be close to Gaussian on linear scale; tails not so much Gaussian
- the difference from Gaussian distribution is obvious on log scale
- realistic (measured) distribution must be used for realistic modeling
- especially is the calculations are intended for large dynamic range effects

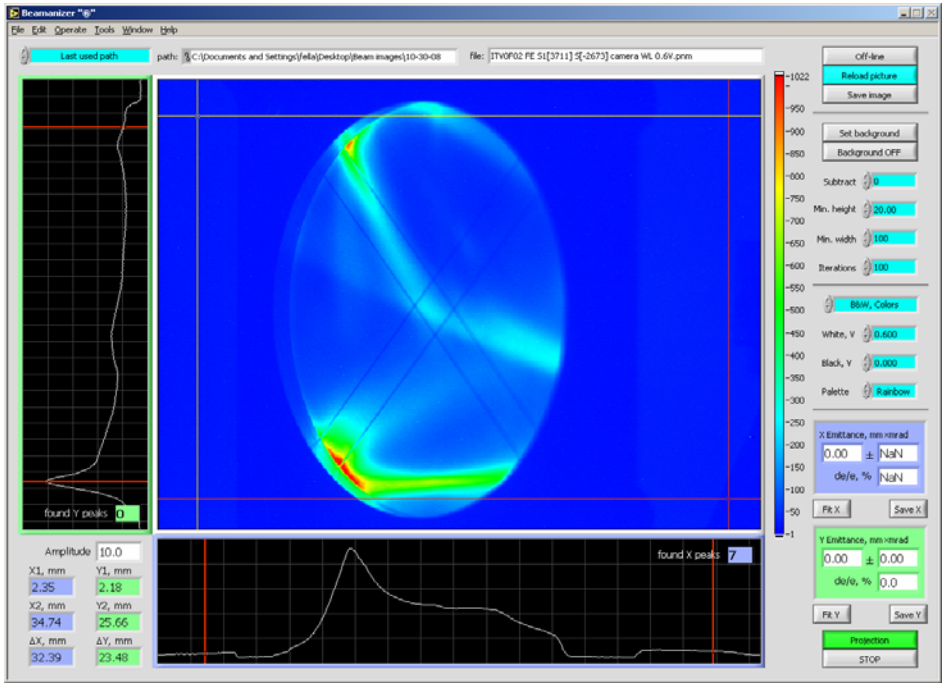
Case 1: from the gun to wiggler

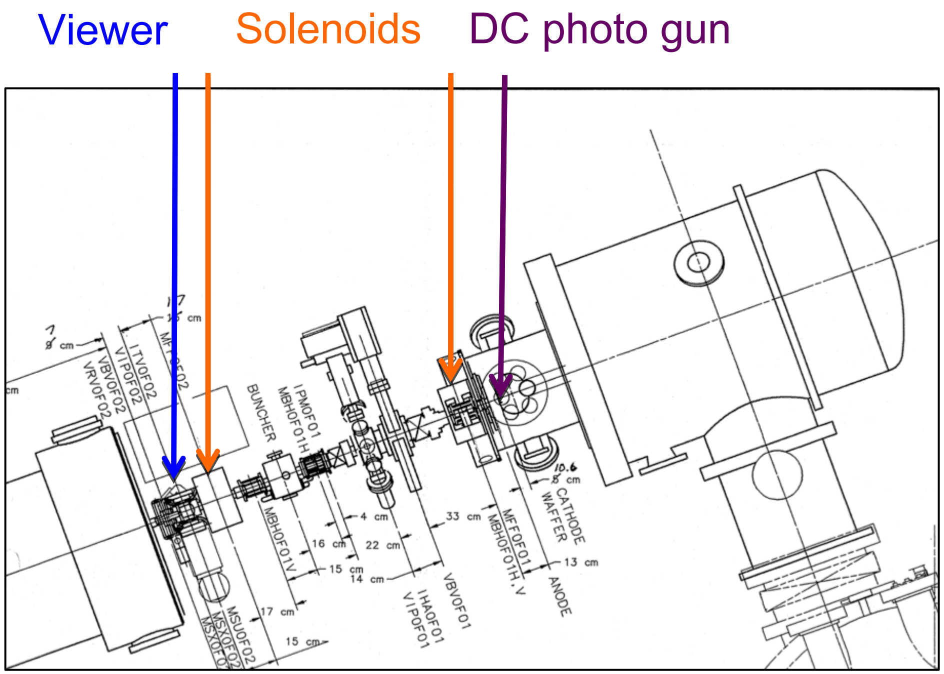




We noticed that we see and electron beam on the 4F06A viewer with the shutter closed. We checked and that were not the EO cells. Putting the 0F04 viewer made it go away so it is from the injector. Changing the first injector solenoid, as Joe has suggested, makes difference for this beam profile. Also bringing the gun voltage to 340 kV makes it go away as well. So it is probably field emission from the gun. We also can see this beam on the 0F04 viewer. Attached are the screen shots of this beam profile on the 0F04 and 4F06A viewers.

Case 2: from the gun to first viewer





To have a better idea where the field emission is coming from (the cathode or the ball) we made a screen shot of the 0F02 viewer with HV on (290 kV) and the solenoids at their nominal settings MFF0F01[3711] MFF0F02[-2673]. The screen shot is attached.

The idea is to make the same screen shot at the same settings of the solenoid at the HV after a heat clean.

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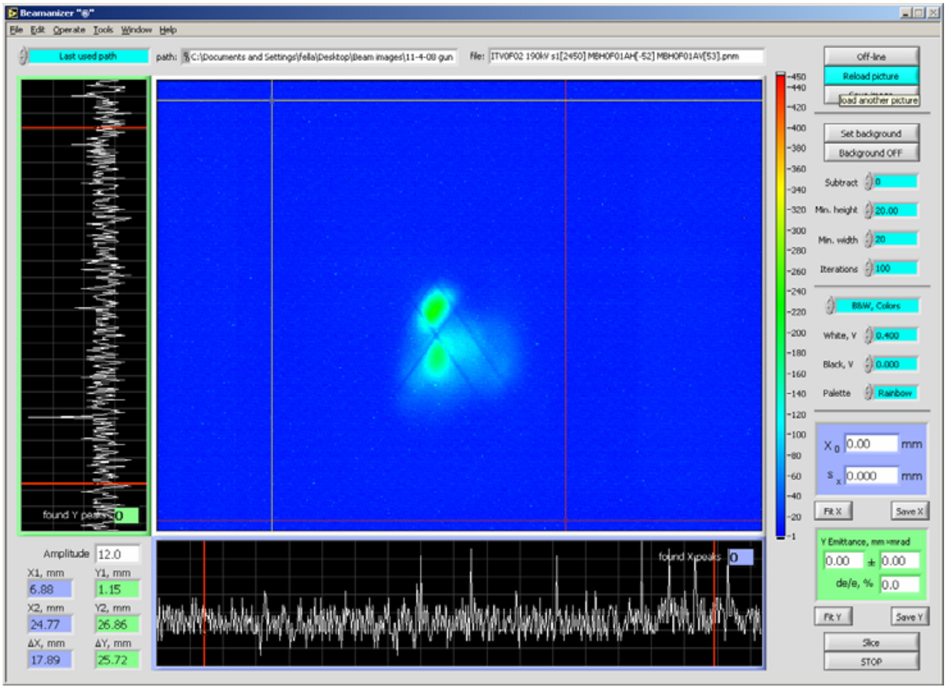
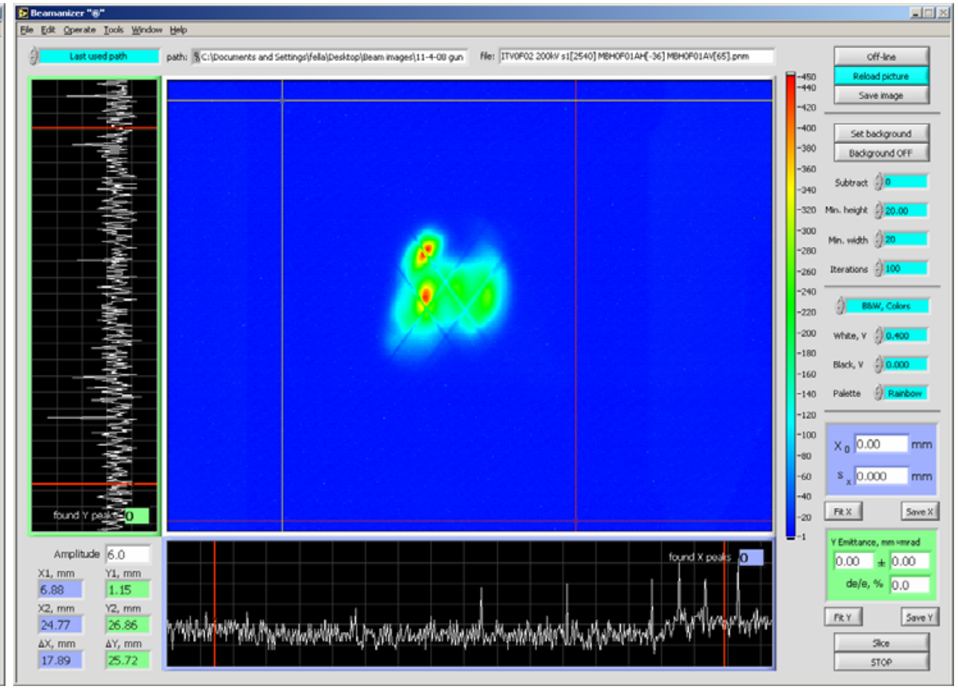
Case 3: from the gun vs. voltage





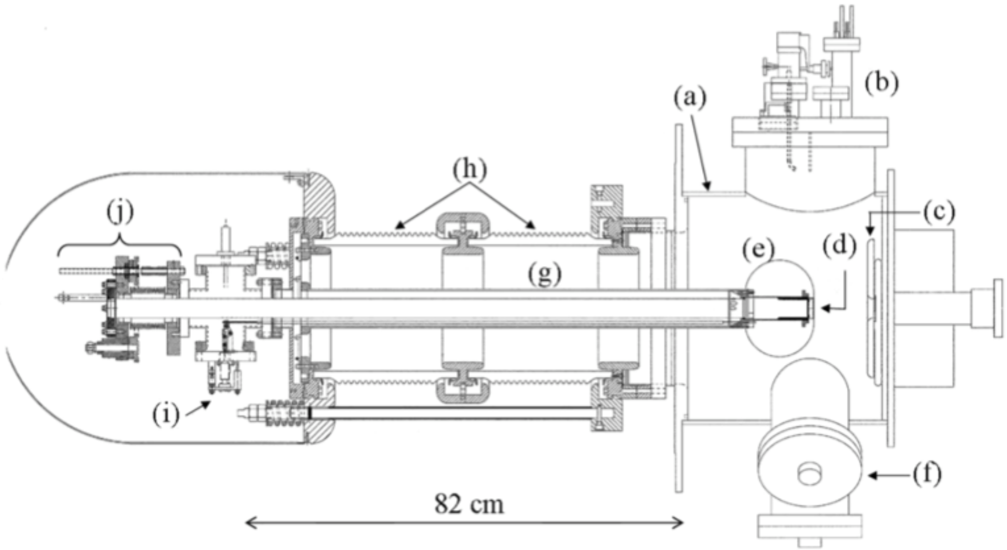
At 290 kV the field emission from the gun was too high to make measurements with the 0F02 viewer. We did two measurements one at 200 kV and another at 190 kV.

The second solenoid was turned off, i.e., set to 0 G/cm and put through the hysteresis loop.

Figure left: shows the measurement made at 190kV.

Figure right: shows the first measurement made at 200 kV.

Kr/HV gun processing



- Field emission in the gun, practically, is the most difficult FE related problem, although does not result in *unwanted beam*
- Unfortunate features of the gun design aggravate the problem

  - strongest field not at the cathode

  - no load lock
- Adopted He processing from SRF, replacing He with Kr; big help with HV processing of FE; essentially is a ion back bombardment localized to FE centers
- All in all HV-processing of the gun without load-lock system is a "Catch-22" between training the electrodes and preserving the cathode
- Described in: http://proceedings.aip.org/resource/2/apcpcs/1149/1/1071_1

General FEL remarks

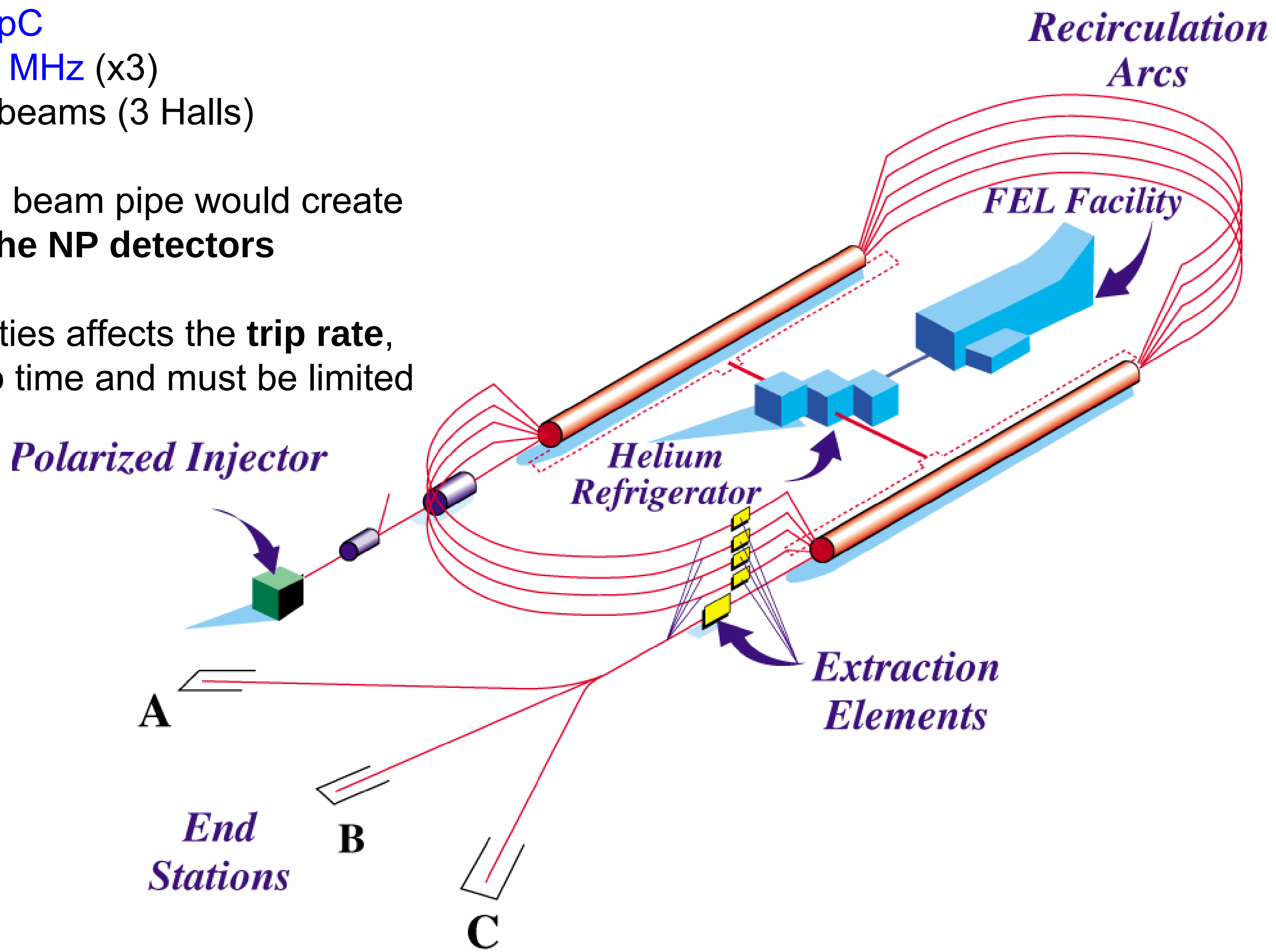
1. JLab FEL is a 9 mA average current machine, despite the fact that all four sorts of beam halo are present
2. Setting up for high current operation requires some time, but can be done
3. To properly (and quickly) deal with *first kind* of beam halo Large Dynamic Range diagnostics are needed; until then takes time and trail and error
4. For Drive Laser transport Brewster angle windows (input and output); essentially light tight beam line; laser transport with spatial filter to mitigate diffraction
5. Scattered DL light on the cathode is a reality one has to leave with, i.e., run beam when it is small enough and replace cathode when it is not.
6. Gradient in the LINAC is limited via requirements to keep dose rate below certain level (especially at the wiggler), but also due to other effects the same as at CEBAF (trip rate)
7. Instruments are:
   - ✓ Beam Loss Monitors (BLM) of the MPS
   - ✓ Rad.Con. calibrated ionization chambers
   - ✓ Radiation survey just after beam operation ended (for chronic losses)

CEBAF: overview

E_{beam} was 6 GeV is being upgrade to 12 GeV
Bunch charge: 0.2 pC
Repetition rate: 499 MHz (x3)
Three independent beams (3 Halls)

1. Beam halo hitting beam pipe would create **background in the NP detectors**

2. FE in LINAC cavities affects the **trip rate**, which reduces up time and must be limited



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CEBAF: trip rate, statistics

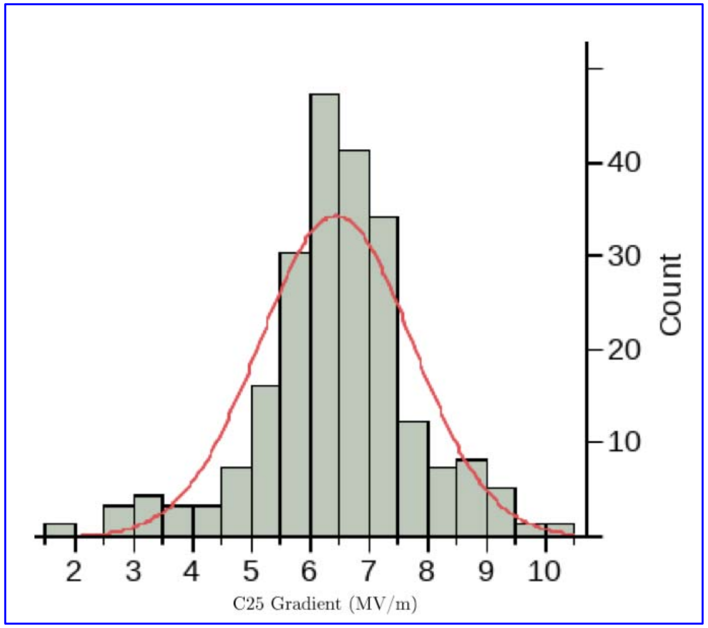
JLAB-TN-05-57 J. Benesch,
Field Emission in CEBAF's Superconducting RF Cavities and Implications for Future Accelerators

JLAB-TN-10-008 J. Benesch,
Comparison of arc models from March 2003/Nov 2004 and December 2009

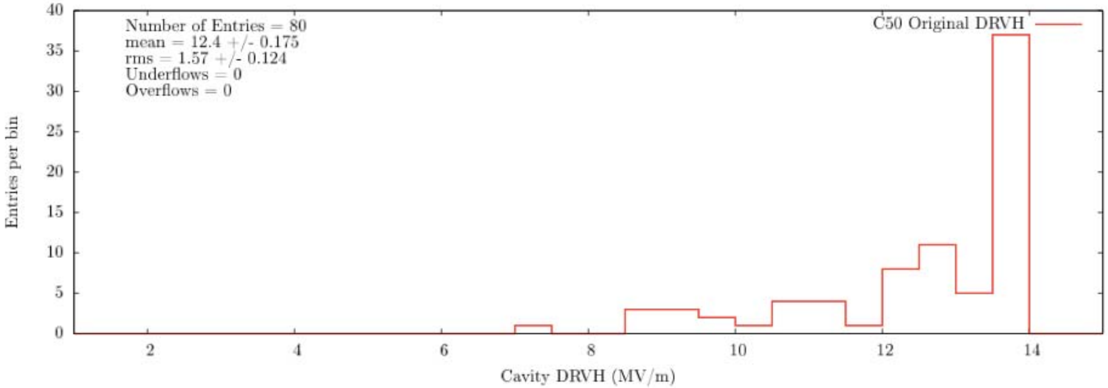
JLAB-TN-12-049 J. Benesch, A. Freyberger,
CEBAF Energy Reach and Gradient Maintenance Needs

- Uses “accounting” and statistical analysis of the trip rate and its dependence on the cavities gradient
- For 12 GeV CEBAF; 400 cavities + each cavity trips 1/(2 days) would result in on average 8 RF trips per hour
- Original C25 design / unfortunate feature / RF window has a direct line of sight to the beam – charges up / eventually break down
- With time performance of cavities degrades i.e. at the same gradient trip rate goes up exact mechanism is not known (speculated that # of FEs goes up)
- Conclusion – gradient maintenance is needed (reprocessing cavities and refurbishing the cryo modules)

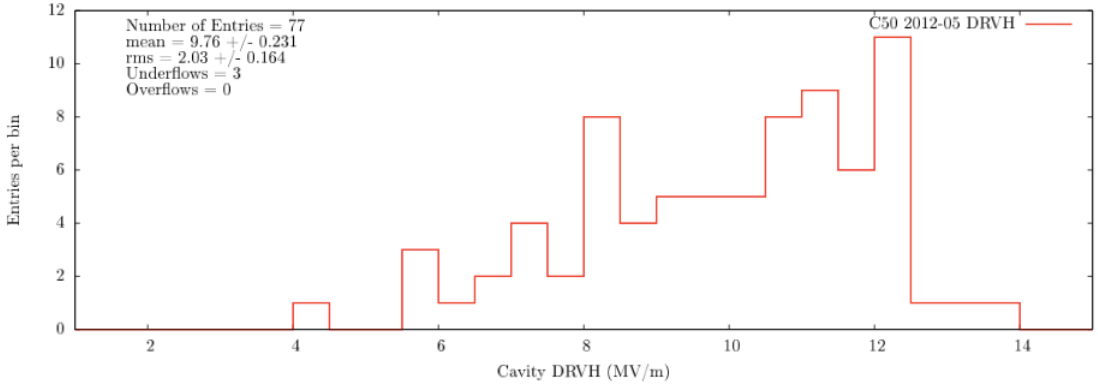
CEBAF: trip rate



Distribution of gradients in C25 cavities that resulted in 1/(2 days) trip par cavity



Initial distribution of gradients of C50 cavities

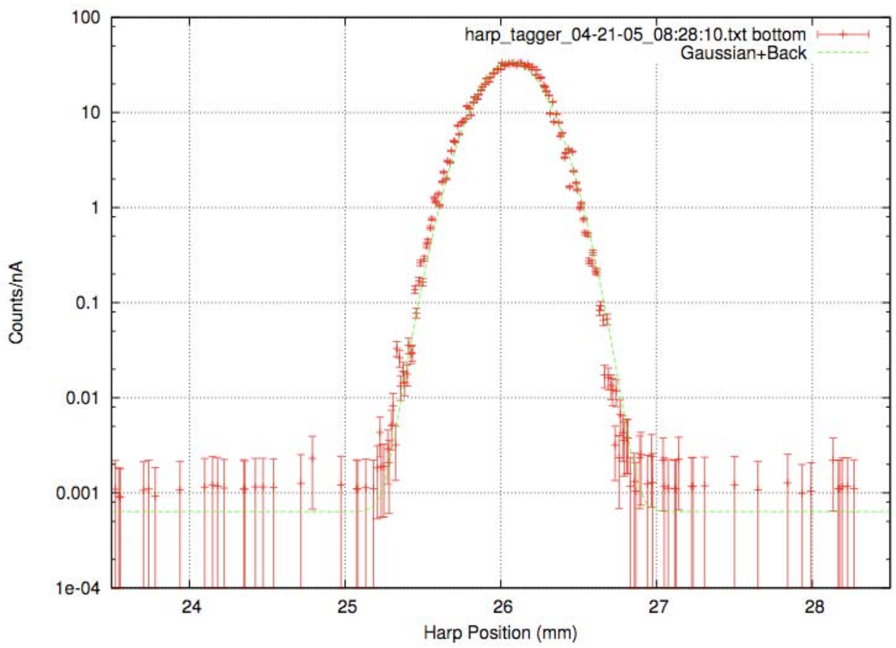


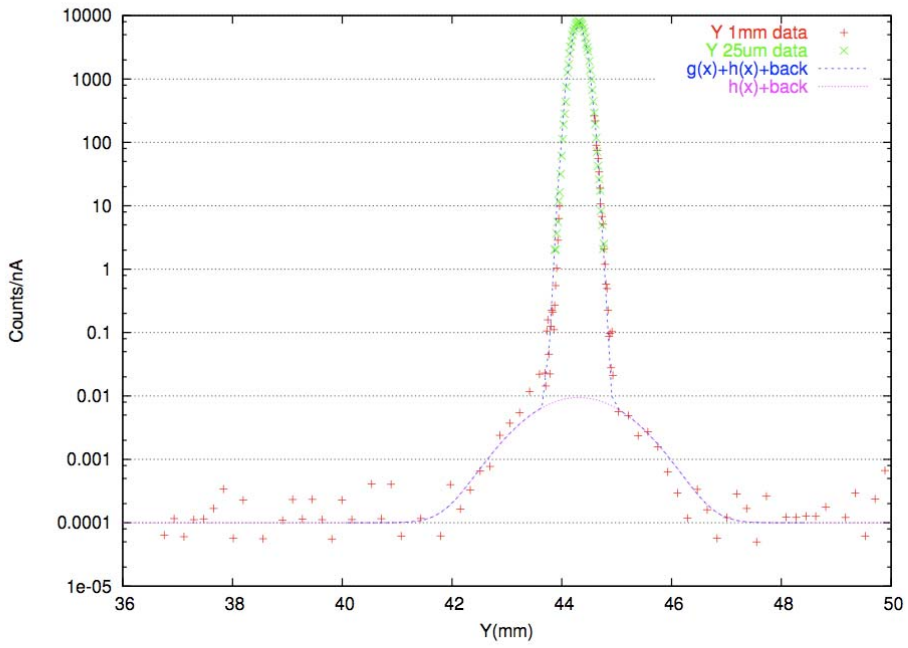
Distribution of gradients of the same C50 cavities at the end of 6 GeV operation (~ 4 years later)

Courtesy of J. Benesch

CEBAF: no Halo ?

- One ways to make large dynamic range measurement is to arrange it to be frequency measurement
- Then make it work for 1 Hz and for 100 MHz and this is 10^8 dynamic range.
- For instance use PMT and keep them working in counting mode





Courtesy of A. Freyberger

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CEBAF: vacuum

- Despite the idea/claim that CEBAF beam is quite Gaussian and has no or very little large amplitude non Gaussian tails, there are vacuum “events”
- Two types of events:
  1. Burn through that require a new piece of beam pipe to be fabricated as it has a hole drilled into it.
  2. Low current, very low intensity lose (chronic lose) that heats up a flange. This requires Rad. Con. to identify the hot spot, and then the flange is tighten up and the region recovers quickly.
- Frequency of such events is 1-2 per year (35 weeks of operation)
- Type2 is due to some kind of beam that is not seen (not looked for)
- Type1 (some of them) related to rapid energy change due to RF changes
- Fortunately it did not happen close to the SRF LINAC

Conclusion / Summary

- **JLab FEL (IR/UV Upgrade)**
  - RF gradients in **LINAC** always require attention, **set** radiation **background** level (FE)
  - HV-DC **gun** very **tricky** to process (new gun should improve it a lot) “Catch-22”
  - Drive Laser transport if made very carefully, seems to be not a problem
  - Drive Laser rep. rate control (EO cells) always need attention (extinction ration drifts)
  - Cathode suffers when conditioning and from breakdowns, still makes beam as needed, but scatters DL light – generates some halo
  - Non-linear beam dynamics is responsible for some fraction of the halo. When setting up for high current operation, a lot of effort and time goes in to **“fitting” the halo through the recirculator**, such that peak beam brightness does not suffer.
  - Radiation monitors, BLMs and vacuum are used as tuning diagnostics
- **CEBAF**
  - NP detectors (background) require essentially no beam halo
  - Large statistics of cavity performance and its evolution (FE)
  - Direct effects of FE – RF trip rate, reduction of max. possible energy
  - Vacuum events related to beam loss (both high and very low current)

The End