PXIE LEBT Commissioning Update

Lionel Prost

on behalf of, R. Andrews, B. Brooker, K. Carlson, J.-P. Carneiro, J. Czajkowski, R. D'Arcy, F.G. Garcia, B. Hanna, S. Hays, W. Johnson, M. Kucera, A. Saewert, G. Saewert, V. Scarpine, A. Shemyakin, D. Slimmer, D. Snee, J. Steimel, T. Zuchnik, mechanical, electrical and other technical support

PIP-II Technical Meeting

January 6th, 2015

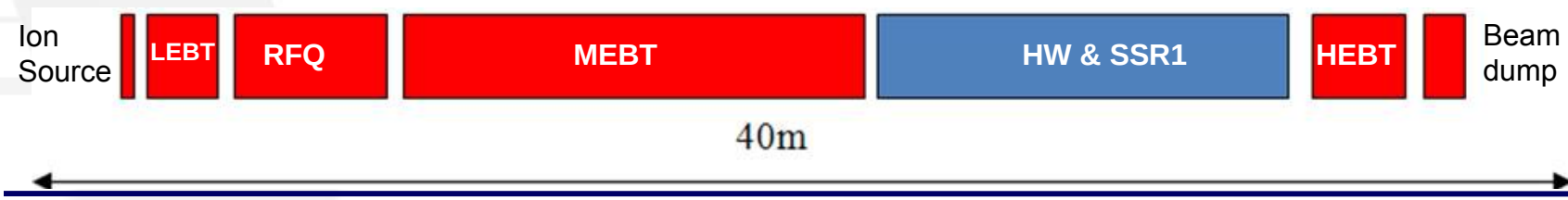
Fermilab

Content

- Context and setup
- Machine reliability
- Optics
  - Matching
  - Stability
- Final comments

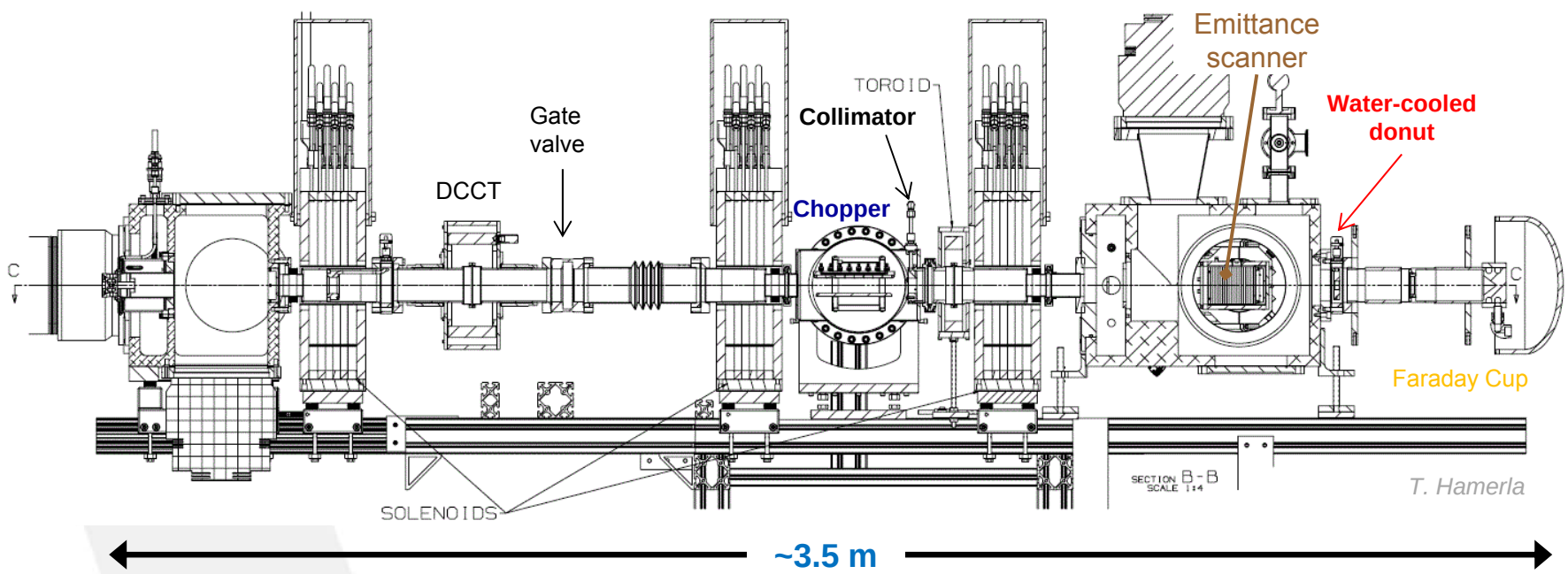
Role of LEBT in PXIE

- Prepare beam for RFQ (i.e. α, β) and machine protection
- DC operation
  - 5 mA, reliable and 'stable'
    - $\varepsilon_{n,rms} \leq 0.25$ mm mrad
  - Uncontrolled losses <10%
- Pulse operation
  - 1-16667 μs, 60 Hz
  - Twiss functions representative of DC beam operation
    - To transition from short pulse (commissioning) to DC (normal operation)
      - *If not the same, DC Twiss functions should be predictable from short pulse measurements*

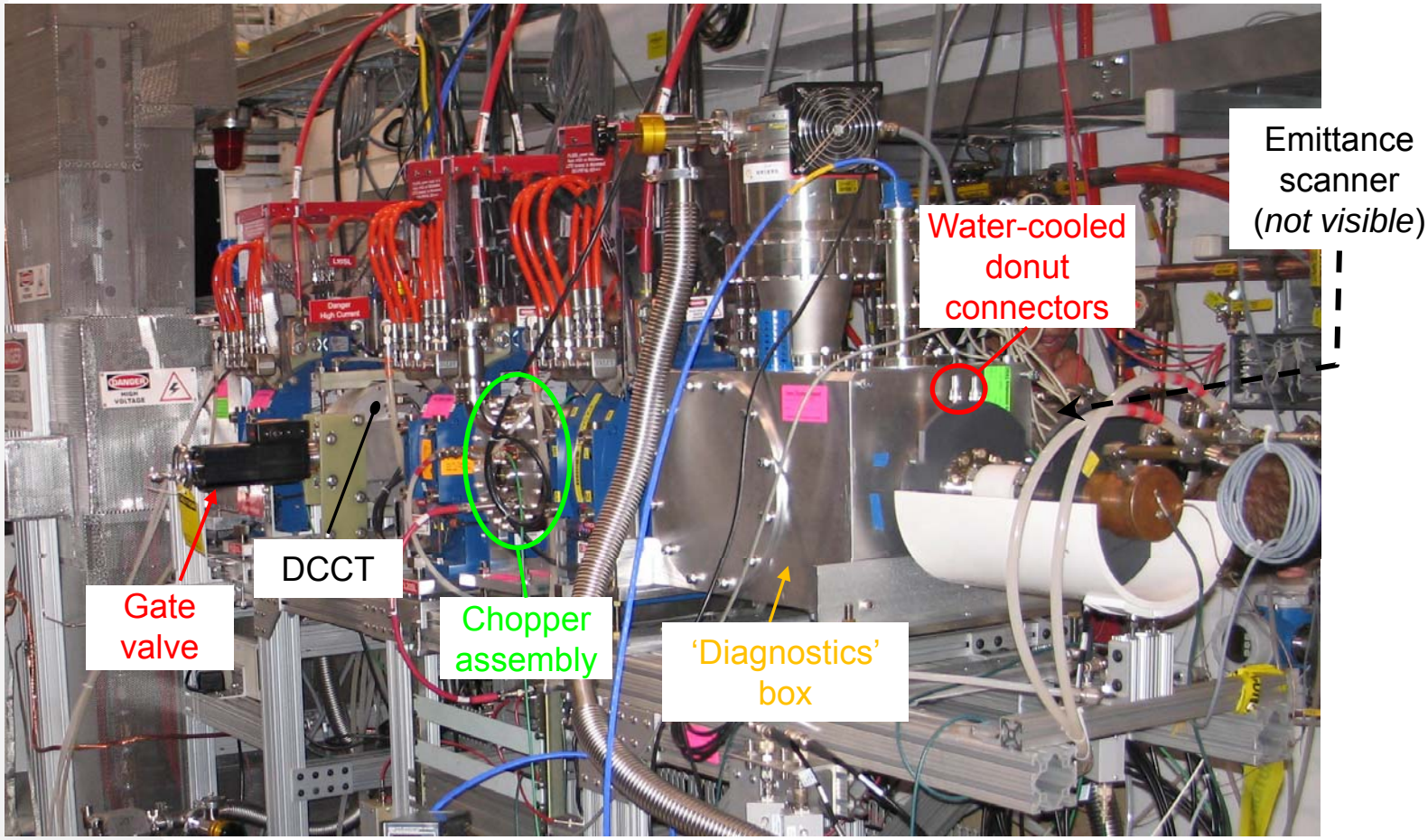


Current setup

- Same as last LEBT update (November 11, 2014) with minor additions
  1. Linear motion encoder installed on emittance scanner
     - Feedback loop for motion control
  2. IR camera pointed toward absorber plate to monitor spot size

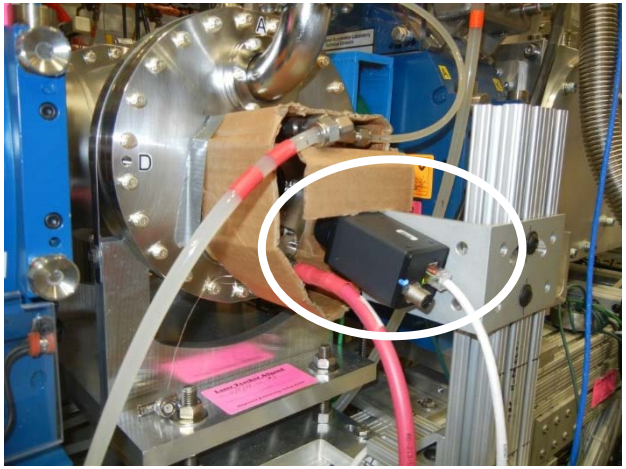


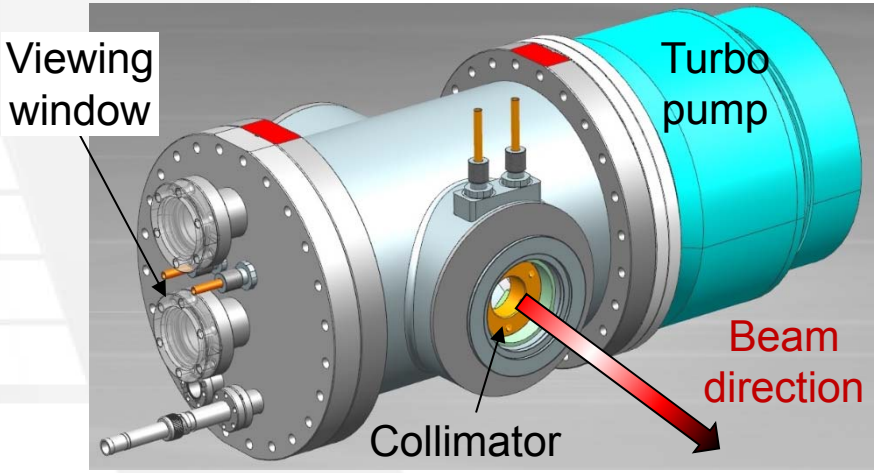
Setup in picture
(w/o IR camera)

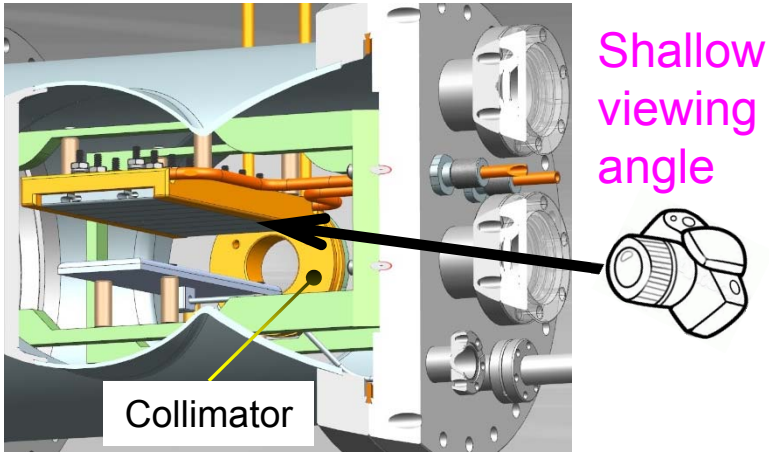


IR camera focused on absorber plate

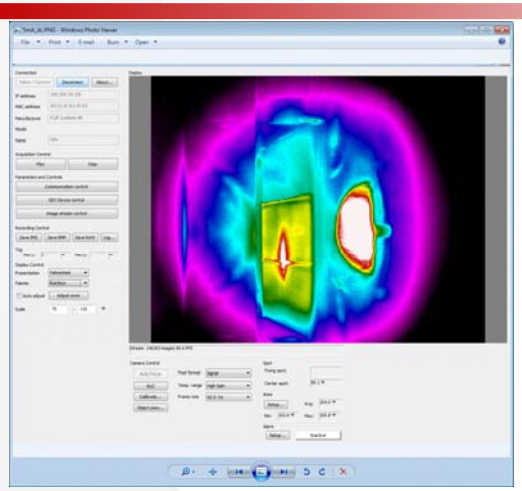
- FLIR A35 IR Camera
  - 320 x 256 pixels
  - Uncooled microbolometer pixels
  - 7.5 – 13 mm spectral range
  - 1.32 mrad spatial resolution
  - GigaE compliant



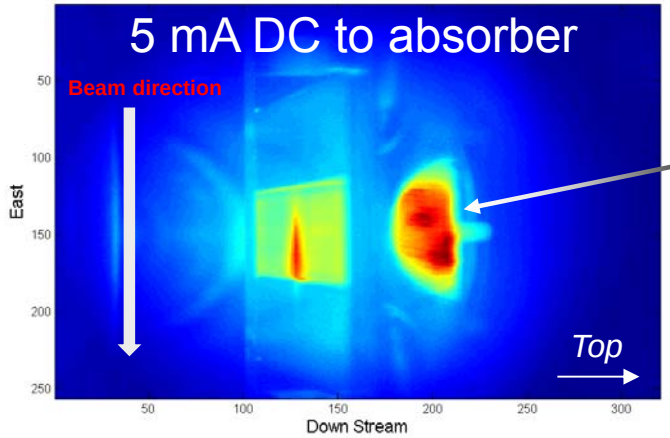




Sample images – DC beam to absorber

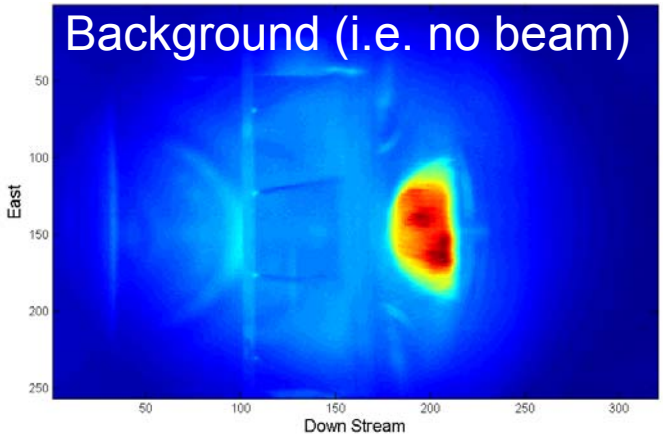


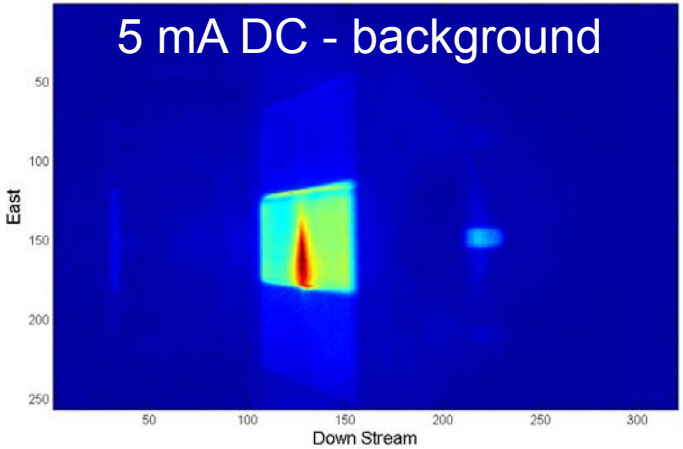
Data acquisition GUI



Hot spot from ion gauge

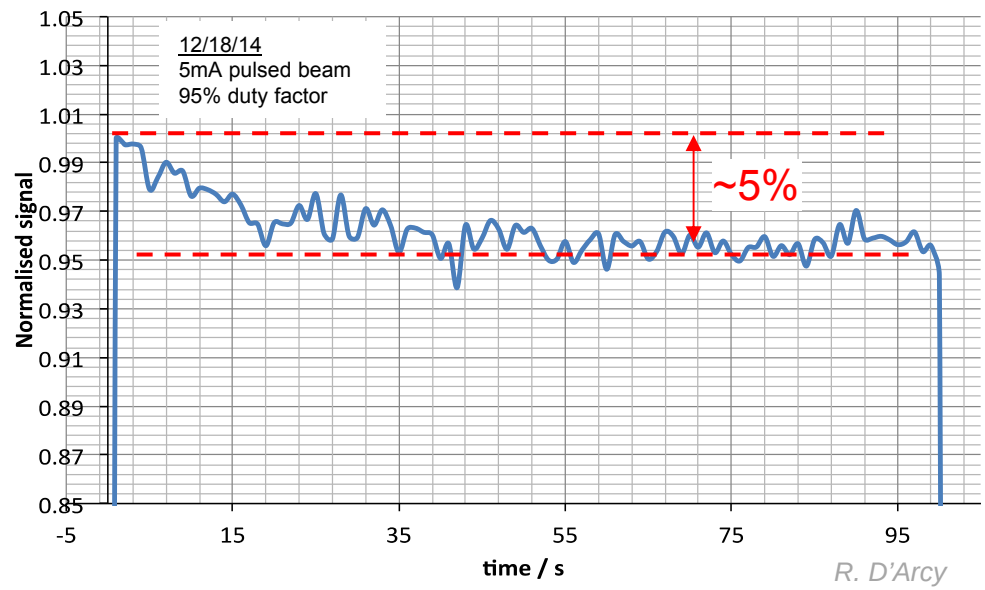
V. Scarpine





Emittance scanner characterization

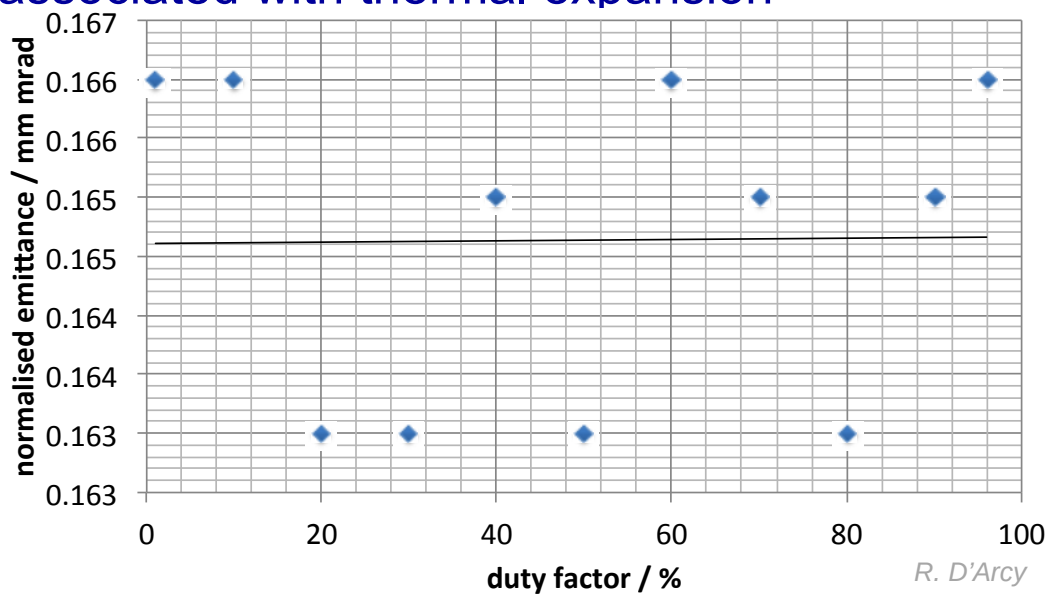
- Measurements have been carried out in order to quantify various sources of error
  - Most of analyses are in progress
  - Most recent focus on thermal effects
    - Thermal simulations indicate a possibility for the slit width to change quite significantly depending on the beam properties (e.g.: spot size, density distribution…)
    - With fixed slit position, signal intensity decays over time
    - May be important for DC vs. pulse beam measurements



R. D'Arcy

Emittance vs. duty factor

- To address the possible effect of slit width variations on the measurement of the beam emittance, full phase space distributions were acquired for fixed optics settings but different duty factors
  - Absence of a correlation between duty factor and emittance indicate that the error associated with thermal expansion of the slits is of the order of ±1%
  - More importantly, short pulse and DC beam emittance measurements can be compared without introducing additional uncertainties



R. D'Arcy

LEBT performance

- Demonstrated up to 10 mA, DC and pulse
  - Low *uncontrolled* beam loss (<2%)
  - Up to 60 Hz pulses *New*
    - Typically 1-ms long
  - Over 4-8 hours

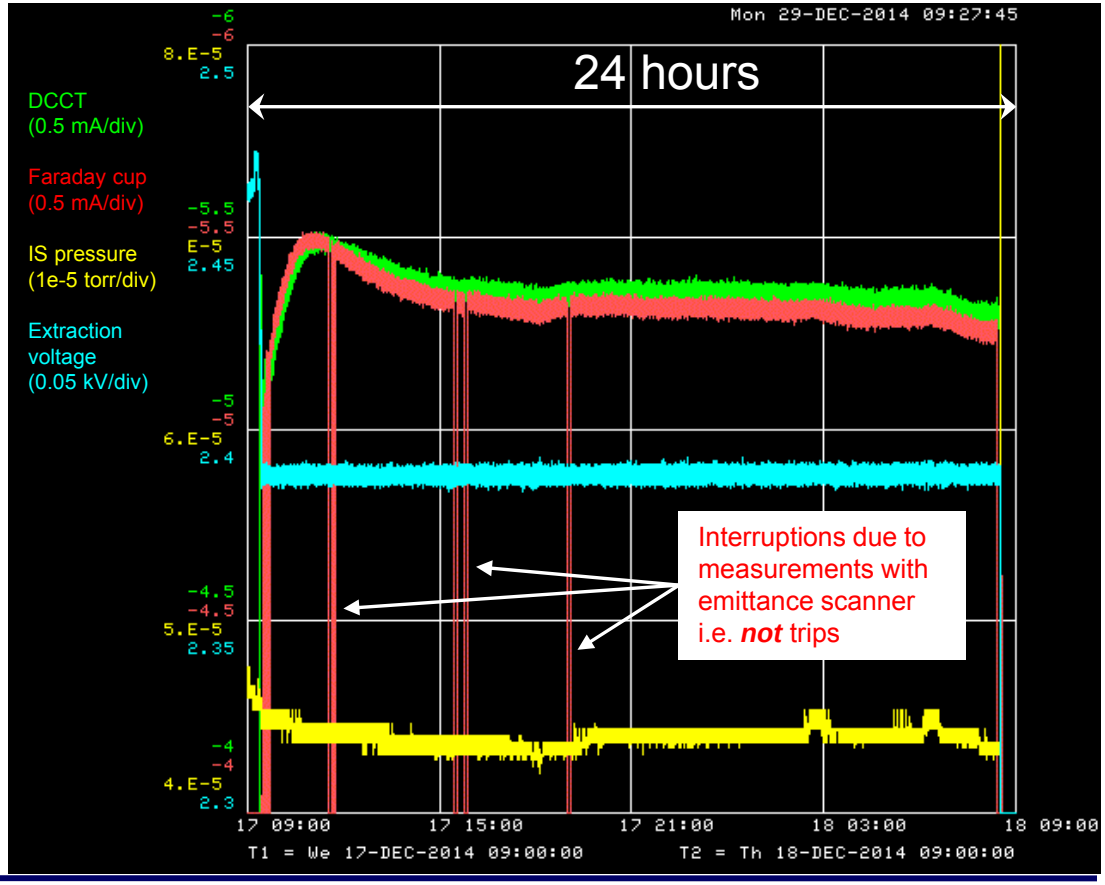
- Demonstrated chopping
  - Ion Source DC or long pulse (~10 ms)
  - 1μs to 16.6 ms pulses at 60 Hz
    - Faster rise/fall times than the IS pulse

LEBT reliability

- Need to demonstrate potential for continuous operation
  - Conducted two 24-hour runs with nominal beam current (5 mA)
    - DC and chopped
- Main questions: Frequency of beam interruptions and stability of beam parameters
  - Experienced beam trips in DC mode during 'regular' shifts before Oct'14
    - None since (other than related to known/understood issues, e.g.: water trips)
      - *Minimized current to extraction electrode*
  - Worked on how to deal with interruptions if they occur
    - Remote resets
    - Finite State Machines
      - *Eventually, try to limit need for human inputs*
  - Currents (DCCT, FC, electrodes) are data logged; Twiss functions were measured a few times during long runs

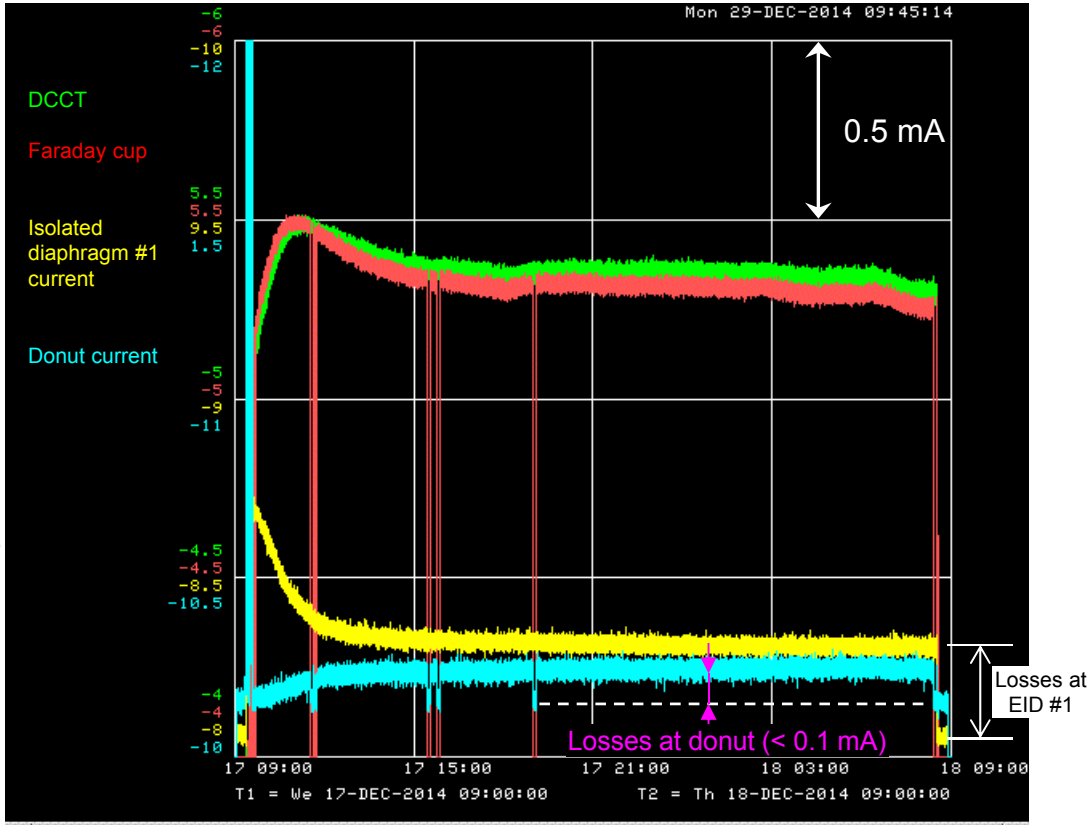
Successful long run demonstration - DC
(Dec. 17-18, 2014)

- 5 mA DC to Faraday cup for 24 hours without any trip
  - Had to install additional blocks and gates to close up cave during unattended operation (e.g.: at night)
  - Off-hours monitoring by Operators in MCR
    - Setup 'comfort' displays
    - Alarm blocks have been created



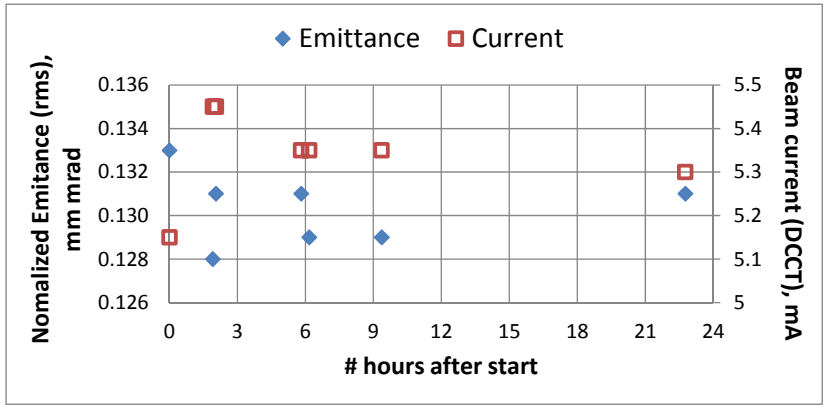
Beam current evolution

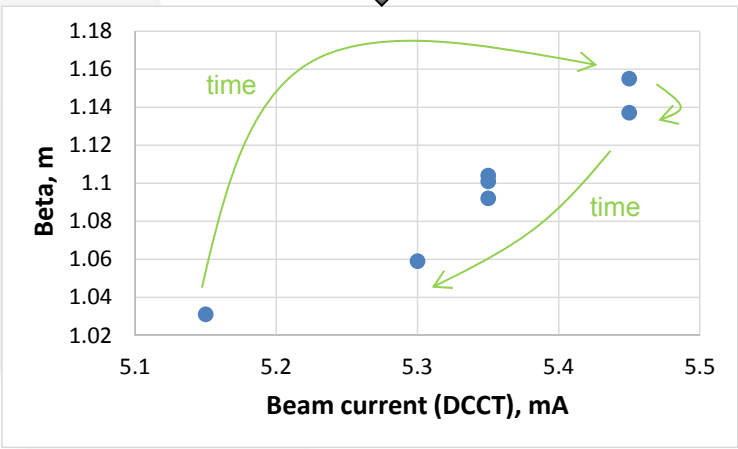
- Beam current increased by ~0.4 mA over the first ~2 hours of running
  - Typical behavior
  - Another ~4 hours for the current to 'stabilize' at ~5.35 mA
  - No attempt to regulate the beam current
    - Arc power is kept constant via adjustments to the filament current
- Balance of currents maintained throughout

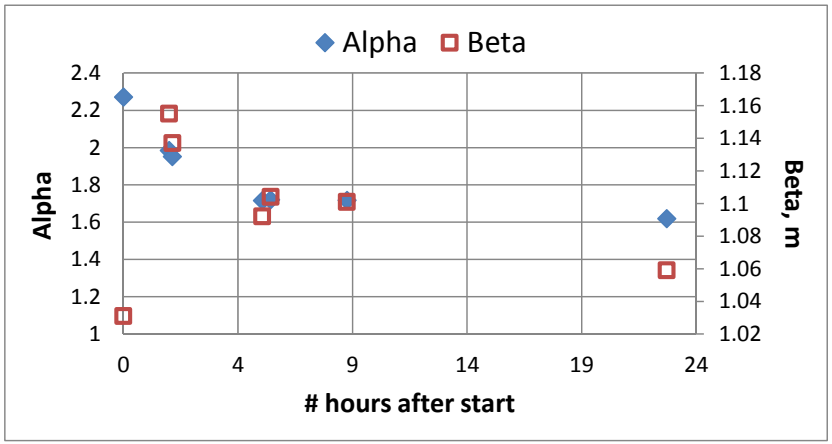


Beam parameters evolution

- Emittance constant to within ±2 %
  - Beam current changed by 5.6% (min-max) over the entire run
  - Alpha changed (min-max) by 35% and beta by 11%
- If any, possible correlation between beam size and current

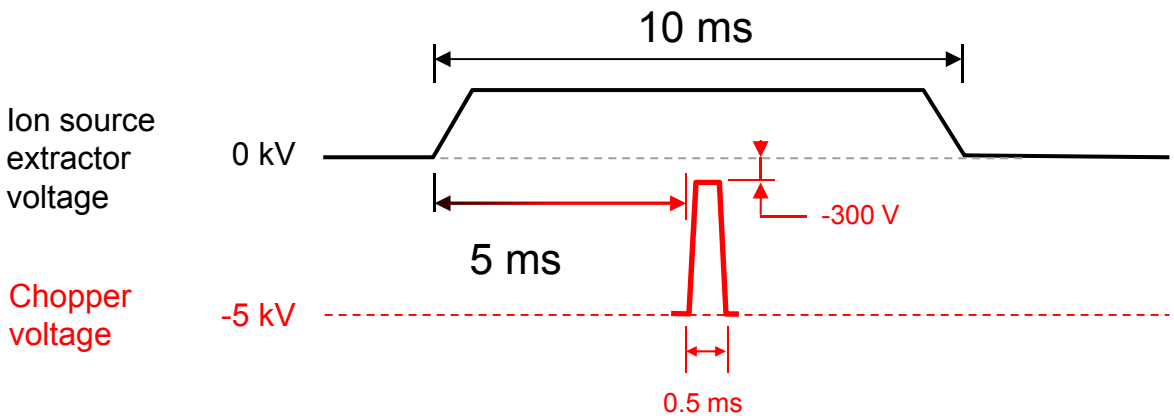






Chopped pulse formation

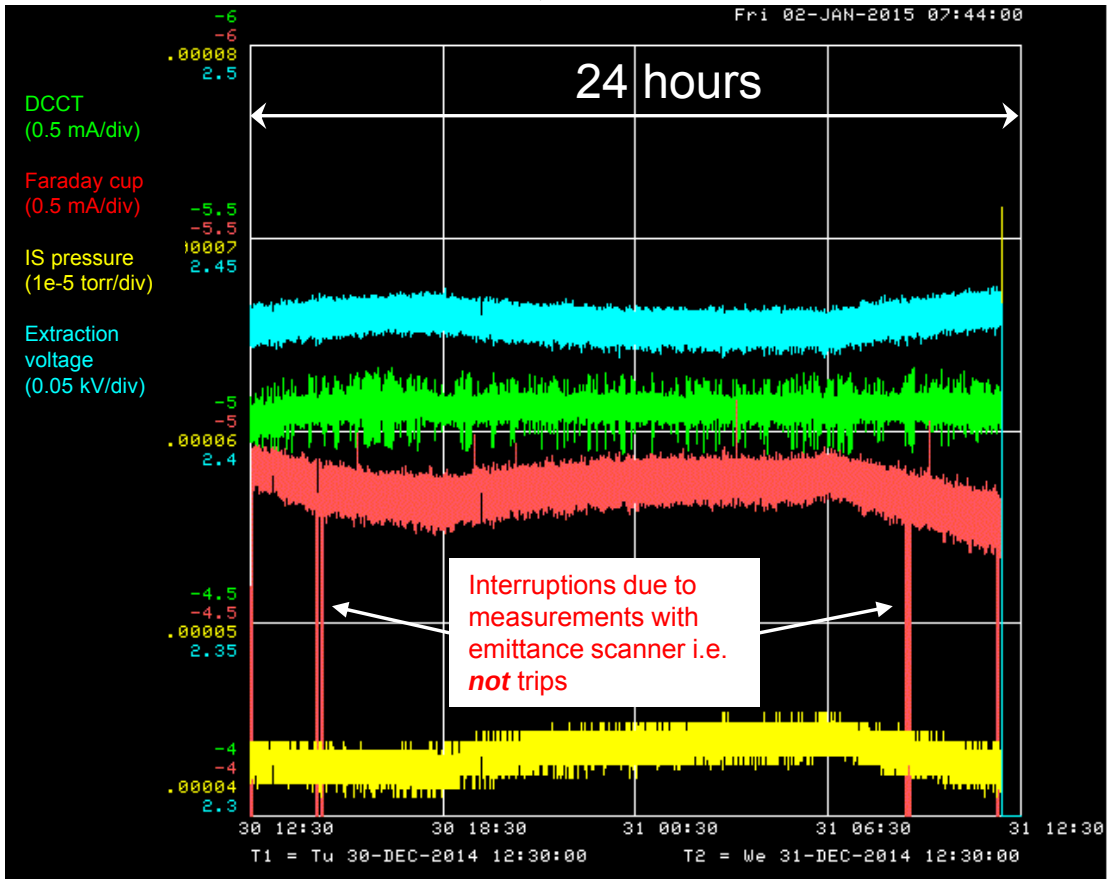
- Demonstrate reliability of the modulators
  - 10 ms pulse from the Ion Source at 60 Hz
  - 0.5 ms pulse from the chopper, ~5 ms after the start of the IS pulse



  - 'Ion Clearing' on
    - Kicker plate biased to -300 V

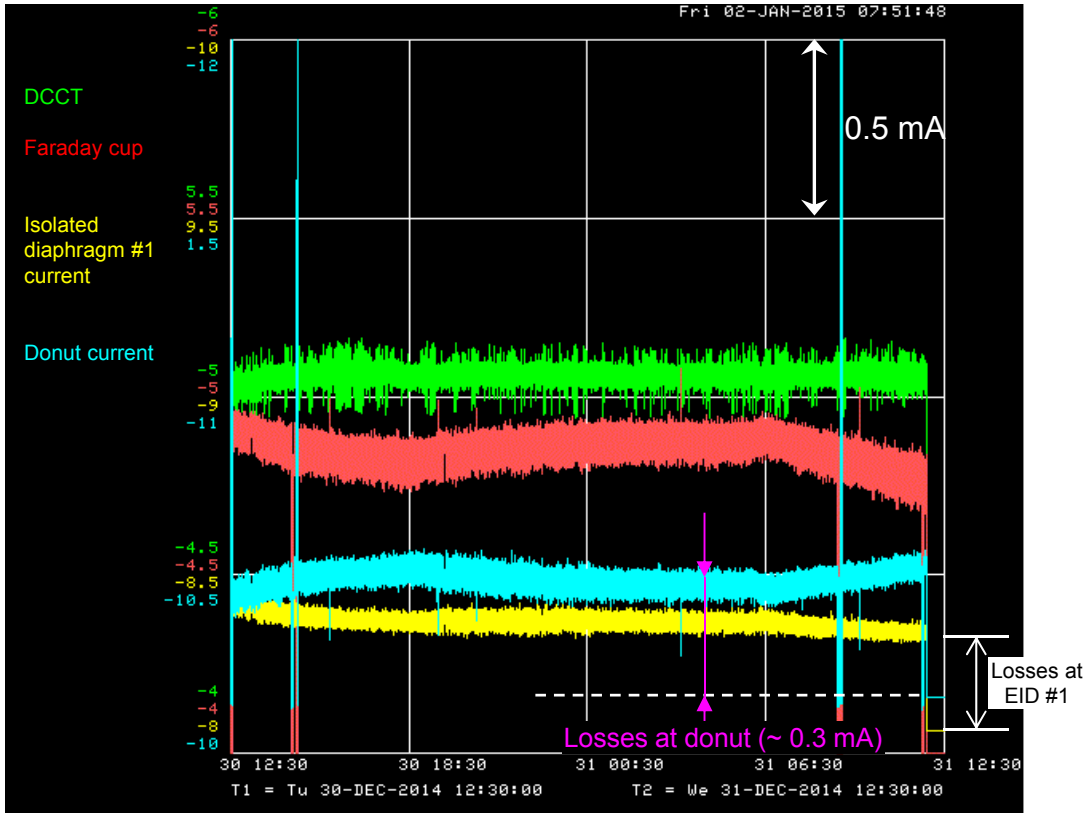
2nd long run demonstration - Pulsed (Dec. 30-31, 2014)

- 5 mA, 10 ms pulse at 60 Hz from IS, 500 μs chopped pulse to Faraday cup for 24 hours without any trip
  - Current out of the IS more stable than previous run b/c it had been running in the morning (studies)
  - 'Noisier' read backs than for DC run



Beam current evolution

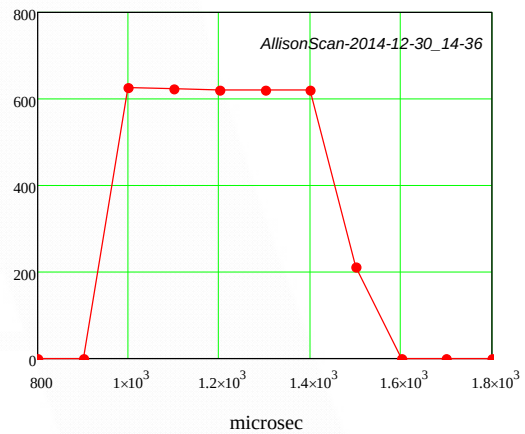
- Steady current out of the ion source, however…
  - Beam parameters must have changed
    - Losses to donut and FC signal not as steady as DCCT (but mirror one another)
- Balance of currents ~maintained throughout



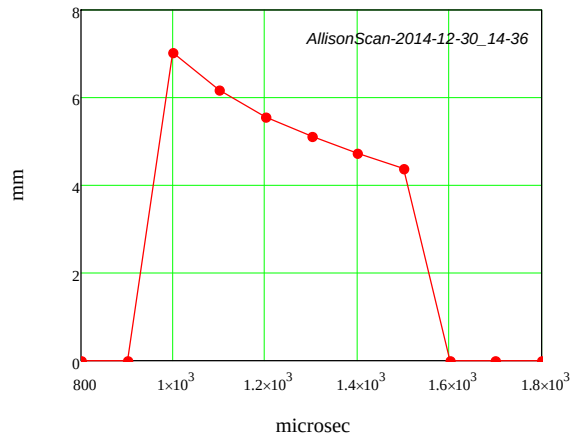
Beam parameters evolution

- Like for DC:
  - Emittance constant to within ±2 %
  - If any, possible correlation between beam size and current (as measured by the phase space image integral)
- Large variations *within* the pulse (chopped)

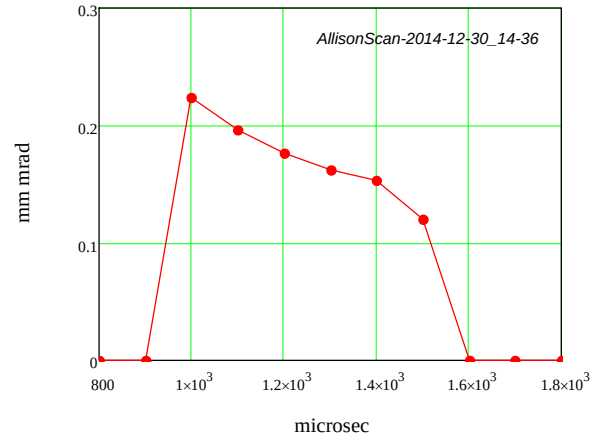
Image integral vs. time



Beam size vs. time



Normalized emittance (rms) vs. time



Beam spot on absorber during the run

- Taken throughout 24-hour run (57% duty factor) with IR camera
- Not calibrated: with shallow angle scale just indicates the *direction* of the changes

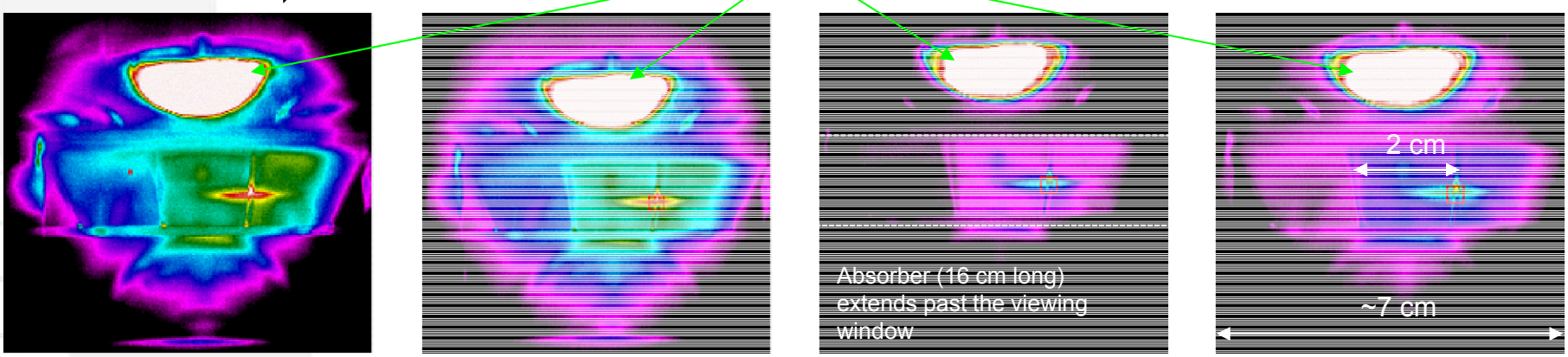
Scale*: 82 – 104°F

* *Absolute calibration is unknown. May be off by 10-100×*

Beam direction

Ion gauge

Top



12:35 15:00 09:05 11:50

Hot spot*:

103°F ----------→ 98°F

Long run tests summary

- High availability
  - 100% during the dedicated tests
- But measurable drift of Twiss functions
  - Origin unknown

- Currently, the short pulse is not a good representation of the DC beam for injection into the RFQ
  - *Caveat*: Present setup without the isolated diaphragm in Solenoid #2 (or its close vicinity) is ***not*** the one envisioned
    - No positive ion blocking upstream of the kicker ⇨ Dynamic (i.e. time dependent) neutralization effects may occur downstream

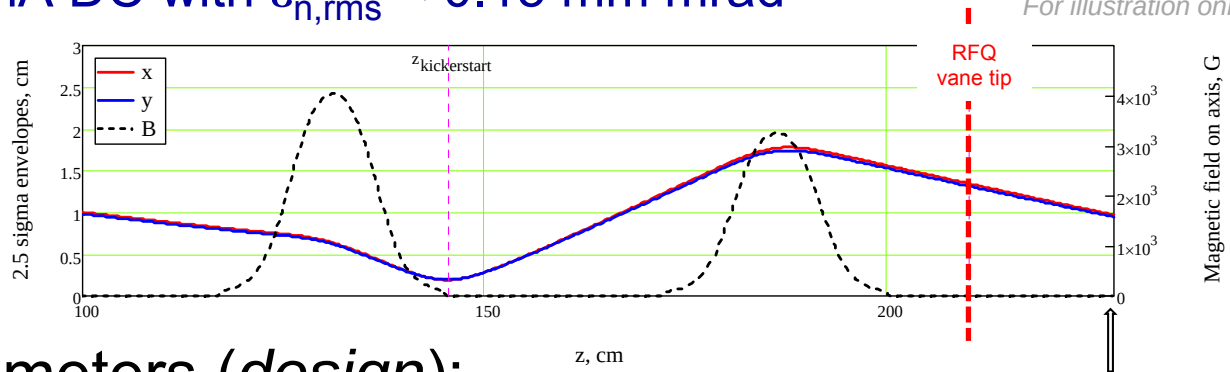
Optics

- Good model still needed to understand:
  - How to match the beam to the RFQ
  - Observed drifts of the Twiss parameters
- Simulations in progress
  - In-solenoid correctors have been implemented in TRACK by Jean-Paul
- Do not have quantitative model of neutralization

RFQ matching

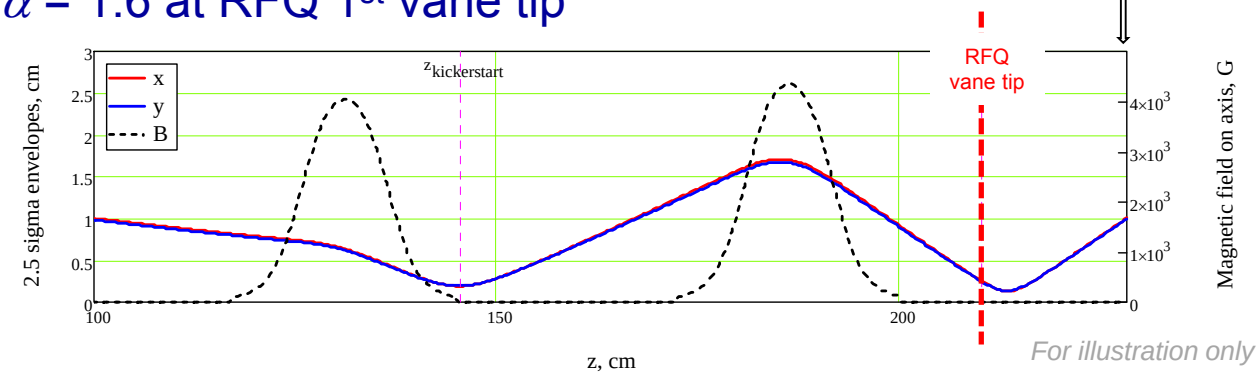
- Without matching constraints:
  - Achieved 5 mA DC with $\varepsilon_{n,rms}$ < 0.15 mm mrad

For illustration only



- Matched parameters (*design*):
  - β = 7 cm and α = 1.6 at RFQ 1st vane tip

Emittance scanner front slit



For illustration only

Extrapolation to interpret data

- 'Simple' drift between RFQ 1st vane tip location and location of measurement with emittance scanner
  - Without space charge and constant emittance:

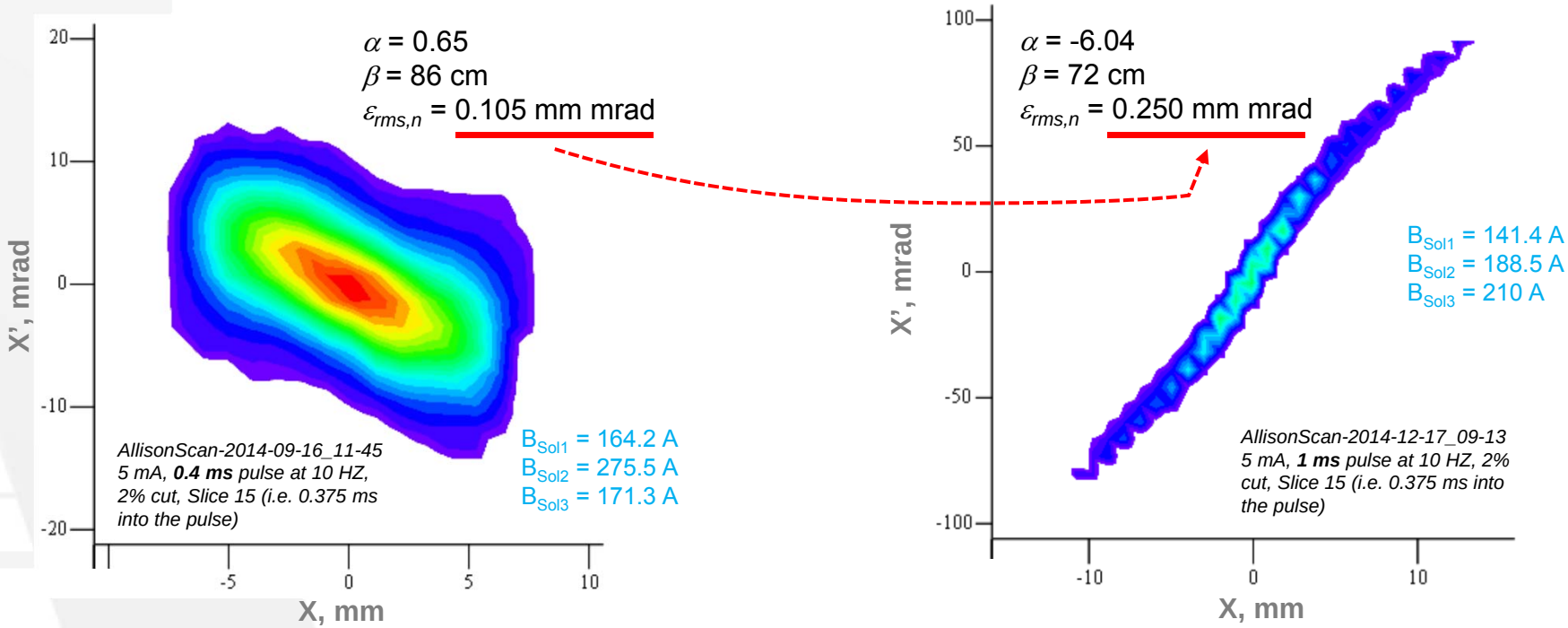
$$\beta(z) = \beta_0 - 2\alpha_0 \cdot z + \gamma_0 \cdot z^2$$
$$\alpha(z) = \alpha_0 - \gamma_0 \cdot z$$

⇨ Matched Twiss functions at scanner location:
β = 106.9 cm, α = -7.31

  - Assumptions for extrapolation are a source errors for matching
    - Also, measurements carried out in one direction only (currently horizontal) and beam is assumed to be axisymmetric

‘Matched’ solution

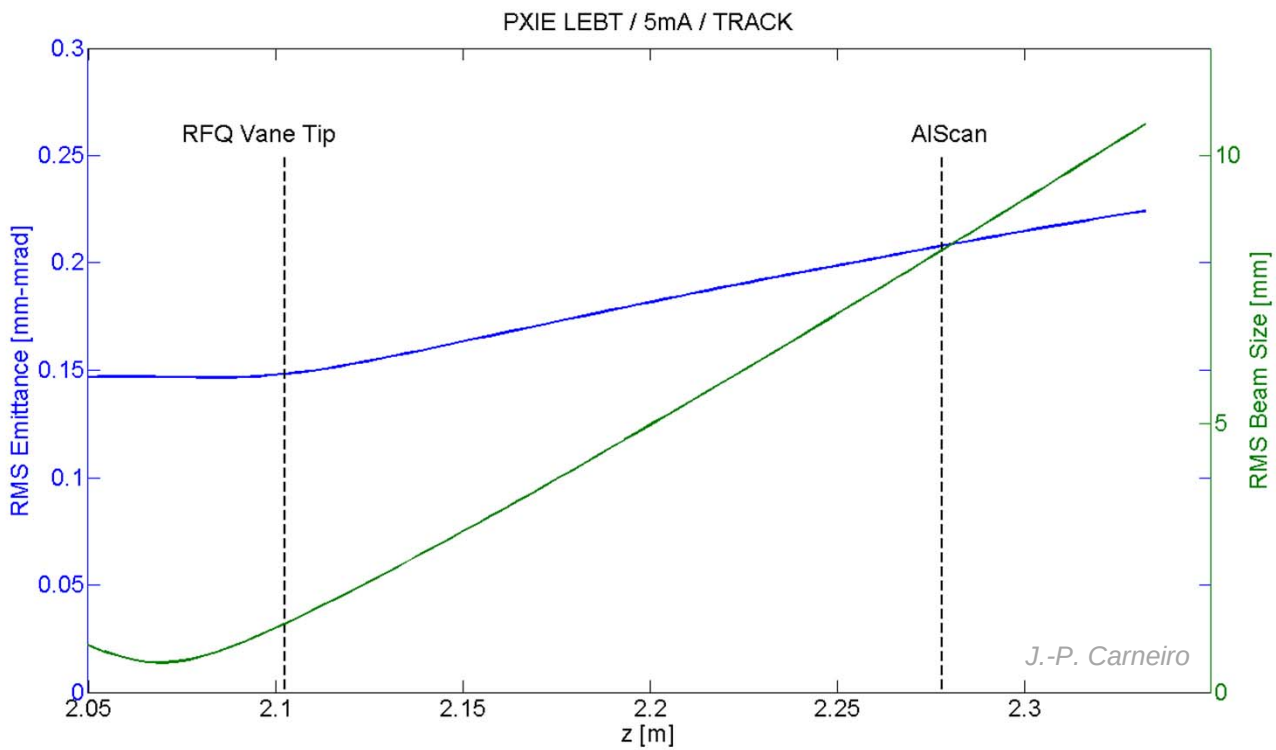
- Lead to emittance growth with respect to what has been achieved before



Extrapolation uncertainties

- *In theory*, emittance measured at Allison scanner may be different (higher) than the emittance at the RFQ entrance

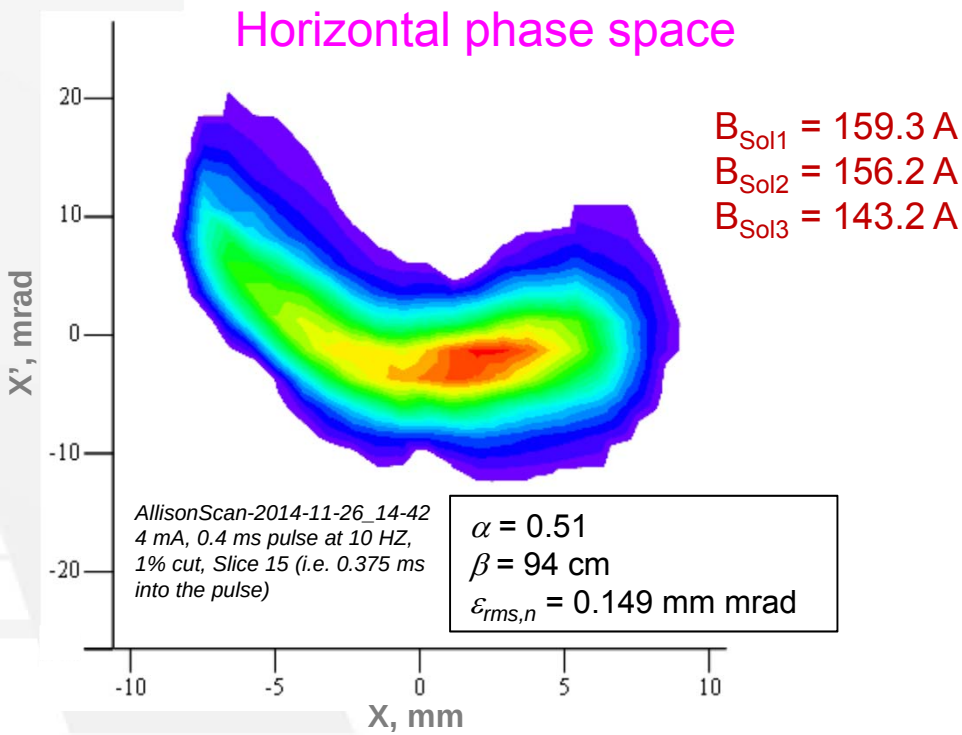
TRACK simulation:
5 mA, 3D space charge field (154.7, 189 and 230 A for the solenoids #1-#3, respectively)



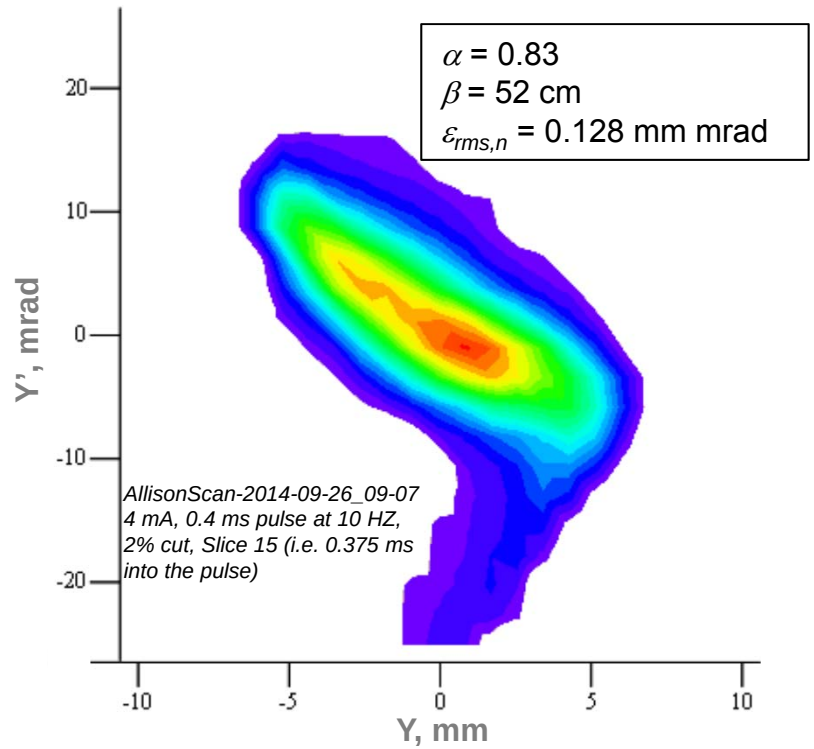
Vertical vs. Horizontal (I)

- Same settings gave different result
  - *Not exactly* the same beam line (*BPM before, chopper now…*). Data taken months apart.

Horizontal phase space



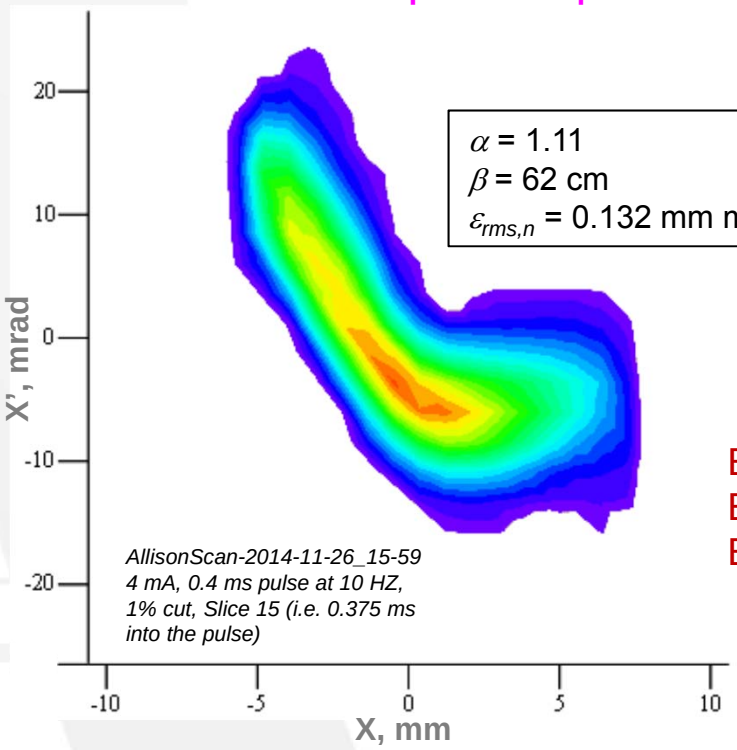
Vertical phase space



Vertical vs. Horizontal (II)

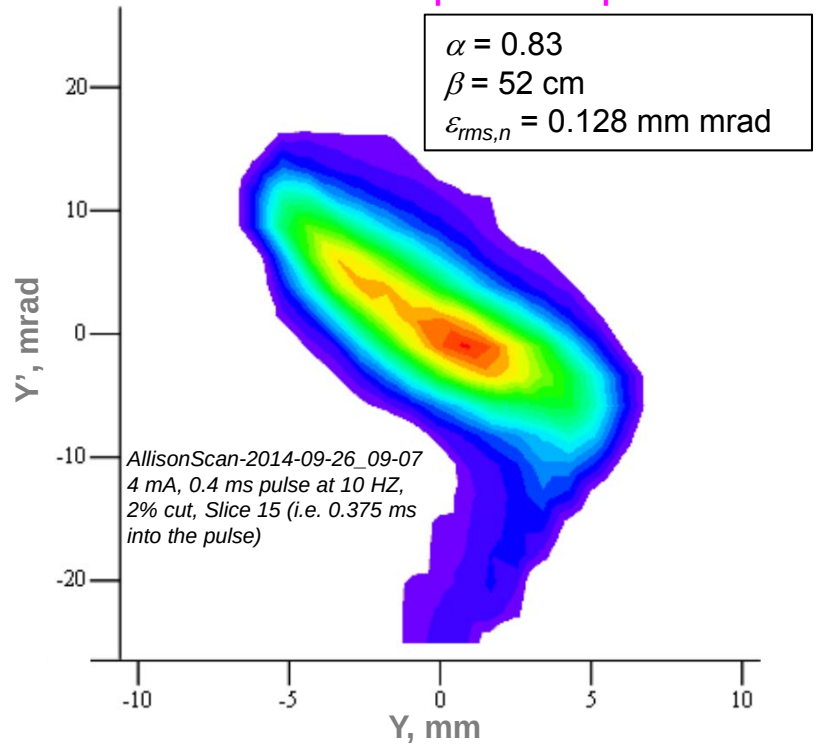
- Only difference with previous slide: chopper turbo pump off
  - Significant differences but no agreement with vertical phase space data

Horizontal phase space



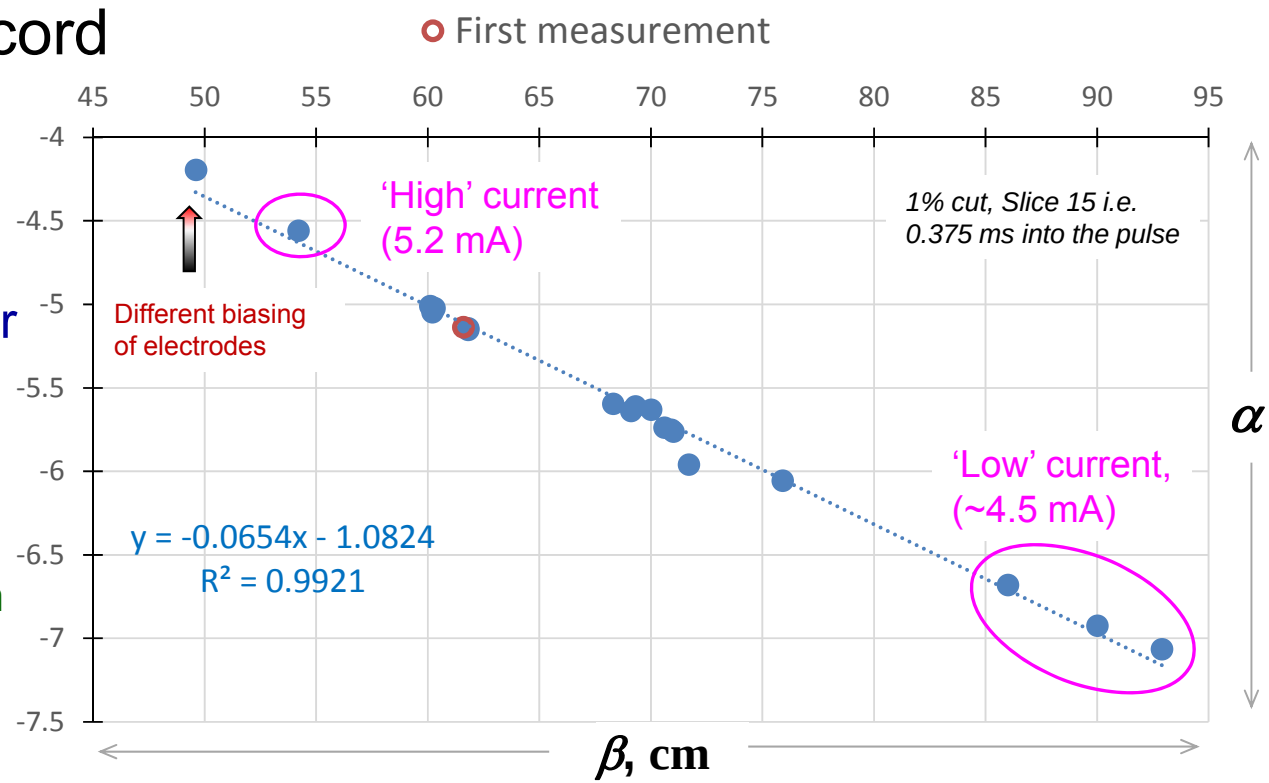
B_{Sol1} = 159.3 A
B_{Sol2} = 156.2 A
B_{Sol3} = 143.2 A

Vertical phase space



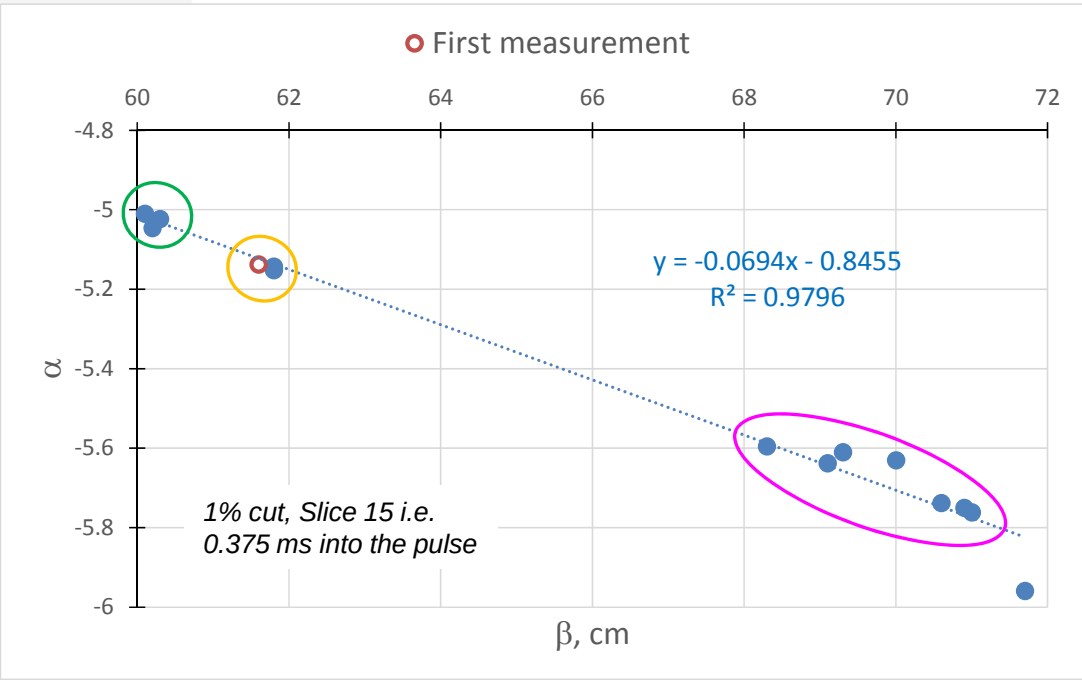
Beam/machine stability/reproducibility (I)

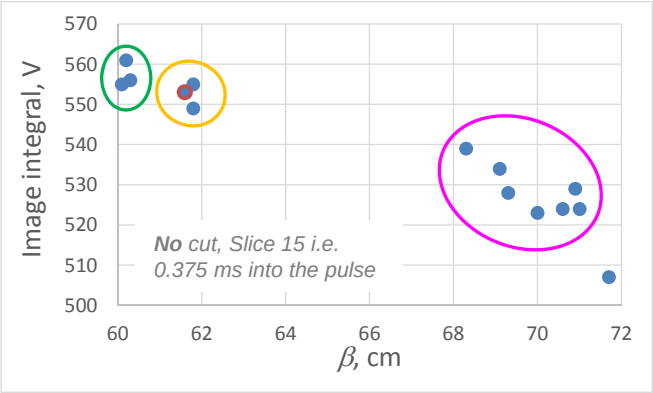
- Standard file (#1553) with settings close to 'matched'
  - 5 mA (DCCT), 1 ms pulse at 10 Hz
- Periodically record phase space
  - Significant spread
  - Linear behavior (α vs. β)
    - Could be explained by changes in neutralization

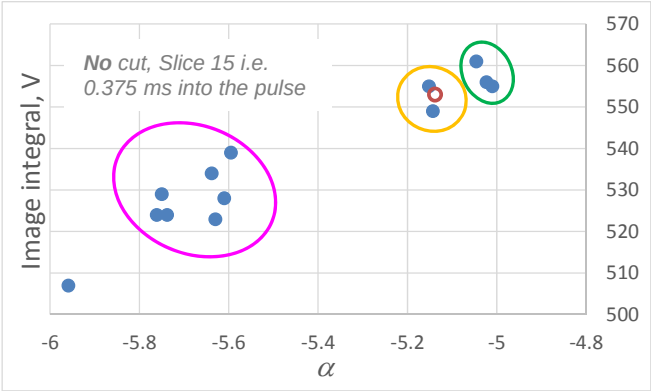


Beam/machine stability/reproducibility (II)

- Some correlation with small variations of the beam current
  - $\Delta V_{ImageIntegral} \sim 4\% \Rightarrow \Delta\beta \sim 14\%;\ \Delta\alpha \sim 11\%$







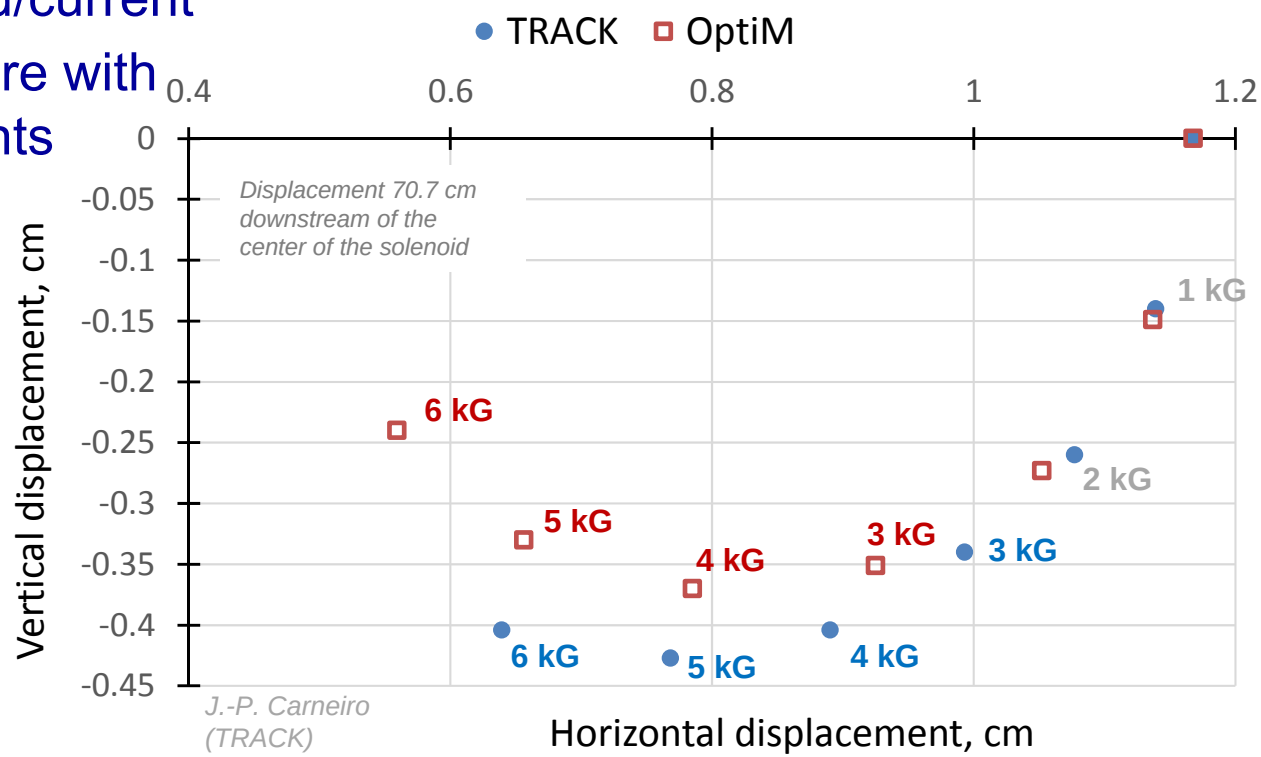
Note on simulations (I)

- One step is to match ‘differential orbit-like’ data with simulations
  - ‘Differential orbit-like’ ≡ Measure beam displacement for a given dipole kick
  - Correctors in solenoid typically modeled with ½ kick before and after the lens
    - Works well if the beam rotation introduced by the solenoid is small
    - Not ‘good enough’ for our case

Implementation of dipole correctors inside the solenoid (3D field map from MWS into TRACK)

Note on simulations (II)

- Preliminary calculations
  - Beam displacement for a 1A horizontal kick as a function of the solenoid field/current
  - Next, compare with measurements



TRACK: 3D field with dipole correctors
OptiM: ½ kick before and after lens

Operational notes

- IS has been run with the same filament for ~420 hours
  - Filament current quite low ⇨ Expect failure '*soon*'
  - Previous filament: 555 hours
    - Changed before failure
    - Ran at lower *beam* current (typically)
- Long run tests' needs lead to improved remote operation capabilities
  - Can remotely power cycle the HV cabinet
    - E.g.: trips which hang up the Filament power supply
  - Can remotely turn on/off the bias PS
    - Still 'configuration controlled' with breaker outside the cave and key to be obtained in the MCR

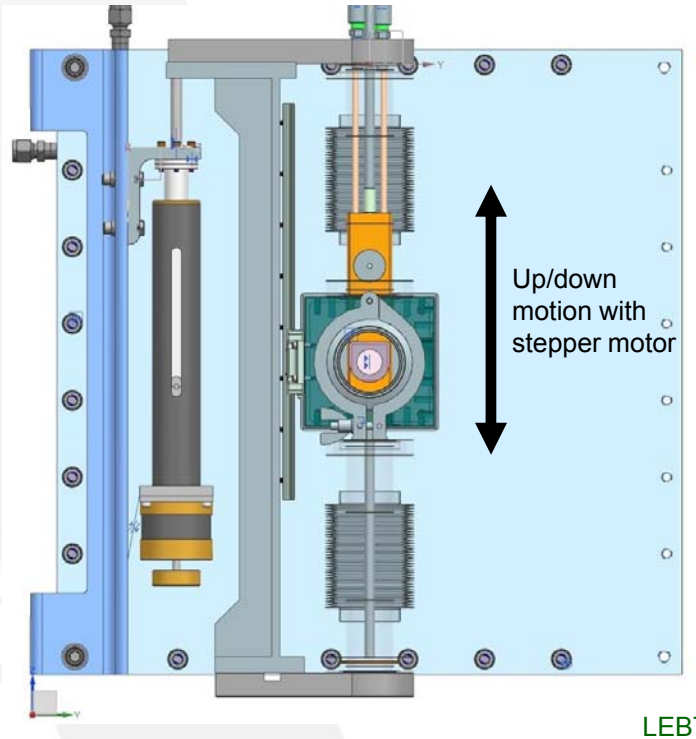
Outlook

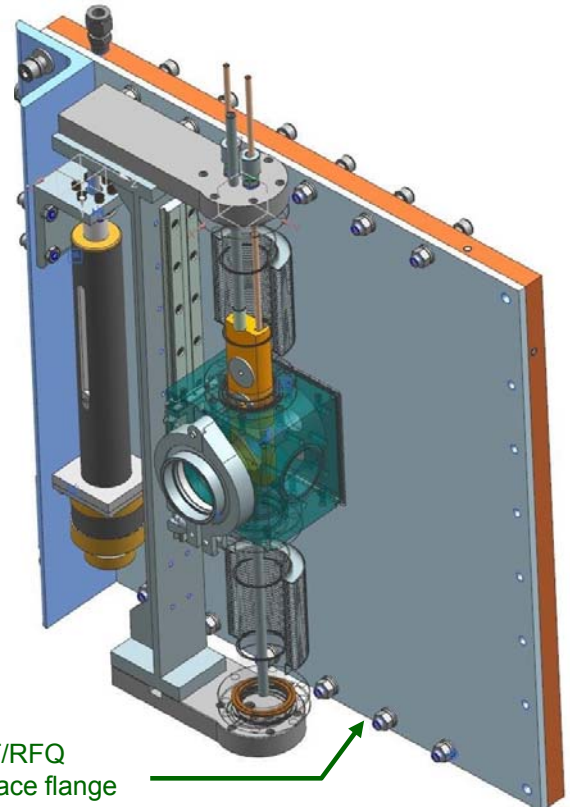
- Re-install Isolated diaphragm #2
- Scraper and beam stop
  - Scraper: RFQ vane protection (and on-line beam measurements)
    - Design almost complete
    - Procured long lead items
      - *Delivery expected 1st week of February '15*
      - *Installation expected mid-February '15*
  - Beam stop: Personnel protection
    - Design to start soon
- On-track to be ready for RFQ arrival in the Spring

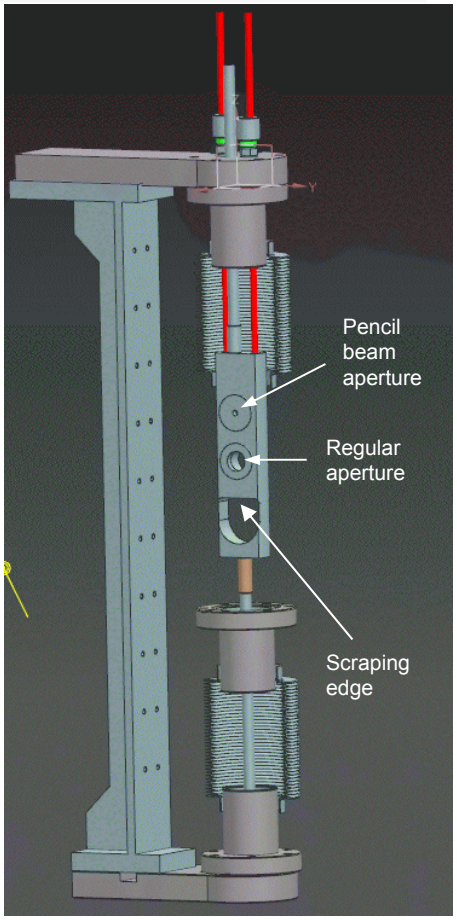
Additional slides

LEBT 'scraper'

- Movable isolated electrode with holes
  - Beam measurements and RFQ protection

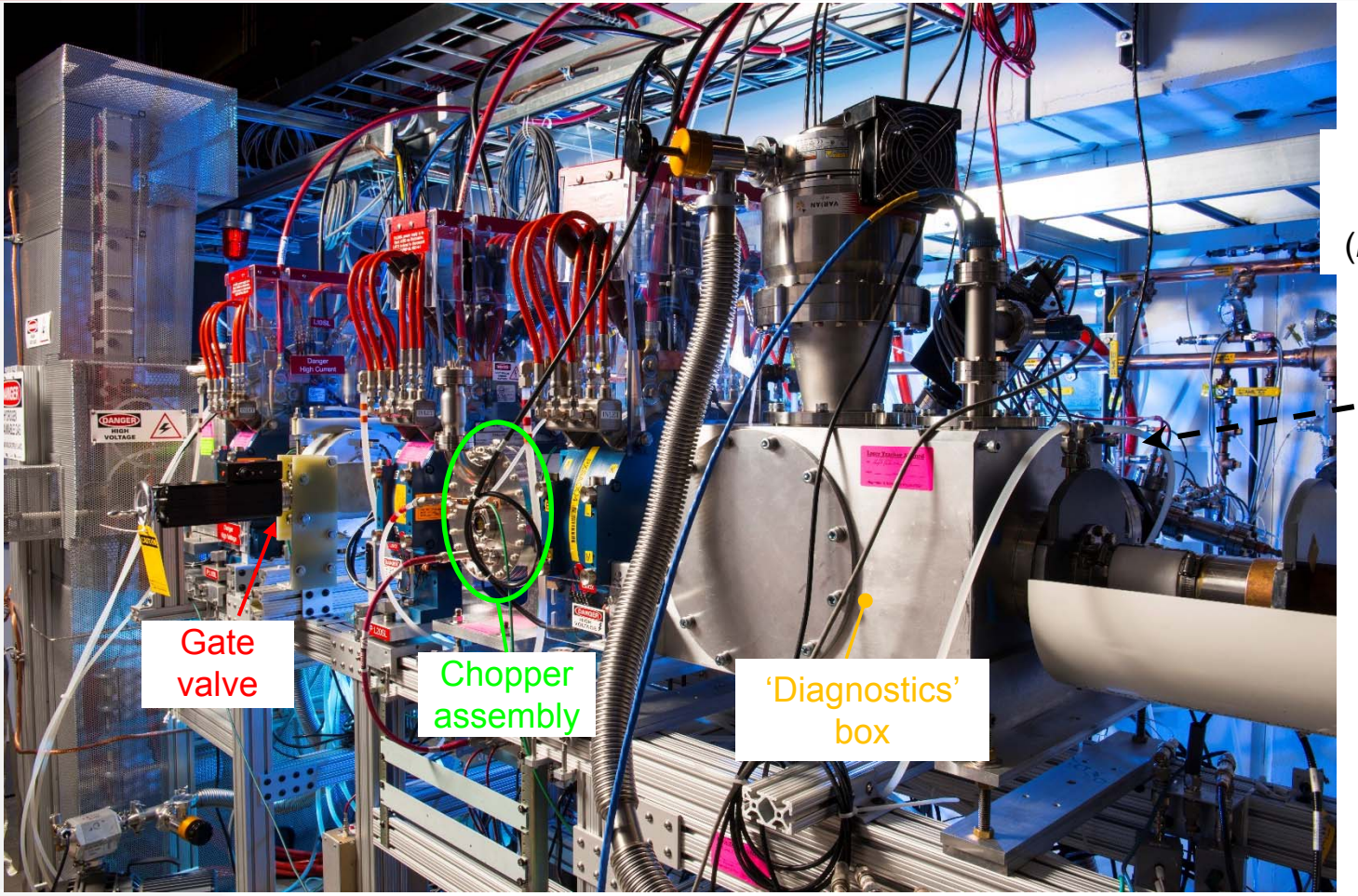






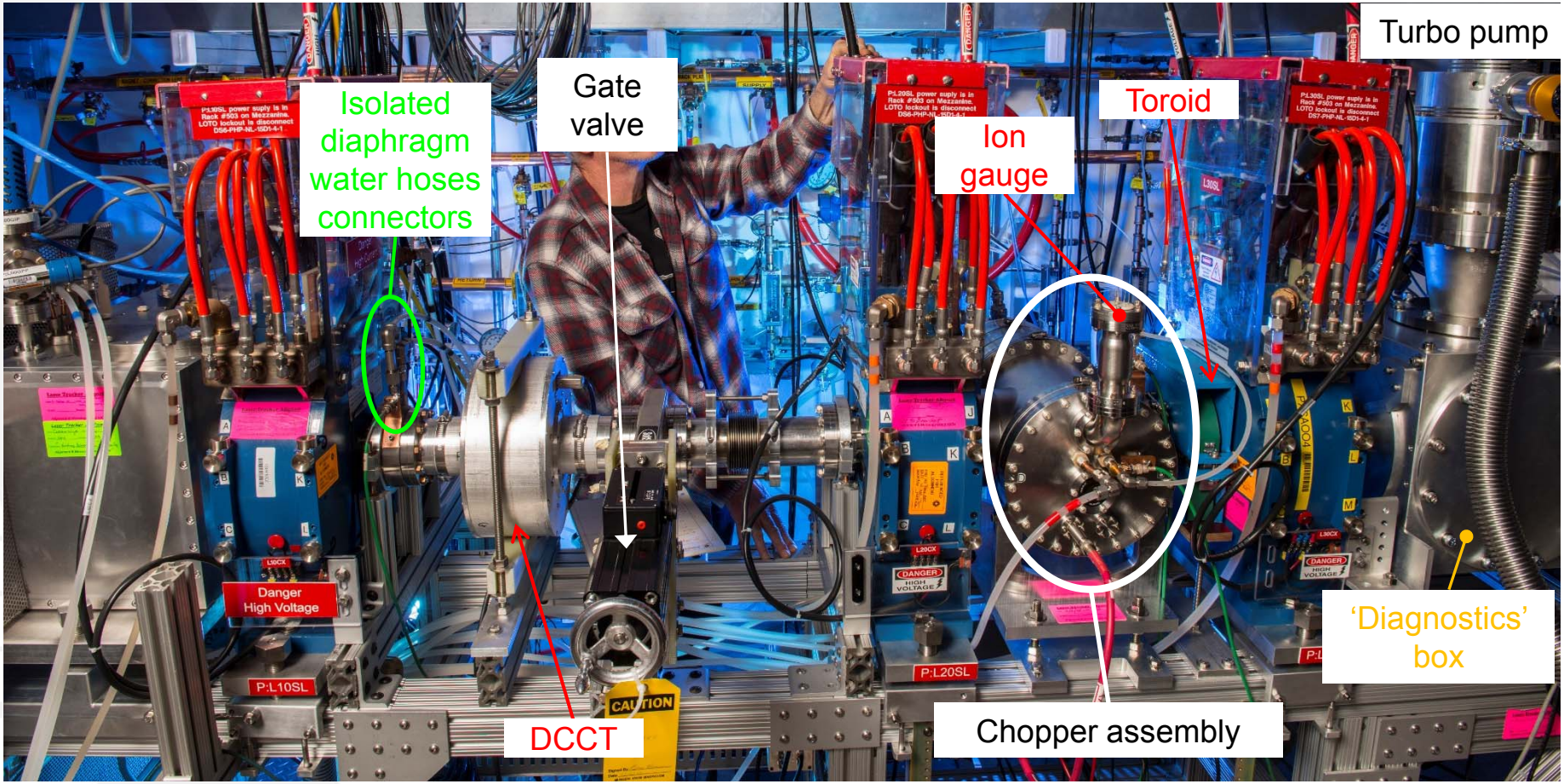
T. Hamerla

Setup in picture

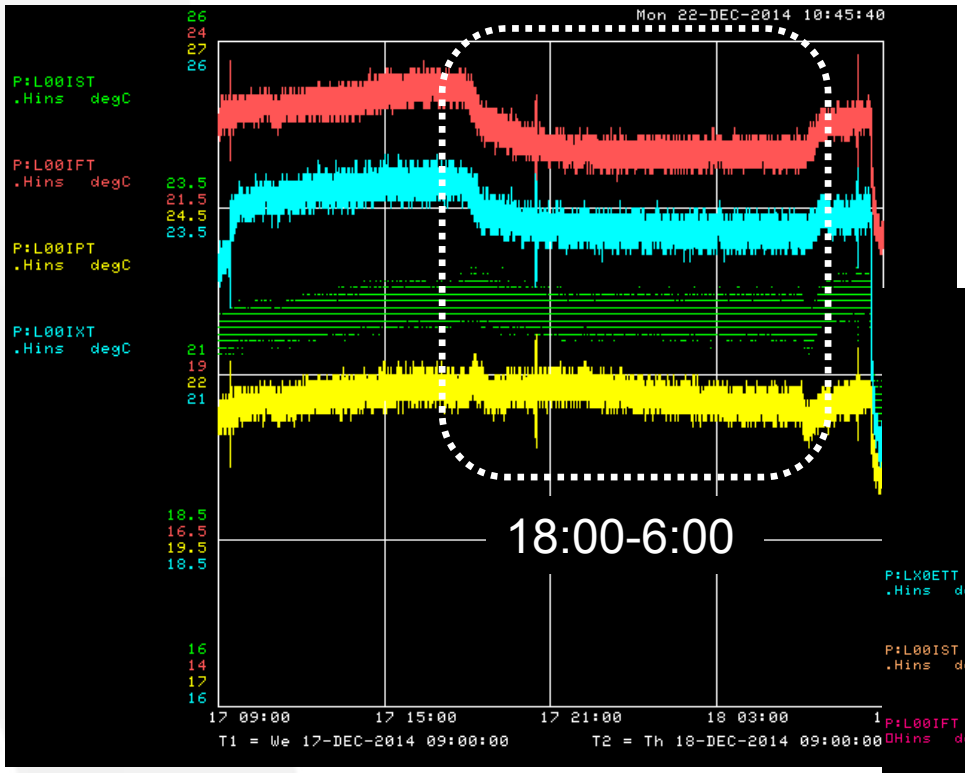


Emittance scanner (*not visible*)

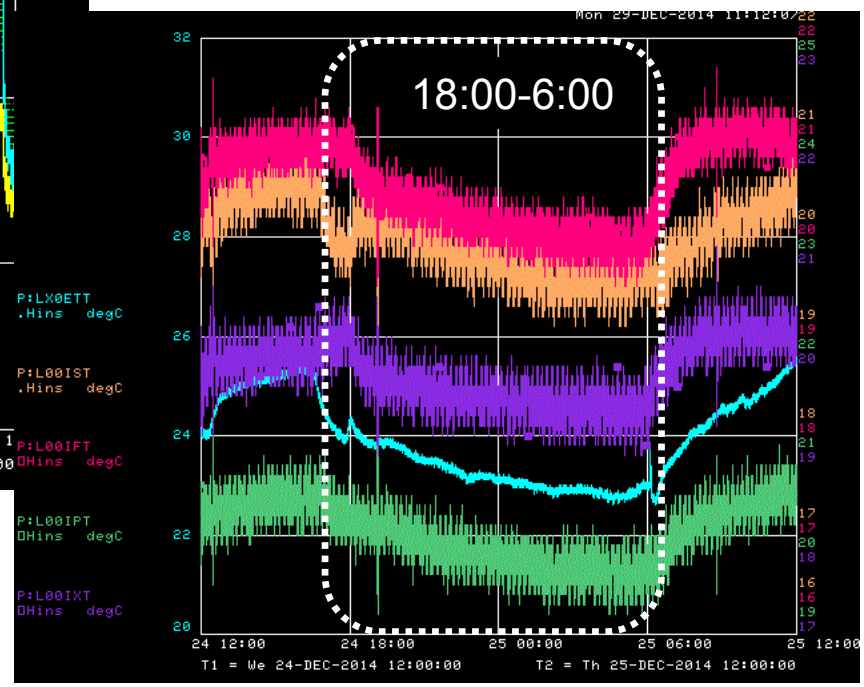
Beam line picture



IS water temps



24-hour run with beam



24-hour over Christmas break