E300 summary of progress and results from FY25 run

FACET-II

Facility for Advanced Accelerator Experimental Tests

FACET-II PWFA Collaboration Meeting

Doug Storey | AARD

7/23/2025

SLAC NATIONAL ACCELERATOR LABORATORY

Stanford University | U.S. DEPARTMENT OF ENERGY

E300: Energy Doubling of Narrow Energy Spread Witness Bunch while Preserving Emittance with a High Pump-to-Witness Energy Transfer Efficiency in a Plasma Wakefield Accelerator

Goals of the E300 collaboration – as stated in 2024 PAC meeting:

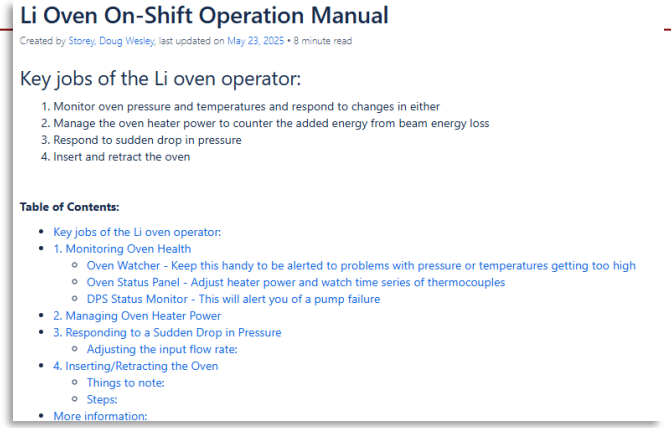
- Demonstration of a single stage with the beam parameters required for a future plasma-based collider or light source
  - Net energy transfer of 40%
  - Minimize energy spread growth in trailing bunch
    - Understand factors that cause energy spread to increase
  - Minimize emittance growth in trailing bunch
    - Understand factors that cause emittance growth – mismatch, alignment error
  - Conserve charge of trailing bunch

Outline:

1) Review of hardware and diagnostics changes from last run
2) Review of FY25 E300 shifts
3) Overview of results from “notched 2 bunch” shifts
4) Overview of results from “Two bunches from cathode” shift
5) Publication plans

Lithium oven

- New oven installed November.
- New oven watcher tools rolled out
- New “Lithium oven on-shift manual”:
  - https://confluence.slac.stanford.edu/spaces/FACET/pages/601691259/Li+Oven+On-Shift+Operation+Manual
- New oven and DPS users gaining experience



Li Oven On-Shift Operation Manual

Created by Storey, Doug Wesley, last updated on May 23, 2025 • 8 minute read

Key jobs of the Li oven operator:

1. Monitor oven pressure and temperatures and respond to changes in either
2. Manage the oven heater power to counter the added energy from beam energy loss
3. Respond to sudden drop in pressure
4. Insert and retract the oven

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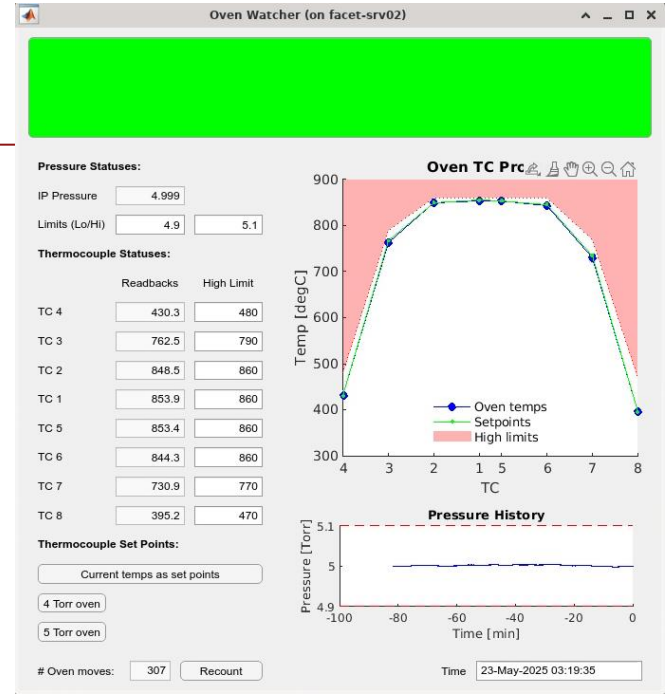
Oven Watcher



- >600 hours of oven usage in FY25 run
- Various oven profiles: 1 to 8 Torr

- Important lesson learned:
  - The main laser burns holes in the beryllium window
  - This seems to be due to the autoaligner missteering one of the motors immediately after the oven moves
  - Solution was to manually block the laser when inserting/retracting the oven

New/updated tools and diagnostics

- **Notch and jaw collimators**
  - Used both in notched 2 bunch and the clean up 2 bunches from the cathode
- **SYAG**
  - Not new – but used significantly with the collimators
- Sextupole tuning
  - Non-ML optimization on Eloss, Egain, etc
- XTCAV SLED upgrade: ~12MV → 20MV
  - Close to double the longitudinal resolution. Still working on increasing this further
- EOS live tool
- Jitter waist tool
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  - Note about limitations
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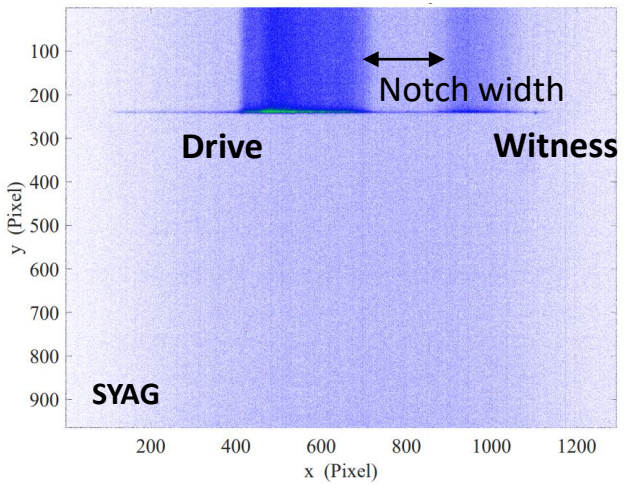
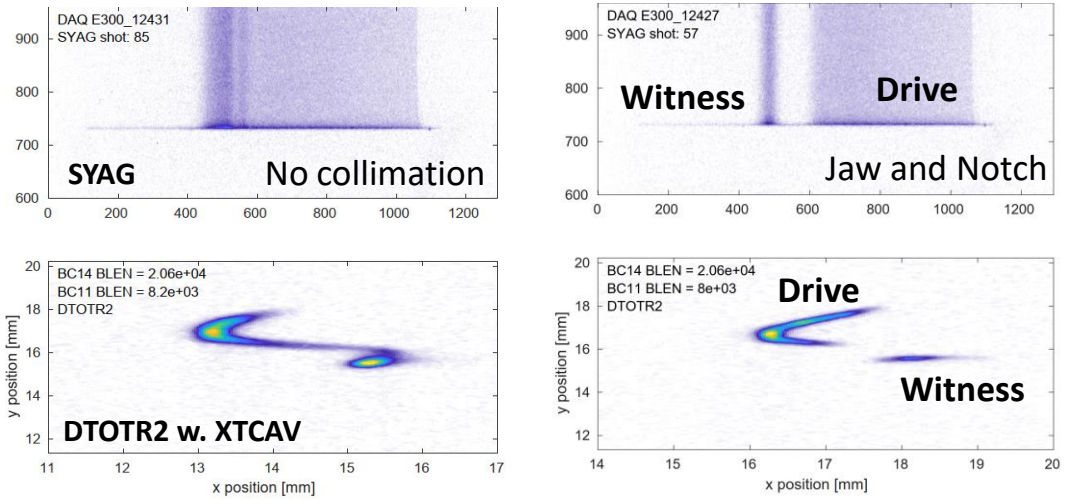
Notched Two Bunch



2 bunch LPS cleaned up with Notch and Jaw



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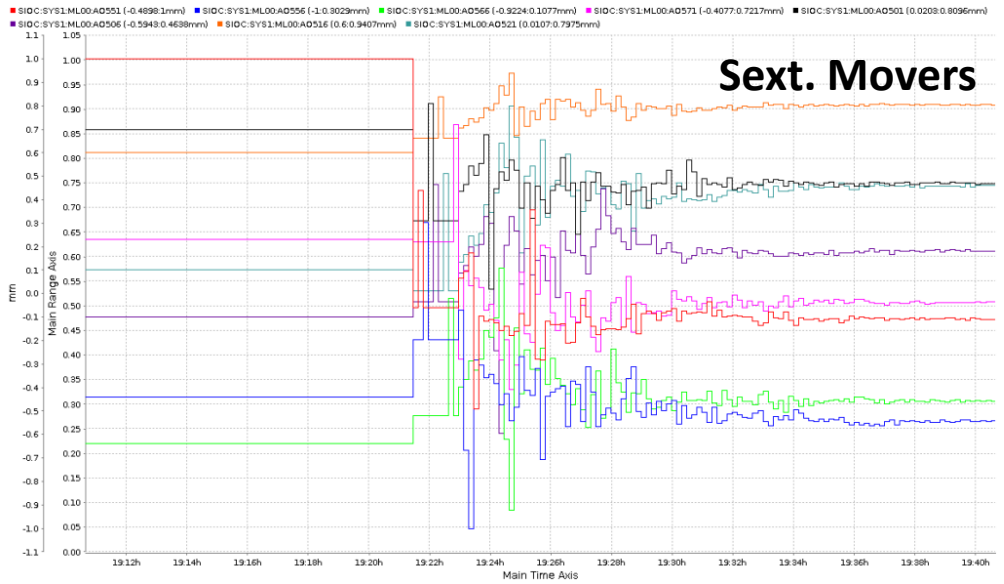

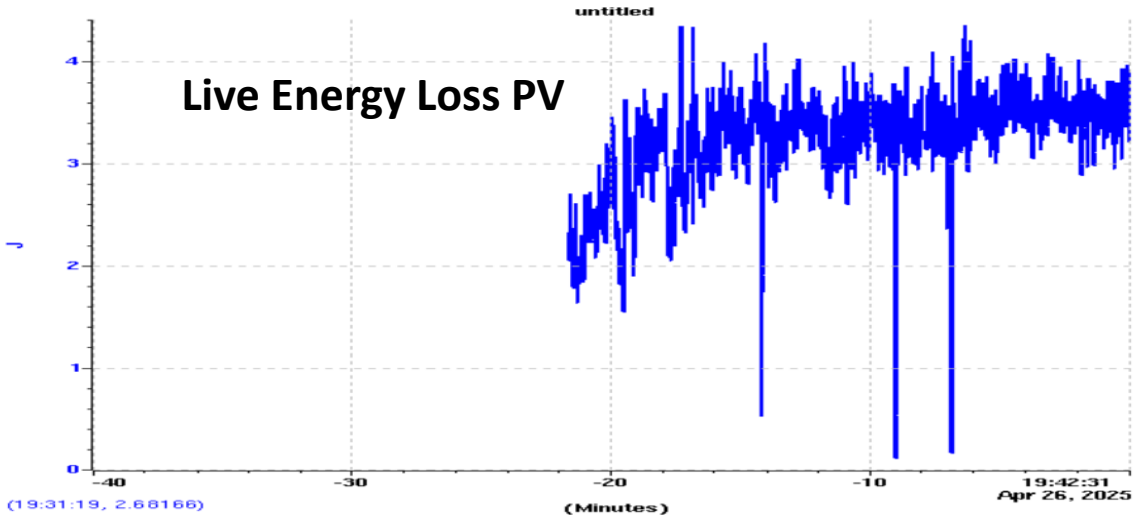

Credit: Nathan's multipurpose sextupole optimizer

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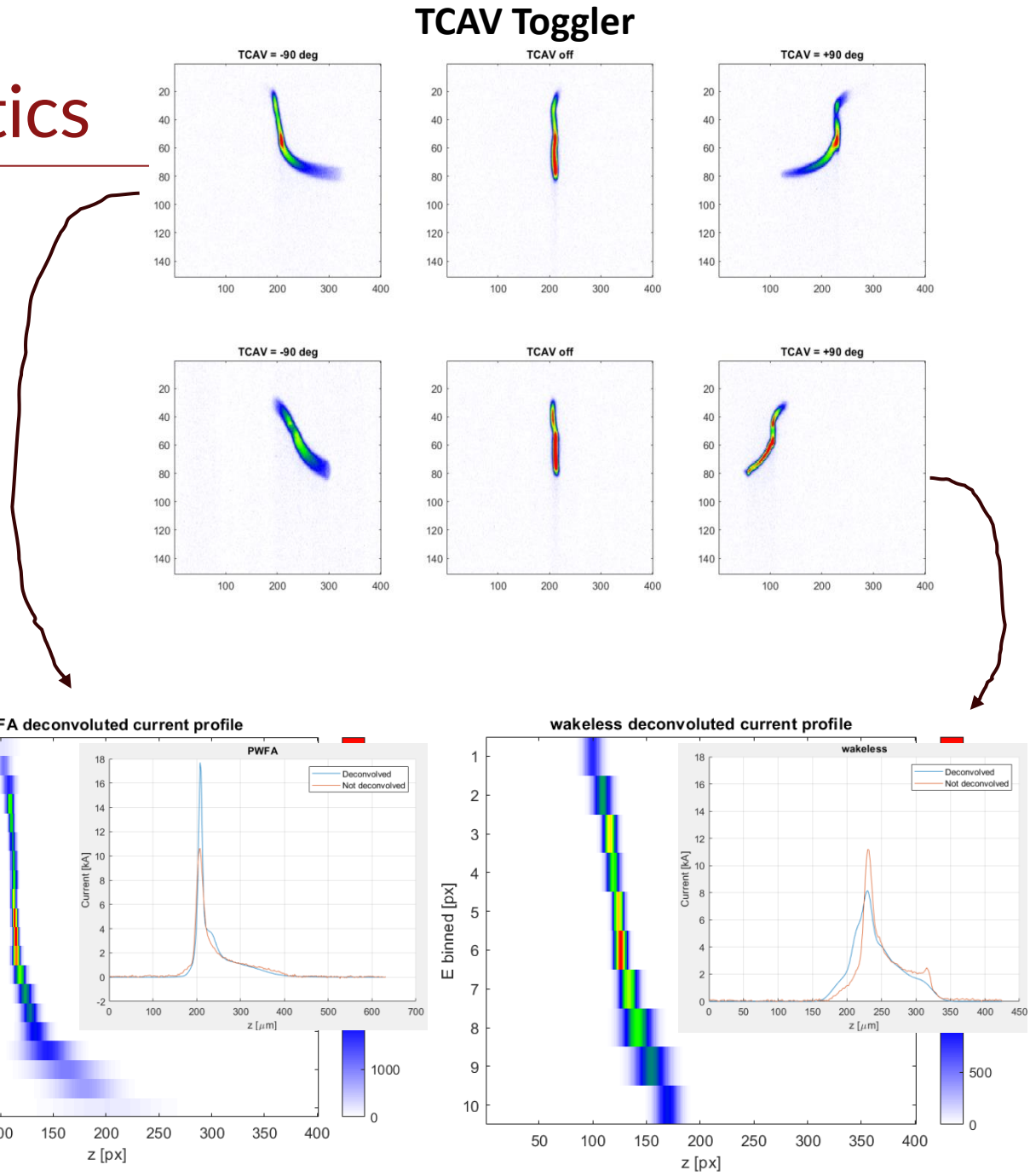

Analysis credit: Sheldon Rego

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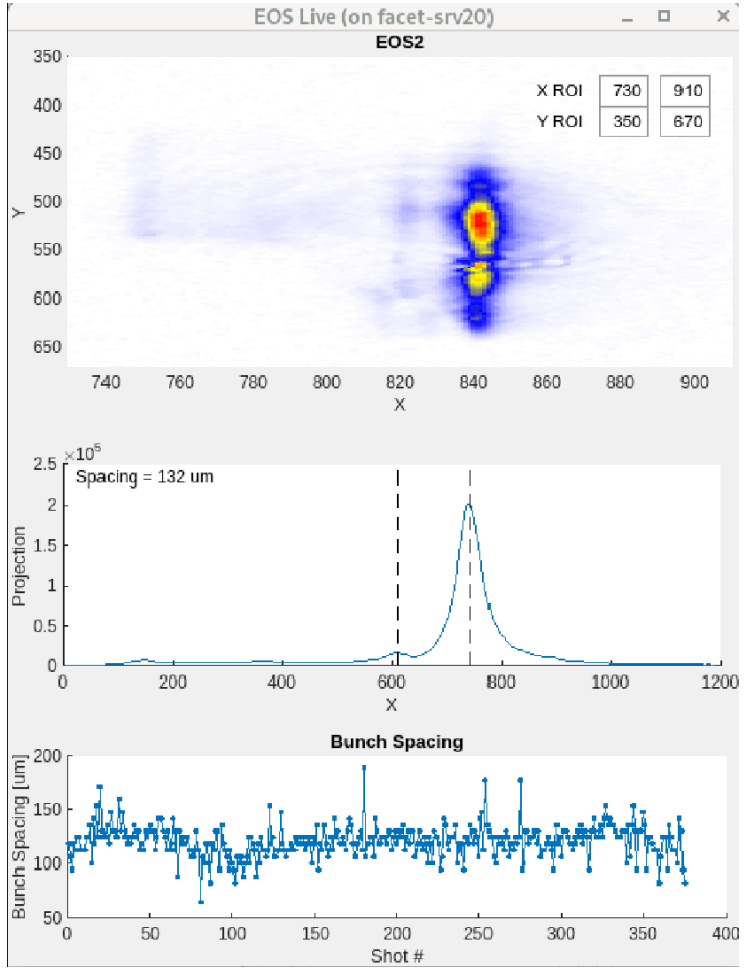
New and improved EOS feedbacks

(Claire and Alex)



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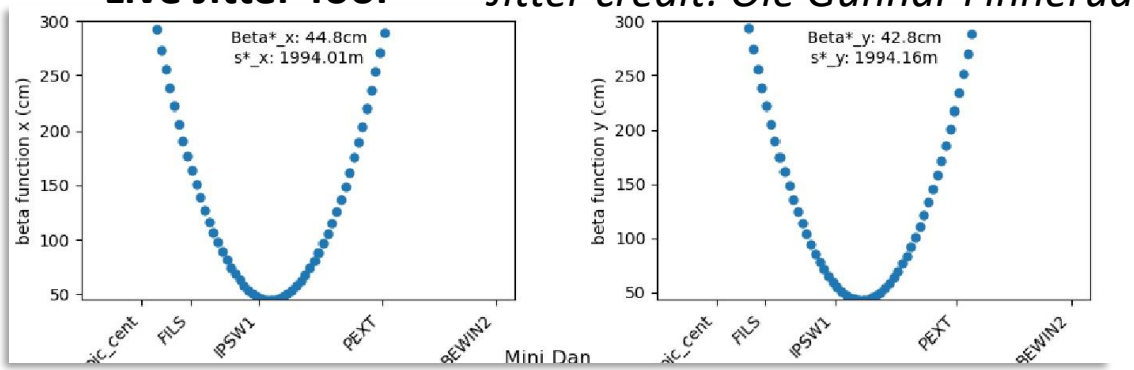
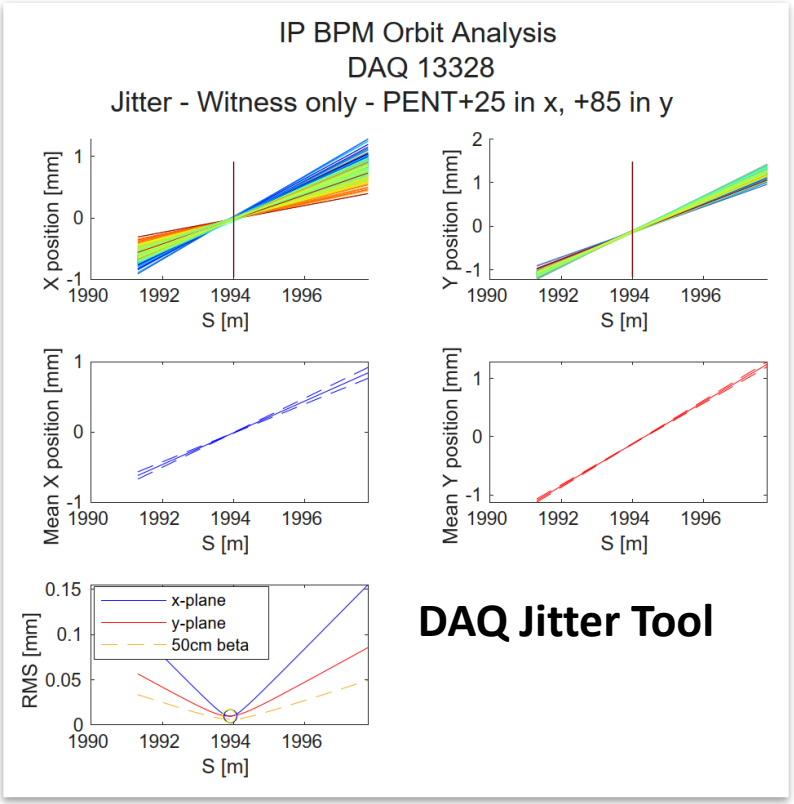
Live Jitter Tool *Jitter credit: Ole Gunnar Finnerud*





DAQ Jitter Tool

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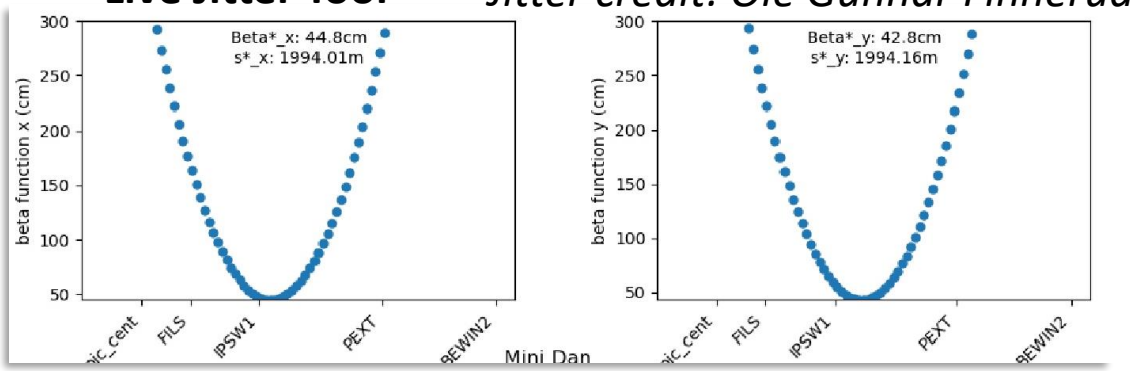

A word of caution:

- For a highly dispersed beam you can end up with a discrepancy between geometric waist position and the jitter waist /plane of zero dispersion
- This can work for small corrections. The better tuning knob is minimizing dispersion while maintain small wire sizes (for example)

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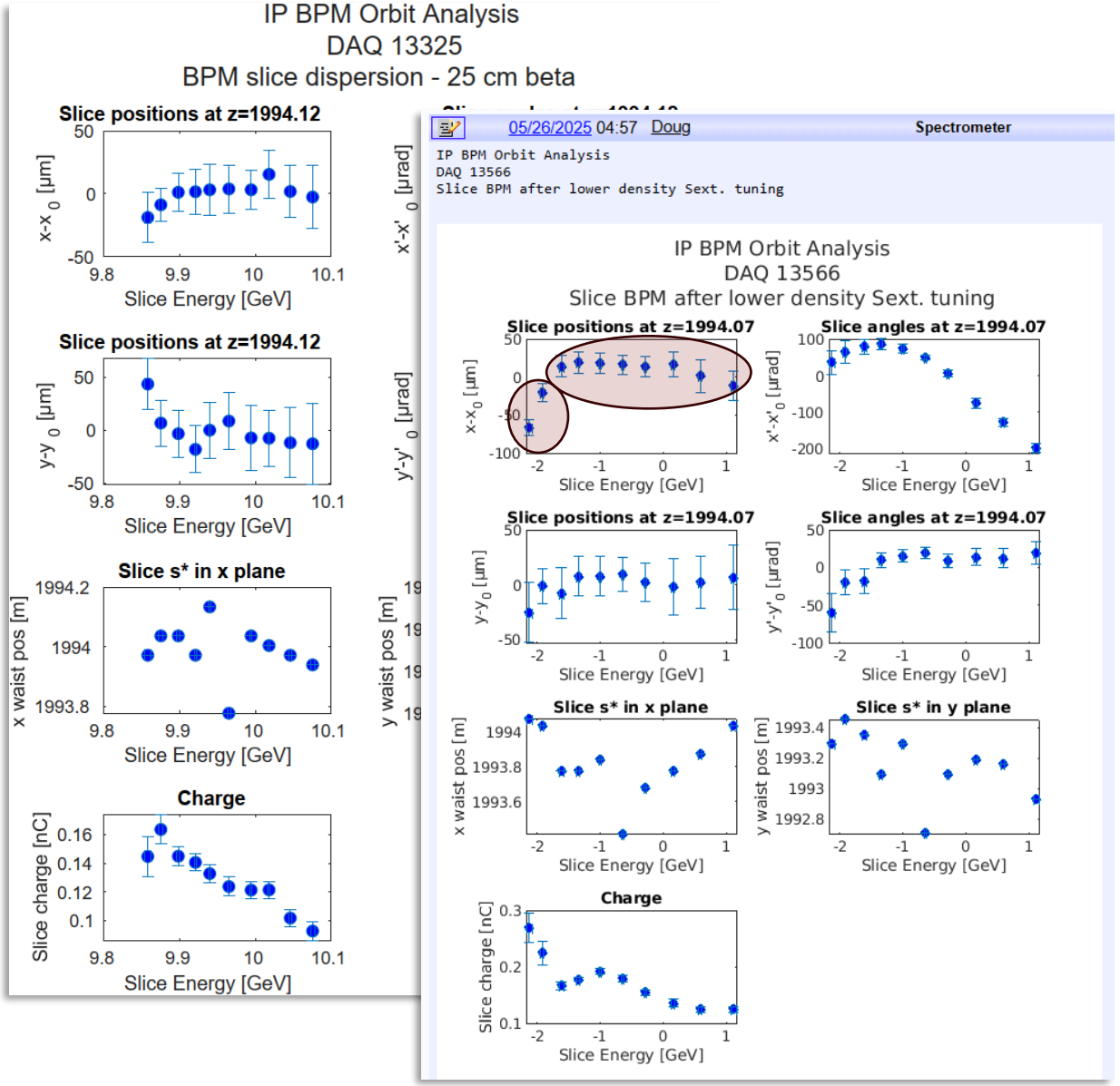

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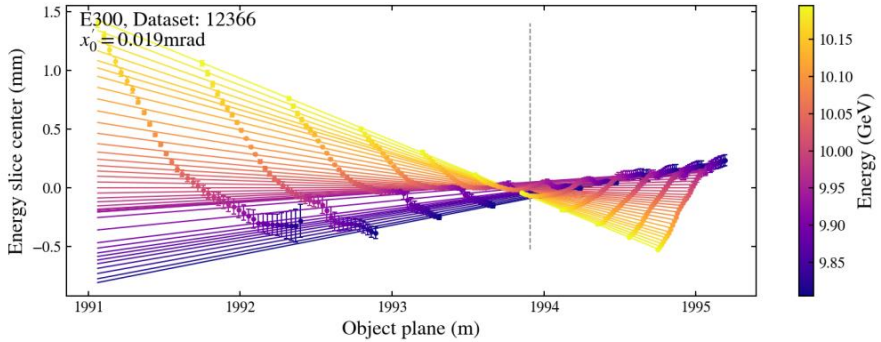

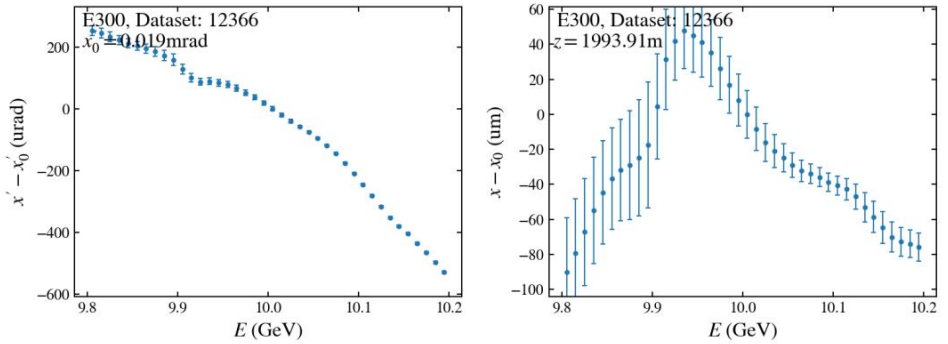

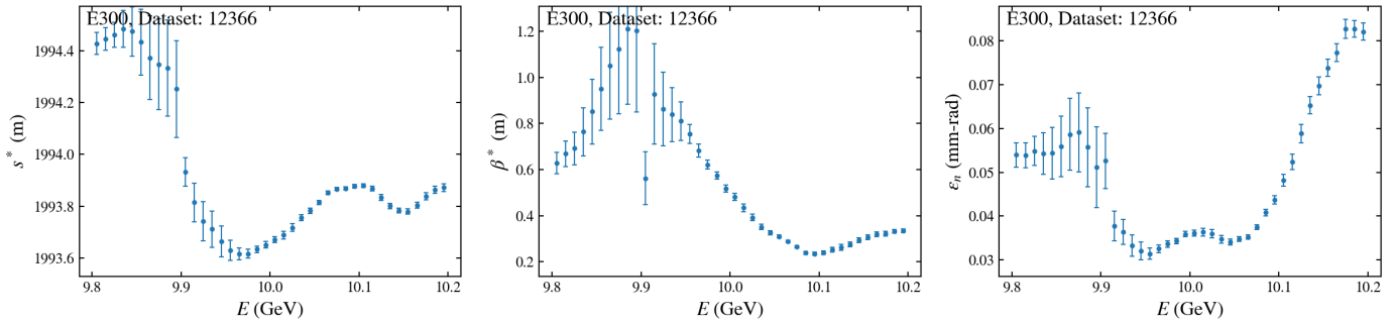

Analysis credit: Robert Ariniello

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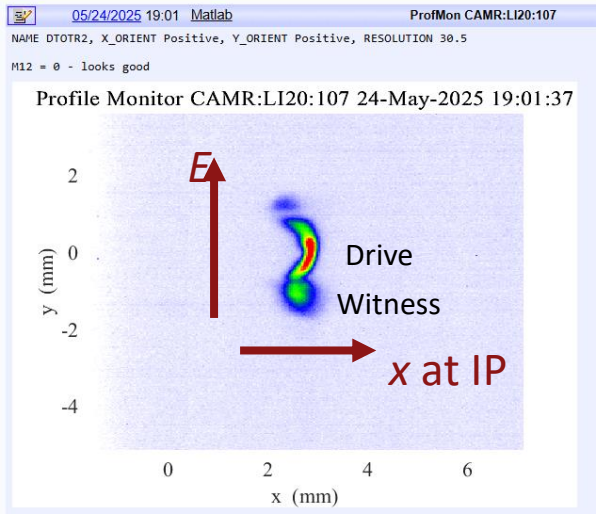
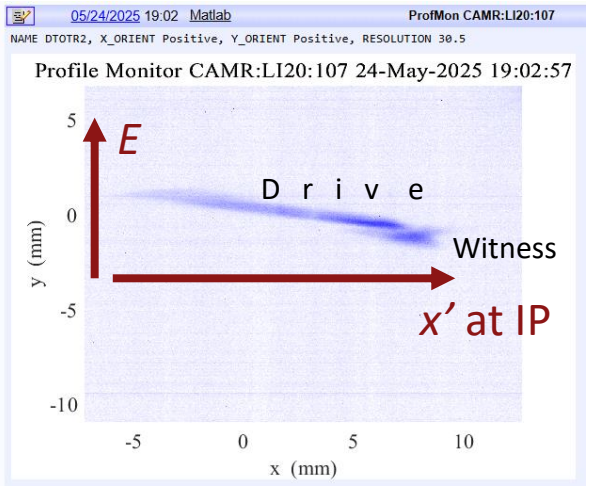
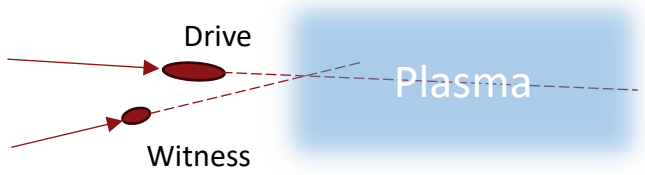
M12 = 0 (point-to-point imaging)



M12 = 15 / M11 = 0 (parallel-to-point)



Δx' ~ 15mm/15m = 1mrad !



More tools, diagnostics, etc

- **BLEN Sinusoidaler**
  - Smooth variation in L2 phase provides simple/repeatable phase scans

- New live PWFA diagnostics

More tools, diagnostics, etc

- BLEN Sinusoidaler
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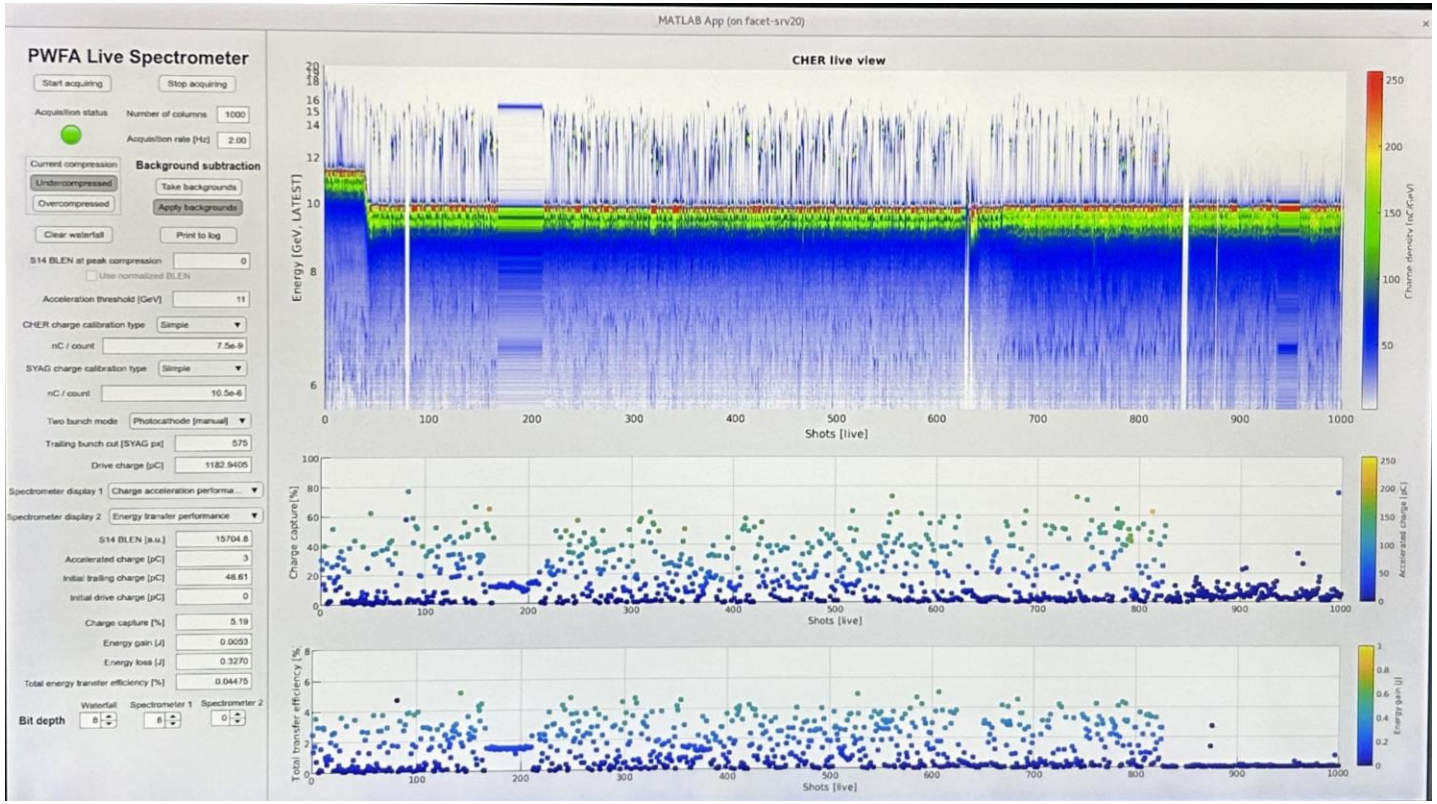
- **New live PWFA diagnostics**
  - Real time calculation of:
    - Charge capture
    - Egain/loss
    - Transfer efficiencies,
    - And more



Credit: Sheldon Rego

Summary of FY25 E300 shifts (with plasma only)

Dates	Conditions	Oven hours	Main outcomes
Nov 8-9	Checkout of the new oven	40	Oven profiles at various pressures/heater powers
Nov 13-16	Two bunch from cathode 4/6/8 Torr Li	130	Developed sextupole optimizer which becomes very important later on Up to 3 GeV energy gain with TR=1
Feb 25-26	Notched 2 bunch 5e16/cc H2		First attempt at notched two bunch Achieved ~1GeV acceleration in laser ionized 5e16/cc H2 plasma
Mar 10-13	Notched 2 bunch 5.7 Torr Li oven (5e16/cc)	68	First laser preionization in Li plasma Up to 3 GeV energy gain, full datasets in over+undercompressed
Mar 22-23	Single bunch 5 Torr Li oven	58	Developed BSA-ML optimization code Broke the LI11 micro
Apr 11-13 (technically E302)	Notched 2 bunch 4 Torr Li oven	41	PWFA with transverse offsets Up to 2 GeV energy gain
Apr 25-28	Two bunch from cathode Li oven	95	New transverse tuning tools, notching witness/drive Up to 6 GeV energy gain, ~50% charge capture, 5-10% efficiency
May 8-9 (May 7 with E338)	Notched 2 bunch Li oven	74	Wakefield mapping, 3D chirp-notch position-angle scan, Gamma2 Up to 5 GeV energy gain, good energy spread, efficiency
May 20-25	Two bunch from cathode 5 and 1 Torr Li oven, 2.1 nC	100	Decreased beta and plasma density to improve matching/charge capture 4 GeV/1 GeV gain, 0.5% energy spread, >80% charge capture, **efficiency?**

Total = 606 hours / 25 days on

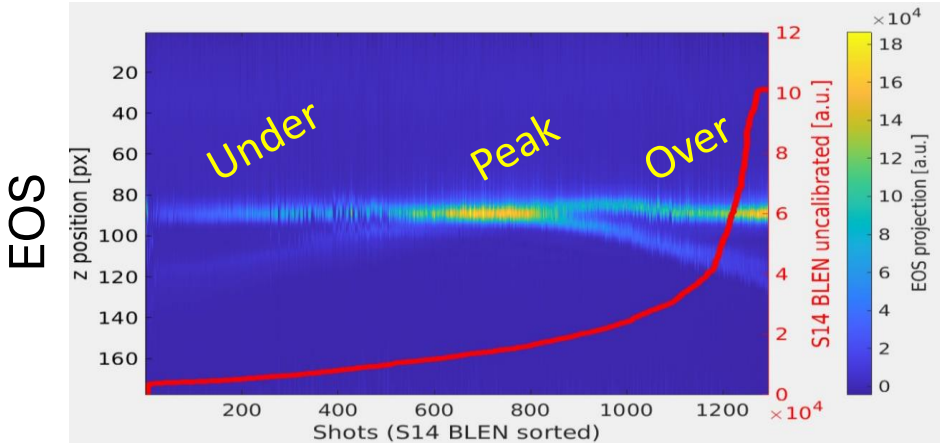
Notched 2 bunch results – Highlights of results

Linac behaves more stably in the single bunch config

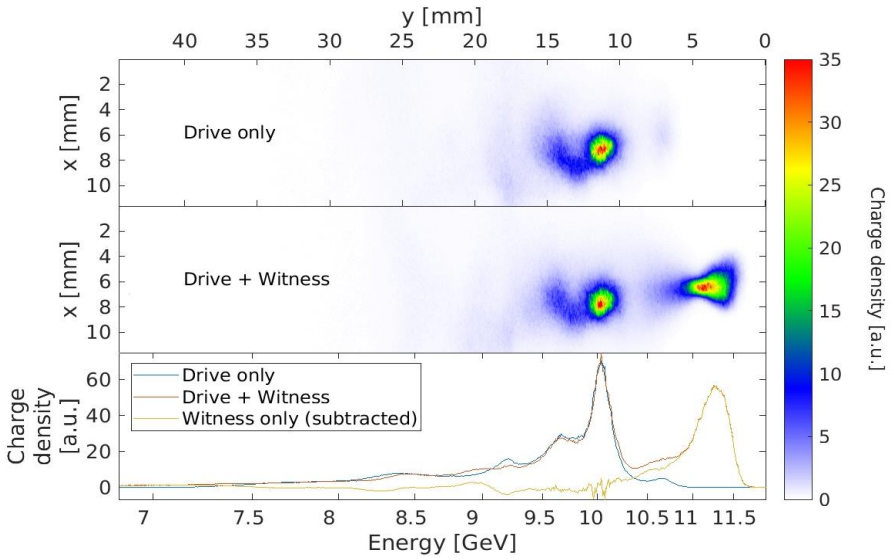
- Can systematically vary bunch spacing/charge by manipulating collimators and L2 phase
- But – this technique lowers charge, peak current, etc
- Typical charge break down:
  - Drive: 600 - 750 pC
  - Witness: 200 - 300 pC
  - Bunch spacing ~40 to 150 μm

Ran with beam and laser ionized H2 and Li plasmas

- Overall results in this mode:
  - Acceleration up to 3-4 GeV observed
  - Field uniformity ~4%
  - Charge participation up to ~80% level
  - Wakefield mapping at two densities with E338
  - Transverse instability study with E302

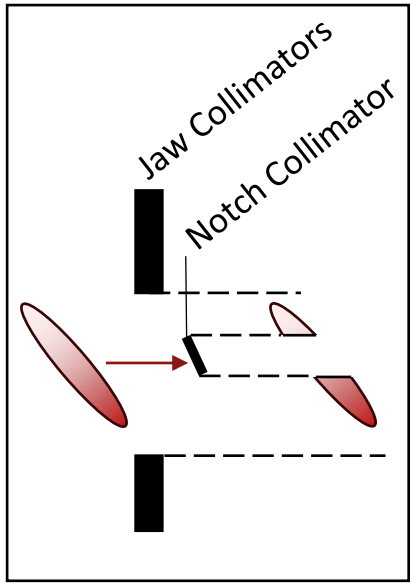


L2 phase scan in laser ionized H2 plasma

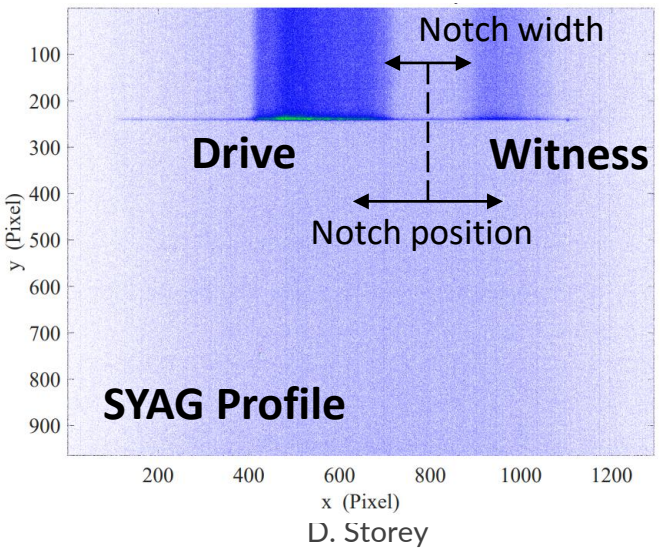


~260 accelerated here out of ~294 incoming

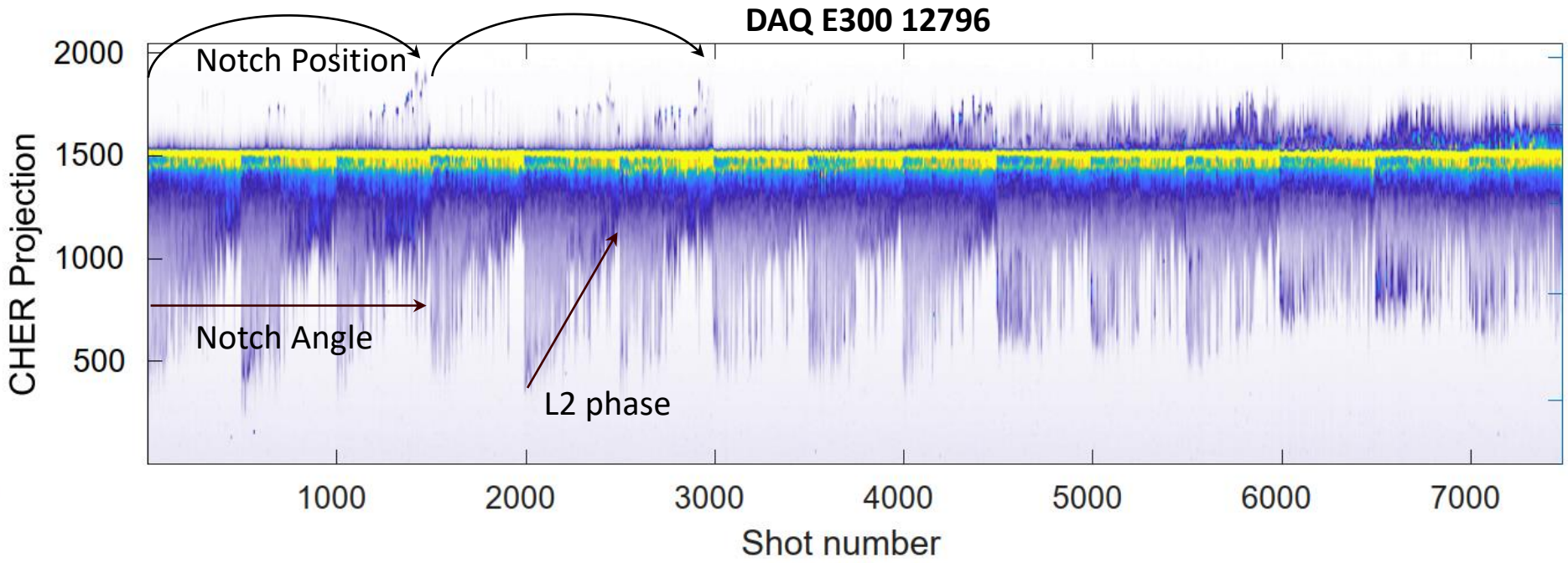
Notched two bunch – Notch collimator optimization



- 3-D optimization: notch position, notch angle, and L2 phase (compression)
  - All 3 speak to bunch spacing, charge, and charge profile
- Goal: optimize the wake amplitude, field uniformity, etc

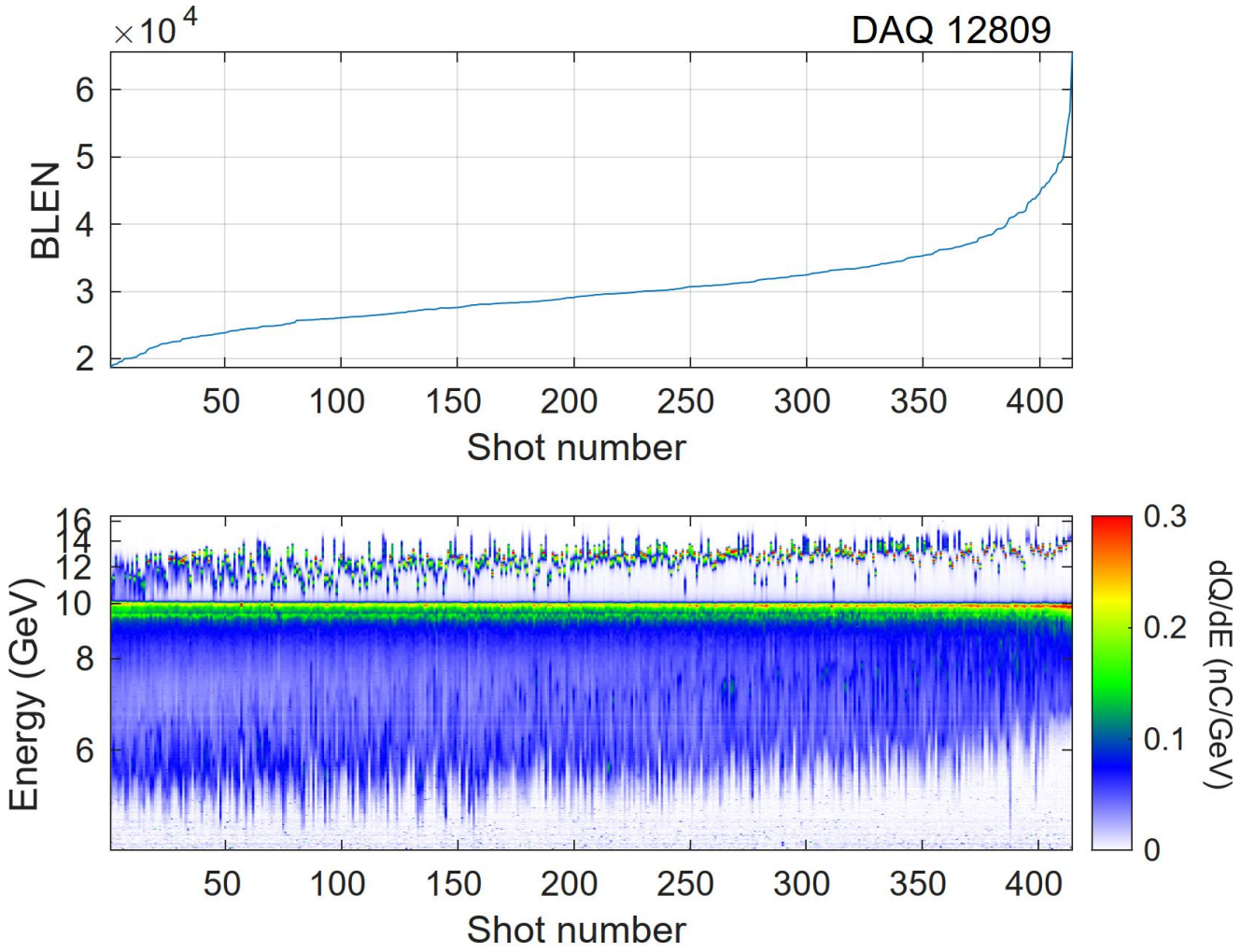


D. Storey



Notched two bunch – Optimization figure of merit (in progress)

Manually selected optimum working point: DAQ E300 12809



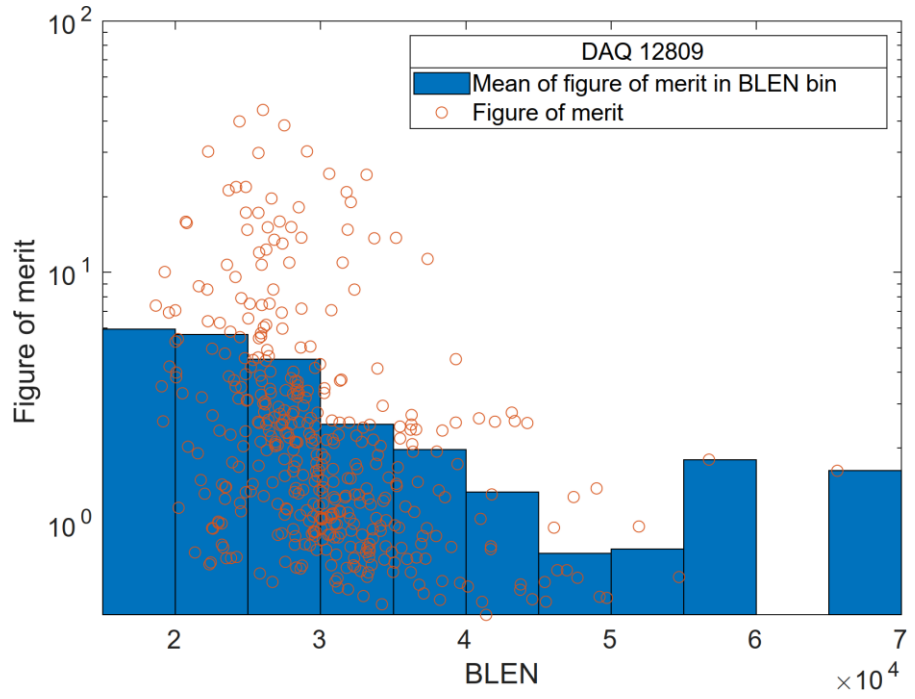
- Developing a figure of merit for optimization that combines:
  - Energy gain, ΔE_w
  - Field uniformity, $\sigma_E/\Delta E_w$
  - Accelerated charge, Q_{acc}
- Figure of merit (FOM) based on CHER image alone:

$$FOM = \frac{\left(\frac{\sigma_{E,w}}{\Delta E_w}\right)}{\left(\frac{Q_{acc}}{500\ \mathrm{pC}}\right)\left(\frac{\Delta E_w}{10\ \mathrm{GeV}}\right)}$$

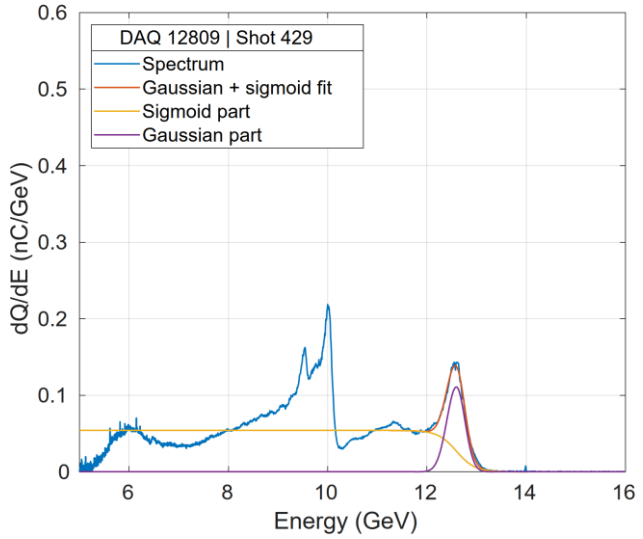
To-do: Add in SYAG and EOS analysis to get incoming drive/witness charges/spacing

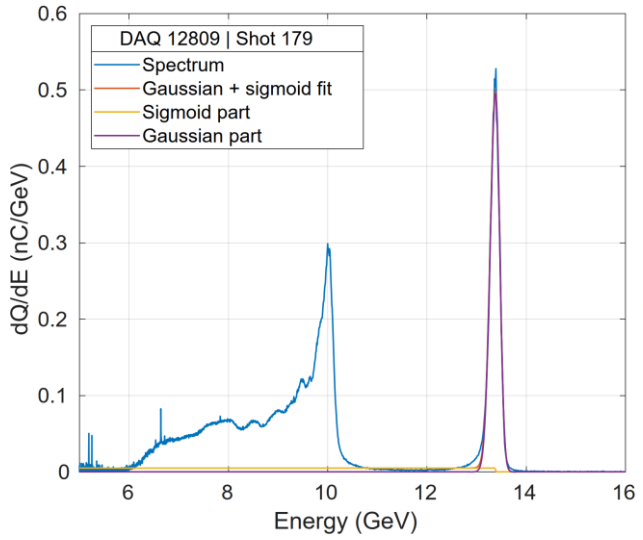
Credit: Clément Vovard

Notched two bunch – Optimization results



- More work to be done here
- But great tools being developed for robustly quantifying performance across many datasets





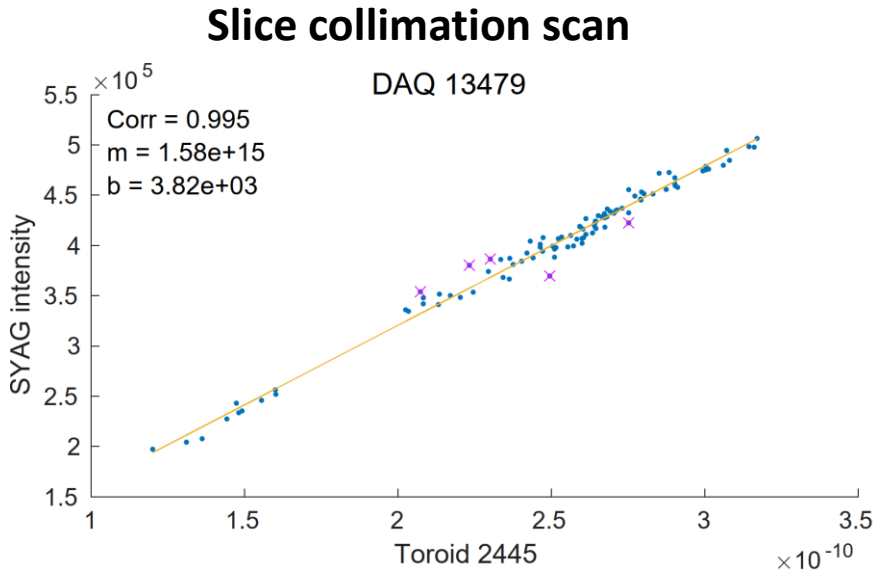
In progress: Applying this analysis to range of datasets

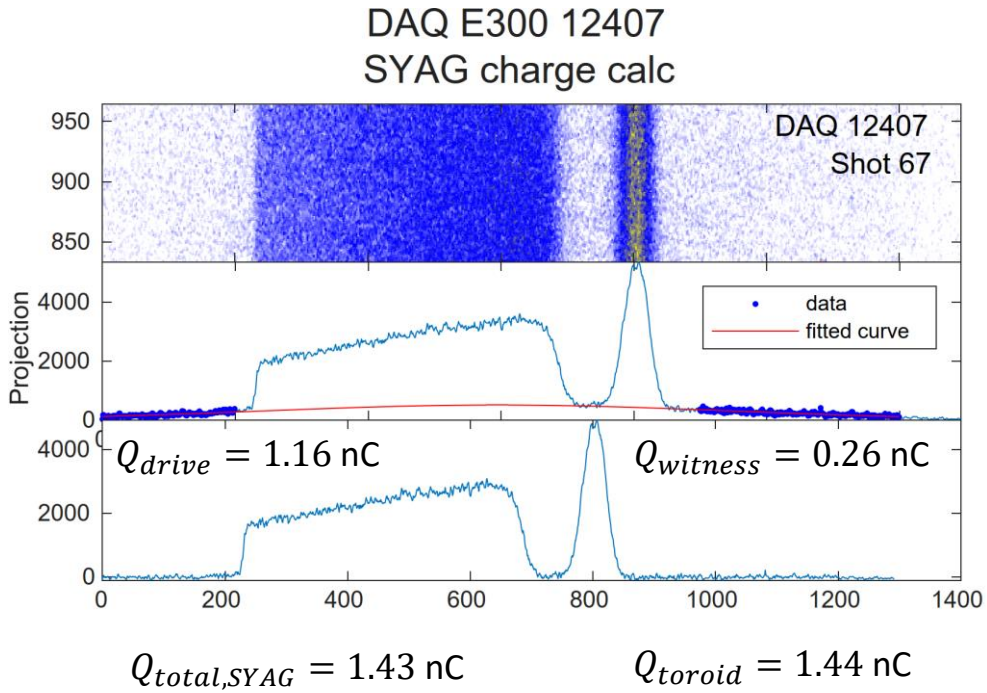
```
Best shot according to figure of merit
Accelerated charge: 0.136 nC
Energy gain: 0.44 J
Center energy: 13.4 GeV
Energy spread: 0.13 GeV
Relative energy spread: 1.01 %
Field uniformity: 3.99 %
```

Credit: Clément Vovard

Incoming drive and witness charge estimates

- Can we use SYAG as a reliable tool to estimate the incoming witness charge?





- Good correlation between SYAG intensity and toroid over collimator scan
  - Relatively linear response across SYAG crystal
- Total charge estimate from SYAG agrees with toroid reading

To-do: Cross check estimate from SYAG with DTOTR image (no plasma data)

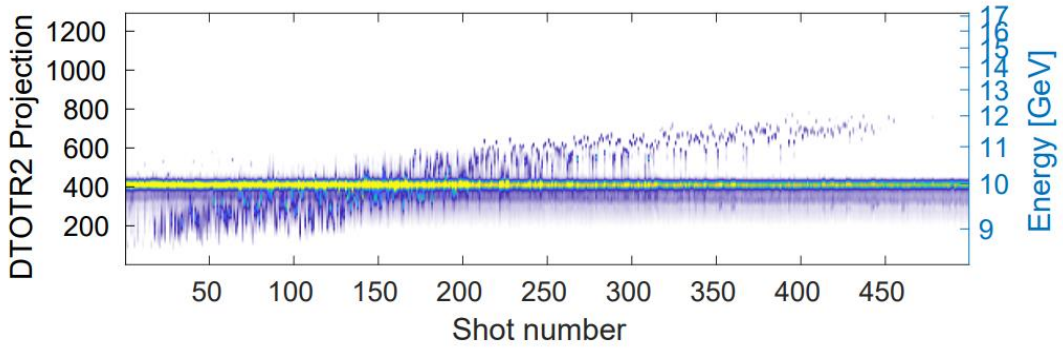
Attempt to verify SYAG charge calibration against DTOTR2

- TBD

Two bunches from the cathode

- Improvements from last year
  - L1 LLRF upgrades
  - Updated longitudinal feedbacks

Old feedbacks



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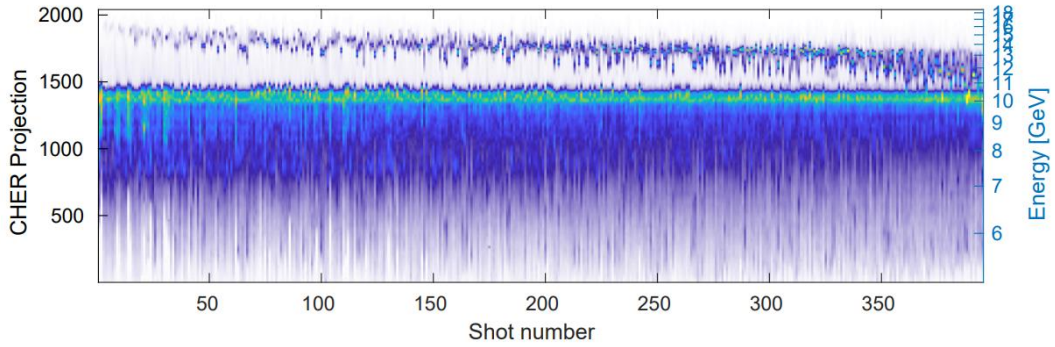
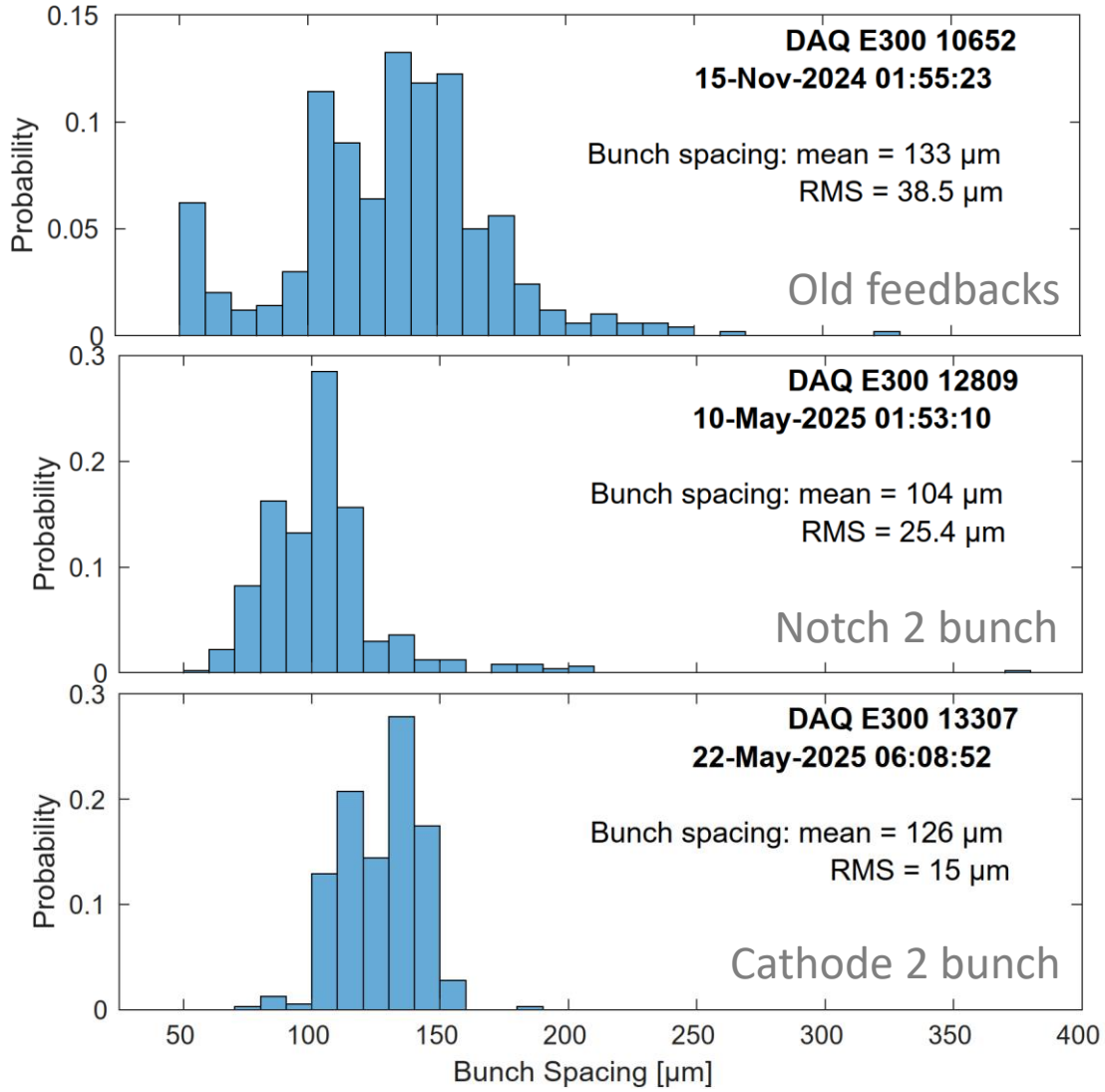
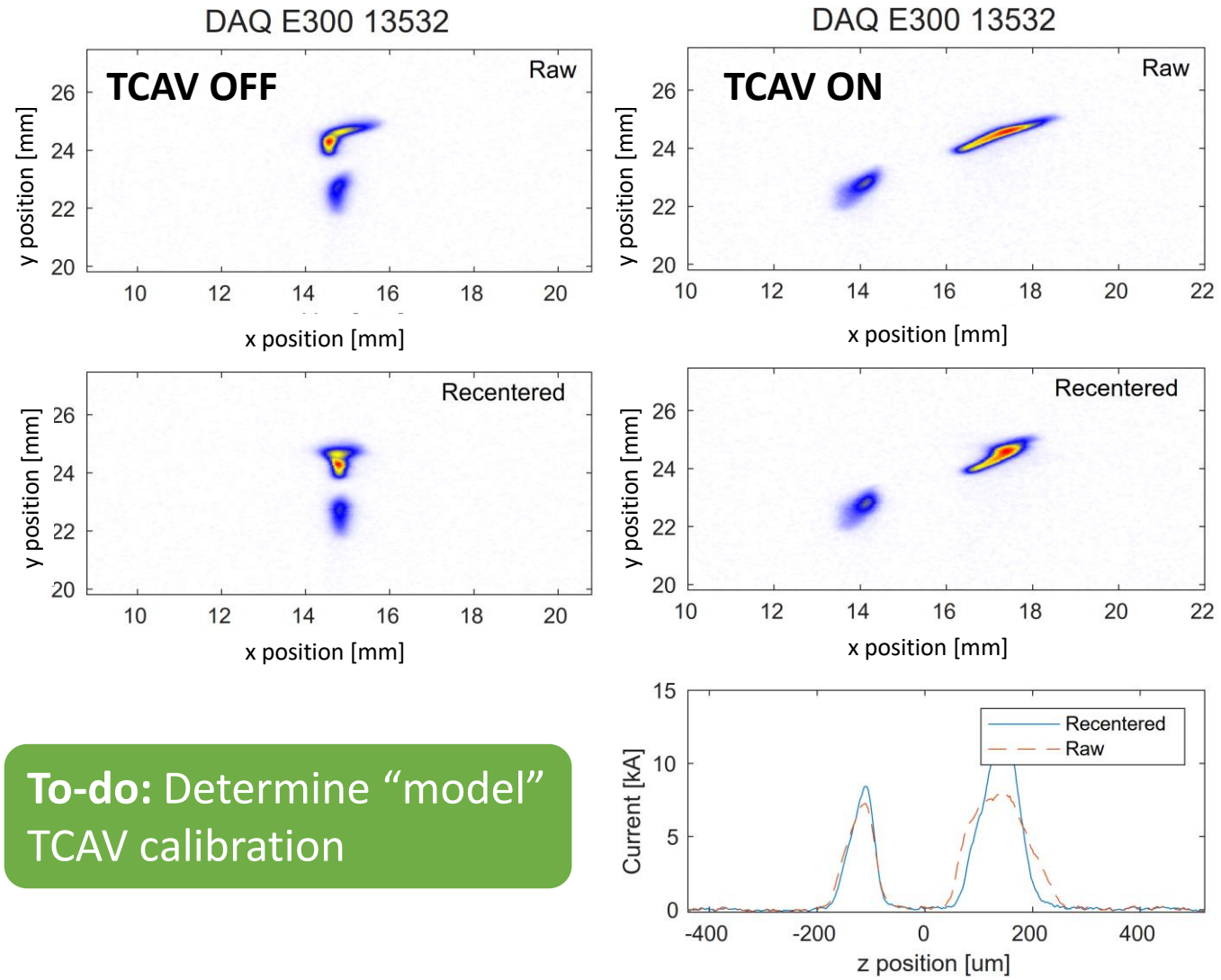




Longitudinal phase space from the XTCAV

- Resolution ~doubled since last year with addition of SLED
- Incoming curvature/correlations on the beam complicate the analysis of XTCAV images
  - "Recentering" and/or deconvolution techniques can help to recover a better estimate of the LPS and current profiles

To-do: Apply deconvolution to XTCAV images to recover more accurate current profile

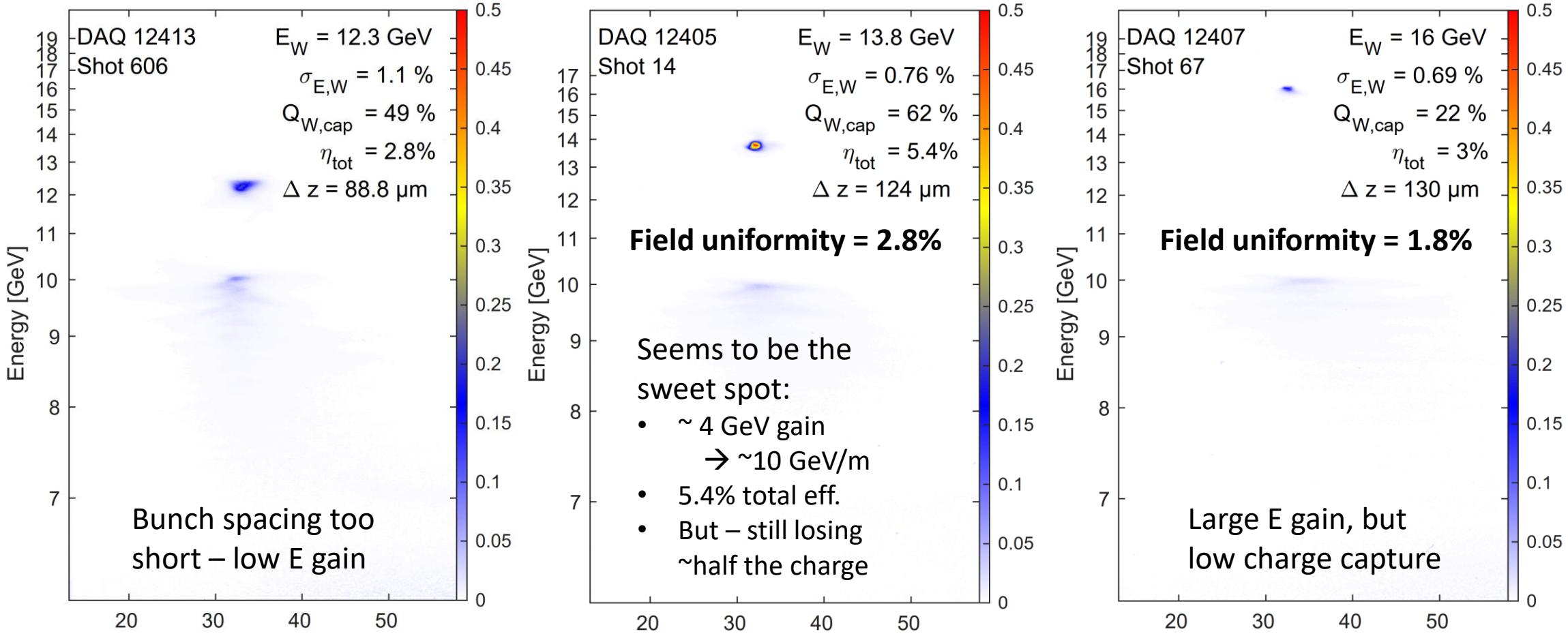


To-do: Determine "model" TCAV calibration

Note – missing TCAV calibrations?

April run - Maximum acceleration from this run

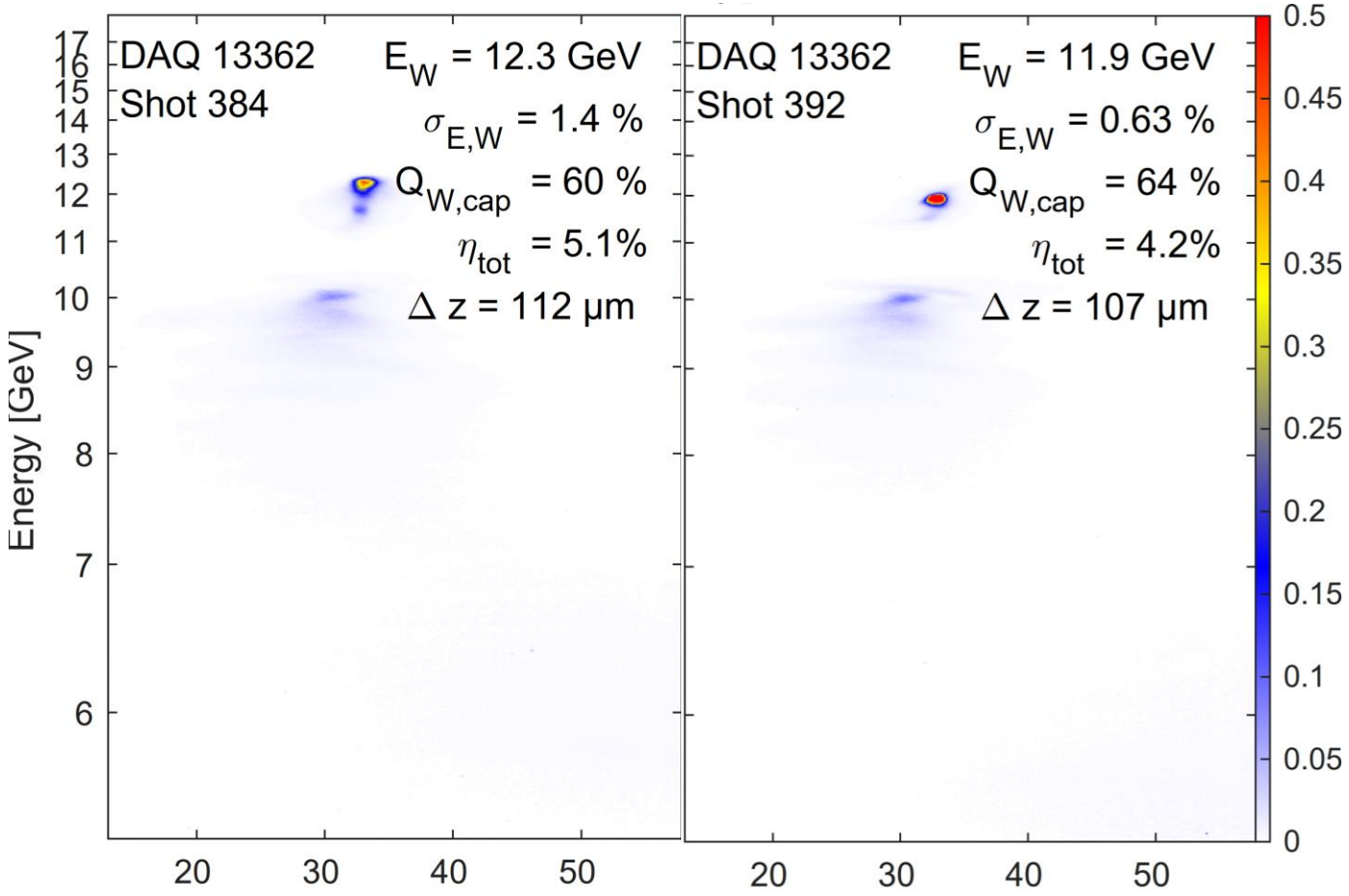
- Achieved up to 6 GeV acceleration of the witness, but – with low charge capture
- Better charge capture, efficiency with 4 GeV energy gain
- Field uniformity 2-3%



May run – Oven at 5 Torr, beta = 25 cm

- Reduced β^* (beam size) to 25 cm
- Achieved similar efficiency at smaller gradient
- *Note the double peak structure*

To-do: Keep looking through the data to see if there was a working point with > 5% energy transfer and > 60% charge capture

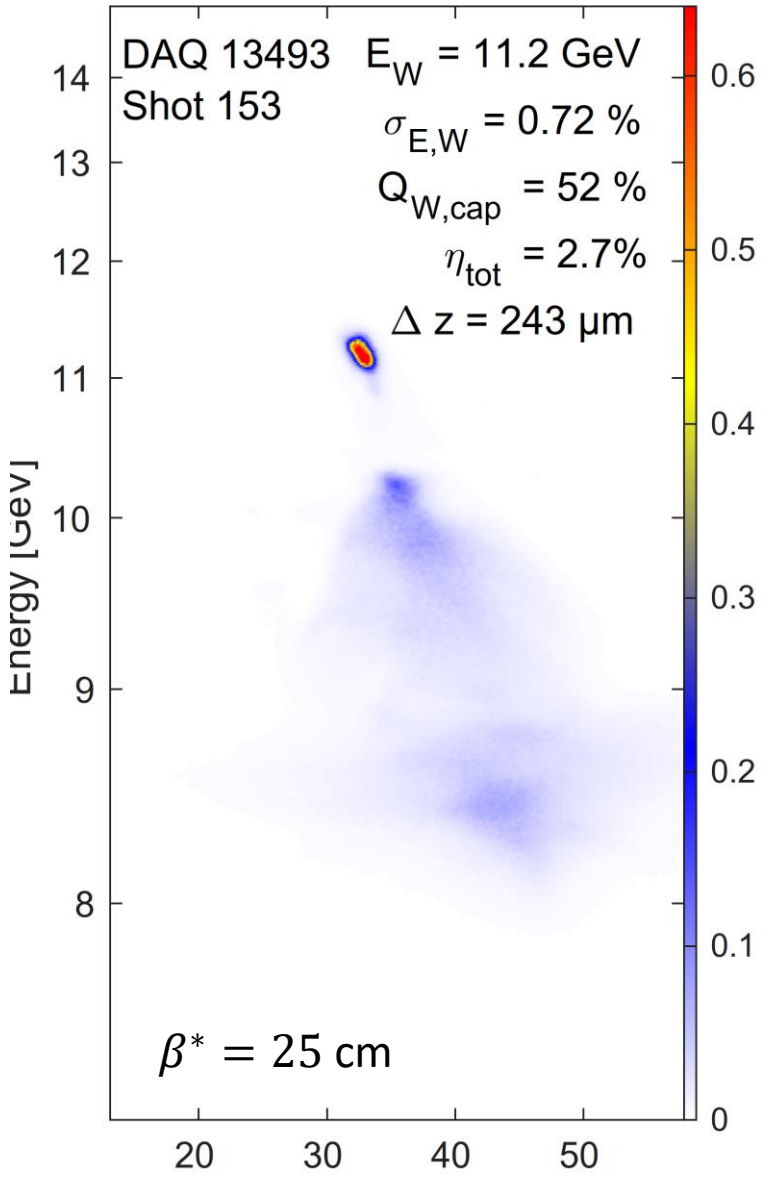


May run – Reduced oven density, 1 Torr and beta* = 25 and 10 cm

- Reduced the oven pressure from 5 Torr to 1 Torr
- This reduces the density from 4.4e16/cc to 1e16/cc
- Blowout bubble size increases by factor of ~2
- Bunch spacing need to go from ~125 µm to 250 µm

- Full datasets at 25cm and 10 cm beta
  - Waist scan → optimize matching into plasma
  - M12 scan in vacuum → incoming beam quality
  - M12 = 15 in vacuum → incoming beam divergence
  - M12 scan in oven → PWFA beam quality / energy spread
  - M12 = 15 → divergence of accelerated beam
  - TCAV data, Slice BPM data

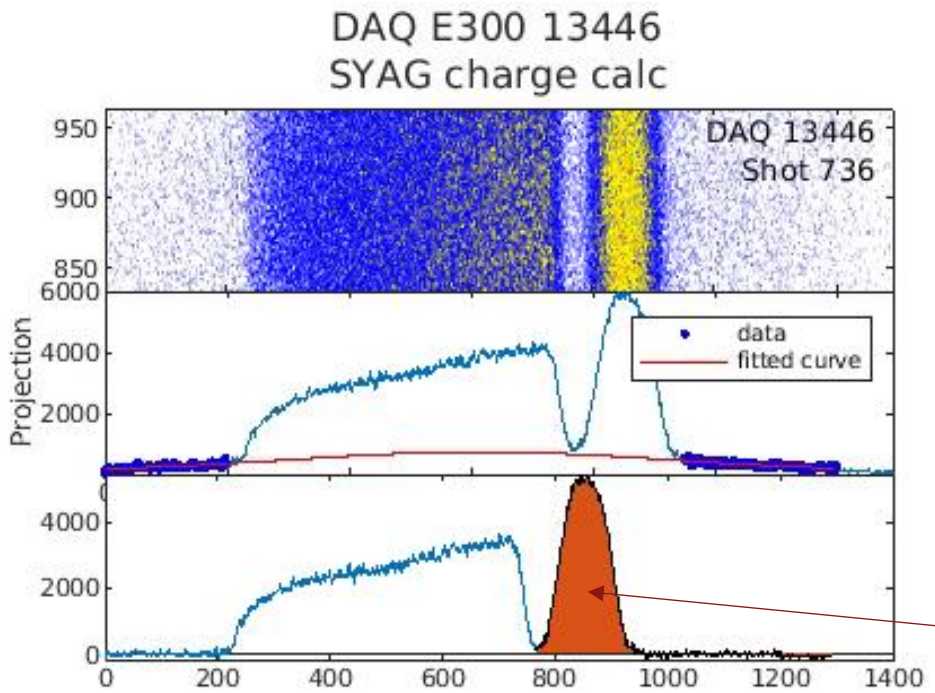
To-do: Analyze all of this

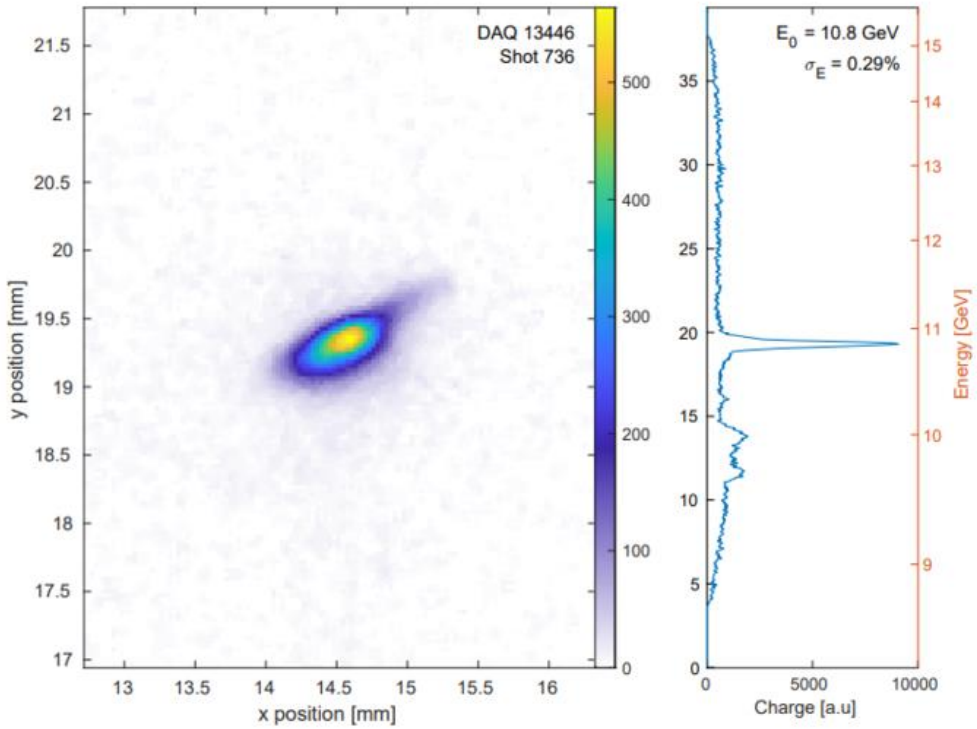


Beam quality – at 1 Torr

- Incoming
  - Charge ~ ??
  - $\sigma_E = 0.4\% \sim 40$ MeV
- Accelerated witness
  - E gain = 1 GeV
  - Charge capture ~300 pC
  - $\sigma_E = 0.29\% \sim 30$ MeV

To-do: More of this, Look at emittance, divergence, etc



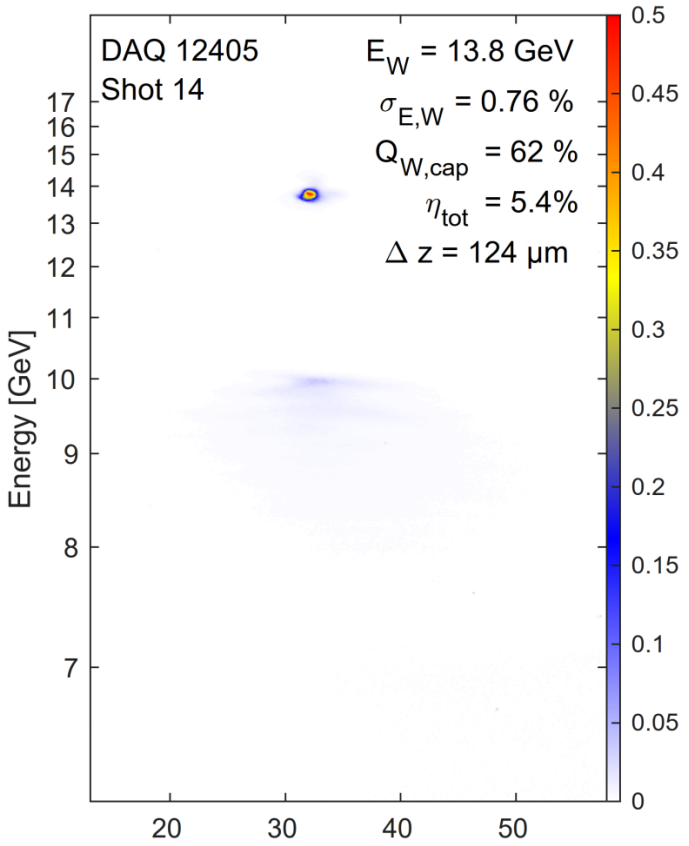


520 pC on SYAG, but this could include some drive charge

Goals summarized from Brendan for this run

Current long-term strategy

Parameter	Units	2016 AAC	FACET-II results 2024	FY25	Achieved simultaneously? (Work in progress)
Emittance (post plasma)	μm	10	>200*	>200	TBD
Energy Spread	%	<5	4	<5	< 1% total *~2-3% field uniformity*
Energy Gain	GeV	10	1.5	3	~4 GeV optimally
Total Efficiency	%	>10	4	10	5%
Gradient	GV/m	>1	2.5	5	9.5 GeV/m
Charge	pC	~100	~100	>100	180 pC
Plasma Source			40 cm Li Oven	40 cm	40cm oven, 5 Torr



Publication topics

- Multi-GeV witness acceleration with high field uniformity
  - Max 6-7 GeV acceleration with highest field uniformity
  - Closer to 1-4 GeV acceleration with better charge capture
  - Importance of beam loading
    - Optimal beam loading vs over/under loaded from notched 2 bunch studies, with simulation

- Matching – depends on what the data says
  - Work towards matching. Depends on what we find from changing density and beta*
  - Multiple densities, beta* = 10, 25, 50cm

Summary

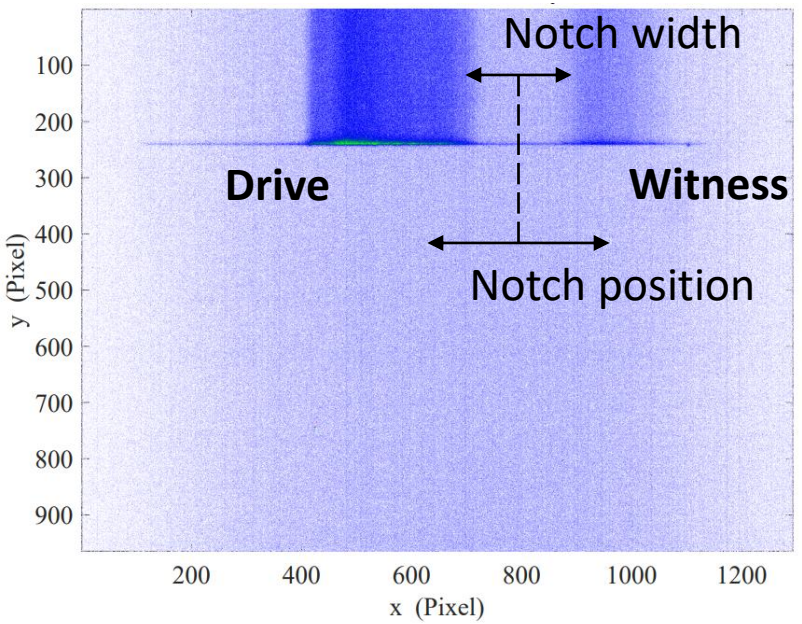
- Transfer efficiencies of 5-6% for good shots with order 60% charge capture

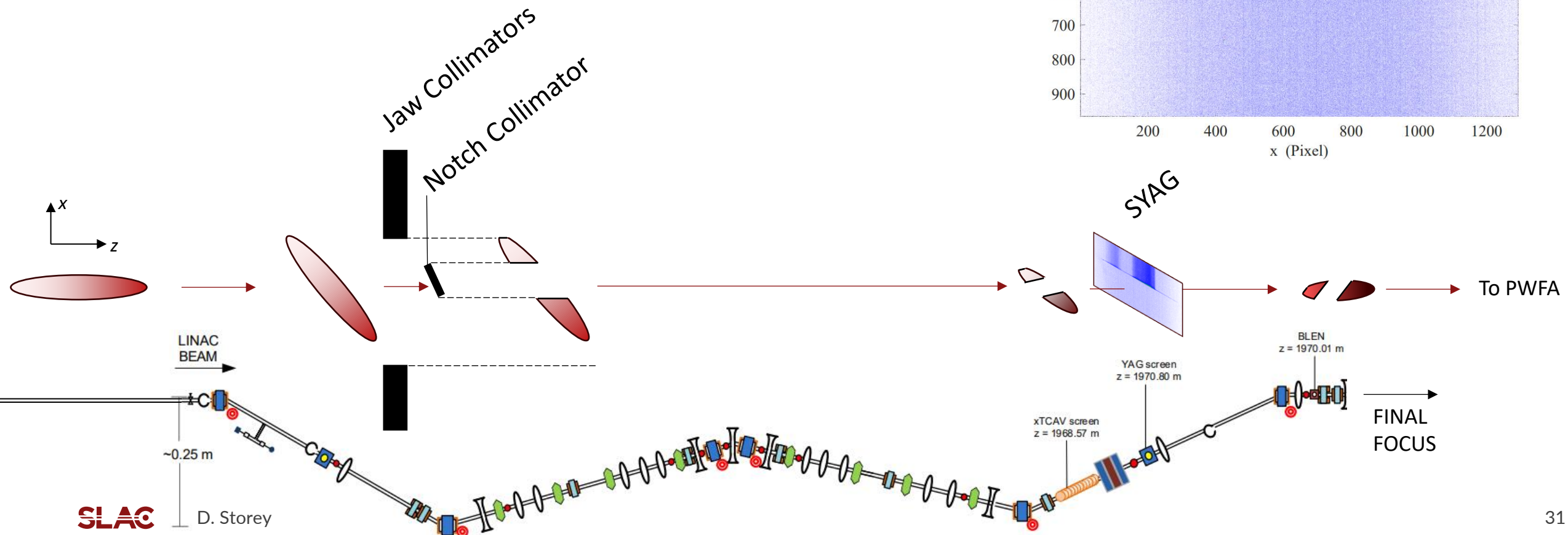
- Left to do (short term):
  - Calibrations, SYAG, TCAV, etc
  - Keep looking at transfer efficiencies to verify if 5-6% is our limit for this run
  - Look at beam quality (divergence) in 5 vs 1 Torr data, 50cm vs 25cm vs 10cm data
  - Emittance estimates, if possible?

- Everything needs to be verified…

Notched two bunches – Why and how

- Linac behaves more stably in the single bunch config
- Can systematically vary bunch spacing/charge by manipulating collimators
- But – this lowers charge, peak current, etc





What diagnostics do we have on the incoming bunches?

- With plasma:
  - Linac scalars – phases, etc
  - BC11 and BC14 BLENs
  - SYAG
  - EOS
  - BPMS/toroids
- Without plasma
  - Plus XTCAV
  - Diagnostics downstream of IP
  - BPM energy slice analysis

To-do: Use a larger parameter set to find comparable shots.
Can we use the virtual TCAV here?