E-300 FY22 Progress and Plans for FY23

Energy Doubling (10-20+ GeV) with <1% Energy Spread, Pump Depletion and > 40% Pump to trailing bunch energy transfer efficiency, while minimizing emittance growth

Chan Joshi (UCLA) and Mark Hogan (SLAC) P.I.s

C Joshi, E Adli, W An, CE Clayton, S Corde, S Gessner, MJ Hogan, et al., Plasma wakefield acceleration experiments at FACET II Plasma Physics and Controlled Fusion 60 (3), 034001

Work supported by DOE-HEP

What are the science goals: definition of success and target time for each goal (from the last PAC meeting)

The Grand Science Goal is to reach the beam parameters needed of a single stage of a future linear collider as far as FACET II infrastructure will allow.

1 Significant energy depletion of the drive bunch with bulk of the particles fully energy depleted	Year 1
2 Efficient (>30%)energy extraction from the wake by the trailing bunch while close to doubling it's energy	Year 1 and 2
3Understand the conditions for optimum beam loading to minimize the energy spread	Year 2
4 Understand and optimize the beam matching for emittance preservation at 10 micron or less level	Year 2 and 3
5 Quantify the extent of transverse BBU or hosing instability	Year 3
6 Perform preliminary experiments for next set of pressing issues	Year 3

UCLA

Experimental timeline: First E 300 Experimental run

UCLA

Commissioning diagnostics: (throughout the year)
- T-CAV, EOS for bunch length and bunch separation measurements
- S-YAG and DT-OTR screens for details of the longitudinal phase space
- Quad-scan and butterfly techniques for slice & projected emittance
- Wire-scanner for focused spot size >20um
- 3 side view ports with cameras to visualize the plasma
- Minimizing Betatron yield as diagnostic of beam matching
- Torroid to measure charge, BPMs to set beam orbit, OTR screens for beam profile

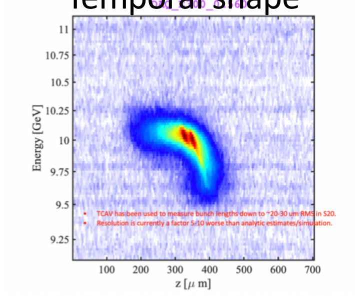
Li Plasma and differential pumping
- LI oven with a bypass-line was installed
- A 4m sect ion of the experimental area isolated from the high vacuum two xx um Be windows
- A differential pumping is installed, partially tested and almost ready to go
- The Be windows sustained significant damage/ not catastrophic failure
- Another unforeseen issue – oven floating was noticed
- (It can be fixed but limited access during LCLS operation made the fix impossible to schedule without loss of crucial experimental time)

Beam Ionized H and He & Wake generation June-Sept
- Simplest solution was fill the bypass tube with H_2 /He and try ionizing the gas with a 25 $(um)^3$ electron beam. Useful information obtained
- need for a laser heater to remove longitudinal current spikes in the beam, preionized H or beam- ionized Li plasma is needed to move forward.
- Approximately 16, 8 hour shifts were devoted to these studies. Obtained experience and data

Red: Development needed

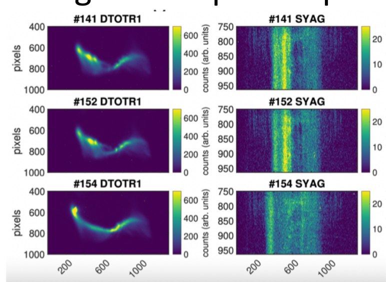
Experimental layout and diagnostics

Temporal shape



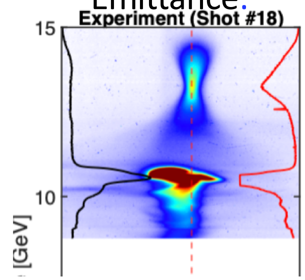
TCAV

Longitudinal phase space



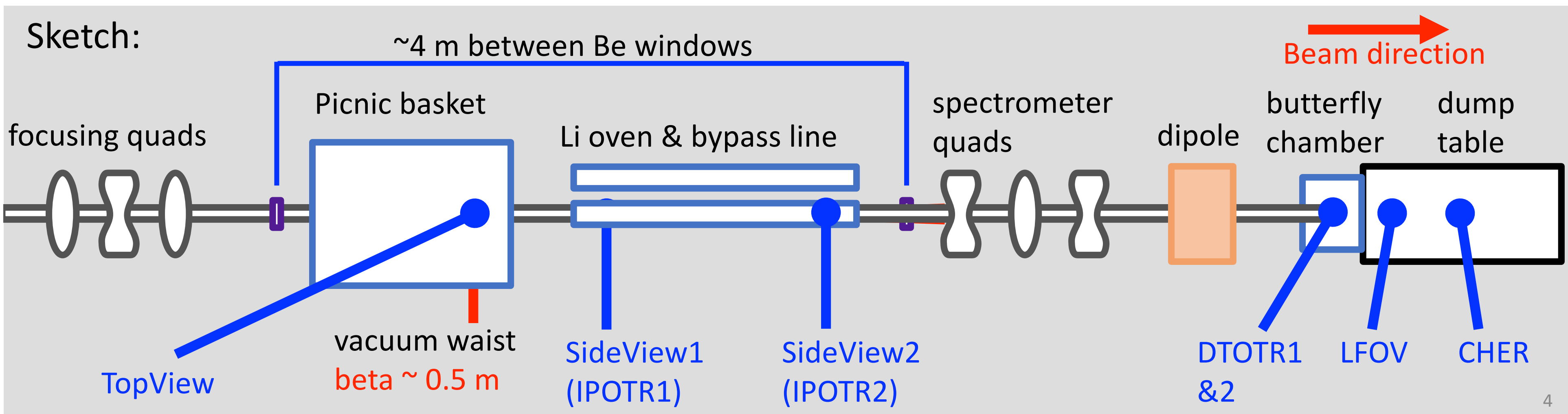
DSOTR SYAG

Emittance:



butterfly

Charge	torroids, spectrometer
Emittance	Quad-scan and butterfly
Beam matching	Minimizing betatron radiatior
Separation	T-CAV and EOS
Bunch length	T-CAV and EOS
Spot size	Wire scanners
Energy gain/loss /spread	Spectrometer



Progress to-date: What did E300 collaboration achieve in Yr 1?

- 1 Diagnostic readiness
- 2 Facility development specific to E300, differential pumping system, imaging spectrometer with two different field of view, ability to field Li plasma source as well as laser-preformed H plasma

3 During beam transport to the dump the Be windows on either side of the Li source were damaged

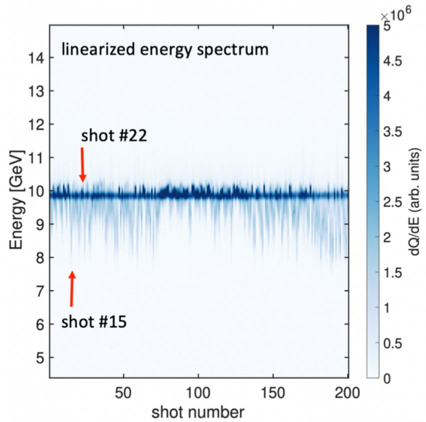
4 The Li oven was moved transversely and the gas fill tube was filled with H to explore if H could be beam ionized as a means of determining the beam brightness.

5 A 2 m long plasma could be formed in H, wakes formed in H and He . Energy loss down to <1 GeV and energy gain of up to 5 GeV could be observed at 2 torr or 6×10^{16} cm^{-3} plasma .

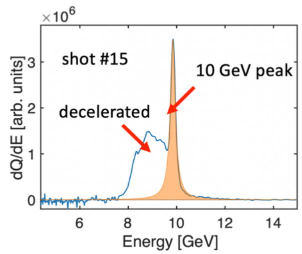
6 A new model based on experimental observations is able to explain the ionization of ,He, energy loss, energy gain and betatron oscillations data.

Energy loss of the drive e bunch in 0.08 T, H_2

UCLA



Separate the unaffected (remains at 10 GeV) and the decelerated part:



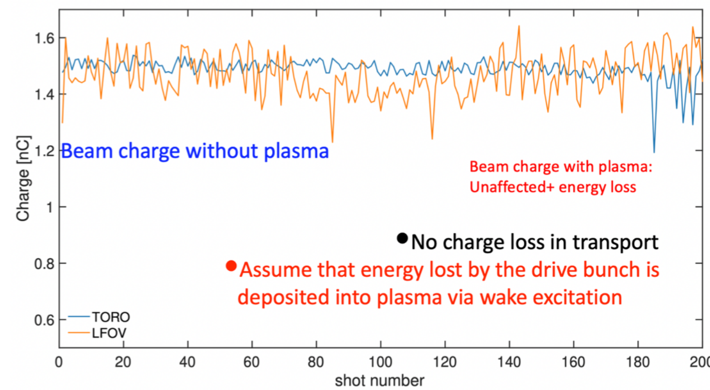
Nominal beam parameters

Charge	1.5 nC
Transverse emittance	25 um
Bunch length r.m.s.	25 um
Focal spot r.m.s.	25 um
Peak current	10 KA

Dataset: 20220817 E300_02781, H2, 0.08 Torr

No charge loss in transporting dispersed beam to spectrometer

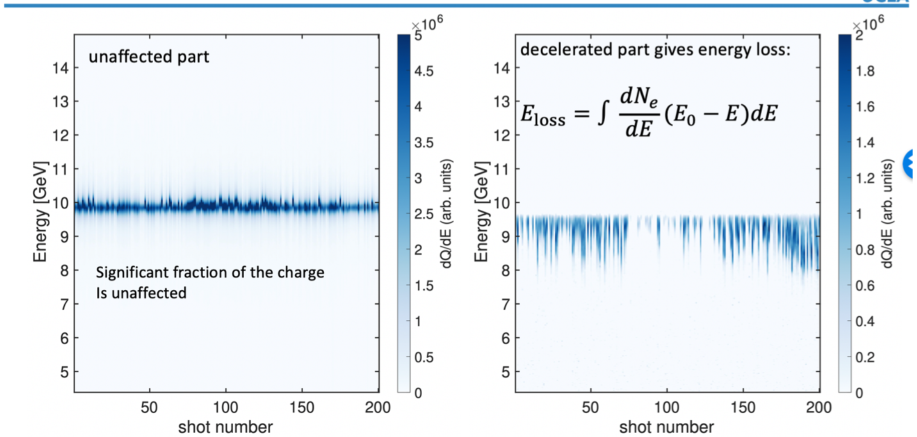
UCLA



Dataset: 20220817 E300_02781, H2, 0.08 Torr

Separate the unaffected (at 10 GeV) and the decelerated part

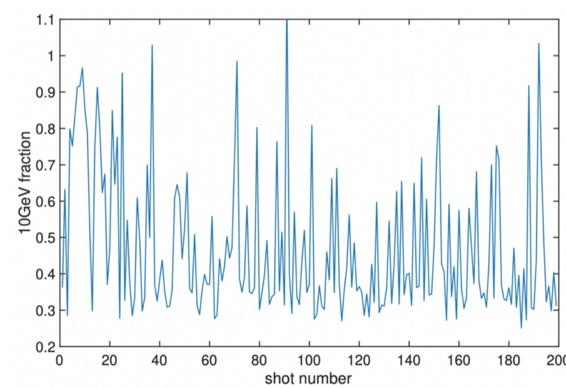
UCLA



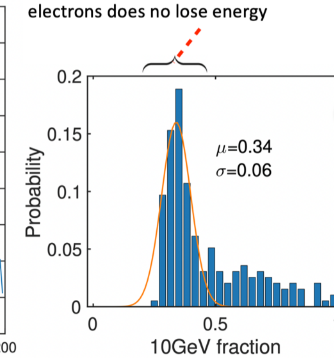
Dataset: 20220817 E300_02781, H2, 0.08 Torr

Unaffected fraction distribution (1.0 Torr)

UCLA



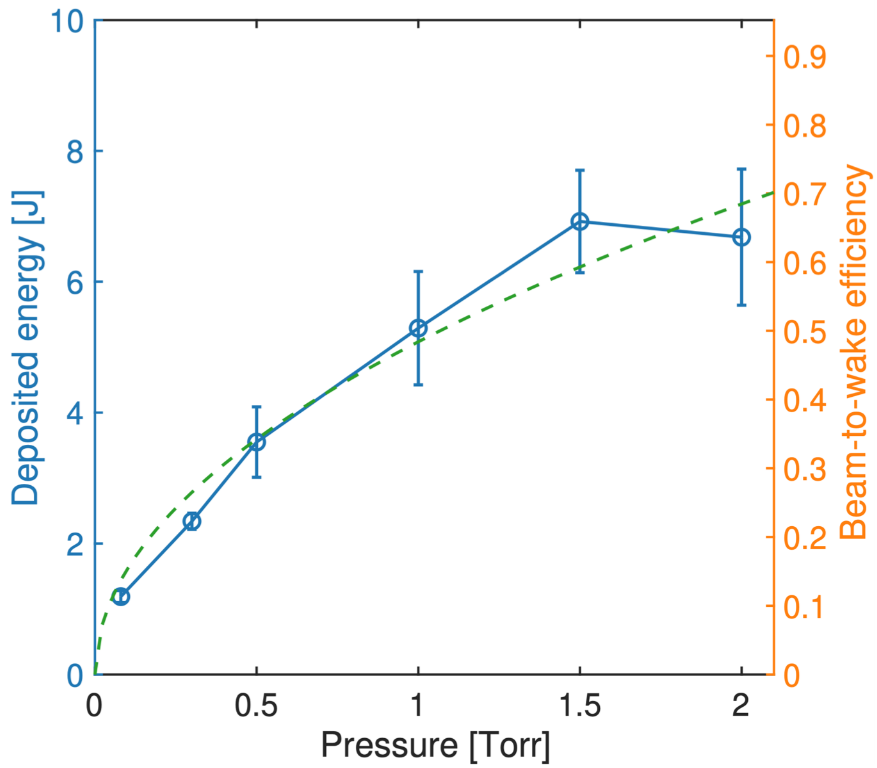
In most shots, 34% of the drive beam electrons does no lose energy



Dataset: 20220817 E300_02817, H2, 1.0 Torr

Beam-to-wake energy transfer efficiency vs. backing pressure

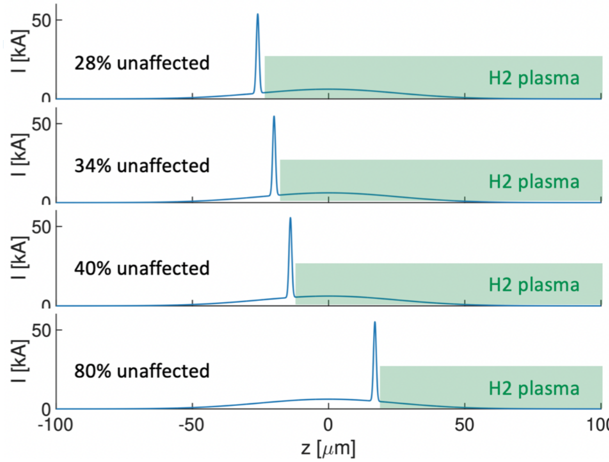
UCLA



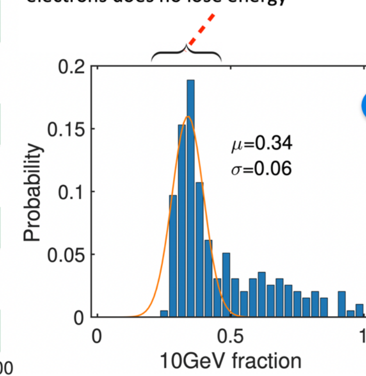
- ~7 J energy was deposited into the plasma for the highest pressure 2.0 Torr
- This corresponds to a **beam-to-wake efficiency of ~70%** (corrected: 7J/(15J*2/3), or : 7J/10 J)
- Data agrees with the fit: $E = Ap^{1/2} + B$ implies that
  - same plasma length
  - deposited energy $\propto E_{\text{dec}} \propto n_e^{1/2} \propto p^{1/2}$, therefore same ionization fraction for these pressures
  - same ionization fraction for different pressure —> most likely 100% ionization? (Zan will talk about the ionization physics)

Fraction of unaffected charge depends on location of the current spike

UCLA

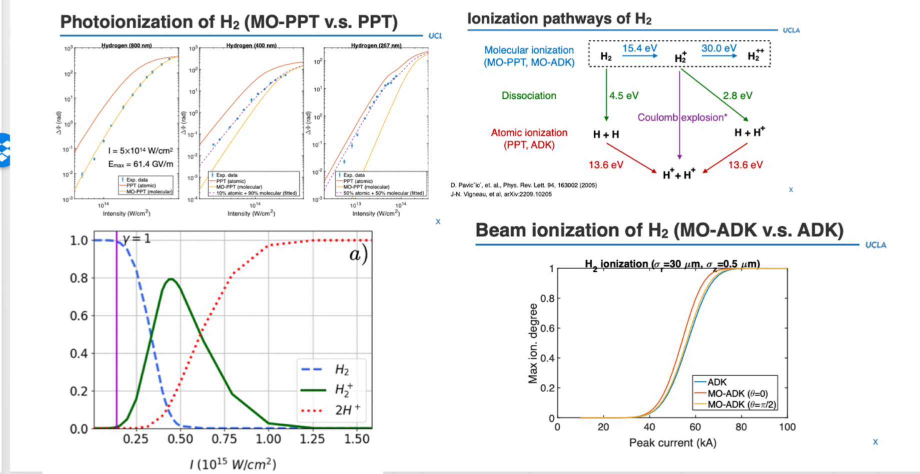


In most shots, 34% of the drive beam electrons does no lose energy



Dataset: 20220817 E300_02817, H2, 1.0 Torr

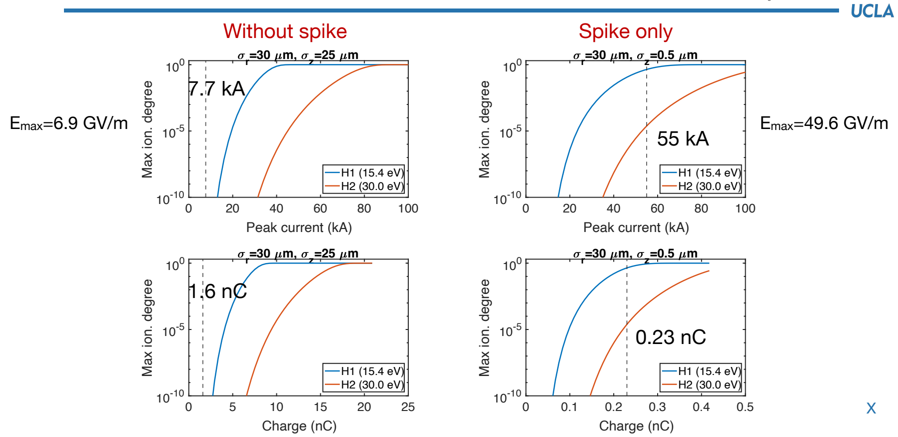
Molecular PPT theory identifies likely pathway of H_2-ionization



Beam ionization of H_2

$$E_{r,max} = 10.4\,\frac{N}{10^{10}}\,\frac{10}{\sigma_r\,[\mu m]}\,\frac{50}{\sigma_z\,[\mu m]}\;[GV/m]$$

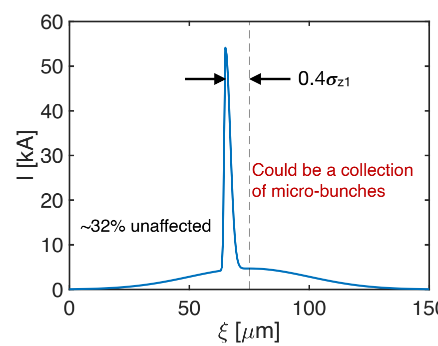
UCLA



X

Modeled new beam current profile

UCLA



Main bunch		Spike	
Charge	0.98 nC	Charge	0.52 nC
Peak current	4.7 kA	Peak current	49.8 kA
σ_r	25 μm	σ_r	25 μm
σ_{z1}	25 μm	σ_{z2}	rise: 0.5 μm fall: 2.0 μm
ε_N	25 μm	ε_N	25 μm
β^*	0.5 m	β^*	0.5 m

X

QuickPIC with Azimuthal Decomposition

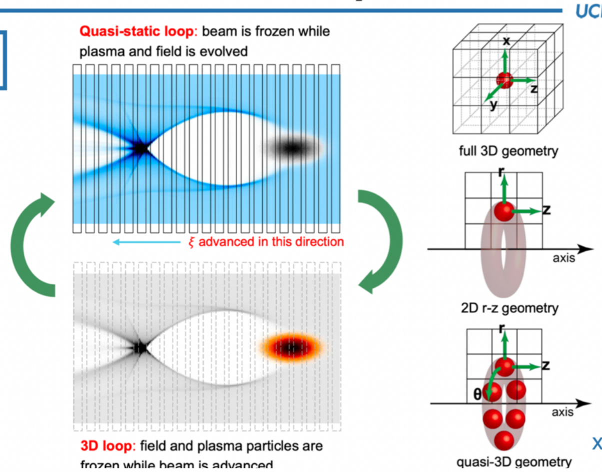
UCLA

Quasi-static + Quasi-3D

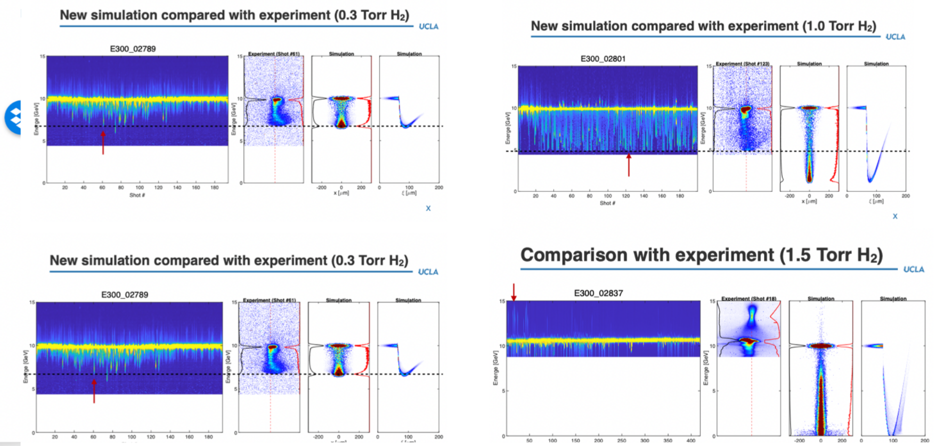
Quasi-static approximation

Cartesian coordinates $(x, y, z; t)$
⬇
Co-moving coordinates
$(x, y, \xi = ct - z; s = z)$
⬇
$\partial_s \ll \partial_\xi$
⬇
Plasma: $(x, y; \xi)$
Beam: $(x, y, \xi; s)$

F. Li, et al., CPC 261, 107784 (2021)



Excellent agreememt between simulations and experimental energy loss, gain and betatron oscillations oscillations

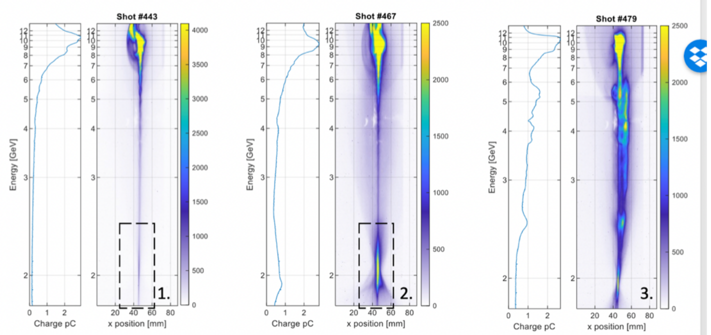


H2 static fill – Some electrons ~fully depleted of energy

- Turning the dipole low shows energy depletion to <2 GeV
  - Spectrometer quads focused at 2 GeV
  - Note – saw <1 GeV in He fill data with the dipole set to an even lower level

Sample images:

1. Most shots look like this – smooth energy profile down to <2GeV
2. Some shots show a charge accumulation at low energy
   - 300pC in box 2 at 2 GeV vs box 1.
3. Some shots show a lot of structure
   1. Scalloping due to betatron oscillations
   2. A few discrete charge bunches

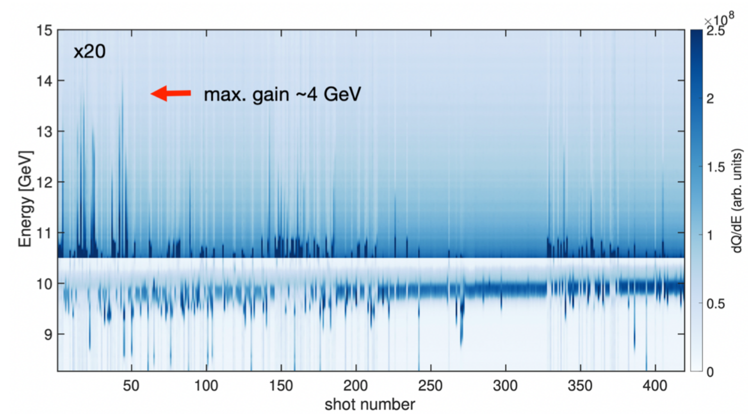


 Slide from Doug Storey

At 1.8 torr we see acceleration of tail particles out to 4 GeV

UCLA

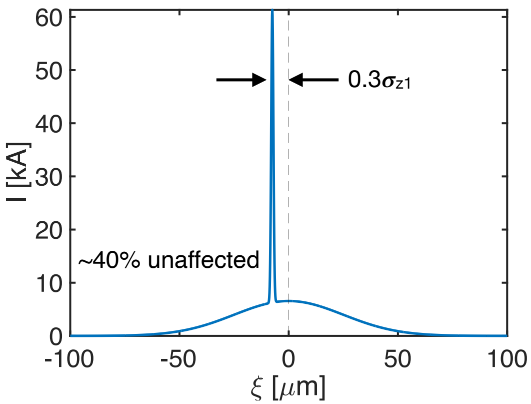
Dataset E300_02813: 1.8 Torr H2. Quads re-image beam vacuum waist (at FILS) at 10 GeV. Dipole at 10 GeV.



Dataset: 20220817 E300_02813, H2, 1.8 Torr

Modeled beam current profile for He case

UCLA

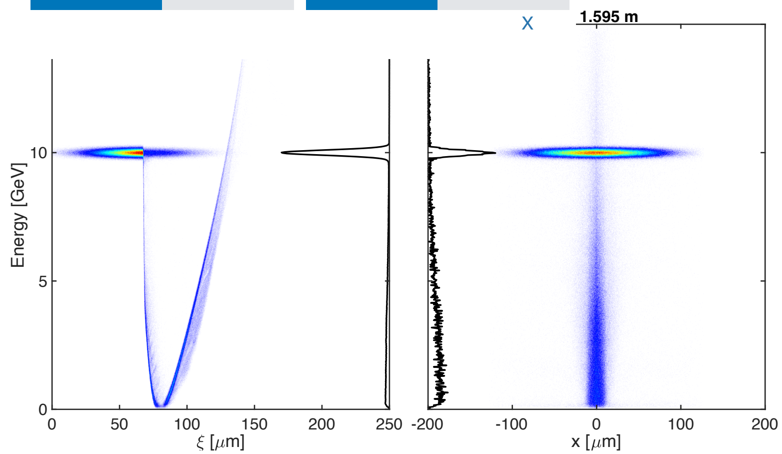


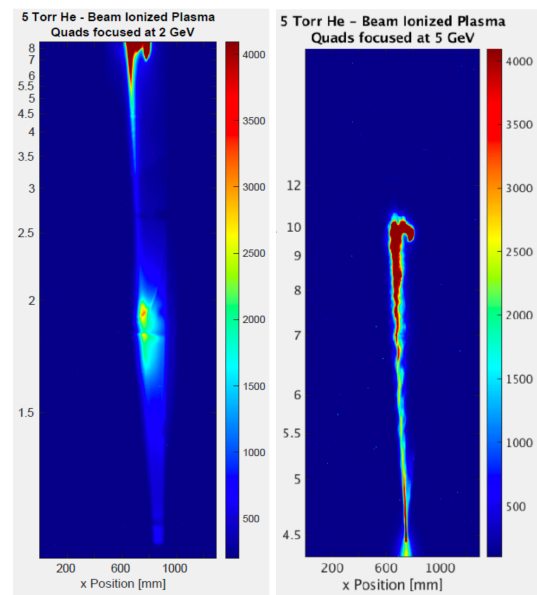
	Main bunch		Spike
Charge	1.37 nC	Charge	0.23 nC
Peak current	6.6 kA	Peak current	55 kA
σ_r	30 μm	σ_r	18 μm
σ_{z1}	25 μm	σ_{z2}	0.5 μm
ε_N	20 μm	ε_N	7.2 μm
β^*	0.88 m	β^*	0.88 m

UCLA

experiment (5.0 Torr He)

UCLA





X

X

Conclusions: What's next?

UCLA

If there is a significant chunk of time available before year's end spend it on

1 Laser heater to get rid of mico-structures in the current bunch

2 Improve the emittance diagnostics to validate the beam emittance without the plasma and measure emittance growth of the decelerated electrons.

3 Get a good correlation between EOS and T-CAV so we have an online bunch separation diagnostic. Ressurect the old pyro (C-CTR) diagnostic as a relative measure of bunch duration.

3 Get the differential pumping operational

4 Try out the laser preionization of hydrogen with and without Be windows as a plasma source.

5 Try out the wake excitation work again to see if we can get > 80% energy transfer from the beam to the wake with < 5% unaffected charge.

Next year 2023

6 If laser preionization of hydrogen runs into problems fix the floating oven with differential pumping.