Energy Doubling and Emittance Preservation through Beam Driven Plasma Wakefield Acceleration at FACET-II

FACET-II
Facility for Advanced Accelerator Experimental Tests

20th Advanced Accelerator Concepts Workshop

Doug Storey, FACET-II, SLAC National Accelerator Laboratory
On behalf of the E300 Collaboration

November 6-11, 2022

SLAC NATIONAL ACCELERATOR LABORATORY

Stanford University | U.S. DEPARTMENT OF ENERGY

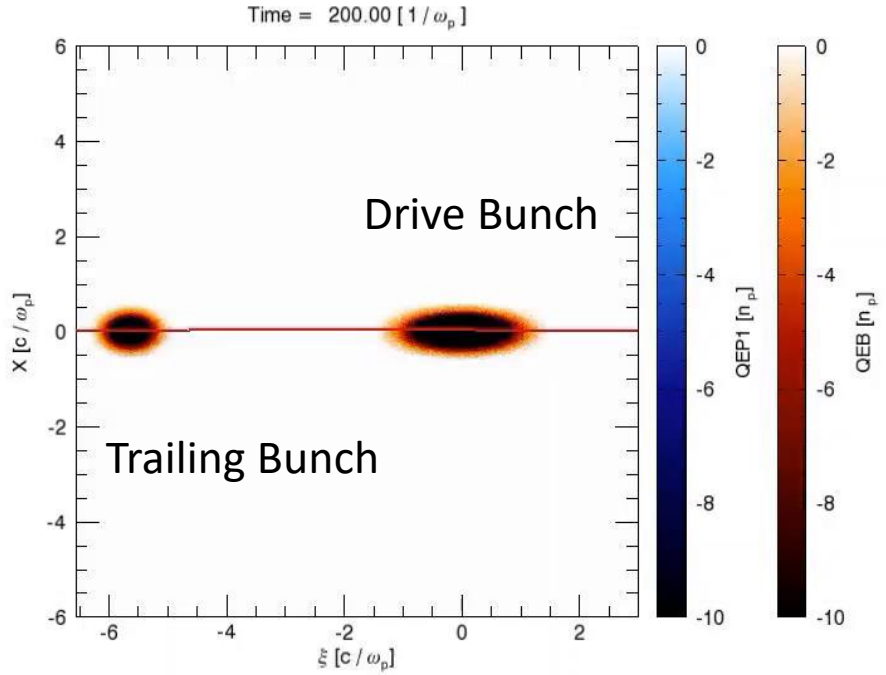
E300 Collaboration

- Presenting on behalf of the E300 collaboration:
  - PIs: C. Joshi (UCLA) and M. Hogan (SLAC)
- SLAC team: J. Allen, R. Ariniello, C. Clarke, C. Emma, E. Gerstmayr, S. Gessner, B. O'Shea, D. Storey, G White, M. Hogan

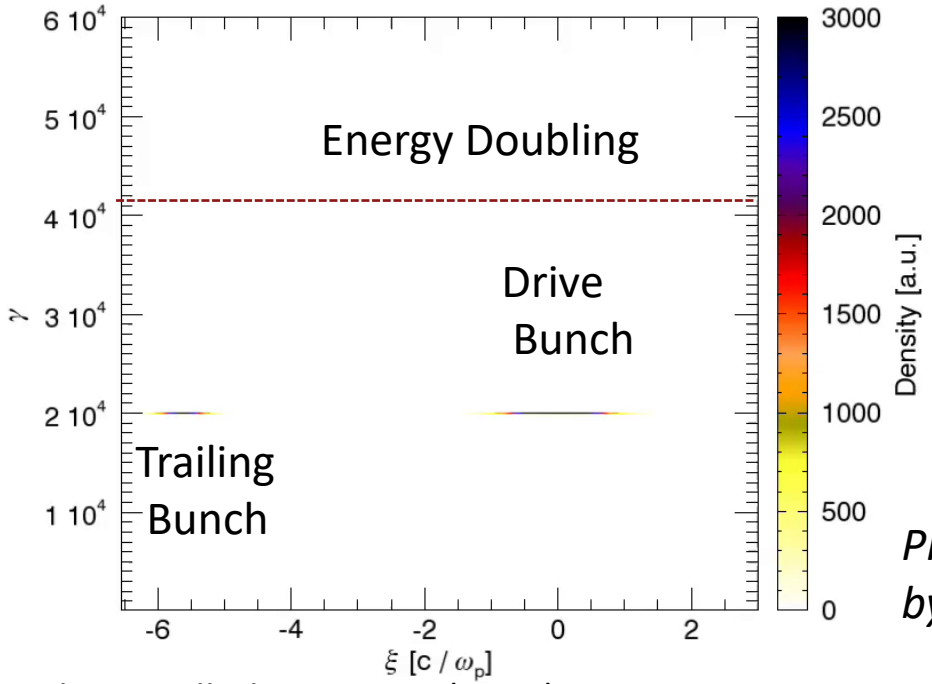
Energy doubling, <1% energy spread, pump depletion

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

Plasma and beam density with on-axis Ez line out:



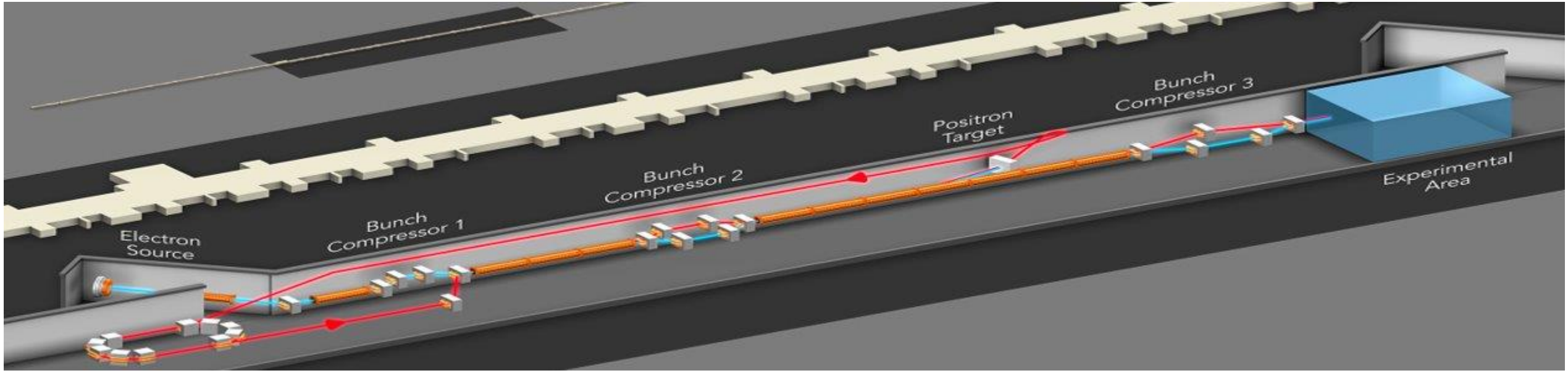
Energy evolution of drive and trailing bunches:



PIC simulations by W. An

C. Joshi, et al., Plasma Physics and Controlled Fusion **60** (2018) 034001

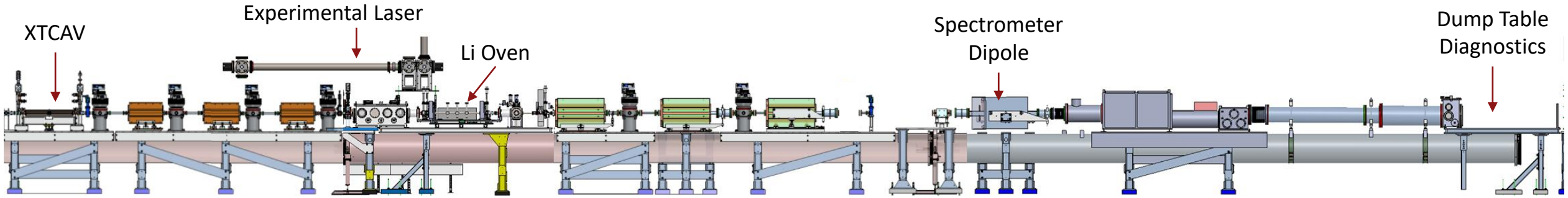
FACET-II National User Facility



- New photoinjector for FACET-II
  - Smaller and round emittances
- 3 stages of bunch compression
  - Up to 100's kA peak current
- Positron capabilities do not exist yet, but plans are in the works

Electron Beam Parameter		FACET Parameters	Current FACET-II Parameters	Operational Ranges
Final energy	[GeV]	23	10	4 – 13.5
Charge per pulse	[nC]	3	1.6	0.7 – 5
$\gamma\epsilon_{x,y}$ at S19	[μm]	100×10	~20	3 – 6
Min bunch length	[μm]	20	~20	0.7 – 20
Max peak current	[kA]	22	--	10 - 200

FACET-II experimental area

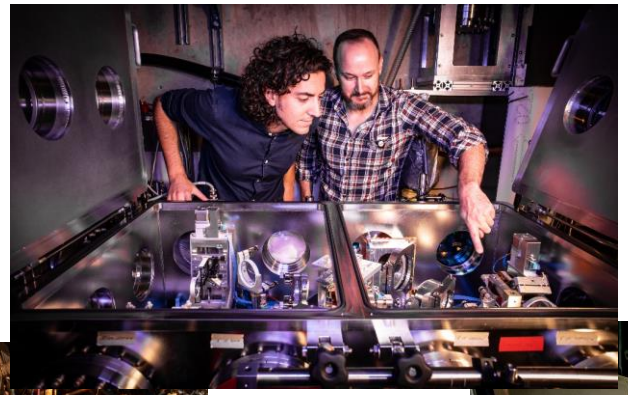


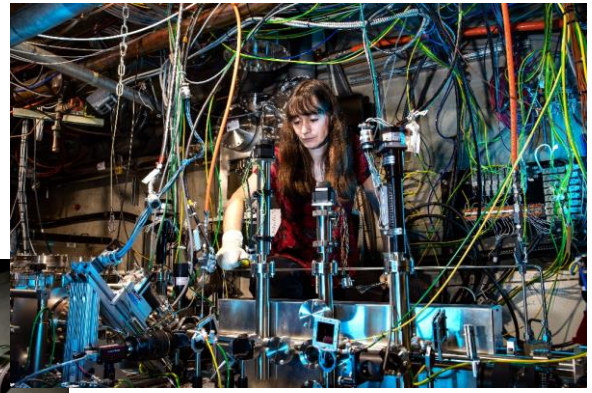
Final Focus

IP Area

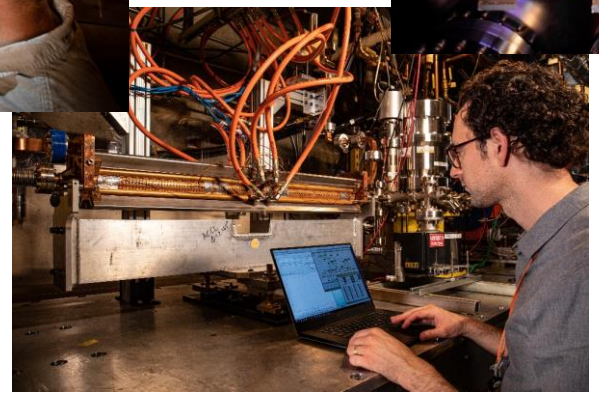
Spectrometer Beamline

SYAG energy diagnostic





Li oven plasma source



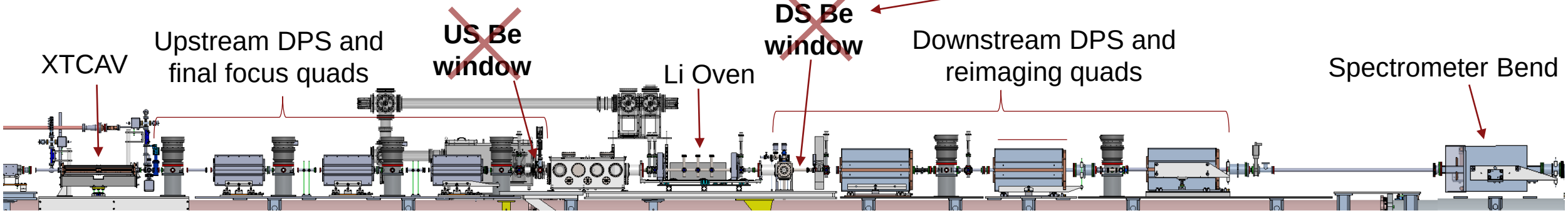
XTCAV and DPS

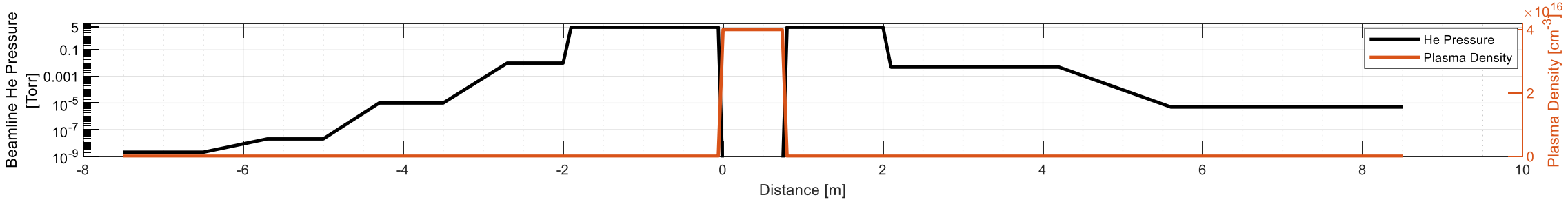
Laser integration chamber
i.e. the “Picnic Basket”

Li oven plasma source and Differential Pumping

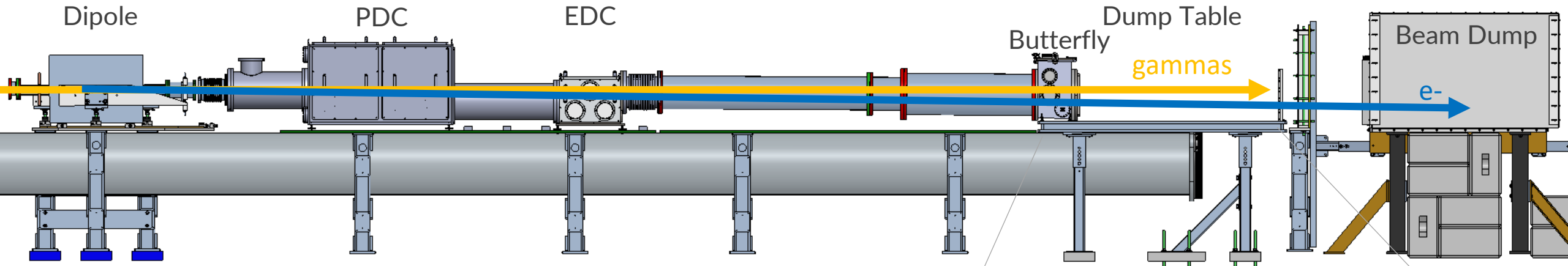
- Main plasma source for E300 is a laser ionized Li plasma
  - Hot lithium vapour contained by a He buffer gas
  - Max density ~ 4×10^{16} cm^{-3} @ 5 Torr He
- Differential pumping system removes Be windows from beamline
  - Can provide 5 Torr He or H_2 gas at IP

Be window after 2022 run

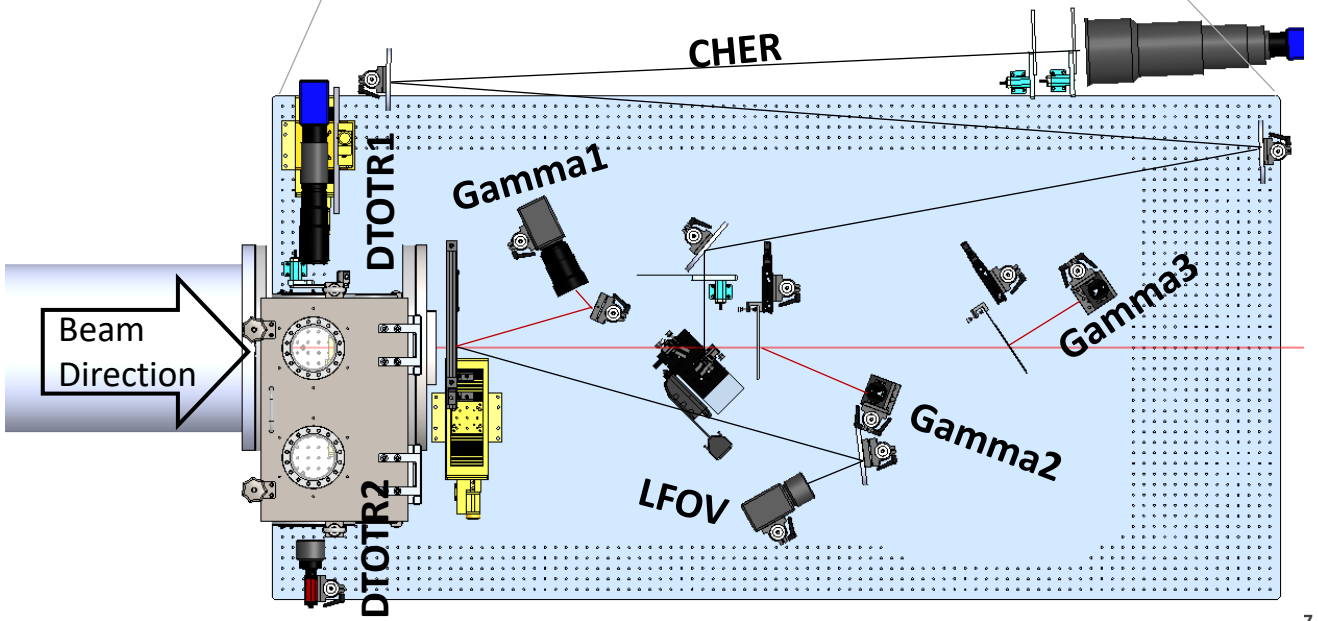




Spectrometer diagnostics



- Reimaging spectrometer after plasma source
  - Quadrupole triplet and spectrometer dipole
- Electron diagnostics
  - **DTOTR**: High resolution profile monitors
  - **LFOV** and **CHER**: electron profiles ~2GeV to >20 GeV with <0.5% energy resolution
- Betatron radiation diagnostics:
  - **GAMMA1/2/3:** Intensity and spectral info



Emittance diagnostic

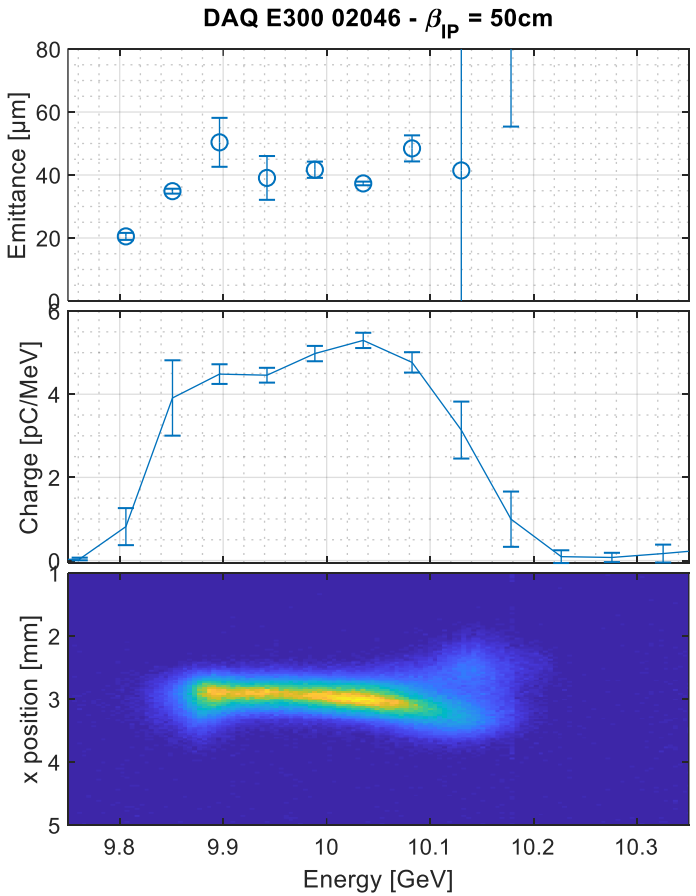
- Beam size at high resolution DTOTR screen:

$$(\sigma_x(E))^2 = \frac{\epsilon_n}{\gamma_b}\left[M_{11}(Q_{0,1,2},E)^2\beta_0 - 2M_{11}(Q_{0,1,2},E)M_{12}(Q_{0,1,2},E)\alpha_0 + M_{12}(Q_{0,1,2},E)^2\left(\frac{1+\alpha_0^2}{\beta_0}\right)\right]$$

  - M11 and M12 are transport matrix through spectrometer
  - ϵ_n, β_0, and α_o are bunch properties at plasma exit

1. Dispersive quad scan – multi-shot
- Extract $\epsilon_n(E)$
- Requires shot-to-shot stability

2. Butterfly measurement – single shot
- Lower limit of resolution ~5% for matched beams
- Development ongoing: susceptible to existing correlations and phase mismatch



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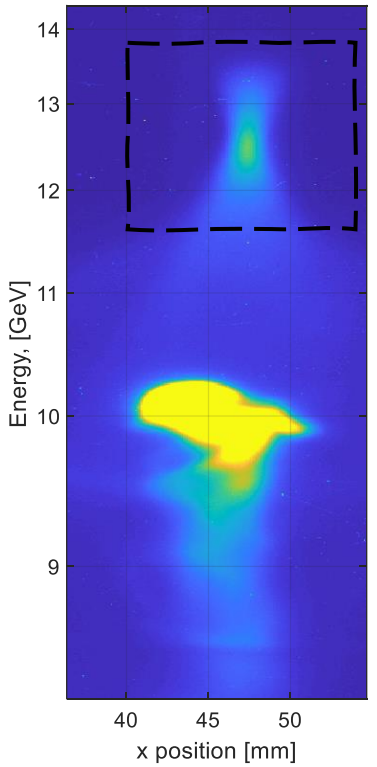
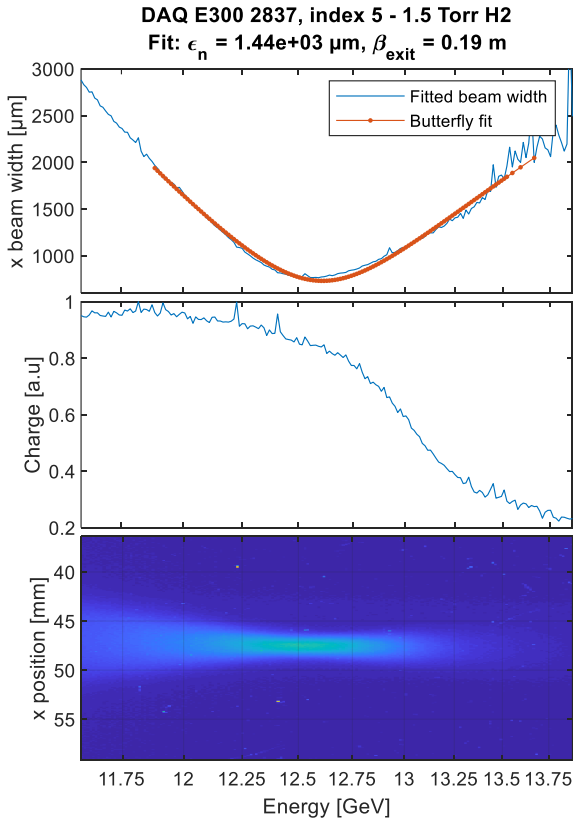
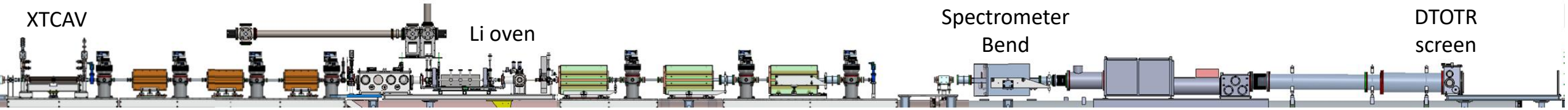
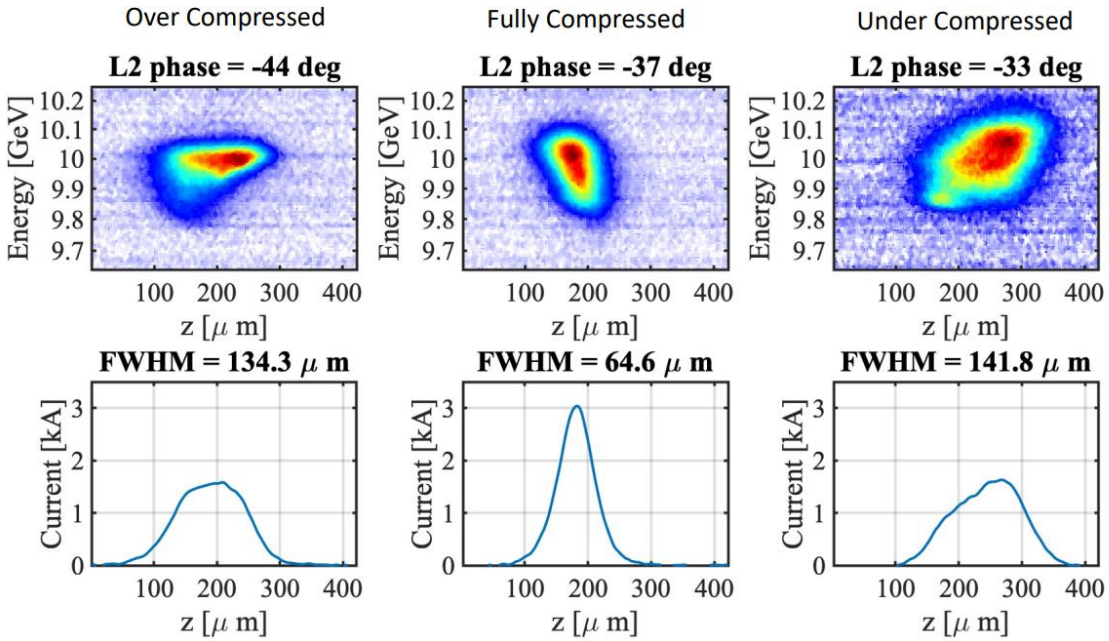




Longitudinal phase space measurements via XTCAV

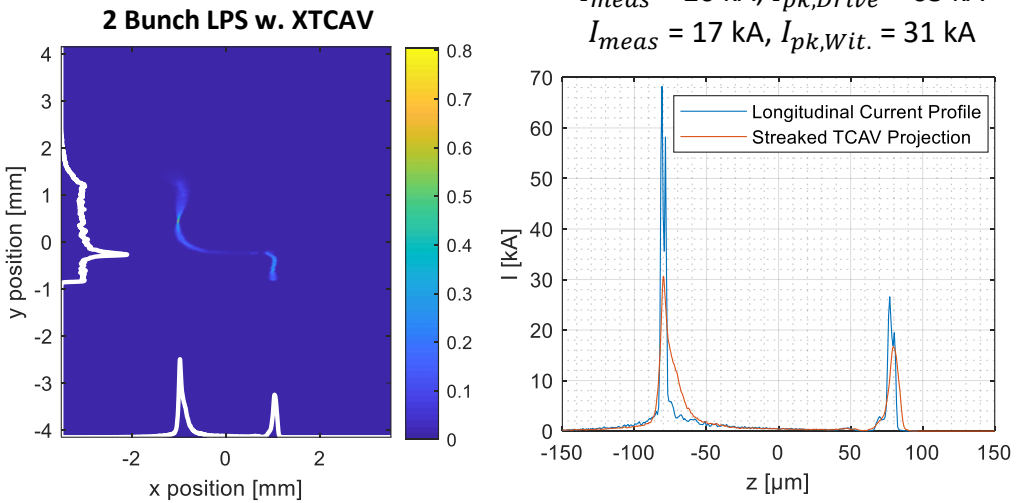


- X-band deflecting cavity streaks beam in x-direction
  - Ultimately resolution capability of ~1μm
- Spectrometer dipole disperses the beam vertically



Analysis by C. Emma

I_{meas} = 26 kA, $I_{pk,Drive}$ = 65 kA
I_{meas} = 17 kA, $I_{pk,Wit.}$ = 31 kA



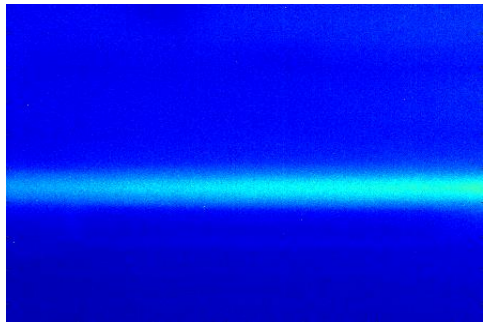
- Used as part of a machine learning based virtual diagnostic to provide non-destructive longitudinal phase space measurements

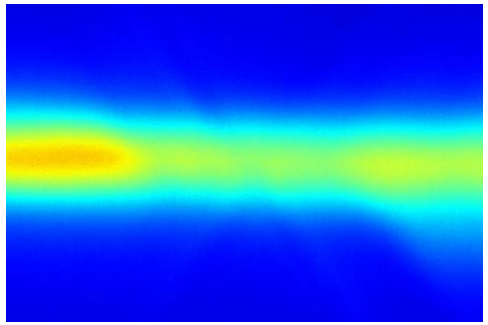
See talk by C. Emma on Wednesday in WGs 2+5

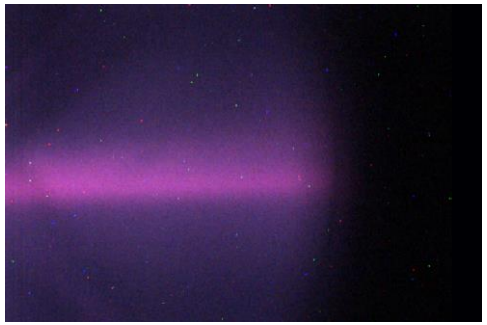
Beam ionized H_2 PWFA

- Static H2 fill between the US and DS Be windows (with holes)
  - Static fill of up to 2 Torr supported by the differential pumping system
  - Beam self-ionized a plasma of ~3m length
  - Plasma afterglow light visible on OTR cameras throughout IP area

Be window after 2022 run







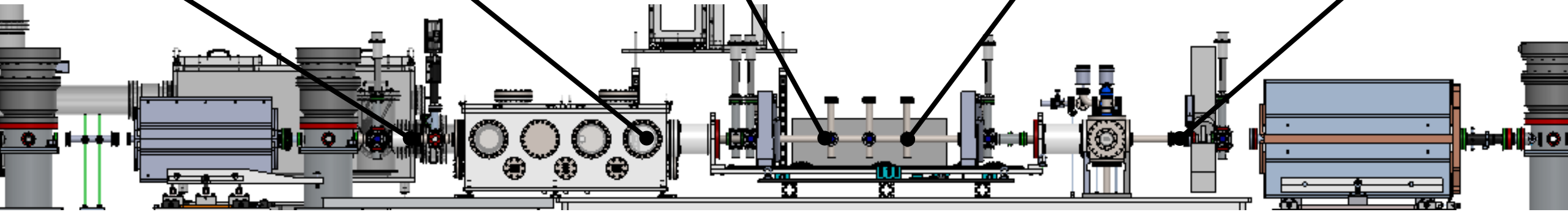
US Be window

TopView: Z=1993.3

IPOTR1: Z=1993.8

IPOTR2: Z=1995.1

DS Be window: Z=1996

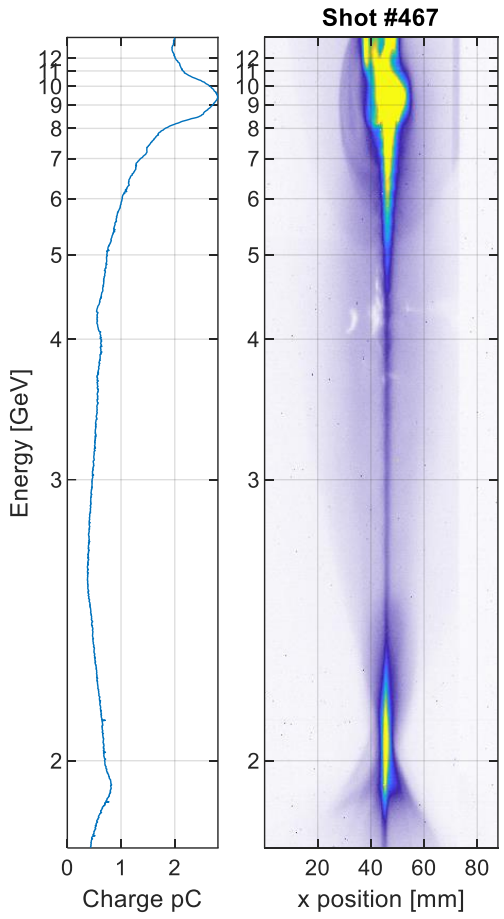


Beam ionized H_2 PWFA – Energy depletion and acceleration

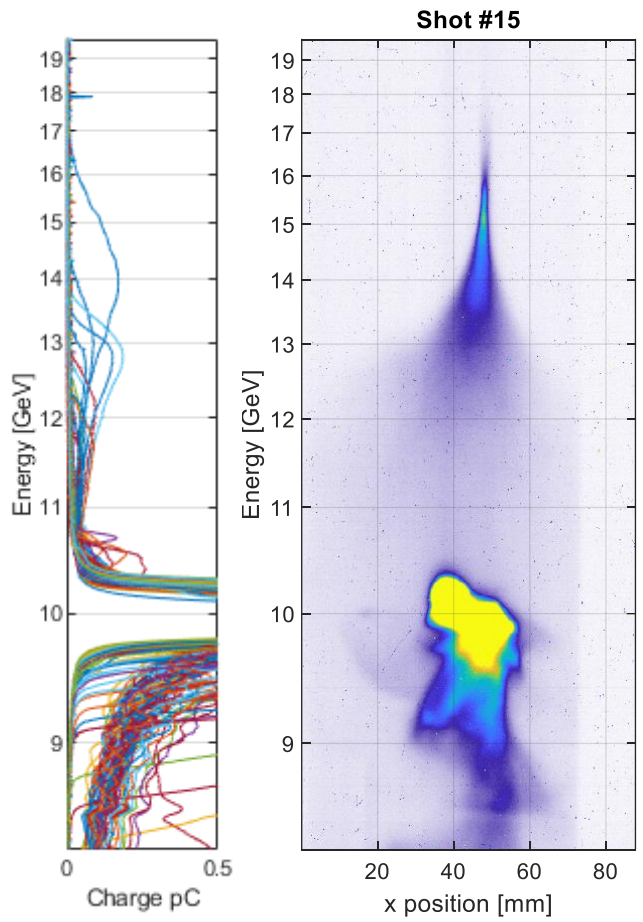
- Spectrometer measurements of the single bunch after PWFA
  - Scanned H_2 pressures from 0.1 to 2 Torr
    - Results here from 1.5 – 2 Torr
- Energy depletion down to <1 GeV
  - Charge counting indicates beam-to-wake transfer efficiencies of up to ~70%
- Acceleration of up to 15+ GeV

More details by C. Zhang and Z. Nie in the next WG 4 talks

Energy Depletion

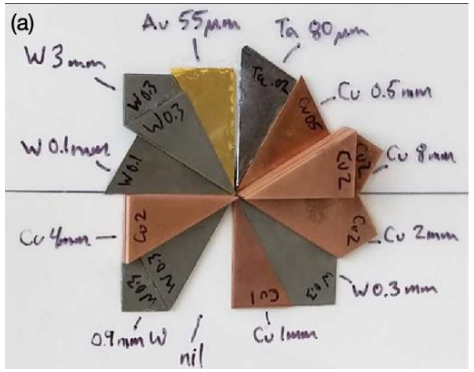


Acceleration via PWFA

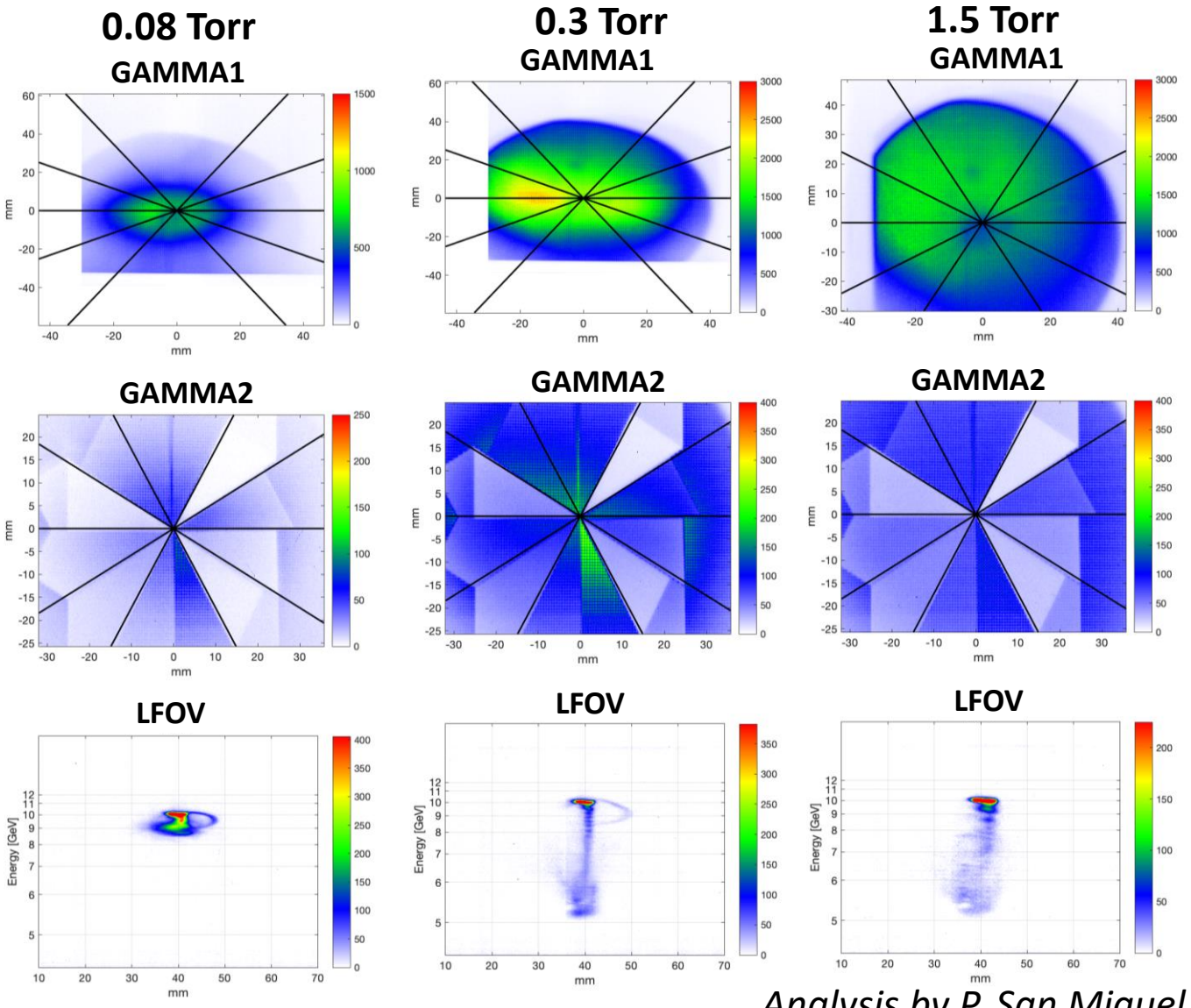


Betatron radiation diagnostics with H_2 PWFA

- GAMMA1 detector measures intensity and angular profile
  - DRZ scintillator or CsI crystal array
- GAMMA2 provides spectral info by measuring conversion signal behind filters
  - Filter set:
  - DRZ scintillator immediately sits behind



- Provides information on matching dynamics, trailing bunch offsets, etc



Analysis by P. San Miguel

See talk by P. San Miguel on Wed. in WGs 4+7

Summary

- FACET-II is an ideal facility for demonstrating beam parameters required for a single stage of a PWFA future linear collider

- Goal of E300 – demonstrate energy doubling (10-20+ GeV) with
  - <1% Energy Spread,
  - Pump Depletion and > 40% pump to trailing bunch energy transfer efficiency,
  - while minimizing emittance growth

- Delivery to user programs has begun:
  - Progress made in diagnostics development and readiness for PWFA at FACET-II
  - First beam-ionized plasmas generated in He and H_2
  - Measured energy depletion and acceleration through beam ionized PWFA

FACET-II | Facility for Advanced Accelerator Experimental Tests

Questions?

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Next steps for E300

- FACET-II machine development is ongoing
  - Further improvements beam properties and stability
  - Laser heater to provide increased longitudinal control

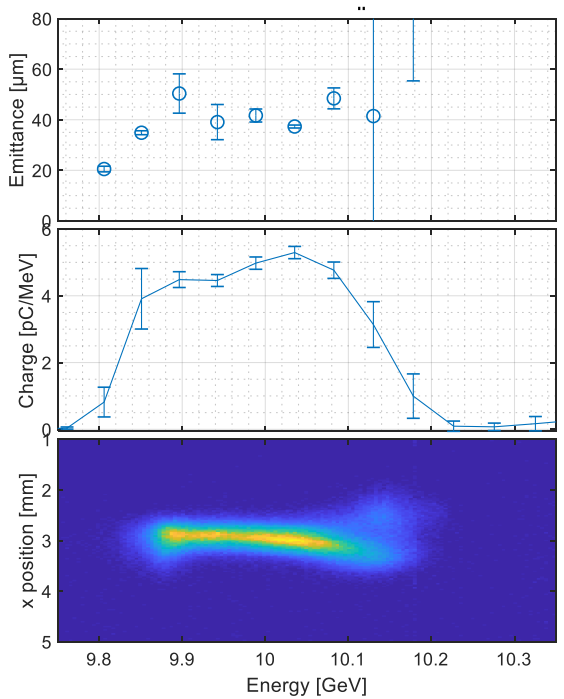
- Diagnostics commissioning and development is ongoing
  - Emittance diagnostics, EOS, XTCAV systems

- Stable operation of the differential pumping system → Li oven operation

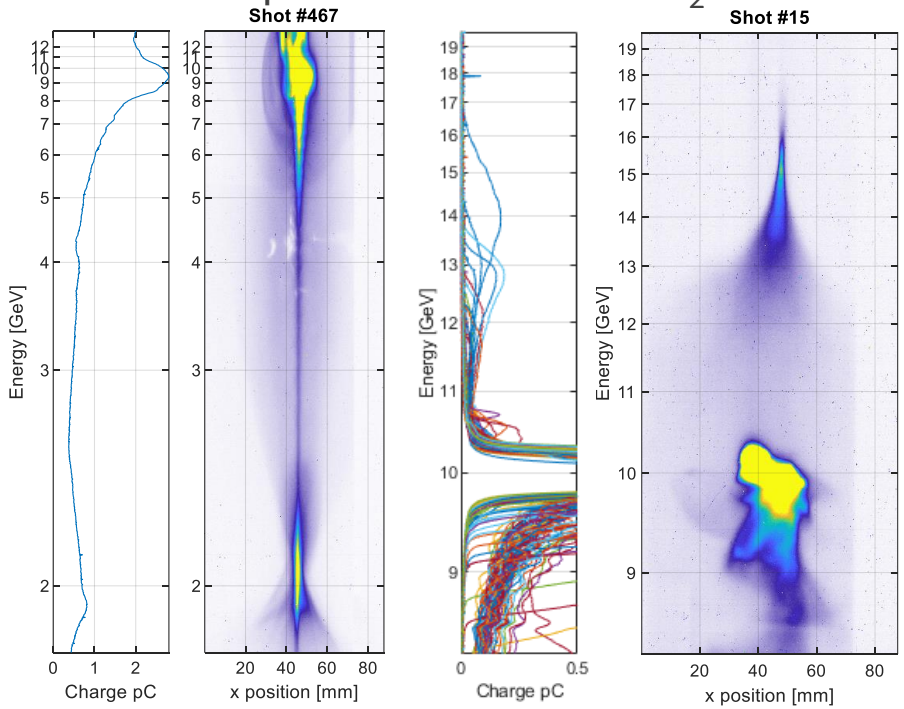
E300: Energy Doubling and Emittance Preservation through Beam Driven Plasma Wakefield Acceleration at FACET-II

- Goal of E300: demonstrate beam parameters required for a single stage of a PWFA future linear collider
- Progress made in diagnostics development (below) and readiness for PWFA at FACET-II
- First beam-ionized plasmas generated in He and H_2 up to 5 Torr in pressure, with differential pumping
- Measured energy depletion and acceleration through beam ionized PWFA

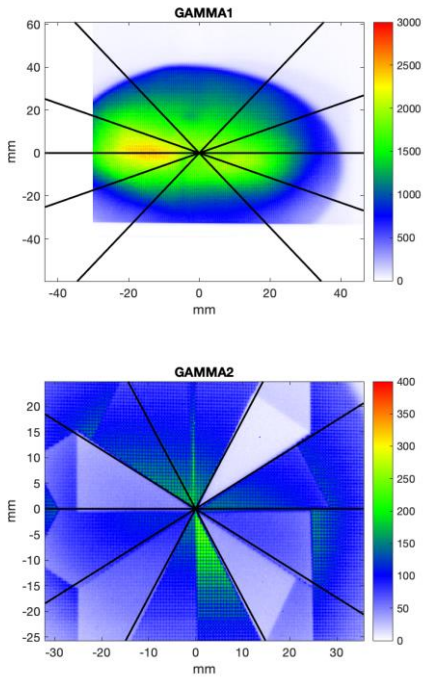
Emittance of incoming beam



Electron Spectra from 1.5 Torr H_2 PWFA



PWFA Betatron radiation



LPS via XTCAV