FACET-II

Facility for Advanced Accelerator Experimental Tests

International Linear Accelerator Conference 2022, Liverpool

Christine Clarke / FACET-II User Manager / FACET & Test Facilities

August 31st, 2022

FACET-II Mission Need

- Accelerator facilities with high quality beam parameters are essential to support the necessary research into new acceleration techniques with the potential to dramatically reduce the size and cost of future colliders

Key Elements for FACET-II program:

- **Beam quality** – build on 9 GeV high-efficiency FACET results with focus on emittance
- **Injection** – ultra-high brightness sources, **staging studies**
- Develop concept for PWFA demonstration facility
- **Positrons upgrade** – use positron beam to identify optimum regime for positron PWFA

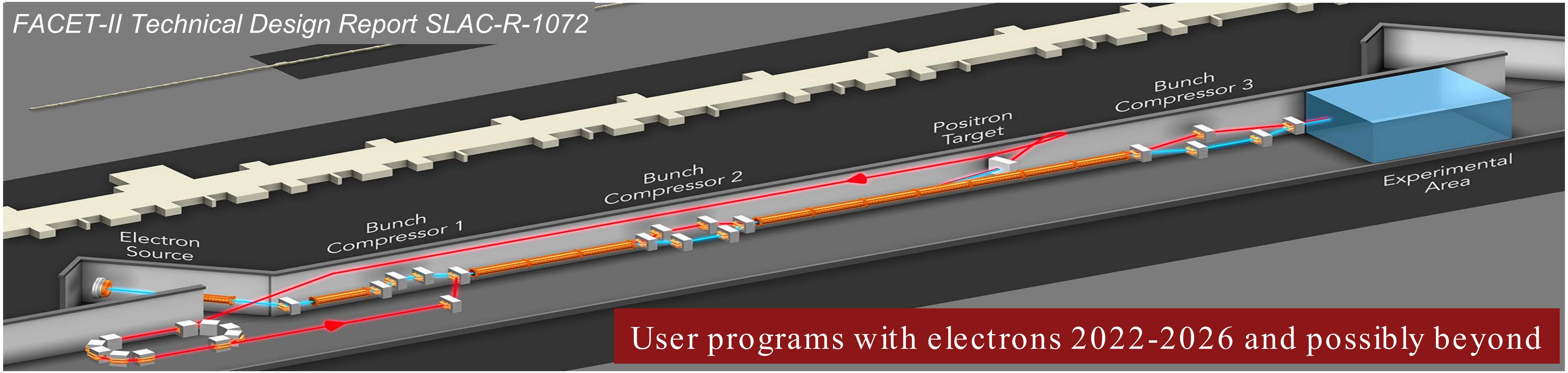
- Plasma Wakefield Acceleration (PWFA) is a scheme initially proposed four decades ago for high (GV/m) gradient acceleration, 1,000 times the acceleration in a given distance compared to conventional RF technologies

- The only facility where research on beam driven plasma wake-field accelerators can be conducted at collider intensities is the FACET-II facility at SLAC.

Litos, M., Adli, E., An, W. *et al.* High-efficiency acceleration of an electron beam in a plasma wakefield accelerator. *Nature* **515**, 92–95 (2014). https://doi.org/10.1038/nature13882

FACET-II experimental program will enable well informed decisions about the viability of the technology

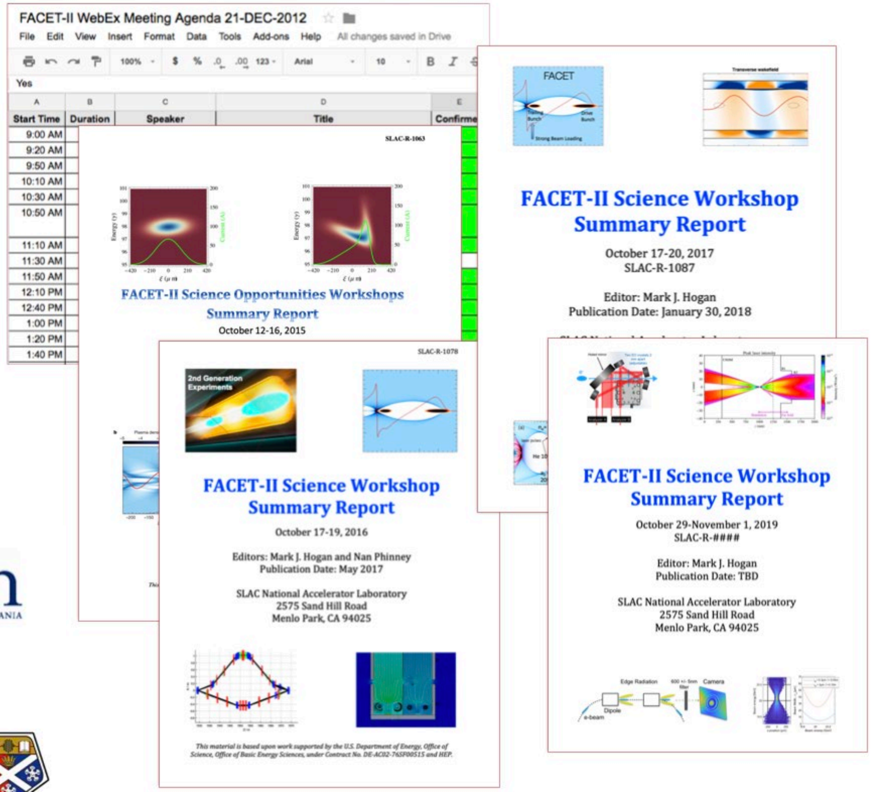
FACET-II National User Facility



FACET-II Science Program and Program Advisory Committee

Science Program developed through seven years of science workshops


First Program Advisory Committee Meeting 2018



47 proposals reviewed
11 invited for beam time in FY22

PAC Meetings in Oct 2018, 2020, 2022

FACET-II science developed by international community and overseen by peer review

FACET-II proposals by fields

PWFA Beam Quality (5 proposals, 2 'Excellent')

- PIs: Andonian, Joshi/Rosenzweig (UCLA), Hogan (SLAC), Litos (CU Boulder), Adli (U Oslo), Nagaitsev (FNAL), Gessner (CERN)…

PWFA Injection (6 proposals, 1 'Excellent')

- PIs: Hidding/Ullmann/Habib (U Strathclyde), Vafei (Stony Brook), Zhang/Xu (UCLA), Corde (Ecole Polytechnique), Rosenzweig (UCLA)…

PWFA Other (13 proposals, 2 'Excellent')

- PIs: Corde (Ecole Polytechnique), Joshi/Marsh/Rosenzweig (UCLA), Litos (UCBoulder), Fiuza/Marinelli (SLAC), Heinemann/Hidding/Habib (U Strathclyde)…

Machine Learning & Diagnostics (12 proposals, 1 'Excellent')

- PIs: Osterhoff (DESY), Marksteiner/Scheinker (LANL), Emma/O'Shea/White (SLAC), Downer (UTAustin), Hidding/Scherkl/Sutherland (U Strathclyde), Fiorito, Andonian/Ruelas (Radiabeam)…

Other: Dielectrics, Extreme Beams… (11 proposals, 2 'Excellent')

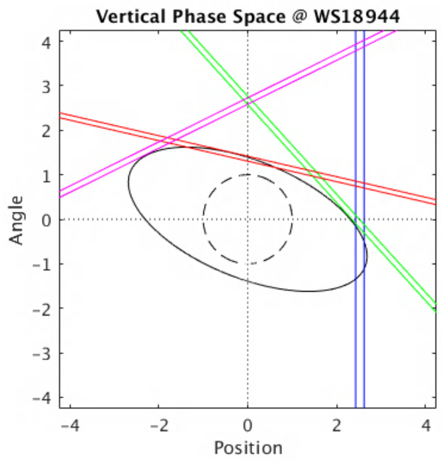
- PIs: Meuren (PPPL), Litvinenko (Stonybrook), O'Shea (SLAC), Rosenzweig (UCLA), Chen (UPenn)…

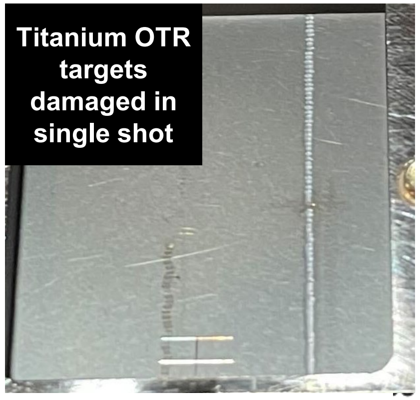
FACET-II facility is designed around PWFA but attracts proposals in Machine Learning, Diagnostics and other science that needs FACET-II's extreme beams

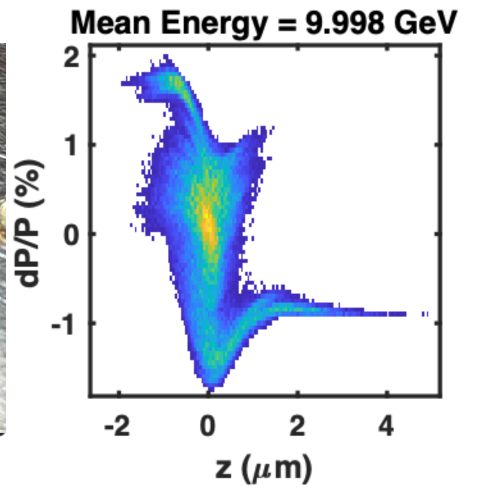
FACET-II accelerator is accessing new regimes

- FACET-II commissioning started September 2020
- First experiment run May – August 2022
- Key upgrades: Photocathode Injector, final focus
- Designed for:
  - ~10 µm Emittance
  - ~100 kA Peak current (sub-µm bunch length)
  - ~10^{12} V/cm radial electric field
  - ~10^{24} e^-/cm^3 beam density

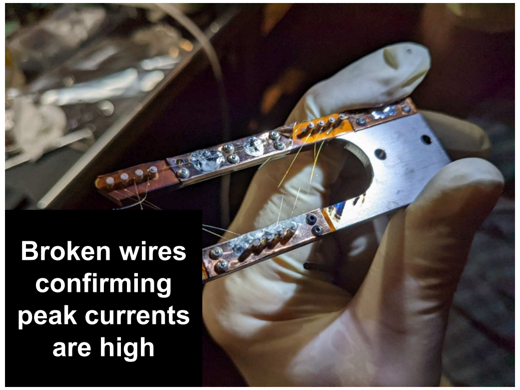
Electron Beam Parameter	Nominal 2022	Range
Energy [GeV]	10	4.0 - 13.5
Charge per pulse [nC]	2	0.5 – 3
Repetition Rate [Hz]	10	1 – 30
Spot Size [µm]	30	5 – 200
Minimum bunch length [µm]	20	1 - 100
Max peak current [kA]	>10	10-200

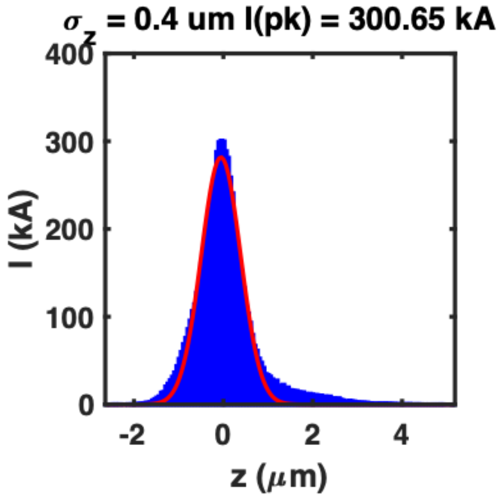






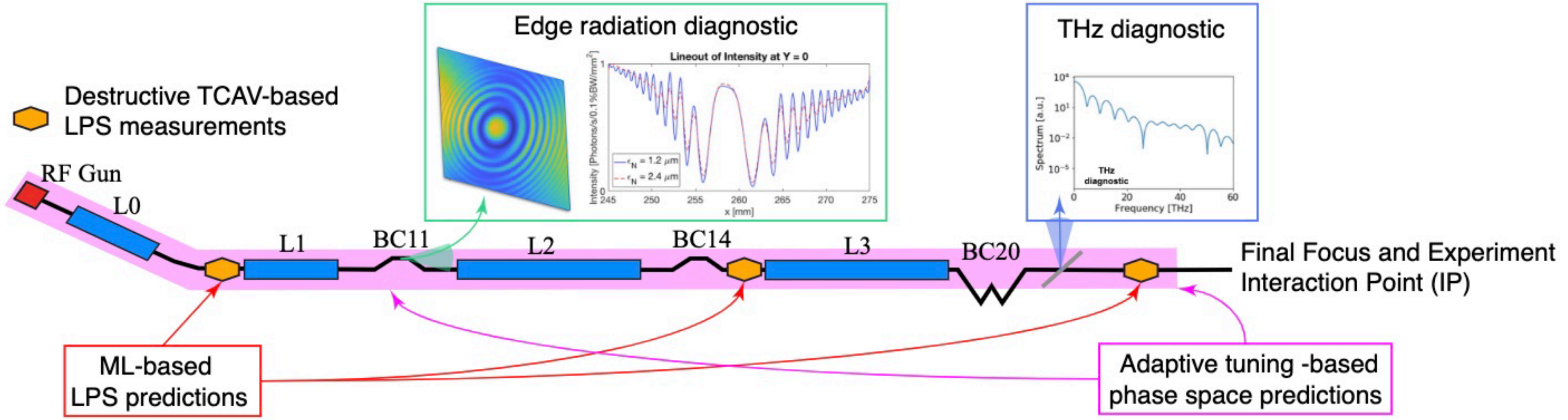
Single bunch configuration commissioned, two bunch configuration to be commissioned this autumn

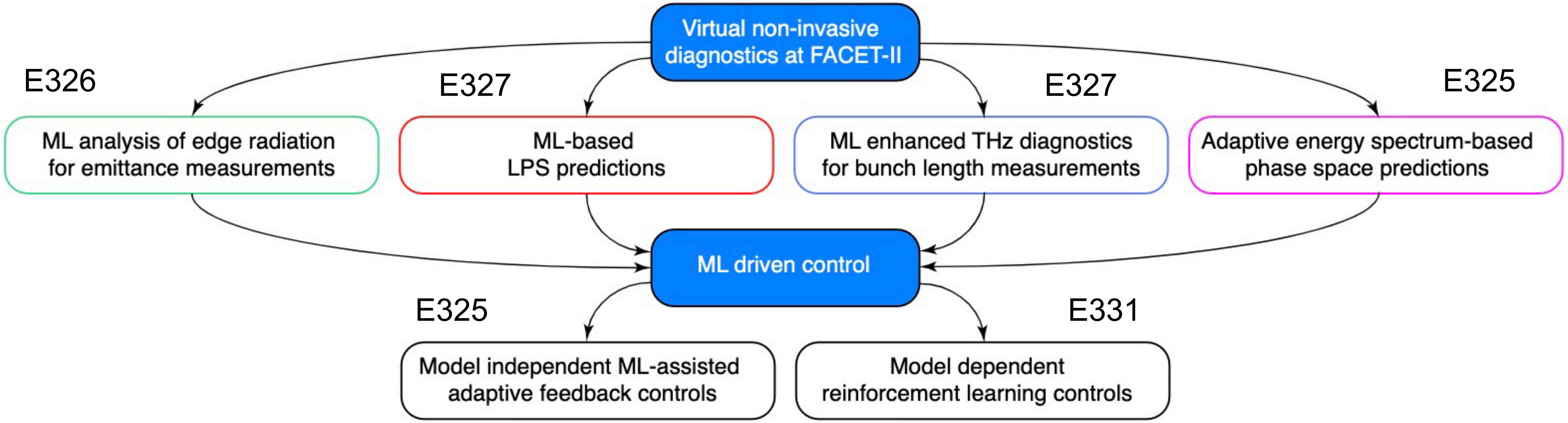




Improved longitudinal and transverse emittance from the photoinjector allows FACET-II to deliver beams with unprecedented intensities and open new science directions

AI/ML Activities at FACET-II

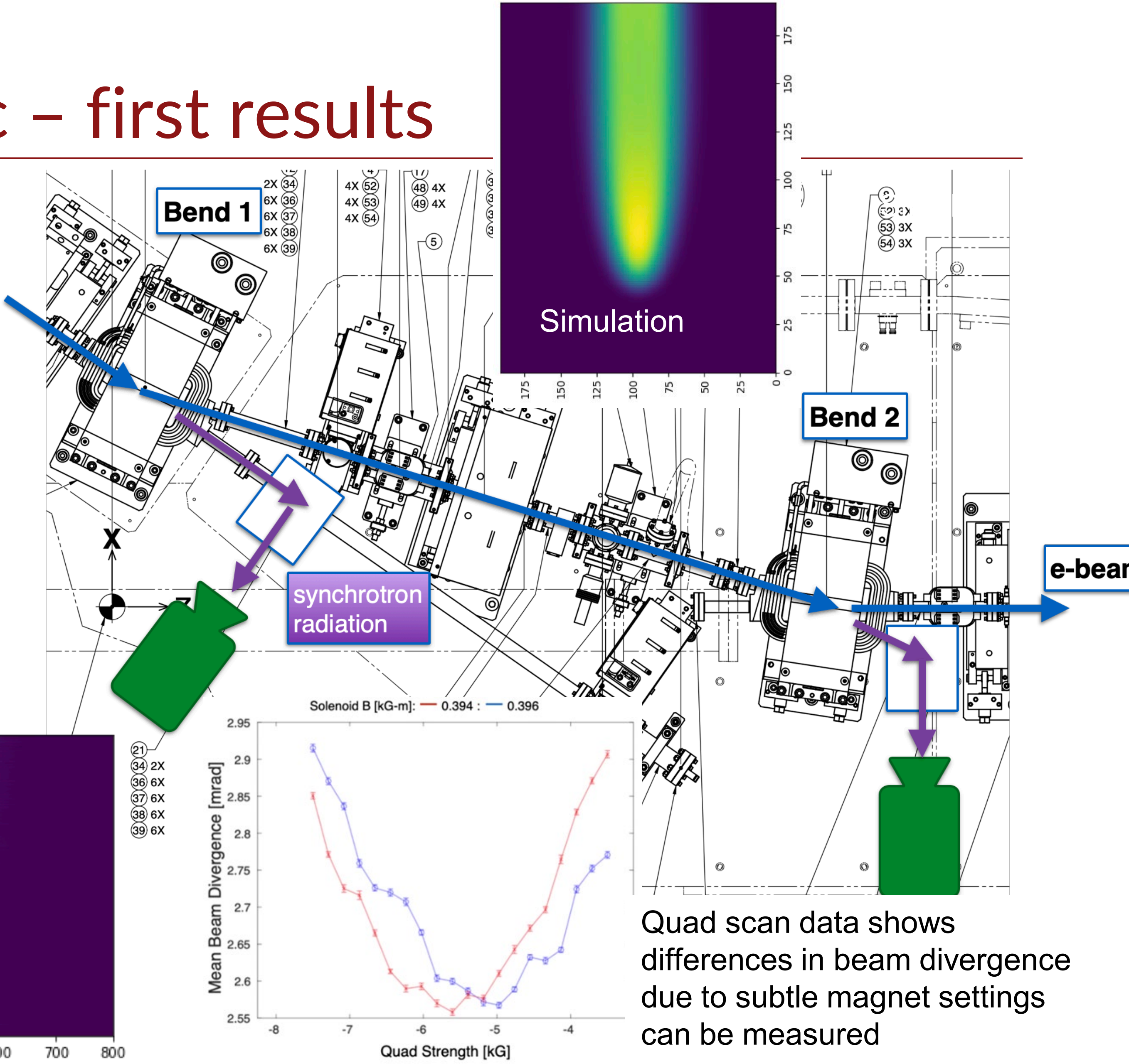




FACET-II extreme beams require virtual diagnostics and machine learning controls

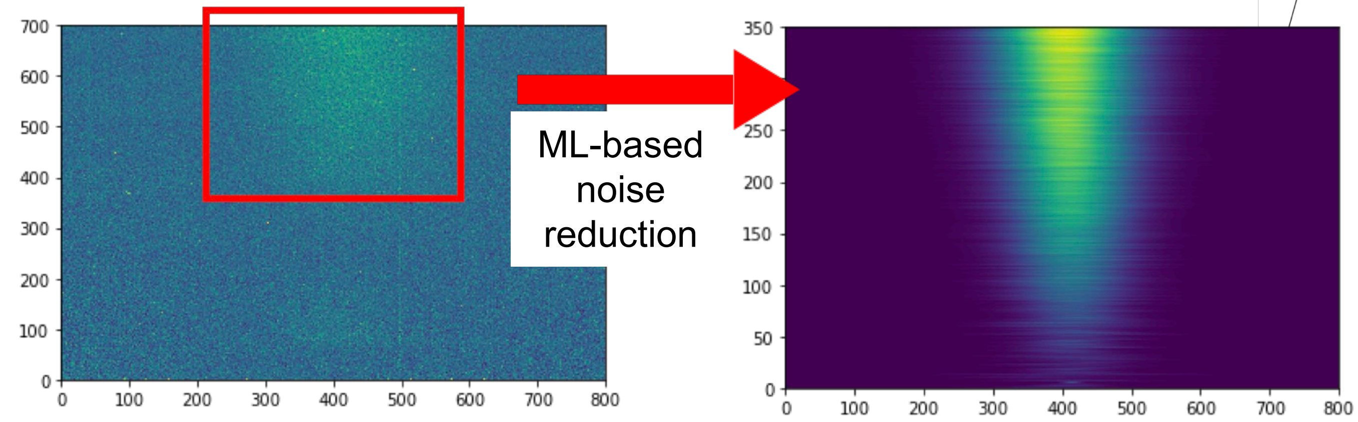
Injector emittance diagnostic – first results

- Non-destructive measurement diagnostic collects radiation from dogleg
- On-the-fly Machine Learning-based image analysis extracts beam emittance, mismatch from radiation pattern
- Future plans for additional measurements at 3 downstream compression stages.



Data from edge rad camera 4/19/22

Noise filtered image

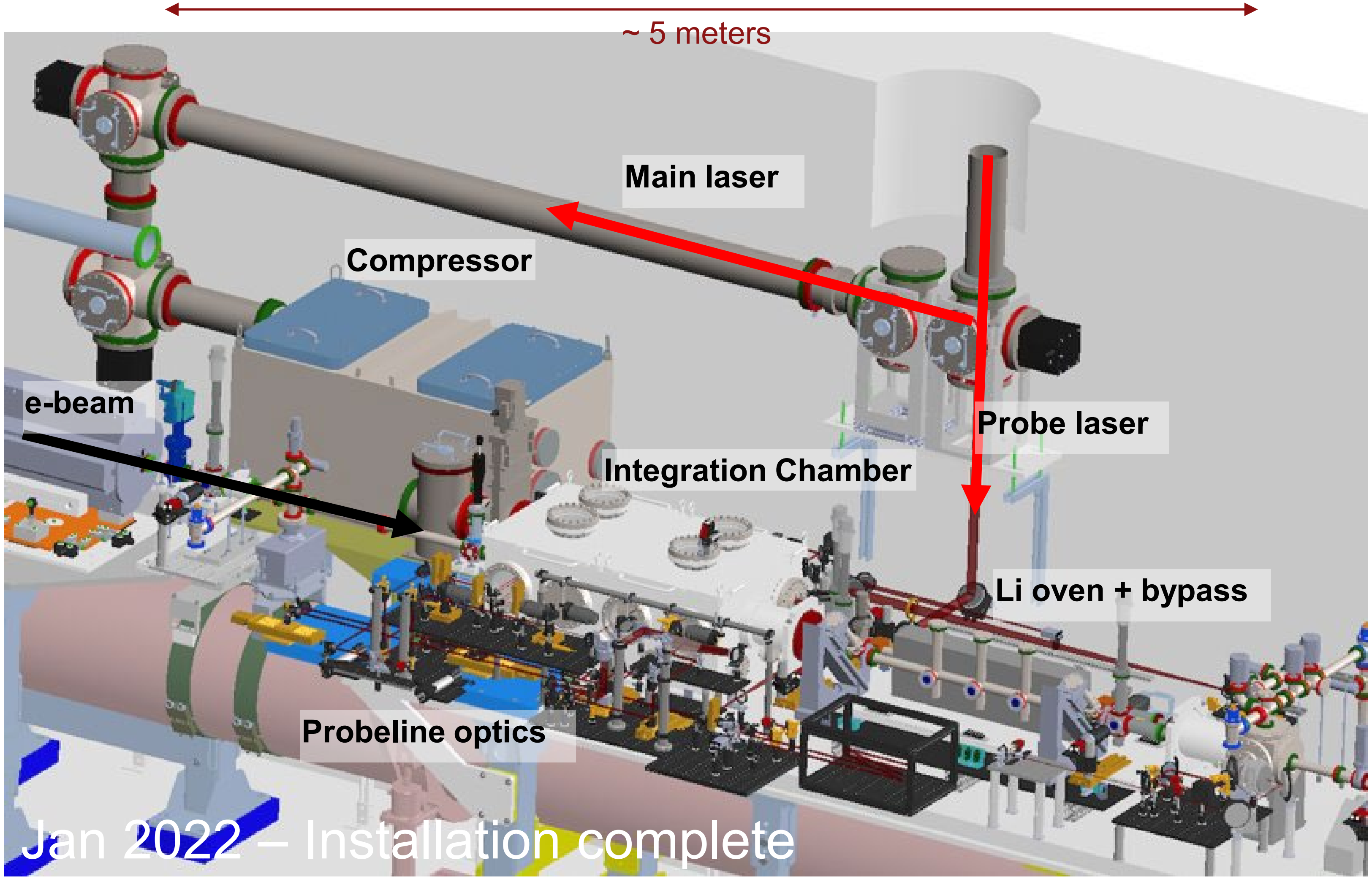


Quad scan data shows differences in beam divergence due to subtle magnet settings can be measured

Non-destructive single shot diagnostic will use ML-analysis to give emittance evolution along accelerator

Take a “streetview” tour at https://my.matterport.com/show/?m=E6rRJHvAB27

FACET-II Interaction Area

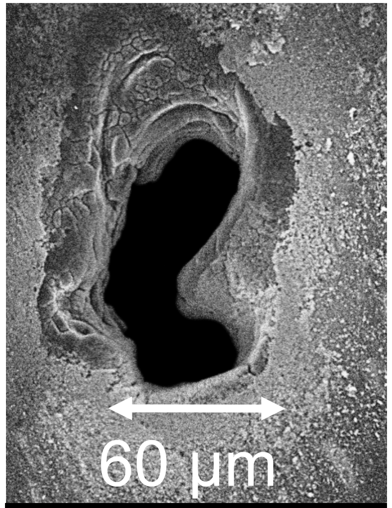


The User Area is designed for ~17 experiments without major reconfigurations of the hardware

- Two main interaction areas:
  - Integration Chamber
  - Li oven + bypass line for H2 and He plasma experiments
- Experimental laser* split into:
  - Main laser (~220 mJ) including 14 main laser diagnostic cameras
  - 4 laser probe lines (~10 mJ) including 9 diagnostic cameras
- High degree of collaboration and CAD!

Experimental area was designed in collaboration with users to be compatible with 17+ experiments

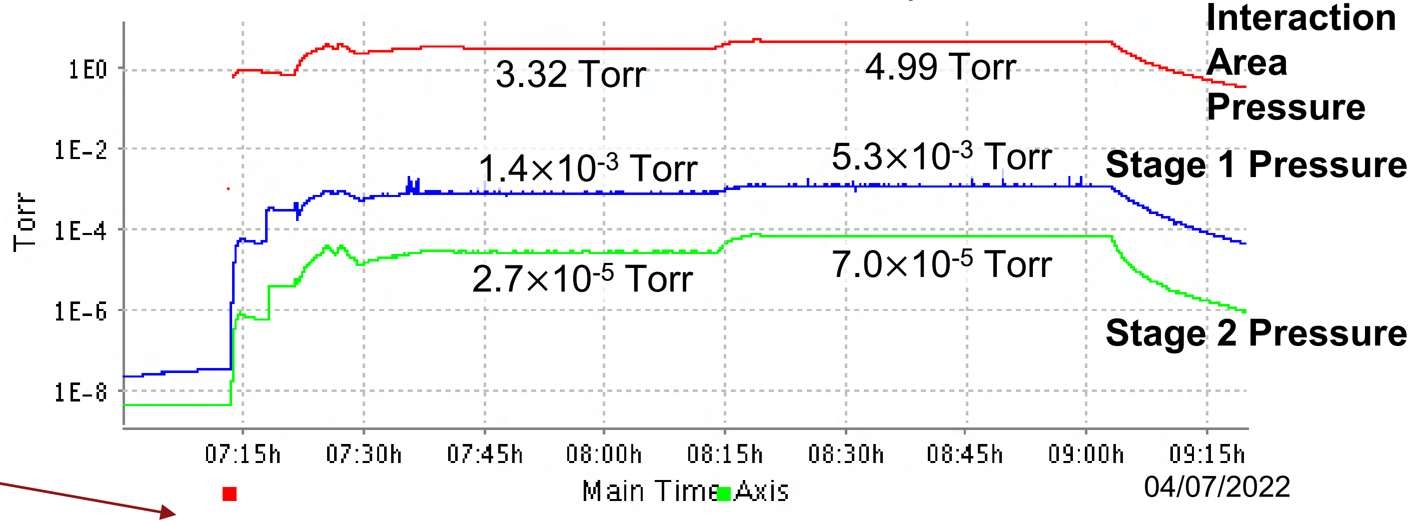
Commissioning the differential pumping system (DPS)

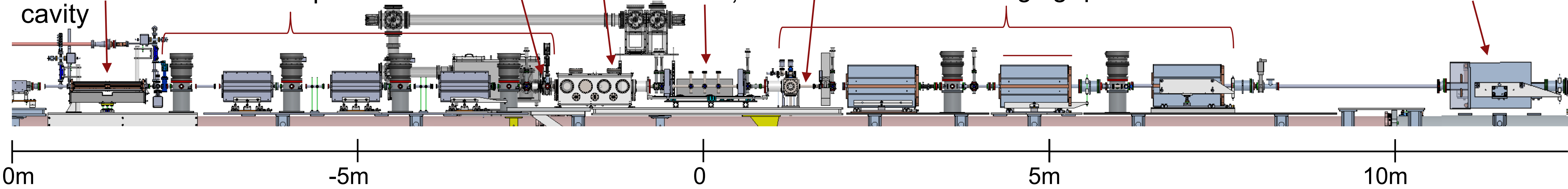


Beams intense enough to punch holes in beryllium windows

- Designed and installed (2021 – ongoing) differential pumping system to isolate gases used in experiments from RF structures

Initial tests with helium, also tested with hydrogen (2 Torr max)

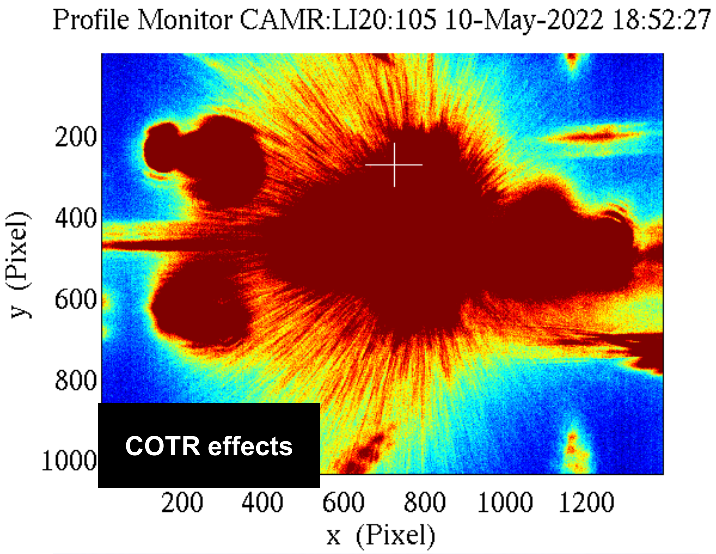


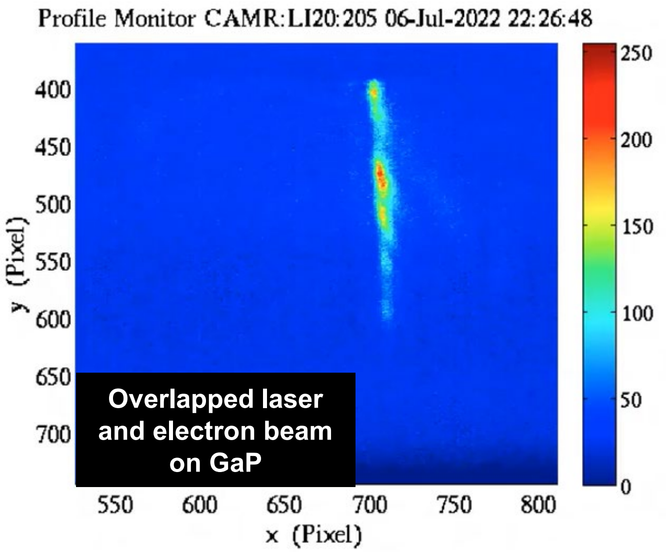


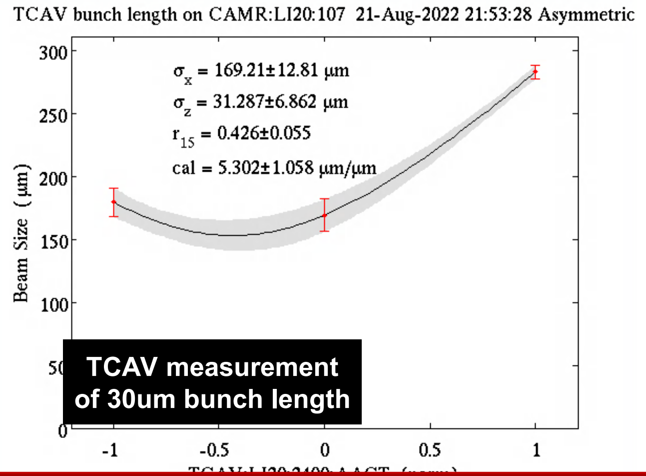
FACET-II extreme beams require differential pumping, commissioned this run

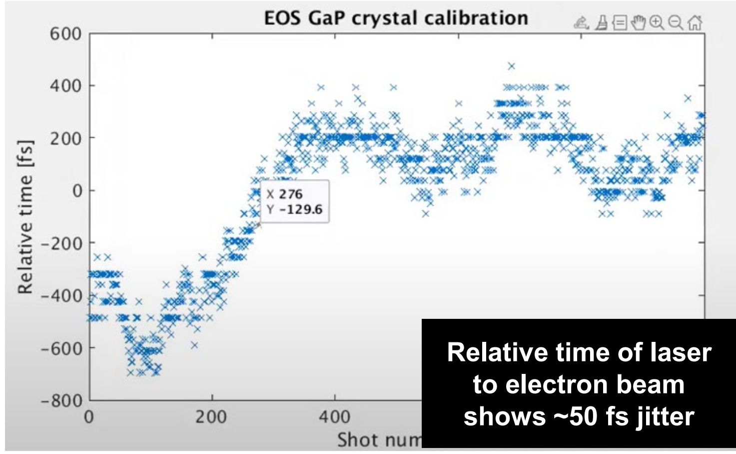
Commissioning Interaction Area Diagnostics

- Interaction Area includes YAG and OTR screens for position and profile measurements
  - COTR however has been an issue
  - To be mitigated with laser heater installation later this year
- Also includes transverse deflecting cavity
  - However this is invasive measurement
- Goal of EOS-BPM is to provide non-destructive tool for measuring transverse and longitudinal beam positions for each bunch on a shot-by-shot basis
  - Ultimate transverse resolution expected 1 μm,
  - Ultimate longitudinal resolution expected 10 fs
- Commissioned a single GaP crystal ~20 fs resolution
- Measured that the e-beam to laser timing drifts ~1ps with typical jitter ~50 fs





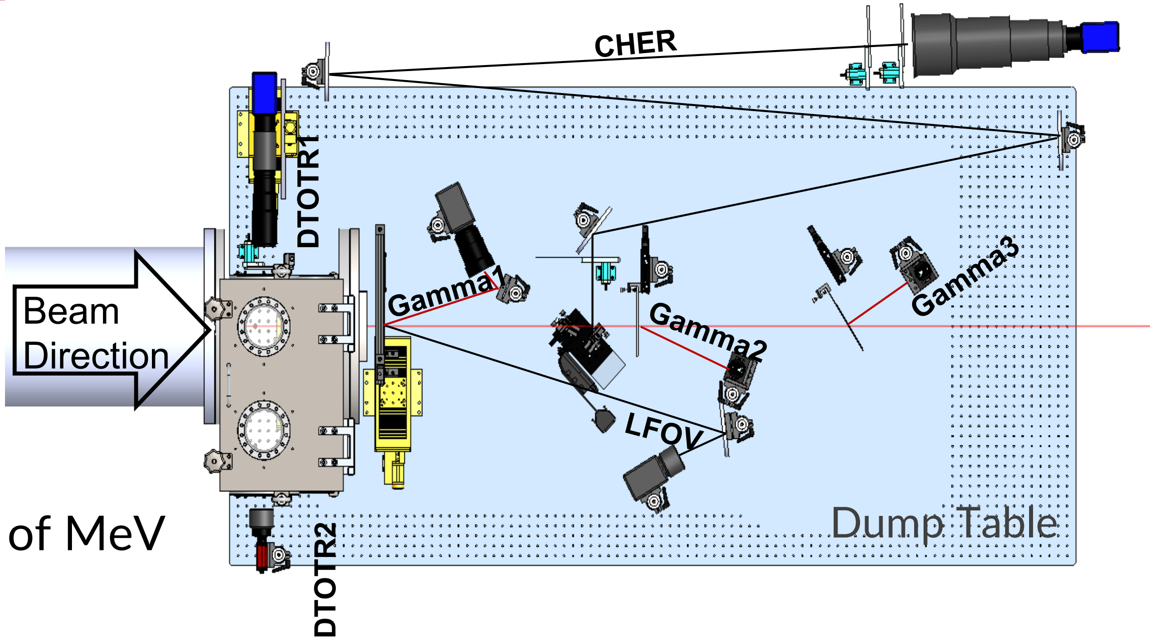


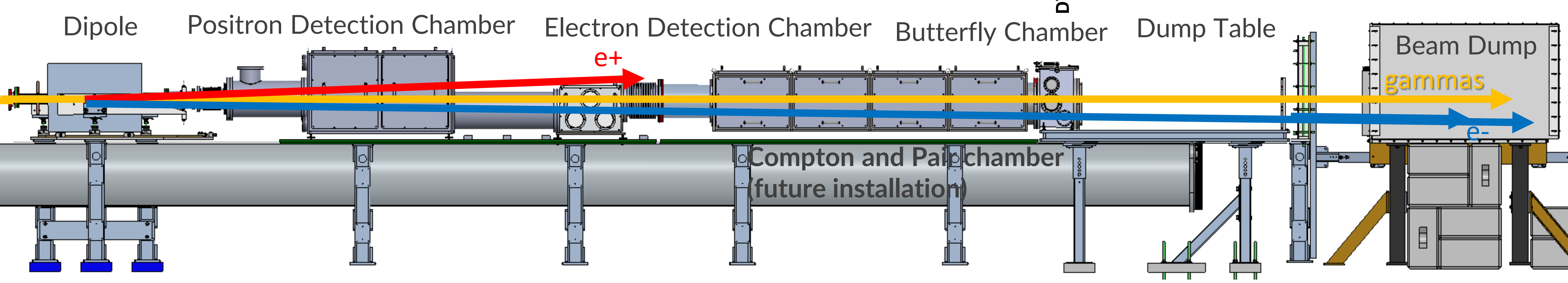


FY22 beam time used to commission hardware, virtual diagnostics, machine learning

Downstream electron beam and photon diagnostics

- Electron beam diagnostics
  - DTOTR – high resolution, single shot emittance and TCAV (transverse deflecting RF cavity) measurements
  - LFOV – large field of view electron profile monitor
  - CHER – beam spectrometer using Cherenkov light
- Photon diagnostics:
  - Gamma1: photon profile monitor
  - Gamma2 and 3: spectral information from <100keV to ~10s of MeV





Downstream diagnostics characterize outcome of interaction, fully installed

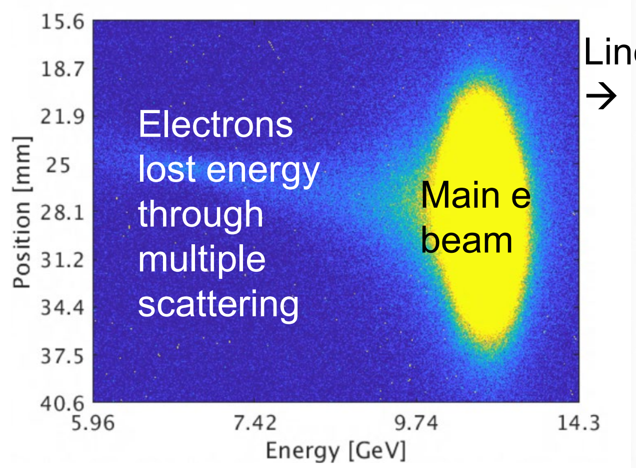
Commissioning downstream diagnostics

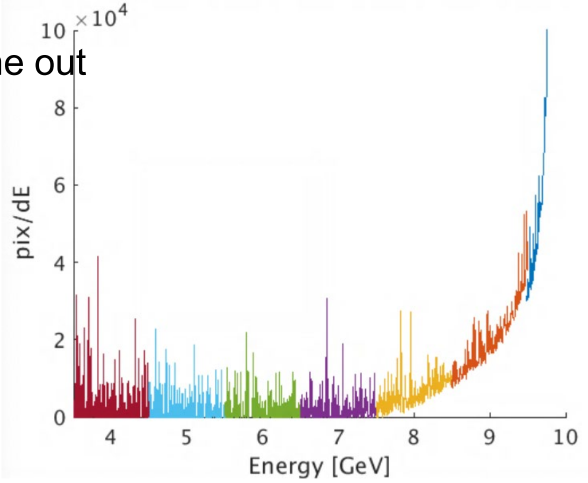
- Commissioning of spectrometer diagnostics initially used solid targets
- Emittance and energy spectrum diagnostics characterized using multiple scattering in 1 mm Al target in integration chamber

- Energy spectrum: G. Cao, *University of Oslo*
  - Images acquired on CHER spectrometer show energy loss through multiple scattering
  - Future use: energy gain/depletion through PWFA

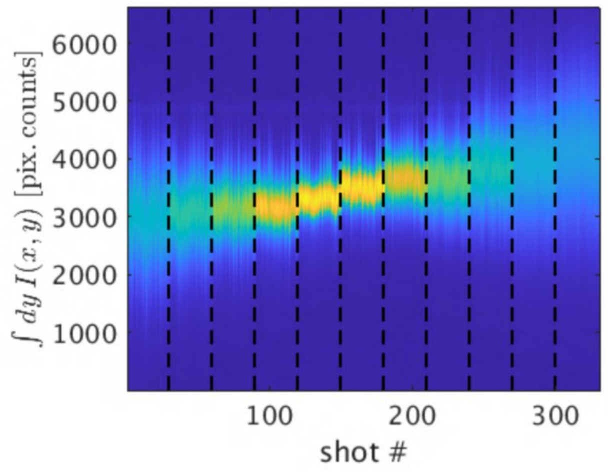
- Emittance scans: P. San Miguel, *LOA*
  - Quad scans of emittance spoiled by passing beam through solid target
  - Future use: emittance preservation through PWFA

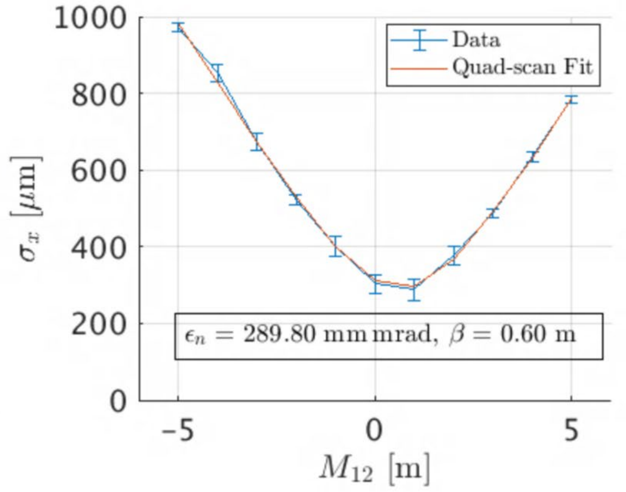
Electron energy spectrum of scattered beam





Dispersive quad scan of scattered beam

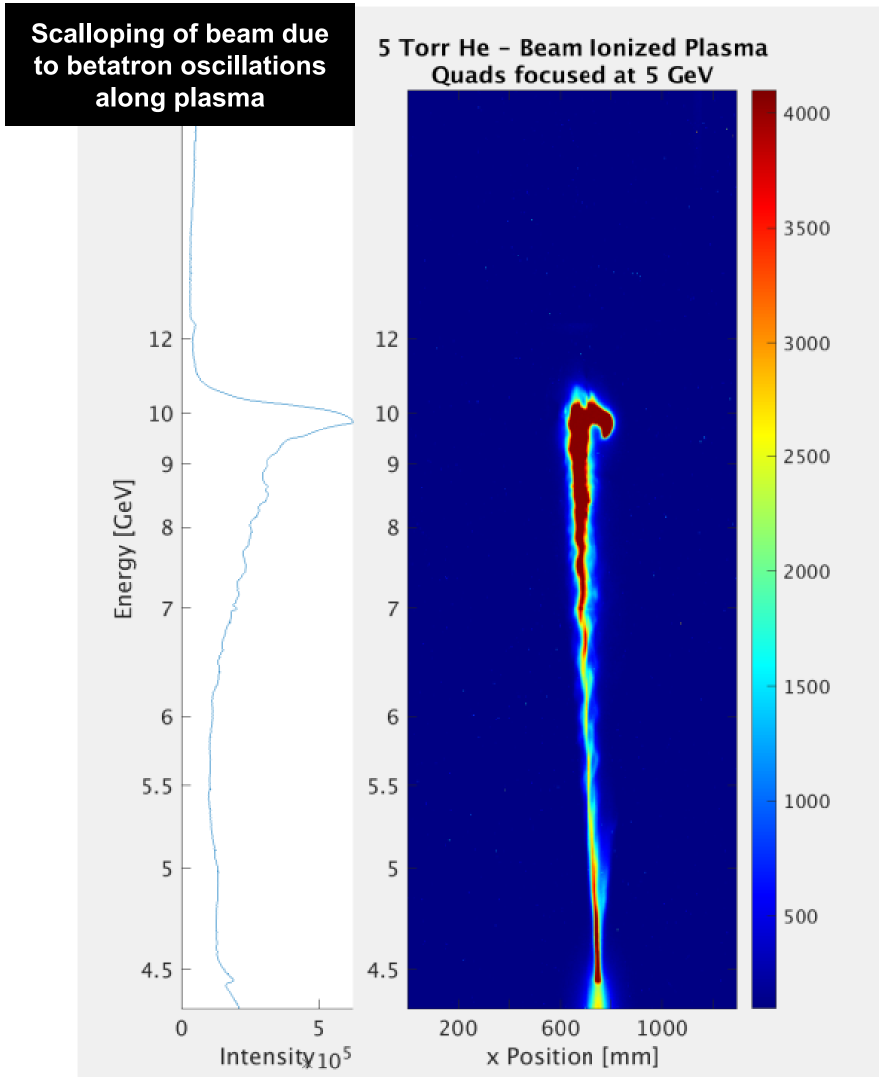


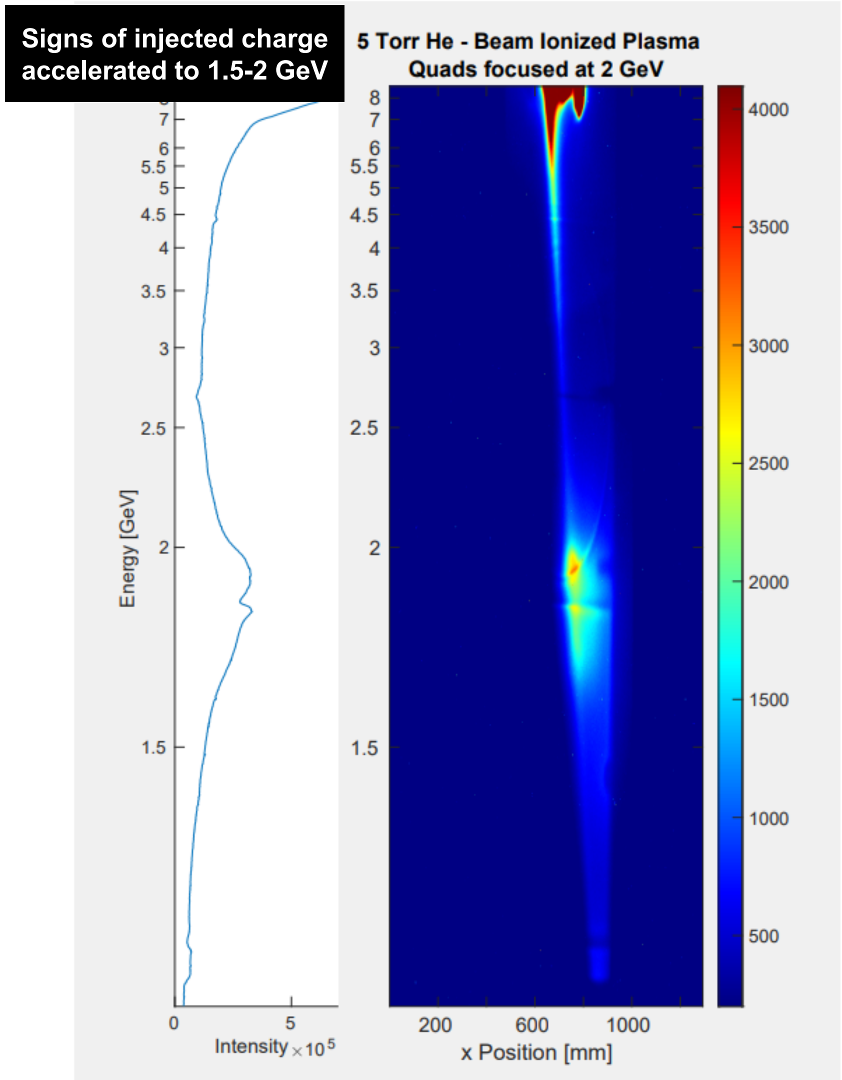


FY22 beam time used to commission hardware, virtual diagnostics, machine learning

First results – First beam ionized helium plasma at FACET-II

- Commissioning differential pumping system at 5 Torr demonstrated capability of FACET-II's intense beam to field ionize helium
  - Showed depletion of energy of beam from 10 GeV to < 1 GeV
  - Demonstrates that the drive beam has sufficient intensity to drive a strong wakefield and transfer a large portion of its energy into the wake
- Also demonstrates spectrometer and Cherenkov light diagnostic at dump table work

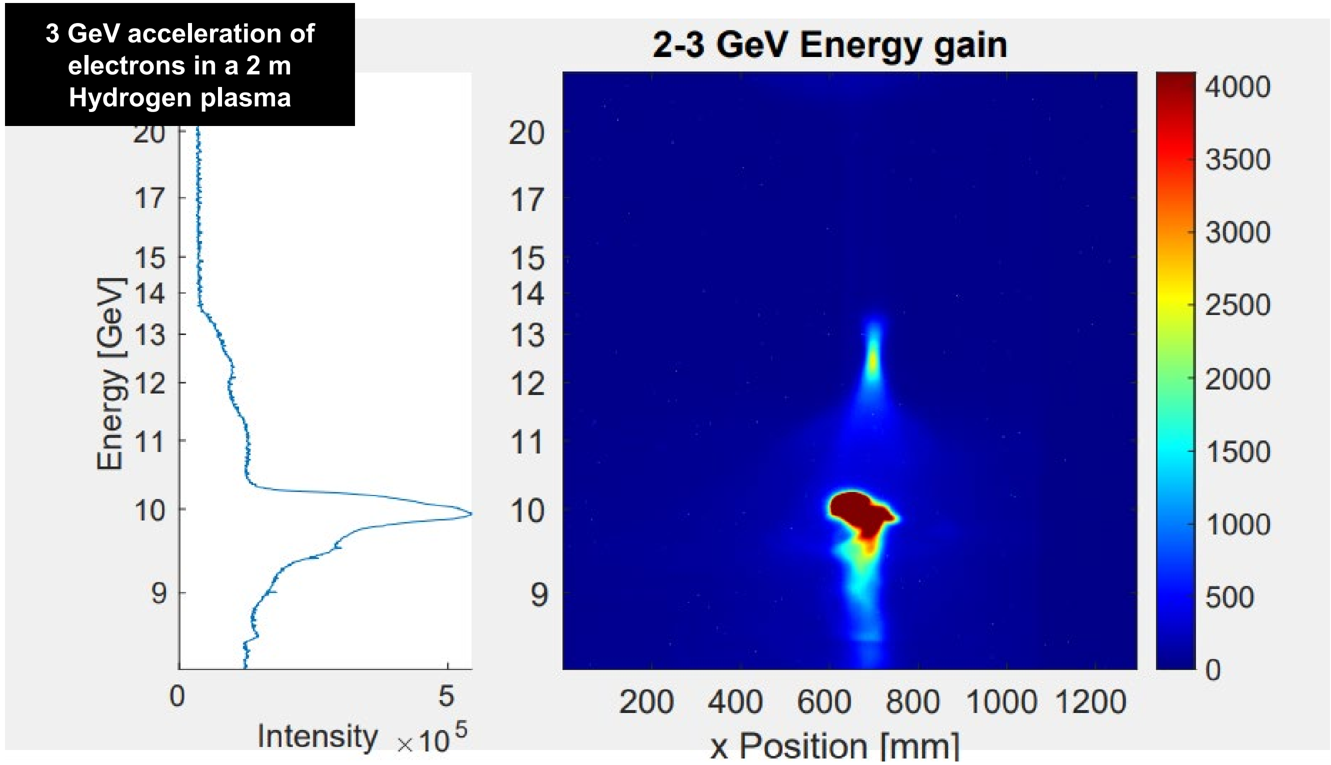


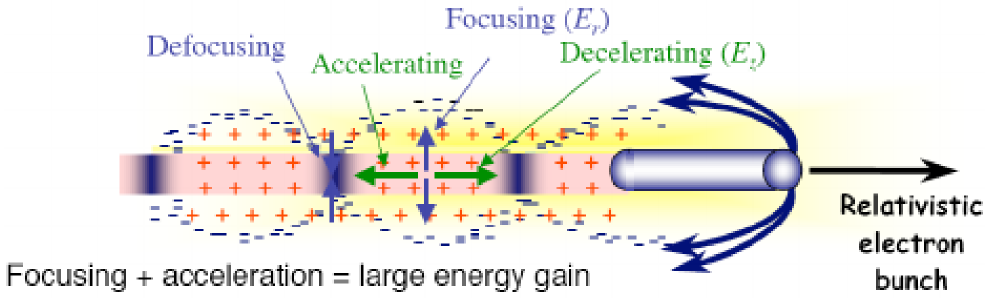


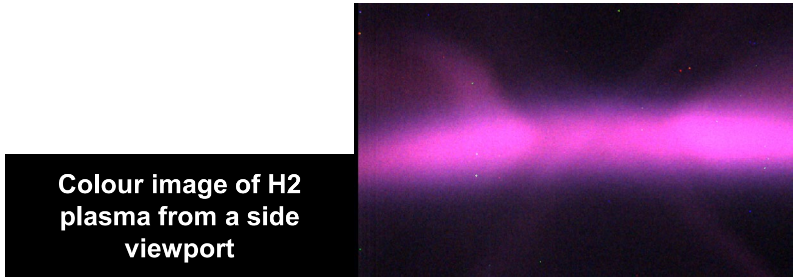
FACET-II electron beam ionization of helium demonstrates extreme beam capabilities

First results – Multi-GeV acceleration by PWFA

- Multi-GeV acceleration by PWFA was observed for the first time at FACET-II, and greater than 3 GeV
- Head of electron bunch ionizes and drives a wake in the H2 plasma
- In 2 bunch config, we'd accelerate trailing bunch
  - In this case we suspect the bunch had a long tail
- ~2 meter long beam ionized H2 plasma
- Studies ongoing to understand why we ionize hydrogen so well

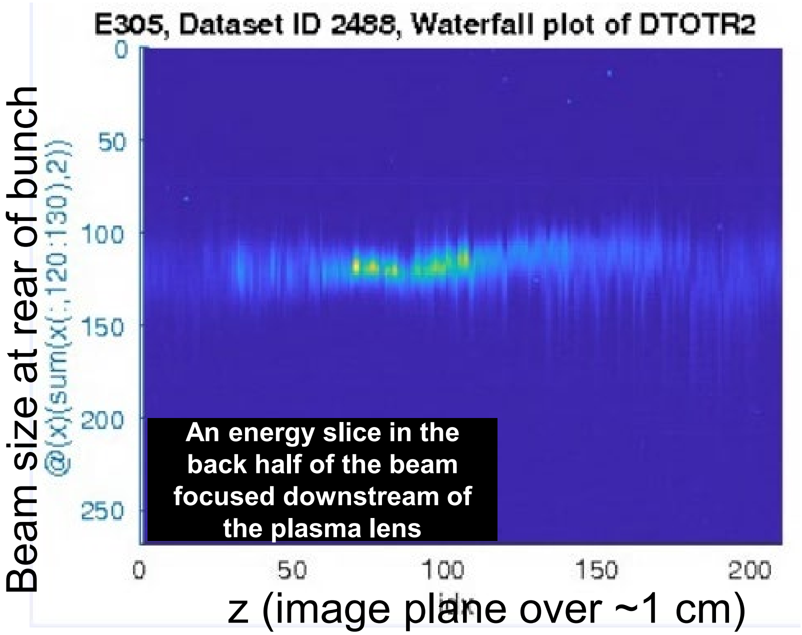


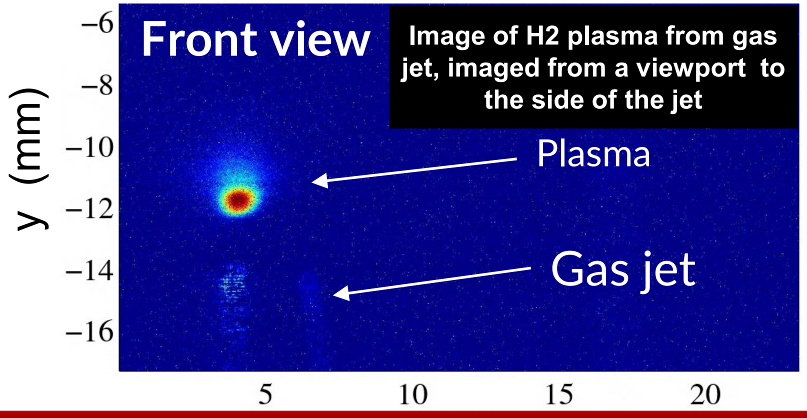




First multi-GeV acceleration at FACET-II – 3 GeV in a 2 m long hydrogen plasma

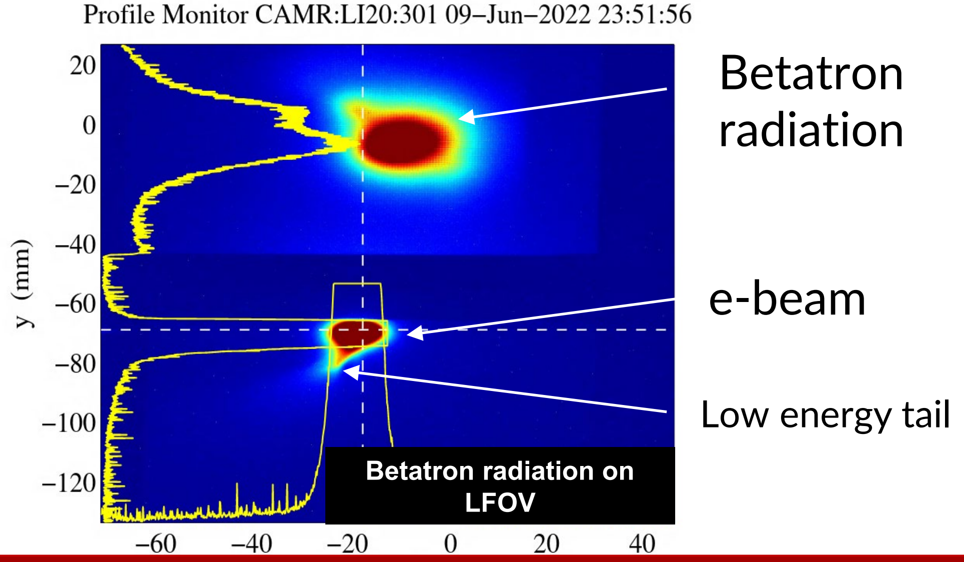
First results – Gas-jet plasmas at FACET-II

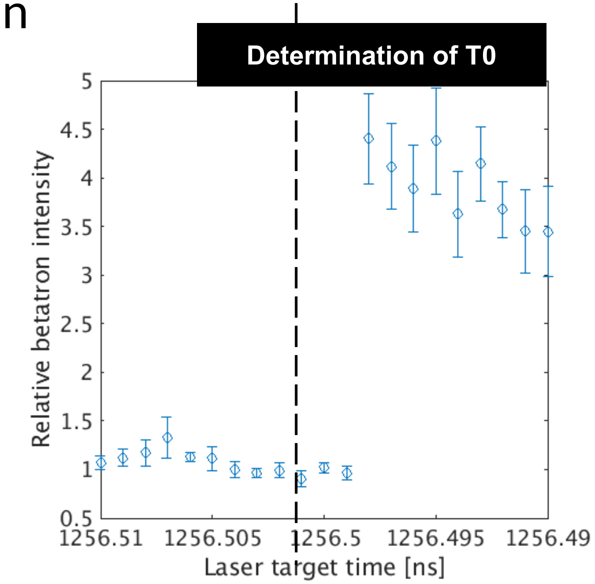




- Laser ionized plasma formed in H_2 elongated 2 cm gas jet
  - At sub atmospheric pressures, betatron wavelength < gas-jet

  → Plasma lens regime
- Dump table diagnostics show energy loss of the e-beam and generation of betatron radiation in the plasma
- Determined relative timing between laser and e-beam
- Evidence of plasma lensing was found on downstream profile screen
- Next steps – plasma interaction optimization

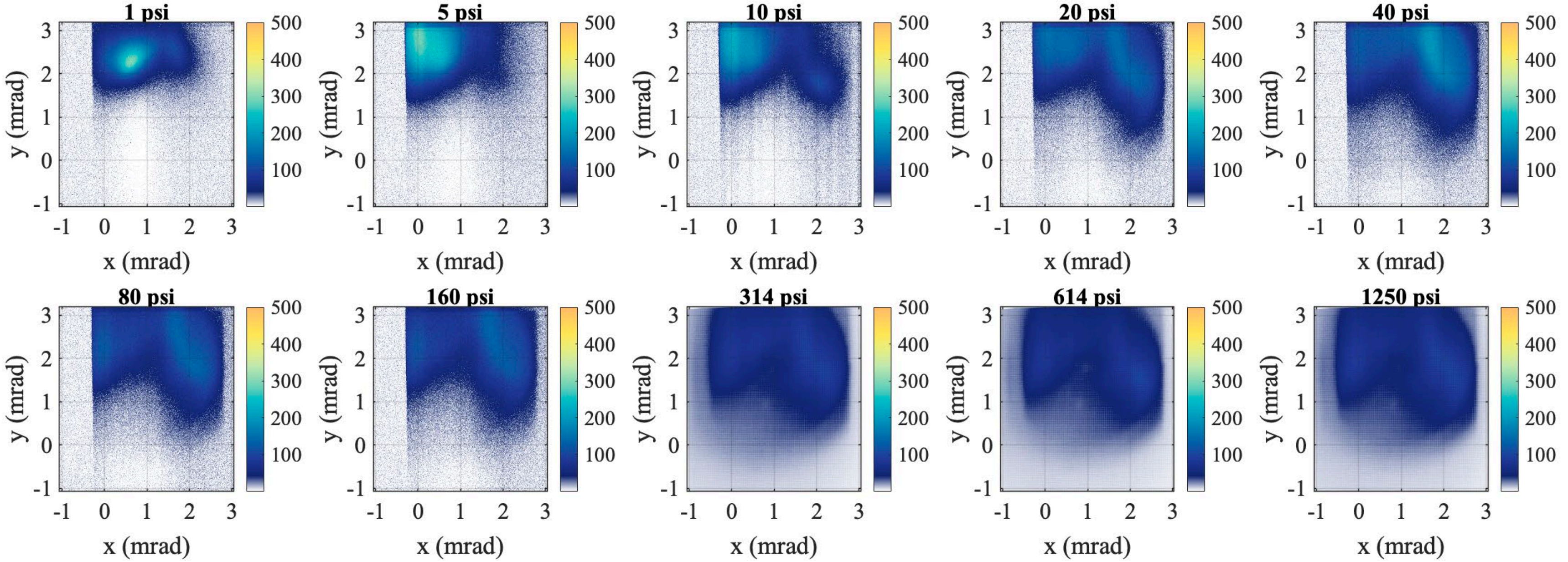




FY22 beam time used to commission hardware, virtual diagnostics, machine learning

First Results - Beam Filamentation Instabilities and γ-Ray Generation

Beam size much larger than bubble size → Beam modulation & filamentation → Large fields → Bent trajectories for filaments → Gamma-ray emission



- Studies of beam plasma instabilities have fundamental importance for astrophysics and ultrafast condensed matter physics and has a potential to be a bright gamma ray source with applications for defence, industry, medicine and scientific research.
- Study of gamma-ray yield as a function of plasma density in the gas jet at high pressures
- A first look at Gamma diagnostics looks as if a signal reduction at higher pressure might have been measured
- Diagnostics so far inconclusive on where this transition would occur
- To prove an effect changes in pointing and divergences of photons needs to be tracked much better

High density plasmas are used to investigate astrophysical plasma instabilities

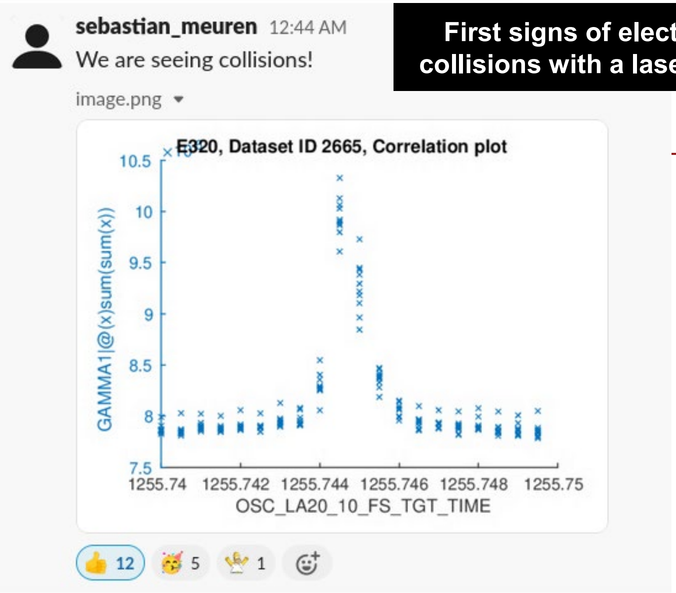
First results - Strong-field QED

Basic Concept:

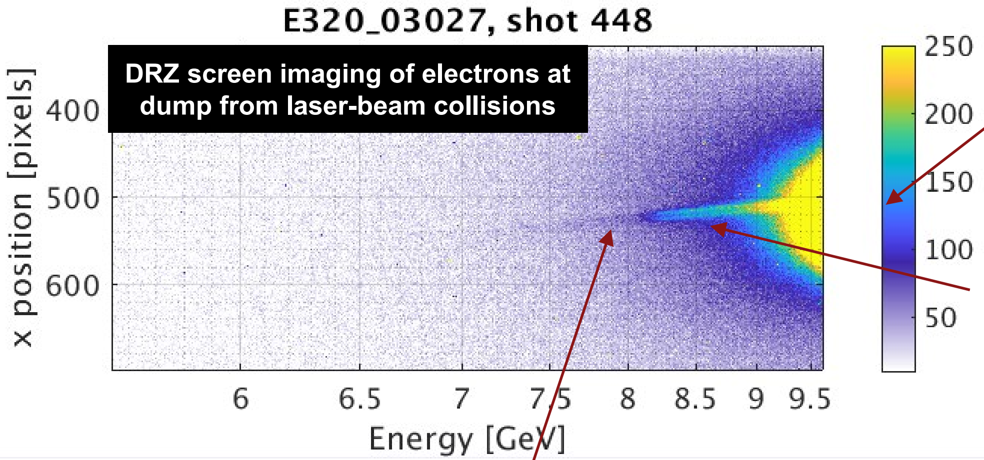
- Reaching the QED critical field $E_{cr}=m^2c^3/(e\hbar)$ ~ 10^{18} V/m: 20 TW @ 2.5 µm implies ~10^{29} W/cm^2 (rest frame intensity)
- Continuation of experiment at SLAC's FFTB facility

Progress this run:

- Successfully aligned laser to electron beam, focused laser to micron-level and achieved spatio-temporal overlap of the laser pulse and the electron beam
- Observed consistently linear Compton scattering and saw first indication of higher harmonics
- Future shifts will aim to improve our understanding to achieve and control the nonlinear Compton scattering process more consistently



First signs of electron-gamma collisions with a laser timing scan



Main beam at 10 GeV

Down-scattered electrons to 1st Compton edge – linear, one electron one photon interaction

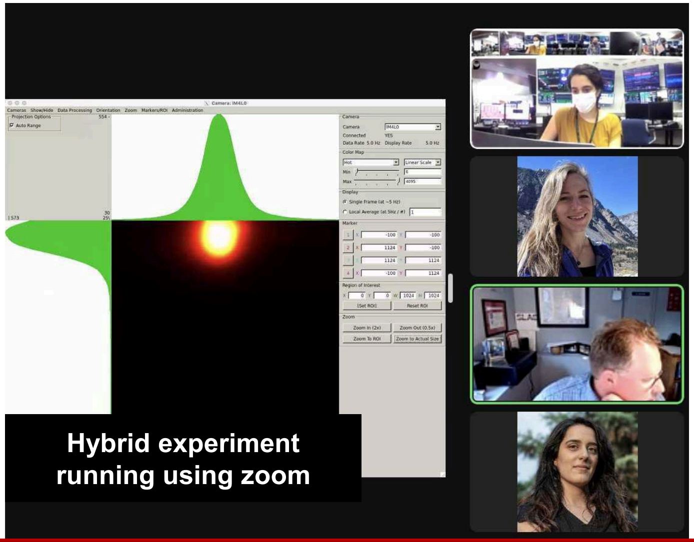
Non linear Compton scattering

E-320 SFQED experiments at FACET-II will test new physics and serve as a stepping-stone towards laboratory based astrophysics experiments

Summary

- FACET-II is delivering high-intensity beams that open new scientific directions strongly aligned with HEP roadmaps
- Unique property of FACET-II is the extreme beams
  - Virtual diagnostics and machine learning being developed
  - Differential pumping being deployed
  - Electron, gamma and positron diagnostics being commissioned by multiple user groups to cover wide spectrum
  - First plasmas created with gas jets, helium and hydrogen, solid targets
  - First Compton interactions between laser and electron beam

FACET-II Users running experiments



Hybrid experiment running using zoom

FACET-II presents unique opportunities to study beam-driven plasma wakefield acceleration at collider intensities and expand science program into new fields (QED and astrophysics)

Acknowledgements

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