FACET-II | Facility for Advanced Accelerator Experimental Tests

Plans for Transverse Wakefield Measurements at FACET-II

ALEGRO 2019
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Mark J. Hogan
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U.S. DEPARTMENT OF ENERGY
Office of Science

SLAC NATIONAL ACCELERATOR LABORATORY

Plasma Wake Field Acceleration Collaboration

- 21 P.I.s C. Joshi (UCLA) and Mark Hogan (SLAC)-
- Programatic Proposal

  Individual P.I.s looking at Discovery Science and diagnostics
- 22/42/45 M. Litos (U. Colorado)
- 23 E. Adli (Oslo U.)
- 24 Spencer Gessner (CERN)
- 32 N. Vafaei-Najabafadi (Stonybrook U.)
- 33 Chaojie Zhang (UCLA)
- 43 S. Corde (LOA)
- 48 K. Marsh (UCLA)
- 52 Brenden O'Shea (SLAC)
- 53 Claudio Emma (SLAC)

Flexibility of the photo-injector allows two bunches creation at the gun with order of magnitude better emittance and without collimation

Science deliverables:

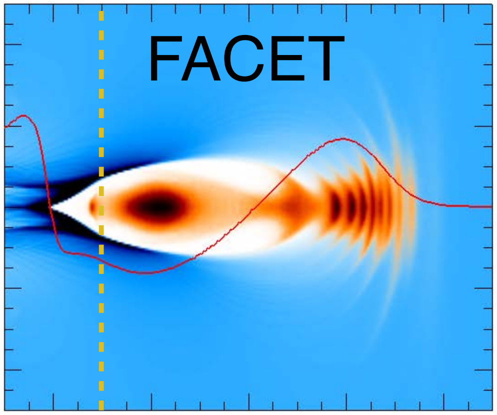
- Pump depletion of drive beam with high efficiency & low energy spread acceleration
- Beam matching and emittance preservation

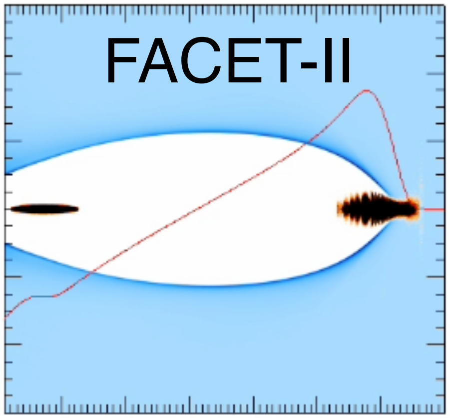
Key upgrades:

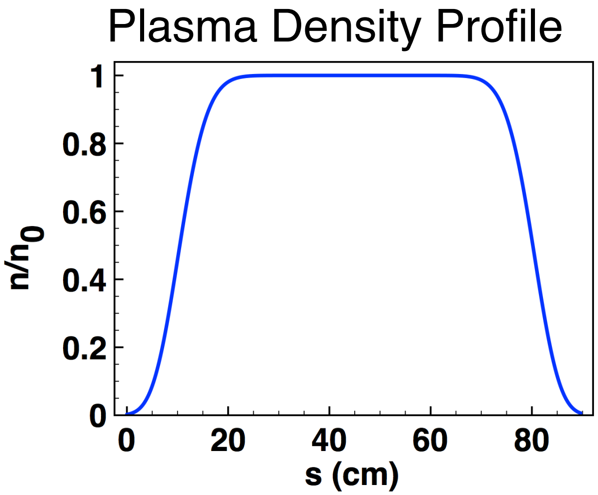
- Photoinjector beam
- Matching to plasma ramps
- Differential pumping
- Single shot emittance diagnostic

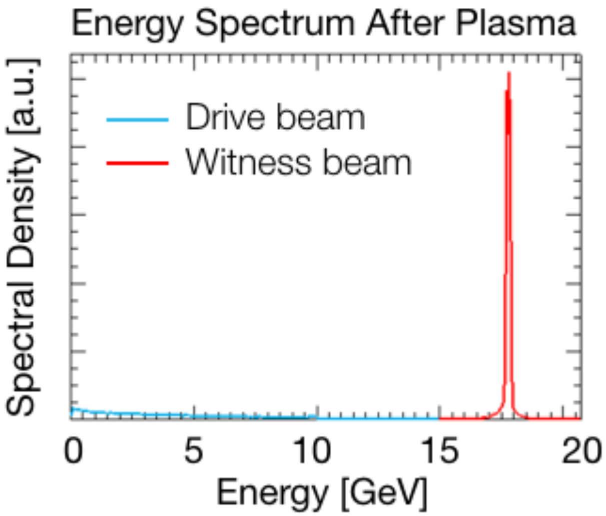
Plasma source development:

- Between 10-20μm emittance, beam expected to ionize He in down ramp
- Next step laser ionized hydrogen source in development at CU Boulder







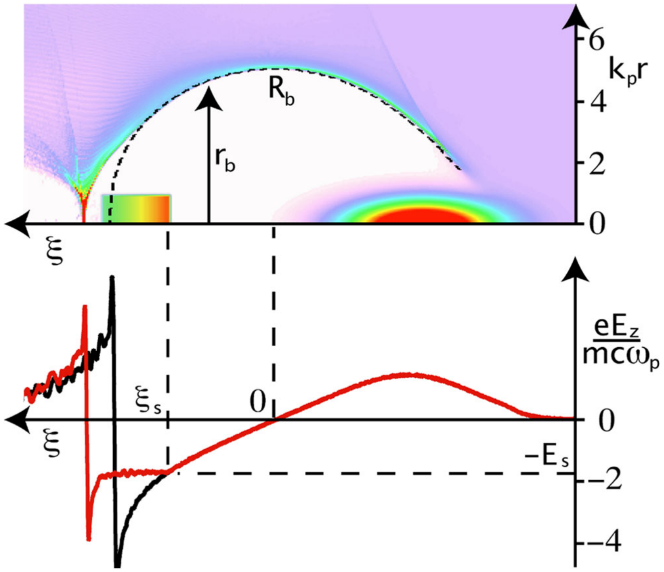


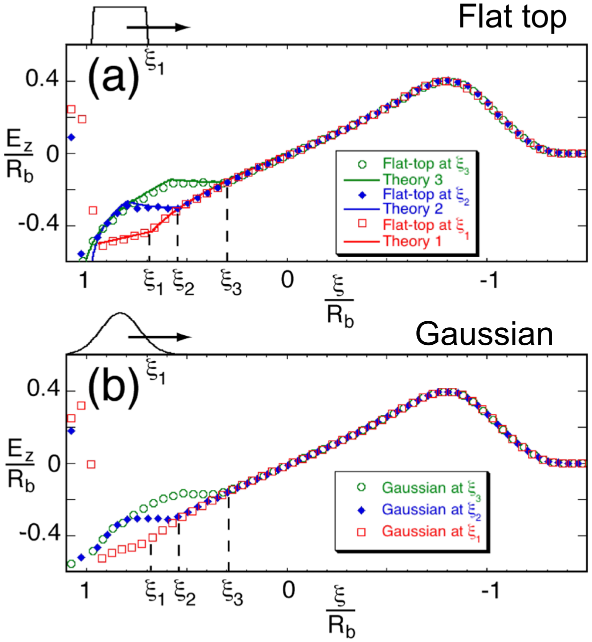
C Joshi et al 2018 Plasma Phys. Control. Fusion 60 034001

PAC 'Excellent' rankings re-iterated that roadmap priorities are well developed in proposed experimental program

Beam Loading in Non-linear Wakes

Theoretical framework, augmented by simulations, provides a recipe





Roadmap emphasizes the need to answer the question: Is it possible to strongly load the longitudinal wake without strong transverse wakes and BBU?

- Relativistic Beams provide a non-evolving wake
- Possible to nearly flatten accelerating wake – even with Gaussian beams
- Gaussian beams provide a path towards ΔE/E ~ 10^{-2} - 10^{-3}
- Applications requiring narrower energy spread, higher efficiency or larger transformer ratio → Shaped Bunches

$$\mathcal{L} = \frac{P_b}{E_b}\left(\frac{N}{4\pi\sigma_x\sigma_y}\right)$$

See: M. Tzoufras et al, Phys. Plasmas ***16****, 056705 (2009); M. Tzoufras et al, Phys. Rev. Lett.* ***101****, 145002 (2008); W. Lu et al., Phys. Rev. Lett.* ***96****, 165002 (2006) and References therein*

From S. Nagaitsev

Assuming the above wake expressions :

The efficiency-instability relation in a blowout regime

$$\boxed{\eta_t \approx \frac{{\eta_P}^2}{4(1-\eta_P)}, \quad \frac{r_{t2}}{R_b} \leq 0.7}$$

- This formula does not include any details of beams and plasma, being amazingly universal!
- Note: this formula is an estimate on a "low side". On a "high side", we estimate it as:

$$\eta_t \approx {\eta_P}^2 / \left(4(1-\eta_P)^2\right)$$

- Example:

$$\eta_P = 50\% \qquad 0.125 < \eta_t < 0.25$$

$$\eta_P = 25\% \rightarrow \quad 0.021 < \eta_t < 0.028$$

See: "Efficiency versus instability in plasma accelerators", PRAB **20**, 121301 (2017)

Can this be tested at FACET-II?

Motivation for Experiments

- We have a recipe for beam loading and a well defined experiment to demonstrate high-high-gradient acceleration with high-efficiency and narrow energy spread
- Using ‘The Lu Equation’, Lebedev et al. have derived expressions for the transverse wakefields inside the bubble
- Implications are that under strong beam loading the beam will be unstable
- Will we see hosing at FACET-II?
- How does it depend on degree of loading, drive/witness emittance, transverse offsets etc?

FACET-II proposal:

Transverse wakefields and instabilities in plasma wakefield accelerators

PI: Erik Adli
University of Oslo, Norway

in collaboration with :
W. An, co-PI; C.E. Clayton, K.A. Marsh, W. Mori, C. Joshi (UCLA, Los Angeles, USA)
M.J. Hogan, B. O’Shea, C. Clarke, V. Yakimenko (SLAC, Stanford, USA)
S. Nagaitsev (Fermilab, USA)
N. Vafaei-Najafabadi (Stony Brook, USA)
M. Litos (University of Colorado, Boulder, USA)
S. Corde (Ecole Polytechnique, France)
S.J. Gessner (CERN)
Ben Chen (CERN and University of Oslo, Norway), Daniel Schulte (CERN)

FACET-II PAC, SLAC, Stanford, USA
October 10, 2018

For the Proposal

The instability was studied in simulation:

- The instability was studied as a function of various beam parameters: offsets, emittance, mismatch, loading errors from phase and charge
- Sets expectations for what to try and control, what we want to measure and what we should look for

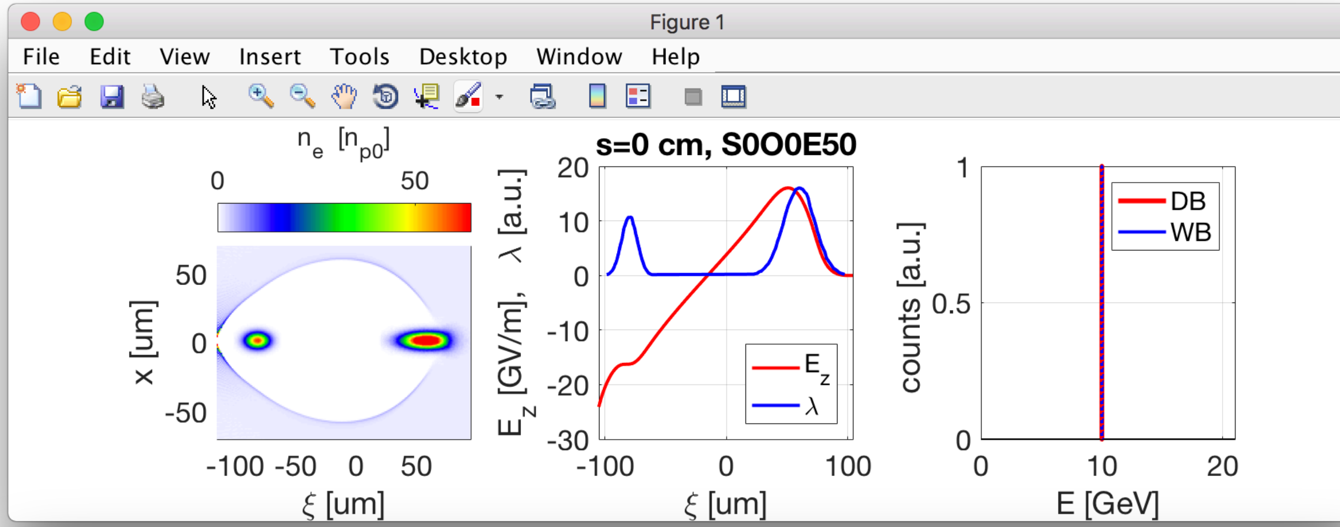
Goals of the experimental program:

- Establish two-bunch experiment baseline
- Control and measure instability
- Study instability mitigation

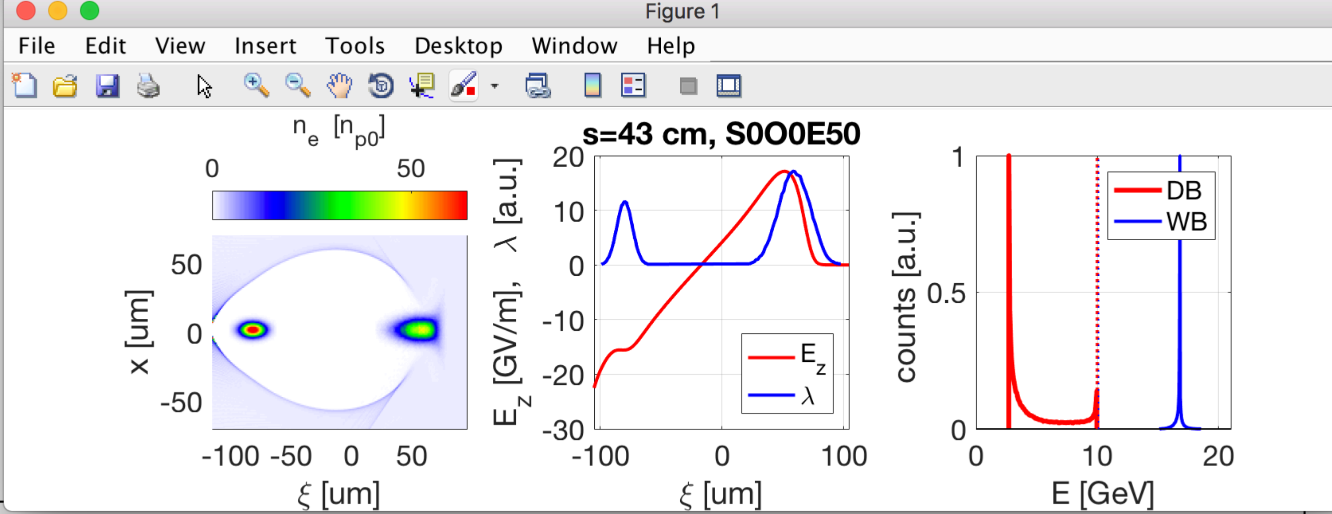
FACET-II transverse study baseline parameters

Simulation: QuickPIC@hoffman2, UCLA

MOVIE



(initial timestep,
both bunches on-axis)



(after propagation,
both bunches on-axis)

DB to WB energy transfer efficiency:
$\eta_{DB\text{-}WB}$ **= 43%**

Plasma density: n_0 = 4e16 cm^{-3} (flat-top, uniform pre-ionized)

DB: Q=1.6 nC, σ_z = 12.8 um (I_{peak} = 17 kA)

MB: Q=0.53 nC, σ_z = 6.38 um (I_{peak} = 12 kA)

DB and MB : $\varepsilon_{nx,y}$ = 50 um (or $\varepsilon_{nx,y}$ = 5 um), $\beta_{x,y} = \beta_{mat}$ = 5 mm ($\sigma_{x,y}$ = 3.7 um), $\alpha_{x,y}$ = 0, E = 10 GeV, σ_E=0, $z_{DB\text{-}WB}$ = 140 um

Simulation settings: Box_X=481, Box_Y=481, Box_Z=230, INDX = 9 , INDY = 9, INDZ = 8 NP2 = 1024

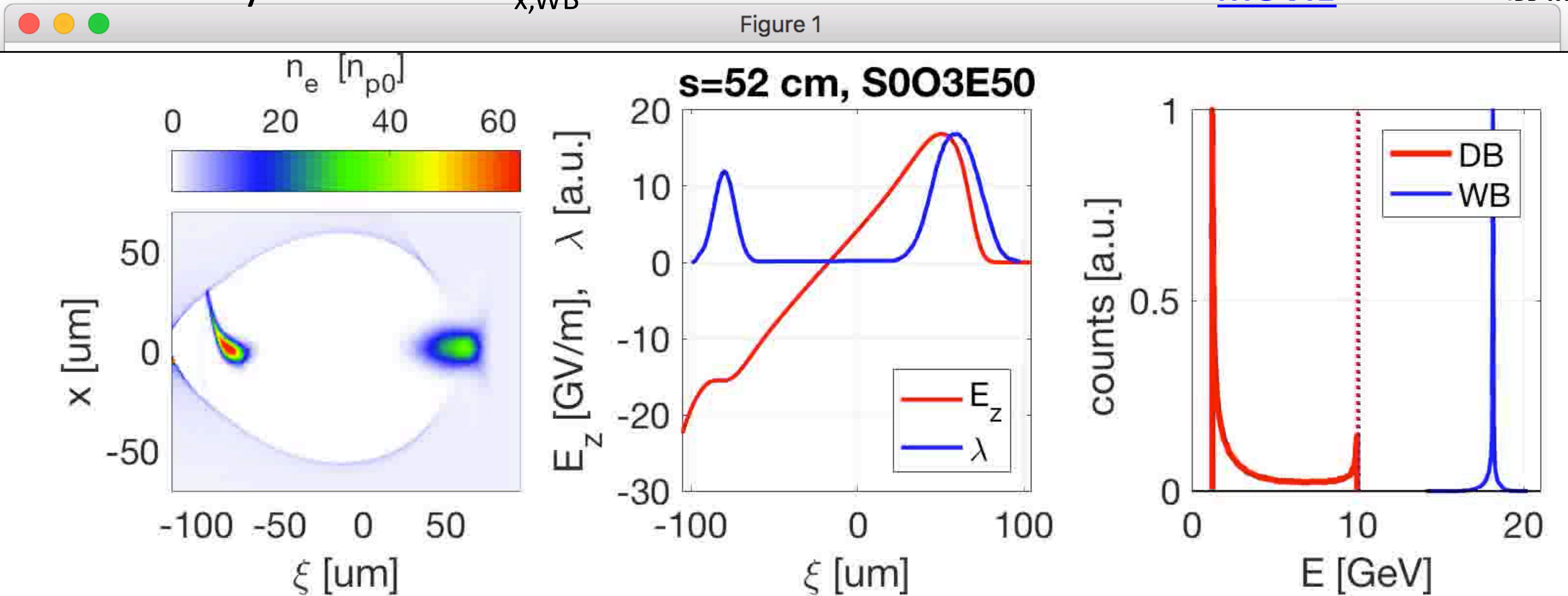
The baseline is based on the PWFA pump-depletion simulations, with a minor changes to optimize for the stability. The emittance is larger than the best expected at FACET-II. This is to resolve the simulations well without having to go to very high simulation resolution. I do show later in the slides that the instability is very similar for x10 smaller emittance, which is closer to the FACET-II facility emittance.

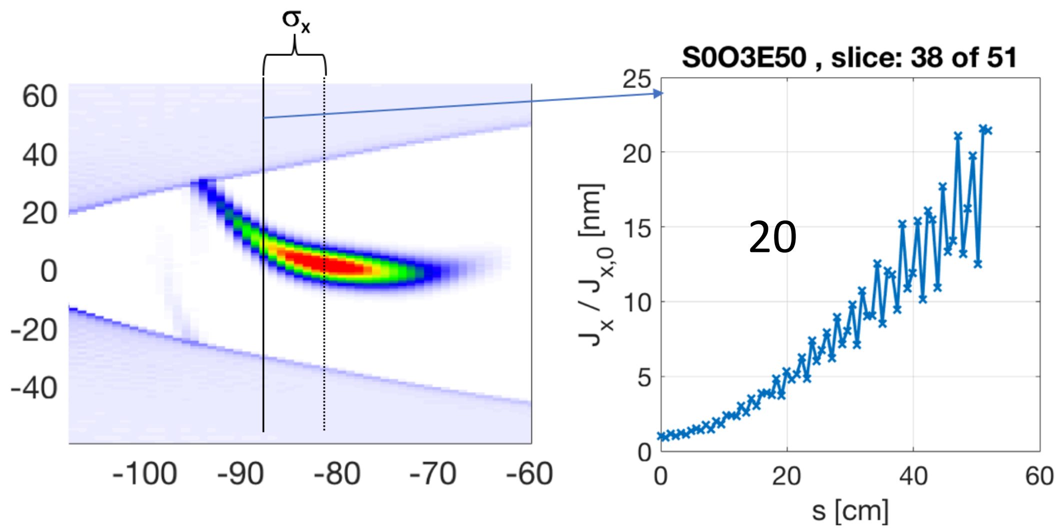
Instability for baseline parameters strong enough to be measured?

MB initially offset of 1 $\sigma_{x,WB}$

MOVIE

$\eta_{DB\text{-}WB} = 43\%$





Baseline sim. : no ion motion, zero initial energy spread.

To quantify the BBU with a single number we use the amplification of an "action" of a slice 1 σ_z behind bunch center.

NB: a simplified calculation is used :

$$J \sim \sigma_{x,slice}^2/\beta_{mat} + \beta_{mat}\,\sigma_{x',slice}^2$$

(i.e. model of phase-advance not included, and weak γ-dependence not included)

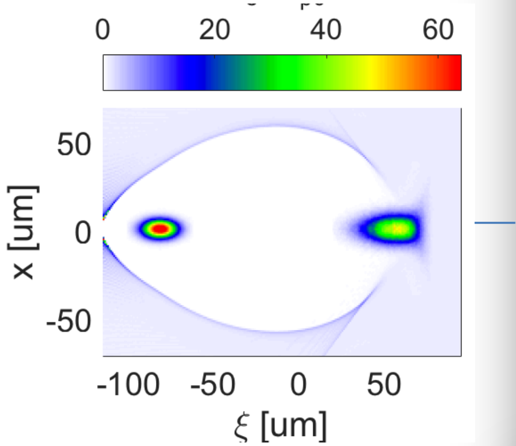
Use slice-action instead of the emittance growth to quantify the BBU as it shows the strength of the instability better than the projected emittance growth and more importantly it does allow the BBU to be quantified independently of other effects for beams which has mismatch or other sources of projected emittance growth.

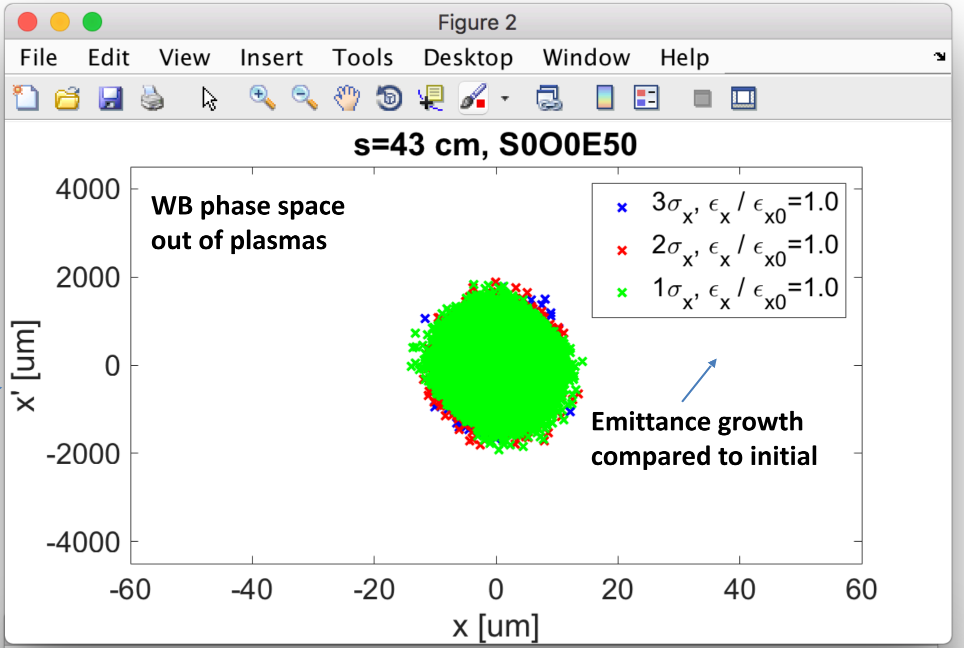
Instability strong enough to be measured?

- Possible, but need good measurements.

Observability in experiment:

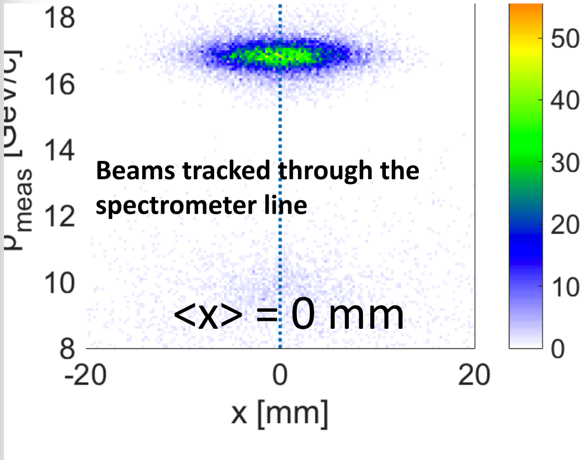
Case 1: On-axis MB





WB phase space out of plasmas

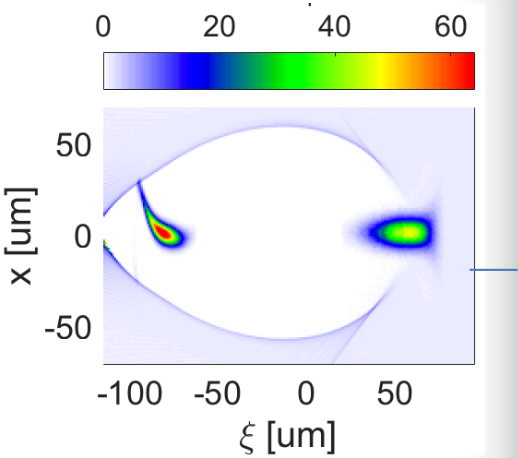
Emittance growth compared to initial

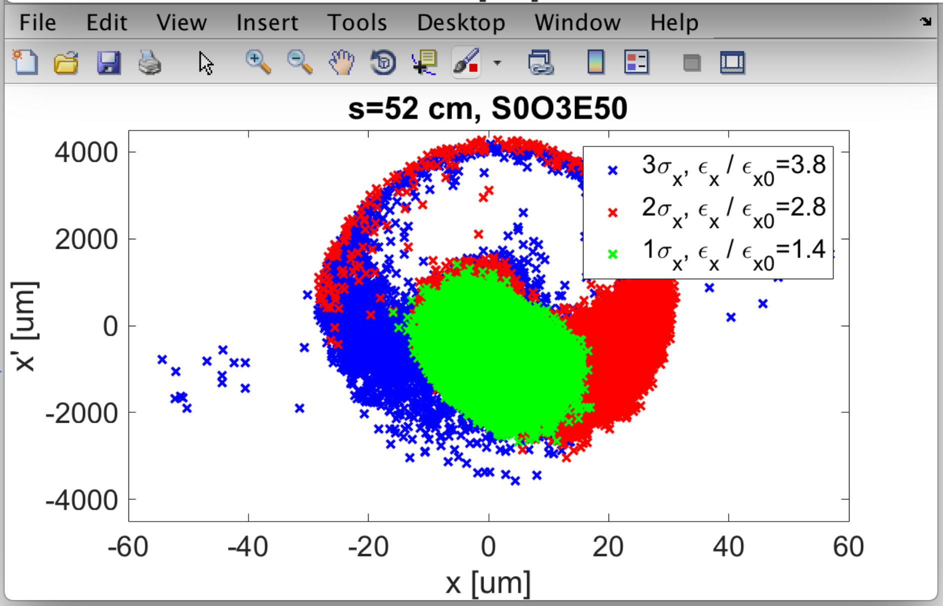


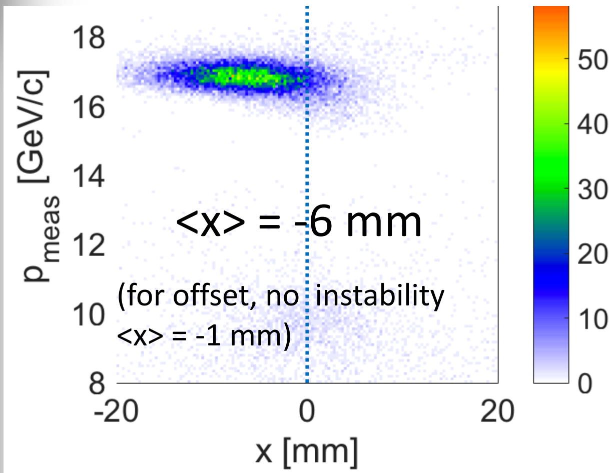
Beams tracked through the spectrometer line

<x> = 0 mm

case 2: Off-axis MB







<x> = -6 mm

(for offset, no instability
<x> = -1 mm)

A factor 3 of emittance growth for $2\sigma_z$ of beam is significant,
but may be hard to distinguish from other sources (e.g. mismatch).
Similar arguments situation for σ_x (directly observable on profile monitors)

Observables:

- emittance
- spot sizes
- kicks
- as function of energy

Many Parameters Studied – Experiment Will Benefit by Developing Good Knobs for These Parameters and Good Diagnostics to Measure

Emittance (note will change ion motion):

- Change emittance from 5-50µm, still matched, same growth (if no ion motion)

Beta-match errors:

- Unmatched, beta factor x10, emittance/10, gives similar amplification (20)
- Same for Unmatched factor x2, emittance/2
- However, emittance growth from unmatched propagation dwarfs emittance growth from BBU:
  - x10: Factor 22 @2σ_z and x2: Factor 5 @2σ_z

Loading jitter (also changes correlated energy spread):

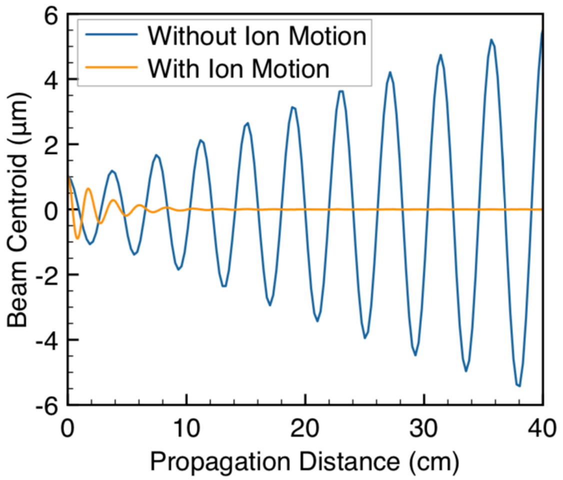
- Overloading: MB: Q=2 x 0.53nC (other parameters baseline)
  - DB-MB efficiency increases from 43 to 68%, growth x25
- Underloading: MB: Q=1/2 x 0.53nC (other parameters baseline)
  - DB-MB efficiency decreases from 43 to 24%, growth x5

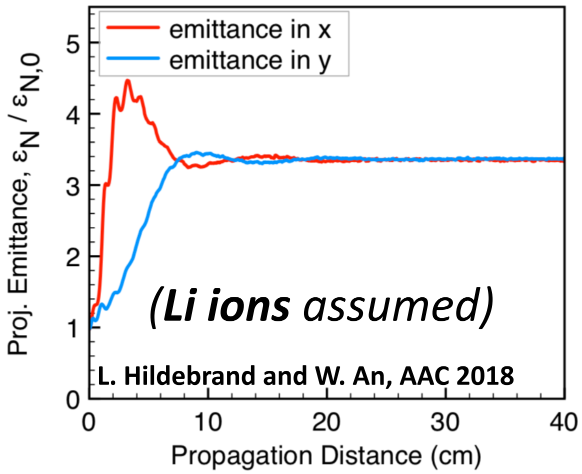
DB-MB phase jitter:

- MB: Q=1/2 x 0.53nC, $z_{DB\text{-}MB}$ = 140 - 40µm (other parameters baseline)
  - DB-MB efficiency decreases from 43 to 7%, growth x2

Mitigation by Ion motion, work by UCLA (W. An et al.) and Fermilab (S. Nagaitsev et al.)

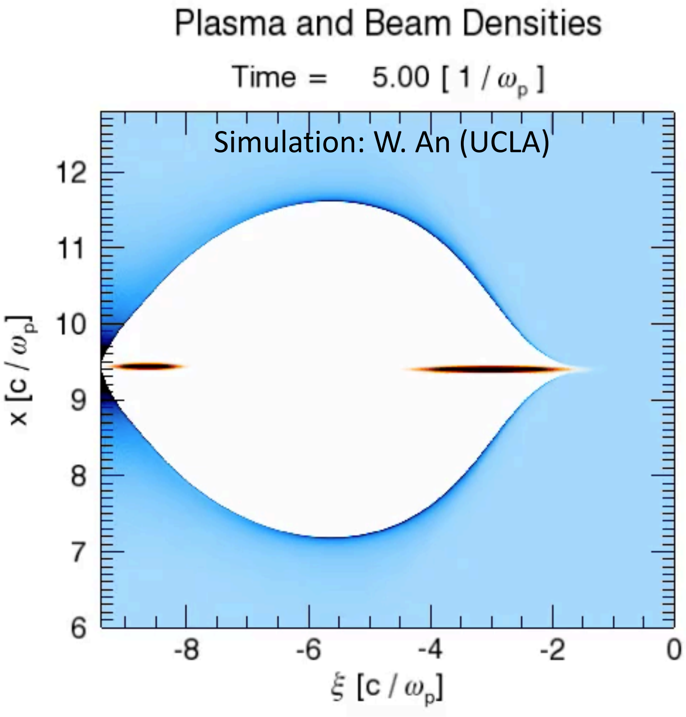
1) Ion collapse around MB (large phase advance) due to DB passage :





(Li ions assumed)

L. Hildebrand and W. An, AAC 2018



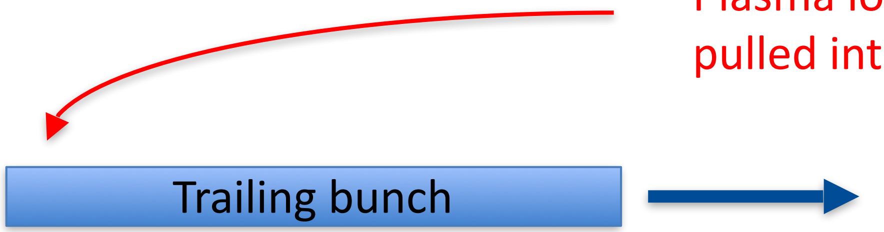
- May be observed at FACET-II with Li, and 1 um DB emittances
- Fully suppressed for Li for **few 10 um DB emittance.**

2) BNS-like effect from ion motion (smaller effect), generated within the MB itself :

A. Burov, S. Nagaitsev, V. Lebedev, arXiv:1808.03860

$$\Delta\phi \simeq k_i\Delta\zeta = \sqrt{\frac{2\pi Z r_a \sigma_z N_b}{A\epsilon_{n,x}}(r_e n_0 \gamma)^{1/4}}.$$

Plasma ions are pulled into the beam



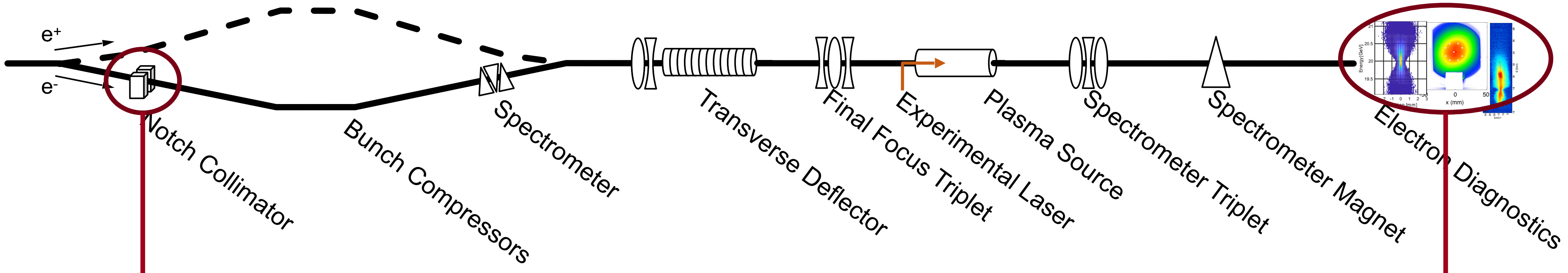
Trailing bunch

*(**H ions** assumed)*

- For the rms norm **MB emittance 1 μm** we should observe BNS damping due to ion moblity (at 50% power efficiency)
- For the rms norm **MB emittance 10 μm** we will not observe BNS damping due to ions (at 50% power efficiency)

Study of ion-motion requires possibility to reach order 1 um emittances, and vary ion species (**H, Li, Rb?**)

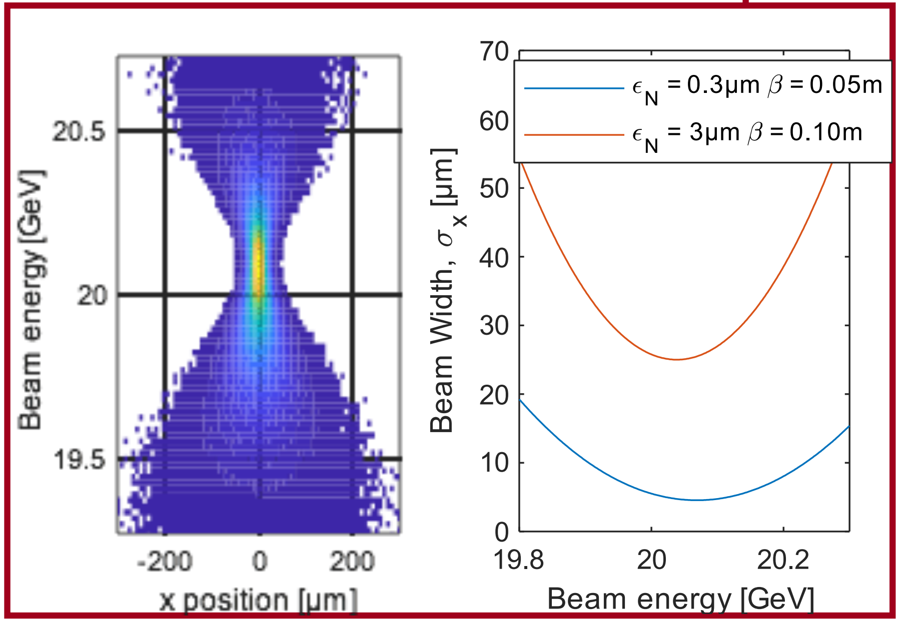
Control and Measurement of Emittance



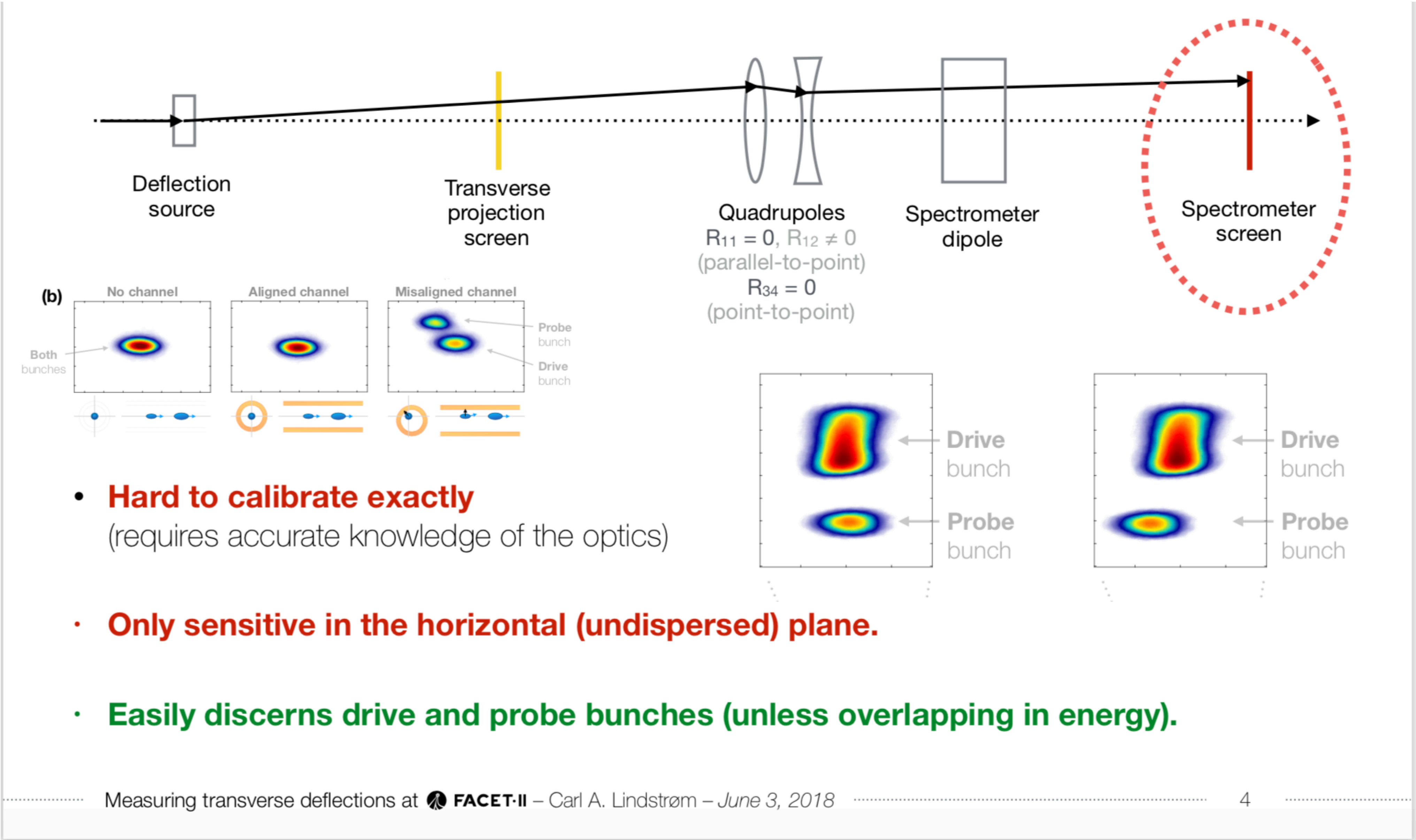
Spoilers for independent control (increase) of MB & DB emittance

Butterfly emittance measurement technique:

- Witness bunch imaged on a high resolution screen
- Beam width extracted as a function of particle energy is analogous to a quad scan
- Provides sensitivity for determining sub mm-mrad emittances



Spectrometer Screen (point-to-point imaging)



$R_{11} = 0$, $R_{12} \neq 0$
(parallel-to-point)
$R_{34} = 0$
(point-to-point)

- **Hard to calibrate exactly**
  (requires accurate knowledge of the optics)

- **Only sensitive in the horizontal (undispersed) plane.**

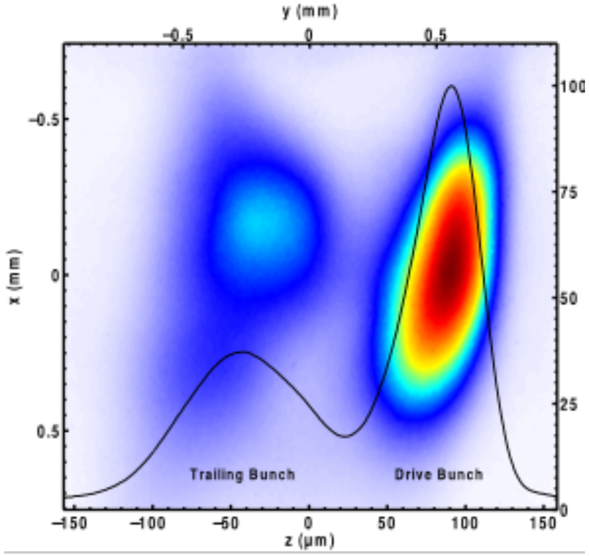
- **Easily discerns drive and probe bunches (unless overlapping in energy).**

Measuring transverse deflections at FACET-II – Carl A. Lindstrøm – *June 3, 2018* 4

Shot-to-shot measurement of the beam separation in the transverse and the longitudinal dimensions is likely required (e.g. EOS BPM, M. Litos CU Boulder)

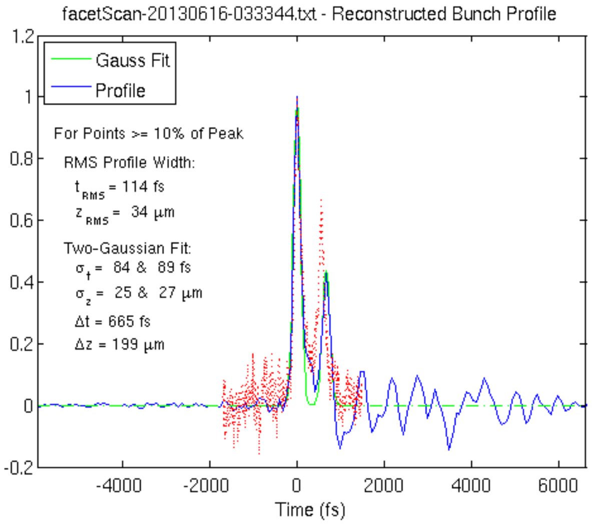
Longitudinal Beam Diagnostics at FACET

TCAV



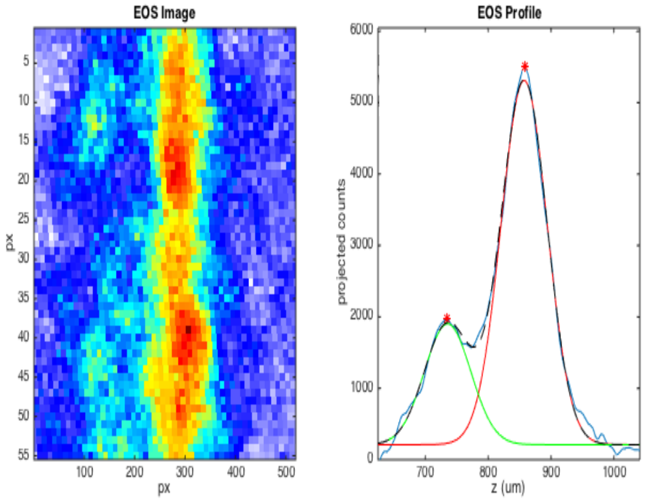
- Single Shot
- Resolution: ~10μm
- Destructive
- Subject to Chromatic Distortions

THz Michelson Interferometer



- Multi-Shot
- Resolution: ~5μm
- Non-Destructive
- Subject to Distortion from Beam Fluctuations

Electro-Optic Sampling

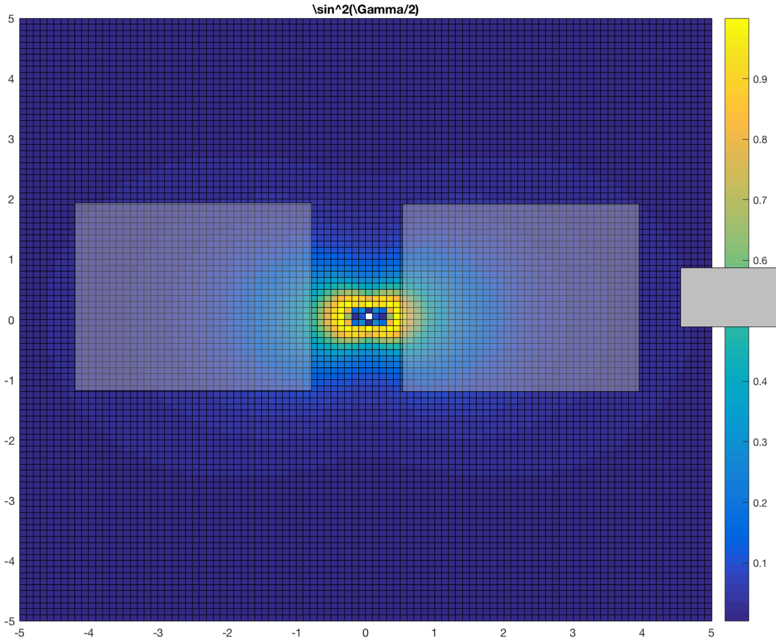


- Single Shot
- Resolution: ~10μm
- Non-Destructive
- Subject to Distortion from Laser Fluctuations

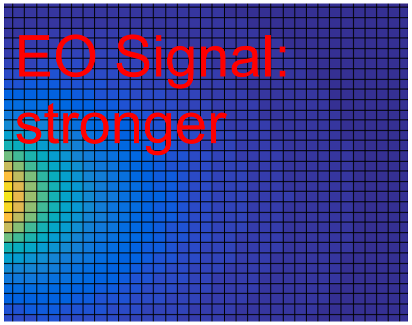
Courtesy M. Litos CU Boulder

EOS-BPM, Single Bunch

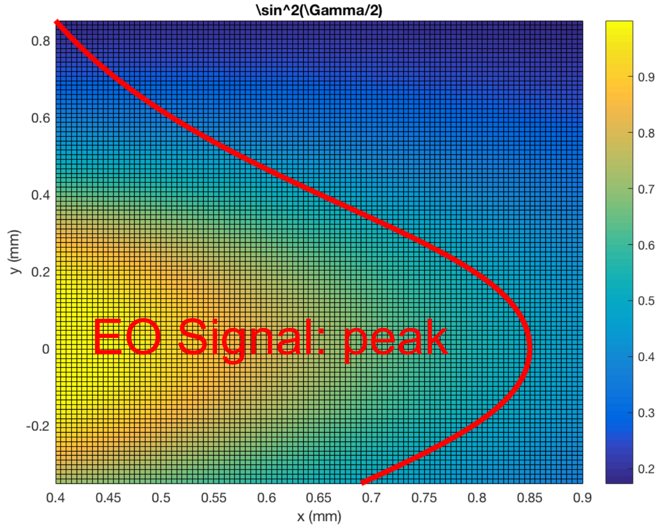
EO Crystals



Integrated signal from each crystal: x-position



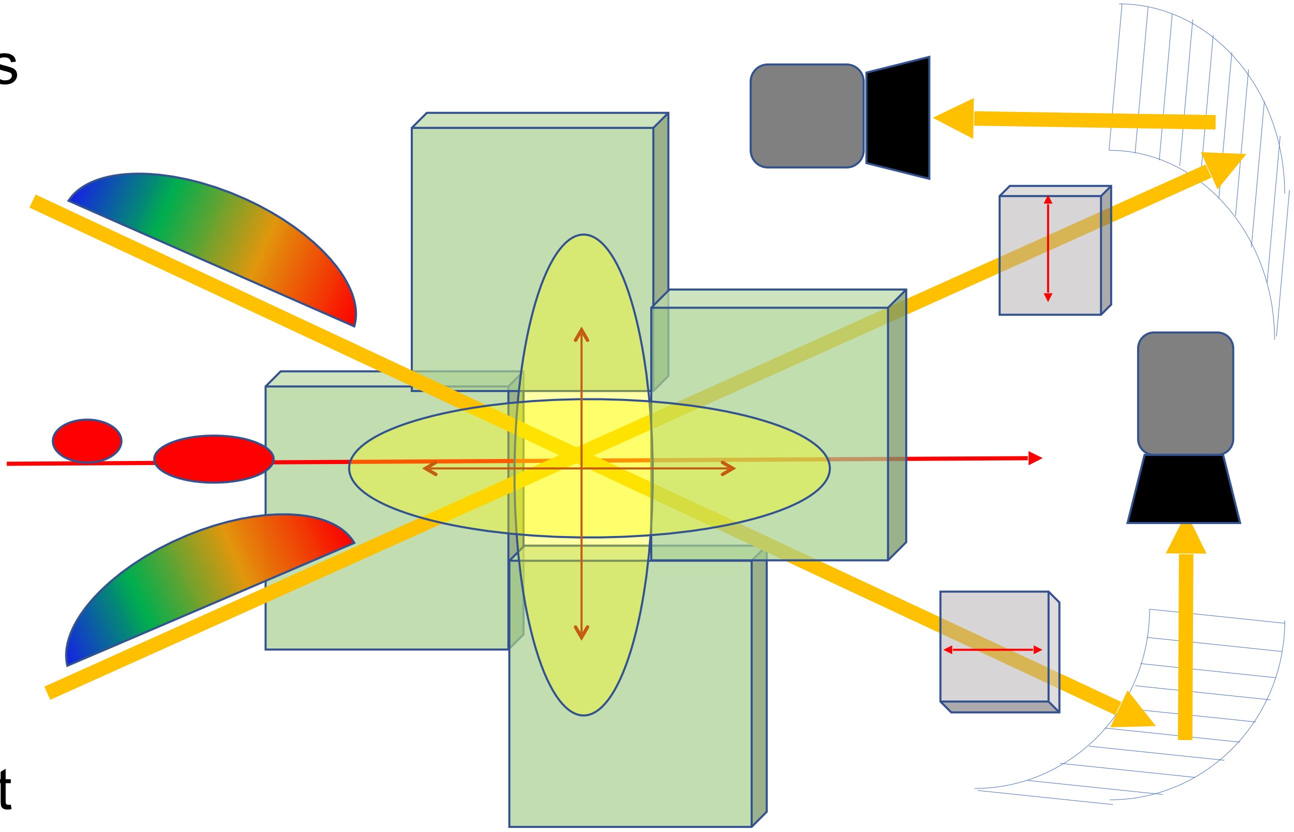
1-D integral peak from either/ both crystals: y-position



Courtesy M. Litos CU Boulder

Single-Shot, 3-D Profiler

- One or two pairs of crystals
- Use chirp for longitudinal profile and to distinguish drive and witness signals
- Use spatial signal to determine position of drive and witness separately
- Imaging spectrometer inherently 1-D spatially, but can use optical fibers to get around that



Maybe two pulses with crossed polarization(?)
Note: vert. and horiz. crystal pairs rotated by 90º w.r.t. each other

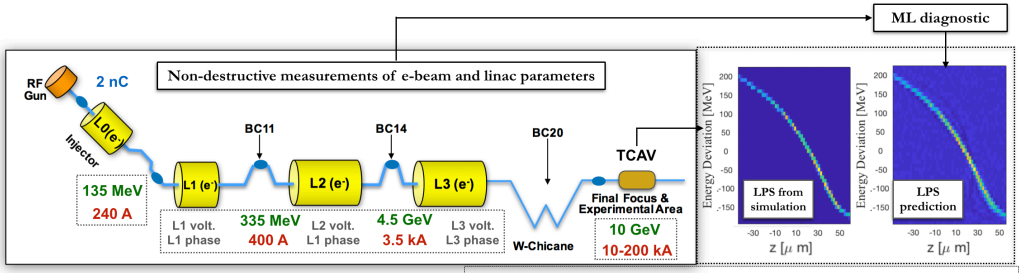
Courtesy M. Litos CU Boulder

ML-based LPS diagnostics for FACET-II

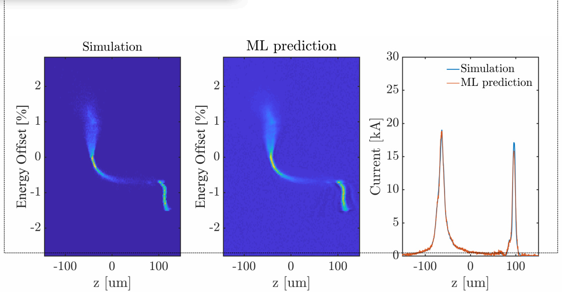
Scientific Capabilities

- ML diagnostics provide *non-destructive, single-shot* prediction of LPS along FACET-II and at the IP.
- Can be used to determine current profile for single bunch and the charge/current ratio/ spacing for two-bunch configurations.
- Facilitate machine set-up and enable finer beam control.
- Boost scientific discovery by improving data analysis/understanding of experimental results.

Schematic



- Single and two-bunch prediction tested in simulation



C. Emma, A. Edelen *et al.*, PRAB **21** 112802 (2018)
A. Scheinker, A. Edelen *et al*, PRL **121** 044801 (2018)

Current Diagnostic Gap

- Many diagnostics cannot be used continuously or in conjunction with experiments
  - Destructive to the beam (e.g. TCAVs)
  - At risk of damage if intercepting fully compressed beam

Importance and Urgency

- Limitations with existing LPS diagnostics
- Important to test novel ML diagnostic systems early (commissioning phase)
- Additional information can be used to inform accelerator tuning and optimization (tailoring beam for specific users)

Seeding the Instability in a Controlled Way

- The seeding of the instability – the offset and angle of the witness beam with respect to the drive beam before the plasma - must be controller and/or measured in order to the estimate growth rate of the instability.
- Experience from FACET: relying on dispersion to create seeding is challenging
  - Hard to control linear dispersion independent of other optics
  - Many simultaneous constraints for two-bunch generation
- TCAV rotation to horizontal to independently control offset of rear part of bunch (2 deg X-band phase between DB and MB)
  - Still hard to control beam size, emittance, beta function of both bunches simultaneously

It is likely that a separate witness injector can better provide the required MB and DB independence - parameter study to be done

PWFA Research Priorities at FACET-II
Stage 1 Funded. Stage 2 & 3 will Fully Exploit the Potential of FACET-II

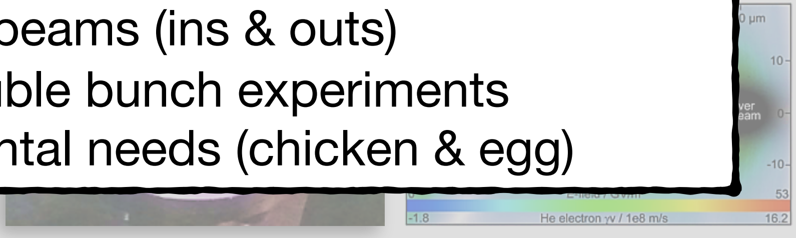
Emittance Preservation with Efficient Acceleration

- High-gradient
been demons
- Full pump-dep
Emittance pre
at µm level pla
first experimen

Stage 1

High Brightness Beam Generation & Characterization

r collider apps
d to first apps



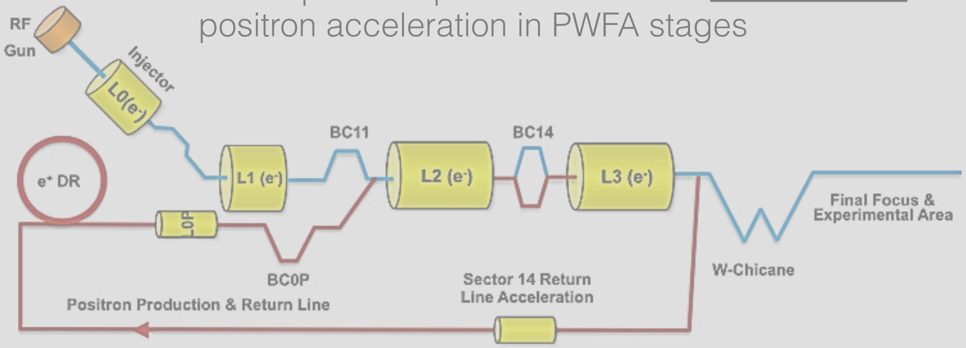
Stage 1

Possibility to add an independent witness injector has been studied:
- Independent control of drive & witness bunches
- More flexibility for shaping and higher transformer ratio studies
- Staging studies with independent beams (ins & outs)
- Incorporate lessons learned in double bunch experiments
- Requirements will follow experimental needs (chicken & egg)

Positron Acceleration
FY21-24

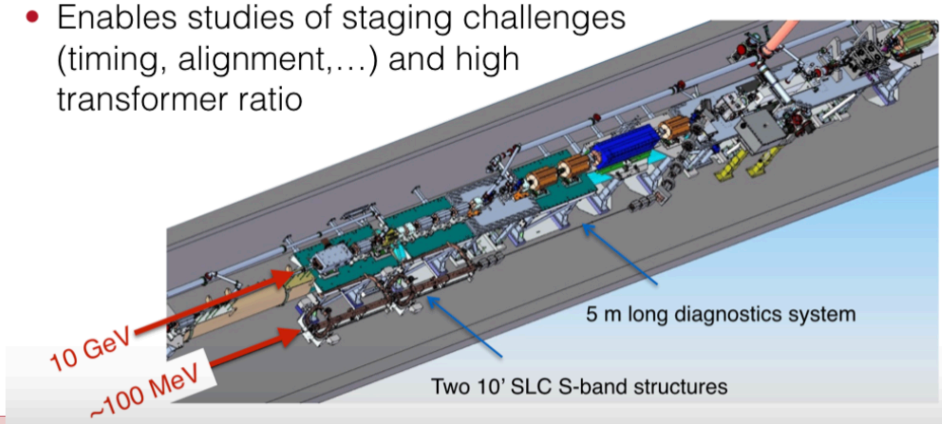
- Only high-current positron capability in the world for PWFA research will be enabled by Phase II
  - Develop techniques for positron acceleration in PWFA stages

Stage 2



Staging Studies
FY22-25

- Independent witness injector planned to be added to FACET-II as an AIP project
- Enables studies of staging challenges (timing, alignment,…) and high transformer ratio



User Community is engaged with annual science workshops. Gradual introduction of capabilities are aligned with User needs.

Summary

Goals:

- Control and measure the BBU-instability in the witness bunch by varying bunch charge, phase and emittance
- Study mitigation by controlled energy spread (i.e BNS-damping)
- Study mitigation by ion motion

Challenges:

- Clean observation requires a successful two-beam emittance preservation experiment to start from
- Independent and precise control MB parameters required

Ultimate Goal:

- Understand both instability, mitigation methods in PWFA two-beam experiments, and related parameter dependencies, well enough to with confidence be able to optimize a plasma-based collider design