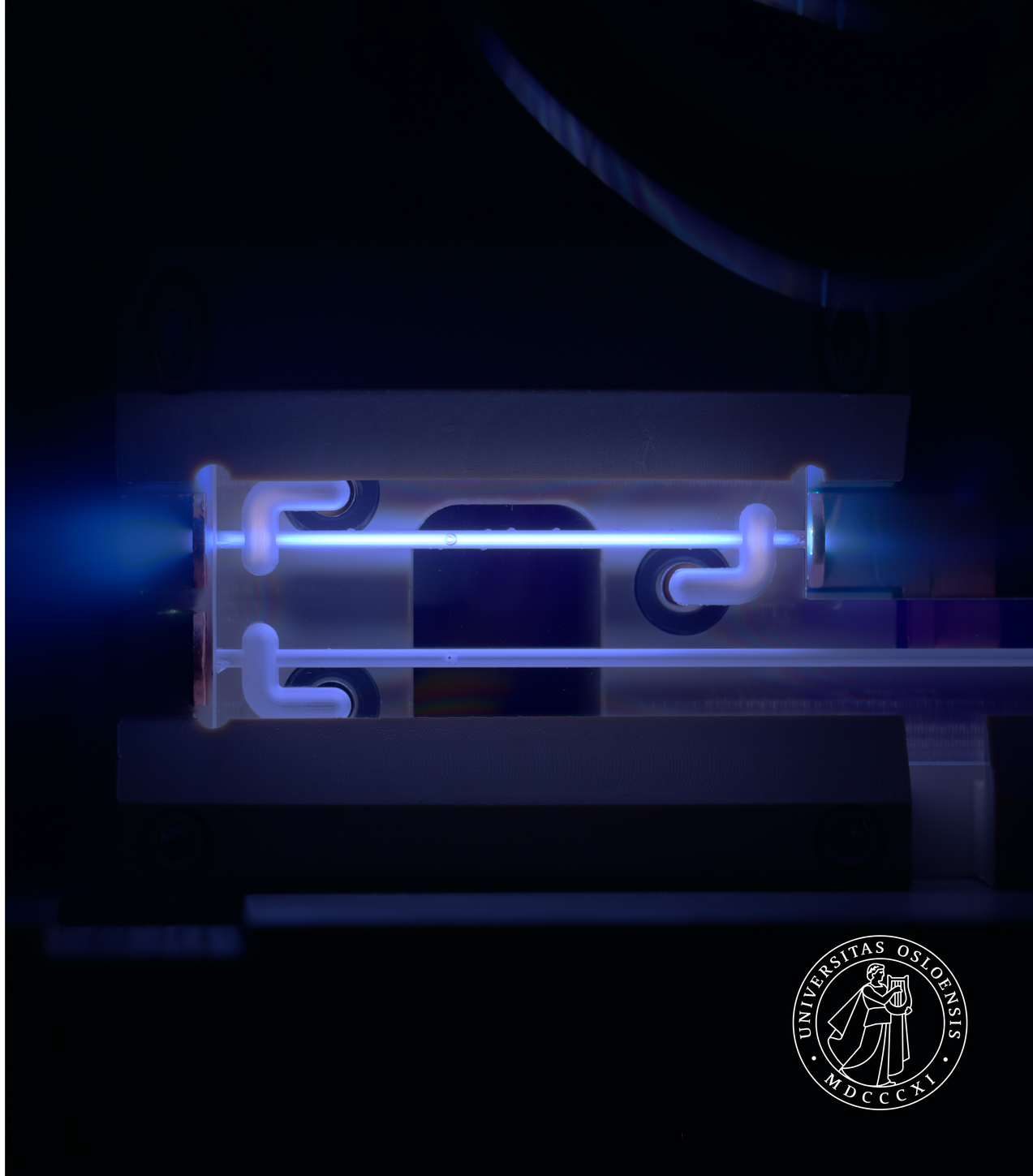
UNIVERSITY OF OSLO

UCLA

SLAC

Plans for the E302 experiment:
Transverse-instability studies



Dr. Carl A. Lindstrøm

Postdoctoral Fellow

Department of Physics, University of Oslo

(on behalf of the Oslo team)

6 Oct 2022 | E300 collaboration meeting | UCLA / virtual

Transverse instabilities: **It depends on the bunch**

Driver
(hosing instability)

- Mitigated by induced energy spread
  — *Mehrling et al., PRL 118, 174801 (2017)*
- Mitigated by large beam sizes
  — *Martinez de la Ossa et al., PRL 121, 064803 (2018)*

Trailing bunch
(beam-breakup instability)

- Ideally, no energy spread
- Ideally, small beam sizes (matched)
- …

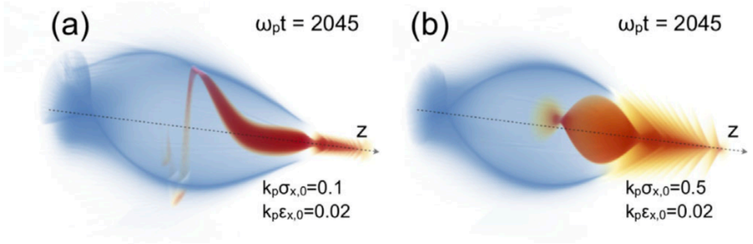


Image source: Martinez de la Ossa et al. [PRL 121, 064803 (2018)]

Core problem: **Energy-transfer efficiency vs. transverse instability**

- Two separate goals in plasma acceleration:
  - 1. Maximum energy-transfer efficiency
  - 2. Minimum emittance (maximum beam quality)
- How to achieve high efficiency?
  - High current — **beam loading** (driving a longitudinal wakefield “out of phase” from that of the driver)
- Problem: Transverse instability — a resonance occurs between the offset of the beam and the plasma wake.
  - Small offset — small transverse wakefield (deflecting) — larger offset — larger transverse wakefield = **an instability**
  - The instability grows faster with higher current
- Fundamental question: **is it possible to achieve high energy efficiency without a strong transverse instability?**
  - Proposals exist to break this connection—do they work?

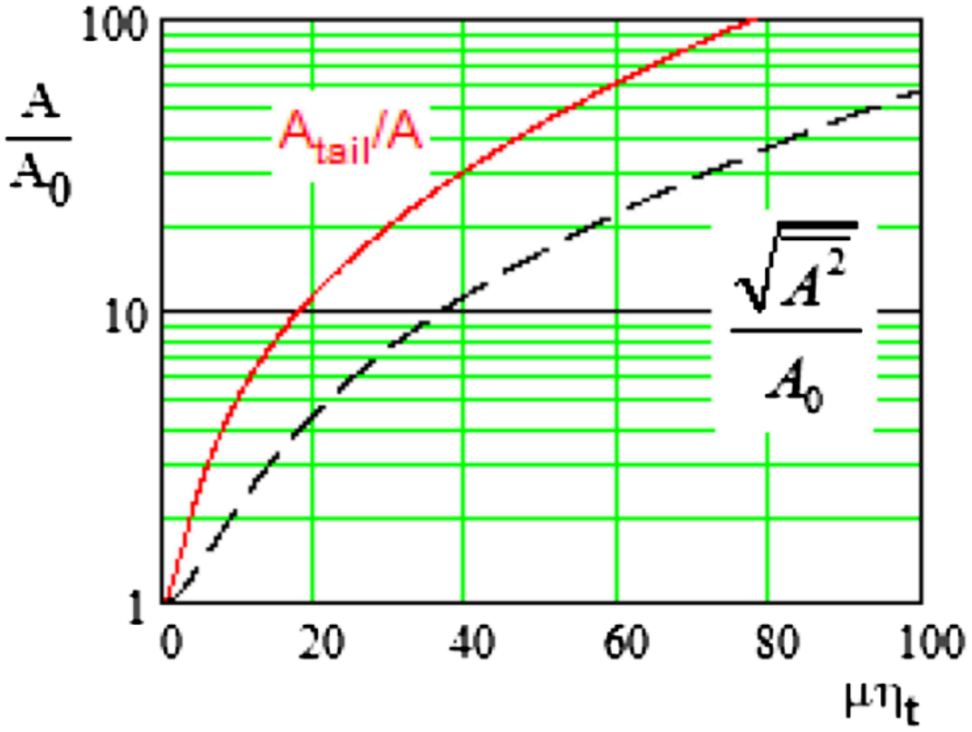
E302 part 1: **Testing the prediction**

- Lebedev, Burov and Nagaitsev formulated a prediction for the growth rate of the transverse oscillation amplitude based on the power efficiency.
  - *"Efficiency versus instability in plasma accelerators", PRAB 20, 121301 (2017).*

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

$$\frac{\sqrt{\overline{A^2}}}{A_0} = \exp\left(\frac{(\mu\eta_t)^2}{60+2.2(\mu\eta_t)^{1.57}}\right); \quad \mu\eta_t \leq 100, \quad \eta_t \leq 0.1.$$

$$\frac{A}{A_0} = \exp\left(\frac{(\mu\eta_t)^2}{10+1.4(\mu\eta_t)^{1.57}}\right); \quad \mu\eta_t \leq 100, \quad \eta_t \leq 0.1,$$

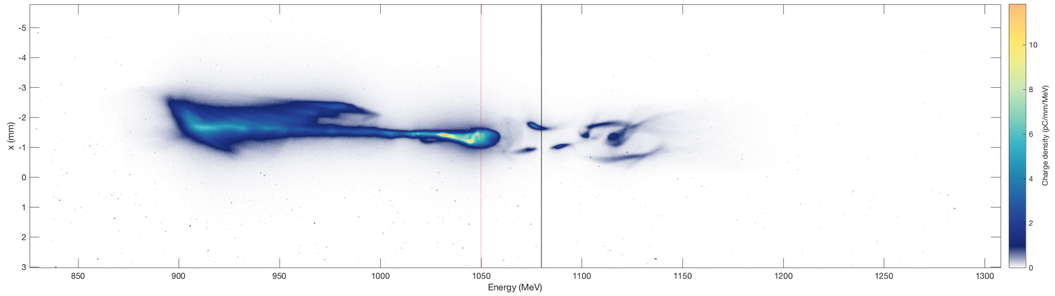


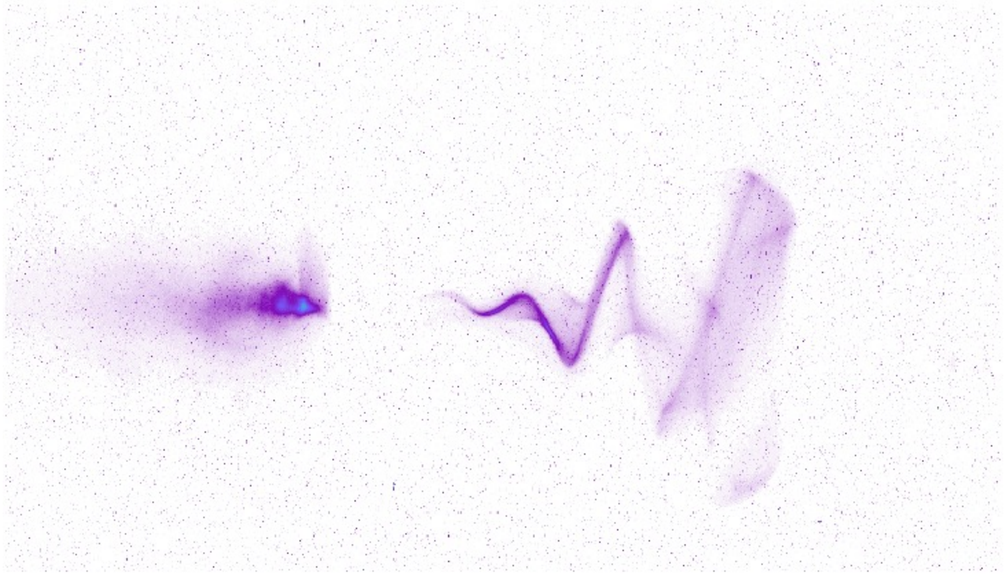
Source: Lebedev et al., PRAB 20, 121301 (2017).

- **E302 (part 1) will be to test this prediction.**

Methodology #1: **Imaging spectrometer**

- Setup:
  - Imaging quadrupoles, dispersive dipole, screen
- Pros:
  - Standard method
  - Separates driver from trailing bunch
  - Can measure transverse offsets, energy spread, emittance.
- Cons:
  - Spatially integrated
  - Only shows surviving charge (transverse instabilities often lead to charge loss)
  - Imaging is complicated: not enough to just observe transverse wiggles with increasing amplitude.

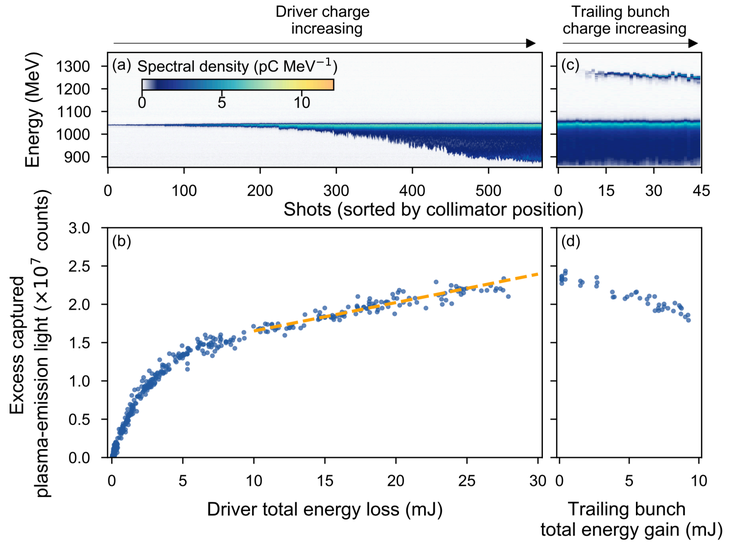


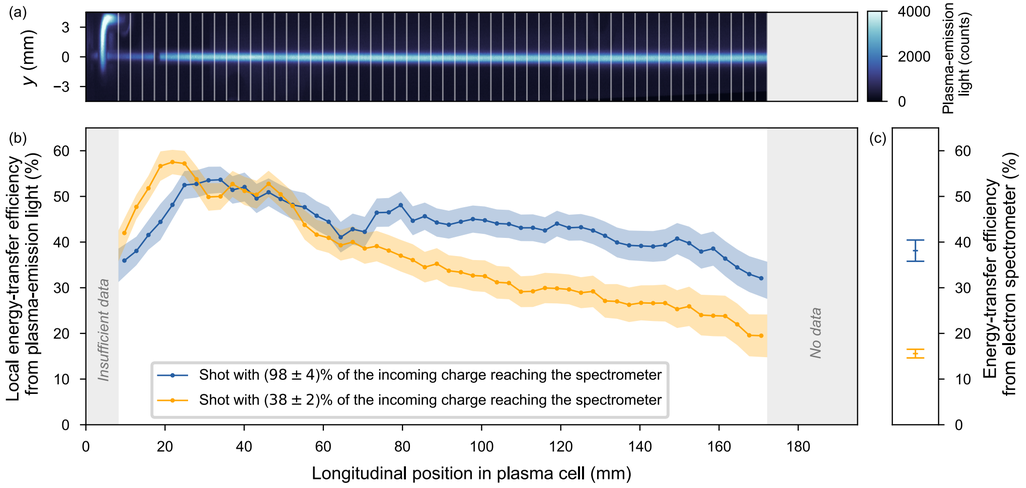


FLASHForward (March 2020)

Methodology #2: **Plasma-light based efficiency measurement**

- Setup: Observe plasma light transversely
- Concept:
  - Driver energy loss increases plasma light. Establish the connection between light and energy left in the plasma.
  - Beam loading extracts energy—less plasma light.
- Pros:
  - Energy-transfer efficiency can be measured with longitudinal resolution (i.e., locally).
  - Allows measurement of growth rate of the instability through observation of efficiency loss (via charge loss). Not direct, but comparable to simulation.
  - Simple, and single-shot.
- Cons:
  - Requires plasma viewports (more complete is better).
  - Requires knowledge driver energy loss (stability or shot-by-shot measurement using spectrometer)



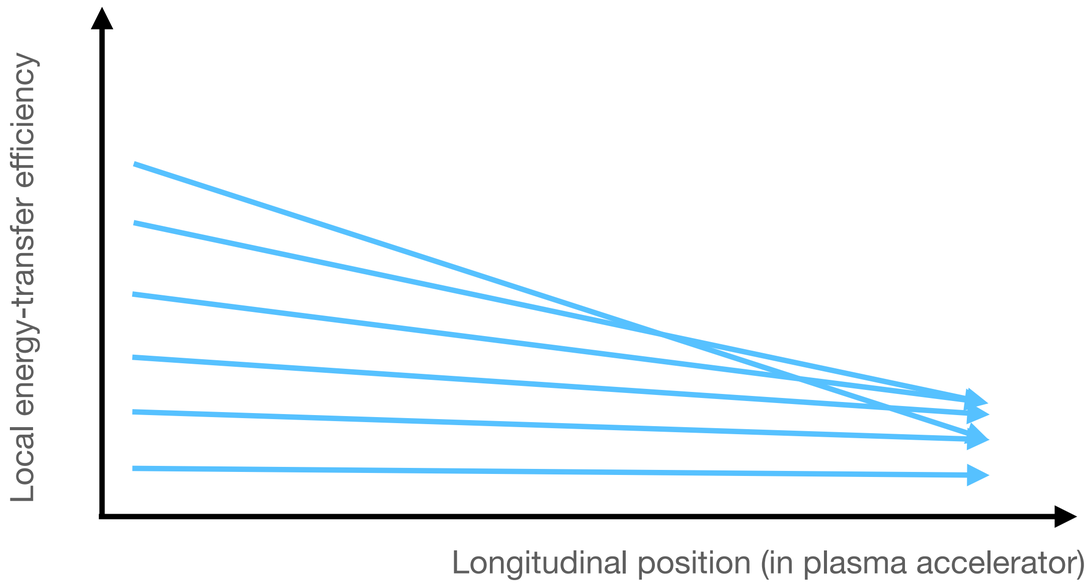


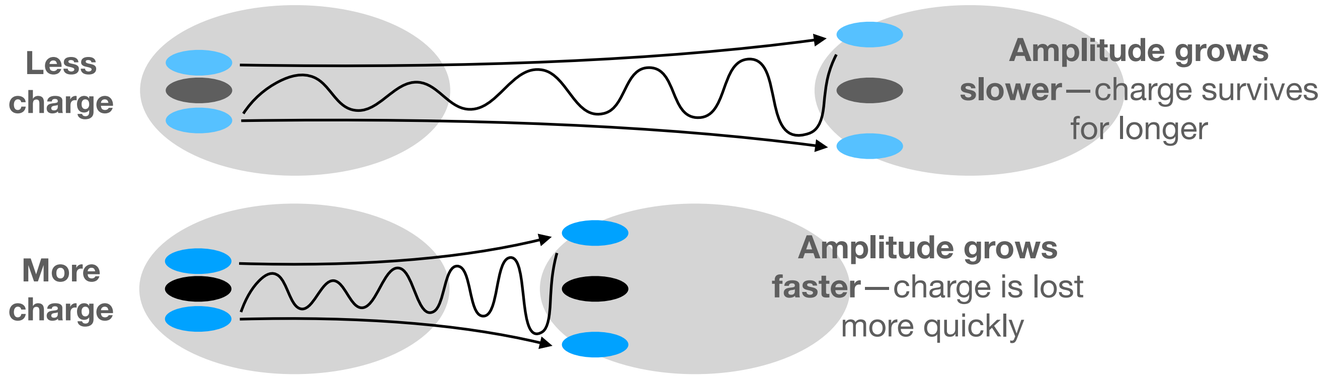
Source: Boulton et al., arXiv:2209.06690 (2022)

The measurement: **Scan incoming charge, observe growth rate**

- **Main scan (or correlation):**
  - **Scan the incoming trailing-bunch charge**
  - (Changes the initial local efficiency)
  - (Changes the transverse wakefield)
- Assume that the initial transverse offset jitters randomly across the full size of the plasma wake (if not, scan it across)
  - Charge loss rate varies every shot
  - Measure the distribution charge-loss rates

- **Prediction (currently qualitative):**
  - **The charge loss rate will increase with higher initial efficiency.**



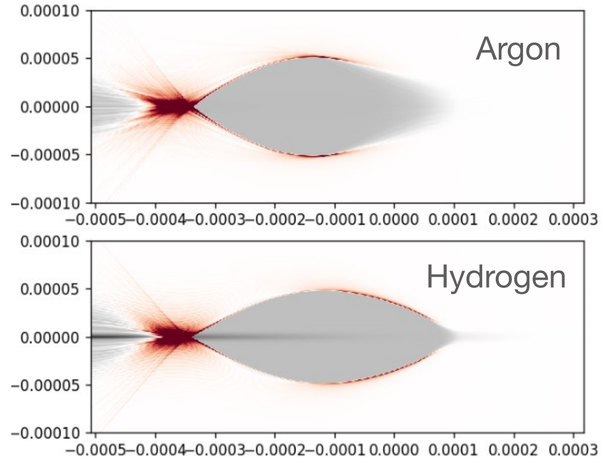


E302 part 2: **Testing mitigation strategies**

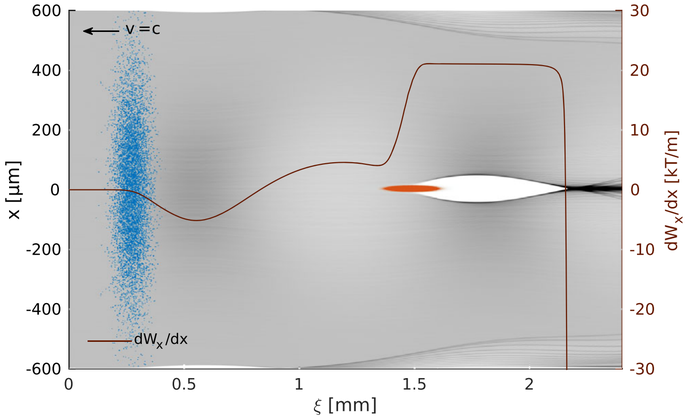
- **Mitigating the beam-breakup instability requires BNS damping:**
  - (Detuning the resonance with varying focusing strength)
  - Ideally, without the traditional energy chirp

- Two strategies proposed:
  - **Quasi-linear regime, nonlinear focusing (Lehe 2017)**
  - **Controlled ion motion (Benedetti et al. 2017)**

- Experimentally: measure a charge loss rate smaller than what is allowed by the “efficiency–instability relation”.
- If it works: Measure beam quality, in particular the emittance (on the spectrometer) — compare the techniques.



Simulations by Severin Diederichs (HiPACE++).



Quasi-linear regime (extreme version, AWAKE).
Source: Olsen et al., PRAB 21, 011301 (2018).

Conclusions

> Transverse instabilities and mitigation strategies are important to the operation of high-quality, high-gain plasma accelerators.

> **The plan for E302 is to validate (and then break) the efficiency–instability relation.**

> Currently, these plans are mainly qualitative ideas.

> > Next up: Perform simulations to determine quantitatively what the signal is.

> > A new PhD student will start working on this topic in December 2022.

> Will wait until two-bunch PWFA has been established by E300 (but may also be required to establish it).