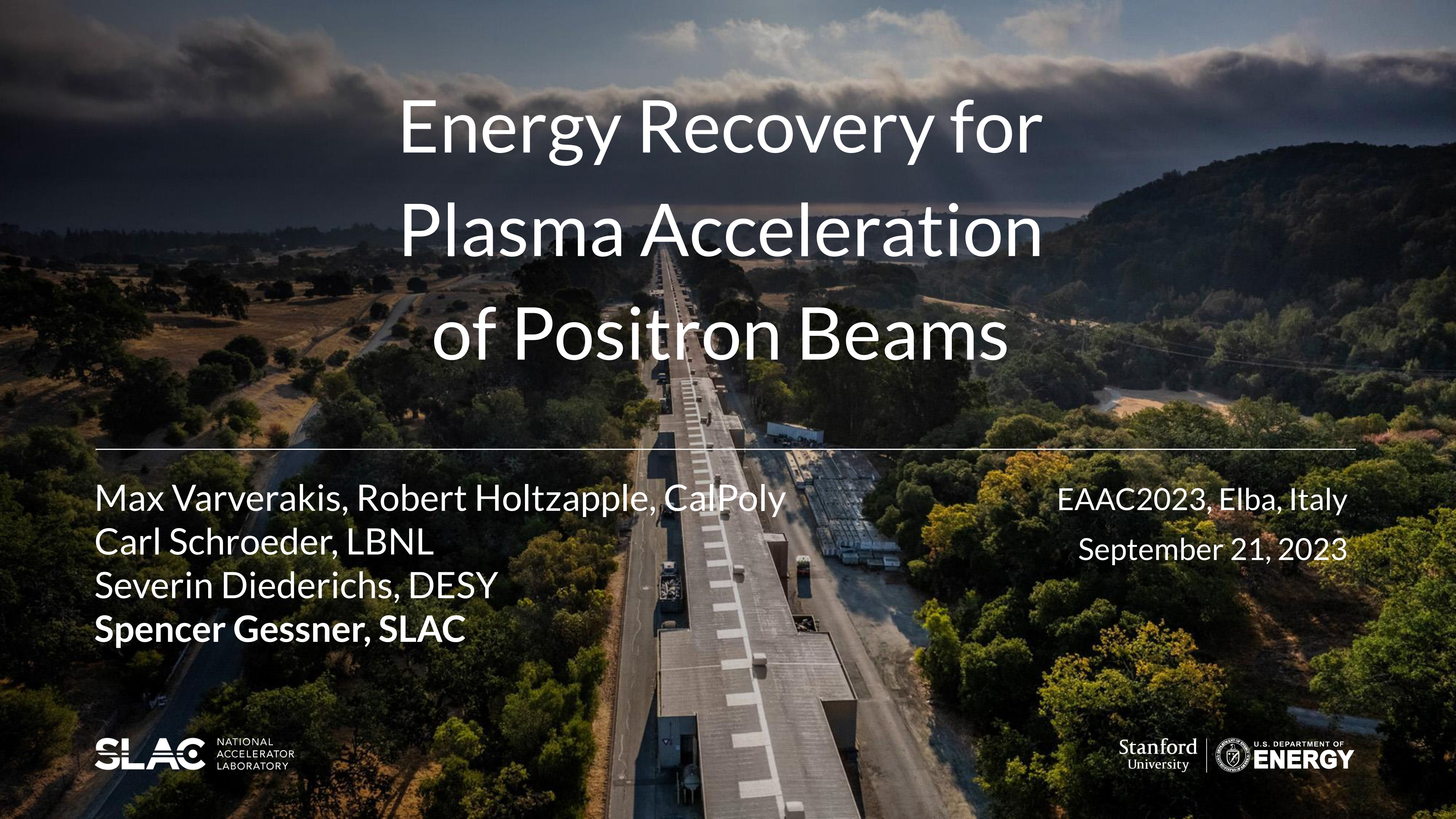


Energy Recovery for Plasma Acceleration of Positron Beams

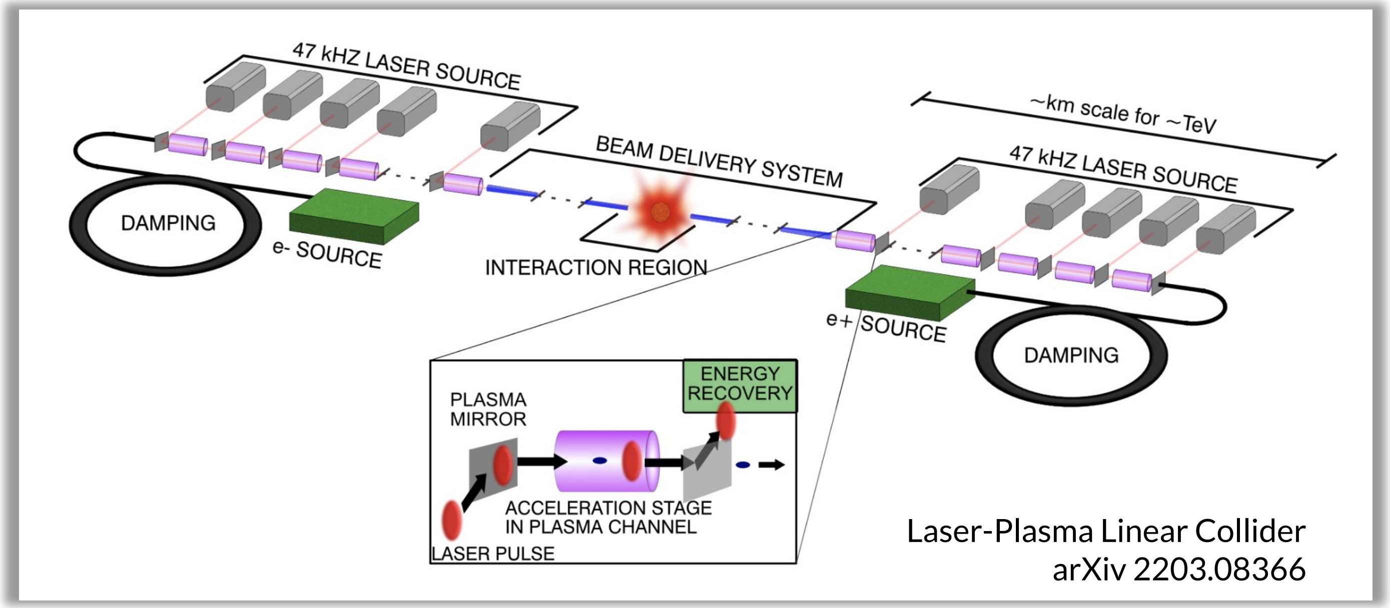
Max Varverakis, Robert Holtzapple, CalPoly
Carl Schroeder, LBNL
Severin Diederichs, DESY
Spencer Gessner, SLAC

EAAC2023, Elba, Italy
September 21, 2023

SLAC NATIONAL ACCELERATOR LABORATORY

Stanford University | U.S. DEPARTMENT OF ENERGY

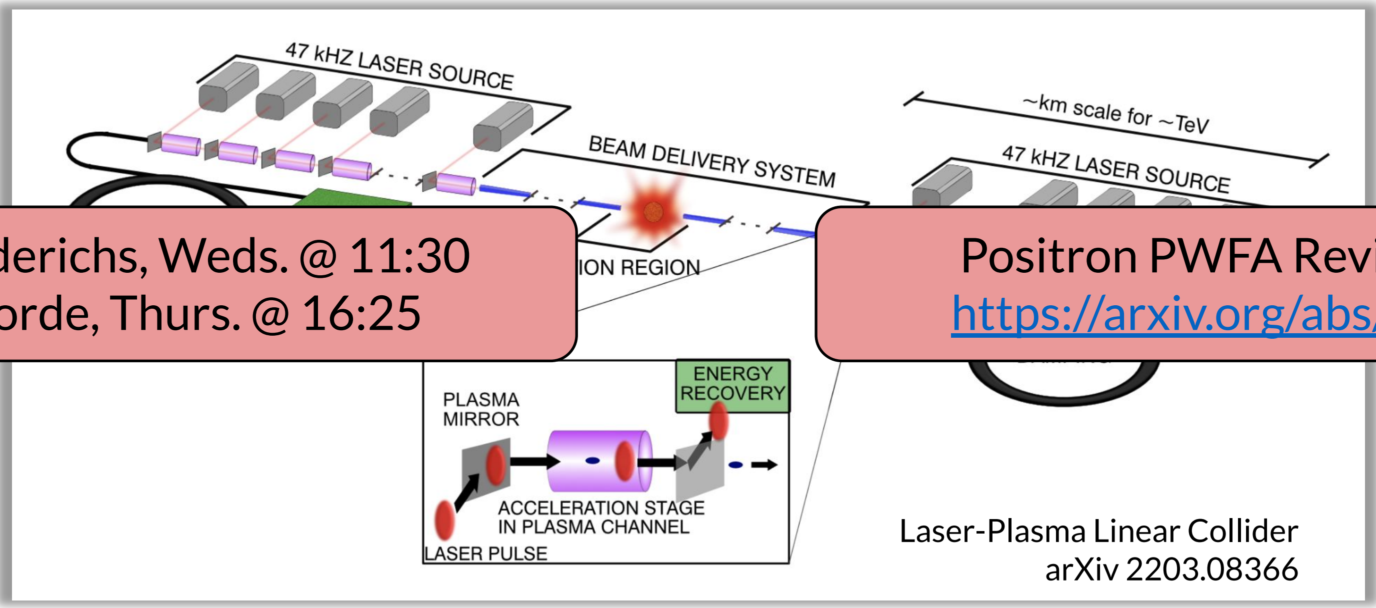
Plasma Linear Colliders



Laser-Plasma Linear Collider
arXiv 2203.08366

Challenge for our field: *How do we accelerate positron bunches in plasma?*

Plasma Linear Colliders



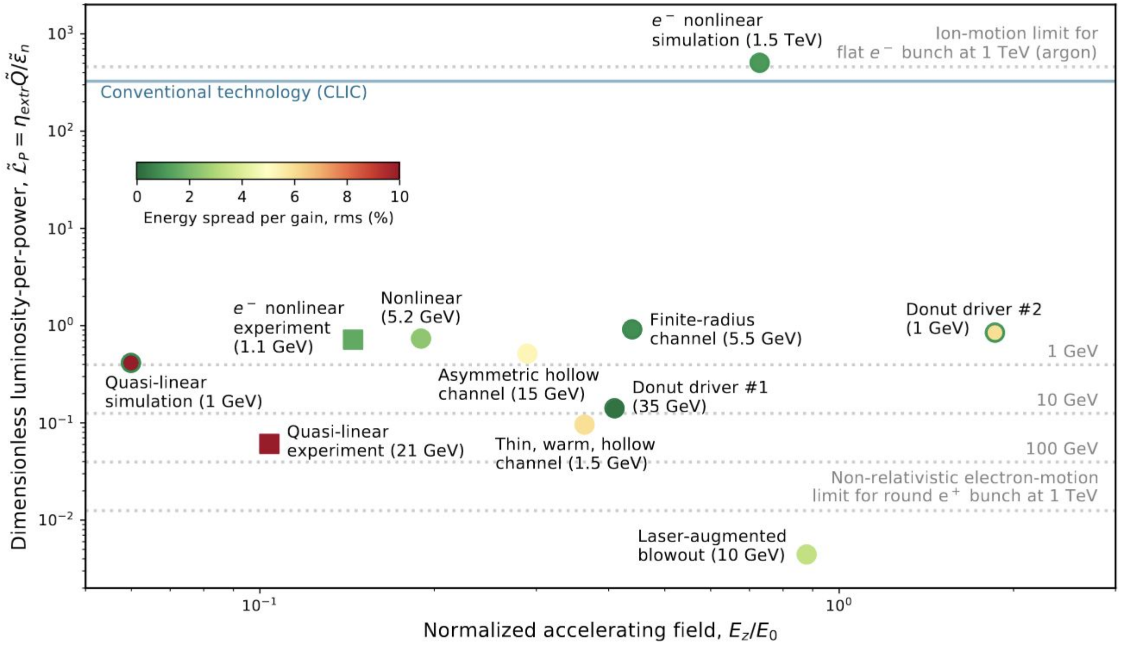
Talk by S. Diederichs, Weds. @ 11:30
Talk by S. Corde, Thurs. @ 16:25

Positron PWFA Review out now!
https://arxiv.org/abs/2309.10495

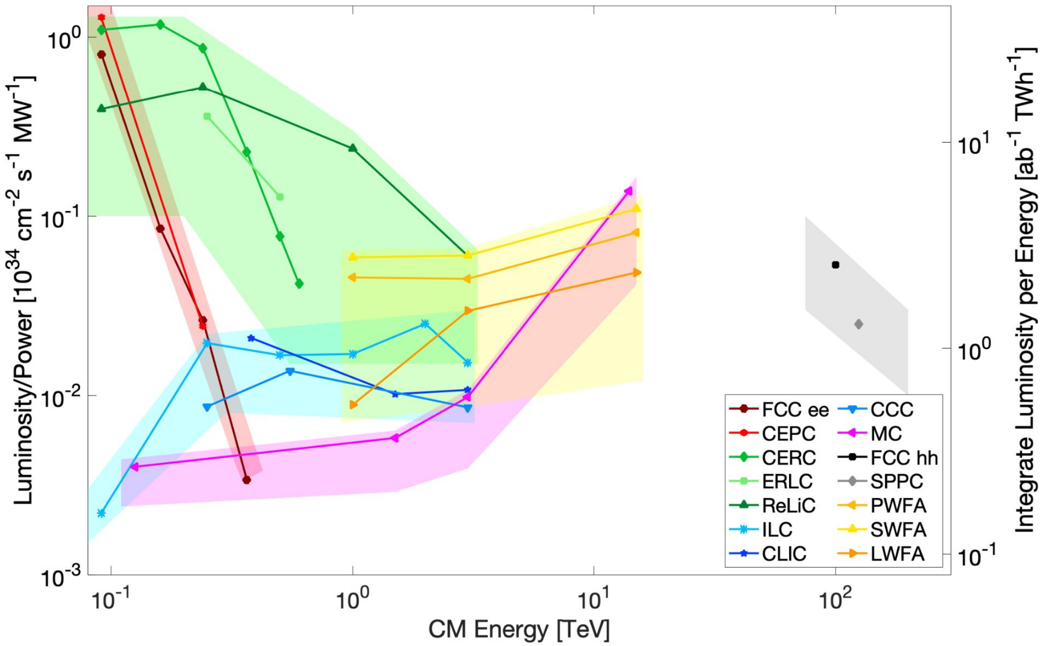
Laser-Plasma Linear Collider
arXiv 2203.08366

Challenge for our field: *How do we accelerate positron bunches in plasma?*

Comparing Collider Concepts


Comparison of Positron PWFA Concepts

Review: G. Cao et. al. “Positron Acceleration in Plasma Wakefields.”
arXiv:2309.10495 (2023)


Comparison of Collider Concepts

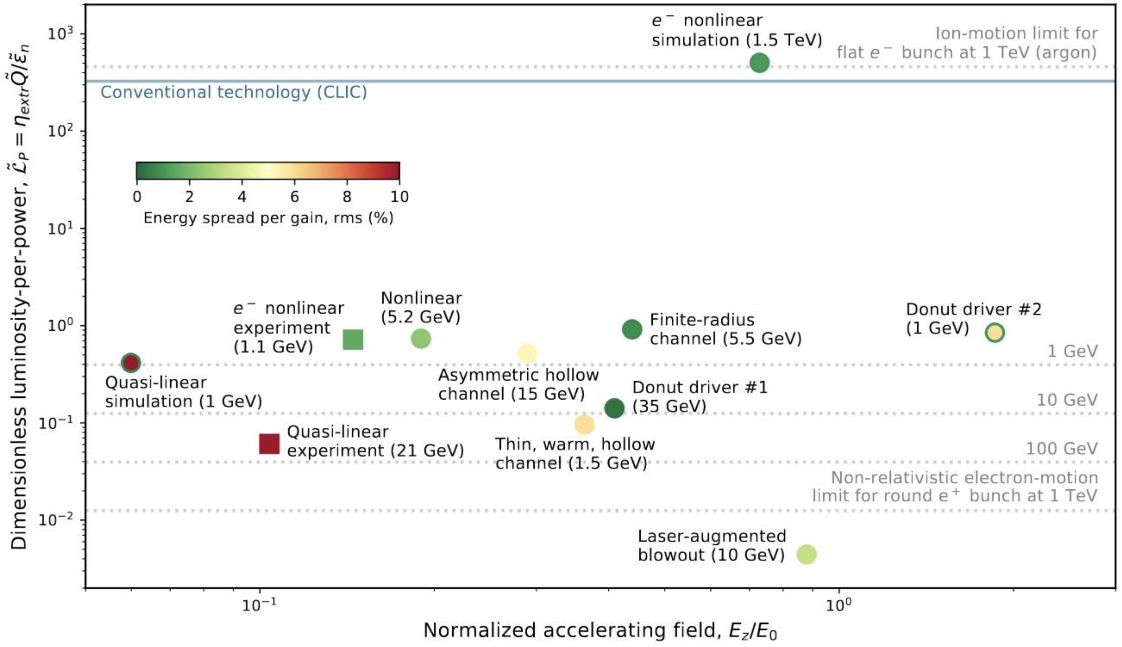
Snowmass ITF: T. Roser et. al. “On the feasibility of future colliders.”
JINST 18, P05018 (2023)

Luminosity-per-power is a key figure of merit for future colliders.

Comparing Collider Concepts

T. Barklow et al. “Beam delivery and beamstrahlung considerations for ultra-high energy linear colliders” *JINST* **18** P09022 (2023)

Comparison of Positron PWFA Concepts



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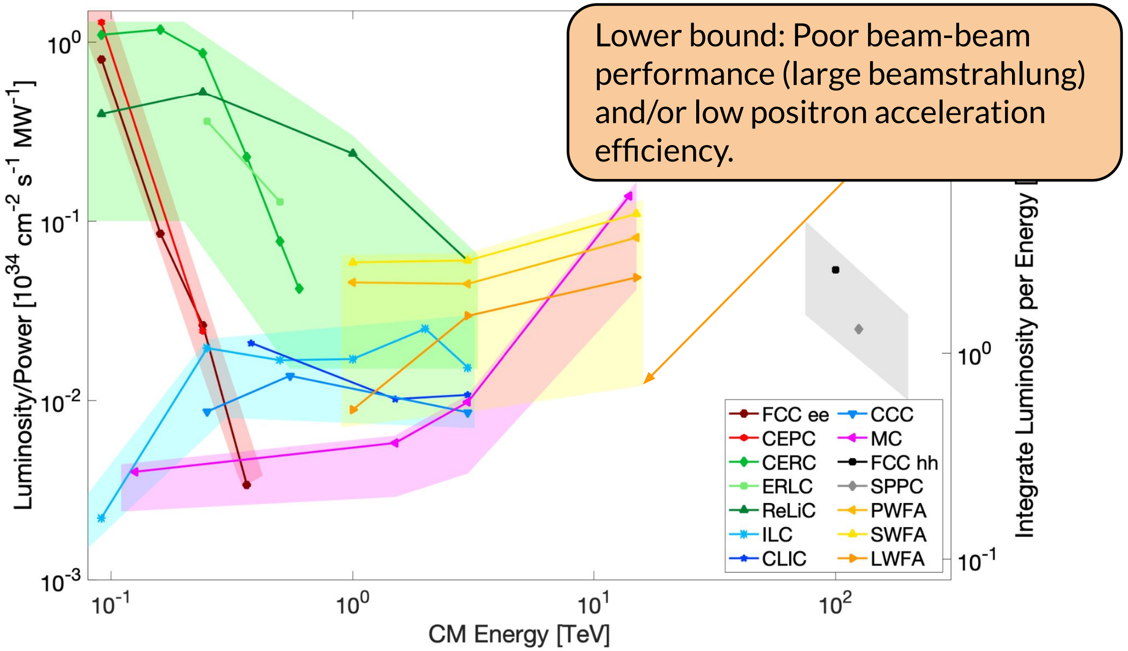
Comparison of Collider Concepts

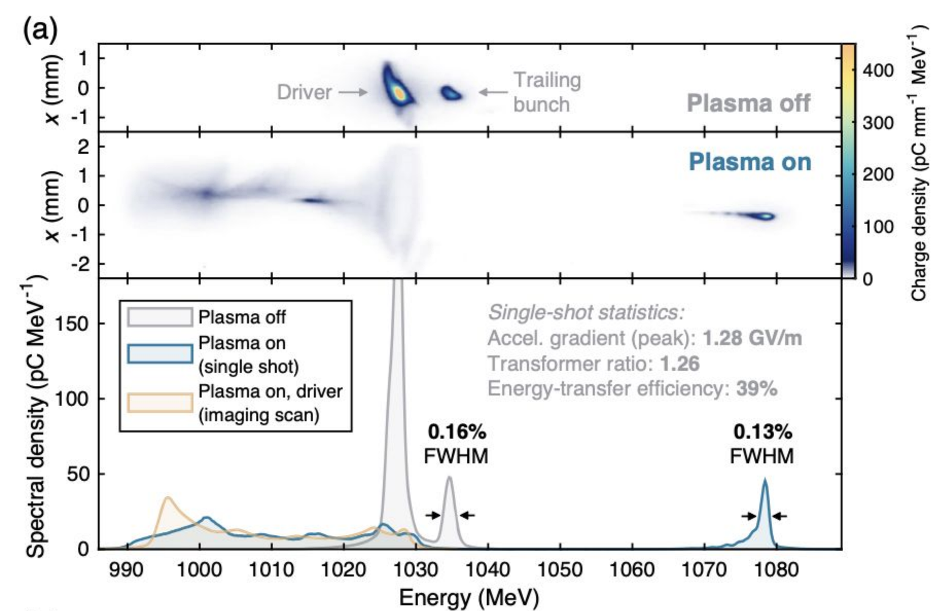


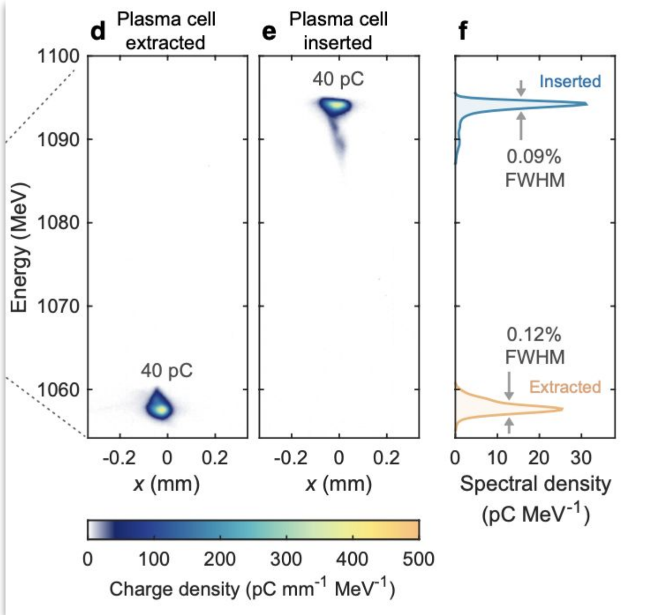
Lower bound: Poor beam-beam performance (large beamstrahlung) and/or low positron acceleration efficiency.

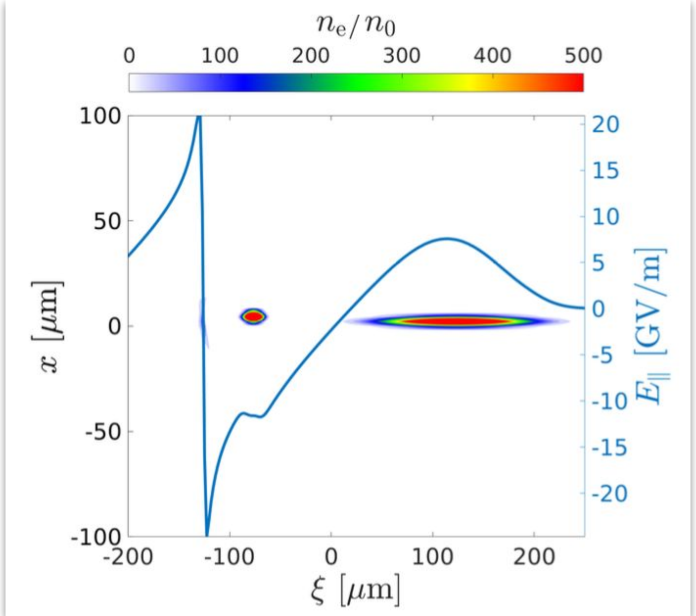
Snowmass ITF: T. Roser et. al. “On the feasibility of future colliders.” JINST 18, P05018 (2023)

Luminosity-per-power is a key figure of merit for future colliders.

Efficiency in Plasma Acceleration of Electrons







Eff. = 42%
Lindstøm et al, Phys. Rev. Lett. 126, 014801 (2021)

Eff. = 22%
Lindstøm et al, Submitted

Eff. = 37.5%
Chen et al, .J Phys. 1596 012057 (2020)

Electron PWFA efficiency in range of 20-40%. Snowmass ITF assumed 37.5%.

Efficiency of Positron Acceleration in Plasma Column Regime

The efficiency of positron PWFA is much lower than the efficiency of electron PWFA.

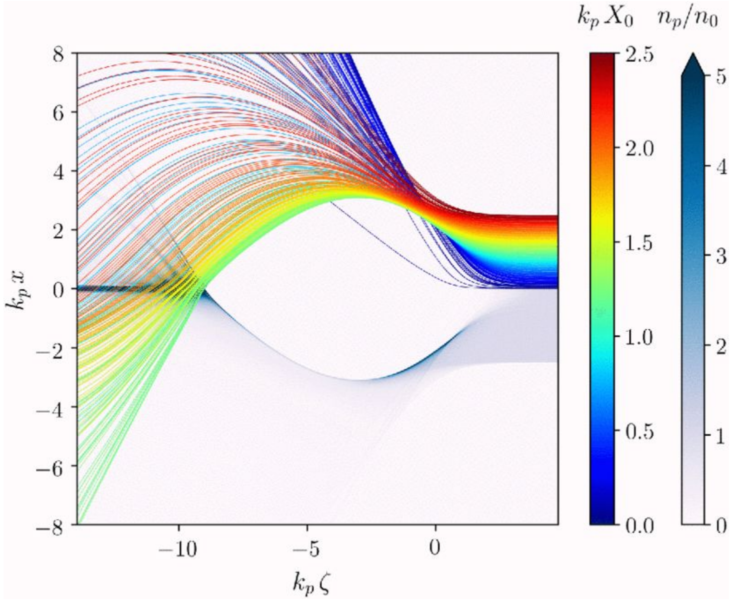
Why?

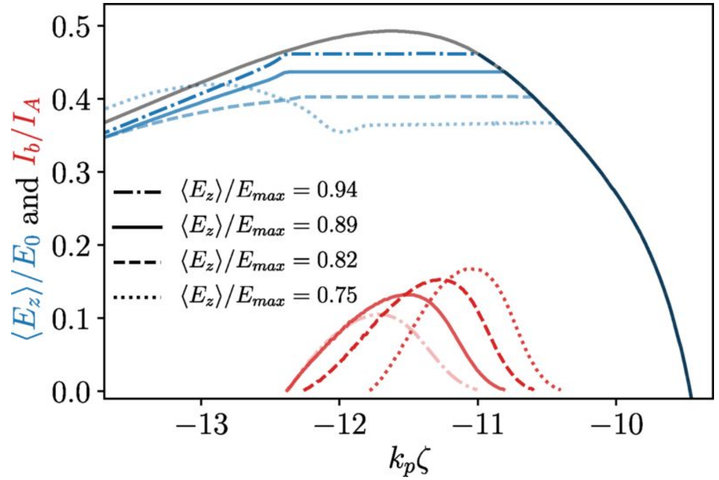
In the plasma column regime, focusing is provided by electrons crossing the beam axis.

The loaded positron beam should not modify the focusing fields “too much”.

Plasma electrons carry away energy after they cross the axis.

Diederichs et al, Phys. Rev. Acc. Beams 22, 081301 (2019)





Eff. = 3%

Diederichs et al, Phys. Rev. Acc. Beams 25, 091304 (2022)

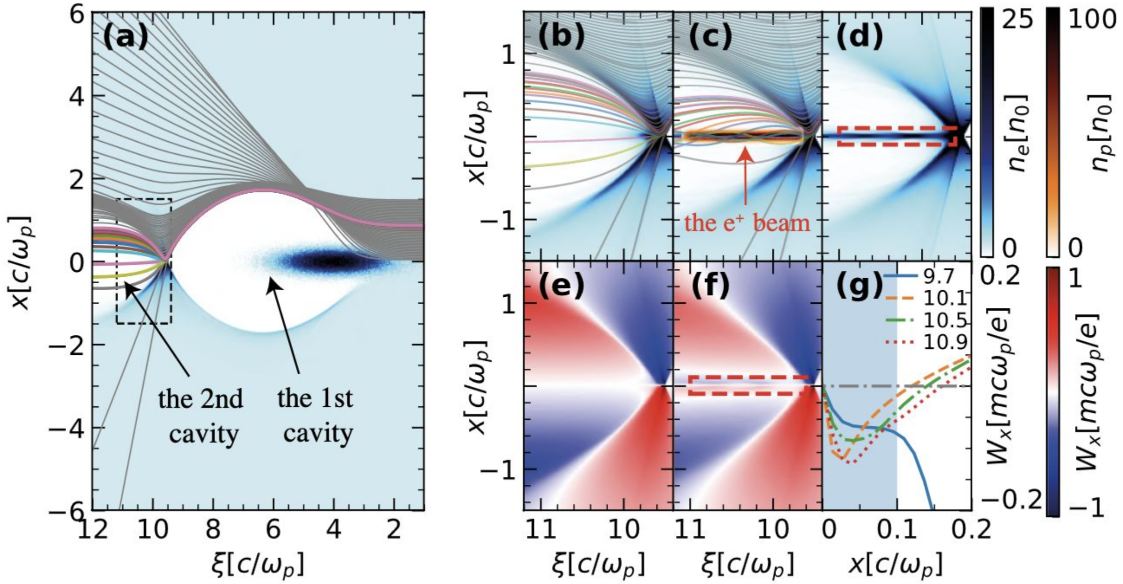
Efficiency of Positron Acceleration in Uniform Regime

Promising new result: Positron acceleration in uniform, nonlinear regime.

The efficiency is 26%!

But. . .

Focusing force is the result of positron beam loading → if the positron bunch is offset, the focusing force will be offset as well.



Eff. = 26%

Zhou et al, arXiv:2211.07962 (2022)

Energy Recovery in Plasma Accelerators

The efficiency of LWFA stages is also low.

Proposal from Schroeder, Turner, others: use a “recovery laser pulse” to remove excess energy from plasma wakefield.

Open question: How do we recover energy from laser pulses?

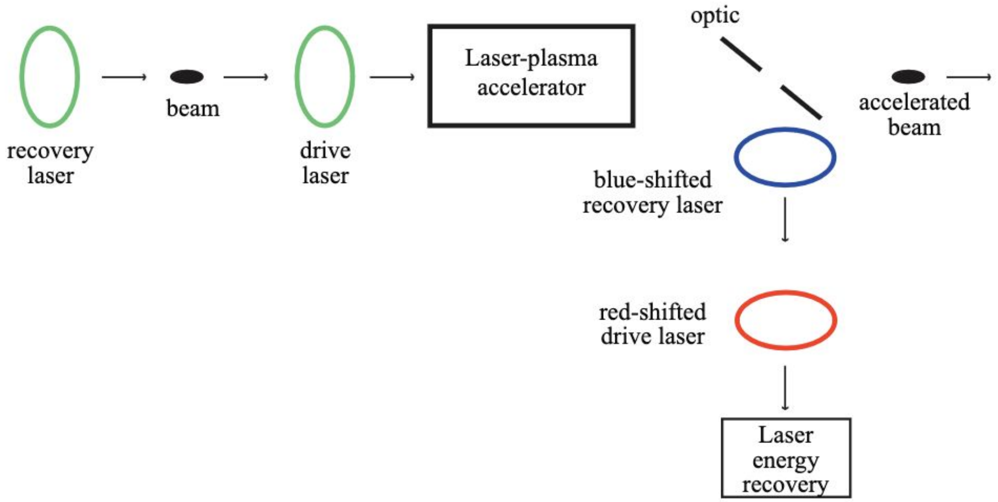


FIGURE 1. Schematic of an LPA stage using laser energy recovery.

C. B. Schroeder et. al. “Efficiency considerations for high-energy physics applications of laser-plasma accelerators.”
AIP Conf. Proc. 1777, 020001 (2016)

Our proposal: Use trailing electron beam bunches for energy recovery.

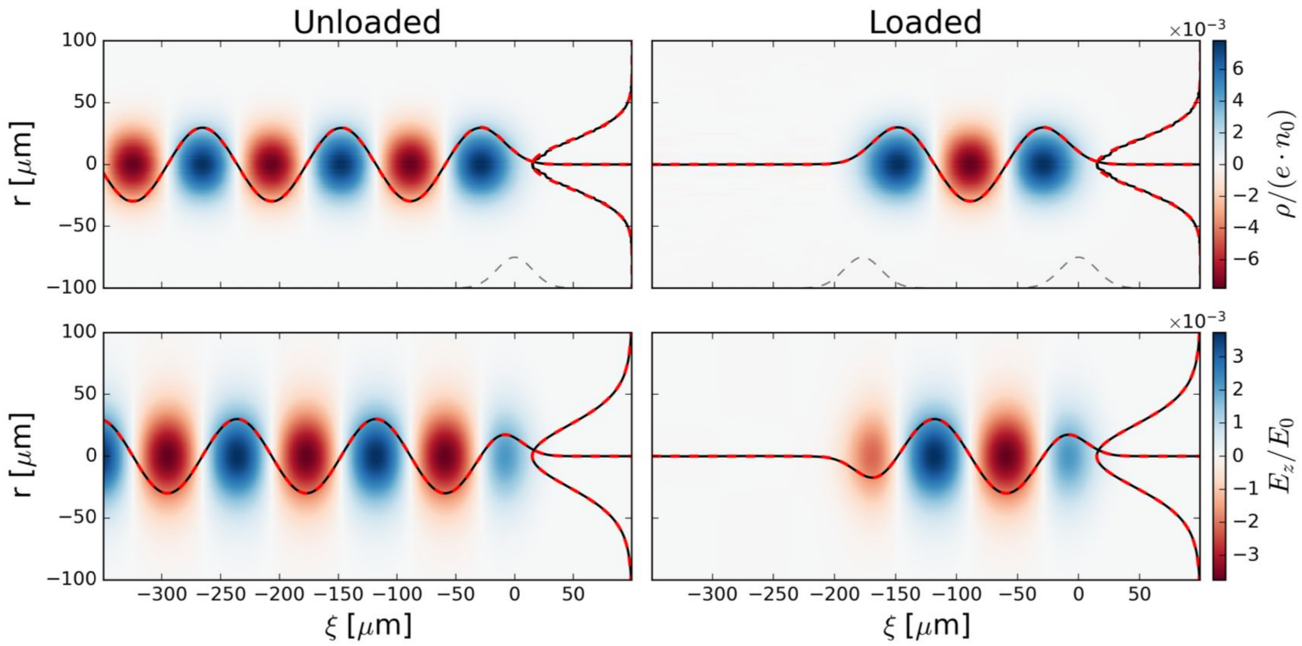
Energy Recovery in Linear Regime

Reminder: It is possible to extract 100% of the energy in the plasma wakefield in the linear regime, albeit at the expense of beam quality.

See Katsouleas et al. "Beam Loading in Plasma Accelerators", Part. Accel. 22 (1987)

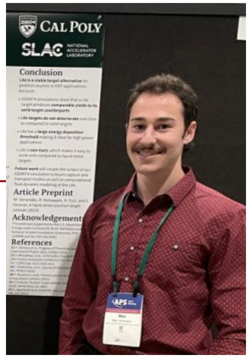
In Sebastien's talk, he discussed trade-offs in efficiency vs. quality.

See Hue et al. "Efficiency and beam quality for positron acceleration in loaded plasma wakefields", Phys. Rev. Res 3, 043063 (2021).

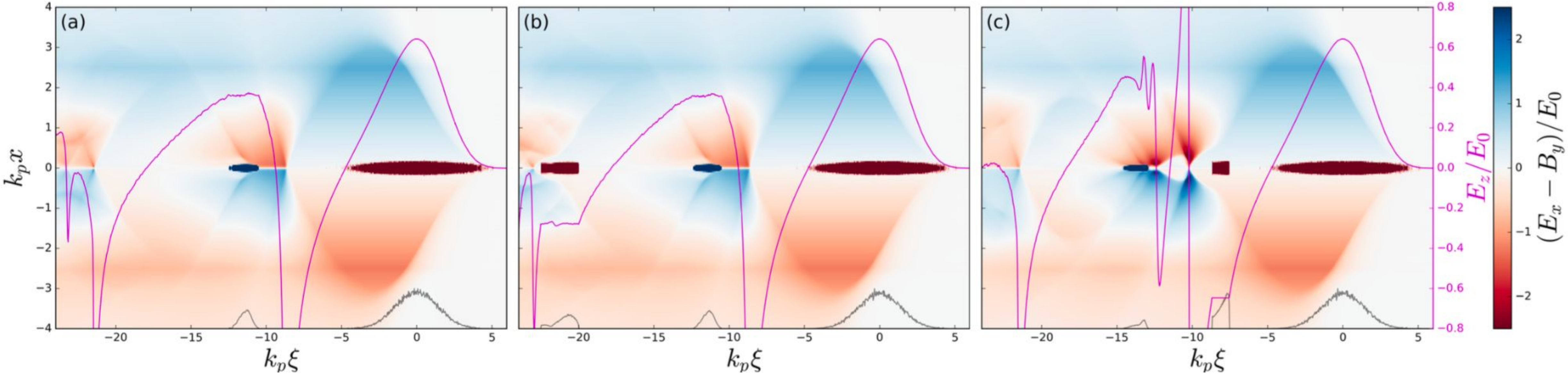


Energy Recovery in Filament Regime

Max Varverakis
Undergraduate
CalPoly



HiPACE++



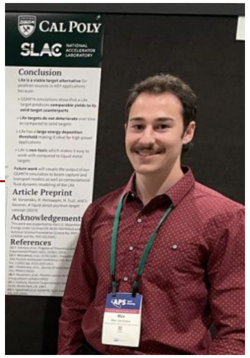
Electron beam driver
Positron beam witness
No recovery bunch
Eff. = 3.8%

Electron beam driver
Positron beam witness
Trailing electron recovery bunch
Eff. = 12%

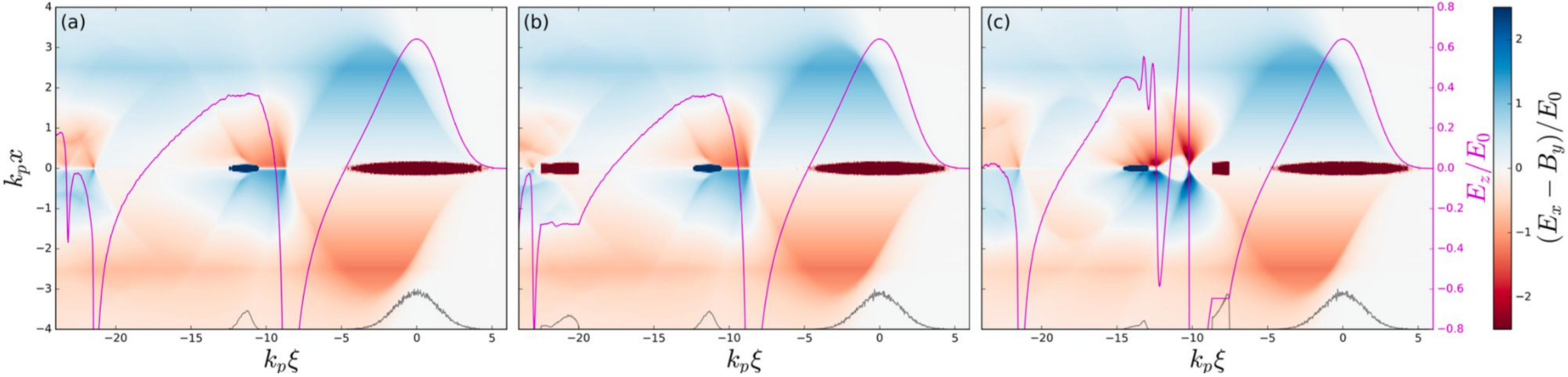
Electron beam driver
Positron beam witness
Leading electron recovery bunch
Eff. = 27.4%

Energy Recovery in Filament Regime

Max Varverakis
Undergraduate
CalPoly



Trailing bunch current profiles calculated using SALAME.

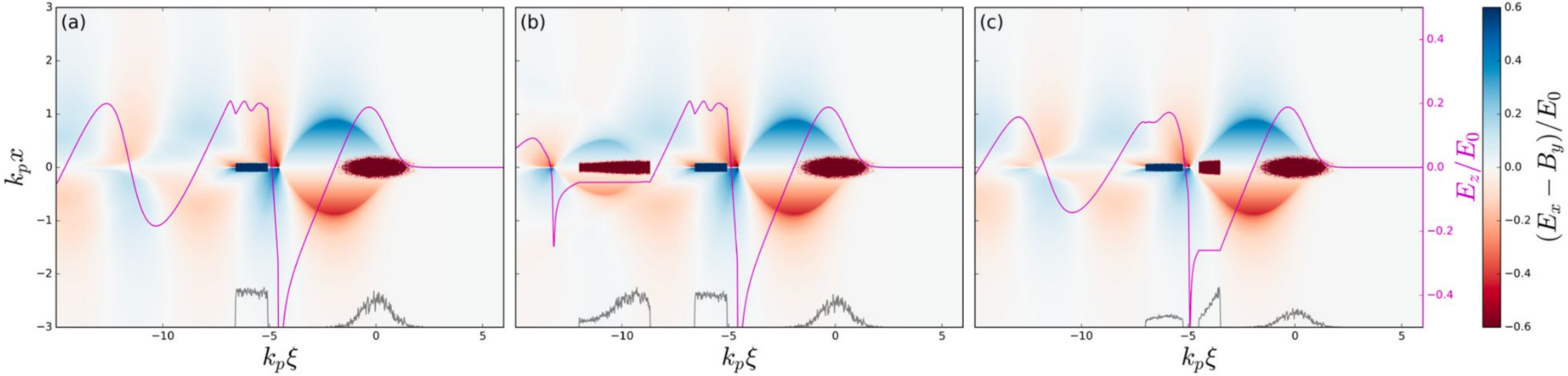


Electron beam driver
Positron beam witness
No recovery bunch
Eff. = 3.8%

Electron beam driver
Positron beam witness
Trailing electron recovery bunch
Eff. = 12%

Electron beam driver
Positron beam witness
Leading electron recovery bunch
Eff. = 27.4%

Energy Recovery in Uniform Regime



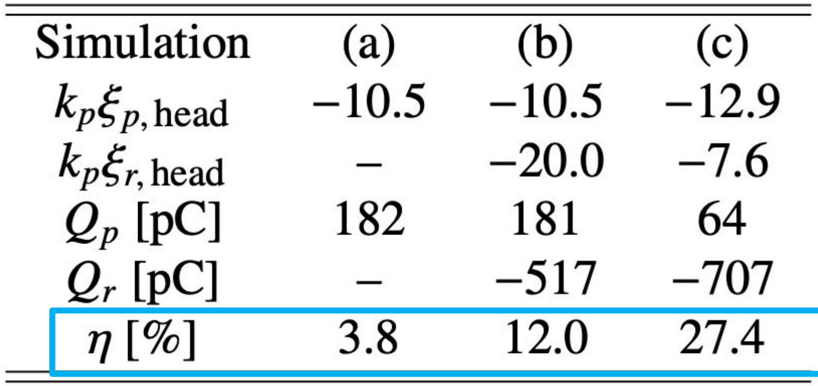
Electron beam driver
Positron beam witness
No recovery bunch
Eff. = 25.9%

Electron beam driver
Positron beam witness
Trailing electron recovery bunch
Eff. = 45%

Electron beam driver
Positron beam witness
Leading electron recovery bunch
Eff. = 73.5%

Regime Comparison

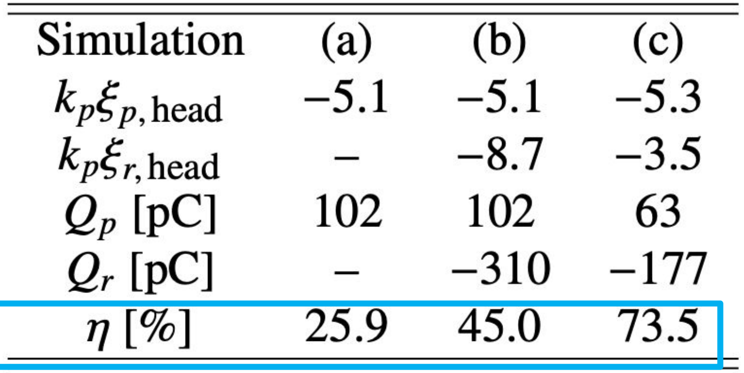
Plasma Column Regime



Simulation	(a)	(b)	(c)
$k_p\xi_{p,\text{head}}$	-10.5	-10.5	-12.9
$k_p\xi_{r,\text{head}}$	–	-20.0	-7.6
Q_p [pC]	182	181	64
Q_r [pC]	–	-517	-707
η [%]	3.8	12.0	27.4

Table 1: Trailing beam parameters for plasma column simulations. Subscripts p and r correspond to the positron and electron (recovery) beam, respectively.

Uniform Nonlinear Regime



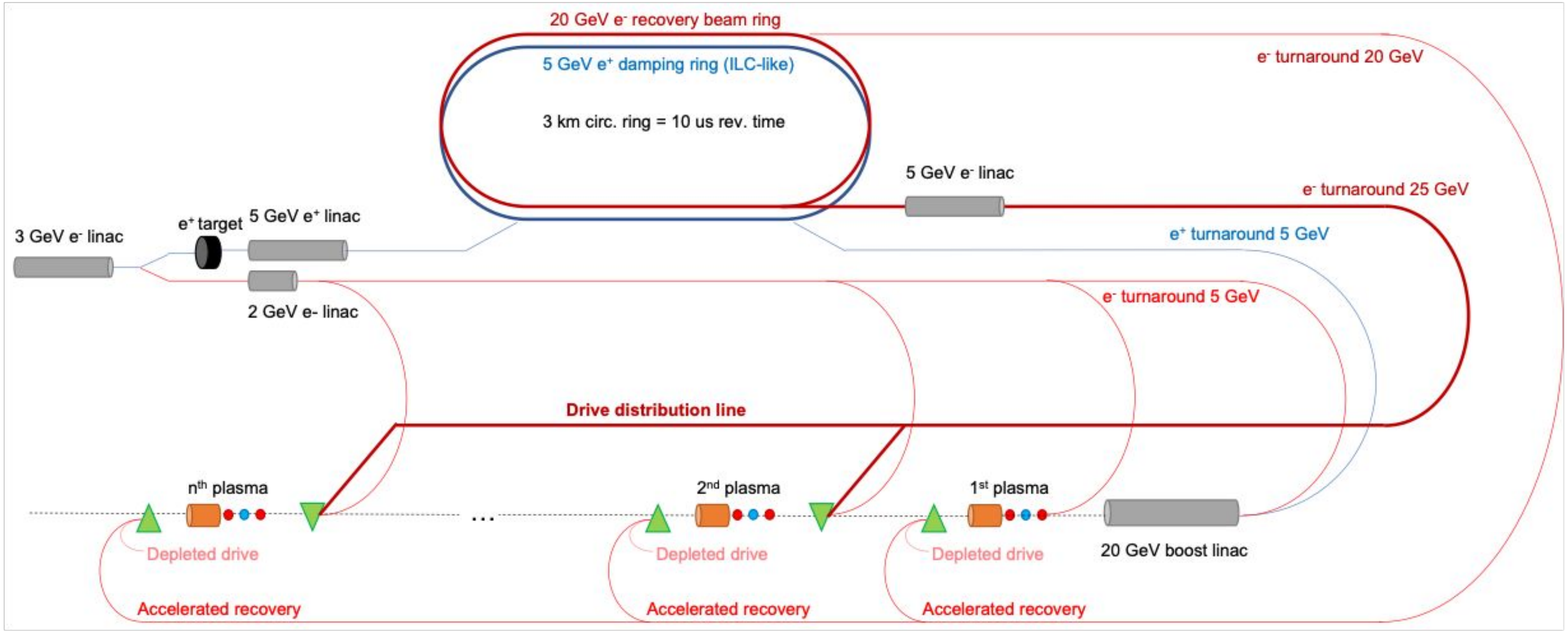
Simulation	(a)	(b)	(c)
$k_p\xi_{p,\text{head}}$	-5.1	-5.1	-5.3
$k_p\xi_{r,\text{head}}$	–	-8.7	-3.5
Q_p [pC]	102	102	63
Q_r [pC]	–	-310	-177
η [%]	25.9	45.0	73.5

Table 2: Trailing beam parameters for uniform plasma simulations. Subscripts p and r correspond to the positron and electron (recovery) beam, respectively.

Best case efficiency for the plasma column regime corresponds to baseline efficiency (no recovery) for the uniform nonlinear regime.

But there is reason to believe that the plasma column regime will be more stable than the uniform nonlinear regime.

Collider Concept #1: Energy Recovery Scheme



Concept: Accelerated recovery bunches become drivers for subsequent stages.
Challenge: The beamline is quite complicated!

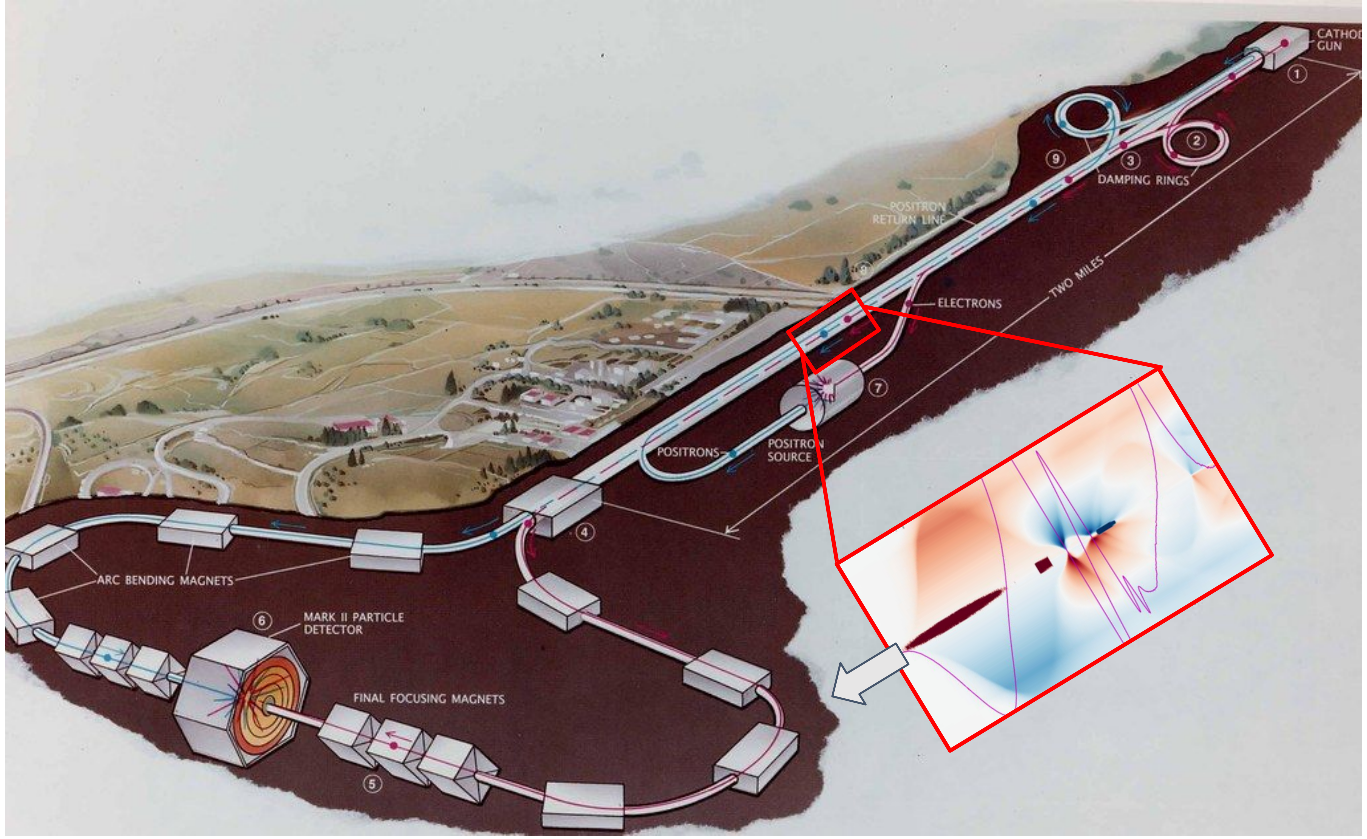
Collider Concept #2: SLC Design

Emittance degradation in bending sections:

$$\Delta\gamma\epsilon \approx (4\times10^{-8}\,\mathrm{m}^2\,\mathrm{GeV}^{-6})E^6 \sum_i \frac{L_i}{|\rho_i|^3}\mathcal{H}_i$$

Common assumption is that length of bending section goes at E^2:

Arc circ = 13.5 km @ 250 GeV CM



Concept: The electron recovery bunch is the colliding bunch!
Challenge: The arc length scales unfavorably with collision energy.

*Credit C. A. Lindstrøm

Collider Concept #3: NLC Design*

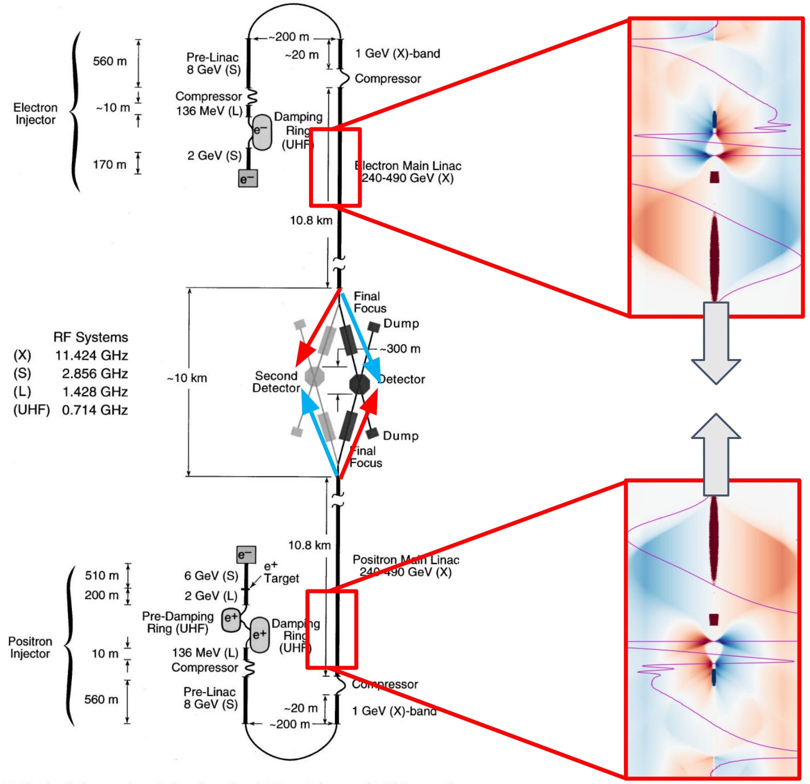


FIG. 1. Schematic of the Stanford Next Linear Collider, a future 1-TeV linear collider.

Concept: Two Final Focus Systems and Two Detectors.
Favorable scaling with energy!

Next Steps

1. Re-run and re-optimize simulations at higher plasma temperature and with mesh refinement.

Talk by S. Diederichs, Weds. @ 11:30
Talk by M. Thévenet, Weds. @ 16:25

2. Tolerance studies: how do offsets in the trailing bunches affect themselves and each other?

3. Strawman design of a collider concept.
   a. Determine beam parameters.
   b. Calculate beam power.
   c. Simulate collisions (GUINEA-PIG and WarpX).

Thank you for your attention!