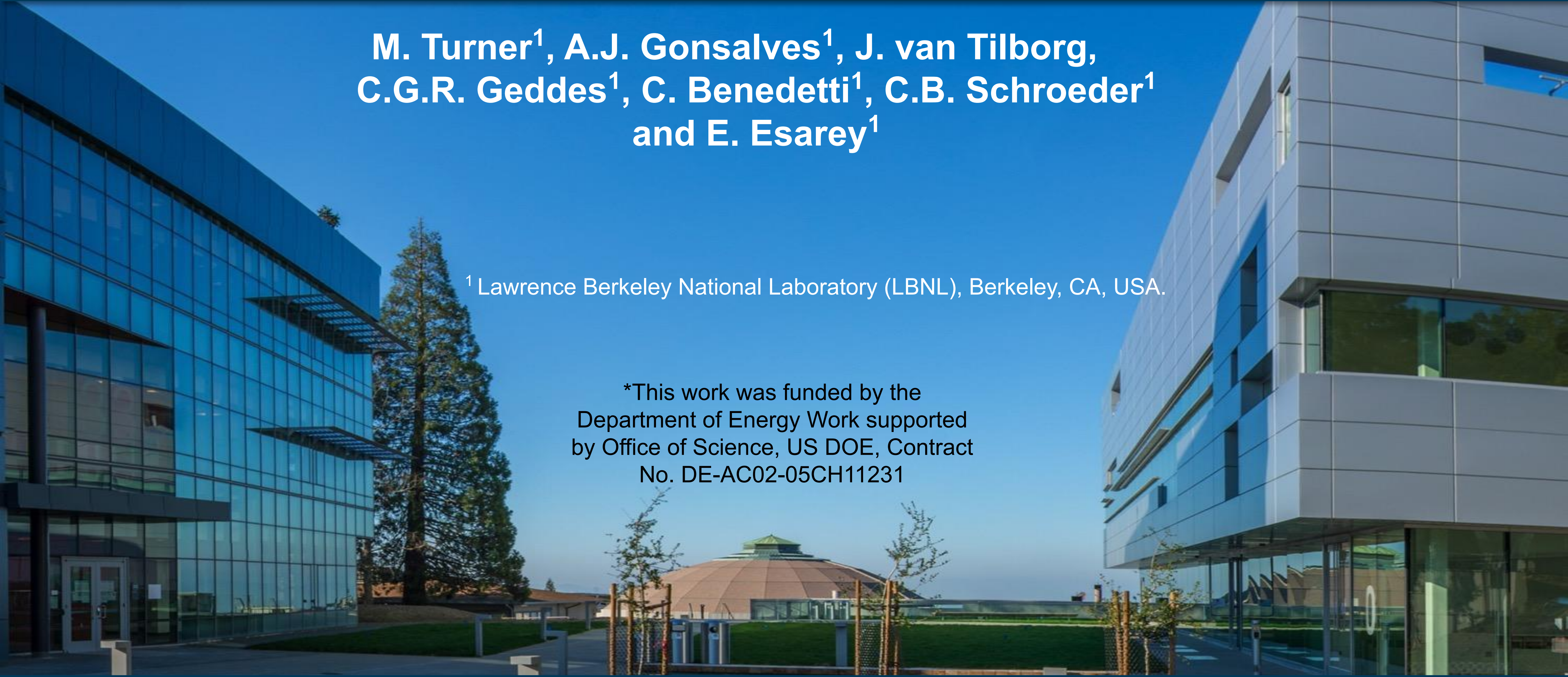
Snowmass Workshop
on Carbon Emissions
at Future Facilities.
Nov. 9 2021

Energy Recovery for Plasma-Based Colliders



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BERKELEY LAB

ACCELERATOR TECHNOLOGY & APPLIED PHYSICS DIVISION ATAP

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Outline

- **Power requirements** of Future Accelerators.
- **Laser-Driven** Plasma Wakefield Acceleration.
- How to implement **Energy Recycling** for a Laser Driven Plasma Wakefield Collider.
- Summary & Conclusions.

Future Accelerator Power Consumption

Accelerator	Beam Energy (TeV)	Site Power (MW)	Single Beam Power (MW)	Number of Beams	Beam Power/Site Power	Lu[illegible]	[illegible]	[illegible]
ILC	0.125	111	3	2	0.02	[illegible]	[illegible]	[illegible]
ILC 6X	0.125	270	16	2	0.06	[illegible]	[illegible]	[illegible]
ILC 55 MV/m, 2	1	345	24	2	0.07	[illegible]	[illegible]	[illegible]
ILC 70 MV/m, 2	1	315	24	2	0.08	[illegible]	[illegible]	[illegible]
ILC 70 MV/m, 3	1.5	400	30	2	0.08	[illegible]	[illegible]	[illegible]
ILC 80 MV/m, 3	1.5	525	30	2	0.06	[illegible]	[illegible]	[illegible]
CCC 250	0.125	30	1	2	0.03	2.00E+34	2.00E+34	6.67E+32
CCC 2000	1	200	9	2	0.05	[illegible]	[illegible]	[illegible]
CLIC 380	0.19	170	3	2	0.02	[illegible]	[illegible]	[illegible]
CLIC 3000	1.5	580	14	2	0.02	[illegible]	[illegible]	[illegible]
CEPC 91	0.045	267	2,000	2	7.49	[illegible]	[illegible]	[illegible]
CEPC 240	0.12	267	21,000	2	78.65	[illegible]	[illegible]	[illegible]
FCC-ee 91	0.045	259	63,400	2	244.79	[illegible]	[illegible]	[illegible]
FCC-ee 160	0.08	277	63,400	2	228.88	[illegible]	[illegible]	[illegible]
FCC-ee 240	0.12	282	63,400	2	224.82	[illegible]	[illegible]	[illegible]
FCC-ee 365	0.182	340	63,400	2	186.47	1.55E+34	2.44E+29	4.56E+31
ERL 91	0.045	70	169	2	2.41	9.60E+35	5.68E+33	1.37E+34
ERL 160	0.08	80	270	2	3.38	9.60E+35	3.56E+33	1.20E+34
ERL 240	0.12	85	297	2	3.49	9.60E+35	3.23E+33	1.13E+34
ERL 365	0.182	90	184	2	2.04	9.60E+35	5.22E+33	1.07E+34
ERL 500	0.25	95	88	2	0.93	9.60E+35	1.09E+34	1.01E+34
ERL 600	0.3	100	49	2	0.49	9.60E+35	1.96E+34	9.60E+33

CERN peak Site Power:
~200 MW (~115 MW for LHC operation)
or ~1.3 TWh / year
~48 M Euros (from CERN website)

Coal Power Plant:
~500 MW or ~3.5 TWh per year

Nuclear Power Plant:
~1 TW or ~ 5 TWh per year

(These numbers were collected from the Snowmass, Accelerator Frontier Implementation Task force)

Accelerator Energy Consumption

Accelerator	Beam Energy (TeV)	Site Power (MW)	Single Beam Power (MW)	Number of Beams	Beam Power/Site Power	Luminosity cm^-2 s^-1	Lumi/Beam Power	Lumi/Site Power
Collider Under the Sea	250	2000	25,000	2	12.50	5.00E+35	2.00E+31	2.50E+32
FCC-hh	50	560	26,000,000	2	46428.57	3.00E+35	1.15E+28	5.36E+32
SPPC	37.5	400	3	2	0.01	1.00E+35	3.33E+34	2.50E+32
SWFA 1	0.5	100	2.5	2	0.03	1.00E+34	4.00E+33	1.00E+32
SWFA 3	1.5	185	15.6	2	0.08	5.90E+34	3.78E+33	3.19E+32
SWFA 15	7.5	925	78	2	0.08	5.00E+35	6.41E+33	5.41E+32
LWFA 3	1.5	315	12	2	0.08	1.00E+35	8.33E+33	3.17E+32
LWFA 15	7.5	1100	64	2	0.12	5.00E+35	7.81E+33	4.55E+32
PWFA 1	0.5	67	1	2	0.01	1.00E+34	1.00E+34	1.49E+32
PWFA 3	1.5	200	3	2	0.02	5.90E+34	1.97E+34	2.95E+32
PWFA 15	7.5	1000	15	2	0.02	5.00E+35	3.33E+34	5.00E+32
MC Higgs	0.063	200	1	2	0.00	[illegible]	[illegible]	[illegible]
MC 1.5	0.75	216	4	2	0.02	[illegible]	[illegible]	[illegible]
MC 3	1.5	230	6	2	0.03	[illegible]	[illegible]	[illegible]
MC 10	5	260	7	2	0.03	[illegible]	[illegible]	[illegible]
MC 14	7	290	10	2	0.03	[illegible]	[illegible]	[illegible]

⇒ Power consumption should be an important consideration for any TeV-collider.

(These numbers were collected from the Snowmass, Accelerator Frontier Implementation Task force)

Laser-Driven Plasma Wakefield Acceleration

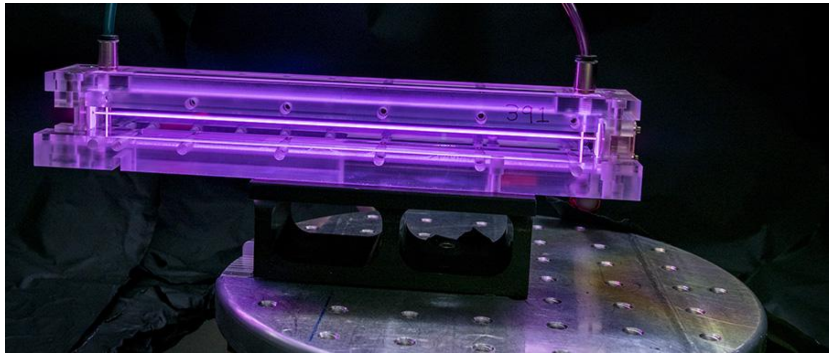
Laser-Driven Plasma Wakefield Acceleration

$$eE = m_e \omega_{pe} c \sim 100 \frac{eV}{m} \sqrt{n_{pe}[cm^{-3}]}$$

i.e. **~1 GeV/m** for a plasma electron density n_{pe} of $10^{14} cm^{-3}$

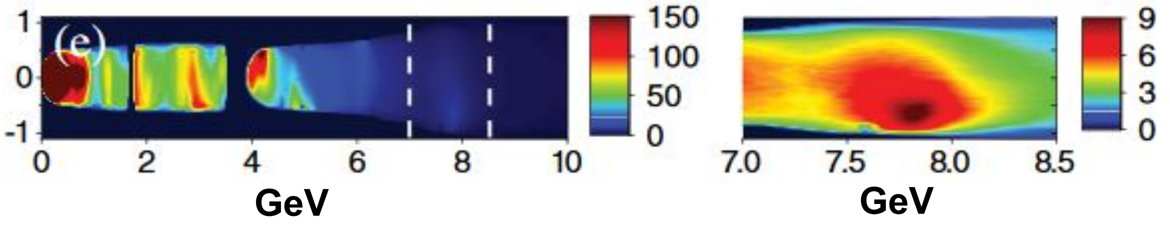
~100 GeV/m for 10^{18} electrons/cm^3

10 TeV Linear Collider:
~100 km of RF structures
~1 km of plasma



7.8 GeV in 20 cm
10.1103/PhysRevLett.122.084801

acc. gradient = 39 GV/m

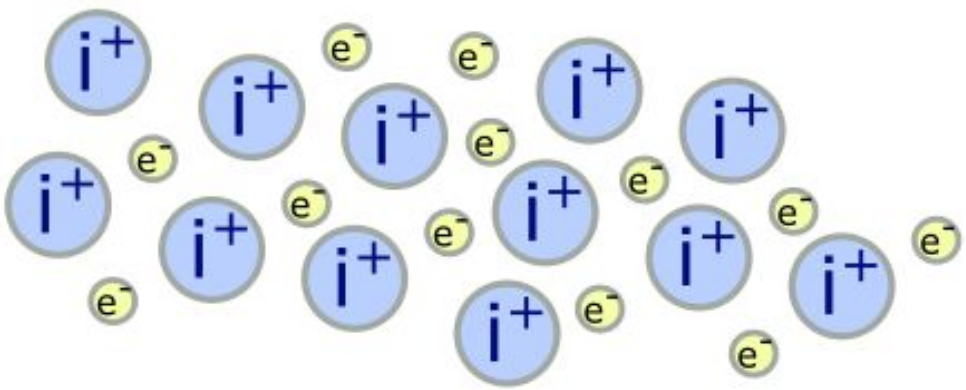


Plasma Wakefield Acceleration

**Energy transfer from the driver (energy source) to the witness,
plasma acts as the transformer.**

drive bunch or pulse:
typically a relativistic **charged particle** bunch
or
laser pulse/s.

Plasma:



ions are heavy compared to the electrons.

Plasma Wakefield Acceleration

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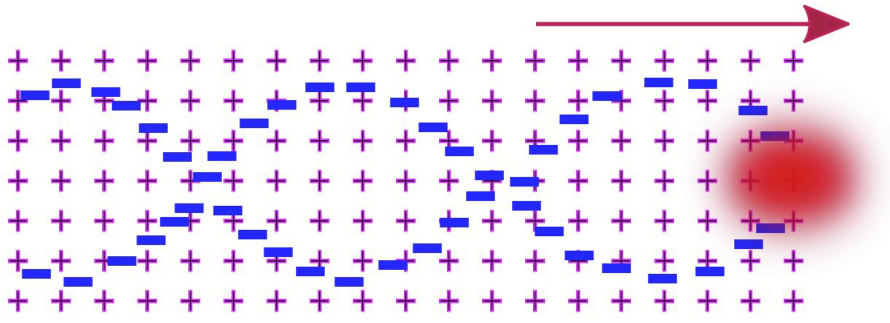
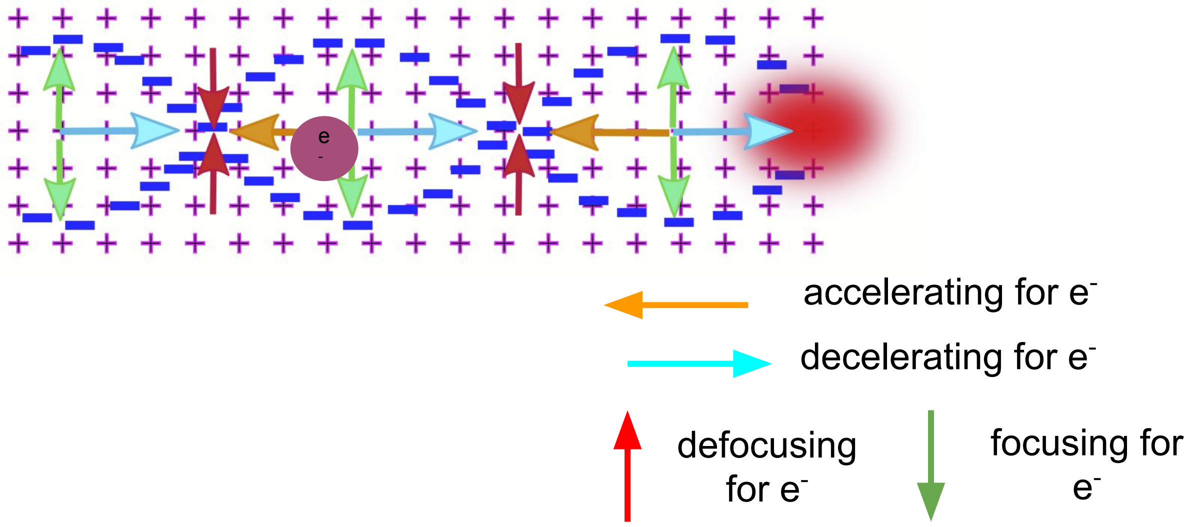
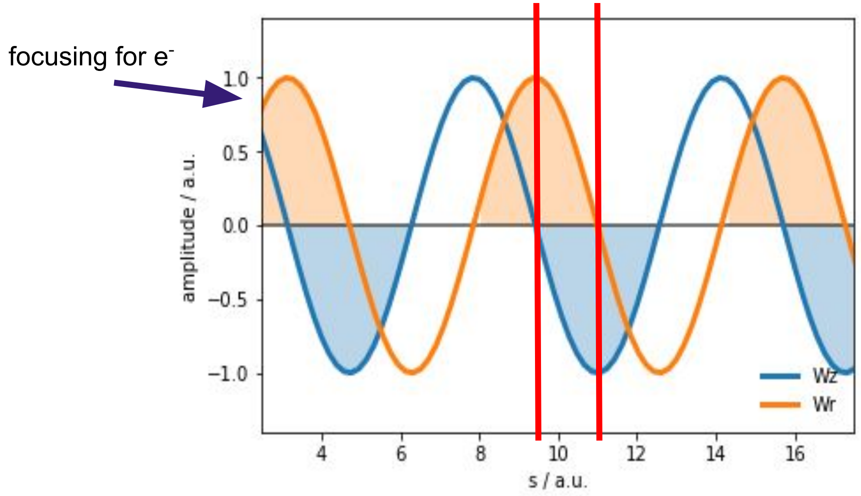
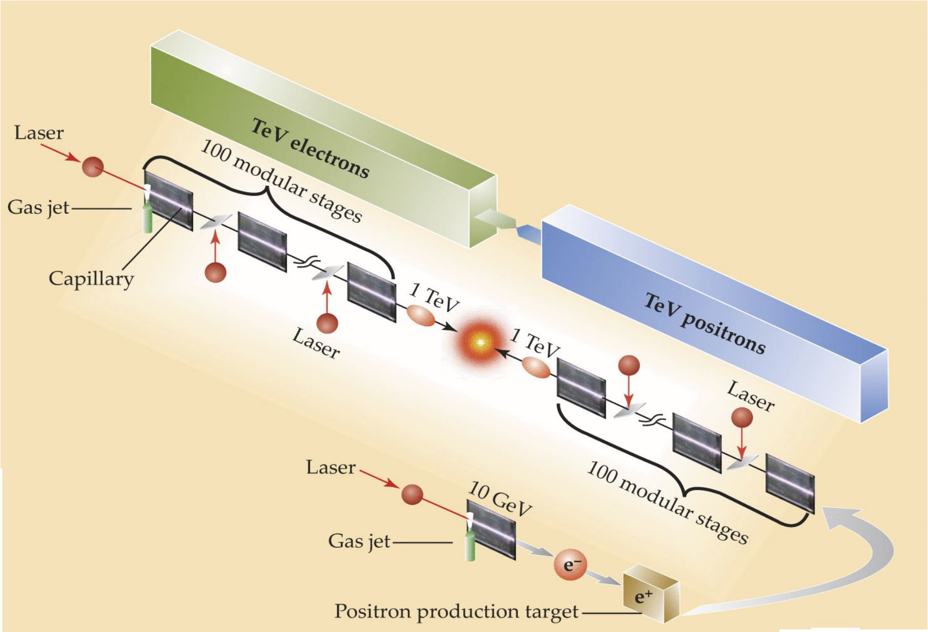






- Pulse enters an underdense plasma.
- Ponderomotive force of the laser pulse (radiation pressure) or the transverse electric field of a particle bunch expels plasma electrons.

Energy-Recovery Scheme for Plasma-Based Colliders



Physics Today **62**, 3, 44 (2009);
https://doi.org/10.1063/1.3099645

Laser-Driven Plasma Wakefield Collider Concept:

- Sequence of Laser-Driven Plasma Wakefield Acceleration Stages.
- Laser Pulse Advantage: Compared to beams, laser pulses are easily coupled in and out of plasma stages with plasma mirrors.

Energy Source: Laser Pulse

Drive Pulse Laser Energy (Energy Source) ⇒

1) **Witness Beam** (Goal)
2) **Left-over Wakefield,** because of the trade-off between gradient, efficiency and accelerated bunch quality, some significant fraction of the wake energy remains following acceleration.
3) Remaining **Drive Laser Pulse** Energy after Plasma.

Energy Source: Laser Pulse

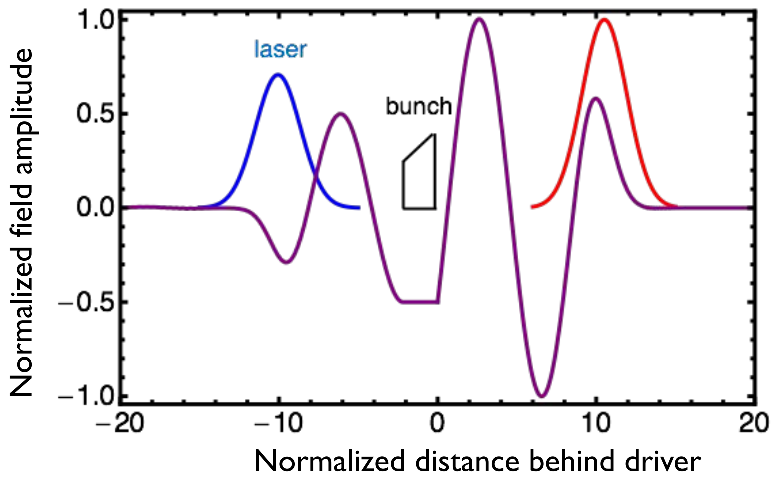
Drive Pulse Laser Energy (Energy Source) ⇒

1) **Witness Beam** (Goal)
2) **Left-over Wakefield,** because of the trade-off between gradient, efficiency and accelerated bunch quality, some significant fraction of the wake energy remains following acceleration.
3) Remaining **Laser Pulse** Energy after Plasma.

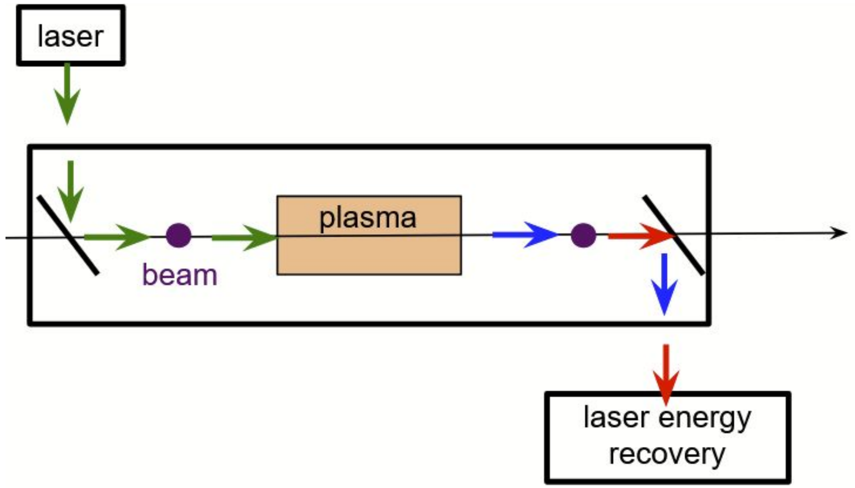
Laser-Plasma Wakefield Interaction:

- Plasmas offer ultra-high gradients, both for acceleration and deceleration of beams.
- Laser pulses can gain/lose energy (blue/red shift) from the plasma wave (Photon Acceleration)

Energy-Recycling by Using a Trailing Laser Pulse



One collider plasma-stage:



- Drive laser deposits energy into plasma wave (frequency red-shifts)
- Idea: Add an energy-recovery laser after the witness bunch to absorb energy from plasma wave (frequency blue-shifts)

Benefits of Energy-Recovery:

- Re-use laser in another LPA stage
- Send to photovoltaic (targeted to laser wavelength) – energy recovery

- **Double-win:** Additional energy-recovery laser pulse allows for no energy to remain in coherent plasma oscillations after energy transfer to beam – heat management

Slide provided by C. Schroeder (LBNL)

Energy Recovery Concept

Drive Pulse Laser Energy ⇒
1) **Witness Beam**
2) **Left-over Wakefield**
3) Remaining **Laser Pulse** Energy after driving the plasma wakefields

Summarize Collider Recycling Idea:

- To recover energy from the **witness beam after the IP** ⇒ a compact energy-recovery beamline following the interaction: exciting a wake with the energetic beam and absorbing with a laser.

- To recover energy from the **wakefields** ⇒ trailing pulse to ‘sweep-up’ remaining energy.

- To recover energy from the **depleted laser pulse** ⇒ either reuse (use as trailing pulse, top up wakefields,...) or sent onto photovoltaic cells.

Energy Recovery Concept

Drive Pulse Laser Energy ⇒
1) **Witness Beam**
2) **Left-over Wakefield**
3) Remaining **Laser Pulse** Energy after Plasma

Recycling Concept:

- To recover energy from the witness beam ⇒ a compact energy-recovery beamline following the interaction: exciting a wake with the energetic beam and absorbing with a laser.
- To recover energy from the wakefields ⇒ trailing pulse to ‘swe
- To recover energy from the depleted laser pulse ⇒ either reus wakefields,...) or sent onto photovoltaic cells.

Potential for conventional accelerators (1):

using a plasma beam dump to compactly reduce the beam power before dumping the beam.

Conclusions & Summary

- Energy consumption is an important factor to consider for any HEP particle accelerator, especially TeV colliders.

- We started working on an energy-recovery scheme for plasma based particle accelerators that is especially effective for laser-driven plasma wakefield accelerators.
  - Idea is to transfer energy to laser pulses as laser pulses can be coupled in and out with plasma mirrors.
  - Reuse or recycle the energy in the laser pulses.