The Concept of a Plasma Wakefield Acceleration Based Electron/Positron Collider

Materials for discussion at special session of CLIC08 workshop

Presented by

Tor Raubenheimer and Andrei Seryi

(SLAC)

on behalf of collaboration (next page):

October 15, 2008

Present collaborators

*	B. Allen	USC
*	W. An	UCLA
*	K. Bane	SLAC
*	L. Bentson	SLAC
*	I. Blumenfeld	SLAC
*	C.E. Clayton	UCLA
*	S. DeBarger	SLAC
*	F.-J. Decker	SLAC
*	R. Erickson	SLAC
*	R. Gholizadeh	USC
*	M.J. Hogan	SLAC
*	C. Huang	UCLA
*	R.H. Iverson	SLAC
*	C. Joshi	UCLA
*	T. Katsouleas	Duke University
*	N. Kirby	SLAC
*	N. Li	SLAC
*	W. Lu	UCLA
*	D.B. MacFarlane	SLAC
*	K.A. Marsh	UCLA
*	W.B. Mori	UCLA
*	P. Muggli	USC
*	Y. Nosochkov	SLAC
*	S. Pei	SLAC
*	T.O. Raubenheimer	SLAC
*	J.T. Seeman	SLAC
*	A. Seryi	SLAC
*	R.H. Siemann	SLAC
*	P. Tenenbaum	SLAC
*	J. Vollaire	SLAC
*	D. Walz	SLAC
*	X. Wang	USC
*	W. Wittmer	SLAC

Motivation for this special session at CLIC08

- * Drive beam based Plasma Wake-Field Acceleration (PWFA) has shown very high, ~50GeV/m acceleration
- * Simulations show high efficiency of energy transfer from drive beam, via plasma, to experimental beam
  - from 30% (for Gauss. drive bunch), up to 95% (for shaped in z bunch)
- * This opens an opportunity to design a linear collider that could be compact, efficient and more affordable
- * A concept of PWFA-LC was created by PWFA collaboration
  - A lot of common issues with CLIC (drive beam, IP parameters, beam distribution, short bunch collimation effects, etc)
- * Joint work on optimization of the concept may be beneficial for both designs → motivation for this session!

SLAC Duke UNIVERSITY UCLA USC

Plan

* Describe (very briefly) recent progress of Plasma Wake-Field Acceleration

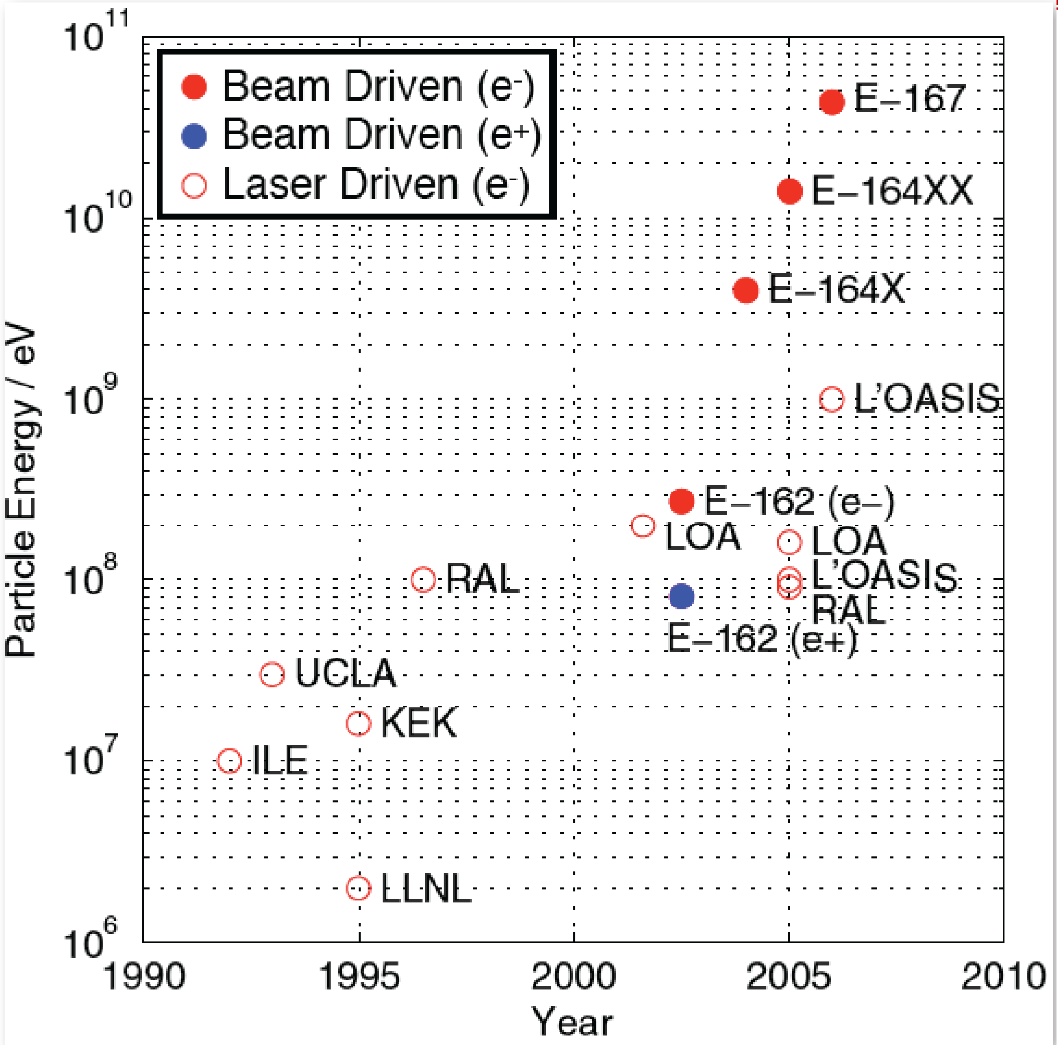
* Describe a concept of PWFA based linear collider

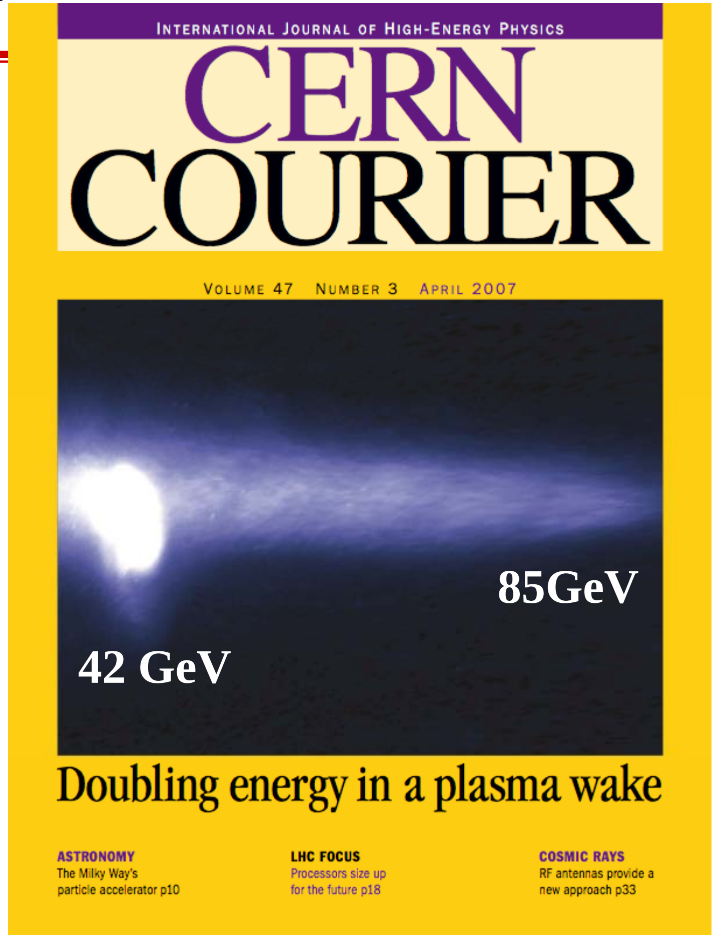
* Discuss common issues where studies with CLIC colleagues may be mutually beneficial

* Discuss possible next joint steps

- For more information on plasma acceleration, see for example talks presented at AAC08 http://aac08.lbl.gov/

Recent tremendous progress in plasma acceleration

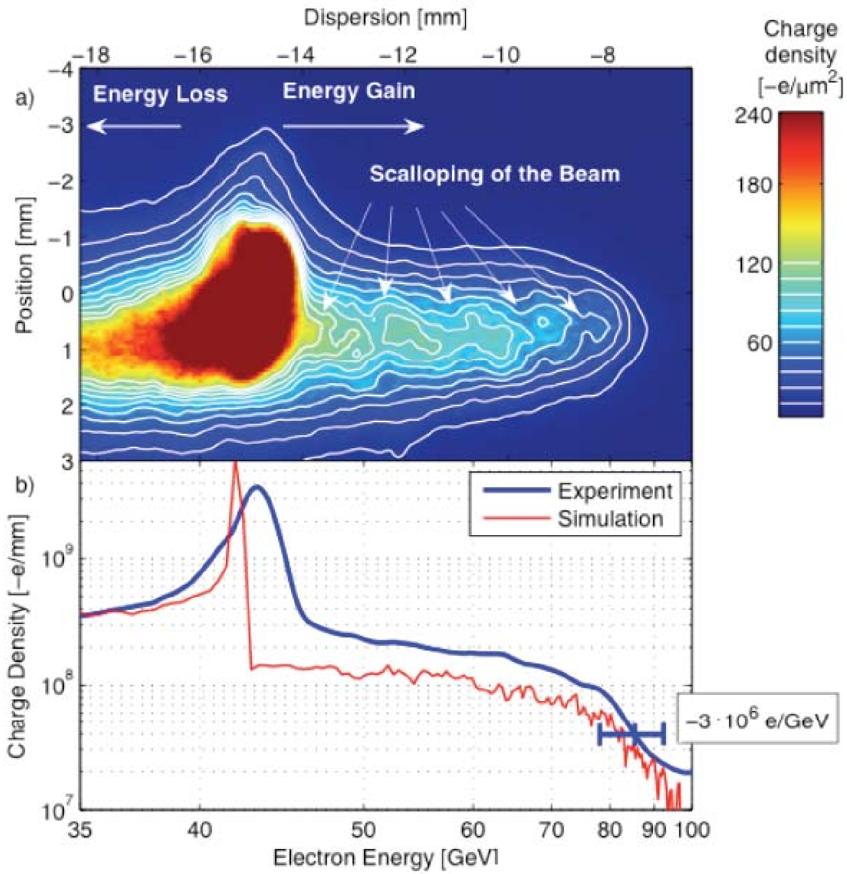




- Energy Doubling of 42 Billion Volt Electrons Using an 85 cm Long Plasma Wakefield Accelerator

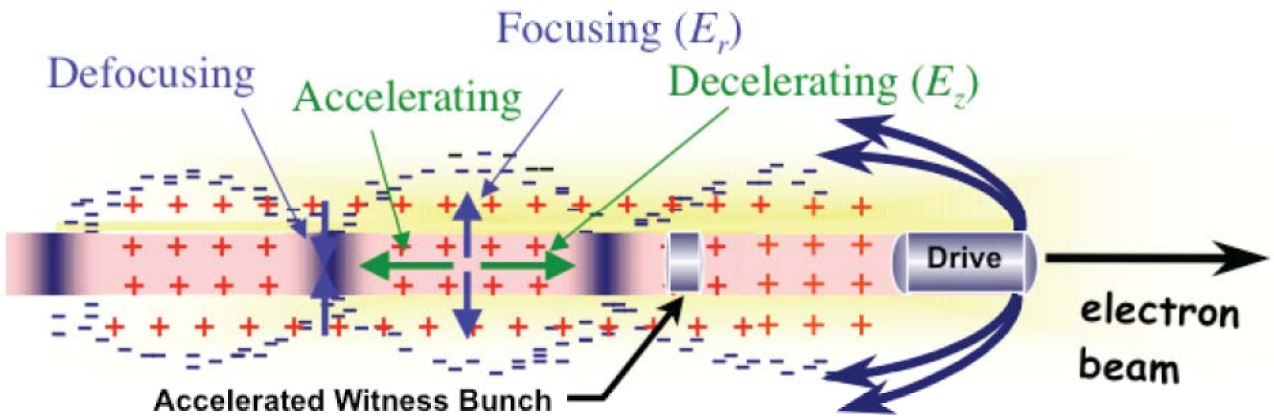
Nature v 445,p741 (2007)

SLAC Duke UNIVERSITY UCLA USC



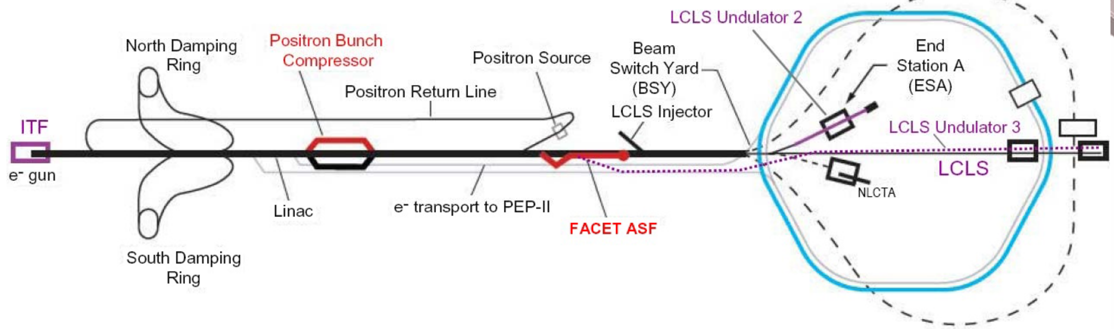
Experiments at FFTB demonstrated 50GeV/m

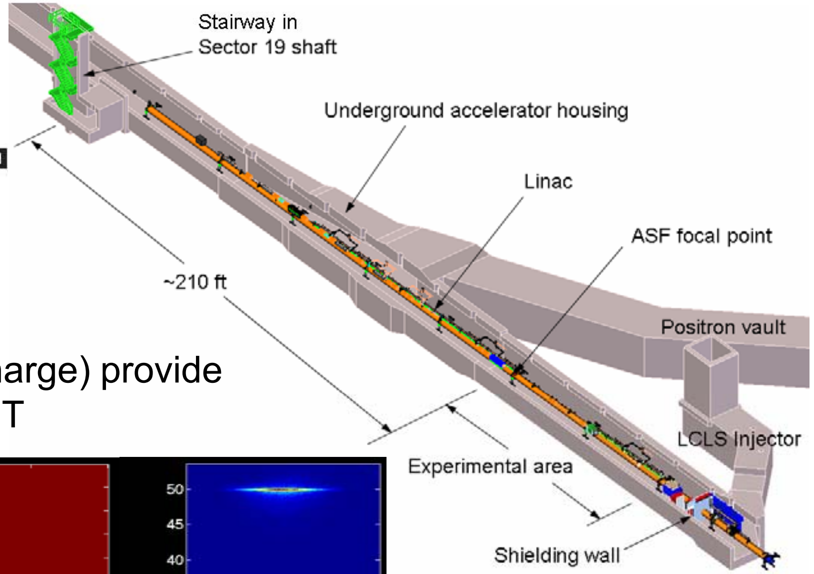
Further experiments (proposed to be done at FACET) will allow studying acceleration of **separate** witness bunch by a drive bunch and most of issues relevant for collider concept



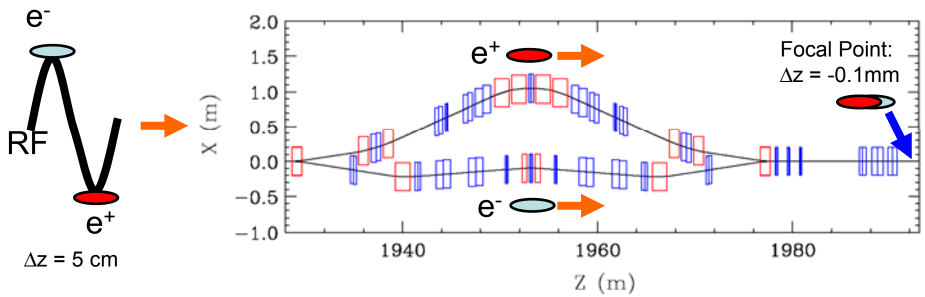
SLAC Duke UNIVERSITY UCLA USC

Facility for Advanced Accelerator Experimental Tests

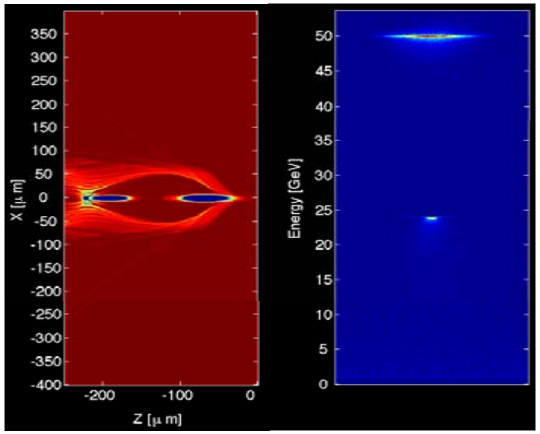




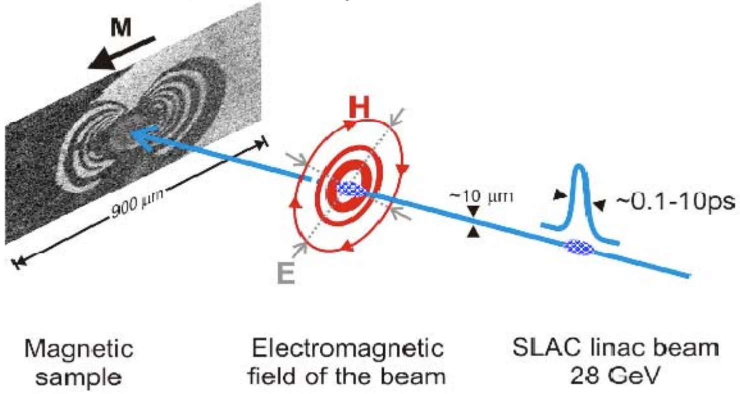
Unique properties of SLAC e+ and e- beams (ultra-short, high charge) provide worldwide unique opportunities for accelerator research at FACET



"Sailboat" dual chicane will give unique opportunity to study acceleration of positrons by an electron bunch



Two electron bunches formed by notch collimator will allow study energy doubling, high efficiency acceleration, emittance preservation



Short bunches and their Tera-Hz radiation open new possibilities to study ultrafast magnetization switching

Unique science opportunities for variety of fields:

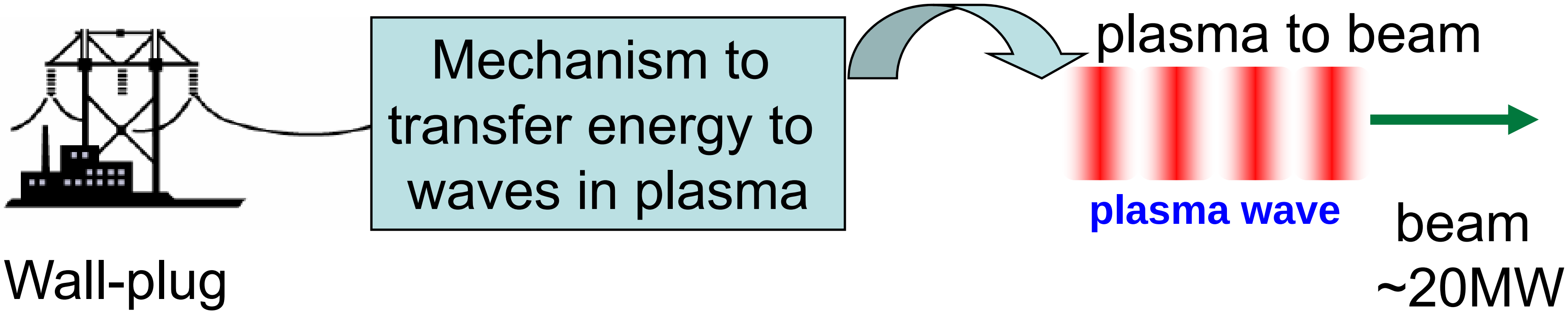
- Plasma beam source for LC concepts or BES
- Plasma lens for compact focusing
- Bent crystal for beam collimation or photon source
- e+ and e- acceleration study essential for LWFA & PWFA
- Dielectric wakefield acceleration
- Energy-doubling for existing facilities such as FEL's
- Generation of THz radiation for materials studies

Description of the PWFA-LC concept

* Linear Collider requirements
* PWFA-LC concept and design features
  - drive beam linac
  - beam distribution system
  - IP parameters and luminosity
  - overall parameters
  - other systems, DR, injectors, etc
* Flexibility of PWFA-LC concept

Plasma WF LC, Luminosity & Efficiency

* TeV collider call for P_{beam} ~10 MW of continuous power, small emittances and nanometer beams at IP



* An efficient approach to transfer several tens of MW of continuous power to plasma is to use drive beam

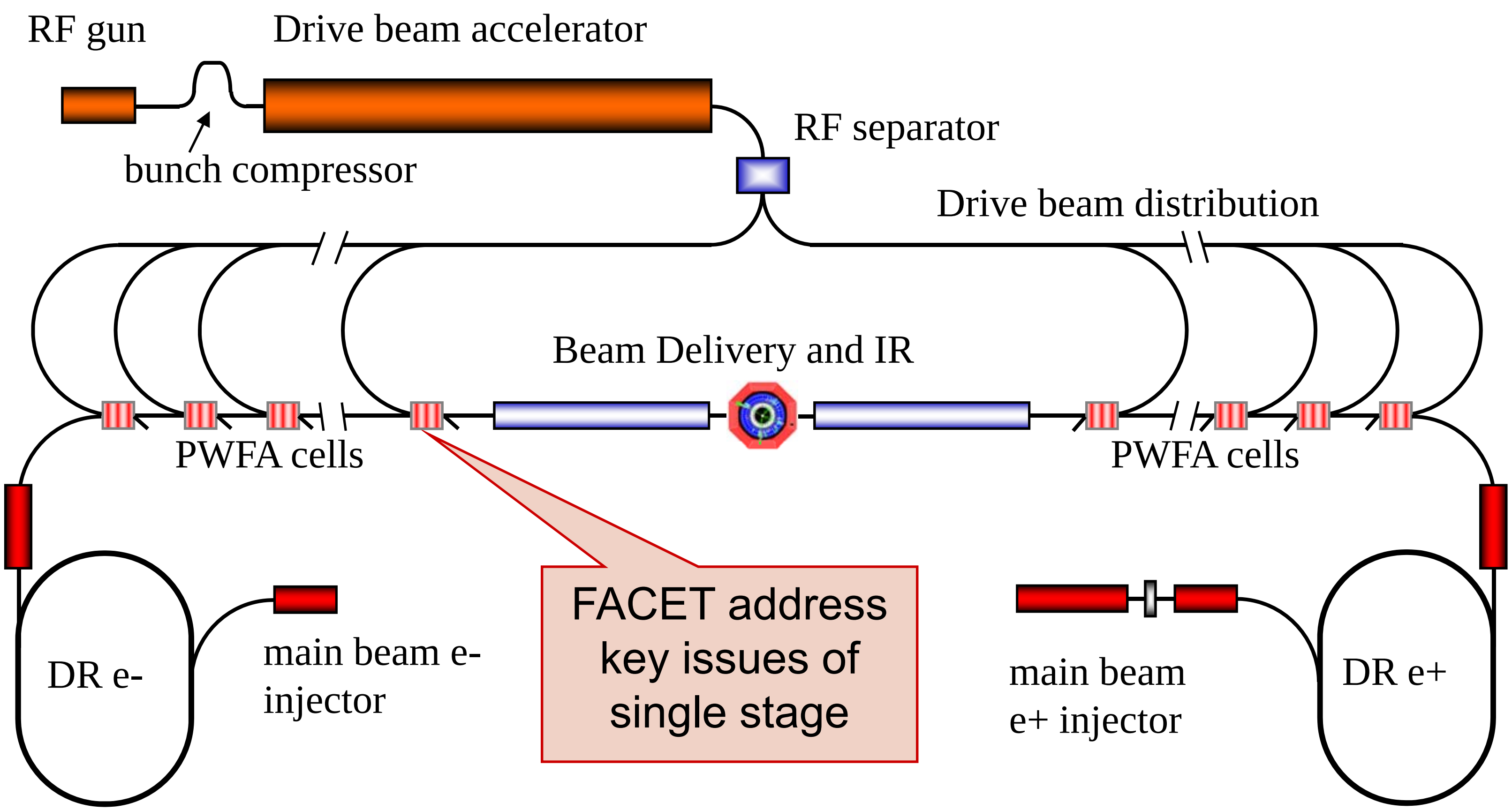
SLAC Duke UNIVERSITY UCLA USC

Approach to PWFA-LC concept

* Ideas for plasma wakefield-based linear colliders suggested in the past
  - "Afterburner" double energy of a conventional rf linear collider just before the IP
  - Multi-stage afterburner
* Our present concept for a PWFA-LC:
  - best benefits from extensive R&D performed for conventional RF linear colliders
  - reasonable set of R&D milestones that could be realized over the next ten years
  - has relatively relaxed requirements on the plasma acceleration systems while still having the potential for a comparably low cost
  - optimized to take advantage of the PWFA method

A concept for Plasma Wake Field Acceleration 1TeV CM Linear Collider

* Combines breakthrough performance of plasma acceleration & wealth of 30+ yrs of LC development



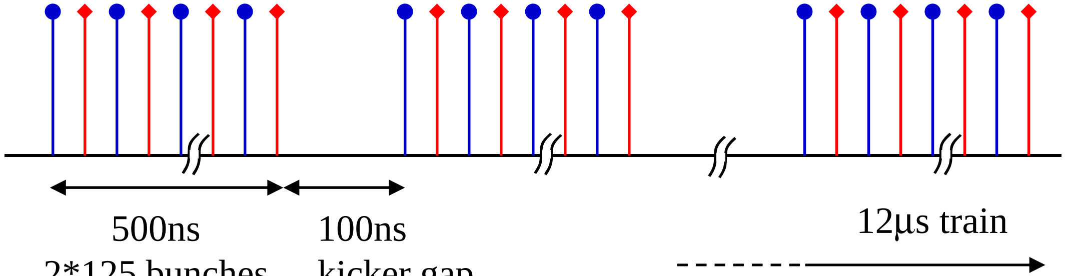
Key features of PWFA-LC concept

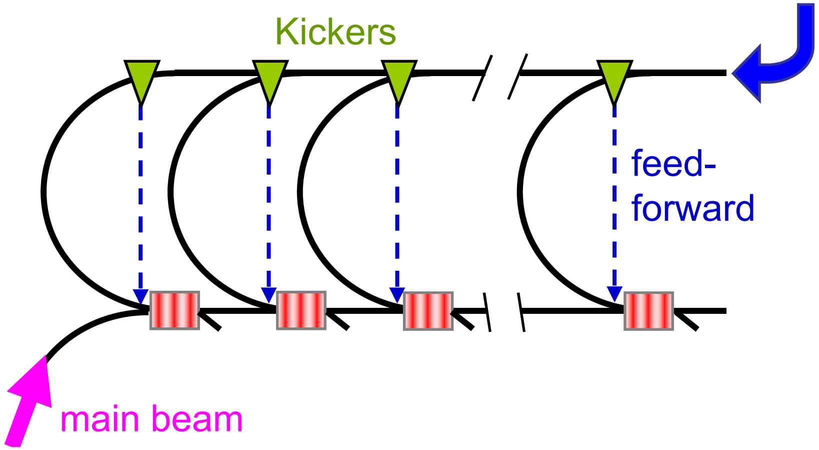
* Electron drive beam for both electrons and positrons
* High current low gradient efficient 25GeV drive linac
  – similar to linac of CERN CTF3, demonstrated performance
* Multiple plasma cells
  – 20 cells, meter long, 25GeV/cell, 35% energy transfer efficiency
* Main / drive bunches
  – 2.9E10 / 1E10

* Concept helped to shape the FACET research program
* PWFA-LC concept will continue to evolve with further study and simulation
  – Bunch charge; Flat vs round beams; SC vs NC pulse format; ...

Drive beam distribution

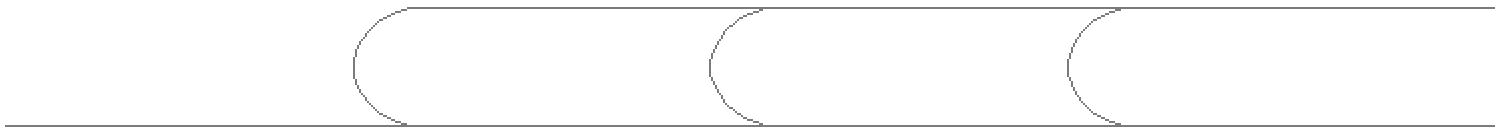
Single train for e+ and e- sides
Separation by RF deflectors





Kickers with ~100ns rise time
Possibility for feed-forward
Plasma cell spacing c*600ns/2

animation of beam drive distribution:



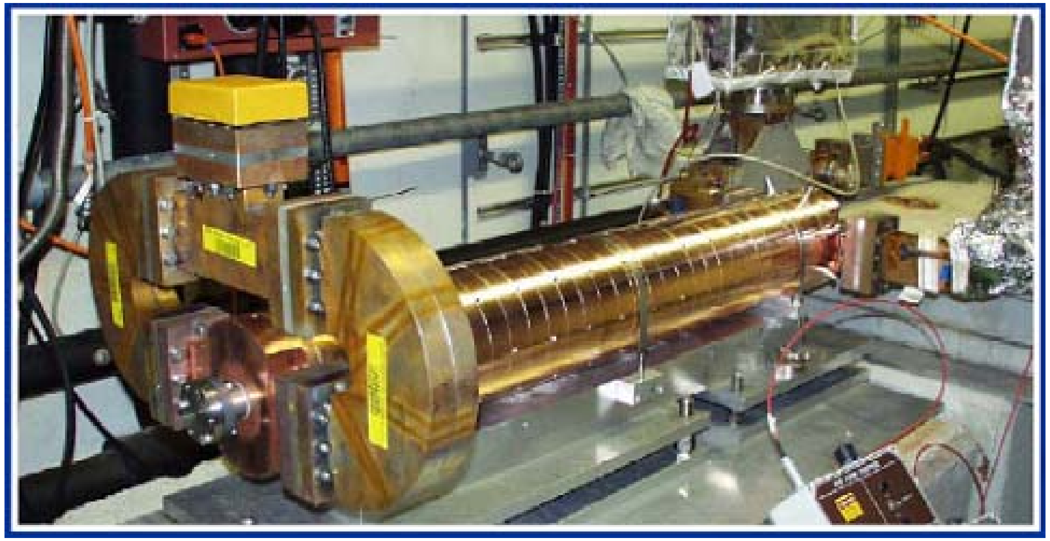
SLAC Duke UNIVERSITY UCLA USC

PWFA-LC drive beam linac

* Heavily loaded linac with high efficiency power transfer to the beam
  - High efficiency achieved by high peak current and low gradient
* Options for the design
  - CLIC drive linac has similar features and demonstrated 95% RF to beam efficiency without emittance growth (CTF3)
    - Slotted-iris, constant aperture (SICA) structure significantly reduces dipole Q and decouples dipole motion of the drive beam bunches
  - We used S-band structure: can take advantage of SLAC linac S-band klystrons if a prototype would need to be built and tested
    - Optimized to have 2.3 A peak current, 6.7 MV/m loaded gradient and 90% RF to beam efficiency
* Collaboration with CERN/CLIC colleagues on drive beam optimization for PWFA-LC would be most useful

PWFA-LC drive linac & CLIC/CTF3

* CTF3 linac accelerating structures



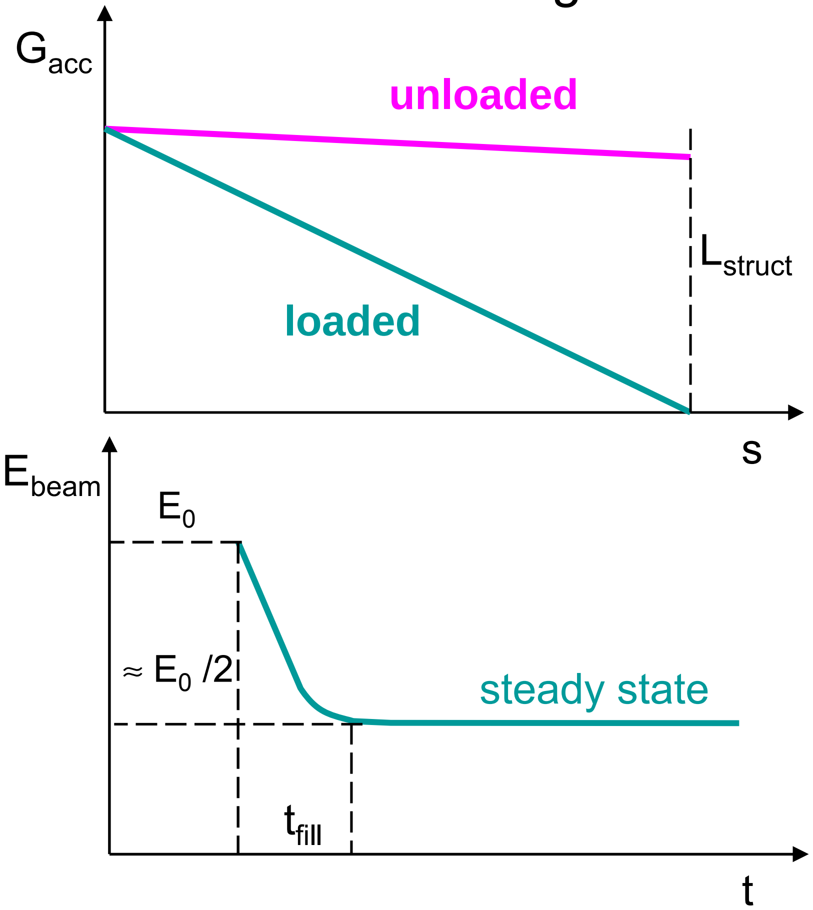
Dipole modes suppressed by slotted iris damping (first dipole's Q factor < 20) and HOM frequency detuning

- 3 GHz $2\pi/3$ TW constant aperture
- Slotted-iris damping + detuning with nose cones
- More than 4 A – 1.4 μs beam pulse accelerated – no BBU
- Measured RF power to beam energy transfer efficiency of 95 %
- Routine 24h, 7 days a week operation

CLIC07 Workshop, CTF3 team

PWFA-LC drive linac & CLIC/CTF3

Full beam-loading acceleration in CTF3

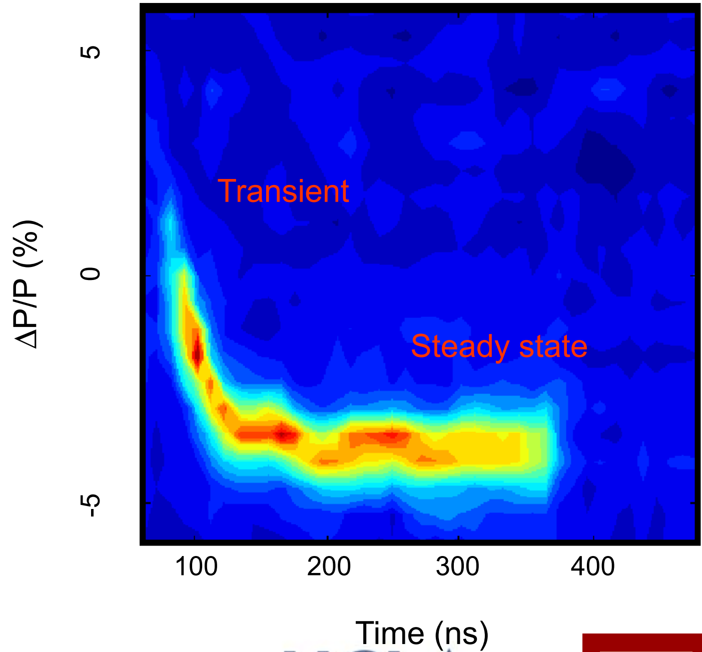


no power flows into load

$V_{ACC} \approx 1/2\ V_{unloaded}$

Measured RF-to-beam efficiency : 95.3 %
Theory : 96% (~ 4 % ohmic losses)

Time resolved beam energy spectrum measurement in CTF3



CLIC07 Workshop, CTF3 team

PWFA-LC drive linac with S-band structures

* Conceptual design of structures for the drive linac:

RF frequency and structure operating mode	2856 MHz , 2π/3
Structure Type	Slotted Iris – Constant Aperture (SICA)
Structure length	1.5m
Attenuation Factor & Filling Time	~0.17, 250 nsec
Fundamental Mode Q, Dipole Mode Q	~13000, ~20
Peak Current	2.3 A
Loaded gradient	6.7 MV/m
RF to Beam Efficiency	**90%**

[Shilun Pei, SLAC]

* Optimized for high efficiency and good damping of the dipole modes
* The structure optimized for S-band, which allowed, if needed, to perform structure tests with SLAC klystrons

Klystrons for PWFA-LC drive linac

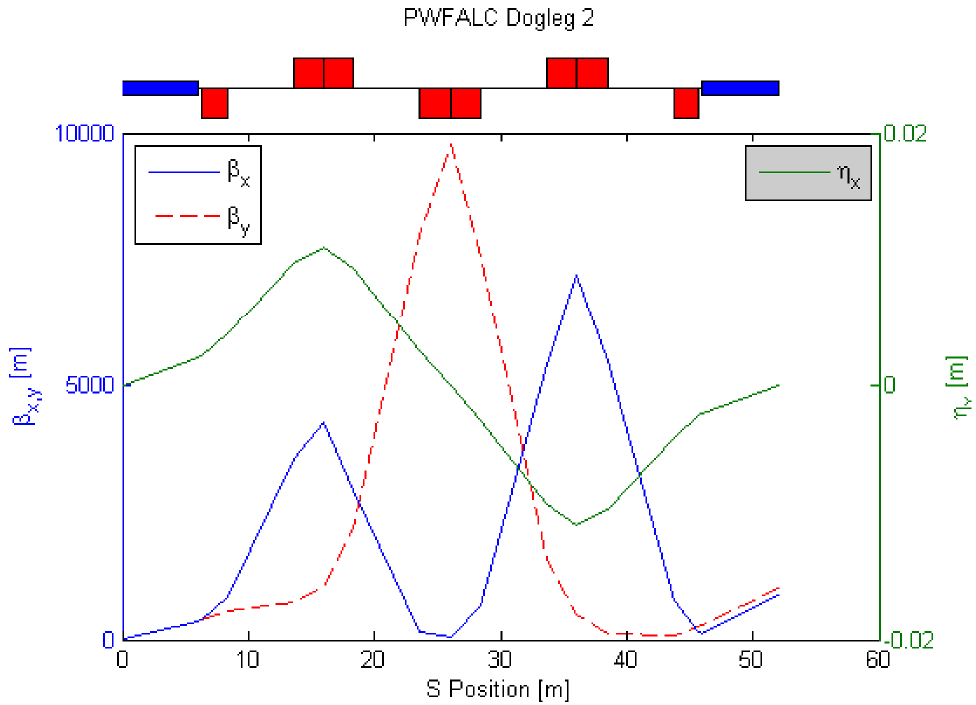
- * Klystron performance
  - SLAC 5045: 67MW at 3.5μs
  - Klystron of S-Band facility [DESY,ca.1995]: 150MW, 3μs
- * Have proof-of-principle solution of using the SLAC 5045 klystron and modulator to produce
  - ~15-20MW, 0.1% duty (125Hz), ≥ 8μs pulse-width
    - Involves running with reduced voltage
  - Close to the specs of PWFA-LC demo, if it would be needed

[Daryl Sprehn, Arnold Vlieks, SLAC]

- * Guesstimate that an optimized multi-beam klystron will be 50~100 MW (similar average power to ILC MBK)
  - About ~600-1000 of klystrons would be required for the drive linac of 1TeV PWFA-LC

Isochronous magnetic combiner

- At the plasma cell, the main and drive beams are combined in a magnetic system, using their different energies
- Different challenges at different energies
  - High main beam energy: emittance growth from SR
  - Low main beam energy: separation tricky because of ~equal beam energies



Tentative 500 GeV/beam separator. First bend and quad separate drive and main beam in x (they have different E); combiner is same in reverse. System is isochronous to the level of ~1 μm R56. Emittance growth < 0.3 mm-mrad. Initial β_0=10cm.

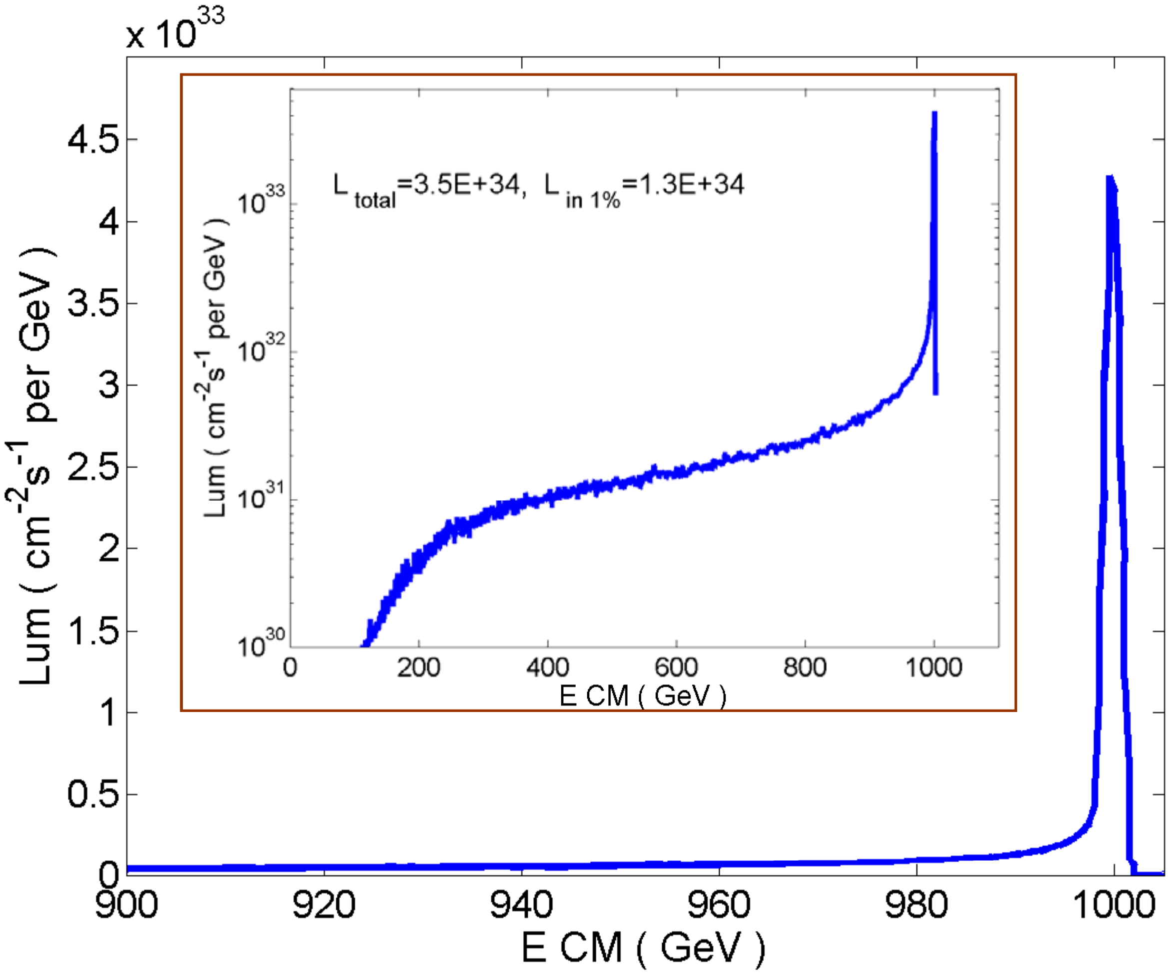
IP parameters optimization

- Conventional <1TeV LC is typically in low quantum beamstrahlung regime (when $Y = 2/3\ \omega_c \hbar / E < 1$)
  - The luminosity then scales as $L \sim \delta_B^{1/2}\ P_{beam} / \varepsilon_{ny}^{1/2}$ (where δ_B is beamstrahlung induced energy spread)
- High beamstrahlung regime is typical for CLIC at 3TeV
- PWFA-LC at 1TeV is in high beamstrahlung regime
- Scaling and advantage of high beamstrahlung regime
  - $L \sim \delta_B^{3/2}\ P_{beam} / [\ \sigma_z\ \beta_y\ \varepsilon_{ny}\ ]^{1/2}$ and $\delta_B \sim \sigma_z^{1/2}$
  - short bunches allow maximizing the luminosity and minimizing the relative energy loss due to beamstrahlung
- Optimization of PWFA-IP parameters performed with high quantum beamstrahlung regime formulae and verified with beam-beam simulations

PWFA-LC Luminosity Spectrum

IP $\beta_{x/y}$=10/0.2mm, δ_B~30%, close to CLIC numbers

IP parameters and spectrum are close to those for CLIC, and moreover, the wealth of particle physics studies for the interaction region and detector design, background and event reconstruction techniques in the high beamstrahlung regime are all applicable to the PWFA-LC concept



Calculated w. beam-beam code Guinea-Pig [D.Schulte, ca.1995]

PWFA-LC main parameters

Luminosity	3.5×10^{34} cm^{-2}s^{-1}
Luminosity in 1% of energy	1.3×10^{34} cm^{-2}s^{-1}
Main beam: bunch population, bunches per train, rate	1×10^{10}, 125, 100 Hz
Total power of two main beams	20 MW
Main beam emittances, $\gamma\varepsilon_x$, $\gamma\varepsilon_y$	2, 0.05 mm-mrad
Main beam sizes at Interaction Point, x, y, z	140 nm, 3.2 nm, 10 μm
Plasma accelerating gradient, plasma cell length, and density	25 GV/m, 1 m, 1×10^{17}cm^{-3}
Power transfer efficiency drive beam=>plasma =>main beam	35%
Drive beam: energy, peak current and active pulse length	25 GeV, 2.3 A, 10 μs
Average power of the drive beam	58 MW
Efficiency: Wall plug=>RF=>drive beam	50% × 90% = 45%
Overall efficiency and wall plug power for acceleration	15.7%, 127 MW
Site power estimate (with 40MW for other subsystems)	170 MW

Other subsystems of PWFA-LC

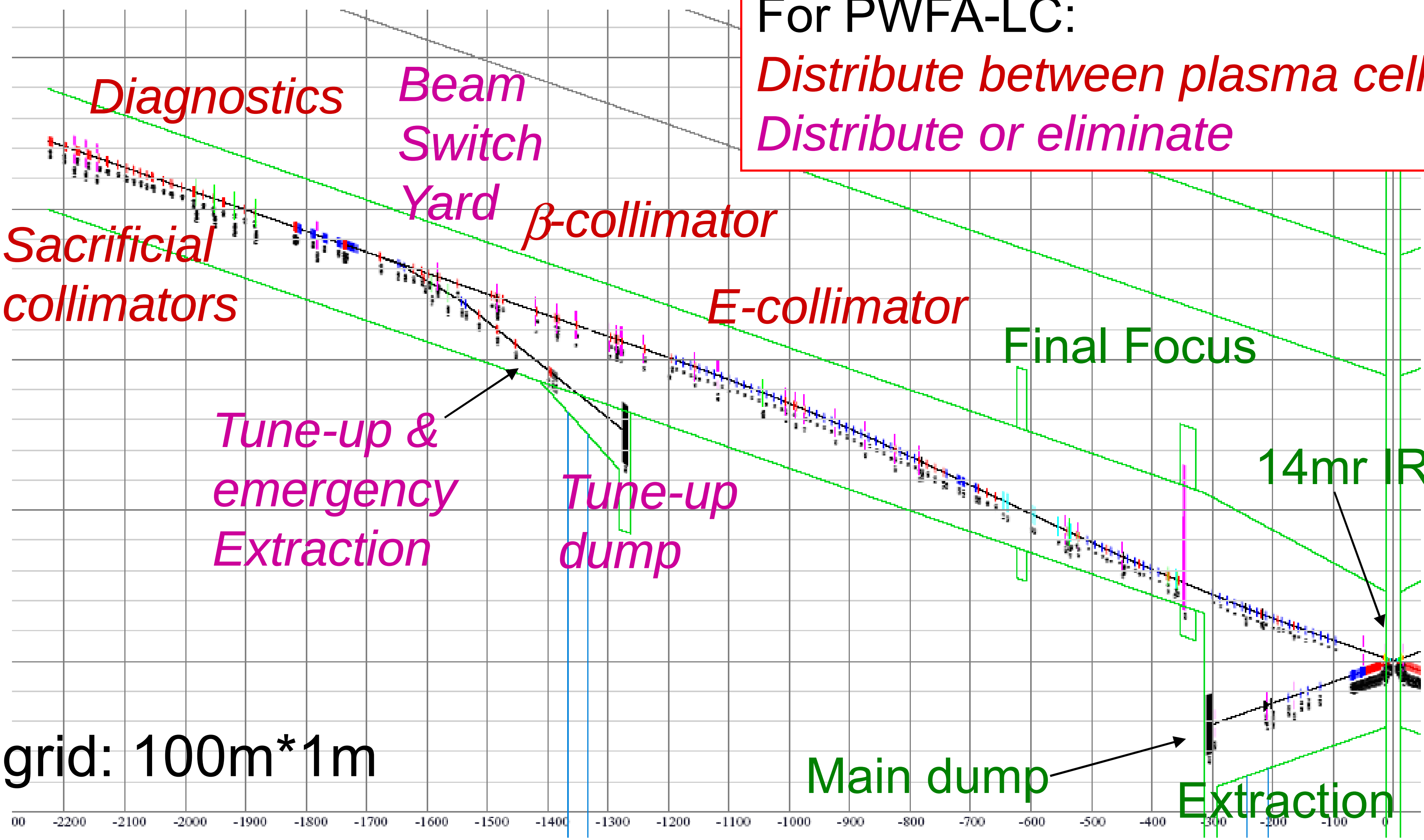
* Design of injectors, damping rings, bunch compressors, are similar to designs considered for LC and the expertise can be reused
  – Extensive tests of damping ring concepts at KEK ATF Prototype Damping Ring and the CESR-TA Test Facility
* Final focus system similar to conventional LC designs
  – Tested at Final Focus Test Beam and soon at the ATF2 at KEK
* Present design of Final focus and collimation has full energy acceptance of slightly greater than 2%
  – may need to deal with a factor of two larger energy spread for PWFA-LC
  – Further optimization of Final Focus and Collimation will need to be performed

ILC Beam Delivery for 1TeV CM

For PWFA-LC:

Distribute between plasma cells

Distribute or eliminate



SLAC Duke UNIVERSITY UCLA USC

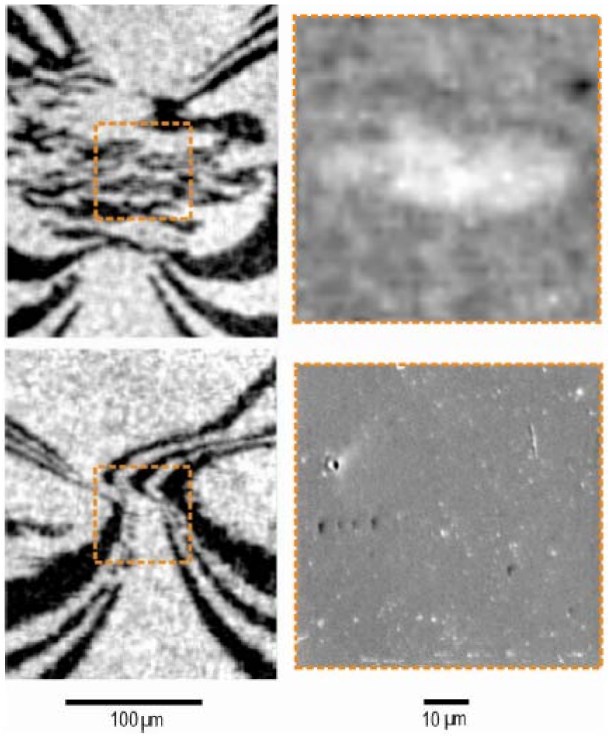
Systems in BDS for ILC and PWFA-LC

* For ILC: expect very small emittance or dE/E growth in the linac:
  - → diagnostics and collimation only after the linac, included into the BDS
  - → Tune-up & emergency extraction dump (full power) after the linac, to keep DR and linac “warm” while BDS and detector is accessed and if dE/E or amplitude is larger than collimation acceptance
* For PWFA: may need to collimate the beam after each plasma cell, and measure its properties
  - → distribute collimation and diagnostics from BDS to the optics between plasma cells
  - → Then the reason to have the emergency extraction in the BDS is also weakened, and may consider low power dump in between some plasma cells or eliminating the system

→ Then the length of BDS for PWFA-LC is ~700m per side

- → However, if L* is decreased, even ~300m may be considered
- → (Still not discussing any plasma length)

Ultra-short, ultra-strong field pulse shows no heating and damage



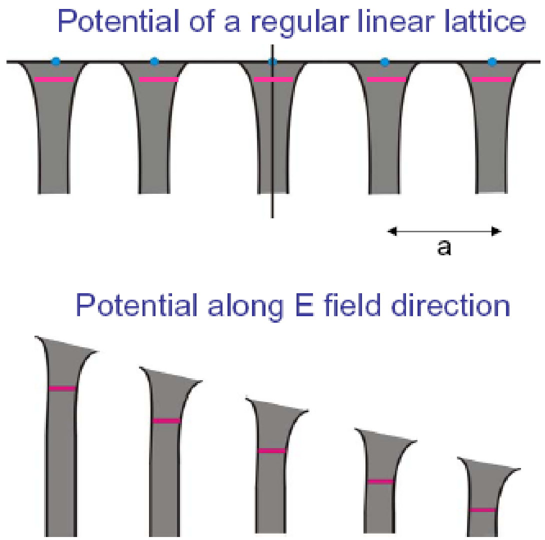
Pulse length: 4 ps

Pulse length: 140 fs

Peak field 35 times stronger

J. Stohr et al

Collimation system of PWFA-LC, as well as of CLIC, may benefit from recently observed phenomena that short bunches produce much less damage



Co bandwidth ~ 3eV

$E \sim 10^{10}$ V/m

$a = 0.25$ nm

↓

$\Delta V = e\,E\,a \sim 2.5$ eV

potential gradient leads to breakup of conduction path
no current flow due to field – not heating

SLAC Duke UNIVERSITY UCLA USC

Emittance preservation

* Various phenomena were studied and found to be not limiting
  – Synchrotron radiation in plasma channel
  – Scattering in plasma (for low Z plasma)
* Issues which require further studies and parameter optimization
  – Ion motion is a potential issue, mitigating may require use of partially ionized plasmas, higher plasma atomic mass, lower plasma density (and lower gradient) and shorter bunches, tighter focusing at the IP and increasing the main beam power
  – If the main beam power to be increased, it would be beneficial to increase the PWFA efficiency by shaping the drive bunch. Plasma focusing may facilitate tighter focusing at the IP
  – Both the higher PWFA efficiency and plasma focusing studies are part of the FACET extended experimental program

Plasma cells & flexibility of the concept

* Plasma cell is a heart of the PWFA-LC concept
  - The cell must provide acceleration with high throughput
* FACET will be able to produce a wide variety of beams to study the beam loading and acceleration with different plasmas
  - The initial tests will be done with lithium plasma
* In the PWFA-LC, the plasma in each cell needs to be renewed between bunches and stability of the plasma parameters is crucial
  - A high speed hydrogen jet is a possible candidate
* PWFA-LC concept is flexible:
  - bunch spacing presently assumed to be 4 ns
  - it can be doubled with the addition of RF separators and delay beamlines that can run along the drive linac
  - Increasing the bunch spacing by orders of magnitude could be done with a stretching ring, where the entire drive train would be stored and then bunches would be extracted one-by-one with fast rise kickers
  - Alternately could use a SC drive linac for very long spacing

Common CLIC-PWFA-LC topics

* Drive beam parameters, design, generation
  - frequency (1 or 3GHz)
  - energy (25GeV may be too high?)
  - RF system (and gaps in the train)
  - drive beam distribution system (isochronosity, compactness)
* Final focus and collimation
  - especially short bunch collimation survivability issues
* Drive bunch shaping
  - to allow increase of efficiency drive → witness to ~95%
  - and/or to allow higher transformer ratio ($E_{acc}/E_{decelerate}$)
    - may reduce number of stages but require larger charge/bunch

SLAC Duke UNIVERSITY UCLA USC

Discussions