Acceleration in plasma wakefield driven by lasers

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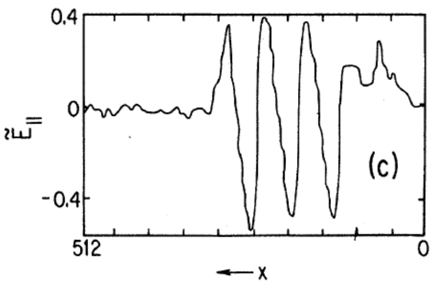
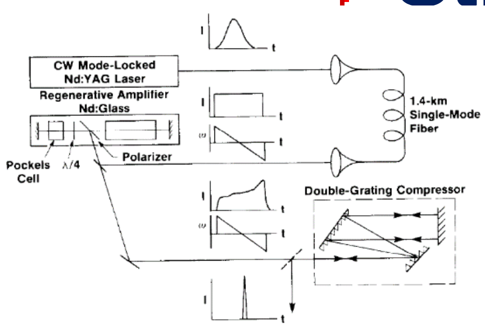
LWFA associates new concepts to innovative technology

➡ Tajima et Dawson, Phys. Rev. Lett. 1979



- A plasma wave can be associated to very high accelerating gradients
- Concept of laser wakefield to excite a relativistic plasma wave

➡ Strickland et Mourou, Opt. Comm. 1985



- Concept of laser system using laser chirped pulse amplification (CPA)
- Short and intense laser pulse facilities became available at the beginning of the 1990s

The field of LWFA is young and its progress is linked to the progress of lasers

- First **resonant demonstration** of LWF electron acceleration in **2004** when intense short-enough laser pulses became available

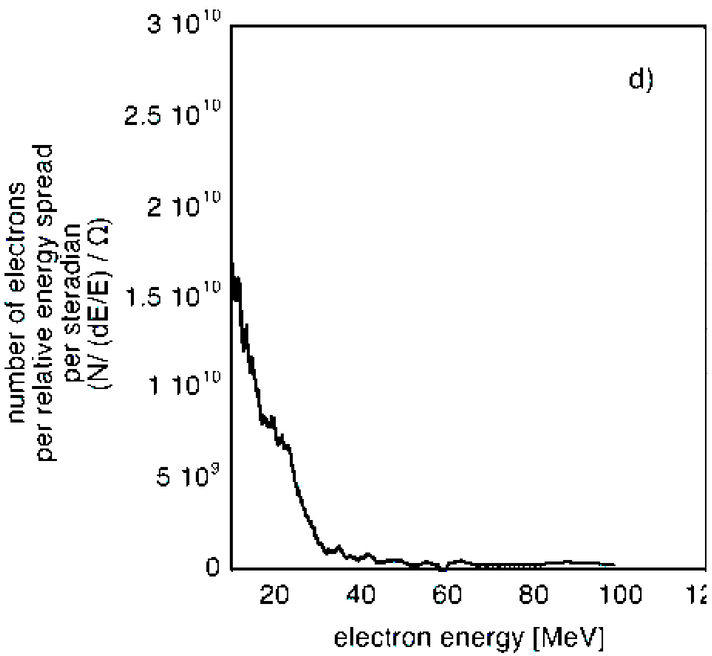
Breakthrough in 2004: from Maxwellian to peaked e- spectra

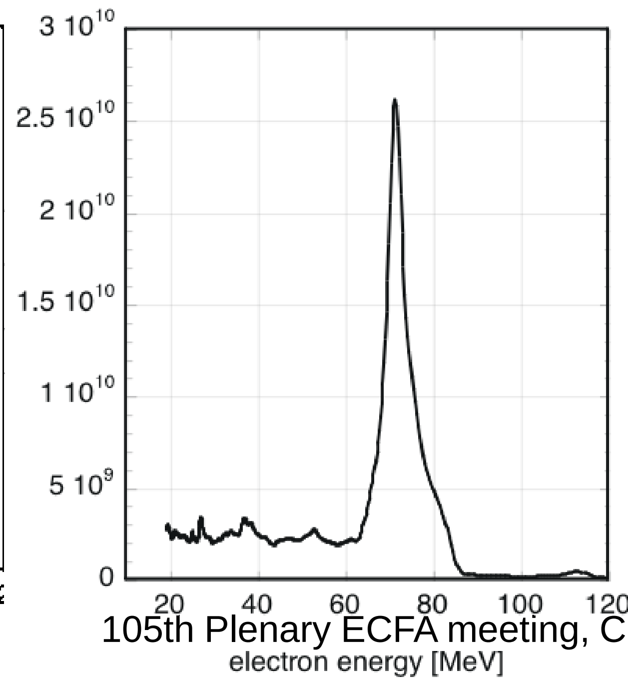
- Obtained by 3 groups
  - RAL/IC/UK: Mangles et al.
  - LOA/France: Faure et al.
  - LBNL/USA: C.G.R. Geddes et al.

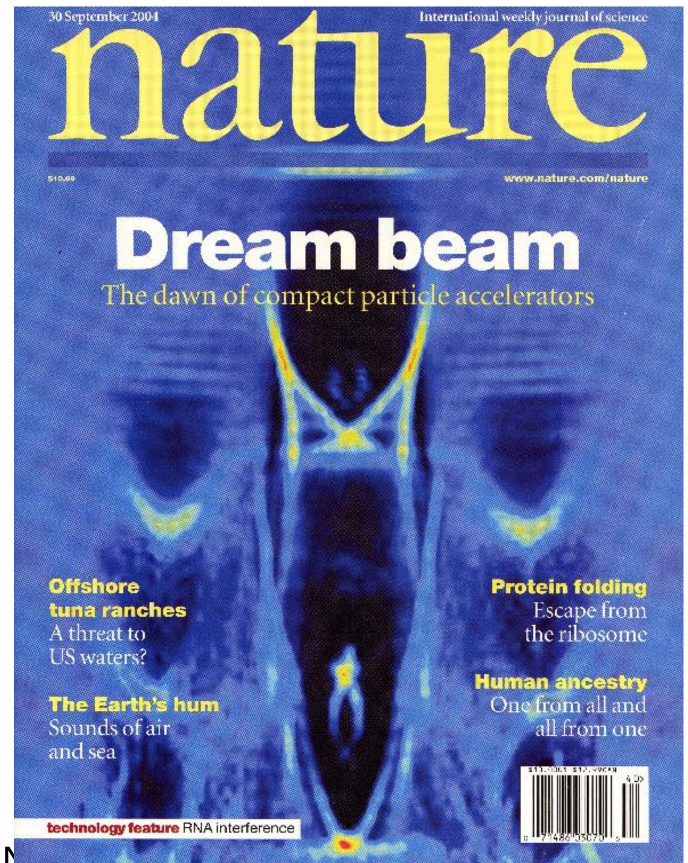
$L_{laser} \sim \lambda_p$

High intensity

$L_{laser} > \lambda_p$ ⟹ **$L_{laser} \sim \lambda_p$**



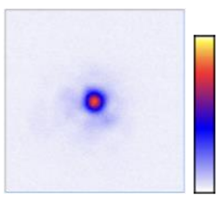




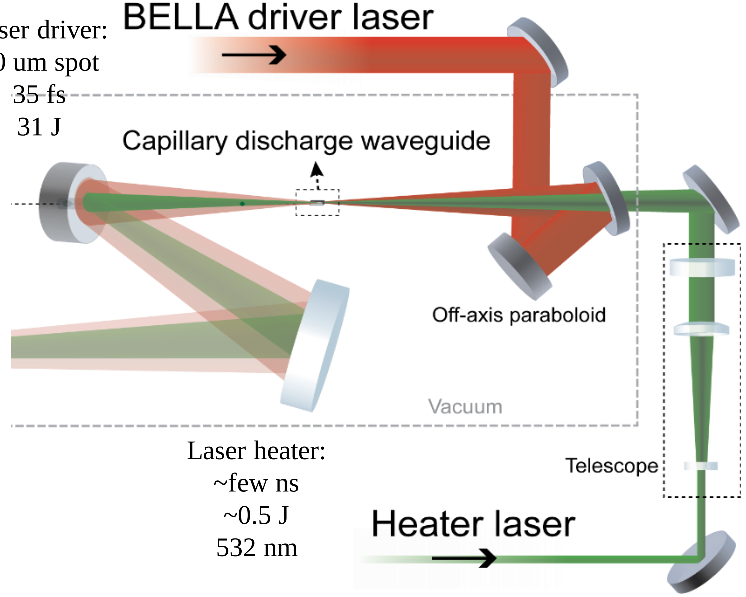
Today PW class lasers drive multi-GeV electron beams in plasma channels

Laser-plasma accelerated electron beam to 8 GeV in 20 cm at LBNL

spot size 60 micron

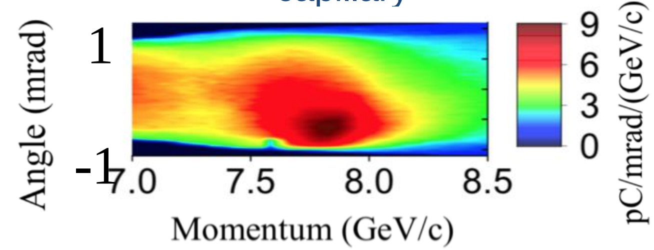


exit of cap (20 cm) with plasma channel



Guiding of PW laser in laser-heated, discharge capillary ~15 Z_R

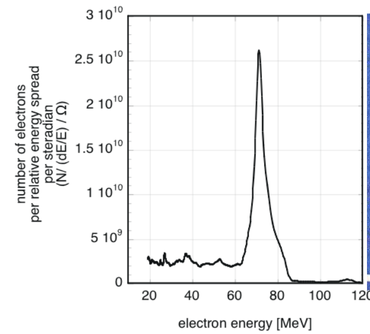
BELLA @ 0.85PW with laser-heated capillary

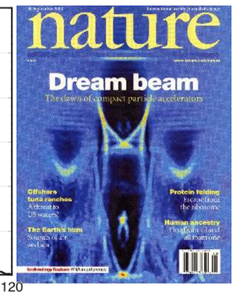


- Laser heater (inverse Bremsstrahlung heating) implemented on BELLA laser system: improves guiding at low density; yields 8 GeV generated at plasma density of 2.7×10^{17} cm^{-3}

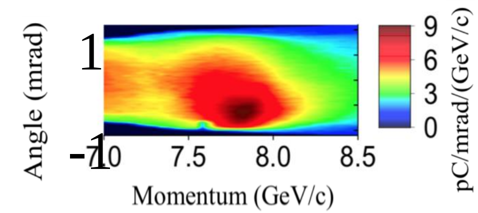
Gonsalves et al., PRL (2019)

Important milestones for the development of future accelerators have already been achieved





- First **resonant demonstration** of LWF electron acceleration in **2004** when intense short-enough laser pulses became available



Gonsalves et al., PRL (2019)

- **GeV level** reached in 2006, current energy range approaching 10 GeV

- Peak accelerating gradients up to ~100 GV/m demonstrated
- **Good understanding of physics** and agreement with theory
- **Several options** can be explored to optimise electron beam parameters

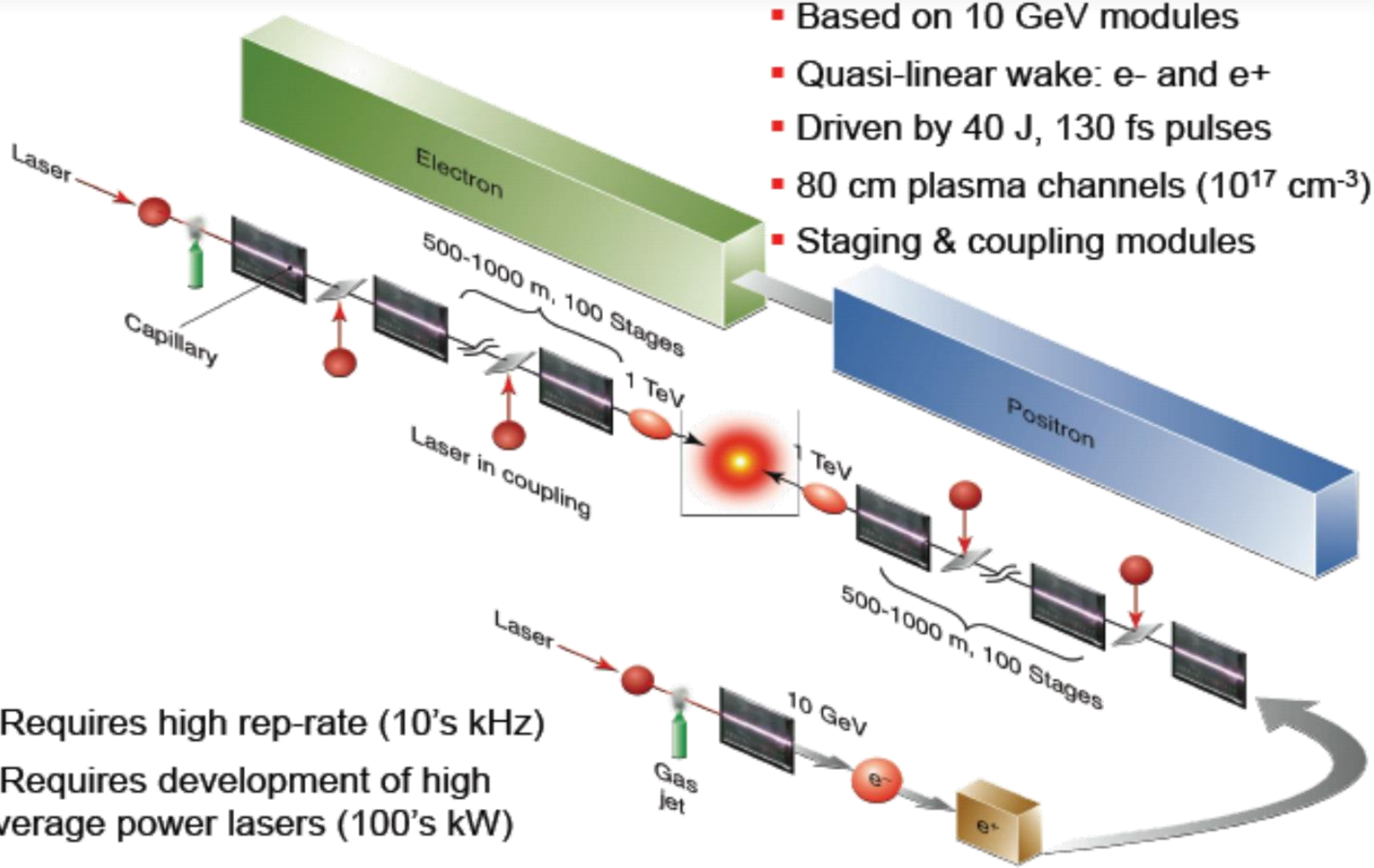
Laser driven plasma wakefield R&D has mostly been performed outside accelerator labs

- LWFA R&D performed mostly by **University labs and at laser facilities** of various sizes around the world, operating as user facilities (RAL, LOA, LULI, BELLA, LLC, LUX, HZDR, …..)
- Research is driven by the exploration of new concepts, with a large number of publications in physics journals

- However, over the last ten years the involvement of large accelerator labs has increased (DESY, INFN, CEA, LAL, …), which should be a game changer

Strawman design for linear e-e+ collider gives a frame for accelerator R&D

- Based on 10 GeV modules
- Quasi-linear wake: e- and e+
- Driven by 40 J, 130 fs pulses
- 80 cm plasma channels (10^{17} cm^{-3})
- Staging & coupling modules



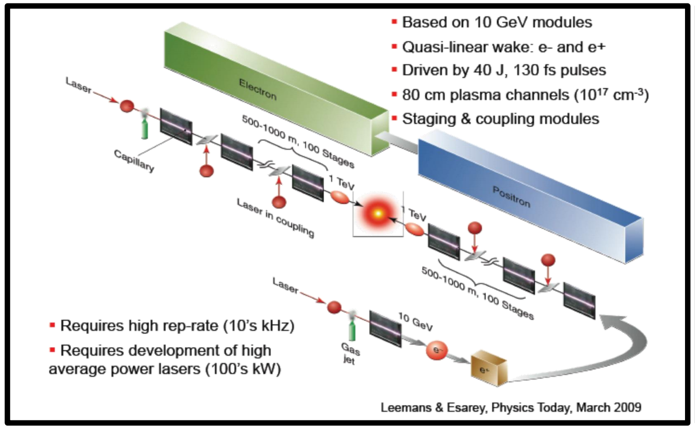
- Requires high rep-rate (10's kHz)
- Requires development of high average power lasers (100's kW)

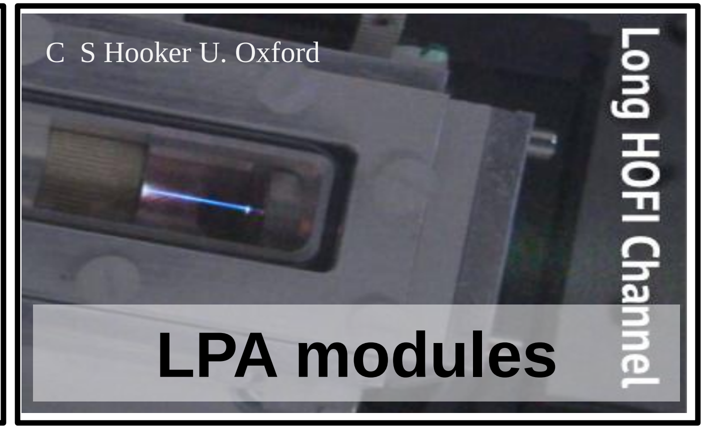
Leemans & Esarey, Physics Today, March 2009

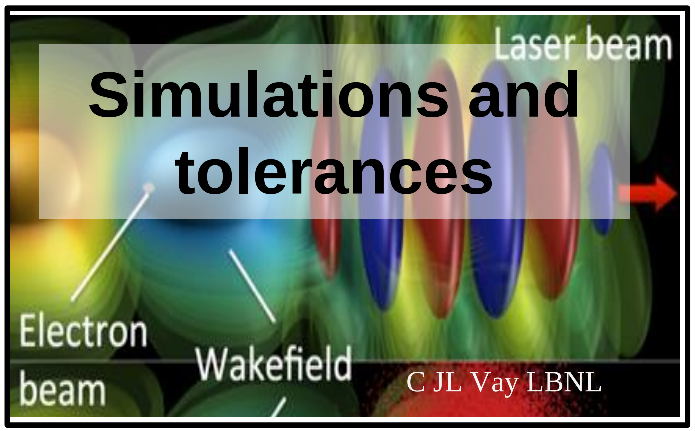
Multi-stage schemes are a way to achieve high energy reliable beams

- **Purpose of multiple stages:** control properties of the accelerated beams and increase their energy
  - Mitigate laser depletion and dephasing
  - Optimise particle beam properties (energy spread, emittance, reliability)
  - Increase particle energy using successive modules
- **Main challenges**
  - Laser reliability and performance (efficiency, average power, stability, quality)
  - Increase acceleration length
  - Inject electrons in the accelerating structure in a precise and controlled way

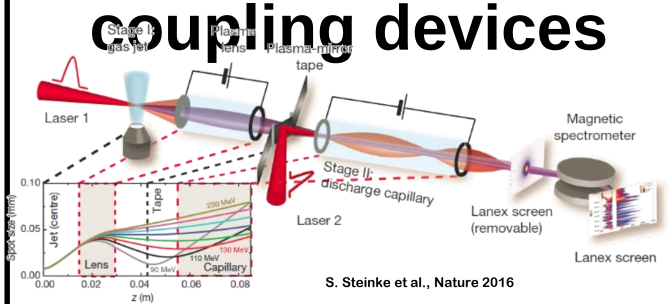
Work is in progress on components relevant for high energy linear accelerators R&D





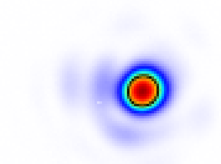


Staging and coupling devices



Reliability of laser drivers

2% rms energy stability over 24h measured at LUX



C S Hooker U. Oxford

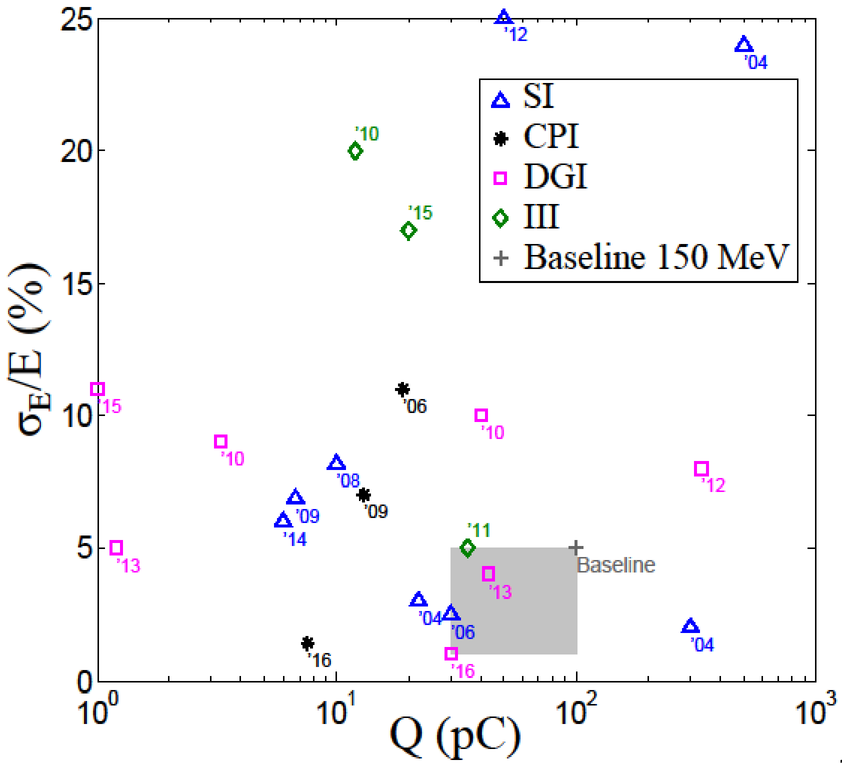
Electron sources driven by laser in plasmas can reach the quality required for an injector

- Available laser systems allow to develop laser driven injectors in plasmas:

Electrons generated during laser plasma interaction :

- Energy can be selected in the range 100-500MeV
- Short pulse duration <10fs
- 1pC to 10pC/MeV range
- Peaked spectra with energy spread 1-10% FWHM
- Divergence mm mrad

SI : Self Injection
CPI : Colliding Pulse Injection
DGI : Density Gradient Injection
III : Ionization Induced Injection



Experimental achievements in the energy dispersion versus charge plane

Current Status of LWFA Electron Bunch Properties

M. Downer intro talk
ANAR2017

Property	State of Art*	Reference	Remarks
Energy	**2 GeV** (± 5%, 0.1 nC) **3 GeV** (±15%, ~0.05 nC) **8 GeV** (±2%, 0.005 nC)	Wang (2013) - Texas Kim (2013) – GIST Gonsalves (2019) - LBNL	Accelerates from E ≈ 0
Energy Spread	**1%** (@ .01 nC, 0.2 GeV) **5-10%**	Rechatin (2009a) – LOA more typical, many results	0.1% desirable for FELs & colliders
Normalized Trans-verse emittance	**~ 0.1 π mm-mrad**	Geddes (2008) - LBNL Brunetti (2010) - Strathclyde Plateau (2012) - LBNL	Measurements at resolution limit
Bunch Duration	**~ few fs**	Kaluza (2010) – Jena (**Faraday**) Lundh (2011) – LOA; Heigoldt (2015) – MPQ/Oxford (**OTR**) Zhang (2016) – Tsinghua	Measurements at resolution limit
Charge	**0.02 nC** @ 0.19 GeV ±5% **0.5 nC** @ 0.25 GeV ±14%	Rechatin (2009b) – LOA Couperus (2017) - HZDR	Beam-loading achieved. FOM: **Q/ΔE** ?
Repetition Rate & Repeatability	~ **1 Hz** @ > 1 GeV **1 kHz** @ ~ 1 MeV	Leemans (2014) - LBNL He – UMIch ('15); Salehi ('17) – UMd; Guénot ('17) -- LOA	Limited by lasers & gas targets

*** No one achieves all of these simultaneously!**

- Brunetti, *PRL* **105**, 215007 ('10)
- Couperus, *submitted* ('17)
- Geddes, *PRL* **100**, 215004 ('08)
- He, *Nat. Comms* **6**, 7156 (2015)
- Heigoldt, PR-STAB **18**, 121302 ('15)
- Kaluza, *PRL* **105**, 115002 ('10)
- Kim, *PRL* **111**, 165002 (2013)
- Gonsalves, *PRL* (2019)
- Lundh, *Nat. Phys.* **7**, 219 (2011)
- Rechatin, *PRL* **102**, 164801 (2009)
- Rechatin, *PRL* **103**, 194804 ('09b)
- Salehi, *Opt. Lettt.* **42**, 215 ('17)
- Wang, *Nat. Comms* **4**, 1988 (2013)
- Zhang, *PRST-AB* **19**, 062802 (2016)

Current Status of LWFA Positron Properties: no results yet

Progress towards a laser driven plasma stage

Plasma density (wall), $n_0[\mathrm{cm}^{-3}]$	10^{17}
Plasma wavelength, λ_p[mm]	0.1
Plasma channel radius, $r_c[\mu\mathrm{m}]$	25
Laser wavelength, $\lambda[\mu\mathrm{m}]$	1
Normalized laser strength, a_0	1
Peak laser power, P_L[TW]	34
Laser pulse duration (FWHM), τ_L[fs]	133
Laser energy, U_L[J]	4.5
Normalized accelerating field, E_z/E_0	0.14
Peak accelerating field, E_L[GV/m]	4.2
Plasma channel length, L_c[m]	2.4
Laser depletion, η_{pd}	23%
Bunch phase (relative to peak field)	$\pi/3$
Loaded gradient, E_z[GV/m]	2.1
Beam beam current, I[kA]	2.5
Charge/bunch, $eN_b = Q$[nC]	0.15
Length (triangular shape), $L_b[\mu\mathrm{m}]$	36
Efficiency (wake-to-beam), η_b	75%
e^-/e^+ energy gain per stage [GeV]	5
Beam energy gain per stage [J]	0.75

- **Example 5GeV stage from ALEGRO** work on LWFA ALIC
- **ALEGRO collaboration *arXiv:1901.10370v2***
- Plasmas need to be developed over meter scale length and up to kHz rep rate
  - Today discharges can reach 0.2 m long plasma at kHz repetition rate
  - Free standing plasmas are also considered for 24/7 operation
- **e- and e+ need to be injected externally, e- sources** are available and experimental demonstration is pending **e+ sources** need to be developed

ALEGRO

Advanced LinEar collider study GROup

An accelerator test facility based on LWFA is needed for accelerator development

Table 2.1: US laser facilities (>100 TW) performing LWFA R&D.

Facility	Institute	Location	Gain media	Energy (J)	Peak power (PW)	Rep. rate (Hz)
BELLA [7]	LBNL	Berkeley, CA	Ti:sapphire	42	1.4	1
Texas PW [8]	U. Texas	Austin, TX	Nd:glass	182	1.1	single-shot
Diocles [9]	U. Nebraska	Lincoln, NE	Ti:sapphire	30	1	0.1
Hercules [10]	U. Michigan	Ann Arbor, MI	Ti:sapphire	9	0.3	0.1
Jupiter [11]	LLNL	Livermore, CA	Nd:glass	150	0.2	single-shot

Table 2.2: Laser facilities ($\gtrsim$100 TW) performing LWFA R&D in Europe.

Facility	Institute	Location	Energy (J)	Peak power (PW)	Rep. rate (Hz)
ELBE [16]	HZDR	Dresden, Ge	30	1	1
GEMINI [17]	STFC, RAL	Didcot, UK	15	0.5	0.05
LLC [18]	Lund Univ	Lund, Se	3	0.1	1
Salle Jaune [19]	LOA	Palaiseau, Fr	2	0.07	1
UHI100 [20]	CEA Saclay	Saclay, Fr	2	0.08	1
CALA* [21]	MPQ	Munchen, Ge	90	3	1
CILEX* [22]	CNRS-CEA	St Aubin, Fr	10-150	1-10	0.01
ELIbeamlines* [23]	ELI	Prague, TR	30	1	10
ILIL* [24]	CNR-INO	Pisa, It	3	0.1	1
SCAPA* [25]	U Strathclyde	Glasgow, UK	8	0.3	5

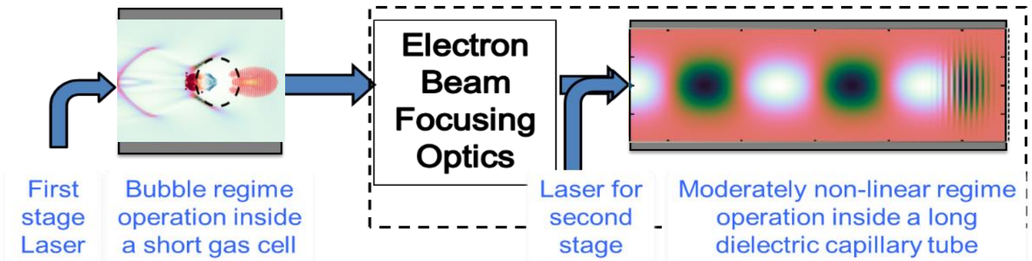
Table 2.3: Laser facilities ($\gtrsim$ 100 TW) performing LWFA R&D in Asia

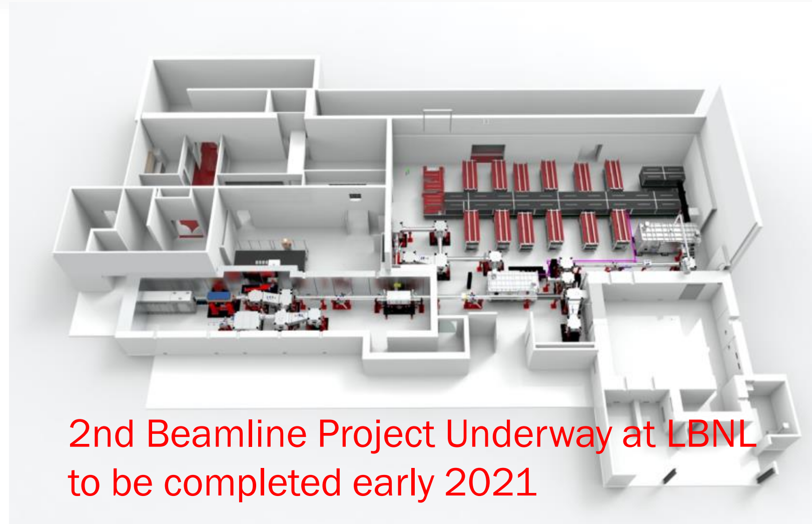
Facility	Institute	Location	Energy (J)	Peak power (PW)	Rep. rate (Hz)
CLAPA	PKU	Beijing, PRC	5	0.2	5
CoReLS [28]	IBS	Gwangju, Kr	20-100	1-4	0.1
J-Karen-P* [29]	KPSI	Kizugawa, Jn	30	1	0.1
LLP [30]	Jiao Tong Univ	Shanghai, PRC	5	0.2	10
SILEX*	LFRC	Myanyang, PRC	150	5	1
SULF* [31]	SIOM	Shanghai, PRC	300	10	1
UPHILL [32]	TIFR	Mumbai, In	2.5	0.1	
XG-III	LFRC	Myanyang, PRC	20	0.7	

- R&D on LWFA is performed Today at several laser facilities world wide (tables for lasers with peak power >100TW)

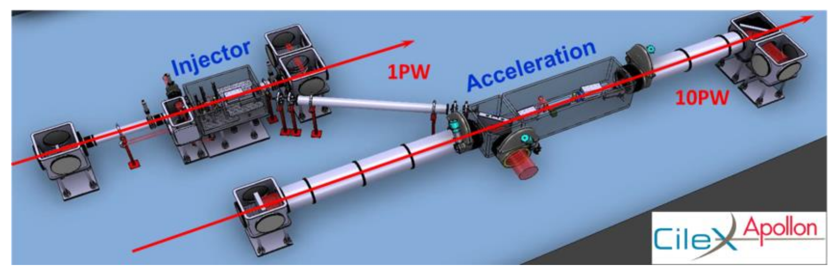
- Laser development lab or laser user facility or university lab
- Existing laser systems are PW class laser systems but low rep rate

Future multi-GeV demonstrations of LWFA

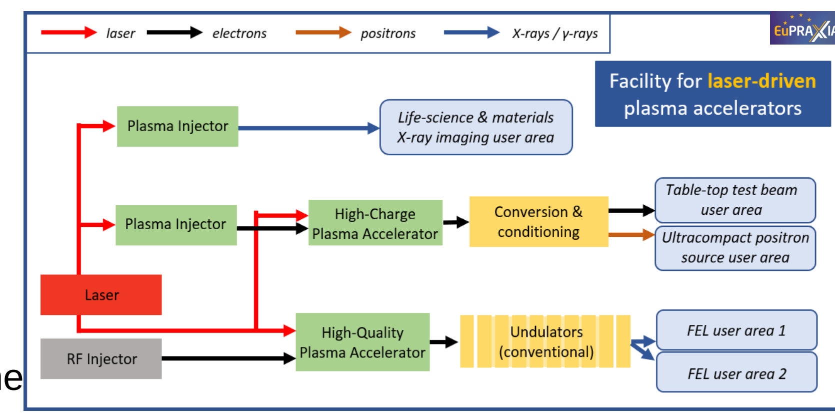




- Facilities about to start operation where external injection will be studied: LBNL **Bella** US, **Apollon CILEX** CNRS-CEA FR



- **EUPRAXIA** (EU) longer term, could be the first accelerator facility



Conclusion

- Several concepts for electron injector and plasma stage are **available, acceleration module to multi-GeV** needs to be build and tested
- **Positron sources** need to be developed
- Next steps: put **resources on accelerator development** paths:
  - Higher efficiency and repetition rate drivers and concepts
  - Machine oriented designs
  - Test facility for accelerator components and subsystems prototyping
- At present, components are studied by independent small groups, **accelerator designs need to be coordinated** around larger scale projects

Acknowledgements

- Based on input from ALEGRO meetings and documents
- http://www.lpgp.u-psud.fr/icfaana/alegro/

ALEGRO

Advanced LinEar collider study GROup

arXiv:1901.10370v2 [physics.acc-ph]

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ALEGRO collaboration members as of September 2018 : Erik Adli[1], Weiming An[2], Nikolay Andreev[3], Oznur Apsimon[4], Ralph Assmann[5], Jean-luc Babigeon[6], Robert Bingham[7], Tom Blackburn[8], Christopher Brady[9], Michael Bussmann[10], Bruce Carlsten[11], James Chappell[12], Jian Bin Ben Chen[13], Sebastien Corde[14], Laura Corner[15], Benjamin Cowan[16], Brigitte Cros[17], Joel England[18], Eric Esarey[19], Ricardo Fonseca[20] , Brian Foster[5,21], Spencer Gessner[13], Leonida A Gizzi[22], Daniel Gordon[23] , Edda Gschwendtner[13], Anthony Hartin[5], Bernhard Hidding[24], Mark Hogan[18], Simon Hooker[21], T. Hughes [25], Alexei Kanareykin[26], Stefan Karsch[27], Valentin Khoze[28], Pawan Kumar[29], Wim Leemans[19], Francois Lemery[5], Ang Li[30], R. Li[18], Vladyslav Libov[5], Emily Sistrunk Link[31], Michael Litos[32], Gregor Loisch[5], Nelson Lopes[20,33], Olle Lundh[34], Alexey Lyapin[35], Edu Marin[13], Mattias Marklund[8], Timon Mehrling[19], Patric Muggli[13,27], Pietro Musumeci[2], Zulfikar Najmudin[33], Uwe Niedermayer[36], Jens Osterhoff[5], Marc Palmer[41], Rajeev Pattathil[7], Michael Peskin[18], Philippe Piot[38], John Power[39], Alexander Pukhov[40], Heather Ratcliffe[41], Marc Riembau [42], Veronica Sanz[43], Gianluca Sarri[44] , Yuri Saveliev[7], Levi Schachter[45], Lucas Schaper[5], Norbert Schoenenberger[30] , Carl Schroeder[19], Sarah Schroeder[5], Daniel Schulte[13], Andrei Seryi[46], Sergey Shchelkunov [XX], Craig Siders[31], Evgenya Simakov [11], Christophe Simon-Boisson[47], Michael Spannowsky[28], Christina Swinson[37], Andrzej Szczepkowicz[48], Roxana Tarkeshian[5], Johannes Thomas[40], Junping Tian[49], J.V. Tilborg[19], Paolo Tomassini[22], Vasili Tsakanov[50], Jean-Luc Vay[19], Jorge Vieira[20], Henri Vincenti[51], Roman Walczak[21], Dan Wang[52], Stephen Webb [53], Glen White [18] Guoxing Xia[4], Hitoshi Yamamoto[54], Tevong You[55], Igor Zagorodnov[5]