Advanced and Novel Accelerators for High Energy Physics Roadmap Workshop 2017
April 25-28, 2017 at CERN

ANAR2017 workshop

25-28 April 2017, CERN 6-2-024 - BE Auditorium

ANA DVANCED OVEL CCELERATORS

WG1 report: Laser wakefield accelerator (LWFA)

Dan Gordon (NRL)

Carl Schroeder (LBNL)

Arnd Specka (Ecole Polytechnique – CNRS/IN2P3)

Nikolay Andreev, Ralph Wolfgang Assmann, David Bruhwiler, Benjamin Cowan, Brigitte CROS, Alexander Debus, Andreas Döpp, Ulrich Dorda, Michael Downer, Almantas Galvanauskas, Daniel Gordon, Simon Hooker, Zhirong Huang, Arie Irman, Mohammad Islam, Masaki Kando, Igor Kostyukov, Pawan Kumar, Wim Leemans, Olle Lundh, Philippe Martin, Oznur Mete, Alban Mosnier, Patric Muggli, Zulfikar Najmudin, Federico Nguyen, Mark Palmer, Igor Pogorelsky, Alexander Pukhov, Andrei Seryi, Christophe SIMON-BOISSON, Jonathan Smith, Arnd Specka, Christina Swinson, Christopher Thornton, Jorge Vieira, Barney Williamson, Xueqing Yan

*) presentations underlined

WG1: organization and schedule

- **37 participants (rather 30)**
- **2 short overview presentations**
- **14 short communications**
- **session topics:**
  - **issues in LWFA e⁻ acceleration**
  - **new and alternative schemes**
  - **injector improvement, positron production, <- gamma sources**
  - **modelling, testing, diagnostics and drivers**
  - **discussion on "strategy", future work, drivers (laser)**
  - **definition of ~~bottlenecks~~ milestones**
- **extra Final Focus session on Tuesday**

date	time	speaker	topics
25-avr	**14:30-16:00**	**LWFA electron Acceleration**	
		Conveners	Charge to to the WG
		Alban Mosnier	Electron acceleration - Introductory Overview
		Arie Irman	Recent result in ionization induced injection
		Masaki Kando	Improvement in beam pointing stability
		Oznur Mete-Apsimon	Witness beam scattering by plasma ions and electrons"
		discussion	**State of the art of the acceleration scheme relevant to HEP** Identify parameters/elements necessary for the scheme
25-avr	**16:30-18:00**	**Alternative and Novel Acceleration Schemes (electrons and positrons)**	
		Simon Hooker	Excitation and control of plasma wakefields by trains of laser pulses".
		Alexander Debus	Traveling-Wave Electron Acceleration (TWEAC) -- Electron acceleration
		Andreas Döpp	PWFA with LWFA generated electrons
		discussion	**State of the art of the acceleration scheme relevant to HEP** Determine to what extend they have been proved and demonstrated Identify key experiments to be performed
26-avr	**09:00-10:30**	**Injection / Positron production**	
		Nikolay Andreev	external injection strategy of an electron bunch to minimize the energy spread of accelerated electrons
		Igor Pogorelsky	positron prodution?
		Mike Downer	Compton x-rays, gamma-rays from self-aligned combination of LWFA and plasma mirror
		Xueqing Yan	Beam Chirp and electron rephasing to improve electron brightness and beam quality
		discussion	electron and positron sources **cross-fertilization with XFEL application of LWFA** Identify realistic time scales?
26-avr	**11:00-12:30**	**Modeling and testing of concepts, Diagnostics, Drivers**	
		David Bruhwiler	Simulation Codes - Introductory Overview
		Mike Downer	Single-shot diagnostics of LWFA structures: holography, shadowgraphy, streak camera, tomography, Faraday rotation
		Christina Swinson	10 um laser-wakefield mapping using an electron beam probe.
		Wim Leemans	Bella and kBella
		discussion	Key technologies: Laser and plasma sources Identify existing or new facilities to perform key experiments
26-avr	**14:00-16:00**	**Work session on parameter ranges, technologies, interfaces, strategies,**	
			laser parameters
			plasma source developments
			Identify panorama, what is in the making?
			fill in the spreadsheet table?
26-avr	**16:30-18:00**	**synthesis**	
			State of the art LWFA
			Main challenges 5y
			Main challenges 10y
			Long term view for HEP:
			Technologies to be developed

Current Status of LWFA Electron Bunch Properties

Mike DOWNER

Property	State of Art*	Reference	Remarks
Energy	**2 GeV** (± 5%, 0.1 nC) **3 GeV** (±15%, ~0.05 nC) **4 GeV** (±5%, 0.006 nC)	Wang (2013) - Texas Kim (2013) – GIST Leemans (2014) - 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 Transverse 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)
- Leemans, *PRL* **113**, 245002 (2014)
- 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

Current Status of LWFA Electron Bunch Properties

Mike DOWNER

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Energy	**2 GeV** (± 5%, 0.1 nC) **3 GeV** (±15%, ~0.05 nC) **4 GeV** (±5%, 0.006 nC)	Wang (2013) - Texas Kim (2013) – GIST Leemans (2014) …	…s
Energy Spread	**1%** (@ .01 nC, 0.2 GeV) **5-10%**	Rechati… m…	…r
Normalized Trans-verse emittance	~ **0.1 π mm** …		…nents at …solution limit
Bunch Duration		…goldt …xford (**OTR**) …016) – Tsinghua	Measurements at resolution limit
		…echatin (2009b) – LOA Couperus (2017) - HZDR	Beam-loading achieved. FOM: **Q/ΔE** ?
R…	…GeV …Hz @ ~ 1 MeV	Leemans (2014) - LBNL He – UMIch ('15); Salehi ('17) – UMd; Guénot ('17) -- LOA	Limited by lasers & gas targets

individual beam parameters are getting closer to values required by TeV collider…
… but rarely all at the same time

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- Geddes, *PRL* **100**, 215004 ('08)
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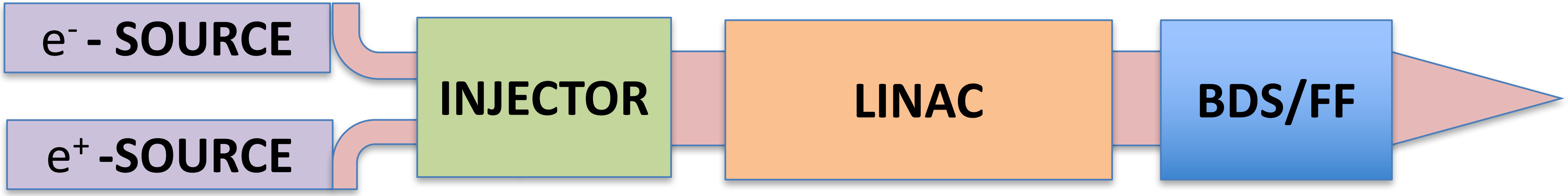
Current Status of LWFA Positron Properties: no results yet

general (trivial?) considerations on collider design



- **final focus requirements have to be "transposed" from ILC or CLIC**
- **some parametric studies (scalings) for LWFA linac designs exist**
- **E>100GeV => linac mainly using quasilinear LWFA => e^- ~ e^+**
- **most experimental progress is made on injector-type experiments: acceleration of e^- from rest (Non-linear)**
- **conventional e^- sources for ultra-short bunches (fs) problematic**
- **concepts for e^+ sources from LWFA are discussed, still far away from conventional e^+ sources**

define parameter/requirement interfaces between blocks

laser wakefield acceleration: frequent criticisms

- **beam parameters vary from shot-shot, day-to-day, site-to-site**

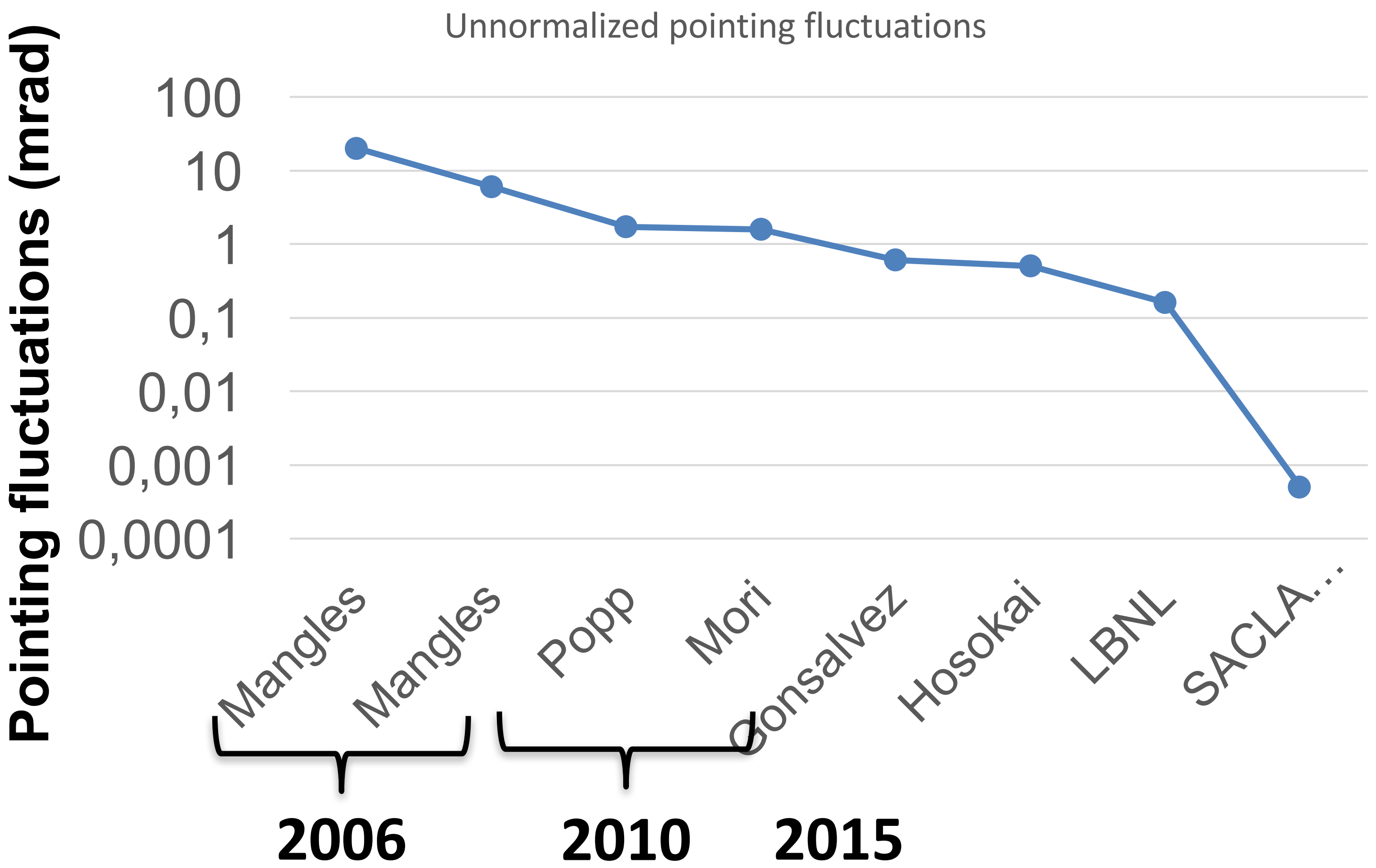
  => e.g. pointing fluctuations –> M Kando

  => need for reliable diagnostics and performance intercalibration

- **low spectral charge (dQ/dp) -> A Irman**
- **high energy spread -> rephasing -> Xueqing Yan**
- **Coulomb scattering on plasma ions degrades emittance -> Oznur Mete**
- **laser's are 1000 to 10000 less efficient drivers than RF**

Masaki KANDO

Pointing fluctuations

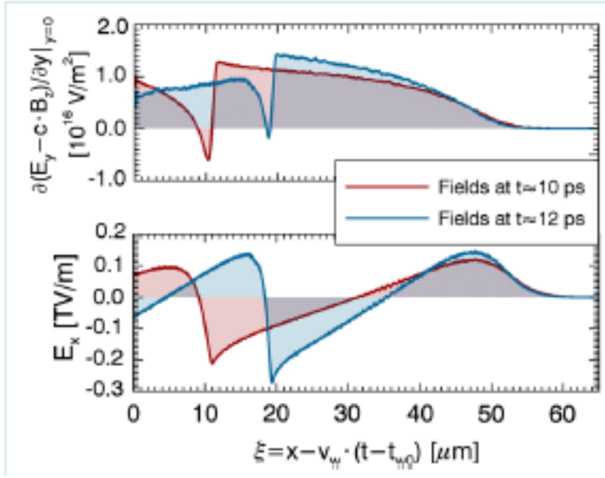


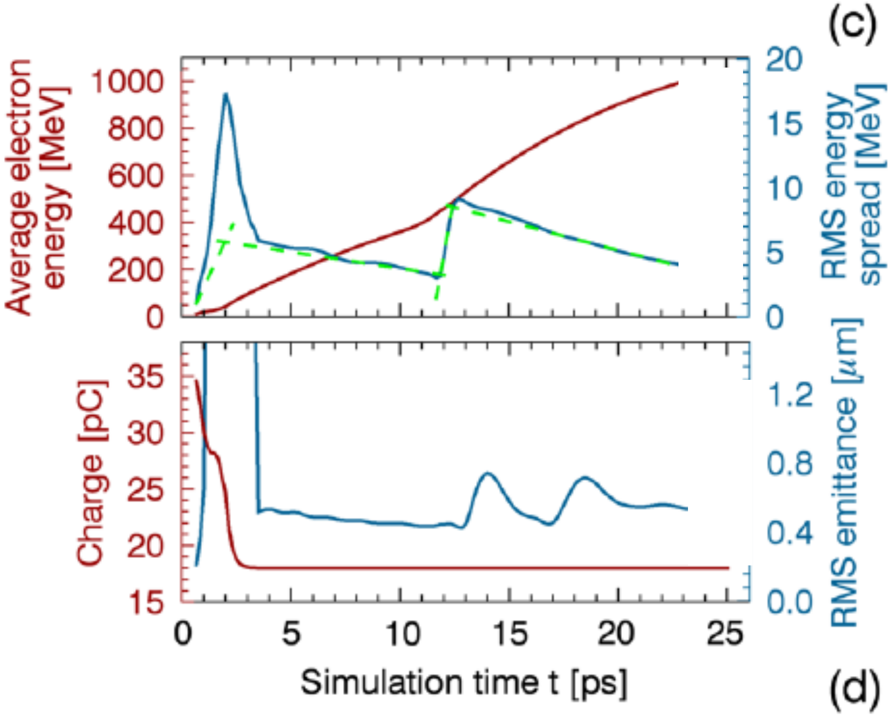
e- beam pointing fluctations ~ 100 x laser pointing fluctuations observed in controlled or self-injection, causes not fully understood systematic studies needed

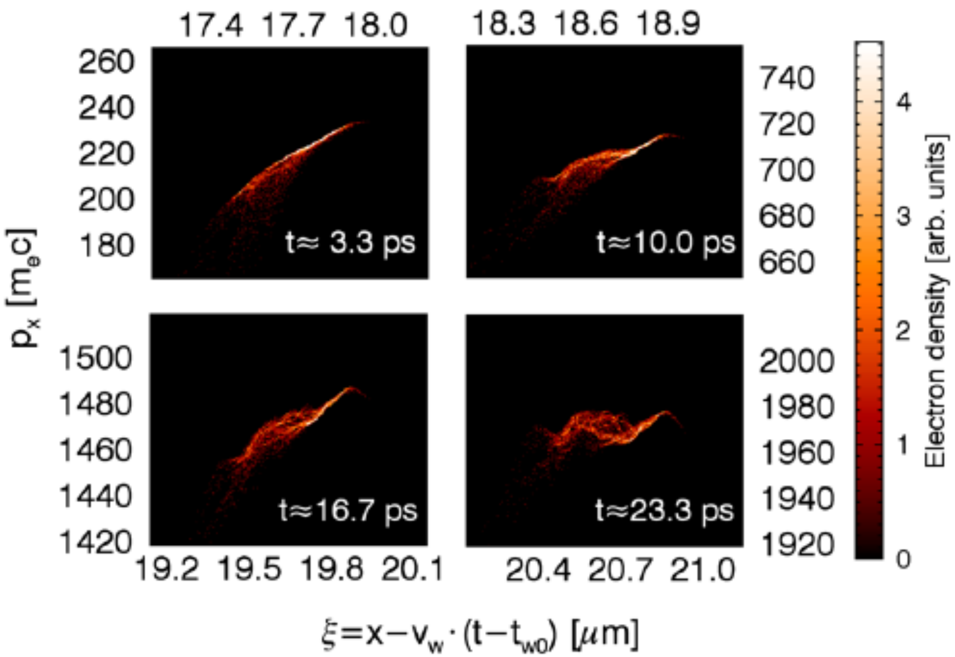
Beam Chirp and electron rephasing

- Energy spread ~0.5%
- Emittance ~0.5 um (RMS)
- Charge ~20pC
- Energy ~GeV

Xueqing YAN







Hu et al, Phys. Rev. Accel. Beams, 19, 091301(2016)

Multi-laser-bunch wake excitation

Simon HOOKER

Results for N ≈ 7-pulses in good agreement with linear theory

John Adams Institute for Accelerator Science

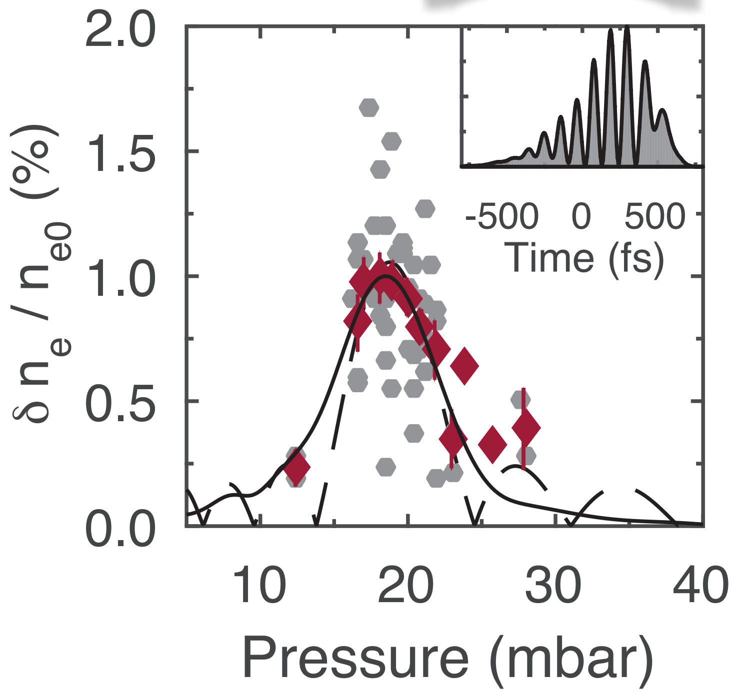
For train of identical drive pulses:

$$\left(\frac{\delta n_{\mathrm{e}}}{n_{\mathrm{e}0}}\right)_N \propto \left(\frac{\delta n_{\mathrm{e}}}{n_{\mathrm{e}0}}\right)_{N=1} \times \left|\frac{\sin\left(\frac{1}{2}N\omega_{\mathrm{p}0}\delta\tau\right)}{\sin\left(\frac{1}{2}\omega_{\mathrm{p}0}\delta\tau\right)}\right|$$

- Strong resonance observed for $N \approx 7$ pulses
- First demonstration of beat-wave with chirped laser pulses
- Good agreement with analytic expression above (dashed line)
- Better agreement with wake calculated for measured pulse train (solid line)

J. Cowley *et al. submitted*

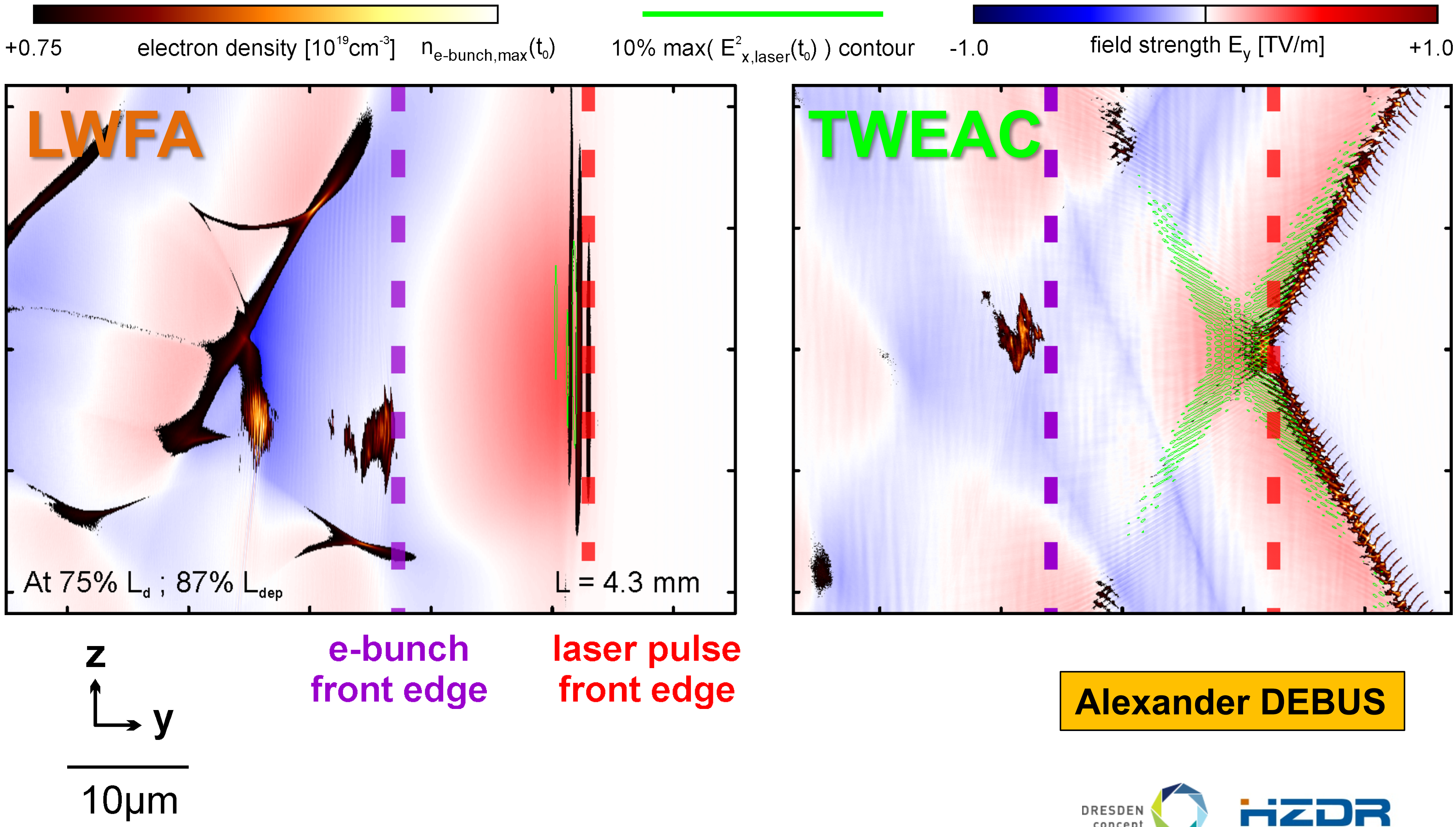
N:	~ 7
E:	170 mJ
w0:	(35 ± 5) µm
ζ:	1.3 ps
δτ:	(112 ± 6) fs



Simon Hooker,
University of Oxford

ANAR workshop, CERN
25 - 28 April 2017

TWEAC eliminates the dephasing and depletion limit.



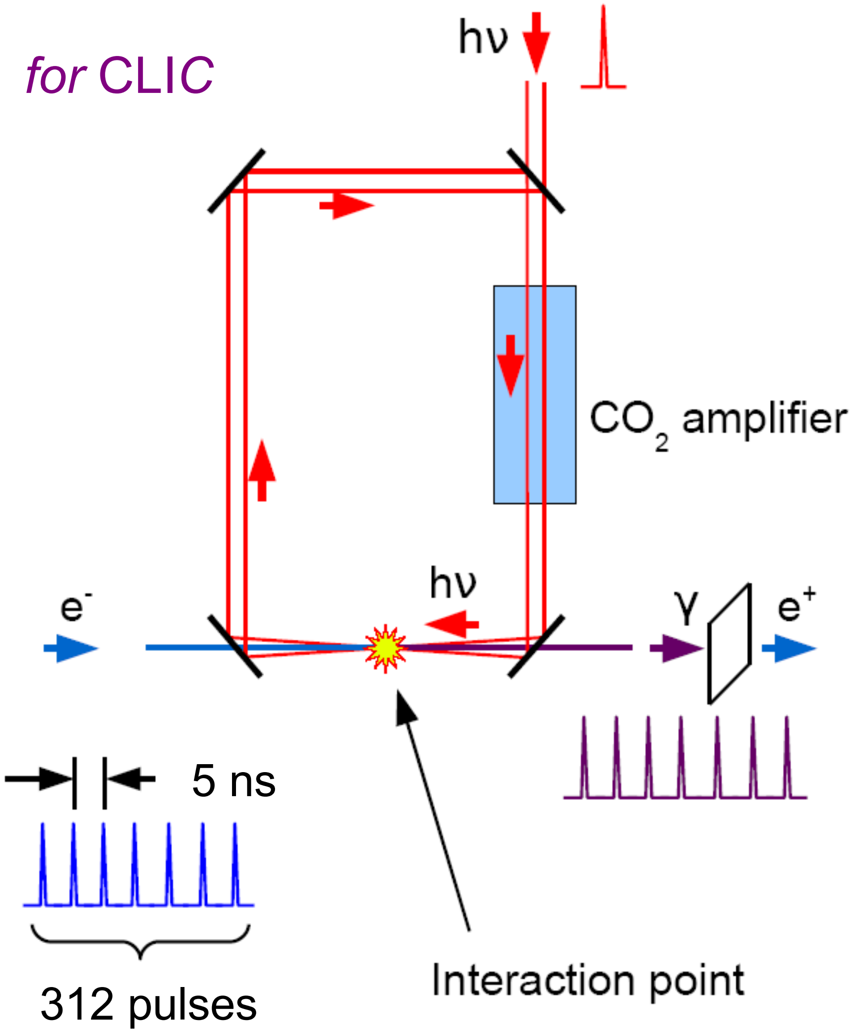
Alexander DEBUS

DRESDEN concept

HZDR

Concept of a high-repetition e^+-source

for CLIC



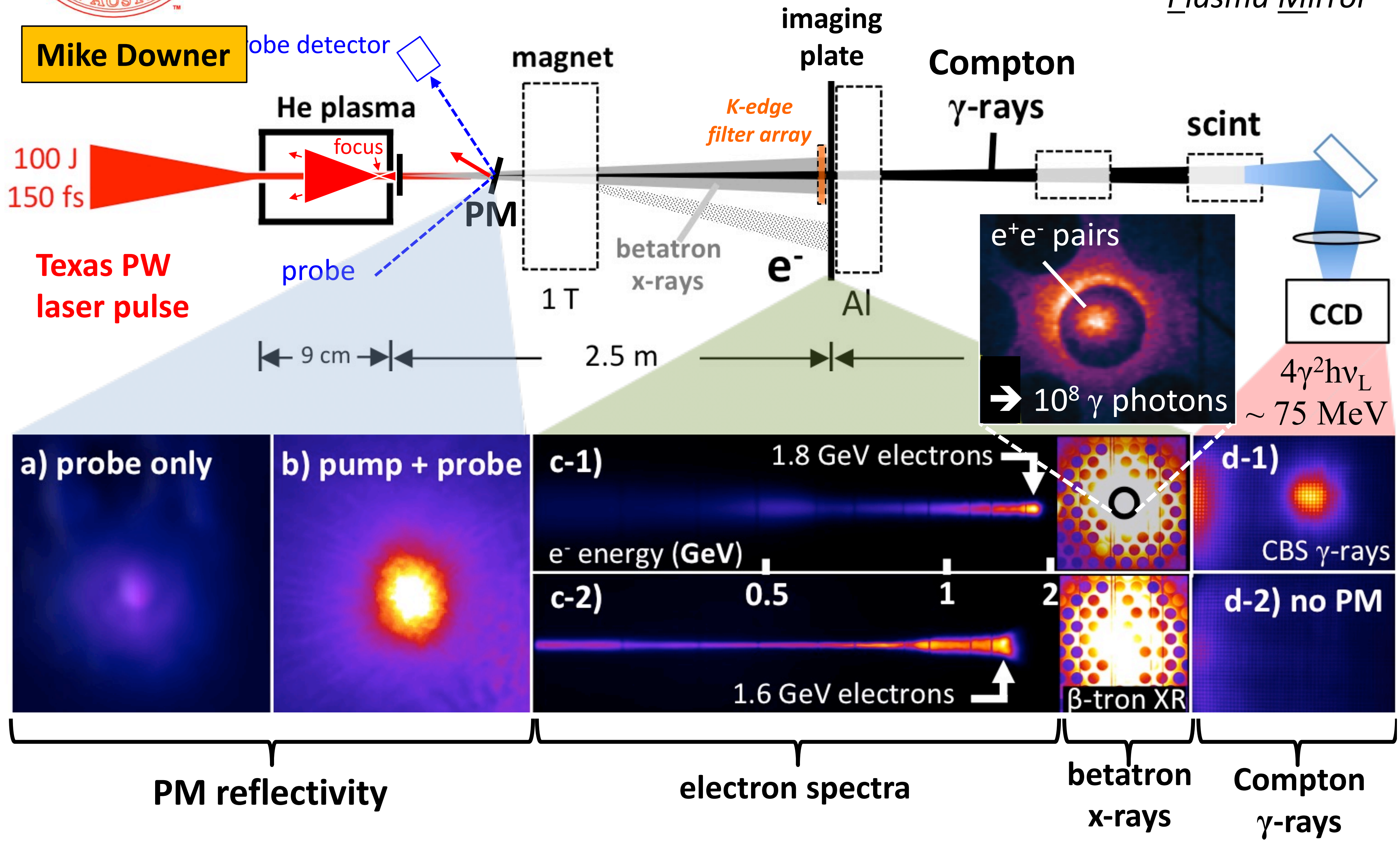
- V. Yakimenko and I. Pogorelsky, Phys. Rev. ST Accel. Beams **9**, 091001 (2006)
- We propose to multiply the Compton γ-source repetition rate by placing it inside the laser cavity.
- At each pass through the cavity the laser pulse interacts with a counter-propagating electron pulse generating γ-quanta via Compton scattering.
- Optical losses are compensated by intracavity amplifier.
- For CLIC need reformatting to 0.5 ns in a damping ring.

To increase γ-ray yield, we will move the PM to the LPA exit and exploit its focusing properties

J. M. Shaw *et al*., CLEO 2016 and AAC 2016

*Plasma Mirror

Mike Downer



List of Codes (courtesy of J.-L. Vay)

David BRUHWILE

Table 1. List of simulation PIC codes for the modeling of plasma accelerators.

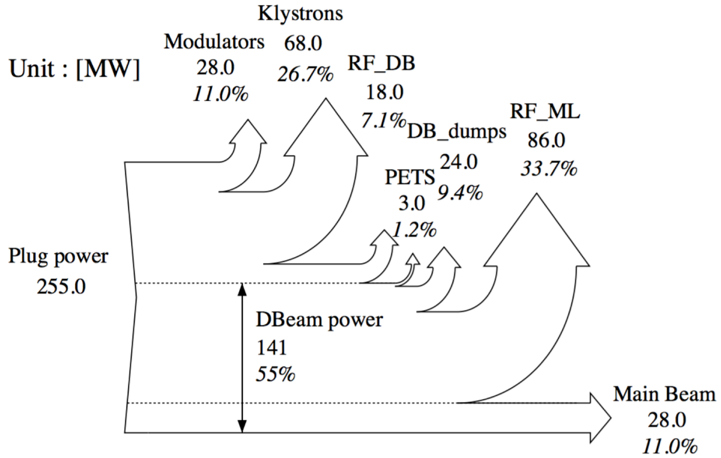
Code	Type	Website/reference	Availability/license
ALaDyn/PICCANTE	EM-PIC 3D	http://aladyn.github.io/piccante	Open/GPLv3+
Architect	EM-PIC RZ	https://github.com/albz/Architect	Open/GPL
Calder	EM-PIC 3D	http://iopscience.iop.org/article/10.1088/0029-5515/43/7/317	Collaborators/Proprietary
Calder-Circ	EM-PIC RZ^+	http://dx.doi.org/10.1016/j.jcp.2008.11.017	Upon Request/Proprietary
CHIMERA	EM-PIC RZ+	https://github.com/hightower8083/chimera	Open/GPLv3
ELMIS	EM-PIC 3D	http://www.diva-portal.org/smash/record.jsf?pid=diva2%3A681092&dswid=-8610	Collaborators/Proprietary
EPOCH	EM-PIC 3D	http://www.ccpp.ac.uk/codes.html	Collaborators/GPL
FBPIC	EM-PIC RZ^+	https://fbpic.github.io	Open/modified BSD
HiPACE	QS-PIC 3D	http://dx.doi.org/10.1088/0741-3335/56/8/084012	Collaborators/Proprietary
INF&RNO	QS/EM-PIC RZ	http://dx.doi.org/10.1063/1.3520323	Collaborators/Proprietary
LCODE	QS-PIC RZ	http://www.inp.nsk.su/~lotov/lcode	Open/None
LSP	EM-PIC 3D/RZ	http://www.lspsuite.com/LSP/index.html	Commercial/Proprietary
MAGIC	EM-PIC 3D	http://www.mrcwdc.com/magic/index.html	Commercial/Proprietary
Osiris	EM-PIC 3D/RZ^+	http://picksc.idre.ucla.edu/software/software-production-codes/osiris	Collaborators/Proprietary
PHOTON-PLASMA	EM-PIC 3D	https://bitbucket.org/thaugboelle/ppcode	Open/GPLv2
PICADOR	EM-PIC 3D	http://hpc-education.unn.ru/en/research/overview/laser-plasma	Collaborators/Proprietary
PIConGPU	EM-PIC 3D	http://picongpu.hzdr.de	Open/GPLv3+
PICLS	EM-PIC 3D	http://dx.doi.org/10.1016/j.jcp.2008.03.043	Collaborators/Proprietary
PSC	EM-PIC 3D	http://www.sciencedirect.com/science/article/pii/S0021999116301413	Open/GPLv3
QuickPIC	QS-PIC 3D	http://picksc.idre.ucla.edu/software/software-production-codes/quickpic	Collaborators/Proprietary
REMP	EM-PIC 3D	http://dx.doi.org/10.1016/S0010-4655(00)00228-9	Collaborators/Proprietary
Smilei	EM-PIC 2D	http://www.maisondelasimulation.fr/projects/Smilei/html/licence.html	Open/CeCILL
TurboWave	EM-PIC 3D/RZ	http://dx.doi.org/10.1109/27.893300	Collaborators/Proprietary
UPIC-EMMA	EM-PIC 3D	http://picksc.idre.ucla.edu/software/software-production-codes/upic-emma	Collaborators/Proprietary
VLPL	EM/QS-PIC 3D	http://www.tp1.hhu.de/~pukhov/	Collaborators/Proprietary
VPIC	EM-PIC 3D	http://github.com/losalamos/vpic	Open/BSD clause-3 license
VSim (Vorpal)	EM-PIC 3D	https://txcorp.com/vsim	Commercial/Proprietary
Wake	QS-PIC RZ	http://dx.doi.org/10.1063/1.872134	Collaborators/Proprietary
Warp	EM-PIC 3D/RZ^+	http://warp.lbl.gov	Open/modified BSD

EM = electromagnetic; QS = quasistatic; PIC = particle-in-cell; 3D = three-dimensional; RZ = axisymmetric; RZ^+ = axisymmetric with azimuthal Fourier decomposition.

J.-L. Vay and R. Lehe, "Simulations for Plasma and Laser Acceleration", Reviews of Accelerator Science and Technology **9**, 165 (2016).

Energy Efficiency chart

- driver = laser; structure = plasma
- RF Collider: also ancillary systems! Here: only main Linac
- energy recuperation (PV), plasma wake E sweep-up
- need for full energy balance of strawman design



	now	2022 (5y)	2027 (10y)	long-term
wall-plug →driver	0.1% 1)	3–10% 2)	>10% 3)	~50% TARGET
driver→structure	strong regime dependence non-linear: **10% (nC, GeV) lowQ** quasilinear régime: **?**	>10% gain tailoring		
structure→beam		> 3% 4)	optimal beam-loading	
driver→beam				L_{DEPLET}~L_{DEPHAS}: >50% possible?
total	10^{-4}—10^{-3}	1%		>20% TARGET

1) LBL: BELLA 70W/60kW (TiSa; flash pumped, SS pump lasers), double P with cooling
2) LBL: kBELLA (TiSa 0.8µm, Yb fiber pumped, coherently combined)
3) not based on TiSa! Yb 1.03µm, thin disc amplifiers, multipulse drivers
4) LBL aim for 10 GeV single stage: 10GeV 100pC w/30J Laser (optimal phase matching)

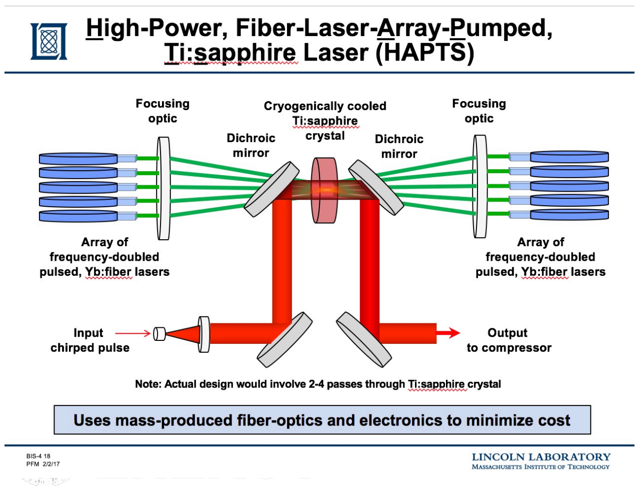
Laser driver: future improvements

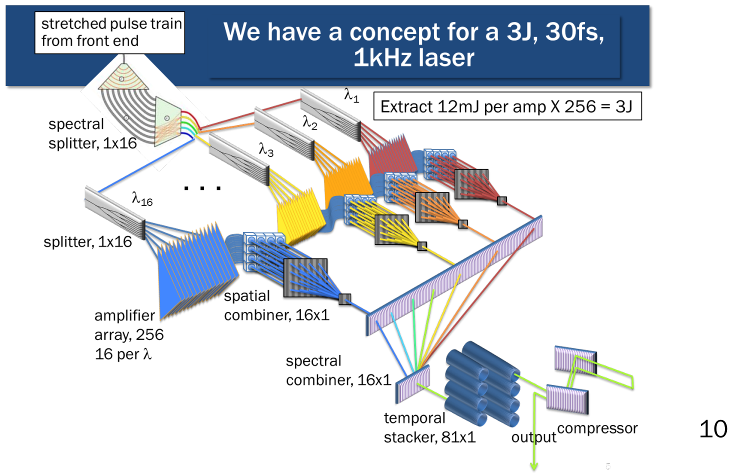
- **increase repetition rate:**
  - Higher rep-rate: present <10Hz (LWFA operation ~1Hz)
  - future needs: 100Hz (EuPRAXIA), 1kHz (kBELLA), and beyond
  - different techniques

k-BELLA: a high average power (multi-kW), high peak power laser system for kHz rep rate LPA

Wim LEEMANS

- High average power demonstrator for laser plasma accelerator technology:
  - kW-class ultrafast laser: 3 J at 1 kHz, suitable for driving 1 GeV linac at 1 kHz – opens many applications
  - Discussed in P5 and ARD HEPAP subcommittee reports,
  - Proposed to HEP as next major investment—on strategic roadmap
- Base technology options (more exist but no details yet):
  - Yb-fiber pumped Ti:sapphire (joint with MIT-LL and LLE): most mature
  - Coherently combined fibers (joint with UMichigan and LLNL)





Laser driver: future improvements

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  - different techniques

Wim LEEMANS

- **mode control and mode quality**
  - Most solid state lasers not gaussian
  - gaussian transverse profile best for guiding
  - energy outside central spot is detrimental to plasma structures with small apertures.
- **stability**
- **operational reliability**
- **lower wavelength (CO2 lasers: 10µm) -> Igor Pogorelsky**

collider parameter definition flow

particles

physics requirements
detector requirements/constraints

↓

beam at interaction point:
E, ΔE/E, (bunch rate), luminosity, background

↓

parameters of beam to final focus
(more generally: beam delivery system (BDS))

↓

accelerating section design :
beam out = f(beam in), E efficiency

↓

injector/ source: emittance, charge, rate
(for e^- and e^+,consider polarization)

parameters

Daniel SCHULTE

Interaction Point Beam Sizes

Parameter	Symbol [unit]	ILC	CLIC	LPA	PWFA	PWFAx	DLA
CMS energy	E_{cm} [GeV]	500	3000	3000	3000	3000	3000
Particl./bunch	N [10^9]	20	3.72	1.2	10	10	$3x10^{-5}$
Bunch length	σ_z [μm]	300	44	8	20	20	0.003
Energy spread	[%]	0.1	0.35	?	?	?	?
Emittances	$\varepsilon_{x,y}$ [nm]	10^4/35	660/20	50/5	10^4/35	2500/35	0.1/0.1
$N/(\varepsilon_x\varepsilon_y)$	[10^5/nm^2]	0.6	2.8	48	0.6	2.4	30
IP beam size	$\sigma_{x,y}$ [nm/nm]	474/6	40/1	18/0.5	194/1.1	97/1.1	0.75/0.75
Beta-functions	$\beta_{x,y}$[mm]	11/0.48	6/0.07	20?/0.15 ?	11/0.1	11/0.1	16.5/16.5

LPA has small emittances
- need new concept

DLA has very tiny emittance
- totally new concept required

Might be quite challenging
- in particular for positrons

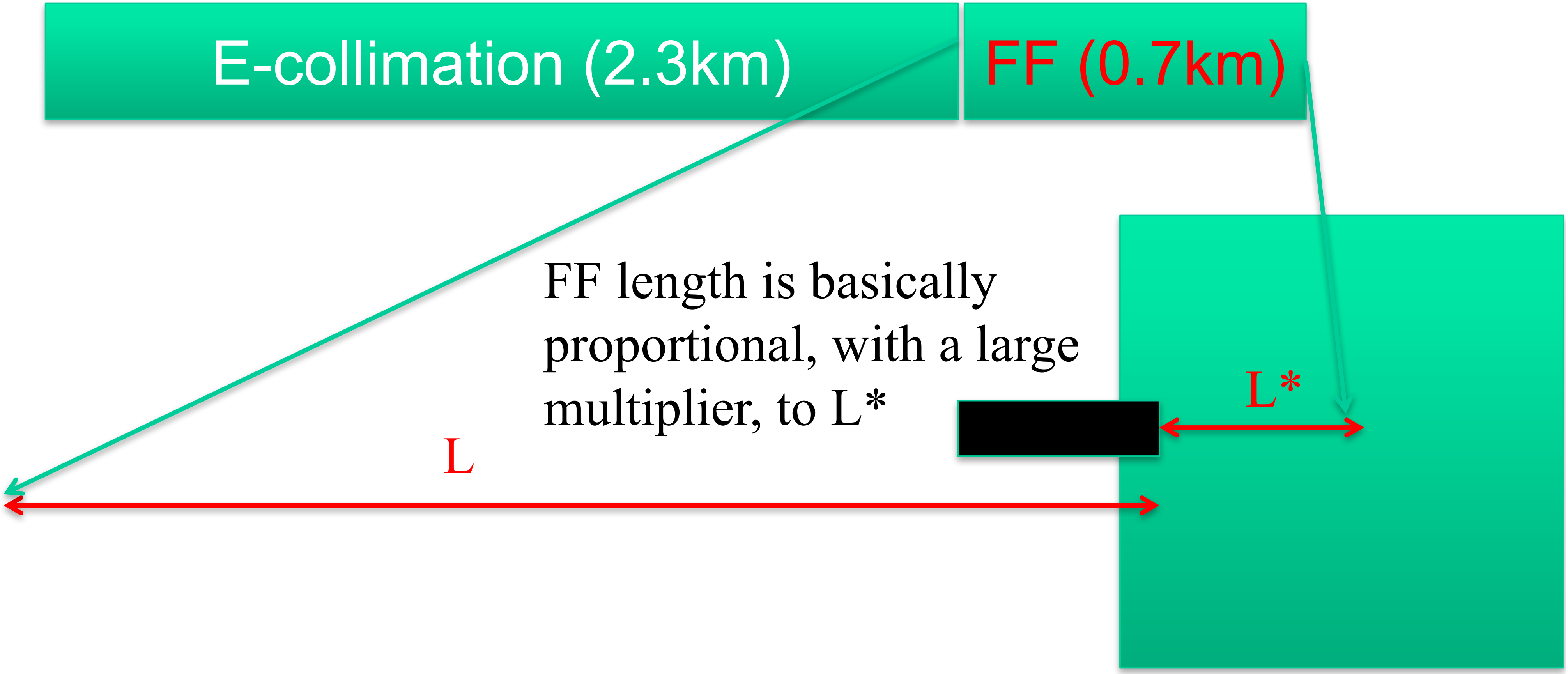
Some concern at high energy
- Radiation effects
- Non-linearities

In CLIC effective vertical beamsize is 140% of nominal value

⇒ May have to use smaller emittances

CLIC FF length – what defines it?

Andrei SERYI



FF length is basically proportional, with a large multiplier, to L*

To derive very rough scaling assume that chromaticity of final lenses (which is L*/beta*) dominates. This gives

$$L \sim L^* \ (L^* / \beta^*)\ \Delta E/E$$

Assume L*=5m, beta*=0.1mm, deltaE/E=0.2% => L~ 500m

proposed steps

- **Define collider case (E_{CMS},$\mathcal{L}$). Need HEP input.**
  do alternative physics cases exist (<100GeV)???
- **Define beam parameters into BDS (CLIC-like, alternative)**
  alternative BDS (for LWFA beams) needs dedicated study
- **Define optimized ideal "reference design" (strawman)**
  e.g. based on: Adli et al., SLAC-PUB-15426C , Schroeder et al., PRST-AB 15, 051301 (2012)
  What is the best we can expect? (like Carnot eff'cy in TD)
  loaded gradient target: x GeV/m
- **Define optimized realistic "reference design" (strawman)**
  assess effects of imperfections, inefficiencies
- **Define prototype LWFA accelerator section for demonstrator**
  known beam in , known beam out
- **Define e– injector prototype parameters**
  already for e–, classical v/s all optical

FCC (Future Challenge Chart)

Scientific bottleneck / challenge	Milestones		
	5 years	**5 - 10 years**	**10 - 20 years**
femtosecond Injector >200MeV performance charge, dE/E, pointing stability	dQ/Q<2%, 100 pC, dE/E<2%, dE0/E0<1%, do<0.1 mrad **(2/5)**	dQ/Q<2%, 100 pC, dE/E<2%, dE0/E0<1%, do<0.1 mrad **(5/5)**	All parameters, structured pulse? Polarized?
Repetition rate (laser)	>10 Hz	>100 Hz	>1 kHz
Repetition rate (experiment)	10 Hz	100 Hz	1 kHz
Efficiency (laser)	>1%	>10%	50%
Laser beam quality	>90% in design mode		
Scalable single stage	>10 cm, 0.1 GeV/cm	1 meter, 0.1 GeV/cm	1 meter, 0.1 GeV/cm
Staging/Transport	~unity charge throughput and emittance preservation	Scalability (multi-staging)	
Positron prod. & acceleration	Identify and test injection method	Acceleration demonstration (low emittance and dE/E)	Parity with electrons
Fluctuations and feedback control	chargex1, Ex2, E0x2, mradx2	Active control of multiple fluctuations	all factors 1.01
Efficient beamloading (longitudinal bunch shaping)	ramped or multi-pulses		

Further Challenges

Scientific bottleneck / challenge	Milestones		
	5 years	5 - 10 years	10 - 20 years
Diagnostic resolution (bunch length and emittance)	fsec resolution, 0.1 mm-mrad normalized	energy/phase correlation, single shot	
Diagnostic : plasma structure (single shot, high resolution)	Inline 1/2+1D	1 parameter in feedback loop	single shot 4D
Multi-bunch acceleration	Generation and separation control	Acceleration	
electron/positron polarization			
Fully predictive simulations			
Availability of test facilities			
Collider parameter (re)definition	Preliminary design study	CDR	TDR
BDS/FF design	Preliminary design study	CDR	TDR
LWFA collider baseline design	Preliminary design study	CDR	TDR

Conclusions/ Next steps

- **very active, many labs involved, variety of technologies**
- **work on Non-lin regime drives most of the progress**
- **laser technology is crucial**
- **plasma source technology has to follow rate step-up**
- **examine synergy with LWFA applications! (e.g. light source, HEP?)**
- **build on existing collider studies to broaden design study taken into account accelerator and detector constraints/alternatives**

- **write 5 page summary**
- **reiterate on “bottleneck/milestone” table**

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