

**WG5-PWFA:
Plasma wakefield Accelerators introduction,
status and objectives**

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J. Osterhoff (DESY)

P. Muggli (MPP,CERN)

WG5 organization



Purpose engage the PWFA community, in particular facility leaders as points of contact

WG leaders:

E. Gschwendtner (CERN)

J. Osterhoff (DESY)

P. Muggli (MPP,CERN)

Sub-WG leaders, from experimental programs

FACET-II	(SLAC)	M. Hogan, V. Yakimenko
FF>>	(DESY)	J. Osterhoff
SPARC_LAB	(INFN)	M. Ferrario
EuPRAXIA@SPARC_LAB	(INFN)	M. Ferrario
AWAKE	(CERN)	E. Gschwendtner/P. Muggli (MPP)
CLEAR	(CERN)	E. Adli (Oslo U.)
MAX IV	(MAX IV)	O. Lundh (Lund U.)
CLARA	(Daresbury Laboratory)	G. Xia (Manchester U.)

Possible application to:

✧ e^-/e^+ collider

✧ e^-/e^- collider

✧ γ/γ collider

✧ e^-/p^+ collider

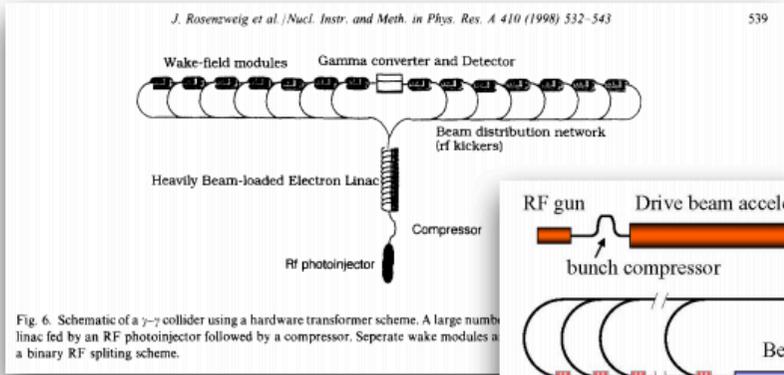
✧ μ -collider?

Note: do not directly address e^+ acceleration (WG8)

PWFA FOR e⁻/e⁺ COLLIDER

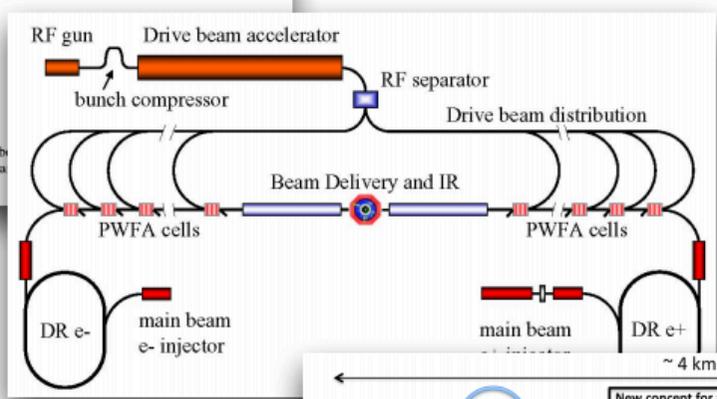
PWFA Research Roadmap for Electron Driver: Goal is to Get to a TeV Scale Collider for High Energy Physics

SLAC

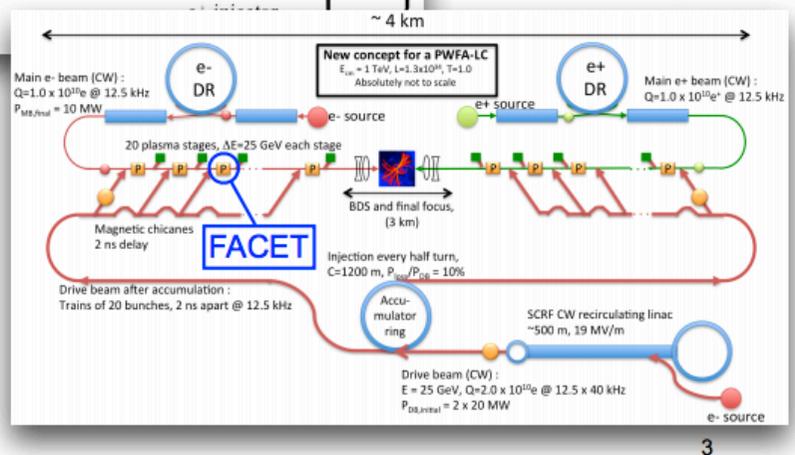


Rosenzweig *et al* (1998)

Fig. 6. Schematic of a γ - γ collider using a hardware transformer scheme. A large number of linacs fed by an RF photoinjector followed by a compressor. Separate wake modules use a binary RF splitting scheme.

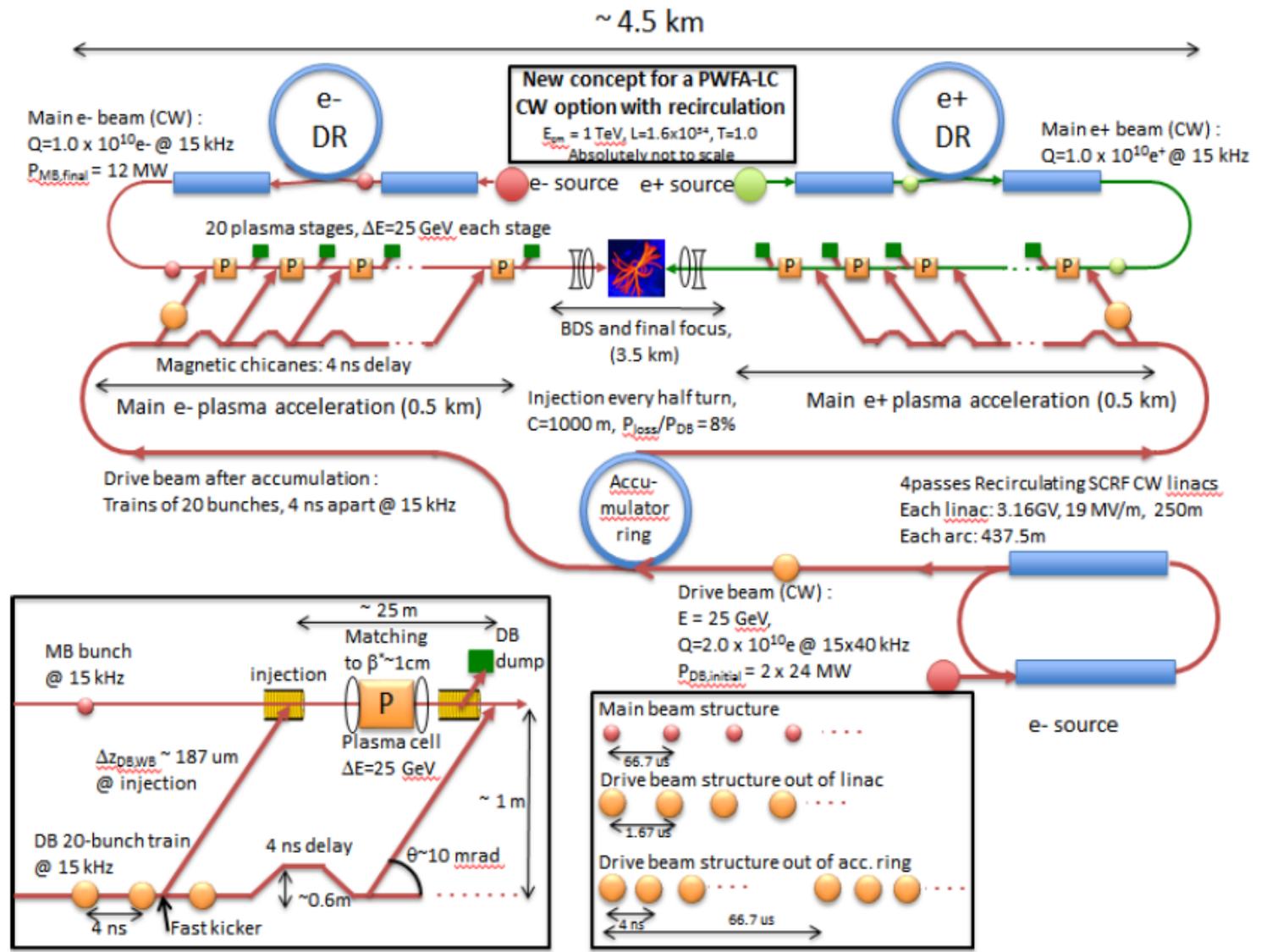


Seryi *et al* (2008)



PWFA-LC concepts highlight key issues and help us prioritize our research programs e.g. efficiency, positrons

Figure 1: Layout of a 1 TeV PWFA Linear Collider



Mega Table

Table 1: Main parameters at various beam collision energies

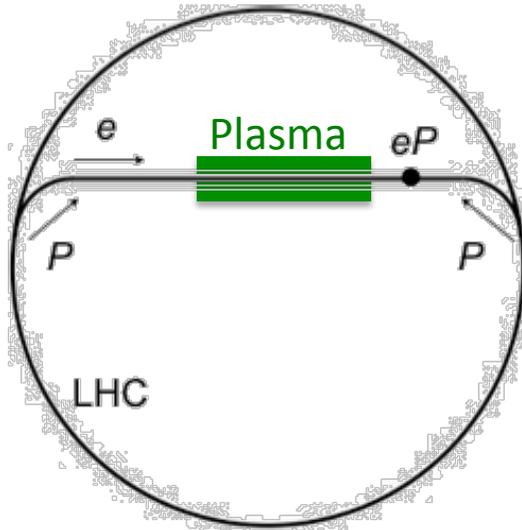
E at IP, CM	GeV	250	500	1000	3000	6000	10000
N _e experimental bunch		1.0E+10	1E+10	1.0E+10	1.0E+10	1.0E+10	1.0E+10
Main beam bunches / train		1	1	1	1	1	1
Main beam bunch spacing,	nsec	3.33E+04	5.00E+04	6.67E+04	1.00E+05	1.43E+05	2.00E+05
Repetition rate,	Hz	30000	20000	15000	10000	7000	5000
n exp.bunch/sec,	Hz	30000	20000	15000	10000	7000	5000
Avg current in exp beam	uA	48.06	32.04	24.03	16.02	11.21	8.01
peak current in exp beam	A	4.81E-05	3.20E-05	2.40E-05	1.60E-05	1.12E-05	8.01E-06
Power in exp. beam	W	6.0E+06	8.0E+06	1.2E+07	2.4E+07	3.4E+07	4.0E+07
Effective accelerating gradient	MV/m	1000.00	1000.00	1000.00	1000.00	1000.00	1000.00
Overall length of each linac	m	125	250	500	1500	3000	5000
BDS (both sides)	km	2.00	2.50	3.50	5.00	6.50	8.00
Overall facility length	km	2.25	3.00	4.50	8.00	12.50	18.00
IP Parameters							
Exp. bunch gamepsX,	m	1.00E-05	1.00E-05	1.00E-05	1.00E-05	1.00E-05	1.00E-05
Exp. bunch gamepsY,	m	3.50E-08	3.50E-08	3.50E-08	3.50E-08	3.50E-08	3.50E-08
beta-x,	m	1.10E-02	1.10E-02	1.10E-02	1.10E-02	1.10E-02	1.10E-02
beta-y,	m	1.00E-04	1.00E-04	1.00E-04	1.00E-04	1.00E-04	1.00E-04
sigx,	m	6.71E-07	4.74E-07	3.35E-07	1.94E-07	1.37E-07	1.06E-07
sigy,	m	3.78E-09	2.67E-09	1.89E-09	1.09E-09	7.72E-10	5.98E-10
sigz,	m	2.00E-05	2.00E-05	2.00E-05	2.00E-05	2.00E-05	2.00E-05
Y		8.44E-02	2.39E-01	6.75E-01	3.51E+00	9.93E+00	2.14E+01
Dx		1.03E-02	1.03E-02	1.03E-02	1.03E-02	1.03E-02	1.03E-02
Dy		1.83E+00	1.83E+00	1.83E+00	1.83E+00	1.83E+00	1.83E+00
Uave		0.17	0.48	1.35	7.00	19.79	42.59
delta_B	%	2.75	6.66	12.76	23.10	27.67	29.88
P_Beamstrahlung [W]	W	1.7E+05	5.3E+05	1.5E+06	5.6E+06	9.3E+06	1.2E+07
ngamma		0.57	0.73	0.88	1.05	1.11	1.14
Hdx		1.00	1.00	1.00	1.00	1.00	1.00
Hdy		4.62	4.62	4.62	4.62	4.62	4.62
Hd		1.7	1.7	1.7	1.7	1.7	1.7
Geometric Lum (cm ⁻² s ⁻¹)		9.41E+33	1.25E+34	1.88E+34	3.76E+34	5.27E+34	6.27E+34
Total Luminosity (cm ⁻² s ⁻¹)		1.57E+34	2.09E+34	3.14E+34	6.27E+34	8.78E+34	1.05E+35
Integrated Lum. (fb ⁻¹ per 1E7s)		157	209	314	627	878	1045
Lum1%		9.41E+33	1.15E+34	1.57E+34	2.51E+34	3.07E+34	3.14E+34

μs spacing for plasma and drive beam linac

Plasma parameters:
 $L_p = 3.3\text{m}$
 $G_{\text{peak}} = 7.6\text{GeV/m}$
 $\Delta E = 25\text{GeV/stage}$



p⁺-DRIVEN PWFA FOR e⁻/p⁺ COLLIDER



- Emphasis on using current infrastructure, i.e. LHC beam with minimum modifications.
- Overall layout works in powerpoint.
- Need high gradient magnets to bend protons into the LHC ring.
- One proton beam used for electron acceleration to then collider with other proton beam.
- High energies achievable and can vary electron beam energy.
- What about luminosity ?
- Assume

$$\mathcal{L} = f \frac{N_e \cdot N_p}{4\pi\sigma_x \cdot \sigma_y}$$

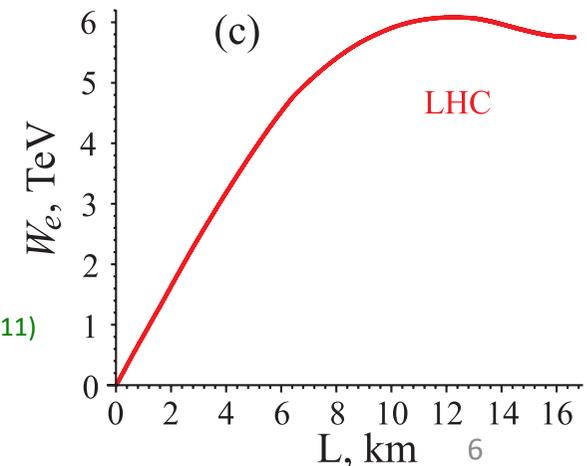
$$\approx 5 \cdot 10^{28} \text{ cm}^{-2} \text{ s}^{-1}$$



- ~3000 bunches every 30 mins, gives $f \sim 2$ Hz.
- $N_p \sim 4 \times 10^{11}$, $N_e \sim 1 \times 10^{11}$
- $\sigma \sim 4 \mu\text{m}$

simulation of existing LHC bunch in plasma with trailing electrons ...

A. Caldwell, K. V. Lotov, Phys. Plasmas **18**, 13101 (2011)



Parameters:

7 TeV LHC p^+ bunch \rightarrow 3 TeV e^- bunch (p^+ -PWFA)

CM Energy: 9 TeV (30 times greater than HERA)

Integrated luminosity: $10\text{--}100 \text{ pb}^{-1}$

Physics case:

Parton momentum fractions, x , down to about 10^{-8} are accessible for photon virtualities, Q^2 , of 1 GeV^2 .

The energy dependence of hadronic cross sections at high energies, such as the total photon–proton cross section, which has synergy with cosmic-ray physics, can be measured and QCD and the structure of matter better understood in a region where the effects are completely unknown.

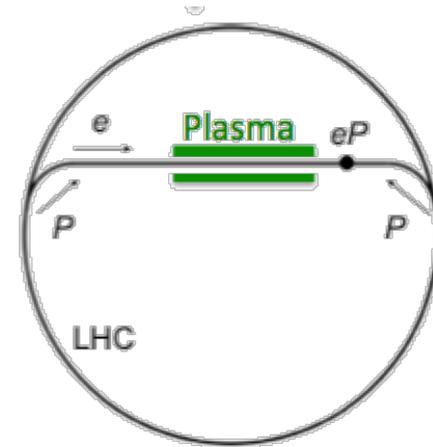
Searches at high Q^2 for physics beyond the Standard Model will be possible, in particular the significantly increased sensitivity to the production of leptoquarks.

Workshops to build physics case with particle

physics community: Munich, June 2017

2018 Workshop planned

A. Caldwell, M. Wing, Eur. Phys. J. C (2016) 76:463



Eur. Phys. J. C (2016) 76:463

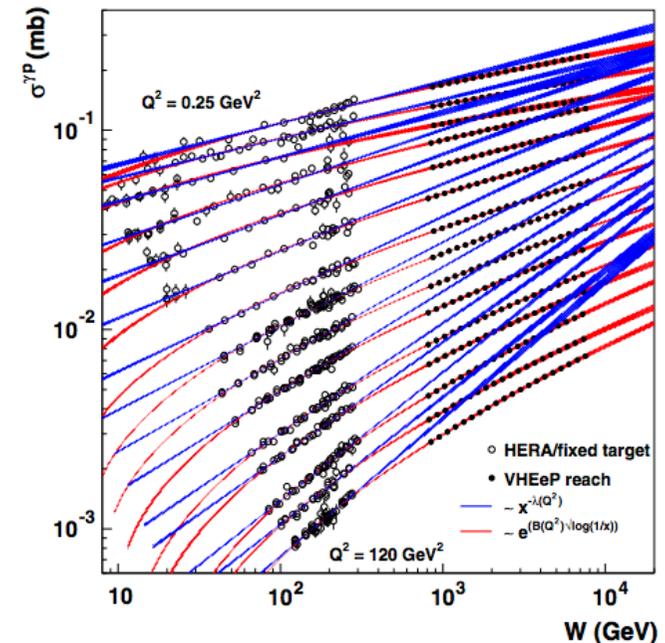


Fig. 8 Measurements (*open points*) of $\sigma^{\gamma p}$ versus W for $0.25 < Q^2 < 120 \text{ GeV}^2$ from HERA and fixed-target experiments. The *blue lines* show fits to the data, performed separately for each Q^2 value, of the form given in Eq. 8. The *red lines* show fits of the form given in Eq. 9. The reach of VHEeP is shown as projected data points (*closed points*). The points are placed on the *red curve*. The uncertainties are assumed to be of order 1 %, given the increased cross section expected and similar systematics to those at HERA and are not visible as *error bars* on this plot

Applications:

e^-/e^+ collider:

- e^+ acceleration
- Very low emittance
- Efficiency very important ...
- Very high energy ($>3\text{TeV}$)
- Staging
- Large peak gradient/high plasma density (10^{16}cm^{-3}), small sizes and times
- Single bunch/forced regime

e^-/p^+ collider:

- No need for e^+ acceleration
- Larger beam size at collision point, larger emittance beam
- Efficiency not important ...
- High energy (3TeV)
- No staging but very long plasma
- Large average gradient/low plasma density ($\sim 10^{15}\text{cm}^{-3}$), larger sizes and times
- Multi-bunch, SSM

Color scheme:

Good, done, easy, low priority

No so good, not done, challenging but doable, urgent but not too much

Serious challenge, facility not available, urgent

Note!



Goals:

Determine what are the (scientific) topics to be addressed

Determine their state of advancement (achieved, to be achieved in ..., challenge)

Determine priorities

Determine timescales

Identify facilities that are available

Identify (additional) facilities that are needed for topics not covered

Determine where we are in terms of proposing a design. Are we?

Determine R&D needed, with priorities

Determine parameters for which a PWFA-based collider design is better than a conventional design (high energy?)

Fill mega-table

Starting the writing of document for ESG 2018

Long term goal:

Better understand collider designs (optimization and compromise)

Take advantage of the large overlap with the “conventional” accelerator community

Design collider around the plasma



Achievements:

Large accelerating gradient: $>50\text{GeV/m}$

Large energy gain: 42GeV

Acceleration of witness bunch, finite energy spread

Energy transfer efficiency

Beam loading

PWFA issues, single stage (physics, talk by M. Hogan):

Emittance preservation, so far: μm -level, need nm -level, need single-shot diagnostic

Beam-beam efficiency

$\Delta E/E$, Beam Loading

External injection

Issues with collider parameters:

Hosing/BBU: μm -level transverse motion with μm -size bunch (talk by T. Mehrling)

Staging: concepts exist ... (talk by E. Adli)

Spin polarization preservation (talk by J. Vieira)

Ion motion

Plasma with MW beam power

Plasma parameters (density uniformity, etc., talk by N. Lopes)

Plasma ramp tailoring for emittance preservation with $\Delta E/E \sim \%$

Plasmas with collider bunches (ionization, etc.)

Plasma optics?

Drive beam: CLIC-like (talk by D. Schulte)

Witness bunch source (e^-), damping ring? Plasma (talk by B. Hidding)?



Facilities and stated main goals

FACET-II (SLAC)	PWFA, High Intensity e^- & e^+ beam driven experiments
FF>> (DESY)	High average power PWFA and LWFA , FEL
SPARC_LAB (INFN)	PWFA and LWFA , FEL
EuPRAXIA@SPARC_LAB (INFN)	PWFA and LWFA , FEL
AWAKE (CERN)	Electron acceleration on p^+ -driven wakes
CLEAR (CERN)	Instrumentation, irradiation, AA technology
MAX IV (MAX IV)	PWFA, Soft X-FELs
CLARA (Daresbury Laboratory)	PWFA, FEL test facility

e^- -beam facilities are few and at “national laboratories”

PWFA may not be main focus (Dielectrics, LWFA injector, ...)

HEP applications may not be the main focus

FEL still seems to be a main topic (reach and applications/impact)

Only one facility provides e^+ bunch (not discussed, WG8)

No facility offers collider-like W-bunches

Talk by M. Hogan

EuPraxia: seems to be more oriented towards LWFA, though PWFA is an option

Do (current) facilities address PWFA issues?

	FACET-II	FF>>	INFN- SPARC_LAB	INFN- EuPRAXIA@S PARC_LAB	AWAKE	CLEAR	MAX IV	CLARA
Emittance Preservation	Yes	Yes	Yes	Yes	Yes	NA	Yes	Yes
Efficiency	Yes	Yes	NA	Yes	NA	NA	Yes	NA
ΔE/E	Yes	Yes	Yes	Yes	Yes	Few per mille possible	Yes	< 1%
Beam Loading	Yes	Yes	Yes	Yes	Yes	NA	Yes	Yes
Efficiency	Yes	Yes	NA	Yes	NA	NA	Yes	NA
Scattering	NA	NA	NA	Maybe	NA	NA	TBD	NA
External Injection	Yes	Yes	No	No	Yes	Yes	No	No
Hosing/BBU	Yes (short range)	Yes (short range)	Maybe	Yes	Yes, major (long bunch), long range	No	Yes	NA
Staging	No	No	No	Maybe	NA, single plasma	No	No	No
Spin Polarization Preservation	No	No	No	No	No	NA	No	No
Ion Motion	Yes	Maybe	Maybe	Maybe	Yes, major, long bunch	NA	TBD	No
High Average Power	No	Yes	NA	No	Maybe	NA	No	NA

PWFA related issues are addressed in experiments

Collider-related issues need collider beam parameters for experiments

Issues must be addressed in theory and simulations whenever possible



Facilities bunch parameters

	FACET-II	FF>>	INFN- SPARC_LAB	INFN- EuPRAXIA@S PARC_LAB	AWAKE	CLEAR	MAX IV	CLARA
Planned operation	2019-2026	2018 - 2027	2017-2022 SPARC_LAB,	2022-2032 EuPRAXIA@SP ARC_LAB	start 2016	mid 2017	TBD	2020
User facility?	Yes	No	no	yes	No	Yes	No	Partially
Unique contribution	Highest Energy, peak-current electrons. Positrons.	<= MHz rep. rate, Up to <=100 kW average power, ~1 fs resolution longitudinal bunch diagnostics, FEL-gain tests	PWFA with COMB beam, LWFA with external injection, test with FEL	X-band Linac, PWFA with COMB beam, LWFA with external injection, test with FEL	proton bunch driver, single plasma, large average gradient	Rapid access/operation cycle	Low emittance, short pulse, high-density e-beam	ultrashort e-bunch
Current status of facility (end of 2017)	Construction	Construction almost complete (done in Feb 2018)	PWFA under test, LWFA external injection under commissioning	Conceptual Design Report almost ready	running + commissioning, shut down 2019-20	Running	Planning and design	Construction
Driver energy	10GeV	0.4 - 1.5 GeV	150 MeV	600 MeV	400GeV	200 MeV	3 GeV	240 MeV
External Injection	Yes	Yes	No	No	Yes	Yes	No	No

Only four facilities operate at high energy, >1GeV, energy gain >1GeV

Only three of them operate with external injection

Other facilities are key to test other issues



Plasma Sources

	FACET-II	FF>>	INFN- SPARC_LAB	INFN- EuPRAXIA@SP ARC_LAB	AWAKE	CLEAR	MAX IV	CLARA
PLASMA:								
Type	Li oven, Hydrogen,...	Hydrogen, noble gases, nitrogen, ... ionized by beam, laser or discharge	Hydrogen, Capillary Discharge	Hydrogen, Capillary Discharge	Laser Ionized Rubidium Vapor	Ar, He capillary	Hydrogen and o	He, capillary
Density	1E15-1E18/cc	1E15-1E18/cc	1E16-1E18/cc	1E16-1E18/cc	1E14-1E15/cc	1E16-1E18/cc	1E15 - 1E18/cc	1E16-1E18/cc
Length	10-100cm	1-30cm	3 cm	>30 cm	10+m	5-20 cm	10 - 50 cm	10-30 cm
Accelerating Gradient	10+GeV/m peak	10+ GeV/m peak	>1 GeV/m	>1 GeV/m	1GeV/m average	NA	10+ GV/m at	few GeV/m
Expected Energy Gain	~10GeV	~1.5 GeV	40 MeV	>500 MeV	1+GeV	NA	3 GeV	200 MeV
Plasma Tapering	Yes	Yes	yes	yes	Yes	NA	Yes	

Plasma sources for single event ~10-20GeV energy gain over m-scale exist

Plasma tailoring is very important for staging emittance preservation

Is pre-ionization necessary? Greatly simplifies if not ..

High repetition rate, high average power, zillions events?

Priorities

Accelerating gradient	L	values routinely achieved
Emittance preservation	H	with μm and nm-emittance values
Beam-beam efficiency	H	unshaped and shaped bunches
Energy spread	M	%-level, unshaped, beam-loading
Staging	H	length for average gradient, bunch quality, W-D separation/combination
Drive beam	M	CLIC-like or SC
Main or witness bunch	M	conventional, damping ring, shaping?
Hosing BBU	H	not observed with μm -emittance, severe with nm-emittance?
Tolerances	M	technology
Stability/reproducibility	M	technology
Plasma source	H	operation with MW average power beams, energy density
Plasma entrance/exit	H	preservation of emittance with %-level $\Delta E/E$
Diagnostics	H	for demonstration of emittance preservation
Optimization	M	$k_{\text{pes}} \sigma_z, k_{\text{pes}} \sigma_z$, experiment operate near optimum regime
High average power	H	plasma issue, plasma source issue

Priority for the workshop: more green fonts ... when?

Determine real priorities (life or death of the concept if not)

Outlook

	5Y	10Y	10 ⁺ Y
Accelerating gradient	~10GeV		
Emittance preservation	μm-rad	μm-rad	nm-rad
Beam-beam efficiency	50%	50%	>50%, shaped bunches
Energy spread	%-level, unshaped, loading		<1% shaped bunches
Staging	Concepts	->	requires facility 2D+W @GeV energies
Drive beam	Concepts	->	requires test facility, CTF-like
Main or witness bunch	Shaping	->	requires test facility, CTF-like
Hosing BBU	No hosing	->	requires collider-like W-bunch
Tolerances	Simulations	->	requires test facility, CTF-like
Stability/reproducibility	Simulations/test	->	requires test facility, CTF-like
Plasma source	Test with multiple D, fluid simulations		requires test facility/laser
Plasma entrance/exit	Designs/experiments		->
Diagnostics	Develop/test , optical?		Adapt to nm-rad levels
Optimization	Continued	->	Test

- ✧ Experimental parameters are limited (not collider-like)
- ✧ Strong need for a collider-like-beam facility
- ✧ Strong need for modeling ...

Program: 1-2 talks per session and mucho discussions



- Session 1 9:00-10:15: 'Strategy'
9:00-9:20: Presentation by WG leaders
9:20-10:15 Discussion
- Session 2 10:15-11:45: 'Plasma based injectors'
10:15-11:15: 'Plasma based injector concepts and beam quality', B. Hidding
11:15-11:45 Discussion
- Session 3 13:00-15:00, 'Drive beam acceleration design', joint with WG2
13:00-13:30 'extension of CLIC-drive beam concept to 20 GeV for a PWFA-based collider', Daniel Schulte
13:30-13:50: 'Origins and mitigation strategies of beam centroid offsets to minimize hosing' Vladyslav Libov
13:50-15:00: discussion
- Session 4 15:30-18:00, Jointly with WG1 and WG2
'Beam driven PWA performance expectations' , J. Osterhoff:
'proton driven PWA schemes', E. Gschwendtner
+WG2
- Session 5 10:45-12:15, 'Positron acceleration', joint with WG8
Discussion
- Session 6 13:30-15:30, 'Beam quality preservation and staging'
13:30-13:50: 'Emittance preservation in plasma wakefield accelerators' T. Mehrling
13:50-14:10: 'Staging of PWAs', E. Adli
14:10-14:30: 'Polarization preservation', J. Vieira
14:30-15:30: Discussion
- Session 7 16:00-18:00, 'Identification of possible facilities and next steps'
16:00-16:30: 'Overview of (current and future) PWFA facilities and their unique capabilities', M. Hogan
16:30-18:00: Discussion and wrap-up.

Of course ... all of this to ...

Charge to the working groups:

- Identify physics programme
- Identify scientific objectives and challenges of advanced accelerators
- Identify an Advanced Accelerator Project (medium/long term)
- Identify required high priority R&D, with possibly the construction of a test facility
- Identify partners and cost of R&D

Detailed charge:

- Identify parameters/elements necessary for the scheme
- Determine to what extent they have been proved and demonstrated
- Evaluate likelihood and timescales for testing/proving solutions
- Identify key experiments to be performed
- Identify existing or new facilities to perform key experiments
- Identify realistic time scales
- Identify panorama, what is in the making?

Main topics:

Inter-stage, plasma+conventional:

- Plasma ramp tailoring
- Conventional optics
- Injection/extraction/through
- Beam quality preservation

Plasma source:

- Plasma ramp tailoring
- Uniformity, beam quality
- High average beam power
- Gzillion events

Addition:

- Positrons
- Polarization

Collider-like injector, nm emittance:

- Emittance preservation
- BBU/hosing
- Ionization

Bunch sources, conventional? Plasma?:

- Drive beam
- Witness beam, plasma injector

Parallel:

- Tolerances
- Stability
- Reproducibility



Proposal, to be discussed

Single stage PWFA challenges addressed with current facilities

Collider-related challenges:

- Collider W-bunch source
- Collider beams: BBU/hosing, emittance preservation, efficiency, ionization, ... and combinations
- Staging: beam quality, average gradient
- Positrons

Many W-bunch issues similar LWFA-PWFA

Propose:

- Strong R&D program(s)
- Strong simulation program(s)
- 50-100GeV, facility to test the above collider challenges, as a principle test for a collider
- Need a team dedicated to working on collider issues



Proposal, to be discussed

Single stage PWFA challenges addressed with current facilities

Collider-related challenges:

Let's get to work!

- Strong simulation program(s)
- 50-100GeV, facility to test the above collider challenges, as a principle test for a collider
- Need a team dedicated to working on collider issues