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(Werner-Heisenberg-Institut)

Progress on Novel Accelerator Techniques

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CERN

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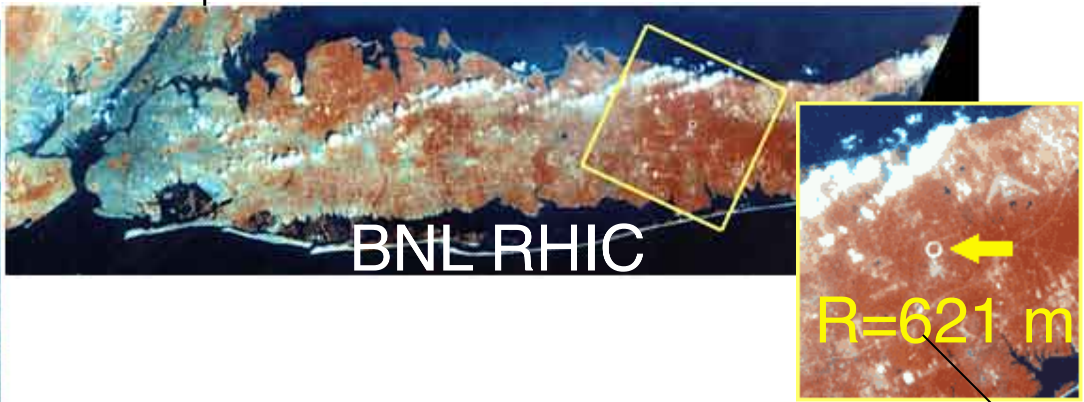
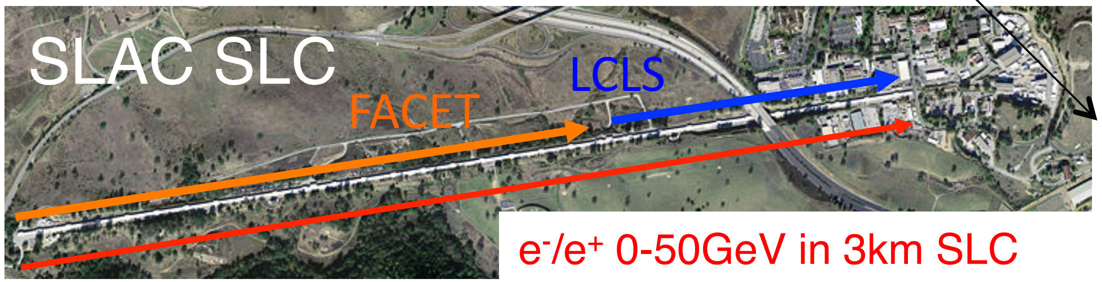
PARTiCLE ACCELERATORS

"The 2.4-mile circumference RHIC ring is large enough to be seen from space"





e^-/e^+ 0-50GeV in 3km SLC
e^-/e^+ 0-20GeV in 2km FACET
e^- 0-14GeV in 1km LCLS

- Some of the largest and most complex (and most expensive) scientific instruments ever built!
- All use RF technology to accelerate particles
- Can we make them smaller (and cheaper) and with a higher energy?

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PARTICLE ACCELERATORS

Light particles (e^-/e^+) accelerator
limited by synchrotron radiation

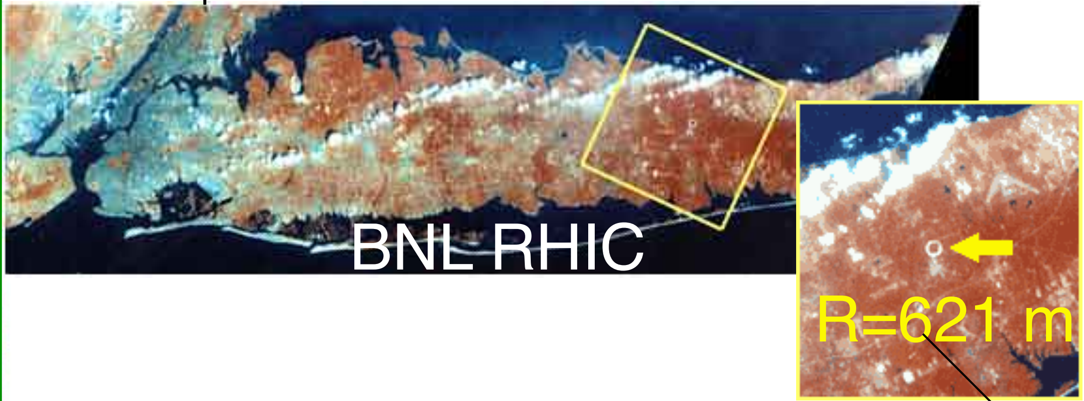
$$P_{synchr} = \frac{e^2}{6\pi\varepsilon_0 c^7}\frac{E^4}{R^2 m^4}$$

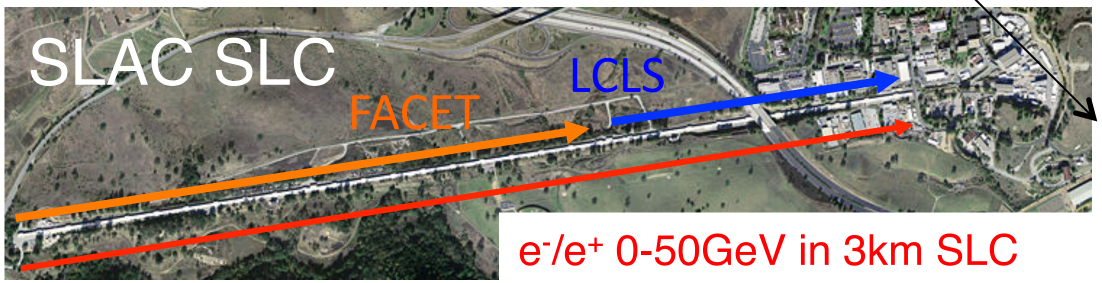
Must be linear and …

$$\searrow \quad L = \frac{E(eV)}{G(eV/m)} \quad \nearrow$$

G : accelerating gradient

"The 2.4-mile circumference RHIC ring is large enough to be seen from space"





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e^- 0-14GeV in 1km LCLS

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erate particles

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PARTiCLE ACCELERATORS

"The 2.4-mile circumference RHIC ring is large enough to be seen from space"

Advanced and Novel Accelerators:

Search for a new technology
to accelerate particles
at high-gradient
(>1GeV/m, ICFA-ANA)
and reduce the size and cost
of a future e^-/e^+, e^-/p^+ collider (or x-ray FEL)

instruments ever built!

- All use RF technology to accelerate particles
- Can we make them smaller (and cheaper) and with a higher energy?

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ADVANCED & NOVEL ACCELERATORS (ANAs)

"Advanced"

⬍

"High-gradient"

⬍

>1GeV/m (ICFA-ANA)

⬍

Average gradient over m–scale

⬍

GeV to TeV e^-/e^+

*do not include laser vacuum/direct acceleration

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ADVANCED & NOVEL ACCELERATORS (ANAs)

"Advanced"

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>1GeV/m (ICFA-ANA)

Average gradient over m–scale

GeV to TeV e^-/e^+

Novel materials with higher damage threshold:

✧Dielectrics (~GV/m)

✧Plasmas (10-100GV/m or ∞)

Novel drivers:

✧Laser pulse(s)*

✧Charged particle bunch(es)

*do not include laser vacuum/direct acceleration

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Driver \ Medium	Dielectric	Plasma
Laser Pulse	Dielectric Laser Accelerator DLA	Laser Wakefield Accelerator LWFA
Particle Bunch	Structure Wakefield Accelerator SWFA	Plasma Wakefield Accelerator PWFA

*do not include laser vacuum/direct acceleration

NEXT

✧Key results: high gradient, high energy gain, %-level energy spread

Medium / Driver	Dielectric	Plasma
Laser Pulse	Dielectric Laser Accelerator DLA	Laser Wakefield Accelerator LWFA
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- ✧ANA community strategy (ICFA-ANA)
  - ✧Need to organize
    - ✧Relevance, size (multi GeV, PW, …) and cost
  - ✧Advanced and Novel Accelerators (scientific) Roadmap Workshop (ANAR 2017)
  - ✧ALEGRO towards a European strategy (2018) input and CDR for an ALC* (2030's)

- ✧Summary & Conclusions

*Advanced Linear Collider

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APPLiCATiONS OF ANAs

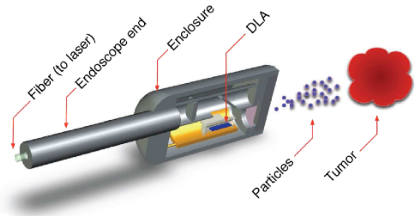
✧X-ray for radiography (advanced: phase contrast, etc.)
✧e^- for medical applications

✧Require low energy <GeV
✧Can operate at very large peak gradient, mm-cm accelerator
✧Efficiency not an issue
✧Luminosity "not an issue"
✧Special characteristics: ultra-short, synchronized (laser), pump probe, etc.
✧Biological advantage …
✧Unique applications, compact

<1GeV

GeV-TeV

Dielectric Laser Accelerator DLA	Laser Wakefield Accelerator LWFA
Structure Wakefield Accelerator SWFA	Plasma Wakefield Accelerator PWFA



England, Rev. Mod. Phys., 86, 1337, (2014)

✧Powerful radiation source, THz to γ-rays (x-ray FEL)
✧High-energy physics (HEP)
- ✧e^-/e^+ collider
- ✧e^-/p^+ collider
- ✧Energy upgrade for a conventional, future collider (ILC, CLIC)

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NEXT

For a review and an extensive list of references, see: R. J. England et al., “Dielectric laser accelerators”, Rev. Mod. Phys. 86, 1337 (2014)

Medium / Driver	Dielectric	Plasma
Laser Pulse	Dielectric Laser Accelerator DLA	Laser Wakefield Accelerator LWFA
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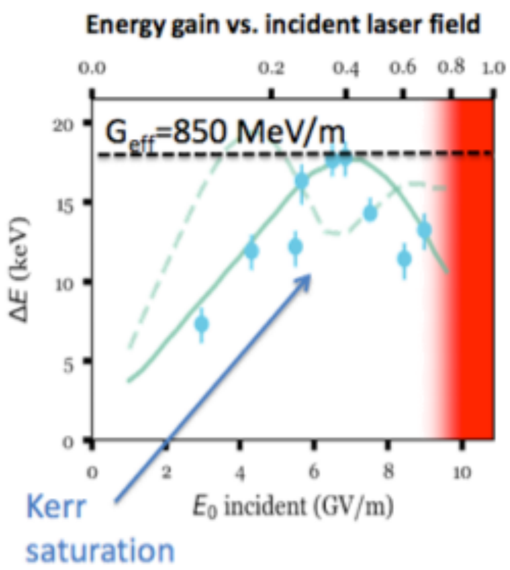
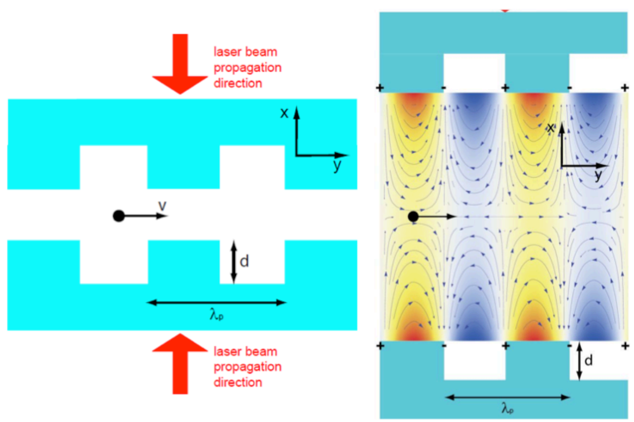
Presented by D. Cesar (UCLA) @ EAAC 2017

✧Directly use the laser E- field in a ~λ^3 (micro) structure





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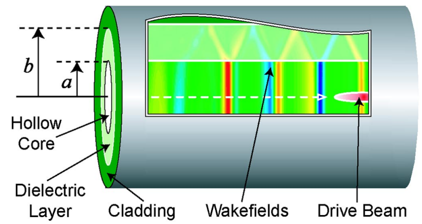
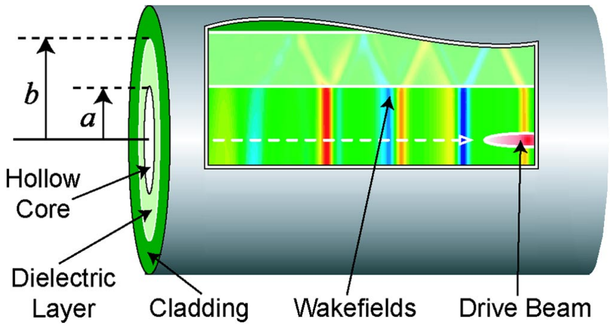
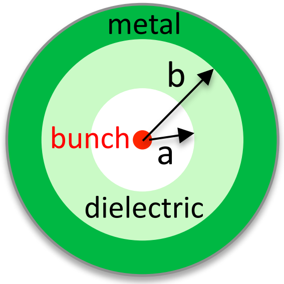
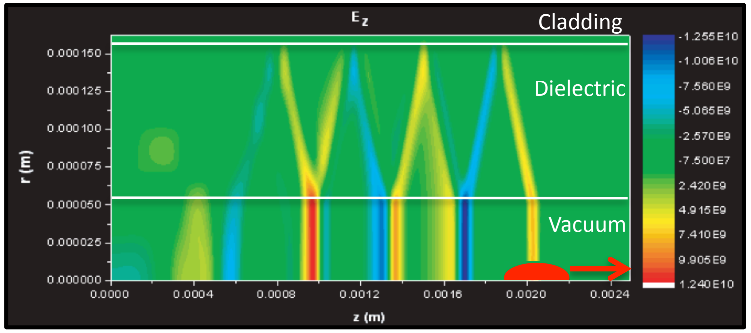
✧Cherenkov wakes in dielectric layers



SWFA







- Peak decelerating field (heuristic)

$$eE_{z,dec} \approx \frac{-4N_b r_e m_e c^2}{a\left[\sqrt{\frac{8\pi}{\varepsilon-1}}\varepsilon\sigma_z + a\right]}$$

- Very simple “accelerating structure”

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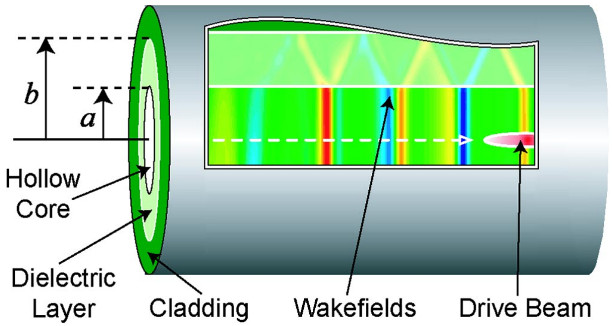
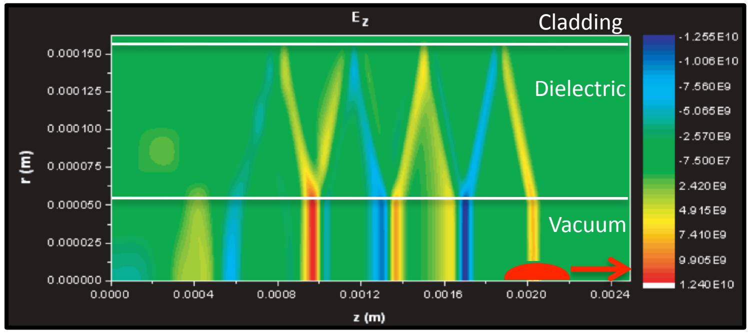
SWFA





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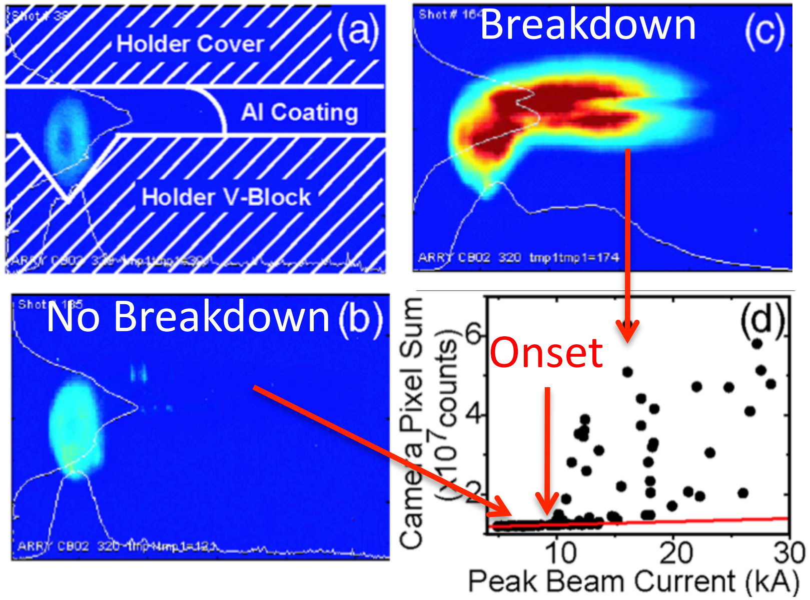
- Very simple "accelerating structure"

PRL 100, 214801 (2008) PHYSICAL REVIEW LETTERS week ending 30 MAY 2008

Breakdown Limits on Gigavolt-per-Meter Electron-Beam-Driven Wakefields in Dielectric Structures

M. C. Thompson,[1,2,*] H. Badakov,[1] A. M. Cook,[1] J. B. Rosenzweig,[1] R. Tikhoplav,[1] G. Travish,[1] I. Blumenfeld,[3] M. J. Hogan,[3] R. Ischebeck,[3] N. Kirby,[3] R. Siemann,[3] D. Walz,[3] P. Muggli,[4] A. Scott,[5] and R. B. Yoder[6]



✧σ_z=100-10µm, N=2×10^{10} e^-
✧a=50µm, b=162µm, fused silica, ε~3, L=10mm, f_1~470GHz
✧Breakdown field at 13.8±0:7GV/m
✧Estimated max. decelerating field: 11GV/m
✧Estimated max. accelerating field: 17GV/m

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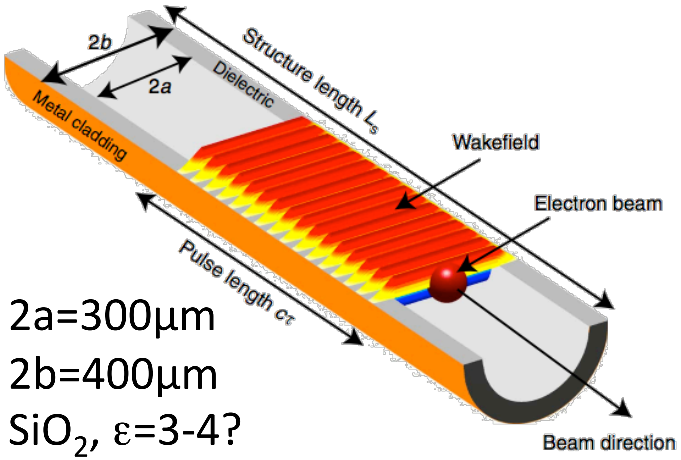
SWFA RESULTS

O'Shea et al., Nat . Comm. 7, 12763 (2016)

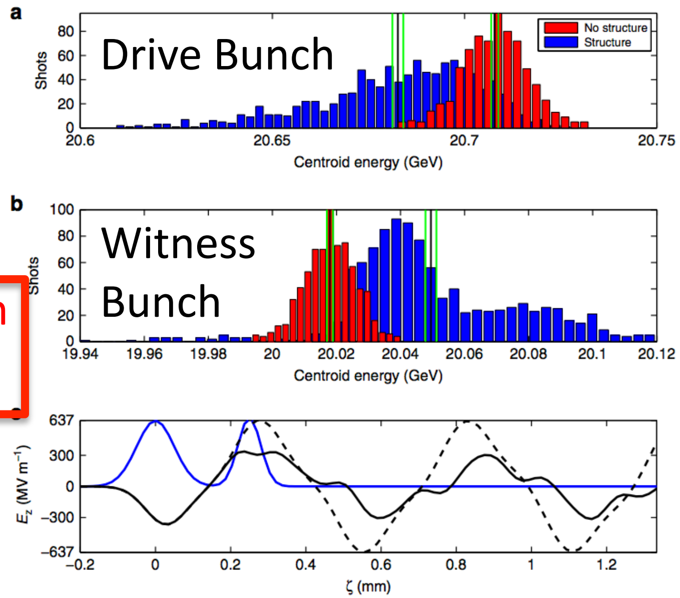


2a=300µm
2b=400µm
SiO_2, ε=3-4?
Cu cladding

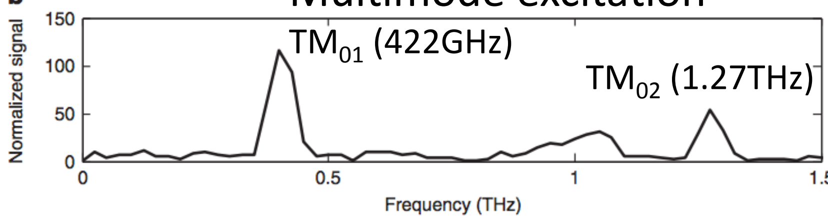
9.4×10^9e
G_d=252±14MeV/m

$6 \times 10^9 e^-$
G_a=320±17MeV/m
$E_{extraction}$=80%

Dielectric	No Dielectric



Multimode excitation



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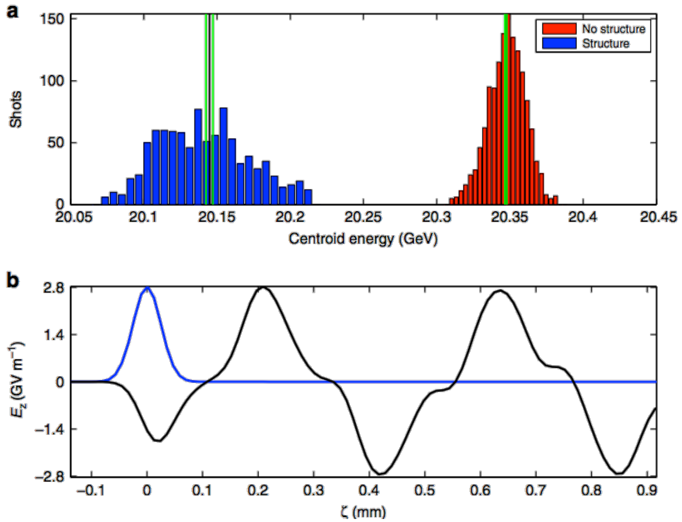
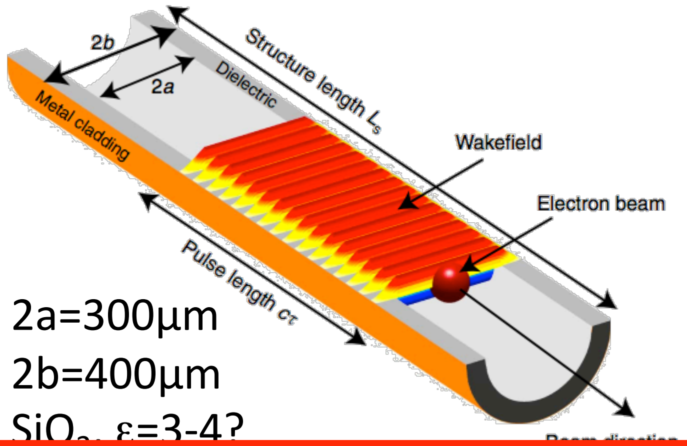


$2 \times 10^{10} e^-$
ΔE=220±3MeV in 15 cm
-> G_d=1.347±0.020GeV/m

- ✧GV/m demonstrated
- ✧Energy gain by W bunch!
- ✧Large extraction efficiency
- ✧Lack of proper beams

SWFA RESULTS

O'Shea et al., Nat . Comm. 7, 12763 (2016)



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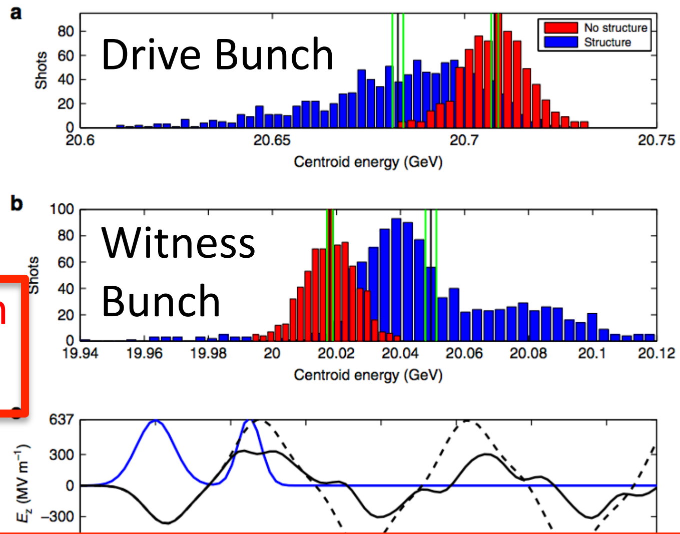


Take advantage of:

✧Simple dielectric lining + metalic coating
✧Large gradient, ~10GV/m
✧Scheme similar to CLIC (non-co-linear version)
✧Symmetric e^-/e^+

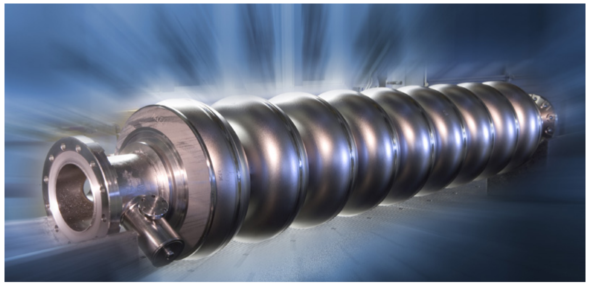
✧Need suitable D+W bunches (FACET 2)

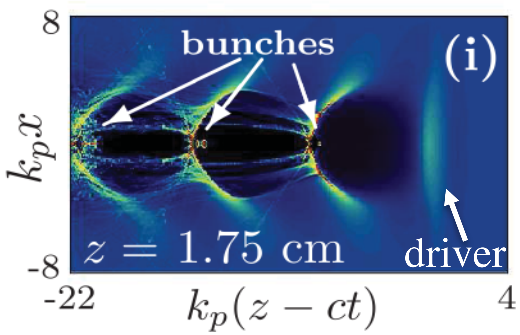
NEXT

Driver \ Medium	Dielectric	Plasma
Laser Pulse	Dielectric Laser Accelerator DLA	Laser Wakefield Accelerator LWFA
Particle Bunch	Structure Wakefield Accelerator SWFA	Plasma Wakefield Accelerator PWFA

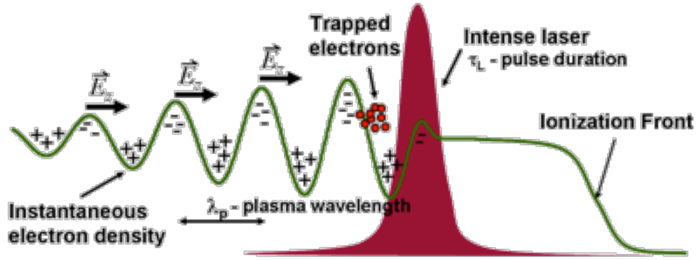
✧Intense laser pulse to drive wakefields in plasma

✧Summary





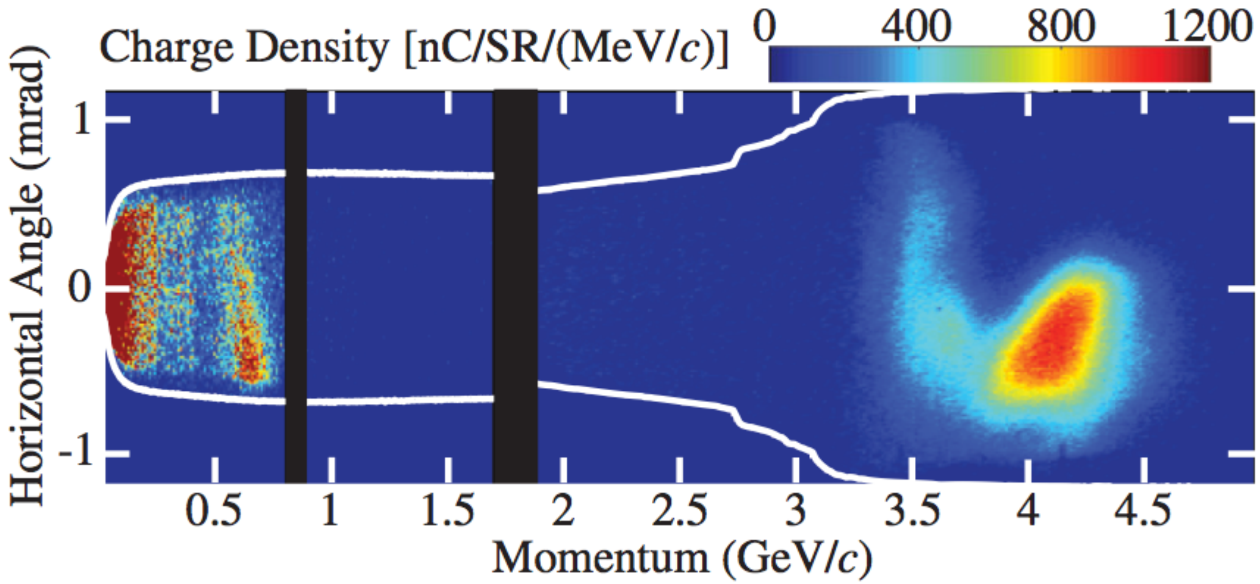
LWFA



Selected for a Viewpoint in *Physics*
PRL **113,** 245002 (2014) PHYSICAL REVIEW LETTERS week ending 12 DECEMBER 2014

Multi-GeV Electron Beams from Capillary-Discharge-Guided Subpetawatt Laser Pulses in the Self-Trapping Regime

W. P. Leemans,[1,2,*] A. J. Gonsalves,[1] H.-S. Mao,[1] K. Nakamura,[1] C. Benedetti,[1] C. B. Schroeder,[1] Cs. Tóth,[1] J. Daniels,[1] D. E. Mittelberger,[2,1] S. S. Bulanov,[2,1] J.-L. Vay,[1] C. G. R. Geddes,[1] and E. Esarey[1]
[1]*Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA*
[2]*Department of Physics, University of California, Berkeley, California 94720, USA*
(Received 3 July 2014; revised manuscript received 11 September 2014; published 8 December 2014)



P_{laser}≈0.3PW,λ=800nm
W=16J, σ_r≈52µm, τ≈42fs

E_{av}=4.2 GeV, $\Delta E/E_{RMS}$=6%
Q=6 pC
$\Theta_{rms=}$0.3 mrad
L_p=9cm, n_e≈7×10^{17}cm^{-3}

✧Peak energy gain 4.2GeV in 9cm (46GeV/m)
✧Self-trapped plasma e⁻ (no injector needed)

✧Needed: controlled external injection

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LWFA ACHiEVEMENTS

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 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)
- 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

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LWFA ACHiEVEMENTS

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Take advantage of:

✧Plasma, no structure, driven by the laser pulse
✧Very large gradient, 4GeV in 9cm …
✧Plasma injector, accelerator, focusing, …

✧Need laser like klystrons …

Presented at ANAR 2017

LWFA Laser Development

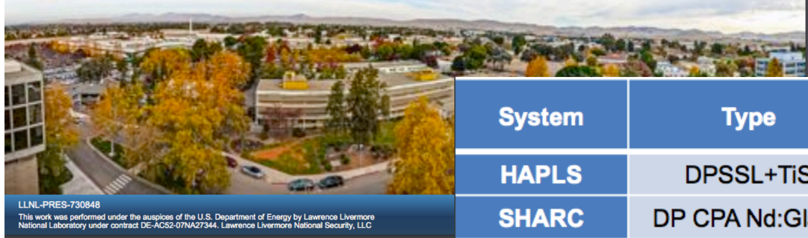
Presented at EAAC'17, C. Haefner (LLNL)

High efficiency, diode pumped Petawatt lasers for the next generation particle accelerators and secondary sources

EAAC 2017

Sept 24-30, 2017

Constantin Haefner, Craig Siders, Andy Bayramian, David Alessi, Kyle Chestnut, Al Erlandson, Eyal Feigenbaum, Tom Galvin, Paul Leisher, Emily Link, Dan Mason, Bill Molander, Paul Rosso, Margareta Rehak, Kathleen Schaffers, Tom Spinka



HAPLS for ELI

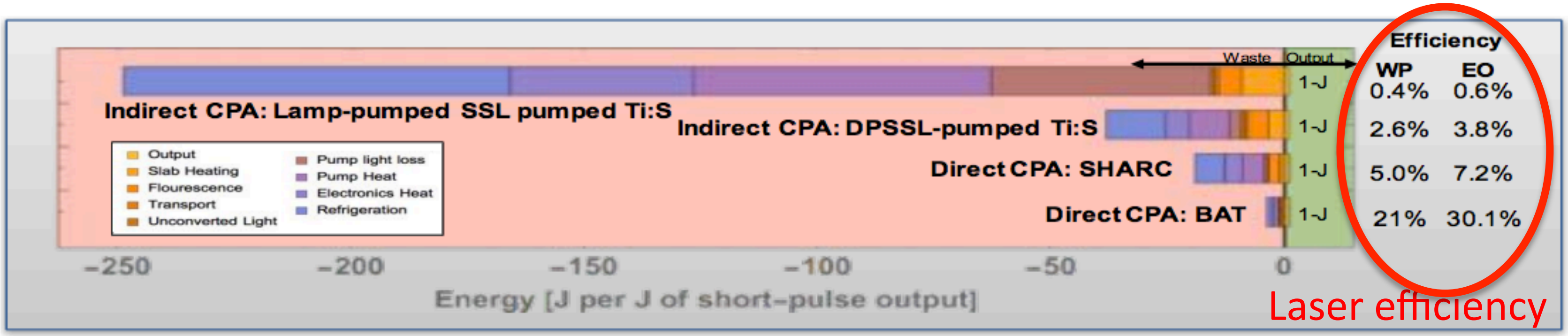
20 years later:
HAPLS laser runs 200,000 times faster than the original 1996 Petawatt

BAT=Big Aperture Thulium (lanthanide: Erbium, Ytterbium), λ=1.9μm

System	Type	TRL Estimate	Integration Challenge	delivery horizon	E (J)	t (fs)	P_{av} (kW)	P_{peak}(PW)
HAPLS	DPSSL+TiS	7	Low	today	30	<30	0.3	1
SHARC	DP CPA Nd:Glass	6	Low	3yrs	150	150	1.5	1
Mini-BAT	DP CPA Tm:YLF	3-4	Medium	3-5yrs	3	40 or 100	3	.075
BAT	DP CPA Tm:YLF	3	Medium	5-7yrs	30	40 or 100	300	.75

Lawrence Livermore National Laboratory — 9.2017 – LLNL- C.Haefner-EACC 2017 Italy — 43

Laser average power



Laser efficiency

✧Tremendous laser progress driven by large scale ELI (NIF) projects
✧Orders of magnitude …

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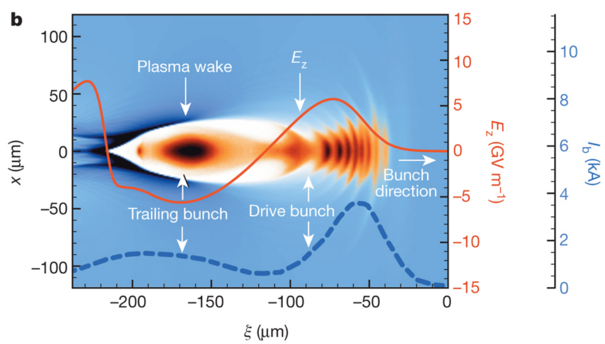
OUTLiNE

✧Novel Accelerator Techniques "Goals"

Medium / Driver	Dielectric	Plasma
Laser Pulse	✧ Dielectric Laser Accelerator DLA	✧ Laser Wakefield Accelerator LWFA
Particle Bunch	✧ Dielectric Wakefield Accelerator DWA	✧ Plasma Wakefield Accelerator PWFA

✧Dense, relativistic particle bunch to drive wakefields in a plasma

✧Summary



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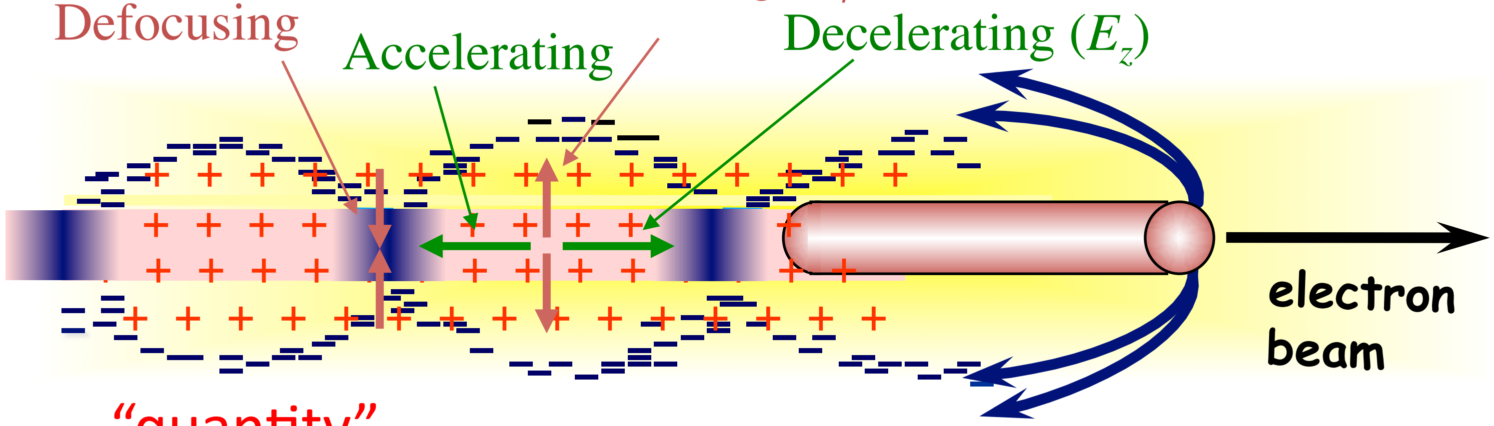
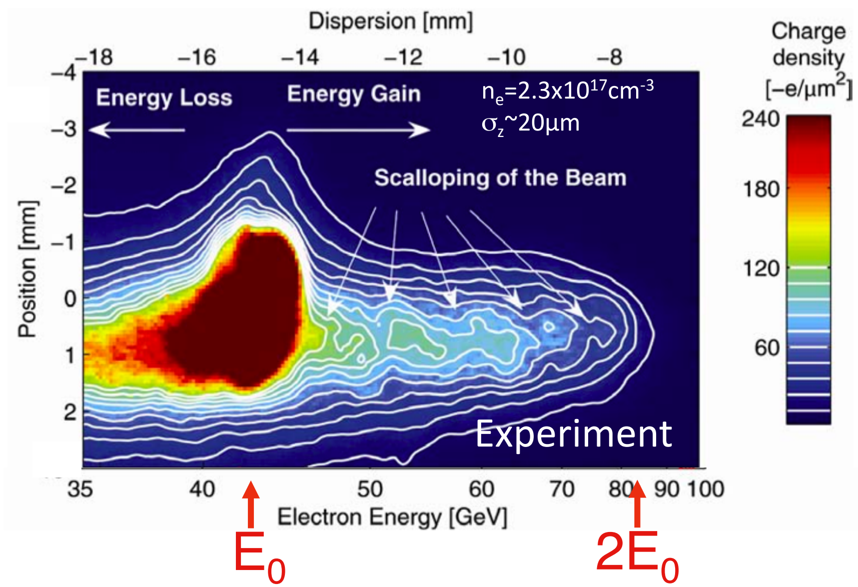
PWFA (e^-)



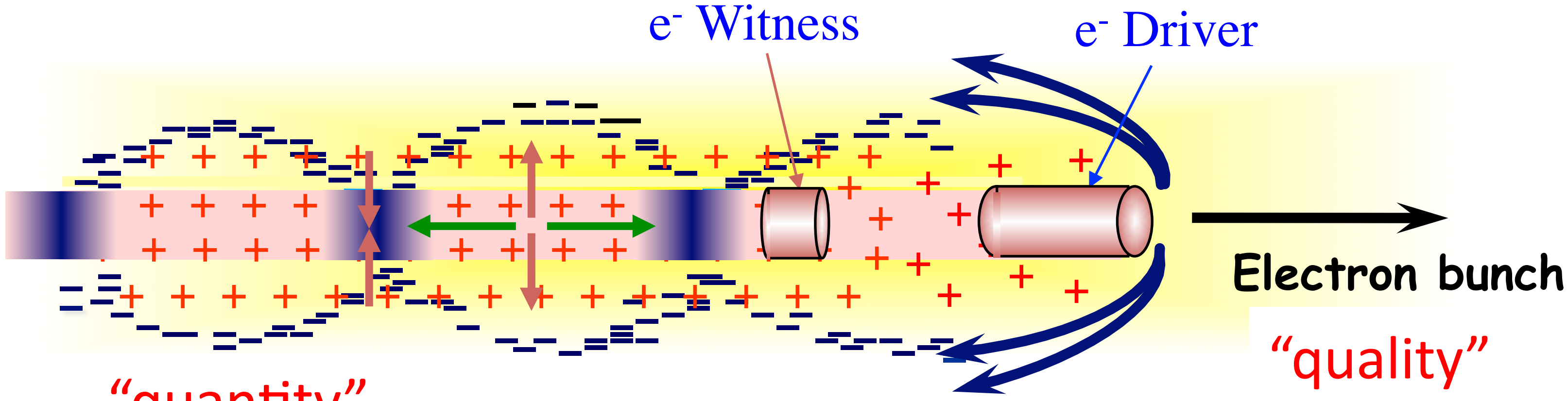
"quantity"

Blumenfeld, Nature 445, 741 (2007)



42 => 84GeV in 85cm! 50GeV/m

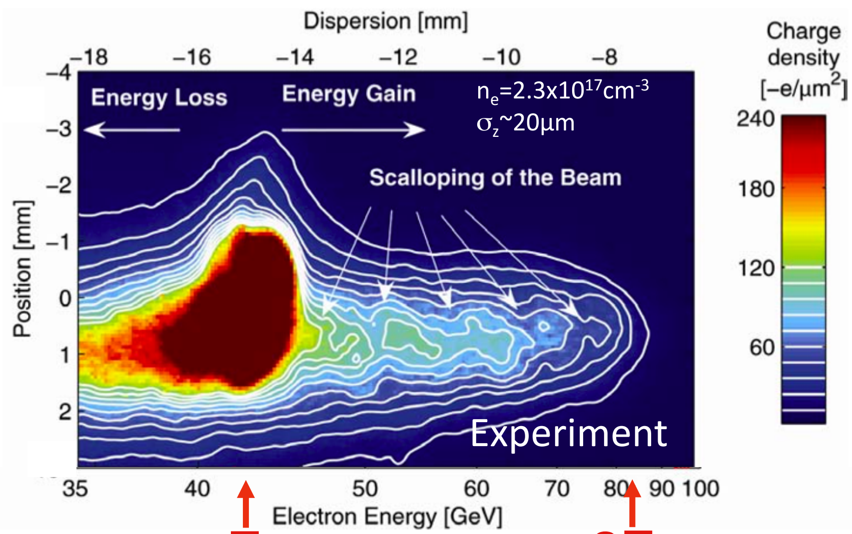
PWFA (e^-)



"quantity"

"quality"

Blumenfeld, Nature 445, 741 (2007)



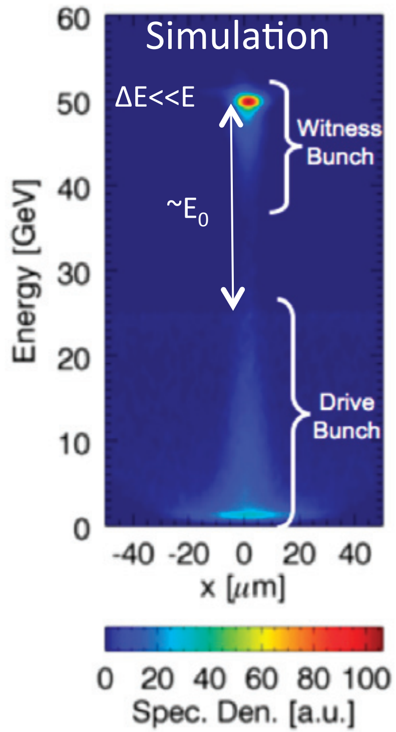
E_0 $2E_0$

42 => 84GeV in 85cm! 50GeV/m

SLAC FACET

E200

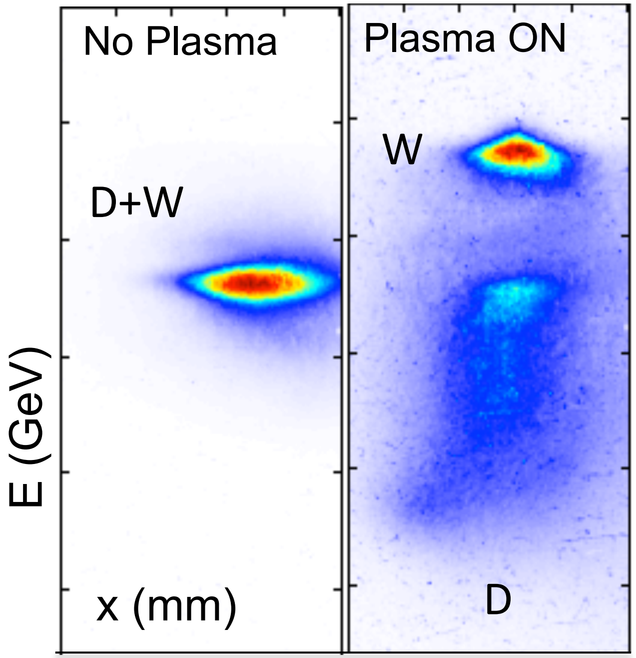
Hogan, NJP 12, 055030 (2010)



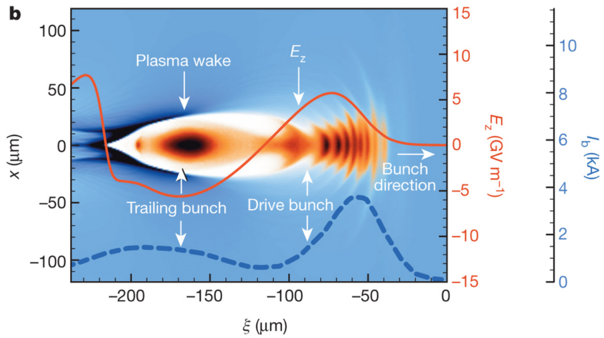
High-Efficiency Acceleration of an Electron Bunch in a Plasma Wakefield Accelerator

UCLA SLAC

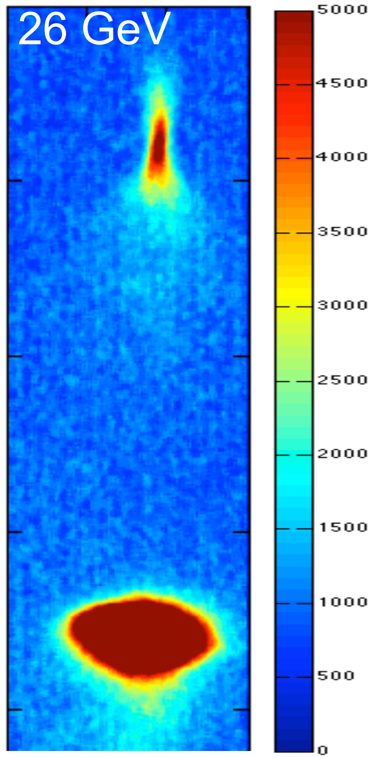
- Focus on energy gain, efficiency, optimization of accelerated beam quality
- Measure, repeat/confirm, publish, improve…



2 GeV Energy Gain (~30cm)
~2% ΔE/E
~30% efficiency



Nature ***515****, 92-95*
(November 2014)



Single shot with
6 GeV Energy Gain (~1m)

Courtesy M.J. Hogan, SLAC

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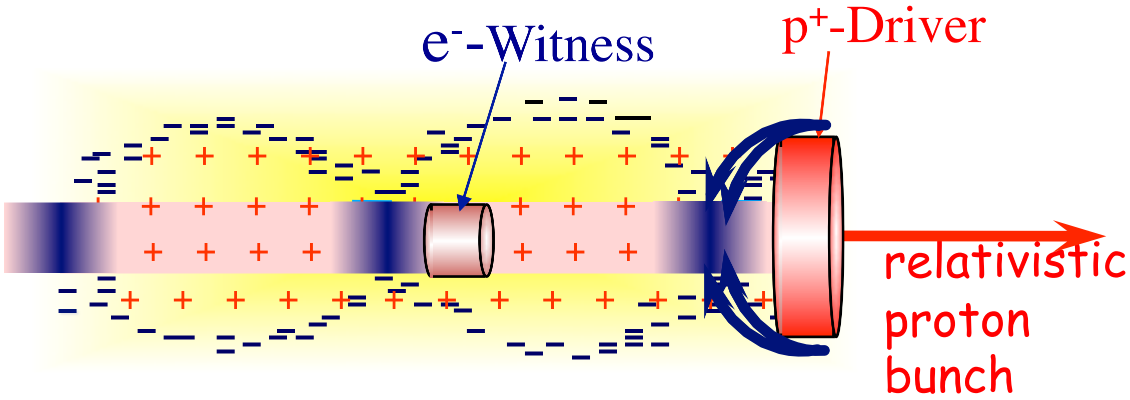
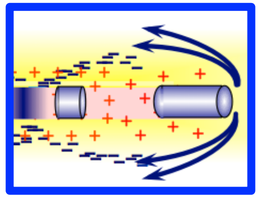
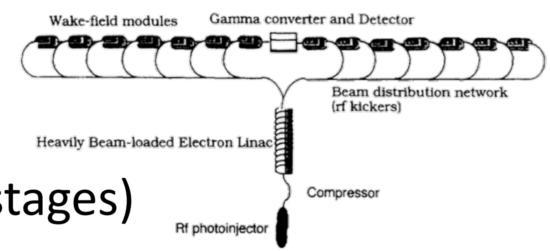
p^+-DRiVEN PWFA



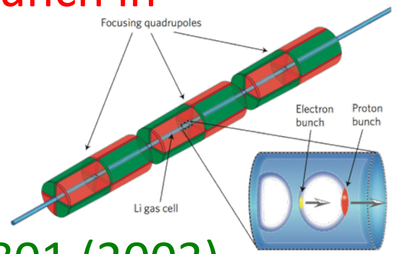


- ✧ILC, 0.5TeV bunch with $2\times10^{10}e^-$ ~1.6kJ
- ✧SLAC, 20GeV bunch with $2\times10^{10}e^-$ ~60J
- ✧SLAC-like driver for staging (FACET= 1 stage, collider 10^+ stages)

J. Rosenzweig et al. /Nucl. Instr. and Meth. in Phys. Res. A 410 (1998) 532–543



- ✧SPS, 400GeV bunch with $10^{11}p^+$ ~6.4kJ
  LHC, 7TeV bunch with $10^{11}p^+$ ~112kJ
- ✧A single SPS or LHC bunch could produce an ILC bunch in a single PWFA stage!
- ✧Large average gradient! (≥1GeV/m, 100's m)
- ✧Wakefields driven by e^+ bunch: Blue, PRL 90, 214801 (2003)



Caldwell, Nat. Phys. 5, 363, (2009)

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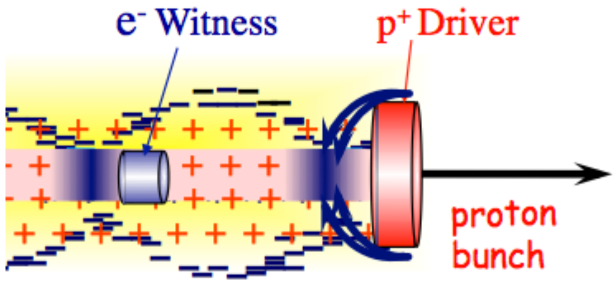
p^+-DRiVEN PWFA

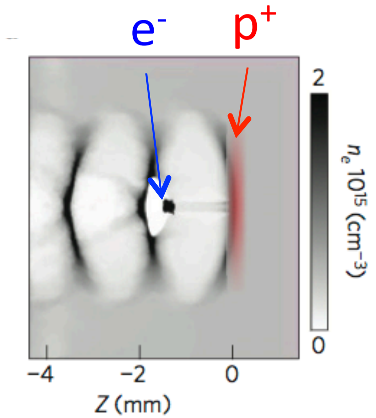
Caldwell, Nat. Phys. 5, 363, (2009)



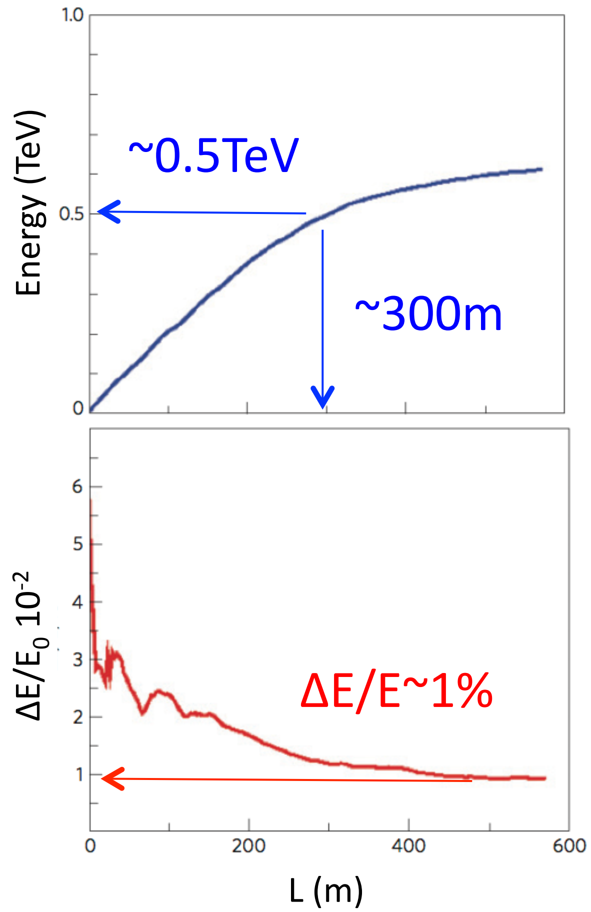
e^-:
E_0=10GeV
$N=10^{10}$
W_0=16J
W_f=1kJ

p^+:
E_0=1TeV
σ_z=100µm
$N=10^{11}$
W_0=16kJ

Single Stage



Parameter	Symbol	Value	Units
Protons in drive bunch	N_P	10^{11}	
Proton energy	E_P	1	TeV
Initial proton momentum spread	σ_p/p	0.1	
Initial proton bunch longitudinal size	σ_z	100	µm
Initial proton bunch angular spread	σ_θ	0.03	mrad
Initial proton bunch transverse size	$\sigma_{x,y}$	0.43	mm
Electrons injected in witness bunch	N_e	1.5×10^{10}	
Energy of electrons in witness bunch	E_e	10	GeV
Free electron density	n_p	6×10^{14}	cm^{-3}
Plasma wavelength	λ_p	1.35	mm
Magnetic field gradient		1,000	T m^{-1}
Magnet length		0.7	m



- ✧Accelerate an e^- bunch on the wakefields of a p^+ bunch
- ✧Single stage, no gradient dilution
- ✧Gradient ~1 GV/m over 100's m (average!!!)
- ✧Operate at lower n_e (6×10^{14}cm^{-3}), larger $(\lambda_{pe})^3$, easier life …

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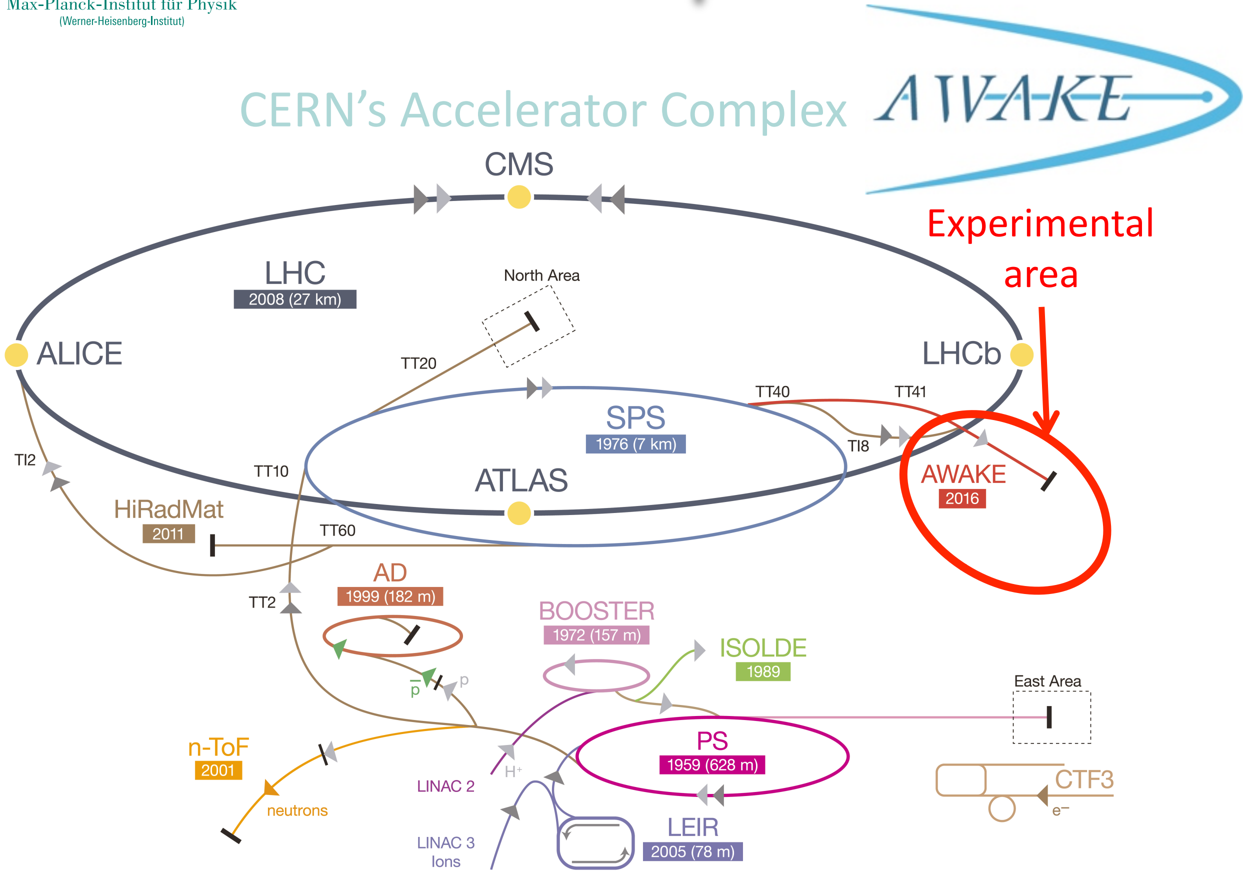
p+-DRiVEN PWFA



✧SPS beam: high energy, small σ_r*, long β*

✧Initial goal: ~GeV gain by externally injected e^-,in 5-10m of plasma in self-modulated p^+ driven PWFA

✧Setup a comprehensive PWFA program at CERN

AWAKE Collaboration, Plasma Phys. Control. Fusion 56 084013 (2014)

p^+-DRiVEN PWFA

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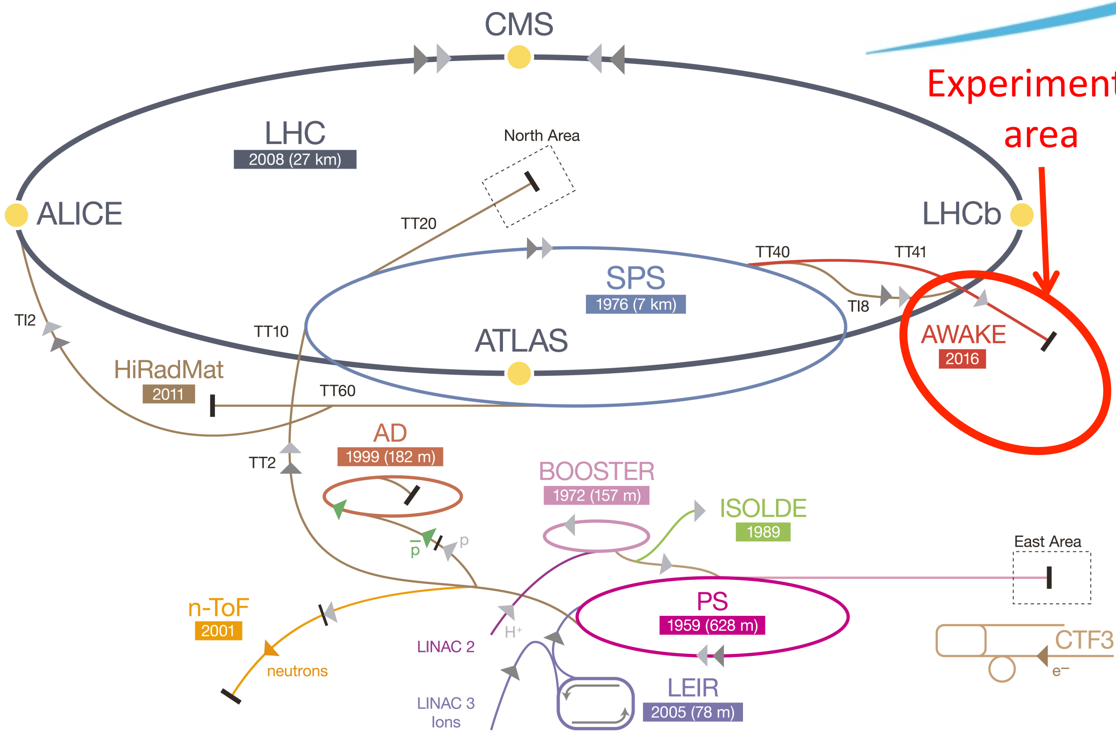
AWAKE

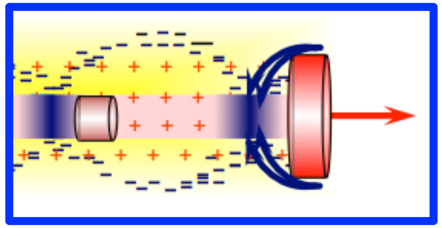
CERN's Accelerator Complex



$3x10^{11}$, 400GeV SPS p^+

10m plasma, $n_e=1\text{-}10x10^{14}cm^{-3}$

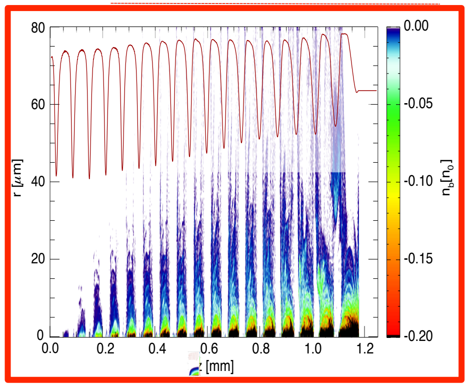
σ_z~6-12cm



λ_{pe}~σ_z

→n_e~$8x10^{10}cm^{-3}$

→$E_{WB}=2\pi mc^2/e\lambda_{pe}$ ~27MV/m!!



→n_e~$7x10^{14}cm^{-3}$

→λ_{pe}~1.2mm

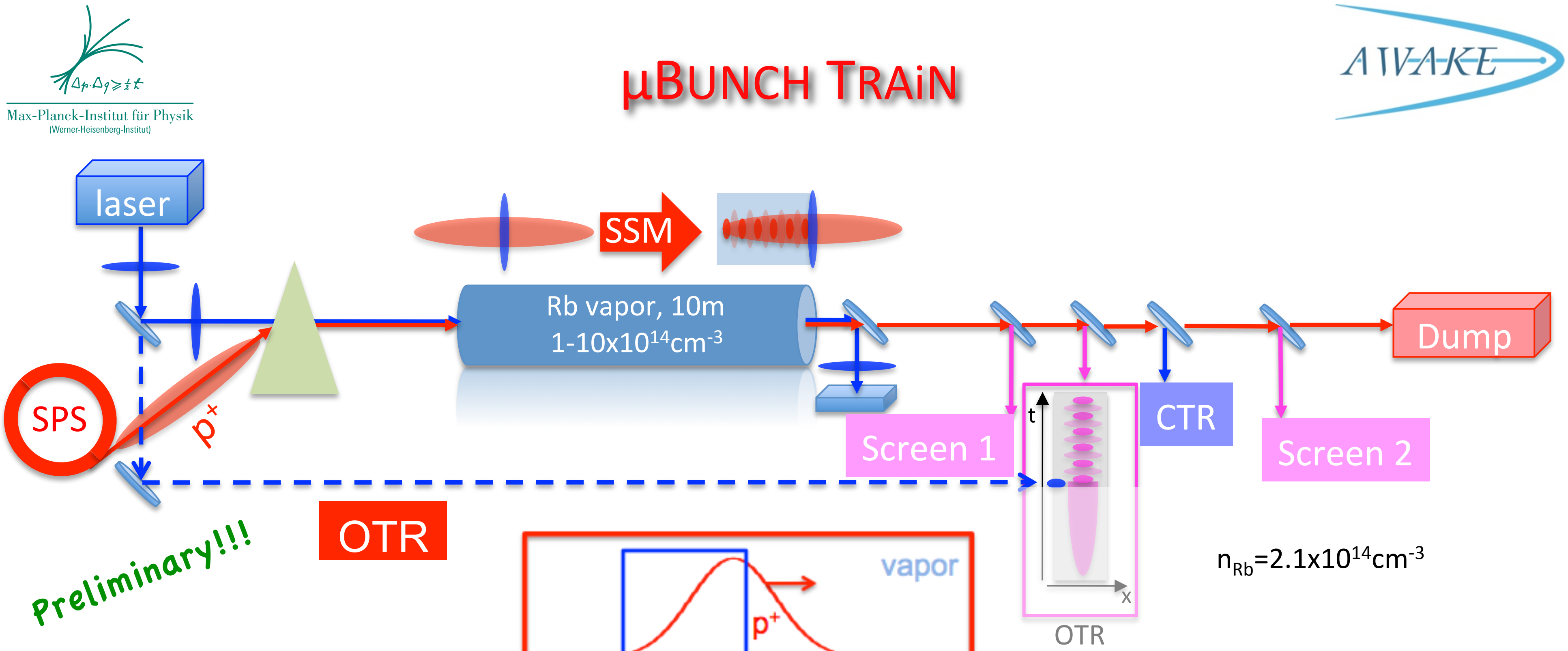
→E_{WB}~2.5GV/m, f_{pe}~237GHz

→Seeded self-modulation (SSM)

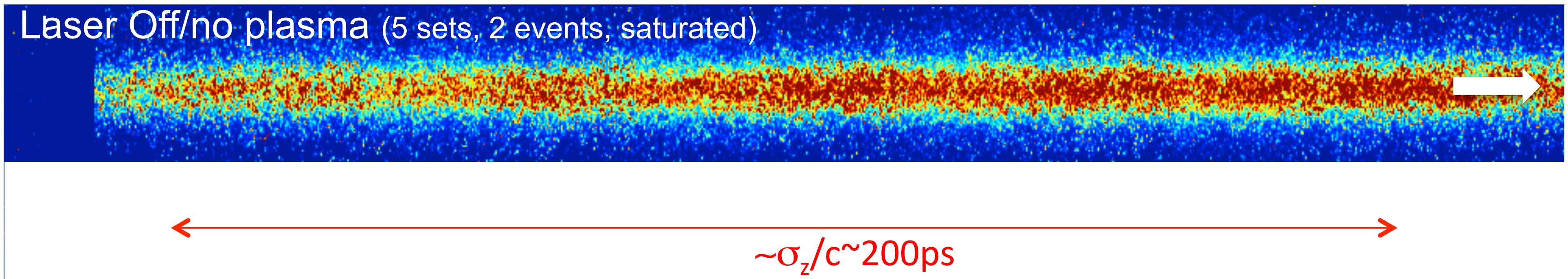
- ✧SPS beam: high energy, small σ_r*, long β*
- ✧Initial goal: ~GeV gain by externally injected e^-,in 5-10m of plasma in self-modulated p^+ driven PWFA
- ✧Setup a comprehensive PWFA program at CERN

AWAKE Collaboration, Plasma Phys. Control. Fusion 56 084013 (2014)

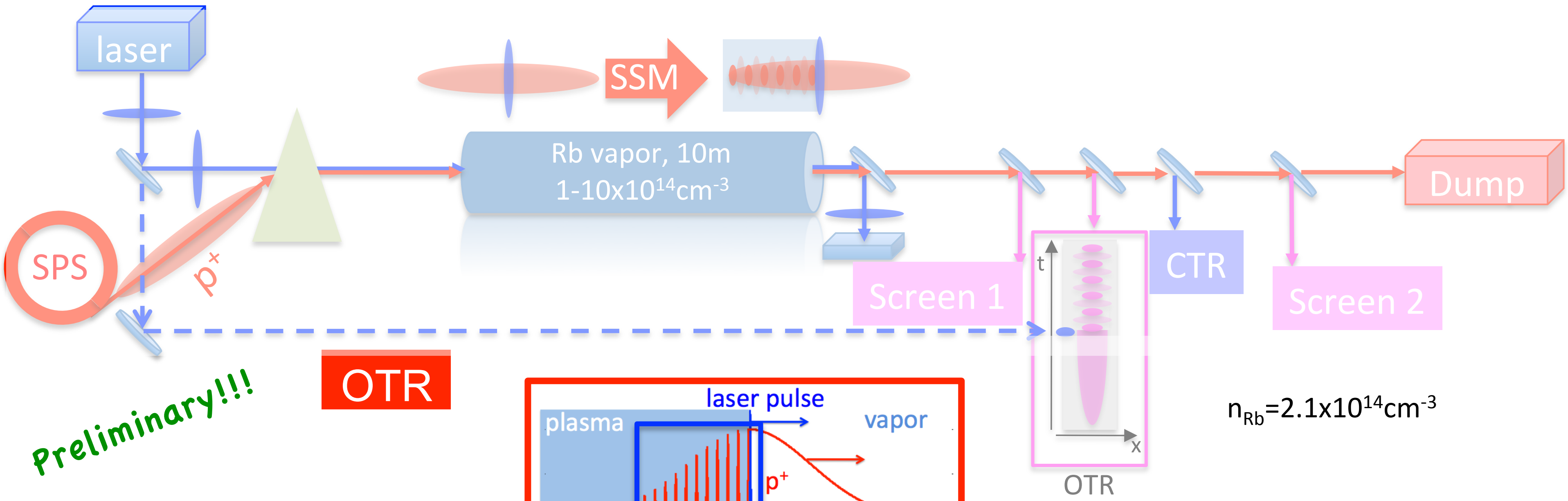
µBUNCH TRAiN



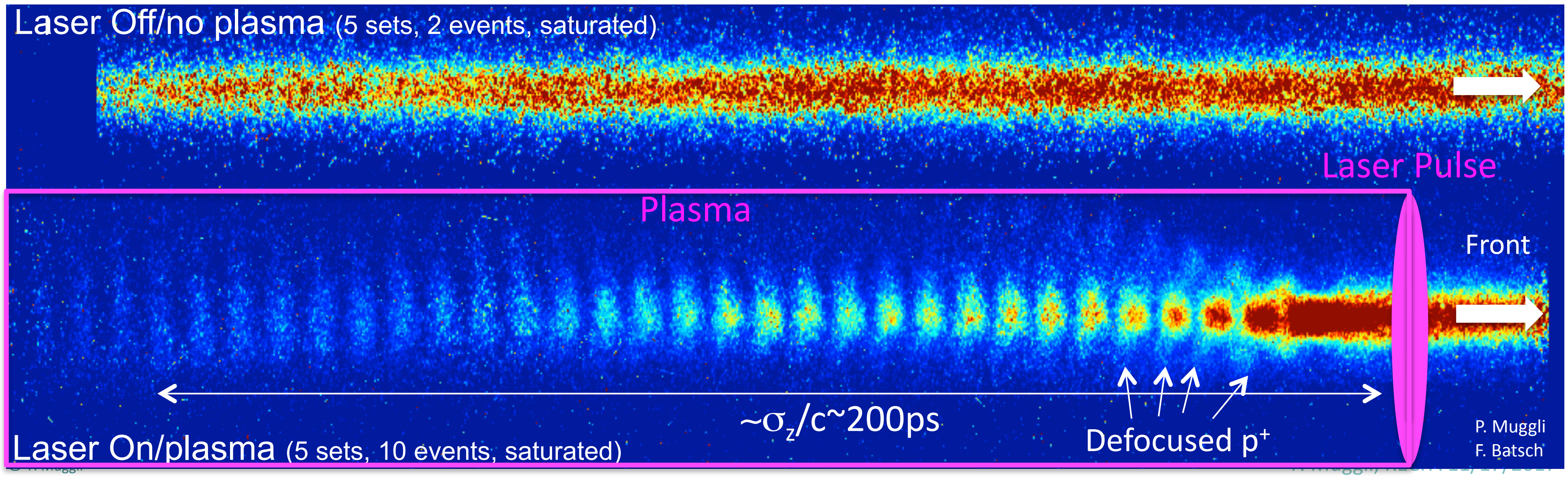
Streak camera Images



μBUNCH TRAIN



Streak camera Images



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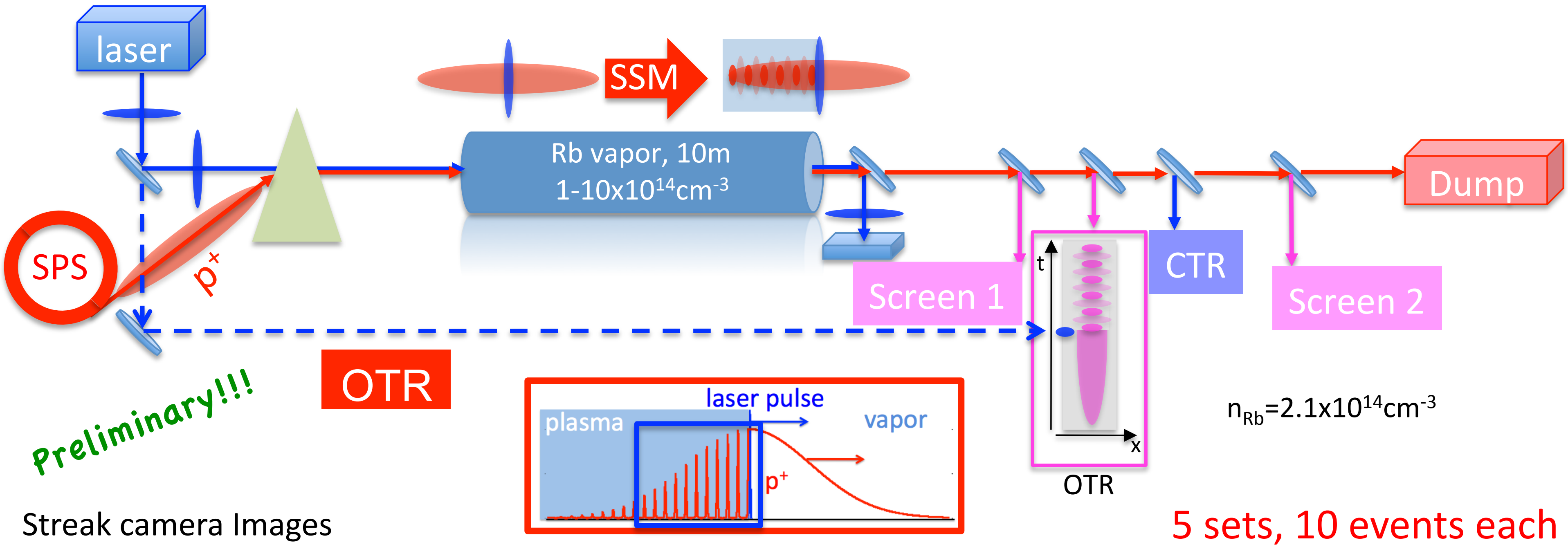
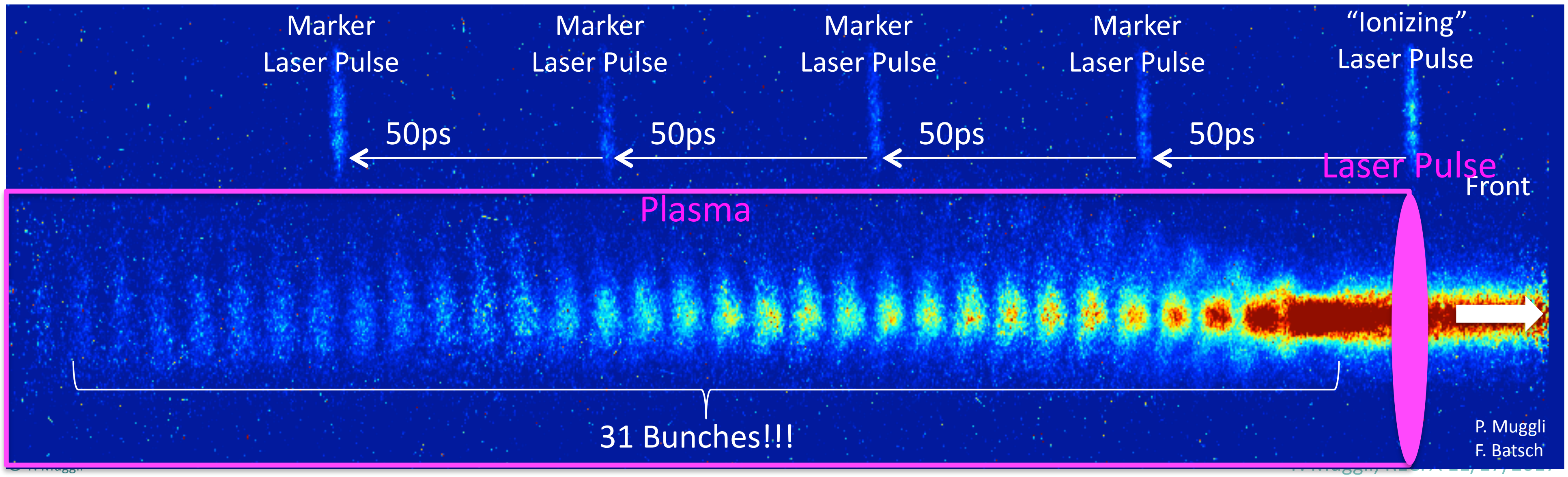
μBUNCH TRAiN



Streak camera Images

5 sets, 10 events each



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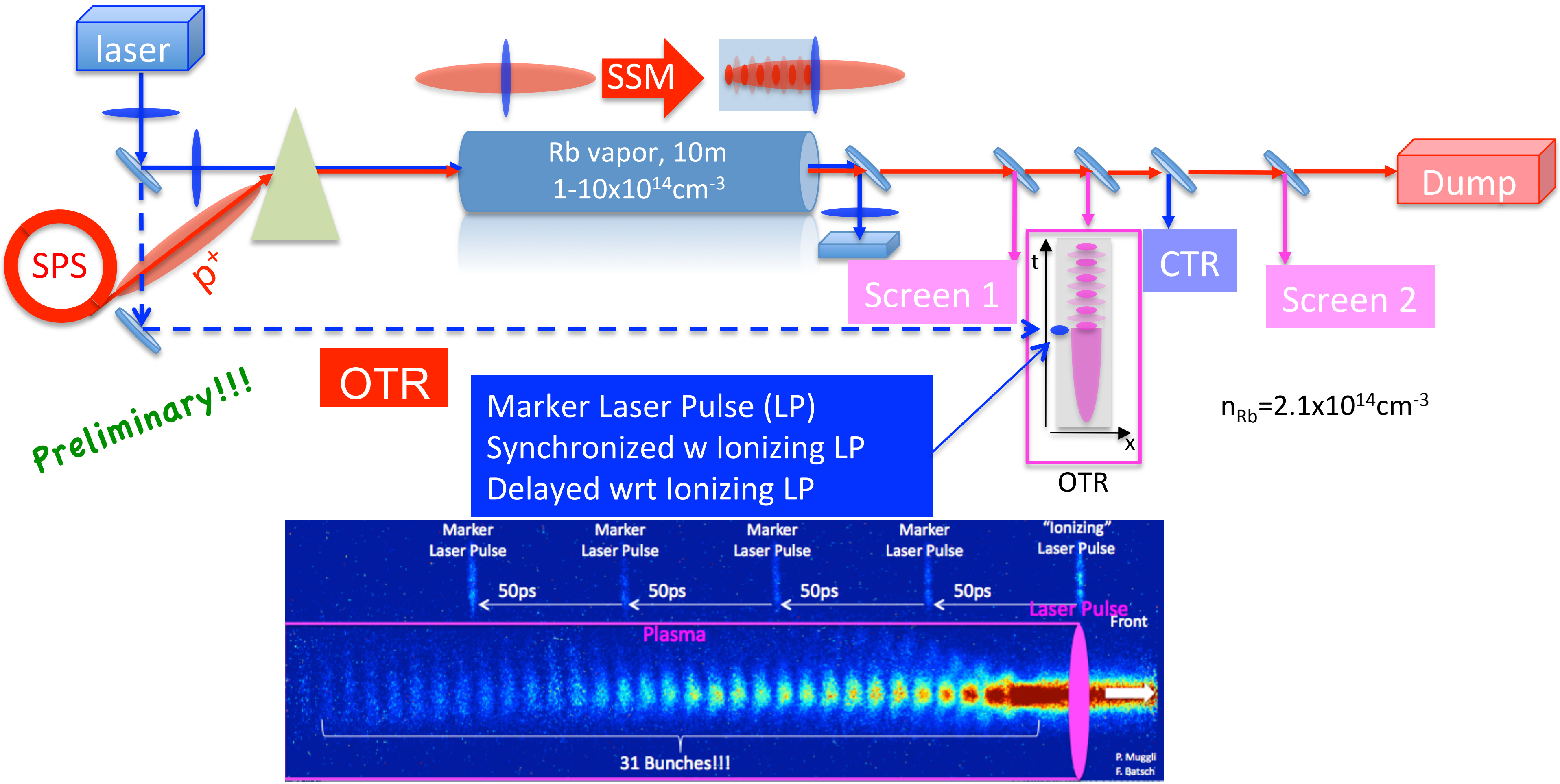
μBUNCH TRAIN



- ✧ Micro-bunches present over long time scale ~σ^+_z/c from seed point
- ✧ "Stitching" demonstrates reproducibility of the μ-bunch process against bunch parameters variations (N=2.5x10^{11}±10%, σ_{zt}=220±10ps, σ_r)
- ✧ Phase stability essential for e$^-$ external injection: SSM not SMI!!! Wakefields "amplifier"

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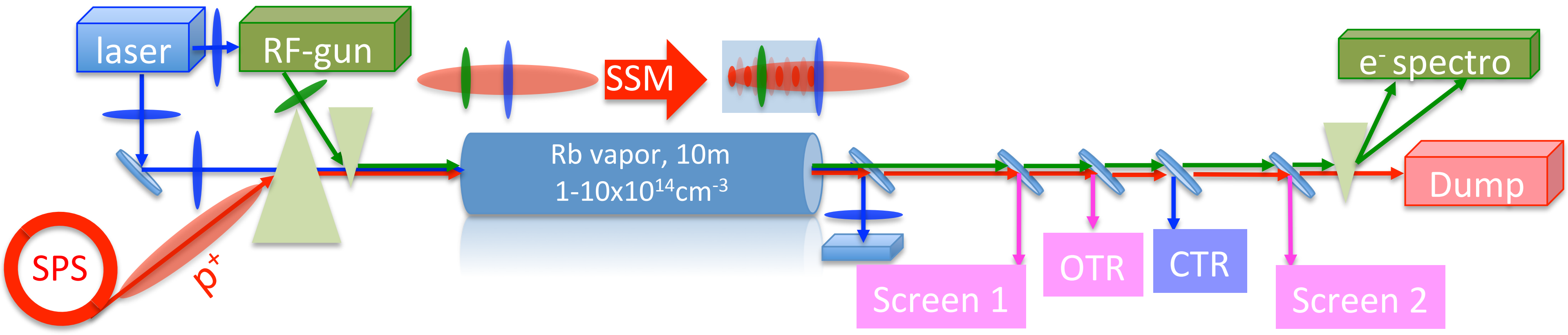
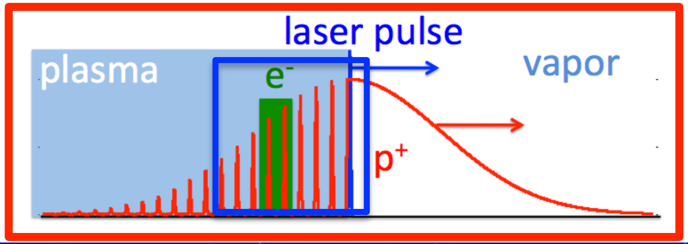
AWAKE NEXT STEP



Preliminary!!!

OTR

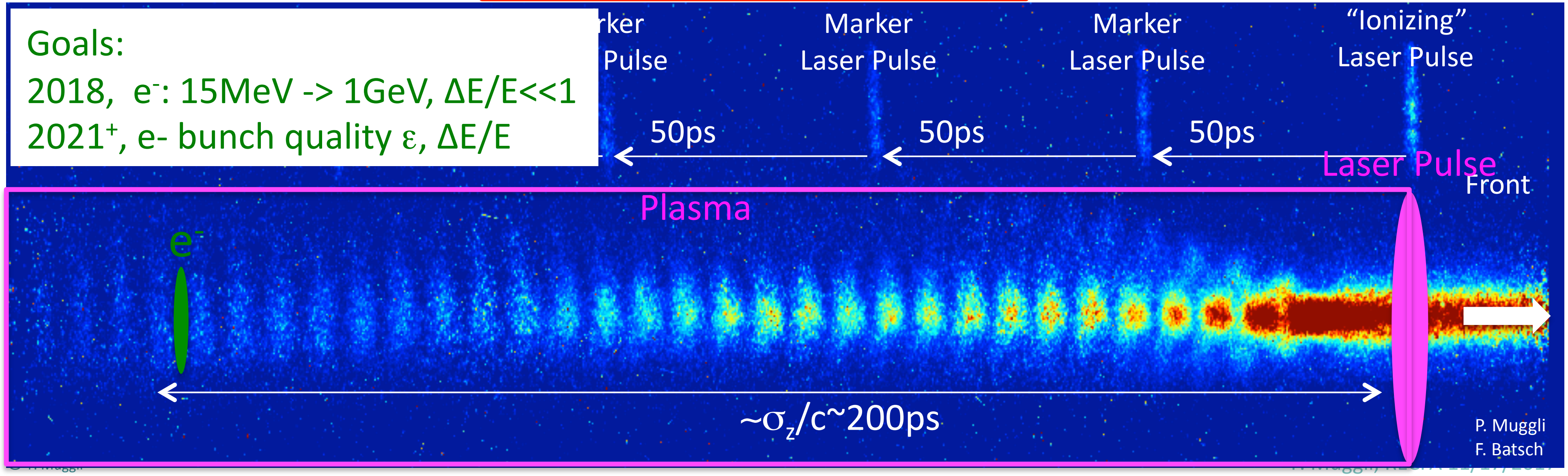


$n_{Rb}=2.1\times10^{14}cm^{-3}$

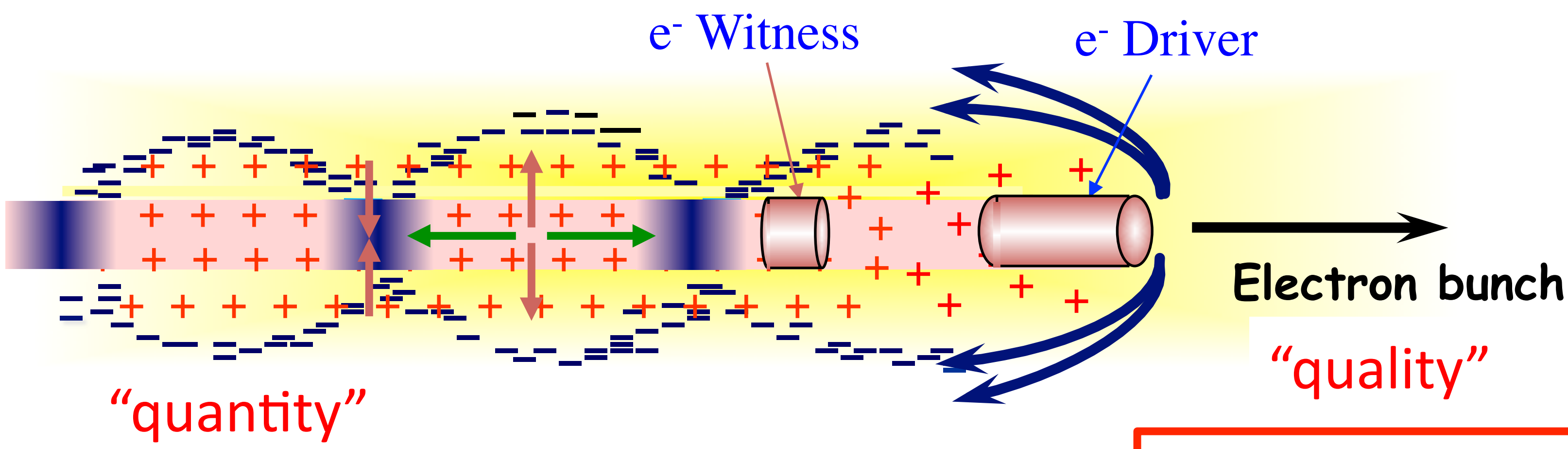
Streak camera Images

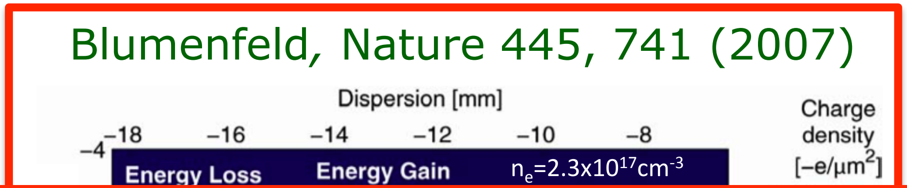
5 sets
10 events each

Goals:
2018, e^-: 15MeV -> 1GeV, $\Delta E/E<<1$
2021+, e- bunch quality ε, $\Delta E/E$

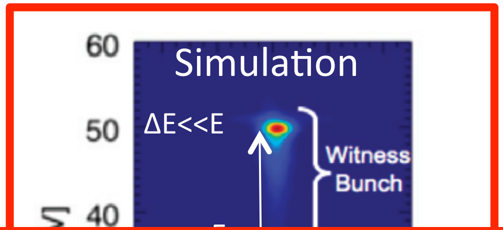


PWFA





SLAC
FACET



Take advantage of:

✧Large plasma gradients, large energy gain
✧Existing relativistic drivers (e^-, p^+)

✧Need suitable D+W bunches (AWAKE, FACET 2, DESY-FLASHFwd, INFN)

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ANAR Workshop 2017

✧ANAs can accelerate particles at high gradient (GeV/m)
✧Could they be relevant for a future HEP collider?

Organised at the initiative of the ICFA panel for Advanced and Novel Accelerators (chaired by B. Cros and P. Muggli), the ANAR2017 workshop aims at discussing issues to be addressed in the near future to be in a position to identify promising technologies for future advanced accelerators, and to establish an international scientific and strategic roadmap. The general goal is to define an international roadmap towards colliders based on advanced accelerator concepts, including intermediate milestones, and to discuss the needs for international coordination.

The workshop is open to the scientific community at large. It is organized around working groups that will examine the various schemes that are currently under active investigation (LWFA, PWFA, DWA, DLA) as well as those that need to be addressed in the near- mid- and long-term to reach parameters relevant to a high-energy collider.

The last part of the workshop will be dedicated to discussion of the working group results and to the strategy to push forward the development of advanced accelerators in the context of the next international project at the TeV scale.

The results will be synthesized in a document that will be broadly distributed.

https://indico.cern.ch/event/569406/

ANAR WORKSHOP 2017

Max-Planck-Institut für Physik
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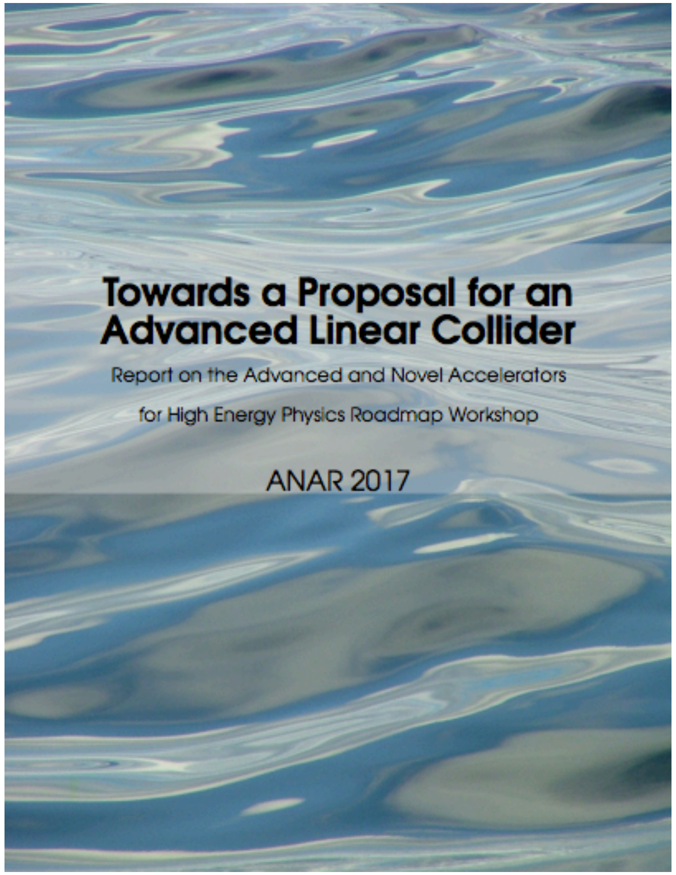
Contents



http://www.lpgp.u-psud.fr/icfaana/ANAR2017_report.pdf

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ANAR SCiENTiFiC ROADMAP

2017 - 2022	2022 - 2027	2027 - 2032	2032-2037
e- sources: optimization	**e- acceleration :** Optimization of all parameters		
e+ sources: Concept devt	**e+ acceleration:** demonstration		
Driver development			
Accelerating structures			
Beam transport and coupling			

5 Ys – Injector, Accelerator stages with controlled parameters

10 Ys – x10 Improved beam quality at higher energy

15 Ys – Reliable staged accelaration, 10 GeV module

20 Ys – Advanced Linear Collider CDR and TDR

Address specific challenges :

Staging →
Reliability →
Polarization →
Efficiency →
Beam Delivery System →

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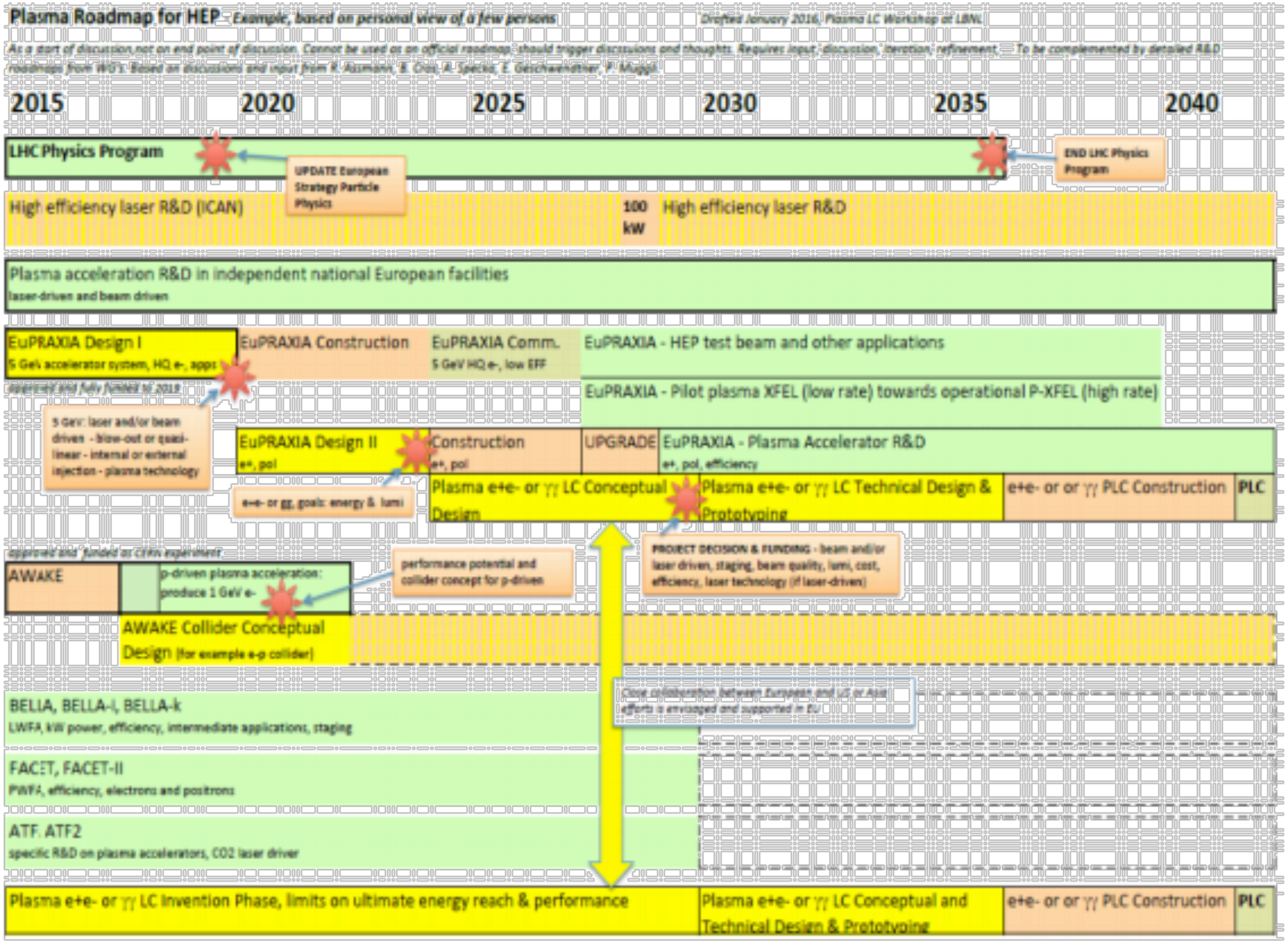
EuroNAcc2 ROADMAP



https://edms.cern.ch/ui/file/1325207/2/EuCARD2_Del7-2-Final.pdf

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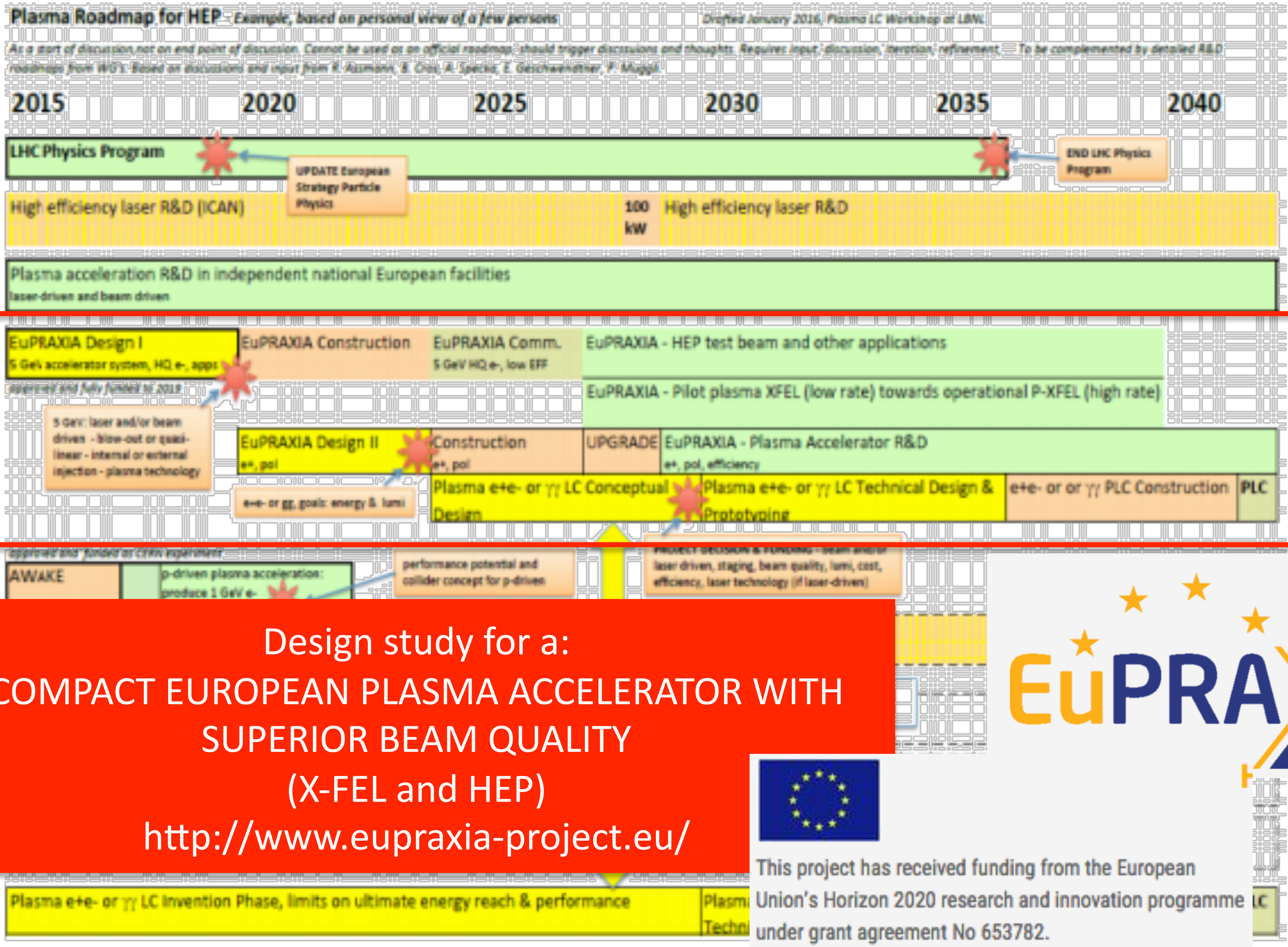
EuroNAcc2 ROADMAP



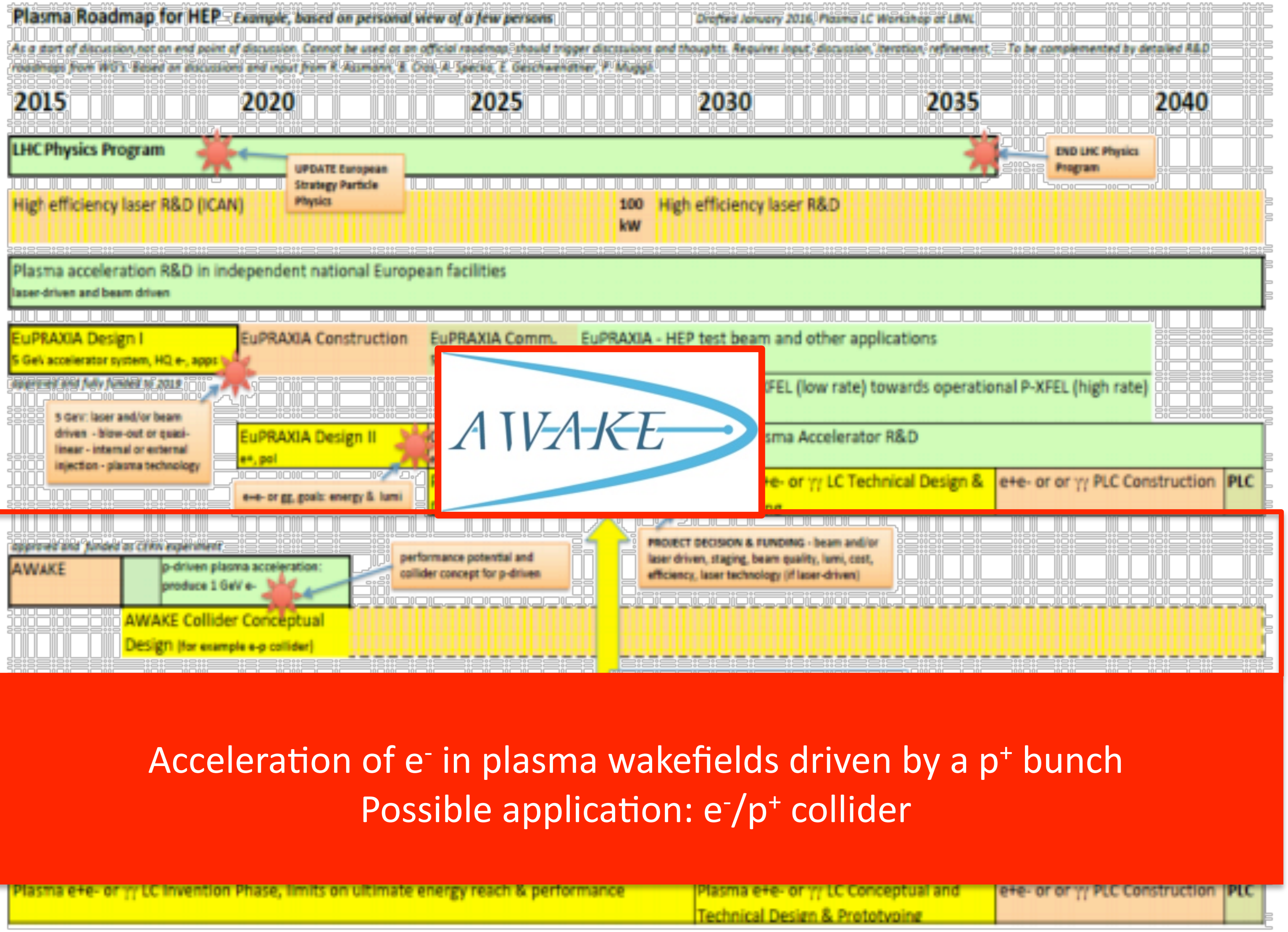
Design study for a:
COMPACT EUROPEAN PLASMA ACCELERATOR WITH SUPERIOR BEAM QUALITY
(X-FEL and HEP)
http://www.eupraxia-project.eu/

EuPRAXIA

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 653782.

https://edms.cern.ch/ui/file/1325207/2/EuCARD2_Del7-2-Final.pdf

EuroNAcc2 ROADMAP



Acceleration of e^- in plasma wakefields driven by a p^+ bunch
Possible application: e^-/p^+ collider

https://edms.cern.ch/ui/file/1325207/2/EuCARD2_Del7-2-Final.pdf

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ANAR WORKSHOP OUTCOME

ALEGRO 2018

As an outcome of the workshop, it was decided to constitute a study group towards Advanced Linear Colliders, named ALEGRO for Advanced LinEar collider study GROup. ALEGRO's general charge will be to coordinate the preparation of a proposal for an advanced linear collider in the multi-TeV energy range.
The ALEGRO will consist of (30) scientists with expertise in advanced accelerators concepts or accelerator physics and technology, drawn from national institutions or universities in Europe, America and Asia.

The ALEGRO will organize a series of workshops on relevant topics where the scientific community should, in a first phase, discuss and iterate the roadmaps, discuss ways to tackle key challenges, and, over time, monitor the progress of the community as a whole on collider-oriented R&D.

The first objective of ALEGRO is to prepare and deliver by the end of 2018 a document detailing the roadmap and strategy of ANAs with clear priorities as input for the European Strategy Research Group (ESRG).
In order to prepare the document for the ESRG, three workshops are planned:
the first is scheduled during the EAAC 2017 where a WG on colliders is organized; a second at the beginning of 2018 hosted by the JAI, and a third jointly with the AAC2018.

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ALEGRO WORKSHOP (A. Seryi, P. Muggli)

ALEGRO 2018

Advanced LinEar collider study GROup Workshop 2018

26-29 March 2018, University of Oxford, JAI

https://indico.cern.ch/event/677640/

- Physics Case (PC); WG1: Michael Peskin (SLAC), TBD ()
- Collider machine design/definitions (CMD) ; WG2: Daniel Schulte (CERN), Andrei Seryi (JAI)
- Theory, Modeling, Simulations (TMS); WG3: Jean-Luc Vay (LBNL), Jorge Vieira (IST)
- LWFA; WG4: Carl Schroeder (LBNL), Simon Hooker (JAI/Oxford), Brigitte Cros (CNRS/U Paris Sud)
- PWFA; WG5: Jens Osterhoff (DESY), Edda Gschwendter (CERN), Patric Muggli (MPP)
- SWFA; WG6: Philippe Piot (NIU), John Power (ANL)
- DLA; WG7: Joel England (SLAC), Ben Cowan (Tech-X)
- Joint sub-WG on positron acceleration (PAC); WG8: Sebastien Corde (LOA), Spencer Gessner (CERN)

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

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ALEGRO WORKSHOP (A. Seryi, P. Muggli)

ALEGRO 2018

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- DLA; WG7: Joel England (SLAC), Ben Cowan (Tech-X)

Open to community at large

Prepare document for ESRG (2018)

Mark the date in your calendar, <u>you</u> are invited!

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SUMMARY

- ✧ANA's have made remarkable progress over the last decade
  - ✧All have demonstrated accelerating gradients large than ~1GeV/m!!! Advanced!!!
  - ✧Very large gradients reached (>100GV/m)
  - ✧Very large energy gains achieved (>4GeV in ~10cm LWFA, >40GeV in 85cm PWFA)
  - ✧Witness bunch acceleration, transfer efficiency (80% bunch to bunch) demonstrated (PWFA, SWFA)
  - ✧Next milestones: high quality acceleration (ΔE/E, ε small), staging/long accelerator
- ✧Complex experiments for small groups
- ✧Number of technical challenges towards producing collider beams, but no <u>physics</u> roadblocks/show stopper
- ✧"Large scale" experiments: FACET, DESY Flash Forward, INFN SPARC_LAB, AWAKE-CERN, BELLA, CILEX, ELI, etc., design study EuPRAXIA
- ✧Concepts for "collider-like" accelerators exist, i.e., issues start to be addressed …
  - ✧Quality, efficiency, reproducibility, stability, reliability, etc.

MAX-PLANCK-GESELLSCHAFT

SUMMARY

✧Still a diverse field: 4 ANAs

✧Strengthen collaboration between laboratories and university groups

- "The next collider will not be built by faculties at universities"

✧Need appropriate facilities (D+W, etc.) to determine ANAs potential

✧Effort at gathering the ANA community, ICFA-ANA panel, ANAR'2017 Workshop, ALEGRO …

✧Update of the European strategy for particle accelerators

✧Work towards a CDR for an ALC in 2030's

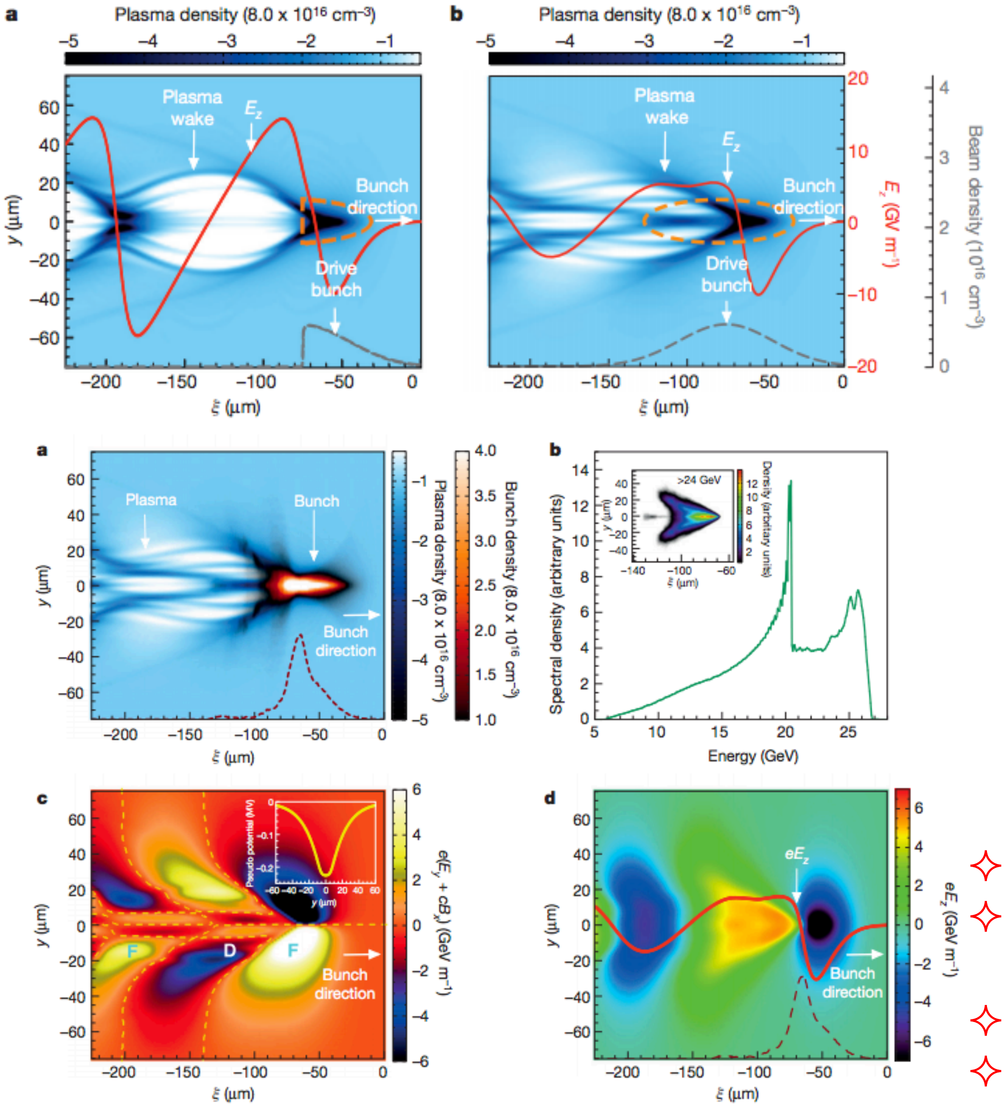
✧Learn from the "conventional" accelerator community, synergies … involvement …

✧Field mature for accelerator laboratories to adopt a concept and take it to the limit …

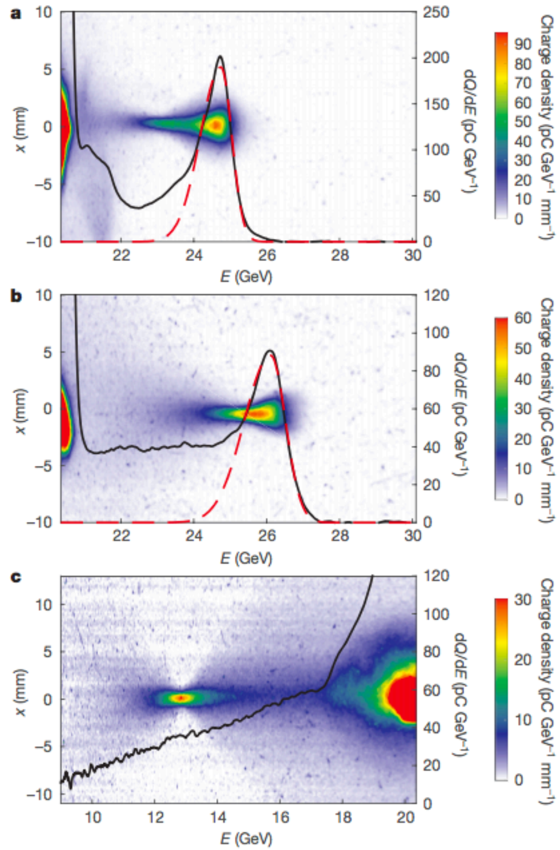
http://www.mpp.mpg.de/~muggli
muggli@mpp.mpg.de

PLASMA WAKEFIELD ACCELERATOR (e^+)

Simulations



Experiment



- n_e=8x10^{16}cm^{-3}, L_p=1.35m
- N=1.4x10^{10}e$^+$, σ_r=70μm, σ_z=30-50μm, E_0=20.35GeV, n_b=(0.2-1)x10^{16}cm^{-3},
- Peak in energy spectrum
- Plasma e$^-$ arrange themselves for focusing and self-loading

Corde et al., Nature 524, 442 (2015)

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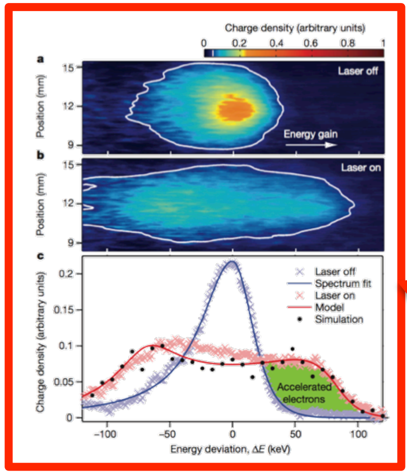
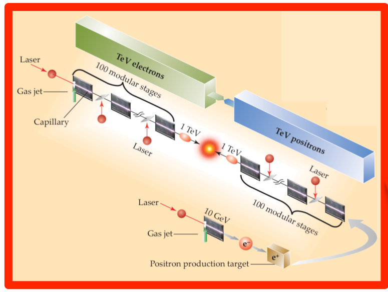
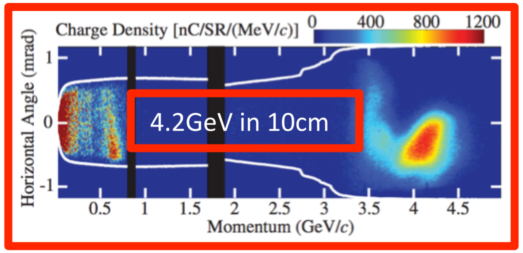
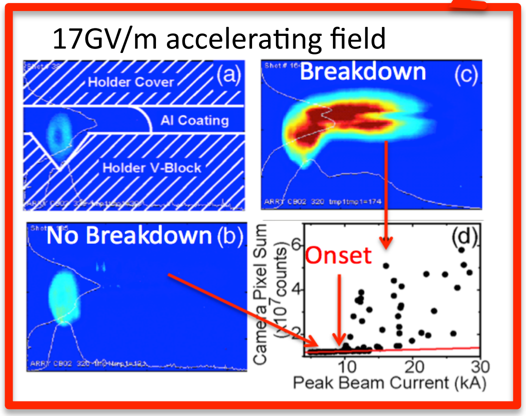
NOVEL ACCELERATOR TECHNiQUES

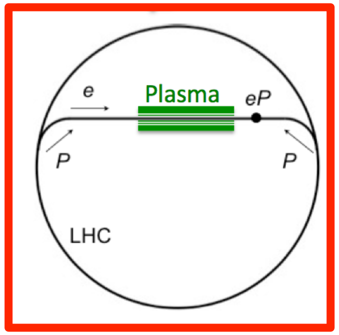


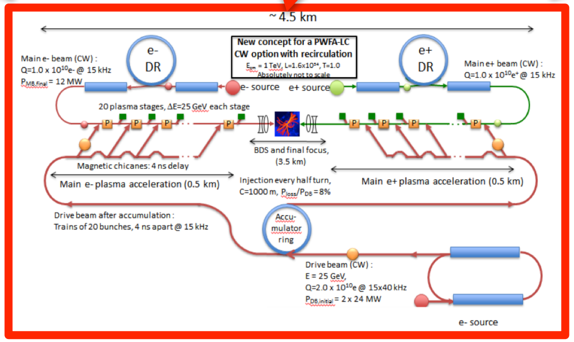


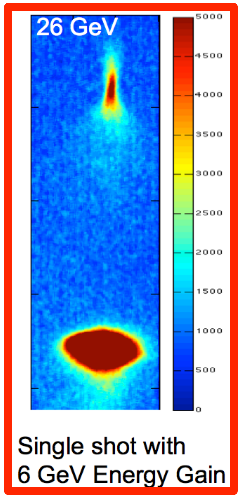


Dielectric Laser Accelerator DLA	Laser Wakefield Accelerator LWFA
Dielectric Wakefield Accelerator DWA	Plasma Wakefield Accelerator PWFA



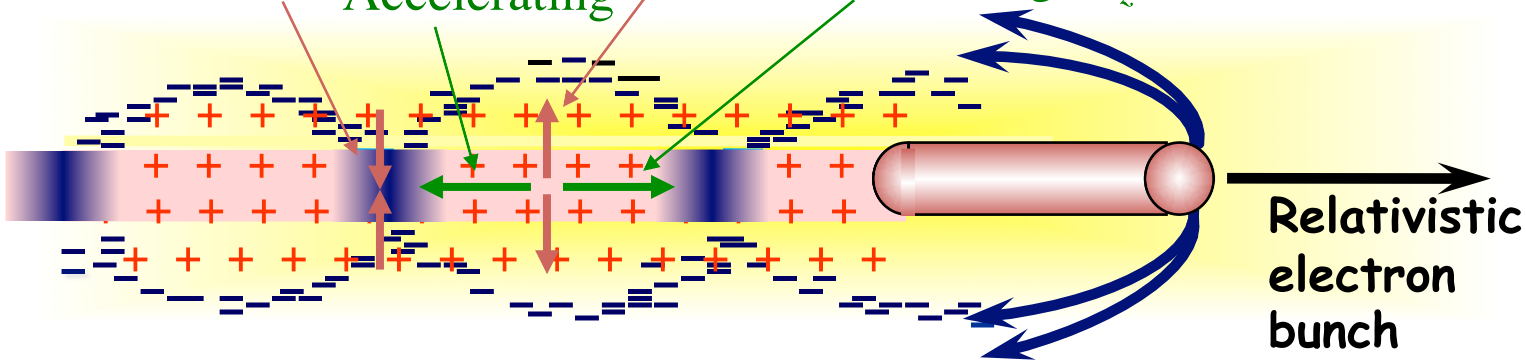






- ✧Very active field that has demonstrated large accelerating gradients: 1-10GeV/m
- ✧Very large energy gains (4-20GeV) in <1m in plasmas
- ✧No physics showstoppers towards high energy, high luminosity accelerator
- ✧Straw man "designs" for HEP colliders exist: e^-/e^+ and e^-/p^+ colliders
- ✧Field mature for accelerator laboratory to take it to the limit

PLASMA WAKEFIELD ACCELERATOR (PWFA) (e^-)



- Plasma wave/wake excited by a relativistic particle bunch
- Plasma e^- expelled by space charge force => deceleration + focusing (MT/m)
- Plasma e^- rush back on axis => acceleration, GV/m
- Ultra-relativistic driver => ultra-relativistic wake
  => no dephasing
- Particle bunches have long "Rayleigh length"
  (beta function $\beta^*=\sigma^{*2}/\varepsilon$~cm, m)
- Acceleration physics identical PWFA, LWFA

TECHNIQUES

$$\mathcal{L} \propto \frac{N^+N^- f_{rep} n_b}{\sigma_x^*(\varepsilon_x)\sigma_y^*(\varepsilon_y)} \quad \Leftrightarrow \quad \mathcal{L} \propto \frac{NP_b}{E\sigma_x^*(\varepsilon_x)\sigma_y^*(\varepsilon_y)}$$

Small N^2, large $f_{rep}n_b$ => f_{cont}
Very small λ (~μm)
$\varepsilon_{x,y}$?

No RF involved

Strongly depends on laser rep rate
ILC-like

"Linear" systems with structure

Dielectric Laser Accelerator DLA	Laser Wakefield Accelerator LWFA
Dielectric Wakefield Accelerator DWA	Plasma Wakefield Accelerator PWFA

No "structure"
Plasma "prefers" continuous rate

CLIC-like driver

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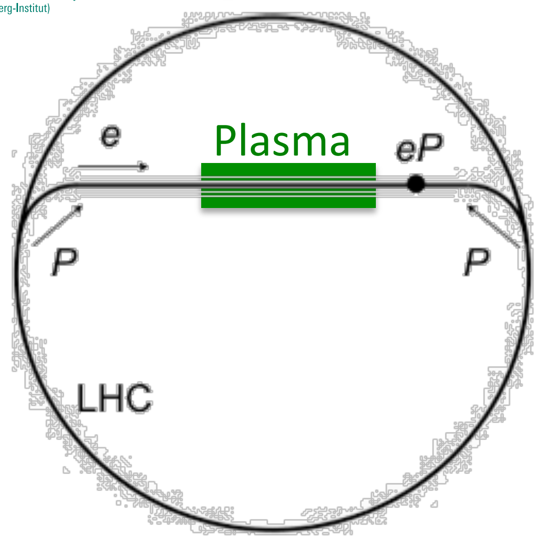
p^+-DRIVEN PWFA FOR e^-/p^+ COLLIDER

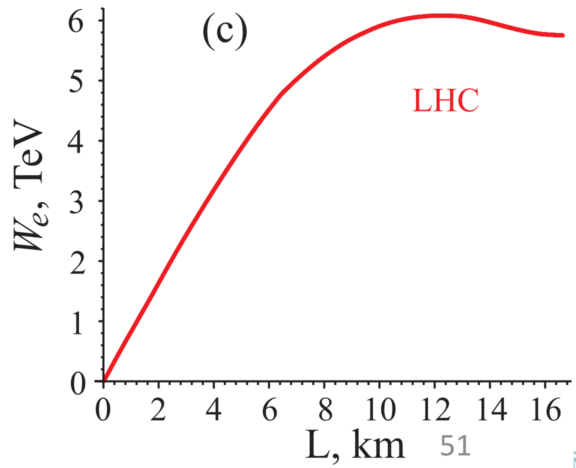


- Emphasis on using current infrastructure, i.e. LHC beam with minimum modifications.
- Overall layout works in powerpoint.
- Need high gradient magnets to bend protons into the LHC ring.
- One proton beam used for electron acceleration to then collider with other proton beam.
- High energies achievable and can vary electron beam energy.
- What about luminosity ?
- Assume
  - ~*3000* bunches every *30 mins*, gives *f ~ 2 Hz*.
  - $N_p \sim 4 \times 10^{11}$, $N_e \sim 1 \times 10^{11}$
  - $\sigma \sim 4\ \mu m$

$$\mathcal{L} = f\frac{N_e \cdot N_p}{4\pi\sigma_x \cdot \sigma_y}$$
$$\approx 5 \cdot 10^{28}\mathrm{cm}^{-2}\mathrm{s}^{-1}$$

simulation of existing LHC bunch in plasma with trailing electrons …

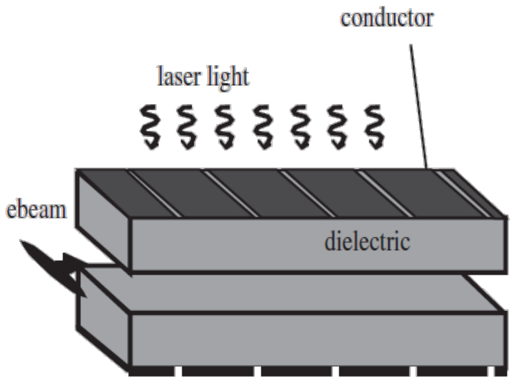
A. Caldwell, K. V. Lotov, Phys. Plasmas **18**, 13101 (2011)



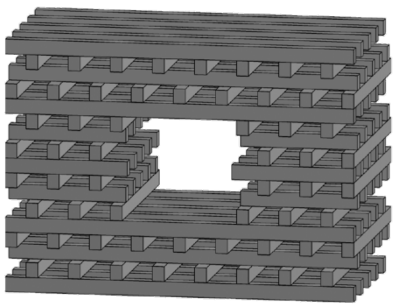
Courtesy A. Caldwell

DiELECTRiC LASER ACCELERATOR (DLA)

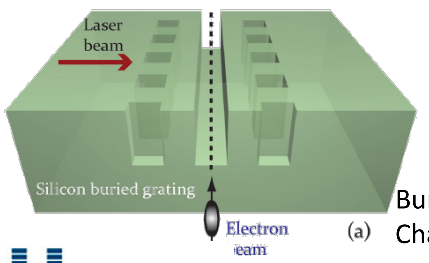
Proposed dielectric structures



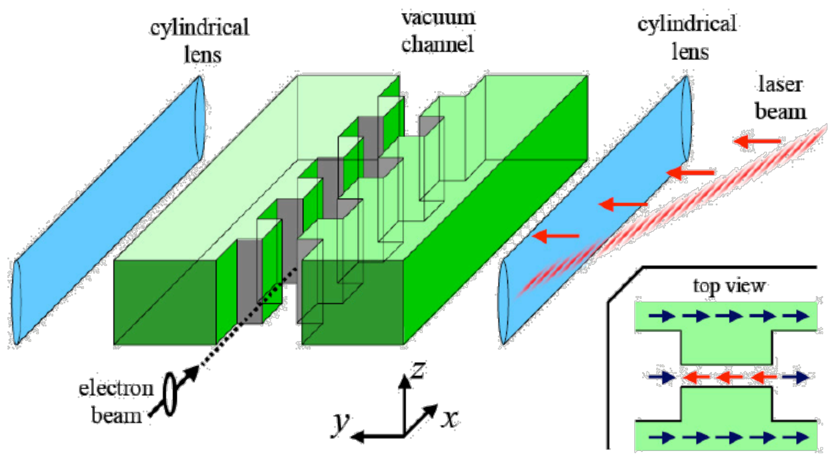
Yoder, Rosenzweig, 2005



Woodpile
Cowan, 2008



Buried Grating
Chang, Solgaard, 2014



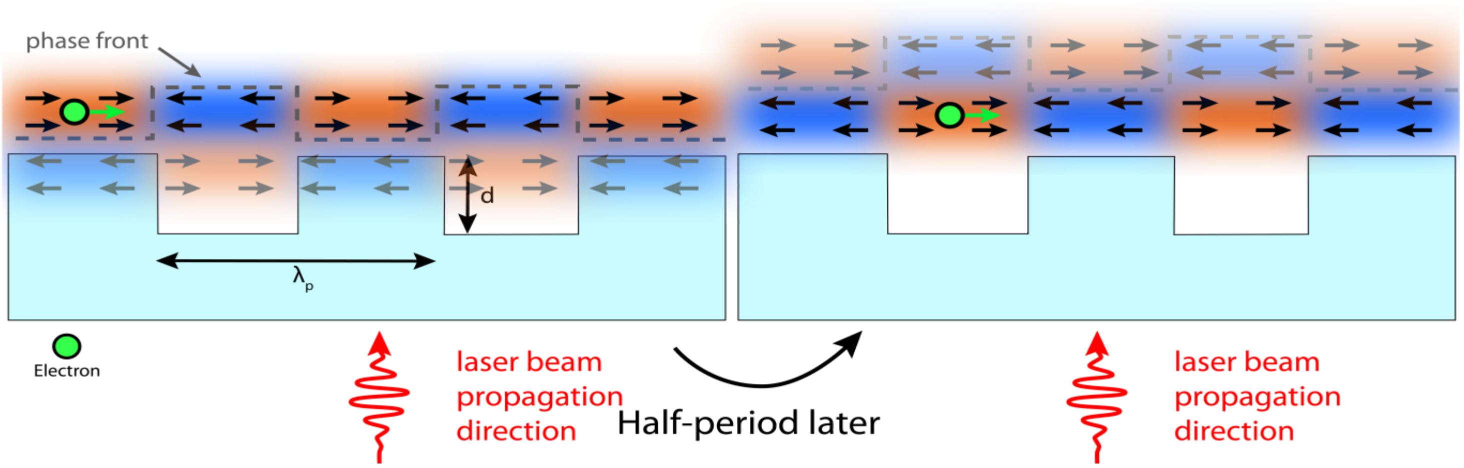
Plettner, Lu, Byer, 2006

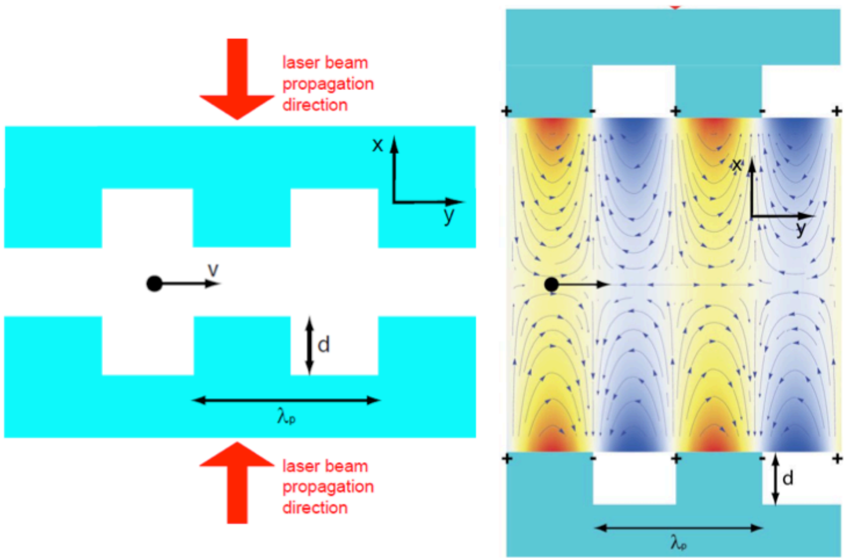
… and variants

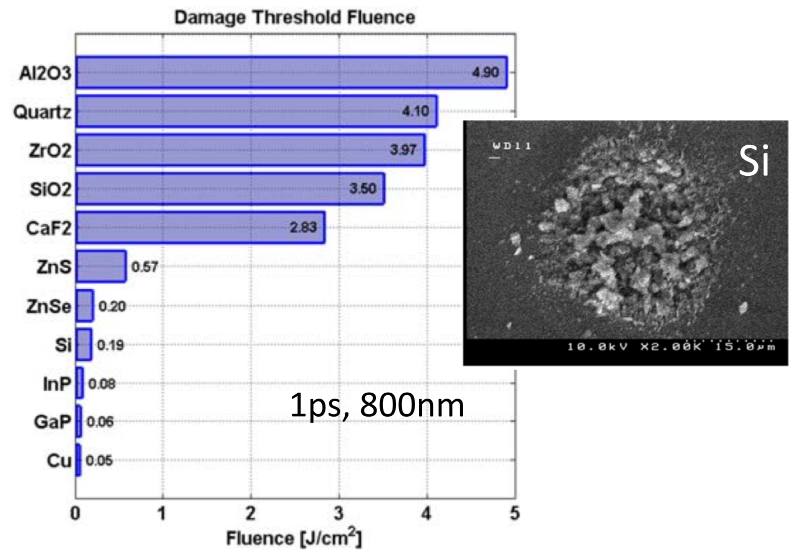
- Goal: generate a mode that allows momentum transfer from laser field to electrons
- Use first order effect (efficient!)
- Second order effects (ponderomotive) too inefficient

For a review and an extensive list of references, see: R. J. England et al., “Dielectric laser accelerators”, Rev. Mod. Phys. 86, 1337 (2014)

DiELECTRiC LASER ACCELERATOR (DLA)







Soong, AIP Conf. Proc. 1507, 511 (2012)

- ✧ Take advantage of large laser E-field
- ✧ Take advantage of large damage threshold
- ✧ Structure = phase mask for velocity matching

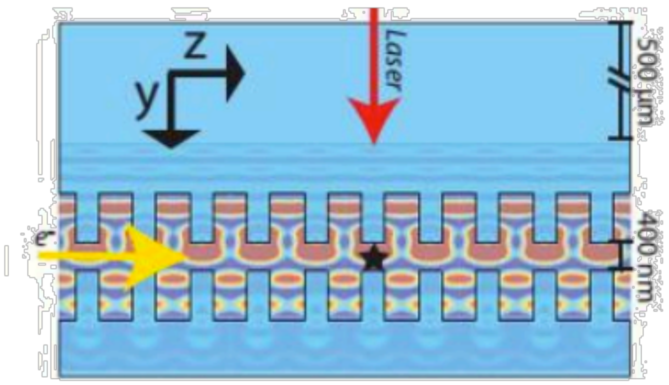
 Courtesy P. Hommelhoff

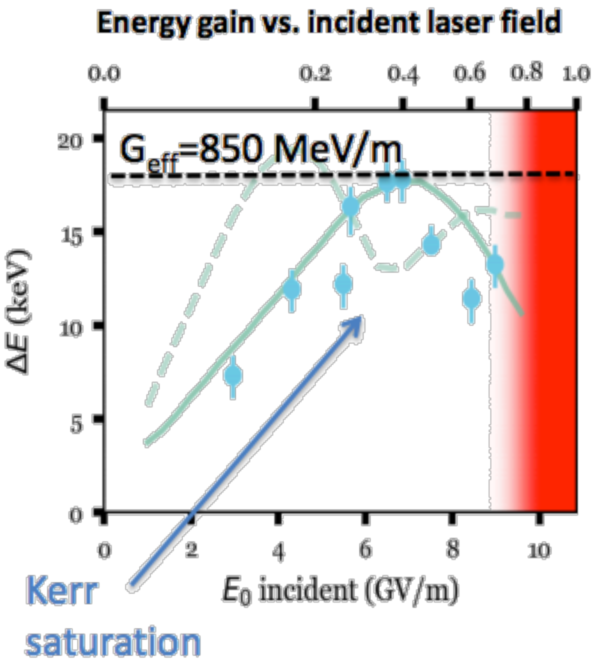
P. Hommelhoff, Accel. Med. Appl., Vösendorf, Austria, 2015

DiELECTRiC LASER ACCELERATOR (DLA)

Measurement of Nonlinear DLA Response

Presented by D. Cesar (UCLA) @ EAAC 2017





- Peak 'gradient' 850 MeV/m ($E_{z,max}$ 1.8 GV/m)
- First use of ebeam to probe nonlinear dielectric structure response in the near field at optical wavelengths
- Fully reversible saturation explained by simulation (solid green curve) of non- linear Kerr effect
  - Dashed green curve shows theoretical prediction for perfectly aligned beam.

arXiv: "Nonlinear response in high-field dielectric laser accelerators" http://arxiv.org/abs/1707.02364

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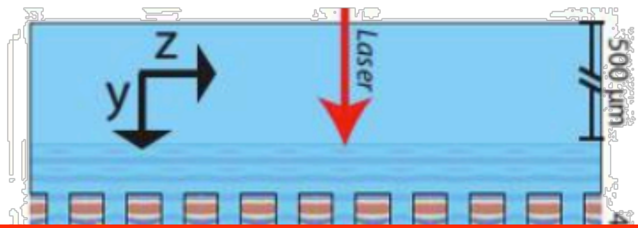

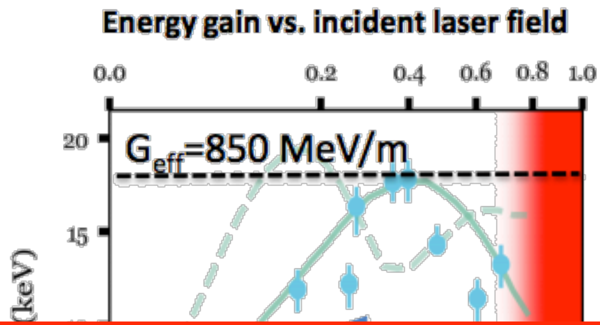

Take advantage of:

✧Micro-fabrication (semi-conductor) technology
✧Fiber laser (communication) development
✧Optical diagnostics
✧High rep-rate (MHz-GHz), low charge (fC), high gradient

✧Need suitable W bunch

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CHARACTERiSTiCS OF ANAs (HEP)

- ✧High gradient: >1GeV/m, >100GeV/m (peak) demonstrated
- ✧High energy gain (multi GeV, some)
- ✧High frequency: >100GHz -> 375THz (λ=800nm)
- ✧Small "structure" size (mm -> µm)
- ✧Short, small pulses (particles, radiation, <1ps, 300µm)
- ✧Easy or no fabrication
- ✧Low Q systems (traveling waves)

- ✧Novel
  - ✧SWFA, PWFA: HEP beams as drivers (20GeV)
- ✧"Totally" novel
  - ✧LWFA: lasers and plasmas
  - ✧DLA: lasers and micro-fabrication

} For all components:
-Source
-Accelerator
-Optics
-Diagnostics
-…

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LWFA LASER DEVELOPMENT

✧International Committee on Ultra-high Intensity Lasers (ICUIL)

- "Our mission is to stimulate, strengthen and expand ultra-intense laser science and related technologies."

The International Committee on Ultra-High Intensity Lasers

✧The International Coherent Amplification Network (ICAN)

- "The network is looking into existing fiber laser technology, which we believe has fantastic potential for accelerators"
- "CERN's contribution to the ICAN project is part of a wider strategy to encourage the development of laser acceleration technologies. By supporting ICAN and similar research projects, CERN will be contributing to the R&D of potentially ground-breaking accelerator technologies."

Xcan Coherent Amplification Network POLYTECHNIQUE / THALES

https://portail.polytechnique.edu/izest/en

✧Strong effort to develop high peak power/high average power, short pulse fiber lasers

✧The future is fiber lasers?

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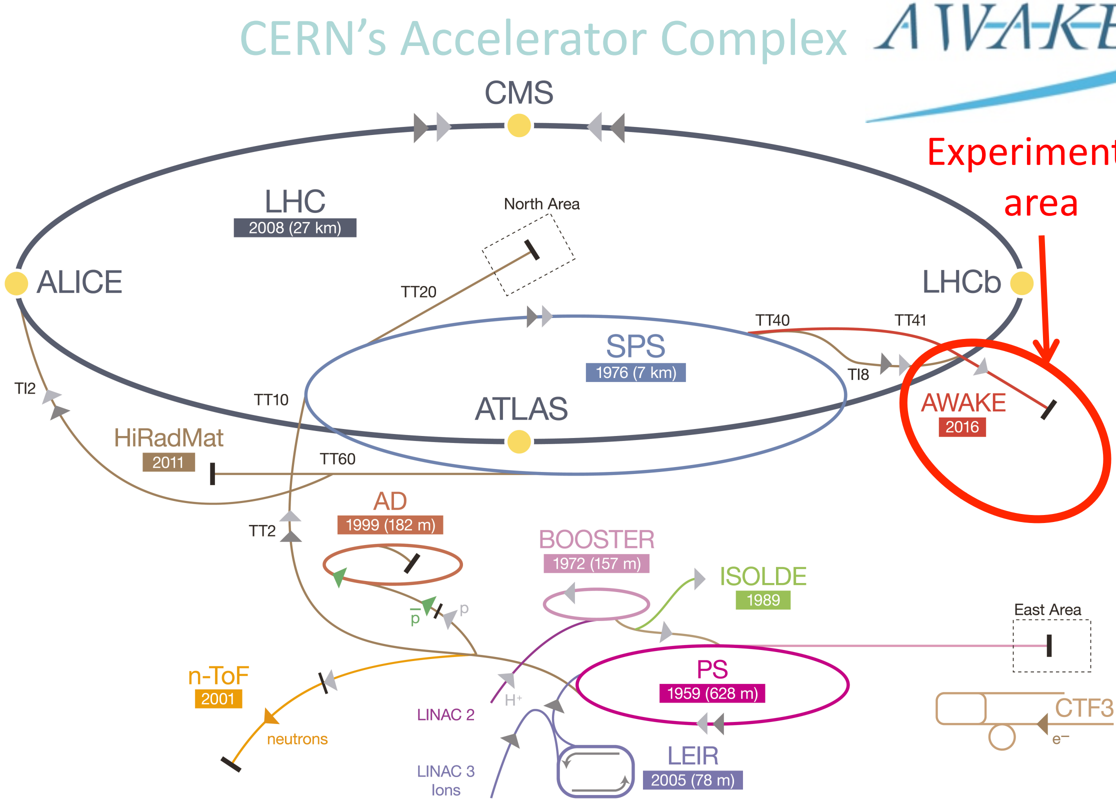
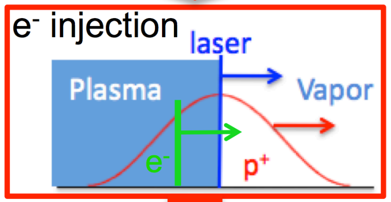
p^+-DRiVEN PWFA

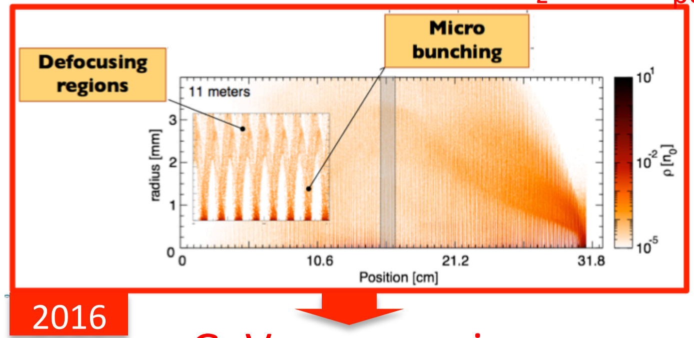


3x10[11], 400GeV SPS p^+

10m plasma, n_e=1-10x10[14]cm[-3]

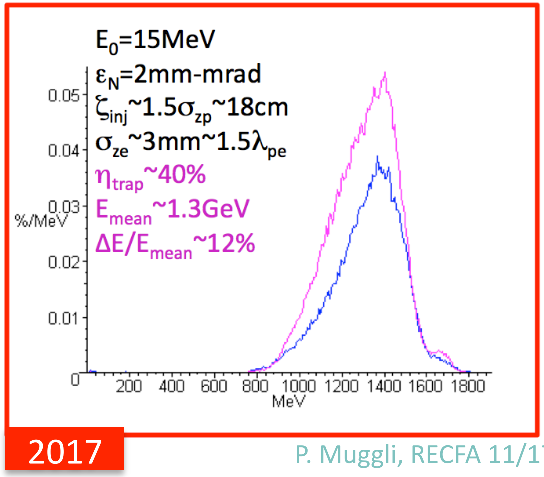


p^+ bunch self-modulation: σ_z~$100\lambda_{pe}$



GeV energy gain

by externally injected e^-



✧SPS beam: high energy, small σ_r^*, long β^*

✧Initial goal: ~GeV gain by externally injected e^-,in 5-10m of plasma in self-modulated p^+ driven PWFA

✧Setup a comprehensive PWFA program at CERN

AWAKE Collaboration, Plasma Phys. Control. Fusion 56 084013 (2014)