The AWAKE Proton-Driven Plasma Wakefield Acceleration Experiment at CERN

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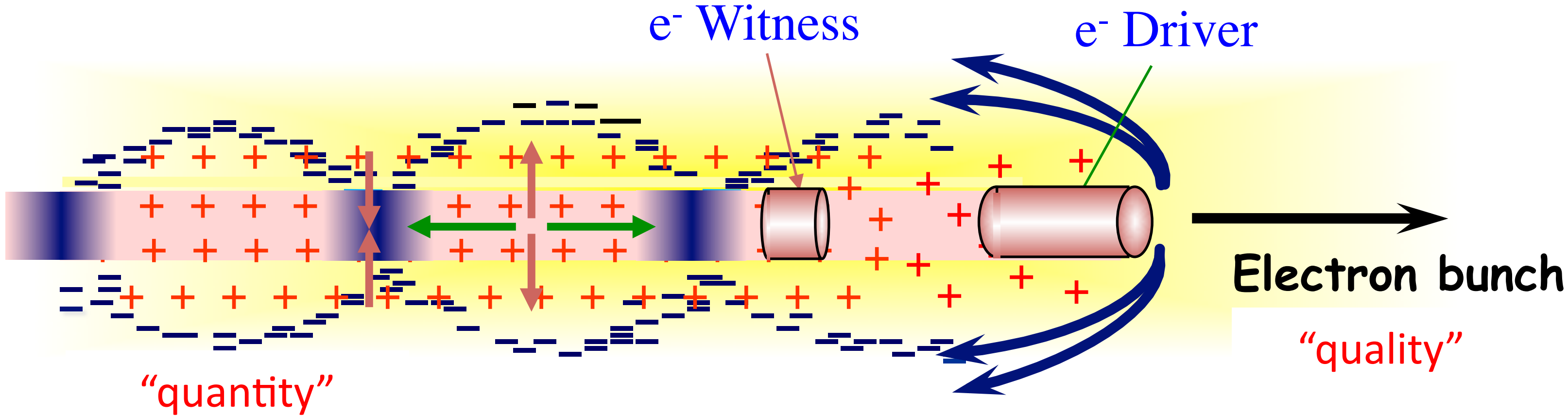
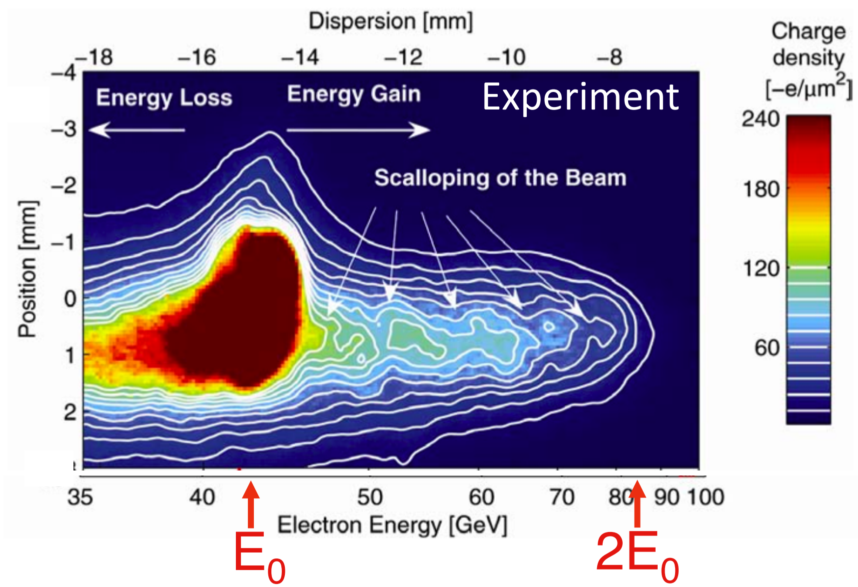
For the AWAKE Collaboration

PLASMA WAKEFIELDS (e^-)



Blumenfeld, Nature 445, 2007



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

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SLAC FACET

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> acceleration

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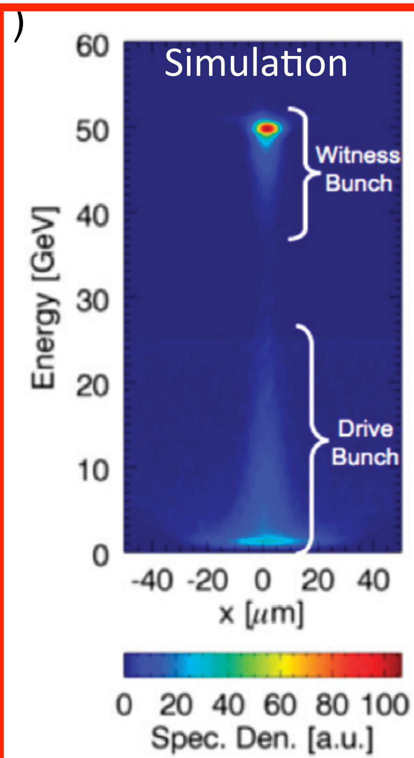
Hogan, NJP 12, 2010

LWFA



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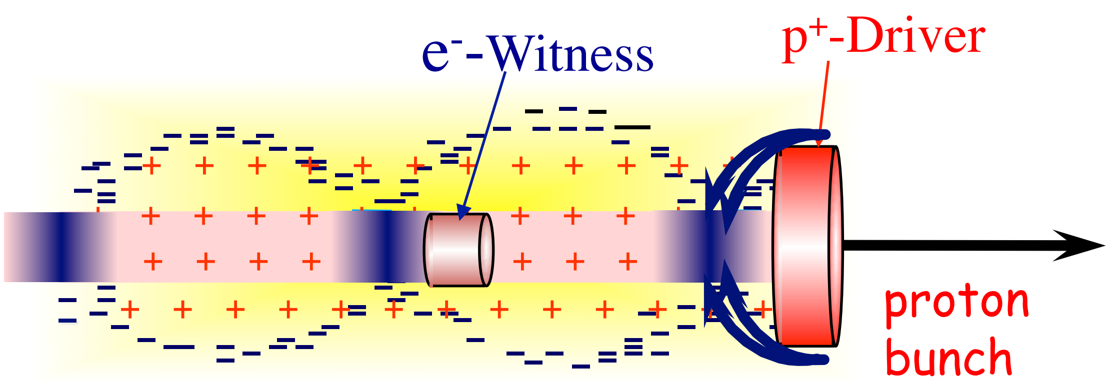
p^+-DRIVEN PWFA? WHY?

AWAKE

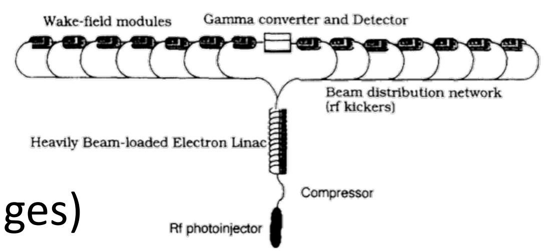


✧ILC, 0.5TeV bunch with $2\times10^{10}e^-$ ~1.6kJ

✧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

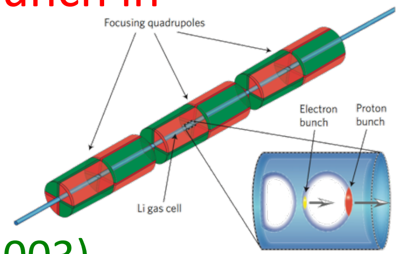


✧SPS, 400GeV bunch with $10^{11}p^+$ ~6.4kJ
LHC, 7TeV bunch with $10^{11}p^+$ ~112kJ

✧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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PROTON-DRIVEN PWFA

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

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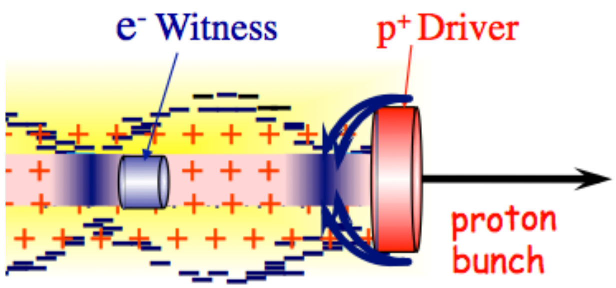
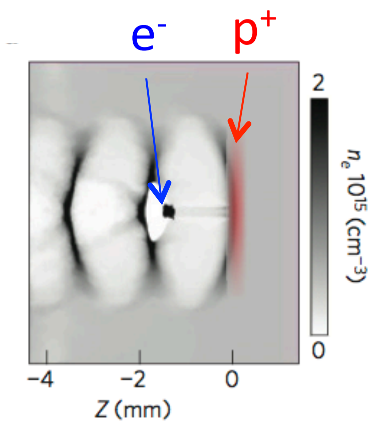
AWAKE

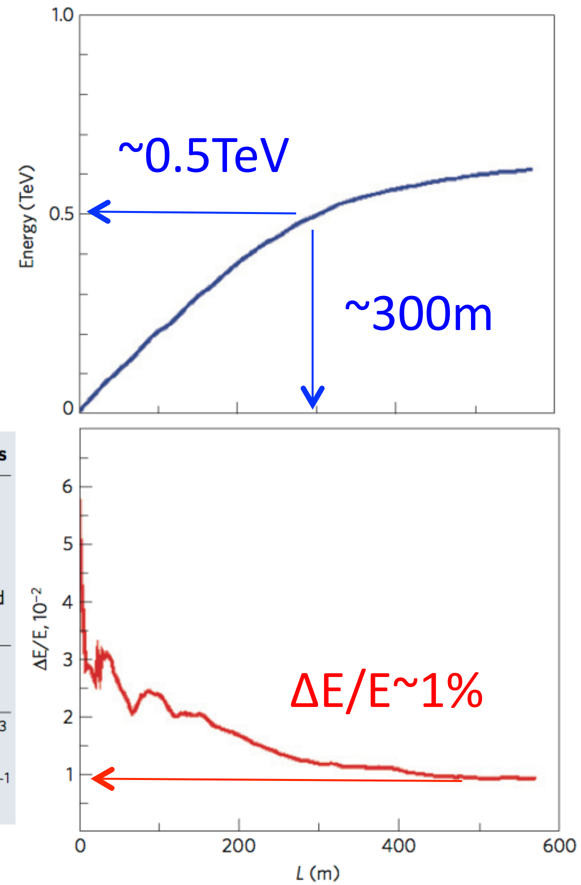


e^-:	p^+:
E_0=10GeV	E_0=1TeV
	σ_z=100µm
N=10^{10}	N=10^{11}
W_0=16J	W_0=16kJ
W_f=1kJ	

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

✧Operate at lower n_e, larger $(\lambda_{pe})^3$, easier life …

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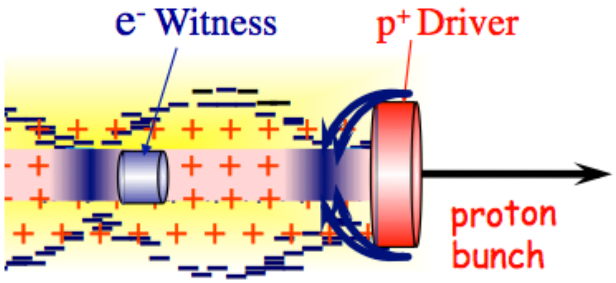
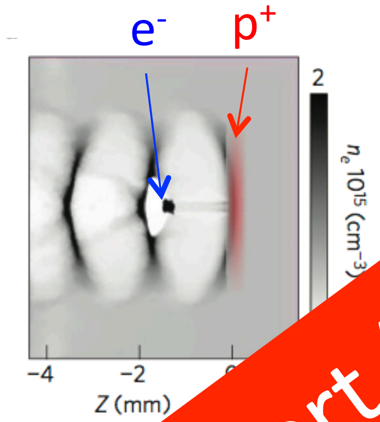
PROTON-DRIVEN PWFA

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

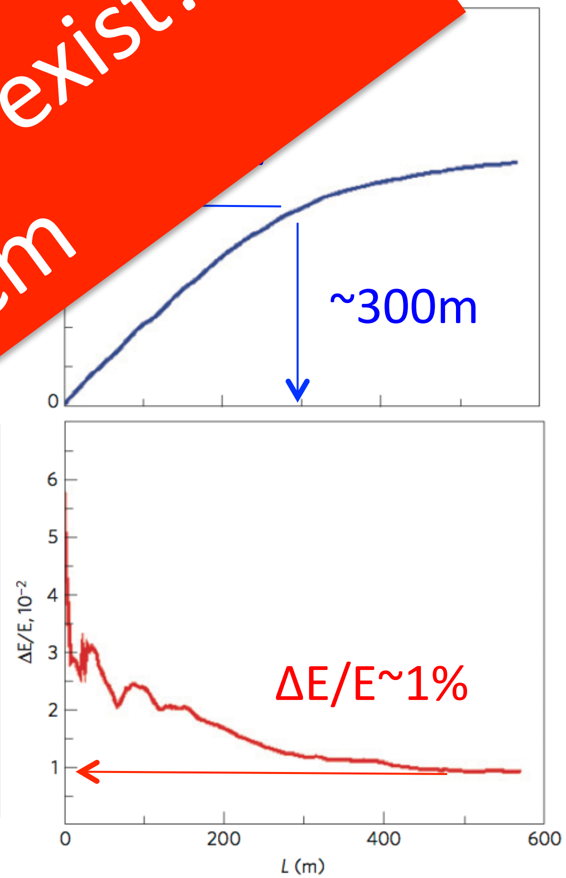


e^-: E_0=10GeV, N=10^{10}, W_0=16J, W_f=1…

p^+: E_0=1TeV, σ_z=10…, N…



		…e	Units
		10^{11}	
		1	TeV
	…$_p/p$	0.1	
	σ_z	100	µm
…ad	σ_θ	0.03	mrad
…se size	$\sigma_{x,y}$	0.43	mm
…witness bunch	N_e	1.5×10^{10}	
…ns in witness bunch	E_e	10	GeV
…on density	n_p	6×10^{14}	cm^{-3}
…a wavelength	λ_p	1.35	mm
…agnetic field gradient		1,000	$T m^{-1}$
Magnet length		0.7	m

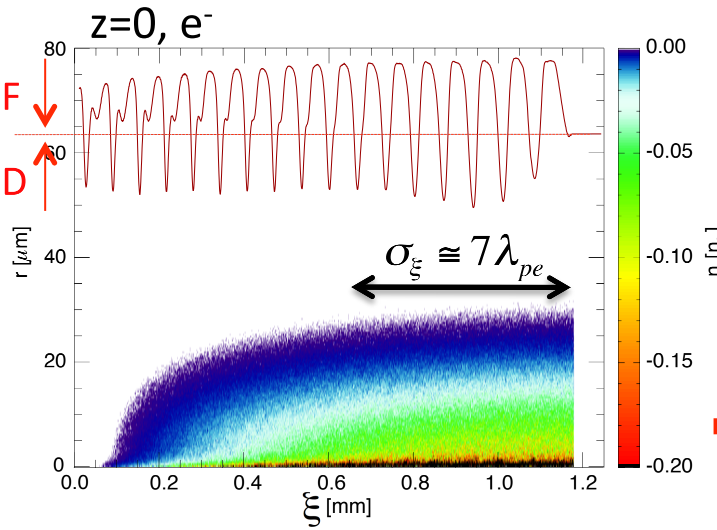


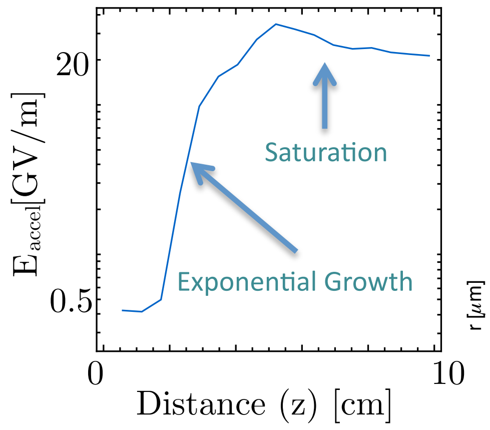
Short (100µm) bunches do not exist!!!
CERN SPS-LHC σ_z ~12cm

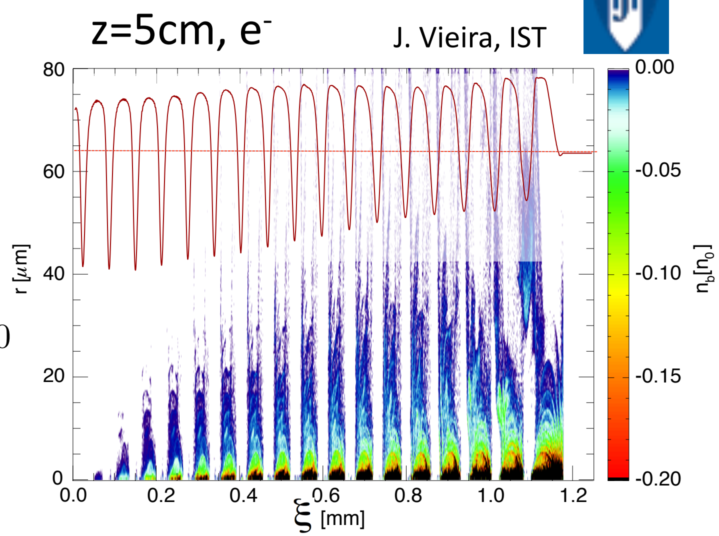
- ✧… n on the wakefields of a p^+ bunch
- ✧S… gradient dilution
- ✧Gra… GV/m over 100's m
- ✧Opera… e at lower n_e, larger $(\lambda_{pe})^3$, easier life …

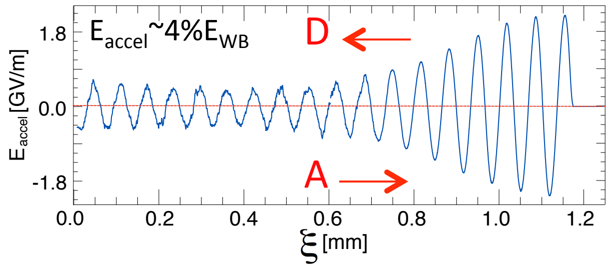
SELF-MODULATION INSTABILITY (SMI)

Kumar, PRL 104, 255003 (2010)

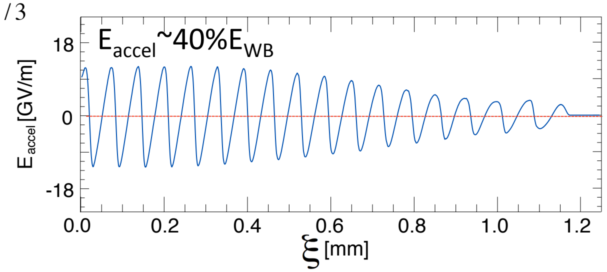








$$N_{\exp} \cong \frac{3\sqrt{3}}{4}\left(\frac{n_b}{n_e}\frac{m_e}{\gamma M_b}\left(k_p|\xi|\right)\left(k_p z\right)^2\right)^{1/3}$$



Grows along the bunch & along the plasma
Convective instability

Pukhov et al., PRL 107, 145003 (2011)
Schroeder et al., PRL 107, 145002 (2011)

- Radial focusing/defocusing with longitudinal period!
- Initial small transverse wakefields modulate the bunch density

J. Vieira et al., Phys. Plasmas 19, 063105 (2012)

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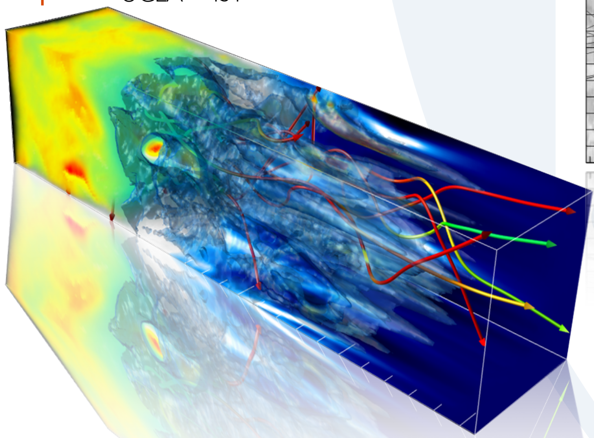
SMI-PWFA SIMULATIONS

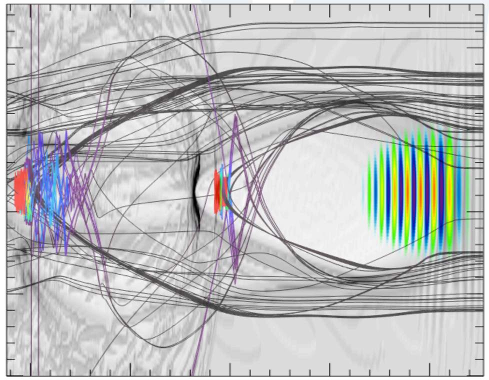
OSIRIS 2.0

UCLA

osiris framework

- Massivelly Parallel, Fully Relativistic Particle-in-Cell (PIC) Code
- Visualization and Data Analysis Infrastructure
- Developed by the osiris.consortium
  ⇒ UCLA + IST





New Features in v2.0

VisXD

- Bessel Beams
- Binary Collision Module
- Tunnel (ADK) and Impact Ionization
- Dynamic Load Balancing
- PML absorbing BC
- Optimized higher order splines
- Parallel I/O (HDF5)
- Boosted frame in 1/2/3D

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Frank Tsung: tsung@physics.ucla.edu

http://cfp.ist.utl.pt/golp/epp/
http://exodus.physics.ucla.edu/

Patric Muggli | May 23rd 2012 | IPAC - New Orleans Louisiana, USA

Benchmarking with (for AWAKE only!):

✧OSIRIS: R. A. Fonseca et al., Lect. Notes Comput. Sci. 2331, 342 (2002)

✧VLPL A: Pukhov, J. Plasma Phys. 61, 425 (1999)

✧LCODE: K. V. Lotov, Phys. Rev. ST Accel. Beams 6, 061301 (2003)

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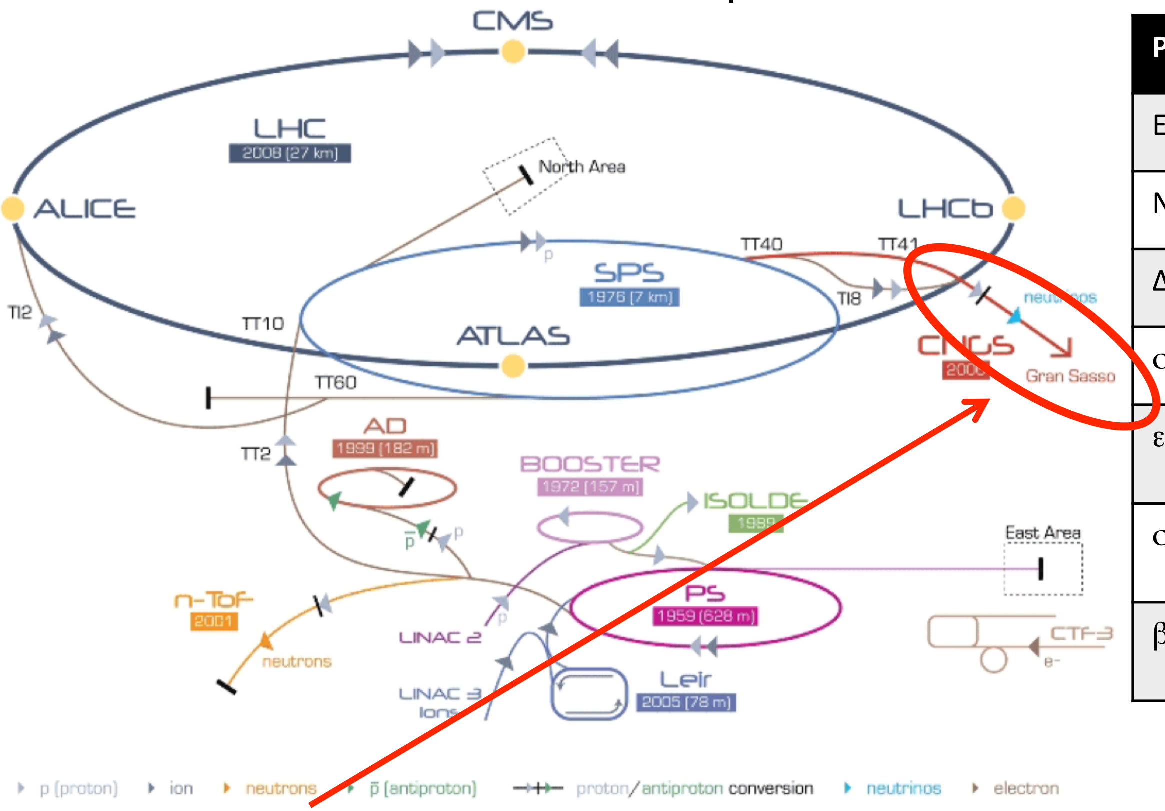
PROTON BEAMS @ CERN

AWAKE

CERN Industrial Beam Complex



CNGS experimental area

Parameter	PS	SPS	SPS Opt
E_0 (GeV)	24	400	400
N_p (10^{10})	13	10.5	30
$\Delta E/E_0$ (%)	0.05	0.03	0.03
σ_z (cm)	20	12	12
ε_N (mm-mrad)	2.4	3.6	3.6
σ_r^* (μm)	400	200	200
β^* (m)	1.6	5	5

n_e~7×10^{14}cm^{-3} for $k_p\sigma_r\approx1$

λ_{pe}~1.3mm<<σ_z

f_{pe}~240GHz

L_p~10m~2β^*

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

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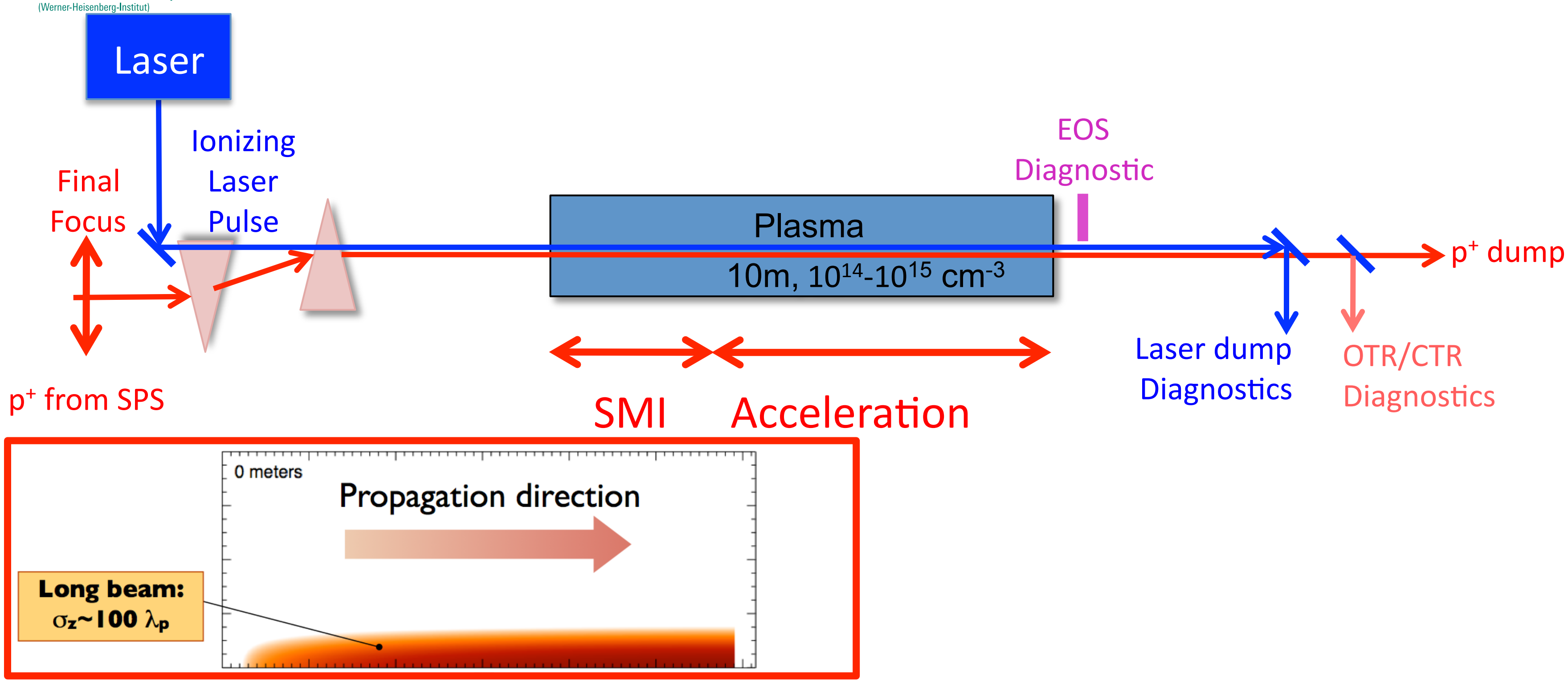
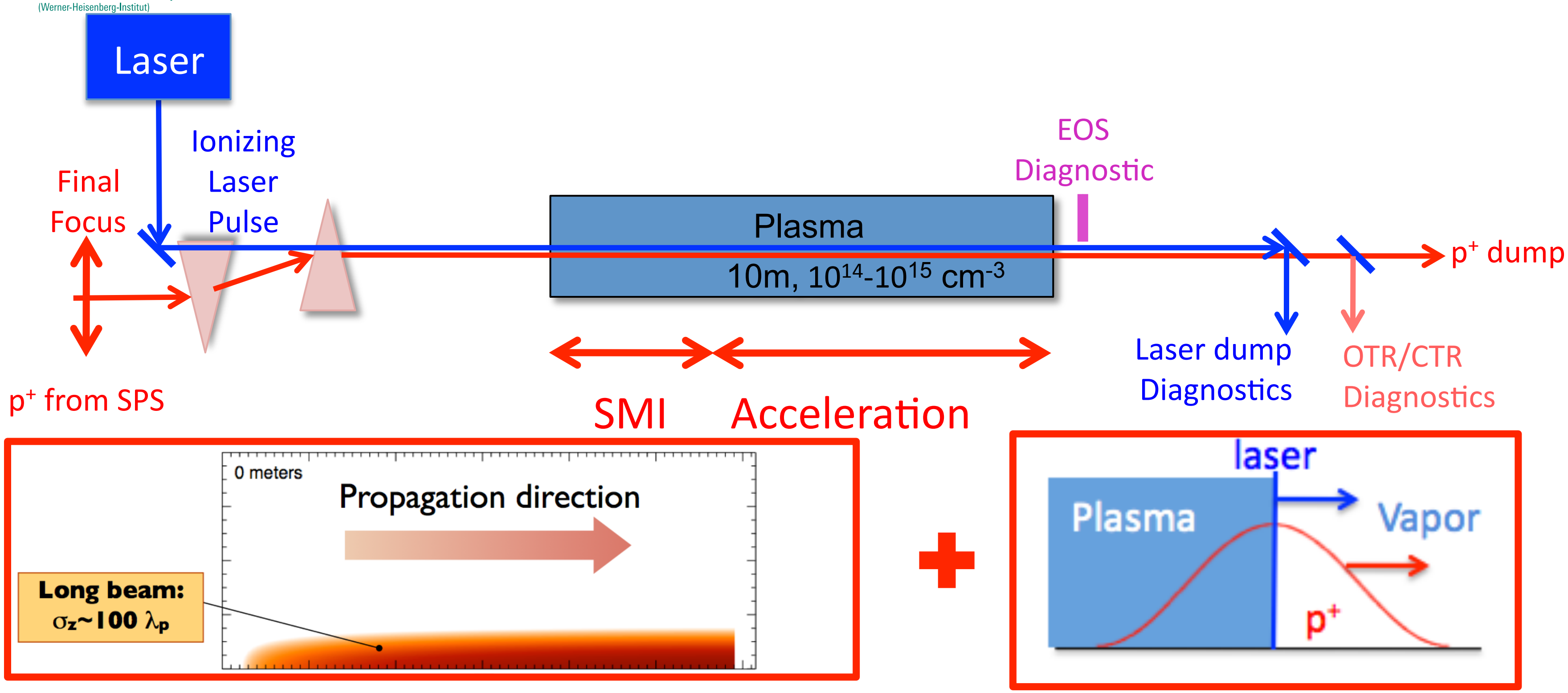
AWAKE EXPERIMENT @ CERN



*Kumar, Phys. Rev. Lett. 104, 255003 (2010)

AWAKE EXPERIMENT @ CERN

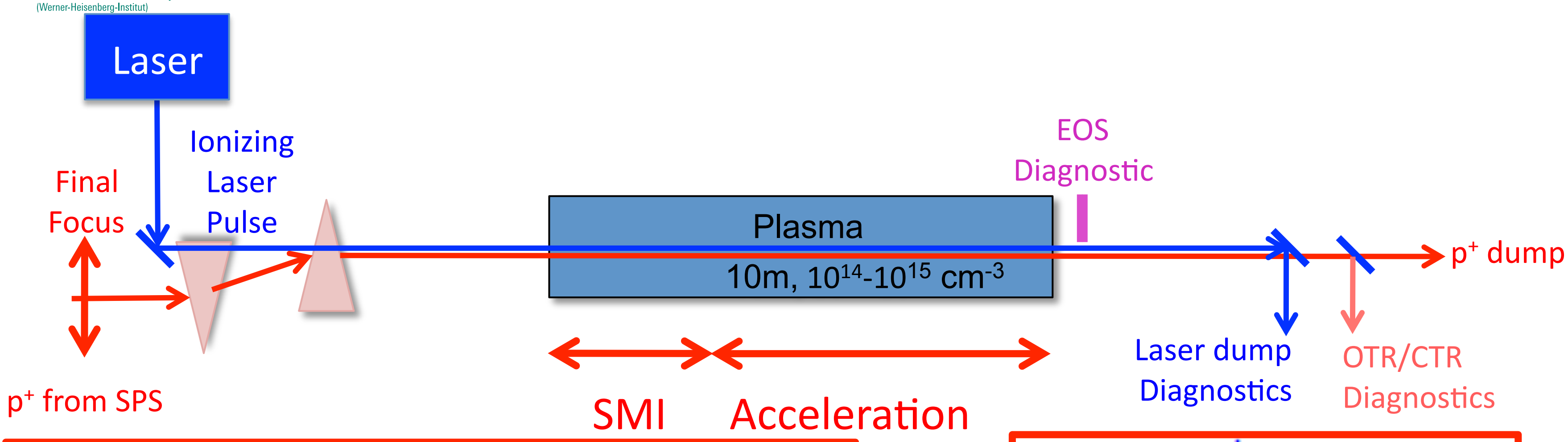


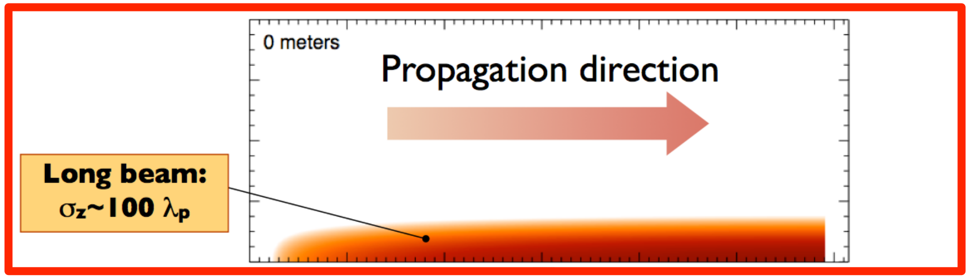
✧Short laser pulse creates the plasma and seeds the SMI

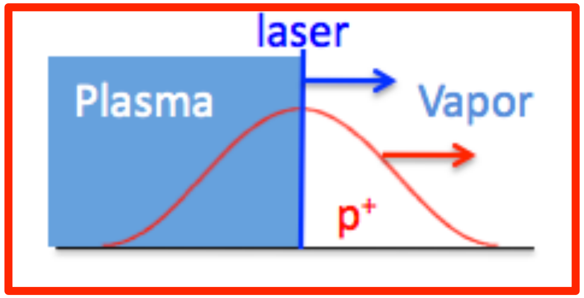
✧σ_z~12cm >> λ_{pe}~1.2mm (n_e~10^{14}cm^{-3}) => Self-modulation Instability (SMI)*

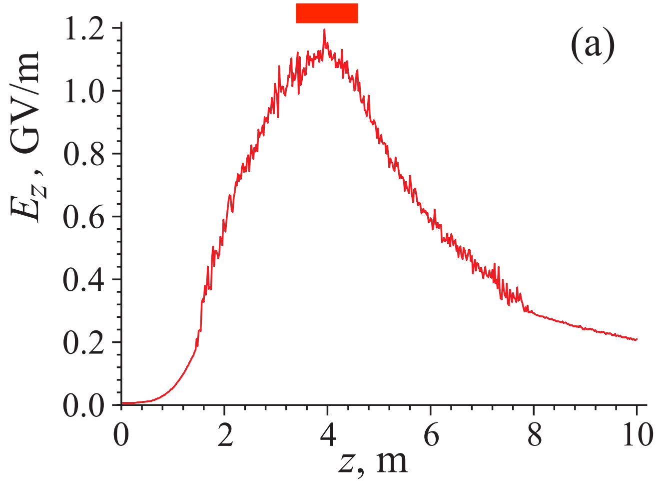
*Kumar, Phys. Rev. Lett. 104, 255003 (2010)

AWAKE EXPERIMENT @ CERN



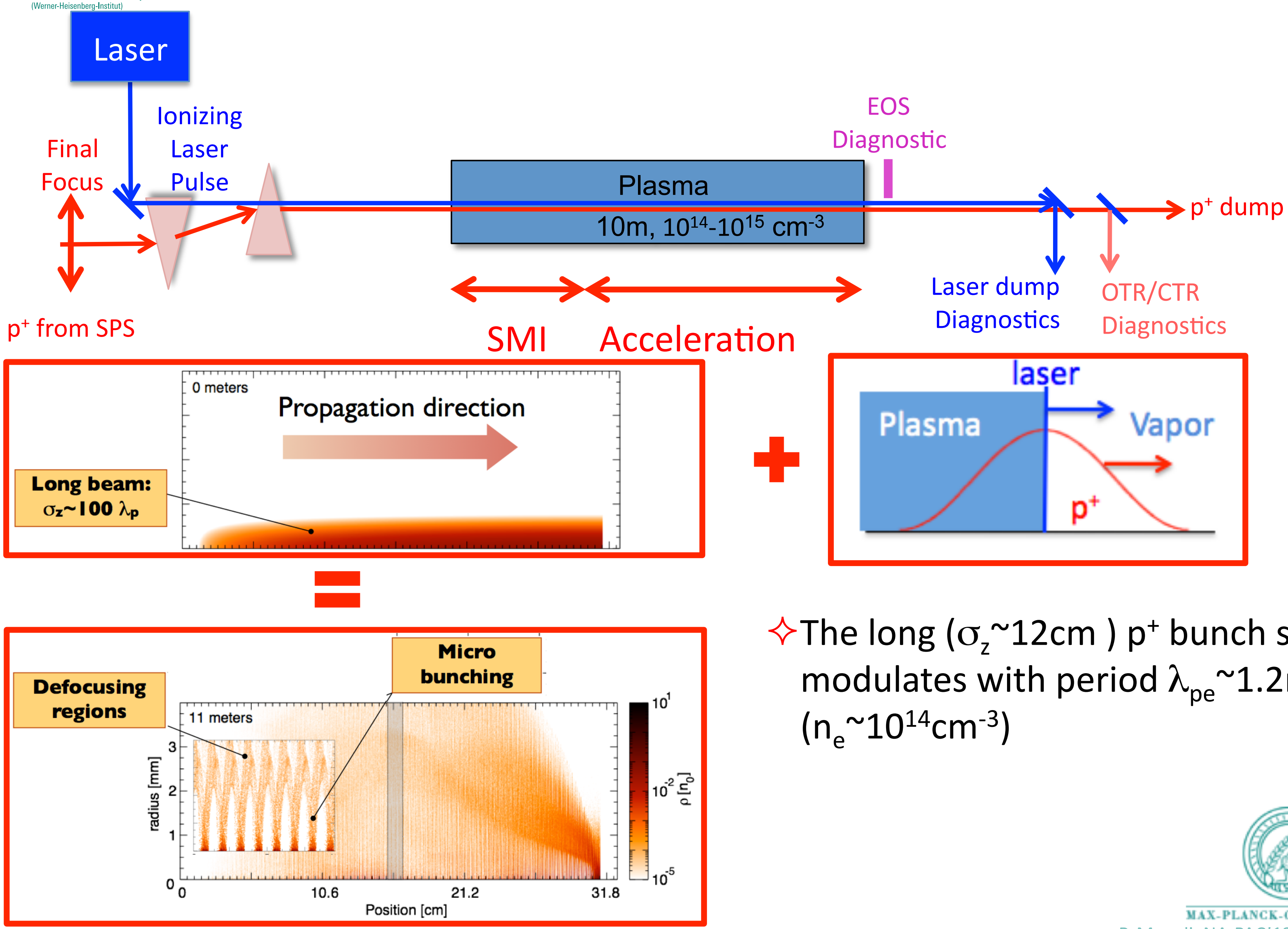






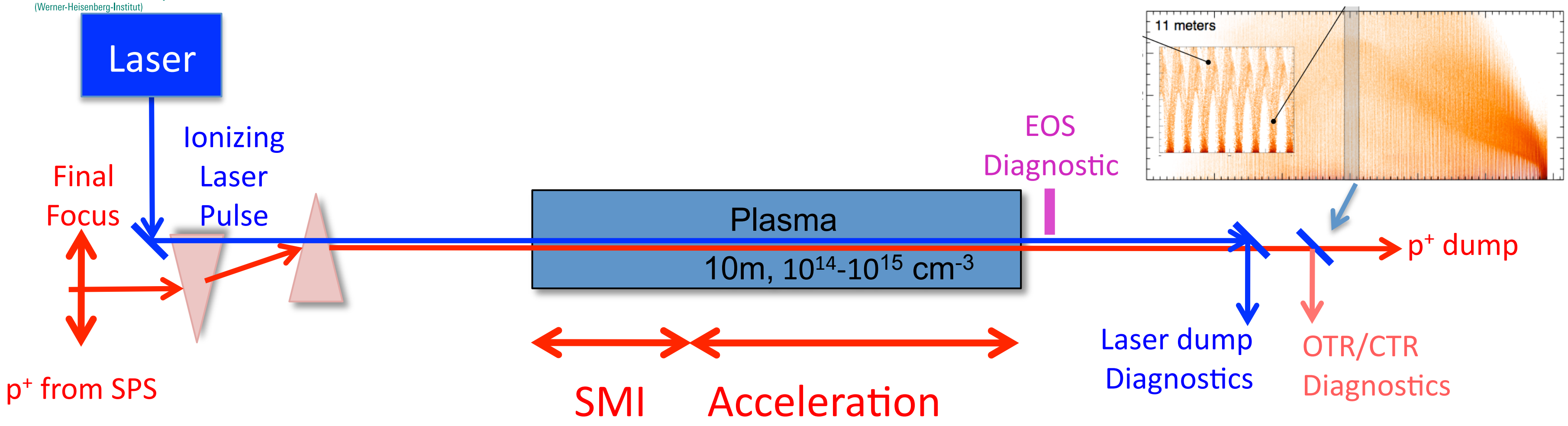
✧The wakefields grow …

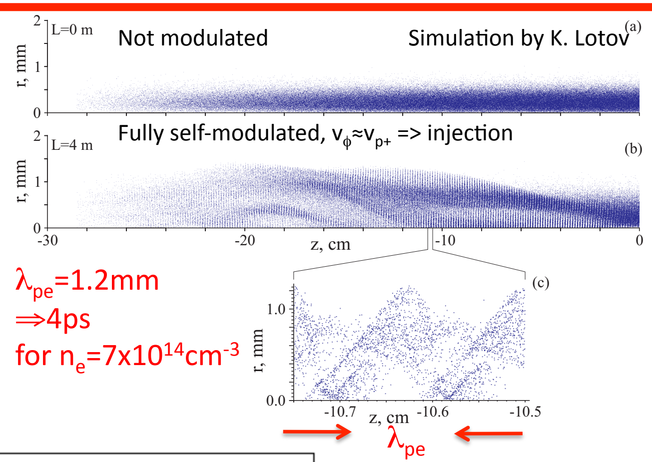
AWAKE EXPERIMENT @ CERN



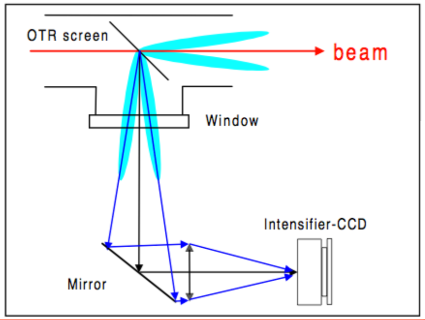
✧The long (σ_z~12cm) p^+ bunch self-modulates with period λ_{pe}~1.2mm (n_e~10^{14}cm^{-3})

SMI Diagnostics



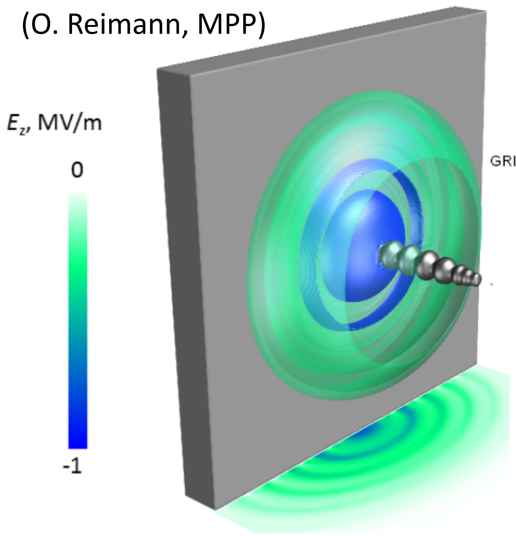


λ_{pe}=1.2mm
$\Rightarrow$4ps
for n_e=7x10^{14}cm^{-3}

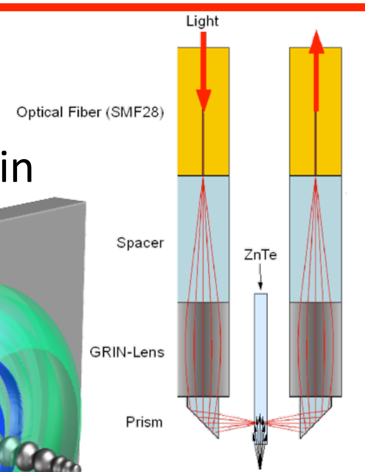


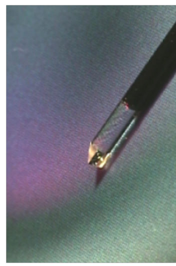
Streak Camera

Electro-optic Sampling in Frequency Domain
(O. Reimann, MPP)



from Pukhov, PRST-AB 2012





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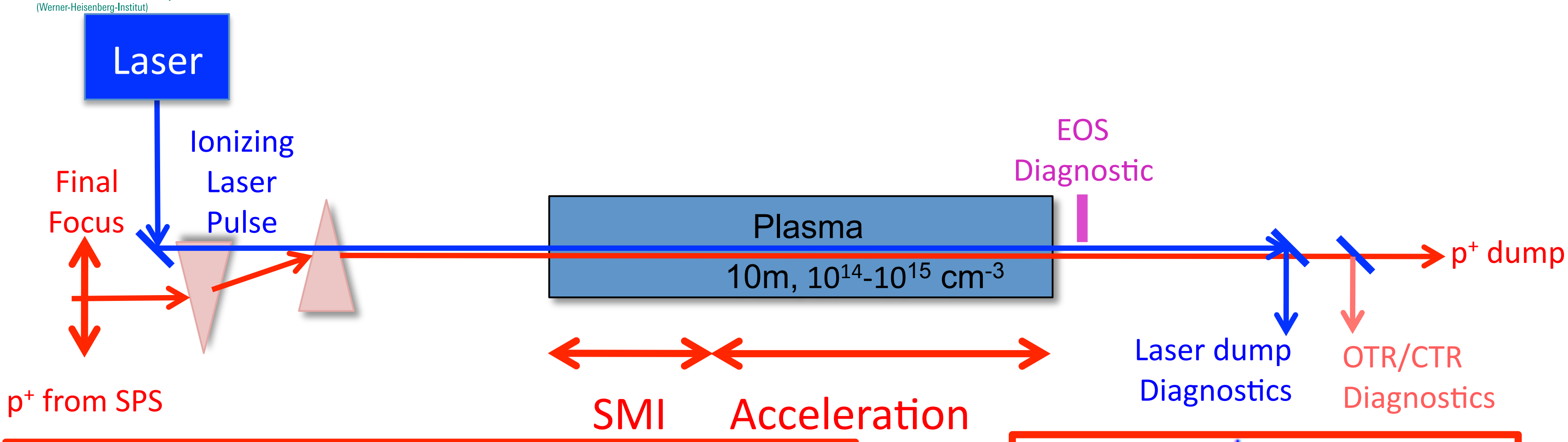

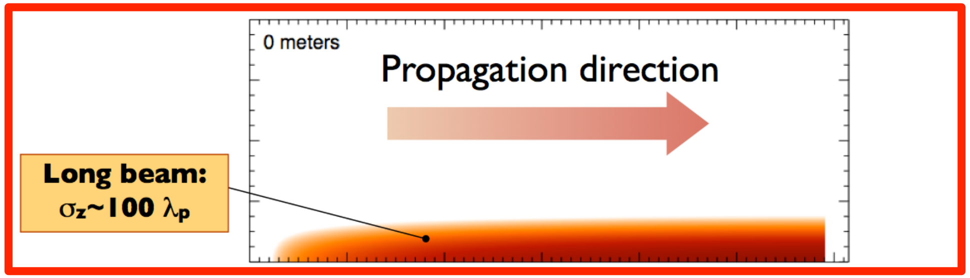

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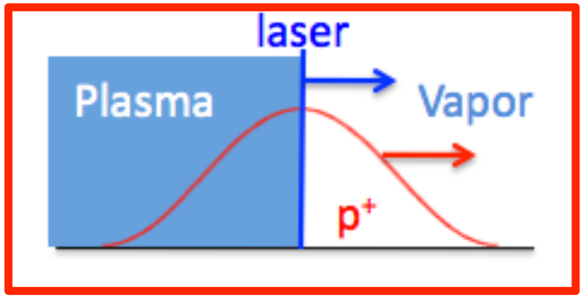

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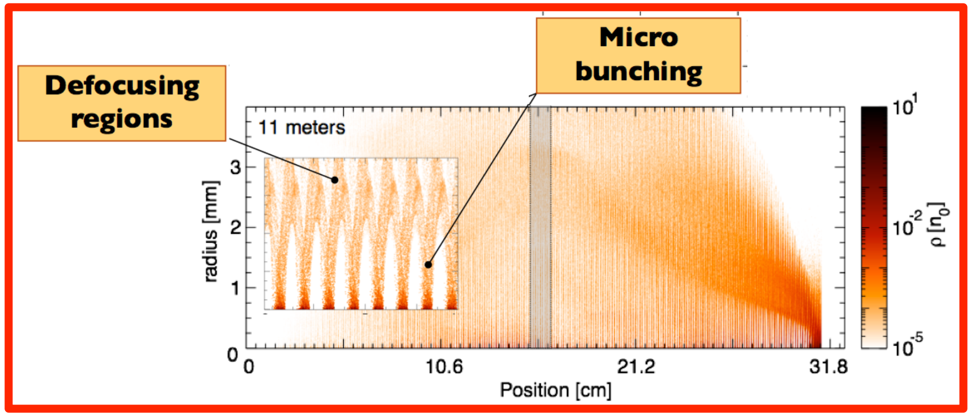
✧The SM p^+ bunch resonantly drives wakefields



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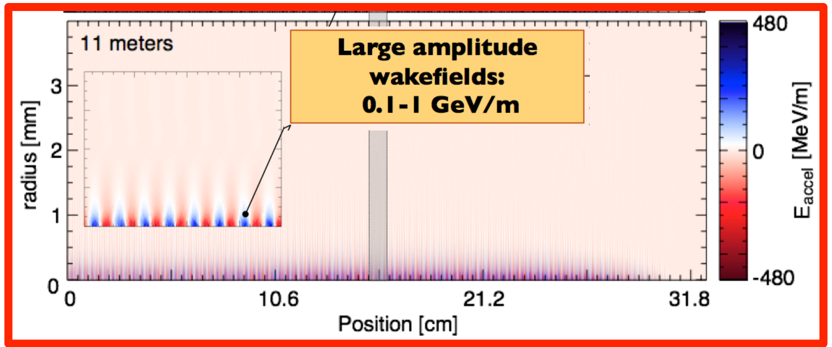
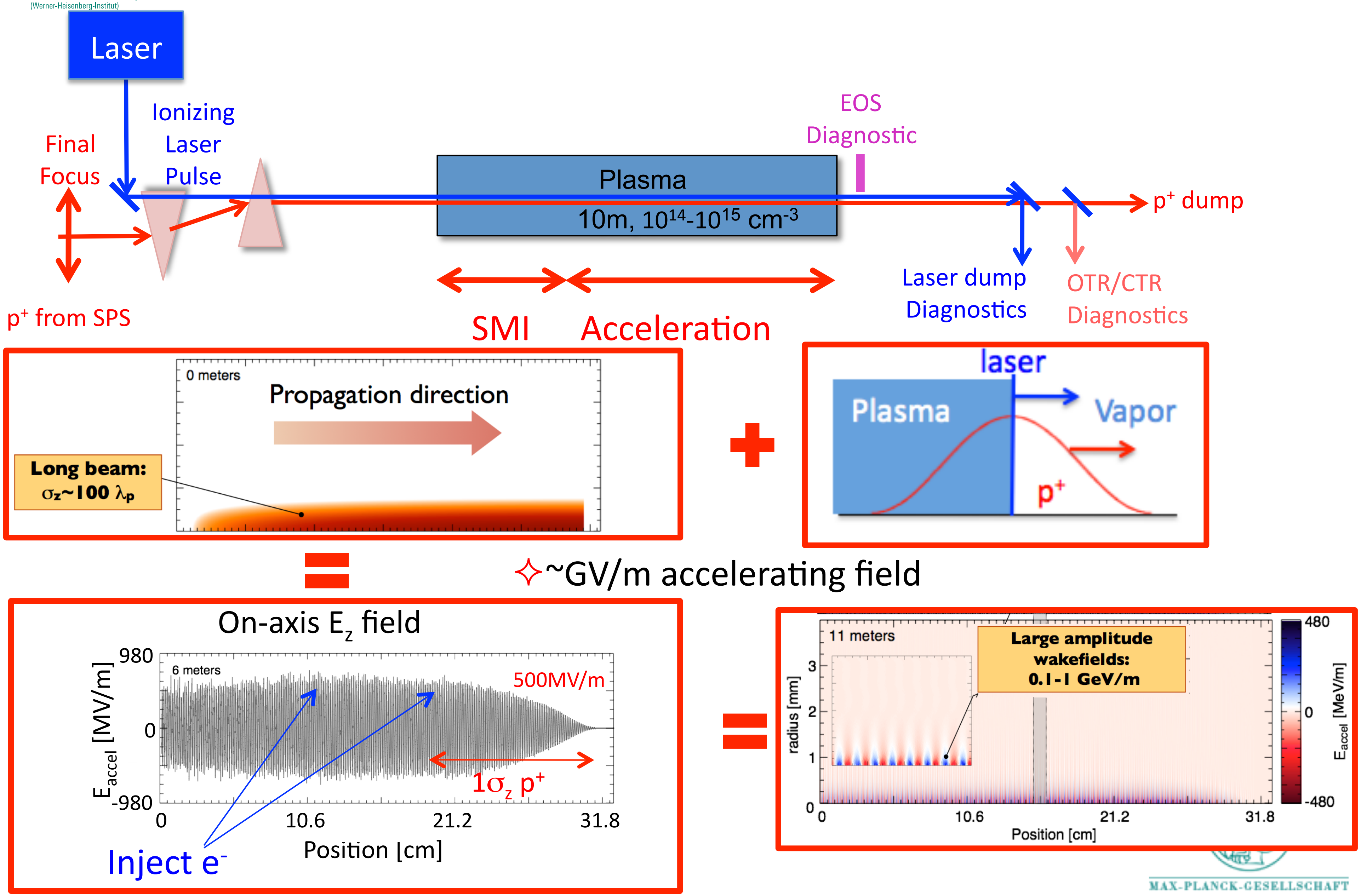


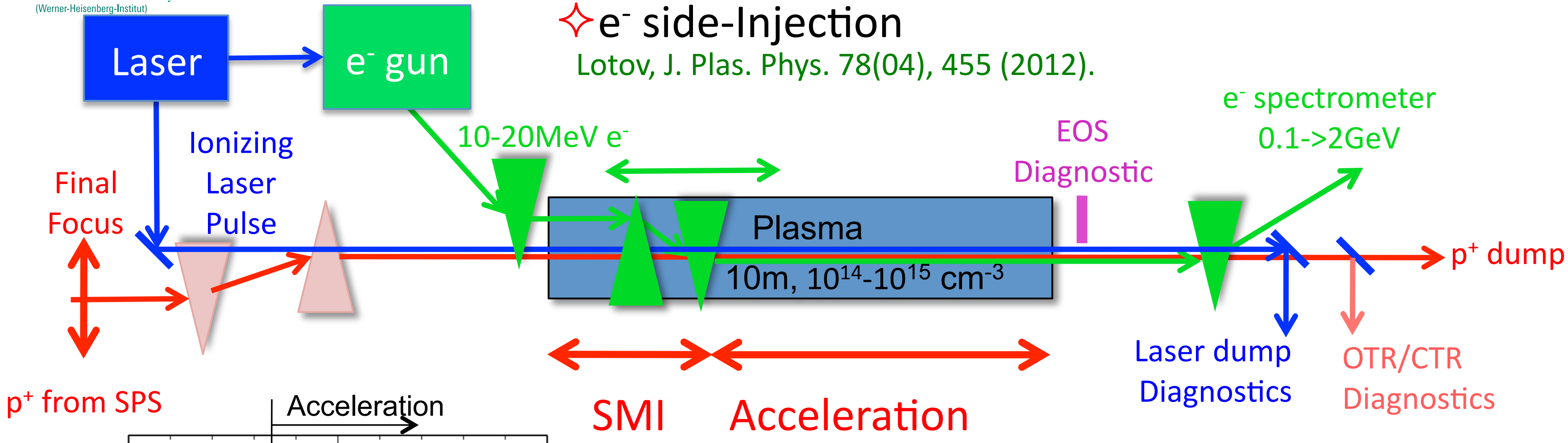
AWAKE EXPERIMENT @ CERN

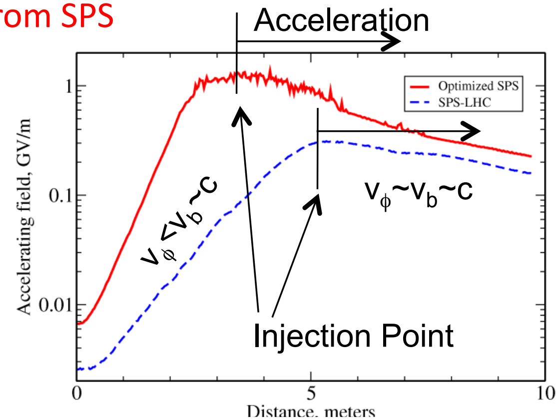


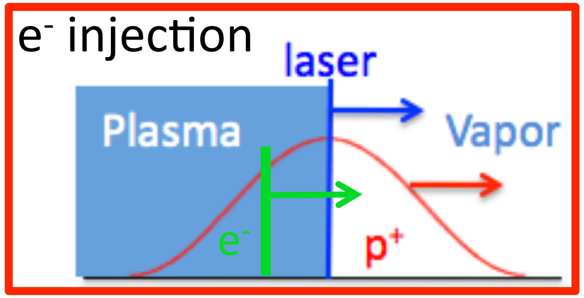
WAKEFIELDS SAMPLING / ACCELERATION

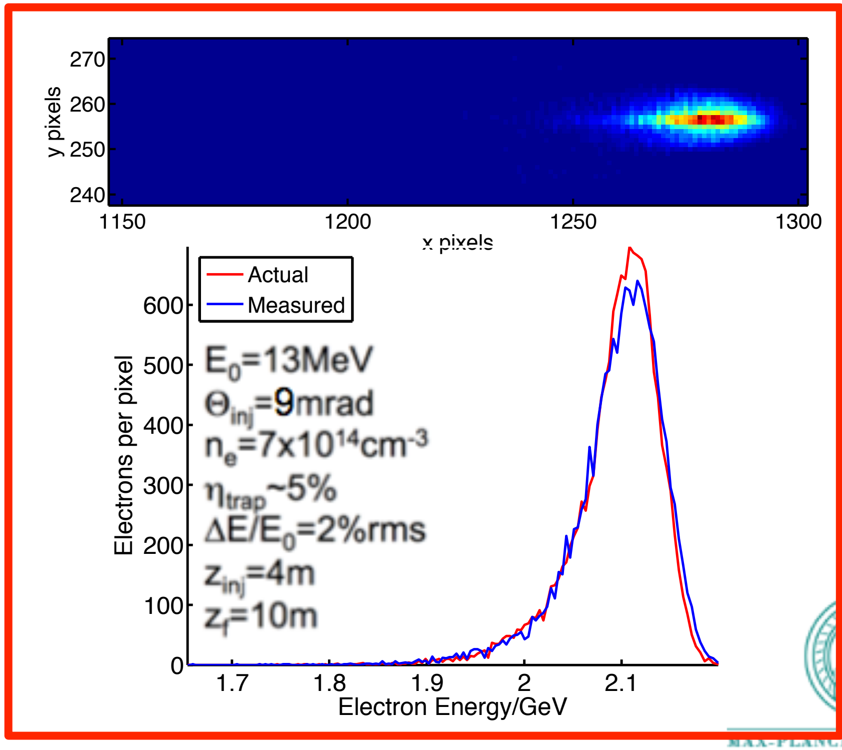
✧ e^- side-Injection

Lotov, J. Plas. Phys. 78(04), 455 (2012).



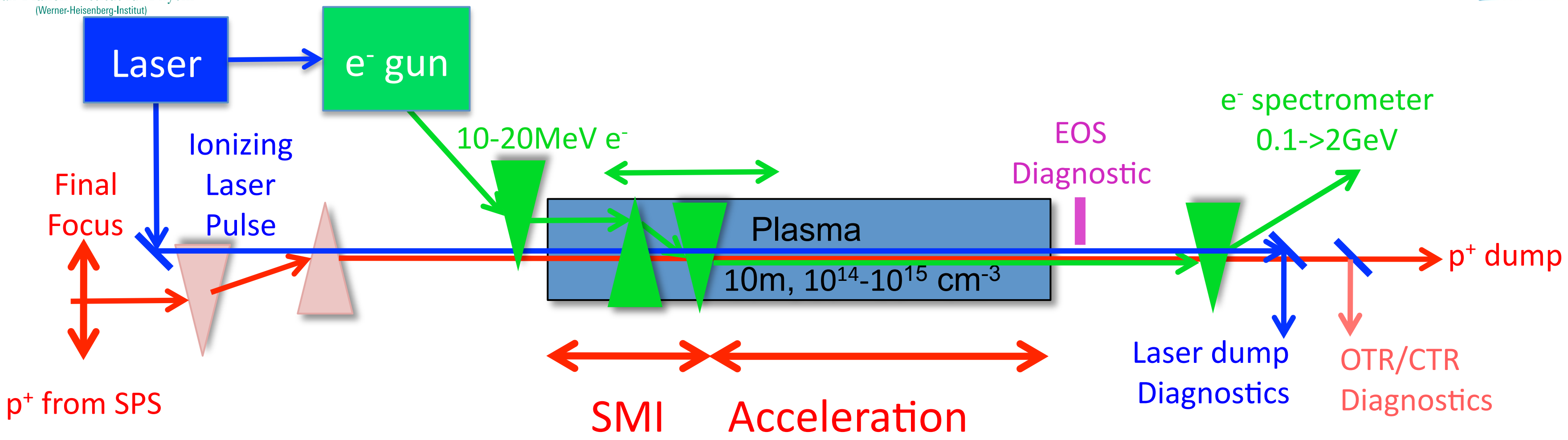


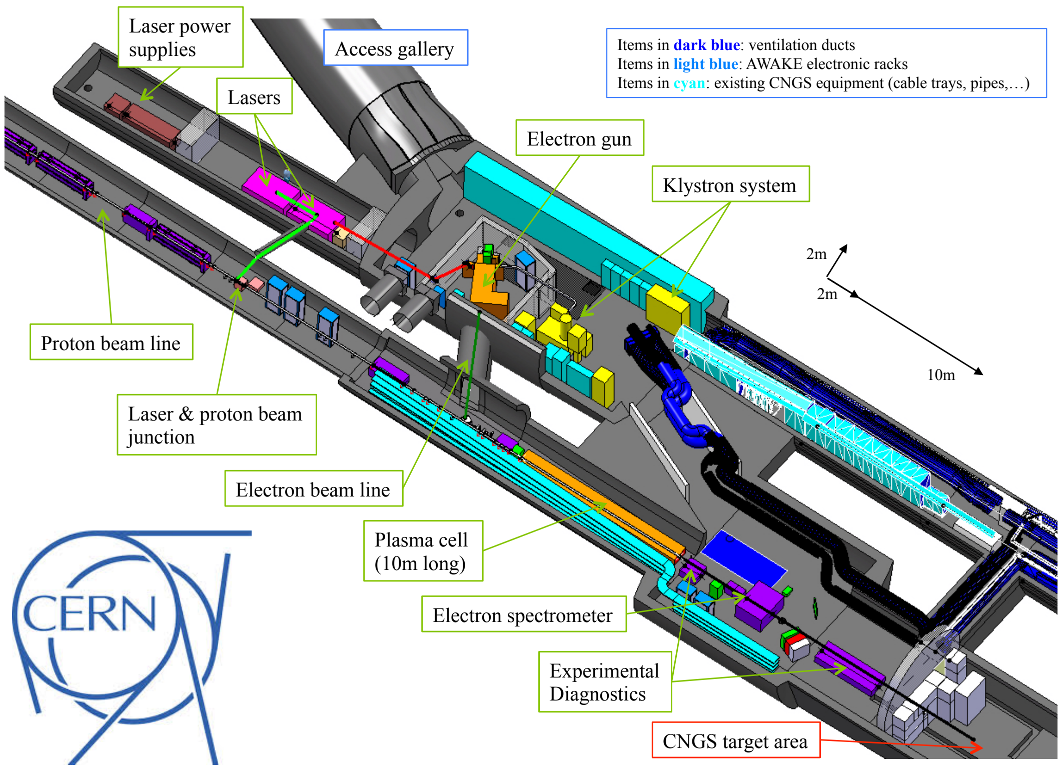




✧ Accelerate e^- to ~GeVs with ~GeV/m gradient

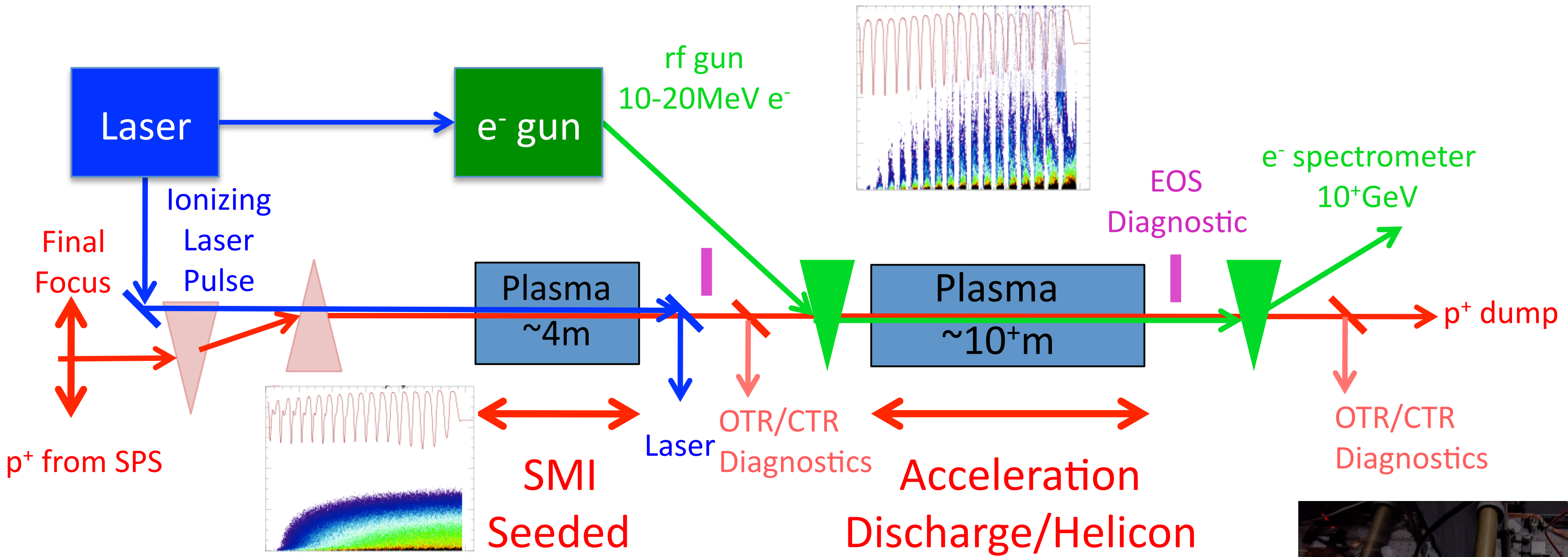
AWAKE EXPERIMENT @ CERN



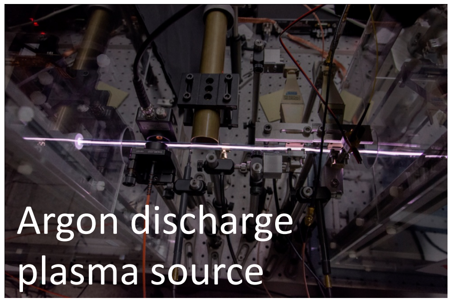


- ✧ CERN team already translated our dreams into CAD drawings
- ✧ Next step: make it real!

p⁺-PWFA ACCELERATOR PHYSICS



N. Lopes



✧Laser ionization of a metal vapor (Rb),
3-4m plasma for p⁺ self-modulation only, SEEDING NECESSARY!

✧~10m discharge or helicon source for acceleration only

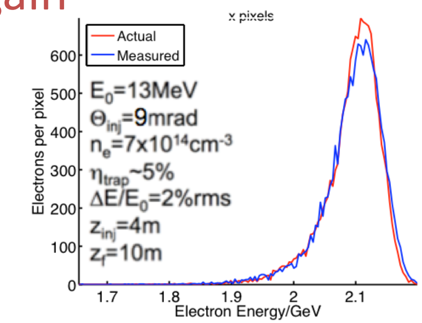
✧Helicon plasma source scales well to very long plasmas (>100m)

✧Maybe able to tune plasma densities to maintain accelerating gradient

SUMMARY

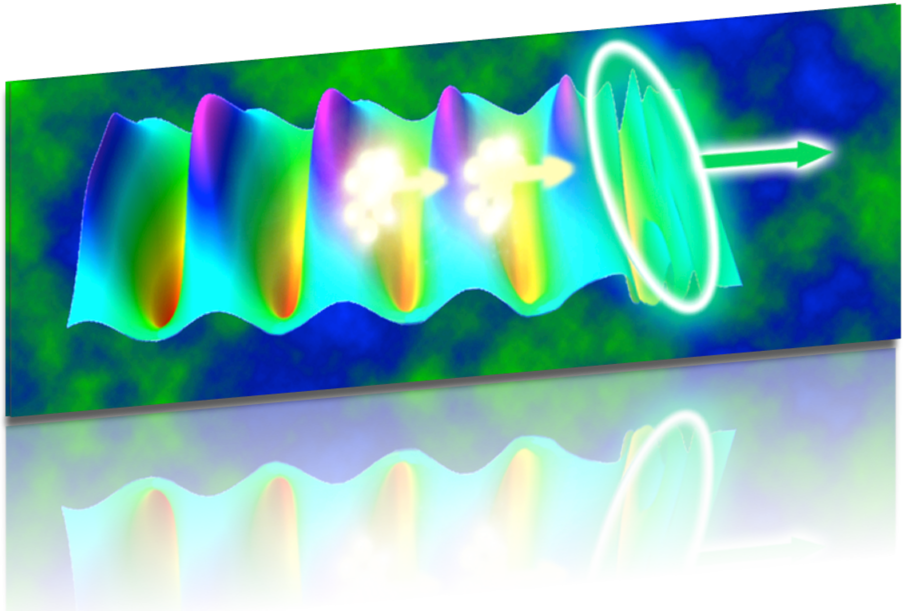
AWAKE

- First p^+-driven PWFA experiment
- Take advantage of large energy (J) of p^+ bunches; lower gradient, larger size structure approach
- Initially use self-modulation of long (~12cm) of p^+ bunches in dense plasma (λ_{pe}~1,2mm)
- Study physics of p^+ bunch SMI (growth seeding, parametric dependencies, etc.)
- Sample wakefields with externally "side-injected" e^-: GeV energy gain
- Accelerator experiments with on axis injection, beam loading, etc
- Many challenges (plasma, stability, injection, etc.)
- Long term project: short p^+ bunches, long plasma sources, etc.
- Collaboration formed …
- Experiment "corridor-approved" at CERN
- Experiments planned for 2016 …



Advanced WAKefield Experiment

Proton-driven Plasma Wakefield Accelerator at CERN



- Proof-of-principle experiment: accelerate in a short distance charged particles
- Candidate for future high energy accelerators
- Toward single-stage TeV lepton accelerator

Thank you!

MOPAC02, Muggli
MOPAC49, Fang
THYAA2, Litos
THOCA1, Marsh
MOPAC37, MOPAC38, MOPAC46, MOPAC49

MAINTAINING HIGH GRADIENT

Max-Planck-Institut für Physik
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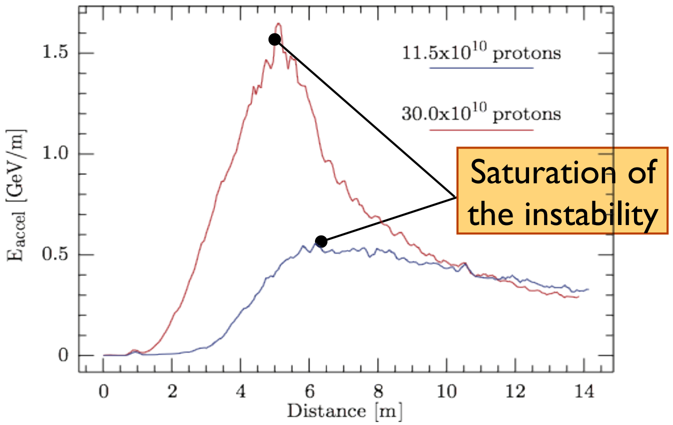

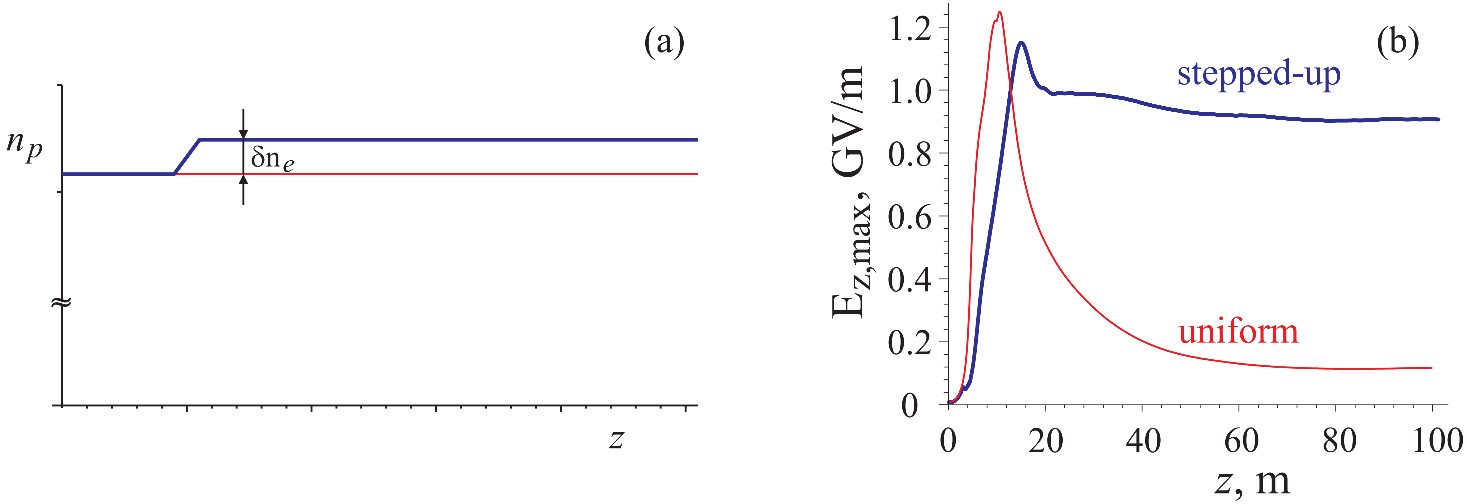

- ✧ Peak gradient can be maintained over long distances with a plasma density step!
- ✧ Possibility for ~100GeV in ~100m?

Lotov, Phys. Plasmas 18, 103101 (2011)

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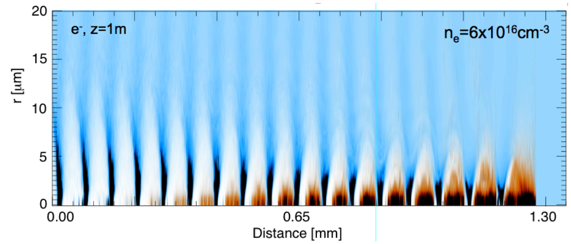
Plasma Density Requirements

✧SMI-PWFA: instability + resonantly driven

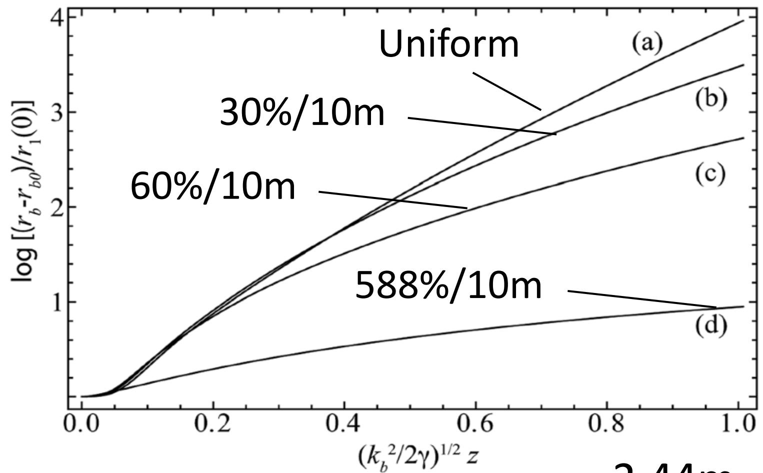
✧Requirements for SMI growth rate

For a linear gradient: $$\frac{n_e(z)}{n_{e0}}=1+\frac{z}{L}$$

Instability suppressed if: $$L<\left(\frac{2\gamma n_{e0}m_p}{n_{b0}m_e}\right)^{1/3}\sigma_z^{2/3}L_p^{1/3}$$



Schroeder, Phys. Plasmas 19, 010703 (2012)



2.44m

✧Requirements witness bunch acceleration

If λ_{pe} changes locally injected electron will be defocused

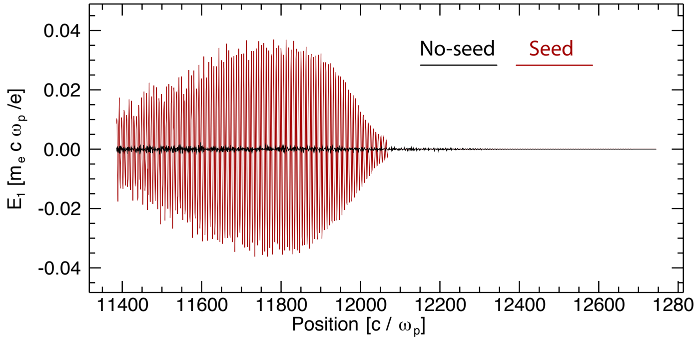
$$\Delta\phi=\frac{2\pi\xi}{\lambda_{pe0}}\frac{1}{2}\frac{\delta n_e}{n_{e0}}<\frac{\pi}{2}\quad\Rightarrow\quad\frac{\delta n_e}{n_{e0}}<\frac{\lambda_{pe0}}{4\xi}\cong\frac{\lambda_{pe0}}{4\sigma_z}\cong 0.25\%$$

✧Tight requirement!

Lotov, Phys. Plasmas 20, 013102 (2013).

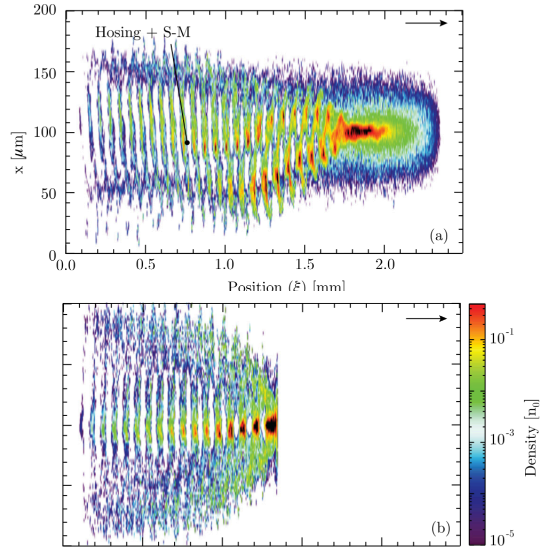
SMI SEEDING

Seeding of SMI is NECESSARY

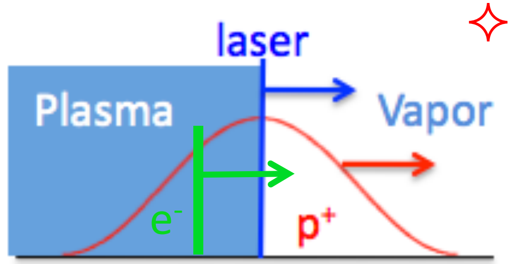


✧No seed no SMI (over 10m)

SLAC e- beam case, Vieira et al., PoP (2012)



✧Hosing mitigation



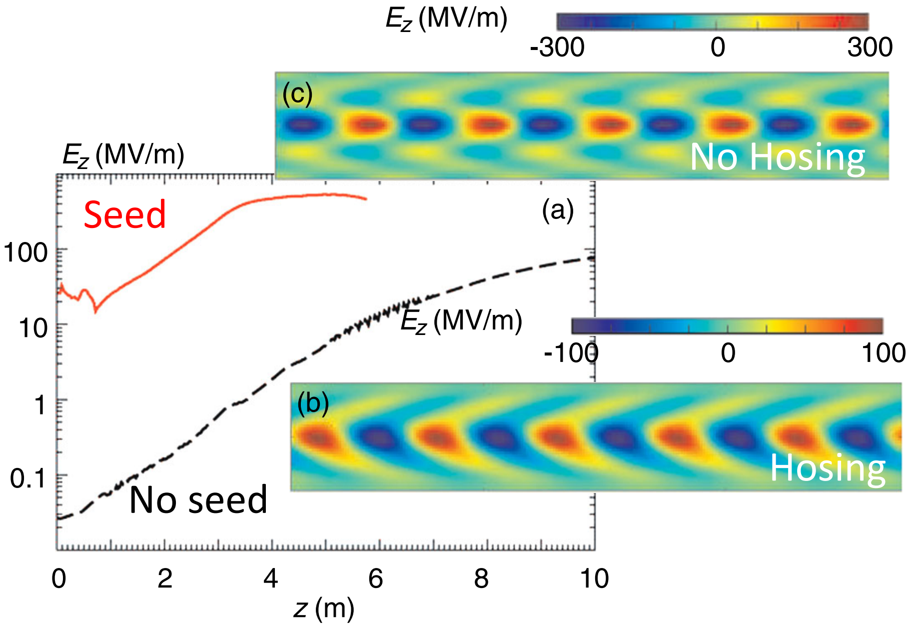
✧Deterministic e- injection

✧Need to keep laser-ionized source for seeding

SMI SEEDING

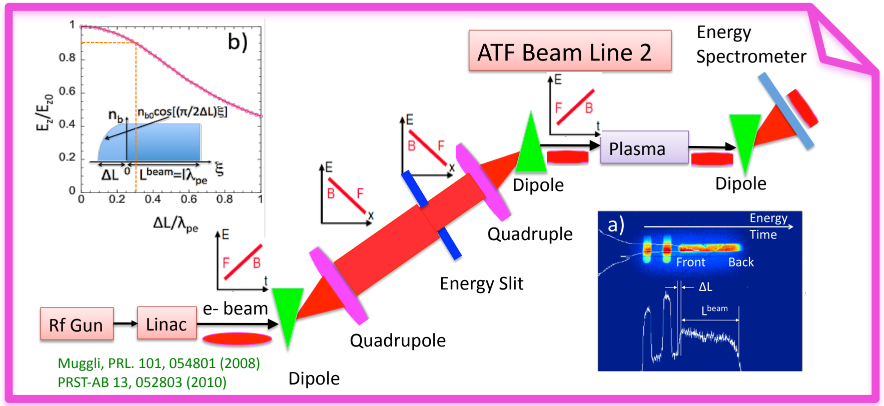
- ✧SM Instability, grows from noise, “random”
- ✧Instabilities can be seeded by a larger-than-noise signal

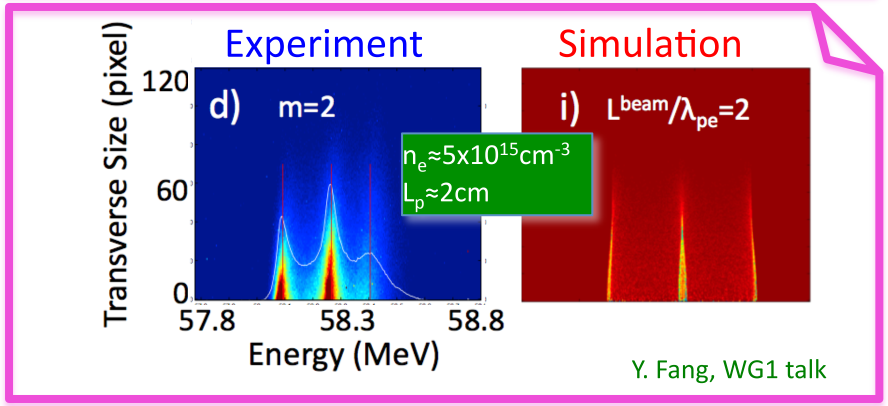
Preceding e^--bunch



Lotov, PRST-AB 16, 041301 (2013)

“Cut” bunch or plasma





Fang, to be published

- ✧Shortens length to saturation
- ✧Suppresses hosing

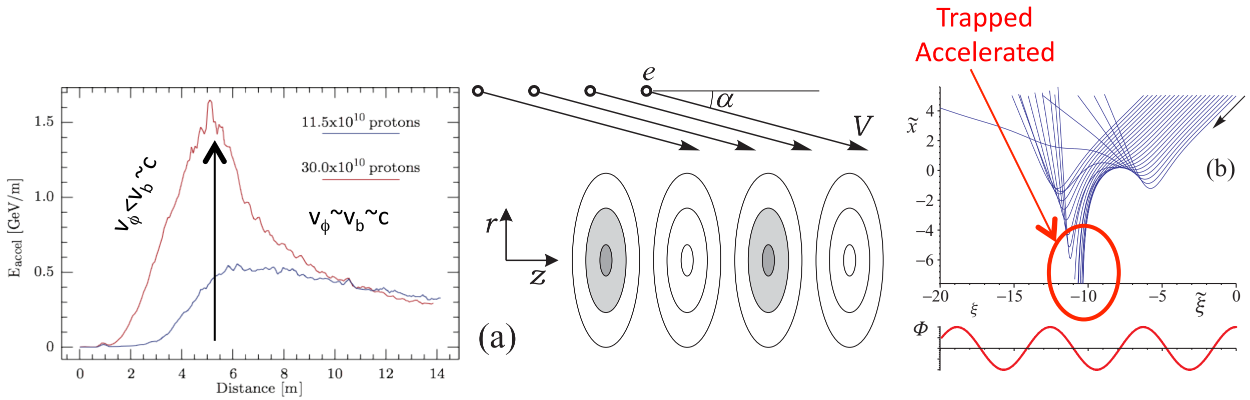
- ✧Generates periodic wakefield

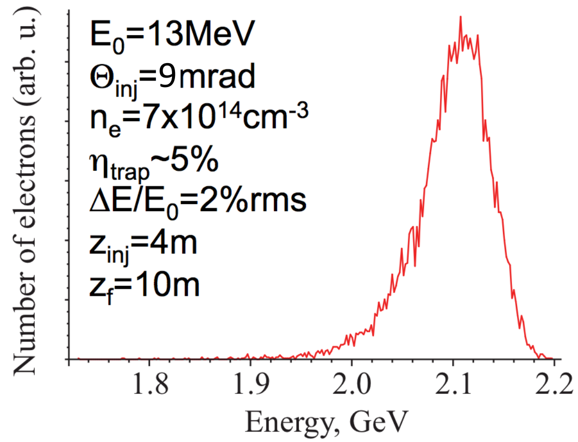
e^- SIDE INJECTION

Lotov, J. Plasma Phys. (2012)

✧Single, long plasma

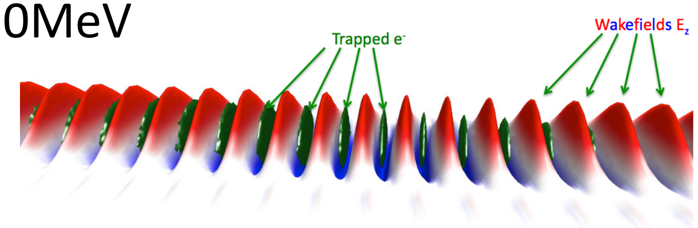
✧Low energy test e^- injected sideways are trapped and bunched in a few wake buckets





$$\alpha_{opt} \sim \frac{v_\phi - v_{e-}}{c} \sim \frac{1}{2\gamma_{e-}^2} \sim mrad$$

for E_{e-}=5-20MeV



Pukhov, Phys. Rev. Lett. 107, 145003 (2011)

✧Inject in saturated SMI, $v_\phi = v_b \approx c$

✧Generates narrow final energy spectrum

✧Trapping efficiency <60%, test particles

COMPARISON +/- DRIVEN PWFA

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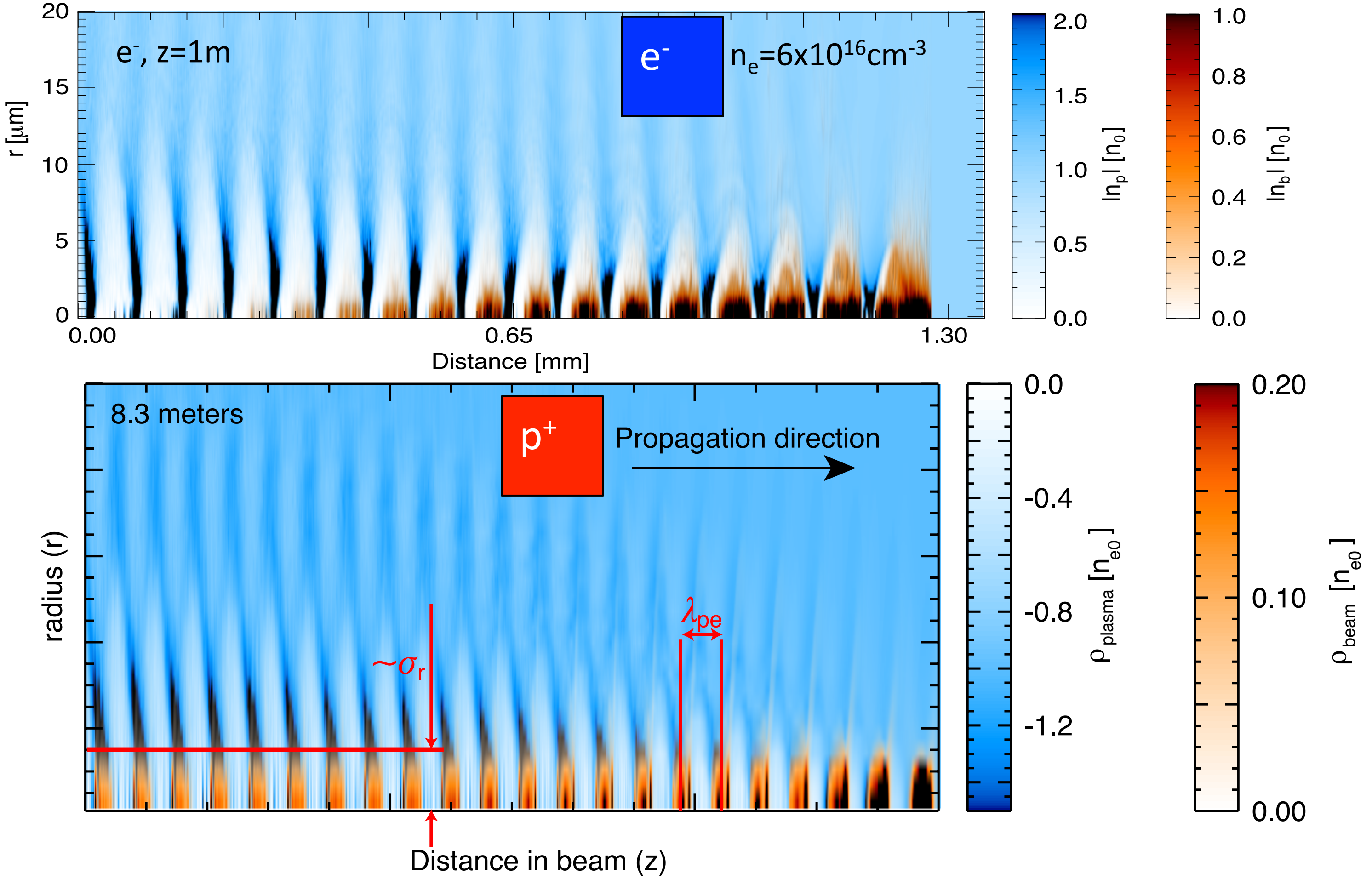
AWAKE

✧Comparison positively/negatively charged bunches after SMI saturation



Simulations: J. Vieira

✧Phase difference, as expected from simple physics

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