Development at MPP of Laser-ionized Source with Extremely Uniform Plasmas

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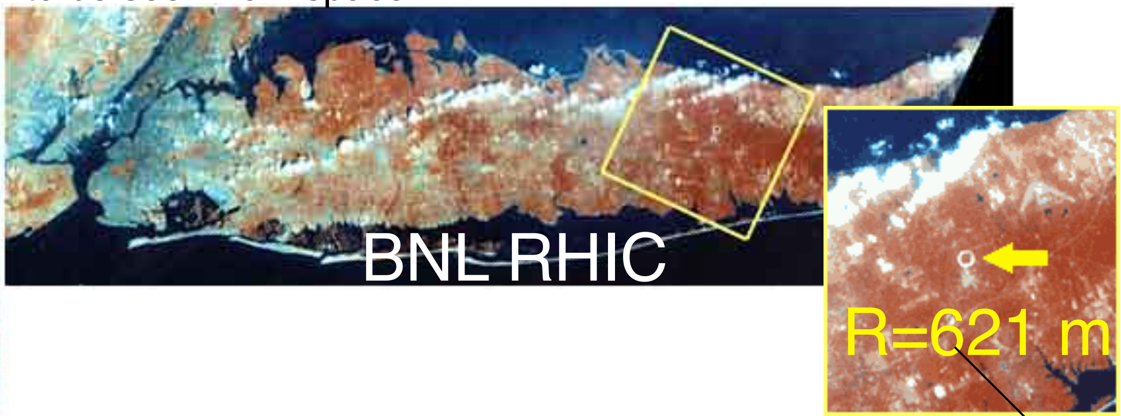
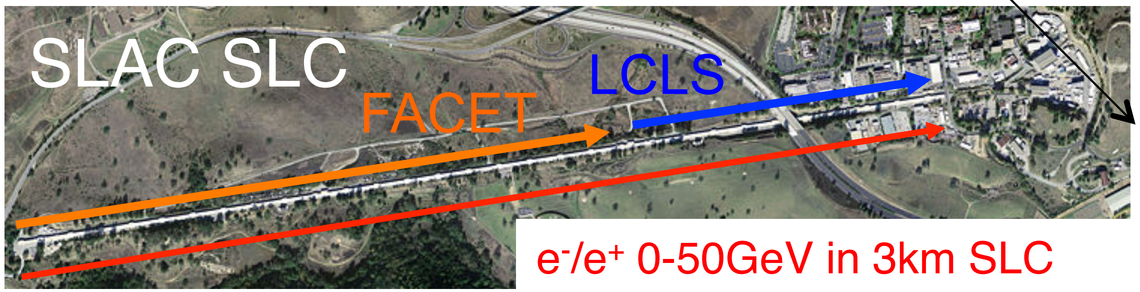
PARTICLE ACCELERATORS

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



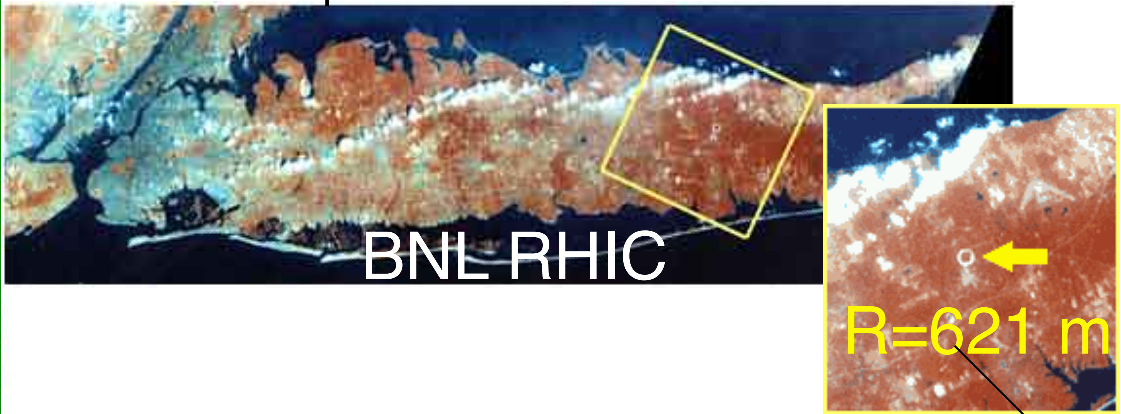


e^-/e^+ 0-50GeV in 3km SLC
e^-/e^+ 0-20GeV in 2km FACET
e^- 0-14GeV in 1km LCLS

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

PARTICLE ACCELERATORS

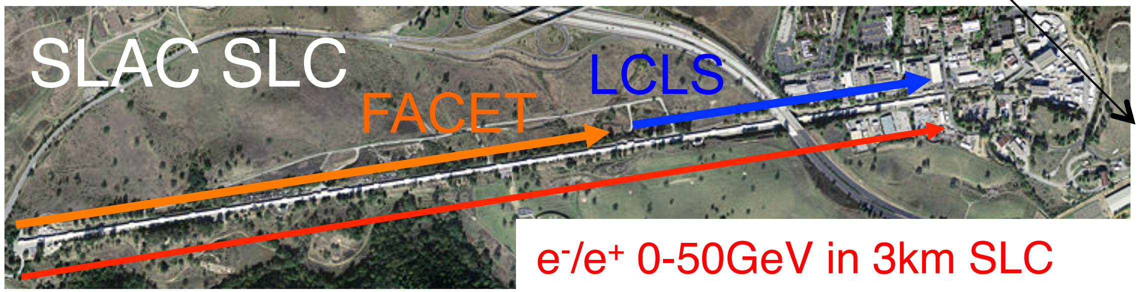
"The 2.4-mile circumference RHIC ring is large enough to be seen from space"



Light particles (e^-/e^+) accelerator

Limited by synchrotron radiation

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



e^-/e^+ 0-50GeV in 3km SLC

e^-/e^+ 0-20GeV in 2km FACET

e^- 0-14GeV in 1km LCLS

Must be linear

But …

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

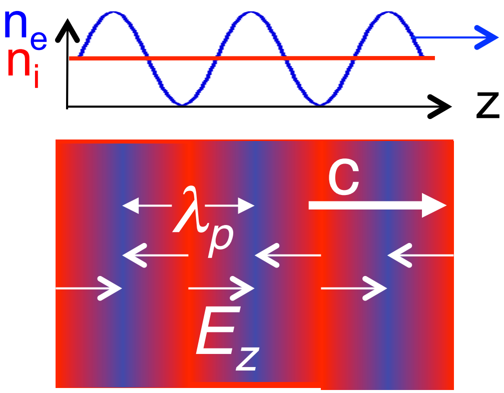
complex (and most expensive) scientific

chnology to accelerate particles

Can we make them smaller (and cheaper) and with a higher energy using plasmas?

PLASMAS

✧Relativistic Electron, Electrostatic Plasma Wave (E_z//k, B=0):



LARGE
Collective response!

$$\vec{\nabla}\cdot\vec{E}=\frac{\rho}{\varepsilon_0}$$

$$\omega_{pe}=\left(\frac{n_e e^2}{\varepsilon_0 m_e}\right)^{1/2}$$ Plasma Frequency

$$k_{pe}E_z=\frac{\omega_{pe}}{c}E_z=\frac{n_e e}{\varepsilon_0}$$

$$E_z=\left(\frac{m_e c^2}{\varepsilon_0}\right)^{1/2} n_e^{1/2}\cong 100\sqrt{n_e\left(cm^{-3}\right)}=1\,GV/m$$

$n_e=10^{14}$ cm^{-3}

Cold Plasma "Wavebreaking" Field

$$E_{WB}=m_e c\,\omega_{pe}/e$$

✧Plasmas can sustain very large (collective) E_z-field, acceleration

✧Wave, wake phase velocity = driver velocity (~c when relativistic)

✧Plasma is already (partially) ionized, difficult to "break-down", no fabrication

✧Plasmas wave or wake can be driven by:

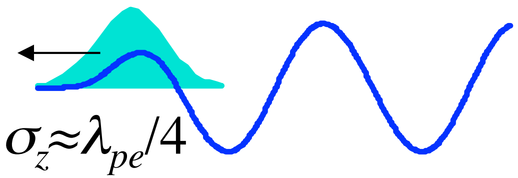
- Intense laser pulse
- Dense particle bunch

4 PLASMA ACCELERATORS*

- Plasma Wakefield Accelerator (PWFA)

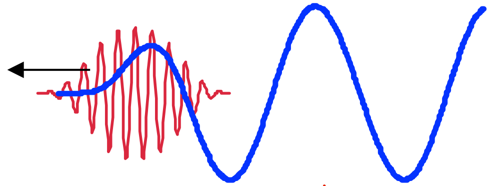
  A high energy particle bunch (e^-, e^+, ...)

  P. Chen et al., Phys. Rev. Lett. 54, 693 (1985)



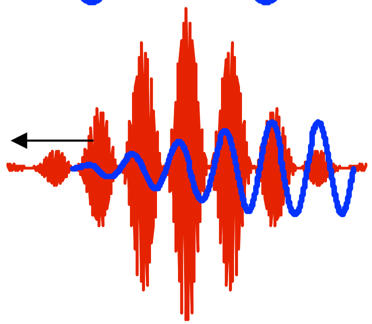
- Laser Wakefield Accelerator (LWFA) *

  A short laser pulse (photons, ponderomotive)



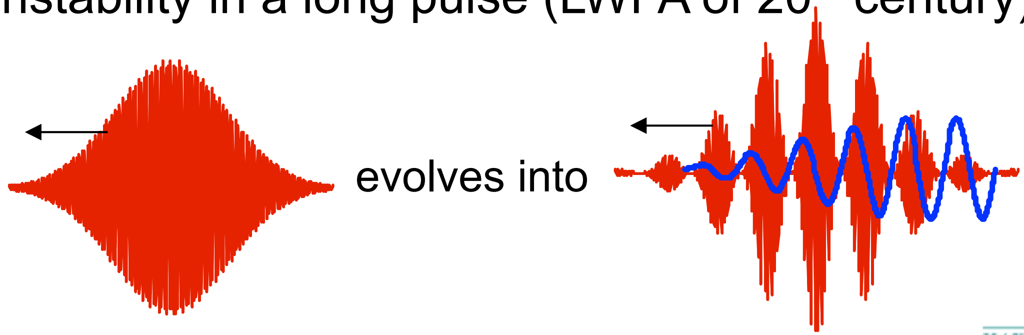
- Plasma Beat Wave Accelerator (PBWA) *

  Two frequencies laser pulse, i.e., a train of pulses



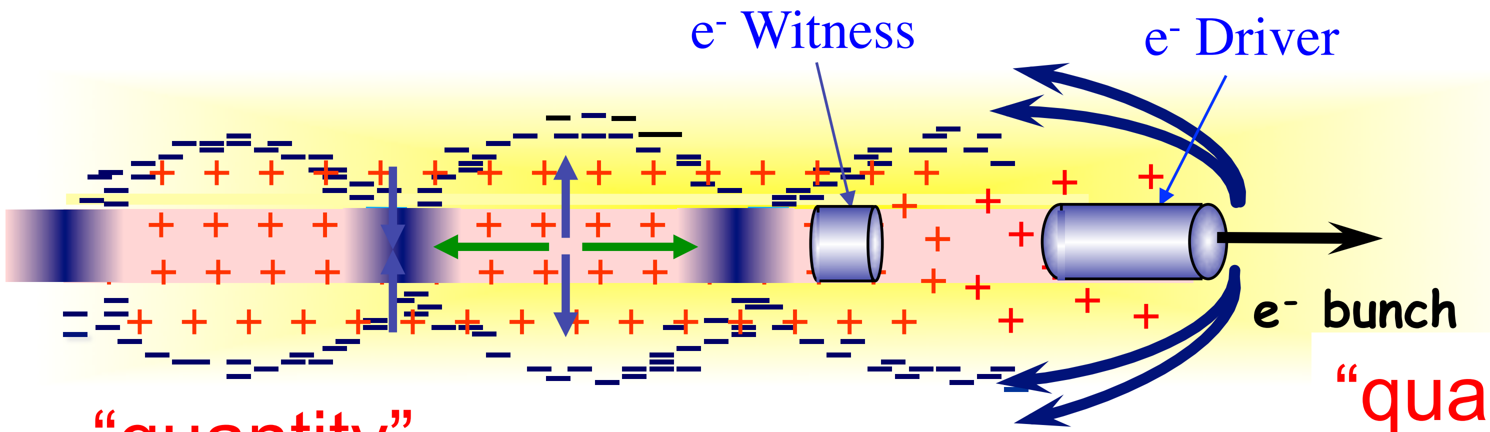
- Self-Modulated Laser Wakefield Accelerator (SMLWFA) *

  Raman forward scattering instability in a long pulse (LWFA of 20th century)



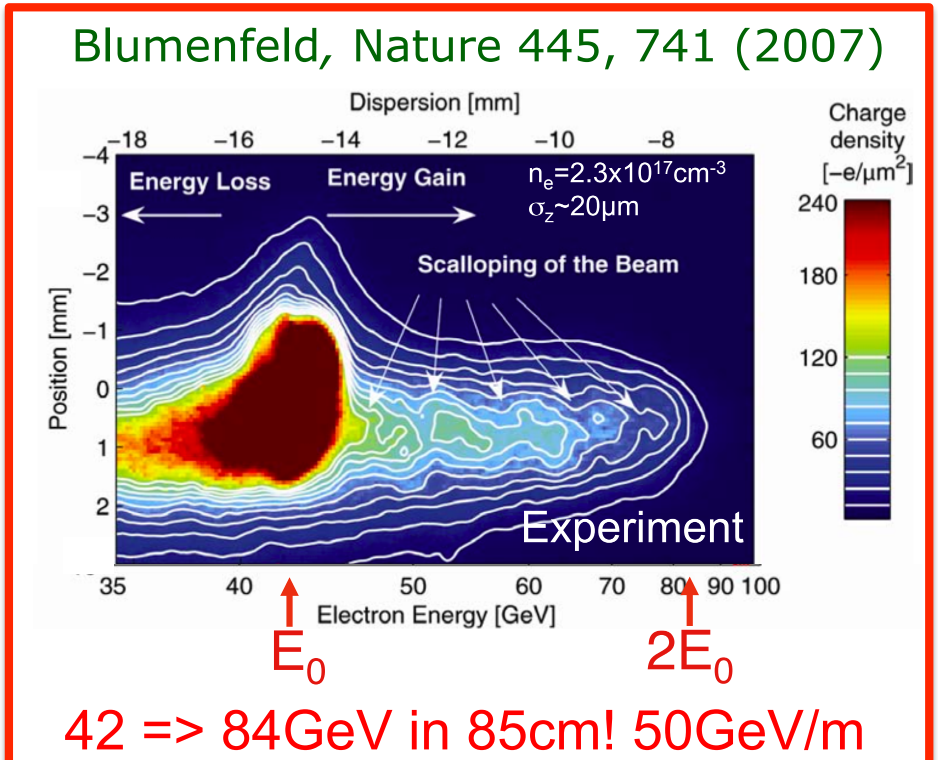
*Pioneered by J.M. Dawson, Phys. Rev. Lett. 43, 267 (1979)

PLASMA WAKEFIELD ACCELERATOR (e^-)



"quantity"

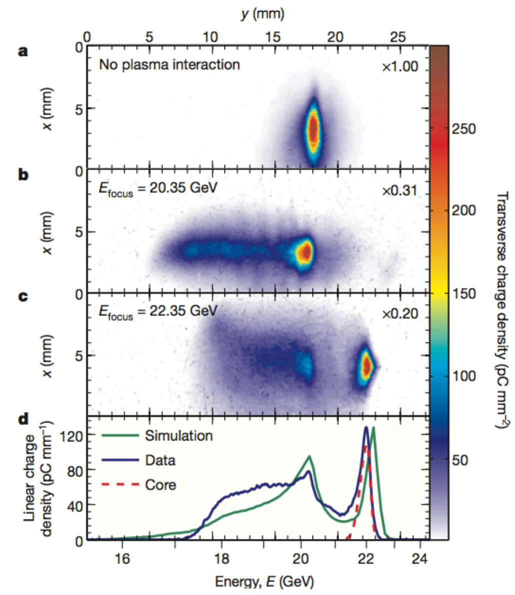
"quality"



SLAC
FACET

E200

Litos,
Nature 515(6)
92 (2014)



$\Delta E/E$~%
η~30%

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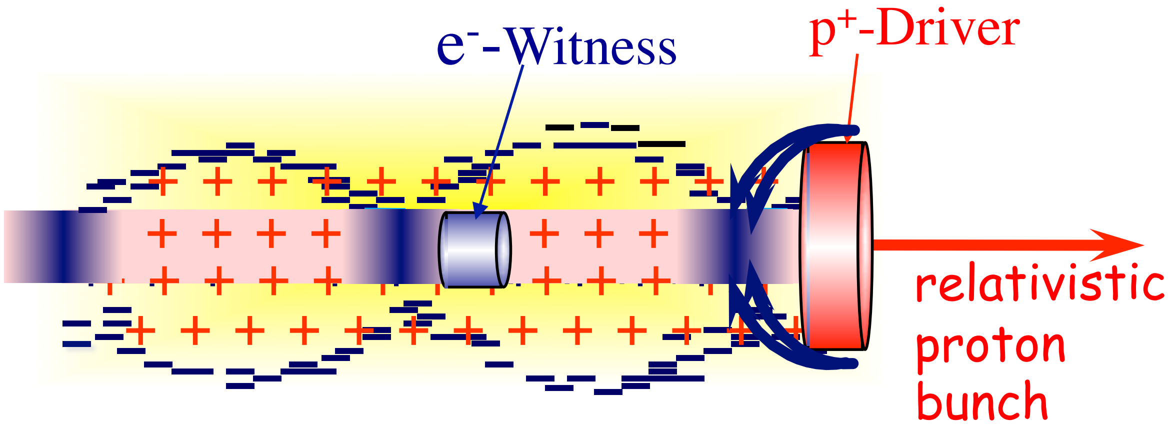
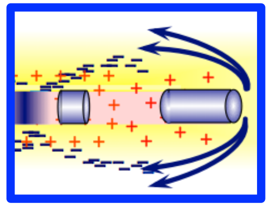
AWAKE

p^+-DRiVEN PWFA? YES BUT WHY?



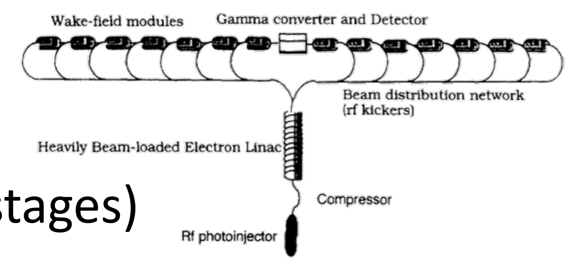


✧ILC, 0.5TeV bunch with $2\times10^{10}e^-$ ~1.6kJ

✧SLAC, 20GeV bunch with $2\times10^{10}e^-$ ~60J

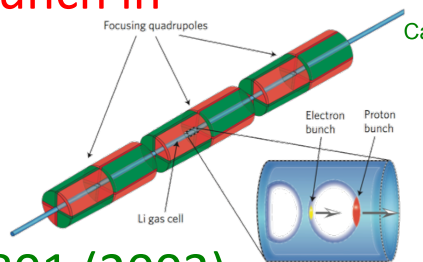
✧SLAC-like driver for staging (FACET= 1 stage, collider 10^+ stages)

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 <u>single</u> PWFA stage!



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

✧Large <u>average</u> gradient! (≥1GeV/m, 100's m)

✧Wakefields driven by e^+ bunch: Blue, PRL 90, 214801 (2003)

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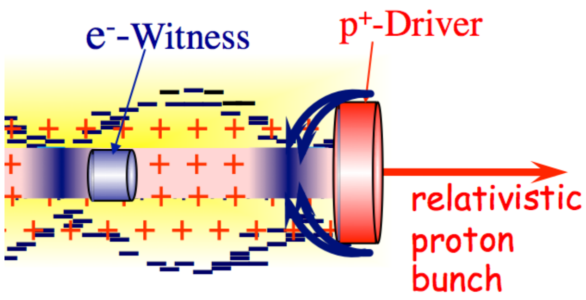
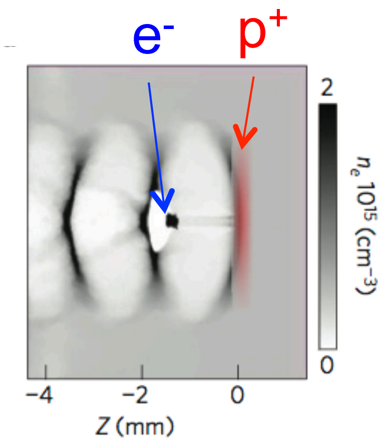
PROTON-DRIVEN PWFA

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

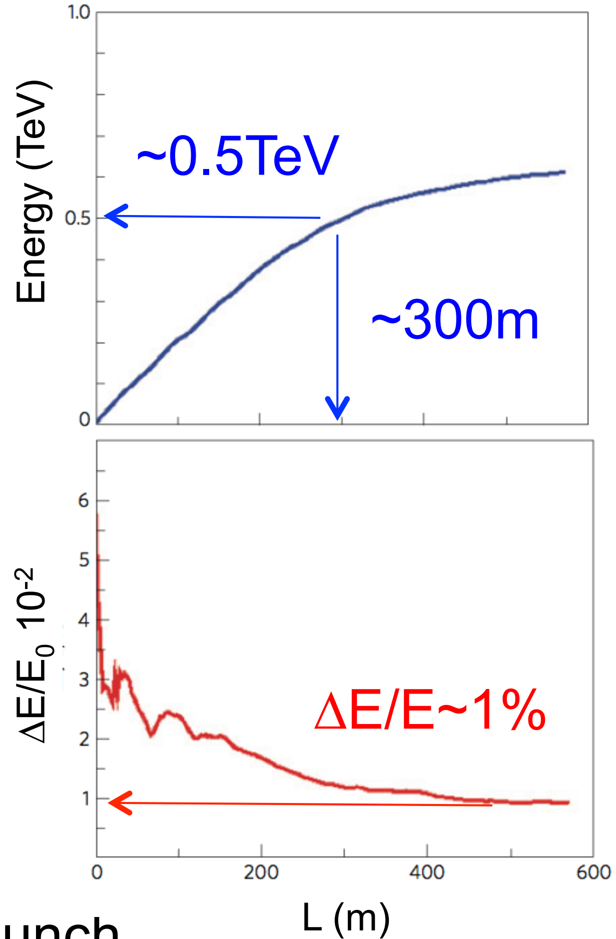


e^-:	p^+:
E_0=10GeV	E_0=1TeV
	σ_z=100µm
N=10^{10}	N=10^{11}
W_0=16J	W_0=16kJ
W_f=1kJ	

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 ($6\times10^{14}cm^{-3}$), larger $(\lambda_{pe})^3$, easier life …

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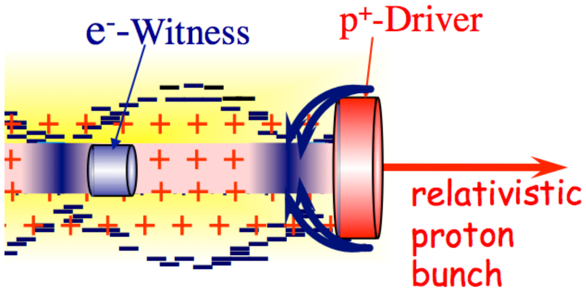
PROTON-DRIVEN PWFA

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



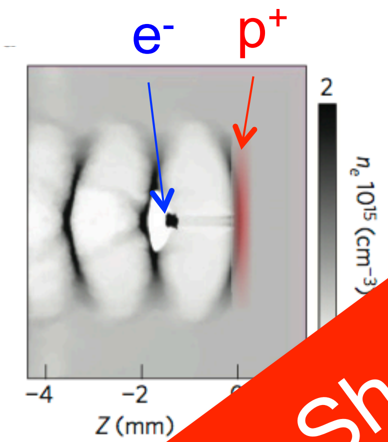
Single Stage

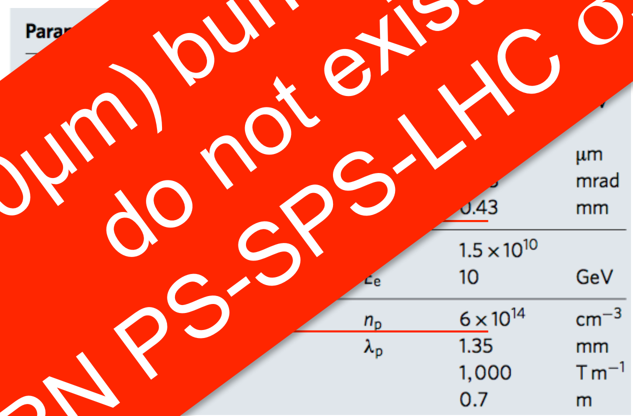
e^-: E_0=10GeV

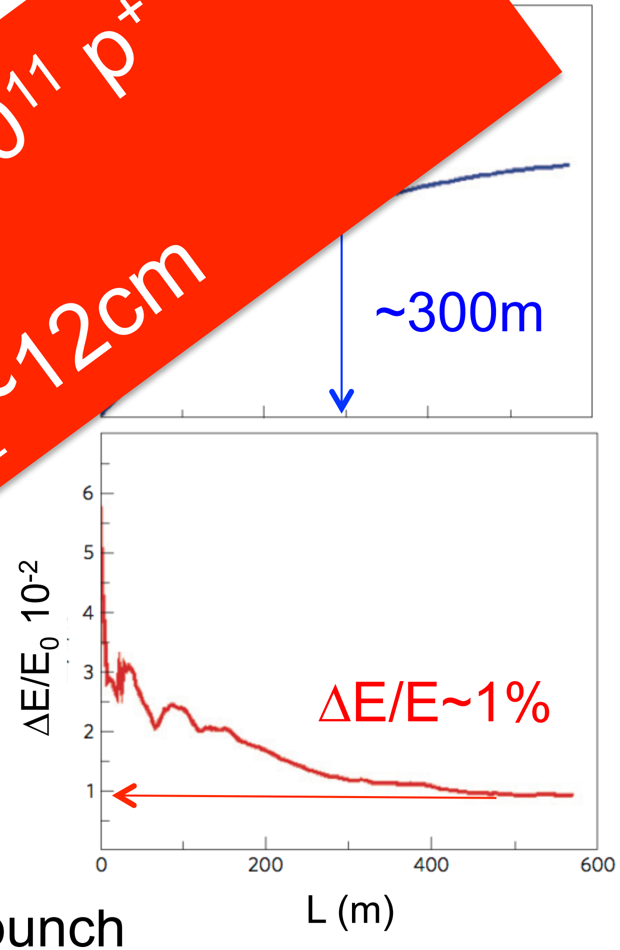
p^+: E_0=1T

N=10^{10}

W







Short (100µm) bunches with 10^{11} p^+ do not exist!!!

CERN PS-SPS-LHC σ_z~12cm

✧ …n the wakefields of a p^+ bunch

✧ …dient dilution

✧ Gr… n over 100's m

✧ Oper… ower n_e ($6x10^{14}cm^{-3}$), larger $(\lambda_{pe})^3$, easier life …

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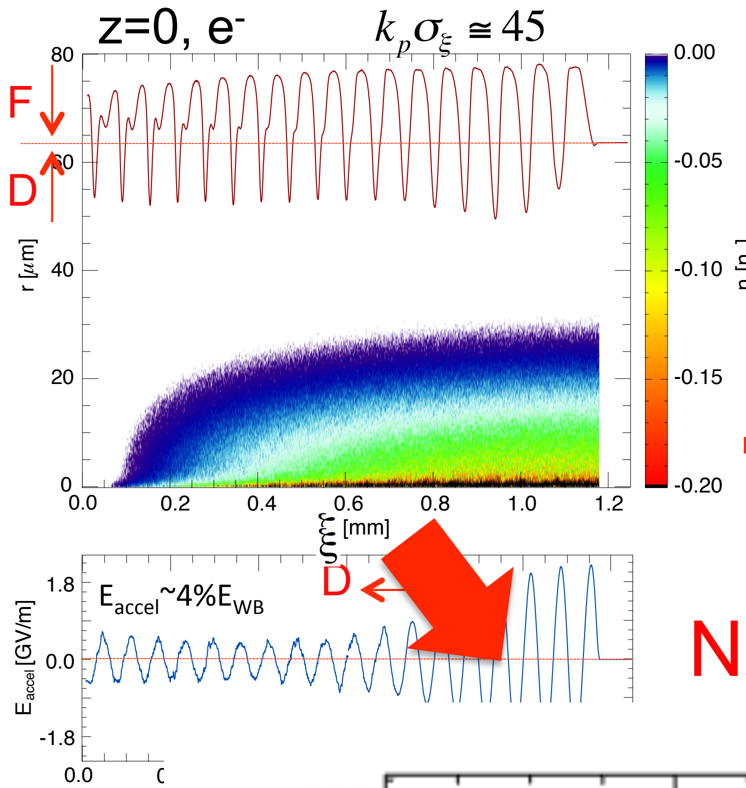
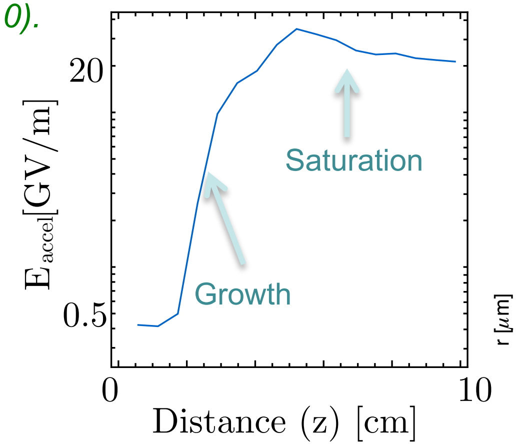
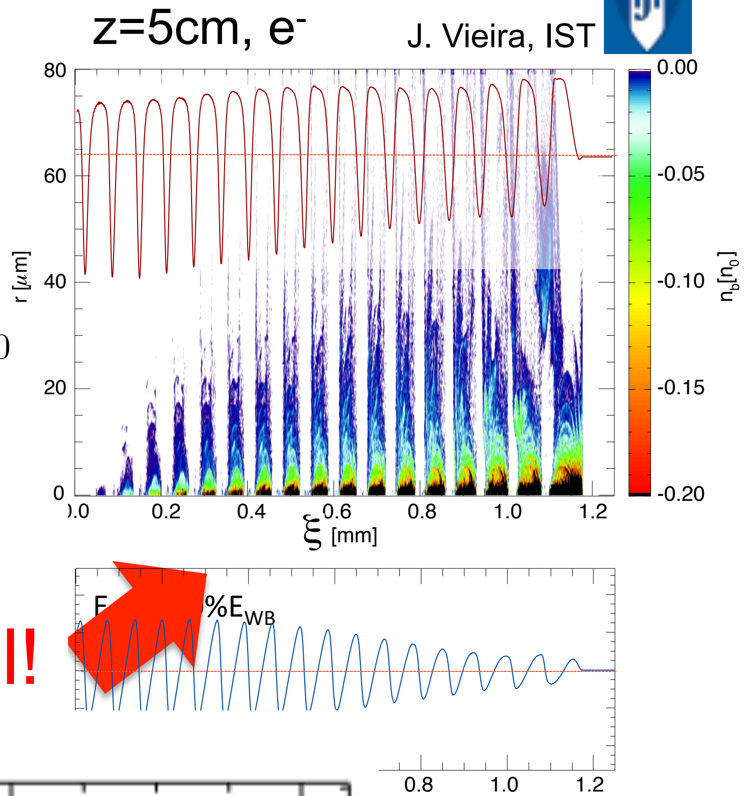
SELF-MODULATION INSTABILITY (SMI)

Kumar et al., PRL 104, 255003 (2010).

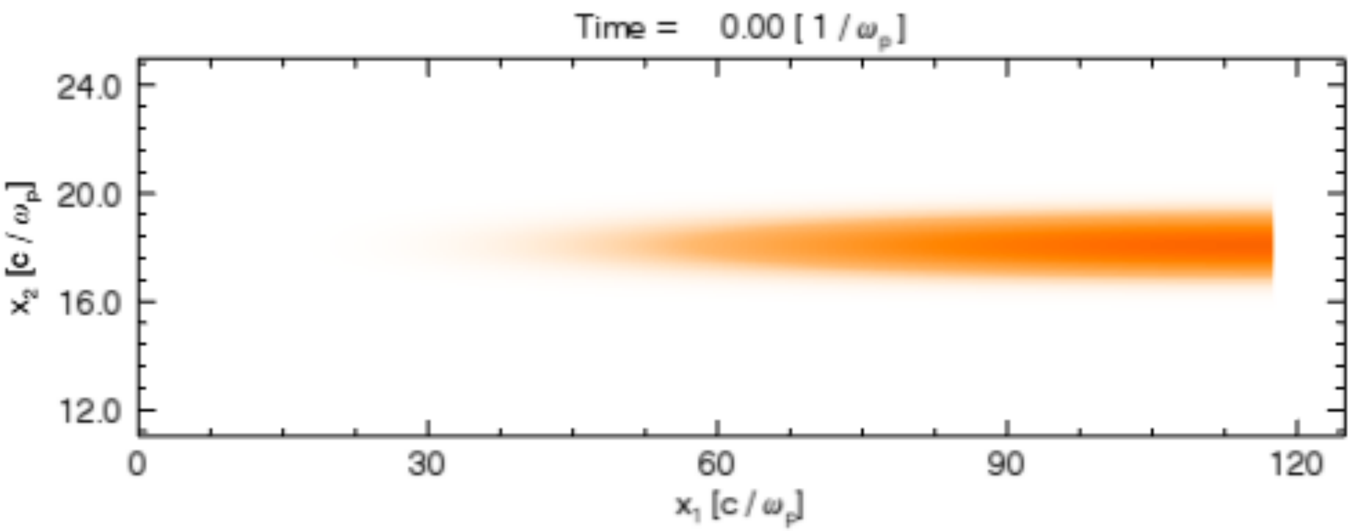






Radial!

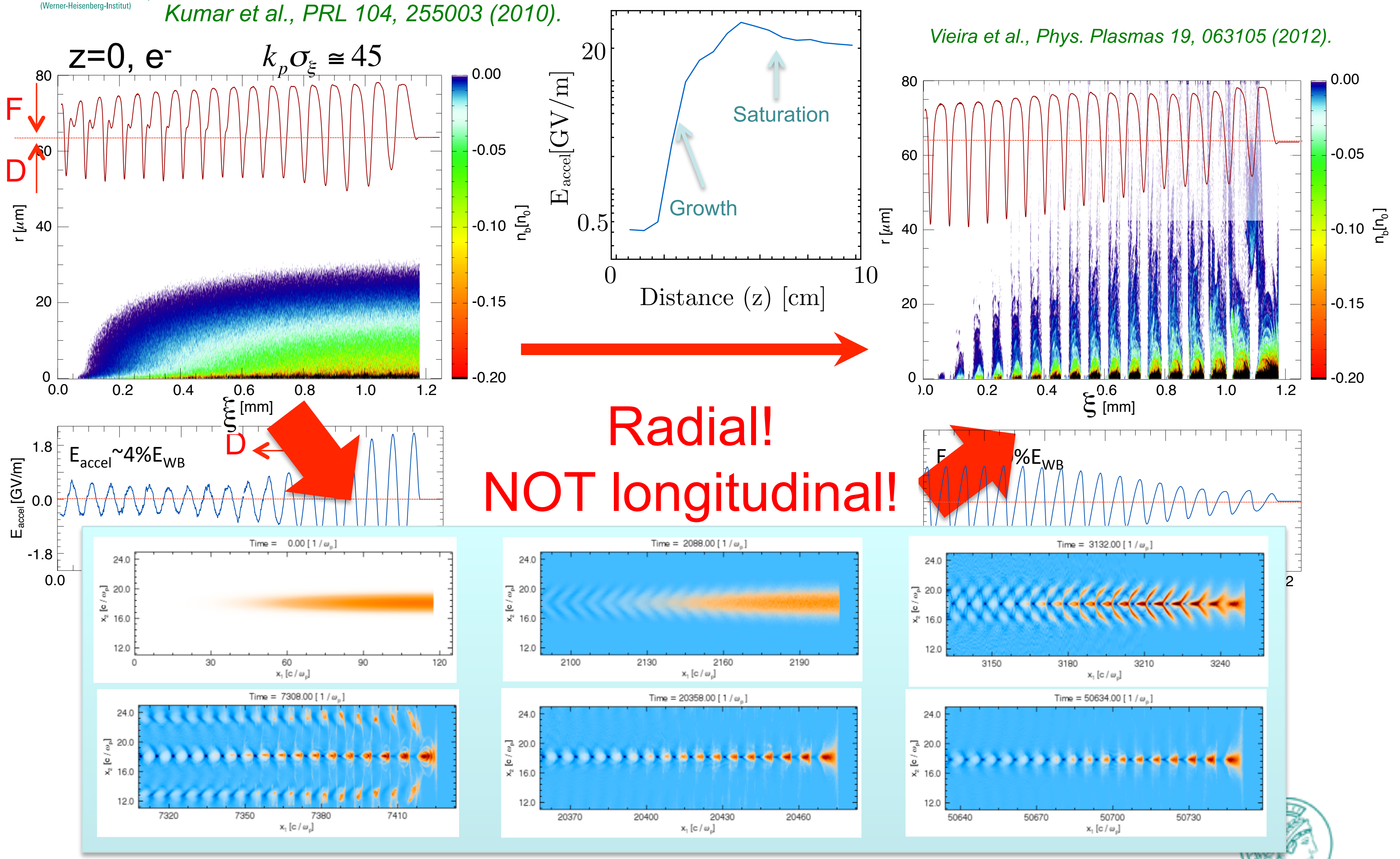
NOT longitudinal!



SELF-MODULATiON INSTABiLiTY (SMI)

Kumar et al., PRL 104, 255003 (2010).

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

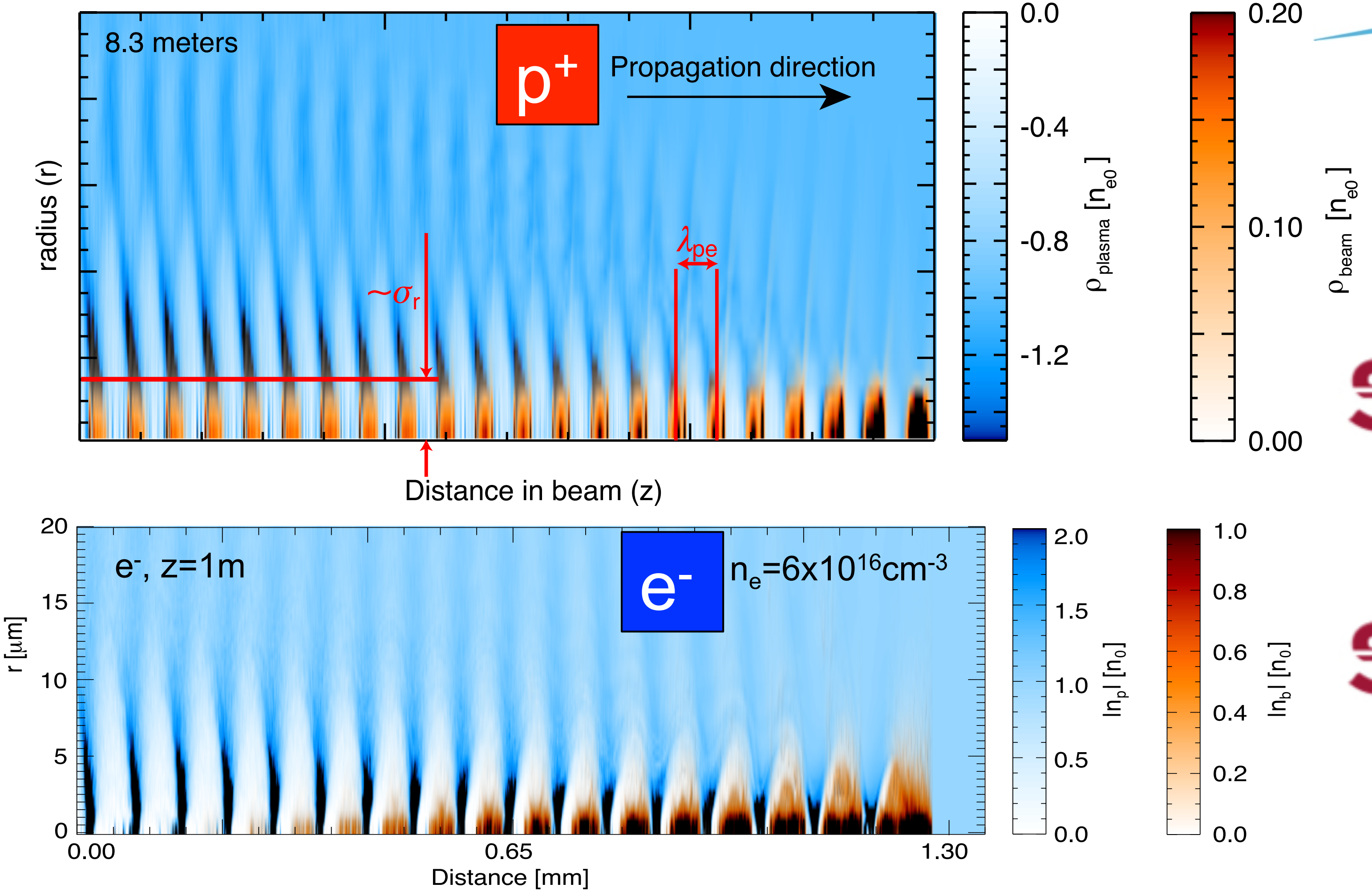


Radial!

NOT longitudinal!

COMPARiSON +/- DRiVEN PWFA

✧ Comparison positively/negatively charged bunches



AWAKE p^+

SLAC e^+

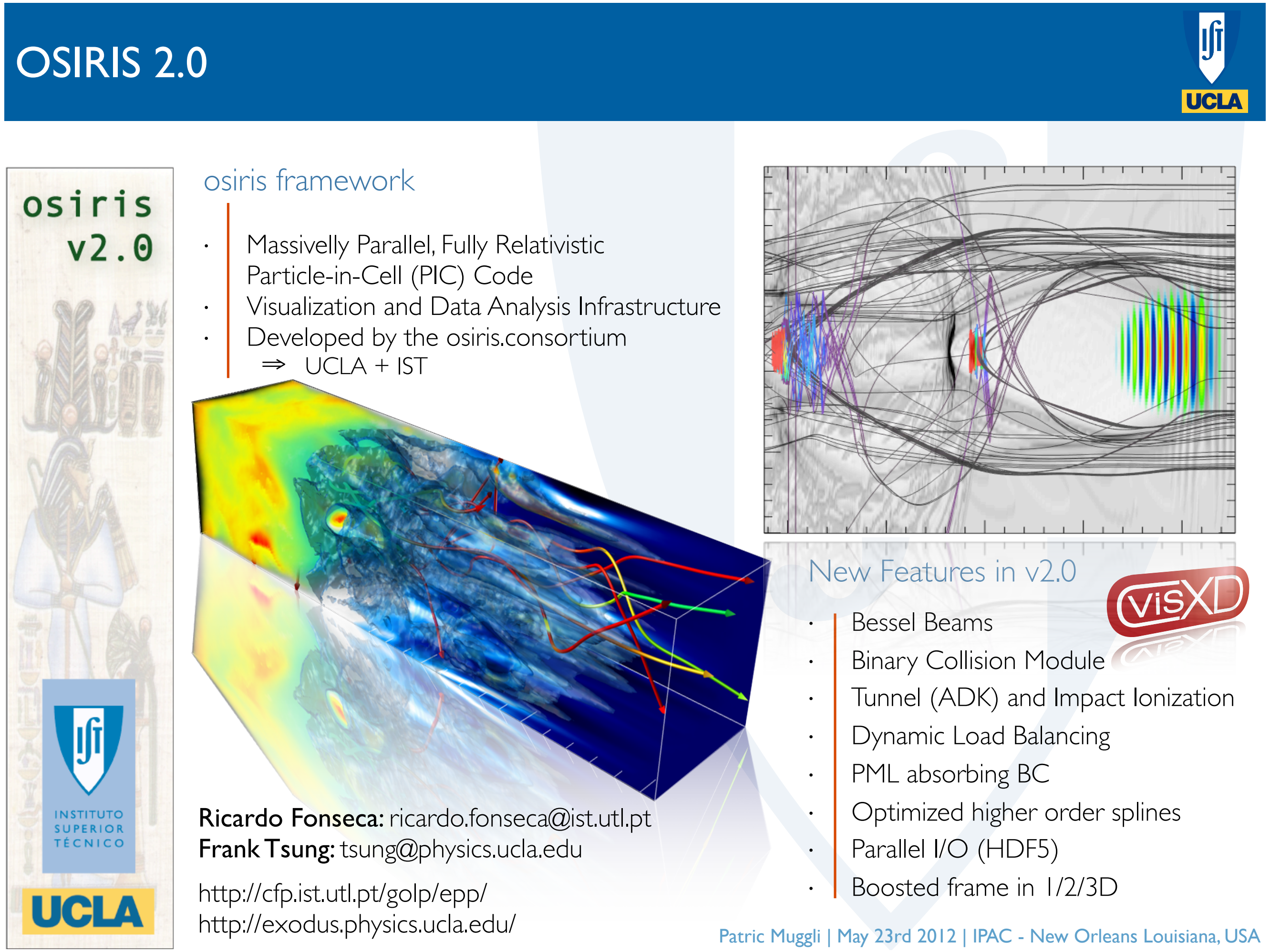
SLAC e^-

Simulations: J. Vieira

✧ Phase difference, as expected from simple physics

Vieira, Phys. Plasmas 19, 063105 (2012)

SMI-PWFA SiMULATiONS



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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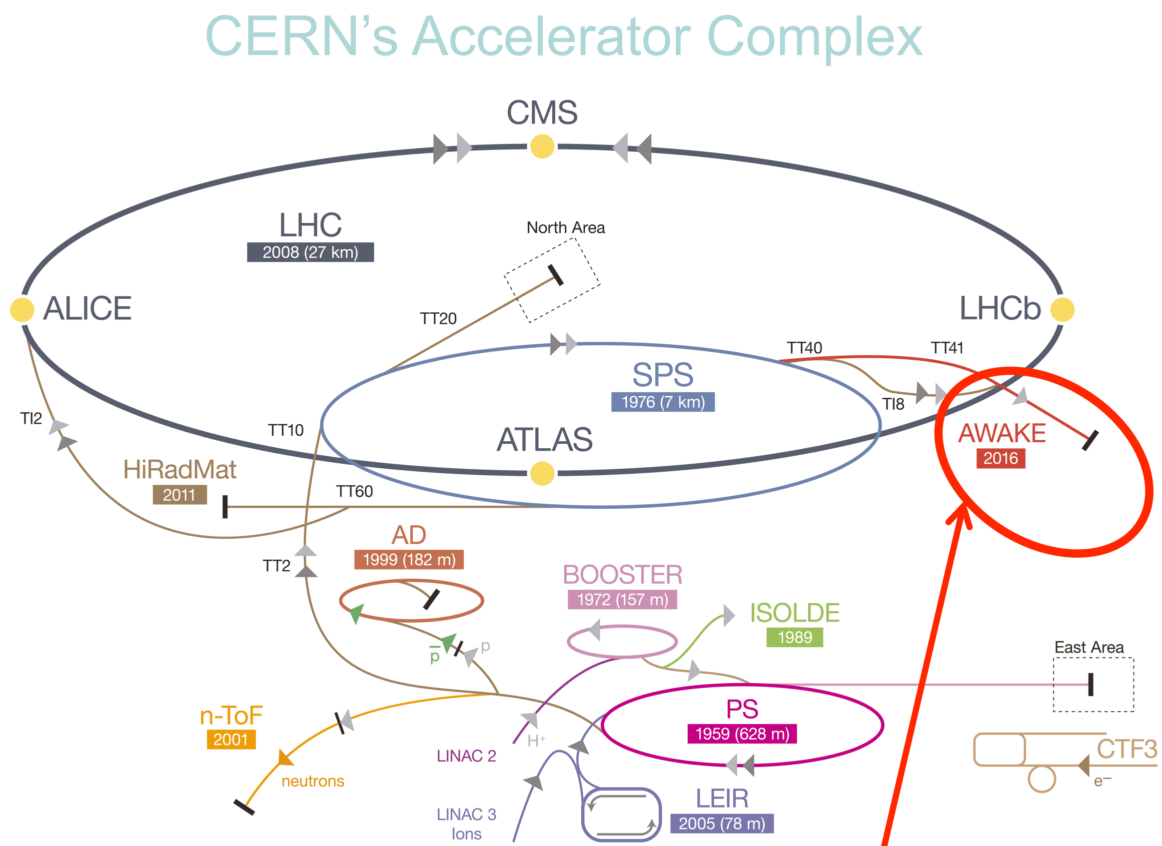
PROTON BEAMS @ CERN



AWAKE 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

$n_e \sim 7\times10^{14}$cm^{-3} for $k_p\sigma_r \approx 1$
$\lambda_{pe} \sim 1.3$mm$<<\sigma_z$
$f_{pe} \sim 240$GHz
$L_p \sim 10$m$\sim 2\beta^*$

- 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

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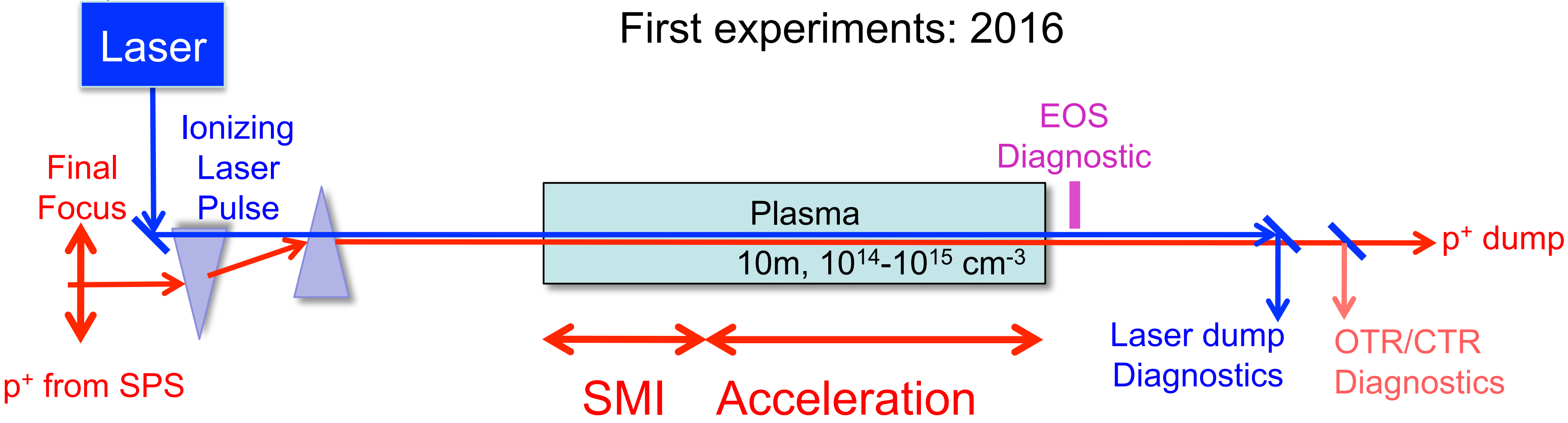
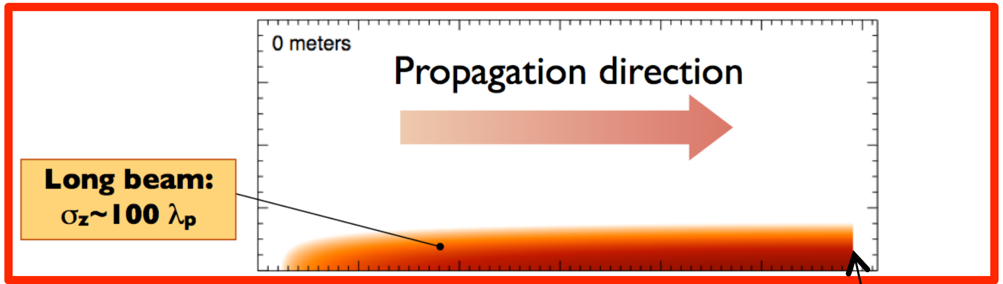
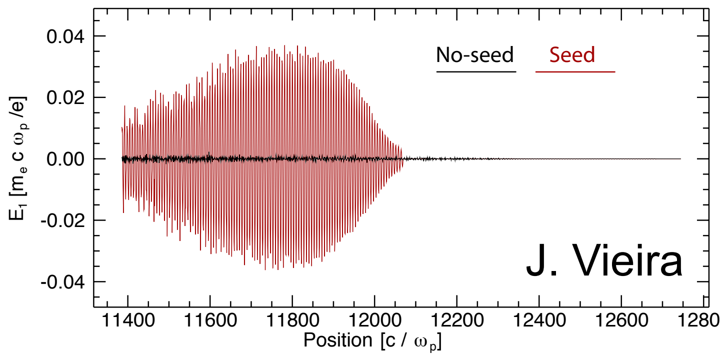
AWAKE EXPERIMENT @ CERN

First experiments: 2016







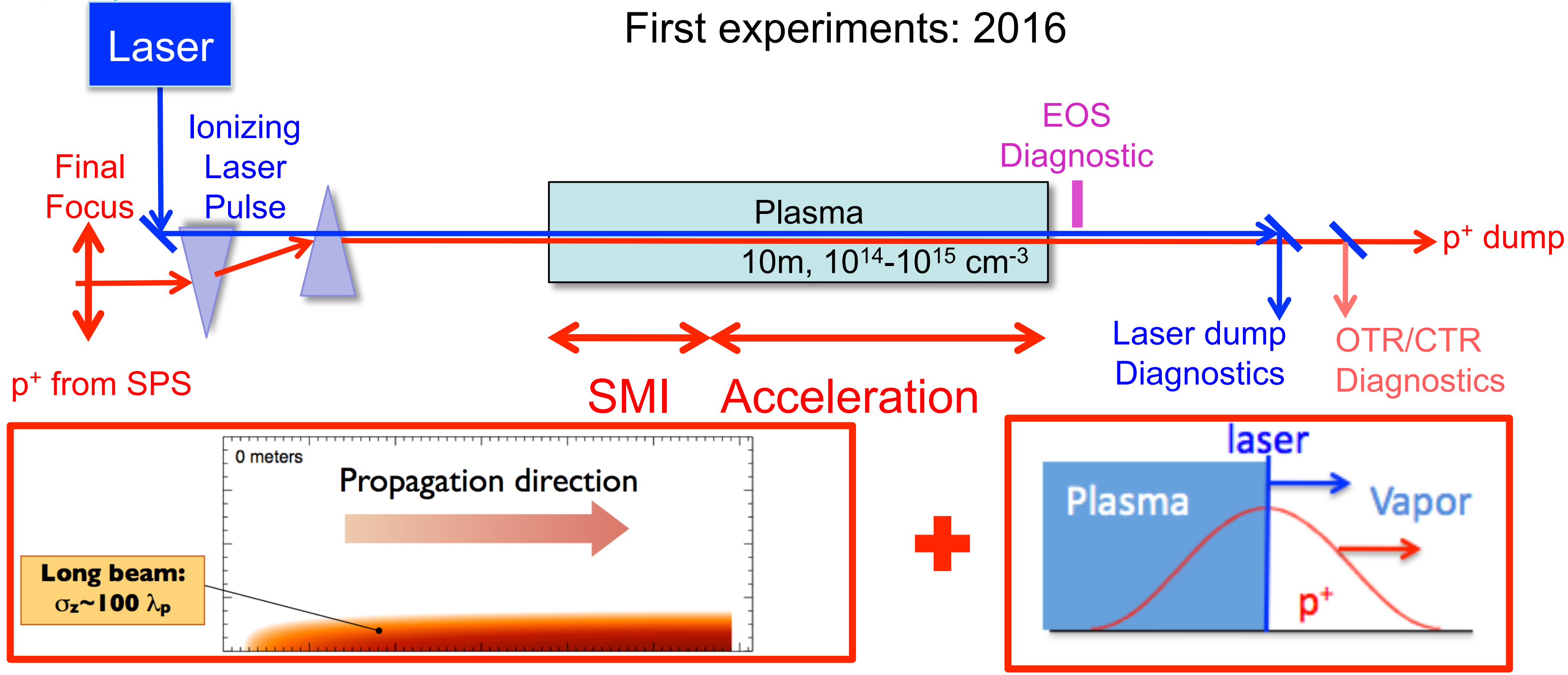
✧No seed no SMI (over 10m)

"Sharp" ($<<\lambda_{pe}$) start of the beam/plasma interaction for SMI seeding
AWAKE: will seed with ionization front!

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

AWAKE EXPERIMENT @ CERN

First experiments: 2016



✧Short laser pulse creates the plasma and seeds the SMI

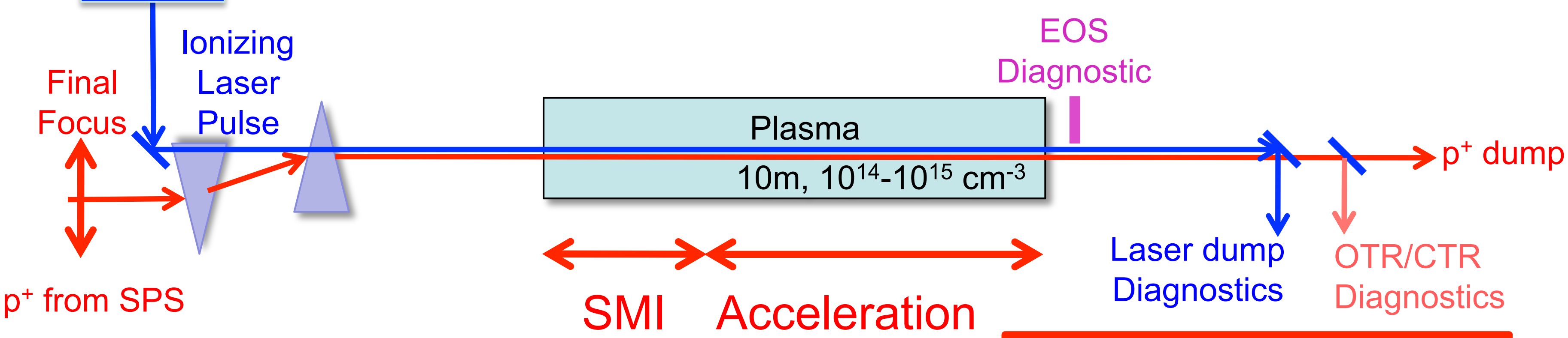
✧σ_z~12cm >> λ_{pe}~1.2mm (n_e~7x10^{14}cm^{-3}) => Self-modulation Instability (SMI)*

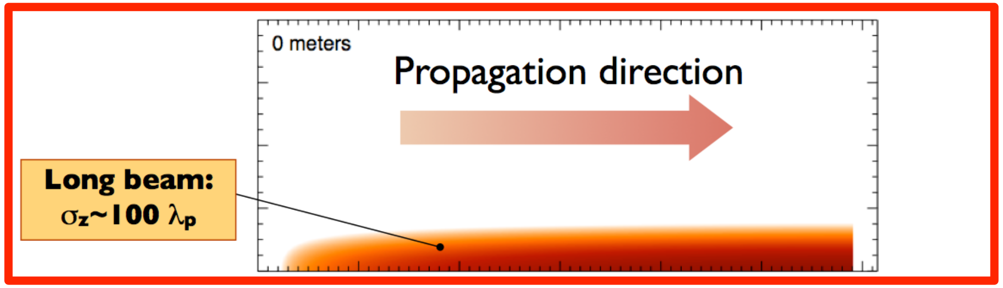
✧$\sigma_{z\ laser}$~30µm<<λ_{pe} => good seed

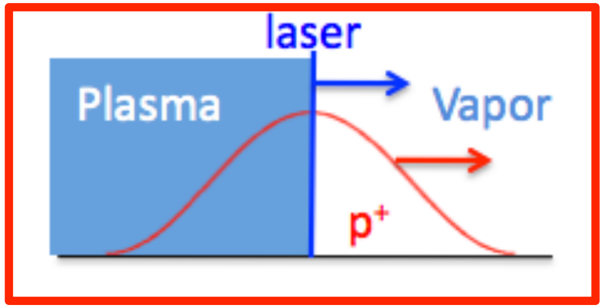
*Kumar, Phys. Rev. Lett. 104, 255003 (2010)

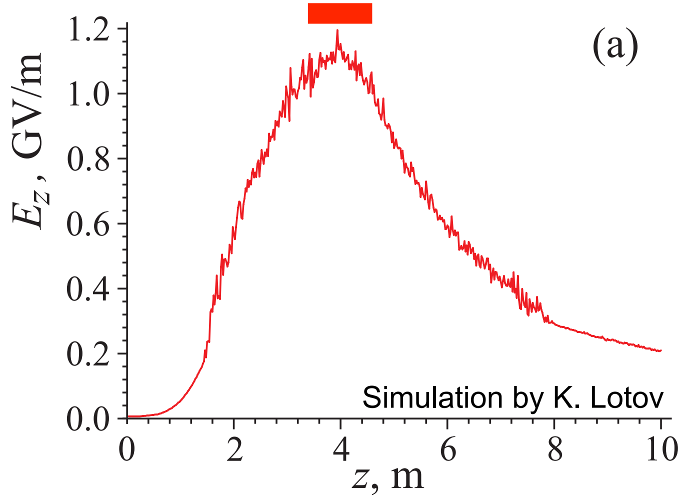
AWAKE EXPERIMENT @ CERN

First experiments: 2016





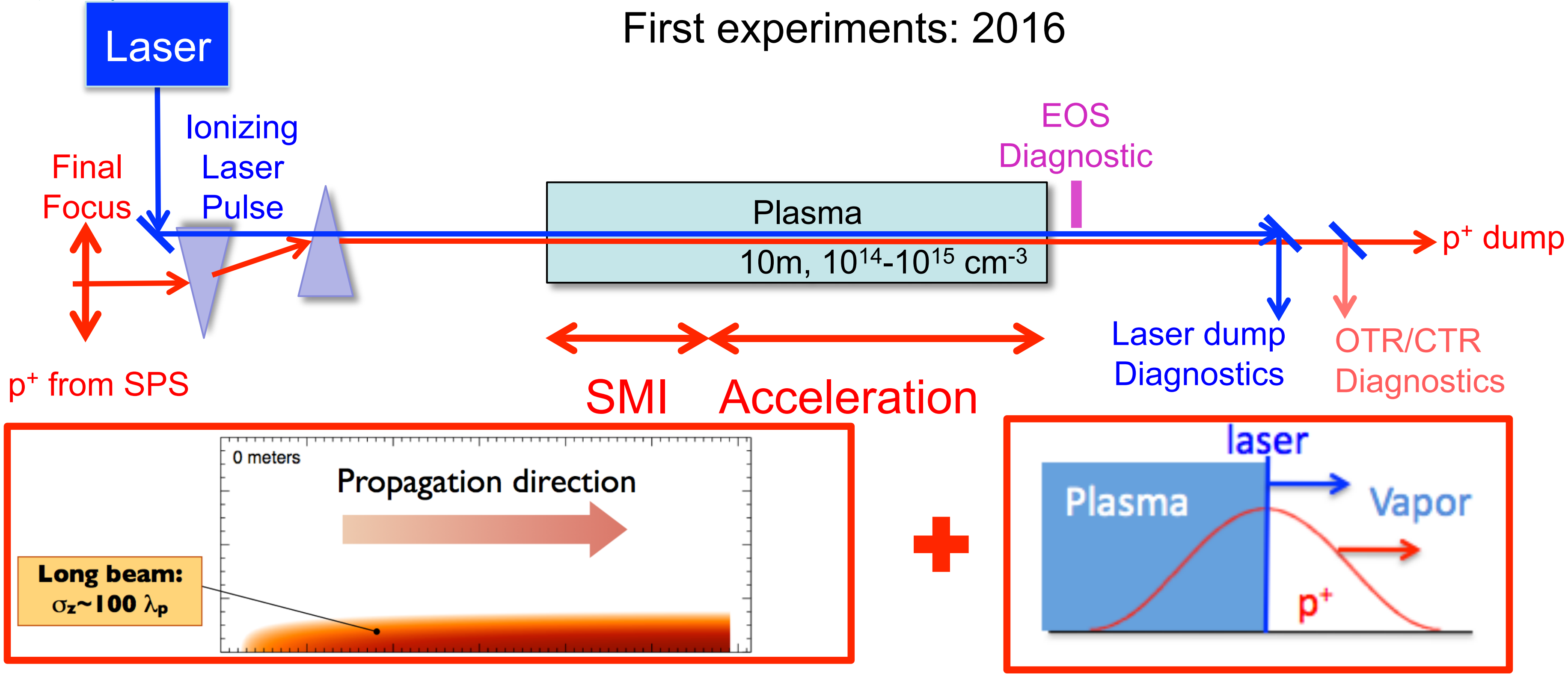


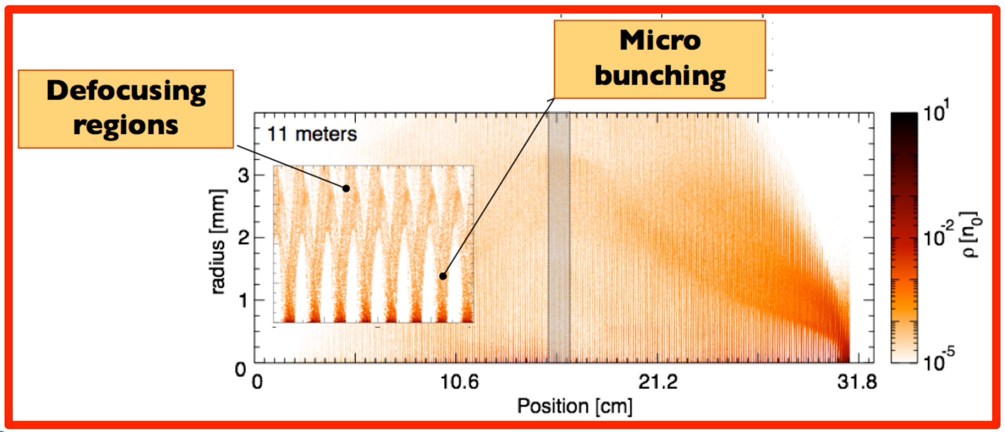


✧ The wakefields grow …

AWAKE EXPERIMENT @ CERN

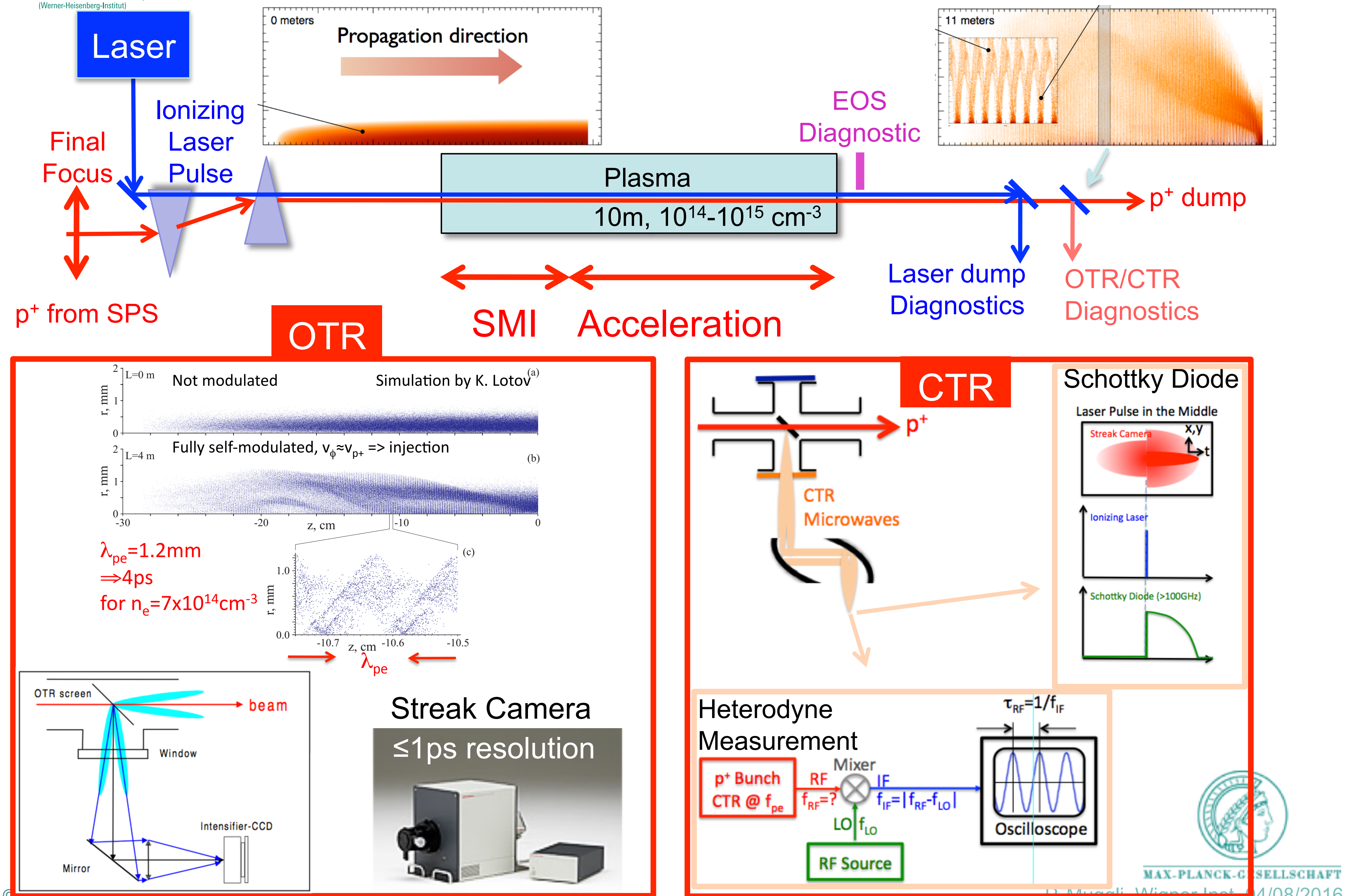
First experiments: 2016





- The long (σ_z~12cm) p⁺ bunch self-modulates with period λ_{pe}~1.2mm (n_e~7x10^{14}cm^{-3})
- ~100λ_{pe} per σ_z

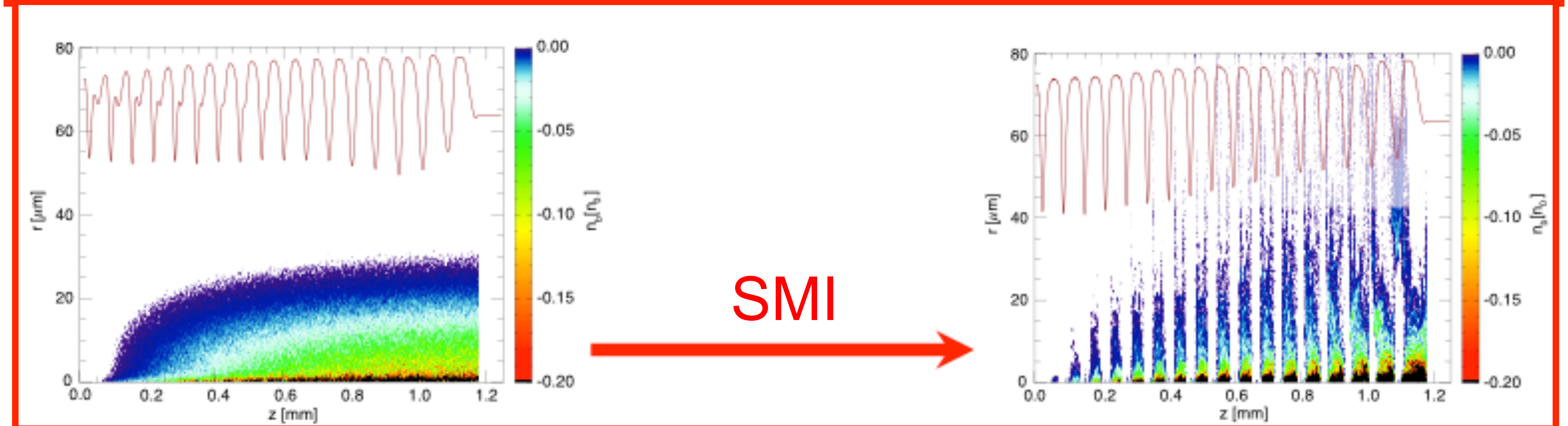
SMI DIAGNOSTICS



SMI DiAGNOSTiCS

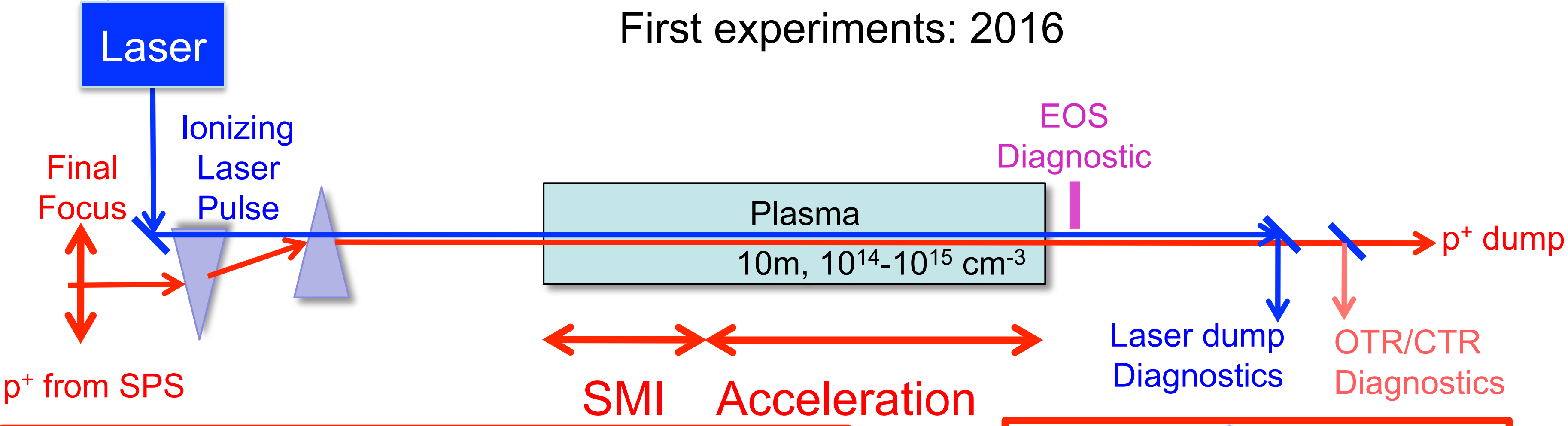
1st goal of AWAKE (2016-17): demonstrate and study the self-modulation instability (SMI) of a long p^+ bunch in a dense plasma

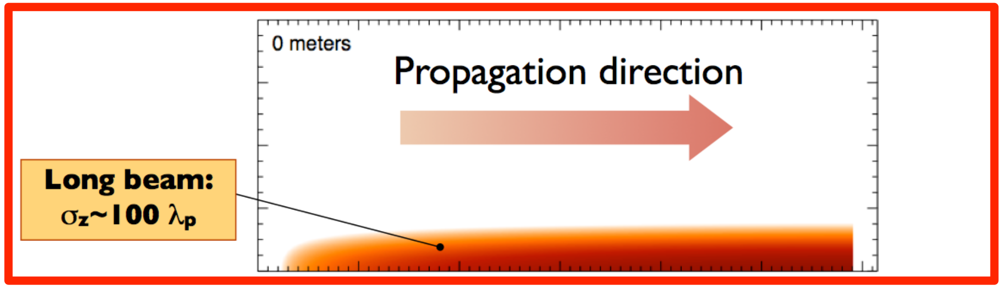
$\sigma_z >> \lambda_{pe} \sim n_e^{-1/2}$



AWAKE EXPERiMENT @ CERN

First experiments: 2016





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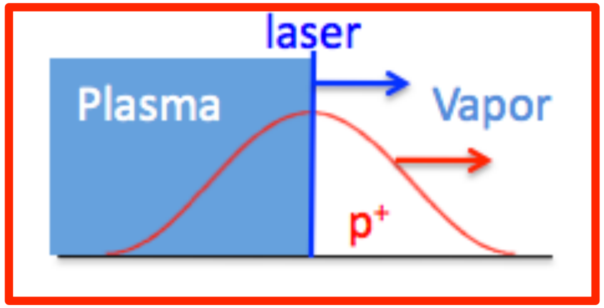

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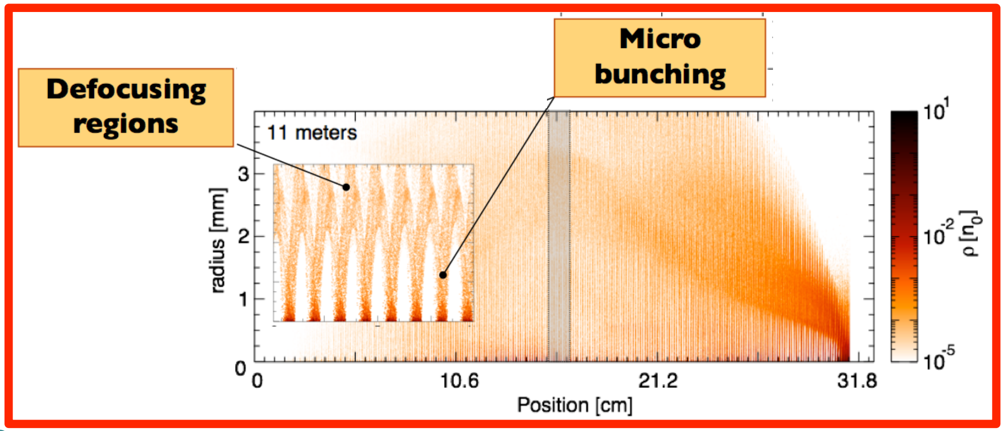
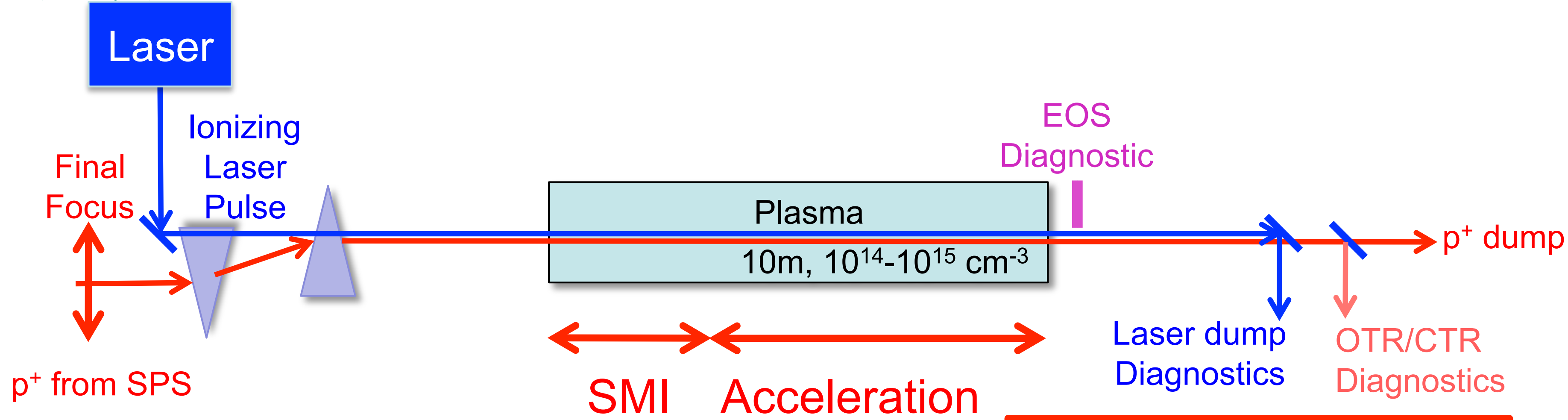
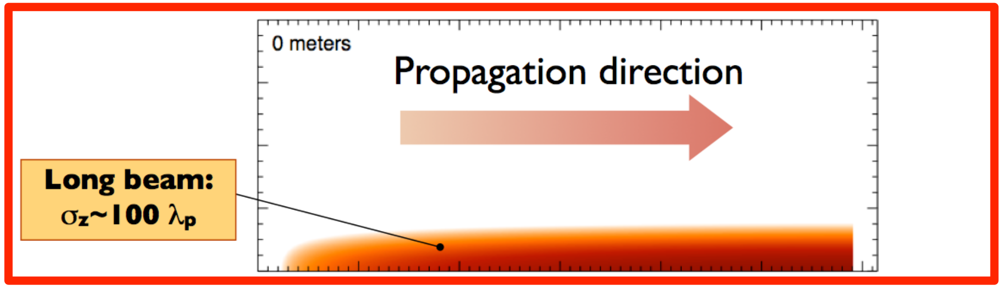
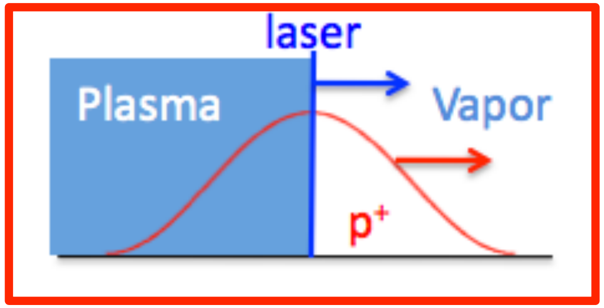


✧ The long (σ_z~12cm) p^+ bunch self-modulates with period λ_{pe}~1.2mm (n_e~$7\times10^{14}cm^{-3}$)

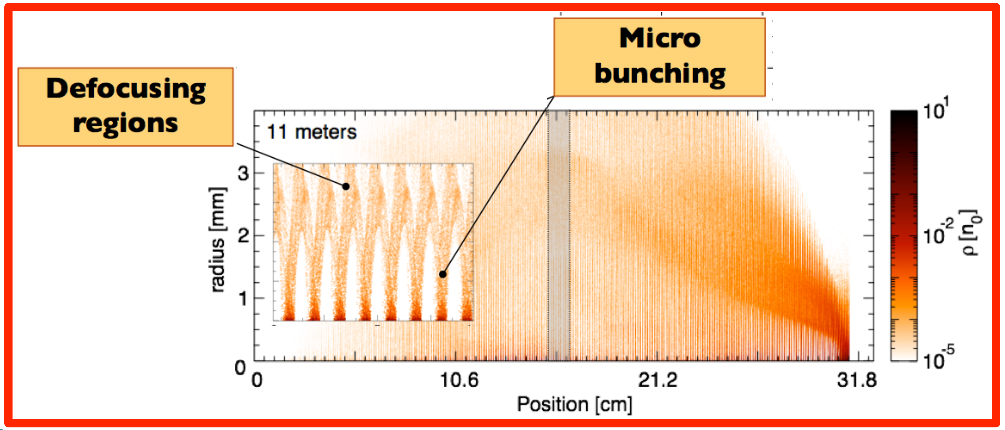
AWAKE EXPERiMENT @ CERN

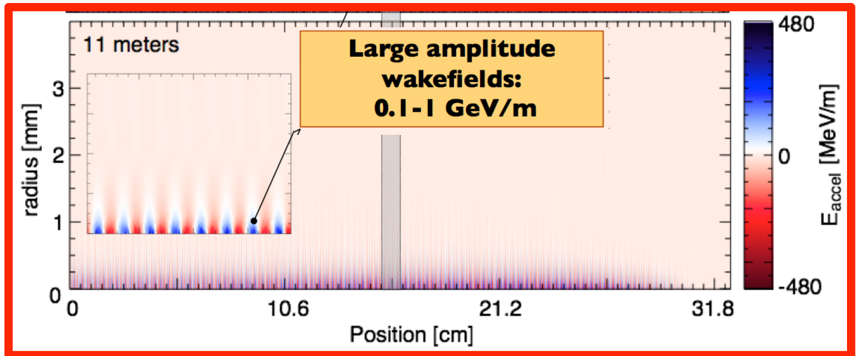






✧The SM p^+ bunch resonantly drives wakefields





AWAKE EXPERIMENT @ CERN

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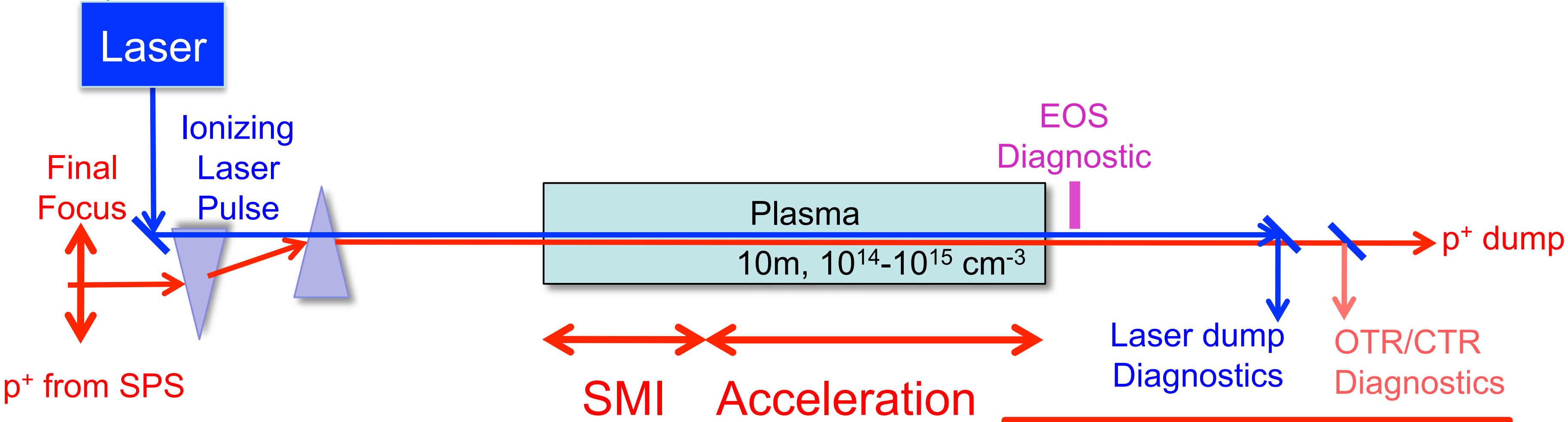

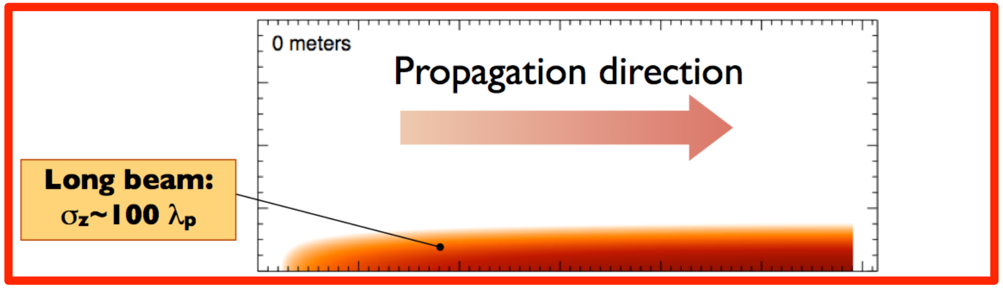

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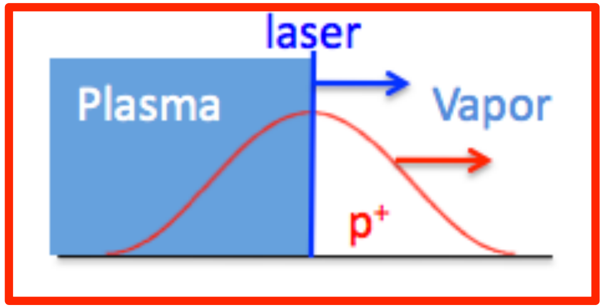

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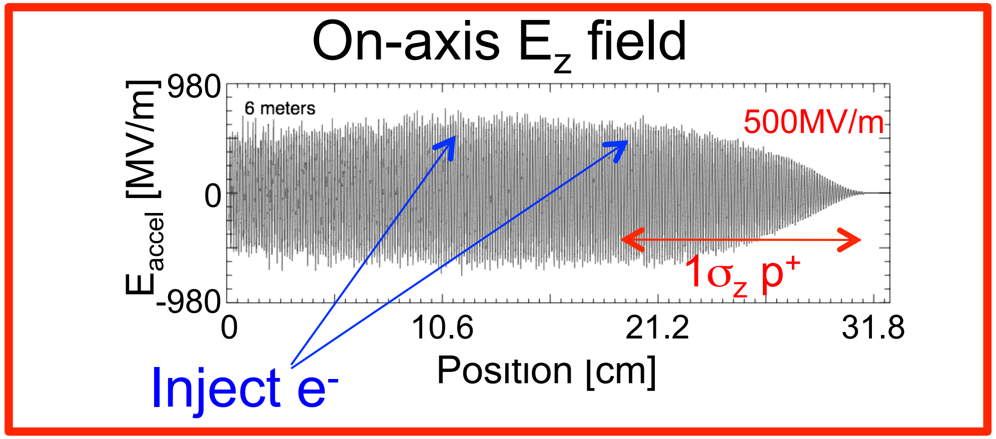
✧~GV/m accelerating field



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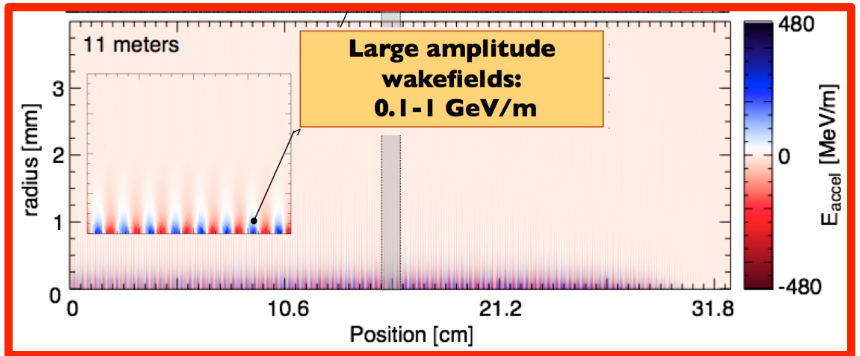
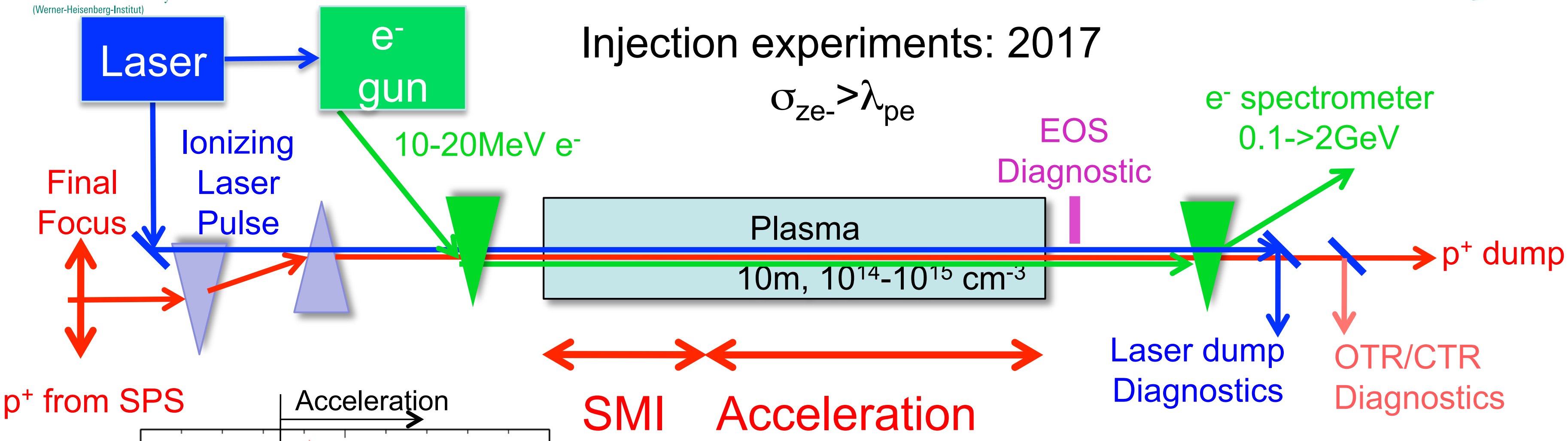
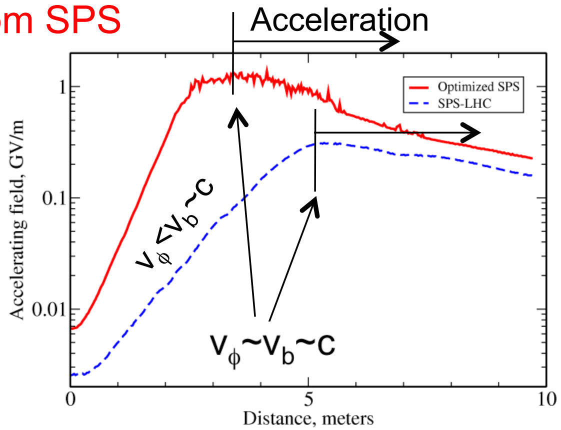


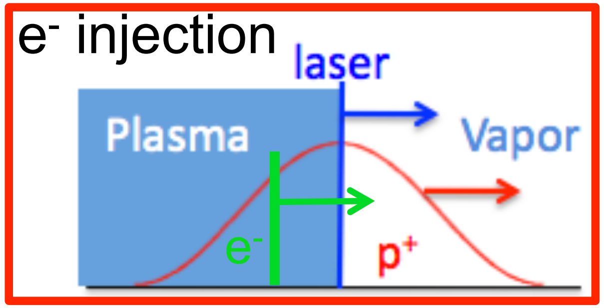
WAKEFIELDS SAMPLING / ACCELERATION

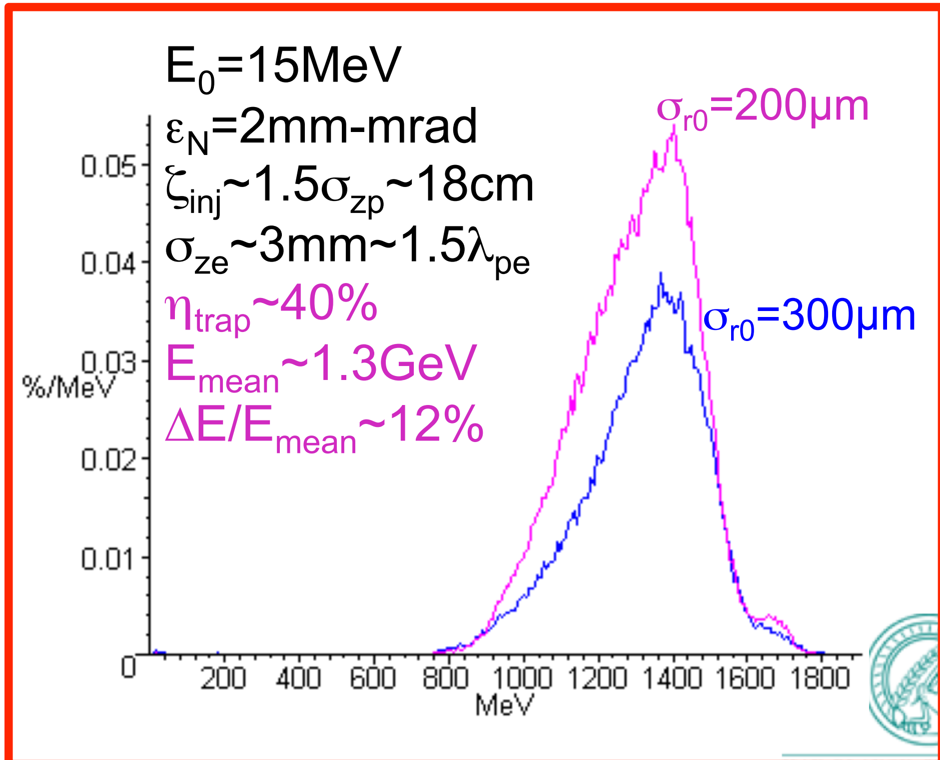
Injection experiments: 2017

$\sigma_{ze-} > \lambda_{pe}$









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

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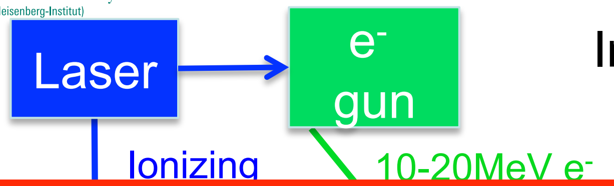
WAKEFIELDS SAMPLING / ACCELERATION



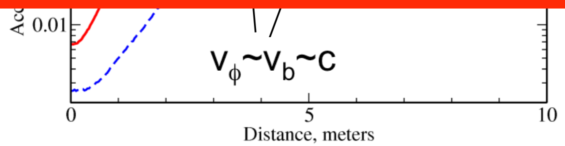
Injection experiments: 2017

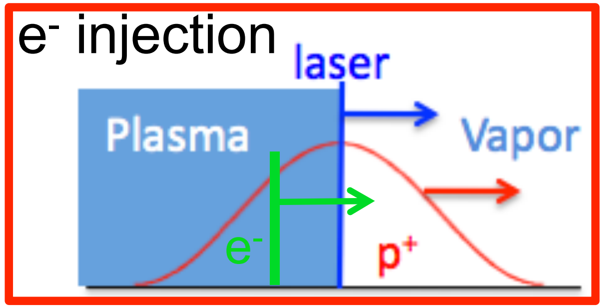
$\sigma_{ze-} > \lambda_{pe}$

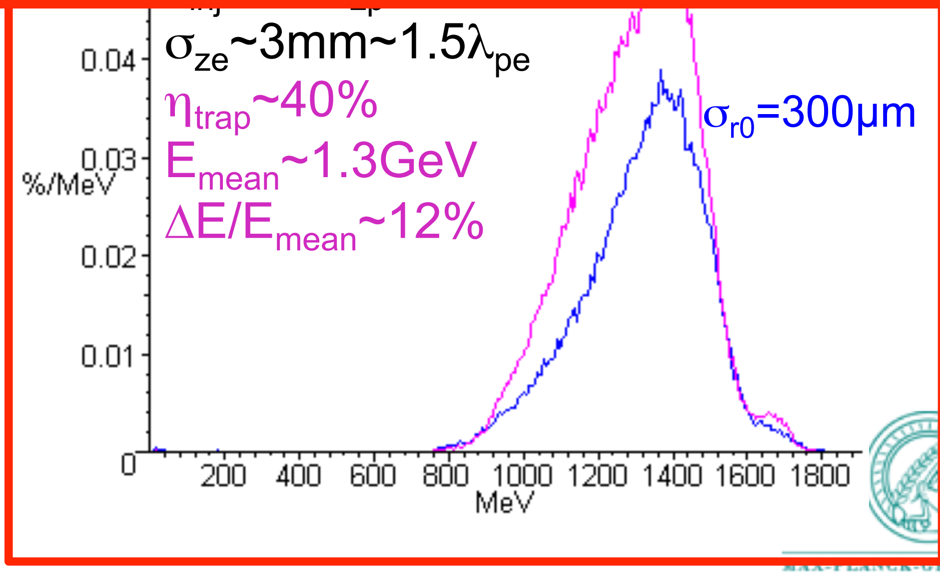
EOS

e^- spectrometer
0.1->2GeV

2nd goal of AWAKE (2017-18):
Externally inject (~15MeV) electrons into the wakefields and reach ~GeV energy gain







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

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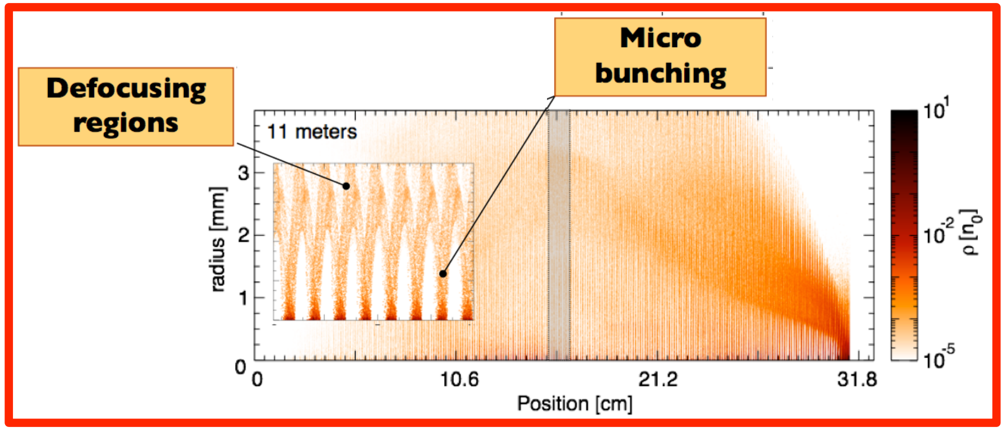
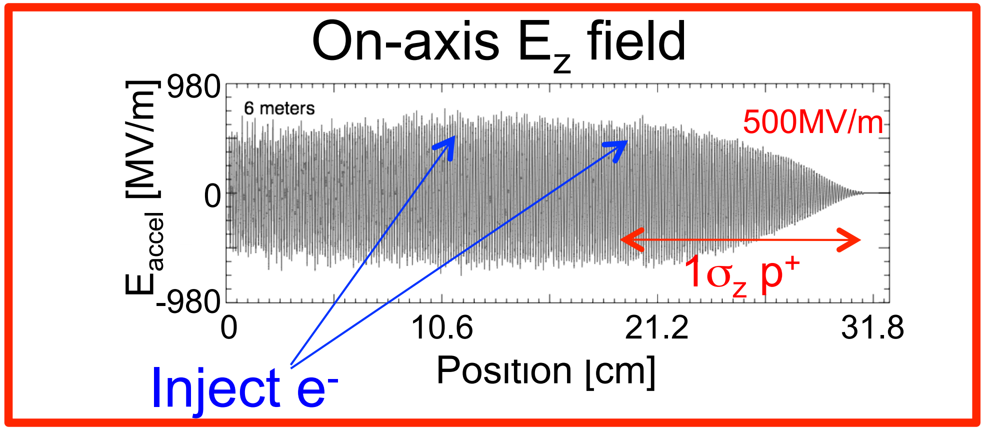
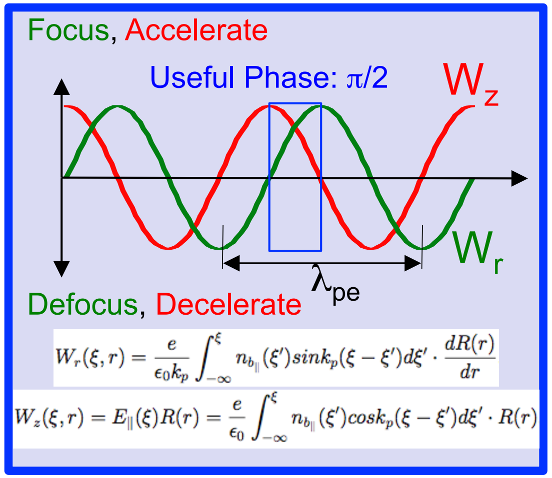
PLASMA SOURCE DENSITY UNIFORMITY

AWAKE





- ✧SMI grows over $\sim\sigma_{zp+}$ or $\sim N_{\lambda pe}\sim 100\lambda_{pe}$ (@$n_e\sim 7\times 10^{14}$cm^{-3})
- ✧Drive the wakefields resonantly



$$\lambda_{pe}=\frac{2\pi c}{\omega_{pe}}=\left(\frac{4\pi^2\varepsilon_0 mc^2}{e^2}\right)^{1/2} n_e^{-1/2} \Rightarrow d\lambda_{pe}=-\frac{1}{2}\lambda_{pe}\frac{dn_e}{n_e}$$

➡ At position $\xi=N_\lambda\lambda_{pe}$ want: $d\xi=\left|-N_\lambda\frac{1}{2}\lambda_{pe}\frac{dn_e}{n_e}\right|<<\frac{\lambda_{pe}}{4}$

➡ $\frac{dn_e}{n_e}<<\frac{1}{2N_\lambda}$ for $N_\lambda\sim 100$ $\frac{dn_e}{n_e}<<0.5\%$

➡ $\frac{dn_e}{n_e}<0.2\%$ ➡ $\frac{dT}{T}=\frac{dn_e}{n_e}<0.2\%$ ➡ $dT<1K \quad at\sim 500K$

- ✧Requirement for acceleration over 10⁺m:

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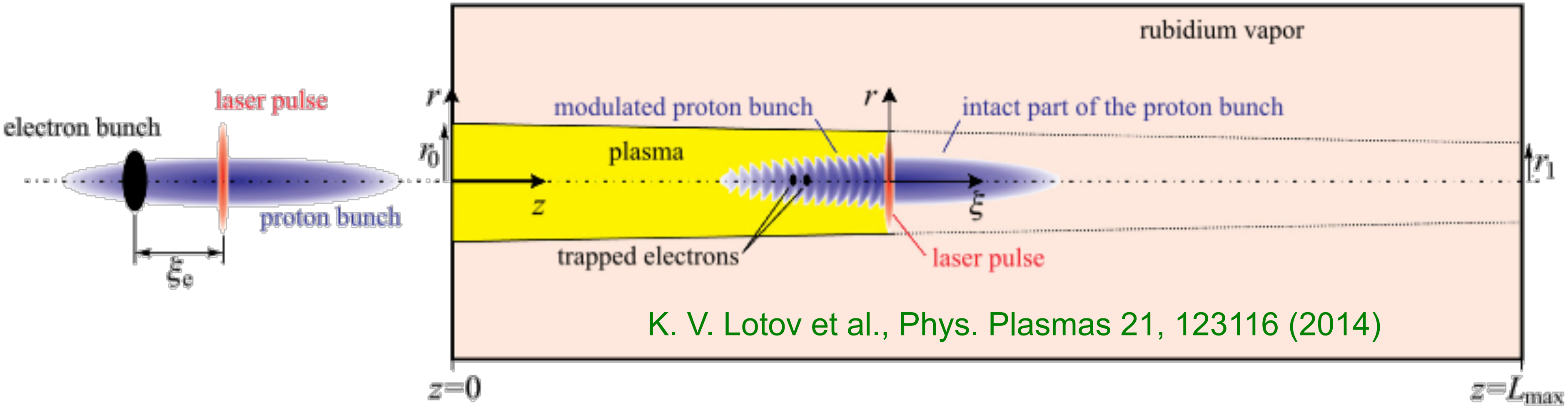
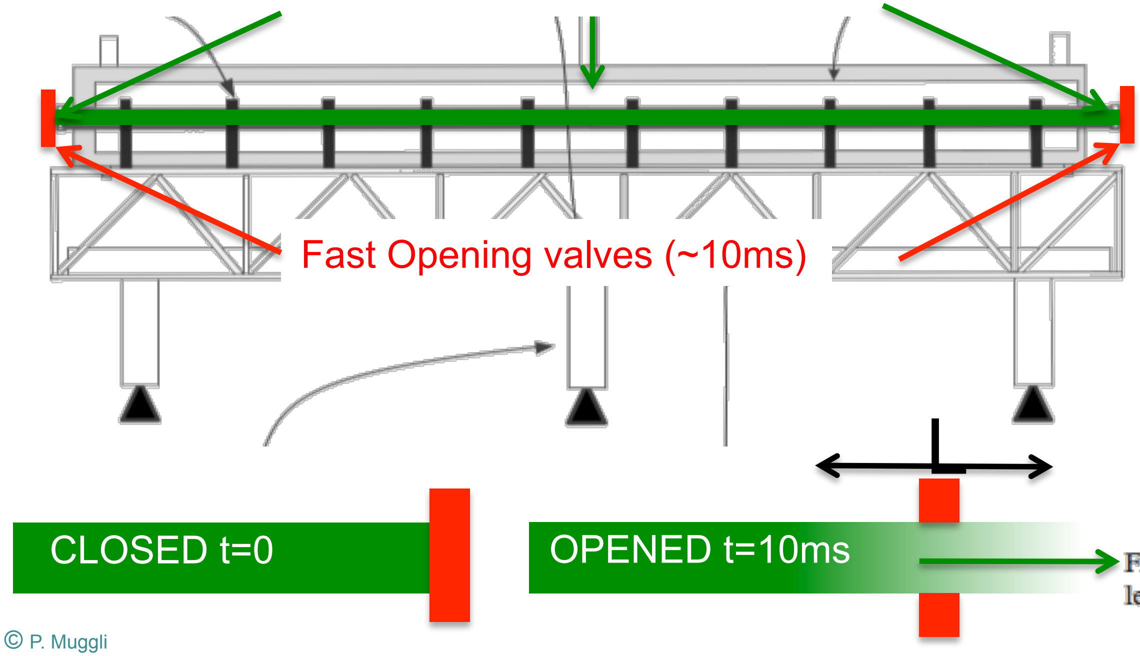
PLASMA SOURCE ENDS



Imposing temperature uniformity ⬄ imposing density uniformity (no flow)

Very uniform n_0 rubidium vapor ($\Delta n_0/n_0<0.2\%$)



e- injection experiments

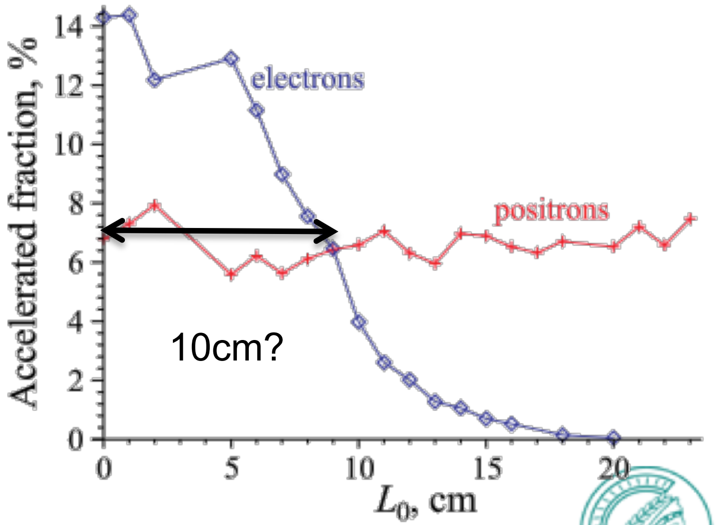
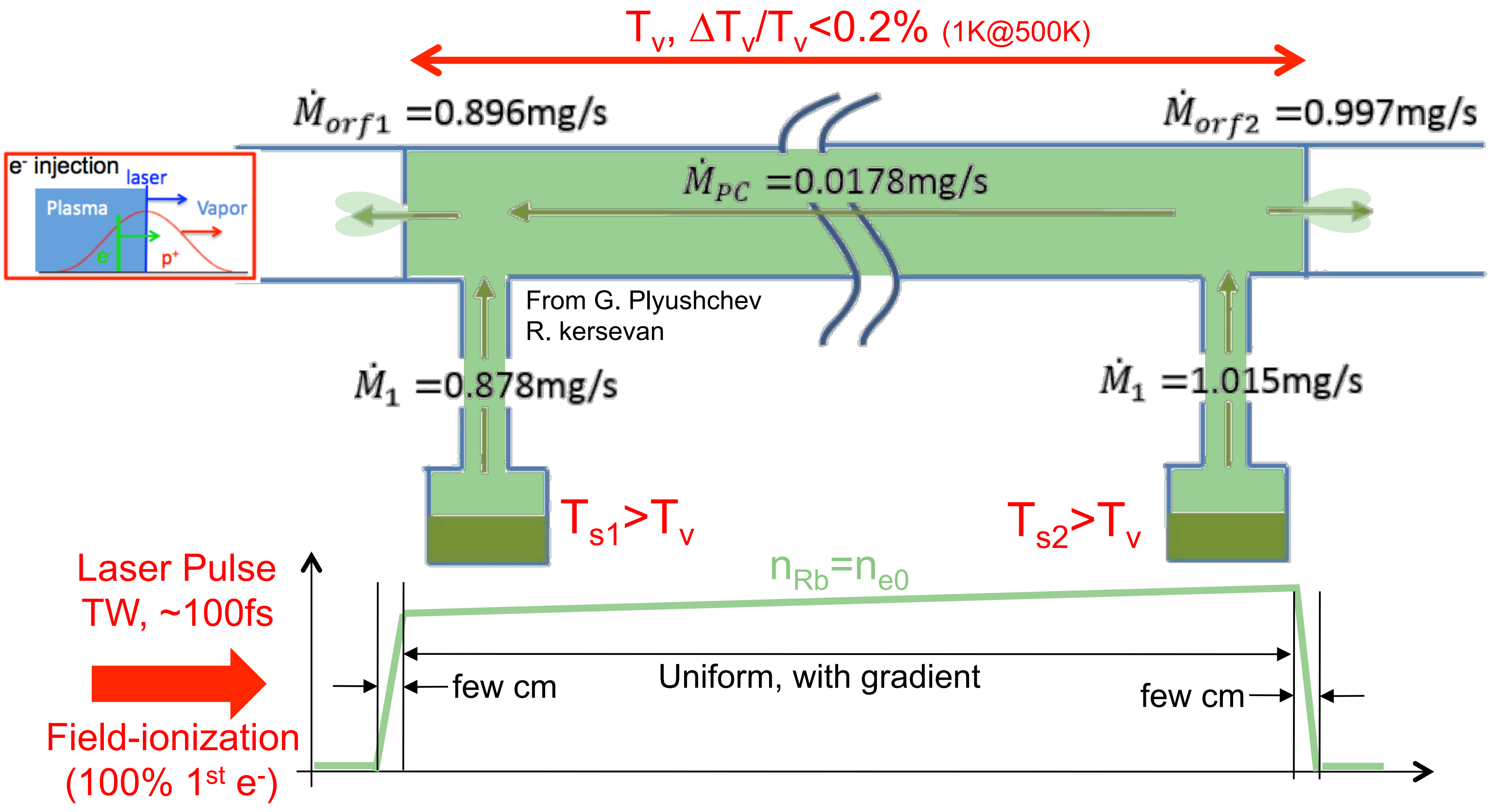


FIG. 9. Accelerated fraction of electron and positron beams versus the length of the transition region L_0.

Plasma Source Concept



- ✧Temperature ⇔ vapor density ⇔ plasma density uniformity
- ✧Expansion in vacuum ⇔ sharp end ramps
- ✧Two Rb reservoirs ⇔ possibility of density gradient
- ✧Laser field ionization ⇔ seeding SMI ⇔ short lived plasma

Rb VAPOR SOURCE (heat exchanger)

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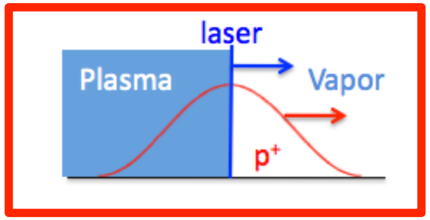
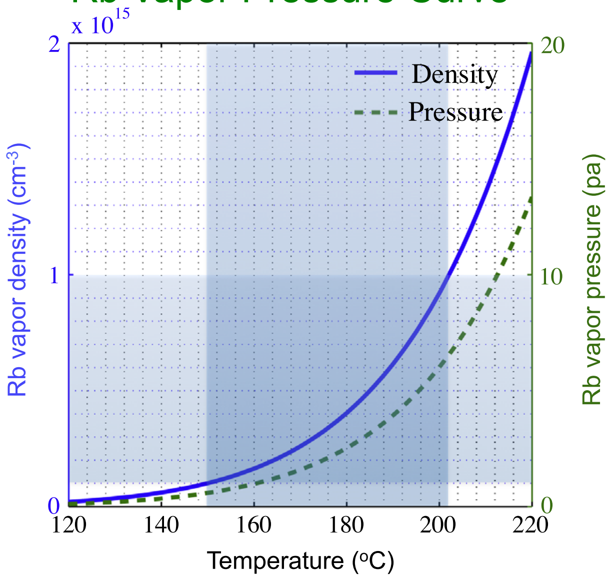
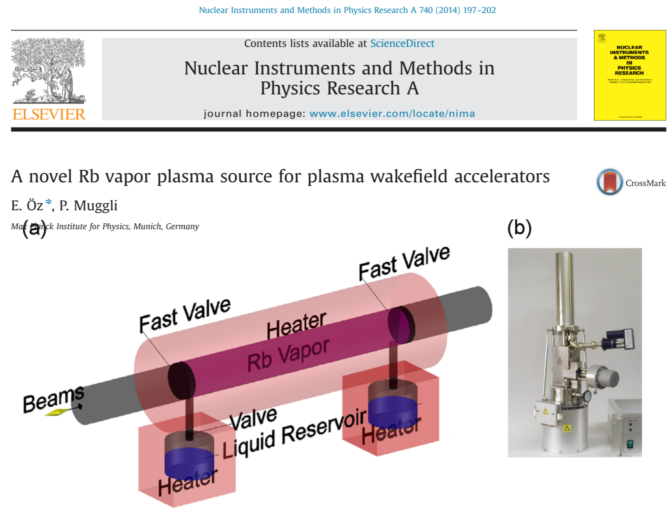
<u>Plasma requirements:</u>

✧L_p~10m, r_p>1mm
✧Easy to produce, to (laser) ionize
✧Allow for SMI seeding
✧$\delta n_0/n_0$<0.2% (e^- injection)
✧=> Rubidium
✧U_p=4.177eV
✧$I_{th}=1.7\times10^{12}W/cm^2 \sim U_p^4$
✧T<230°C



Rb Vapor Pressure Curve





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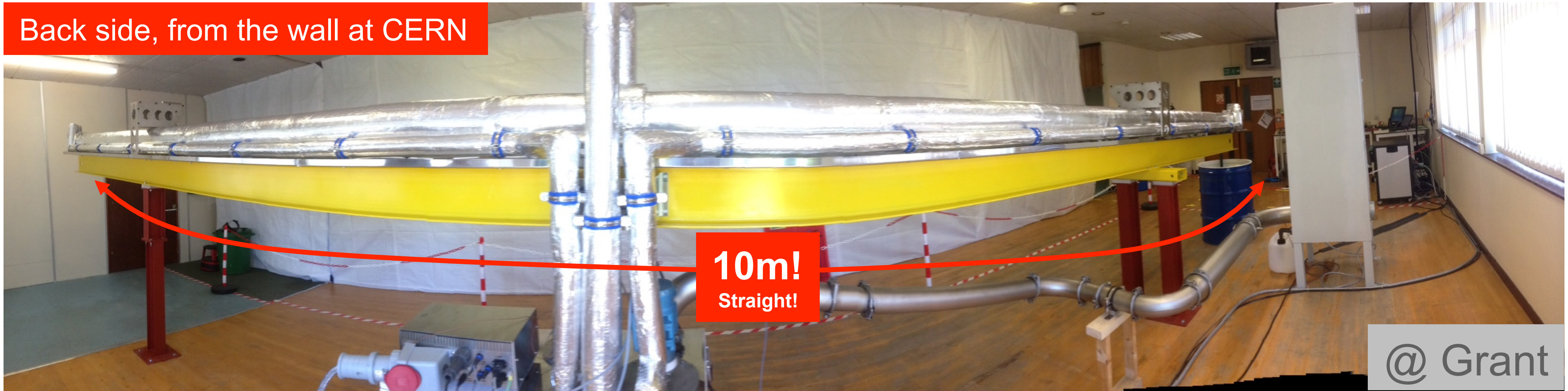
A novel Rb vapor plasma source for plasma wakefield accelerators

E. Öz*, P. Muggli

Max Planck Institute for Physics, Munich, Germany

Fig. 2. (a) Sketch of the plasma source. Two independently heated sections consist of a 10 m long Rb vapor section with fast valves for proton, electron and laser beam access and valved Rb liquid reservoirs. (b) Photo of the valved Rb liquid reservoir by MBE Komponenten incorporated.

Back side, from the wall at CERN



✧The longest compact accelerator in the world!

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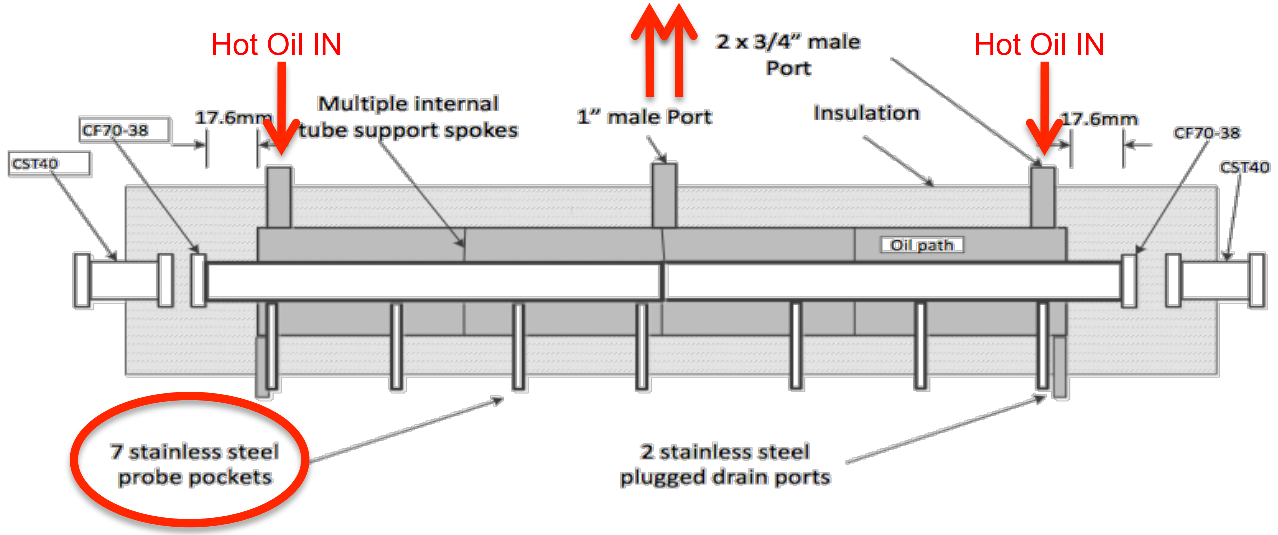
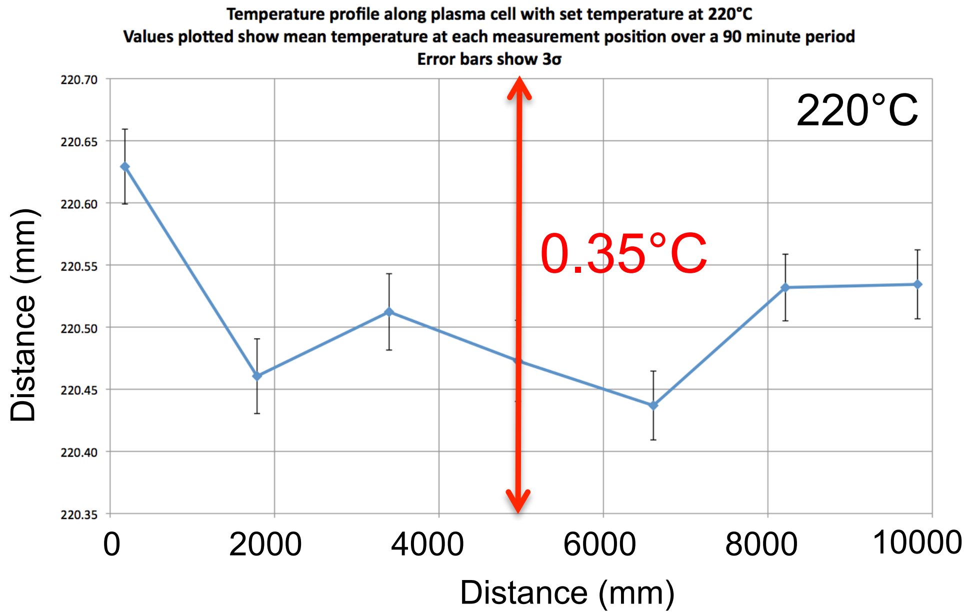
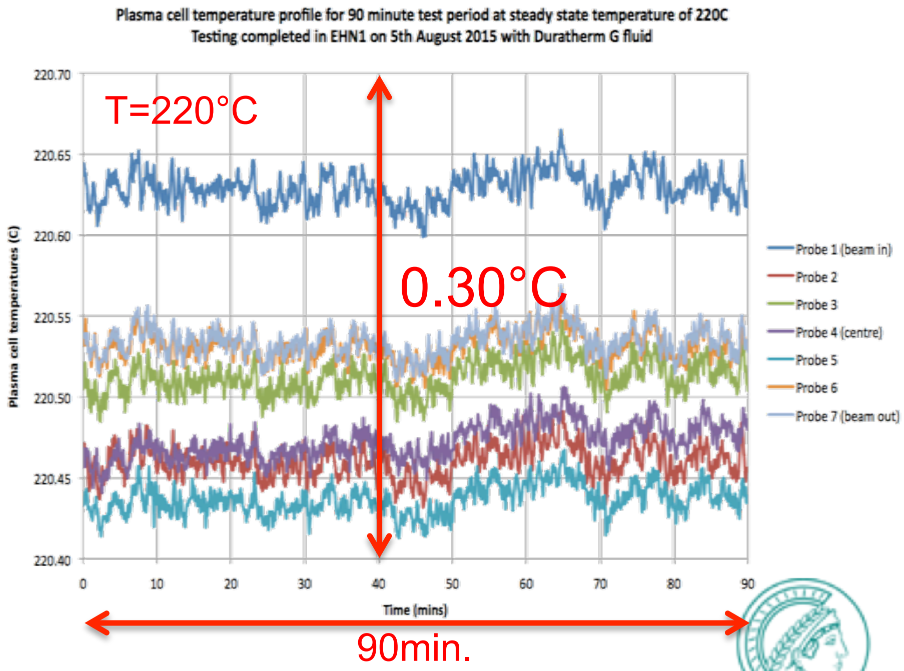
Rb VAPOR SOURCE (heat exchanger)

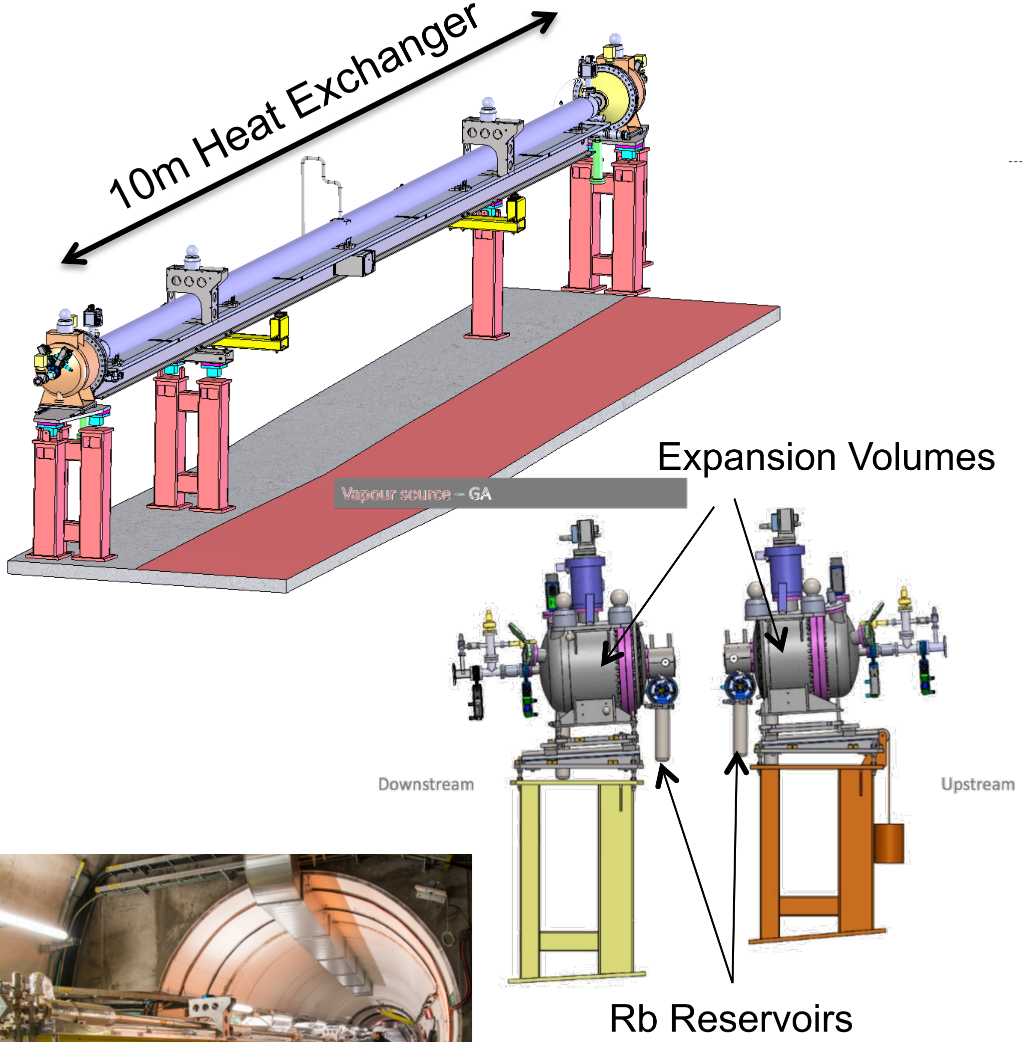




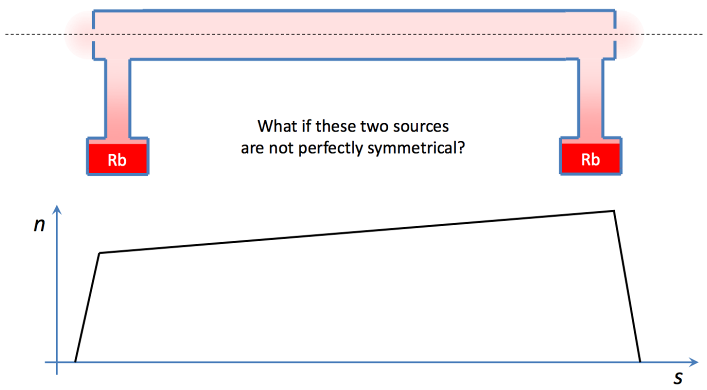


✧Meet the specifications … <1K …

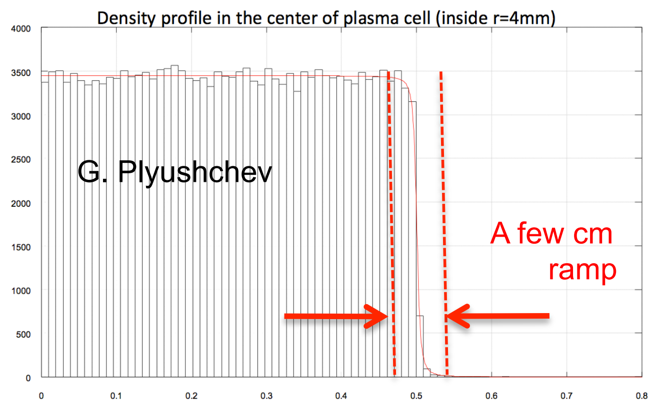
Rb Vapor Source Today



Vapor source with continuous flow (R. Kersevan)



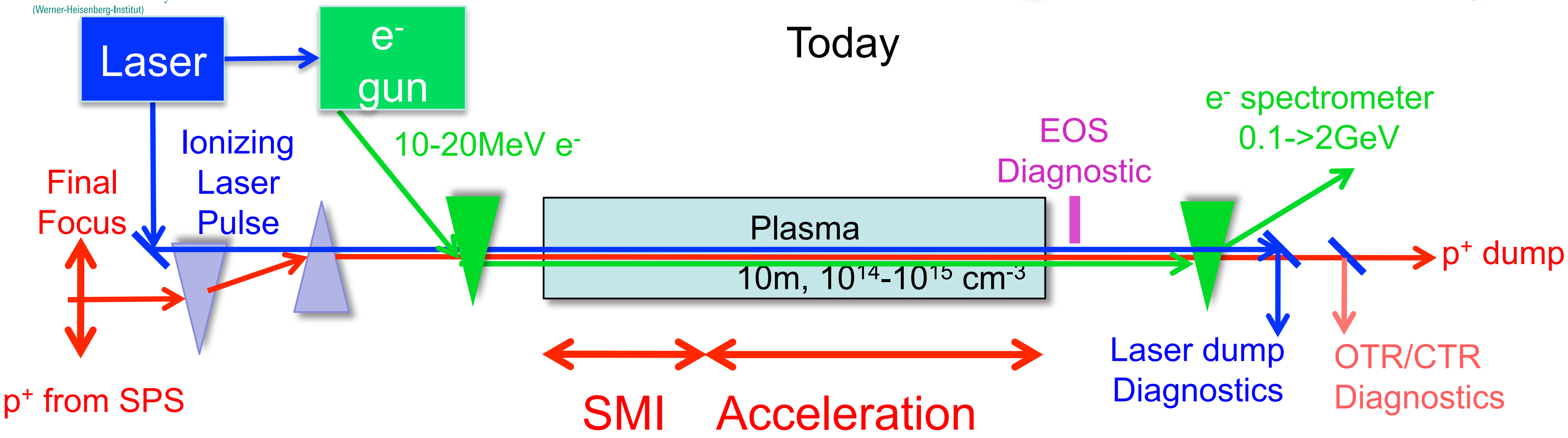
3D DSMC simulation Single Orifice with Source: density profile

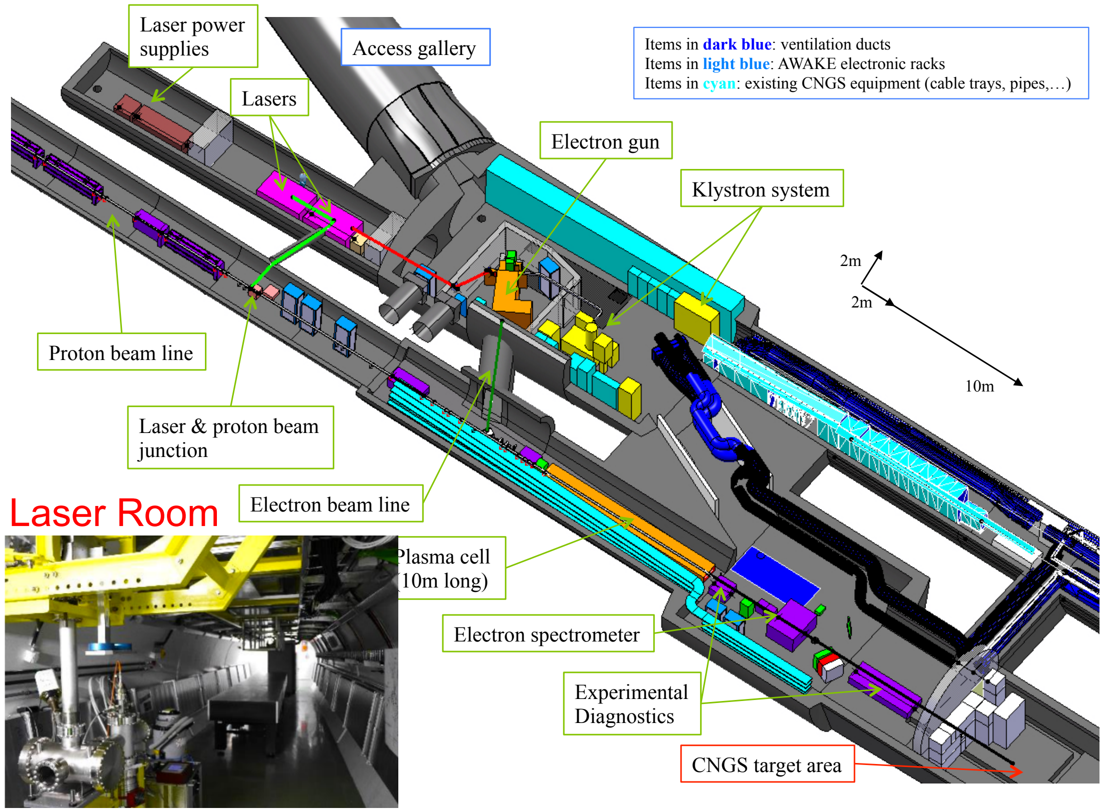


✧Satisfy short ramp condition
✧Has a gradient by default

✧Laser being installed at CERN

AWAKE EXPERIMENT @ CERN





Laser Room

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

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PRESENT - FUTURE

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- ✧Rb-based vapor source currently built/developed

- ✧Ionization laser (Er-fiber):
  λ=780±5nm ~ λ_{RbD2}~780nm, ~ λ_{RbD1}~794nm ⇔ anomalous dispersion (Josh)
- ✧Laser propagation (Jerome)
- ✧Need full ionization over 10m and r~c/ω_{pe}~1mm (Anna-Maria)
- ✧Spent laser pulse can damage diagnostics (Mathias)

- ✧Laser pulse propagation ionization calculations
  - ✧Ionization fraction (100% 1^{st} e^-)
  - ✧Evolution (r,z)
  - ✧Propagation velocity
- ✧Plasma density diagnostics

Wigner
UNIVERSITÉ DE GENÈVE
AWAKE
Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

- ✧Important (AWAKE) and interesting problems
- ✧Many good topics for experiment/simulation/theory collaboration …

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Thank you to my collaborators!

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