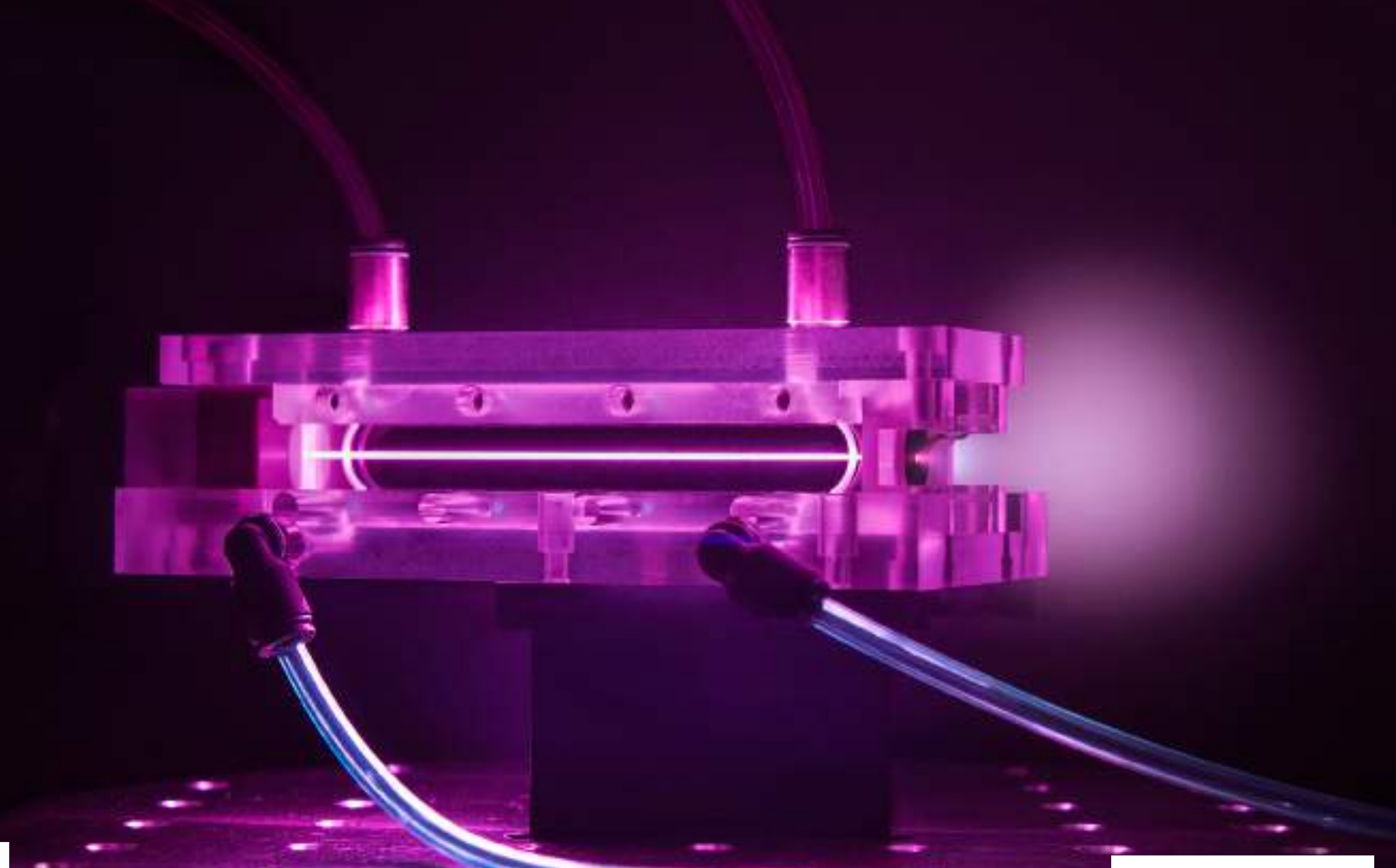
Beam Driven Plasma Acceleration

Massimo.Ferrario@LNF.INFN.IT

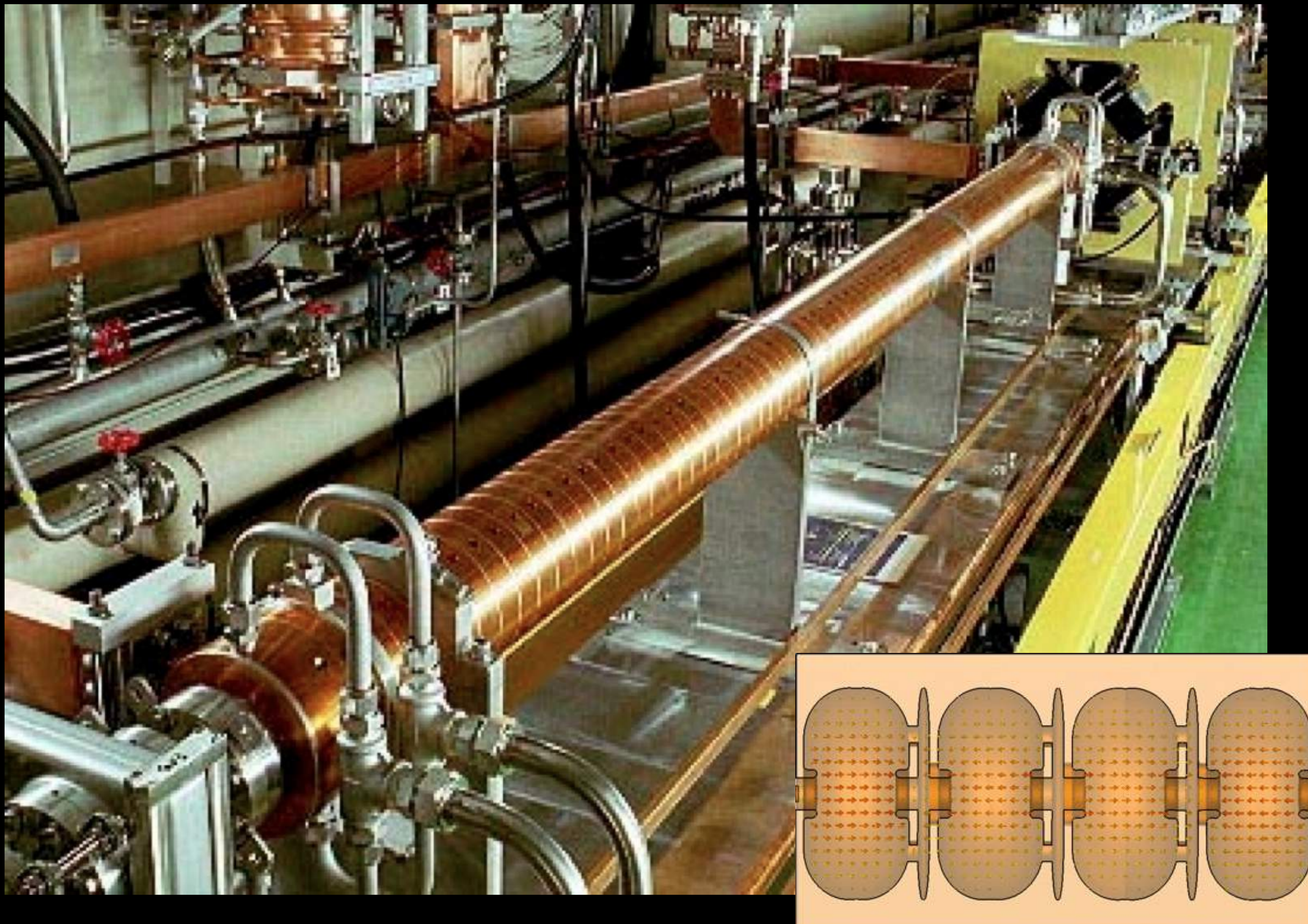


The CERN Accelerator School

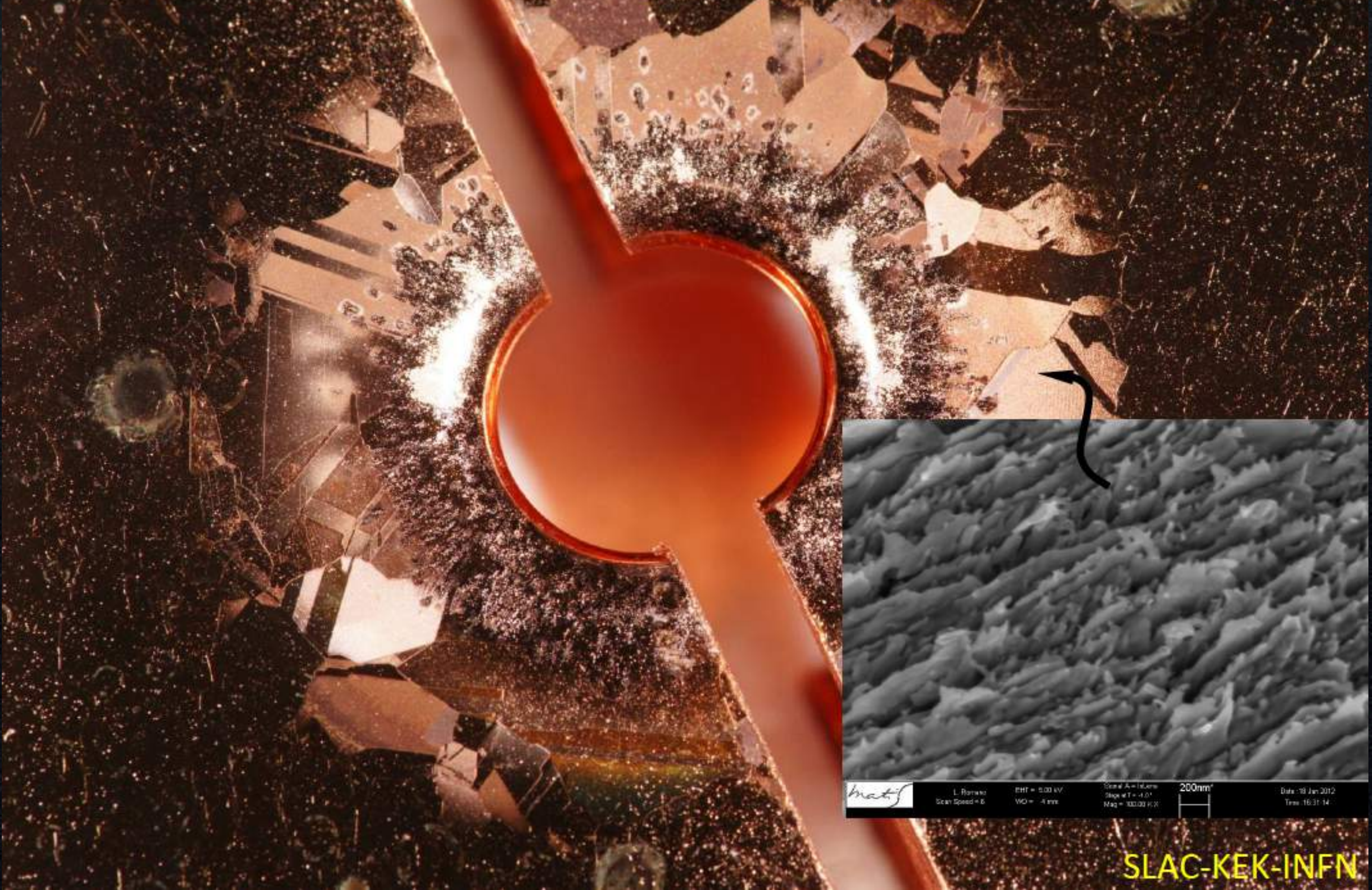
Egham – September 9th 2017

SPARC LAB

Conventional RF accelerating structures

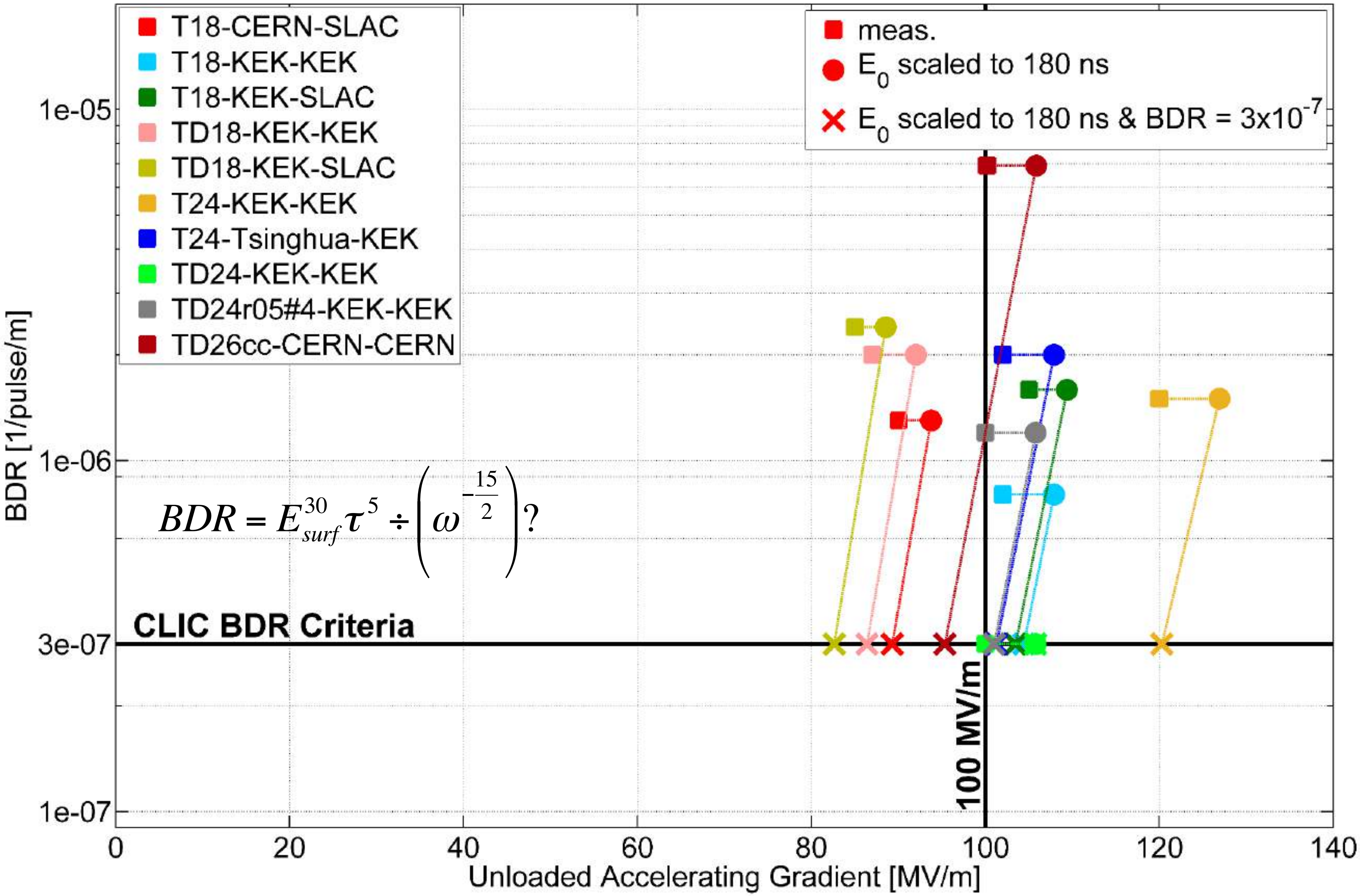


Typical breakdown and pulse heating damage is standing-wave structure cell

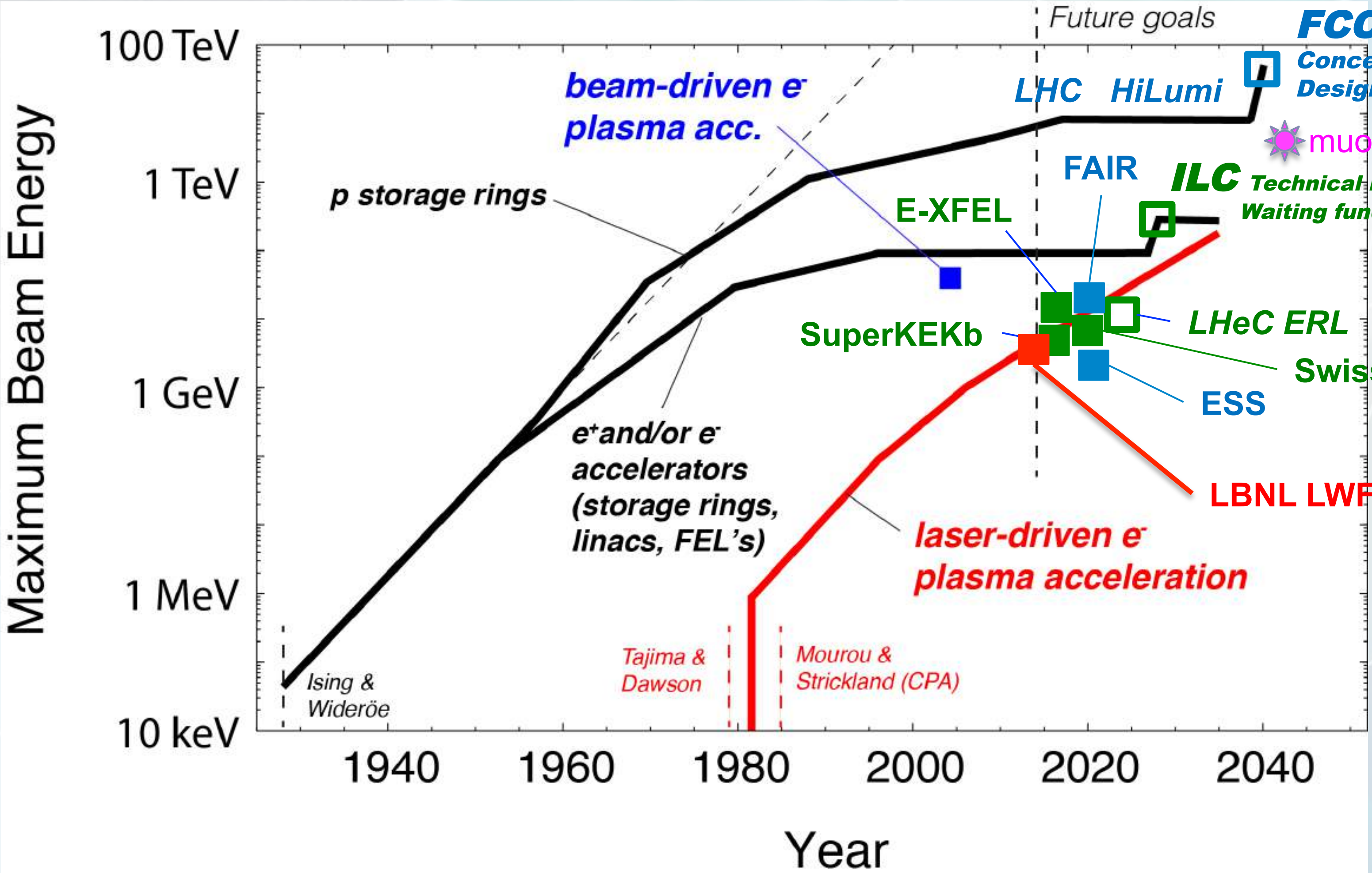


SLAC-KEK-INFN

Performance summary at CLIC specifications



Future of Accelerators



- Hadron acc. project
- Lepton acc. project
- Hadron acc. proposal
- Lepton acc. proposal

VOLUME 43, NUMBER 4 PHYSICAL REVIEW LETTERS 23 JULY 1979

Laser Electron Accelerator

T. Tajima and J. M. Dawson
Department of Physics, University of California, Los Angeles, California 90024
(Received 9 March 1979)

An intense electromagnetic pulse can create a weak of plasma oscillations through the action of the nonlinear ponderomotive force. Electrons trapped in the wake can be accelerated to high energy. Existing glass lasers of power density 10^{18}W/cm^2 shone on plasmas of densities 10^{18} cm^{-3} can yield gigaelectronvolts of electron energy per centimeter of acceleration distance. This acceleration mechanism is demonstrated through computer simulation. Applications to accelerators and pulsers are examined.

VOLUME 54, NUMBER 7 PHYSICAL REVIEW LETTERS 18 FEBRUARY 1985

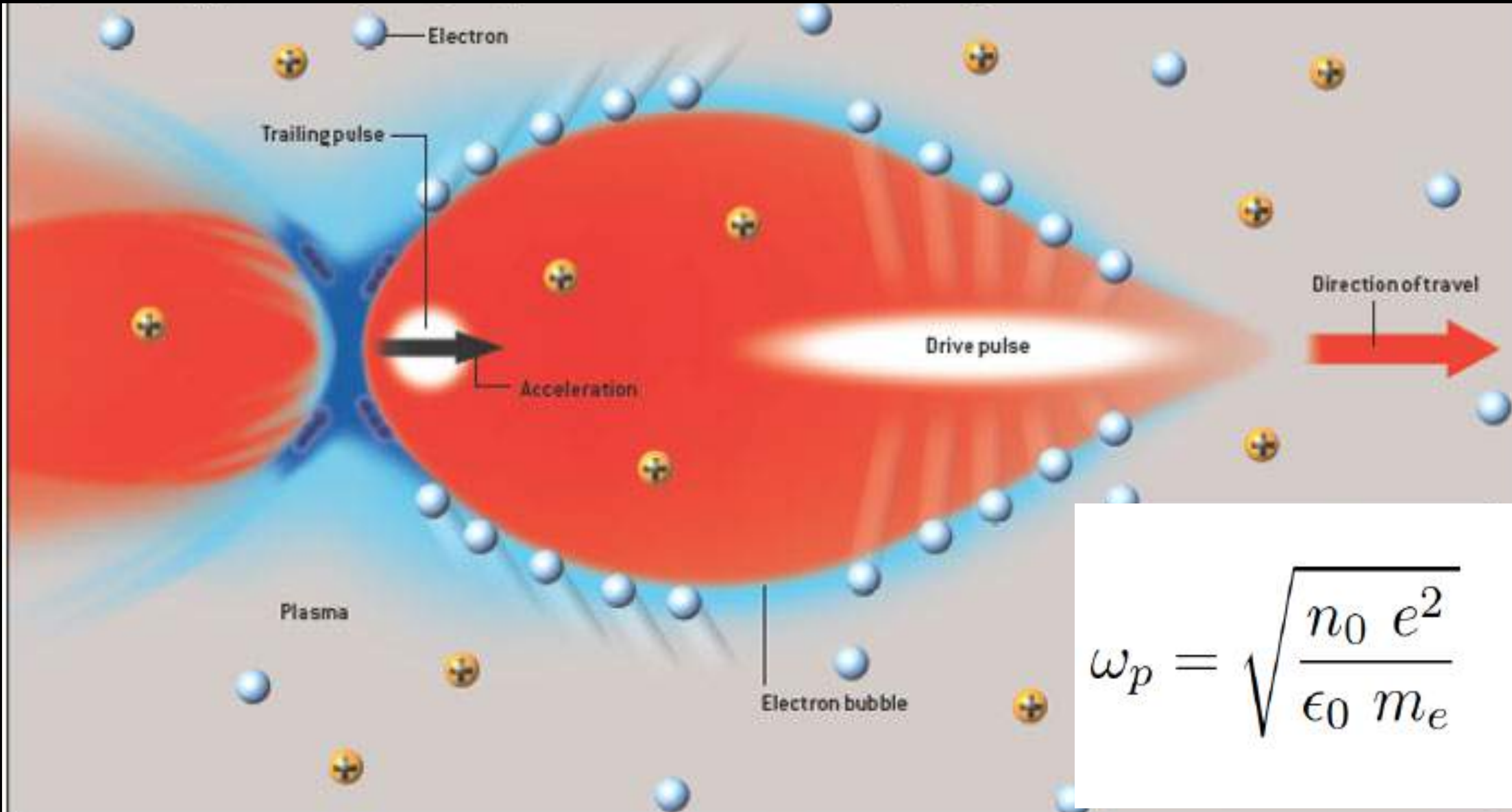
Acceleration of Electrons by the Interaction of a Bunched Electron Beam with a Plasma

Pisin Chen[a]
Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305

and

J. M. Dawson, Robert W. Huff, and T. Katsouleas
Department of Physics, University of California, Los Angeles, California 90024
(Received 20 December 1984)

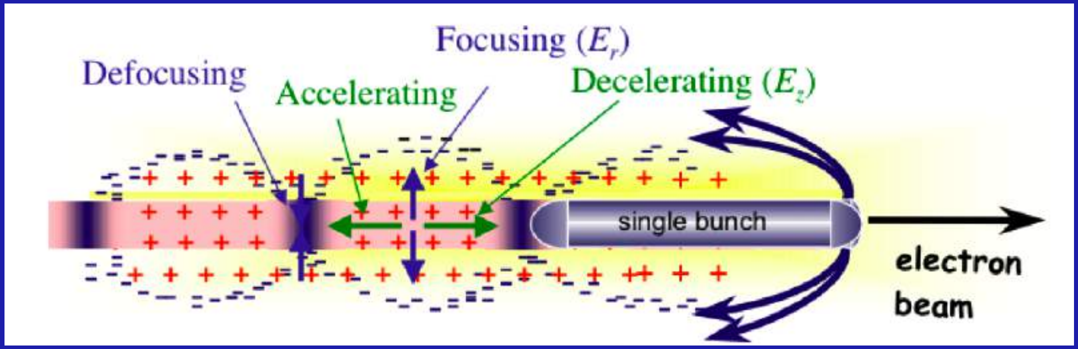
A new scheme for accelerating electrons, employing a bunched relativistic electron beam in a cold plasma, is analyzed. We show that energy gradients can exceed 1 GeV/m and that the driven electrons can be accelerated from $\gamma_0 mc^2$ to $3\gamma_0 mc^2$ before the driving beam slows down enough to degrade the plasma wave. If the driving electrons are removed before they cause the collapse of the plasma wave, energies up to $4\gamma_0^2 mc^2$ are possible. A noncollinear injection scheme is suggested in order that the driving electrons can be removed.

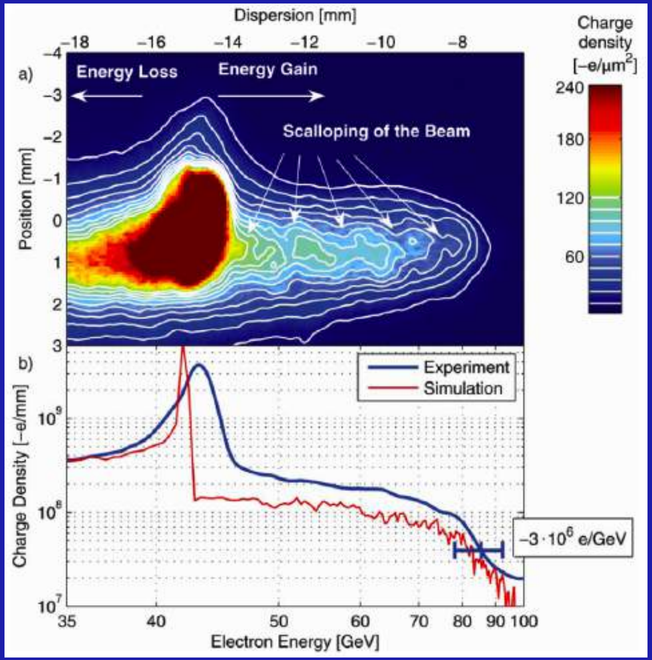


$$\omega_p = \sqrt{\frac{n_0 \; e^2}{\epsilon_0 \; m_e}}$$

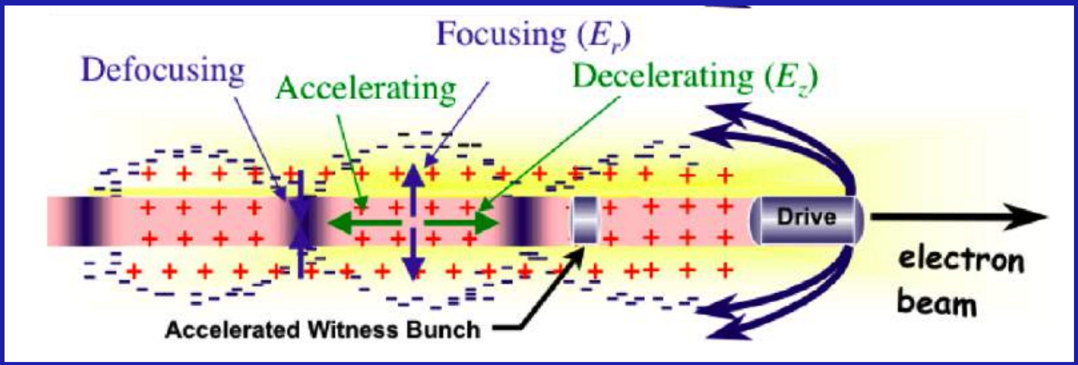
$$\lambda_p \approx 1\mathrm{mm} \cdot \sqrt{\frac{10^{15}\mathrm{cm}^{-3}}{n_0}}$$

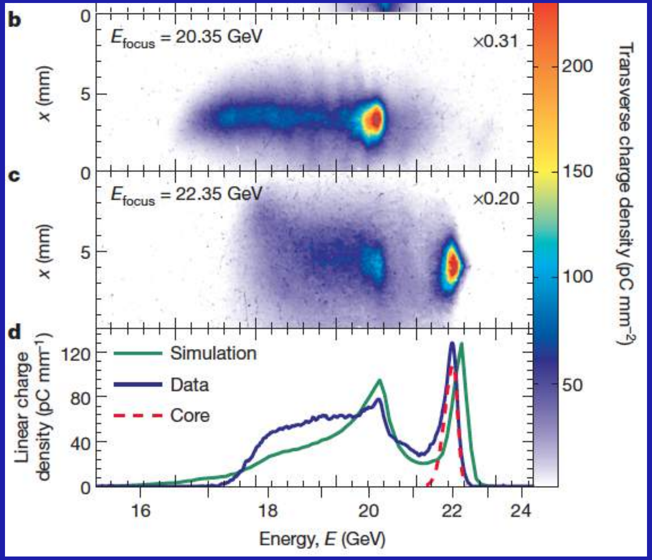
0.3 mm for $n_0 = 10^{16}$ cm^{-3}





Blumenfeld, I. et al. *Energy doubling of 42 GeV electrons in a metre-scale plasma wakefield accelerator*. **Nature** 445, 741–744 (2007).



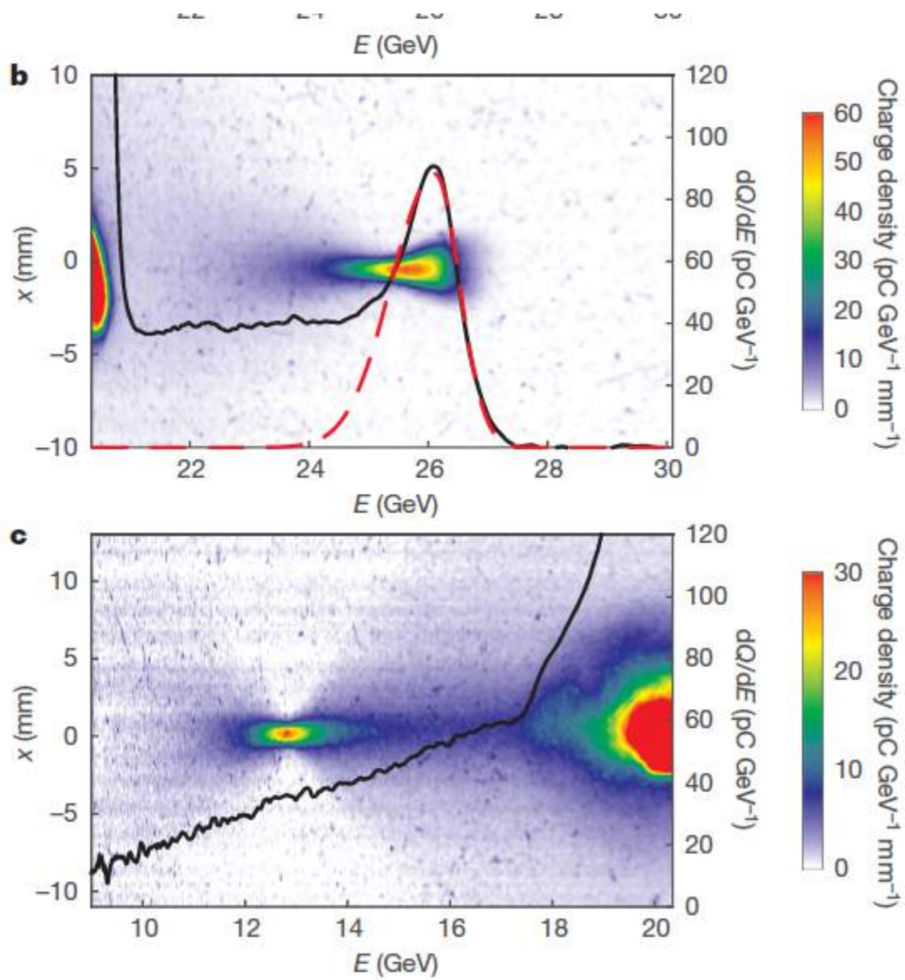


Litos, M. et al. *High-efficiency acceleration of an electron beam in a plasma wakefield accelerator*. **Nature** 515, 92–95 (2014).

doi:10.1038/nature14890

Multi-gigaelectronvolt acceleration of positrons in a self-loaded plasma wakefield

S. Corde[1,2], E. Adli[1,3], J. M. Allen[1], W. An[4,5], C. I. Clarke[1], C. E. Clayton[4], J. P. Delahaye[1], J. Frederico[1], S. Gessner[1], S. Z. Green[1], M. J. Hogan[1], C. Joshi[4], N. Lipkowitz[1], M. Litos[1], W. Lu[6], K. A. Marsh[4], W. B. Mori[4,5], M. Schmeltz[1], N. Vafaei-Najafabadi[4], D. Walz[1], V. Yakimenko[1] & G. Yocky[1]



CONCEPTUAL DESIGN OF THE DRIVE BEAM FOR A PWFA-LC*

S. Pei[#], M. J. Hogan, T. O. Raubenheimer, A. Seryi, SLAC, CA 94025, U.S.A.
H. H. Braun, R. Corsini, J. P. Delahaye, CERN, Geneva

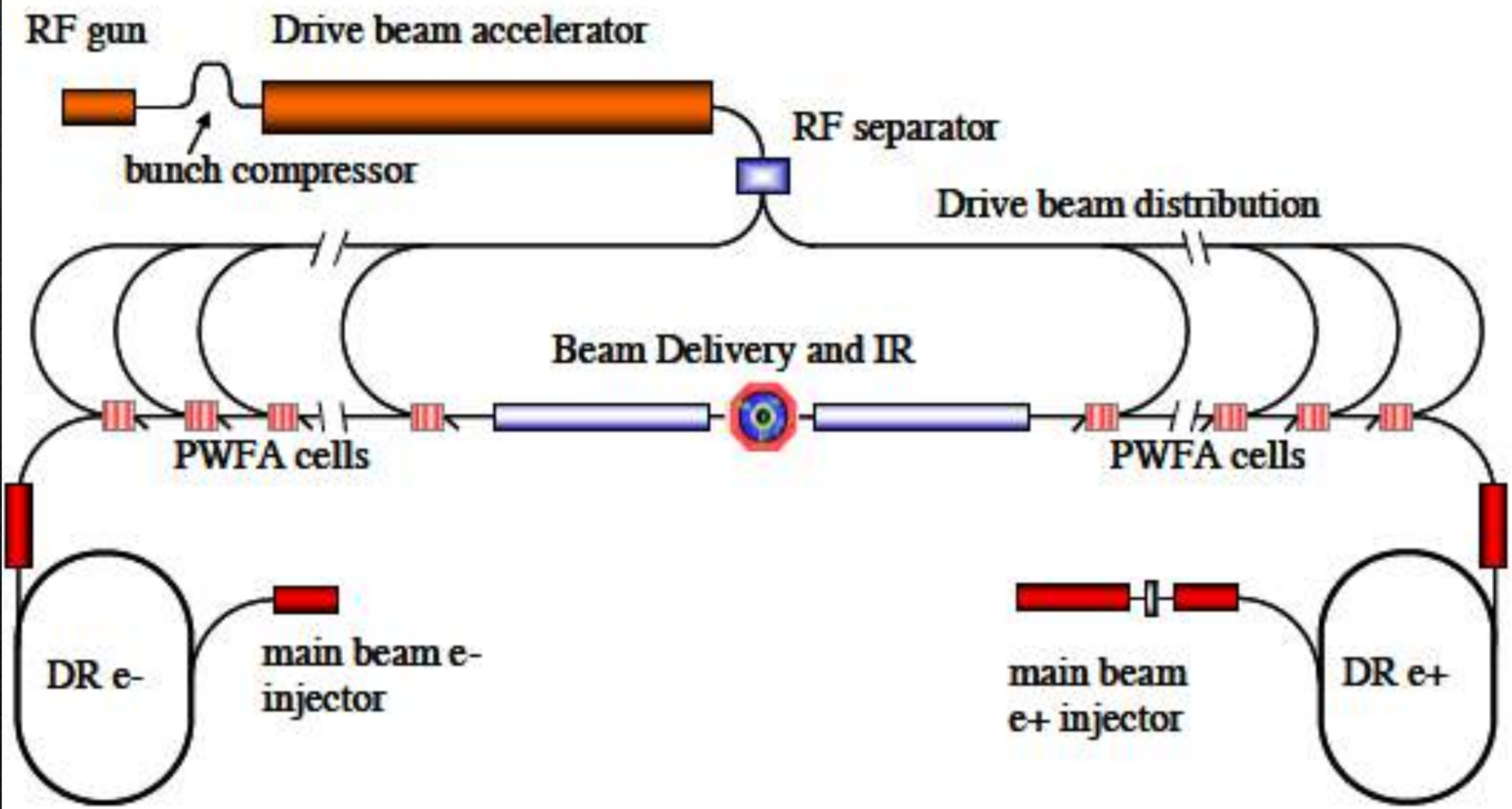


Fig. 1: Concept for a multi-stage PWFA Linear Collider.

Table 1: Key Parameters of the Conceptual Multi-Stage PWFA-based Linear Collider

Main beam: bunch population, bunches per train, rate	1×10^{10}, 125, 100 Hz
Total power of two main beams	20 MW
Drive beam: energy, peak current and active pulse length	25 GeV, 2.3 A, 10 μs
Average power of the drive beam	58 MW
Plasma density, accelerating gradient and plasma cell length	$1\times10^{17}cm^{-3}$, 25 GV/m, 1 m
Power transfer efficiency drive beam=>plasma =>main beam	35%
Efficiency: Wall plug=>RF=>drive beam	50% × 90% = 45%
Overall efficiency and wall plug power for acceleration	15.7%, 127 MW
Site power estimate (with 40MW for other subsystems)	170 MW
Main beam emittances, x, y	2, 0.05 mm-mrad
Main beam sizes at Interaction Point, x, y, z	0.14, 0.0032, 10 μm
Luminosity	3.5×10^{34} $cm^{-2}s^{-1}$
Luminosity in 1% of energy	1.3×10^{34} $cm^{-2}s^{-1}$

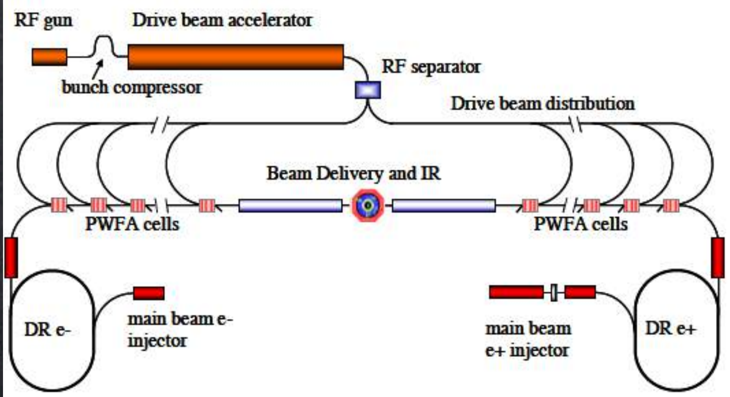


Fig. 1: Concept for a multi-stage PWFA Linear Collider.

MAX-PLANCK-GESELLSCHAFT

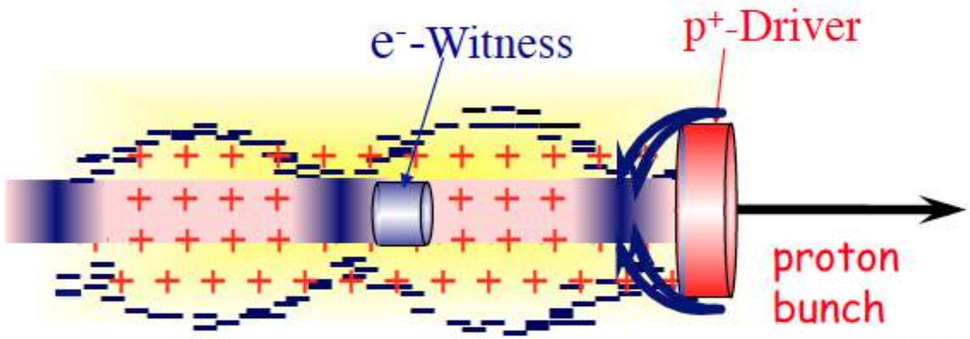
AWAKE

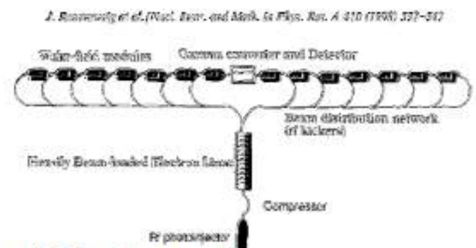
Proton-driven Plasma Wakefield Acceleration Collaboration: Accelerating e⁻ on the wake of a p⁺ bunch

MAX-PLANCK-GESELLSCHAFT

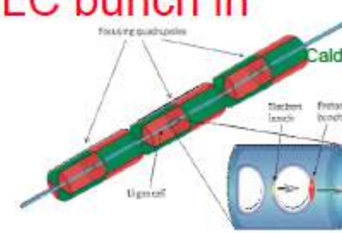
AWAKE

WHY p+-DRIVEN PWFA?





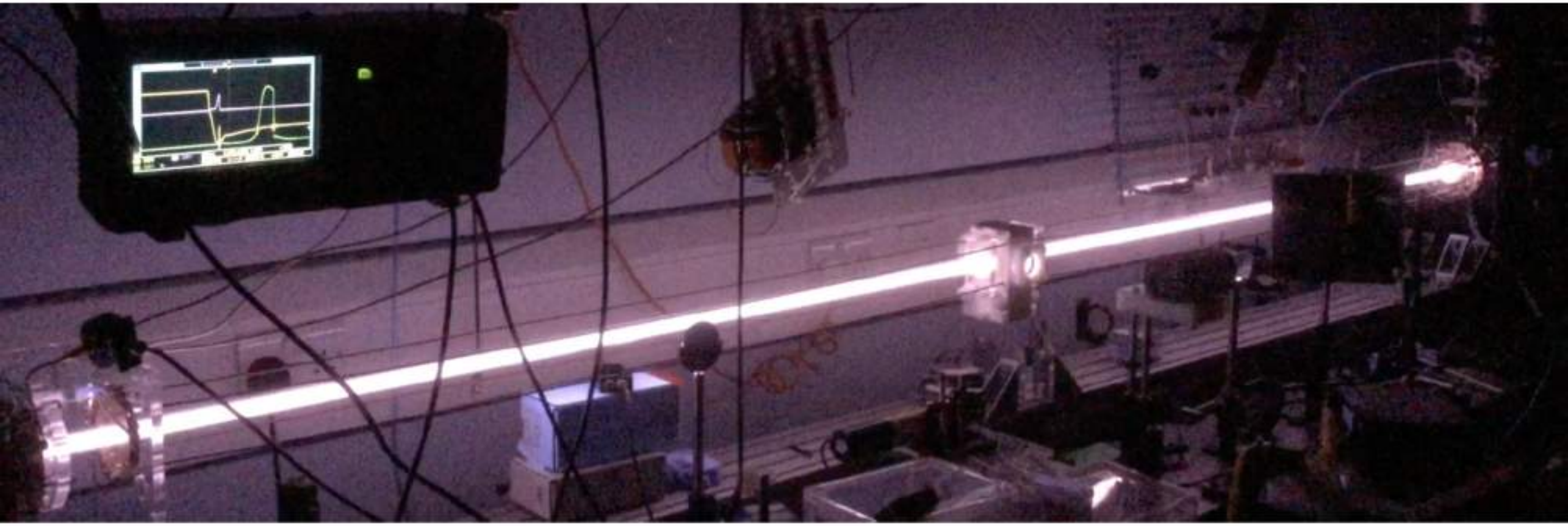
- ✧ILC, 0.5TeV bunch with $2\times10^{10}e^-$ ~1.6kJ
- ✧SLAC, 20GeV bunch with $2\times10^{10}e^-$ ~60J
- ✧SLAC-like driver for staging (FACET= 1 stage, collider 10^+ stages)
- ✧SPS, 400GeV bunch with $10^{11}p^+$ ~6.4kJ
  LHC, 7TeV bunch with $10^{11}p^+$ ~112kJ
- ✧A single SPS or LHC bunch could produce an ILC bunch in a single PWFA stage!
- ✧Large average gradient! (≥1GeV/m, 100's m)



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

Discharge configuration II

preliminary tests with the AWAKE 3 meter test tube at IC - 2016



very promising results

… reliable, low jitter plasma formation

scalability of electric circuit for plasmas > 10 m seem achievable…

EUROPEAN PLASMA RESEARCH ACCELERATOR WITH EXCELLENCE IN APPLICATIONS

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

Motivations

Horizon2020

PRESENT EXPERIMENTS

Demonstrating **100 GV/m** routinely

Demonstrating **GeV** electron beams

Demonstrating basic **quality**

EuPRAXIA INFRASTRUCTURE

Engineering a high quality, compact plasma accelerator

5 GeV electron beam for the 2020's

Demonstrating user readiness

Pilot users from FEL, HEP, medicine, ...

PRODUCTION FACILITIES

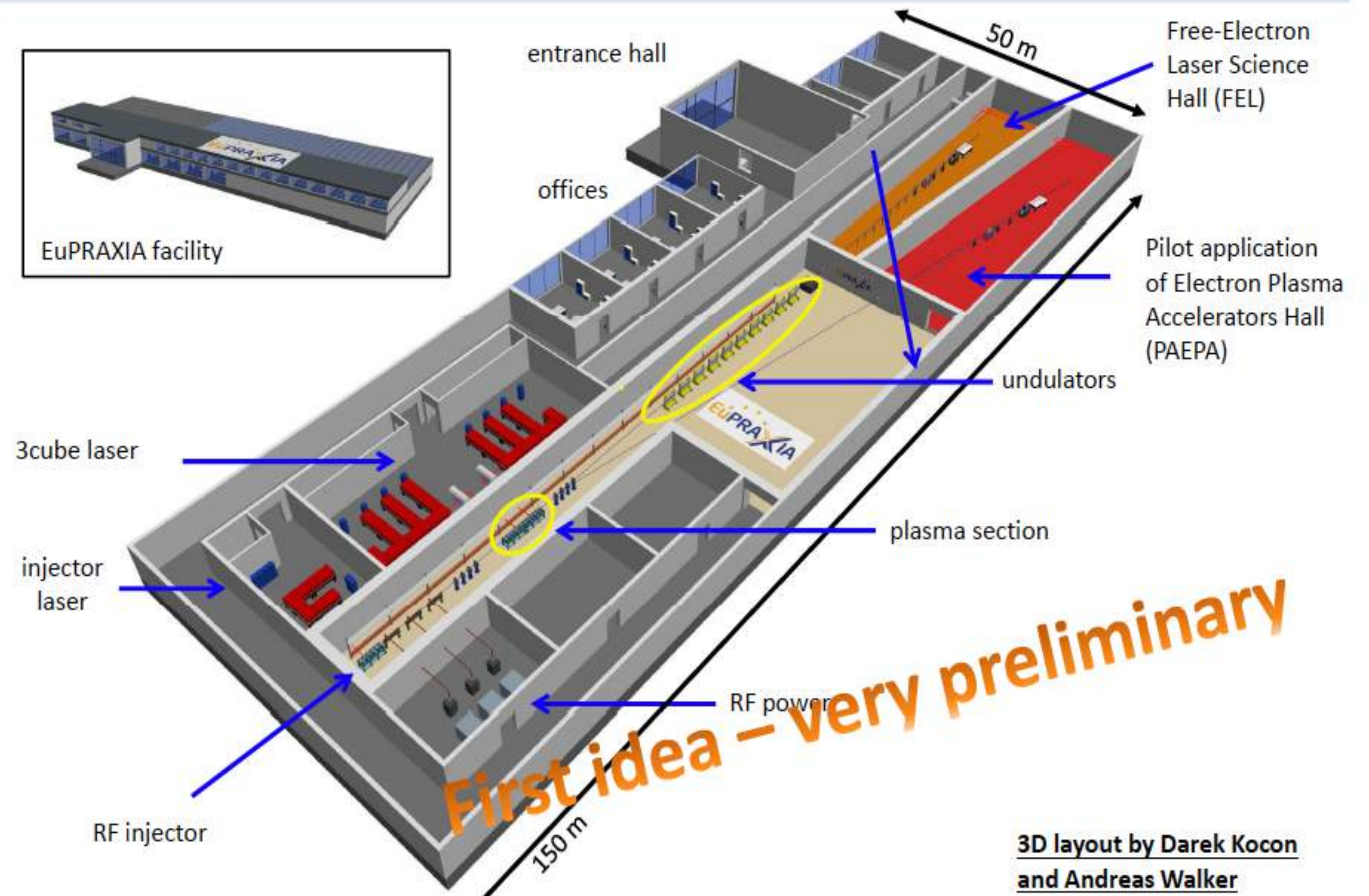
Plasma-based **linear collider** in 2040's

Plasma-based **FEL** in 2030's

Medical, industrial applications soon

Courtesy R. Assmann

EuPRAXIA Design Study
Approved as HORIZON 2020 INFRADEV, 4 years, 3 M€
Coordinator: Ralph Assmann (DESY)

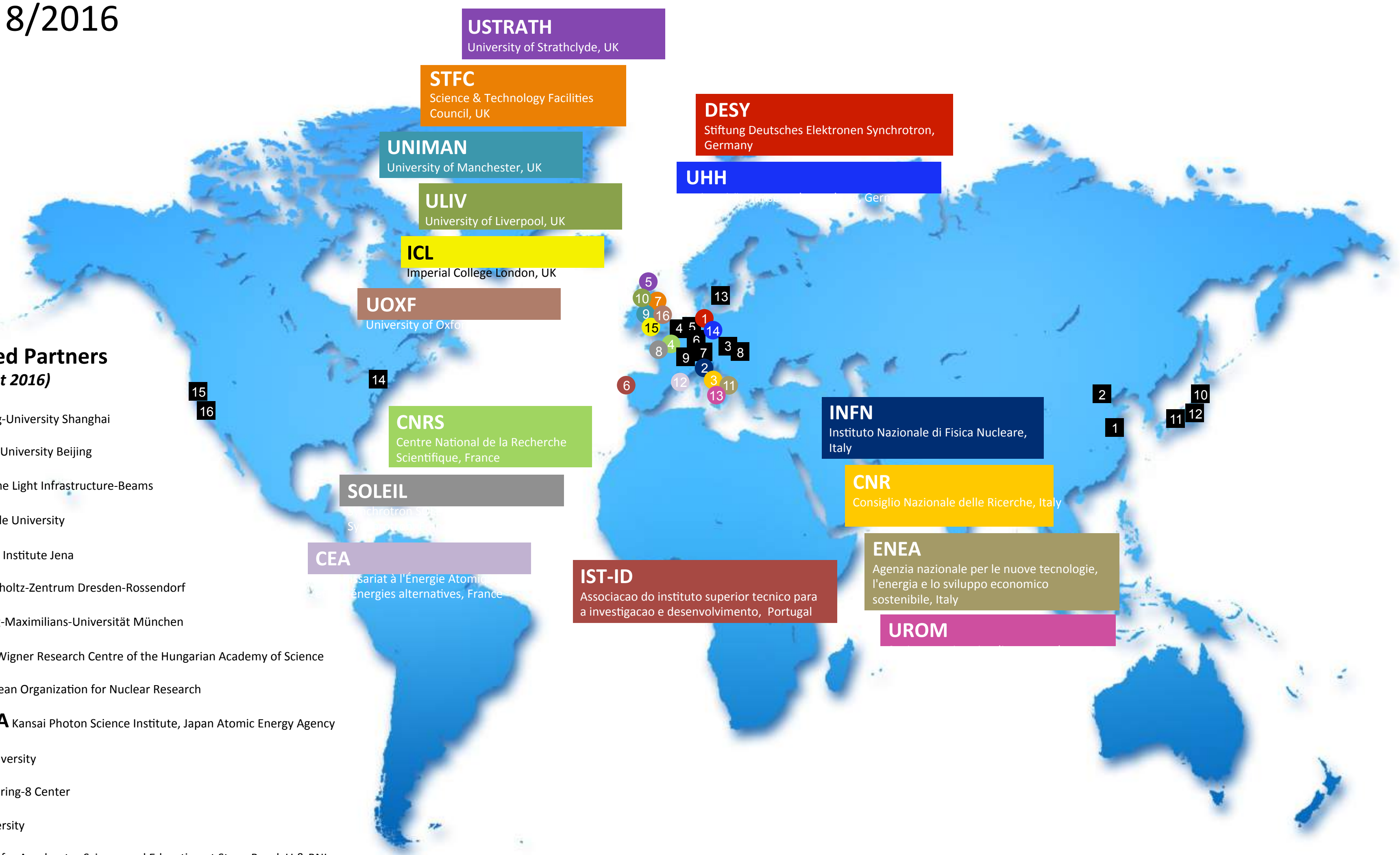


Participating Institutions

16 beneficiaries, 16 associated partners

Horizon2020

Status 8/2016

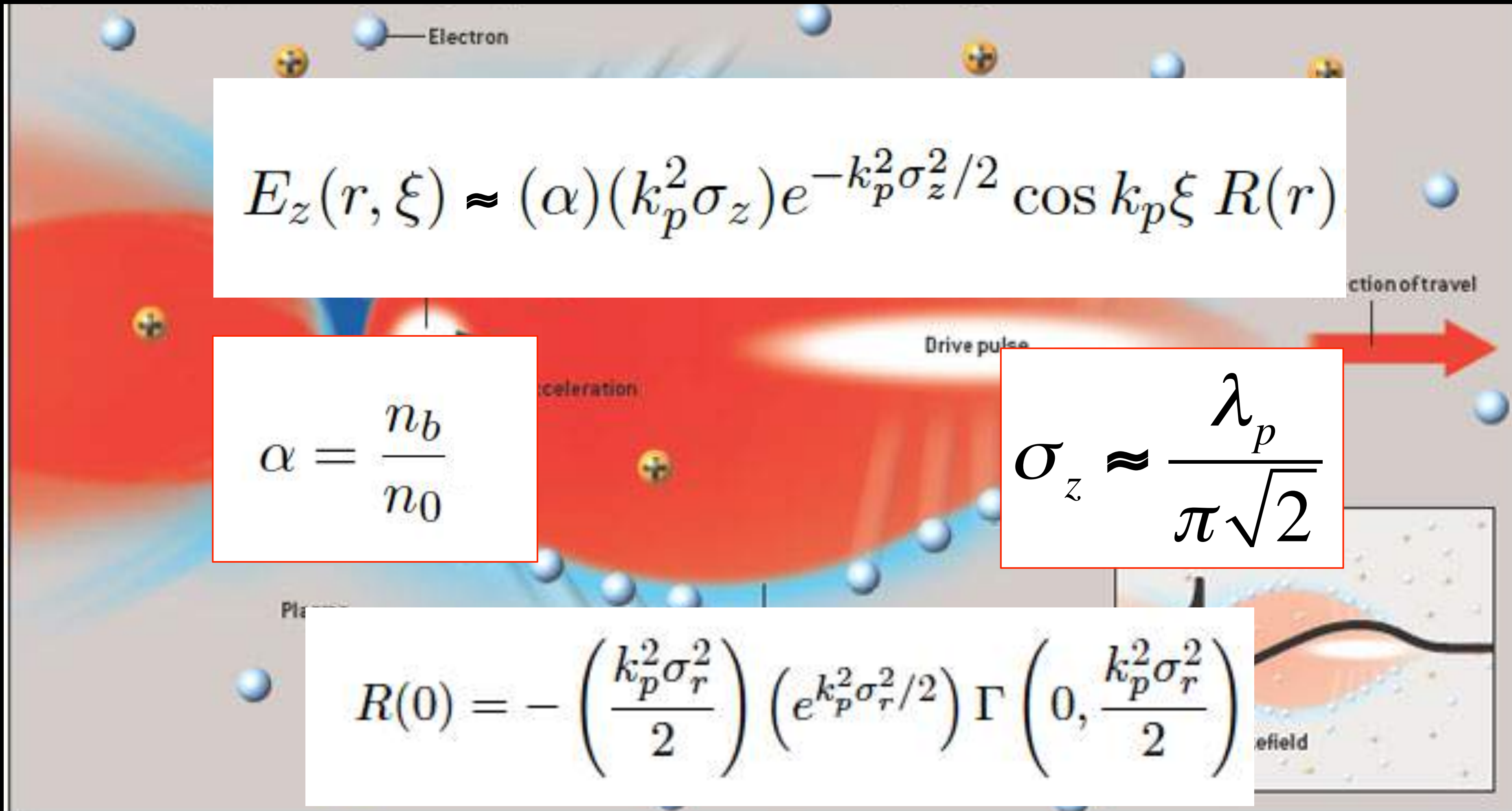


Associated Partners

(as of August 2016)

1. **JUS** Jiao Tong-University Shanghai
2. **TUB** Tsingua University Beijing
3. **ELI-B** Extreme Light Infrastructure-Beams
4. **PHLAM** Lille University
5. **HIJ** Helmholtz Institute Jena
6. **HZDR** Helmholtz-Zentrum Dresden-Rossendorf
7. **LMU** Ludwig-Maximilians-Universität München
8. **WIGNER** Wigner Research Centre of the Hungarian Academy of Science
9. **CERN** European Organization for Nuclear Research
10. **KPSI/JAEA** Kansai Photon Science Institute, Japan Atomic Energy Agency
11. **OU** Osaka University
12. **RSC** RIKEN SPring-8 Center
13. **LU** Lund University
14. **CASE** Center for Accelerator Science and Education at Stony Brook U & BNL
15. **LBNL** Lawrence Berkeley National Laboratory
16. **UCLA** University of California, Los Angeles

PWFA accelerating field



$$E_z(r,\xi) \approx (\alpha)(k_p^2\sigma_z)e^{-k_p^2\sigma_z^2/2}\cos k_p\xi\, R(r)$$

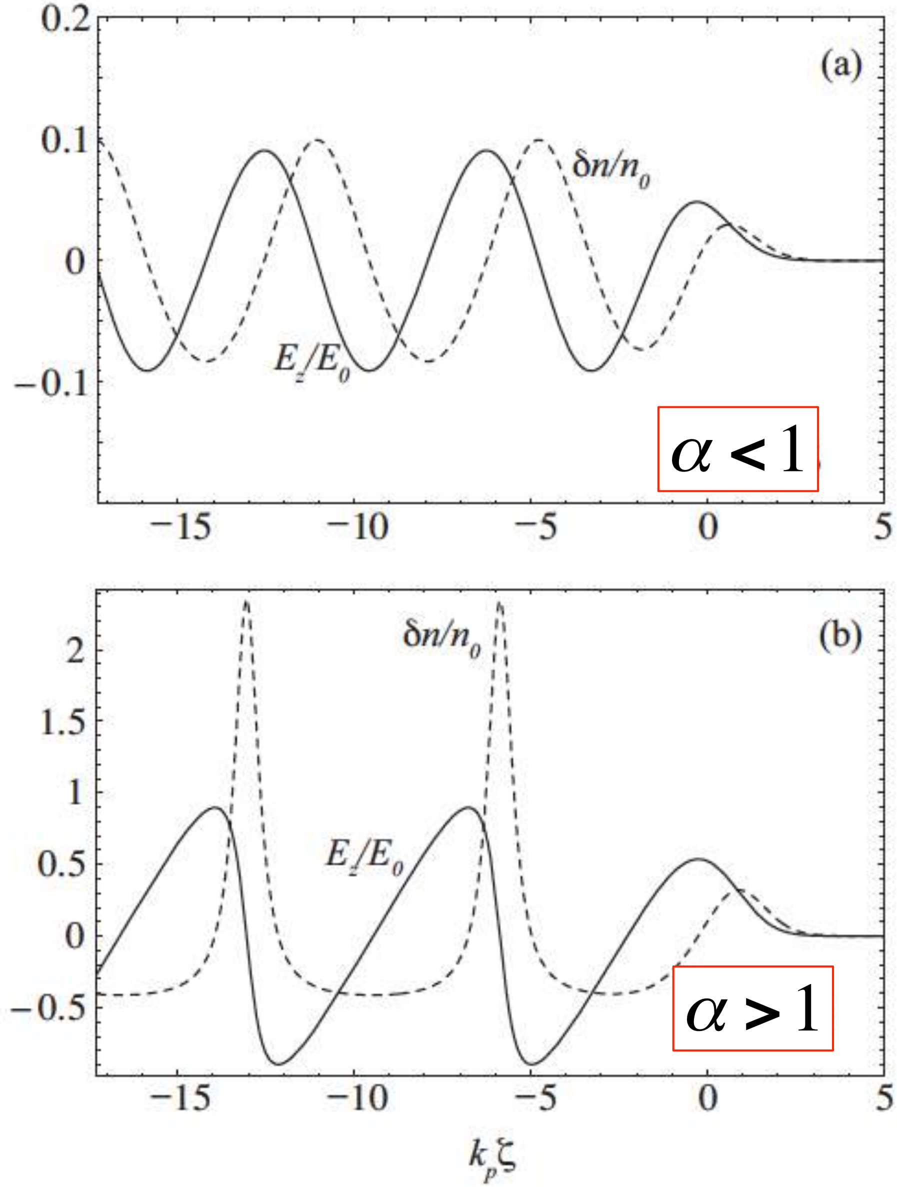
$$\alpha = \frac{n_b}{n_0}$$

$$\sigma_z \approx \frac{\lambda_p}{\pi\sqrt{2}}$$

$$R(0) = -\left(\frac{k_p^2\sigma_r^2}{2}\right)\left(e^{k_p^2\sigma_r^2/2}\right)\Gamma\left(0, \frac{k_p^2\sigma_r^2}{2}\right)$$

$$E_z \propto \frac{n_b}{n_o}\sigma_z\sigma_r^2 \propto Q$$

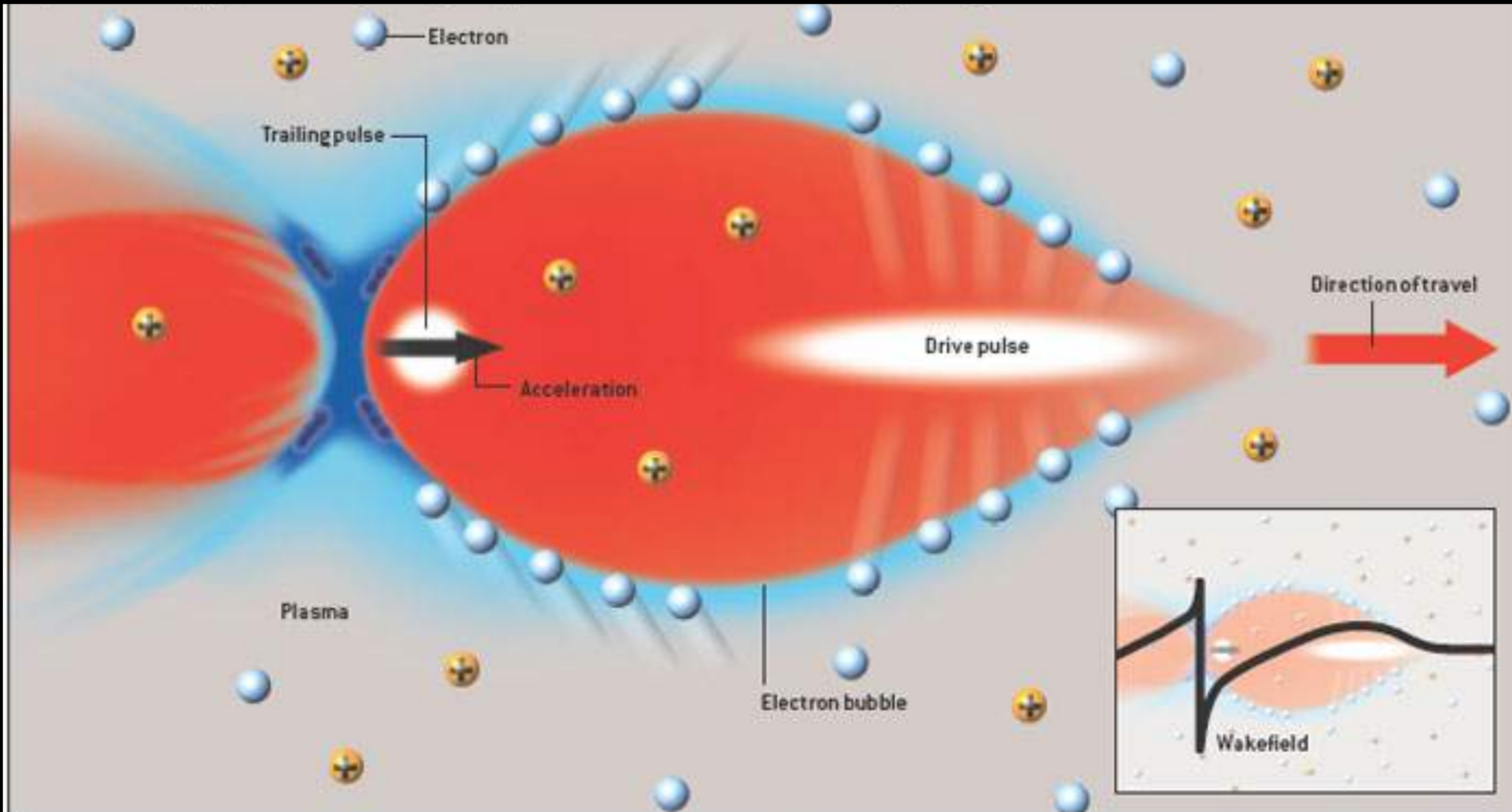
Regimes: Linear & Non-Linear



Linear

FIG. 8. Time-averaged density variation $\delta n/n_0$ (dashed curve) and axial electric field E_z/E_0 (solid curve) in an LWFA driven by a Gaussian laser pulse (pulse is moving to the right, centered at $k_p\zeta=0$ with rms intensity length $L_{\rm rms}=k_p^{-1}$) for (a) $a_0=0.5$ and (b) $a_0=2.0$.

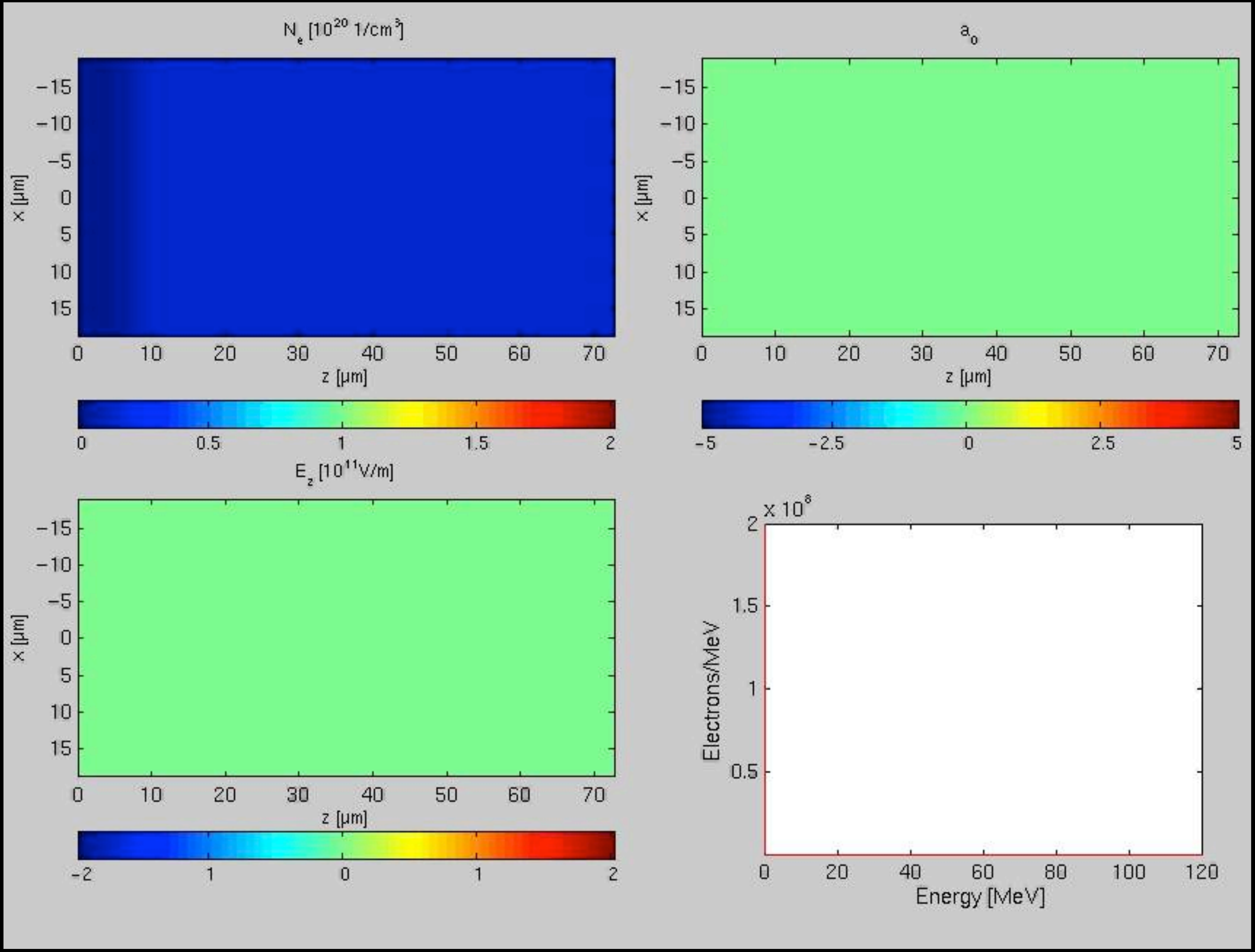
Non-Linear



Breakdown limit?

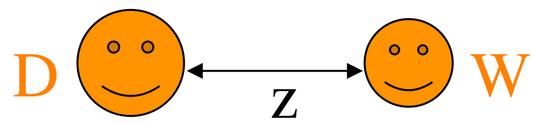
$$E_0 = \frac{m_e c \omega_p}{e} \approx 100[\frac{GeV}{m}] \cdot \sqrt{n_0[10^{18} cm^{-3}]}$$

Self-injection



External-injection

Wilson theorem for collinear wake field acceleration



Energy lost by an infinitely short bunch: $U_d = -q_d^2 w_{//}(0)$

Energy change of the second bunch $U_w = -q_w^2 w_{//}(0) + q_d q_w w_{//}(z_w)$

The sum of the energy exchange by the two bunches must be smaller or equal to zero:

$$U_d + U_w = -q_d^2 w_{//}(0) - q_w^2 w_{//}(0) + q_d q_w w_{//}(z_w) \leq 0$$

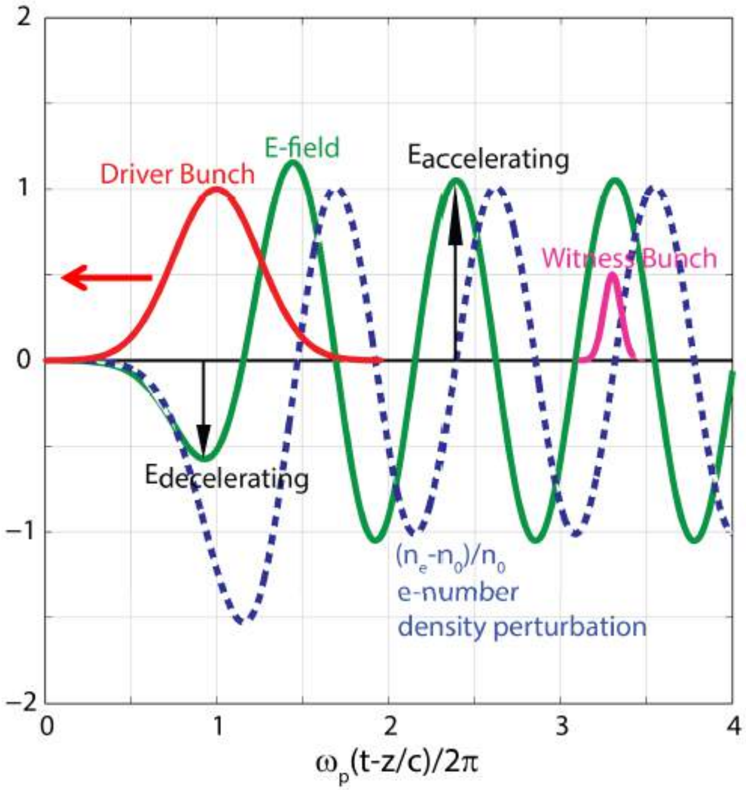
$$w_{//}(z_w) \leq \frac{q_d^2 + q_w^2}{q_d q_w} w_{//}(0)$$

This relation has to be true for all values of charges (the w-potential doesn't depend on q), also when $q_d = q_w$ which minimize the r.h.s, we obtain:

$$w_{//}(z_w) \leq 2 w_{//}(0)$$

The transformer ratio R_T is a figure of merit of the accelerating field.

According to previous discussion is defined as the ratio between the peak accelerating field behind drive bunch and the peak decelerating field within drive bunch:



$$R_T = \frac{E_+}{E_-}$$

$$R_T \leq 2$$

Beam loading

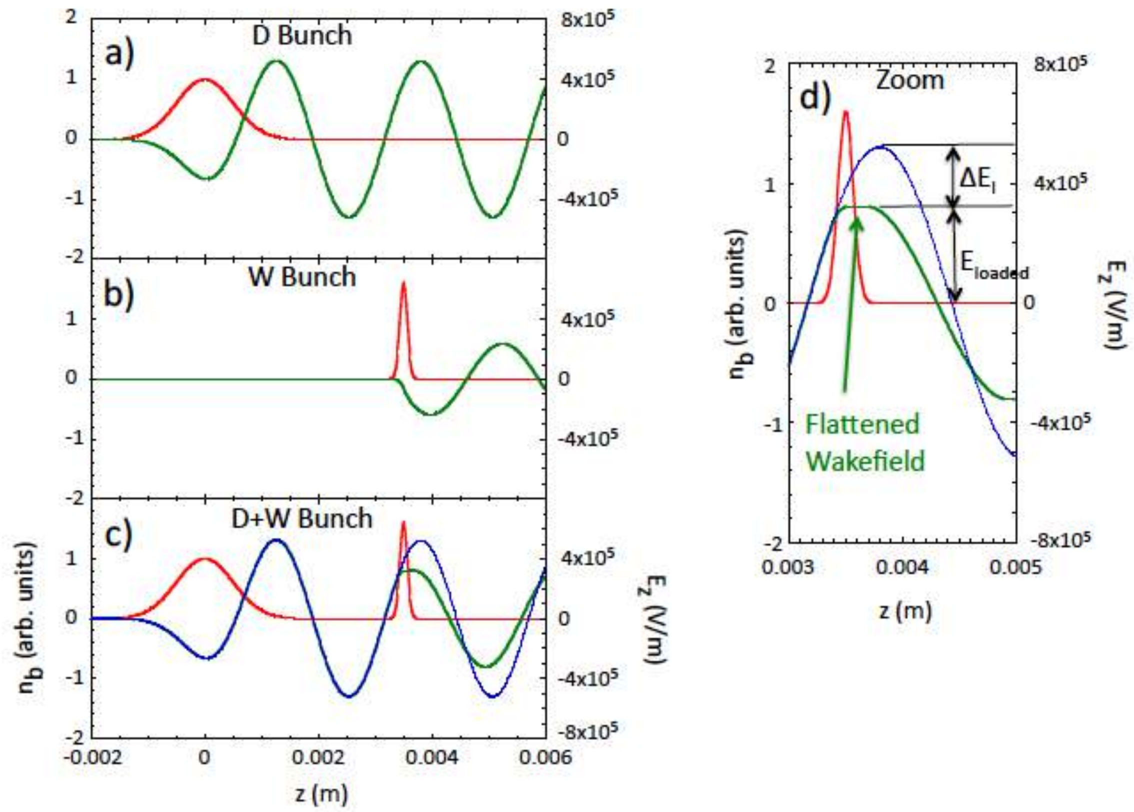


Fig. 5: Linear beam loading example: (a) drive bunch density profile (red line) and longitudinal wakefield E_z (green line), (b) same for the witness bunch, (c) same for the drive and witness bunches together. The field of the drive bunch only is shown as the blue line in panel (c). A zoom around the witness bunch is shown in panel (d). The bunches move to the left.

Energy gain and efficiency

Assuming R_T=2 and that the Driver will loose all its energy in the plasma, the active length can be defined as:

$$\Delta T_d = eE_- L_{act} \qquad L_{act} = \frac{\Delta T_d}{eE_-} = \frac{2\Delta T_d}{eE_+}$$

The Witness energy gain is:

$$\Delta T_w = eL_{act}E_+ - eL_{act}E_-^w$$

Where the second term on the r.h.s is the energy lost in the plasma by the witness itself.

Substituting the definition of L_{act}, and using the field scaling $E_z \propto Q$ w.r.t the charge it results:

$$\Delta T_w = 2\left(1 - \frac{E_+^w}{2E_+}\right)\Delta T = \left(2 - \frac{q_w}{Q_d}\right)\Delta T_d$$

And the efficiency of the process is given by:

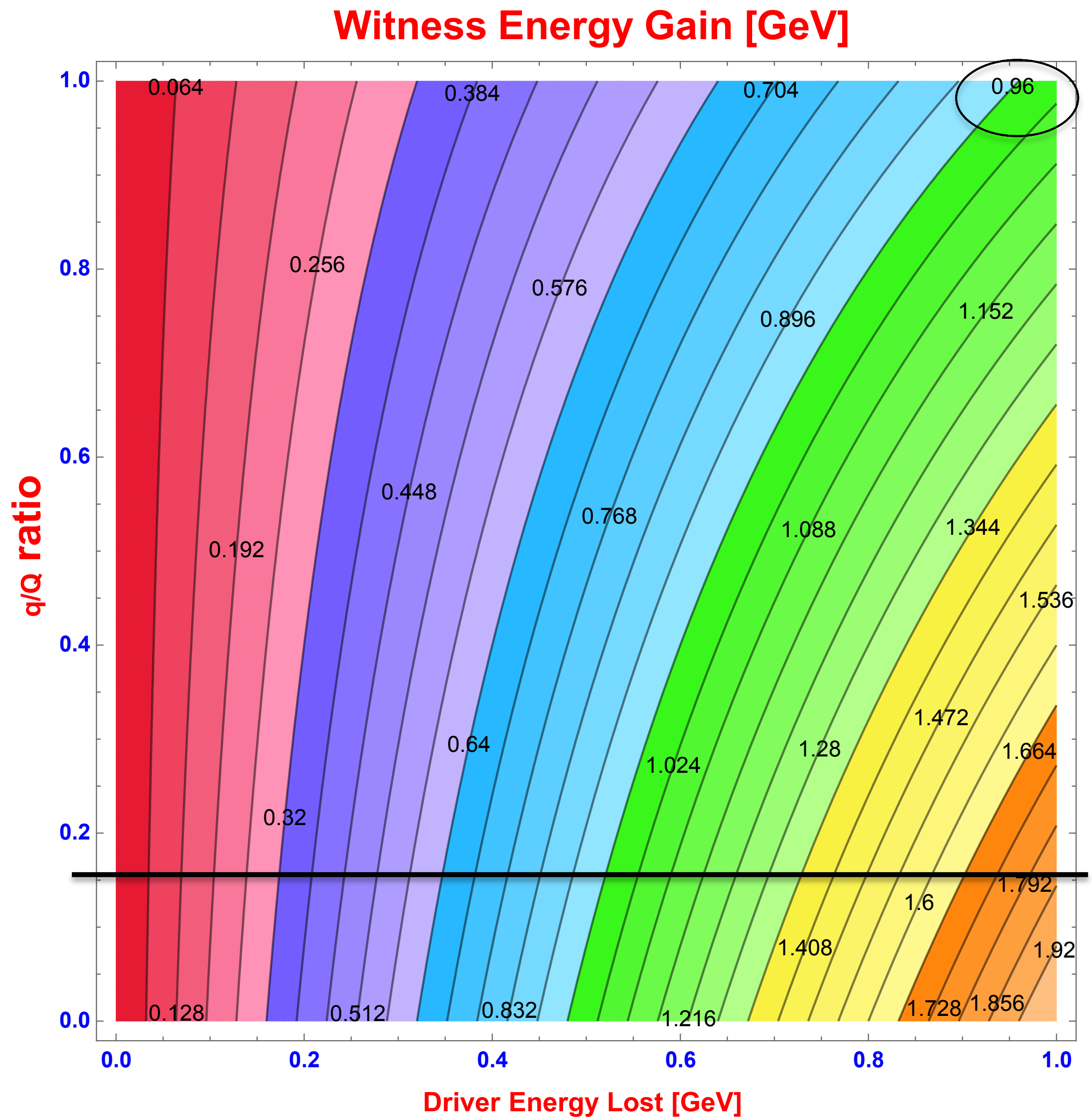
$$\eta = \frac{q_w \Delta T_w}{Q_d \Delta T_d} = \left(2 - \frac{q_w}{Q_d}\right)\frac{q_w}{Q_d}$$

$$\Delta T_w \propto \left(2 - \frac{q}{Q}\right)\Delta T_d$$

q=30 pC

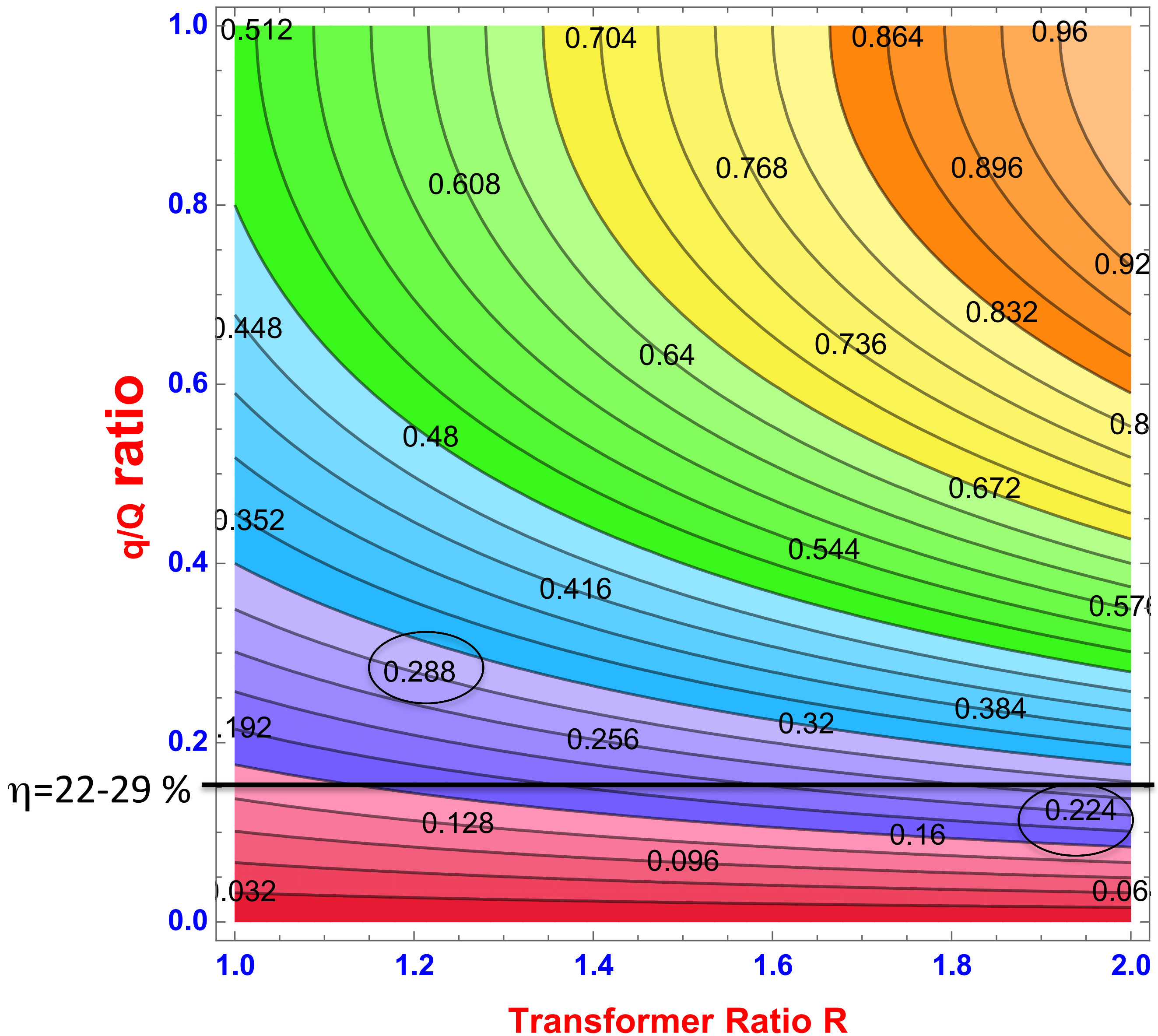
Q=200 pC

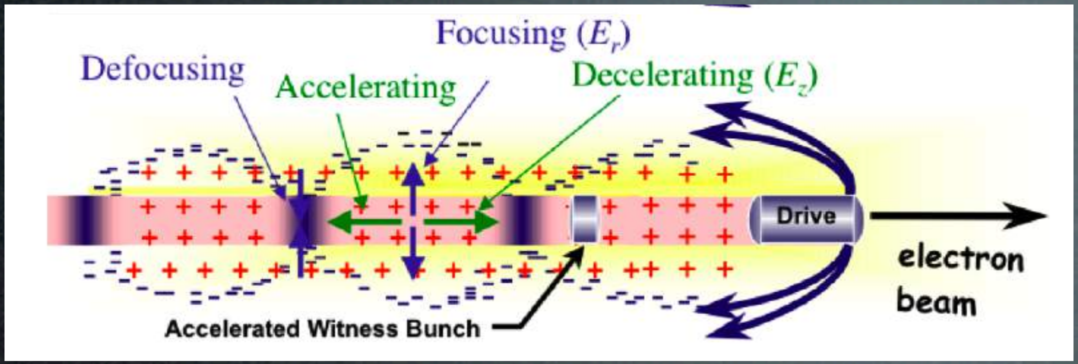
q/Q=0.15

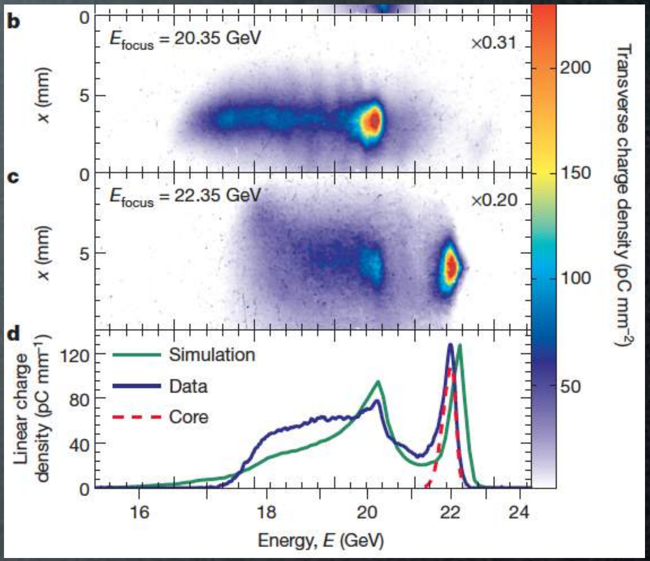


$$\eta = \frac{\Delta U_w}{\Delta U_d} = R\left(1 - \frac{q}{2Q}\right)\frac{q}{Q}$$

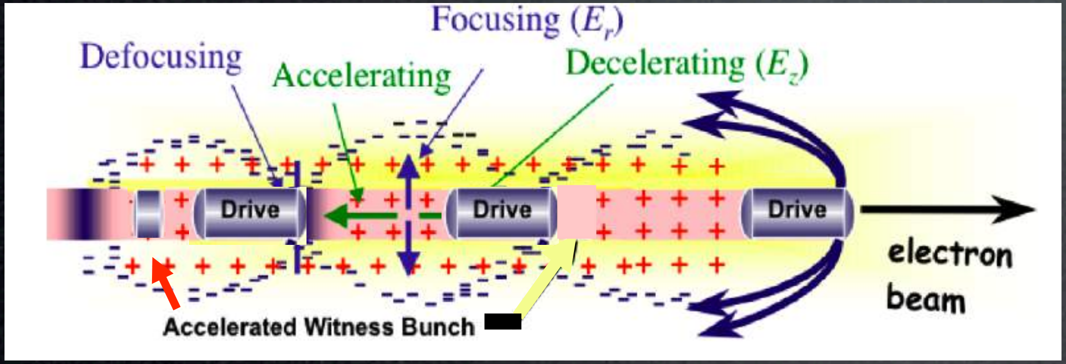
Energy Transfer Efficiency

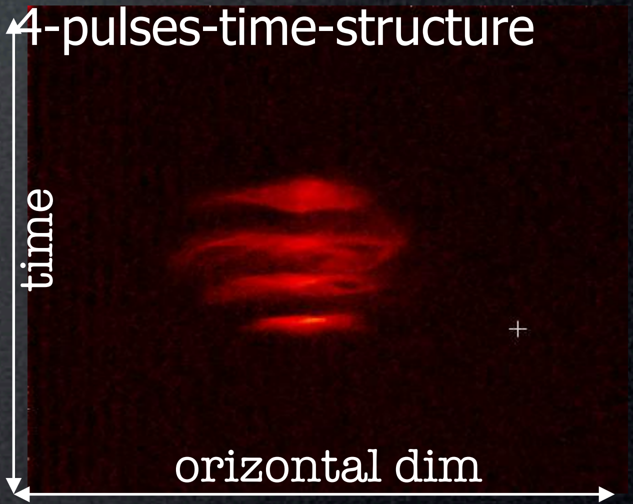






Litos, M. et al. *High-efficiency acceleration of an electron beamin a plasma wakefield accelerator*. **Nature** 515, 92–95 (2014).





In progress at SPARC_LAB

MULTIBUNCH PWFA

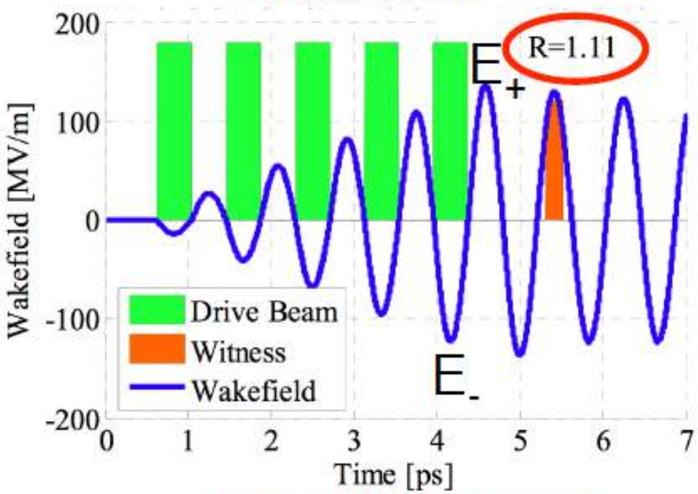
Transformer Ratio: $R = E_+/E_-$ Energy Gain: $\leq RE_0$

σ_r=125 μm, n_e=1.8x10^{16} cm^{-3}, λ_p=250 μm

E_0: incoming energy

Q=30 pC/bunch, Δz=250 μm≈λ_p

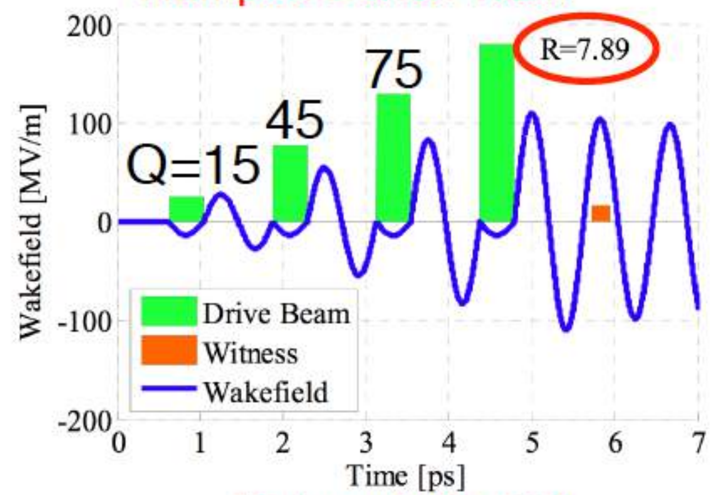
Bunch Train



Kallos, PAC'07 Proceedings

Δz=375 μm≈1.5λ_p

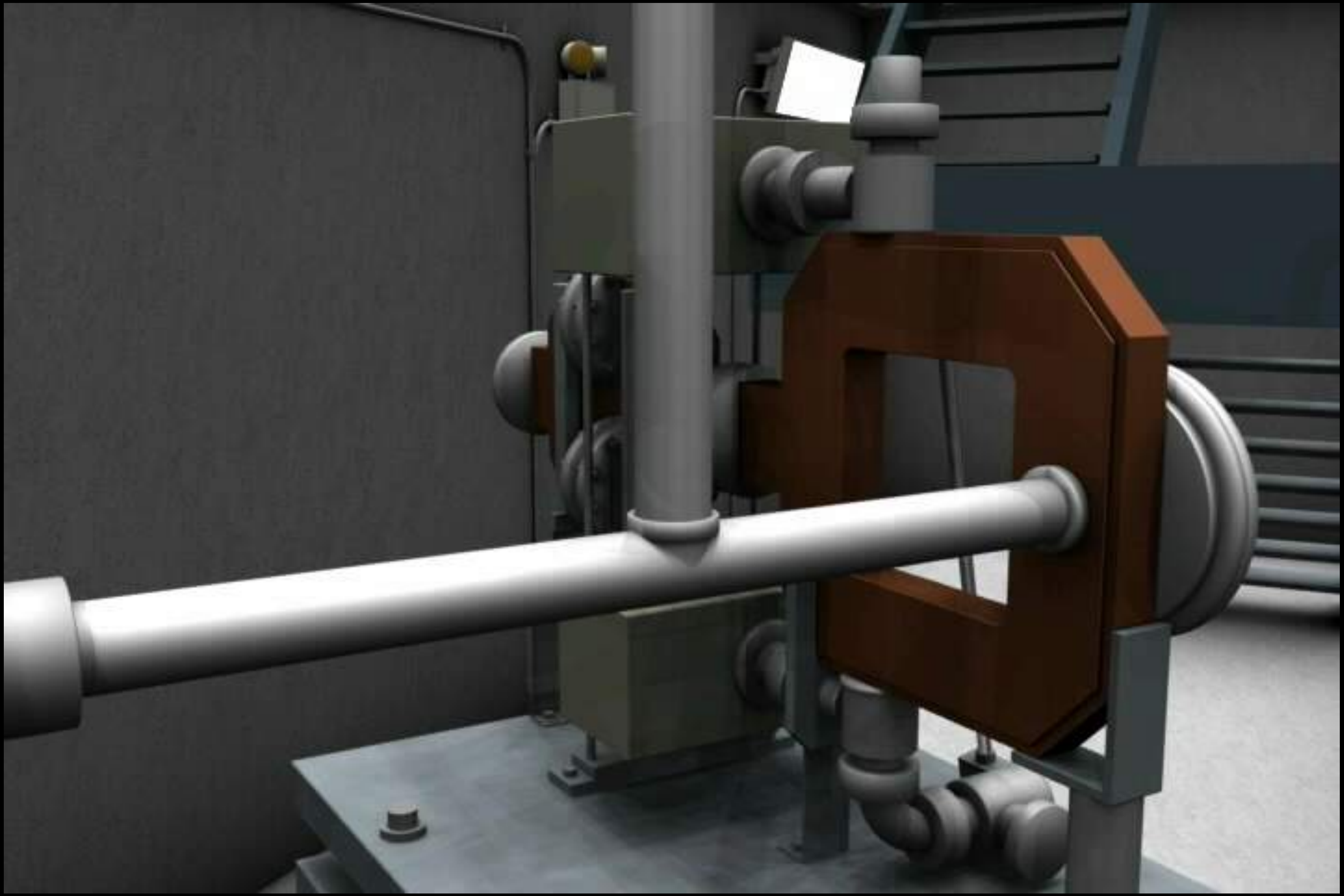
Ramped Bunch Train*



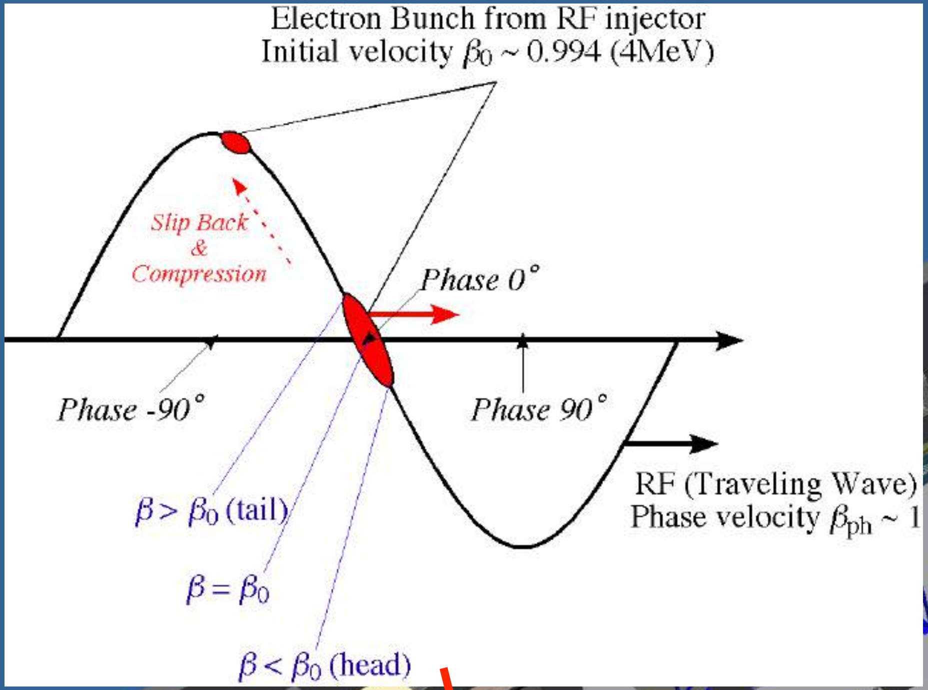
*Tsakanov, NIMA, 1999

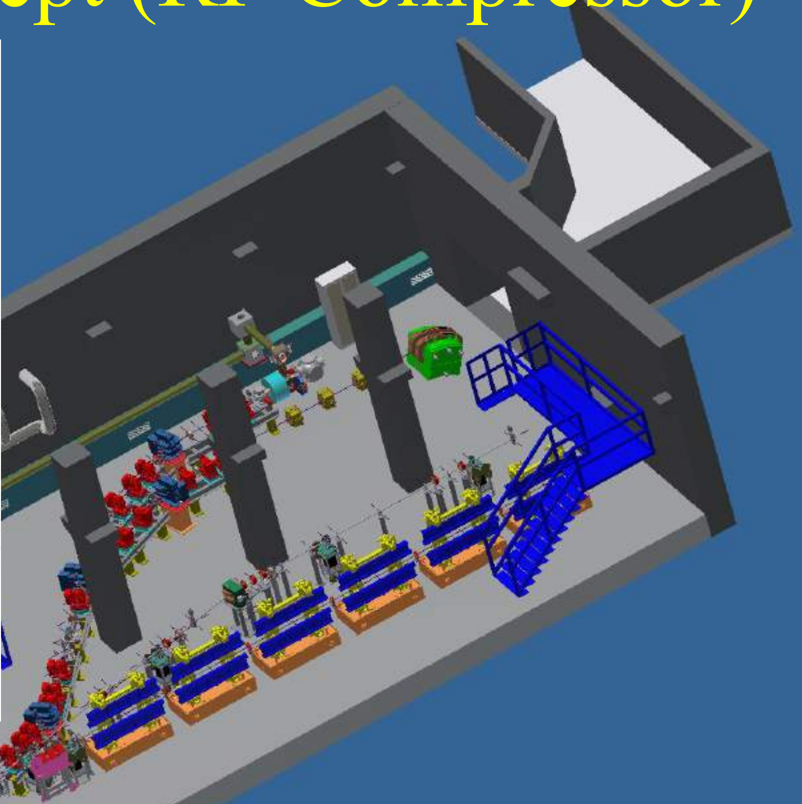
- Linear (2D) theory for n_b<<n_e!
- R=7.9 => multiply energy by ~8 in a single PWFA stage!

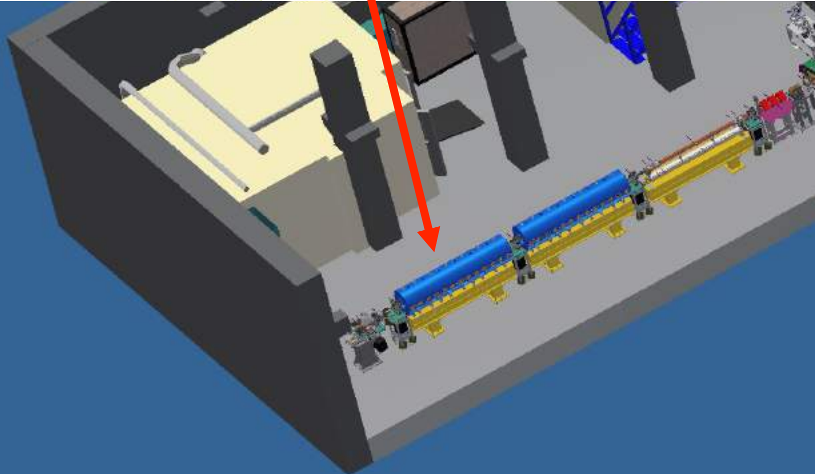
High Brightness Photo-Injector



Velocity bunching concept (RF Compressor)







If the beam injected in a long accelerating structure at the crossing field phase and it is slightly slower than the phase velocity of the RF wave , it will slip back to phases where the field is accelerating, but at the same time it will be chirped and compressed.

Laser Comb technique: generation of a train of short bunches

(Parmela code)

Charge vs. Time

Energy vs. Time

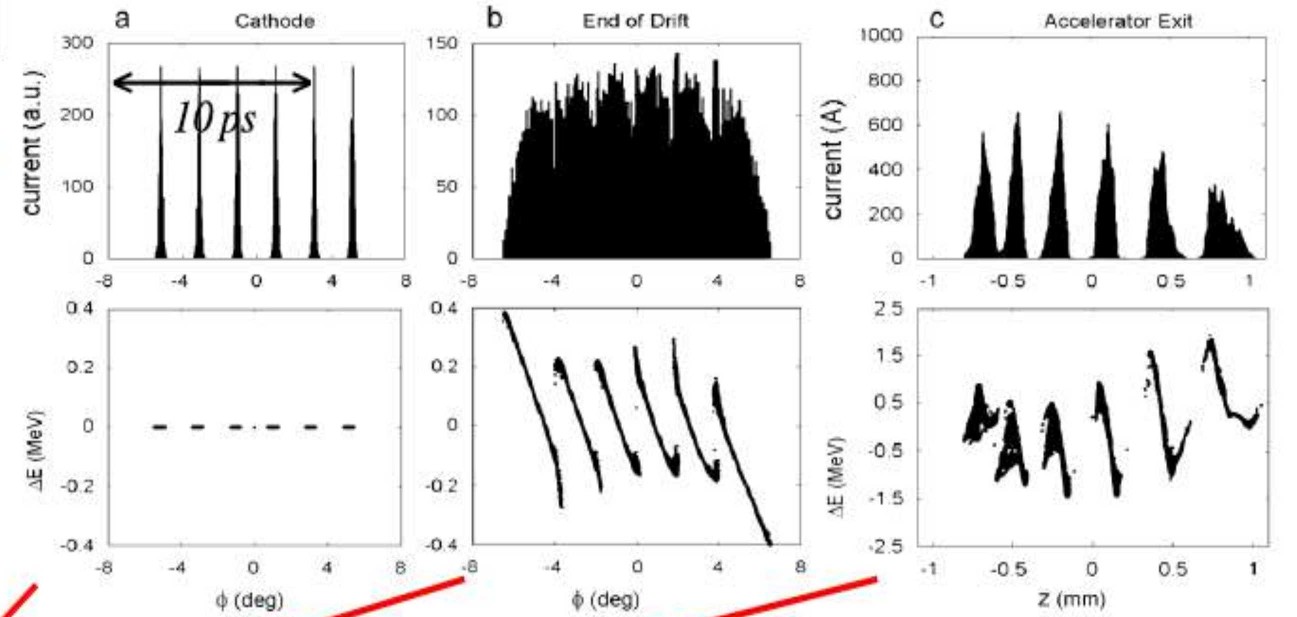
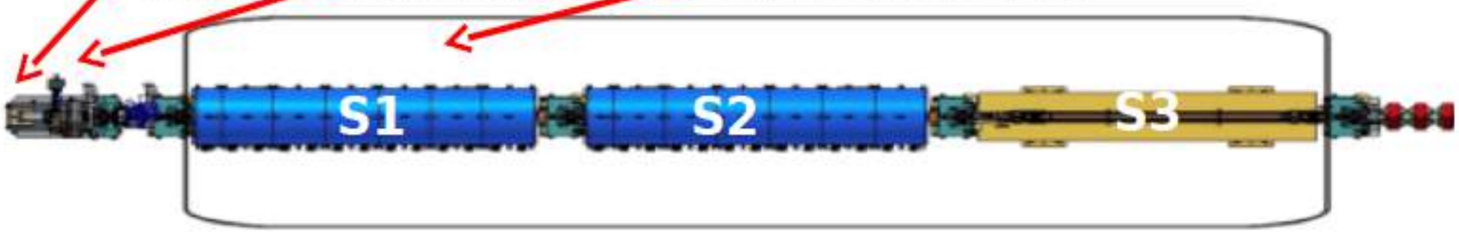
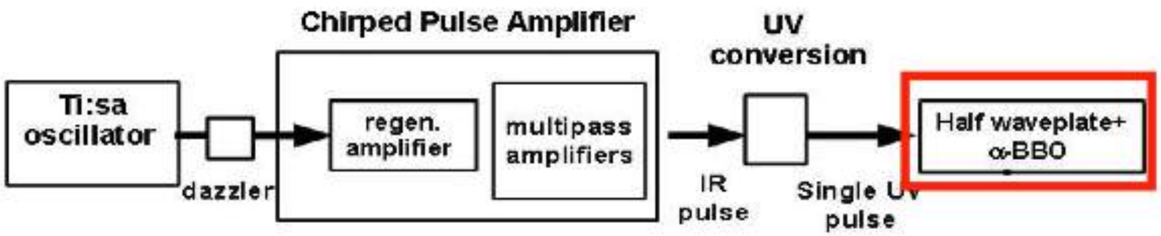


Fig. 1. Evolution of a six bunches electron beam train: the columns from left refer, respectively, to (a) the cathode, (b) the end of the drift at 150 cm and (c) the end of linac at 12 m far from cathode. The rows from top refer, respectively, to longitudinal profile and to energy modulation ΔE (MeV).

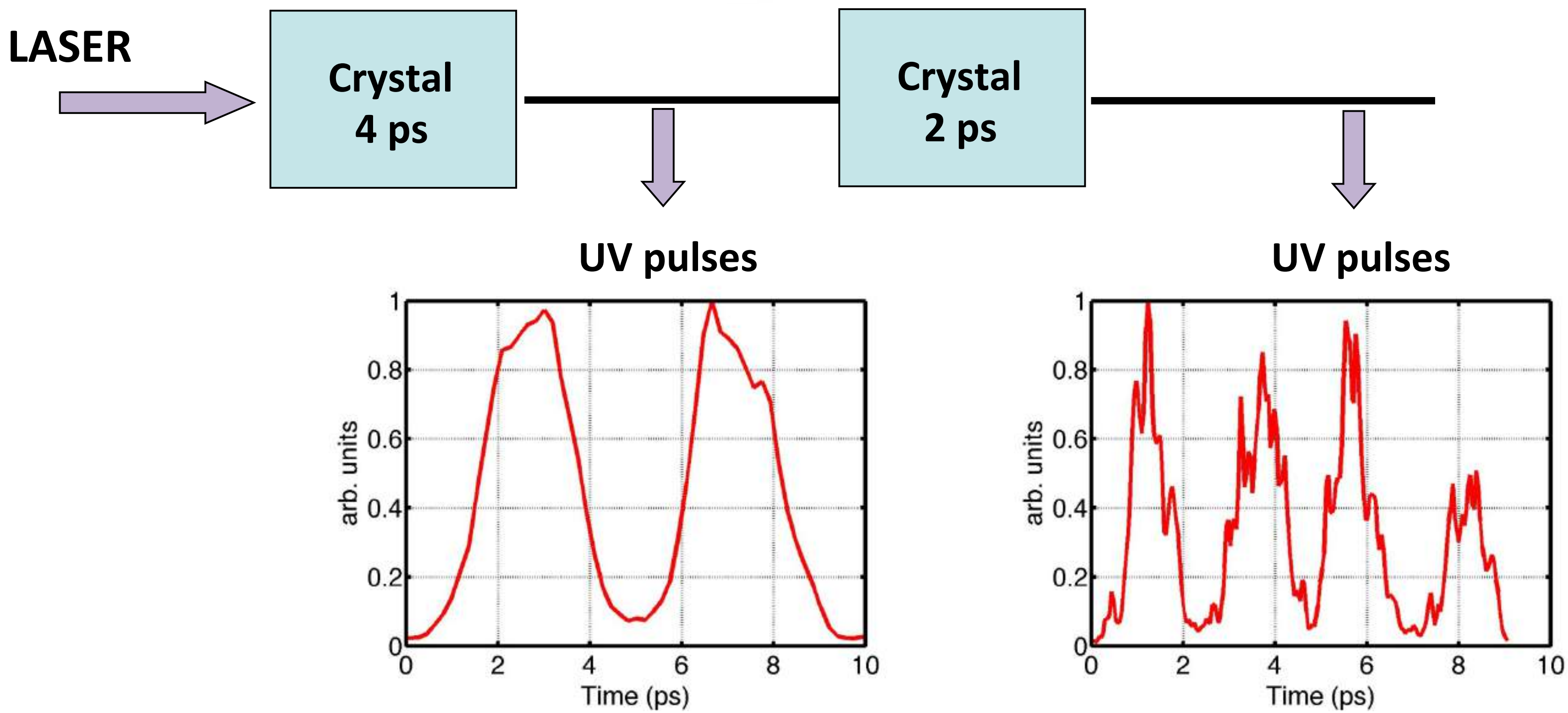


- P.O.Shea et al., Proc. of 2001 IEEE PAC, Chicago, USA (2001) p.704. (Low charge regime only)
- M. Ferrario. M. Boscolo et al., Int. J. of Mod. Phys. B, 2006 (High charge, Beam Echo)

Laser Pulse Train Generation



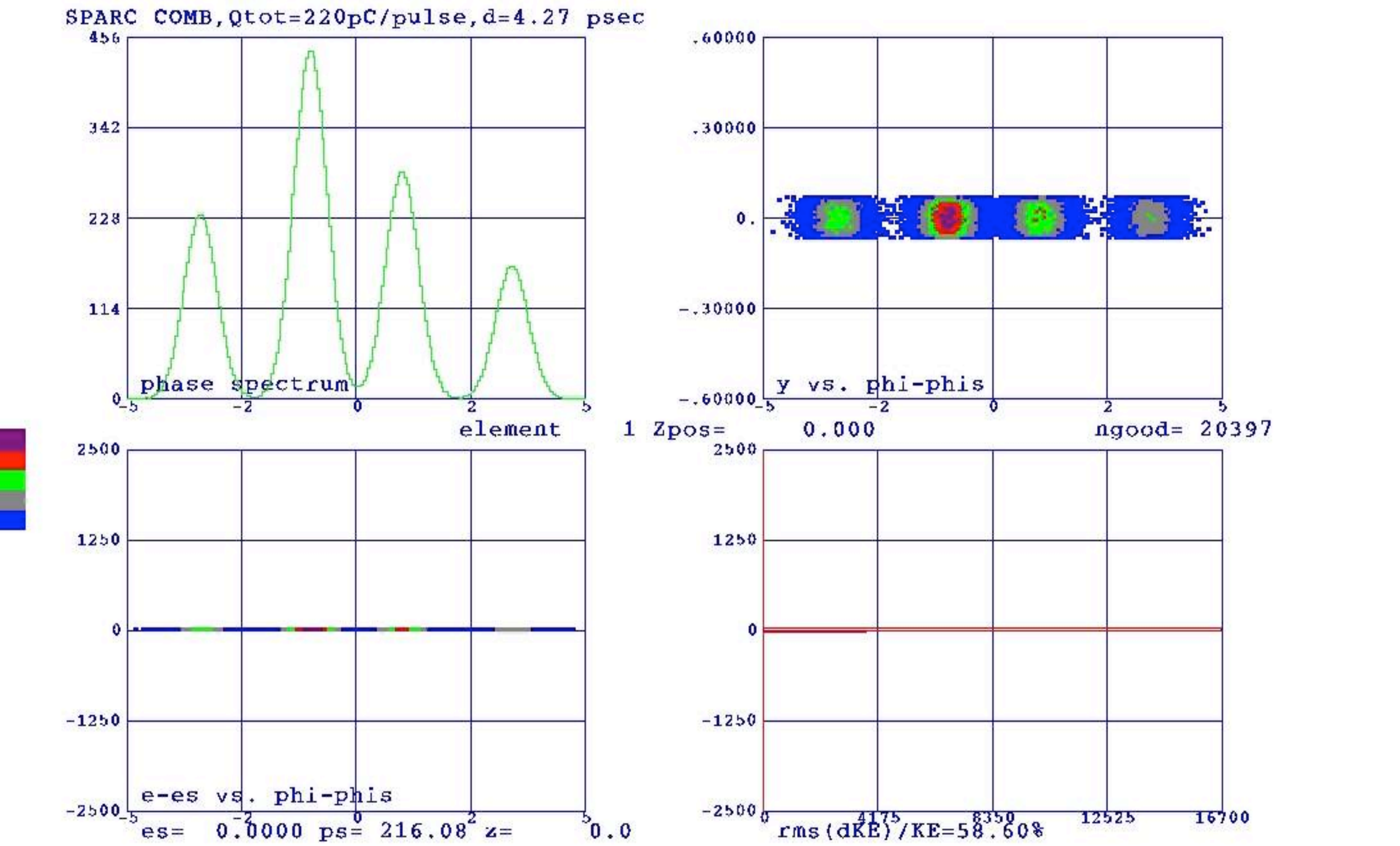
$$\Delta\tau = \left| \frac{1}{v_{ge}} - \frac{1}{v_{go}} \right| L_{crystal}$$



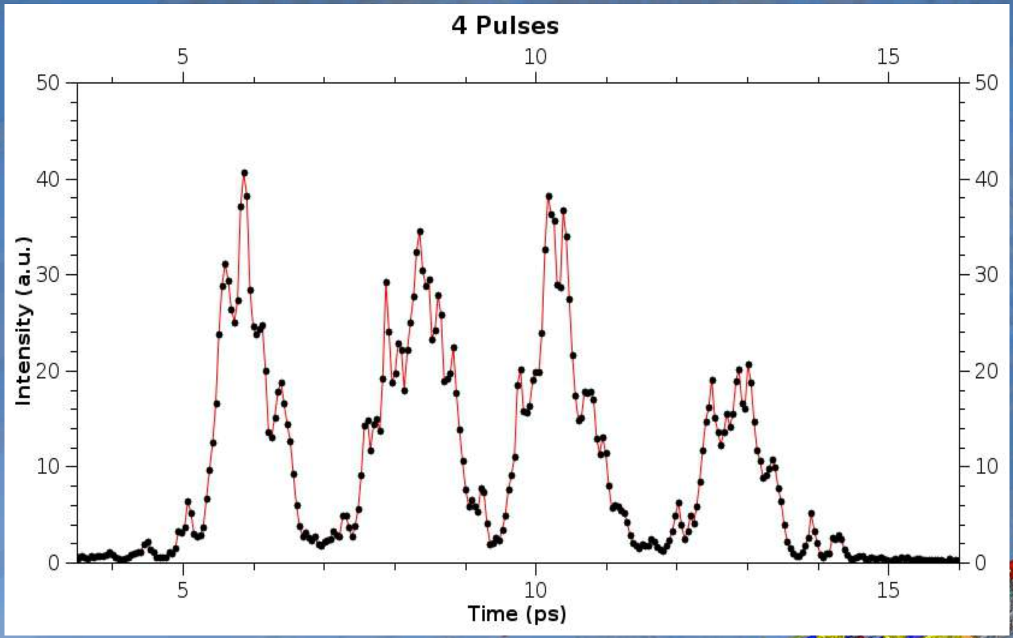
Streak camera

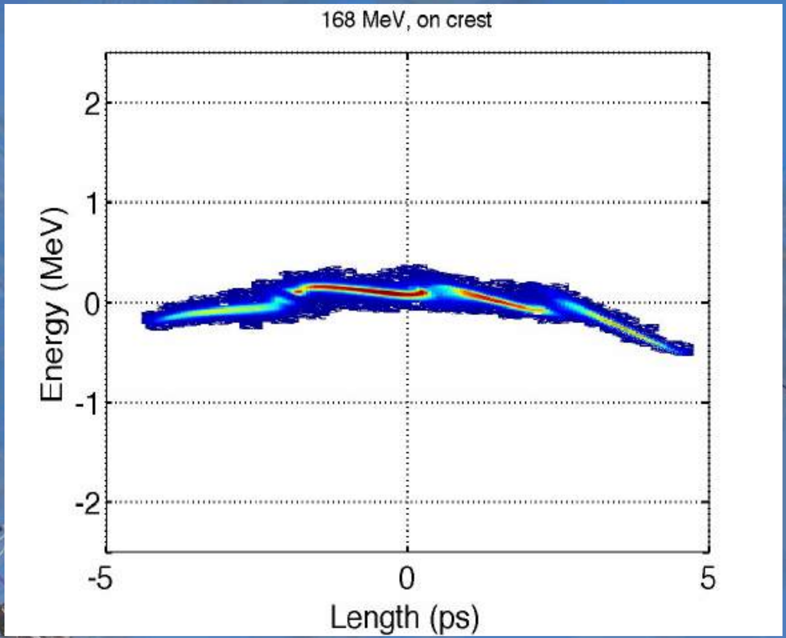
Streak camera

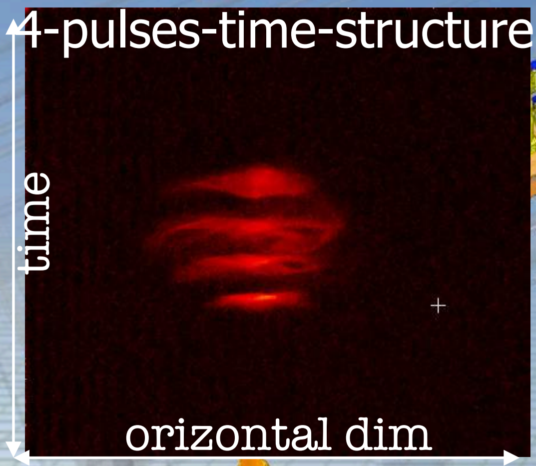
Overcompression

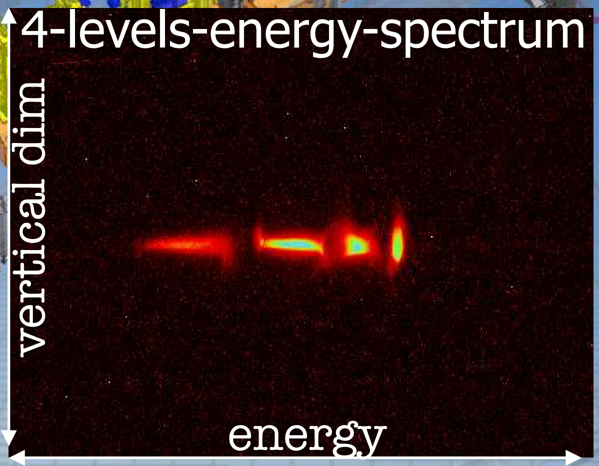


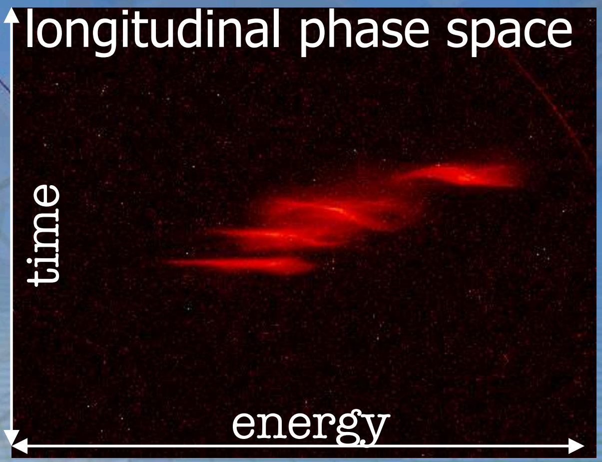
Laser COMB: experimental results





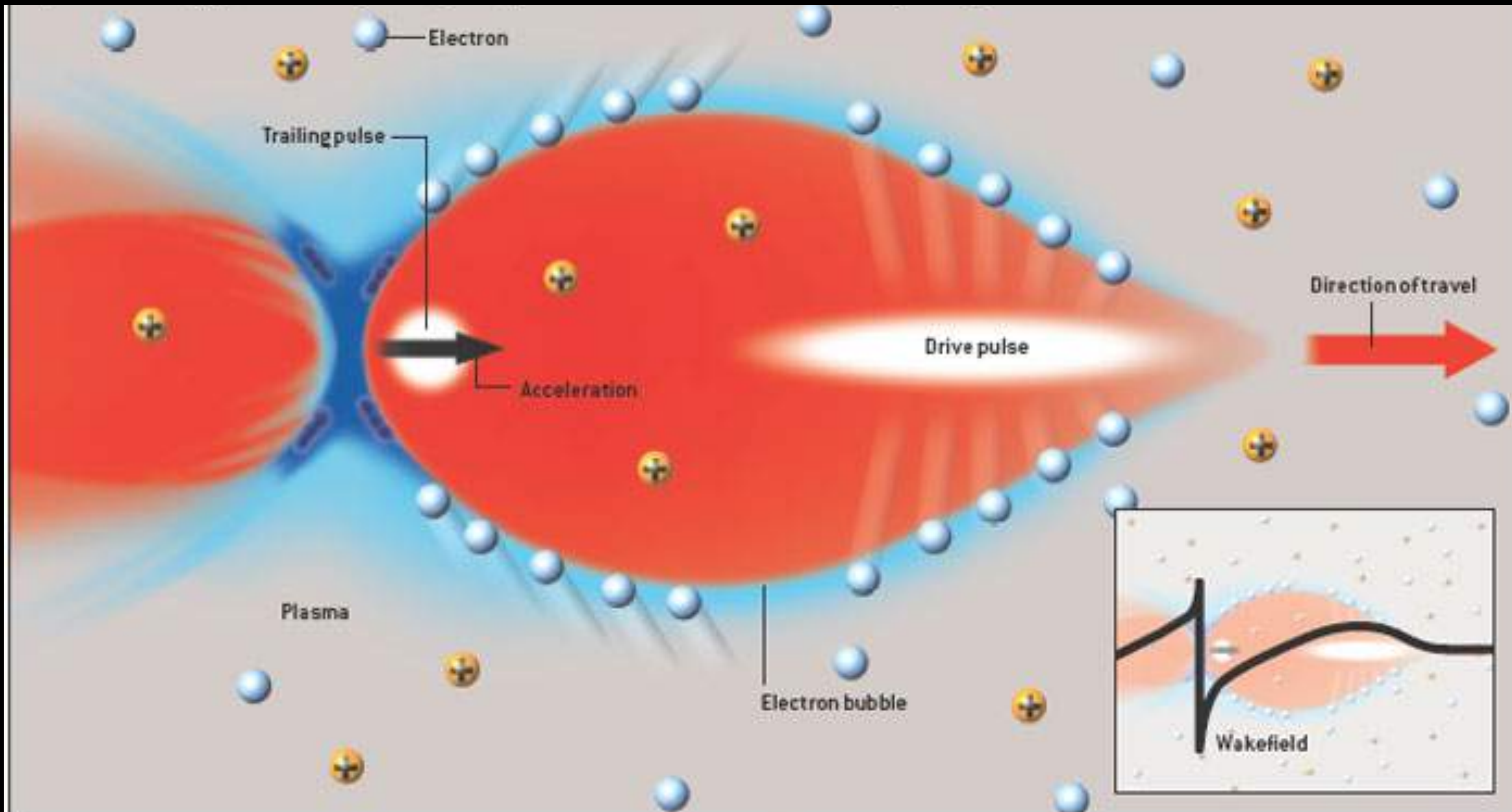




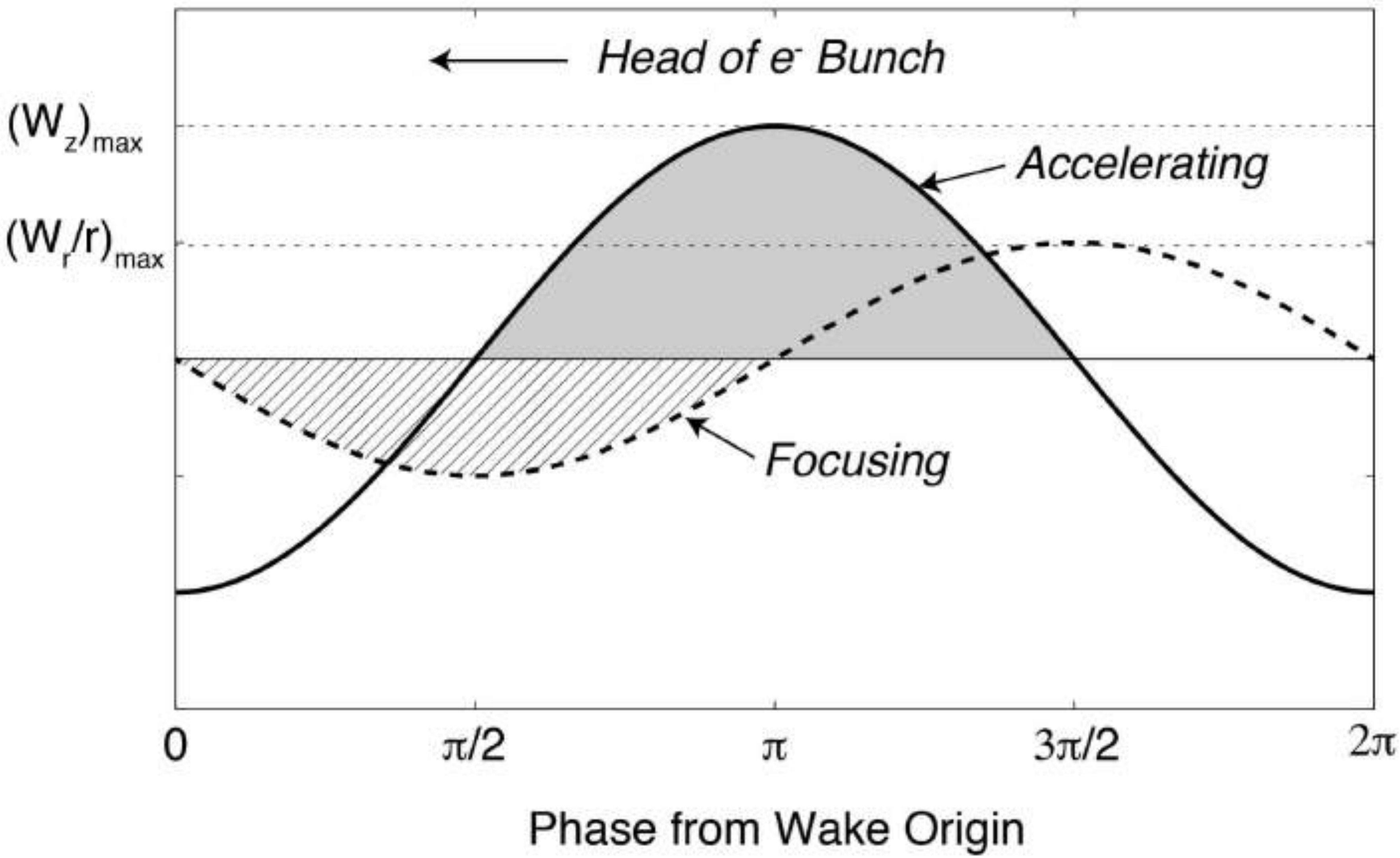


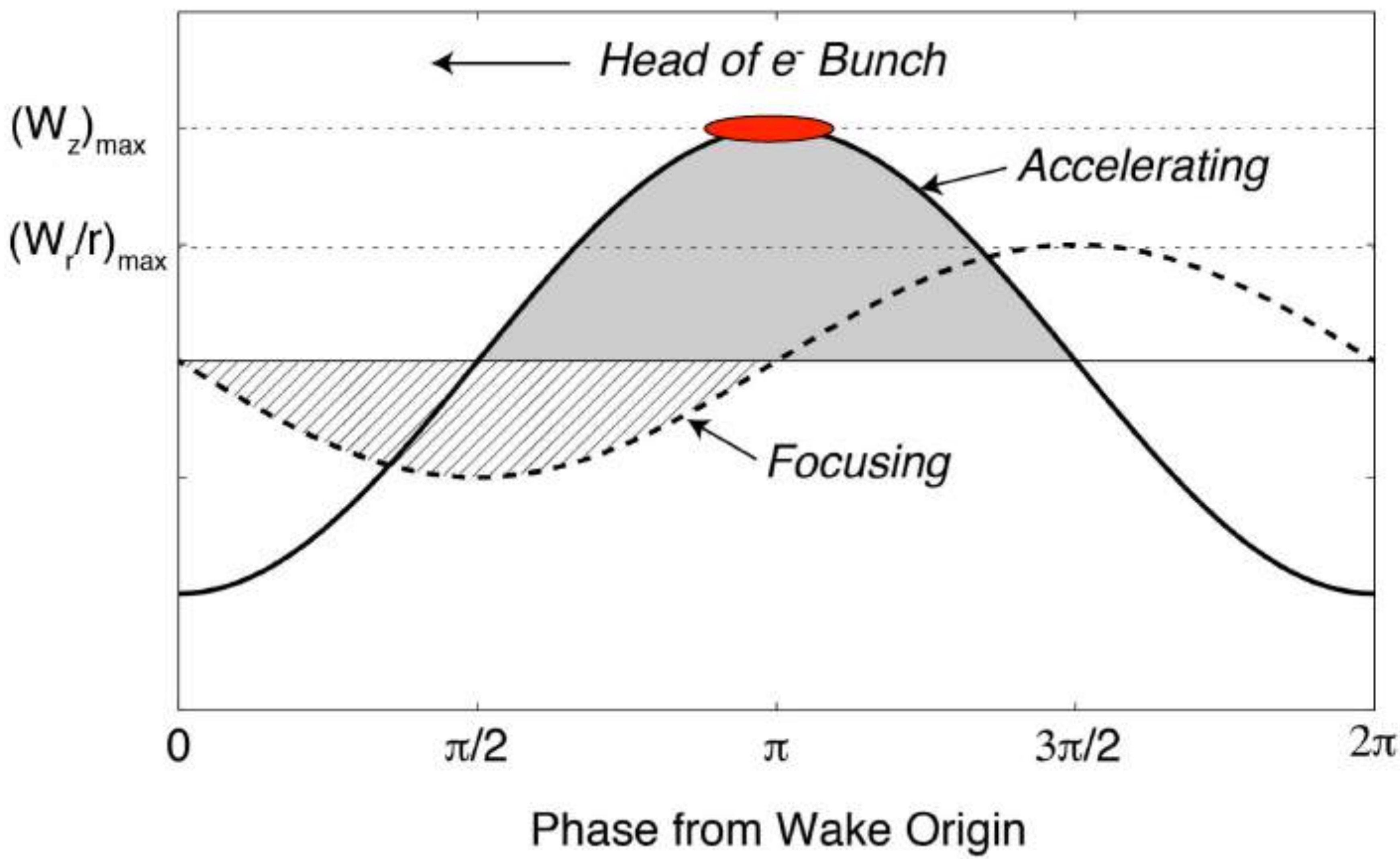
- M. Ferrario et al., Nucl. Inst. and Meth, A 637 (2011)
- A. Mostacci et al., Proc. of IPAC 2011, Spain

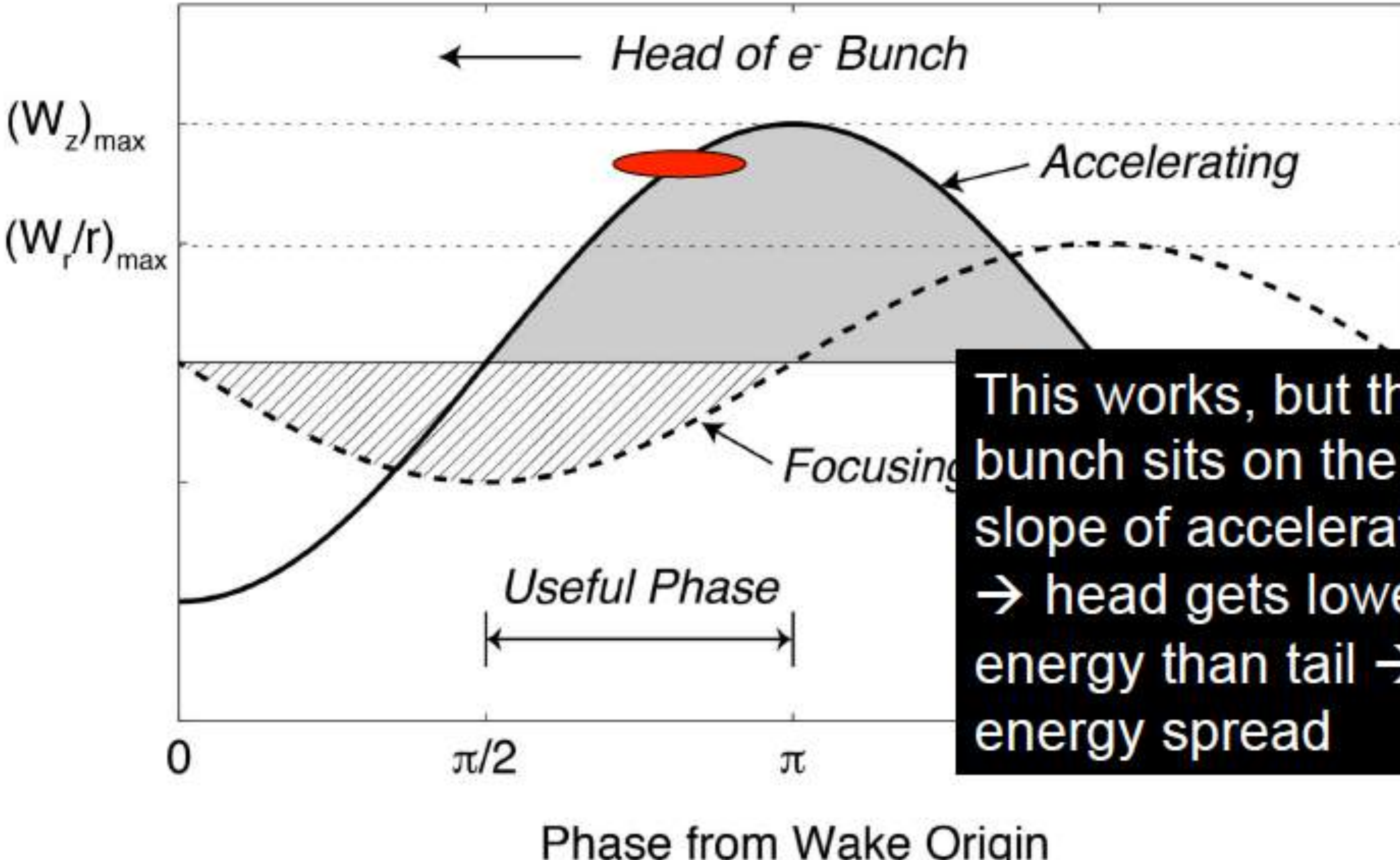
PWFA transverse field



$$E_r(r,\xi) \approx (\alpha)(k_p\sigma_z)e^{-k_p^2\sigma_z^2/2}\sin k_p\xi\, R'(r)$$


Head of e⁻ Bunch
$(W_z)_{max}$
$(W_r/r)_{max}$
Accelerating
Focusing
0
π/2
π
3π/2
2π
Phase from Wake Origin


Head of e⁻ Bunch
$(W_z)_{max}$
Accelerating
$(W_r/r)_{max}$
Focusing
0
π/2
π
3π/2
2π
Phase from Wake Origin



This works, but the bunch sits on the slope of acceleration → head gets lower energy than tail → energy spread

Energy spread compensation with beam loading

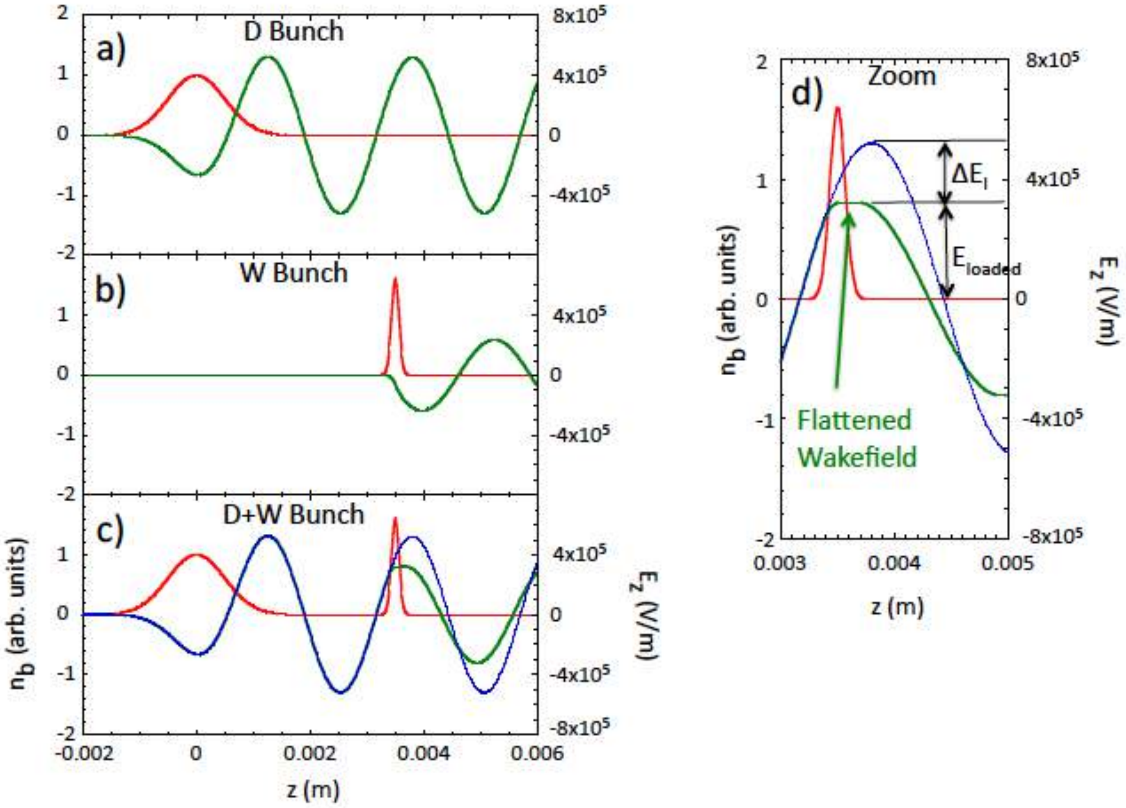
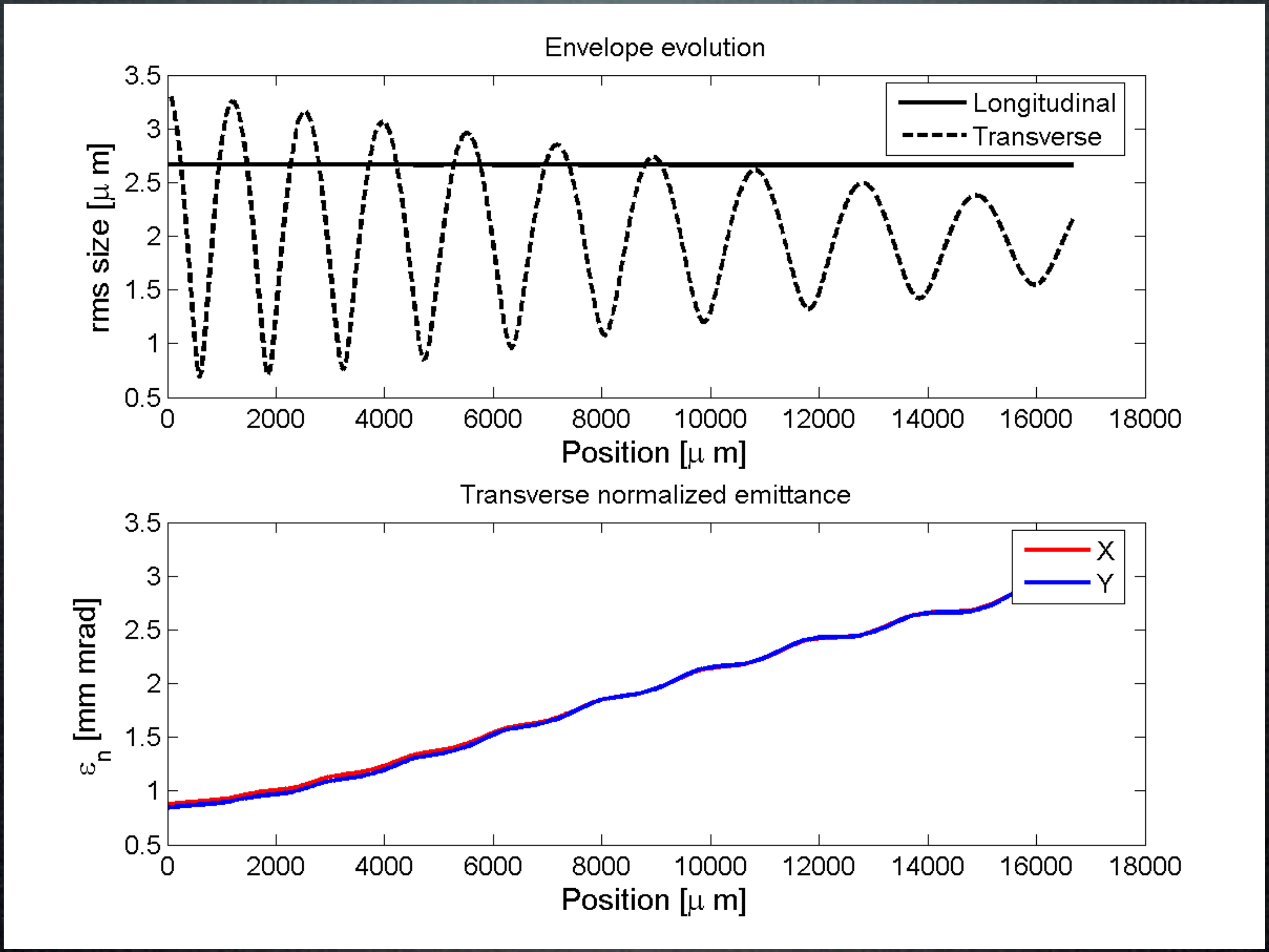


Fig. 5: Linear beam loading example: (a) drive bunch density profile (red line) and longitudinal wakefield E_z (green line), (b) same for the witness bunch, (c) same for the drive and witness bunches together. The field of the drive bunch only is shown as the blue line in panel (c). A zoom around the witness bunch is shown in panel (d). The bunches move to the left.

Transverse beam dynamics inside the plasma



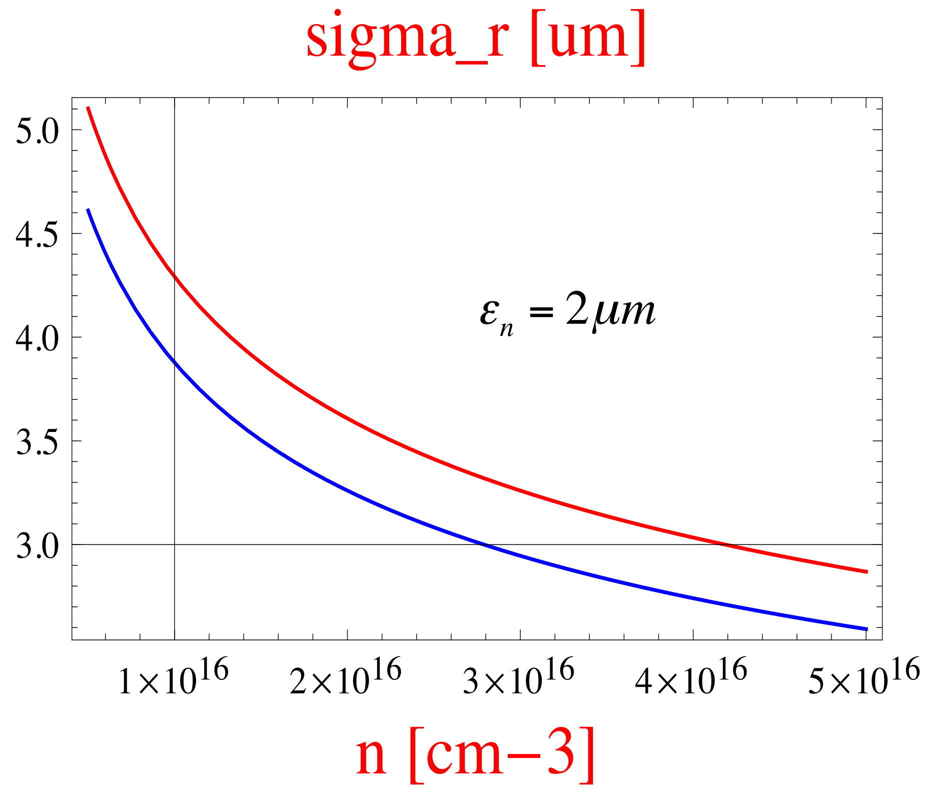
Courtesy P. Tomassini

matching condition with the plasma:

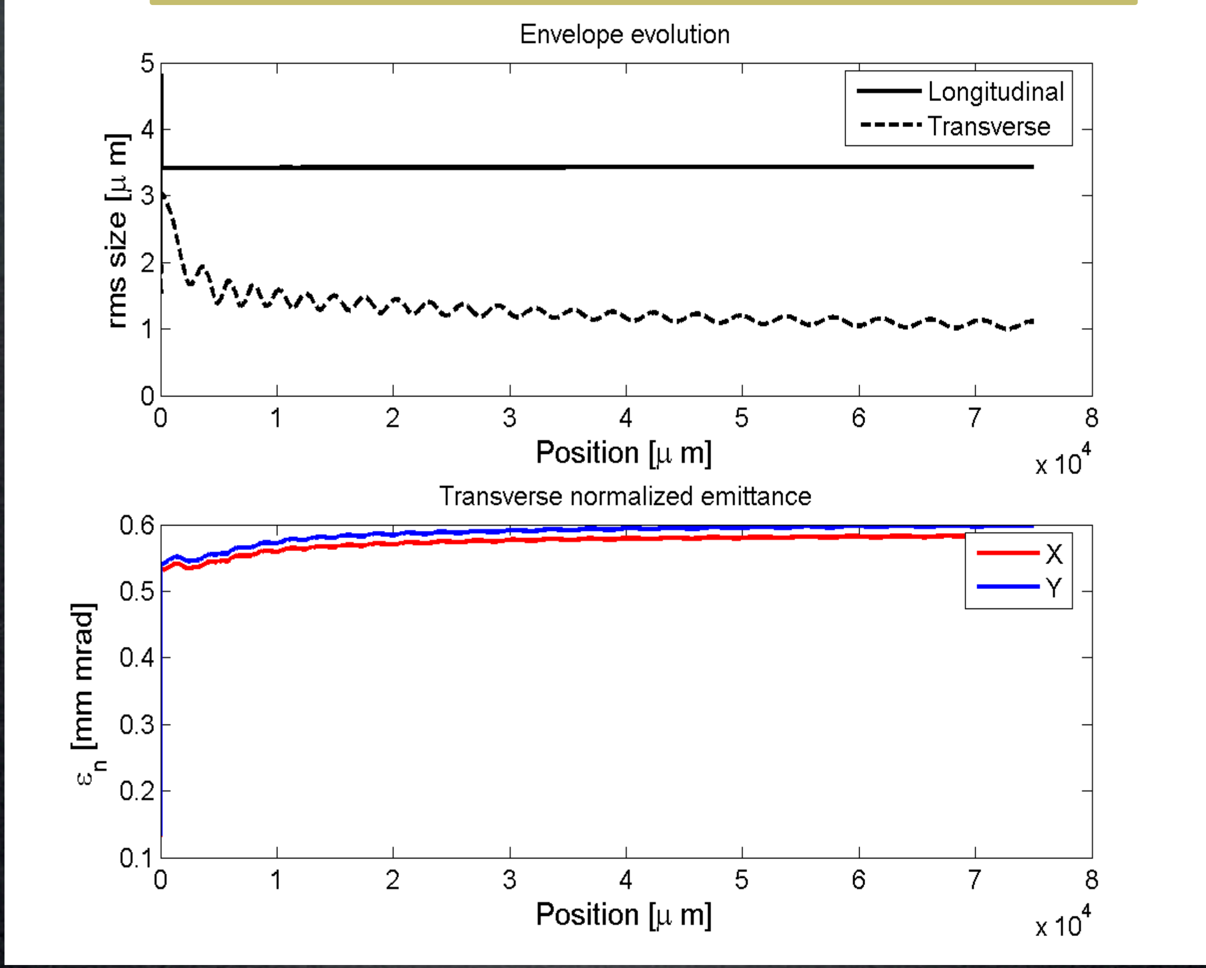
$$\sigma_x'' + \frac{k_p^2}{3\gamma}\sigma_x = \frac{\varepsilon_n^2}{\gamma^2\sigma_x^3}$$

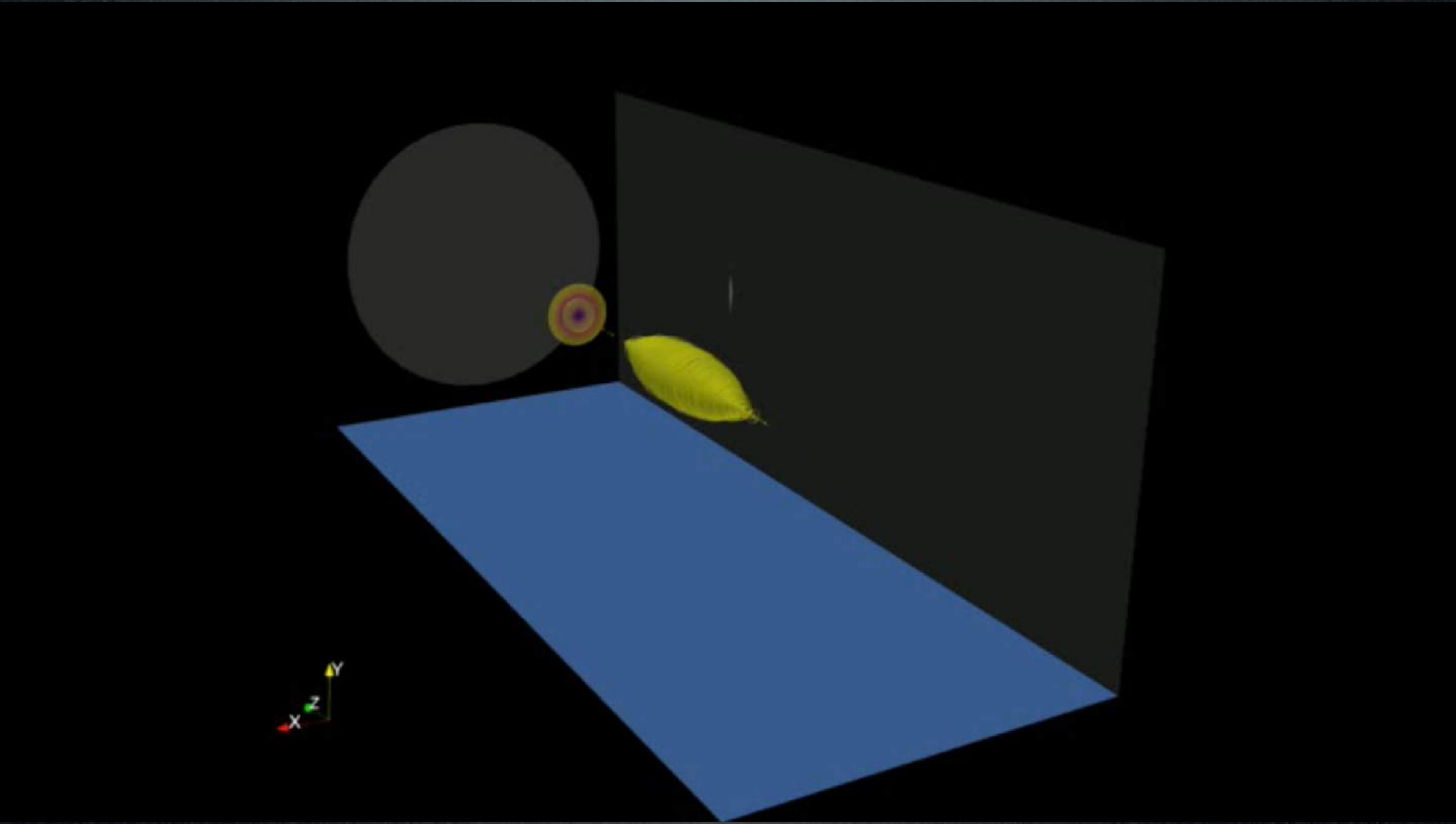
$$\sigma_\varepsilon = \sqrt[4]{\frac{3}{\gamma}}\sqrt{\frac{\varepsilon_n}{k_p}}$$

$$k_p^2 = \frac{e^2 n_1}{\varepsilon_o m c^2}$$



$$\sigma_\varepsilon = \sqrt[4]{\frac{3}{\gamma}}\sqrt{\frac{\varepsilon_n}{k_p}}$$

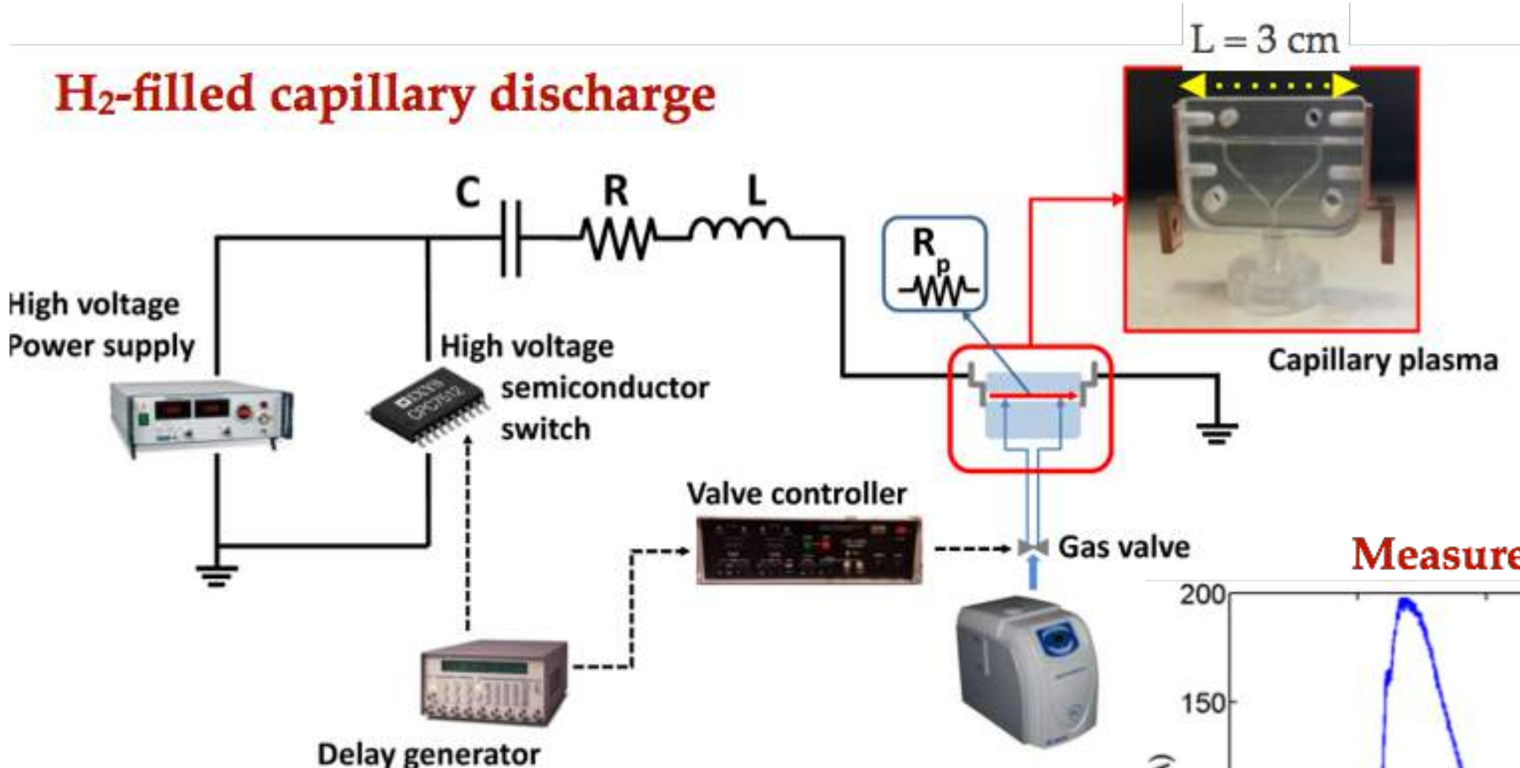


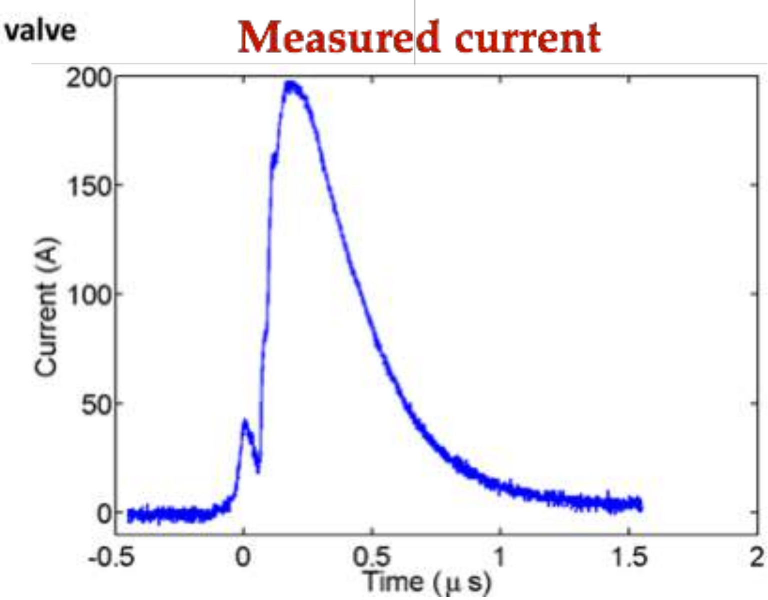

Y
Z
X

Beam Manipulation

Capillary Discharge at SPARC_LAB

Plasma Source

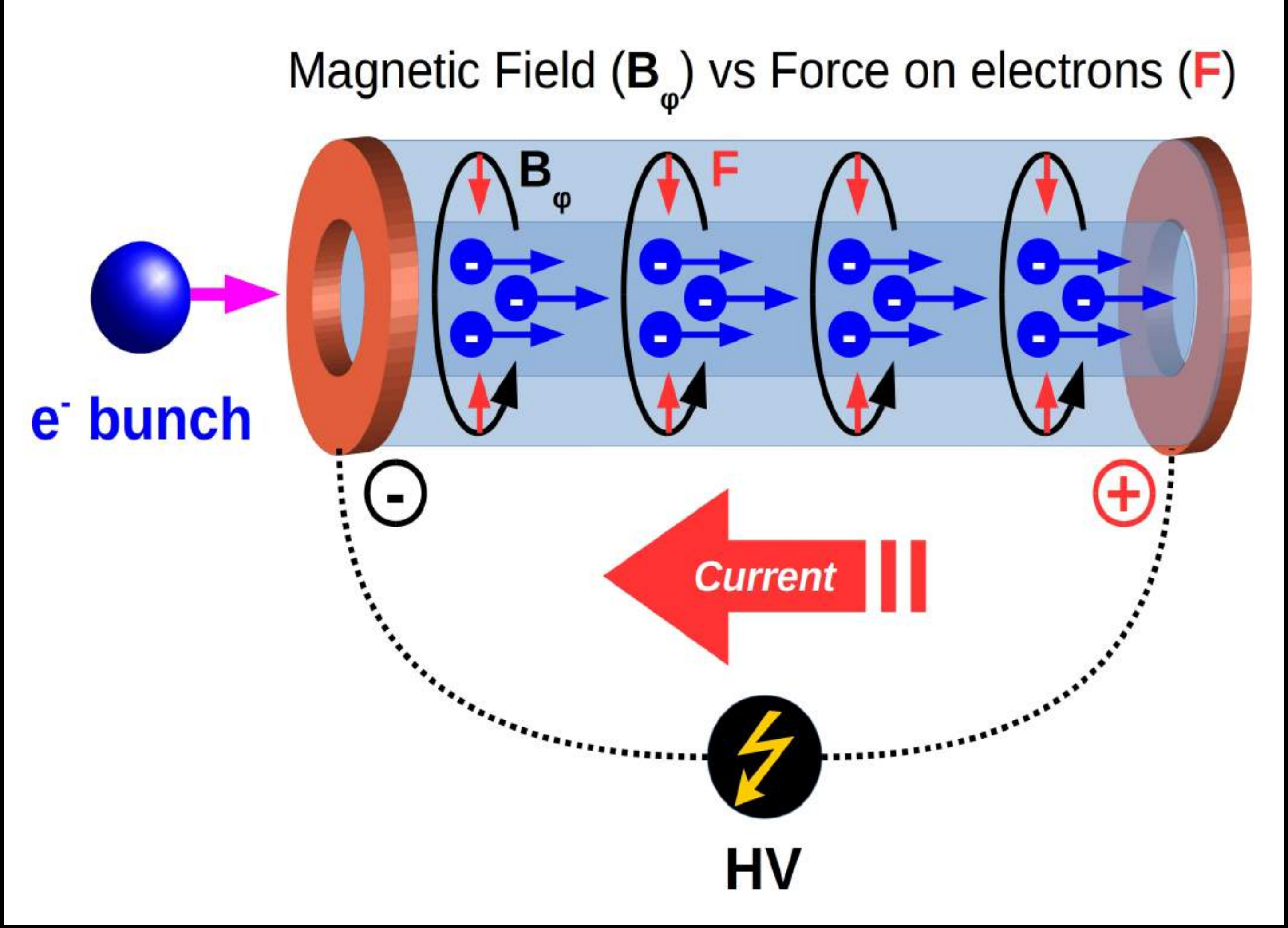




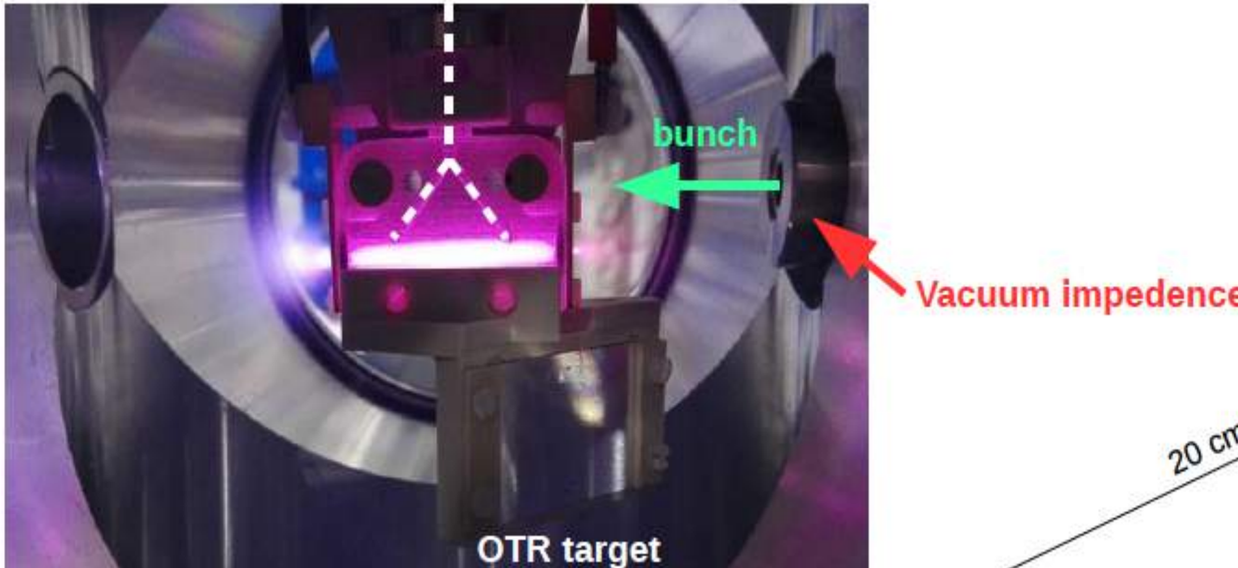
P_{H2} = 10 mbar
Total discharge duration: 800 ns
Voltage: 20 kV
Peak current: 200 A
Capacitor: 6 nF

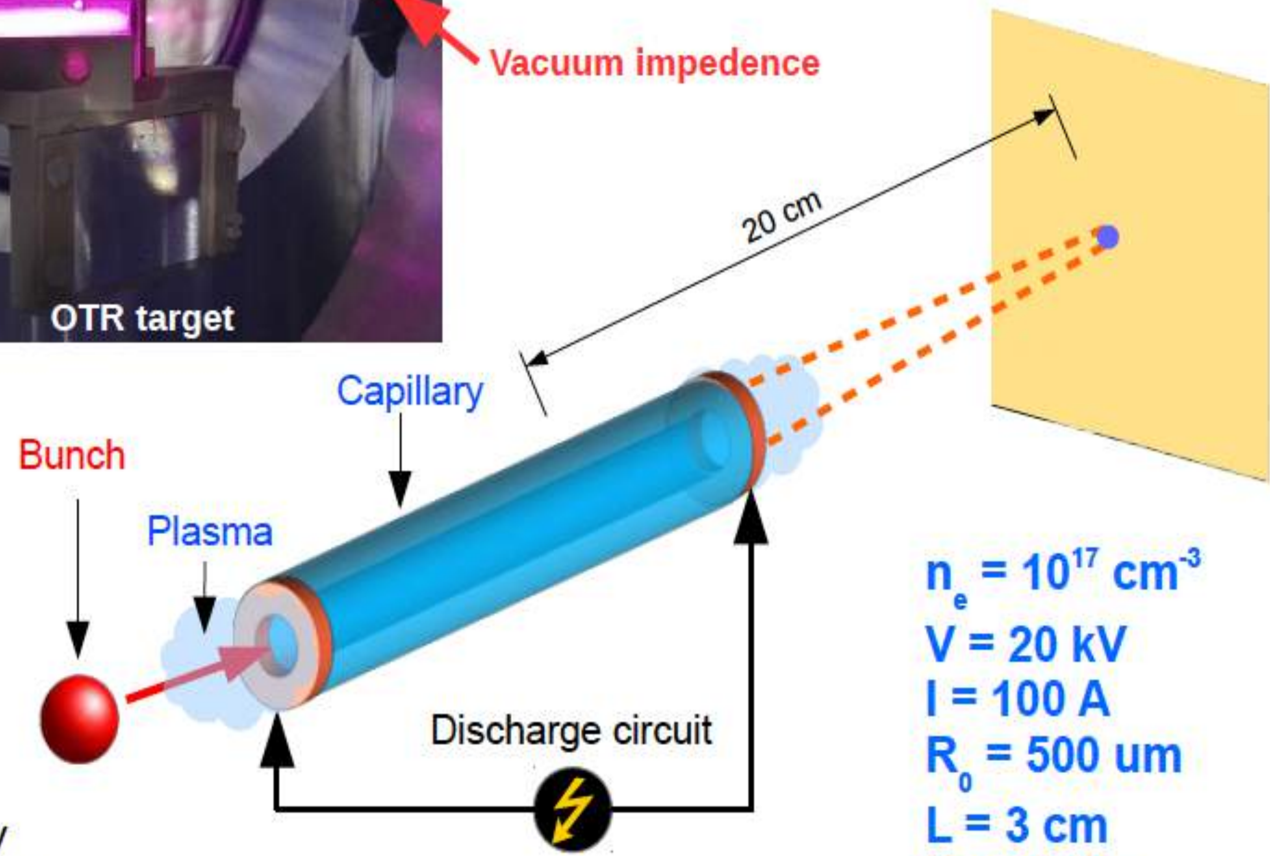
Courtesy of M. P. Anania, A. Biagioni, D. Di Giovenale, F. Filippi, S. Pella

Active Plasma Lens



Experimental layout

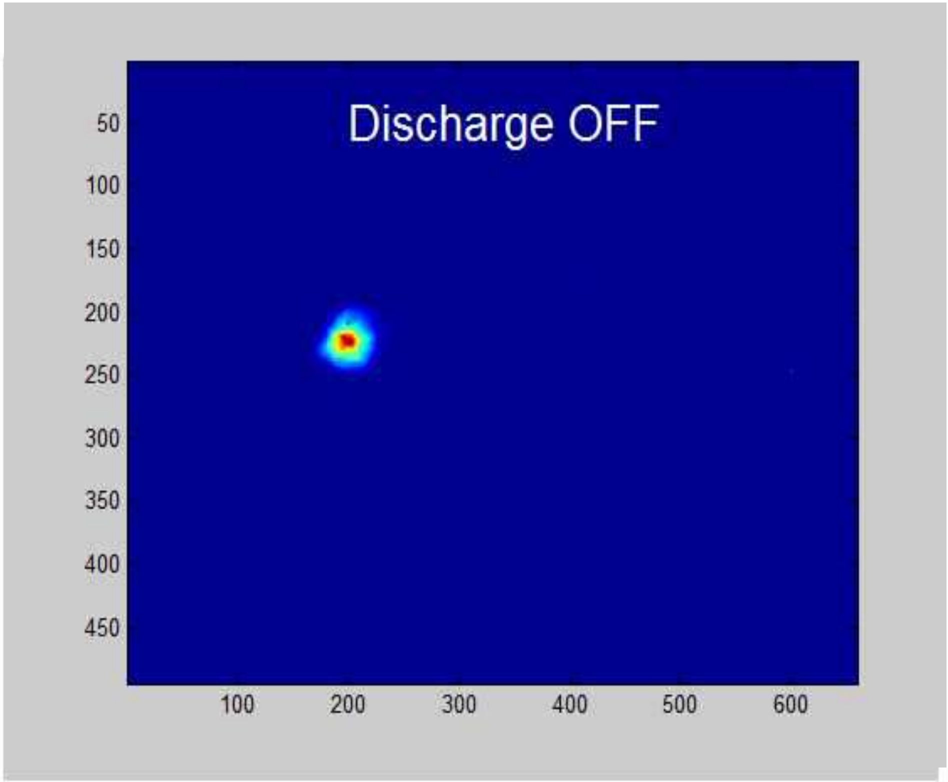


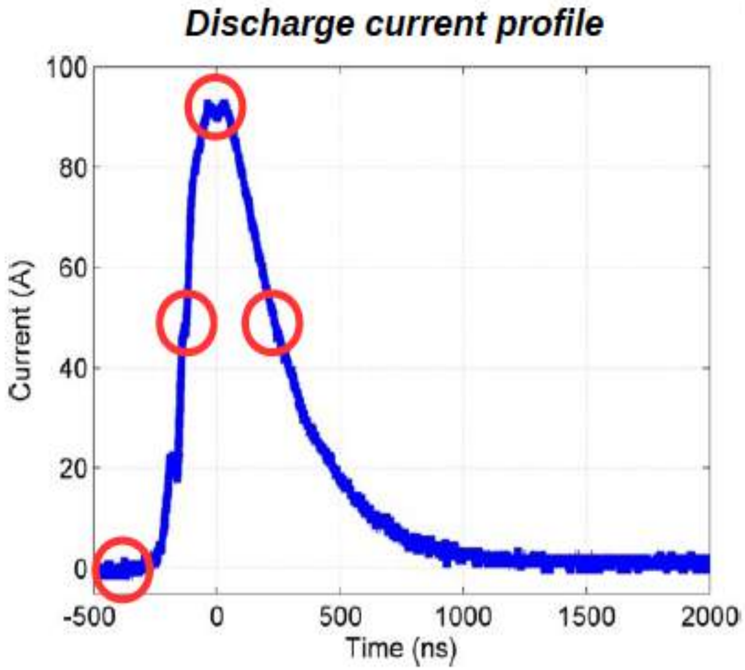


50 pC
1 ps
130 um
120 MeV
1 mm mrad

$n_e = 10^{17}$ cm^{-3}
V = 20 kV
I = 100 A
R_0 = 500 um
L = 3 cm
Sapphire

Preliminary results





APPLIED PHYSICS LETTERS **110**, 104101 (2017)

Experimental characterization of active plasma lensing for electron beams

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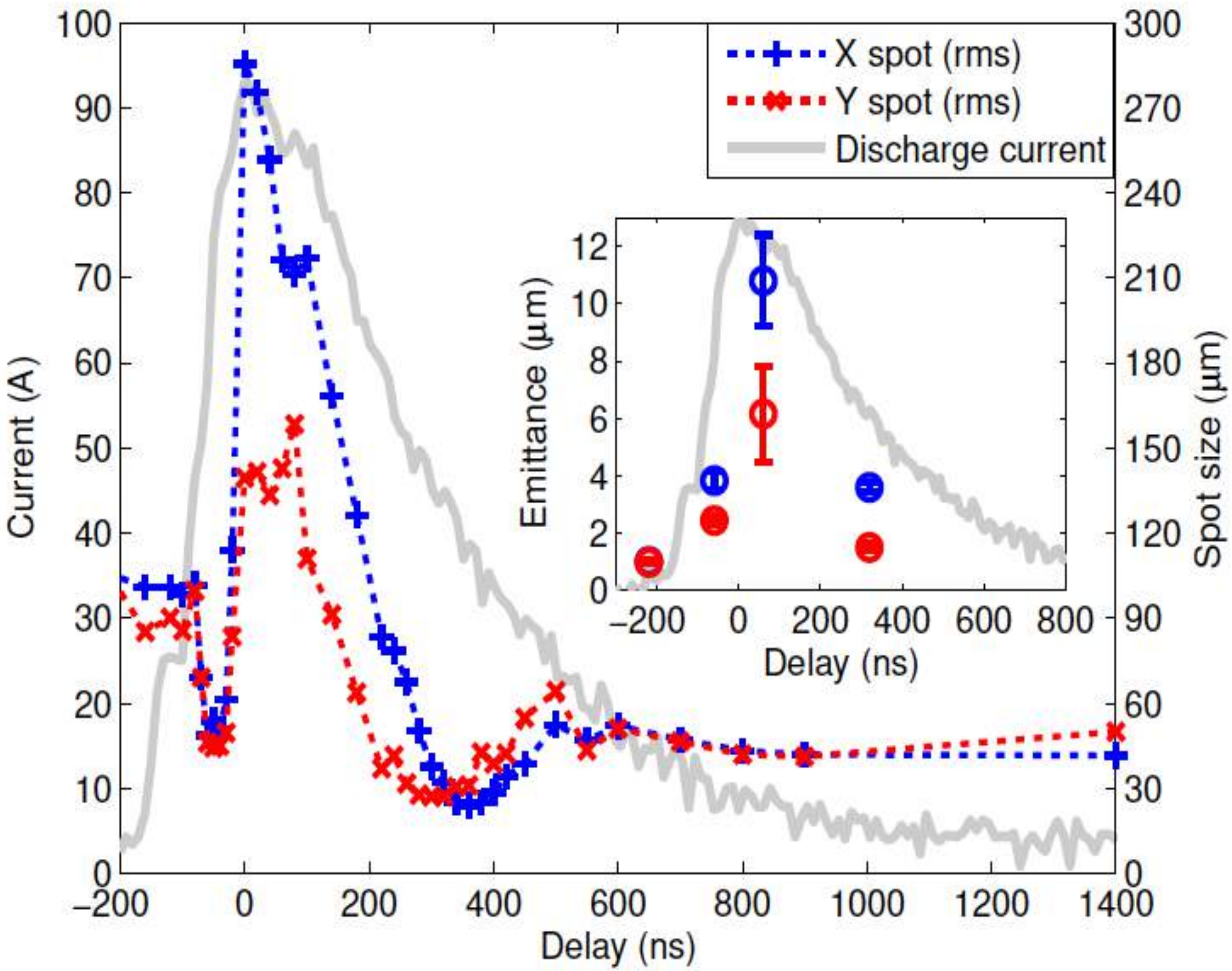
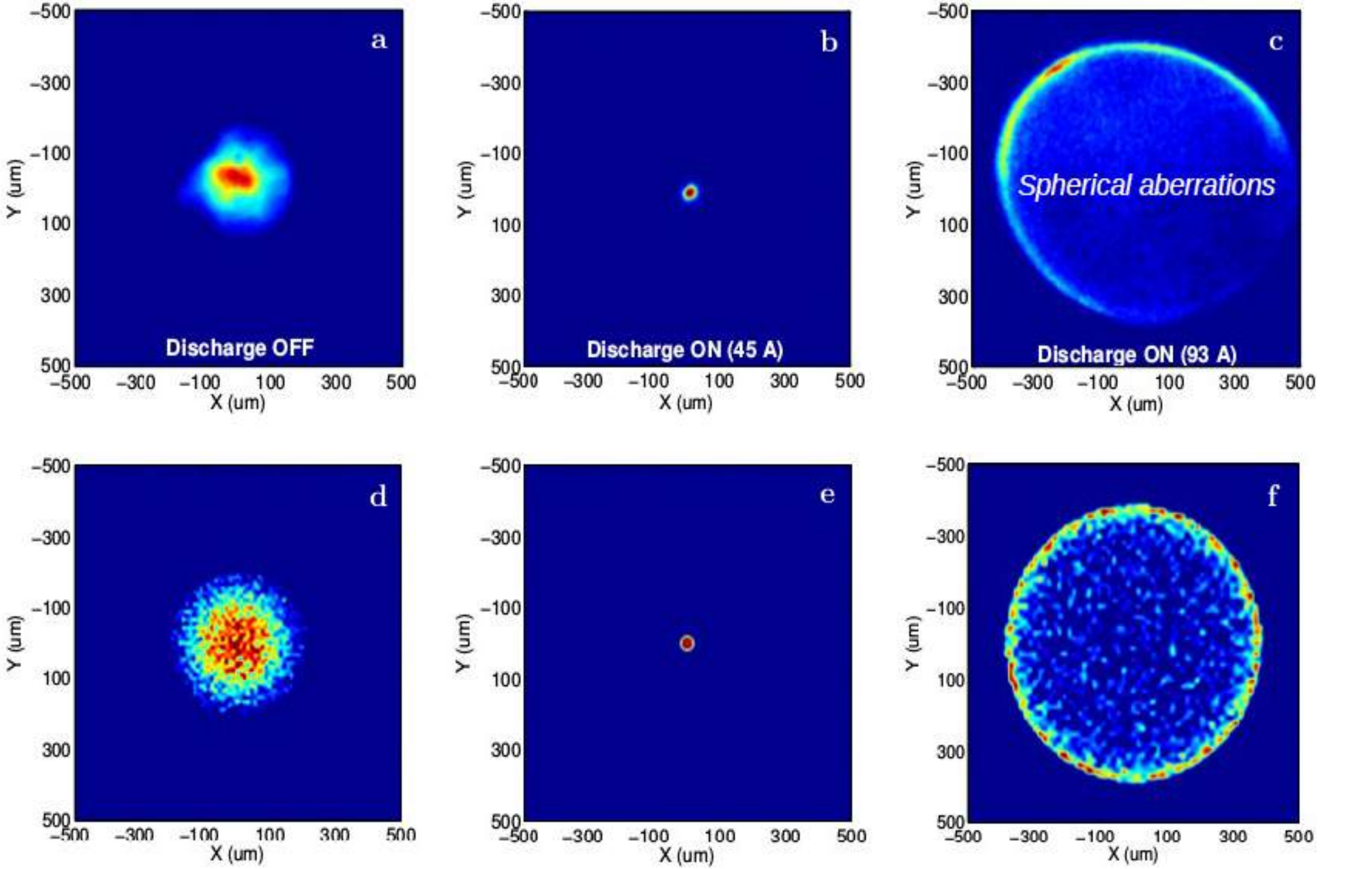
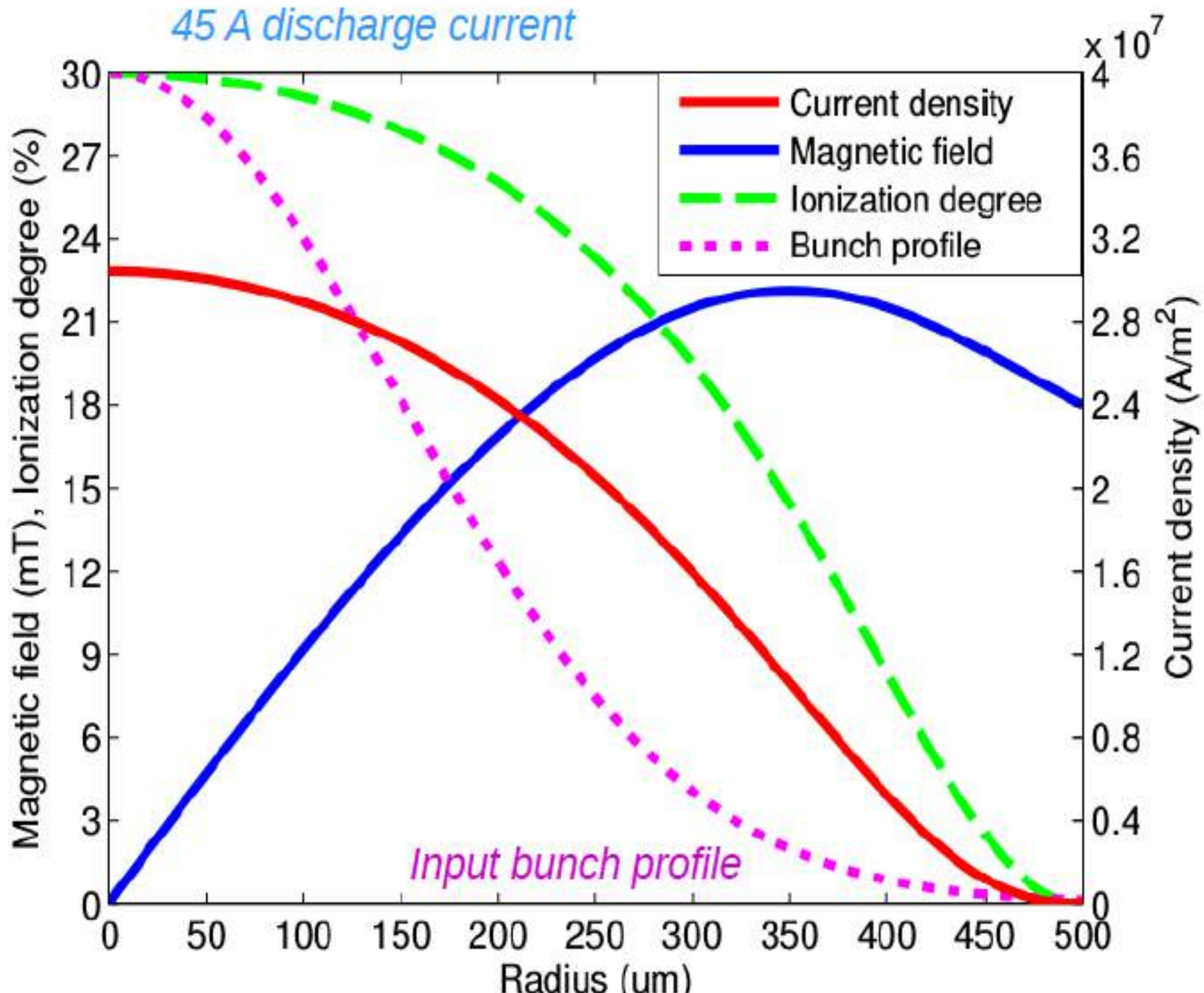
E. Brentegani,[1] G. Castorina,[1,2] E. Chiadroni,[1] A. Cianchi,[3] M. Croia,[1] D. Di Giovenale,[1]
M. Ferrario,[1] F. Filippi,[1] A. Giribono,[4] V. Lollo,[1] A. Marocchino,[1] M. Marongiu,[4] A. Mostacci,[4]
G. Di Pirro,[1] S. Romeo,[1] A. R. Rossi,[5] J. Scifo,[1] V. Shpakov,[1] C. Vaccarezza,[1] F. Villa,[1]
and A. Zigler[6]



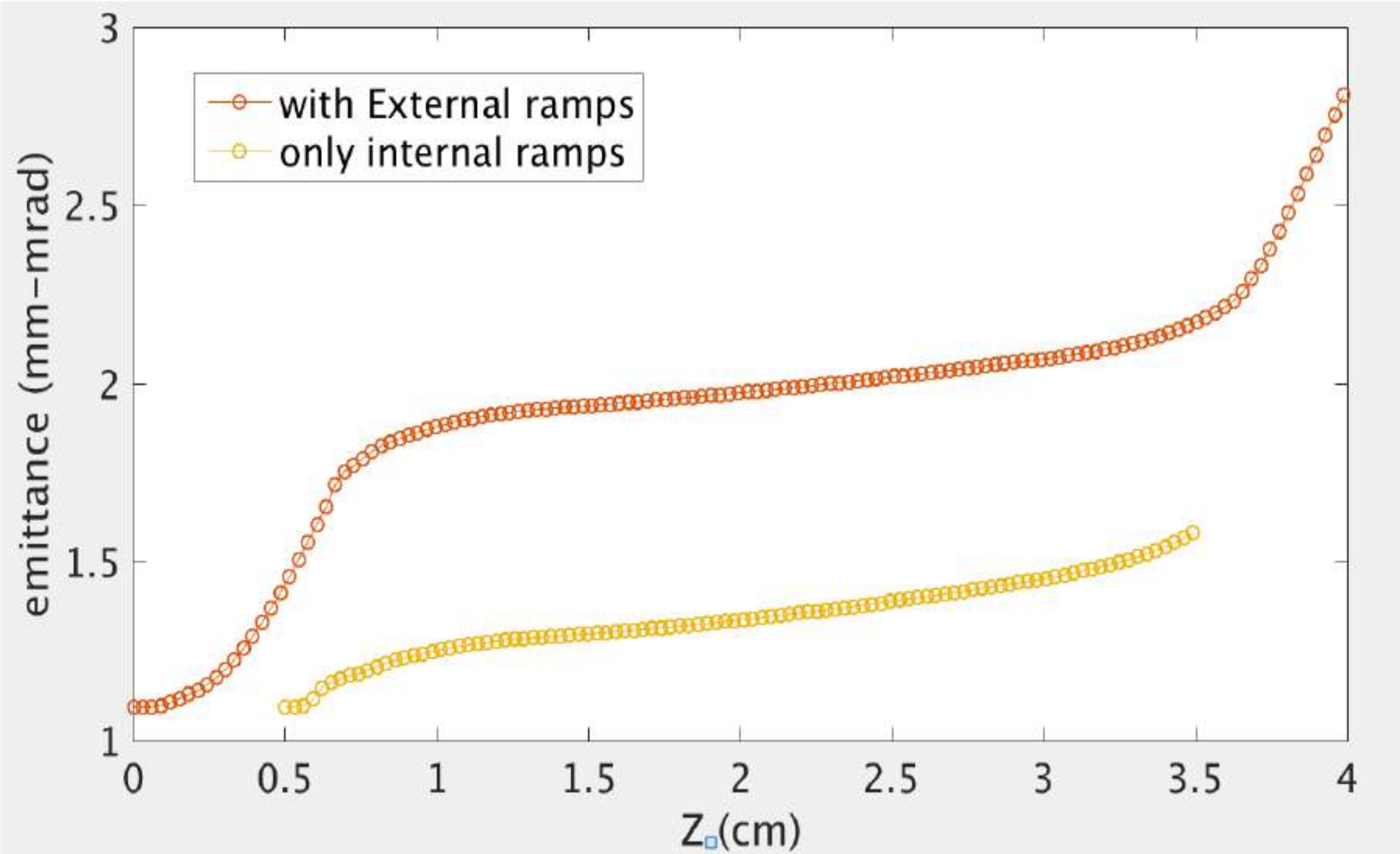
Results vs simulations



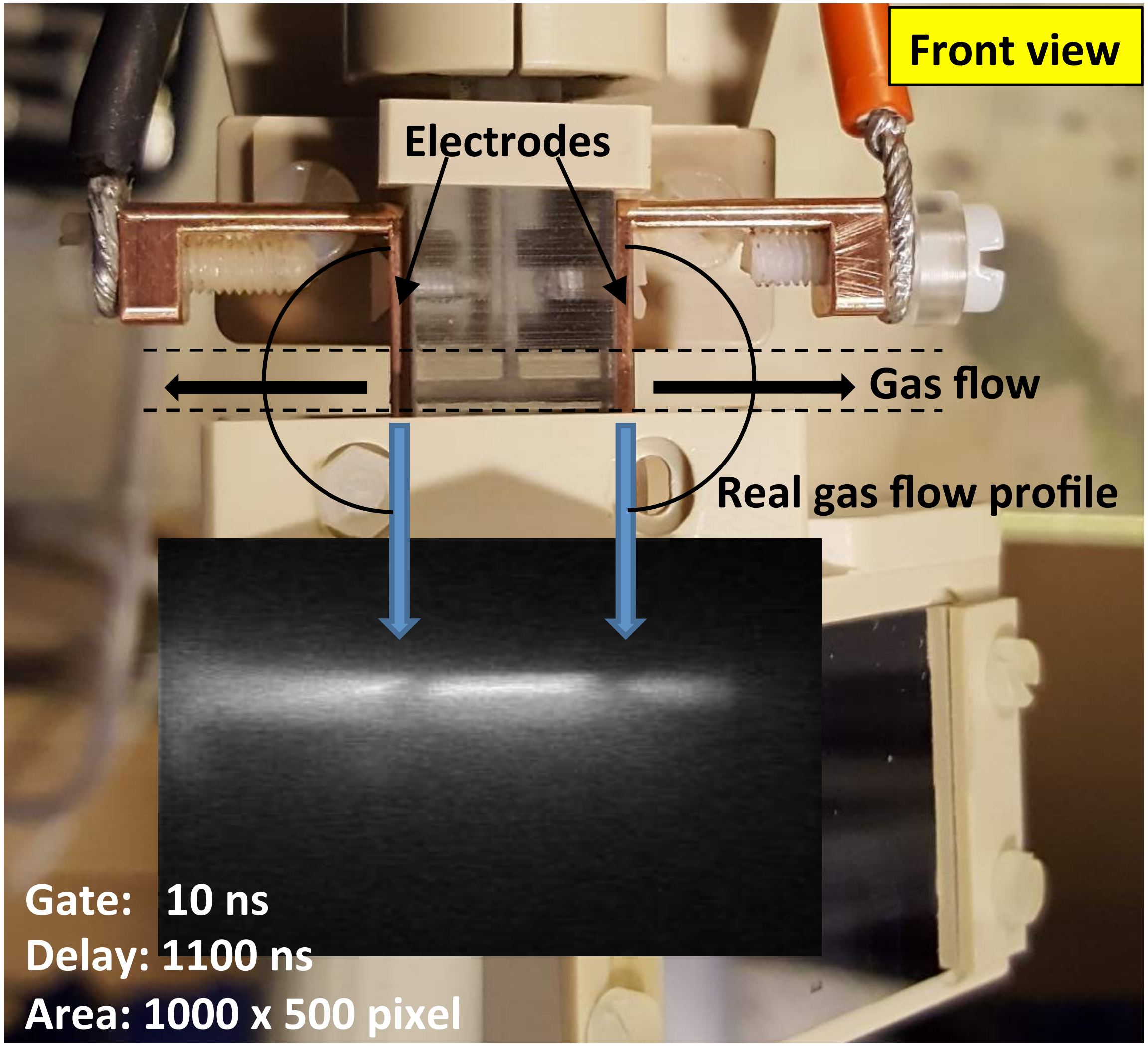
Nonlinear focusing field

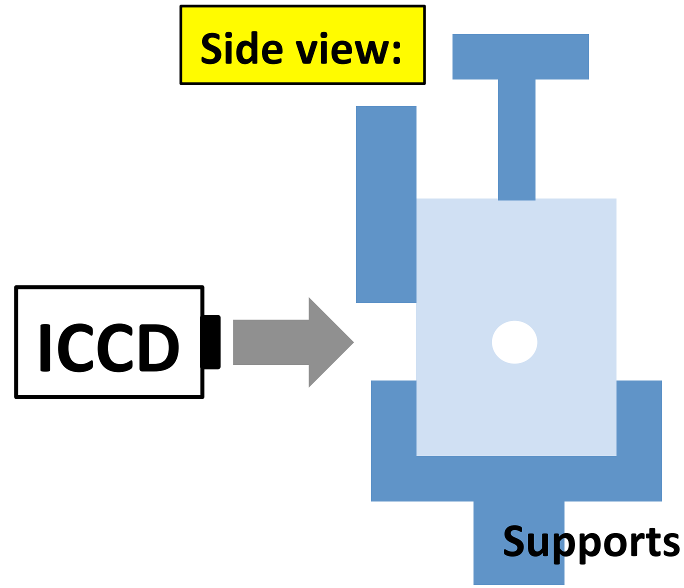


Ramps effects on emittance without discharge



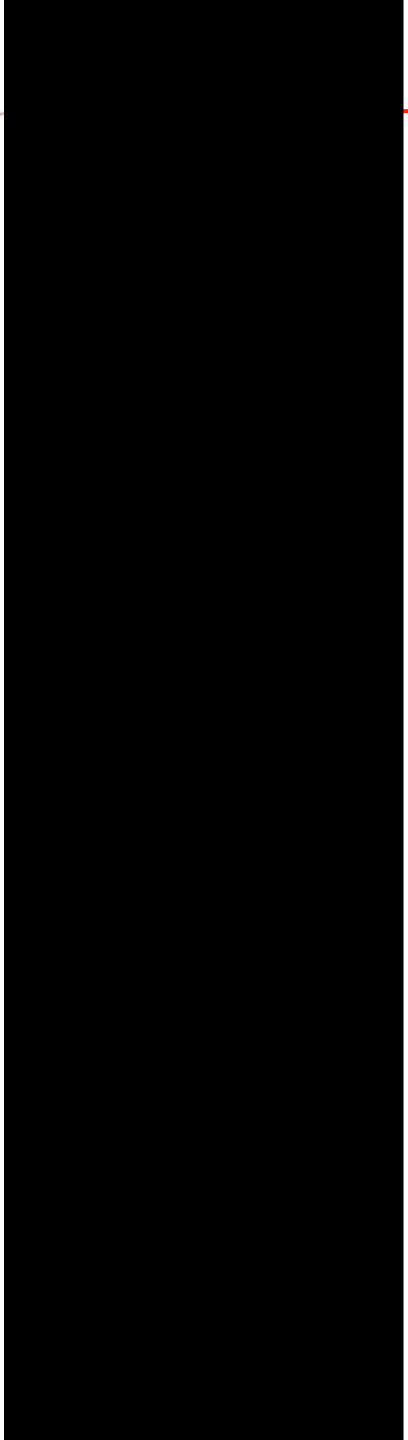
velocity of plasma

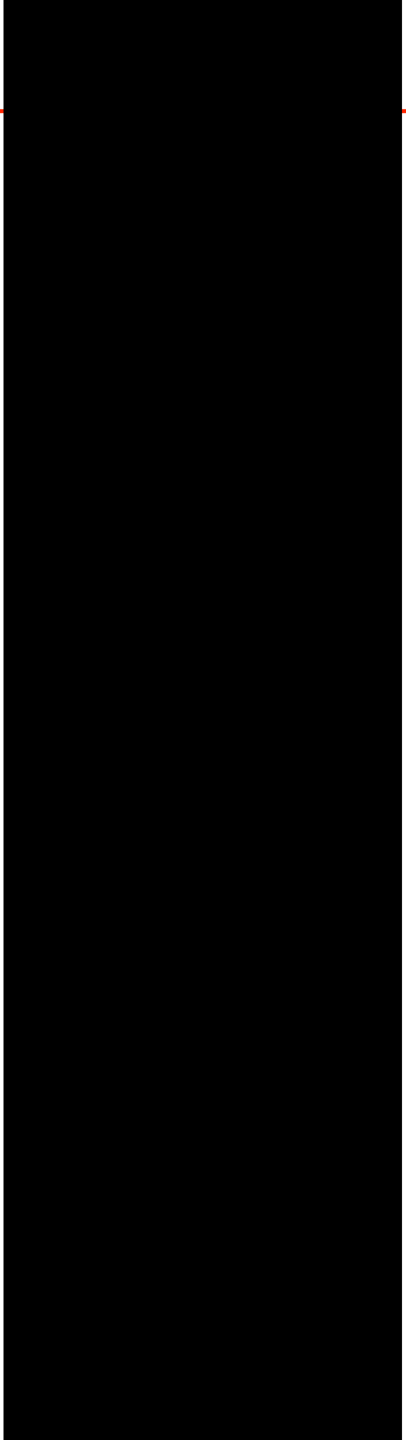




In order to see the real expansion of the plasma we have to mount the capillary of 3 cm length so that we will not see the cutting due to the supports

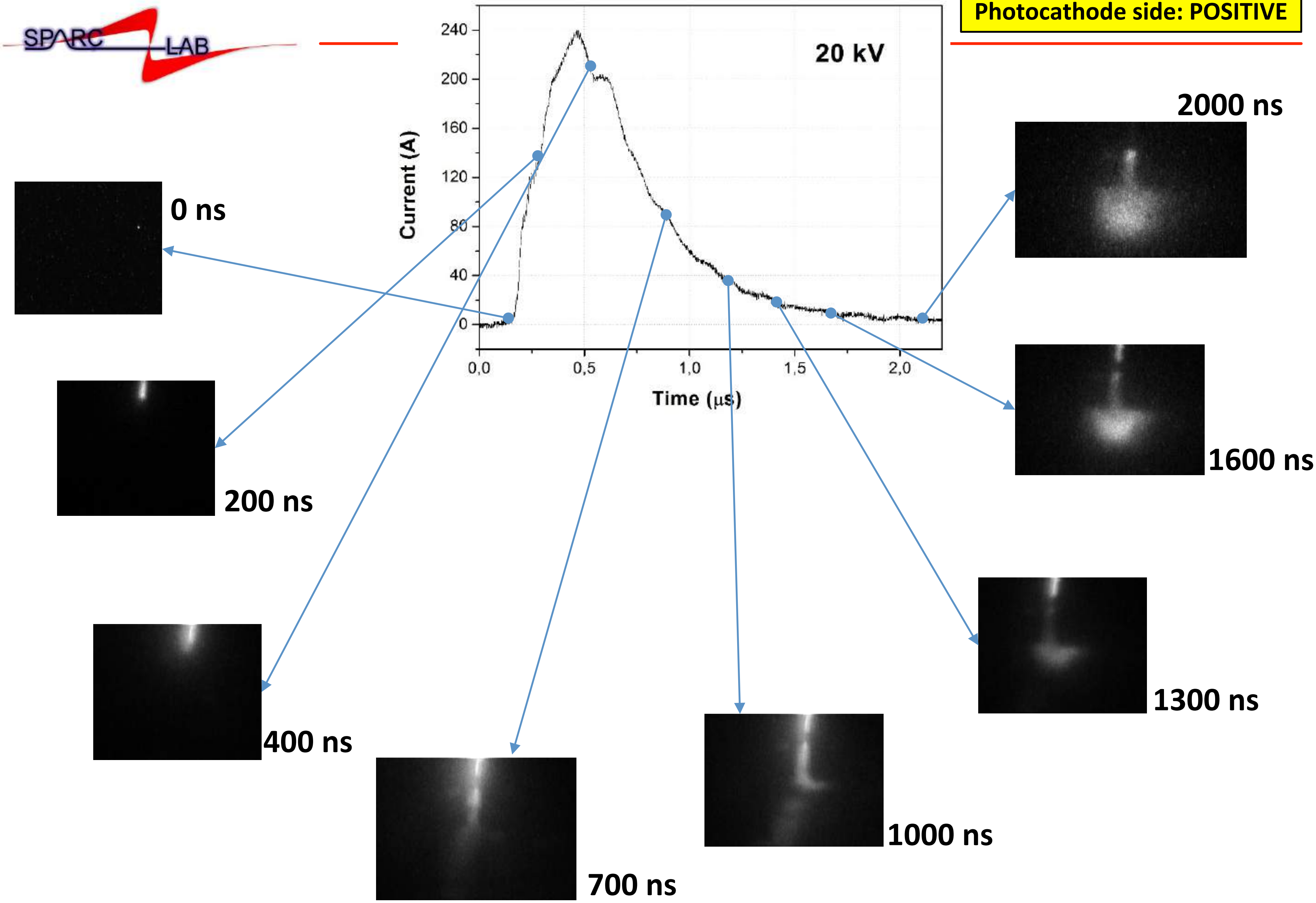
velocity of plasma





Delay: 20 images separated by 100 ns = 2 μs
Gate: 10 ns
Area: 1000 x 500 pixel

Photocathode side: POSITIVE



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The course will be of interest to staff and students in accelerator laboratories, university departments and companies working in or having an interest in the field of new acceleration techniques.
Following introductory lectures on plasma and laser physics, the course will cover the different components of a plasma wake accelerator and plasma beam systems. An overview of the experimental studies, diagnostic tools and state of the art wake acceleration facilities, both present and planned, will complement the theoretical part. Topical seminars and a visit of CERN will complete the programme.
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CERN Accelerator School
CH - 1211 Geneva 23
Tel.: +41 22 767 8607 / Fax: +41 22 767 5460
email: barbara.strasser@cern.ch
http://cas.web.cern.ch/cas
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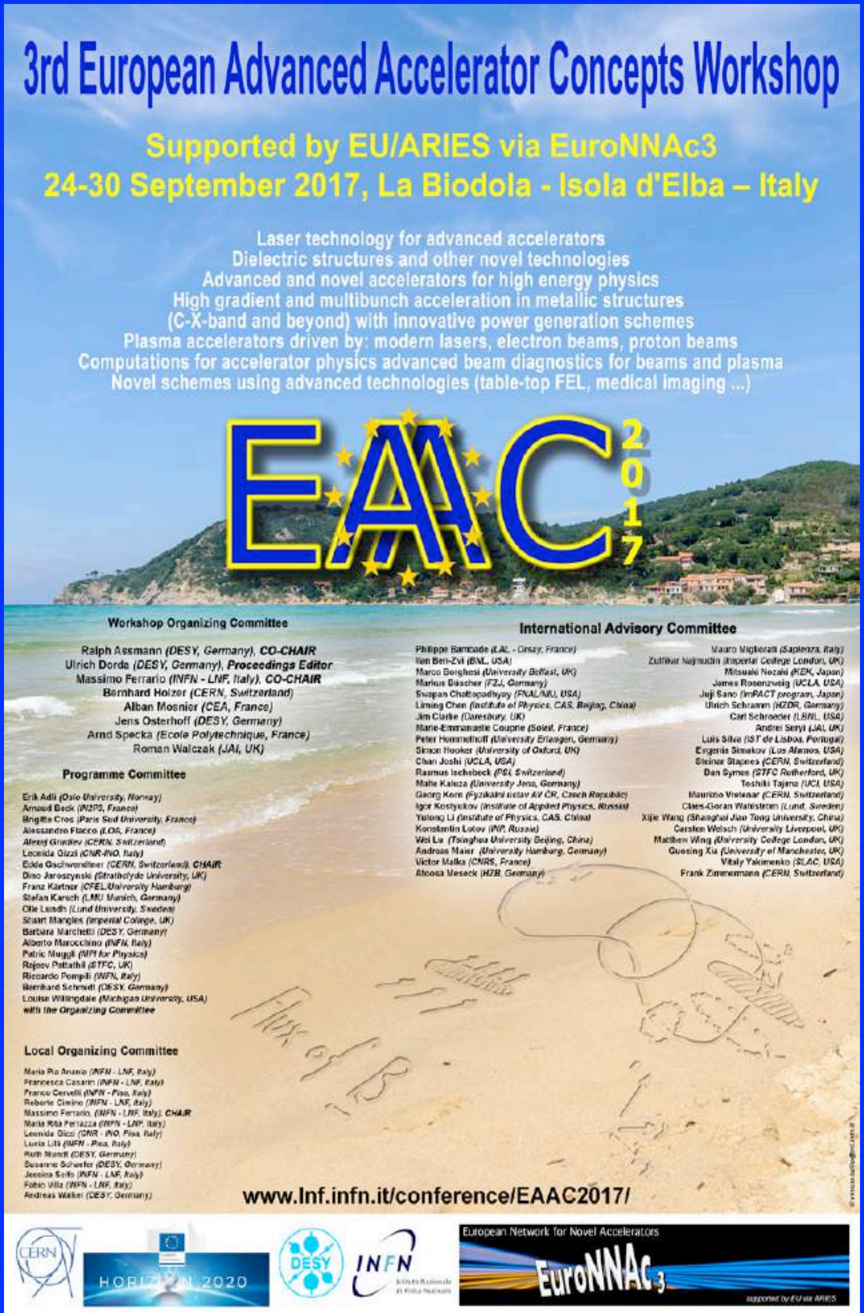

3rd European Advanced Accelerator Concepts Workshop
Supported by EU/ARIES via EuroNNAc3
24-30 September 2017, La Biodola - Isola d'Elba – Italy
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Dielectric structures and other novel technologies
Advanced and novel accelerators for high energy physics
High gradient and multibunch acceleration in metallic structures
(C-X-band and beyond) with innovative power generation schemes
Plasma accelerators driven by: modern lasers, electron beams, proton beams
Computations for accelerator physics advanced beam diagnostics for beams and plasma
Novel schemes using advanced technologies (table-top FEL, medical imaging ...)
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