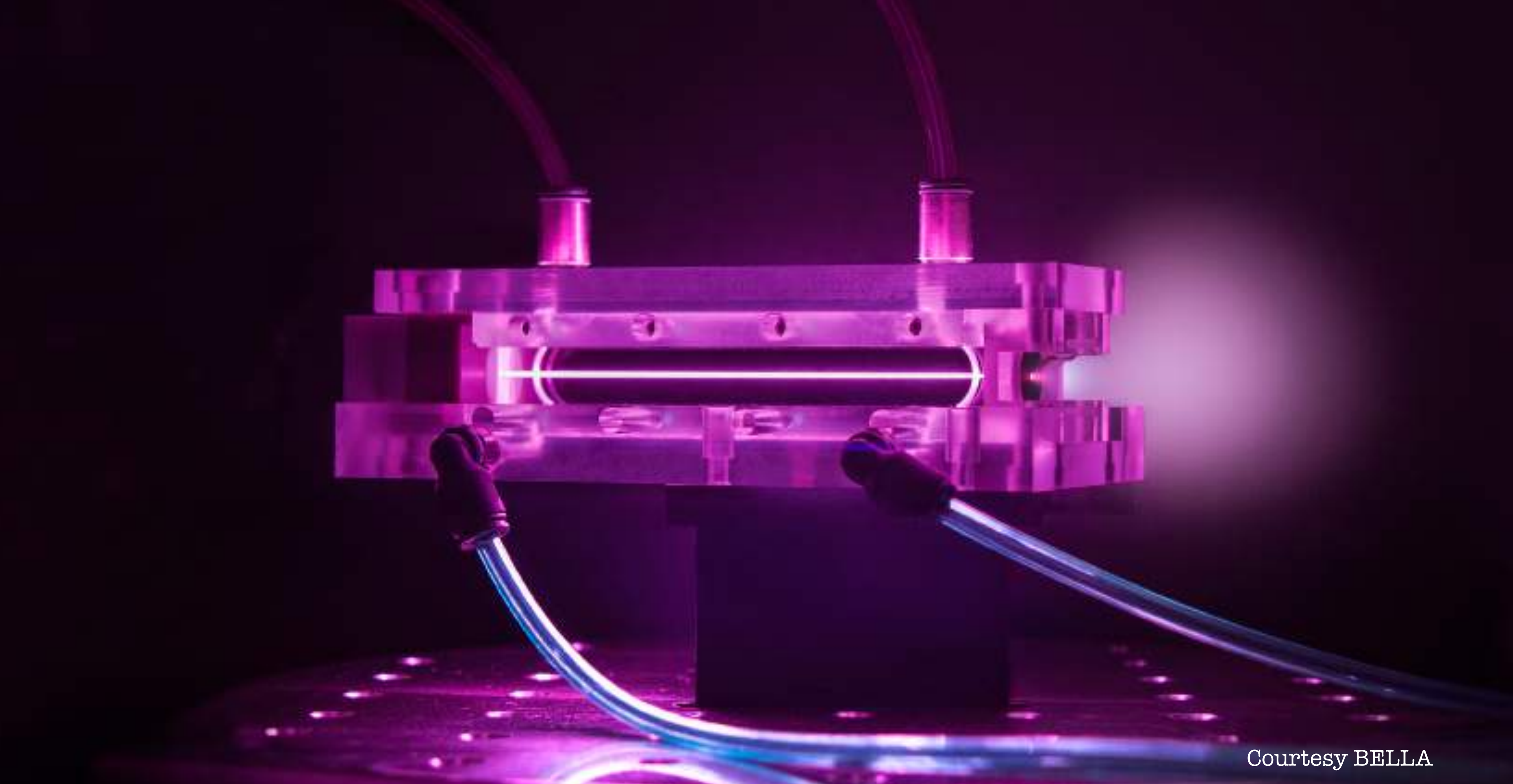
From SPARC_LAB to EuPRAXIA

Massimo.Ferrario@LNF.INFN.IT



Courtesy BELLA

LAL – Orsay, 7 March 2017

Hawking: the Solartron

Towards the Planck scale: 1.22×10^{19} GeV

Without further novel technology, we will eventually need an accelerator as large as Hawking expected.

“The Universe in a Nutshell”, by Stephen William Hawking, Bantam, 2001

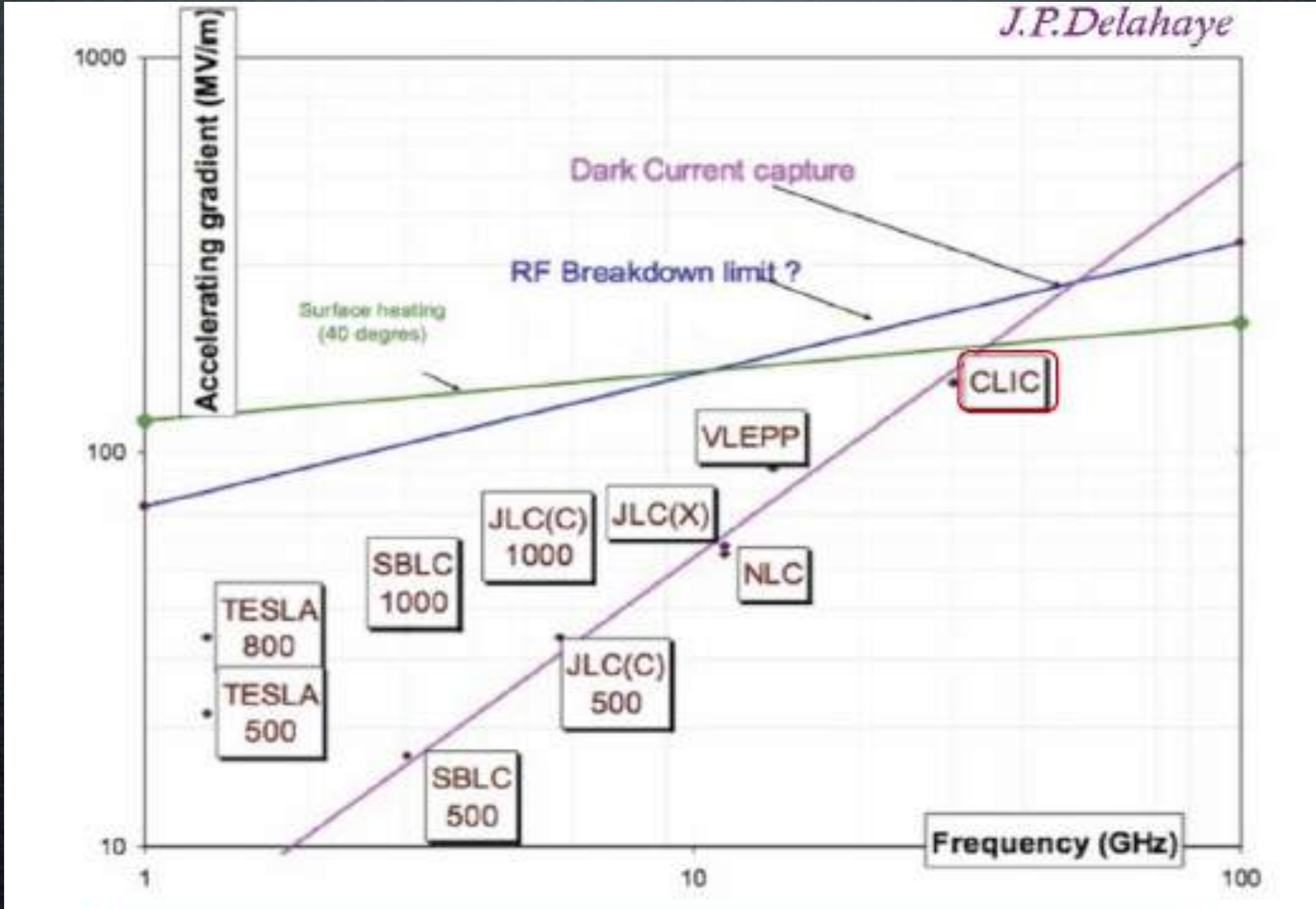
HIGH GRADIENT AAC ROAD MAP

① Miniaturization of the accelerating structures (~resonant) and beam manipulation components

② Wake Field Acceleration (~transient) (LWFA, PWFA, DWFA)

- Power sources
- Accelerating structures
- High quality beams

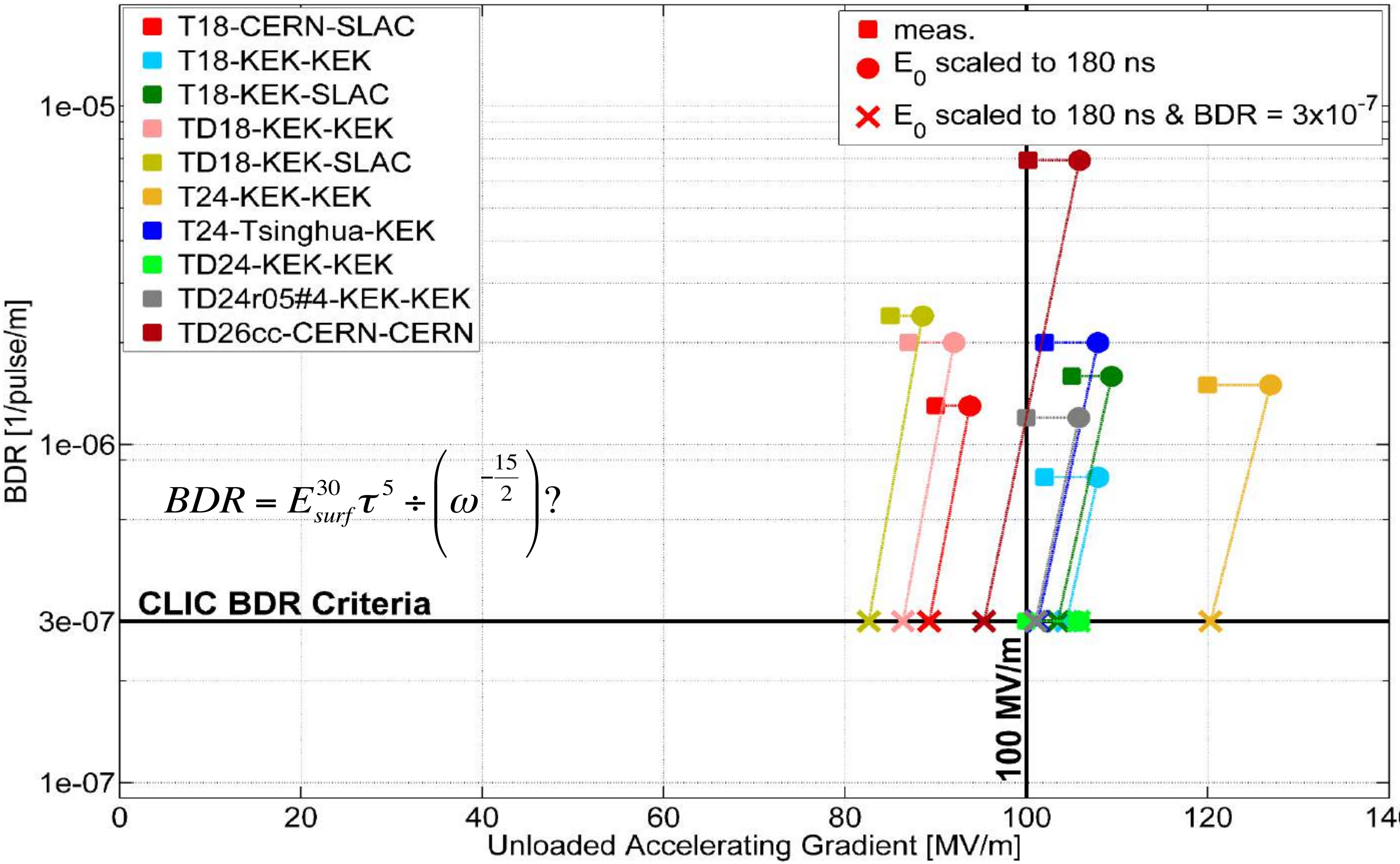
High field ->Short wavelength->ultra-short bunches-> low charge



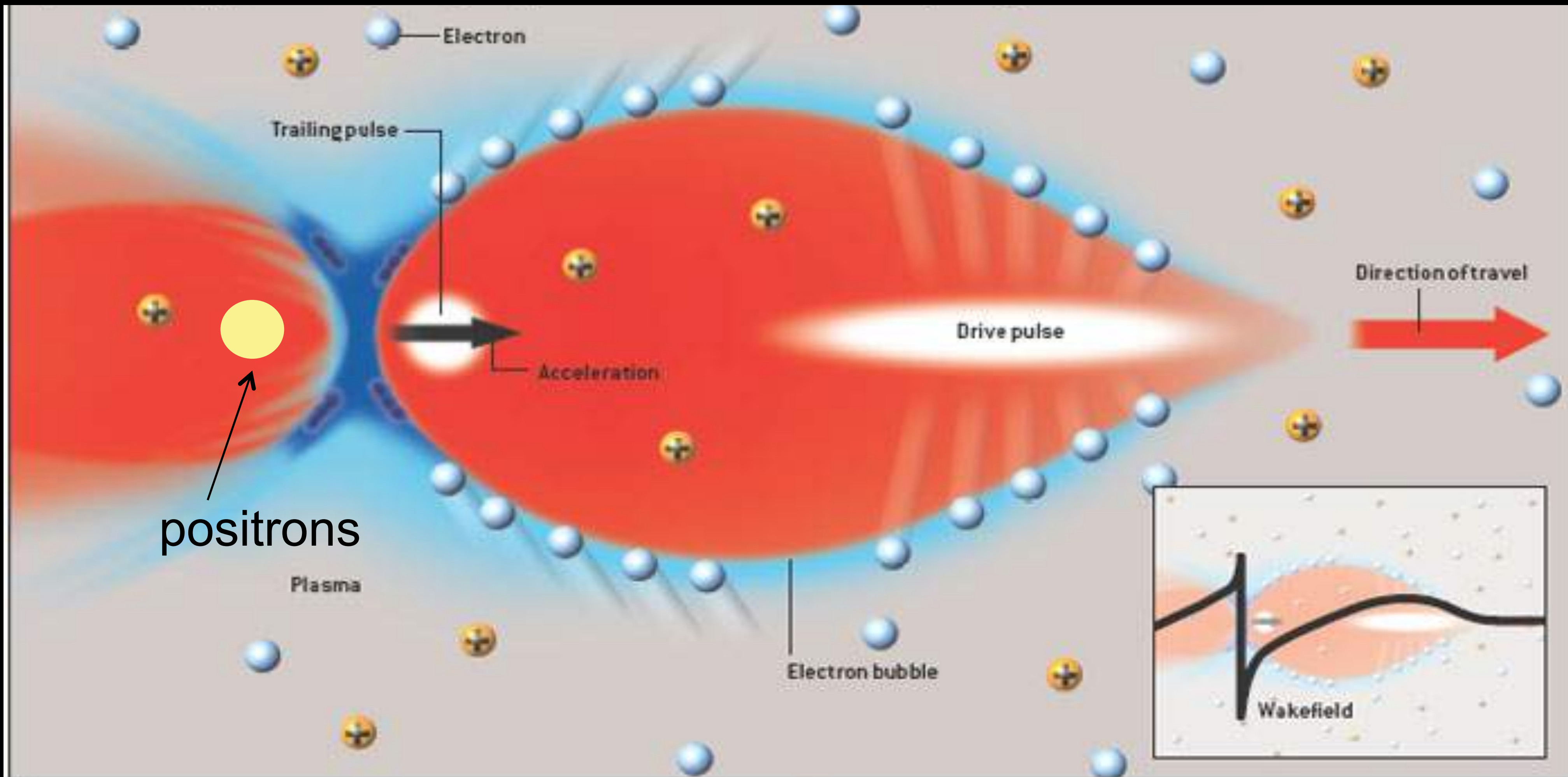
Breakdown limits metal:

$$E_s = 220(f\,[\mathrm{GHz}])^{1/3}\ \mathrm{MV/m}$$

Performance summary at CLIC specifications



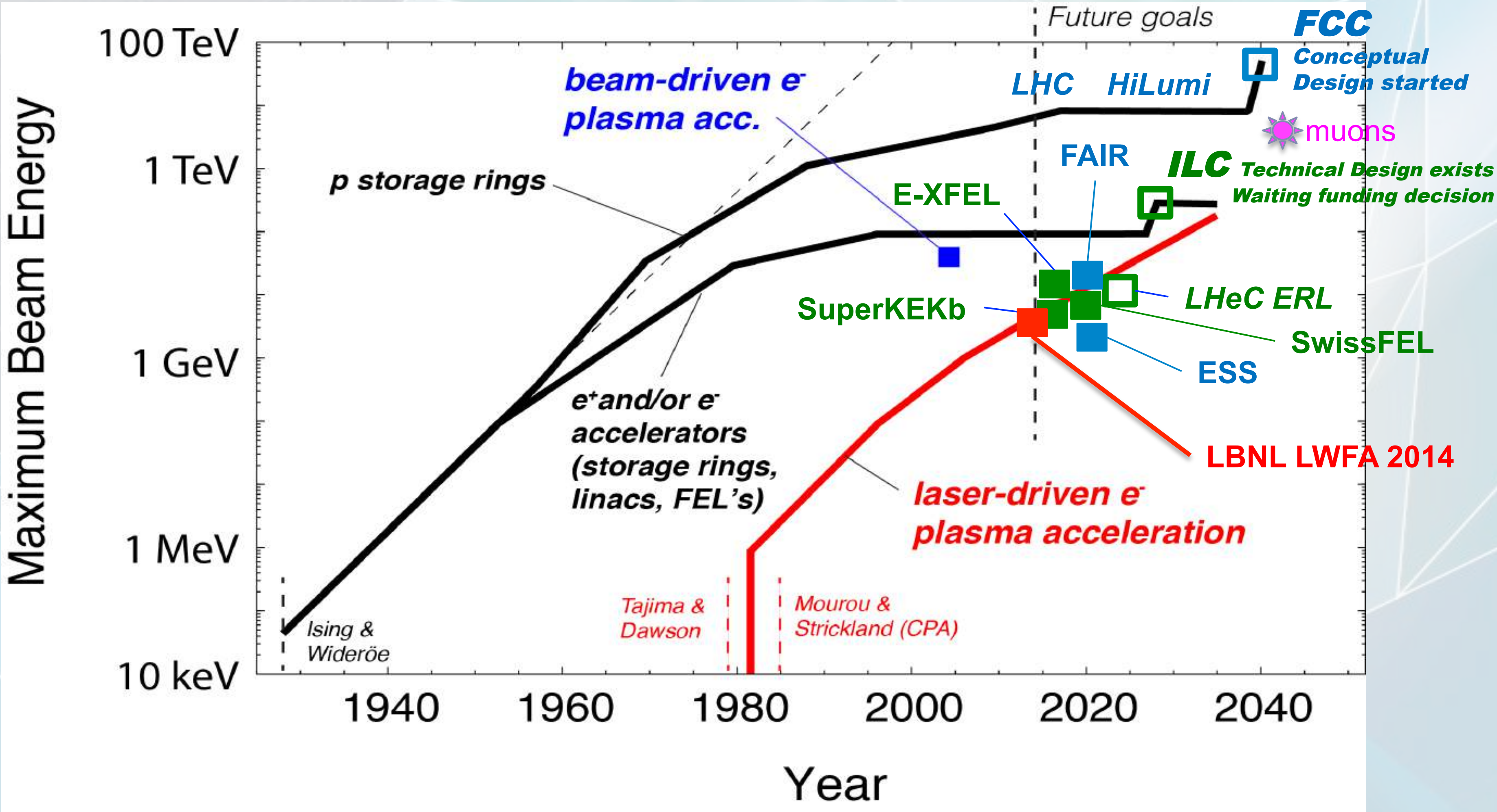
Plasma Accelerator



Breakdown limit?

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

Future of Accelerators



■ Hadron acc. project ■ Lepton acc. project

□ Hadron acc. proposal □ Lepton acc. proposal

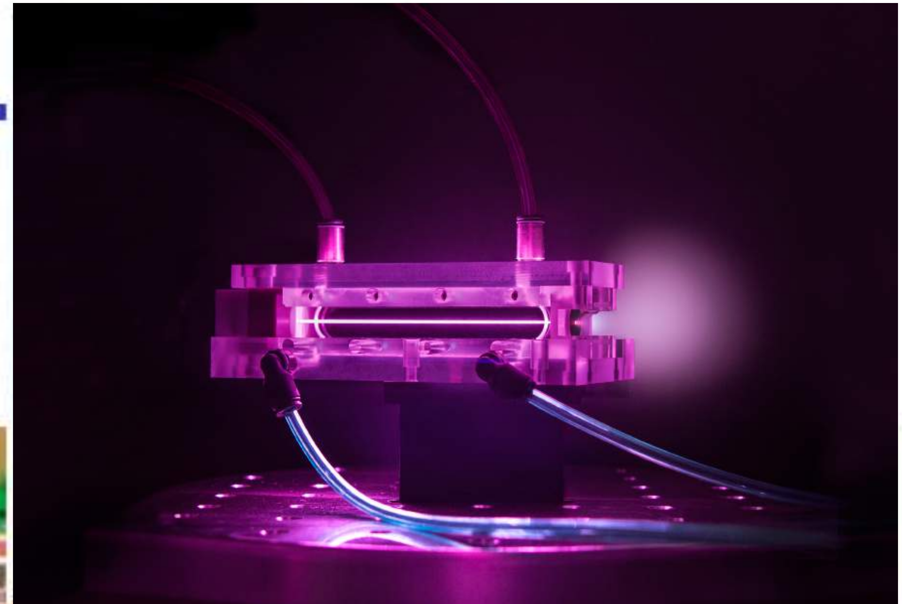
R. Assmann, EAAC 2015, 9/2015

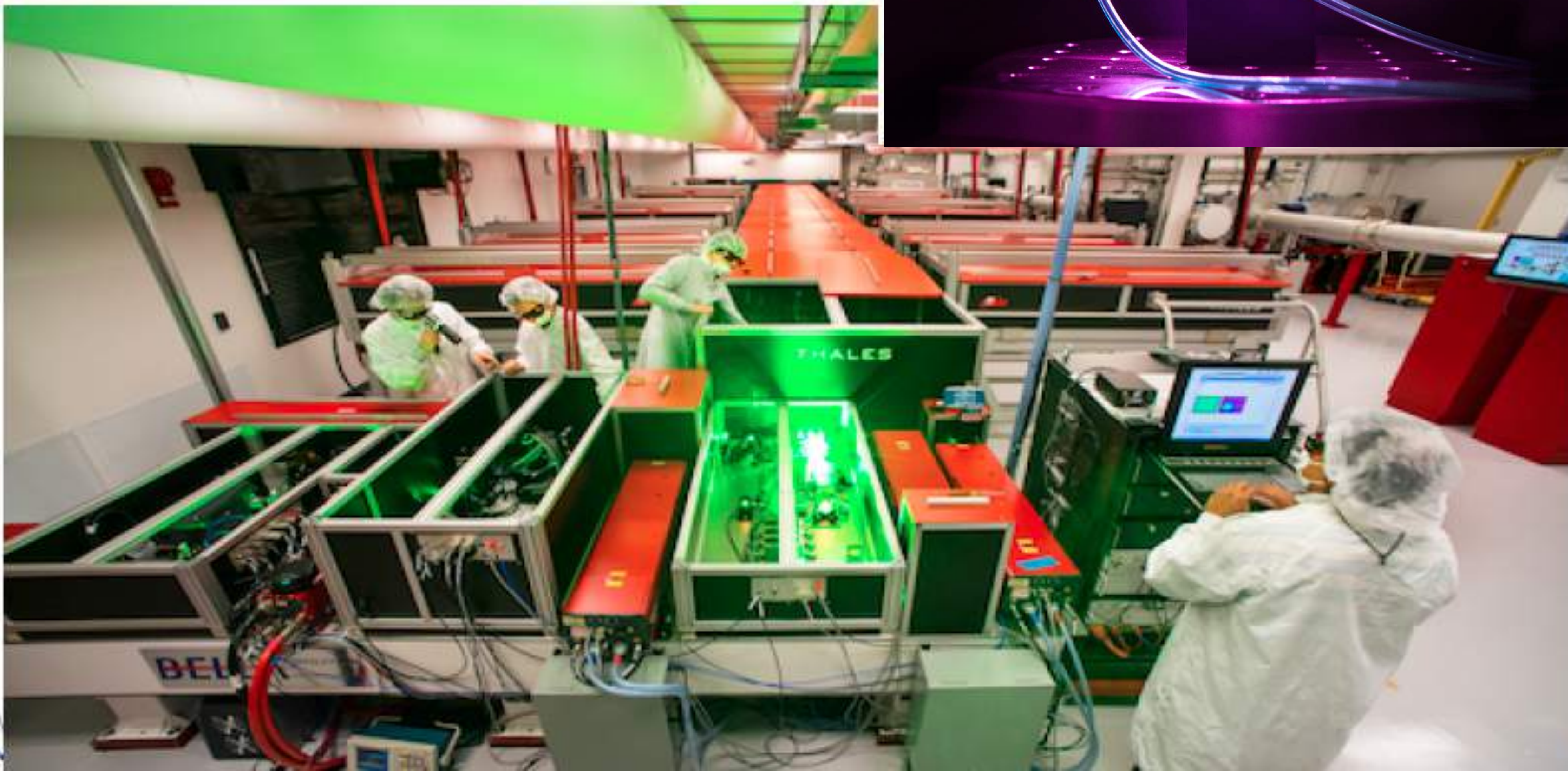
World Leader

BELLA LPWA facility:

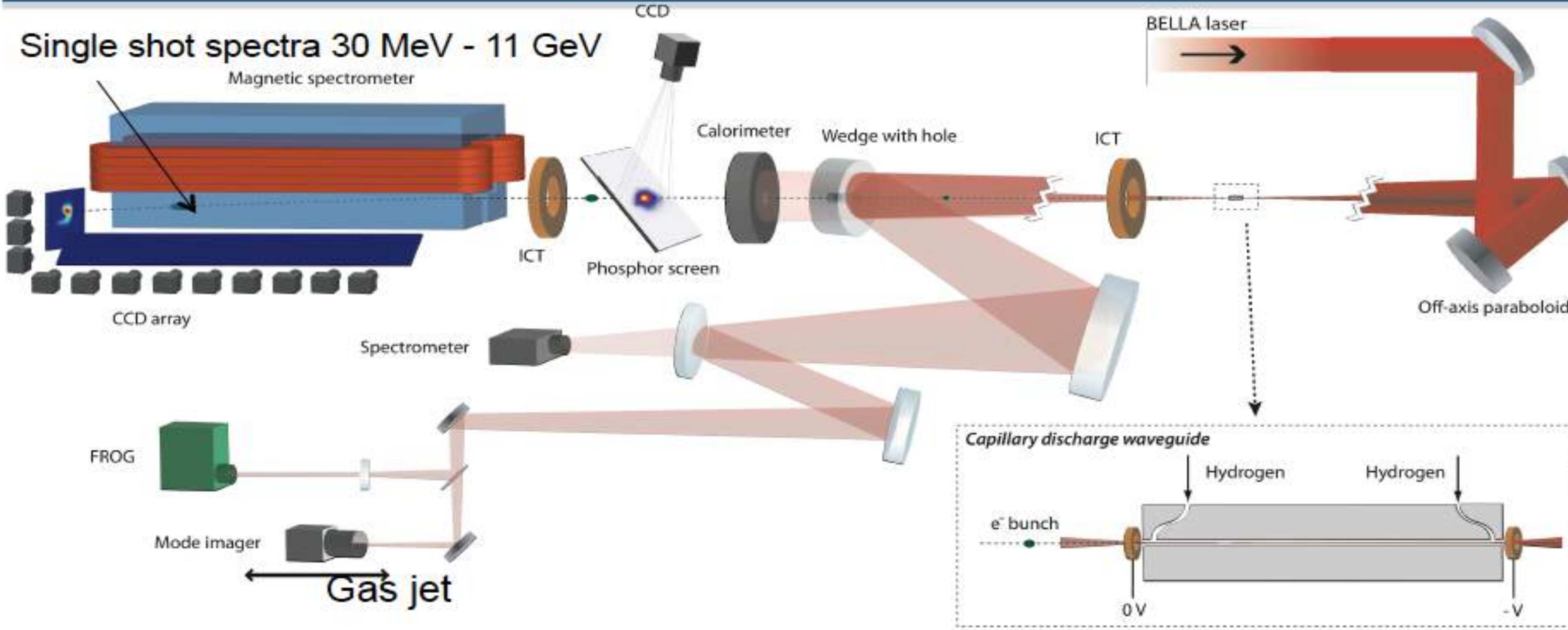
3 cm 1 GeV 40 TW laser ~1Hz

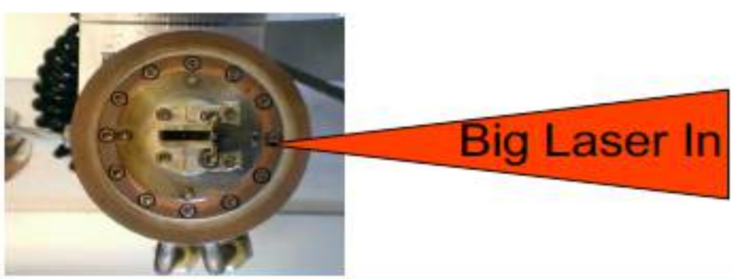
10-30 cm 5-10 GeV PW laser, ~1 Hz





Experiments at LBNL use the BELLA laser focused by a 14 m focal length off-axis paraboloid onto gas jet or capillary discharge targets

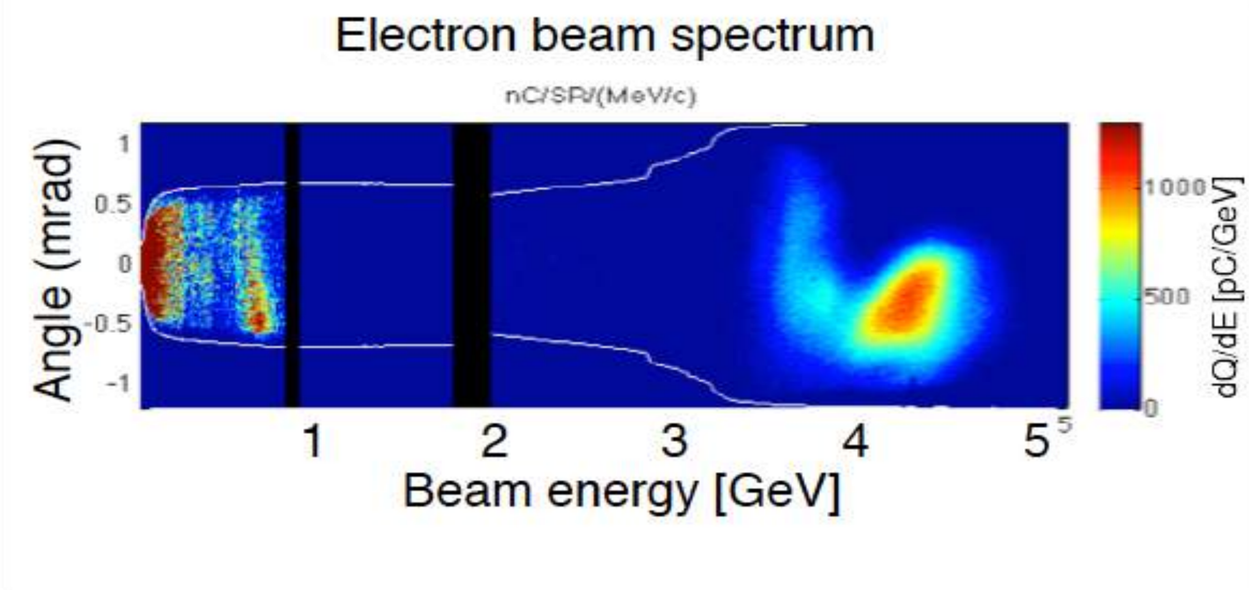


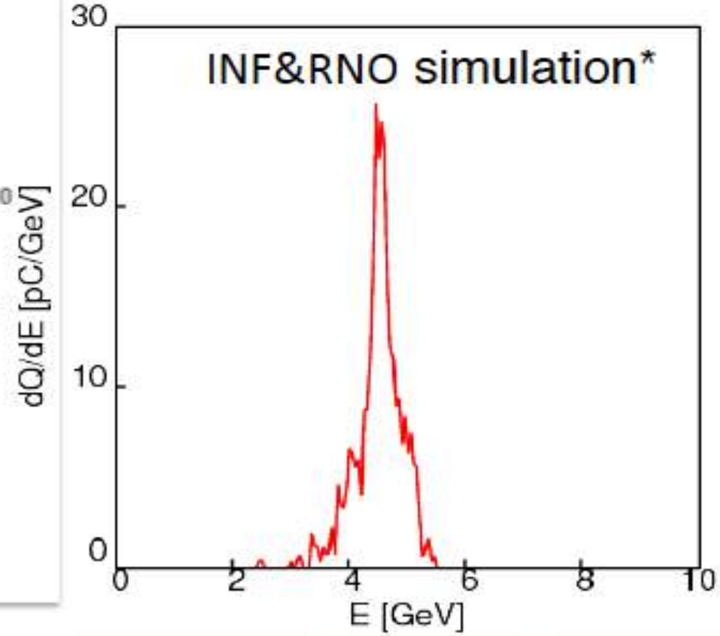


Capillary discharge

4.25 GeV beams have been obtained from 9 cm plasma channel powered by 310 TW laser pulses (15 J)

*C. Benedetti et al., proceedings of AAC2010, proceedings of ICAP2012





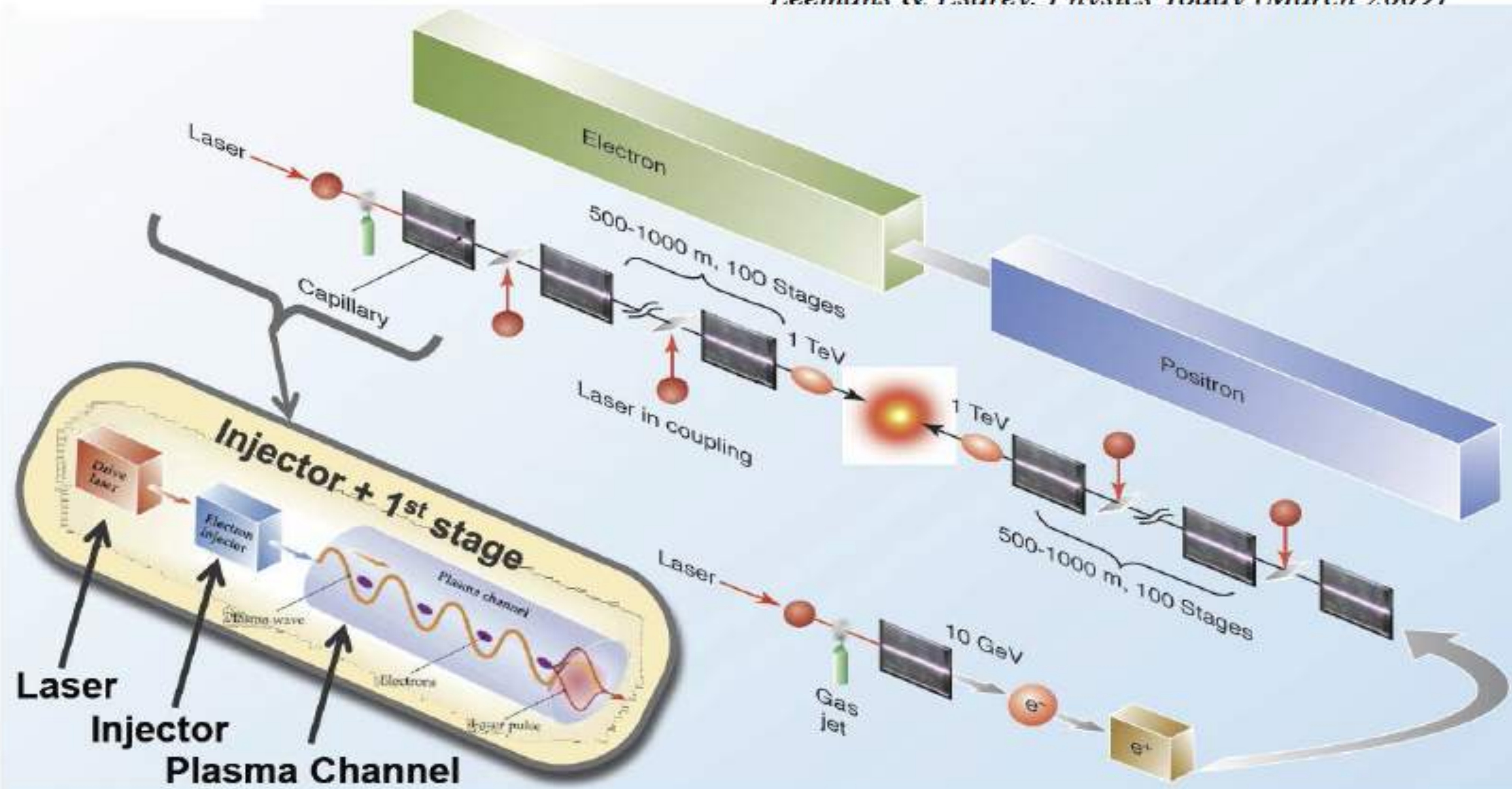
- **Laser** (E=15 J):
  - Measured) longitudinal profile (T_0= 40 fs)
  - Measured far field mode (w_0=53 µm)
- **Plasma:** parabolic plasma channel (length 9 cm, n_0~6-7x10^{17} cm^{-3})

	Exp.	Sim.
Energy	4.25 GeV	4.5 GeV
ΔE/E	5%	3.2%
Charge	~20 pC	23 pC
Divergence	0.3 mrad	0.6 mrad

W.P. Leemans et al.,PRL 2014

Laser-Plasma-Accelerator LC

Leemans & Esarey, Physics Today (March 2009)

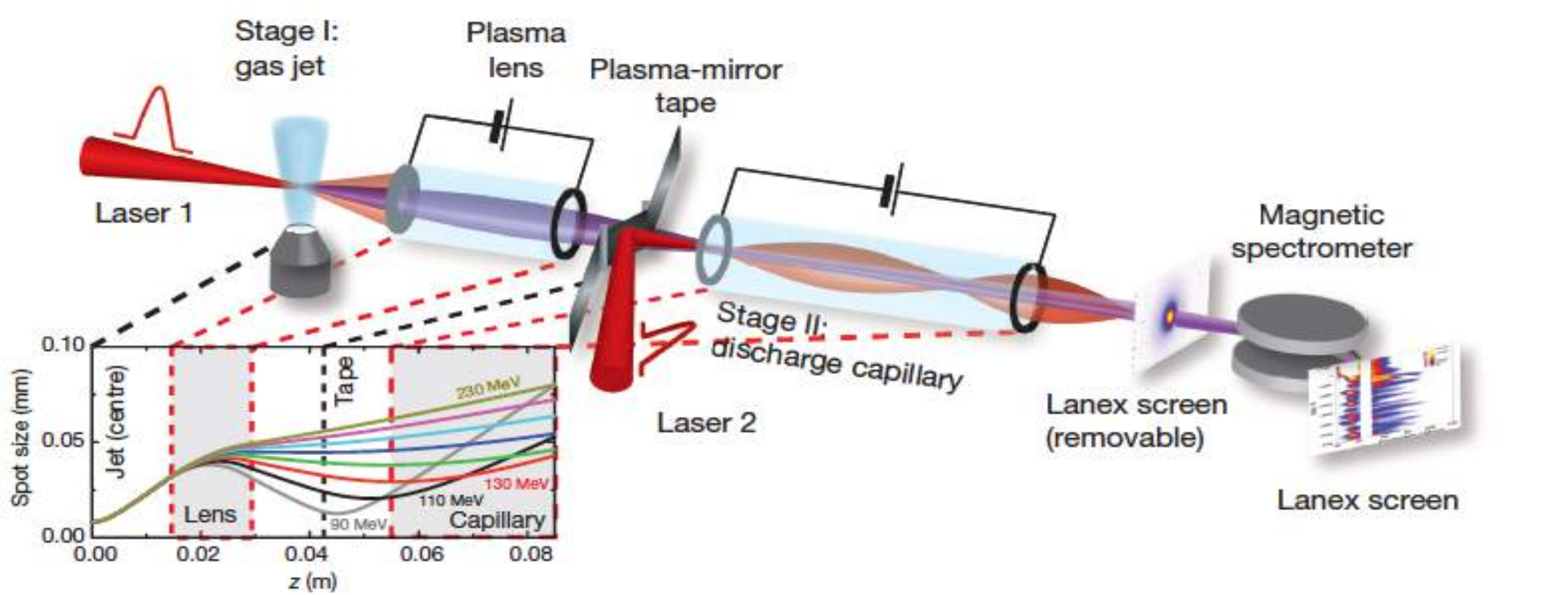


LETTER

doi:10.1038/nature16525

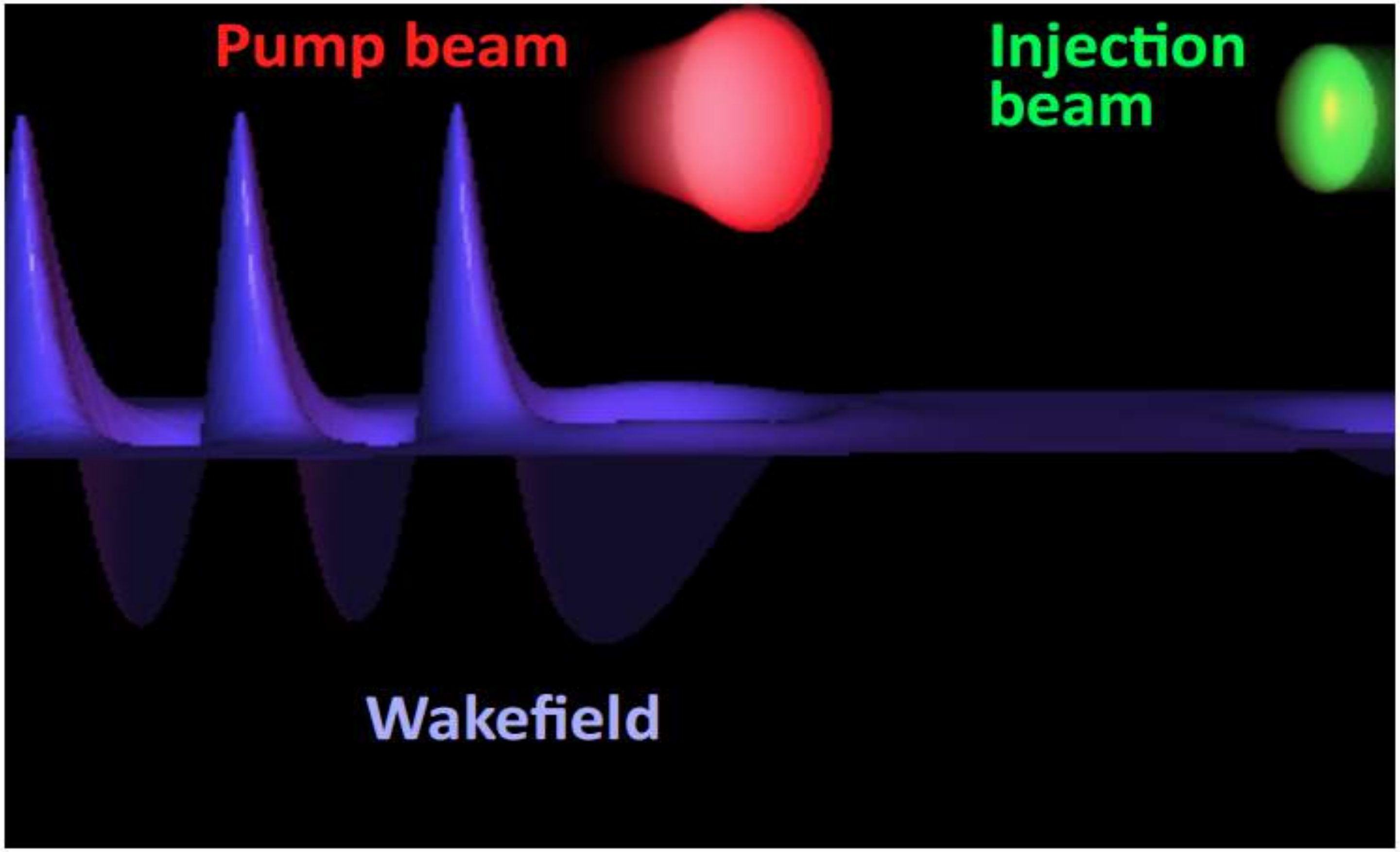
Multistage coupling of independent laser–plasma accelerators

S. Steinke[1], J. van Tilborg[1], C. Benedetti[1], C. G. R. Geddes[1], C. B. Schroeder[1], J. Daniels[1,3], K. K. Swanson[1,2], A. J. Gonsalves[1], K. Nakamura[1], N. H. Matlis[1], B. H. Shaw[1,2], E. Esarey[1] & W. P. Leemans[1,2]



Colliding Laser Pulses Scheme

The first laser creates the accelerating structure, a second laser beam is used to heat electrons



Theory : E. Esarey *et al.*, PRL **79**, 2682 (1997), H. Kotaki *et al.*, PoP **11** (2004)
Experiments : J. Faure *et al.*, Nature **444**, 737 (2006)

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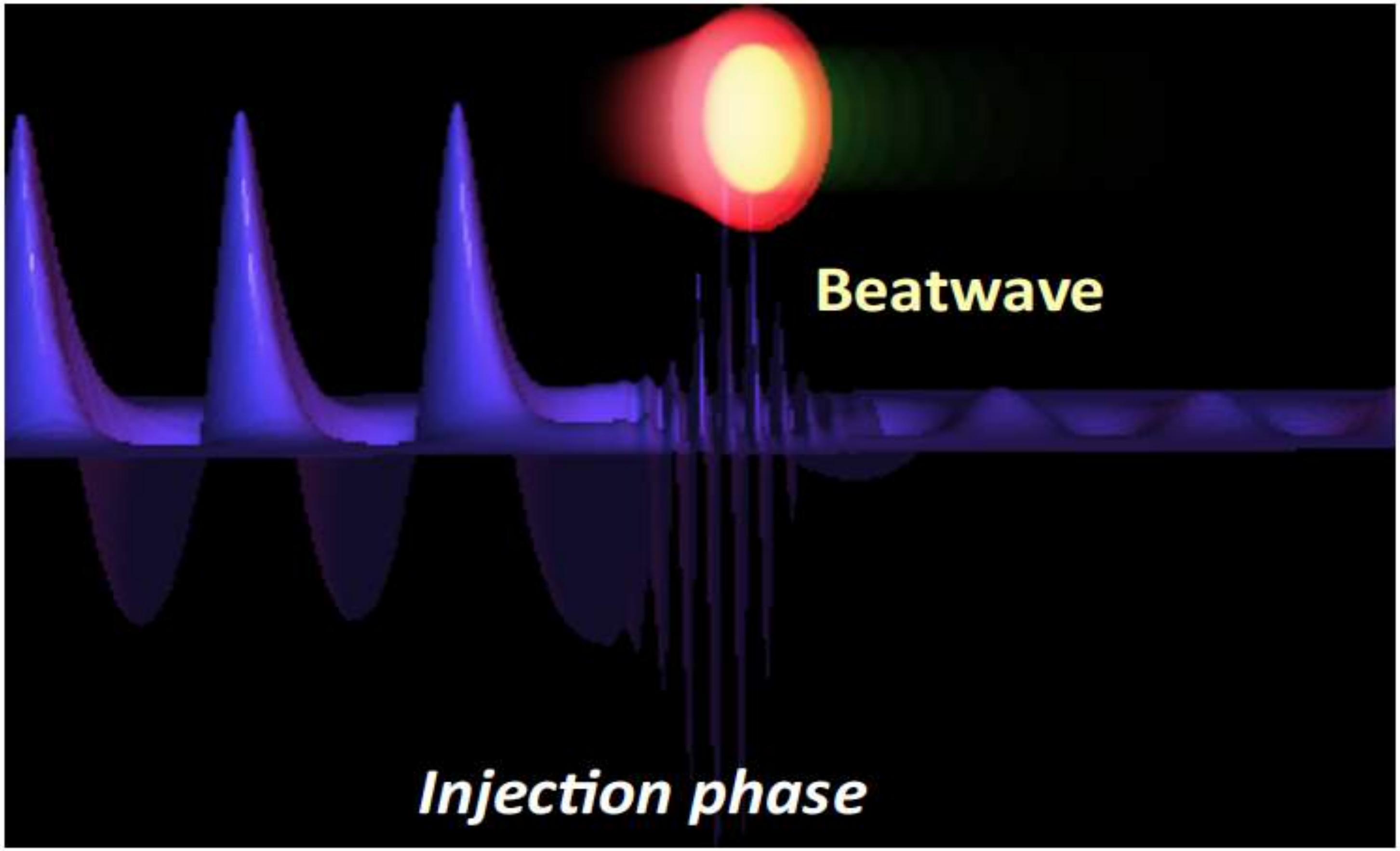

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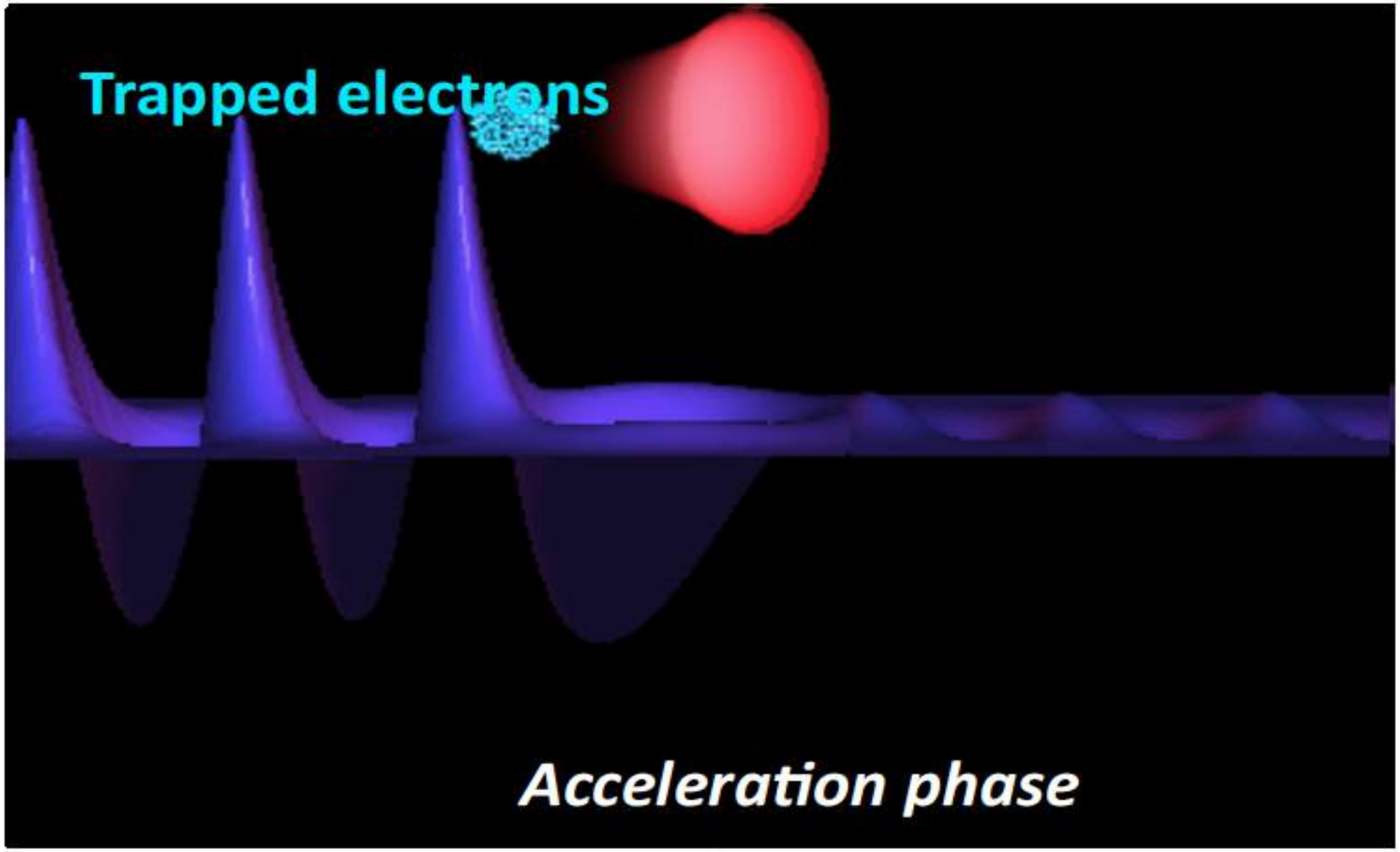
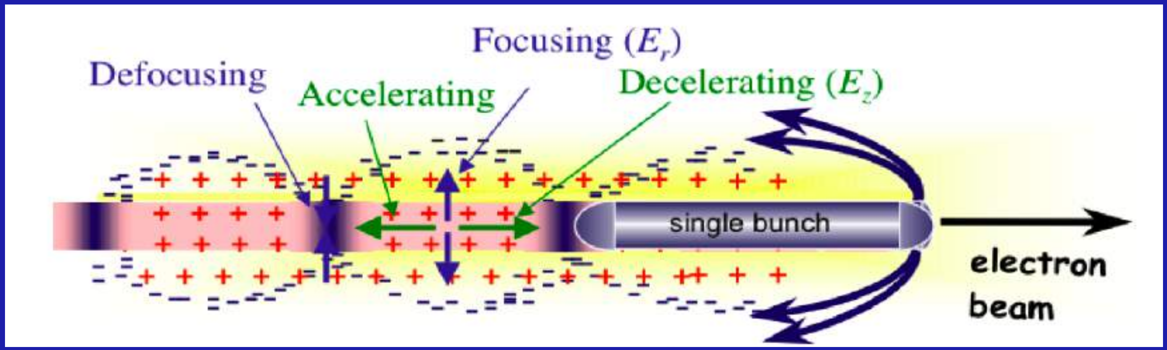
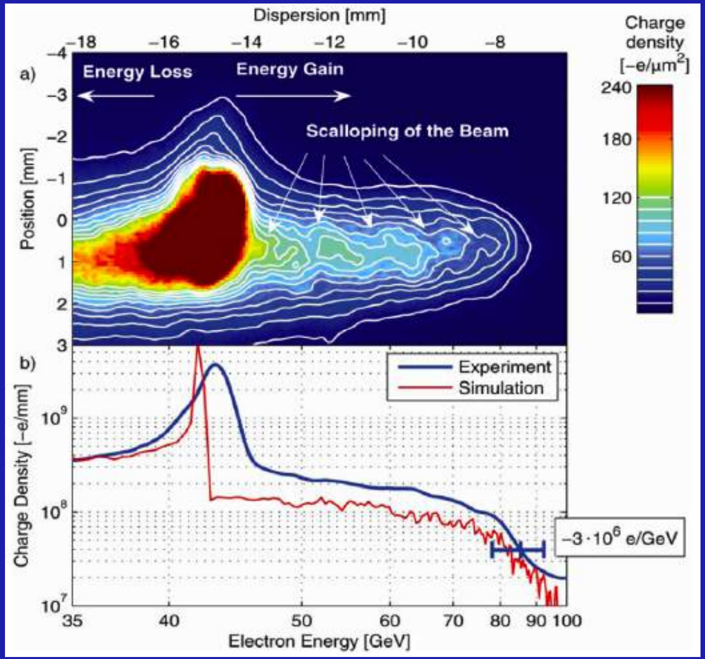


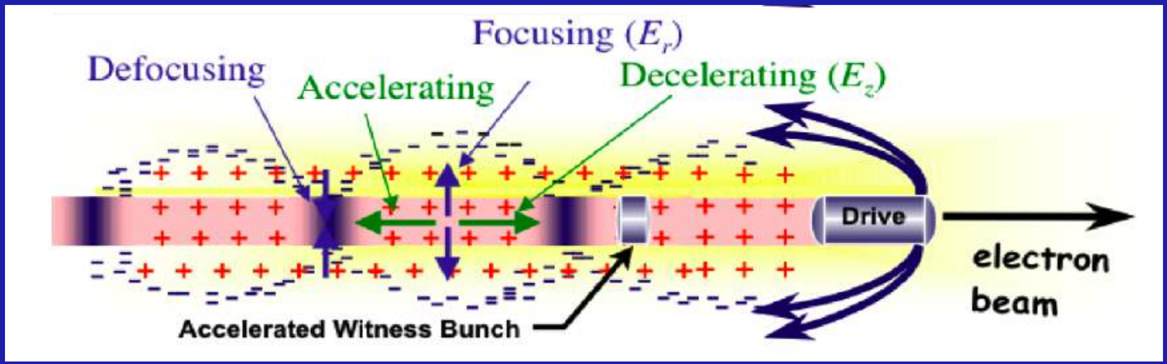
Theory : E. Esarey *et al.*, PRL **79**, 2682 (1997), H. Kotaki *et al.*, PoP **11** (2004)
Experiments : J. Faure *et al.*, Nature **444**, 737 (2006)

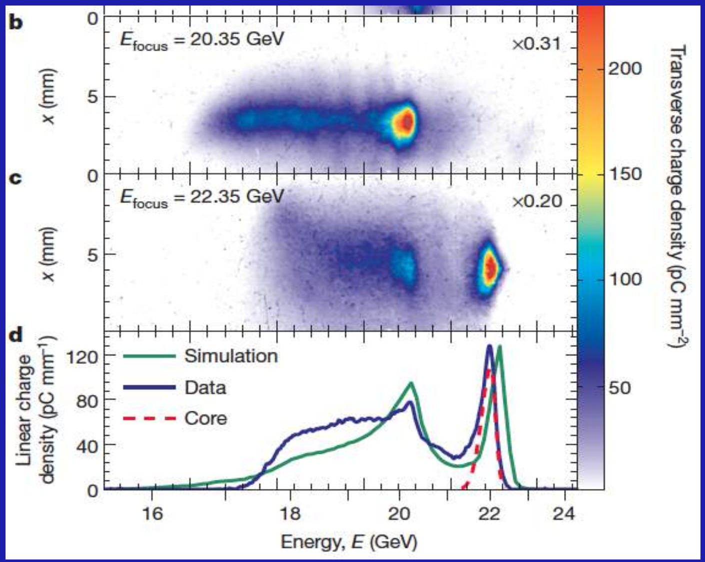
Beam Driven Plasma





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).

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

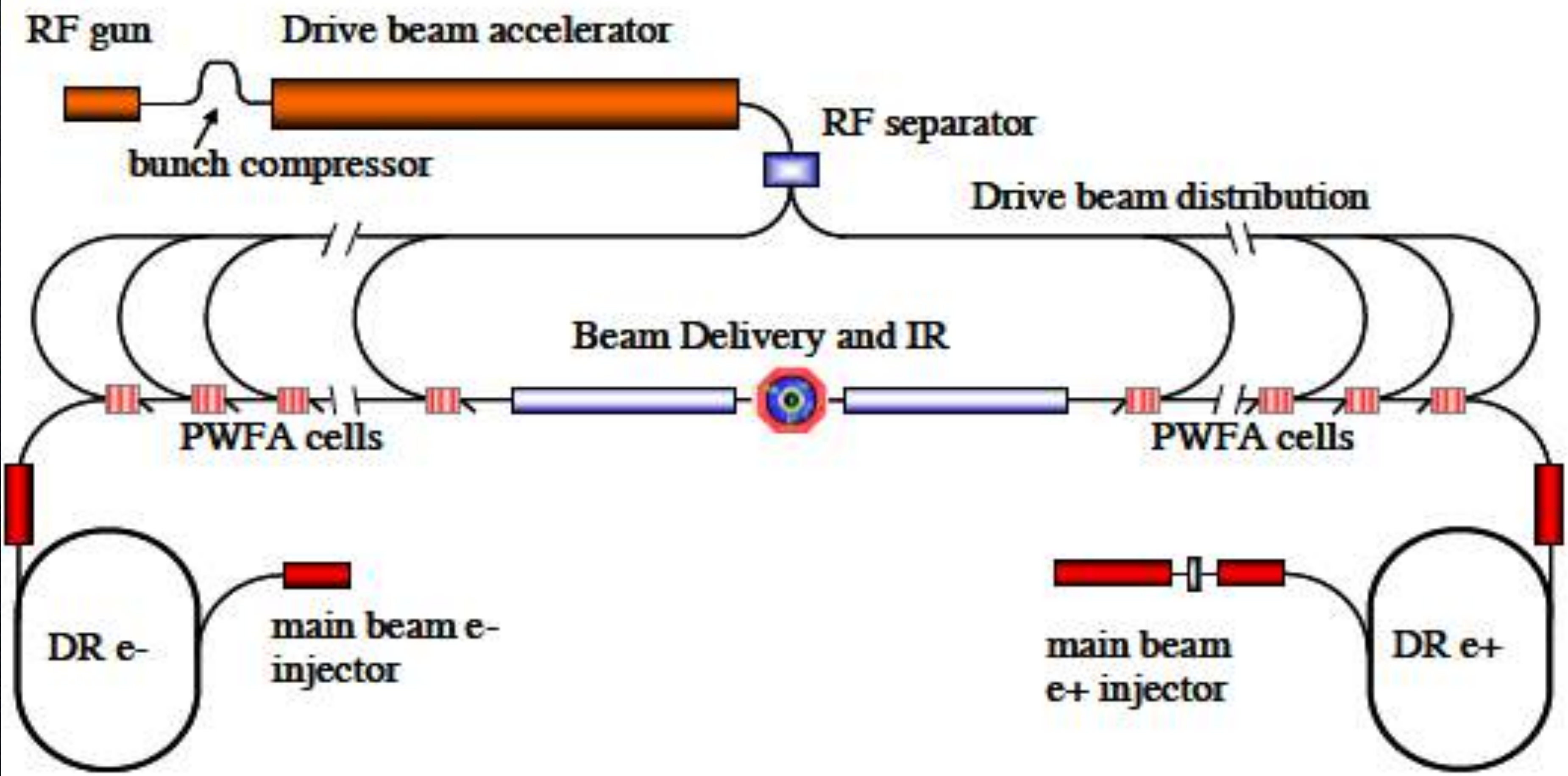
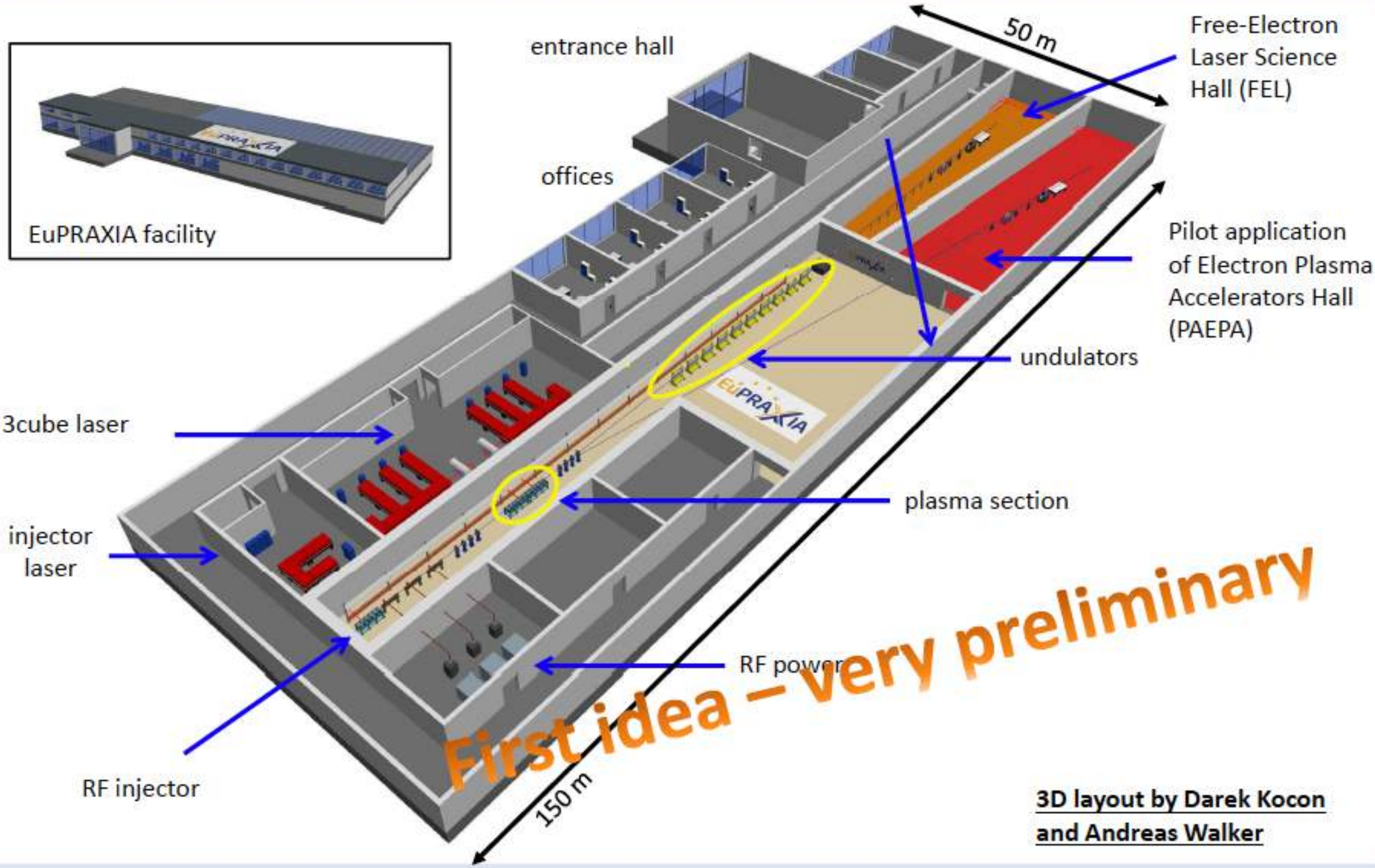


Fig. 1: Concept for a multi-stage PWFA Linear Collider.

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.

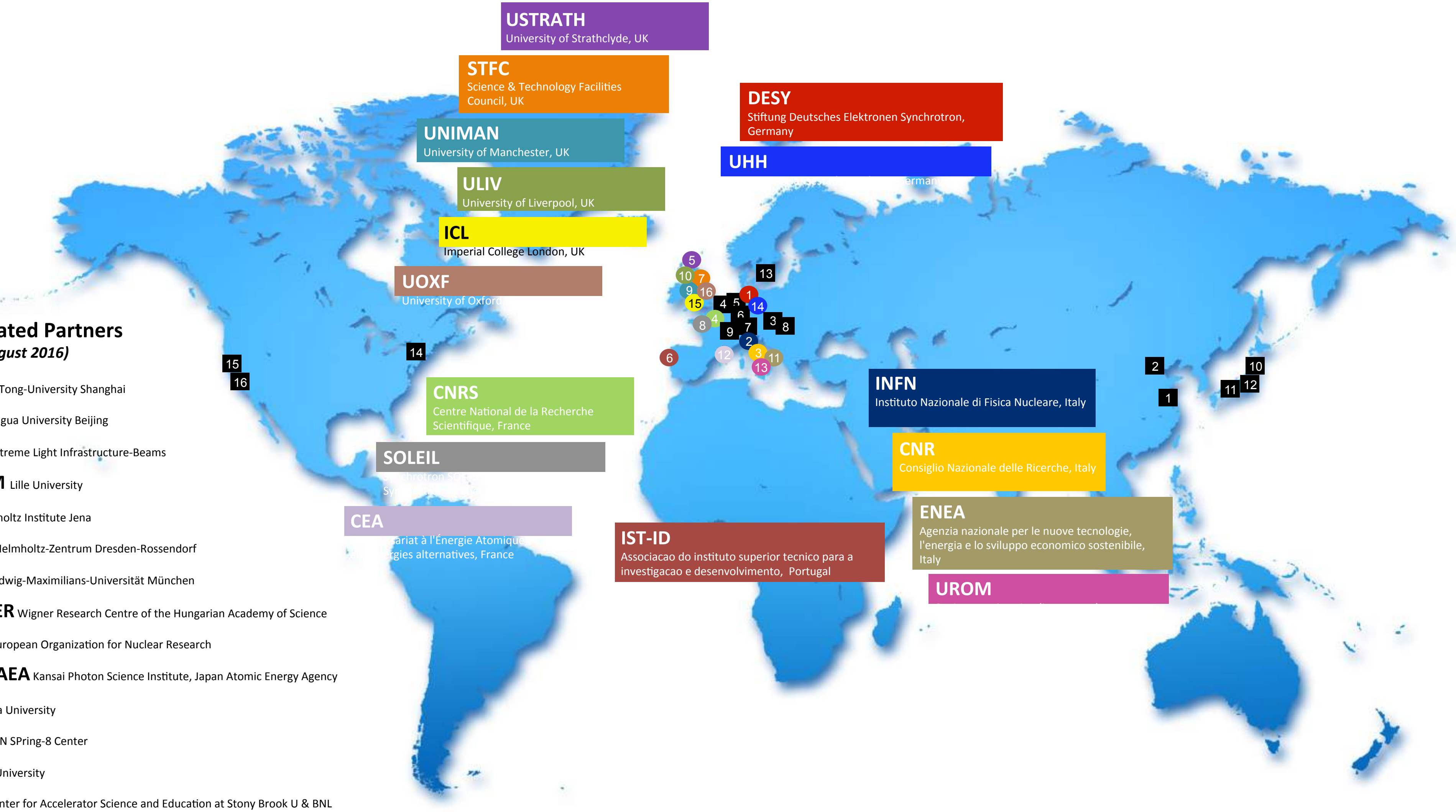
draft of facility layout



3D layout by Darek Kocon and Andreas Walker

Participating Institutions

Horizon 2020

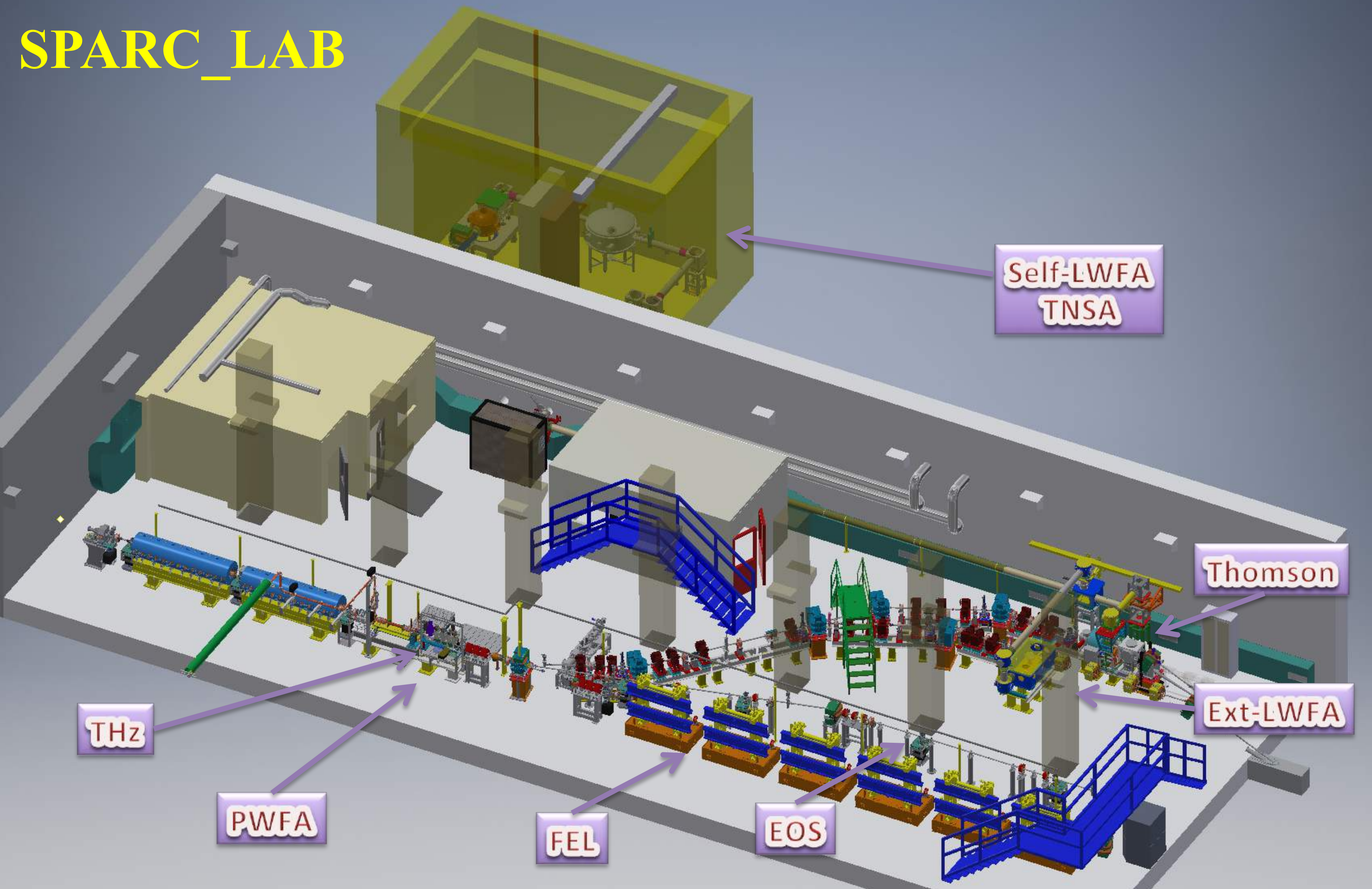


Associated Partners

(as of August 2016)

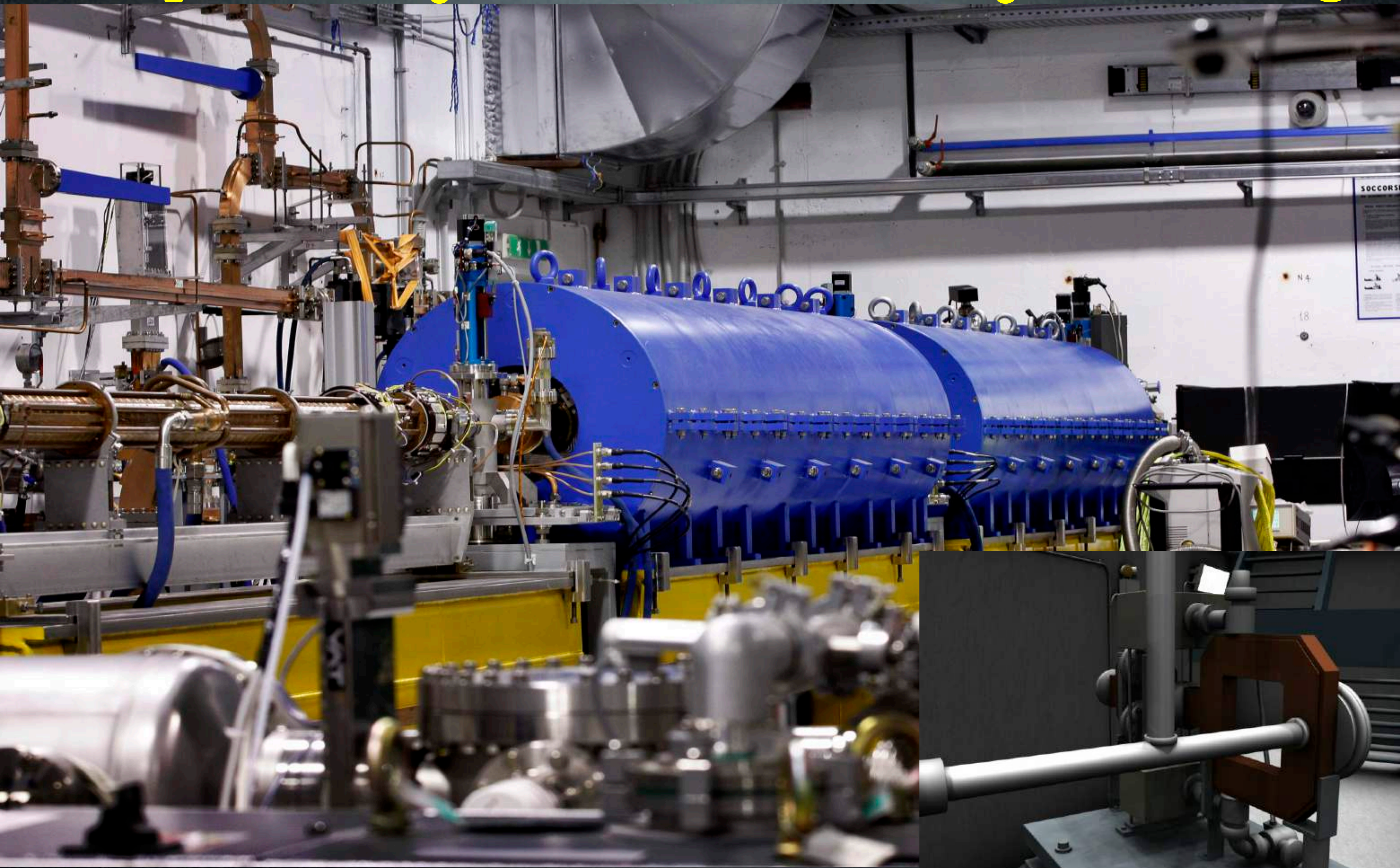
1 **JUS** Jiao Tong-University Shanghai
2 **TUB** Tsingua University Beijing
3 **ELI-B** Extreme Light Infrastructure-Beams
4 **PHLAM** Lille University
5 **HIJ** Helmholtz Institute Jena
6 **HZDR** Helmholtz-Zentrum Dresden-Rossendorf
7 **LMU** Ludwig-Maximilians-Universität München
8 **WIGNER** Wigner 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

SPARC_LAB

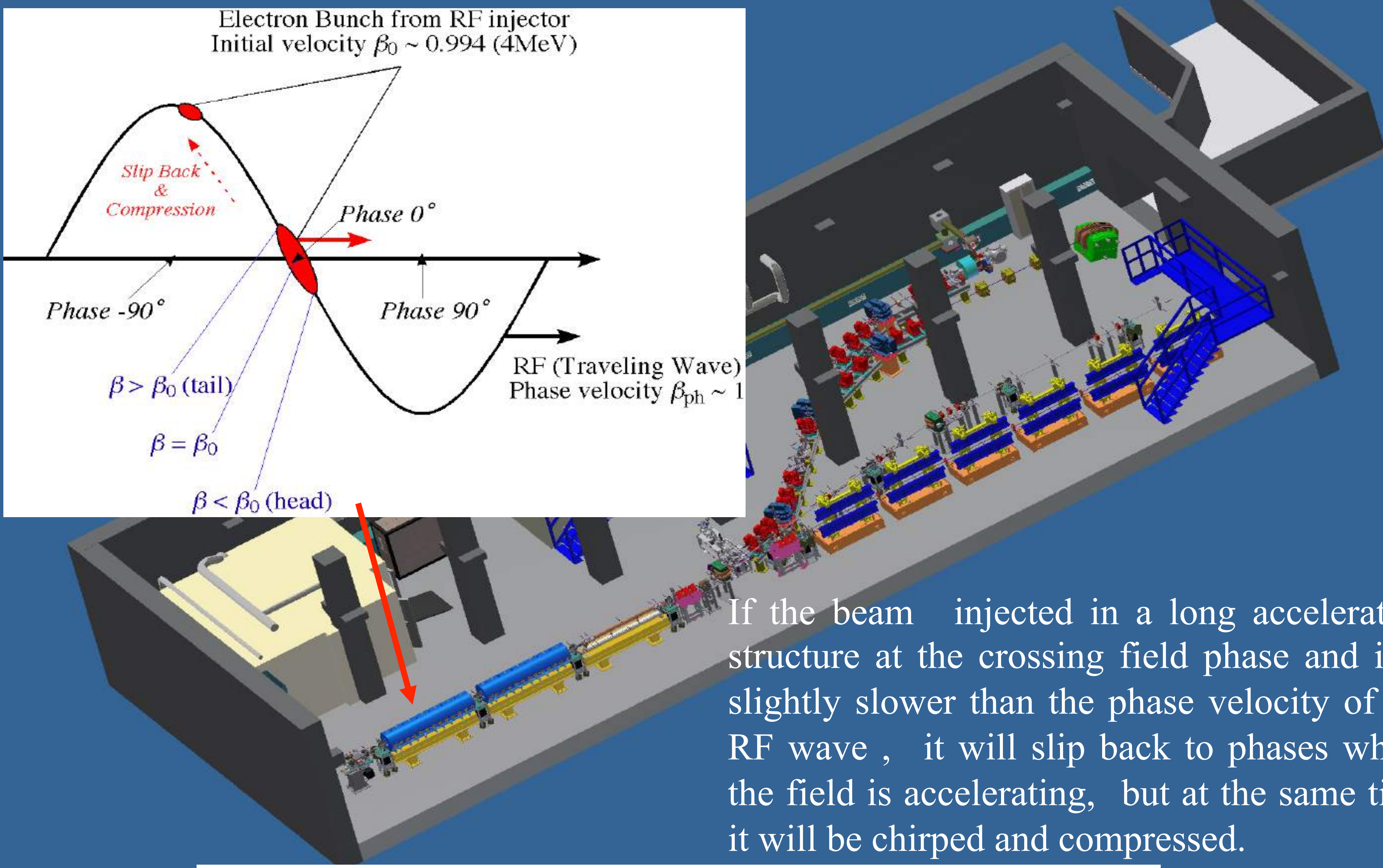


Ferrario, M., et al. "SPARC_LAB present and future." NIMB 309 (2013): 183-188.

HB photo- injector with Velocity Bunching



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.

Serafini L., Ferrario M. "Velocity bunching in photo-injectors." AIP conference proceedings. 2001.

Ferrario, M.et al. "Experimental demonstration of emittance compensation with velocity bunching." PRL 104.5 2010.

Thz source

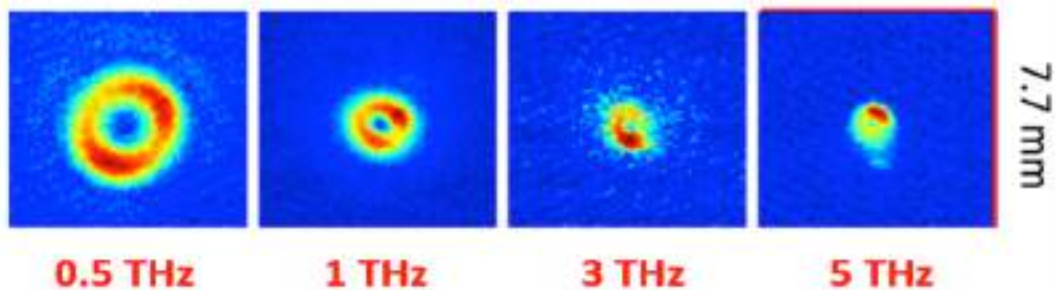
nature COMMUNICATIONS

ARTICLE

Received 16 Jun 2015 | Accepted 23 Mar 2016 | Published 26 Apr 2016 DOI: 10.1038/ncomms11421 OPEN

Strong nonlinear terahertz response induced by Dirac surface states in Bi_2Se_3 topological insulator

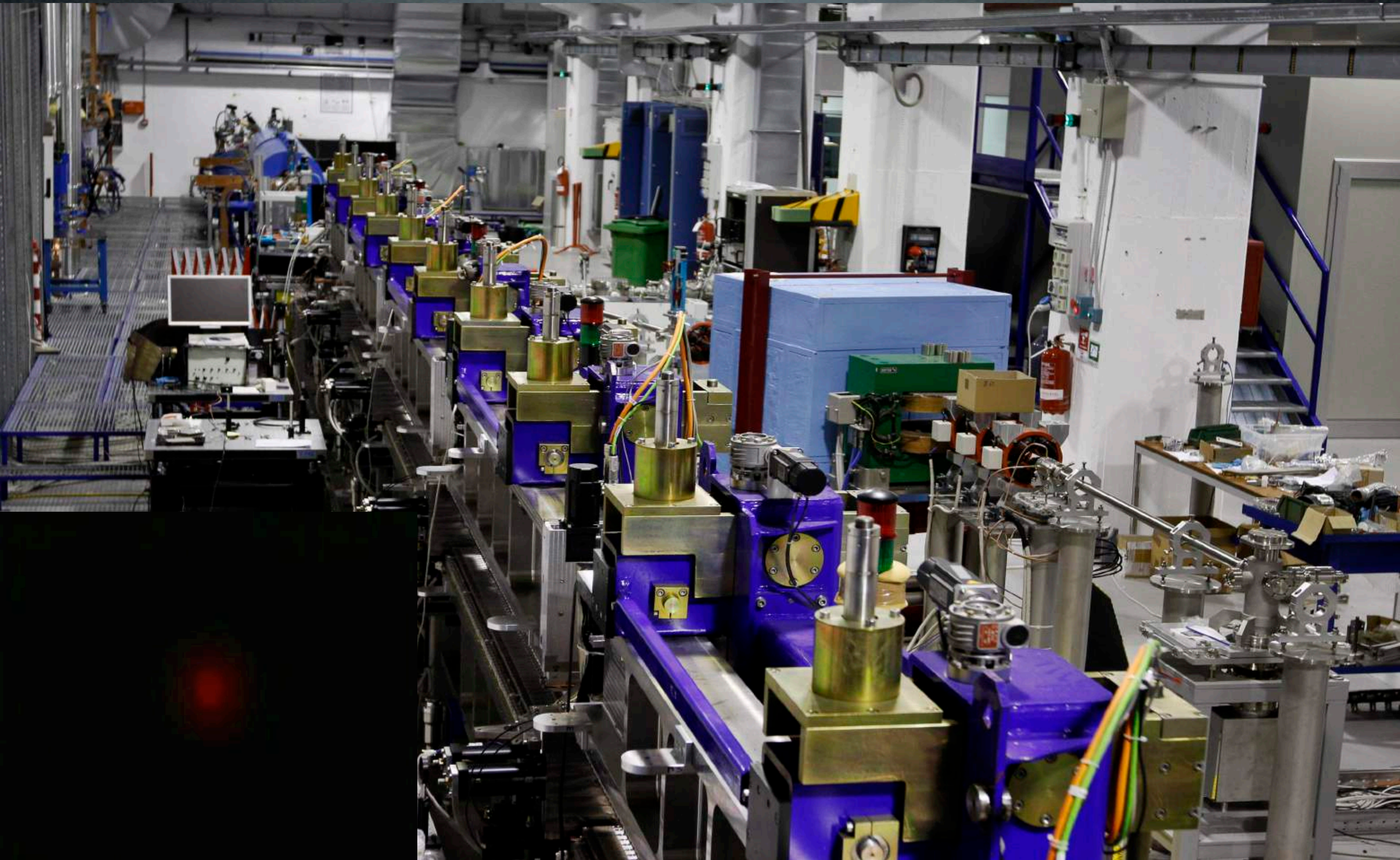
Flavio Giorgianni[1], Enrica Chiadroni[2], Andrea Rovere[1], Mariangela Cestelli-Guidi[2], Andrea Perucchi[3], Marco Bellaveglia[2], Michele Castellano[2], Domenico Di Giovenale[2], Giampiero Di Pirro[2], Massimo Ferrario[2], Riccardo Pompili[2], Cristina Vaccarezza[2], Fabio Villa[2], Alessandro Cianchi[4], Andrea Mostacci[5], Massimo Petrarca[5], Matthew Brahlek[6], Nikesh Koirala[6], Seongshik Oh[6] & Stefano Lupi[1]



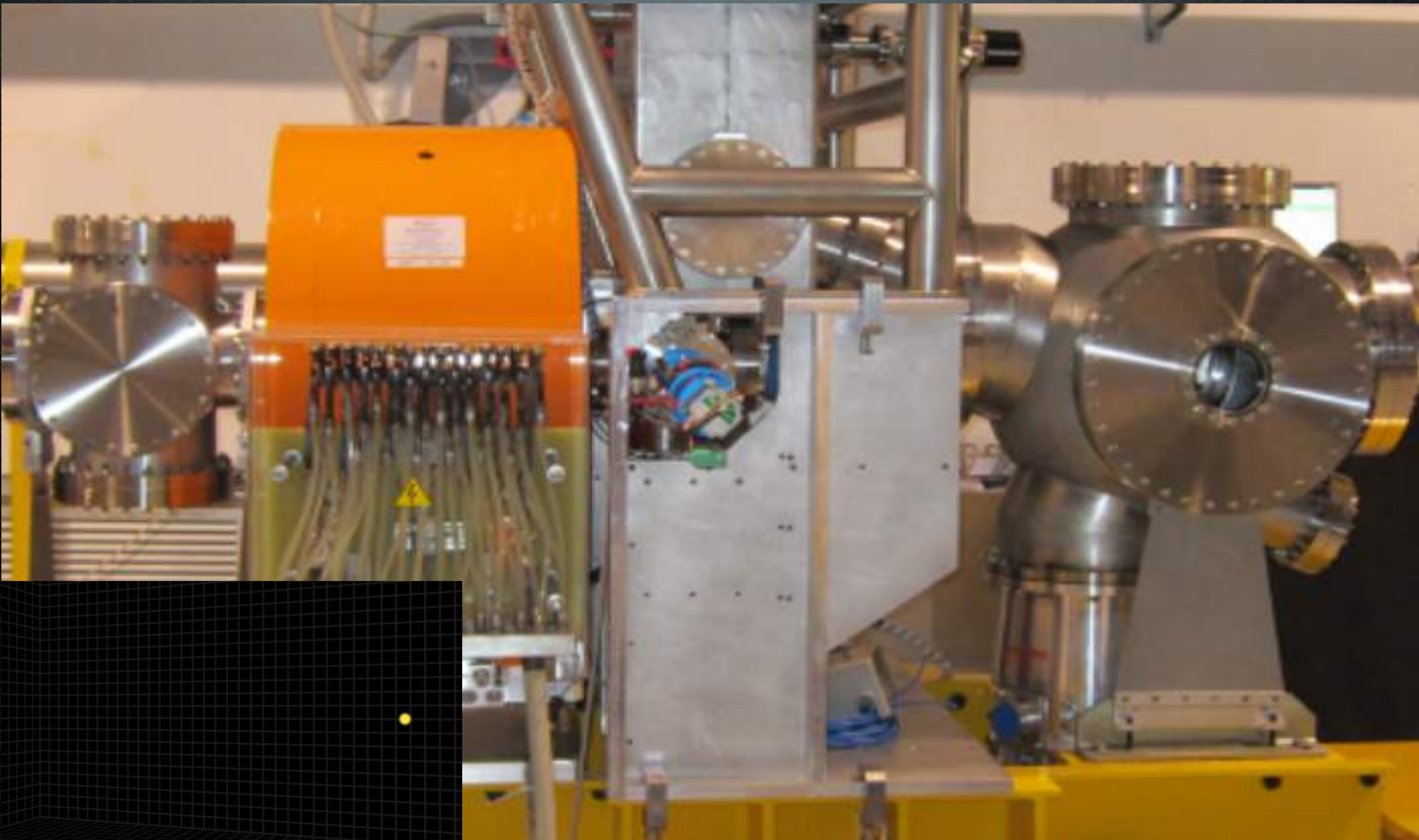
THz radiation parameters	
Integrated Energy/pulse (uJ)	35
Electric field (MV/cm)	1.6
Pulse duration (fs)	~100
BW (THz)	0.3* - 5**

E. C… 2013)

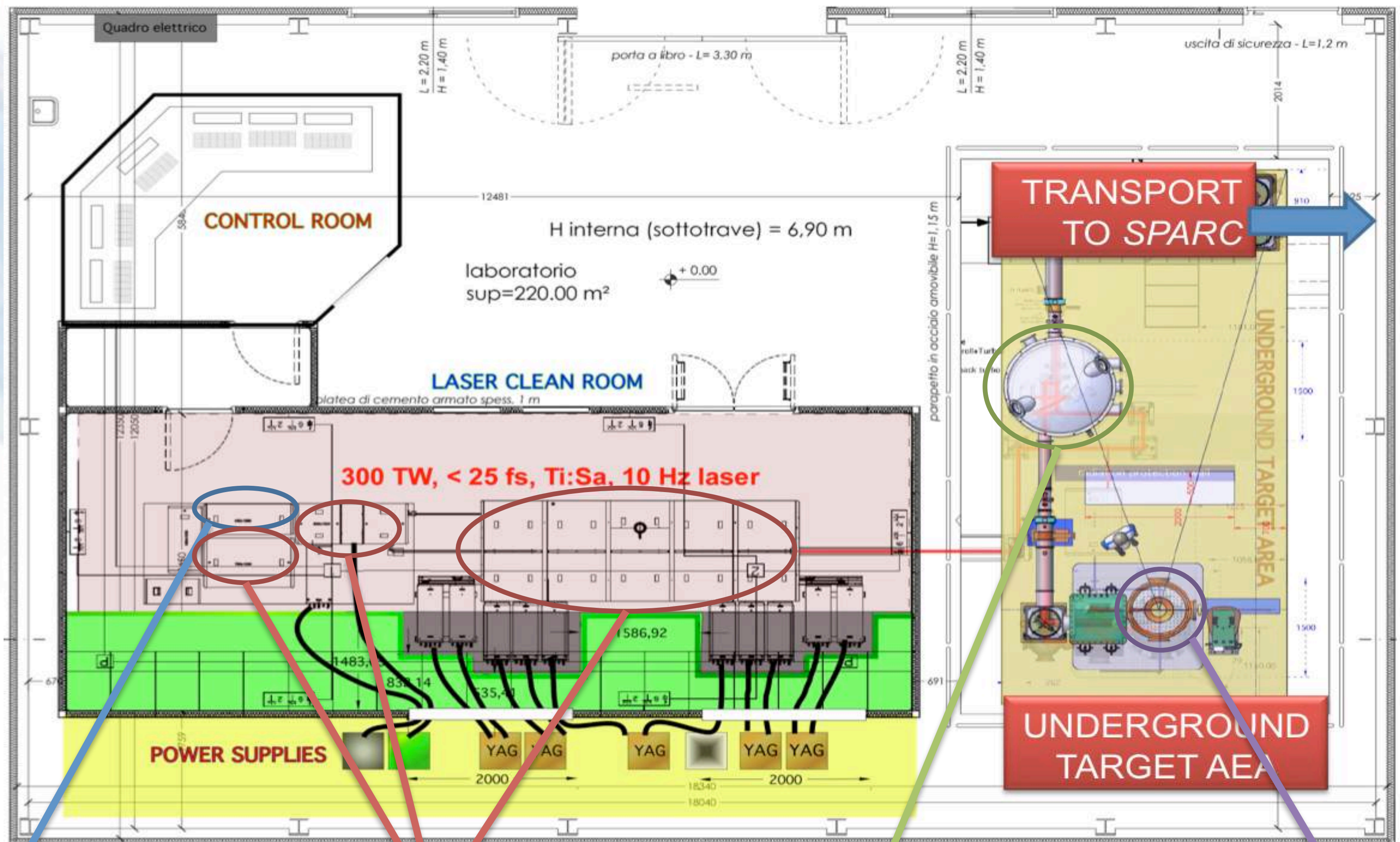
Free Electron Laser



Thomson back-scattering source



Ti:Sa FLAME laser



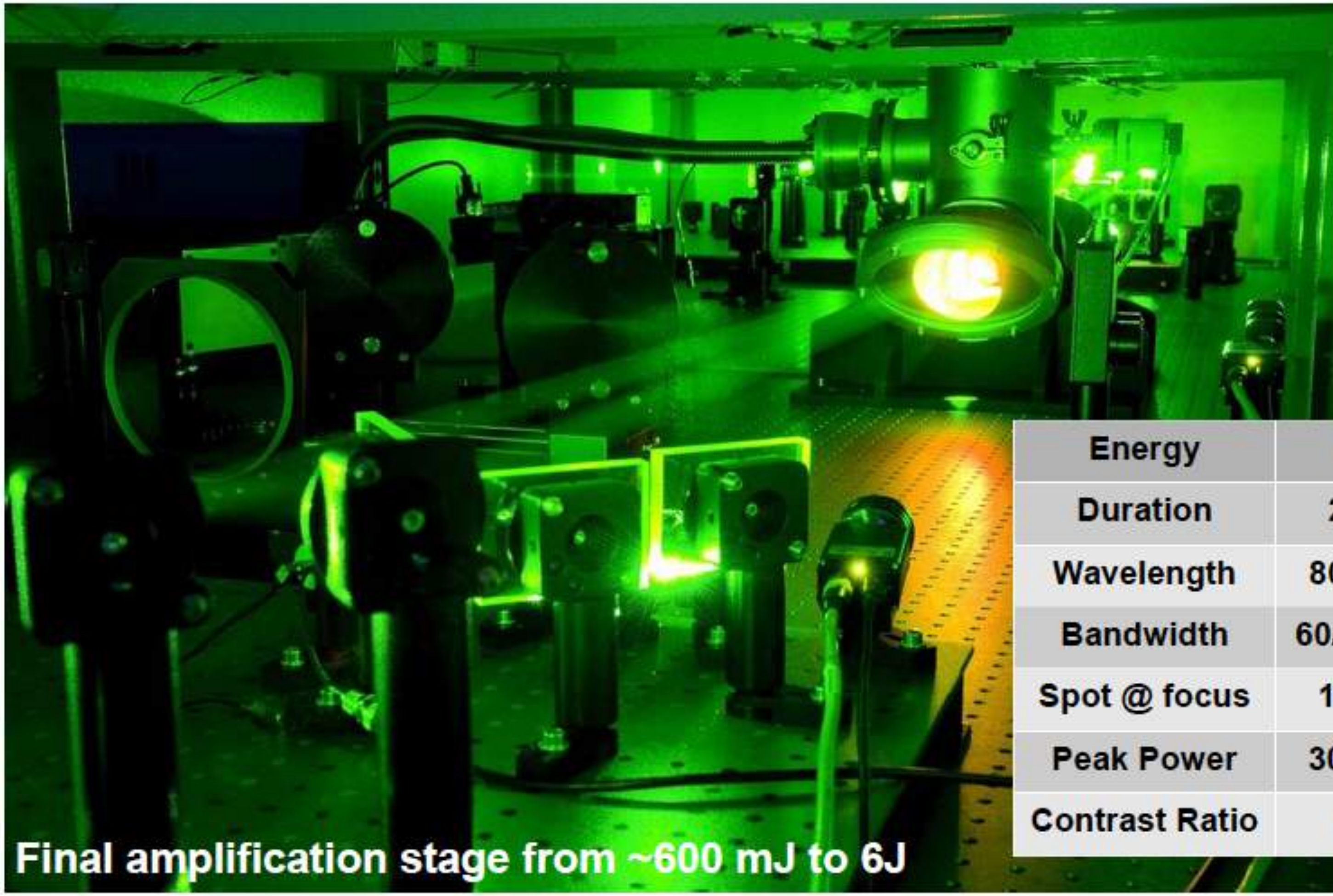
Stretcher

Amplifiers

Compressor

LWFA
Electron Self Injection
And
Protons

Ti:Sa FLAME laser

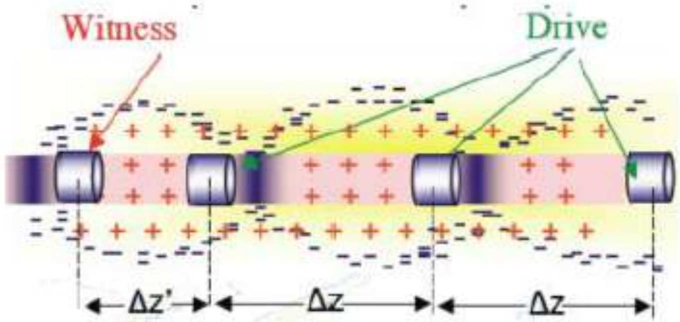


Final amplification stage from ~600 mJ to 6J

Energy	6 J
Duration	23 fs
Wavelength	800 nm
Bandwidth	60/80 nm
Spot @ focus	10 μm
Peak Power	300 TW
Contrast Ratio	10^{10}

Plasma-based acceleration techniques

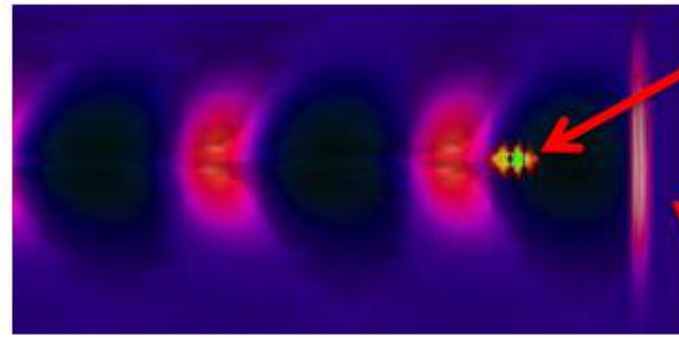
resonant-PWFA



- A train of three electron bunches (driver bunches) is sent through a capillary discharge
- A resonant plasma wave is then excited in plasma
- A fourth electron beam (witness beam) uses this wave to be accelerated

$n_e = 2 \times 10^{16}$ cm^{-3}
$\lambda_p = 300 \mu m$
Capillary 1mm
Hydrogen

external injection LWFA



- A laser beam excites plasma waves in a capillary filled with gas
- A high brightness electron beam uses this wave to be accelerated

$n_e = 1 \times 10^{17}$ cm^{-3}
$\lambda_p = 100 \mu m$
Capillary 100 μm
Hydrogen

Laser Comb technique: generation of a train of short bunches

(Parmela code)

Charge vs. Time

Energy vs. Time

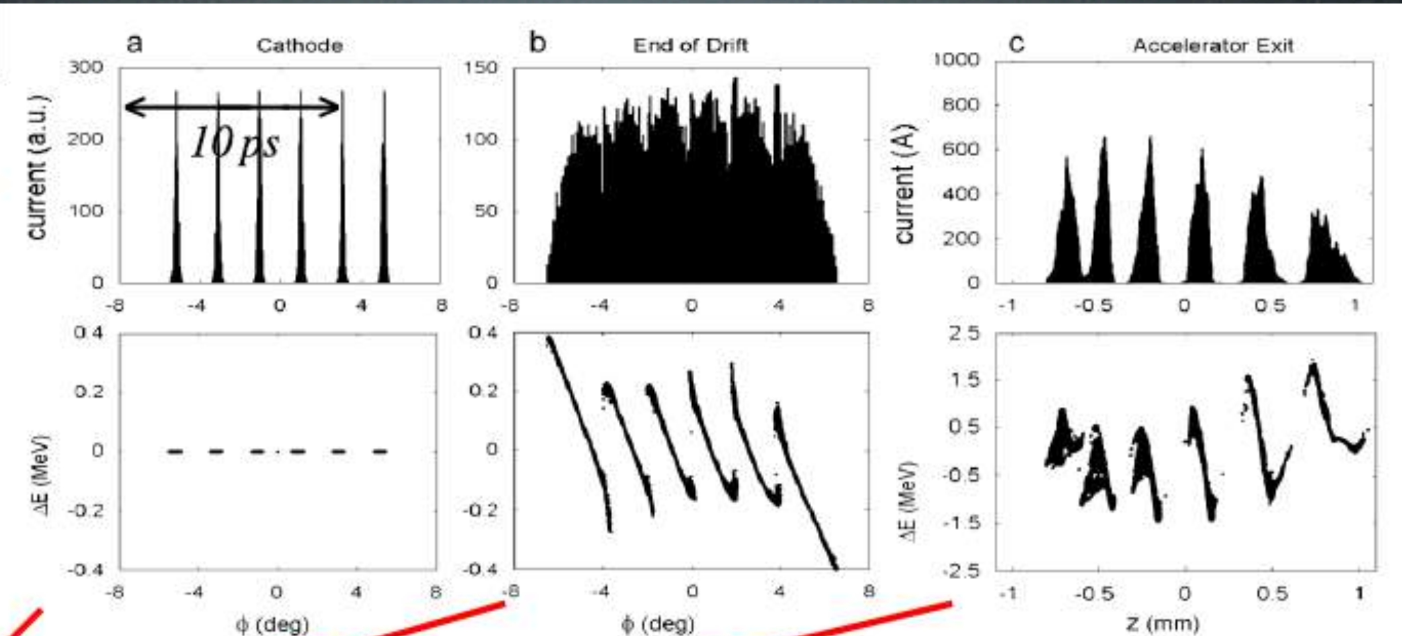
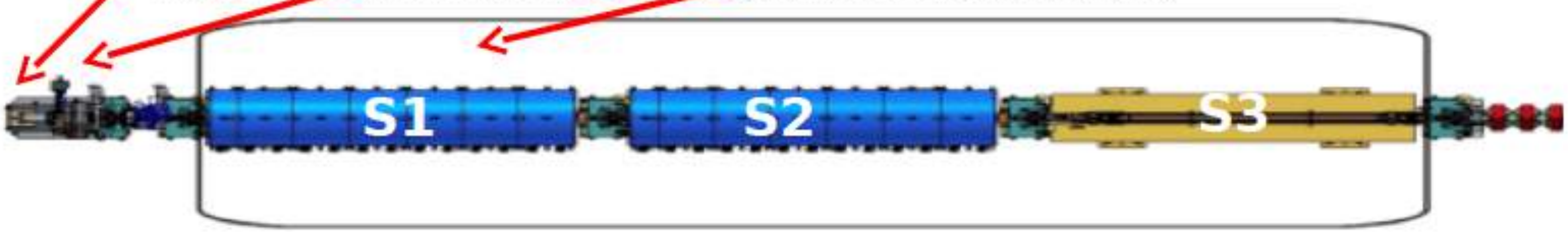
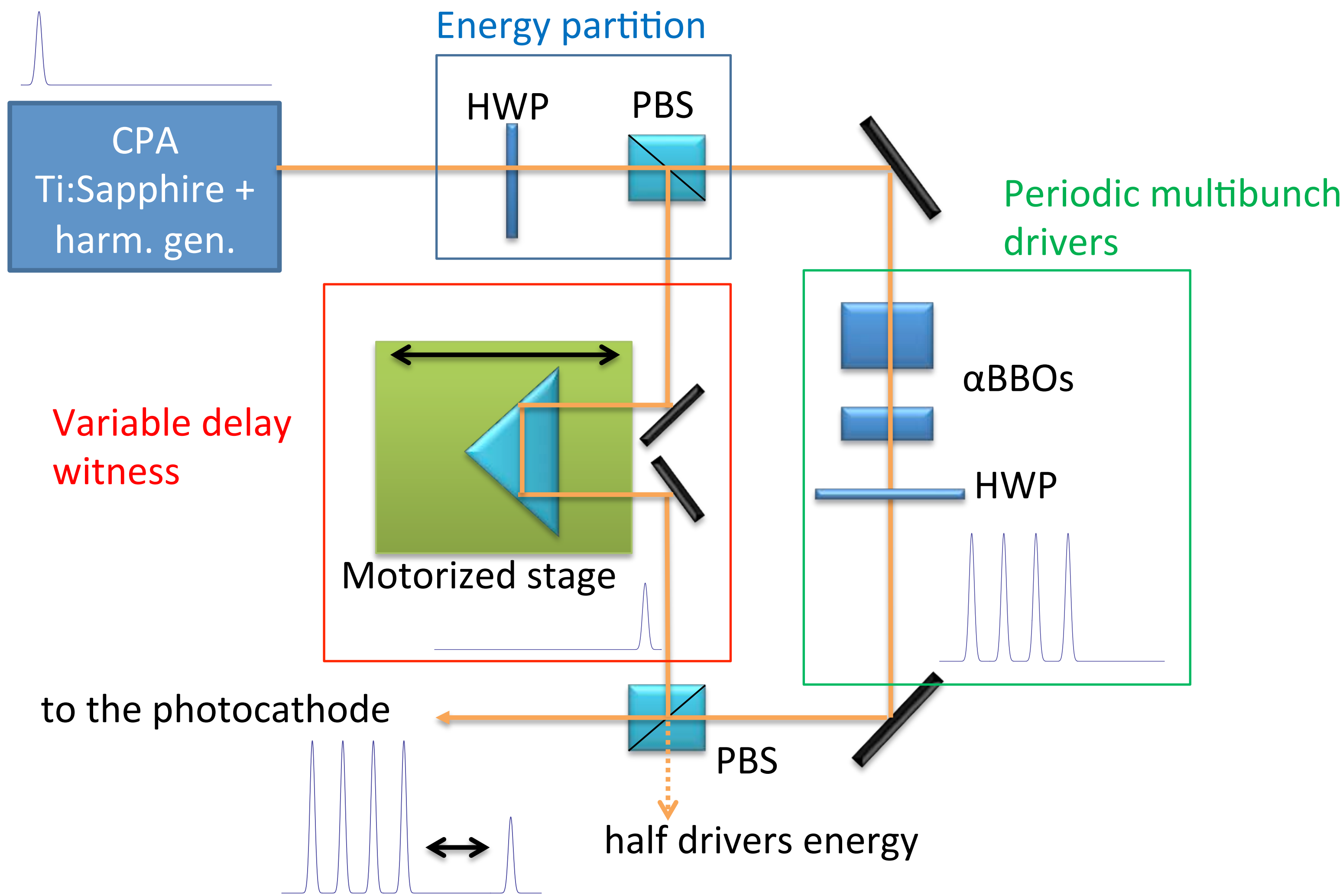


Fig. 1. Evolution of a six bunches electron beam train: the columns from left refer, respectively, to (a) the cathode, (b) the end of the drift at 150 cm and (c) the end of linac at 12 m far from cathode. The rows from top refer, respectively, to longitudinal profile and to energy modulation ΔE (MeV).



- 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)

Driving and witness bunches generation



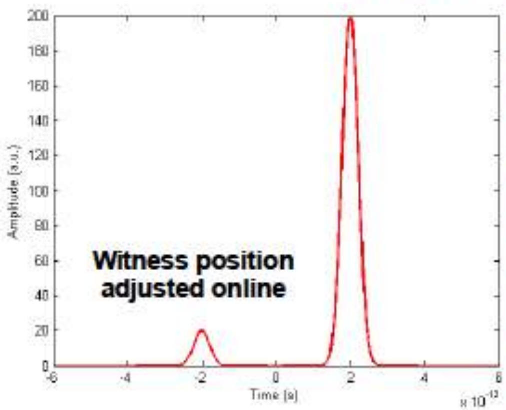
Villa, F., et al. "Laser pulse shaping for multi-bunches photo-injectors." NIM A 740 (2014): 188-192.

VB dynamics: 1 driver + witness

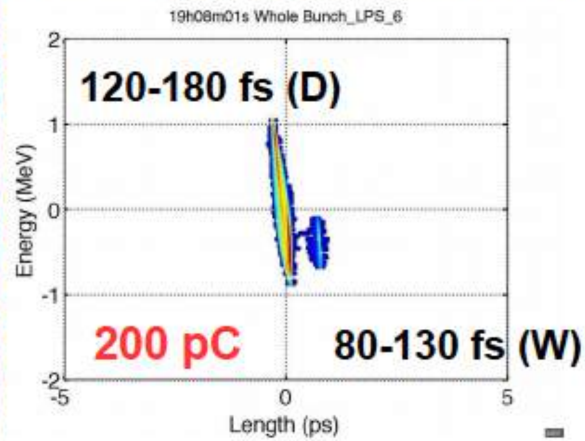
Experimental results!

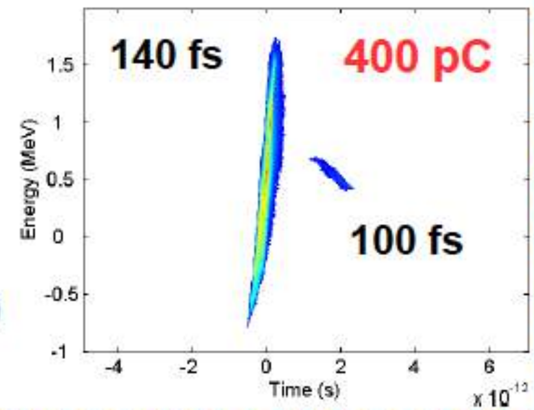
Laser profile on photo-cathode

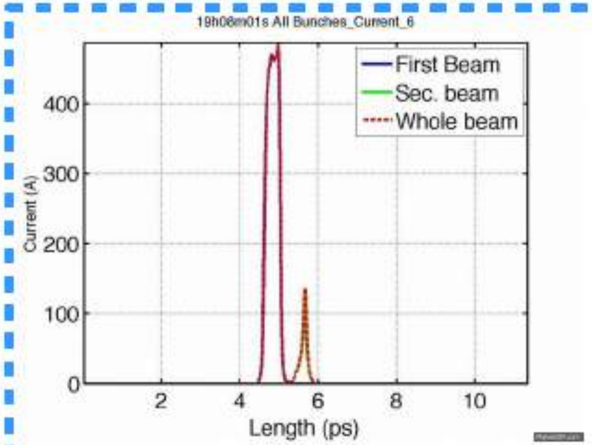
Driver + witness (20 pC)

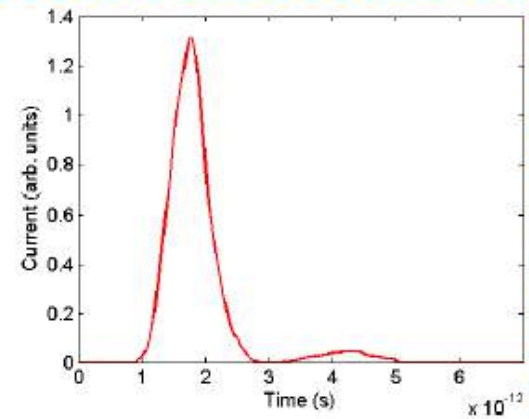


LPS at linac exit









Current profile

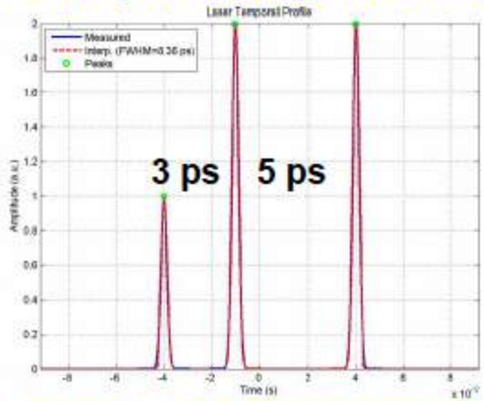
VB dynamics: N driver + witness

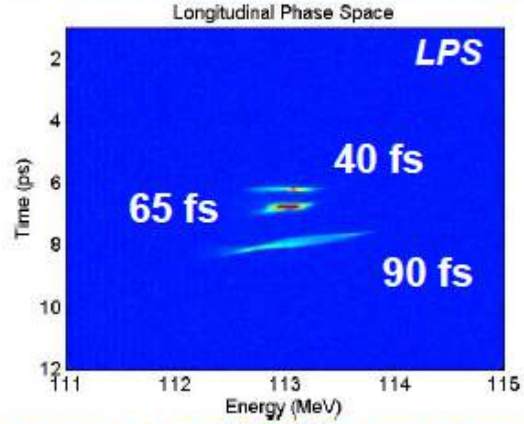
Experimental results!

50 pC drivers + 20 pC witness

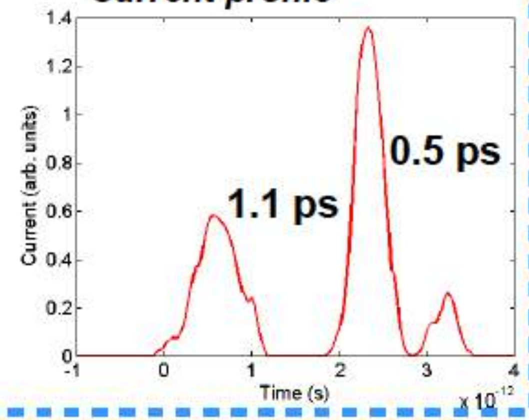
resonant scheme @ $n_p = 10^{16}$ cm^{-3} → bunch distance = λ_p ~ 1.1 ps

Laser profile on photo-cathode

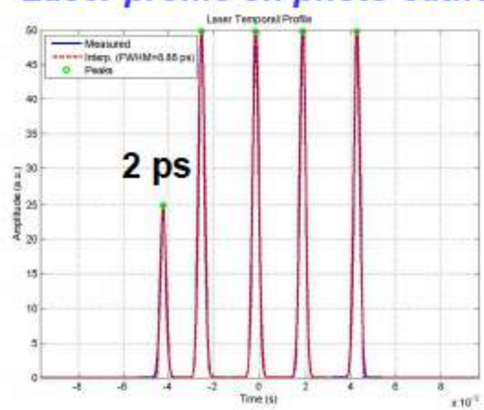


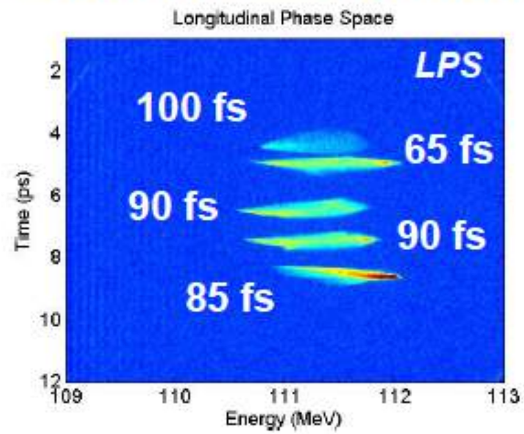


Current profile

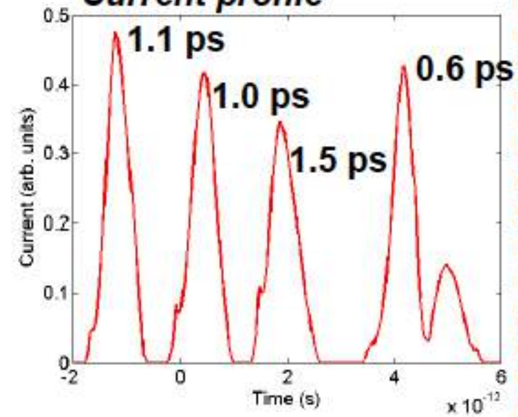


Laser profile on photo-cathode

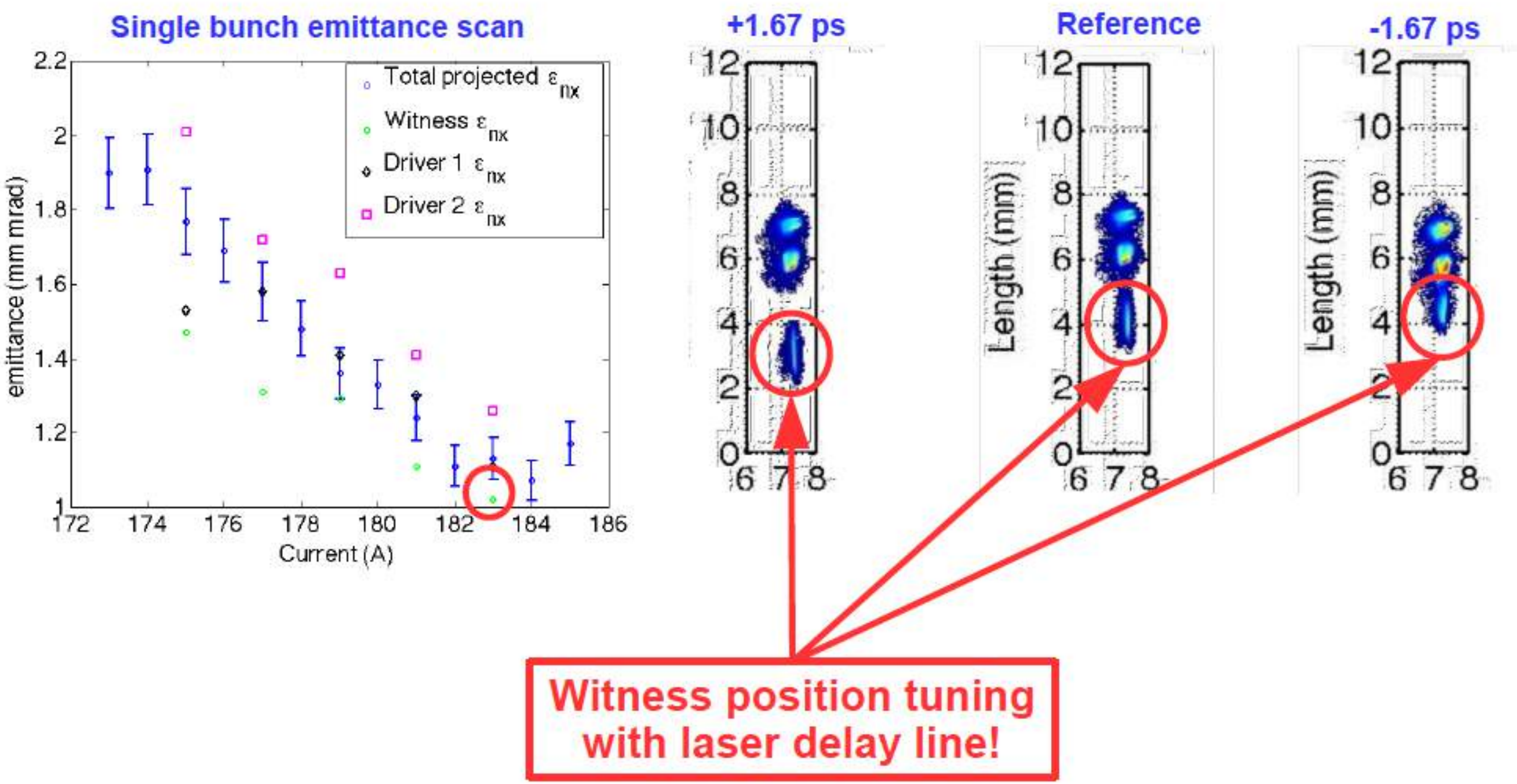




Current profile

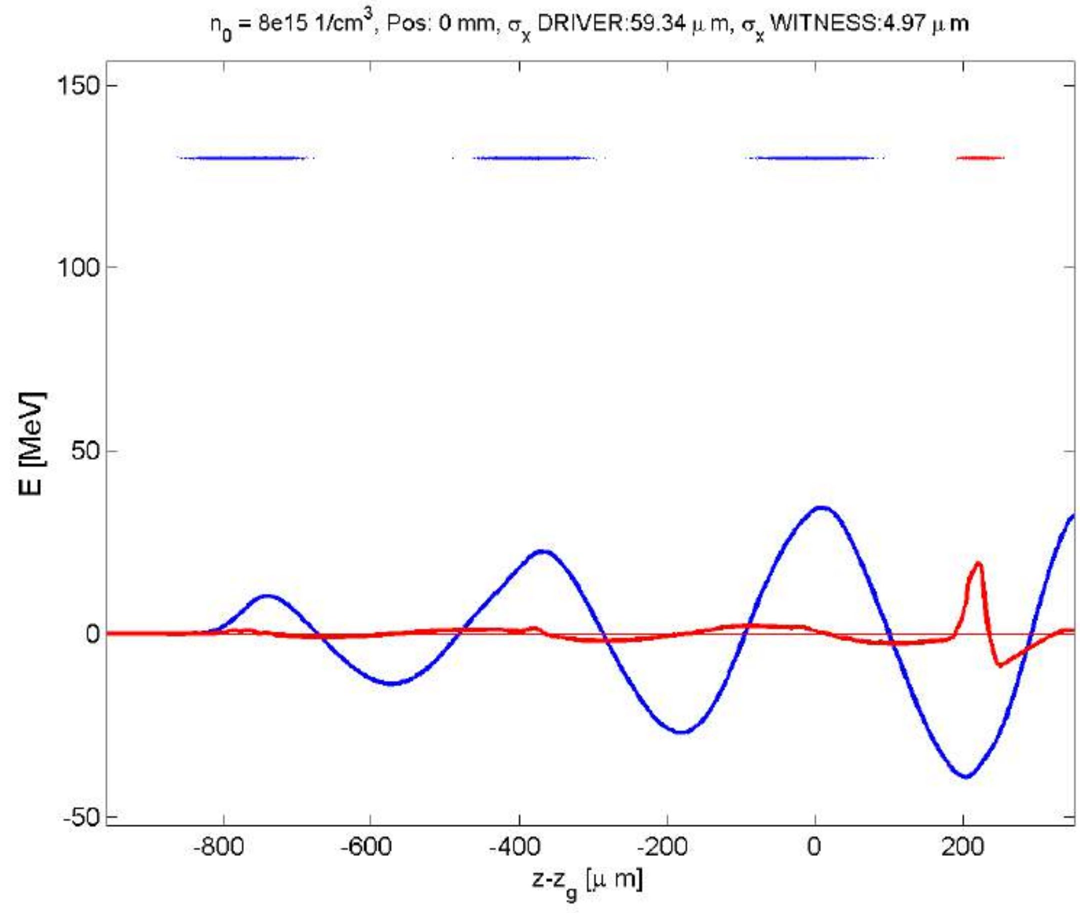


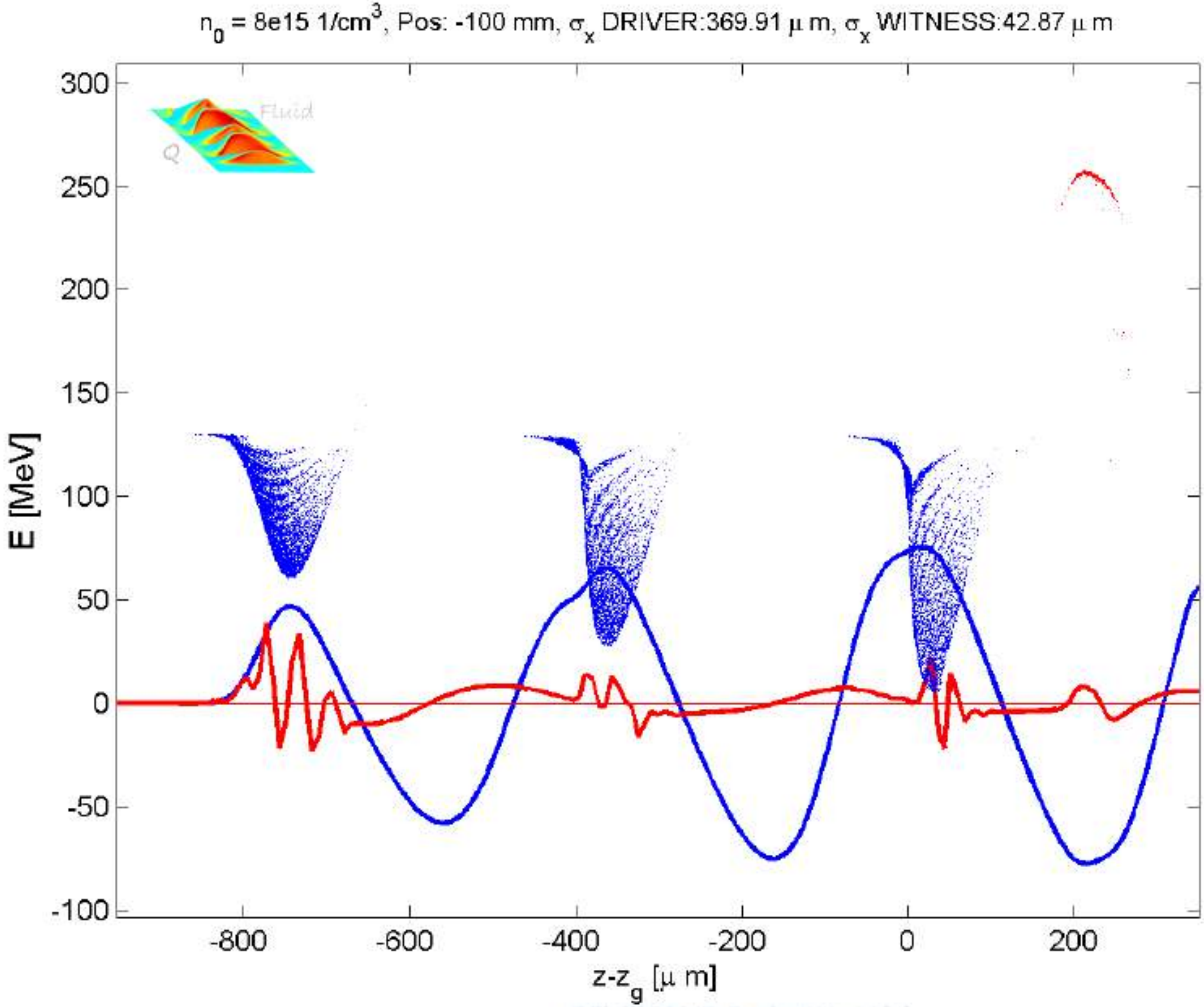
Witness – tuning and characterization



no=0.75e16 1/cm^3 Lambda_p=383 um,
Lacc=10cm Ez=1.2GV/m

	DRIVER (each, pC)	WITNESS
Charge (pC, each)	200	20
sigma_x (um)	**60**	**5**
Sigma_z (um)	25	10




n0 = 8e15 1/cm3, Pos: -100 mm, σx DRIVER:369.91 μ m, σx WITNESS:42.87 μ m
Fluid
Q
E [MeV]
z-zg [μ m]
300
250
200
150
100
50
0
-50
-100
-800
-600
-400
-200
0
200

MULTIBUNCH PWFA

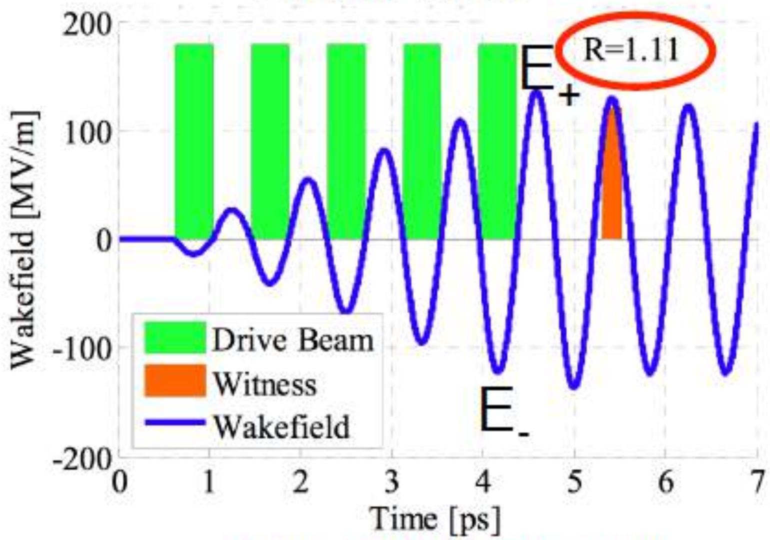
Transformer Ratio: $R = E_+/E_-$ Energy Gain: $\leq RE_0$

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 $\mu m \approx \lambda_p$

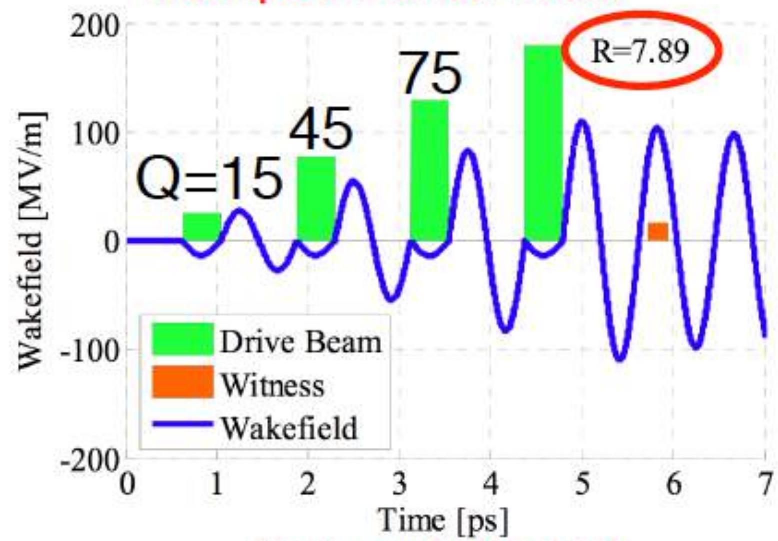
Bunch Train



Kallos, PAC'07 Proceedings

Δz=375 $\mu m \approx 1.5\lambda_p$

Ramped Bunch Train*

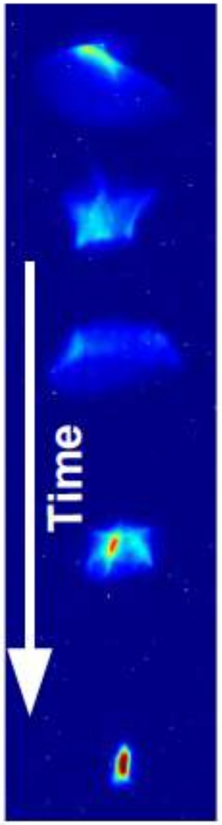


*Tsakanov, NIMA, 1999

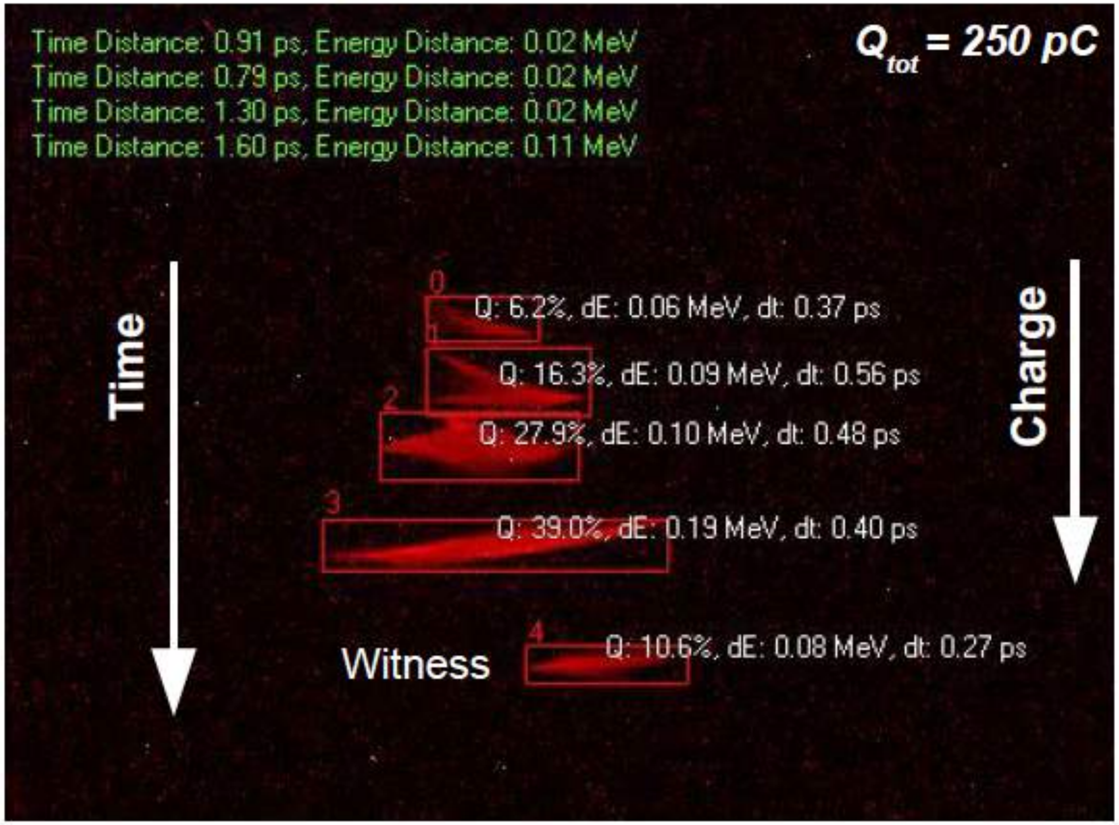
- Linear (2D) theory for $n_b << n_e$!
- R=7.9 => multiply energy by ~8 in a single PWFA stage!

Ramped comb beams

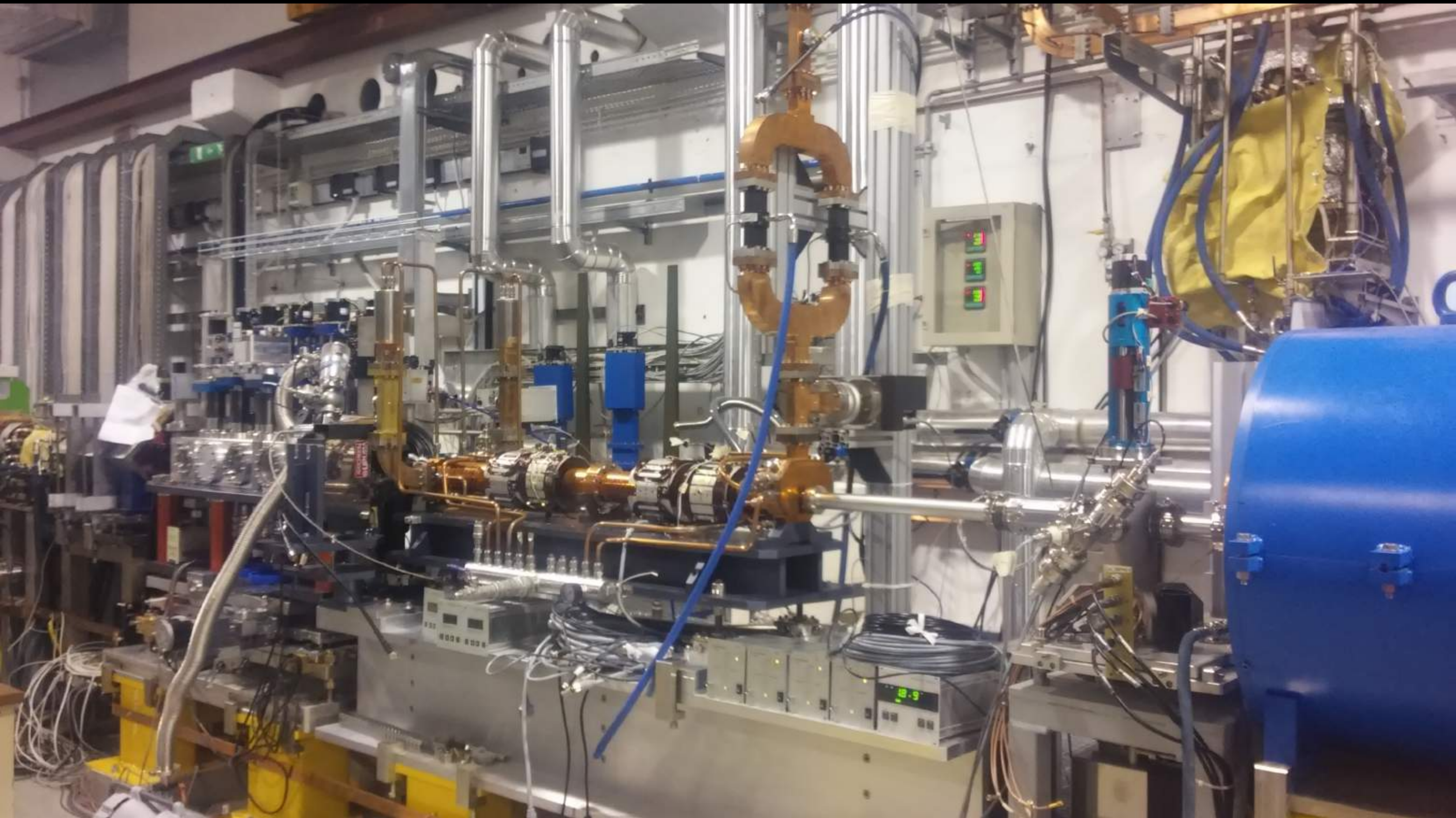
z-x view



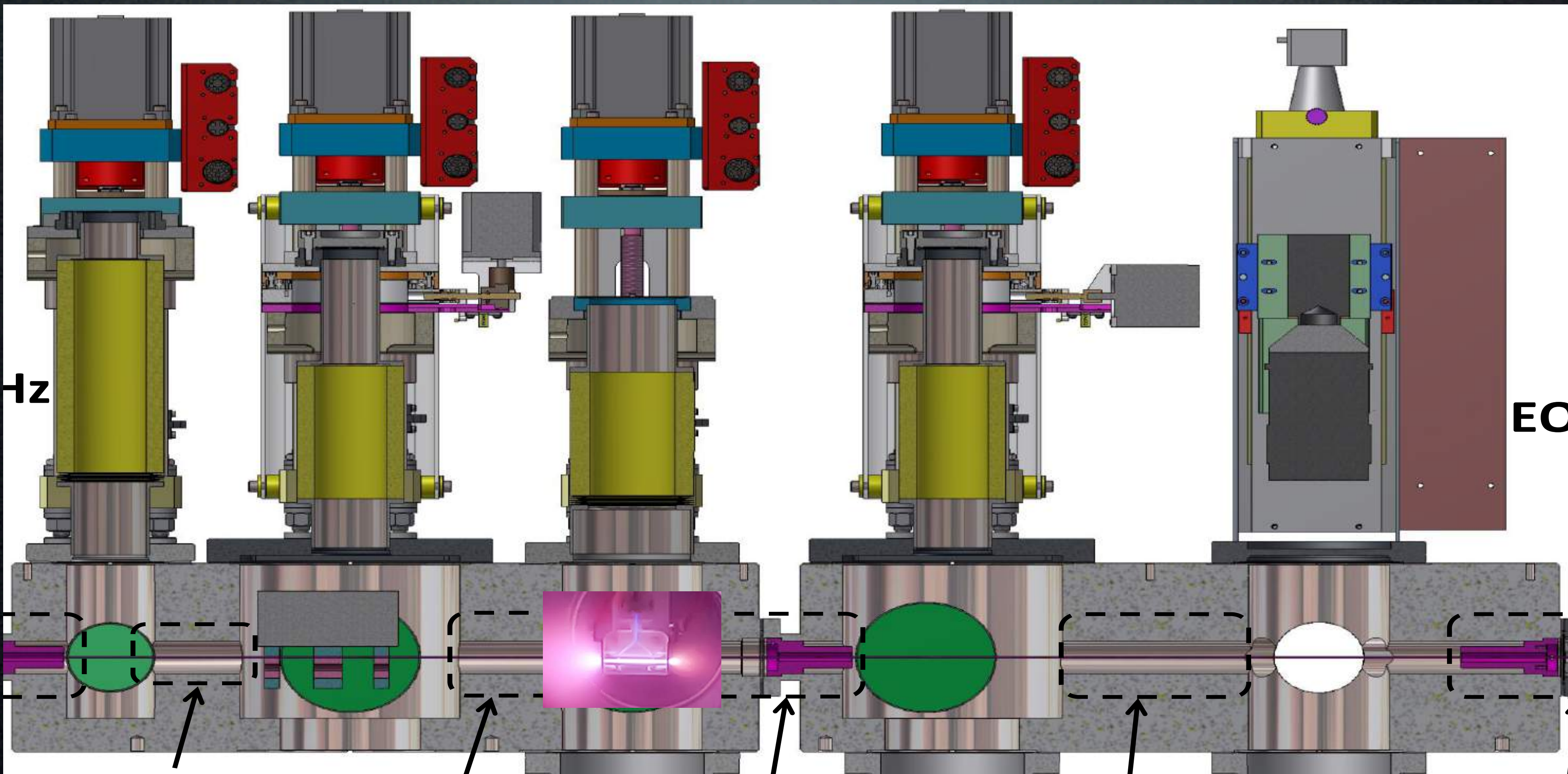
Longitudinal Phase Space



C-Band accelerating structure and PWFA chamber



PWFA – Particle Wake Field Accelerator

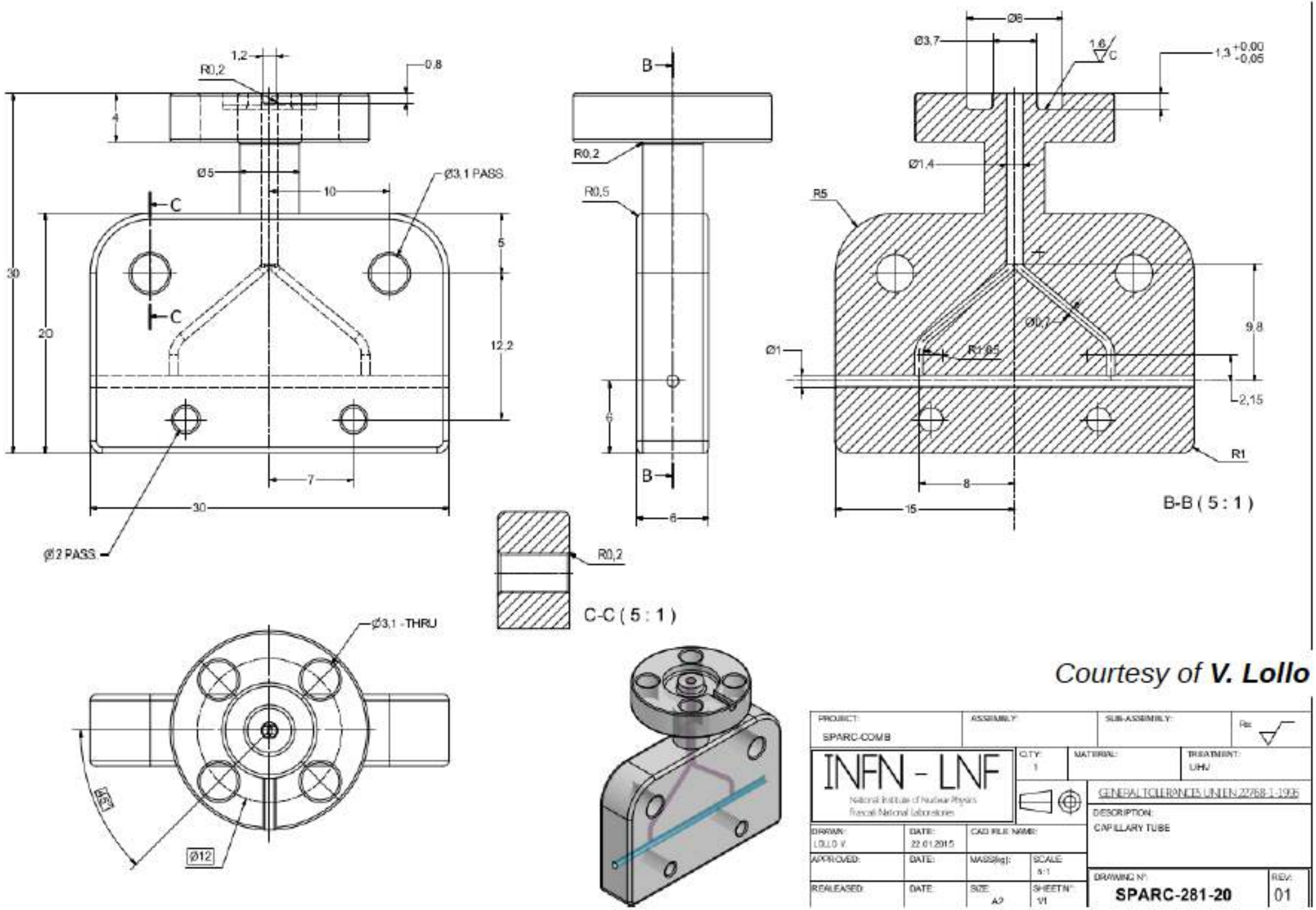


Focusing PMQ

PWFA module

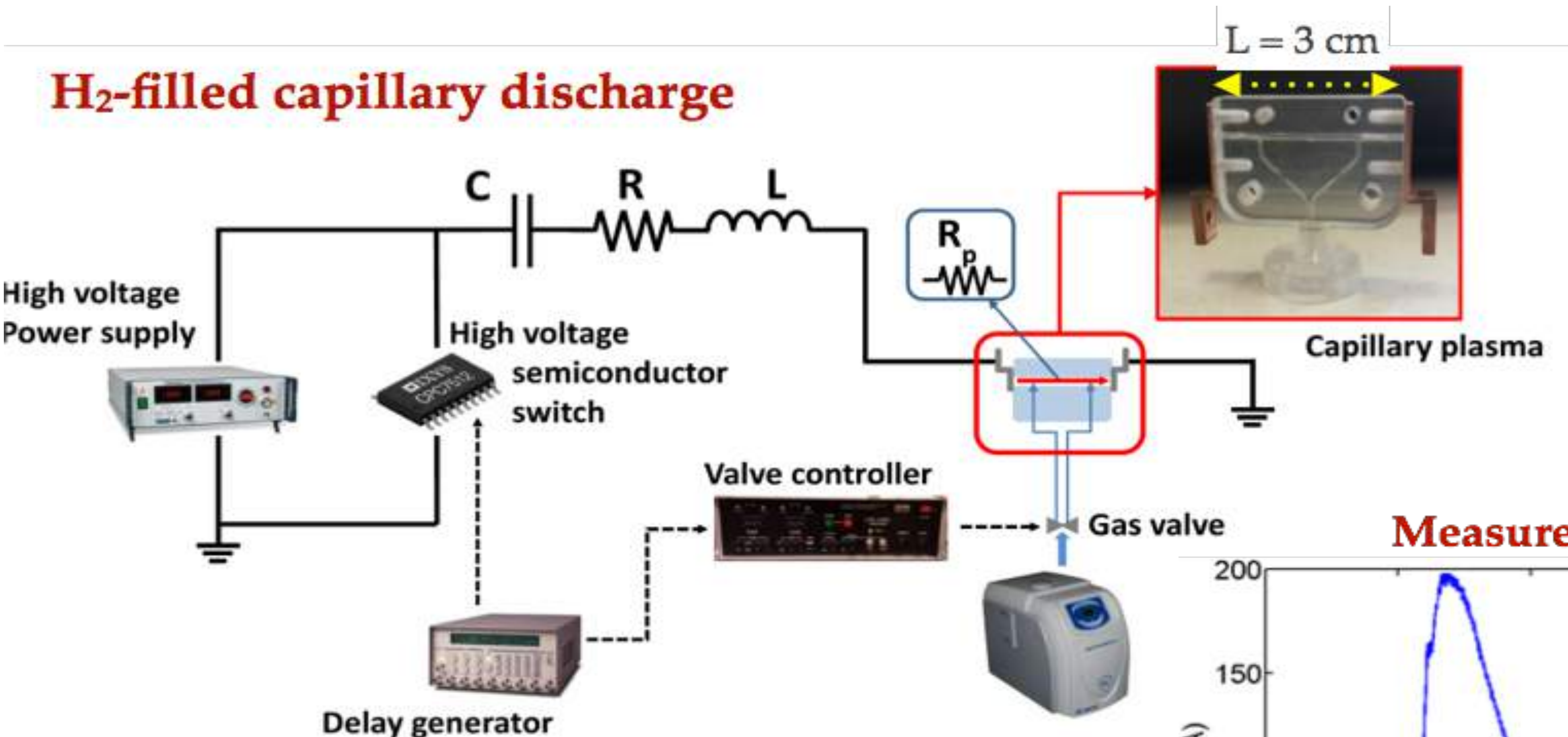
Capture PMQ

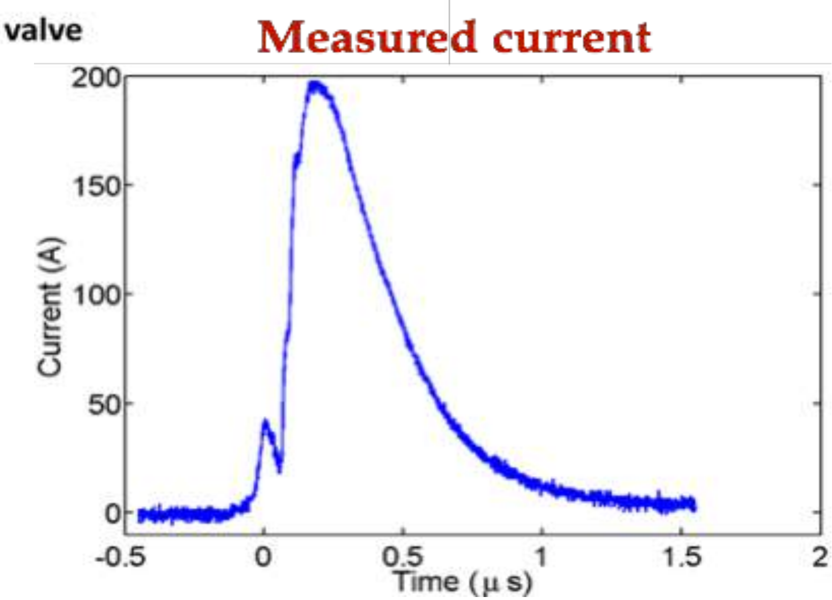
Plasma capillary



Courtesy of ***V. Lollo***

Plasma Source

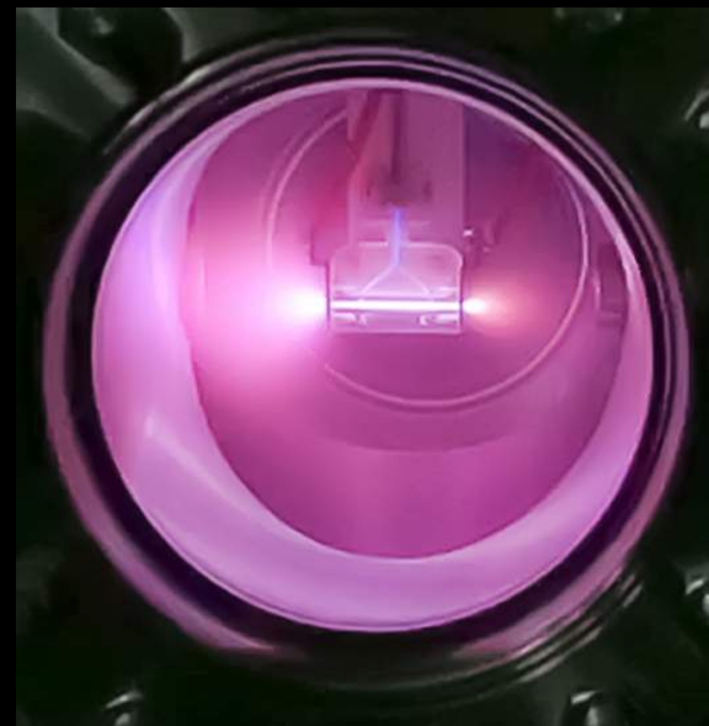




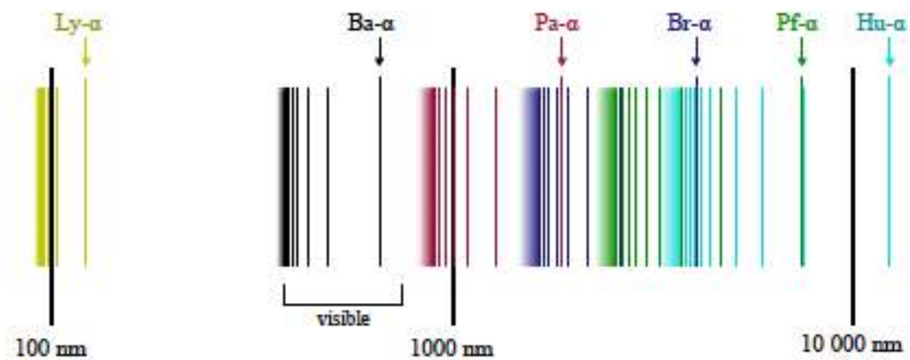
P_{H2} = 10 mbar
Total discharge duration: 800 ns
Voltage: 20 kV
Peak current: 200 A
Capacitor: 6 nF

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

Capillary Discharge at SPARC_LAB



Stark broadening diagnostics

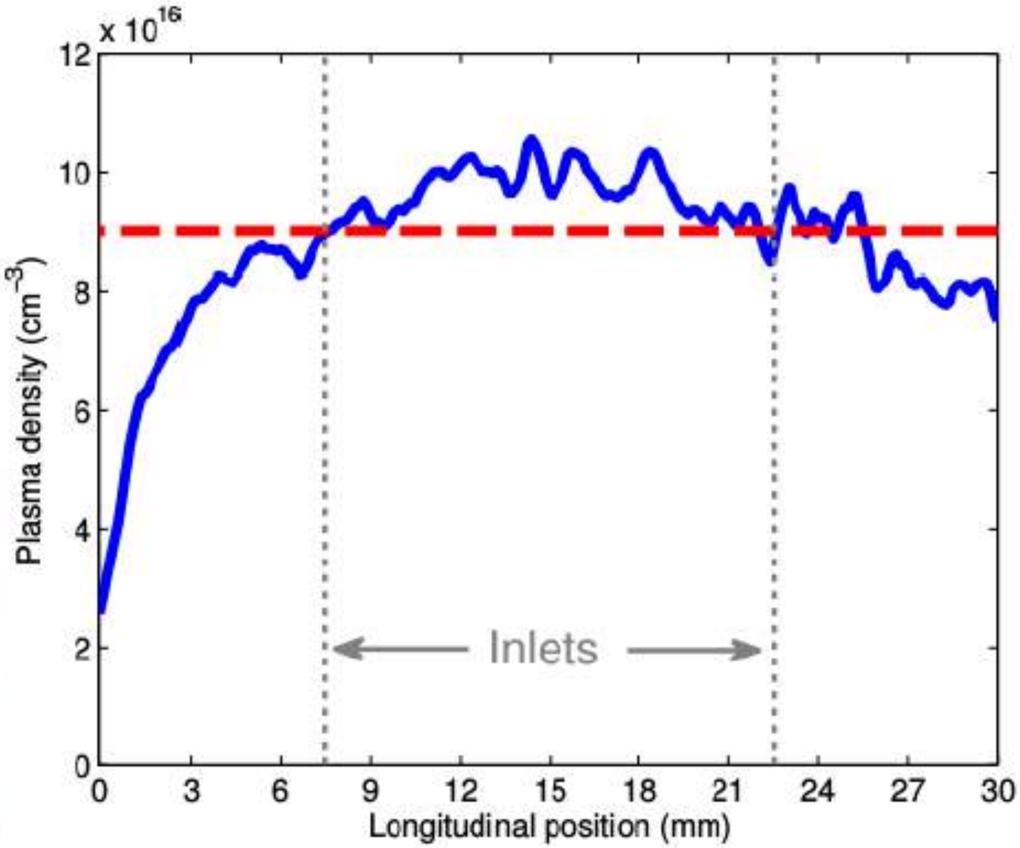


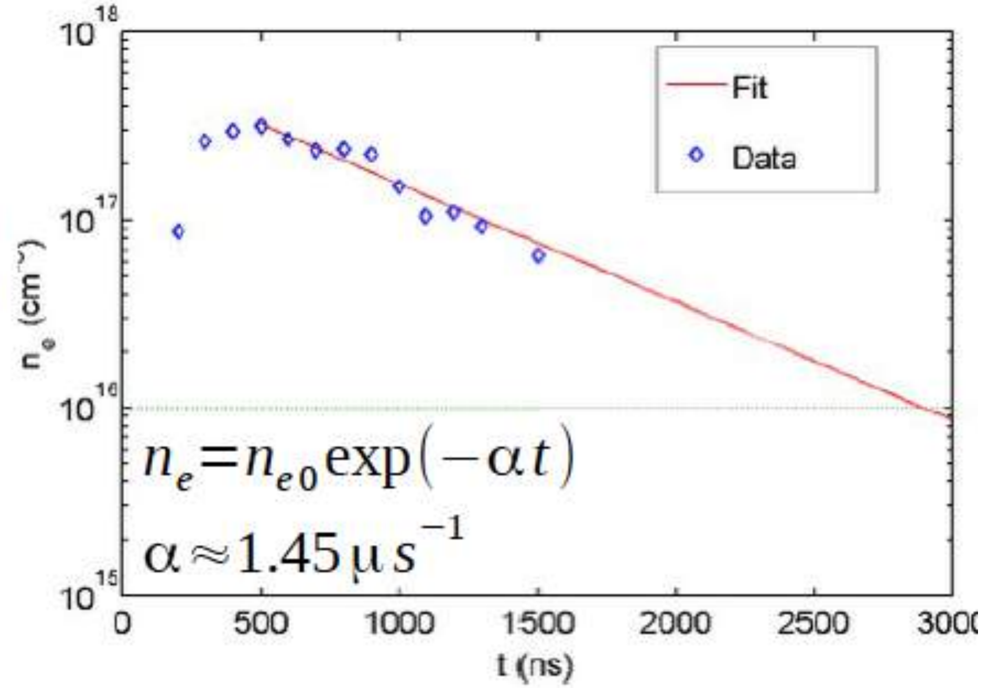
Hydrogen emission spectrum lines in the Balmer series

- Based on the **light emitted by plasmas** → measure of **electron plasma density**
- Plasma density can be determined by means of **Stark broadening effect**
  - *Spectral lines of Hydrogen are broadened as a result of the emitter interaction with the electric field produced by nearby ions.*
- The line-width is directly related to the plasma density → $\Delta\lambda \propto \alpha(T)\, n_0^{2/3}$
  - For Hydrogen, the H_β line (486 nm) is usually used → **α** is *less temperature dependent*.

Plasma characterization in capillary

Plasma density measurement from H_β Stark broadening





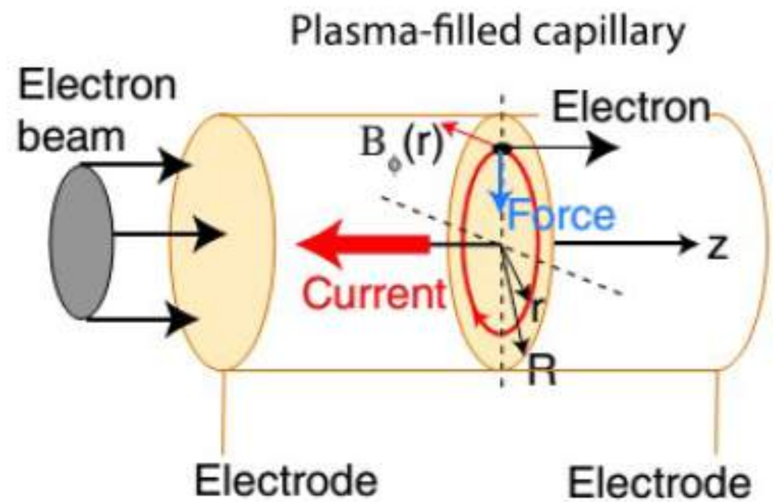
The plasma density is controlled through the delay after the discharge

Beam Manipulation

Active plasma lens

- Focusing field produced by electric discharge in a plasma-filled capillary
  - *Focusing field produced, according to Ampere's law, by the discharge current*

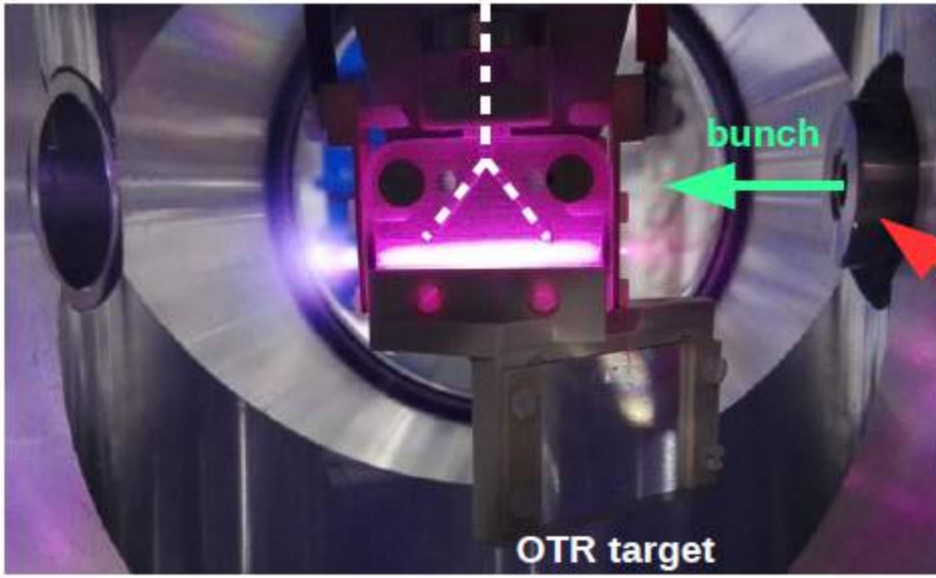
$$B_\phi(r) = \frac{1}{2}\int_0^r \mu_0 J(r')\,dr'$$

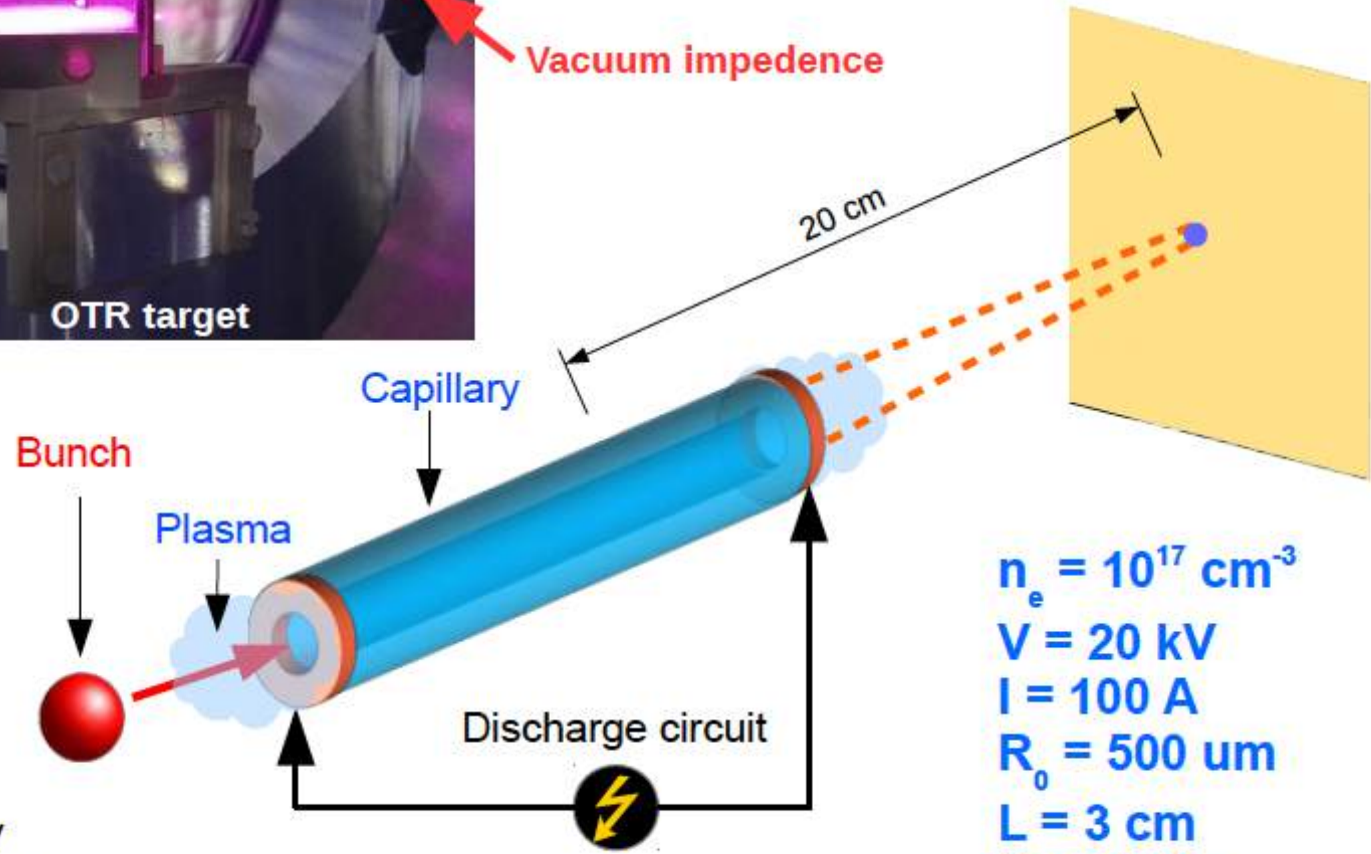


Van Tilborg, J., et al. "Active plasma lensing for relativistic laser-plasma-accelerated electron beams." Physical review letters 115.18 (2015): 184802.

- ✔ Radial focusing
  - *X/Y planes are not dependent as in quads*
- ✔ Weak chromaticity
  - *Focusing force scales linearly with energy*
- ✔ Compactness
  - *Higher integrated field than quad triplets*
- ✔ Independent from beam distribution
  - *Not sensitive to longitudinal/transverse charge profile as in passive plasma lenses*

Experimental layout

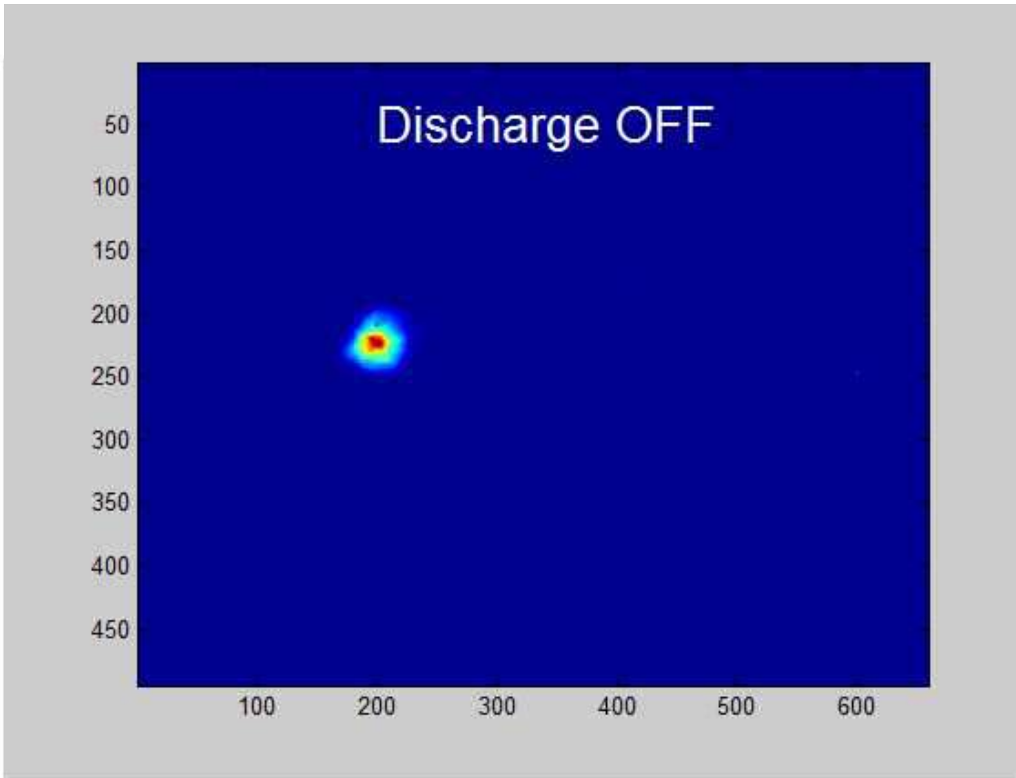


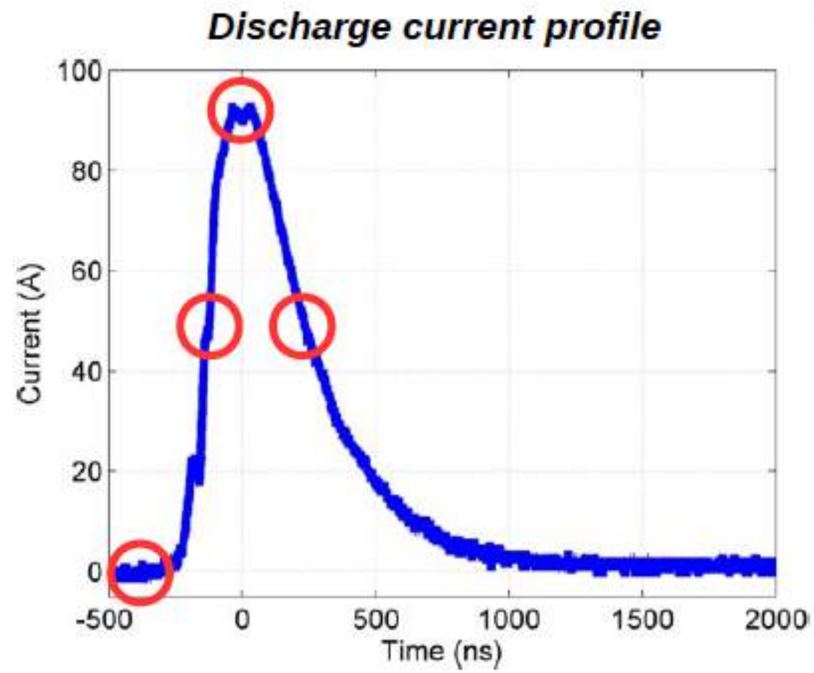


50 pC
1 ps
130 um
120 MeV
1 mm mrad

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

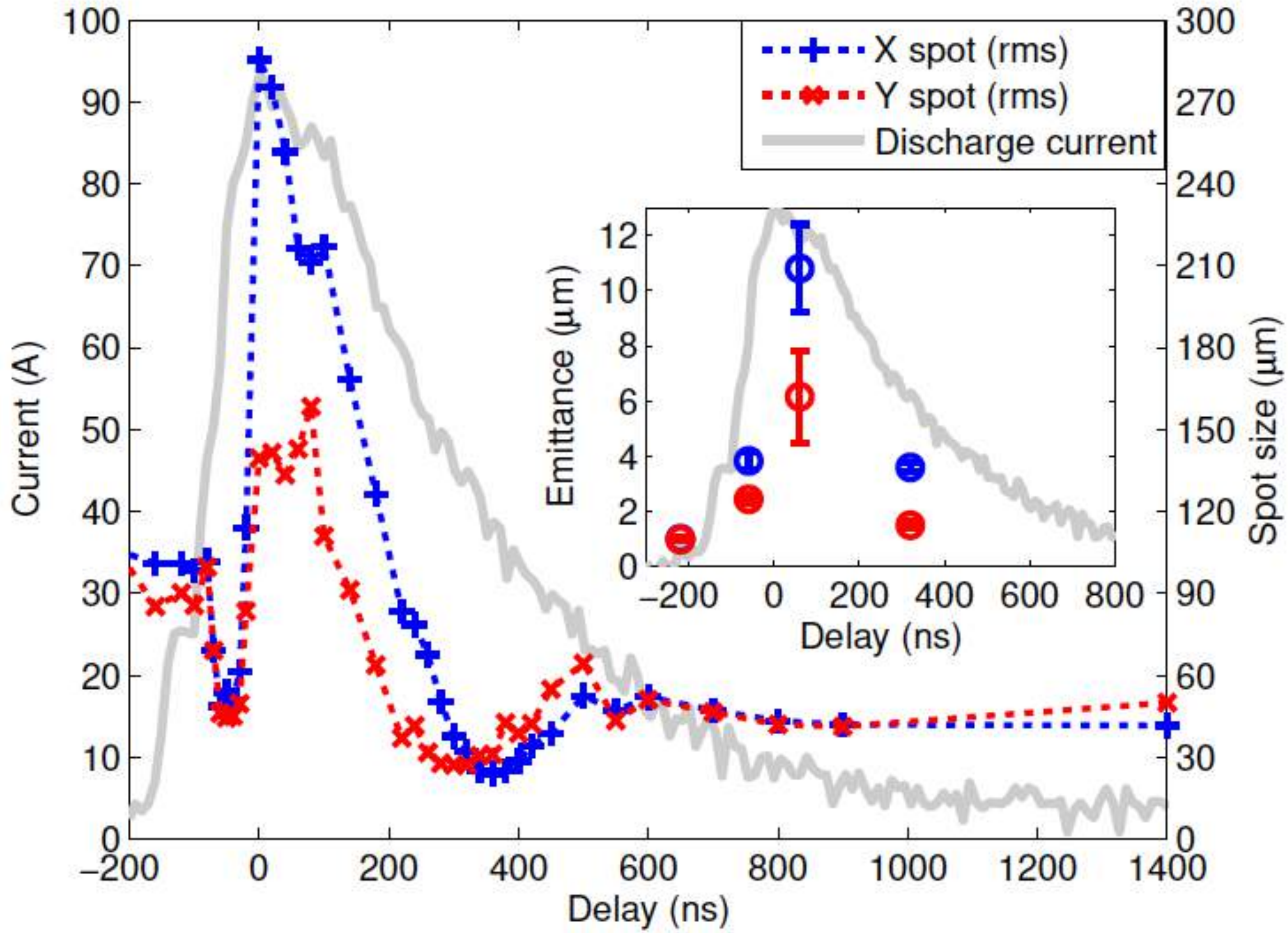
Preliminary results



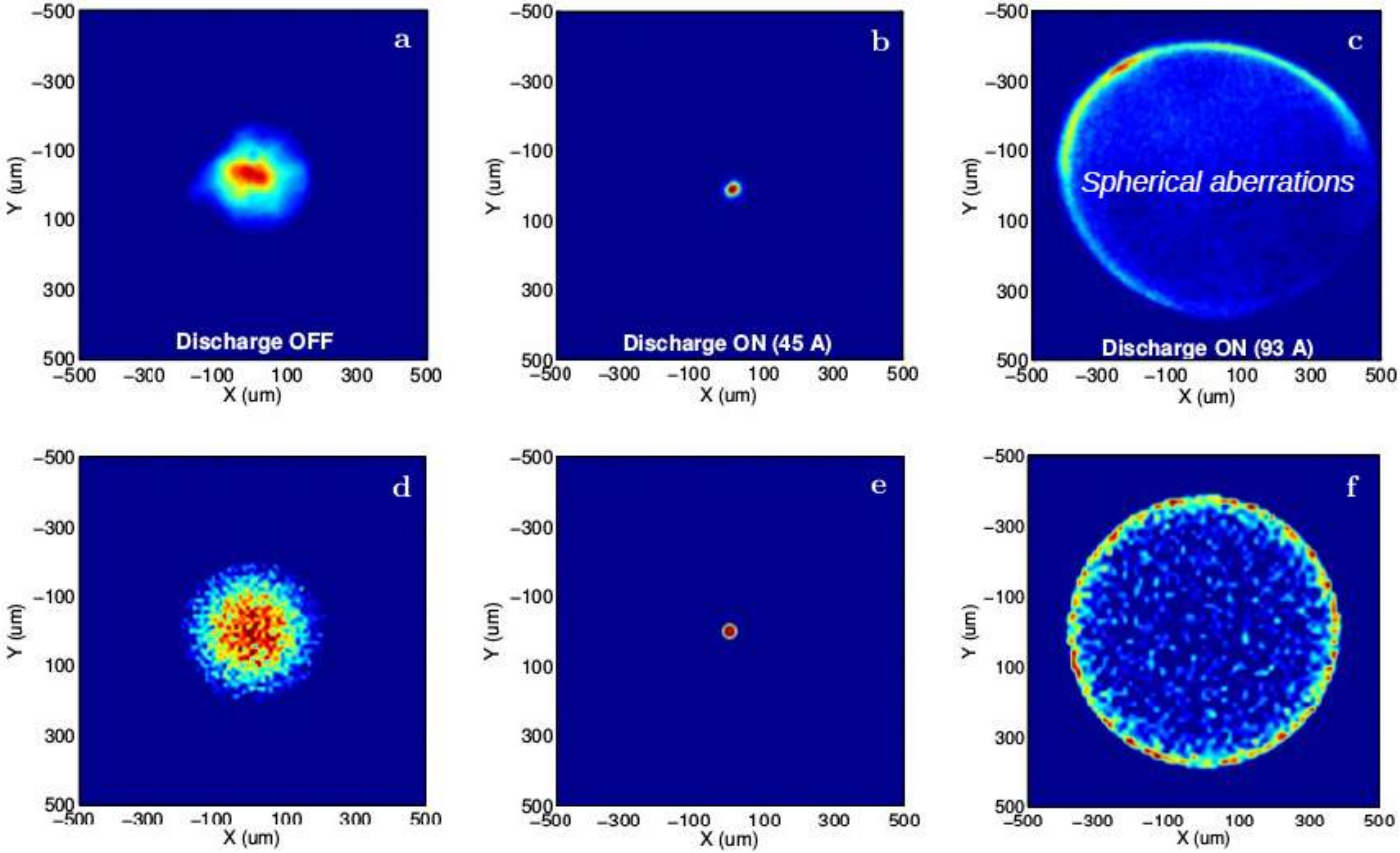


Experimental characterization of active plasma lensing for electron beams

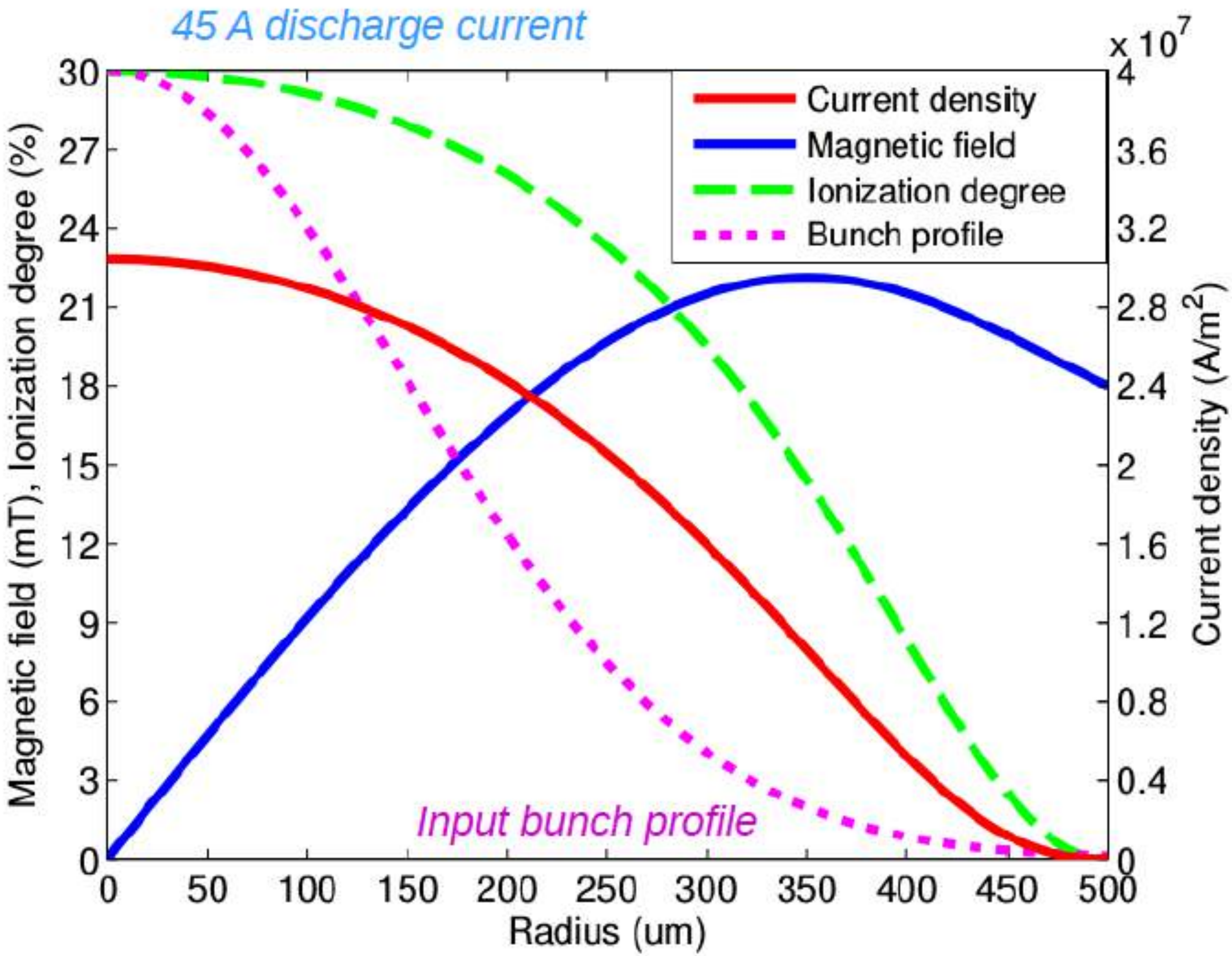
R. Pompili,[1,a)] M. P. Anania,[1] M. Bellaveglia,[1] A. Biagioni,[1] S. Bini,[1] F. Bisesto,[1] E. Brentegani,[1] G. Castorina,[1,2] E. Chiadroni,[1] A. Cianchi,[3] M. Croia,[1] D. Di Giovenale,[1] M. Ferrario,[1] F. Filippi,[1] A. Giribono,[4] V. Lollo,[1] A. Marocchino,[1] M. Marongiu,[4] A. Mostacci,[4] 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

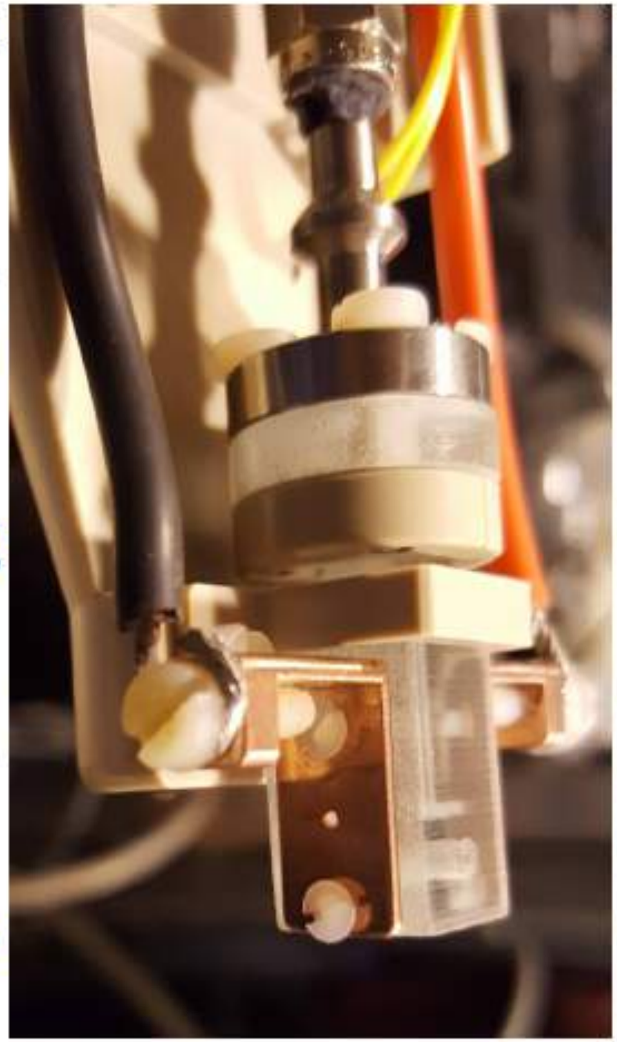


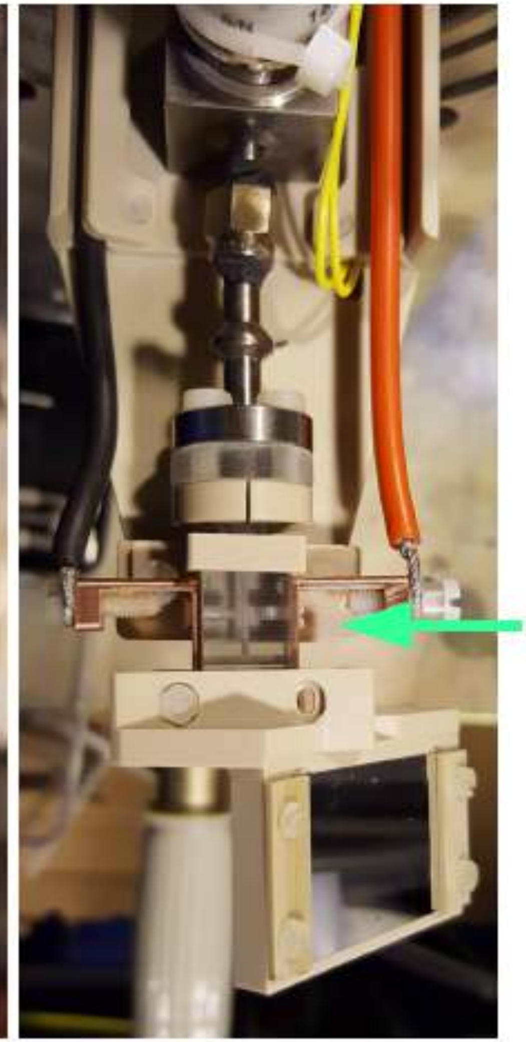
Nonlinear focusing field



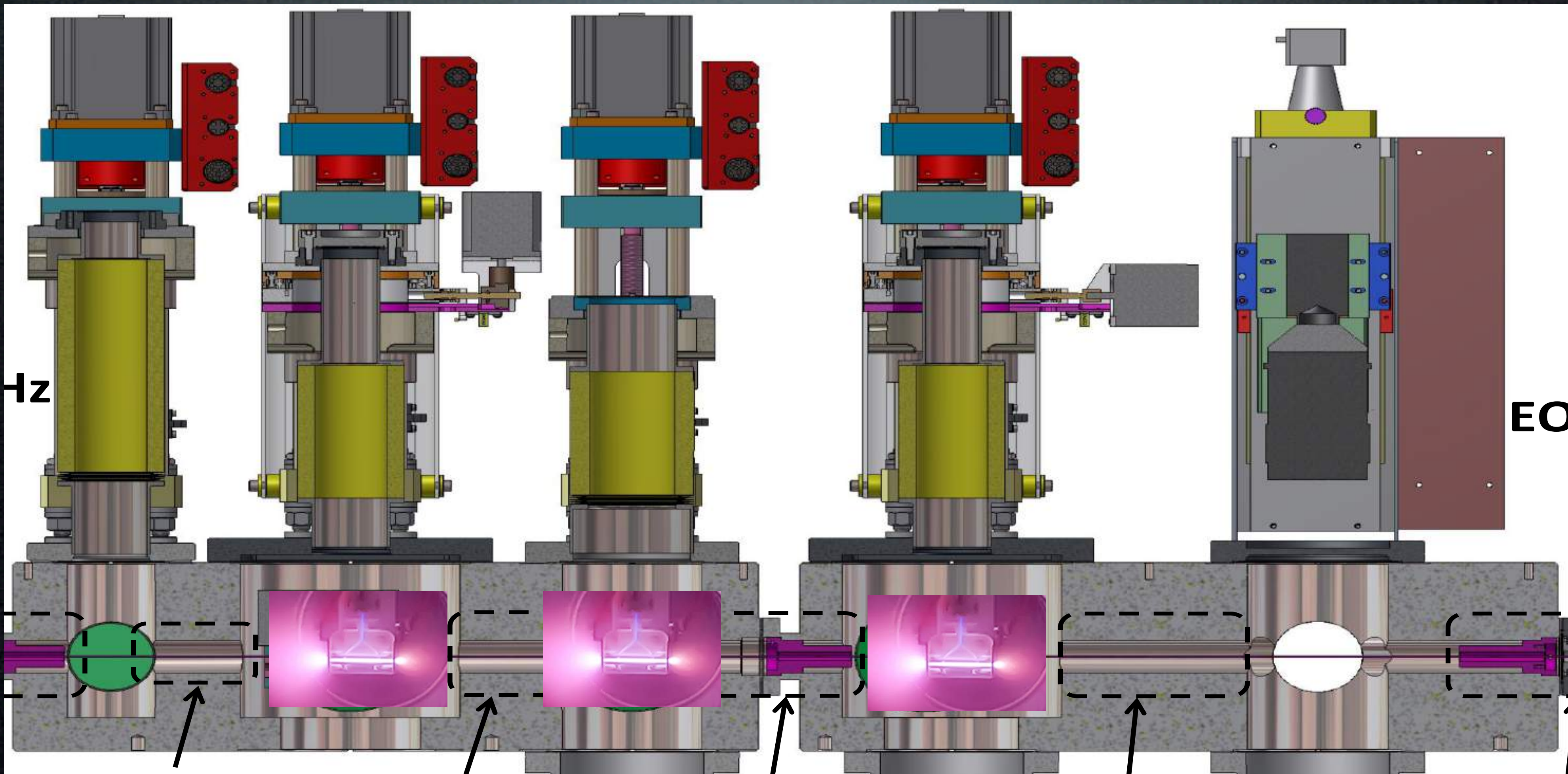
Preliminary results

- Preliminary results @ max focusing strength (140 A)
  - *Min spot size: 19-20 um*
  - *Normalized emittance: 1.5 um*
- First results show that the emittance after active lensing is still not preserved but much lower than before
  - *It indicates that the magnetic field felt by the beam is "more" linear*
- We will continue with tests on such setup and then move to the last configuration
  - *3 cm-long capillary*
  - *2 mm hole diameter to increase the linear region of the B field*





Plasma Driven FEL under investigation



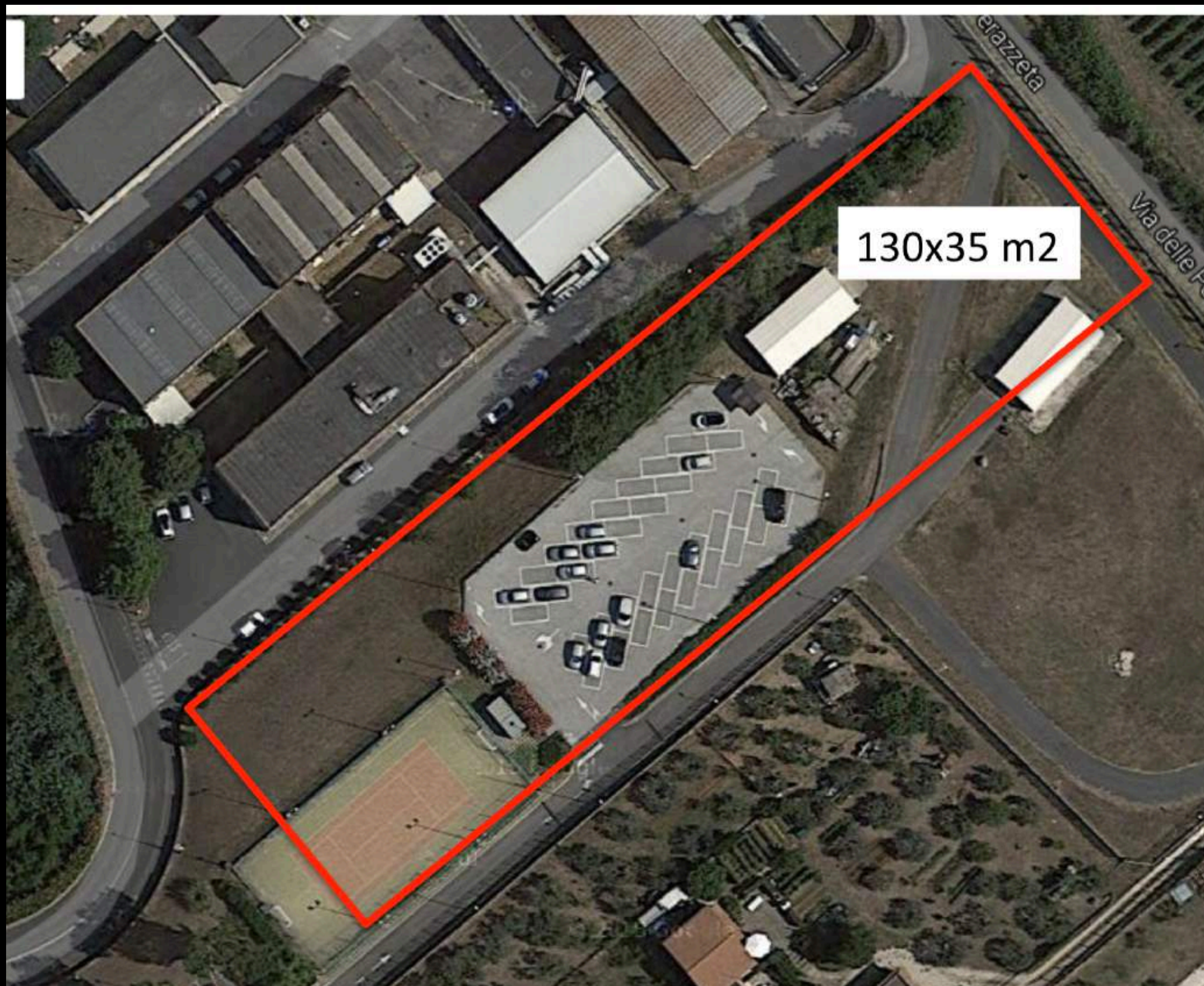
Focusing Plasma Lens

PWFA module

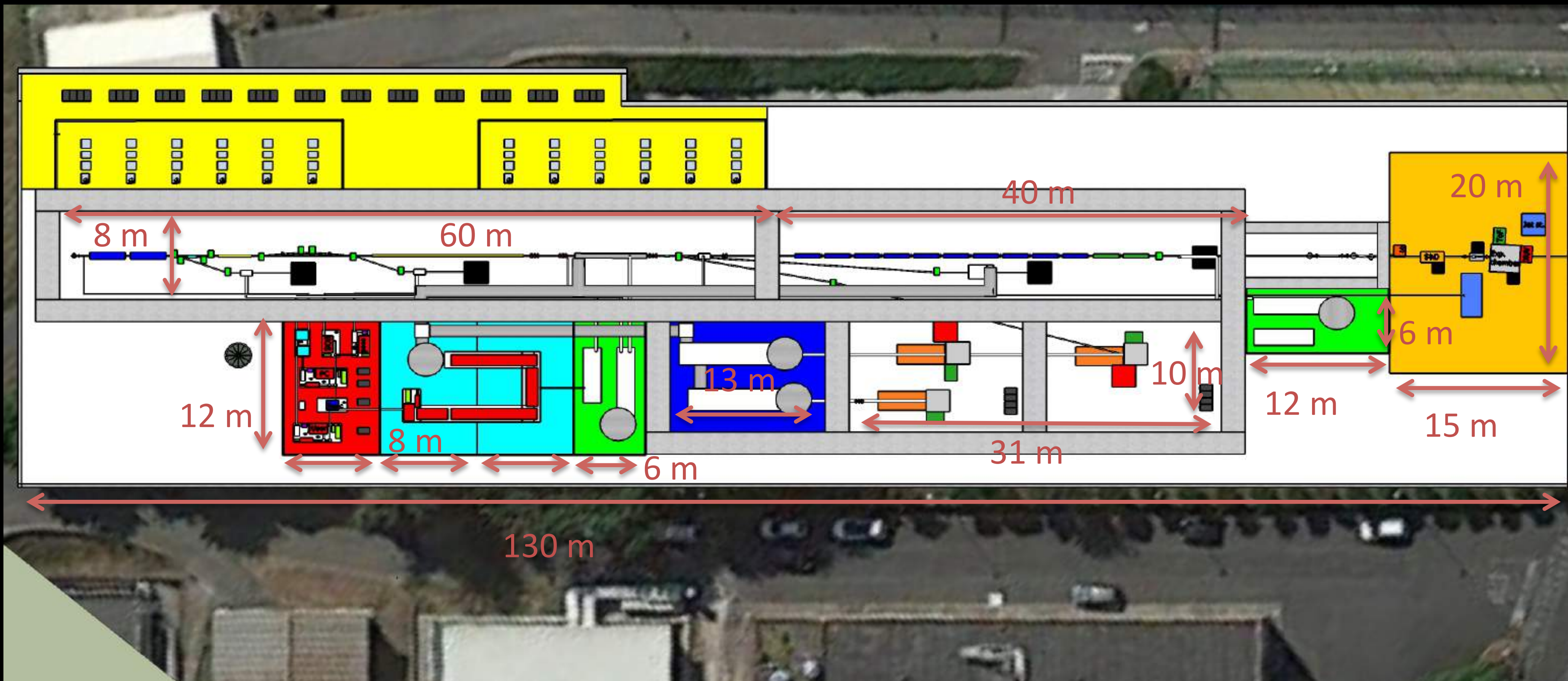
Capture Plasma Lens

The Future

EuPRAXIA@SPARC_LAB




SPARC
FLAME
Users



20 m
40 m
60 m
8 m
12 m
8 m
6 m
13 m
10 m
31 m
6 m
12 m
15 m
130 m

WG 0 – Project Management
- 0.1 Executive summary (M. Ferrario)

WG 1 – Electron beam design and optimization
- 1.1 Advanced High Brightness Photo-injector (E. Chiadroni)
- 1.2 HB Linac technology, (A. Gallo)
- 1.3 Linac design and parameters (C. Vaccarezza)

WG 2 – Laser design and optimization
- 2.1 FLAME upgrade (M. P. Anania)
- 2.2 Advanced Laser systems (L. Gizzi)

WG 3 – Plasma Accelerator
- 3.1 PWFA beam line (A. Marocchino)
- 3.2 LWFA beam line (A. R. Rossi)
- 3.3 Plasma and Beam Diagnostics (A. Cianchi)

WG 4 – FEL pilot applications
- 4.1 Conventional and Plasma driven FEL (V. Petrillo)
- 4.2 Advanced FEL schemes (G. Dattoli)
- 4.3 Photon beam lines (F. Villa)
- 4.4 FEL user applications (F. Stellato)

WG 5 – Radiation sources and user beam lines
- 5.1 Advanced (dielectric) THz source (S. Lupi)
- 5.2 Compton source (C. Vaccarezza)
- 5.3 Secondary Particle Sources (LNS)?
- 5.4 Laser-driven neutron source (Cianchi)
- 5.4 User beam lines (P. Valente)

WG 6 – Low Energy Particle Physics
- 6.1 Advanced positron sources (A. Variola)
- 6.2 Fundamental physics experiments , LabAstro (C. Gatti)
- 6.3 Plasma driven photon collider (L. Serafini)

WG 7 – Infrastructure
- 7.1 Civil Engineering and conventional plants (U. Rotundo)
- 7.2 Control system (G. Di Pirro)
- 7.3 Radiation Safety (A. Esposito)
- 7.4 Machine layout

3rd EAAC 25-29 September, 2017
Isola d'Elba
TALKS
DINNER
BREAKFAST
COFFEE
LUNCH
DISCUSSIONS
WAVE-BREAKING

Acknowledgments

- M.P. Anania, M. Bellaveglia, A. Biagioni, E. Chiadroni, M. Croia, D. Di Giovenale, M. Ferrario, F. Filippi, V. Lollo, A. Marocchino, S. Pella, G. Di Pirro, S. Romeo, J. Scifo, V. Shpakov, C. Vaccarezza, F. Villa (INFN, Frascati)
- A. Cianchi (Tor Vergata University of Rome)
- A. Giribono, A. Mostacci (Sapienza University of Rome)
- A.R. Rossi (INFN, Milano)
- A. Zigler (Hebrew University of Jerusalem)