Advanced Accelerator Developments at EuPRAXIA@SPARC_LAB

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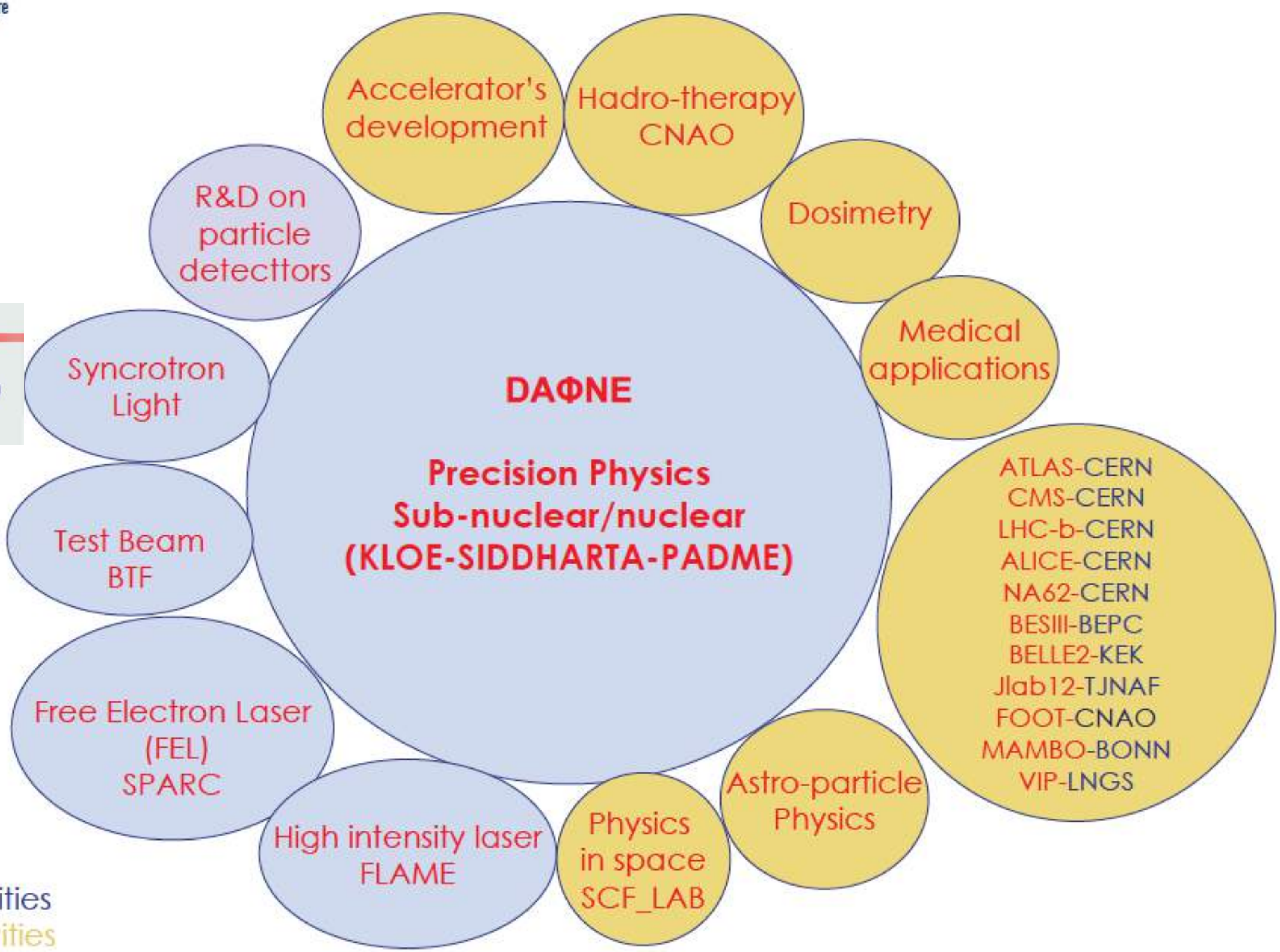
INFN
Istituto Nazionale di Fisica Nucleare

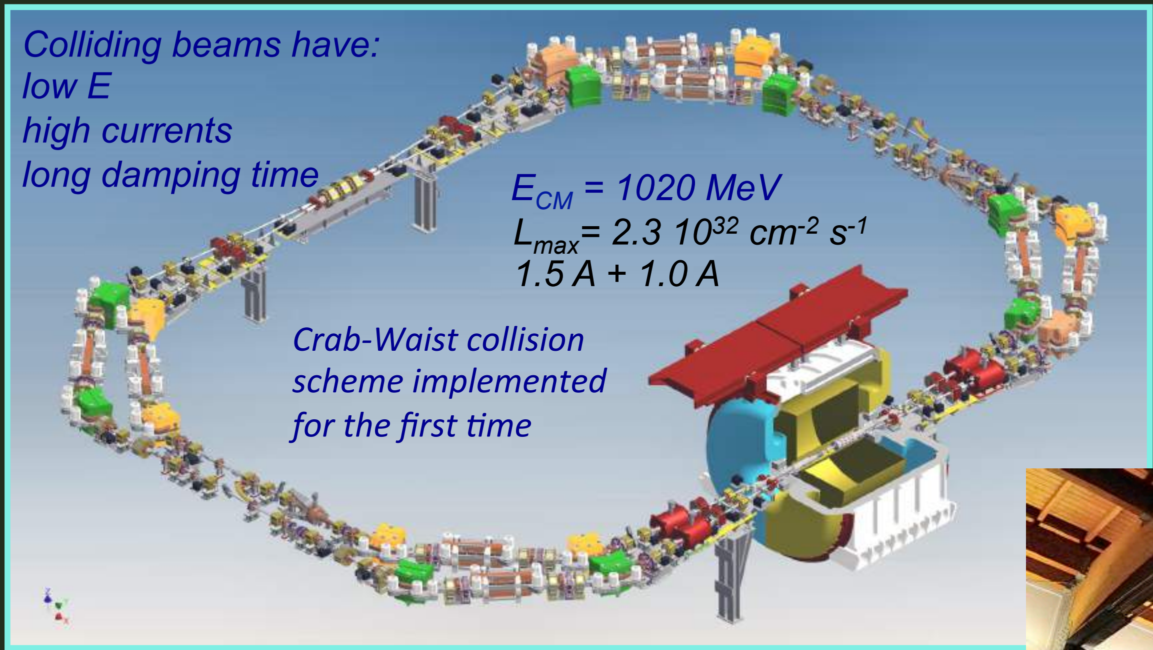
Research Activities at LNF



Internal Activities
External activities

KLOE-2 data-taking closing ceremony

March 30th 2018 at 11:00 in the Bruno Touschek Auditorium

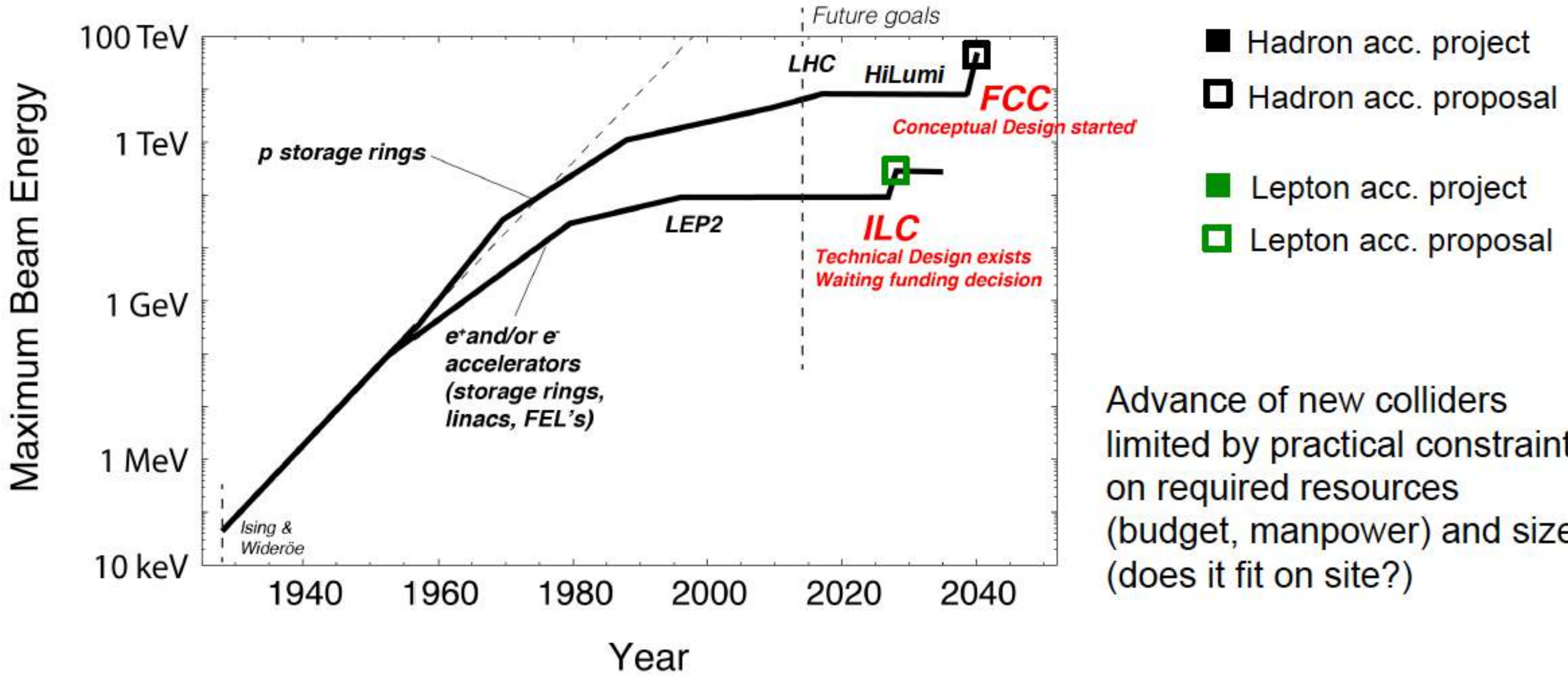


“What Next at LNF site?”

is an often addressed question in many other labs
See for ex. SLAC, DESY, CERN

Slow-down in Energy Increase of Frontier Accelerators

Livingston plot leveling off – here our version, giving beam energy versus time



Advance of new colliders limited by practical constraints on required resources (budget, manpower) and size (does it fit on site?)

Courtesy R. Assmann, DESY

"How to advance?"

Hadron (p) circular collider

$$p = e \cdot R \cdot B_y$$

Increase bending field
SC bend magnet work (FCC-hh)

Increase radius = size (FCC-hh)

Lepton (e-,e+) circular collider

$$p \propto E_0 \cdot \sqrt[4]{\rho \cdot U_0}$$

Increase supplied RF voltage (FCC-ee)

Increase mass of acc. particle (muon)

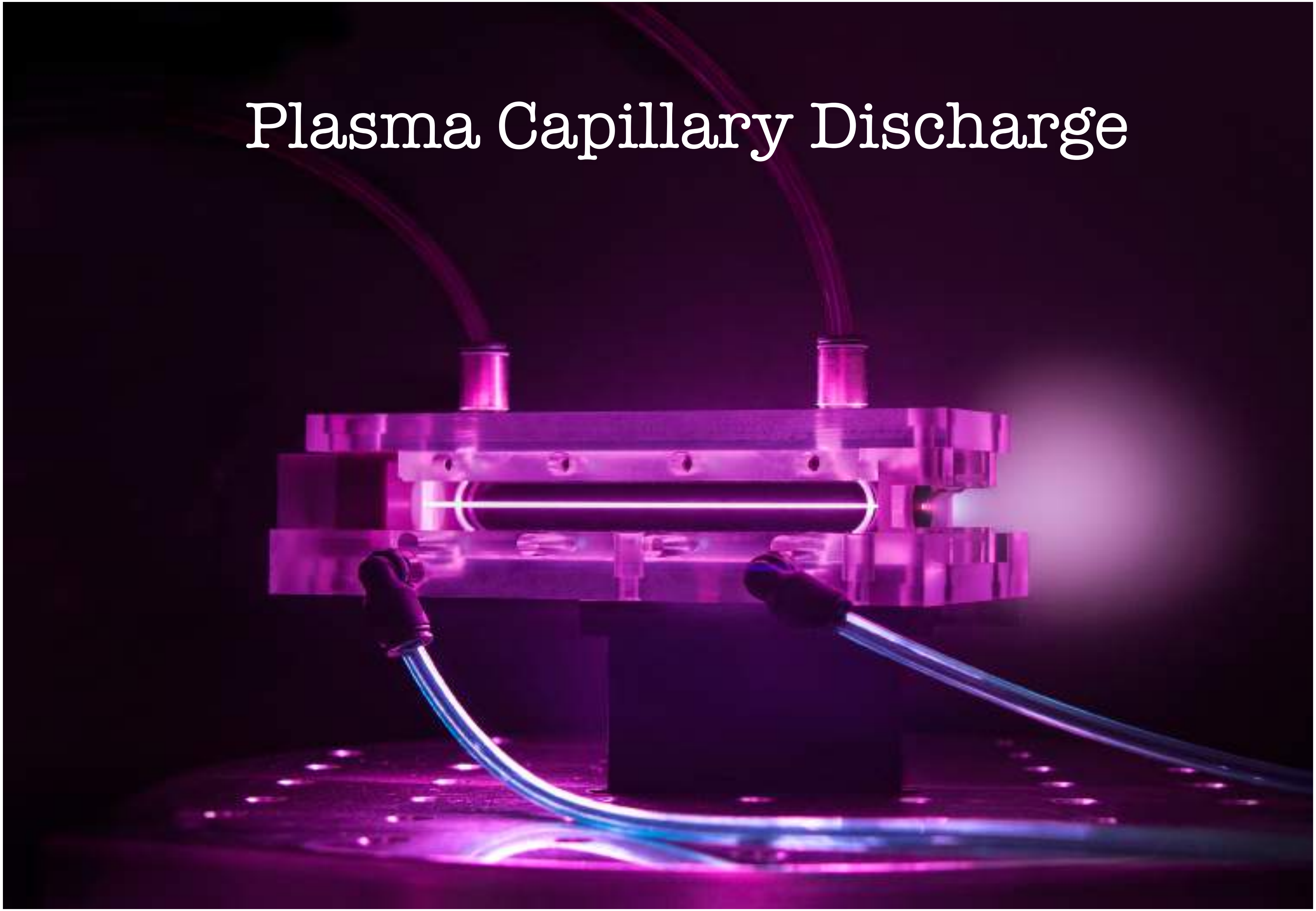
Increase radius = size (FCC-ee)

Lepton (e-,e+) linear collider

$$p = L \cdot G_{acc}$$

Increase accelerating gradient
(a) Pushing existing technology (ILC, CLIC)
(b) New regime of ultra-high gradients (plasma, dielectric accelerators)

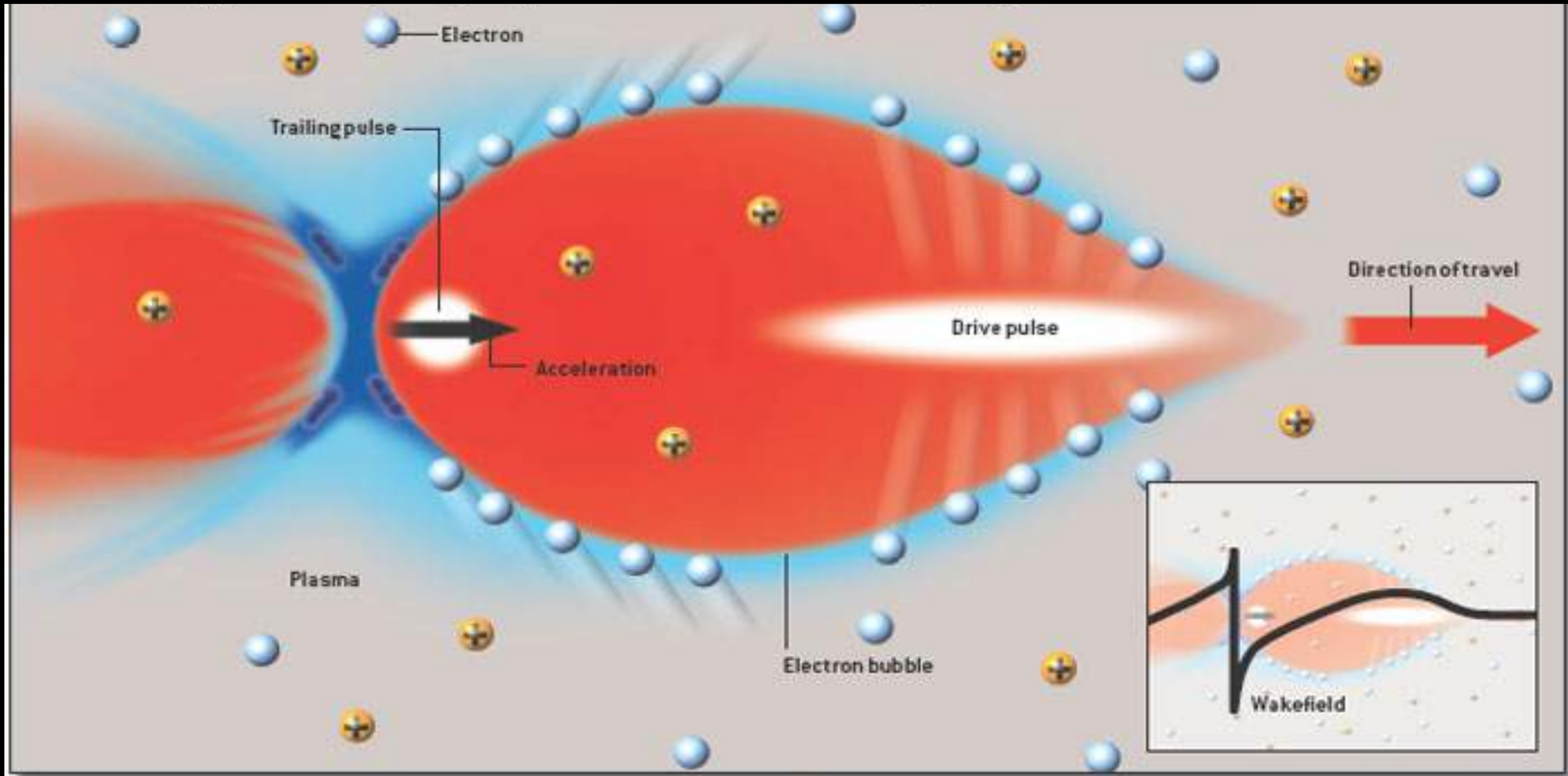
Increase length (ILC, CLIC)


Plasma Capillary Discharge

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)



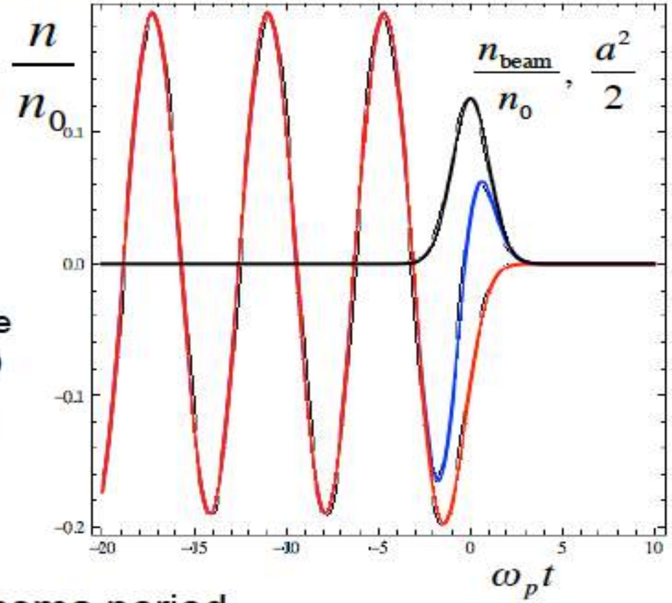
Plasma acceleration: ultrahigh accelerating gradients

Tajima & Dawson, PRL (1979)
Chen et al., PRL (1985)

$$\left(\frac{\partial^2}{\partial t^2} + \omega_p^2\right)\frac{n}{n_0} = -\omega_p^2 \frac{n_{\text{beam}}}{n_0} + c^2\nabla^2 \frac{a^2}{2}$$

- Plasma wave: electron density perturbation
- Space-charge force of particle beam
- Ponderomotive force (radiation pressure)

$$a = \frac{eA}{mc^2} \propto \lambda I^{1/2}$$



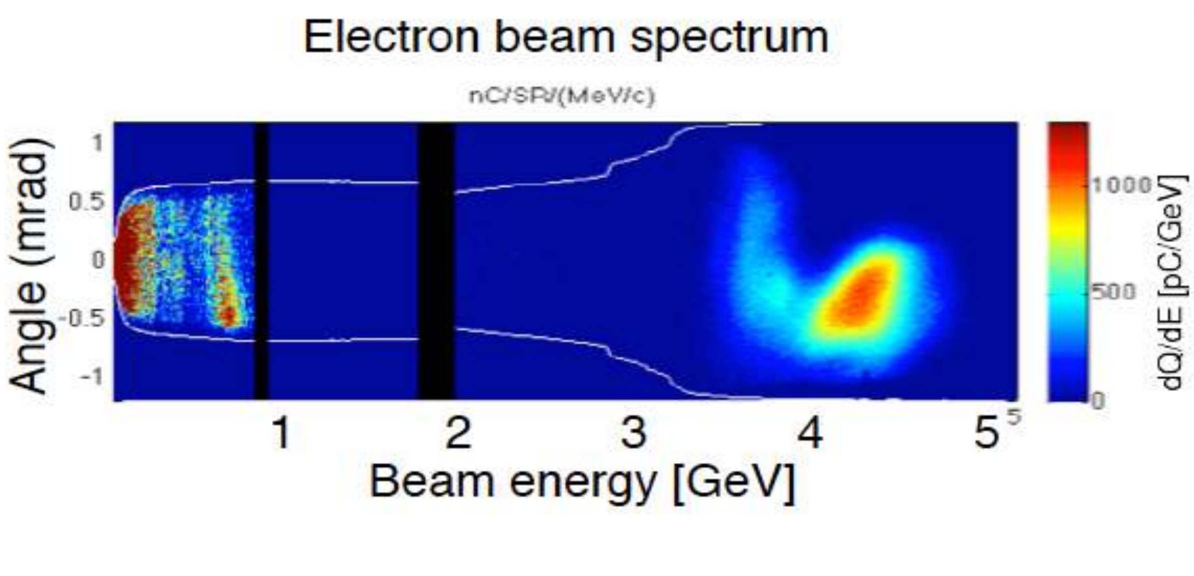
Common features:

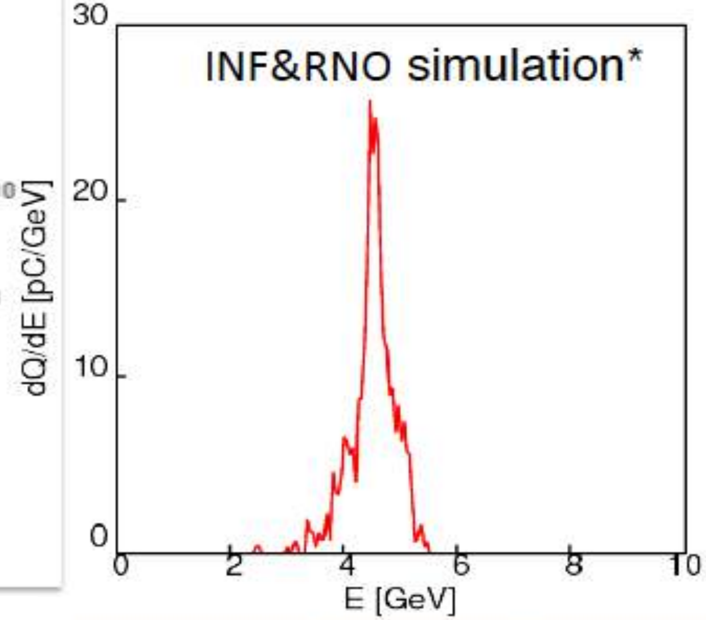
- Wave excitation efficient for driver duration ~ plasma period
- Bucket size ~ plasma wavelength: $\lambda_p = 2\pi c/\omega_p = (\pi r_e^{-1/2})\, n_p^{-1/2} \sim 10\text{-}100\ \mu m$
- Large waves excited for $n_{beam}/n_0 \sim 1$ or $a \sim 1$
- Characteristic accelerating field: $E \sim \left(\frac{mc\omega_p}{e}\right) \approx (96\text{V/m})\sqrt{n_0[\text{cm}^{-3}]}$
- Phase velocity of wave determined by driver velocity

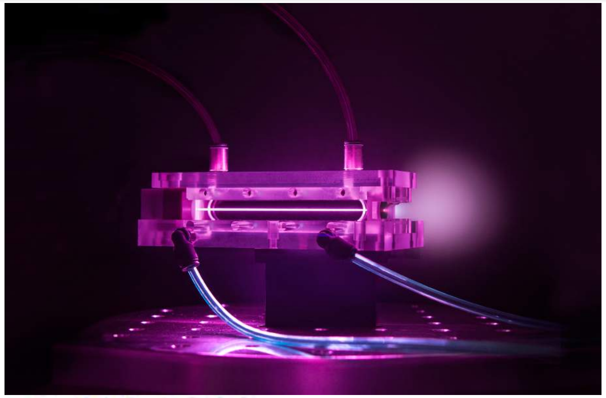
Courtesy C. Schroeder

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

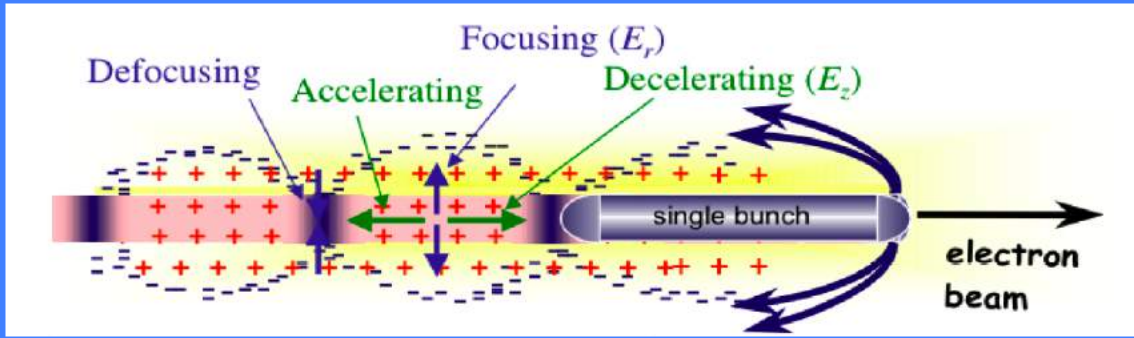


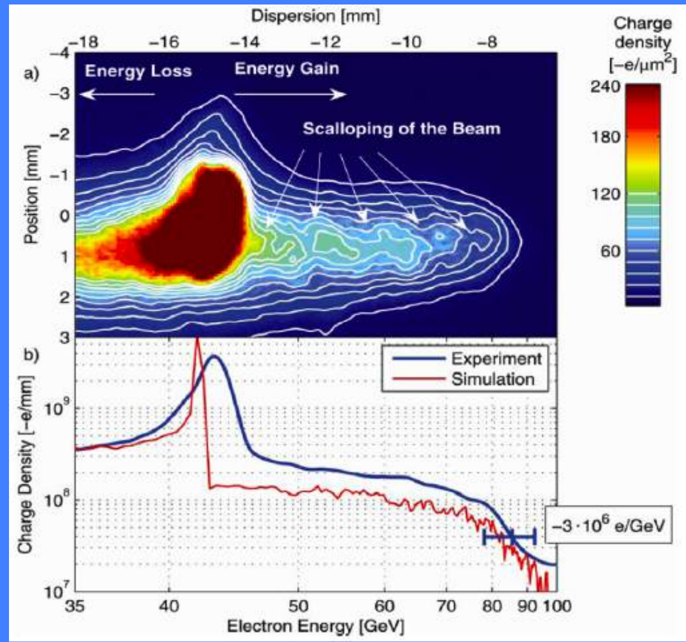




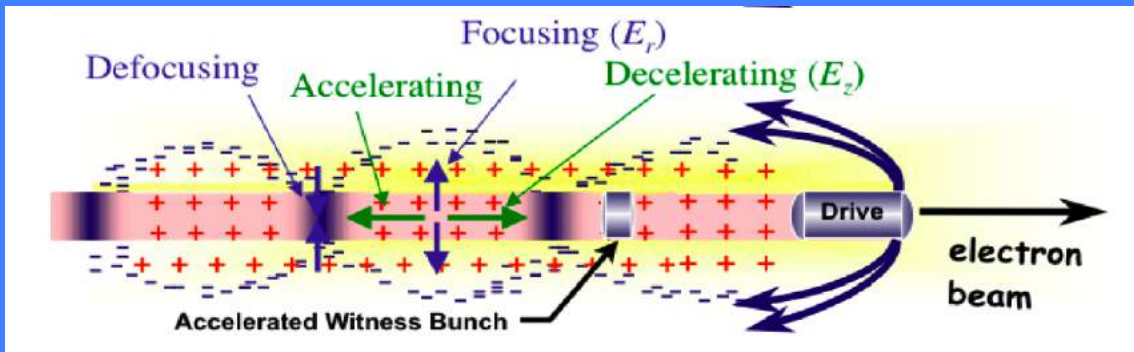
	Exp.	Sim.
Energy	4.25 GeV	4.5 GeV
ΔE/E	5%	3.2%
Charge	~20 pC	23 pC
Divergence	0.3 mrad	0.6 mrad

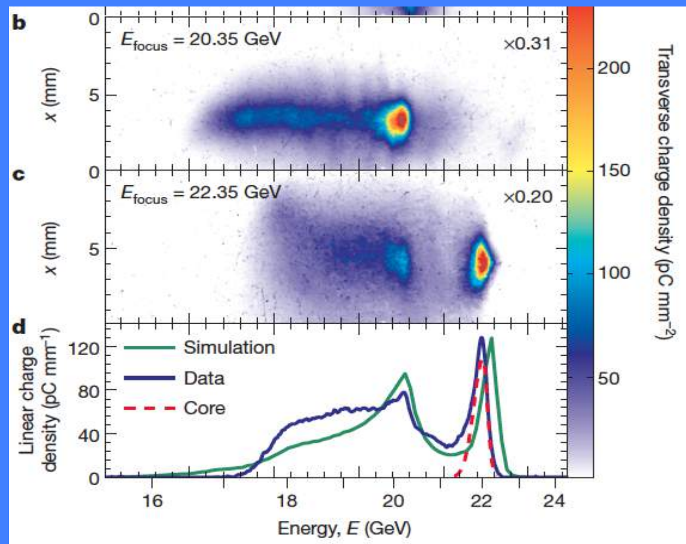
W.P. Leemans et al.,PRL 2014





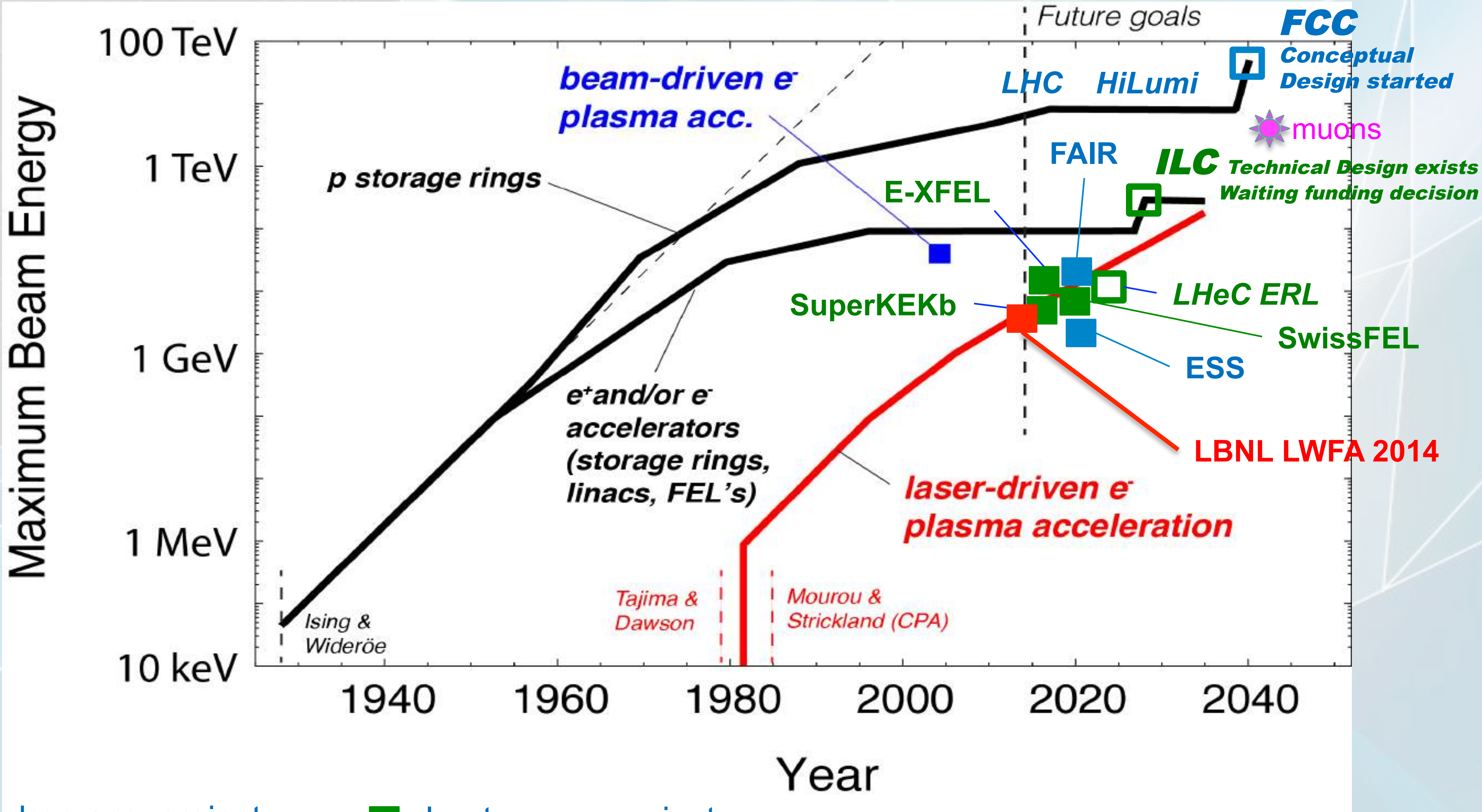
Blumenfeld, I. et al. *Energy doubling of 42 GeV electrons in a metre-scale plasma wakefield accelerator*. **Nature** 445, 741–744 (2007).





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

Future of Accelerators



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

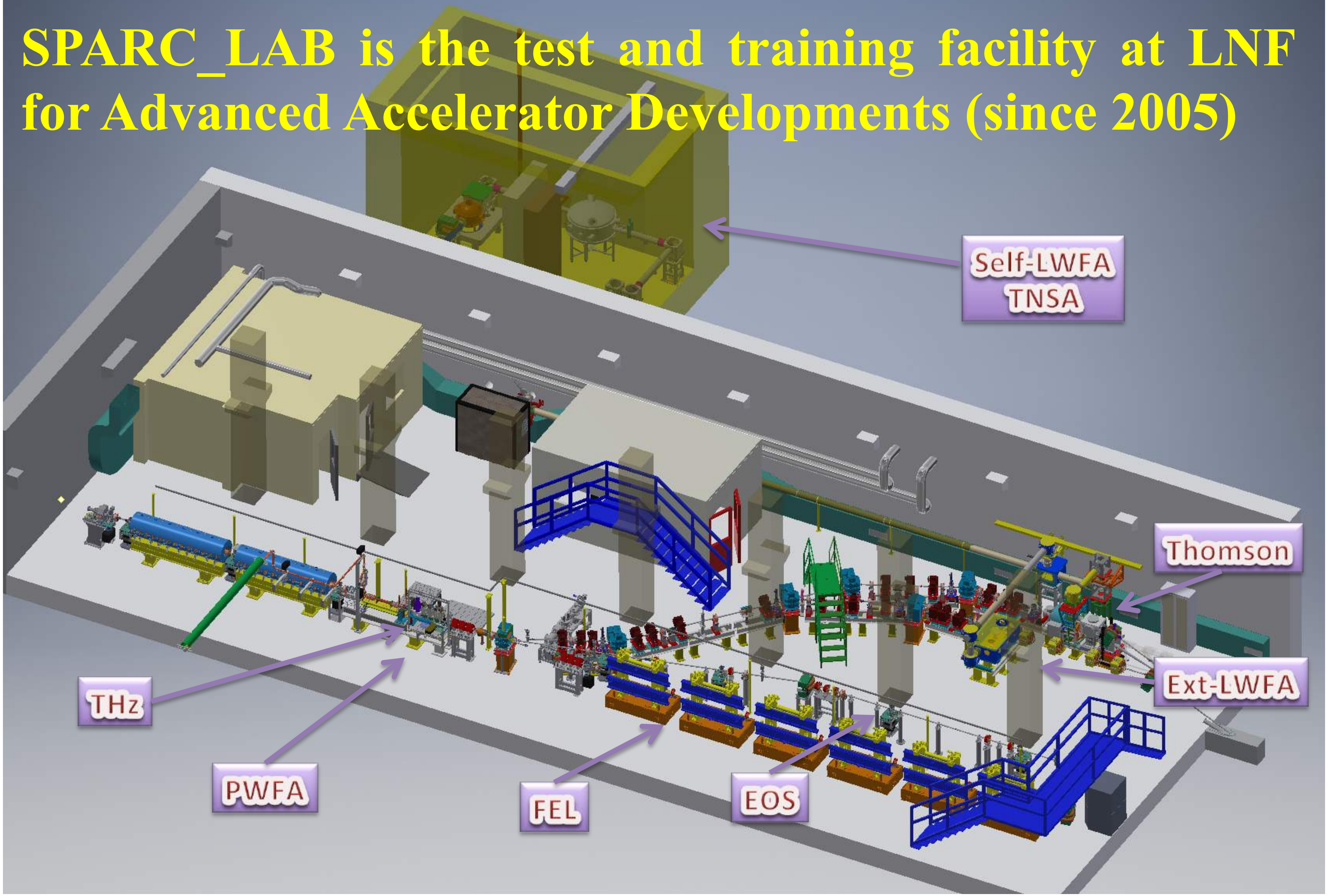
R. Assmann, EAAC 2015, 9/2015

Worldwide effort towards high quality plasma beams

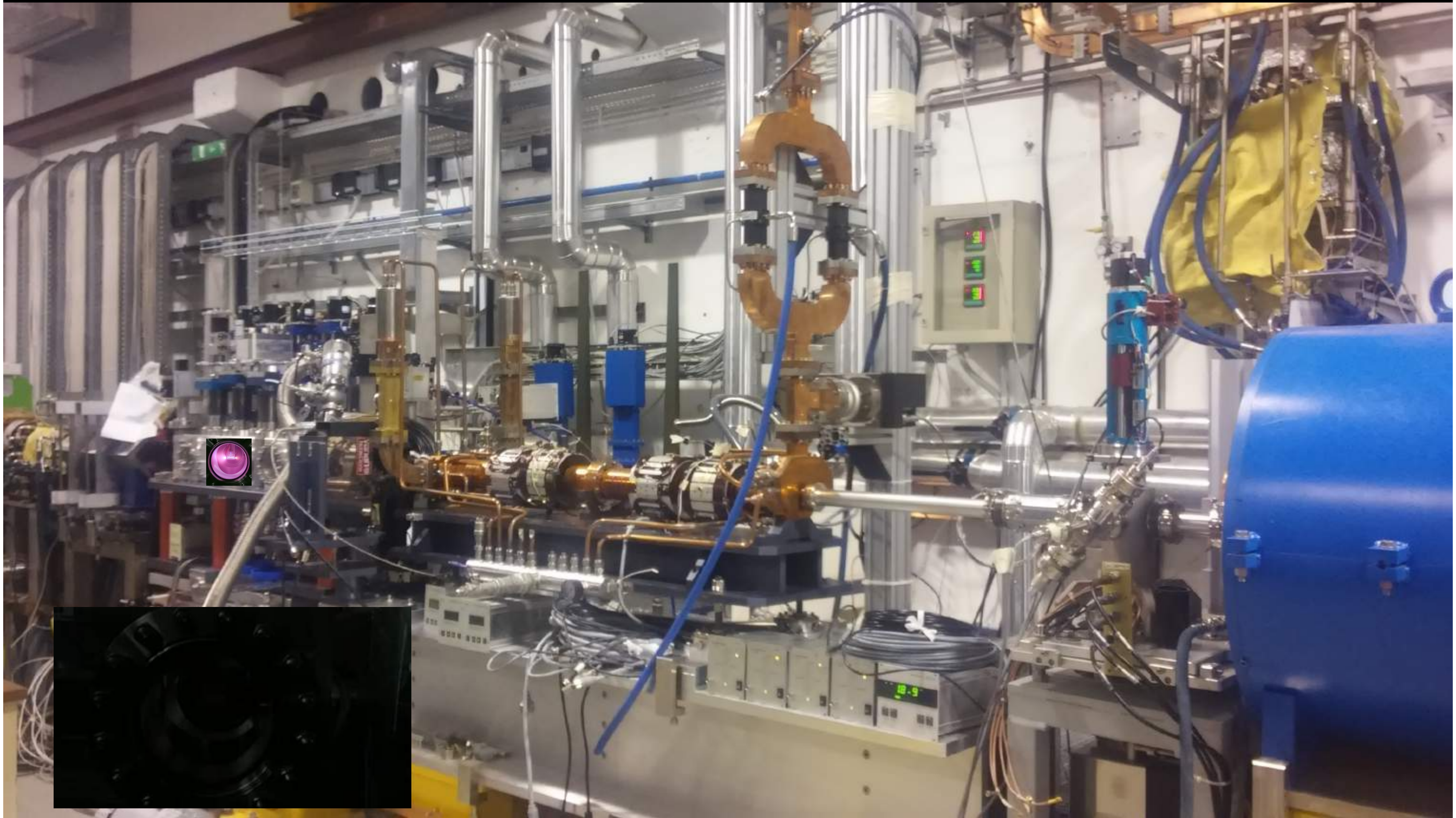
Associated Partners
(as of December 2017)

1 **Shanghai Jiao Tong-University**, China
2 **Tsinghua University Beijing**, China
3 **ELI Beamlines**, International
4 **PHLAM, Université de Lille**, France
5 **Helmholtz-Institut Jena**, Germany
6 **HZDR (Helmholtz)**, Germany
7 **LMU München**, Germany
8 **Wigner Fizikai Kutatóközpont**, Hungary
9 **CERN**, International
10 **Kansai Photon Science Institute**, Japan
11 **Osaka University**, Japan
12 **RIKEN SPring-8**, Japan
13 **Lunds Universitet**, Sweden
14 **Stony Brook University & Brookhaven NL**, USA
15 **LBNL**, USA
16 **UCLA**, USA
17 **Karlsruher Institut für Technologie**, Germany
18 **Forschungszentrum Jülich**, Germany
19 **Hebrew University of Jerusalem**, Israel
20 **Institute of Applied Physics**, Russia
21 **Joint Institute for High Temperatures**, Russia
22 **Università di Roma 'Tor Vergata'**, Italy
23 **Queen's University Belfast**, UK
24 **Ferdinand-Braun-Institut**, Germany

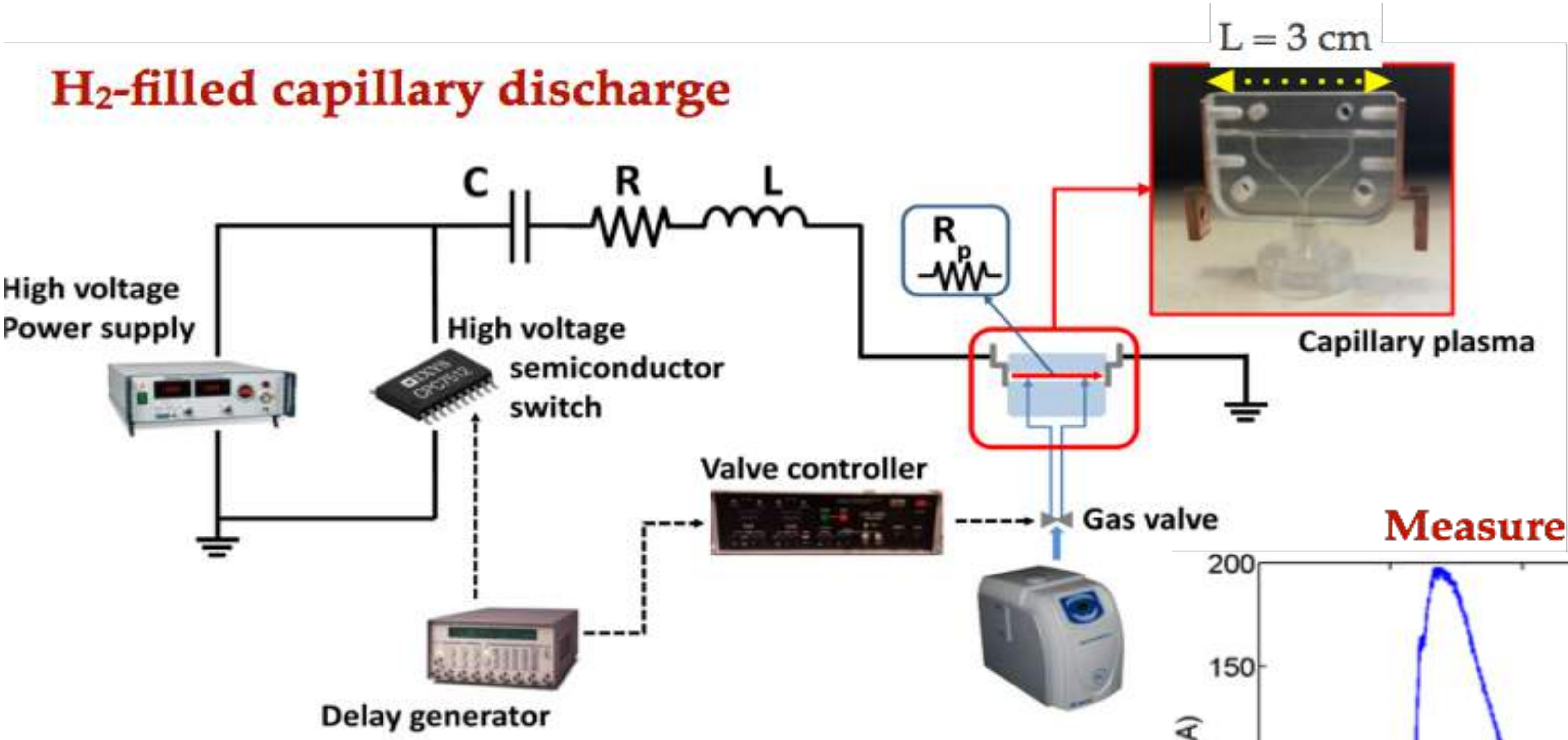
SPARC_LAB is the test and training facility at LNF for Advanced Accelerator Developments (since 2005)

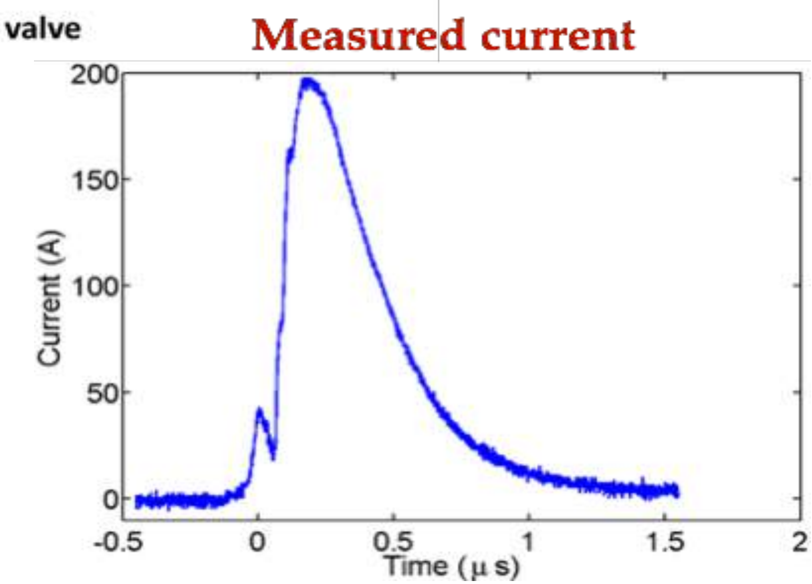


PWFA vacuum chamber at SPARC_LAB



Plasma Source





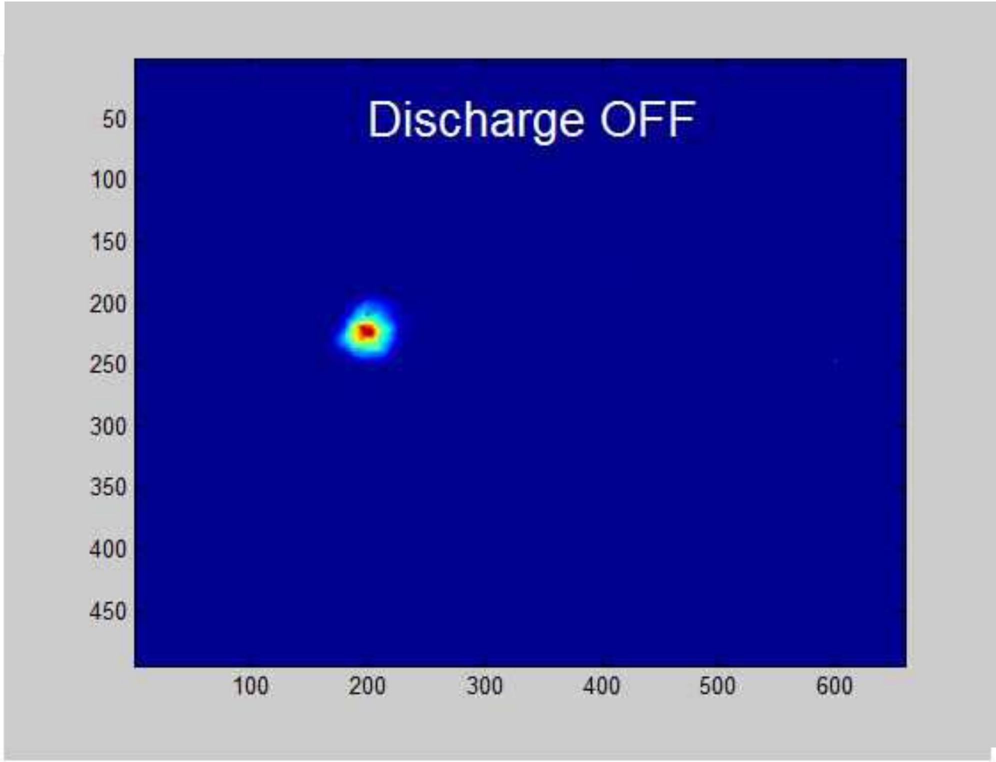
P_{H2} = 10 mbar
Total discharge duration: 800 ns
Voltage: 20 kV
Peak current: 200 A
Capacitor: 6 nF

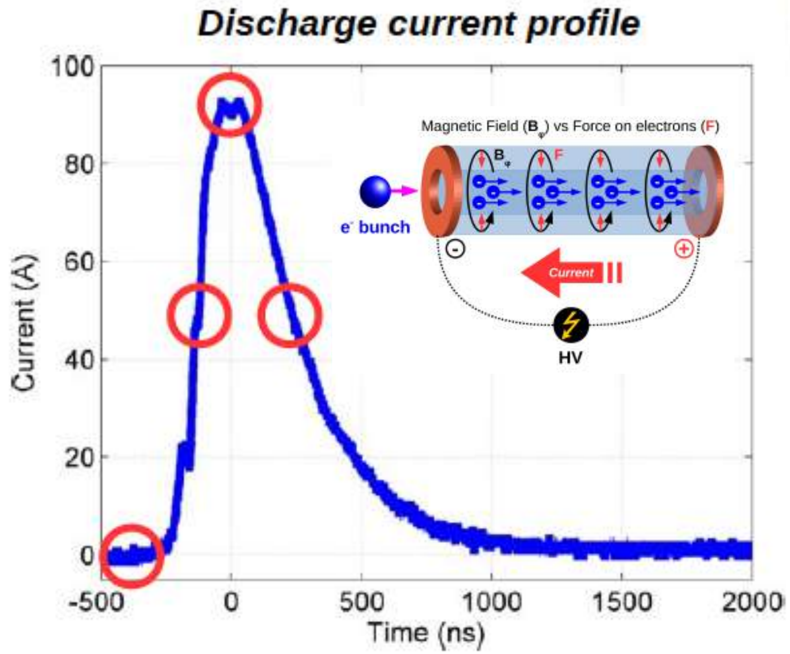
Courtesy of M. P. Anania, A. Biagioni, D. Di Giovenale, F. Filippi, S. Pella

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

Experimental characterization of active plasma lensing for electron beams

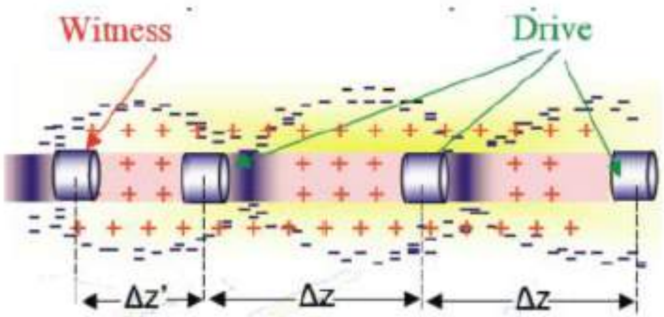
R. Pompili,[1,a)] M. P. Anania,[1] M. Bellaveglia,[1] A. Biagioni,[1] S. Bini,[1] F. Bisesto,[1] E. Brentegani,[1] G. Castorina,[1,2] E. Chiadroni,[1] A. Cianchi,[3] M. Croia,[1] D. Di Giovenale,[1] M. Ferrario,[1] F. Filippi,[1] A. Giribono,[4] V. Lollo,[1] A. Marocchino,[1] M. Marongiu,[4] A. Mostacci,[4]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





Plasma-based acceleration techniques

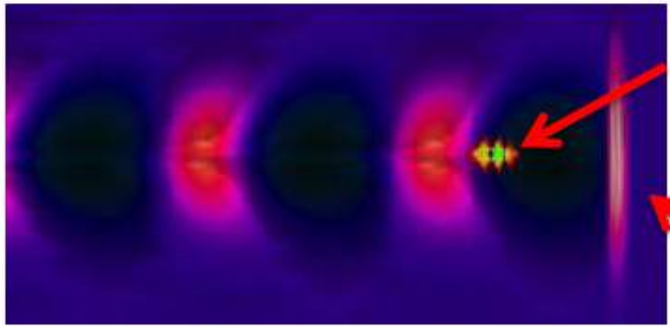
resonant-PWFA



•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

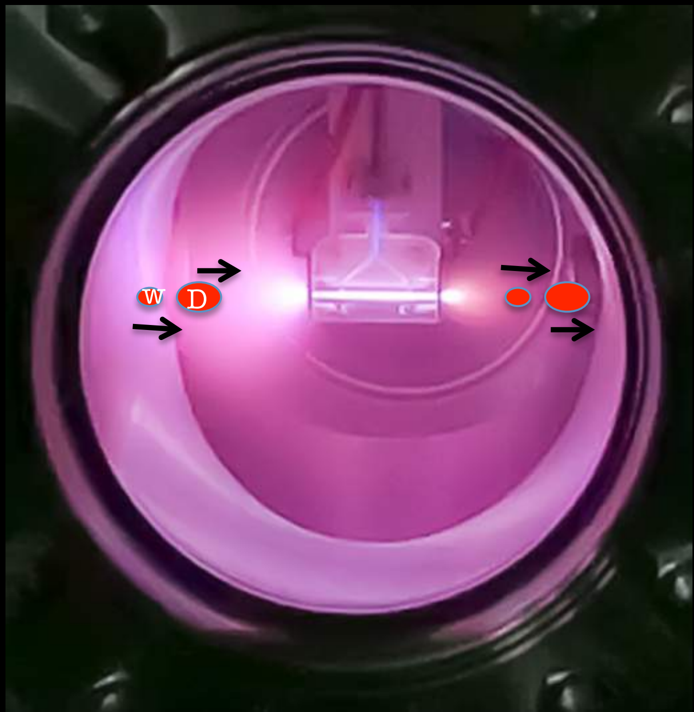
external injection LWFA



•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

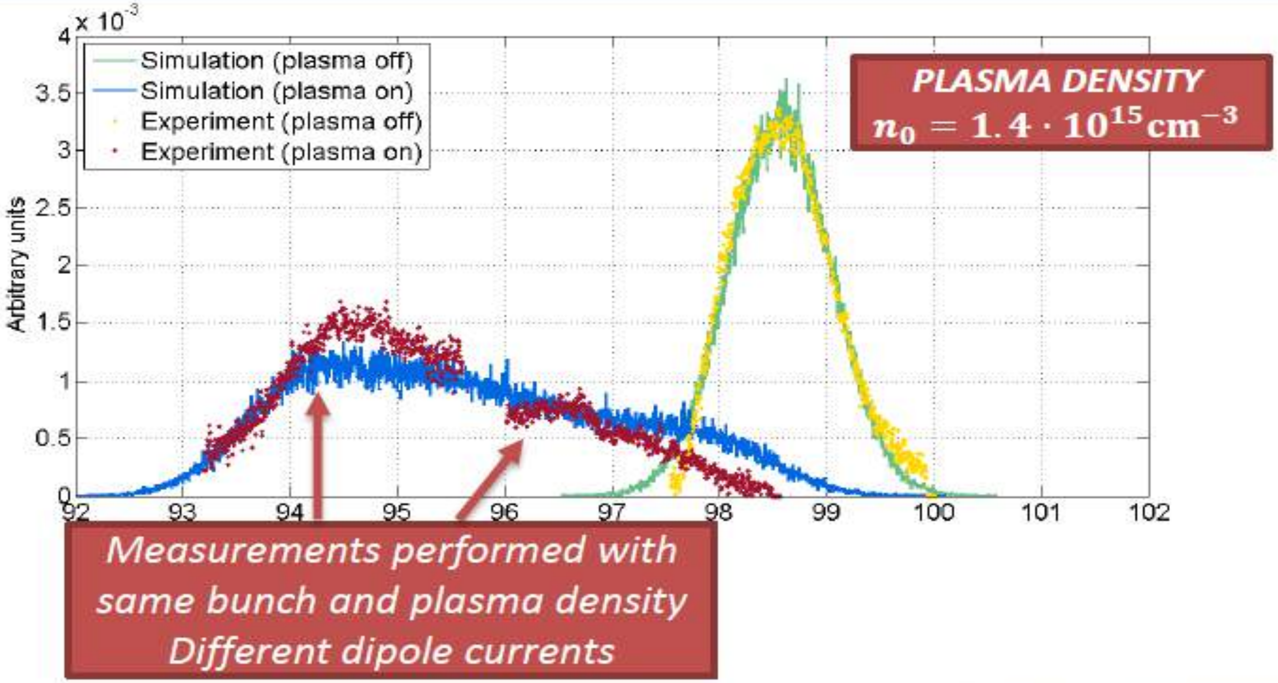
External Injection



$$\Delta T_w = \left(R - \frac{q}{Q}\right)\left|\Delta T_D\right|$$

$$R \cong 2$$

Deceleration test - July 2018

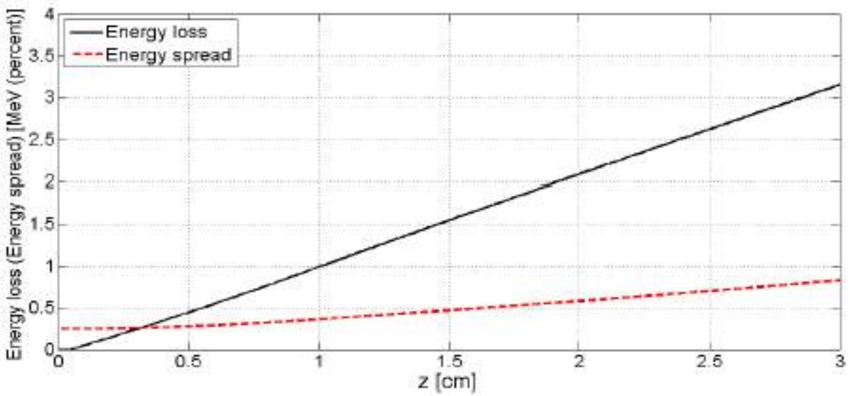


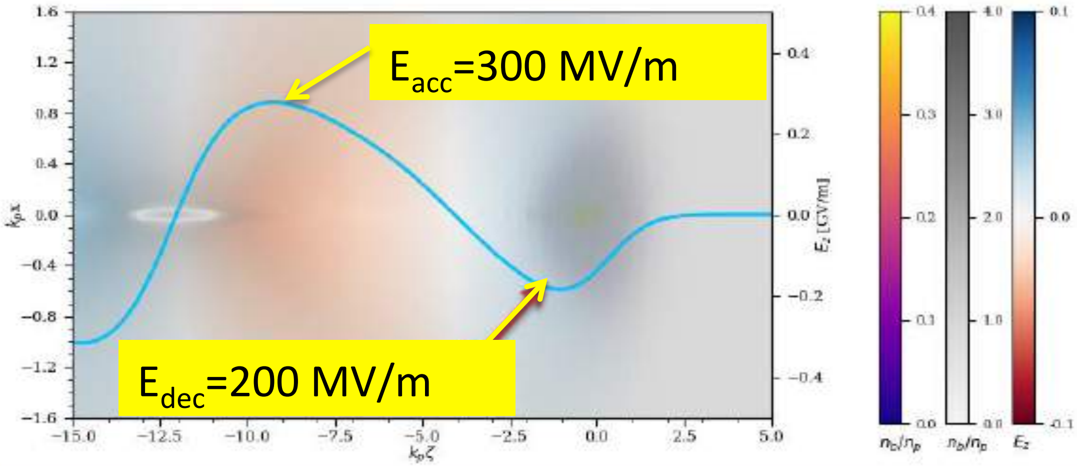
Experimental data at injection

$\sigma_{x,(y)} = 24(33)\mu\mathrm{m}$
$\sigma_z = 50\mu\mathrm{m}$
$\varepsilon_{x,(y)} = 1.7(1.8)\mathrm{mm\ mrad}$
$\sigma_E = 0.5\%$

Simulation parameters

$\sigma_{x,y} = 28.3\mu\mathrm{m}$
$\sigma_z = 50\mu\mathrm{m}$
$\varepsilon_{x,y} = 1.75\mathrm{mm\ mrad}$
$\sigma_E = 0.5\%$





EUROPEAN
PLASMA RESEARCH
ACCELERATOR WITH
EXCELLENCE IN
APPLICATIONS

EuPRAXIA

EuPRAXIA Design Study started on Novemebr 2015

Approved as HORIZON 2020 INFRADEV, 4 years, 3 M€

Coordinator: Ralph Assmann (DESY)

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

http://eupraxia-project.eu

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

Consortium

16 Participants

DESY
INFN
Consiglio Nazionale delle Ricerche
cnrs
University of Strathclyde Glasgow
IST-ID Associação do Instituto Superior Técnico para a Investigação e Desenvolvimento
Science & Technology Facilities Council
SOLEIL SYNCHROTRON
MANCHESTER 1824 The University of Manchester
UNIVERSITY OF LIVERPOOL
ENEA Italian National Agency for New Technologies, Energy and Sustainable Economic Development
cea
SAPIENZA UNIVERSITÀ DI ROMA
UHH Universität Hamburg
Imperial College London
UNIVERSITY OF OXFORD

24 Associated Partners

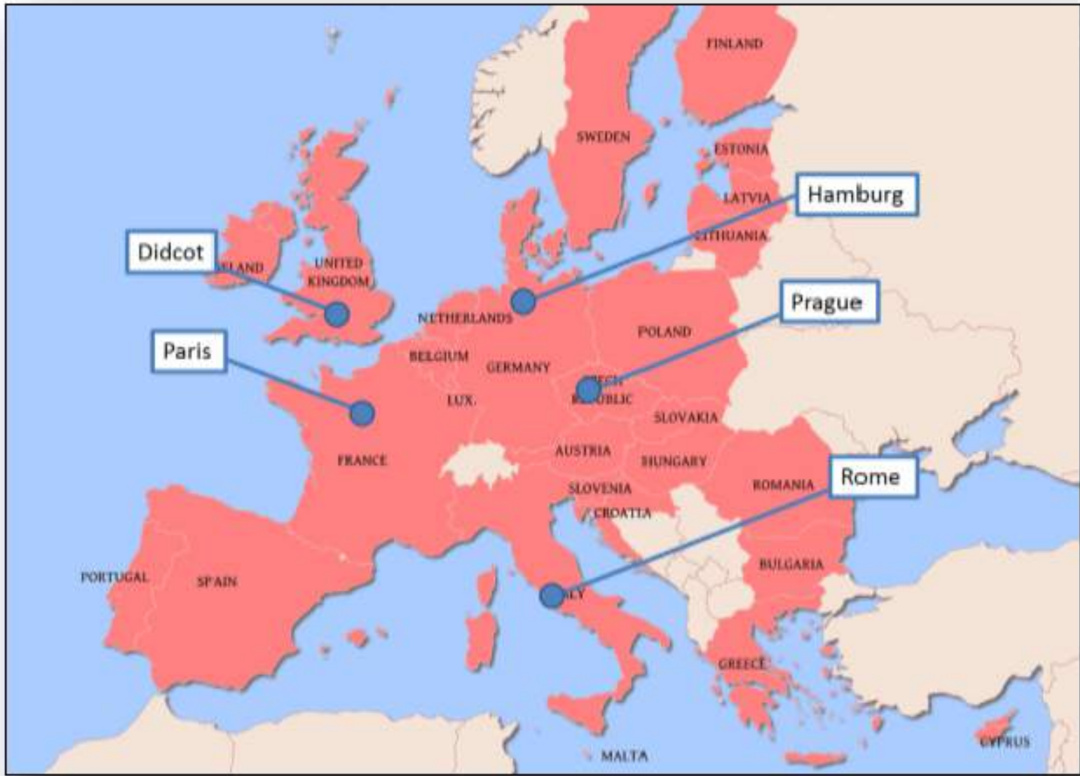
(as of December 2017)

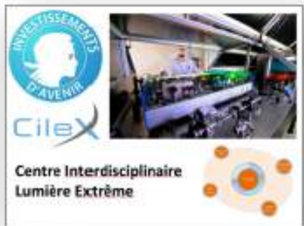
上海交通大学 SHANGHAI JIAO TONG UNIVERSITY
Université de Lille 1 SCIENCES ET TECHNOLOGIES
eli beamlines
HI Jena Helmholtz Institute Jena
清華大学 Tsinghua University
HZDR HELMHOLTZ ZENTRUM DRESDEN ROSSENDORF
LMU LUDWIG-MAXIMILIANS-UNIVERSITÄT MÜNCHEN
wigner
KPSI JAEA
大阪大学 OSAKA UNIVERSITY
RIKEN
Stony Brook University CASE
CERN
LUND UNIVERSITY
BERKELEY LAB
UCLA
KIT Karlsruhe Institute of Technology
Università di Roma Tor Vergata
האוניברסיטה העברית בירושלים THE HEBREW UNIVERSITY OF JERUSALEM
ОБЪЕДИНЕННЫЙ ИВТАН
ИЯФ РАН
JÜLICH FORSCHUNGSZENTRUM
QUEEN'S UNIVERSITY BELFAST
FBH Ferdinand Braun Institut

Location of possible sites within EU

EuPRAXIA site studies:

- Design study is site independent
- Five possible sites have been discussed so far
- We invite the suggestions of additional sites

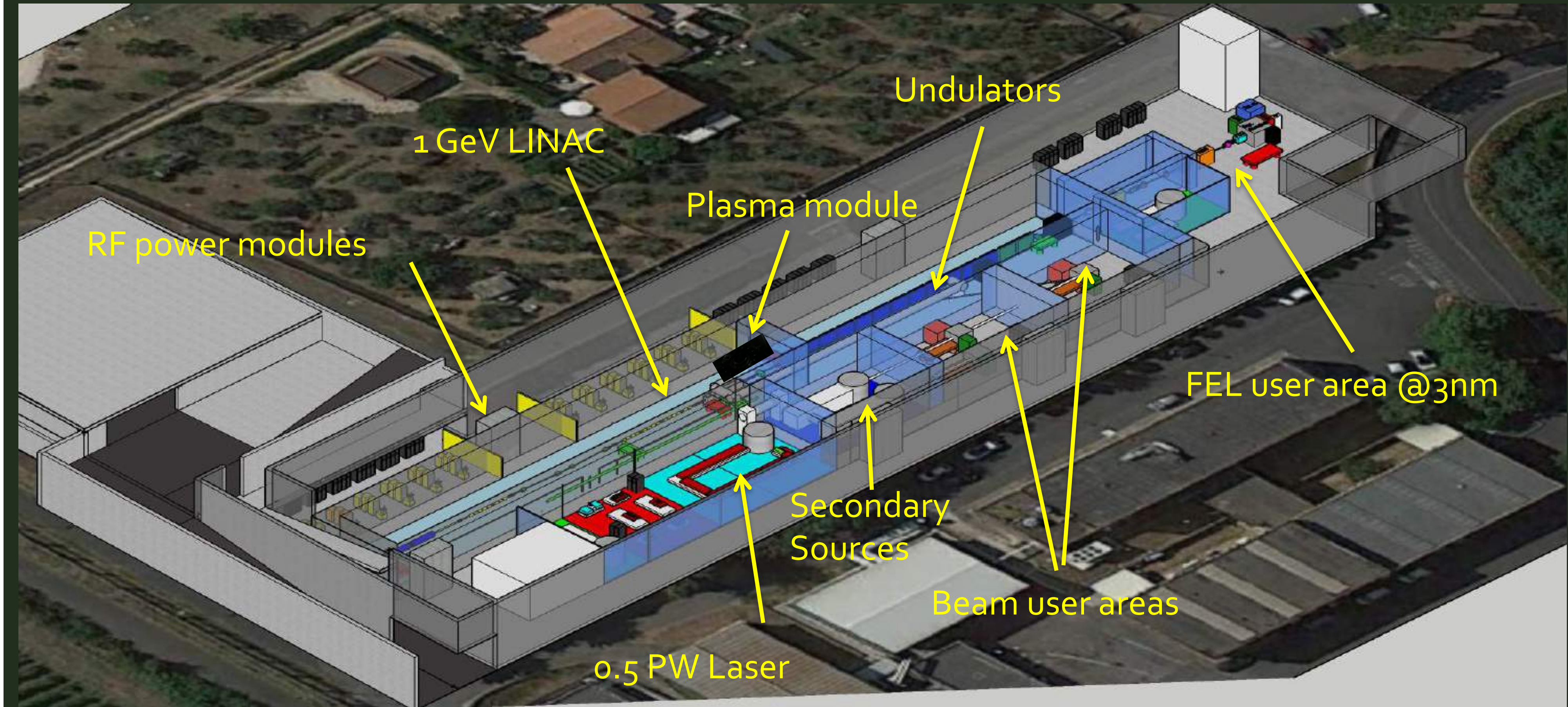




Central Laser Facility
Didcot, United Kingdom

Eli Beamlines
Prague, Czech Republic

EuPRAXIA@SPARC_LAB



http://www.lnf.infn.it/sis/preprint/pdf/getfile.php?filename=INFN-18-03-LNF.pdf

D. Alesini[a], M. P. Anania[a], M. Artioli[b], A. Bacci[c], S. Bartocci[d], R. Bedogni[a], M. Bellaveglia[a], A. Biagioni[a], F. Bisesto[a], F. Brandi[e], E. Brentegani[a], F. Broggi[c], B. Buonomo[a], P. Campana[a], G. Campogiani[a], C. Cannaos[d], S. Cantarella[a], F. Cardelli[a], M. Carpanese[f], M. Castellano[a], G. Castorina[g], N. Catalan Lasheras[h], E. Chiadroni[a], A. Cianchi[i], R. Cimino[a], F. Ciocci[f], D. Cirrincione[j], G. A. P. Cirrone[k], R. Clementi[a], M. Coreno[l], R. Corsini[h], M. Croia[a], A. Curcio[a], G. Costa[a], C. Curatolo[c], G. Cuttone[k], S. Dabagov[a], G. Dattoli[f], G. D'Auria[l], I. Debrot[c], M. Diomede[a,g], A. Drago[a], D. Di Giovenale[a], S. Di Mitri[l], G. Di Pirro[a], A. Esposito[a], M. Faiferri[d], M. Ferrario[a], L. Ficcadenti[g], F. Filippi[a], O. Frasciello[a], A. Gallo[a], A. Ghigo[a], L. Giannessi[f,l], A. Giribono[a], L. A. Gizzi[e], A. Grudiev[h], S. Guiducci[a], P. Koester[e], S. Incremona[a], F. Iungo[a], L. Labate[e], A. Latina[h], S. Licciardi[f], V. Lollo[a], S. Lupi[g], R. Manca[d], A. Marcelli[a,m,n], M. Marini[d], A. Marocchino[a], M. Marongiu[g], V. Martinelli[a], C. Masciovecchio[l], C. Mastino[d], A. Michelotti[a], C. Milardi[a], M. Migliorati[g], V. Minicozzi[i], F. Mira[g], S. Morante[i], A. Mostacci[g], F. Nguyen[f], S. Pagnutti[f], L. Palumbo[g], L. Pellegrino[a], A. Petralia[f], V. Petrillo[o], L. Piersanti[a], S. Pioli[a], D. Polese[d], R. Pompili[a], F. Pusceddu[d], A. Ricci[m], R. Ricci[a], R. Rochow[l], S. Romeo[a], J. B. Rosenzweig[p], M. Rossetti Conti[o], A. R. Rossi[c], U. Rotundo[a], L. Sabbatini[a], E. Sabia[f], O. Sans Plannell[a], D. Schulte[h], J. Scifo[a], V. Scuderi[k], L. Serafini[c], B. Spataro[a], A. Stecchi[a], A. Stella[a], V. Shpakov[a], F. Stellato[i], P. Tomassini[e], E. Turco[d], C. Vaccarezza[a], A. Vacchi[j], A. Vannozzi[a], G. Vantaggiato[e], A. Variola[a], S. Vescovi[a], F. Villa[a], W. Wuensch[h], A. Zigler[q], M. Zobov[a]

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[b] *ENEA - Centro Ricerche Bologna, Via Martiri Monte Sole 4, 40129 Bologna, Italy*
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[d] *Universitá degli Studi di Sassari, Dip. di Architettura, Design e Urbanistica ad Alghero, Palazzo del Pou Salit - Piazza Duomo 6, 07041 Alghero, Italy*
[e] *Intense Laser Irradiation Laboratory (ILIL), Istituto Nazionale di Ottica (INO), Consiglio Nazionale delle Ricerche (CNR), Via G. Moruzzi 1, 56124 Pisa, Italy and INFN Pisa section, Pisa, Largo Pontecorvo 3, 56127 Pisa, Italy*
[f] *ENEA - Centro Ricerche Frascati, Via E. Fermi 45, 00044 Frascati, Italy*
[g] *Sapienza University of Roma and INFN, P.le Aldo Moro 2, 00185 Rome, Italy*
[h] *CERN, CH-1211 Geneva 23, Switzerland*
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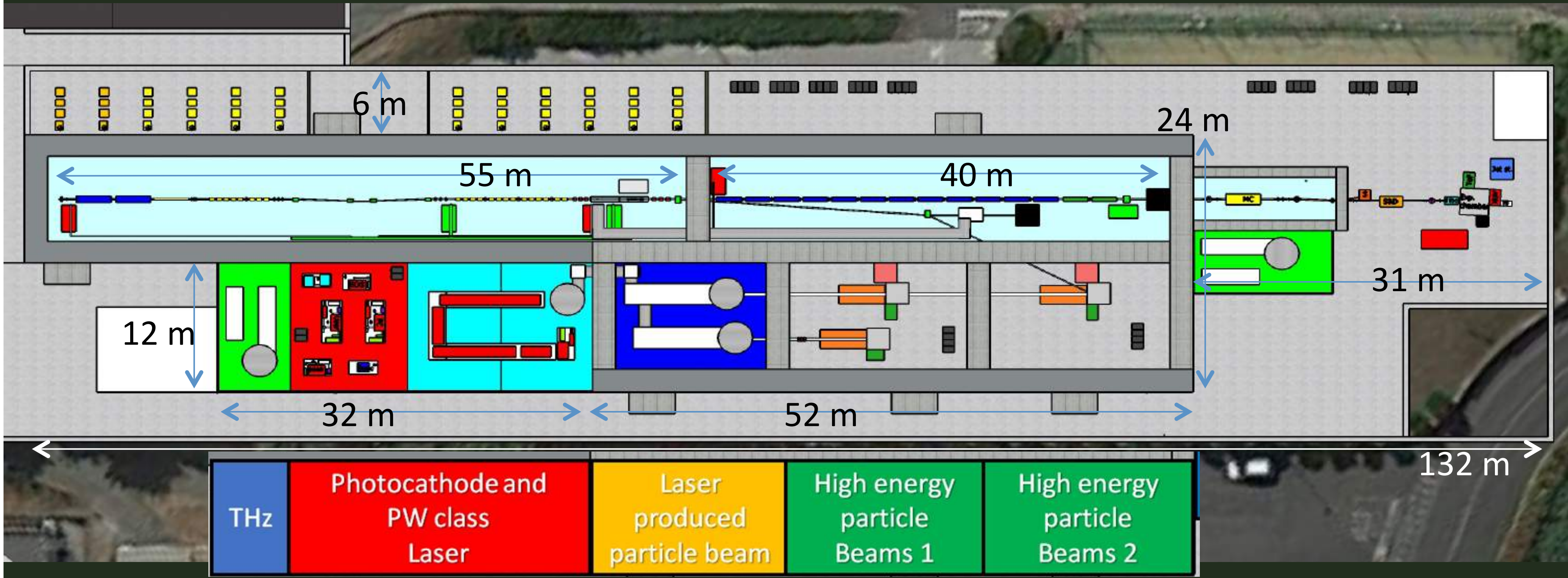
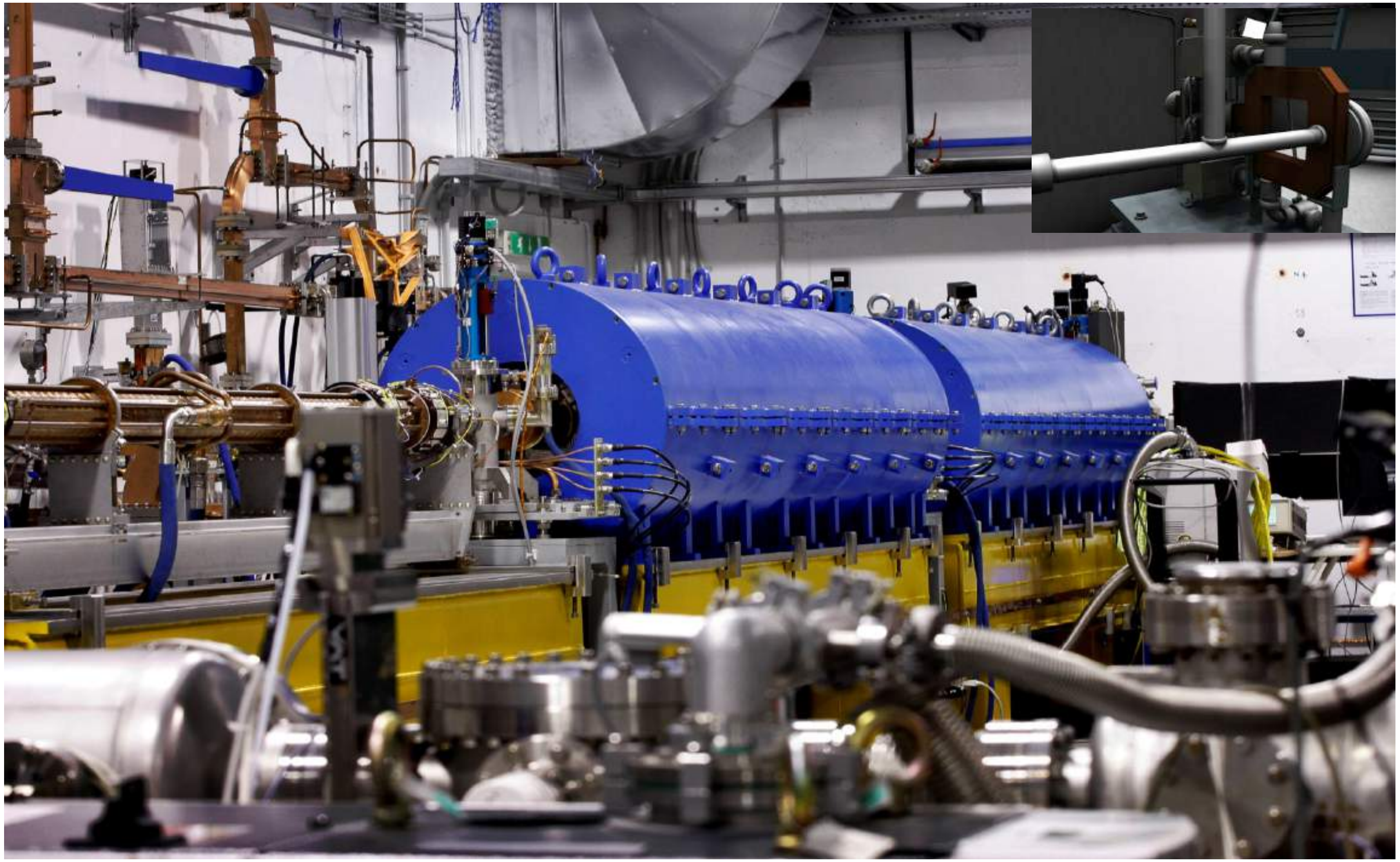
[m] *RICMASS, Rome International Center for Materials Science Superstripes, 00185 Rome, Italy*
[n] *ISM-CNR, Basovizza Area Science Park, Elettra Lab, 34149 Trieste - Italy*
[o] *Universitá degli Studi di Milano and INFN, Via Celoria 16, 20133 Milan, Italy*
[p] *Department of Physics and Astronomy, University of California Los Angeles, Los Angeles, California 90095, USA*
[q] *Racah Institute of Physics, The Hebrew University of Jerusalem, 91904 Jerusalem, Israel*

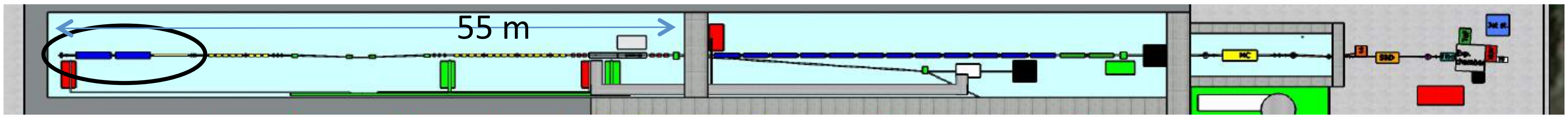
- Candidate LNF to host EuPRAXIA (1-5 GeV)
- FEL user facility (1 GeV – 3nm)
- Advanced Accelerator Test facility (LC) + CERN



- 500 MeV by RF Linac + 500 MeV by Plasma (LWFA or PWFA)
- 1 GeV by X-band RF Linac only
- Final goal compact 5 GeV accelerator

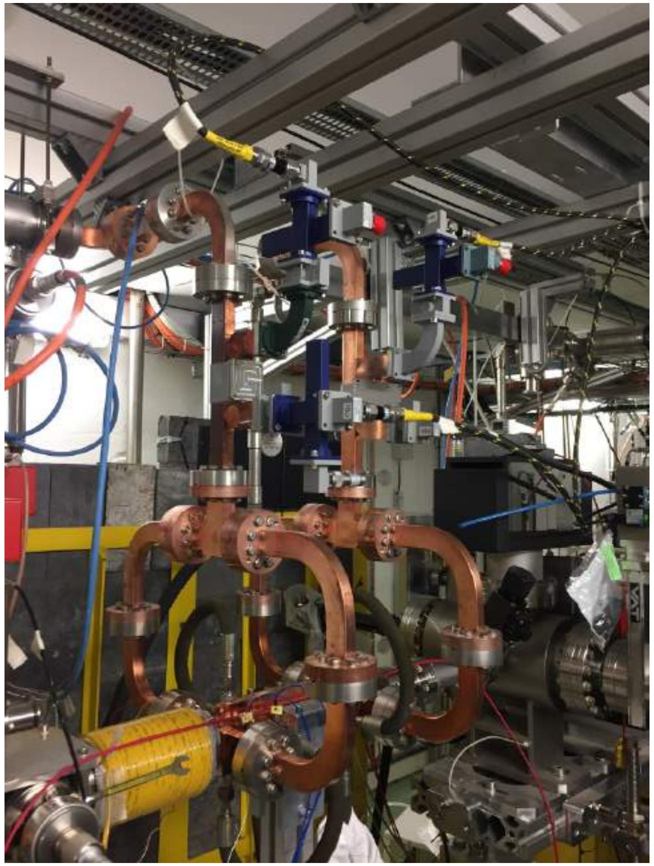
SPARC_LAB HB photo- injector





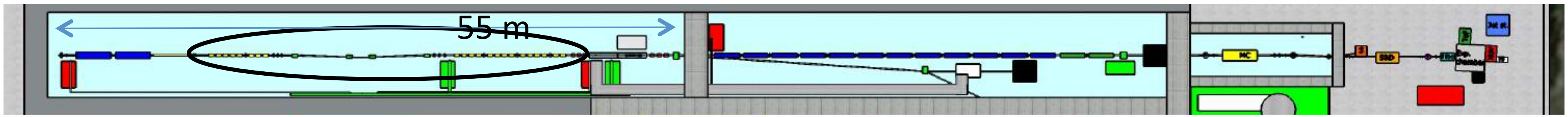
SPARC LAB

X-band Linac and High Power Laser

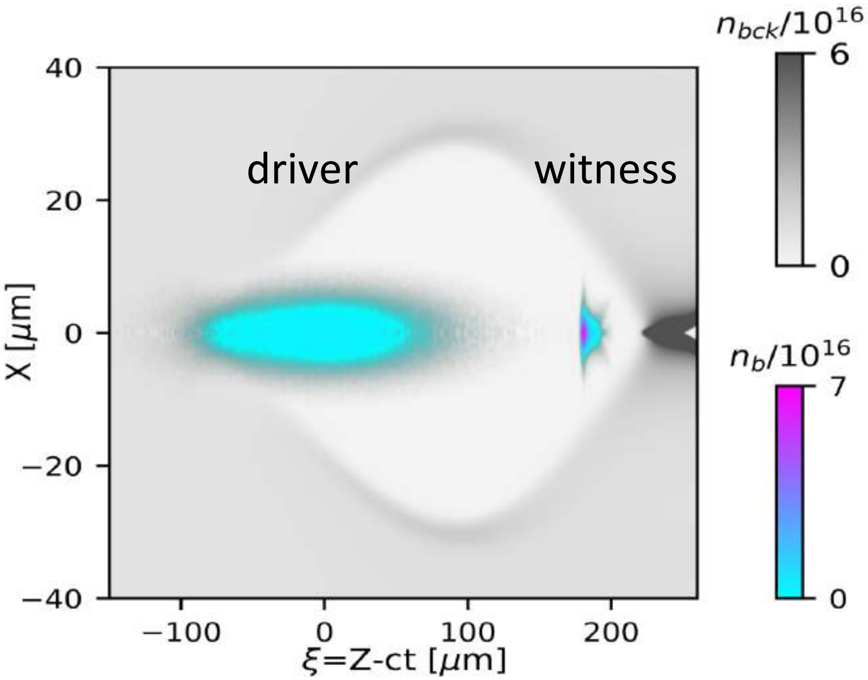


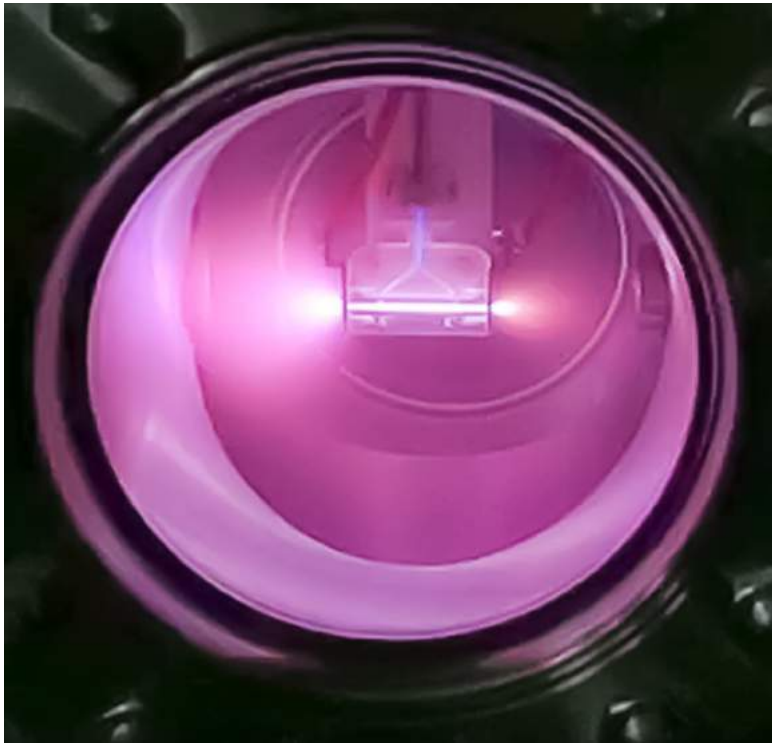
Energy	6 J
Duration	23 fs
Wavelength	800 nm
Bandwidth	60/80 nm
Spot @ focus	10 μm
Peak Power	300 TW
Contrast Ratio	10^{10}

See F. Bisesto talk later

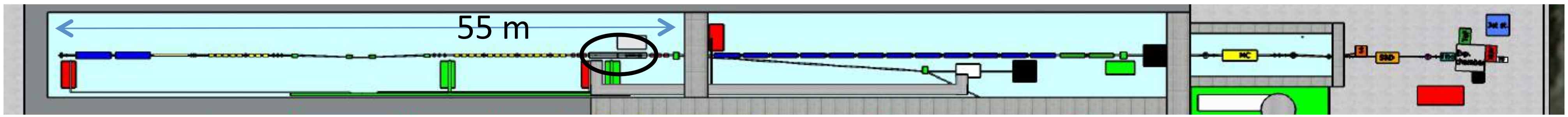


Plasma WakeField Acceleration – External Injection

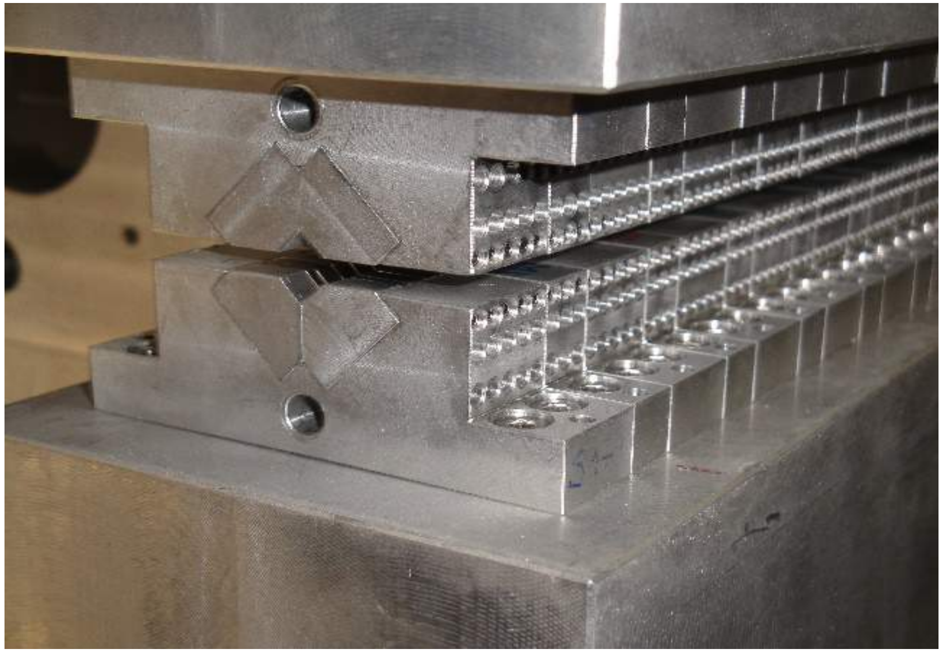




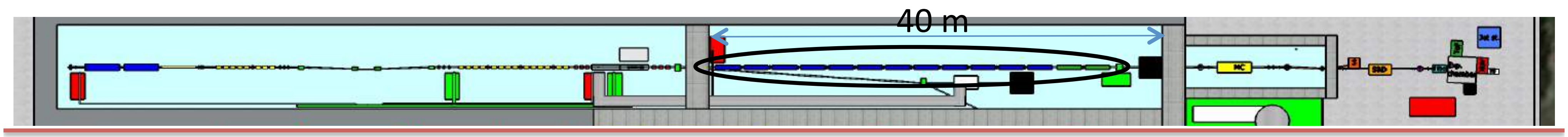
Capillary discharge at SPARC_LAB



Undulators



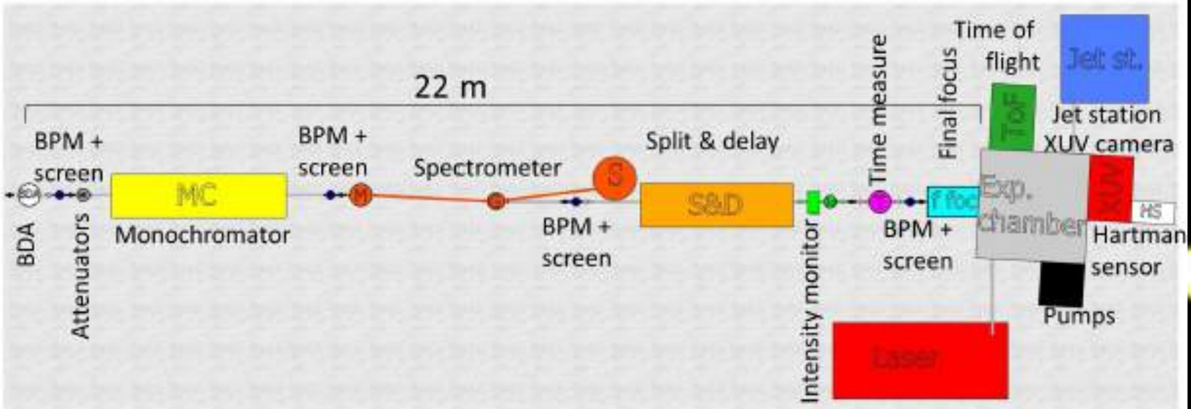
KYMA Δ udulator at SPARC_LAB: λ=1.4 cm, K1

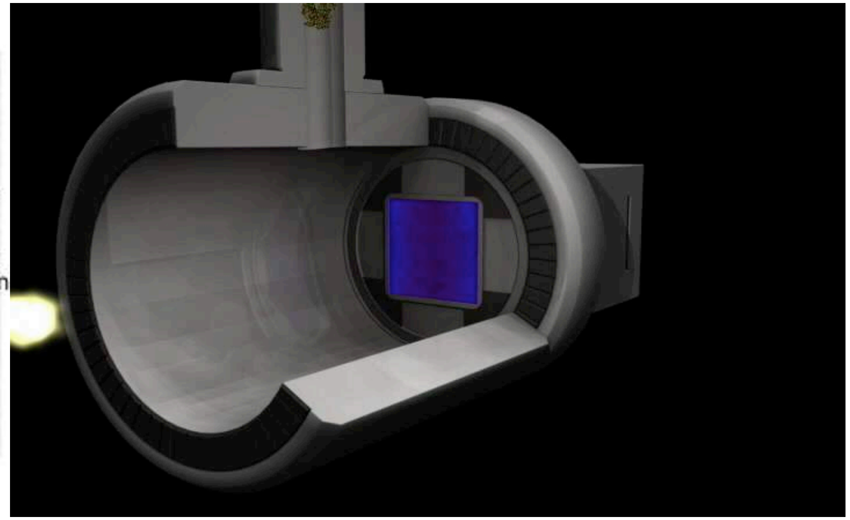


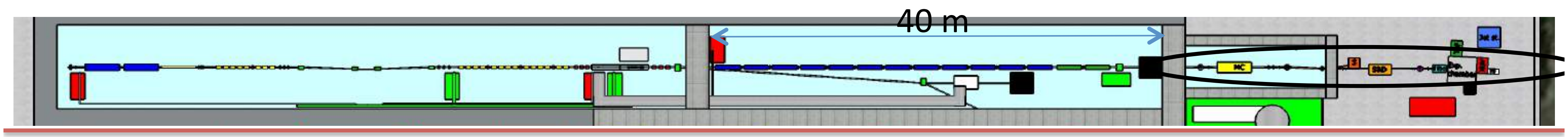
	Units	Full RF case	Plasma case
Electron Energy	GeV	1	1
Bunch Charge	pC	200	30
Peak Current	kA	2	3
RMS Energy Spread	%	0.1	1
RMS Bunch Length	fs	40	4
RMS matched Bunch Spot	μm	34	34
RMS norm. Emittance	μm	1	1
Slice length	μm	0.5	0.45
Slice Energy Spread	%	0.01	0.1
Slice norm. Emittance	μm	0.5	0.5
Undulator Period	mm	15	15
Undulator Strength K		1.03	1.03
Undulator Length	m	12	14
Gain Length	m	0.46	0.5
Pierce Parameter ρ	x 10^{-3}	1.5	1.4
Radiation Wavelength	nm	3	3
Undulator matching β_u	m	4.5	4.5
Saturation Active Length	m	10	11
Saturation Power	GW	4	5.89
Energy per pulse	μJ	83.8	11.7
Photons per pulse	x 10^{11}	11	1.5

See C. Vaccarezza talk tomorrow morning

Photon beam line





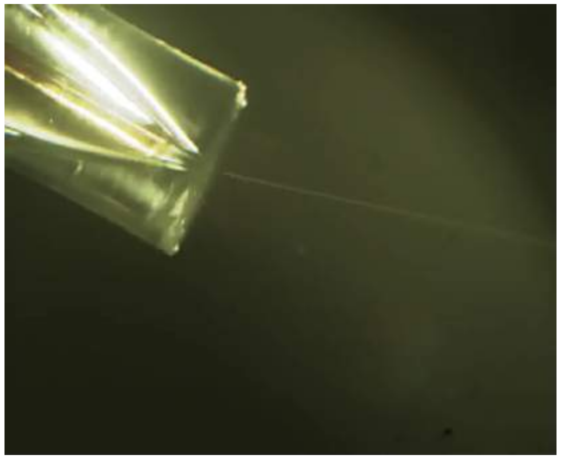


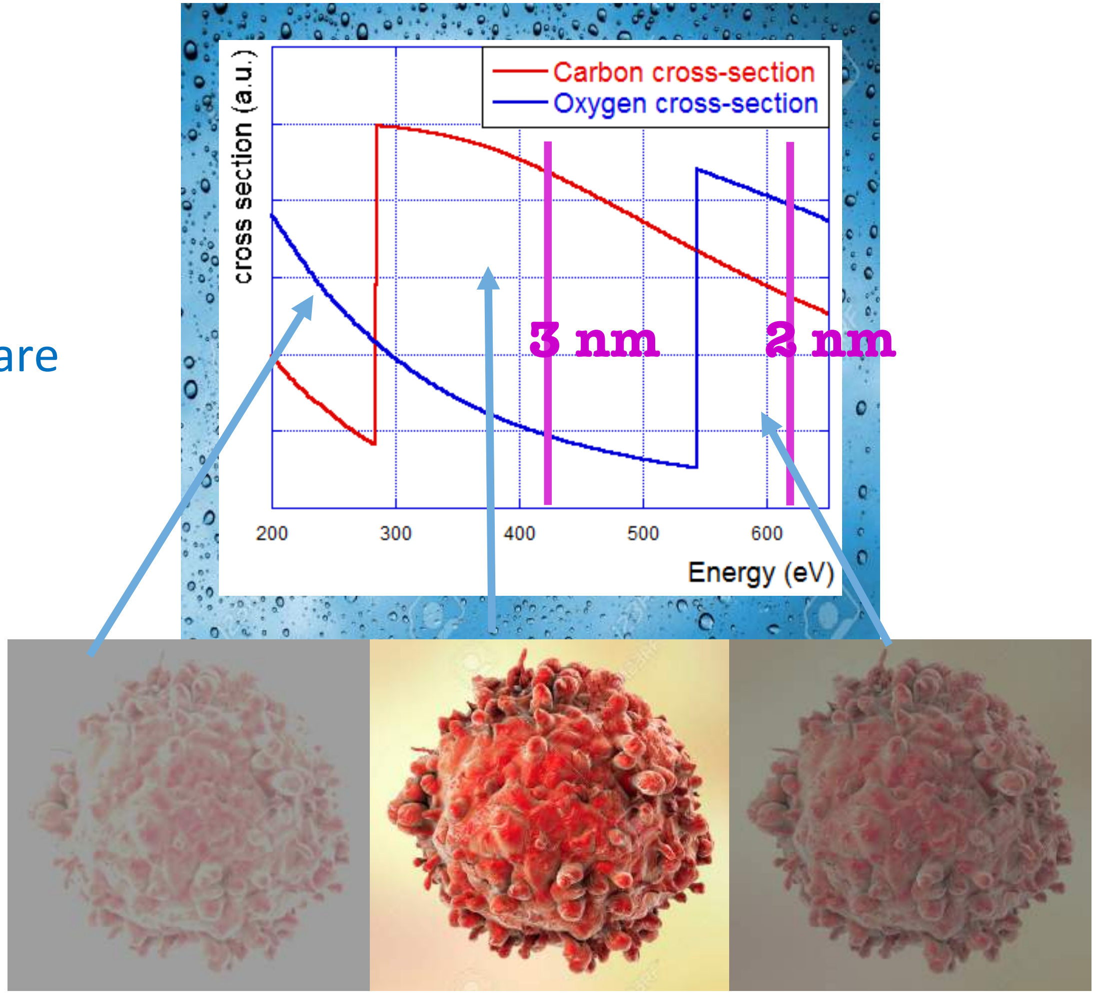
Water Window Coherent Imaging

Energy region between Oxygen and
Carbon K-edge 2.34 nm – 4.4 nm
(530 eV -280 eV)

Water is almost transparent to radiation in this range while nitrogen and carbon are absorbing (and scattering)

Coherent Imaging of biological samples living in their native state
Possibility to study dynamics





Courtesy F. Stellato, UniToV

R&D perspectives

- X-band RF technology implementation,➔ CompactLight => CERN collaboration
- Science with short wavelength Free Electron Laser (FEL)
- Physics with high power lasers and secondary particle source
- Channeling
- R&D on compact radiation sources for medical applications
- Detector development and test for X-ray FEL and HEP
- Science with THz radiation sources
- Nuclear photonics with γ-rays Compton sources
- R&D on polarized positron sources
- R&D in accelerator physics and industrial spin – off

The future EUPRAXIA@SPARC_LAB Facility

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