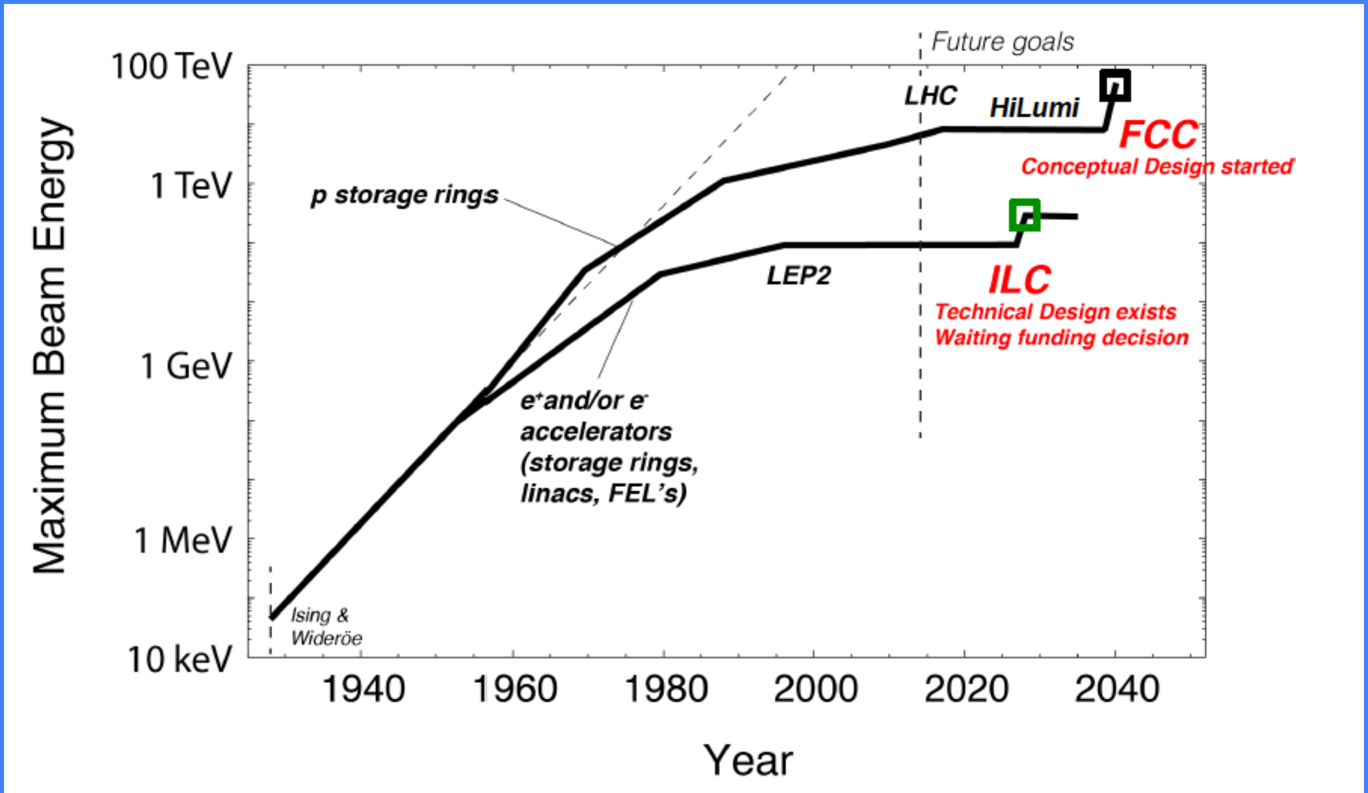
Nuove Tecniche di Accelerazione

Massimo.Ferrario@lnf.infn.it



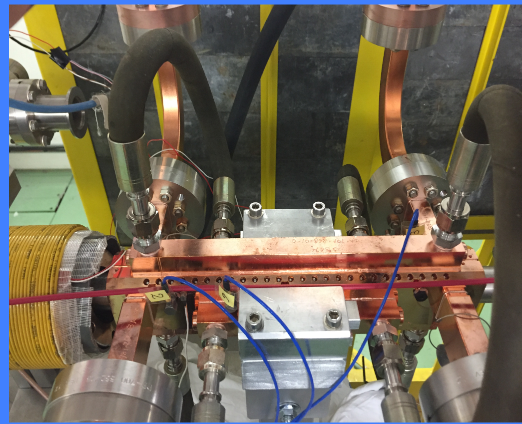
Previous strategic recommendations

- The European Strategy for Particle Physics in 2013 calls for a *"... vigorous accelerator R&D programme, including high-field magnets and **high-gradient accelerating structures**..."*.

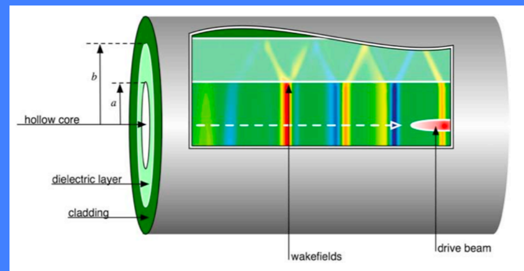
- The May 2014 Particle Physics Project Prioritization Panel report on "Building for Discovery – Strategic Plan for U.S. Particle Physics in the Global Context" identifies the *"**critical need for technical breakthroughs that will yield more cost-effective accelerators**. For example, ultrahigh gradient accelerator techniques will require the development of power sources ..., and accelerating structures (plasmas, metallic, and dielectric) that can sustain high average power, have high damage threshold, and can be cascaded."*

High Gradient Options

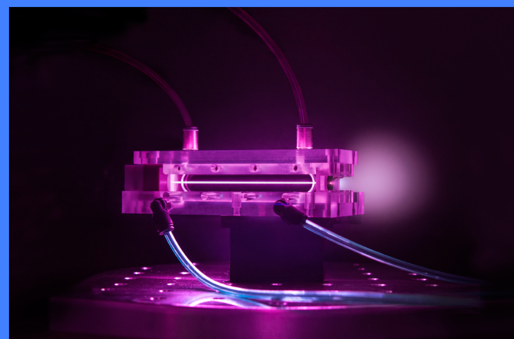
- RF accelerating structures, from X-band to K-band => 100 MV/m < E_{acc} < 1 GV/m



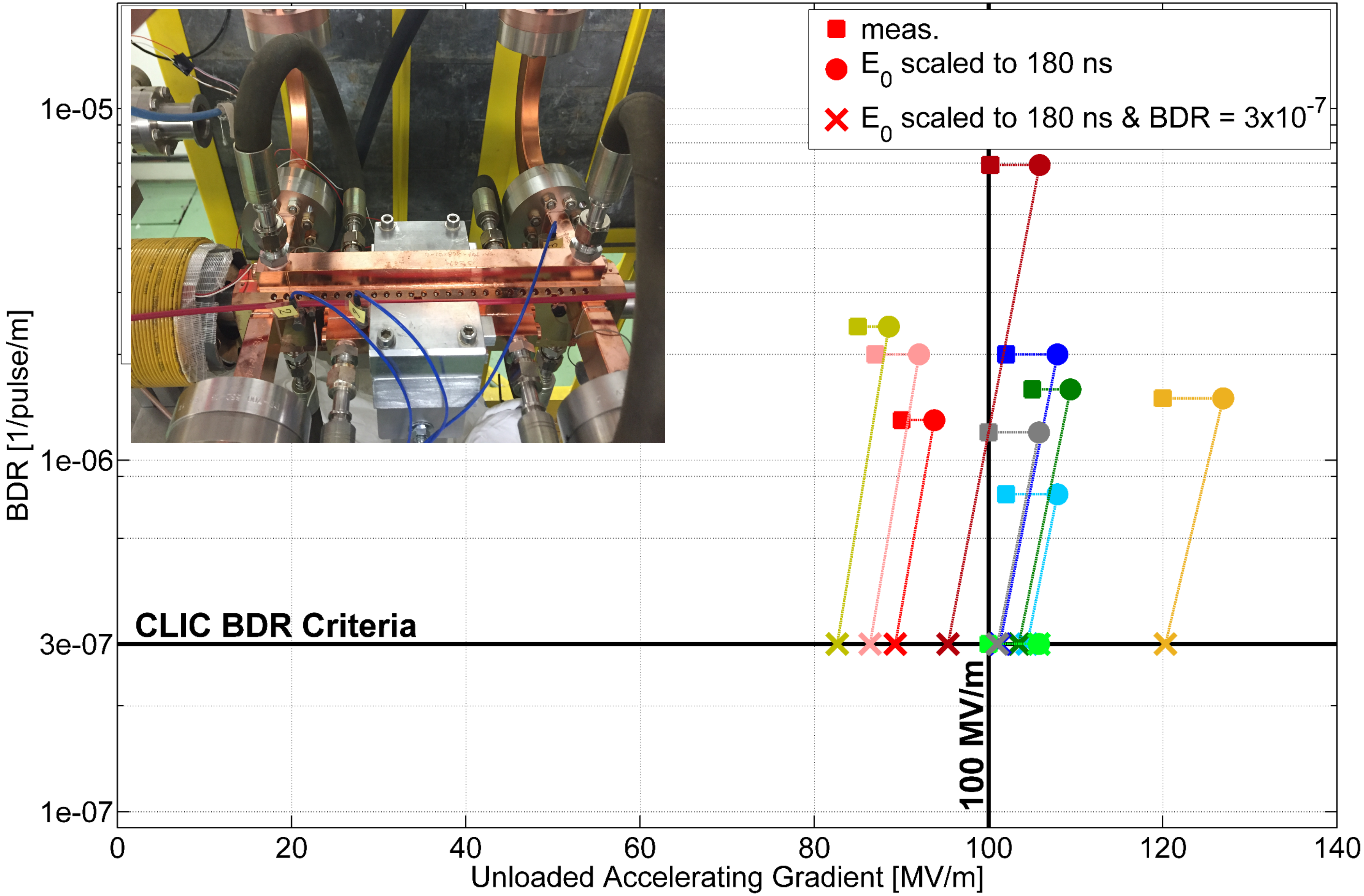
- Dielectrict structures, laser or particle driven => 1 GV/m < E_{acc} < 5 GV/m



- Plasma accelerator, laser or particle driven => 1 GV/m < E_{acc} < 100 GV/m



X-band RF structures best performances

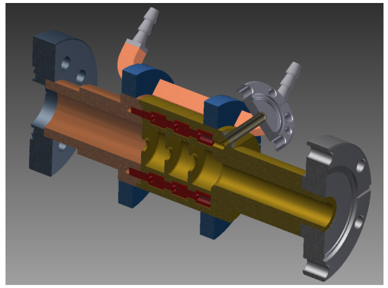


Innovative compact braze-free joints accelerating cavity at X band (SLAC/INFN-LNF)

[submitted on July 2018 to Journal of Instrumentation (JINST) for publication]

Motivations for future innovative accelerators:

- Avoids high tempersture processes
- Cells joined together by means of specifically designed and proprietary screws which ensure good vacuum and RF contacts
- Use the Electron beam welding (EBW) and Tungsten Inert gas (TIG) processes
- Remarkable improvements of the RF perfomance
- Strong costs reductions
- Strong increase of the accelerating field Eacc >> 100 MV/m

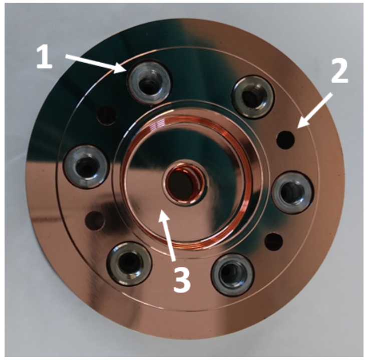


Solid model

Secondary pumping

Secondary pumping

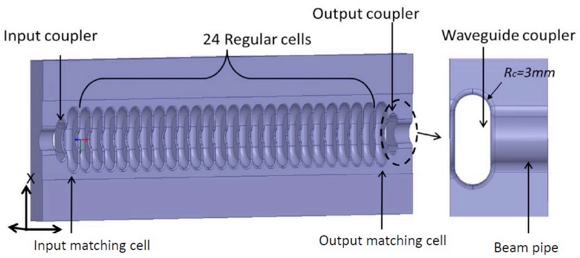
Side-view of the two structures

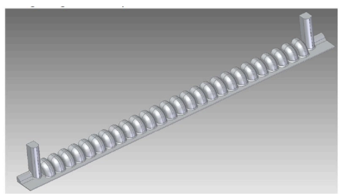


1. Special hollow screws
2. Channel for pumping the secondary vacuum chamber
3. Primary RF chamber

Both structures are under high power tests at SLAC

- Next step is to fabricate 24 regular cells by using the TIG process;
- Study for scaling to 100 GHz by using the braze-free technique is undergoing.





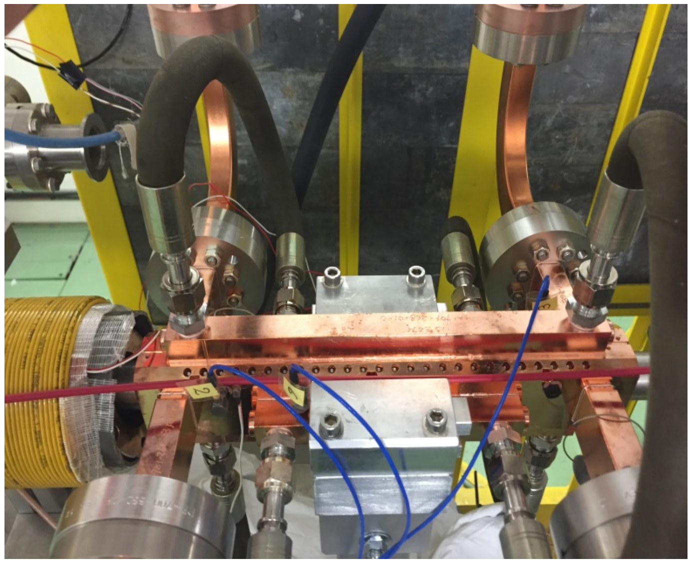
Compact

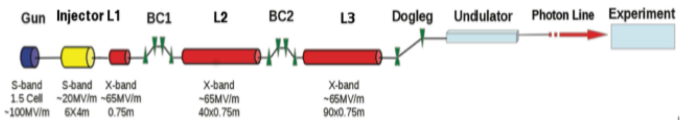
EU Design Study Approved

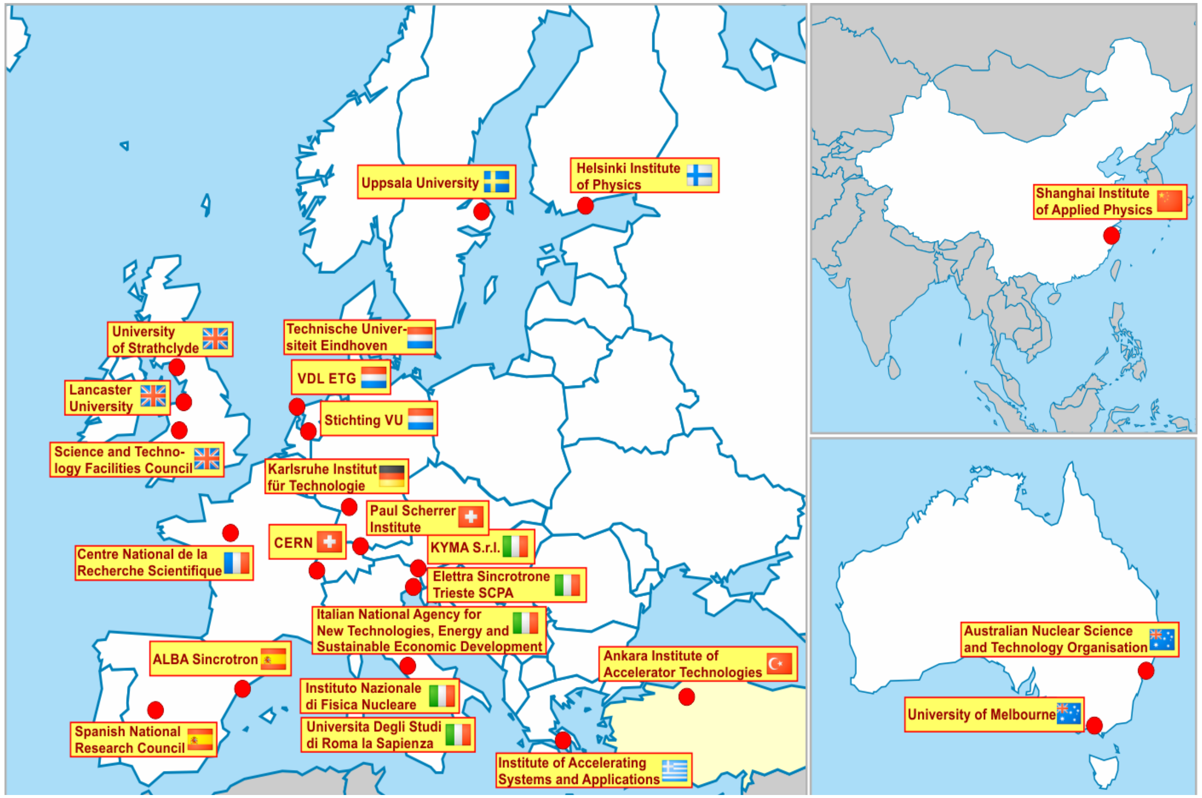
3 years – 3 MEuro

Coordinator: G. D'Auria (Elettra)

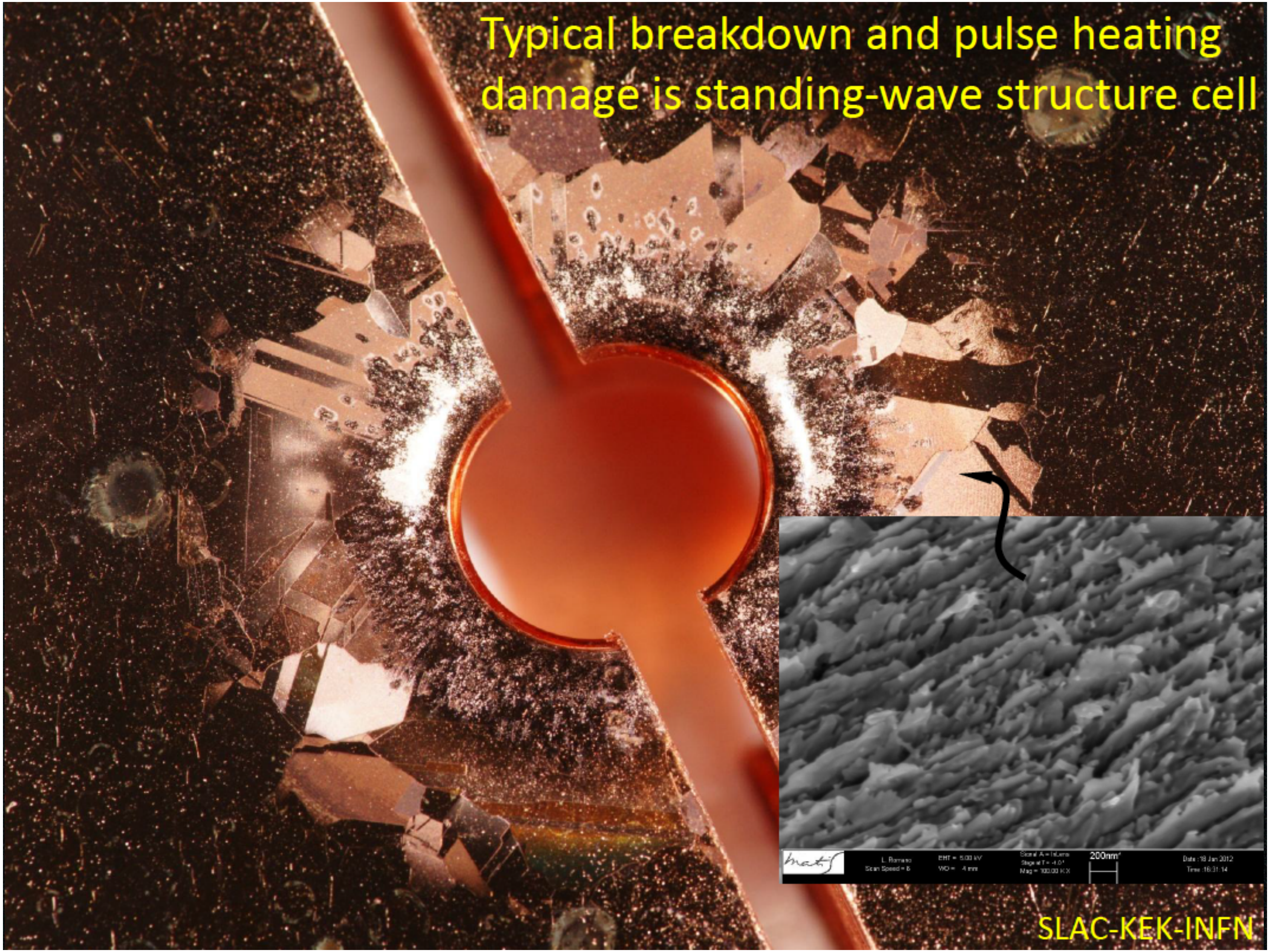
Focus on X-band technology

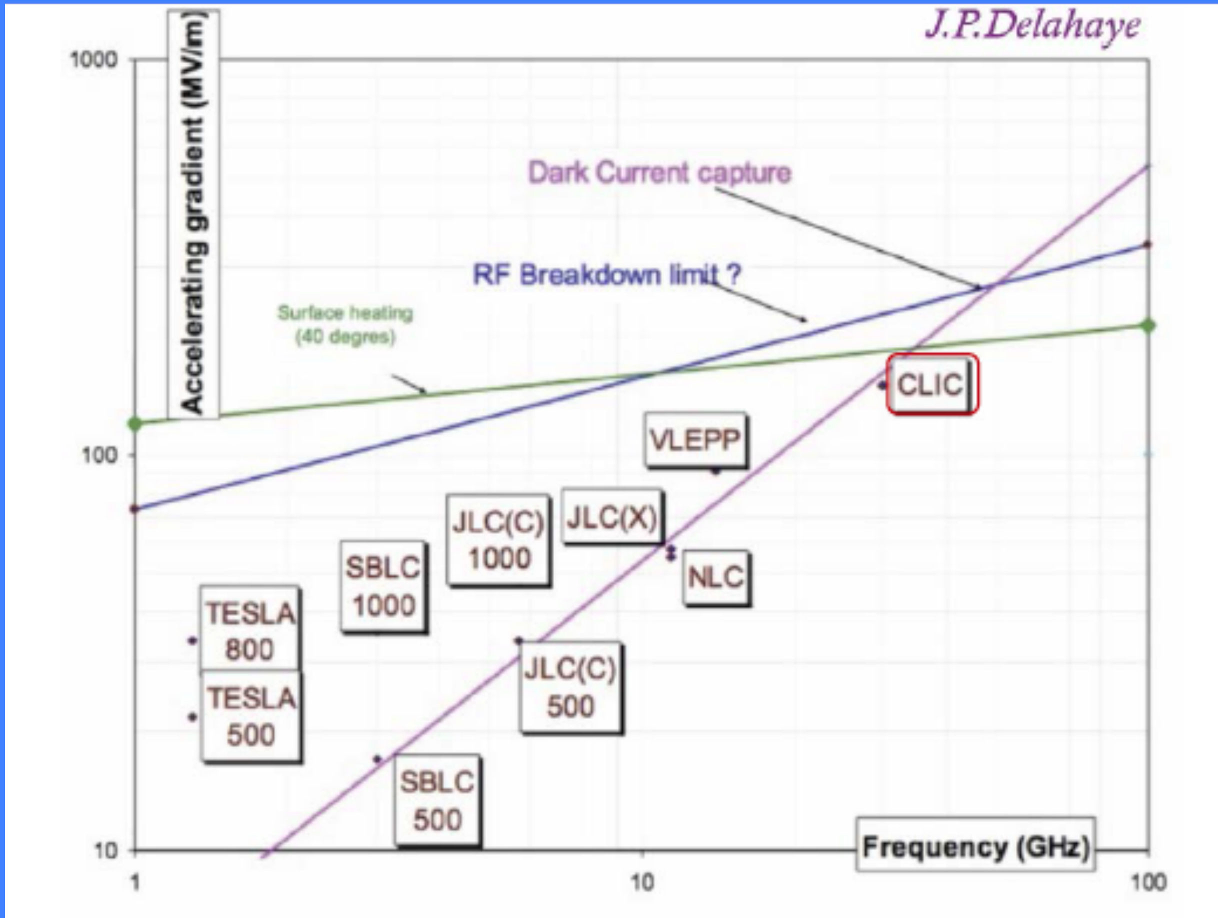






The key objective of the CompactLight Design Study is to demonstrate, through a conceptual design, the feasibility of an innovative, compact and cost effective FEL facility suited for user demands identified in the science case.


Typical breakdown and pulse heating damage is standing-wave structure cell
L. Romano
Scan Speed = 6
EHT = 5.00 kV
WD = 4 mm
Stage at T = -1.0°
Mag = 100.00 K X
200nm
Date :18 Jan 2012
Time :16:31:14
SLAC-KEK-INFN



Breakdown limits metal:

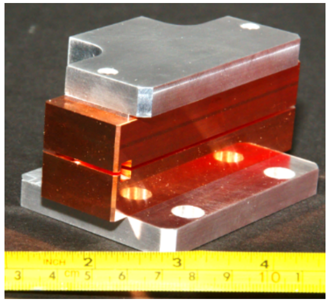
$$E_s = 220(f[\mathrm{GHz}])^{1/3}\ \mathrm{MV/m}$$

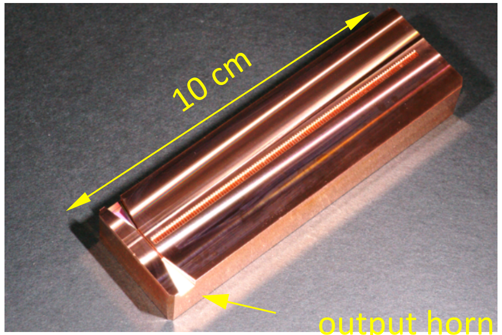
High field ->Short wavelength->ultra-short bunches-> low charge

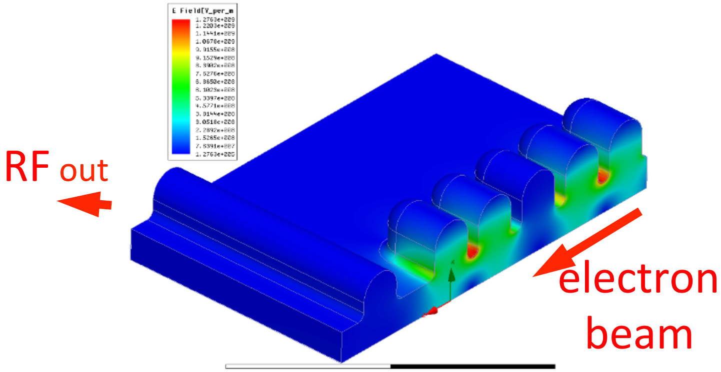
First 110 GHz Open Structure → PRST – AB (4 papers)

M. Dal Forno, V- Dolgashev et al. (SLAC) – INFN/LNF

Eacc = 300 MV/m **Esup = 1.5 GV/m**



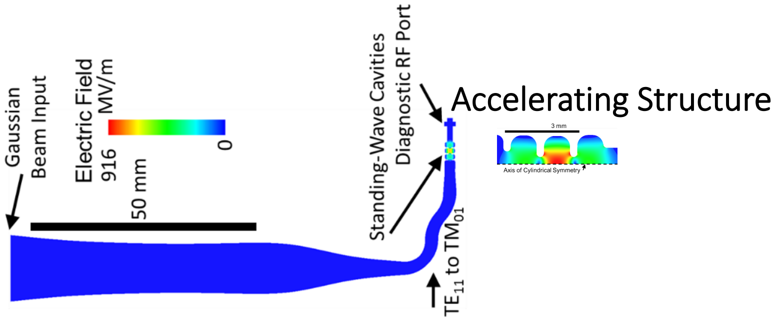


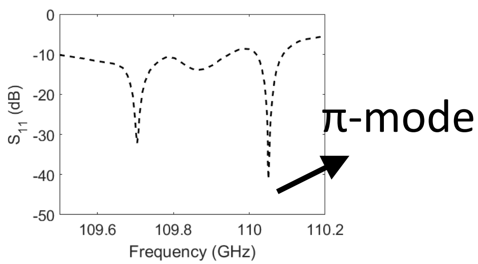


High- Gradient Acceleration structure at 110 GHz at MIT

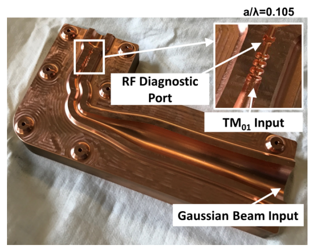
E. Nanni – V Dolgachev et al. (SLAC) – INFN/LNF

Moving Forward to Test @ MIT, Target 1 MW
Eacc > 400 MeV/m

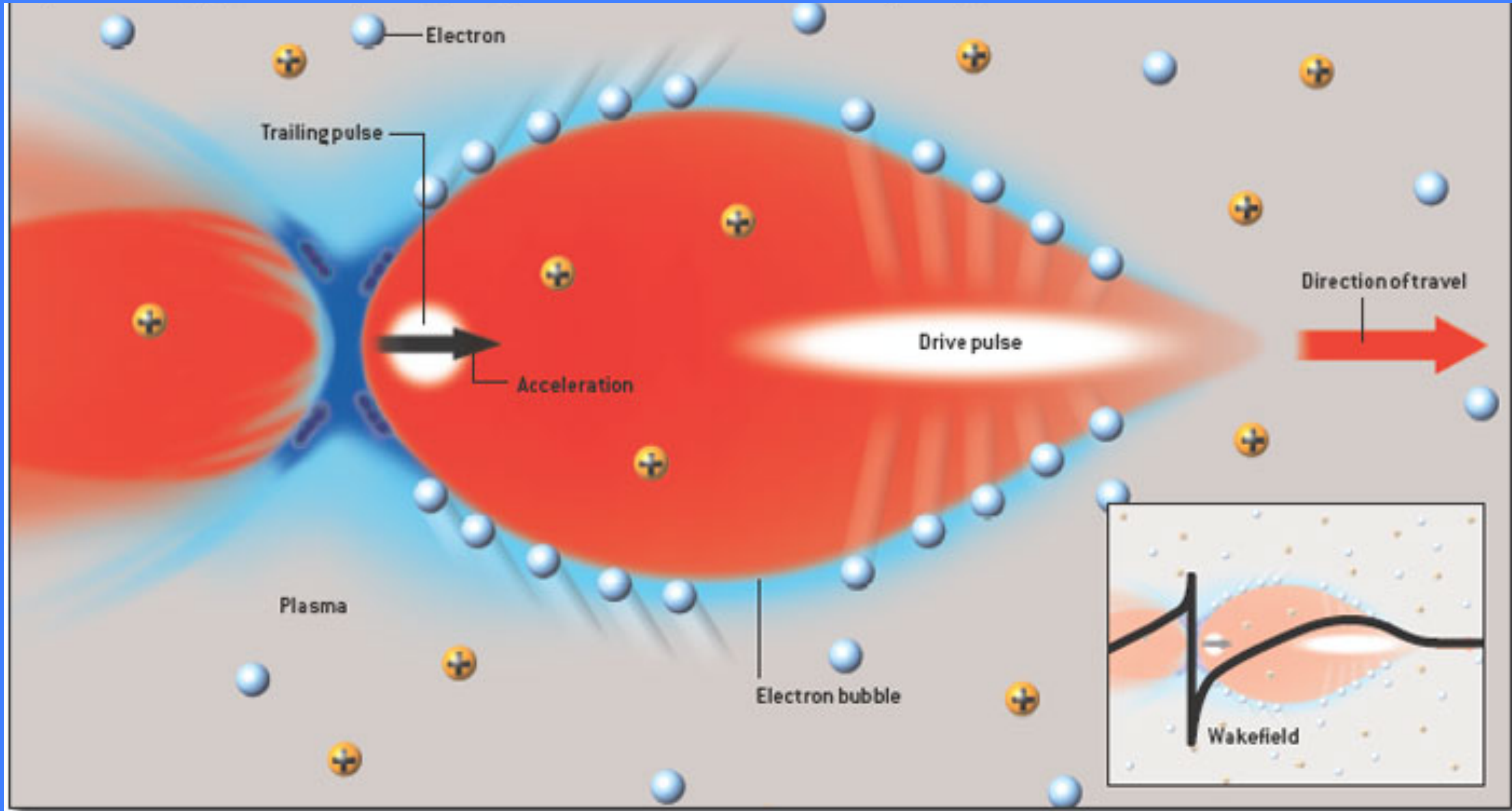




Split-Cell Structure with Mode Converter and Cavities



Plasma Wakefield Acceleration



Breakdown limit?

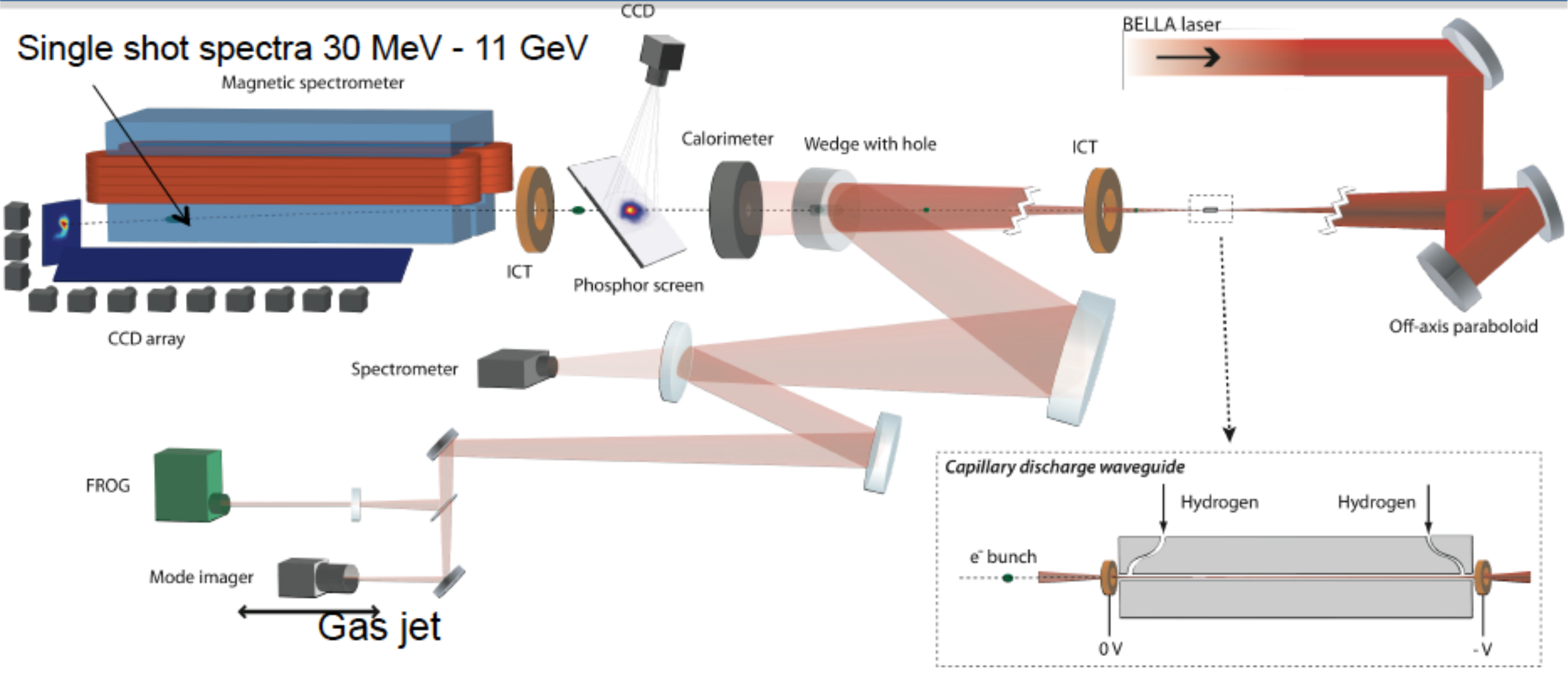
$$E_0 = \frac{m_e c \omega_p}{e} \approx 100[\frac{GeV}{m}] \cdot \sqrt{n_0[10^{18} cm^{-3}]}$$

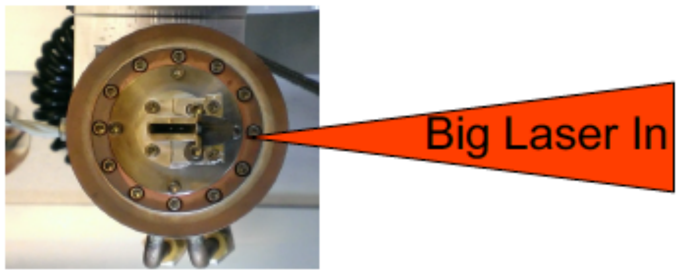
Capillary Discharge

Laser Driven

LWFA

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

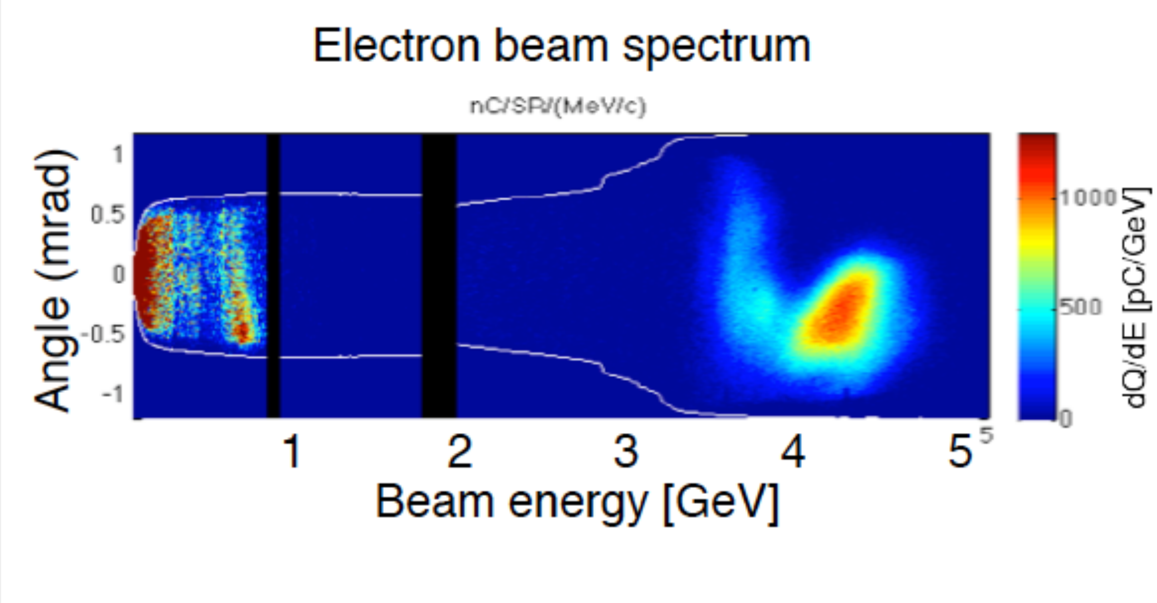


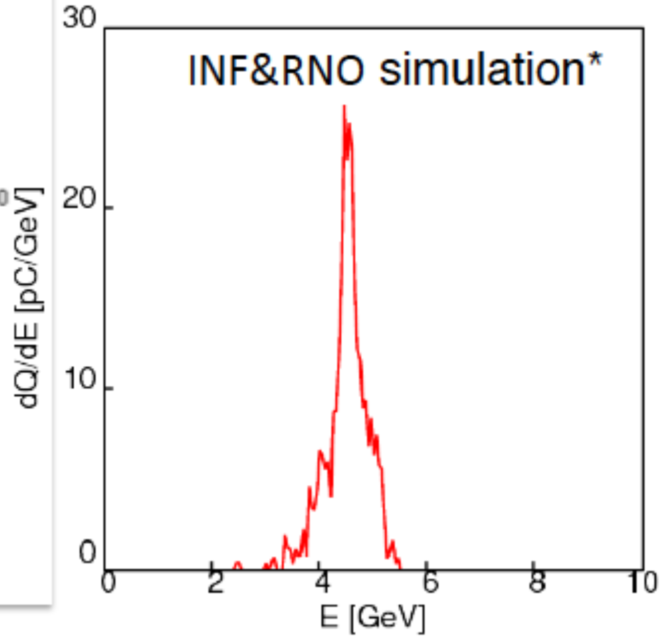


Capillary discharge

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





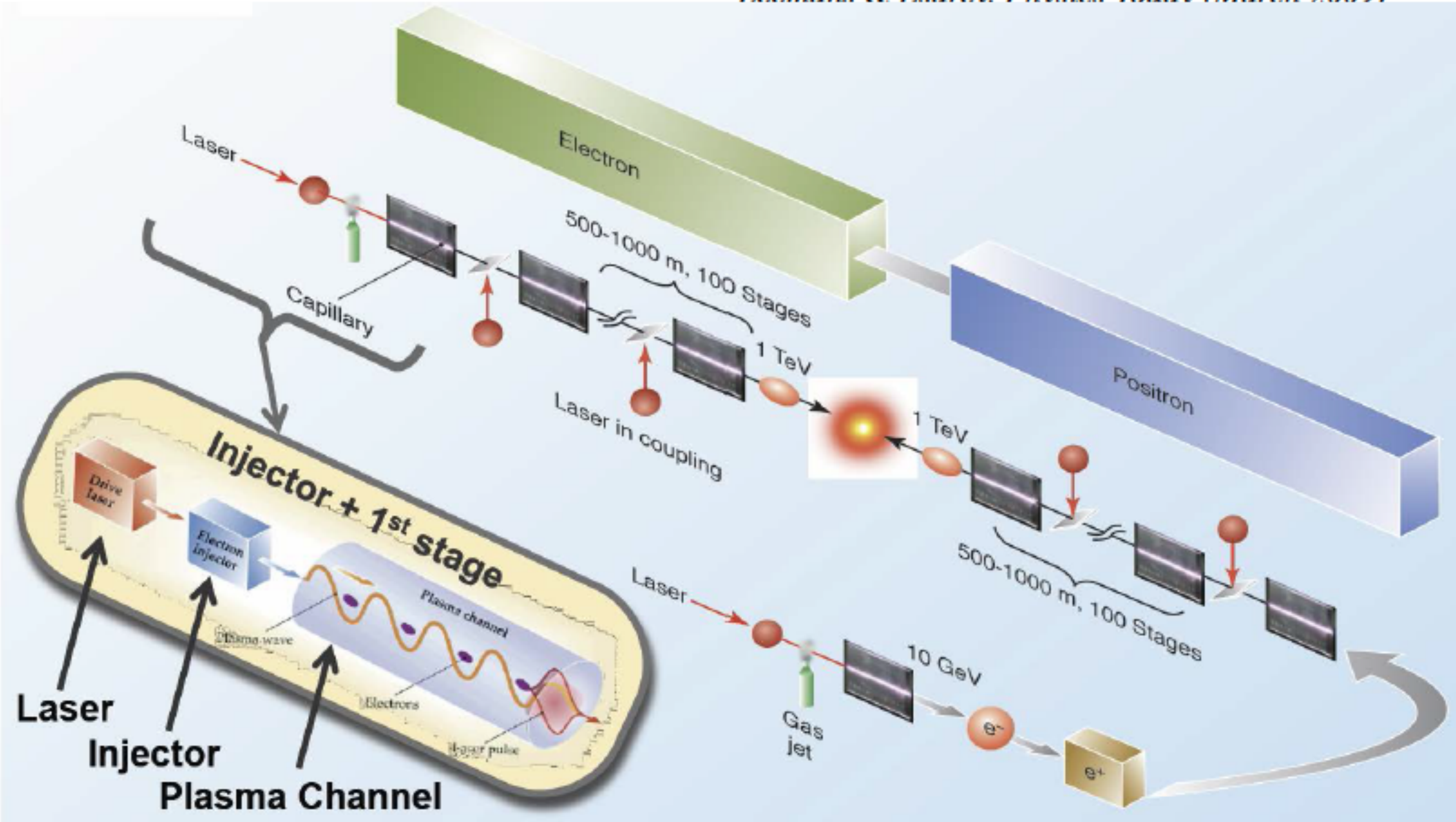
	Exp.	Sim.
Energy	4.25 GeV	4.5 GeV
ΔE/E	5%	3.2%
Charge	~20 pC	23 pC
Divergence	0.3 mrad	0.6 mrad

- **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})

W.P. Leemans et al.,PRL 2014

Laser-Plasma-Accelerator LC

Leemans & Esarey, Physics Today (March 2009)

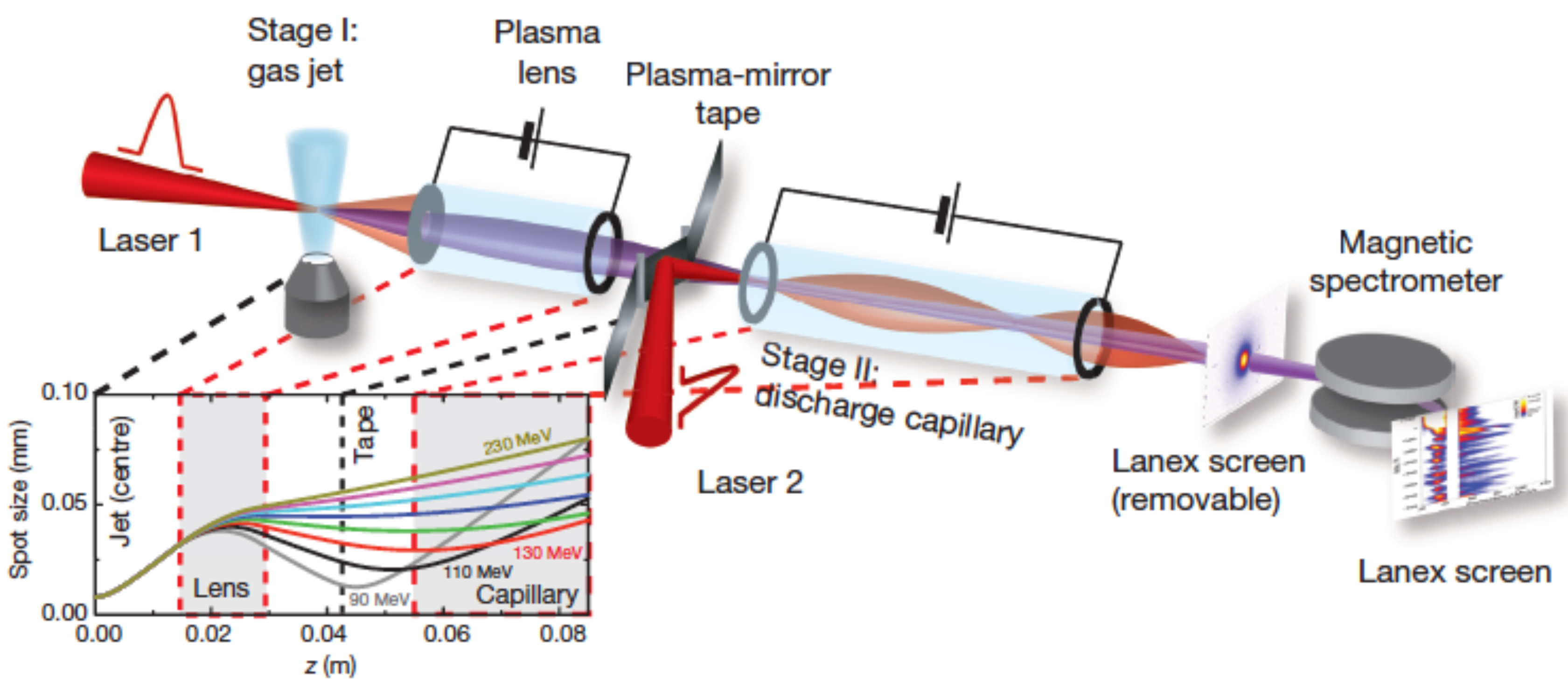


LETTER

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]

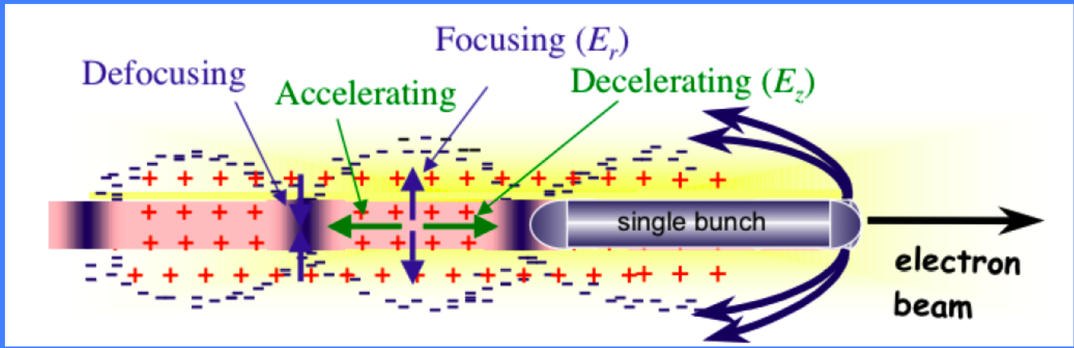


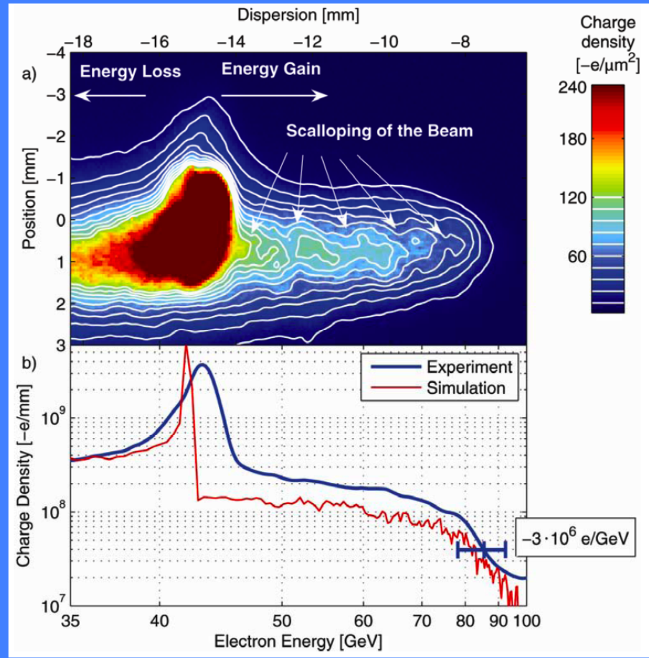
Parameter Set for LPWA LC

Case: CoM Energy (Plasma density)	**1 TeV** (10^{17} cm^{-3})	**1 TeV** (2×10^{15} cm^{-3})	**10 TeV** (10^{17} cm^{-3})	**10 TeV** (2×10^{15} cm^{-3})
Energy per beam (TeV)	0.5	0.5	5	5
Luminosity (10^{34} cm^{-2}s^{-1})	2	2	200	200
Electrons per bunch ($\times10^{10}$)	0.4	2.8	0.4	2.8
Bunch repetition rate (kHz)	15	0.3	15	0.3
Horizontal emittance $\gamma\varepsilon_x$ (nm-rad)	100	100	50	50
Vertical emittance $\gamma\varepsilon_y$ (nm-rad)	100	100	50	50
β^* (mm)	1	1	0.2	0.2
Horizontal beam size at IP σ^*_x (nm)	10	10	1	1
Vertical beam size at IP σ^*_y (nm)	10	10	1	1
Disruption parameter	0.12	5.6	1.2	56
Bunch length σ_z (μm)	1	7	1	7
Beamstrahlung parameter Υ	180	180	18,000	18,000
Beamstrahlung photons per e, n_γ	1.4	10	3.2	22
Beamstrahlung energy loss δ_E (%)	42	100	95	100
Accelerating gradient (GV/m)	10	1.4	10	1.4
Average beam power (MW)	5	0.7	50	7
Wall plug to beam efficiency (%)	6	6	10	10
One linac length (km)	0.1	0.5	1.0	5

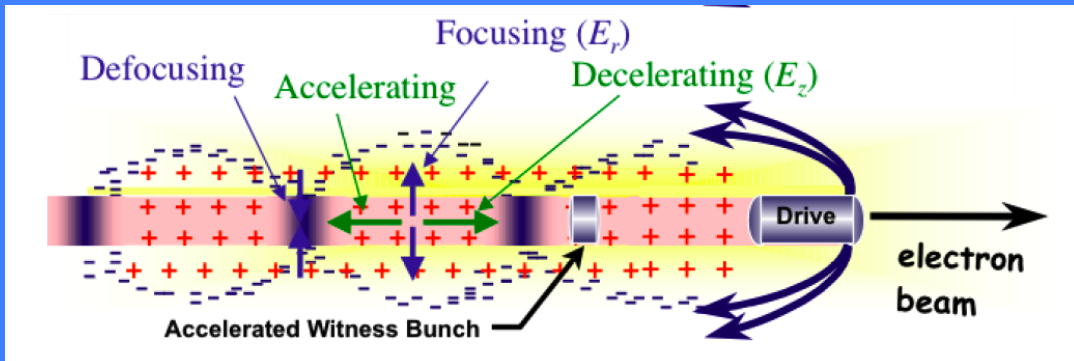
×2+FF

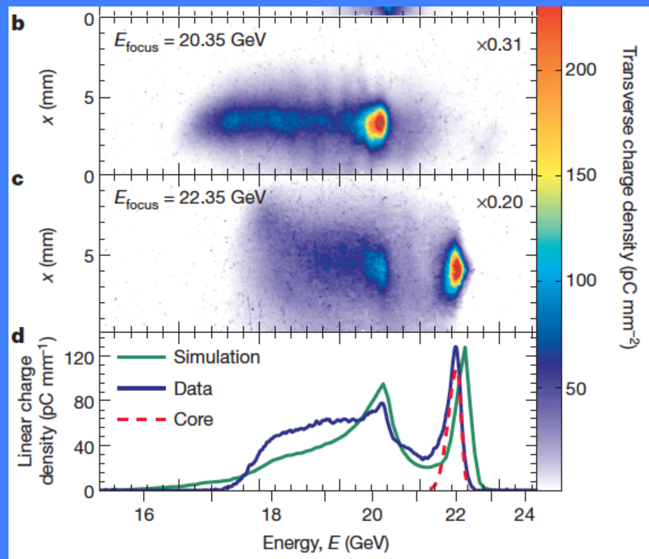
Beam Driven
PWFA





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



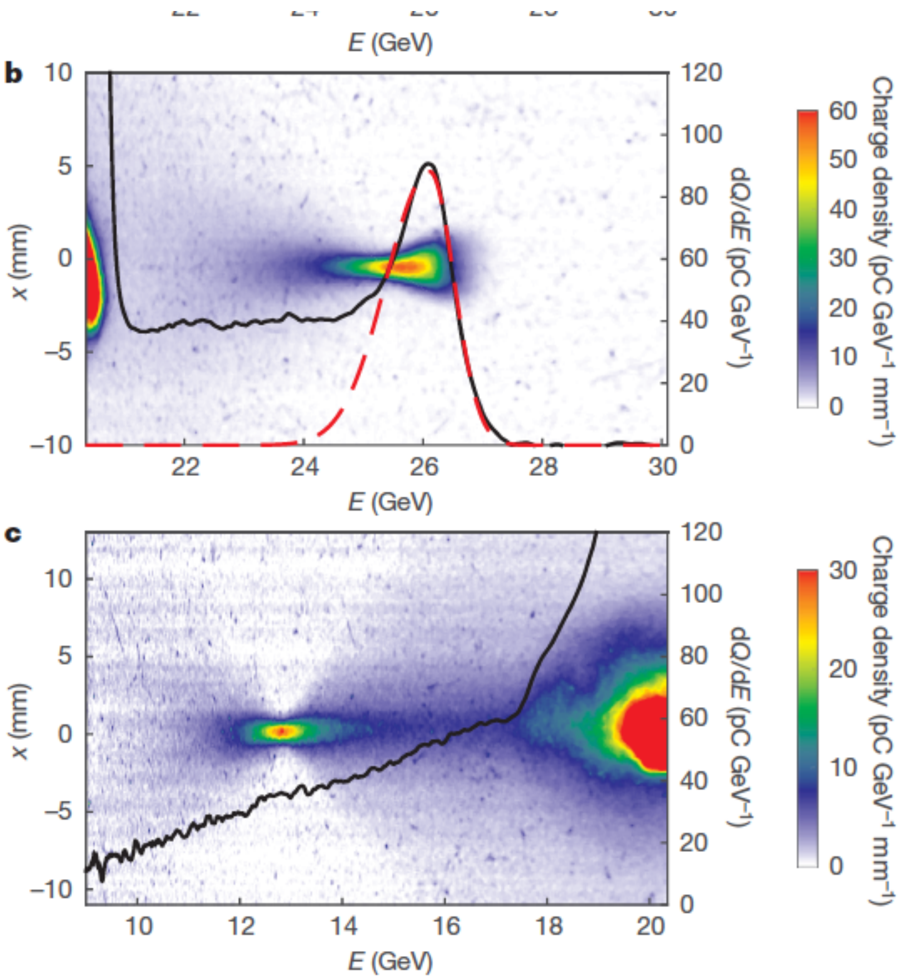


Litos, M. et al. *High-efficiency acceleration of an electron beam in a plasma wakefield accelerator*. **Nature** 515, 92–95 (2014).

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

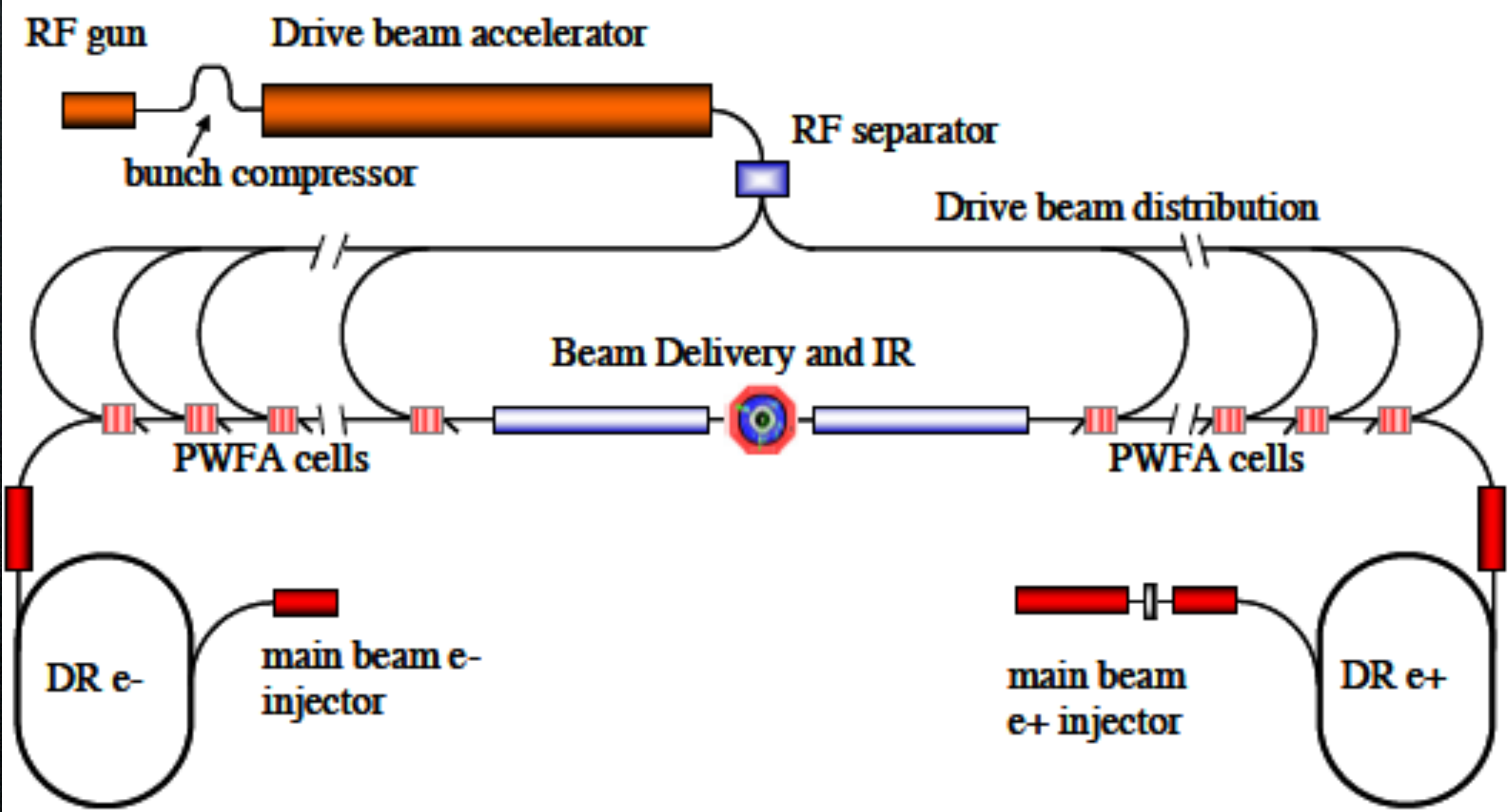


Fig. 1: Concept for a multi-stage PWFA Linear Collider.

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	1×10^{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}

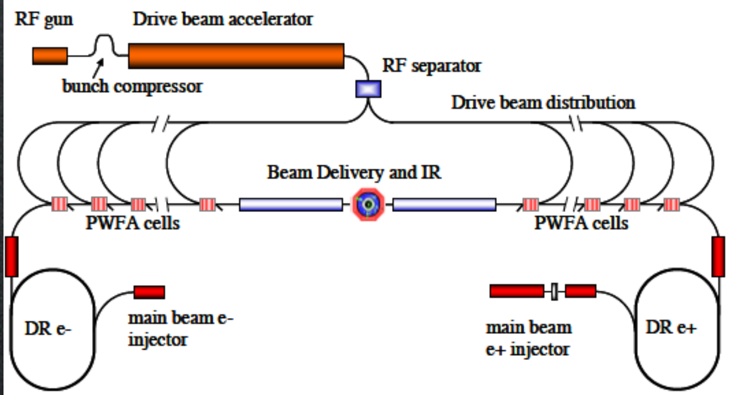


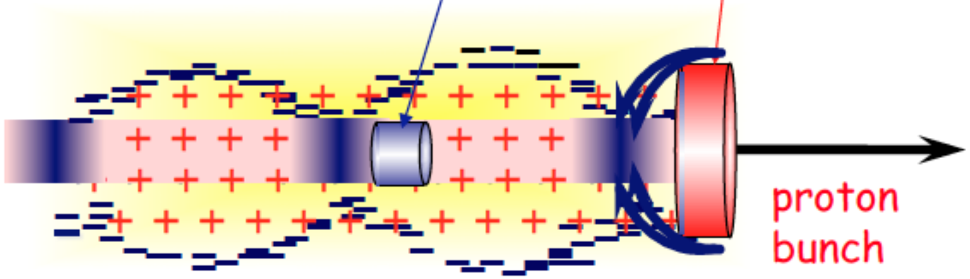
Fig. 1: Concept for a multi-stage PWFA Linear Collider.

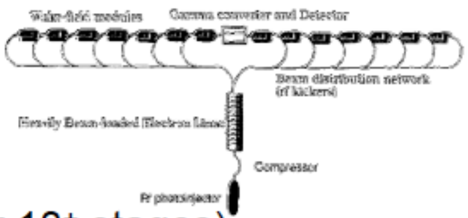
European Network

P. Muggli, 06/04/2013, EAAC 2103

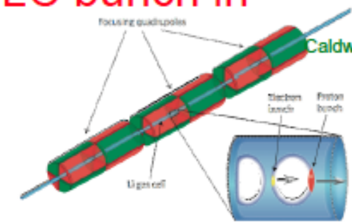
Proton-driven
Plasma Wakefield Acceleration
Collaboration:
Accelerating e^- on the wake of a p^+ bunch

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)

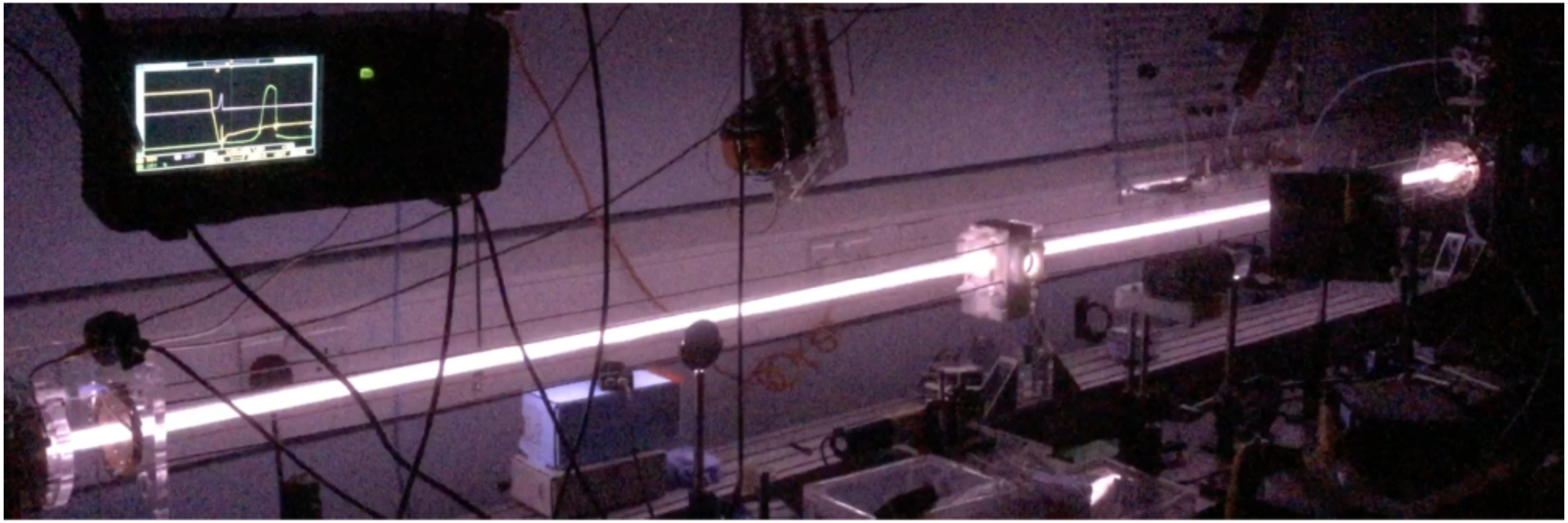


Caldwell, Nat. Phys. 5, 363, (2009)

P. Muggli, 06/04/2013, EAAC 2103

Discharge configuration II

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



very promising results

… reliable, low jitter plasma formation

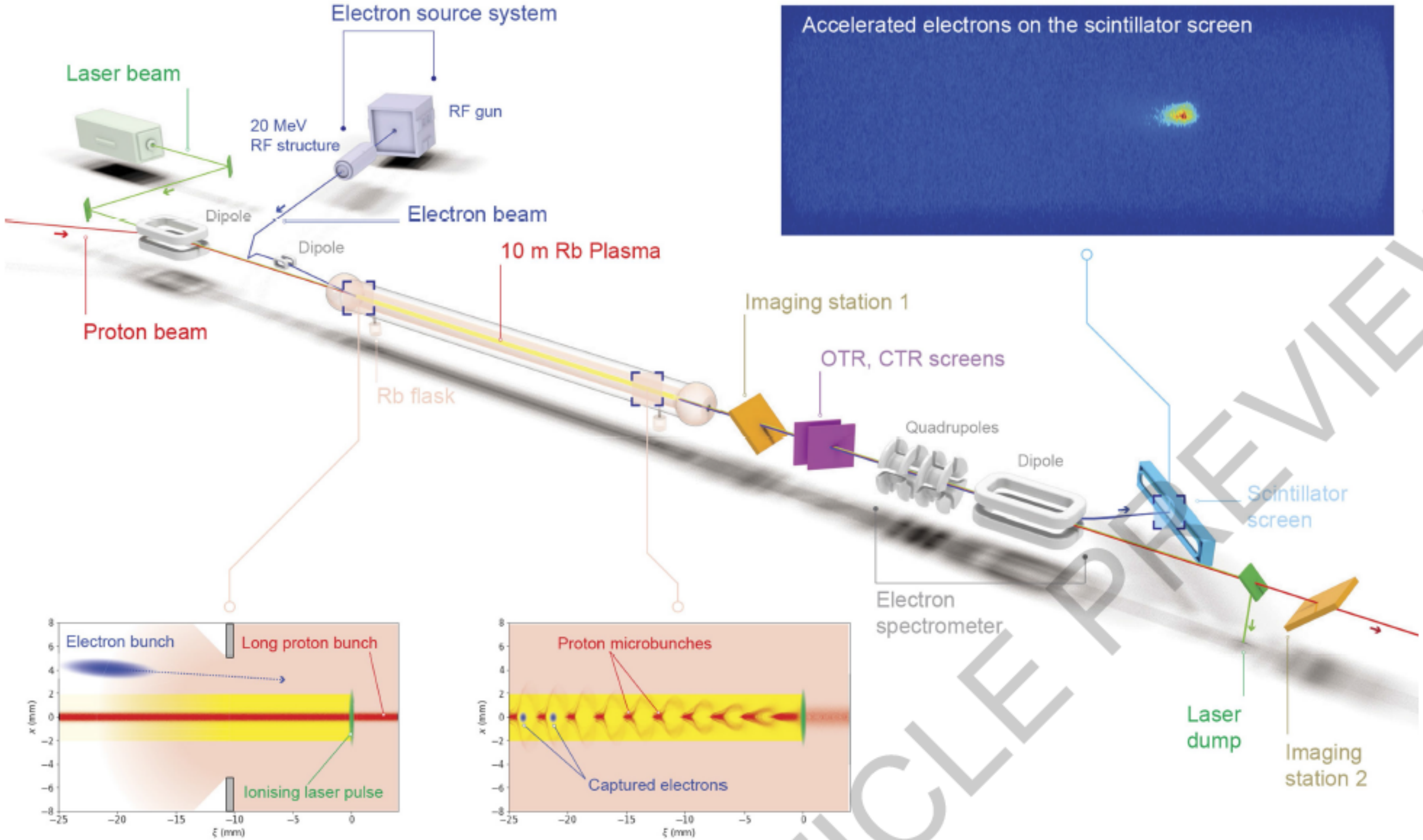
scalability of electric circuit for plasmas > 10 m seem achievable…

nature Accelerated Article Preview

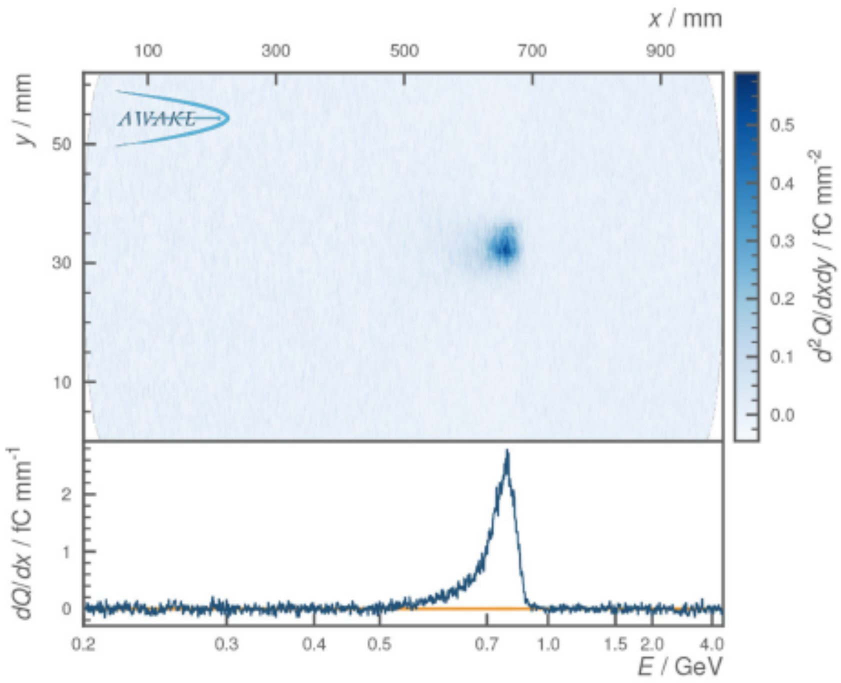
LETTER
doi:10.1038/s41586-018-0485-4

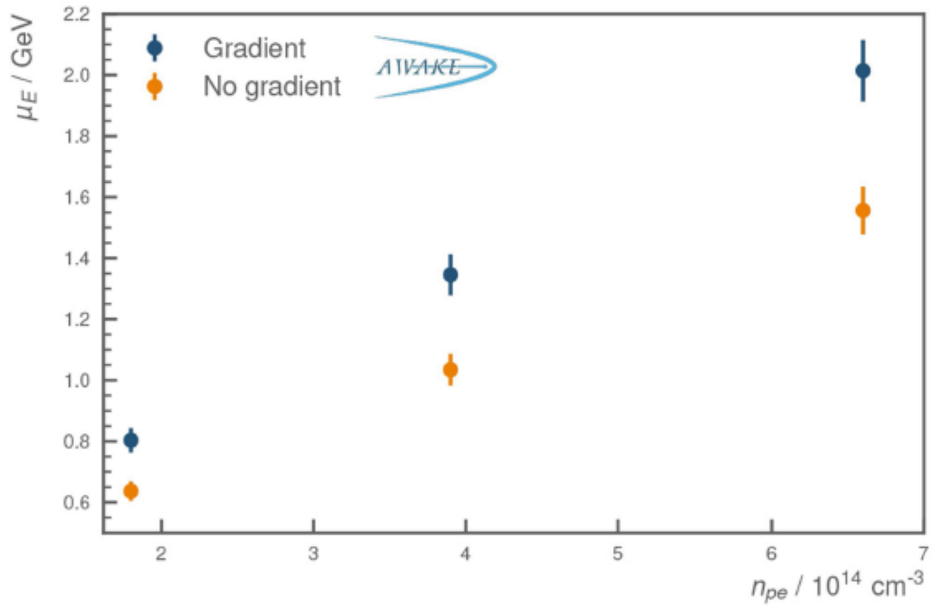
Acceleration of electrons in the plasma wakefield of a proton bunch

E. Adli, A. Ahuja, O. Apsimon, R. Apsimon, A.-M. Bachmann, D. Barrientos, F. Batsch, J. Bauche, V.K.Berglyd Olsen,



Experimental Results





- Mean energy of 800 ± 40 MeV, => E_{acc}~150 MV/m
- FWHM of 137.3 ± 13.7 MeV => Spread >10%
- Total charge of 0.249 ± 0.074 pC => Low charge transmission

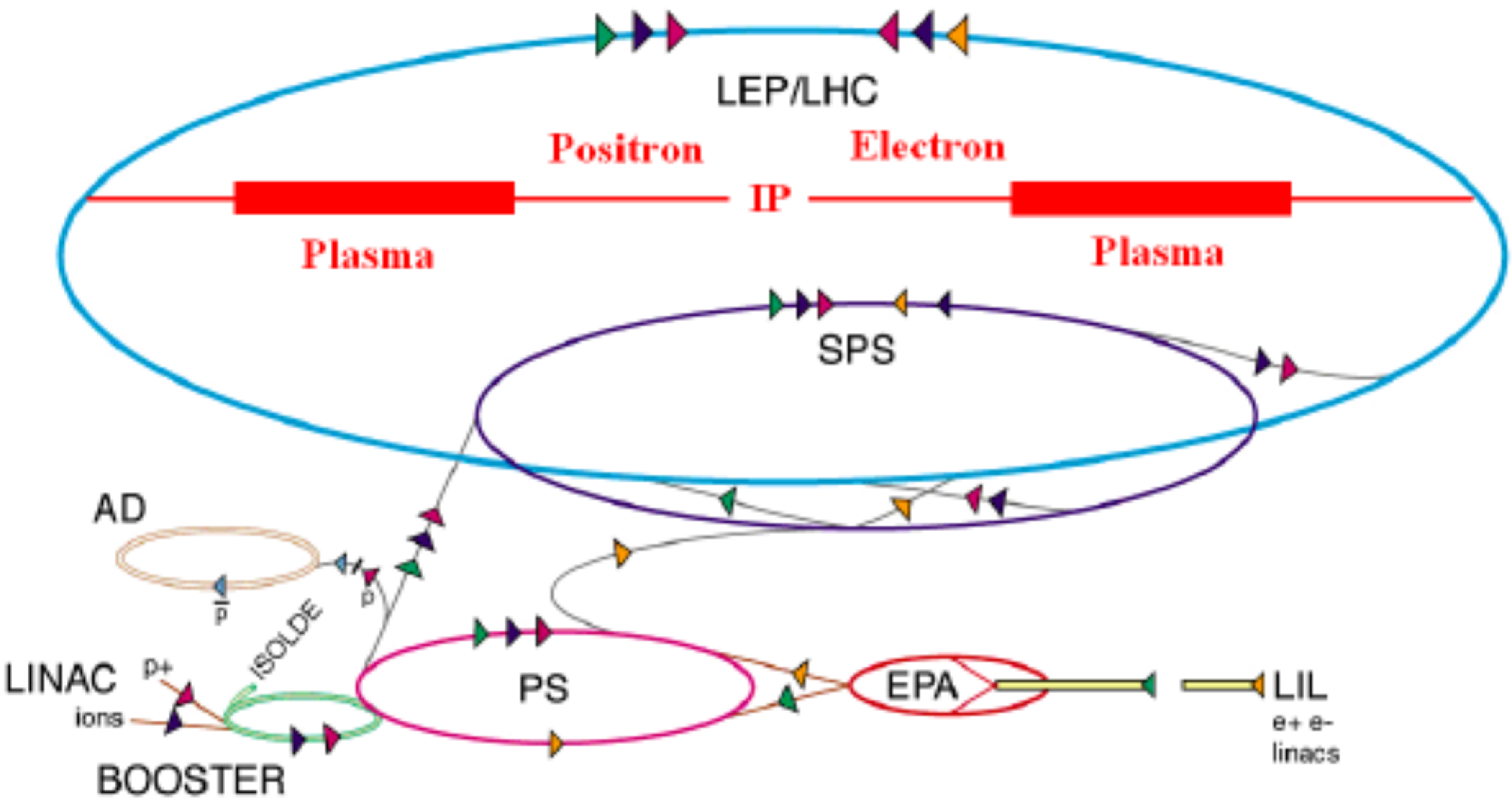
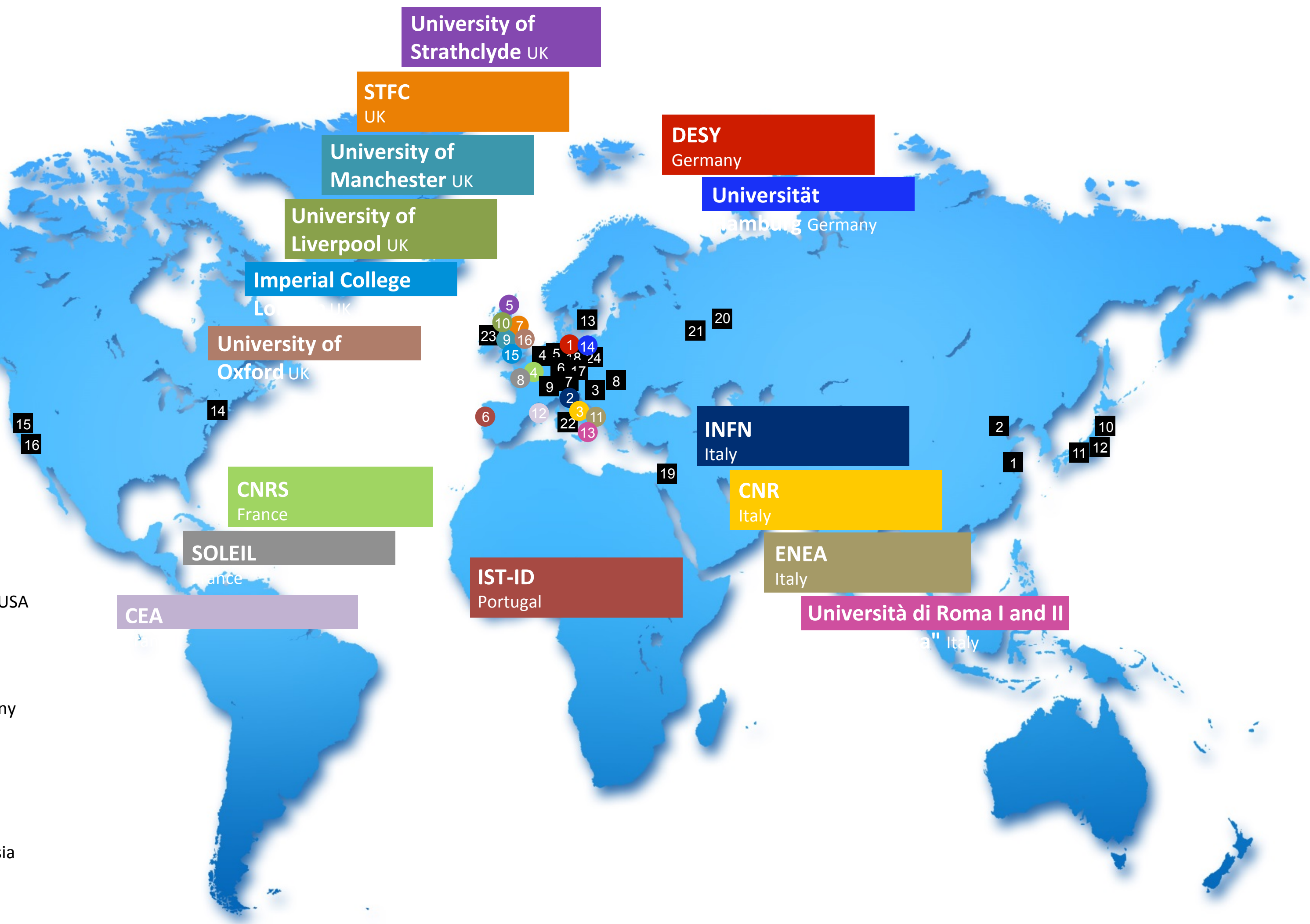


Figure 1: Schematic layout of a 2 TeV CoM electron-positron linear collider based on a modulated proton-driven plasma wakefield acceleration.

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



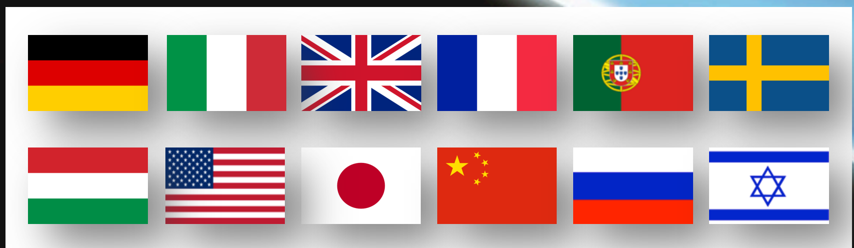
EUROPEAN
PLASMA RESEARCH
ACCELERATOR WITH
EXCELLENCE IN
APPLICATIONS

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



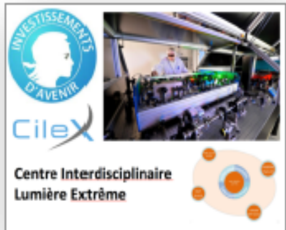


Courtesy R. Assmann

Location of possible sites within EU

EuPRAXIA site studies:

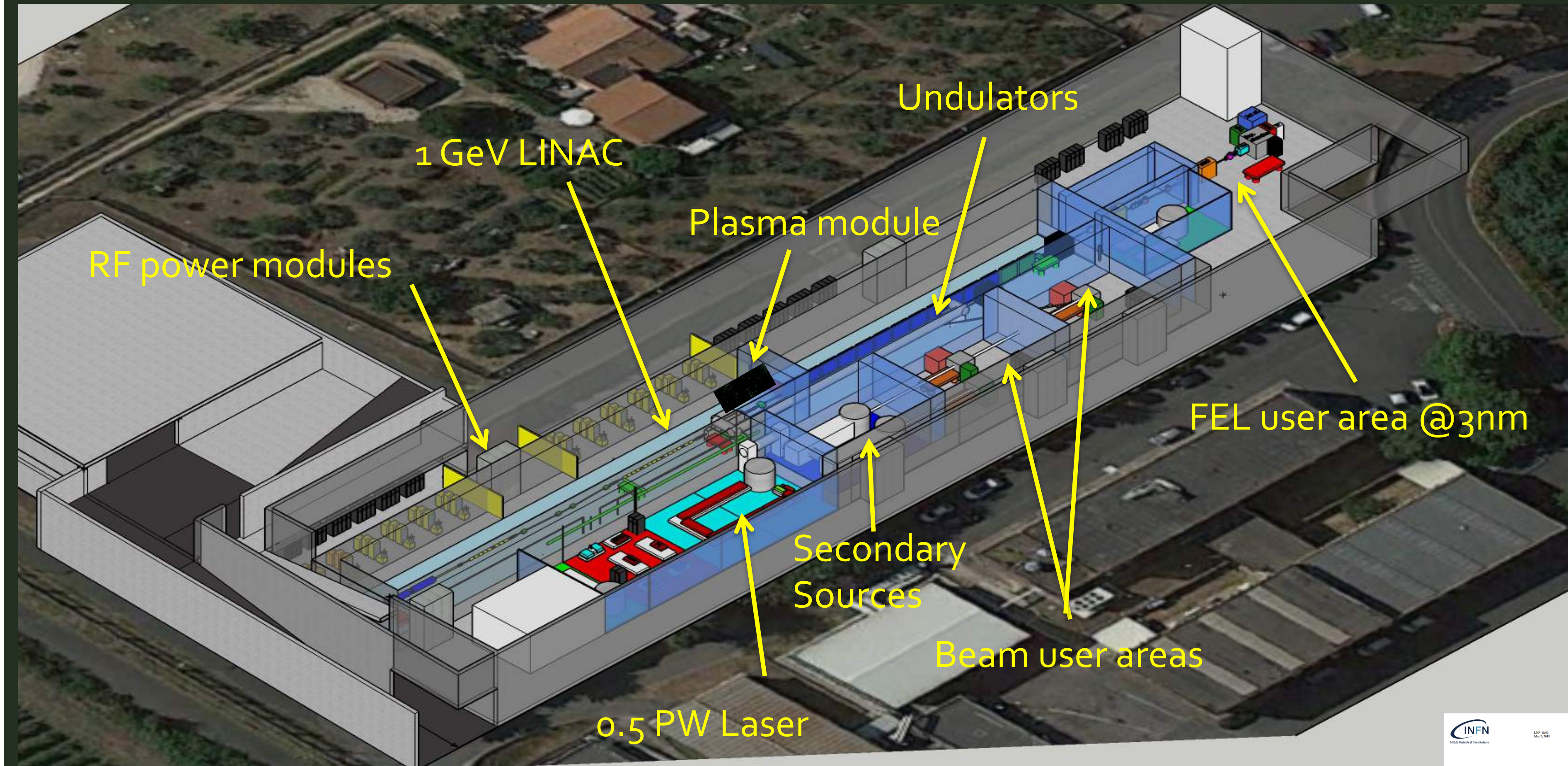
- Design study is site independent
- Five possible sites have been discussed so far
- We invite the suggestions of additional sites



Central Laser Facility
Didcot, United Kingdom

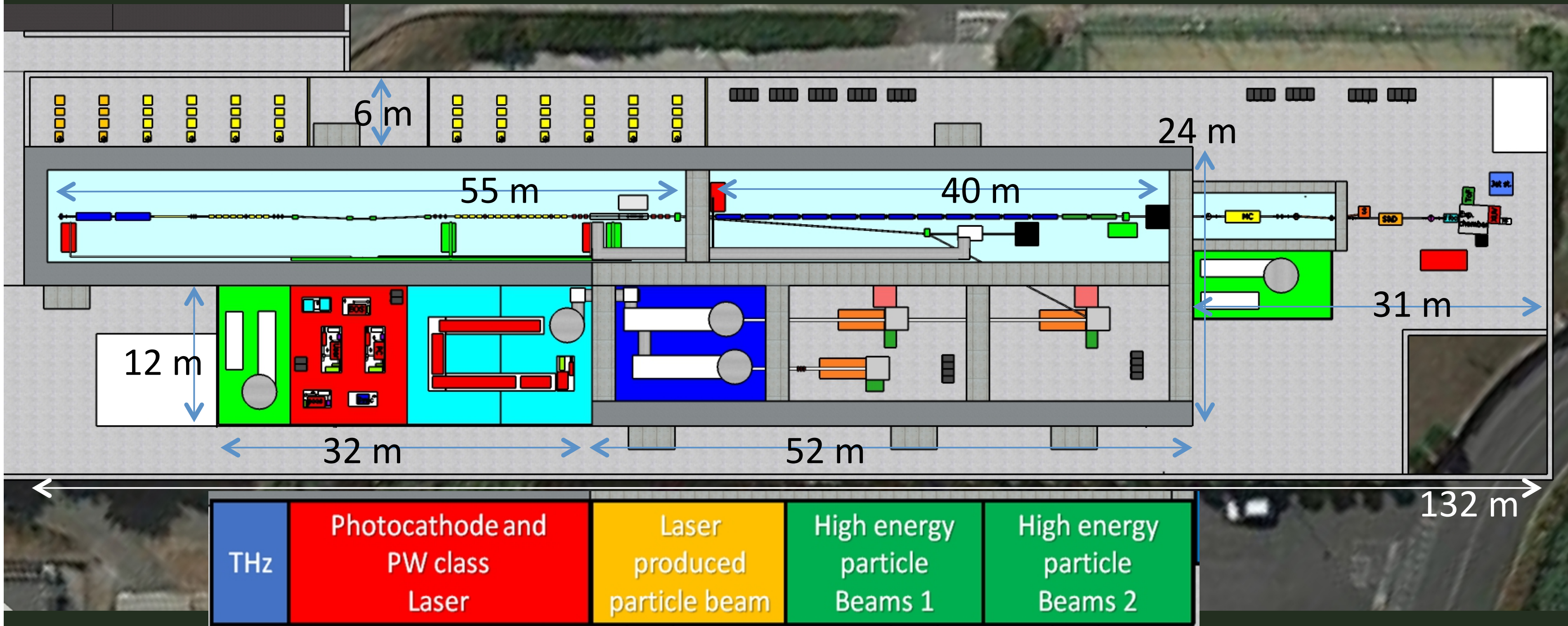
Eli Beamlines
Prague, Czech Republic

EuPRAXIA@SPARC_LAB



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

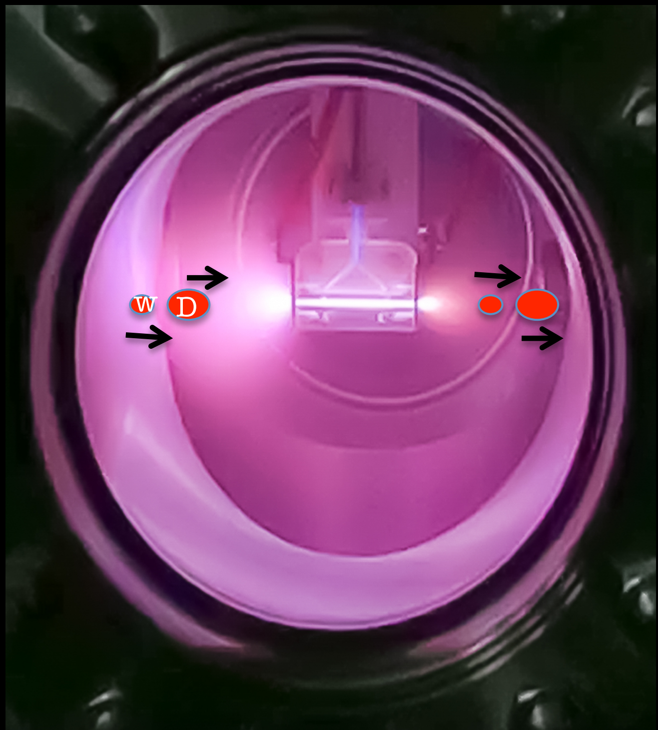
- Candidate LNF to host EuPRAXIA (1-5 GeV)
- FEL user facility (1 GeV – 3nm)
- Advanced Accelerator Test facility (LC) + CERN



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

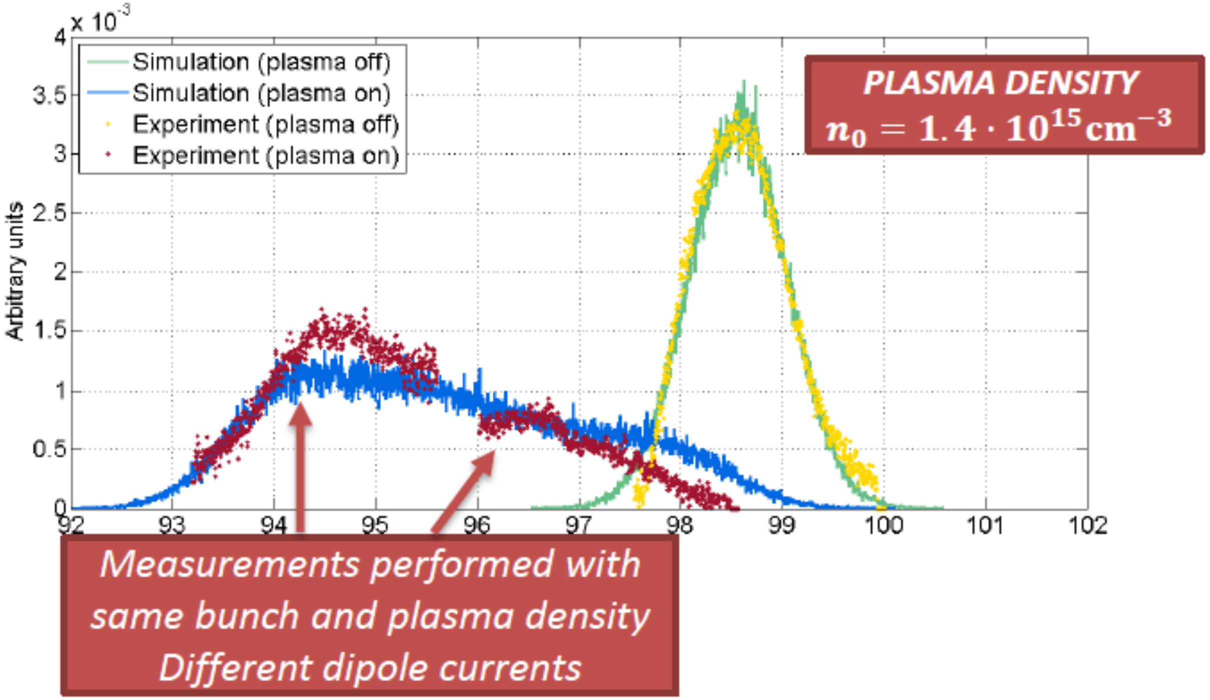
External Injection



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

$$R \cong 2$$

Deceleration test - July 2018

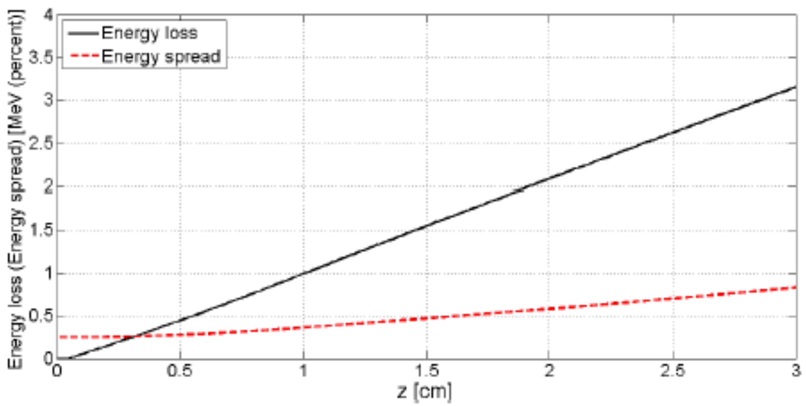


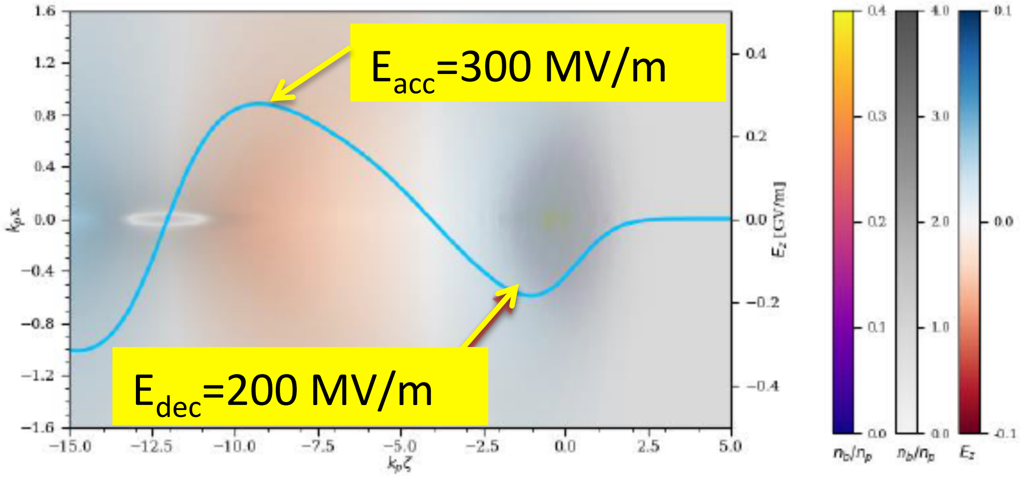
Experimental data at injection

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

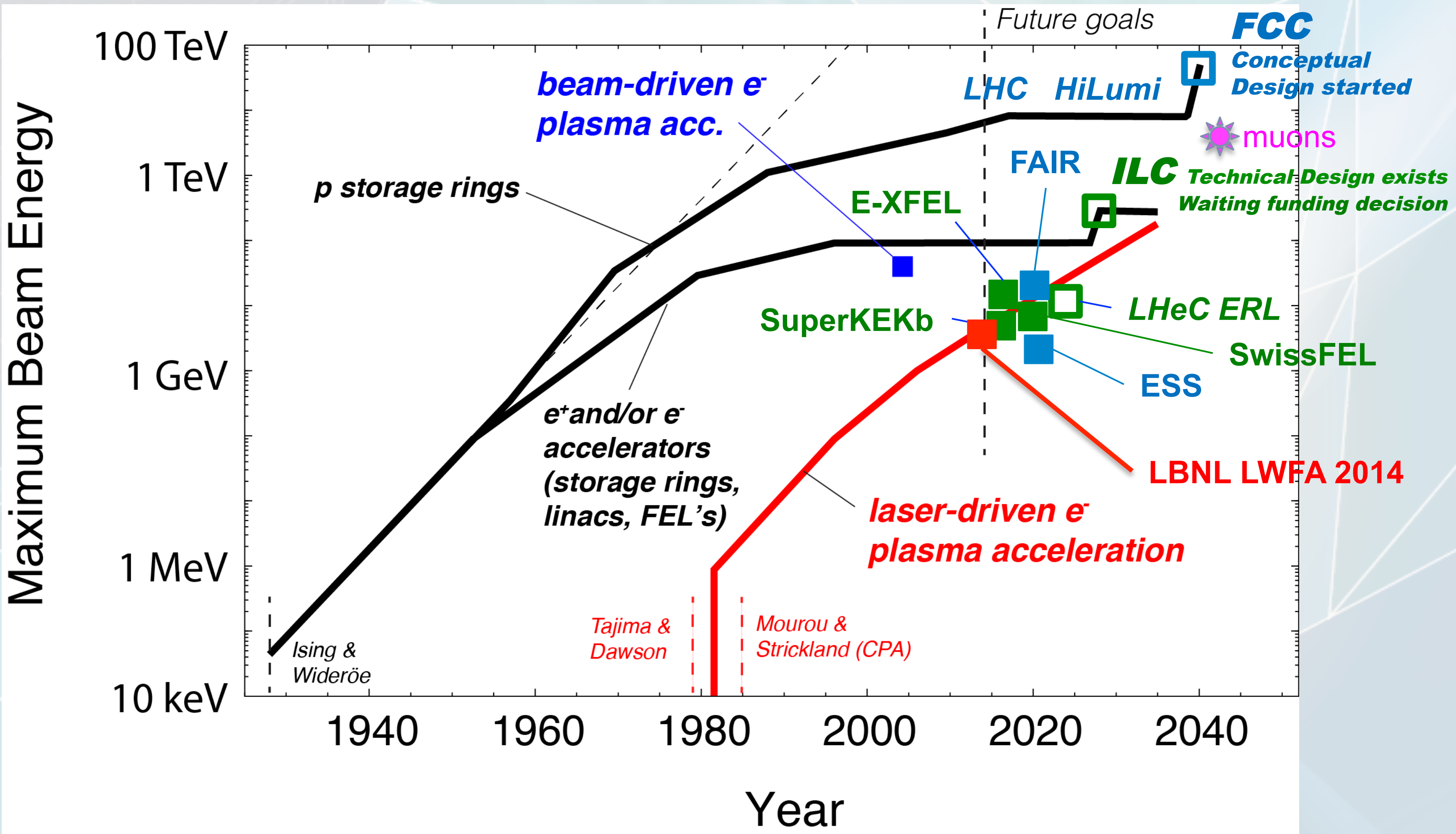
Simulation parameters

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





Future of Accelerators



Hadron acc. project

Lepton acc. project

Hadron acc. proposal

Lepton acc. proposal

R. Assmann, EAAC 2015, 9/2015

Conclusions

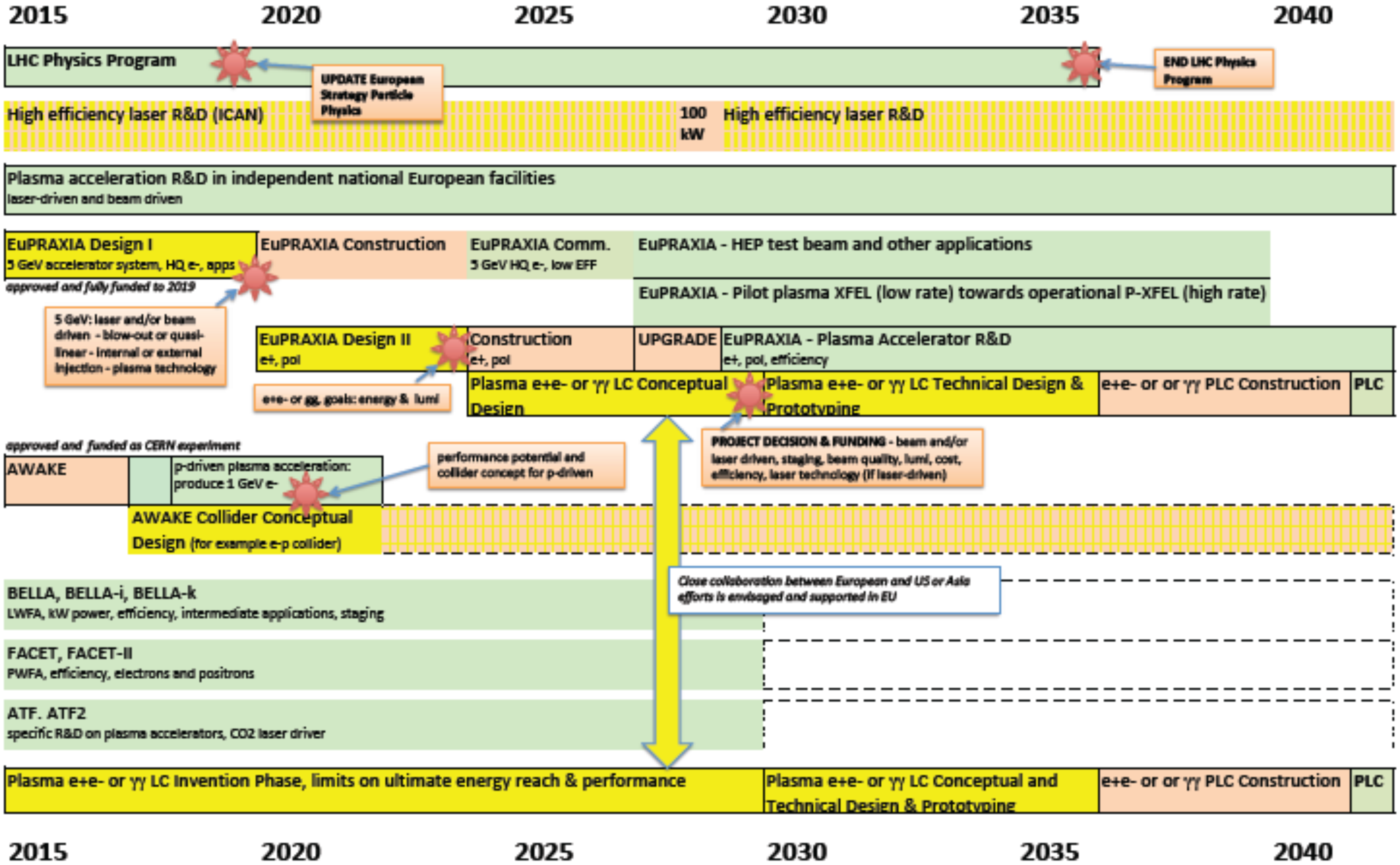
(Statement from the European Network for Novel Accelerators (EuroNNAc))

- Accelerator-based High Energy Physics will at some point become practically limited by the size and cost of the proposed e^+e^- colliders for the energy frontier.
- Plasma-based acceleration techniques have demonstrated accelerating gradients up to 3 orders of magnitudes beyond presently used RF technologies.
- **Plasma-based, ultra-high gradient accelerators therefore open the realistic vision of very compact accelerators for scientific, commercial and medical applications.**
- The R&D now concentrates on **beam quality, stability, staging and continuous operation**. These are necessary steps towards various technological applications.
- The progress in advanced accelerators benefits from strong synergy with general advances in technology, for example in the laser and/or high gradient RF structures industry.
- **A major milestone is an operational, 1 GeV compact accelerator. Challenges in repetition rate and stability must be addressed. This unit could become a stage in a high-energy accelerator..➔ PILOT FACILITY Needed**
- An increased support from Particle Physics will foster the R&D on advanced acceleration techniques and will provide important help and guidance.
- **Ultra-high gradient plasma accelerators should be recognized and listed as essential inter-disciplinary R&D towards future e^+e^- colliders for HEP**.


Grazie per l’attenzione

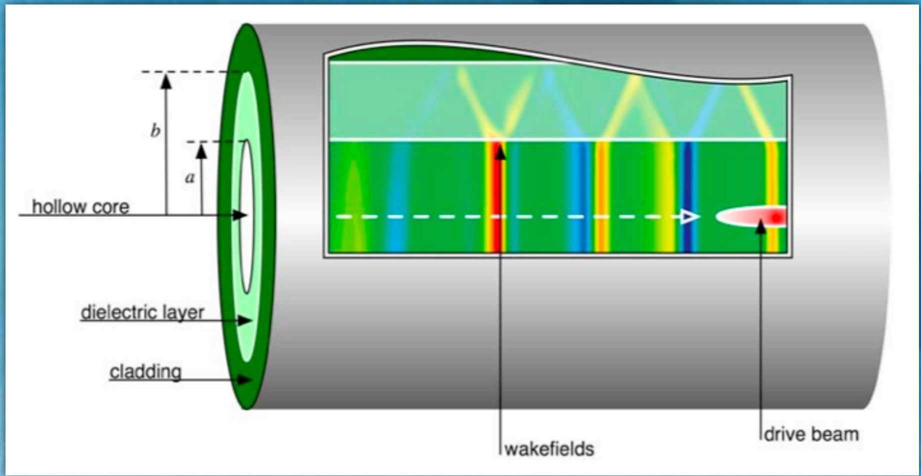
European Plasma Roadmap for HEP - ***Example, based on personal view of a few persons*** *Drafted January 2016, Plasma LC Workshop at LBNL*

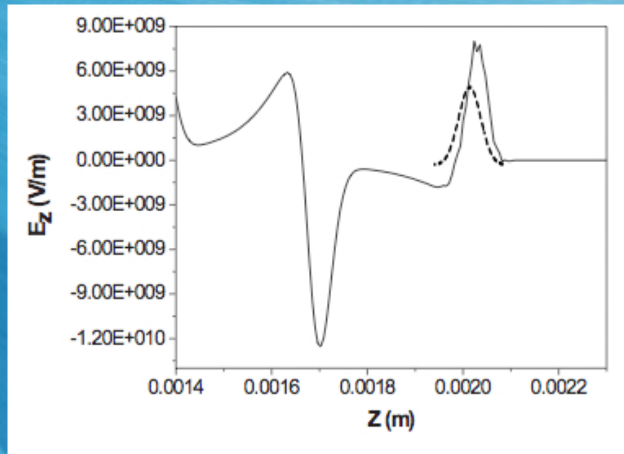
As a start of discussion,not an end point of discussion. Cannot be used as an official roadmap, should trigger discssuions and thoughts. Requires input, discussion, iteration, refinement, ... To be complemented by detailed R&D roadmaps from WG's.

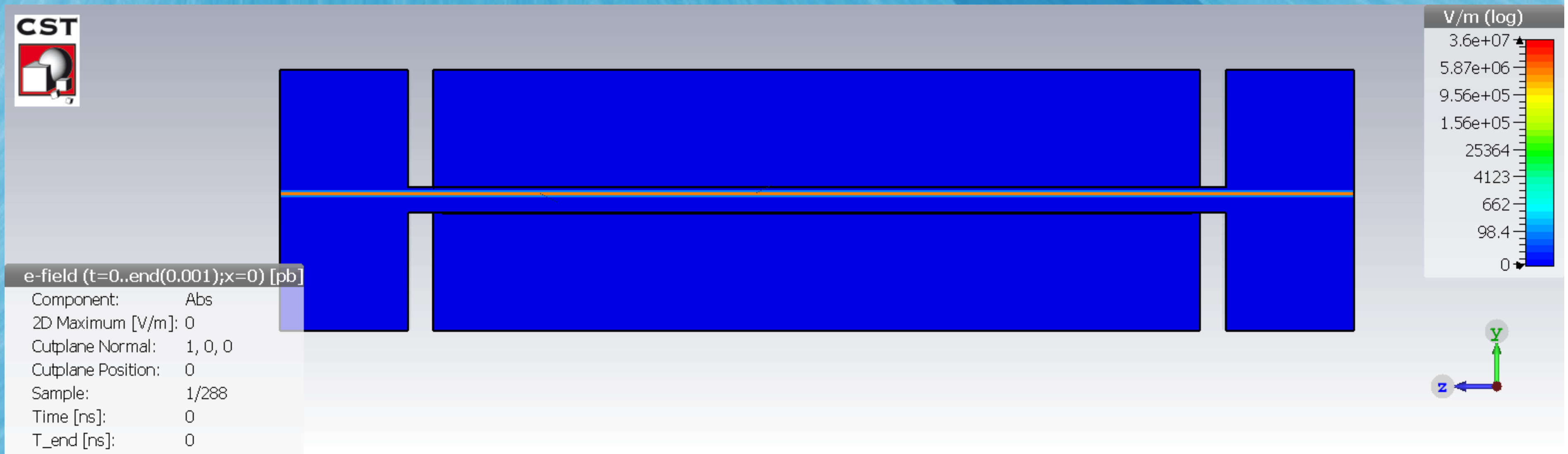


Direct Wakefield Acceleration
DWA

Dielectric Wakefield Accelerator

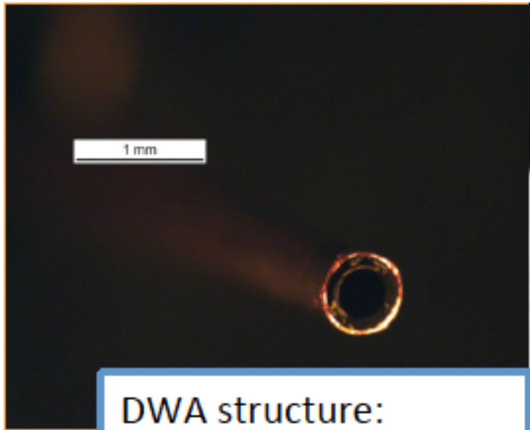




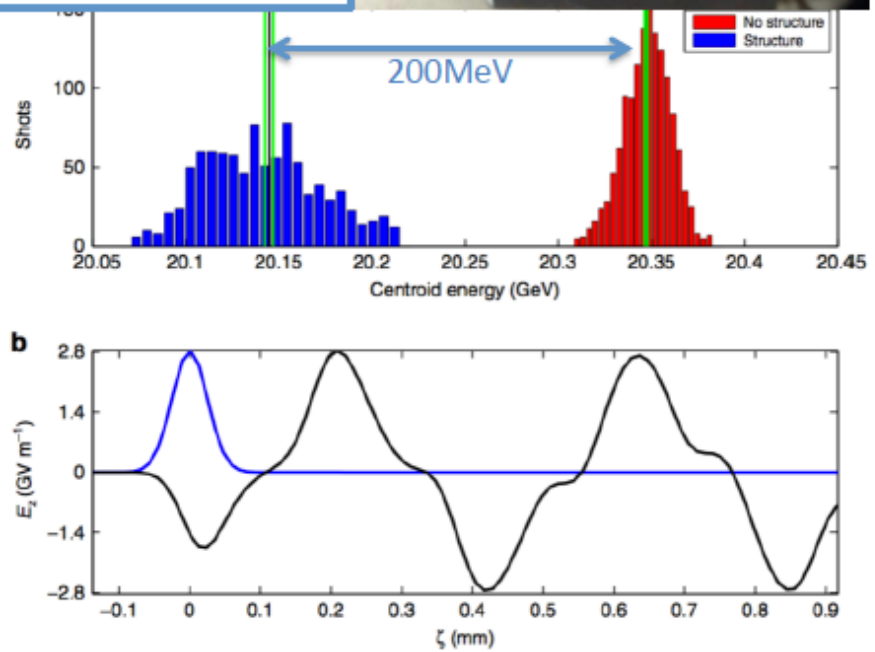


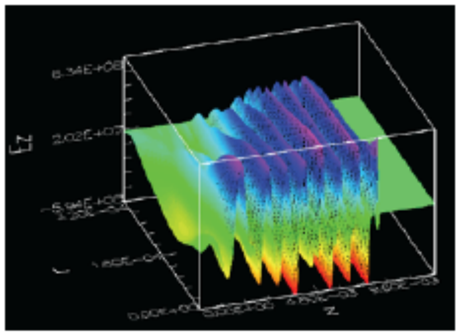
GV/m fields in DWA

- High-fields with small ID structures
  - Compressed beam (<25µm)
  - High charge (3nC)
- Beam centroid data
  - Measured Energy loss of 200 MeV
  - 1.3 GeV/m deceleration
  - 2.6 GeV/m peak field
  - Strong agreement with PIC simulations
- Continuous operation of >28hours (>100k shots at 10 Hz rep)
- No signs of damage or performance deterioration

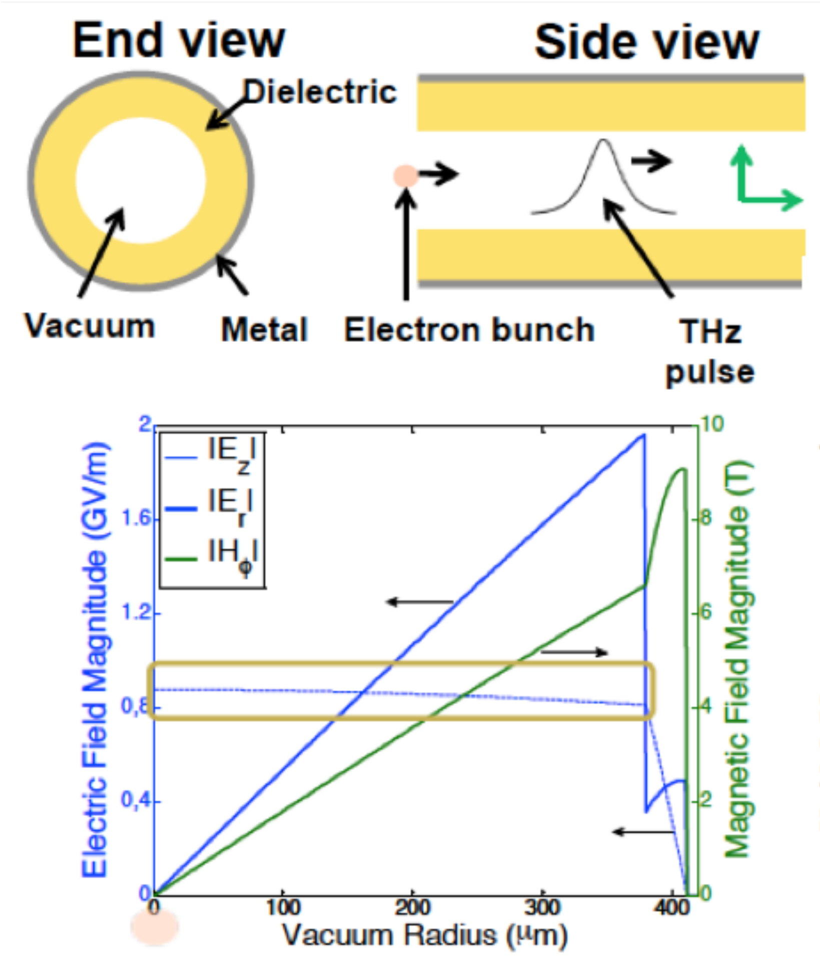


DWA structure:
- a/b = 150/200 µm
- L = 15cm
- Cylindrical, SiO_2





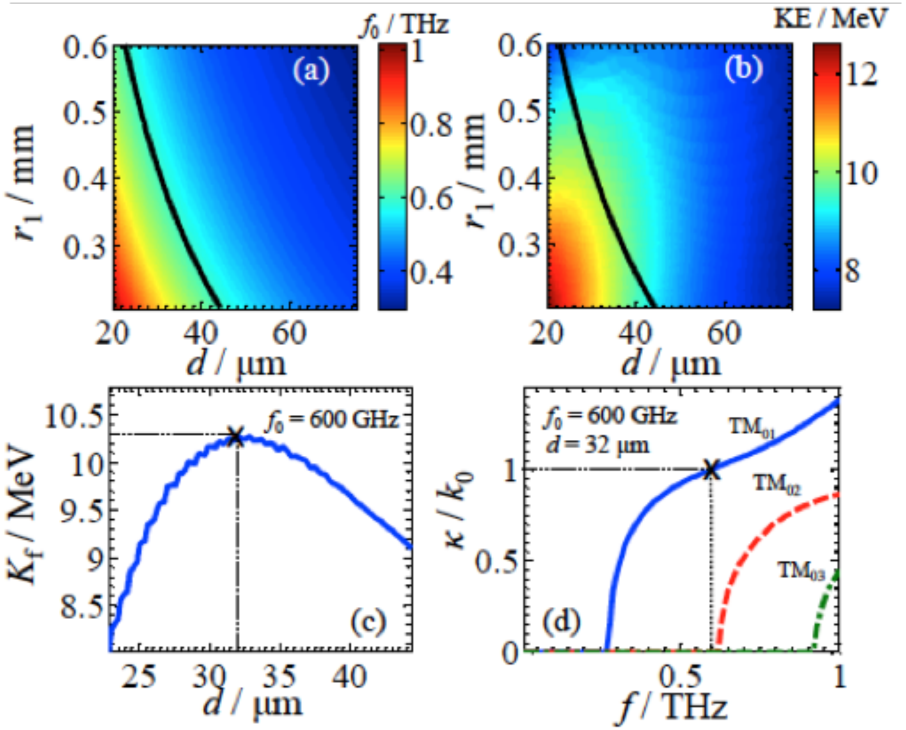
Electron Acceleration using THz waveguide



Uniform longitudinal field
suitable for particle acceleration

20 mJ pulse centered at 0.6 THz

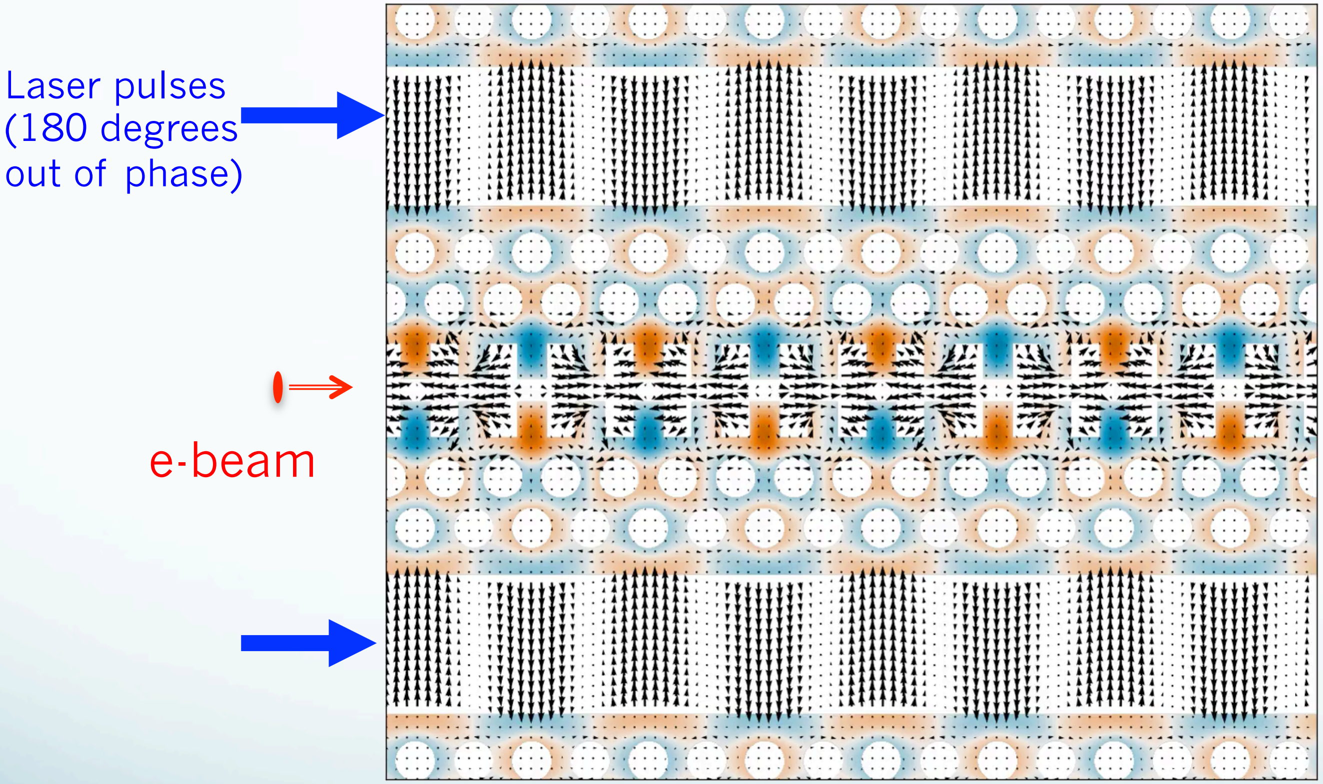
in a dielectric loaded metallic
waveguide



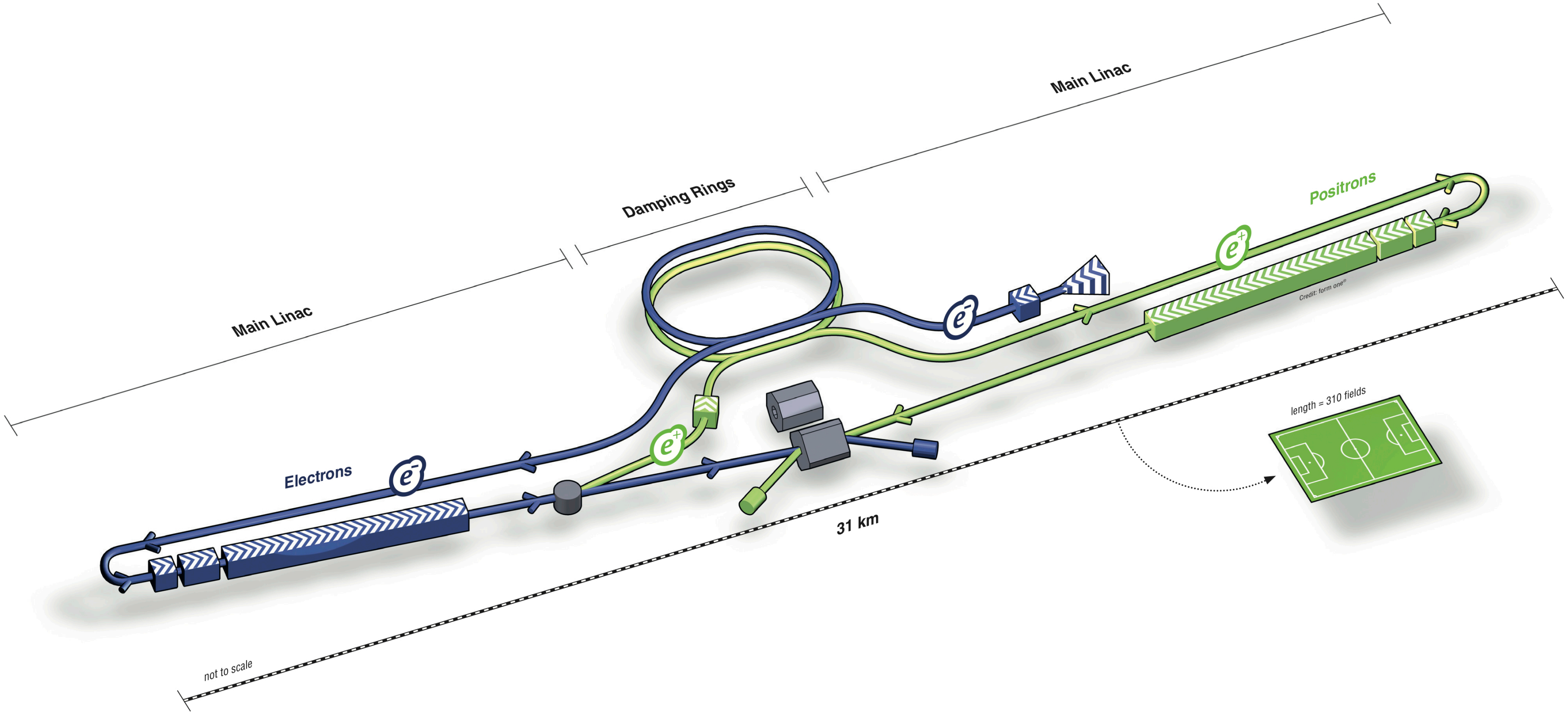
L.J. Wong et al., Opt. Exp. 21, 9792 (2013).

Laser-Structure Coupling: TW

GALAXIE Dual laser drive structure, large reservoir of power recycles



ILC – International Linear Collider



LEAPS League of European Accelerator-based Photon Sources

- Members of LEAPS: Photon science labs in Europe with user facilities.
- Federates potentially the EU funding of the super advanced community of photon science from 2021
- Includes a section on accelerator technology and a work package on **future compact light sources**.
- Present funding discussed presently: 198 M€ for acc. R&D over 7 years from 2021.
- About 20% might directly/indirectly profit advanced accelerators (amongst others EuPRAXIA coll.)

International Initiatives

How can we develop plasma accelerators towards usability?

ALEGRO for Advanced LinEar collider study GROup, has been set up to coordinate preparation of **proposal for an Advanced Linear Collider in multi-TeV energy range**.

Objective of ALEGRO workshop: prepare and deliver, by the end of 2018, a document detailing the **international roadmap and strategy of advanced novel accelerators (ANAs)** with clear priorities as input for the European Strategy Group, as well as input to ICFA

- "**Accelerator on a Chip**" grant from Moore foundation for work by/at **Stanford**, SLAC, **U Erlangen**, DESY, U Hamburg, PSI, EPFL, U Darmstadt, CST, UCLA
- Lasers drive structures that are engraved on microchips (e.g. Silicium)
- Major breakthroughs can be envisaged:
  - Mass production
  - Implantable accelerators for in-body irradiation of tumors
  - Accelerators for outer space