EUROPEAN
PLASMA RESEARCH
ACCELERATOR WITH
EXCELLENCE IN
APPLICATIONS
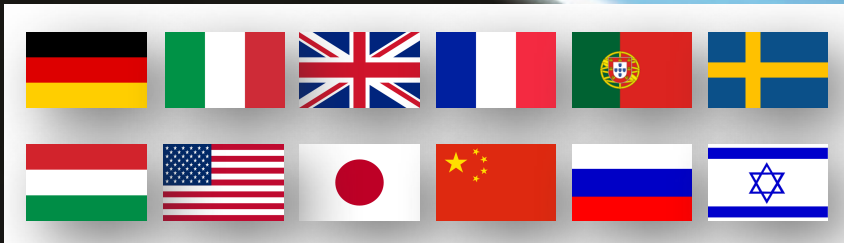
EuPRAXIA

Horizon 2020 EuPRAXIA design study

Paul Andreas Walker (DESY)

On behalf of the EuPRAXIA collaboration

38th International Free Electron Laser Conference

August 25th, 2017, Santa Fe, USA

- EuPRAXIA is a **conceptual design study** for a **5 GeV electron plasma research accelerator** as an European research infrastructure

- 125 scientists work in 38 international partners
  - 16 EU laboratories are beneficiaries
  - 22 associated partners contribute in-kind
  - DESY is coordinator laboratory (R.W. Assmann)

UK
- University of Strathclyde
- STFC
- University of Manchester
- University of Liverpool
- Imperial College London
- University of Oxford

GERMANY
- DESY
- Universität Hamburg

FRANCE
- CNRS
- CEA
- SOLEIL

PORTUGAL
- IST-ID

ITALY
- INFN
- CNR
- ENEA
- Università di Roma "La Sapienza"

ASSOCIATED PARTNERS

CHINA
- Shanghai Jiao Tong University
- Tsinghua University Beijing

FRANCE
- PhLAM Université de Lille

GERMANY
- HZDR (Helmholtz)
- Helmholtz-Institut Jena
- LMU München
- Karlsruher Institut für Technologie
- Forschungszentrum Jülich

HUNGARY
- Wigner Fizikai Kutatóközpont

INTERNATIONAL
- CERN
- ELI Beamlines

ISRAEL
- Hebrew University of Jerusalem

ITALY
- Università di Roma "Tor Vergata"

JAPAN
- Kansai Photon Science Institute
- Osaka University
- RIKEN SPring-8

RUSSIA
- Institute of Applied Physics
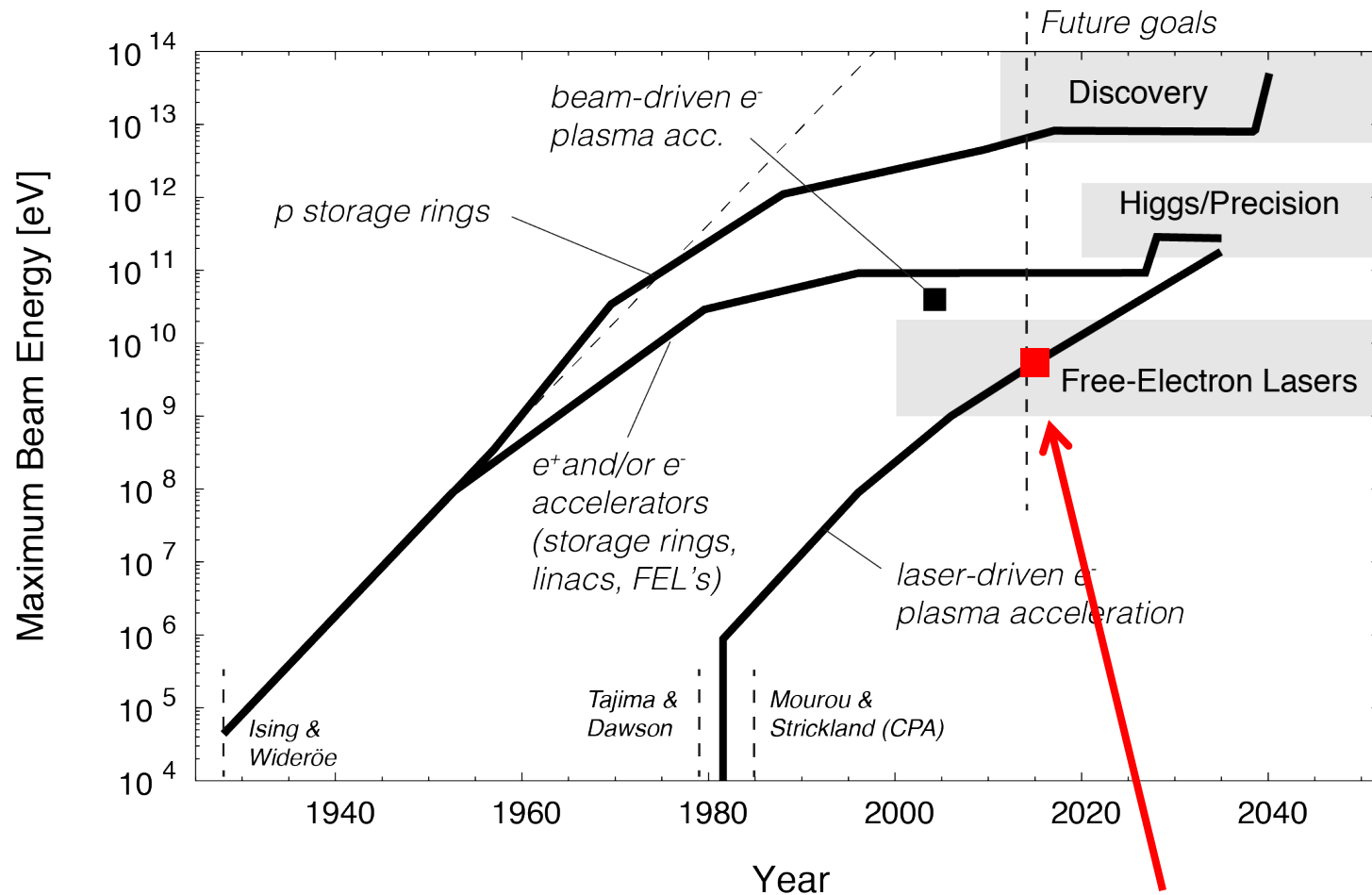- Joint Institute for High Temperatures

SWEDEN
- Lunds Universitet

USA
- Stony Brook University & Brookhaven NL
- LBNL
- UCLA

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- EuPRAXIA is an EU Horizon 2020 project
  - One of two accelerator related design studies funded, other is EuroCirCol (FCC) from CERN
  - Final CDR will be published in October 2019

- Develop plasma technology for user readiness:
  - Incorporate established accelerator technology for optimal quality
  - Combine expertise from accelerator and laser labs, industry, and international partners

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- Plasma accelerators reach energy regime of ongoing construction projects
- Acc. length of 9 cm instead of 100 m for multi GeV e⁻ beams [1]
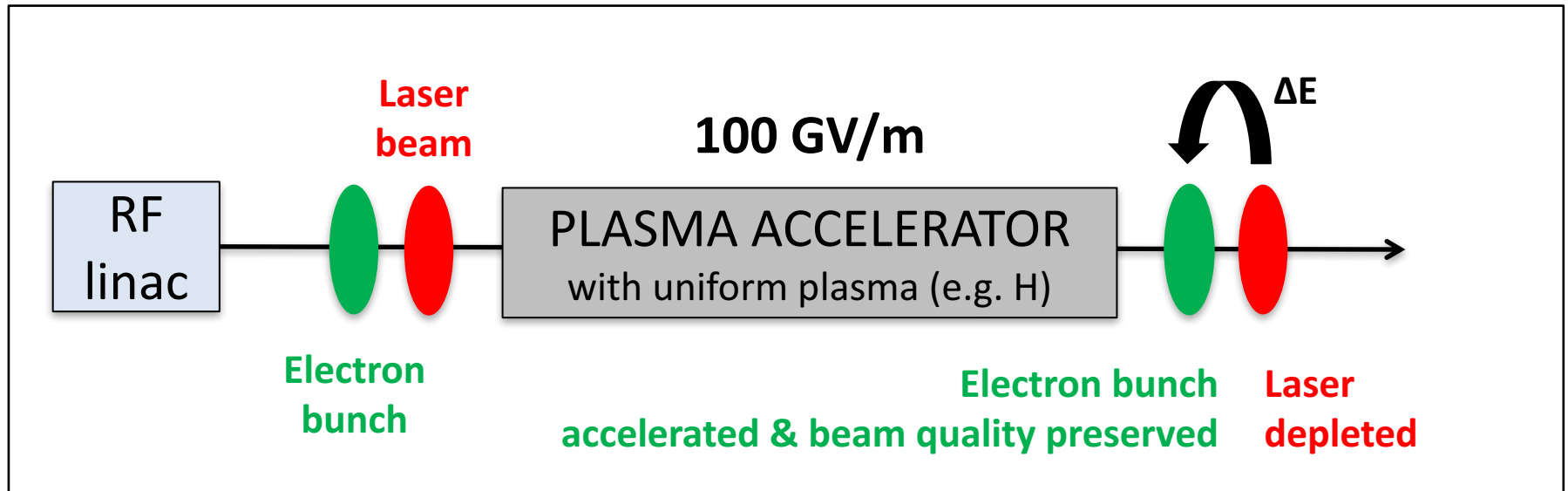- EuPRAXIA is **required stepping stone** to bring plasma accelerators to user readiness

[1] Leemans et al., Phys. Rev. Lett. 113, 245002 (2014)

Why use plasma accelerators?

Plasma accelerator techniques offer an innovative path to new parameters and to reduced size and cost with **novel applications** such as:

1) **FEL's with new properties for research centers** (complimentary to high power FEL's): *ultra-short pulses, pump-probe, excellent synchronization with low power (at least initially)*

2) **Ultra-compact FEL's at universities** (fit available space)

3) Laser-driven electron beams as medical imaging sources in hospitals

4) Compact electron irradiation

5) Portable industrial applications for X-ray inspections

6) Table-top beams for HEP detector tests

7) Compact plasma HEP collider

- Plasma accelerators can be driven by lasers or electron beams
- EuPRAXIA studies 5 different approaches, here we concentrate on laser driven because of available time (other approaches see reserve slides)

Laser beam

100 GV/m

ΔE

RF linac

PLASMA ACCELERATOR
with uniform plasma (e.g. H)

Electron bunch

Electron bunch
accelerated & beam quality preserved

Laser depleted

- 100 GV/m acceleration gradient: 5 GeV in ≥ 5 cm acceleration length (4.2 GeV in 9 cm shown at LBNL [1])

[1] Leemans et al., Phys. Rev. Lett. 113, 245002 (2014)

- Detailed tables of electron and X-ray parameters exist and simulation results are approaching our goals

- In a nutshell: 5 GeV and FEL radiation in the 1 - 0.1 nm range

Quantity	Symbol	Baseline value	Simulations	
			LWFA	PWFA
Particle type	e⁻	Electrons	Electrons	
Energy	E	5 GeV	1 GeV	
Charge	Q	30 pC	27 pC	29 pC
Bunch length (FWHM)	τ	10 fs	12 fs (rms)	10 fs
Peak current	I	3 kA	2.7 kA	2.9 kA
Repetition rate	f	10 Hz	-	-
Number of bunches	N	1	1	
Total energy spread (RMS)	σ_E/E	1%	0.3 %	>1 %
Slice energy spread (RMS)	$\sigma_{E,s}/E$	0.1 %	0.09 %	0.7 %
Transverse normalized emittance	$\varepsilon_{N,x}, \varepsilon_{N,y}$	1 mm mrad	0.5 mm mrad	0.6 mm mrad

Simulations data courtesy of M. Ferrario, E. Chiadroni et al. Simulations done with hybrid code Architect, Marocchino et al, Nucl. Instr. Meth. Phys. Res. vol. 829, 2016.
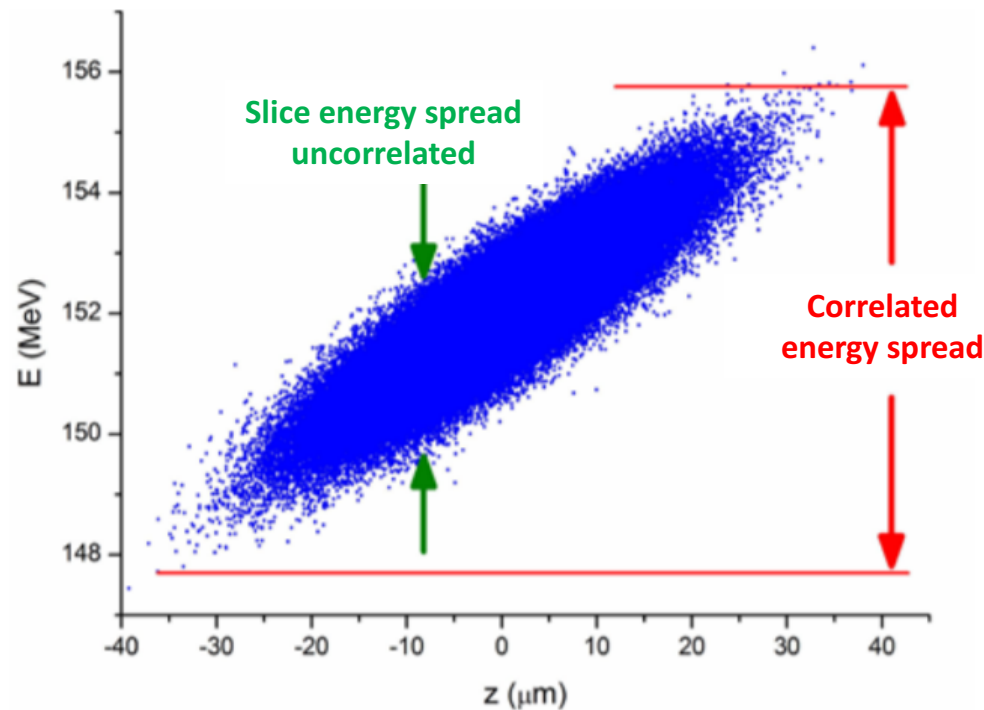
- Acceptable energy spread (σ_δ) criteria for FEL operation:

$$\sigma_\delta < \rho \quad \text{with } \rho < 0.1\% \text{ for classical FEL}$$

- Requirement challenging for LPA's to fulfill ($\sigma_\delta \sim 1\%$ typically)
- Energy spread is fundamental feature of plasma acceleration (acc. + foc.)
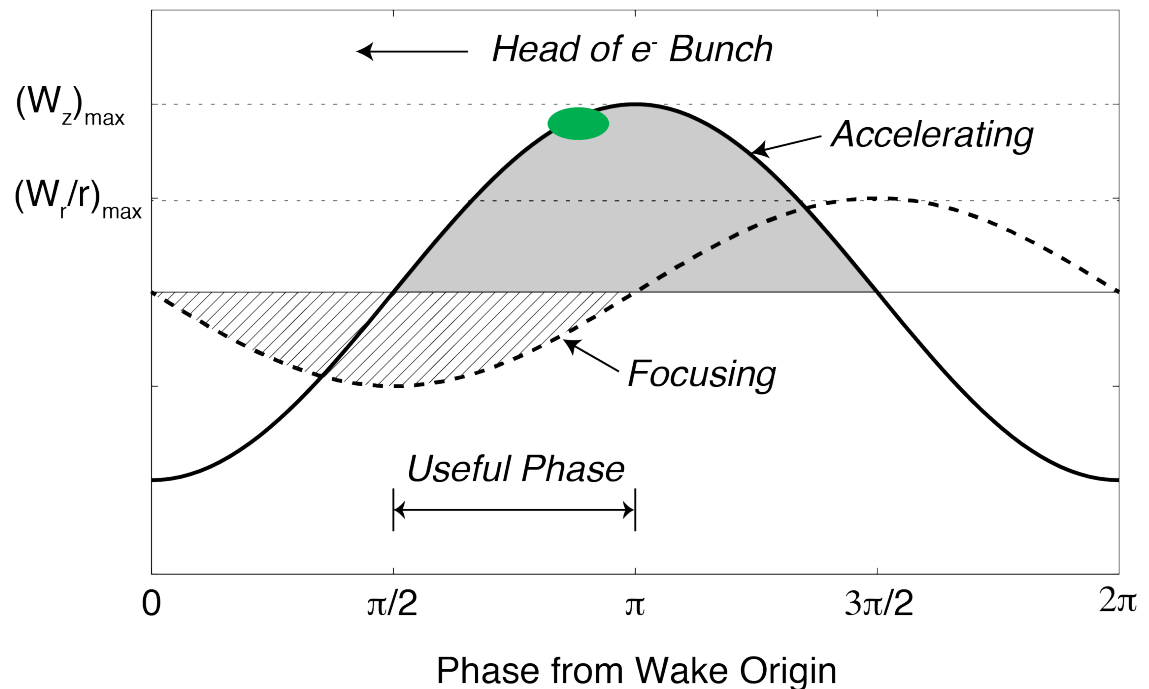
Plot courtesy R. W. Assmann from publication: „Challenges and Goals for Accelerators in the XXI Century", O. Brüning and S. Myers, April 2016, ISBN: 978-981-4436-39-7

- Acceptable energy spread (σ_δ) criteria for FEL operation:

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EuPRAXIA plasma injector simulation

Plot courtesy A. Mosnier

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- Requirement challenging for LPA's to fulfill ($\sigma_\delta \sim 1\%$ typically)
- Energy spread is fundamental feature of plasma acceleration (acc. + foc.)
- To fulfill energy spread criteria:

Possibility 1	Possibility 2
Minimize energy spread in plasma accelerator	**Build FEL which handles high correlated energy spread**

- **Beam loading**: field of electron beam and wakefield add up to flat acceleration field (proposal S. van der Meer)

  => zero energy spread possible in principle
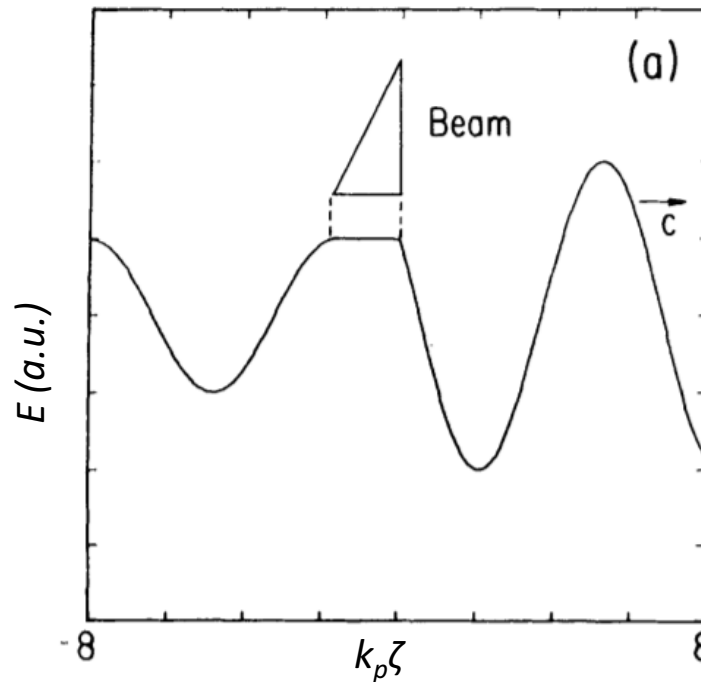
Concept: S. van der Meer, CLIC Note No. 3, CERN/PS 85-65 (AA) (1985).
Figure: T. Katsouleas et al., Particle Accelerators, 1987, Vol. **22**, pp. 81-99

- **Modulated plasma density**: FODO type acc. with electrons accelerated on both acceleration slopes
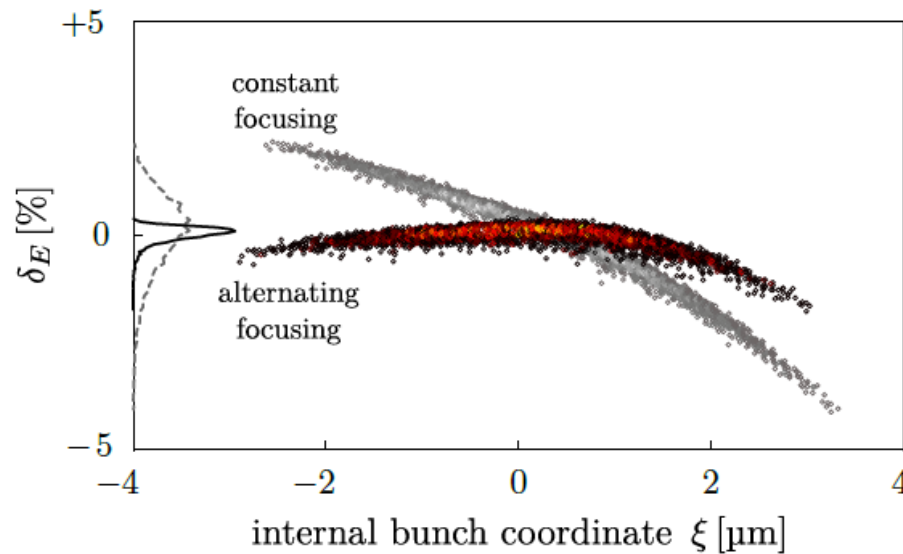
Plot from: R. Brinkmann et al., PRL **118**, 214801 (2017)

- Simulated energy spread reduced by factor 4

- Additional new ideas being pursued (unpublished)

- In plasma accelerators, currently the total energy spread is larger than the Pierce parameter:

$$\sigma_\delta > \rho$$

- Stretching bunch of length σ_z *longitudinally* reduce slice energy spread

$$\sigma_z \mapsto n \times \sigma_z$$
$$I \mapsto I/n$$
$$\sigma_{\delta,s} \mapsto \sigma_{\delta,s}/n$$
$$\rho \mapsto \rho/n^{1/3}$$

Feasible regime
$\sigma_{\delta,s} < \rho$

- For sufficient stretching, the slice parameters fulfill:

$$\sigma_{\delta,s} < \rho$$
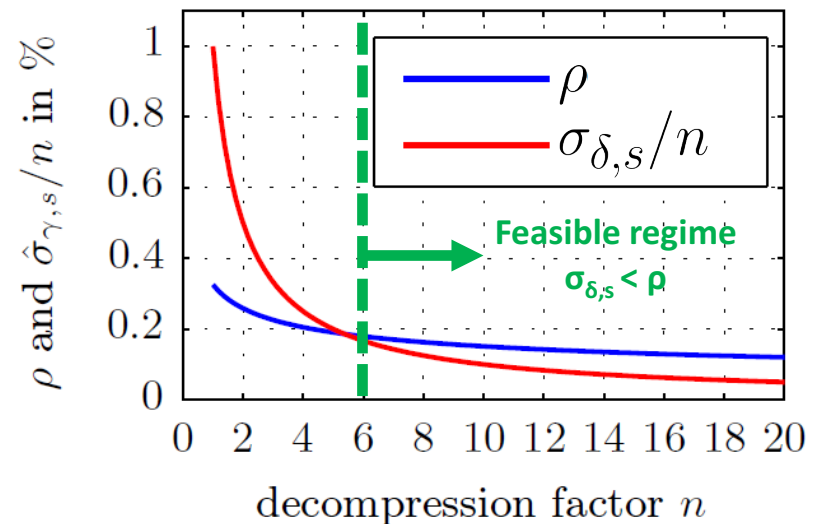
Concept and figure A.R. Maier et al., PRX 2, 031019, 2012

- Similar principle can be applied by stretching/sorting bunch *transversely*:

  - Canting magnetic poles results in linear x dependence of K
    $$K(x) = K_0(1 + \alpha x)$$
  - Dispersing beam along x results in energy dependent x position
    $$\gamma(x) = \gamma_0(1 + x/\epsilon)$$
  - Energy dispersion chosen to have certain E at required x in magnetic field to have wavelength independent of x:

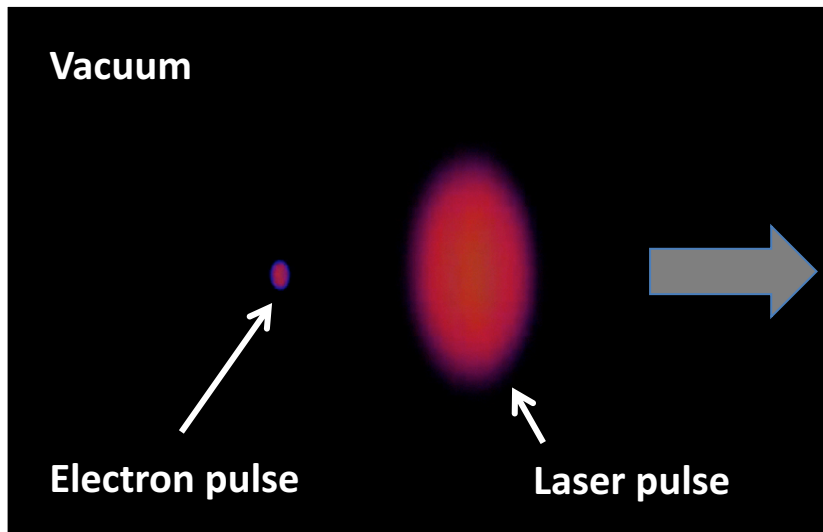$$\lambda_r = \frac{\lambda_u}{2\gamma(x)^2}\left(1 + \frac{K(x)^2}{2}\right)$$
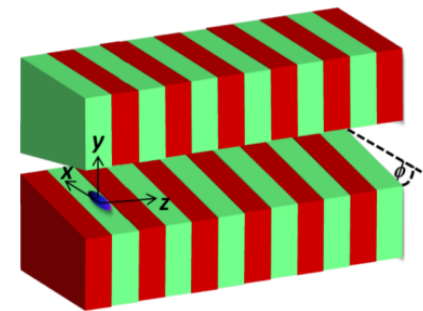
Z. Huang et al. PRL 109, 204801, 2012

EuPRAXIA simulations

- Simulations and design work at the core of this project

- Goal is start to end simulations, demonstrating required performance including FEL

- Various codes being used

PIC code used	Users
OSIRIS	IST, DESY
WARP	CNRS/LPGP, CEA
CALDER-Circ	LOA
SMILEI	CNRS/LLR
ALaDyn, Architect	INFN_SparcLab (PISA_ILIL)
HiPACE	DESY
PIConGPU	DESY

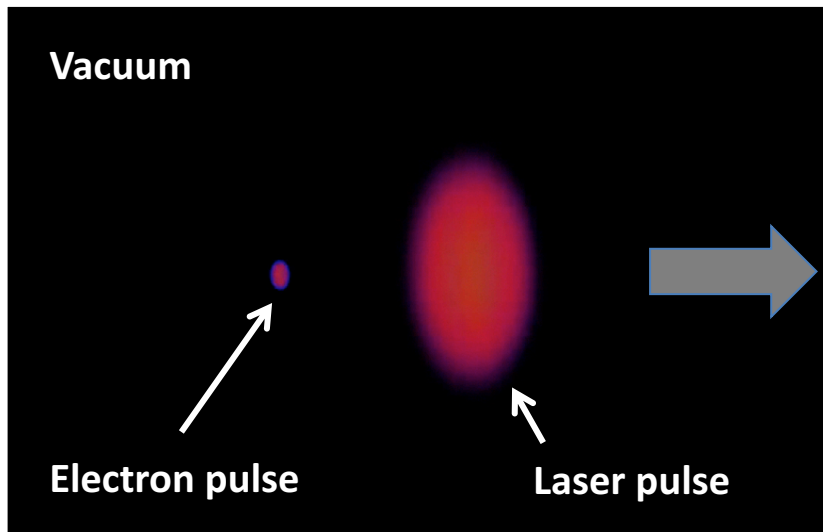A. Mosnier, J. Vieira, L. Silva et al., M2.3 Sim. tools and theory set-up, February 2017

*Á. Ferran Pousa, R. Assmann, A. Martinez de la Ossa. IPAC17 paper **TUPIK007**.*
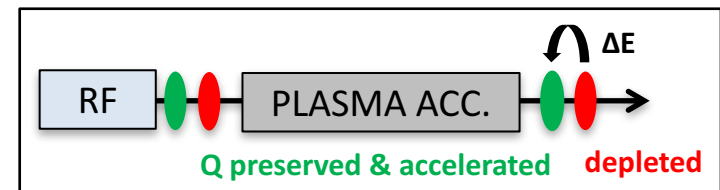
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Initial electron beam:
E = **100 MeV**,
Relative energy spread = **0.1 %**
Norm. trans. emittance = **1 mm mrad**
Q = 1 pC, τ = 3.3 fs (rms), σ_x = 1.3 µm

Laser pulse:
a_0 = 3.1, λ = 800 nm, I_{FWHM} = 100 fs,
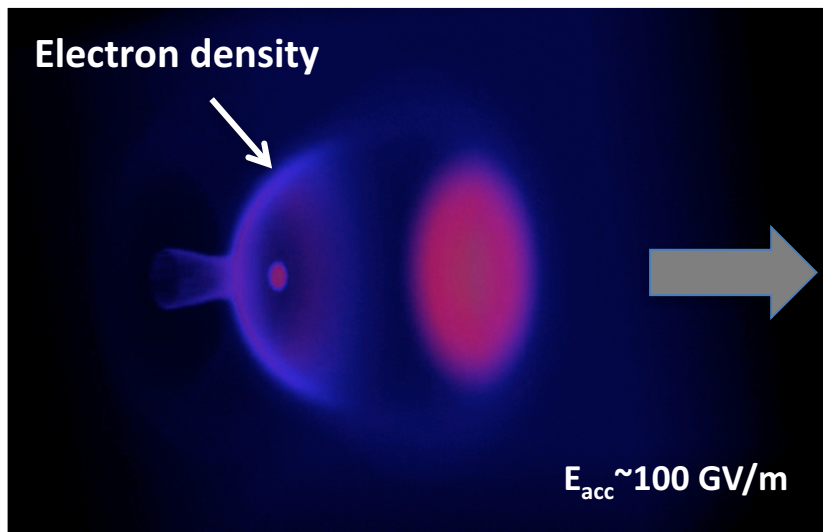w_0 = 54 µm, E = 100 J, 1 PW peak power

*Á. Ferran Pousa, R. Assmann, A. Martinez de la Ossa. IPAC17 paper **TUPIK007**.*

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Electron density

$E_{acc} \sim 100$ GV/m

The acceleration regime:
close to blowout
2D simulation: the 3D animation was made assuming cylindrical symmetry

Plasma:
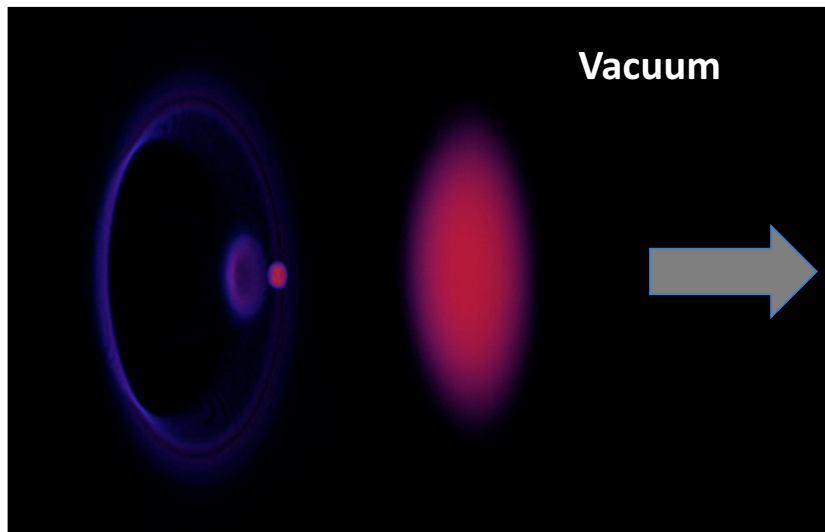Density = 1.2 x 10^{17} cm^{-3}
Length = **2.5 cm**

*Á. Ferran Pousa, R. Assmann, A. Martinez de la Ossa. IPAC17 paper **TUPIK007**.*

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Vacuum

Electron beam after plasma:
Energy = **1 GeV** (initial 100 MeV)
Relative energy spread **= 1.5%** (initial 0.1 %)
Normalized emittance = **0.995 μrad m**
(initial 0.99 μrad m)

*Á. Ferran Pousa, R. Assmann, A. Martinez de la Ossa. IPAC17 paper **TUPIK007**.*
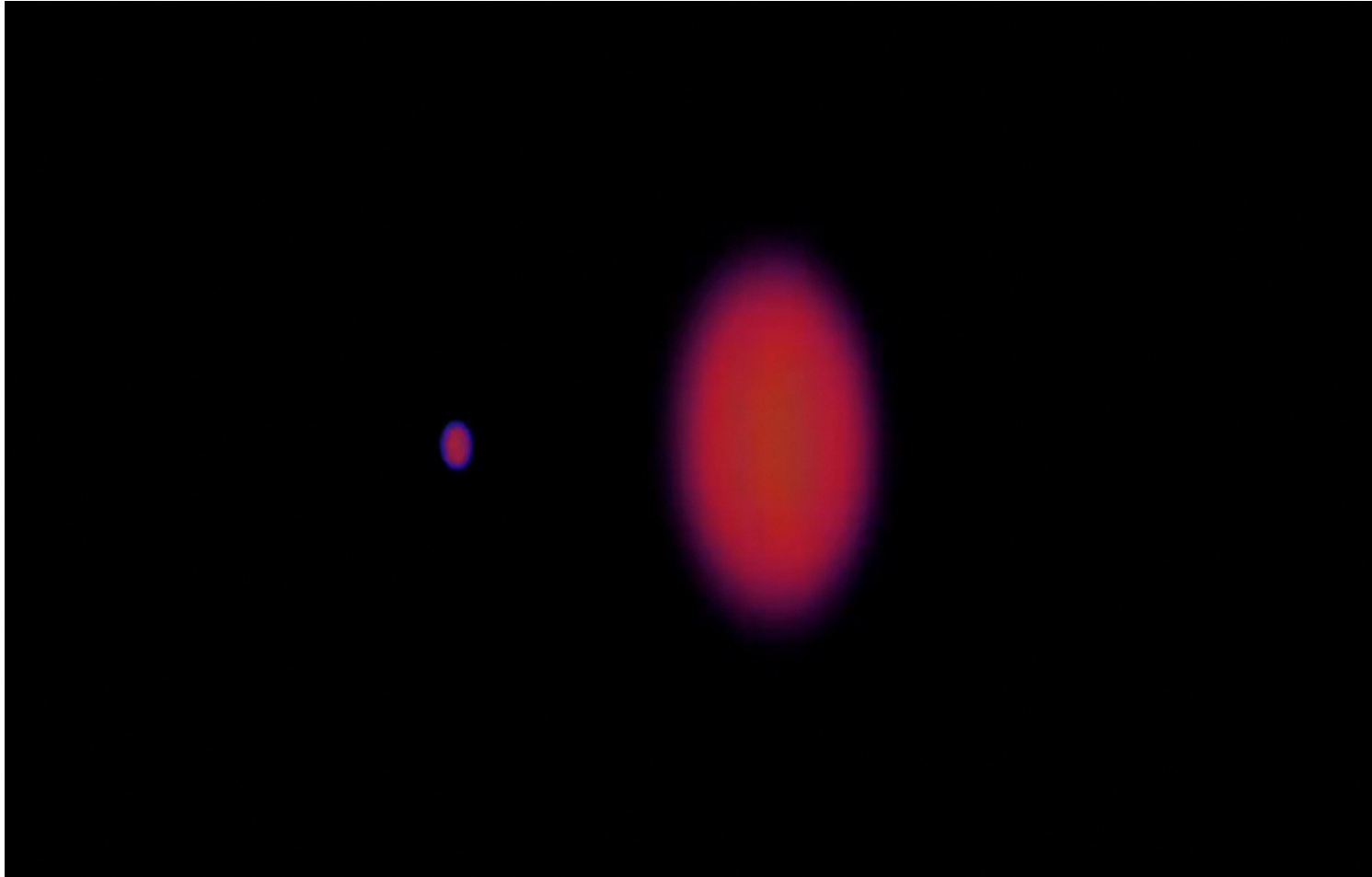
*Á. Ferran Pousa, R. Assmann, A. Martinez de la Ossa. IPAC17 paper **TUPIK007**.*

Studying acceleration to 5 GeV

- Energy gain is given by integral of acc. field times length of acceleration:

$$\Delta\gamma_b = \frac{2}{\pi} k_p L_{dp} \frac{E_{z,max}(0)}{E_0} \left[\left(1 + \frac{L_{acc}}{L_{pd}}\right) \sin\left(\frac{\pi}{2}\frac{L_{acc}}{L_{dp}}\right) + \frac{2}{\pi}\frac{L_{dp}}{L_{pd}}\left(\cos\left(\frac{\pi}{2}\frac{L_{acc}}{L_{dp}}\right) - 1\right)\right]$$
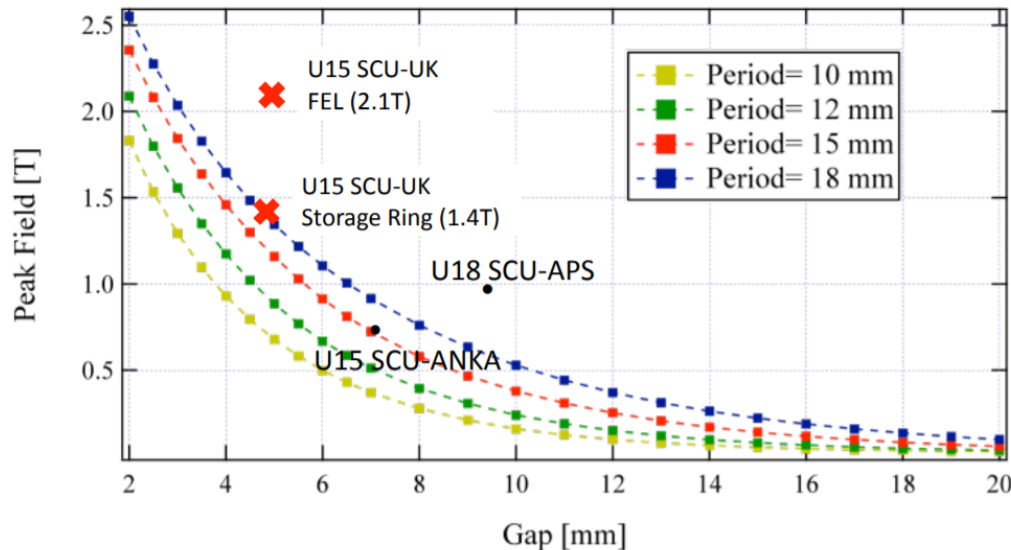
- Fixing parameters such as energy gain, laser strength, and spot size one can plot acceleration length as a function of density
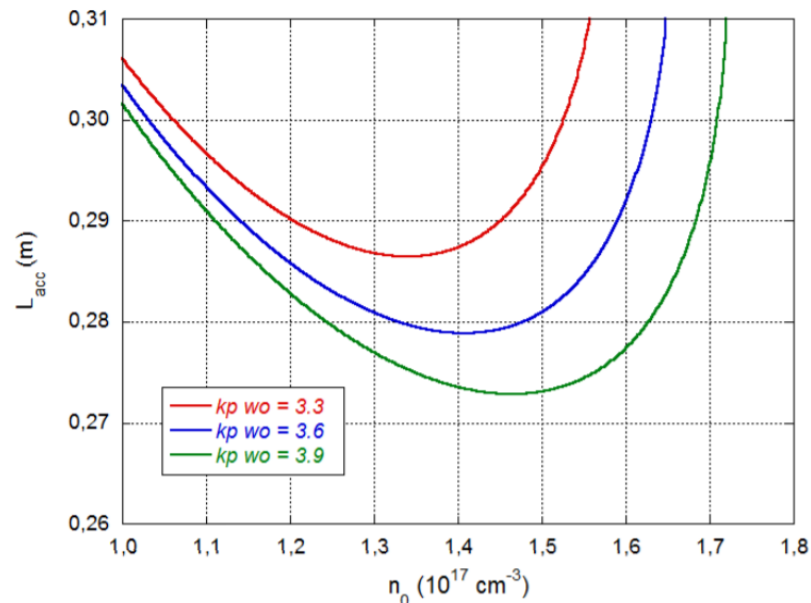
Courtesy A. Mosnier et al, EuPRAXIA Deliverable report D 2.1 Report designing baseline designs, April 2017

- Review of undulator materials and types in 2016 (update in 2017)

- FEL simulation with 1 GeV beam with 2.7 nm wavelength

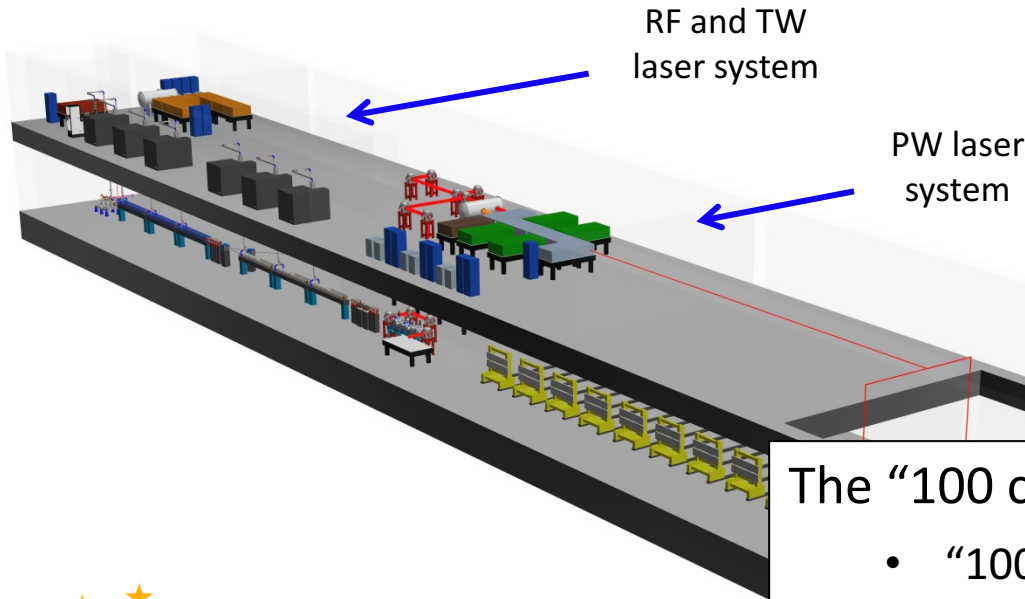| Slice parameters	
beam energy [GeV]	1.2
current intensity [A]	20 000
norm. emittance [mm×mrad]	1.5
energy spread σ_E/E (%)	0.3
Undulator parameters	
undulator period [cm]	1.2
deflection parameter	1.7
Output FEL parameters	
FEL wavelength [nm]	2.66
Twiss β [m]	3.73
Pierce parameter ρ	0.0026
inh. broad. gain length [m]	0.4
saturation power [MW]	34 350
saturation length [m]	11.7

M.E. Couprie et al., EuPRAXIA Collaboration Week, Hamburg 19.-23.June 2017

Accelerator research, undulators and user areas are located on the first level

accelerator tunnel   laser path

undulator hall
(assumed conventional)

X-ray transport
and user areas
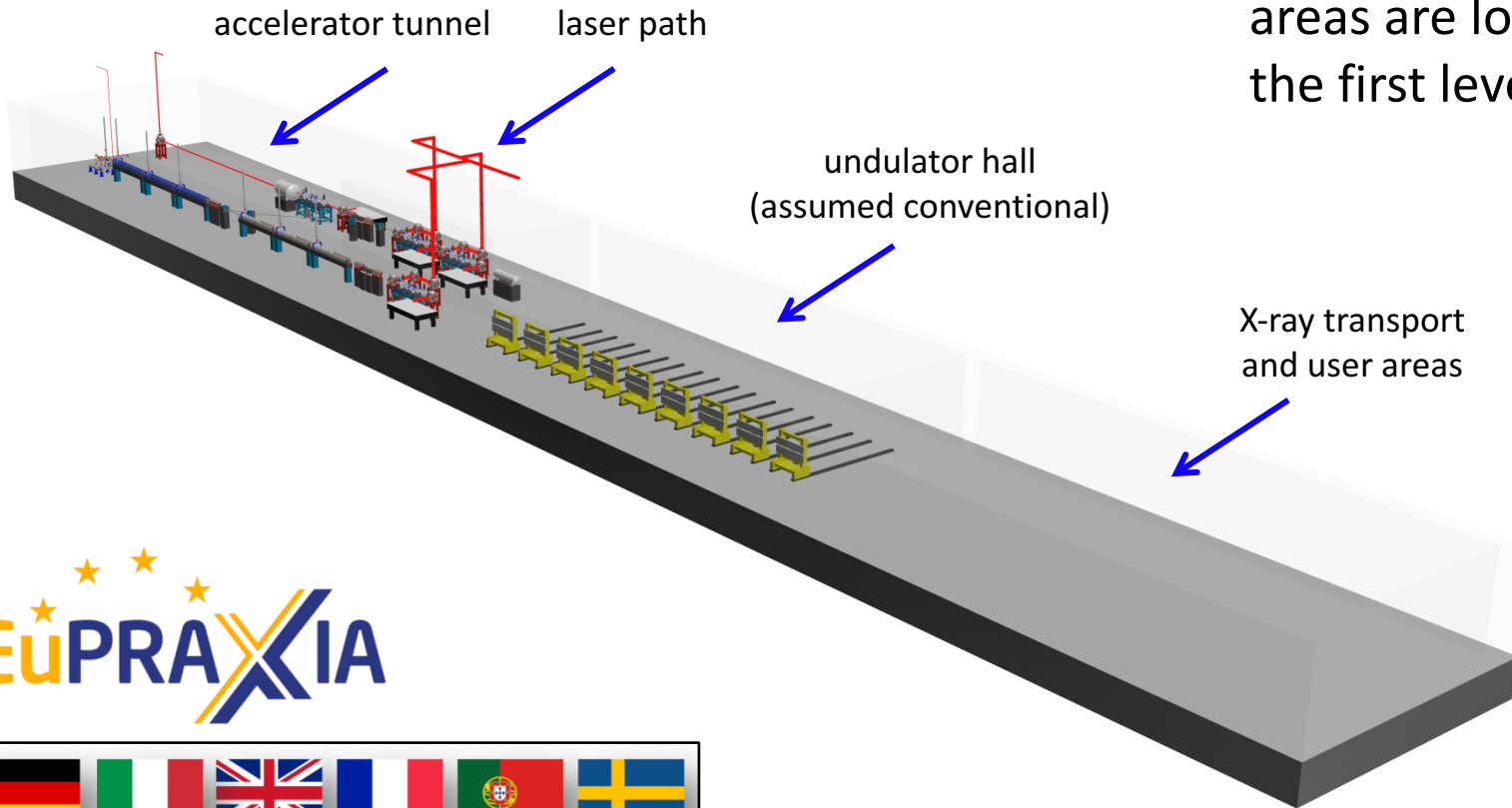
3D design by Dariusz Kocoń (ELI-Beams)

RF and laser infrastructure on second level

RF and TW laser system

PW laser system

The "100 cube laser challenge":

- "100 cube" = 100 J, 100 fs, 100 Hz
   => 1PW @ 100Hz
- Not a complete Ti:Sa laser system
- Diode-pumped solid-state laser scheme
- 2nd laser system (Ti:Sa) operates at lower energy and shorter pulse length
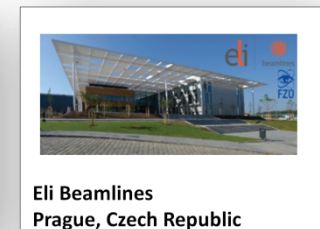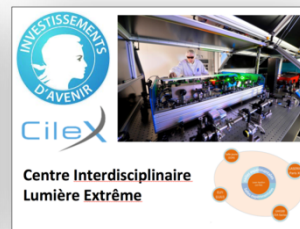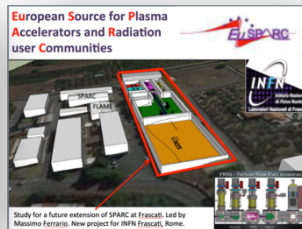
Demo-FEL projects ongoing:

- X-ray produced after undulator in August 2017 at DESY by LUX group at 5 Hz (A.R.Maier et al.)
- Beamtime in Paris planned for November 2017 (M.E. Couprie & V. Malka et al.)
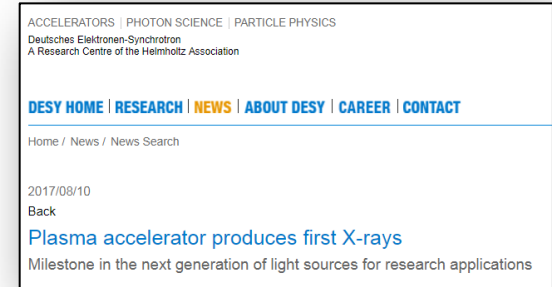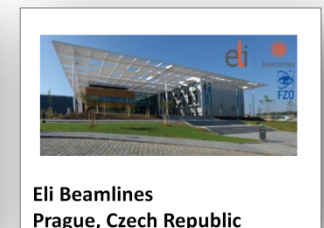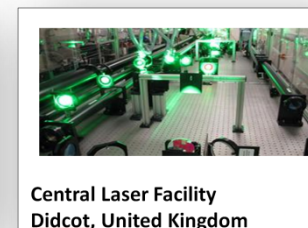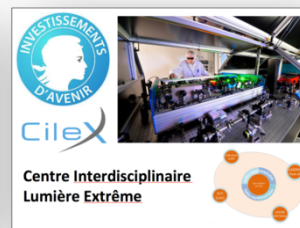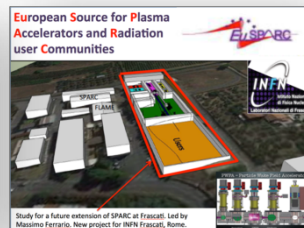

DESY news (10th August 2017)

EuPRAXIA site studies:

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

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SINBAD
Facility for Short INnovative Bunches and Accelerators at DESY (ex DORIS collider)

- dedicated acc. R&D facility
- 280 m beam tunnel
- accelerator science programs
- adjacent laser laboratories
- photon science labs
- central campus location
- home for future ATHENA, facility, if funded by Helmholtz

European Source for Plasma Accelerators and Radiation user Communities
Study for a future extension of SPARC at Frascati. Led by Massimo Ferrario. New project for INFN Frascati, Rome.

Centre Interdisciplinaire Lumière Extrême

Central Laser Facility
Didcot, United Kingdom

Eli Beamlines
Prague, Czech Republic

Rigshospitalet Copenhagen

3D design by Dariusz Kocoń (ELI-Beams). Photo credit: google.

Rigshospitalet Copenhagen

3D design by Dariusz Kocoń (ELI-Beams). Photo credit: google.

Conclusion

Horizon 2020

- EuPRAXIA is a EU **design study for a novel European accelerator-based research facility** with applications in science, industry & medicine.

- Strongly linked major research centers and to leading European industry.

- Goal is to provide a design report for a **5 GeV electron beam facility** based on laser and/or beam driven **plasma acceleration**, which shall be compact and cost efficient.

- Design will include pilot user areas for **FEL radiation**, "table-top" **test beam for HEP detectors tests**, **compact X-ray source** for medical imaging, and other applications.

- This is a Horizon 2020 project and we acknowledge the support from the EU under grant agreement No. 653782.

The EuPRAXIA team

P. D. Alesini, A. S. Alexandrova, M. P. Anania, N. E. Andreev, R. W. Assmann, T. Audet, A. Bacci, I. F. Barna, A. Beaton, A. Beck, A. Beluze, A. Bernhard, S. Bielawski, F. G. Bisesto, J. Boedewadt, F. Brandi, O. Bringer, R. Brinkmann, E. Bründermann, M. Büscher, G. C. Bussolino, A. Chance, M. Chen, E. Chiadroni, A. Cianchi, J. Clarke, M. Croia, M. E. Couprie, B. Cros, J. Dale, G. Dattoli, N. Delerue, O. Delferriere, P. Delinikolas, J. Dias, U. Dorda, K. Ertel, Á. Ferran Pousa, M. Ferrario, F. Filippi, J. Fils, R. Fiorito, R. A. Fonseca, M. Galimberti, A. Gallo, D. Garzella, P. Gastinel, D. Giove, A. Giribono, L. A. Gizzi, F. J. Grüner, A. F. Habib, L. C. Haefner, T. Heinemann, B. Hidding, B. J. Holzer, S. M. Hooker, T. Hosokai, B. Imre, D. A. Jaroszynski, C. Joshi, M. Kaluza, O. S. Karger, S. Karsch, E. Khazanov, D. Khikhlukha, A. Knetsch, D. Kocon, P. Koester, O. Kononenko, G. Korn, I. Kostyukov, L. Labate, C. Lechner, W. P. Leemans, A. Lehrach, F. Y. Li, X. Li, A. Lifschitz, V. Litvinenko, W. Lu, A. R. Maier, V. Malka, G. G. Manahan, S. P. D. Mangles, B. Marchetti, A. Marocchino, A. Martinez de la Ossa, J. L. Martins, K. Masaki, F. Massimo, F. Mathieu, G. Maynard, T. J. Mehrling, A. Y. Molodozhentsev, A. Mosnier, A. Mostacci, A. S. Müller, Z. Najmudin, P. A. P. Nghiem, F. Nguyen, P. Niknejadi, J. Osterhoff, D. Papadopoulos, B. Patrizi, R. Pattathil, V. Petrillo, M. A. Pocsai, K. Poder, R. Pompili, L. Pribyl, D. Pugacheva, S. Romeo, A. R. Rossi, A. A. Sahai, Y. Sano, P. Scherkl, U. Schramm, C. B. Schroeder, J. Schwindling, J. Scifo, L. Serafini, Z. M. Sheng, L. O. Silva, C. Simon, U. Sinha, A. Specka, M. J. V. Streeter, E. N. Svystun, D. Symes, C. Szwaj, G. Tauscher, A. G. R. Thomas, N. Thompson, G. Toci, P. Tomassini, C. Vaccarezza, M. Vannini, J. M. Vieira, F. Villa, C.-G. Wahlström, R. Walczak, P. A. Walker, M. K. Weikum, C. P. Welsch, J. Wolfenden, G. Xia, M. Yabashi, L. Yu, J. Zhu, A. Zigler

www.eupraxia-project.eu