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

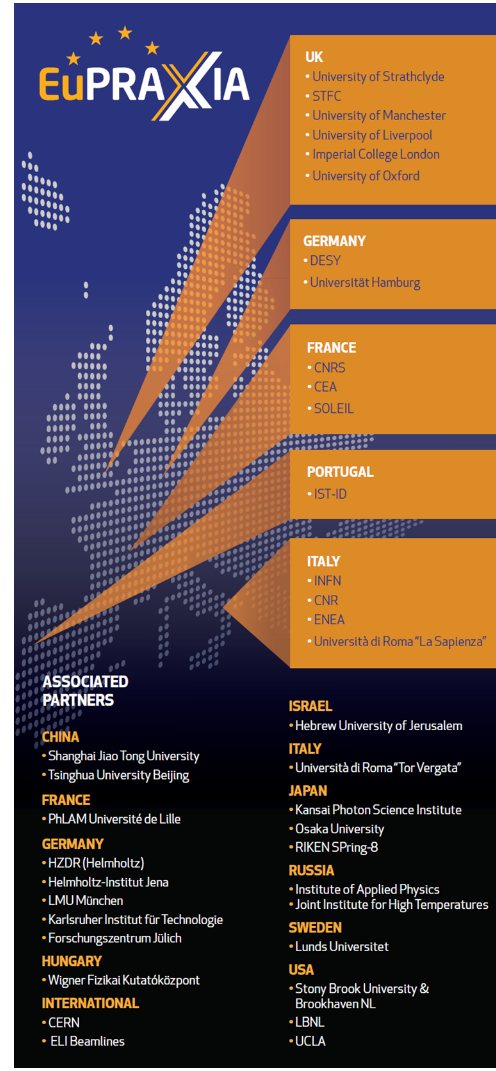
This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 653782.

European Plasma Research Accelerator with eXellence In Applications

Horizon 2020

- 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)



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

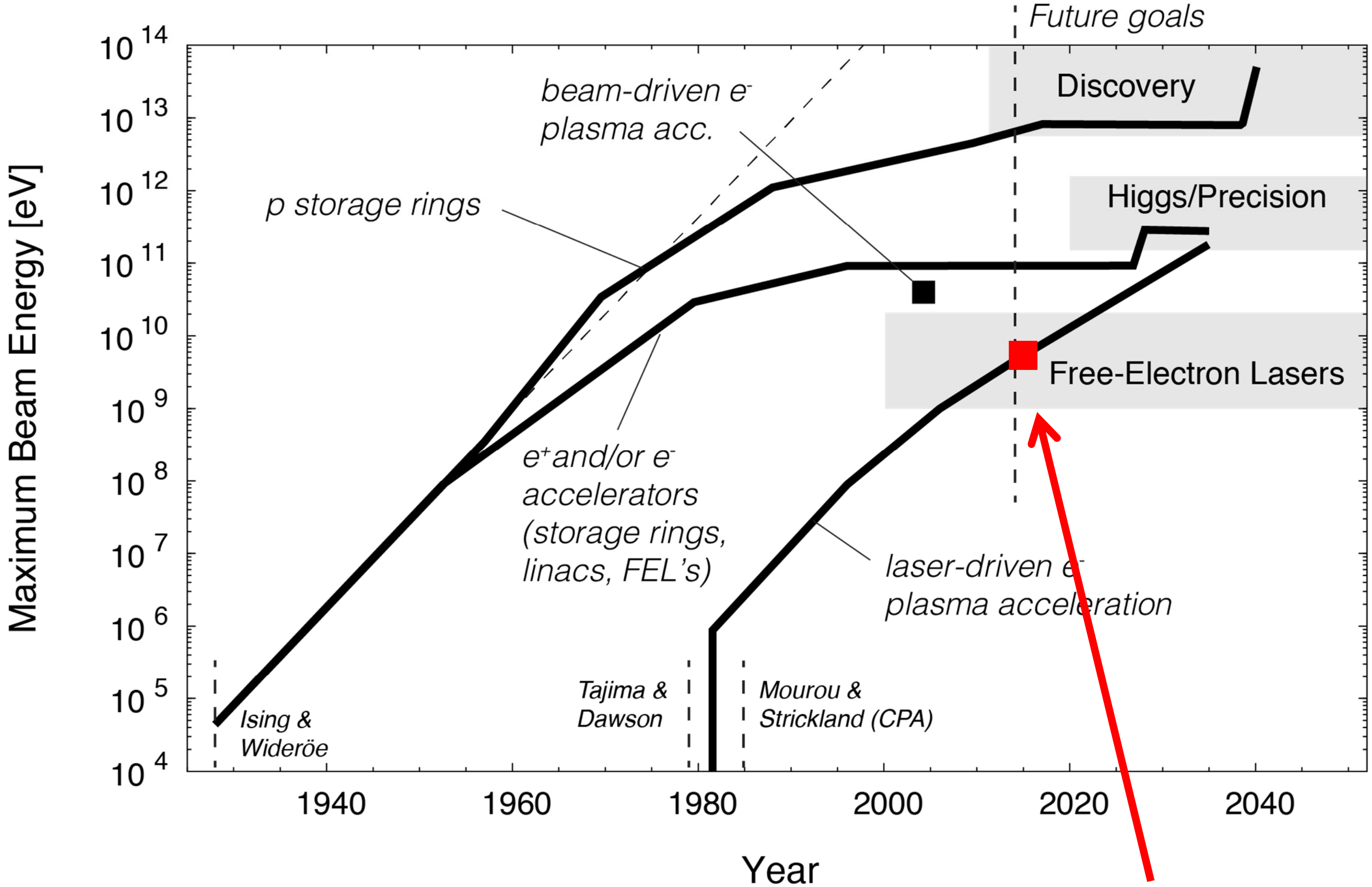
- 125 scientists work in 38 international partners
  - 16 EU laboratories are beneficiaries
  - 22 associated partners contribute in-kind
  - DESY is coordinator laboratory (R.W. Assmann)

- 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

Livingston Curve

EuPRAXIA as stepping stone to users readiness



Plot R. W. Assmann („Challenges and Goals for Accelerators in the XXI Century", O. Brüning & S. Myers, April 2016)

- 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

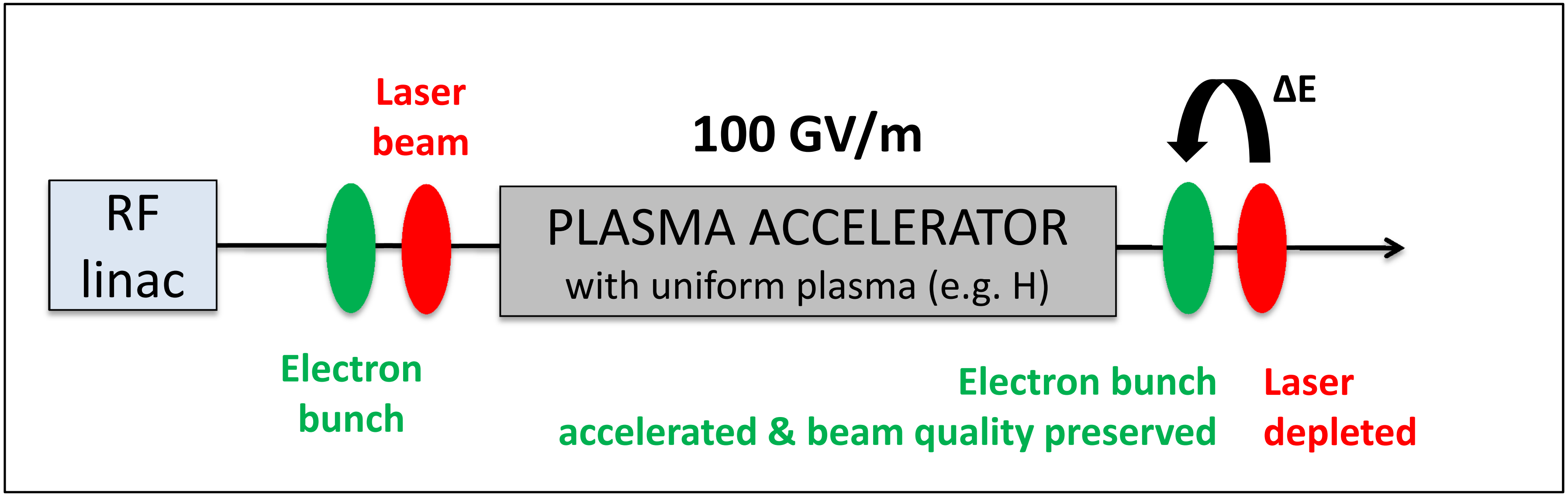
5) Portable industrial applications for X-ray inspections

6) Table-top beams for HEP detector tests

7) Compact plasma HEP collider

Plasma accelerator concepts: example one

- 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)



- 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)

Goals and simulation results

- 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

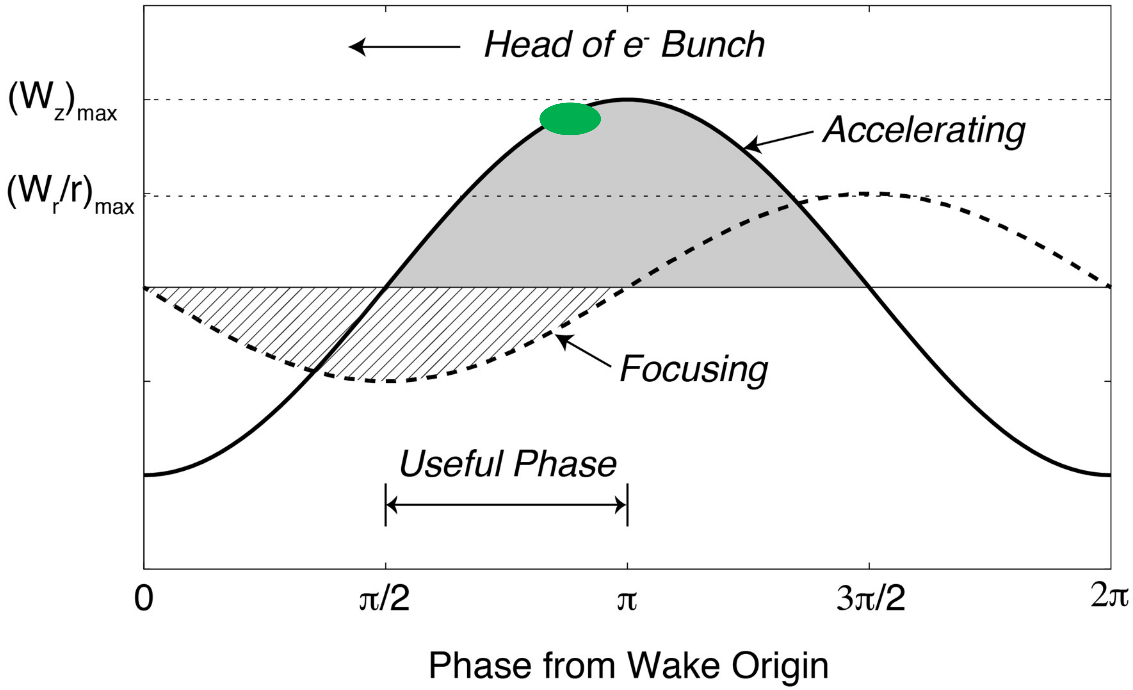
Simulations data courtesy of M. Ferrario, E. Chiadroni et al. Simulations done with hybrid code Architect, Marocchino et al, Nucl. Instr. Meth. Phys. Res. vol. 829, 2016.

Energy spread limitation for FEL operation

- 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 (σ_δ ~ 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

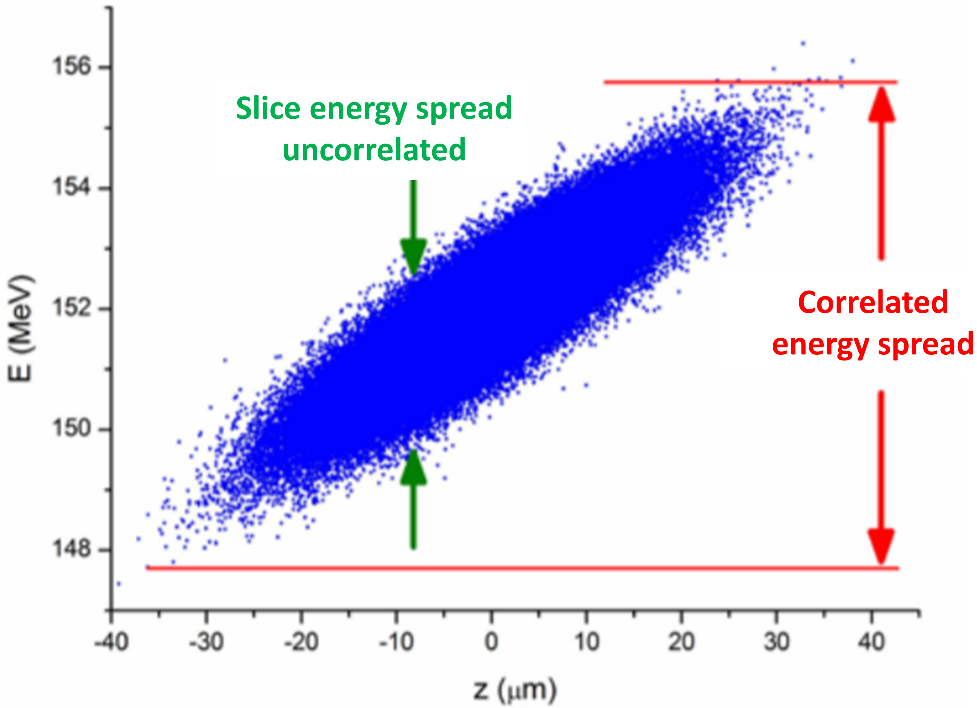
Energy spread limitation for FEL operation

- 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 (σ_δ ~ 1% typically)
- Energy spread is fundamental feature of plasma acceleration (acc. + foc.)

EuPRAXIA plasma injector simulation



Plot courtesy A. Mosnier

Energy spread limitation for FEL operation

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

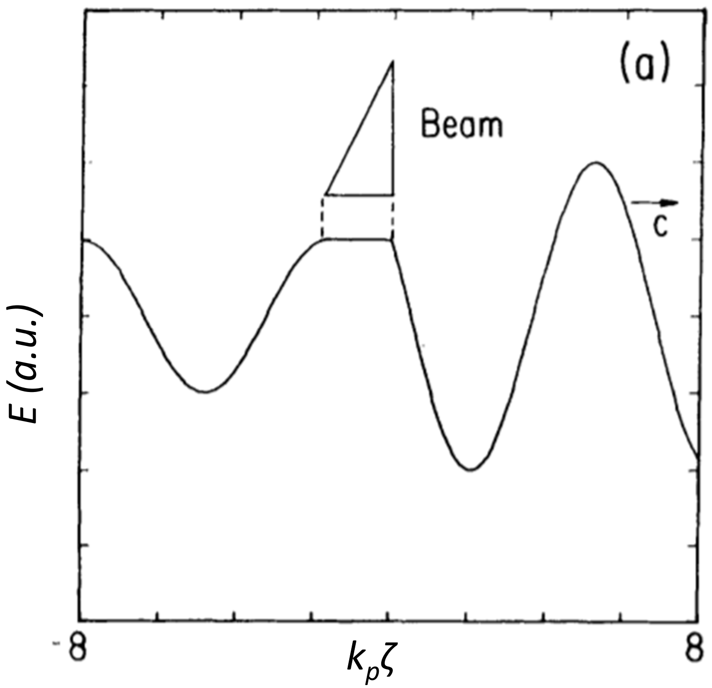
$$\sigma_\delta < \rho \quad \text{with } \rho < 0.1\% \text{ for classical FEL}$$

- Requirement challenging for LPA's to fulfill (σ_δ ~ 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)

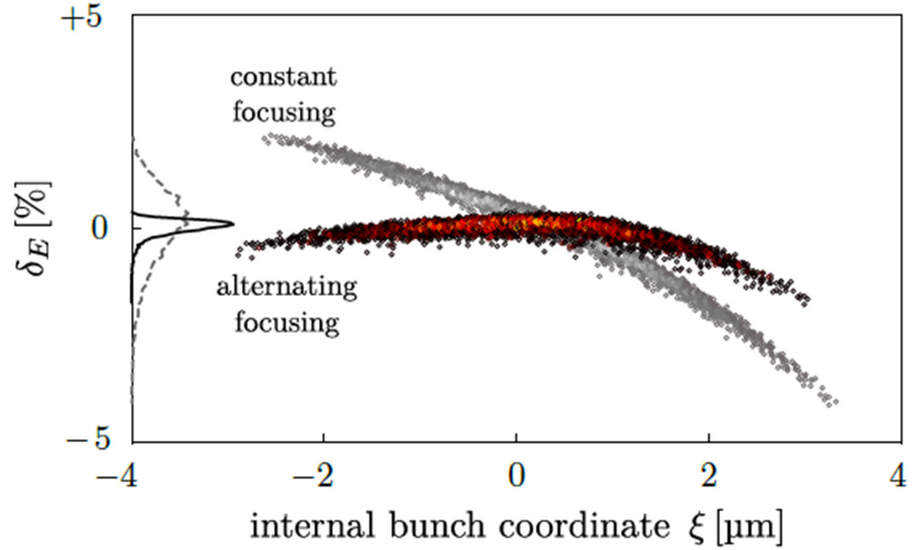
  => zero energy spread possible in principle



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

Possibility 1: Minimize energy spread in plasma accelerator

- **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)

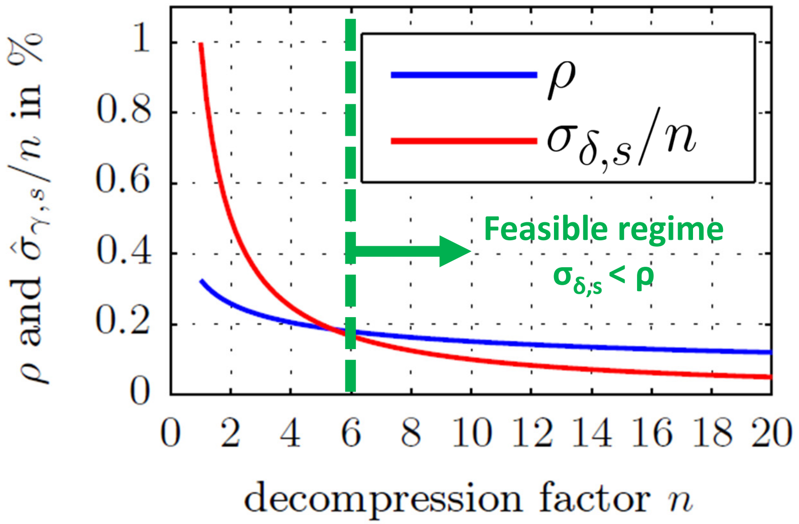
Poss. 2: Build FEL which handles high correlated energy spread: "Decompression" scheme

- 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

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



- For sufficient stretching, the slice parameters fulfill:

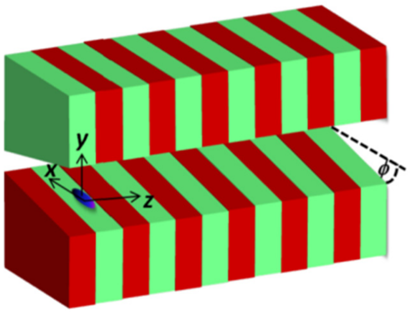
$$\sigma_{\delta,s} < \rho$$

Concept and figure A.R. Maier et al., PRX 2, 031019, 2012

Poss. 2: Build FEL which handles high correlated energy spread:"Transverse gradient undulator"

- 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:

$$\lambda_r = \frac{\lambda_u}{2\gamma(x)^2}\left(1 + \frac{K(x)^2}{2}\right)$$



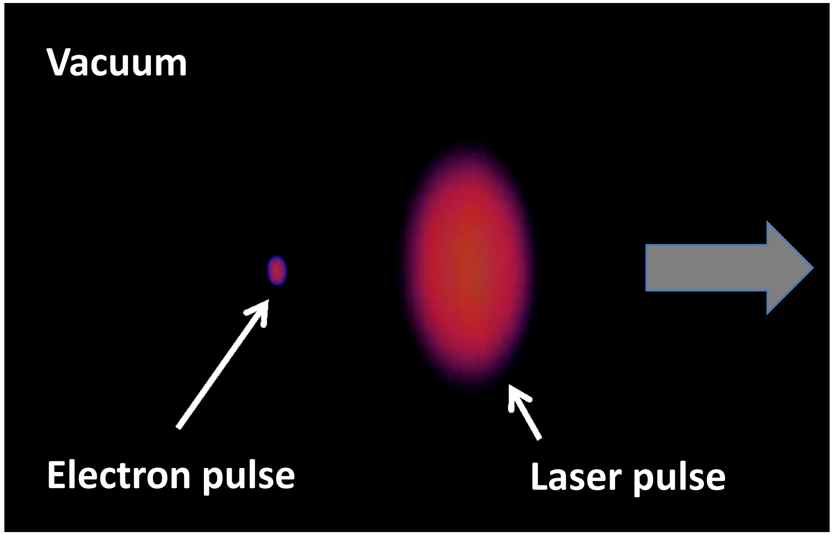
Z. Huang et al. PRL 109, 204801, 2012

EuPRAXIA simulations

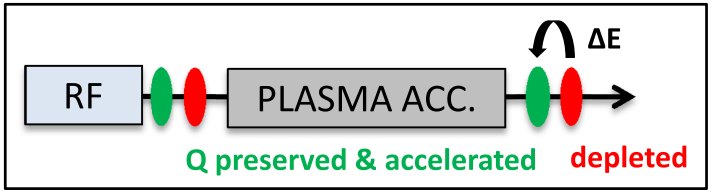
- Simulations and design work at the core of this project
- Goal is start to end simulations, demonstrating required performance including FEL
- Various codes being used

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



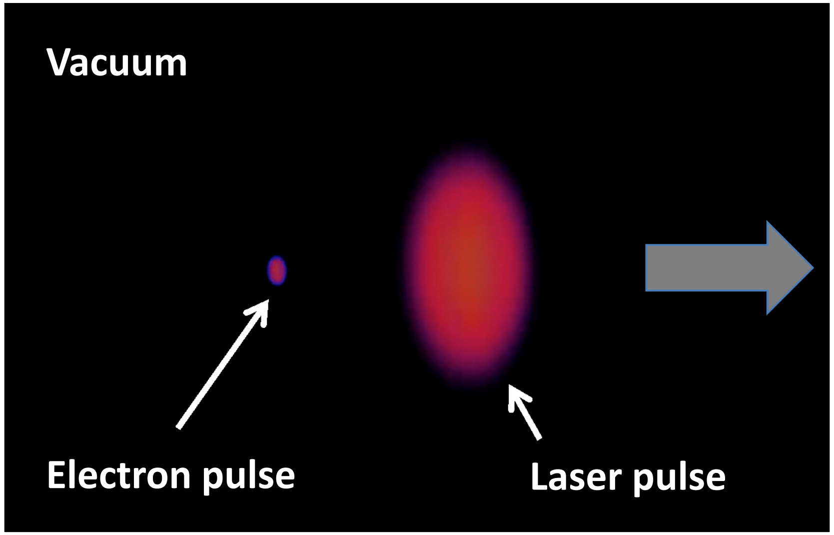
Á. Ferran Pousa, R. Assmann, A. Martinez de la Ossa. IPAC17 paper ***TUPIK007***.



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



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

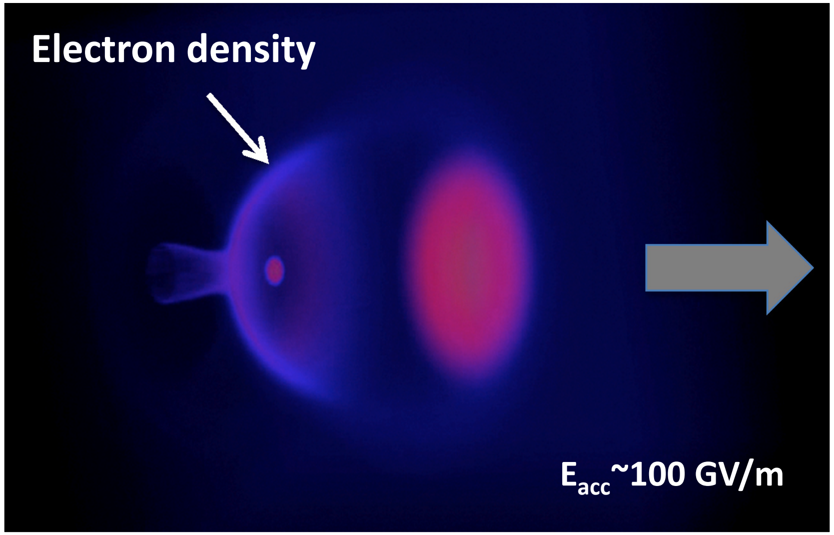
Laser pulse:
a_0 = 3.1, λ = 800 nm, I_{FWHM} = 100 fs,
w_0 = 54 µ m, E = 100 J, 1 PW peak power

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

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



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**

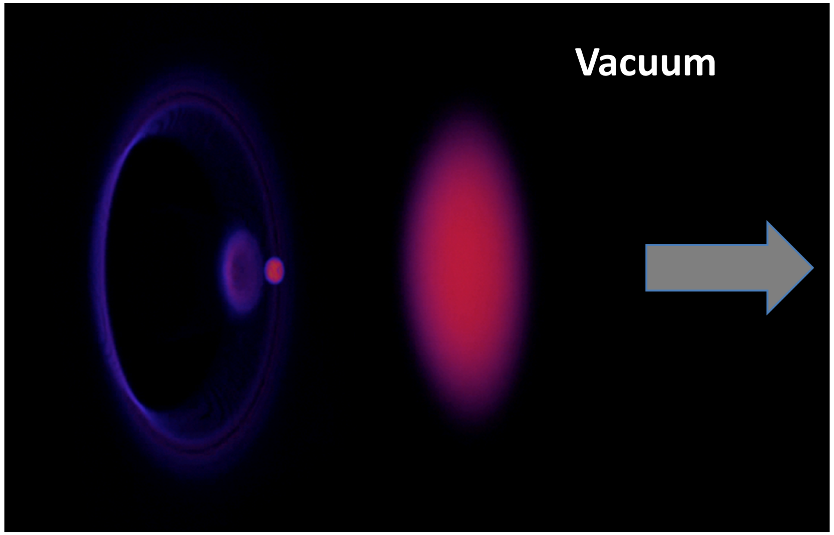
Á. Ferran Pousa, R. Assmann, A. Martinez de la Ossa. IPAC17 paper ***TUPIK007***.

EuPRAXIA simulations

Horizon 2020

- 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



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***.

EuPRAXIA simulations

One example

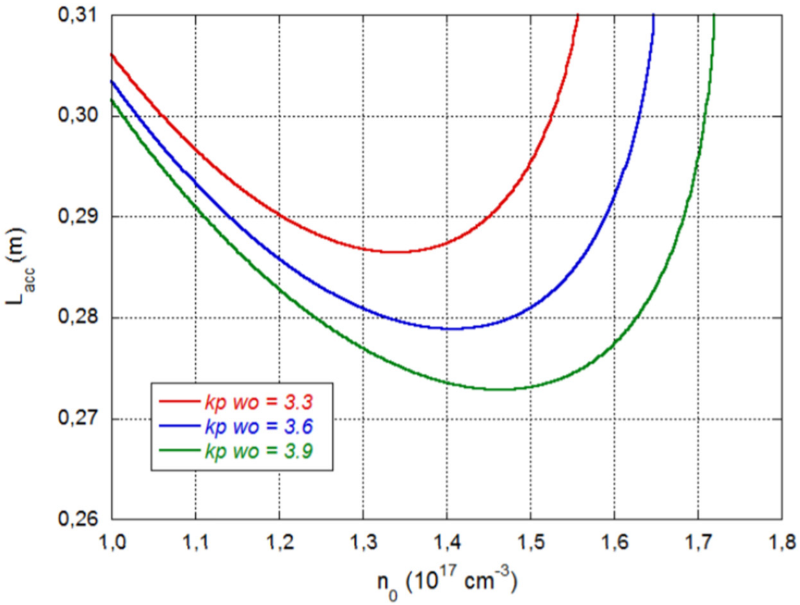
*Á. Ferran Pousa, R. Assmann, A. Martinez de la Ossa. IPAC17 paper **TUPIK007**.*

Studying acceleration to 5 GeV

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

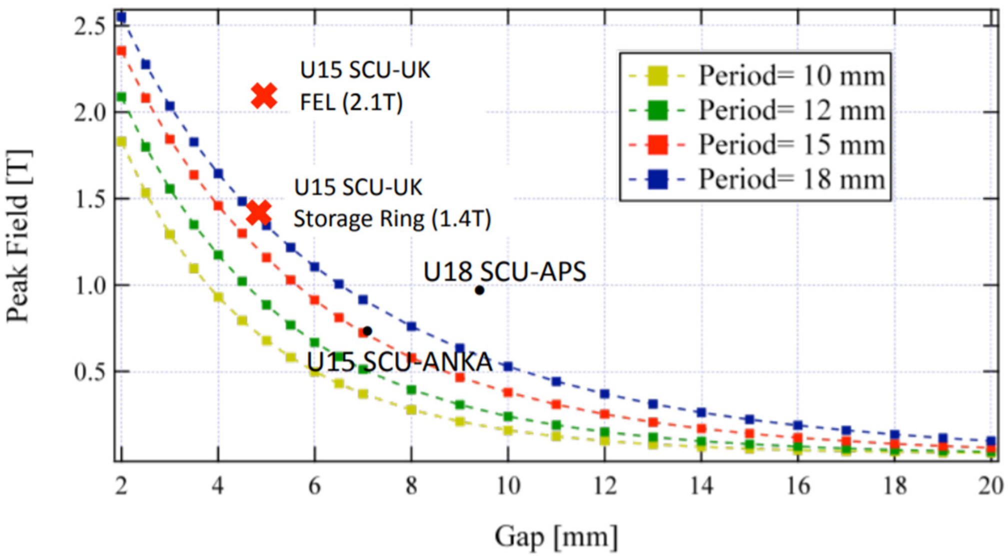
$$\Delta\gamma_b = \frac{2}{\pi} k_p L_{dp} \frac{E_{z,max}(0)}{E_0} \left[\left(1 + \frac{L_{acc}}{L_{pd}}\right) \sin\left(\frac{\pi}{2}\frac{L_{acc}}{L_{dp}}\right) + \frac{2}{\pi}\frac{L_{dp}}{L_{pd}} \left(\cos\left(\frac{\pi}{2}\frac{L_{acc}}{L_{dp}}\right) - 1 \right) \right]$$

- 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

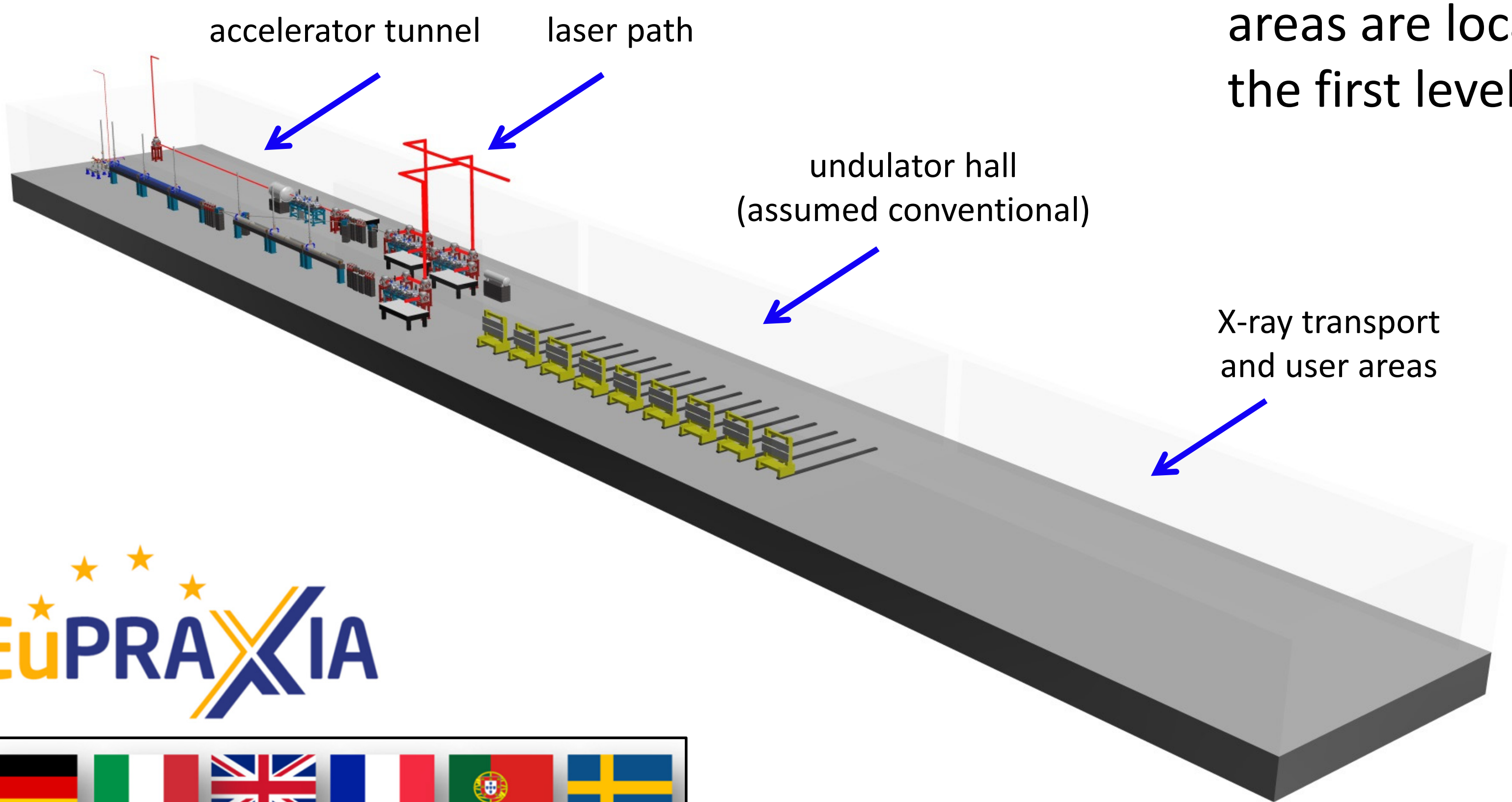
- Review of undulator materials and types in 2016 (update in 2017)
- FEL simulation with 1 GeV beam with 2.7 nm wavelength



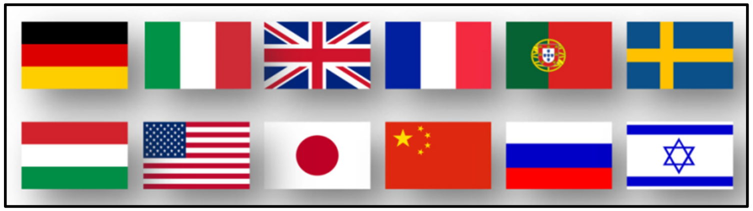
Slice parameters	
beam energy [GeV]	1.2
current intensity [A]	20 000
norm. emittance [mm×mrad]	1.5
energy spread σ_E/E (%)	0.3
Undulator parameters	
undulator period [cm]	1.2
deflection parameter	1.7
Output FEL parameters	
FEL wavelength [nm]	2.66
Twiss β [m]	3.73
Pierce parameter ρ	0.0026
inh. broad.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

Overall layout status (ongoing)



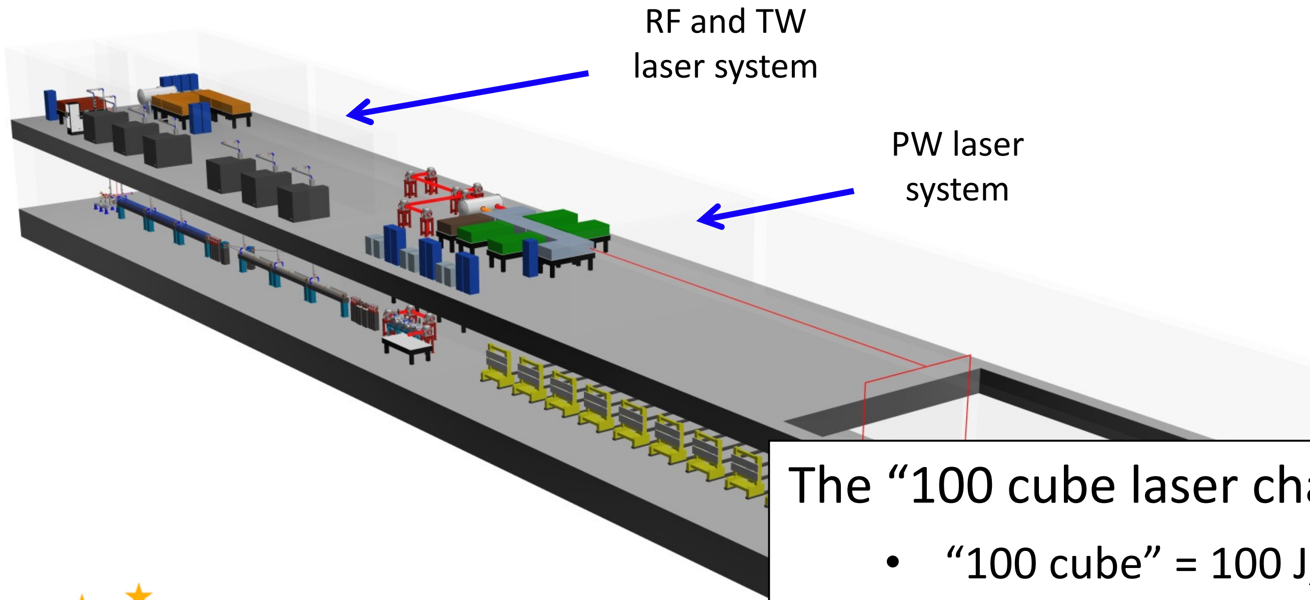
Accelerator research, undulators and user areas are located on the first level



3D design by Dariusz Kocoń (ELI-Beams)

… with 1st floor for laser infrastructure

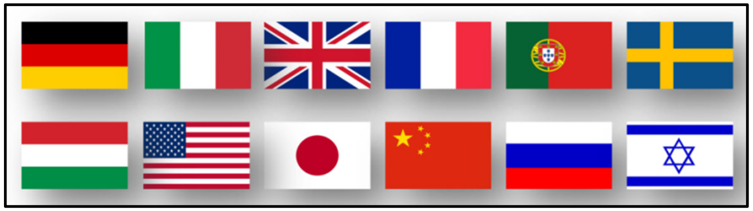
Horizon 2020



RF and laser infrastructure on second level

The "100 cube laser challenge":

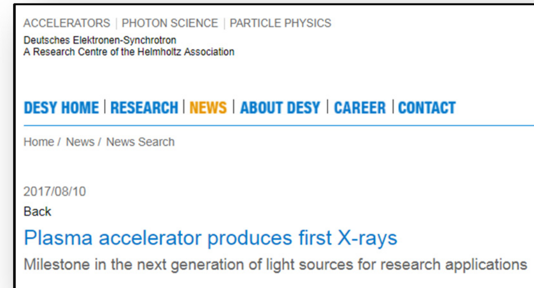
- "100 cube" = 100 J, 100 fs, 100 Hz
  => 1PW @ 100Hz
- Not a complete Ti:Sa laser system
- Diode-pumped solid-state laser scheme
- 2nd laser system (Ti:Sa) operates at lower energy and shorter pulse length



Ongoing experiments and site study

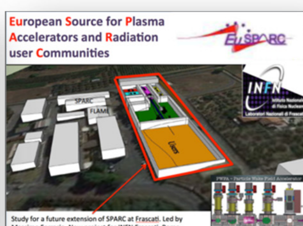
Horizon 2020

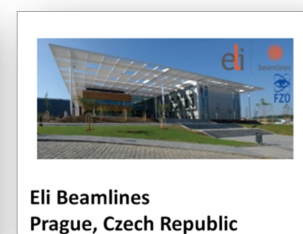
Demo-FEL projects ongoing:
- X-ray produced after undulator in August 2017 at DESY/U.Hamburg by LUX group (A.R.Maier et al.)
- Beamtime in Paris planned for November 2017 (M.E. Couprie & V. Malka et al.)



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





EuPRAXIA next to Copenhagen Hospital

Horizon 2020

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

Conclusion

- 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.

Thank you for your attention

Horizon 2020

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