High Brightness Beam Research at SINBAD

B. Marchetti, R. Assmann, U. Dorda, M. Weikum, J. Zhu (DESY)

Physics and Applications of High Brightness Beams
March 28 - April 1, 2016
Havana, Cuba

HELMHOLTZ | ASSOCIATION

European Network EuroNNAc for Novel Accelerators

erc European Research Council Established by the European Commission

DESY

Outline

- The SINBAD strategy at DESY
- The ARES linac at SINBAD: A Design for High Brightness Sub-Femto Second Bunches
- Plasma Acceleration at SINBAD, ATHENA a German Initiative
- Towards a European Plasma Accelerator EuPRAXIA?
- Summary

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High Gradient Accelerators

High Gradients (1-100 GV/m) → High Frequencies (> 100 GHz) → Small Dimensions (< 1 mm)

- No **klystrons** for high frequencies! → Use particle bunches or laser pulses as drivers.
- Material limitations → dielectric materials, plasma cavities, …

Two main directions:

1 Microstructure Accelerator
Laser- or beam driven
Vacuum accelerators
Conventional field design

2 Plasma Accelerator
Laser- or beam driven
Dynamic Plasma Structure
Plasma field calculations

Intensive research world-wide going on …

> Plasma wake-field acceleration

- Beam driven (e.g. *M. Litos et al. Nature 515 (7525) 262 (2014) 92–95*)
- Laser driven (e.g. *W. P. Leemans, et al., PRL 113 245002 (2014)*)

> Dielectric wake-field acceleration

- Beam driven (e.g. *M. C. Thompson, et al., Phys. Rev. Lett. 100 310 (2008) 214801*)
- Laser driven (e.g. *E. A. Peralta, et al., Nature 503 (2013) 91–94*)

> THz based acceleration on dielectric loaded structures

- Laser driven (e.g. *E. A. Nanni, et al., Nat. 312 Comm. 6 (2015) 8486*)

… Common features

- Novel accelerators operate with **short wavelengths**
- Require **short bunch lengths** for injection to minimize RF curvature effect
- In some cases relativistic beam energies help with the phase velocity matching

- … Very **short**, **relativistic** bunches **not** easily **available**,
- Accelerator R&D needs a dedicated DESY facility with **sufficient space**, therefore

→ SINBAD facility and ARES linac.

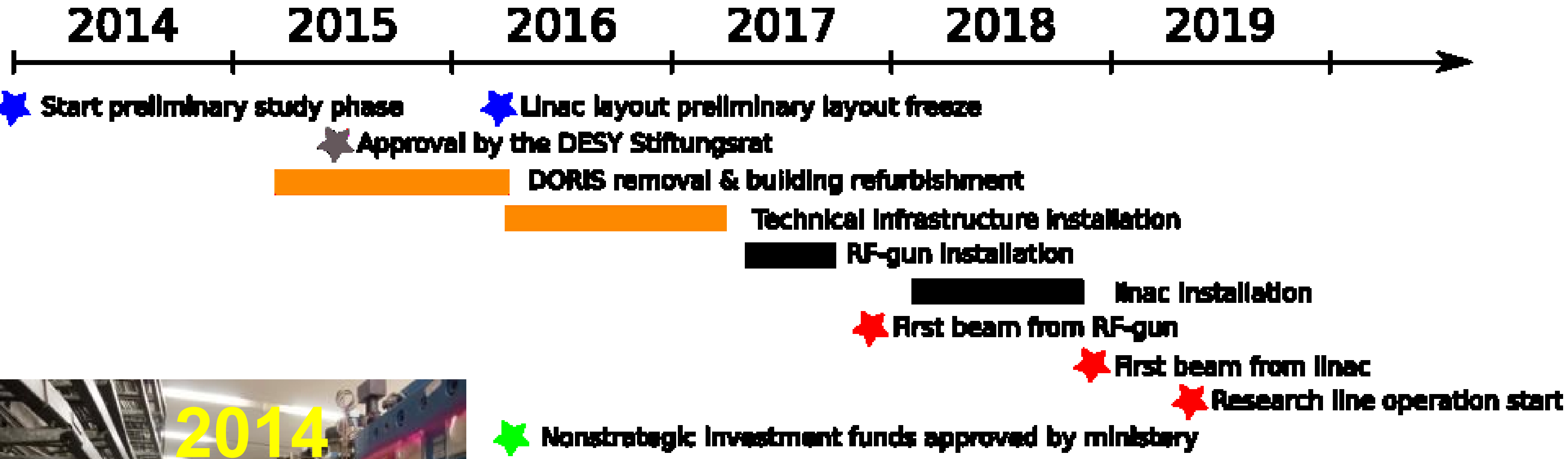
SINBAD at DESY, Hamburg - location

R. Assmann responsible as leading scientist for Accelerator R&D at DESY.

- In the old DORIS facilities
- Next to the central DESY control room

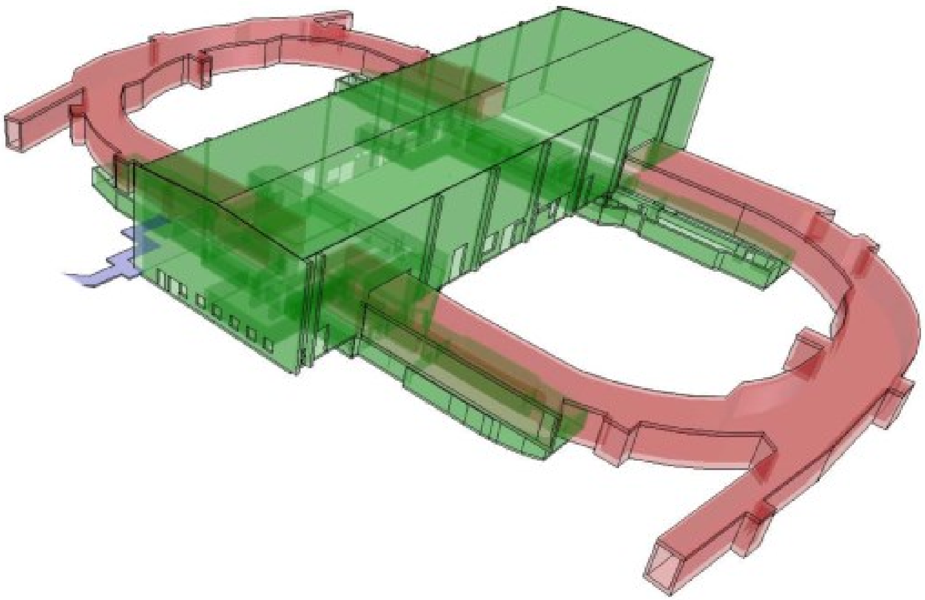
SINBAD
Project Leader:
Ulrich Dorda

SINBAD
(Short and INnovative Bunches and Accelerators at Desy)

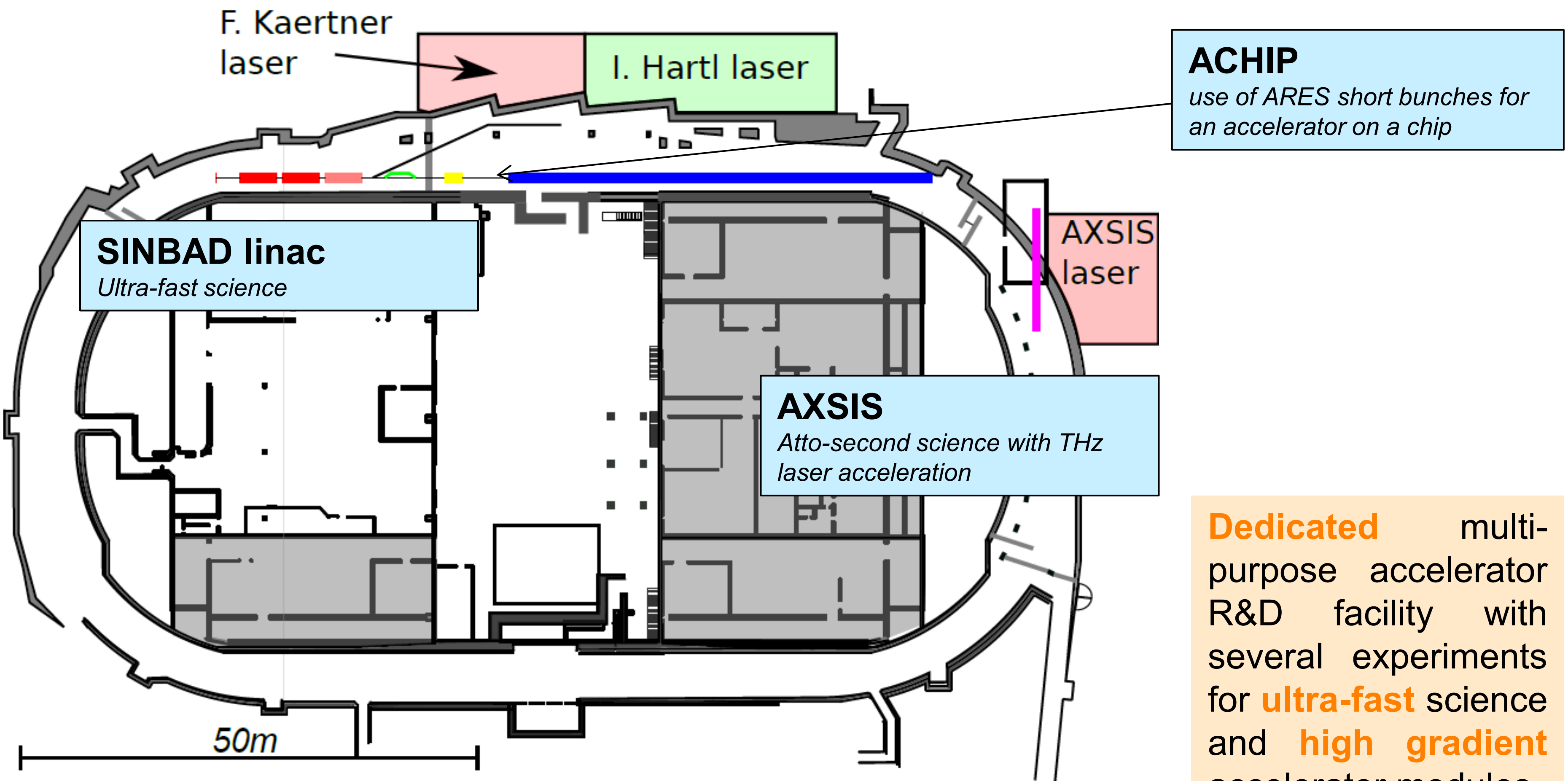


SINBAD – Short INnovative Bunches and Accelerators at Desy

- 290 m long, 5-9m wide RP-shielded tunnel in racetrack shape
  - 2 long straight sections of >70m length
- Central hall (650m^2) + additional side rooms & cellars
- 1m thick shielding
- Multiple laser labs directly adjacent

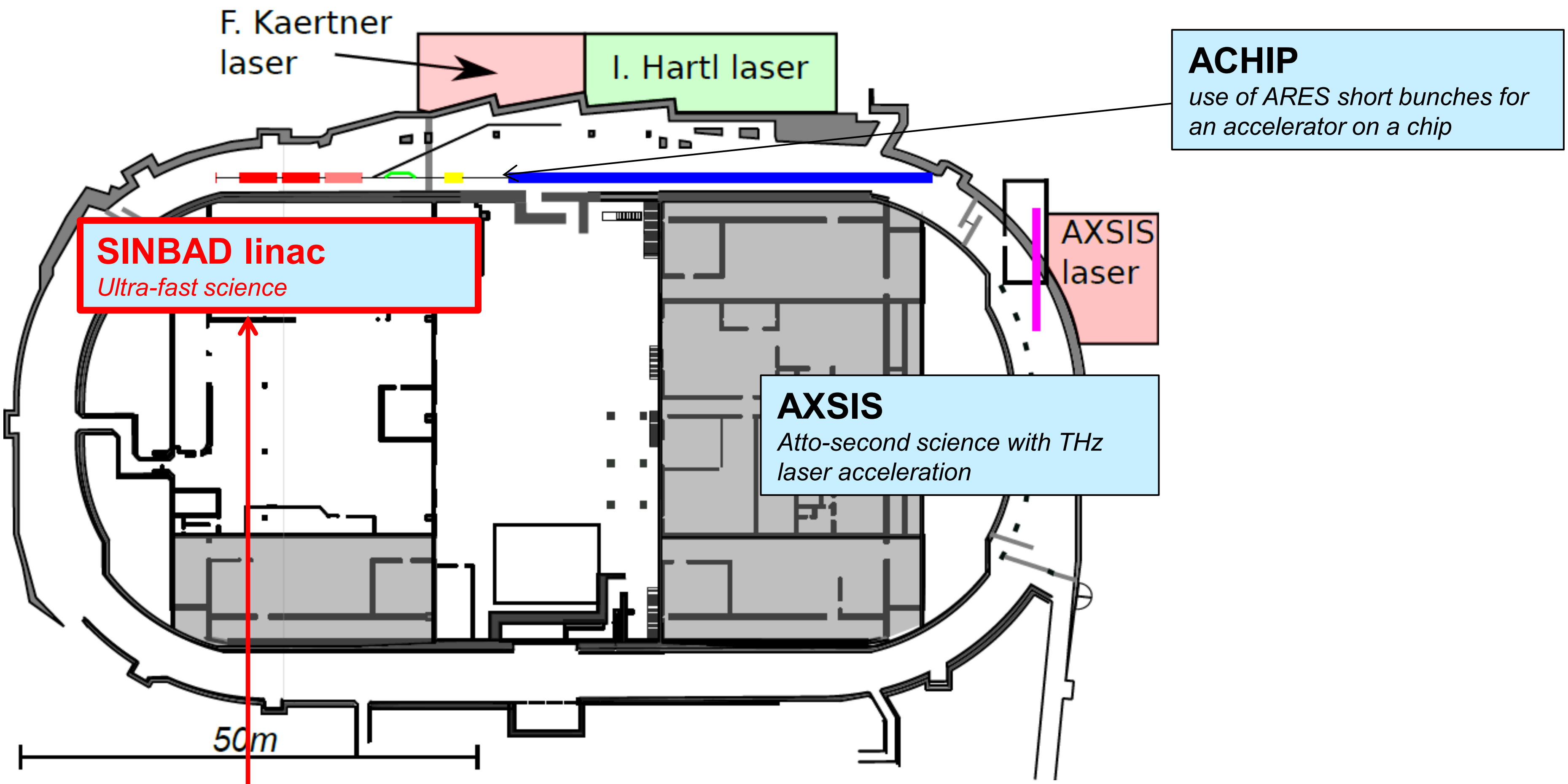


Science at SINBAD



Dedicated multi-purpose accelerator R&D facility with several experiments for **ultra-fast** science and **high gradient** accelerator modules.

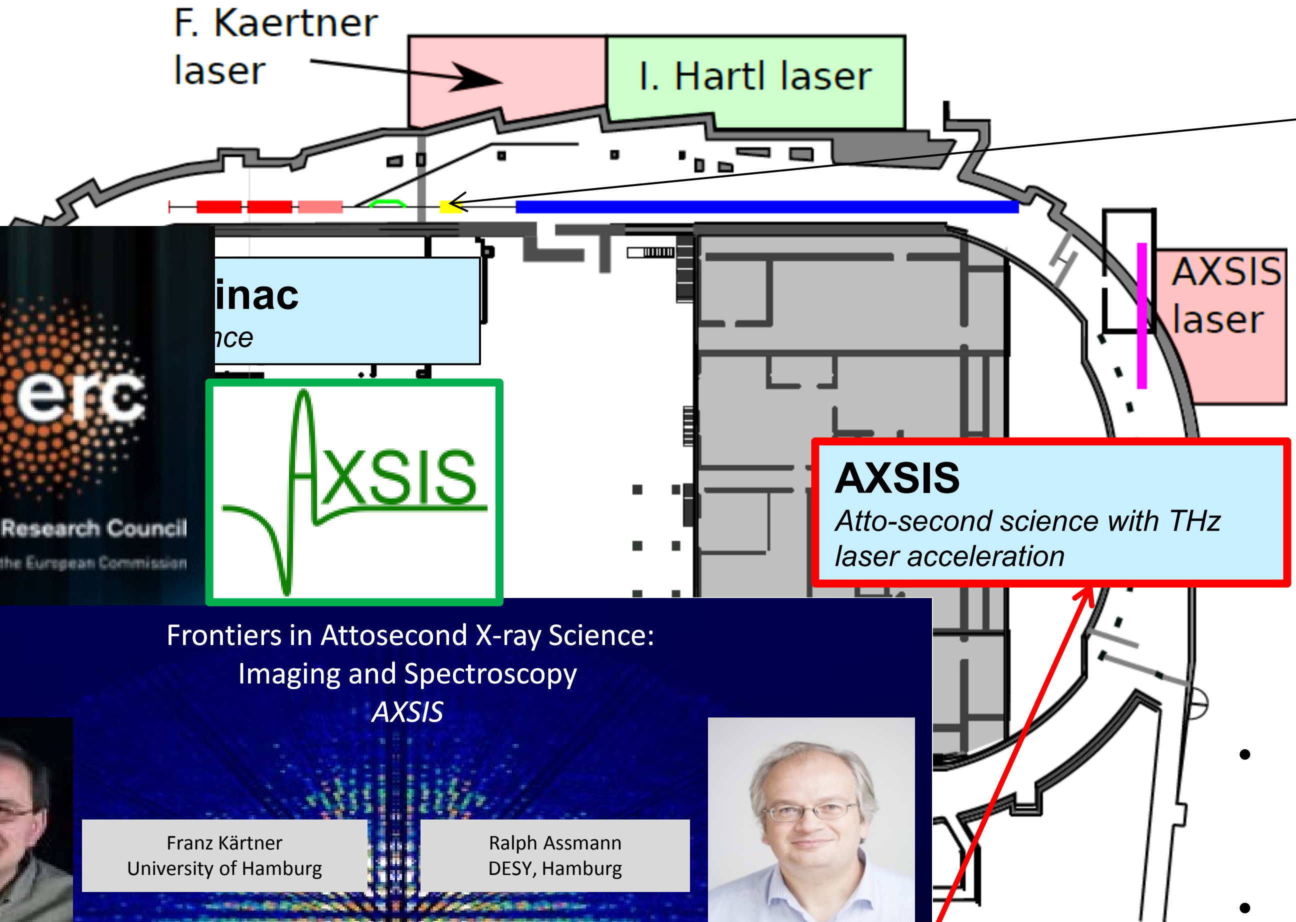
Science at SINBAD

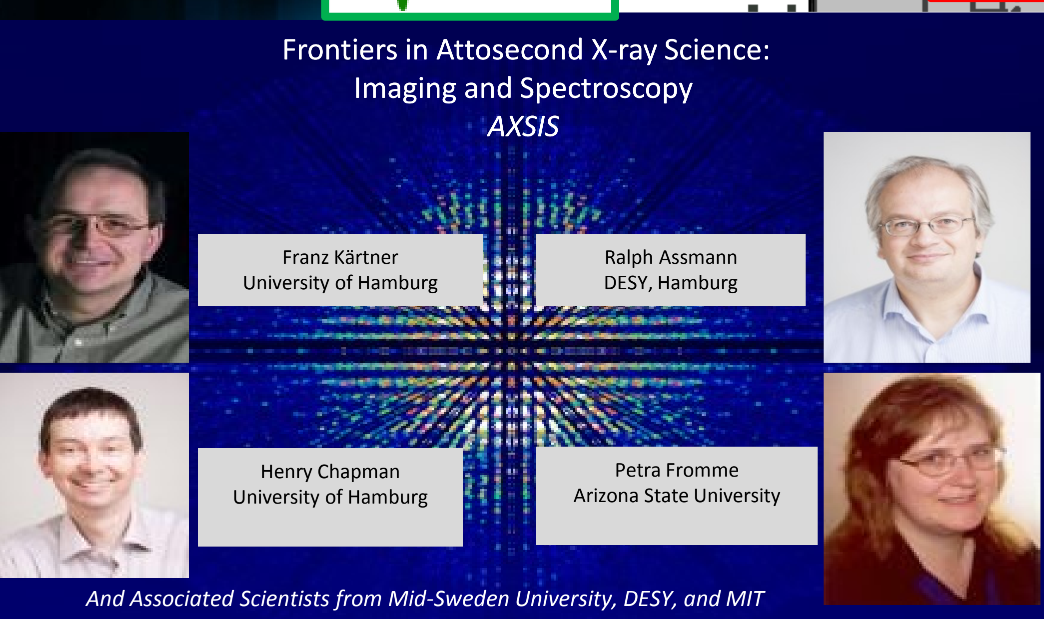


Production of ultra-short bunches with conventional RF technology

PI ARES linac at SINBAD: B. Marchetti

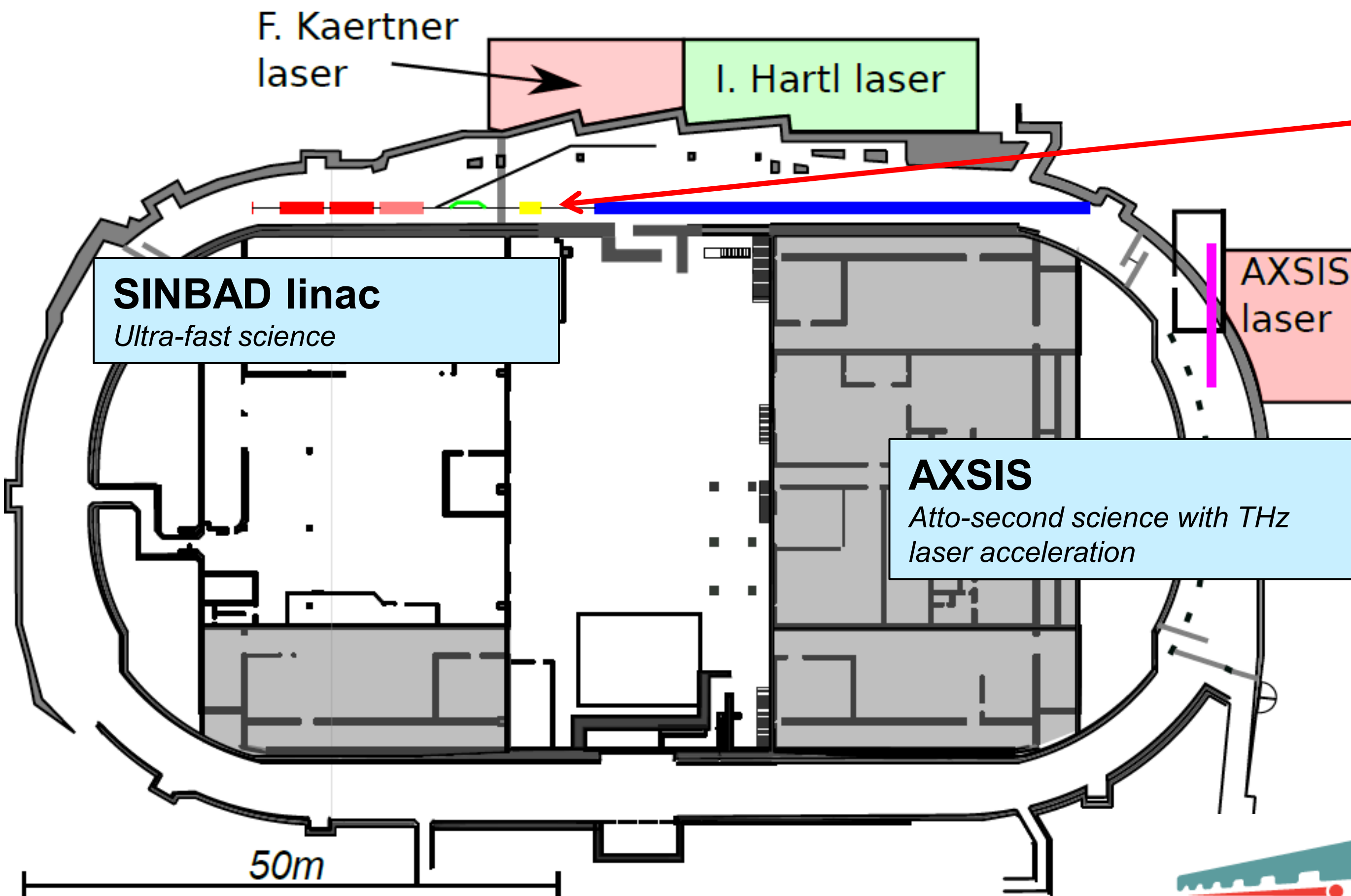
Science at SINBAD



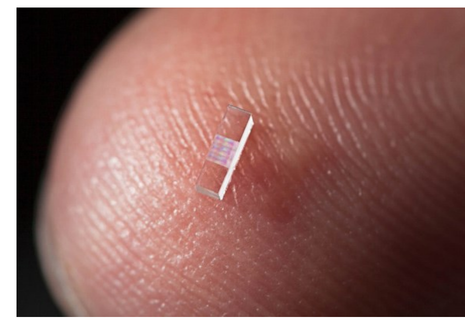


- Realization of a compact THz laser based accelerator
- Development of a coherent atto-second X-ray source based on ICS.

Science at SINBAD



ACHIP
use of ARES short bunches for an accelerator on a chip



Accelerator on a Chip International Program

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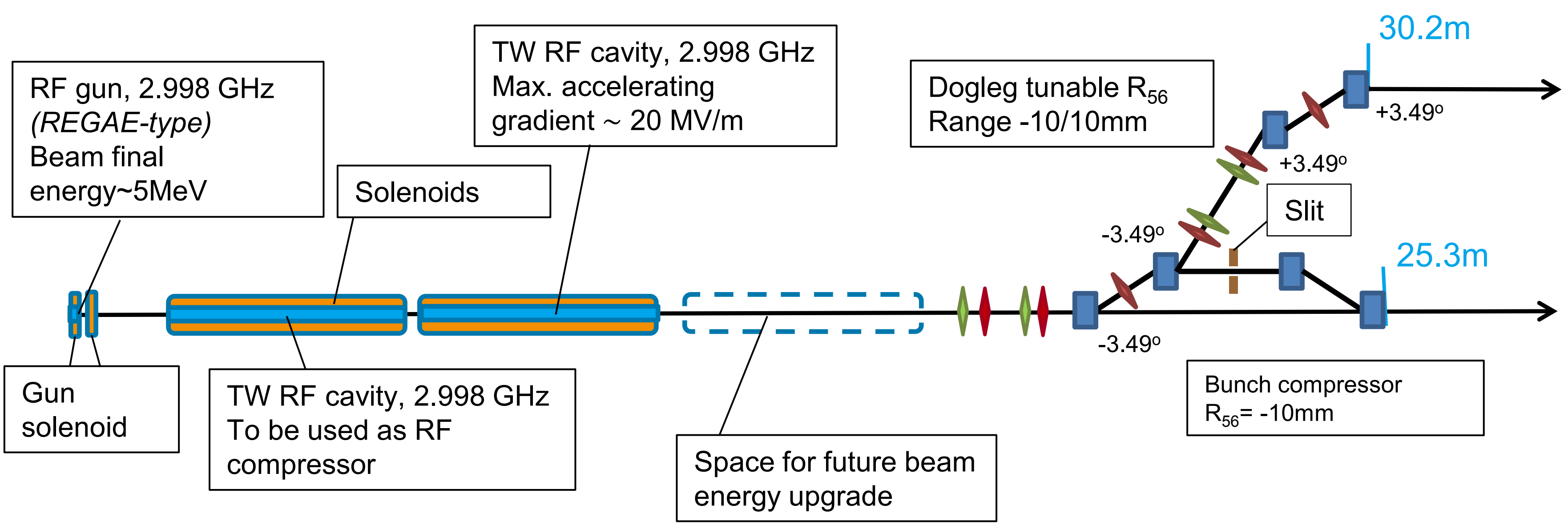
ARES (Accelerator Research Experiment at Sinbad)

- **Conventional linac (S-band norm. cond.) for the production of ultra-short bunches:**

→ Charge: 0.5-20 pC (up to 1nC)
→ Energy ~ 100 MeV
→ **Bunch length: few fs / sub-fs**
→ Transverse norm. emittance < 0.5 mm*mrad
→ **Arrival Time jitter stability < 10 fs RMS**

GOALS



LAYOUT

DESY

Bunch compression

> Three techniques studied and possible to implement:

- Velocity Bunching (VB)
  - *L. Serafini and M. Ferrario, AIP Conf. Proc. 581, 87-106 (2001).*
  - *S.G. Anderson et al. PRSTAB 8 014401 (2005).*
  - *M. Ferrario et al. PRL 104 054801 (2010).*
  - *A. Bacci, A.R.Rossi NIM A 740 (2014) 42-47.*
- Magnetic Compression with slit (MC)
  - *M. Borland, Proceed. PAC'01, (2001).*
  - *P. Emma et al., PRL 92 7 (2004).*
  - *S. Di Mitri et al., PRSTAB 16, 042801 (2013).*
- Hybrid combination of VB and MC:
  - In the chicane (fixed R_{56}= -10 mm)
  - In the dogleg (variable -10mm< R_{56} <+10mm) → not covered by this talk.

Reference: *B. Marchetti et al.* doi:10.1016/j.nima.2016.03.041

> Start to End Similations run by using different codes (ASTRA, Elegant, CSRtrack, IMPACT-T)

> Each technique has its advantages and disadvantages

Bunch compression

> Three techniques studied and possible to implement:

- Ve
- Ma
- Hy

> Start
(AST

More **details** about the **beam dynamics studies** can be found in:

B. Marchetti at al. *doi:10.1016/j.nima.2016.03.041*

The **magnetic compression** at ARES was studied by **Jun Zhu** – PhD student working in our team:

J. Zhu, R. Assmann, M. Dohlus, U. Dorda, B. Marchetti, „Sub-fs electron bunch generation with sub-10-fs bunch arrival-time jitter via bunch slicing in a magnetic chicane“, submitted to PRAB.

P Conf. Proc. 581, 87-106

8 014401 (2005).
801 (2010).
) (2014) 42-47.

(2001).
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> Each technique has its advantages and disadvantages

Working points for the main beamline

	VB (Velocity Bunching)	MC (Magnetic Compression)	VB+MC
Q final [pC]	0.5	0.7	2.7
Q initial [pC]	0.5	20	10
t_{RMS} [fs]	2.486	0.21 (0.27)	0.66 (0.87)
t_{FWHM} [fs]	4.1	0.14 (0.29)	1.53 (1.42)
E [MeV]	110.9	100.2 (100.2)	101.6 (101.8)
ΔE/E	0.3%	0.20% (0.18%)	0.18% (0.16%)
x_{RMS} [mm]	0.009	0.058 (0.057)	0.084 (0.083)
y_{RMS} [mm]	0.009	0.059 (0.058)	0.092 (0.088)
$n\varepsilon_x$ [µm]	0.054	0.068 (0.072)	0.19 (0.21)
$n\varepsilon_y$ [µm]	0.054	0.063 (0.065)	0.16 (0.15)
Peak current I [A]*	57	953 (759)	1173 (879)
Local peak current I_L [A]**	85	2390 (1487)	1432 (1358)
B [A/m^2]***	1.97 * 10^{16}	2.13 (1.63) * 10^{17}	3.74 (2.71) * 10^{16}

*Peak current:

$$I = \frac{Q_{tot}}{3.5 t_{RMS}}$$

**Local peak current:

$$I_L = \frac{Q_{tot}}{t_{FWHM}}$$

*** Brightness:

$$B = \frac{I}{n\varepsilon_x n\varepsilon_y}$$

Tolerances (start to end simulation)

Jitter source	Unit	Sensitivity for 10-fs timing jitter			RMS tolerance		
		0.7 pC MC	2.7 pC VB+MC	0.5 pC VB	0.7 pC MC	2.7 pC VB+MC	0.5 pC VB
Laser-to-RF	fs	42437.1	159.8	125.1	200.0	50.0	50.0
Gun charge	%	5.8	301.6	1010.1	1.0	4.0	4.0
Gun phase	deg	1.75	0.61	0.49	0.06	0.06	0.06
Gun voltage	%	0.61	0.72	0.40	0.06	0.06	0.06
TWS1 phase	deg	**0.021**	**0.011**	**0.0098**	0.013	0.009	0.009
TWS2 phase	deg	**0.022**	0.13	4.21	0.013	0.011	0.011
TWS1 voltage	%	0.055	0.073	0.10	0.013	0.009	0.009
TWS2 voltage	%	0.064	0.040	1.2	0.013	0.011	0.011
BC B-field	%	0.030	0.030	\	0.01	0.01	0.01
σ_{t_b}	fs	\	\	\	9.98	9.72	10.24

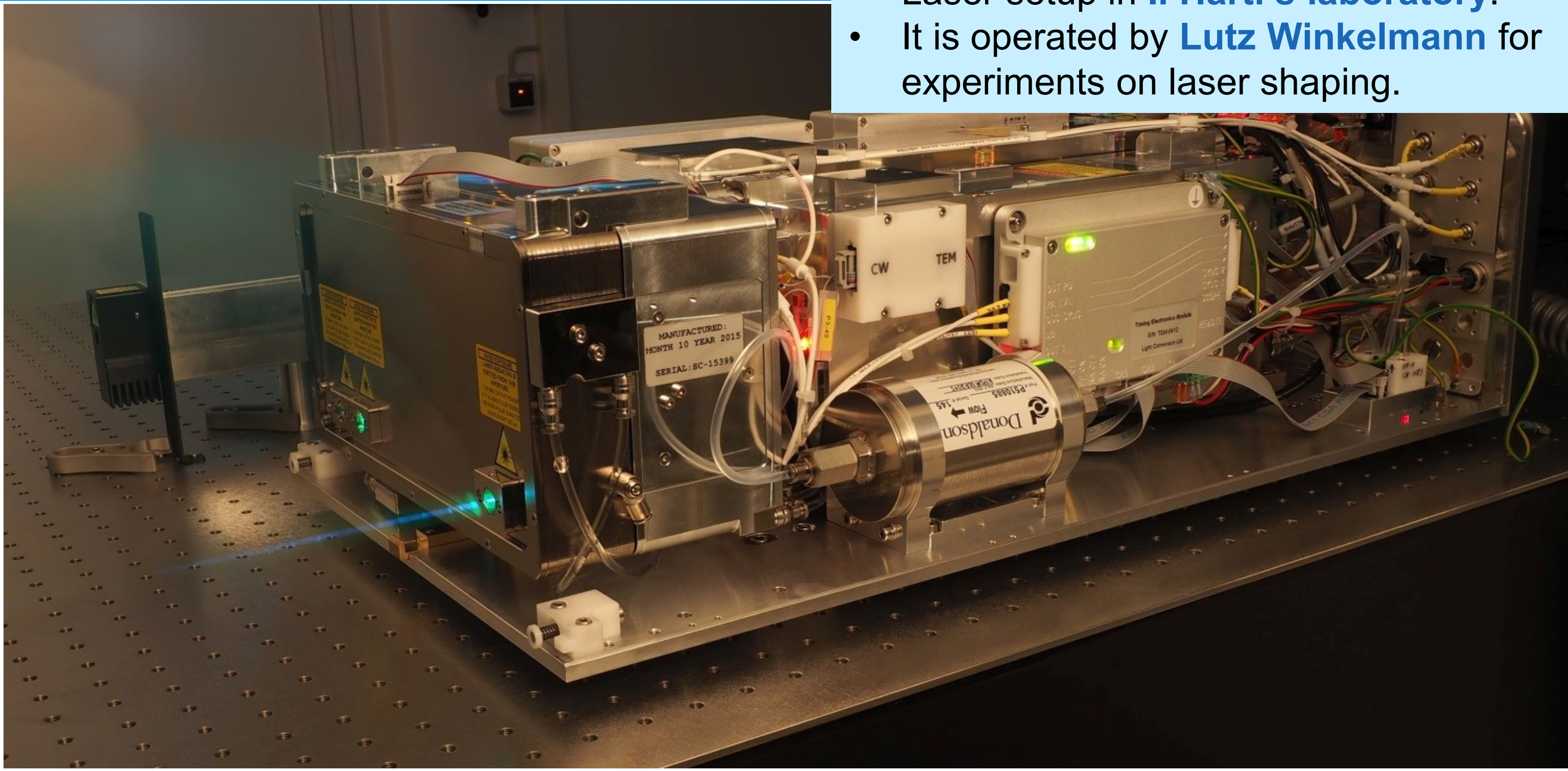
Status of ARES

- Start to end simulations show feasibility of target parameters
- Procurement and construction ongoing
- **Unique combination of low charge and high energy:**
  - Challenges in low charge beam diagnostics
  - Challenges in fs level synchronization
  - **→ We rely strongly on the experience of the techical groups at DESY gained for REGAE, European XFEL, etc…**

- No time to present the detailed design work here
- Instead focus on a couple highlights

ARES Photo-Cathode laser at DESY

- Laser setup in **I. Hartl's laboratory**.
- It is operated by **Lutz Winkelmann** for experiments on laser shaping.



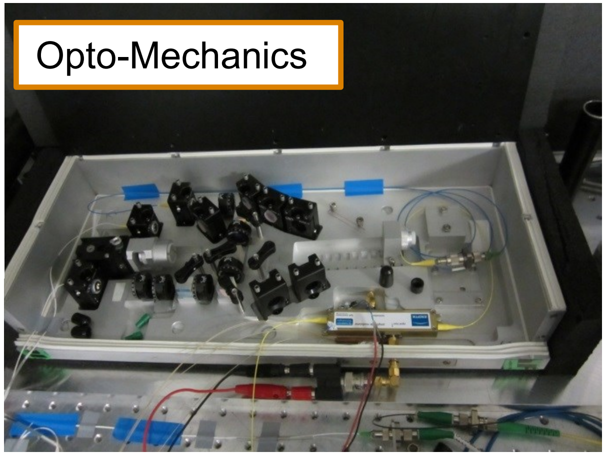
- Yb doped laser
- Pulse energy ≥1mJ
- Central wavelength 1030 nm (4th harmonic 257 nm)
- Pulse length tunable range 180fs-10ps

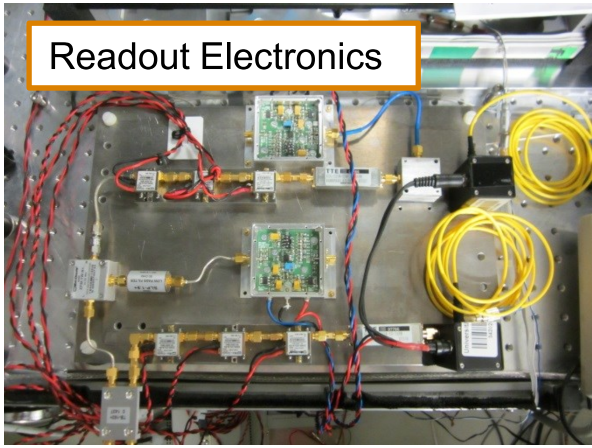
PHAROS-SP-200-1.0
Topag Lasertechnik GmbH

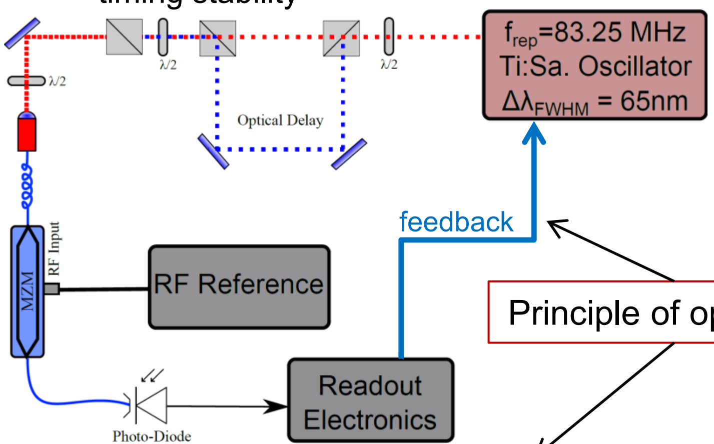
Drift Free Laser-to-RF Synchronization

(thanks to Holger Schlarb and his group)

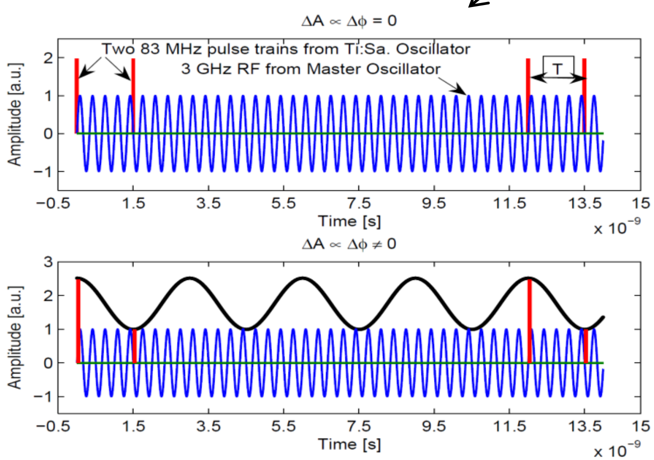
- Main Idea
  - Convert relative phase error to amplitude mismatch of laser pulses.
  - Mitigate AM-PM effects & ensure long term timing stability



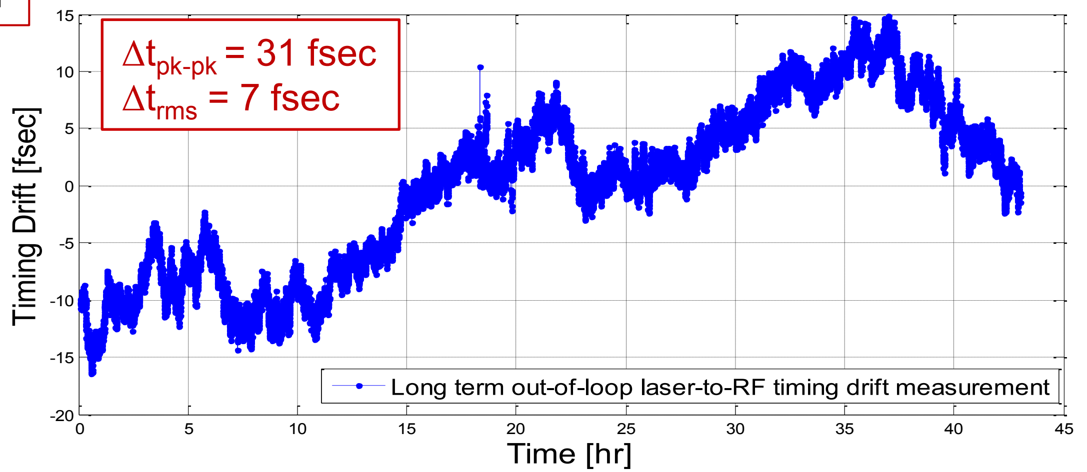




Principle of operation



Long term ~ 45 hours, out-of-loop timing drift measurement at REGAE photo-injector Laser Oscillator



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LAOLA Collaboration Hamburg

Laser: Ti:Sa 200 TW, 25 fs pulse length, 5 Hz repetition rate

- *Initially: Laser-driven wakefields in REGAE. LUX exp. towards FEL*
- *Later: Move to SINBAD facility.*

F. Grüner

A. Maier

Beams:

- **REGAE**: *5 MeV, fC, 7 fs bunch length, 50 Hz*

- **FLASH**: *1.25 GeV, 20 – 500 pC, 20 - 200 fs bunch length, 10 Hz. Beam-driven plasma wakefields. Beam-driven plasma wakefields with shaped beams and innovative injection methods. Helmholtz VI with UK collaboration.*

FLASHForward▸▸

J. Osterhoff

- **PITZ**: *25 MeV, 100 pC, 20 ps bunch length, 10 Hz. Beam modulation experiment in a plasma cell, preparation to CERN experiment AWAKE*

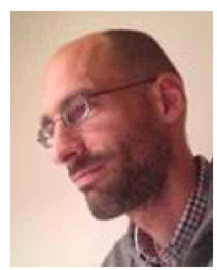
F. Stephan

- **SINBAD**: dedicated R&D, multi purpose, *150 MeV, 0.01 – 3 pC, down to < 1 fs bunch length, pulse rate 10 – 1000 Hz*

  → Home of AXSIS ERC Synergy Grant

  → Home of ATHENA$_e$

R. Aßmann



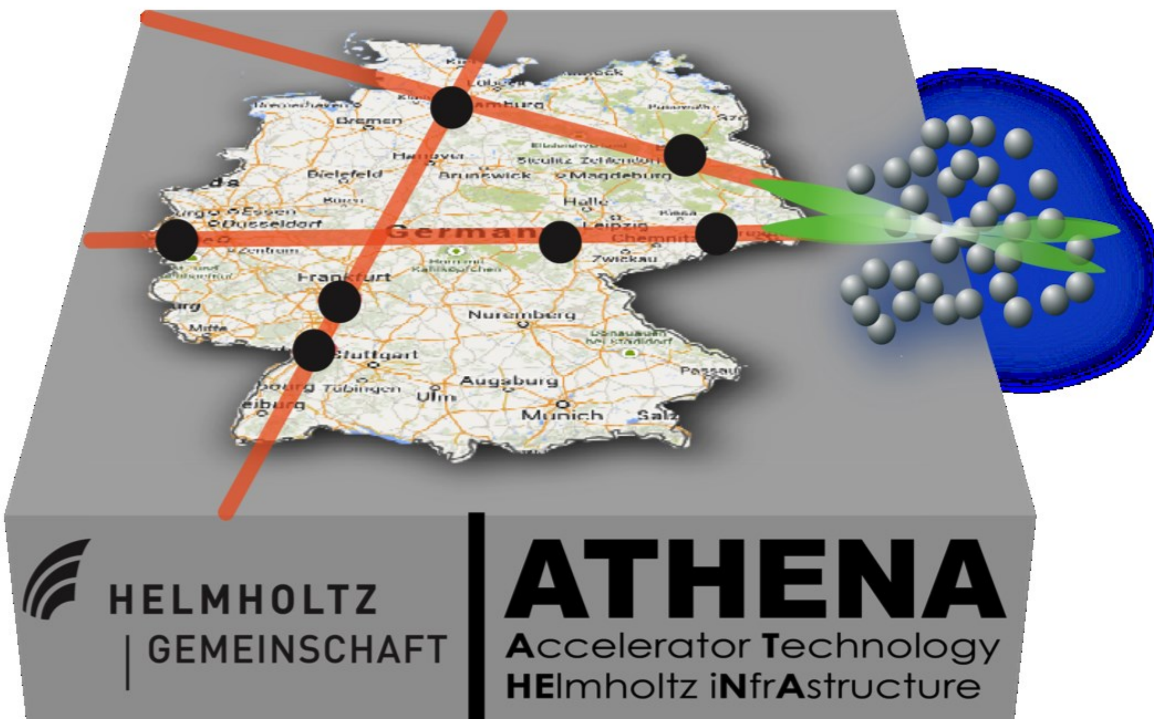
U. Dorda

B. Marchetti

ATHENA – A Helmholtz Project for Germany

Development of ultra-compact* plasma accelerators and radiation facilities for science and medicine

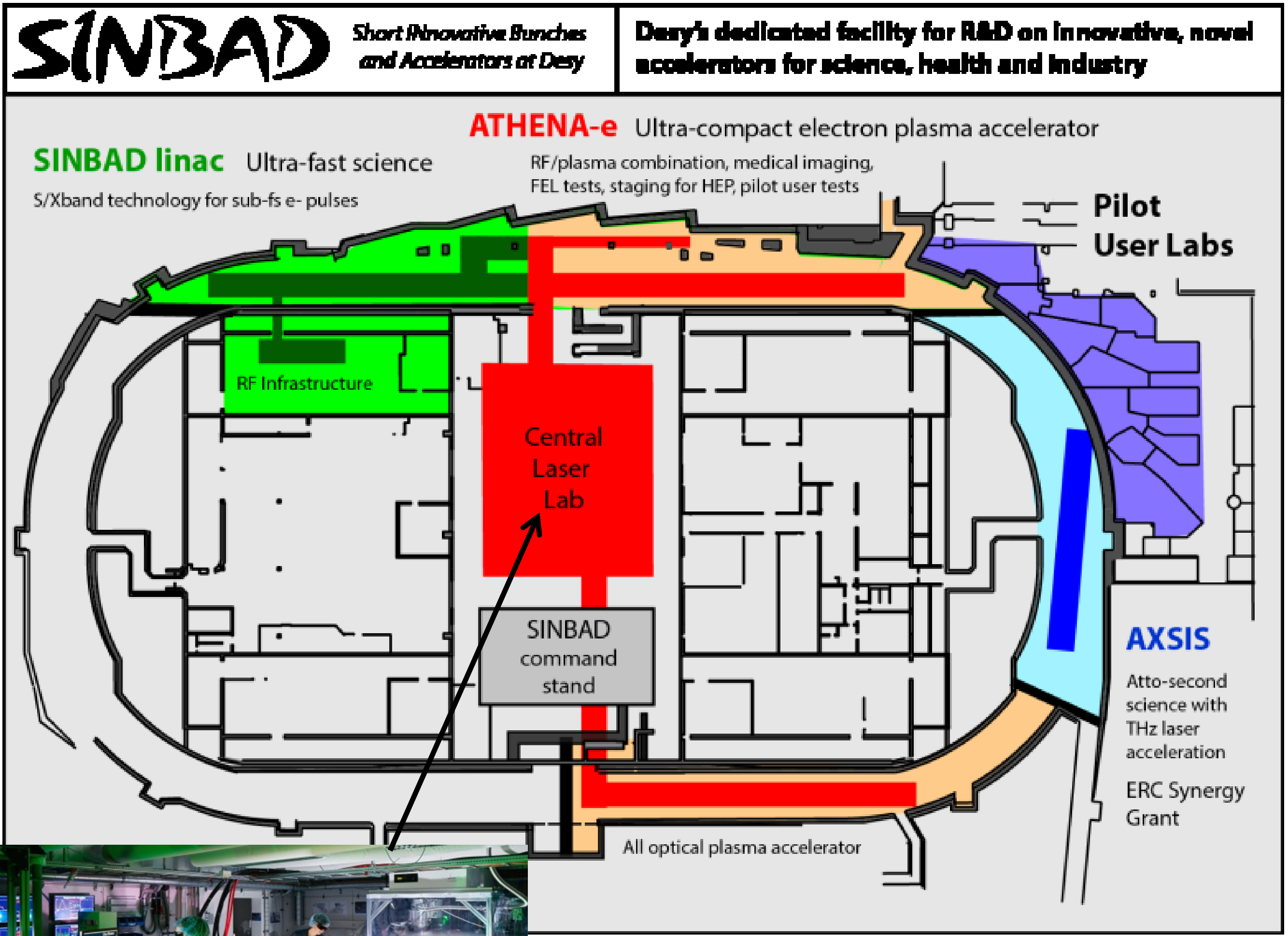
***and highly cost-efficient*

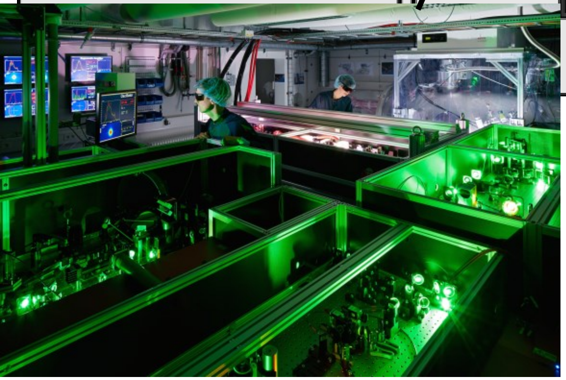


- Submitted a 30M euros proposal for Helmholtz Strategic Investment founding
- 7 institutes in Germany involved
- Reviewed with result OUTSTANDING by external review that Helmholtz conducted on this proposal

Waiting for official decision for funding approval (2016 or later?)

SINBAD as host to ATHENA$_e$





DESY-M University HH Laser Lab Angus
Currently operated by A. Maier's group

- One of the 2 **flag-ship projects**
- Substantial **extension** of the **SINBAD-ARES linac**
- Direct **comparison** of performances of **conventional acceleration** vs **PWFA** (internal + external injection). Both driven by lasers (baseline) and e-beams.
- Pilot user experiments involving **plasma based FEL**

Plasma acceleration with external injection at SINBAD

- Work at low plasma density (10^{16}-10^{17}cm^{-3})
  - Accelerating gradient: $E_0(V/m) \cong 96\sqrt{n_0(cm^{-3})}$
  - Plasma wavelength: $\lambda_p \sim \frac{1}{\sqrt{n_0}}$
  - Acceleration length (depends on diffraction and dephasing): $L \sim \frac{1}{\sqrt{n_0{}^3}}$

Plasma density [cm^{-3}]	Wavelength	Period	Skindepth
10^{19}	10.6 μm	35.3 fs	1.68 μm
10^{18}	33.4 μm	101.3 fs	5.31 μm
10^{17}	106 μm	353.3 fs	16.8 μm
10^{16}	334 μm	1.0 ps	53.1 μm
10^{15}	1.06 mm	3.53 ps	0.168 mm
10^{14}	3.34 mm	10.0 ps	0.531 mm

- ARES = 100MeV → less de-phasing issue at the injection

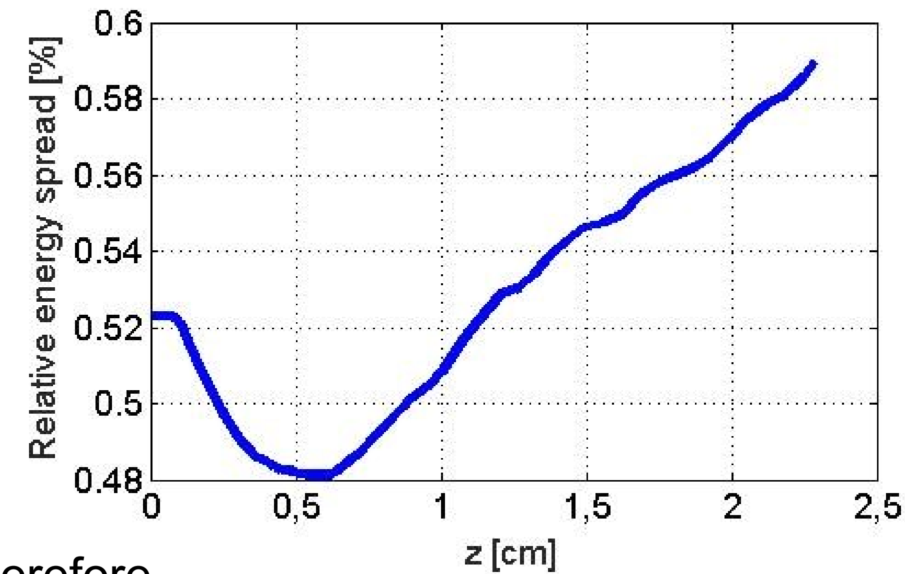
Start to end simulation using the ARES beam

Simulations by Maria Weikum

Almost hard-edge plasma model + laser guiding

n=4.25*10^{16} cm^{-3}

Solution for doubling the energy of the e-beam while keeping the energy spread less than 0.6%



- Final energy :190 MeV
- β_{CS} at the entrance ~2 cm, therefore the transverse emittance increases up to 1.2 um
- Beam transverse matching can be reached by tailoring the plasma density profile → *Cfr: I. Dornmair et al. PRSTAB 18, 041302 (2015).*

ATHENAe final goal ext. Inj.: 1 GeV e-beam for FEL

Study:
J. Grebenyuk

Plasma density [cm^{-3}]	10^{18}	10^{17}	10^{16}	0.5×10^{16}
Skindepth, k_p^{-1} [μm]	5.31	16.8	53.1	75.2
Plasma wavelength, λ_p [μm]	33.4	106	334	472
Injection beam energy [MeV]	100	100	100	100
Laser pulse duration [fs]	25	25	25	25
Field gradient (OSIRIS) [GV/m]	62	7.58	0.46	0.21
Accelerating region, $\lambda_p/4$ [μm]	8.35	26.5	83.5	118
200 MeV stage length [m]	1.6×10^{-3}	13.2×10^{-3}	0.22	0.48
1 GeV stage length [m]	16×10^{-3}	0.13	2.2	4.8
Matched β [mm]	0.1	0.3	1	1.5

Preliminary studies for a working point for **FEL radiation generation in soft X-rays** has been done by **A. Maier** in the context of the **ATHENA proposal**.

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EU Design Study → DESY/Helmholtz ARD Coordinated

http://www.eupraxia-project.eu

EuPRAXIA as EU Design Study:

> **2nd accelerator design study financed by EU in Horizon2020** after the FCC/EuroCirCol led by CERN.

Goal: produce a **conceptual design report** for the world-wide first high energy plasma-based accelerator that can provide industrial beam quality and user areas.

Fully funded design study

European Network EuroNNAc for Novel Accelerators

DESY

EuPRAXIA Consortium

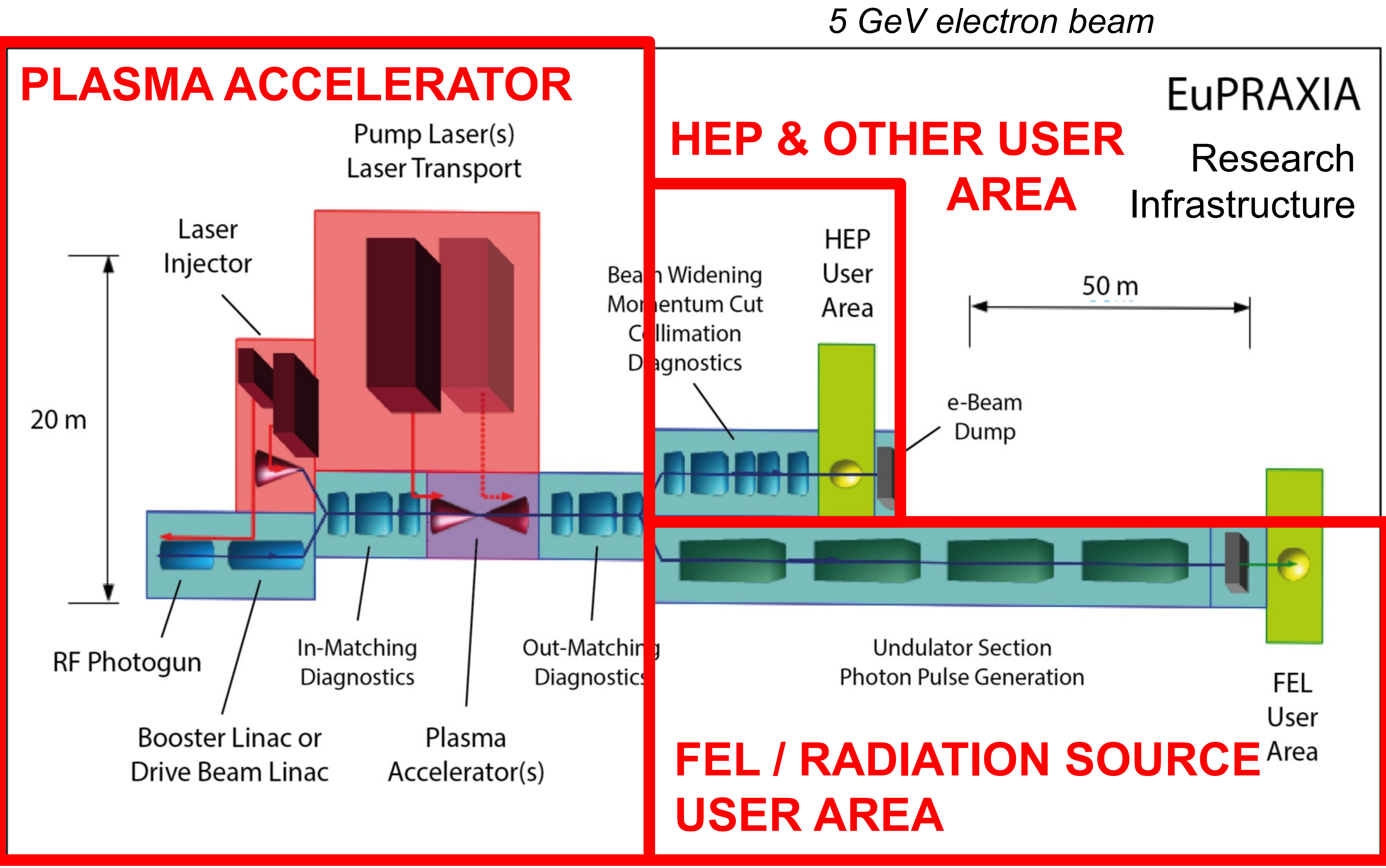
DESY
INFN
Consiglio Nazionale delle Ricerche
cnrs
University of Strathclyde Glasgow
cea
SAPIENZA UNIVERSITÀ DI ROMA
SOLEIL SYNCHROTRON
UNIVERSITY OF LIVERPOOL
IST-ID Associação do Instituto Superior Técnico para a Investigação e Desenvolvimento
Imperial College London
UNIVERSITY OF OXFORD
ENEA Italian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

plus 18 associated partner institutes

Kick-off meeting at DESY on Nov 26th – 27th

DESY

EuPRAXIA Research Infrastructure for the 2020's



Outline

- Introduction: Why Short Bunches and the SINBAD Facility?
- The ARES linac: A Design for Sub-Femto Second Bunches
- Plasma Acceleration with the ARES linac
- Future perspectives: EuPRAXIA
- **Summary**

Summary

- SINBAD will be one of the **biggest world-wide accelerator R&D facilities**.
- It will host several experiments for **ultra-fast** science and **high gradient** accelerator modules.
- The **SINBAD-linac (ARES)** will allow the production of fully relativistic **ultra-short high brightness e-bunches**, with **excellent arrival time stability**, that can be injected into novel accelerators.
- Experiments/research activity involving the use of the ARES's beam are already planned (**Laser Plasma Wake-field Acceleration, THz driven acceleration in dielectric loaded structures, dielectric wake-fields acceleration**…) and they attracted third party funding.
- DESY is also **strongly embedded** in the **European environment.**

Acknowledgments

- SINBAD is built on the support of **all involved DESY groups**! (MEA, MSK, MIN, MDI, FS-LA, MKK, MCS, MVS, MPS, D3, D5, IT, BAU …)
- A special thank you goes to the **colleagues in the MPY and ARD collaborating with the SINBAD project**.
- I would like to thank the colleagues part of the **LAOLA collaboration** and the **AXSIS team**!
- In particular I would like to thank: **R. Assmann, U. Dorda, J. Zhu**, R. Brinkmann, J. Grebenyuk, M. Weikum, M. Hachmann, Y. Nie, F. Mayet, M. Huening, H. Schlarb, I. Hartl,, K. Floettmann, L. Winkelmann, F. Kaertner , A. Maier… and MANY others!

European Network EuroNNAc for Novel Accelerators

erc European Research Council Established by the European Commission

DESY

Backup

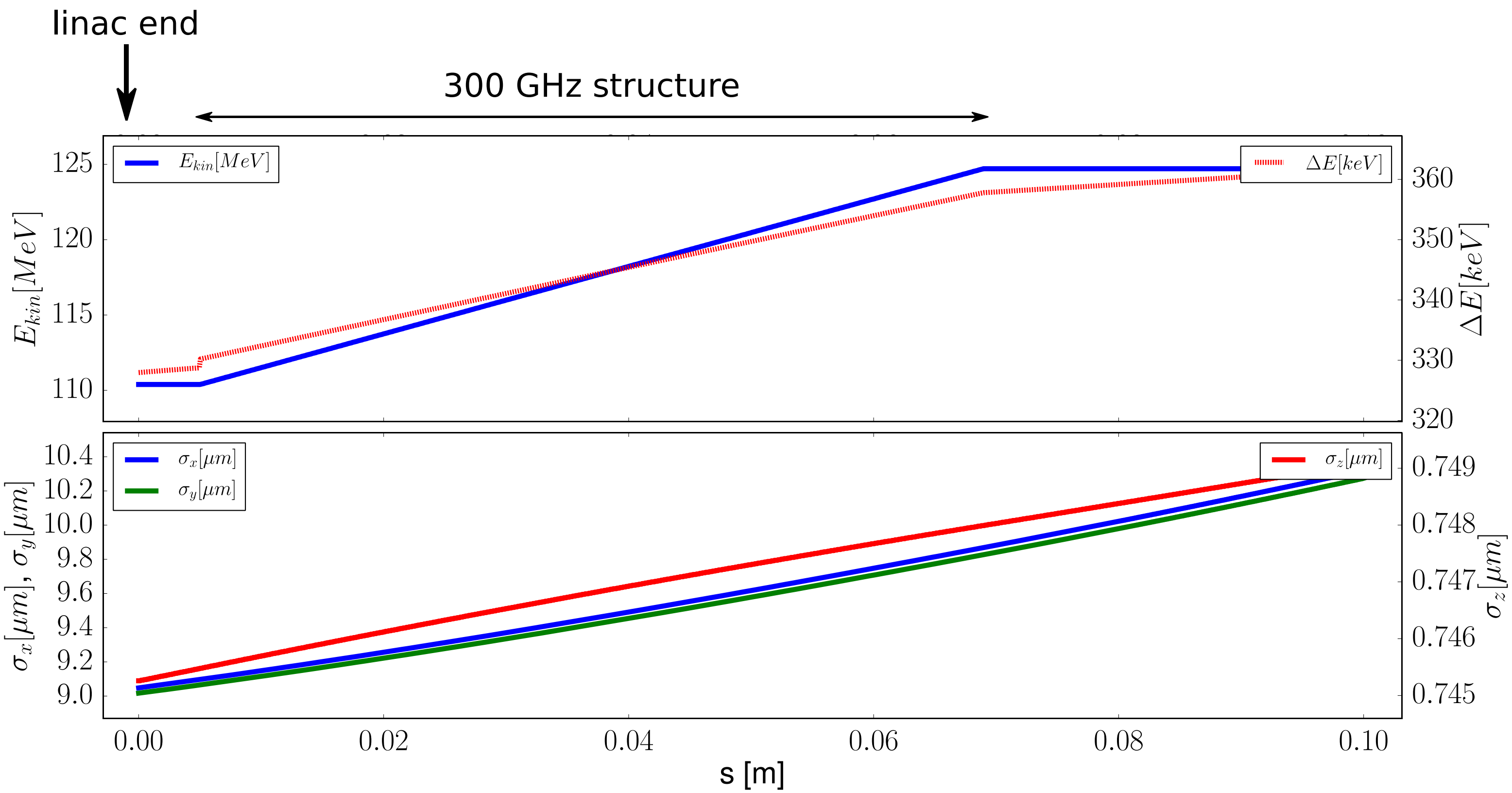
EuPRAXIA parameters from the grant agreement

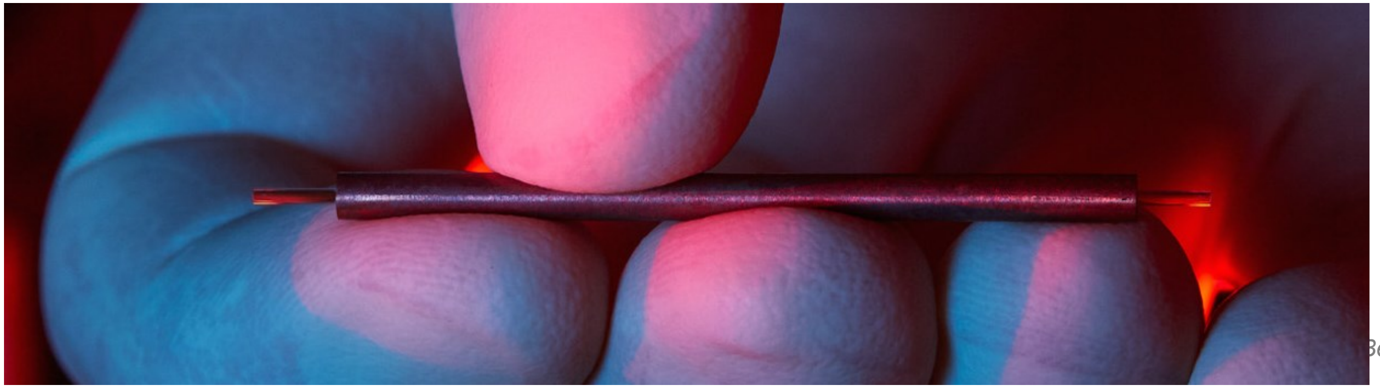
Beam Parameter	Unit	Value
Particle type	-	Electrons
Energy	GeV	1 – 5
Charge per bunch	pC	1 – 50
Repetition rate	Hz	10
Bunch duration	fs	0.01 - 10
Peak current	kA	1 – 100
Energy spread	%	0.1 – 5
Norm. emittance	mm	0.01 – 1
FEL wavelength	nm	1 - 15

Iterations on these values is ongoing in the first steering meetings!

Injection of WP3 in a THz driven dielectric loaded structure

AXSIS
THz driven dielectric loaded structure





U. Dorda et al.
doi:10.1016/j.nima.2016.01.067