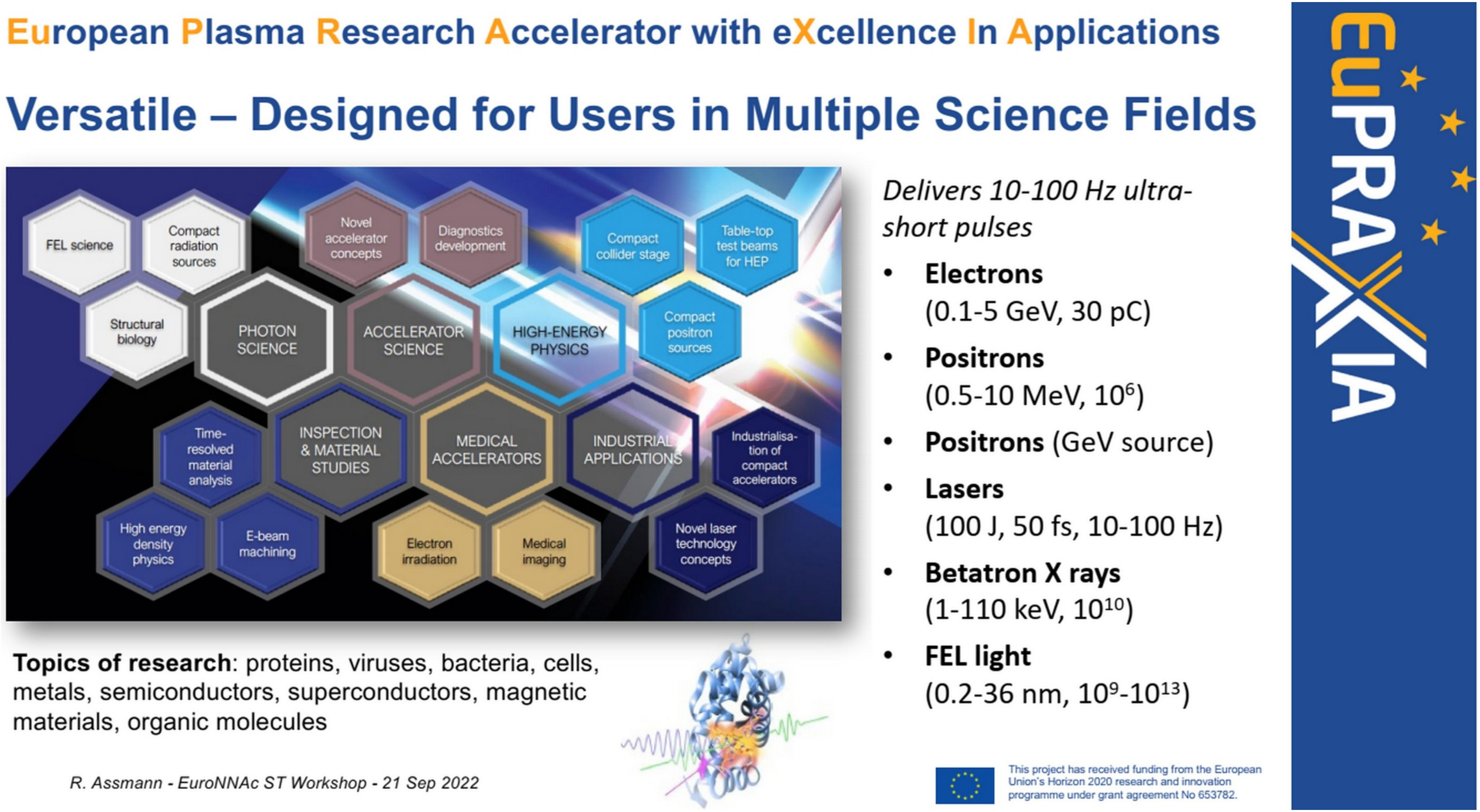
S-ST4-a Summary

Distributed Plasma Accelerator Landscape in Europe and Technical Progress towards Applications (EuPRAXIA ESFRI and others)

Riccardo Pompili (INFN-LNF) and Enrica Chiadroni (Sapienza University)

EuPRAXIA – R. Assmann



European Plasma Research Accelerator with eXcellence In Applications

Versatile – Designed for Users in Multiple Science Fields

Delivers 10-100 Hz ultra-short pulses

- **Electrons**
  (0.1-5 GeV, 30 pC)
- **Positrons**
  (0.5-10 MeV, 10^6)
- **Positrons** (GeV source)
- **Lasers**
  (100 J, 50 fs, 10-100 Hz)
- **Betatron X rays**
  (1-110 keV, 10^{10})
- **FEL light**
  (0.2-36 nm, 10^9-10^{13})

Topics of research: proteins, viruses, bacteria, cells, metals, semiconductors, superconductors, magnetic materials, organic molecules

R. Assmann - EuroNNAc ST Workshop - 21 Sep 2022

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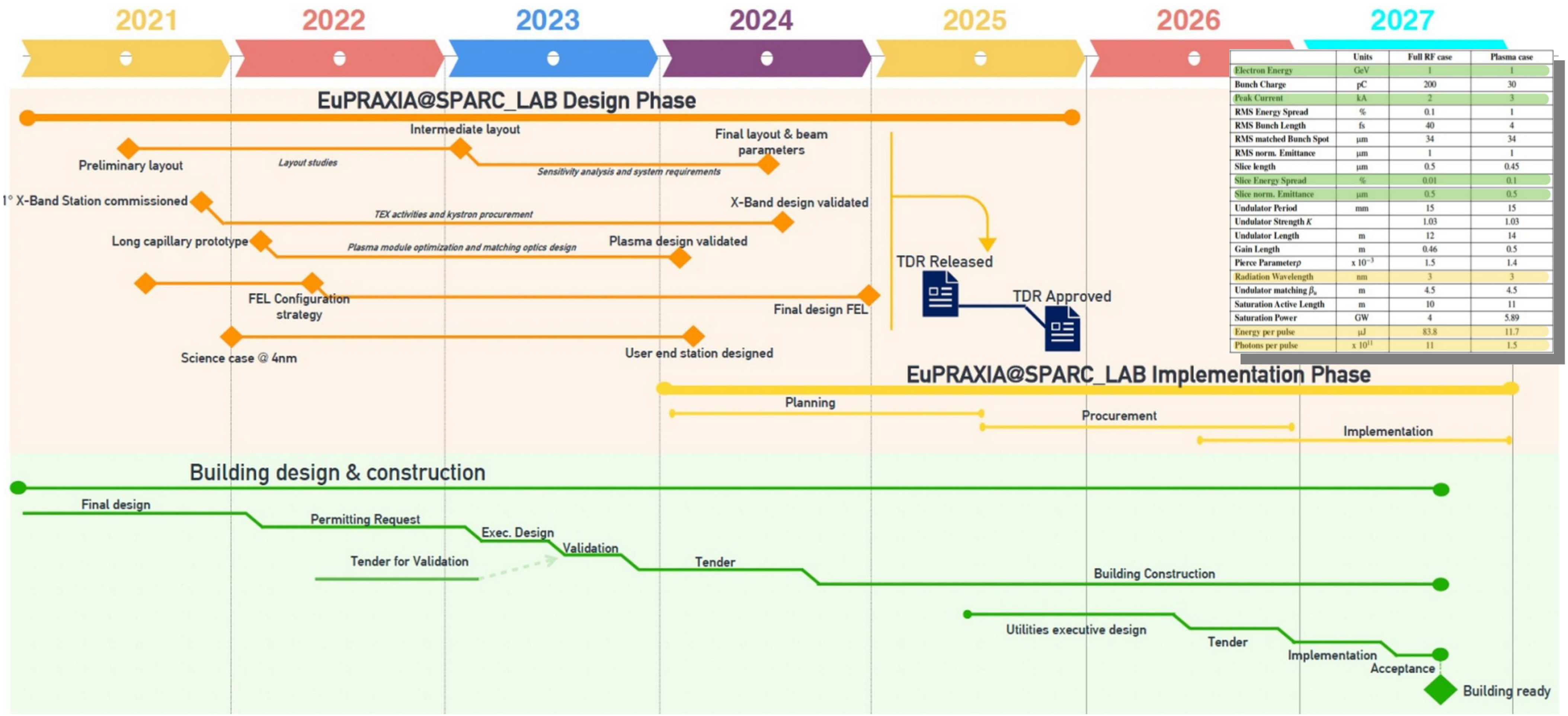
Status of the EuPRAXIA@SPARC_LAB project – M. Ferrario



2021 2022 2023 2024 2025 2026 2027

EuPRAXIA@SPARC_LAB Design Phase

Intermediate layout
Final layout & beam parameters
Preliminary layout
Layout studies
Sensitivity analysis and system requirements
1° X-Band Station commissioned
X-Band design validated
TEX activities and kystron procurement
Long capillary prototype
Plasma design validated
Plasma module optimization and matching optics design
FEL Configuration strategy
Final design FEL
Science case @ 4nm
User end station designed
TDR Released
TDR Approved

EuPRAXIA@SPARC_LAB Implementation Phase

Planning
Procurement
Implementation

Building design & construction

Final design
Permitting Request
Exec. Design
Validation
Tender for Validation
Tender
Building Construction
Utilities executive design
Tender
Implementation
Acceptance
Building ready

	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	$\times 10^{-3}$	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	$\times 10^{11}$	11	1.5

Laser-plasma acceleration at ELI-Beamlines

EUROPEAN NETWORK FOR NOVEL ACCELERATORS

EuroNNAc4

NPACT supported by EU via I-FAST

EuroNNAc Special Topics Workshop

Alexander Molodozhentsev / ELI-Beamlines

TECHNOLOGY READINESS for USER-OPERATION

L1-ALLEGRA laser system and laser beam transport at ELI-Beamlines

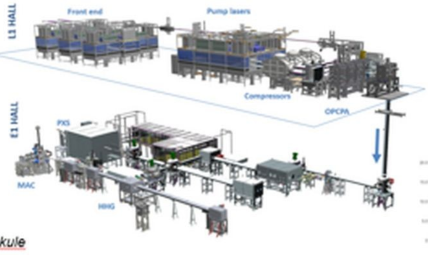
Optically synchronized 5 thin-disk commercial pump lasers
Total available pump power @515 nm: >370 W @ 1 kHz

7 OPCPA stages based on BBO and LBO crystals
Design: 100 mJ / <15 fsec (plan: end of 2023)

Current performance

>62 mJ OPCPA output (~16% pump-to-signal efficiency)
>55 mJ / 14.2 fs after compression
L1-to-E1 beam transport: ~ 10 m → **READY**

Fully available



Routine user operation:
85 full experimental days in 2021

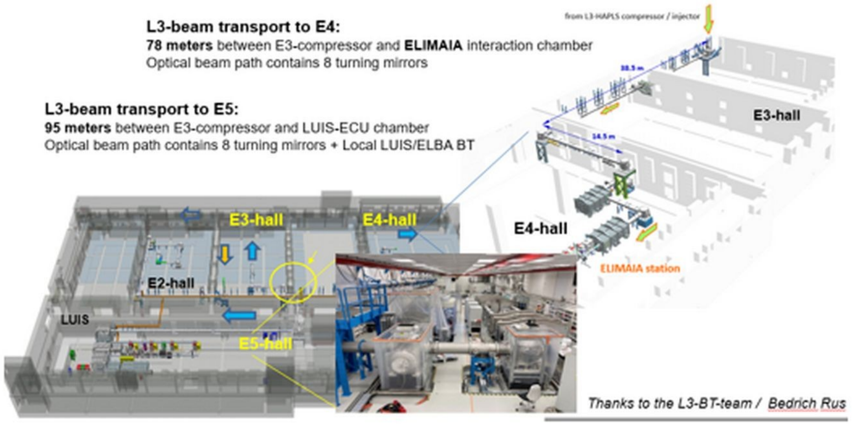
Typical operation day for experiments

Thanks to the L1-team / Pavel Bakule

L3-HAPLS laser system and laser beam transport at ELI-Beamlines

L3-beam transport to E4:
78 meters between E3-compressor and **ELIMAIA** interaction chamber
Optical beam path contains 8 turning mirrors

L3-beam transport to E5:
95 meters between E3-compressor and LUIS-ECU chamber
Optical beam path contains 8 turning mirrors + Local LUIS/ELBA BT

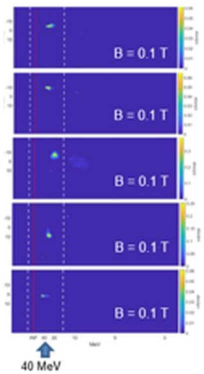


Thanks to the L3-BT-team / Bedrich Rus

LASER-PLASMA ACCELERATION: main achievements

L1-ALLEGRA (55 mJ/1 kHz)

(C) He(98%)/ N_2 (2%)
$n_e \sim 5.7 \times 10^{19}$cm^{-3}



Laser parameters on parabola (measured)

- Energy: **32 mJ**
- Pulse duration: 16 fs
- Energy in the focal spot: ~ 60 %
- Repetition rate: **1 kHz**

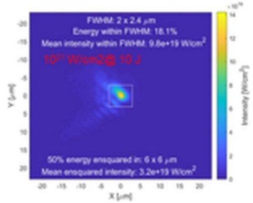
Measured electron beam parameters: Case (C)

Electron beam energy **~ 40 MeV**
Estimated divergence FWHM **~ 5 mrad**
FWHM average energy spread **~ 30%**
Total charge **~ 10pC/pulse**

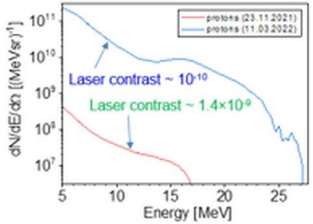
L1-LPA-Electron beam (kHz)

L3-HAPLS (10 J/3 Hz)

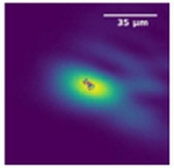
- Thin foil target (Al) … thickness = 5 µm
- Laser Intensity ~ 10^{21} W/cm^2
- Focal spot (FWHM) ~ 4.8 µm (f#3 OAP)
- Laser contrast ~ 1.4×10^{-9} (Dec.2021)



L3-LPA-Proton beam



L3-LPA-Electron beam: all technology setups (LUIS, ELBA, BETATRON) are prepared for coming experimental campaign.
L3(mJ) laser in focus for the LUIS setup.



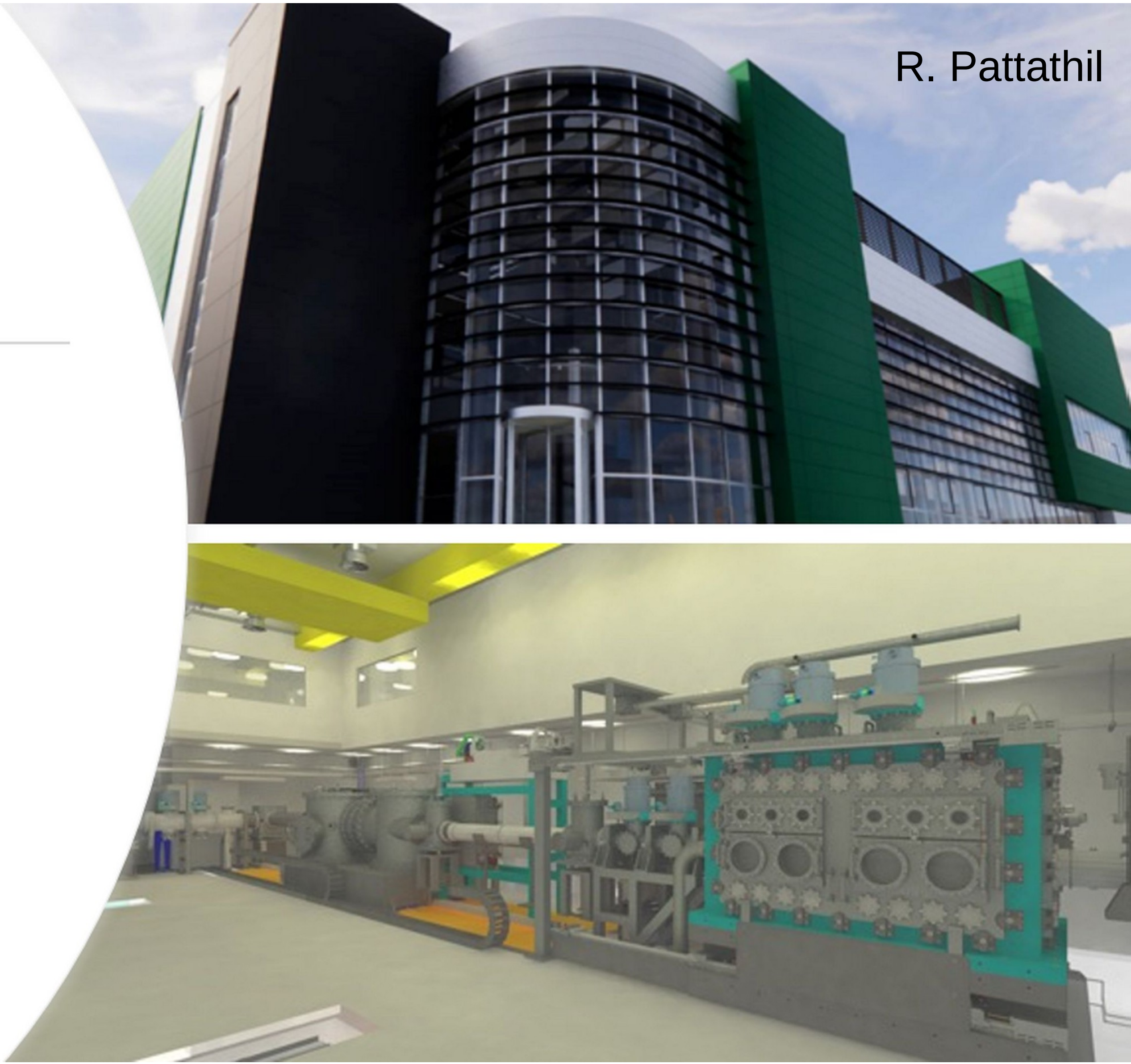
beamlines
eli

R. Pattathil

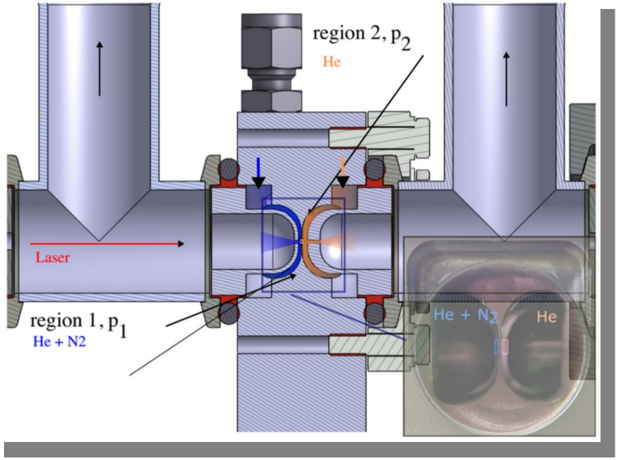
Extreme Photonics Applications Centre

- A new UK facility for applications of laser-driven sources in industry, medicine, security etc.
- Wiill produce LWFA driven beams at 1PW, 10Hz: Expected up to 10GeV beams, x-rays
- Significant Industrial backing based on proof-of-principle tests

Building completed; installations ongoing; first operations in 2025



PALLAS, a laser-plasma injector test facility, development status – K. Cassou



LPI parameters

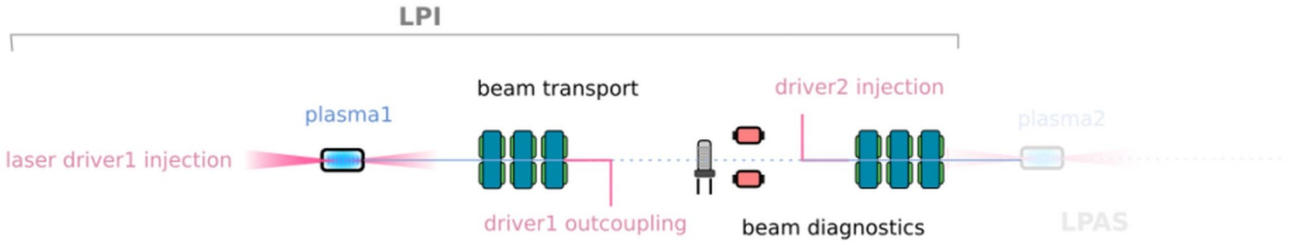
Parameters	phase 1	phase 2	phase 3	unit
laser strengh, a_0	1.15-1.4	1.15-1.4	**>1.8**	
laser duration, t_L	40	**30**	**30**	fs (FWHM)
laser waist, w_0	18	18	18	um
Strehl ratio, S_r	**> 0.8**	**> 0.8**	**> 0.8**	-
beam pointing, δu_i	**<0.5**	**<0.5**	**<0.5**	urad
stability	1%	**<1%**	**<1%**	-
frep	10	10	10	Hz
target type	multi-cell	multi-cell	multi-cell	-
injection	ionisation	ionisation	ionisation	-
electron beamline	*CL1*	*CL1*	*TBD*	-

Electron beam parameters

Parameters	phase 1	phase 2	phase 3	unit
energy	150	**200**	200	MeV
charge	15-30	**30**	**30**	pC
frep	10	10	10	Hz
energy spread	<5%	**< 5%**	**< 2%**	peak (std)
ε_n^{rms}	1	**<1**	?	μm
stability	5%	**3%**	**1%**	-
reproducibility	5%	**3%**	3%	-

Build a laser-plasma **accelerator test facility** aiming to achieve **reliability** and **control** comparable to conventional **RF accelerator** standards.

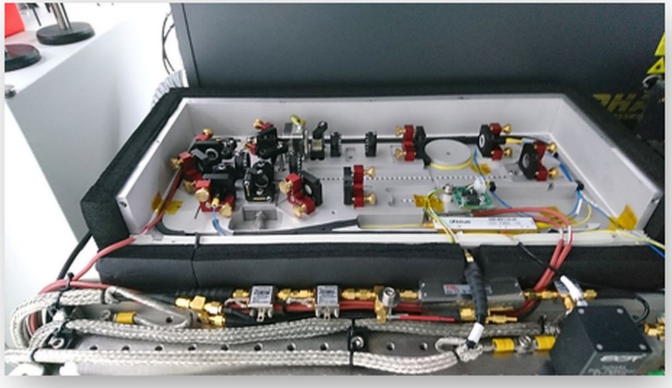
Push **technological development** starting with a **10 Hz** 150-250 MeV *"high-quality beam"* **laser-plasma injector** (**LPI**) prototype for staging to high energy



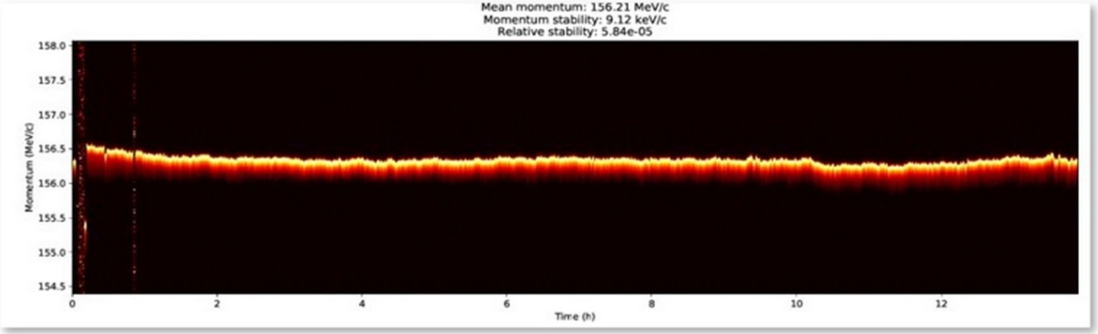
ARES at DESY

Stable infrastructures for highest stability, ultra-short electron bunches

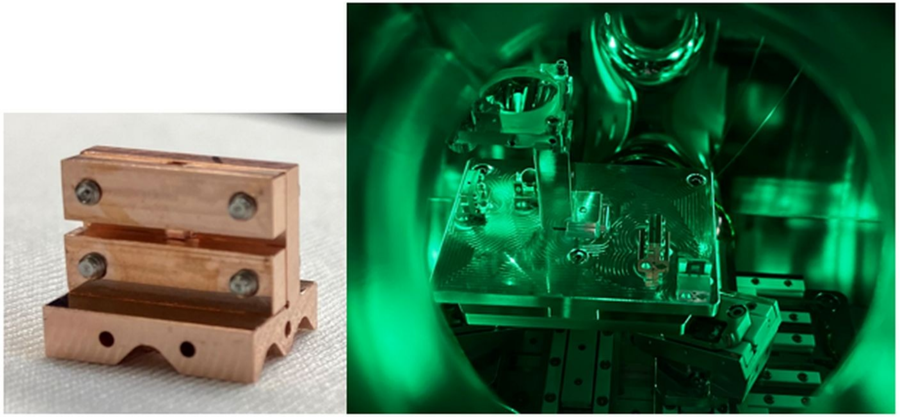
- single digit fs synchronization upgrade ongoing
- stable infrastructures (Modulators, LLRF, water cooling)
- high quality, high brightness ultra-short electron beams
- used for accelerator R&D, dielectric laser acceleration and medical applications



MZM-based Laser-to-RF Syncronization Setup with 7fs jitter



5.8e-5 rms relative energy stability



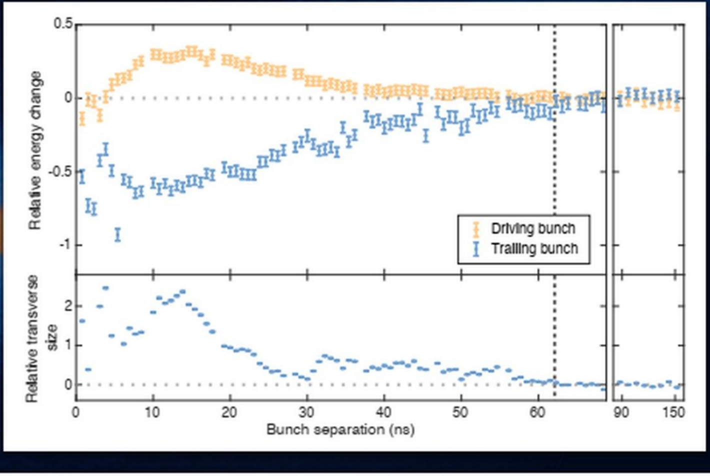
DLA structures and UHV experimental chamber

Plasma-wakefield accelerators at high repetition rates

Richard D'Arcy (on behalf of the **FLASHForward** ▸ ▸ team)

- The ***recovery time of a plasma-wakefield accelerator*** indicates compatibility with conventional accelerator schemes… develop a plasma-booster at pre-existing FELs!
- This is a great first step… but still ***just a first step***
- The big challenge is bridging the up-to-five order-of-magnitude gap from state-of-the-art to what is required
- Parallels with conventional accelerator technology help us to contextualise and better define the challenges
- ***Many outstanding scientific and technical goals*** to be reached with emphasis on simulation tools and plasma-source technology → overlap between LWFA and PWFA
- A ***huge international effort will be required*** to solve all the problems in the next decade

R. D'Arcy *et al.*, Nature **603**, 58-62 (2022)

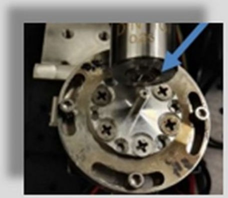


	FLASH	**Plasma-based facility**
Inter-bunch separation	333 ns	100 ns
Bunch-train length	800 μs	*10 μs ?*
Macro-pulse separation	100 ms	*10 ms ?*
Bunches per second	**18000**	**10000**

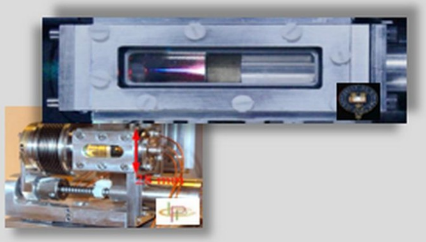
Design of plasma sources for compact accelerators – A. Biagioni

Depending on the plasma formation technique, application, dimensions..., the plasma sourse will assume a large variety of shapes

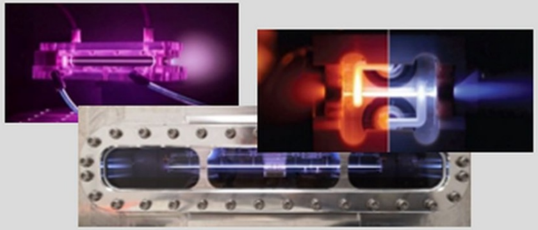
Heat-pipe ovens (both Lithium and Rubidium sources) provide very long and uniform plasma channels but require more complicate and higher costs equipments to realize them



Compactness and low costs characterize the *Gas jet plasma sources* but operation at kHz repetition rates will require strong efforts to respect the vacuum requirments (tens of bar)



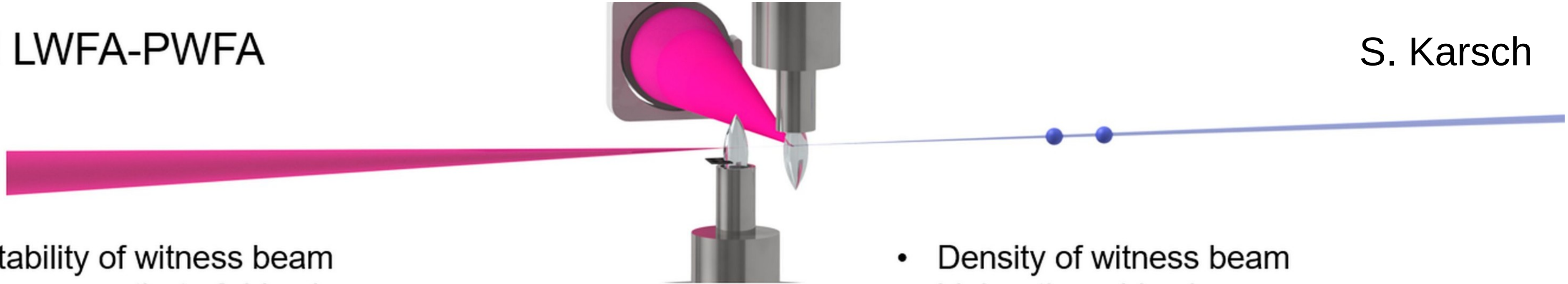
The use of *Gas cell plasma sources* (HOFI plasma channels) has demonstrated operation at high repetition rates (200 Hz but 1 kHz is possible to be reached) in a statically-filled gas cell. CHOFI plasma channels seem ideally suited to multi-GeV accelerator stages operating at high rep-rates but some 'engineering' challenges remain associated with cell design



capillary discharges are versatile plasma sources (possible use for beam focusing) which present limits to reach large dimensions. Appropriate materials have to be used to design capillary discharges to operate at high repetition rate.

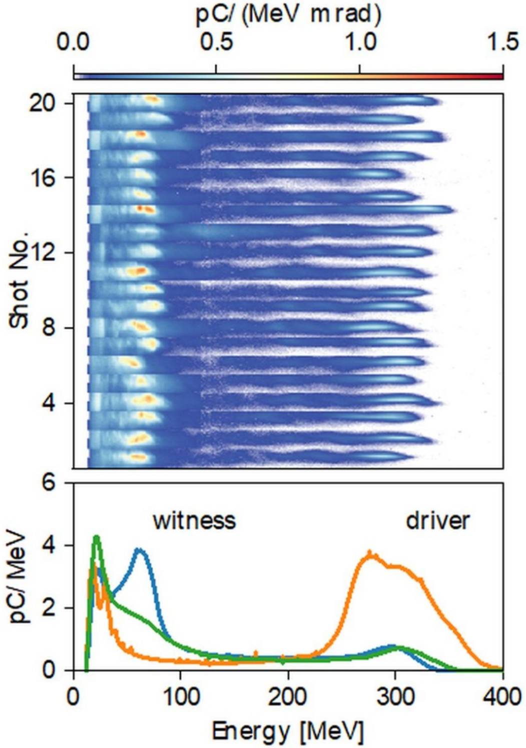
Hybrid LWFA-PWFA

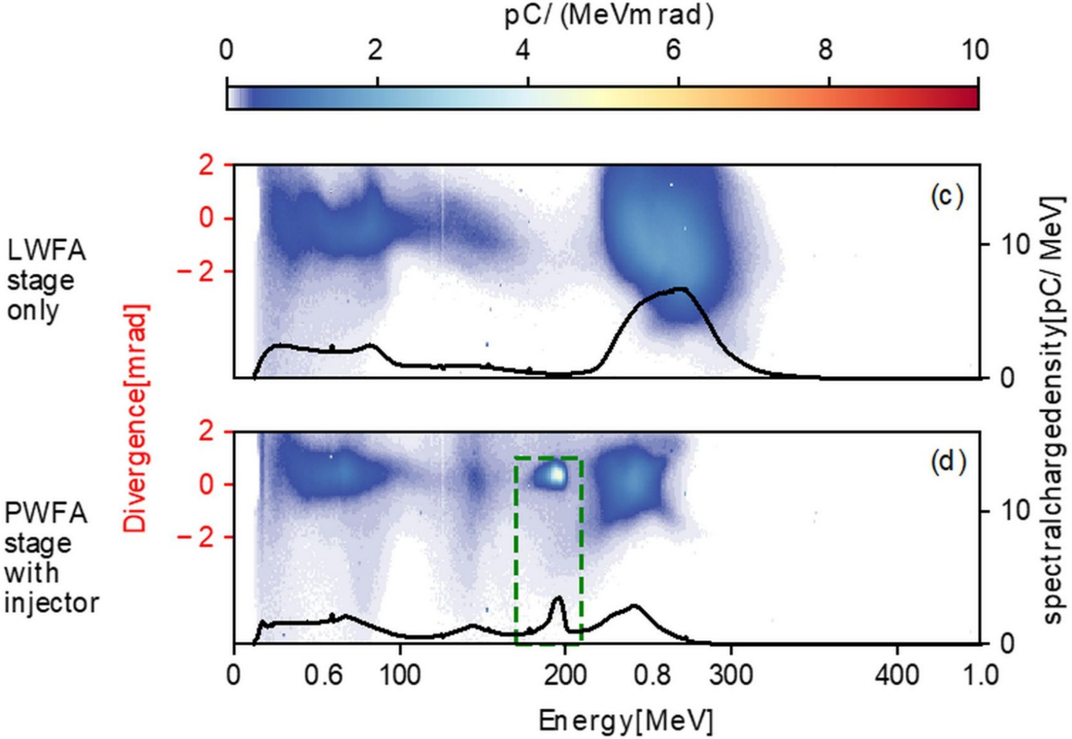
S. Karsch



- Stability of witness beam surpasses that of drive beam

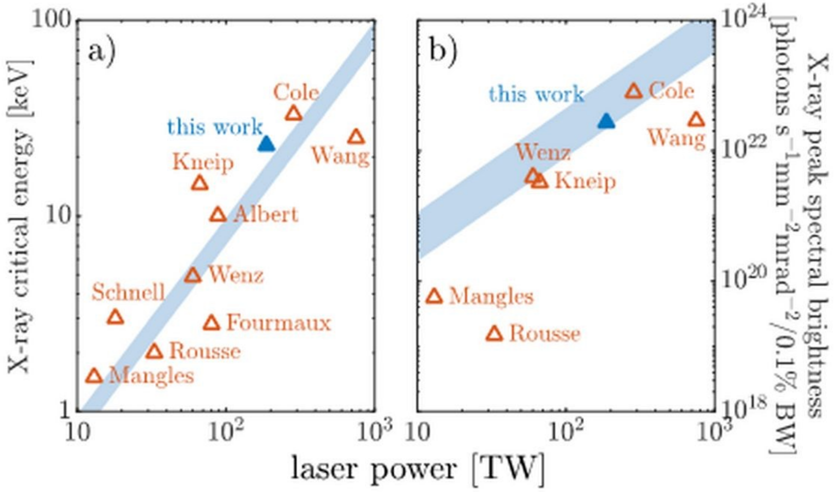
- Density of witness beam higher than drive beam



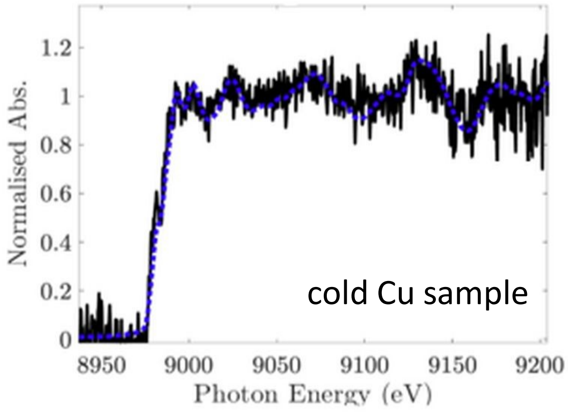


Overview of betatron radiation sources and applications – S. Mangles

- **Betatron radiation:** femtosecond synchrotron radiation from LWFAs
  - Betatron properties strongly dependent on electron beam energy, and therefore the driving laser power
- **Applications of betatron radiation**
  - imaging
  - absorption spectroscopy



Single shot X-ray absorption spectroscopy



Laser Wakefield Accelerators for Tomographic Imaging

Conclusions

- There will be several facilities in Europe adopting plasma-based accelerators
- Common goal: beam quality → real user applications
  - Betatron radiation, FEL
- Dealing with compact microscopic accelerators, several requirements are needed
  - Stability, fs-level synchronization
  - Novel approaches (hybrid LWFA-PWFA schemes) can be helpful
  - Efforts for high rep. rates but plasma recovery time and heating dissipation must be taken into account