KAIO ACCELERATOR

Boosting the dissemination of Laser-Plasma Accelerators

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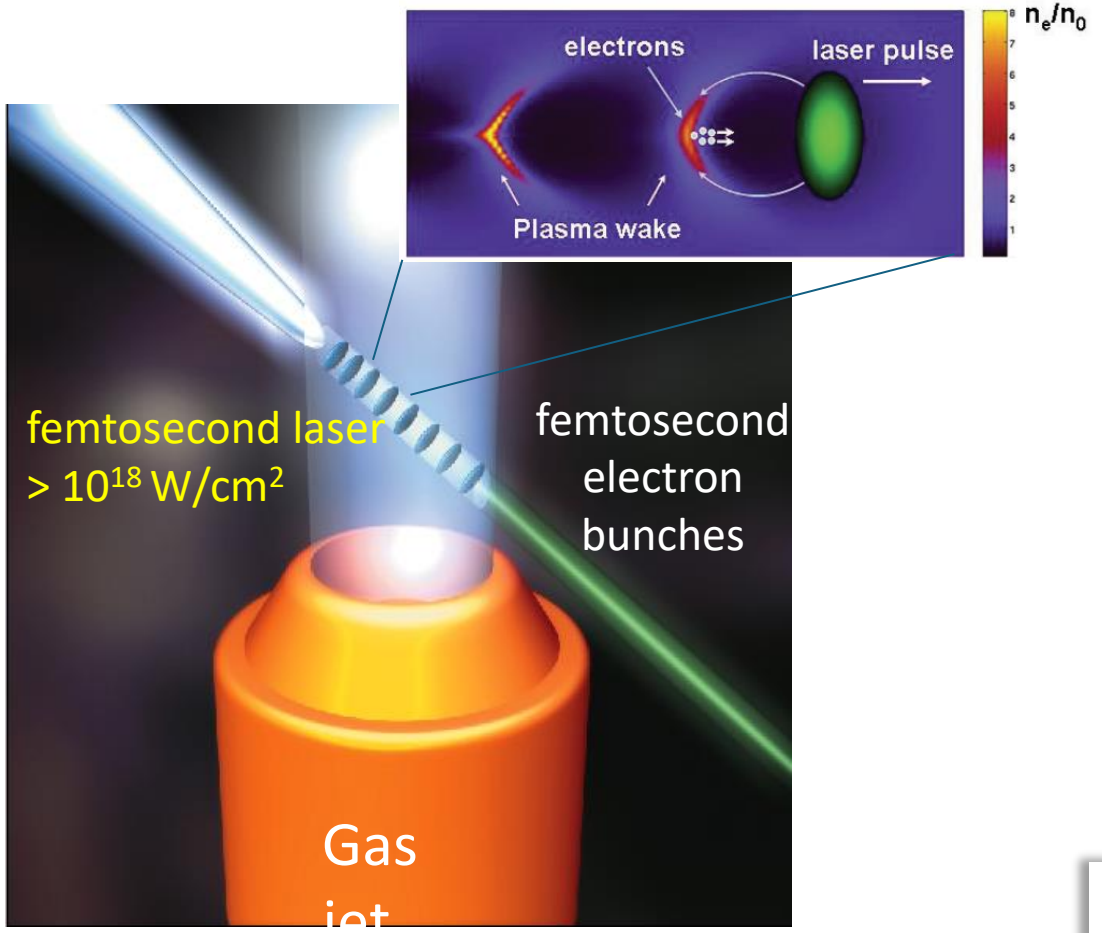
Laboratoire d'Optique Appliquée

3rd I.FAST Annual Meeting
Paris-France
16-19 April 2024

loa.ensta-paris.fr

Laser-plasma accelerator (LPA)

Electrons accelerated in laser-plasma wakefield



Faure et al. Nature 2004
Mangles et al. Nature 2004
Geddes et al., Nature 2004

❑ Laser beam

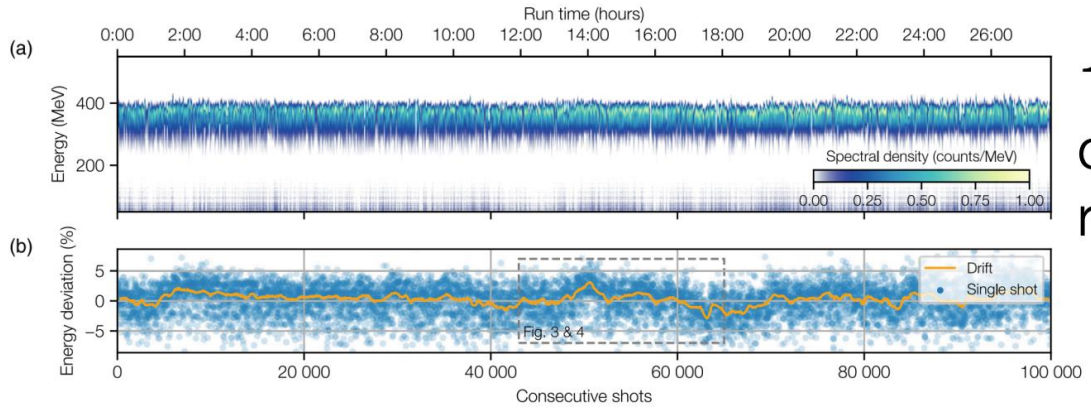
Ti:Sa laser: 1 J, 30 fs, 1-10 Hz
Peak power: 10-100 TW

❑ Electron beam

Collimated (few mrad)
MeV to GeV in mm to cm (1-10% spread)
Micrometer source size
(Glinec et al., Phys. Rev. Lett. 2005)
Few-fs bunch duration
(Lundh et al., Nat. Phys. 2011)
Ultra-high dose rate
(Favaudon et al. Sci. Trans. Med. 2005)

❑ Compact LPA for applications:
✓ High resolution imaging
✓ Pulsed radiotherapy

Demonstration of long-term LPA operation (1-10 Hz)

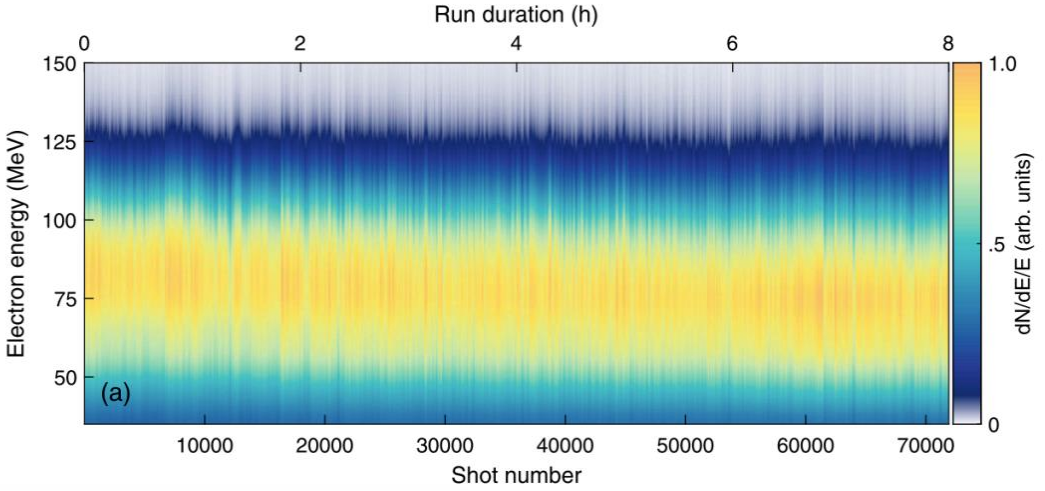


100-TW LPA operated 28h in a row!

Maier et al, Phys Rev X 10, 031039 (2020)

Bohlen et al, Phys. Rev. Accel. B 25, 031301 (2022)

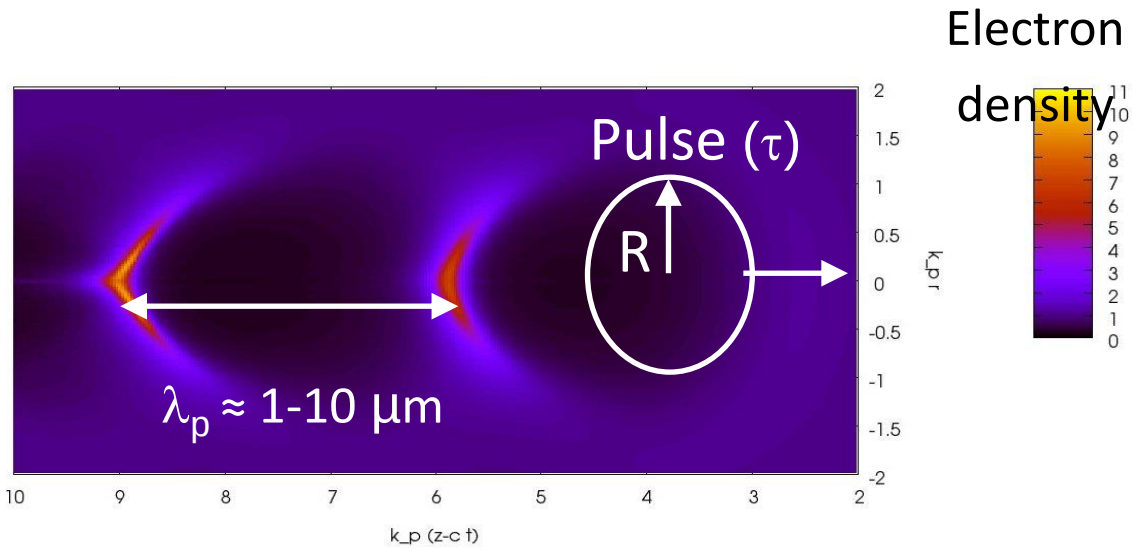
12-TW LPA operated 8h in a row!



Machine-learning optimization: Shalloo et al, Nat Comm 11, 6355 (2020) (26)
Jalas et al, Phys Rev Lett 126, 104801 (2021)

Scaling laws of LPA in « bubble » regime

Lu *et al.*, Phys. Rev. ST Accel. Beams **10**, 0613001 (20



Laser pulse has to be resonant with plasma wave:

$$R \approx \lambda_p/2 \approx c.\tau$$

Laser energy scaling: $E_L \propto \tau^3 \propto \lambda_p^3$

Electron energy gain: $\Delta E \propto \tau^2 \propto \lambda_p^2$

30 fs , 1 J (Hz) → 0.1 - 1 GeV

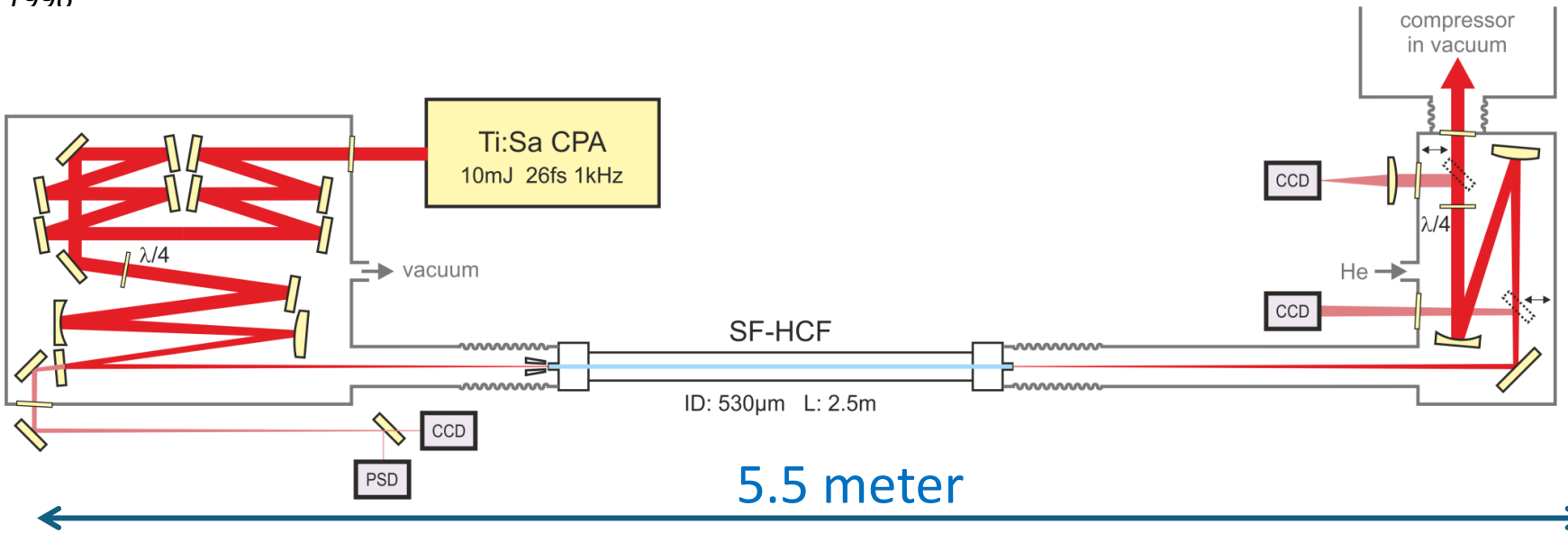
3 fs , mJ (kHz) → 1 - 10 MeV

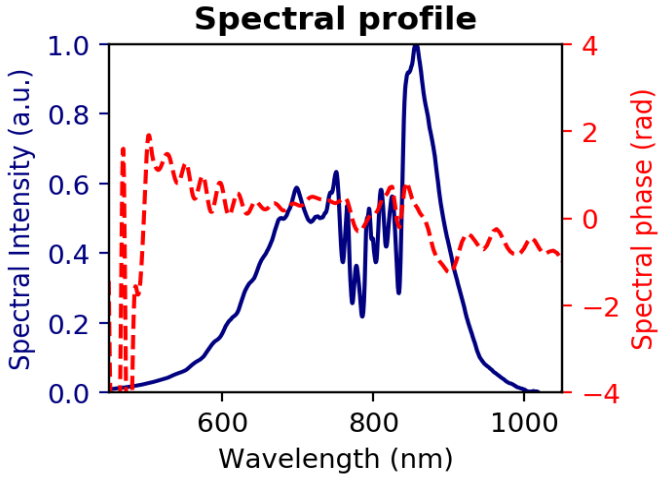
→ LPA @ kHz rep. rate

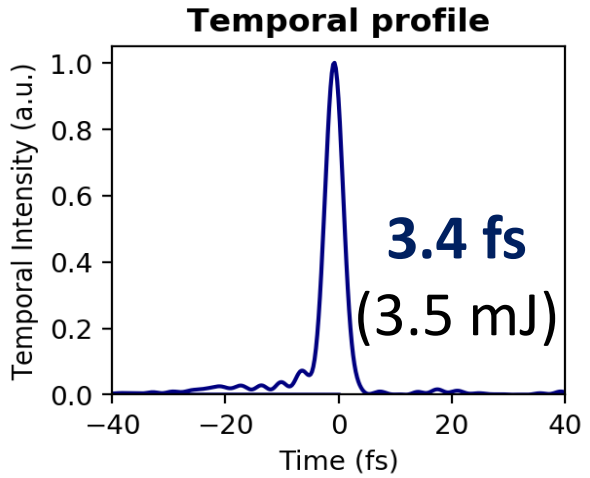
State-of-the-art kHz LPA driver @ LOA

Few-fs / few-mJ pulses by nonlinear spectral broadening and compression in gas-filled hollow-fiber:

Nisoli M et al., "Generation of high energy 10 fs pulses by a new pulse compression technique", Appl Phys Lett. 1996







Ouillé M. et al., Relativistic-intensity near-single-cycle light waveforms at kHz repetition rate. Light Sci Appl 2020

5-hour continous LPA operation at 1 kHz!

L. Rovige J. Huijts A. Vernier J.

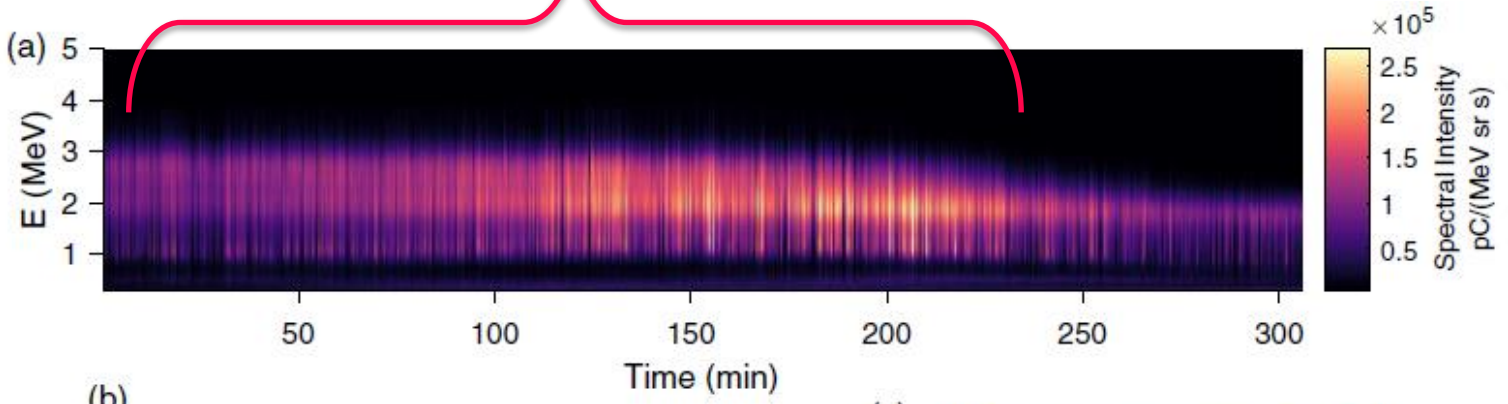


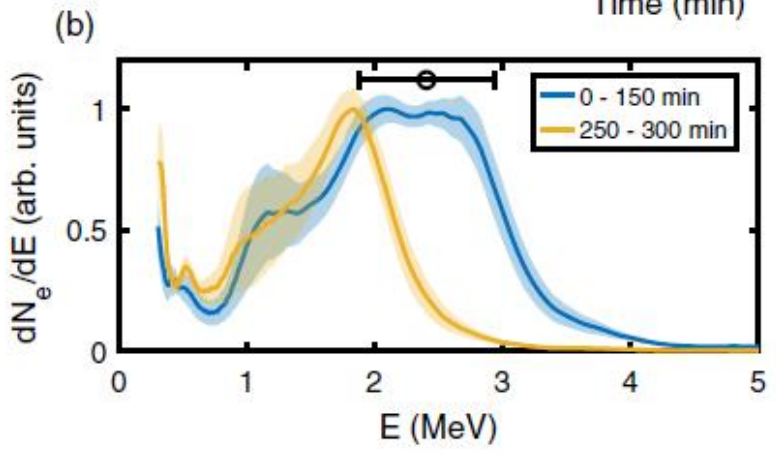

L. Rovige et al., Phys. Rev. Accel. Beams **23**, 093401 (2020)

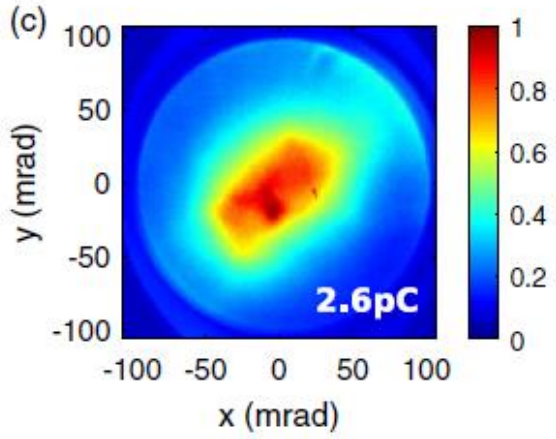
12 million shots

3 mJ, 4 fs pulses @ kHz
I ~ 10^{18} W/cm^2

Supersonic N_2 gas jet







KAIO ACCELERATOR: « Kit-All-In-One » LPA value chain

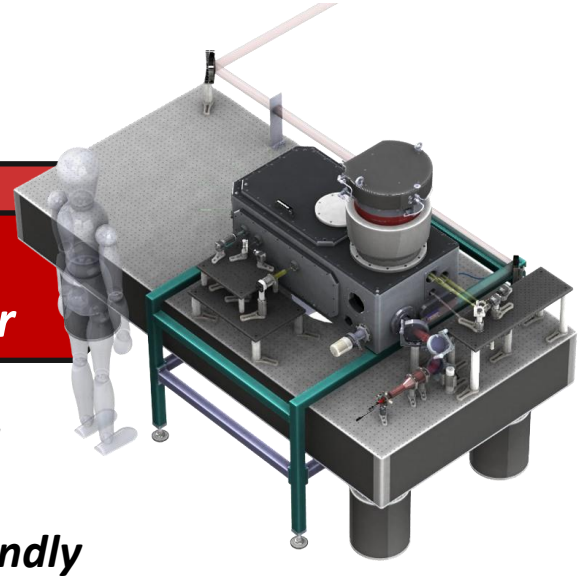
Commercial kHz LPA → Electron & secondary beams (e.g. x-rays) → Applications

Enabling technologies:

Laser driver
- ❑ High-power (kHz)
- ❑ Turn-key
- ❑ Reliable
- ❑ Cost-effective

Pulse compressor
- ❑ Efficient
- ❑ Adaptable
- ❑ Robust

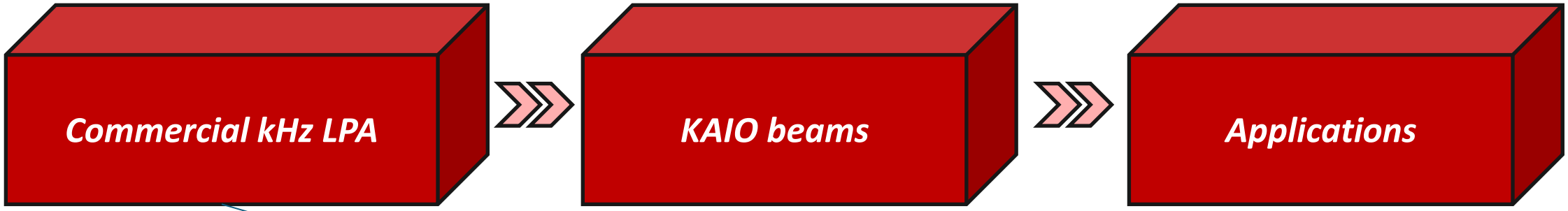
KAIO accelerator
- ❑ Compact
- ❑ Versatile
- ❑ User-friendly



e-KAIO module by SourceLAB

Scope of KAIO-ACCELERATOR

KAIO ACCELERATOR: Consortium



Prototyping:

Rodrigo Lopez-Martens

François Sylla

Pulse compressor

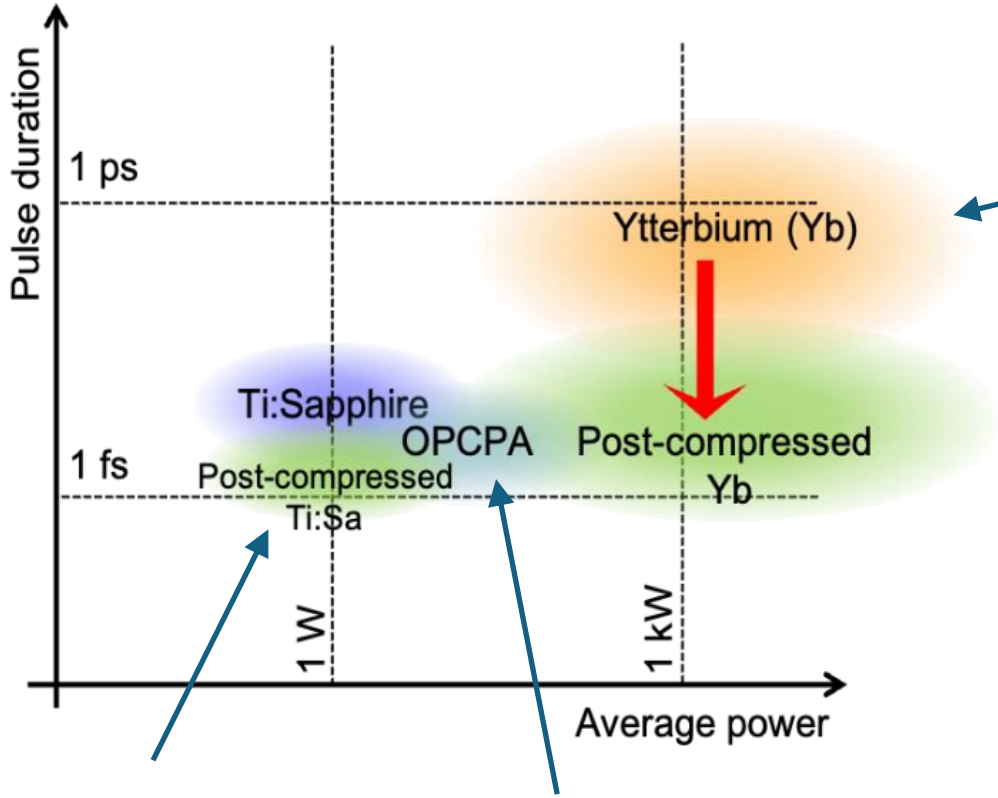
- ❑ High-power Ytterbium lasers
- ❑ Compact & efficient
- ❑ Sustainable LPA technology

Radiobiological testing:
Leo Gizzi

Market study:
Federico Canova

Scope of KAIO-ACCELERATOR

Enabling technology for LPAs: laser post-compression



Yb-based lasers:
- ✓ ***High wall-plug efficiency (10 - 30%)***
- ✓ ***Industrial grade***

Post-compressed Yb lasers:
- ✓ ***Efficient & simple***
- ✓ ***Advantages of Ti:Sa & Yb***

Ti:sapphire lasers:
- ✓ ***Short pulses***
- ✗ ***Wall-plug efficiency < 1%***

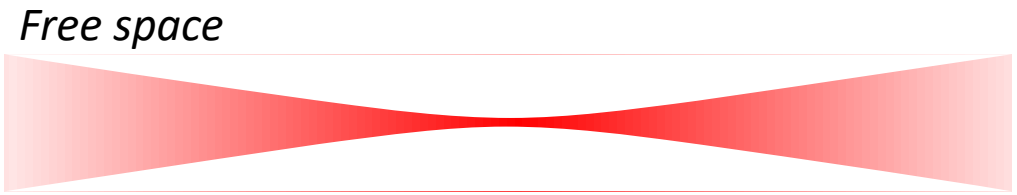
OPCPA systems:
- ✓ ***Versatile***
- ✗ ***low efficiency***

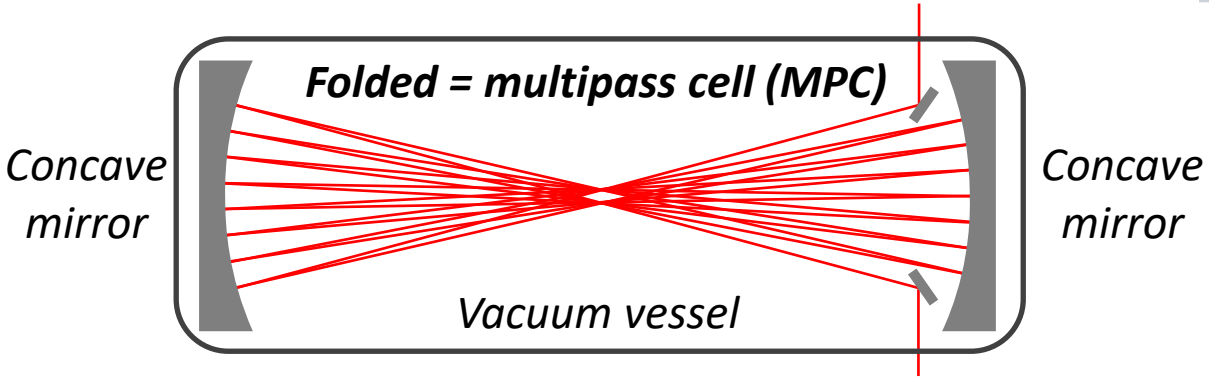
Future LPA drivers?
- ❑ ***TW peak power***
- ❑ ***kW average power***

Nagy et al., *High-energy few-cycle pulses: post-compression techniques*, Advances in Physics X 6, 1845795 (2021).

Viotti et al., *Multi-pass cells for post-compression of ultrashort laser pulses*. Optica 9, 197–216 (2022).

Nonlinear laser post-compression in a MultiPass Cell (MPC)



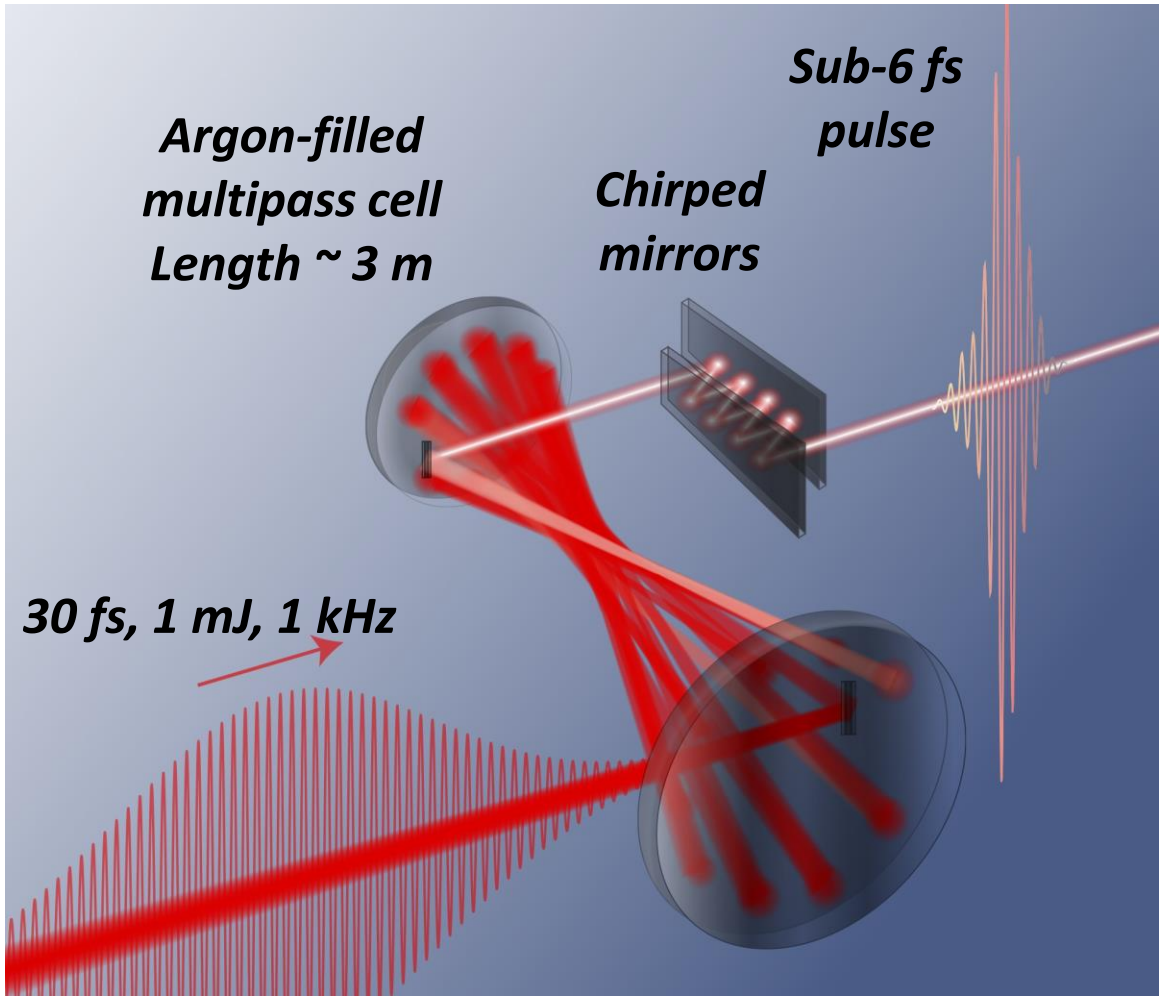


NL interaction length	Spectral/phase control	High power / Energy
✓ ✓	✓	✗
✗	✗	✓ ✓
✓ ✓	✓ ✓	✓ ✓

Hanna et al., « Nonlinear temporal compression in multipass cells: theory », J. Opt. Soc. Am. 2017

Hanna et al., « Nonlinear Optics in Multipass Cells », Laser Photon. Rev. 2021

MPC compression of Ti:Sa pulses: few-fs pulses @ mJ level



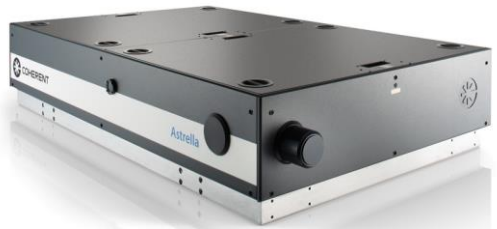
Efficiency ~ 70%

Daniault et al., « Single-stage few-cycle nonlinear compression of milliJoule energy Ti:Sa femtosecond pulses in a multipass cell », Optics Letters 46 (2021)

MPC compression: key to LPA value chain

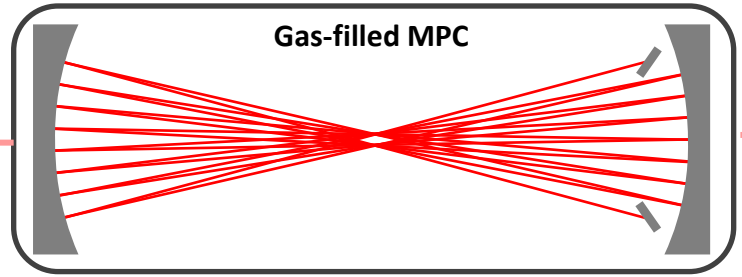
Commercial lasers

Ti:Sa laser:
ASTRELLA from Coherent
7 mJ, 40 fs, 1 kHz, 800 nm



Yb laser:
MAGMA from Amplitude Laser Group
20 mJ, 400 fs, 1 kHz, 1030 nm

Few-fs, few-mJ MPC compressor



Prototype benchmarking

Commercial LPA module (e-KAIO by SourceLAB)

Few-MeV electron beam @ kHz

Radiobiology testing with CNR-INO

e-KAIO Specifications	
Pulse energy	2 – 500 mJ
Laser spectrum	500 – 1000 nm
Laser aperture	< 50 mm
Pulse duration	3 - 30 fs

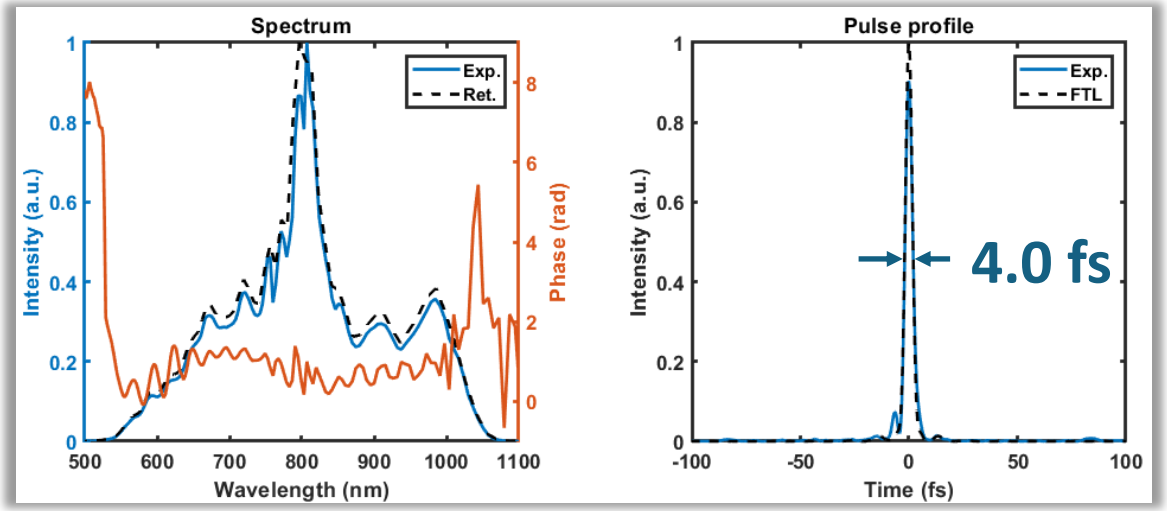
MPC compression of ASTRELLA laser

COHERENT

ASTRELLA parameters:
7 mJ, 40 fs, 1 kHz

Efficiency ~ 60%

MPC compressor:
4 mJ, 4 fs, 1 kHz
Peak power ~1 TW



To be published…

KAIO ACCELERATOR: project timeline

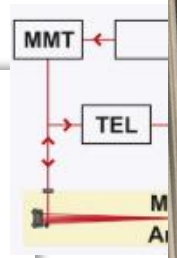
Q1 2023

WP 1
CNRS/LOA
SourceLAB

- ❑ *Post-compression of ASTRELLA las*
- ❑ *Single-stage MPC: 4 mJ, 4 fs @ 1 k*
- ✓ ***Reproduce Ti:Sa LPA driver specifications***

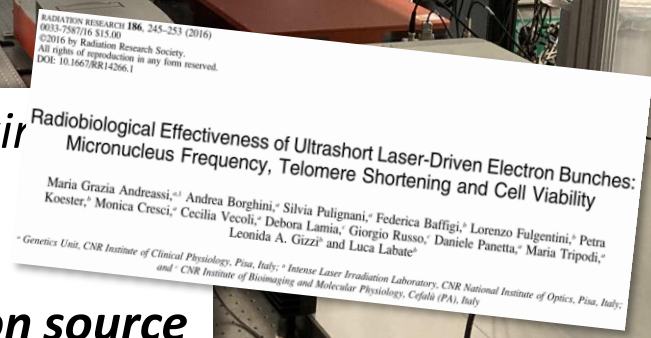
WP 2
CNRS/LOA
SourceLAB

- ❑ *Post-compression of MAGMA*
- ❑ ***Cascaded** MPC compression*
- ❑ *First LPA tests with e-KAIO*



WP 3
CNR/INO
CNRS/LOA
SourceLAB

- ❑ *Radiobiology tests (DNA single-strand breakin*
- ❑ *Dosimetry of e-KAIO electron source*
- ❑ *Dose escalation study with e-KAIO*
- → ***Viability compared to conventional electron source ?***



WP 4
DF Consulting
SourceLAB

- ❑ *Managment, dissem*
  exploitation

Q4 2024

Thank you for your attention !

Contacts:

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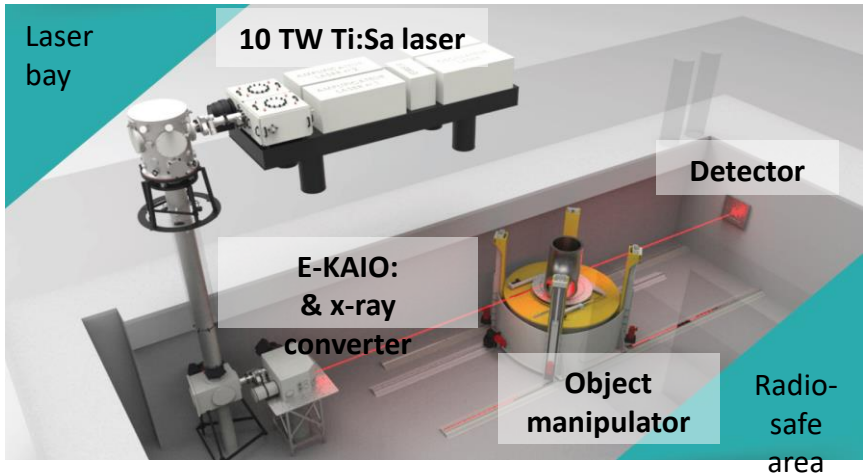
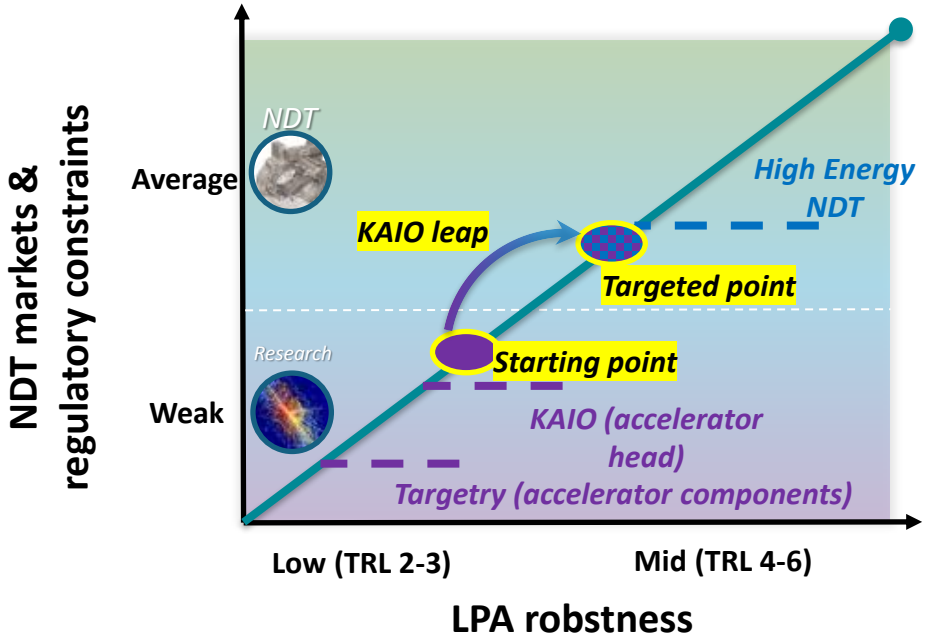
KAIO ACCELERATOR: prospects



KAIO-based NDT platform with a 10 Hz Ti:Sa laser (SHERIL platform at LOA)



Commercial LPA devices for applications

- ❑ *Post-compressed Yb laser: Industrial, cost-effective, sustainable*
- ❑ *e-KAIO: integrated, adaptable, user-friendly*
  - ✓ *reliable LPA beams for applications*
  - ✓ *increased TRL to address NDT market*
  - ✓ *few-10 to few-100 LPA devices/year*

Non-destructive testing (NDT) by X-ray radiography: *The market*

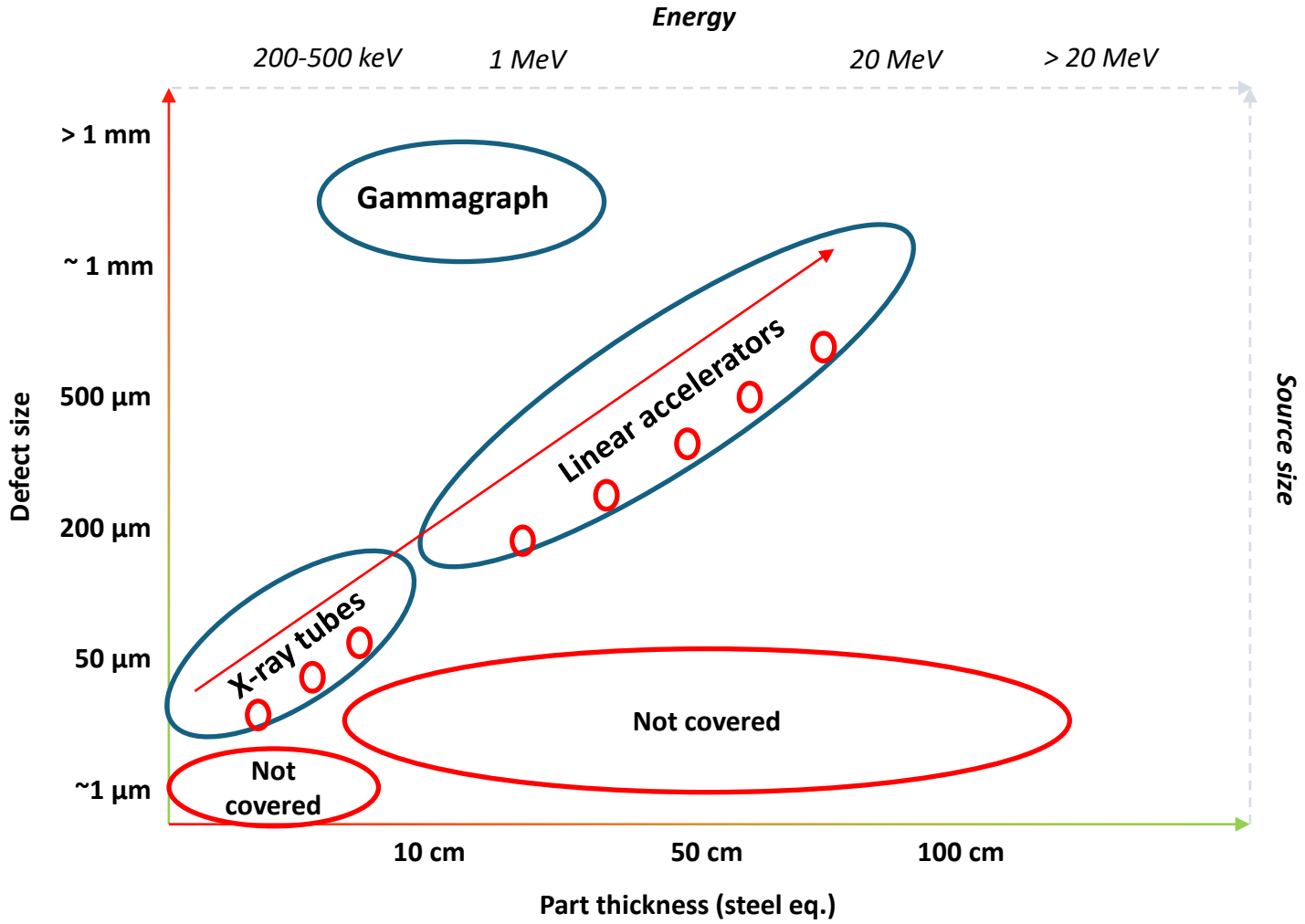
1500 installed sources

~100 new each year

~100 M€ market for sources

covered by 3 technologies

Industrial NDT by X-ray radiography: *What drives the end-users and what do they get?*



What drives end-users?

Energy

Resolution

Cost

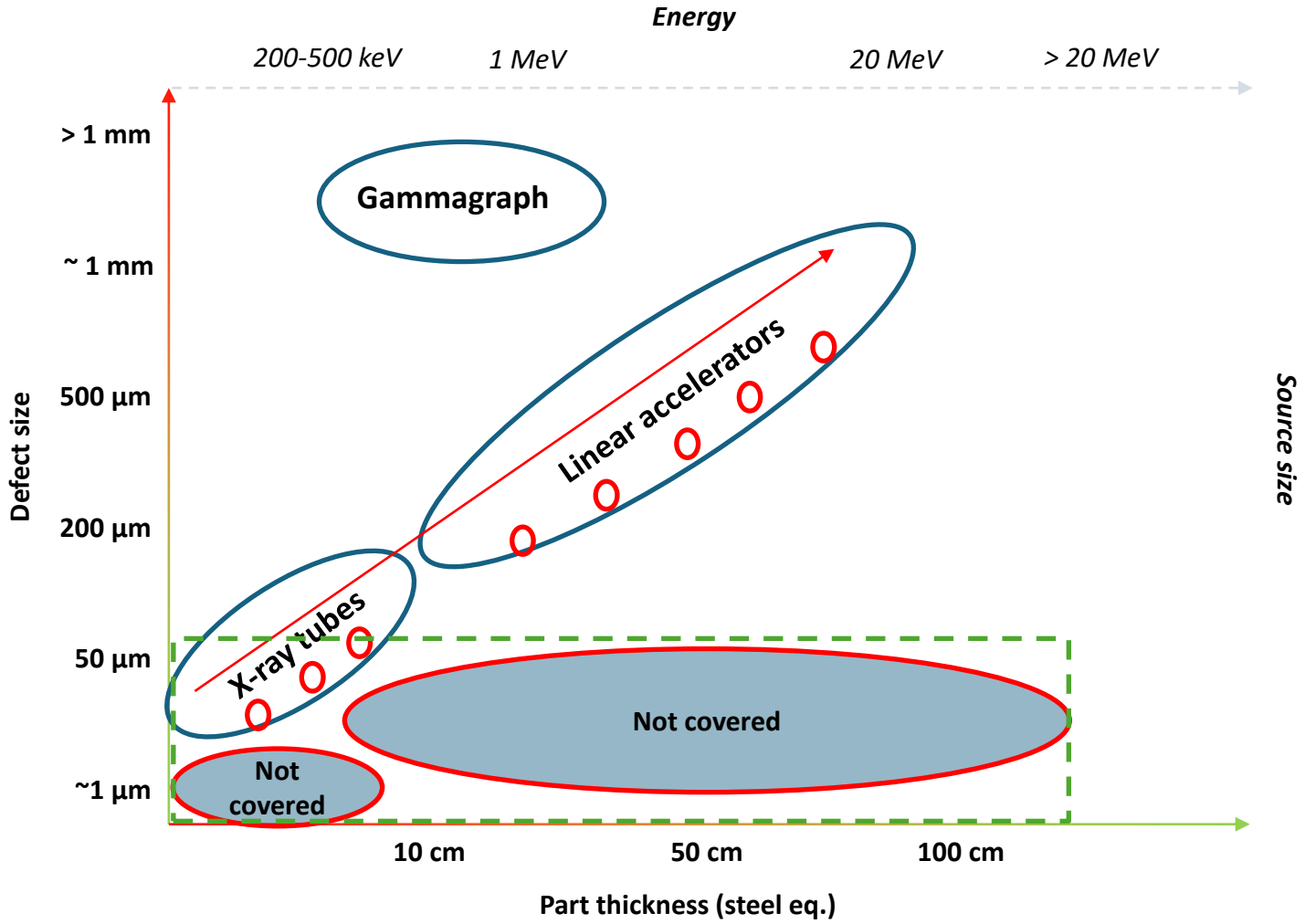
What do they get?

The higher the energy, the worse the resolution

No access to high added value micro-tomography

One system per energy

Industrial NDT by X-ray radiography: *What drives the end-users and what do they get?*



0-20 MeV with constant 50 µm source size

Real micro-tromography 1µm resolution ~400 keV

One system fully tunable covering all the current range