EUROPEAN
PLASMA RESEARCH
ACCELERATOR WITH
EXCELLENCE IN
APPLICATIONS

EuPRAXIA
Preparatory Phase

High energy physics and detector testing applications at EuPRAXIA

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This project has received funding from the European Union´s Horizon Europe research and innovation programme under grant agreement No. 101079773

Applications of electron beams other than FEL

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- Applications of plasma generated radiation
  - imaging with betatron radiation -> EuAPS, EPAC, and many other
- With primary e- beam
  - test facility for bunch length diagnostics
  - medical (VHEE and ultra-high dose rate)
- Applications of primary & secondary e- beam high energy physics (HEP)
  - low E positron -> material science (e.g. PALS)
  - high E positrons -> positrons source for PA collider studies
  - high flux, high flux density: HE EM shower “simulation” in the lab
  - high flux, low flux density: big detector module calibration, timing, pile-up

Funded by the European Union

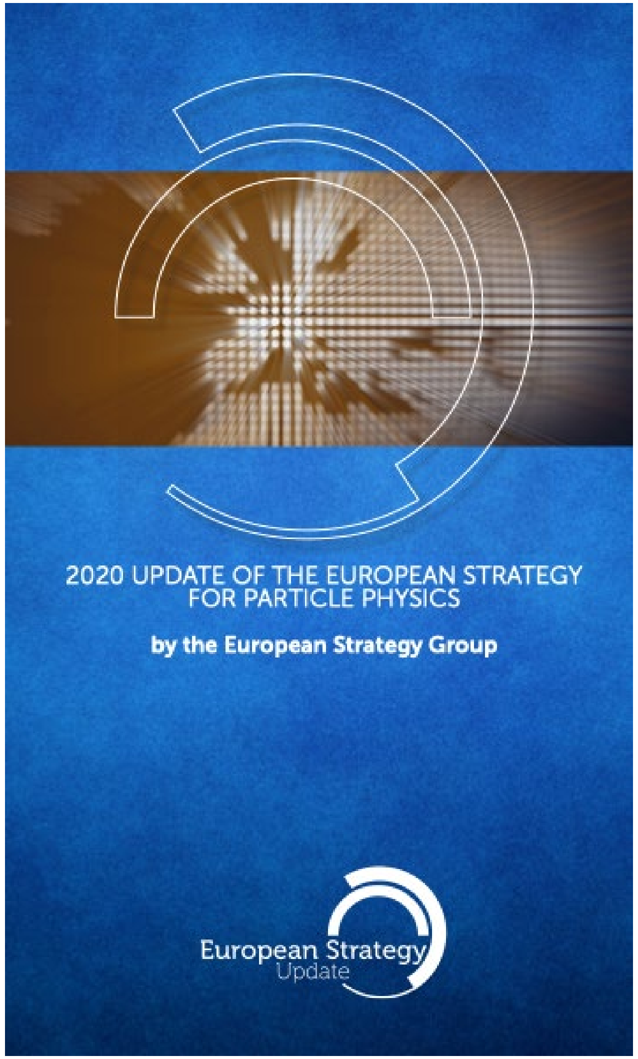
Detector R&D and testing are vital

- **ESPP 2020 Update:**

Detector R&D programmes and associated infrastructures should be supported at CERN, national institutes, laboratories and universities. ***Synergies between the needs of different scientific fields and industry should be identified and exploited*** *to boost efficiency in the development process and increase opportunities for more technology transfer benefiting society at large. Collaborative platforms and consortia must be adequately supported to provide coherence in these R&D activities.*

- **P5 report (Snowmass 2021):**

Test beams *and irradiation facilities[…])****are a vital element*** *of detector technology development and should be supported.*



2020 UPDATE OF THE EUROPEAN STRATEGY FOR PARTICLE PHYSICS

by the European Strategy Group

European Strategy Update

HEP detector testing & calibration with PA

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- modern big particle detectors require extensive R&D, simulation and testing
- test beams are available only at big accelerator labs (CERN, FNAL, DESY, LNF,…)
- e- from PA may pioneer complementary ways to test & calibrate detectors

but there are considerable differences:

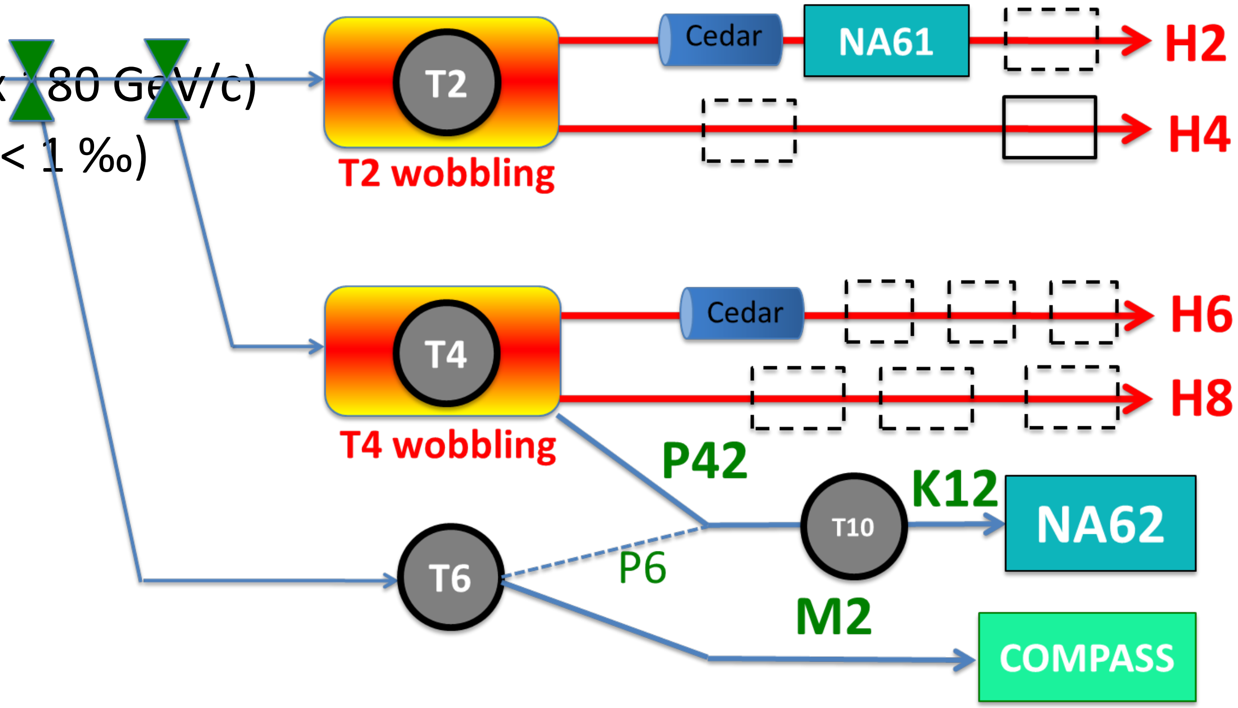
- in conventional test beams
  - variety of available particles: $\pi^{\pm}$, $K^{\pm}$, p, n, $\mu^{\pm}$, $e^{\pm}$, gamma
  - particles arrive randomly «one at a time» (= time that can be resolved by the detector, e.g. 1000 in 1sec), low average current, low pile-up (desired)
- in plasma accelerator generated beams (in framework of EuPRAXIA)
  - only electrons (primary beam)
  - electrons arrive at the same time: massive “pile-up”, $p < 5$–10 GeV/c

-> turn differences to advantages

currently available test beams

classical demand: **measure single-particle response of a detector (module) with high statistical precision**

- example: CERN North Area secondary beam
    - SPS: p(450GeV) ➔ primary target ➔ π^+,π^-,π^0
    - π^+,π^- ➔ secondary target ➔ $\mu^+\ \mu^-$, neutrinos
    - π^0 ➔ decay to 2γ ➔ secondary target ➔ e^+,e^- (max 180 GeV/c)
    - energy selection by dipole and collimator slit ($\Delta p/p < 1$ ‰)
    - one SPS "spill" (4sec) every 17sec
    - also: ions, neutrons, kaons, ….
- users are happy with (and actually want)
    - less than one particle every few ns (on average)
- large panel of users
    - physics experiments
    - particle detector development and calibration



Snowmass 21 survey of TB needs and

*) and irradiation facilities

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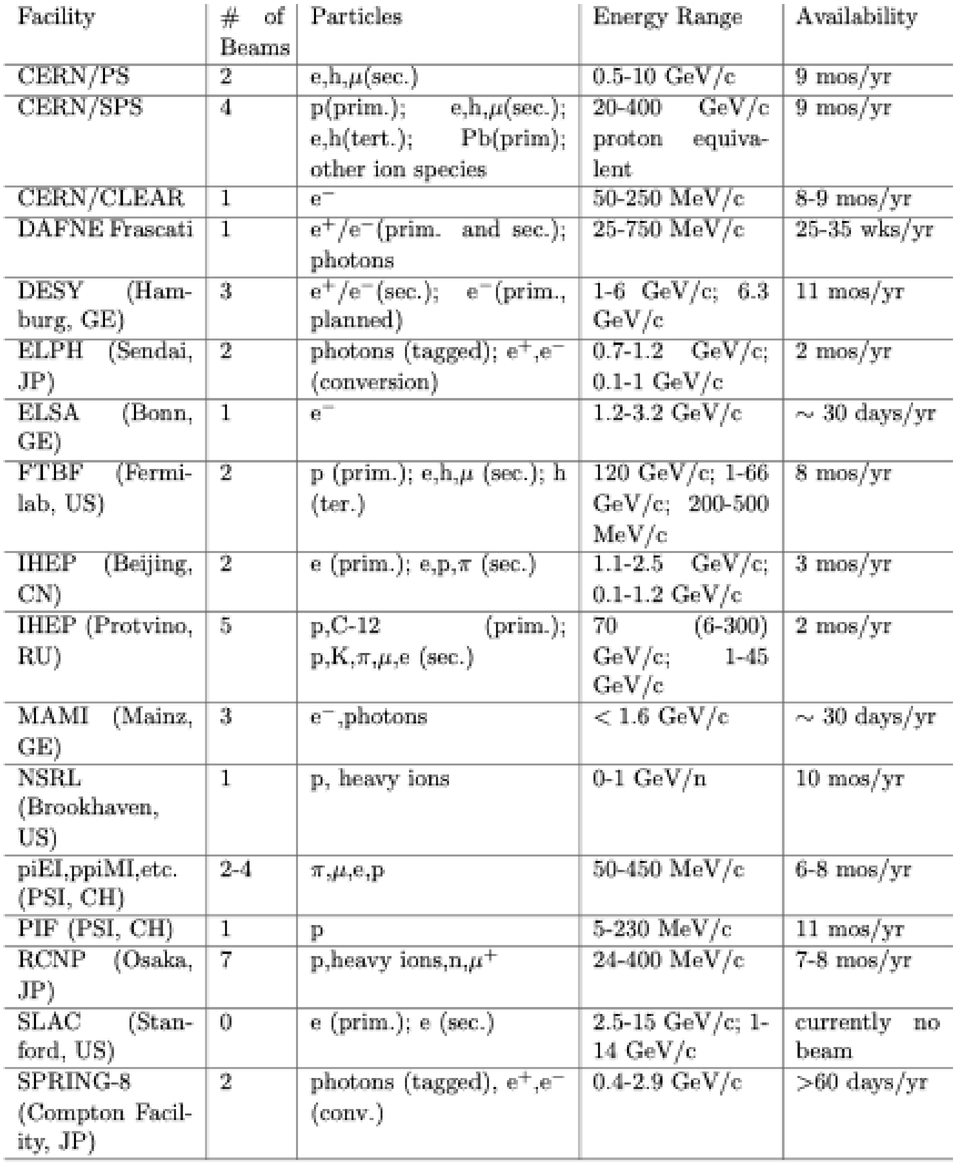
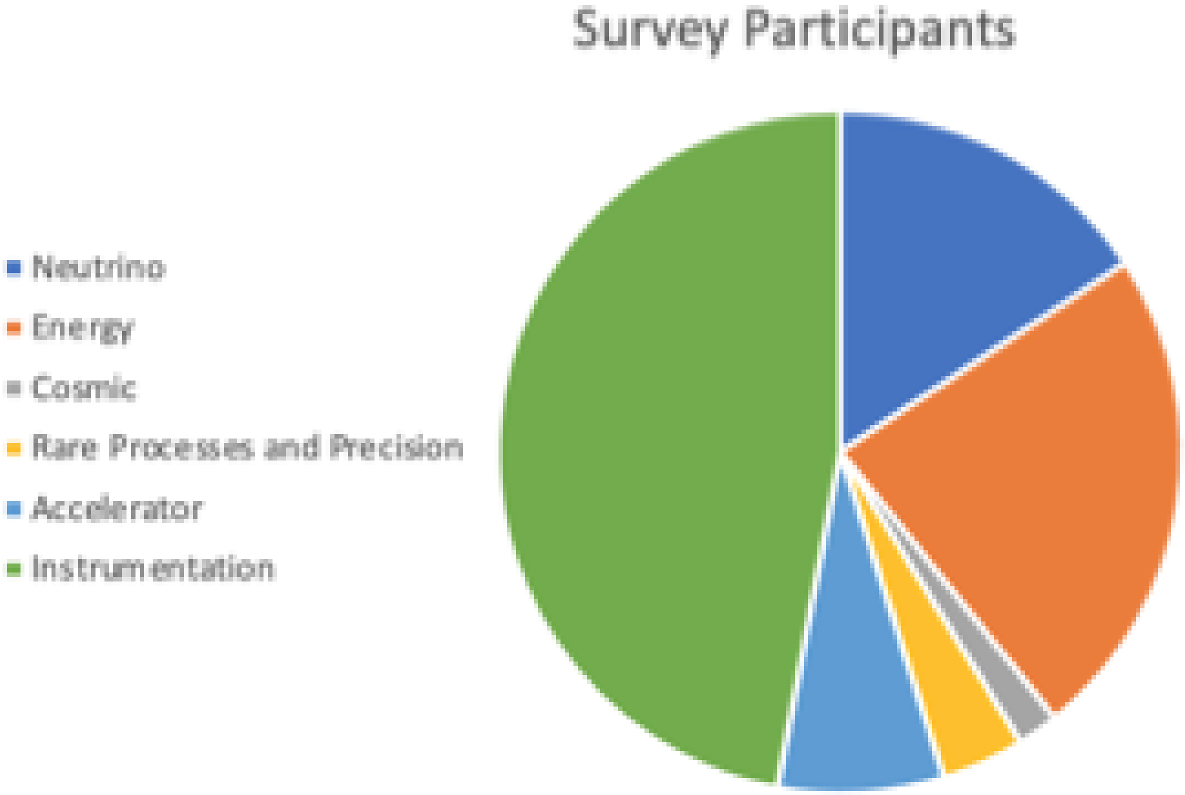


Facility	# of Beams	Particles	Energy Range	Availability
CERN/PS	2	e,h,μ(sec.)	0.5-10 GeV/c	9 mos/yr
CERN/SPS	4	p(prim.); e,h,μ(sec.); e,h(tert.); Pb(prim); other ion species	20-400 GeV/c proton equivalent	9 mos/yr
CERN/CLEAR	1	e^-	50-250 MeV/c	8-9 mos/yr
DAFNE Frascati	1	e^+/e^-(prim. and sec.); photons	25-750 MeV/c	25-35 wks/yr
DESY (Hamburg, GE)	3	e^+/e^-(sec.); e^-(prim., planned)	1-6 GeV/c; 6.3 GeV/c	11 mos/yr
ELPH (Sendai, JP)	2	photons (tagged); e^+,e^- (conversion)	0.7-1.2 GeV/c; 0.1-1 GeV/c	2 mos/yr
ELSA (Bonn, GE)	1	e^-	1.2-3.2 GeV/c	$\sim$ 30 days/yr
FTBF (Fermilab, US)	2	p (prim.); e,h,μ (sec.); h (ter.)	120 GeV/c; 1-66 GeV/c; 200-500 MeV/c	8 mos/yr
IHEP (Beijing, CN)	2	e (prim.); e,p,π (sec.)	1.1-2.5 GeV/c; 0.1-1.2 GeV/c	3 mos/yr
IHEP (Protvino, RU)	5	p,C-12 (prim.); p,K,π,μ,e (sec.)	70 (6-300) GeV/c; 1-45 GeV/c	2 mos/yr
MAMI (Mainz, GE)	3	e^-,photons	$<$ 1.6 GeV/c	$\sim$ 30 days/yr
NSRL (Brookhaven, US)	1	p, heavy ions	0-1 GeV/n	10 mos/yr
piEI,ppiMI,etc. (PSI, CH)	2-4	π,μ,e,p	50-450 MeV/c	6-8 mos/yr
PIF (PSI, CH)	1	p	5-230 MeV/c	11 mos/yr
RCNP (Osaka, JP)	7	p,heavy ions,n,μ^+	24-400 MeV/c	7-8 mos/yr
SLAC (Stanford, US)	0	e (prim.); e (sec.)	2.5-15 GeV/c; 1-14 GeV/c	currently no beam
SPRING-8 (Compton Facility, JP)	2	photons (tagged), e^+,e^- (conv.)	0.4-2.9 GeV/c	>60 days/yr

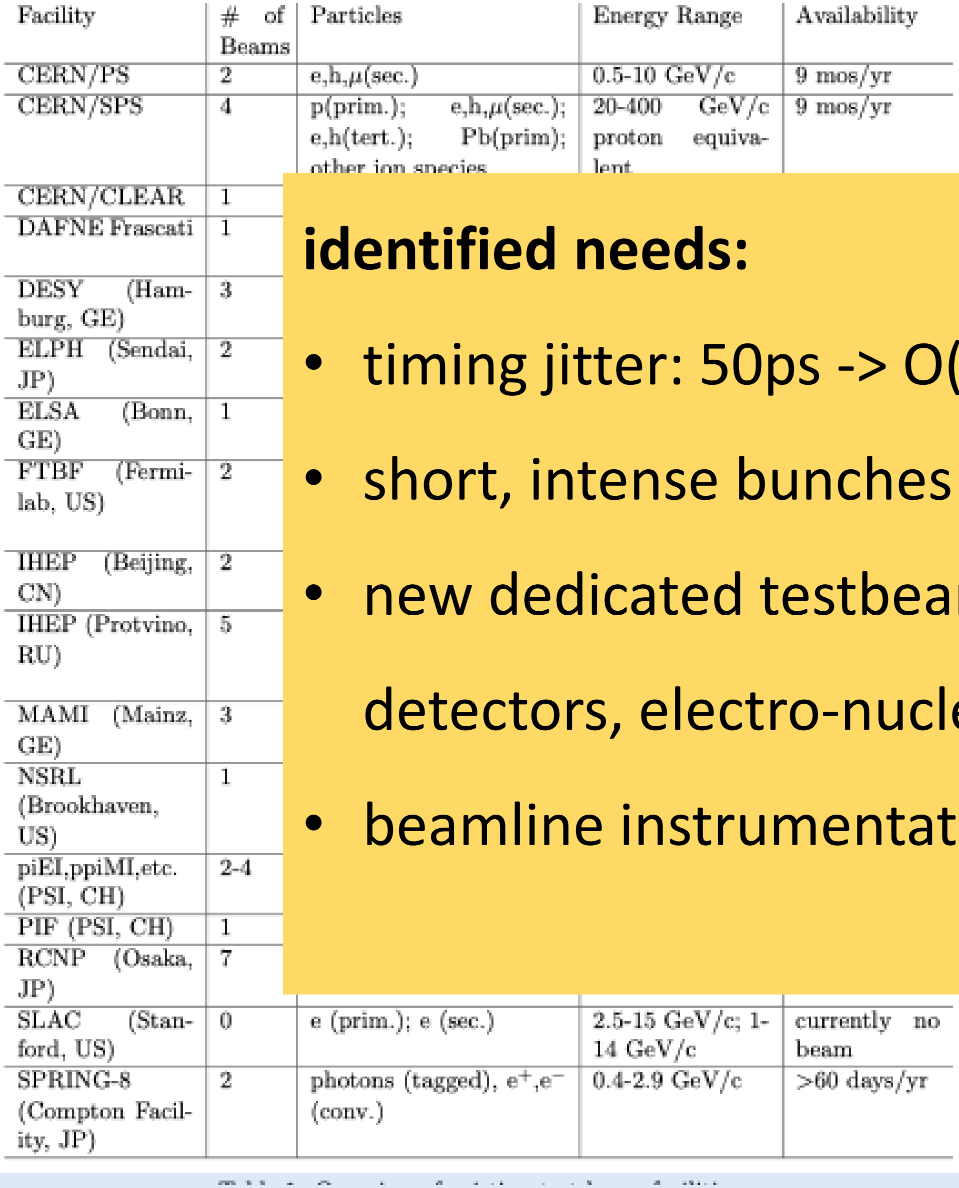


M. Hartz, et al., Proceedings of Snowmass 2021

arXiv:2203.09944v1 [physics.acc-ph] 16 Mar 2022

Snowmass 21 survey of TB*) needs and

*) and irradiation facilities



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CERN/CLEAR	1			
DAFNE Frascati	1			
DESY (Hamburg, GE)	3			
ELPH (Sendai, JP)	2			
ELSA (Bonn, GE)	1			
FTBF (Fermilab, US)	2			
IHEP (Beijing, CN)	2			
IHEP (Protvino, RU)	5			
MAMI (Mainz, GE)	3			
NSRL (Brookhaven, US)	1			
piEI,ppiMI,etc. (PSI, CH)	2-4			
PIF (PSI, CH)	1			
RCNP (Osaka, JP)	7			
SLAC (Stanford, US)	0	e (prim.); e (sec.)	2.5-15 GeV/c; 1-14 GeV/c	currently no beam
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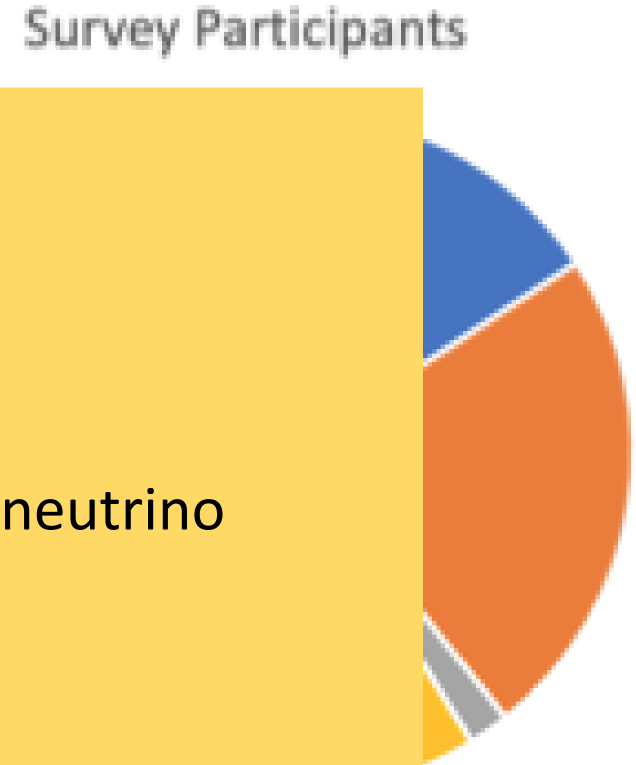
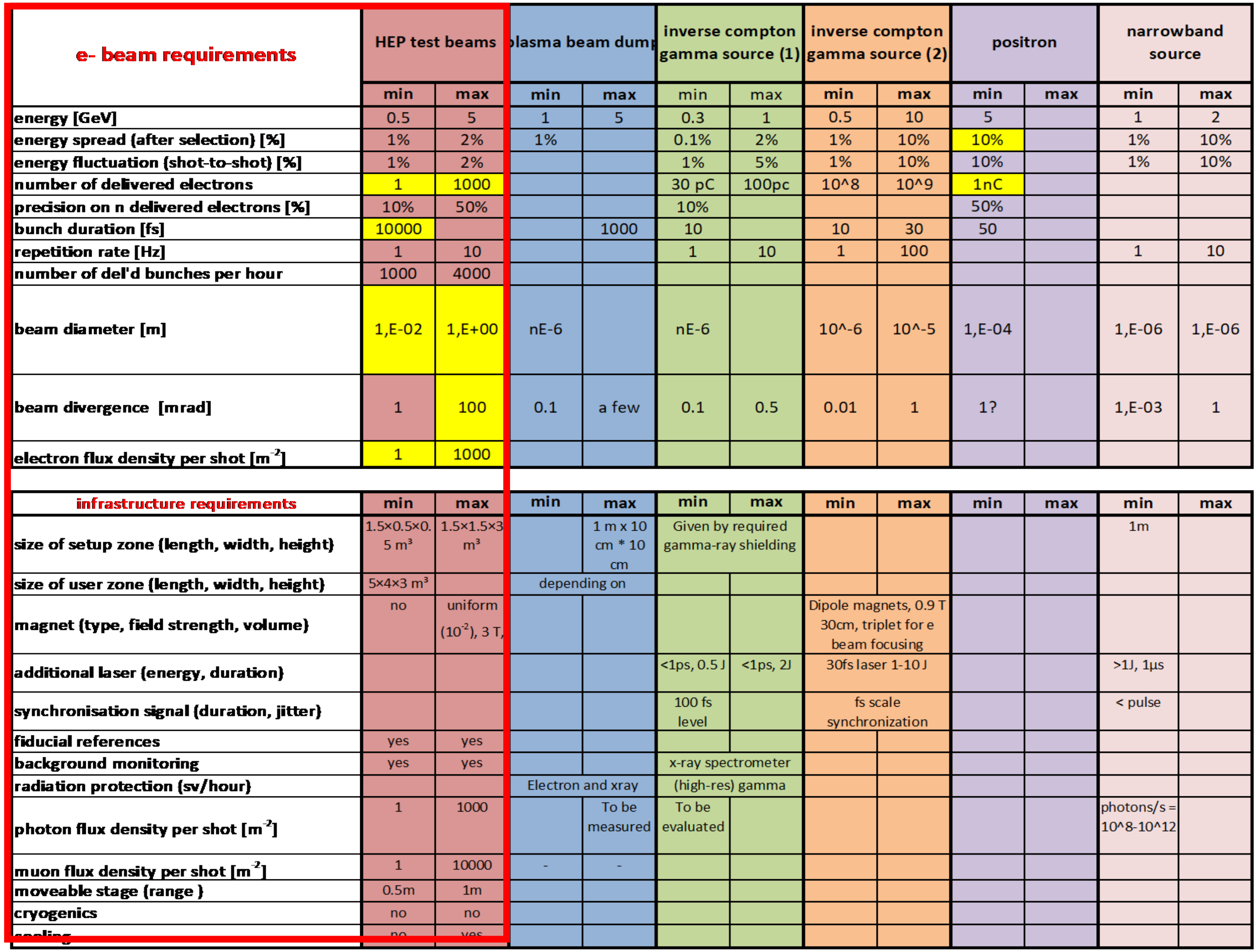


identified needs:

- timing jitter: 50ps -> O(1ps)
- short, intense bunches
- new dedicated testbeams, e.g. for water Cherenkov neutrino detectors, electro-nuclear scattering
- beamline instrumentation

M. Hartz, et al., Proceedings of Snowmass 2021
arXiv:2203.09944v1 [physics.acc-ph] 16 Mar 2022

EuPRAXIA: HEP test beam requirements



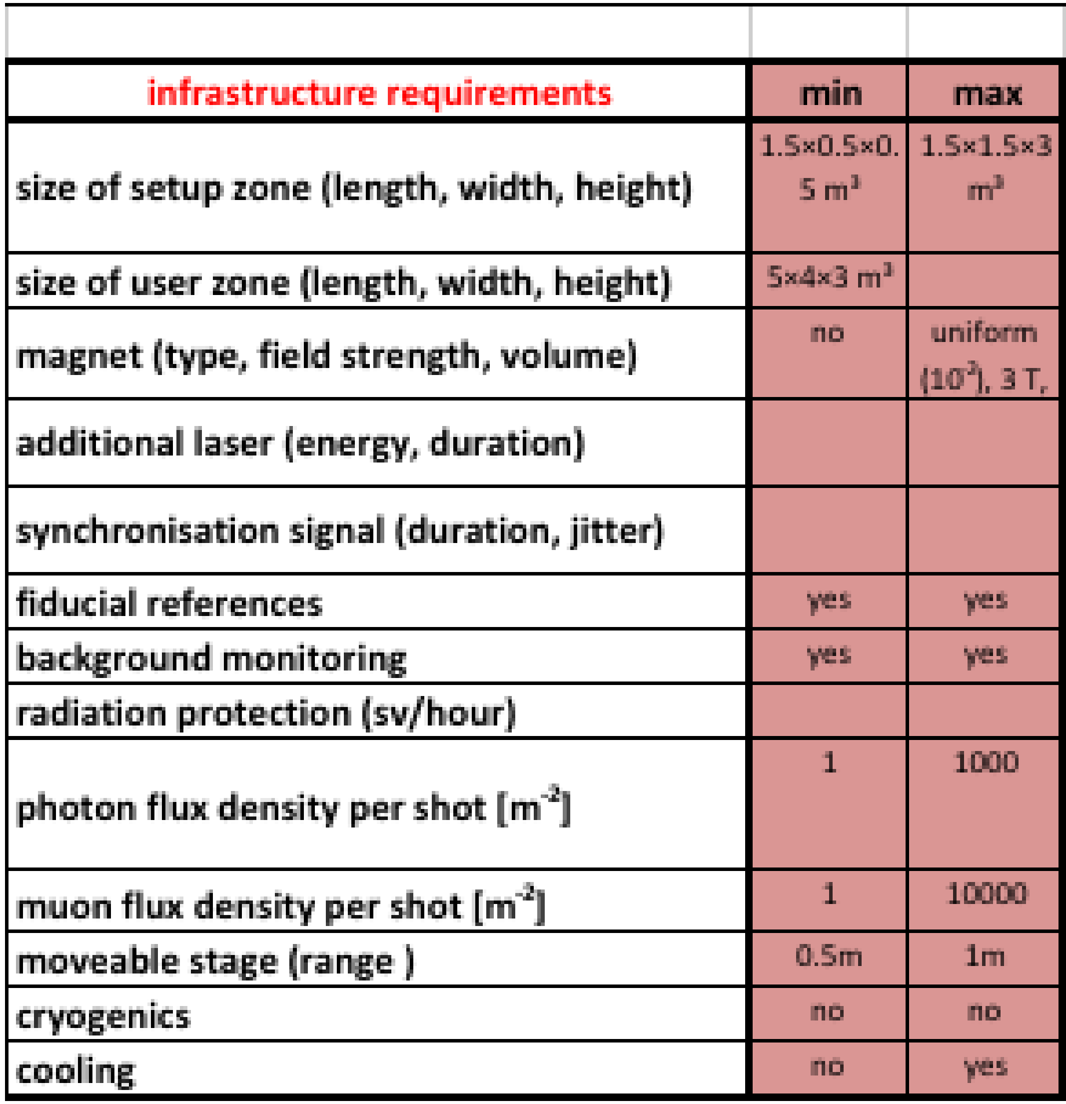
e- beam requirements	HEP test beams		lasma beam dum		inverse compton gamma source (1)		inverse compton gamma source (2)		positron		narrowband source	
	min	max	min	max	min	max	min	max	min	max	min	max
energy [GeV]	0.5	5	1	5	0.3	1	0.5	10	5		1	2
energy spread (after selection) [%]	1%	2%	1%		0.1%	2%	1%	10%	10%		1%	10%
energy fluctuation (shot-to-shot) [%]	1%	2%			1%	5%	1%	10%	10%		1%	10%
number of delivered electrons	1	1000			30 pC	100pc	10^8	10^9	1nC			
precision on n delivered electrons [%]	10%	50%			10%				50%			
bunch duration [fs]	10000			1000	10		10	30	50			
repetition rate [Hz]	1	10			1	10	1	100			1	10
number of del'd bunches per hour	1000	4000										
beam diameter [m]	1,E-02	1,E+00	nE-6		nE-6		10^-6	10^-5	1,E-04		1,E-06	1,E-06
beam divergence [mrad]	1	100	0.1	a few	0.1	0.5	0.01	1	1?		1,E-03	1
electron flux density per shot [m^{-2}]	1	1000										

infrastructure requirements	min	max	min	max	min	max	min	max	min	max	min	max
size of setup zone (length, width, height)	1.5×0.5×0.5 m³	1.5×1.5×3 m³		1 m x 10 cm * 10 cm	Given by required gamma-ray shielding						1m	
size of user zone (length, width, height)	5×4×3 m³		depending on									
magnet (type, field strength, volume)	no	uniform (10^{-2}), 3 T,					Dipole magnets, 0.9 T 30cm, triplet for e beam focusing					
additional laser (energy, duration)					<1ps, 0.5 J	<1ps, 2J	30fs laser 1-10 J				>1J, 1µs	
synchronisation signal (duration, jitter)					100 fs level		fs scale synchronization				< pulse	
fiducial references	yes	yes										
background monitoring	yes	yes			x-ray spectrometer							
radiation protection (sv/hour)			Electron and xray		(high-res) gamma							
photon flux density per shot [m^{-2}]	1	1000		To be measured	To be evaluated						photons/s = 10^8-10^12	
muon flux density per shot [m^{-2}]	1	10000	-	-								
moveable stage (range)	0.5m	1m										
cryogenics	no	no										
cooling	no	yes										

PAEPA Workshop Oct 2016 Paris,
Pilot Applications of electron plasma accelerators

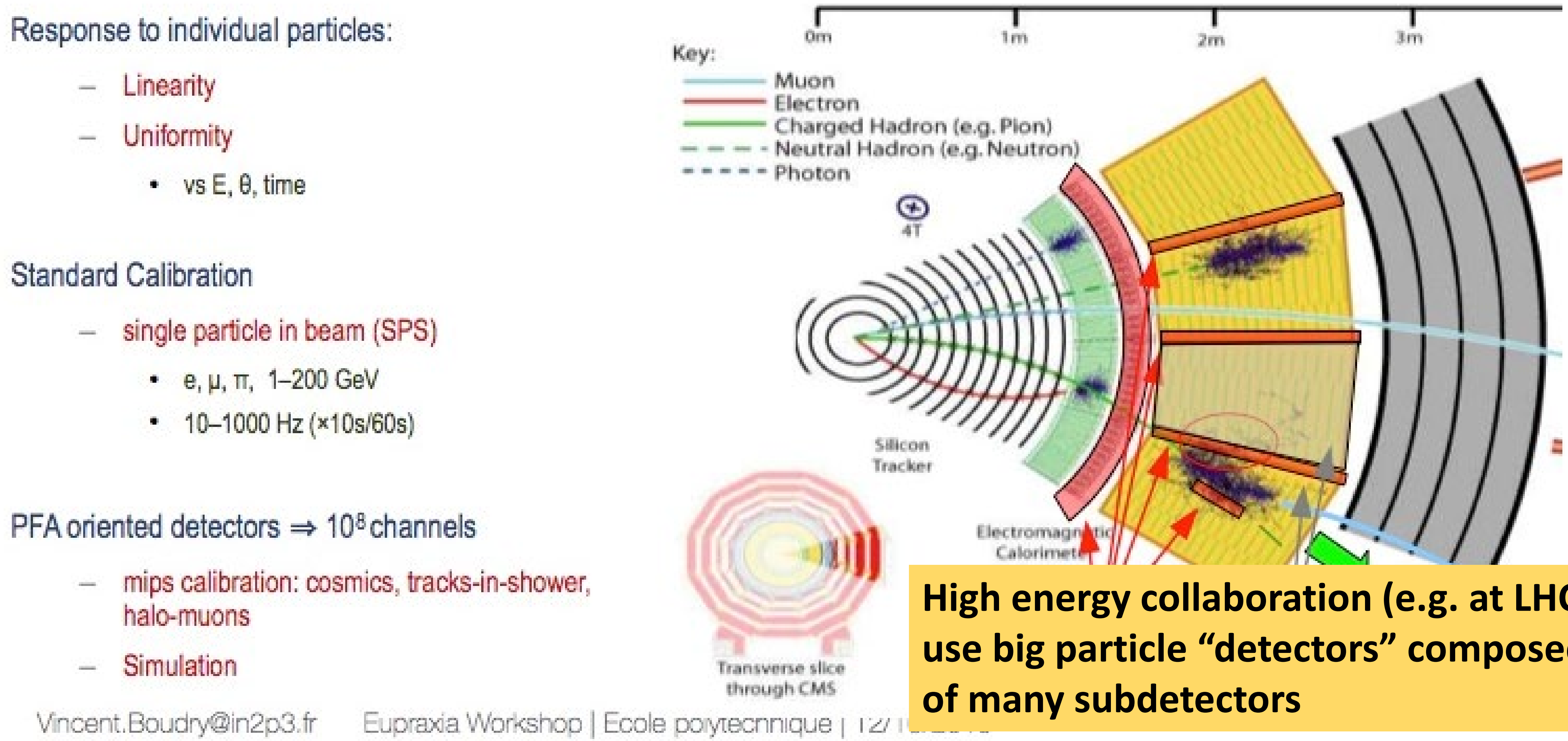
EuPRAXIA: HEP user area requirements

- (!!!) Manipulation space (50m^2,4m height)
- (!!!) Timing signal (laser sync)
- (!!) Flux monitor with ind. particle capability
- (!) wide area pos. sensitive detector (tracker)
- (!!!) Crane and (!) moveable table
- (!!) Cooling water



infrastructure requirements	min	max
size of setup zone (length, width, height)	1.5×0.5×0.5 m^3	1.5×1.5×3 m^3
size of user zone (length, width, height)	5×4×3 m^3	
magnet (type, field strength, volume)	no	uniform (10^3), 3 T,
additional laser (energy, duration)		
synchronisation signal (duration, jitter)		
fiducial references	yes	yes
background monitoring	yes	yes
radiation protection (sv/hour)		
photon flux density per shot [m^{-2}]	1	1000
muon flux density per shot [m^{-2}]	1	10000
moveable stage (range)	0.5m	1m
cryogenics	no	no
cooling	no	yes

Example : Particle Flow Analysis oriented detectors (e.g. HGCAL, CALICE)



Response to individual particles:

- Linearity
- Uniformity
  - vs E, θ, time

Standard Calibration

- single particle in beam (SPS)
  - e, μ, π, 1–200 GeV
  - 10–1000 Hz (×10s/60s)

PFA oriented detectors ⇒ 10^8 channels

- mips calibration: cosmics, tracks-in-shower, halo-muons
- Simulation

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High energy collaboration (e.g. at LHC) use big particle "detectors" composed of many subdetectors

Use case 1: High flux density scanning of detector components/ detector cells

Particle Flow ⇒ Compact Showers

- ⇒ High density of particles in Shower core
  - (3000 mips in $5\times5\,\text{mm}^2$)
  - ⇒ sensitivity to small non-uniformities
    - Dead regions,
    - Special regions (e.g. Guard rings)
    - Electronics
    - Amplifiers

Pencil beams :

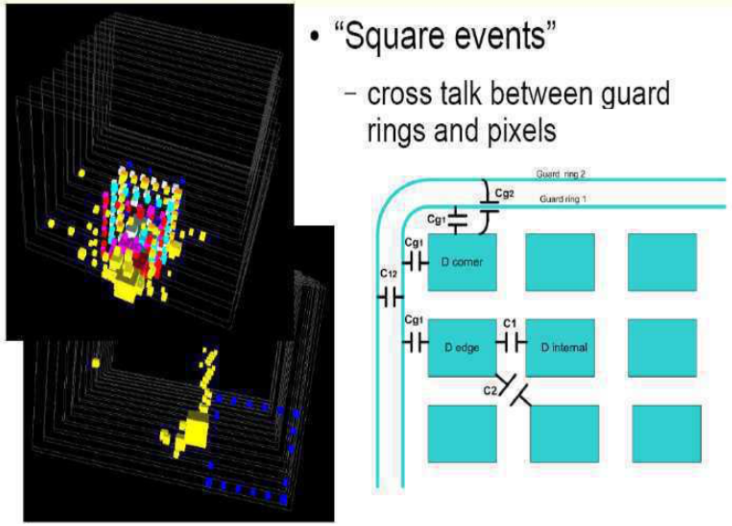
1000–10000 e^- (as mips ≥ 100 MeV) in a few $1\times1\,\text{mm}^2$ on thin elements

- Sensor studies (Scintillators, Silicon Wafers edges, μ-strips, local saturation [Birk's])
- SiPM, APD, ...
- Embedded ASICs (S.E.U.), FPGA, PCB, …

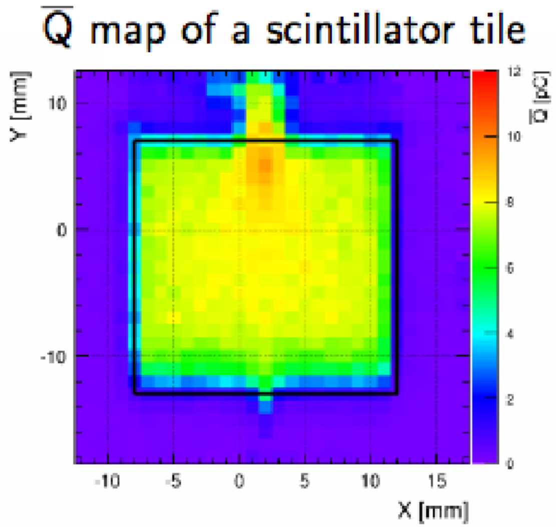
Q?

⇒ Collimator…

⇒ Measure of Nb(e-) ~ 10% ?



- "Square events"
  - cross talk between guard rings and pixels



$\overline{Q}$ map of a scintillator tile

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Lab simulation of high energy el.-mag. showers

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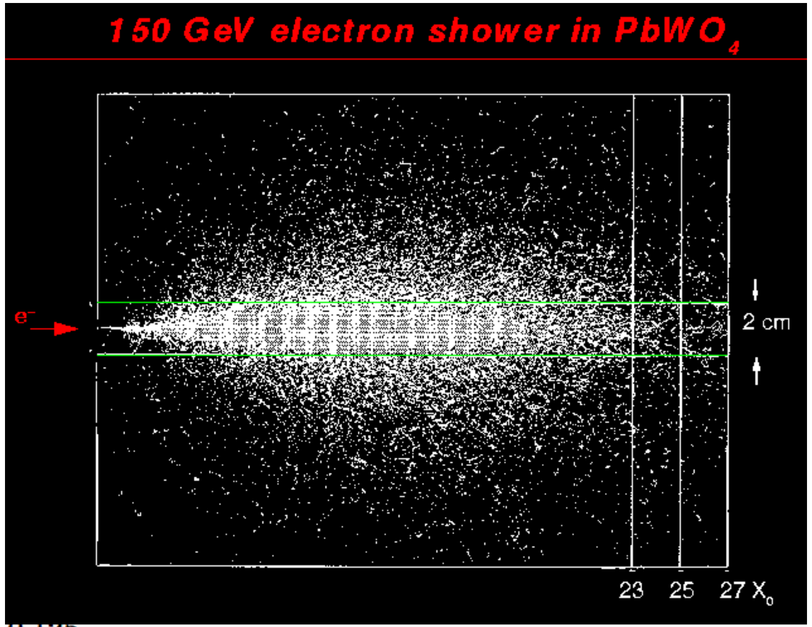
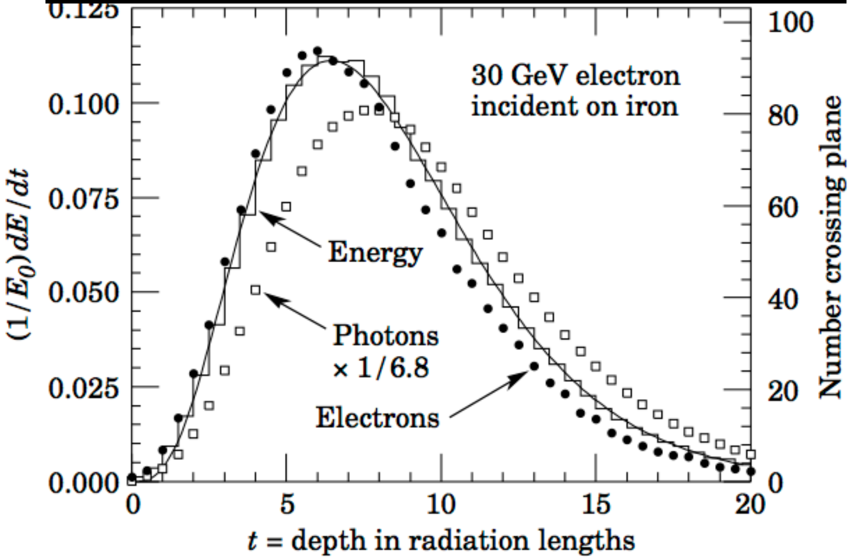
Calorimetry (in HEP):
measurement of single particle kinetic energy by total absorption ➔ particle shower

- **Motivation**
  - response linearity
  - readout saturation
  - detector calibration at unavailable energies
- **Method**
  - Produce bunch of N e- with identical energy E_e (by momentum selection)
  - Measure N precisely (enough): $\Delta E_B \sim \Delta N/N \times E_B$
  - concentrate to spot of the size of an EM shower after a few X0
  - What bunch characteristics are needed to simulate best energy deposit of one particle E_0?





turn differences to advantages (1)

- High flux (10^3-10^4 e/shot) – high flux density -> **fine effects**
  -> study detailed active element response (saturation, linearity)
  -> study effect on embedded read-out electronics (ASICS)

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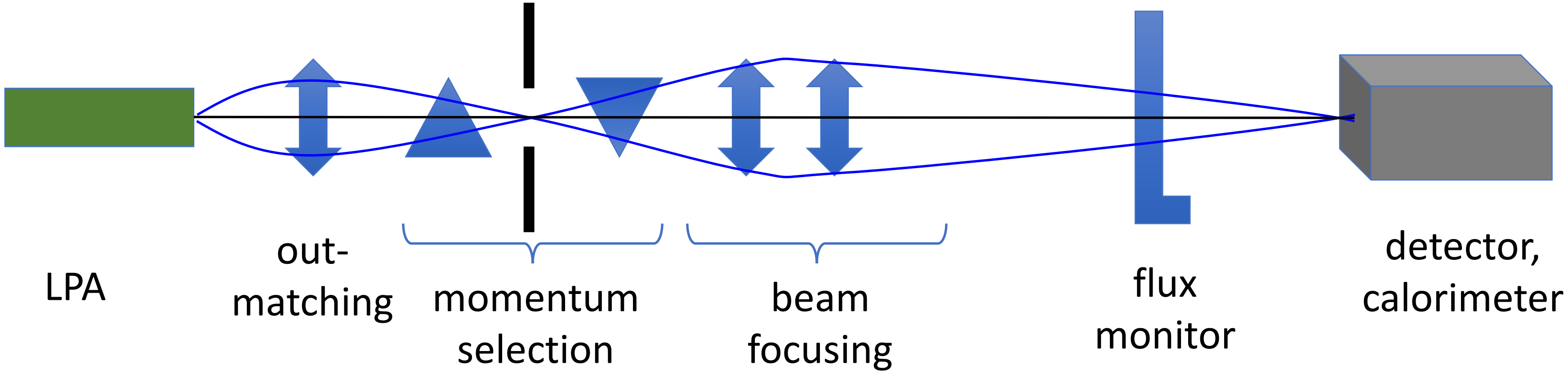
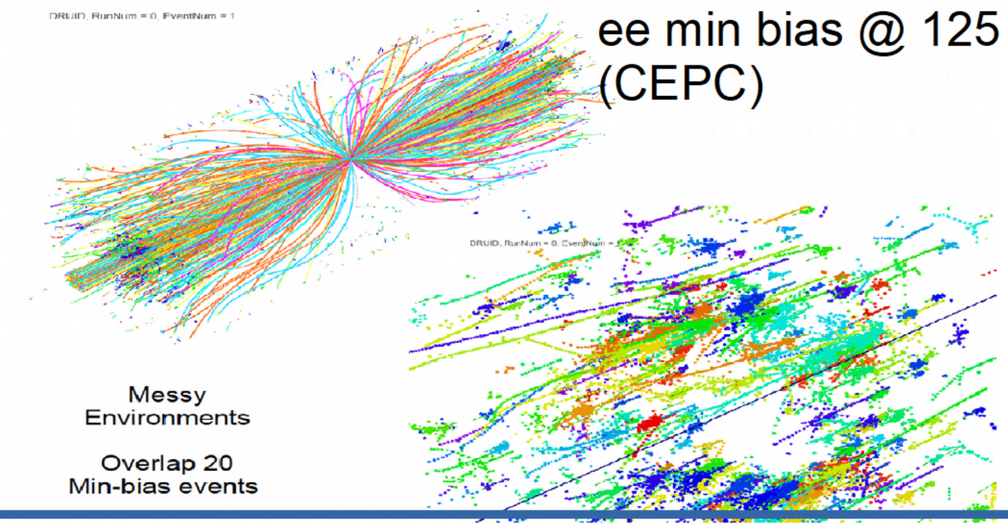
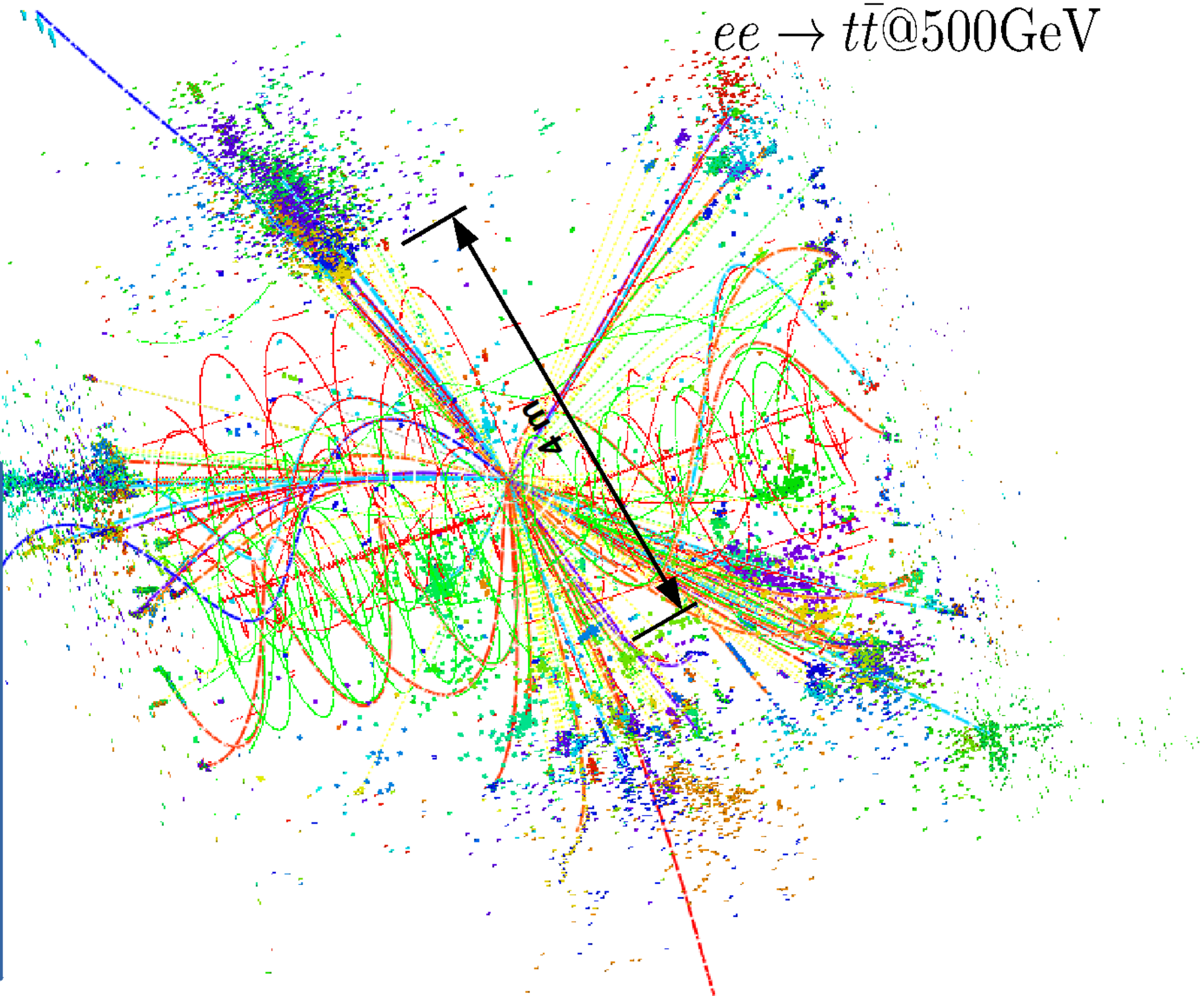


Use case 2: industrial calibration of a high granularity large detectors module



ee min bias @ 125 GeV (CEPC)


$ee \rightarrow t\bar{t}@500\mathrm{GeV}$

Electron Plasma Accel:

- ~1000 e- of 1–5 GeV on 1×1 m²
- max ☐dist(e-e)☐~ 2–3 R_M ~ 3 cm
  - position = tracker (TPC ?)

☐ Gain of 1000 in time; medium energy point for lin.
☐ Physical overlap of known particles (count by tracks);

- collective effects
- SW overlaps req. noise treatment

> On full calorimeter or single sensitive layer (e- as mips)

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turn differences to advantages (2)

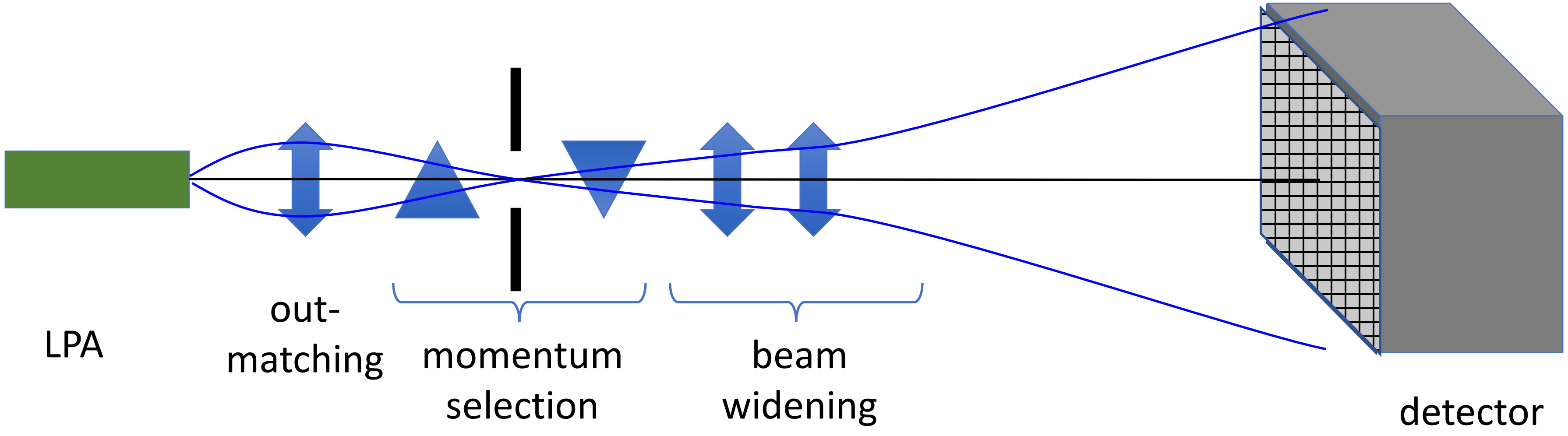
- High flux (10^3-10^4 e/shot) – high flux density -> **fine effects**
  -> study detailed active element response (saturation, linearity)
  -> study effect on embedded read-out electronics (ASICS)

- High flux (10^3-10^4 e/shot) – low flux density -> **faster/more stat**
  -> simultaneous irradiation instead of scanning
  -> no internal triggering capability required-> absolute calibration of timing uniformity -> DAQ stress testing in real condition

suitable for detectors with high granularity (particle separation capacity)

Testing particle detectors at high occupancies

- Trackers, calorimeters
  - in general: detectors with intrinsic particle separation capabilities
  - fine granularity: CMS HGCAL, CALICE, detectors
- occupancy: number of particles arriving simultaneously in one detector cell (transverse)



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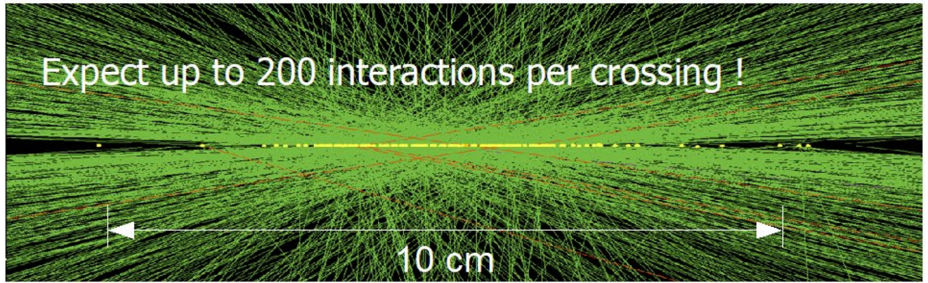
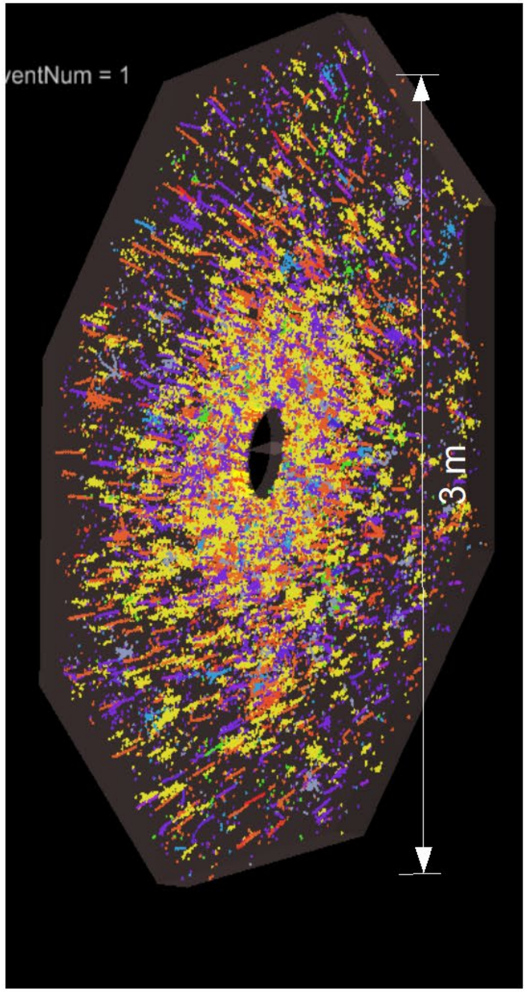
Use case 3: uniformity of timing response

High-Lumi LHC:

- HGCAL requir't


Expect up to 200 interactions per crossing !

- Spatial separation ⇒ -spacing of vertices down to ~ 500 mm == 150 ps
- test of calorimeters with 20–30 ps time resolution.
  - 10-15 ps in Clock distribution



EAP: 1000 particles en ≤ 10 ps

⇒ Time calibration (uniformity)

Q? possibility to generate Δt ~ 150 ps ? (chicane ?)

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turn differences to advantages (3)

- High flux (10^3-10^4 e/shot) – high flux density -> **fine effects**
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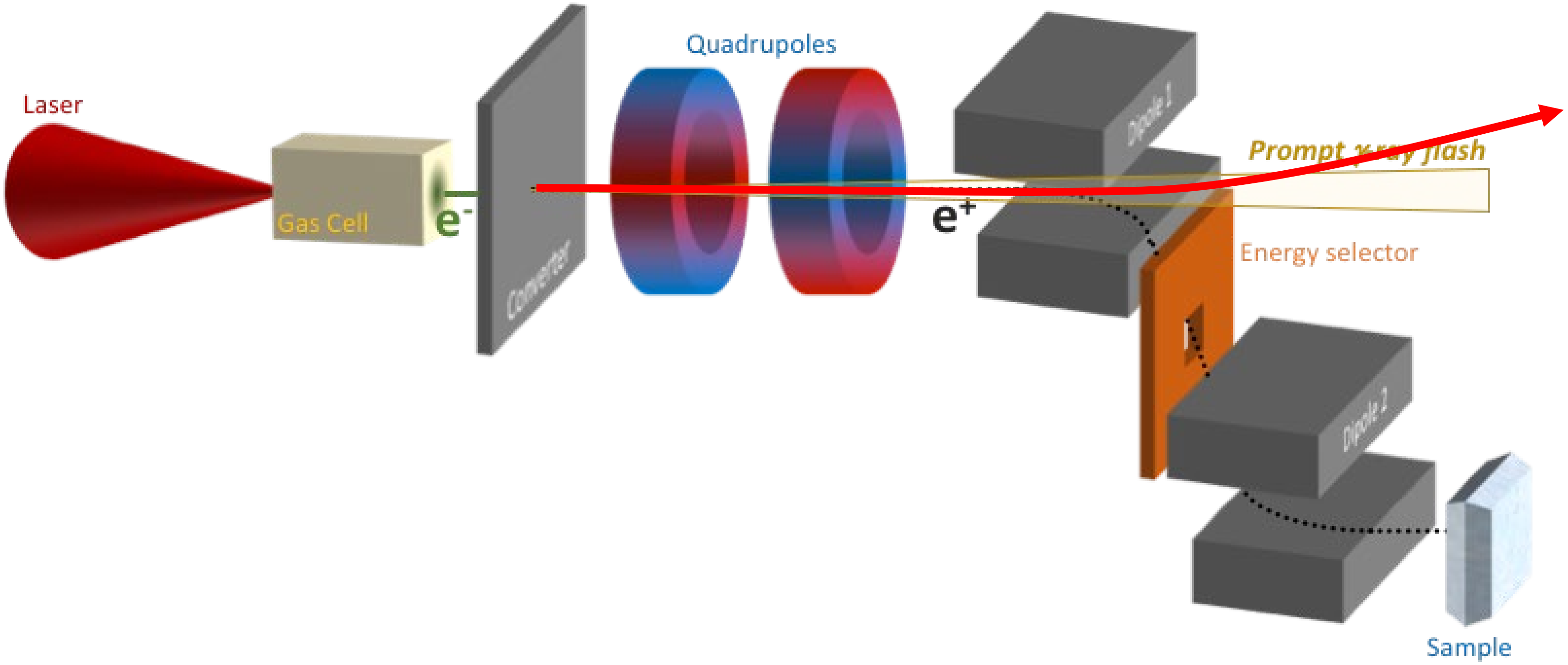
- High flux (10^3-10^4 e/shot) – low flux density -> **faster/more stat**
  -> simultaneous irradiation instead of scanning **unique selling point**
  -> no internal triggering capability required
    -> absolute calibration of timing uniformity **unique selling point**
  -> DAQ stress testing in real condition **unique selling point**

- Controlled bunch stretching (needs dedicated study)
  -> calibration of timing
    -> identification of interaction bunch

Feasibility study of controlled bunch lengthening to O(100ps) ?

Electron-positron cogeneration: e^- - arm



- **Use a dog-leg spectrometer to separate the high energy electrons and photons from the low energy positrons**

From Jim Clarke's presentation (EuPRAXIA week Frascati, Nov2018), source: Aarón Alejo, QUB

Challenges for HEP applications

- reducing the peak particle flux (➔ secondaries, momentum selection)
- focusing the selected beam to e.m. shower size dimensions
- expanding the beam to detector size
- Collimation, background and radiation protection studies (GEANT, BDSIM)
- Develop a robust flux monitoring (e.g. scintillator telescopes)

FEL is the flagship application.

HEP detector test beams for selected use cases could be “low hanging fruit” application

HEP detector test beams could help to promote PA in HEP community

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Thank you for your attention