Recent results from DESY on PWFA & Prospects for Future e^+e^- Colliders

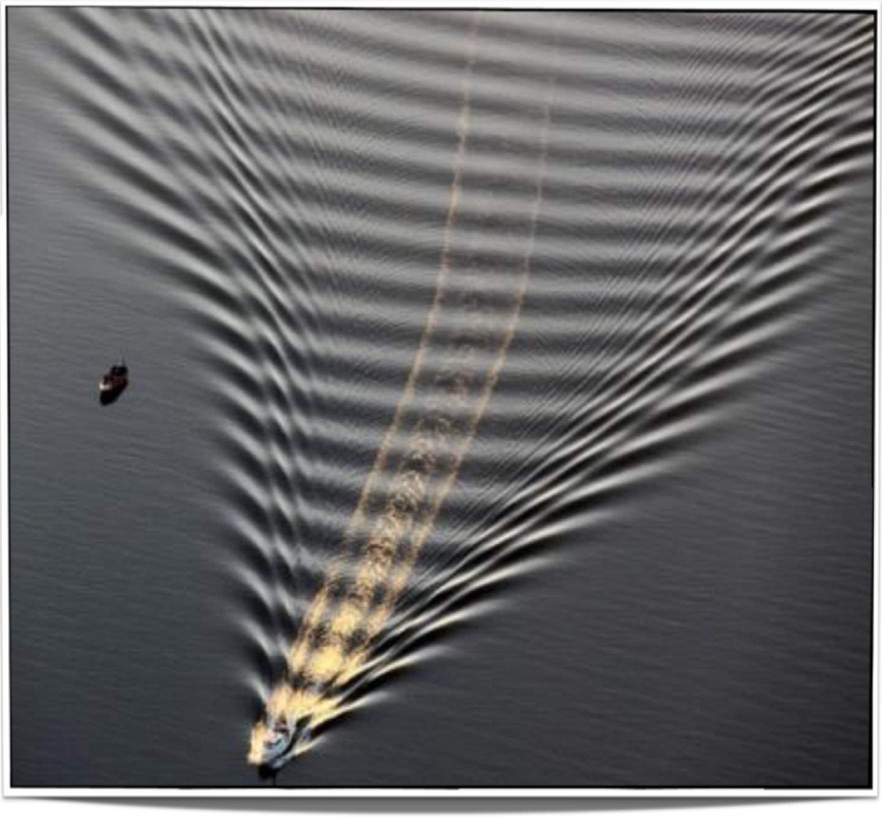
Brian Foster (Uni Hamburg/DESY/Oxford)

Humboldt Kolleg on Particle Physics
Mayfhofen
June 24th 2019

Outline

- **Plasma Acceleration**
- **FLASHForward@DESY**
- **European strategy - Granada in 3 slides**
- **ALEGRO - fast forward to the future**

Plasma Wave Acceleration

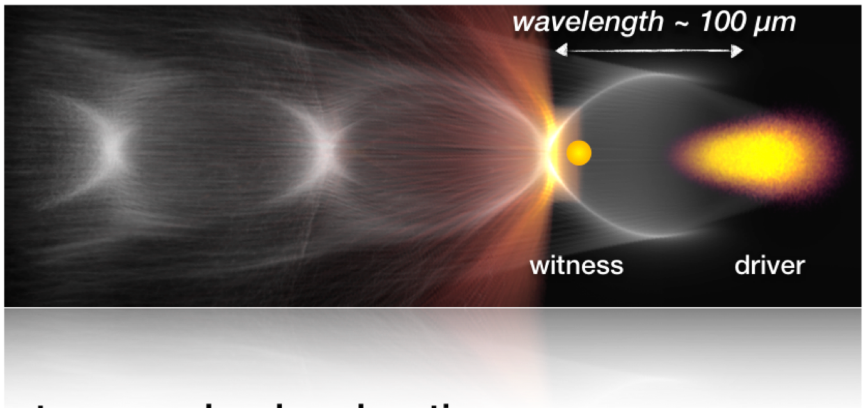


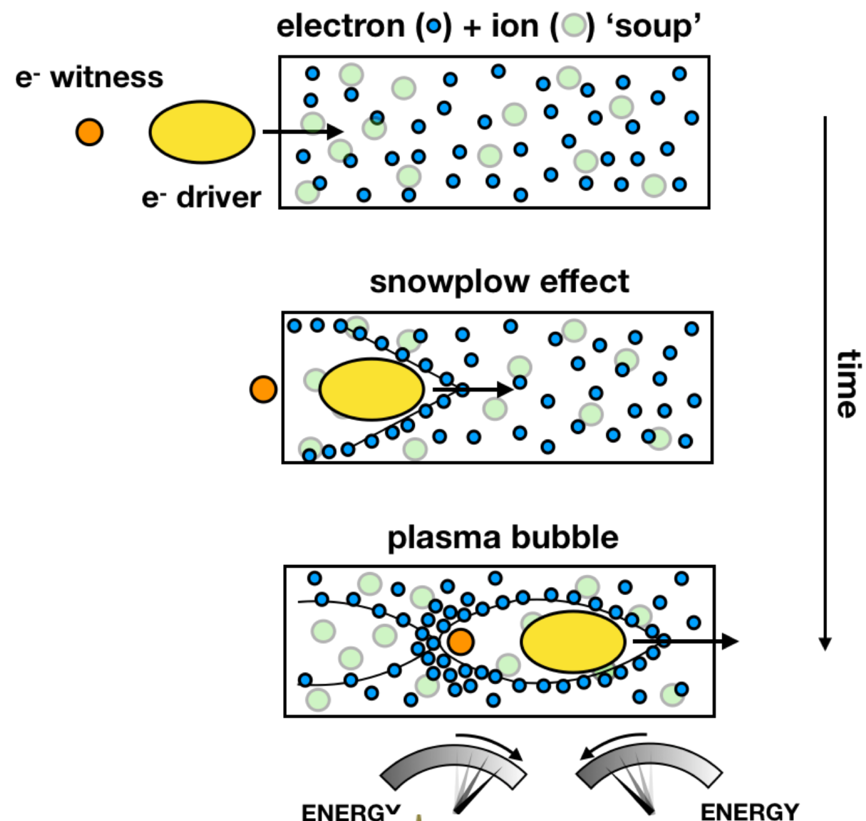
Wake excitation

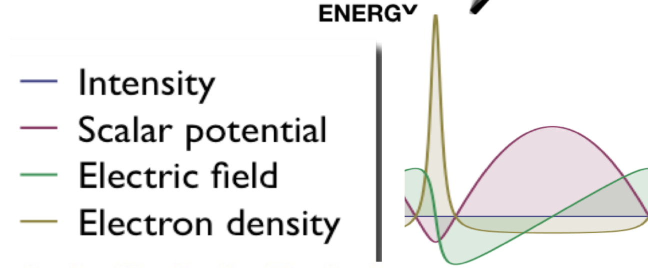
Particle injection

Plasma Wave Acceleration

Charge density wave in a plasma







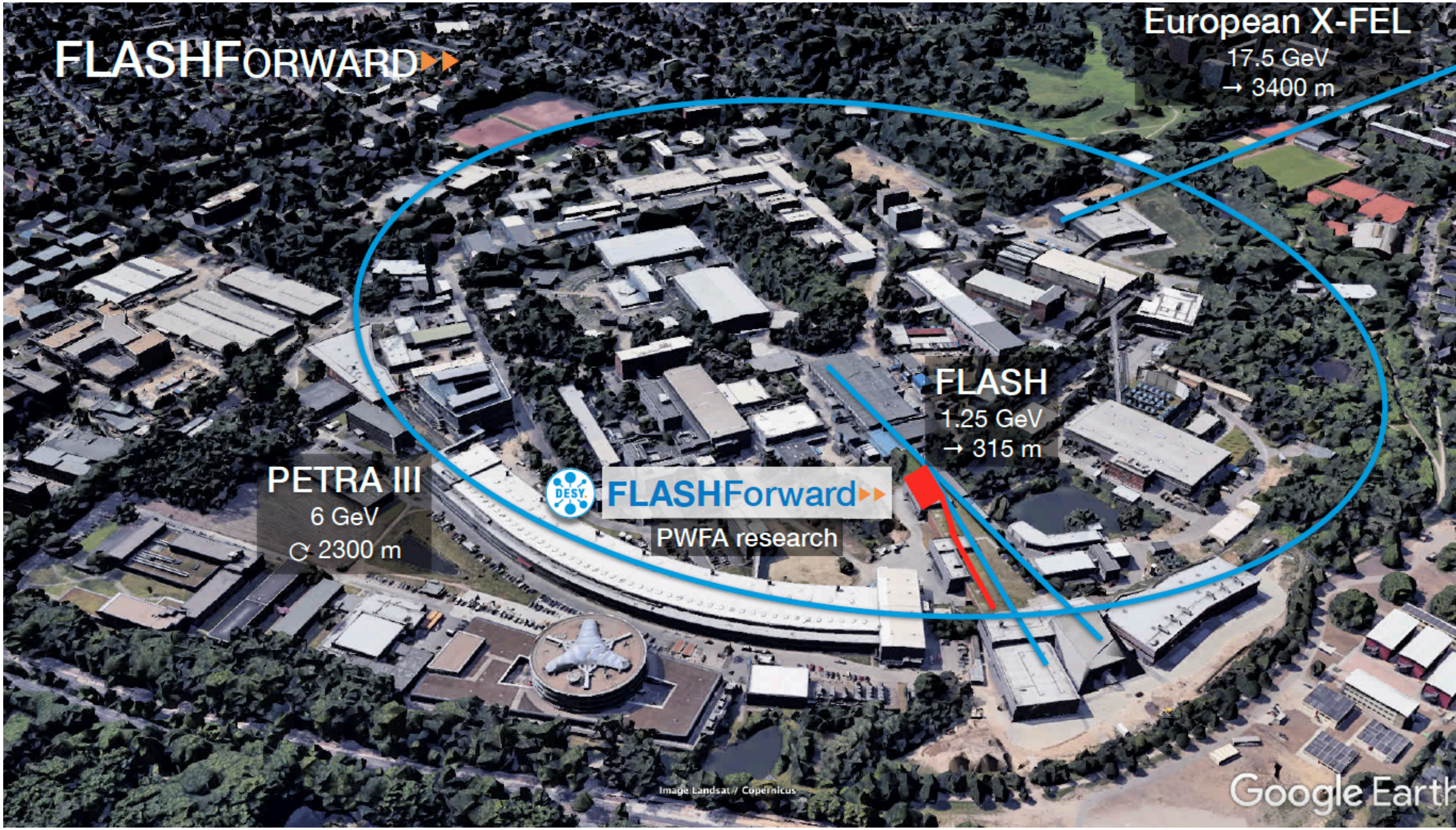
Femtosecond pulse duration

Intrinsically short due to short plasma wavelength

GV/m acceleration gradients

No surface quality limitations → **E_z in GV/m range**

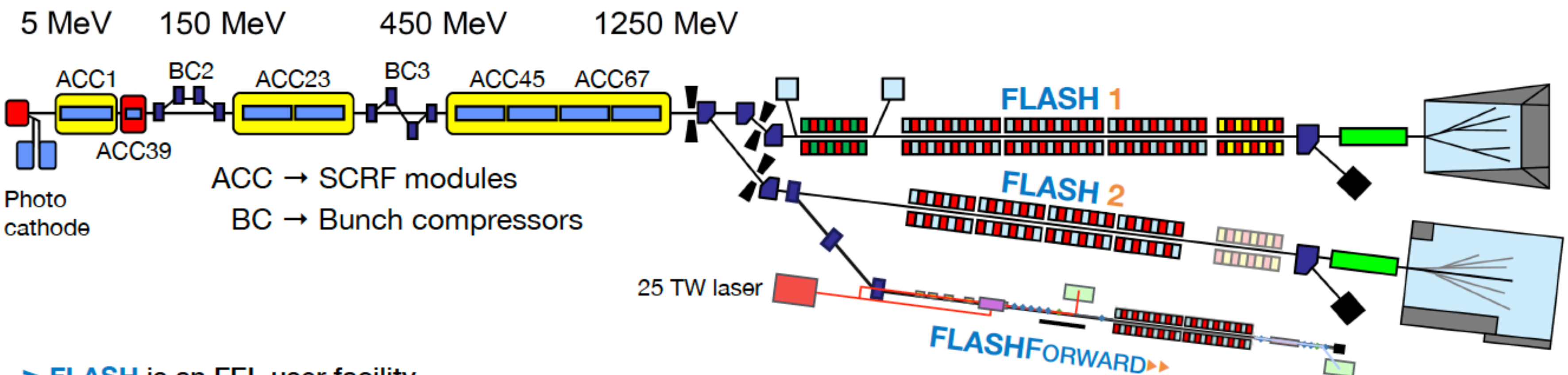
FLASHforward @ DESY



FLASHforward @ DESY

FLASHForward▸▸

The facility for high-quality, high-precision, high-average-power beam-driven PWFA science

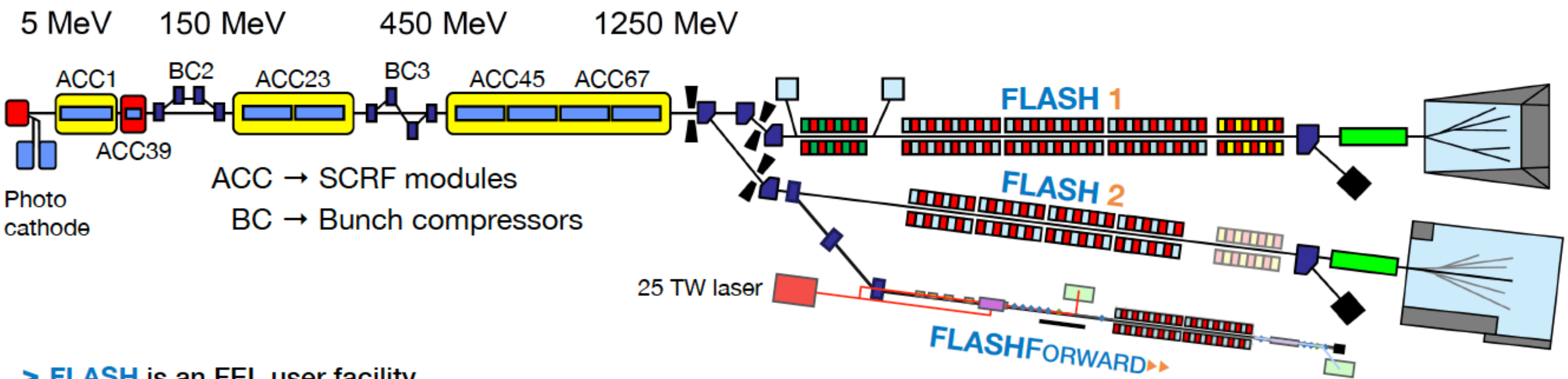


- FLASH is an FEL user facility
  - 10% of beam time (750 h / year) dedicated to accelerator research
- FLASHForward▸▸ is a beam line for PWFA research

FLASHforward @ DESY

FLASHFORWARD▸▸

THE FACILITY FOR HIGH-QUALITY, HIGH-PRECISION, HIGH-AVERAGE-POWER BEAM-DRIVEN PWFA SCIENCE



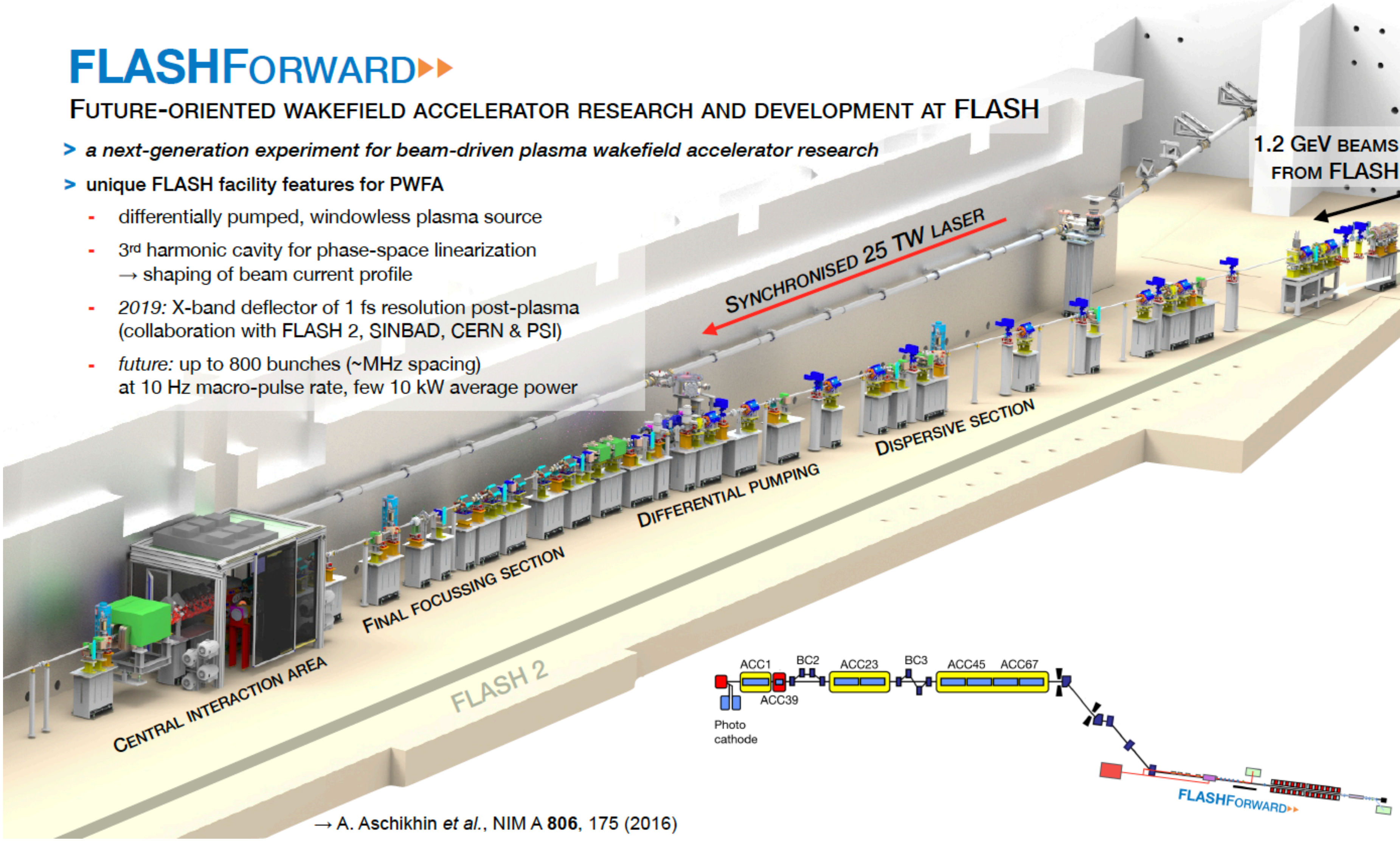
- **FLASH is an FEL user facility**
  - 10% of beam time (750 h / year) dedicated to accelerator research
- **FLASHForward▸▸ is a beam line for PWFA research**
- **Both share the same superconducting accelerator based on ILC/XFEL technology. Typical electron beam parameters:**
  - ≲ 1.25 GeV energy with a few 100 pC at ~100 fs rms bunch duration
  - ~2 µm trans. norm. emittance
  - Exquisite stability, timing, and reproducibility through FEL-standard feedback systems

FLASHforward @ DESY

FLASHForward▸▸

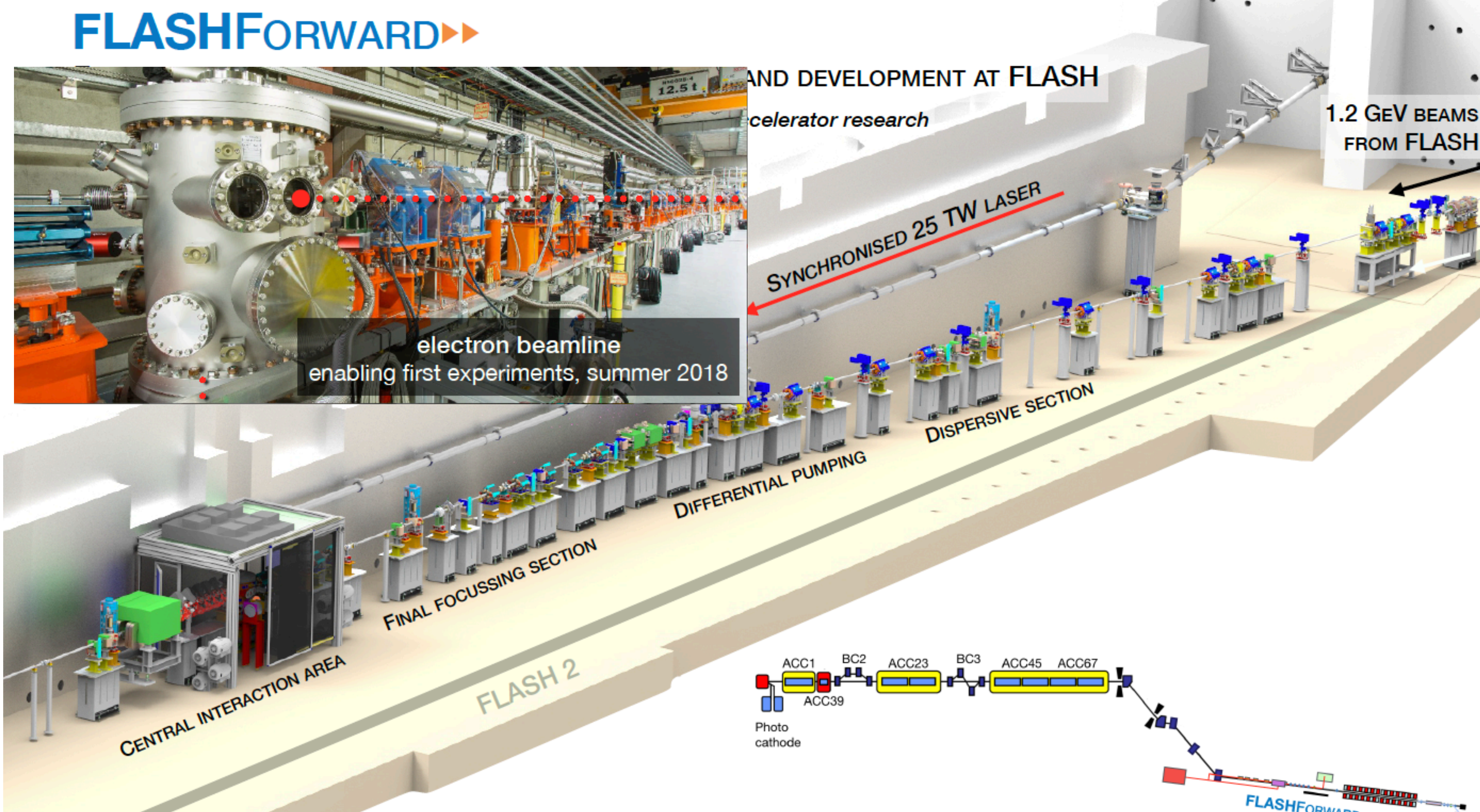
Future-oriented wakefield accelerator research and development at FLASH

- *a next-generation experiment for beam-driven plasma wakefield accelerator research*
- unique FLASH facility features for PWFA
  - differentially pumped, windowless plasma source
  - 3rd harmonic cavity for phase-space linearization → shaping of beam current profile
  - *2019:* X-band deflector of 1 fs resolution post-plasma (collaboration with FLASH 2, SINBAD, CERN & PSI)
  - *future:* up to 800 bunches (~MHz spacing) at 10 Hz macro-pulse rate, few 10 kW average power



→ A. Aschikhin *et al.*, NIM A **806**, 175 (2016)

FLASHforward @ DESY



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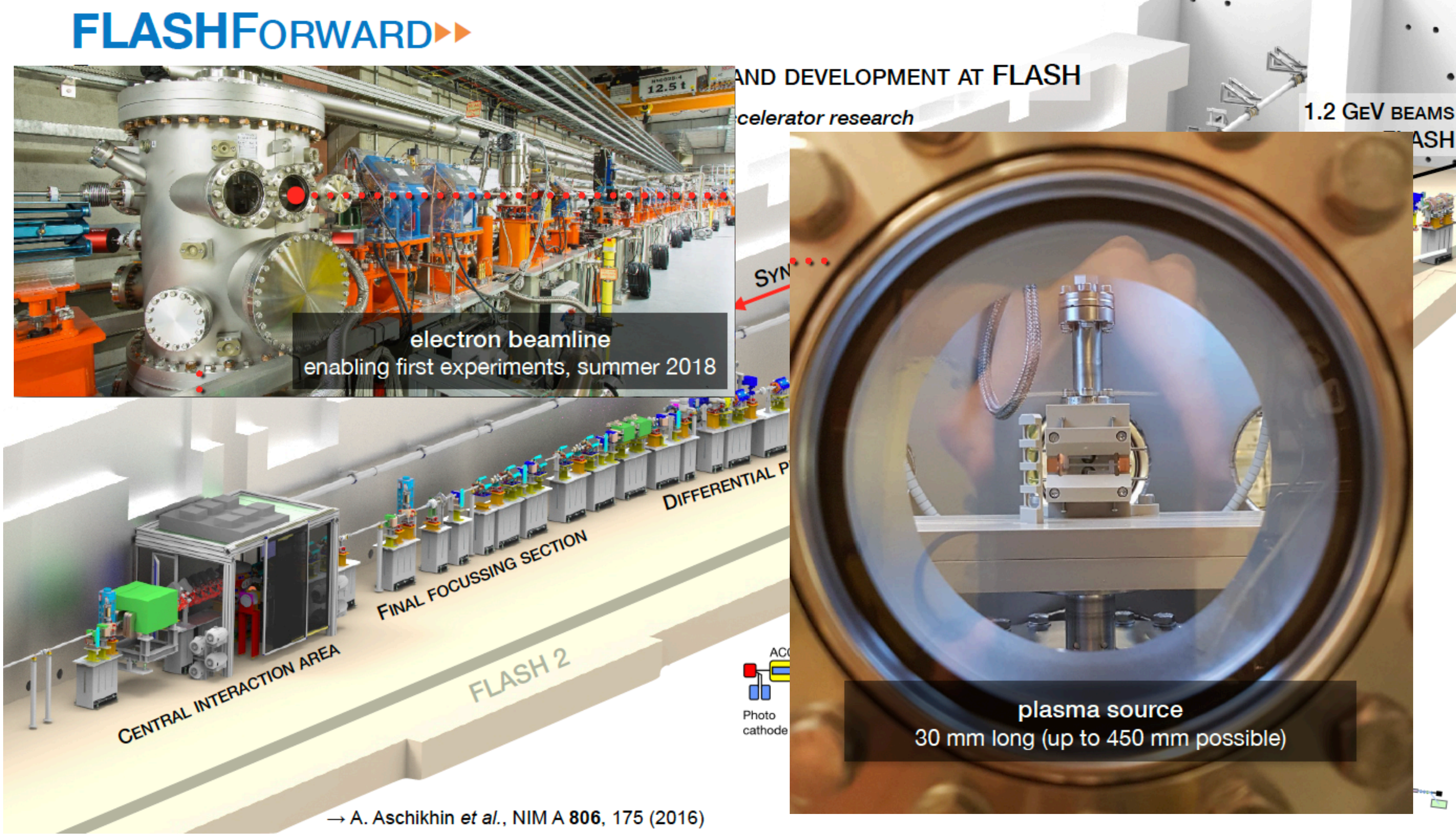
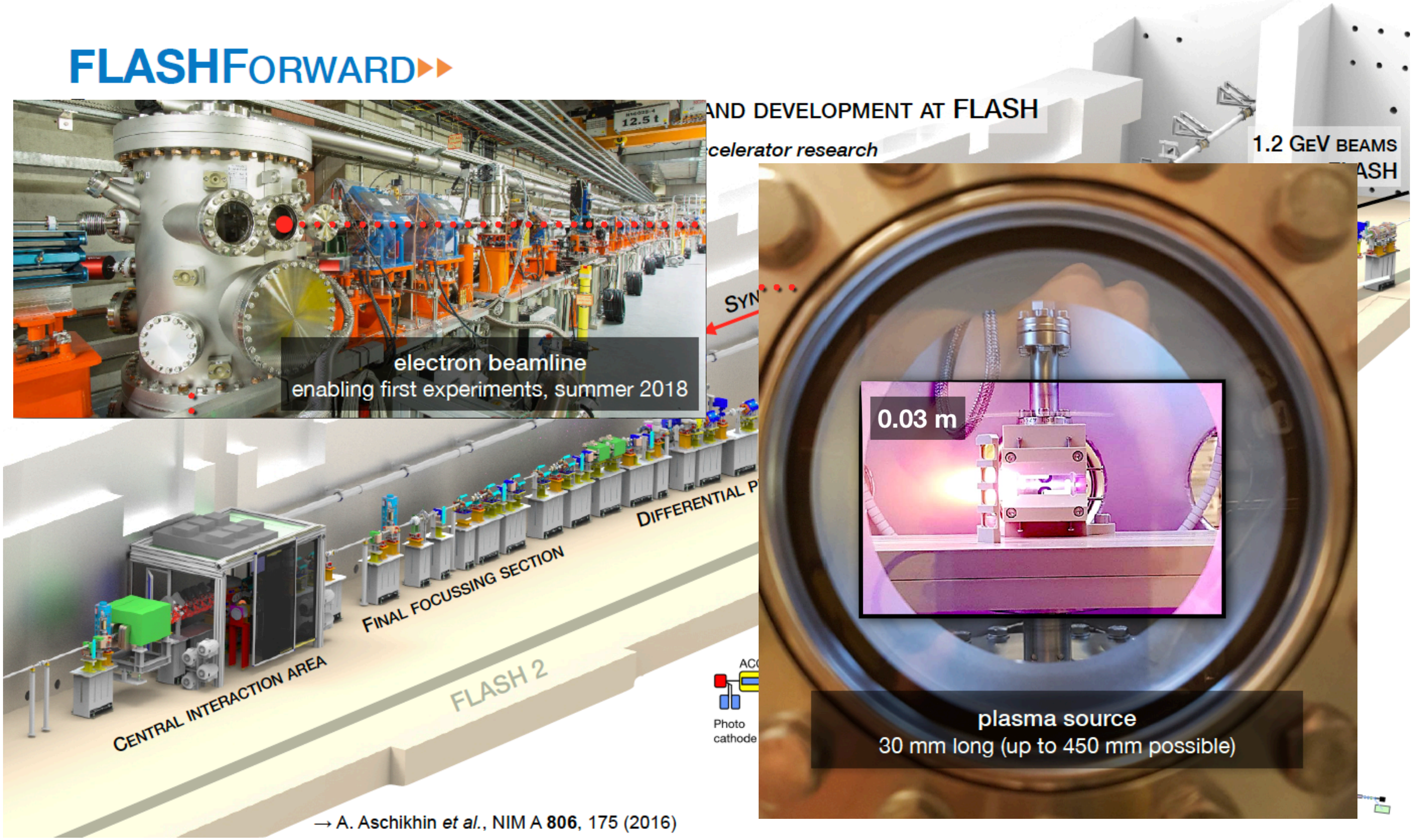
FLASHforward @ DESY



FLASHforward @ DESY

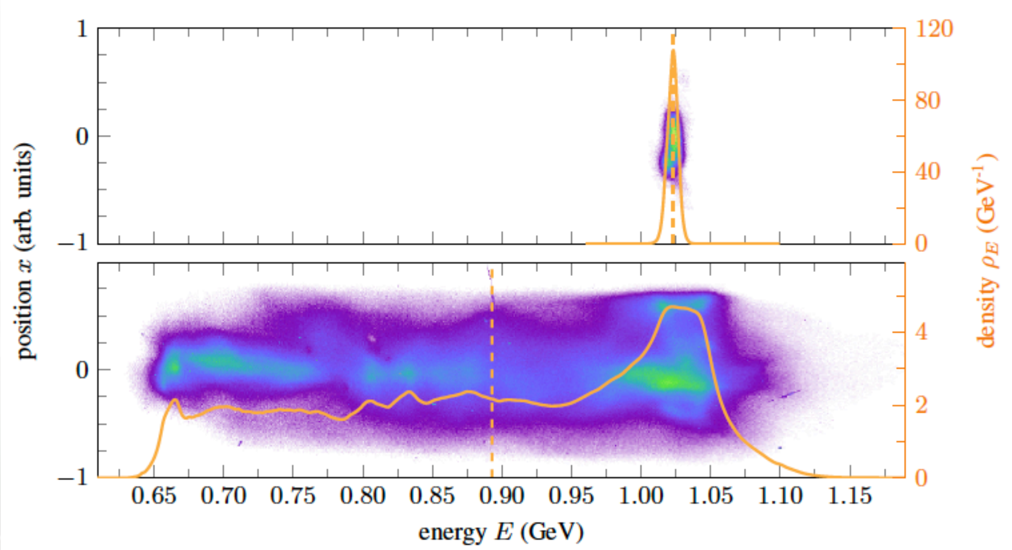


First results

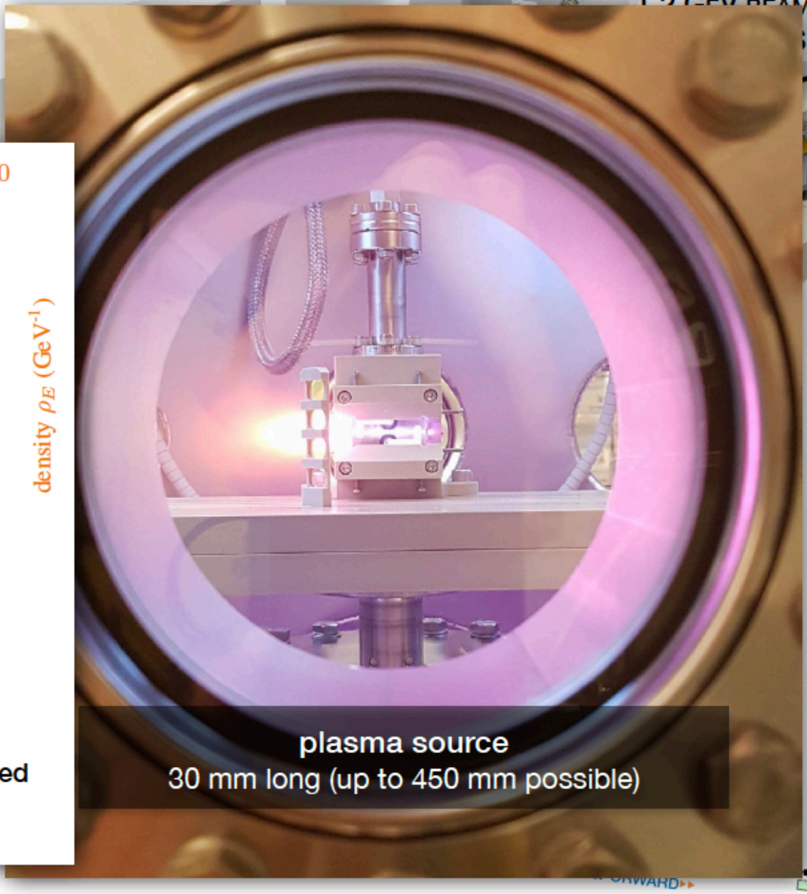
FLASHForward

Future-oriented wakefield accelerator research and development at FLASH

- first PWFA beam-plasma interaction on June 19th, 2018
- commissioning successful and finished June 30th, 2018
- installation ready for first experiments since July 15th, 2018



- (12.3 ± 1.7) GV/m wakefield generated in 30 mm plasma cell
  → plasma cell scale length ~100 mm for GeV energy gain confirmed
- 12.7% total energy loss to plasma wakefield

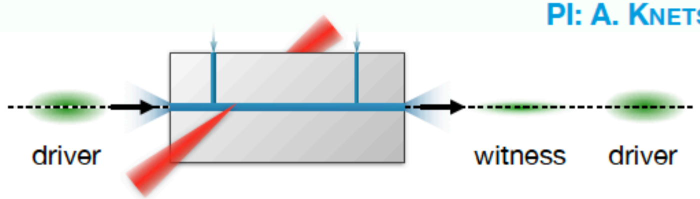


Research Projects

FLASHForward▸▸ collider-related scientific packages

Core Study I — X-1: Plasma cathode

PI: A. Knetsch



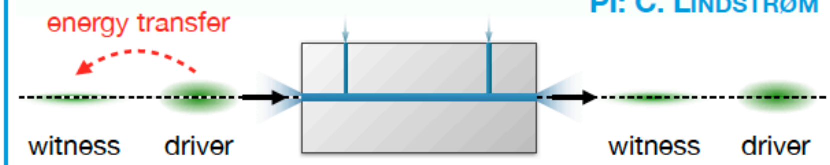
Goals:

- 1 GeV energy gain of in-plasma injected beam
- transverse normalised beam emittance ~ 100 nm
- peak current ≳ 1 kA
- femtosecond bunch duration

> Beam generation for collider

Core Study II — X-2: Plasma booster

PI: C. Lindstrøm



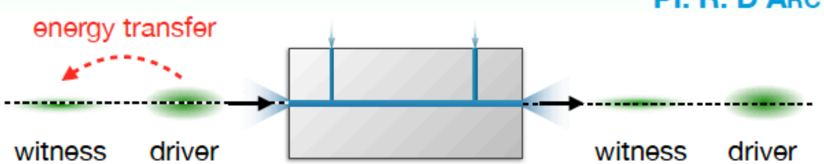
Goals:

- 1 GeV energy gain
- conserve beam energy spread
- conserve beam normalised transverse emittance
- deplete drive beam energy
- 20% energy extraction efficiency from drive to witness

> Energy boosting section for collider staging

Core Study III — X-3: High-average power PWFA

PI: R. D'Arcy



x *MHz*

Goals:

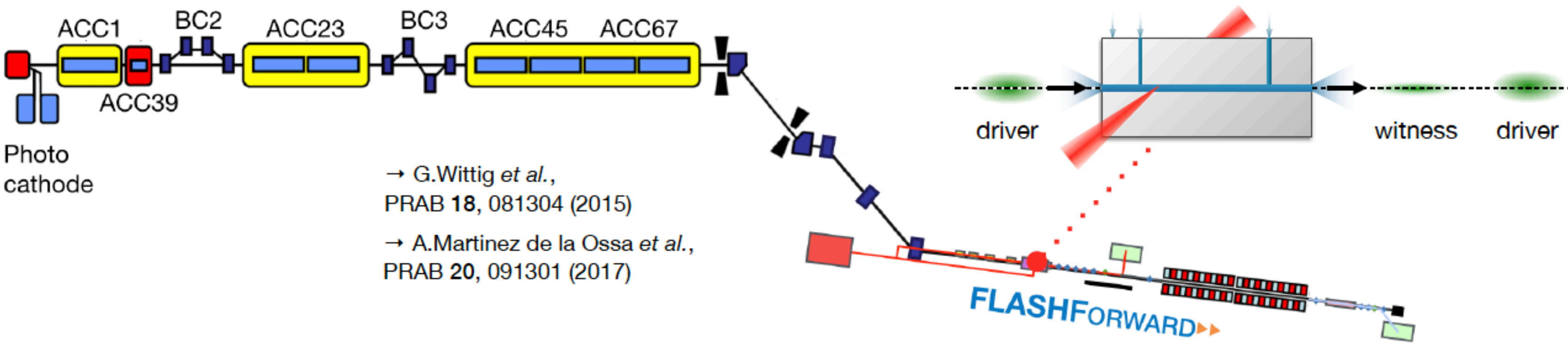
- GeV energy gain, beam quality preservation, depletion @ MHz
- plasma relaxation studies
- investigation into multi-discharge plasma recovery time
- MHz thermal management
- driver-witness beam separation

> Test bed to address high-average-power challenges

X-1: Plasma Cathodes

X-1: Plasma cathode for high-brightness beam generation

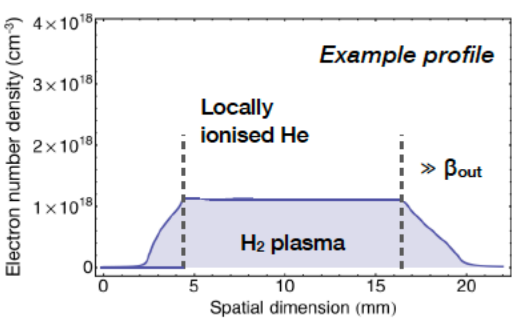
GENERATION OF NM-SCALE NORMALISED EMITTANCE BEAMS FOR COLLIDER FINAL FOCUS

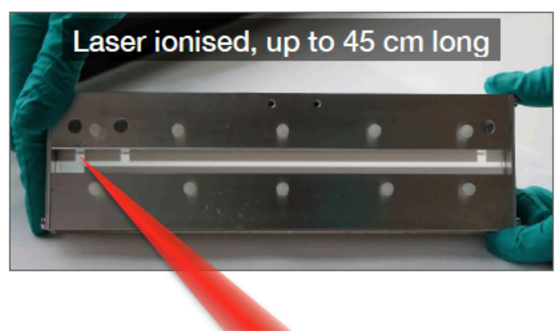


→ G.Wittig *et al.*, PRAB **18**, 081304 (2015)

→ A.Martinez de la Ossa *et al.*, PRAB **20**, 091301 (2017)

> **X-1 Plasma Cathode:** beam-brightness converter → emittance shrinker
  > 1.25 GeV energy, trans. norm. emittance ~100 nm, current ≳ 1 kA, ~fs bunch duration





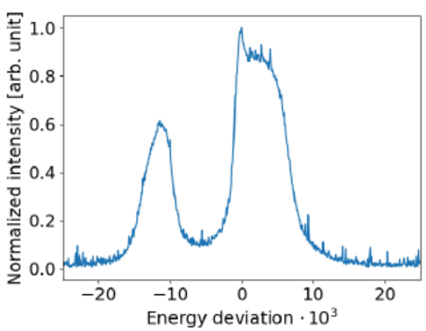
- first studies comparing laser- and HV discharge-generated plasma underway
- *in summer 2019*:
  - → transverse laser in-coupling
  - → 5 cm plasma cell with 300 μm transverse hole
  - → accelerator of internally injected electrons

X-2: Energy booster

X-2: Plasma-based energy booster module

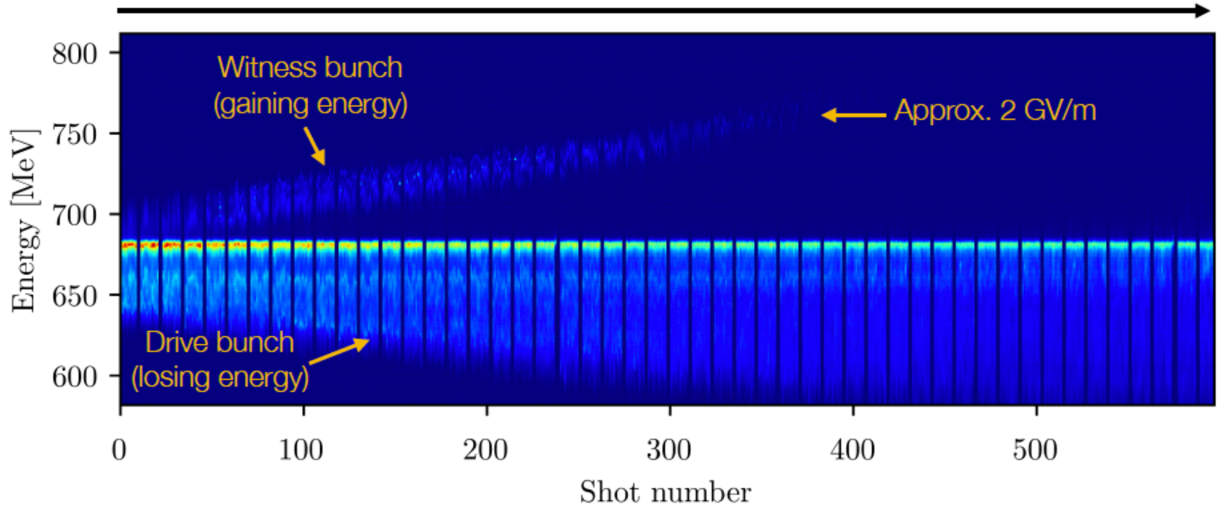
HIGH GRADIENT ENERGY BOOSTING, BEAM-QUALITY PRESERVATION, AND STABILITY STUDIES

Driver/witness creation using a wedge-shaped scraper in a dispersive section



plasma interaction

Plasma density increases (beam–discharge delay decreases)

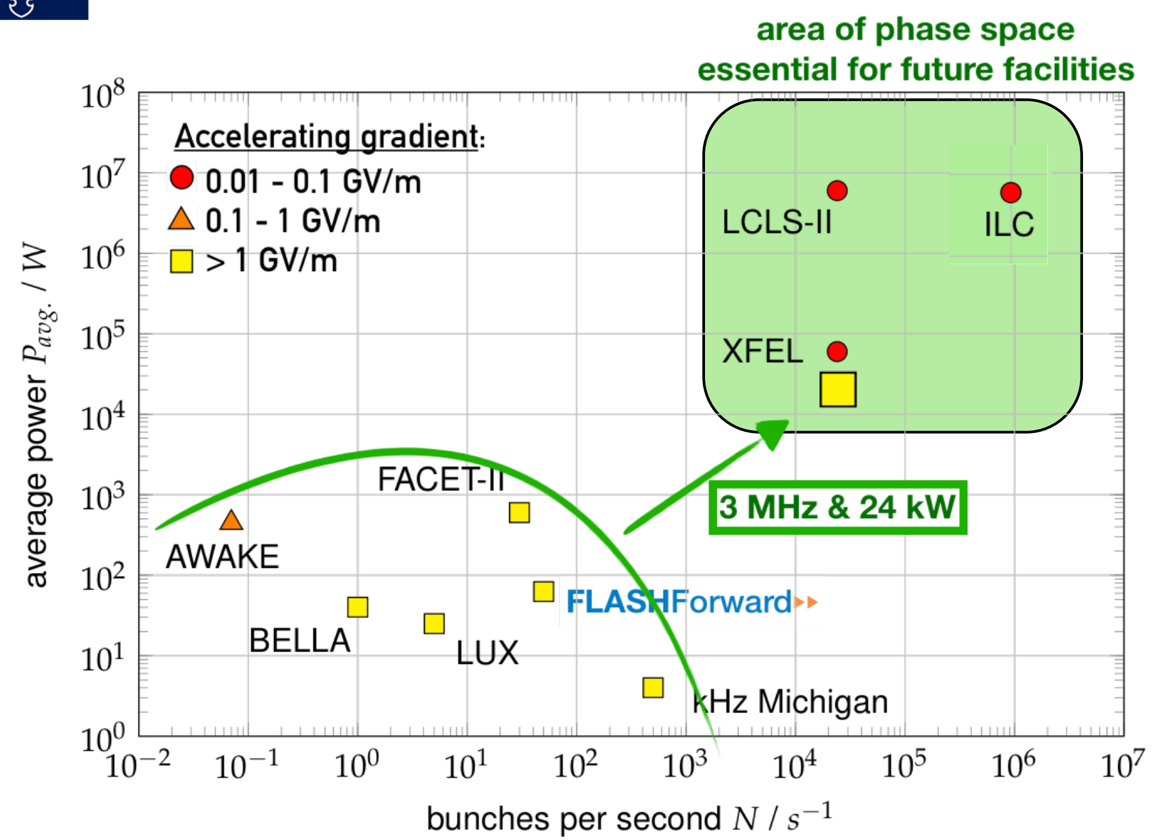


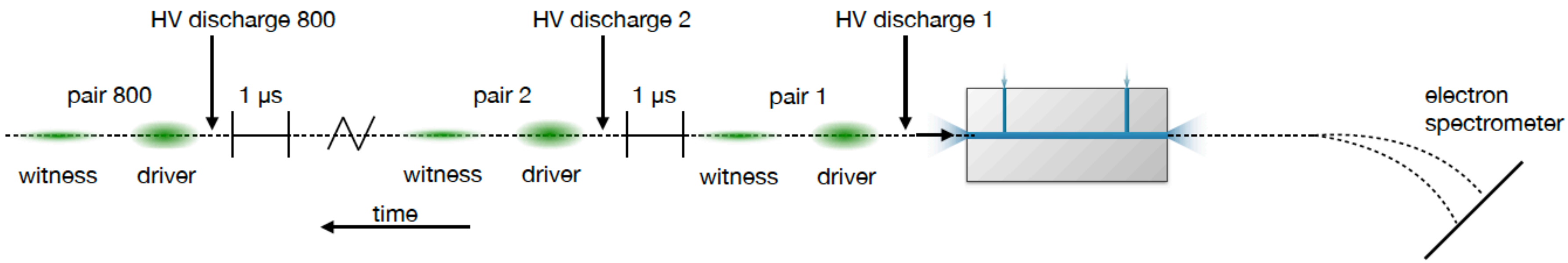
Double-bunch plasma interaction

- First observation of witness acceleration with GV/m fields (parameters: 1 kA driver peak current, 30 mm plasma cell, 10^{15} - 10^{16} cm^{-3} plasma density)
- *in summer 2019:* 20 cm plasma cell → multi-100 MeV energy gain + drive depletion; beam loading control → explore energy spread and emittance conservation

- No shot selection or preferential ordering
- Excellent stability over short and long term (multiple hours) thanks to stability of the SCRF cavities and FEL-quality feedback systems

X-3: High Average Power





X-3: High Average Power

X-3: High-average-power PWFA research

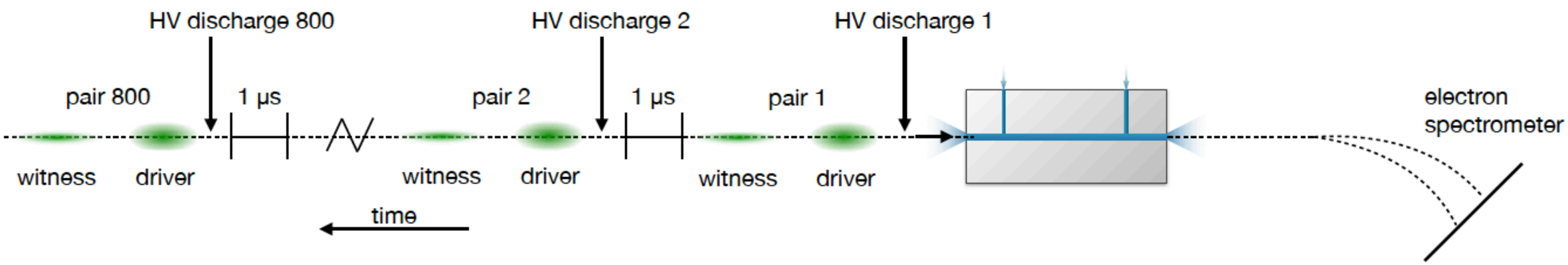
MHz REPETITION RATE PWFA FOR HIGH-AVERAGE-POWER APPLICATIONS

Technical challenges

- MHz repetition rate plasma discharge
- Driver and witness beam separation
- Gas flow and high rep. rate plasma cell
- Imaging diagnostics with high temporal resolution

Scientific questions

- How is the lifetime of plasma relaxation affected by perturbations generated by a particle beam driving a wakefield?
- What is the recovery time of the system between the generation of a first plasma through a high-voltage discharge and a second?
- Can the deposition of heat into the plasma from the drive bunch be managed at MHz rates?

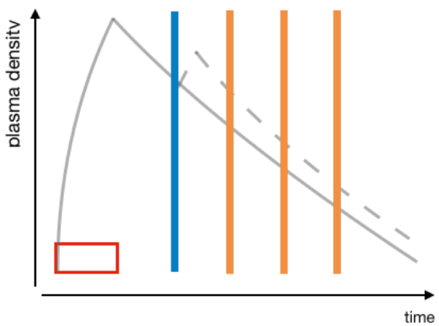


X-3: High Average Power

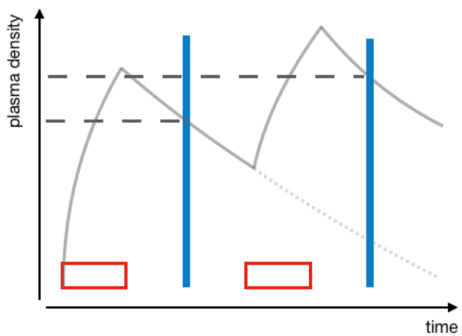
Generation of plasma at high frequencies

Novel measurement of MHz PWFA

→ 100 discharges
100 bunch pairs

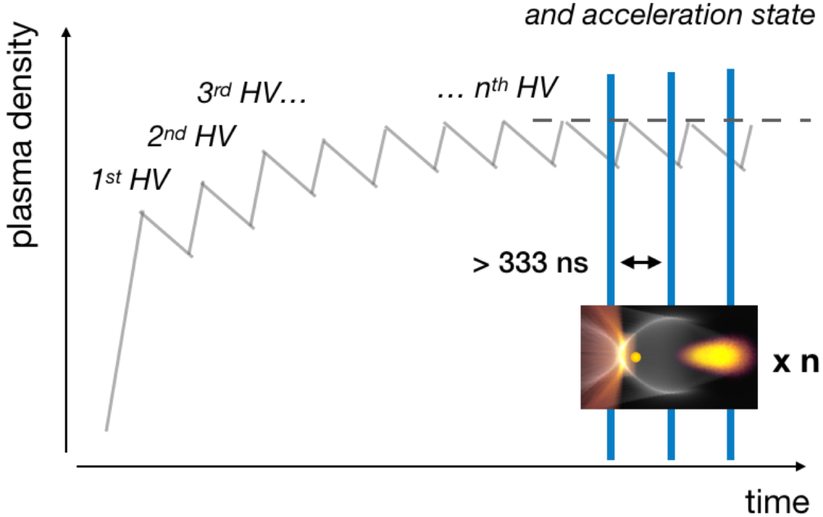


WP1
1 discharge
2 bunch pairs



WP2
2 discharges
2 bunch pairs

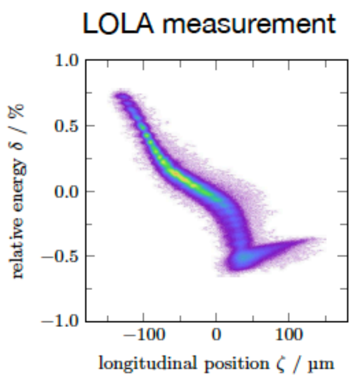
GOAL: Test validity of plasma-wakefield processes at MHz rates and establish lower bound on repetition rate



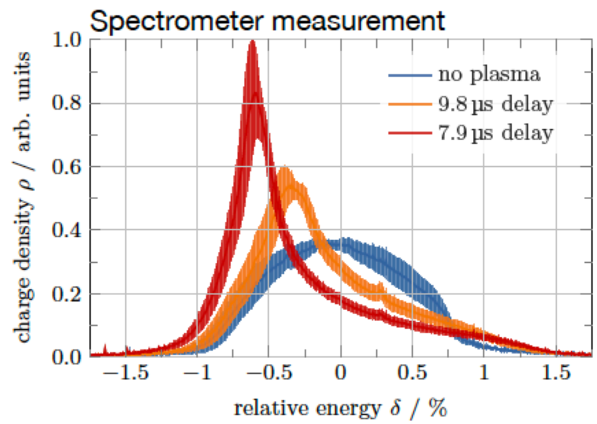
First FLASHForward Publication

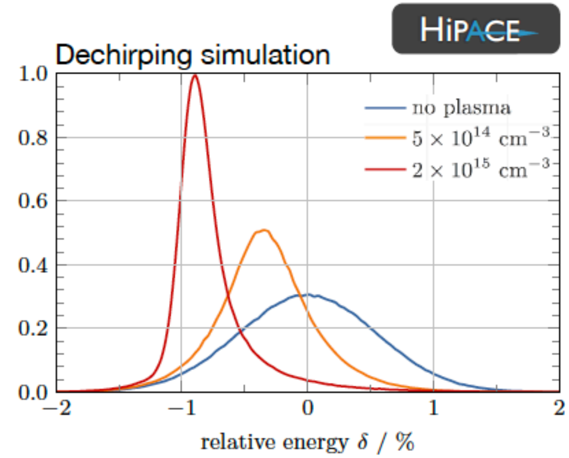
Scientific highlight: Tunable plasma-based energy dechirper

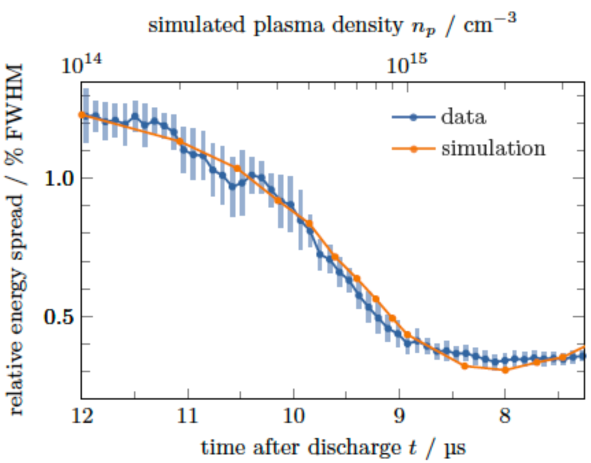
REMOVE REMANENT ENERGY CHIRP FOR INTRA-STAGING AND COLLIDER FINAL FOCUS



plasma interaction







- Reduction of energy spread from 1.3% to 0.3% FWHM
- Experimental demonstration of 1.8 GeV/mm/m dechirping strength, orders of magnitude higher than other state-of-the-art devices

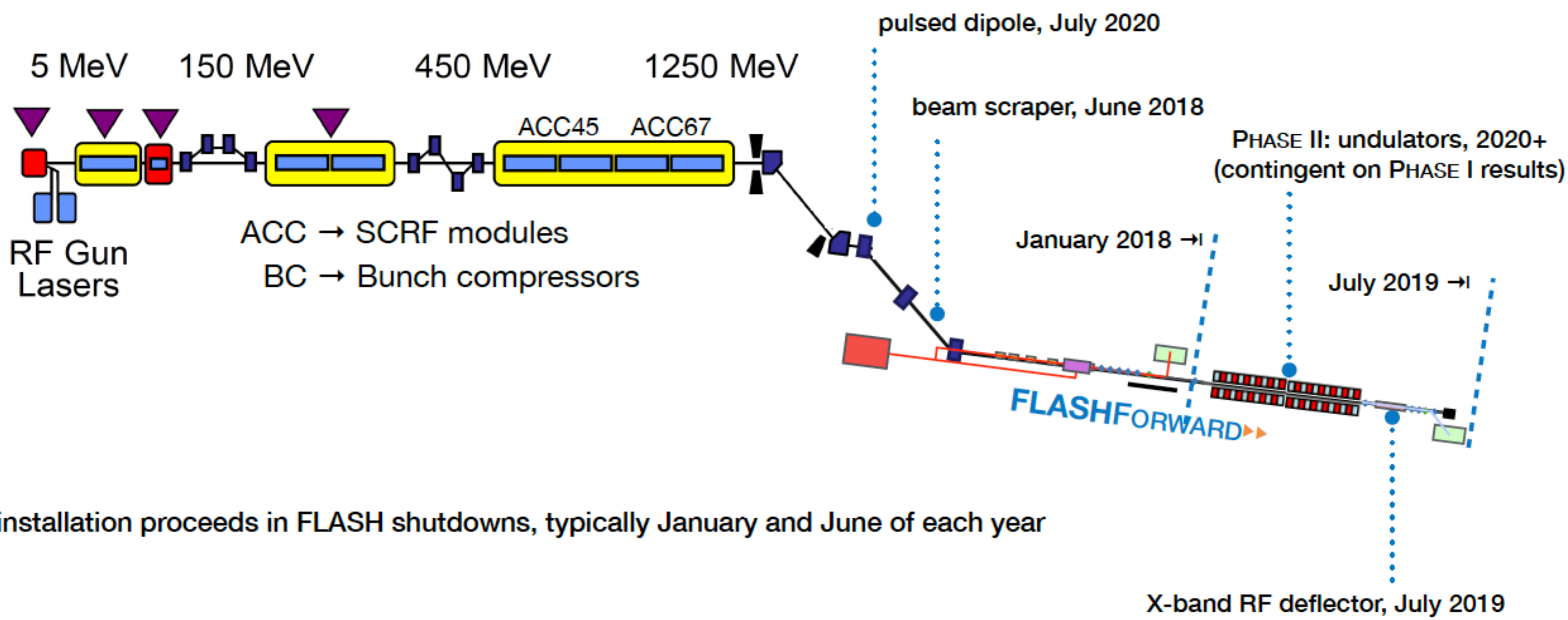
- First experimental demonstration of dechirping in plasma
- Proof of principle results, utilising an artificially chirped FLASH beam, published in January
- May dramatically improve applicability of PWFA beams to future facilities

R. D'Arcy et al.,
Phys. Rev. Lett. 122, 034801 (2019)

FLASHforward Future

FLASHFORWARD▸▸ follows a staggered installation plan

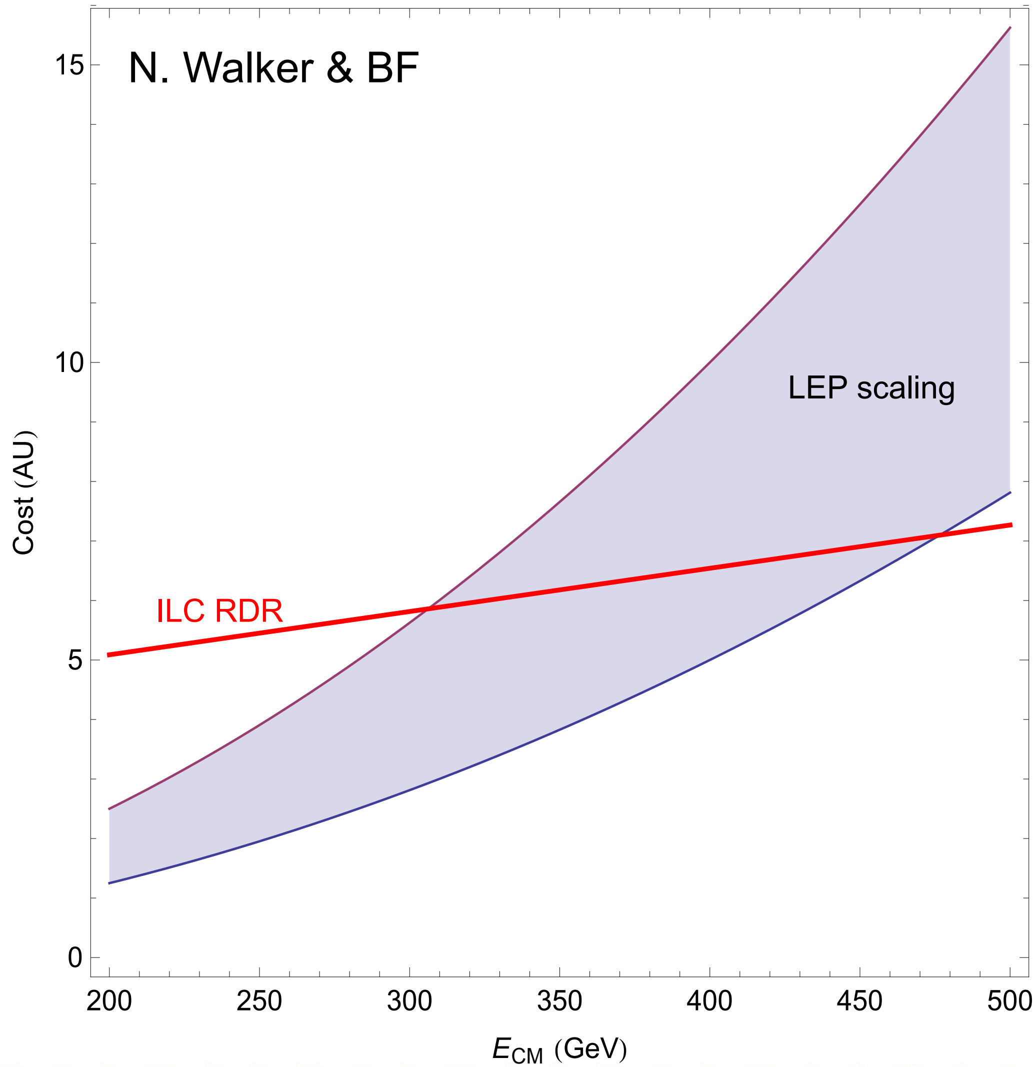
PROJECT PHASE I: PLASMA WAKEFIELD BEAMLINE AND DIAGNOSTICS — PHASE II: UNDULATOR INTEGRATION



> installation proceeds in FLASH shutdowns, typically January and June of each year

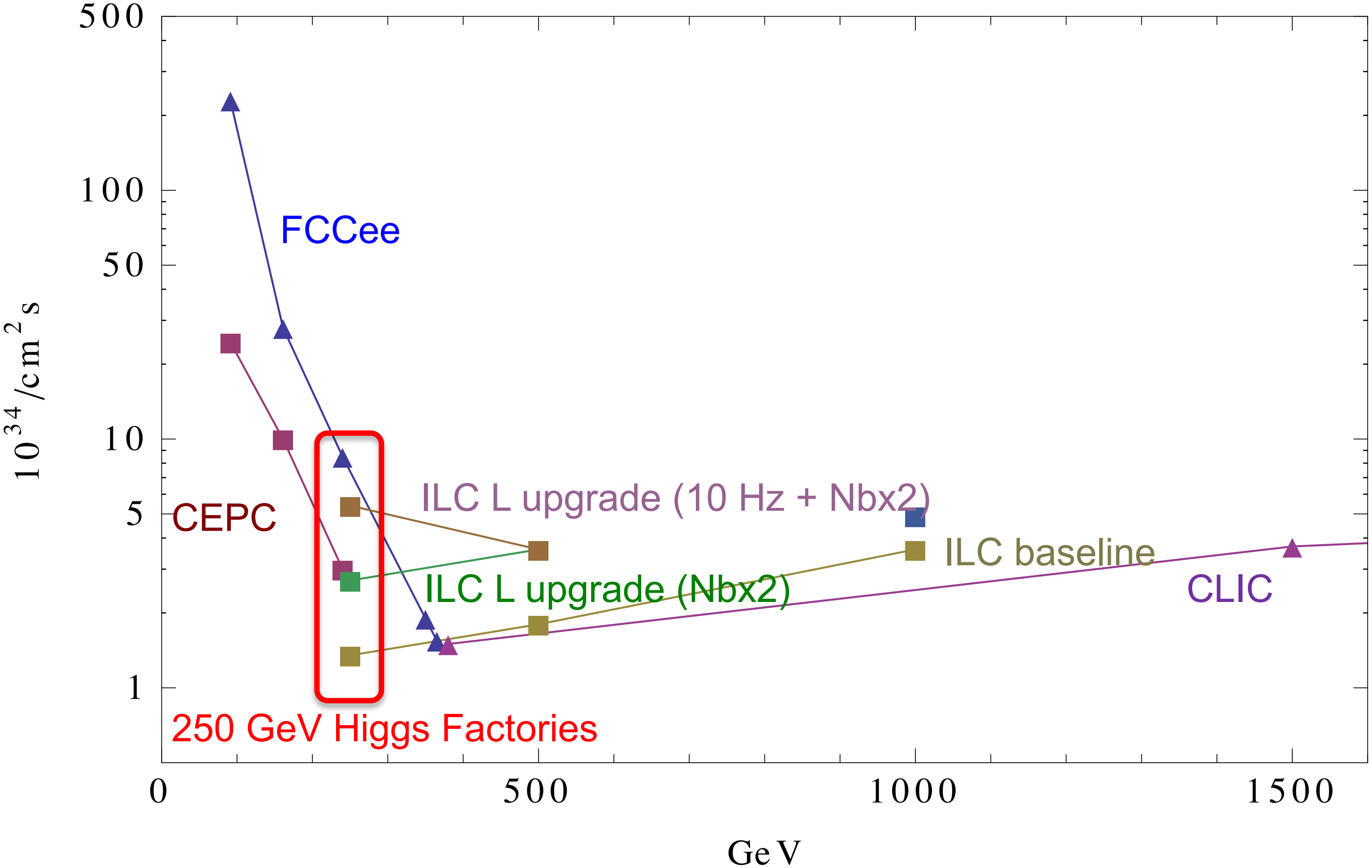
Granada in 3 slides
Background – circles vs lines

Very approximate cost LC vs circular based on minimum of cost model Cost = $aE^4/R + bR$ where a,b "fixed" from LEP – two curves are most optimistic and pessimistic LEP cost.



BUT – luminosity of circular machine in this picture dropping steeply with E.

Future e⁺e⁻ Colliders



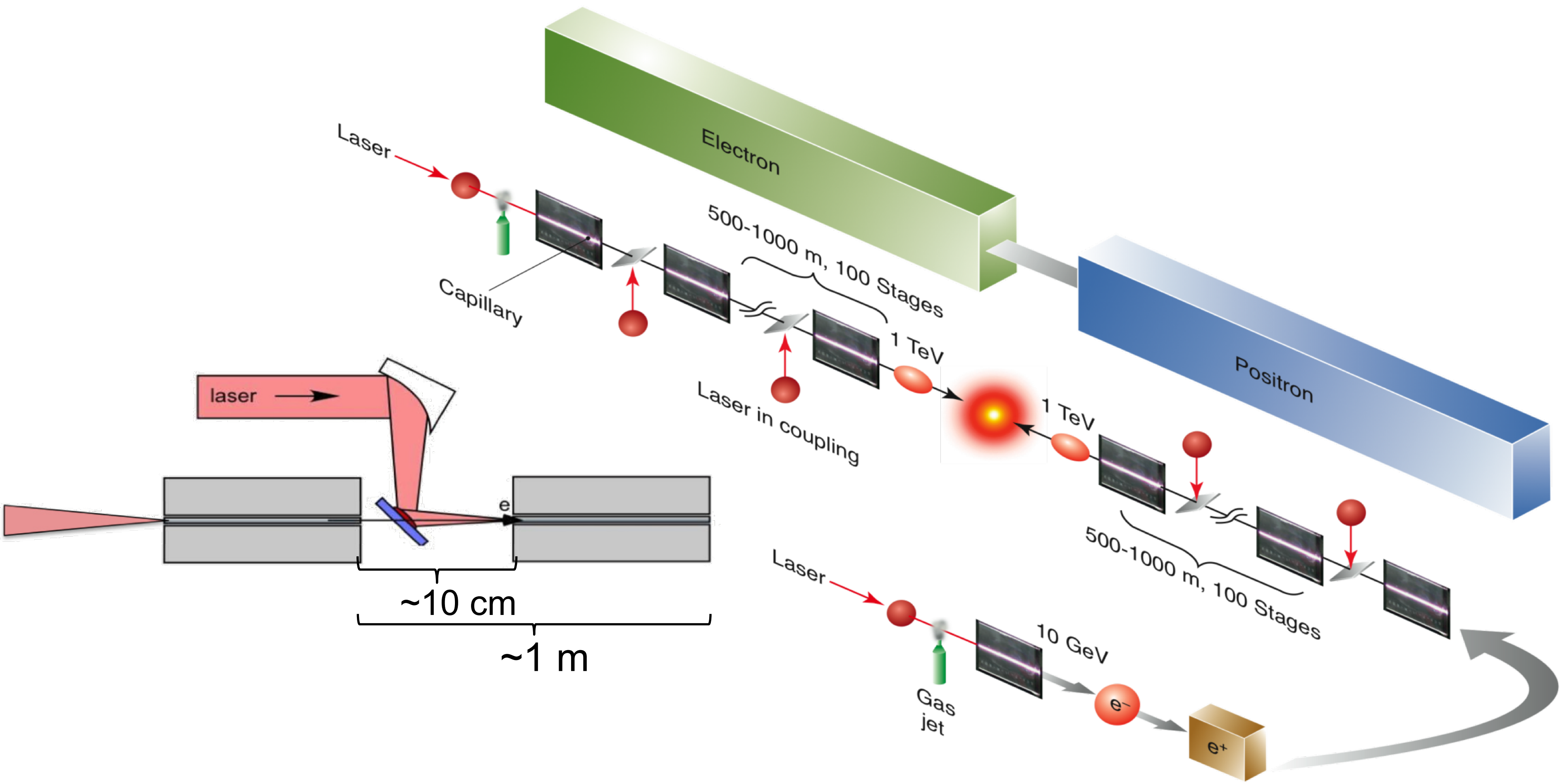
- FCCee/CEPC are for 1 IP (their CDR have 2 IPs)
- ILC Higgs Factory numbers do not include effective x∼2.5 by polarization
- ILC 10 Hz collision requires ~ILC500

Granada

- **“Consensus”**
  - there is a strong physics case for an e+e collider as a Higgs factory
  - the Japanese government needs to make a decision soon on whether it wants to proceed with hosting ILC
- **No consensus**
  - What sort of e+e- collider should be built
  - Linear or circular
  - If linear, ILC or CLIC
  - If circular, FCCee or CepC
  - What to do in Europe if Japan did say “yes”
  - etc.
  - etc.

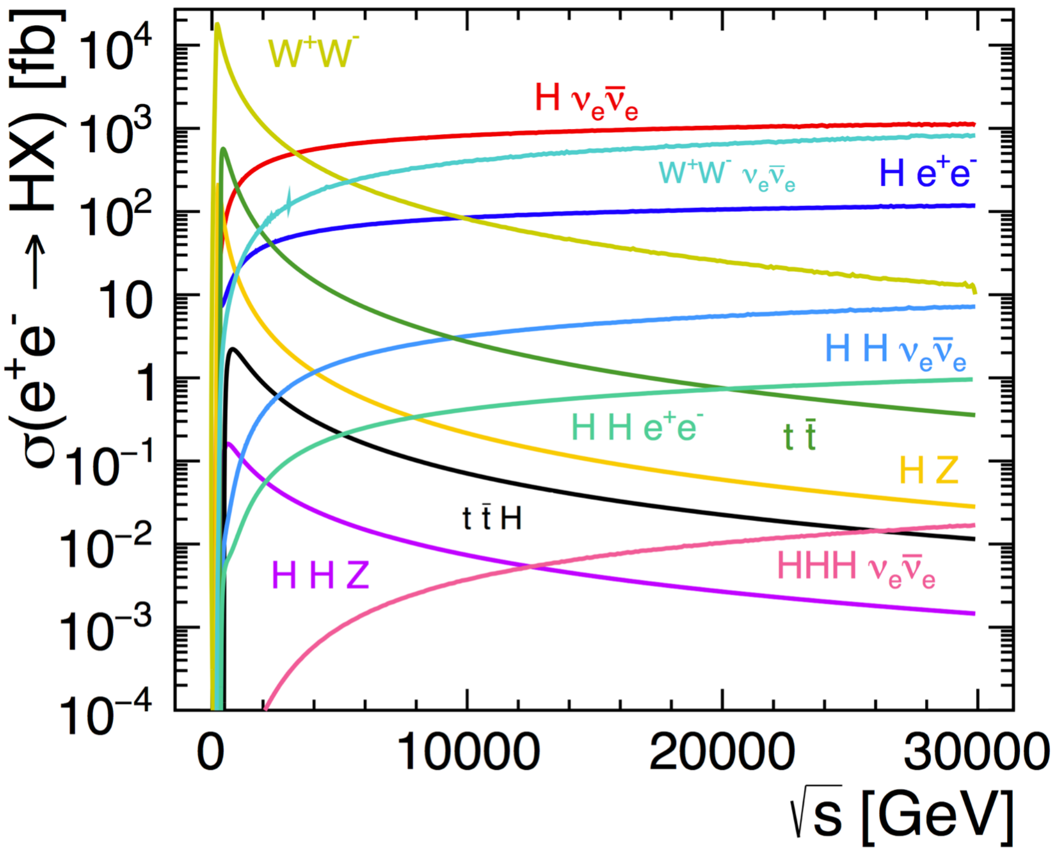
Realising the dreams?

- **A laser-plasma-driven linear collider?**



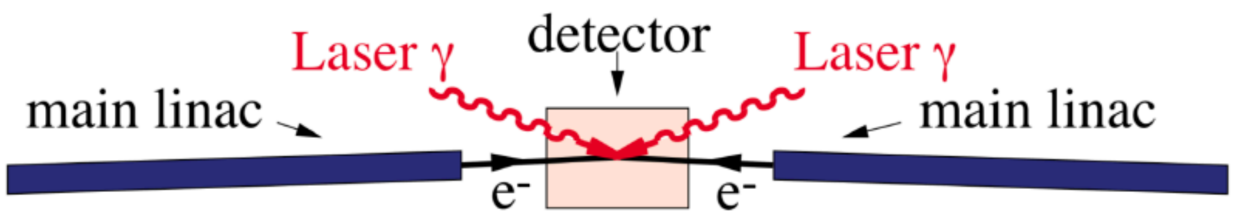
Think big - ALIC

Alegro aims for a collider with 30 TeV in centre-of-mass

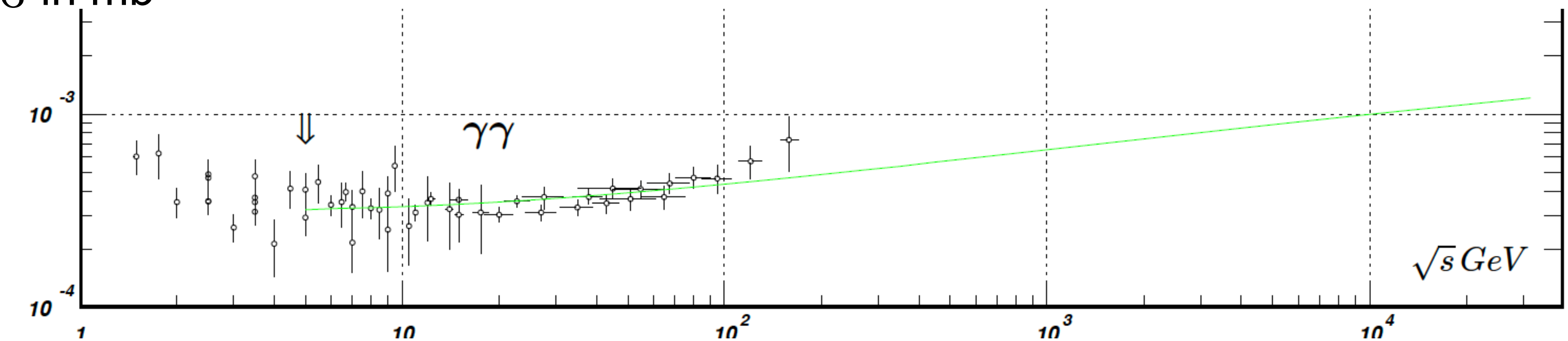


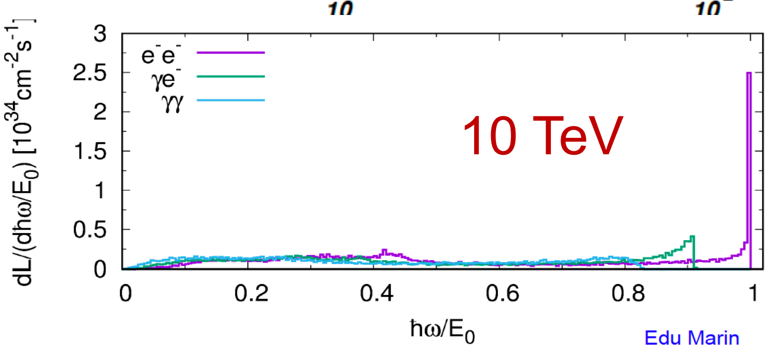
Gamma-Gamma

Beamstrahlung at 15*15 TeV is appalling – accelerating e^+ in PWFA difficult. Obvious thought is gamma-gamma



σ in mb

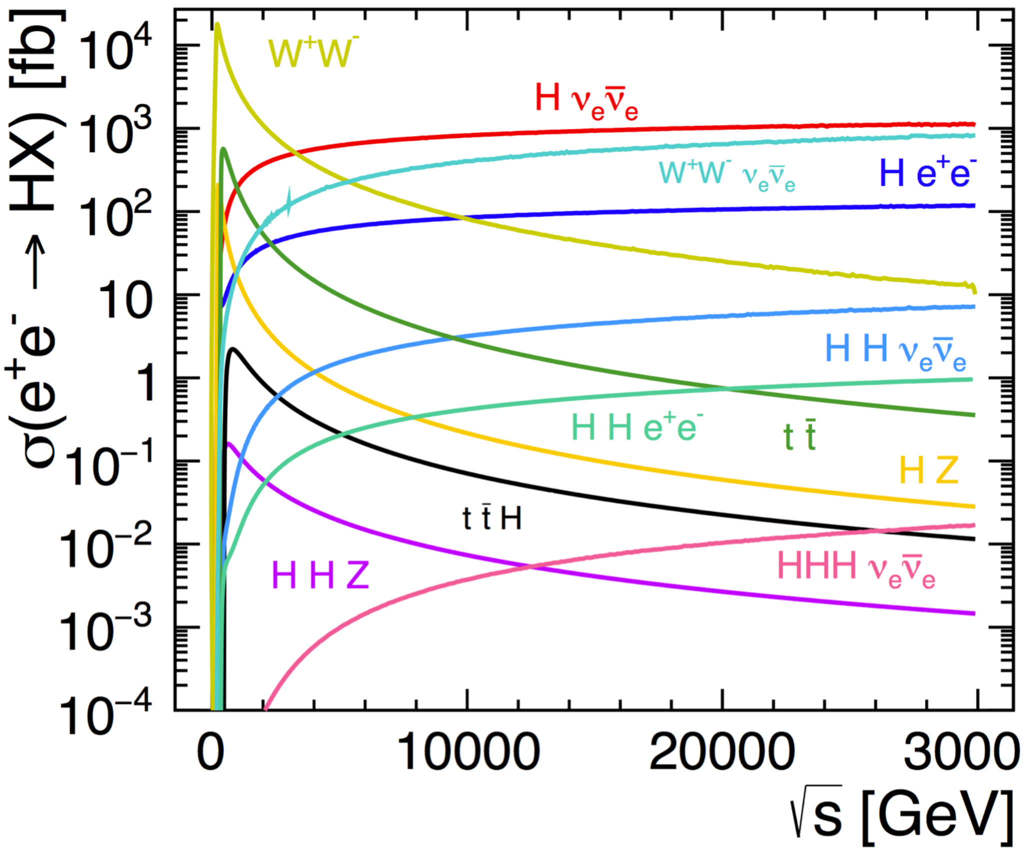


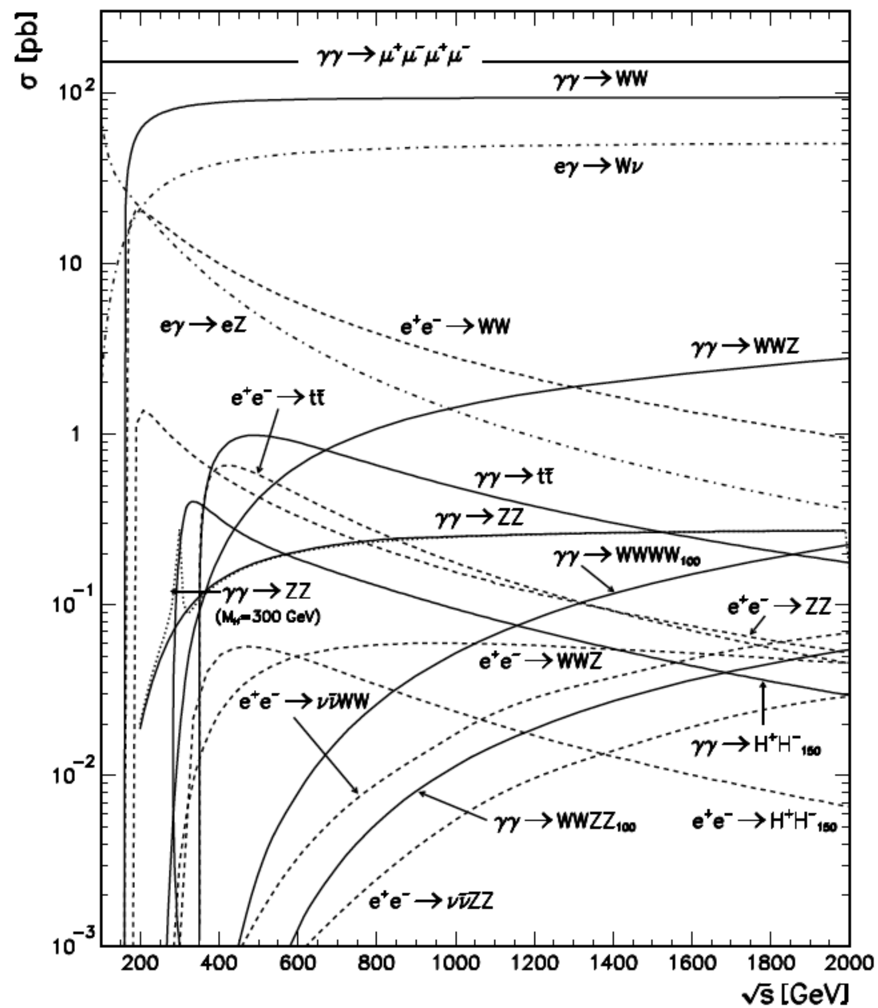


@1 TeV , "useful"
$\mathcal{L}(\gamma\gamma)/\mathcal{L}(ee) \sim 10\%$

Think big - ALIC

Alegro aims for a collider with 30 TeV in centre-of-mass





Reach

BUT – $\gamma\gamma$ can't access all new physics cf e^+e^-

Particle pair	Mass [GeV]	$\sigma(e^+e^- \to XX)$ [fb] Circe2 + ISR, unpol.	$\sigma(\gamma\gamma \to XX)$ [fb] Circe2, unpol.
$\tilde{d}_L\tilde{d}_L$	1009	0.61	0.07
$\tilde{u}_L\tilde{u}_L$	1006	0.89	1.2
$\tilde{s}_L\tilde{s}_L$	1009	0.61	0.07
$\tilde{c}_L\tilde{c}_L$	1006	0.89	1.2
$\tilde{b}_1\tilde{b}_1$	1997	0.19	0.01
$\tilde{t}_1\tilde{t}_1$	1866	0.28	0.22
$\tilde{e}_L\tilde{e}_L$	1869	0.95	0.37
$\tilde{\nu}_{eL}\tilde{\nu}_{eL}$	1867	4.6	/
$\tilde{\mu}_L\tilde{\mu}_L$	1869	0.25	0.37
$\tilde{\nu}_{\mu L}\tilde{\nu}_{\mu L}$	1867	0.11	/
$\tilde{\tau}_1\tilde{\tau}_1$	1328	0.30	0.93
$\tilde{\nu}_\tau\tilde{\nu}_\tau$	1364	0.15	/
$\tilde{d}_R\tilde{d}_R$	988	0.13	0.08
$\tilde{u}_R\tilde{u}_R$	989	0.53	1.2
$\tilde{s}_R\tilde{s}_R$	988	0.13	0.08
$\tilde{c}_R\tilde{c}_R$	989	0.53	1.2
$\tilde{b}_2\tilde{b}_2$	2032	0.07	0.01
$\tilde{t}_2\tilde{t}_2$	2108	0.26	0.16
$\tilde{e}_R\tilde{e}_R$	1856	1.4	0.38
$\tilde{\nu}_{\mu R}\tilde{\nu}_{\mu R}$	1856	0.21	0.38
$\tilde{\tau}_2\tilde{\tau}_2$	1365	0.31	0.86
$\tilde{\chi}_1^0\tilde{\chi}_1^0$	954	≈ 0	/
$\tilde{\chi}_2^0\tilde{\chi}_2^0$	954	≈ 0	/
$\tilde{\chi}_1^+\tilde{\chi}_1^-$	955	2.7	1.4
$\tilde{\chi}_3^0\tilde{\chi}_3^0$	1294	1.1	/
$\tilde{\chi}_4^0\tilde{\chi}_4^0$	2262	0.53	/
$\tilde{\chi}_2^+\tilde{\chi}_2^-$	2262	1.3	1.3
H^0A^0	3046	0.04	/
H^+H^-	3046	0.10	0.08

What is required?

CM energy, luminosity, and beam polarization are crucial.

Can advanced acceleration technologies provide this?

Figure of merit for point-like cross-section is

$$10^5 \text{ events/yr}/10^{35}/(E_{\text{CM}} \text{ (TeV)})^2$$

For linear colliders, $\mathcal{L} \sim \frac{P}{\sigma_x \sigma_y}$

For ILC at 500 GeV, this scaling is

$$2 \times 10^{34} \sim \frac{10 \text{ MW/beam}}{500 \times 6 \text{ nm}^2}$$

Scaling to a 50 TeV collider at 10^{36}

$$10^{36} \sim \frac{10 \text{ MW/beam}}{0.6 \text{ nm}^2}$$

To inject some realism here (!), I think if is fair to say that we haven't the slightest idea how to do any of this – but it is great fun thinking about it!

Summary & Outlook

- PWFA is a vibrant and exciting field
- FLASHForward @ DESY is a new facility already producing exciting results; unique capability to explore some aspects relevant to collider applications
- "Everyone" agrees that e^+e^- Higgs factory is next best step
- No-one agrees whether it should be linear or circular, what technology or where to put it
- Looking into the (distant) future, perhaps PWFA holds the key to the next steps in particle physics

Many thanks to Richard D'Arcy, Michael Peskin & Philipp Roloff for figures and helpful discussions