ANAC2
Novel Acceleration Techniques

Glasgow, 28-30 March 2017

EuCARD-2 is co-funded by the partners and the European Commission under Capacities 7th Framework Programme, Grant Agreement 312453

Missions of ANAC2

The Anac2 team :
8 contractors, CNRS, DESY, UDUS, HZDR, INFN, LUND, STRATH, UCL+ One invited CERN.

Task 13.1. Coordination and Communication (V. Malka)
- Coordination and scheduling of the WP tasks and WP budget follow-up
- Monitoring the work, informing the project management and participants within the JRA

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- Feasibility study of external injection done at INFN and HFZD
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- Two stage laser plasma accelerator done at STRATH

Task 13.3. Ultra-fast accelerator science (H. Schlarb)
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- Determine opportunistic effects causing slow and fast femtosecond bunch arrival time variations at FLASH
- Further improvements of the low level RF regulation system for pulse superconducting accelerators towards 2e-5 field instability

Task 13.4. Modulation of long plasmas (M. Wing)
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- Understand instabilities and modulations in long plasma, driver and accelerated beam
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Task 13.1. Coordination and Communication: Summary

- Publication of 48 scientific papers
- 21 publications in refereed journals in 2016-2017
- 1 International workshop LPAW in Guadeloupe in 2015
- 2 PhD prizes (John Dawson)
- 4 communications in H2020 portal
- 1 communication in Accelerator News
- 6 ANAC2 meetings

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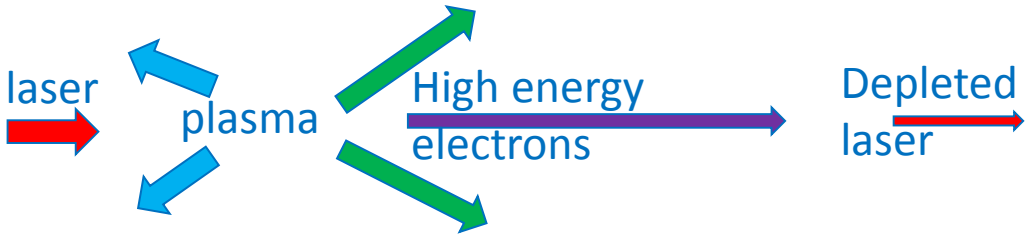
Conundrum: What happens to the laser energy in a LWFA?

- **100s keV** electrons in backward direction
- **1-2 MeV** beam with **10s nC** in forward direction in a **30-40°** opening angle
- **1-10 MeV**, **5-10 nC** beam fills the cone – forming a halo around the higher energy (**100s MeV**) beam

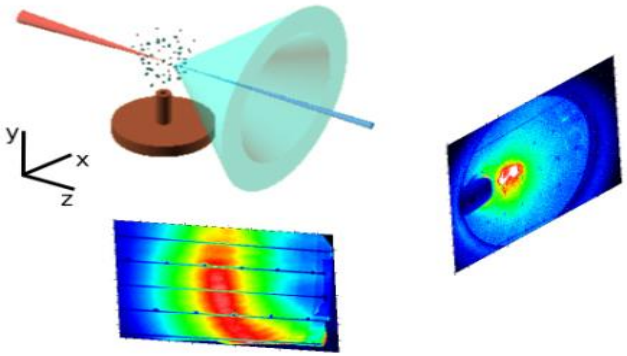


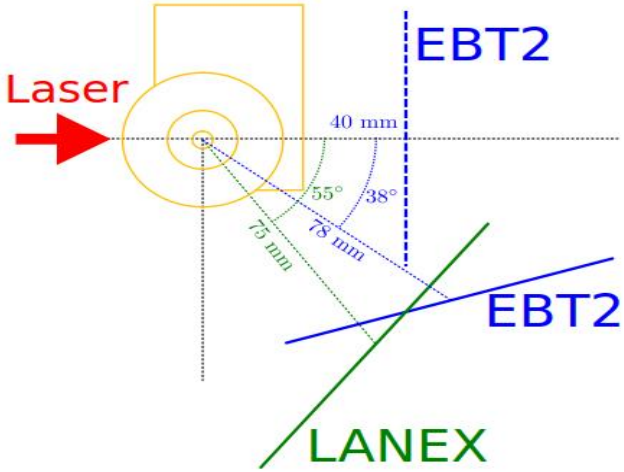
- 1 J, 30 fs laser
- Up to **50%** delivered to plasma wave
- **5-10%** of laser energy transferred to side electrons
- **0.1 – 1 ps** bunch duration

- Peak current can be extremely high **(>10 kA)**
- Consequences for capillary staged LWFA

X. Yang, E. Brunetti et al., Scientific Reports 2017

Side electron experiment: energy spectra and imaging



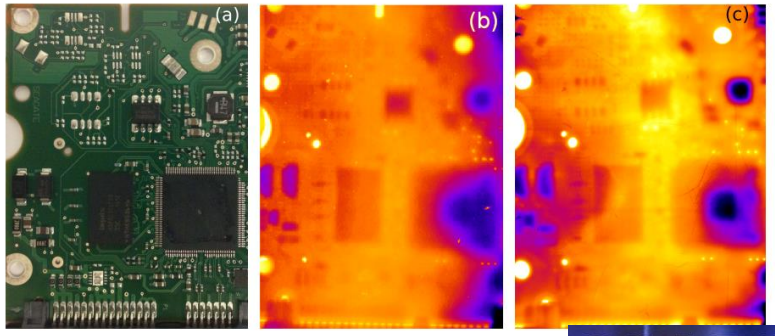


Hard disk controller

imaging

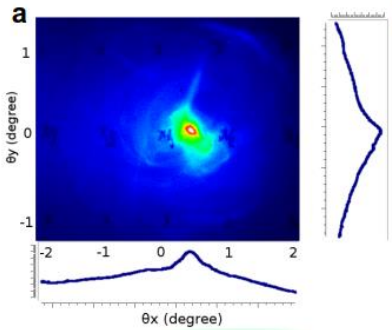
20 shots

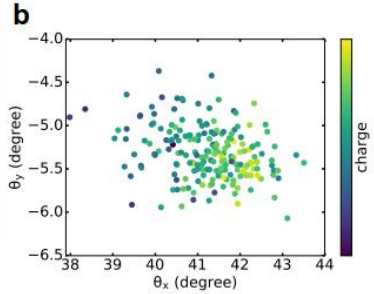
1 shot

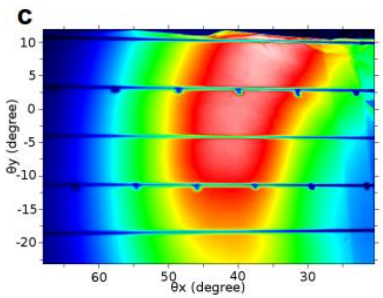


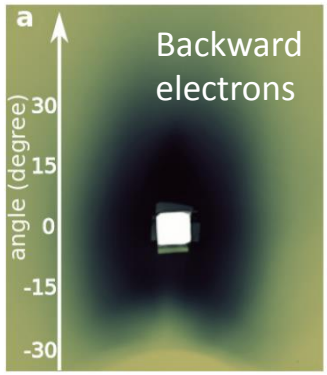
Easy to mistake high charge, oblique angled beams from injected beams – Halo can have quite high energy.

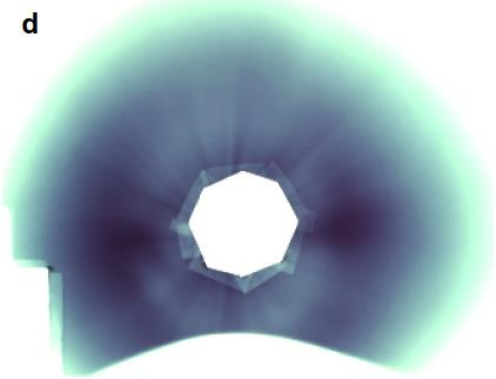
Experimental results

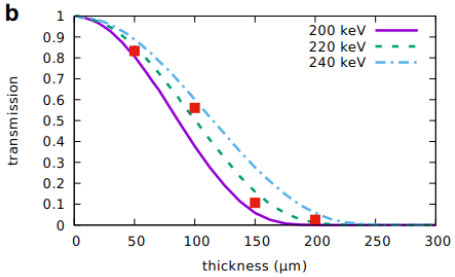


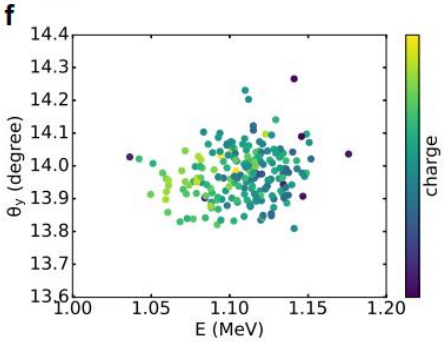


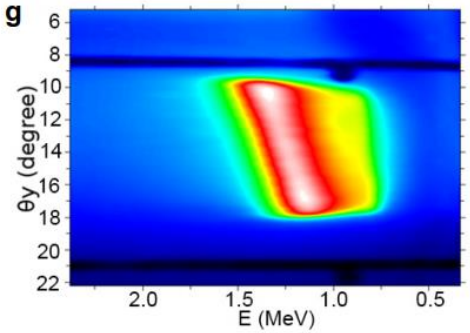






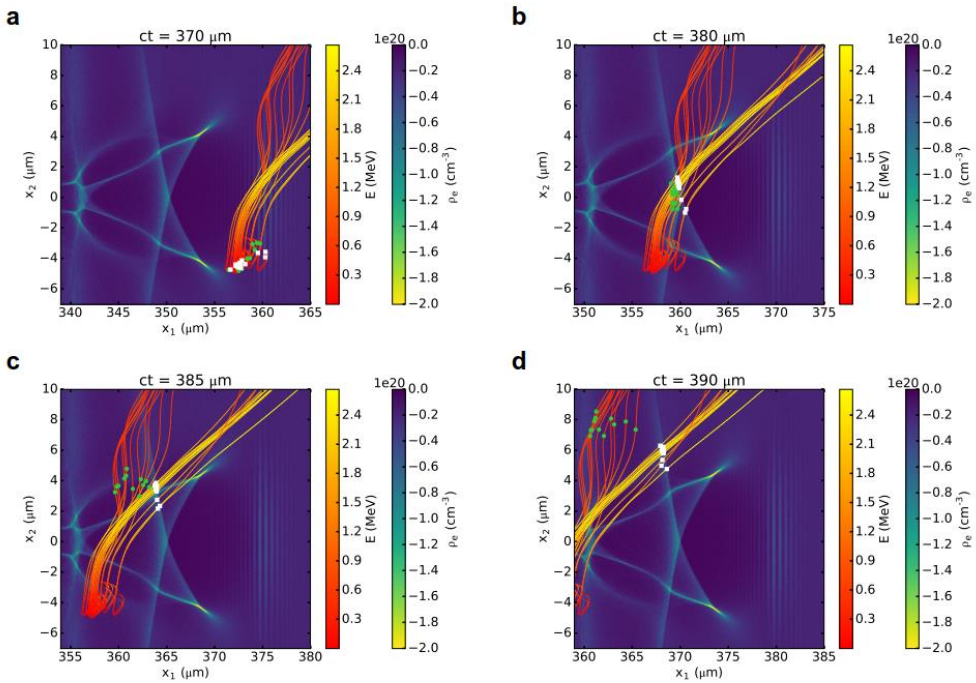


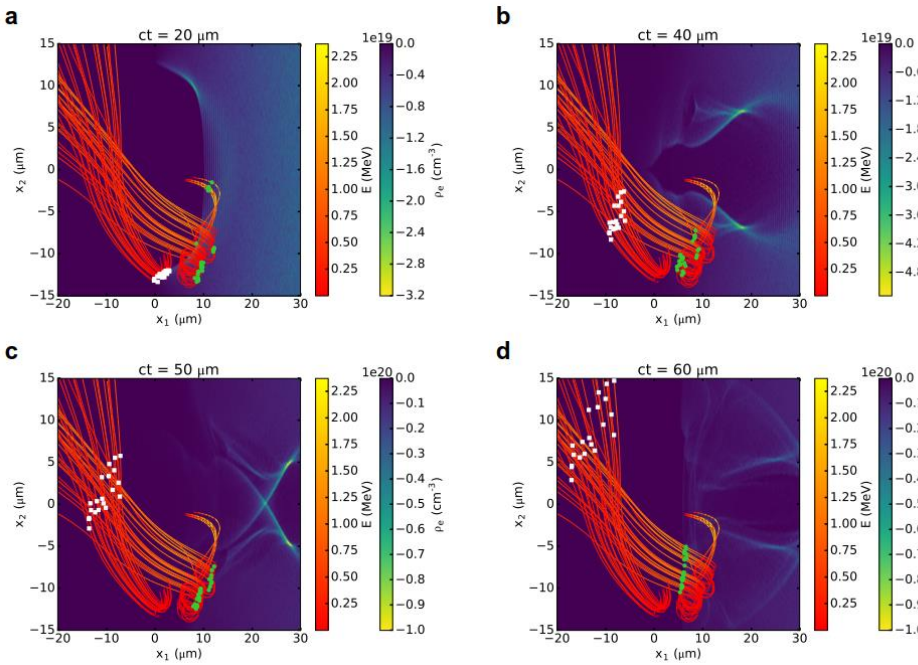




(a) Forward direction
(b) Emission angle
(c) 200 shot accumulation
(d) 70 shot accumulation
(e) Single shot
(f) Mean energy vs angle
(g) 200 shots
(h) Backward electrons distribution
(i) Backward electrons energy measure

Snapshots of oblique angle and backward beams

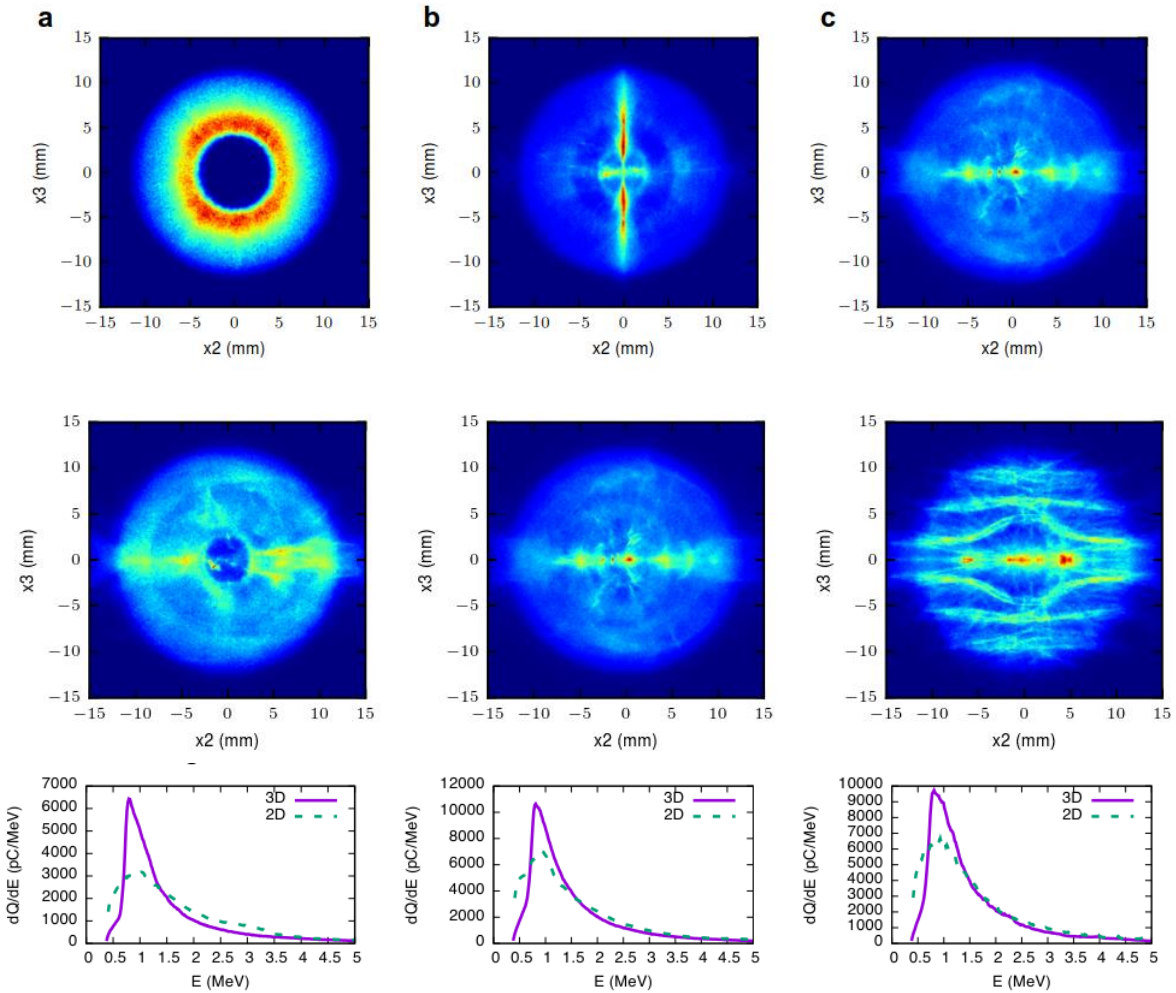




Backward beams

Oblique beams

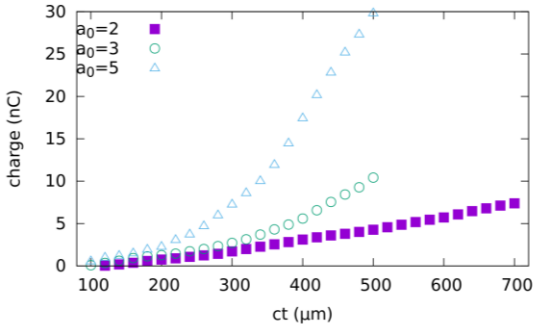
Snapshots of oblique angle and backward beams



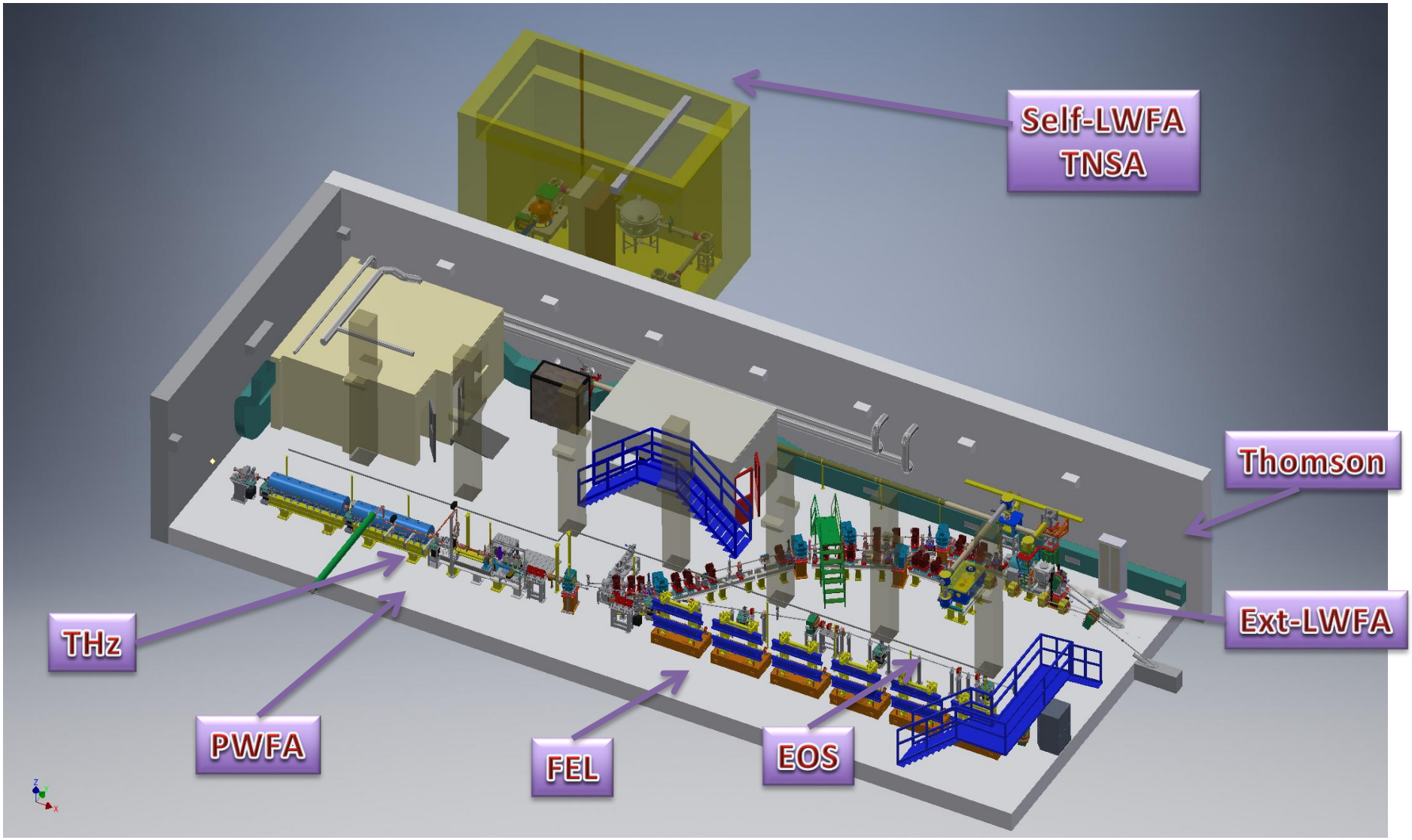
LHS: $a_0 = 2$; $w_0 = 5\ \mu m$
Centre: $a_0 = 2$; $w_0 = 7\mu m$
RHS: $a_0 = 3$; $w_0 = 7\ \mu m$

LHS & centre: $2 \times 10^{19}\ cm^{-3}$
RHS: $10^{19}\ cm^{-3}$

Laser parameters
LHS $a_0 = 2$; $w_0 = 10\ \mu m$
Centre & RHS:
$a_0 = 3$, $w_0 = 7\ \mu m$

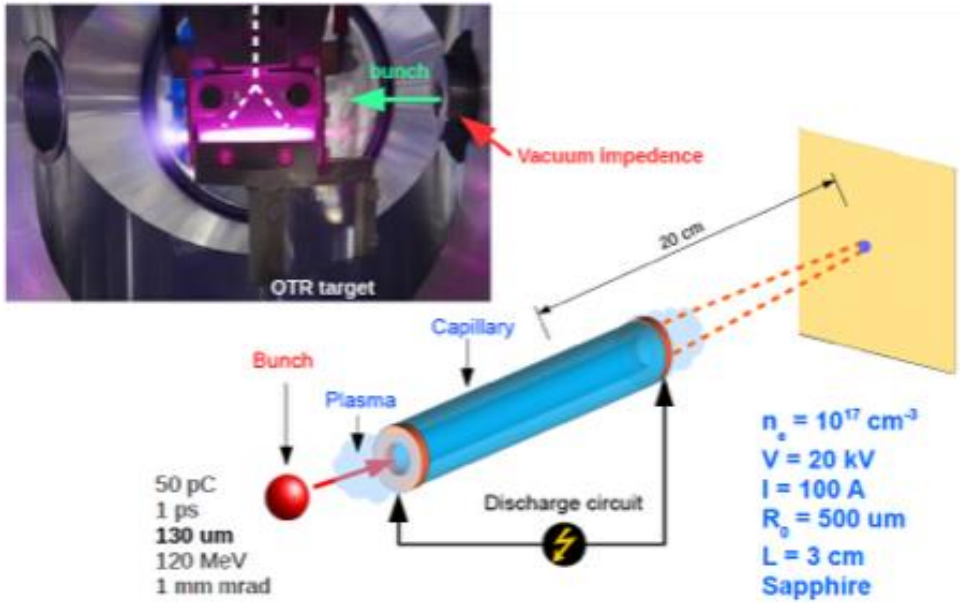


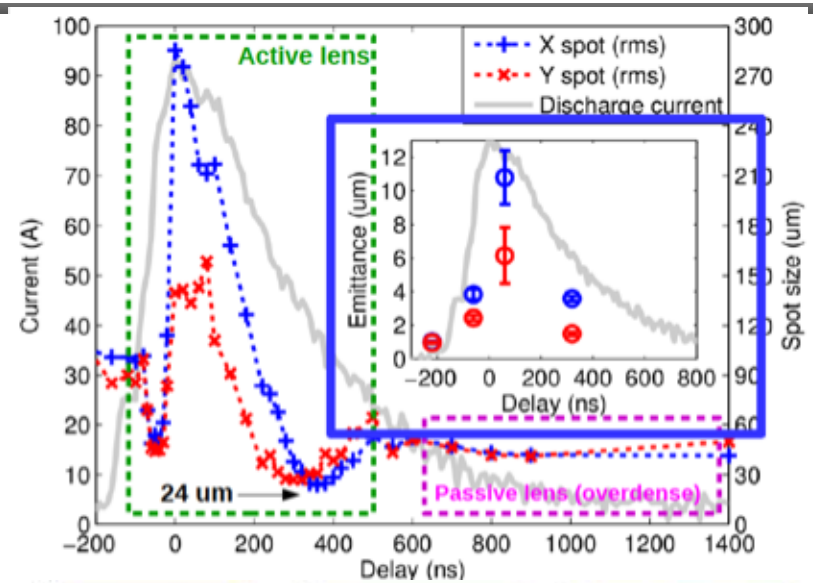
WP13.2 SPARC-INFN Activity

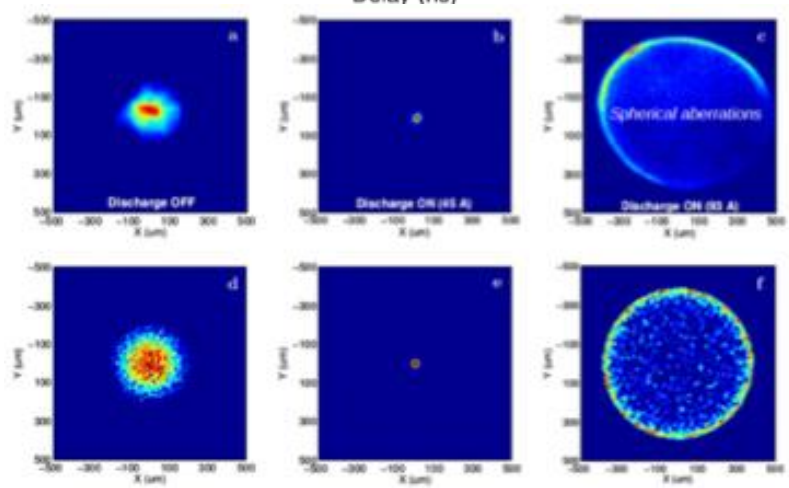


Active Plasma Lens

Discharge current in a gas-filled capillary







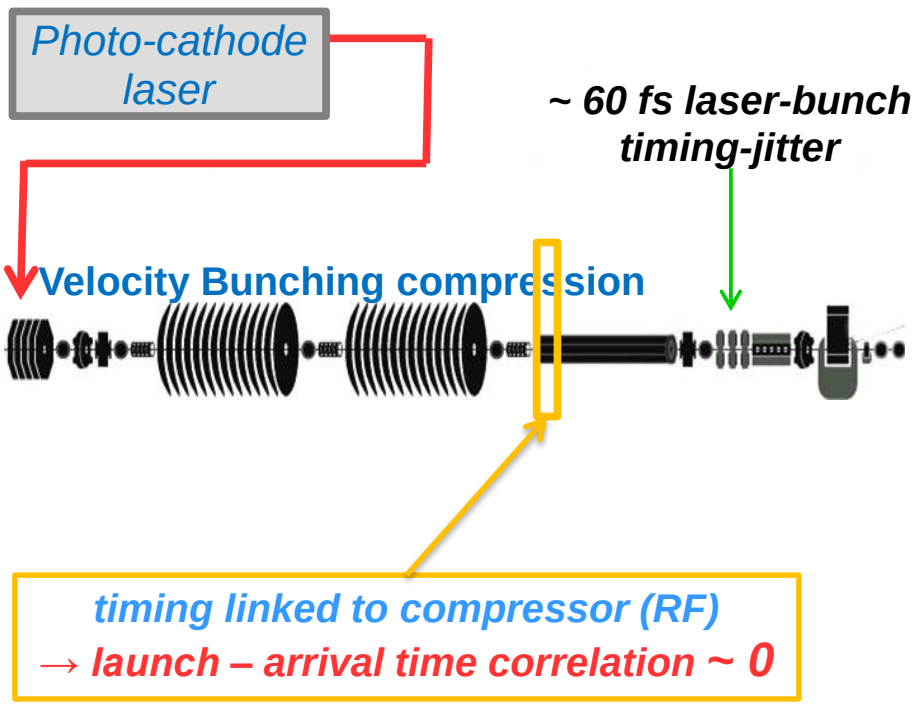
The bunch is focused by the azimuthal magnetic field generated by the discharge current, according to Ampere's law

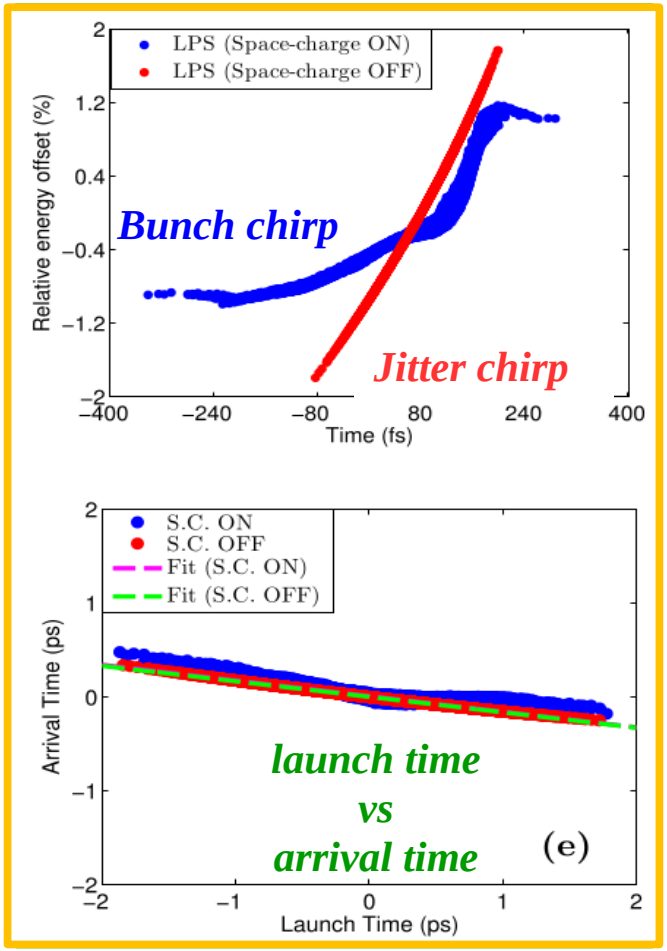
R. Pompili et al., Appl. Phys. Lett. ***110****, 104101 (2017)*

RF + magnetic hybrid compression scheme to minimize laser-bunch timing jitter

- **Ultra-short bunches with ultra-low jitter wrt photo-cathode laser pulses**
- **Seeded FELs**
- **External injection in laser-driven plasmas**

RF compression (linac)





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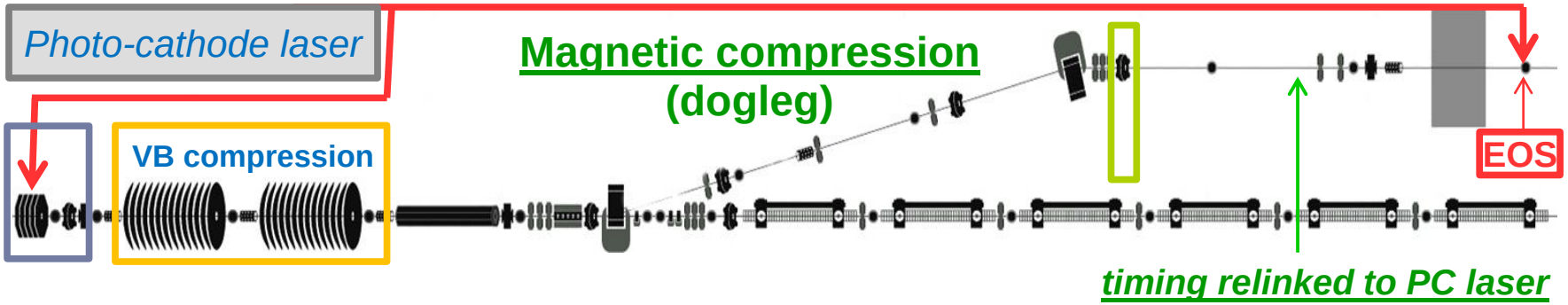
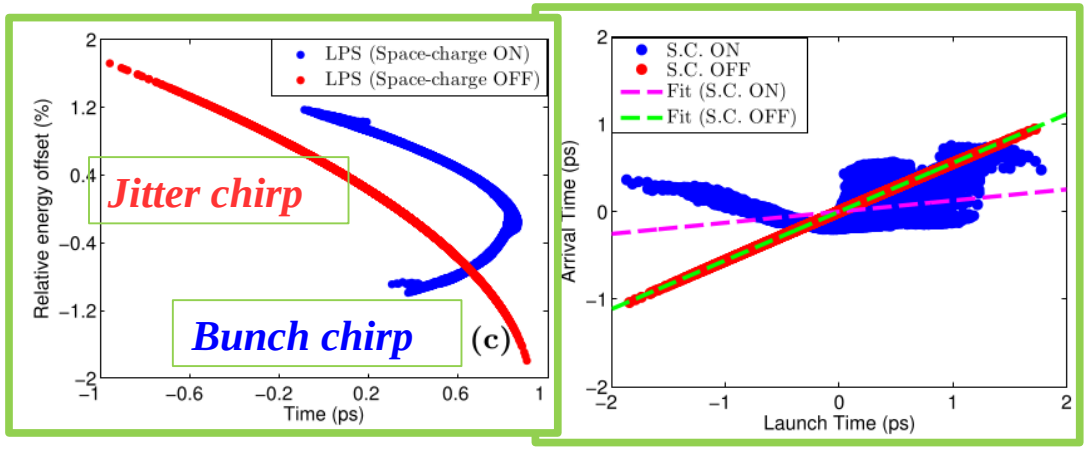
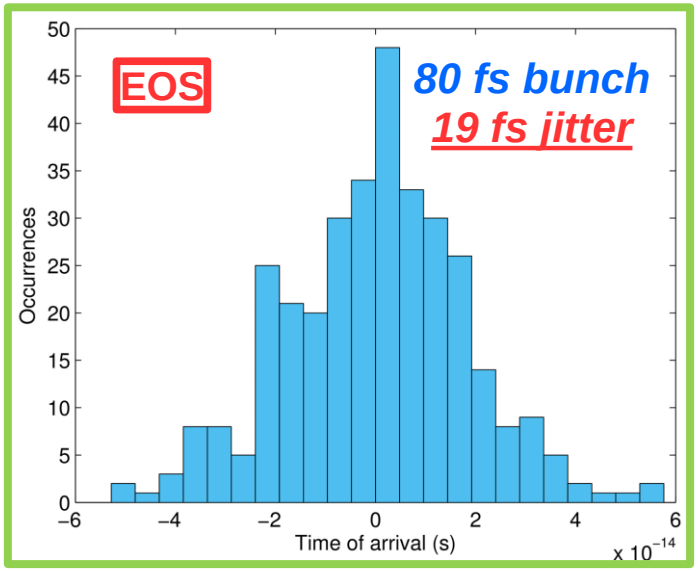


***Hybrid compression**: bunch shortening and relative jitter reduction*

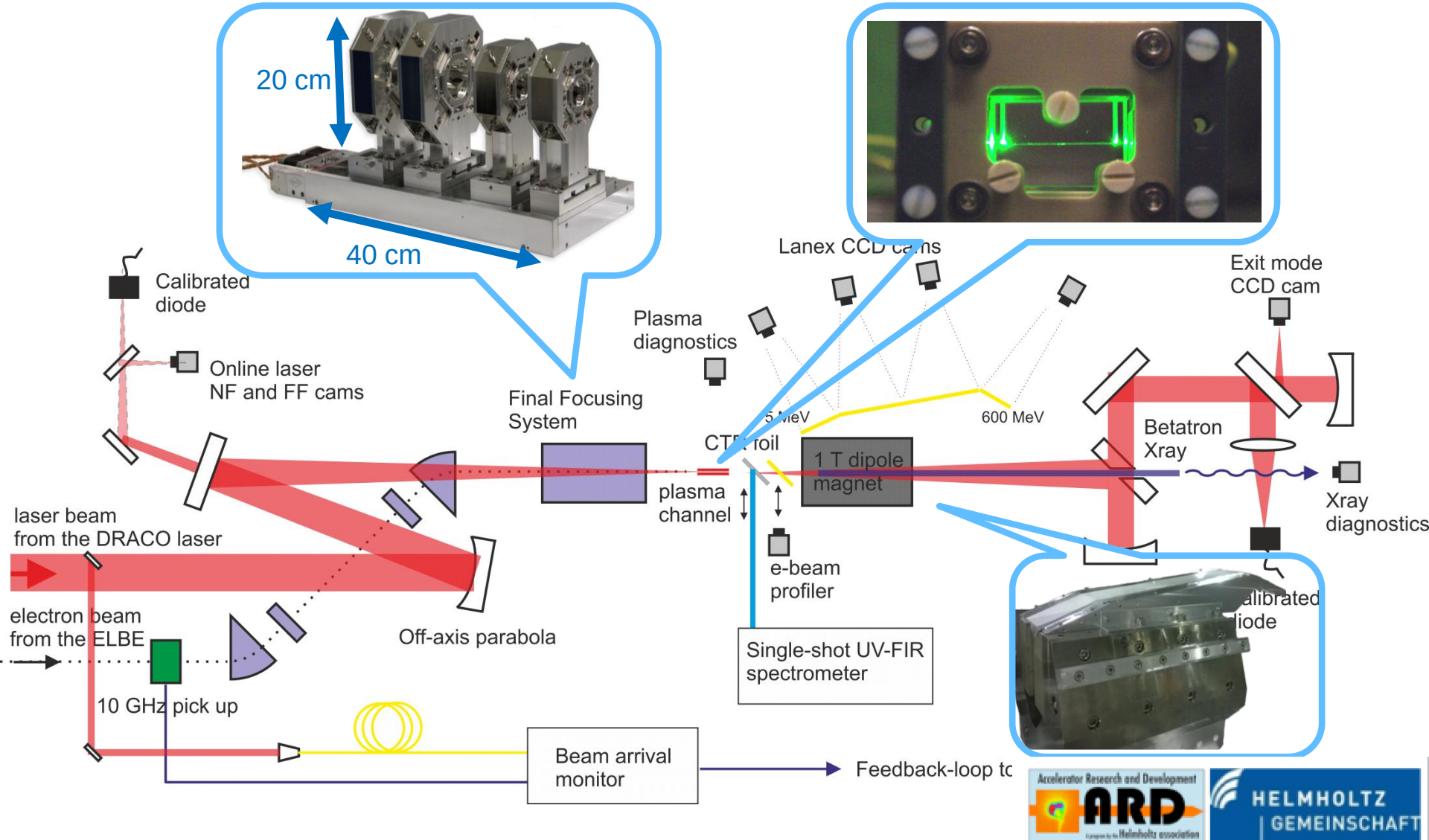
Pompili, R., et al. "Femtosecond timing-jitter between photo-cathode laser and ultra-short electron bunches by means of hybrid compression." New Journal of Physics 18.8 (2016): 083033.



→ *launch time- arrival time correlation ~1*

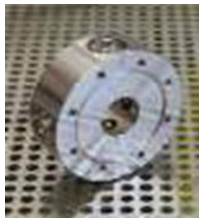


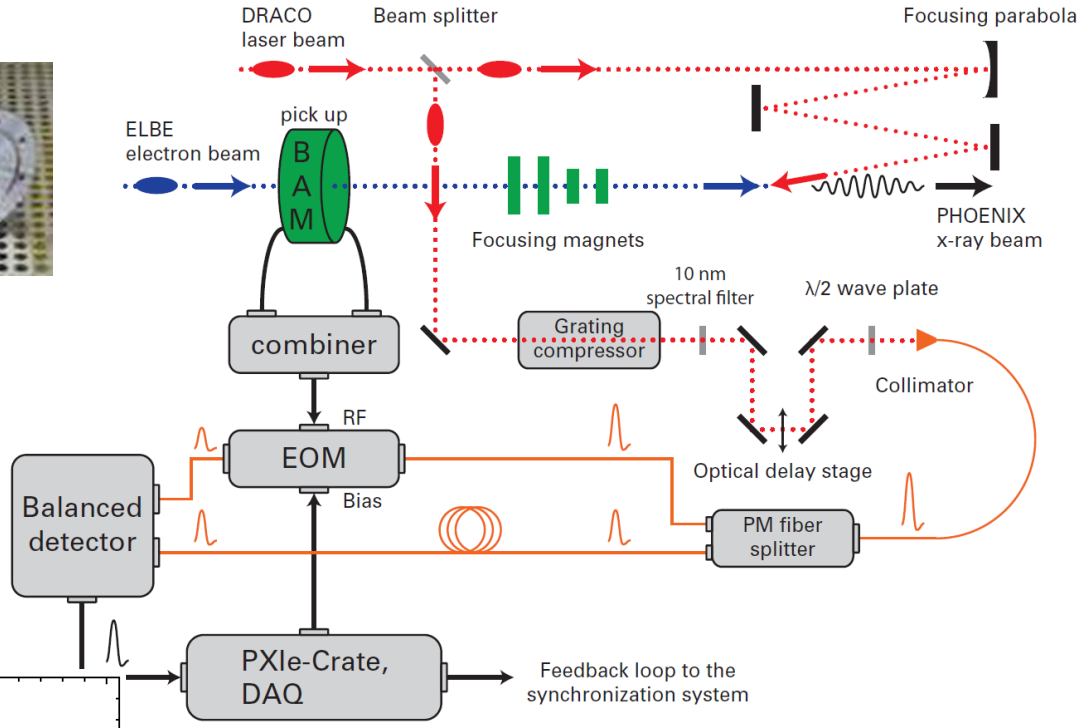
LWFA with external bunch injection

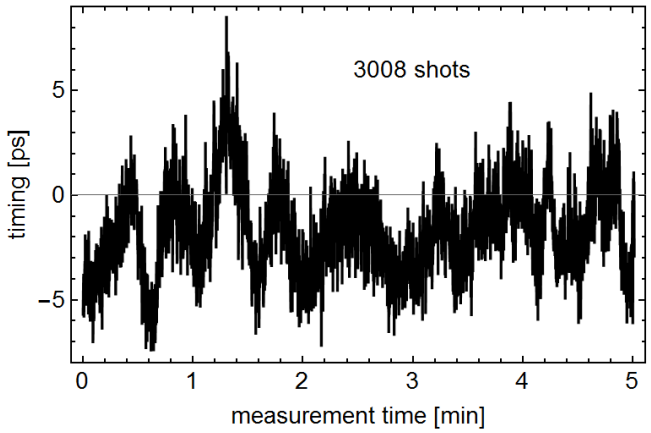


Single-shot beam arrival monitor

Measurement of single-shot arrival time jitter
ELBE beam and Draco laser beam on target

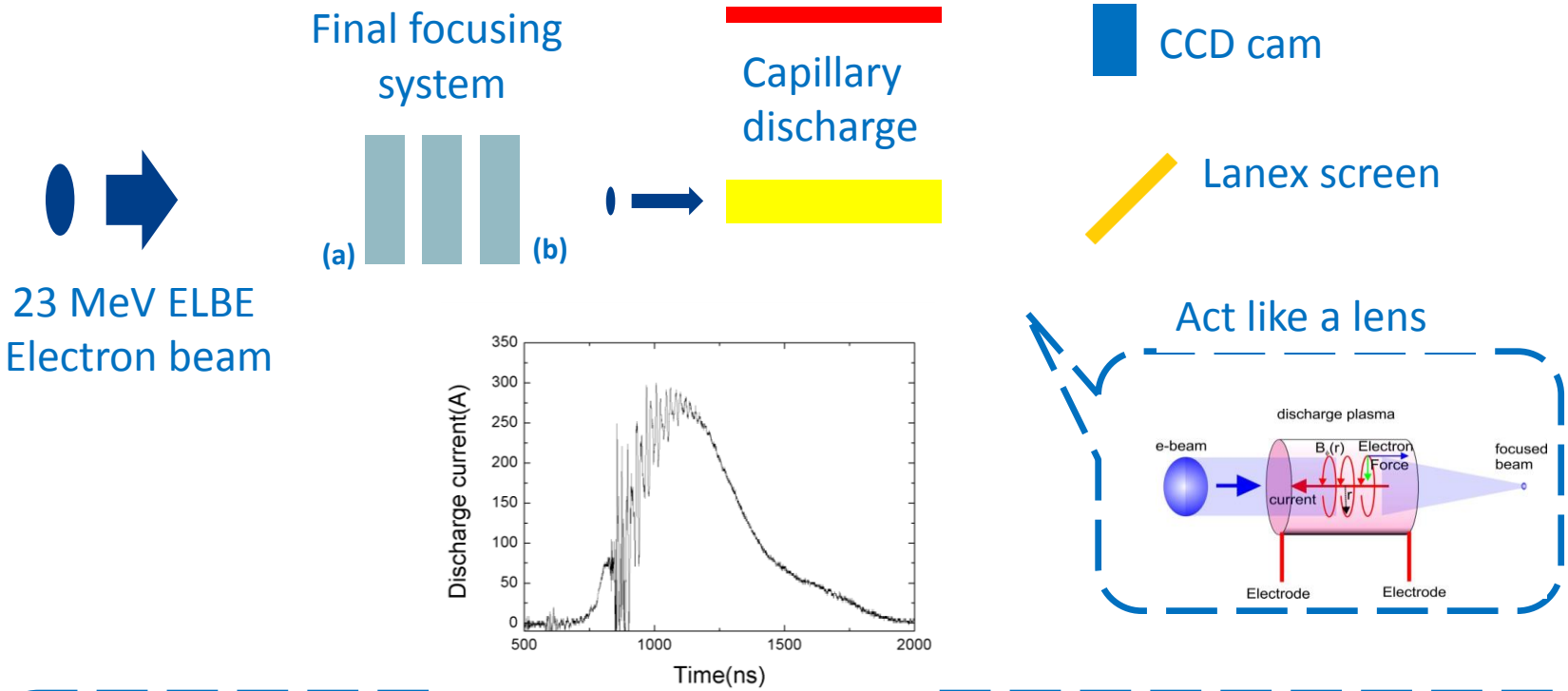


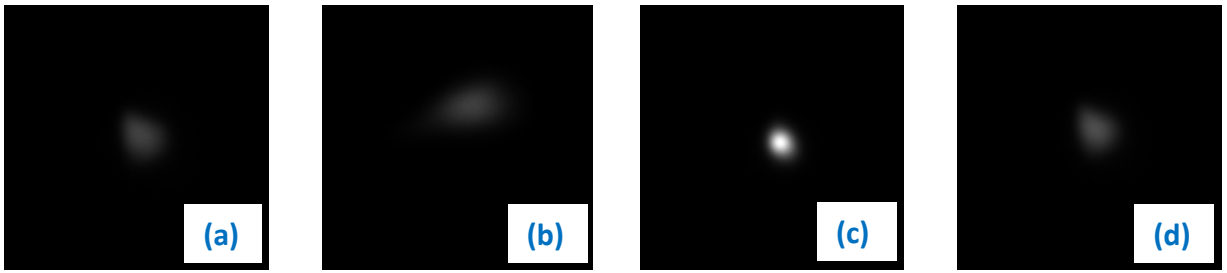




- Resolution <200fs
- Arrival time jitter : 2.2 ps (RMS)
- Mean shot-to-shot jitter: 1.4 ps
- Mainly caused by the thermionic injector

ELBE electron beam guiding in plasma channel





Electron beam spot on lanex versus injection delay with respect to the discharge current

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WP13.3 DESY Final Results

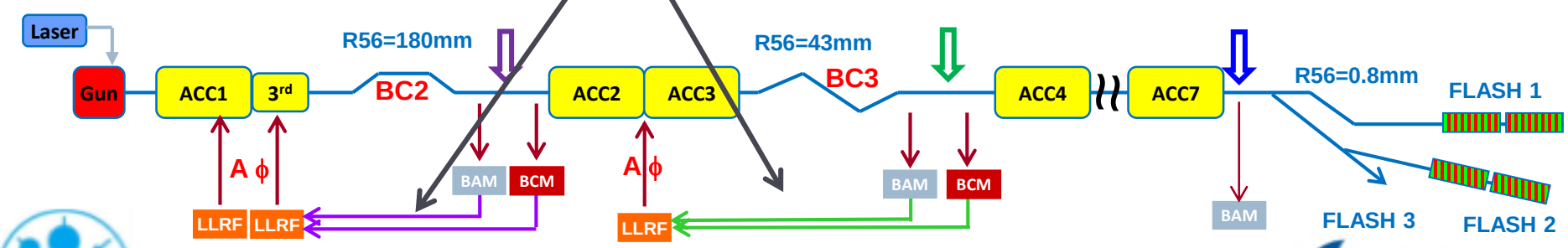
H. Schlarb, S. Pfeiffer, M. Fakhari (*Machine Beam Controls, DESY)*

Goal/Question to be addressed:

What is the ultimate time stability reached in large scale accelerators?

- Studies at the Free-electron Laser in Hamburg
- Ultra-fast beam-based feedbacks for arrival time stabilization (micro-second bunch spacing)
  - including bunch arrival time (BAM) and compression feedback (BCM)

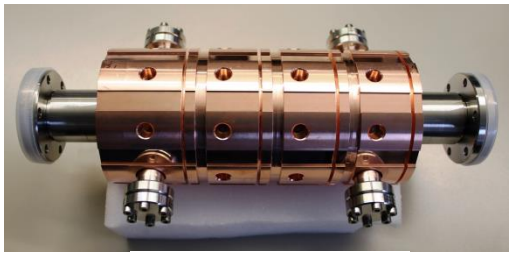
⇒ key feature of all linear Superconducting RF accelerators

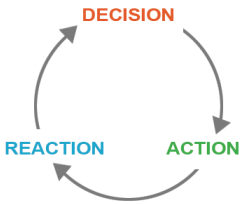


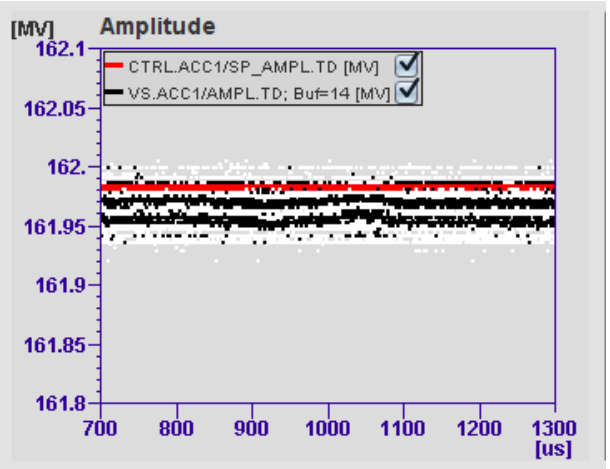
WP13.3 DESY Final Results

Working plan

1. Design a normal conducting energy corrector cavity
   - Special requirements (frequency mode separation, adjustable half bandwidth, field flatness)
2. Design the signal chain (feedback loop) to drive the cavity
   - MicroTCA.4 based electronics
   - High power amplifier driving the cavity
3. Fast fiber-link communication between the sensor (bunch arrival time monitor) and the actuator (cavity) – mandatory for fast feedback
4. Additional developments/considerations
   - Precise temperature regulation (essential for all normal conducting RF cavities)
   - Digital LLRF regulation improvement towards bit level



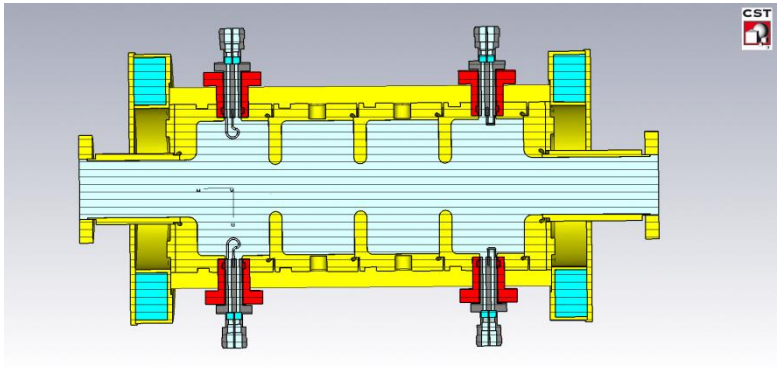




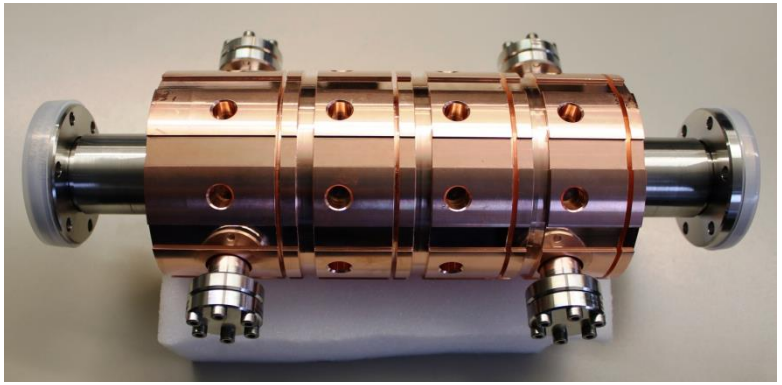
WP13.3 DESY Final Results

Normal conducting RF Cavity

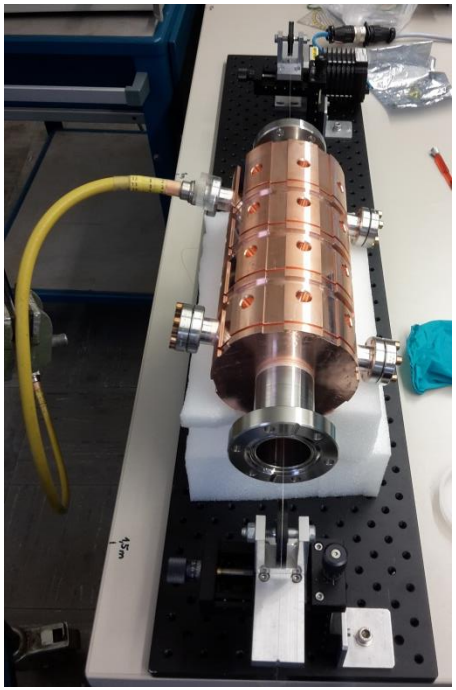
- Cavity design completed ✓



- Cavity production – finished ✓



Measurements performed with network analyzer and applying bead-pull method

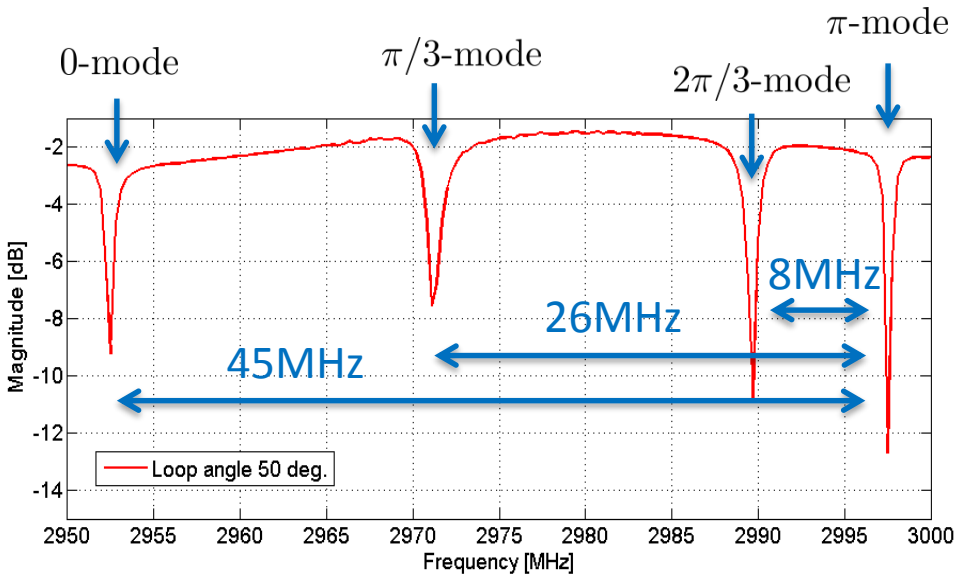


Some main results will be outlined.

WP13.3 DESY Final Results

Mode separation of the 4 resonant modes

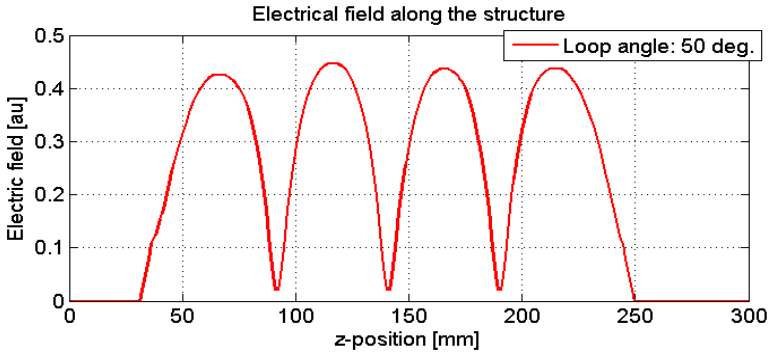
Only pi-mode is used for acceleration; the other should be shifted towards higher frequencies



The measurement results match the simulation. A slight difference is present which will not affect its operation.

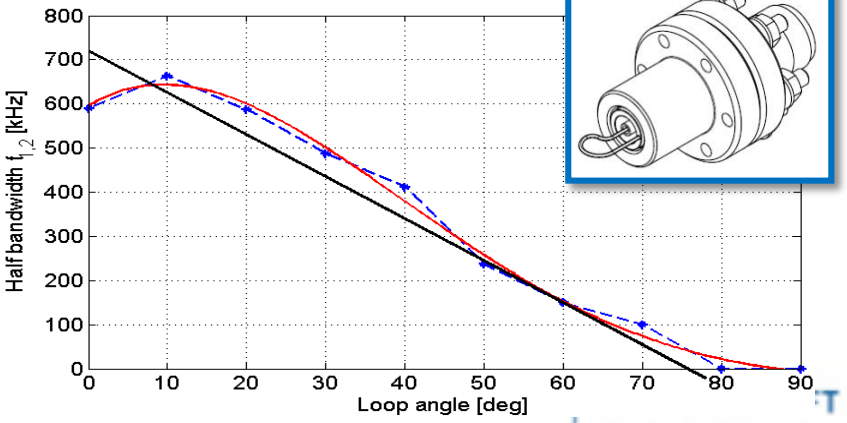
RF field distribution

As expected flat along the structure

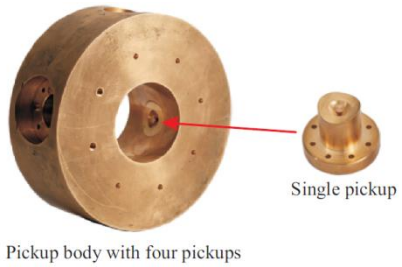


Half bandwidth as function of input loop

Measured max. half bandwidth of 650 kHz (required: 400 kHz to 500 kHz)

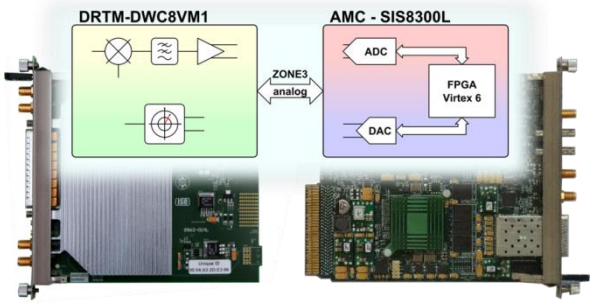


WP13.3 DESY Final Results



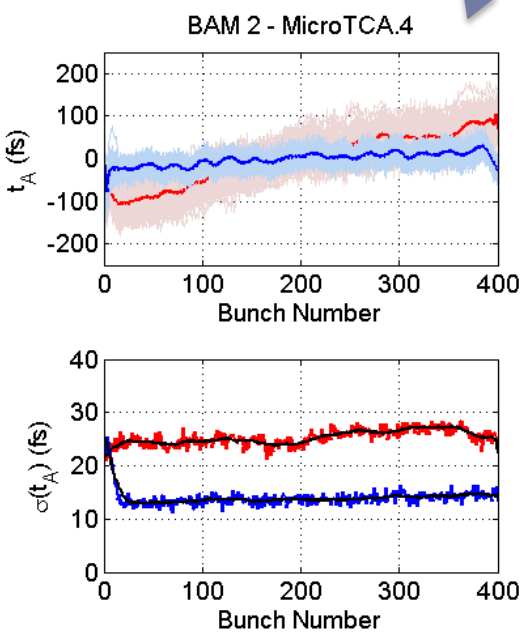
Bunch arrival time monitor as sensor

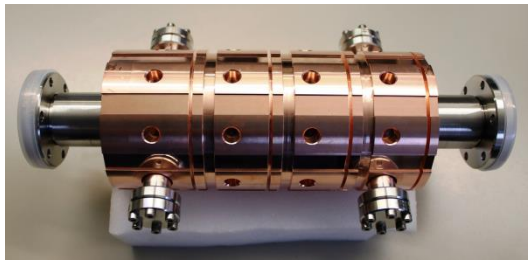
Fast optical communication; Tested by revival of beam-based feedback using SRF modules



LLRF system driving the cavity

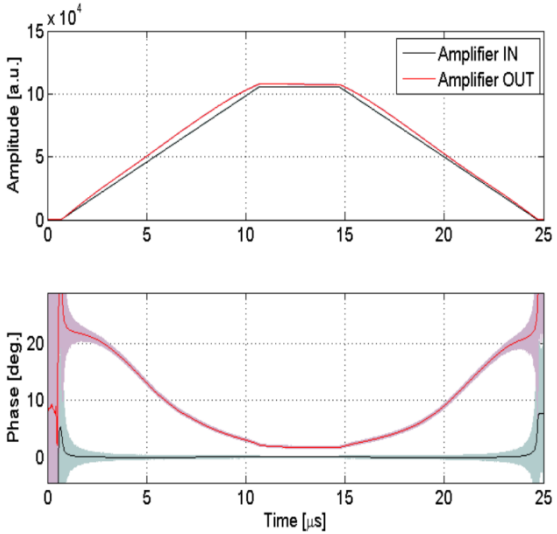
All sub-components within the feedback loop were evaluated and measured





NRF cavity as actuator

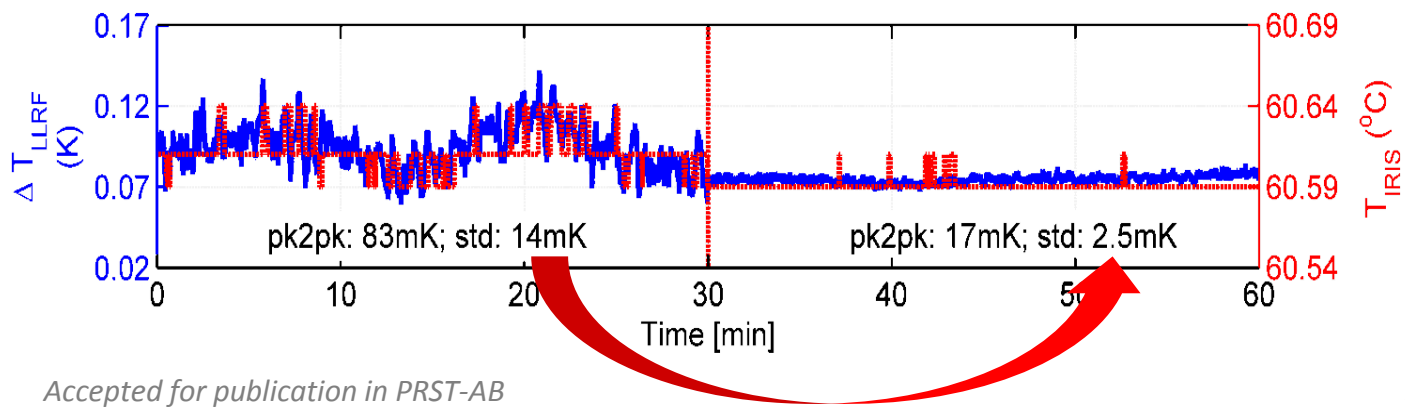
Non-linear amplifier behavior
→ correctable in digital system



WP13.3 DESY Final Results

- **Precise temperature control for NRF cavities**
  - Essential for all NRF cavities due to limited feedback gain

Without high precision feedback **With high precision feedback**



Accepted for publication in PRST-AB

Temperature improvement 14 mK → 2.5 mK

Deliverable D13.5 (04/2017) - currently finalizing the report

"FLASH NRF cavity and FB system: Report on the achievable arrival time stability and the limitations of using NRF & SRF beam-based feedbacks at FLASH"

Missions of ANAC2

The Anac2 team :
8 contractors, CNRS, DESY, UDUS, HZDR, INFN, LUND, STRATH, UCL+ One invited CERN.

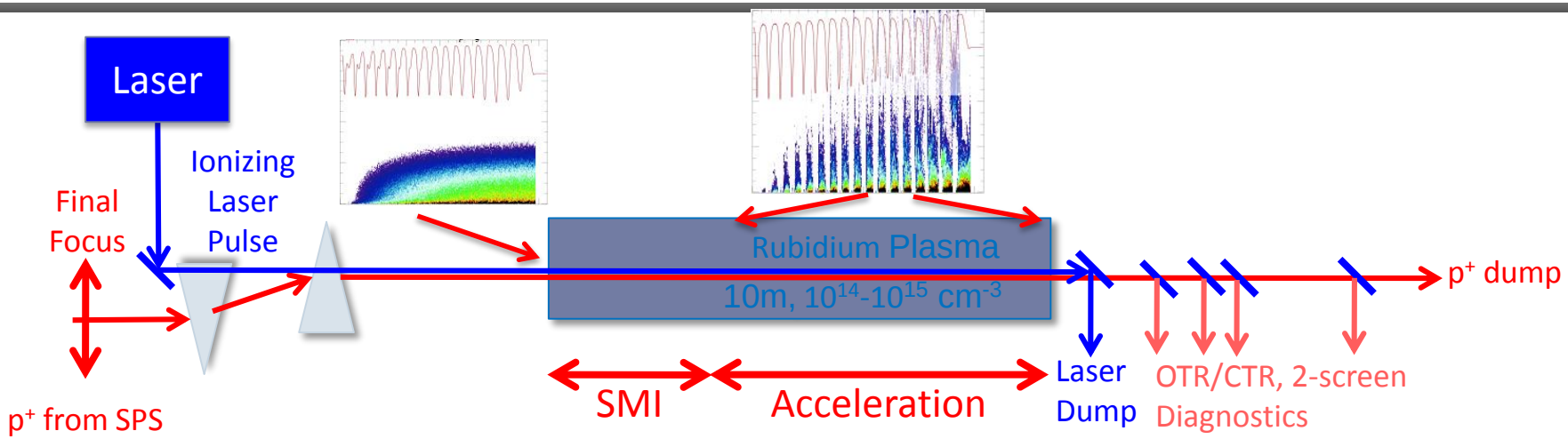
Task 13.1. Coordination and Communication (V. Malka)
- Coordination and scheduling of the WP tasks and WP budget follow-up
- Monitoring the work, informing the project management and participants within the JRA

Task 13.2. Achievement of high brightness electron beam with laser plasma accelerators (O. Lundh)
- Feasibility study of external injection done at INFN and HFZD
- Optical injection done at LOA and LLC
- Two stage laser plasma accelerator done at STRATH

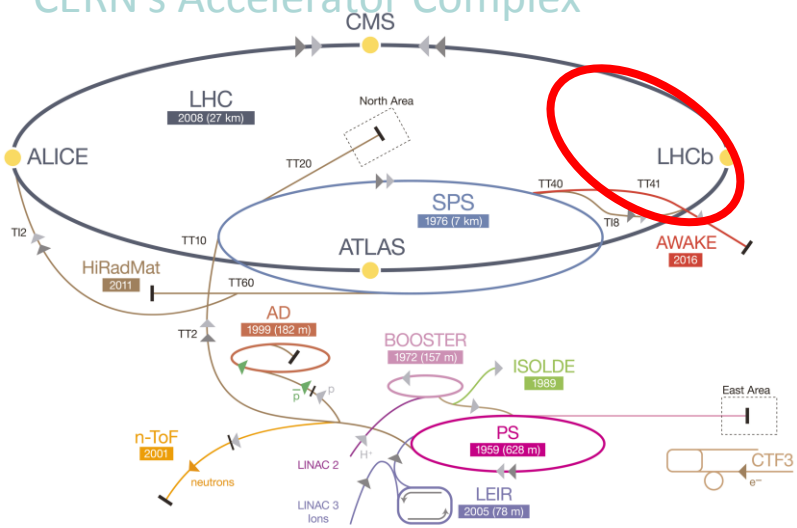
Task 13.3. Ultra-fast accelerator science (H. Schlarb)
- Digital intra-bunch-train feedback for femtosecond arrival-time control of electron bunches
- Determine opportunistic effects causing slow and fast femtosecond bunch arrival time variations at FLASH
- Further improvements of the low level RF regulation system for pulse superconducting accelerators towards 2.10^{-5} field instability

Task 13.4. Modulation of long plasmas (M. Wing)
- Concept for plasma cells for beam acceleration with a length of equal or above 10m
- Understand instabilities and modulations in long plasma, driver and accelerated beam
- Prototyping and development of diagnostics for long plasma cells to be used in CERN experiment testing proton-driven plasma wakefield acceleration

AWAKE experimental set-up



CERN's Accelerator Complex



- ✧SPS bunch: 400GeV, $3\times10^{11}p^+$,
- ✧10m, laser ionized Rb plasma $1\text{-}10\times10^{14}cm^{-3}$

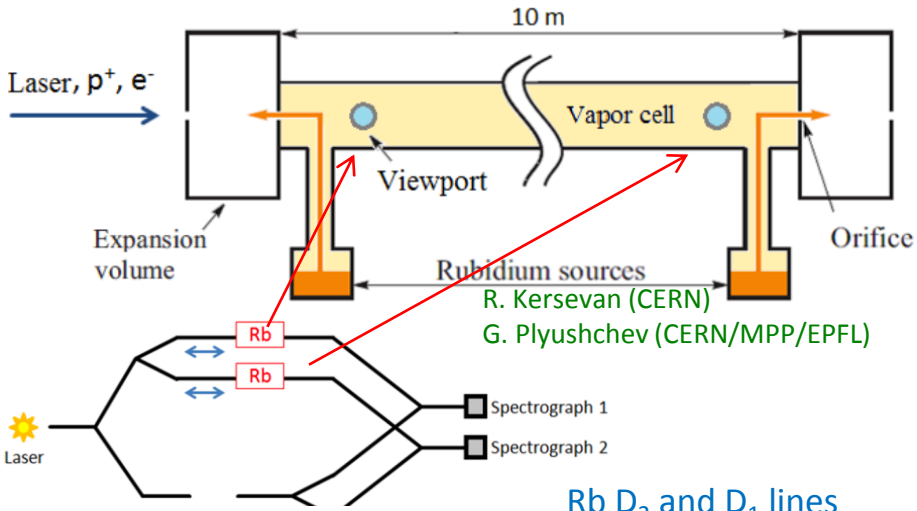
<u>2016-17: self-modulation instability (SMI) studies</u>

Three observables

- ✧Defocused p^+
- ✧p^+ bunch modulation at λ_{pe}
- ✧Emission of coherent transition radiation at λ_{pe}

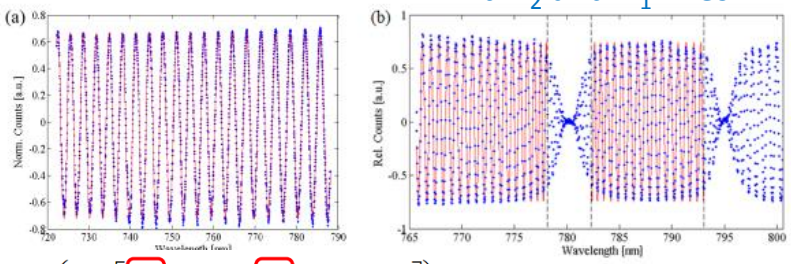
Rb Vapor/Plasma source

- ✧ $1\times10^{14}<n_e<1\times10^{15}\,cm^{-3}$
- ✧ Very uniform density: $\Delta n_{Rb,e}/n_{Rb,e}<0.2\%$
- ✧ Sharp ramps: a few cm
- ✧ Heat exchanger + free expansion of Rb
- ✧ Laser field ionization



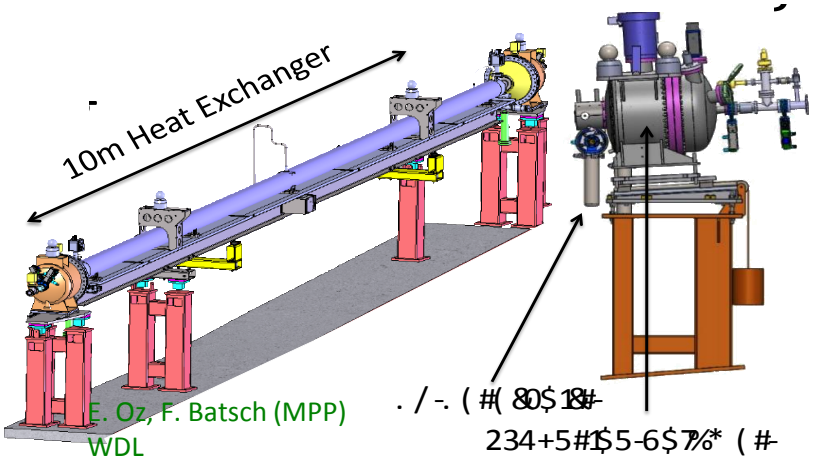
R. Kersevan (CERN)
G. Plyushchev (CERN/MPP/EPFL)

Rb D_2 and D_1 lines



$$S(\lambda)=\tilde{A}\cdot\cos\left(\frac{2\pi}{\lambda}\cdot\left[\frac{\tilde{n}l\,r_0 f_1\lambda_1^3}{4\pi(\lambda-\lambda_1)}+\frac{\tilde{n}l\,r_0 f_2\lambda_2^3}{4\pi(\lambda-\lambda_2)}+\tilde{\xi}\right]\right)$$

Öz et al., NIMA 829, 321 (2016)



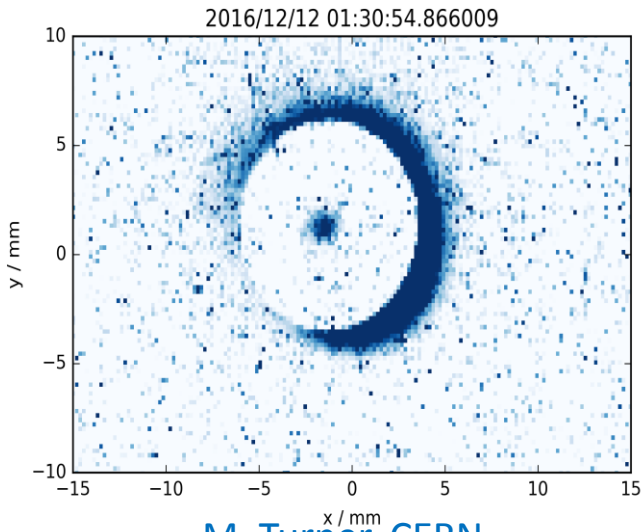
E. Oz, F. Batsch (MPP)
WDL

E. Oz & P. Muggli., NMA 740(11), 197 (2014).

- ✧ Meet density requirements
- ✧ Measure n_{Rb} with <0.5% accuracy

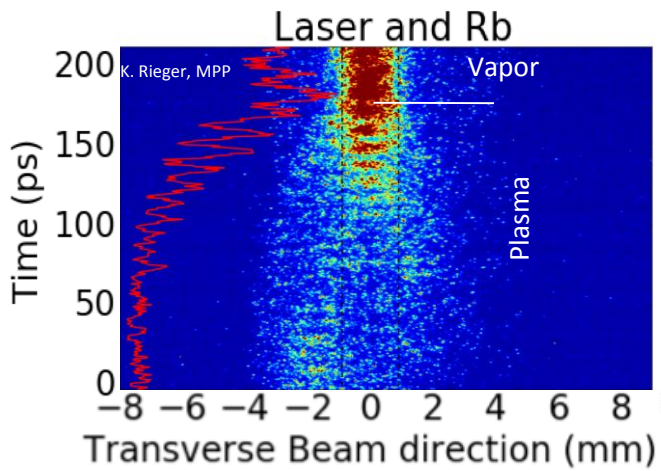
AWAKE: Results

✧Defocused p^+



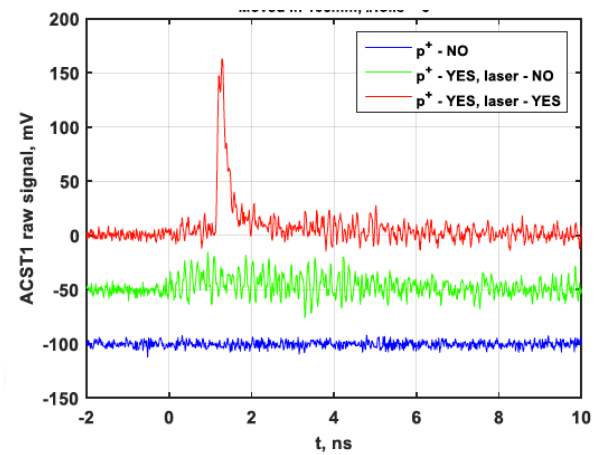
M. Turner, CERN

✧OTR:Modulation at 10 ps scale



K. Rieger, MPP

✧CTR emission



M. Martyanov
F. Braunmueller, MPP

✧Successful first SMI physics run: 48h

✧Operation at low plasma density: $1.5 \times 10^{14} cm^{-3}$

✧Signal detected on all three diagnostics

See P. Muggli's talk for more details

Liste des publications 2016-2017

1 Energy boost in Laser-Wakefield Accelerator using sharp density transitions
A. Döpp, E. Guillaume, C. Thaury, A. Lifschitz, K. Ta Phuoc, and V. Malka, Phys. of Plasma 23, 056702 (2016)
2 Particle-in-Cell Codes for plasma-based particle acceleration
A. Pukhov, CERN Yellow reports, 1 (2016), doi/10.5170/CERN-2016-001.181
3 Voronoi Particle Merging Algorithm for PIC Codes
P.T. Luu, T. Tückmantel, A. Pukhov, Comput. Phys. Commun. 202 (2016) 165-174, doi :10.1016/j.cpc.2016.01.009
4 Injection of electrons by colliding laser pulses in a laser wakefield accelerator
M. Hansson, B. Aurand, H. Ekerfelt, A. Persson, C.-G. Wahlström, O. Lundh, Nuclear Instruments & Methods in Physics Research A (2016)
5 Localization of ionization-induced trapping in a laser wakefield accelerator using a density down-ramp
M. Hansson, T. L. Audet, H. Ekerfelt, B. Aurand, I. Gallardo González, F. G. Desforges, X. Davoine, A. Maitrallain, S. Reymond, P. Monot, A. Persson, S. Dobosz Dufrénoy, C.-G. Wahlström, B. Cros, and O. Lundh,
Plasma Physics and Controlled Fusion 58, 055009 (2016).
6 Optmized stability of a modulated driver in a plasma wakefield accelerator
R. Martorelli, A. Pukhov, arXiv preprint, arXiv:1603.04326 (2016)
7 Characterization of the equilibrium configuration for modulated beams in a plasma wakefield accelerator
R. Martorelli, A. Pukhov, Physics of Plasmas **23**, 053109 (2016); Laser and Particle Beams, 34, 3 (2016), 519-526, doi/10.1017/S02630346000409
8 Bright X-Ray Source from a Laser-Driven Microplasma Waveguide
L. Yi, A. Pukhov, P. Luu-Thanh, and B. Shen, Phys. Rev. Lett. 116, 115001 (2016)
9 A non-linear theory for the bubble regime of plasma wake fields in a plasma channels for special applications and control
J. Thomas, I.Y. Kostyukov, J. Pronold, A. Golovanov, A. Pukhov, Phys. of Plasmas 23, 053108 (2016)
10 Investigation of ionization-induced electron injection in a wakefield driven by laser inside a gas cell
T. L. Audet, M. Hansson, P. Lee, F. G. Desforges, G. Maynard, S. Dobosz Dufrénoy, R. Lehe, J. -L. Vay, B. Aurand, A. Persson, I. Gallardo González, A. Maitrallain, P. Monot, C.-G. Wahlström, O. Lundh, and B. Cros, Physics of Plasmas 23, 023110 (2016).
11 Supersonic jets of hydrogen and helium for laser wakefield acceleration
K. Svensson, M. Hansson, F. Wojda, L. Senje, M. Burza, B. Aurand, G. Genoud, A. Persson, C.-G. Wahlström, and O. Lundh, Physical Review Accelerators and Beams 19, (2016

Liste des publications 2016-2017

12 AWAKE, A proton-driven plasma wakefield acceleration experiment at CERN
AWAKE Collaboration, E. Gschwendtner *et al.*, Nucl. Inst. Meth. A 829 (2016) 76-82, DOI/10.1016/ nima.2016.02.026
13 AWAKE, The advanced proton driven plasma wakefield acceleration experiment at CERN
AWAKE Collaboration, C. Bracco *et al*., Nucl. Inst. Meth. A 273-285 (2016), DOI/10.1016/ nima.2015.09.022
14 Single shot betatron source size measurement from a laser-wakefield accelerator
A.Köhler, J.P. Couperus, O. Zarini, A. Jochmann, A. Irman, U. Schramm, Nuclear Instruments and Methods in Physics Research A 829, 265-269 (2016), doi:10.1016/j.nima.2016.02.03
15 Tomographic characterisation of gas-jet targets for laser wakefield acceleration
J.P. Couperus, A. Köhler, T.A.W. Wolterink, A. Jochmann, O. Zarini, H.M.J. Bastiaens, K.J. Boller, A. Irman, U. Schramm, Nuclear Instruments and Methods in Physics Research A, 830, 504-509 (2016), doi:10.1016/j.nima.2016.02.099
16 3D printing of gas jet nozzles for laser-plasma accelerators
A.Döpp, E. Guillaume, C. Thaury, J. Gautier, K. Ta Phuoc, and V. Malka, *Review of Scientific Instruments* **87**, 073505 (2016), http://dx.doi.org/10.1063/1.4958649
17 Quasi-stable injection channels in a wakefield accelerator
M. Wiltshire-Turkay, J. P. Farmer, A. Pukhov, Phys. Of Plasmas, 23, 5 053112 (2016), doi :10.1063/1.49508038
18 Raman amplification in the coherent wave-breaking regime
J. P. Farmer, A. Pukhov, Phys. Rev. E, 92, 6 063109 (2015), doi :10.1103/PhysRevE.92.063109
19 Three electron beams from a laser-plasma wakefield accelerator and the energy apportioning question
X. Yang, E. Brunetti, D. Reboredo Gil, G. H. Welsh, F. Y. Li, S. Cipiccia, B. Ersfeld, D. W. Grant, P. A. Grant, M. R. Islam, M. P. Tooley, G. Vieux, S. M. Wiggins, Z. M. Sheng & D. A. Jaroszynski, *Scientific Reports* **7**, 43910 (2017), doi:10.1038/srep43910
20 Femtosecond timing-jitter between photo-cathode laser and ultrashort electron bunches by means of hybrid compression
R. Pompili, M. P. Anania, M. Bellaveglia, A. Biagioni, G. Castorina, E. Chiadroni, A. Cianchi, M. Croia, D. Di Giovenale, M. Ferrario, F. Filippi, A. Gallo, G. Gatti, F. Giorgianni, A. Giribono, W. Li, S. Lupi, A. Mostacci, M. Petrarca, L. Piersanti, G. Di Pirro, S. Romeo, J. Scifo, V. Shpakov, C. Vaccarezza and F. Villa, New J. Phys. 18 (2016) 083033
21 Experimental characterization of active plasma lensing for electron beams
R. Pompili, M. P. Anania, M. Bellaveglia, A. Biagioni, S. Bini, F. Bisesto, E. Brentegani, G. Castorina, E. Chiadroni, A. Cianchi, M. Croia, D. Di Giovenale, M. Ferrario, F. Filippi, A. Giribono, V. Lollo, A. Marocchino, M. Marongiu, A. Mostacci, G. Di Pirro, S. Romeo, A. R. Rossi, J. Scifo, V. Shpakov, C. Vaccarezza, F. Villa, and A. Zigler, Appl. Phys. Lett. **110**, 104101 (2017); doi: 10.1063/1.4977894

Milestones and Deliverables

Report no. (D/M)	Title	Due date	Status
DL13.1	Technical design report on ultra-fast longitudinal feedback for FLASH	31.10.2014	Done
MS90	Development and characterization of a new gas target system	31.10.2014	Done
MS91	Simulation of SPS beam self-modulation in plasma with seeding by laser	31.10.2014	Done
DL13.2	Simulation of external injection into bubble	31.04.2015	Done
DL13.2	Optimal realizable SPS configuration	31.04.2015	Done
MS92	NRF operation established with closed beam based FB loop	31.10. 2015	=>DL13.5
MS93	Diagnostic system installed and performance determined	31.10.2015	Done
MS94	Simulation of modular plasma configuration	31.04.2016	Done
DL13.4	Experimental characterization of e-beams	31.04.2016	Done
DL13.5	FLASH NRF cavity and FB system	31.04.2017	On going
DL13.6	Optimum beam-plasma configuration	31.04.2017	On going