ANAC2
Novel Acceleration Techniques
Glasgow, 28-30 March 2017
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 2e-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
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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 measurement
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: \(2 \times 10^{19} \, \text{cm}^{-3}\)
RHS: \(10^{19} \, \text{cm}^{-3}\)

Laser parameters
LHS \(a_0 = 2; \; w_0 = 10 \, \mu m\)
Centre & RHS:
\(a_0 = 3, \; w_0 = 7 \, \mu m\)
The bunch is focused by the azimuthal magnetic field generated by the discharge current, according to Ampere’s law.

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)**

- Photo-cathode laser
- Velocity Bunching compression
- Timing linked to compressor (RF) → launch – arrival time correlation ~ 0

**Bunch chirp**

**Jitter chirp**

- Launch time vs arrival time (e)
RF + magnetic hybrid compression scheme to minimize laser-bunch timing jitter

**Photo-cathode laser**

**VB compression**

**Magnetic compression** (dogleg)

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


→ 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
23 MeV ELBE Electron beam

Final focusing system

Capillary discharge

CCD cam

Lanex screen

Act like a lens

Electron beam spot on lanex versus injection delay with respect to the discharge current
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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
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
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.
Mode separation of the 4 resonant modes
Only pi-mode is used for acceleration; the other should be shifted towards higher frequencies.

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)

The measurement results match the simulation. A slight difference is present which will not affect its operation.
WP13.3 DESY Final Results

- **Bunch arrival time monitor as sensor**
- **NRF cavity as actuator**
- **LLRF system driving the cavity**
- **Non-linear amplifier behavior** → correctable in digital system

**Fast optical communication**: Tested by revival of beam-based feedback using SRF modules.

**All sub-components within the feedback loop were evaluated and measured**.
**Precise temperature control for NRF cavities**

- Essential for all NRF cavities due to limited feedback gain

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"
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CERN’s Accelerator Complex

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

**2016-17: self-modulation instability (SMI) studies**

- Defocused $p^+$
- $p^+$ bunch modulation at $\lambda_{pe}$
- Emission of coherent transition radiation at $\lambda_{pe}$

**Three observables**

- Defocused $p^+$
- $p^+$ bunch modulation at $\lambda_{pe}$
- Emission of coherent transition radiation at $\lambda_{pe}$
Rb Vapor/Plasma source

- $1 \times 10^{14} < n_e < 1 \times 10^{15}$ cm$^{-3}$
- Very uniform density: $\Delta n_{Rb}/n_{Rb} < 0.2$
- Sharp ramps: a few cm
- Heat exchanger + free expansion of Rb
- Laser field ionization

### Diagram

- Laser, $p^+$, $e^-$
- Vapor cell
- Rubidium sources
- Viewport
- Orifice
- 10m Heat Exchanger
- R. Kersevan (CERN)
- G. Plyushchev (CERN/MPP/EPFL)

### Rb D$_2$ and D$_1$ lines

$$S(\lambda) = \hat{A} \cdot \cos \left( \frac{2\pi}{\lambda} \cdot \frac{\vec{m} \cdot \vec{f}}{4\pi(\lambda - \lambda_1)} + \frac{\vec{m} \cdot \vec{f}}{4\pi(\lambda - \lambda_2)} + \theta \right)$$

Öz et al., NIMA 829, 321 (2016)

### References

- E. Oz, F. Batsch (MPP)
- WDL
- Meet density requirements
- Measure $n_{Rb}$ with <0.5% accuracy
AWAKE: Results

- **Successful first SMI physics run:** 48h
- **Operation at low plasma density:** $1.5 \times 10^{14} \text{cm}^{-3}$
- **Signal detected on all three diagnostics**

See P. Muggli’s talk for more details
1 Energy boost in Laser-Wakefield Accelerator using sharp density transitions

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

4 Injection of electrons by colliding laser pulses in a laser wakefield accelerator

5 Localization of ionization-induced trapping in a laser wakefield accelerator using a density down-ramp

6 Optimized stability of a modulated driver in a plasma wakefield accelerator

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

9 A non-linear theory for the bubble regime of plasma wake fields in a plasma channels for special applications and control

10 Investigation of ionization-induced electron injection in a wakefield driven by laser inside a gas cell

11 Supersonic jets of hydrogen and helium for laser wakefield acceleration
Physical Review Accelerators and Beams 19, (2016)
12 AWAKE, A proton-driven plasma wakefield acceleration experiment at CERN

13 AWAKE, The advanced proton driven plasma wakefield acceleration experiment at CERN

14 Single shot betatron source size measurement from a laser-wakefield accelerator

15 Tomographic characterisation of gas-jet targets for laser wakefield acceleration

16 3D printing of gas jet nozzles for laser-plasma accelerators

17 Quasi-stable injection channels in a wakefield accelerator

18 Raman amplification in the coherent wave-breaking regime

19 Three electron beams from a laser-plasma wakefield accelerator and the energy apportioning question

20 Femtosecond timing-jitter between photo-cathode laser and ultrashort electron bunches by means of hybrid compression

21 Experimental characterization of active plasma lensing for electron beams
# Milestones and Deliverables

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