AWAKE External Review Report

Edda Gschwendtner, CERN

AWAKE Collaboration Meeting, 11 – 13 March 2024

AWAKE External Review

External Review on the Scientific and Technological Objectives of the AWAKE Project

At CERN, Monday, February 5th, 2024

Reviewers

Chair: Andrei Seryi (JLAB)

Members: Ralph Assmann (GSI), Enrica Chiadroni (INFN), Roberto Corsini (CERN), Mark Hogan (SLAC), Simon Hooker (Oxford).

Mandate

The Review

The Review Panel is tasked with the following evaluations:

1. Assess the feasibility and coherence of the full AWAKE Run 2 roadmap.
2. Evaluate the scientific merits of the accelerator physics and technological advancements expected from the AWAKE Run 2c and 2d programmes, their complementarity with other ongoing initiatives, and their impact on the overall PWFA field.
3. Evaluate whether by the end of the AWAKE Run 2c and 2d programmes all technologies and beam parameters required to allow for a future particle physics experiment based on proton driven wakefield acceleration will have been demonstrated.
4. Determine whether AWAKE is the most appropriate facility for the realization of the anticipated advancements of AWAKE Run 2c and 2d.

Agenda

09:00 → 09:05 **Welcome**
Speaker: Mike Lamont (CERN)

09:05 → 09:10 **Introduction**
Speaker: Andrei Seryi (Jefferson Lab)

09:10 → 09:40 **AWAKE: An Experiment at CERN with an International Collaboration and a Well-Defined Program of Work**
Speaker: Edda Gschwendtner (CERN)
2024-02-05-AWAKE-... 2024-02-05-AWAKE-...

09:40 → 09:50 **Discussion**

09:50 → 10:10 **AWAKE Achievements to Date**
Speaker: Marlene Turner (CERN)
AWAKEreview2024-... AWAKEreview2024-...

10:10 → 10:20 **Discussion**

10:20 → 10:40 **The Next AWAKE Runs: Technological Advancements, Scientific Merit and Expected Parameter Reach**
Speaker: Patric Muggli (Max Planck Institute for Physics)
AWAKEReview2024... OLD.pdf

10:40 → 10:50 **Discussion**

10:50 → 11:10 **Coffee break**

11:10 → 11:25 **Developing Expectations with Plasma Simulations**
Speaker: John Patrick Farmer (MPP / CERN)
AWAKE_Review_Far...

11:25 → 11:35 **Discussion**

11:35 → 12:30 **Complementarity with and Impact on the Global Advancement of Plasma Wakefield Acceleration**

- 11:35 **External Electron Injection: from Electron Source to Plasma**
  Speakers: Steffen Doebert (CERN), Vittorio Bencini (John Adams Institute for Accelerator Science (GB))
  External Injection - ... External Injection - ...
- 11:50 **Discussion**
- 12:05 **Scalable Plasma Source R&D**
  Speaker: Alban Sublet (CERN)
  20240205_PlasmaS... 20240205_PlasmaS...
- 12:20 **Discussion**

12:30 → 12:35 **Short Wrap-Up**
Speaker: Edda Gschwendtner (CERN)
2024-02-05-AWAKE-... 2024-02-05-AWAKE-...

12:35 → 13:00 **Discusssion**

13:00 → 14:00 **Lunch**

14:00 → 16:00 **Closed session**

16:00 → 16:15 **Coffee break**

16:15 → 16:45 **Panel recommendations and close-out**

17:00 → 18:00 **Visit to AWAKE**

AWAKE Visit

AWAKE Review Report

On EDMS at https://edms.cern.ch/document/3038236/0.1

EDMS Nr.: 3038236

Report of the External Review on the Scientific and Technological Objectives of the AWAKE Project

February 5, 2024
in-person meeting at CERN

Review Panel: Andrei Seryi (JLAB), Ralph Assmann (GSI), Enrica Chiadroni (Sapienza University and INFN), Roberto Corsini (CERN), Mark Hogan (SLAC), Simon Hooker (Oxford).

The Review Panel is tasked with the following evaluations:

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2. Evaluate the scientific merits of the accelerator physics and technological advancements expected from the AWAKE Run 2c and 2d programmes, their complementarity with other ongoing initiatives, and their impact on the overall PWFA field.
3. Evaluate whether by the end of the AWAKE Run 2c and 2d programmes all technologies and beam parameters required to allow for a future particle physics experiment based on proton driven wakefield acceleration will have been demonstrated.
4. Determine whether AWAKE is the most appropriate facility for the realization of the anticipated advancements of AWAKE Run 2c and 2d.

Overview

The Committee thanks the AWAKE team for great organization of the review, and for the coherent set of presentations and pre-reading materials that greatly facilitated the work of the review committee.

The Committee commends the AWAKE team for their spectacular achievements to date, for fulfilling all so far planned milestones and experimental results, as well as for building up an impressive international collaboration where many partners are engaged and contributing. There is an excellent impact on training of the next generations of accelerator physics experts and leaders of the field, demonstrated via a large number of high-level publications, PhD thesis defended, and prestigious prizes awarded to AWAKE colleagues.

The achievements of the Run 1 and Runs 2a include the demonstration of seeded proton bunch self-modulation and the acceleration of internally injected electrons to 2 GeV, and the ongoing Run 2b aims at maintaining the accelerating wake over long distance.

- ➔ Report sent to CERN management as input for MTP discussion
- ➔ MTP
  - ➔ discussion currently ongoing
  - ➔ CERN AWAKE requested 15MCHF (2024-2029)
    - ➔ Workforce needs discussed in parallel with groups
  - ➔ Decision during June Council Meeting

Review Report: Overview

The Committee **thanks the AWAKE team for great organization of the review, and for the coherent set of presentations and pre-reading materials that greatly facilitated the work of the review committee.**

The Committee **commends the AWAKE team for their spectacular achievements to date**, for **fulfilling all so far planned milestones and experimental results**, as well as for **building up an impressive international collaboration** where many partners are engaged and contributing. There is an **excellent impact on training of the next generations** of accelerator physics experts and leaders of the field, **demonstrated** via a large number of high-level publications, PhD thesis defended, and prestigious prizes awarded to AWAKE colleagues.

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AWAKE is a **unique experiment, with capabilities and opportunities that cannot be reproduced in a practically reasonable time anywhere else in the world**. The development of AWAKE technologies will have a **profound impact on any future** plasma accelerator colliders and facilities. AWAKE is **well-integrated** into European strategy planning and roadmaps.

The efforts of the AWAKE collaboration on developing technologies of plasma acceleration for electron beams, and in particular of developing an adequate electron injector and electron beam merging **address a variety of beam dynamics and technological challenges**. The work is **very synergistic with CERN's plans to ramp-up efforts on FCCee, as experts on electron acceleration trained on AWAKE, can definitely contribute to the success of any future CERN project involving electron accelerators.**

The committee strongly endorses AWAKE's plan for future runs. We provide detailed responses to the four charge questions below.

1. "*Assess the feasibility and coherence of the full AWAKE Run 2 roadmap*"

Response

The Run 2 program has **identified all the key challenges** that the AWAKE program will need to meet to enable future particle physics experiments. These include: realizing high quality electron injection, combining a plasma modulator and plasma accelerator stage, and developing plasma sources that have the required degree of high density uniformity and are scalable to 10's of meter in length. **The AWAKE collaboration has developed a well thought through and appropriately phased approach to meet these requirements** on the way to particle physics applications. The AWAKE collaboration has a **demonstrated track record of successfully meeting their milestones** (Run 1a, 1b, 2a…). This, coupled with the extensive simulations validated by previous experimental results and design efforts, **give the committee high confidence that the presented plan is coherent and feasible.**

Comments

AWAKE is an **integral part of European and world-wide accelerator planning** and is **prominently featured** in European roadmaps, ALEGRO program, etc., demonstrating the global coherence of the AWAKE program.

Recommendations

None

2.a "*Evaluate the scientific merits of the accelerator physics and technological advancements expected from the AWAKE Run 2c and 2d programmes, their complementarity with other ongoing initiatives, and their impact on the overall PWFA field*"

Response:

The AWAKE Run 2 will take the proton-driven plasma wakefield acceleration **from proof of concept to a technology,** which can provide beams for particle physics experiments. This is foreseen in the AWAKE Run 2c and 2d programmes, which concentrate on quality and scalability, respectively, going through the optimization of the overall system.

In particular,

- the **implementation of a second electron injector** to accelerate electrons up to 150 MeV, before injection into the plasma module, helping in the emittance preservation during plasma acceleration;
- the **development of a plasma source**, scalable to 100s of meters that could in principle be used in other plasma-based accelerators.

Specifically, the **R&D on the plasma source is common to other plasma-based accelerators**, therefore this will have a strong impact on the community in terms of length, density uniformity, reproducibility, tunability, and stability.

Comments

Runs 2c and 2d are aimed at: (i) controlled injection of particles into the plasma wakefield; and (ii) large particle energy gain whilst controlling bunch emittance**. These are two key challenges for plasma accelerators, and as such the results obtained will benefit the AWAKE program as well as being of significant interest to the entire field.**

Several international facilities (EuPRAXIA, FLASHForward, FACET-II) are tackling issues associated with the physics of a single plasma stage. The **AWAKE Run 2 program complements these other efforts** as one of the few programs taking an integrated approach to developing a plasma based accelerator for particle physics applications.

Other plasma accelerator concepts for particle physics, such as HALHF and multi-TeV collider concepts, will **benefit from outputs of the AWAKE program, such as the development of multi-meter plasma stages.**

2.b "*Evaluate the scientific merits of the accelerator physics and technological advancements expected from the AWAKE Run 2c and 2d programmes, their complementarity with other ongoing initiatives, and their impact on the overall PWFA field*"

Comments

Many systems being developed in AWAKE are developing people/skills experienced with state of the art electron systems that will **benefit CERN in the FCC era**.

The first experiments proposed to follow Run 2 are **likely to be the first to benefit the HEP community** (most of the AAC community is pursuing photon science applications) and hence will be an **important opportunity to connect the advanced accelerator community with the traditional high energy physics community.**

The AWAKE collaboration has developed a **successful model that integrates CERN strengths** (engineering, beamline design) with **specialized skills** (plasma sources, modeling, diagnostics) provided by **collaborating institutes**.

The AWAKE collaboration has a **strong record of achieving scientific results** that address topics specific to AWAKE, the application of plasma accelerator technology broadly, and fundamental plasma physics.

AWAKE has an **excellent track record of training and educating students** recognized with multiple PhD and early-career awards for young scientists.

Recommendations

Detailed simulation studies of the electron beam dynamics in the injector, including short-range wakefields effects, and up to the plasma source, including the dogleg beamline:

- **Start-to-end simulations** should be extended to define the nominal working point and sensitivity studies to assess its robustness. Detailed simulation studies of the **proton-electron beam separation** at the end of the acceleration process, paying particular attention to the preservation of witness beam parameters.

Implementation of virtual measurements, in particular emittance and bunch length at the end of the driver-witness separation beamline.

3. "*Evaluate whether by the end of the AWAKE Run 2c and 2d programmes all technologies and beam parameters required to allow for a future particle physics experiment based on proton driven wakefield acceleration will have been demonstrated*"

Response:

If the AWAKE Run2c-d program is fully successful, basic beam parameters and technologies needed to propose a first particle physics experiment would be available.

Comments

a) The **projected beam parameters** (charge, emittance, repetition rate) for AWAKE Run 2c-d **are consistent with a proposed initial experiment for Dark Photon** search, with 10^{15} - 10^{16} e- on target. The required beam energy of ~50 GeV should in principle be reachable using the technologies developed in AWAKE run2-c-d, in particular the scalable plasma cell. However, acceleration over long distances might be prevented by instabilities or other effects only partly addressed by the AWAKE Run 2c-d program, so not all risks will be averted**. A more ambitious version of the previous experiment (in term of more e- on target, or higher beam energies) would likely entail further developments or higher risks.**

b) A **strong-field quantum electrodynamics (QED) experiment** based on electron–laser collisions is **also compatible** with beam parameters from Run 2-cd. The extrapolation to higher energies (~ 10 GeV) is smaller, however the high-power laser technology needed for the laser beam, although most likely existing elsewhere, is not part of the AWAKE program.

c) The **electron-proton/ion collider proposals are more ambitious**, in requiring further extrapolations of the parameters, and would be somewhat limited in luminosity, or would need some further technological developments.

Commendable that CERN has recognized the risk of the plasma source development and organized a collaborative effort at CERN.

Recommendations

Make the Run 2d installation compatible with a future potential extension to longer plasma cells, aimed at a reduction of the extrapolation risks.

Consider in the choice of technologies and in their development the potential for future uses outside of AWAKE/CERN, e.g., for the scalable plasma cell, the high repetition rate capability, the possibility of rapidly disposing of high deposited power and the stability requirements, which might be critical for future plasma based colliders.

4.a "*Determine whether AWAKE is the most appropriate facility for the realization of the anticipated advancements of AWAKE Run 2c and 2d*"

Response to charge question

Yes, AWAKE is the most appropriate facility for the realization of the anticipated advancements of AWAKE Run 2c and 2d. We explain the reasons:

The AWAKE Run 2c aims at demonstration of external injection of an electron bunch into a proton-driven plasma wakefield accelerator while the electron beam should maintain its charge and high quality. **The large difference in beam energies and rigidities of proton and electron bunches (400 GeV/c vs 0.15 GeV/c) are a unique advantage for AWAKE**. The electron bunch can be injected with a dipole magnet that has a very small disturbing effect on the proton bunch. The schemes to achieve external injection of good quality with laser-driven or electron-driven plasma accelerators are much more complicated and more difficult to achieve. **AWAKE is the most appropriate facility to achieve external injection** and will likely **set the overall standard for this**.

The AWAKE Run 2d aims at demonstration of scalability towards very long plasmas and high energy gain. Here AWAKE takes profit from the large rigidity of the proton bunch and its high stored energy**. Much longer plasmas can be driven in AWAKE** than possible with laser pulses or electron bunches, as lasers and electrons both carry orders of magnitude lower energy for driving wakefields. In addition, **AWAKE takes profit from the tunnel length and technical infrastructure at CERN**, most often not available in plasma accelerator laboratories. AWAKE will **set the world-wide standard of very long plasma cells for electron acceleration.**

4.b "*Determine whether AWAKE is the most appropriate facility for the realization of the anticipated advancements of AWAKE Run 2c and 2d*"

Comments

The existing investment of 77 MCHF (material plus person-power) from CERN and collaborators into the AWAKE experiment are significant and set a firm basis for the proposed runs 2c and 2d.

The return over investment (15 MCHF in addition) will be very high, if the expected scientific outputs of run 2c and 2d are weighed in (ground-breaking and unique accelerator achievements, high level publications, academic forming of a new generation of accelerator scientists).

Recommendations

The accelerated electron bunch and the driving proton bunch should be **separated at the end of the experimental setup to demonstrate also extraction of a high quality electron bunch** from the plasma accelerator for the first time, e.g. the witness e- bunch at 10 GeV, 100 pC and a few mm-mrad emittance.

The use of the extracted electron bunch for some first proof-of-principle particle physics experiments in the AWAKE tunnel should be investigated (e.g. 10 GeV, low duty cycle beam dump experiment). This would directly assess usability and promise for future experiments and could be realized with very small additional effort.

MANY THANKS!!