Run 2 Meeting 08-02-19

Present: Edda Gschwendtner, Patric Muggli, Spencer Gessner, Marlene Turner, Brennan Goddard, Daniel Groselj (MPP-Plasma Physics), Stefano Mazzoni, Steffen Doebert, Allen Caldwell, Joshua Moody, Konstantin Lotov, Alexey Petrenko, Matthew Wing, Erik Adli, Valentin Fedosseev.

Introduction (Edda)

Edda stresses that the AWAKE Collaboration needs to decide on a baseline layout. To that aim she prepare a list of open questions including the people working on it so far as as well as a summary of results so far. The aim of this meeting is to either:

- make a decision (on open issues);
- or define a clear strategy on when to decide and what information is needed then as well as a responsible person.

Many of the open questions are addressed in presentations, therefore a conclusive summary and/or strategy is presented at the end of this document.

Proposals for a Run 2 phased approach (Allen)

Allen summarized the advantages of the single stage approach:

- no pre-plasma in acceleration section;
- only one laser path to create both acceleration and self-modulation plasma;
- no emittance blow up in foils.

The scheme also has disadvantages or challenges:

- technical realization complicated: magnetic elements need to be integrated in the hot zone; Patric adds that the density in detuned region can only be higher (not compatible with the limit imposed by Galden) or a maximum of 3% lower due to condensation.
- limited flexibility;
- density ramps at the transition zone;
- electron injection in plasma.

Emittance preservation during the injection process (when crossing the plasma boundary and the wakefields; at the plasma density transition region) is yet to be demonstrated in simulations.

Allen also summarizes the two stage option. The advantages are:

- more flexibility: the electron beam-line is standalone; acceleration plasma can be changed;
- electron injection in vacuum;
- sharp plasma density entrance.

The challenges and disadvantages:

- the plasma in acceleration section is preformed: possible evolution of the proton bunch head; Allen explains that this is a challenge that needs to be solved for the future of this scheme. Patric mentions that electron bunch seeding could be a solution; studies of plasma recombination show that the plasma density constant within 500 ns.
- two laser paths and laser dumps inside the plasma; possible effects from laser-foil-plasma interaction: do the foils survive the electron bunch passage? First simulation results show that the electron bunch emittance growth is limited if foils are thin;

Valentin points out that for this two stage plasma approach, another proton beam bending magnet will be needed downstream the acceleration plasma cell for insertion of the counter-propagating laser beam merging mirror.

Since there is limited person-power available, **Allen suggests to take the separate two stage approach as the baseline**, as the design is more flexible and allows for testing different plasma options.

For Run 2 he proposes a four-phase plan:

1) **Experiments with the SSM plasma:** confirm the effect of the plasma density step, measure the saturation length of the SSM, test implementation of laser dump, implement additional laser and proton diagnostics…
2) **Addition of the electron bunch:** easy access to beam for diagnostics, study electron bunch parameters…
3) **Installation of the acceleration plasma** (Rb vapor source)**:** study wakefield phase stability in the acceleration plasma, the effect of the laser dump on the electrons and plasma density evolution before the real acceleration experiment.
4) **Exchange plasma of acceleration stage** (e.g. with a Helicon source)**:** test requirements on density uniformity, effect of density ramp at entrance and exit…

The planning and implementation must be organized with the final goal in mind and should be realistically accommodated until LS3 (starts in 2024).

Electron bunch injection into radially bounded plasma (Konstantin)

Konstantin shows the transverse motion of electrons from a full 3D PIC simulation. He notes that the electron bunch is generally focused by the plasma boundary. He explains that witness electrons generally behave in five ways:

1) Electrons reflect after entering the plasma (typically for head particles).
2) Electrons are reflected from the plasma after making small amplitude oscillations in a potential well (most particles).
3) After travelling in and out of the potential well, electrons stick to the plasma boundary; eventually shift back and are focused, but not trapped.
4) Similar to three, but electrons are trapped and gain energy (few electrons).
5) Electrons squeezes through boundary wakefields, come to axis and gain some energy (rare).

Konstantin explains that particles gain a huge transverse momentum when crossing the plasma boundary. He proceeds to study the problem analytically: mathematics shows that an electron propagating parallel to the plasma boundary is attracted to it and focused. The force is radially symmetric and grows linearly with distance from the drive charge. Inside the plasma the electron experiences a repulsive defocusing force. Konstantin compared the transverse momentum gain predicted by theory to VLPL simulations and found good agreement.

Concerning Run 1, these results potentially explain the large transverse emittance due to plasma boundary crossing and the small amount of trapped and accelerated charge. For Run 2 these results suggest that the momentum gain increases with: the total electron bunch charge, the bunch length and the plasma electron density. It decreases with energy and injection angle and is only weakly depended on the bunch radius. Konstantin states that the emittance growth is negligible if the injection angle is larger than 30 mrad (order of magnitude estimate). This requires a bending radius smaller than 4m and a dipole magnetic field larger than 400 Gauss. Konstantin points out that the bending field must sharply stop after the plasma boundary. Patric remarks that it must be shown from simulations that the effect is negligible when taking into account a ‘real’ (and not ideal) transverse plasma channel profile.

Konstantin also studied bunch erosion in plasma. He explains that the electron beam head needs to be focused by the wakefield of the driver, otherwise the head undergoes free expansion (and thus reduces the useful charge). Consequently, the higher the charge and the energy and the lower the emittance and propagation (without focusing field) of the electron bunch, the larger fraction of the beam remains.

He summarizes the optimization strategy for a single-cell variant: low emittance, strong dipole magnetic field, use plasma boundary to focus, control density for electron injection, electron energy as high as possible, electron charge as high as possible. Concerning the two-cell option he mentions that there could be a physical challenge from the proton bunch head evolution that cannot safely be predicted from simulations.

From these results Konstantin thinks that the neither single nor the double cell variant guarantees success. He thus suggests to currently follow up both options to increase the chances of success. Further studies though should be carried out to understand the effects better.

Electron beam line studies (Brennan Goddard)

The requirements from the experiment side are: spot size of 4-7 micrometer at the injection point; a bunch length of 200 fs. Brennan asks for numbers on the pointing stability, adjustment range of focal depth in plasma, adjustment range of transverse position and angle.

The following numbers were decided:

- **time of arrival jitter: <40 fs**

- **adjustment depth of focal point: ~50 cm**
- **adjustment of transverse position: 4 mm**

Brennan explains that a beta function of (2-10) mm can be reached at 100 MeV if the final triplet magnet can be placed within ~1 m of the delivery point (from a linear calculation). He also points out that to keep the beam size on the micro-meter level, the maximum parasitic dispersion needs to be extremely small (< 0.2 mm as opposed to 3cm in Run 1). Evidently a smaller energy spread relaxes the restraint (<3 mm for dp/p = 0.2%, < 1.3 mm for 0.6% or <0.2mm for 2%). Brennan explains that these restraints are very challenging. Sophisticated dispersion free steering will be needed (on top of tight constraints on isochronity and achromaticity and precise alignment of magnetic elements).

Brennan points out that the beam centroid at the injection point will need to be measured much better than 150 um for dp/p = 0.2% (65 um for 0.6% and 10 um for 2%). Chromatic behavior will dominate the limits of this beamline, a lower momentum spread is therefore desired.

In case an electron extraction after injection would be implemented, Brennan needs input on: what is the drift distance between injection and extraction; the layout constraints for the extraction dipole; the extraction electron energy. (**Action: Konstantin & Team, see open question 7**) On the electron injection, Brennan remarks that one will need an opposite sign compensation dipole (40 urad kick if not present); that straight through diagnostics is possible but the optics is different as the dipole adds dispersion (there is also an effect of edge focusing); he needs to know how much free space there will be between the two plasmas. **Decision: Brennan will study the following three space options: 0.1, 0.3 and 1m.** He adds that the injection would be even more difficult if it needs to be compatible with both designs. A PJAS will be hired to work on the topic.

Brennan also looked into the possibility of moving the proton focal point upstream. Two meters could be won by removing the electron beamline. **Around 12-14 m could be won by removing the two final proton dipole magnets and powering the last nine magnets for 488 GeV (needs a new power converter) or leave them at 400 GeV and lower the proton bunch energy to 330 GeV. Action: Ans to study integration, Brennan to study proton trajectory**.

The stability of the proton bunch could be improved by upgrading the extraction septum (cost: 3-5 MCHF). The stability of the transverse proton bunch jitter would improve by a factor of 3-5. Brennan might request a summer student to study the issue.

Brennan remarks that: for the final experiments it might me easier to align the proton bunch and laser pulse to the electron bunch; that there will be constraints on the location of the electron beam source; that diagnostics on the injection location is a must; that it will be difficult to fulfill transport and geometric constraints.

Electron source update (Steffen)

Steffen explains that there is an RF-gun being built by INFN for CLIC CLEAR (1.5 cell, S-band gun, 120 MV/m peak field on cathode). In addition it is planned at CLIC/CLEAR to expand the electron source with X-band systems to reach higher energies. The parameters are the same as needed for AWAKE Run 2, therefore both AWAKE and CLIC/CLEAR would profit from the synergy in development, studies and tests. Currently the CLIC/CLEAR system is planned to be installed in 2020. A possible scenario for an AWAKE high energy gun would then be to copy the design CLIC/CLEAR design. Steffen adds that the current S-band AWAKE gun could be reused for Run 2 and only the X-band system needs to be newly built..

Simulations show that the following parameters could be achieved:
- 85 MeV: 72 fs bunch length, 0.48 mm mrad transverse emittance, 0.51 momentum spread.
- 105 MeV: 138 fs bunch length, 0.29 mm mrad transverse emittance, 0.27 % momentum spread.
- 165 MeV: 72 fs bunch length, 0.48 mm mrad transverse emittance, 0.24 % momentum spread.
- 165 MeV: 207 fs bunch length. 0.44 mm mrad transverse emittance, 0.09% momentum spread

Decision on the baseline parameters:
- **go to higher electron beam energy (165 MeV);**
- **transverse emittance 2mm mrad;**
- **Momentum spread 0.2%.**

Steffen explains that, in synergy with clear, the gun and instrumentation could be tested before installation in AWAKE.

Summary/Discussions of open Run 2 questions and decisions

Q1) What are the baseline electron bunch parameters?

The **electron bunch baseline parameters** have been set to:

Bunch energy: 165 MeV
Transverse normalized emittance: 2 mm mrad
Rms bunch length: 200 fs
Charge: 100-200 pC
Momentum spread 0.2%
Time of arrival jitter: <40 fs
Focal spot size at injection: 4-7 um
Adjustment depth of focal point: ~50 cm
Adjustment of transverse position: 4 mm
Pointing stability at the the injection location: 0.1*sigma_r

Note: improve laser-timing jitter by 2-stage locking of the laser pulse (to improve laser arrival jitter from ~300 fs to < 40 fs).

Q2) What are the baseline proton bunch parameters?

The **proton bunch baseline parameters** are:

> **Bunch population: 3e11**
> **Rms bunch length: 4.5 cm**
> **Transverse focal spot size at plasma: 0.15 mm**
> **Momentum: 400 GeV/c**
> **Transverse normalized emittance: 2.2 mm mrad**

Action: **Brennan** to clarify the current proton bunch stability as well and **Edda** to define the requirements for Run 2.

Q3) What should be the length of the SSM plasma section (to also be able to perform experiments at n_pe= 2e14/ccm)?

Action: **Konstantin** (as the simulation coordinator) to study the question from simulations.

Action: **Patric** (as the physics coordinator) to study whether any information on SSM saturation can be extracted from the Run 1 data.

Q4) Density step: Should there be a plasma density step? If yes, what is the magnitude of the step? Where along the plasma should it be (is the location the same for all densities)? Is it technically feasible?

Alexey explains that the plasma density step has a different effect on the development on the SSM for depending on the number of dimensions in the simulations (2D cylindrical or 3D).

Action: **Konstantin & team** to answer from 3D simulations and for plasma electron densities 2e14/ccm and 7e14/ccm: what is the optimum location of the density step and how sensitive is its location to the SSM? What must be the minimum amplitude of the density change? What is its optimum amplitude?

Action: **Patric** investigates whether a density step in the SSM plasma is technically feasible and study limitations.

Q5) Gaining more experimental space:

> **a) how much space do we need?**
> **b) can we move the focal point of the proton bunch further upstream? How much space can be made available from emptying CNGS or moving the radiation shielding wall? How long does emptying CNGS take?**

Action: **Edda** (after Q3 has been answered) to follow-up how much experimental space is needed.

Brennan mentioned that 2m of space could be easily won by removing electron beamline elements, 12-14m could be gained by modifications to the proton transport line.

Action: **Brennan** to investigate whether the modification of the proton line is compatible with laser/proton merging.

Actions: **Ans** to investigate how much space can be gained from CNGS and how much time it takes.

Q6) Electron injection: How to inject electrons without spoiling emittance in a real plasma profile?

Action: **Konstantin & team** studies electron injection for the two-plasma and single plasma variant (unless one of the options will be eliminated by decision) with full PIC 3D simulations with realistic radial plasma profiles (including density ramps / changes).

Q7) Gap between plasmas: What is the proton evolution of the gap? What is the maximum limit from plasma simulations? What is the minimum limit from the technical implementation?

Konstantin explains that simulations of the electron bunch emittance (along the plasma) have been performed (parameters and details in https://doi.org/10.1063/1.5048263):

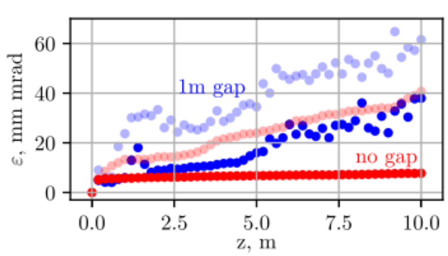

FIG. 3. Dependence of the normalized witness emittance ε on the propagation distance in the second plasma cell z in the presence of 1 m vacuum gap between the cells (blue) and with no gap (red). Pale colors show the results of lower-resolution simulations with $\Delta r = \Delta\xi = 0.01\, c/\omega_p = 2\,\mu\text{m}$, and $\Delta z = 200\, c/\omega_p = 4\,\text{cm}$.

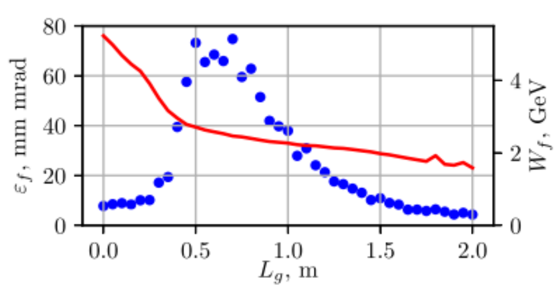

FIG. 4. Dependence of the final witness emittance ε_f (blue points) and energy W_f (red line) after propagating 10 m in the plasma on the length L_g of the vacuum gap between the plasma sections.

Thus for a final emittance on the order of 6 mm mrad and an electron energy of ~3 GeV (after 10 m of propagation), the gap needs to be shorter than 30 cm.

Action: Konstantin & team to simulate the effect of the gap on the emittance for the AWAKE run 2 baseline parameters and study possible negative effects on electron injection in the acceleration plasma. Study whether the emittance can be – even if not preserved – 'controlled' for large gap sizes.

Action: Brennan to study the electron beam line design for gap sizes 0.1, 0.3 and 1m.

Q8) Electron injector: What is the design of the electron source? What is its footprint? Where should the source be installed? Is civil engineering needed?

Steffen mentions that either the current AWAKE gun could be kept or a copy from the INFN design could be produced. Nevertheless the X-band system needs to be added. Test on electron beam quality could be performed in CLEAR, before the AWAKE installation is ready.

Action: Steffen studies the where the source could be installed (in coordination with **Ans** and **Brennan**).

Q9) Electron beam transport: Design of the transport optics and beamline for the baseline energy, emittance and electron bunch length (given the requirements from the experiment). What is the footprint?

Action: Brennan studies the layout and footprint of the electron transport line.

Q10) Beam instrumentation: What diagnostics is needed? How to implement it?

The electron spectrometer should be able to measure emittances on the order of mm-mrad with micron size beams. A beam size measurement with micron size resolution is needed at the injection location. Downstream the plasma, both the electron and the proton bunch need to be analyzed separately. **Upstream injection the proton will be separated from the electron transport. Common diagnostics is thus not needed upstream the plasma**. Precise time of arrival measurements of all beams are needed (~100 fs).

Action: Stefano to coordinate with the different equipment owners (**UCL,…)** the study of the realization of the electron spectrometer, high resolution transverse beam size diagnostics at the injection point, time-of arrival measurements via electro-optical sampling and proton and electron diagnostics downstream the plasma.

Q11) Can we move the vacuum separation window?

Action: **Brennan** to study where the vacuum window could be installed and follow-up studies that insure that the new location decreases the radiation of secondaries in the diagnostics area.

Q12) What should be the plasma design (single-stage or two-stafe)?

Action: **Allen** (as the AWAKE spokesperson) to lead discussions on whether there is enough person-power to follow up with both design options. If not, decide on one of the options.

For single stage plasma:

Q13) Electron injection: How do the detuned plasma wakefields affect the electron bunch emittance? How does the transition from one plasma density to the other one affect the bunch quality?

Action: **Konstantin & team** to perform 3D simulations with realistic transverse plasma profiles.

For separate stage plasma:

Q14) Proton bunch head: Does the head evolution disturb the wakefields? Can the problem be mitigated by e.g. electron bunch seeding?

Action: **Patric** to look into this topic and possible solutions. Analyze the corresponding Run 1 data.

Q15) Laser pulse transport: How should the layout of the second laser transport line be? Will there be two laser systems? If one, should be pulse be split before or after the compressor?

Action: **Valentin and Josh** look into laser transport to the first and second plasma.

Q16) How do thin windows affect the electron bunch quality? Can one window dump the laser and avoid the ramp? Evolution of the preformed plasma density channel?

First studies have been performed: very thin windows increase the emittance of a 200 MeV electron bunch by only little; the ionizing laser could be dumped on thin aluminum foils.

Action: **Patric** and **Allen** to study the design and injection of the two plasma design.

Q17) Scheduling Run 2:

Allen proposed a phased Run 2 approach. Steffen expressed interest in testing the electron source in CLEAR before installation in AWAKE. Stefano expressed interest in testing beam instrumentation in CLEAR before installation in AWAKE.

Action: **Edda** defines together with **Ans** a realistic schedule for Run2 that allows for at least 2 years of experimental time before LS3.

The next meeting will be organized by Edda and the invitation will be sent out in due time.

Marlene Turner, 13 January 2019