Highlights and requests from HiRadMat and AWAKE

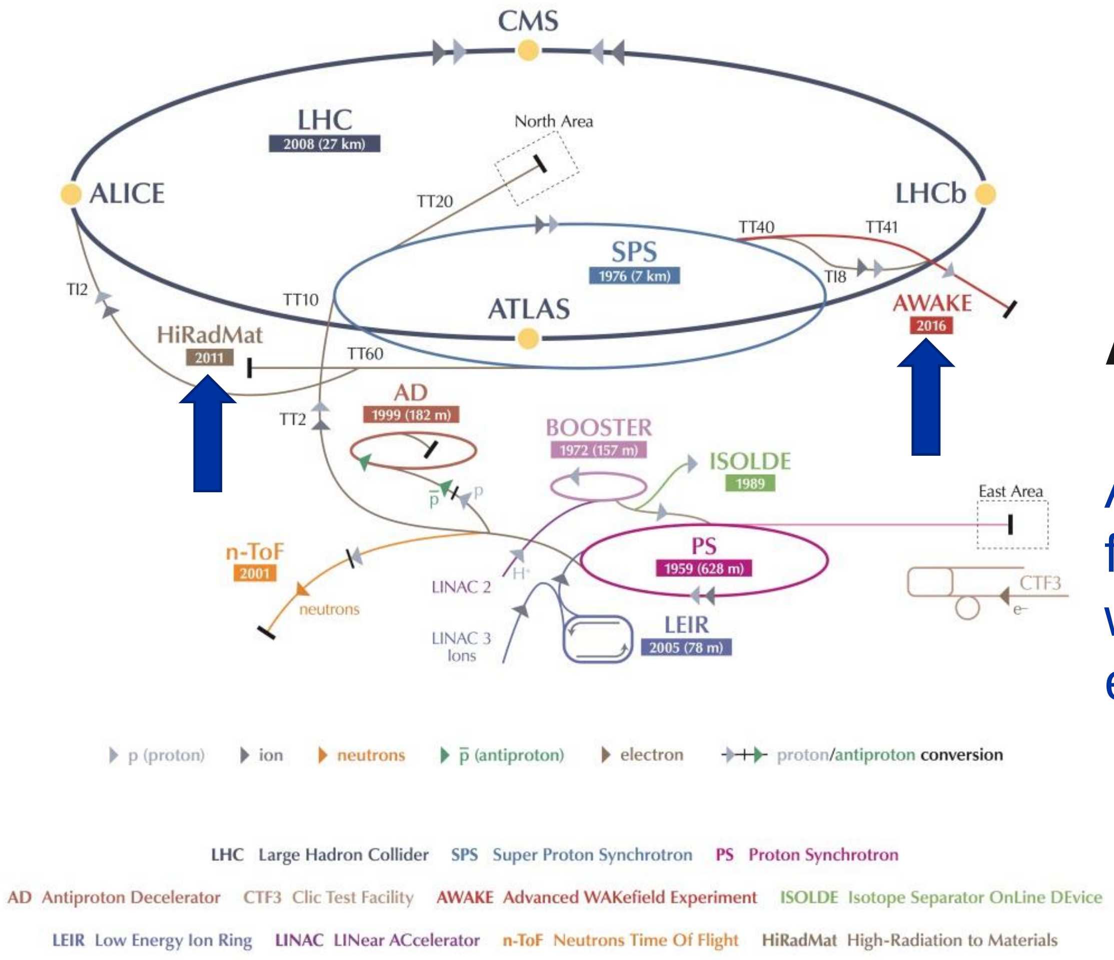
G. Zevi Della Porta, P. Simon on behalf of the AWAKE collaboration and the HiRadMat team

5 December 2022, Joint Accelerator Performance Workshop

HiRadMat and AWAKE: fast extraction at SPS

HiRadMat at TT66:

Facility for beam tests of accelerator components



AWAKE at TT41:

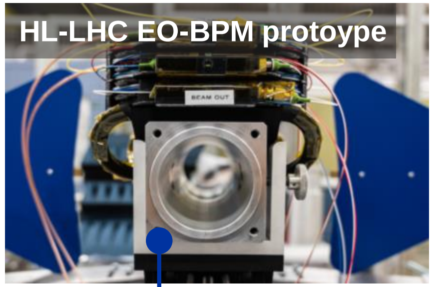
Accelerator R&D experiment for proton-induced plasma wakefield acceleration of electrons

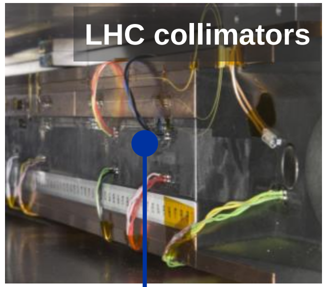
HiRadMat Facility

Short-pulse high-energy proton irradiation facility

LHC-like Beam Parameters
Up to 288 bunches, **≤1.6×10^{11} protons per bunch**
≤4.6×10^{13} protons per pulse at **440 GeV/c (3.2 MJ)**
~**1.5 ns** long bunches, 25 ns bunch spacing
Beam size at target: **≥0.25 mm** (1 σ)

- **Maximum flexibility to accommodate any request**
- **Completed a total of 44 experiments since 2012**
- **Supported more than 50 external users during 400 days of transnational access, supported by Horizon Europe's EURO-LABS project until 2026:**





Targetry — Beam diagnostics — Beam intercepting devices
Superconducting magnets, Particle detectors, Plasma physics
Experiments

Beam Diagnostics
Transverse spot size
Bunch-to-bunch beam position
Beam losses

Test Stands
Remote plug'n'play
~300 signal connections
Cooling water, vacuum, press. air

HiRadMat Highlights 2022

- **HRMT58 ATLAS-ITk – JSI, EP-UAT**

  Initial test of ATLAS-ITk BCM prototype with LHC-like beams

- **HRMT55 BLM3 – ESS, GSI/FAIR, SY-BI**

  Qualification of production BLMs for CERN, ESS, GSI/FAIR

- **HRMT59 SMAUG – TE-VSC, SY-STI, BE-EA**

  Assessment of beam windows for LIU beams at HiRadMat

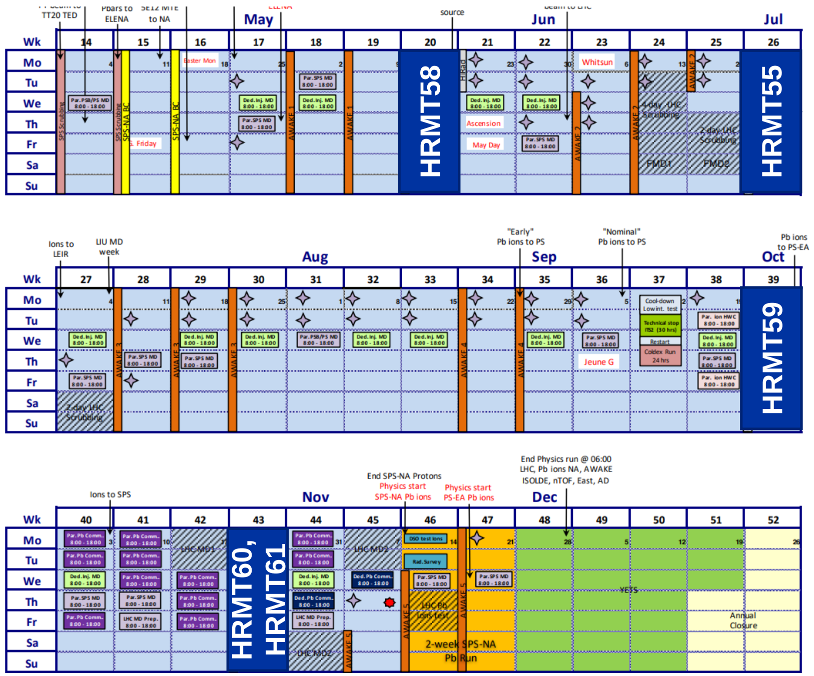
- **HRMT60 RaDIATE2022 / FNAL, J-PARC/KEK, STFC**

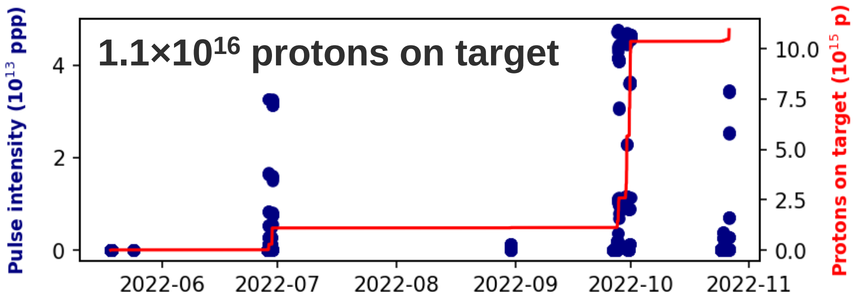
  Single pulse effects in (pre-irradiated) targetry materials

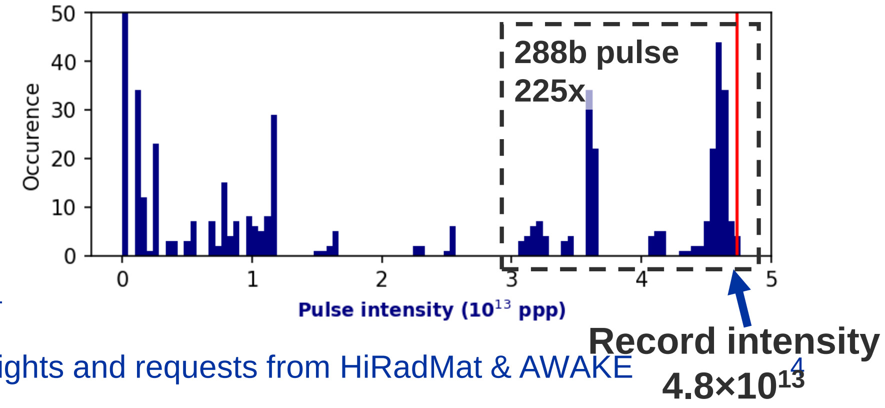
- **HRMT61 SCcoils – TE-MPE, KIT**

  Damage limit in Nb_3Sn and NbTi superconducting miniature coils

3 Experiments in 2 beam time slots within 4 very intense weeks!







HiRadMat Obstacles in 2021
Impact on 2022?

The largest obstacle in 2021

- **MKDV (SPS internal beam dump kicker) vacuum condition**

  Injection of 4 batches at 1.2e11 ppb impossible without scrubbing } Dedicated scrubbing, increase of bunch length

- **MKP (SPS injection kicker) heat up** } Careful ad hoc tuning during beam time

- **Emittance of LHC 25 ns beams beyond LIU target (~1.5 µm·rad)**

  HRMT beam optics designed for 2.5 µm·rad } Dedicated HRMT 72b beam in PSB with software interlock on emittance

- **User request for pre-LS2 performance**

  Tight limits on design intensity and beam sizes } Dedicated optics checks, wirescans along the injector chain

- **TT66 Beryllium beam window**

  Broke twice in 2021, reason for failure not fully understood yet } Displacement of window, procedure for replacement during operation

Hardware changes for 2022 successfully eliminated biggest showstopper! Enabled us to extract record intensity!

HiRadMat Feedback and Requests

- **HiRadMat runs in 2022 were very smooth (in comparison to 2021)**
  - SPS upgrades and restart of LHC immensely stabilized machine performance for our high-intensity beams
  - Excellent communication with LHC OP to anticipate windows of stable beam conditions
- **No showstopping issues from the SPS machine side**
  - Faulty power converter in TT60/TT66 splitter region: 40 hours downtime
  - Problem with BTV optical filters: a day of lost beam time until problem has been identified

  No impact on other physics users
- **Operation in parallel to a single North Area cycle is standard procedure**
  - Switching between short and long HiRadMat cycles in the SPS does not impact beam quality in TT66
  - Increased efficiency with short HiRadMat cycle for beam-based alignment and beam set-up
- **Improve reproducibility of delivered beam properties, for example:**
  - Observed since week 38: 2.5 mm·mrad normalized emittance from PS, but 3 mm·mrad in SPS at injection

HiRadMat Feedback and Requests

- **Nonetheless, operation of HiRadMat is not yet routine!**
  - Stakes are high: experiments need to complete program within one week and have little contingency. Our schedule is planned more than a year in advance.
- **Parallel activities take a large toll on SPS & LHC operational efficiency, for example:**
  - Multiple occasions have shown and were reported in the IEFC to have detrimental impact on both HiRadMat, parallel activity and NA physics
- **Reminder: once the experiment program of a run is completed, HiRadMat is out of the cycle until its next run!**

Improve communication and preparation of all parallel activities to increase efficiency!

This also includes LHC activities that are blocking access during installation weeks.

HiRadMat Upgrade Study Group

- **HiRadMat was designed for SPS ultimate beam parameters, but several broken beam windows in 2021 have clearly shown facility limitations with nominal beam performance (228b with 1.2×10^{11} ppb, ~0.25 mm σ)**

Goal: Identify necessary upgrades to safely deliver LIU beam intensities to HiRadMat with the same minimum beam spot size that is available today.

- **Study group involves all stakeholders, support teams and users:**

  BE-EA, SPS-OP, SY-ABT, SY-BI, HSE-RP, BE-CEM, TE-VSC, SY-STI, EN-MME

- **In addition to the required upgrades, compiled a list of user requests to improve service quality for experiments, with one specific highlight:**

Availability of beams with lower momentum of, e.g., 50 or 120 GeV/c, but same time structure, is critical for CERN and the scientific community!

2023
Decision on and implementation of HiRadMat upgrades

2023/24
Dump upgrade

2024
LIU beams at HRMT
3 Experiments waiting

2024++
Standard operation with LIU beams

HiRadMat Outlook for 2023+

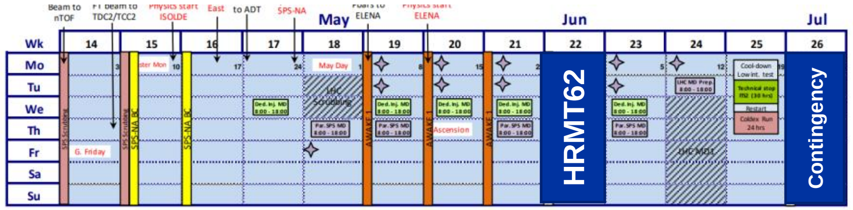
- **3 [+1 tentative] experiments scheduled for 2023**
- **HRMT62 FIREBALL – Uni. of Oxford**

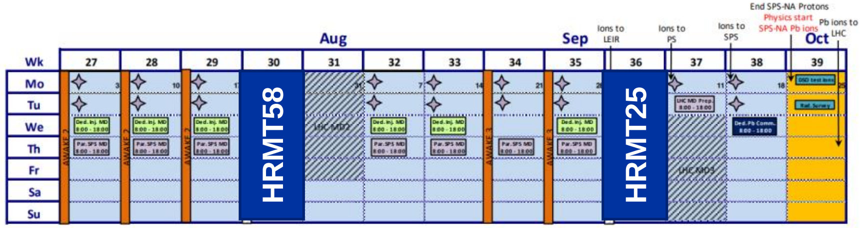
  Electron/positron pair beam-driven plasma filamentation instabilities
- **HRMT58 ATLAS-ITk – JSI, EP-UAT**

  Continued test of ATLAS-ITk BCM prototype with LHC-like beams
- **HRMT25 TPSG4-2 – SY-ABIT**

  Verification of TPSG4 septum protection with SPS ‘ultimate’ beam

- **3 slots (+1 contingency for challenging HRMT62 experiment)**
- **Early end of beam activities to enable work on beam dump**





YETS23/24 – Enable LIU beams:
Dump + beam window upgrades

2024 – Experiments

LIU beam requests

- **CRY3 – SY-STI, INFN**

  Robustness of pre-irradiated Si crystals for beam steering
- **HED-2 – SY-STI**

  HL-LHC dump material qualification
- **SMAUG-2 – TE-VSC, SY-STI, BE-EA**

  Verification of HRMT LIU beam window designs
- **DPA – J-PARC/KEK, TE-MPE**

  Displacement damage cross-section measurements at 440 GeV/c

HiRadMat Desiderata

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   - Necessity for HRMT62 experiment in 2023!
2. **Deliver more tightly controlled beam parameters to our users**
   - Enhance understanding and on-the-fly rematching of HiRadMat optics
3. **Faster change-over between HiRadMat cycles and faster SPS SC changes in general**
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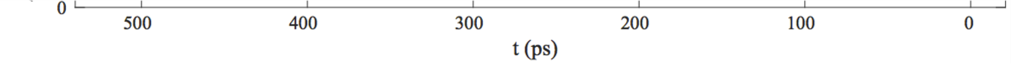
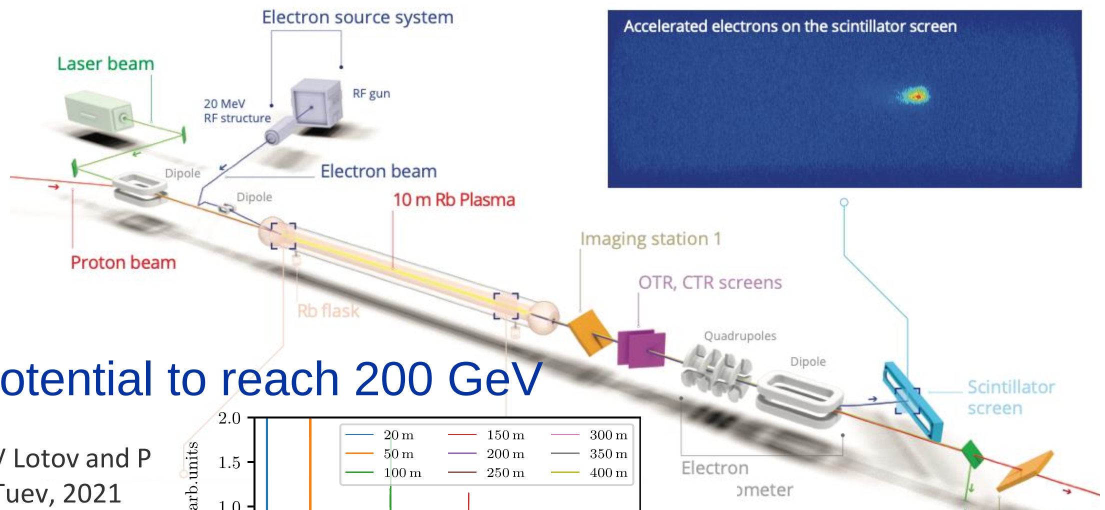


AWAKE Facility

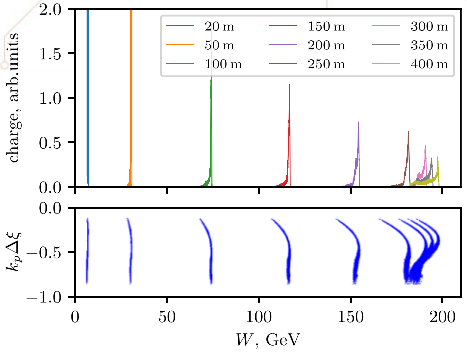
Proton-driven plasma wakefield acceleration of electrons

1. Laser ionizes Rb vapor, forming a plasma
2. Rb plasma creates micro-bunches in the proton beam
3. Micro-bunched proton beam excites plasma wakefields
4. Wakefields accelerate and focus electrons



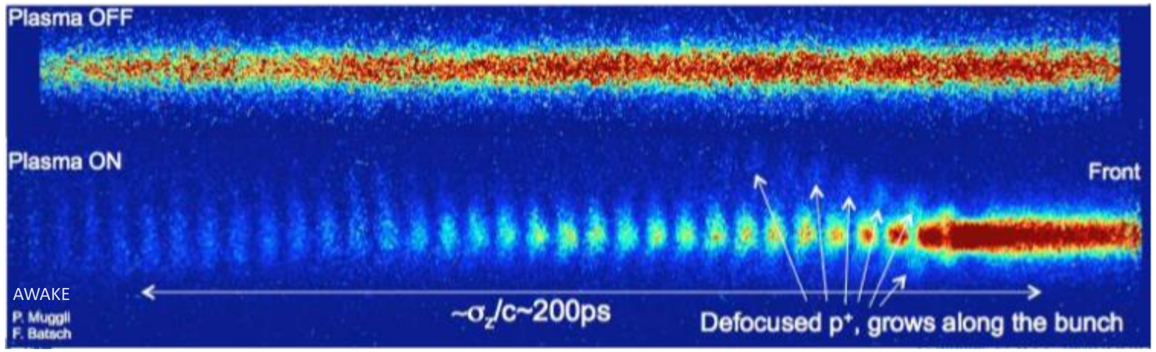
Potential to reach 200 GeV

K V Lotov and P V Tuev, 2021 *Plasma Phys. Control. Fusion* **63** 125027



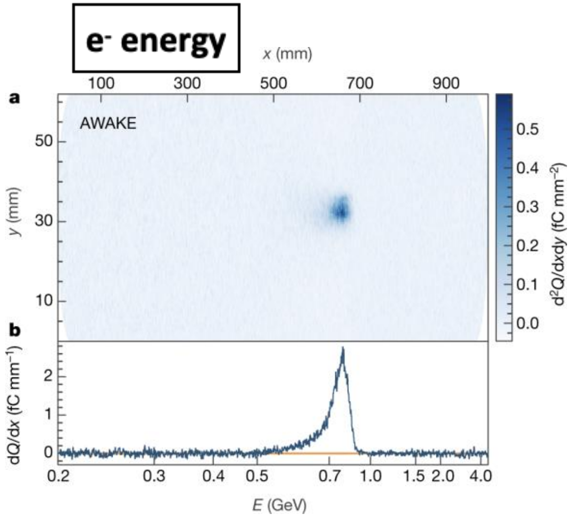
2016-17: first seeded self-modulation of proton bunch

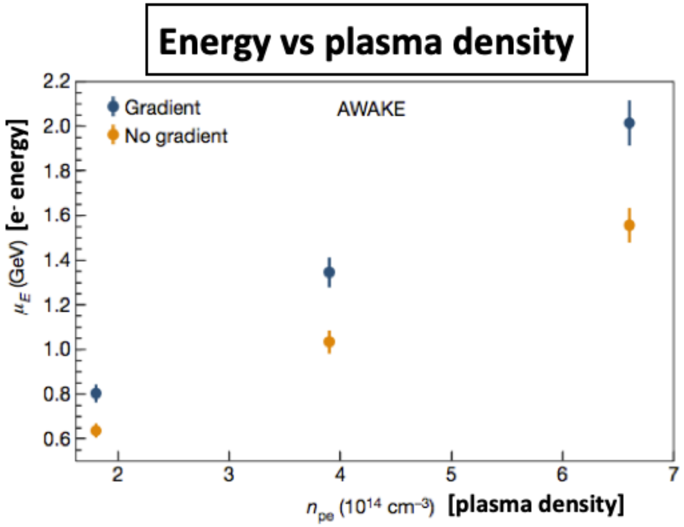
→ Demonstration that SPS bunch can be used for acceleration



AWAKE Collaboration, PRL 122, 054802 (2019)

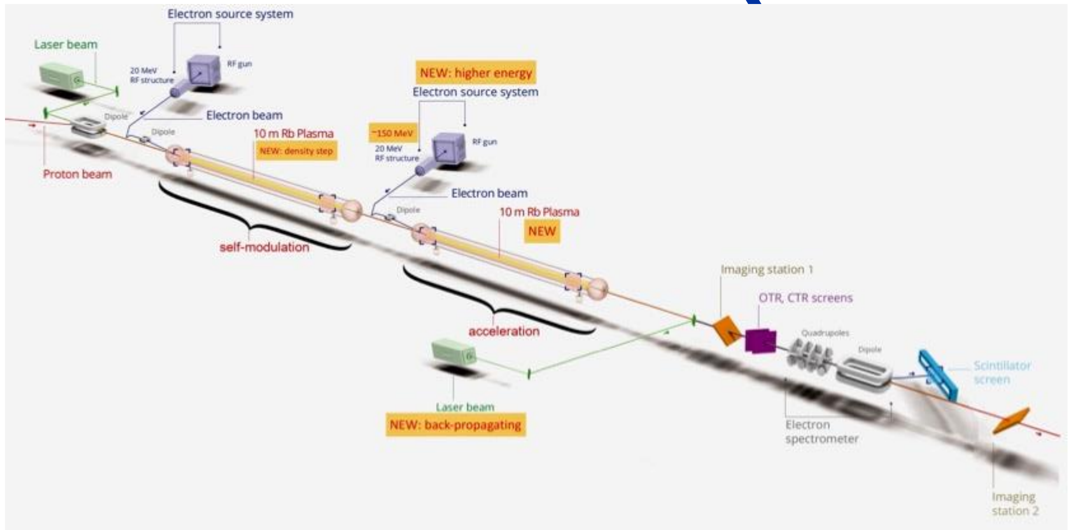
2018: acceleration from 19 MeV to 2GeV

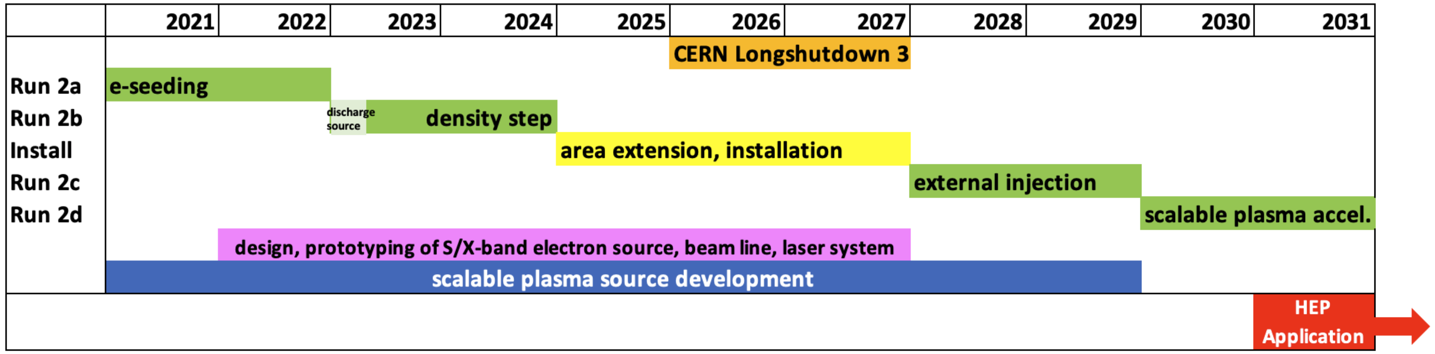




AWAKE Collaboration, Nature 561, 363 (2018)

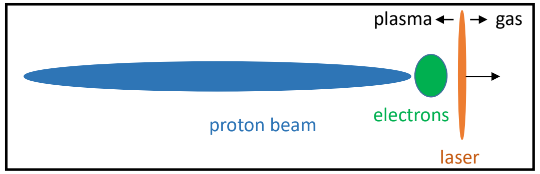
AWAKE Run 2 (2021 – 2030): Towards an Accelerator





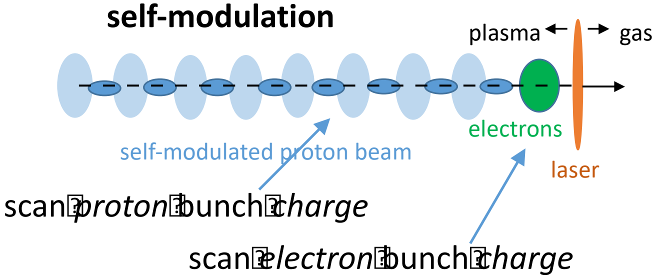
- **Milestones for AWAKE Run 2**
  - Run 2a (2021/22): demonstrate the seeding of the self-modulation of the entire proton bunch with an electron bunch
  - Run 2b (2023/24): maintain large wakefield amplitudes over long plasma distances by introducing a step in the plasma density
  - CNGS dismantling and installation of Run 2c (2025/26/27)
  - Run 2c (after LS3, 2028/29): demonstrate electron acceleration and emittance preservation of externally injected electrons
  - Run 2d (2029/30..): development of scalable plasma sources to 100s meters length with sub-% level plasma density uniformity
  - → Propose first applications for particle physics experiments with 50-200 GeV electron bunches!

AWAKE Highlights 2022

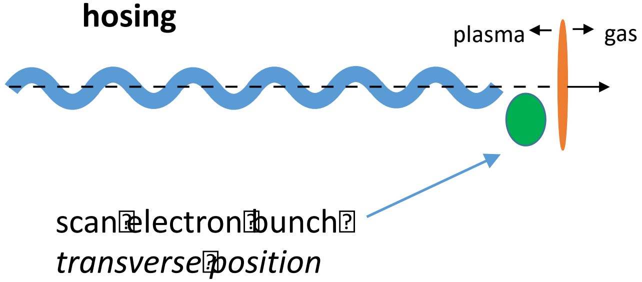


- 11 Weeks of proton beam
- Study proton bunch self-modulation using electron bunch to seed instabilities

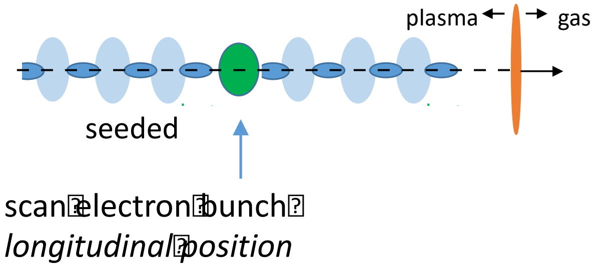
Seeding and growth of **self-modulation**



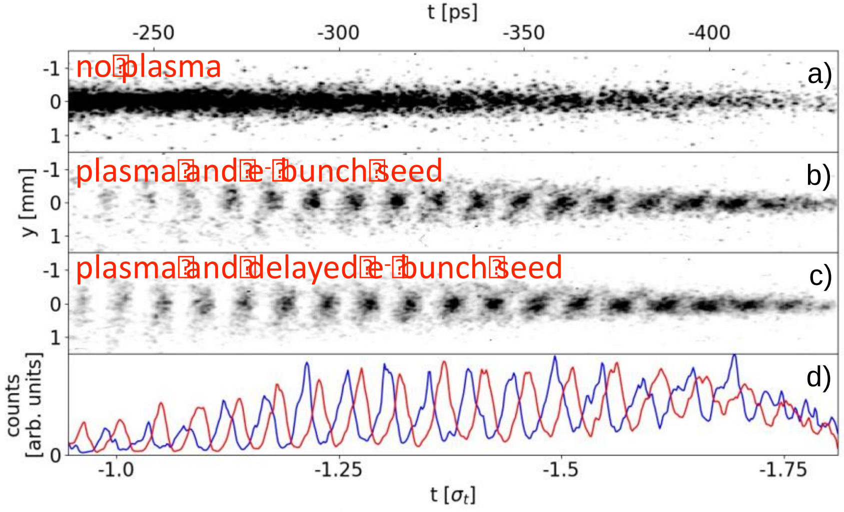
Seeding and growth of **hosing**



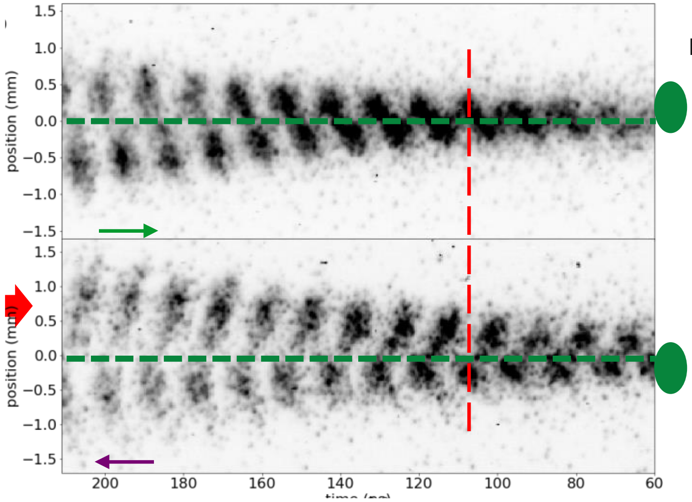
Ability to seed when **inside proton bunch**



- Run 2a Milestone : Demonstrated the seeding of the <u>self-modulation of the entire proton bunch</u> with an electron bunch



L. Verra, *et al.* (AWAKE Collaboration), *Phys. Rev. Lett.* 129, 024802 (2022)

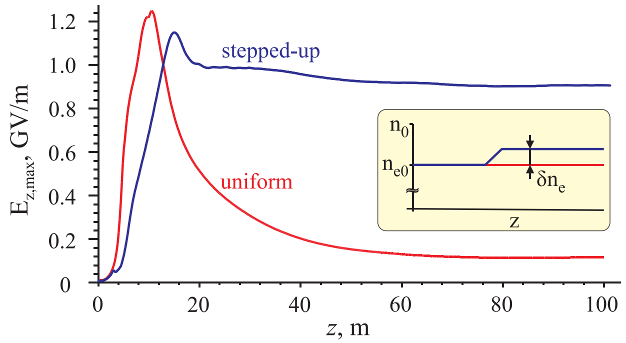


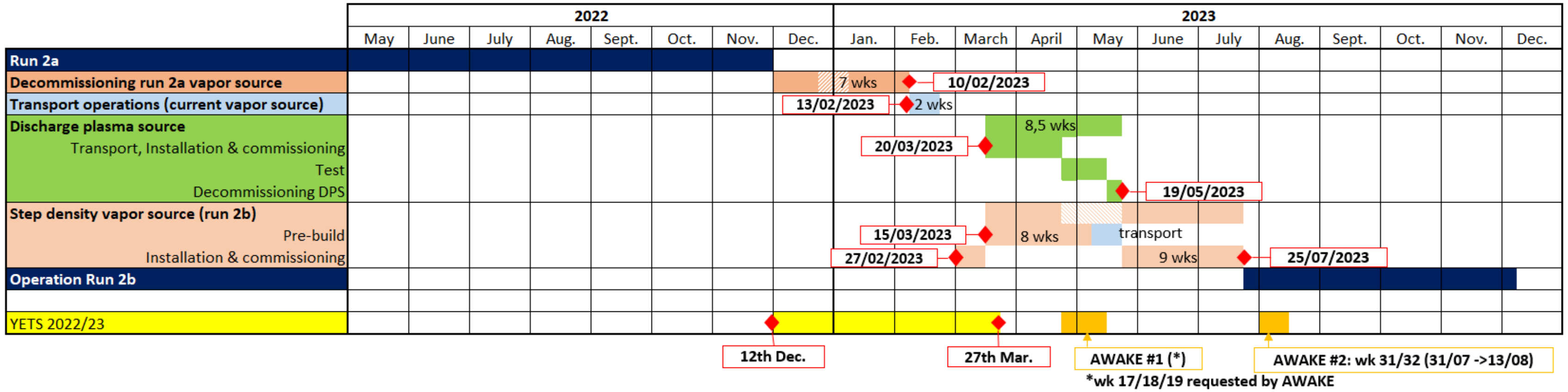
PRELIMINARY, T. Nechaeva, AWAKE Collaboration
CERN-SPSC-2022-033

- **Additional densities explored**
  - Propagation of proton bunch in very-low-density plasma
  - Propagation of a proton bunch wider than plasma skin depth
  - Seeded self-modulation at different plasma densities

AWAKE Program 2023

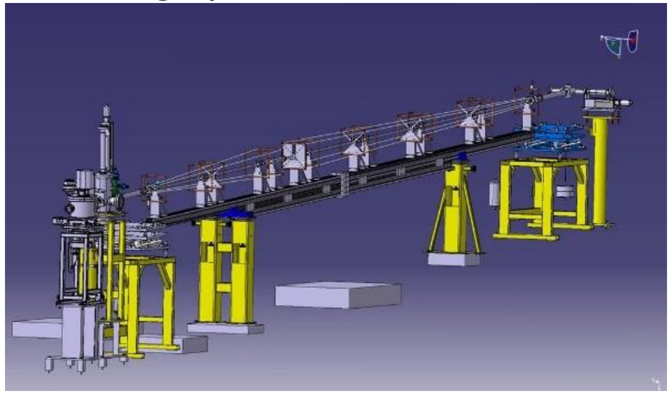
- **Run 2b (2023-2024): new plasma sources**
- **Discharge plasma**
  - Candidate for O(100) m acceleration plasma in Run 2d (2028+)
- **Plasma density step**
  - Required to stabilize proton-driven wakefields to ~ GeV/m over O(100)m
- **Dense installation/run schedule**



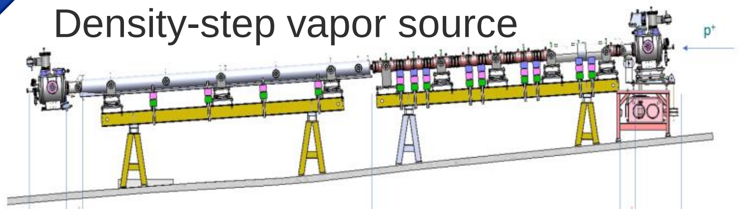


Current
Density-gradient vapor source

May 2023
Discharge plasma source



July 2023
Density-step vapor source



AWAKE: Progress, Issues and Feedback for 2022

- **AWAKE is very happy of the support from all technical groups involved in the experiment infrastructure and from the SPS operation team!**
- **Run for 2 out of 3 shifts and get out of the cycle as soon as there is an issue**
- **Improved precision and speed of Laser/Electron/Proton beam alignment**
  - Further precision requires addressing subtle effects: BTV screen angle motion, magnet hysteresis
- **Only showstopper from SPS: RF settings for 3E11p bunch**
  - Longitudinal instabilities identified in June run, preventing seeded self-modulation
  - Resolved during July run after several half-days of tests and lots of help from RF experts
- **Best data collected when NA/LHC were off in late July/August**
  - Higher repetition rate (7s instead of the usual 20s), fewer interruptions (no LHC fills)
  - We should find a way able to take good data even when NA and LHC are running

AWAKE: Progress on IEFC 2021 Feedback/Requests

- <u>**Four issues highlighted in 2021 IEFC. Progress made on most of them**</u>

- **1. Proton beam fine ALIGNMENT (final two correctors)**
  - AWAKE moved from BPM- to BTV-based calculation for faster correction (higher resolution)
  - At least one supercycle lost every correction to mask FE Interlock. Could it be masked during alignment?

- **2. Proton beam STABILITY**
  - Long stable periods needed for complete datasets. Interruptions require re-starting setup
  - AWAKE improved speed of laser/e/p alignments (now <1h) to improve recovery from p^+ interruptions

- **3. Proton beam to AWAKE during LHC FILLING**
  - Confirmed that it is not possible for now . Not an issue when LHC is stable and fills are few and short
  - Difficult/impossible to take data when LHC is commissioning or suffering from any issues

- **4. FLEXIBILITY when changing supercycle**
  - AWAKE/SPS/LHC communication improved: granted occasional flexibility to complete

AWAKE Desiderata

1. **Stable beam with higher repetition rate in dedicated periods**
   - Example: 8 hours of stable beams with higher repetition rate (1/10-1/15s)
   - For reference: 1/22s (2 NA + 2 AW), 1/18s (1 NAions + 3 AW), 1/11s (4 AW July 30)

2. **Continue maintaining availability of laser and electron beams during YETS**
   - Maintenance, optimization and technical upgrades on different subsystems

3. **[LS3] Upgrade of power converter to reduce proton beam jitter**
   - Proton trajectory jitter is acceptable for current physics objectives, but not for Run 2c
   - Upgrading TT40/TT41 converters and MSE will increase usable proton shots in Run 2c from 3% to 30%

Summary of Desiderata

HiRadMat

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CERN

Long Term Trajectory jitter for AWAKE after LS3

IEFC 2021

- **Proton trajectory jitter acceptable for current physics objectives, but not for Run 2c**

  2026+ much stricter requirements for Electron/proton alignment

  Key parameter to avoid electron charge loss and emittance growth in the acceleration phase

- **Main source of jitter are the magnet power converters**

Only 3% usable shots if not improved by Run 2c

- **Discussions and preliminary studies underway, countermeasures proposed**
  - Upgrade of converters output filters to reach Class 3 performance
  - Upgrade of all Control Electronics in TT41/TT41 to FGC3
  - Upgrade of MSE: synergy with LHC and NA in the context of SPS-CONS project
    - Perform upgrades **already during LS3?**

(First two upgrades: **~15%**; all three upgrades: **~30% usable shots**)