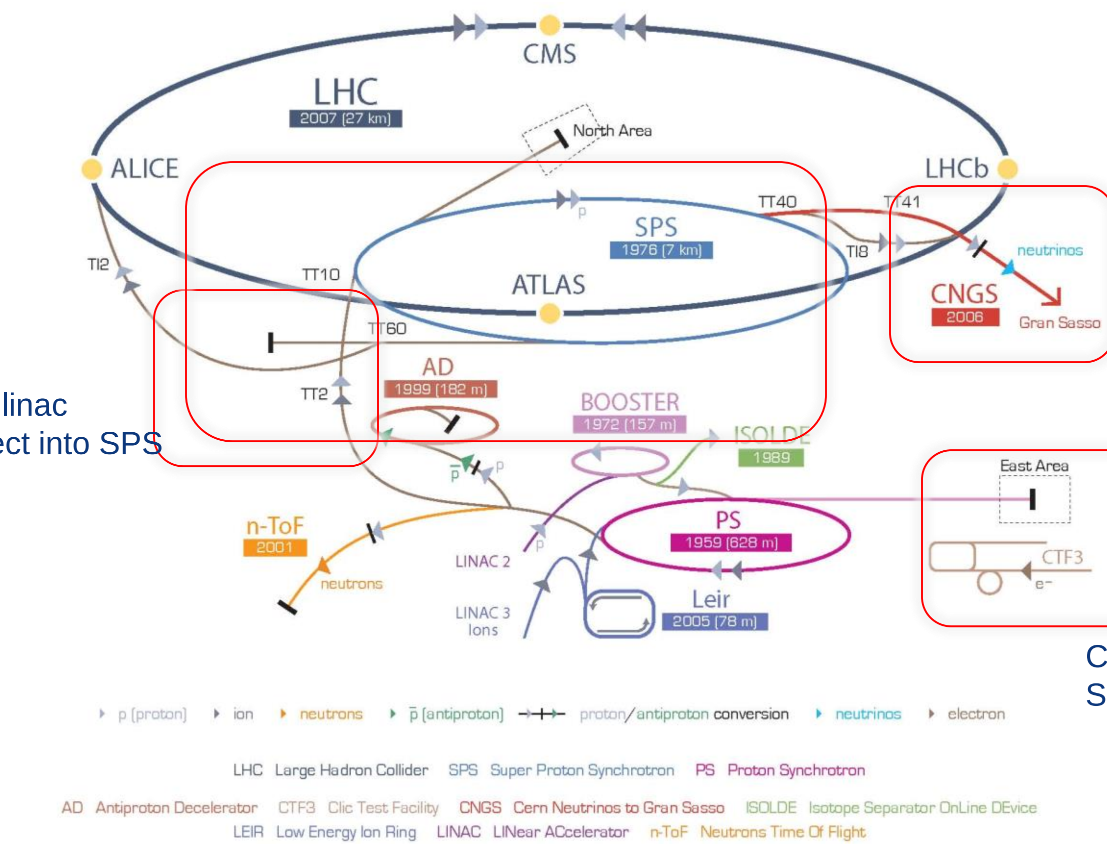
Electron beams at CERN

LCWS - Sendai October 2019

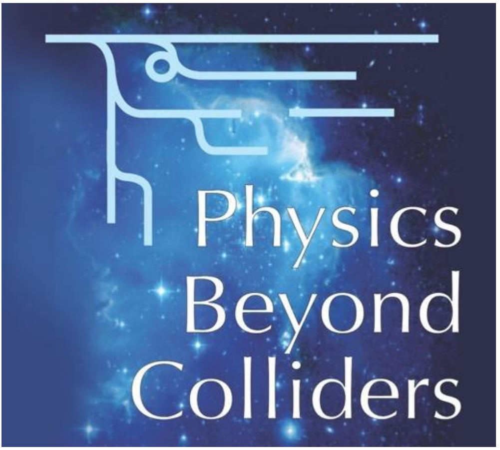
S. Stapnes (CERN)



eSPS x-band linac
proposed, inject into SPS

Now AWAKE, plasma
acc. experiment

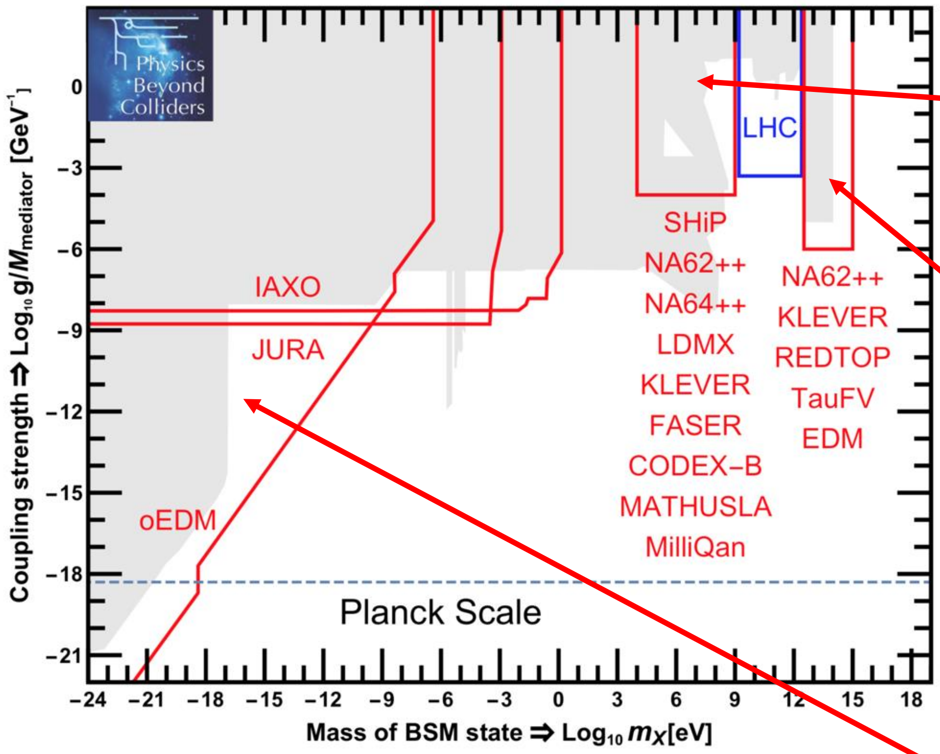
CTF3 - now CLEAR
See talk of Roberto Corsini



Next workshop next week: https://indico.cern.ch/event/827066/

- Exploitation of SPS/North Area
  - Conventional North Area beams (NA62+, KLEVER, NA64+, COMPASS…)
  - Beam Dump Facility for SHiP/TauFV
  - eSPS for LDMX
  - nuSTORM for neutrino cross-section etc.
- Novel approaches
  - EDM proton storage ring, Gamma Factory, AWAKE++
- LHC
  - LHC fixed target (gas, crystals)
  - Long Lived Particles (FASER, MATHUSLA, CODEX-b, milliQan)
- Technology
  - Various options (Helioscopes, “light-shining-through-walls”…)

Schematic overview of the BSM landscape



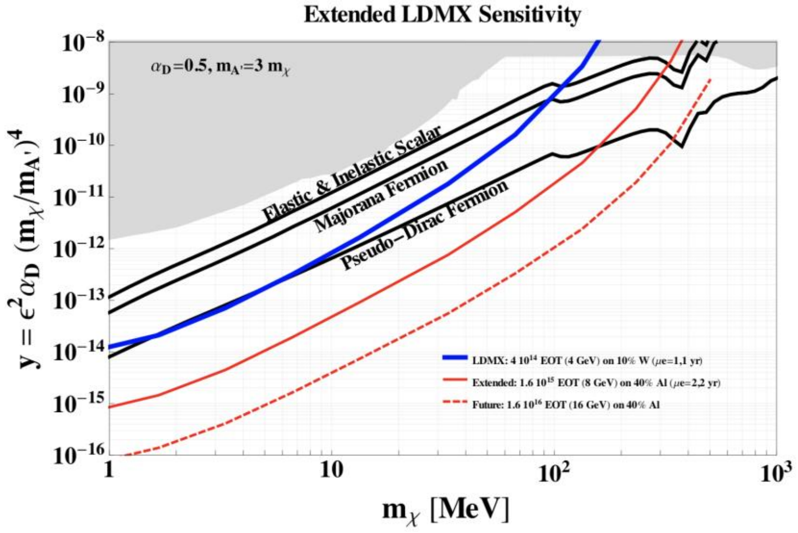
Beam dumps, Long Lived Particles
MeV – GeV (HNL, ALPS, Light Dark Matter)

Precision experiments
>>TeV (search for NP in clean and very rare flavour processes or in EDMs)

Non-accelerator projects
Sub-eV (axions, ALPs)

Motivations for eSPS

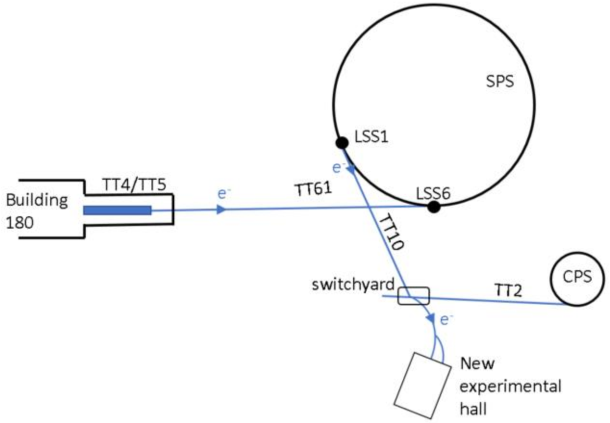
Physics: Large increasing interest in Light Dark Matter – using e-beams, the original trigger for the ”eSPS proposal” – LDMX talks: Granada slides, EPS slides



Accelerator R&D:

Any next machine at CERN is “beyond LHC”, i.e. 15+ years away – what can be done using smaller setups on a much shorter timescale ?

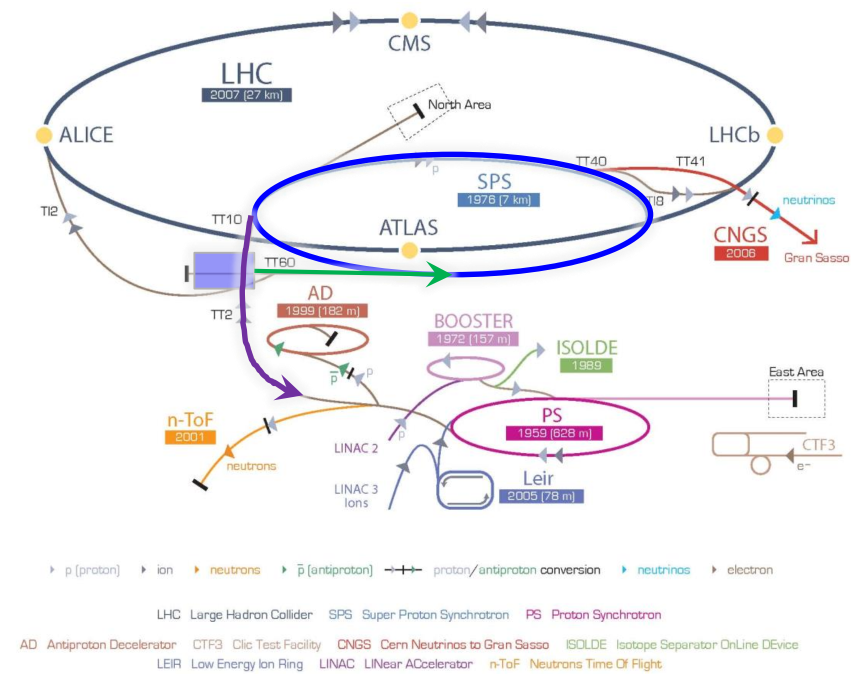
- Linac an important next step for X-band technology
- Relevant for FCC-ee, possible RF tests for example
- Strategic: Will bring electrons back at CERN fairly rapidly (linacs and rings) – important relevance for the developments and studies needed for future e+e- machines at CERN – being linear or circular
- Future accelerator R&D more generally: Accelerator R&D and project opportunities with e-beams as source
- Main directions: Novel Acc. studies (ALIC) and CLEARER



eSPS, overview

Accelerator implementation at CERN of LDMX type of beam

- X-band based 70m LINAC to ~3.5 GeV in TT4-5
- Fill the SPS in 1-2s (bunches 5ns apart) via TT60
- Accelerate to ~16 GeV in the SPS
- Slow extraction to experiment
- Experiment(s) considered by bringing beam back on Meyrin site using TT10

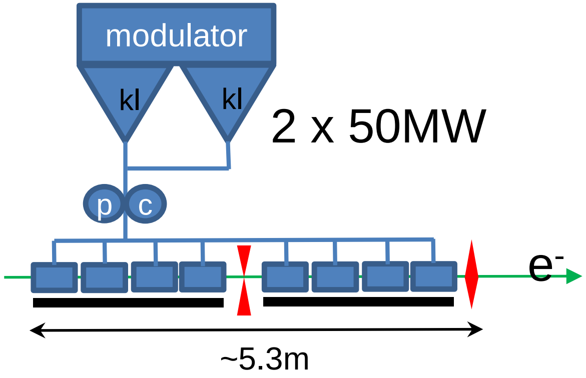


Beyond LDMX type of beam, other physics experiments considered (for example heavy photon searches)

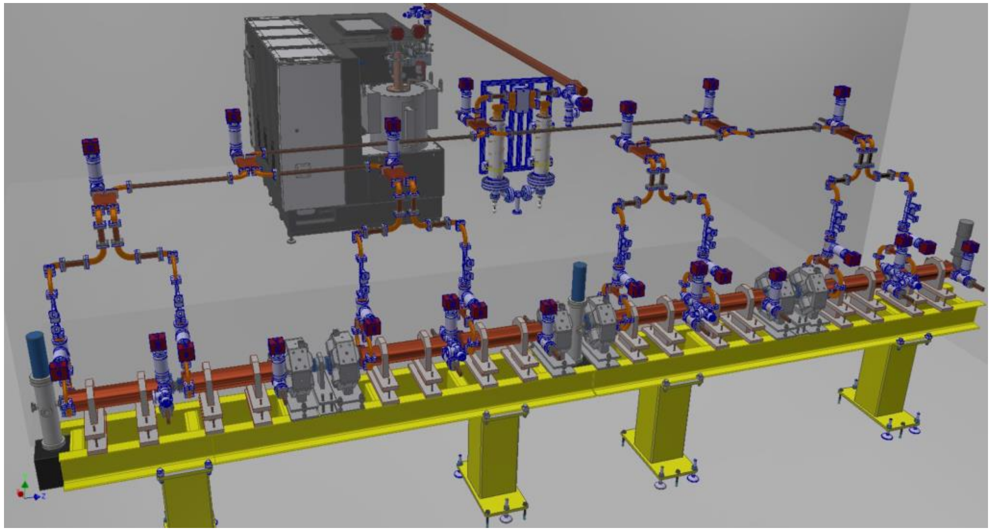
Acc. R&D interests (see later): Overlaps with CLIC next phase (klystron based), future ring studies (FCC-ee), FEL linac modules, e-beams for plasma, medical/irradiation/detector-tests/training, impedance measurements, instrumentation, positrons and damping ring R&D

Linac parameters

- 0.1GeV S-band injector
- 3.4GeV X-band linac
  - High gradient CLIC technology
  - 13 RF units to get 3.4 GeV in ~70 m



Possible parameters	
Energy spread (uncorrelated*)	<1MeV
Bunch charge	52 pC
Bunch length	~5ps
Norm. trans emittance	~10um
N bunches in one train	40
Train length	200 ns
Rep. rate	50/100 Hz



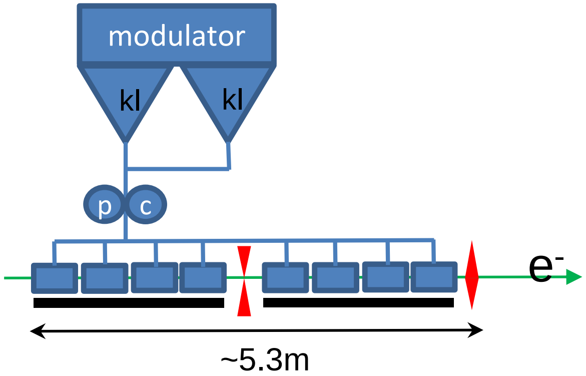
RF design of the X-BAND linac for the EUPRAXIA@SPARC_LAB project
M. Diomede Et al., IPAC18

Linac components available

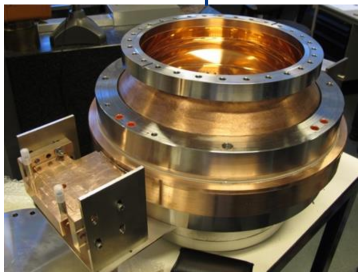
- Examples:

Klystron

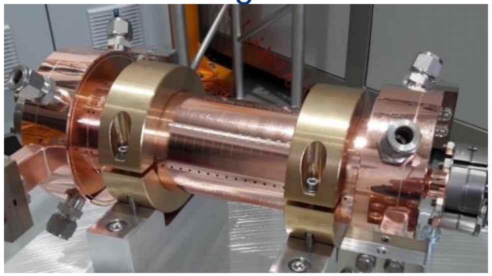
Modulator



Pulse compressor

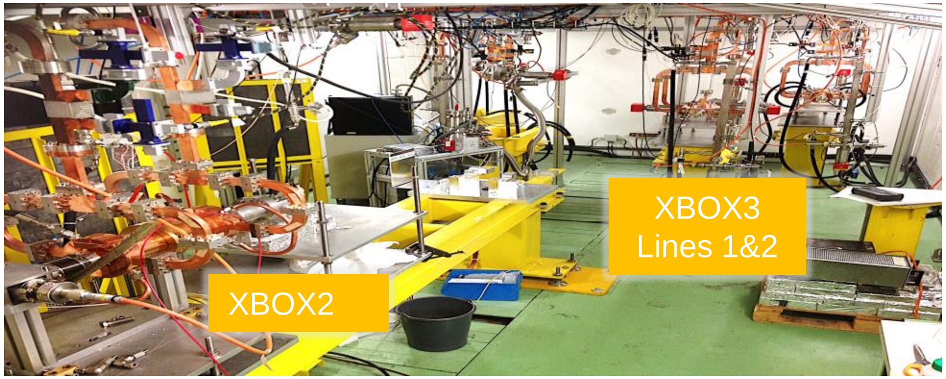


Accelerating structure



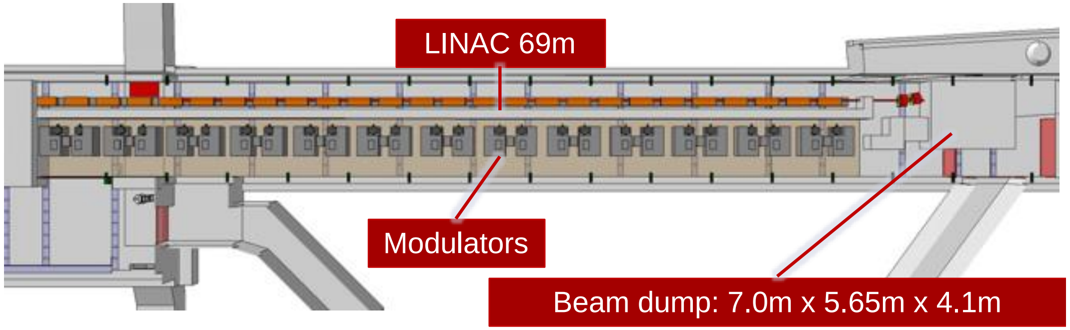
- One RF unit accelerates 200ns bunch train up to 264 MeV

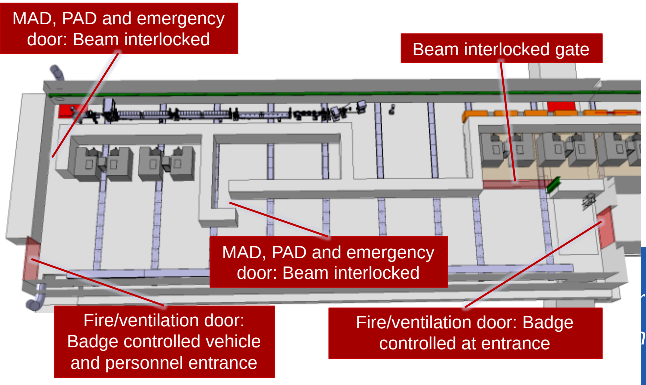
Assembled systems in continues operation at CERN



Linac in TT5/TT4

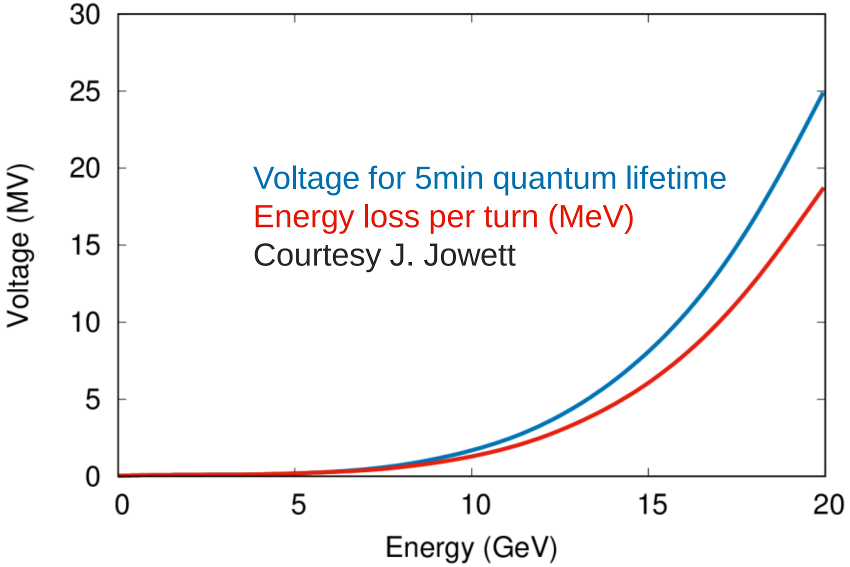
- Flexible bunch pattern provided by photo-injector 5ns, 10ns, … 40ns bunch spacing (only constrained by the SPS) – consider now 800 MHz (1.25 ns)
- High repetition rate, for example
  - 200 ns trains at 100 Hz
- To be installed in the available transfer tunnels TT4, in line with the SPS
- Room for accelerator R&D activities at end of linac (duty cycle in many cases low for SPS filling so important potential)

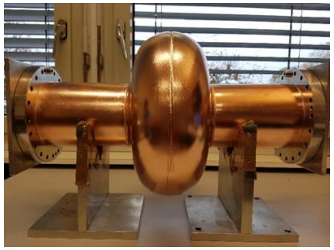




SPS RF system

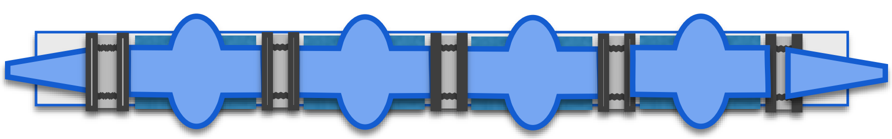
- Acceleration to 16 GeV can safely be achieved, need ~10 MV
- Studies show that a superconducting RF system is the most appropriate. The preferred frequency is 800 MHz – two options seem possible in this case (see below)
- Installation in LSS6 (LHC extraction region) is the preferred location to exploit the existing infrastructure from the crab cavity installation
- Use the mechanical bypass, a pulsed bypass, or inline



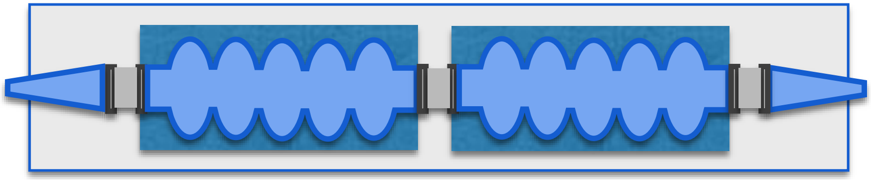


FCC-800 MHz prototypes

Sample Configuration $(10\ \mathrm{MV})$

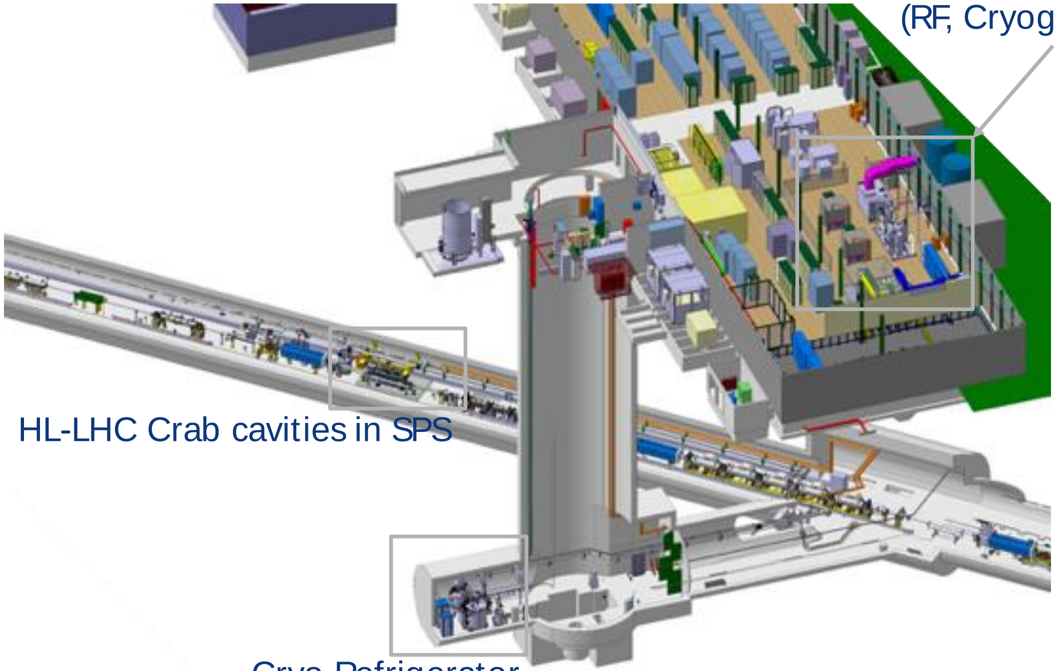


Four 1-cell in a CM $\sim 5\mathrm{m}$

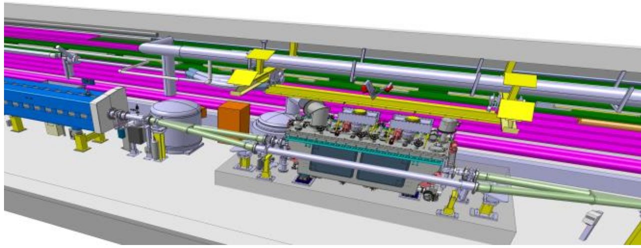


Two 5-cells in a CM $\sim 5\mathrm{m}$

RF: use Crab Cavity Bypass – SPS-LSS6



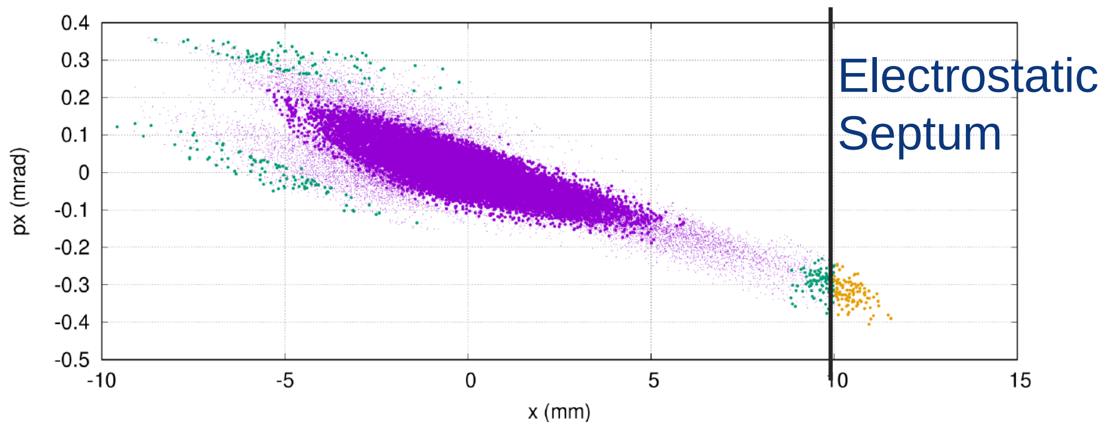
Talk yesterday by Rama Calaga: (LINK)

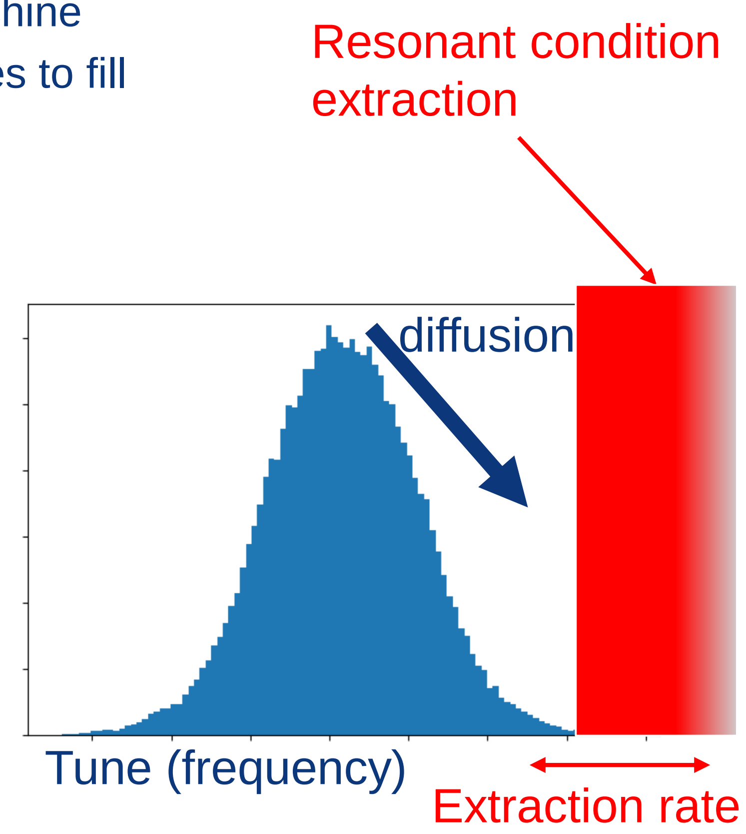


- Movement in/out of SPS-ring by 510mm – movement approx. 10 min with 2K Helium
- Independent vacuum system

Slow extraction principle, in frequency space

- Spread in oscillation frequency within the beam follows
  - Transverse distribution
  - Longitudinal distribution in presence of chromatic lattice
- Position of the resonant condition is set by the machine
- Synchrotron radiation constantly diffuse the particles to fill the tail in the distribution
- The extraction rate can be controlled by changing the position of the resonant condition

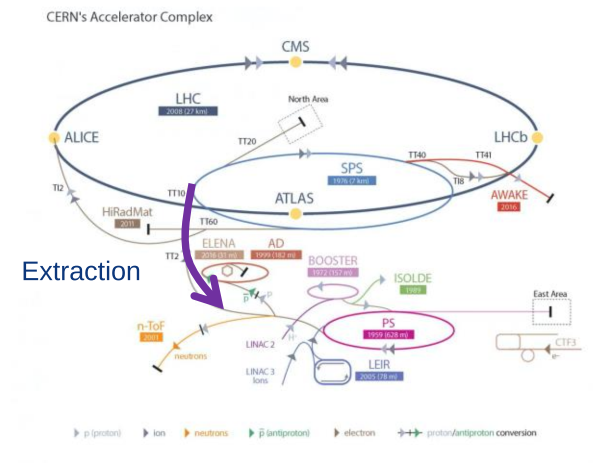




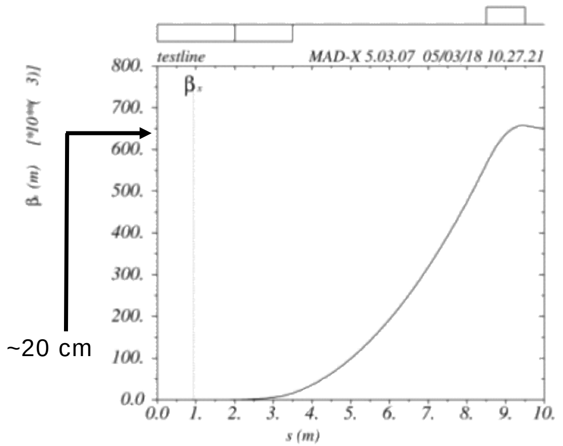
Electron beam transfer line from the SPS to experiments

- Uses existing TT10 line, designed to transport 10/20 GeV beams

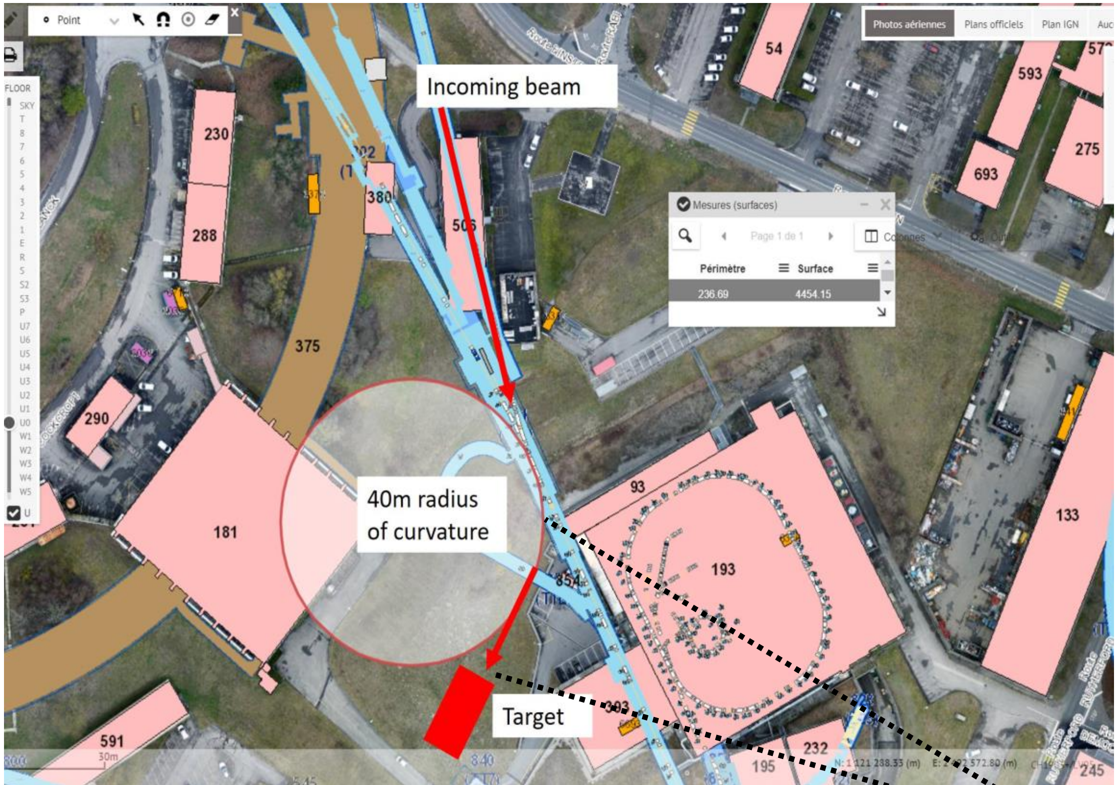
- Collimation in the line for control of beam distribution and intensity
  - ~ Gaussian beam can be made almost flat by careful collimation



- Beam size might be increased greatly at the target
  - Size of beam-spot chosen to deliver number of electrons/cm^2/bunch-crossing on target
  - For instance a 2cm vertical and 20cm horizontal beam is feasible
  - There is flexibility on the choice of both horizontal and vertical beam sizes



Extracted beam and experimental area



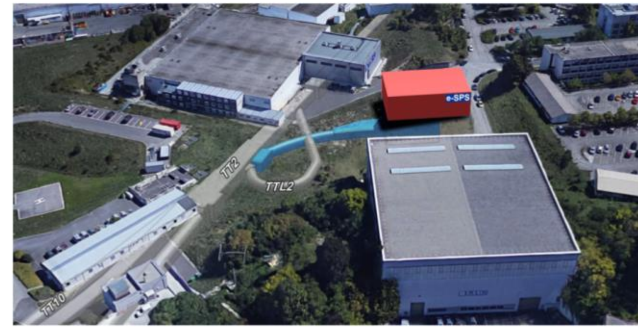


FIG. 43: Visualisation of the proposed underground (shown in blue) and overground (shown in red) facilities

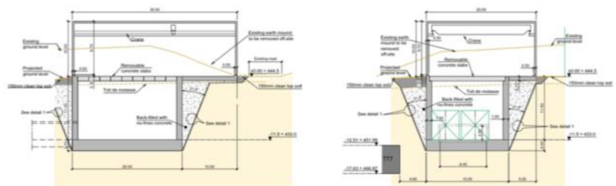


FIG. 41: Typical Sections through the experimental hall parallel to the beam-line (left) and transverse to the beam-line (right)

In total ~50 m new tu

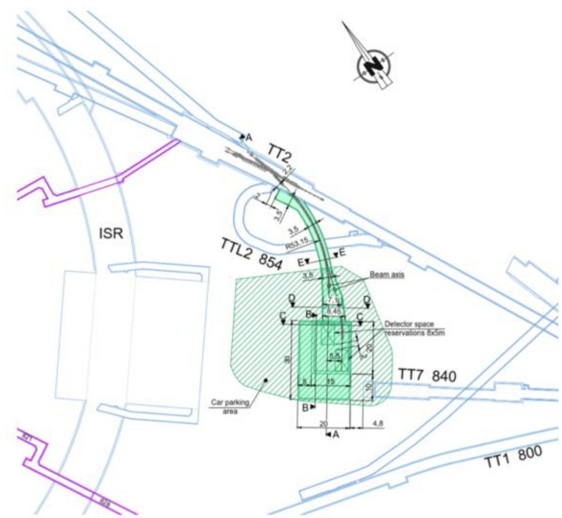
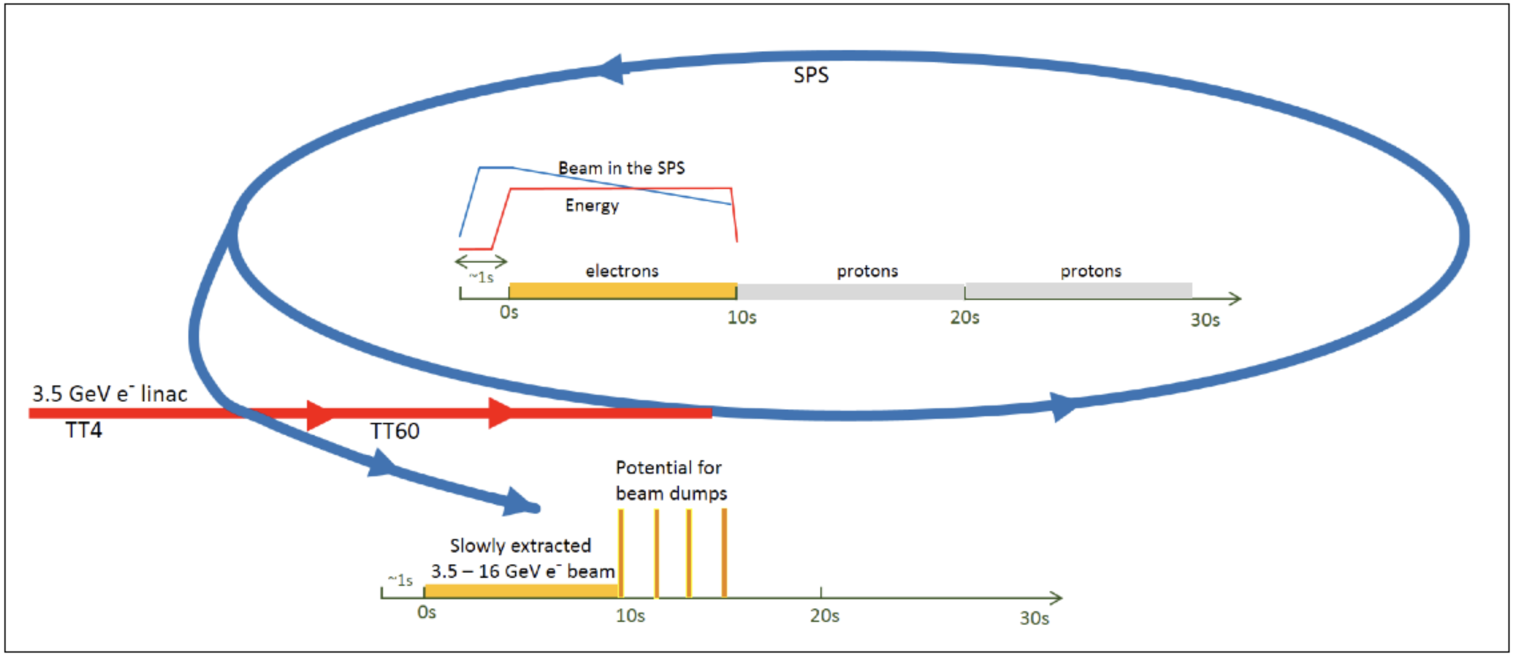


FIG. 38: Plan view of proposed layout

Beam structures – can also use dedicated run



Dark Sector Physics with a Primary Electron Beam Facility at CERN

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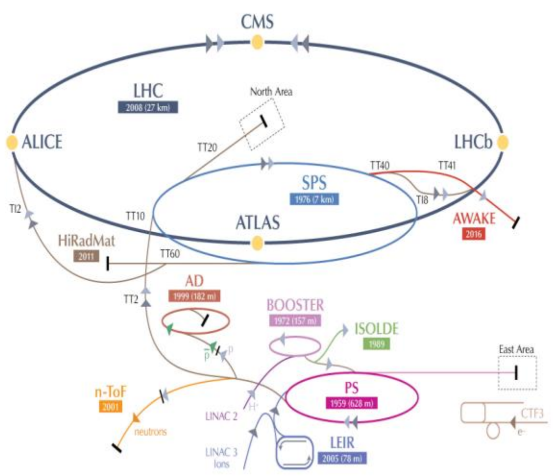
CERN-SPSC-2018-023 / SPSC-EOI-018
05/10/2018

EoI to the SPSC Oct 2018: https://cds.cern.ch/record/2640784

Also submitted in "compact form" to ESPP update 18.12:
https://indico.cern.ch/event/765096/contributions/3295600/

AWAKE

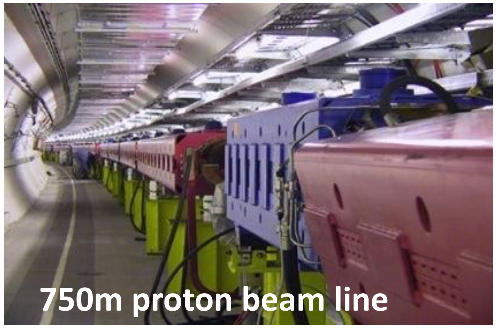


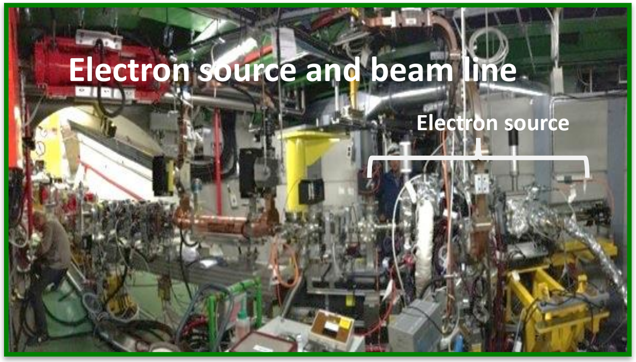
Advanced WAKEfield Experiment: Use protons beam as drive beam → powerful drivers at CERN, allow acceleration of electron to very high energies

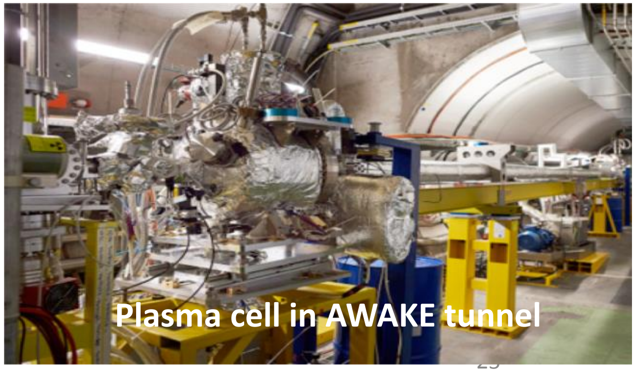
➔ PWA experiment dedicated to high energy physics applications!

International Collaboration: 20 collaborating institutes, 3 associate institutes

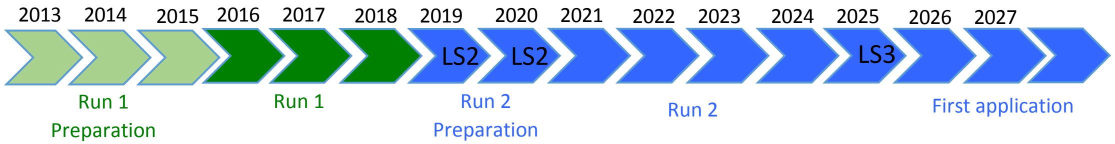
Timeline:
2013: Approved
2016-2018: AWAKE Run 1: proof-of-concept experiment: demonstrated seeded self-modulation of the proton bunch and acceleration of electrons
2020- LS3: AWAKE Run 2: Accelerate electrons to high energies while preserving beam quality
After Run 2: Particle physics applications kick-off







AWAKE Run 2



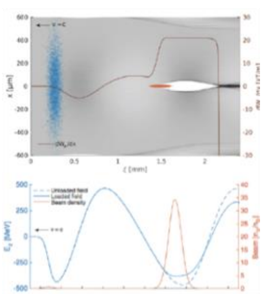
Goal:

Accelerate an electron beam to high energy (gradient of 0.5-1GV/m)

Preserve electron beam quality as well as possible (emittance preservation at 10 mm mrad level)

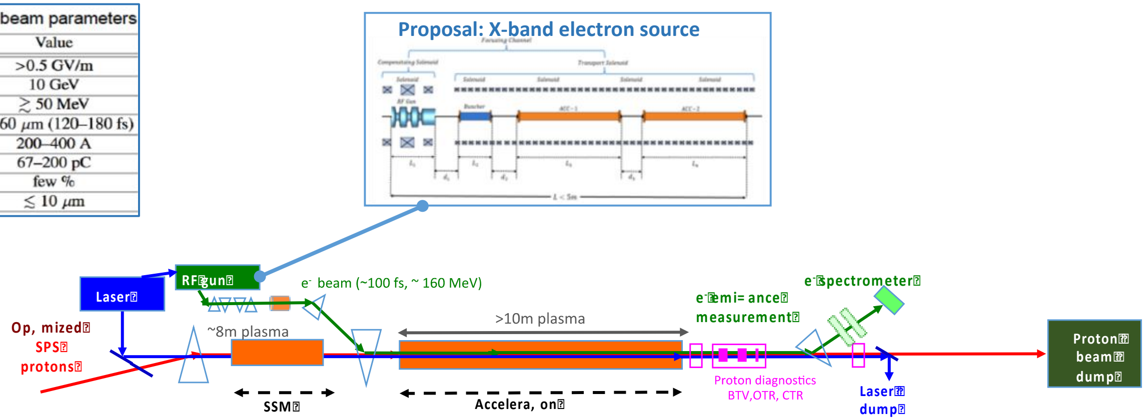
Demonstrate scalable plasma source technology (e.g. helicon prototype)

- ➔ Freeze the modulation with **density step** in first plasma cell
- ➔ For emittance control: need to work in **blow-out regime** and do **beam-loading**
- ➔ R&D on different **plasma source technologies**



Preliminary Run 2 electron beam parameters

Parameter	Value
Acc. gradient	>0.5 GV/m
Energy gain	10 GeV
Injection energy	$\gtrsim$ 50 MeV
Bunch length, rms	40–60 μm (120–180 fs)
Peak current	200–400 A
Bunch charge	67–200 pC
Final energy spread, rms	few %
Final emittance	$\lesssim$ 10 μm



E. Adli (AWAKE Collaboration), IPAC 2016 proceedings, p.2557 (WEPMY008)

V. Olsen, E. Adli, P. Muggli, ***PRL*** *21, 011301 (2018)*
K. Lotov, Physics of Plasmas ***22,*** *10311 (2015)*

➔ **External injection, Independent drive and witness beam, 10m long plasma cell, proton beam**

➔ **Requirements on emittance are moderate for fixed target experiments and e/p collider experiments, so first experiments in not-too far future!**

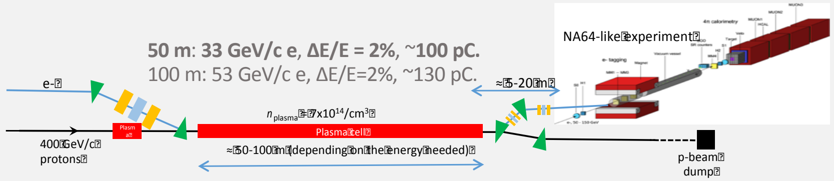
Applications with AWAKE-Like Scheme

→ Requirements on emittance are moderate for fixed target experiments and e/p collider experiments, so first experiments in not-too far future!

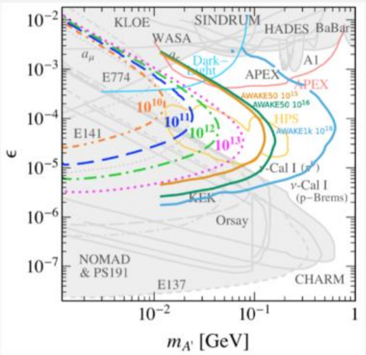
First Application:

→ **Fixed target test facility**: Use bunches from SPS with 3.5 E11 protons every ~5sec,
→ electron beam of up to O (50GeV), **3 orders of magnitude increase in electrons** (compared to NA64)

→ deep inelastic scattering, non-linear QED, **search for dark photons a la NA64**

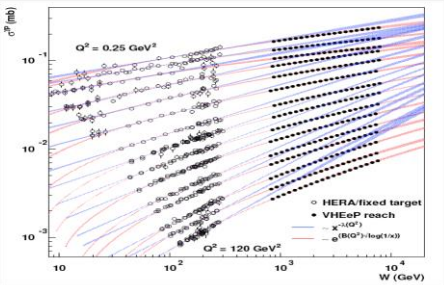


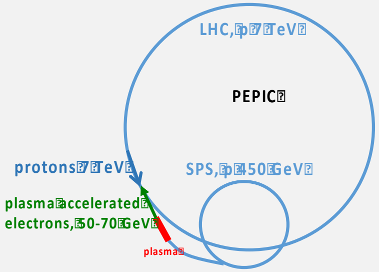
Parameter	AWAKE-upgrade-type	HL-LHC-type
Proton energy E_p (GeV)	400	450
Number of protons per bunch N_p	3×10^{11}	2.3×10^{11}
Longitudinal bunch size protons σ_z (cm)	6	7.55
Transverse bunch size protons σ_r (μm)	200	100
Proton bunches per cycle n_p	8	320
Cycle length (s)	6	20
SPS supercycle length (s)	40	40
Electrons per cycle N_e	2×10^9	5×10^9
Number of electrons on target per 12 weeks run	4.1×10^{15}	2×10^{17}

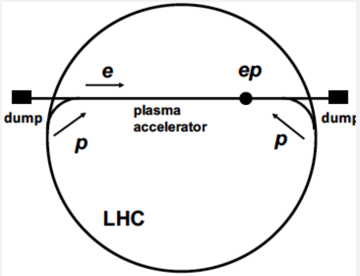


Using **the SPS or the LHC beam as a driver**, TeV electron beams are possible → Electron/Proton or Electron/Ion Collider

- **PEPIC:** LHeC like collider: E_e up to O (70 GeV), colliding with LHC protons → exceeds HERA centre-of-mass energy
- **VHEeP:** choose E_e = 3 TeV as a baseline and with E_p = 7 TeV yields √s = 9 TeV. → CM ~30 higher than HERA. Luminosity ~ 10^{28} – 10^{29} cm^{-2} s^{-1} gives ~ 1 pb−1 per year.



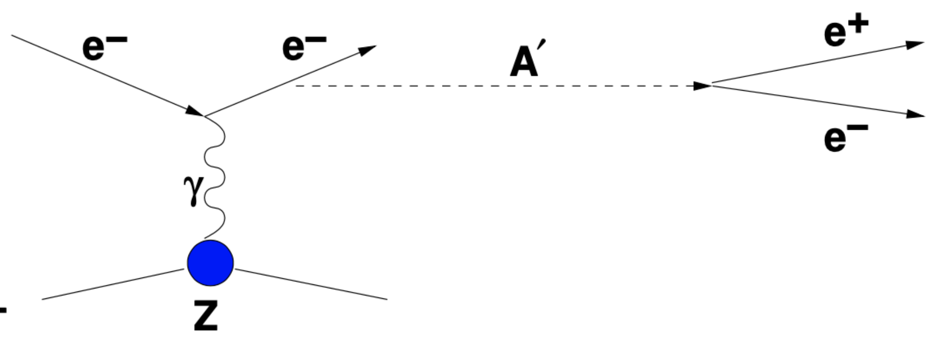




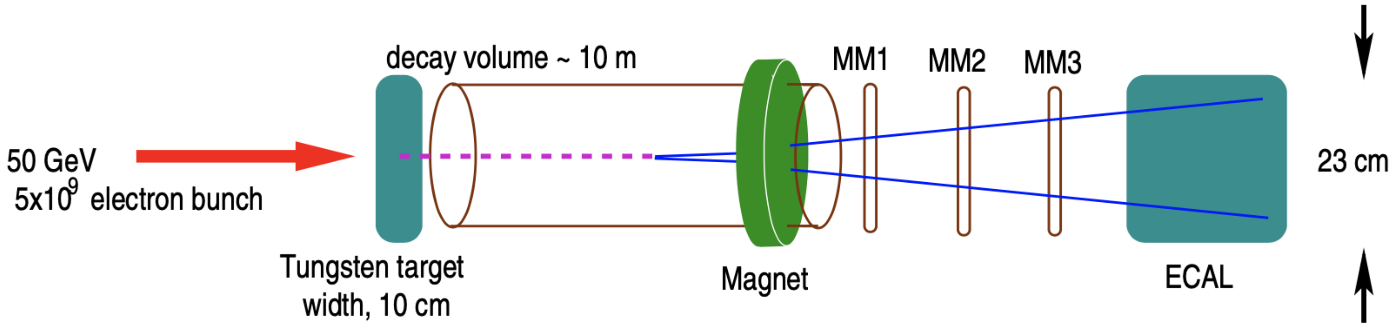
VHEeP: A. Caldwell and M. Wing, Eur. Phys. J. C 76 (2016) 463

Search for dark photons using an AWAKE-like beam

- NA64 are making great progress investigating the dark sector:
  - Dark sectors with light, weakly-coupling particles are a compelling possibility for new physics.
  - Search for dark photons, A', up to *GeV* mass scale via their production in a light-shining-through-a-wall type experiment.
  - Use high energy electrons for beam-dump and/or fixed-target experiments.



- An AWAKE-like beam will have higher intensity than the SPS secondary beam.
- Provide upgrade/extension to NA64 programme.
- Using NA64 software and similar detectors.



Documents submitted to European Strategy

Particle physics applications of the AWAKE acceleration scheme

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Abstract

The AWAKE experiment had a very successful Run 1 (2016–8), demonstrating proton-driven plasma wakefield acceleration for the first time, through the observation of the modulation of a long proton bunch into micro-bunches and the acceleration of electrons up to 2 GeV in 10 m of plasma. The aims of AWAKE Run 2 (2021–4) are to have high-charge bunches of electrons accelerated to high energy, about 10 GeV, maintaining beam quality through the plasma and showing that the process is scalable. The AWAKE scheme is therefore a promising method to accelerate electrons to high energy over short distances and so develop a useable technology for particle physics experiments. Using proton bunches from the SPS, the acceleration of electron bunches up to about 50 GeV should be possible. Using the LHC proton bunches to drive wakefields could lead to multi-TeV electron bunches, e.g. with 3 TeV acceleration achieved in 4 km of plasma. This document outlines some of the applications of the AWAKE scheme to particle physics and shows that the AWAKE technology could lead to unique facilities and experiments that would otherwise not be possible. In particular, experiments are proposed to search for dark photons, measure strong field QED and investigate new physics in electron–proton collisions. The community is also invited to consider applications for electron beams up to the TeV scale.

Input to the European Particle Physics Strategy Update

December 2018

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CERN-PBC-REPORT-2018-004

AWAKE++: the AWAKE Acceleration Scheme for New Particle Physics Experiments at CERN

W. Bartmann[1], A. Caldwell[2], M. Calviani[1], J. Chappell[3], P. Crivelli[4], H. Damerau[1], E. Depero[4], S. Doebert[1], J. Gall[1], S. Gninenko[5], B. Goddard[1], D. Grenier[1], E. Gschwendtner[*1], Ch. Hessler[1], A. Hartin[3], F. Keeble[3], J. Osborne[1], A. Pardons[1], A. Petrenko[1], A. Scaachi[3], and M. Wing[3]

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1 Abstract

The AWAKE experiment reached all planned milestones during Run 1 (2016-18), notably the demonstration of strong plasma wakes generated by proton beams and the acceleration of externally injected electrons to multi-GeV energy levels in the proton driven plasma wakefields.
During Run 2 (2021 - 2024) AWAKE aims to demonstrate the scalability and the acceleration of electrons to high energies while maintaining the beam quality.
Within the Physics Beyond Colliders (PBC) study AWAKE++ has explored the feasibility of the AWAKE acceleration scheme for new particle physics experiments at CERN. Assuming continued success of the AWAKE program, AWAKE will be in the position to use the AWAKE scheme for particle physics applications such as fixed target experiments for dark photon searches and also for future electron-proton or electron-ion colliders.
With strong support from the accelerator and high energy physics community, these experiments could be installed during CERN LS3; the integration and beam line design show the feasibility of a fixed target experiment in the AWAKE facility, downstream of the AWAKE experiment in the former CNGS area. The expected electrons on target for fixed target experiments exceeds the electrons on target by three to four orders of magnitude with respect to the current NA64 experiment, making it a very promising experiment in the search for new physics.
Studies show that electrons can be accelerated to 70 GeV in a 130 m long plasma cell installed in an extended TI 2 extraction tunnel from SPS to the LHC and transported to collision with protons/ions from the LHC. The experiment would focus on studies of the structure of matter and QCD in a new kinematic domain.
The AWAKE scheme offers great potential for future high energy physics applications and it is the right moment now to support further development of this technology leading to unique facilities.

Input to the European Particle Physics Strategy Update

December 2018

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CERN-PBC-REPORT-2018-005

Concluding remarks

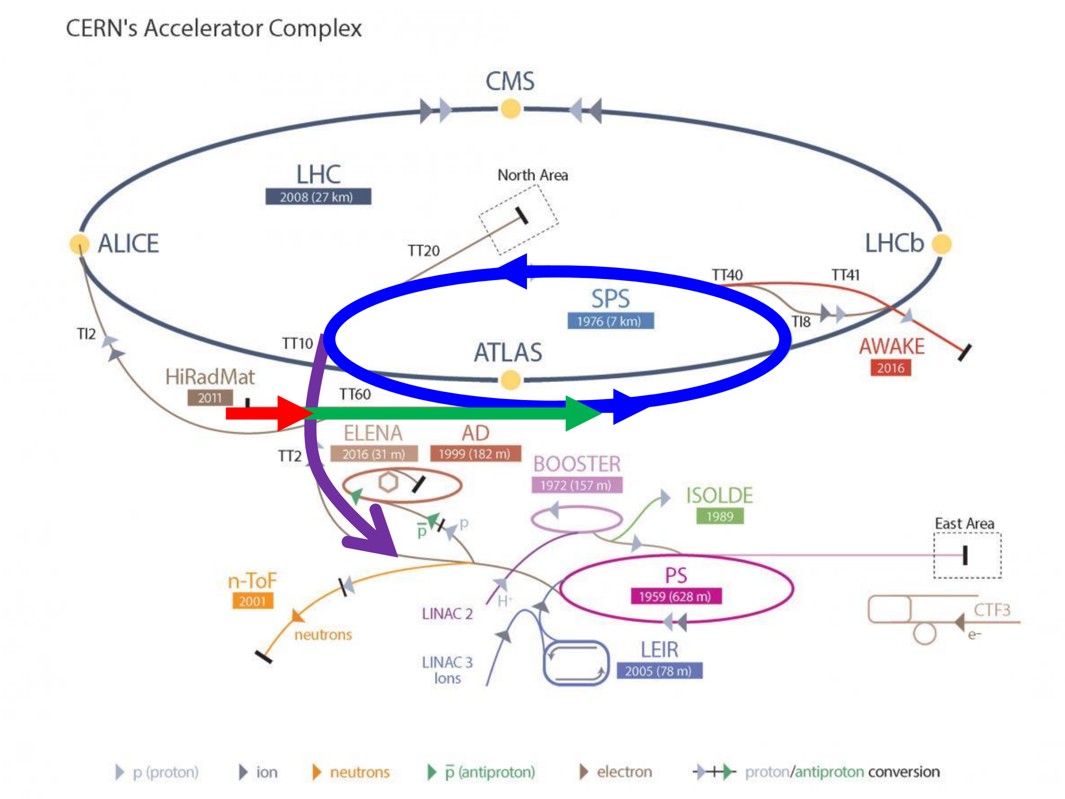
- Important physics opportunities with e-beams at CERN
  - Worth keeping in mind these physics (and acc. R&D) opportunities during construction, commissioning or in parallel with LC operation

- At CERN:
  - eSPS: Based on previous usage of the CERN accelerator complex, and building on the accelerator R&D for CLIC and HiLumi/FCC, an electron beam facility would be a natural next step
    - No show-stoppers have been found when exploring this option
    - LDMX interest in pursuing this option as beam close to ideal
    - Will also provide many opportunities for important and strategic accelerator R&D at CERN – and opens the door to future electron facilities in general

  - AWAKE++ can provide high energy electrons for Dark Photon Searches and e-proton / e-ion studies

Slides “collected” from Mike Lamont, Edda Gschwendtner (link) and Matthew Wing (link) – with thanks

The flow



3.5GeV Linac

Transfer to SPS

Acceleration in SPS

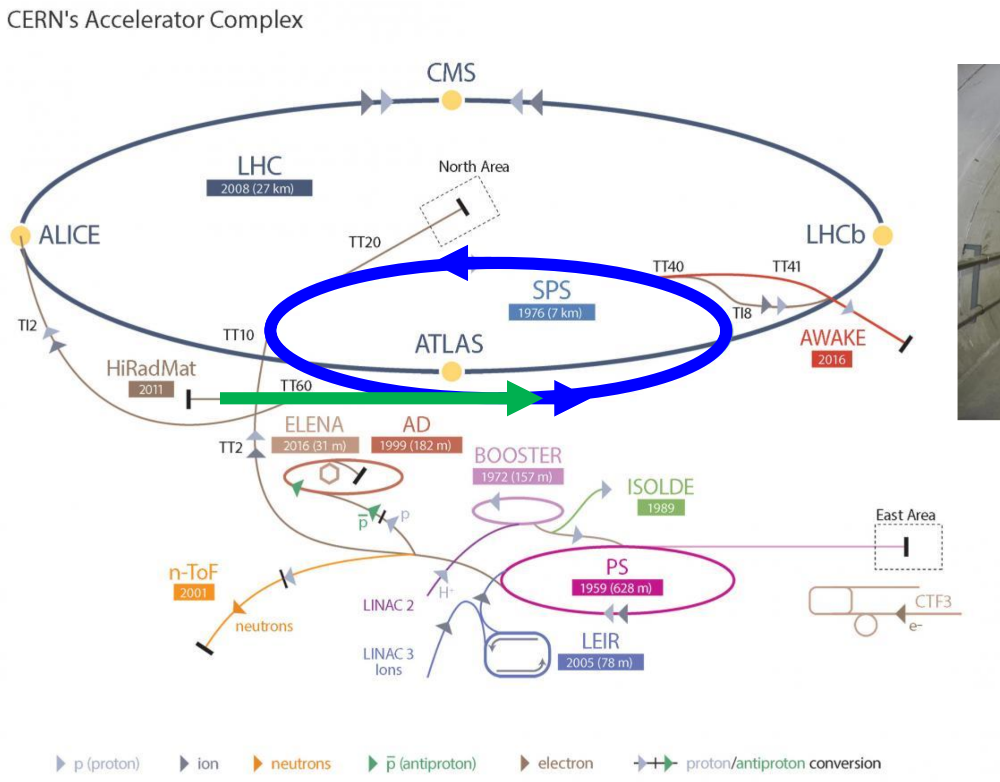
Extraction

Transfer tunnel, TT60, from the Linac into the SPS

Injection into the SPS

Bunch to bucket injection in the SPS longitudinal RF structure.

Total of 75 trains of 40 bunches 3000 bunches 10^{12} electrons in the ring

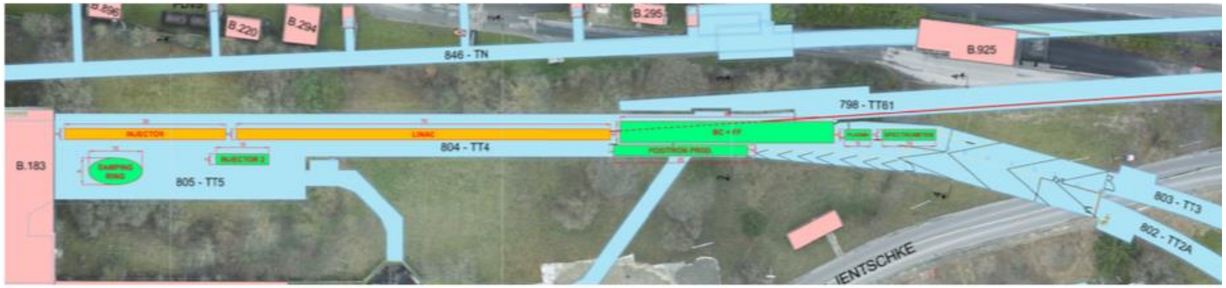


Potential use of such a facility

(linac more than 90% free)

Physics:

LDMX - Other hidden sector exp., incl. dump-type experiments using the available electrons - Nuclear physics



Accelerator physics opportunities (not all studied currently)

CLIC: Linac goes a long way towards a natural next step for use of technology (collaborate with INFN and others also using technology for X-band linacs in coming years)

Relevant also for other potential future facilities using electrons (rings) considered at CERN, for example the RF systems

Plasma studies with electrons

Use electron (3.5 GeV) beam as driver and/or probe – studied by AWAKE WG

General acc. R&D as in CLEAR – existing ~200 MeV linac - today (https://clear.web.cern.ch)

Plasma-lenses, impedance, high grad studies, medical (electron irradiation), training, instrumentation, THz, ESA irradiation. Recent results: https://acceleratingnews.web.cern.ch/article/first-experimental-results-clear-facility-cern

Positron production (interesting for linear or circular colliders and plasma) and studies with positrons for plasma, and possibly LEMMA concept for muon collider

General Linear or Ring related Collider related studies using SPS beam

Example: damped beam for final focus studies (beyond ATF2), FCC-ee related studies

Costs from EoI

Sources

- Industrial (e.g. RF components, structures for linacs)
- ”Standard” rates (e.g. civil engineering)
- PBS with ~80 items, estimates from technical responsible

TABLE I: Cost summary

PBS	Item	Cost MCHF
1.1	Source	6.0
1.2	X-band linac	34.1
2.1	Linac to SPS transfer	4.6
2.2	SPS fast injection	3.4
2.3	SPS ring	10.5
2.4	SPS slow extraction	3.3
2.5	Transfer SPS to Exp. Area	4.2
3.2	Civil Engineering	11.4
3.3	Exp. Area infrastructure	2.0
	Sum	**79.5**

Instrumentation

Linac:
- Position
  - Re-use of CTF3 inductive pick-ups
  - Simple button BPMs would also do the job
- Beam Size
  - OTR screens (can also be combined with streak camera for bunch length)
- Intensity
  - Re-use of CTF3 inductive pick-up or standard beam current transformers

SPS:
- Position
  - Standard orbit system (consolidated in LS2)
  - Should be able to measure to 1e9 (limit ~5e8)
- Beam Size
  - Wirescanners
  - Possible use of synchrotron radiation
- Intensity
  - DC Transformer OK for total current
  - Fast BCT does not distinguish 5ns spaced bunches
  - Could do batch by batch but at limit of resolution (tbc)

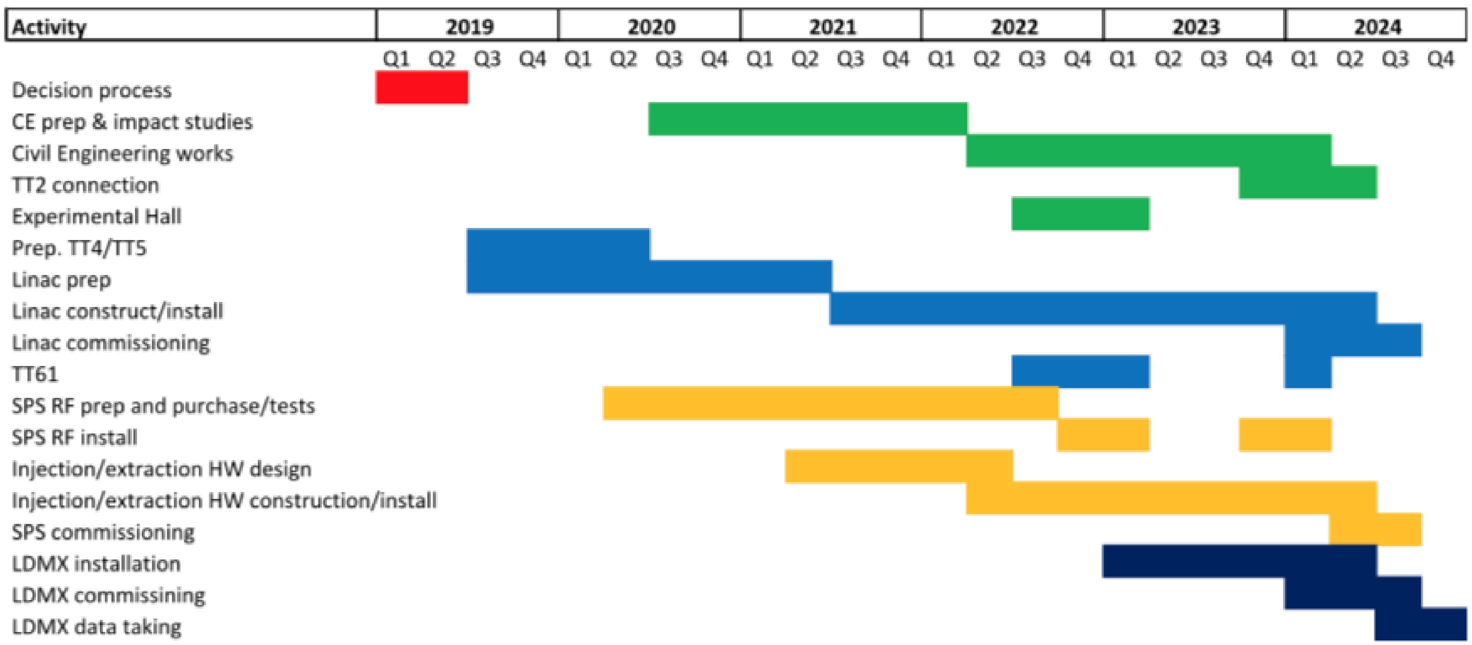
Extracted beam:
- Position & Intensity
  - Use of fibre monitors.
    - Developed for new EHN1 (neutrino platform) secondary lines
    - Scintillating (or Cherenkov) fibres
    - Low material budget
    - > 90% efficiency for single particles demonstrated
  - R&D required to make them UHV compatible

The challenge of measuring very low intensity beam can be circumvented using a higher intensity for beam setup

Schedule in the EoI

Technically based … however

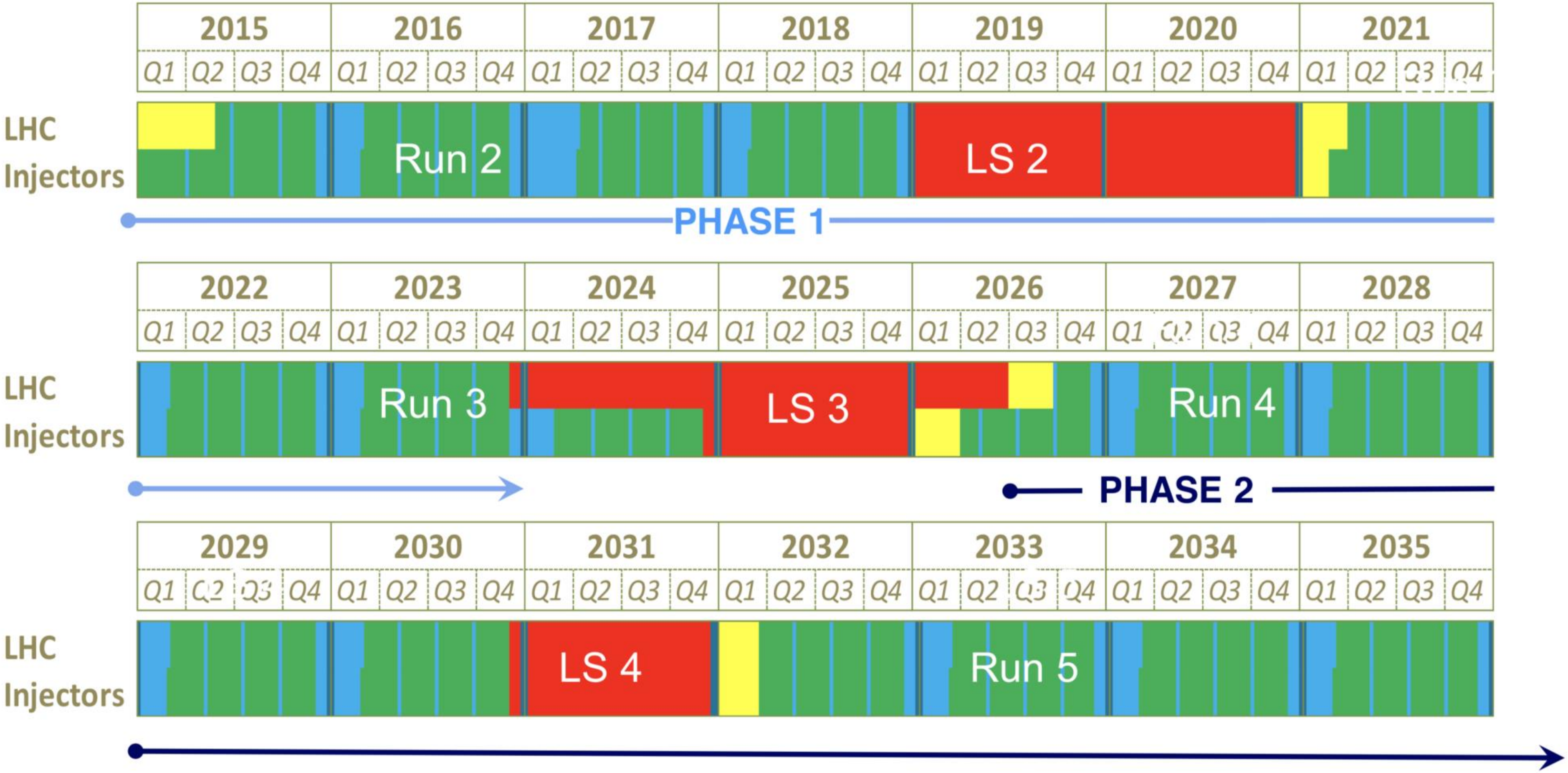
- Respects that efforts during LS2 has to be limited
- No major spending or commitments until Spring/mid 2020 (ESU completion) -> need significant resources from then
- Final connection after end of LHC run in 2023
- Can run during LS3 when/if the SPS is available
- Need to decide now if we move ahead towards a CDR or similar in a years time – resource/priority issue



LHC roadmap: according to MTP 2016-2020 V2

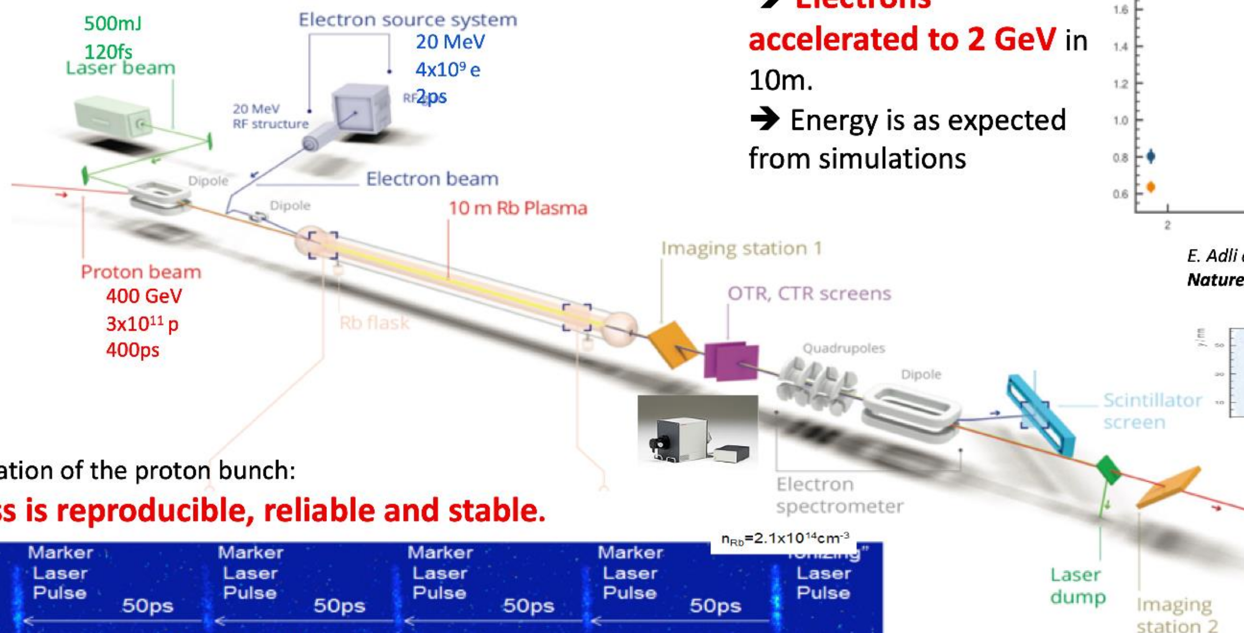
LS2 starting in 2019 => 24 months + 3 months BC
LS3 LHC: starting in 2024 => 30 months + 3 months BC
Injectors: in 2025 => 13 months + 3 months BC

Physics
Shutdown
Beam commissioning
Technical stop



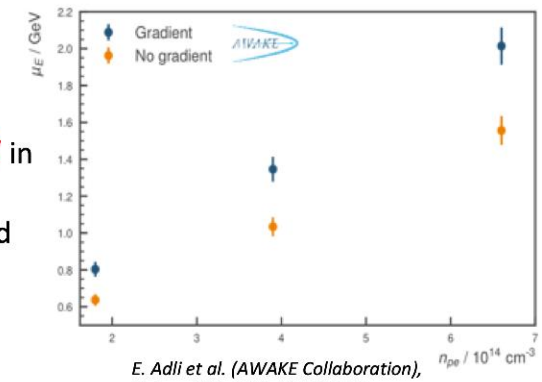
AWAKE, CERN

AWAKE has demonstrated during Run 1 (2016-2018) that the seeded self-modulation is a reliable and robust process and that electrons can be accelerated with high gradients.

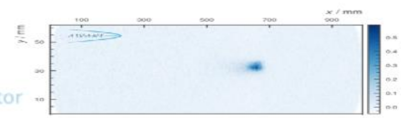


➔ **Electrons accelerated to 2 GeV** in 10m.

➔ Energy is as expected from simulations

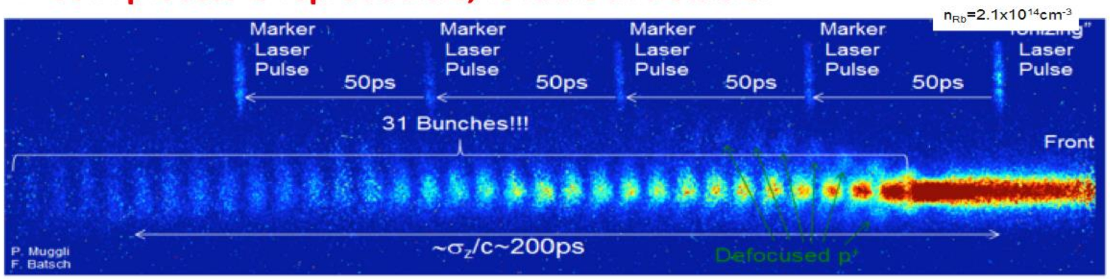


E. Adli et al. (AWAKE Collaboration), ***Nature 561****, 363–367 (2018)*



Seeded self-modulation of the proton bunch:

➔ **SSM process is reproducible, reliable and stable.**



E. Adli et al. (AWAKE Collaboration), ***Phys. Rev. Lett. 122, 054802 (2019).***
M. Turner et al. (AWAKE Collaboration) ***PRL, 122, 054801 (2019).***

AWAKE schematic