Proton-driven plasma acceleration at AWAKE and beyond

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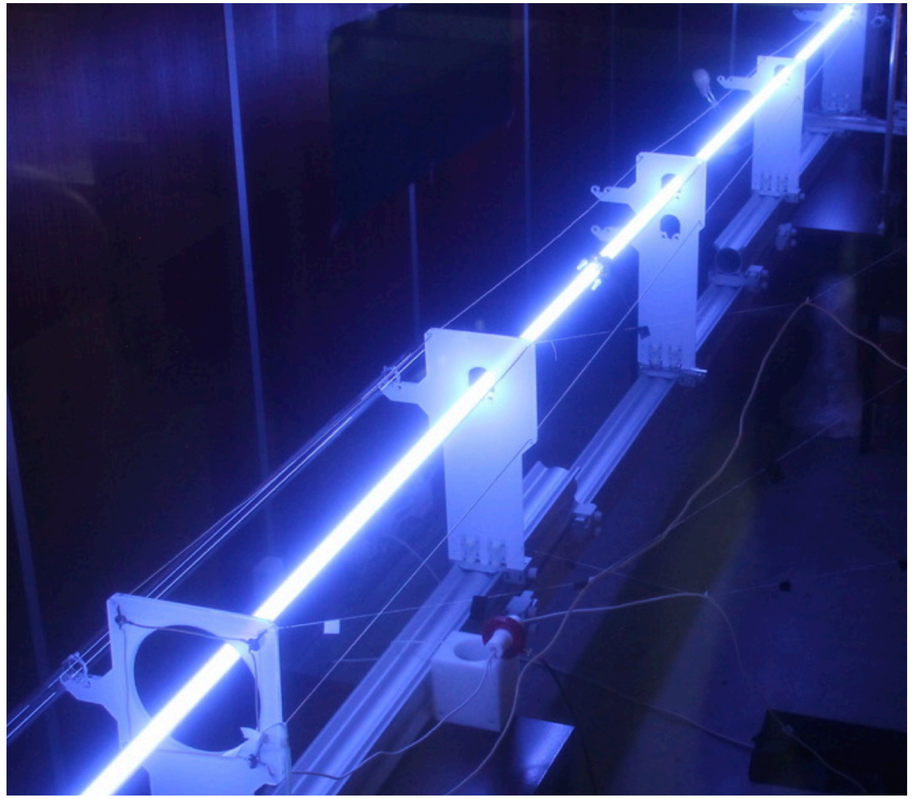
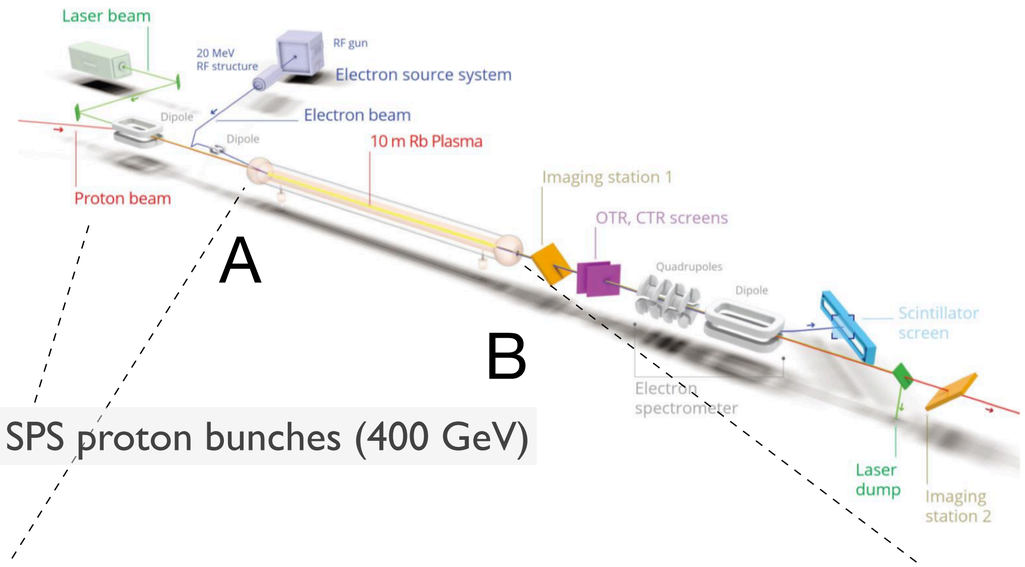
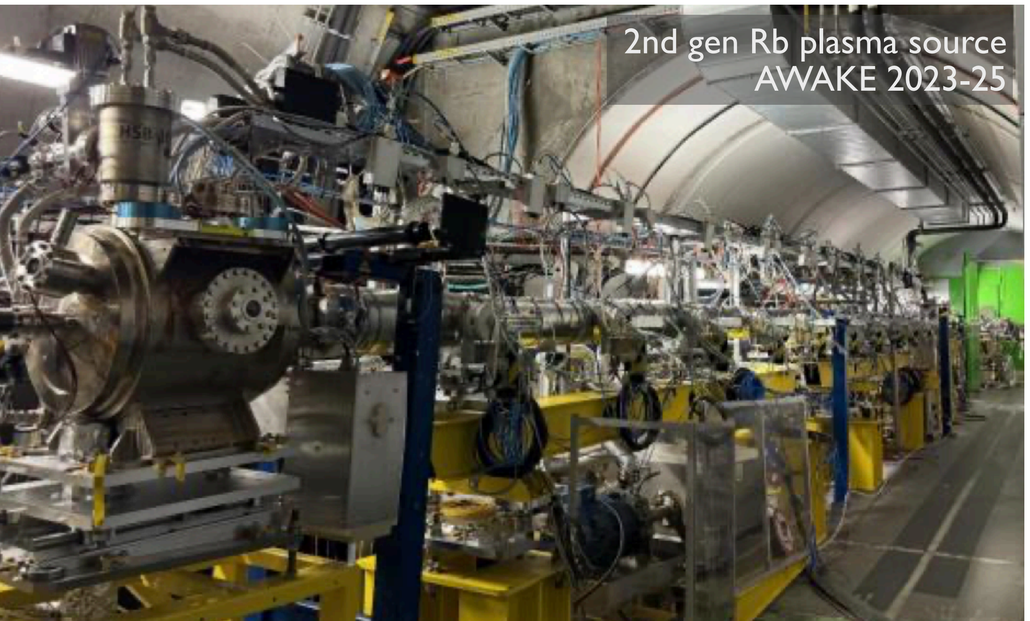
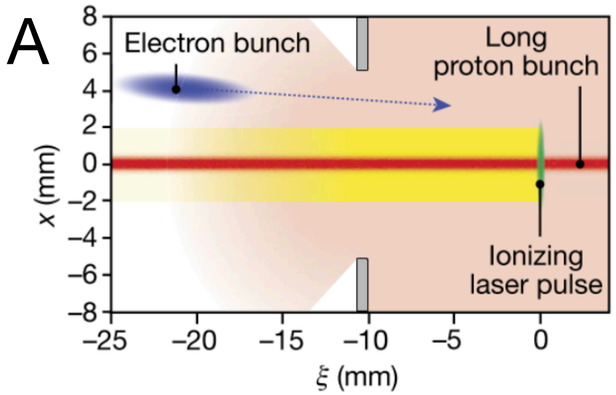


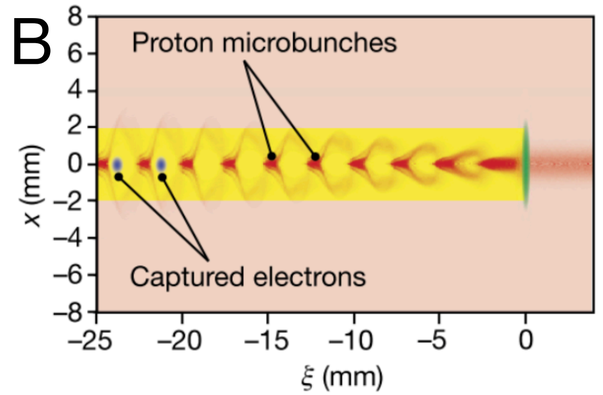
AWAKE: summary of runs 1 and 2 a-b, 2014-2025



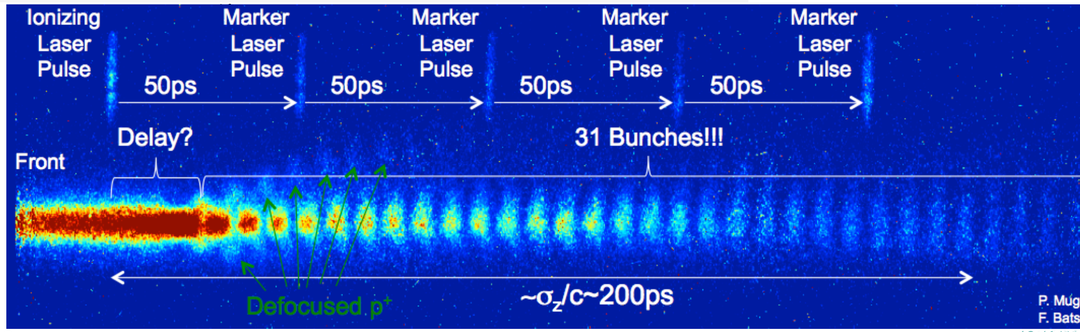
SPS proton bunches (400 GeV)







self-modulation (micro-bunching) of proton beam in dense plasmas
~ 0.1 m to ~ 1 mm

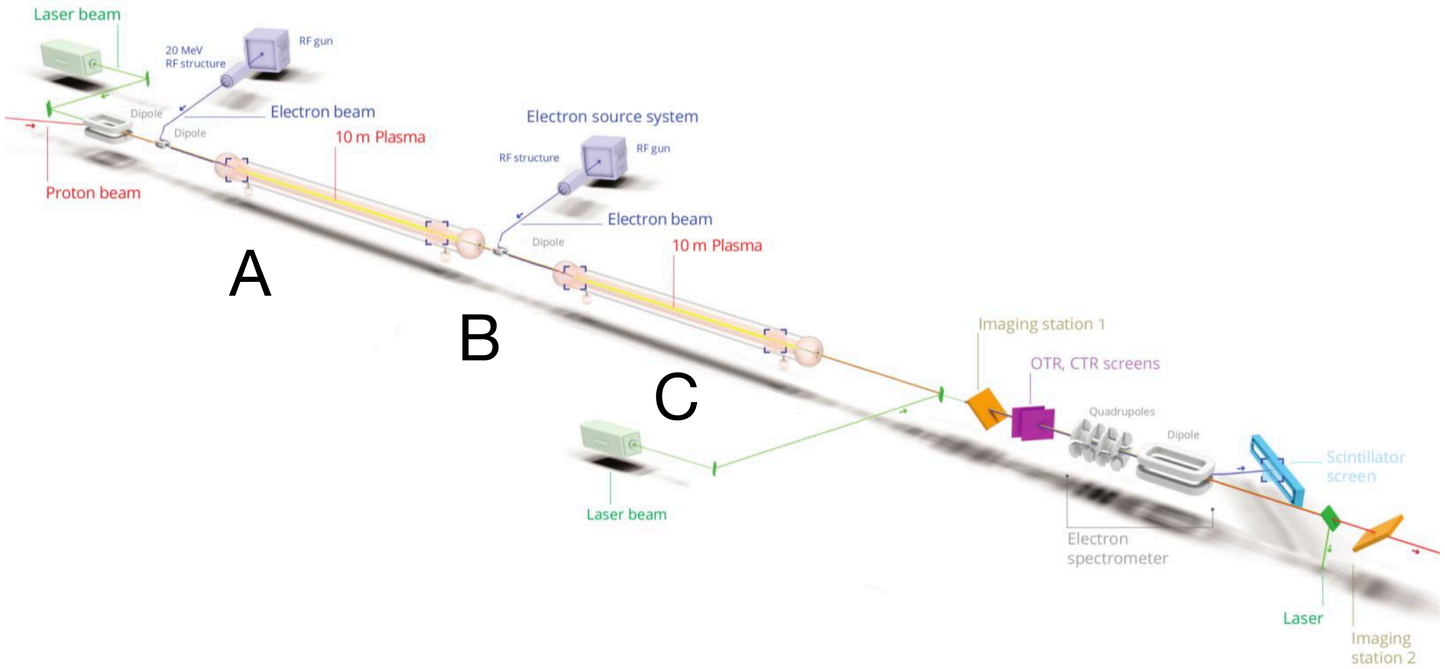


proton micro-bunch synchronisation w/ seeding laser pulse or electron bunch

plasma wakefield probing w/ crossing electron bunch
~ GV/m

effect of density step/gradient on wakefield (in progress)

AWAKE: runs 2c and 2d, > 2027 (in preparation)*



A - self-modulation plasma

B - e-bunch on-axis injection

C - acceleration plasma 10m (Run 2C) to 100 m (Run 2D)

* AWAKE status report (November 2024)
https://cds.cern.ch/record/2917426/files/SPSC-SR-356.pdf

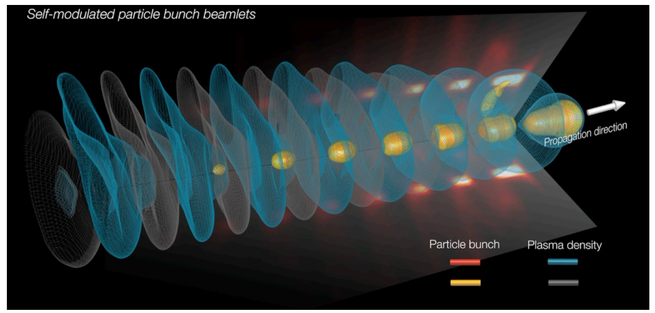
Beam quality
… new 150 MeV electron injector
… on-axis injection on SM proton beam

Acceleration efficiency
… SM plasma section with density step
… preservation of WF amplitude
… fine control of plasma density
… compact electron injection

Energy scalability
… use of length scalable plasma sources
… HPS plasma source
… DPS plasma source
… first readiness tests successful (April 2023)

Theoretical and computational contributions to AWAKE

Plasma accelerator modelling



Osiris 4.0

Most significant outcomes

One-to-one modeling of AWAKE

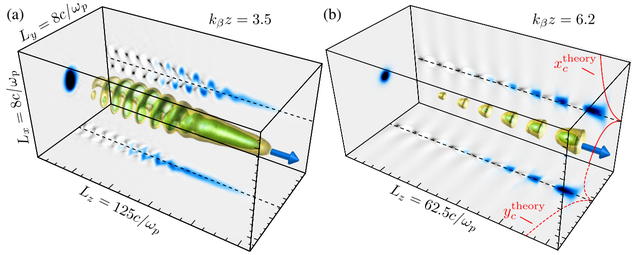
Prediction of acceleration capabilities

Identified conditions for stable propagation and acceleration

First simulations of long-term plasma (ion) dynamics

Theory and simulation support of on-going experiments

Proton driver stability in plasma



Unable Stable

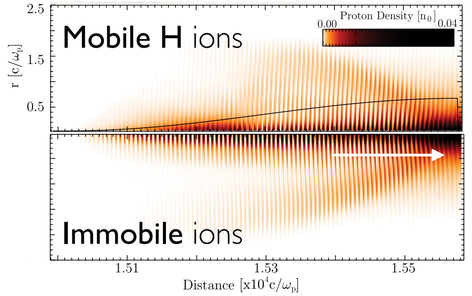
Identified conditions leading to **stable** acceleration over long propagation distances

BNS-like beam breakup supprrssion
J.Vieira et al PRL 112, 205001 (2014).

Novel beam breakup mitigation mechanisms
M. Moreira et al PRL 130, 115001 (2023)

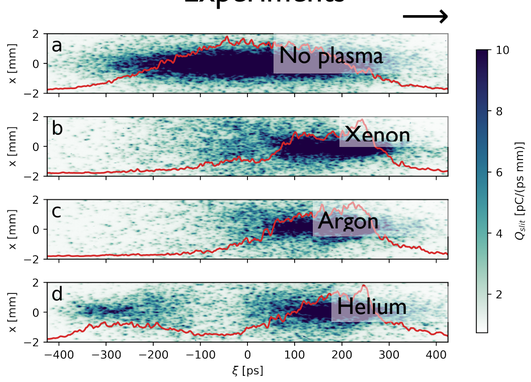
Long term plasma dynamics

Simulations



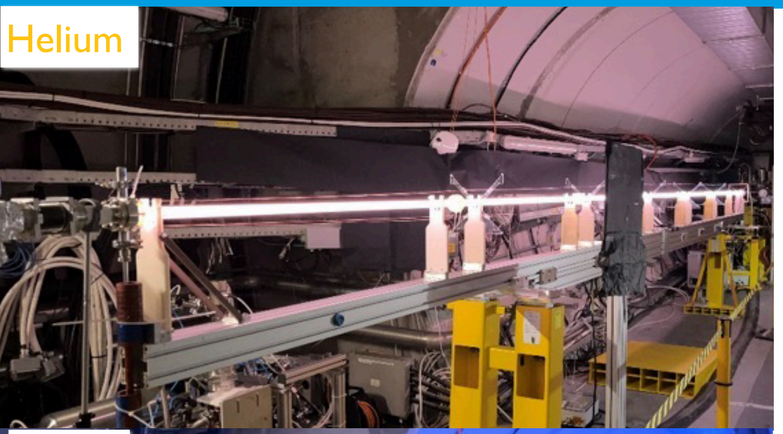
J.Vieira et al. PRL 109, 145005 (2012)

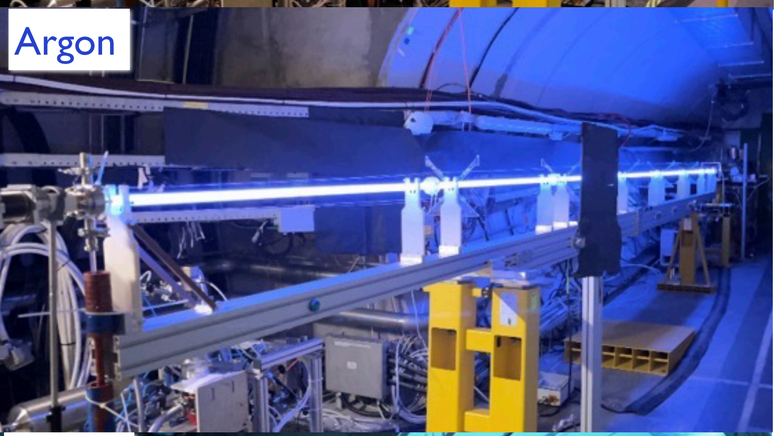
Experiments

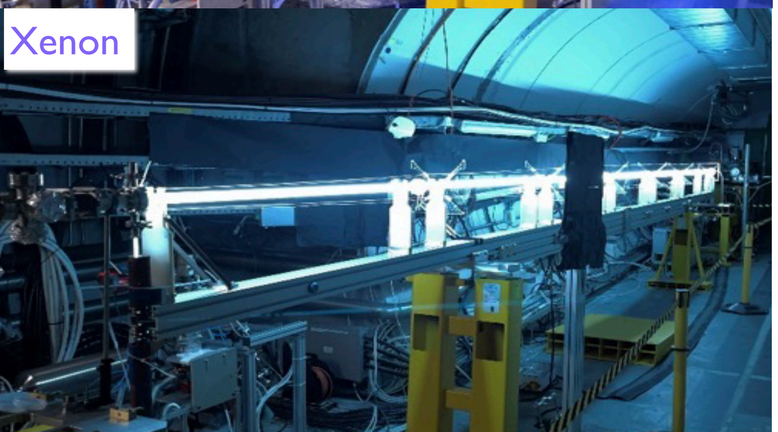


M.Turner et al. (AWAKE collaboration) submitted; arXiv 2406.16361v2 (2025).

Experiments and technology contributions to AWAKE







Direct current (DC) electric Discharge Plasma Source (DPS)

… efficient - ignition (H Voltage) + heating (H current) short pulses
… reduced ion motion - high Z gases (Argon and Xenon)
… uniform plasmas - 50 us shot pulses prevent plasma instabilities
… high ionisation fractions (up to 50%) with J ~ 100 A/cm^2
… 10 m single and double plasmas demonstrated
… plasma source operated in AWAKE (March-April 2023)
  … SMI and proton micro-bunching demonstration
  … plasma ion mass effect on wakefield
  … beam filamentation using DPS at high-density

Preparation for runs 2C and 2D in progress

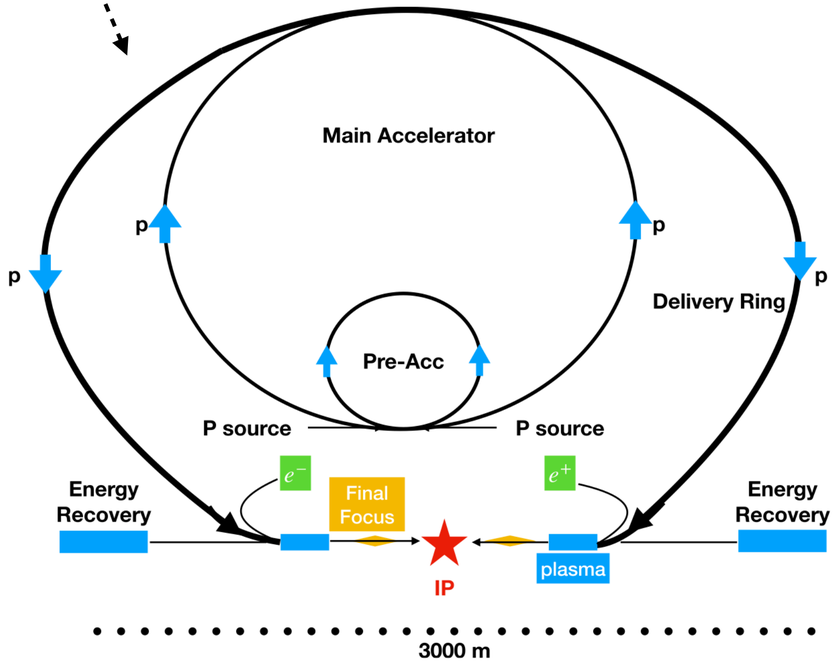
… reproducibility / uniformity from ~ 2.5% to ~ 0.25%
  … temp. controlled electronics, gas/vacuum and plasma tube
… plasma density matching with SM section
… very short gap electron injection
… length scalability to ~ 100 m (run 2D) using multiple plasma modules in series

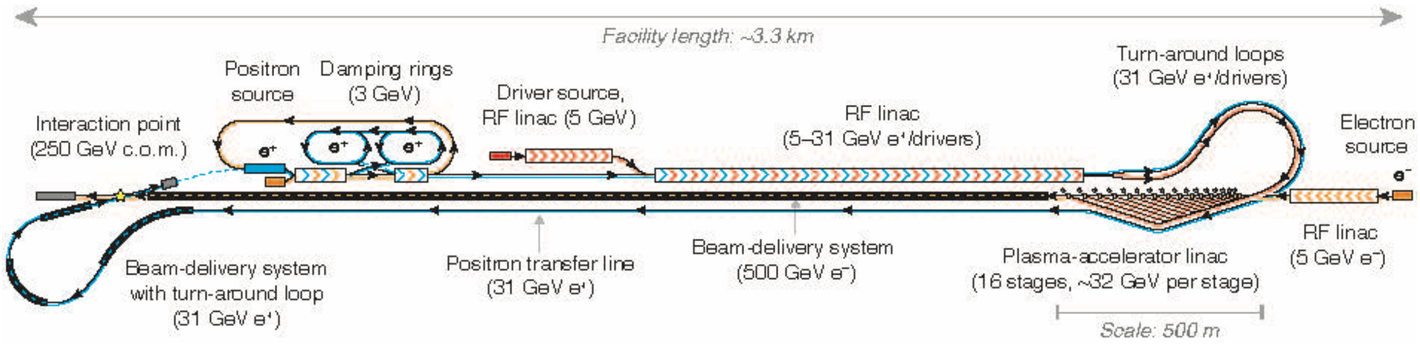
DSP future developments: towards a HEP accelerator

Plasma based accelerator applications under study:

HALHF - hybrid asymmetric linear Higgs factory[1]

ALIVE - … Higgs factory based on proton-driven plasma wakefield acceleration[2]





Both projects projected to use discharge based plasmas

ALIVE** (a follow up of AWAKE technology)

current baseline plasmas…

… Electron density ~ 10^{15} cm^{-3} (similar to AWAKE)

… Plasma length ~ 100 m to ~ km

… Plasma ion mass ~ Ar - Kr (similar to AWAKE)

… Repetition rate ~ 50 KHz (1M x AWAKE)

Work in progress to study long discharge plasmas…

… high repetition rate issues (plasma does not completely recombine)

… understand scaling of power losses

… power reduction with low(er) temperature alkali vapor DPS (Na,K,Rb)

… power loss reduction with solenoid field

… plasma modulation mitigation with bipolar discharge topology

1 B Foster et al 2023 New J. Phys. 25 093037
2 J Farmer et al 2024 New J. Phys. 26 113011