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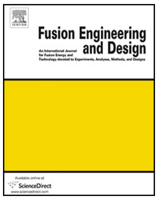

Neutral beam heating on the TCV tokamak

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ARTICLE INFO

Article history:
Received 13 September 2016
Received in revised form 24 January 2017
Accepted 20 February 2017
Available online xxx

Keywords:
TCV tokamak
Neutral beam heating
Upgrades

ABSTRACT

The TCV tokamak contributes to physics understanding in fusion reactor research by harnessing a wide experimental tool set: in particular flexible shaping and high power electron cyclotron heating. Plasma regimes with high plasma pressure, a wider range of temperature ratios and significant fast-ion population are now attainable with a TCV heating system upgrade. In a first stage, a 1 MW neutral beam was installed (2015) and is reported in this paper.

The installation of the NB injector required modifications of the vacuum vessel and considerable work on the machine infrastructure, resulting in a shutdown from late 2013 to mid-2015. TCV is now operating partly as a European Medium-Size Tokamak (MST) facility under the auspices of the EUROfusion consortium. The NBI was intensively operated in the February–July 2016 phase of the MST campaign. Record ion temperatures of 2.0–2.5 keV and toroidal rotation velocities up to 160 km/s were promptly attained in the first few L-mode discharges with NB injection. Ion temperatures up to 3.5 keV were subsequently achieved in ELMy H-mode. The injector produces a focused deuterium neutral beam with 25 keV energy, 1 MW neutral power and 2 s duration.

Highlights:

- Installation of 1 MW, 25 keV neutral beam, direct ion heating, access to $Ti/Te \geq 1$.
- Specific low divergence neutral beam injector with tunable power and energy.
- Ion temperature of 2.0 keV, toroidal rotation of 160 km/s attained with NB heating.

1. Introduction

The Tokamak à Configuration Variable (TCV, $R_O \cong 0.88$ m, $a \leq 0.25$ m, $B_T \leq 1.54$ T) [1] is characterised by the most extreme plasma shaping capability worldwide (plasma elongation κ up to 2.8, positive and negative triangularity $-0.7 \leq \delta \leq 1$), the highest microwave Electron Cyclotron (EC) power density in plasma, and a high degree of flexibility in its heating and control schemes. Main TCV missions [2] are to contribute to the physics basis for more efficient ITER exploitation, and optimisation of the tokamak concept, plasma scenarios, heating and control techniques for DEMO and beyond. This requires access to plasma regimes and configurations with high normalised plasma pressure and a wide range of electron/ion temperature ratios, covering $T_e/T_i \sim 1$. Implementation of preferential ion heating at the MW power level allows the extension of T_i/T_e to beyond unity and fills the gap between predominantly electron heated experiments and fusion reactor conditions.

A phased upgrade program [3] is underway on TCV, mainly consisting of adding ion heating (NB injectors), increasing the available electron heating power (X2 and X3 gyrotrons) and installing a

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http://dx.doi.org/10.1016/j.fusengdes.2017.02.076

Table 1
NBI characteristics.

NB injector reference scenario:	
NB power injected in TCV	1 MW
Nominal beam energy	25 keV
Max. NB pulse duration	2 s
Beam full energy fraction in power	≥ 70 %
NB operation domain:	
Beam power range	0.25…1.05 MW
Beam energy range	15…25 keV
Beam main species	D^o & H^o
Power sweep response (P/(dP/dt))	≤ 5 ms
Full power modulation on-time	5 ms…2 s
Minimal modulation off-time	5 ms
Modulation rise/fall time	≤ 0.5 ms
100% power modulation	up to 200 Hz

divertor structure with variable closure, equipped with gas valves, pumping units and magnetic field coils. A neutral beam injector (NBI), delivering 1 MW power along a tangential (double-pass) line of sight, at energies in the 15–25 keV range, was installed and commissioned, and provided research results in 2016. Two 750 kW, gyrotrons were also commissioned and integrated with three remaining first-generation 500 kW gyrotrons, providing a projected total of 3 MW X2 ECRH power. Two additional 1 MW dual-frequency (X2 and X3) gyrotrons and a second, 1 MW, 50–60 keV neutral beam are planned.

The ASTRA code was used to simulate the plasma response to combined neutral beam and EC heating in TCV geometry [4]. With the upgraded (1.5 → 3.5 MW) X3 EC system, NBH (1–2 MW) TCV could bring the plasma close to the β-limit in H-mode ($\beta_N \sim 2.8$, an important regime for ITER and DEMO), provide direct momentum input to the plasma, and generate a high fast ion fraction for studying wave-particle interaction phenomena of interest for burning plasmas. The $T_e/T_i \sim 1$ condition is already met with ~1 MW of NB power with 1 MW of X3 ECH. The T_e/T_i is expected to vary between 0.5 and 3.0 in TCV's high density (H-mode) confinement regimes.

2. Neutral beam injector

TCV's NBI installation was based on considerations of beam access, shine through and orbit losses [5]. A specific geometric arrangement of the NB injection with the beam line at mid plane oriented tangentially relative to the plasma axis was chosen to maximise heating efficiency whilst satisfying machine access limits.

The basic characteristics of TCV's NB system [5] are listed in Table 1. The 15–25 keV beam energy is safe with respect to orbit losses for $I_P \geq 250$ kA. The 0.25…1.05 MW power, tuneable during TCV discharges, enables studies of the plasma reaction to NBH power variation.

The neutral beam injector design is based on a development of the NBI for plasma heating at Budker INP [6]. The injector incorporates a standard positive ion source and elements shown in Fig. 1. An average nominal current density of 0.3 A/cm^2 was chosen for the ion source [5].

The plasma emitter is formed with up to 40 kW of inductively coupled RF power at ~4 MHz in the plasma box [6] (ceramic aluminium oxide chamber, 346 mm inner diameter 120 mm long, Fig. 2-A). A species mix with full, half and 1/3 of acceleration energy of 76:17:7 % (power ratios) was measured during the beam commissioning (see Fig. 3).

A high power focused neutral beam with small divergence was developed for the TCV device featuring narrow access ports where only small size, high power density beams can pass. The ballistic beam focusing is provided by spherically shaped multi-aperture electrodes in the ion optical system [7]. Slit apertures in the ion optical system reduce the focused beam width in the direction along the slits which is determined by the ion temperature of plasma emitter. 47 mm long slits with a step of 6 mm perpendicular to the slits are placed inside the 250 mm diameter area (Fig. 2-B). The total emission surface of the plasma grid is 224 cm^2, corresponding to a transparency of 46%.

The ion source is connected to the vacuum tank through a DN 400 gate valve and a 700 mm length neutraliser. Two cryo-pumps with total pumping speed of 3×10^5 l/s in molecular flow regime for deuterium gas, are used during beam formation. Each cryopump consists of 1.6 m^2 surface copper cryopanel cooled by two cold-heads (cooling capacity 2 × 1.5 W at 4.2 K) and a chevron 0.83 m^2

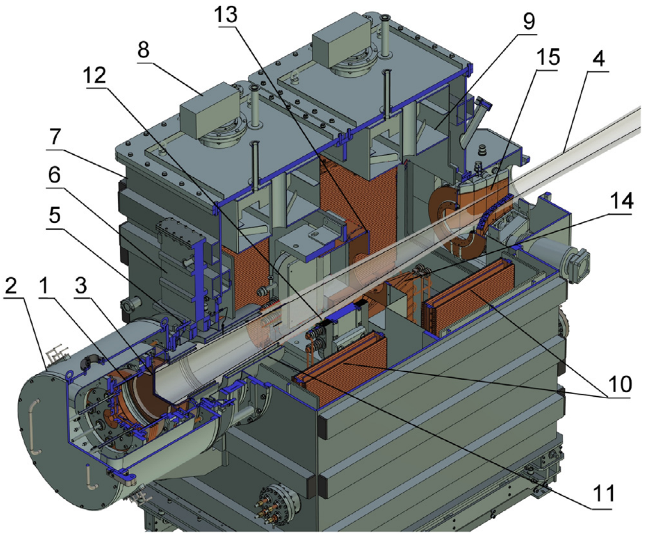

Fig. 1. Neutral beam injector: 1–RF plasma source, 2–magnetic screen, 3–ion-optical system, 4–neutral beam; 5–adjusting device; 6–ions source gate-valve; 7–vacuum tank; 8–cryopump cold head; 9–liquid nitrogen volume; 10–cryo-panels, 11–neutralizer, 12–bending magnet, 13–diaphragm, 14–ion dump for positive ions, 15–calorimeter.

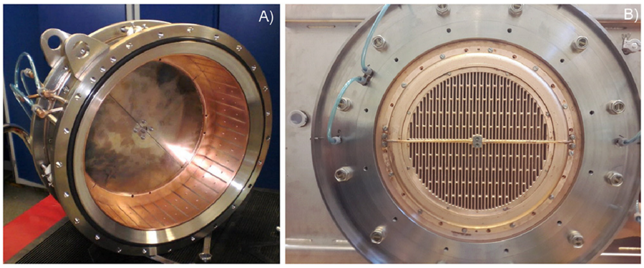

Fig. 2. NBI-TCV plasma box (A) and plasma grid (B).

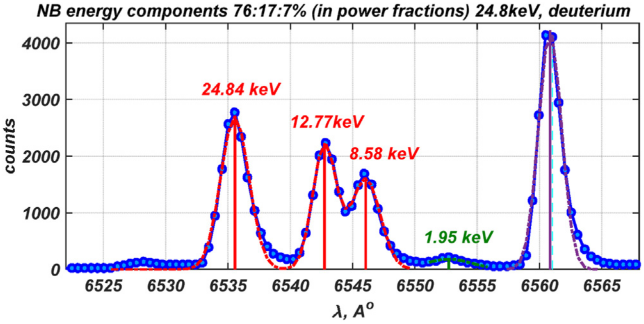

Fig. 3. Neutral beam energy components in power fractions.

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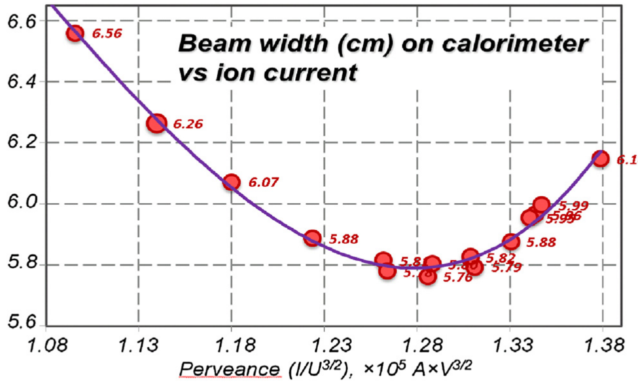

Fig. 4. Example of the perveance scan at 24.8 keV.

radiation shield with a transparency of 25%, cooled with liquid nitrogen.

Detectors for the beam alignment (aiming device) and the movable calorimeter are located at the exit of the vacuum tank. A retractable calorimeter can absorb the full duration (2 s) beam pulse at full power (1 MW).

Neutral beam operation is overseen by an instrumental computer (LCS) and electronic control modules integrated into the TCV plant control system. This system can handle a large variety of low-voltage analog and digital input/output signals. Protection and interlocks are implemented at the hardware level together with several status monitors and controls. All functions necessary for safe NBI operation are included in the LCS that is designed to protect itself from potentially dangerous external situations and commands.

A beam dump protection system is implemented on TCV to protect against overheat of beam facing elements in the area of beam-wall interaction. The combined RT processing beam inhibit signal generated by plasma disruption detector, a plasma density interlock and direct pyrometric measurements of beam dump surface temperatures are available to the NBI control system.

3. NBI optimisation and power control

NBI power control through the plasma discharge is a powerful tool in fusion plasma studies as gradual power ramps up/down permit the investigation of power thresholds for particular processes; e.g. transition between low and high confinement. The 100% ON-OFF pulse–width modulation is successful on JET [8] as the time taken to slow down NB fast ions in the plasma is relatively long (~100 ms) compared to the beam ON/OFF time (40 ms) and the plasma is therefore relatively insensitive to the modulation process. JET employs 16 independently controlled ion sources (PINIs) to provide time averaged power with a resolution smaller than an individual PINI increment (a similar technique is also used on ASDEX Upgrade). In smaller machines, with a small number of beam sources, a faster fast ion slow down and lower plasma confinement time (TCV, MAST), the plasma would respond strongly to beam modulation, so an alternative power modulation approach is required.

As beam divergence is dependent on both beam current and acceleration voltage (through the perveance), ramping the ion

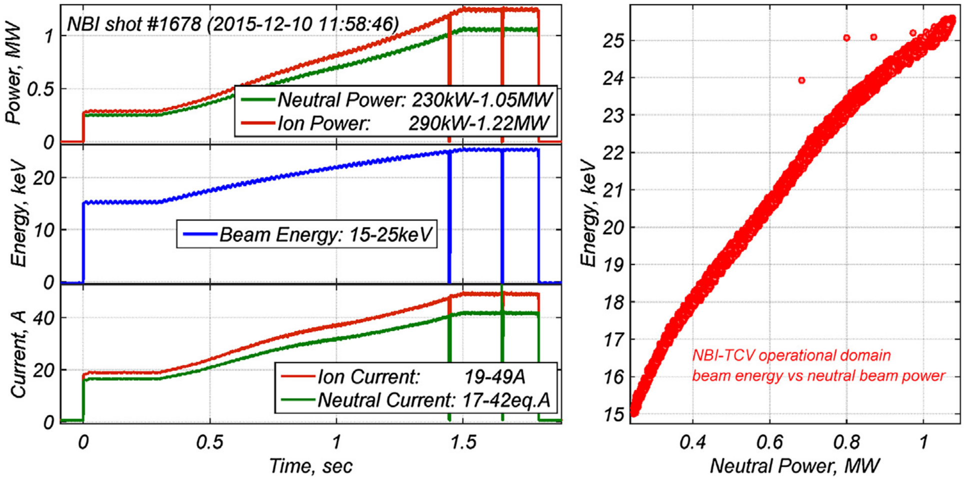

Fig. 5. "Slow" power sweep (0.23…1.05 MW) at minimal divergence.

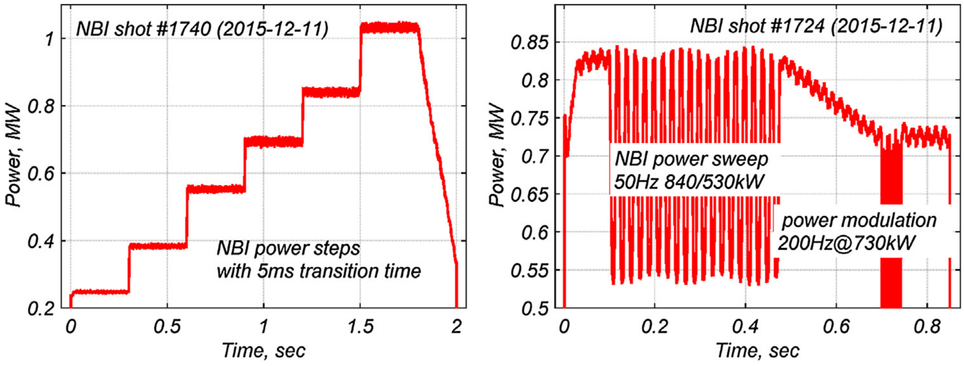

Fig. 6. NBI power steps and modulation during NBI commissioning on the TCV.

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beam current will affect the beam cross section, and beamline transmission. The real time control of an arc current of a high perveance MAST PINI allows variations of the neutral beam power by ∼20% with only minimal effect on the beam footprint [9].

A neutral power variation in the range of 0.25…1.0 MW has been implemented on TCV by simultaneous variation of RF power (plasma density in the RF box) and extraction voltage keeping a minimal beam divergence (optimal perveance). The optimisation procedure for the TCV NBI was performed at several (4–6) extraction energies; the optimal beam currents (RF power levels) were experimentally adjusted to minimise the beam divergence; here, minimal divergence (perveance scans) corresponds a minimum of the beam width on the calorimeter (Fig. 4). The voltage on the suppression (2nd) grid and the bending magnet current were also optimised at each power/energy level.

The desired neutral beam power vs time waveform ($P_0(t)$) is designed in Matlab. The binary beam ON/OFF, beam energy, neutral and ion currents time traces are calculated accounting for their dependencies on $P_0(t)$ in order to retain a minimal footprint beam width. The digital and analog control waveforms are calculated, transmitted to the LabView LCS program, and uploaded in the FPGA memory of PCIe LCS cards. Following trigger reception, the beam pulse control sequence is executed, and analog and digital control waveforms are transmitted to NBI power supplies. Examples of the TCV-NBI pulses with power variation and modulation are shown in Figs. 5 and 6.

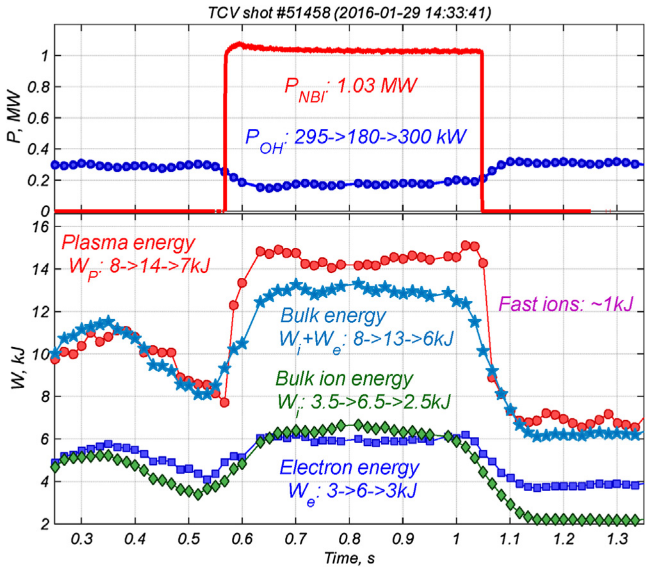

Fig. 7. Global parameters of the TCV plasma with NB heating in L-mode, TCV shot 51458, 5th NBI shot in plasma.

4. First shots with NB heating on the TCV

First experiments with NBH (Figs. 7 and 8) demonstrate a core plasma ion temperature in L-mode increasing from about 600–800 eV (typical in TCV at high density in Ohmic plasmas) to ∼2 keV, in agreement with ASTRA predictions. The plasma rotation with 1 MW NB injection reaches 150–180 km/s (CO-NBI direction), while the typical values for spontaneous intrinsic rotation without NBI are less than 30 km/s.

The heating neutral beam was intensively used in TCV experiments during the period of February-July 2016, mostly in the MST1 (European Medium-Size Tokamak) experimental program of the EUROfusion consortium. More of 60% (20 of 33) MST1 experiments used NB heating. ∼25% of TCV discharges (579 shots) used NB injection into plasma during this period. Beam availability was 85–90%, with most (7–10%) faults in NB injection in TCV related to problems with NBI control electronics and power supplies. The total energy delivered by the NBI into TCV was limited to ¼ (0.5 MJ) of the design

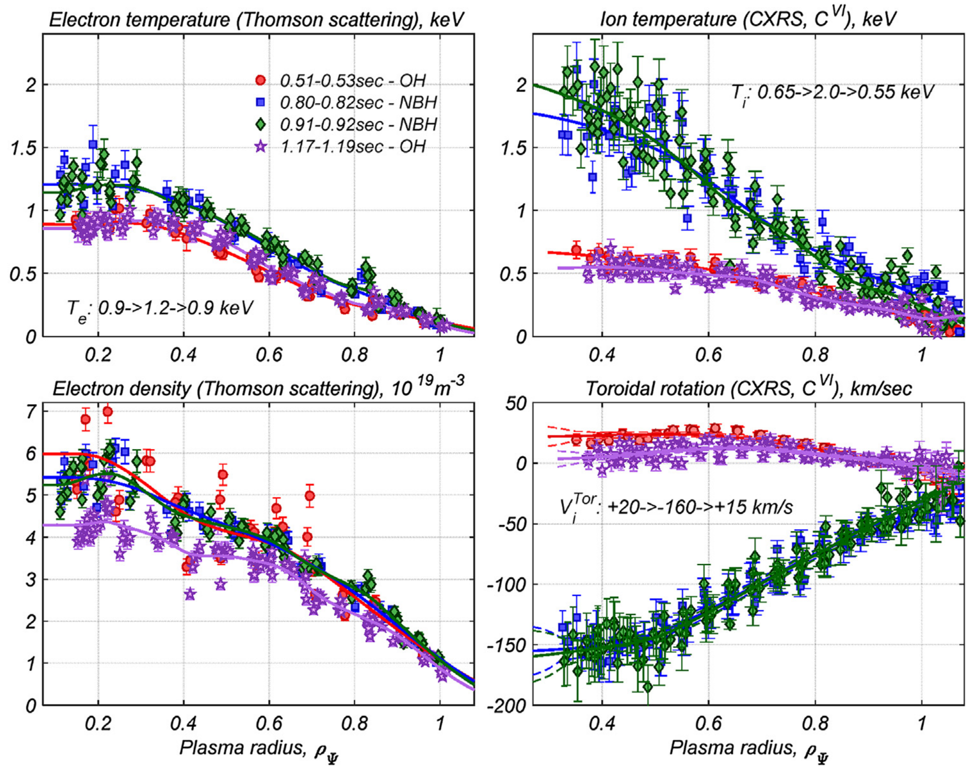

Fig. 8. Plasma radial profiles with and without NBI in L-mode; TCV shot 51458.

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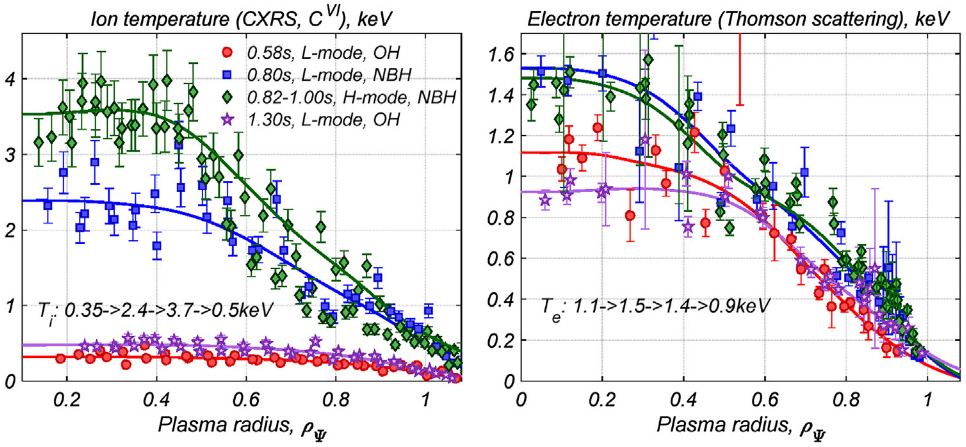

Fig. 9. Ion and electron temperature profiles in the ELMy H-mode discharge, TCV shot #53362.

value (1 MW, 2 s) due to non-optimal angular characteristics (divergence or/and focal length) of the beam compared to the beam duct, and the subsequent overheating that this provoked. Resolution of this problem is ongoing and will include a modification of the beam duct and improved ion optics (grids).

The TCV record ion temperature of 3.7 keV (Fig. 9) was achieved in the MST1 high confinement ELMy H-mode experiments. NB injection on TCV facilitates H-mode access, changes sawtooth and ELM frequencies, and provides a significant (up to 70 kA) plasma current drive.

With the installation of the first 1 MW neutral beam TCV has greatly extended the range of accessible plasma parameters that are highly relevant to tokamak fundamental physics and machine operation studies and will strongly contribute to the ITER and DEMO projects.

Acknowledgments

The authors are very grateful to Manfred Sauer (ex. Inst. fur Plasmaphys., Forschungszentrum Julich GmbH) for participation in the NBI installation and commissioning on TCV, to Dr. David L. Keeling and Tim Robinson (EURATOM/CCFE Fusion Association, Culham Science Centre) for useful discussions and help with NBI operation during the EUROfusion MST1 campaign, to members of SPC-EPFL and Budker INP teams involved in the work on manufacturing, installation, commissioning and operation of heating beam.

This work was supported in part by the Swiss National Science Foundation. This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

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