Role of NBI ion sources in achieving the world record fusion energy at JET

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& the JET team

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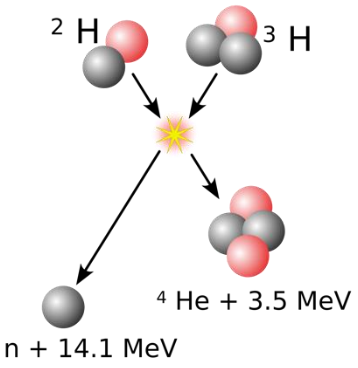
UK Atomic Energy Authority

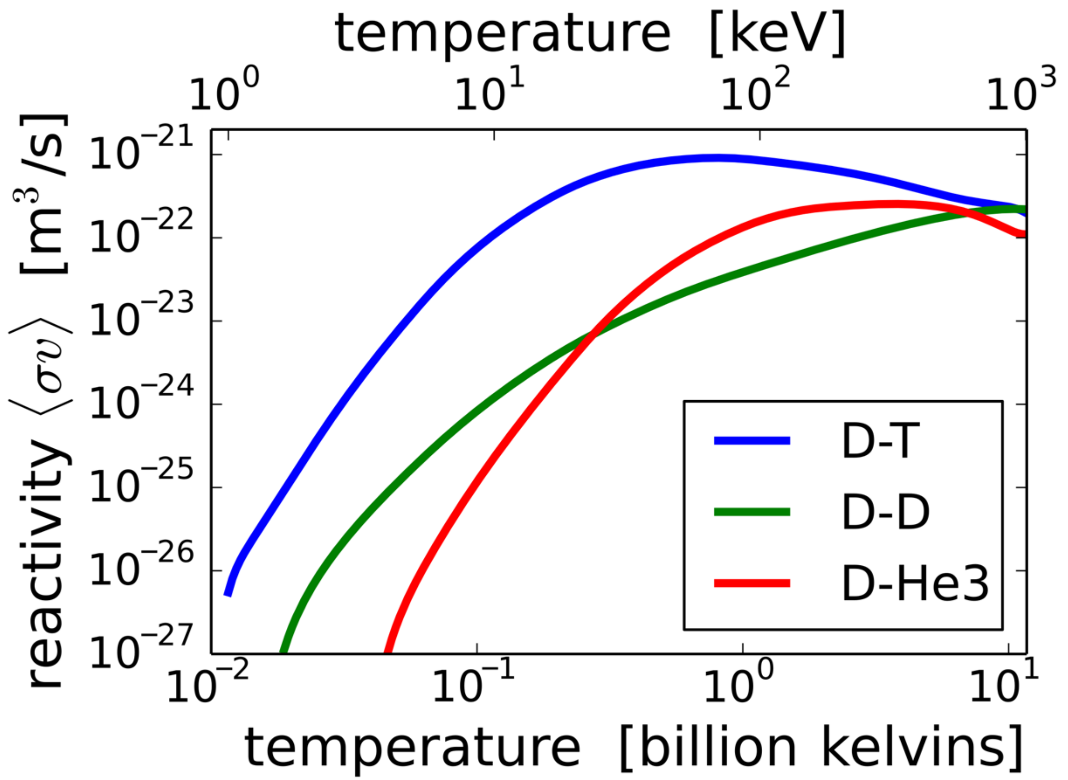
Nuclear fusion, tokamaks & JET

Nuclear Fusion & JET

JET



- Nuclear fusion is the process of light nuclei fusing to form heavier ones and releasing energy
- Research into nuclear fusion for energy has been continuing for decades with the promise of clean & plentiful energy



- Typically, fusion research has focused on isotopes of hydrogen
- Even for the 'easiest' fusion reaction of D-T the temperature of the nuclei must be very high
- Hence the need for experiments involving high temperature plasmas

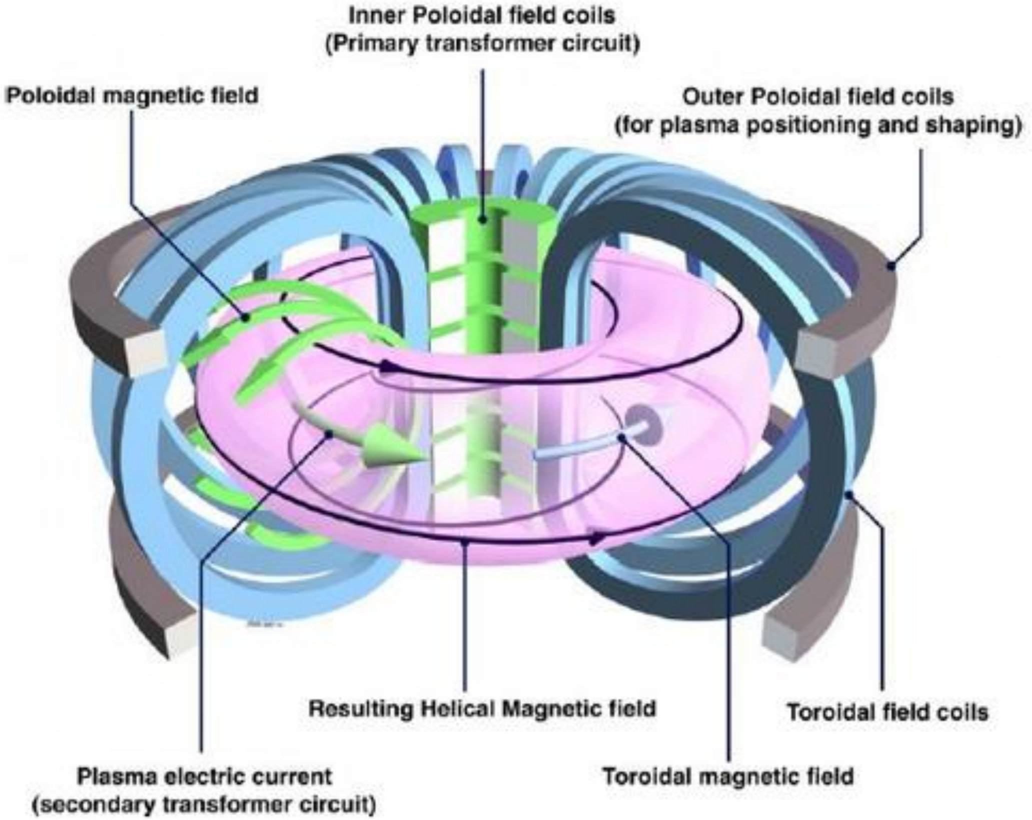
Nuclear Fusion & JET

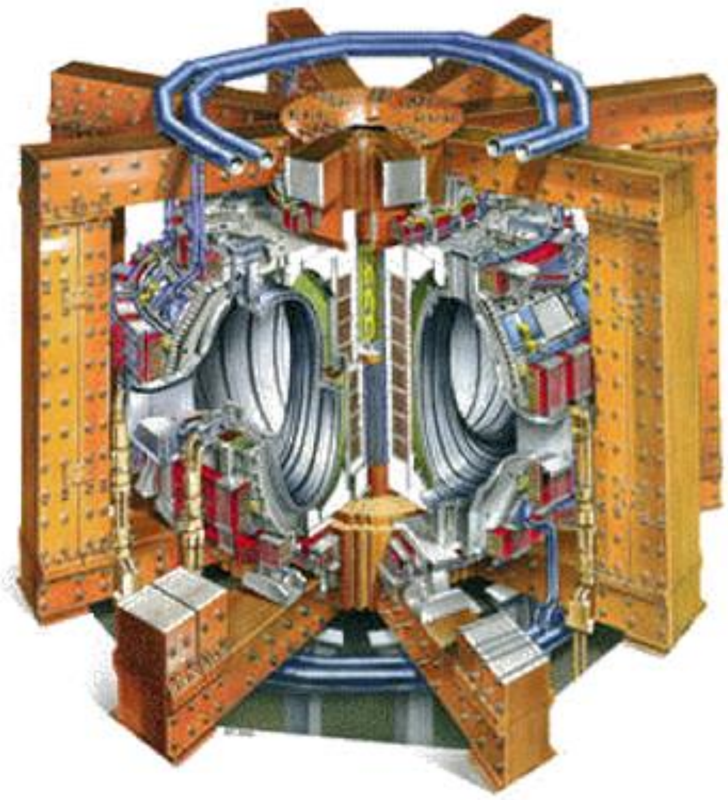
JET

- Research into plasmas for fusion has taken many routes

- The use of toroidal and poloidal magnetic fields to confine the plasma showed promise and the first tokamak was built in 1954 in the Soviet Union.

- Numerous tokamaks were built, culminating in the Joint European Torus (JET), which began operating in the 1980s





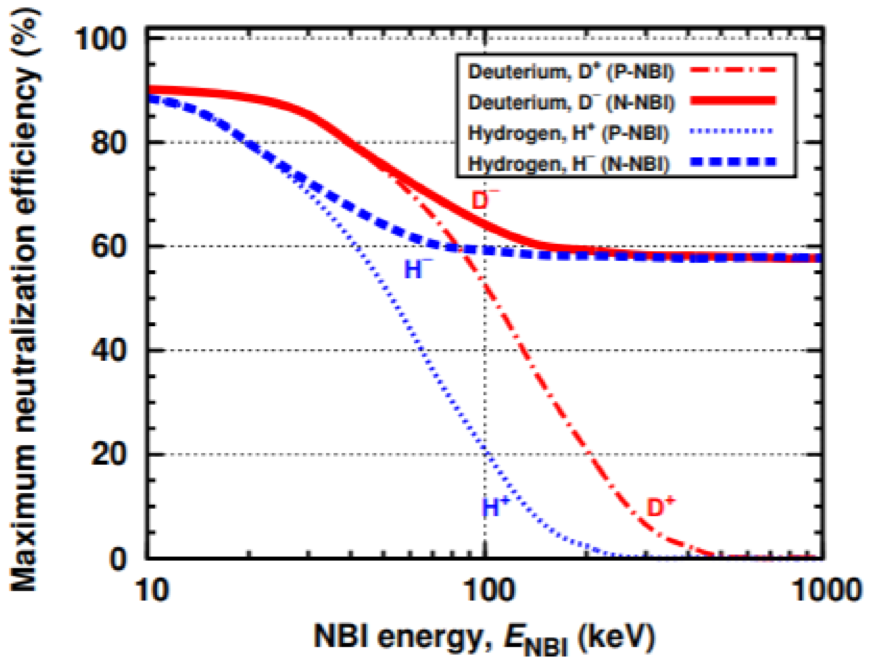
Neutral Beam Injection (NBI) for fusion

NBI for magnetic confinement fusion devices

JET

- Heat the plasma, drive current and plasma rotation, measure plasma parameters
  - neutral to penetrate the tokamak magnetic field, ionised by ion or electron impact
  - ionisation or charge exchange, transfer energy to plasma by Coulomb collisions
  - generated from positive or negative ions
  - Pros: well established technology for positive ion NBI, powerful heating method, flexible
  - injection geometry, efficient coupling to plasma up to high densities
  - Cons: low wall-plug efficiency, expensive, big nuclear island

- Types of ion sources
  - Filament driven arc discharge
    - - e.g. JET and MAST-U NBI
  - Radio Frequency driven discharge
    - e.g. ITER and AUG NBI
  - choice of positive or negative ions dictated by
  - energy needed to penetrate the plasma core



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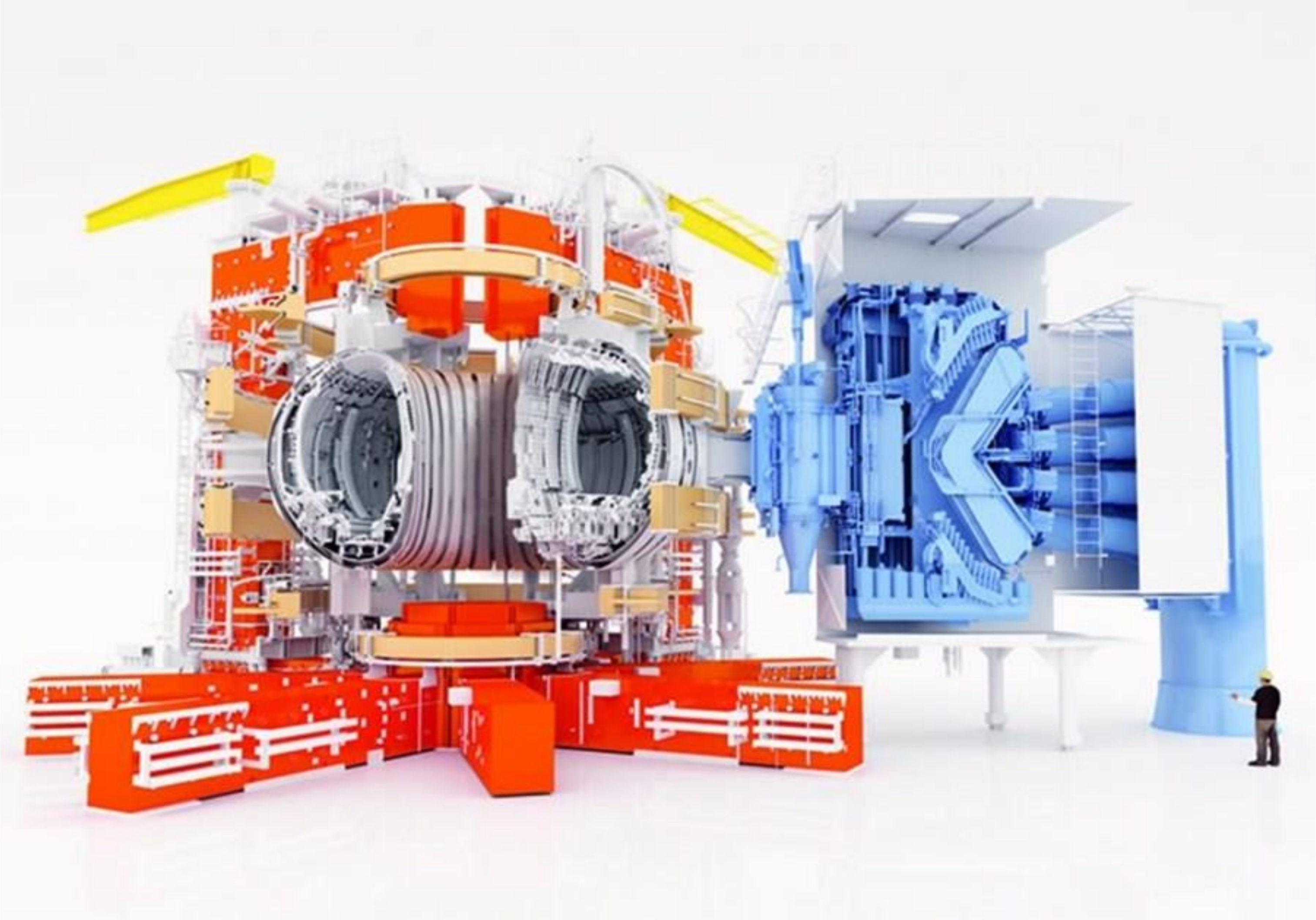
NBI on JET



There are two Neutral Injector Boxes (NIBs) on the JET tokamak.

Each NIB can be equipped with 8 Positive Ion Neutral Injectors (PINIs) (125kV/65A in deuterium).

This gives 2.0-2.3MW per PINI

JET PINIs can operate in hydrogen, deuterium, tritium and helium.

Eight PINIs on each NIB are grouped into two banks of four:

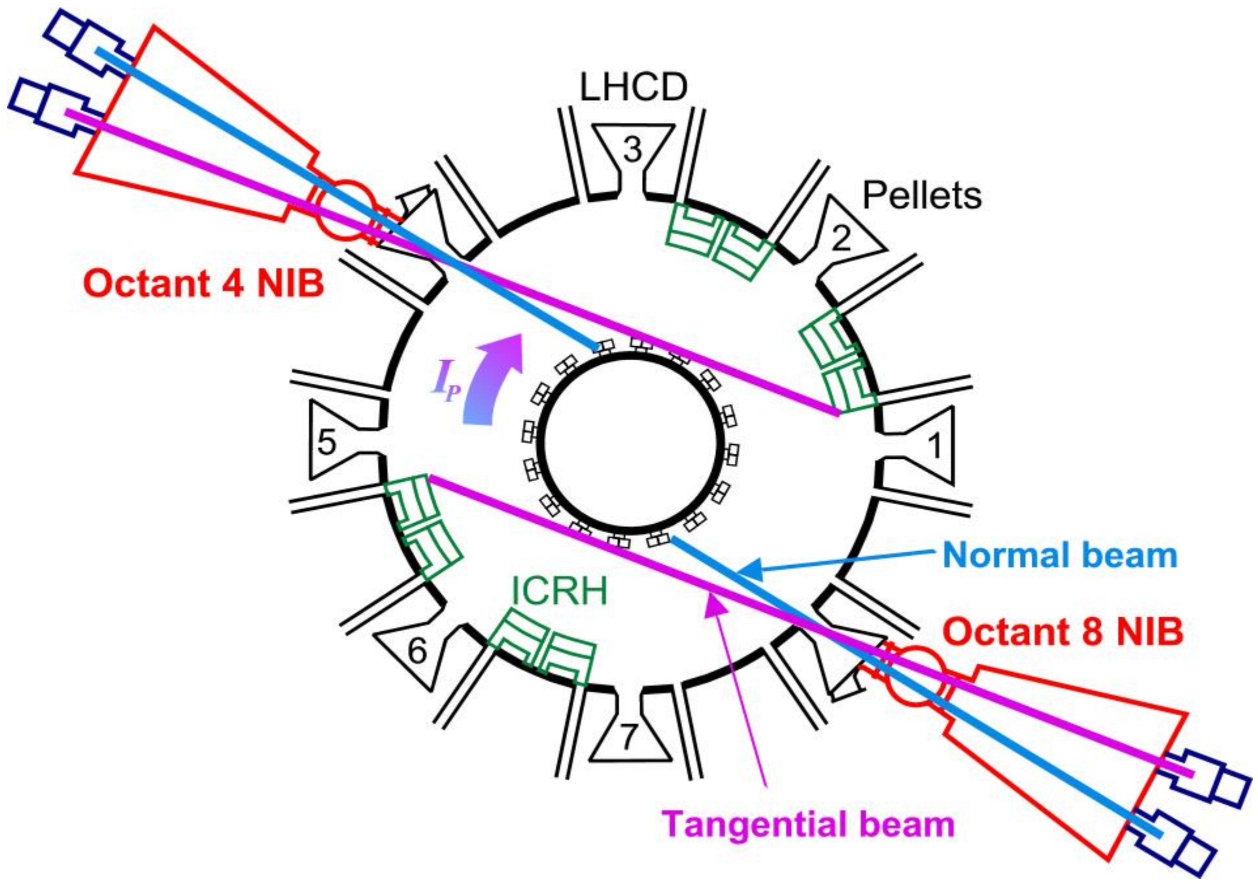
Tangential bank (R_T=1.85m): two passes through the plasma.

Normal bank (R_T=1.31m): one pass through the plasma.

PINIs and beamline components are designed for up to 20s pulse duration.

NBI on JET

JET



Layout of the JET heating systems.

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PINIs and beamline components are designed for up to **20s pulse duration**.

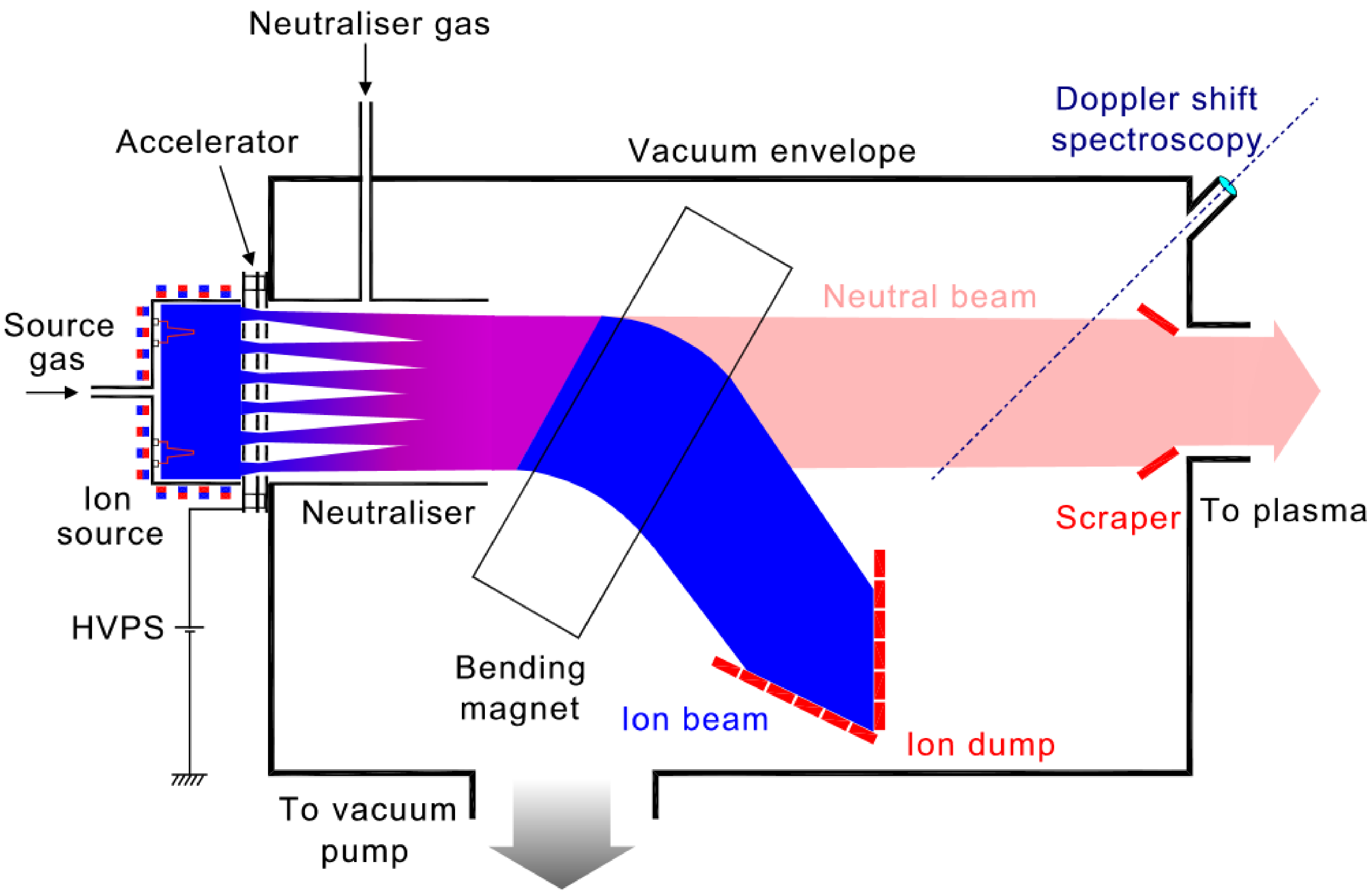
Note that wave heating via ICRH on JET also essential for success

Design of the JET NBI system

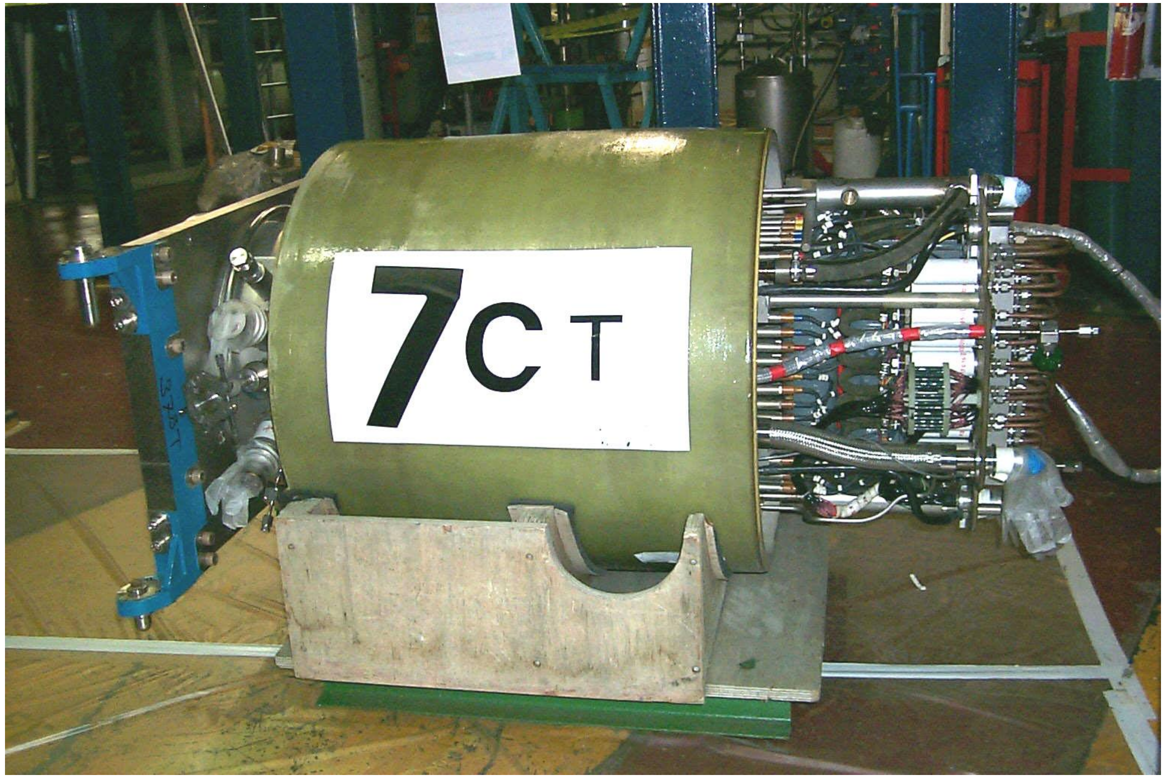
Neutral Beam Injection principle

JET

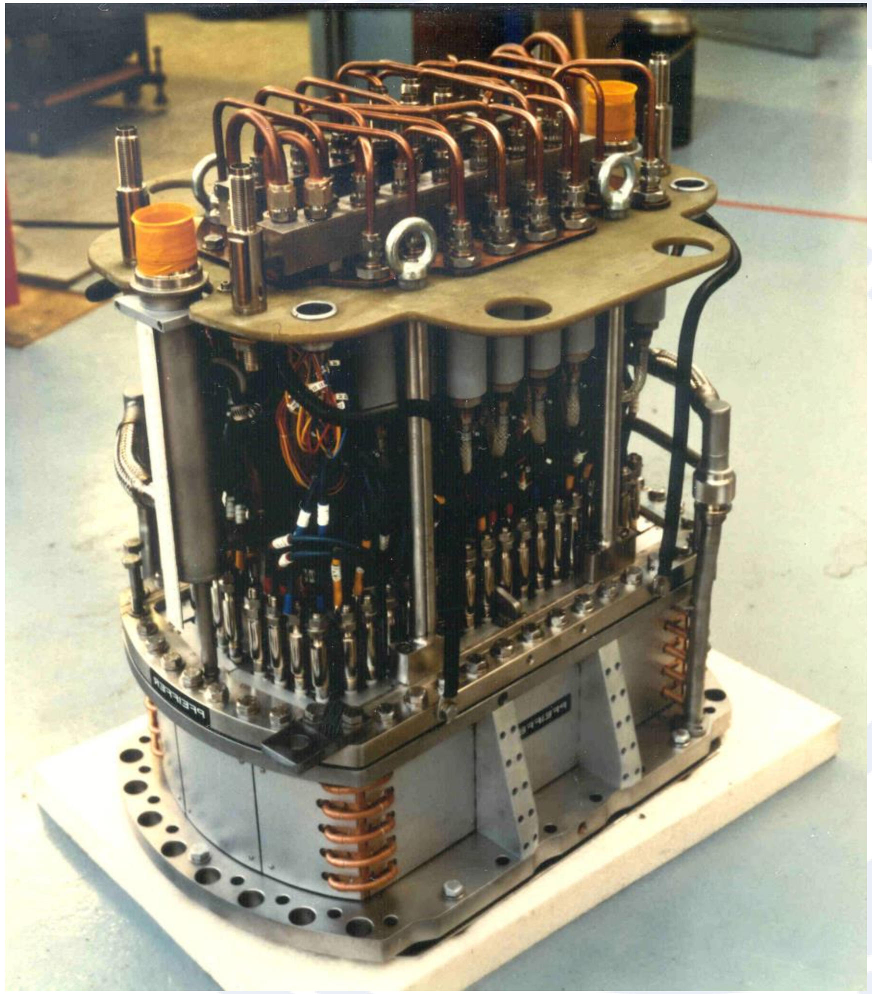
- The heating beam must be energetic & powerful to cause heating & penetrate plasma
- It must also be neutral to pass through the magnetic field of the tokamak
- To achieve this an ion source (RF or filament) and accelerator are used with the addition of a gas-cell neutraliser
- Power limited by fundamental neutralisation process



NBI Principles – Ion Source



JET Positive Ion Neutral Injector - PINI



PINI ion source.

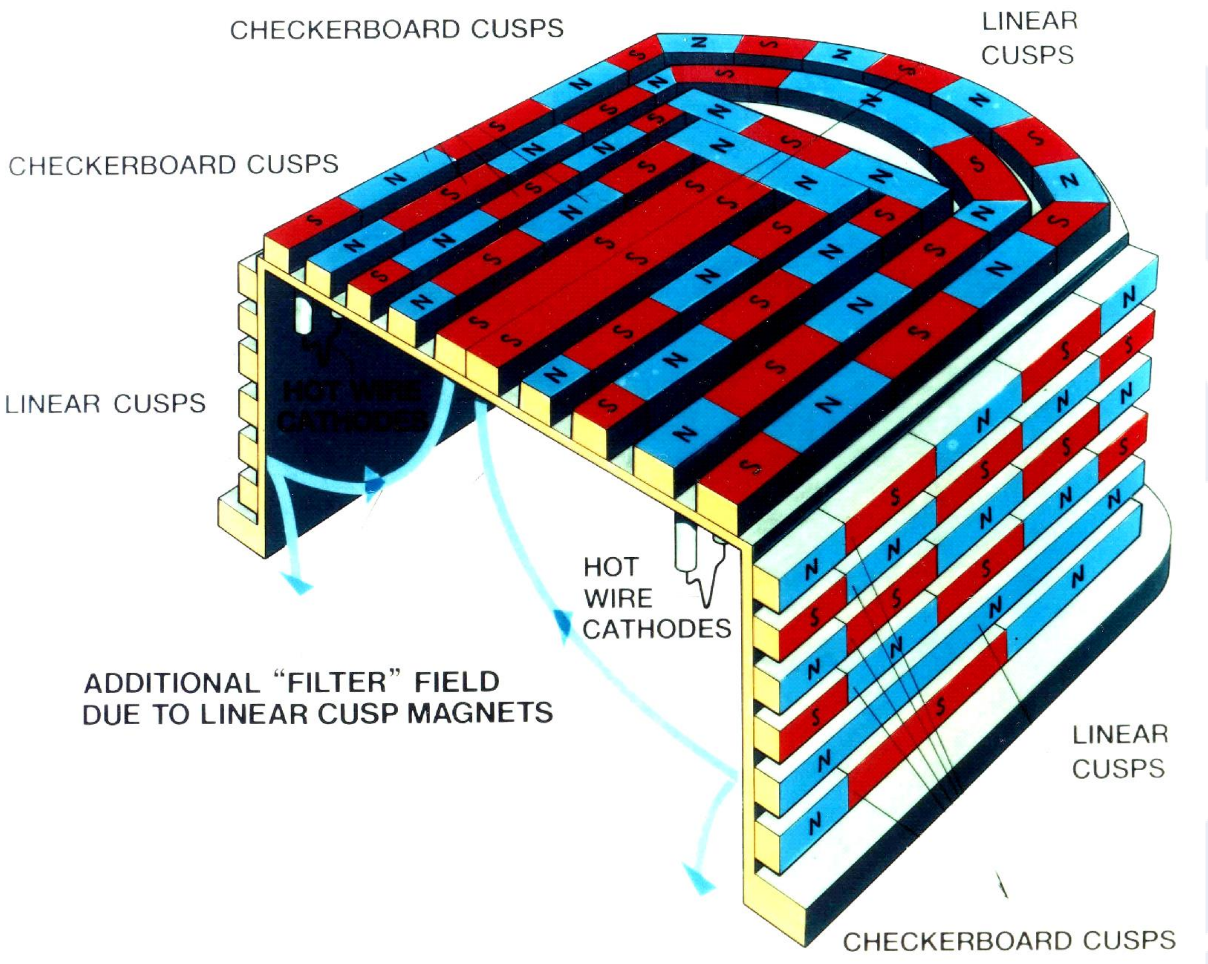
NBI Principles – Ion Source

JET

- Hot-Filament arc discharge
- Magnetic confinement using permanent magnets in chequerboard configuration
- Ions created by various electron-molecule and ion-molecule collisions.
- Typical ion source parameters
  - Primary electron energy (V_{arc}): ~ 100eV
  - Arc Current: < 1500A
  - Gas Flow: 12 mbar.l/s on PINI and 30mbarl/s on neutraliser (increased in 2016)
  - Gas Pressure: ~10^{-3} mbar
- Parameters determined by ion source (fixed magnetic configuration and gas flow)

  Arc Efficiency: Ibeam/Iarc

  Ion Species Fractions: H^+:H_2^+:H_3^+



Magnetic configuration of the JET supercusp ion source

NB – final design used chequerboard to enhance molecular fractions, increase neutralisation and improve transmission

NBI Principles – Accelerator

JET

Various configurations have been used on JET over the decades, both **Triodes** and **Tetrodes**

Deceleration grid (G3) protects the ion source from back-streaming electrons

JET PINI has 262 apertures and two grid halves vertically focused

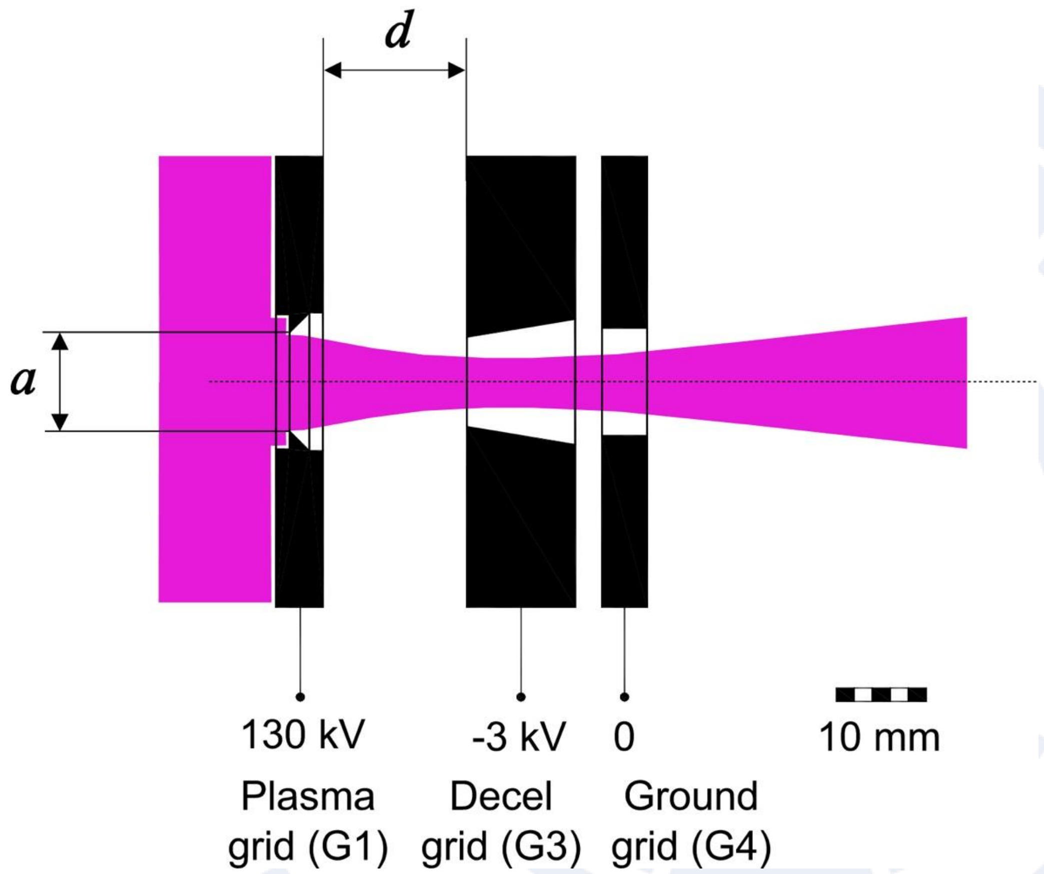
Optimum perveance:
(minimum divergence)

$$\Pi_0 = \frac{I_0}{V^{3/2}} \propto \frac{1}{\sqrt{M_{eff}}} \left(\frac{a}{d}\right)^2$$

I_0 is beam current at minimum divergence

For final PINIs in deuterium optimum perveance is ~ 1.2μP

Minimum divergence: $\theta_0 = 0.3^o$ (He)
$\theta_0 = 0.55^o$ (D_2)
$\theta_0 = 0.9^o$ (H_2)



Geometry of the triode accelerator.

Numerous upgrades & configuration changes over decades

NBI Principles – Accelerator

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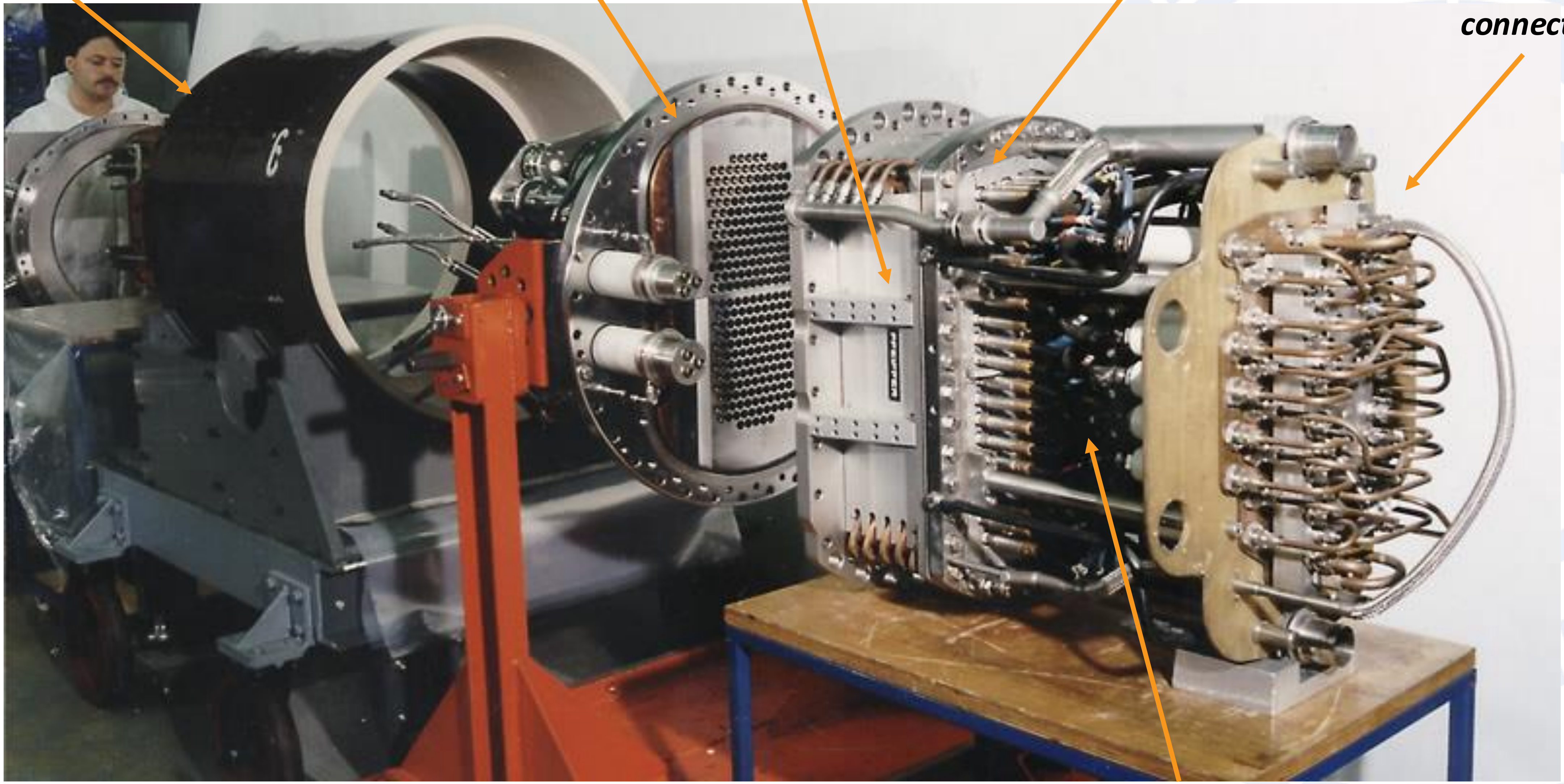
For existing PINIs in deuterium optimum perveance is ~ 1.2

Minimum divergence: $\theta_0 = 0.3^o$ (He)

$\theta_0 = 0.55^o$ (D_2)

$\theta_0 = 0.9^o$ (H_2)

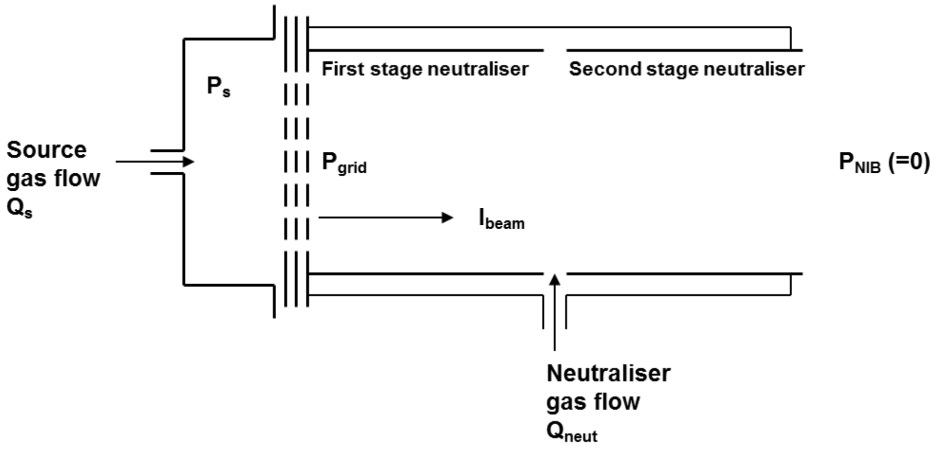
JET PINI


Ceramic insulator
Multi-aperture (262) and multi-grid accelerator (4) with variable offset
Ion source
Backplate with 24 filaments feedthroughs
Water and electrical connections
Filament transformer and arc load resistors

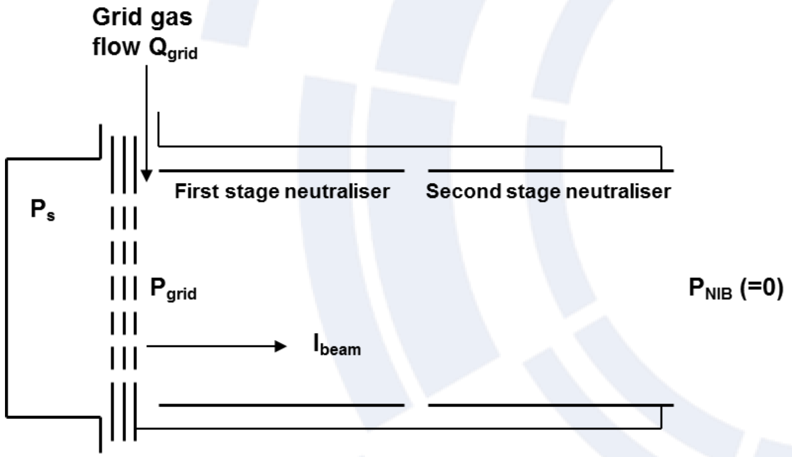
Using Tritium in the NBI System

JET

- The PINIs used on JET were adapted to be compatible with tritium
- It was possible to generate tritium beams
- However, the gas source had to adapt to accommodate this* causing HV conditioning to be more difficult



Normal gas introduction



Grid gas introduction

*due to double-containment requirements and the insulators used for the ion source feed

History of D-T fusion experiments & JET NBI

JET Lifetime, Major Upgrades and Tritium Operation

JOINT EUROPEAN TORUS JET

Assembly, maintenance, commissioning, operation and scientific exploitation carried out by the **JET Joint Undertaking** under the supervision of JET Scientific Council.

EFDA JET / EUROfusion — Scientific exploitation and machine upgrades

UK Atomic Energy Authority — Personnel safety, machine maintenance, upgrades, commissioning and operation

European Commission

Start of JET operations
First plasma

Divertor,
In-vessel coils
In-vessel cryopump

Metal wall (Be/W)
Wall protection
NBI power upgrade

1980	1	2	3	4	5	6	7	8	9	**1990**	1	2	3	4	5	6	7	8	9	**2000**	1	2	3	4	5	6	7	8	9	**2010**	1	2	3	4	5	6	7	8	9	**2020**	1	2	3	4

First DT experiment (PTE)

DT experiment (DTE1)

Trace tritium experiment (TTE)

100% tritium and DTE2 experiments

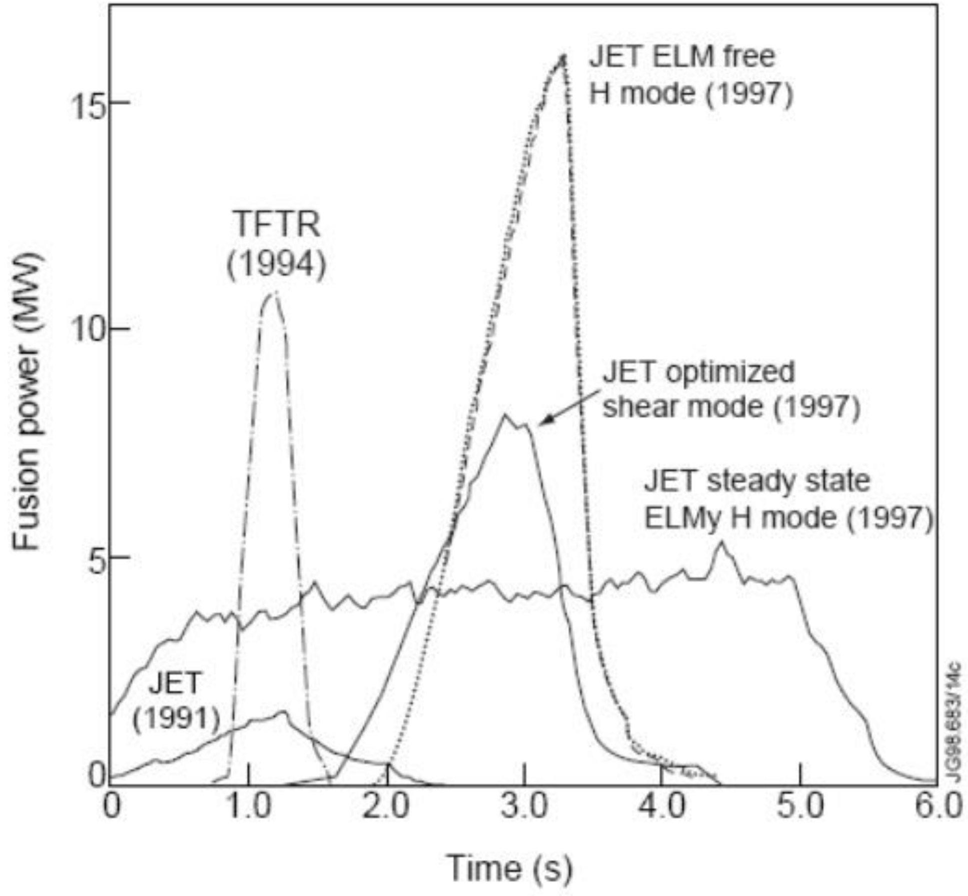
DTE3 experiments

6 years **6 years** **18 years** **2 years**

D-T Experiments in the 1990s

JET

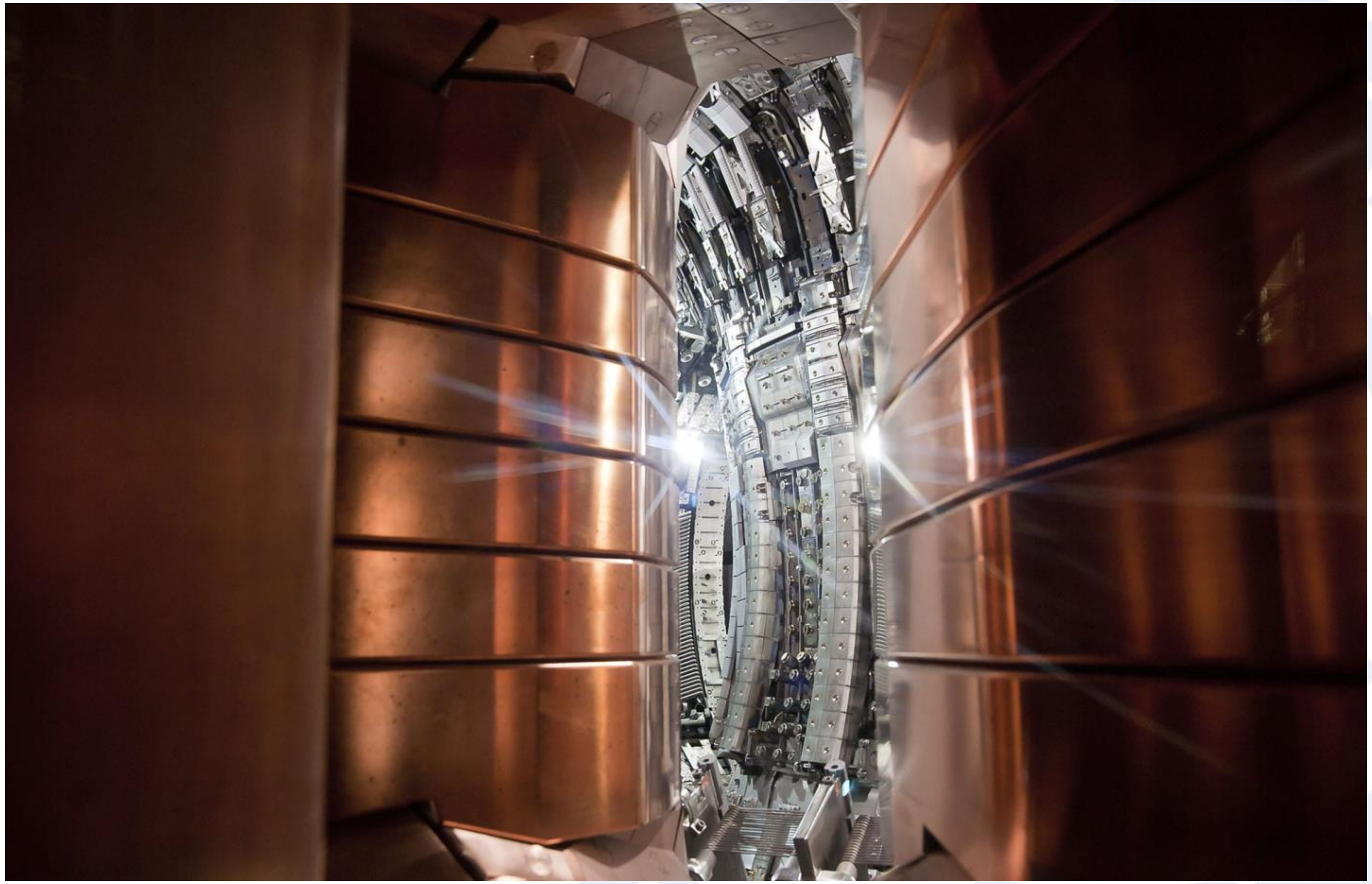
- Two tokamaks were pursuing D-T fusion in the 1990s
- JET and the TFTR experiment in Princeton
- JET achieved the first use of tritium in 1991 with a short test using tritium NBI
- JET then held the peak and sustained fusion power record from 1997 onwards



NBI Progression

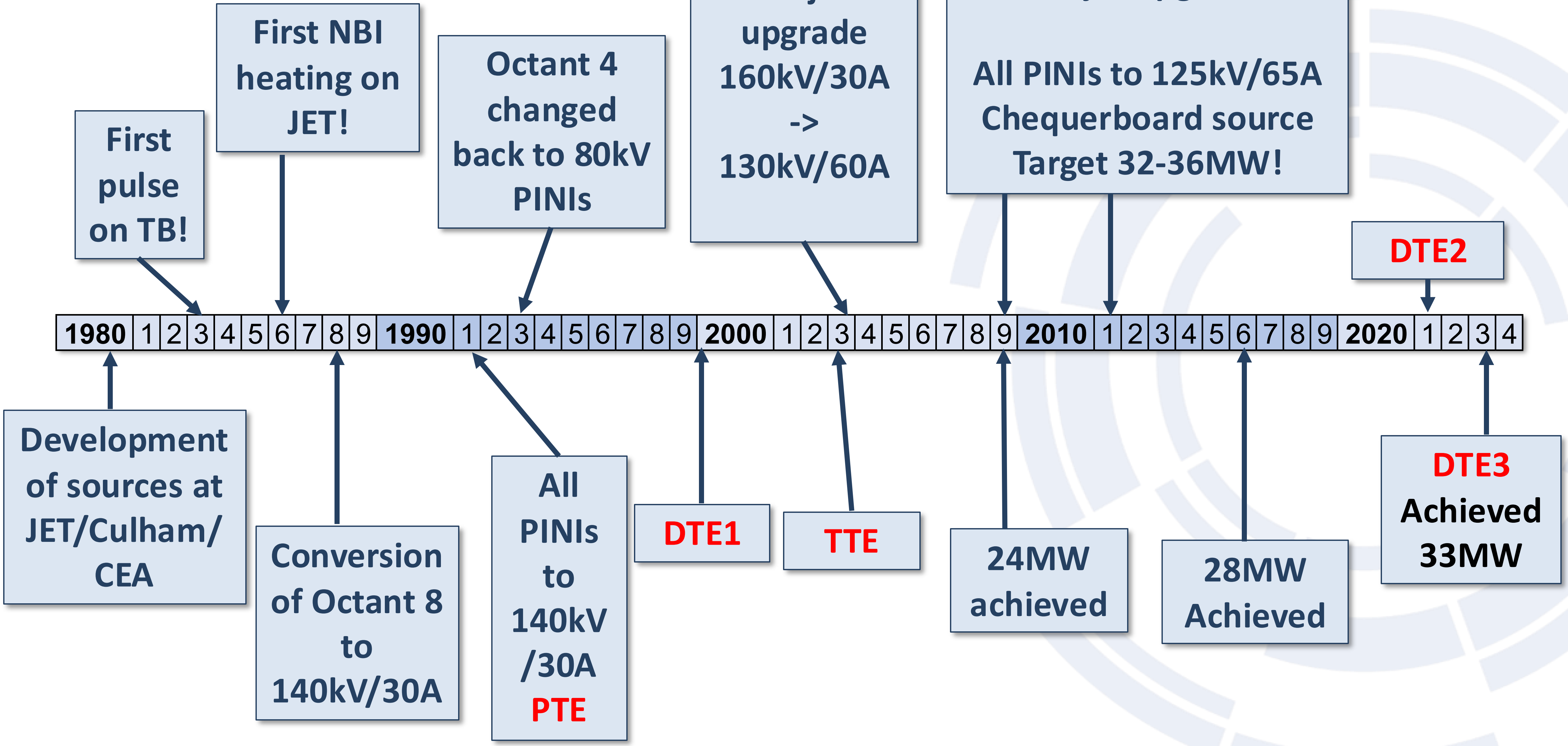
JET

- Over 40 years there were many changes to the NBI system
- Numerous repairs needed
- Upgrades from the original 16MW installed were carried out
- Most significant in 2009 with new PINIs, beamline components & power supplies



JET NBI Progression

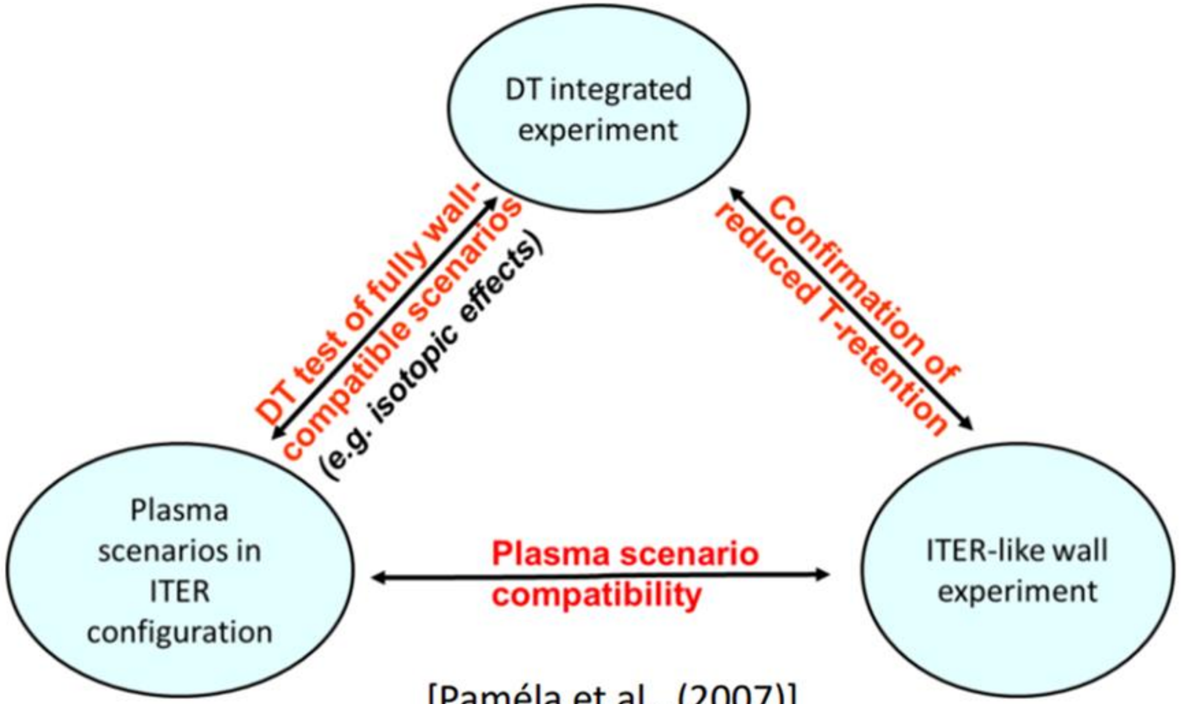
JET



Achieving high NBI power

D-T experiments with a Metallic Wall

- JET with a metallic (Be & W), ITER-like Wall (ILW) project key part of Europe's support to ITER
- Main goals:
  - Confirm reduced fuel retention
  - Assess compatibility of W with ITER relevant scenarios
  - Demonstrate D-T integrated operation
  + Give new generation of scientists, operators and engineers D-T operations experience

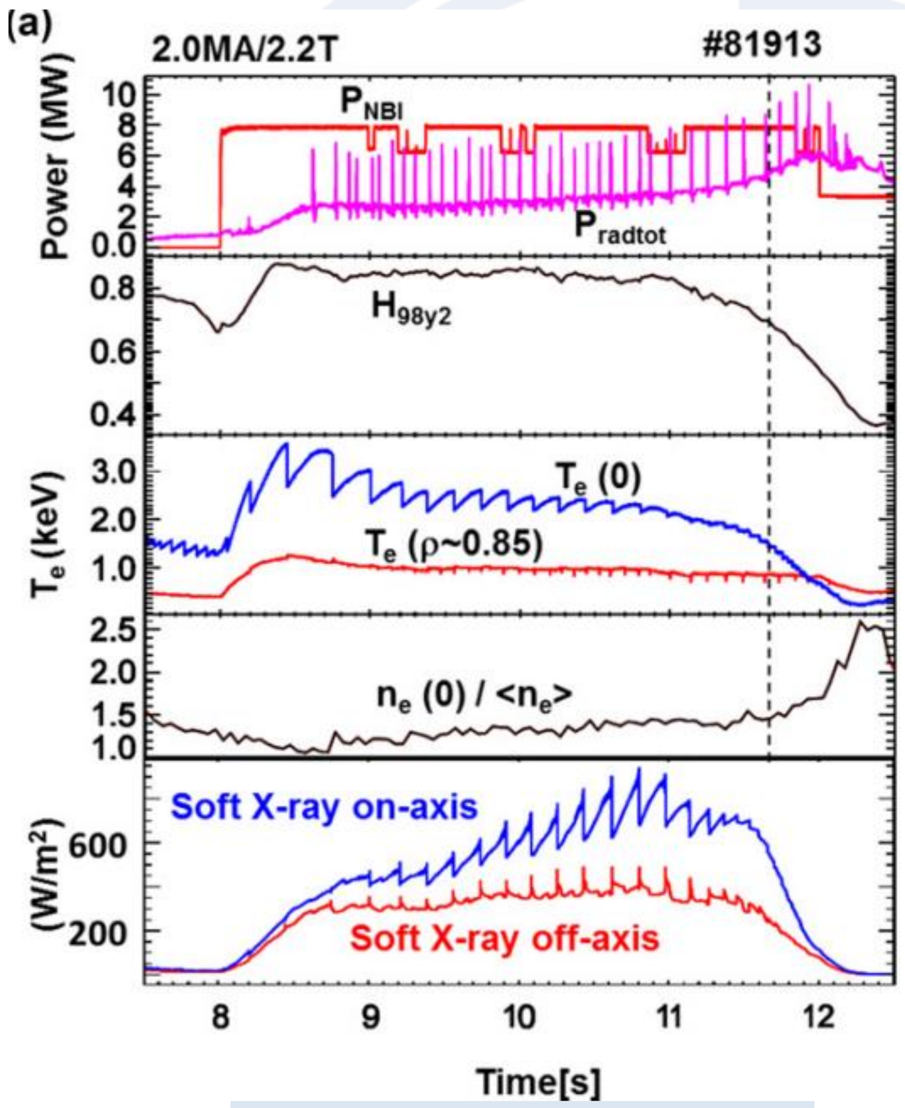


[Paméla et al., (2007)]

Clear to the team that this would require high NBI Power

Plasma operation in JET-ILW challenging due to W

- **In the first campaigns with the metallic wall it was a challenge to recover the previous performance**
- **The tungsten would accumulate in the plasma and lead to excess radiative power lost from the plasma**
- **This would lead to cooling of the plasma and in some cases abrupt termination of the pulse**
- **Increased heating power and the development of improved plasma scenarios was required**

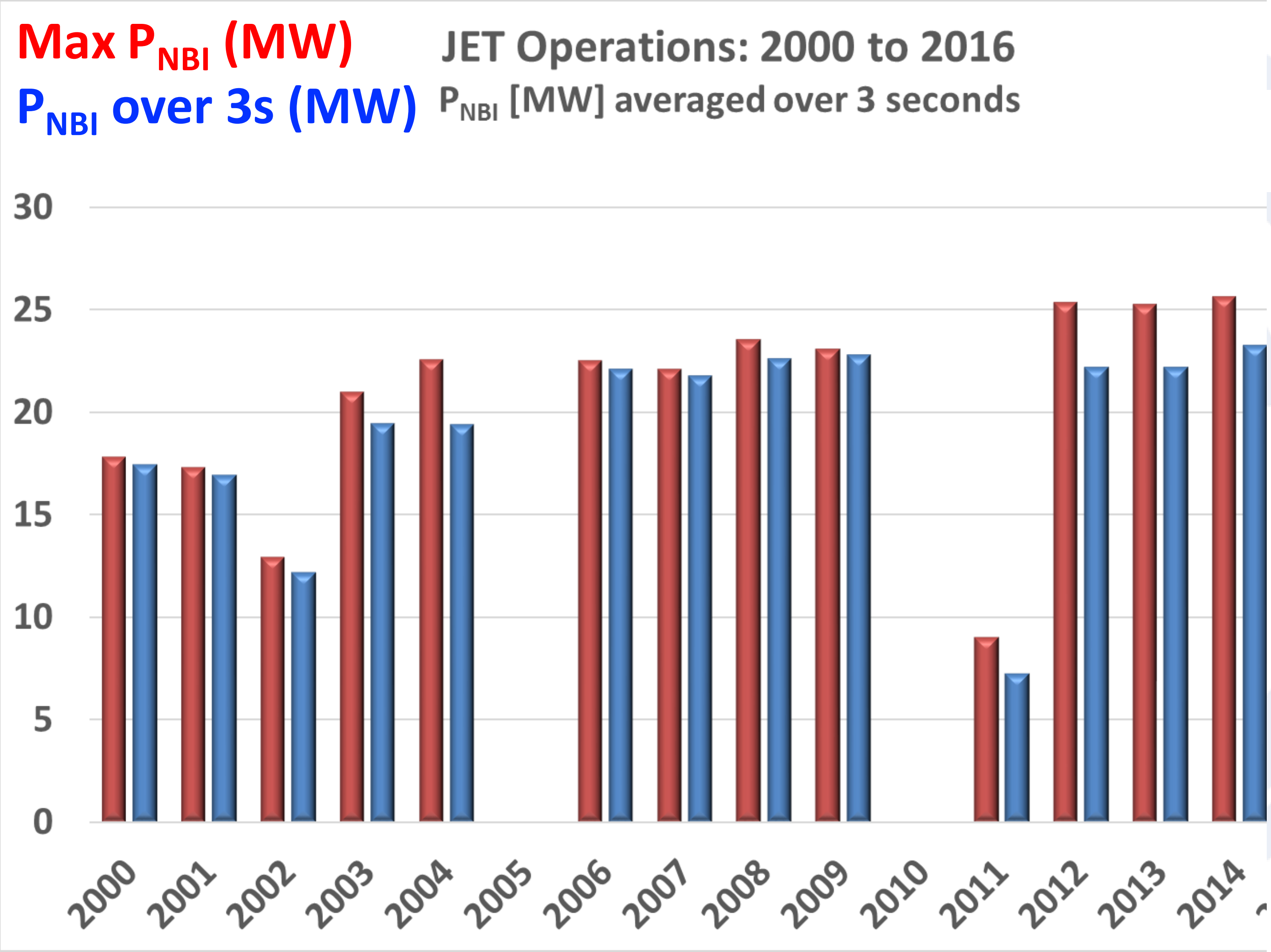


E. Joffrin et al. NF 54 (2014) 013011

NBI Power

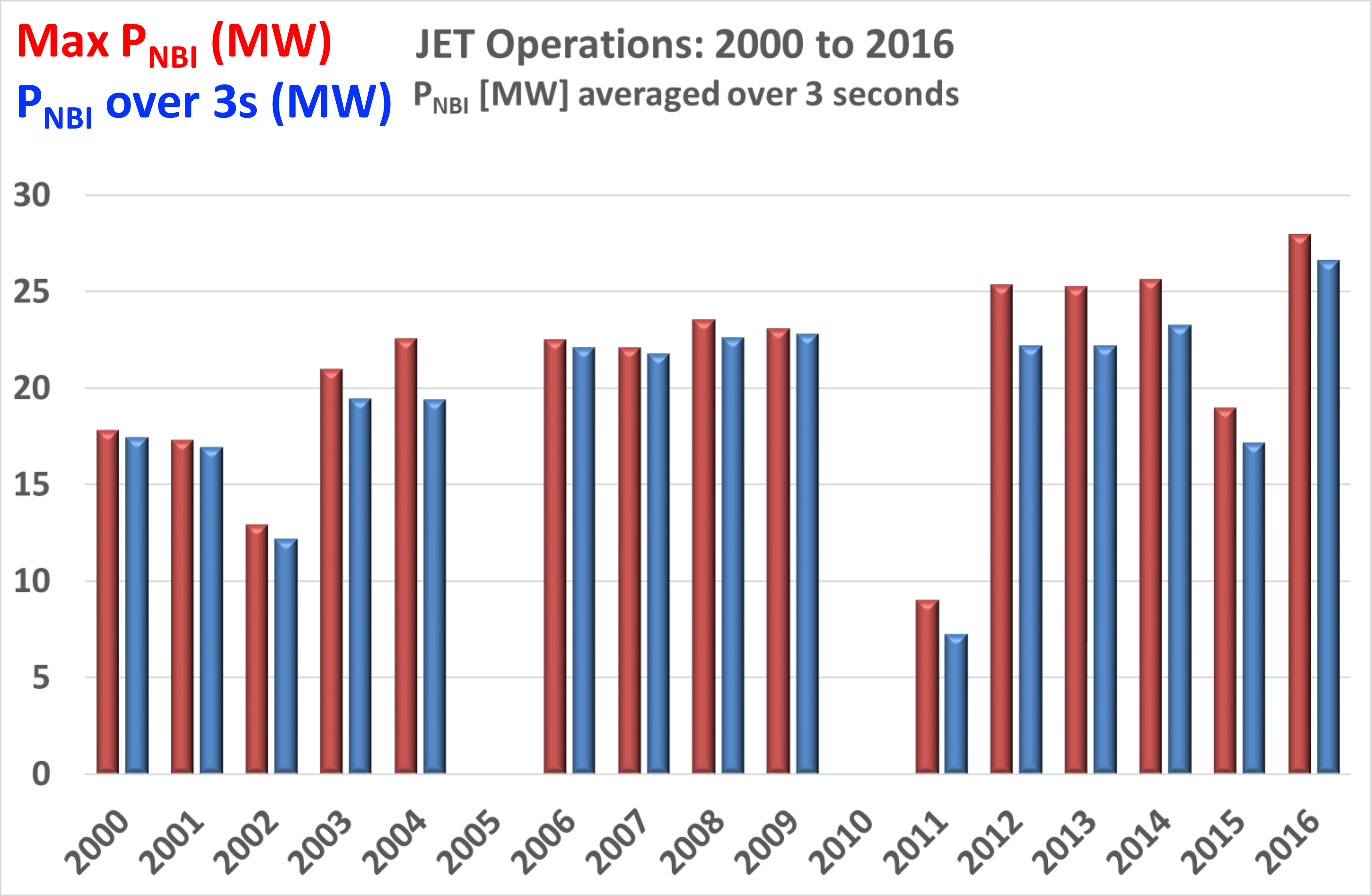
JET

- The upgrade to the NBI was aiming to achieve ~30MW
- During the first campaigns following this upgrade NBI power was insufficient
- This was mainly due to:
  - Configuration of the power supply breakdown damping system
  - Water leaks on major components



NBI Power

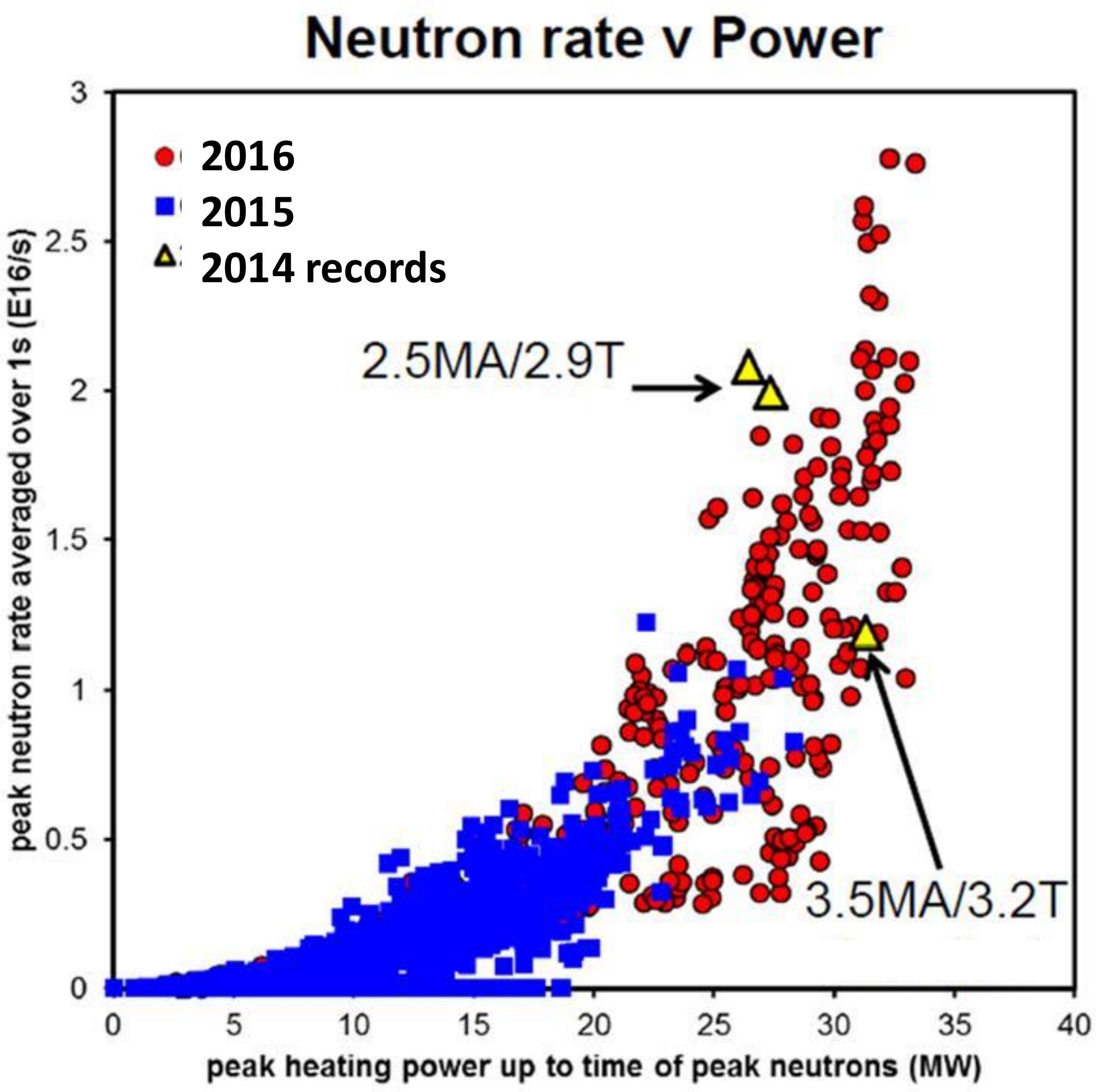
- A further water leak and issues with the HV transmission caused issues in 2015 and 2016
- Acceleration voltage restricted to 110kV due to ion dump limitations
- Achieve higher power (~28MW) in late 2016 leading to improvements to fusion plasma



NBI Power and Fusion Rate

- With higher NBI power available it was possible to increase the fusion power achieved (as measured by neutron rate) in different plasma scenarios

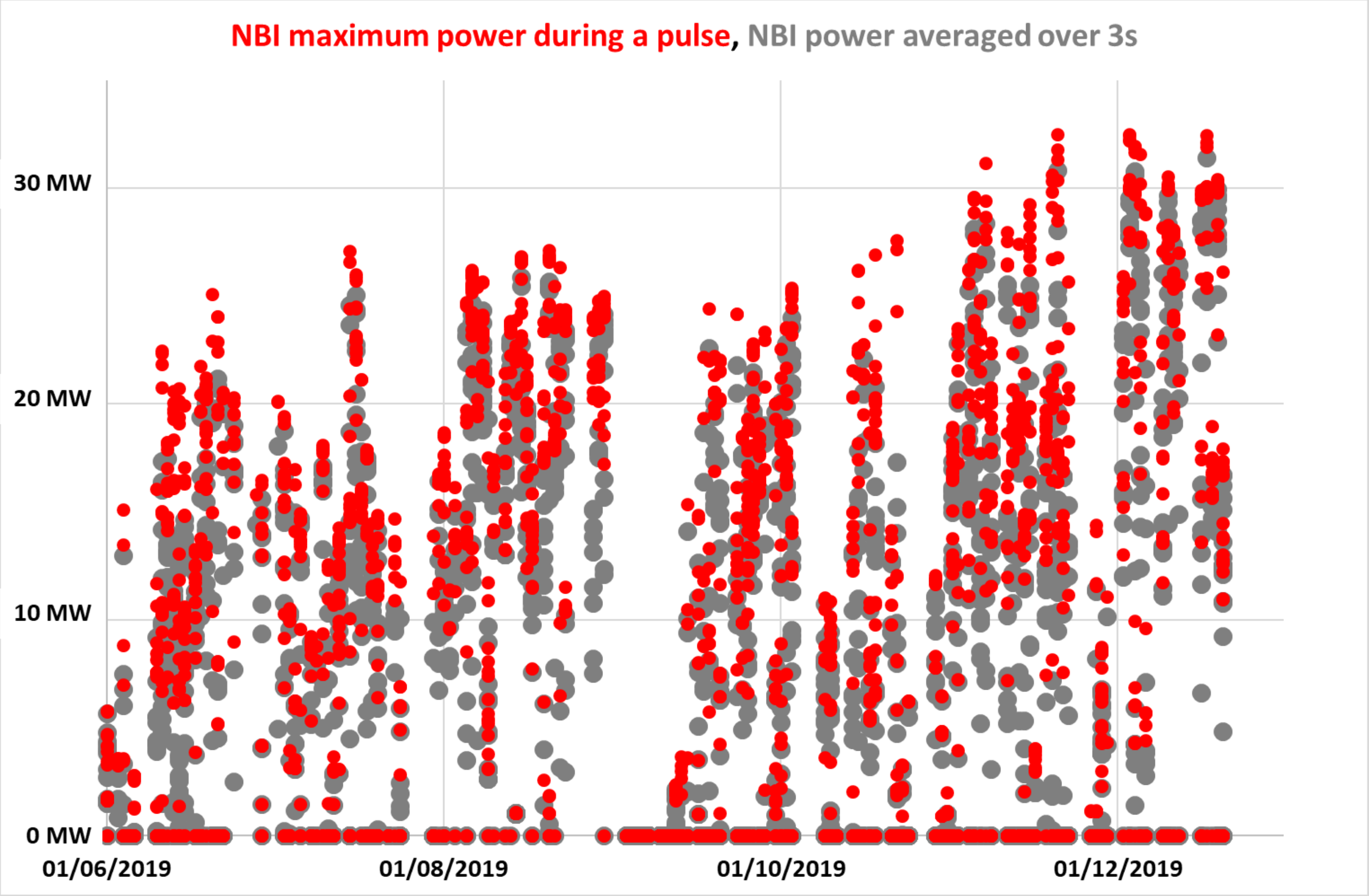
- Appeared to be significant increase in fusion power above 30MW total injected power (including wave heating power)



Preparation for DTE2

JET

- **Further improvement of both NBI power and the plasma scenarios was required before D-T experiments could begin**
- **Target of >30MW of NBI power and further targets on the neutron rate achieved in deuterium plasmas**
- **Repairs and upgrades to NBI during 2017-2018 followed by deuterium experiments in 2019-2020**

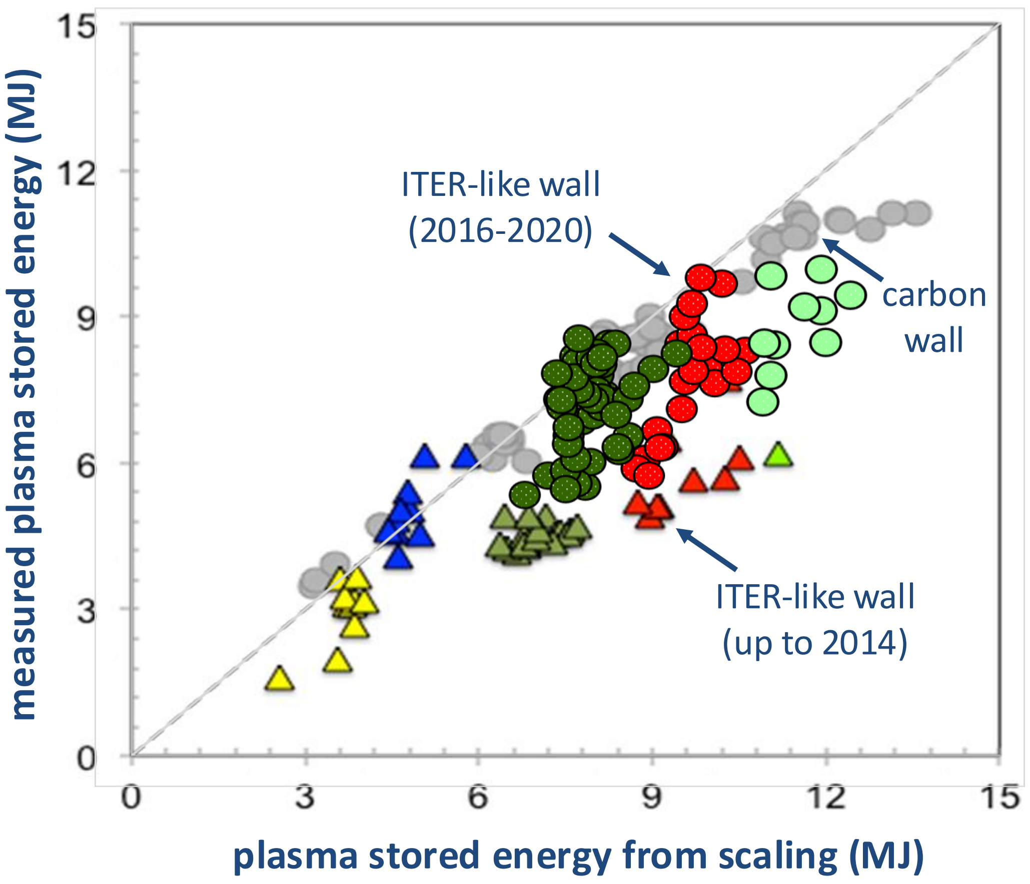


Following further power supply renovations >30MW achieved in late 2019

The NBI Team - 2019

JET

High performance recovered



Plasma development (with deuterium fuel)

- **ILW up to 2014**: Difficult to match plasma performance achieved with carbon wall in early experiments after installation of ILW due to W
- **ILW 2016-2022** confinement recovered thanks to higher available power and plasma techniques:
  - Reduced fuel gas injection rate for increased temperature at plasma edge, improving core energy confinement
  - High frequency frozen fuel pellet injection to pace ELM instabilities, flushing out impurities
  - Use of high pedestal temperature to screen impurities in hybrid plasma scenario

This development (and several others) demonstrated readiness for DTE2

J. Mailloux et al 2022 Nucl. Fusion 62 042026

Deuterium-Tritium Experiments and Fusion Energy Records 2021-2023

Objectives of 100%T and DTE2 Experiments (2021)

JET

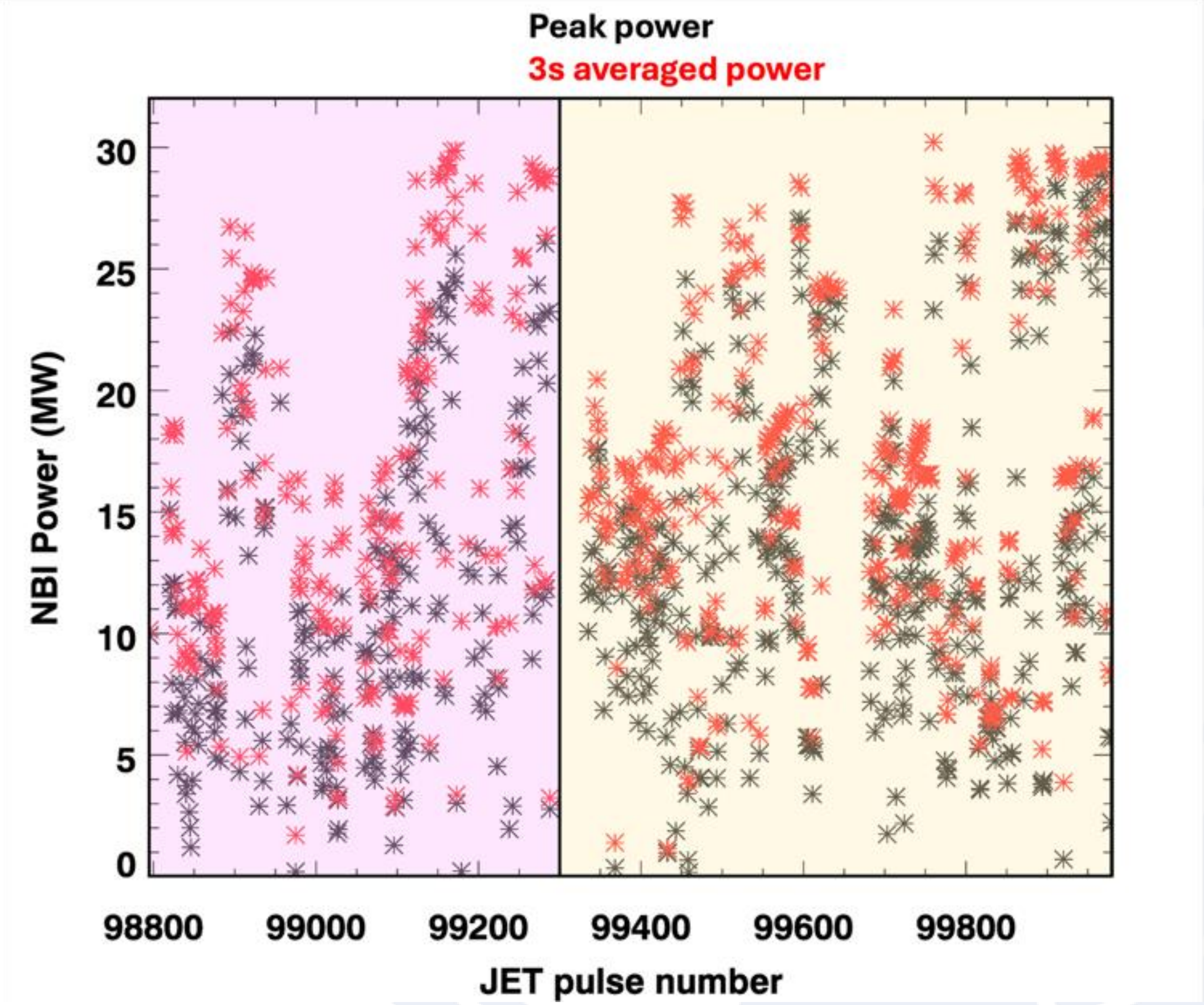
- Demonstrate High D-T fusion power (≥10MW) sustained for 5s
- Develop integrated radiative scenarios in plasma conditions relevant to ITER
- Demonstrate clear α-particle effects
- Address isotope effects on energy and particle transport
- Address key plasma-wall interaction issues
- Develop ICRH schemes relevant to ITER D-T operation

Tritium NBI

JET

- The conversion of the NBI to tritium took some months to complete and required a full characterisation of the system in tritium

- While there were issues with the achievable power with tritium NBI the final result was a successful D-T campaign where some pulses achieved >28MW of NBI

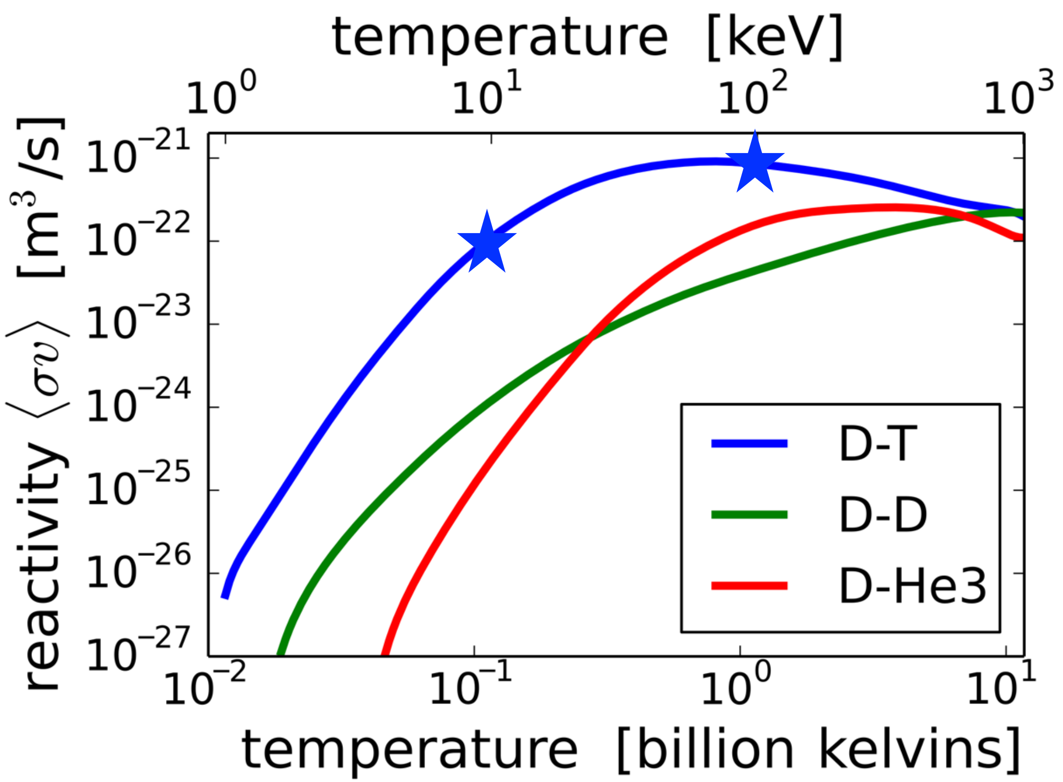


Achieved NBI power during DTE2. Pure tritium experimental campaigns highlighted in pink while D-T campaign highlighted in gold.

JET fusion power boosted by optimising heating & fuel mix

JET

- In a fusion reactor the D-T fusion would occur between thermal ions at very high temperature (10s of keV)
- For NBI on JET at ~120kV they are already near the peak of the D-T fusion reaction
- Non-thermal D-T reactions will dominate in many JET plasmas and are optimum at low D/T ratio
- Further boost with RF ion cyclotron heating of D
- Hence choice of D NBI onto a T target plasma used to boost fusion power



M. Maslov *et al* 2023 Nucl. Fusion 63 112002

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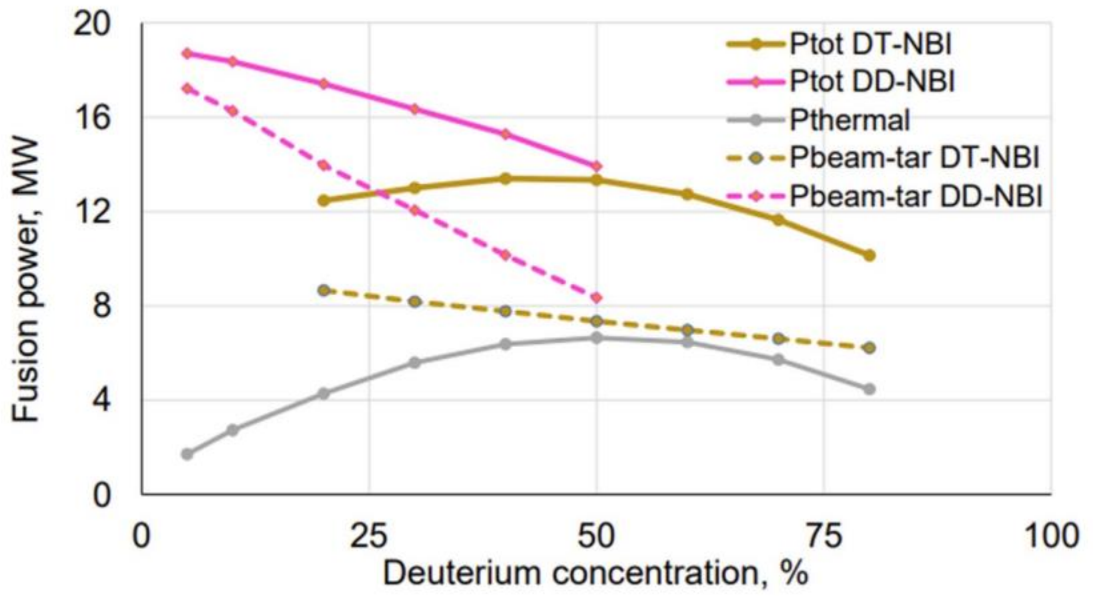

Simulation of fusion power based on deuterium plasma

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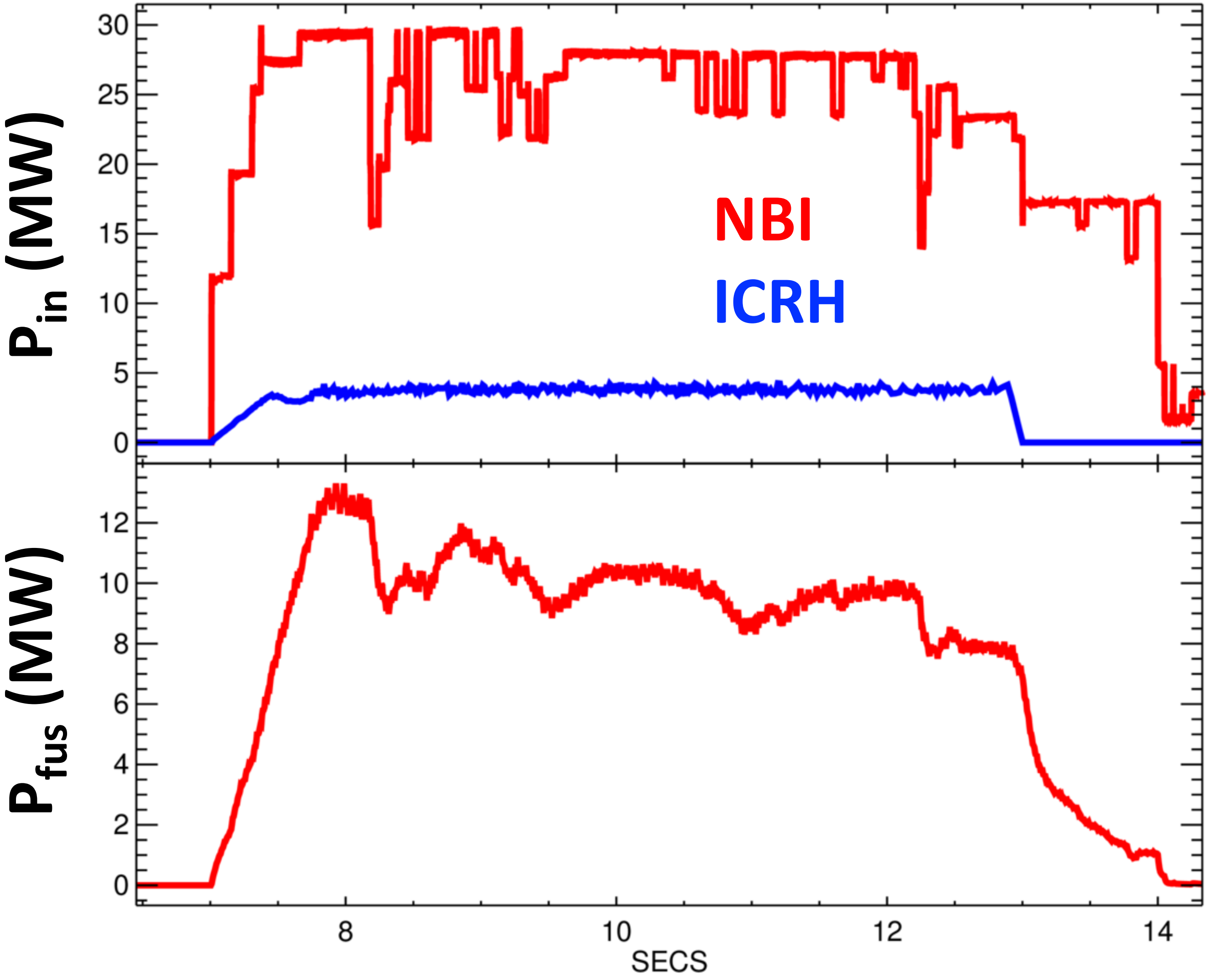
JET Fusion Energy Record

JET

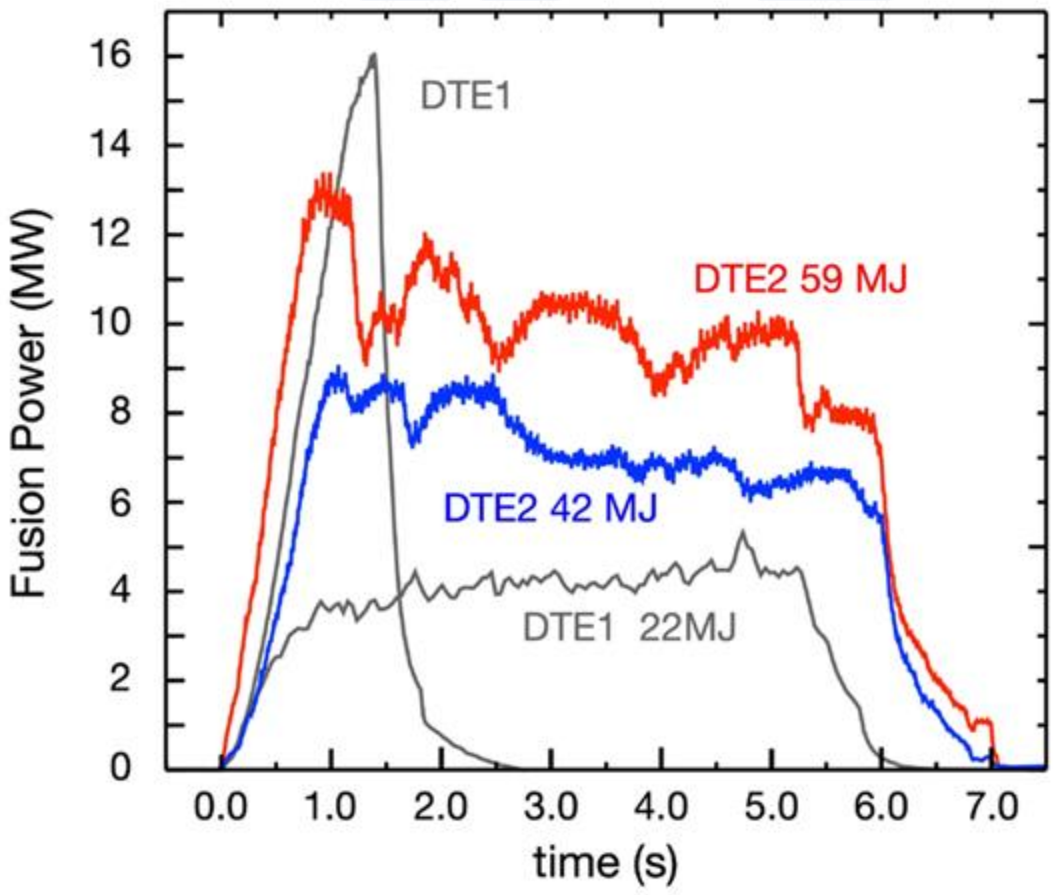
- Fusion record from 1997 was broken multiple times during 2021
- On final days of experiment the optimised scenario with D-NBI was used
- The record pulse is shown here
- Can see the relationship between input power and fusion power output very clearly



JET Fusion Energy Record

JET

- During DTE1 experiment in 1997, JET achieved fusion power record of **~16MW** (transient) and fusion energy record of **~22 MJ** (stationary).
- During DTE2 experiment in 2021, fusion energy record was surpassed several times with hybrid plasma scenarios.
- Fusion energy of **~42MJ** was achieved in the JET pulse #99869 (2.3MA/3.45T, plasma 47%D/53%T with ~14MW of D-NBI and ~12MW of T-NBI).
- Fusion energy of **~59MJ** was achieved in the JET pulse #99971 (2.5MA/3.86T, ~87%T plasma with ~28MW of D-NBI only).
- These results demonstrate compatibility of a metal wall with sustained high fusion performance.



M. Maslov *et al* 2023 Nucl. Fusion 63 112002
J. Hobirk *et al* 2023 Nucl. Fusion 63 112001
C. Maggi *et al* 2023 Nucl. Fusion 63 110201

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Scientific Highlights – DT Special Issue

JET

- The JET hybrid scenario in Deuterium, Tritium and Deuterium-Tritium
- J. Hobirk, C.D. Challis, A. Kappatou, E. Lerche, D. Keeling, D. King, S. Aleiferis, E. Alessi, C. Angioni, F. Auriemma *et al*
- JET D-T scenario with optimized non-thermal fusion
- M. Maslov, E. Lerche, F. Auriemma, E. Belli, C. Bourdelle, C.D. Challis, A. Chomiczewska, A. Dal Molin, J. Eriksson, J. Garcia *et al*
- Modelling performed for predictions of fusion power in JET DTE2: overview and lessons learnt
- J. Garcia, F.J. Casson, L. Frassinetti, D. Gallart, L. Garzotti, H.-T. Kim, M. Nocente, S. Saarelma, F. Auriemma, J. Ferreira *et al*
- Validation of D–T fusion power prediction capability against 2021 JET D–T experiments
- Hyun-Tae Kim, Fulvio Auriemma, Jorge Ferreira, Stefano Gabriellini, Aaron Ho, Philippe Huynh, Krassimir Kirov, Rita Lorenzini, Michele Marin, Michal Poradzinski *et al*
- Tritium neutral beam injection on JET: calibration and plasma measurements of stored energy
- D.B. King, R. Sharma, C.D. Challis, A. Bleasdale, E.G. Delabie, D. Douai, D. Keeling, E. Lerche, M. Lennholm, J. Mailloux *et al*
- Stability analysis of alpha driven toroidal Alfvén eigenmodes observed in JET deuterium-tritium internal transport barrier plasmas
- M. Fitzgerald, R. Dumont, D. Keeling, J. Mailloux, S. Sharapov, M. Dreval, A. Figueiredo, R. Coelho, J. Ferreira, P. Rodrigues *et al*
- Experiments on excitation of Alfvén eigenmodes by alpha-particles with bump-on-tail distribution in JET DTE2 plasmas
- S.E. Sharapov, H.J.C. Oliver, J. Garcia, D.L. Keeling, M. Dreval, V. Goloborod'Ko, Ye.O. Kazakov, V.G. Kiptily, Ž. Štancar, P.J. Bonofiglo *et al*
- Toroidal Alfvén eigenmodes observed in low power JET deuterium–tritium plasmas
- H.J.C. Oliver, S.E. Sharapov, Ž. Štancar, M. Fitzgerald, E. Tholerus, B.N. Breizman, M. Dreval, J. Ferreira, A. Figueiredo, J. Garcia *et al*

Effect of the isotope mass on pedestal structure, transport and stability in D, D/T and T plasmas at similar β_N and gas rate in JET-ILW type I ELMy H-modes

L. Frassinetti, C. Perez von Thun, B. Chapman-Oplopoiou, H. Nyström, M. Poradzinski, J.C. Hillesheim, L. Horvath, C.F. Maggi, S. Saarelma, A. Stagni *et al*

Isotope physics of heat and particle transport with tritium in JET-ILW type-I ELMy H-mode plasmas

P.A. Schneider, C. Angioni, F. Auriemma, N. Bonanomi, T. Görler, R. Henriques, L. Horvath, D. King, R. Lorenzini, H. Nyström *et al*

L-H transition studies in tritium and deuterium–tritium campaigns at JET with Be wall and W divertor

E.R. Solano, G. Birkenmeier, C. Silva, E. Delabie, J.C. Hillesheim, A. Baciero, I. Balboa, M. Baruzzo, A. Boboc, M. Brix *et al*

Isotope mass scaling and transport comparison between JET Deuterium and Tritium L-mode plasmas

T. Tala, A.E. Järvinen, C.F. Maggi, P. Mantica, A. Mariani, A. Salmi, I.S. Carvalho, A. Chomiczewska, E. Delabie, F. Devasagayam *et al*

Divertor power load investigations with deuterium and tritium in type-I ELMy H-mode plasmas in JET with the ITER-like wall

M. Faitsch, I. Balboa, P. Lomas, S.A. Silburn, A. Tookey, D. Kos, A. Huber, E. de la Luna, D. Keeling, A. Kappatou *et al*

Tritium removal from JET-ILW after T and D–T experimental campaigns

D. Matveev, D. Douai, T. Wauters, A. Widdowson, I. Jepu, M. Maslov, S. Brezinsek, T. Dittmar, I. Monakhov, P. Jacquet *et al*

Experiments in high-performance JET plasmas in preparation of second harmonic ICRF heating of tritium in ITER

M.J. Mantsinen, P. Jacquet, E. Lerche, D. Gallart, K. Kirov, P. Mantica, D. Taylor, D. Van Eester, M. Baruzzo, I. Carvalho *et al*

https://iopscience.iop.org/issue/0029-5515/63/11

JET Fusion Energy Record – Part 2 (2023)

JET

- A further D-T campaign was completed in 2023 with the following objectives
  1. Radiative high current scenario (core-edge integration)
  2. No/small ELMs scenarios
  3. Real-time control
  4. Fuel retention studies (including LID-QMS demonstration)
  5. Conclude/complement DTE2 experiments

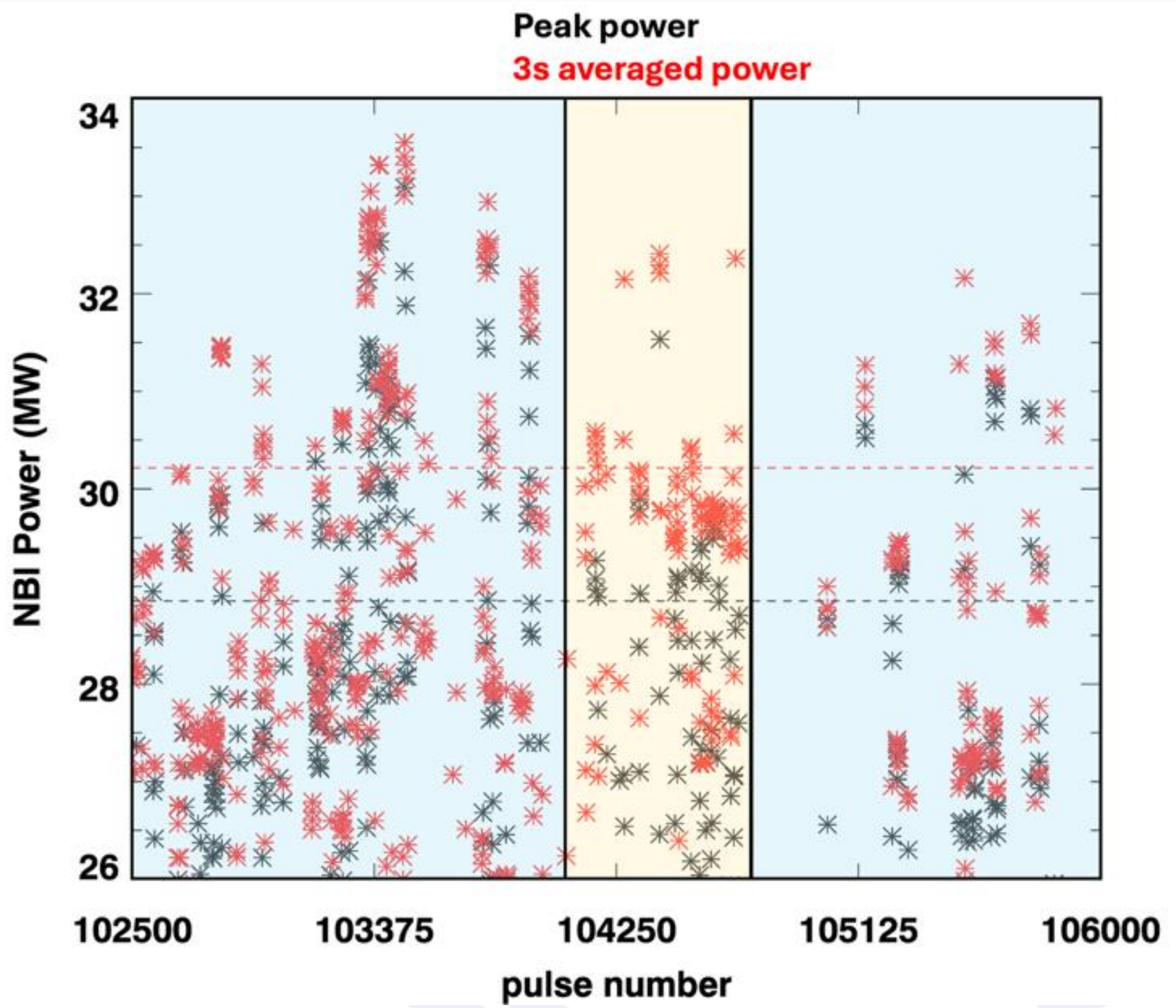
- Completion of DTE2 experiments included attempting to repeat the record pulses from 2021 to demonstrate reproducibility and to better understand the results

- Due to experience in 2021, it was decided to only run the NBI in deuterium with the standard gas feed method

NBI Power in DTE3 (2023)

JET

- The NBI power during 2023 was already improved on that during the previous campaigns
- This was due to further improvements to the power supplies to improve reliability
- Achieved NBI power during 2023 is shown with along with best results from DTE2 shown by dashed lines in same colours.

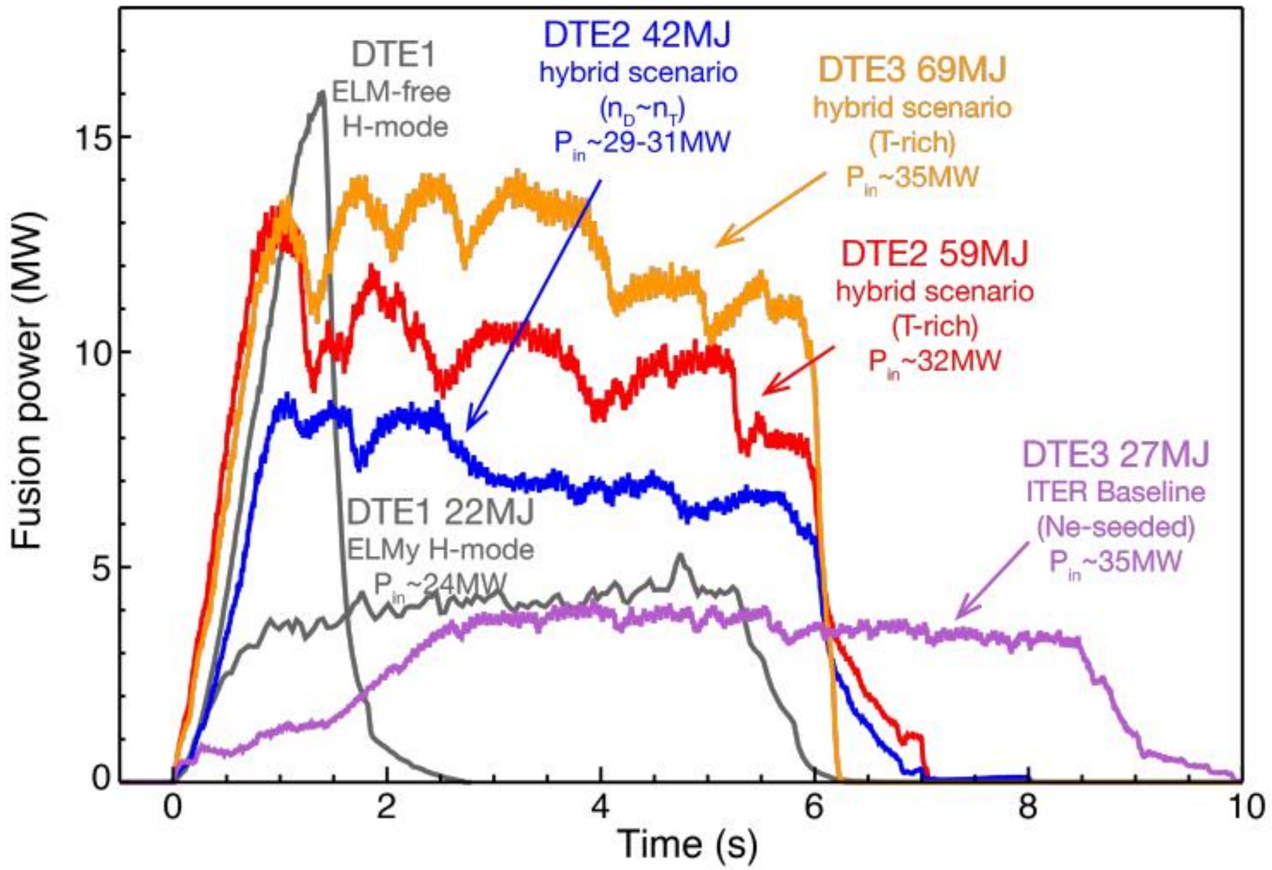


Blue shading is D campaign, gold is D-T campaign

Fusion Record – Final Outcome

JET

#99869 (2.3MA/3.45T) scenario with ~50/50 DT NBI and plasma
#99971 & **#104522** (2.5MA/3.86T) scenario with D-NBI in T-rich plasma



- The NBI power in these pulses was similar to 2021 although more stable
- Key factor to increased fusion power was the higher ICRH power available generating a synergy with the NBI power

Neutron rate of 5E18n/s

DTE2 results: C.F. Maggi *et al*. Nucl. Fusion 2024 https://doi.org/10.1088/1741-4326/ad3e16
DTE3 results: A. Kappatou *et al.*, EPS 2024

Summary

JET

- Fusion energy records on JET were achieved in 2021 and 2023, going beyond the 1997 JET results

- To achieve this result significant additional heating (largely from ion sources) was required

- This method of enhancing fusion power does not translate to a fusion reactor but is of interest for proposals such as a Volumetric Neutron Source (VNS)

- Making that power available took many years of operations, upgrades and repairs from the team

- For future devices (e.g. ITER) negative ion beams are required due the higher energies used (many contributions this conference) and on some reactor concepts only wave-heating will be used

Summary

JET

- Please note that while this talk has discussed NBI & ion sources due to the venue, the achievements of JET were due to a broad team of experts across many disciplines!

References

JET

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JET

backup

Neutral Beams for Fusion

JET

Plasma heating

Fast neutral beam particles injected into plasma are ionised by ion or electron impact ionisation or by charge exchange.

Once charged, the fast ions become trapped in the magnetic field and circulate, losing energy to plasma ions and electrons by electrostatic collisions.

Plasma diagnostics - CXRS, MSE, …

Various plasma parameters are determined by the spectral analysis of light emission generated in collisions of fast neutrals with plasma.

Current Drive

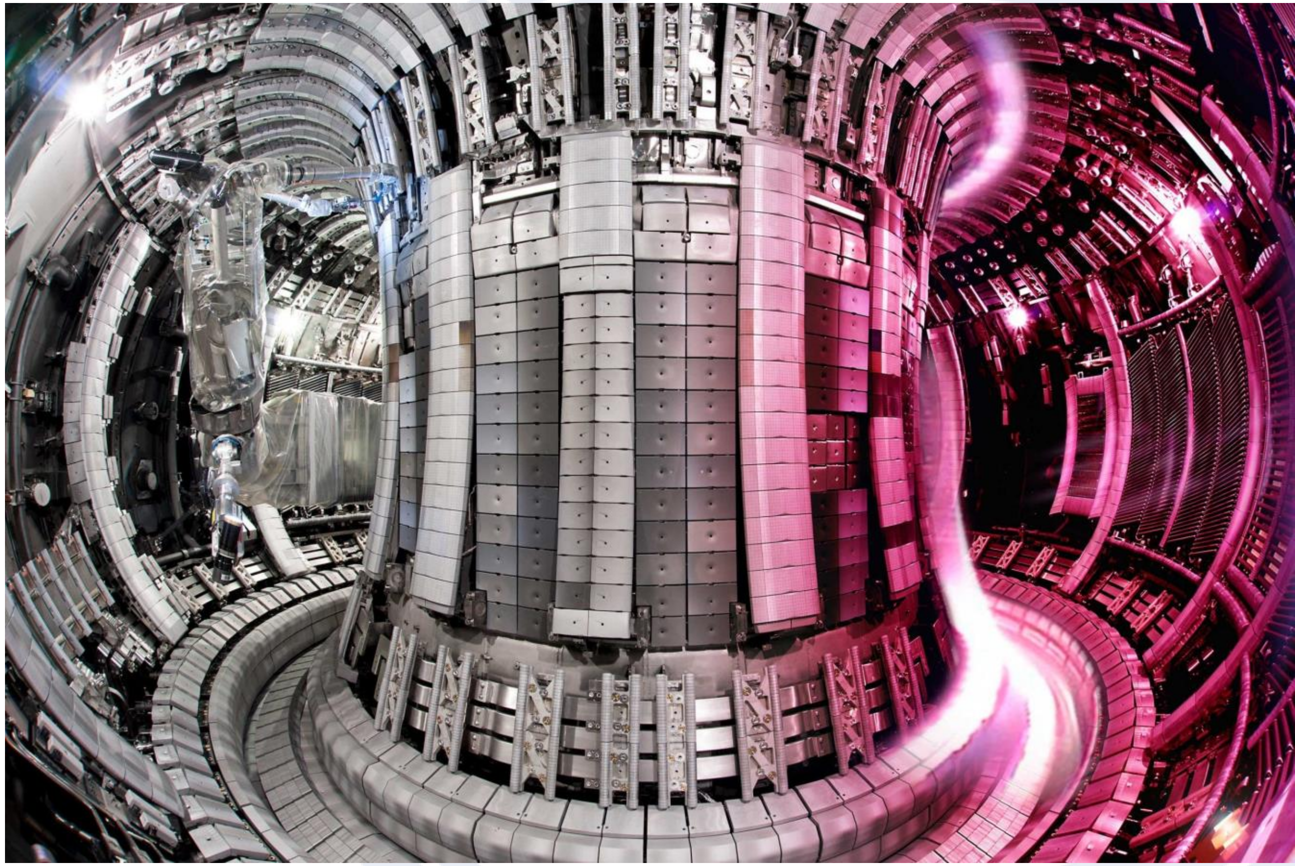
Injected neutral flux can be also used to drive plasma current - important for future devices with long pulse operation

Rotation

Beam Imparts momentum, role in plasma stability

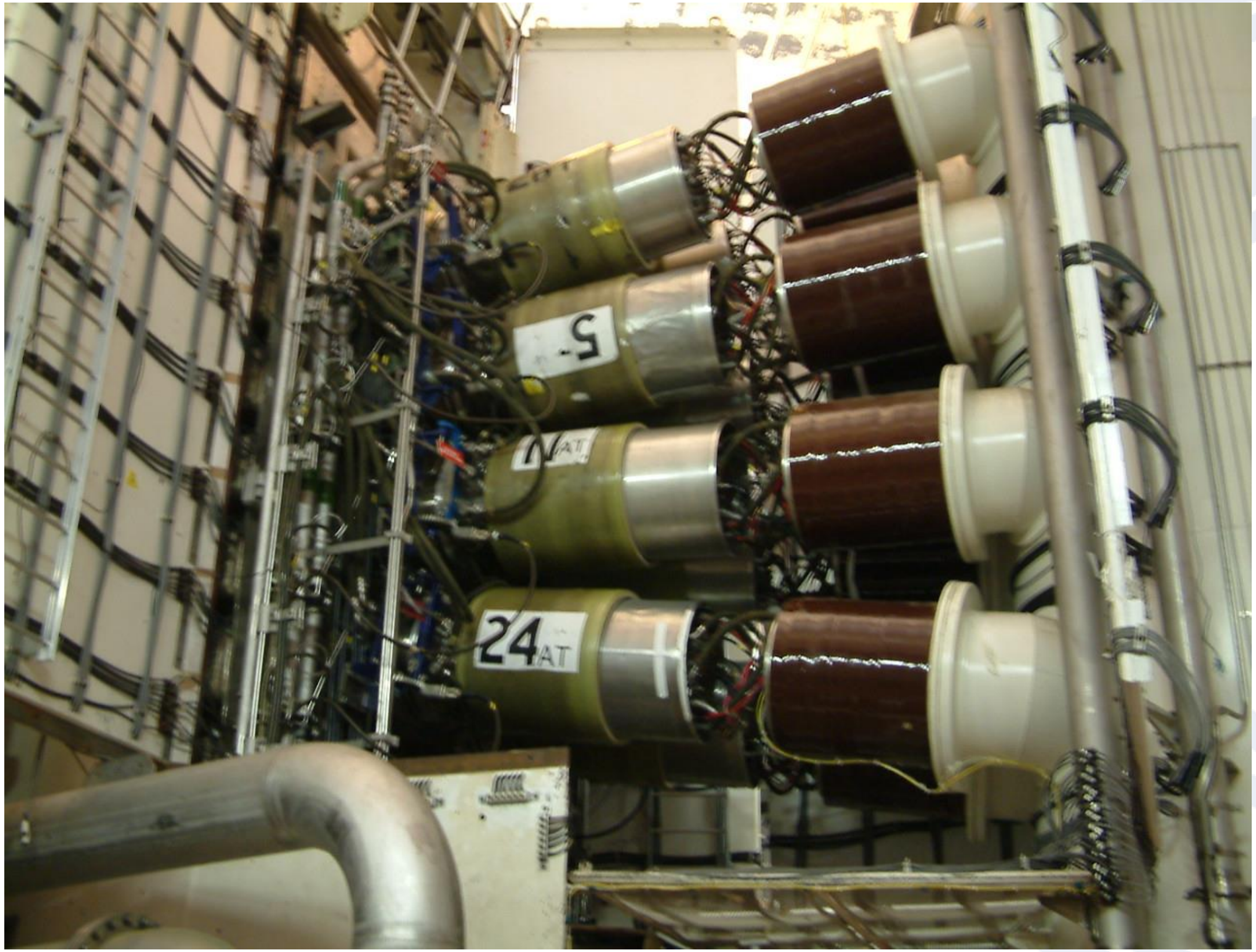
Nuclear Fusion & JET

JET



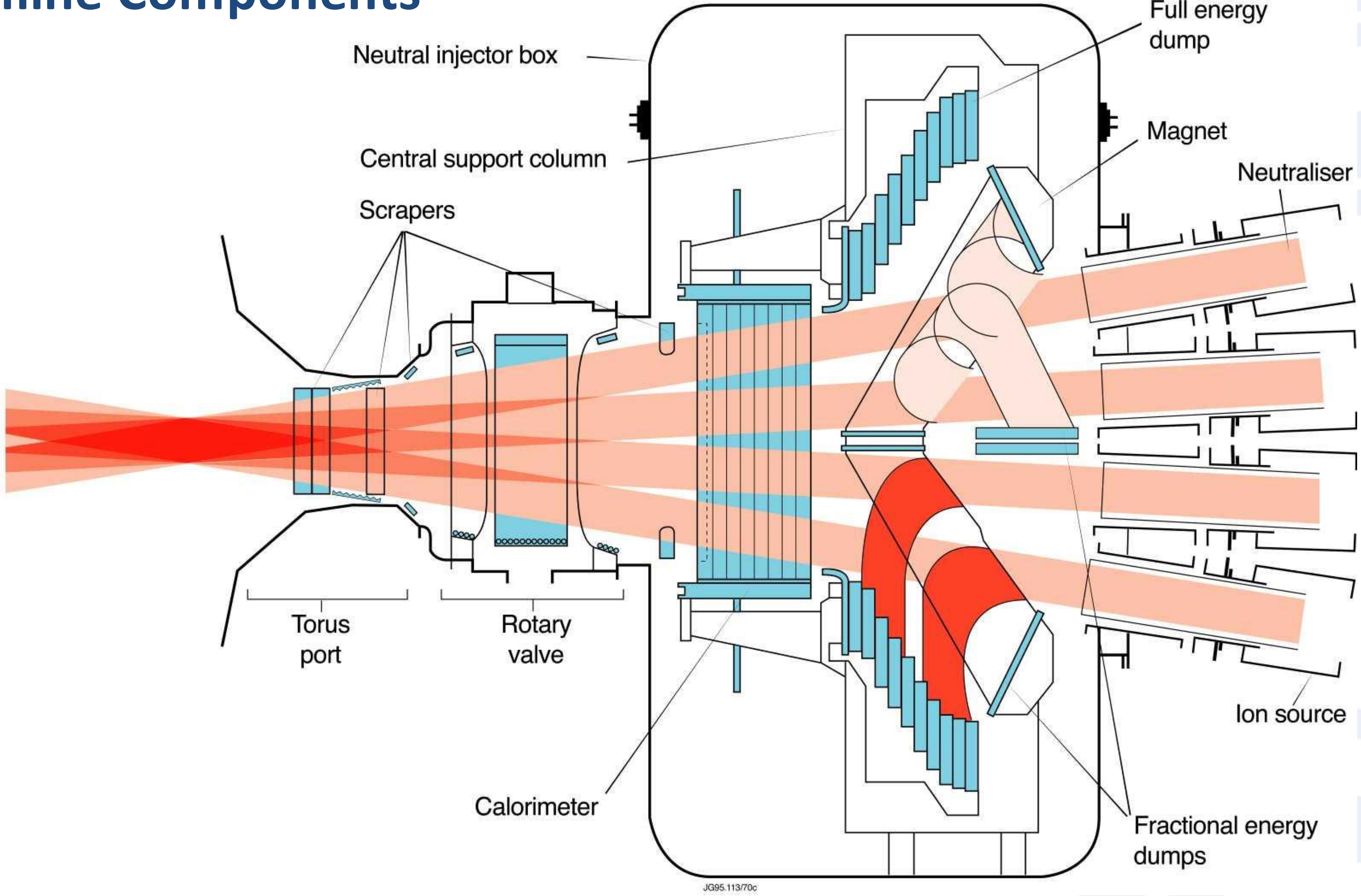
- The JET design team started work in the 1970s and the device continued to operate up to 2023

PINI Layout



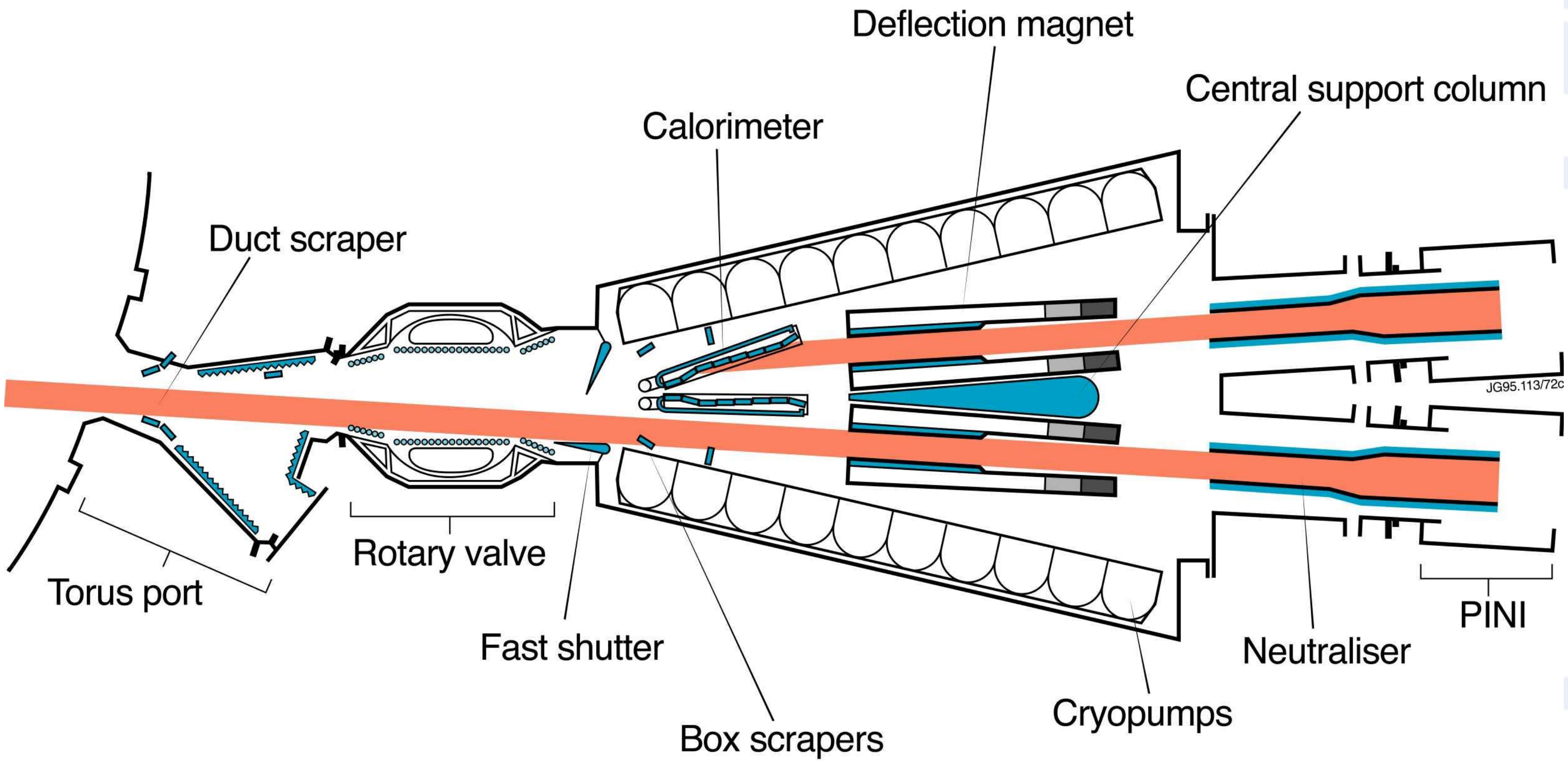
Octant 4 Neutral Injector Box

Beamline Components



Beamline Components

JET



NBI Progression

- Over 40 years there were many changes to the NBI system
- Numerous repairs needed
- Upgrades from the original 16MW installed were carried out
- Most significant in 2009 with new PINIs, beamline components & power supplies