FAFNIR: Facility for Fusion Neutron Irradiation Research

Presented by Tristan Davenne
at the
RAL Applied Science Division meeting
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Collaborators / supporters

Integration
M. Porton (CCFE), A. Seryi (JAI), E. Surrey (CCFE)

Materials
S. Roberts (Oxford), B. Connolly (Birmingham), S. Donnelly (Huddersfield), C. Grovenor (Oxford), J. Marrow (Oxford), P. Mummery (Manchester),

Target
C. Densham (RAL), T. Davenne (RAL), T. Barrett (CCFE), R.Edgecock (RAL,Huddersfield)

Accelerator
D. Findlay (RAL), J. Thomason (RAL), D. Adams (RAL), A. Letchford (RAL), H. Owen (Manchester), J. Pozimski (Imperial)

Neutronics
M. Lis (CCFE), L. Packer (CCFE)

UNIVERSITY OF OXFORD | UNIVERSITY OF BIRMINGHAM | University of HUDDERSFIELD | Imperial College London | MANCHESTER 1824 The University of Manchester | JAI John Adams Institute for Accelerator Science | Science & Technology Facilities Council | CCFE CULHAM CENTRE FOR FUSION ENERGY

Contents

- Background Information on Fusion Power
- Neutron Irradiation Damage
- Requirement for a Fusion Relevant Neutron Source
- FAFNIR proposal
- FAFNIR Target Challenges
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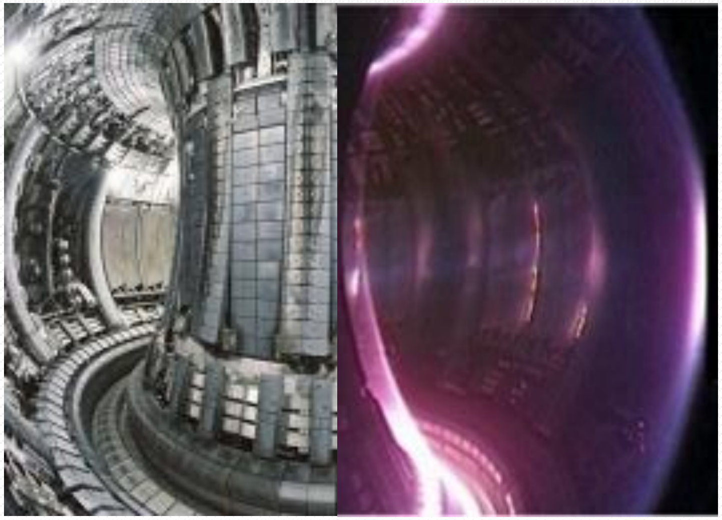
Fusion Power Research Effort

Magnetic confinement fusion

Plasma confined in a Tokomak

Energy input via Ohmic heating,

Neutral beam heating and RF heating



The plasma in the Joint European Torus (JET) at Culham in the UK routinely reaches 200 million degrees Celsius.

JET has produced 16MW of fusion power (70% of input power)

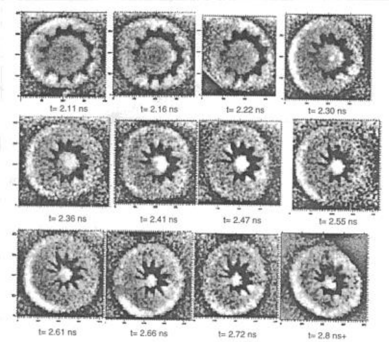
ITER – designed to achieve ignition and generate 500MW with 50MW input power

ITER will be followed by a demonstration power plant – ‘DEMO’ – which is expected to be ready in 25-30 years.

Inertial confinement fusion

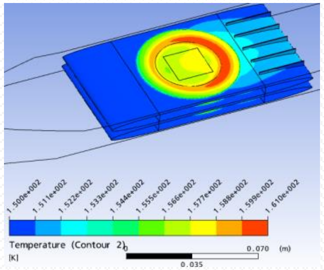
High power laser used to compress a fuel pellet

Shock wave results in very high temp and pressure



target of D-T, being compressed by the Nova Laser. The image shows the compression of the target, as well as the growth of the Rayleigh-Taylor instabilities

ICF targets are manufactured at RAL and tested in VULCAN



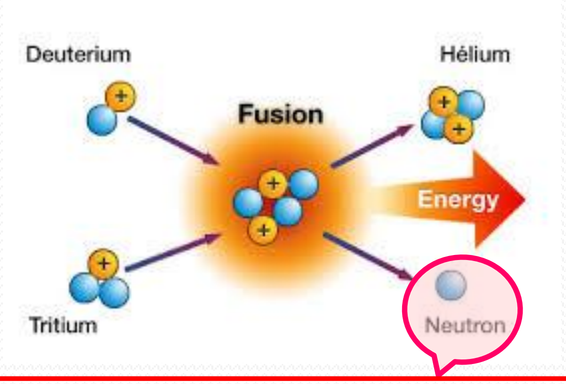
DIPOLE work to design and develop efficient high average power laser technology

Sep 2013: National Ignition facility recently reported a new milestone of generating more fusion energy than energy absorbed by the fuel pellet, still short of ignition target.

Lawson criteria defines the conditions for ignition

Fusion Power Advantages

- ***No carbon emissions.*** The only by-products of fusion reactions are small amounts of helium, which is an inert gas that will not add to atmospheric pollution.
- ***Abundant fuels***. Deuterium can be extracted from water and tritium is produced from lithium, which is found in the earth's crust. Fuel supplies will therefore last for millions of years.
- ***Energy efficiency***. One kilogram of fusion fuel can provide the same amount of energy as 10 million kilograms of fossil fuel.
- ***No long-lived radioactive waste.*** Only plant components become radioactive and these will be safe to recycle or dispose of conventionally within 100 years.
- ***Safety.*** The small amounts of fuel used in fusion devices (about the weight of a postage stamp at any one time) means that a large-scale nuclear accident is not possible.
- ***Reliable power***. Fusion power plants should provide a baseload supply of large amounts of electricity, at costs that are estimated to be broadly similar to other energy sources.



Significant challenge for commercial fusion power whether it be MCF or ICF is containing the plasma and making a ‘plasma facing wall’ that is reliable despite the incident neutron flux

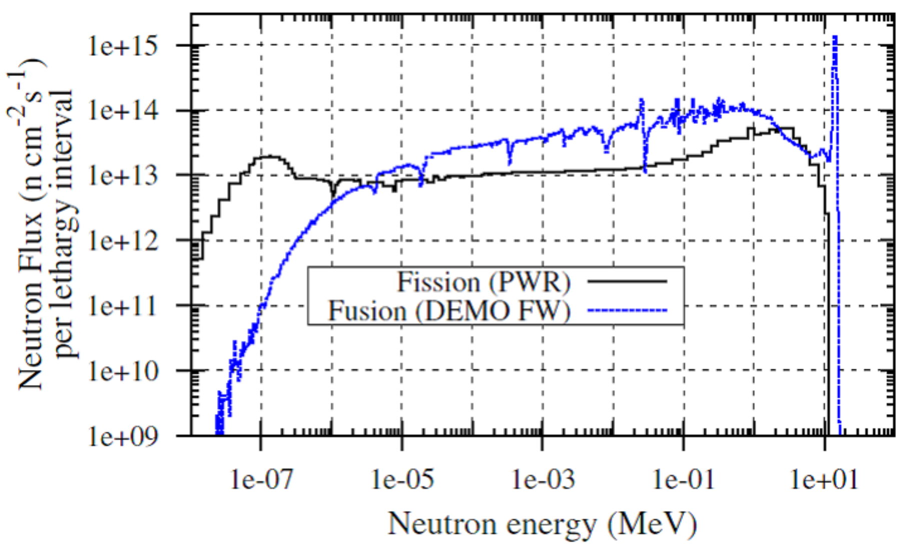
Neutron irradiation damage

The neutrons entering the plasma facing walls result in displacements at the atomic level

- **Gas production**
- **Swelling**
- **Embrittlement**
- **Irradiation creep**

Damage depends on the neutron spectrum

Nucl. Fusion **52** (2012) 083019



V. Barabash et al. / Journal of Nuclear Ma

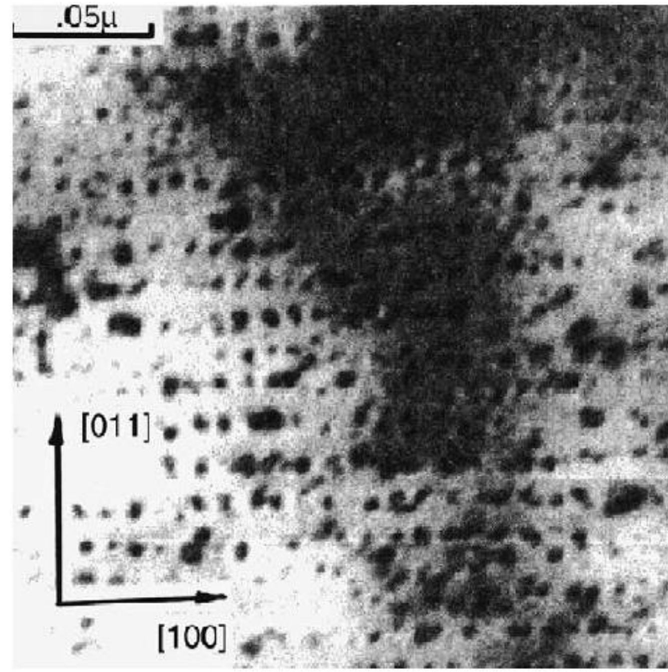


Fig. 3. Ordered array of voids in W irradiated at 550 °C at neutron fluence ~10^{22} n/cm^2 (~7 dpa).

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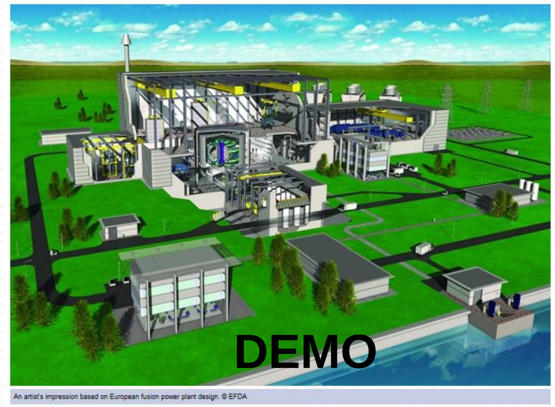
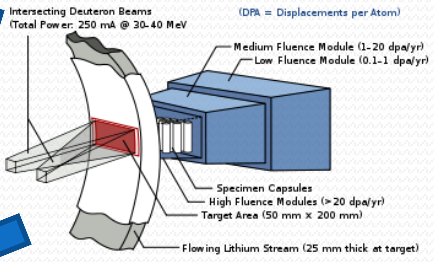
Requirement for a Fusion Relevant Neutron Source

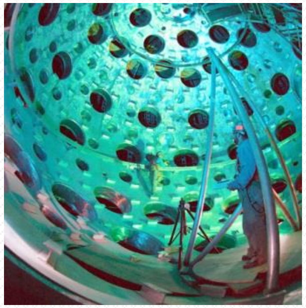


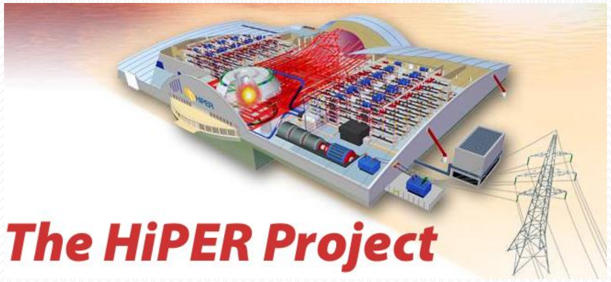
IFMIF

'Gold standard fusion neutron source'



NIF





>100cc test volume
50dpa per fpy
Significant technical challenges

However: **IFMIF now 10 years behind schedule**

Will NOT be ready in time to provide data for DEMO, critical design decisions in 2030.

10dpa thought to be adequate to understand materials degradation phenomena
micromechanical testing allows reduction in test volume

Alternative fusion relevant neutron sources with eased 14MeV spec are being proposed:

Project X energy station, ESS-Bilbao (water cooled beryllium target wheel), several de-scoped versions of IFMIF, FAFNIR (proposal led by CCFE) and others

FAFNIR Proposal:

Neutron stripping source

40MeV 1.2MW accelerator → deuterons → Spinning graphite target → 14MeV neutrons → Material test samples

Achieves fusion relevant 14MeV peak in neutron spectra

1.5dpa/fpy at 5mA and 7dpa/fpy at 30mA

FAFNIR Proposal:

• *uses existing or near term technology*

Existing & Proposed Accelerator Systems

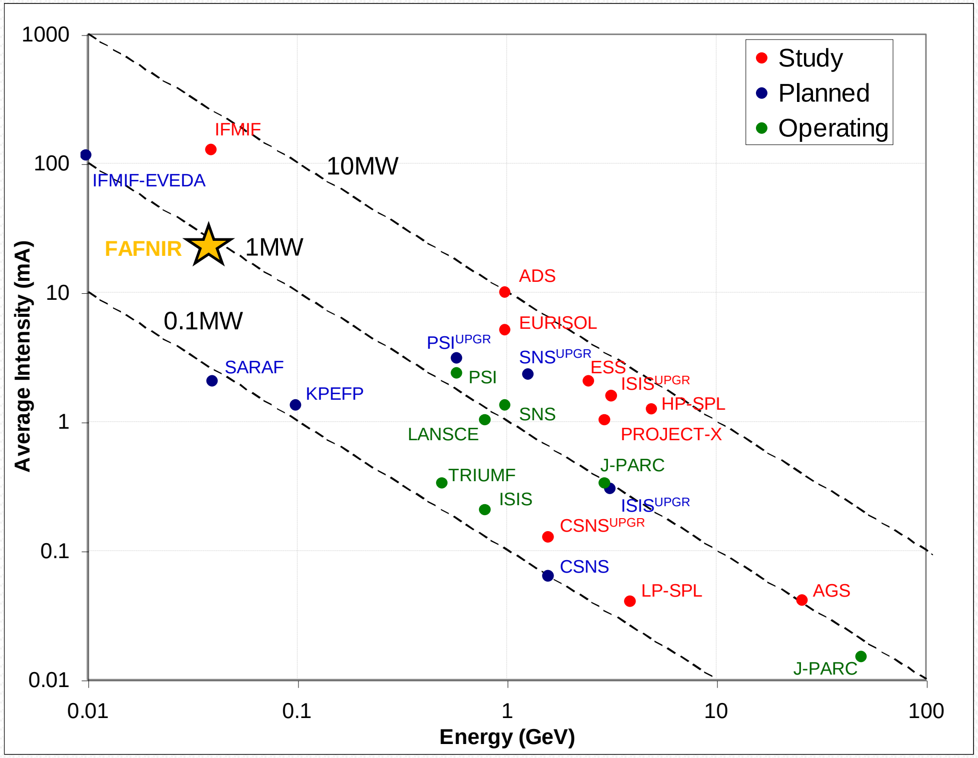
IFMIF power >10 times existing operating system

C.R. Prior
HB2010 MOIA02 6-10 (2010)

Proton sources have demonstrated currents > 100mA

Beam powers of ~1MW have been reached by SNS, Los Alamos.

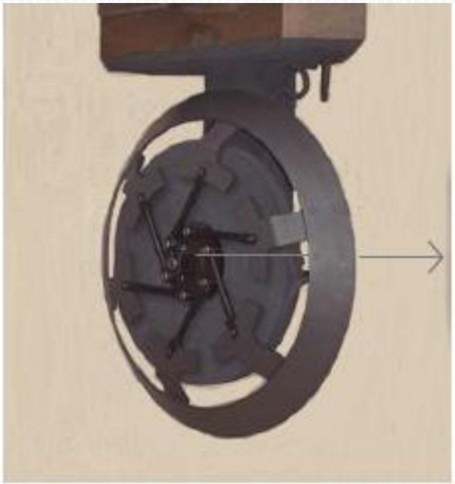
Main challenges are beam losses and power dissipated in structure



FAFNIR Proposal:

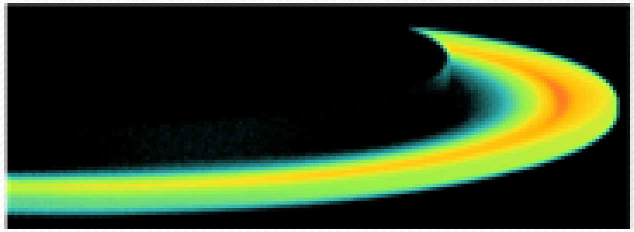
•uses existing or near term technology

Spinning graphite targets in operation for decades at PSI



PSI E-Target (Heidenreich et al.)
Radiation cooled spinning carbon wheel – 60rpm
Diameter – 0.45m
Deposited power - 90kW
Operating Temp - 1427°C
Operation since 1990

Active development of multi layered graphite spinning targets for multiple MW/cc power density



MSU FRIB Target (Pellemoine et al.)
Thermal image of tests at 1200°C
Plans to operate at 1900°C
Deposited power - 200kW and multiple MW/cc

FAFNIR Target Challenges – power density and flux

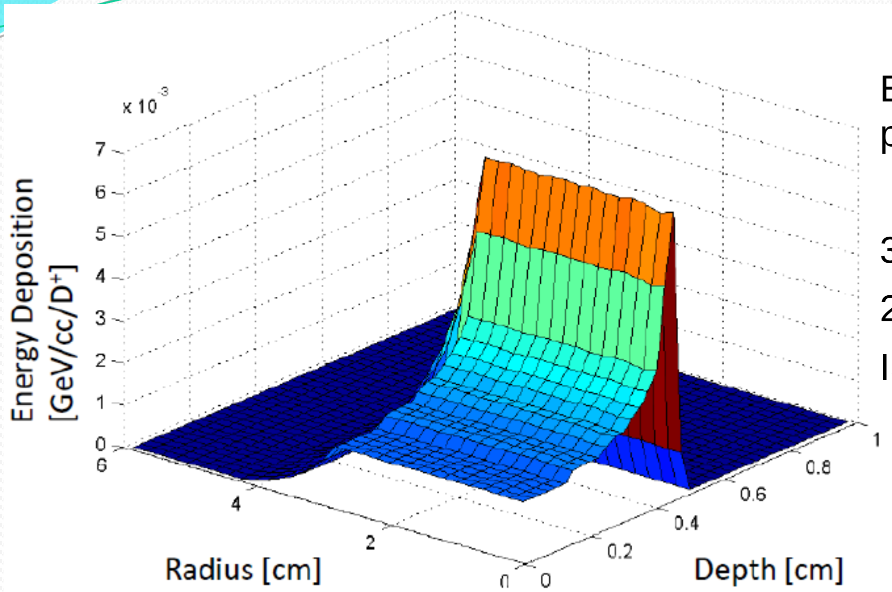


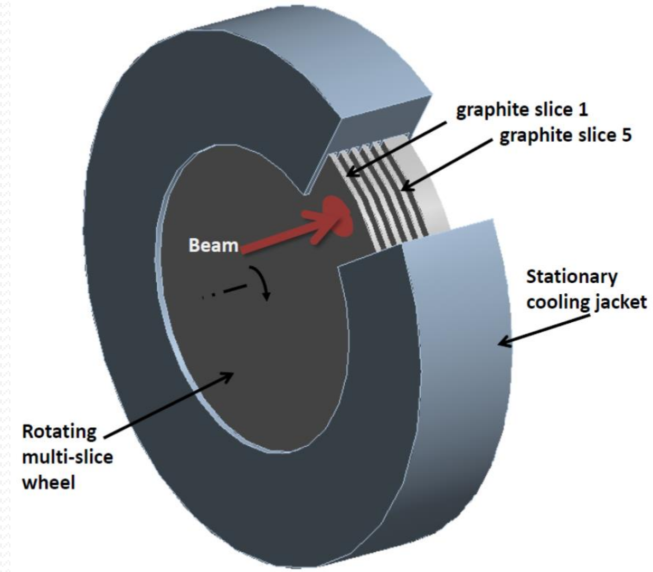
Figure 1 Result from FLUKA simulation of energy deposition in carbon as a result of a 40MeV 30mm radius Deuteron beam

Extremely high power density

35kW/cc at 5mA

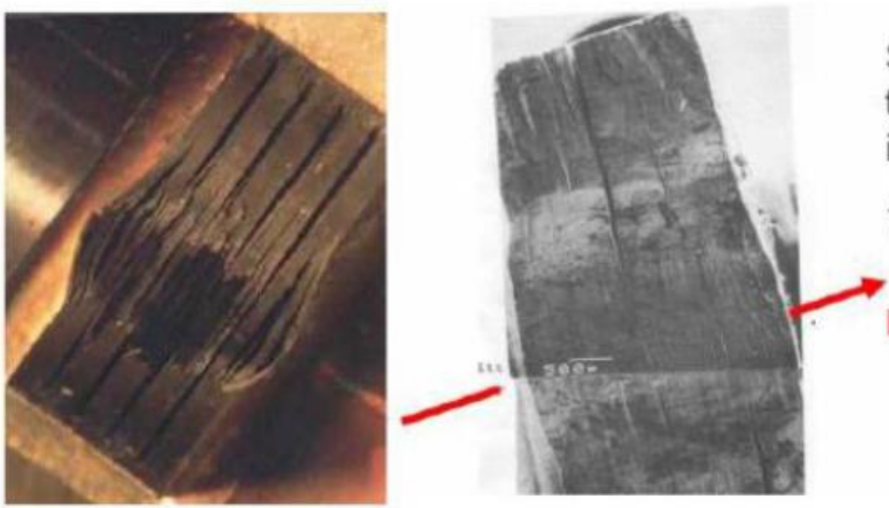
210kW/cc at 30mA

ISIS ~ 0.5kW/cc



High Deuteron Flux

10^{22} protons/cm^2 at higher beam energy known to be a problem in graphite



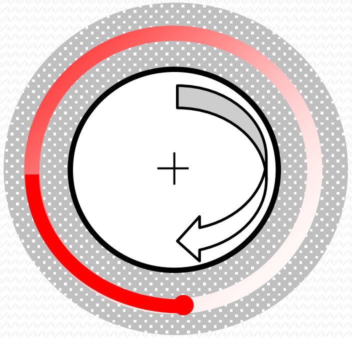
Swelling of the target after irradiation

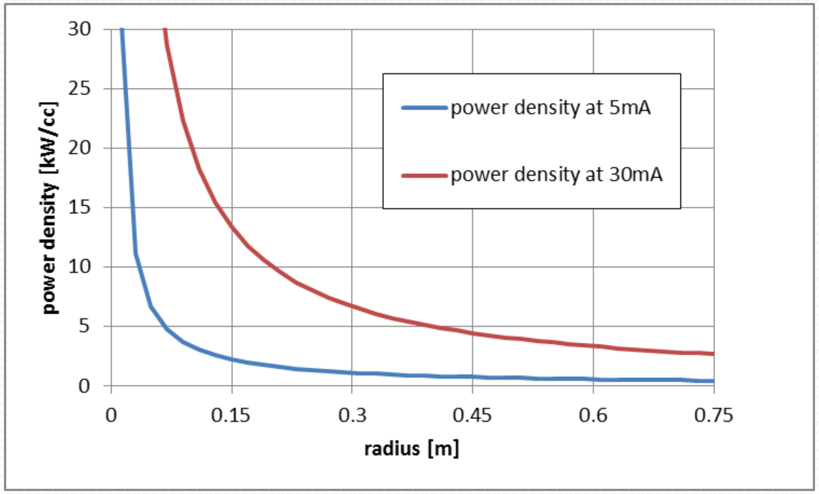
10^{22} p/cm2

Figure 4 radiation damage graphite at TRIUMF (left) radiation damaged graphite at PSI (right)

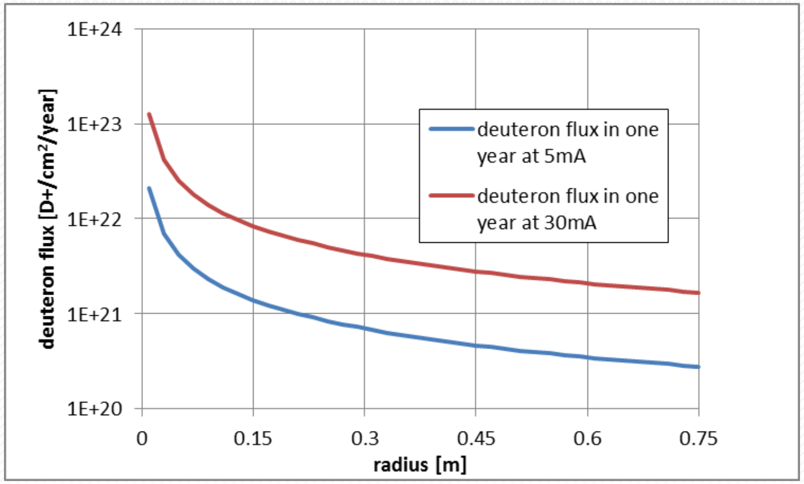
Target Challenges – design optimum to be found

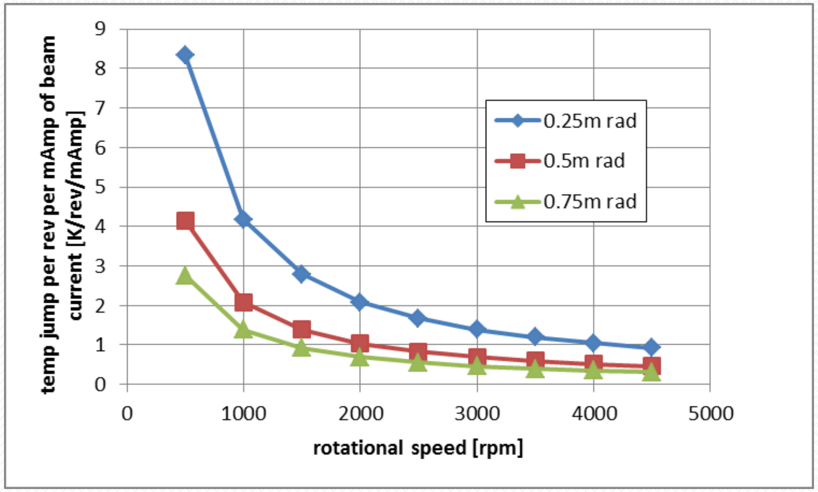
Power density and deuterons/cm^2 inversely proportional to wheel radius



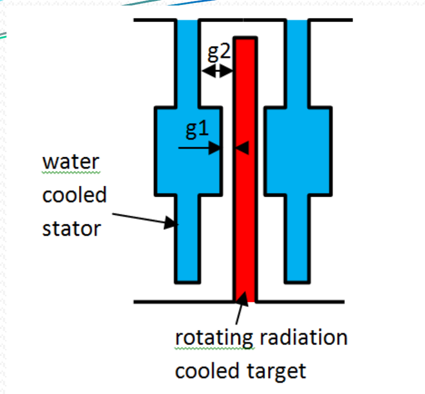


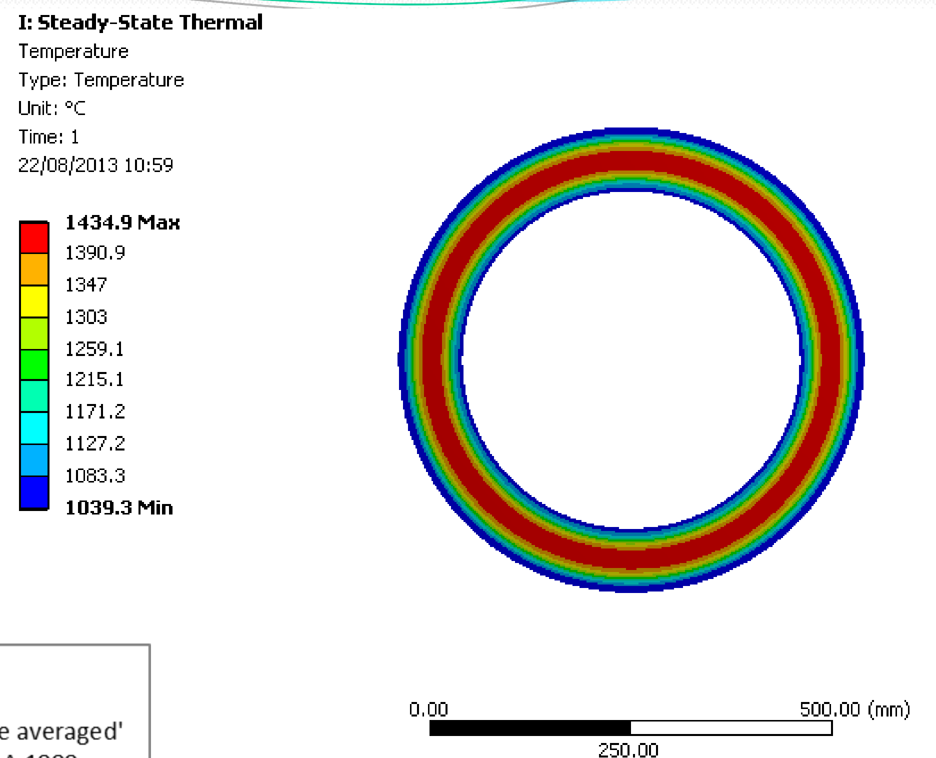
Transient temperature spike per revolution reduced by increasing rotation speed





Target Challenges – operating temperature and stress

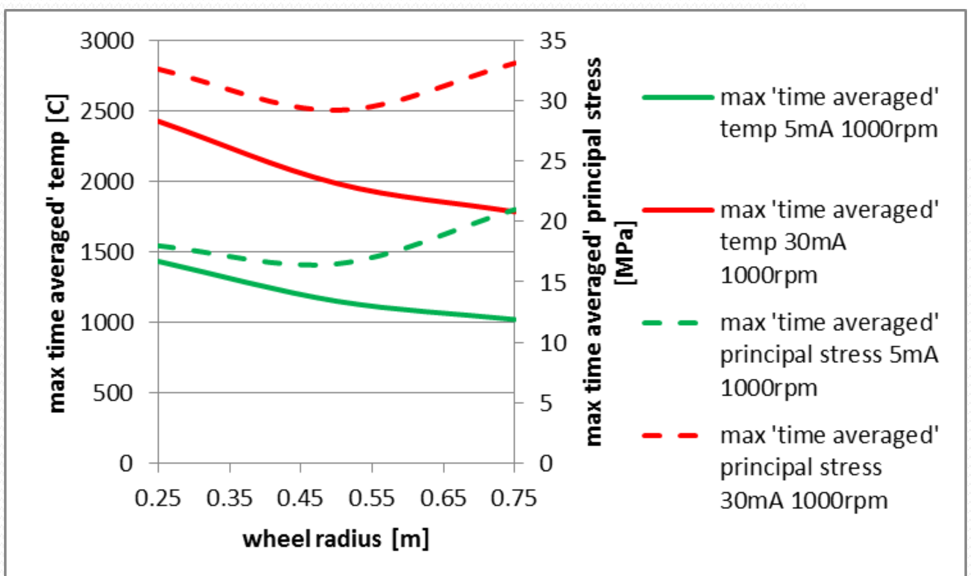




Simulations predict steady state peak temperature of :

1435°C at 5mA for 0.25m radius wheel

2000°C at 30mA for 0.5m radius wheel

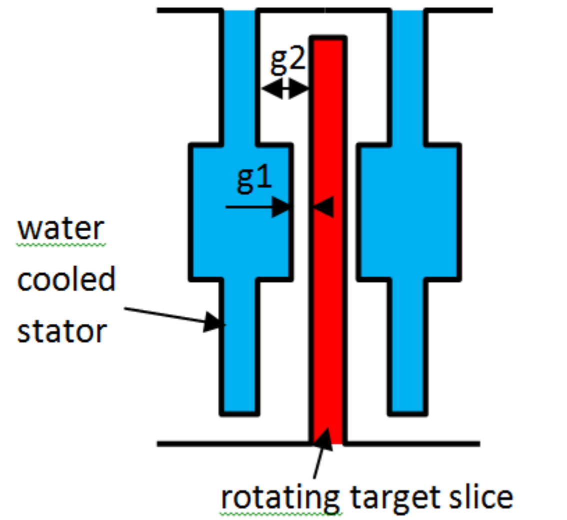


Creep and evaporation a concern at high temperature

Practical operating temperature of graphite is a critical factor for the design

Target Challenges – mitigating risk

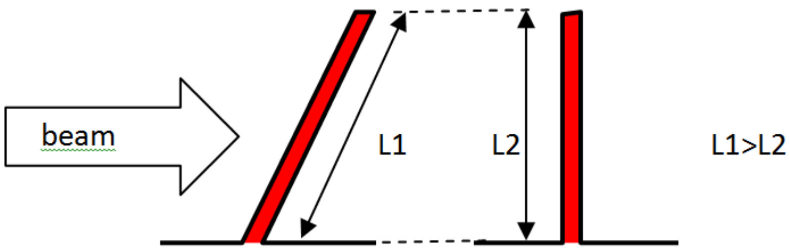
Spinning the target in helium could provide significant heat transfer benefit



Helium provides a useful conduction path between rotor and stator (results for 0.5m radius wheel 30mA)

Cooling scenario	Heat removed from slice 5 by radiation	Heat removed by conduction through helium	Temperature range	Peak Principle Stress
Radiation only	375kW	0W	1418°C – 1988°C	28.8MPa
Radiation plus conduction through uniform helium gap (g1=g2=1mm)	175kW	200kW	932°C – 1672°C	35.6MPa
Radiation plus conduction through non-uniform helium gap (g1=1mm, g2=5mm)	230kW	121kW from g1 region 21kW from g2 region	1309°C – 1671°C	20.5MPa

Angling the target fins with respect to the beam gives an increase in heat transfer area



Target Challenges - Summary

- Deposited power density and deuteron flux push the design towards larger radius
- Transient heating of the graphite wheel and associated stress push the design towards higher rotational speed and thus lower radius
- Detailed design will require input on the reasonable operating temperature and stress of graphite, currently PSI E target has operational experience at 1427°C. GANIL and MSU propose operation at 1850°C and 1900°C but no experience yet.
- Candidate graphite (IG43 & ZXF-5Q) currently being radiated and tested at Birmingham University to investigate change in material properties and exact depth of peak energy deposition
- Preliminary simulations indicate that 5mA operation looks feasible without deviation from the graphite operating temperature at PSI E target station

(radius 0.25m, speed 1000rpm, peak steady state temp 1435°C, transient temp variation per revolution ≤20°C)

- 30mA is much more challenging, however use of helium cooling looks to have potential for helping maintain lower operating temperatures and stresses.

Conclusions

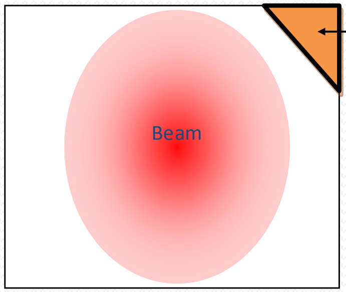
- FAFNIR is a proposal led by the Culham Centre for Fusion energy for a near to mid term fusion relevant neutron source.
- The strategy is to use existing or near term technology.
- The key value is to generate data to support the fusion modelling and engineering design program.
- It will also allow evaluation of the relevance of existing radiation damage data from other irradiation sources such as nuclear fission.
- The proposal has been presented to EFDA (European Fusion Development Agreement) and has been included in their 2013 annual report
- Operation in early 2020s is thought to be possible if project commences soon
- Could provide up to 10 years of irradiation before critical design decisions for DEMO have to be made

- However to maintain DEMO-relevant timescale, prompt engagement now required with:

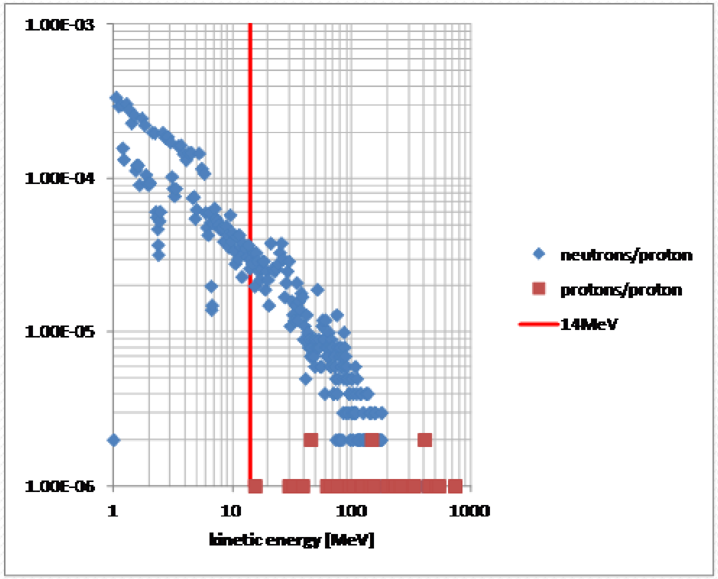
➢ Fusion material experimentalists
➢ Target experts
➢ Accelerator community
➢ Industry
➢ UK and EU Governments

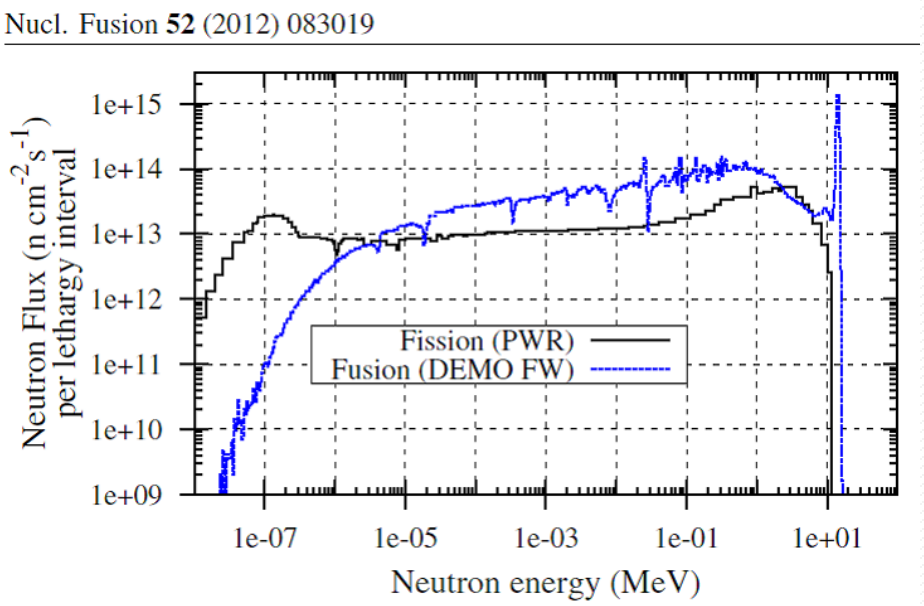
Hi Chris, Well I had a look at a corner of the ISIS target on several plates. The idea being that the corner was not in the line of sight of the beam

i.e.



Here is a result for the sample corner on plate 1 showing both the neutrons/proton and the protons/proton entering the sample corner. The sample corner is an icosolese right angle triangle 12mmx12mmx17mm and is 11mm thick in the beam direction, i.e. thickness of plate 1.





I reckon this corner receives about 5e-23dpa/proton which at 1e15p/s (i.e.160mA) is 1dpa per year (assuming a year is 2e7 s). You can see there are quite a few 14MeV neutrons compared to high energy protons but there are a lot of lower and higher energy neutrons going through the sample as well. Below is the classic neutron spectrum expected from fusion for comparison. Clearly not the same but perhaps the current irradiated target may be of some interest none the less. TS2 may also be of interest.

Original Fusion Requirements for a Neutron Source

Role

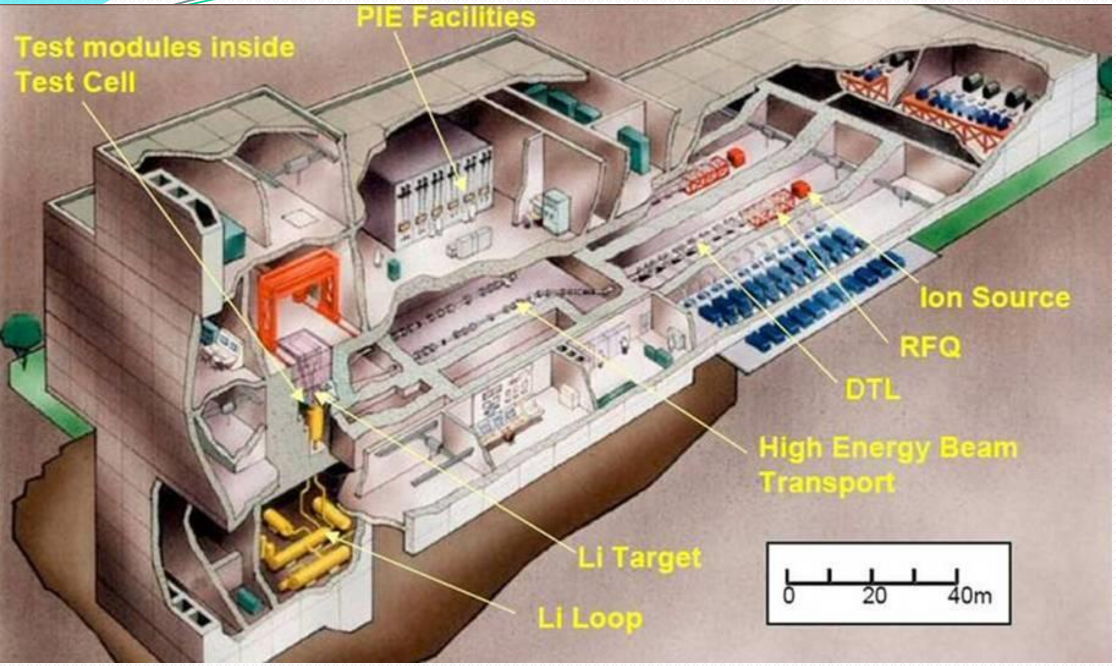
- Design-relevant engineering databases for a DEMO application
- Calibration and validation of fission reactor and ion irradiations
- Strengthen predictive materials modelling capability

Requirements

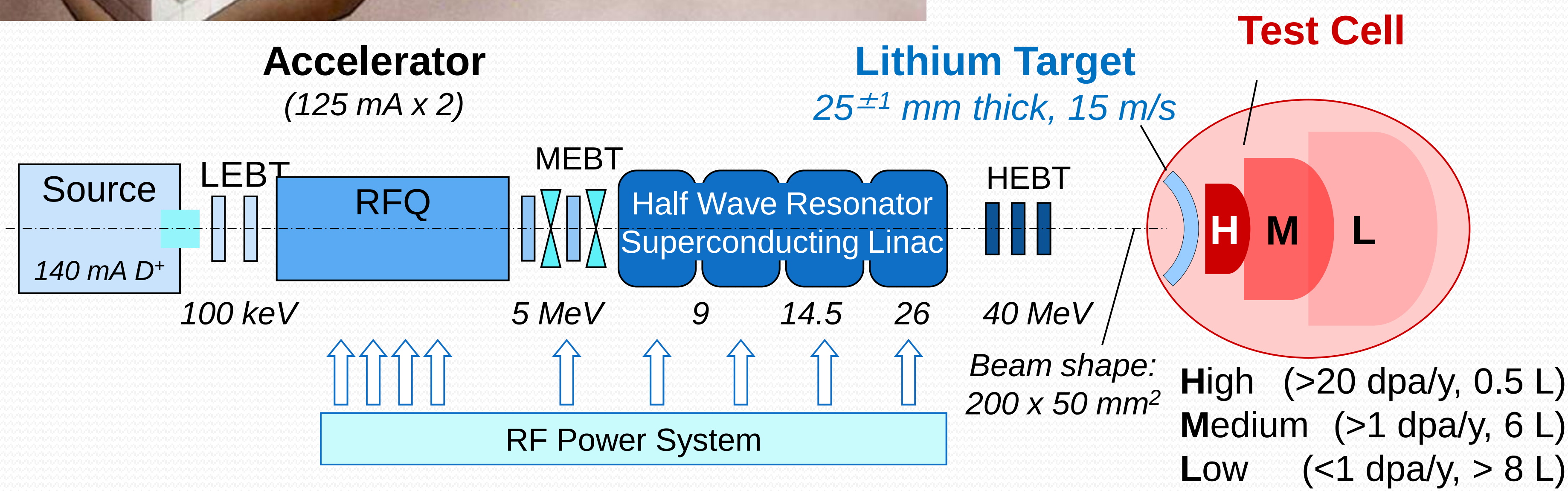
- Simulation of first wall neutron spectrum:
  - primary recoil spectrum (PKA)
  - important transmutation reactions
  - He and H generation
- Appropriate flux to obtain 150dpa within a few years
- High machine availability (~70%) with quasi-continuous operation
- Small flux gradient over the volume (<10%/cm)

IFMIF Comprehensive Design Report (2003)

Satisfying these requirements leads to the IFMIF Facility



- Accelerator driven Li(d,n) source
- 2 x 125mA 40MeV deuteron beams
- Liquid lithium target (~15m/s) subject to 10MW 1GW/m^2
- 2.2x10^{18}n/m^2/s (50dpa/FPY) for HFTM of 100cm^3
- Full range of PIE facilities
- Designed to reach ~150dpa within a few years of full power operation
- €665M estimate in 2003

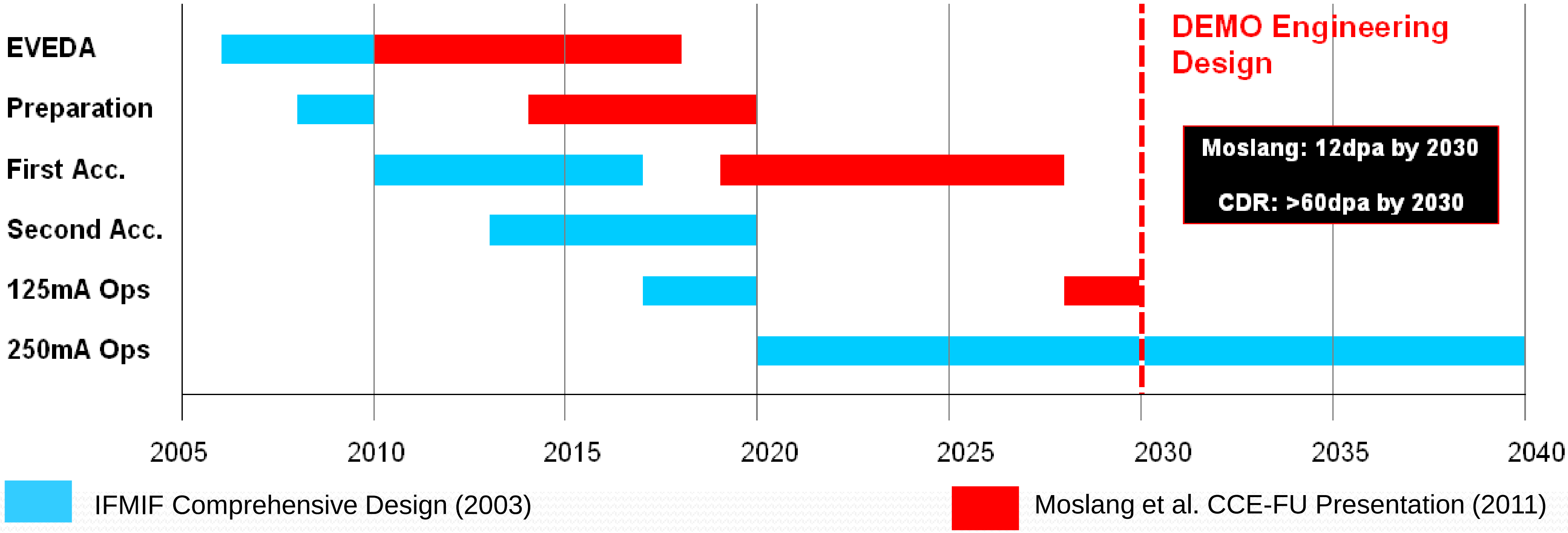


The Challenge of IFMIF…..programme

For DEMO to be ready for commissioning by 2040, the Engineering Design must be completing in ~2030.

The new timescale for IFMIF will be too late to provide the data necessary for the original DEMO first wall spec.

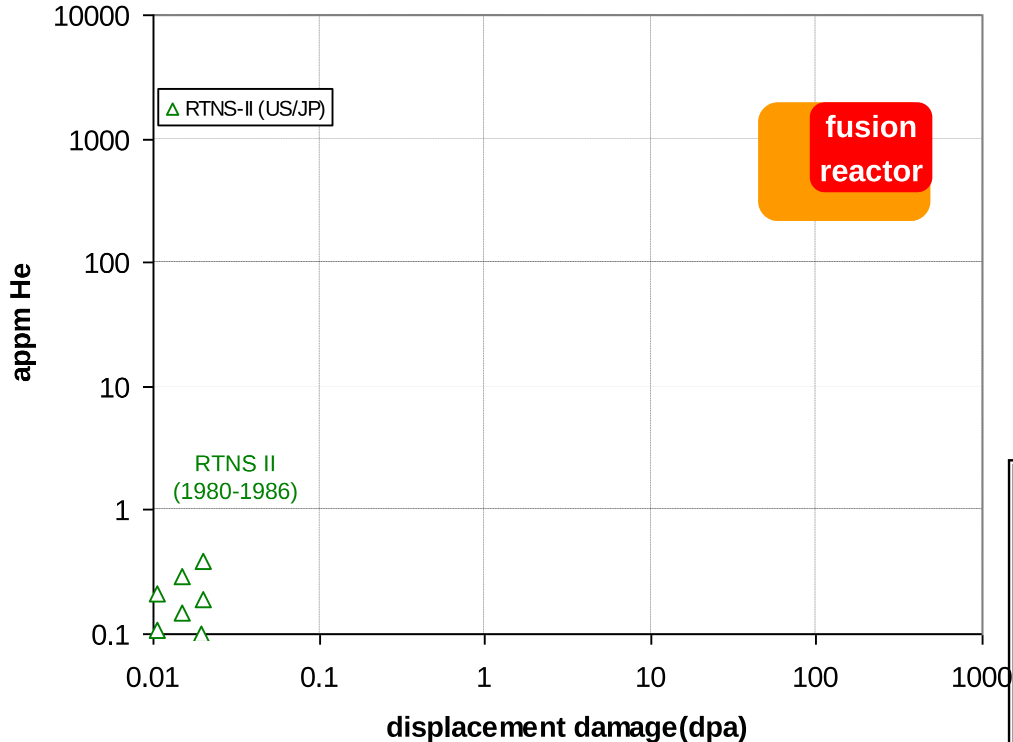
How could we reduce the risk to the timely realisation of DEMO?



To qualify candidate materials before DEMO design finalisation, we need a broad-based materials programme and a reduced scope 14 MeV source.

The Lack of 14MeV Irradiation Data

- Highest damage in 14MeV spectrum < 0.1dpa at Rotating Target Neutron Source-II US (1980-1986)
- Greater damage only achieved via fission spectrum
  → Unrepresentative as transmutation (He and H production) occurs above a few MeV and increases embrittlement
  - insight into helium effects via isotopic tailoring
  - differing transmutations and thus material response



US data from Zinkle (2004) &
EU data from Gaganidze et al. J Nucl Mat **386-388** 349-352 (2009)

25 years with numerous available reactors to generate a reliable data base for fission core structural materials…

There is no 14MeV source operating or planned of sufficient intensity to generate >1dpa/FPY

There is growing consensus in the materials community on the need for small, novel neutron sources to address this shortfall in 14MeV irradiation knowledge

e.g. Kurtz et al. Briefing for Synakowski (2009)

Mitigating the Risk to DEMO

What do we actually need to be able to build DEMO?

- Materials degradation phenomena such as He embrittlement, irradiation creep, volumetric swelling, and phase instabilities manifested at >10 dpa

- Lowered damage rate specification reduces risk and development time of a 14MeV source

  High flux test module of IFMIF >50dpa/fpy only need >5dpa/fpy

- Advances in miniaturised specimen testing allow the irradiation volume to be reduced also eases the 14MeV source specification

  High Flux Test Module of IFMIF 100cm^3 only need 10cm^3

e.g. Armstrong et al. Scripta Materialia 61, 741 (2009)

What could be built using today's technology with low technical risk and rapid deployment?

Back up slides

A Survey of 14MeV Neutron Sources

Facility	Neutron Yield (neutrons/sec)	Damage Rate (dpa/FPY)	Status
RTNS II (US)	$\leq 4\times10^{13}$n/s	<1	Shutdown
ASP (UK) / Valduc (FR) / FNG (IT) / FNS (J)…	$\leq 2.5\times10^{11}$n/s	<0.01	Operational
GANIL (FR)	~~$\sim10^{15}$n/s~~	~~≤ 7~~	~~Original proposal~~
	$<10^{13}$n/s	<0.1	Planned
ESS-Bilbao (ES)	$\sim10^{13}$n/s	~1	Planned
IFMIF (?) ?	$\sim10^{17}$n/s	≤ 50	Planned

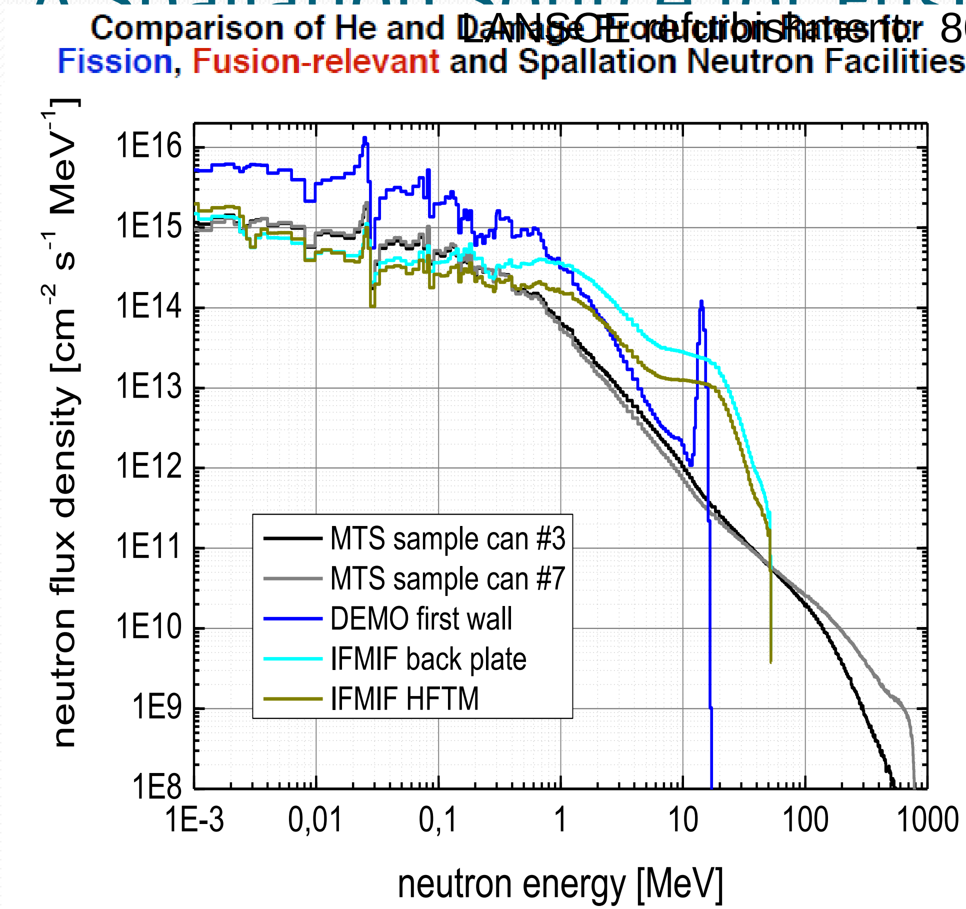
- Issues of capability and availability for each source…

…..at present there is not one high flux fusion neutron facility

Is it possible to approximate fusion requirements with a spallation source?

A Spallation Source for Fusion?

LANSCE refurbishment: 800MeV 1.25mA H+ beam



...ation (MTS) to irradiate candidate ... with overlap to fusion

- Far from ideal for fusion:
  - **- High & Low energy tails**
  - **- High p flux**
  - **- Pulsed time structure**
  - **- Availability issues**

Image courtesy of Zinkle, Adv Comp Sci Presentation (2004)

Image courtesy of D. Rej, LA-UR 09-06728

Comparing Neutron Sources for Fusion

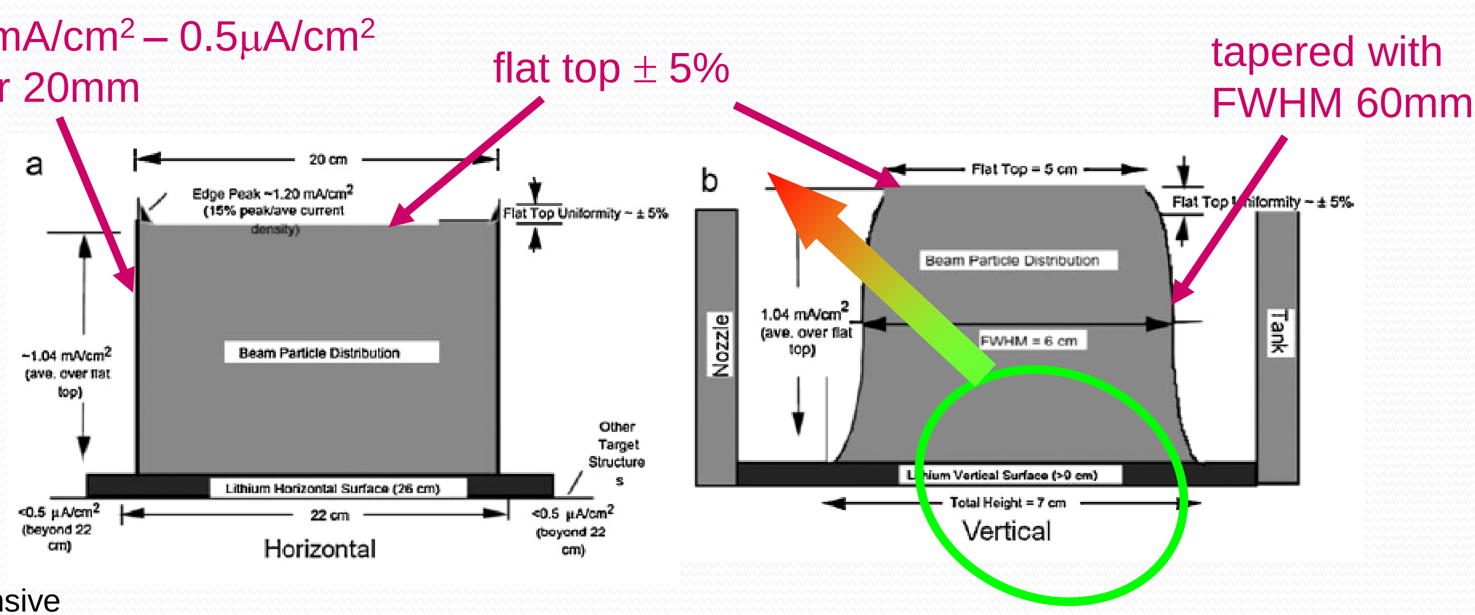
- Spallation
  - \+ Mature technology, High dpa
  - \- Pulsed irradiation, neutron spectrum and co-incident protons → **He production too high & large transmutation rates**
- Stripping
  - \+ **Good mimicry of fusion spectrum**, continuous irradiation
  - \- Limited sample sizes (~cm), **high dpa is technologically challenging**
- Beam-plasma (aka CTF)
  - \+ **Best mimic of fusion spectrum**, large sample sizes, explores synergistic effects
  - \- Large capital cost, **technology gap**, T fuelling needs
- Materials Test Reactor
  - \+ Mature technology, high damage accrual rates, large sample sizes
  - \- Fission neutron spectrum → **He/dpa too low**, availability

Fusion relevant spectrum → ***Stripping*** or Beam-Plasma

Technological maturity → ***Stripping*** or Spallation

The Challenge of IFMIF… technical

- ***Satisfying these requirements simultaneously leads to IFMIF***
  - Technologically challenging
    - accelerator power, beam uniformity & profile, average beam power, beam losses
    - liquid lithium target – flow uniformity & velocity



IFMIF Comprehensive Design Report (2003)

Beam uniformity & profile for IFMIF

profiling essential to avoid thermal shock to Li

uniformity essential for irradiation zone

Capability

	IFMIF[4]	FAFNIR		
		Target Technology Level		
		Existing	**Near-term (Baseline)**	**Prospective (Upgrade)**
Beam	40MeV, 250mA	40MeV, 2.5mA	**40MeV, 5mA**	**40MeV, 30mA**
Target	10MW Liquid Li	100kW Solid rotating C Single-slice	**200kW Solid rotating C Single/multi-slice**	**1.2MW Solid rotating C Various options**
Typical DPA/FPY Contours	≥1 → 6000cm3 ≥20 → 500cm3 ≥50 → 100cm3	≥0.6 → 100cm3 ≥1 → 50cm3 ≥3.8 → 10cm3	**≥1 → 150cm3 ≥1.5 → 100cm3 ≥4 → 25cm3**	**≥5→ 150cm3 ≥7 → 100cm3 ≥20 → 25cm3**

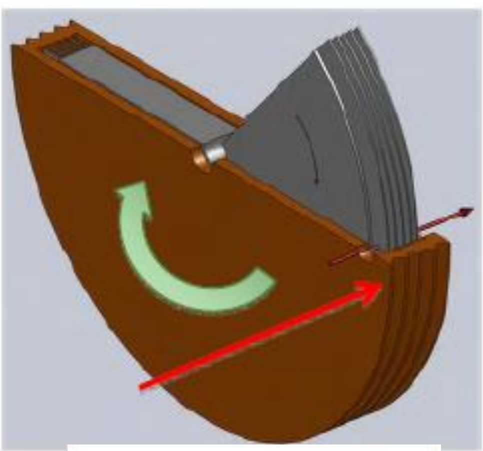
- Build accelerator for final foreseen current
- Progressive increase of target power handling → parallel development programme

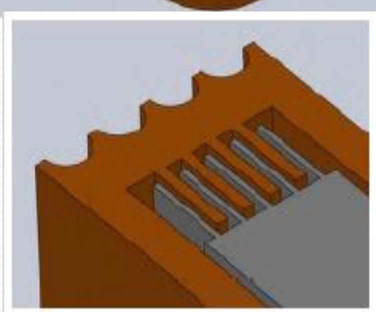
- **Upgrade Path**

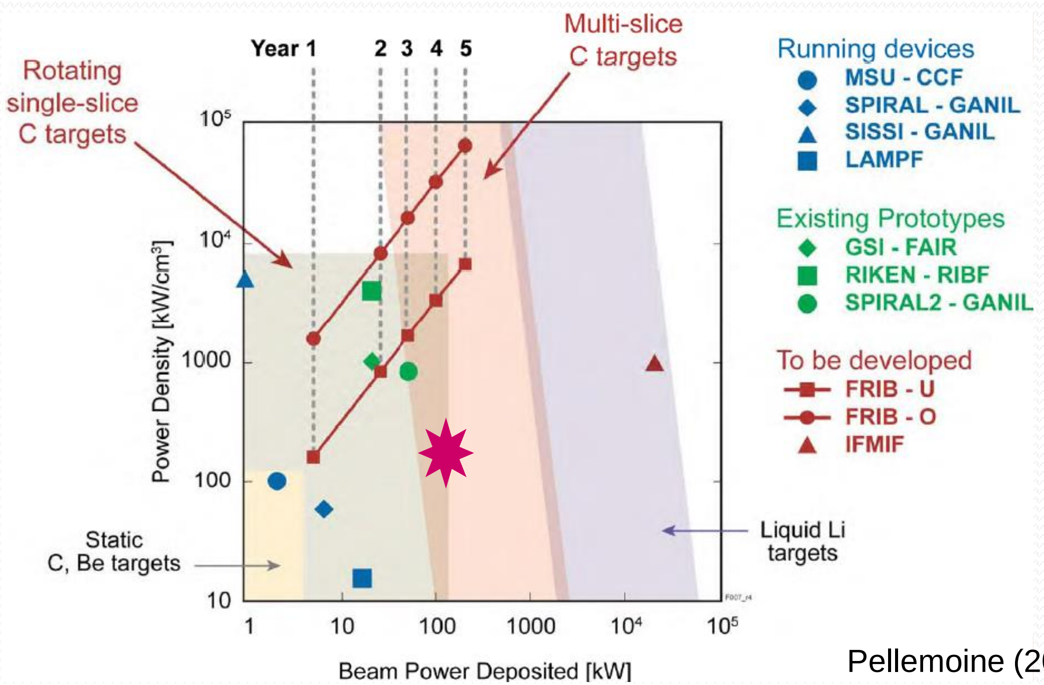
Technology Maturity - Target

- **Target** - Rotating/multi-sliced carbon - 24kW/cm^3 / 240kW
- Static solid targets up to 100kW/cm^3 / 5kW
- Rotating single slice targets 50kW/cm^3 / 7kW or 15kW/cm^3 / 20kW
- Rotating multi-sliced target **prototypes planned to operate at 1900C short operation periods**
  - 800kW/cm^3 / 50kW (SPIRAL 2)
  - 5000kW/cm^3 / 400kW (Michigan State University Radioactive Ion Beam Facility)

  PSI E rotating graphite target operating at 1427C for years







Pellemoine (2010)

The timescale to fusion power could be accelerated with increased funding. Overall research spend on fusion is tiny – less than 0.1% of the total energy market worldwide. This is astonishingly small compared to what a large hi-tech or automotive firm would spend on research (e.g Toshiba, Ford). ITER's expected lifetime cost is less than the amount being spent on the London Olympics.

Thermo-Mechanical Feasibility of the proposed FAFNIR Target

At the heart of the FAFNIR proposal is a target which must produce the 14MeV neutron flux required for fusion materials research. The preferred target material is graphite and the proposed beam parameters for the facility are listed below

Beam particles – Deuterons

Beam time structure – c.w.

Beam kinetic Energy – 40MeV

Beam size – 3cm radius (flat top/rectangular profile)

Beam current – 5 to 30mA – [illegible] to [illegible] Deuterons/s

Beam Power – 0.2 to 1.2MW

The combination of a high deuteron flux and high power density motivate the proposal of a multi-layered spinning radiation cooled graphite target wheel for FAFNIR. The use of a spinning wheel