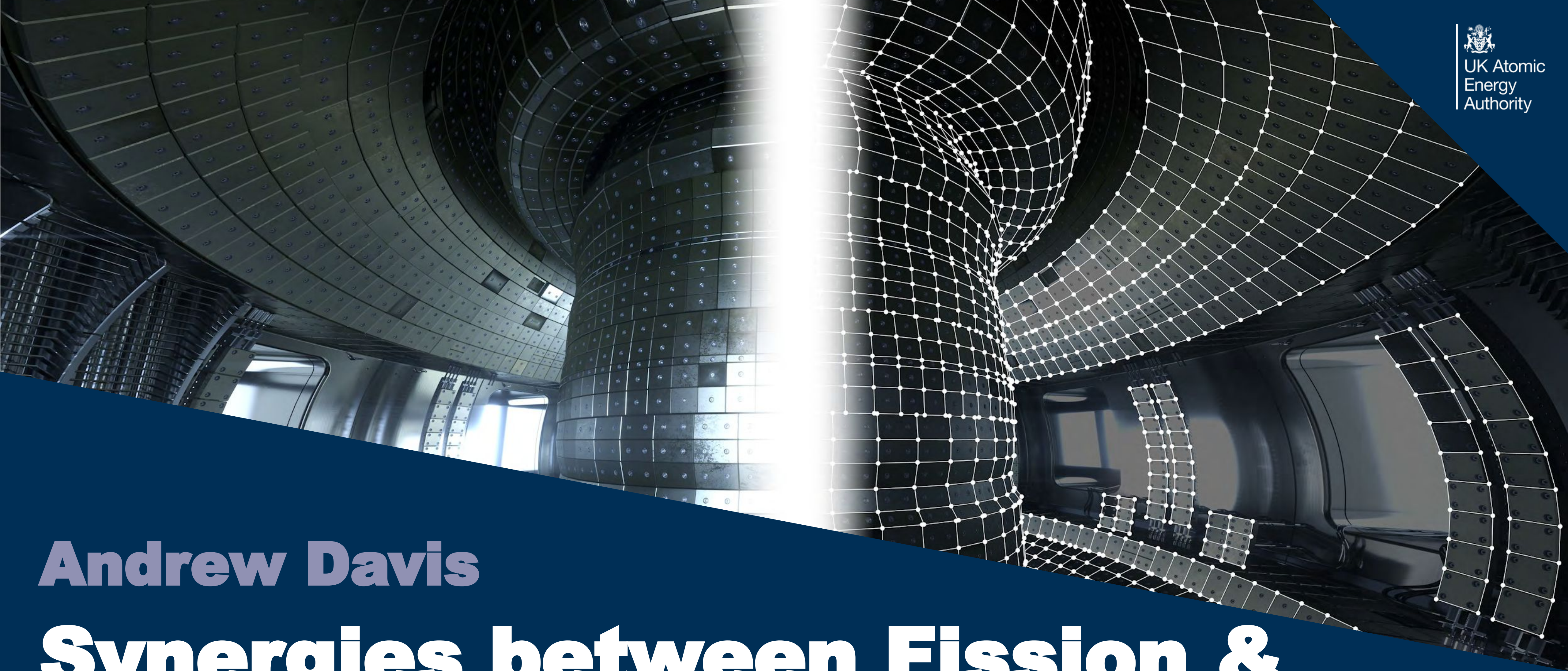

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Andrew Davis

Synergies between Fission & Fusion: Simulation

IAEA Technical Meeting on synergies between technology development between fission and fusion for energy production - June 8th 2022

Official

Use of simulation in Fission & Fusion

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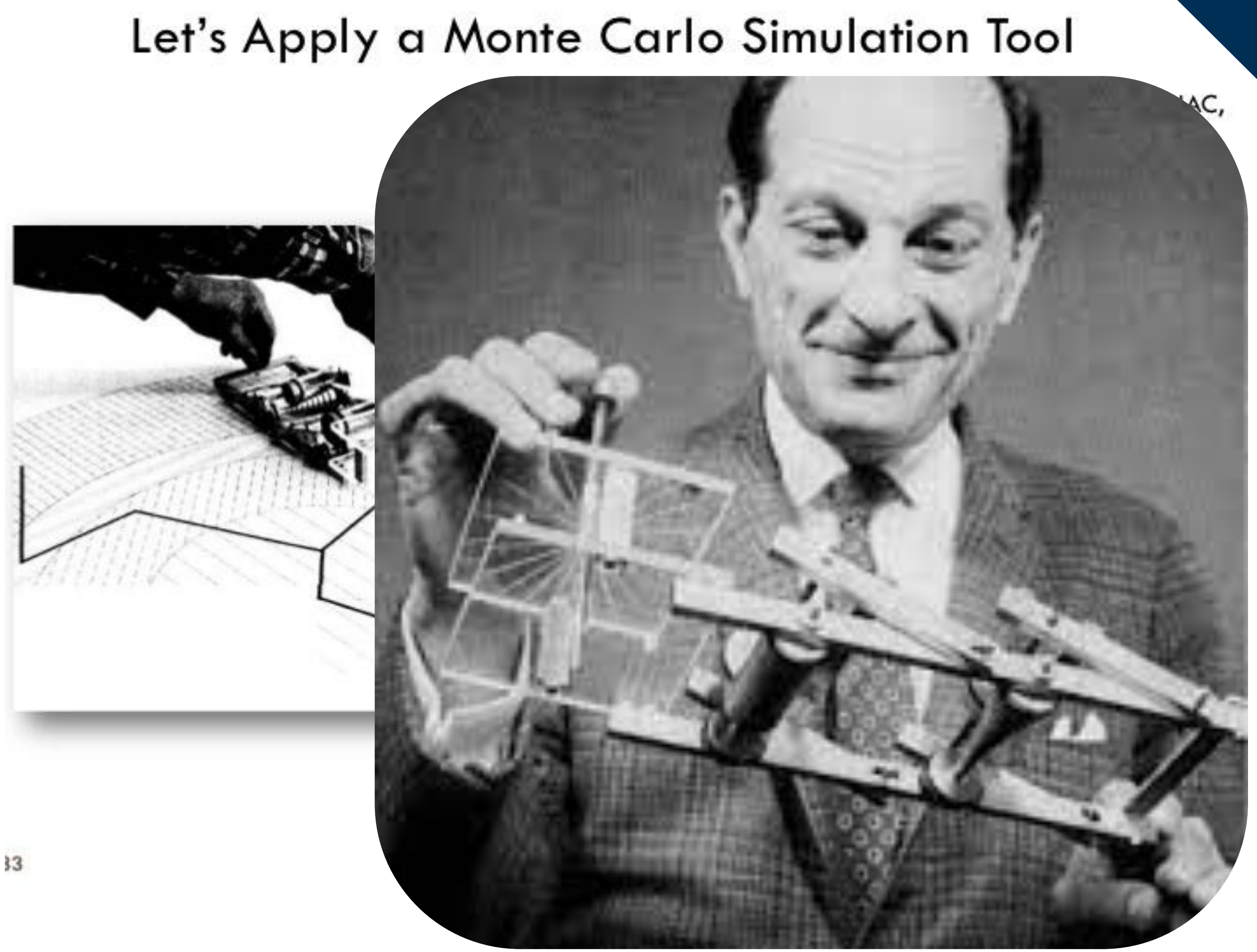
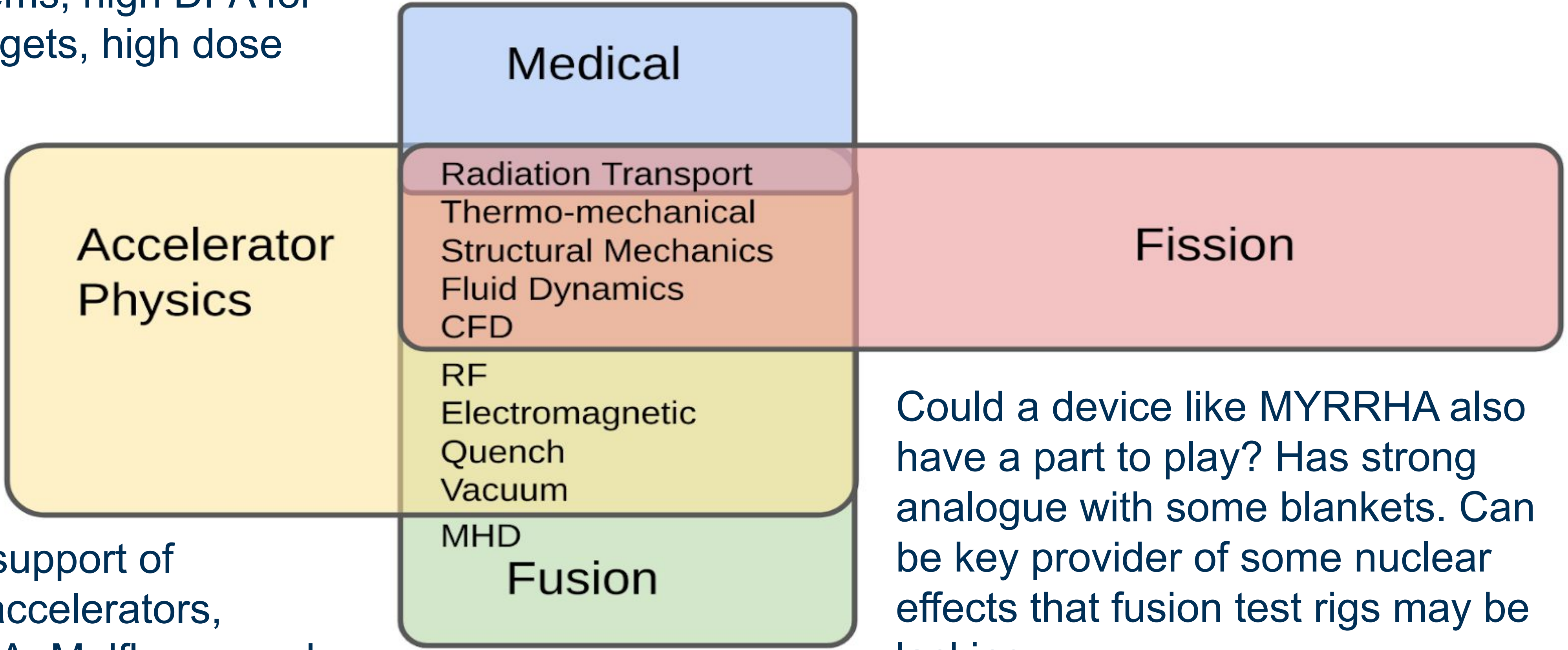
- Calculation in support of nuclear has been done as long as nuclear has been a field
- (Computer) Simulation in support of nuclear technologies dates back at least to the Manhattan Project, when the calculations got too large
- Simulation now pervades many (all?) aspects of nuclear engineering
- Many tools used in fusion engineering are borrowed from fission
    - Show us the validation, is it right for fusion?
    -



Let us not forget other domains

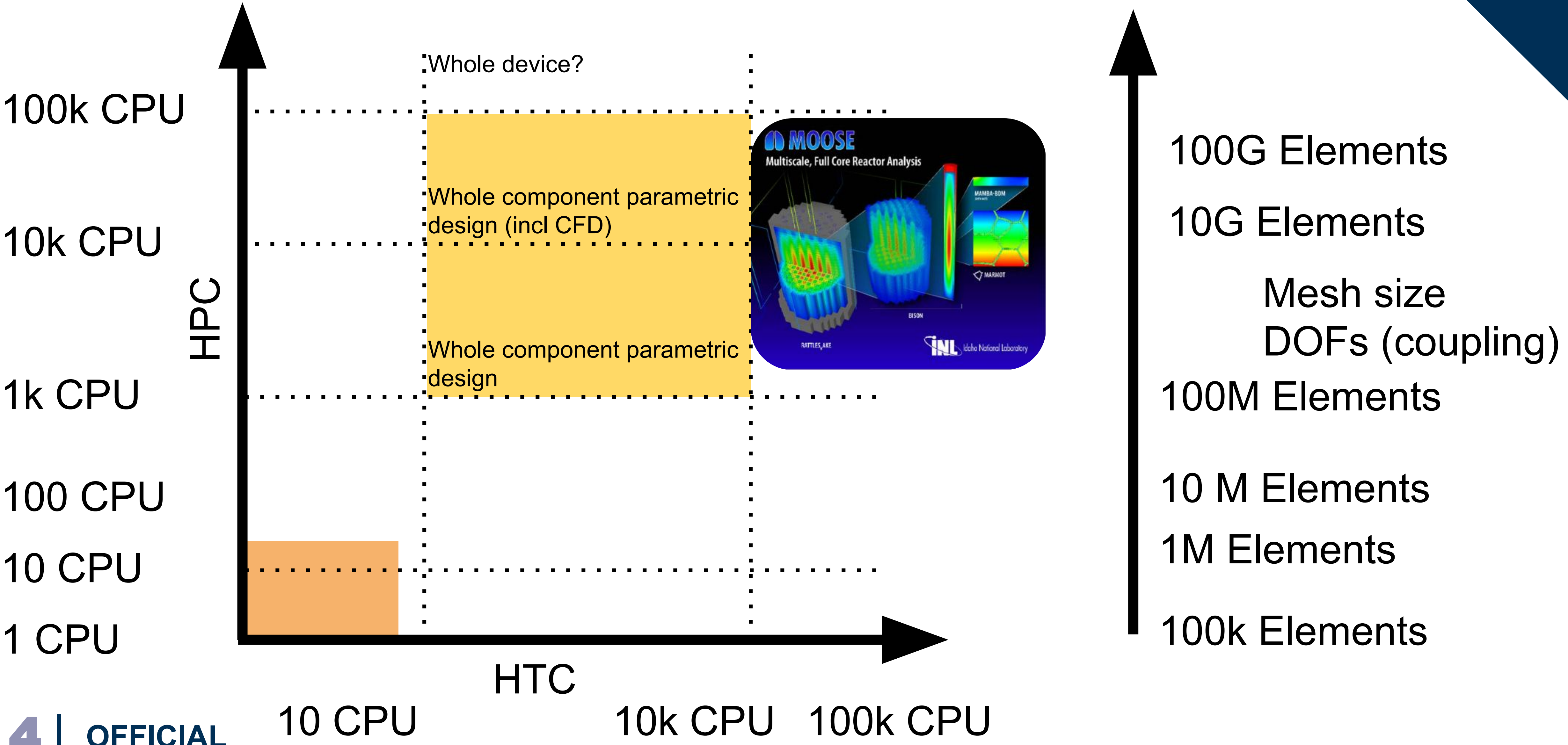
Let us not forget that accelerators experience similar effects to those in fission systems; high DPA for accelerator targets, high dose rates



Tools used in support of experimental accelerators, Geant4, FLUKA, Molflow can also be reused in fusion applications

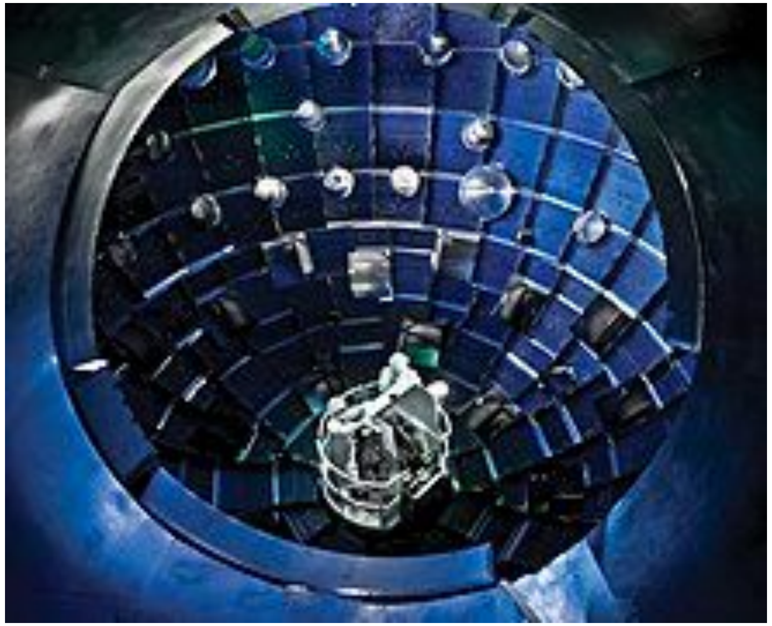
Could a device like MYRRHA also have a part to play? Has strong analogue with some blankets. Can be key provider of some nuclear effects that fusion test rigs may be lacking

Fission & Fusion share scale challenge

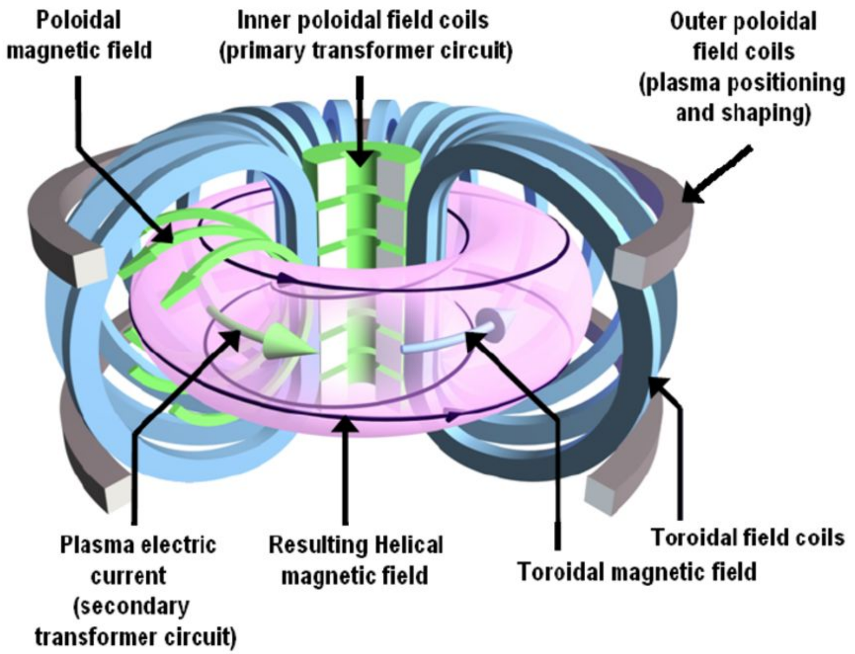


Modelling for Nuclear Fusion

- Computational modelling for nuclear fusion covers a large range of time and length scales depending upon the phenomena
  - From nm ➡ m
  - From ps ➡ thousands of years
- For the purposes of this talk, I will only discuss Inertially Confined Fusion (ICF) and Magnetically Confined Fusion (MCF), there of course are other forms

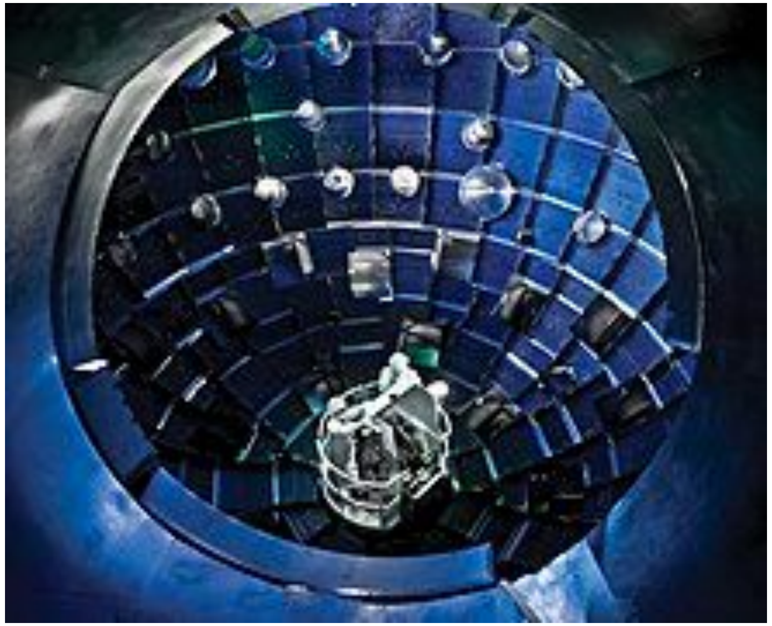


ICF Facility

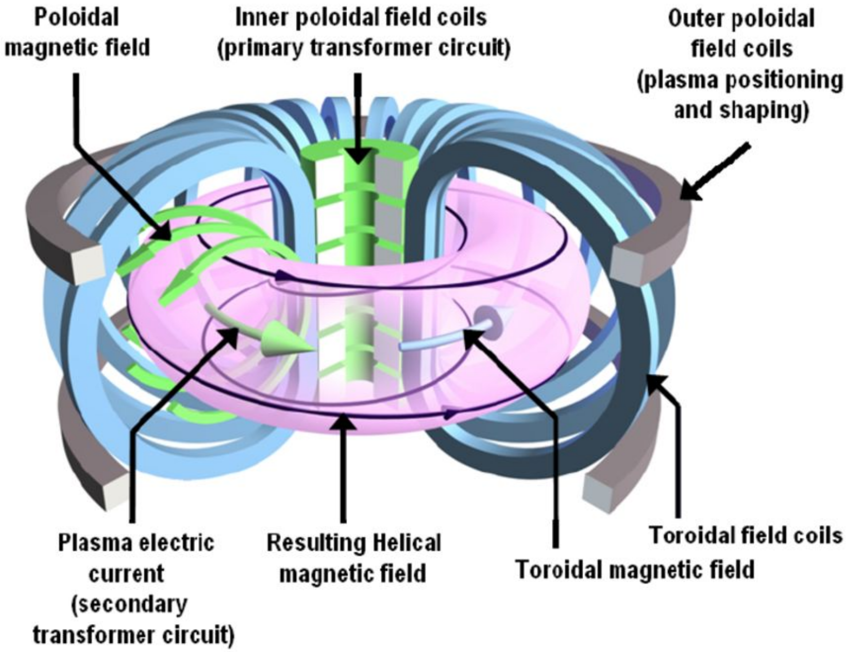


MCF Facility

Modelling for Nuclear Fusion



ICF Facility



MCF Facility

- Pulse length ~ 1 ms (1 ns)
- Repetition Rate ~ 10-60 Hz
- Fusion Power ~ 1000 MW
- Neutron Rate ~ 10^{25} n/s

- Pulse length ~ Hours/Steady State
- Repetition rate ~ 1/3600 - ∞ Hz
- Fusion Power ~ 1000 MW
- Neutron Rate ~ 10^{21} n/s

Modelling for Nuclear Fusion - Radiation

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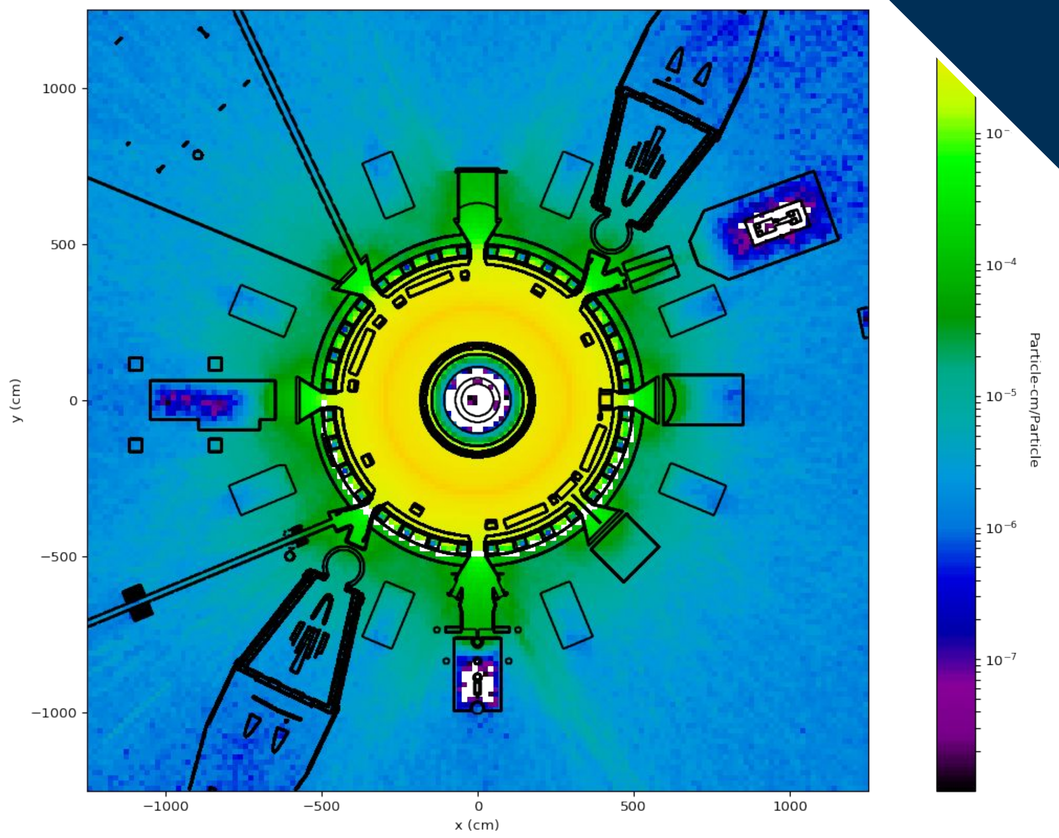
- Radiation modelling - Huge Fission Legacy
  - Neutrons, Photons, Electrons, Positrons
  - Typically want result throughout whole facility
- Traditionally done with MCNP (or Tripoli4, Serpent)
  - Most software not permissively licensed
  - Difficult to deploy at scale on arbitrary HPC systems
- More permissive licencing needed for continued use
- Open source switch likely otherwise
  - **OpenMC, Geant4**
- Typically steady state simulation done
- Usually neglect impact (if any) of magnetic fields

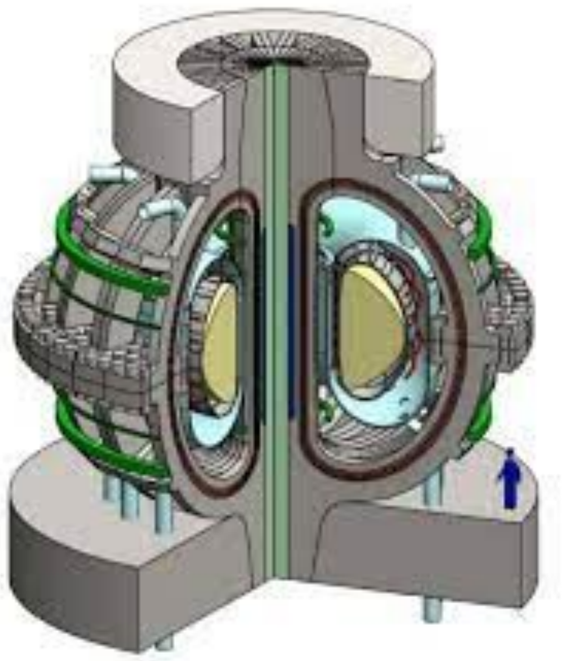


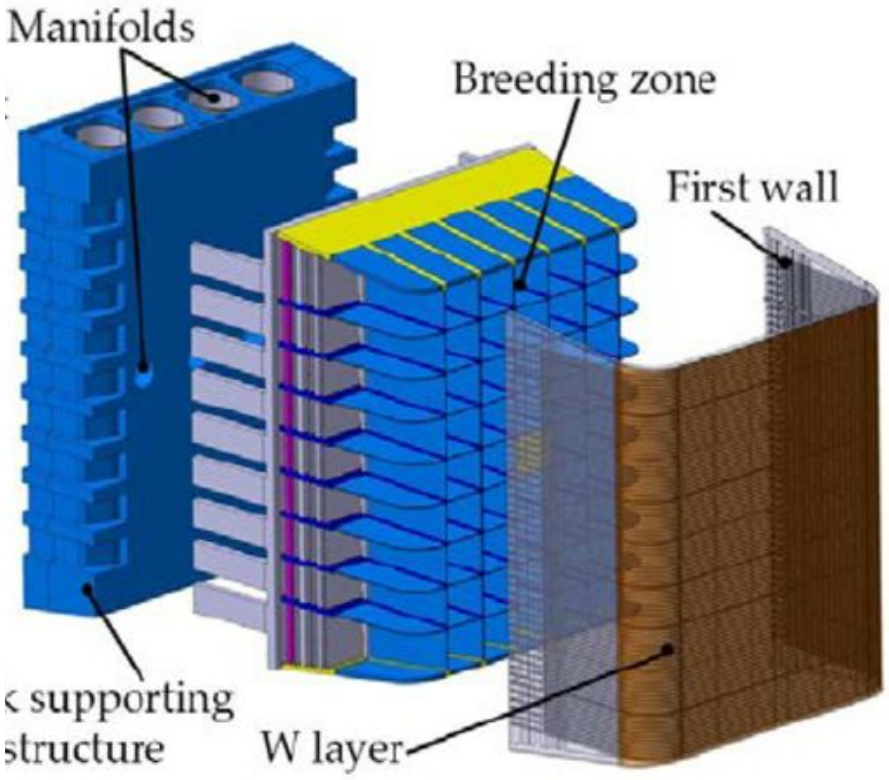
- Deterministic methods usually 3rd rate tools, mostly used to predict VR maps
- Narrow gaps, streaming channels
- CAD Based Analysis e.g. DAGMC

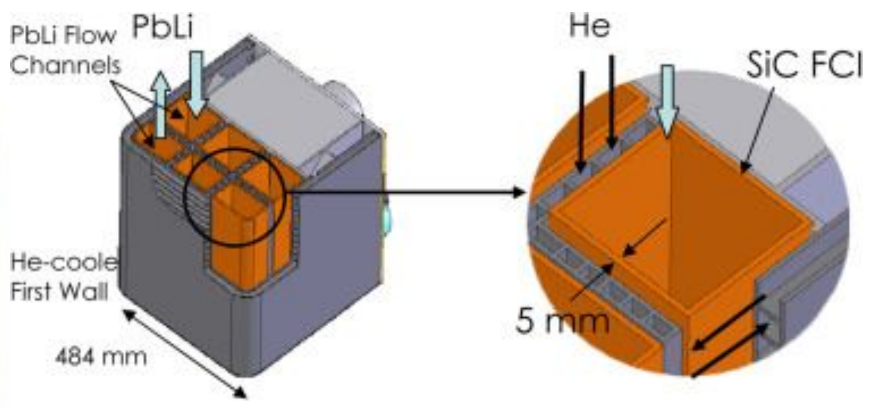
NB ICF has harder neutron spectrum than MCF

Modelling for Nuclear Fusion - Fluids

- Dependent on the blanket technology; CFD for them all but different flow regimes







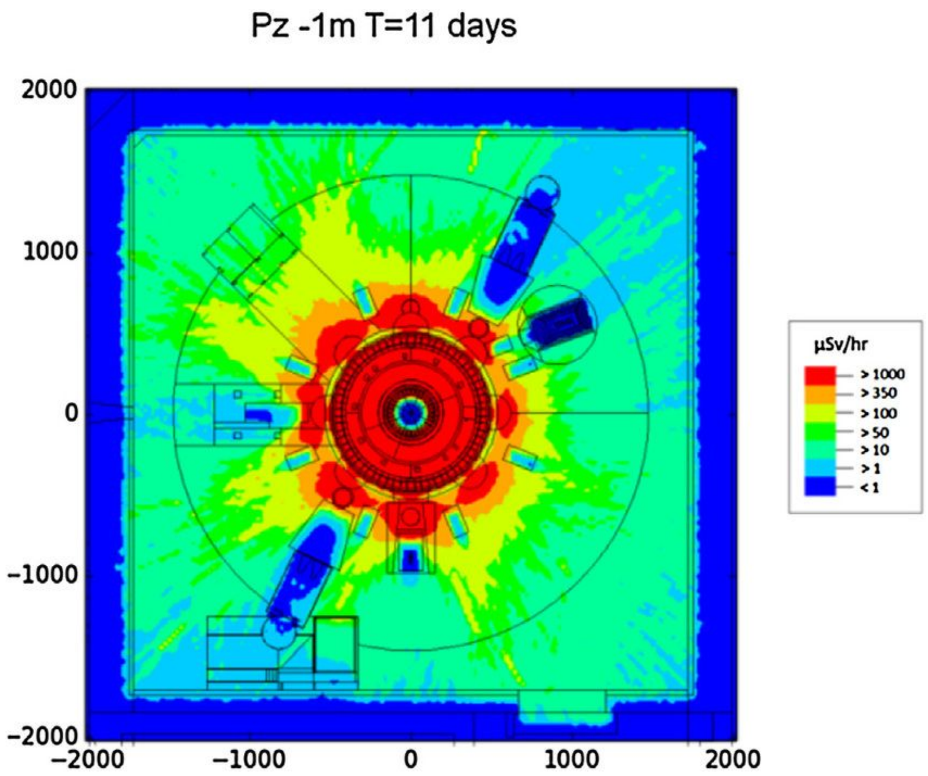
- Bulk Fluid
- High Reynolds number
- Natural convection
- Pumped

- Pipe like flow
- High Reynolds number
- Pressure driven

- Pipe like flow
- High Reynolds number
- Pressure driven
- MHD

Modelling for Nuclear Fusion - Transmutation

- Fusion transmutation calculations are very similar to fission decay chain calculations
- Multiple solution methods: Matrix Exponential, Runge-Kutta, Chebyshev Rational Approximation
  - More complex irradiation schedule
  - Fission - FISPIN, ORIGEN, CINDER (lots of options here)
  - Fusion - FISPACT, ALARA, ACAB, ACTYS, ANITA
- As long as long complex activation/decay chains can be handled then the technology will have continued utility
- Critical for waste assessments
- Important for maintenance activities e.g. shutdown dose rate, or decay heat.



dx.doi.org/10.1016/j.fusengdes.2017.03.131

Modelling for Nuclear Fusion - Nuclear Dat

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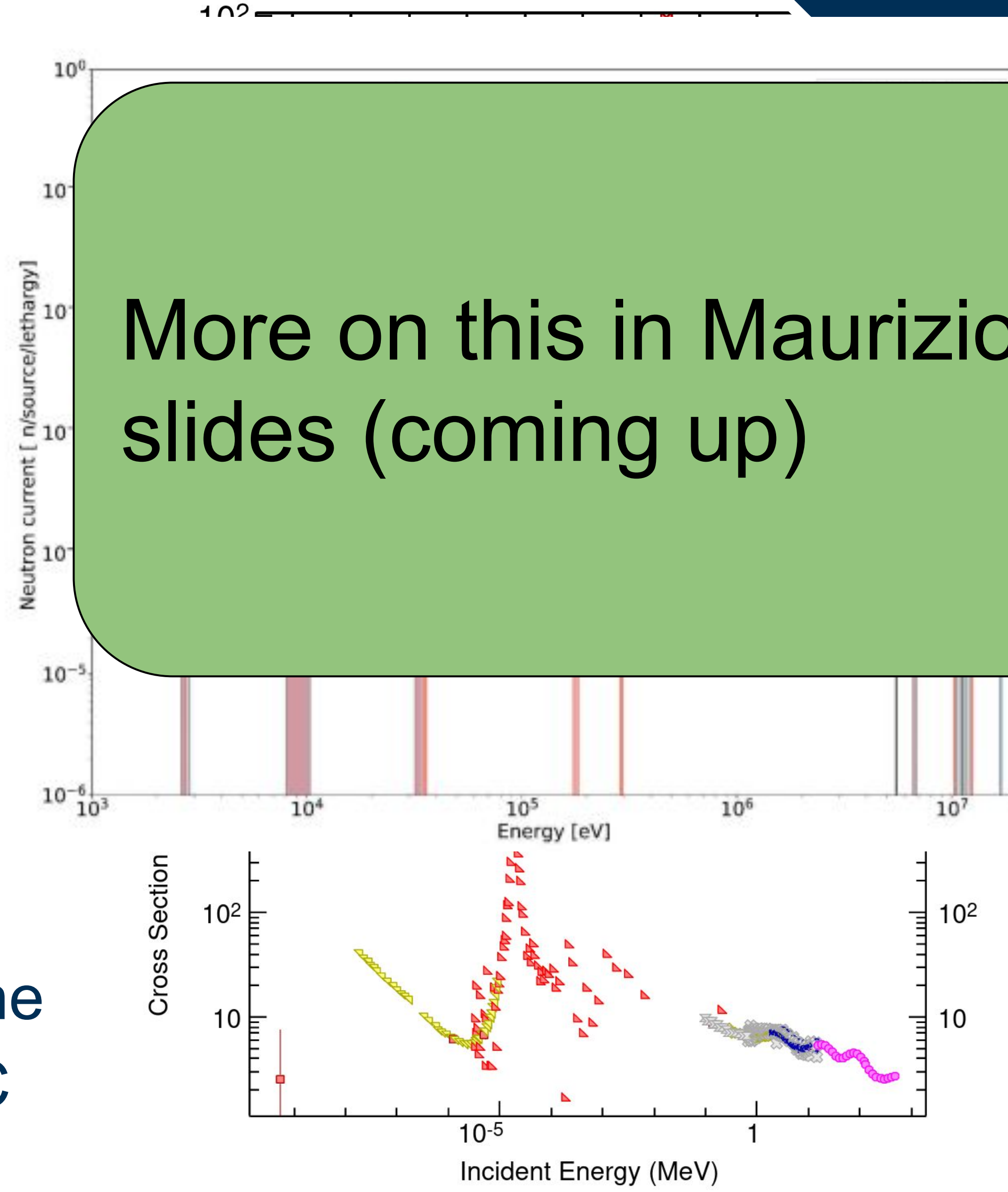
- Nuclear data critical for radiation transport and activation calculations
  - huge legacy of fission investment
- New evaluation tools and formats coming from
  - e.g. GND & Fudge respectively
  - largely legacy formats e.g. ACE, ENDF (deterministic GENDF, MATXS, ISOTXS)
- Fusion leans heavily upon state level & internat efforts in nuclear data
  - EXFOR, FENDL
  - ENDF/B-VIII, JEFF, CENDL, BROND
- Fusion nuclear data needs investment; beyond the golden few - ^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu, ^{1}H, ^{56}Fe, ^{12}C



Modelling for Nuclear Fusion - Multiphysics

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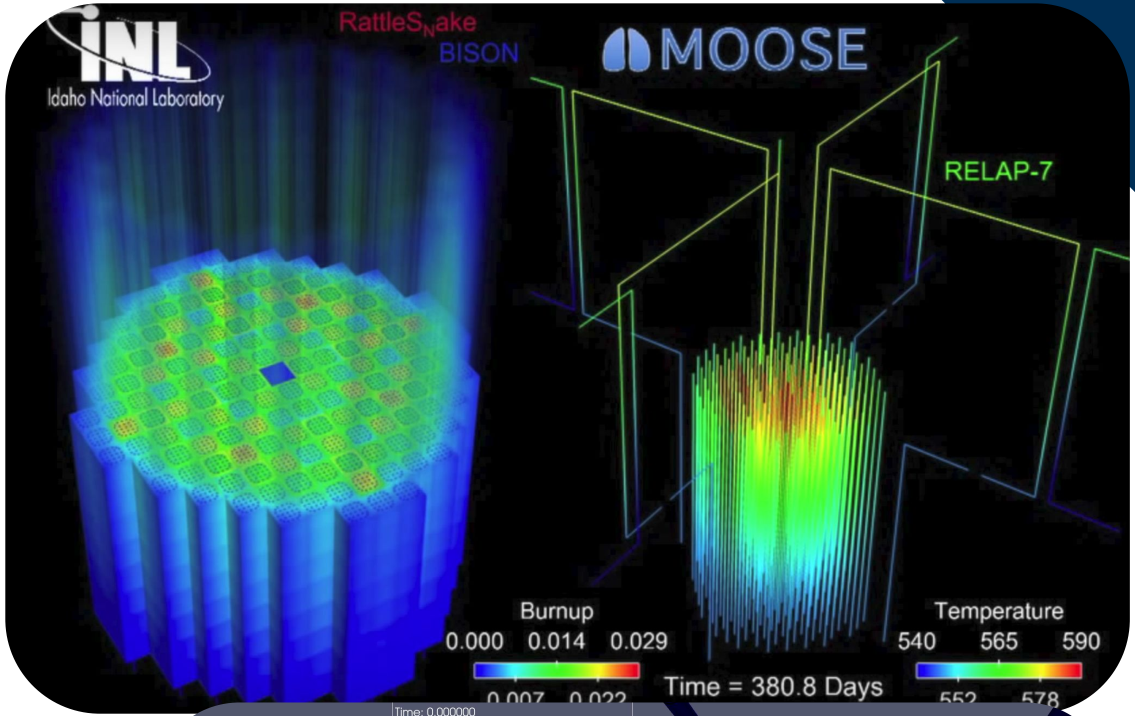
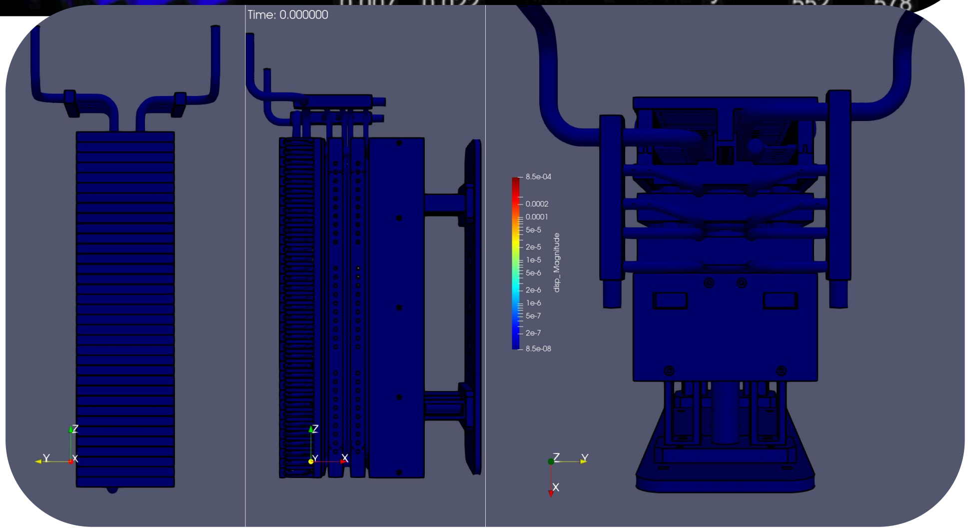
- What is clear is a fusion device (a tokamak specifically) is a highly coupled system;
  - traditional analysis approach is a series of linear steps - “throw it over the wall approach”
  - For complex coupled system, linear steps is an approximation
- Coupling platforms that can integrate many physics into one place **will** allow for more accurate analysis
  - e.g. MOOSE - HPC capable open source multiscale modelling toolkit
  - Single physics becoming less valuable, unless software has an API





Modelling for Nuclear Fusion - Validation & Verification

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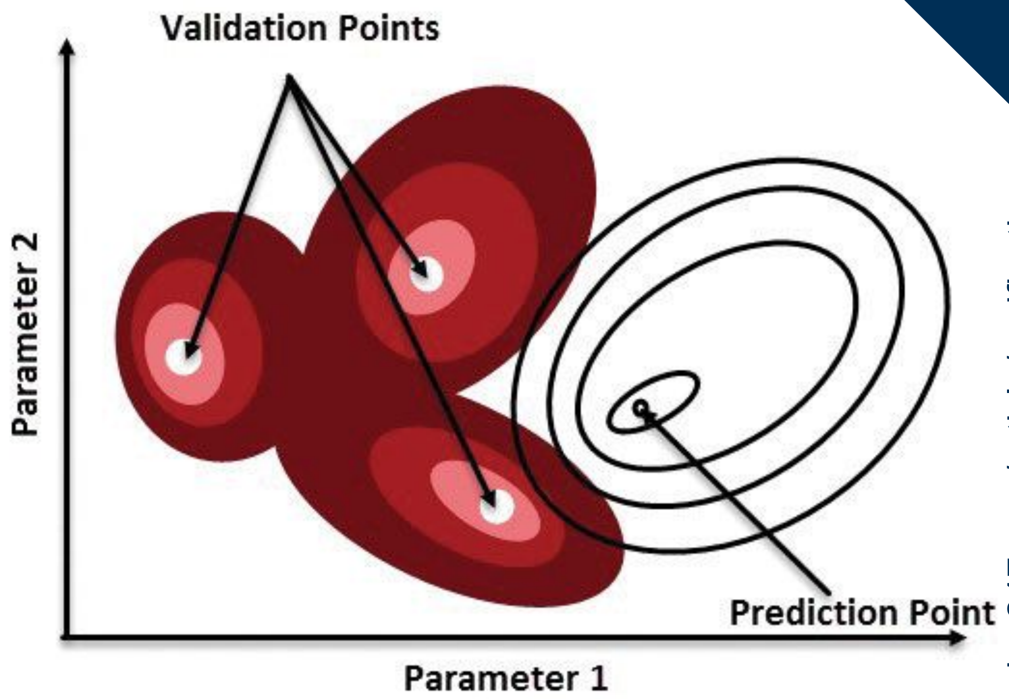
- Many tools used in fusion analysis have a strong fission heritage e.g. ANSYS, MCNP, RELAP, CAST3M, Code Aster, etc…..
  - nearly zero integrated effect benchmarks planned for fusion conditions
    - High Magnetic Field, 10^{15} n/cm^{2}s, 1000 K
- How much historic validation is applicable?
- Fusion needs to embrace Uncertainty Quantification (UQ) - large uncertainty in experimental parameters
- Software agnostic validation problem collection



https://www.digitalengineering247.com/article/verification-vs-validation/

- Regulators **may** need to become more statistically aware
- Open source tools easier to qualify - I can look under the hood

Key take away points

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- Fusion much more able to take benefit from HPC & HTC than fission was(is?)
  - partially due to technology change, part is culture
  - Non permissive licensing (e.g. export control) either needs to change to accommodate multiple sites and arbitrary compute locations (e.g. cloud) or will be left behind
  - Writing new software tools is much less daunting than it used to be
  - **IAEA OnCORE will be very important in this area I think**
- Lots of software that can continue to be used
  - Licensing is key
  - Performance and interoperability is critical
- The future will increasingly be about interfaces (e.g. Application Programming Interface [API])
  - determines how quickly and easily one can integrate software tools together
  - interoperability
- Embrace UQ all the way through the simulation stack

Milano, 20-24th June 2022

Italian National Agency for New Technologies, Energy and Sustainable Economic Development

Nuclear Data for Fission and Fusion : needs and synergies

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Summary

1. Introduction & Background
2. Applications of Nuclear Data
3. Fission-fusion synergies in nuclear data
4. Concluding Remarks

Introduction & Background

- Since the drawn of the nuclear era it has been clear the importance that accurate nuclear data have on the successful design and development of nuclear systems.
- Extensive measurements of nuclear data were made from the 1950s to the 1980s. Since then, computational modeling and simulations of nuclear systems have quickly developed thanks to development of computers and computational tools (e.g. CAD 3D)
- The predictive power of simulations is <u>effectively limited by the fidelity of the used nuclear data</u>
- The increasing complexity of advanced nuclear systems (e.g. advanced reactors, ADS, fusion reactors) renders the design and realization of experiments, mock-up and prototypes more and more expensive
- Necessity to develop <u>*calculation tools*</u> and <u>***sets of nuclear data***</u> that allow for very reliable and cost effective design and safety assessment of the fission and fusion nuclear system
   Here we focus on Nuclear Data (ND)

Introduction & Background

- The implementation of *nuclear data files* requires the complete and accurate information about the different nuclear reactions taking place in fission and fusion reactors.
- For historical reasons *fission and fusion nuclear systems* have developed independently (even within the same country), and so their nuclear data (*Fission is a mature technology while Fusion is still an open question)*
- In the recent years increasing synergy between fission and fusion communities has been developing since *share a common energy range for the nuclear data* : *from thermal neutron energy up to 10 MeV* (e.g. total and scattering cross sections, resonance parameters, kerma values, dpa cross sections, nuclear decay data, gamma-rays data, etc.).
- The synergic effort to merge into common libraries, extending at least up to 20 MeV, the fission and fusion nuclear data led to the production of e.g. ENDF/B, JEFF, JENDL, CENDL, BROND, TENDL etc., nuclear data files

Introduction & Background

- Therefore, effort is needed for validation of these data files and to extend them at least up to 50-60 MeV, to the range of interest to **IFMIF/DONES** neutron source and for **ADS** systems.
- ADS and fusion systems share e.g. the use of liquid metal (Pb) as cooler and/or breeder
- Last, but not least, in the latest years an increasing interest on *hybrid fission-fusion* (HFF) systems has grown.
- In a HFF system a compact fusion reactor is used as neutron source to operate a sub-critical fission reactor with the main goal not only to produce safely electric energy but also to burn spent fuel and actinides so to reduce the nuclear waste, a common goal shared with ADS.
- The ADS and hybrid systems *can play an important role to bridge the gap* between fission and fusion communities and can be thus beneficial also to nuclear data implementation.
- Synergy between fission and fusion can be found also in the re-analysis of experiments with the new extended libraries. To this end the **SINBAD** data base could be very helpful

Applications of Nuclear Data

- A fundamental part of the design of any nuclear system is the so called ***nuclear analysis*.** It serves not only to define the nuclear parameters and quantities of the system but also e.g. to evaluate the doses to materials, electronics, personnel (during both operational and not operational period, e.g. maintenance) and at shut-down, materials activation for disposal prediction, etc
- *Nuclear design of fission and fusion systems* needs neutron and photon transport calculations to provide the *neutron/photon flux spectra* that *when convoluted with related nuclear data* form the basis for the calculation of nuclear responses of interest (e.g. fuel burn-up, nuclear heating in the materials, dpa, doses and dose-rates, etc.).
- Appropriate and qualified neutron transport computational tools and simulations are required to ensure the reliability of calculated nuclear responses as well as **high quality nuclear data are essential for the interpretation of key benchmark experiments needed for performance and safety evaluations of the nuclear systems.**
- The results of benchmarks allows for establishing the quality of the used nuclear data and thus provide very useful information about the reliability of the nuclear analysis

Where to find synergies between fission and fusion ?

FISSION & ADS

- Criticality Data
- Fission Data (Yields, delay neutrons, etc.)
- Fission X-sec for actinides
- Capture X-sec for breeder materials
- Liquid metals
- Structural materials
- dpa
- Safery & Maintenance
- Disposal & Recycling
- Others ……

COMMON INTEREST

- X-sec : (n,g);(n,p);(n,α)...
- Double differential X-sec
- dpa X-sec
- Materials : Be, O, Cu, Cr Fe, Mo, W, Pb……..
- Decay data
- Kerma data
- Shielding
- Liquid metal
- Safety & Maintanence
- Inventory codes & data
- Others …….

FUSION

- Nuclear Analysis
- Shielding
- Tritium Breeding (X-sec for Lithium & BB materials)
- Liquid metal
- X-sec (n,2n); (n,α), (n,d)
- dpa
- Safery & Maintenance
- Disposal & Recycling
- Others …..

Hybrid Fission-Fusion Reactors

Common Fission-Fusion Nuclear Data

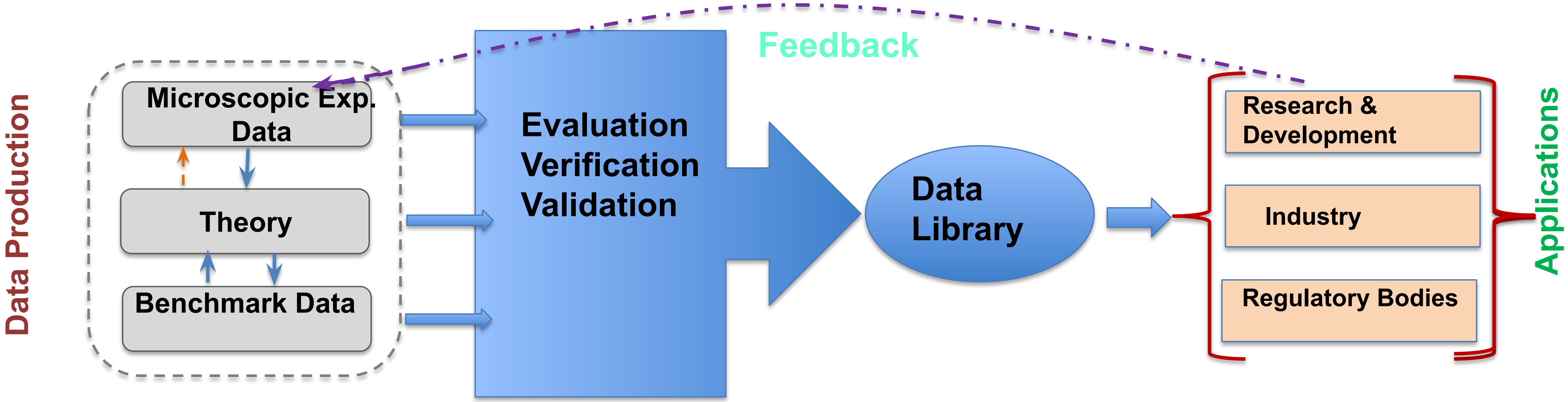
- *Activation and transmutation cross-section* data must be provided for the isotopes of all stable elements that constitute the **structural materials** or may be present as impurities both for fission and fusion systems.
- For the sake of fusion systems (and ADS), also radio-nuclide targets require cross-section data, as *multi-step reactions* could be also important in the *high neutron fluxes* expected in these plants. dpa X-sec are important too.
- Last, but not least, the *decay data* of all possible nuclides must be available to enable activation calculations to be carried out so to foresee the doses in the plant both during operation, the maintenance phases and at shut-down.
- The *information about materials activation* are essential also for the decommission phase since in a more advanced view of the global energy production process the problem of **materials disposal** and of their **potential recycling** has to be considered since the design phase.
- Furthermore, the request from the regulatory authorities for doses as low as reasonable possible is also pushing toward the study and development of the so called **low activation materials** (LAM).
- The inclusion of LAM in the nuclear analysis is part of modern approach to fission and fusion nuclear power plant design and “ad hoc” work is required to render available the nuclear data for such materials *including all the minor isotopes that constitute them.*

Synergy in Nuclear Data Files Production

Production of nuclear data libraries : long lasting, multi-steps, complex and interrelated process.

Usually 5-7 years needed to produce a new library *Feedback from use*

K. Kolos et al. Report LLNL-PROC-824415



Nuclear Data Evaluation process

Once a data file is produced how to evaluate its performances?

- Benchmark with other nuclear data files
- Test against different experiments/mock-up *C/E analysis*
- Sensitivity/Uncertainty analysis
- Covariances
- Feed-back to evaluators

- Extended nuclear data files (e.g. ENDF/B, JEFF, JENDL, CENDL, etc.) are able to cover and meet most of the needs for both fission and fusion nuclear systems *Quality to be proved by experiments*
- ***Re-analysis of experiments*** by people of both fission and fusion communities can be of great importance to develop synergy

The SINDAD Data Base

- ***The Shielding Integral Benchmark Archive and Database*** (**SINBAD**), developed since early 1990's jointly by the Organization for Economic Co-operation and Development's Nuclear Energy Agency Data Bank (**OECD/NEADB**) and the Radiation Safety Information Computational Center (**RSICC**) at Oak Ridge National Laboratory (ORNL), *can play a role of paramount importance to develop synergies between fission and fusion*.
- SINBAD comprises *over 100 benchmark compilations and evaluations* of relevance to fission reactor shielding, pressure vessel dosimetry, fusion blanket neutronics as well as accelerator shielding. These experiments can be analyzed using the different nuclear data files, so providing important information on the used data.
- SINBAD was extensively used in the scope of numerous national and international projects, such as PWR Pressure vessel surveillance, fusion program (ITER reactor studies), different OECD Working Party on Evaluation Cooperation (WPEC) Subgroups, nuclear data validation (e.g. JEFF-4T), IAEA nuclear data projects(FENDL, IRDFF).

Concluding Remarks

- Despite the many differences***, Nuclear Data represent a good example of (partial) cooperation and synergy in between Fission and Fusion*** communities
- Extended data files already available which are routinely used both for fission and fusion activities
- Possibility to further increase the collaboration and develop synergies when considering Fusion and ADS (liquid metal, materials, cross sections) and advanced reactors
- Other possible area of synergies : Shielding, dpa, activation/decay data, structural materials, safety, licensing, LAM, etc…..
- Use of the SINBAD database for testing of nuclear data files and interchange of results
- Communications between fission and fusion communities to be implemented (e.g. listing possible common area of activity, sharing nuclear data, common experiments, meetings, etc.)

Concluding Remarks

- To promote the synergies between fission and fusion communities a first step could be the implementation and coordination of PhD and postdoctoral grants in the common fission-fusion fields and topics concerning the nuclear data, so to promote a new generation of high qualified personnel.

- To note that the required know-how and instruments for a significant improvement of synergies in nuclear data field between fission and fusion are generally available word-wide and especially in the most developed countries.

- Setting up a coherent framework and initiating a sequence of well-directed actions to establish synergies for common fission-fusion nuclear data development and/or improvement, possibly with adequate support and funding, will results in a significant benefits to future nuclear systems development.

Thank You for Your Attention