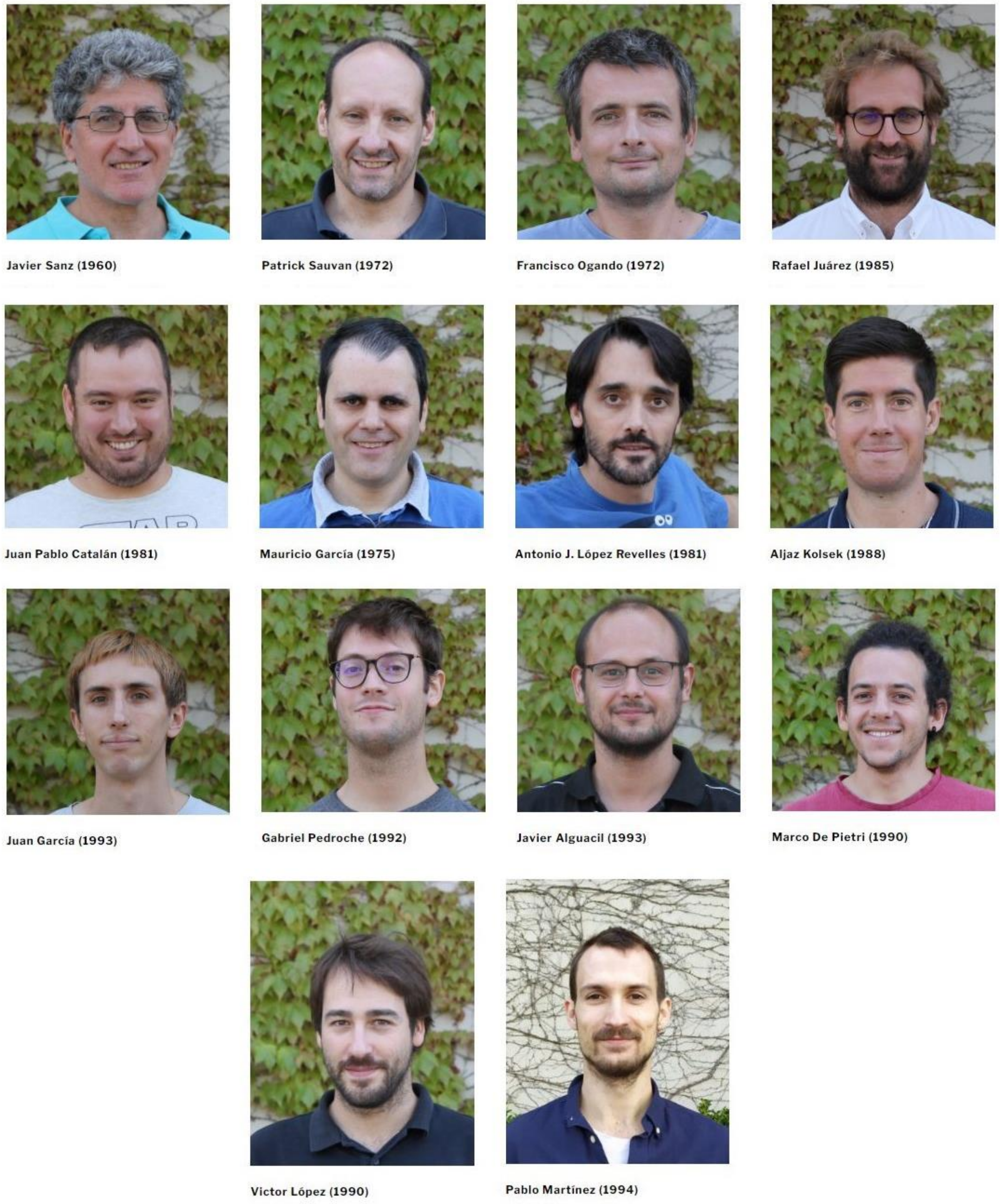
Actividades del grupo de investigación UNED-TECF3IR

Tecnologías de Fisión, Fusión y Fuentes de Irradiación

J. Sanz, R. Juárez, F. Ogando & TECF3IR

Personal del grupo

- Departamento UNED de Ingeniería Energética
  - 4 Profesores
  - 10 Investigadores
  - Total de 8 doctores
- Muchos de nosotros formados en UPM-IFN
- Más datos en nuestras web:
  - Oficial UNED y propia.



¿Qué hacemos?

Descripción concisa e intencionadamente ambigua:

- **Neutrónica** avanzada para el análisis y diseño de instalaciones relevantes para el desarrollo de la **energía de fusión nuclear**.

¿Qué hace el neutrón en un SFN D-T?

- Deposita energía (calentamiento nuclear): generación de electricidad
- Producción de tritio.
- Daño a componentes y materiales.
  - Cambios en dimensiones y degradación de propiedades físicas y mecánicas.
- Daño a la salud de las personas
- Activación: producción de radionucleidos radiactivos y campos de radiación de desintegración.
- Producción de radiación secundaria (fotones)

Preguntas al especialista en neutrónica FN

- Multiplicación de energía, potencia total producida y distribución espacial de densidad de potencia
- Capacidad para ser autosuficiente en tritio (TBR > 1)
- Niveles de radiación (dosis) en componentes y personas.
  - Capacidad de blindaje (imanes superconductores, óptica, dosis biológica)
- Niveles de daño por radiación (dpa, He, H, impurezas solidas).
  - Desafío: seleccionar materiales resistentes al daño por radiación
- Actividad, inventario de nucleidos, calor residual, campos de radiación, daño/dosis a componentes y dosis biológica.
  - Desafío: seleccionar materiales de activación reducida

Respuestas: ¿para qué?; ¿cómo obtenerlas?

- Dar apoyo al proceso de diseño nuclear de la instalación, sistemas y componentes.
- Evaluar y probar la eficiencia y seguridad nuclear de la operación de la instalación, incluyendo apoyo al licenciamiento.
- Ejemplos de análisis requeridos
  - Distribución de densidad de potencia (termo hidráulica, limites de diseño)
  - Definición de blindajes: optimización
  - Activación, calor residual para e seguridad y gestión de residuos.
  - Planificación de mantenimiento: manual y remoto

- La simulación computacional puede proporcionar los datos-respuesta requeridos ¿con la suficiente exactitud?

Neutrónica computacional de FN

- Simulación del **transporte** de neutrones (y fotones)
  - Base para obtener las respuestas nucleares requeridas.
- Esquemas de cálculos **acoplados** de transporte de radiación y **activación**
  - Cálculos de activación, calor residual y campos de radiación y dosis residual
- Requerimientos
  - Simulación del transporte (y activación) en geometrías 3D complejas
  - Capturar la física de los procesos de interacción con las menores aproximaciones. Poder trabajar con **secciones eficaces de alta calidad**.
  - Modelos de simulación que reproduzcan la geometría real sin restricciones importantes. Generación de **modelos neutrónicos muy detallados**.
  - Fiabilidad módulos de transporte y cálculo de inventario y de su acoplamiento
- Cualificación/validación: Métodos/software y secciones eficaces

TECF3IR ¿qué neutrónica hace y por qué?

- IFN: Desafíos para el campo de la neutrónica completamente nuevos.
- Proporcionar soluciones de análisis y diseño nuclear con un alto nivel de confiabilidad en ITER, IFMIF-DONES y DEMO.
- Elaborar procedimientos, modelos de cálculo y desarrollo de métodos y software que permite realizar los análisis requeridos.
  - Simulación de transporte (por Monte Carlo), activación, y cálculos acoplados transporte-activación: respuestas nucleares requeridas y entender los mecanismos que las originan.
  - Generar modelos geométricos muy detallados para códigos de MC.
  - Estimación de incertidumbres en la dosis residual (y otras respuestas)
  - Validación contra experimentos: JET
- Ingeniar soluciones de diseño y desarrollar herramientas para evaluación/optimización.

Principales desarrollos computacionales
(los vínculos llevan a artículos e información relevante)

- Neutrónica computacional
  - ACAB: Cálculos de activación. Código de referencia para el diseño de NIF
  - MCUNED: Código avanzado para transporte e interacciones de iones ligeros. Uno de los recomendado para IFMIF-DONES.
  - R2SUNED: Cálculos acoplados transporte-activación y calculo de dosis residuales para alta fluencia. Algoritmos incorporados en cR2S ("common R2S") europeo/EUROfusion
  - D1SUNED: Transporte avanzado, y cálculo de dosis residuales con alta eficiencia en sistemas determinados. Código de referencia para el diseño de ITER.

- Apoyo a la neutrónica
  - GEOUNED para la conversión de geometría CAD a MCNP.
  - srcUNED: Fuente en *bioshield* de ITER para mapas globales en el edificio del tokamak.
  - srcUNED-Ac: Fuente de radiación (pronta y residual) debida a pérdidas de haz en aceleradores.
  - FLUNED: Activación de fluidos, de aplicación en ITER, DONES y DEMO.

Ahora pasamos a presentaciones de los principales proyectos

R. Juárez, “UNED activities for ITER Neutronics”

F. Ogando, “Nuclear analysis of IFMIF-like high intensity accelerators”

También puedes ir a la sección final “Trabaja con nosotros”

UNED activities for ITER Neutronics

R. Juarez, J. Sanz, F. Ogando & TECF3IR team

Why fusion neutronics?

Fission of U-235

One fission reaction:

- Releases 215 MeV in average
- Releases 2.4 neutrons in average
- <E> carried by neutrons is 4.8 MeV

→ 0.01 neutrons of 2 MeV per MeV released

Fusion of DT

One DT fusion reaction:

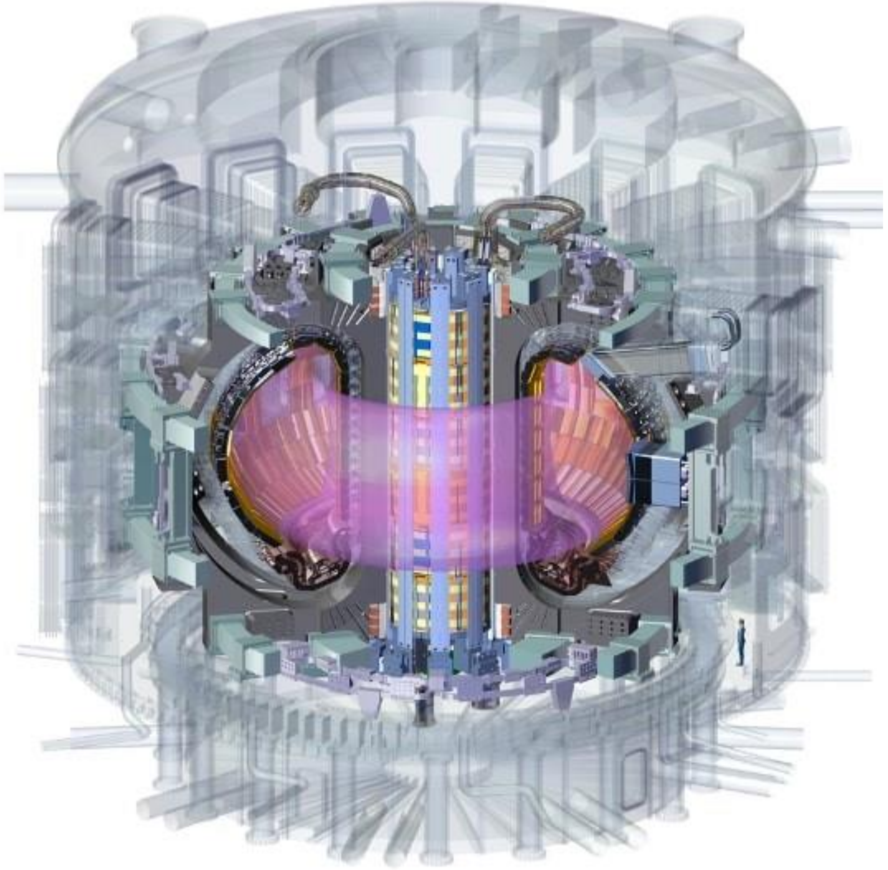
- Releases 17.6 MeV in average
- Releases 1 neutron
- <E> carried by neutrons is 14.1 MeV

→ 0.057 neutrons of 14.1 MeV per MeV released

Nuclear fusion presents:

- **6 times more neutrons per MeV of energy released**
- **More penetrating & damaging neutrons (7 times more energetic neutrons)**
- **Presence of threshold reactions inaccesible to fission → ^{16}N & ^{17}N**

What is ITER?



ITER is the largest Tokamak ever built

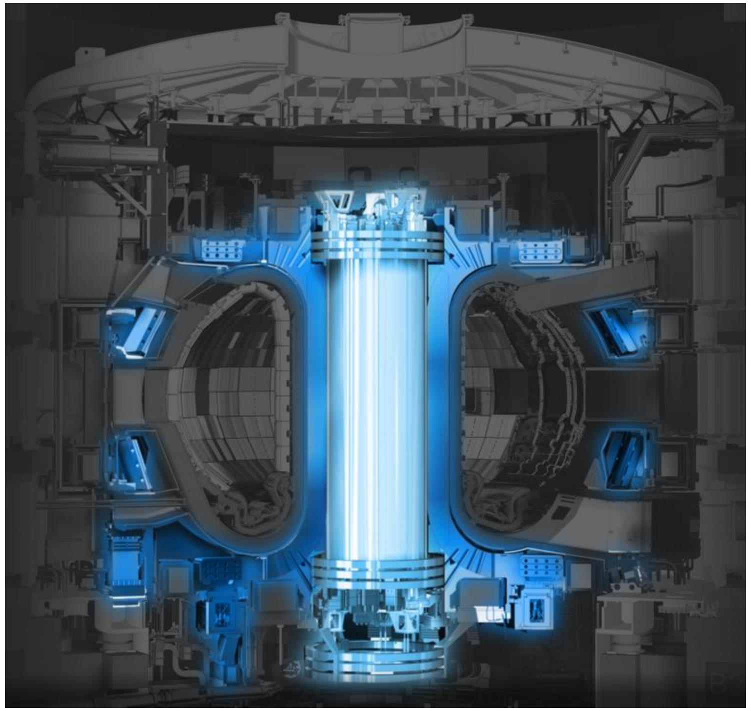
It presents five objectives:

- Produce 500 MW of fusion power with $Q \geq 10$
- Demonstrate the integrated operation of technologies for a fusion power plant
- Achieve a deuterium-tritium plasma in which the reaction is sustained through internal heating
- Test tritium breeding technologies
- Demonstrate the safety characteristics of a fusion device

Current cost estimated in 24,000 M€

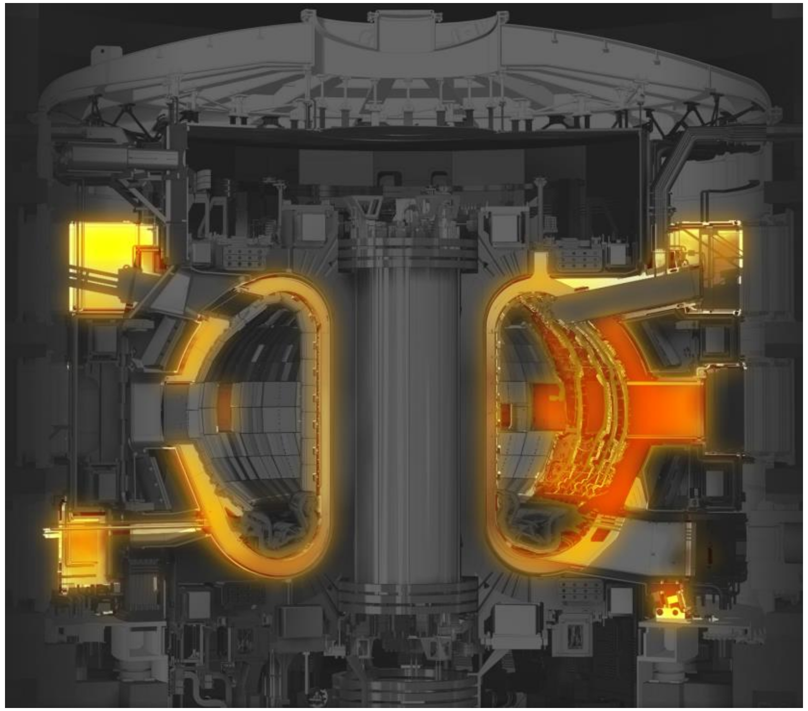
What is ITER?

ITER is a gargantuan machine which design and construction requires going beyond standards



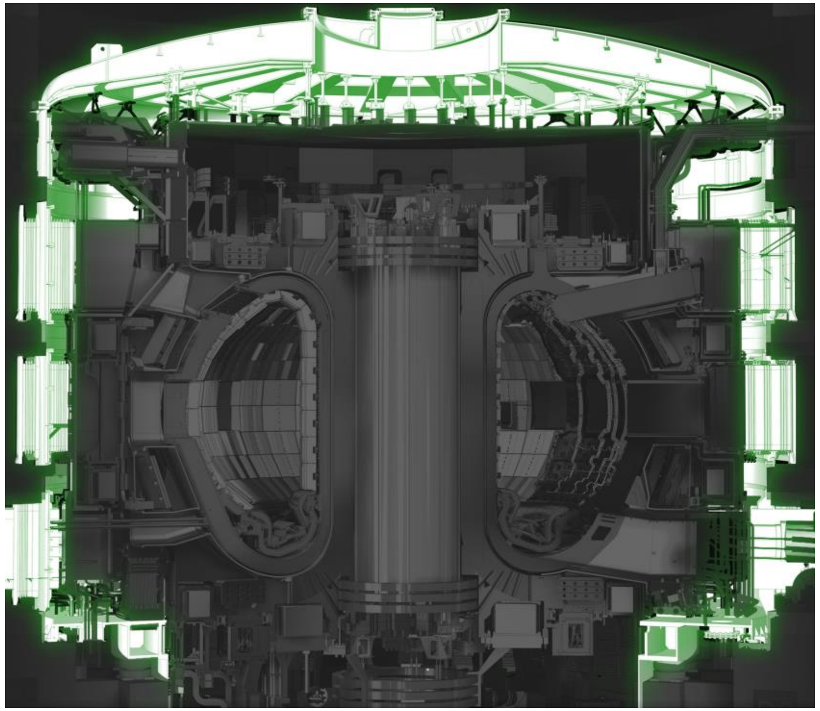
Magnets:

- 13 T magnetic field
- 4 K temperature
- 100.000 km of superconductor strand



Vacuum Vessel:

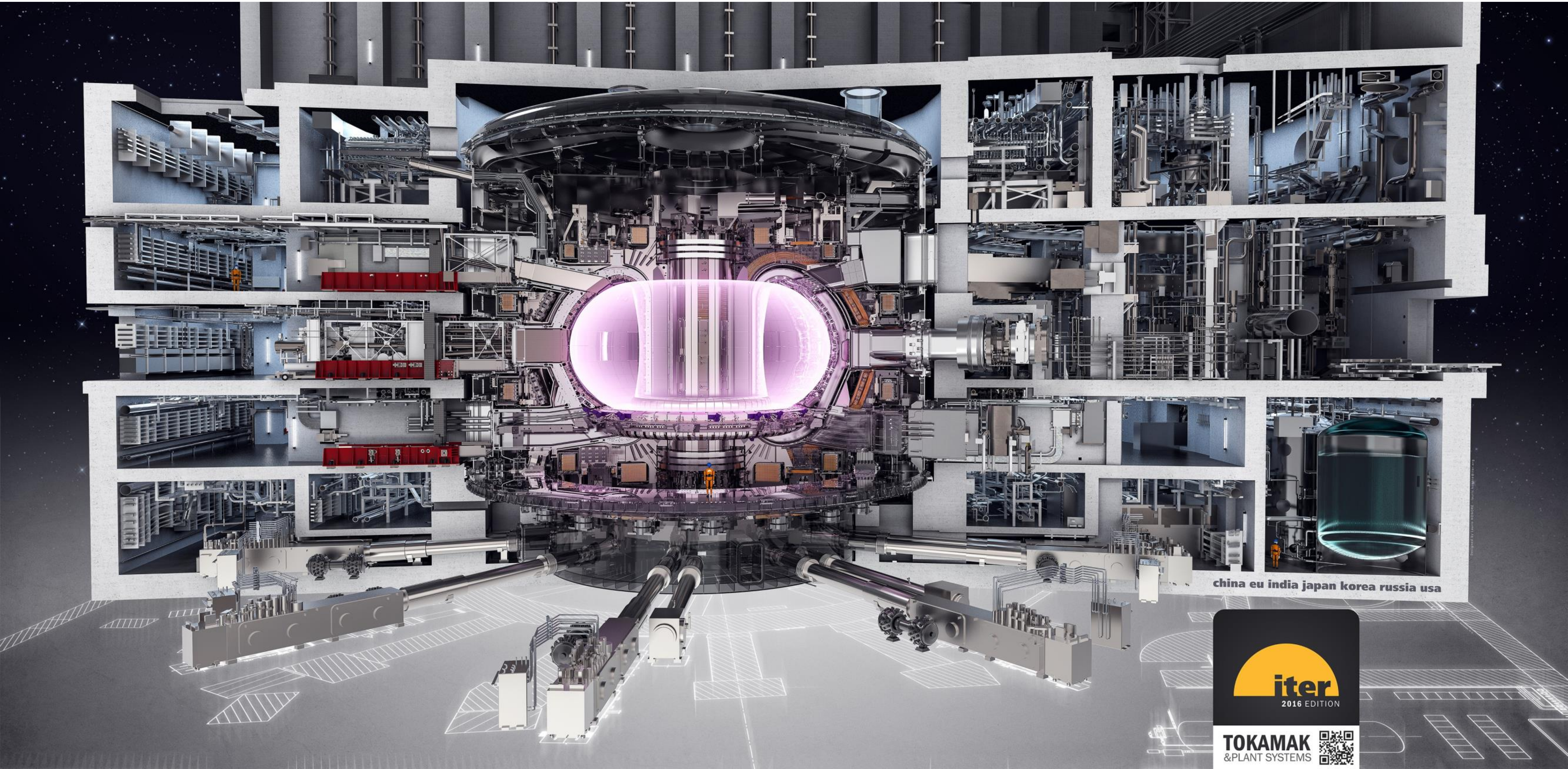
- 8.000 t of steel
- 840 m^3
- 6 m of radius



Cryostat

- 3800 t of steel
- 1 million times less dense than air
- 16000 m^3 volume

What is ITER?


china eu india japan korea russia usa
iter
2016 EDITION
TOKAMAK
&PLANT SYSTEMS

ITER timeline

2005 Decision to site the project in France ✔
2006 Signature of the ITER Agreement ✔
2007-2009 Land clearing and levelling ✔
2010-2014 Ground support structure and seismic foundations for the Tokamak ✔
2012 Nuclear licensing milestone: ITER becomes a Basic Nuclear Installation under French law ✔

2014-2021 Construction of the Tokamak Building ✔
2010-2021 Construction of the ITER plant and auxiliary buildings for First Plasma
2008-2021 Manufacturing of principal First Plasma components
2015-2023 Largest components are transported along the ITER Itinerary

2020-2025 Main assembly phase I
2022 Torus completion

On-going

Dec 2025 First Plasma
2025-2035 Progressive ramp-up of the machine
2035 Deuterium-Tritium Operation begins

To be done

We have 14 more years of design & construction followed by 20 years of operation

ITER timeline

ITER site by Nov 2020

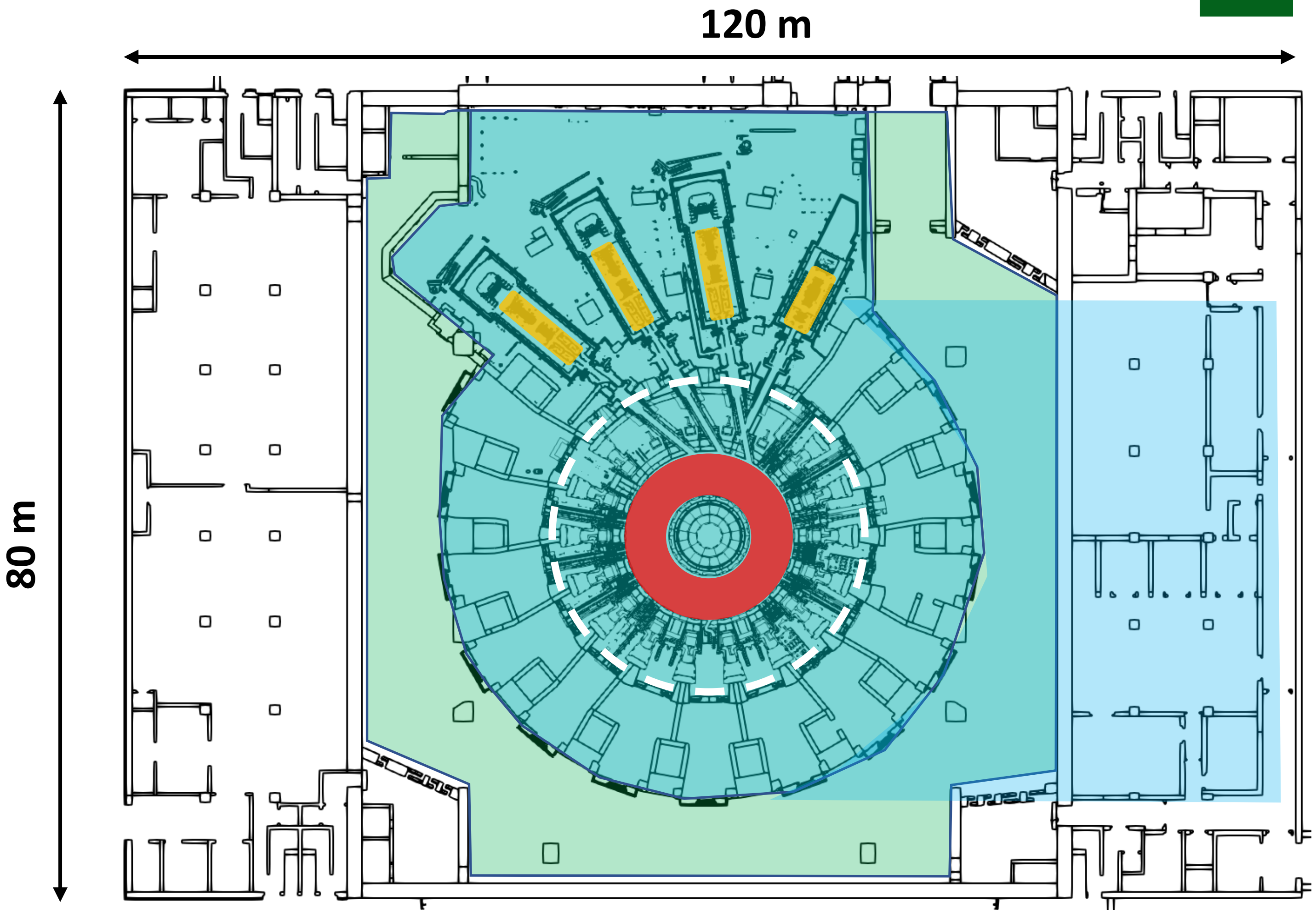
ITER timeline

ITER site by Nov 2020

ITER radiation challenges

Radiation sources in ITER:

- Plasma DT neutrons and subsequent photons
- Plasma DD neutrons and subsequent photons
- Photo-neutrons from run-away electrons
- Photo-neutrons from Be
- NBI beam impact in Be
- Water activation: ^{16}N & ^{17}N
- Activated corrosion products
- ERID & calorimeter source
- Radioactive decay of activated components
- Activated W and SS dust



Intense radiation sources of concern are found beyond the bio-shield

ITER radiation challenges

Challenges associated to the radiation ITER field:

- Protection of public
- Workers exposure control & ORE budget
- Protection of electronic & electric equipment
- Limit the environmental impact
- Forecast and minimization of radwaste stream

Fusion must perform safer than fission

Shielding ➔ tens/hundreds of millions €

Remote handling ➔ hundreds/thousand of millions €

Balance between safety and economics is key for ITER viability

The radiation field in ITER will be very complex due to plant geometry and sources nature

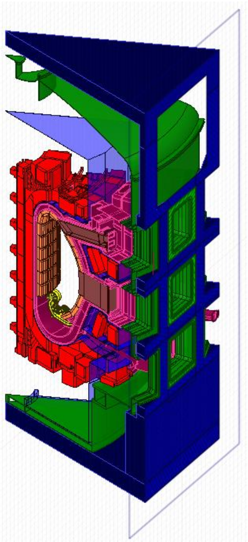
Previous techniques are not enough:

→ new computational technologies to forecast the radiation field

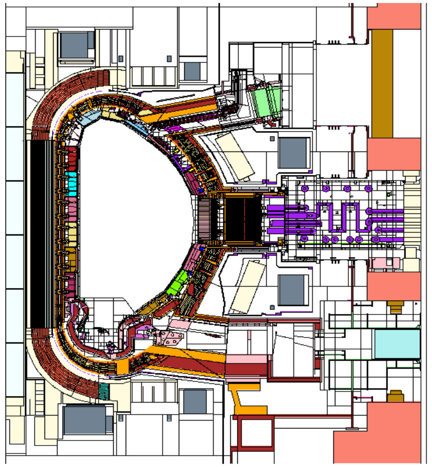
→ new shielding technologies to mitigate radiation field

UNED neutronics workflow

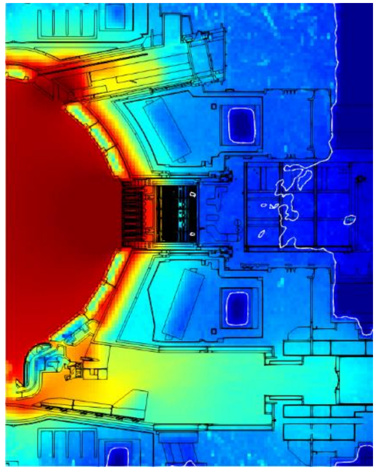
CAD model



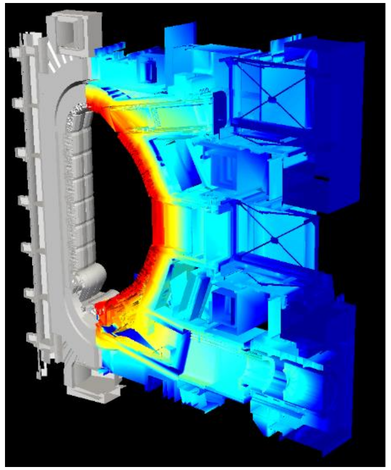
Transport model



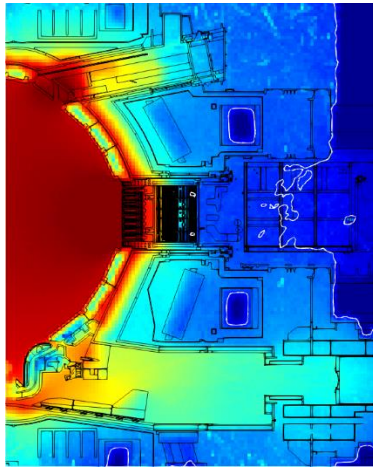
Prompt n-γ transport



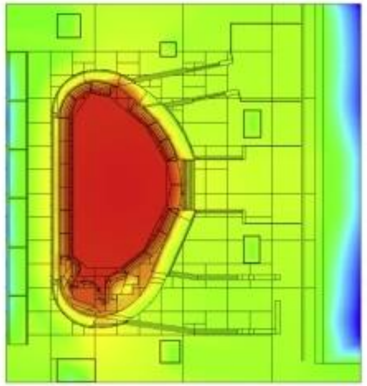
Activation



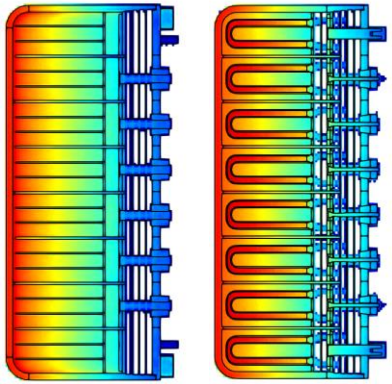
Decay γ transport



Variance reduction



3D high fidelity nuclear responses



Nuclear heating

UNED neutronics workflow

We use a set of tools, of which, many have been developed at UNED (underlined):

CAD modelling: CATIA, Spaceclaim, SuperMC, Geo-UNED

Radiation transport (n & prompt γ): MCNP5, MCNP6, MCUNED

Variance reduction: GVR-UNED

Activation: ACAB

Decay γ calculations: D1SUNED, R2SUNED

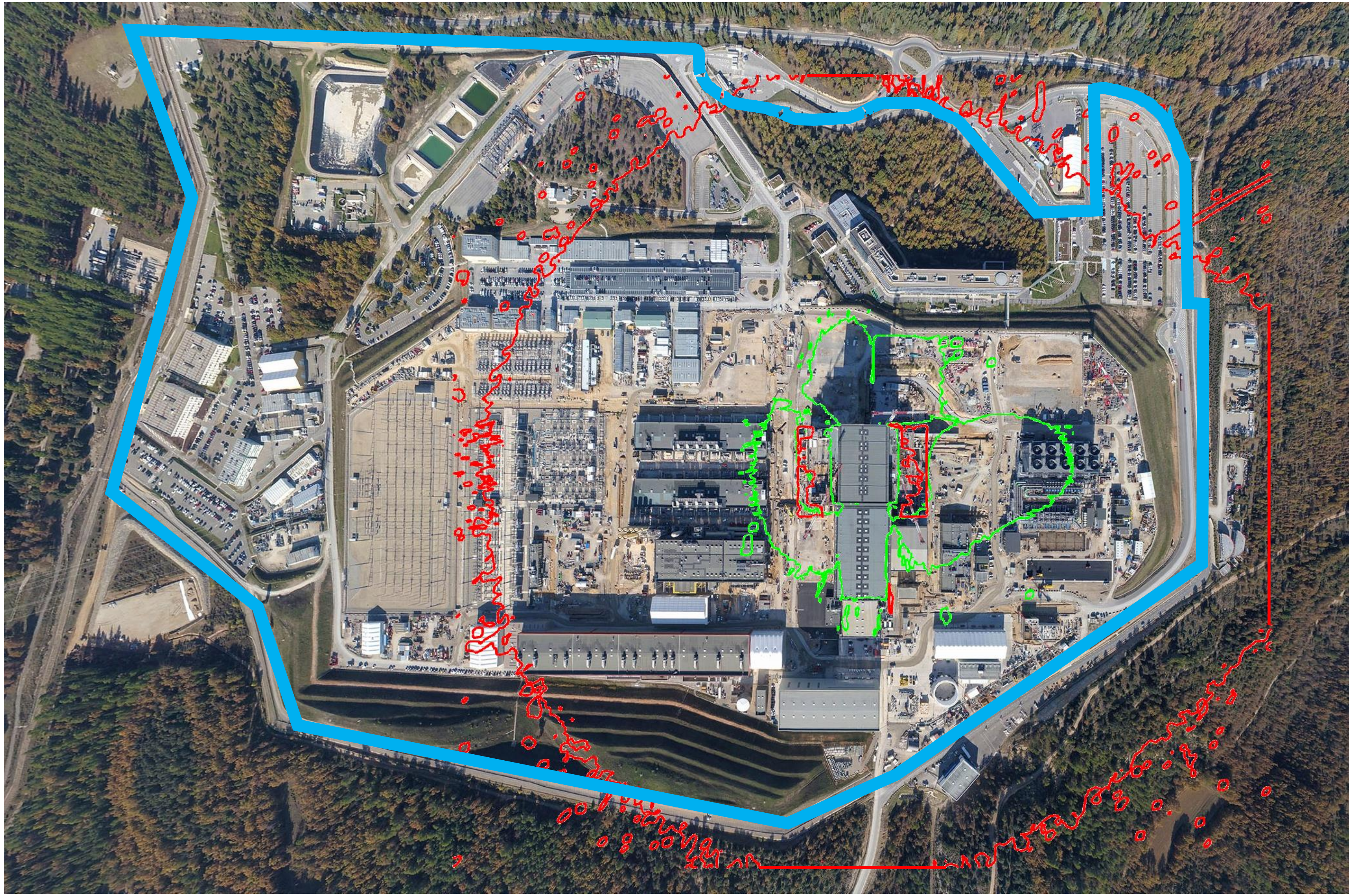
Postprocessing & visulization: mesh2vtk, Paraview, Unreal Engine

Treatment of special sources: SRC-UNED, FLUNED, SUR-UNED

Note UNED's contribution to ITER is recognized as key by the DG in a letter sent by August 2020

Let's see few examples

Example I: Compliance with regulatory limit for public



Limit for public (beyond fence):

1 mSv/year

(780 hours / year) → **1.28 µSv/h**

0.1 µSv/h

0.01 µSv/h

ITER shielding design is compliant with public exposure

Under review by the ASN

Example I: Compliance with regulatory limit for public

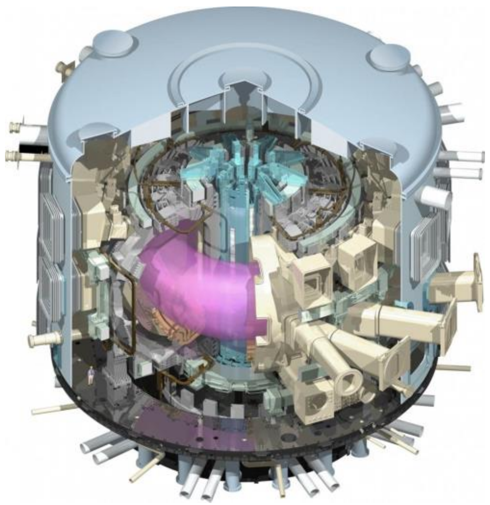
This study took place based on previous works:

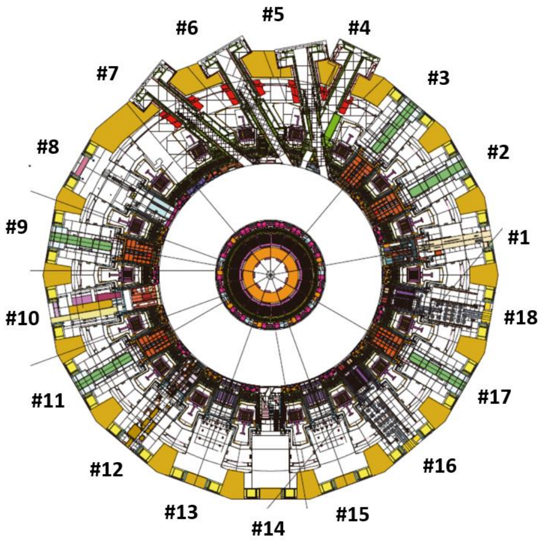
- Ten years of work by multiple institutions: ITER, ORNL, CCFE, AMEC & UNED
- Two previous attempts where many lessons were learnt and methods developed
- Tens of partial studies for decision making during building construction

This study has required:

- **Construction of two of the most complex MCNP models in the world**
- **Dedicated methodology to model the water radiation source**
- **Dedicated methodology to model the plasma source**
- **Over 5,000,000 cpu.hr, among other things, to capture the skyshine**
- **6 people full-time + 2 people part time during 2 years. Contributions to 3 PhD. thesis**
- **New tools: D1S-UNED, SRC-UNED and others**

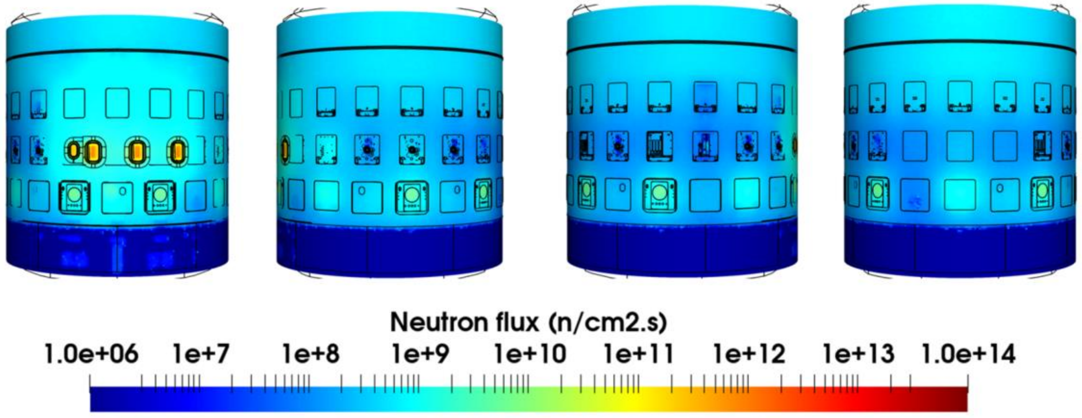
360º MCNP of the ITER Tokamak & plasma source

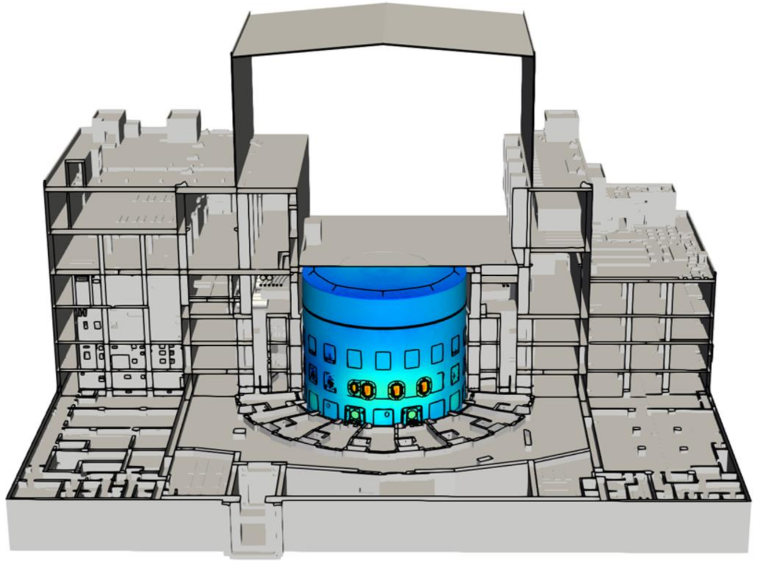




E-lite: the first 360º MCNP model of the ITER Tokamak

- **Published in Nature Energy**
- **Developed as a PhD. at UNED**
- **Used to model the plasma radiation reaching the bio-shield (SRC-UNED)**



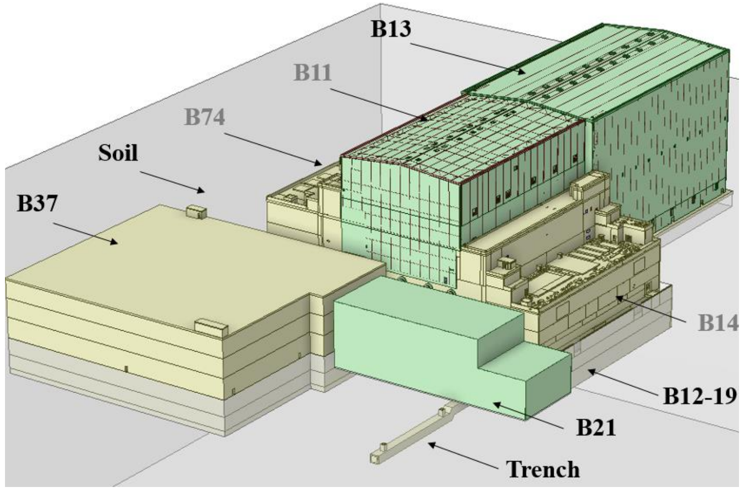


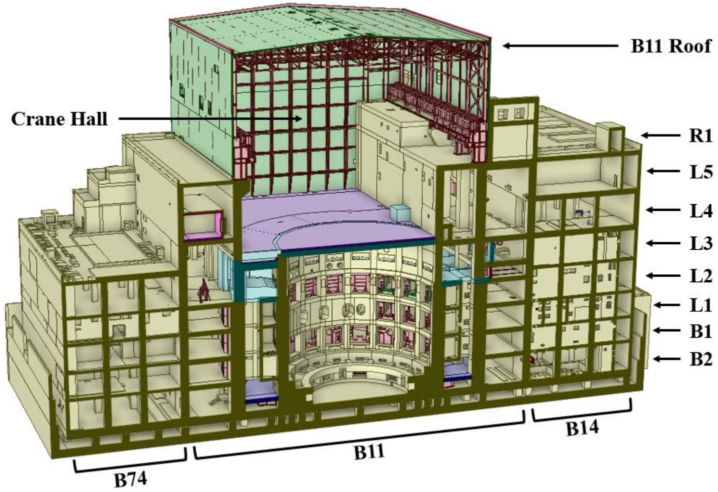
MCNP model of the ITER site

Tokamak Complex

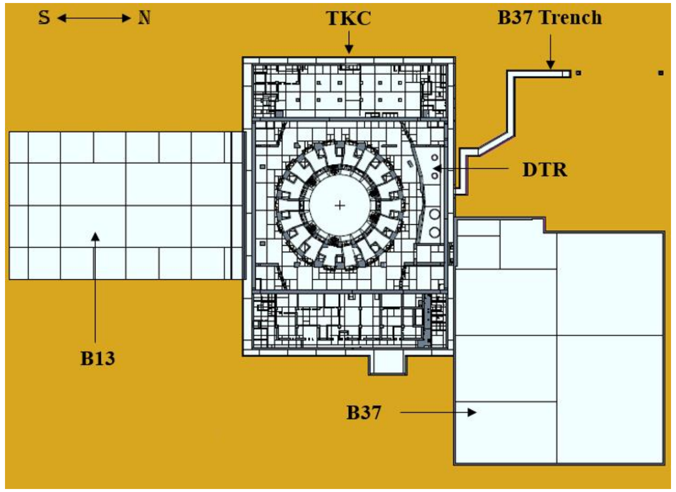
- According to baseline 2020
- Developed as a PhD. at UNED
- It covers 7 edifices and
- Includes soil and 1km of air
- Over 4500 penetrations traced and reviewed one-by-one
- Over 500 rooms
- 14 dedicated shielding measures to meet the limit for public

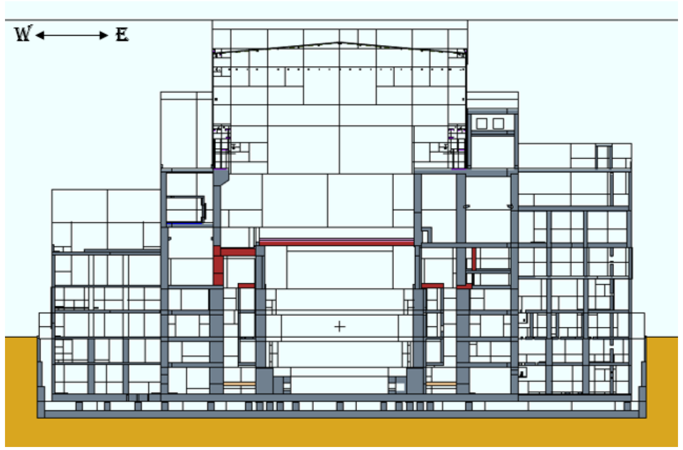
CAD model





MCNP model



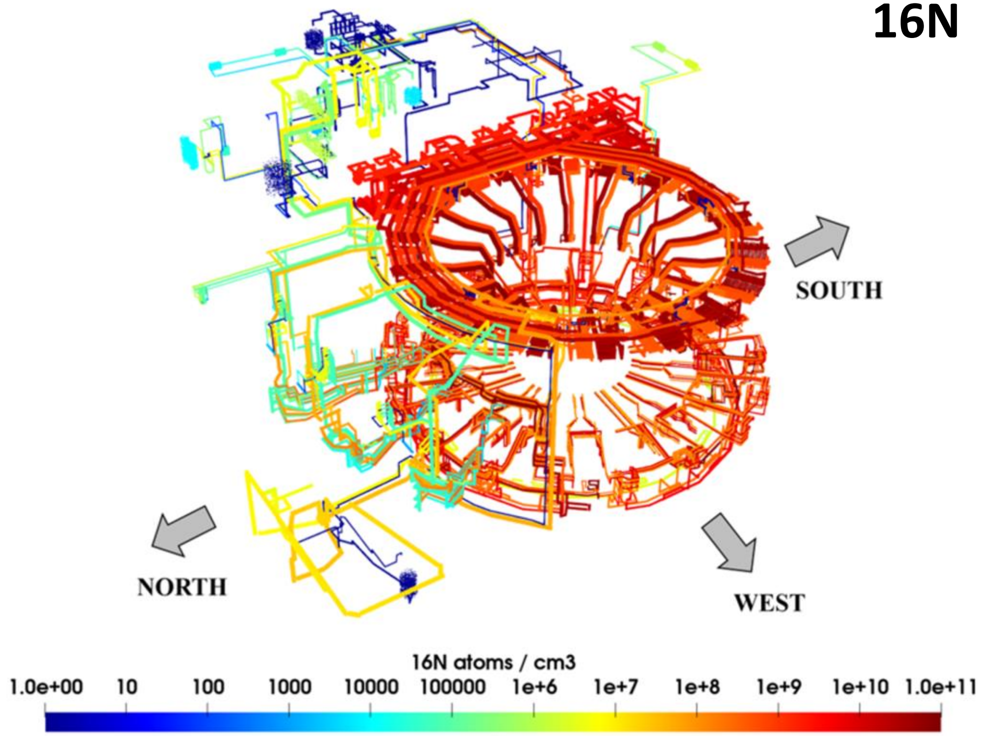


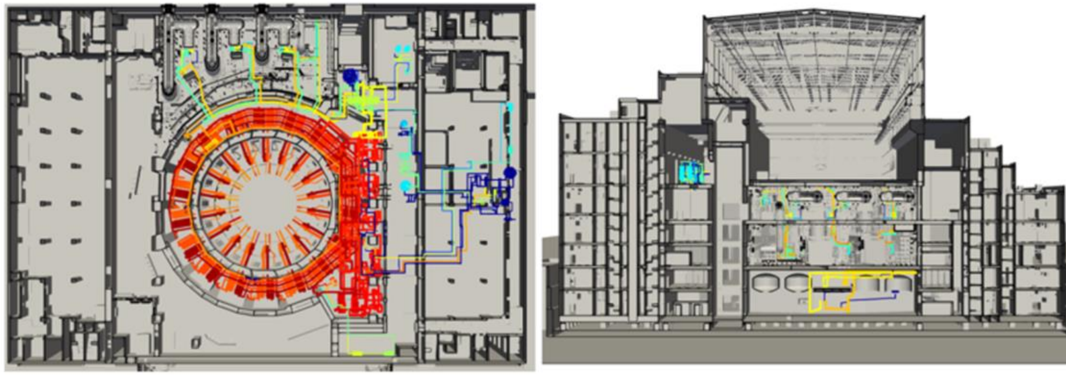
Modeling of the activated water radiation source

ITER Tokamak Cooling Water Circuit

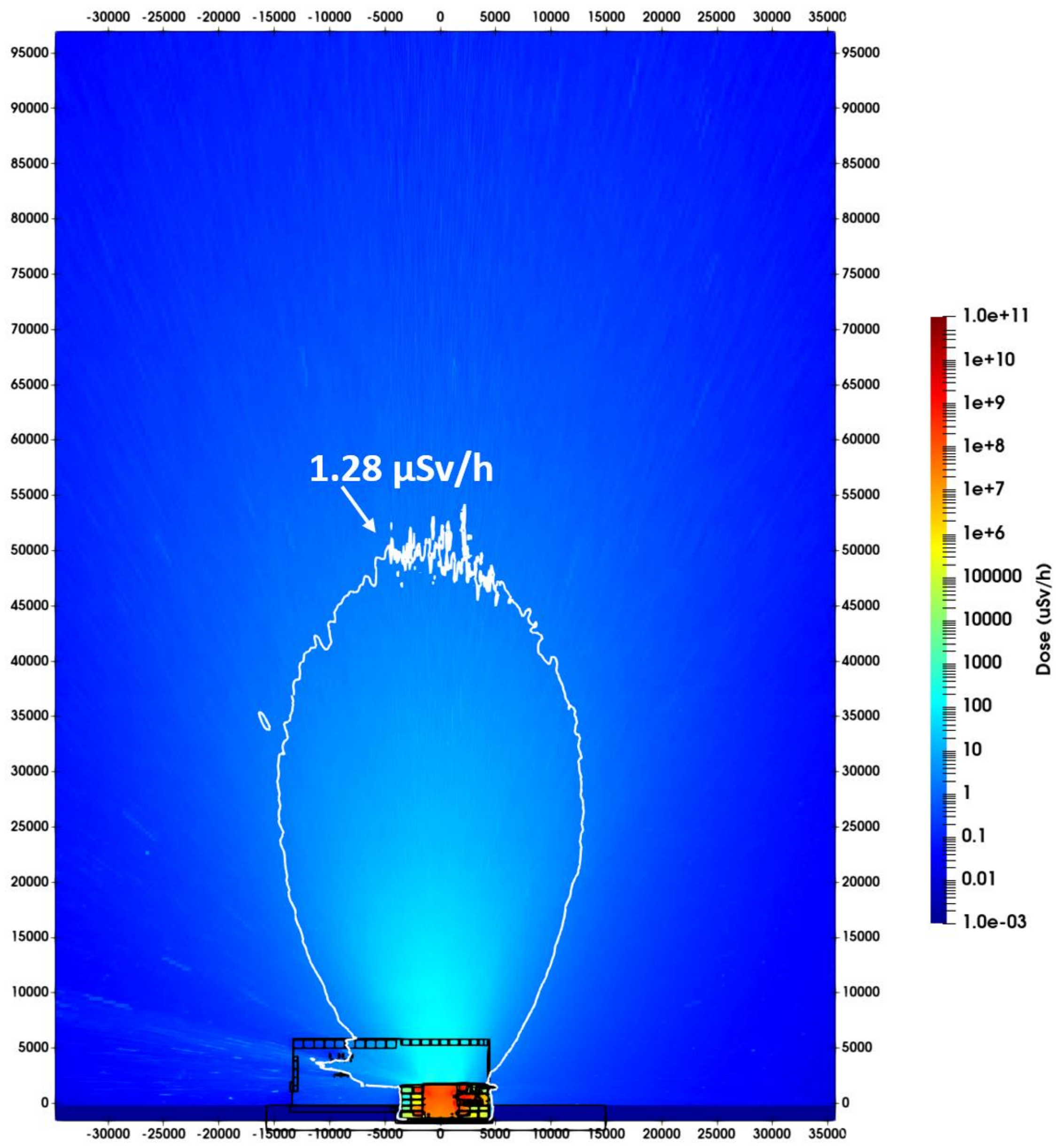
- It contains 500 m^3 of water in 15,000 pipes
- They contain ^{16}N, ^{17}N and ^{19}O decaying as water flows
- Water velocity and pipe shell thickness vary strongly
- Modelled in a PhD. at UNED
- The characterization required:
    - P&ID information for every pipe
    - Scripting to implement it in the CAD model
    - Coding of flow diagrams
    - Scripting to compute the isotopes decay along the thousands of paths

16N



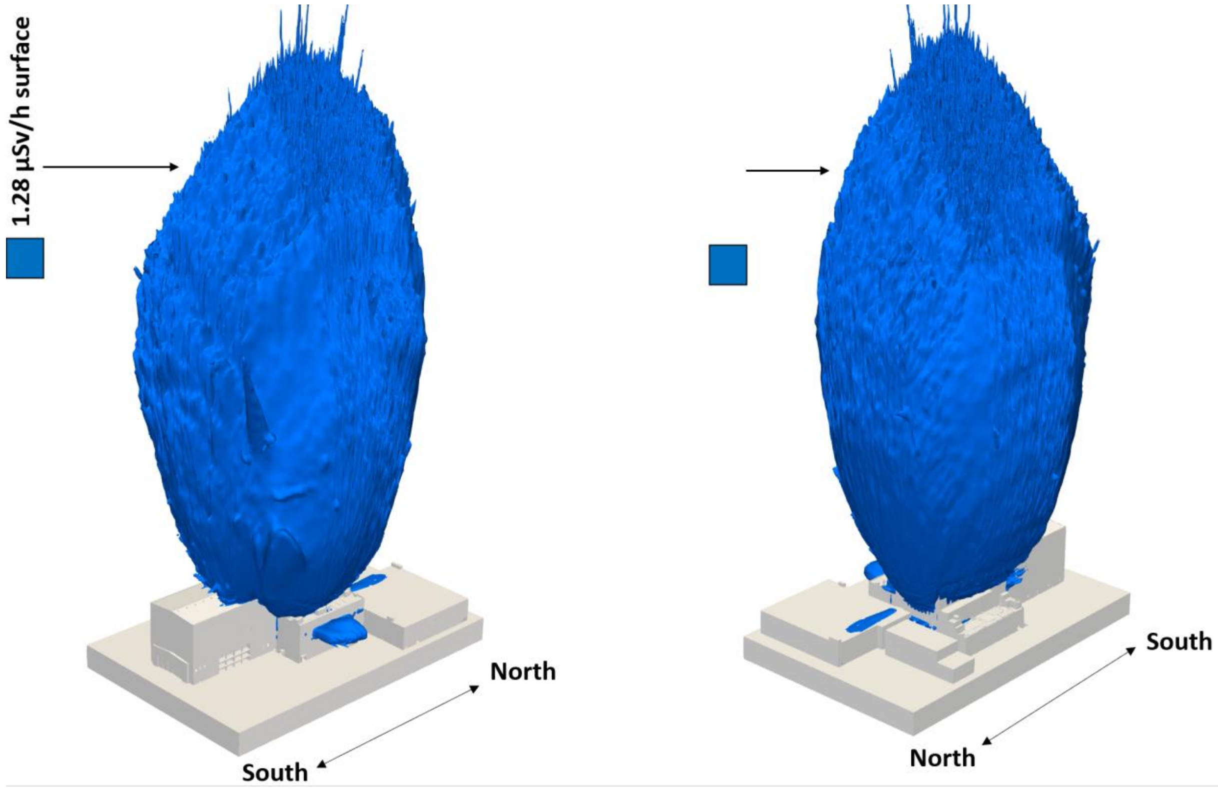


ITER skyshine



ITER skyshine was evaluated for the first time:

- **It is dominated by ^{16}N gammas**
- **It is not a challenge to regulatory limits**
- **It is been computationally expensive to compute**

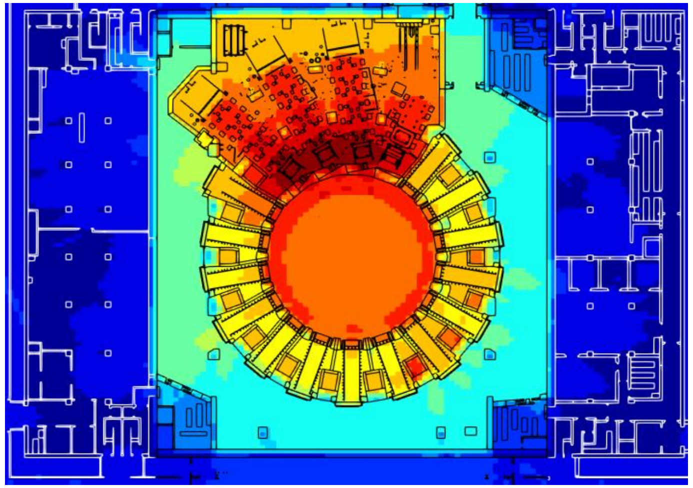


Example I: Compliance with regulatory limit for public

Result of UNED work:

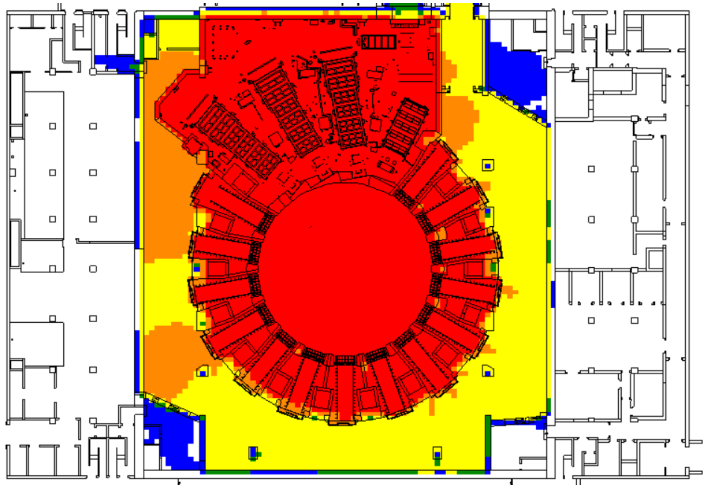
- Compliance of the ITER shielding with regulatory limits for public protection was demonstrated
- Many unknown aspects were faced for the first time
- Autorité de sûreté nucléaire (ASN) is reviewing the work to release the Assembly Hold Point
- Rad levels to define electronic and electric equipment qualification programs was obtained
- Radiological zoning for workers exposure was obtained as well

Rad Map



Radiological zone	Zone	Maximum total effective dose for the entire body - external and internal exposure
White	Unregulated	< 80 µSv/month
Blue	Supervised	1.25 mSv integrated on a month
Green	Controlled	4 mSv integrated on a month
Yellow	Controlled	2 mSv integrated on one hour
Orange	Controlled	100 mSv integrated on one hour AND 100 mSv averaged over a second
Red	Controlled	100 mSv integrated on one hour OR 100 mSv averaged over a second

Zoning



Example II: Workers ORE Budget and interventions design

Maintenance activities in ITER will be:

- Radioactive environments ➔ **UNED field**
- Highly contaminated environments
- Dark rooms & limited visibility
- Assisted breathing with special suits
- Surrounded by sharp objects
- Narrow spaces and limited mobility
- Carrying heavy loads & tools
- Life lines to secure the workers
- Permanent overview of an in-situ supervisor
- Rescue plans
- Time controlled
- Intervention design one-by-one

Really challenging human intervention

Are there similar activities somewhere?

Example II: Workers ORE Budget and interventions design

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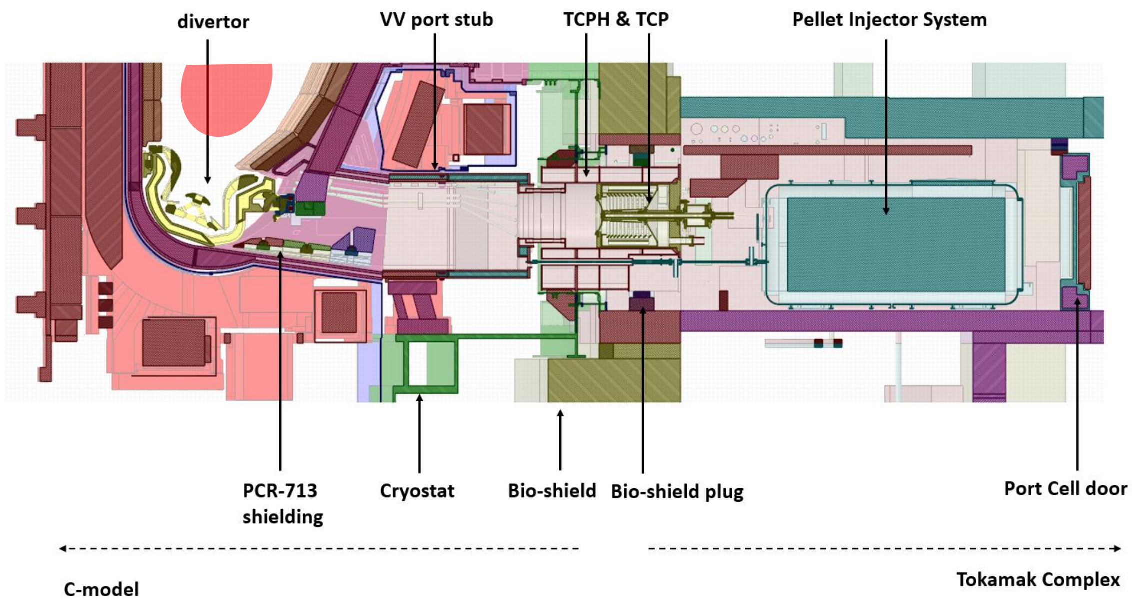
- Intervention design one-by-one

Extravehicular activities at ISS:
237 interventions have taken place at ISS for a total of 1491 hours and 54 minutes in 23 years

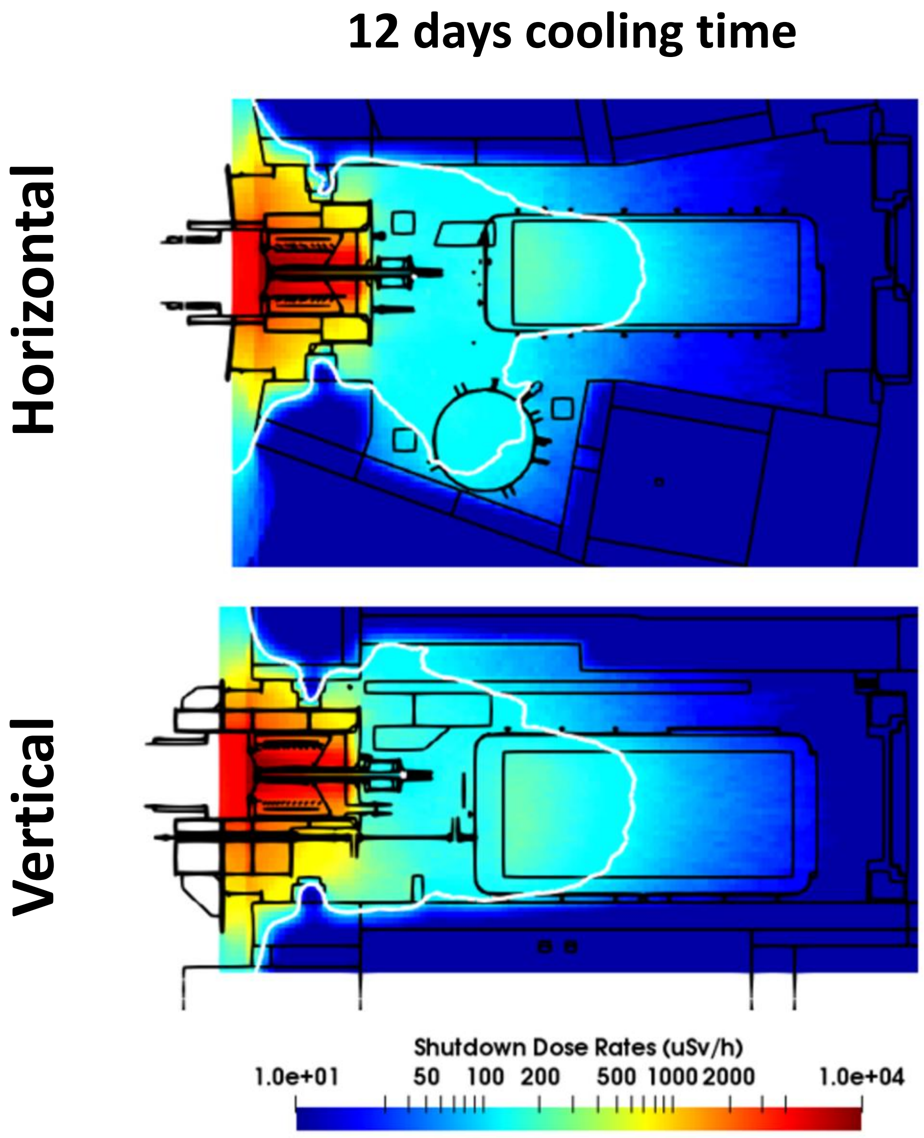
ITER maintenance:
Hundreds of interventions adding even 2500 hours will take place in ITER every year.
A lot of work is needed until 2055 and beyond

Example II: Workers ORE Budget and interventions design

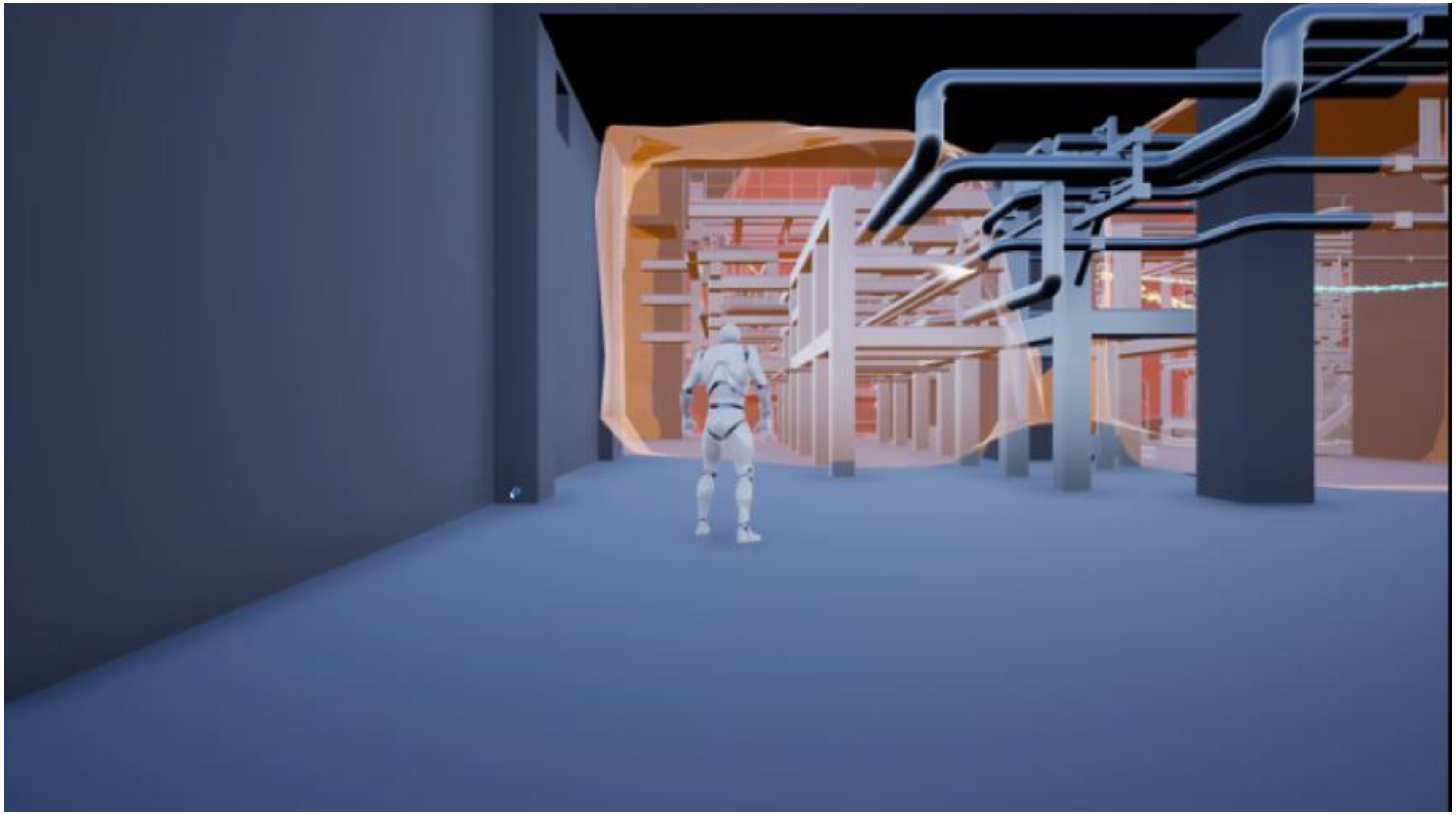


SDDR in the Torus Cryopump Port #12:

- Geometry modelling and translation to MCNP
- Development of variance reduction
- Selection of radioisotopes of concern
- Running simulations with D1S-UNED
- Postprocessing of results



Example II: Workers ORE Budget and interventions design



External file “videoITER.mp4”

UNED work for ITER

UNED remarkable contributions to ITER from 2012:

- > 25 research projects and > 30 papers in scientific journals
- Diverse computational tools have become the standard for ITER nuclear analysis (like D1S-UNED)
- Nuclear analysis for Final Design Review of all the first plasma ports
- Official ITER radiation maps for machine operation in 2016 and 2020
- Demonstration of compliance of regulatory limits to release the Assembly Hold Point

On-going work (2021-2022):

- Radiation mapping for human intervention design in 14 regions for ALARA strategy implementation
- Radiation mapping for remote equipment intervention inside the vacuum vessel
- Radiation mapping for the transportation of activated in-vessel components to the Hot Cell
- Radiation mapping for the hands-on cleaning cell of the ITER Hot Cell

There is a lot of work to do for ITER!

Nuclear analysis of IFMIF-like high intensity accelerators

F. Ogando, P. Sauvan, of behalf of TECF3IR (UNED)

Outline

- Importance of accelerators and radiological impact
- What is IFMIF and what role does it play in the fusion roadmap?
- Nuclear analyses of the IFMIF-DONES accelerator.
  - Radiological challenges during operation and maintenance scenarios.

Accelerators in everyday life

UNED

- Accelerators are used in industry and medicine.
  - Traditionally electron accelerators but nowadays ions as well.
- Accelerators are characterized by:
  - Type of particle (electron, ion…).
  - Energy of particles (MeV).
  - Current (from nA to mA).

  (Energy and current: Power (W))

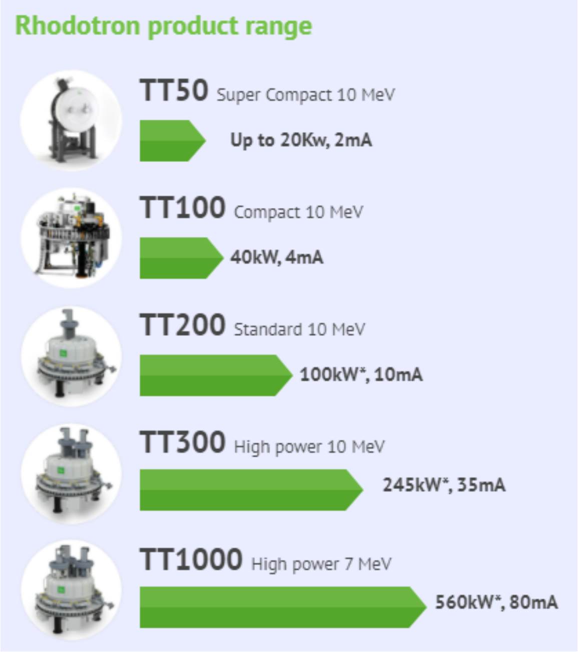
  - Acceleration strategy (electrostatic, RF…).
- Circular or linear.

- Typical applications
  - Sterilization
  - Ion implantation
  - Radioisotope production
  - Radiation therapy
  - Materials research
  - High energy physics
  - X-Ray source
  - Etc…

[Applications | IBA Industrial (iba-industrial.com)](iba-industrial.com)

Typical industrial and medical accelerators

Rhodotron electron accelerator

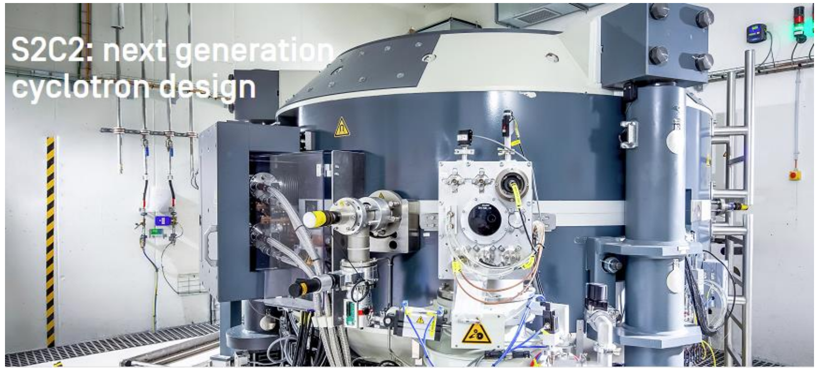


iba

varian
A Siemens Healthineers Company

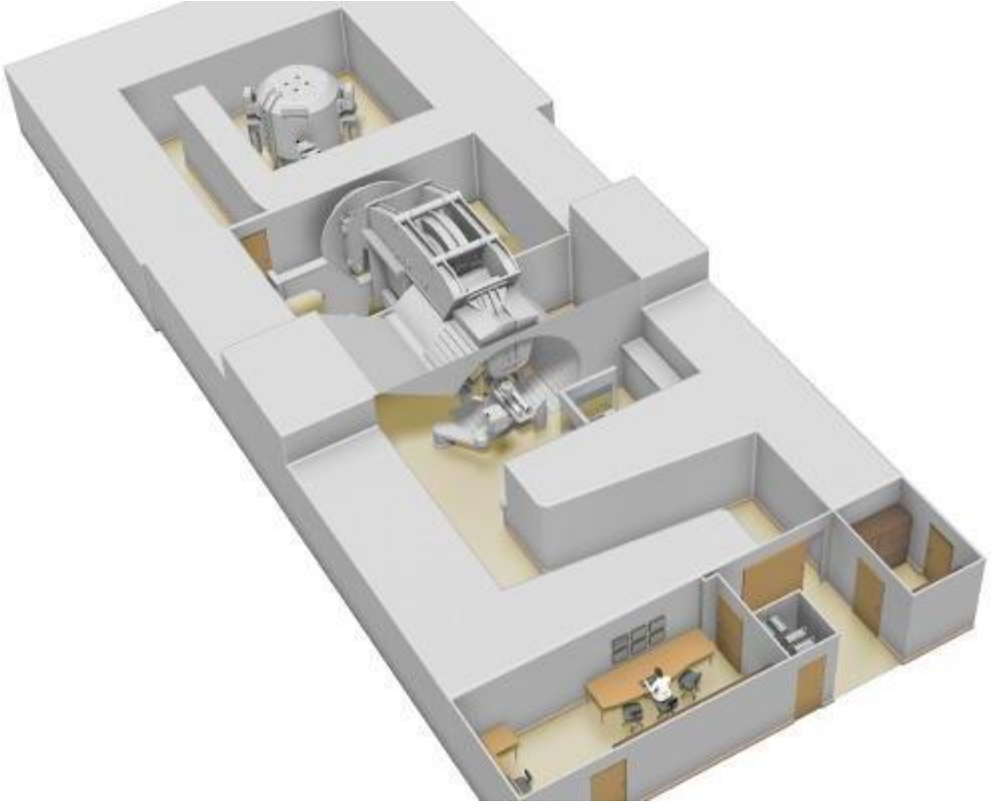
Varían 21ix: Linac
6 -20 MeV, 1 μA

Proton cyclotrons (IBA):
Top: radioisotope production (p, 18 MeV, 300 μA).
Bottom: proton therapy (p, 250 MeV, 500 nA)



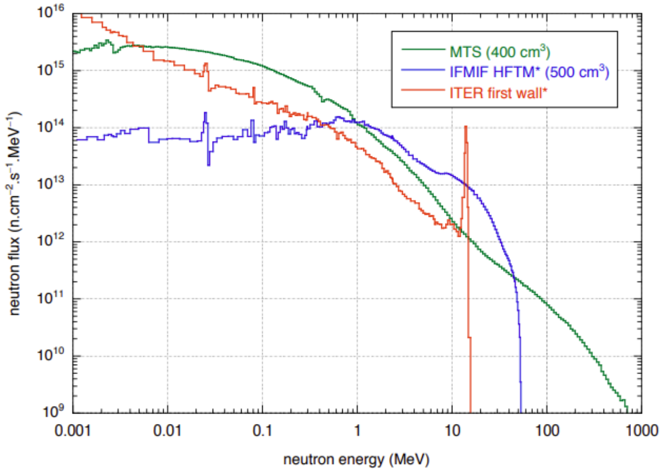
Radioprotection in Accelerator facilities

- Particle interactions
  - Beam losses to vacuum pipe.
  - Beam conformation and target.
- Radiation from interactions:
  - Bremsstrahlung (X-rays from electrons).
  - Nuclear (many products).
- The most challenging radiation is neutrons from nuclear interactions.
  - Electrons over 10 MeV
  - Light ions over (0.1 - 2) MeV



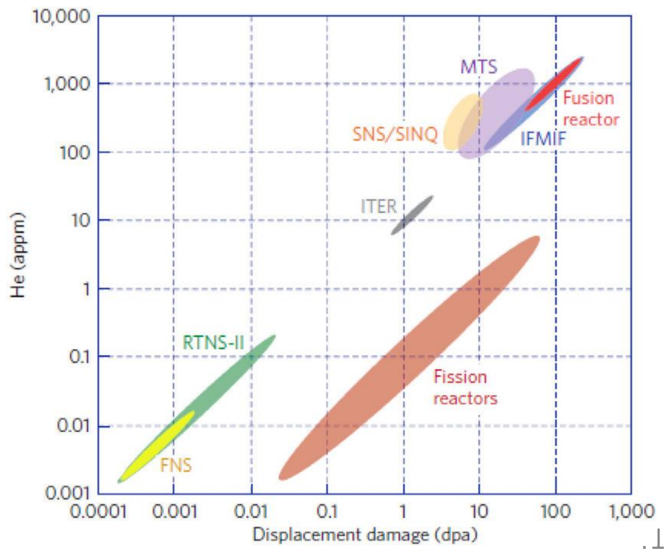
Back to fusion.
Neutron damage: He & dpa

- Neutron irradiation changes the mechanical properties of materials.
- Fusion reactors will produce more, and more energetic neutrons than current fission reactors.
- The characteristics of the damage depends on the fast spectrum of incident neutrons.
- Currently no data on materials resistance in a fusion environment
  - No DEMO without suitable materials

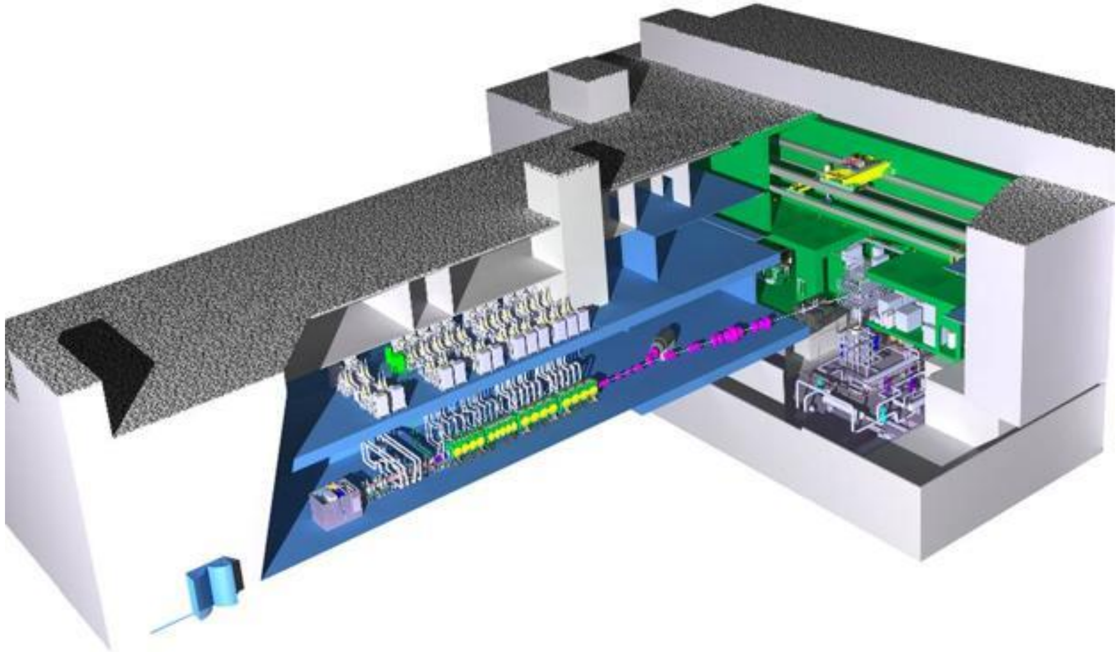


Spallation Sources

- MTS (LANL)
- SINQ (PSI)



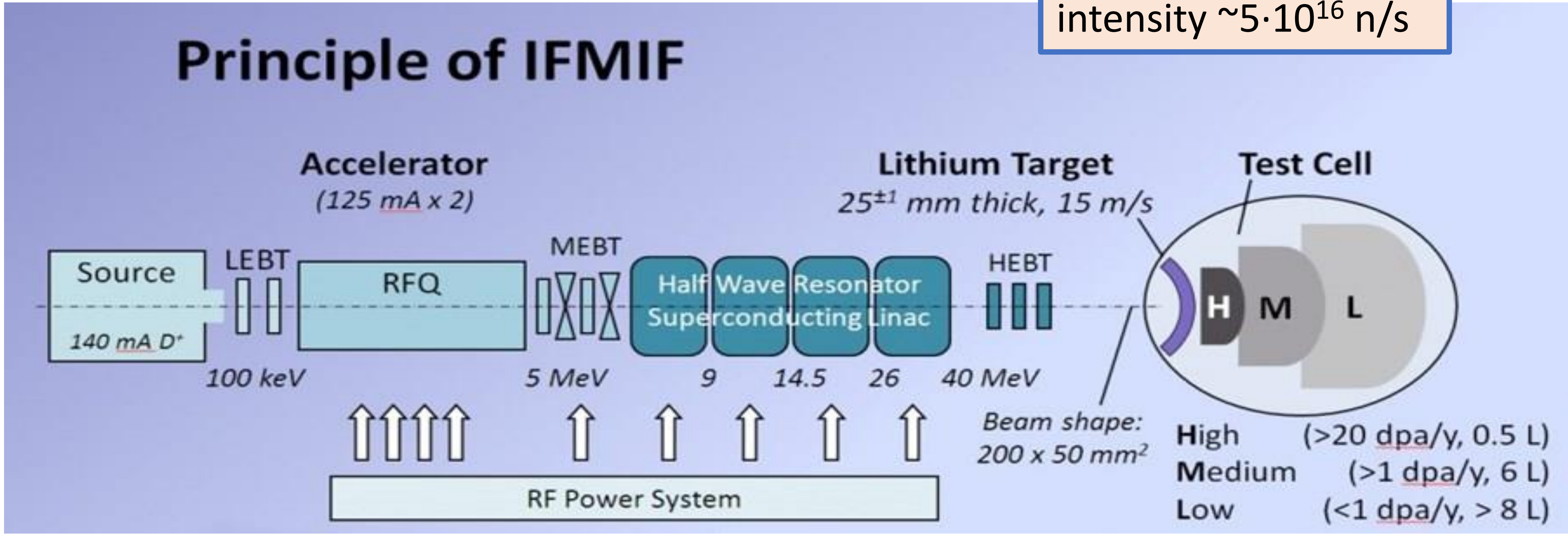
IFMIF-DONES
(DEMO Oriented Neutron Source)



- Fusion-like neutron damage is produced with an accelerator drive source.
- 40 MeV Deuterons onto Li target, resulting in lots of neutrons.
- Proposed by Spanish CIEMAT (led by A. Ibarra).

IFMIF-DONES operation

Neutron source intensity ~$5 \cdot 10^{16}$ n/s



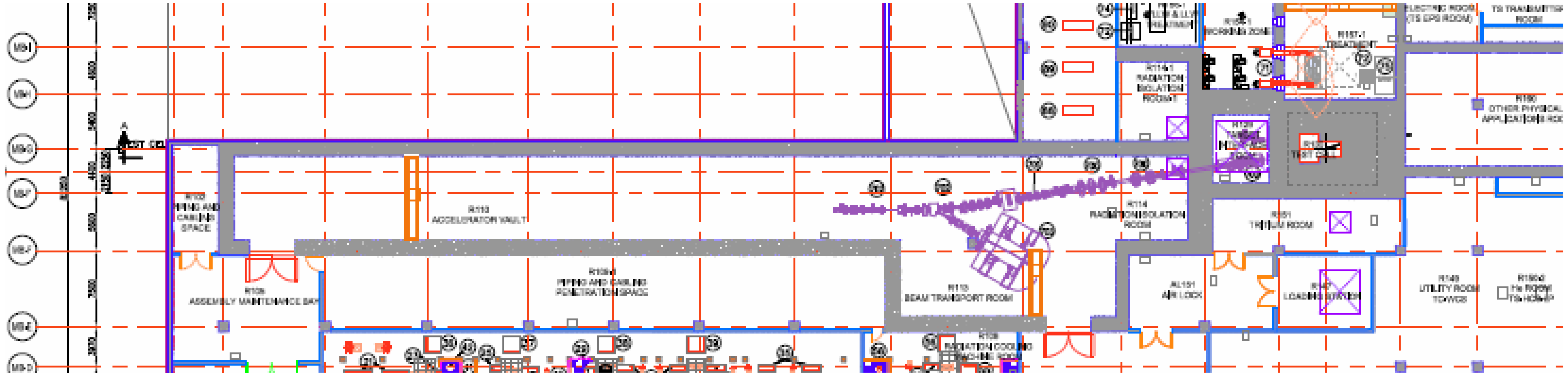
P. Grand et al., *An intense Li(d,n) neutron radiation test facility for controlled thermonuclear reactor materials testing,* **Nuclear Technology, Vol 29 (1976)**

IFMIF-DONES to Spain

- The EU supports the Spanish (CIEMAT) led Project.
- Escúzar (Granada) has been officially proposed by EU to host the facility
- The facility is included in the ESFRI roadmap.
  - European Strategy Forum on Research Infrastructures

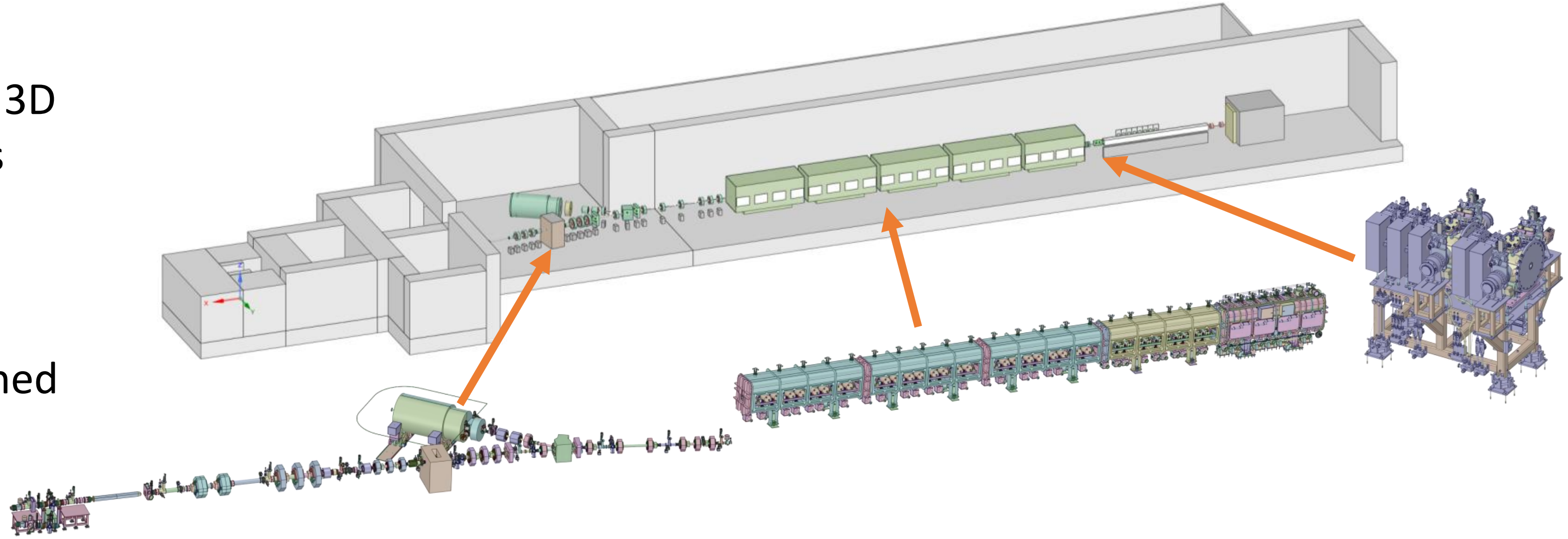
Estimated completion in 2027

Accelerator of IFMIF-DONES: modelling

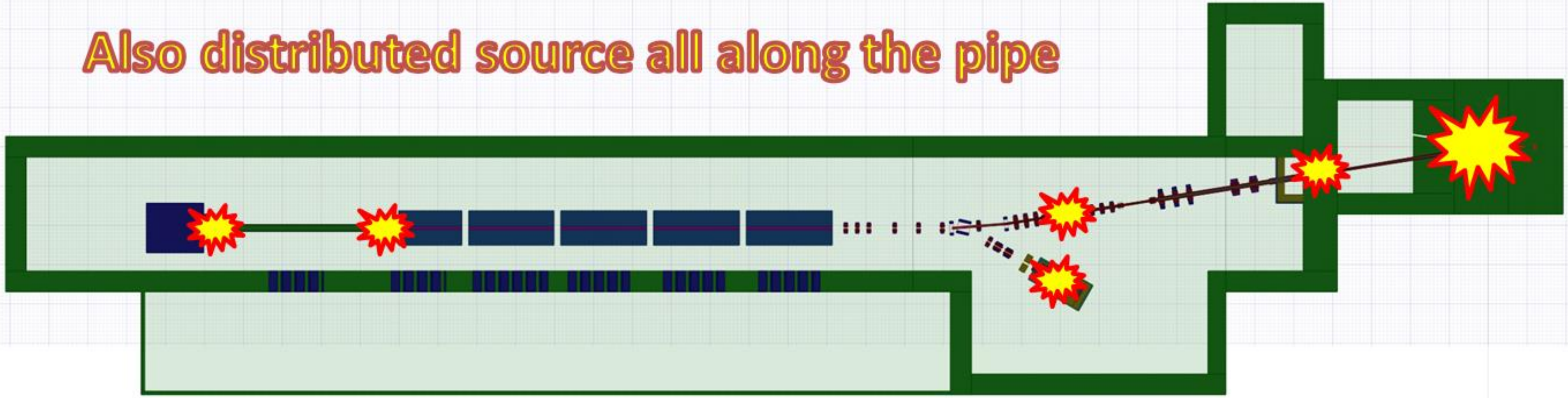


From drawings or 3D CAD to neutronics model.

Only relevant features are retained



Radiation sources



Main sources:

- Target in Test Cell
- Collimators
- Beam dump
- Beam losses

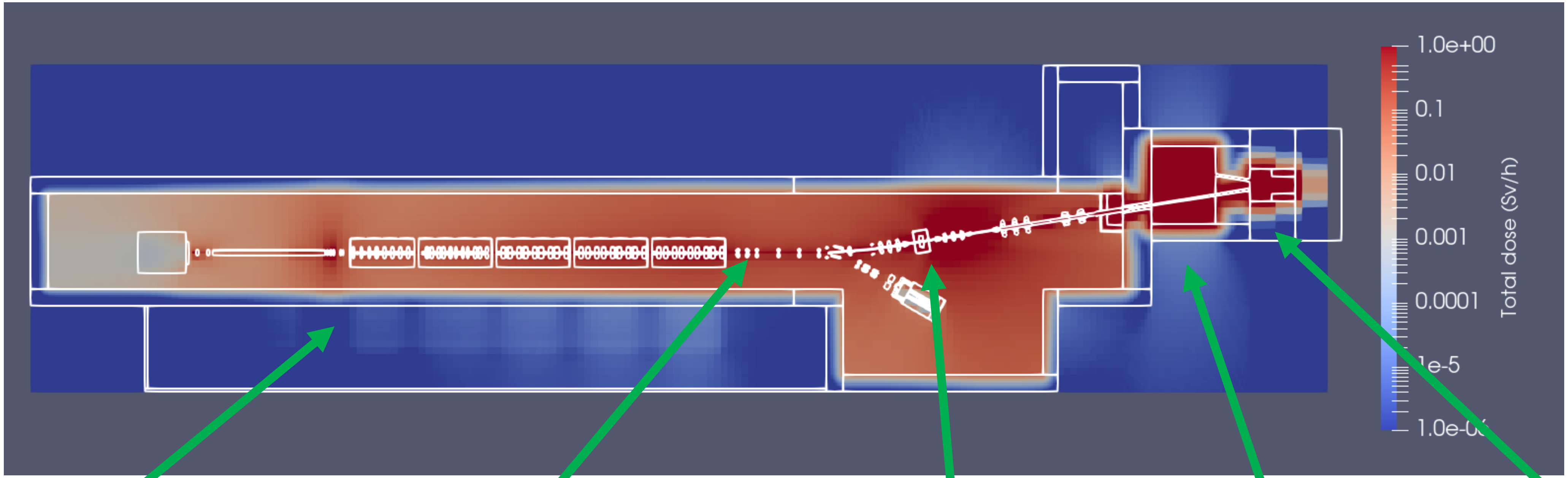
New methodology
MCUNED

Simulation challenges:

- Calculate beam interactions
- Check and improve nuclear data
  - Anisotropic secondary sources
  - Very energetic neutrons (up to 55MeV)
- Optimize calculations

Operation scenario: challenges

Dose rates



Leakage through wall penetrations

Monitor beam with radiation field

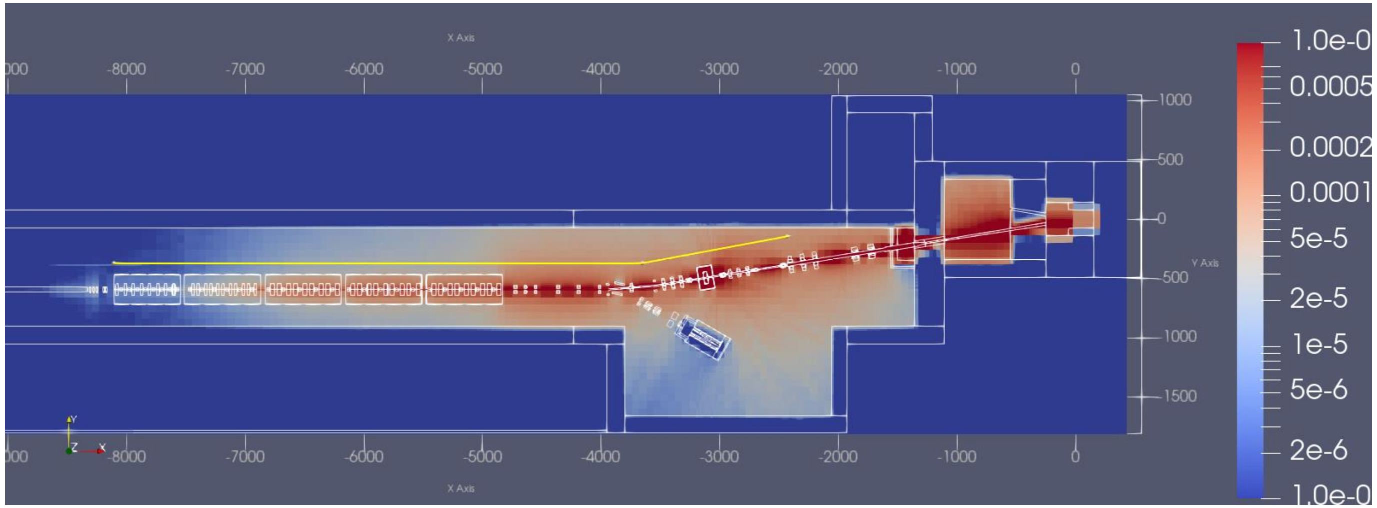
Absorbed doses in insulators & electronic equipment

Outside doses: Shielding efficiency

Activation, radiolysis and corrosion in cooling circuits

Maintenance scenario

Dose rates

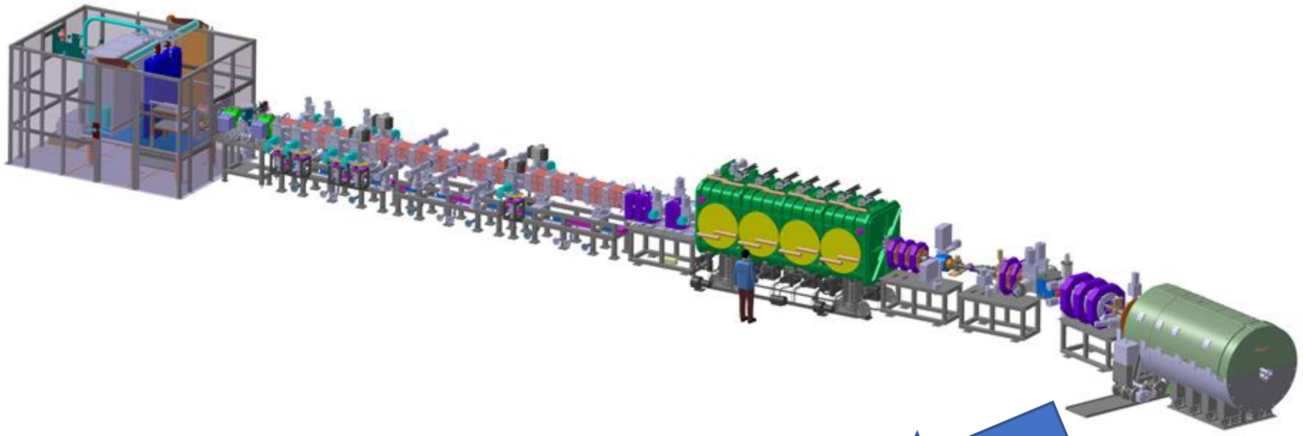


- Radioactive material generated during irradiation
  - Ensure acceptable dose field around the accelerator
  - Select appropriate materials
  - Propose local shields

Other analyses

- Air activation
- Cooling fluid (ACP) activation
- Safe removal of local shields.
- Definition of remote handling operations
- Impact of accidents
- Systems movement & replacement

Our previous experience: IFMIF/EVEDA



- LIPAc: The IFMIF Prototype Accelerator
  - 9 MeV deuterons, 125mA.
- Operating in Rokkasho (Japan)

Recognition to UNED

Conclusions: IFMIF-DONES

- The nuclear analysis of accelerators has specific features, mostly related to the interactions of charged particles with matter.
- UNED produced a simulation code enhancing the reference code MCNP and providing accuracy and flexibility.
  - These methodology and analyses resulted in the shielding design of the LIPAc beam dump.
- This experience and capability is now used for the design of IFMIF-DONES.
  - It is a key facility of the fusion roadmap
  - It will be built in Spain in this decade.

Trabaja con nosotros

Investigación en TECF3IR

- Programa de Doctorado UNED en Tecnologías Industriales (ENLACE)
- Líneas actualmente abiertas a tesis doctoral:
  - Conversión automáticas de CAD a MCNP: GEO-UNED.
  - Cálculo de inventario isotópico y dosis residuales en geometrías complejas: D1S-UNED y R2S-UNED.
  - Evolución isotópica y química en fluidos bajo irradiación: FLUNED.
  - Optimización de la eficiencia en cálculos de Monte Carlo: GVR-UNED.
  - Estimación de las incertidumbres en los cálculos de dosis residuales.
  - Aplicación de las herramientas a retos novedosos en ITER, DEMO e IFMIF.

Cómo saber más de nosotros…

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  - Francisco Ogando (fogando@ind.uned.es)
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  - Web propia: https://www.tecfir.com