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EUROPEAN FUSION DEVELOPMENT AGREEMENT

A roadmap to the realization of fusion energy

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Acknowledgments: P. Barabaschi, D. Borba, G. Federici, L. Horton, R. Neu, D. Stork, H. Zohm

ITER IO, F4E, EFDA CSU and Associates, Fusion Industry Innovation Forum, EFDA STAC

Why a roadmap

- The need for a long-term strategy on energy technologies for security of supply, sustainability and economic competitiveness **requires long term programming and substantial re-direction of the programme**
  - EU Strategic Energy Technology plan, Energy Roadmap 2050

- In this context, Fusion must become a credible energy source

- European Commission proposal for Horizon 2020 (2014-2020), following the advice of an Independent Panel on *Strategic Orientation of the Fusion Programme* (Wagner Panel), states the need of ***an ambitious yet realistic roadmap to fusion electricity by 2050***.

- Hence, the request by the EC to EFDA for a fusion roadmap.

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ITER is the key facility in the roadmap

- ITER is expected to achieve most of the important milestones needed for a decision on a demonstration fusion power plant (DEMO).
- ITER construction has triggered major advances in enabling technologies.
- ITER licensing has confirmed the intrinsic safety features of fusion and incorporated them in the design.
- Vast majority of proposed Roadmap resources on ITER construction and preparation.
- The assumption made here is that ITER will be built according to specification and within cost and schedule.

Background

- Fusion Fast Track (D. King, 2001)
- SET Plan (2007)
- Facility Review (2008)
- AHG on JET and accompanying programme (2010)
- DEMO Working Group (2010)
- Strategic orientation of the fusion programme (2011)
- Common aspects to these reviews
  - Central role of ITER
  - 14 MeV neutron sources (IFMIF) for material qualification
  - DEMO as a single step to the commercial power plant

The present roadmap attempts to put in a logical sequence and within a realistic plan the elements of the Reviews of the last few years taking into account the recommendations by the Review Panels.

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The present roadmap

- **Pragmatic approach to fusion energy**.
  - Define realistic DEMO goals (together with industry)
  - Avoid multiple critical paths by minimizing construction of new large and complex facilities.
    - Roadmap constructed to have a single critical path – ITER
- **Focus the effort of European laboratories**
  - Goal oriented approach articulated around 8 Missions
  - Priority to the items in the roadmap
- **Ensure innovation through early industrial involvement**
  - Industry must be able to take full responsibility for the commercial fusion power plant after successful DEMO operation.
  - Materials development: strong emphasis on the industrialisation
  - Reduction of plant capital costs
- **Exploit the opportunities arising from international collaborations**
  - Not every facility in Europe (but Europe should have all the necessary know-how by 2030 for the construction of DEMO).

The present roadmap

- Increase support to education and training (300PhD/y & 140Post-Doc/y).
- Maintain a sizeable amount of fund to basic (i.e. not Mission oriented) and "curiosity driven" research.
- Three periods considered
  - H2020 (2014-2020) detailed work packages and budget
  - 2021-2030 indicative programme and budget
  - Beyond 2030 – only outline

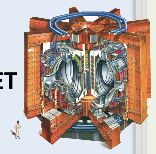
Method of work

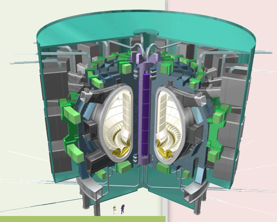
- Work divided in 8 areas (Missions)
- For each mission:
  - Critical aspect for reactor application examined, risks and risk mitigations discussed involving experts.
  - Level of readiness (TRL) now and after ITER discussed
  - Work packages elaborated.
  - Gaps analyzed (i.e. **issues that require new devices**)
- Input from ITER IO, F4E, EFDA CSU and Associates.
- Industry involved through the Fusion Industry Innovation Forum.
- Bilateral meeting with Associates completed by the end of June.
- Workshop (25-26.7.12) in Garching to present the Roadmap to the fusion community and have feedback.
- Assessment by EFDA STAC.
- **Material assessment progressed in parallel and incorporated in the report (Derek Stork Chair).**

The Roadmap in a nutshell

1. Plasma operation
2. Heat exhaust
3. Materials
4. Tritium breeding
5. Safety
6. DEMO
7. Low cost
8. Stellarator

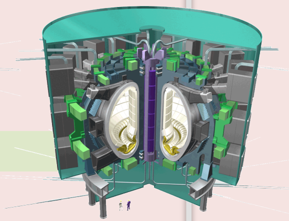
JET





Inductive

Steady state



JT60-SA

European Medium Size Tokamaks
+ International Collaborators

DEMO decision

2010 2020 2030 2040 2050

Mission 1

- No major gaps (i.e. no need of other devices in addition to those existing or under construction)
- Enhancements of ITER and JT60-SA needed
  - Increase in heating power
  - Operation with a full W wall in preparation to DEMO operation (Note: not needed for DEMO decision)

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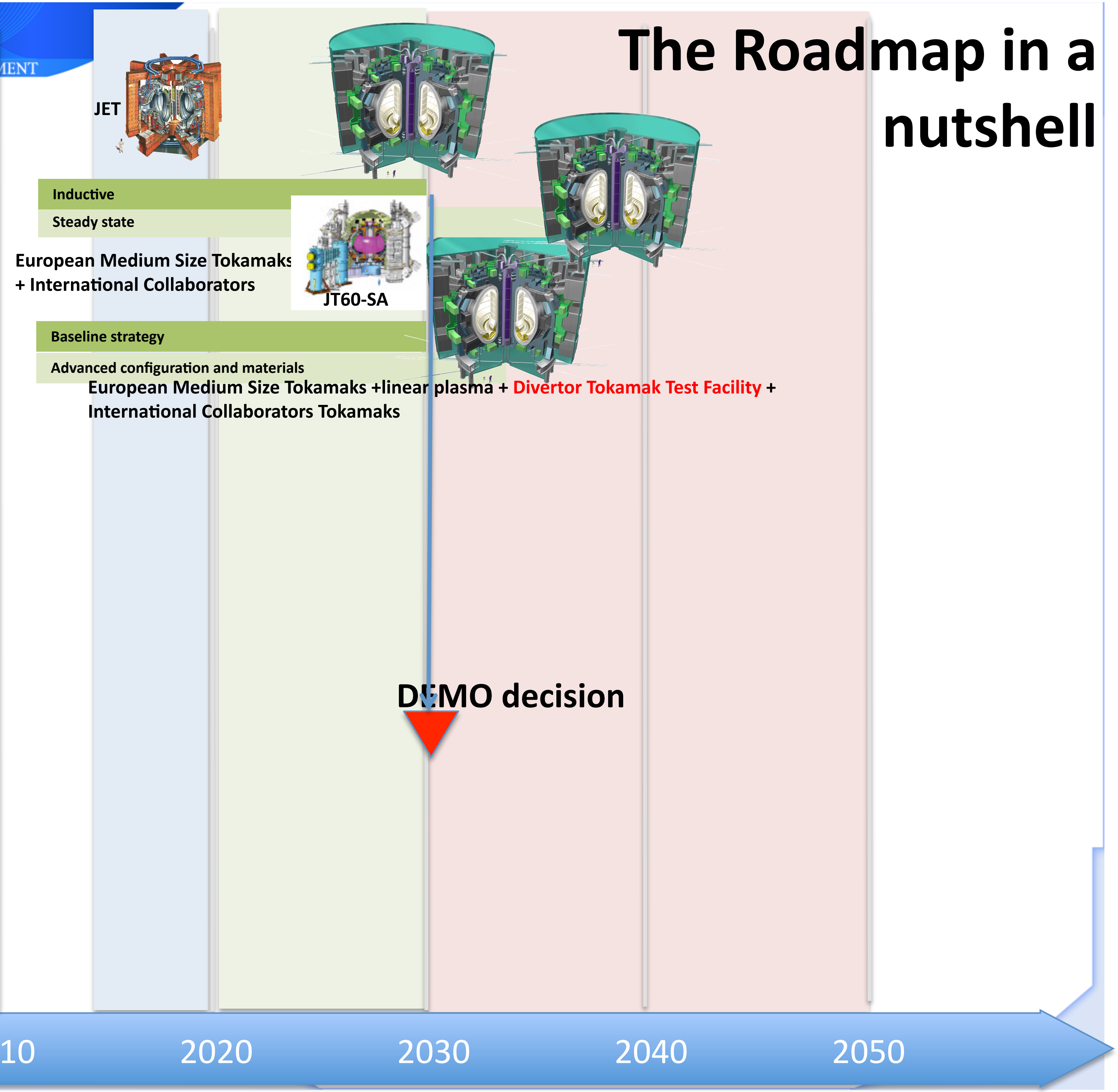
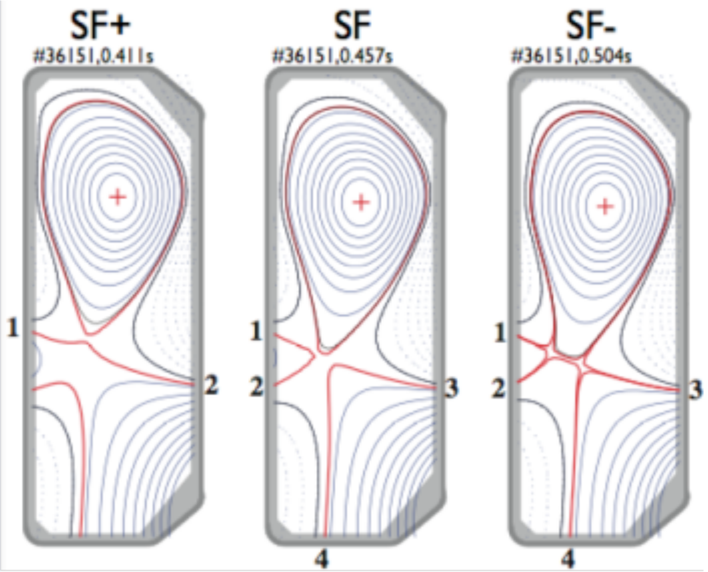
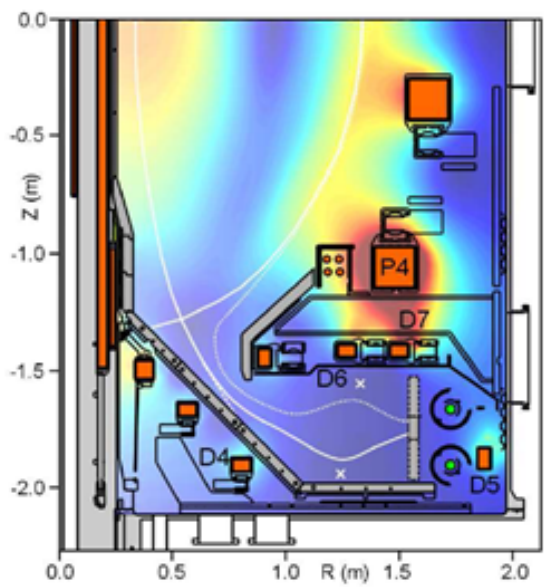
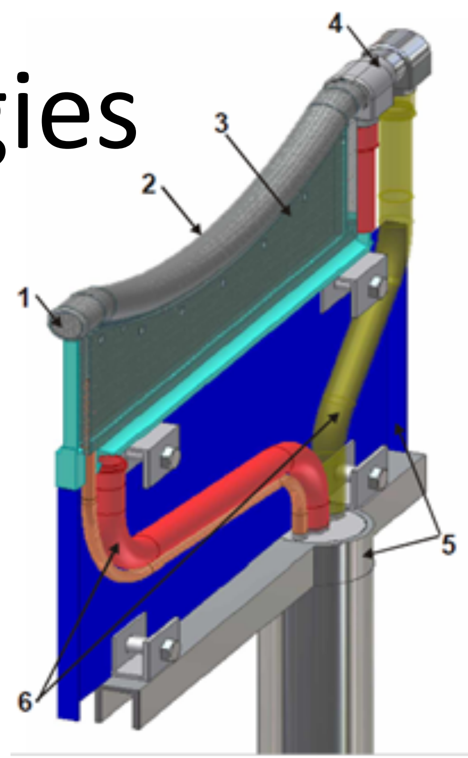


Alternative strategies







- Proof-of-principle on medium size experiments + linear PWI facilities
- Assess DEMO-relevance in parallel (ongoing)
- Select options to be tested on DTT
  - New/upgraded device
  - Non nuclear
  - Opportunity for joint programming and international collaborations

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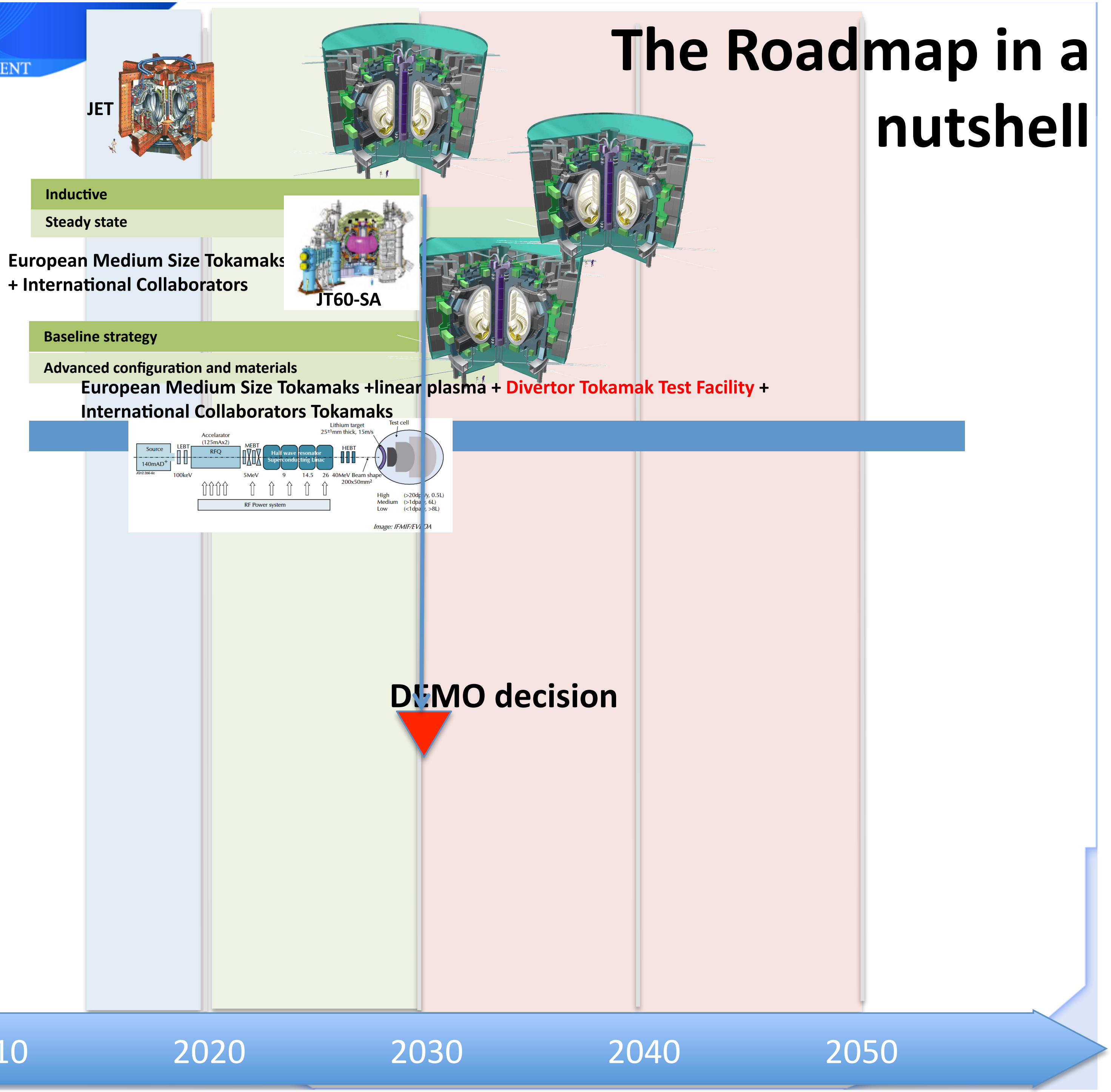


DEMO strategy

PARAMETER	Early DEMO (or DEMO 1)
R (m)	9
a (m)	2.25
B on axis (T)	7.1
I (MA)	16.0
Elongation (95)	1.66
Triangularity (95)	0.33
Fusion Power (MW)	1943
Thermal power, Pth (MW)	2227
Gross Electric (MW)	735
Net Electric (MW)	500
Auxiliary current drive fraction	0
Auxiliary heating, Pinj (MW)	50
Zeff	1.98
H factor	1.0
Divertor pk heat load ($MW.m^{-2}$)	7.9
$\beta_N$thermal, total	2.01, 2.42
Ave neutron wall load ($MW.m^{-2}$)	1.27
Bootstrap fraction	0.36
Safety fac	
T (keV)	
Density, <	
γ_{CD} (10^{20} A	
Power to c	
Pumping p	
Thermody	
Recirculat	
Startup flu	
Available f	
Pulse leng	
i/b blanket	
o/b blanke	

- DEMO n-damage (Gilbert et al. FEC 2012, Stork et al MAG report)
  - FW steel 15dpa/fpy
  - W armour 5dpa/fpy
  - Cu divertor 5dpa/fpy (could be restricted to 3dpa/fpy regions)
- Phase 1 – component test – limited availability (~30%) – starter blanket
- Phase 2 – high availability – adv. components

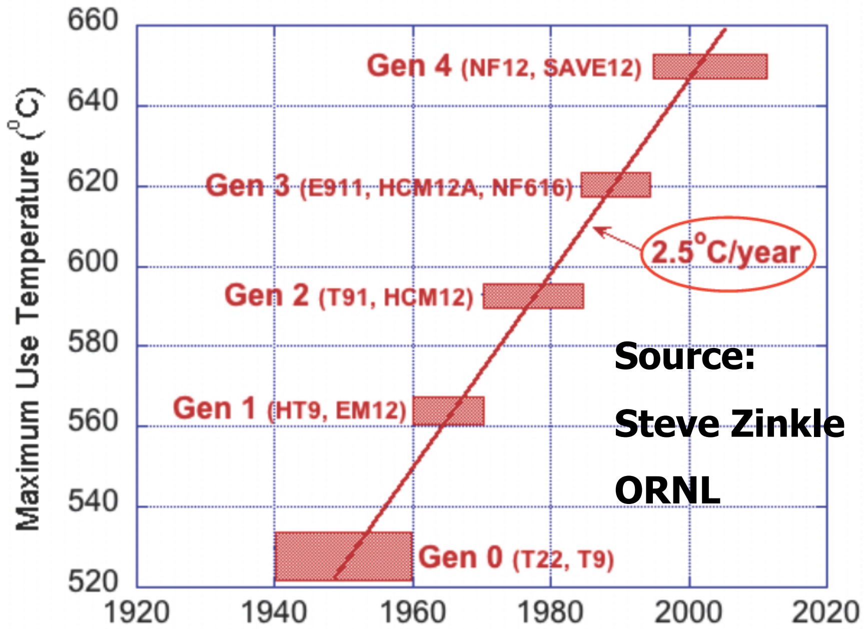
	Onset of 14MeV effects	Calibration of 14Mev effects	Full database for the full exposure
DEMO Phase1	20dpa (Fe) 250-350°C 20cc	20dpa (Fe) 250-550°C 70cc	20dpa (Fe) 250-550°C 300cc
DEMO Phase2	50dpa (Fe) 250-350°C 20cc	50dpa (Fe) 250-550°C 70cc	50dpa (Fe) 250-550°C 300cc
Reactor		100dpa (Fe) 250-1200°C 70cc	100dpa (Fe) 250-1200°C 300cc

Materials

- Baseline
  - EUROFER (but narrow temperature operation range)
  - W armour (but erosion/retention under irradiation?)
  - Cu alloys (but rapid loss of ductility under irradiation?)
- Risk mitigation
  - ODS (but industrialization?)
  - High Temperature FM steels (reduced activation?)
  - W fibre reinforced materials
  - Fibre & foil reinforced Cu and W
  - W-Cu laminates
  - W-Cu composites for divertor
- Down select by 2020

(Stork et al MAG report)

Based on R. Viswanathan, Adv. Mat. Proc. 162 (2004) 73



14 MeV neutron testing

(Stork et al MAG report)

- Strategy
  - 30dpa testing in time for finalization of DEMO design
  - 70dpa testing for the second set of components

	IFMIF	DONES	ENS
Beam	2x125mA/40MeV	1x125mA/40MeV	1x125mA/26.5MeV
Damage	40dpa/fpy 70cc 20dpa/fpy 300cc 2dpa/fpy 2000cc	20dpa/fpy 70cc 10dpa/fpy 300cc 2dpa/fpy 1000cc	15dpa/fpy 20cc 2dpa/fpy 600cc
Cost	750M€/?	364M€/253M€	276M€/164M€

Option with C-taget low current/high energy (FAFNIR) also analyzed

Options to be assessed by early H2020

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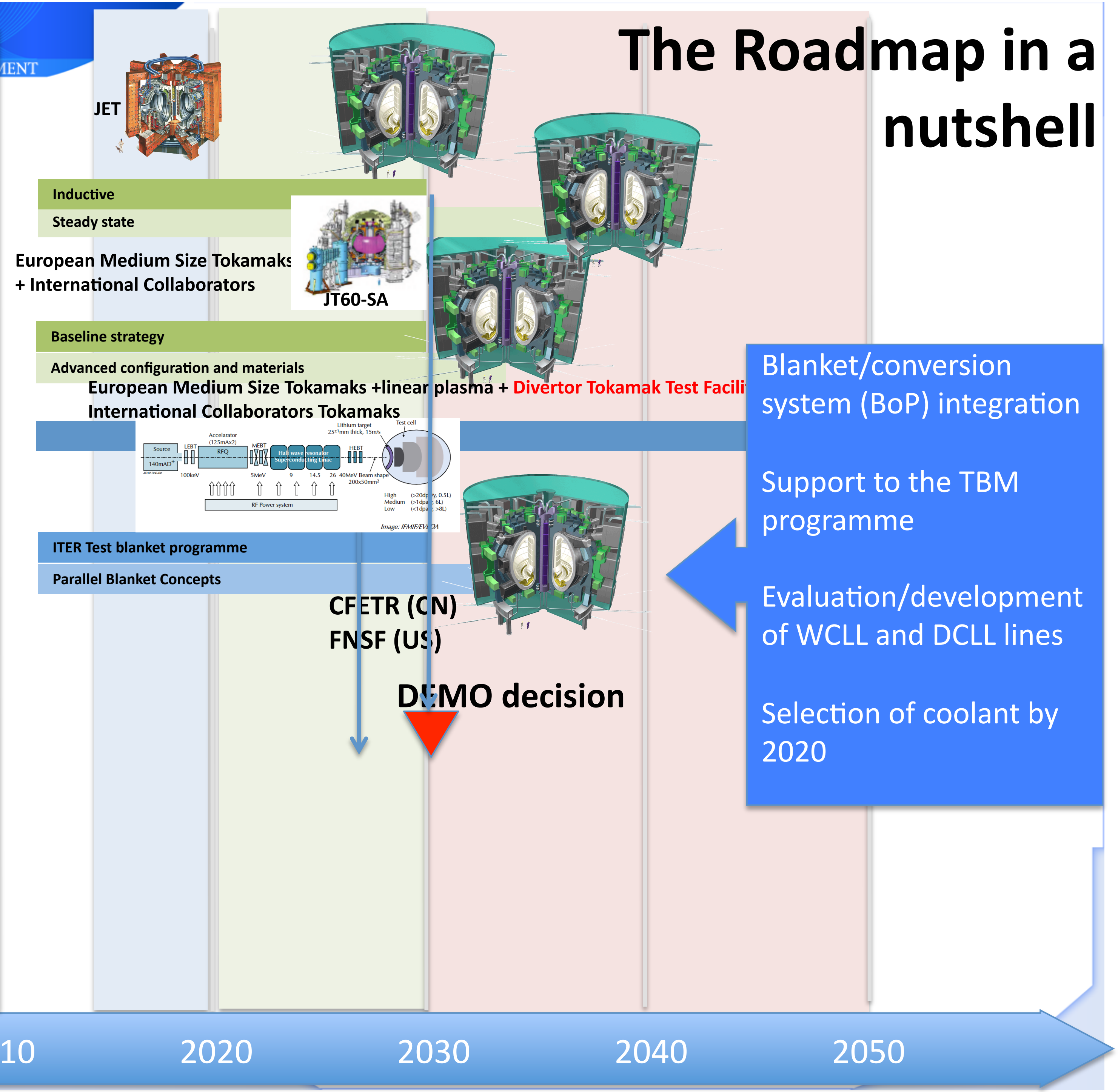

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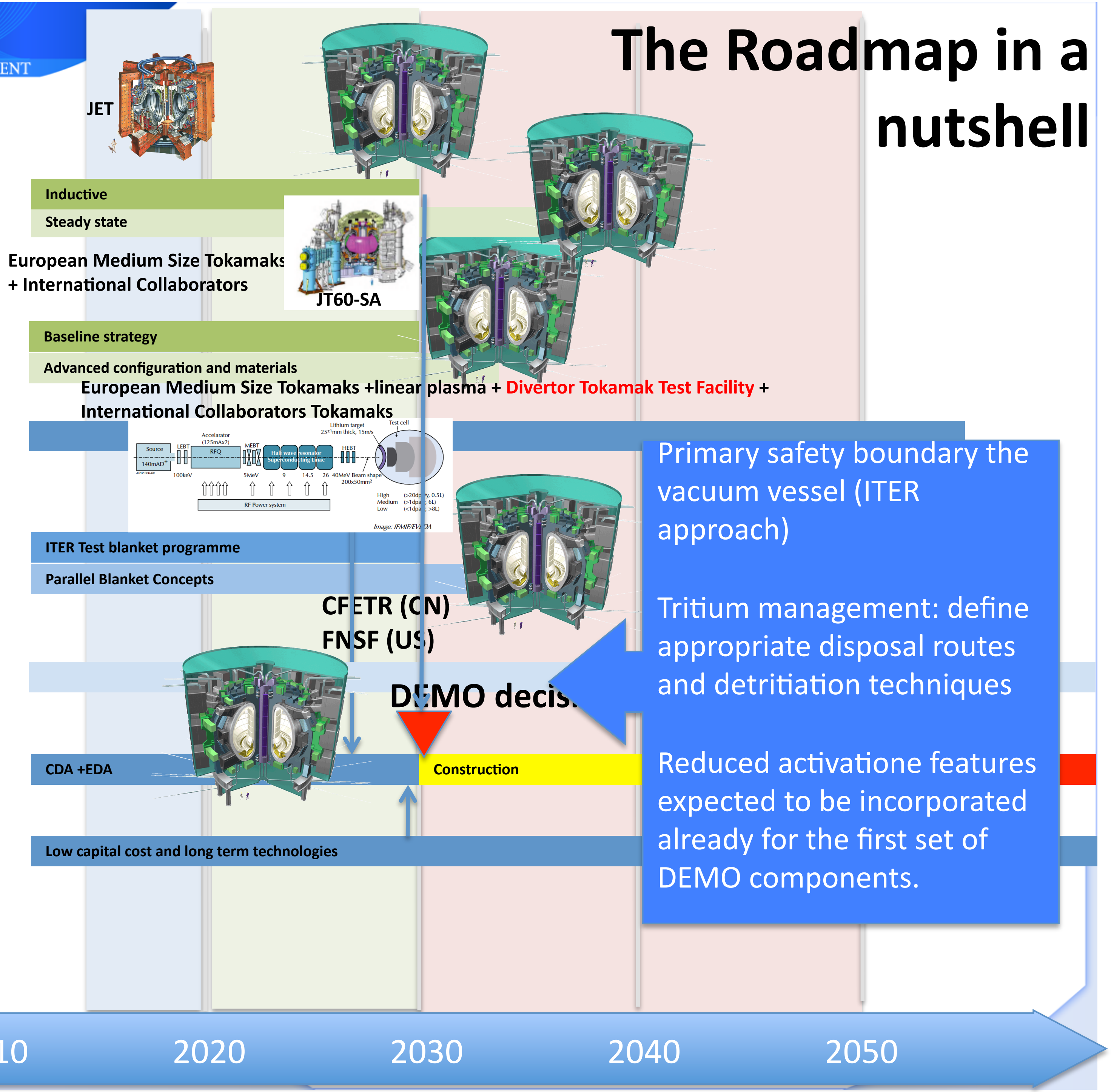

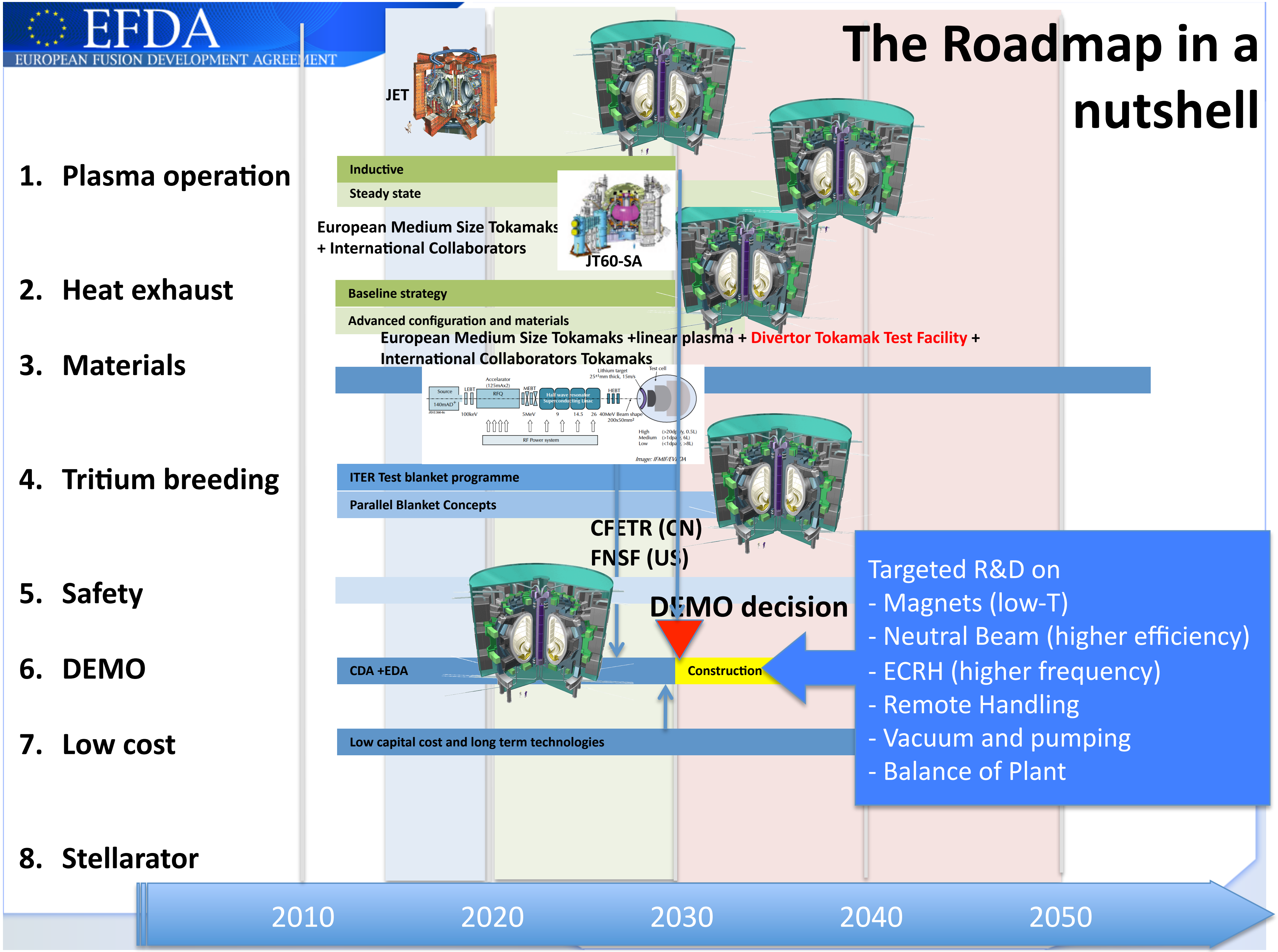

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JET
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European Medium Size Tokamaks
+ International Collaborators
JT60-SA
Baseline strategy
Advanced configuration and materials
European Medium Size Tokamaks +linear plasma + Divertor Tokamak Test Facility +
International Collaborators Tokamaks
ITER Test blanket programme
Parallel Blanket Concepts
CFETR (CN)
FNSF (US)
DEMO decision
CDA +EDA
Construction
Low capital cost and long term technologies
Targeted R&D on
- Magnets (low-T)
- Neutral Beam (higher efficiency)
- ECRH (higher frequency)
- Remote Handling
- Vacuum and pumping
- Balance of Plant
2010
2020
2030
2040
2050

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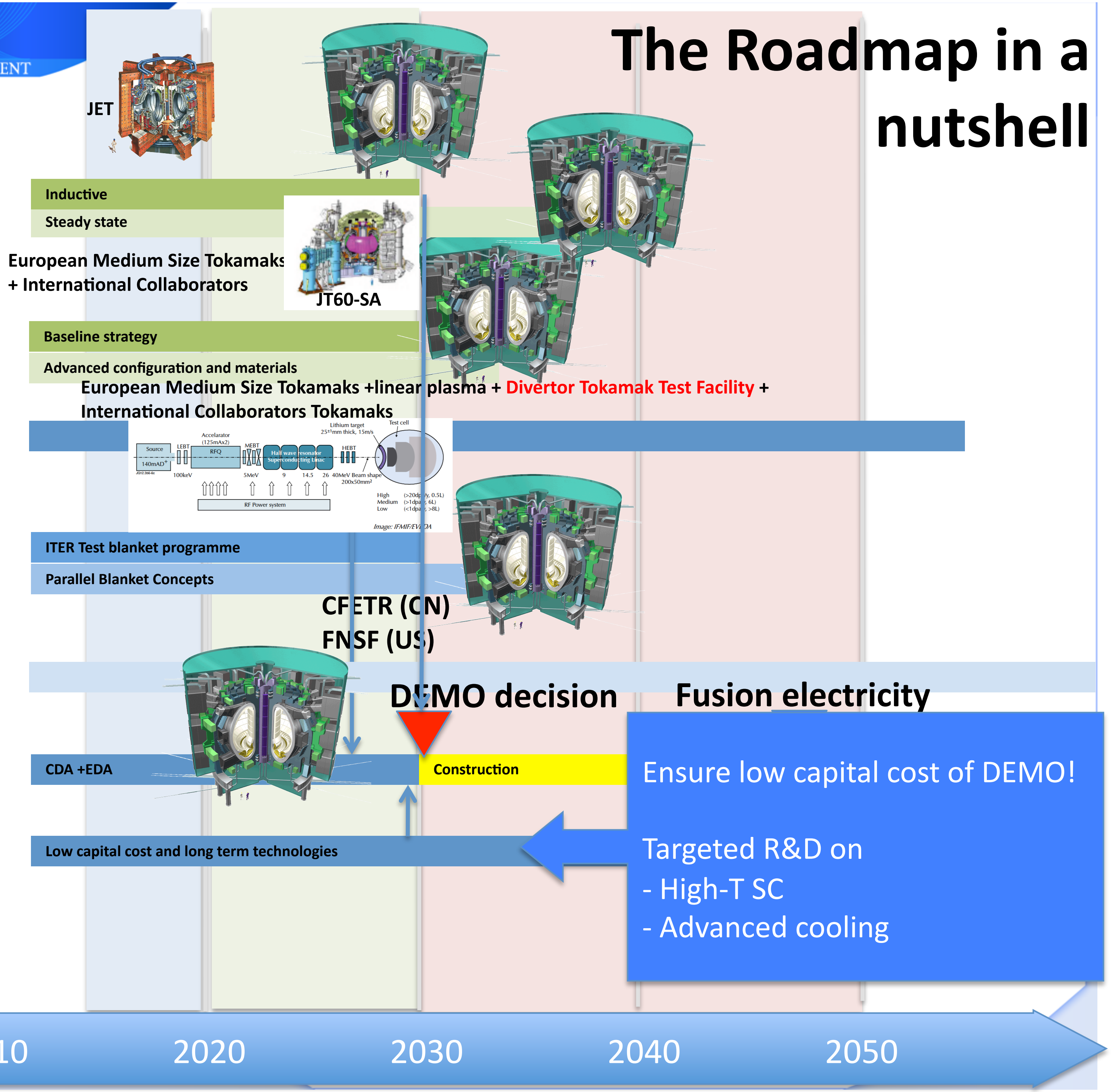

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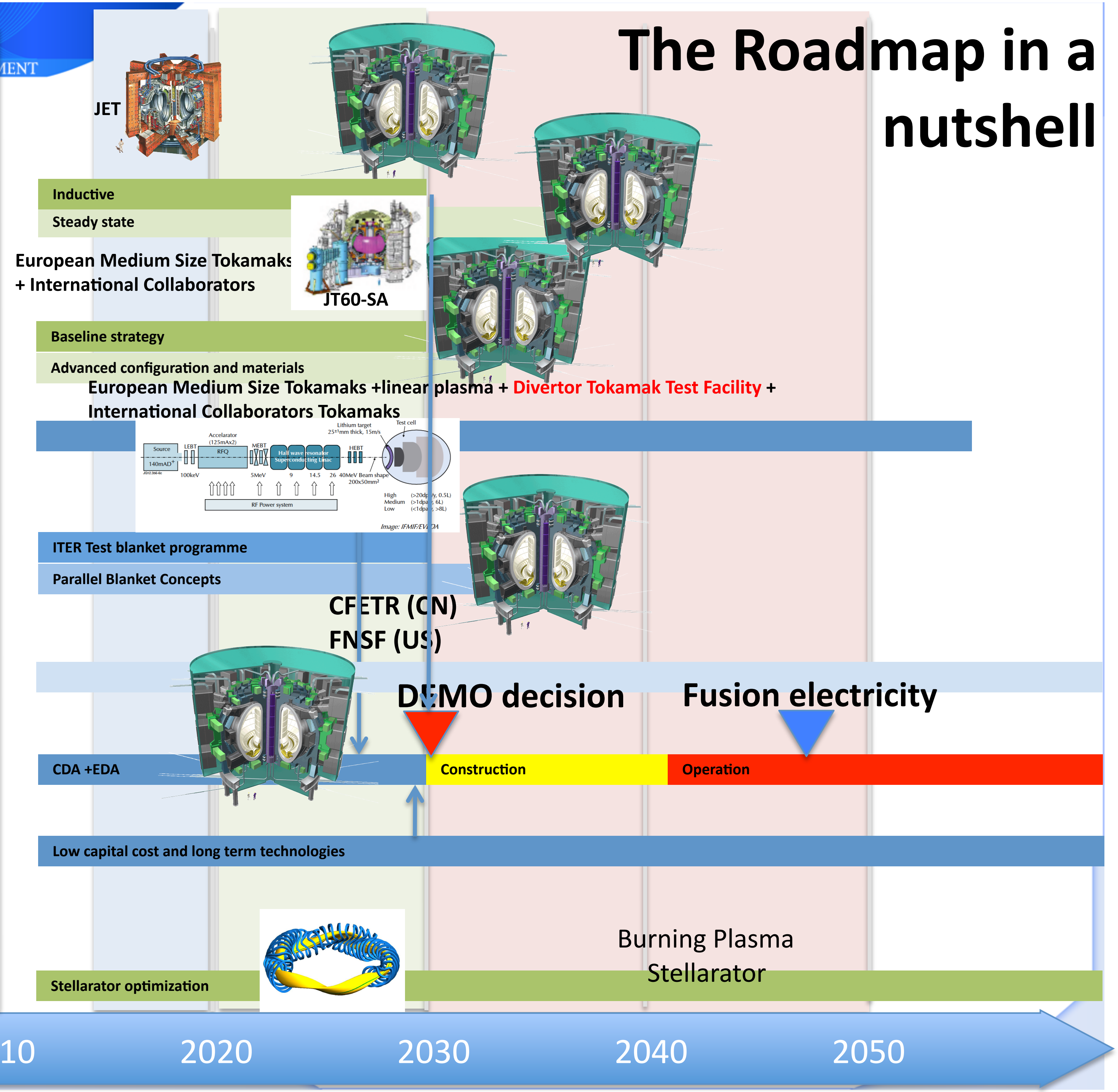
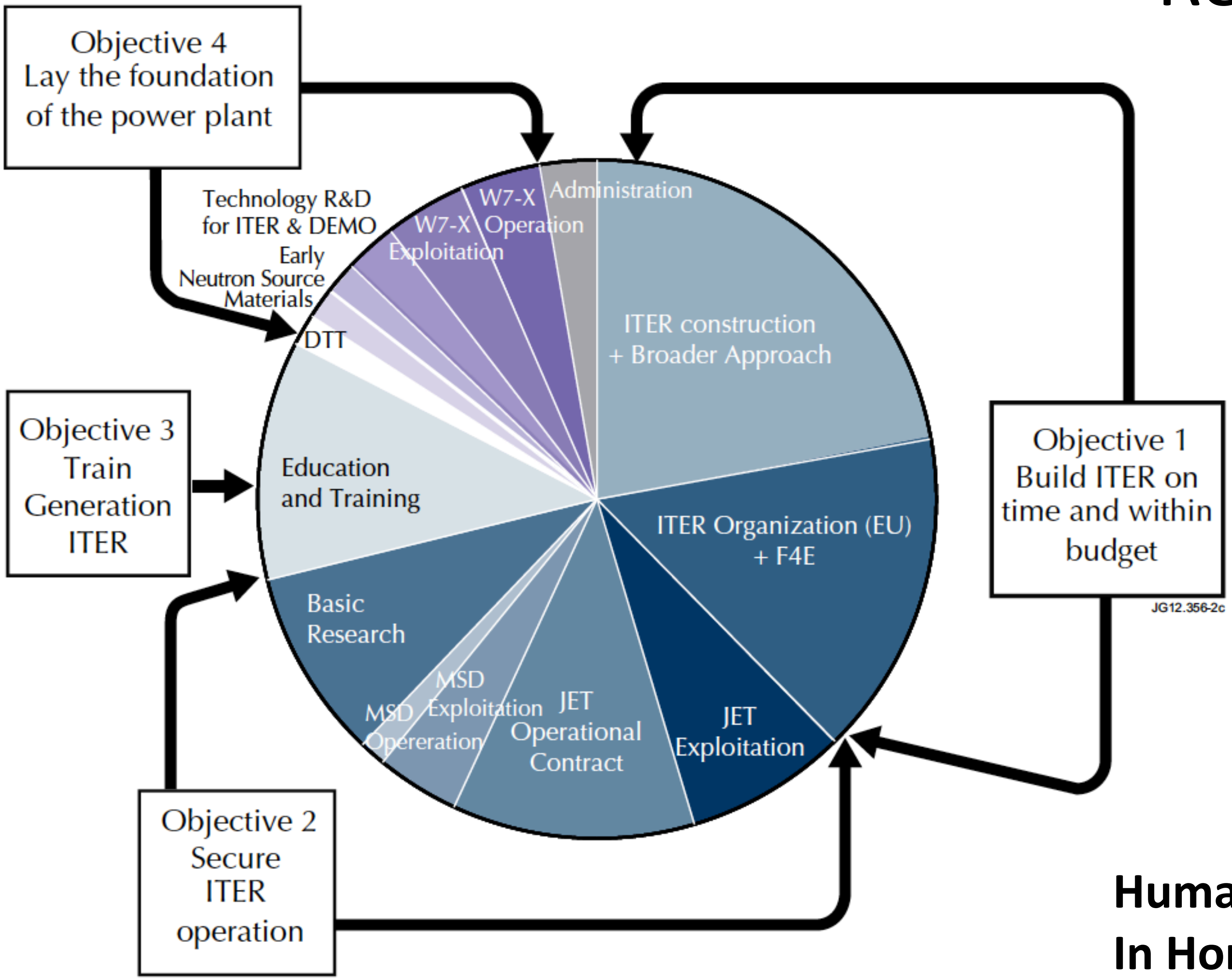


Resources



Human resources
In Horizon 2020

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Resources

	2014-2018 average	2019-2020 average	2021-2030 average
	M€	M€	M€
Mission 1 w/o JET & ITER	20	33	33
Mission 2 w/o JET & ITER	36	70	44
Mission 3	39	67	33
Mission 4 w/o JET & ITER	19	14	In Mission 6
Mission 5	3	2	In Mission 6
Mission 6	13	9	200
Mission 7	5	5	5
Mission 8	45	50	50
Basic research	35	35	35
Computing resources	8	2	8
Education	9	9	9
Training	15	15	15
Administration & Mobility	10	10	10
JET operation	56	68	0
JET exploration	32	30	0
TOTAL w/o ITER	**344**	**418**	**441**
ITER construction	511	115	0
ITER operation	0	0	99
ITER exploration	0	0	42
ITER & JT60SA enhancement	0	0	9

Financial resources
EC + Member States
(FP7 350-400M€)

Note: this are annual figures

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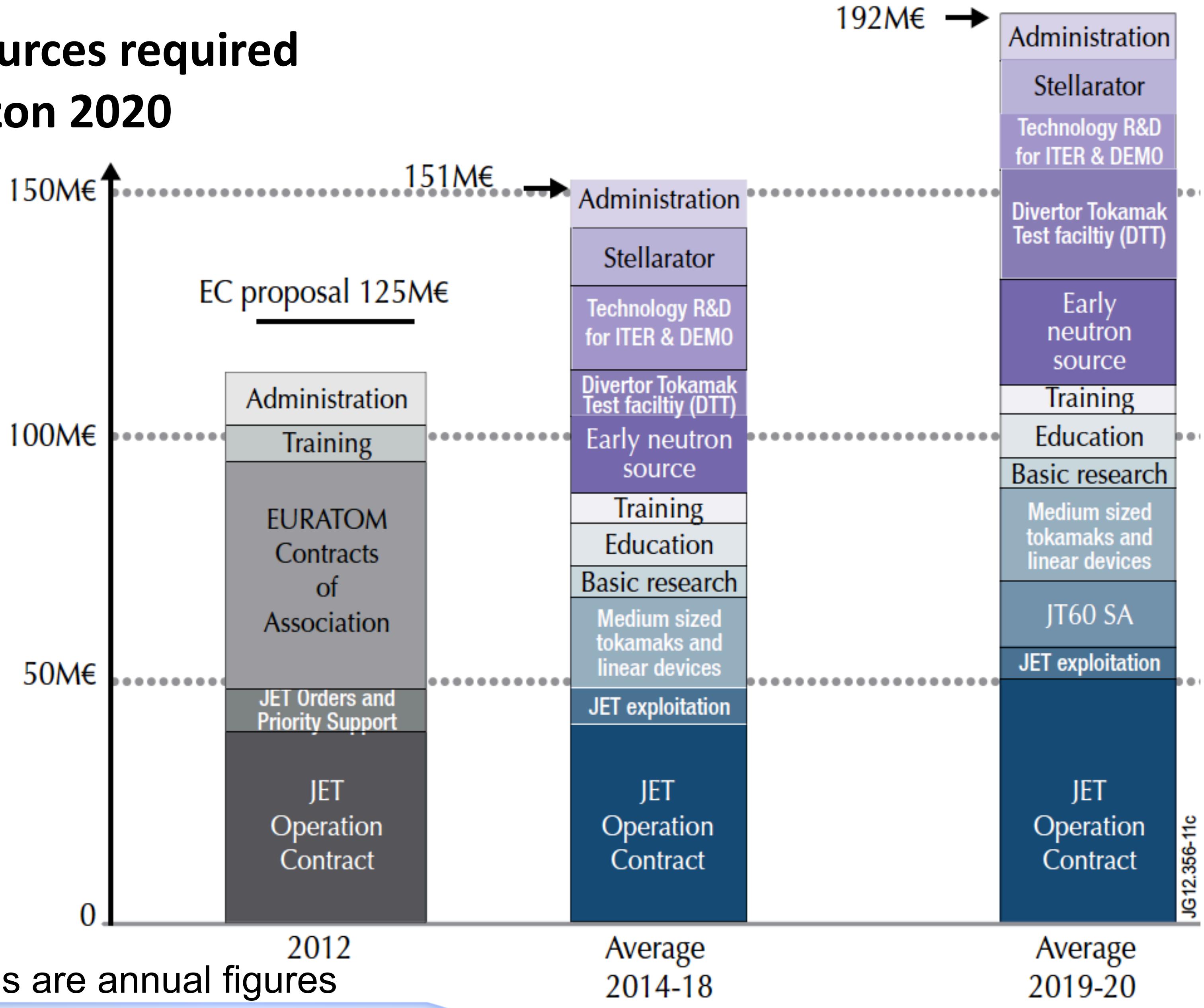
Resources

EC resources required in Horizon 2020



Note: this are annual figures

International collaborations

- In addition to the ITER exploitation and the BA projects, the following opportunities are underlined:
  - The exploitation of JT-60SA in collaboration with Japan for the preparation of ITER Phase 2;
  - The construction of a pilot IFMIF plant (Early Neutron Source) in collaboration with Japan within a post EVEDA phase;
  - The collaboration on a joint Divertor Tokamak Test facility;
  - The collaboration on other smaller scale DEMO R&D (for example making use of the infrastructure developed with Japan during the BA for that purpose);
  - The use of the Chinese Fusion Experimental Tokamak Reactor (CFETR) facility with China and of the Fusion Neutron Science (FNS) facility in US;
  - The share of know-how on the TBM programme with other ITER parties whenever a win-win situation is expected;
  - The use of non-EU research fission reactors;
  - The collaboration on stellarator lines other than the HELIAS (i.e. Heliotron and compact stellarator).
- Europe can offer to the other parties the participation in its facilities, and specifically to JET as training facility for ITER. Specific funds also foreseen for participation to machines abroad.

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Theory and modelling

- Theory and modelling provide the capability of extrapolating to DEMO and fusion power plant the available physics results. This is crucial for the extrapolation of the core and edge plasma dynamics for both tokamaks and stellarators.
- Material computer modelling needs to play an increasing role in the development of fusion materials to guide and interpret fission irradiations using isotopic tailoring and to predict and interpret the fusion irradiations at low doses and hence to help guide and shape the 'accelerated IFMIF' programme.
- Support theory and modelling effort through dedicated facilities (e.g. HPC and Gateway) and the supporting activities included in the resources.

Next steps

- The roadmap will be a living document, reviewed regularly in response to the physics, technology and budgetary developments