Proxima Fusion

Strengthening Europe's modelling ecosystem through public-private collaboration

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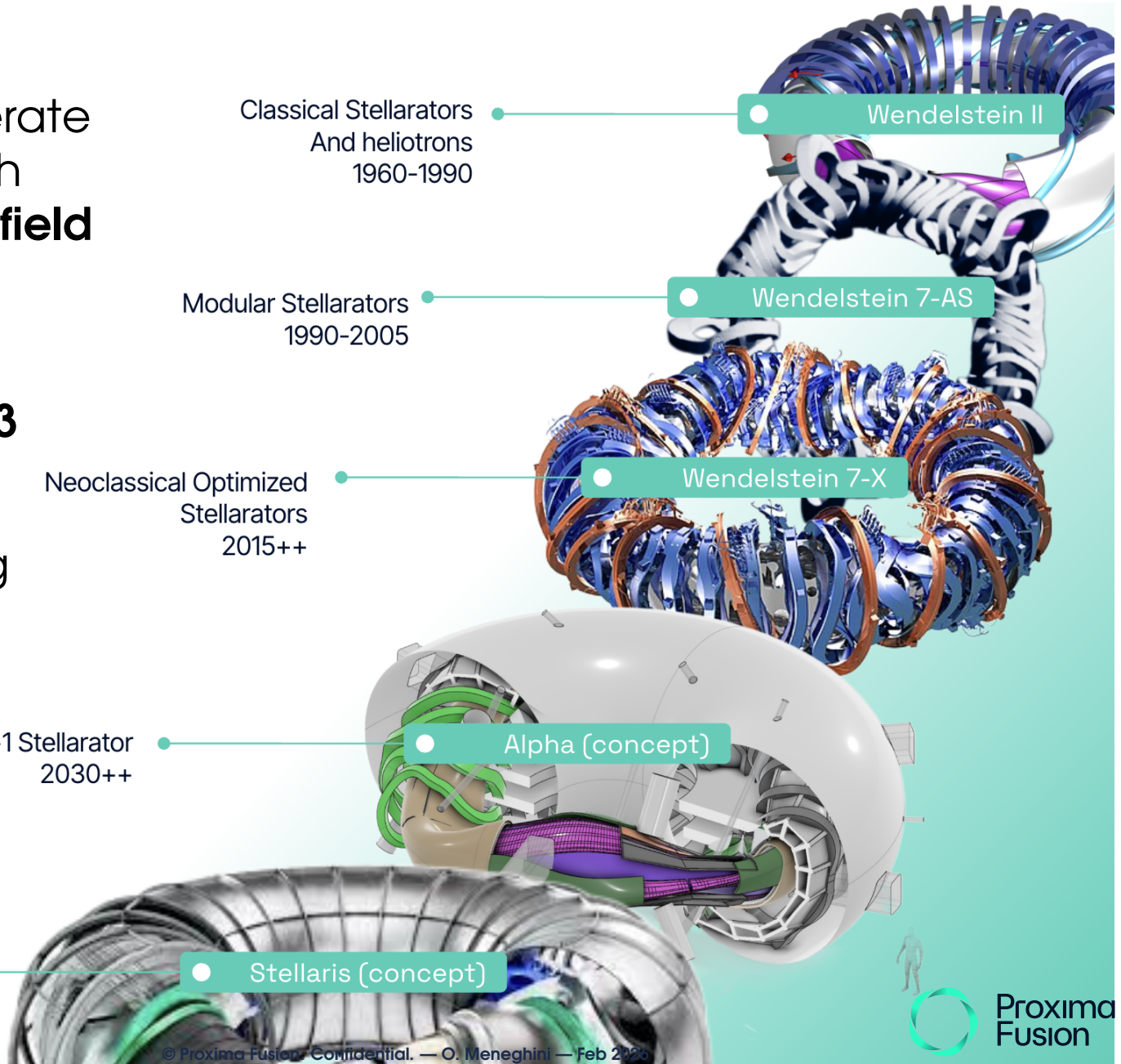
Proxima Fusion: building on IPP's Wendelstein experience

- **Mission:** Accelerate progress through **optimized high-field stellarators**
- Founded in **2023**
- Rapidly growing **team of 140+**
- Tight integ. of **engineering & physics**



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Stellarators avoid tokamaks' issues linked to plasma-current, at the cost of higher engineering complexity

- primary technology choice of the most recently funded MCF fusion companies in Europe and the US
- pursued with priority in Germany

They avoid:

1. Disruptions
2. Density limit
3. Kink, tearing, sawteeth, RWM...
4. Pulsed operations
5. Non-inductive current drive

on the other hand:

1. 3D geometry
2. Vast design space
3. Tighter tolerances
4. Less flexibility once built
5. ~~Worse neoclassical~~ $\Rightarrow$ **W7-X**!

Machine design optimization is critical but difficult because:

- large number of parameters $\Rightarrow$ HPC & AD to the rescue!
- cost/inability of evaluating certain models $\Rightarrow$ we need your help!

How the public sector can help.
Personal thoughts as a private-industry newcomer.

- **Different time horizons**
  Private: deliver now
  Public: long-term science
  Both are needed
- **The keyword is "accelerate"**
  Partnerships must help go faster.
  Long onboarding $\Rightarrow$ capability must be truly unique.
- **Fidelity needs to grow with the company**
  Early: rapid design iteration, systems codes. HPC and high-fidelity come later.
- **Companies want/need to be the integrators**
  More likely to adopt on individual models, than frameworks
- **Cost of writing code is $\rightarrow$ 0**
  Agentic coding is changing everything. More value in the science, less in the software.
- **Open software is essential**
  Trust, no vendor lock-in, and freedom to modify and extend

Three possible collaboration threads...

1) We need further development of fast & open theory-based stellarator models for extrapolation to reactor

Long-term science that industry needs but cannot do alone
Strong alignment with gaps identified by WP-STEL

- **Transport & confinement**
  - Impurity (W, He ash)
  - Turbulence surrogates
  - Pellet fueling with drifts
- **Edge & exhaust physics**
  - Edge-core boundary conditions
  - 3D SOL, divertor & wall
- **MHD & energetic particles**
  - Beyond ideal nested flux surfaces
  - Soft beta limits, EP-MHD coupling
- **Reduced order models**
  - Enable fast design iterations

Ideally everything open:

- Publications
- Code (w/ high QA)
- Permissive license

Win-Win-Win

- Researchers get pubs, code ownership, visibility
- Community gets high-quality models
- Industry improves designs and reduces uncertainties

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2) We need to verify and validate theory-based models, across codes and against multiple experiments

Reducing risk is key: **Verification** to know that a code is correct. **Validation** to know it captures reality. **Redundancy** lowers uncertainty.

- **W7-X data is essential**
  - Most relevant for QI stellarators
- **Multi-machine validation** adds confidence theory can extrapolate
  - LHD, TJ-II, HSX, CTH, ...
  - LHD public database as model for open data sharing
- **Ideally a stellarator-standard as common data interface**
  - IMAS greatly facilitated V&V in tokamak-land
  - A format becomes a standard only when it broadly used by the community

FAIR stellarator data:

- W7-X & codes in IMAS format would be game-changer for V&V

Win-Win-Win

- Researchers get pubs, visibility, new experiments
- Community knows how to prioritize work
- Industry gets extrapolation confidence

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3) We need to build high-fidelity simulation databases, to be used for training ML surrogate models

ML surrogates effectively democratize access to HPC

US companies access DOE HPC
EU private sector needs a similar pathway through EUROfusion

- **High-fidelity codes need leadership-class HPC**
  - GENE for turbulence
  - HINT for eq. w/ magnetic islands
  - EMC3-EIRENE for SOL
- **Often surrogates are device-specific**
  - W7-X ≠ Alpha ≠ Stellaris
  - Need retraining for each configuration
- **Pooling different DBs nice in theory, in practice often not useful**
  - DB uniformity critical for ML

Joint simulation campaigns:

- Leverage EUROfusion HPC to build open datasets that benefit everyone

Win-Win-Win

- Researchers get pubs, data, visibility
- ML community gets open DBs to exercise methods
- Industry gets surrogates in the regime of interest

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What Proxima brings to the table

For European fusion industry:

- **Alpha + Stellaris**
  EU stellarator path to fusion
- **Industrial anchor**
  Expertise and IP in EU
- **Bridge to commercialization**
  Research finds path to impact

Integration expertise:

- **Whole system view**
  Plasma embedded in engineering reality
- **Clear requirements**
  What targets and with what accuracy?

Hardware & software hand in hand

- **Hardware engineering**
  - HTS technology
  - Prototype coil
  - Alpha CDR
- **Software engineering**
  - Model integration
  - Versioning
  - Provenance
  - Sharing
  - Single source of truth

We're extending Proxima's integrated modeling capabilities based on the lessons learned in the tokamak community

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GOAL: Leapfrog process of defining a complete/consistent data model: extending IMAS to stellarators! ⇒ ProxIMAS

Why we're adopting IMAS?

- **Mature ontology**
  saves years of trial-and-error!
- Community-tested,
  well-defined interfaces
- Lower barrier of entry into stellarators from tokamak community

Mostly stellarator ready

- Flux-surface-averaged quantities work as-is
- Actuators and diagnostics already natively 3D
- Extension needed for some 3D eq. and build descriptions

Path towards open sourcing

- Can serve as basis for a **community standard** for stellarators
- ITER already indicated interest
- Looking for engagement with W7-X and EUROfusion

GOAL: Develop the best-in-class integrated modeling framework for stellarators, taking lessons learned from FUSE

Integrating a growing set of models:

- VMEC equilibrium
- Mercier/ballooning stability
- Flux-matching transport
  - temperatures, densities, E_r
  - stationary or time-dependent
- GK and neoclassical surrogates
- Simplified actuators (EC, IC, NBI, pellets, gas)
- Coil optimization

Features

- Natively IMAS
- Julia, JIT
- Fast, scalable
- End-to-end differentiable (critical for optimization and sensitivity analysis)

Designed to support:

- Predictive scenarios

  → current focus ←
- Machine design
- Data analysis

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Engage with us! With your help we can accelerate Europe's stellarator path to fusion energy

- **Models** (Thread 1)
  - Joint research projects
  - Co-publications, co-supervised students
- **V&V** (Thread 2)
  - FAIR IMAS W7-X data access
  - Multi-code verification
  - Multi-machine validation
- **Compute & data** (Thread 3)
  - Joint proposals for HPC
  - Open simulation databases

Win-Win-Win:

- Researchers get publications, code, and visibility
- Community gets tools and open data
- Industry improves machine design and reduces uncertainties

Proxima–**A**cademic **R**esearch **S**eries for **E**uropean **C**ollaboration

One-day twice a year to engage with broad EU research community?

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