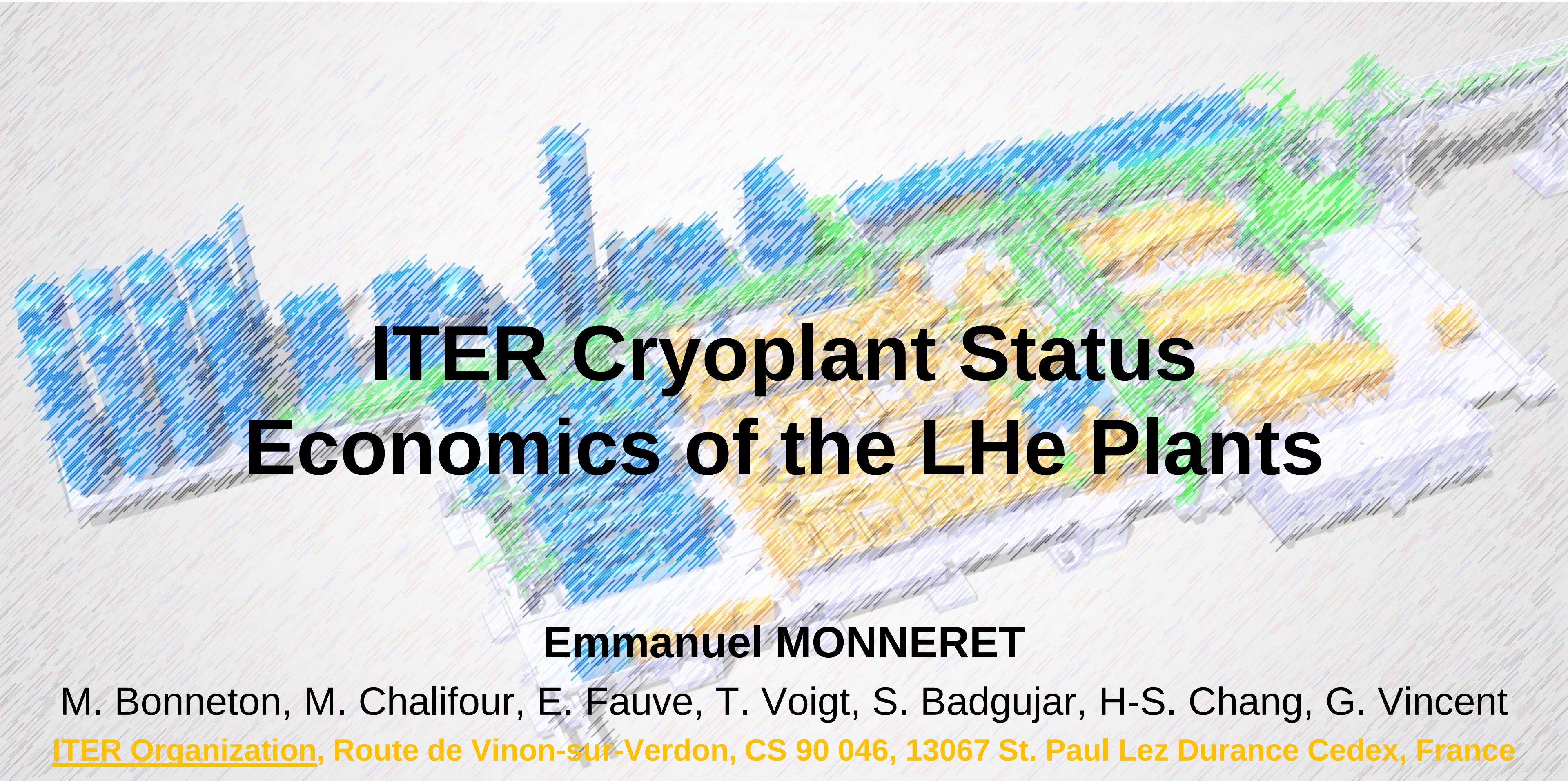

ITER Cryoplant Status
Economics of the LHe Plants

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Summary

1. ITER Cryoplant Status
   - Cryoplant Overview
   - Cryoplant Project Schedule

2. Cryoplant Specifications and Constraints

3. Economics of the LHe Plants

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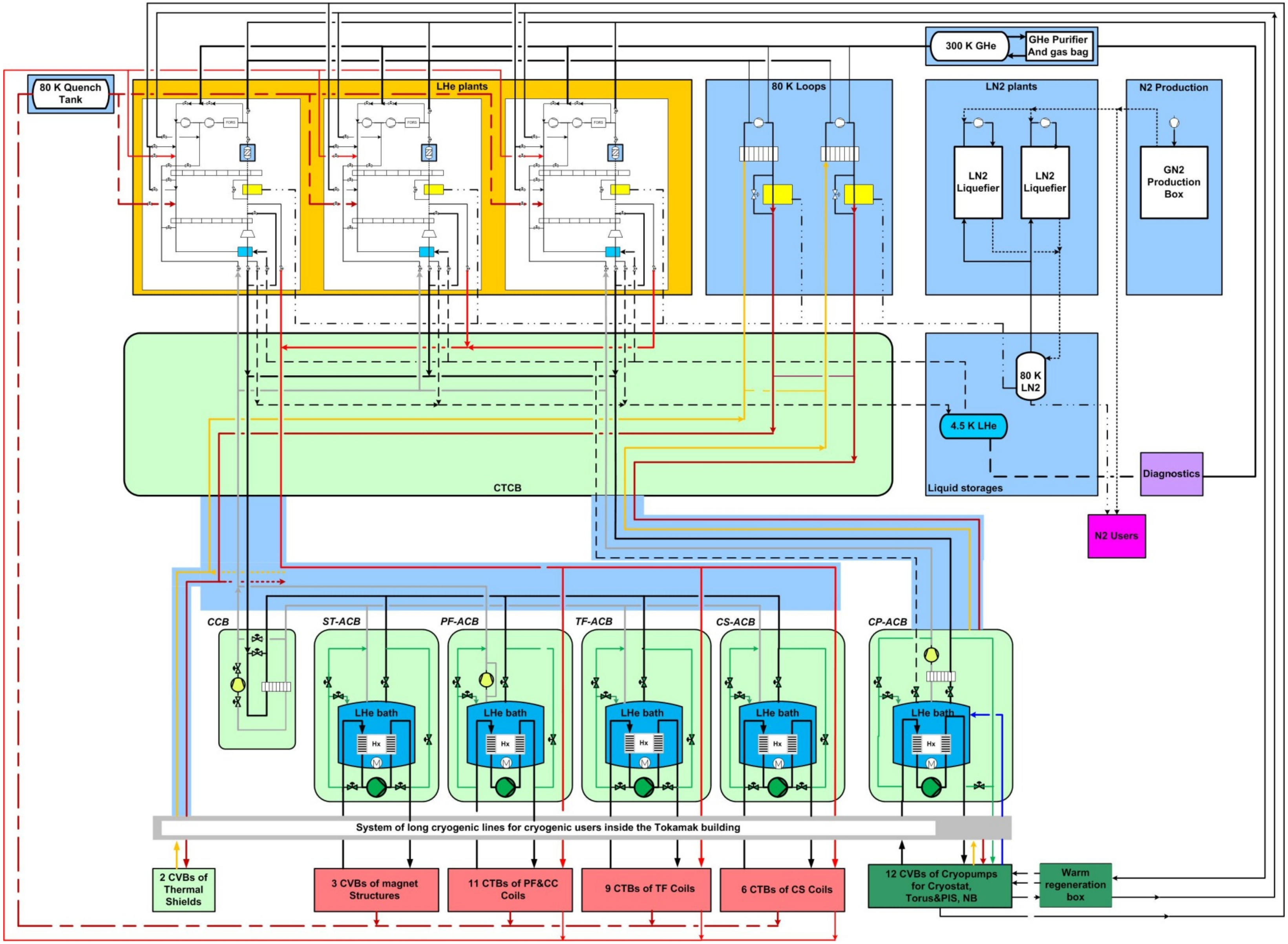
Purpose of Cryogenics

- High fields magnets
- HTS current leads
- Cryogenic pumping
- Reducing of specific project cost
- Saving energy

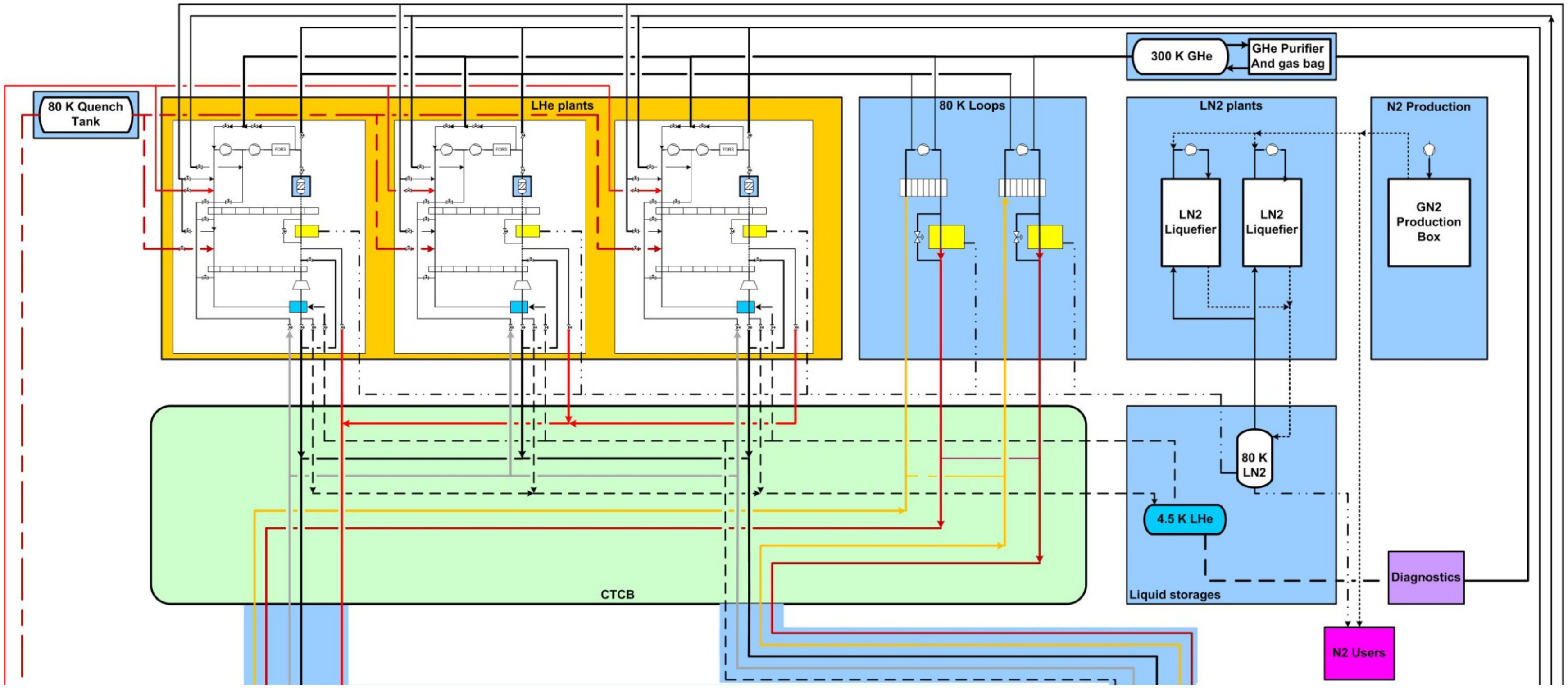
Cryoplant Main Duties

- Basic
  - Gradual cool-down and warm-up in about one month
  - Provide and Recover Helium to Cryodistribution / Magnets / Cryopumps / Thermal Shields
    - Maintain magnets and cryopumps at nominal temperatures over a wide range of operating modes with pulsed heat loads due to nuclear heating and magnetic field variations
    - Accommodate periodic regeneration of cryopumps
  - Accommodate resistive transitions and fast discharges of the magnets and recover from them in few days
  - Enhanced mode to cool magnets at 3.7 K with an extended dwell time
- Additional
  - Ensure high flexibility and reliability
  - Low maintenance

Cryogenic System Architecture



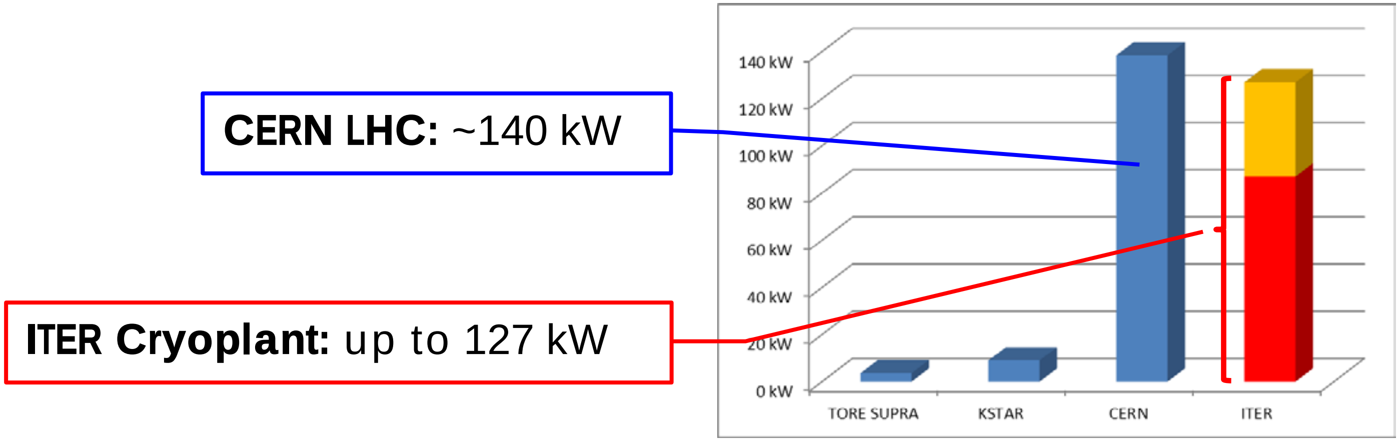
Cryoplant System Architecture



- Main Components in the Cryoplant
  - LHe Plants – 3 x Plants //
  - 80 K helium loops - 2 x Plants in //
  - LN_2 Plants – 2 x Plants in // and GN_2 Generator and Storage
  - Recovery & Purification systems and Heaters
  - Storages – Full helium inventory in warm and cold (4.5 K and 80 K) helium tanks

Cryoplant He and N_2 Cooling Capacities

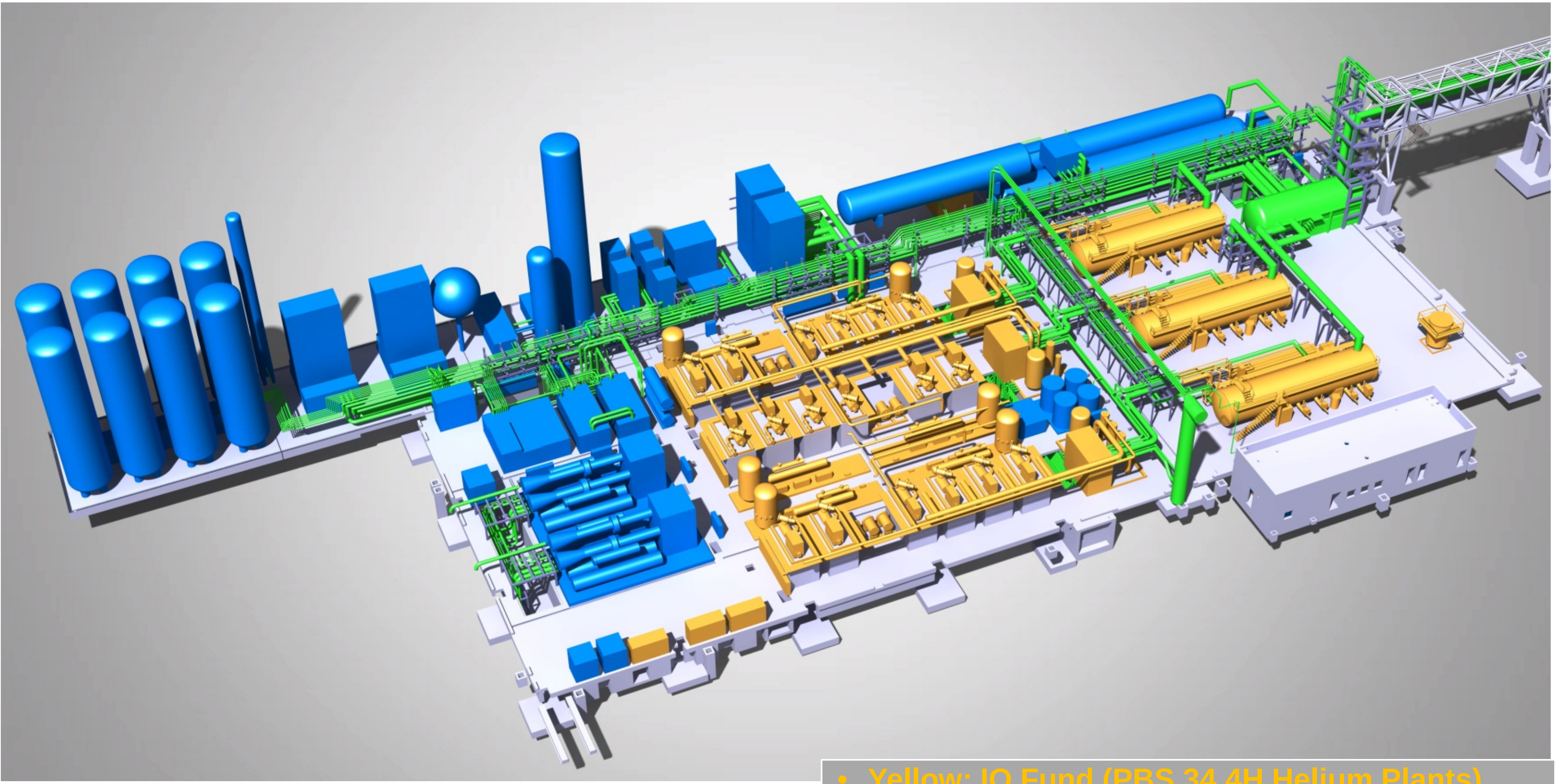
- LHe Plants: avg. 75 kW equiv.@4.5K in POS avg. mode
  87 kW in refrigeration
  - Superconducting magnet system, HTS current leads
  - Cryo-pumps with high regeneration frequency and small users
- 80K He Loops: avg. 40 kW equivalent @ 4.5 K
  - Thermal Shields (2 x 4000 g/s in between 80K to 100K)
- LN_2 Plants: ~1300 kW @ 80 K
  - 80K He Loop, LHe Plants pre-cooling
- GN_2 Generator: ~1550 Nm^3/h
  - Tokamak users, Leaks, Purifier/Dryers, Air Instrument redundancy



Cryoplant Helium & Nitrogen Inventory

- Helium Storage & Inventory Management
  - Helium inventory: 27 t
  - Helium Storage
    - 5 x 400 m^3 of pure GHe tanks @ 300K
    - 1 x 175 m^3 of LHe tank
    - 2 x 360 m^3 of Quench Tanks (storage temperature ~80K)
    - 1 x 400 m^3 of impure GHe tank @ 300K
    - 7 x 120 m^3 of GasBags
- Nitrogen Storage & Inventory Management
  - LN_2 inventory: 250 t
  - GN_2 inventory: 4.5 t
  - Nitrogen Storage
    - 1 x 300 m^3 of LN_2 tank
    - 1 x ~100 m^3 of GN_2 tank

Cryoplant Layout – Buildings 51 and 52, Area 53



- Yellow: IO Fund (PBS 34.4H Helium Plants)
- Blue: Europe PA (3.4.P1.EU.01 – LN2 Plant and Auxiliary Systems)
- Green: India PA (3.4.P2.IN.02 – Cryolines and Warm lines & 3.4.P3.IN.01 - Cryodistribution)

CRYOPLANT PROJECT SCHEDULE

PBS #	Name	Resp. Procure	Contractor	1st Delivery
34.10	LN_2 Plants and Auxiliary Systems	F4E – Europe	Air Liquide Engineering (Champigny - FR)	April 2016
34.2S	Cryolines group Y (“simple” cryolines)	IN-DA - India	Inox India (IN)	Feb. 2016
34.2C	Cryolines Group X (“complex” cryolines)	IN-DA - India	Under Bid phase	March. 2017
34.2W	Warm lines	IN-DA - India	Under Bid phase	Feb. 2016
34.3Y	CTCB (Interconnection box)	IN-DA - India	Under Bid phase	Jan 2017
34.4H	LHe Plants	IO - Cadarche	ALAT (Sassenage-FR)	Dec. 2015

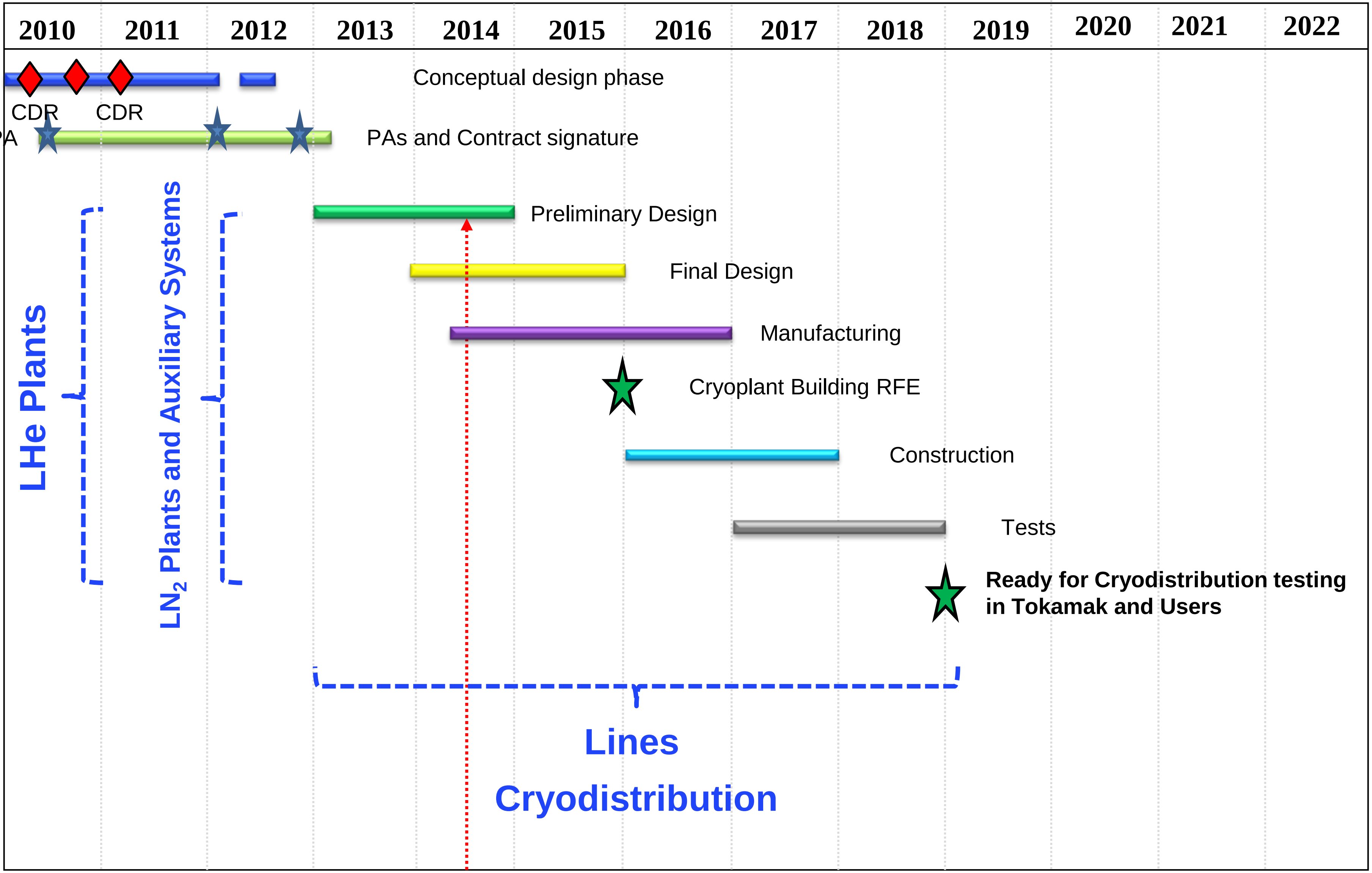
- 6 Cryogenic Contracts to manage + Interfaces (Civil work and Utilities)
- For all procurements IO is responsible for Integration and Operator

CRYOPLANT PROJECT SCHEDULE

PBS #	Interfaces	Ready For Equipment
63	Civil work	2016
63	Building finishing	2017
43	Electricity	2nd semester 2016
26	Cooling water	End 2016
65	Compressed Air	End 2016
45 / 46	I&C Networks	Mid 2016
64 / 69	Security, Environment monitoring	2017

- Interfaces Management and Schedule
  - Intense collaboration with interfaces

CRYOPLANT PROJECT SCHEDULE



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Cryoplant Specifications and Constraints

- State-of-the-art technology adapted to large dynamic loads and parallel refrigerators operation
- High availability and reliability
  - RAMI
- Investment and personal protection
  - HAZOP
  - SIL Study
- Operation costs optimization
  - Overall process cycle and components efficiency
  - Compressors heat recovery for hot water distribution
  - Gas Nitrogen generator on site to produce and distribute GN_2
  - Liquid nitrogen pumps to regulate liquid nitrogen distribution

Cryoplant Specifications and Constraints

- Regulatory requirements
  - French Decree No. 99-1046 – Pressure Vessels
  - French Quality Order - Nuclear environment
- Codes
  - Mainly pressures vessels according to PED
    - Issues: periodic inspection and requalification, use CTP and BSEI in order to proper implement counter measures
- Standards
  - Reliability
    - E.g. Screw Compressor (ISO EN 10440-1, equivalent to API 619)
    - All rotating machineries (centrifugal compressor, pumps, etc.)
    - Heat Exchanger (TEMA and ALPEMA)
  - Standardization
    - International project
    - Minimize costly operation, maintenance and spares management

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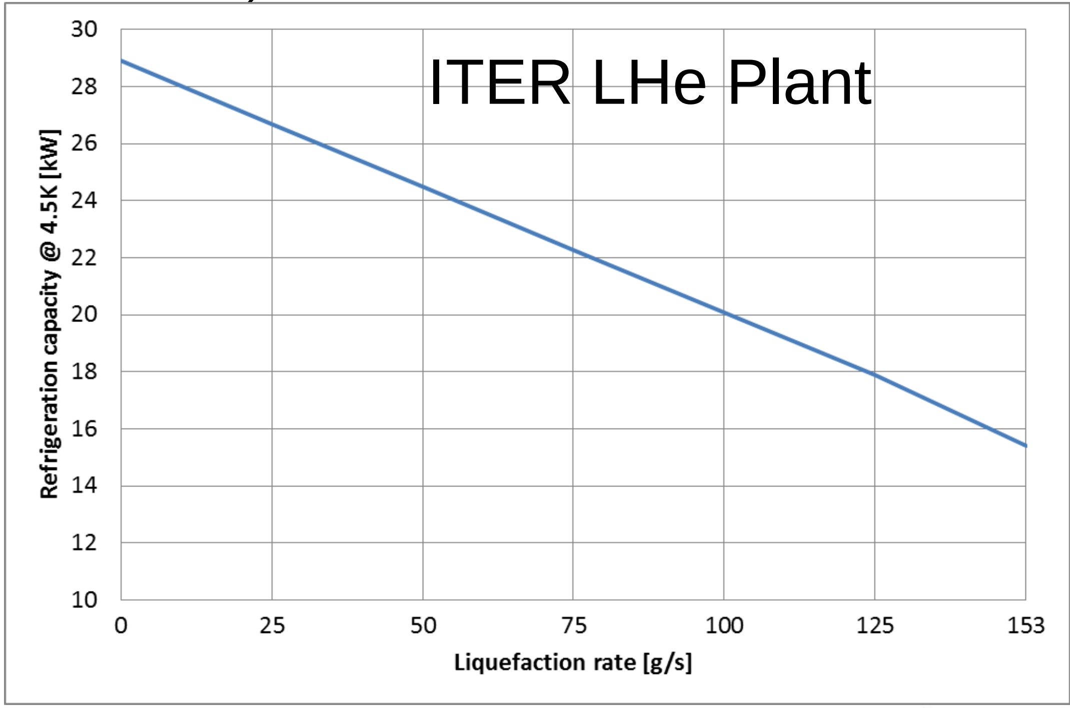
Economics of the LHe Plants

- Economics of the ITER LHe Plants based on:
  - Contract for 3 identical LHe Plants pre-cooled with LN_2
  - Lump Sum Turn Key Contract [LSTK] ~EPCI + Commissioning
  - Excluded
    - Civil work, buildings utilities and security
    - Electricity (Main distribution board)
    - Cooling Water
    - Compressed Air
- Economics studies based on refrigeration power



Economics of the LHe Plants

- Green Formula [1997]

$$COST[M\$] = 2.6 * (Capacity[kW@4.5K])^{0.7}$$

- CERN-LHC Formula [1999]

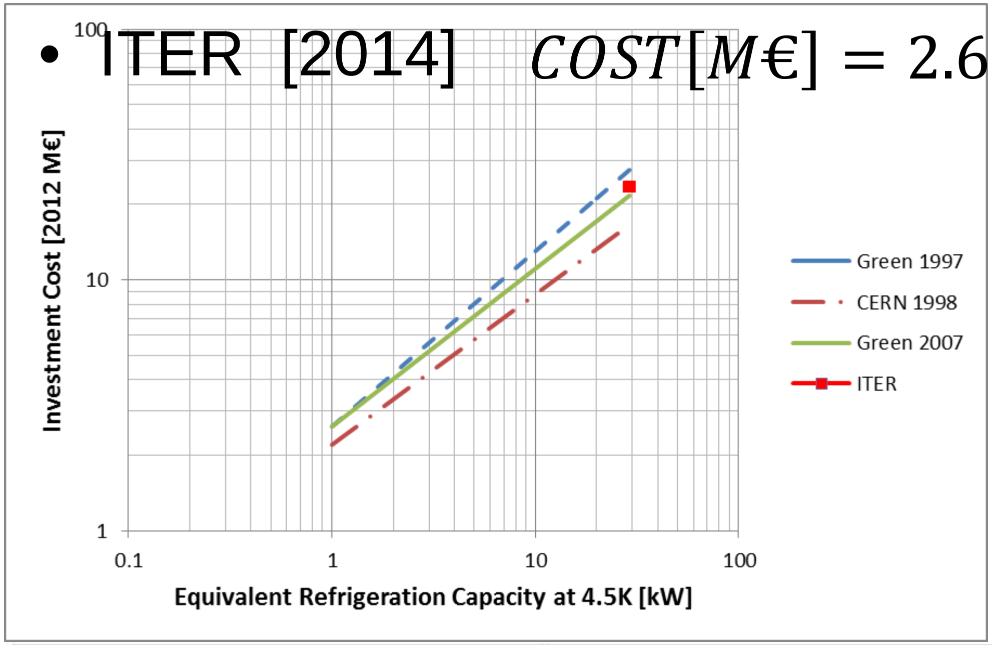
$$COST[1998MCHF] = 2.2 * (Capacity[kW@4.5K])^{0.6}$$

- Green Formula [2007]

$$COST[M\$] = 2.6 * (Capacity[kW@4.5K])^{0.63}$$

- ITER [2014] $COST[M€] = 2.6 * (Capacity[kW@4.5K])^{0.65}$

Coef. [2.6] not enough data to be assessed



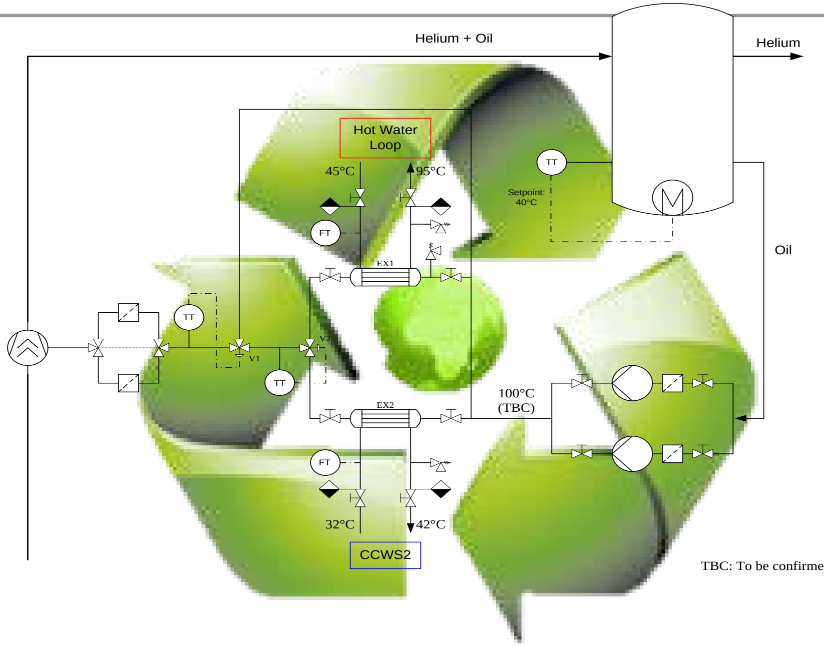
Economics of the LHe Plants

	Eq. Ref. capacity @4.5K [kW]	Investment cost
ITER LHe Plant (one Plant)	29	23.5 M€
Control Syst. (PLC & PIS)		+5.0%
Machine Monitoring System (Rotating Machinery vibration, measurement and analysis)		+1.5%
Heat Recovery System – HRS		+6.5%
Test Tools (fixed for 1 or 3 plants)		+9.0%
Capital Spares – Compressors/Turbines/Oil pumps (fixed for 1 or 3 plants)		+2.0%

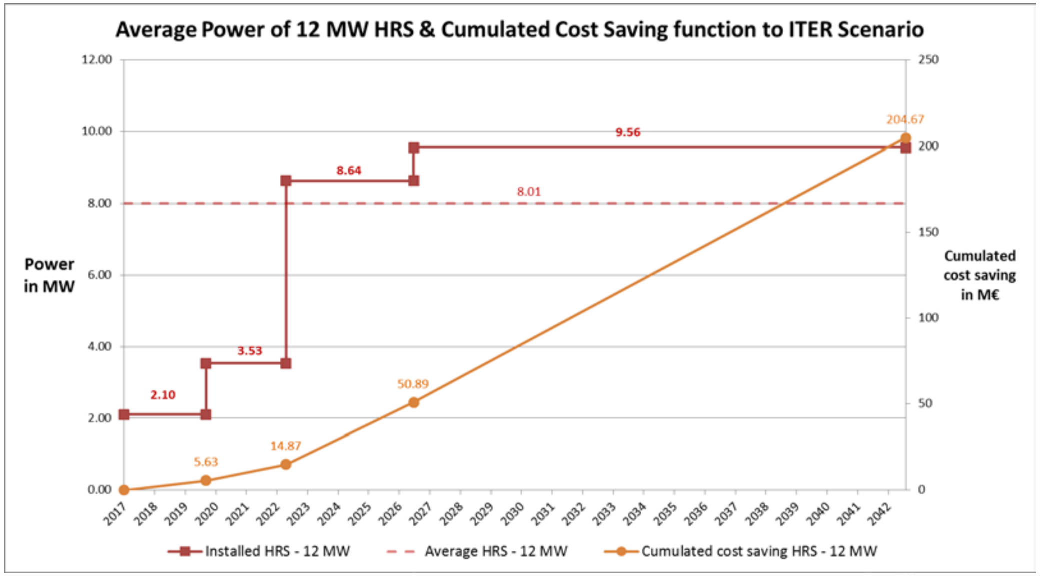
- Confirmation of Green and CERN economics up to 29kW
- Proper tool for pricing at conceptual design phase

Economics of the LHe Plants

- Heat Recovery System [HRS]
  - Heat recovered from compressor oil
  - Heat transferred to “Hot Water” for ITER buildings heating syst. (electrical boiler as back-up)
  - Studies and Design based on ITER scenario
    - 16 months operation (+2 for CD and WU)
    - Heaters “ON” 6 months/year



- Average estimated power recovered ~8 MW for 12MW installed
- Payback after Tokamak commissioning phase
- Highly recommended to study power recovering on large refrigeration plant



Thanks for Your Attention

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- **The cryogenic section colleagues**
- **The Domestic Agencies (F4E and ITER India)**

Disclaimer: The views and opinions expressed herein do not necessarily reflect those of the ITER Organization