Two techniques to enhance particle reconstruction in JUNO:

Liquid Scintillator purification and Waveform analysis

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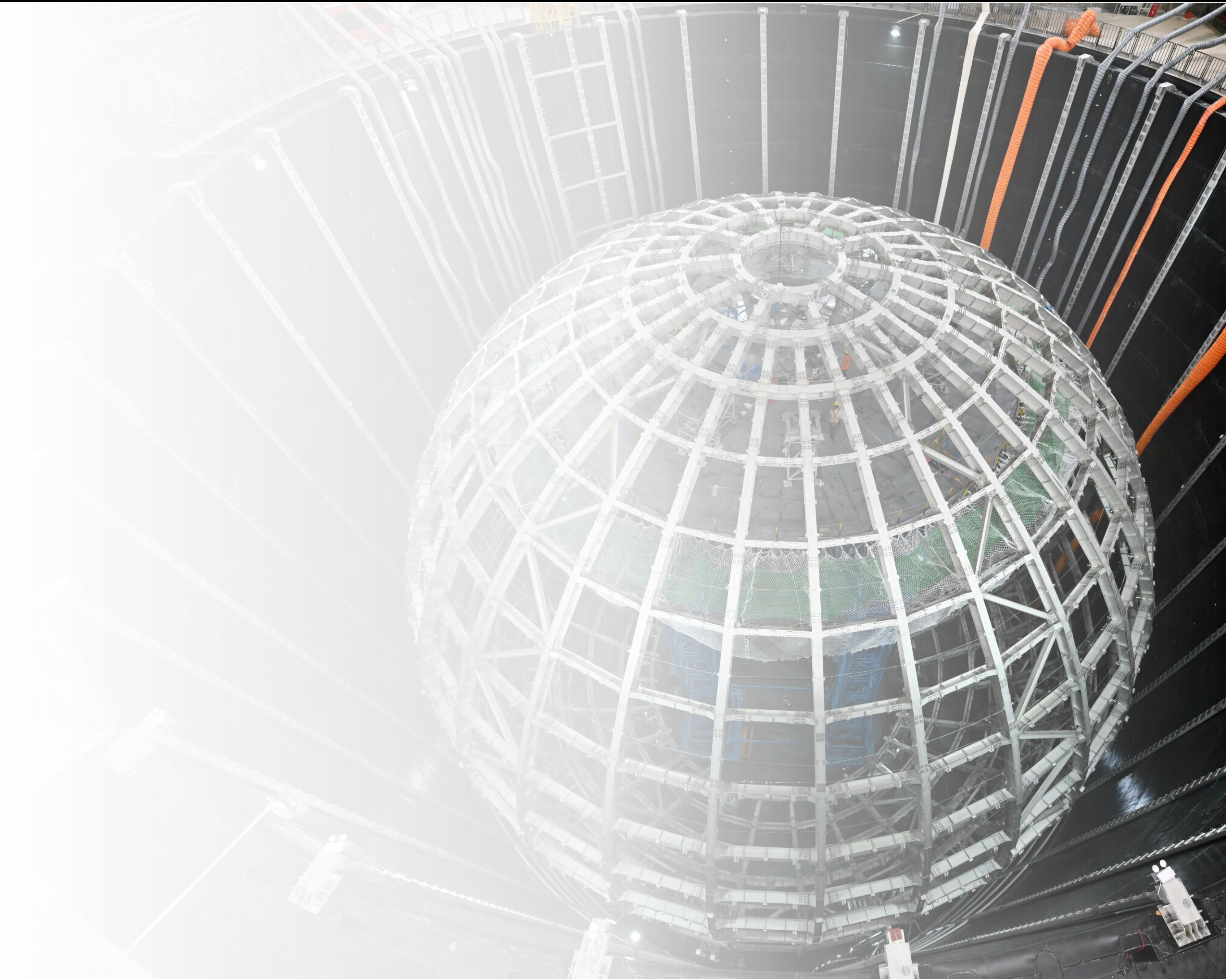
Summary

- JUNO Overview
- Liquid scintillator physics
- Technological challenges
- Distillation Plant
- Steam Stripping Plant
- Realization and assembly
- Conclusions



Jiangmen Underground Neutrino Observatory

Central detector (CD):

- Stainless steel latticed shell ID=40.1 m
- Acrylic sphere with 20 ktons Liquid Scintillator (LS)
- ID=35.4 m
- 17571 large PMTs (20-inch)
- 25600 small PMTs (3-inch)
- 78% PMT coverage

Water Cherenkov muon veto:

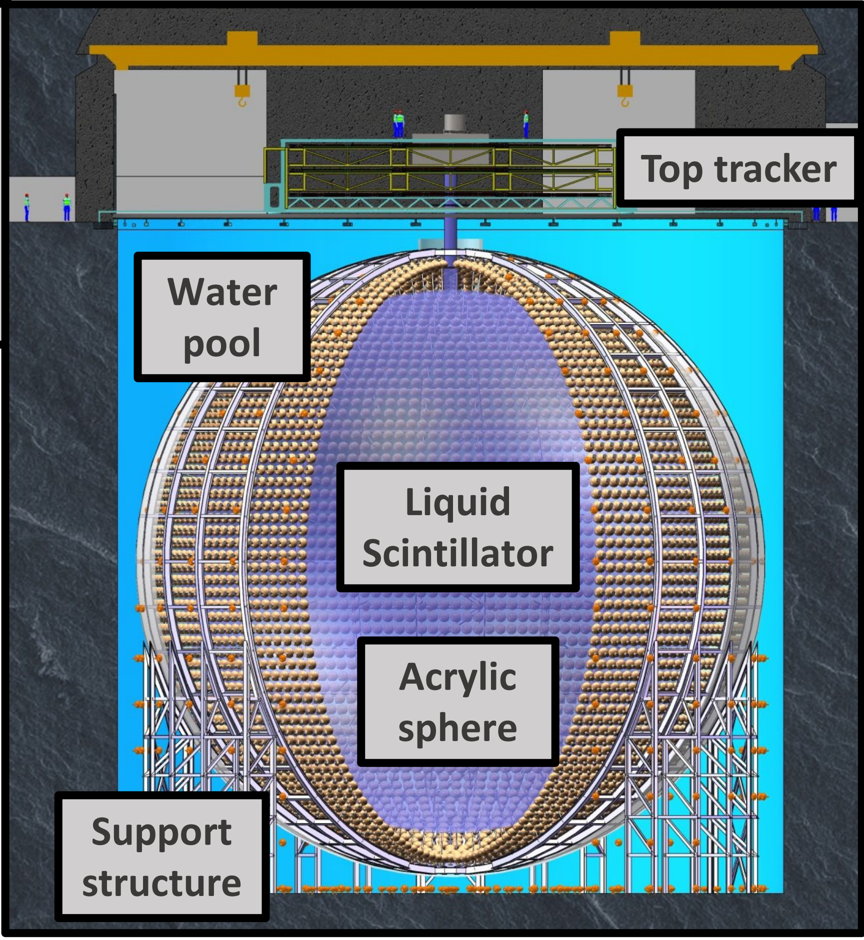
- 2400 20" PMTs
- 35 ktons ultra-pure water
- Efficiency > 99%

Compensation coils:

- Residual Earth magnetic field <10%

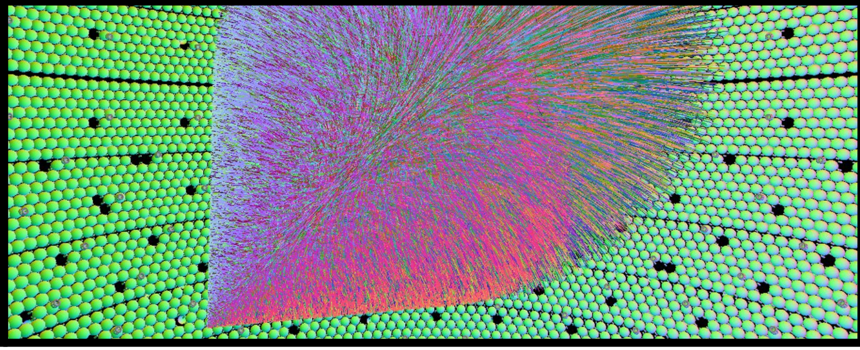
Top tracker:

- Precision muon tracking
- 3 plastic scintillator layers
- Covering half of the top area



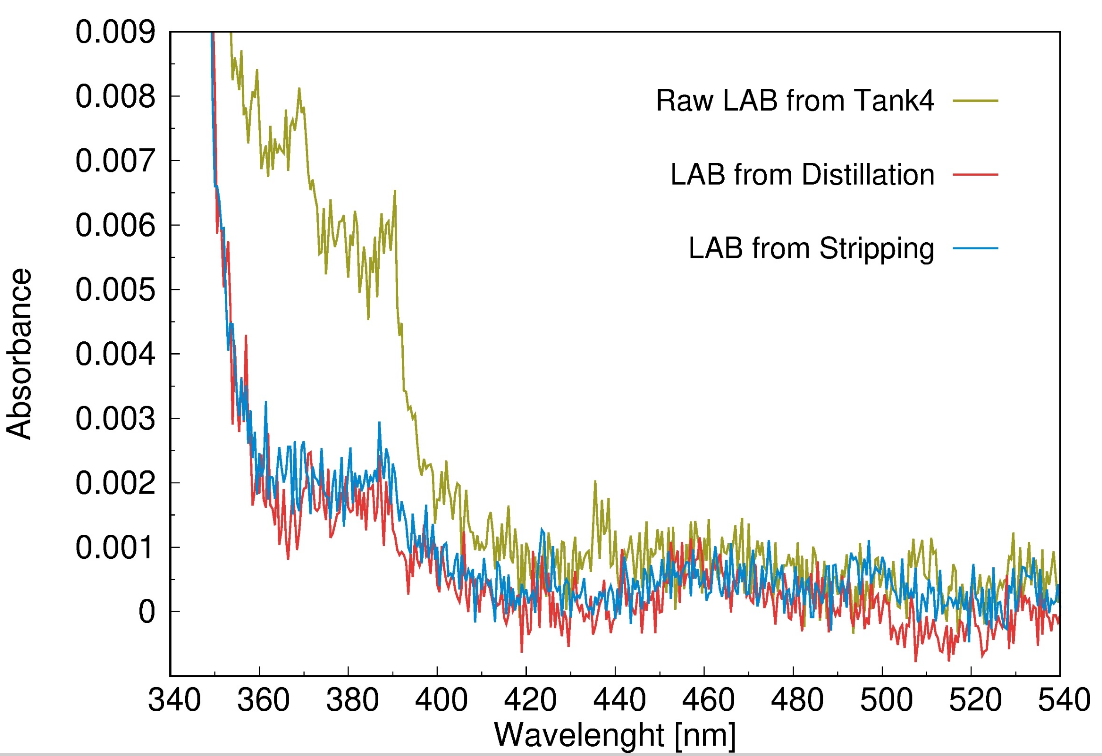
Experiment	Daya Bay	BOREXINO	KamLAND	JUNO
LS mass	8 X 20 ton	~300 ton	~1 kton	**20 kton**
Coverage	~ 12%	~ 34%	~ 34%	**~ 78%**
Energy Resolution	~ 8.5 %/√E [MeV]	~ 5 % /√E [MeV]	~ 6 % /√E [MeV]	**~ 3 %/ √E [MeV]**
Photon-Electron Yield	~160 p.e. /MeV	~500 p.e. /MeV	~250 p.e. /MeV	**>1345 p.e. /MeV**

Energy and Vertex reconstruction



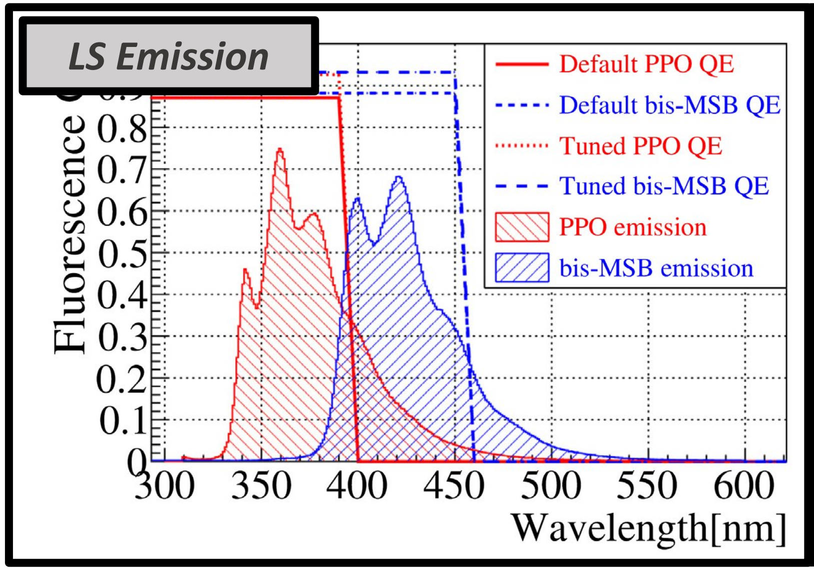
The algorithm and the results are shown in the thesis

Absorption and Background reduction in Liquid Scintillator

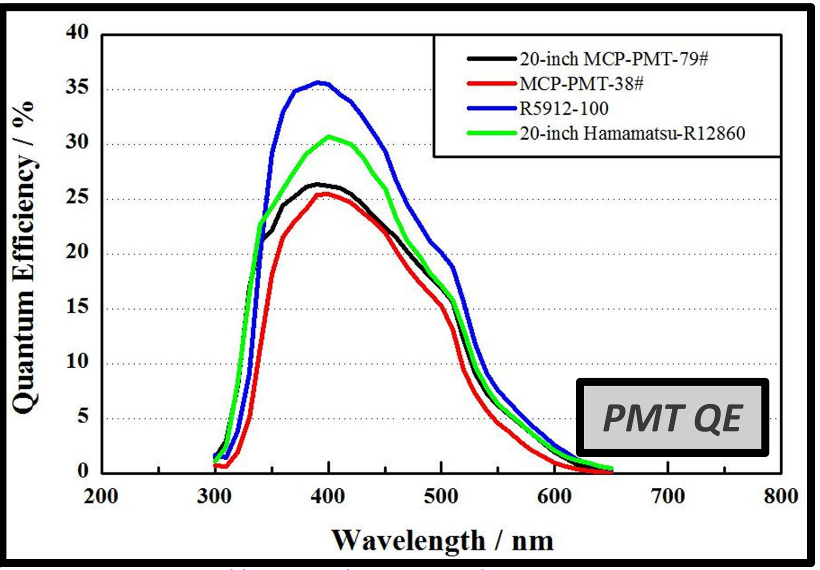


Liquid Scintillator

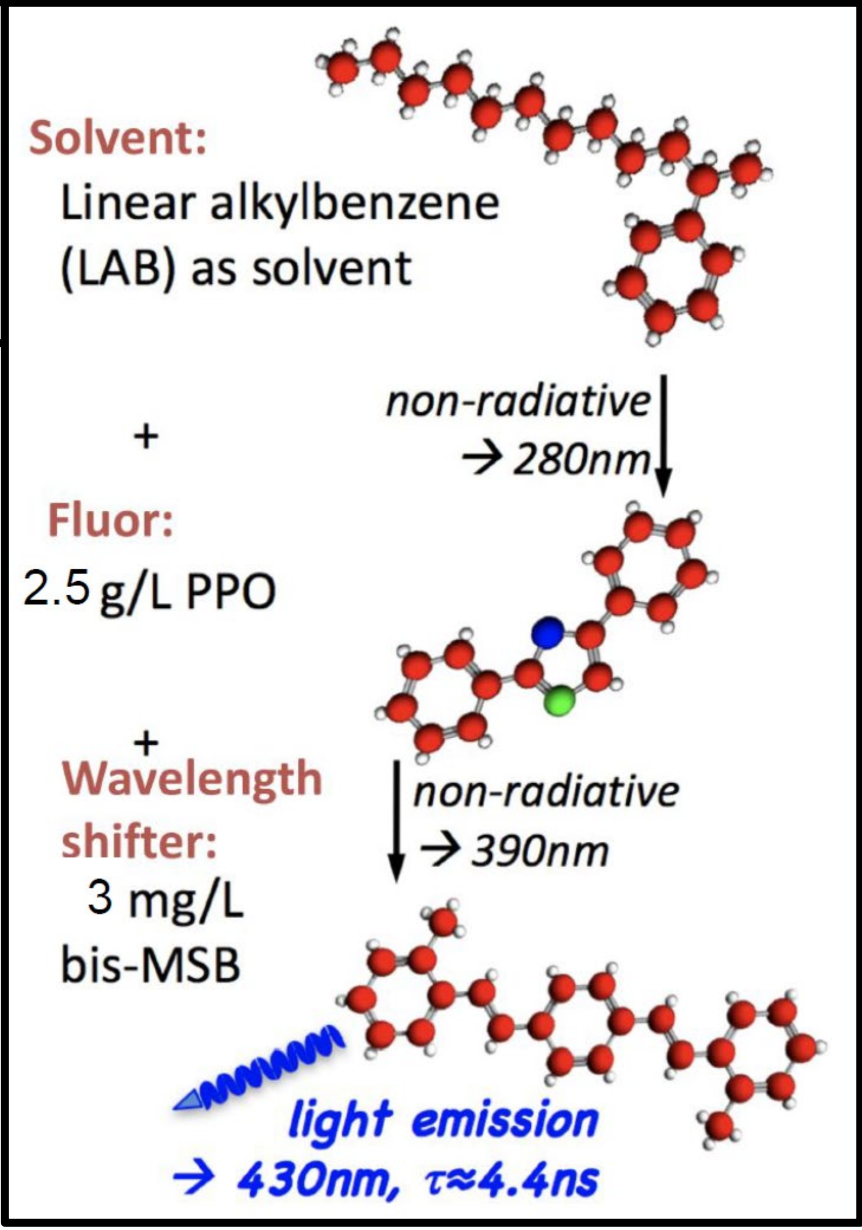
Liquid Solvent: Linear Alkyl Benzene (LAB), forms the bulk of the target material and is excited by the ionizing particles.
Doping material: A two-component system of a fluor (PPO) and a wavelength-shifter (Bis-MSB) increase the wavelength of the emitted photons to 430 nm **avoids spectral self-absorption** and increase **Quantum Efficiency (QE)**



https://doi.org/10.1016/j.nima.2020.164823



https://doi.org/10.48550/arXiv.1508.07166



Requirement for JUNO Liquid Scintillator (LS)

- High Light yield: **>1345 p.e./MeV**

Recipe:

Solvent: LAB / **Doping**: 2.5 g/L PPO + 3 mg/L bis-MSB

Background suppression

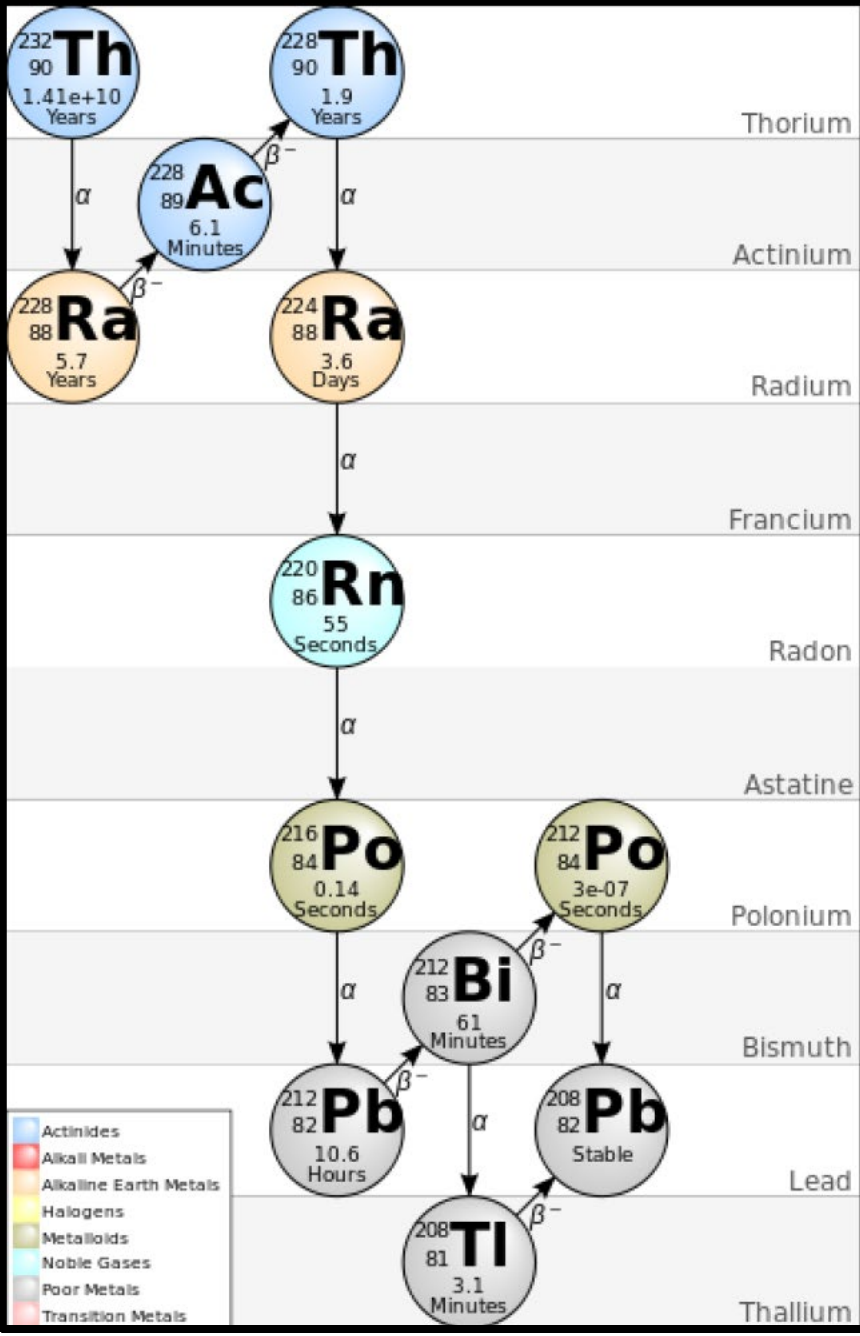
The main radio impurities in the liquid scintillator can be divided in: **Heavy Elements:** ^{238}U, ^{232}Th, ^{40}K, **Volatile Elements:** ^{222}Rn, ^{85}Kr, ^{39}Ar

- **Dust particles** containing elements of the natural U/Th decay chains as well as radioactive potassium ^{40}K.
- **Radon emanation** due to tank and piping surface**.**
- **Ambient air** can introduce ^{85}Kr, ^{39}Ar, ^{222}Rn
- **^{210}Po** from surface contaminations, distilled water or other unknown sources.
- **Radioimpurities of the fluors**, mostly ^{40}K.
- **Radioactive carbon** ^{14}C intrinsic to the hydrocarbons of the LS.

Requirements	^{238}U	^{232}Th	^{226}Ra	^{240}K	^{210}Pb(^{222}Rn)	^{85}Kr/^{39}Ar
Mass Hierarchy	10^{-15} g/g	10^{-15} g/g	-	10^{-16} g/g	10^{-22} g/g	-
Solar Neutrino	10^{-17} g/g	10^{-17} g/g	$5\cdot10^{-24}$ g/g	10^{-18} g/g	10^{-24} g/g	1 μBq/m^3

Solutions

- **Distillation:** separate substances with different volatility.
- **Water Extraction:** separate substances with higher solubility in water than in LAB.
- **Stripping:** separate substances with different solubility in a gas stream



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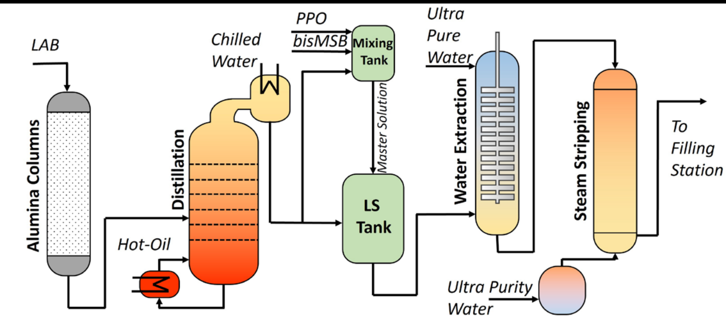
Absorption spectra



The JUNO LS mass will be 20,000 tons, resulting in a **target volume diameter of 35.4 m**. However, if light transmission in the liquid scintillator is low, scintillation photons from a neutrino interaction at the center of the detector will be **absorbed** before reaching the photomultipliers located at the edge of the volume.

Requirement for JUNO Liquid Scintillator (LS)

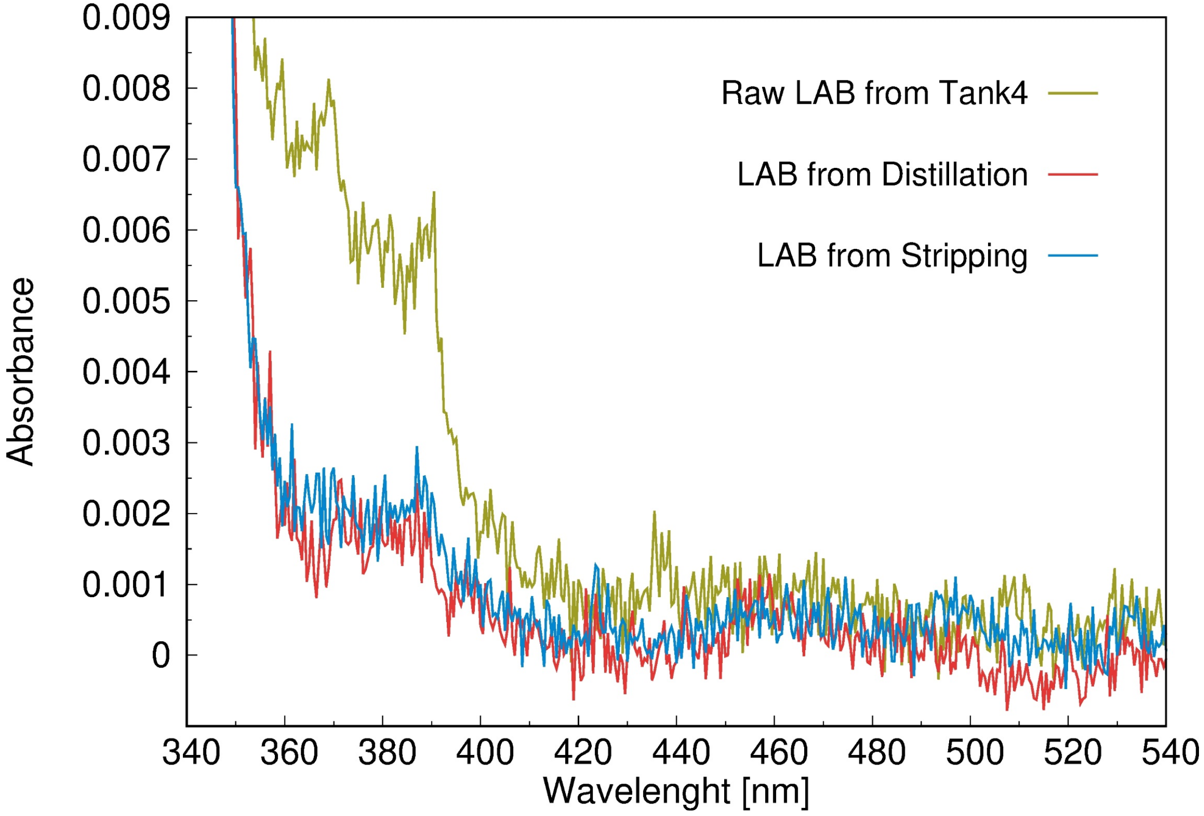
- Long Attenuation length: **> 22m**

Solutions

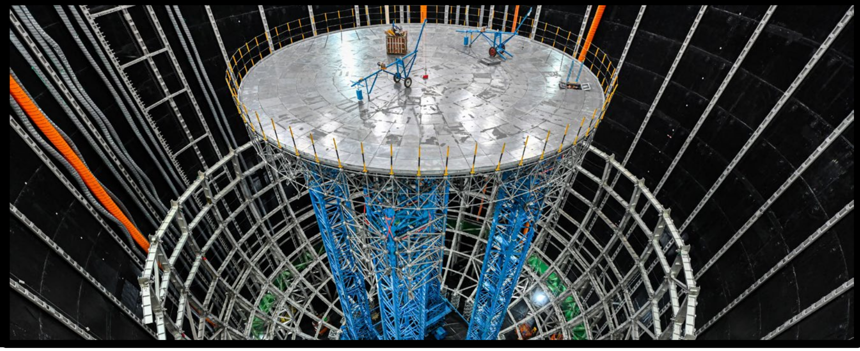
- **Alumina Columns**: increase optical properties
- **Distillation:** separate substances with different volatility.

Pilot Plant @ DayaBay to test the purification capability

Sample	Attenuation Length (m)
Raw LAB	20.0
Al2O3 purified LAB	23.3
Distilled LAB	25.4
Water Extracted LAB	24.6
Steam Stripped LAB	24.4

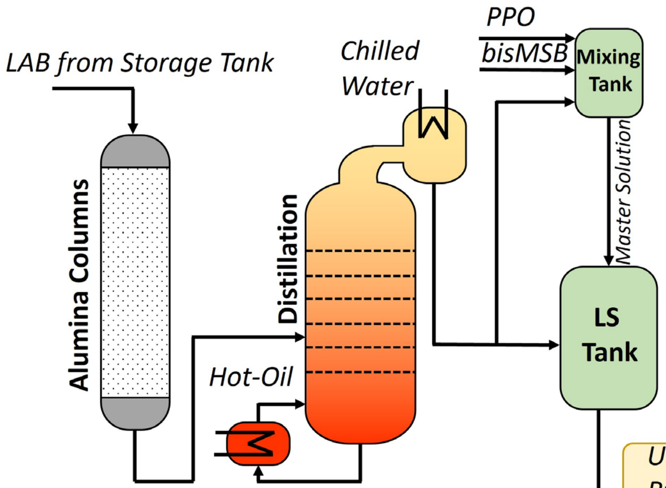


Technological challenges



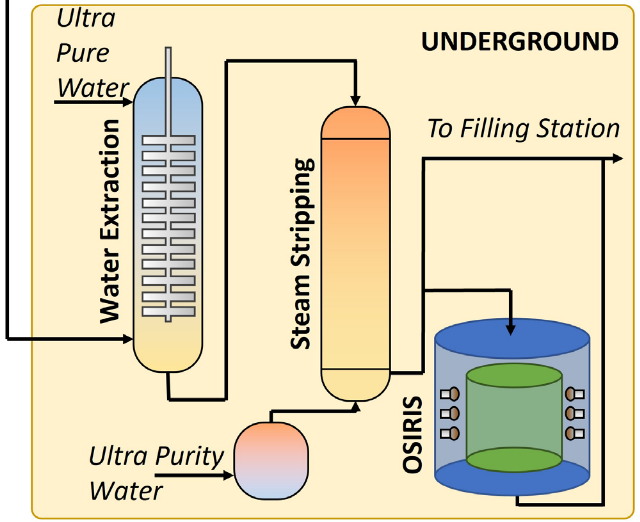
Requirements

- Constant delivery of purified LS at **7000 l/h**
- **Underground** laboratory
- Reduce the **risk of contaminating** the purified LS
- Reduce the **formation of organic compound** in the LS due to the high temperature
- **Safety hazard** (High pressure and high temperature)

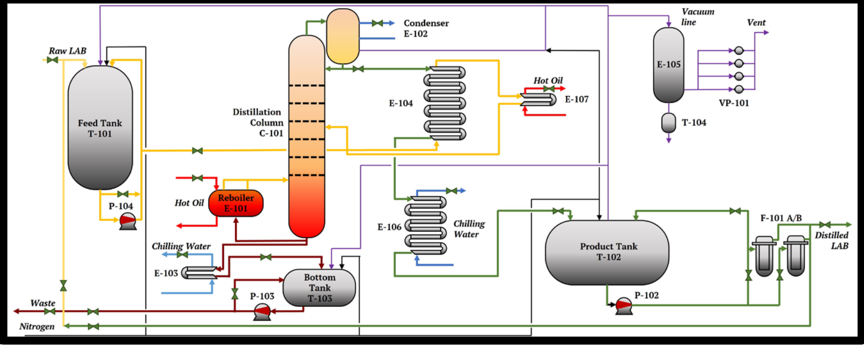


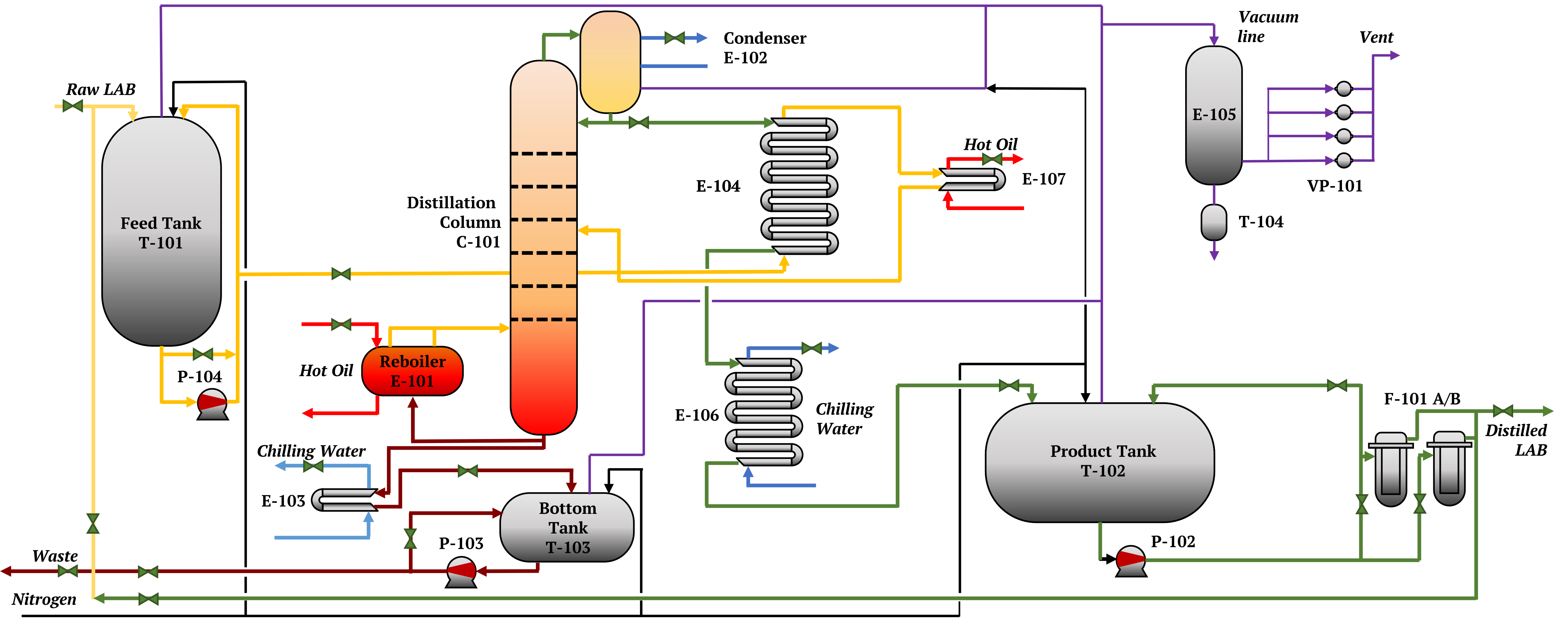
Solution

- **Industrial scale** process
- **Steam** instead of nitrogen for stripping
- **Energy recovery** to reduce the power needed
- Processes under **vacuum** to reduce the boiling temperature and increase the efficiency
- **SELO** and **PED** standards
- **OSIRIS** for on-line purification monitoring

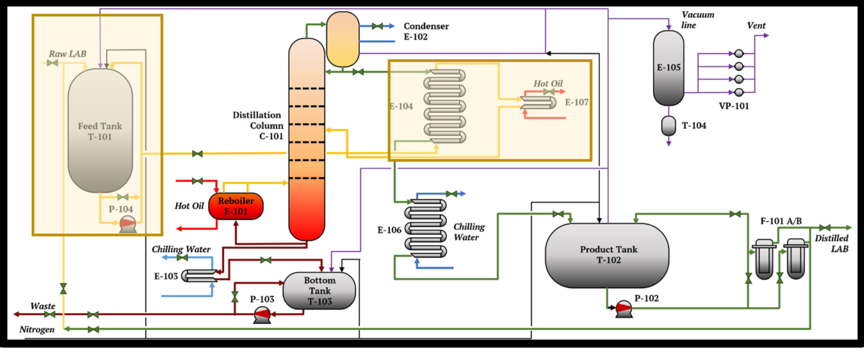


Distillation



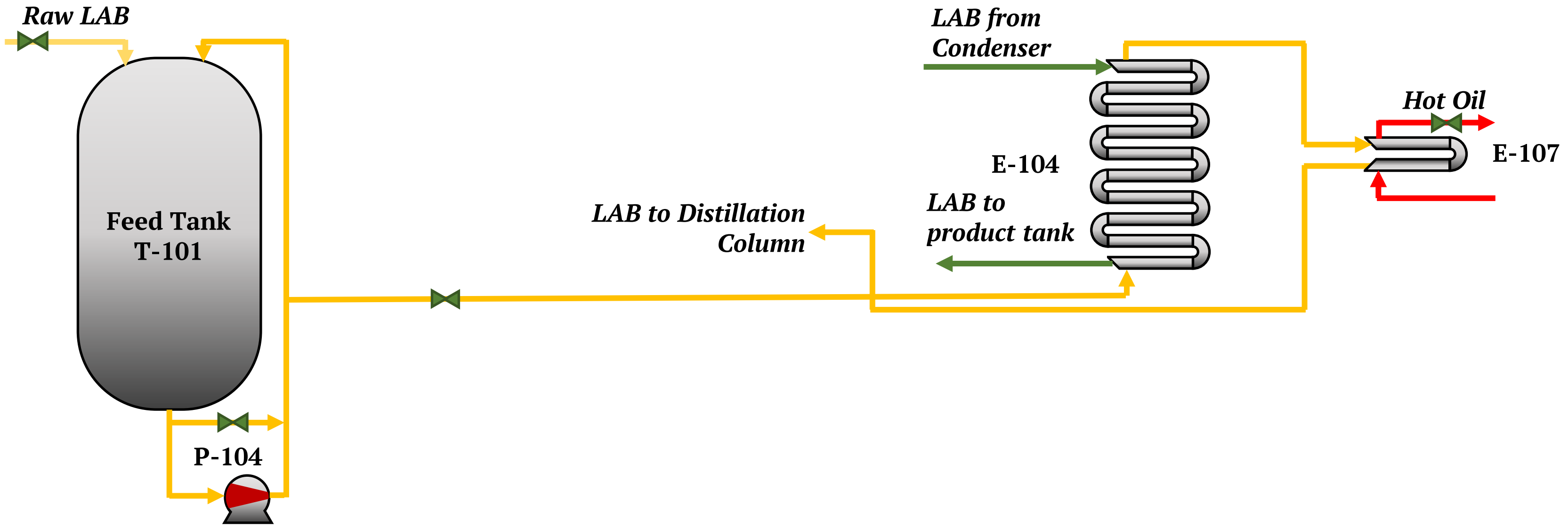


Distillation – Feed flow



Feed Tank:
20 m^3 stainless steel

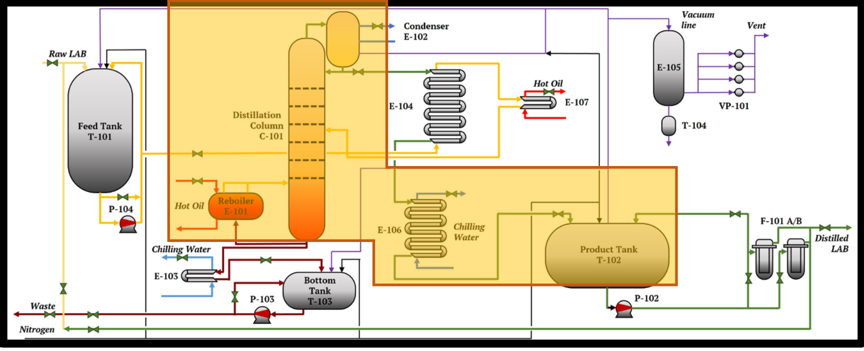
Heat exchanger:
Energy recovery



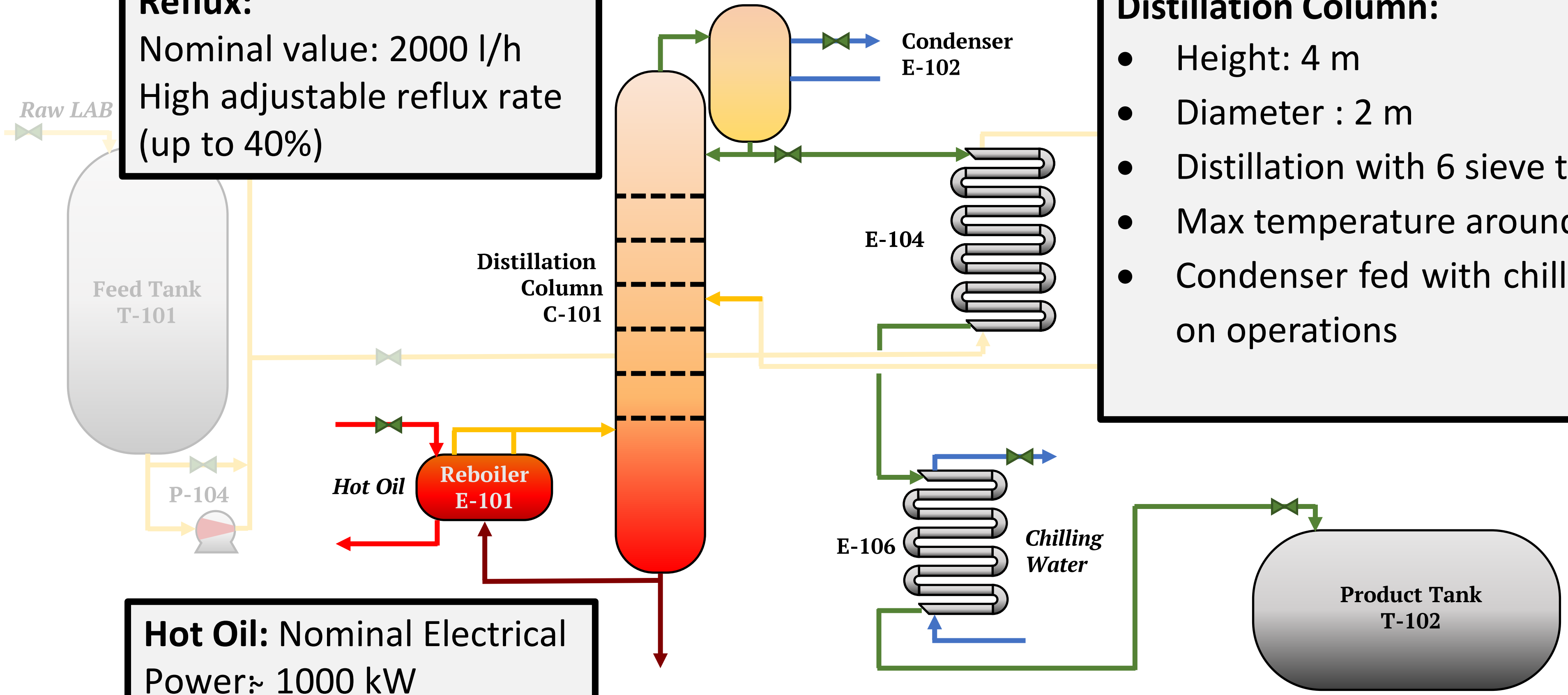
Hot Oil pre-Heater:
Increase the temperature of the feed flow

Magnetic driven pump:
reduce the risk of contamination

Distillation – Column



Reflux:
Nominal value: 2000 l/h
High adjustable reflux rate (up to 40%)



Distillation Column:

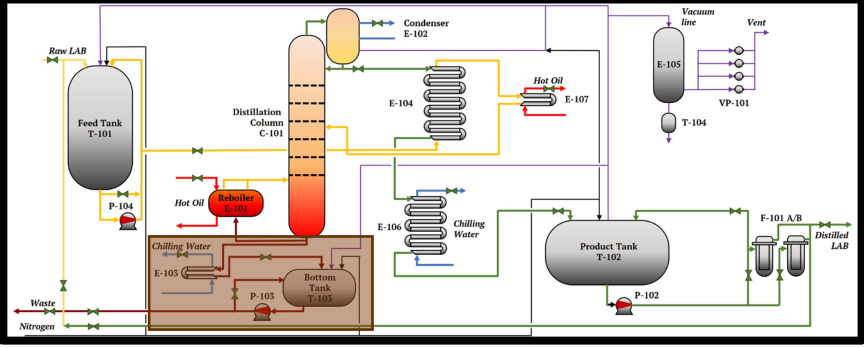
- Height: 4 m
- Diameter : 2 m
- Distillation with 6 sieve trays
- Max temperature around 200 °C
- Condenser fed with chilling water for better control on operations

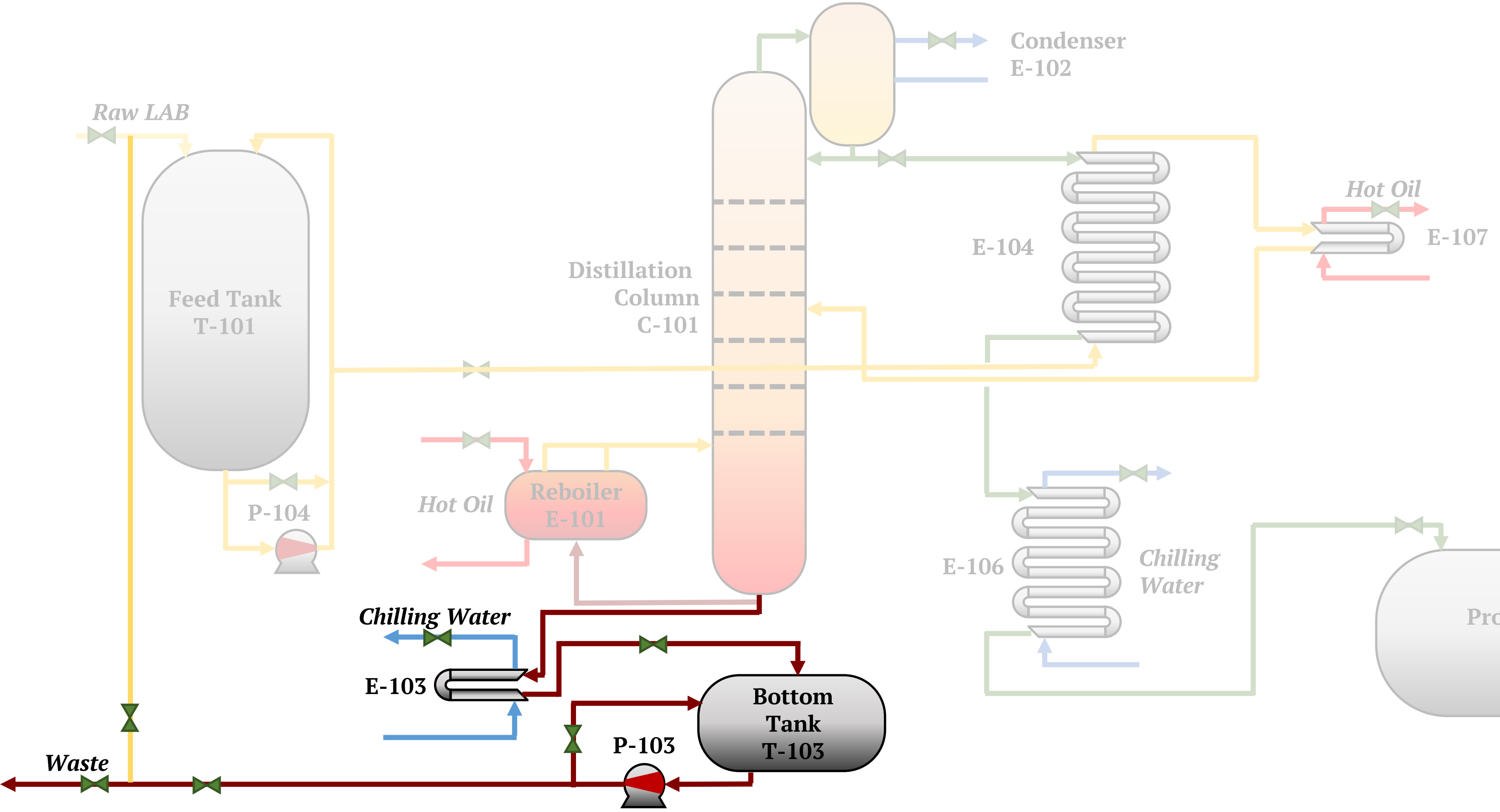
Hot Oil: Nominal Electrical Power:~ 1000 kW

Cooling Water:~ 350 kW electrical power

Product Tank:
20 m^3 electropolished stainless steel

Distillation - Bottoms

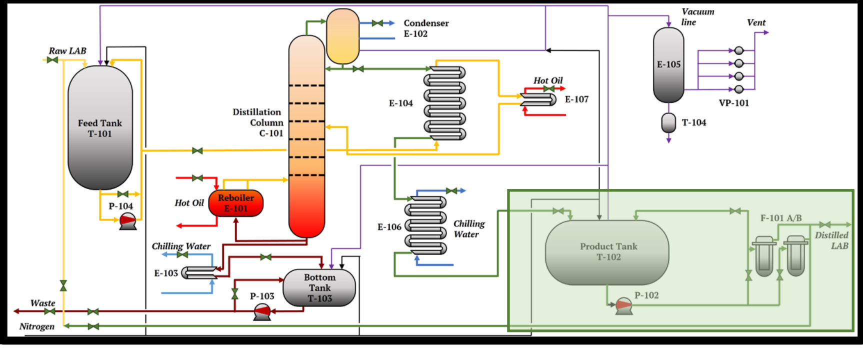


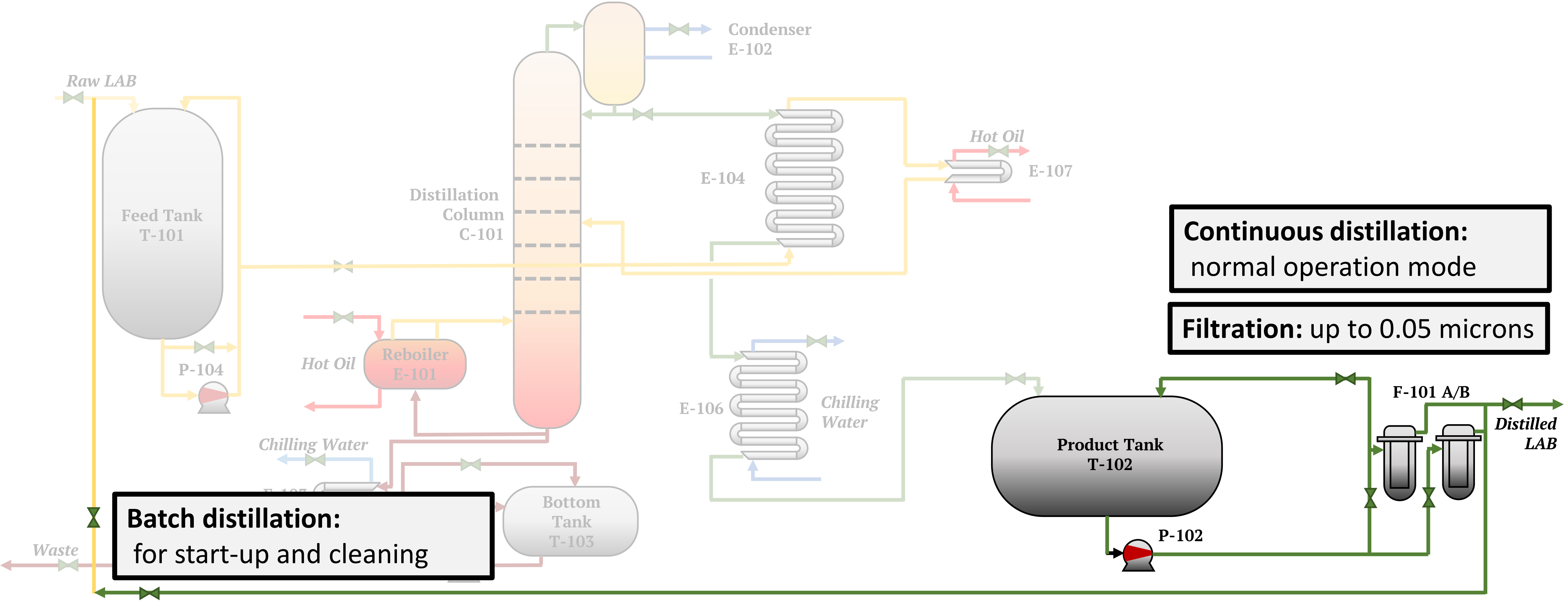


Bottom discharge:

- LAB with high concentration of impurities
- 1-2% bottom column discharge
- Reprocessed to avoid waste

Distillation – Product flow



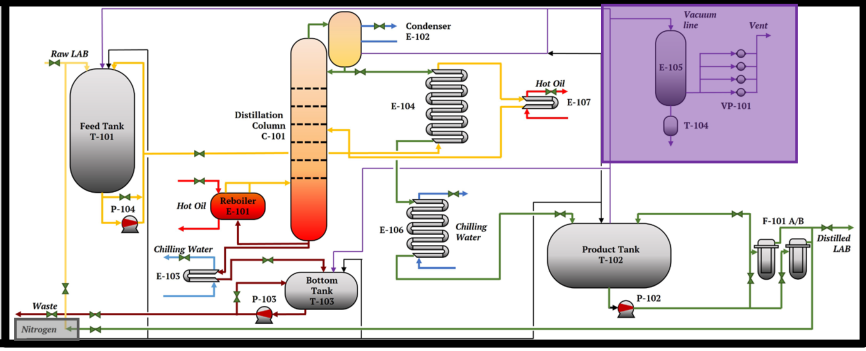


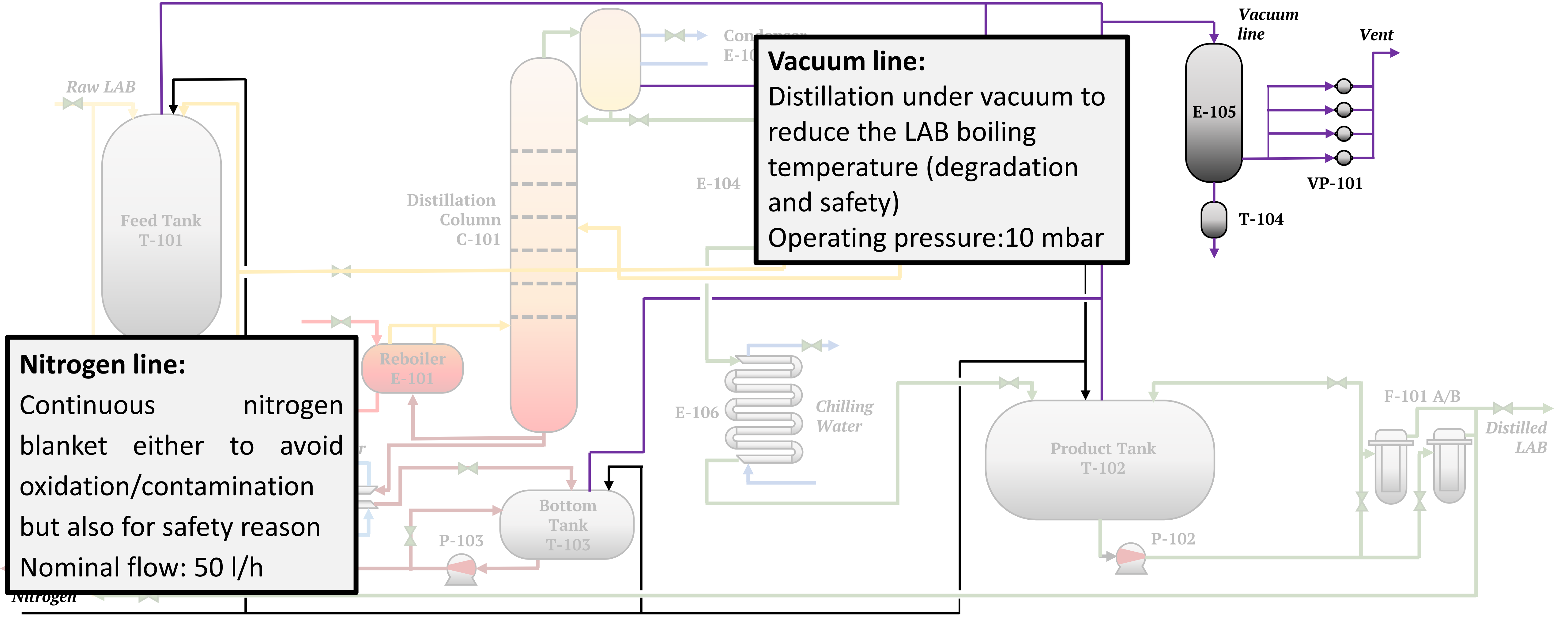
Continuous distillation: normal operation mode

Filtration: up to 0.05 microns

Batch distillation: for start-up and cleaning

Distillation - Auxiliaries





Vacuum line:

Distillation under vacuum to reduce the LAB boiling temperature (degradation and safety)

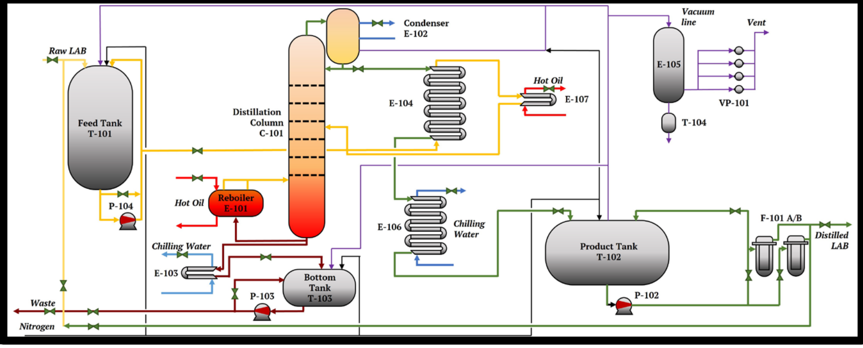
Operating pressure:10 mbar

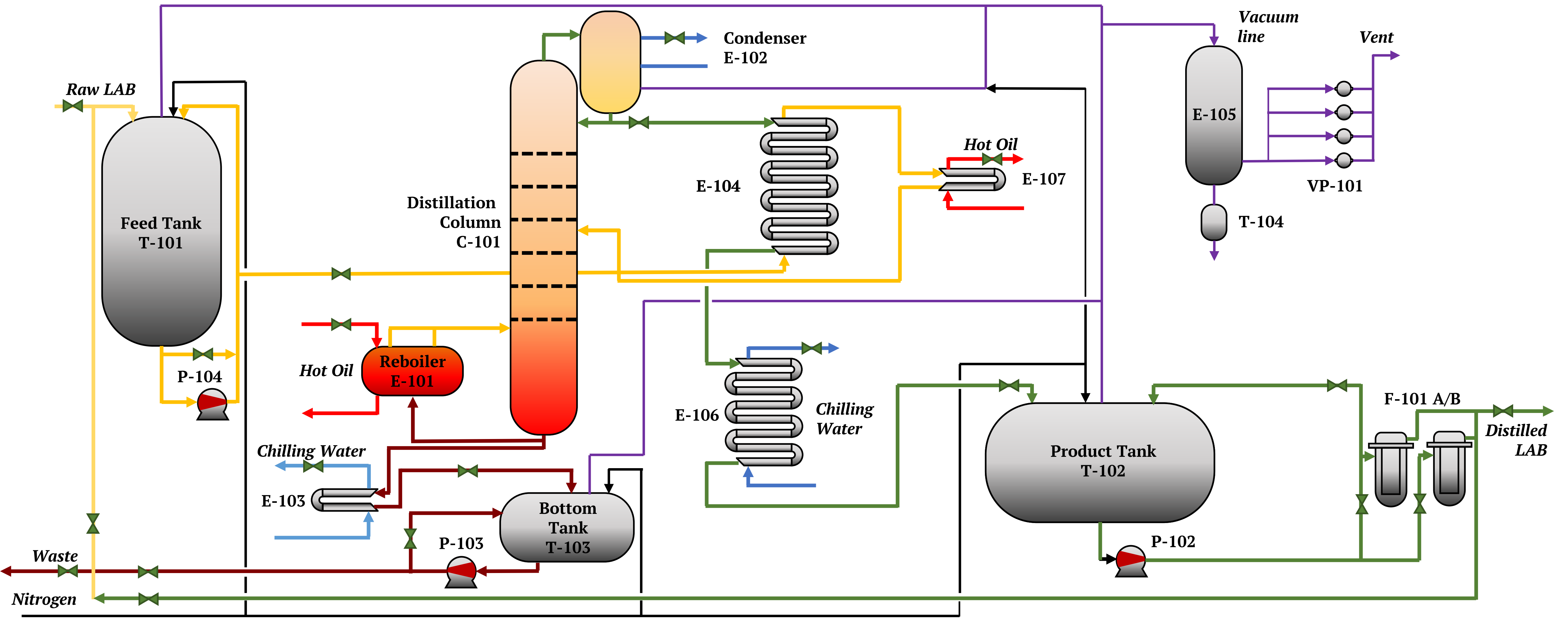
Nitrogen line:

Continuous nitrogen blanket either to avoid oxidation/contamination but also for safety reason

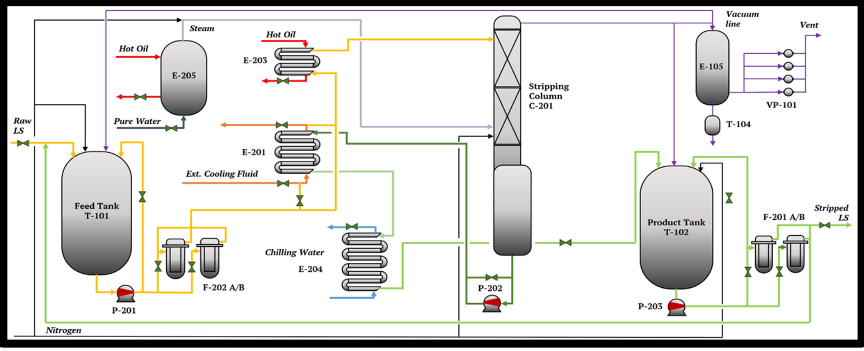
Nominal flow: 50 l/h

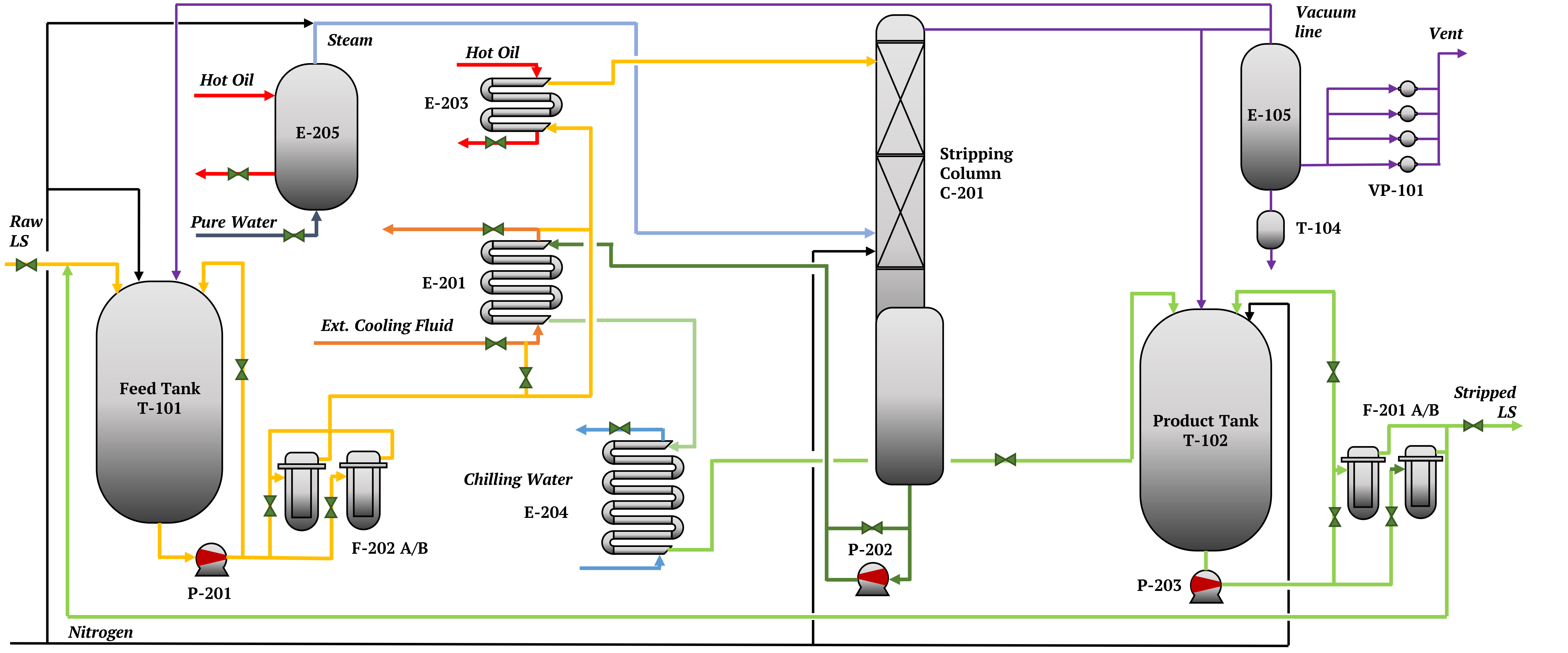
Distillation – The full picture



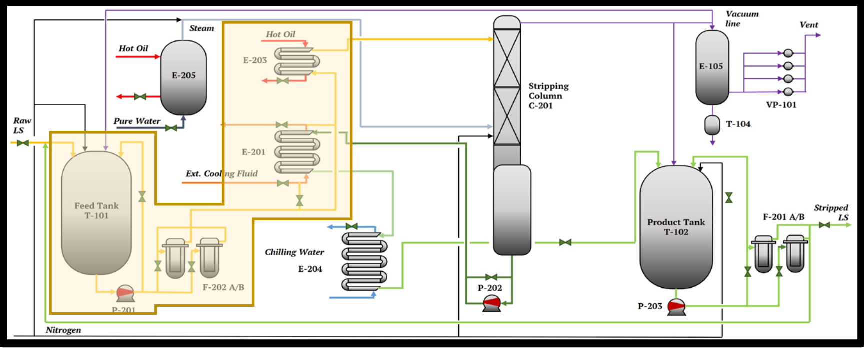


Steam Stripping





Stripping – Feed flow



Flow rate 7000 l/h

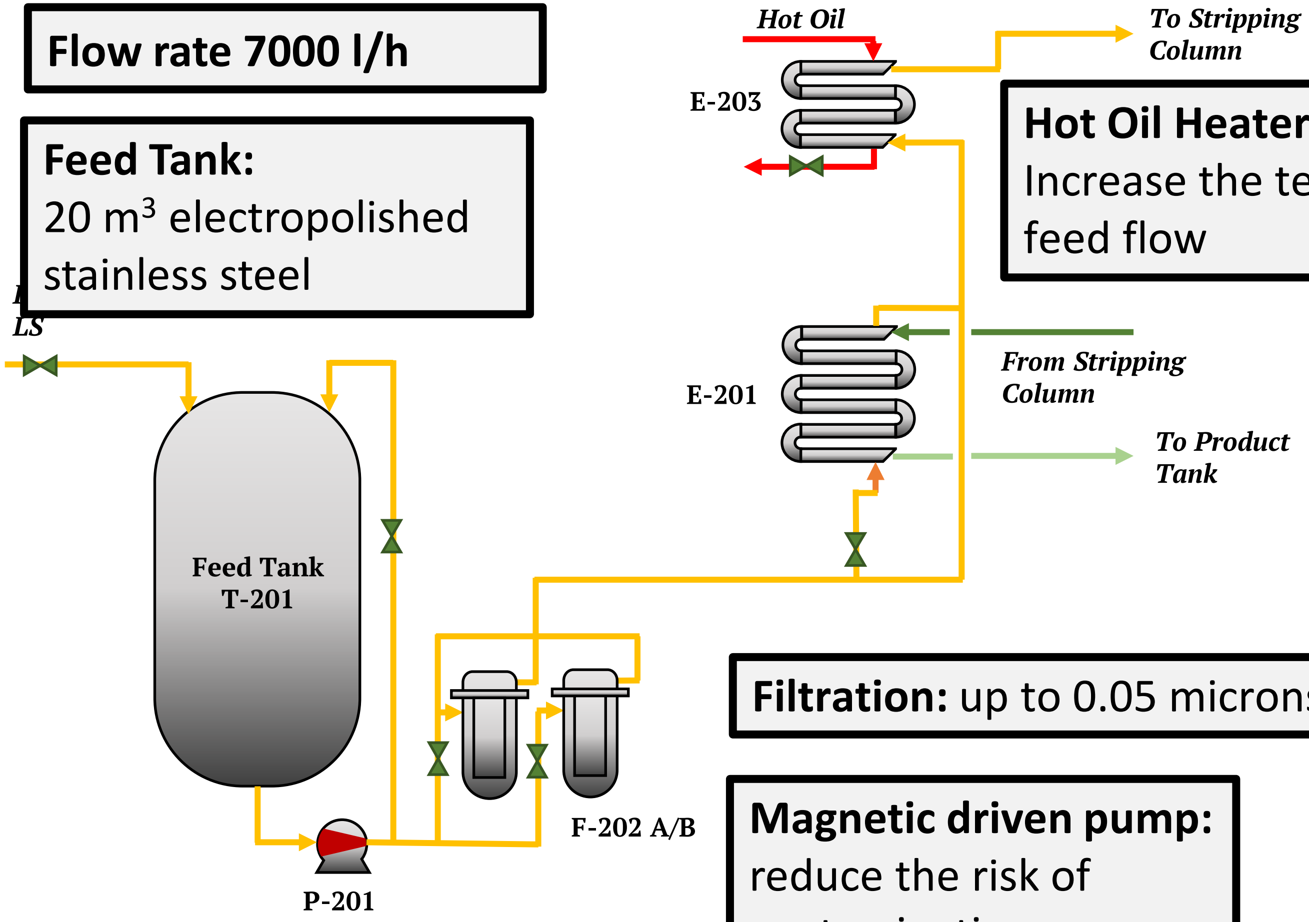
Feed Tank:
20 m^3 electropolished stainless steel

Hot Oil Heater:
Increase the temperature of the feed flow

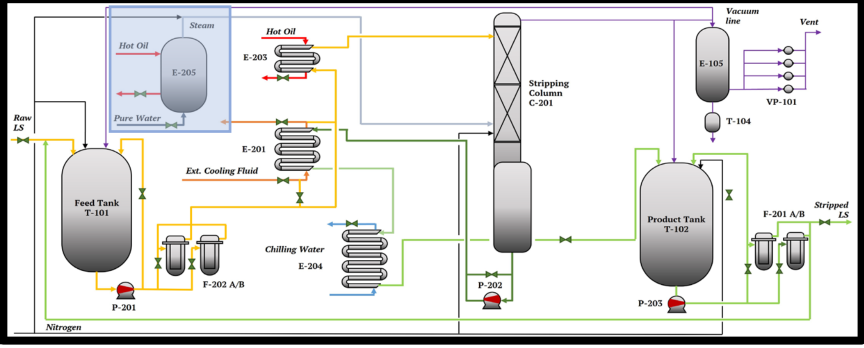
Heat exchanger:
Energy recovery with the product flow

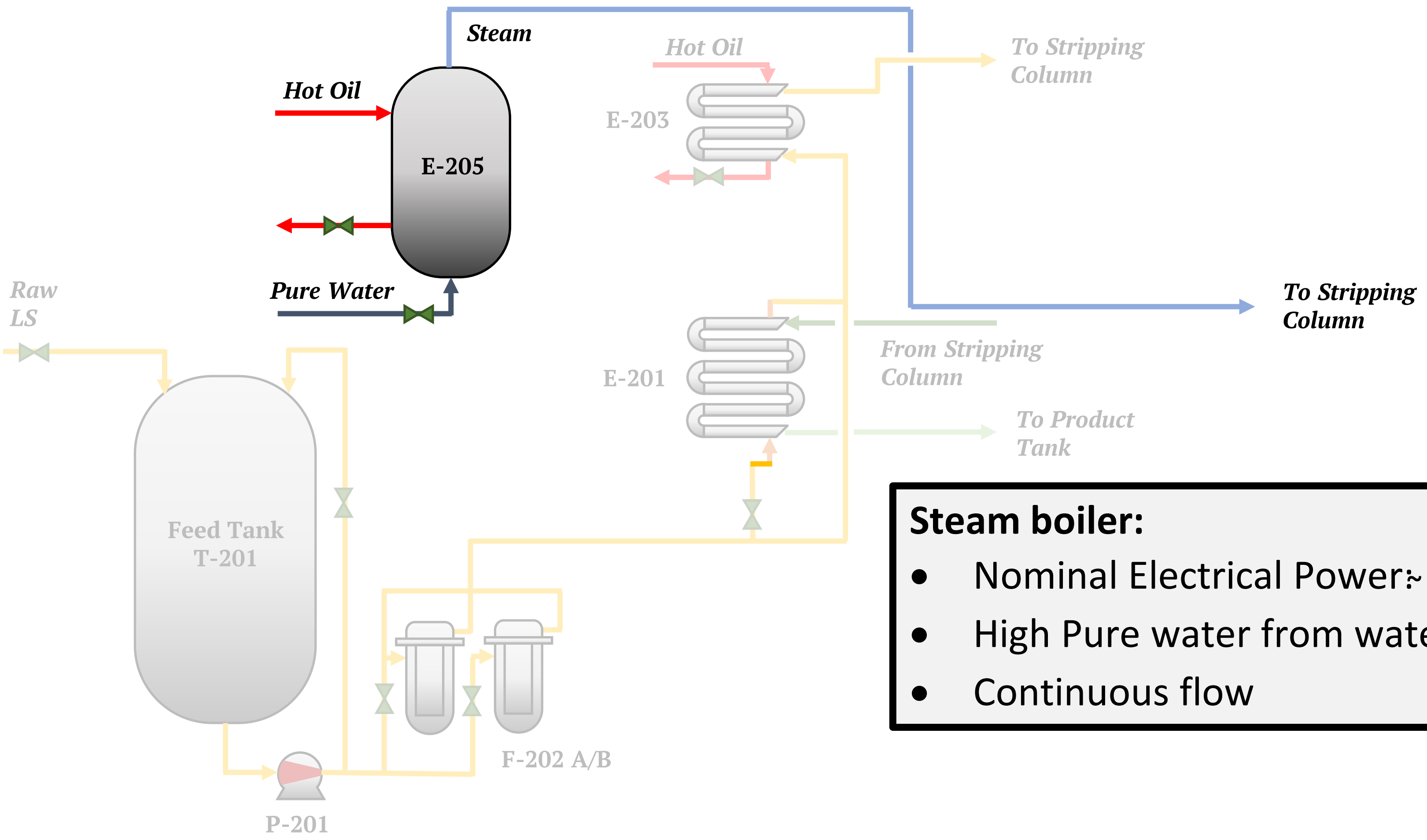
Filtration: up to 0.05 microns

Magnetic driven pump:
reduce the risk of contamination



Stripping – Steam production

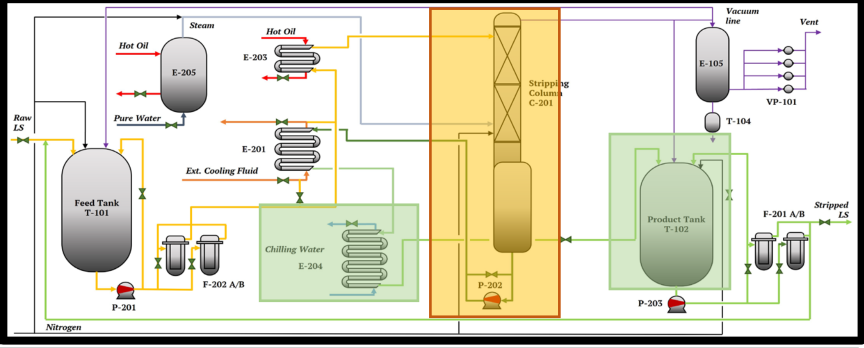


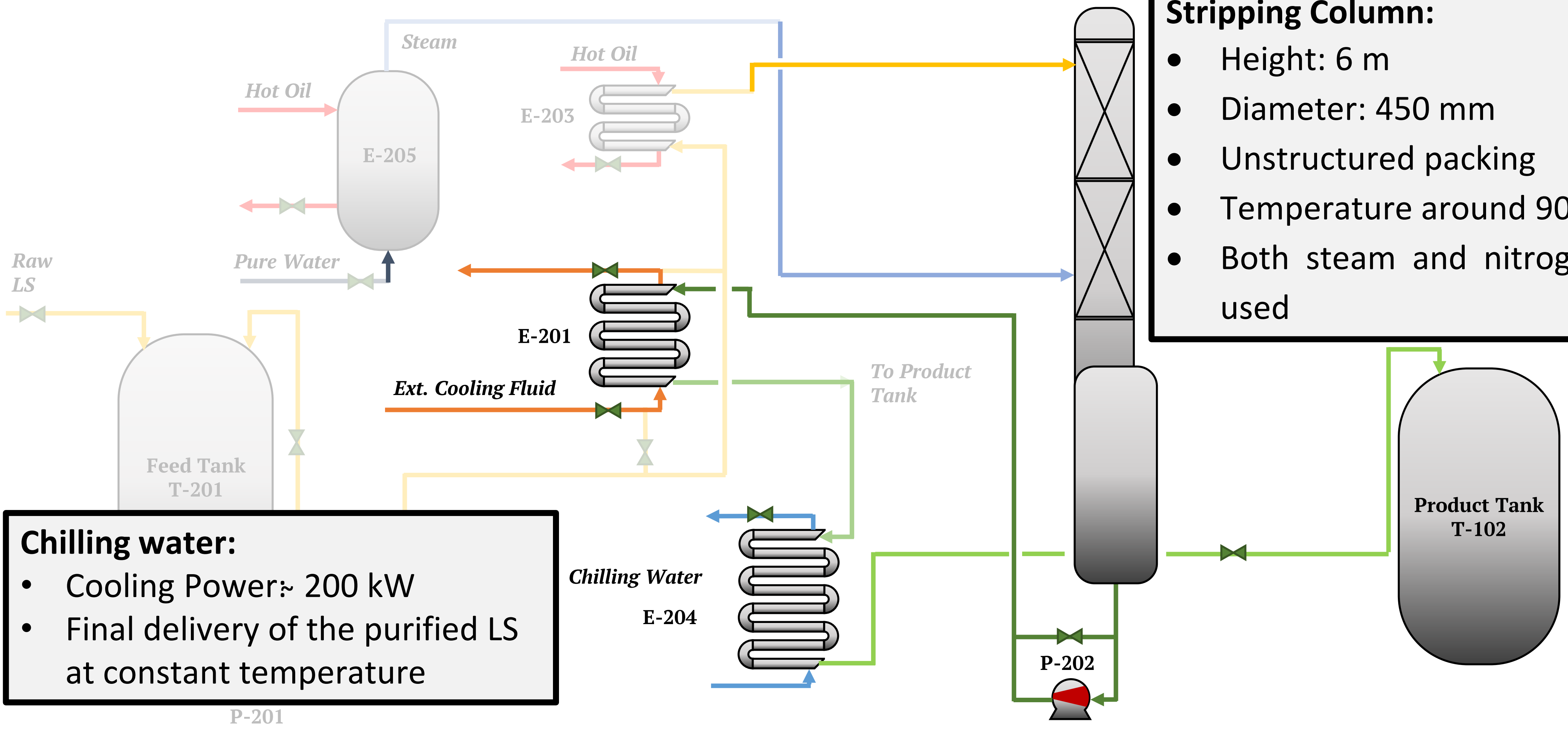


Steam boiler:

- Nominal Electrical Power:~ 200 kW
- High Pure water from water plant (approx. 25 l/h)
- Continuous flow

Stripping - Column





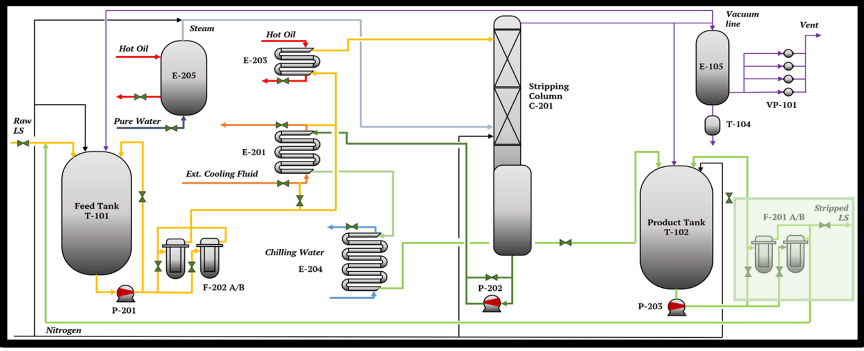
Stripping Column:

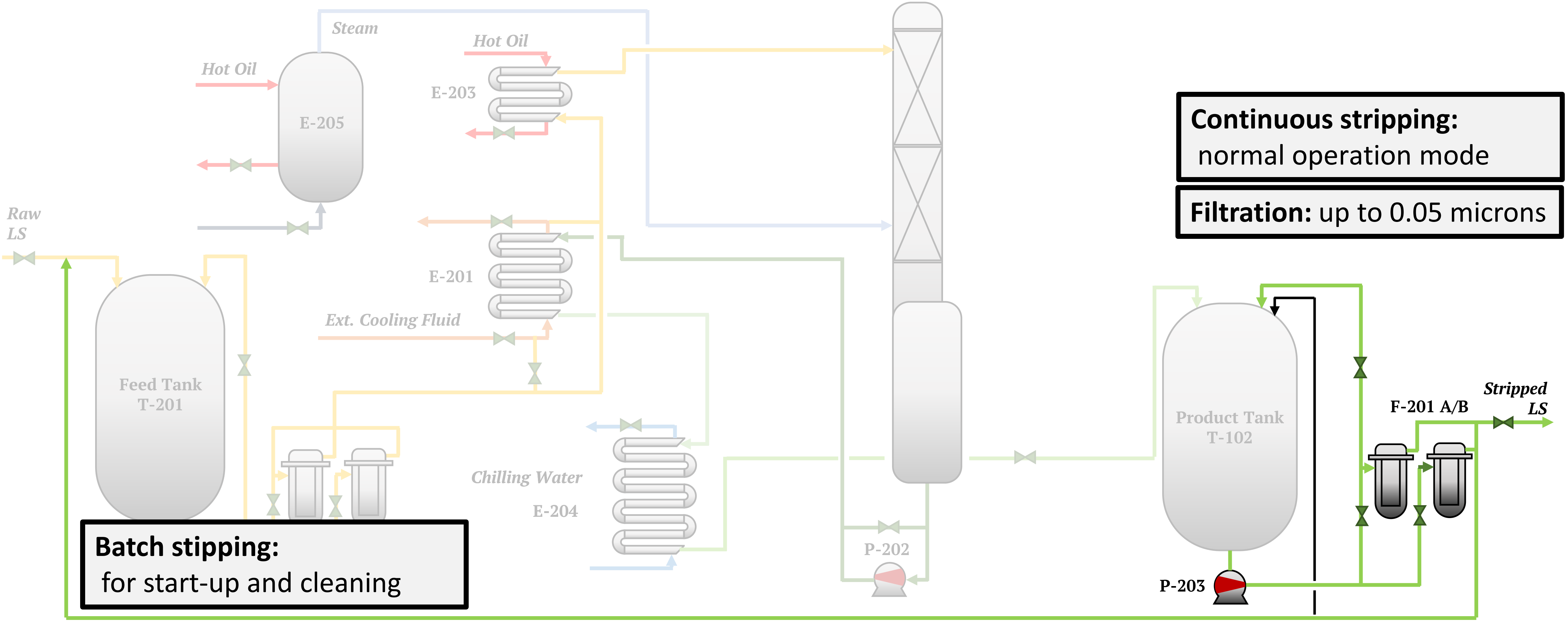
- Height: 6 m
- Diameter: 450 mm
- Unstructured packing
- Temperature around 90 °C
- Both steam and nitrogen stripping could be used

Chilling water:

- Cooling Power:~ 200 kW
- Final delivery of the purified LS at constant temperature

Stripping – Product flow



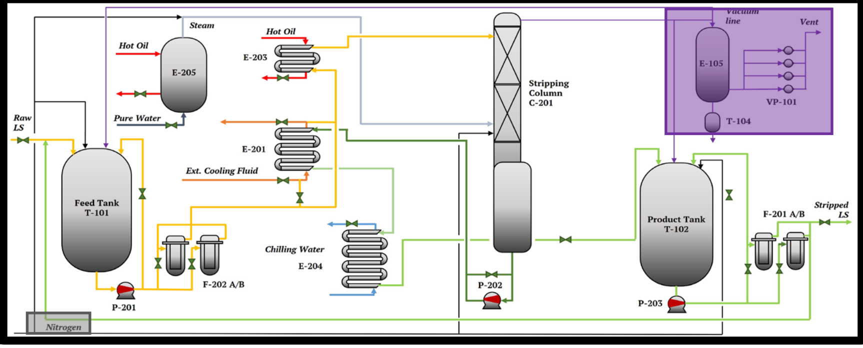


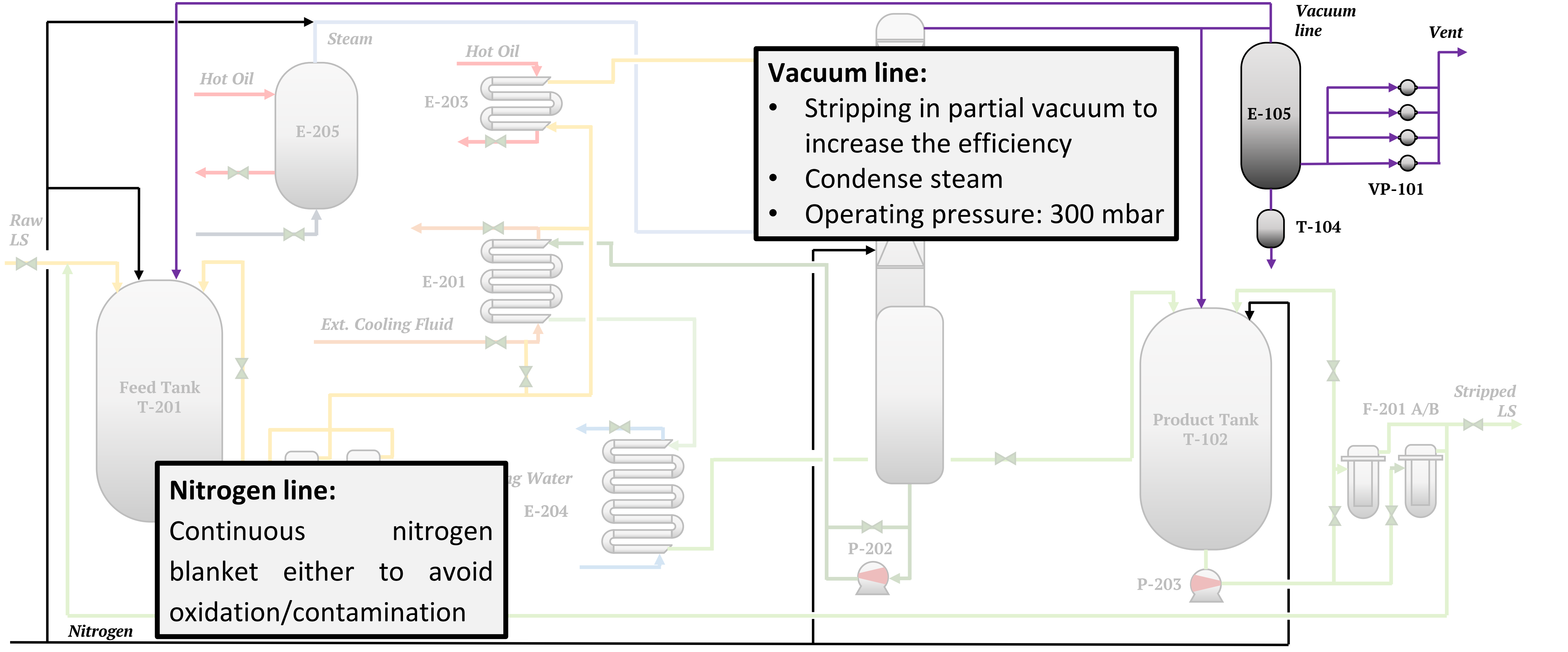
Continuous stripping: normal operation mode

Filtration: up to 0.05 microns

Batch stipping: for start-up and cleaning

Stripping - Auxiliaries





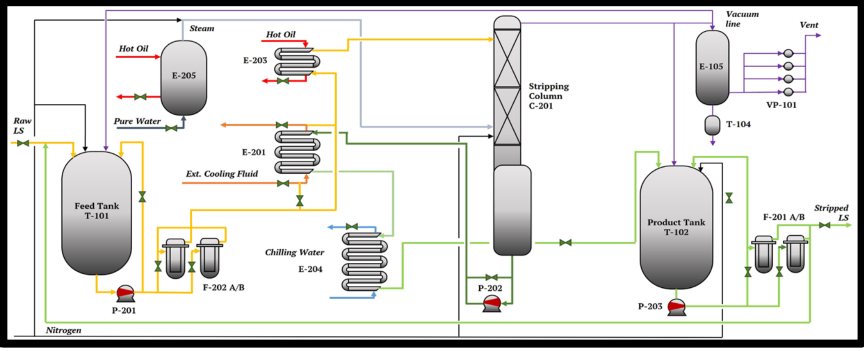
Vacuum line:

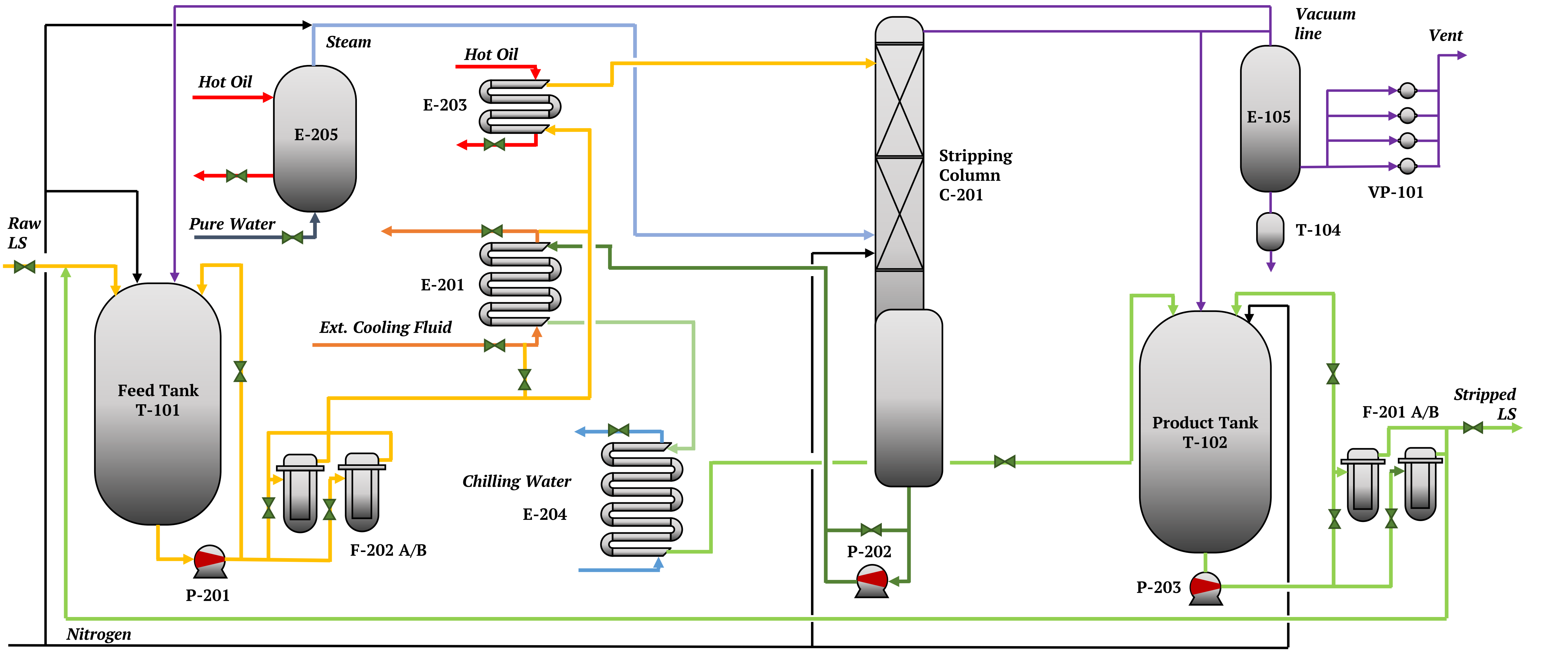
- Stripping in partial vacuum to increase the efficiency
- Condense steam
- Operating pressure: 300 mbar

Nitrogen line:

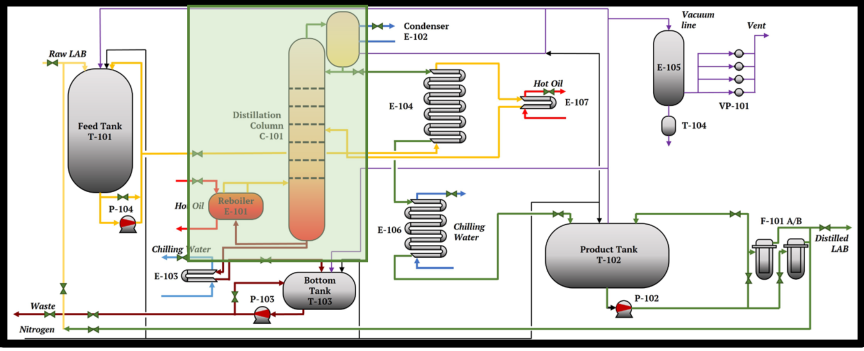
Continuous nitrogen blanket either to avoid oxidation/contamination

Steam Stripping – The full picture



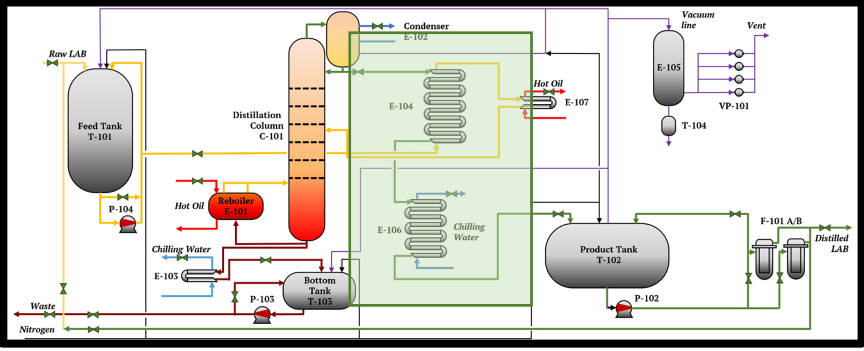


Realization



- **The plants were assembled in skids for an easier shipping and mounting**
- **Skids and tanks were assembled at Polaris s.r.l. (Misinto):**
  - Realization of pipes and connections
  - Pre-assembly carried out horizontally
  - Disassembled system in single skids for shipping
- **All connections and the most delicate parts have been assembled by us**
- **Every component and connection of the system has been tested:**
  - Pneumatic and vacuum test
  - Roughness and cleaning quality control
  - Helium leak test
    - Single leak rate < 10^{-8} mbarL/s
    - Integral leak rate < 10^{-6} mbarL/s

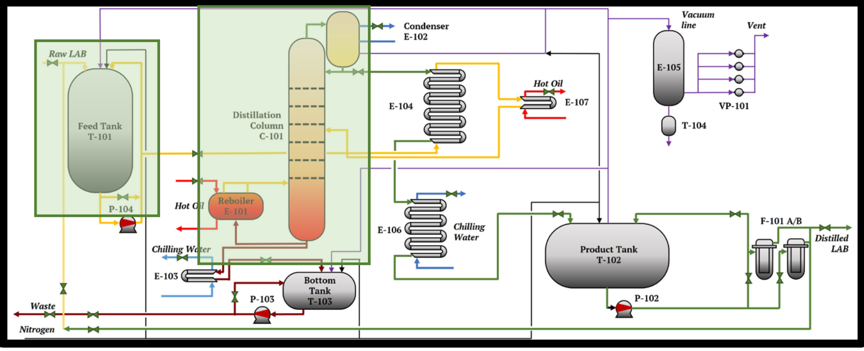
Distillation plant construction



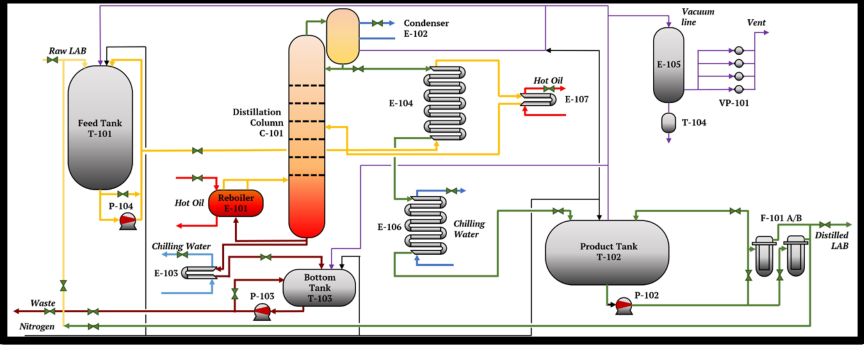
- **Where:**
  installation in the Over Ground LS building
- **When:**
  25 April 2022 - start of the Distillation plant installation
  5 May 2022 - end of "Phase 1" of Distillation plant installation

- **6 skids, 1 vertical tank, 1 horizontal tank, 1 pump skid**
- **Main issues:**
  - Installation to be performed from the roof of the building using dedicated truck cranes (QY220T – 220 tons truck crane; QY25T – 25 tons truck crane)
  - Removal of the roof of the building
  - Some heavy and large flanges need to be mounted (DN500 - DN1000 flanges)
  - Huge plant, a lot of components, to be aligned very precisely (1 mm)

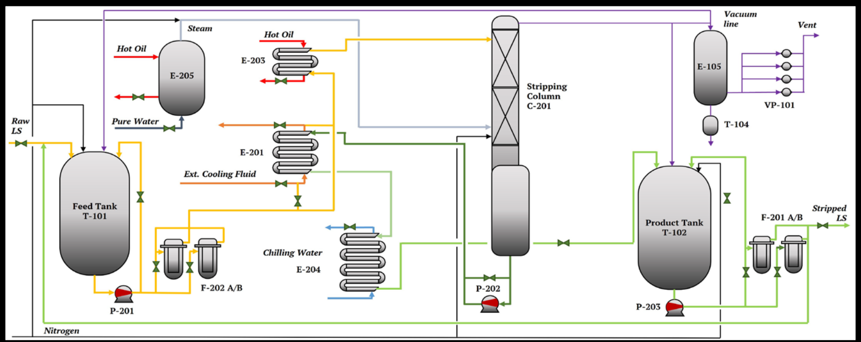
Assembling of the distillation column and vertical tanks



Final Assembly



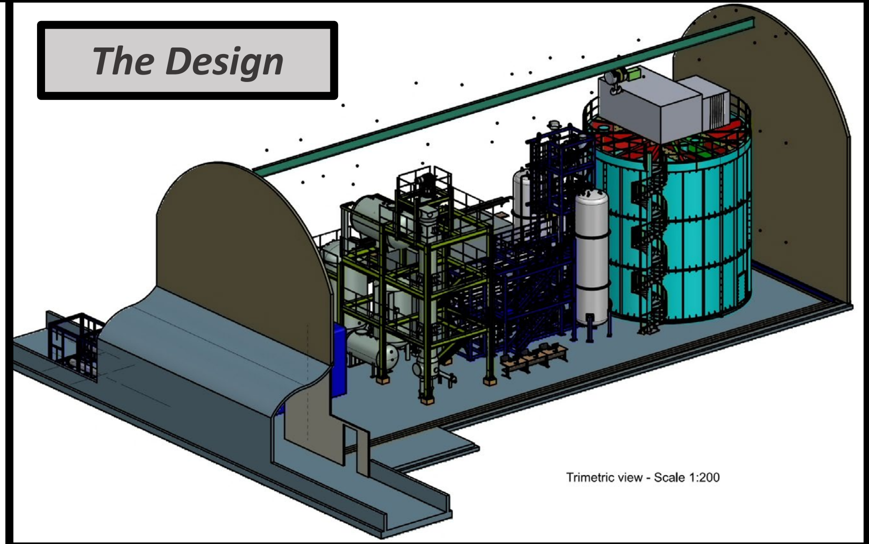
Stripping plant construction



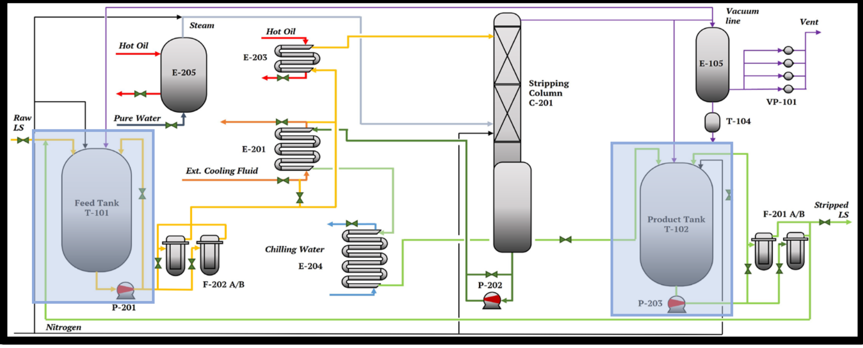
- **Where:**
  installation in the Underground LS building

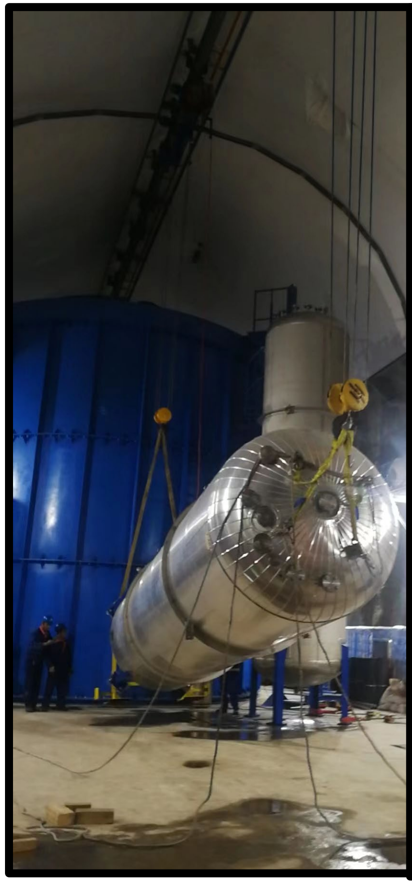
- **When:**
  6 May 2022 - start of the Stripping plant installation
  14 May 2022 - end of "Phase 1" of Stripping plant installation

- **3 skids (1 vertical skid) and 2 vertical tanks**
- **Main issues: :**
  - Transportation to underground through the slope tunnel to be booked and organized in advance
  - Few lifting devices in underground (uniaxial overhead crane of LS Hall). Vertical tanks moved to their installation position through a set of winches and ropes

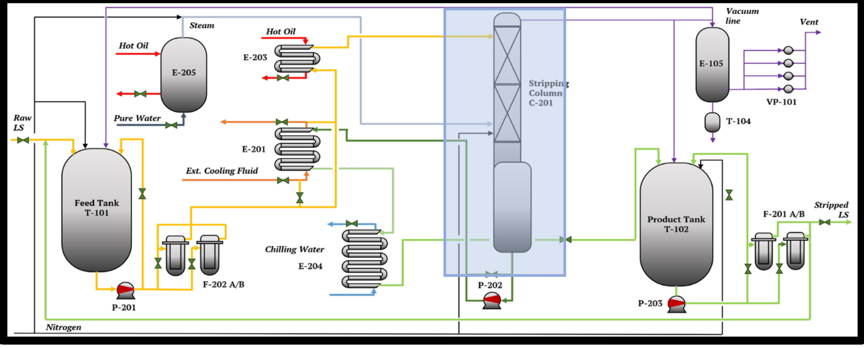


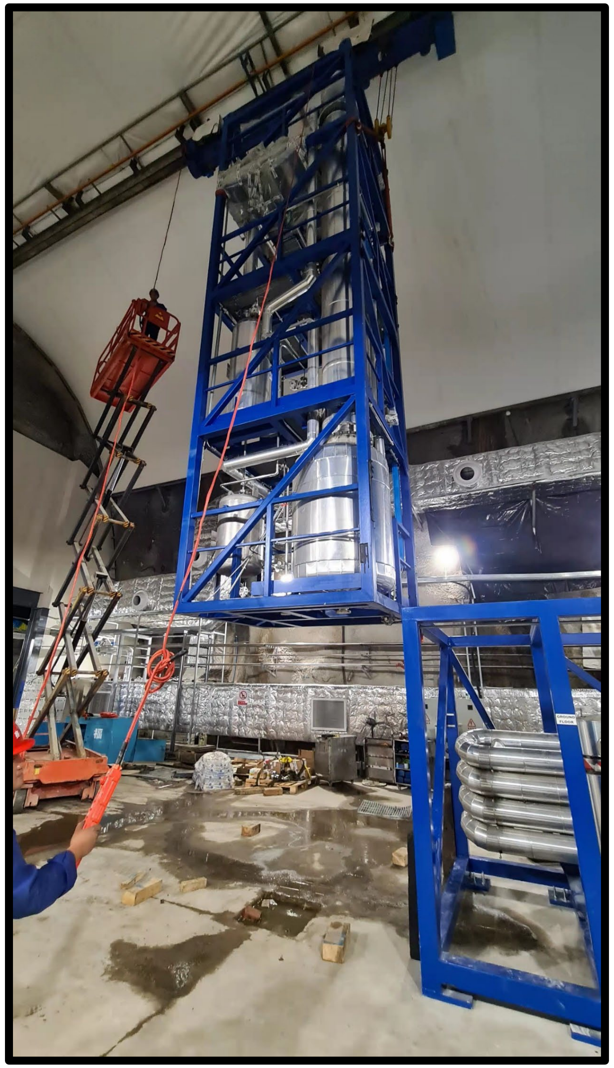
Construction of the vertical tanks



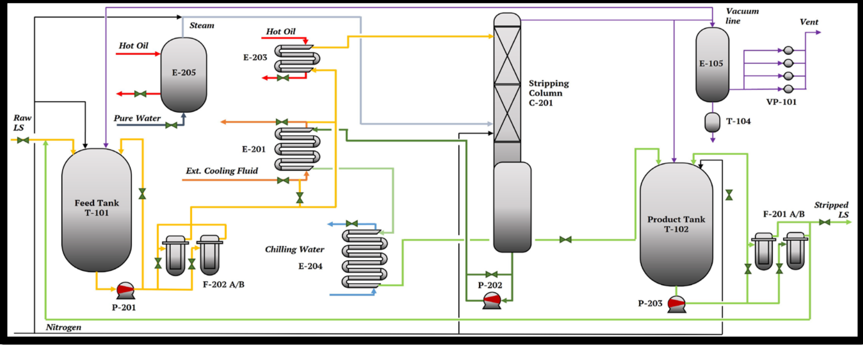


Construction of the column

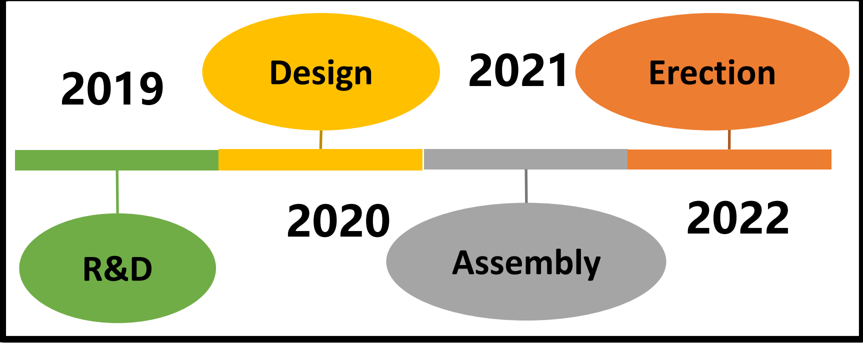




Steam stripping final assembly

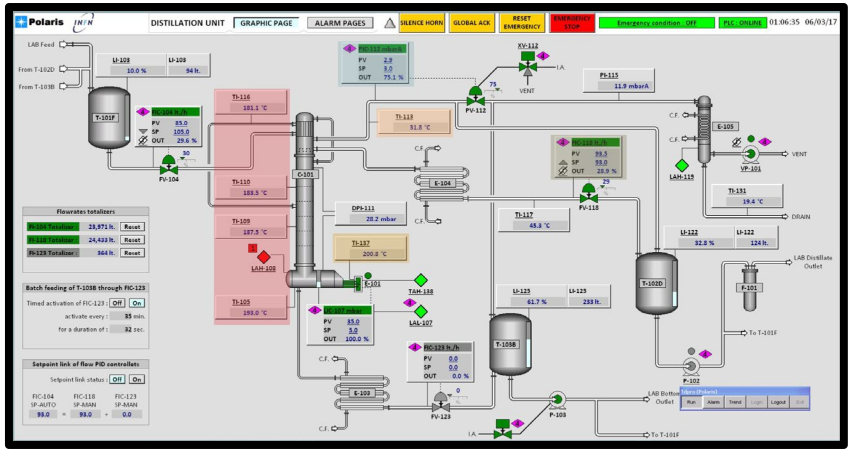


Conclusions



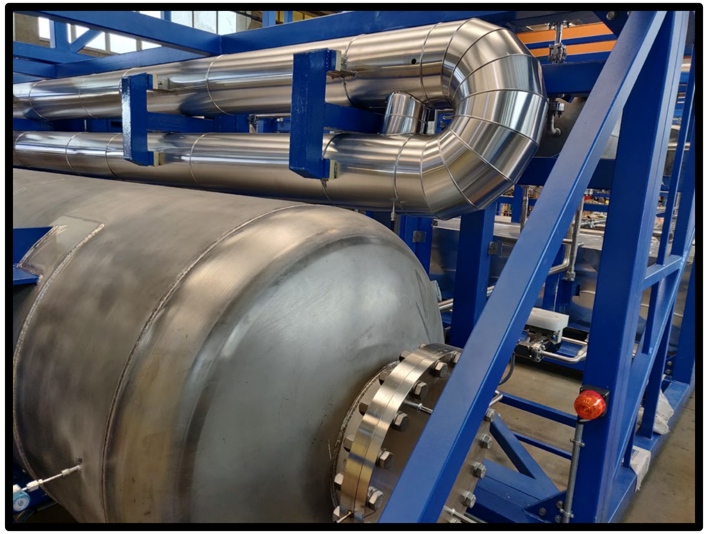
R&D

I helped to design and to build a pilot LS purification system, focusing on the control system and operations. As a result, the LS absorption length increased to 24.4m and Rn content was reduced by 96%

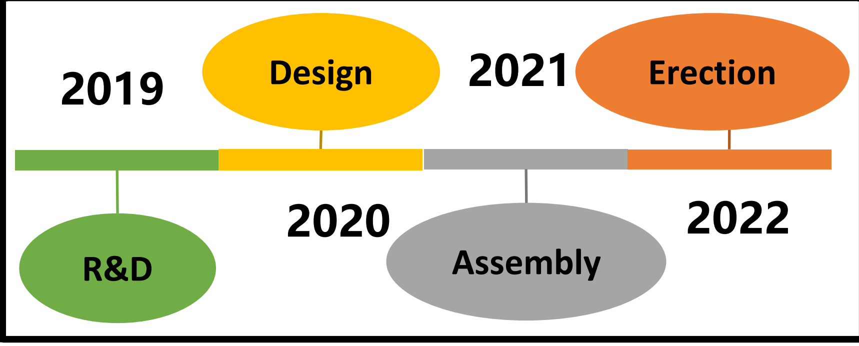


Final Plant Design

I contributed to LS purification plant design, implementing the control system and writing the operative procedures. This allowed to comply with the European (PED and ATEX) & Chinese (SELO) safety standards and JUNO collaboration's physics/technical constraints (Flow = 7000 l/h, T<210 °C, energy recovery).

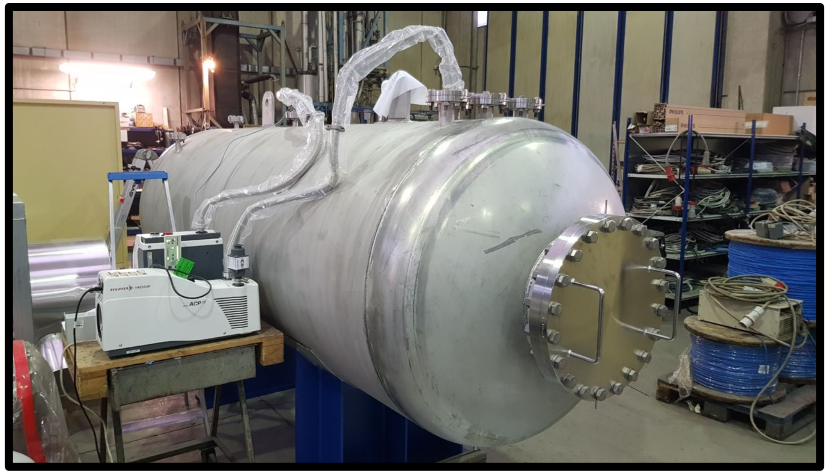


Conclusions



Assembly

While assembling the LS purification plant, I tested the internal connections with a helium leak tester and assessed the cleanliness and roughness of tanks and piping inner surfaces. Electropolished surfaces had a <0.8 µm mean roughness, and all flanges passed a helium leak test at a level better than 10^{-6} mbar l/s.



Construction

In March 2022, we successfully installed the Distillation Plant in the LS Hall and the Steam Stripping Plant in the Underground LS Hall at the JUNO site. I managed the operations following the erection procedures and mounted delicate interconnections, including large flanges on the hot side of the distillation column. The distillation and steam stripping plants were completed at the end of last year and are scheduled for commissioning in April 2023.

Reads

Peer reviewed papers:

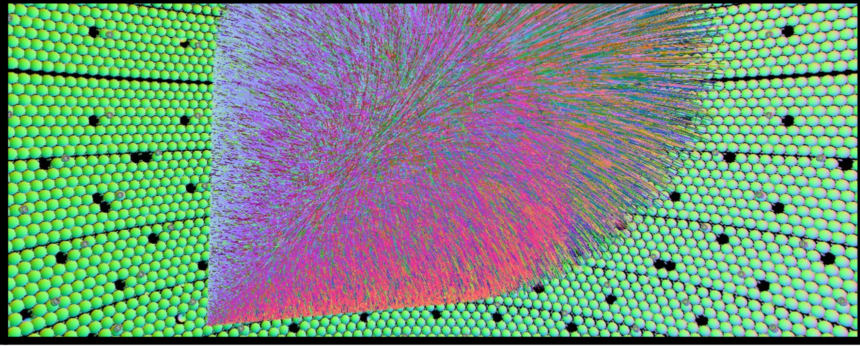
- Abusleme, A., *et al* Calibration strategy of the JUNO experiment. J. High Energ. Phys. 2021, 4 (2021). (I.F.: 5.875)
- Marini, M. *et al*., FPGA Implementation of an NCO Based CDR for the JUNO Front-End Electronics, in IEEE Transactions on Nuclear Science, vol. 68, Aug. 2021, (I.F.: 1.679)
- Marini, M., *et al*. An Easily Integrable Industrial System for Gamma Spectroscopic Analysis and Traceability of Stones and Building Materials. Sensors, 21, 352 (2021). (I.F.: 3.576).
- Abusleme, A., *et al*. Feasibility and physics potential of detecting 8B solar neutrinos at JUNO. Chinese Physics C 45(2) (2021). DOI: 10.1088/1674-1137/abd92a (I.F.: 2.145).
- Abusleme, A., *et al*. Optimization of the JUNO liquid scintillator composition using a Daya Bay antineutrino detector. NIMA, 988, 164823 (2021). (I.F.: 1.455).
- Bellato, M., *et al*. Embedded readout electronics R&D for the large PMTs in the JUNO experiment. NIM-A, 985, 164600 (2021). (I.F.: 1.455).
- Abusleme A., *et al.*, Prospects for detecting the diffuse supernova neutrino background with JUNO, J. of Cos. and Astropart. Physics, 2022(10) (2022) (I.F. =5.839), 10 October 2022
- Maino A., *et al.*, Airborne Radiometric Surveys and Machine Learning Algorithms for Revealing Soil Texture, Remote Sensing, 14(15), 3814 (2022) (I.F. = 5.349), 08 August 2022
- Raptis K.G.C., *et al.*, External effective dose from natural radiation for the Umbria region (Italy), Journal of Maps, 1-11 (2022) (I.F. =2.657), 28 July 2022
- Finco A., *et al.*, Combining Precision Viticulture Technologies and Economic Indices to Sustainable Water Use Management, Water, 14, 1493 (2022) (I.F. =3.530), 06 May 2022
- Wang J., *et al.*, Damping signatures at JUNO, a medium-baseline reactor neutrino oscillation experiment, Journal of High Energy Physics, 62 (2022) (I.F. =6.379), 13 June 2022
- Abusleme A., *et al.*, JUNO physics and detector, 123, 103927 (2022), (I.F. =12.425), 03 December 2021
- Abusleme A.,*et al.*, Radioactivity control strategy for the JUNO detector, Journal of High Energy Physics 2021, Article number: 102 (2021), (I.F. =3.729), 15 November 202

Conferences and Disseminations:

- M. Montuschi on behalf of JUNO collaboration, Challenges in the construction of large neutrino detectors: the JUNO case, 23rd International Workshop on Neutrinos from Accelerators (NUFACT 2022), 06/08/2022
- M. Montuschi, *et al.*, A Web GIS tool for 3D visualization of bathymetric data, EGU 2022, WIEN, GM6.10 Submarine Geology Session, 25/05/2022

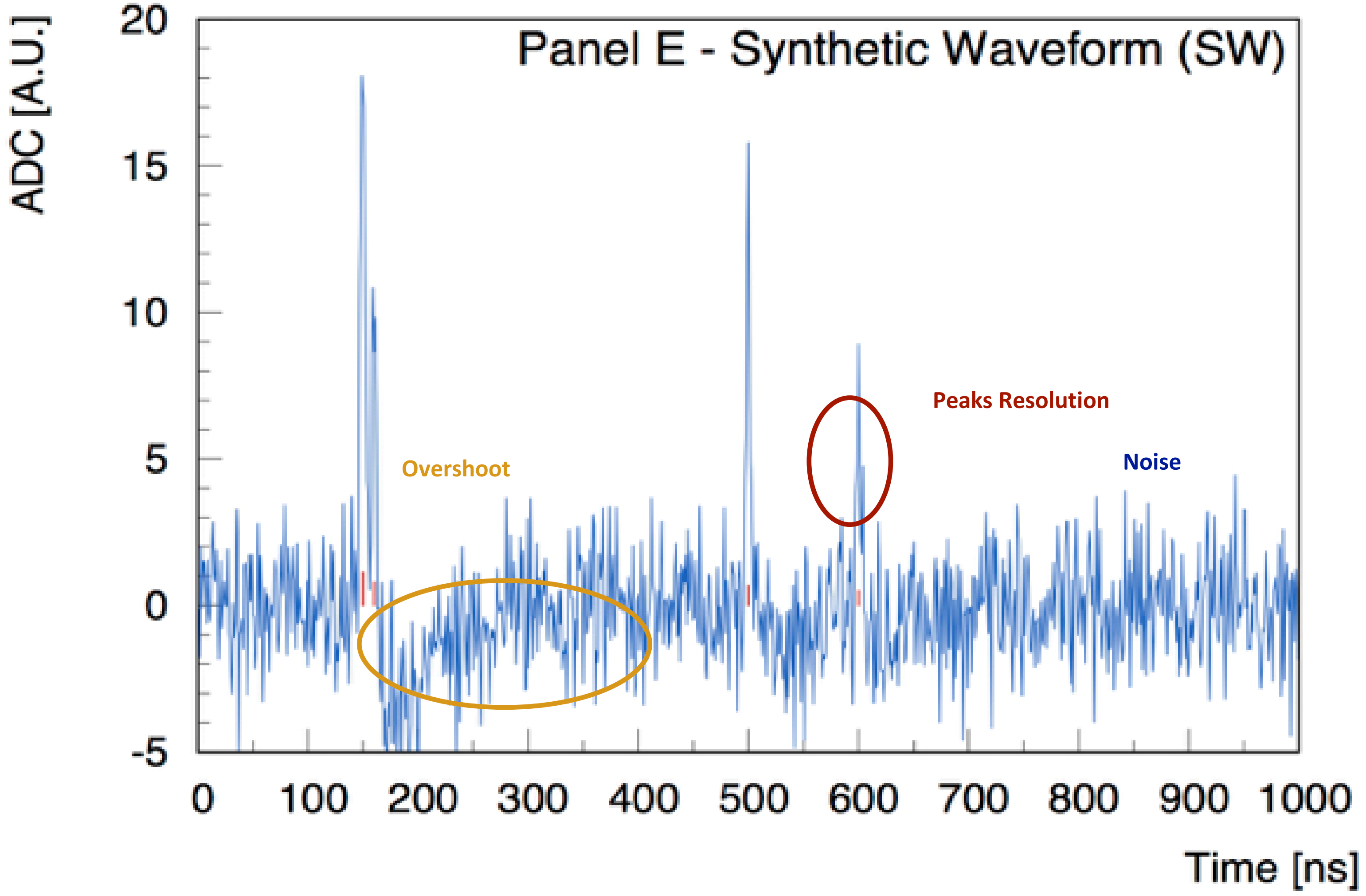
BACK UP SLIDES

GOAL

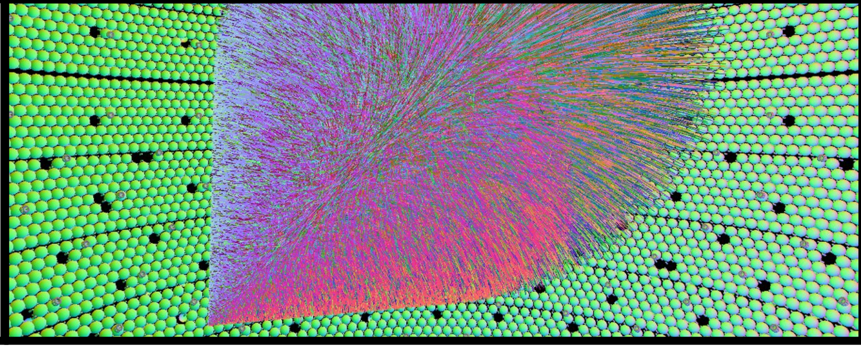


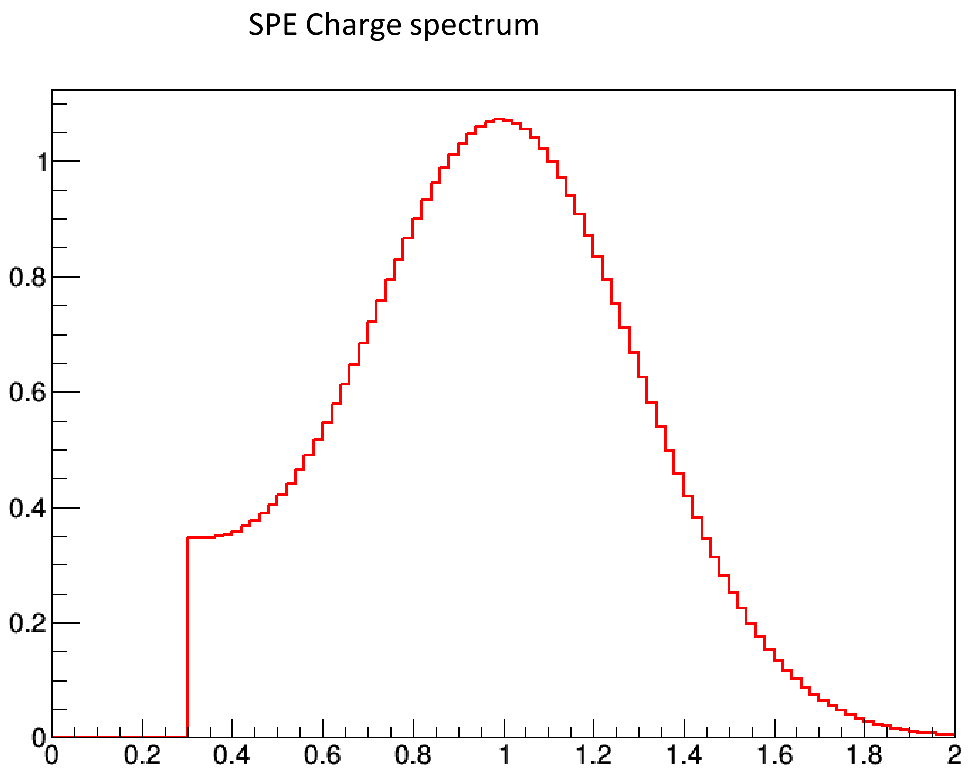
- With Digital Signal Processing Technique we aim to
  - reduce Noise and Overshoot
  - Increase the Peaks Resolution

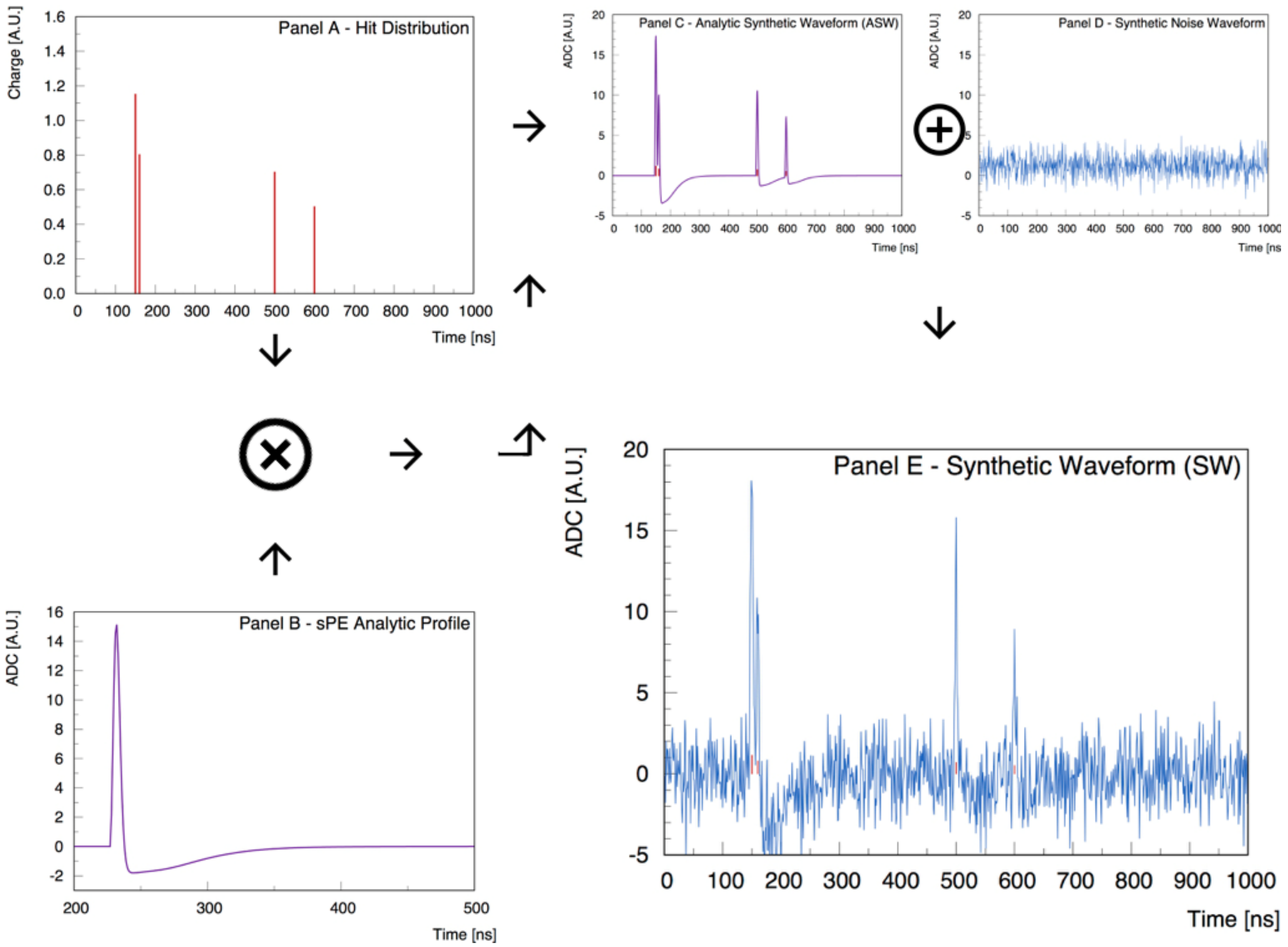
- Have a better reconstruction of the charge



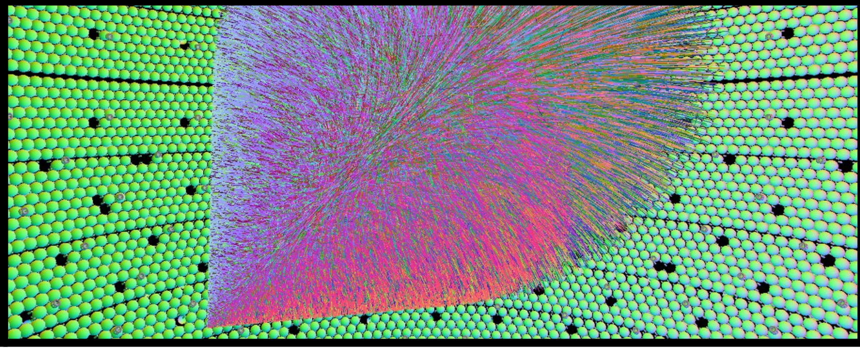
EVENT BUILDING ALGORITHM

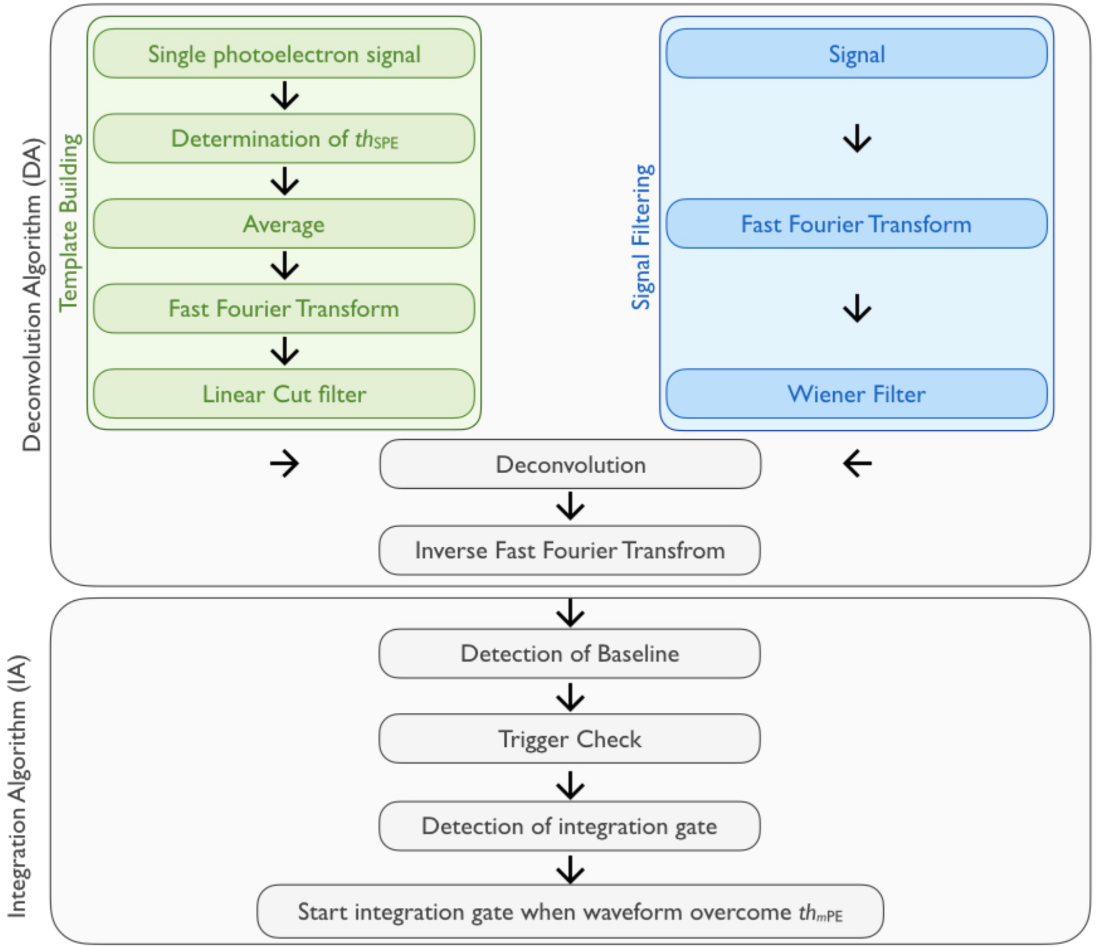






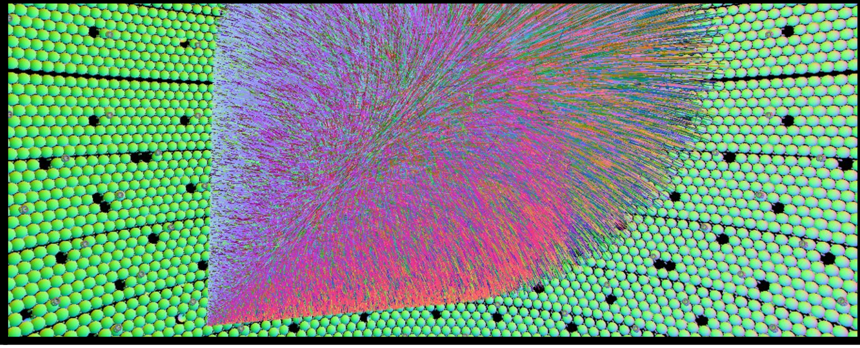
CHARGE RECONSTRUCTION ALGORITHM

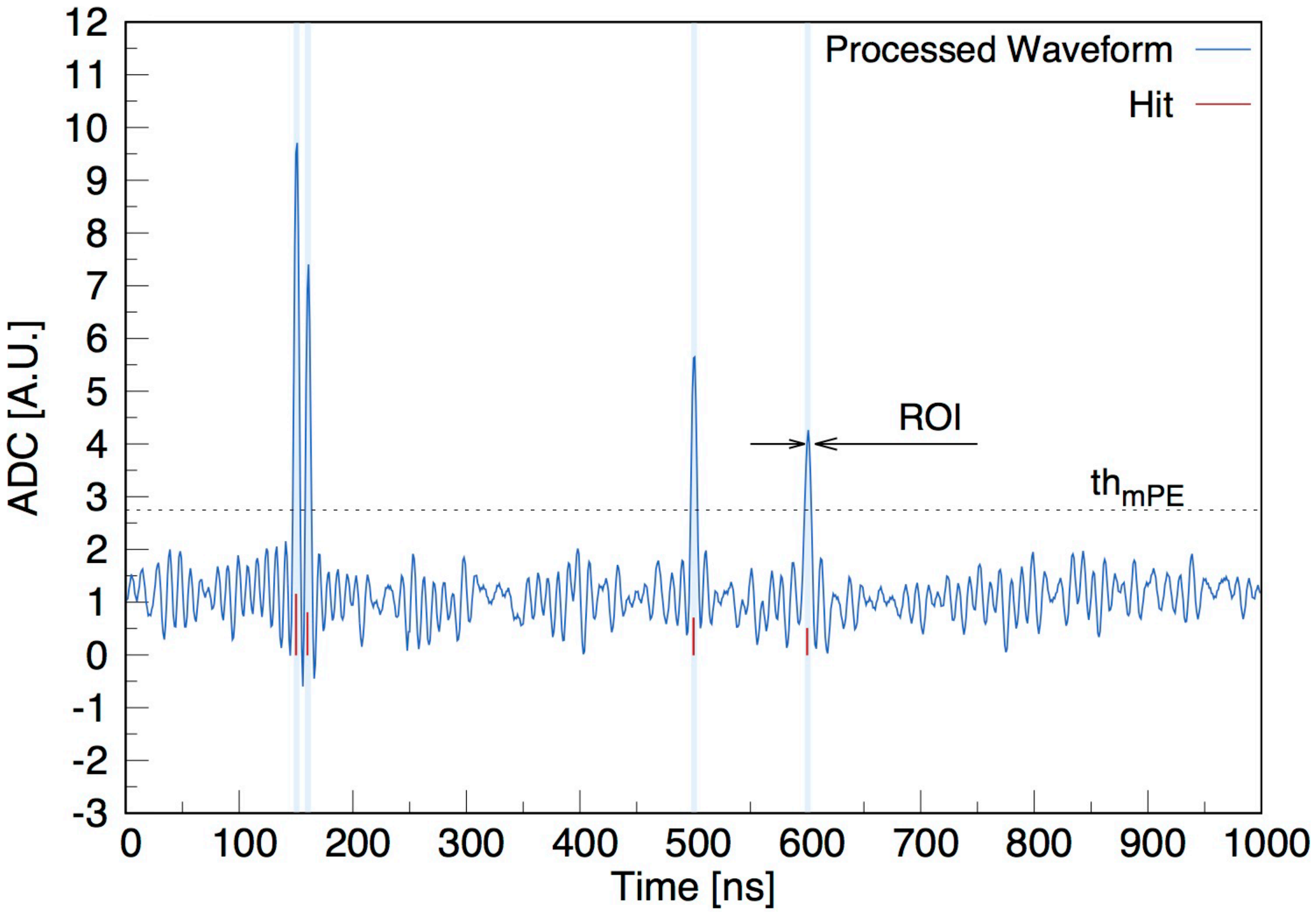




- Deconvolution Algorithm: Application of the Wiener Filter and the Deconvolution
- Integration Algorithm: Detection of the Range of Integration and Charge Reconstruction

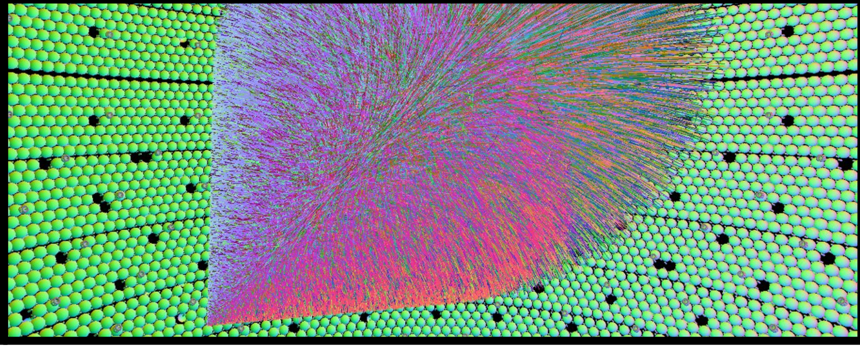
Processed Waveform

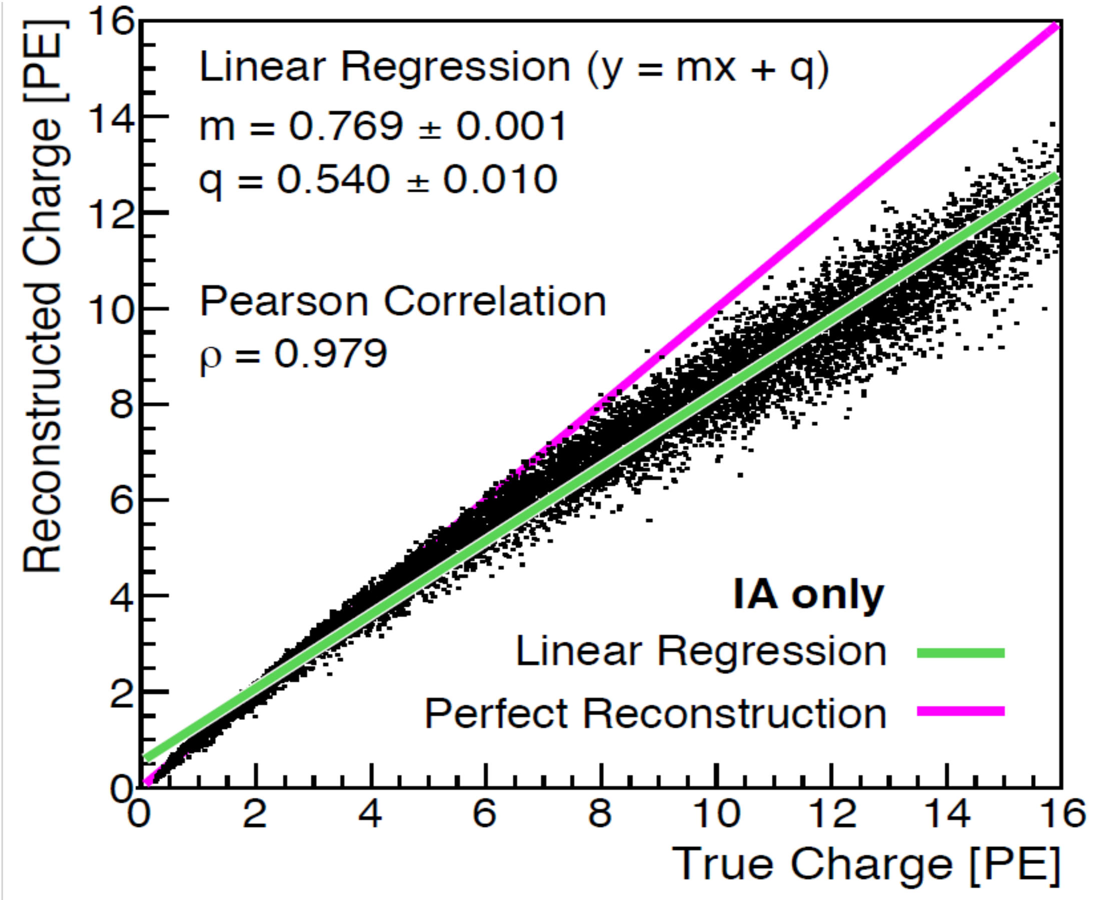


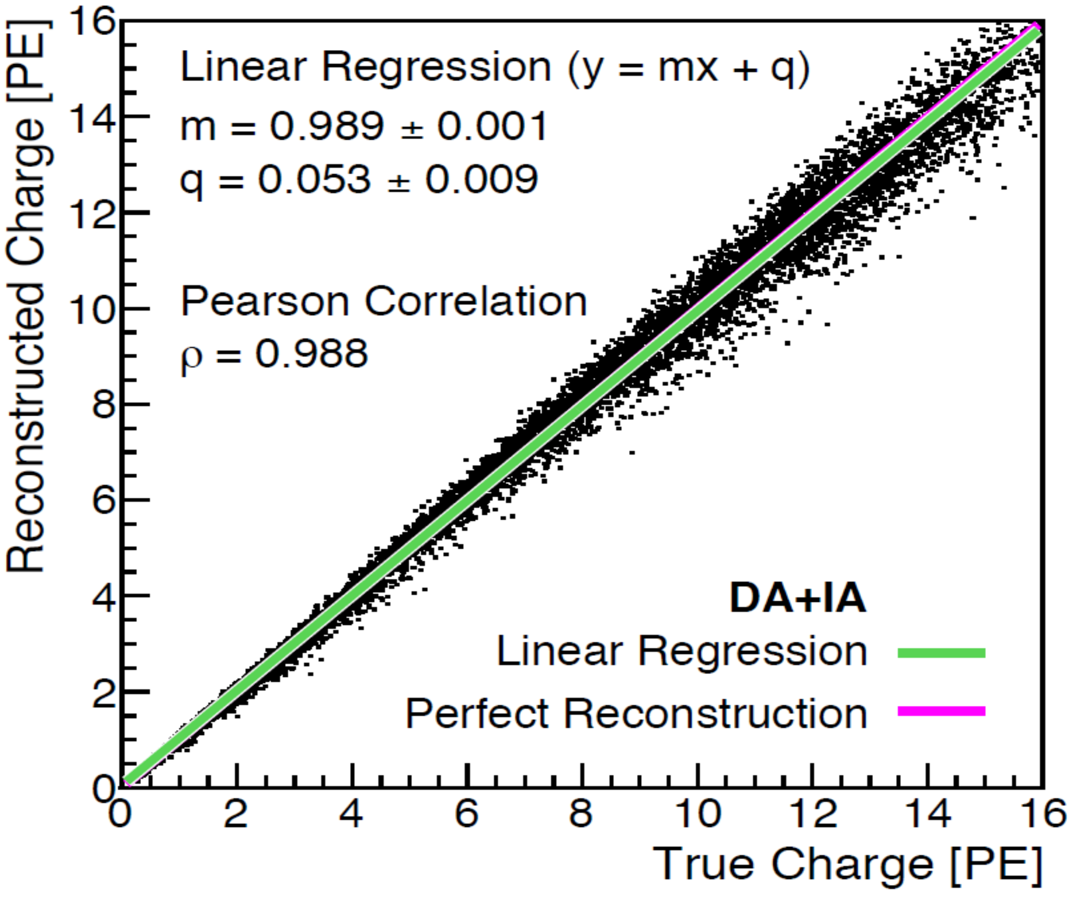


- Strong reduction of the overshoot
- Performance strongly depends on the Template and on the noise
- Better Peak Resolution, but it is still very hard to recognize every single peak if they are very closed in time
- Calculation of th_{mPE} scaling th_{SPE} with the ratio of the not filtered SPE reconstructed charge over the filtered and deconvolved SPE reconstructed charge
- Identification of the ROI (Region of Integration)

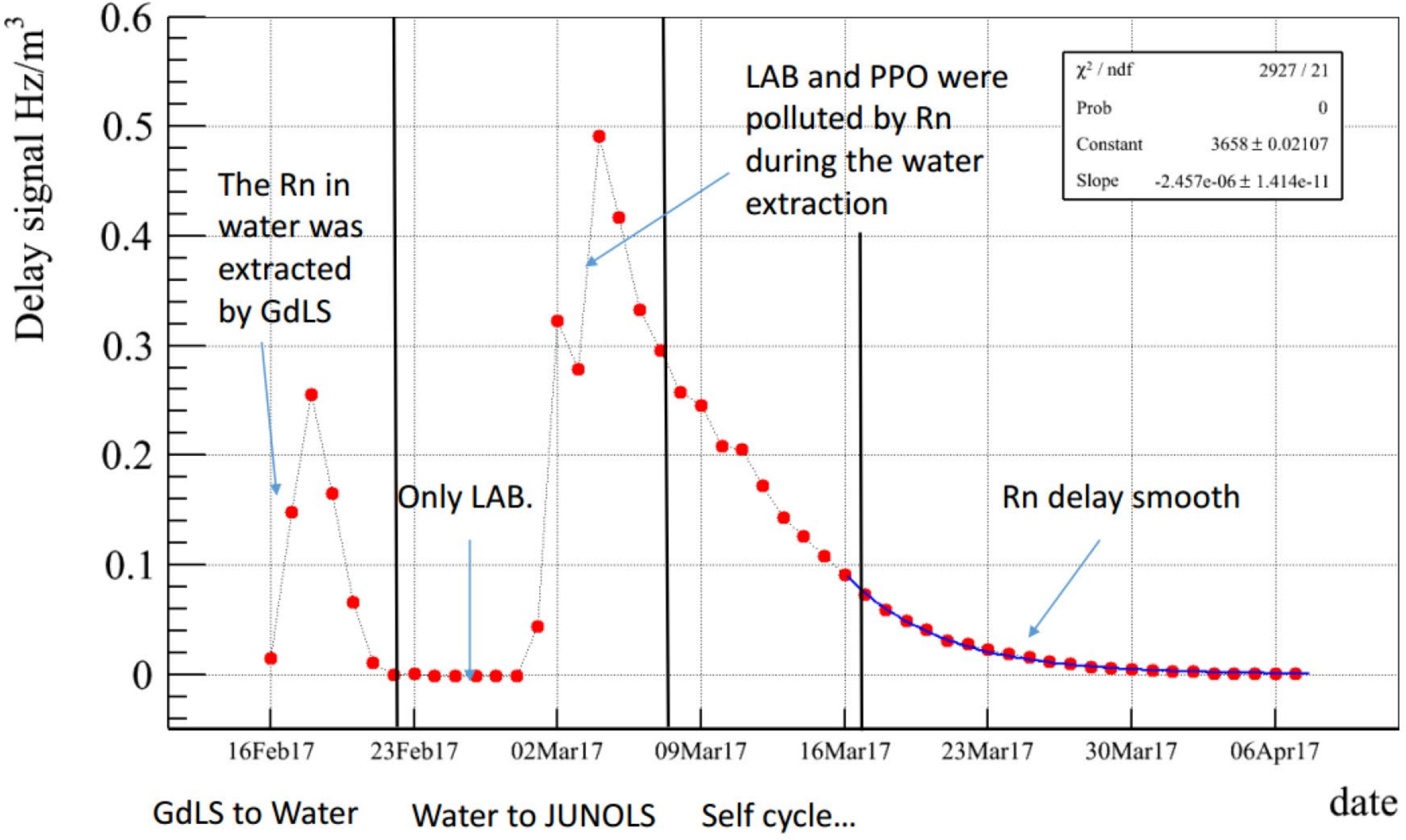
Energy and Vertex reconstruction







Why we waited for two months: ^{222}Rn



- The ^{222}Rn is a daughter of ^{238}U, and their measurement methods are the same
- Huge ^{222}Rn pollution from the water.
- $1*10^{-15}$ g/g ^{238}U: $1*10^{-5}$ Bq/m^3
- ^{222}Rn's pollution was almost 5 orders high than ^{238}U requirement
- So, wait……😭

Rn Reduction