INSTITUTE OF PLASMA PHYSICS
OF THE CZECH ACADEMY OF SCIENCES

HV PS for ECRH system for COMPASS-U

MINISTRY OF EDUCATION,
YOUTH AND SPORTS

IPP COMPASS INSTITUTE OF PLASMA PHYSICS ASCR

Log of revisions

Revision	Date	Description	Responsible
1	30.7.2024	Initial release of presentation for PMC	Bogar, Zak

Institute of Plasma Physics

IPP

- Founded in 1959 (64 years ago)
- IPP has 6 departments and >300 employees

TOKAMAK department

- Created in 1977 (46 years ago)
- Has ~100 employees
- Devices:
  - CASTOR (GOLEM) 1977-2006
  - COMPASS 2006-2021
  - COMPASS Upgrade 2026 on

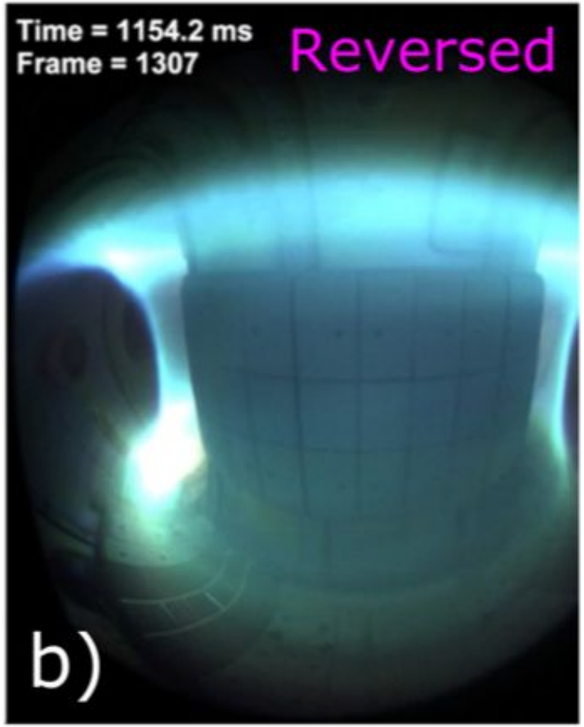
COMPASS

COMPASS was operated in the IPP CAS since 2009 and it was shut down in August 2021. COMPASS was one of few devices with an **ITER-like plasma shape**. Its **flexibility**, extensive set of **diagnostics** and **NBI** contributed in closing the gaps of key issues in fusion research in support of **ITER** and **DEMO**, such as

- edge and SOL physics
- L–H transition
- runaway electrons
- disruption studies
- plasma-wall interaction

COMPASS was very effective for testing new ideas and concepts in the area of **plasma control** and **diagnostics development**, which were implemented on larger devices.

"Overview of the COMPASS results," M. Hron, Nucl. Fusion 62 042021 (2022)



COMPASS-U

Main parameters

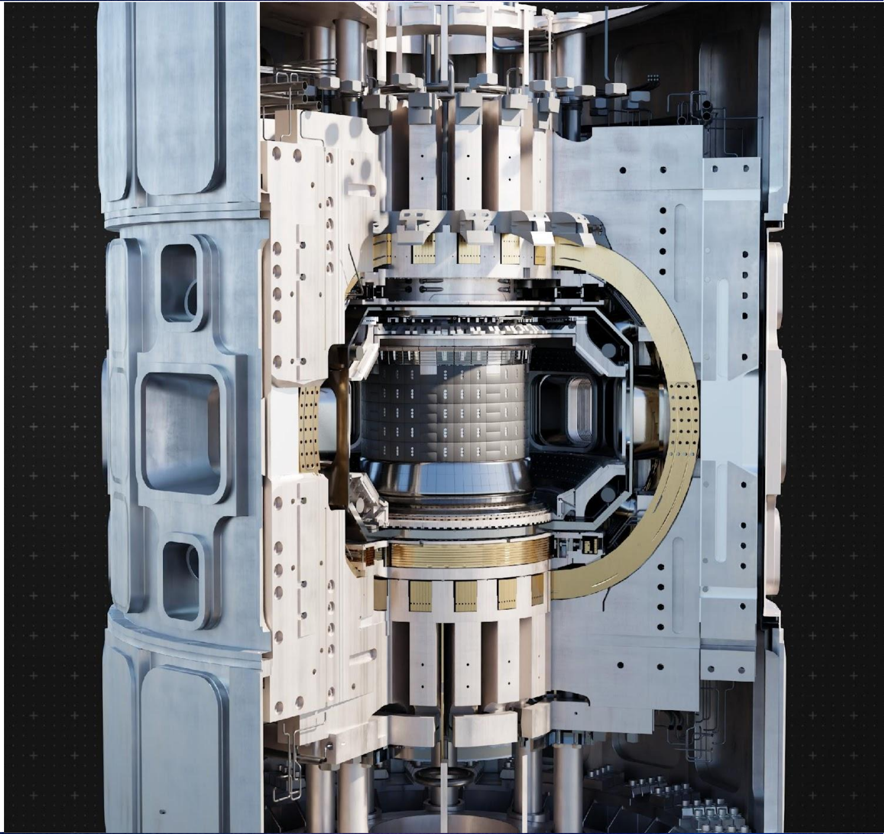
- Toroidal magnetic field $B_t = 5$ T
- Plasma current $I_p = 2$ MA
- Major radius $R_g = 0.894$ m
- Minor radius $a = 0.27$ m
- Aspect ratio $A = 3.3$
- Triangularity $\delta = 0.3\text{-}0.6$
- Elongation $\kappa = 1.8$
- Enough space for different divertors
- Metallic first wall
- Vacuum vessel operation temperature up to 300°C (goal 500°C)

Plasma shapes

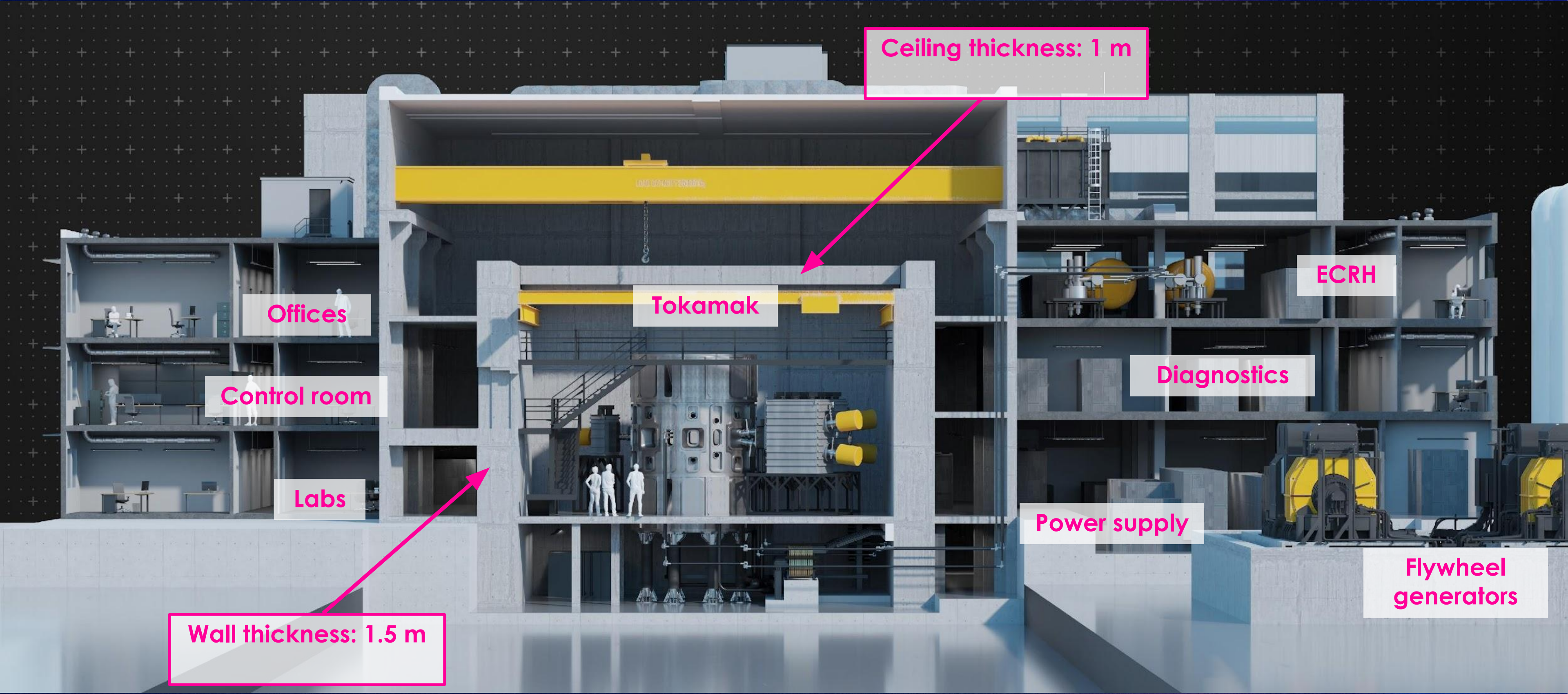
- single lower null, neg. triangularity with limited parameters (Phase 1-2)
- double null (Phase 2-3)
- snowflake, negative triangularity (Phase 3-4)

Plasma heating power

- Phase 1 P_{NBI} >= 3 MW, P_{ECRH} = 1 MW (P*B/R ~ 25)
- Phase 2 up to P_{NBI} = 8 MW, P_{ECRH} = 10 MW (P*B/R ~ 100)



Infrastructure



Extent of delivery

HV PS for triode type gyrotron (ITER like tube)

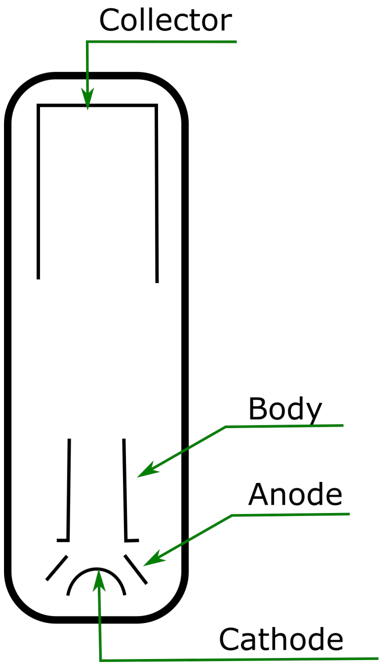
MHVPS (2 x 55 A)
APS, BPS, Anode switch (if required), Dummy load for testing and commissioning (if required)
Cables from PS to the gyrotron
Control system and interface with tokamak control system

Time schedule

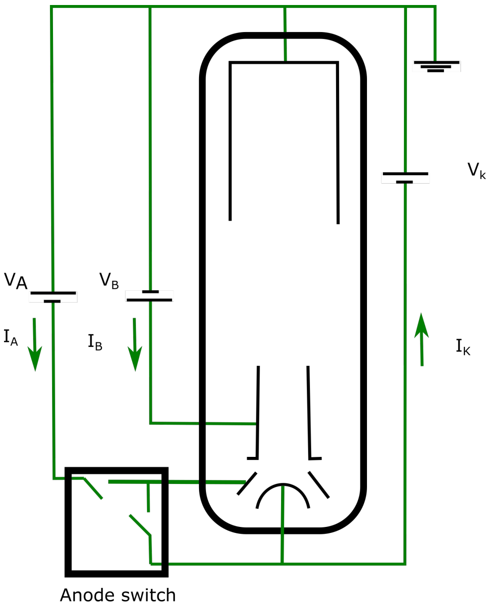
- Open public tender ~ 10/2024 (30 day for preparing the proposal)
- Delivery (assembly and SAT to the dummy load) ~ 11/2026
- Integral commissioning together with gyrotron and EC control system during 2027

Gyrotron feeding scheme

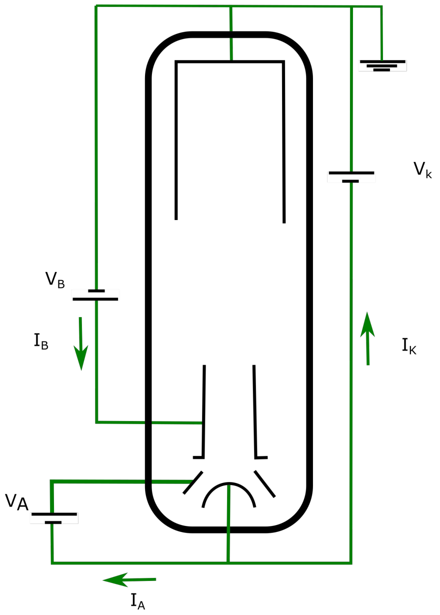
Collector	V_C	Grounded	Grounded electrode
Cathode	V_K	Negative	Supplied by the MHVPS, connected between cathode and collector
Anode	V_A	Positive to Cathode	APS provides a gate to the cathode current. $V_A = V_K$ ==> the beam current is blocked and causes zero RF output
Body	V_B	Positive	Supplied by the BPS, connected between body and collector



Nominal voltage values of HV PS given in the following tables are references to the ground.



Anode switch



“Advanced” APS

Modulation of RF power from gyrotron: 0 - 1 kHz

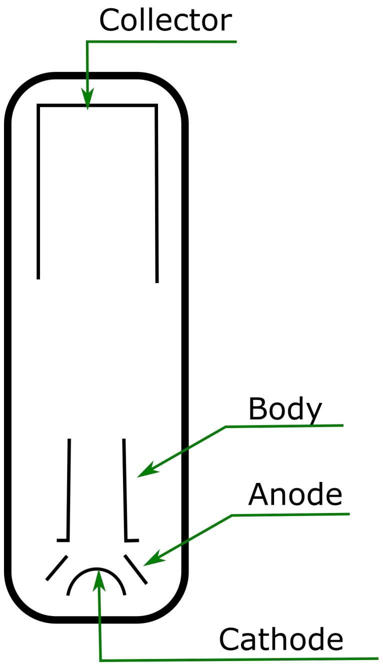
Inputs from the manufacturer are required to make the final decision

Questions to manufacturer:

- **What is the difference in the space required for PS**
- **What is the difference in price**
- **Which configuration requires a longer design phase?**
- **Which configuration is better for our layout and distances.**

Gyrotron load parameters*

Body to Collector, Cbc	< 1500 pF
Cathode to Body, Ckb	< 750 pF
Anode to Collector, Cac	< 750 pF
Anode to Body, Cab	< 500 pF
Cathode to Collector, Ckc	< 1300 pF
Anode to Cathode, Cak	< 550 pF



All values are without connection cables.

* Exact values will be provided only after the selection of the gyrotron supplier in the open call for tenders

Set point resolution: Value of the smallest step in output voltage Intervales to set voltage

Accuracy: Range of achieved voltages relative to the target voltage.

Reproducibility: Range of variation in output voltage from shot to shot for the same setting. Repeatability measures the system's ability to position to the same target value sequentially. Systematic errors can be considered and compensated, but repeatability is the ultimate limit that is reached after all compensation.

Ramp-up/down time: Time at which the voltage and current should return to <10% of nominal value after an arc event.

Duty cycle: The operating cycle for the tokamak is 1.25% assuming 20 min between plasma experiment. 10 to 25% is suggested for faster commissioning of the gyrotron.

Coarse/fine range: In fine range the requirements for set point resolution, accuracy and reproducibility must be fulfilled. Requirements can be relaxed at lower voltages in coars range.

MHVPS (1)

Vk nominal	**-60 kV**
Ik nominal	**>110 A**
PS : Gyrotron ratio	**1:2**
Vk coarse range	0 to -30 kV
Vk fine range	-30 to -60 kV
Ramp-up/down time	<10 ms
Settling time	50 us (TBD)
Ramp speed	dV/dt > 1kV / ms

MHVPS (2)

Max overshoot/undershoot (at nominal voltage and current)	≤ ±1 % (600 V)
Vk accuracy	≤ ±0.6 % (360 V)
Vk reproducibility	≤ ±0.4 % (240 V)
Vk set point resolution	≤ 0.4 % (240 V)
Vk ripple	≤ 0.4 % (240 V)

APS (1)

Va nominal	**35 kV for Anode switch configuration (Vk nominal: -60 kV in “advanced APS”)**
Ia nominal	**80 mA**
Ia maximum	200 mA
Va fine range	0 to Va nominal
Ramp-up/down time	< 0.3 ms (If fast modulation is done by anode switch. Otherwise ~ 0.1 ms for 1 kHz modulation)
Settling time	50 us (TBD) have to be compatible with 1 kHz modulation

APS (2)

Max overshoot/undershoot (at nominal voltage and current)	≤ ±0.5 % (175 V)
Va accuracy	≤ ±0.3 % (105 V)
Va reproducibility	≤ ±0.3 % (105 V)
Va set point resolution	≤ 0.3 % (105 V)
Va ripple	≤ 0.3 % (105 V)

BPS (1)

Vb nominal	**40 kV**
Ib nominal	**100 mA**
Ib maximum	200 mA
Vb fine range	0 to 40 kV
Ramp-up/down time	<10 ms
Settling time	50 us (TBD)
Ramp speed	dV/dt > 1kV / ms

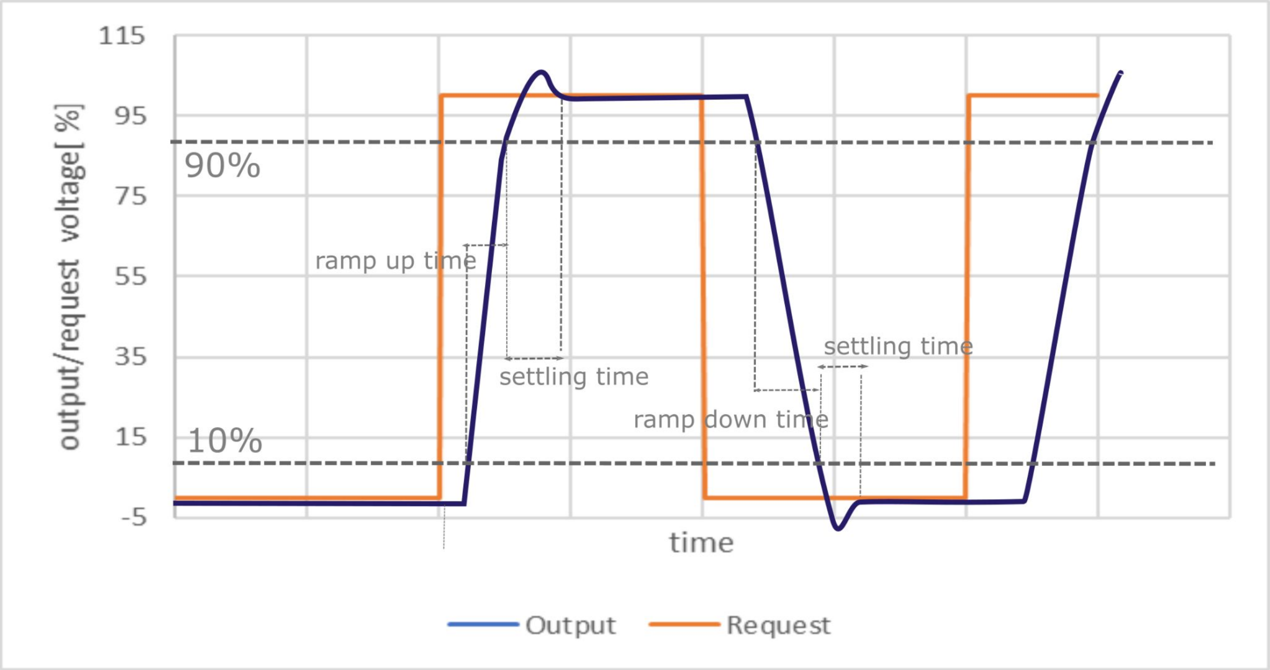
BPS (2)

Max overshoot/undershoot (at nominal voltage and current)	≤ ±0.5 % (200 V)
Vb accuracy	≤ ±0.3 % (120 V)
Vb reproducibility	≤ ±0.3 % (120 V)
Vb set point resolution	≤ 0.3 % (120 V)
Vb ripple	≤ 0.3 % (120 V)

All PS

Pulse Length	15 sec
Duty Cycle	10-25 %
Energy in an Arc event	<10 J
Fast Shutdown time	<10 us (from trigger to 10% of nominal voltage)
Voltage / current measurement resolution	0.05 % / 0.2 % (TBD)
Measurement bandwidth	100 kHz to monitor modulation, 2 MHz to monitor arc event
Voltage stability	<5 % overshoot in transition load to no-load event

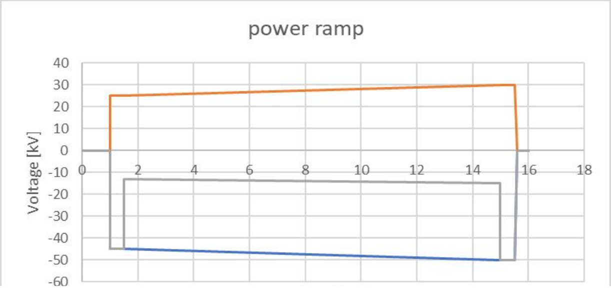
Ramping time and settling time visual representation

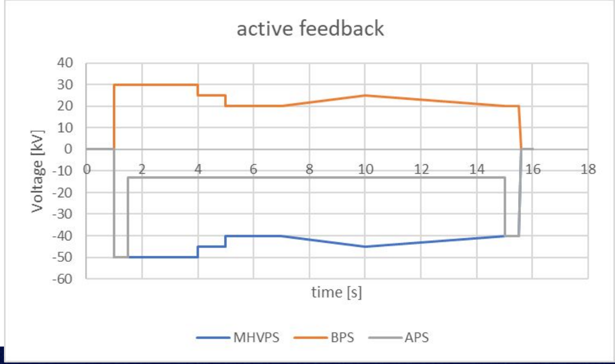


Variation of RF power by the APS

Power ramps and feedback

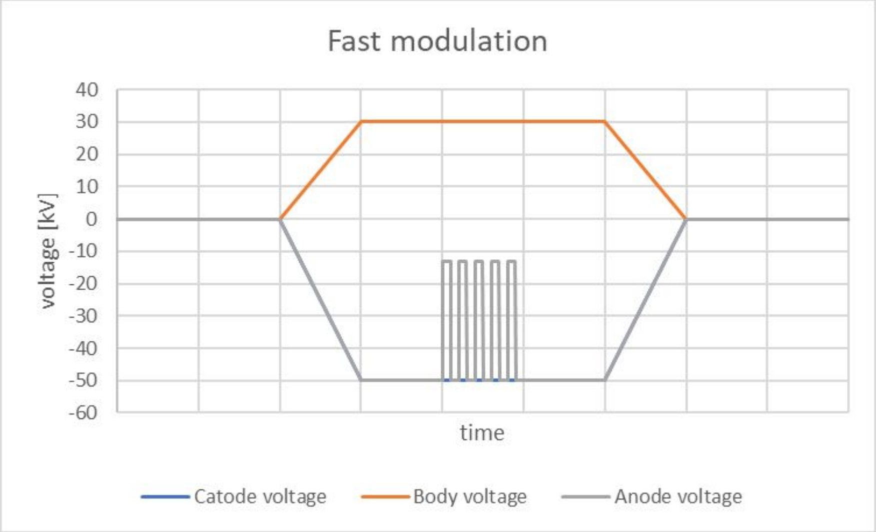
Control of V_K, V_B and V_A in the range of fine tuning
dV/dt > 1kV / ms



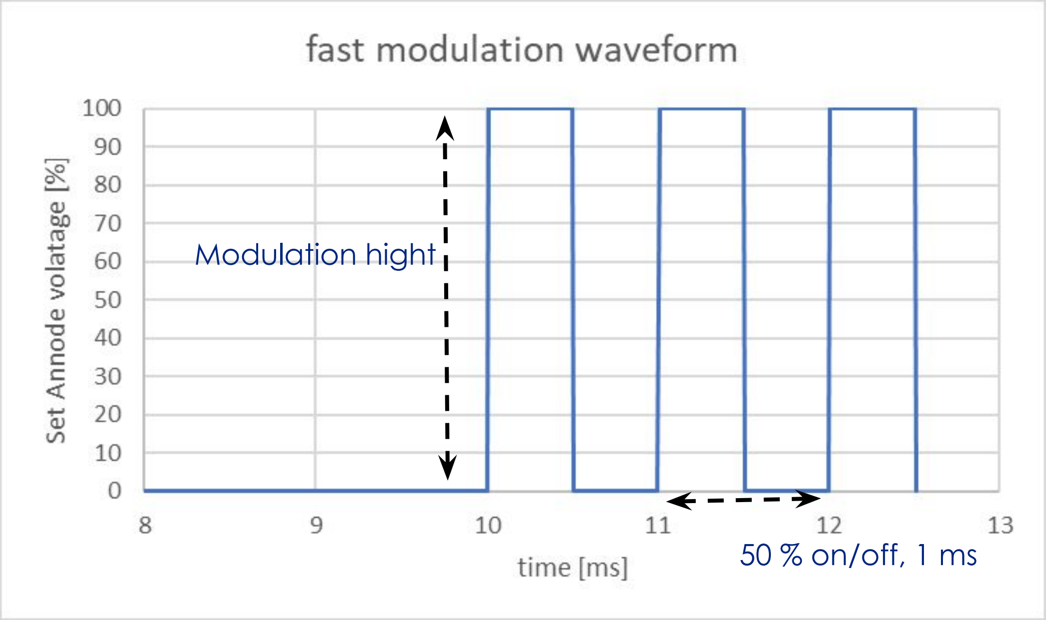


Fast modulation up to 1 kHz

Control of V_A to modulate of output power of gyrotron, Amplitude determined by Vk, Va and Vb and can vary in amplitude in steps or ramp. Both power ramp and fast modulation can be used within one 15s pulse.



Fast modulation waveform



- Fast ON/OFF modulation is realized by the voltage on the anode.
- OFF state (0 % on the plot) happened when Anode and Cathode are on the same potential.
- ON state(100 % on the plot) is the set APS voltage
- 1 kHz modulation means 0.5 ms ON and 0.5 ms OFF state.
- Fast modulation can be realized directly by APS or by Anode Switch connected between APS and gyrotron.

HVPS input parameters

MHVPS must be fed from **HV grid supplied by flywheel generators**, feeding MHVPS from public 400 V grid is not possible.
APS & BPS can be supplied from public **400 V grid.**
For short pulse commissioning the MHVPS should be fed from capacitor bank / battery bank (TBD).

FEEDING HV GRID OUTPUT PARAMETERS

Nominal voltage range: **10 400 – 9250 V** (AC RMS)

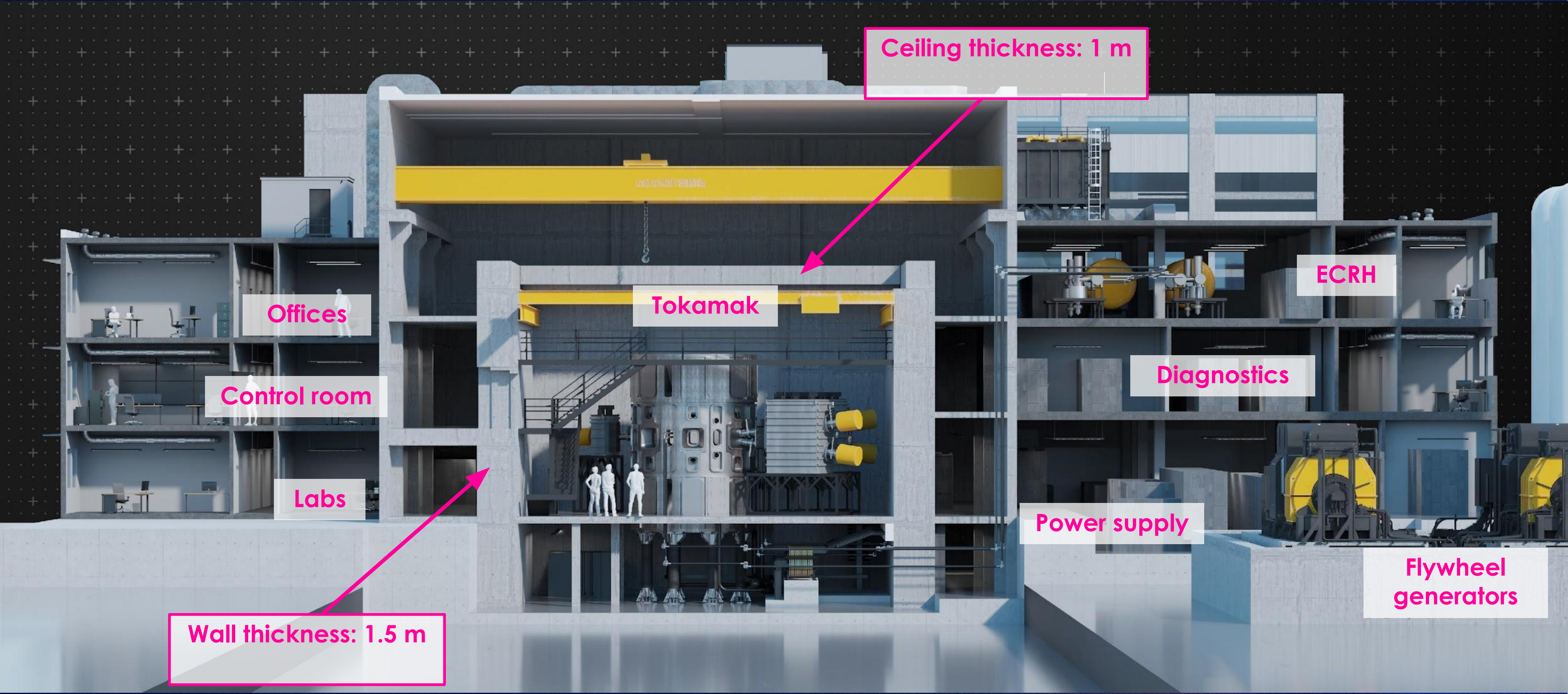
- Output voltage can drop up to 11% from its nominal value during the pulse, therefore the MHVPS should be able to operate within this voltage range.

Nominal frequency range: **85 – 60 Hz**

- Output frequency changes (drops) during the pulse, this is the maximum range of frequencies that can occur in the grid, given by maximum operating RPM range of the flywheel generators.

Duty cycle: **10 sec pulse / 25 min pause**

- After the pulse (~ 10 seconds) the PSS system works with 25 minute pause before the next shot.


Ceiling thickness: 1 m
Tokamak
Offices
Control room
Labs
Wall thickness: 1.5 m
ECRH
Diagnostics
Power supply
Flywheel generators

Distance from HVPS to gyrotron

Future status of fully equipped ECRH system

- **6 gyrotrons, each with output power >1 MW**
  gyrotrons will be in the clusters (2 gyrotron for 1 MHVPS)
- **3 x transformer on the 1st floor (only this floor can handle the weight of transformer)**
- **3 x MHVPS**
- **6 x APS, BPS**
- **2 x dummy load**

The IPP will be happy for consultations on how to distribute the individual components in the allocated space so that it is possible to expand the ECRH system in future years.
We assume that the development of gyrotrons will continue towards higher outputs power (to 1,5-2 MW) and higher electrical efficiency (>50%).

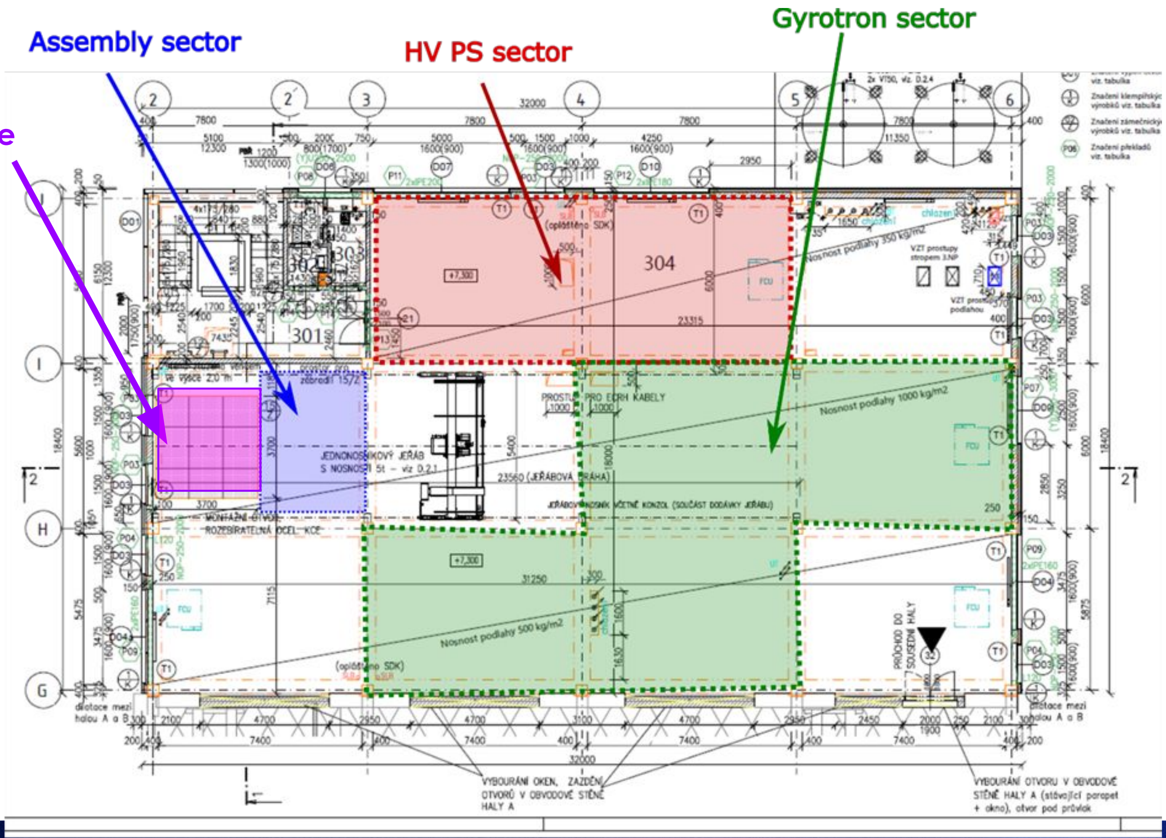
Allocated space (1/6)

3rd floor of hall B

Whole reserved for ECRH equipment.

Area reserved for HV PS sector:

- HV PS area **15.6 m x 6 m**
- Maximum height of cubicles for transport from assembly sector to HV PS sector is **3.9 m**
- Maximum height of the HV PS cubicles together with cables, cooling pipe , …, is **4.1m**



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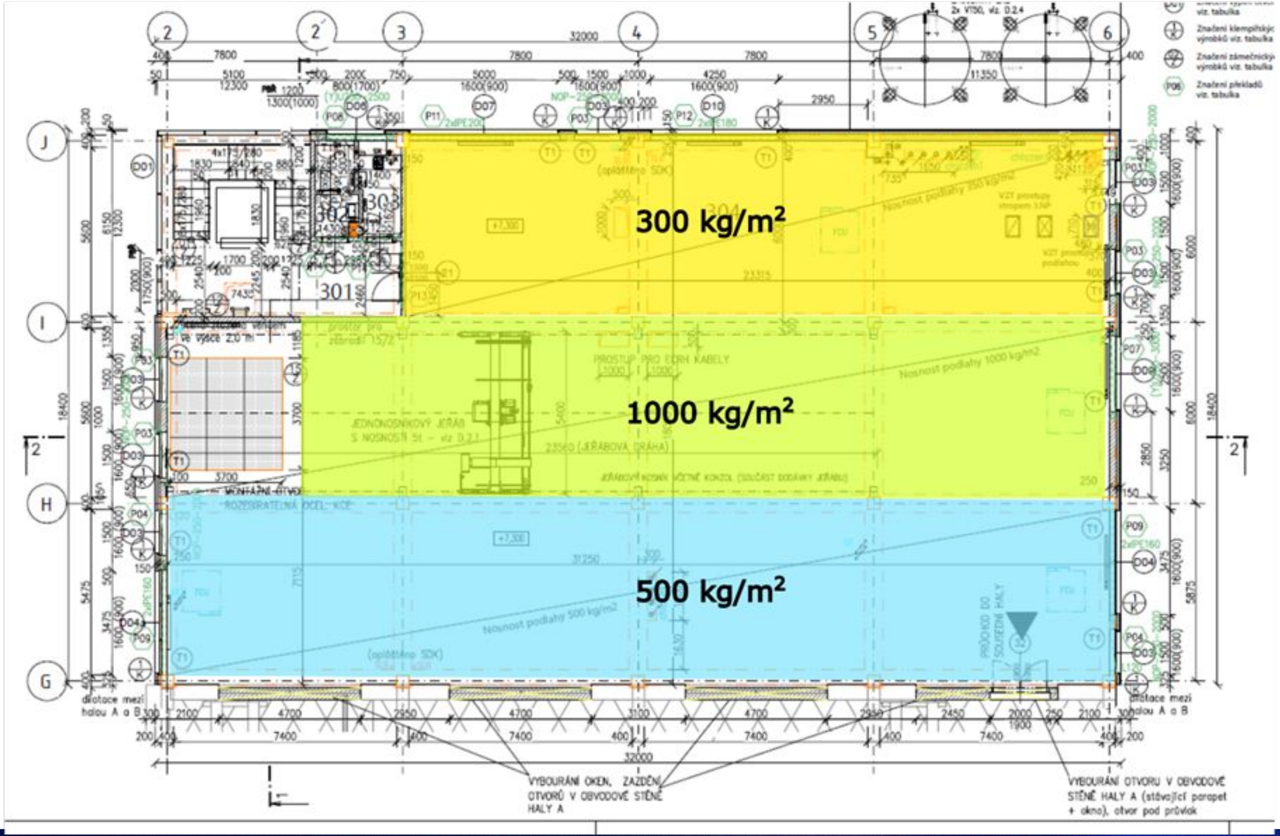
Allocated space (2/6)

3rd floor of hall B

Whole reserved for ECRH equipment.

HV PS sector: 300 kg/m^2



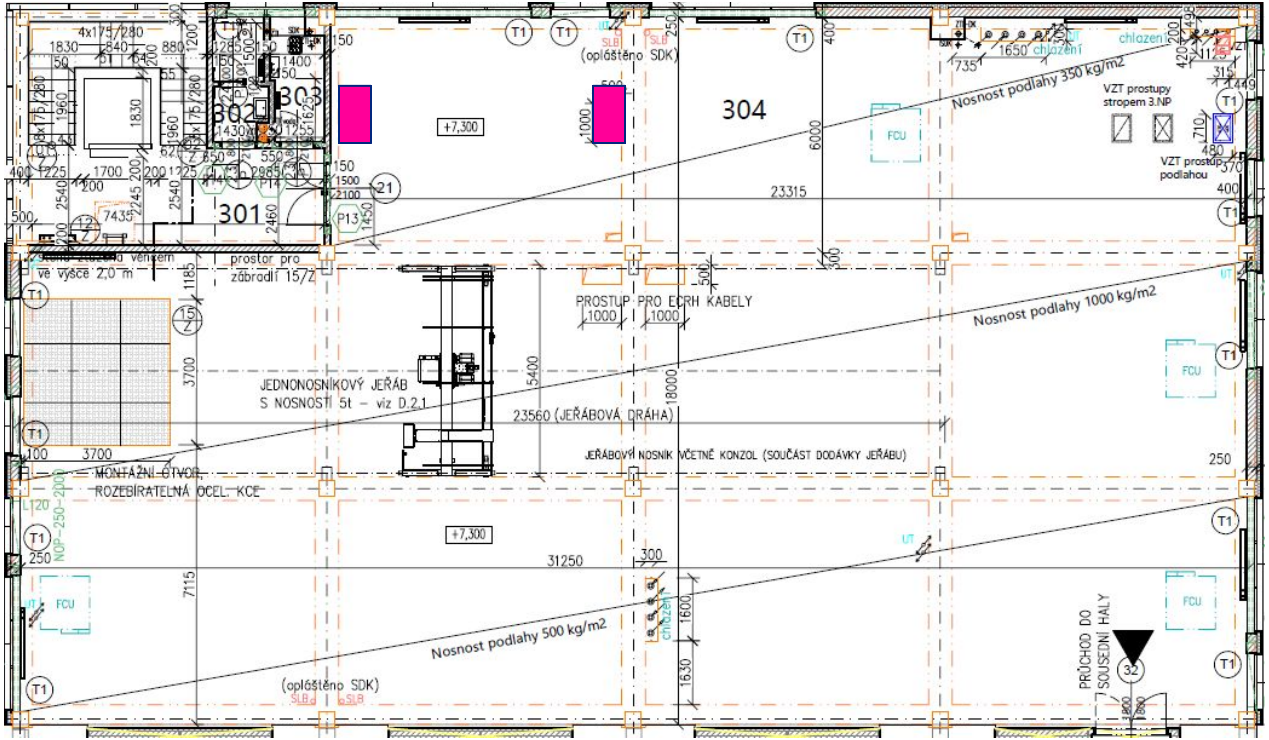
3rd floor of hall B

Whole reserved for ECRH equipment.

- Whole area is protected with restricted personal access

Ducts for cables - 2 pink rectangles:

- 1500 mm x 500 mm



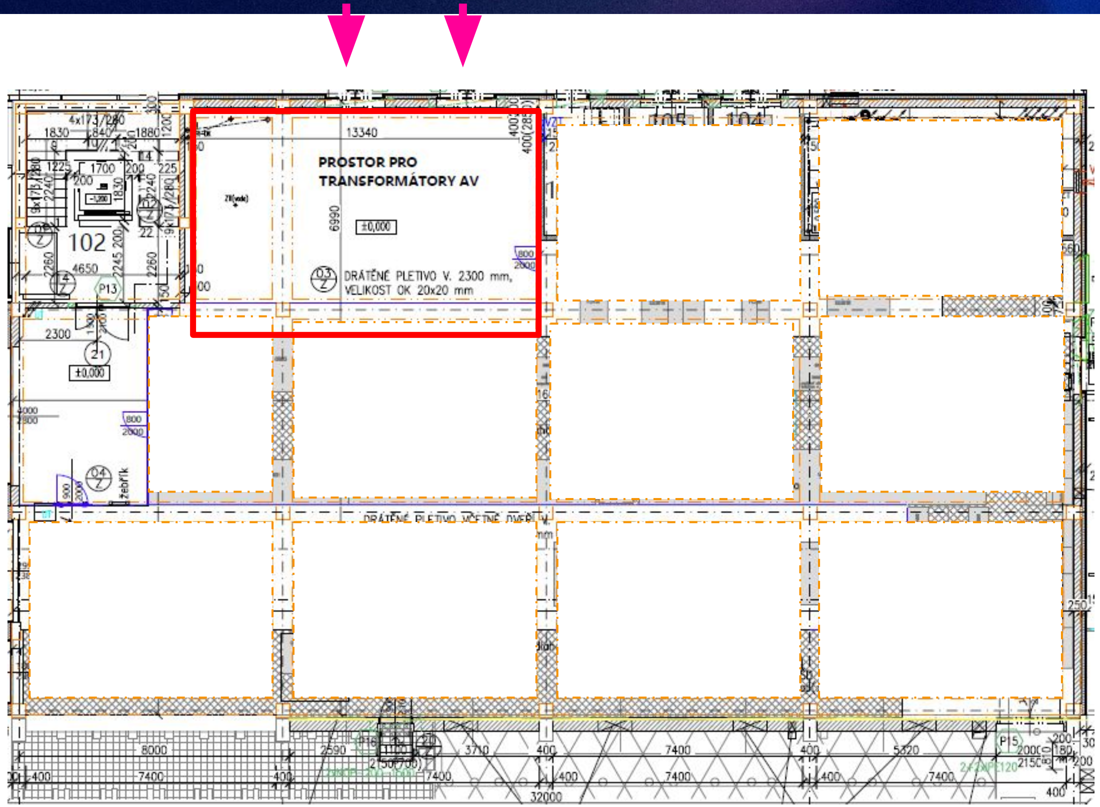
Allocated space (3/6)

1st floor of hall B

Used mainly for Power Supply System.

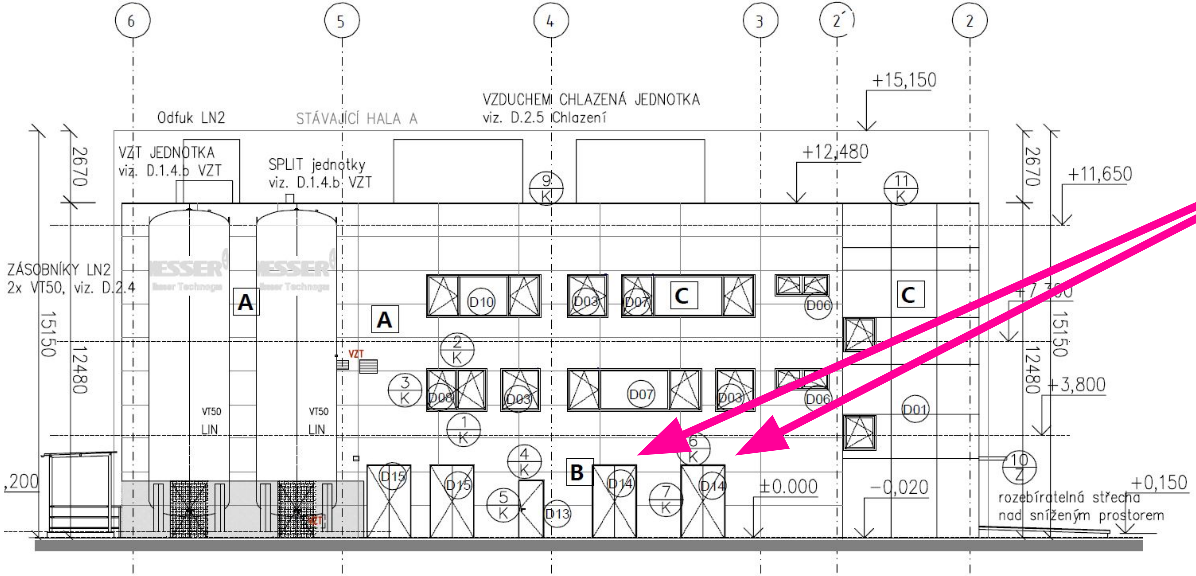
Area reserved for ECRH equipment:

- MHVPS or at least it's transformers
- dimensions **cca 9.9 m x 6.9 m**
- Maximum height is **3.5 m**
- Whole area is protected with restricted personal access

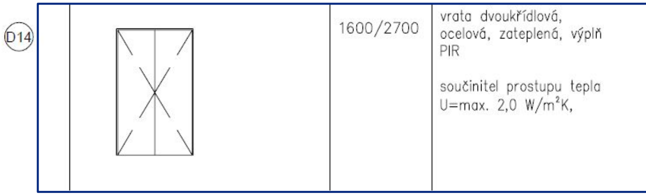


Allocated space (4/6)

side view of hall B and entrances to MHVPS area at 1st floor



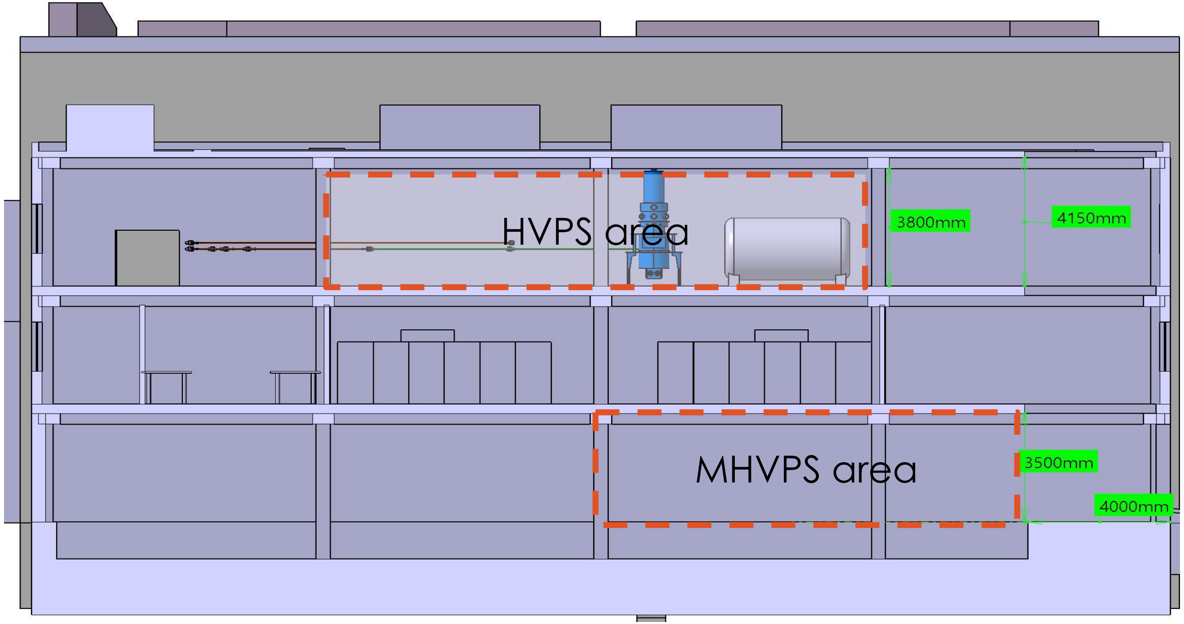
POHLED SEVERNÍ



2 entrances to MHVPS area
1600 mm x 2700 mm

Allocated space (6/6)

Hall B - side view



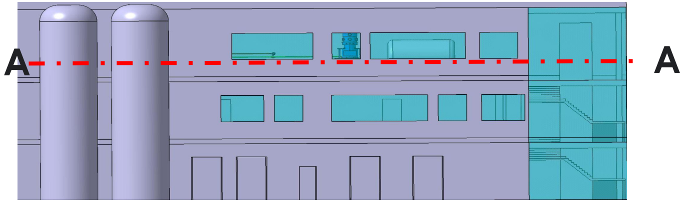
Crane in EC building (1/2)

Components of the HV PS can be lifted up via the crane through a lifting hole in the floor which reaches down to the first (external ground level) floor. Components that this crane can not lift up, can be placed in the assembly area through a hole (2500 mm x 2500 mm inner dimensions) in the ceiling about this area and using an external crane.

Rated lifting capacity	5000 kg
Lifting height (from 3rd floor to hook)	~2700 mm
Maximum Lifting height (from 1st floor to hook)	~11000 mm
Minimum lifting height (from 1st floor to hook)	~1000 mm

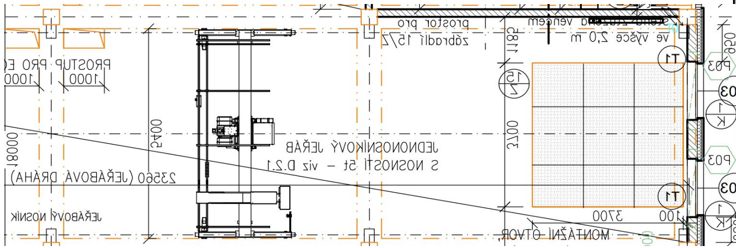
Crane in EC building (2/2)

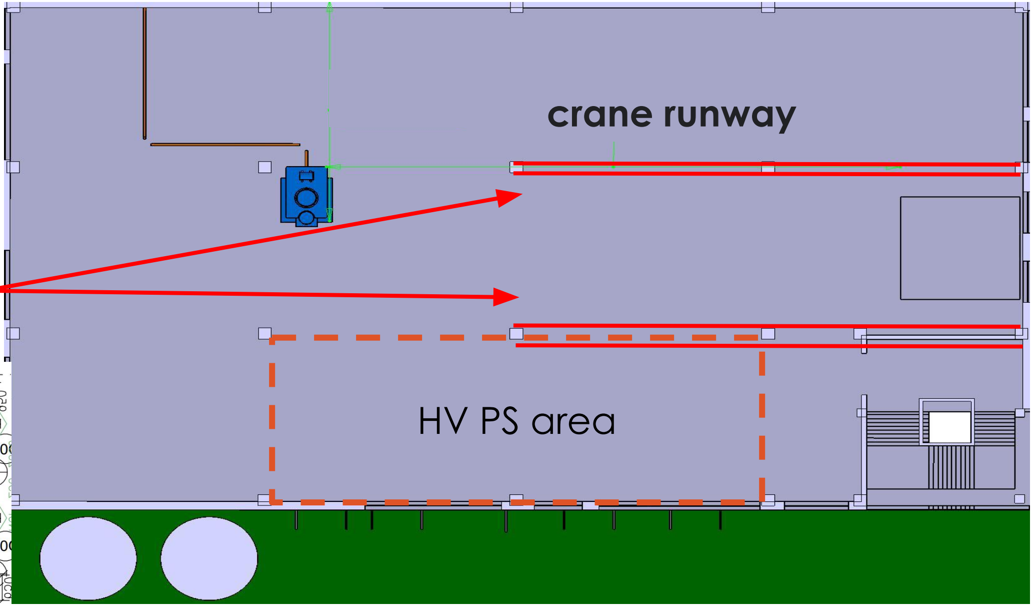
Hall B - front view



A-A

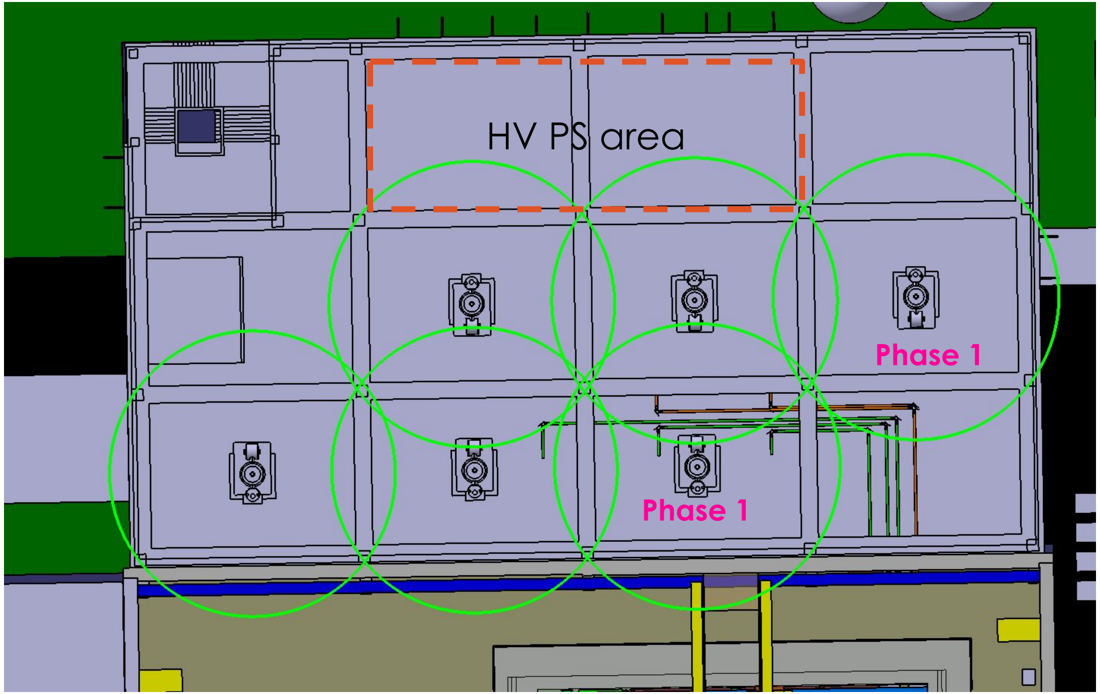
crane runway





Layout of the gyrotron and HV PS on 3nd floor

- Once the ECRH system will be fully equipped with 6 gyrotrons the HV PS will be in the vicinity of the gyrotron.
- Green circle indicates the 5 m radius from gyrotron axis
- The HV PS discussed on ongoing consultation will be used for feeding of one of the gyrotrons planned for Phase 1.



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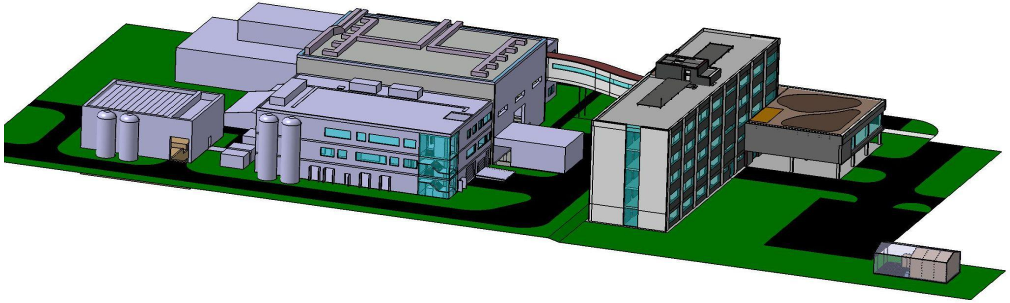
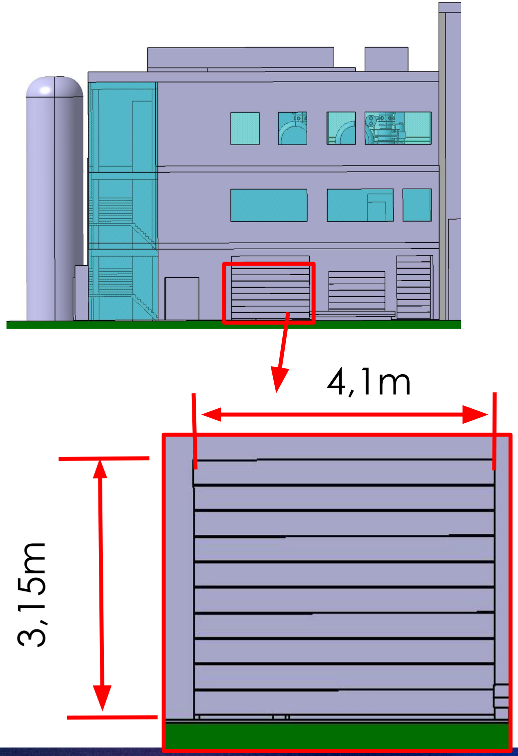
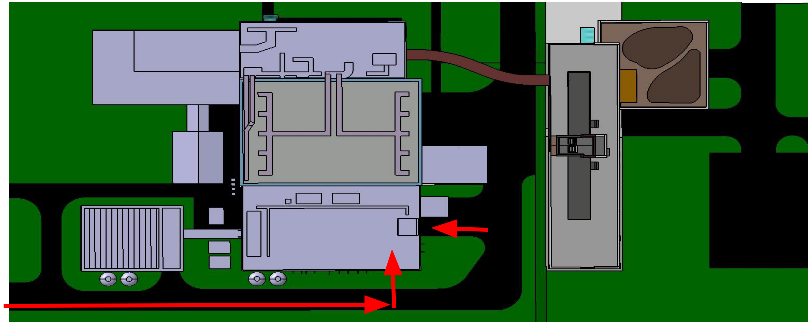
Hall B - situation view



Hall B - gate to lifting hole area



Hall B - top views - driveways



Distance from HVPS to gyrotron

Length of the cables

MHVPS ===> APS, BPS : ~ 10 m => from 1st floor to 3rd floor
APS, BPS ===> GYROTRON : ~ 15-20 m => on 3rd floor to the individual gyrotron (under the ceiling or in the fake floor)

What arrangement of the following components (transformer, MHVPS, APS, BPS, Anode Switch, dummy load, control system) is preferred for you? How flexible is your design to different layouts?

CURRENT STATUS OF EARTHING SYSTEM

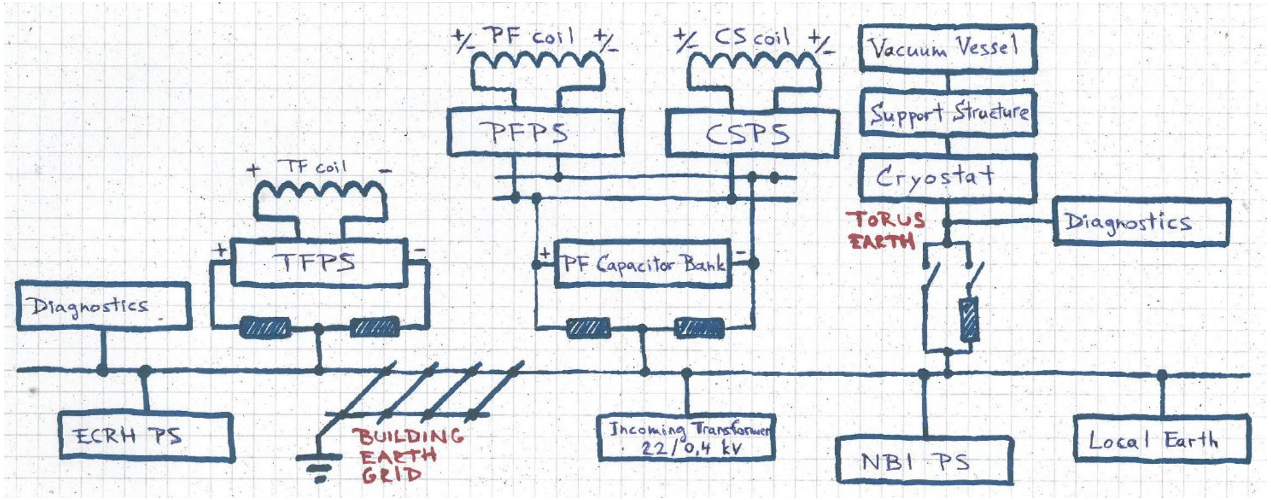
Vessel and systems inside experimental chamber are using separate Torus Earth.

- Connection of the Torus Earth to the Building Earth Grid can vary.

ECRH will be connected directly to Building Earth Grid.

What should we take care of?

We can adjust the Earting system.



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Questions:

- Which HV PS configuration do you recommended for COMPASS Upgrade.
- What is the difference in the recommended configuration of the sources according to the change of modulation frequency from 1 kHz to 5 kHz. Which components are affected by this?
- If the delivery time of the resources? Which part of the specification increases the risk of late delivery?
- How would you handle a request for deposited power in arc <10 J?
- What is the maximum cable length for your proposed solution?
- Can you send us the dimensions and weights of the transformer and individual cubicles?
- What is the standard accuracy and bandwidth of the voltage and current measurement supplied by you?
- What is the control system communication speed and latency.
- Can you send us a price estimate for the proposed solution or a price offer for different variants?
- What documents would you still need from us to answer the above questions?
- What the HV PS design phase, design review and delivery timeline would look like?