Arkwright Society

HYDROPOWER AT CROMFORD MILL (Second Mill Wheelpit)

PRE-FEASIBILITY STUDY

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1. SCHEME SUMMARY

				OPTION A	OPTION B	
Watercourse	Bonsall Brook		Turbine type	Semi-Kaplan	Overshot waterwheel	
Location	Cromford Mill		Gross Head	6.4	6.4	m
Town/Village	Cromford DE4		Design Head	6.2	5.5	m
Grid Ref. Intake	SK 29840 56970		Design Flow	500	200	litres/sec
Grid Ref. Turbine	SK 29840 56970		Peak output	25	6	kW
Grid Ref. Outfall	SK 29840 56970		Annual Energy	110,000	40,000	kWh/year

2. INTRODUCTION

Derwent Hydro were asked to assess the options for generating hydro-electric power from the wheelpit of the 'Second Mill' at Cromford Mills, including consideration for reinstating a waterwheel.

When Cromford Mill had expanded to its full potential by 1775, the Second Mill contained a substantial 'double' waterwheel (over 3m wide and over 5m in diameter) which drove cotton spinning machinery in the 7-storey building above it.

This building was destroyed by fire in 1890, but the wheelpit still receives the full flow of Bonsall Brook, cascading 6.5m into the wheelpit below, before discharging back to the River Derwent via a long tunnel.

The head and flow at the wheelpit provide the raw potential for a new micro-hydro scheme to generate renewable energy for consumption within the Mill complex.

A site survey was completed by Oliver Paish of Derwent Hydro Developments on April 28th 2020. The key observations and conclusions are summarised below, with pictures at the end of the document.

As described below, two options have been considered:

- a traditional overshot waterwheel, of a size and design that would be safe to operate unattended, whilst reflecting the original technology used on the site.

- a modern Kaplan turbine that would exploit the full potential of the site with maximum efficiency.

3. SITE OVERVIEW

The location of the wheelpit is highlighted in Figure 1 and the principal routes for water to flow into and out of the site are summarised in Figure 2.

The proposed scheme layouts for the 2 options are illustrated in the scaled schematic drawings of Annex B.

Figure 1 : Site Layout

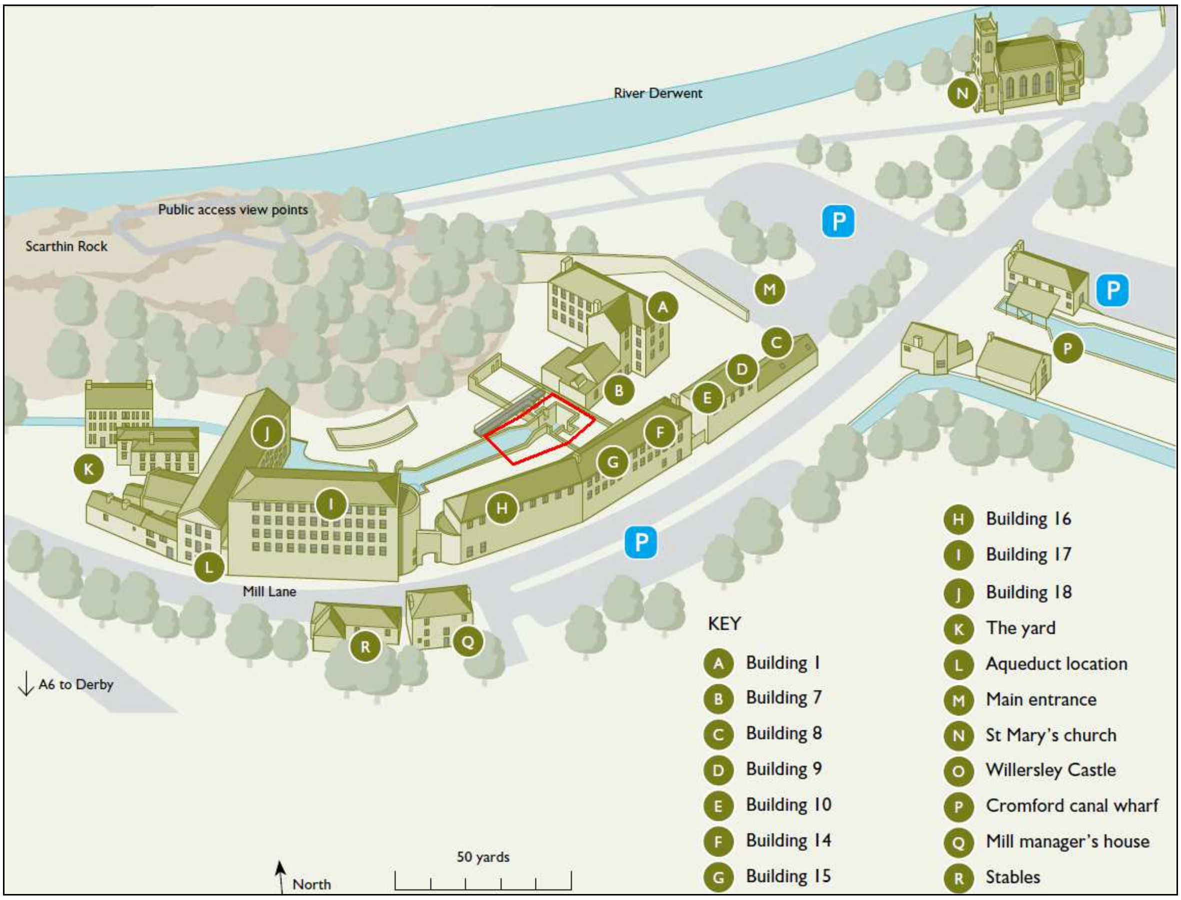
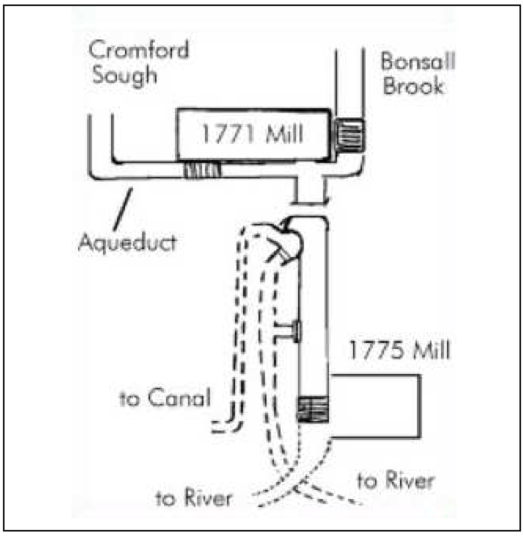


Figure 2 : Watercourses and culverts



3.1 Existing Infrastructure

The wheelpit of the Second Mill is 5m wide and 6m long and drops over 5m below ground level. This takes it below the level of the adjacent River Derwent so a long tunnel is required to discharge back to the Derwent half a mile downstream.

Flow into the wheelpit initially drops 1.4m onto a stone platform, 3.2m wide, before cascading 5m down into the wider wheelpit below.

There are rectangular bearing enclosures on each side of the wheelpit, sunk 1.9m below the side walls.

3.2 Land Ownership and Right of Access

The site is in the heart of Cromford Mills, owned by the Arkwright Society.

3.3 Flood Levels

The site does not experience extreme flood levels due to the nature of the flow regime in Bonsall Brook.

There is a crescent-shaped overspill in the headrace upstream of the wheelpit which can divert excess flows back to the Derwent (also keeping Cromford Canal topped up) and additional flow can be discharged into the wheelpit by raising the stop-log which sits above the overspill (under the control of the EA).

3.4 Grid connection

3-phase power is available on site. The capacity is unknown, but it is expected to be substantial relative to the generation outputs predicted below.

3.5 Environmental Designations

The site itself has no environmental designations, but it lies just upstream of the Cromford Canal, which is both a SSSI and Local Nature Reserve. The canal receives a small, continuous flow from the offtake in the headrace, and it is important that this flow is preserved.

3.6 Planning Designations

The Cromford Mills site is designated as a Grade-I listed building, and the whole area is within the 'Derwent Valley Mills' World Heritage Site.

3.7 Water Framework Directive (WFD)

- All significant UK watercourses have been classified in terms of their ecological status. The EU Water Framework Directive (WFD) requires improvements to be made to ensure that minimum standards are achieved on all watercourses.
- Bonsall Brook is too small have its own classification and sits within the waterbody "Derwent from Wye to Amber". This is a Heavily Modified waterbody with 'moderate' ecological status.

4. HEAD & FLOW

Two quantities make up the available power potential at a hydropower site: a Volume Flow Rate of water ***Q***, and a Pressure Head ***H*** (Head is the available vertical fall in the water, from the upstream level to the downstream level).

4.1 Head

The gross head at the wheelpit (water level in the headrace to tailwater in the wheelpit) was measured at 6.45m.

4.2 Flow

Bonsall Brook is not gauged by the Environment Agency. The flow on the day of the survey was estimated to be in the region of 300 litres/sec (after a long period of dry weather).

Rainfall and catchment area methods can be used to estimate the likely flow variation, but these can be less reliable in a limestone catchment where the rainwater 'disappears' underground before emerging at various springs. Flow may be lost or gained between other catchment areas as a result of these sub-surface flows.

It is therefore advisable to undertake a period of flow monitoring, and this forms a separate element of this project.

In the meantime, to establish an initial flow estimate, the HydrA hydraulic model from the Institute of Hydrology was run for this catchment with an estimated catchment area of 28 km² and average rainfall of 980 mm per year.

The resulting flow parameters for the Brook can be summarised as follows:

Q95	Flow exceeded 95% of the time	130	litres/sec
Q80	Flow exceeded 80% of the time	205	litres/sec
Q50	Median Flow – flow exceeded 50% of the time	341	litres/sec
Q30	Flow exceeded 30% of the time	494	litres/sec
Q10	Flow exceeded 10% of the time	832	litres/sec
Qmean	**Average Flow**	470	**litres/sec**
Q95:Qmean	*Ratio of dry flow to average flow*	*27%*	

Historic Flows

It is worth noting that, when this wheelpit was constructed in 1775, the water supply from Bonsall Brook was being supplemented by the mining sough that fed the 1st waterwheel via the aqueduct, which was discontinued in 1837. This explains the substantial size of the ‘double’ wheel.

4.3 Base Flow

The ratio of Q95:Qmean indicates a relatively high baseflow stream.

4.4 Design Flow and Prescribed Flow

4.4.1 Prescribed Flow

There is no deprived reach of watercourse in this scenario i.e. the flow from a waterwheel/turbine would drop directly back into the wheelpit, so the only flow unavailable for power generation will be the small overspill towards Cromford Canal. This is guaranteed by adjusting the stop-log above the wheelpit overspill. Visual observation suggests that this flow may be in the region of 50 litres/sec.

4.4.2 Design Flow

On this basis we would normally recommend a turbine design flow in the range 400 to 500 litres/sec to maximise the power potential of the site.

However in the case of a waterwheel, the maximum abstraction will be limited by technical constraints as discussed below.

5. TURBINE OPTIONS

5.1 Crossflow

As the best compromise between efficiency and cost, these site parameters would normally suit a crossflow turbine. However the crossflow turbine would be relatively large and would need to be located 1.7m above tailwater level, requiring steel joists spanning the length of the channel, as depicted in Annex B-3. This is unlikely to be realistic in this location, for technical, safety and conservation reasons.

5.2 Kaplan

A Kaplan (propeller-type) turbine and a Francis turbine can both be located well above downstream water level, connecting to the tailwater via a long draft tube, and this feature allows the layout to make use of the bearing enclosure for supporting the turbine, plus providing reasonable maintenance access from above.

The most compact installation that would best fit the existing infrastructure would be a vertical-shaft axial-flow Kaplan turbine (Figure 3). As depicted in the layout of Annex B-1, a new sluice gate set into the north wall of the headrace (approx. 1.2m wide) would draw water into a screening chamber fitted with a 12mm aperture screen. From here a short length of buried 600dia pipe would pass down into the bearing enclosure and connect to a vertical Kaplan via two 90° bends.

The Kaplan turbine and draft tube would overhang into the wheelpit, running down the north wall of the wheelpit, supported on a frame secured to the bearing enclosure.

The appropriate turbine size would have a 400dia. propeller running at 750rpm. It could therefore couple directly to an 8-pole generator, avoiding the need for a belt-drive or gearbox.

The vertical draft tube would typically expand from a 400dia circular cross-section to a square cross-section of 700mm x 700mm where it dips into the tailwater. The purpose of the draft tube is to capture the 2.5m of head below the runner as suction pressure, allowing the turbine to exploit the full 6.4m of head available.

The 12mm debris screen would be a self-cleaning design using a rotating wire-belt mesh to draw debris up into a trough where it is diverted directly back into the wheelpit (Figure 4). This would largely be hidden from view behind the north wall (and below the public walkway).

Figure 3 : Axial-Kaplan turbine (Andritz)

Figure 4 : Wire-belt screen

5.3 Overshot Waterwheel

5.3.1 General layout

The original double-waterwheel would have been at least 3.2m wide with a substantial shaft spanning the wheelpit supported by a bearing at each end. Stopping the wheel would probably have required opening a large trap-door to allow all the water to drop down behind the wheel.

From the perspectives of safety, reliability and flood control, as well as cost, we would recommend that a new waterwheel project should be conservative in design, with fail-safe features to ensure it can be stopped quickly if the need arises..

We therefore recommend a compact design on the north side of the wheelpit, as drawn in Annex B-1.

Flow would be drawn off the headrace through a new screened aperture in the north wall to feed a 400dia pipe buried to the north of the channel. This would supply a header tank for delivering the flow to the overshot waterwheel.

This design does not attempt to span across the 5m-width of the wheelpit with a new shaft, but proposes an overhung design with 2 bearings in a single bearing enclosure.

The width of the wheel is shown as 800mm, which is a size that would allow the existing millrace overspill to continue as at present, without interfering with the waterwheel.

During the detailed design phase, a slightly wider wheel could be considered, with a baffle to divert the overspill flow to the south side, but there will be a limit to the weight of overhung wheel that can be supported on this bearing arrangement before the shaft and bearings become excessive in both size and cost.

5.3.2 Sizing

The recommended rim speed for an overshot waterwheel is not more than 2m per sec.

For good efficiency at this high rim speed, the flow from the header tank needs to be 'jetted' into the buckets at a speed of around 2.5m/s, which requires a water depth in the header tank of 0.35m.

With the bearings located centrally on the base of the existing bearing enclosure, the site dimensions would allow a 5.5m diameter waterwheel. This leaves a gap of only 300mm between the wheel and the far wall, so there is little scope for enlarging the wheel beyond 5.5m. However this also leaves a 500mm gap between the wheel and the tailwater, which is larger than necessary.

A maximum wheel size of 5.8m could be accommodated in theory, by slightly expanding the bearing enclosure both downwards and upstream.

A 5.5m dia wheel would rotate at a maximum speed of 7rpm. A typical design would allow for 48 buckets holding 40 litres each, with roughly 5 buckets being filled per second, hence a maximum design flow of 200 litres/sec. This would result in a shaft torque of 12kNm (or 1.2 tonnes on a lever-arm of 1m). A wheel of this size is shown in Figure 5.

Flow into the top of the wheel is controlled and stopped by an automated undershot sluice gate in the header tank. There needs to be a second automated gate in the system, and a convenient option would be an electrical butterfly valve in the short supply pipe.

5.3.3 Transmission

To bring the drive up to ground level, and reduce the cost of the gearbox, a 4:1 chain-drive is proposed - effectively replacing the first high-torque stage of the gearbox.

To create space for the large pulley would require digging out a narrow channel at the far end of the bearing enclosure, as indicated on the drawing.

The chain-drive would ascend 2m to an industrial 2-stage gearbox which would increase the RPM to a standard generator speed of 750 or 1000rpm.

Figure 5 : HydroWatt waterwheel (Germany)

5.4 Control System

Both Kaplan or Waterwheel options would be controlled by a standard control system which would enable fully automatic operation of the system. The control panel continuously monitors the headrace level, and opens or closes the inlet valve in small adjustments, according to whether the upstream level is rising or falling. If there is insufficient water to generate power, the system would shut down completely, and automatically restart when the Brook is replenished.

The control system also provides the necessary grid-connection switchgear to meet the G99 standard for embedded generators.

5.5 Fisheries & Ecology

5.5.1 Overview

A Phase 1 Habitat Survey would need to be undertaken as part of the planning permission to identify if there are any relevant populations of protected species (water voles, white-claw crayfish, otters, bats, etc.) and to recommend any mitigation measures.

There are not believed to be any significant fish populations in Bonsall Brook itself, due to its small size and heavily modified nature as it passes through Cromford via numerous man-made structures.

5.5.2 Fish Passage

Bonsall Brook is not populated by migratory salmon or eels and is completely impassable due to the underground tunnels, Cromford Wheelpit, etc. which have totally altered the natural watercourse.

6. FLOOD RISK

A Flood Risk Assessment would be provided with any Planning Application, but in summary, neither the completed hydro-scheme, nor the construction works, will present any risk to flood defence for the following reasons:

- The project works will not impinge upon the main river channel, and there will be no obstruction to the main channel flow.
- By drawing up additional flow through the new pipeline, the overall discharge capacity of the site will be increased.
- Any excavated materials will be removed outside the Floodplain.

7. OUTPUT

A Kaplan turbine designed for 6.2m net head and 500litres/sec design flow would generate a peak electrical output of 25kW.

Based on the modelled flow characteristic, the electricity generated over one year is predicted to be close to 110,000 kWh/year. This estimate would be refined once more accurate flow data becomes available.

A modern overshot waterwheel of 5.5m diameter and width 0.8m could draw a flow in the region of 200litres/sec. A wheel efficiency of 70% combined with a chain-drive/gearbox efficiency of 90% and generator efficiency of 90% would lead to a peak electrical output of 6kW.

If the wheel can be operated unattended on a 24/7 basis, then it would potentially generate up to 40,000 kWh/year. Clearly this figure would drop by 66% if the wheel is only operated when there are staff on site.

8. REVENUE

The system would run 'in parallel' with the local network, i.e. any power generated by the turbine/waterwheel would first be consumed in The Mill (reducing the electricity that would otherwise be bought in) and any excess power would pass back into the grid through a meter, and could be sold to an electricity company.

The overall value from the scheme will therefore depend on what proportion of the power would be consumed on site vs. sold into the grid. One way to guarantee that all the power is used on site would be to identify a 'dump' load - usually water heating or space heating - which could usefully absorb the excess electrical power e.g. by making public spaces more comfortable, reducing damp, and displacing the heating fuel that would otherwise be used.

If we assume that 100% of the hydro output will be consumed on site (0% export), displacing electricity otherwise bought in at 16p/kWh, then the maximum 'annual value' of the Kaplan scheme would be:

£0.16 x 110,000 kWh = £17600 per year.

If only 50% is consumed on site, and the rest is exported at 5.5p/kWh, then the annual value would fall to £11,800 per year.

The 6kW from the waterwheel is much more likely to be fully absorbed on site, so the value of the 40,000 kWh can be put at £6400 in displaced imports.

9. COSTS

9.1 Electro-Mechanical Equipment

The initial broad-brush estimates for the electro-mechanical equipment and installation costs are estimated as follows:

9.1.1 Kaplan Turbine

Item	£
400 dia Axial Kaplan Turbine and draft tube	60000
Induction Generator 30kVA 750rpm	3000
Control panel, sensors & cabling	12000
12mm wirebelt screen, drive motor, controls, debris trough	15000
1200mm width Penstock Gate	5000
Assembly, installation and commissioning	15000
Detailed design, engineering & project management	10000
Sundry fixtures, transport, inflation	5000
TOTAL (ex VAT)	**125000**

9.1.2 Overshot Waterwheel

Item	£
5.5m dia Waterwheel (***guesstimate for bespoke manufacture***)	40000
Chain-drive 4:1 ratio	2000
2-stage gearbox	4000
Induction Generator 11kVA 1000rpm	1500
Control panel, sensors & cabling	10000
Automated flow-regulating gate	2000
Automated butterfly valve	3000
Detailed design and project management	10000
Assembly, installation and commissioning	15000
Sundry fixtures, transport and inflation	5000
TOTAL (ex VAT)	**92500**

9.2 Additional Works

Additional works will be required to cover:

1. All civil construction works, including:

- structural design
- temporary works and site clearance,
- intake works, pipeline and forebay tank
- craneage
- enclosures, walkways, fencing
- running the power cable to the network connection.

2. Gaining planning and licensing permissions, as appropriate with possible additional specialist surveys (ecology, archaeology, etc.).

3. Securing a grid connection agreement (expected to be a formality in this case).

10. NEXT STEPS

A formal license from the Environment Agency will be required, as well as planning permission. The main environmental criteria to be satisfied would involve fish-protection and flood defence.

The logical next steps to develop the scheme would be:

- Submit a pre-application enquiry to the Environment Agency, followed by a site meeting to discuss their comments.
- Submit an Application for Embedded Generation to the local electricity company (Western Power) to confirm the ability of the network to accept a generator of this size.
- Undertake the scheme design sufficient to support the license and planning applications, and in order to define the civil works requirements.
- Obtain budgetary quotes for the cost of the electro-mechanical equipment and civil construction works.

11. FURTHER INFORMATION

Further background information on developing a mini-hydro site can be found at:

www.british-hydro.org/wp-content/uploads/2018/03/A-Guide-to-UK-mini-hydro-development-v3.pdf

ANNEX A : SITE PICTURES

Figure 6

Figure 7

Figure 8

Figure 9

Figure 10

Figure 11

ANNEX B : SCHEMATIC DRAWINGS

- Drawing B-1 – Axial-Kaplan Turbine concept design
- Drawing B-2 – Overshot Waterwheel concept design
- Drawing B-3 – Crossflow turbine concept design

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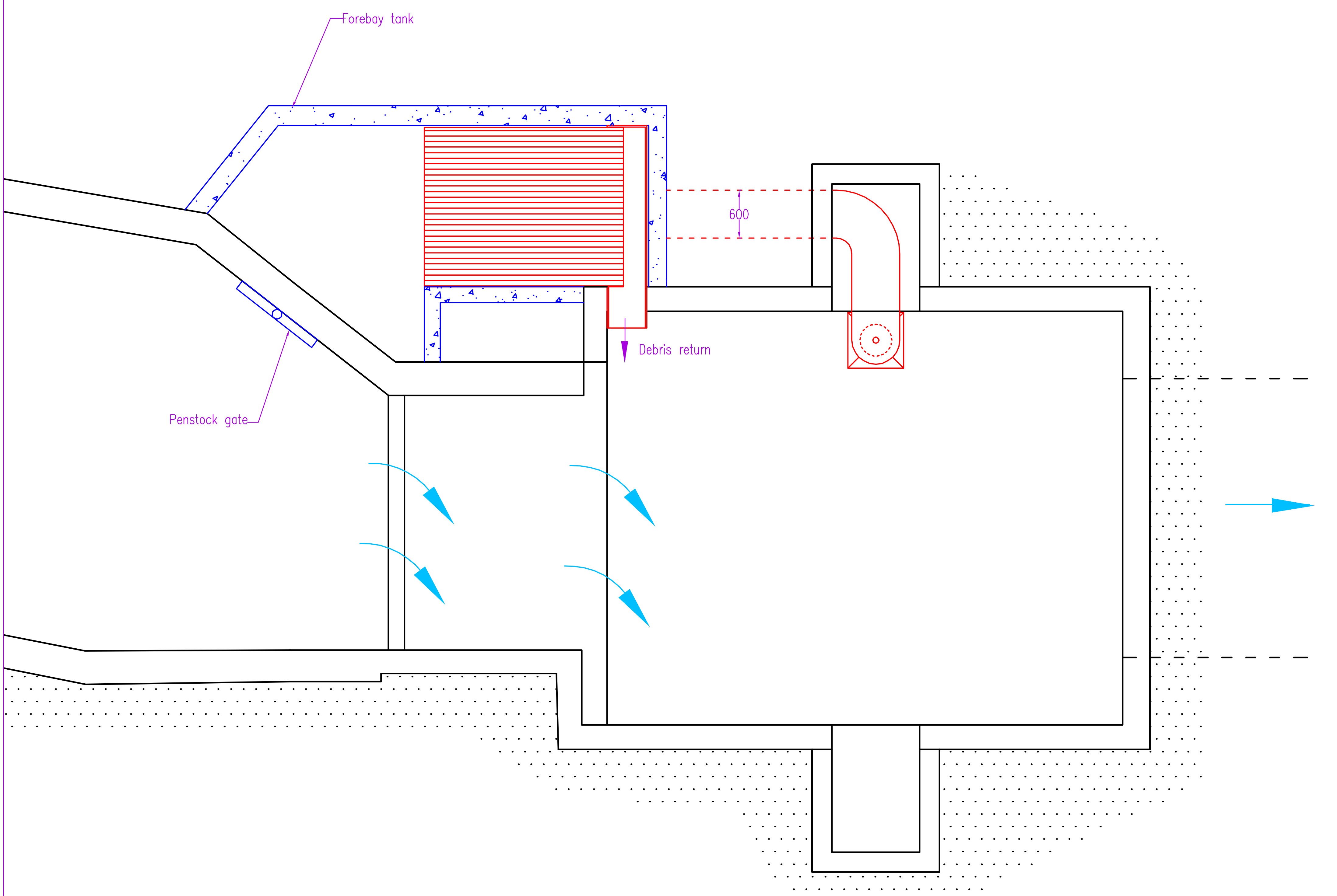
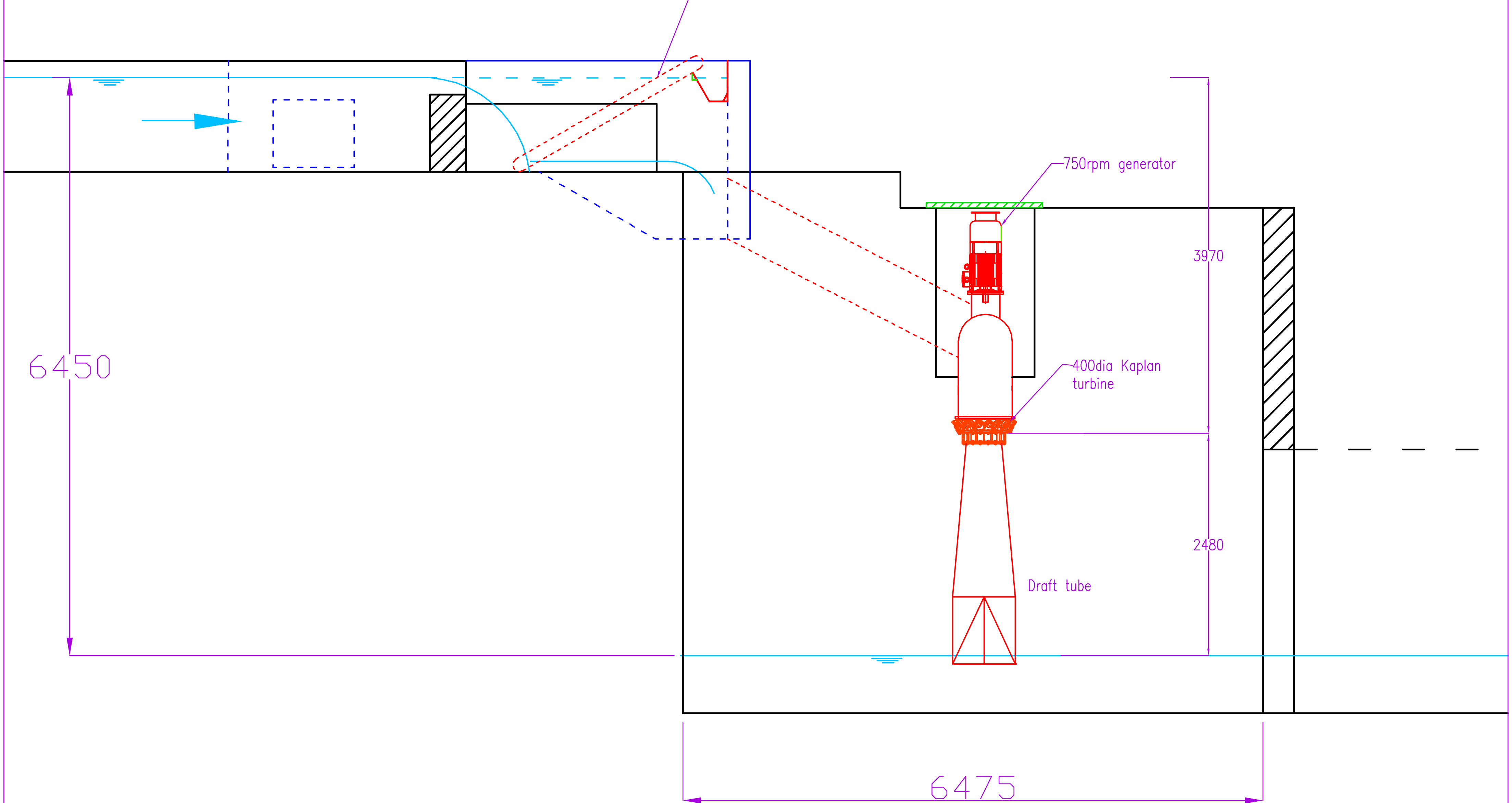
Derwent*HYDRO*	B1 - Cromford Mill - KAPLAN SCHEMATIC			

PLAN



ELEVATION



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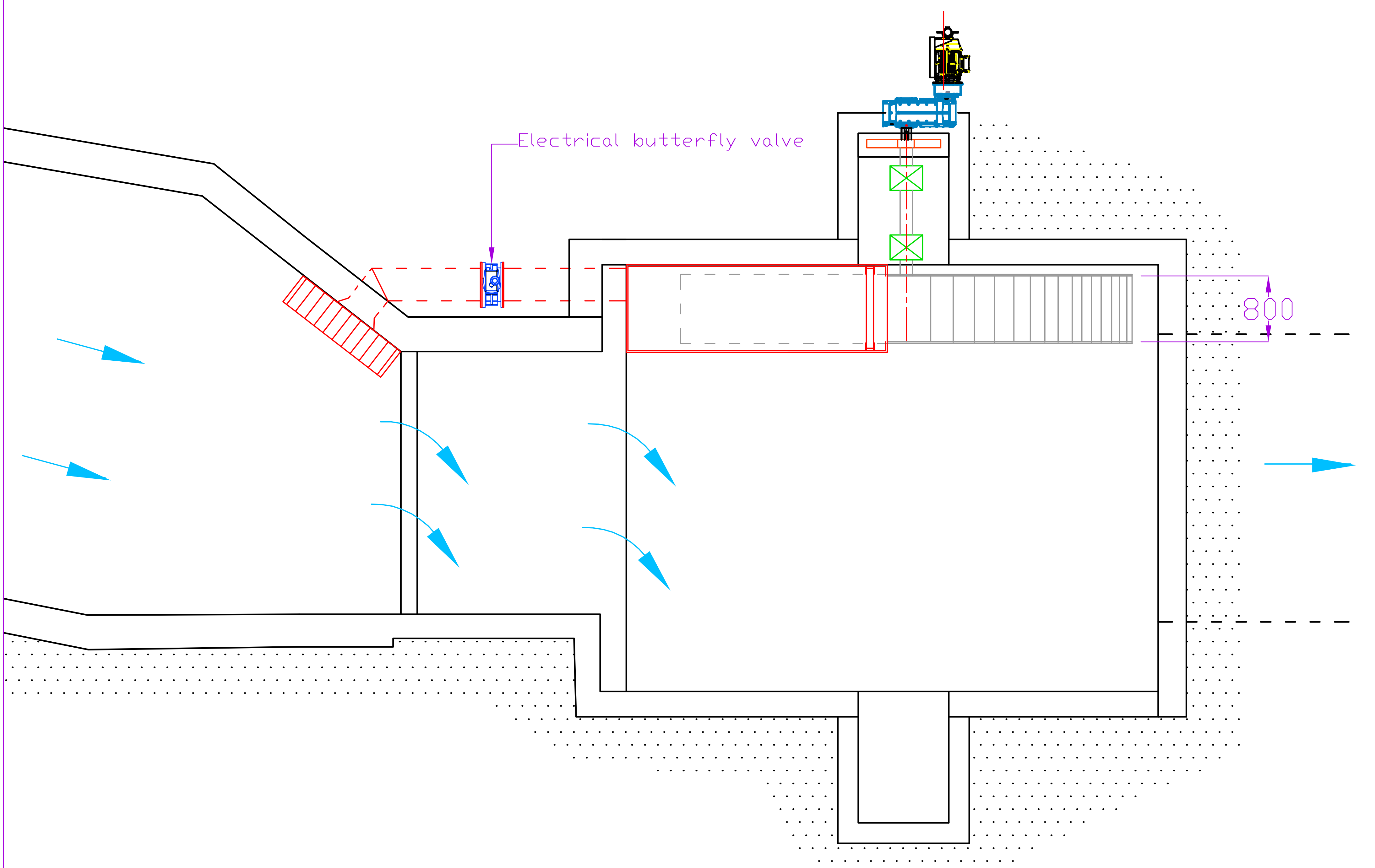
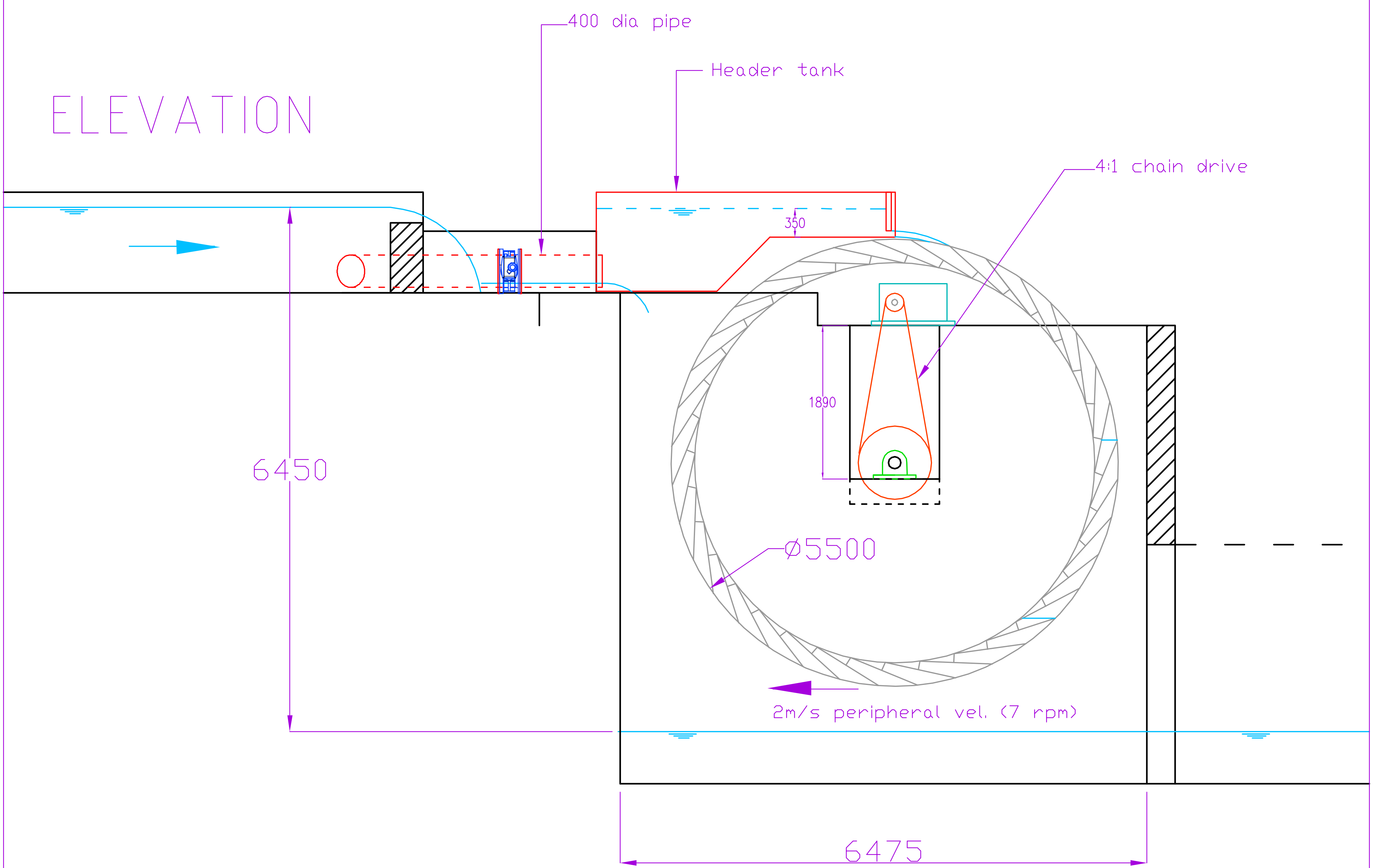
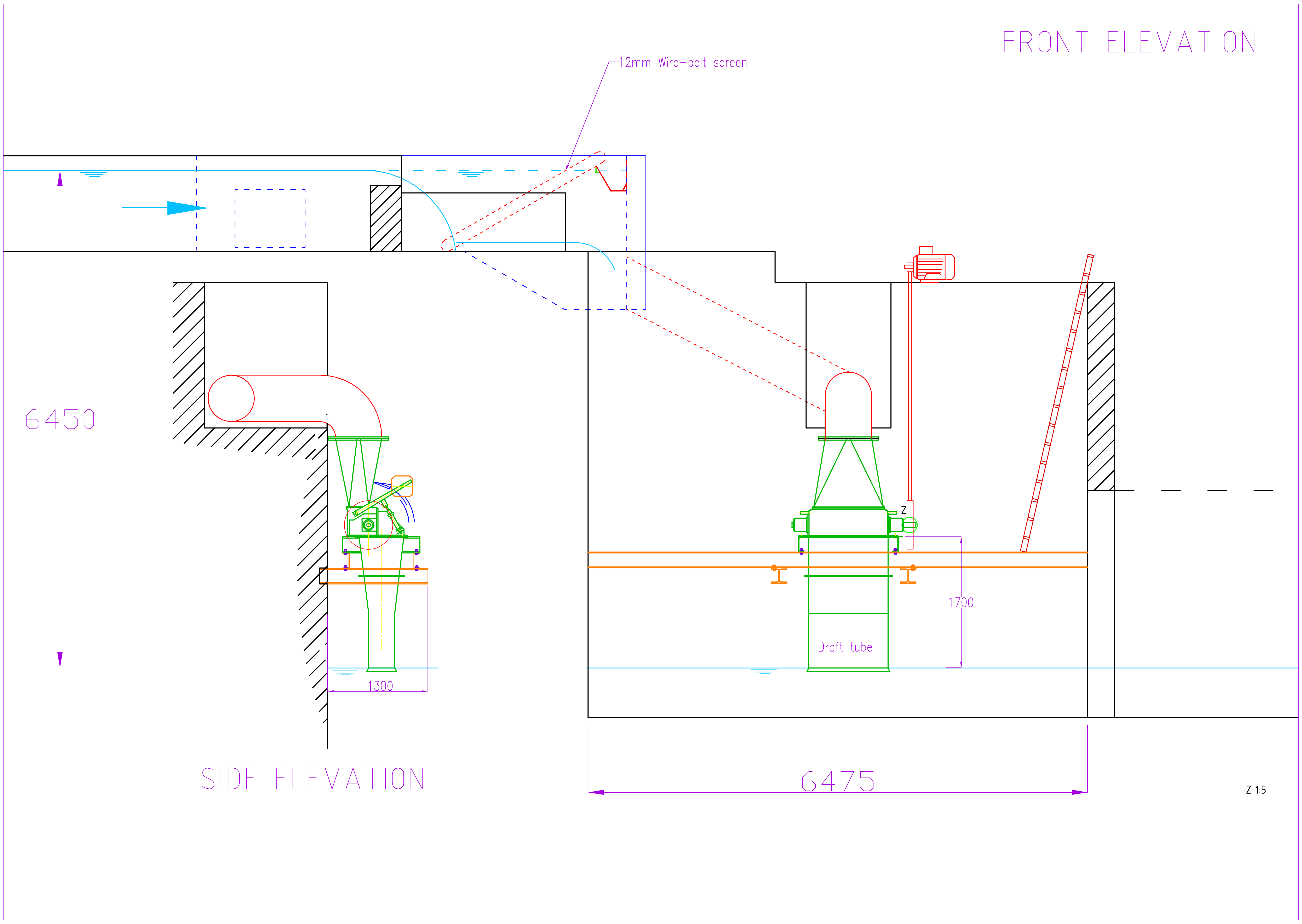
DerwentHYDRO	B2: Cromford Mill - WATERWHEEL SCHEMATIC			

PLAN



ELEVATION





FRONT ELEVATION
12mm Wire-belt screen
6450
Z
1700
Draft tube
1300
SIDE ELEVATION
6475
Z 1:5