PUMPING FROM DEEP HOLES: DEVELOPING OPTIMIZED HYDRAULIC DESIGNS

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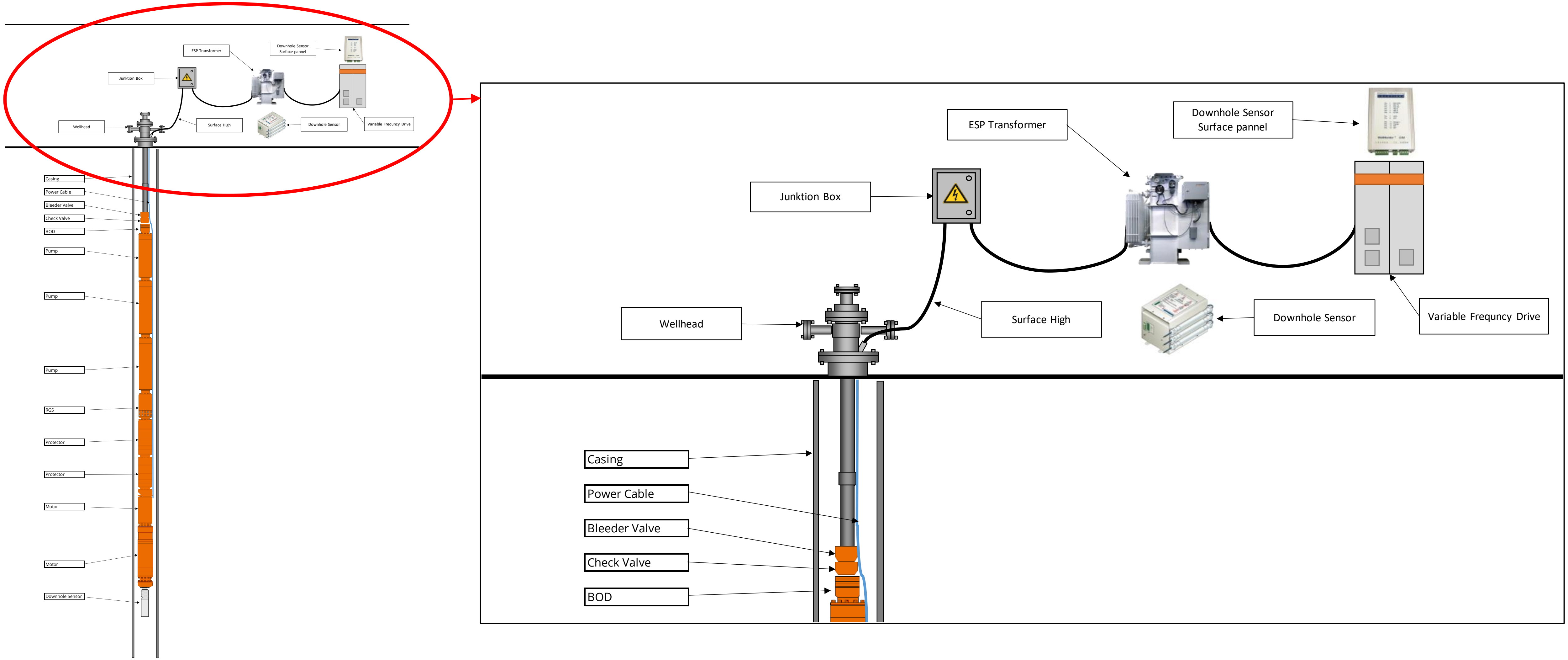
Typical Geothermal Installation - String Diagram



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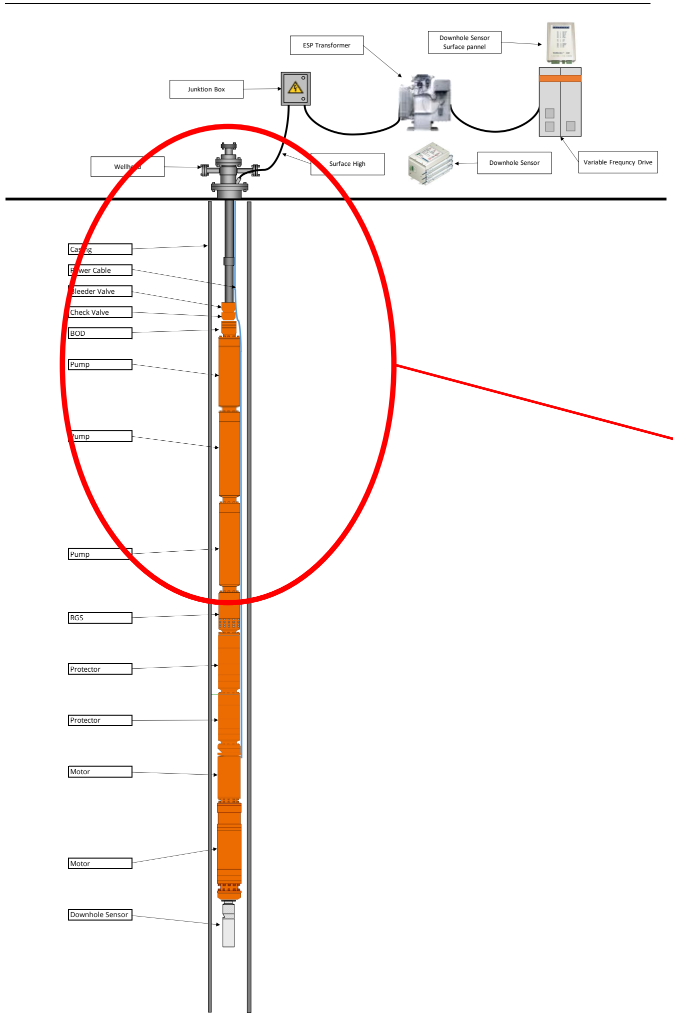

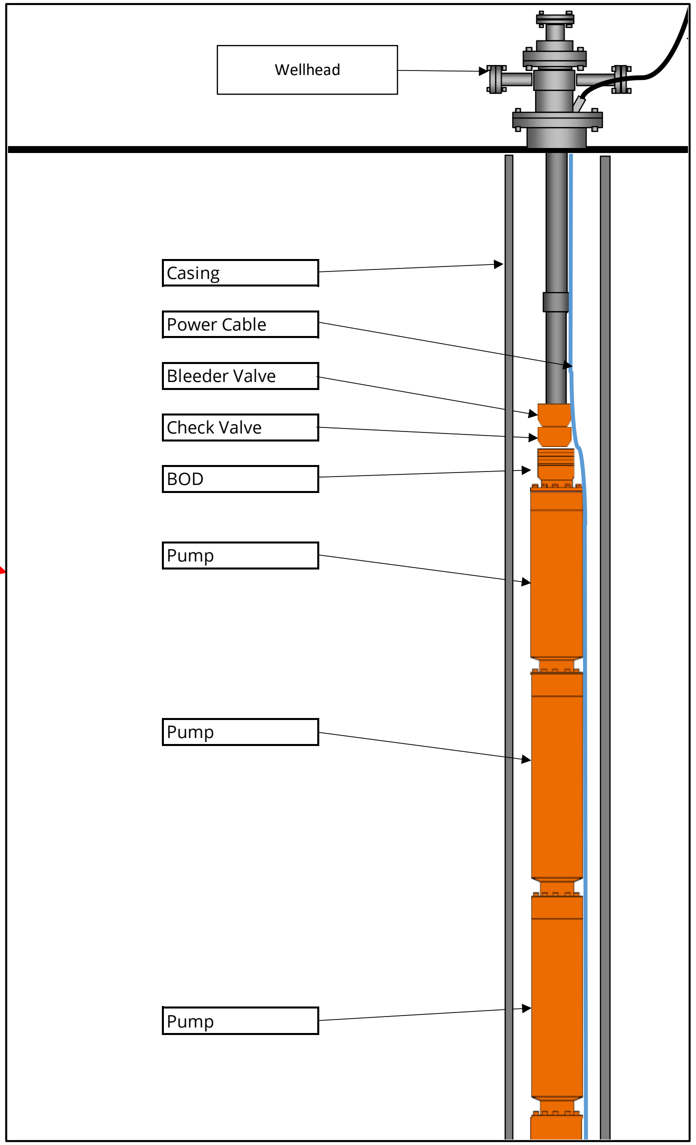

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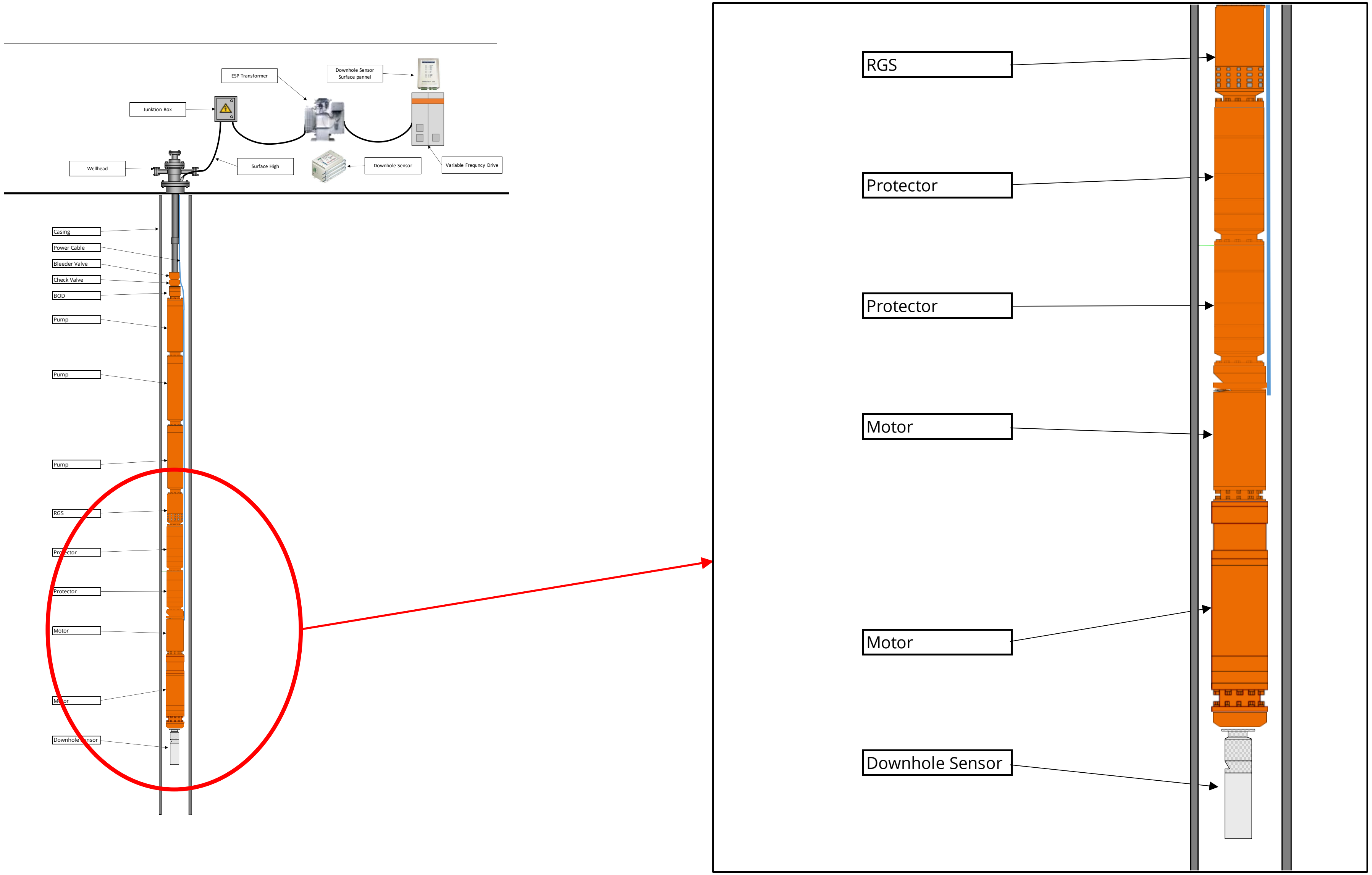
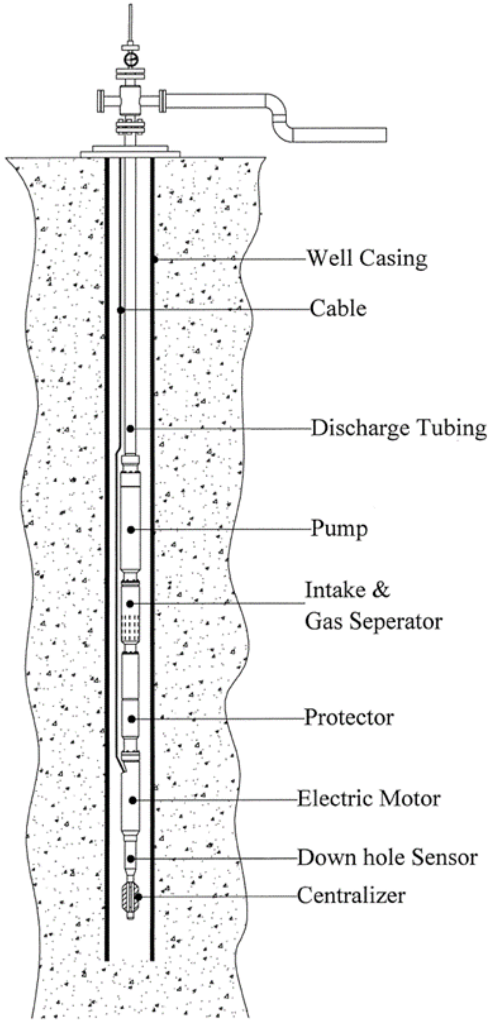


Typical Geothermal Installation



Casing size:

10-3/4” with liner or,
9-5/8” without liner

Maximum acceptable pump diameter 7.7”

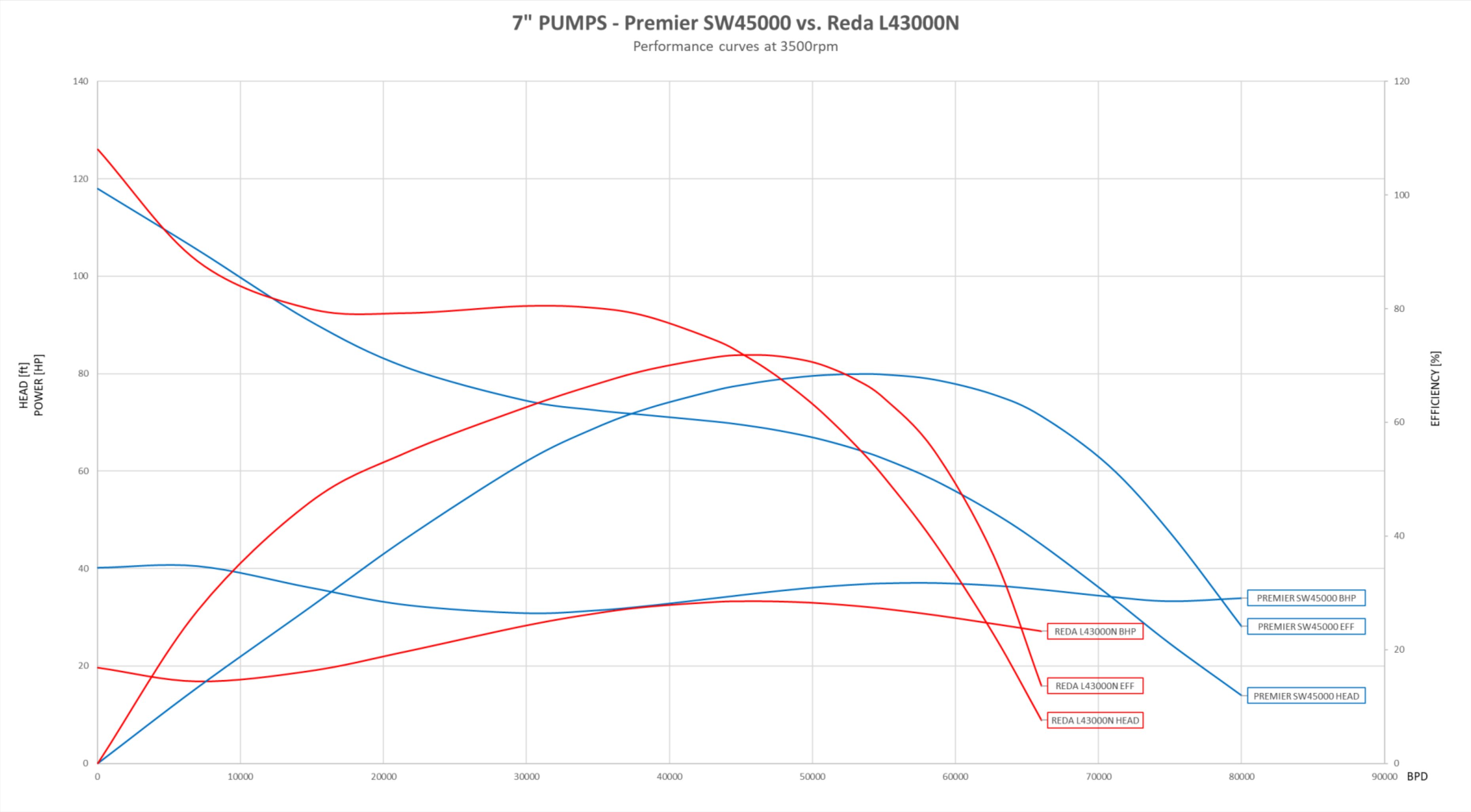
8.75” pumps are too large
6.75” pump cannot deliver required flow rate (36000BPD max)

Required production rates:

winter 45000-50000BPD / 82.8-92[l/s]
summer 15000-20000BPD / 27.6-36.8[l/s]

Production zone at 3000-4000m from surface
Pump landed at 600-1000m from surface

Pumps Available from Competition



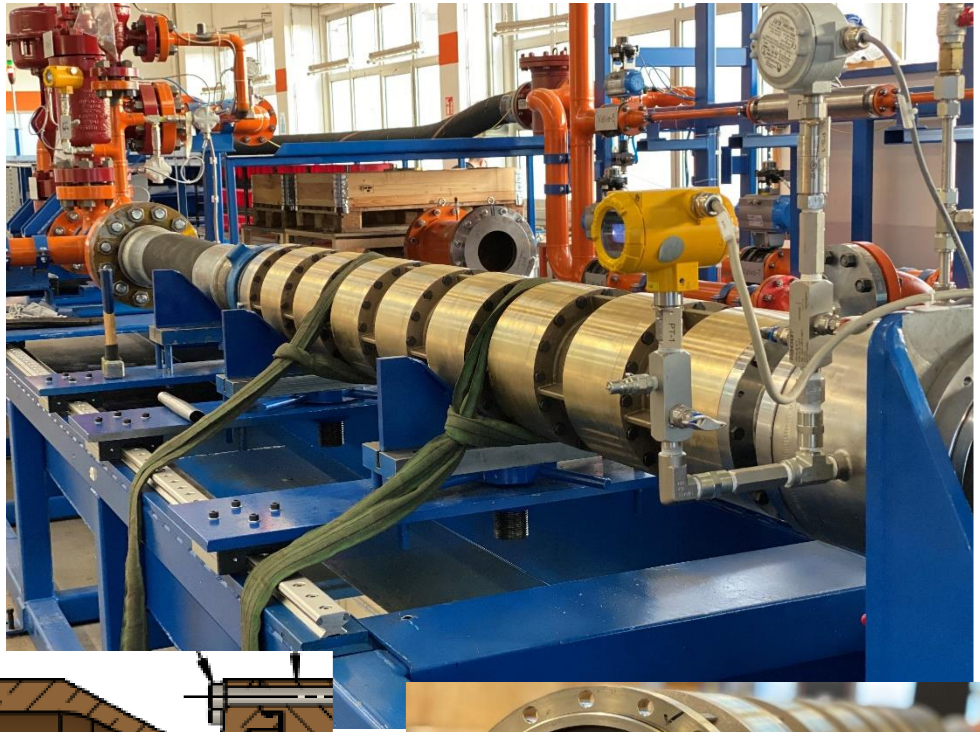
Initial Situation / Task / Goal

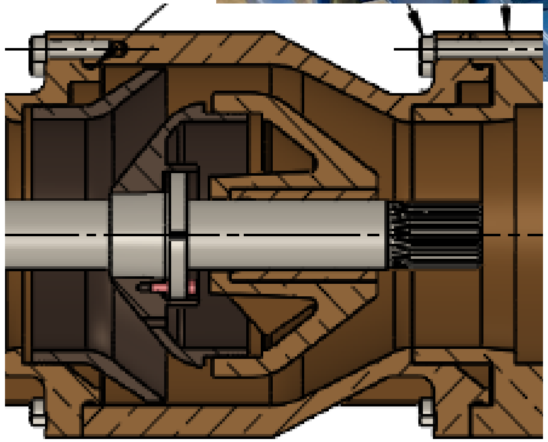
Hydraulic Specifications (n = 3500 rpm)

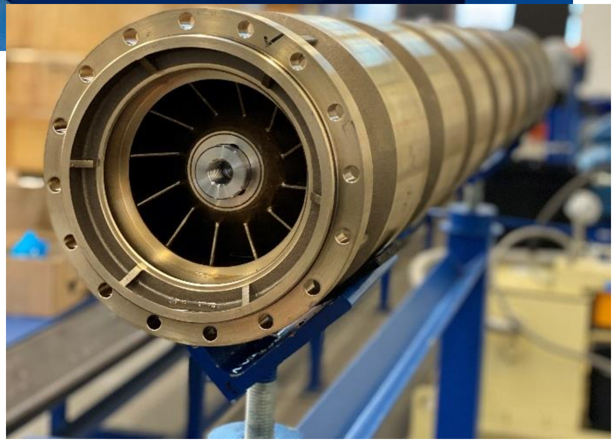
- Expected **head** per stage at BEP **25m**
- Flow rate at BEP **298m³/h or 45,000bpd**
- Expected efficiency at BEP would be close to 80%
- Continuously rising pump head is a must.
  Pump must be stable in whole range from
  no flow to no head conditions.
- No specifications concerning cavitation provided

Design specifications:

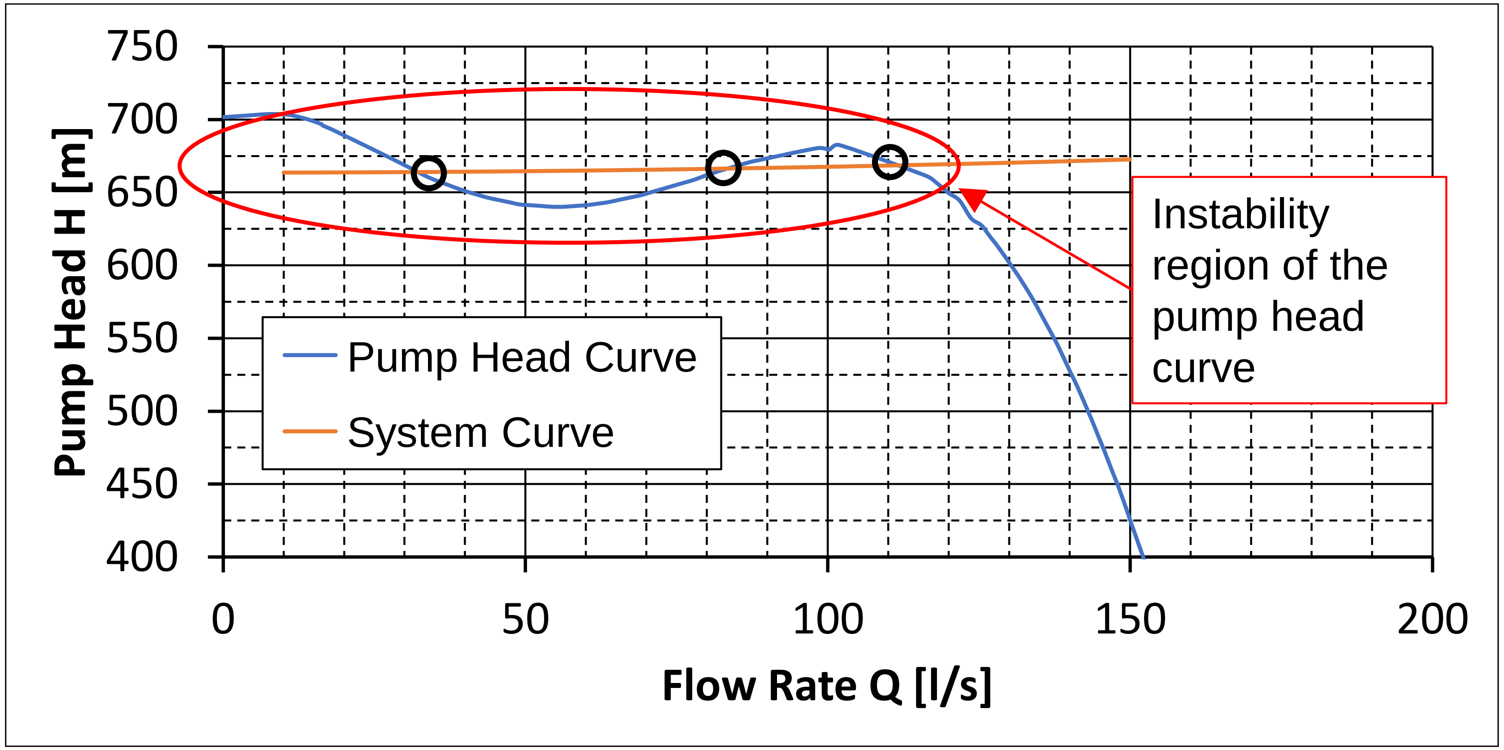
- Diffuser overall diameter **[OD]** must not bigger than **7-1/2" (190.5mm)**
- Max. **wet diameter D_a to 172mm**







Non-stable Pump Head Curve



System curve crosses the instability region:
multiple intersections at different flow rates possible

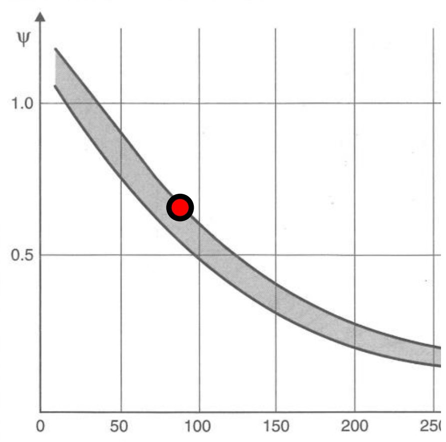
Sudden jumps in flow rate can be described by multiple intersections of the pump head curve and the system resistance curve

Literature study / possible limitations

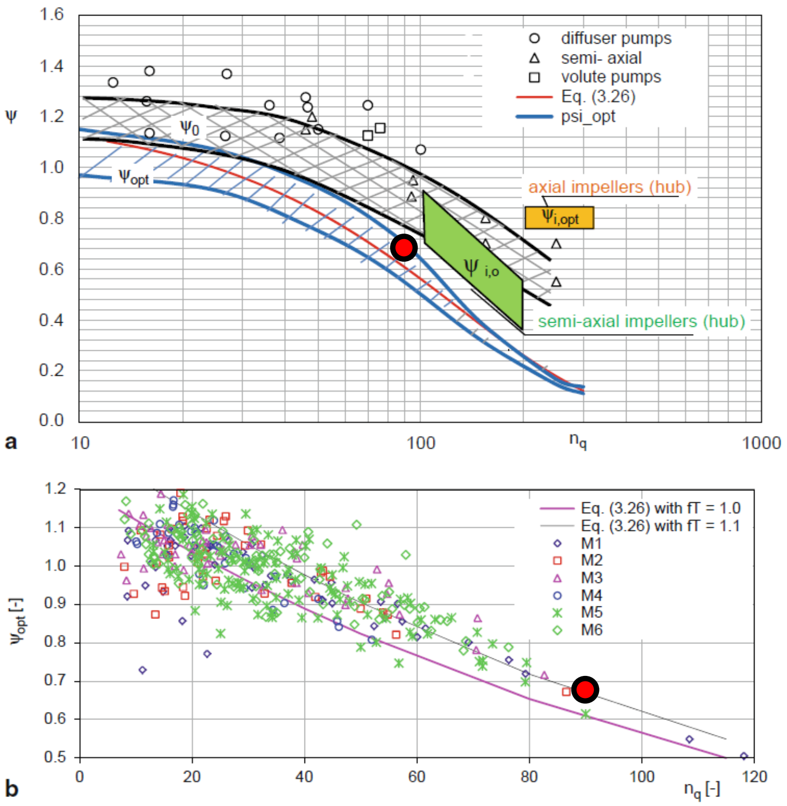
- H_{BEP} = **25 m,** Q_{BEP} = 298 m³/h bzw 82.8 l /s, n = 3500 rpm
- Max. **wet diameter D_a to 172mm**

$$n_q = n\frac{\sqrt{Q_{BEP}}}{H_{BEP}^{3/4}} = 3500\frac{\sqrt{0.0828}}{25^{3/4}} = 90 \qquad \psi = \frac{2\cdot g\cdot H}{u^2} = \frac{2\cdot 9.81\cdot 25}{\left(0.1475\cdot\pi\cdot\frac{3500}{60}\right)^2} = 0.67$$

Ψ = 0,67 @ n_q = 90 can be treated as tough design specification since for both references it is on the upper limit curve;



Source: Sulzer



Source: Gülich

Gülich mentions to take the lower limit curve
if a stable head curve should be achieved

$\Rightarrow$ In our design experience, the maximum permissible impeller diameter for the given combination of Q, H and n is at the very low limit!

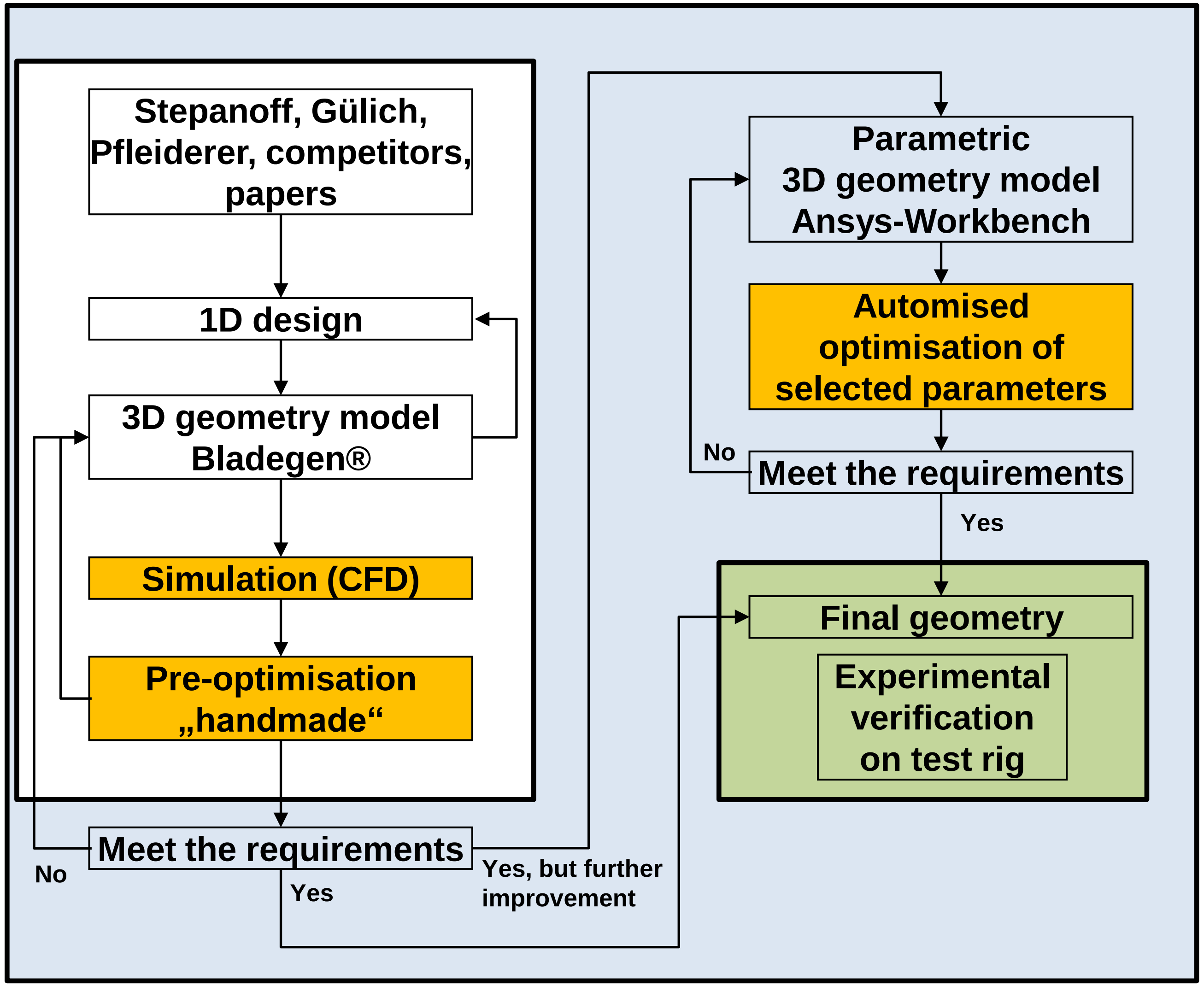
A study of reference pumps from different competitors revealed that **no executed pump with a stable head curve** under these specifications (Q_{BEP} = 298 m³/h @ n = 3500 rpm with D_2 ~ 150 mm) and could be found.

Hydraulic Design / Optimization Procedure

Challenges:

- No reliable design guidelines for mixed flow pump diffusers
- Hardly any references for the given design targets such as **head curve stability** and **limited size**
- Satisfying demanding design targets
- Many degrees of freedom

customized design procedure



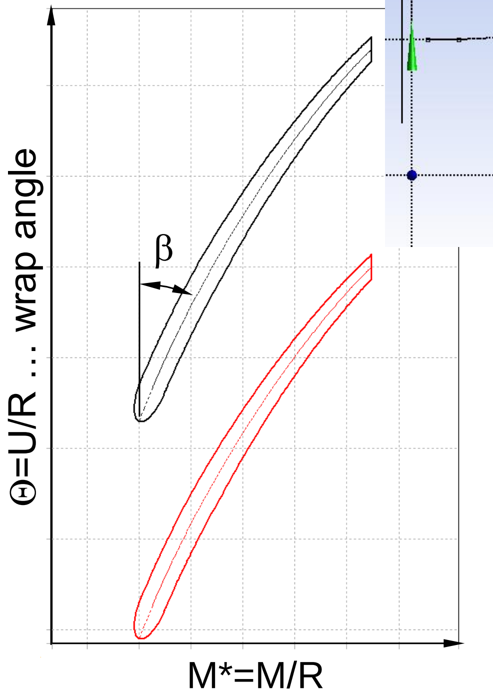
Parametric CAD-Model for Impeller and Diffuser

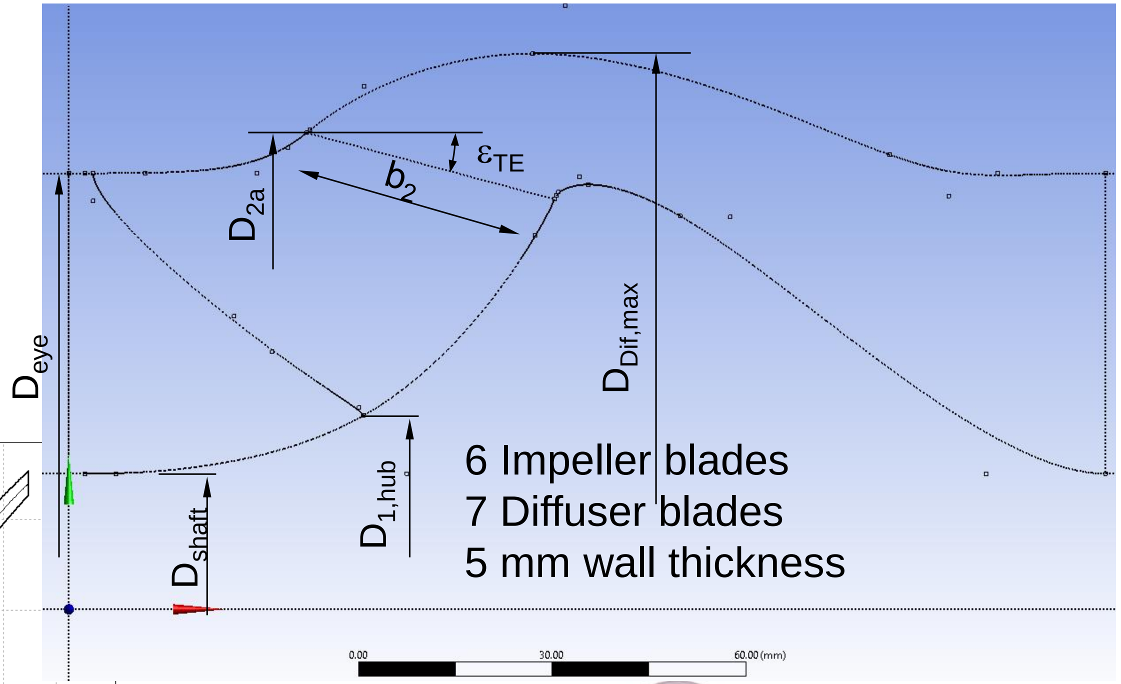
Parametric model for the complete hydraulic geometry

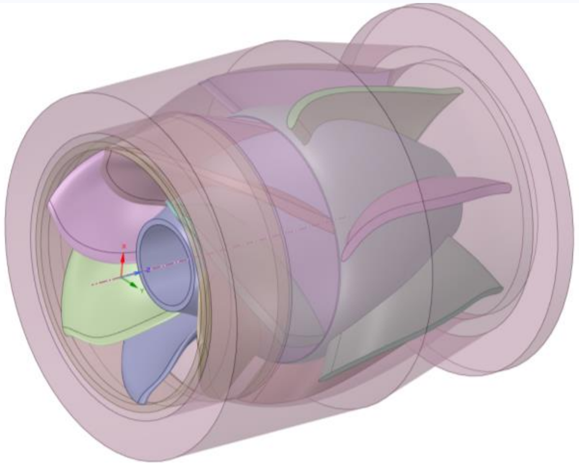
- meridional cross section
- blade shaping

more than 30 degrees of freedom was created.

- Multi-stage suitable; max. dimensions limited
- Minimization of remaining swirl at pump exit
- Smooth flow deceleration;
  Minimal flow separation but rapidly changing meridional curvature (limited diameter);
- Strong influence on head curve stability
- Sensitivity analysis followed by metamodel-assisted multi-objective evolutionary optimization

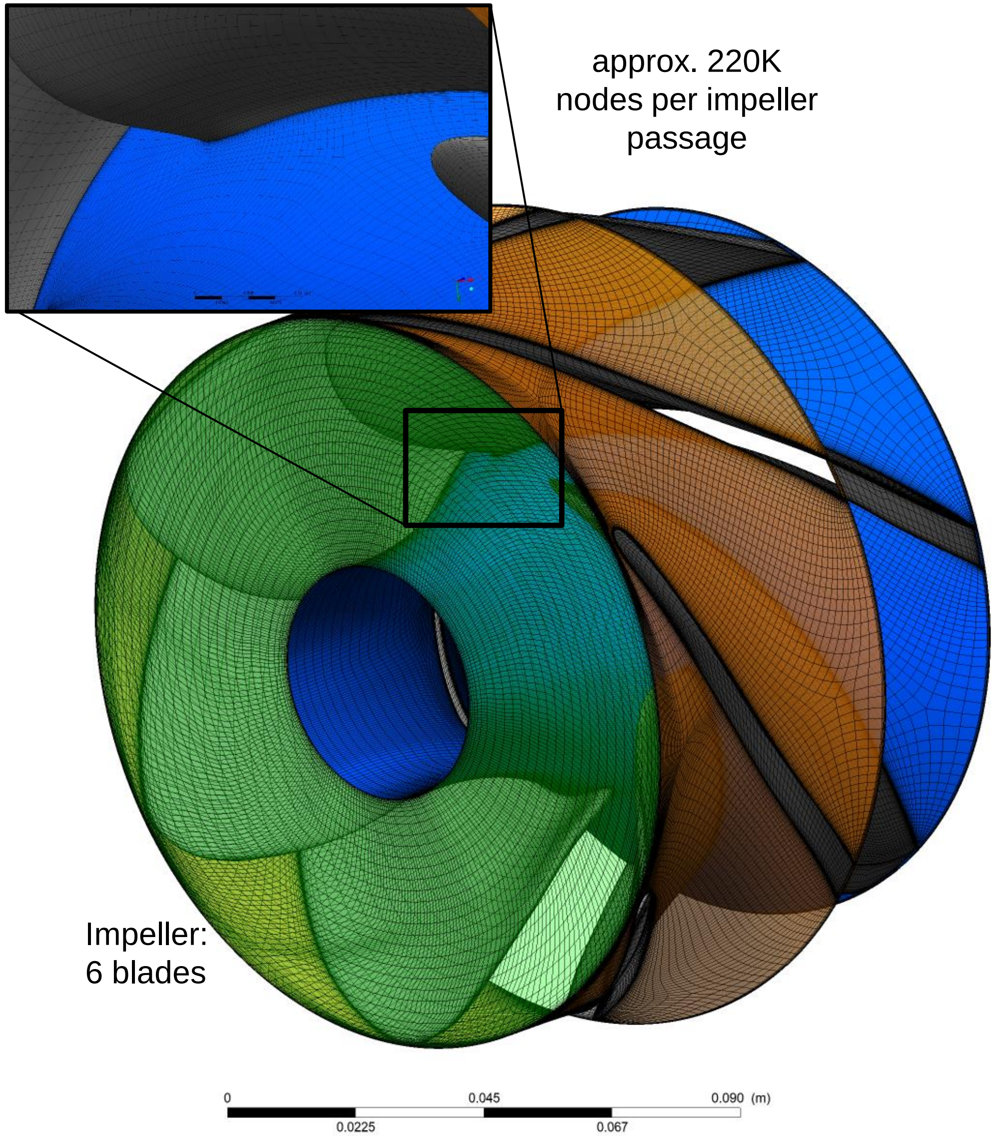






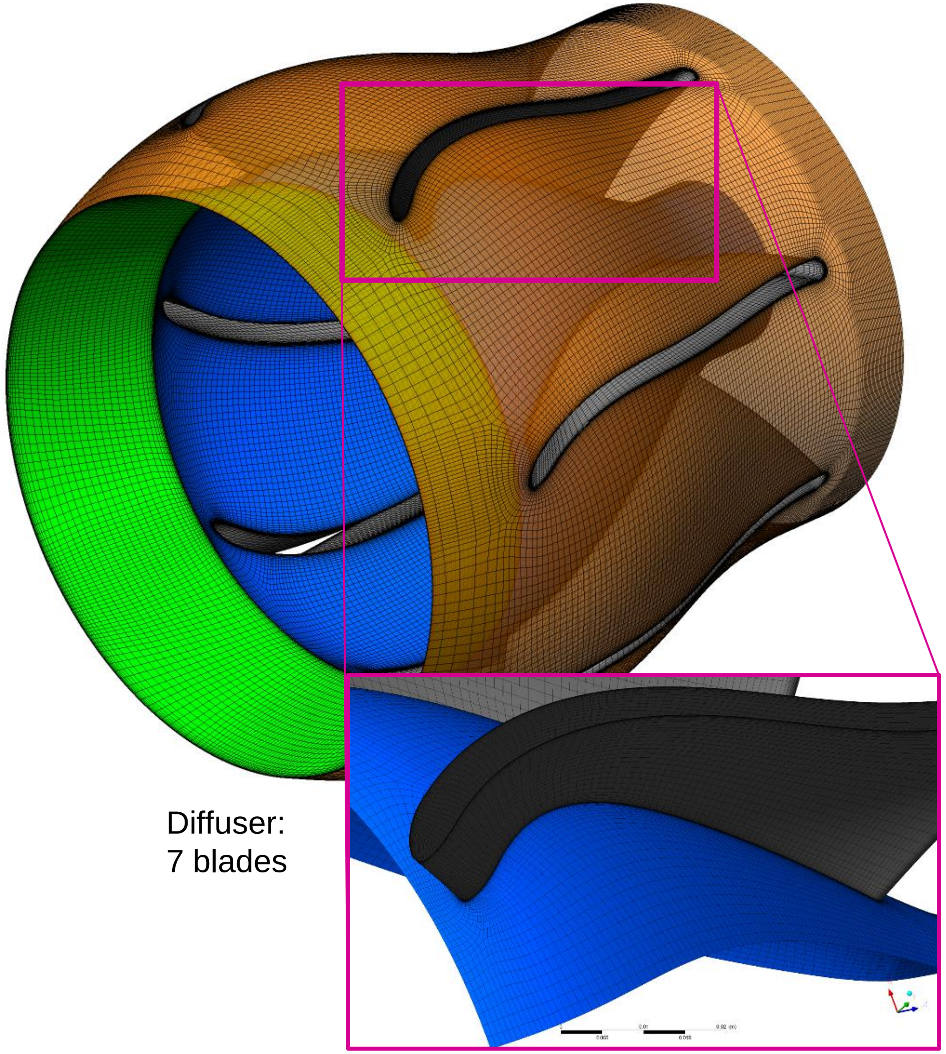
Numerical Meshes Impeller and Diffuser

approx. 220K nodes per impeller passage



Impeller:
6 blades

approx. 350K nodes per diffuser passage



Diffuser:
7 blades

CFD Setup

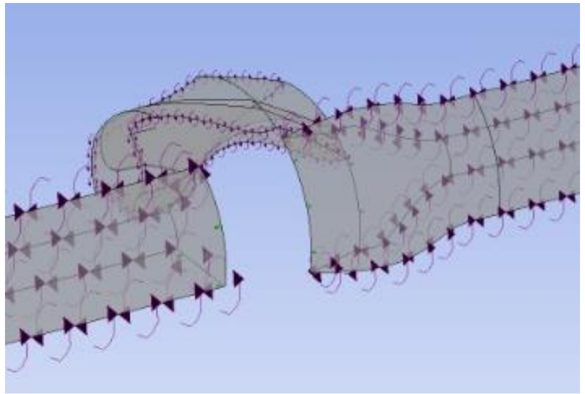
Steady State simulations for optimization

- Single passage models A and B
- Full 360° Model C for verification
- SST turbulence model
- Aggressive time step (speed up calculation time)
- Approx. 15 (A) / 30 (B) minutes on 4 CPU cores;
  8 h (C) on 16 CPU cores
- more than thousand different geometries investigated;
  5 operating points for each geometry (to prove head curve stability)

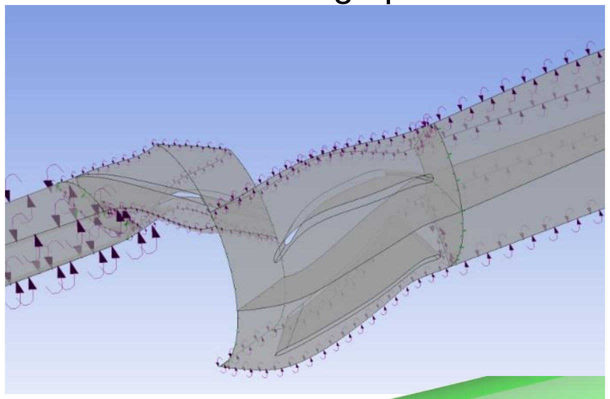
Transient simulations

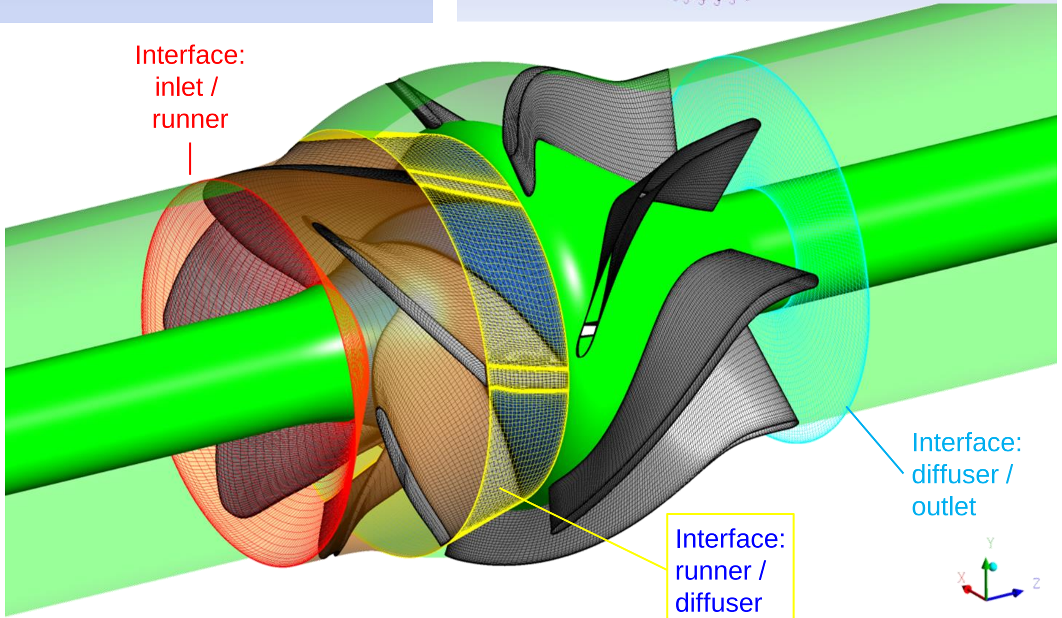
- Full 360°model for all domains, SBES-SST turbulence model
- Before automated optimization + for final geometry
- Approx. 5 to 6 days on 16 CPU cores

“Impeller only” CFD model A
for impeller design process



“Simple” CFD model B
for diffuser design process





“360°” CFD model C for design verification

Post-Processing

$$H_{pump} = \frac{1}{\rho g}\left[\left(\frac{1}{4}\sum_{i=1}^{4} p_i + \frac{\rho}{2}\left(\frac{Q}{A}\right)^2\right)\Bigg|_{out} - \left(\frac{1}{4}\sum_{i=1}^{4} p_i + \frac{\rho}{2}\left(\frac{Q}{A}\right)^2\right)\Bigg|_{in}\right]$$

… Pump Head acc. ISO 9906

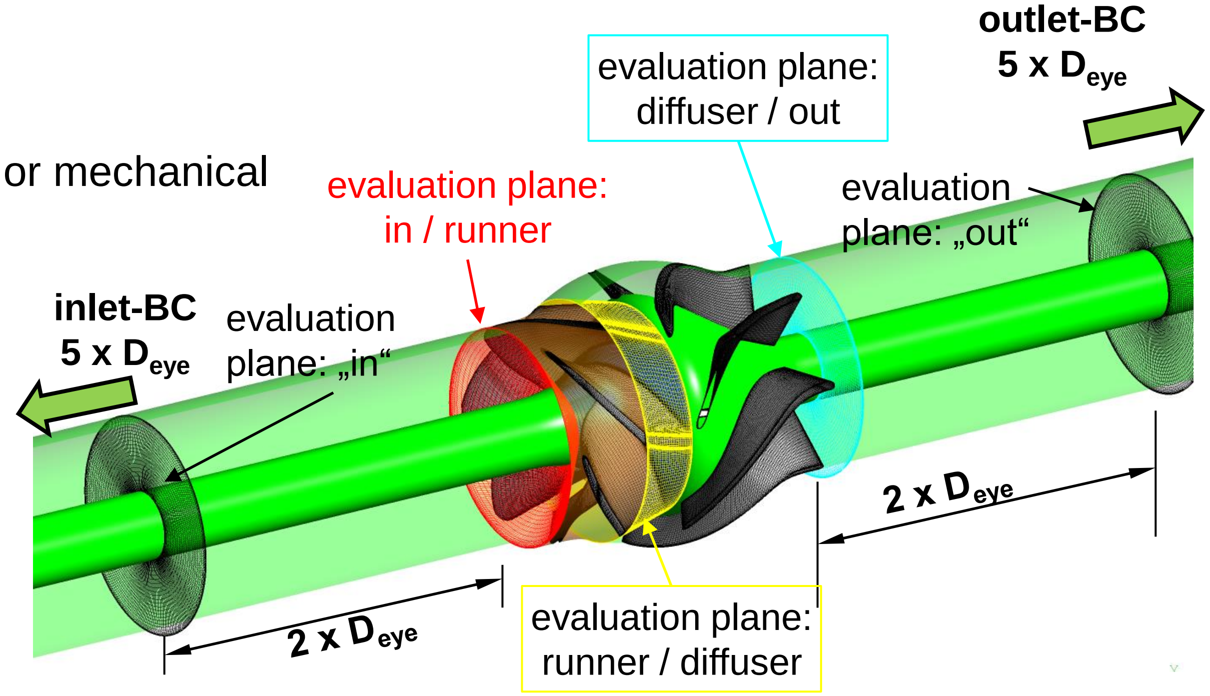
$$H_{pump} = \frac{1}{\rho g}\left[\frac{1}{A_{out}}\left(\int p \cdot dA\right)\Bigg|_{out} - \frac{1}{A_{in}}\left(\int p \cdot dA\right)\Bigg|_{in}\right] + \frac{\left(\frac{Q}{A_{out}}\right)^2 - \left(\frac{Q}{A_{in}}\right)^2}{2g}$$

… Pump Head CFD

$$\eta_{hydr} = \frac{\mathrm{P}_{hydr}}{\mathrm{P}_{mech}} = \frac{\rho \cdot g \cdot Q \cdot H_{pump}}{T_{Runner} \cdot \omega} = \frac{\rho \cdot g \cdot Q \cdot H_{pump}}{(T_{RunnerBlades} + T_{RunnerHub} + T_{RunnerShroud}) \cdot \frac{2 \cdot \pi \cdot n}{60}}$$

no leakage loss, disc friction or mechanical (bearing, sealing) losses

$$\eta_{hydr} = \frac{H_{pump}}{H_{pump} + \sum H_L} = \frac{H_{pump}}{H_{pump} + H_{L-inlet} + H_{L-runner} + H_{L-diffuser} + H_{L-outlet}}$$

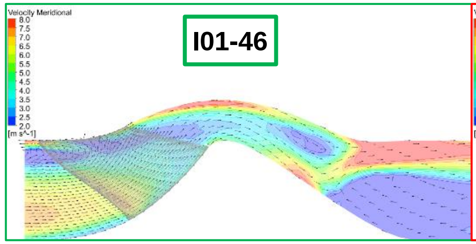


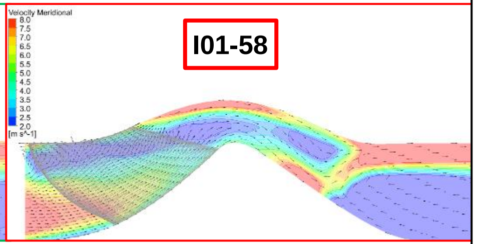
Selected Impeller Designs from Optimization Process

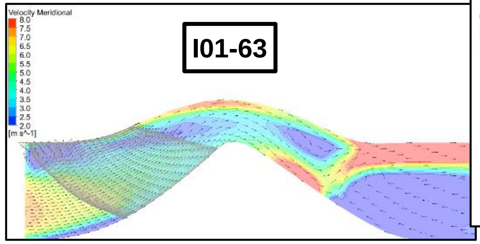
80 impeller designs were investigated further (out of approx. one thousand!);

Main focus on velocity distribution at impeller inlet and outlet at part load operation (stable head curve mandatory!)

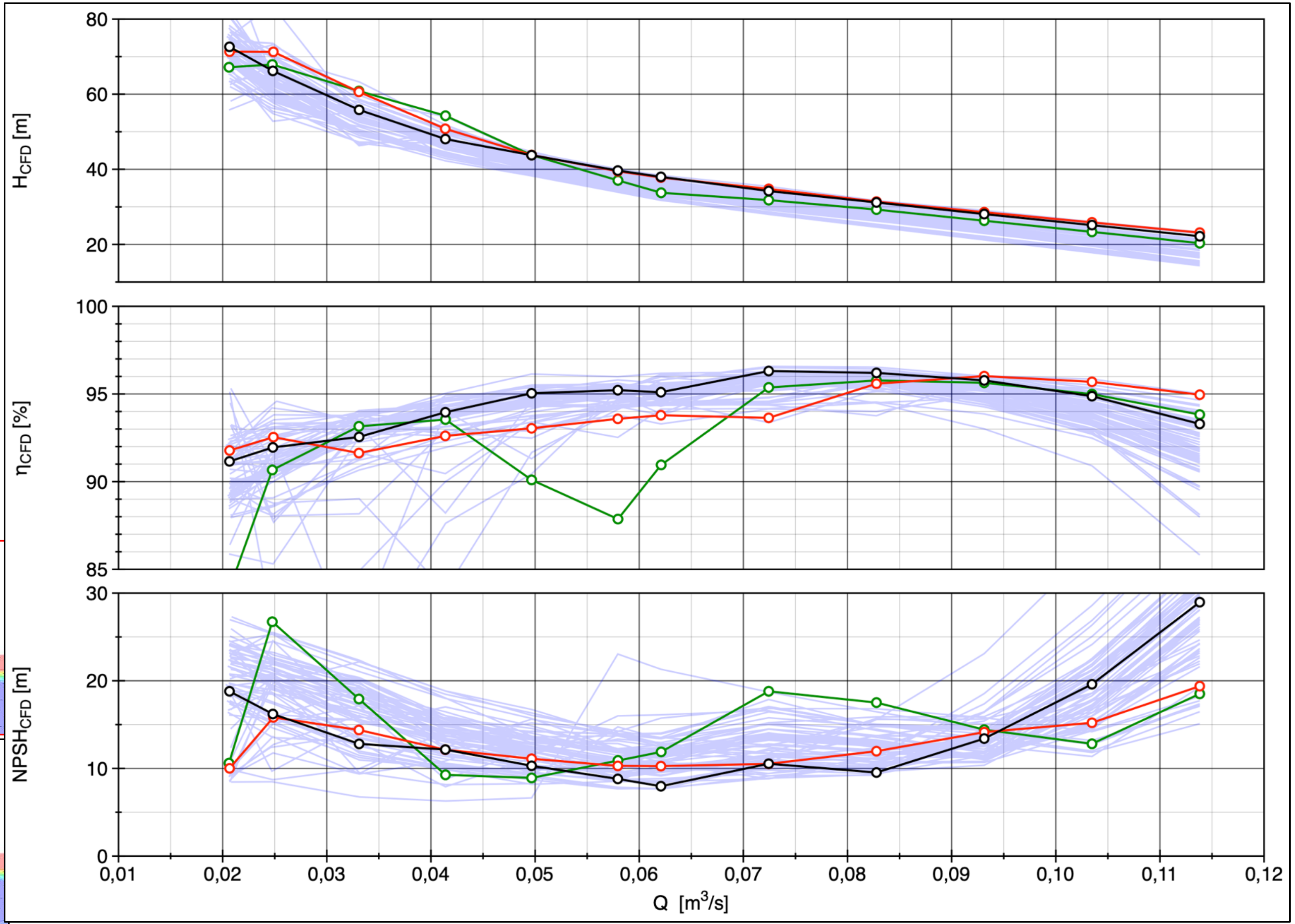
3 examples were chosen in the design process for further diffuser design







pictures show
meridional velocity distribution
at Q = 50% Q_{Design}



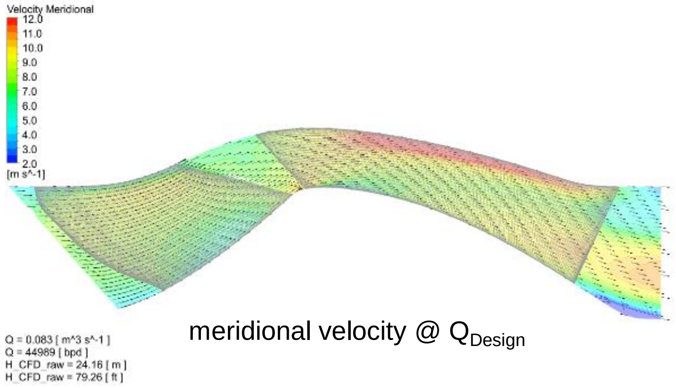
Selected Diffuser Design from Optimization Process

The most challenging task was to find an impeller / diffuser combination with a stable head curve.

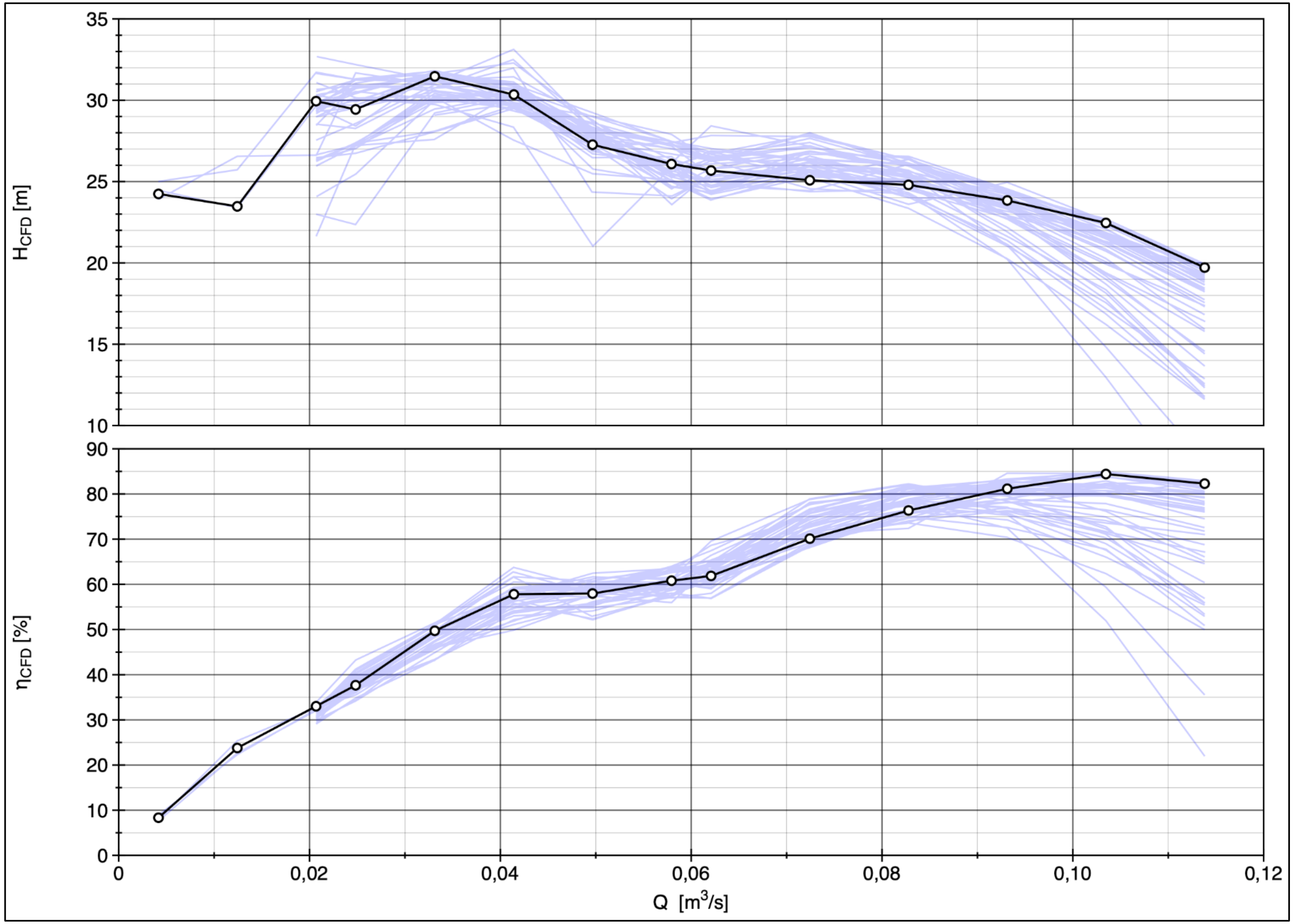
It turned out that in part load an increase of pump head beyond 30 m is not possible.

At least down to a flowrate of Q = 33 l /s (≙ 40% Q_{Design}) the numerical results of the optimized design show a stable head / flowrate behaviour.

To achieve this head curve stability the best efficiency point is shifted to a flow rate above Q_{Design} (approx. 120%)



meridional velocity @ Q_{Design}

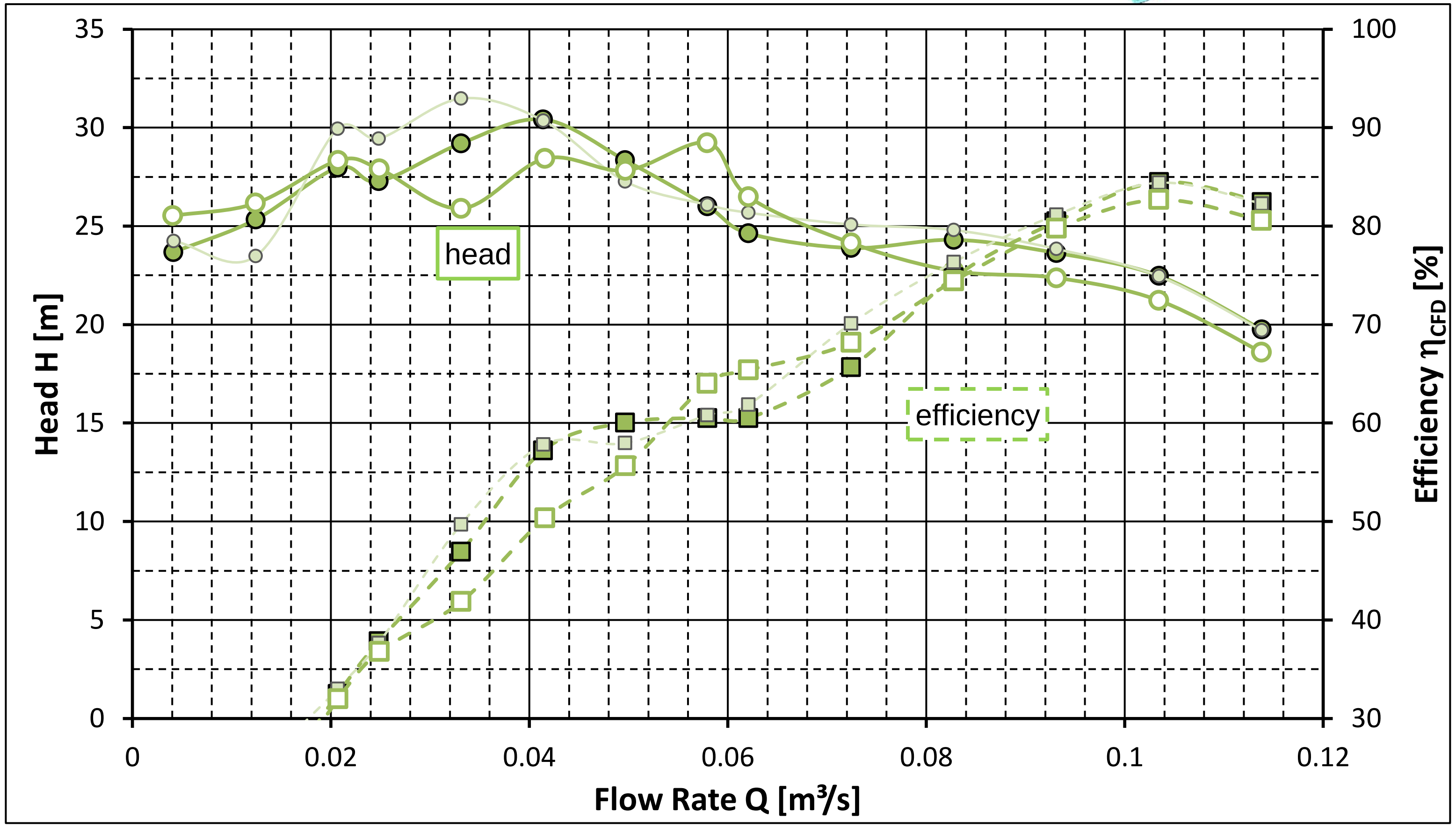


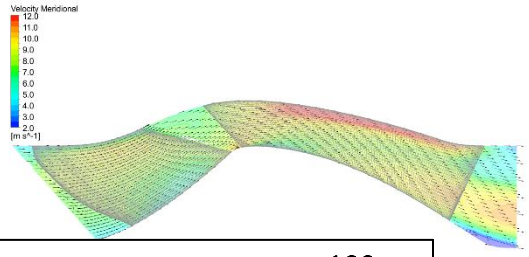
Comparison of different CFD-models

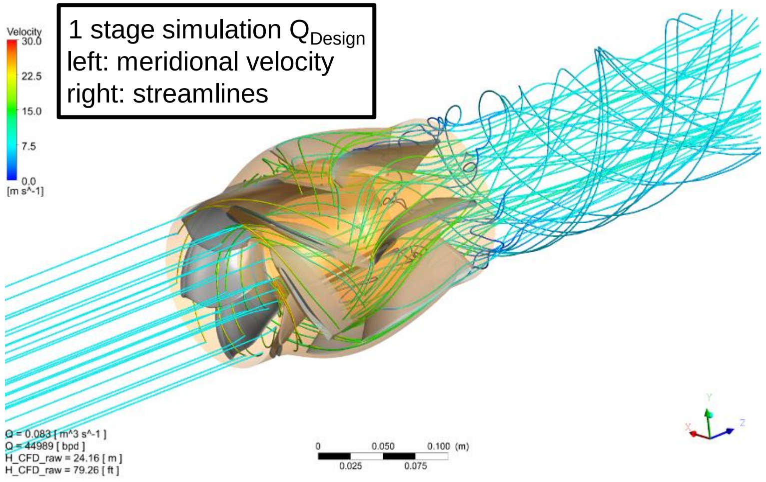
Bright green: simple model;

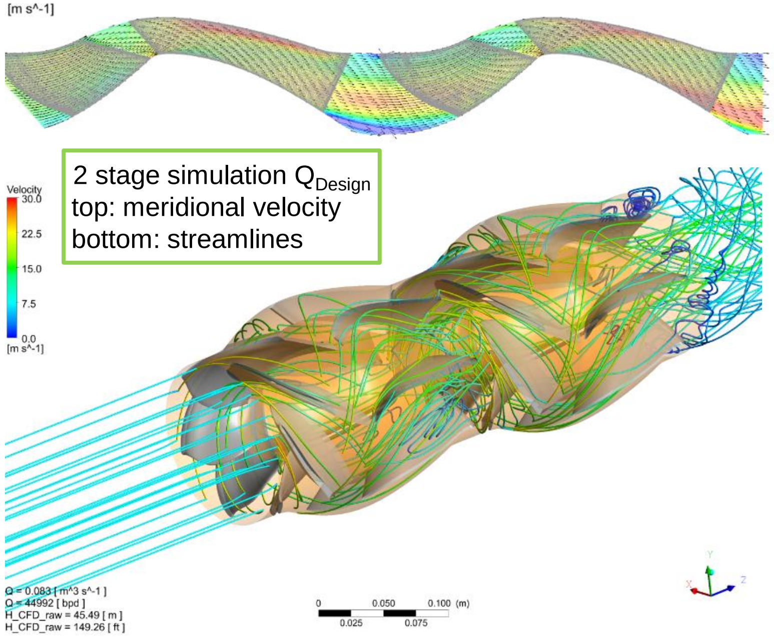
Coloured markers with black lines: full model 1 stage;

Blank markers with green lines: full model 2 stage;

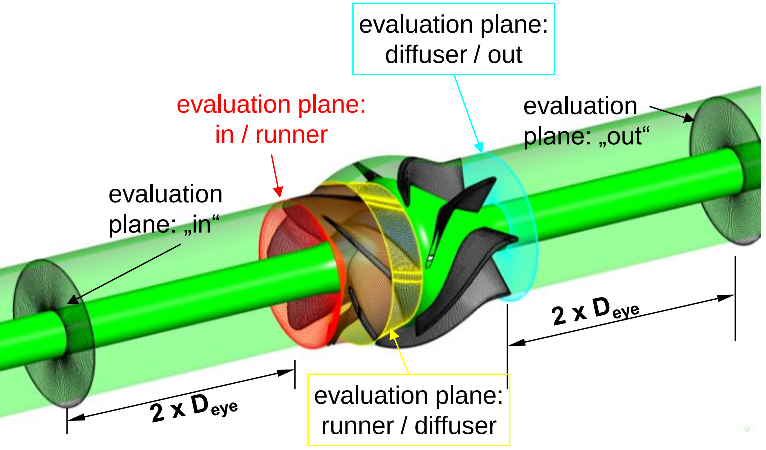


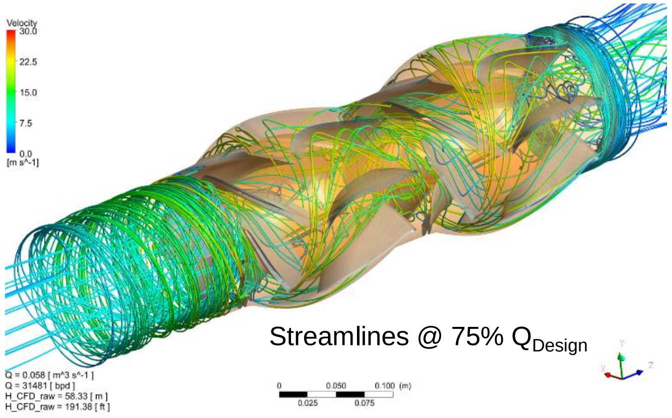




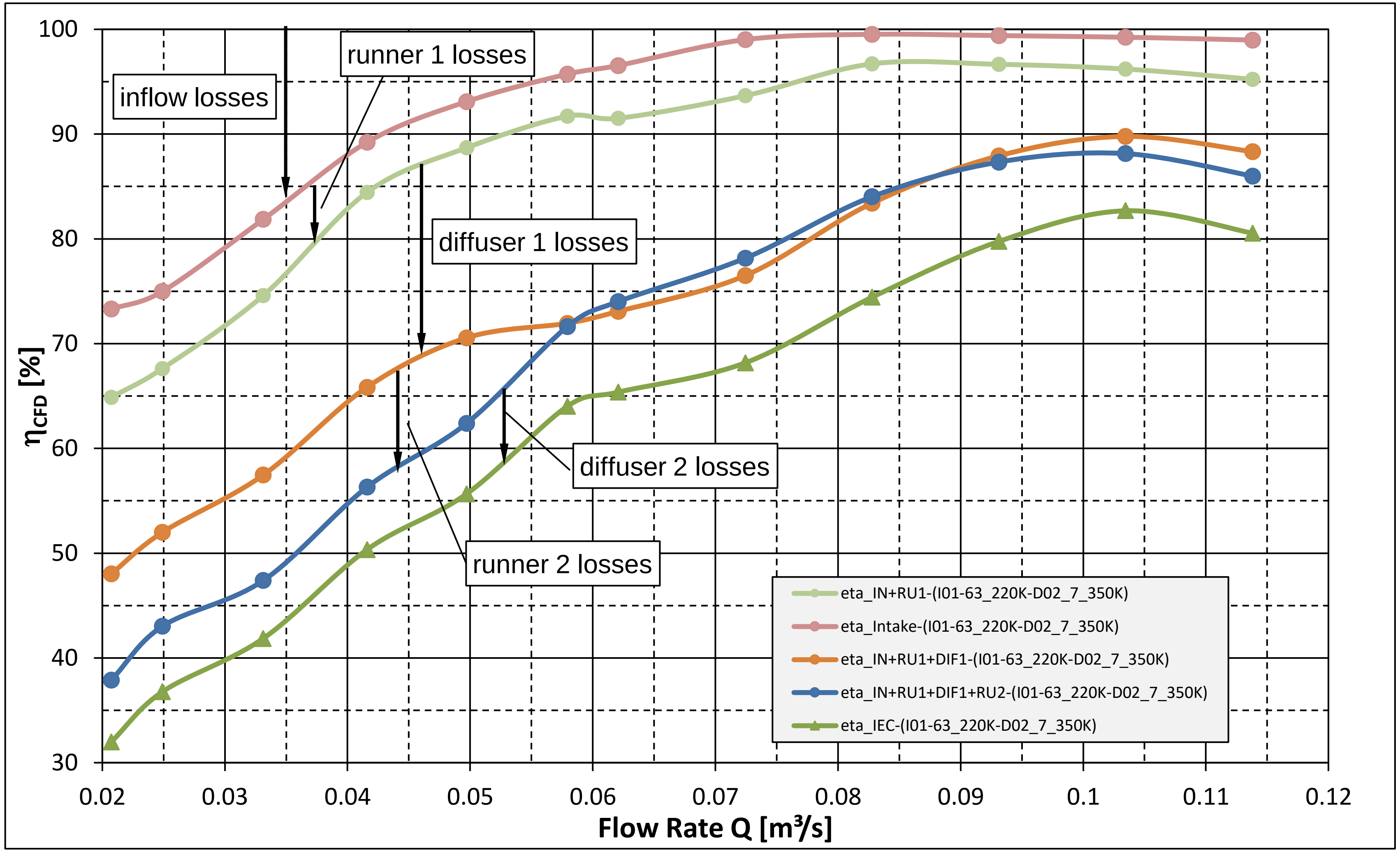


Loss analysis 2 stage-simulation

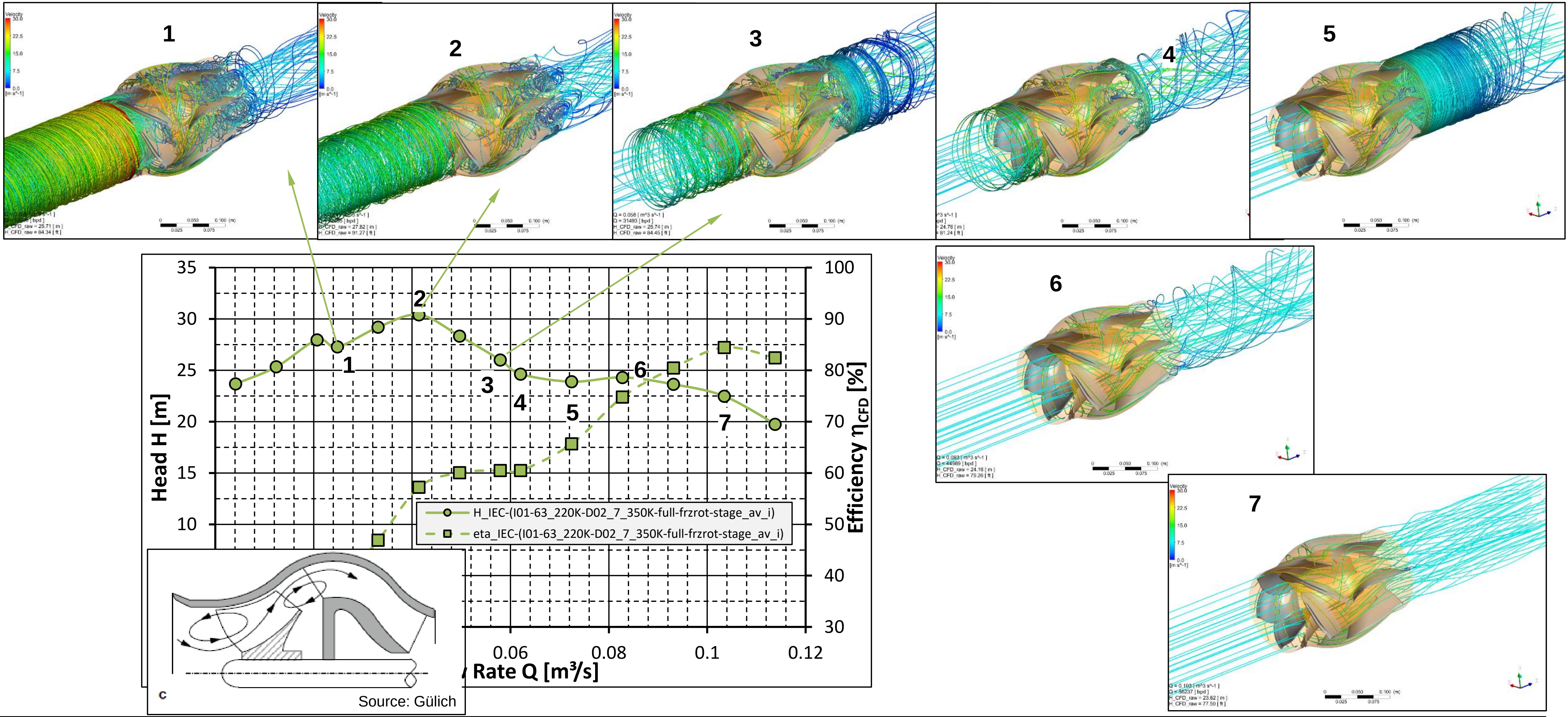




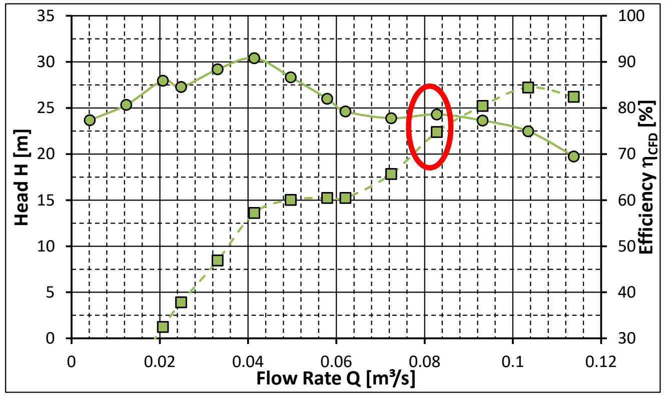
Streamlines @ 75% Q_{Design}



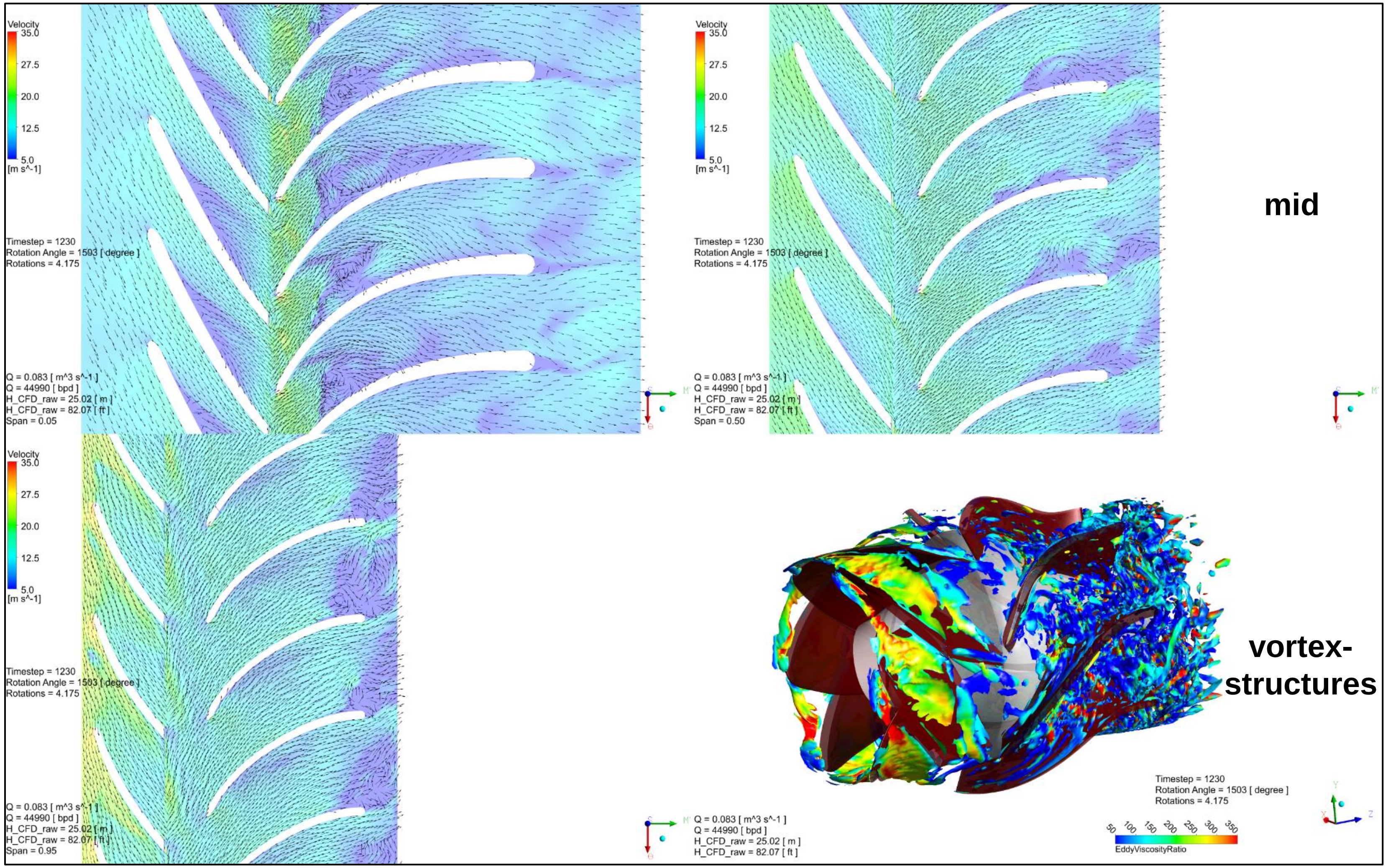
Streamlines reveal strong pre-swirl at part load



Transient CFD: Q_{Design}

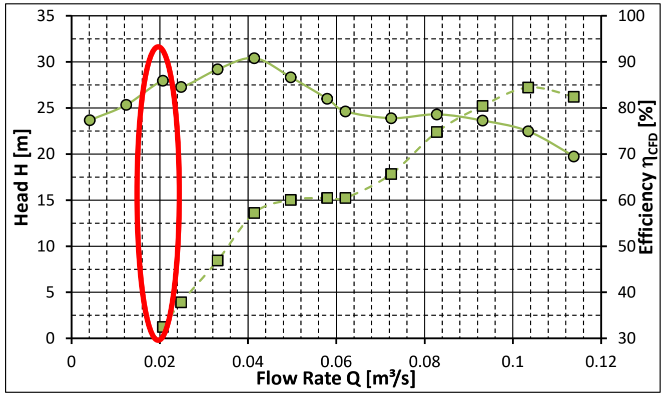


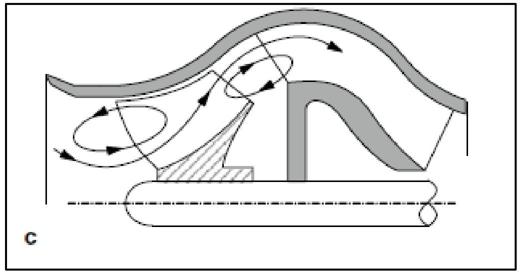
hub



shroud

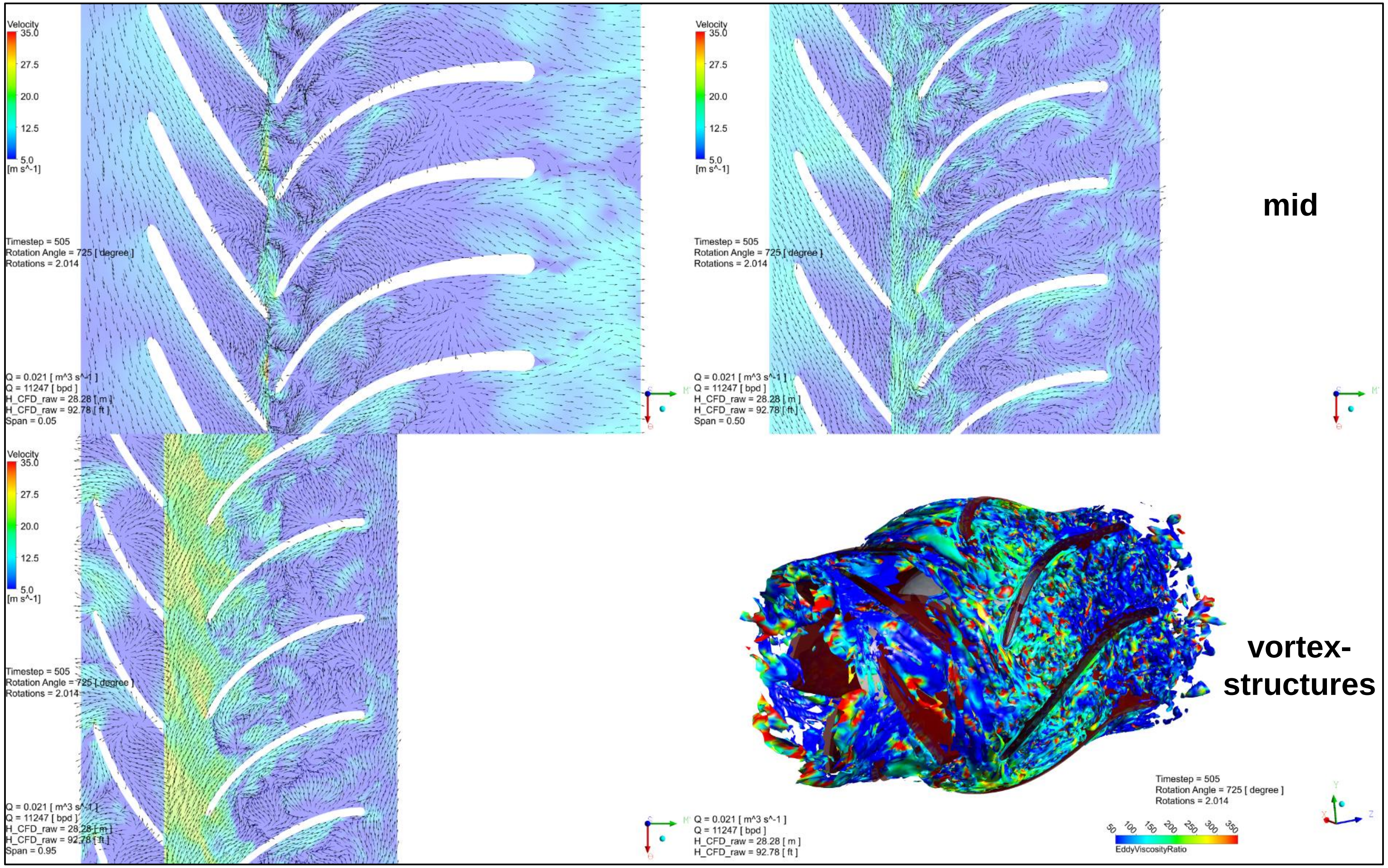
Transient CFD: Part-Load





hub

shroud



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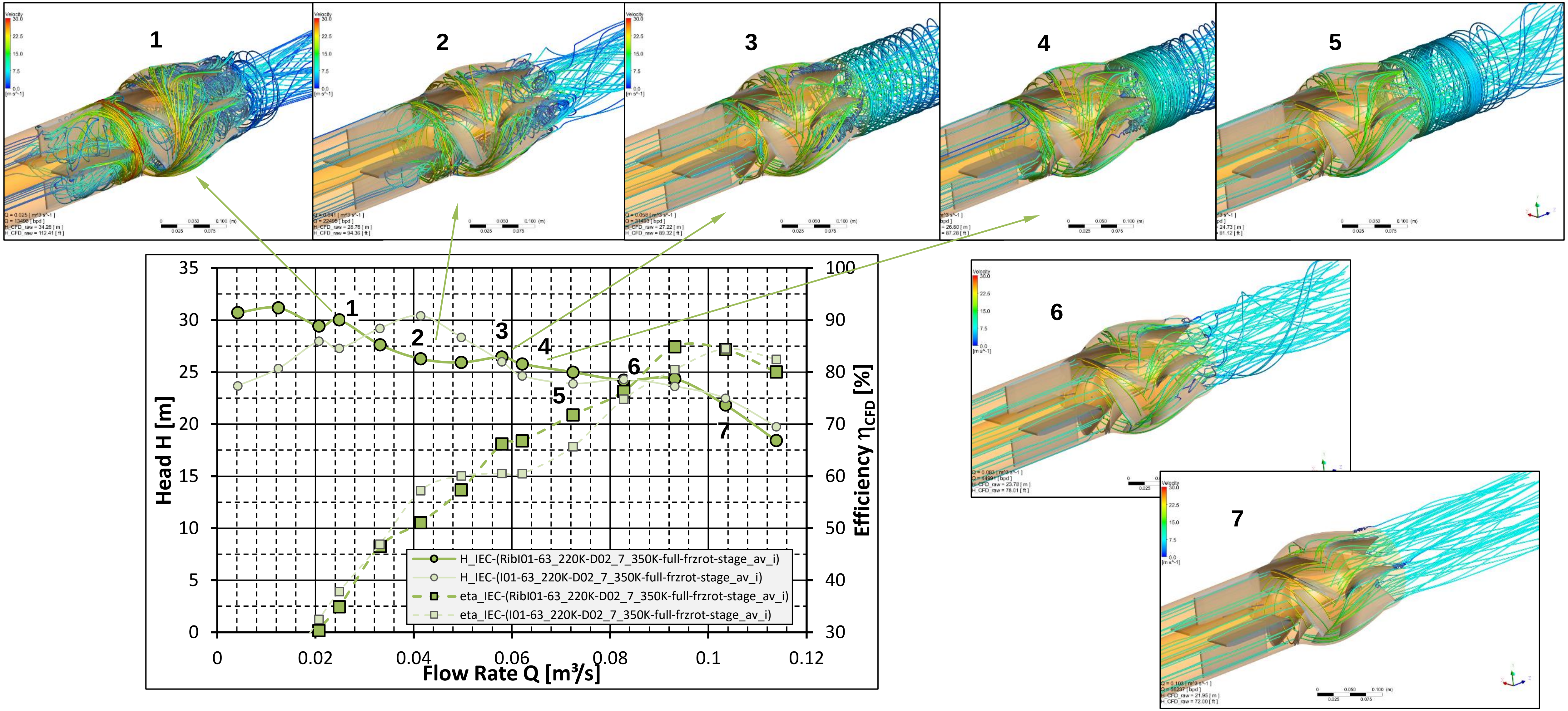
Pre-swirl suppression at part load with flow straightener at inlet



Summary / Outlook: Hydraulic design

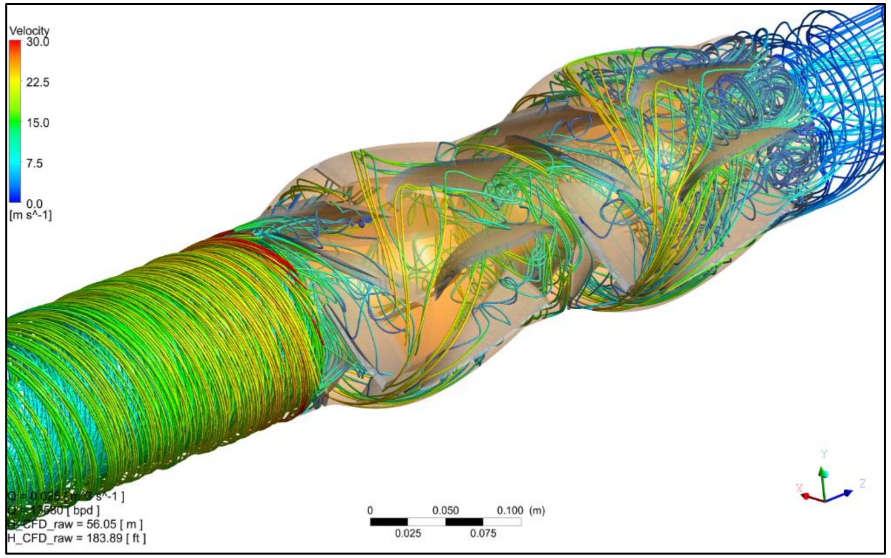
- CFD-results confirm the achievement of the design targets

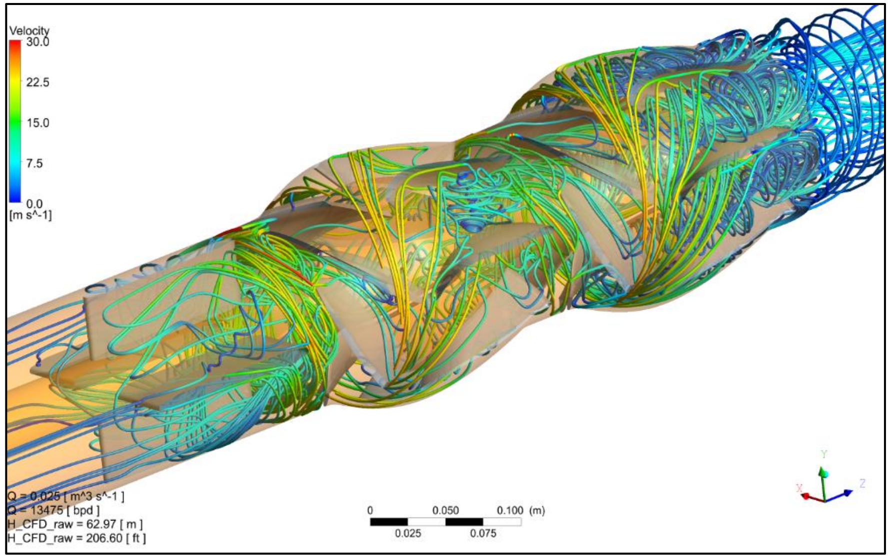
- Suction recirculation at deep part load was identified to be responsible for head curve instability a flow rates < 50 % Q_{Design}

  – Simulations with Ribs / Flow straightener showed the successful head curve stabilization when the Part-load swirl can be suppressed

  ➢ In the multi-stage arrangement the diffuser blades will operate as flow straightener for the following stage

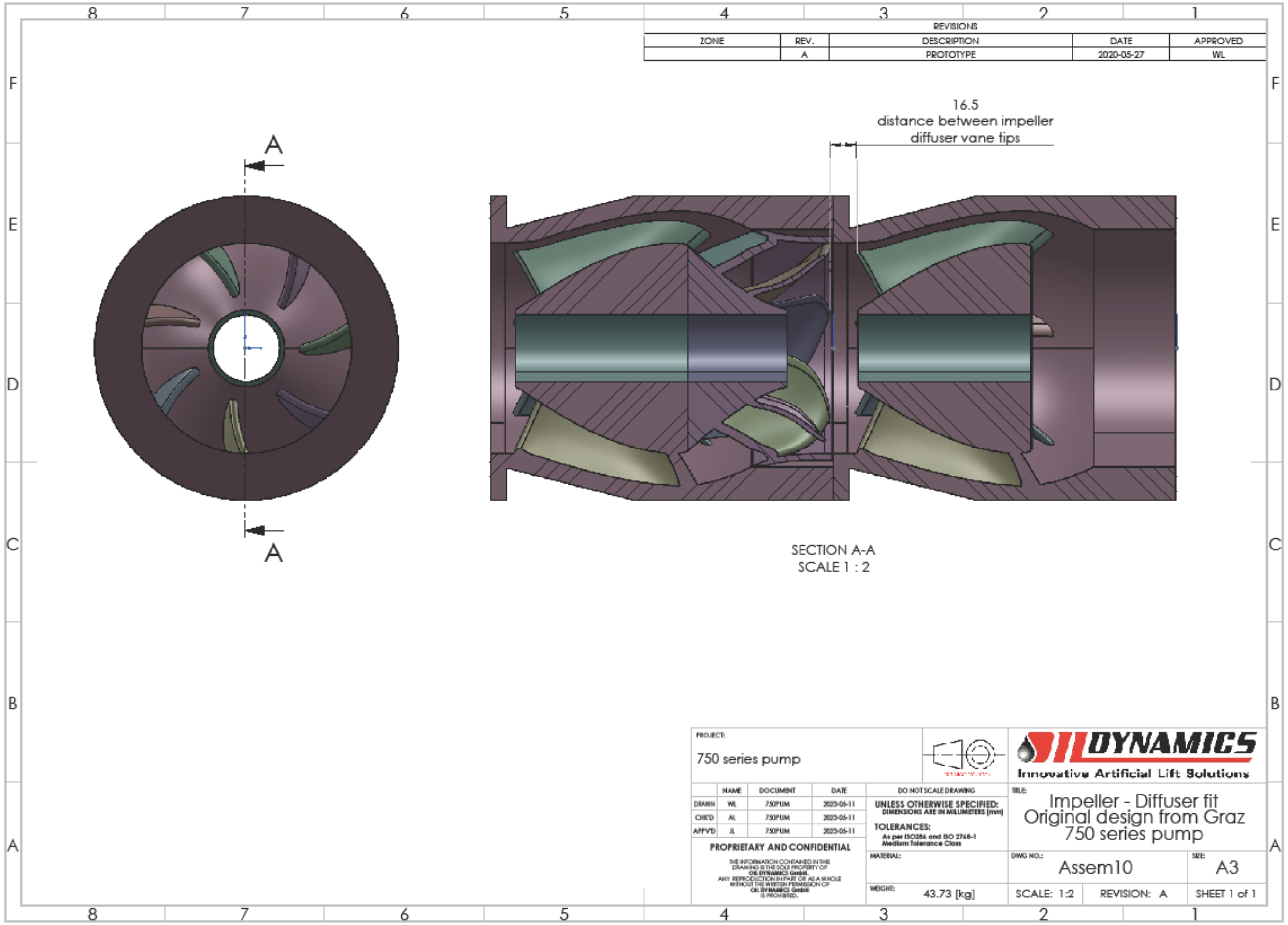
  ➢ The ribs in the pump inlet, which are necessary anyway (for reasons of mechanical stability), can serve as flow straighteners for the first pump stage





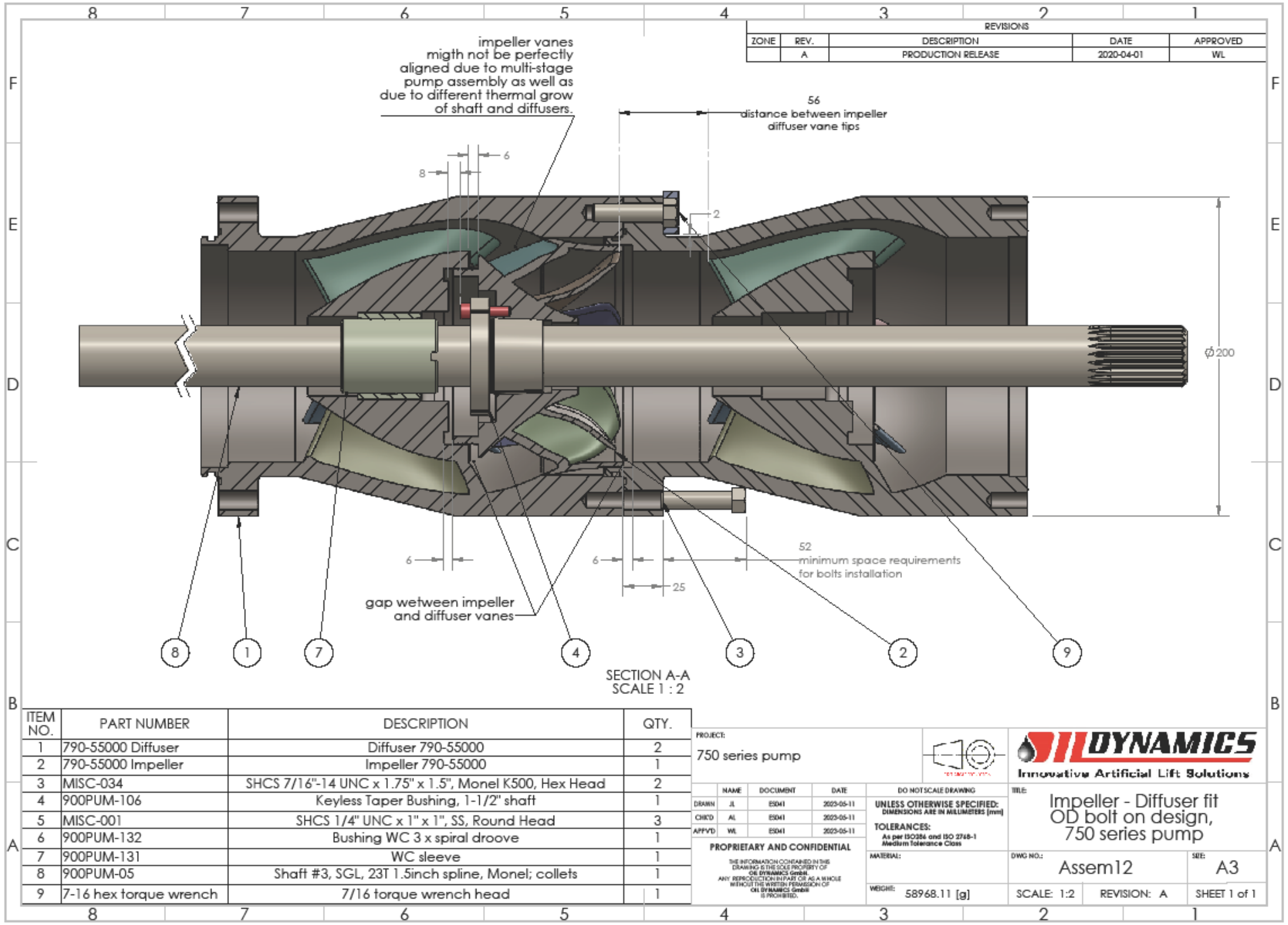
Production Design – starting model

OD = 190.5mm or 7.5” distance between vane tips – 16.5mm



Production Design – step #1

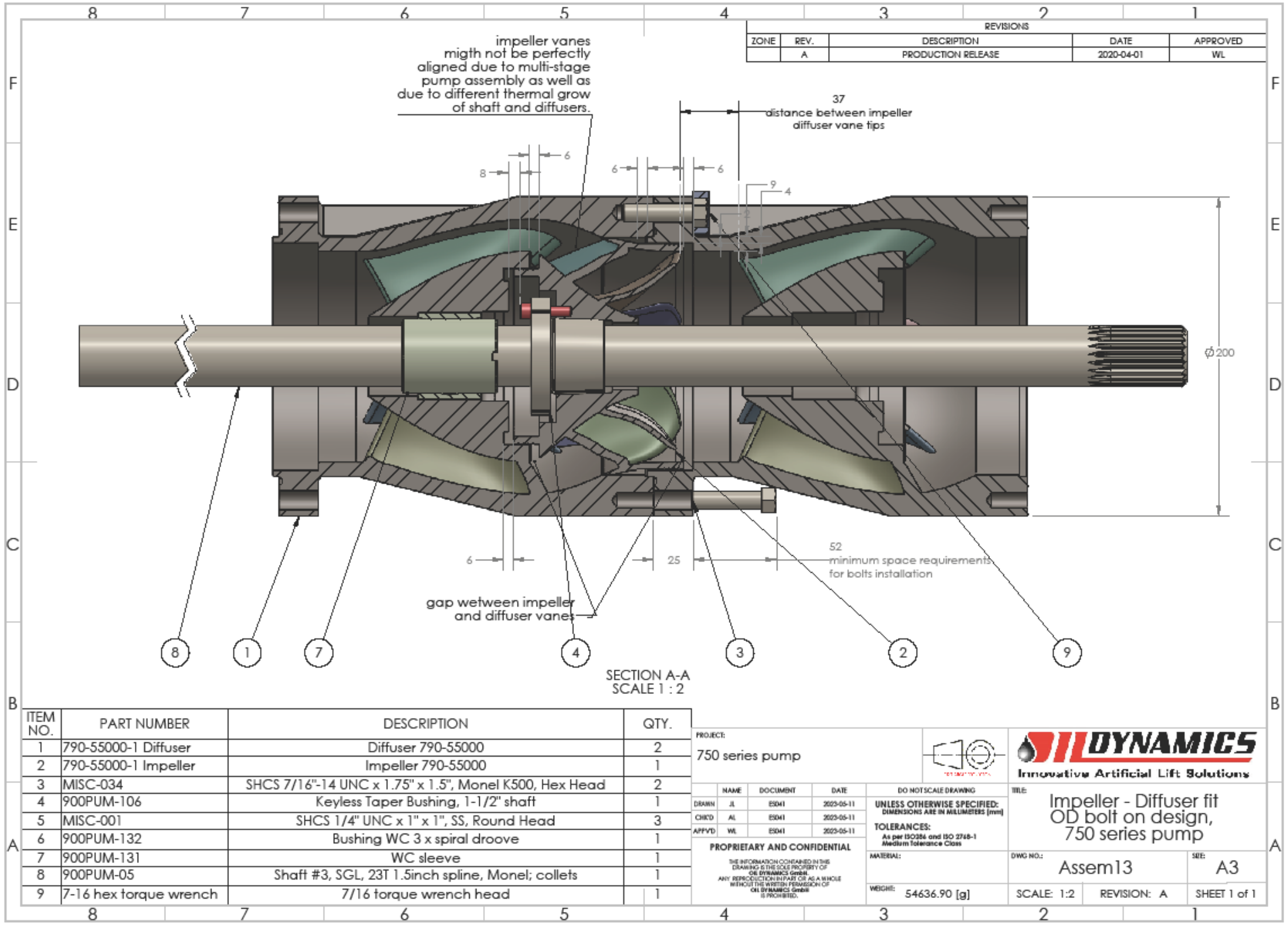
OD = 200mm or 7.87” distance between vane tips – 56mm



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	790-55000 Diffuser	Diffuser 790-55000	2
2	790-55000 Impeller	Impeller 790-55000	1
3	MISC-034	SHCS 7/16"-14 UNC x 1.75" x 1.5", Monel K500, Hex Head	2
4	900PUM-106	Keyless Taper Bushing, 1-1/2" shaft	1
5	MISC-001	SHCS 1/4" UNC x 1" x 1", SS, Round Head	3
6	900PUM-132	Bushing WC 3 x spiral droove	1
7	900PUM-131	WC sleeve	1
8	900PUM-05	Shaft #3, SGL, 23T 1.5inch spline, Monel; collets	1
9	7-16 hex torque wrench	7/16 torque wrench head	1

Production Design – step #2

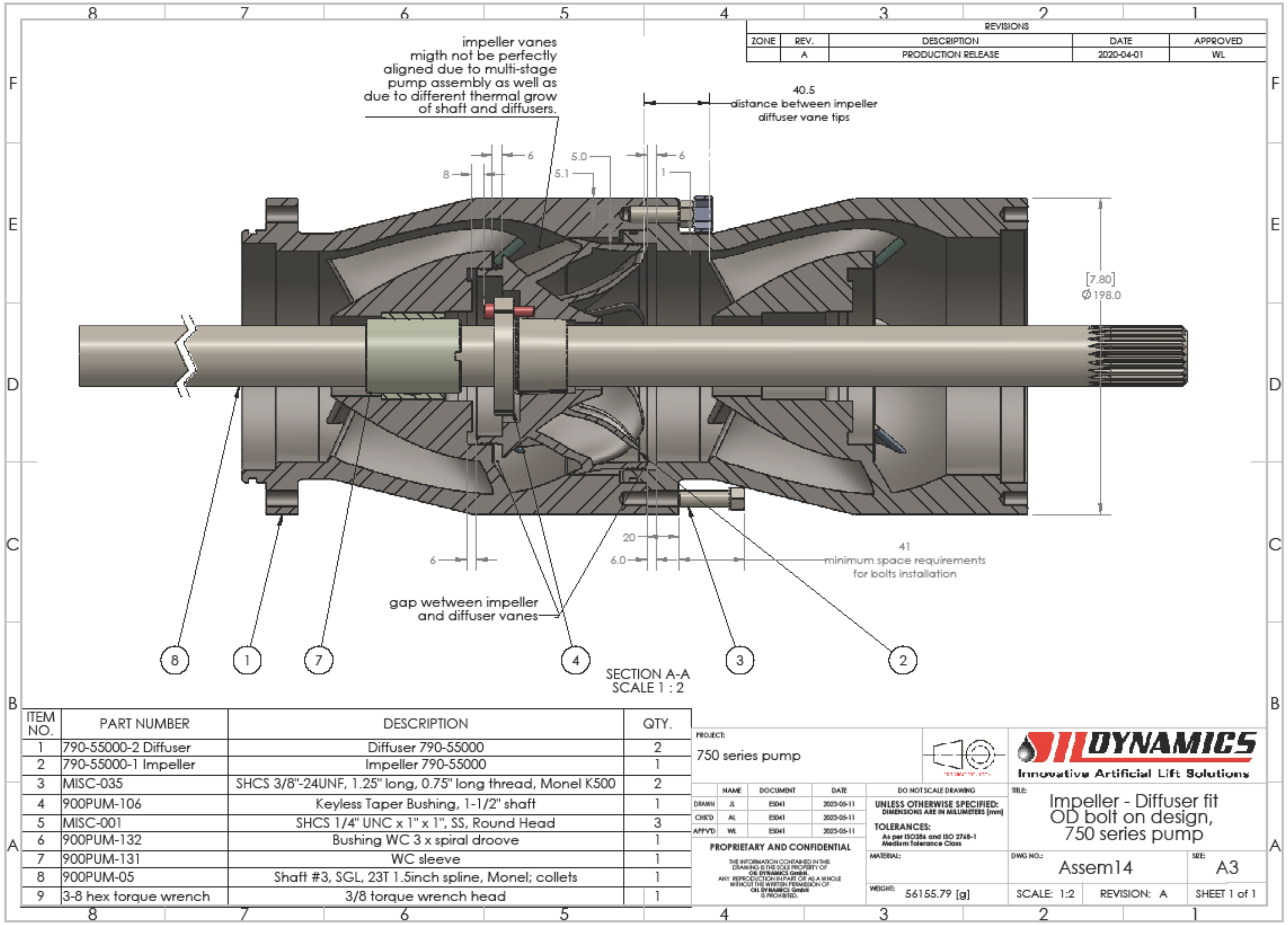
OD = 200mm or 7.87”   distance between vane tips – 37mm



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	790-55000-1 Diffuser	Diffuser 790-55000	2
2	790-55000-1 Impeller	Impeller 790-55000	1
3	MISC-034	SHCS 7/16"-14 UNC x 1.75" x 1.5", Monel K500, Hex Head	2
4	900PUM-106	Keyless Taper Bushing, 1-1/2" shaft	1
5	MISC-001	SHCS 1/4" UNC x 1" x 1", SS, Round Head	3
6	900PUM-132	Bushing WC 3 x spiral droove	1
7	900PUM-131	WC sleeve	1
8	900PUM-05	Shaft #3, SGL, 23T 1.5inch spline, Monel; collets	1
9	7-16 hex torque wrench	7/16 torque wrench head	1

Production Design – step #3

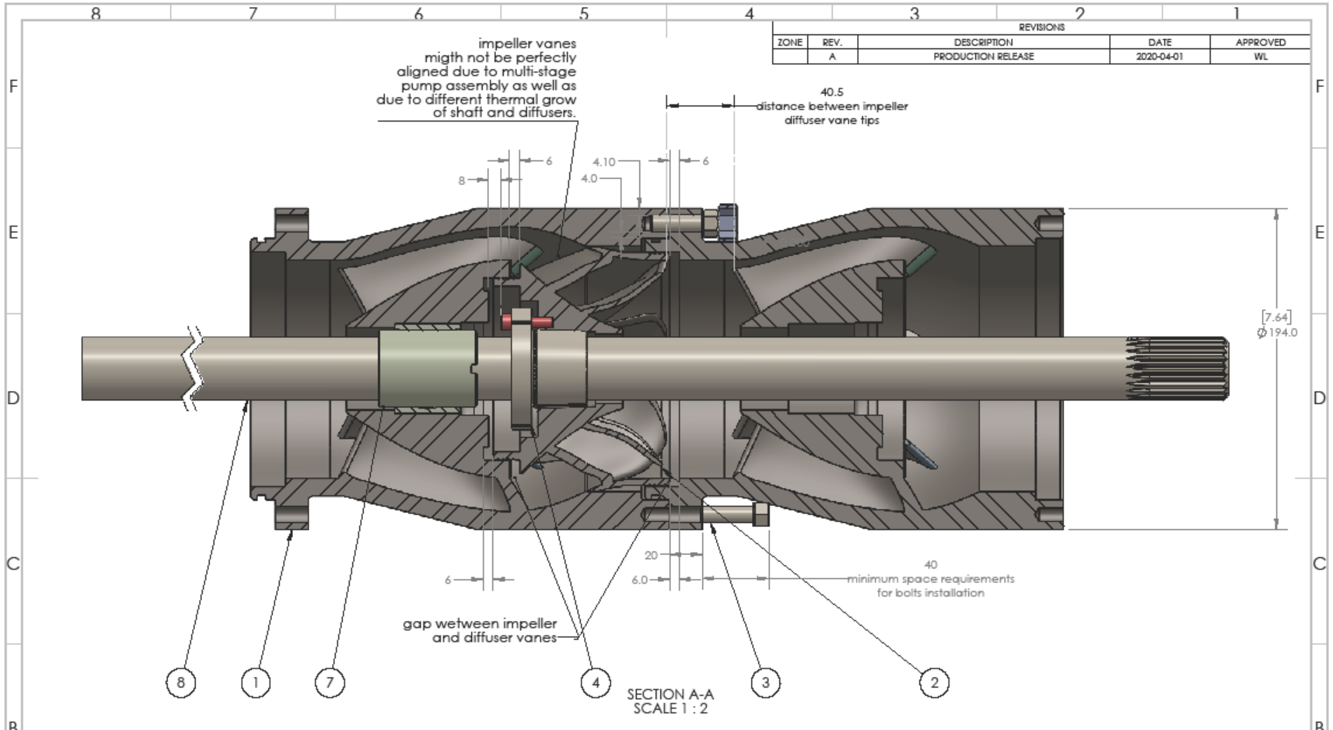
OD = 200mm or 7.8” distance between vane tips – 40.5mm



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	790-55000-2 Diffuser	Diffuser 790-55000	2
2	790-55000-1 Impeller	Impeller 790-55000	1
3	MISC-035	SHCS 3/8"-24UNF, 1.25" long, 0.75" long thread, Monel K500	2
4	900PUM-106	Keyless Taper Bushing, 1-1/2" shaft	1
5	MISC-001	SHCS 1/4" UNC x 1" x 1", SS, Round Head	3
6	900PUM-132	Bushing WC 3 x spiral droove	1
7	900PUM-131	WC sleeve	1
8	900PUM-05	Shaft #3, SGL, 23T 1.5inch spline, Monel; collets	1
9	3-8 hex torque wrench	3/8 torque wrench head	1

Production Design – step #4

OD = 200mm or 7.64”   distance between vane tips – 40.5mm



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	790-55000-3 Diffuser	Diffuser 790-55000	2
2	790-55000-1 Impeller	Impeller 790-55000	1
3	MISC-035	SHCS 3/8"-24UNF, 1.25" long, 0.75" long thread, Monel K500	2
4	900PUM-106	Keyless Taper Bushing, 1-1/2" shaft	1
5	MISC-001	SHCS 1/4" UNC x 1" x 1", SS, Round Head	3
6	900PUM-132	Bushing WC 3 x spiral droove	1
7	900PUM-131	WC sleeve	1
8	900PUM-05	Shaft #3, SGL, 23T 1.5inch spline, Monel; collets	1
9	3-8 hex torque wrench	3/8 torque wrench head	1

PROJECT: 750 series pump

OIL DYNAMICS Innovative Artificial Lift Solutions

	NAME	DOCUMENT	DATE
DRAWN	JL	ESD41	2023-05-11
CHK'D	AL	ESD41	2023-05-11
APPV'D	WL	ESD41	2023-05-11

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DO NOT SCALE DRAWING

UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS [mm]

TOLERANCES: As per ISO286 and ISO 2768-1 Medium Tolerance Class

MATERIAL:

WEIGHT: 53635.77 [g]

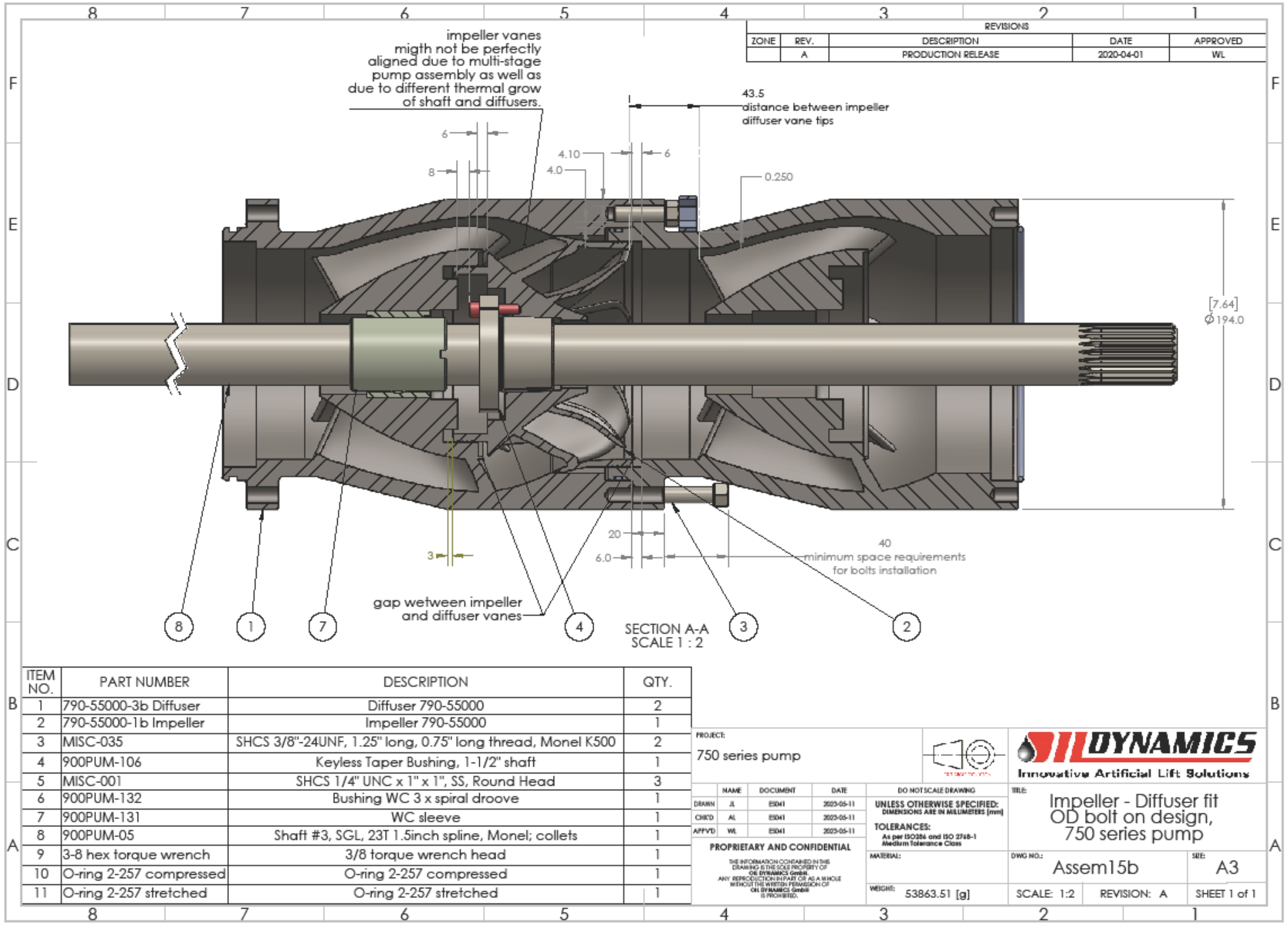
TITLE: Impeller - Diffuser fit OD bolt on design, 750 series pump

DWG NO.: Assem15 | SIZE: A3

SCALE: 1:2 | REVISION: A | SHEET 1 of 1

Production Design – step #5

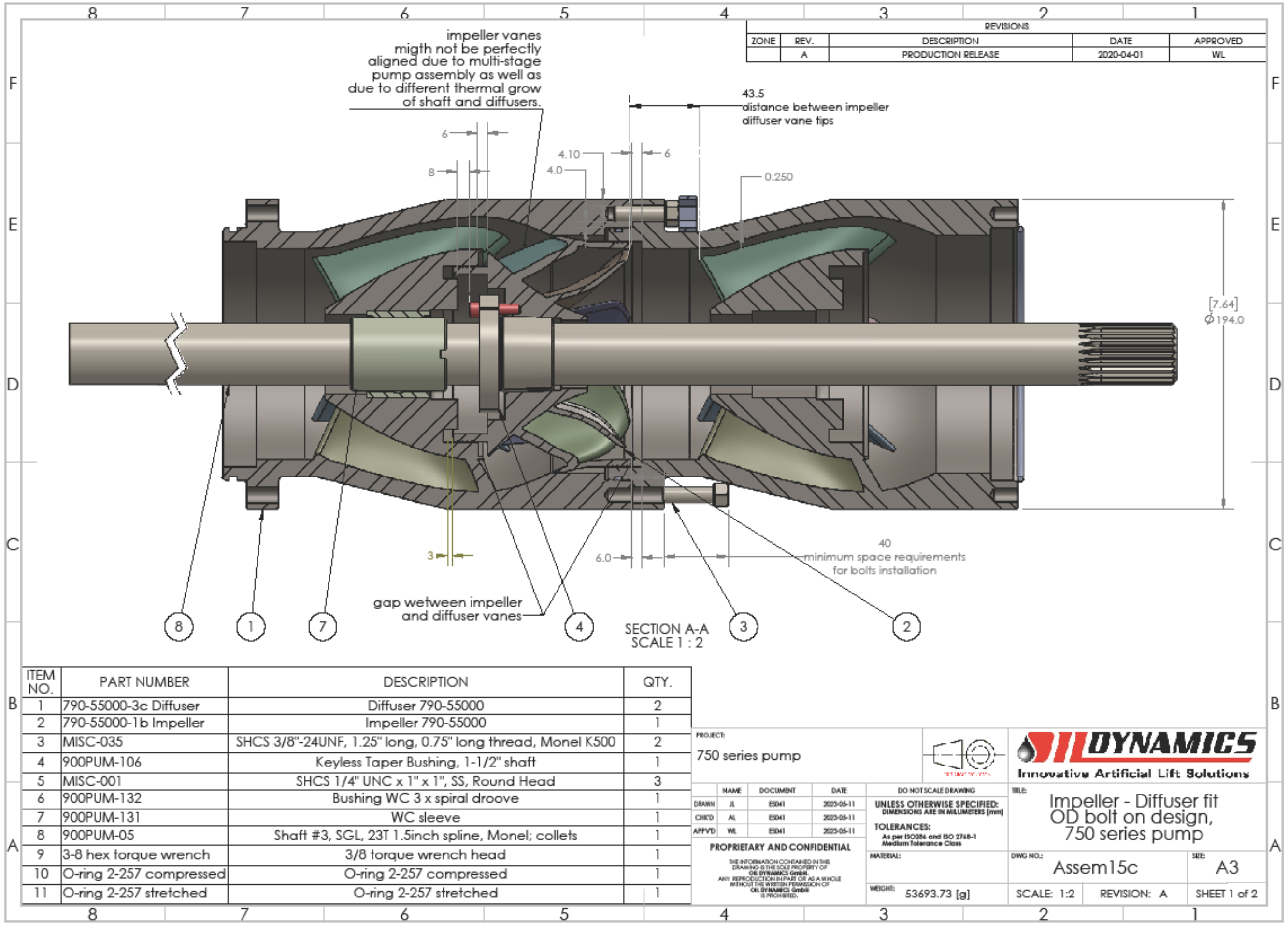
OD = 200mm or 7.64”   distance between vane tips – 43.5mm



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	790-55000-3b Diffuser	Diffuser 790-55000	2
2	790-55000-1b Impeller	Impeller 790-55000	1
3	MISC-035	SHCS 3/8"-24UNF, 1.25" long, 0.75" long thread, Monel K500	2
4	900PUM-106	Keyless Taper Bushing, 1-1/2" shaft	1
5	MISC-001	SHCS 1/4" UNC x 1" x 1", SS, Round Head	3
6	900PUM-132	Bushing WC 3 x spiral droove	1
7	900PUM-131	WC sleeve	1
8	900PUM-05	Shaft #3, SGL, 23T 1.5inch spline, Monel; collets	1
9	3-8 hex torque wrench	3/8 torque wrench head	1
10	O-ring 2-257 compressed	O-ring 2-257 compressed	1
11	O-ring 2-257 stretched	O-ring 2-257 stretched	1

Production Design – step #6

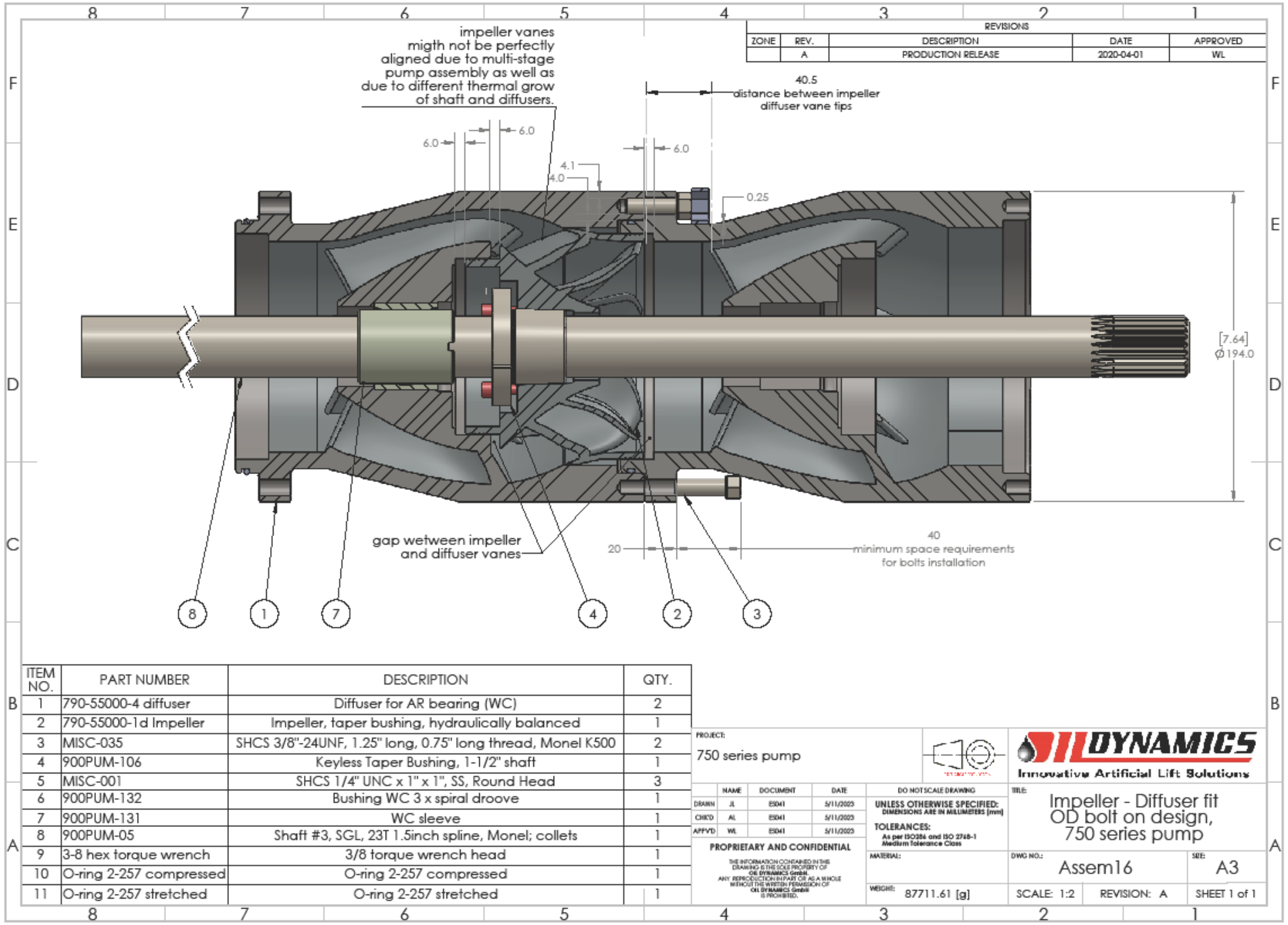
OD = 200mm or 7.64” distance between vane tips – 43.5mm



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	790-55000-3c Diffuser	Diffuser 790-55000	2
2	790-55000-1b Impeller	Impeller 790-55000	1
3	MISC-035	SHCS 3/8"-24UNF, 1.25" long, 0.75" long thread, Monel K500	2
4	900PUM-106	Keyless Taper Bushing, 1-1/2" shaft	1
5	MISC-001	SHCS 1/4" UNC x 1" x 1", SS, Round Head	3
6	900PUM-132	Bushing WC 3 x spiral droove	1
7	900PUM-131	WC sleeve	1
8	900PUM-05	Shaft #3, SGL, 23T 1.5inch spline, Monel; collets	1
9	3-8 hex torque wrench	3/8 torque wrench head	1
10	O-ring 2-257 compressed	O-ring 2-257 compressed	1
11	O-ring 2-257 stretched	O-ring 2-257 stretched	1

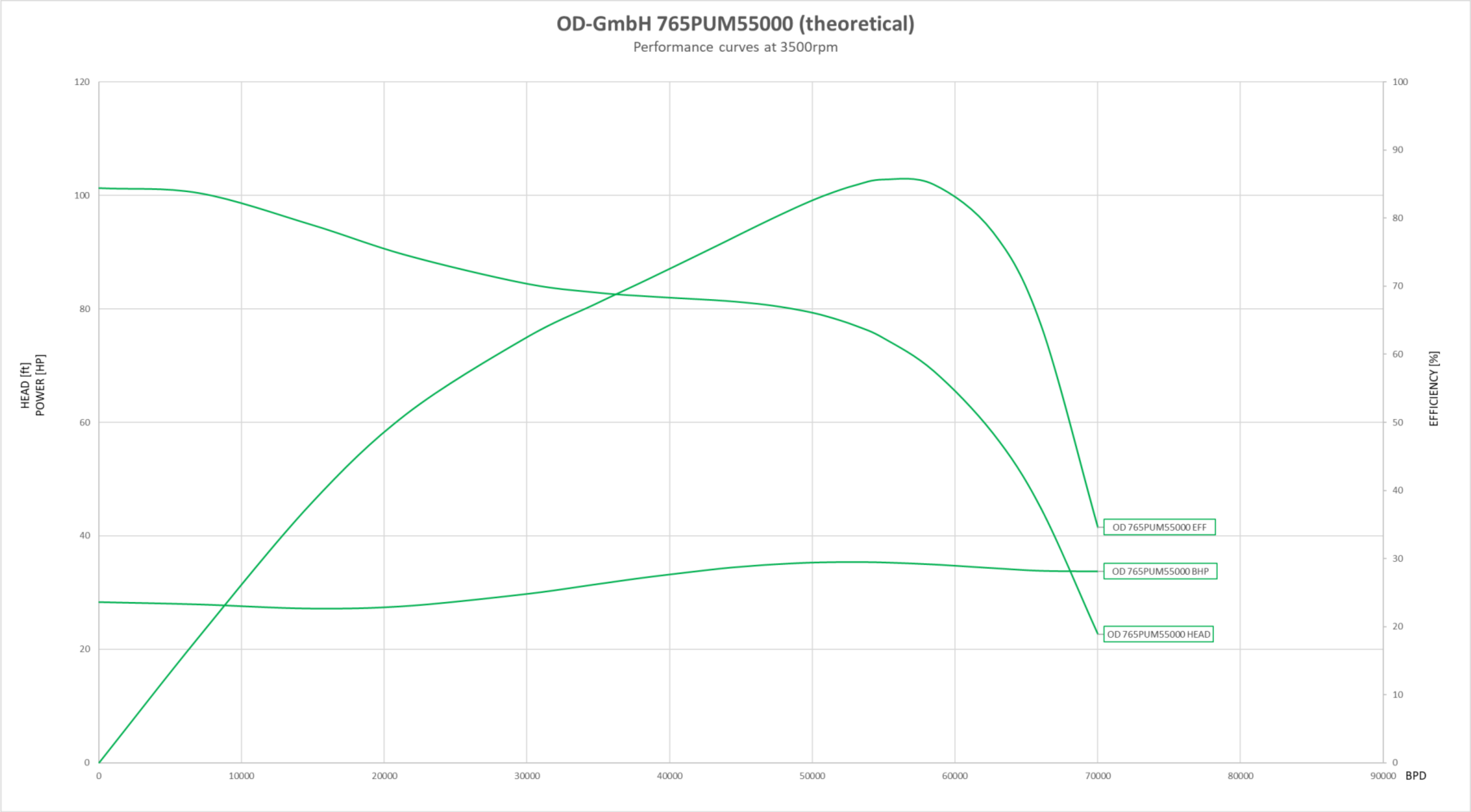
Production Design – Production Release

OD = 200mm or 7.64” distance between vane tips – 40.5mm

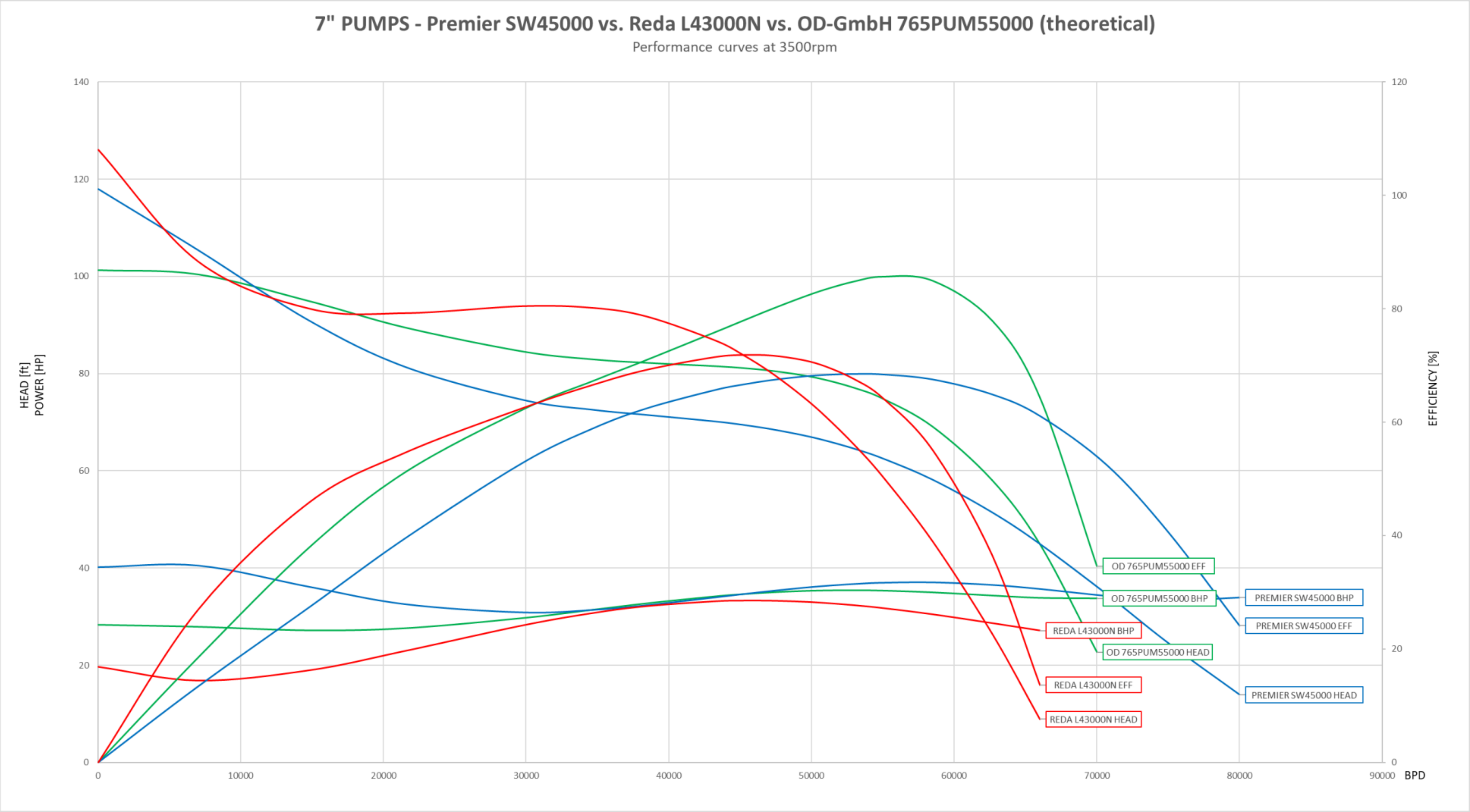


ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	790-55000-4 diffuser	Diffuser for AR bearing (WC)	2
2	790-55000-1d Impeller	Impeller, taper bushing, hydraulically balanced	1
3	MISC-035	SHCS 3/8"-24UNF, 1.25" long, 0.75" long thread, Monel K500	2
4	900PUM-106	Keyless Taper Bushing, 1-1/2" shaft	1
5	MISC-001	SHCS 1/4" UNC x 1" x 1", SS, Round Head	3
6	900PUM-132	Bushing WC 3 x spiral droove	1
7	900PUM-131	WC sleeve	1
8	900PUM-05	Shaft #3, SGL, 23T 1.5inch spline, Monel; collets	1
9	3-8 hex torque wrench	3/8 torque wrench head	1
10	O-ring 2-257 compressed	O-ring 2-257 compressed	1
11	O-ring 2-257 stretched	O-ring 2-257 stretched	1

OD-GmbH 765-55000 (theoretical)

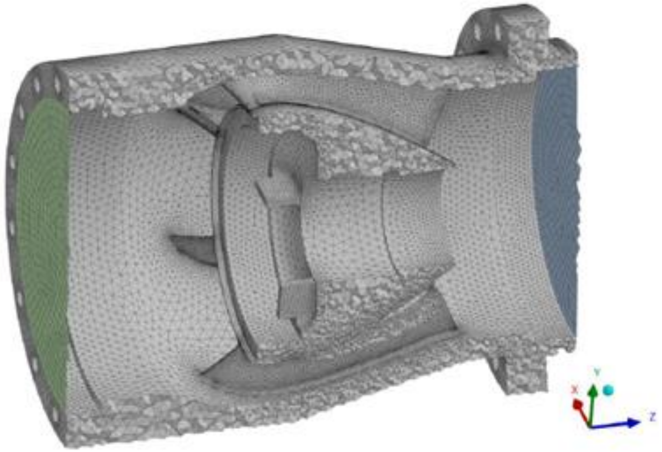


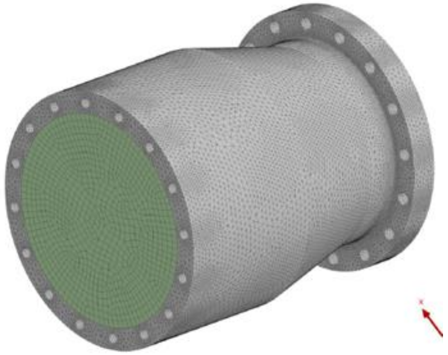
OD-GmbH pump vs. Competition

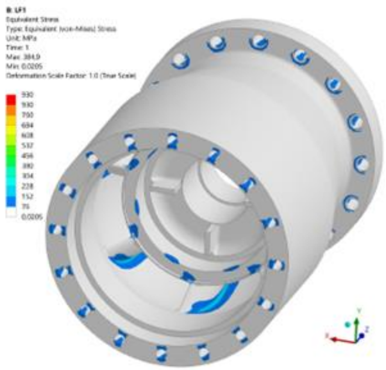


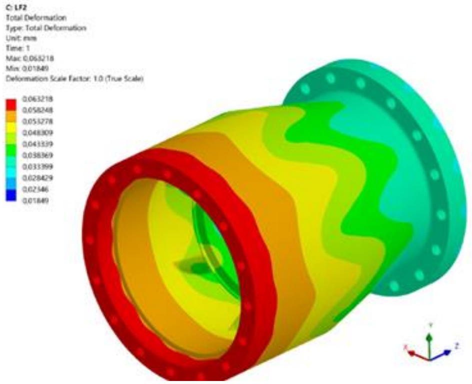
Production Design - FEA

Inner pressure acting on diffuser – 105Bar
Bending moment – 500Nm
Maximum temperature 160°C
Minimum temperature 50°C
Temperature gradient - 110°C
Axial thrust load 120kN
Motor weight below pump – 4T









Production Design