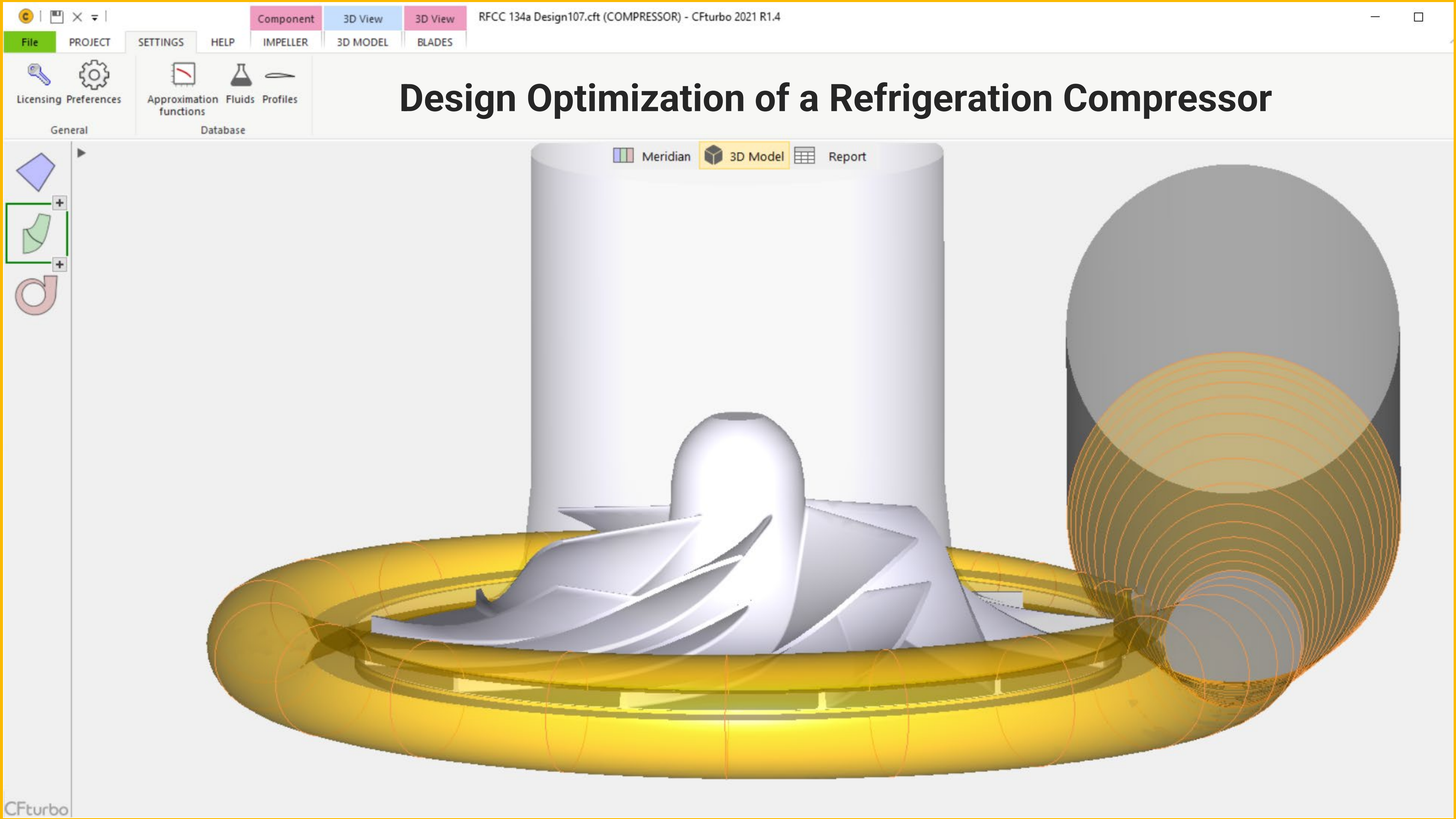
# Design Optimization of a Refrigeration Compressor

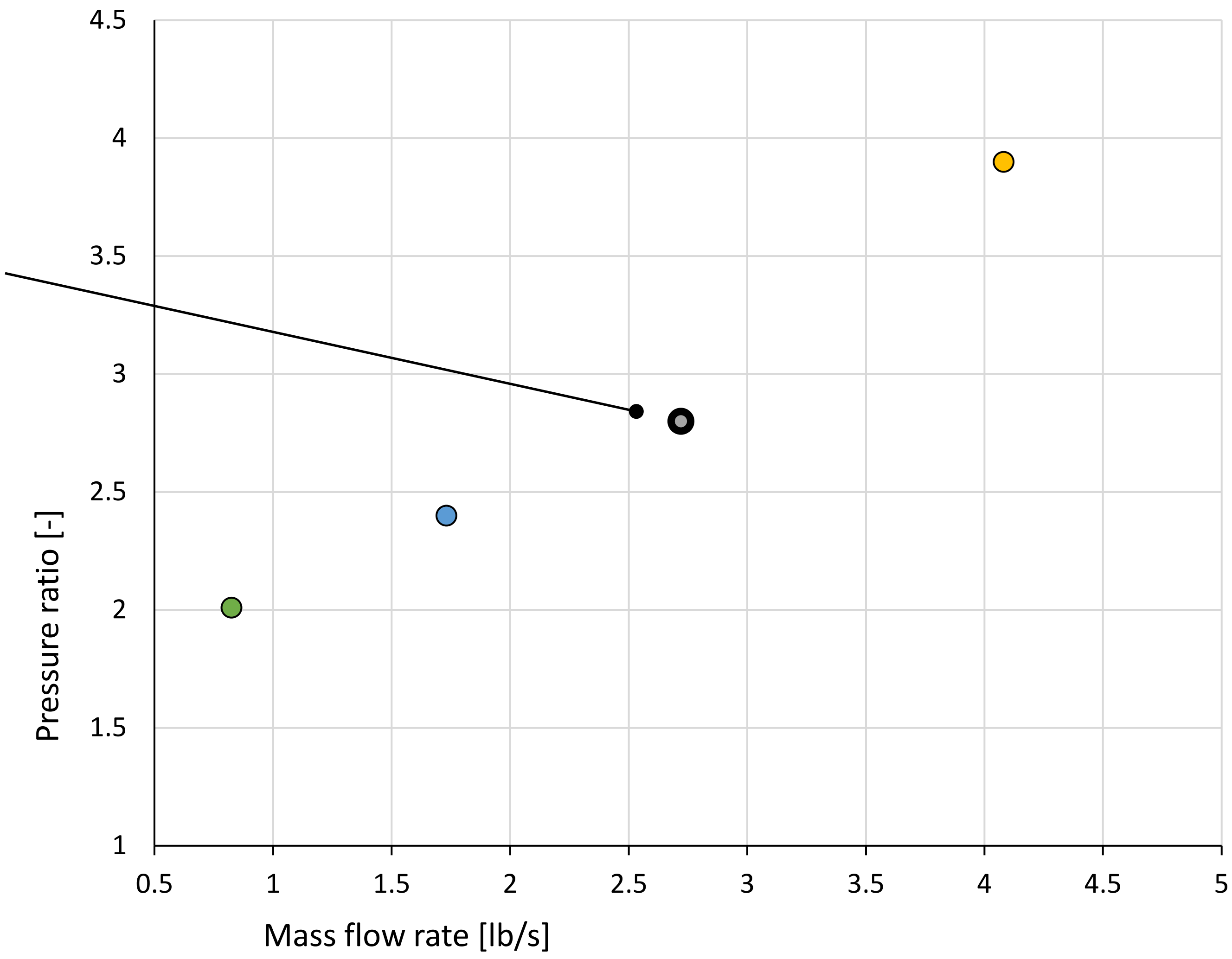


# Summary

- Conceptual design of a centrifugal compressor R134a
- Software: CFturbo, integrated into Ansys Workbench
- One initial design + one manual design variation, “Design2”
- Mathematical optimization using CFturbo/Ansys Workbench/Design Explorer
  - 8 geometry parameters, 141 different designs in total
  - All design points meet the performance requirements at selected rpm
- Substantial stage efficiency improvement at design speed
  - Initial design: $\eta$=56%
  - Manual “Design2”: $\eta$= 59%
  - Optimized “Design107”: $\eta$= 73%
- Total project time: 10 days
- Next steps
  - Adjustments and fine-tuning, for example blade loading variation and volute parameters
  - 360° impeller model and transient simulations for final check of steady-state results

# 1 Design target points

| | Speed | Pt | Tt | Mass flow rate | Pressure ratio Πts |
|---|---|---|---|---|---|
| | rpm | psi | F | lb/s | - |
| | 44000 | 50 | 60 | 4.1 | 3.9 |
| **Design target** | **36000** | **50** | **60** | **2.7** | **2.8** |
| | 32000 | 50 | 60 | 1.7 | 2.4 |
| | 30000 | 50 | 60 | 0.8 | 2.0 |



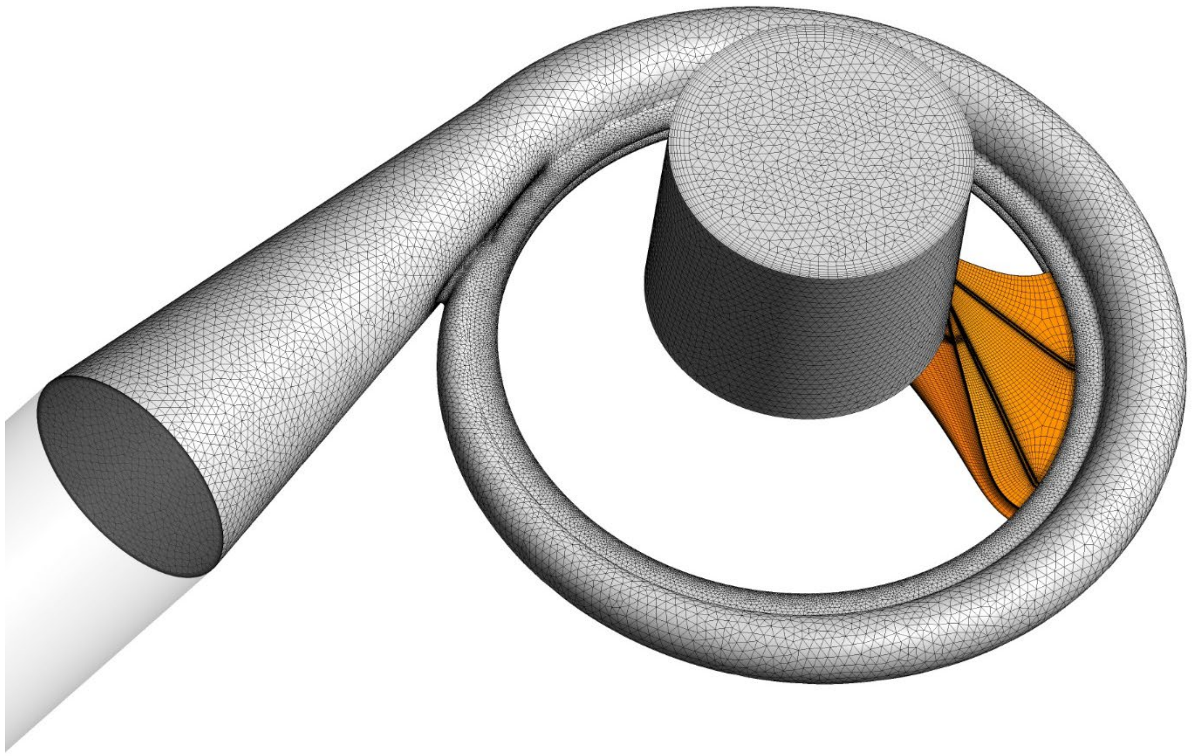

**Inlet** Total pressure p = 50 psi
**Outlet** Mass flow or static pressure

**Fluid** R134a (Real Gas)

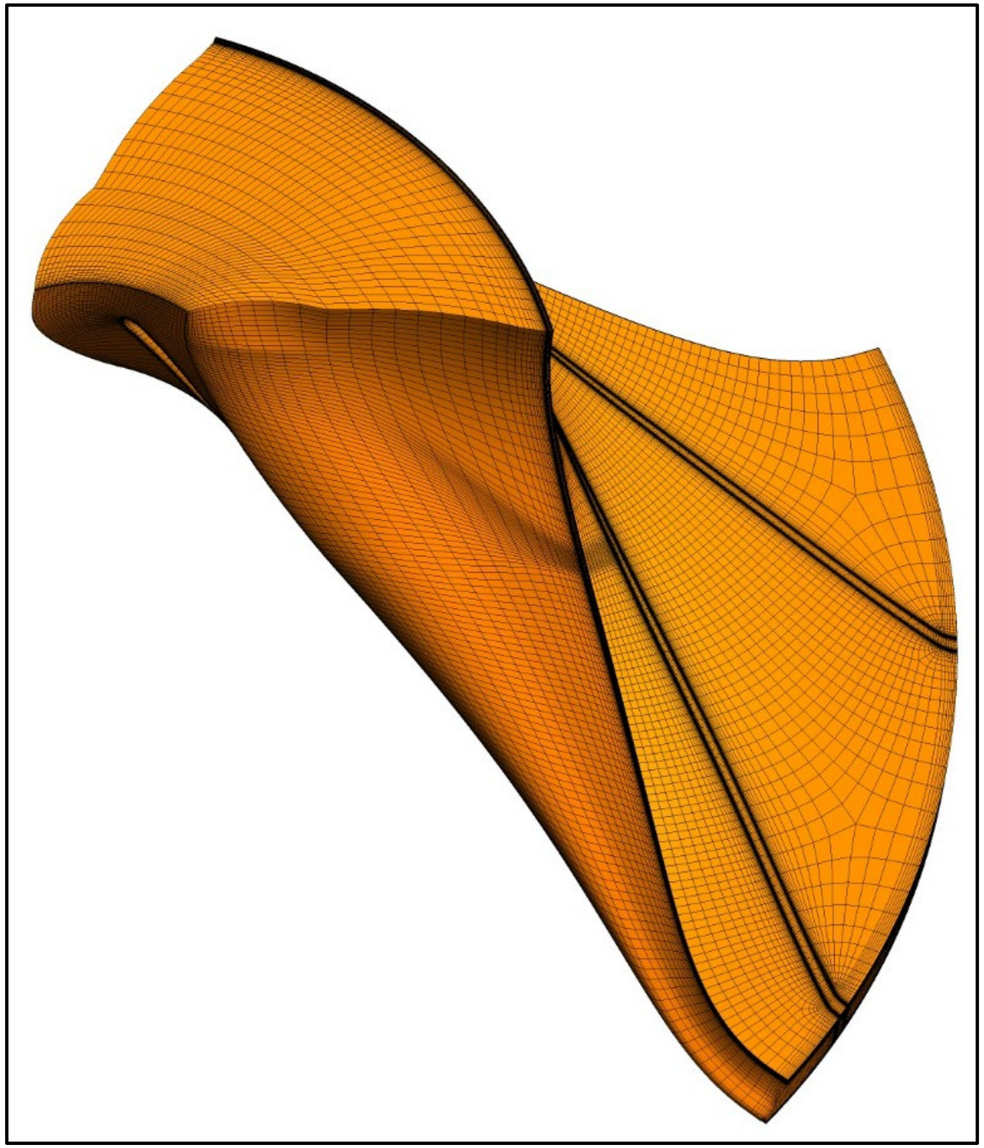
**Rotational speed** numbers for off-design points were determined during the project

# 2 Computational Mesh

CFturbo



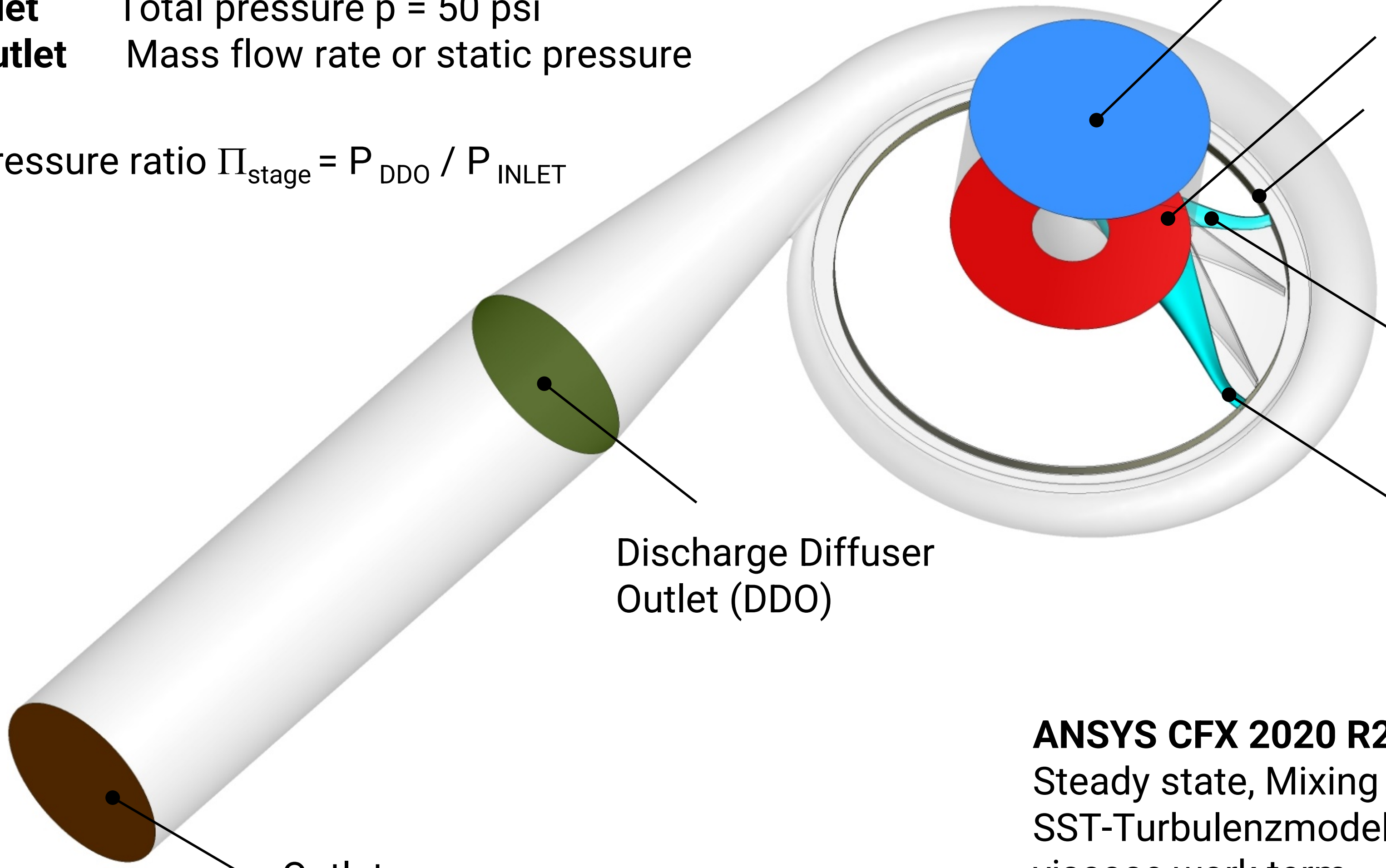
| Mesh statistics | Nodes | Elements |
|---|---|---|
| Impeller (Segment) | ≈ 750k | ≈ 700k |
| Volute | ≈ 875k | ≈ 2.02m |
| Overall (with Pipe,in + Pipe,out) | ≈ 1.76m | ≈ 3.10m |



CFturbo

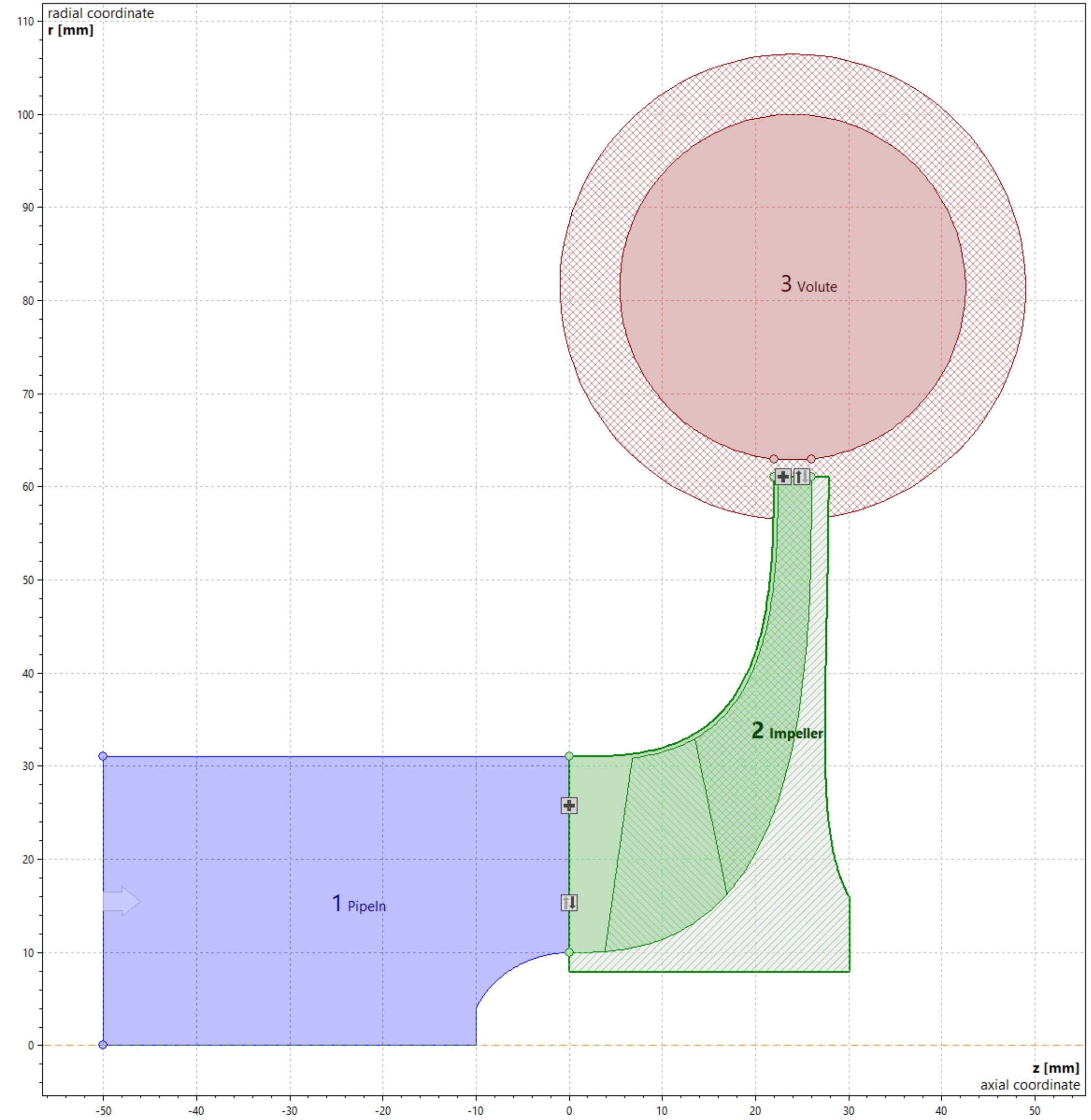
**Inlet** Total pressure p = 50 psi
**Outlet** Mass flow rate or static pressure

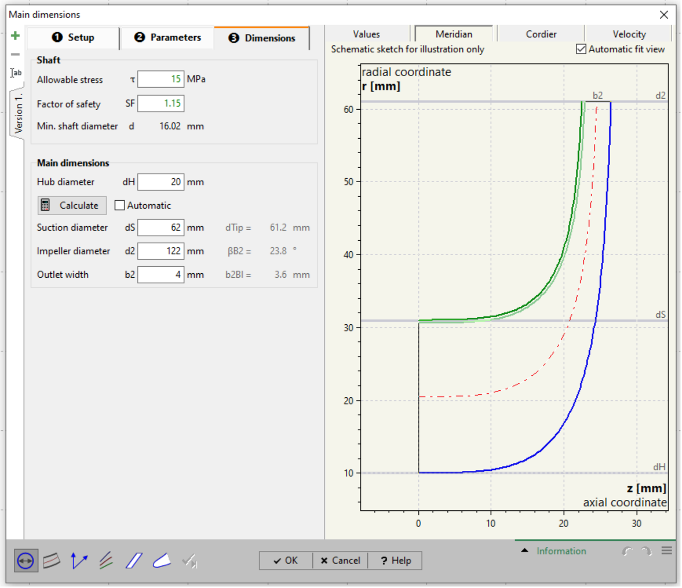
Pressure ratio $\Pi_{stage} = P_{DDO} / P_{INLET}$




**ANSYS CFX 2020 R2**
Steady state, Mixing Plane, Total Energy,
SST-Turbulenzmodel, High-Resolution-Differencing-Scheme,
viscose work term

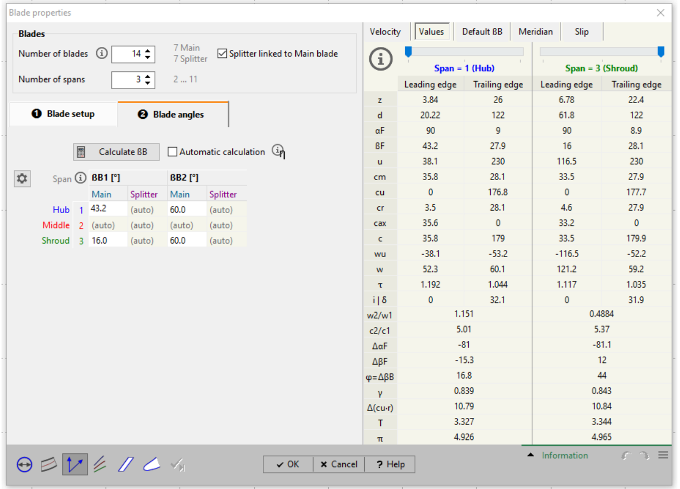
# 3 Initial Design




## Impeller Main Dimensions

DS=62 mm,
D2=122 mm
B2= 4mm

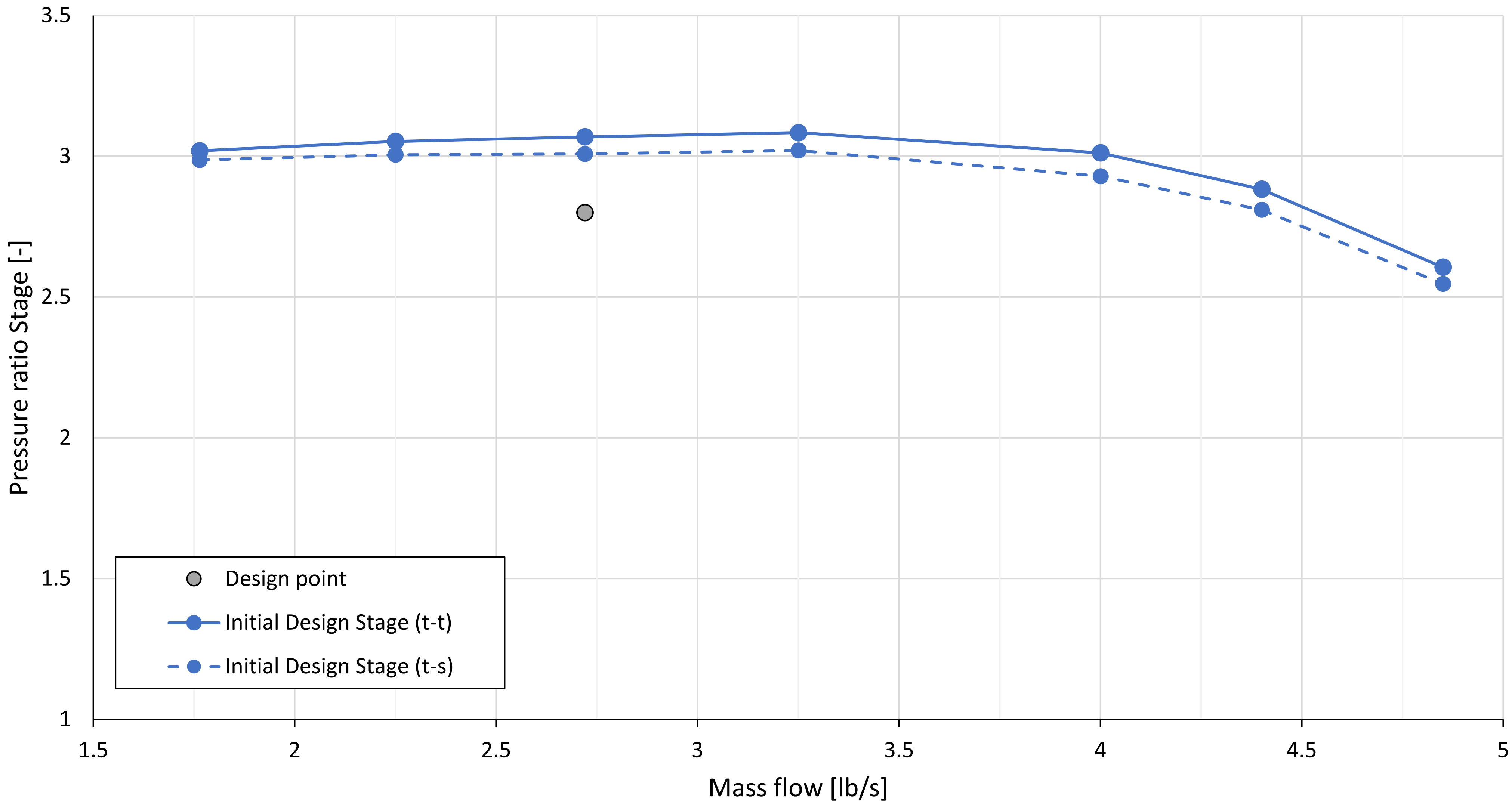



## Impeller Blade Angles

β,B1= 43 ... 16
β,B2= 60

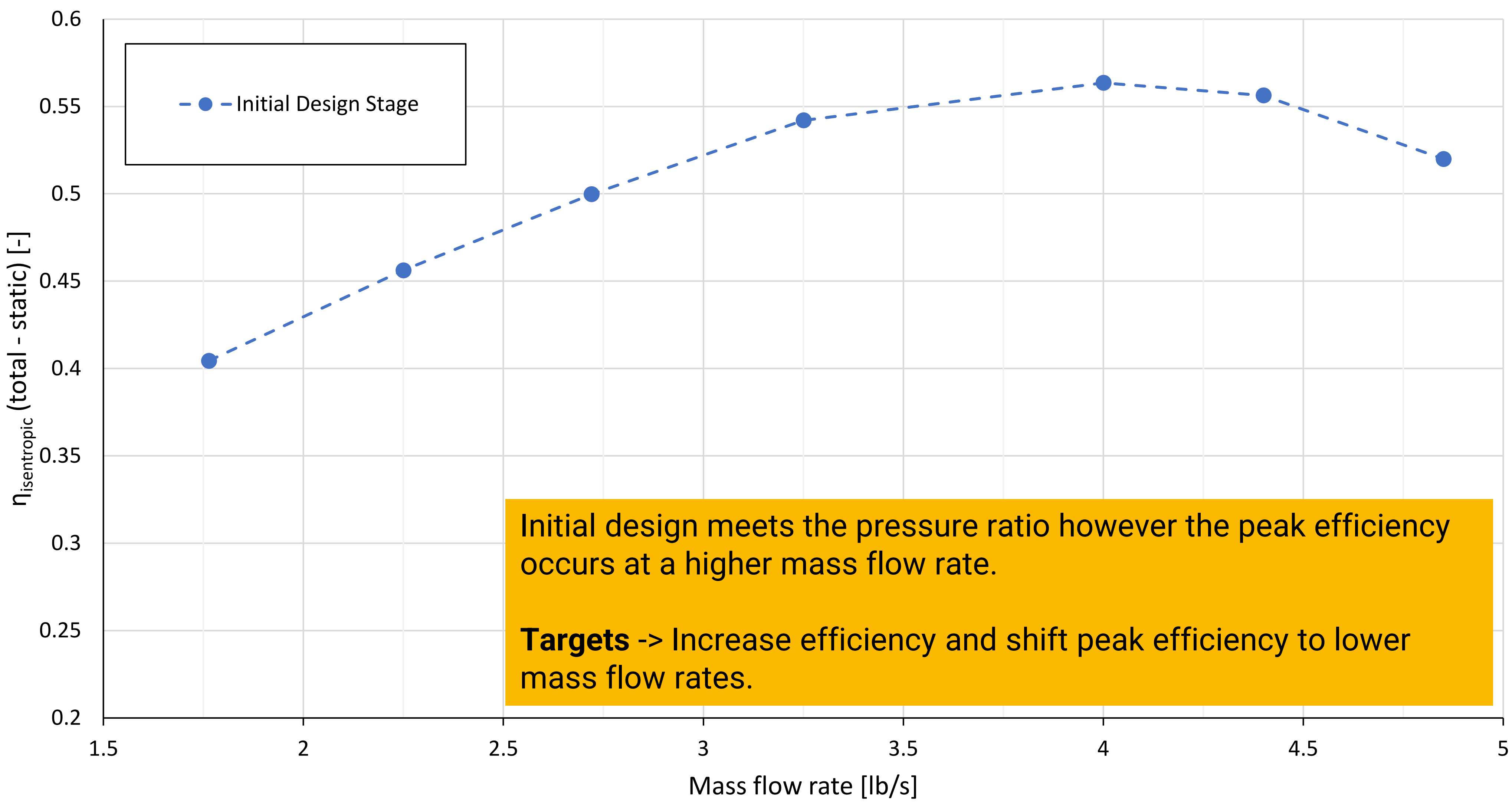
# 3 Initial Design, Pressure ratio (Stage)@36000rpm

CFturbo



# 3 Initial Design, Efficiency $\eta_{isentropic}$ (Stage)@36000rpm

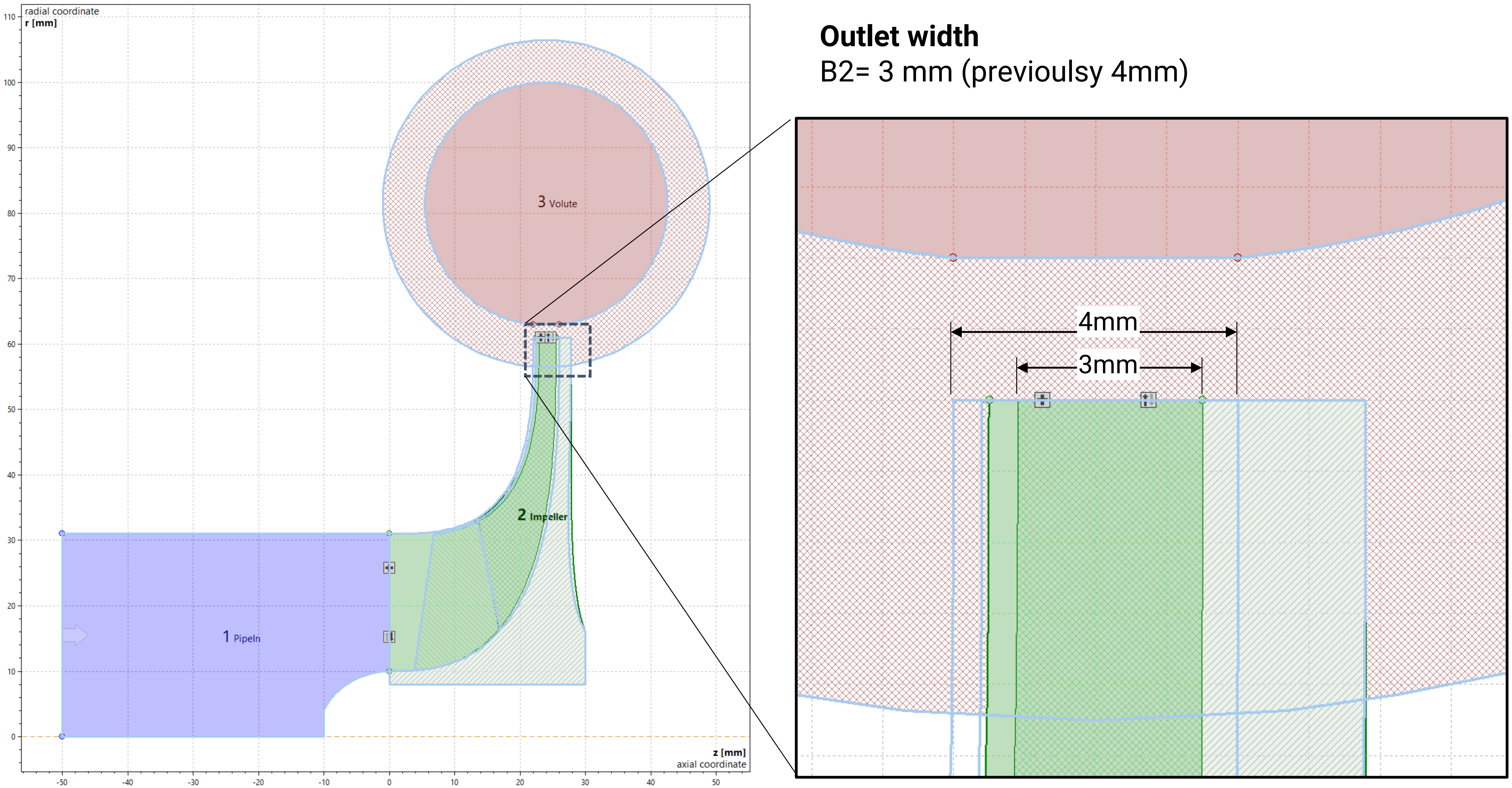
CFturbo




Initial design meets the pressure ratio however the peak efficiency occurs at a higher mass flow rate.

**Targets** -> Increase efficiency and shift peak efficiency to lower mass flow rates.

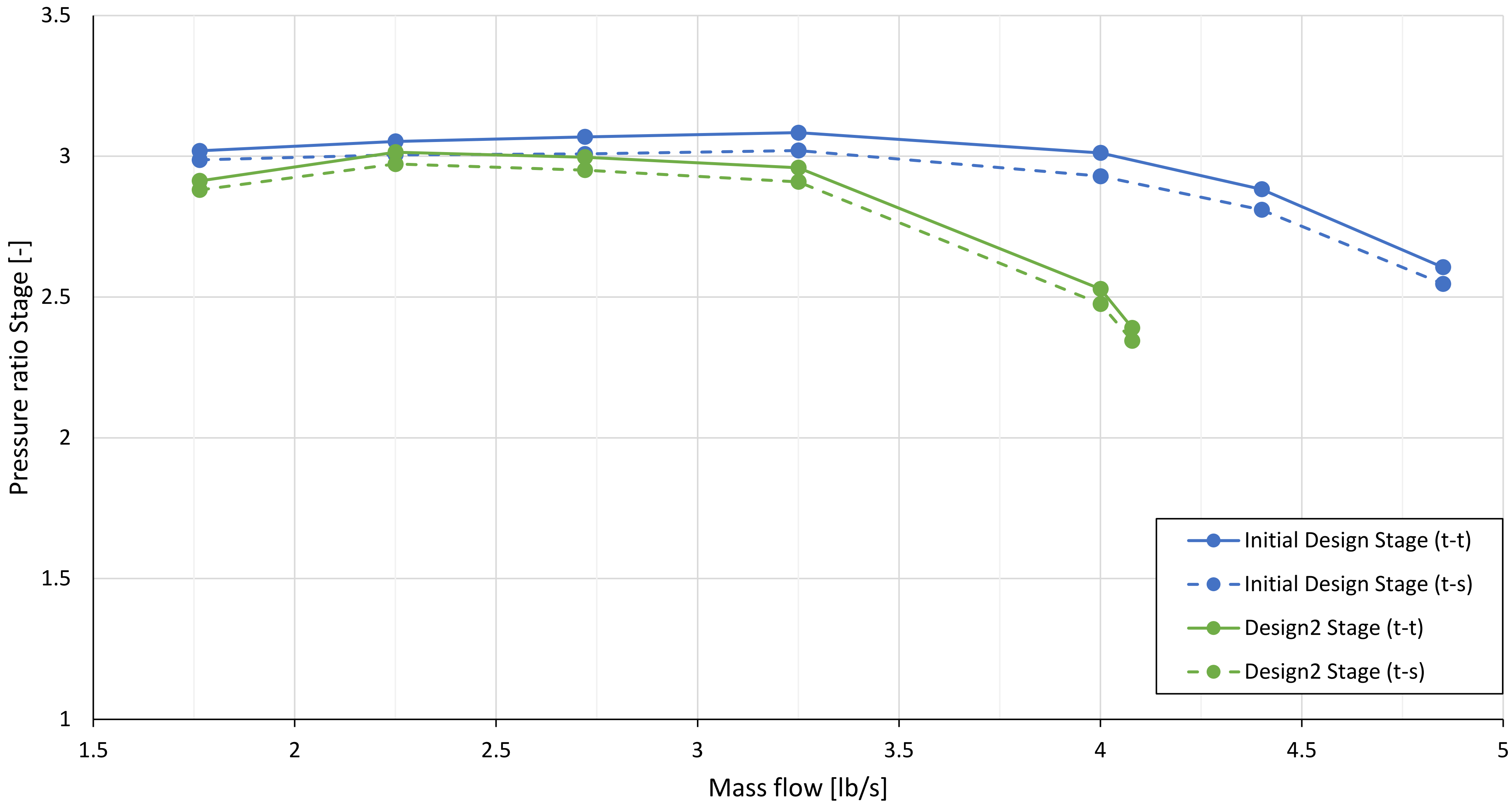
# 4 Design2 – Manual modification, reduced outlet width b2




**Outlet width**

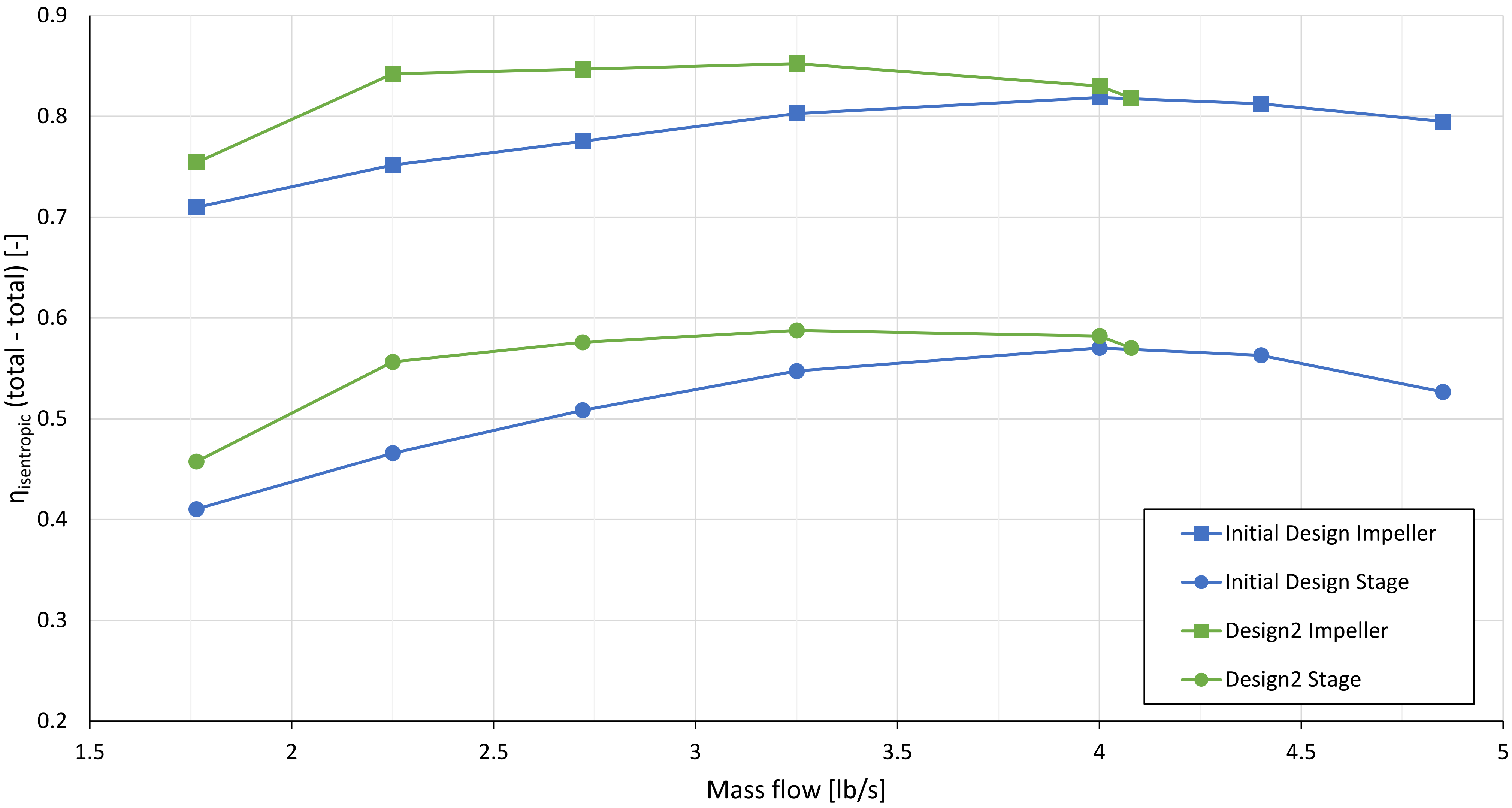
B2= 3 mm (previoulsy 4mm)

# 4 Design2 – Pressure ratio (Stage)@36000rpm



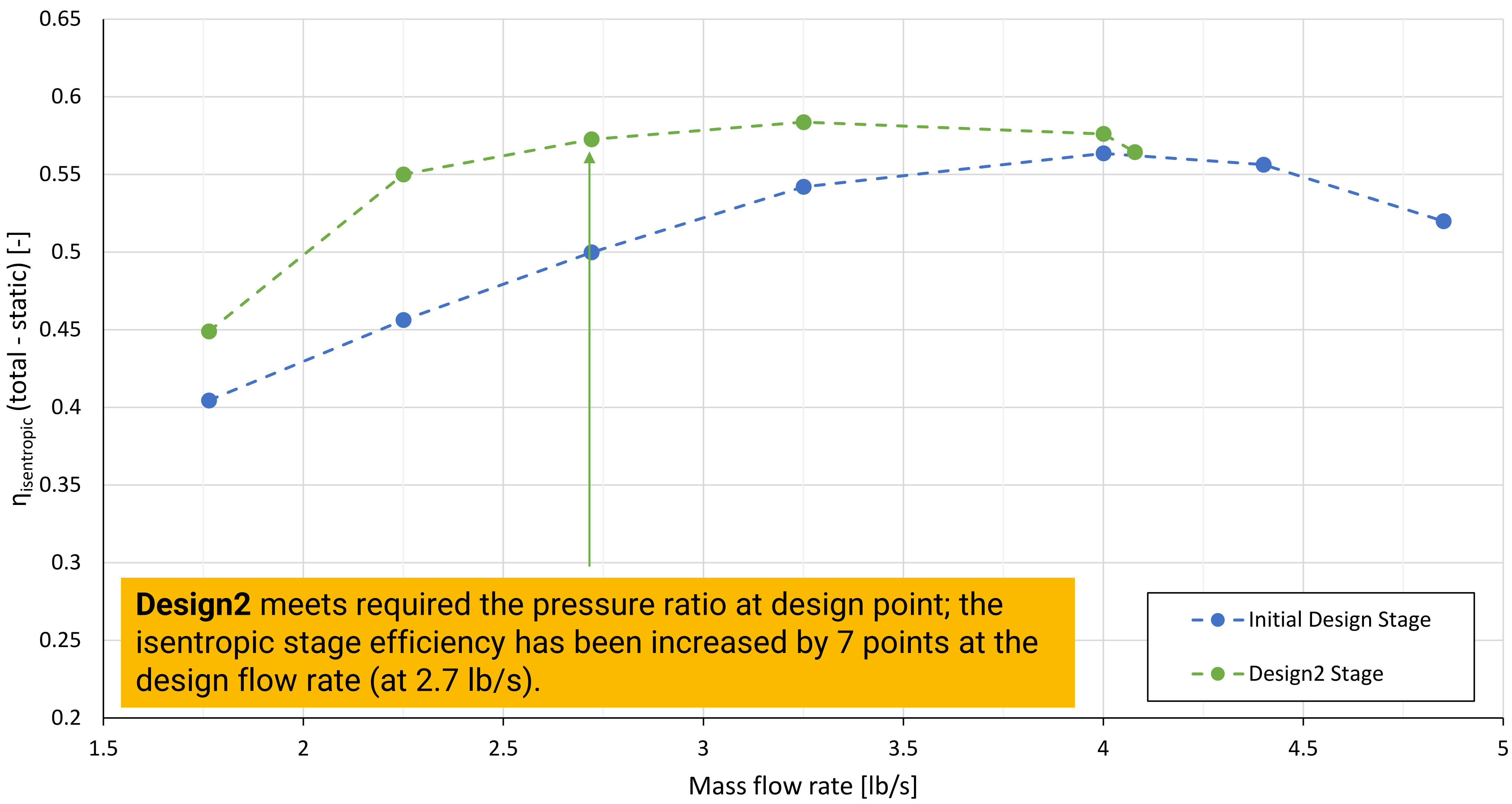
# 4 Design2 – $\eta_{isentropic}$@36000rpm





# 4 Design2, Efficiency $\eta_{isentropic}$ (Stage)@36000rpm

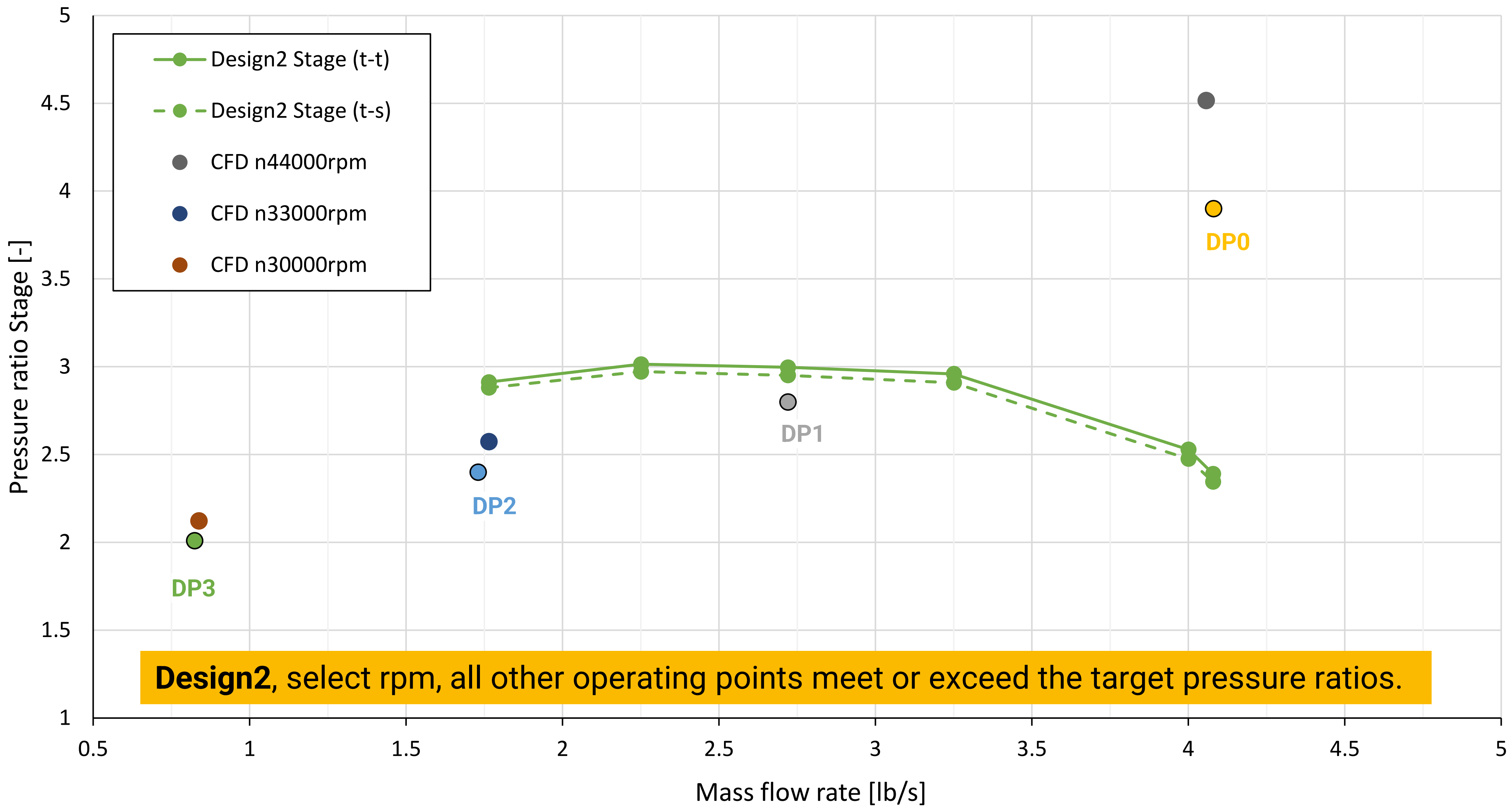
CFturbo




**Design2** meets required the pressure ratio at design point; the isentropic stage efficiency has been increased by 7 points at the design flow rate (at 2.7 lb/s).

# 4 Design2, Other operating points

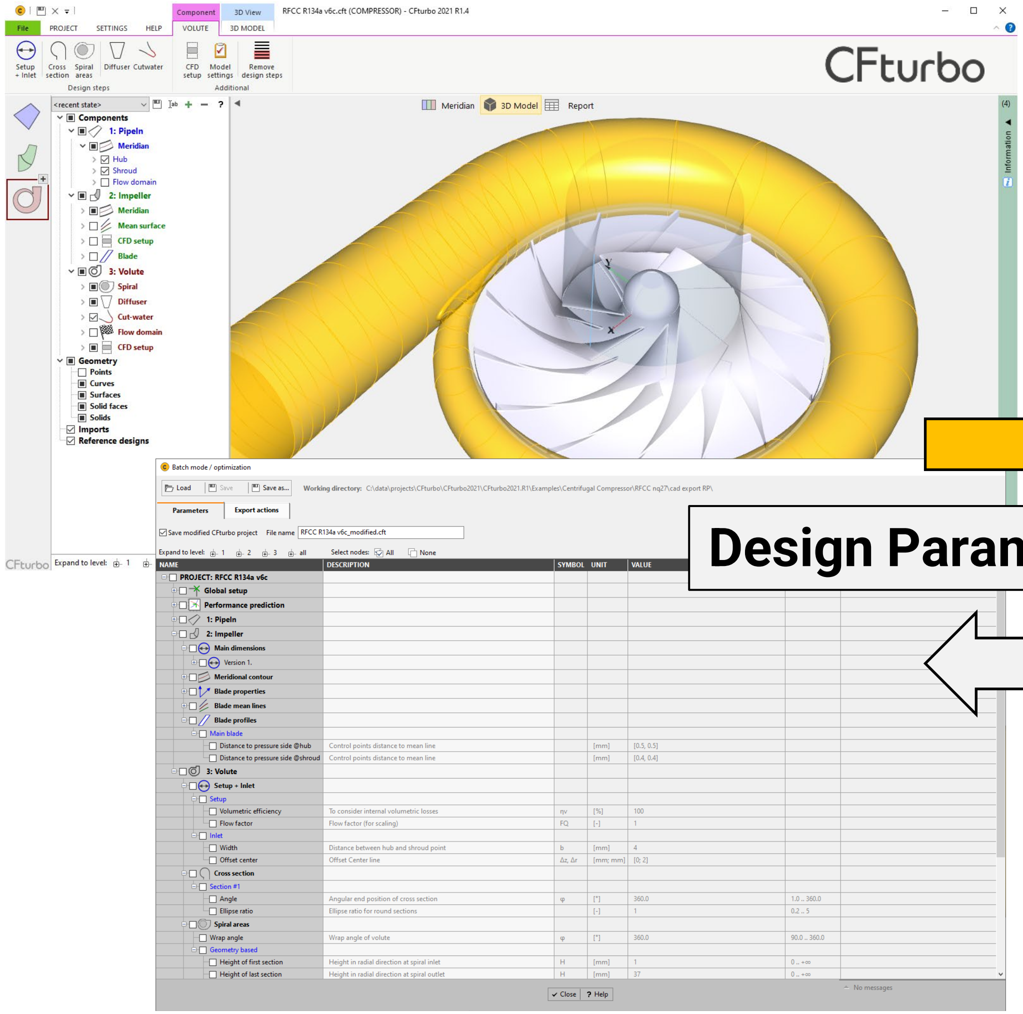
CFturbo



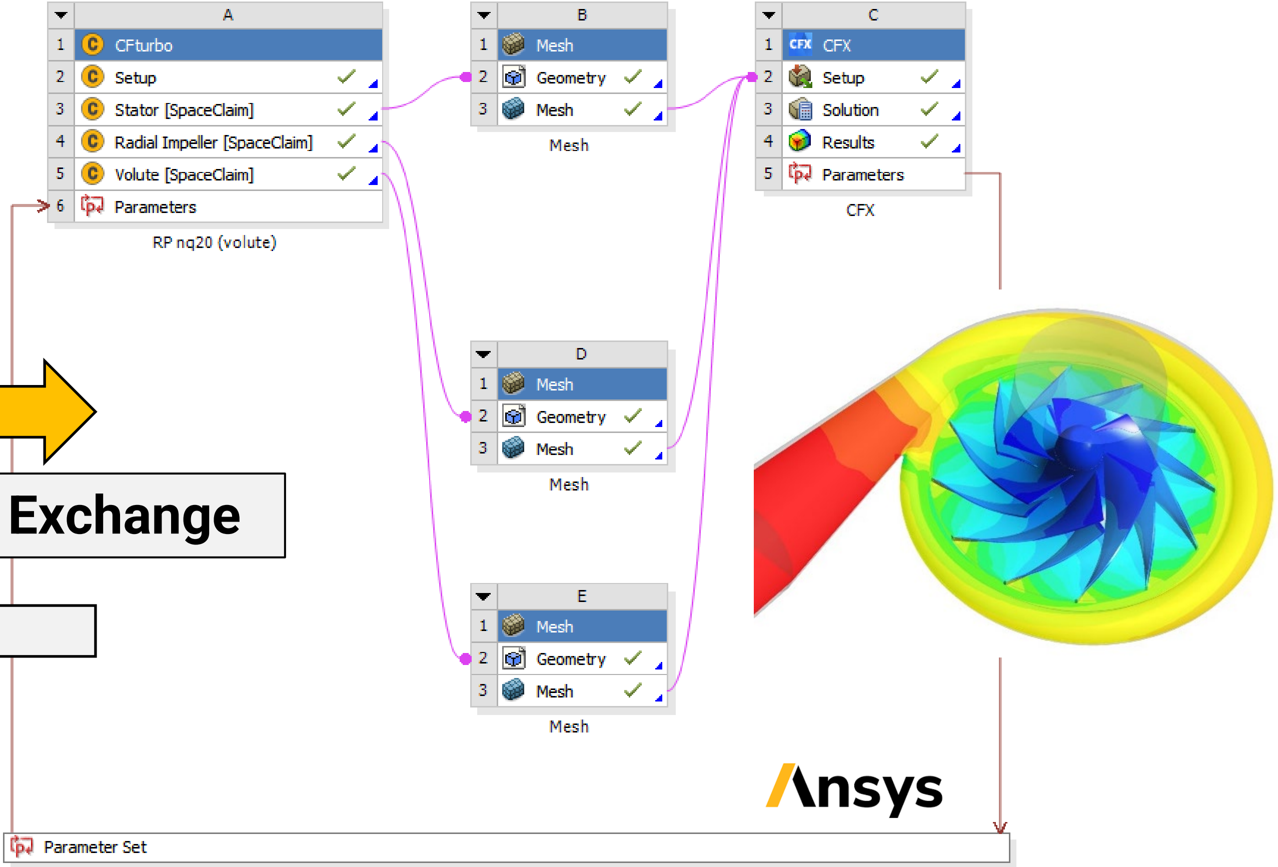

**Design2**, select rpm, all other operating points meet or exceed the target pressure ratios.

CFturbo

# **Bi-directional Integration** for Automated Simulation, Design Space Exploration, Optimization




**Design Parameter Exchange**




Connected **parameter sets** in CFturbo and Workbench!

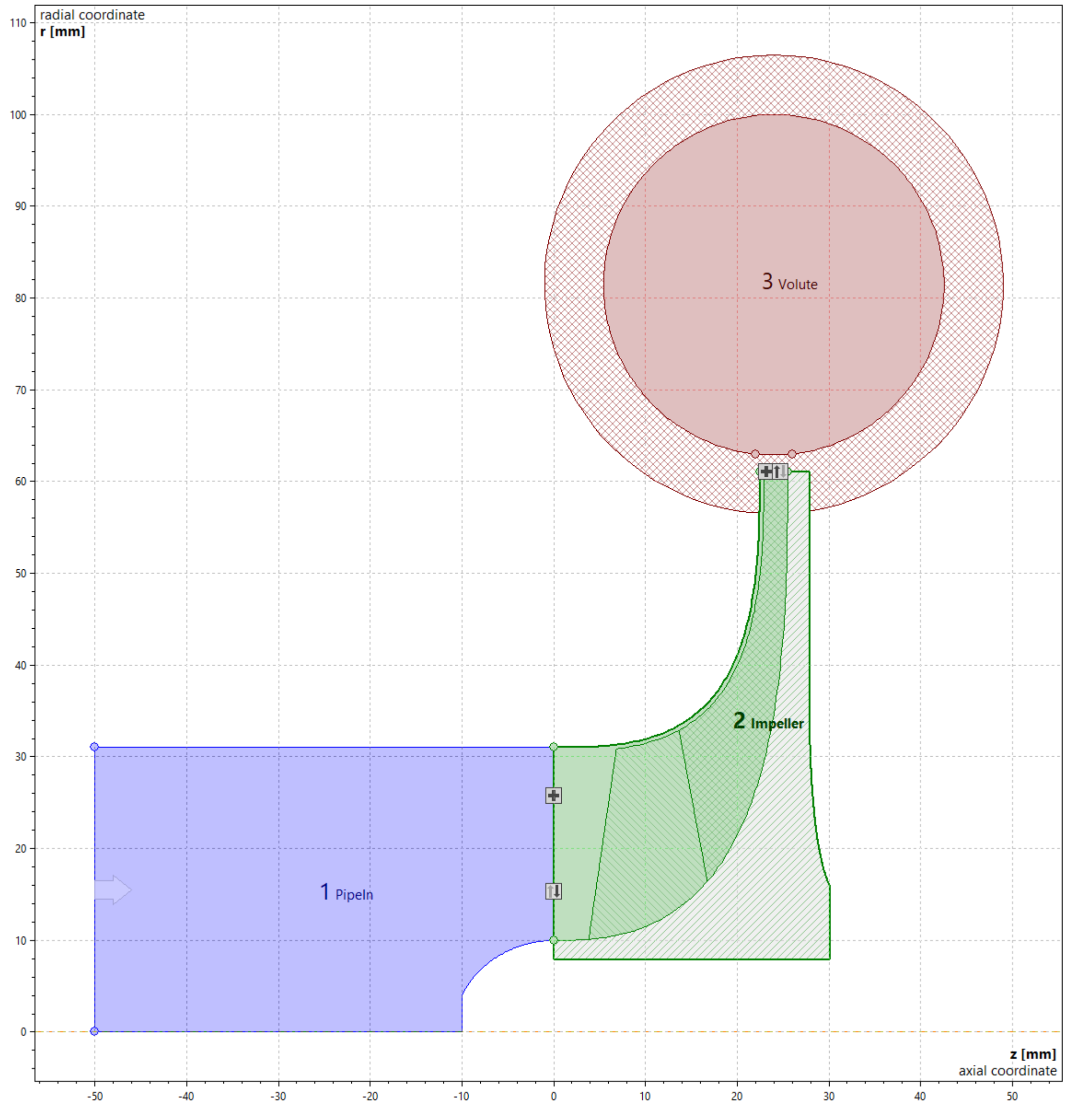
CFturbo

## Start optimization from „Design2“

**8 geometry parameters** were selected for optimization

Table of Schematic F2: Optimization

| | A | B | C | D |
|---|---|---|---|---|
| 1 | ⊟ Input Parameters | | | |
| 2 | Name | Lower Bound | Upper Bound | Starting Value |
| 3 | P1 - Impeller.Version 1.b2.Outlet width (m) | 0,0028 | 0,0033 | 0,003 |
| 4 | P2 - Impeller.Version 1.d2.Impeller diameter (m) | 0,115 | 0,1342 | 0,122 |
| 5 | P3 - Impeller.nBl.Number of blades | 14 12 16 | | 14 |
| 6 | P4 - Impeller.BladeValues.Main blade0.Blade angle trailing edge.Value0 (radian) | 0,95993 | 1,1345 | 1,0472 |
| 7 | P6 - Impeller.Main mean surface0.0.tePos.Trailing edge position (radian) | 1,0472 | 1,3963 | 1,2044 |
| 8 | P9 - Volute.MerInlet.Offset center.y (m) | 0,002 | 0,01 | 0,002 |
| 9 | P10 - Volute.gbRadius.Radius of last section (m) | 0,08 | 0,12 | 0,1 |
| 10 | P22 - Volute.DiffHeight.Height (m) | 0,11 | 0,14 | 0,12 |
| 11 | ⊟ Parameter Relationships | | | |
| 12 | Name | Left Expression | Operator | Right Expression |
| * | *New Parameter Relationship* | *New Expression* | <= | *New Expression* |




## Optimization method

MISQP (ANSYS Design Explorer, default setting)

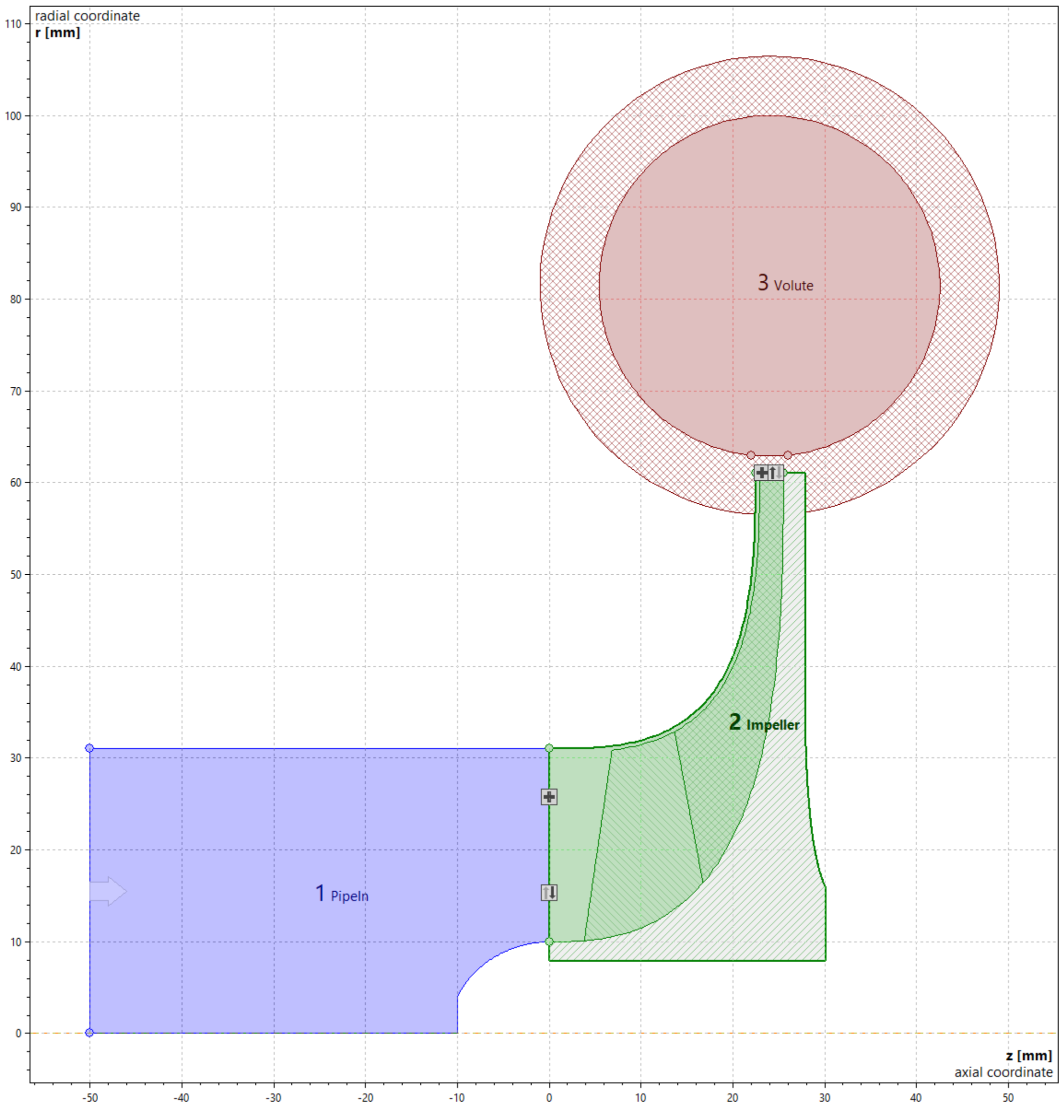
## Objectives and Constraints

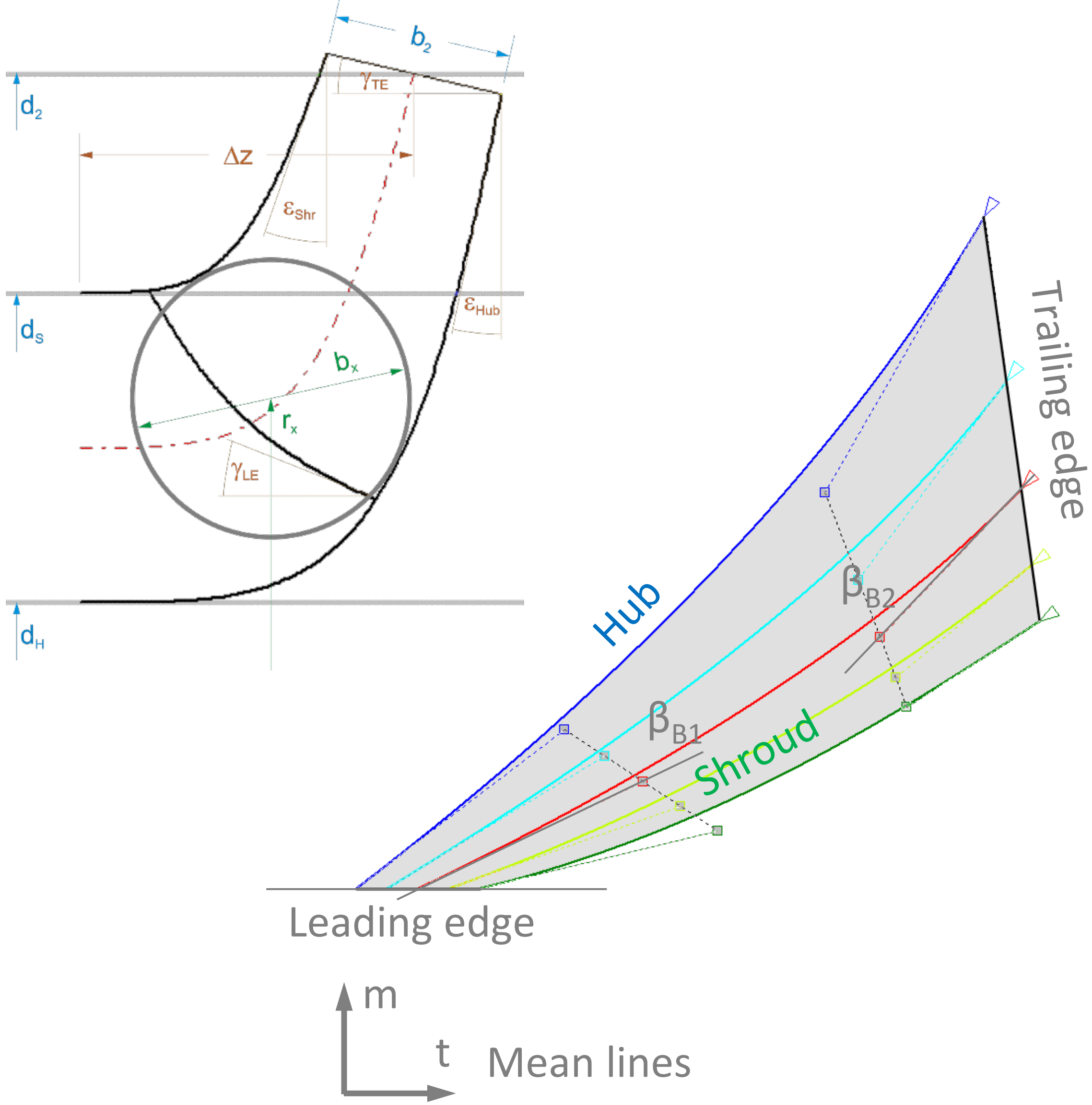
Table of Schematic F2: Optimization

| | A | B | C | D | E | F | G | H | I |
|---|---|---|---|---|---|---|---|---|---|
| 1 | Name | Parameter | Objective | | | Constraint | | | |
| 2 | | | Type | Target | Tolerance | Type | Lower Bound | Upper Bound | Tolerance |
| 3 | Maximize P26 | P26 - PP eta ts Stage | Maximize | 0,65 | | No Constraint | | | |
| 4 | 2,95 <= P30 <= 3,1 | P30 - pi ts Stage | No Objective | | | Lower Bound <= Values <= Upper Bound | 2,95 | 3,1 | 0,001 |
| * | | Select a Parameter | | | | | | | |

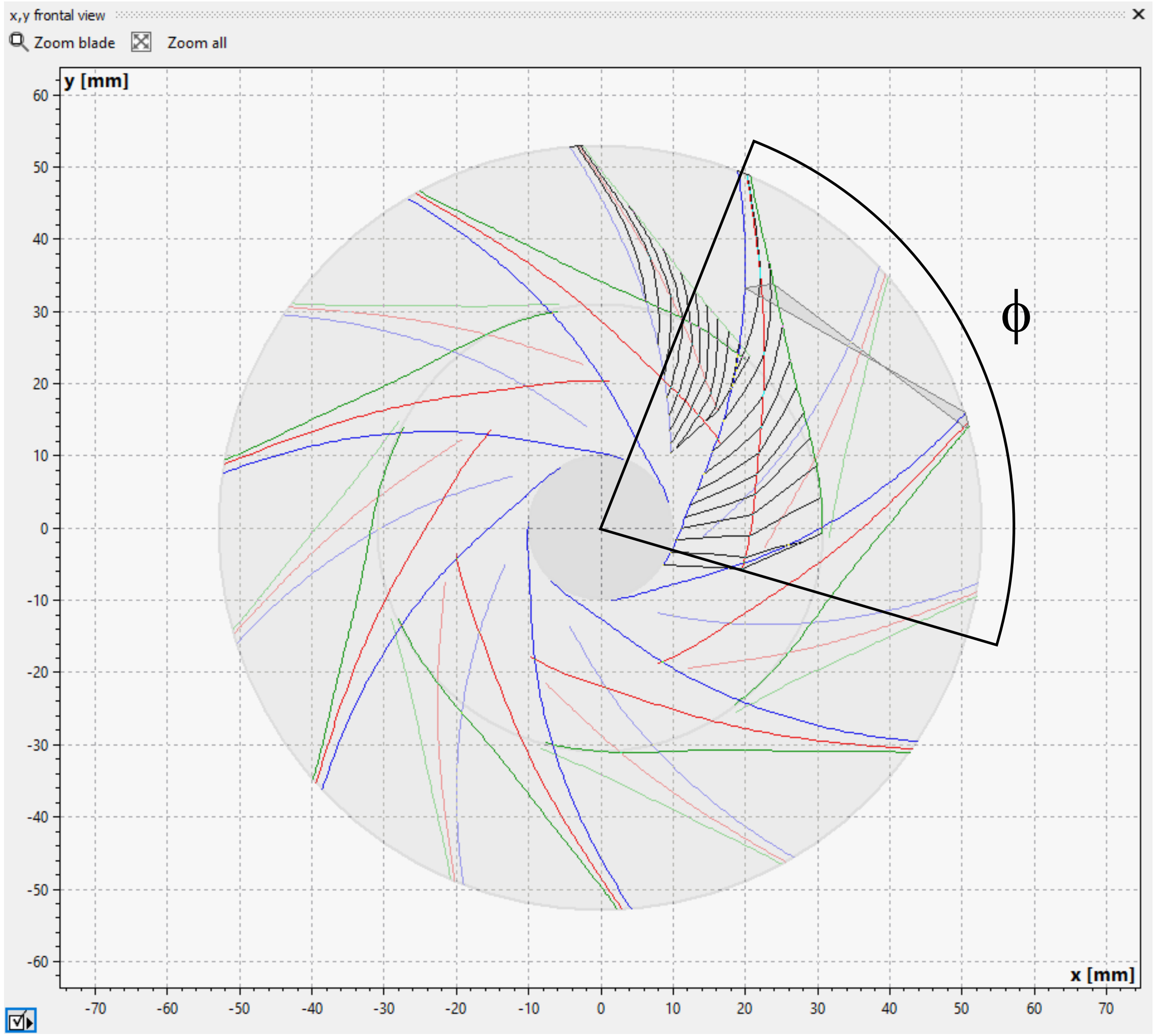
# 5 Mathematical optimization, design parameters $D_2$, $b_2$ , $\beta_2$

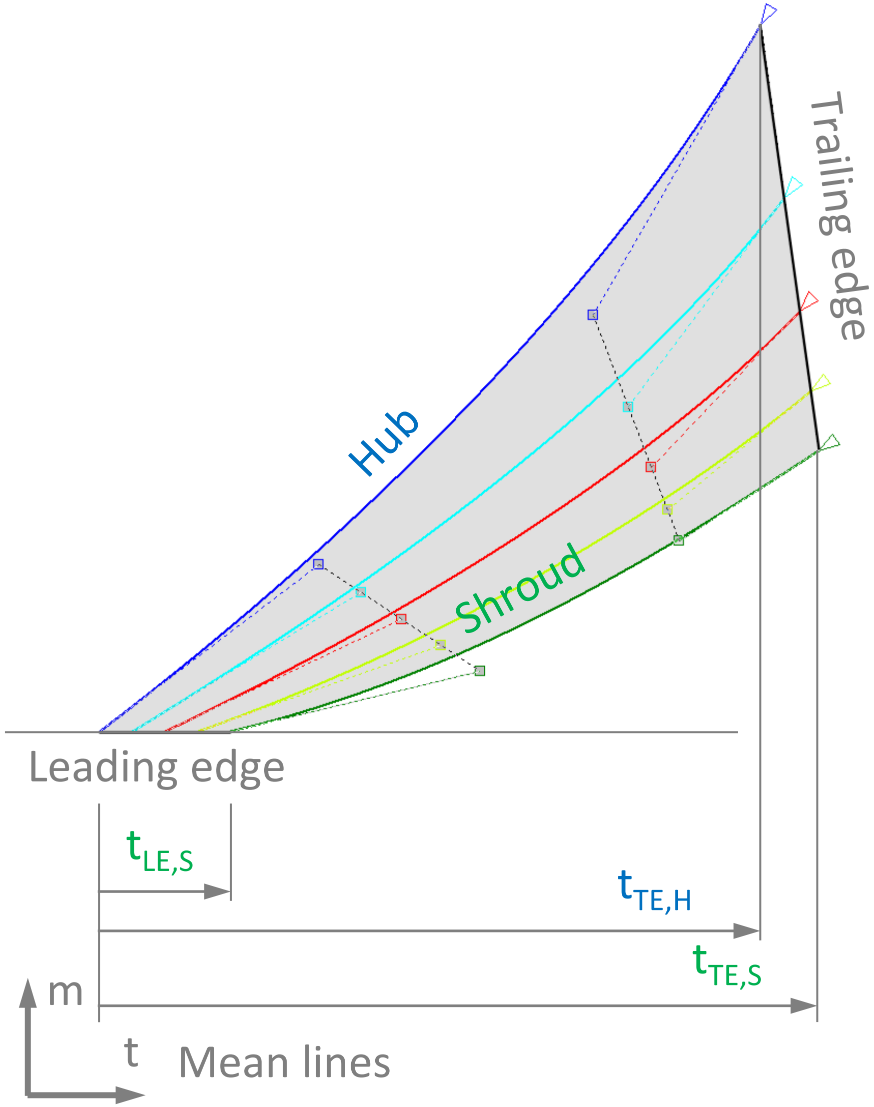
CFturbo



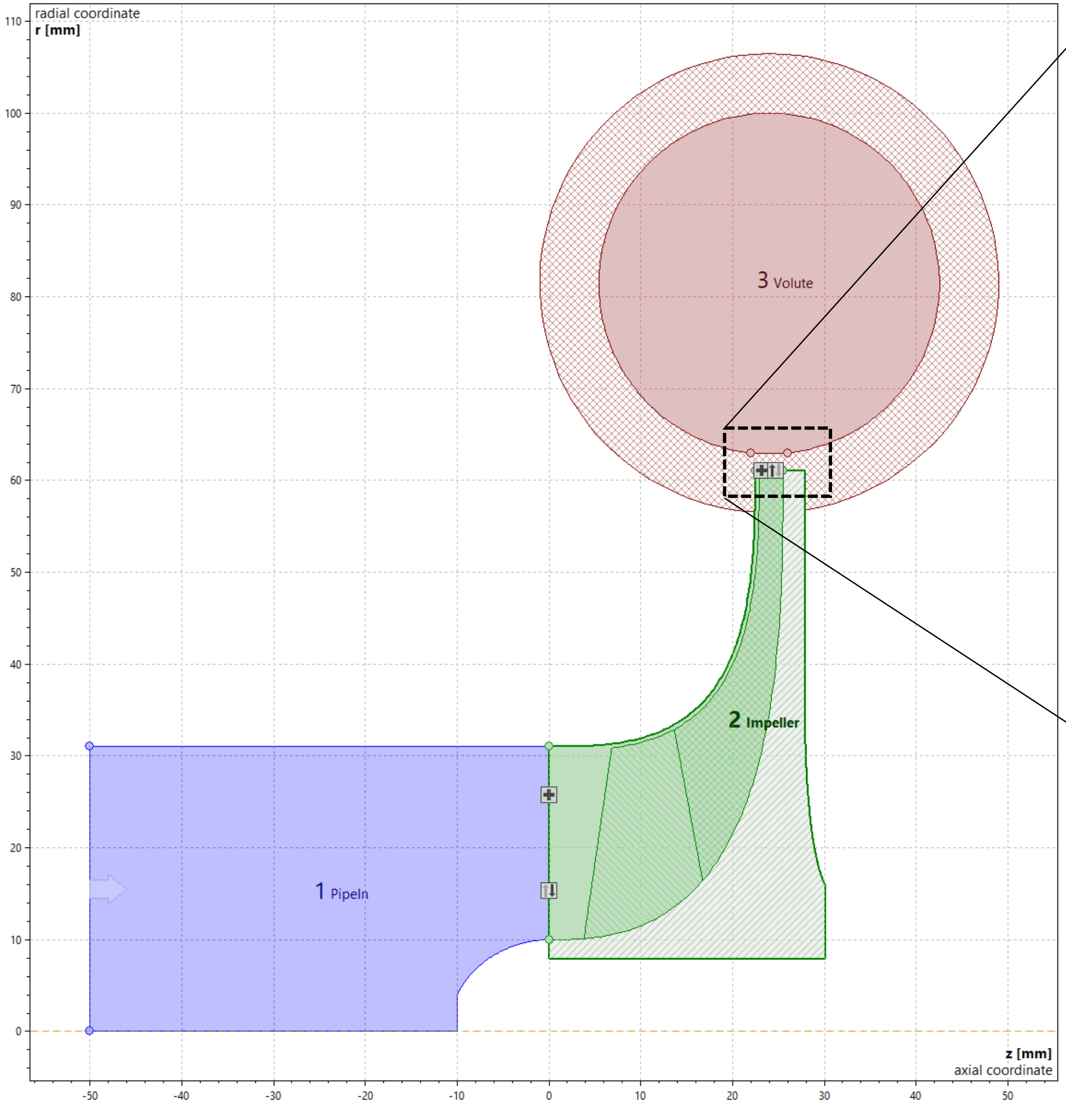



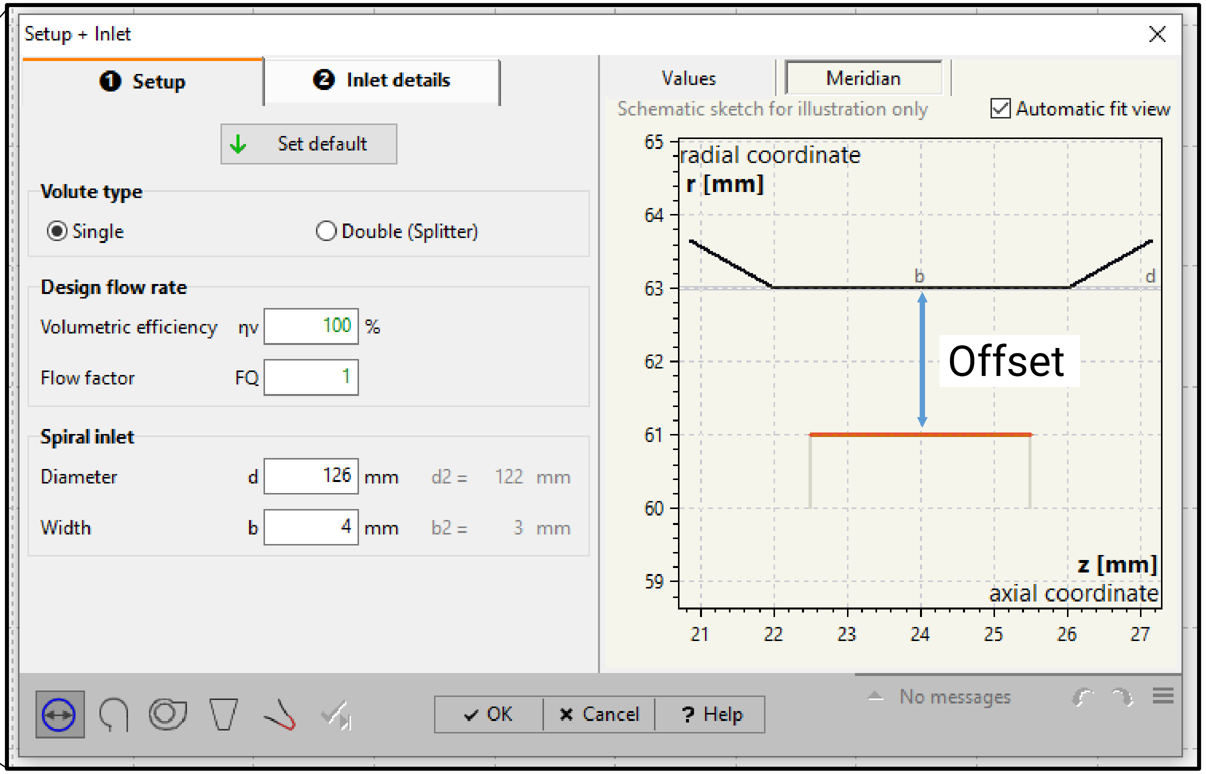
CFturbo


x,y frontal view
Zoom blade
Zoom all
y [mm]
x [mm]
ϕ
60
50
40
30
20
10
0
-10
-20
-30
-40
-50
-60
-70
-60
-50
-40
-30
-20
-10
0
10
20
30
40
50
60
70

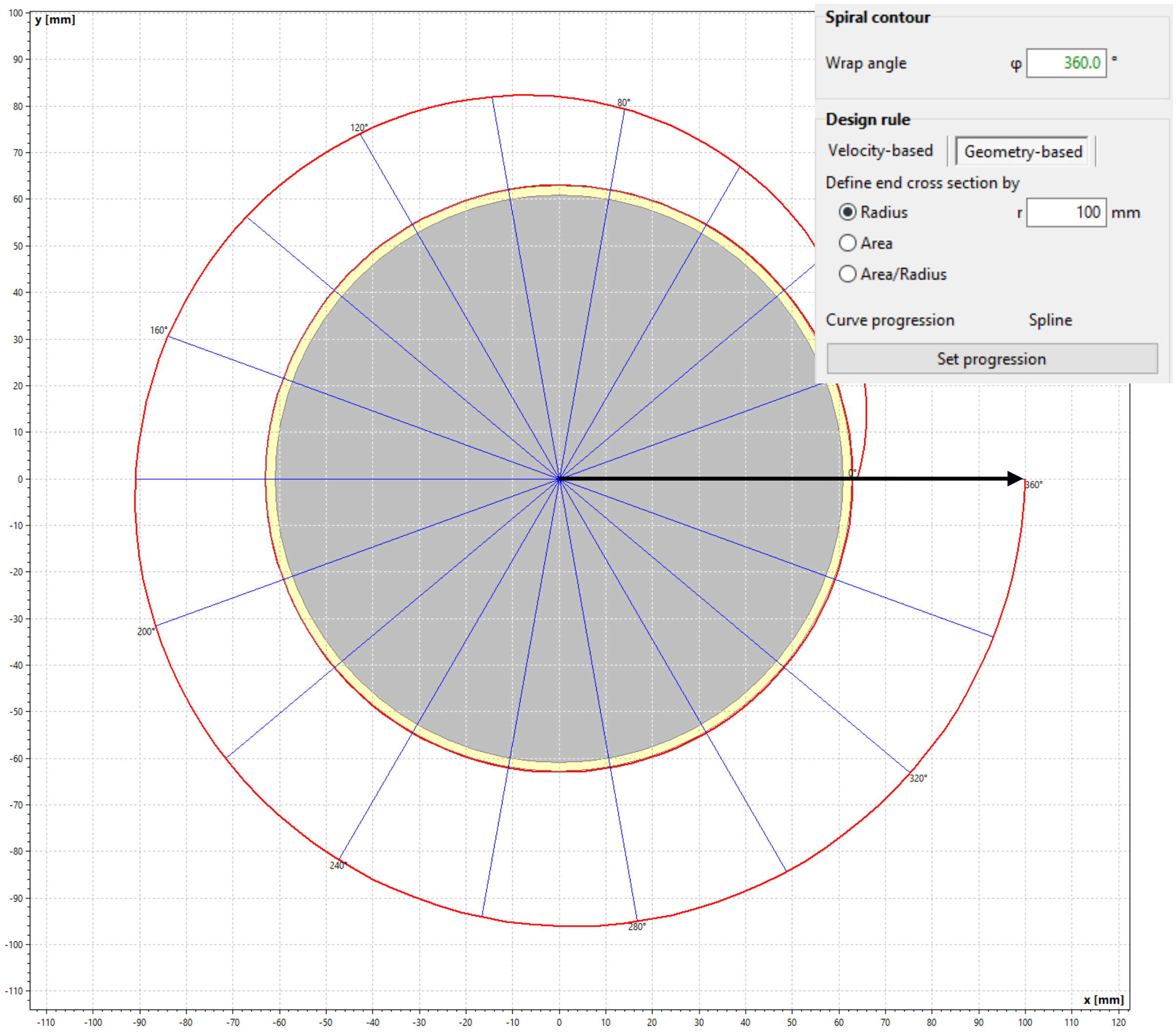

Trailing edge
Hub
Shroud
Leading edge
$t_{LE,S}$
$t_{TE,H}$
$t_{TE,S}$
m
t
Mean lines

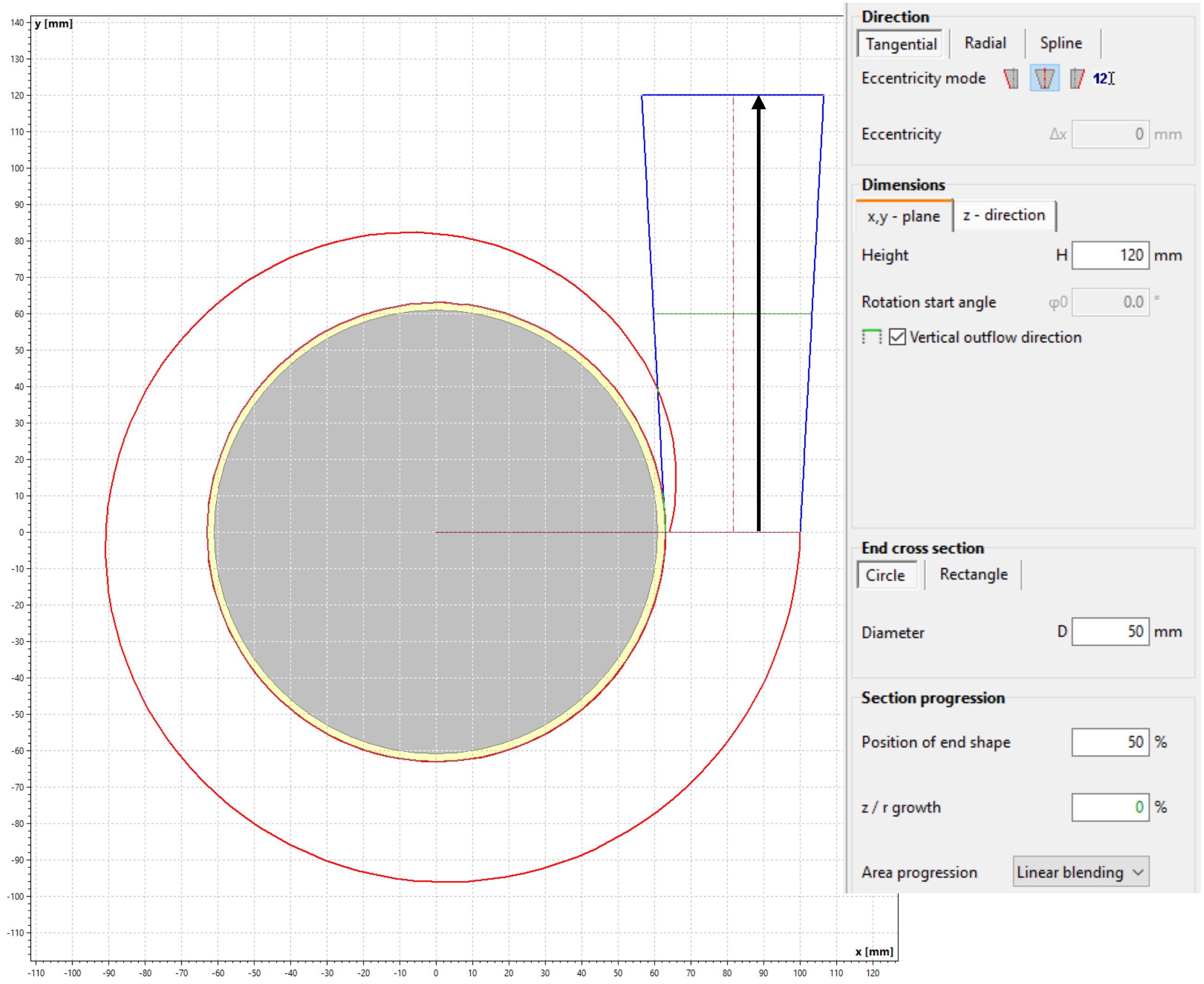
# 5 Mathematical optimization, design parameter „Radial Offset“




The radial offset between impeller outlet and volute inlet is used to add a non-rotating component between impeller and volute. Technically it workd as a short lenght radial diffuser.


y [mm]
x [mm]
80°
120°
160°
200°
240°
280°
320°
360°
0°
Spiral contour
Wrap angle φ 360.0 °
Design rule
Velocity-based
Geometry-based
Define end cross section by
Radius r 100 mm
Area
Area/Radius
Curve progression Spline
Set progression


y [mm]
x [mm]
Direction
Tangential
Radial
Spline
Eccentricity mode
Eccentricity Δx 0 mm
Dimensions
x,y - plane
z - direction
Height H 120 mm
Rotation start angle φ0 0.0 °
Vertical outflow direction
End cross section
Circle
Rectangle
Diameter D 50 mm
Section progression
Position of end shape 50 %
z / r growth 0 %
Area progression Linear blending

# 5 Mathematical optimization, Results

CFturbo

Table of Schematic F2: Optimization

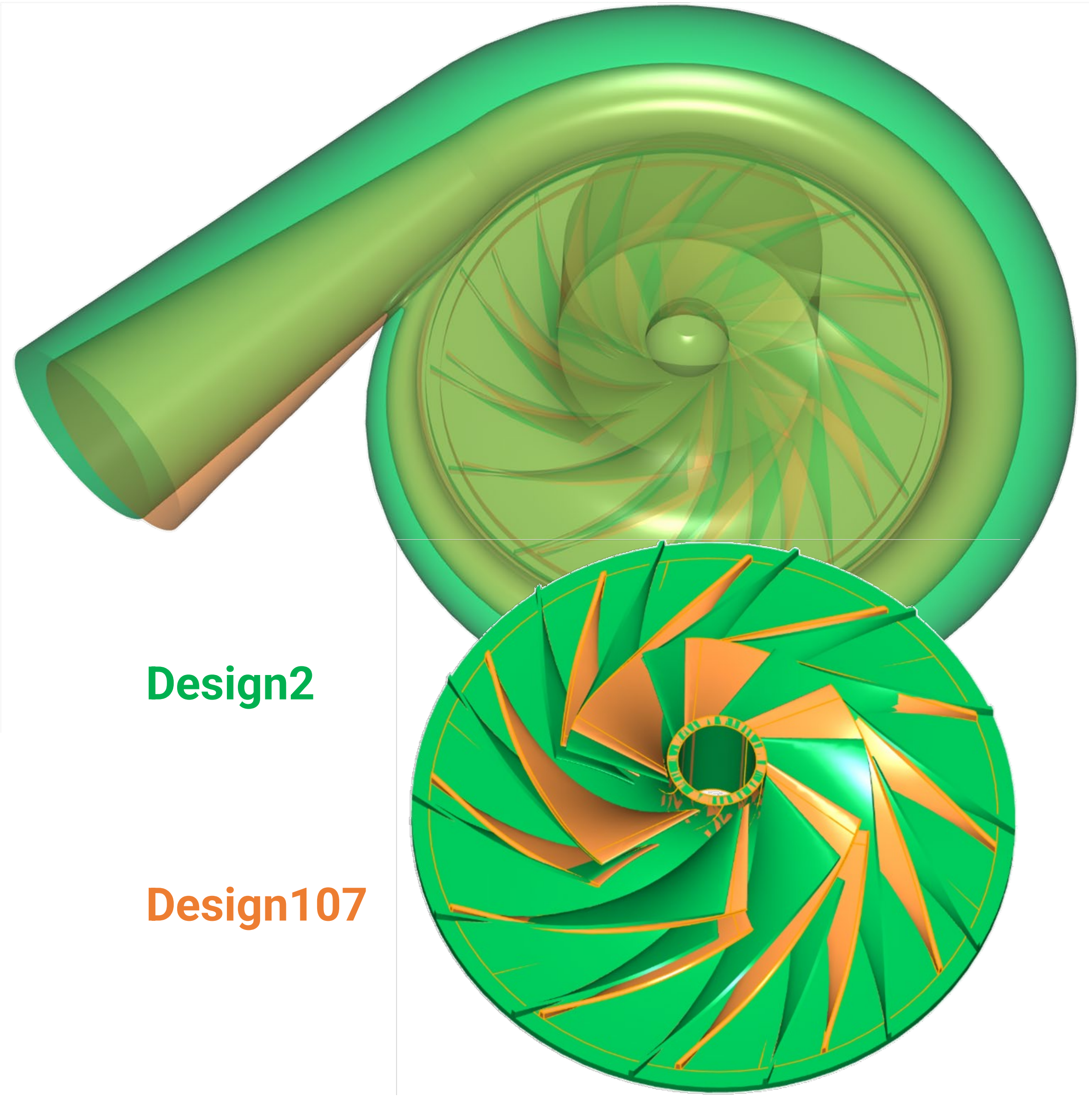
| | A | B | | C | | D | | E | |
|---|---|---|---|---|---|---|---|---|---|
| 1 | ⊟ Optimization Study | | | | | | | | |
| 2 | Maximize P26 | Goal, Maximize P26 (Default importance) | | | | | | | |
| 3 | 2,95 <= P30 <= 3,1 | Strict Constraint, P30 values between 2,95 and 3,1 (Default importance) | | | | | | | |
| 4 | ⊟ Optimization Method | | | | | | | | |
| 5 | MISQP | The MISQP method (Mixed-Integer Sequential Quadratic Programming) solves mixed-integer nonlinear programming problems by a modified sequential quadratic programming (SQP) method. Under the assumption that integer variables have a smooth influence on the model functions, i.e., that function values do not change drastically when in- or decrementing an integer variable, successive quadratic approximations are applied. It supports a single objective and multiple constraints. The starting point must be specified to determine the region of the design space to explore. | | | | | | | |
| 6 | Configuration | Approximate derivatives by Forward difference and find 3 candidates in a maximum of 17 iterations . | | | | | | | |
| 7 | Status | Converged after 141 evaluations. | | | | | | | |
| 8 | ⊟ Candidate Points | | | | | | | | |
| 9 | | Startpunkt | DP 10 | Kandidat 1 | DP 107 | Kandidat 2 | DP 98 | Kandidat 3 | DP 77 |
| 10 | P1 - Impeller.Version 1.b2.Outlet width (m) | 0,003 | | 0,0030079 | | 0,0030132 | | 0,0029653 | |
| 11 | P2 - Impeller.Version 1.d2.Impeller diameter (m) | 0,122 | | 0,115 | | 0,115 | | 0,115 | |
| 12 | P3 - Impeller.nBl.Number of blades | 14 | | 12 | | 12 | | 12 | |
| 13 | P4 - Impeller.BladeValues.Main blade0.Blade angle trailing edge.Value0 (radian) | 1,0472 | | 0,95993 | | 0,95993 | | 0,97293 | |
| 14 | P6 - Impeller.Main mean surface0.0.tePos.Trailing edge position (radian) | 1,2044 | | 1,3517 | | 1,348 | | 1,3207 | |
| 15 | P9 - Volute.MerInlet.Offset center.y (m) | 0,002 | | 0,0066163 | | 0,0065312 | | 0,0059353 | |
| 16 | P10 - Volute.gbRadius.Radius of last section (m) | 0,1 | | 0,084788 | | 0,084887 | | 0,084999 | |
| 17 | P22 - Volute.DiffHeight.Height (m) | 0,12 | | 0,11612 | | 0,11612 | | 0,11836 | |
| 18 | P26 - PP eta ts Stage | ✕✕✕ 0,57253 | | ★★★ 0,73184 | | ★★★ 0,73037 | | ★★★ 0,71764 | |
| 19 | P30 - pi ts Stage | ✕✕ 2,9509 | | ★★★ 3,0261 | | ★★★ 3,0292 | | ★★★ 3,0019 | |

- Optimization process **141 designs**
- Three ecxellent design proposals
  Selected best fit **„Design107“**
- Peak efficiency $\eta_{(t-s)} > 73\%$
- $\Pi_{(t-s)} \approx 3.0$

**Computational effort**:
Approx. 1 hour per design on a 12 core AMD Ryzen Threadripper PRO 3945WX 4.00 GHz workstation

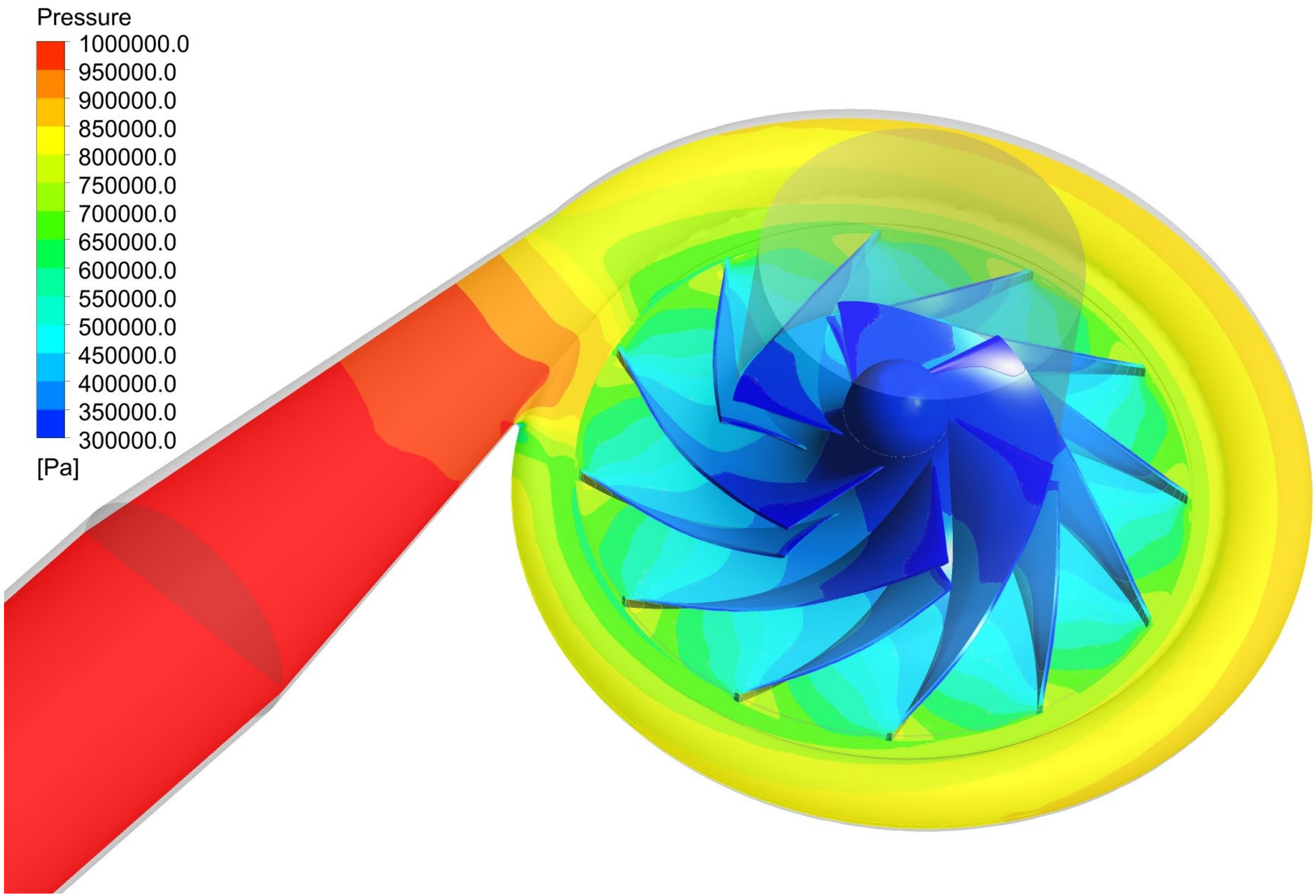
# 5 Mathematical optimization – Comparision

CFturbo




| Impeller Main Dimensions | Design2 | Design107 |
|---|---|---|
| DS [mm] | 62.0 | 62.0 |
| D2 [mm] | 122.0 | 115.0 |
| B2 [mm] | 3.0 | 3.0 |
| **Mean Blade Angles** | | |
| L.E. β,B1 [°] | 43/16 | 43/16 |
| T.E. β,B2 [°] | 60 | 55 |
| **Blade Wrap Angle** φ [°] | 99/70 | 108/79 |
| **Number Blades** Z [-] | 14 (7/7) | 12 (6/6) |
| **Radial Diffuser** L [mm] | 2.0 | 6.6 |
| **Discharge Diffuser** H [mm] | 120.0 | 116.6 |

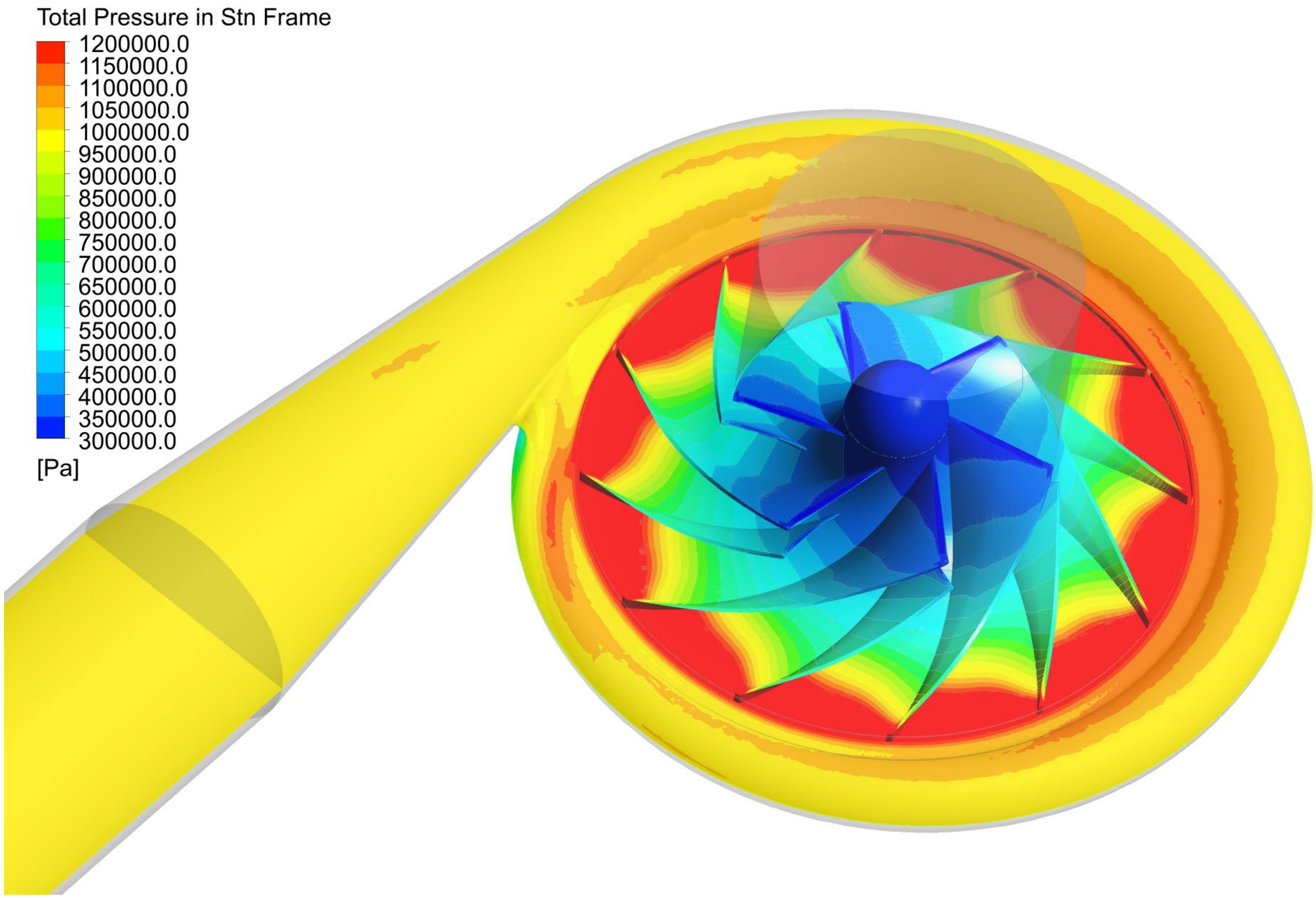
# 5 Mathematical optimization, Results Design 107




n=36000 rpm
ṁ=2.7 lb/s

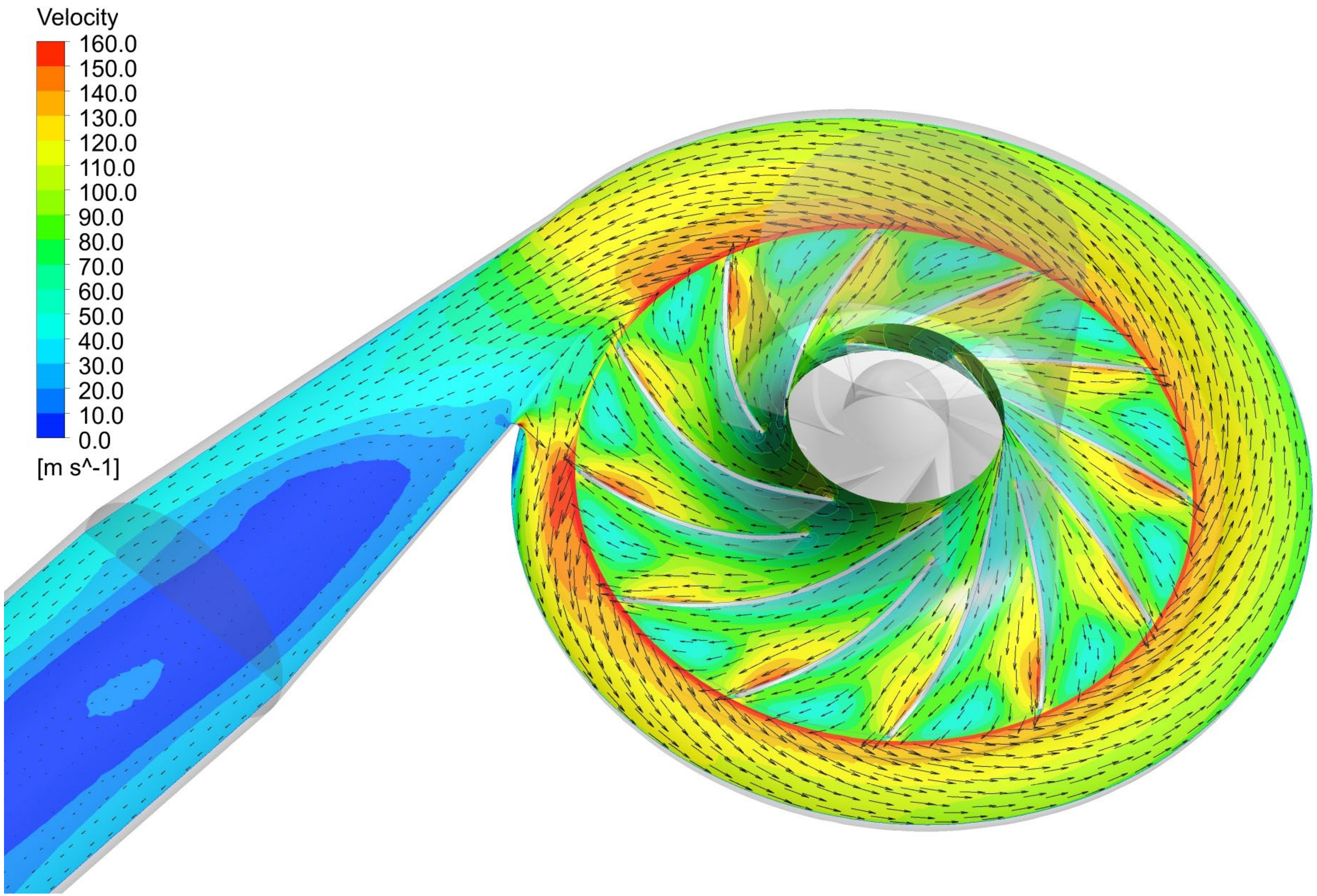
# 5 Mathematical optimization, Results Design 107

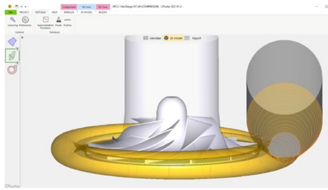
CFturbo




n=36000 rpm
ṁ=2.7 lb/s

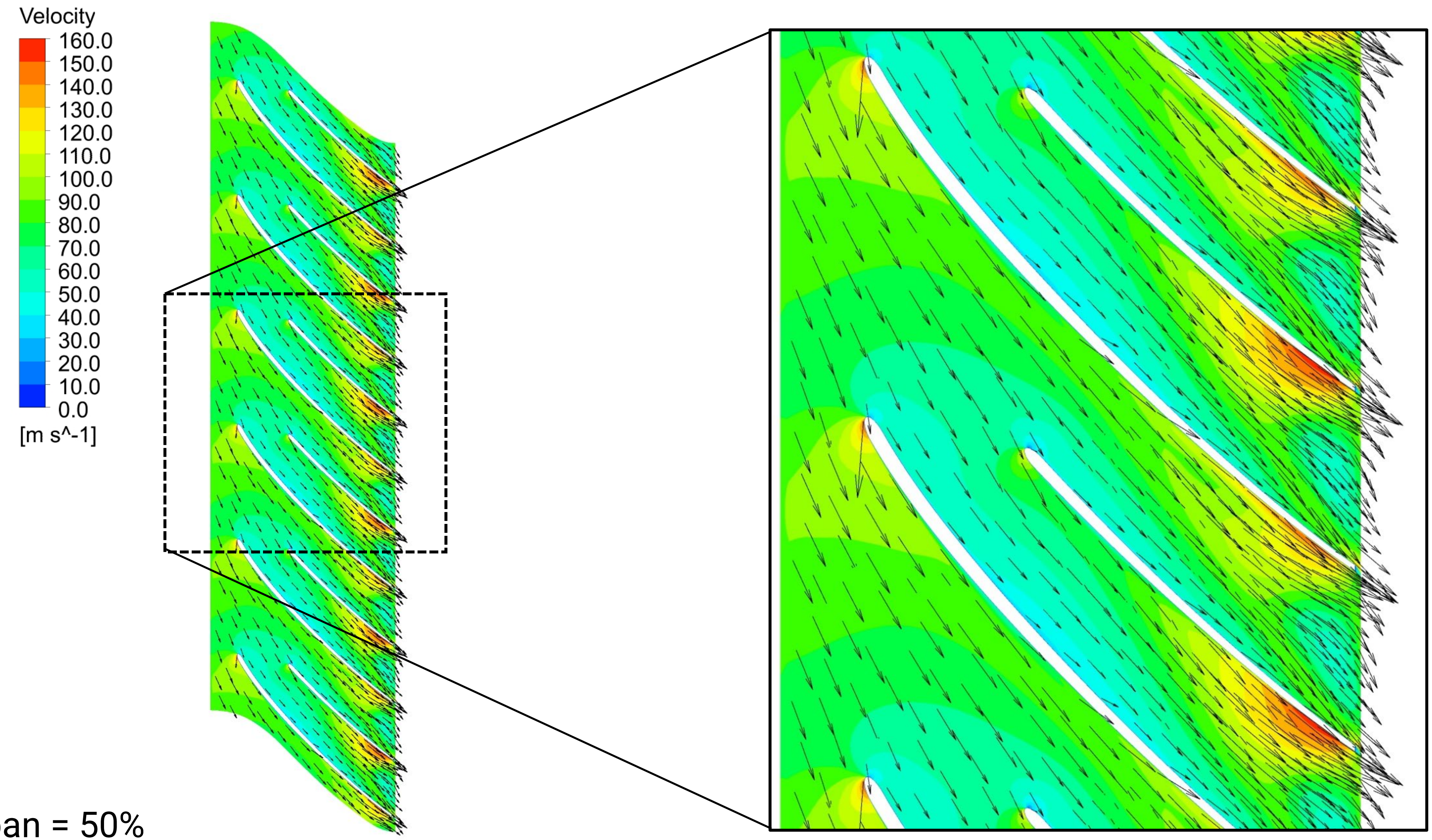
CFturbo

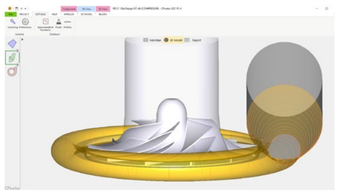


n=36000 rpm
ṁ=2.7 lb/s

# 5 Mathematical optimization, Results Design 107

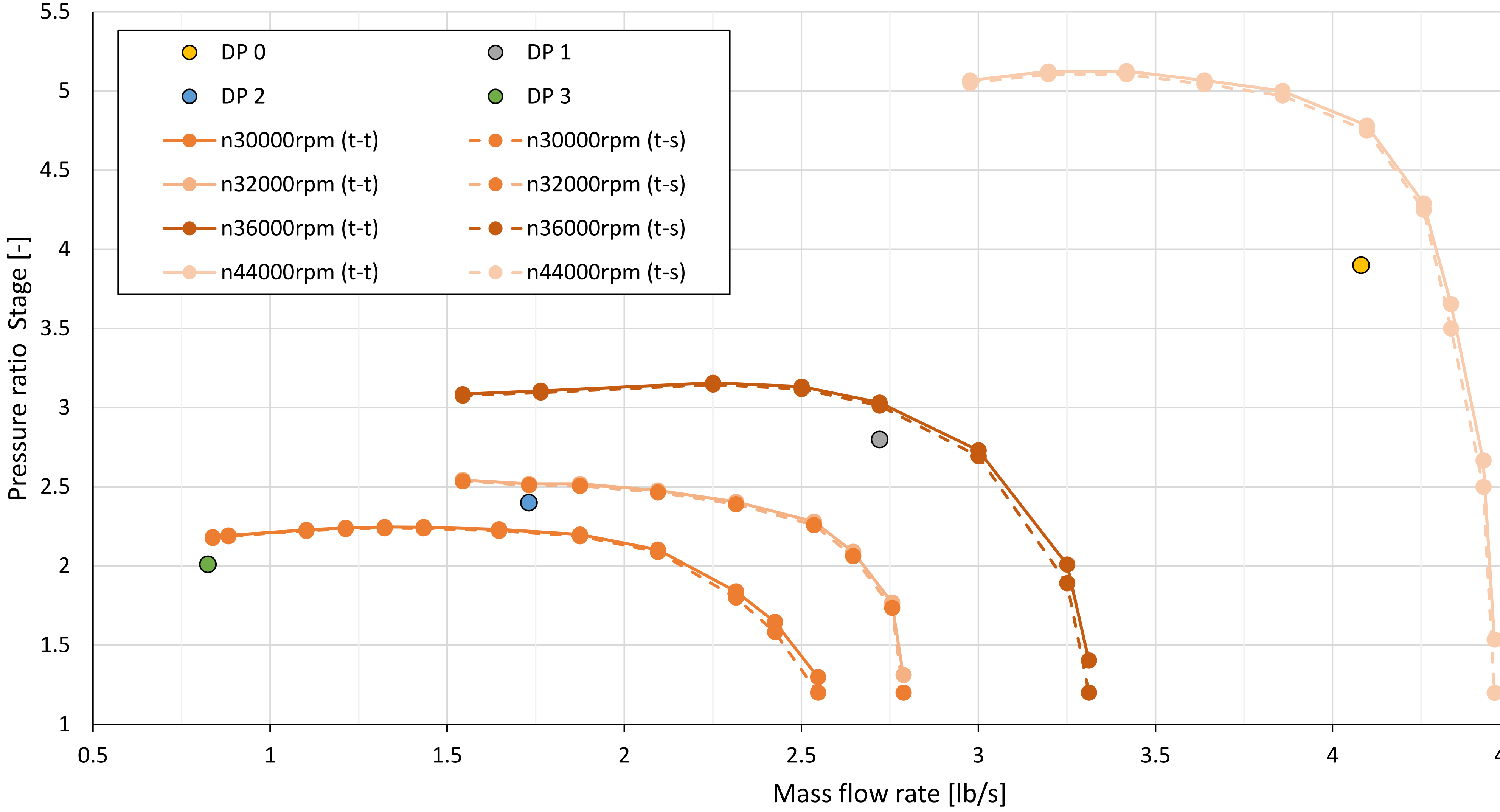


n=36000 rpm
ṁ=2.7 lb/s

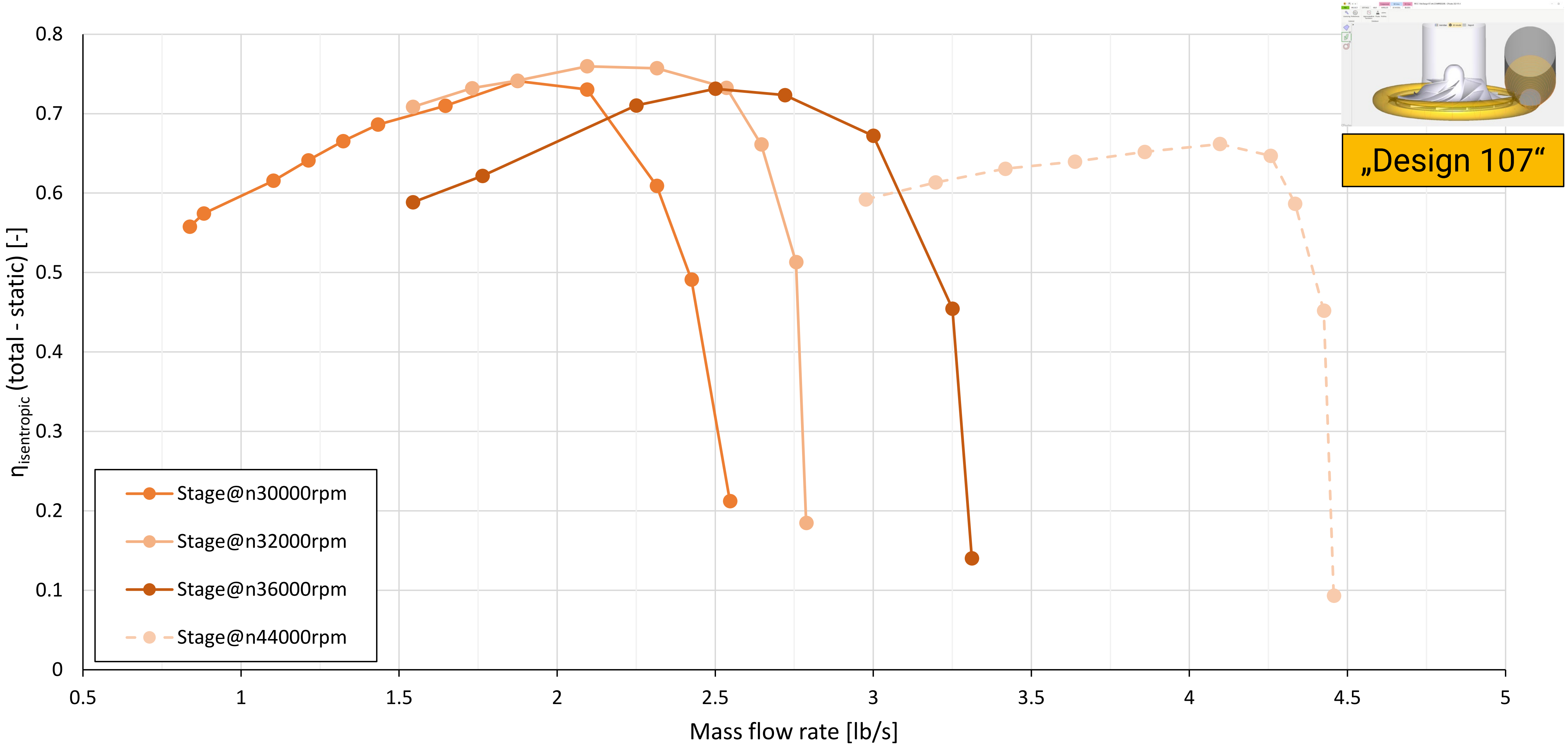
Span = 50%

CFturbo




„Design 107“

# 5 Mathematical optimization – $\eta_{isentropic}$ (Stage)@36000rpm




„Design 107“