A Member of
The Linde Group

KRYOTECHNIK

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ICEC/ICMC
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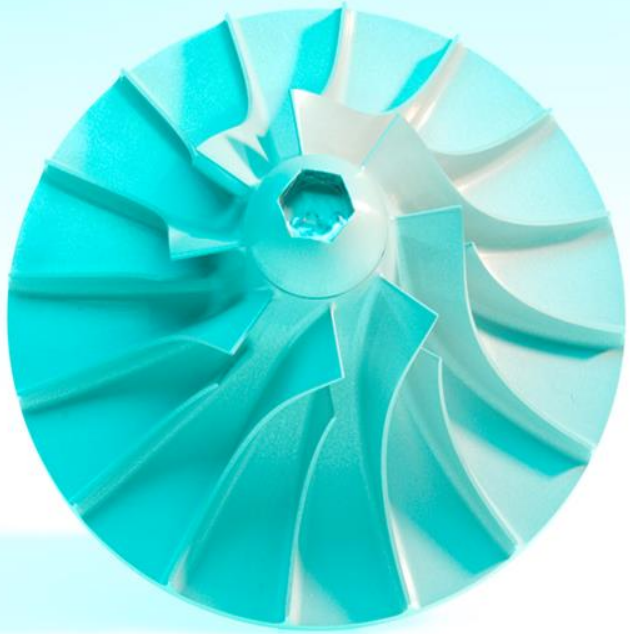
University of Twente, Enschede, The Netherlands

Cold Compressor String.

for the Superfluid Cryogenic Plant at Fermilab's CMTF.



Content

Cold Compressor Development
From the past to the present

PAST

- Custom-made machine design
- Long commissioning duration
- Control system design from scratch
- Long pump-down time
- First observation of performance during commissioning
- System observation only based on sensor values

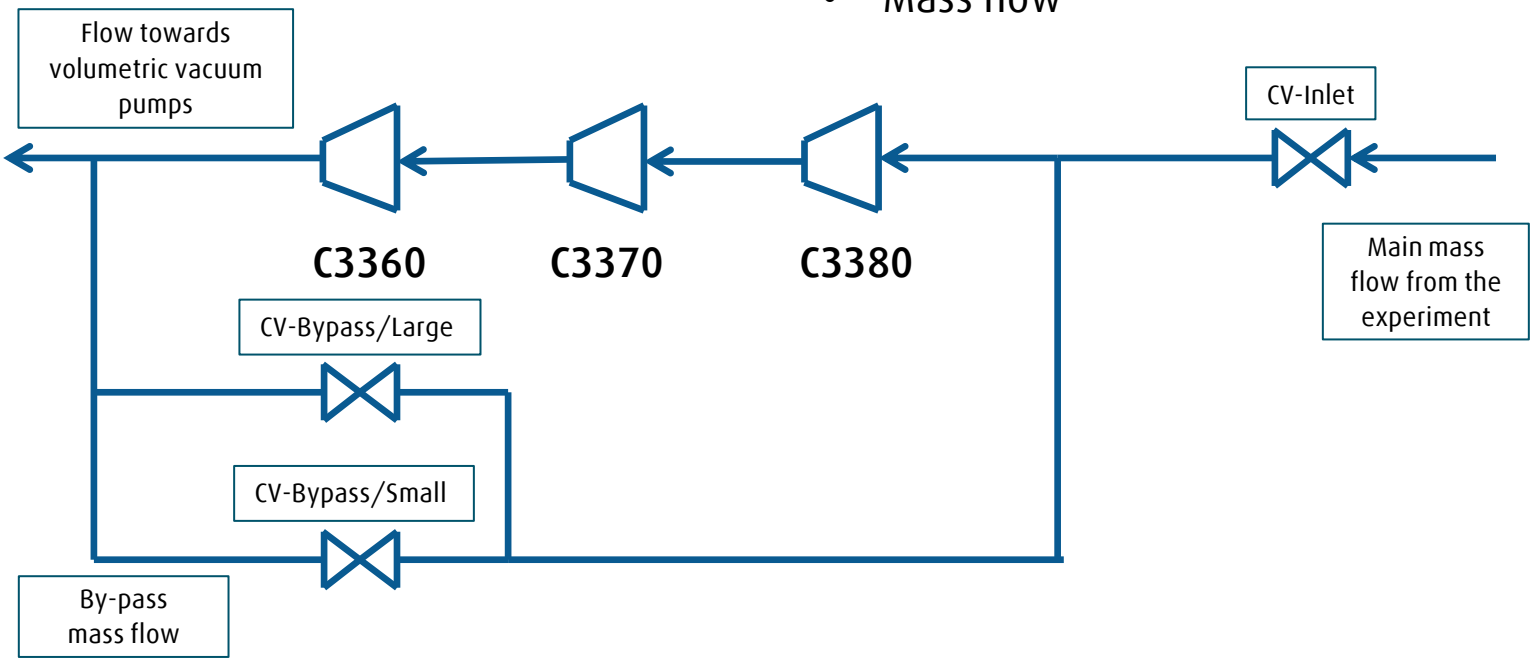
PRESENT

- Standard machinery, custom-made flow parts
- Very fast commissioning
- Standardized control system
- High pump-down speed
- Dynamic simulation of system model prior to commissioning
- Dynamic operating point visualization on compressor maps

Compression Process Design
Flow diagram

Measured variables

- Rotational speed
- Temperature
- Pressure
- Mass flow



Cold Compressor Design
Specifications

2K Mode	1.8K Mode
500W	250W
M^*=26.8 g/s	M^*=14.0 g/s
P_{in} = 24 mbar	P_{in} = 13 mbar

$CC_1 \rightarrow N_{des}$ = 540 Hz ; N_{max} =767 Hz

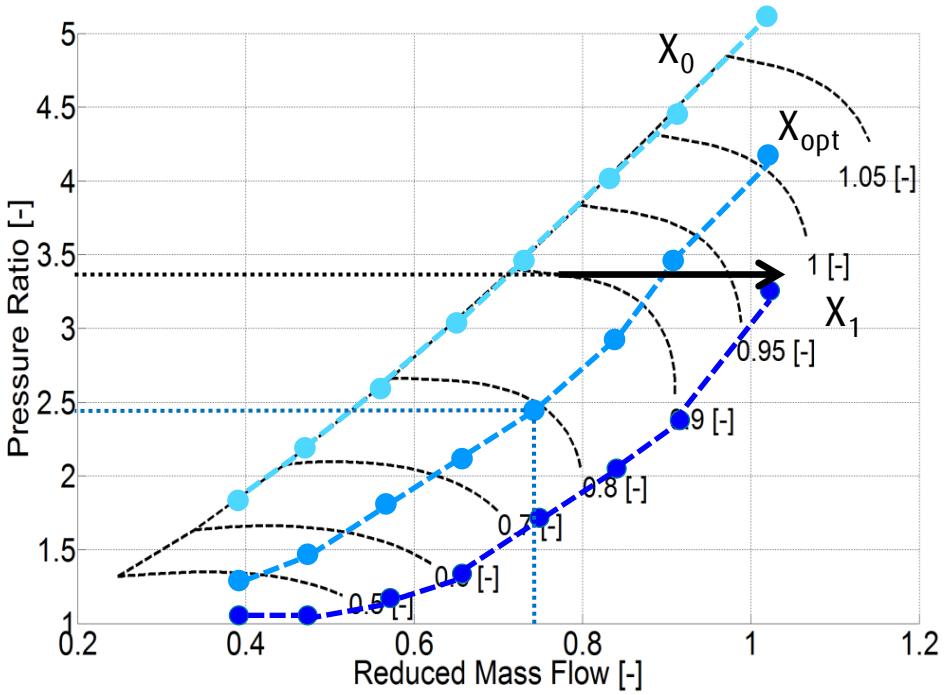
$CC_2 \rightarrow N_{des}$ = 706 Hz ; N_{max} =917 Hz

$CC_3 \rightarrow N_{des}$ = 706 Hz ; N_{max} =917 Hz

Cold Compressor String Model

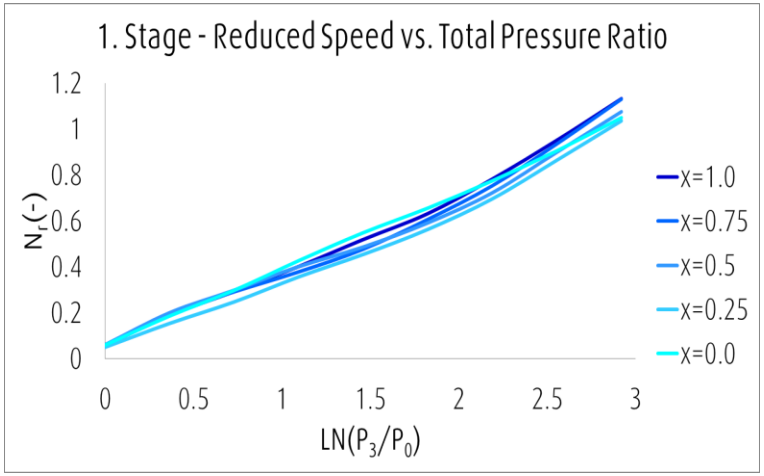
Concept – Example Stage 1 (CC1)

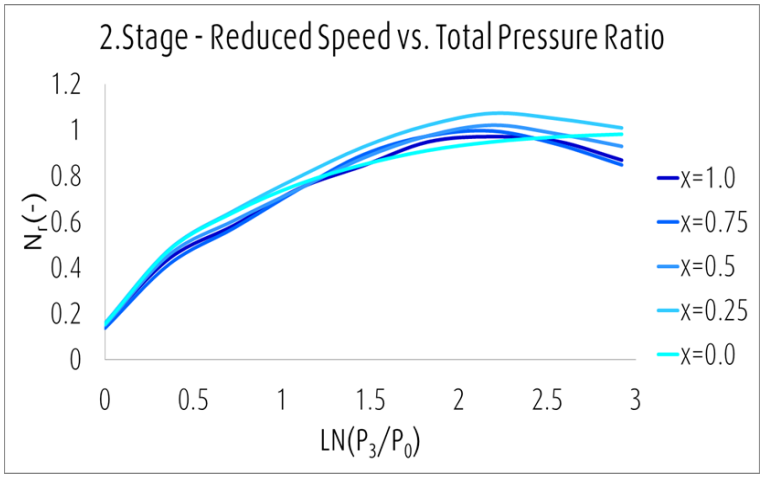
- At each reduced flow different reduced speed lines
- Effect on the input conditions of the next stage
- Capacity (X) curves are created along the map
- Capacity (X) value is the control variable

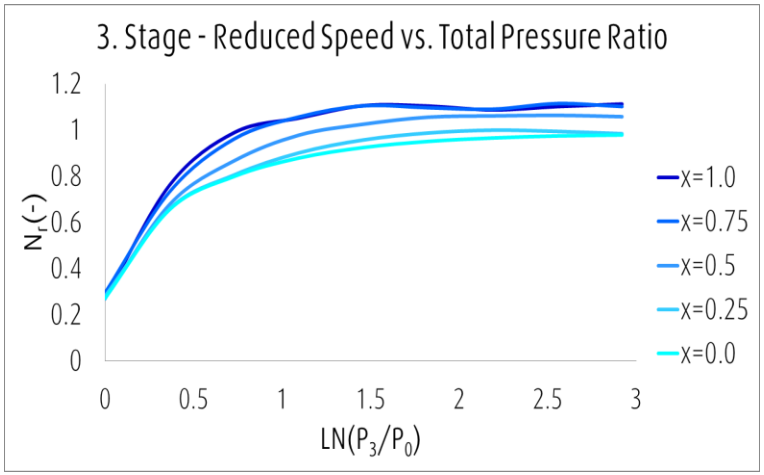


Cold Compressor String Model
Look-up graphs

- X is the output of the PI controller
- The same X for all compressors
- For saturated X at 0.9, the controller increases $LN(P_3/P_0)$



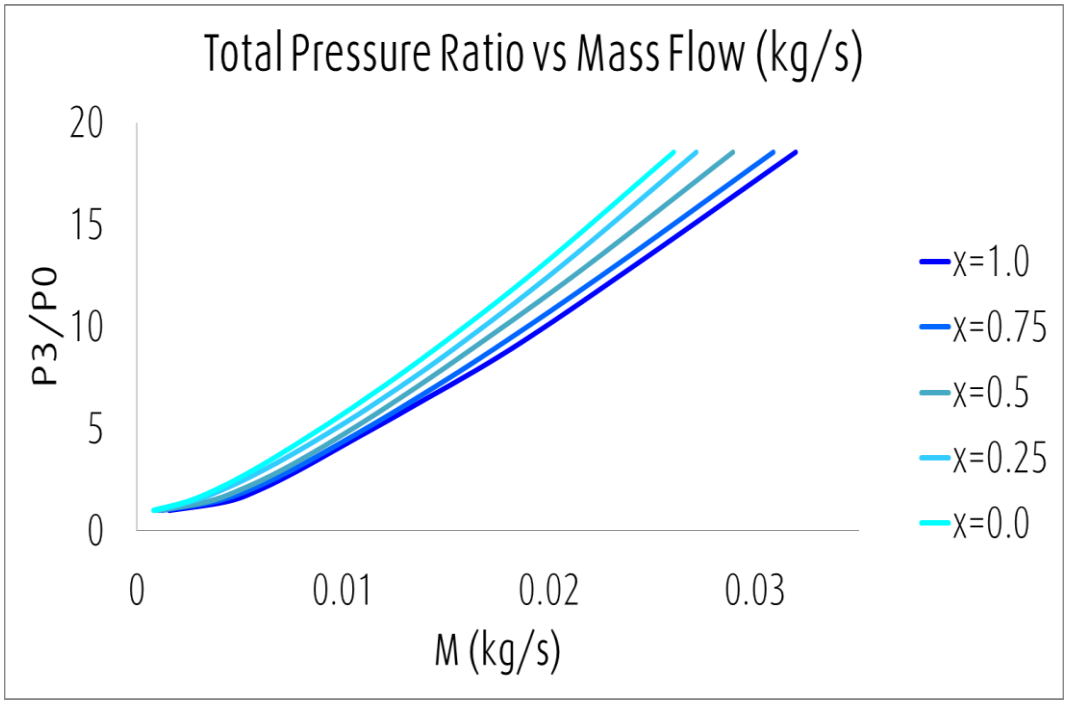




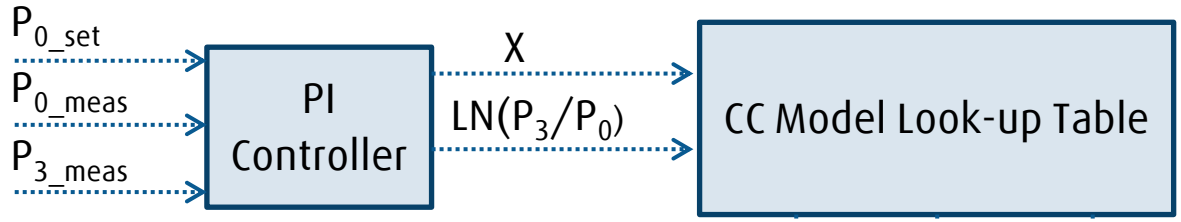
Cold Compressor String Model

Range of the real mass flow

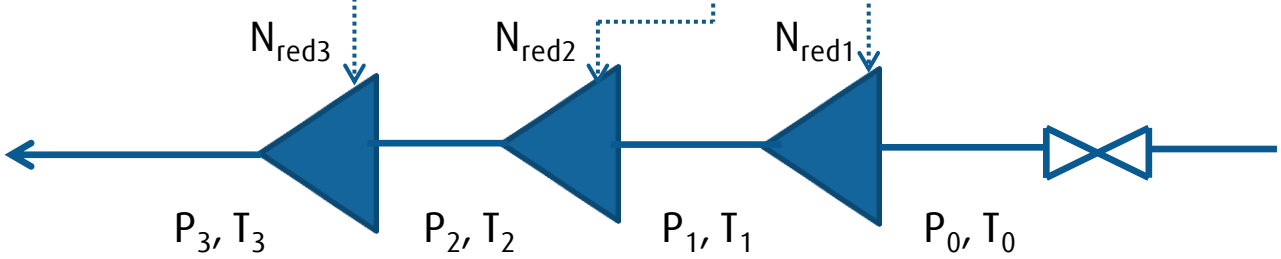
- At high P_3/P_0 mass flow range becomes higher
- X and P_3/P_0 can be used to find mass flow set point



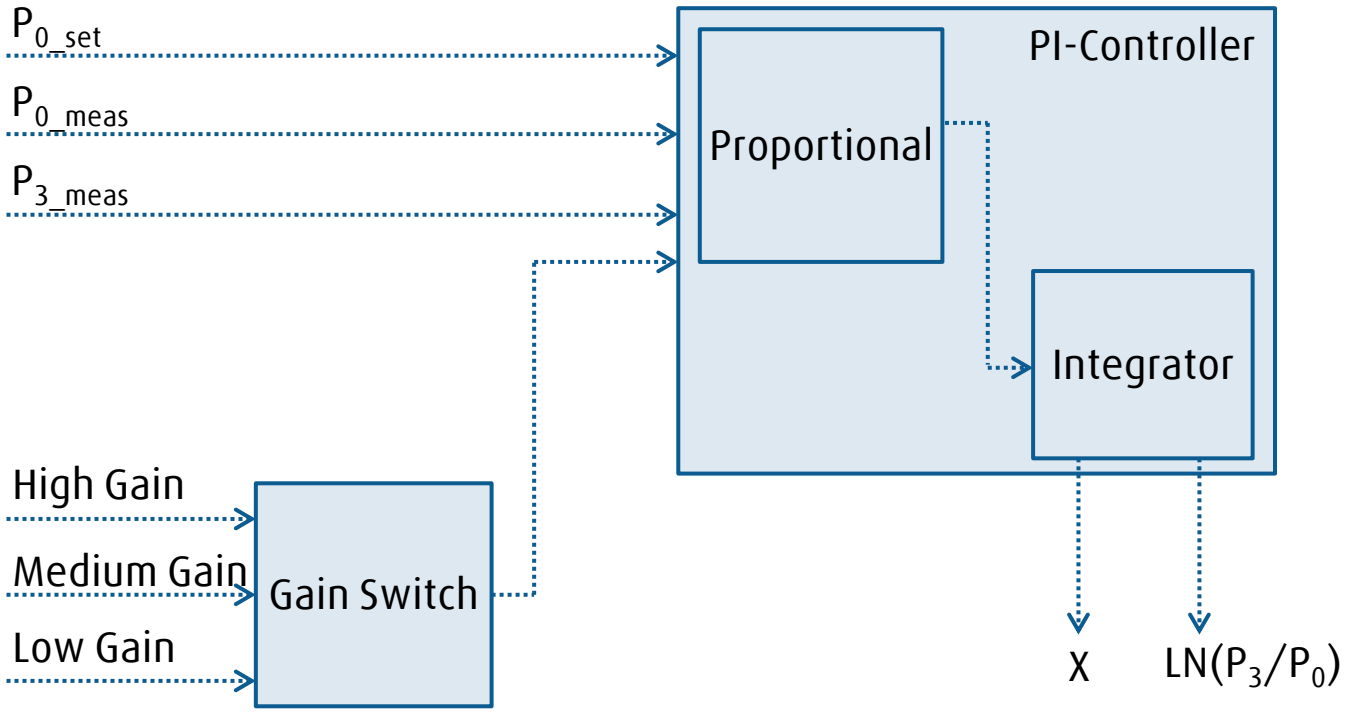
Controller Design
Overview



- X and $LN(P_3/P_0)$ are inputs to the model
- X_{max} is 0.9 to avoid choke
- X_{min} is 0.05 to avoid surge

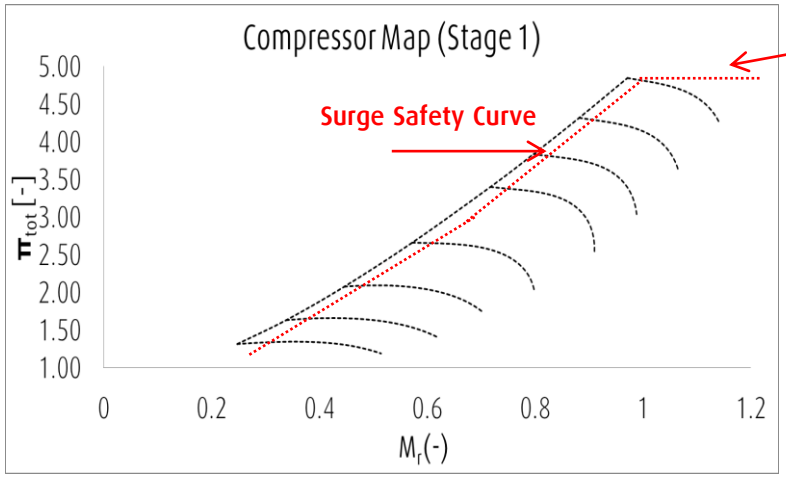


Controller Design
Control System Detail



- High gain is activated during pump-down to saturate X faster
- Saturated X increases the speed of pump-down

Surge and High Speed Protection
Safety Levels



Before setting the speeds

Safety Level 1 (Controller switch/Option)

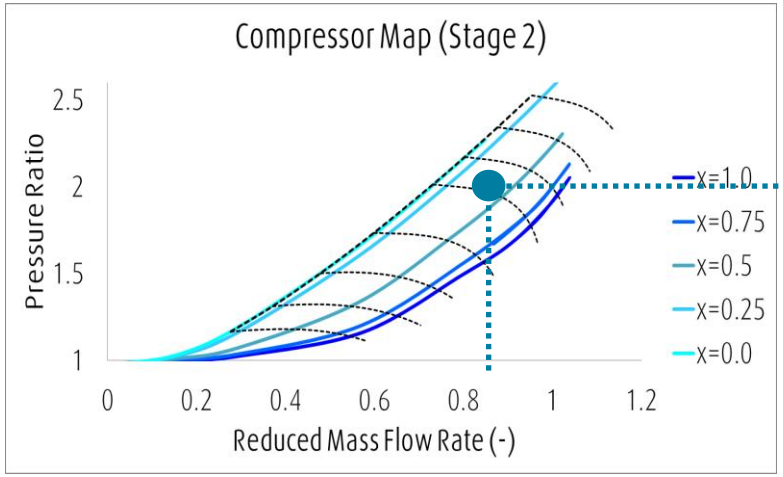
Safety Level 2 (X limit)

Safety Level 3 (Set speed limit)

Speed measurement and surge counter

Safety Level 4 (Smooth operation)

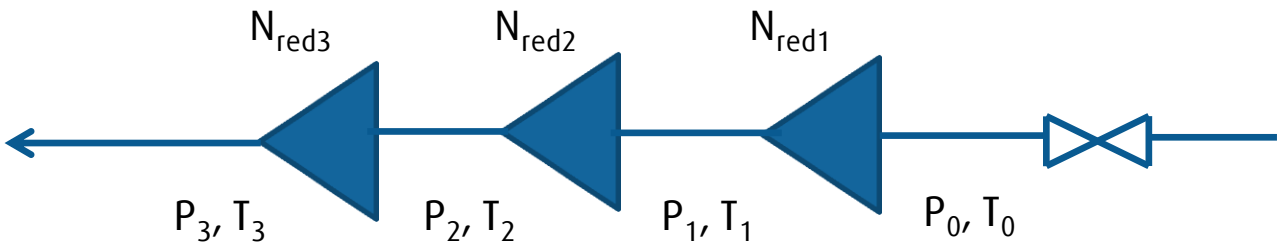
Correction of Measured Data



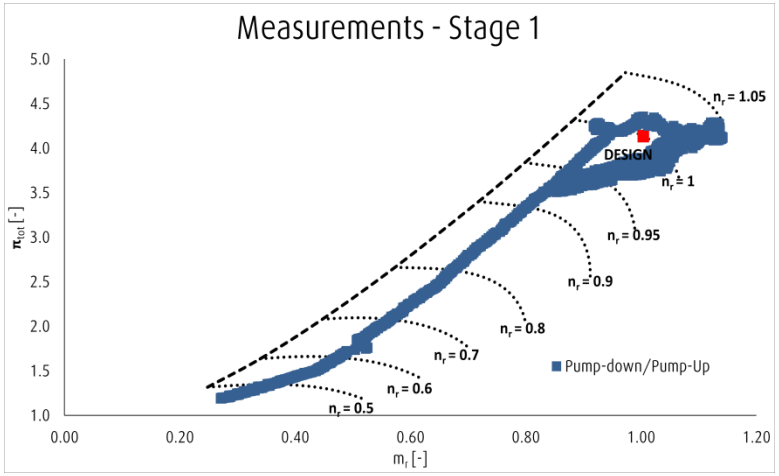
Model Output

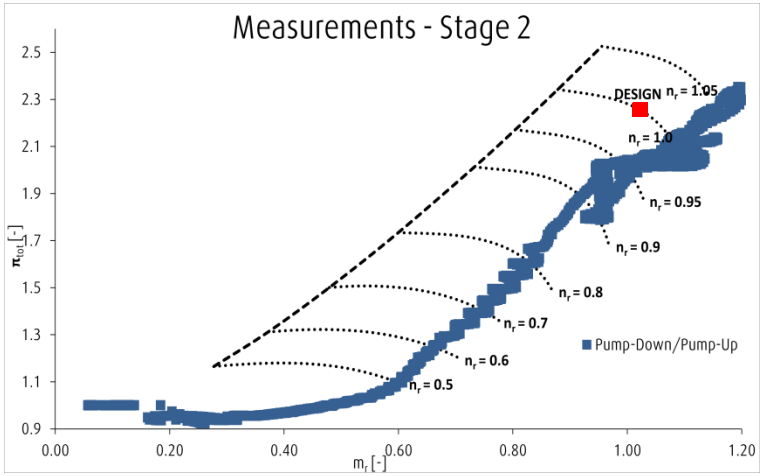
- Expected Pressure Ratio
- Expected Efficiency
- Expected Temperature Ratio

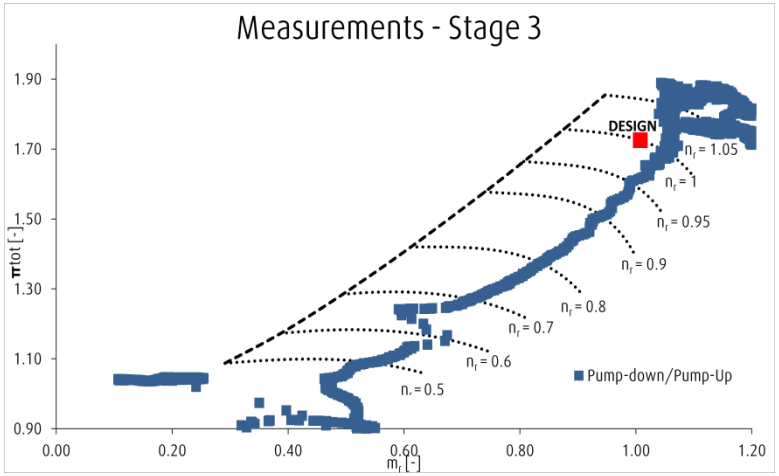
- Compensation of measurement errors



Real System Performance
Transient and steady state







- Pump-down to 24 mbar
- Pump-up to 30 mbar

Summary

- **Modularized approach which can be easily adapted to systems with different number of compressors**
  (e.g. for the cryoplant of DESY's XFEL Project with 4 compressors)
- **Extremely quick and uncomplicated commissioning within a few days only**
- **Reliable and robust operation**
- **Pump-down, steady-state, pump-up for 2K and 1.8K covered by the same control logic**
- Different levels of surge and over-speed protection
- Model-based control algorithms derived using Euler turbo-machinery equations
- Single PI controller with adjustable gains for fast pump-down performance
- One control variable for all compressors
- Integrated mass flow and inlet temperature control

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Thank you for your attention.