**Institute for
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Design Concept for
Large Output Graz Cycle Gas Turbines

Presentation at the
ASME Turbo Expo 2006
Barcelona, Spain, May 8 - 11, 2006

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Motivation

How do you want your egg(s)? - Sunny side up?

But do not have it burned!

Background

- Toronto Conference 1988, a Call for Action
- Kyoto Protocol demands the reduction of greenhouse gases, mainly CO2
- In EU: strong pressure on utilities and companies to reduce CO2 emissions
- In 2005: emission allowances to about 10 000 companies within the EU covering about 46 % of the overall EU CO2 emissions
- As emission allowances become scarce: CO2 generates costs (European Emission Allowances in March 2006: 27 €/ton CO2)
- CO2 and N2 from ASU can be utilized for
  Enhanced Oil Recovery (EOR)
  Return: 20 – 40 $/ton CO2

Oxy-Fuel Cycles

• Oxy-fuel cycles with internal combustion with pure oxygen are a very promising technology (Global Gas Turbine News 10/2005)

+ CO2 can be easily separated by condensation from working fluid consisting of CO2 and H2O, no need for very penalizing scrubbing

+ Very low NOx generation (fuel bound N2)

+ Flexibility regarding fuel: natural gas, syngas from coal, biomass or refinery residue gasification

- New equipment required

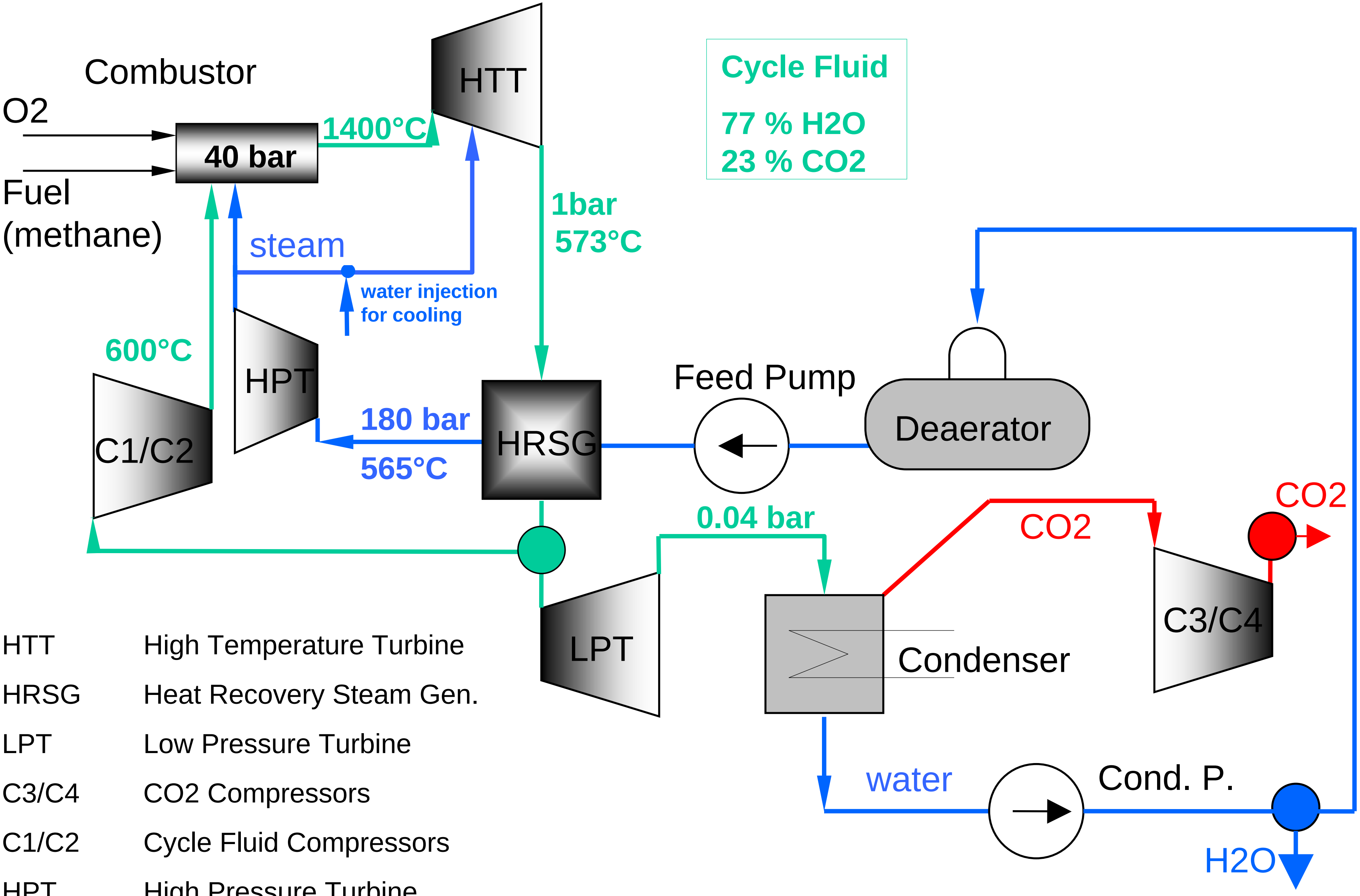
- Additional high costs of oxygen production

+ These new cycles show higher efficiencies than current air-based combined cycles (Graz Cycle, Matiant cycle, Water cycle,...)

History of the Graz Cycle

- 1985: presentation of a power cycle without any emission (CIMAC Oslo)
  - H2/O2 internally fired steam cycle, as integration of top Brayton steam cycle and bottom Rankine cycle
  - efficiency 6 % - points higher than state-of-the art CC plants
- 1995: Graz cycle adopted for the combustion of fossil fuels like methane (CH4) (CIMAC Interlaken & ASME Cogen Vienna)
  - cycle fluid is a mixture of H2O and CO2
  - thermal cycle efficiency: 64 %
- 2000: thermodynamically optimized cycle for syngas from coal gasification (VDI Essen)
- 2002/2003: conceptual layout of prototype Graz Cycle power plant: detailed design of components (ASME Amsterdam, VDI Leverkusen, ASME Atlanta)
- 2004/2005: presentation of S-Graz Cycle with 69% thermal efficiency and 57 % net efficiency for syngas firing (ASME Vienna, ASME Reno)

Graz Cycle Basic Configuration (ASME 04/05)



HTT	High Temperature Turbine
HRSG	Heat Recovery Steam Gen.
LPT	Low Pressure Turbine
C3/C4	CO2 Compressors
C1/C2	Cycle Fluid Compressors
HPT	High Pressure Turbine

Power Balance ASME 2005

- **Electrical cycle efficiency for methane firing:**

  Efficiency: 64.6 % **(same for syngas firing)**

- **Oxygen production (0.15 - 0.3): 0.25 kWh/kg**

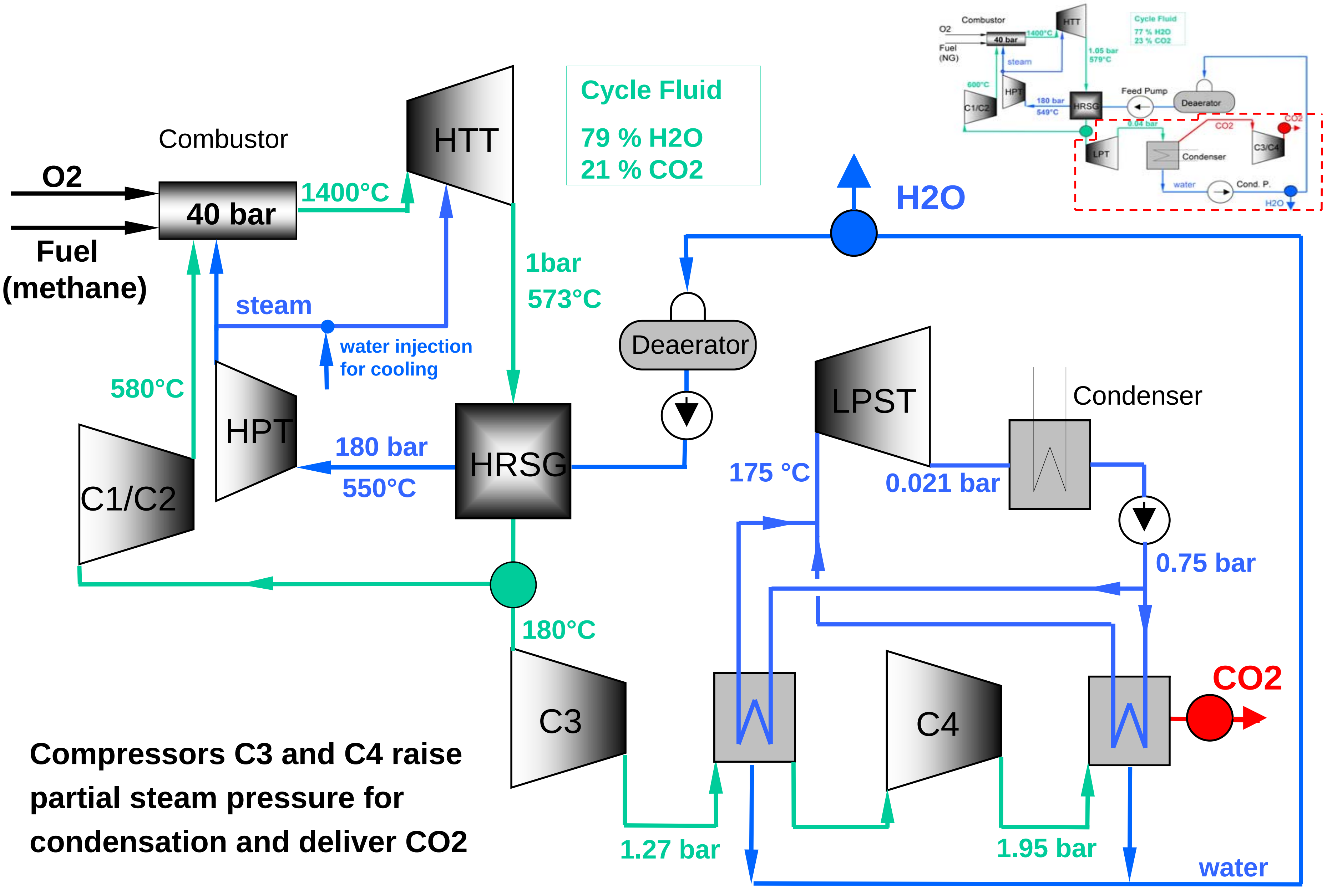
  Oxygen compression (2.38 to 40 bar, inter-cooled): 325 kJ/kg

  Efficiency: 54.8 %

- **Compression of separated CO2 for liquefaction (1 to 100 bar, inter-cooled): 270 kJ/kg (3.7 MW)**

  Efficiency: 52.7 %

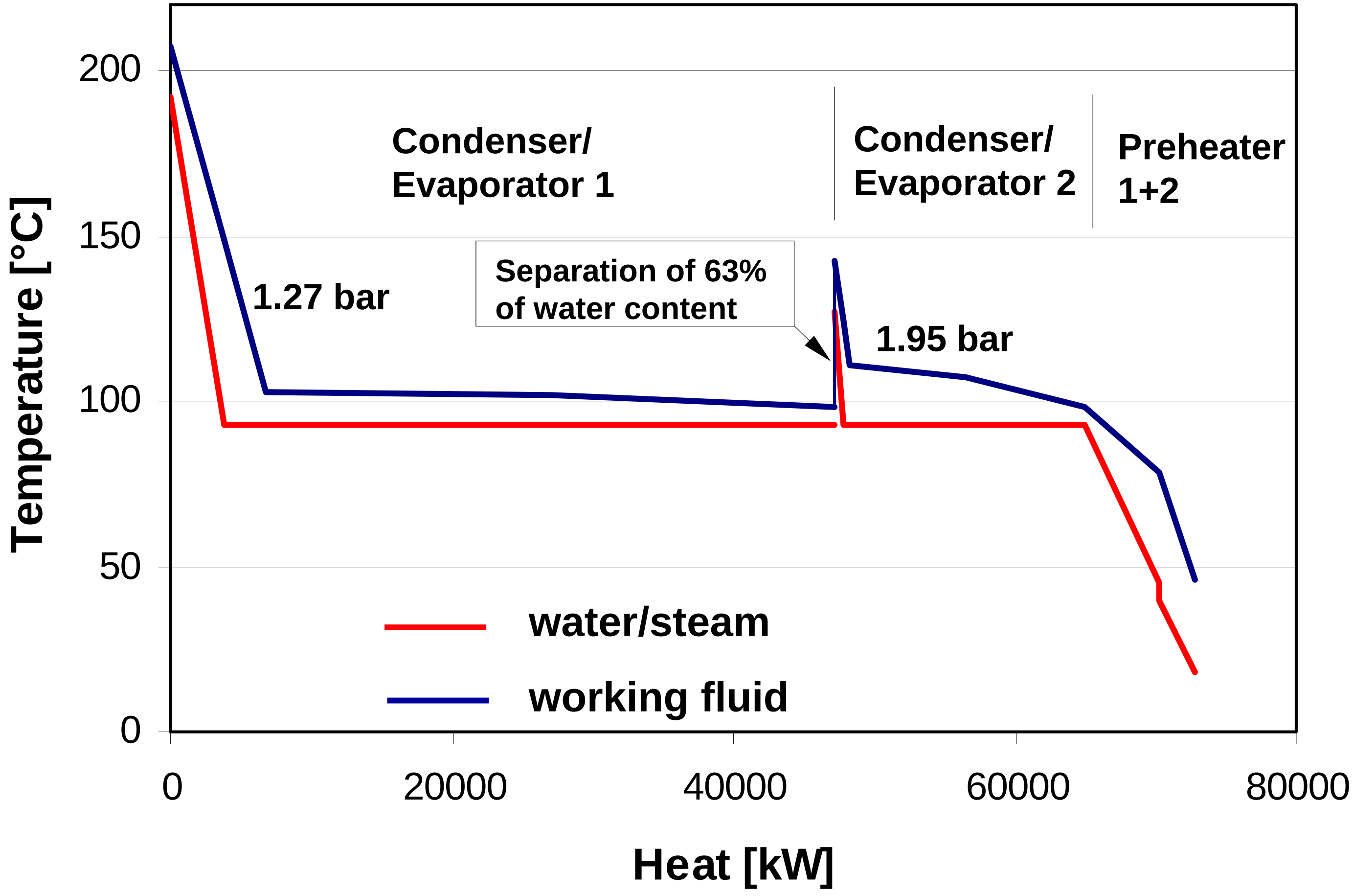
Condensation/Re-Vaporization at around 1 bar



Compressors C3 and C4 raise partial steam pressure for condensation and deliver CO2

Heat Transfer in Condenser/Evaporator

- **Constant re-evaporation pressure of 0.75 bar for the bottoming steam cycle**
- **LPST inlet temperature of 175 °C; expansion line crosses Wilson line at last blade inlet, thus low humidity losses**



S-Graz Cycle Power Balance for 400 MW net power

	Basic Layout	**New Layout**
HTT power [MW]	635	638
Total turbine power [MW]	753	739
Total compression power [MW]	249	235
Net shaft power [MW]	**504**	**505**
Total heat input [MW]	759	759
Thermal cycle efficiency [%]	**66.5**	**66.5**
Electrical cycle efficiency [%]	**64.6**	**64.6**

Additional Losses and Expenses

- **Oxygen production: 0.25 kWh/kg = 900 kJ/kg Oxygen compression (2.38 to 42 bar, inter-cooled): 325 kJ/kg**

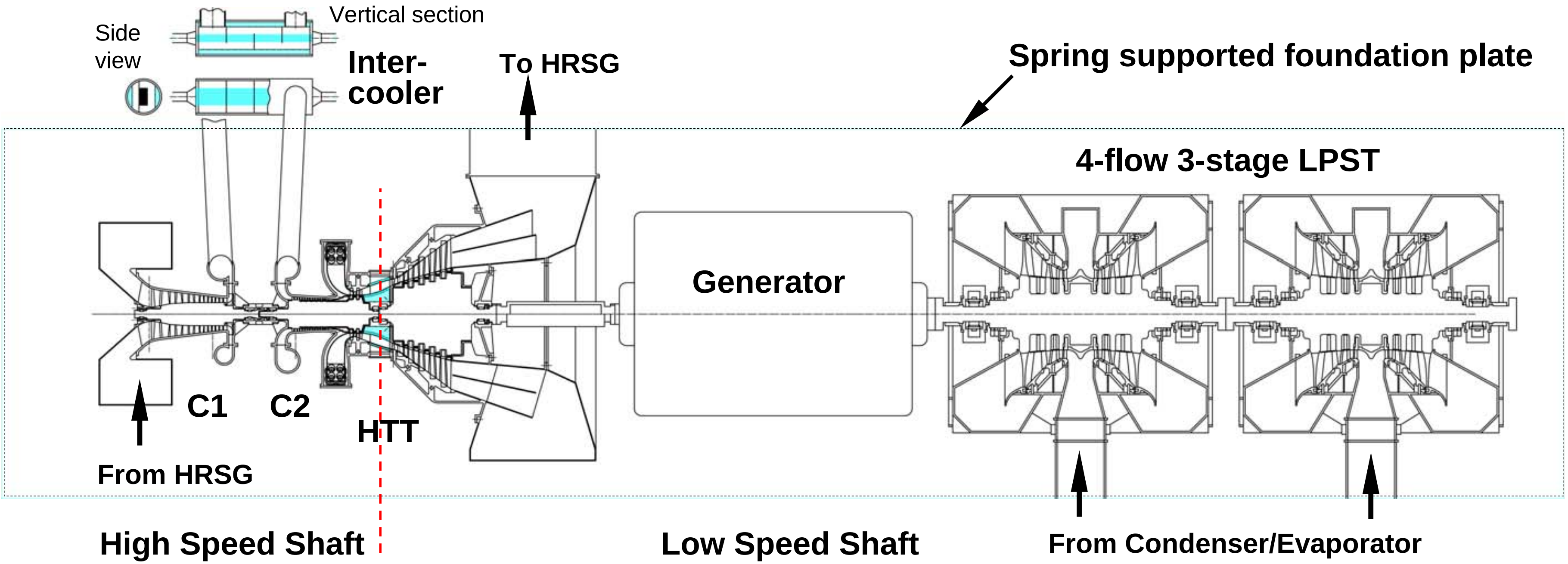
  Efficiency: 54.8 %

- **Compression of separated CO2 for liquefaction (1.9 to 100 bar): 13 MW (1 to 100 bar: 15.6 MW)**

  Efficiency: 53.1 % **(compared to 52.7 %)**

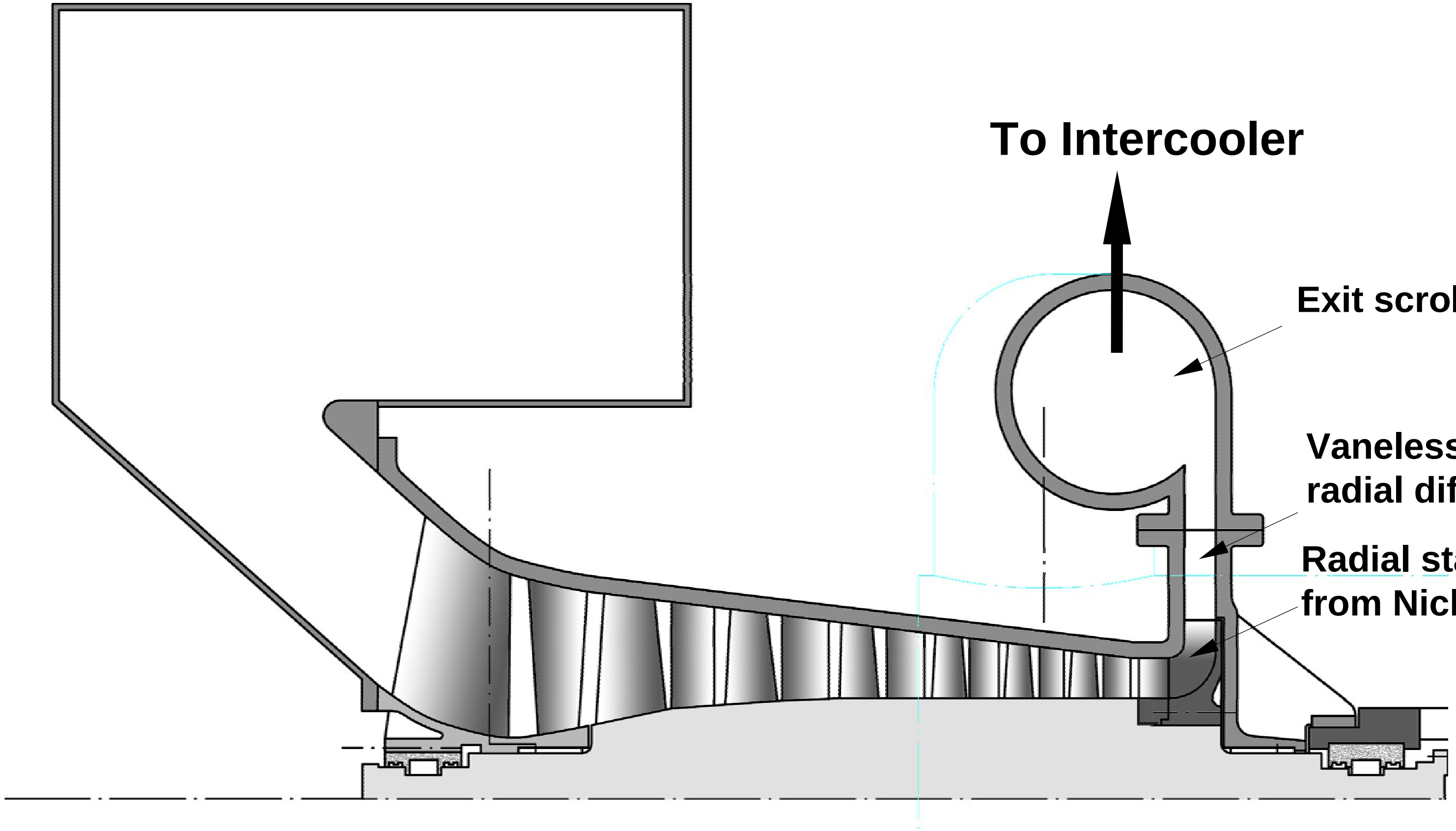
490 MW Turbo Shaft Configuration

- Main gas turbine components on two shafts for 400 MW net output
- Compression shaft of 8500 rpm: cycle compressors C1 and C2, driven by first part of HTT, the compressor turbine HTTC
- Power shaft of 3000/3600 rpm: power turbine HTTP as second part of HTT drives the generator
  Four-flow LPST at the opposite side of the generator
- Shafts on same spring foundation
  Intercooler between C1 and C2 on fixed foundation connected to HRSG



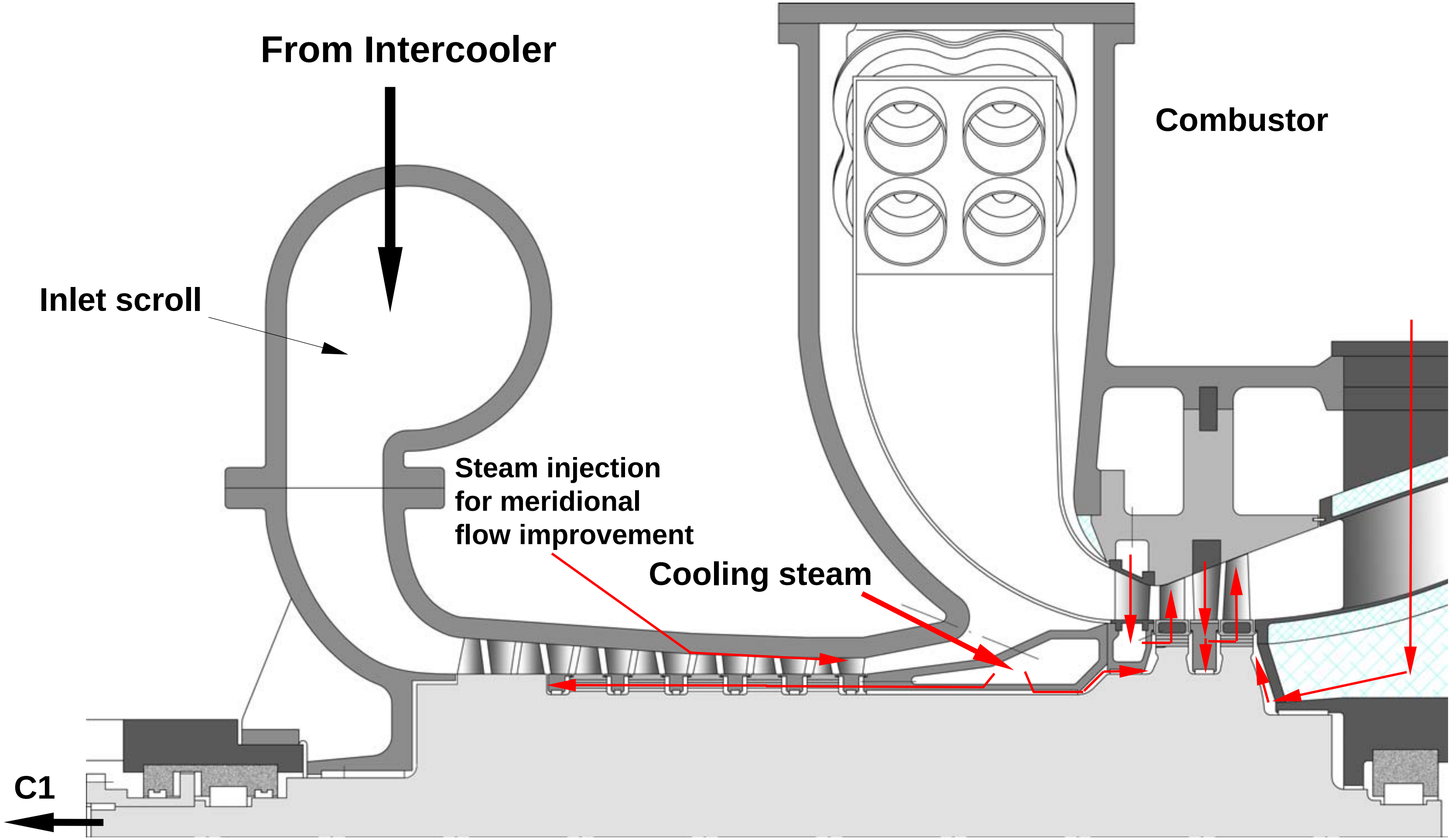
Working Fluid Compressor C1

- Compression 1 -> 13 bar, 106° -> 442°C
- Speed of 8500 rpm leads to inlet tip Mach number of 1.3
- 7 axial and 1 radial stage, 8500 rpm
- Uncooled drum rotor of ferritic steel (high temperature 9 %-chrome steel)



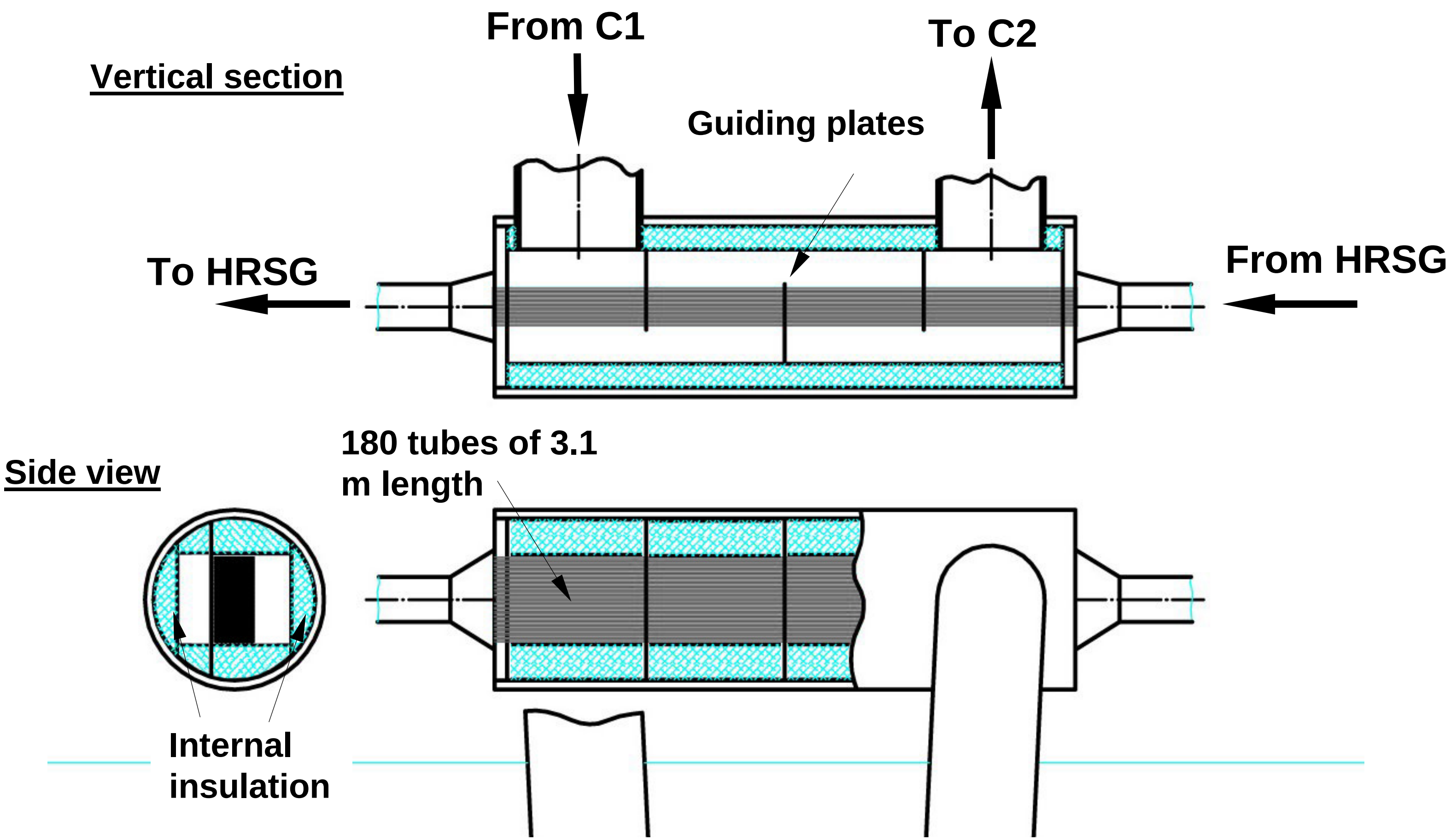
Working Fluid Compressor C2

- Compression 13 -> 40 bar, 380° -> 580°C , 7 stages, 8500 rpm
- Cooled drum rotor of ferritic steel with counterflow of cooling steam
- Blade length of 90 to 40 mm, small radial tip clearances

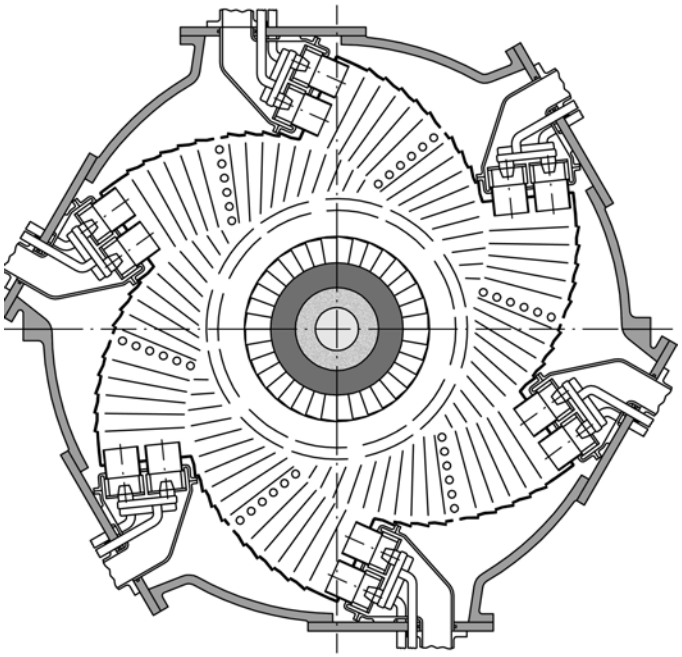


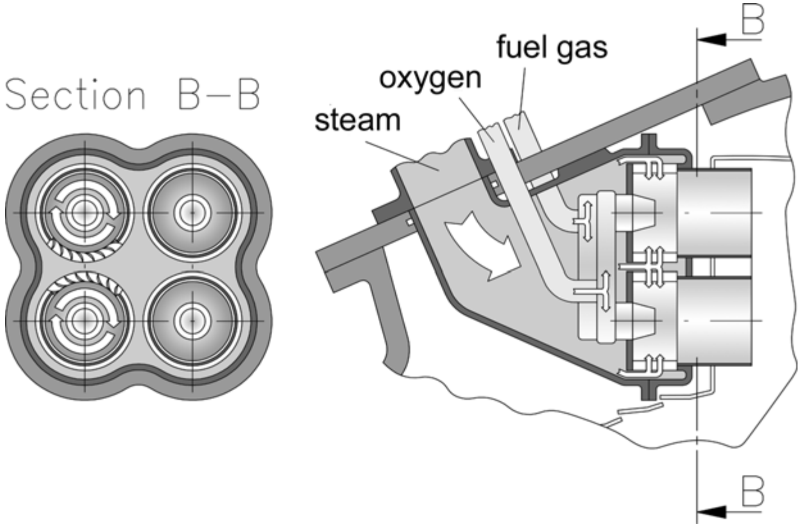
Intercooler between C1 and C2

- Heat transfer between working fluid and high pressure steam from HRSG
- Outer shell is a solid tube with internal insulation



Combustion Chamber

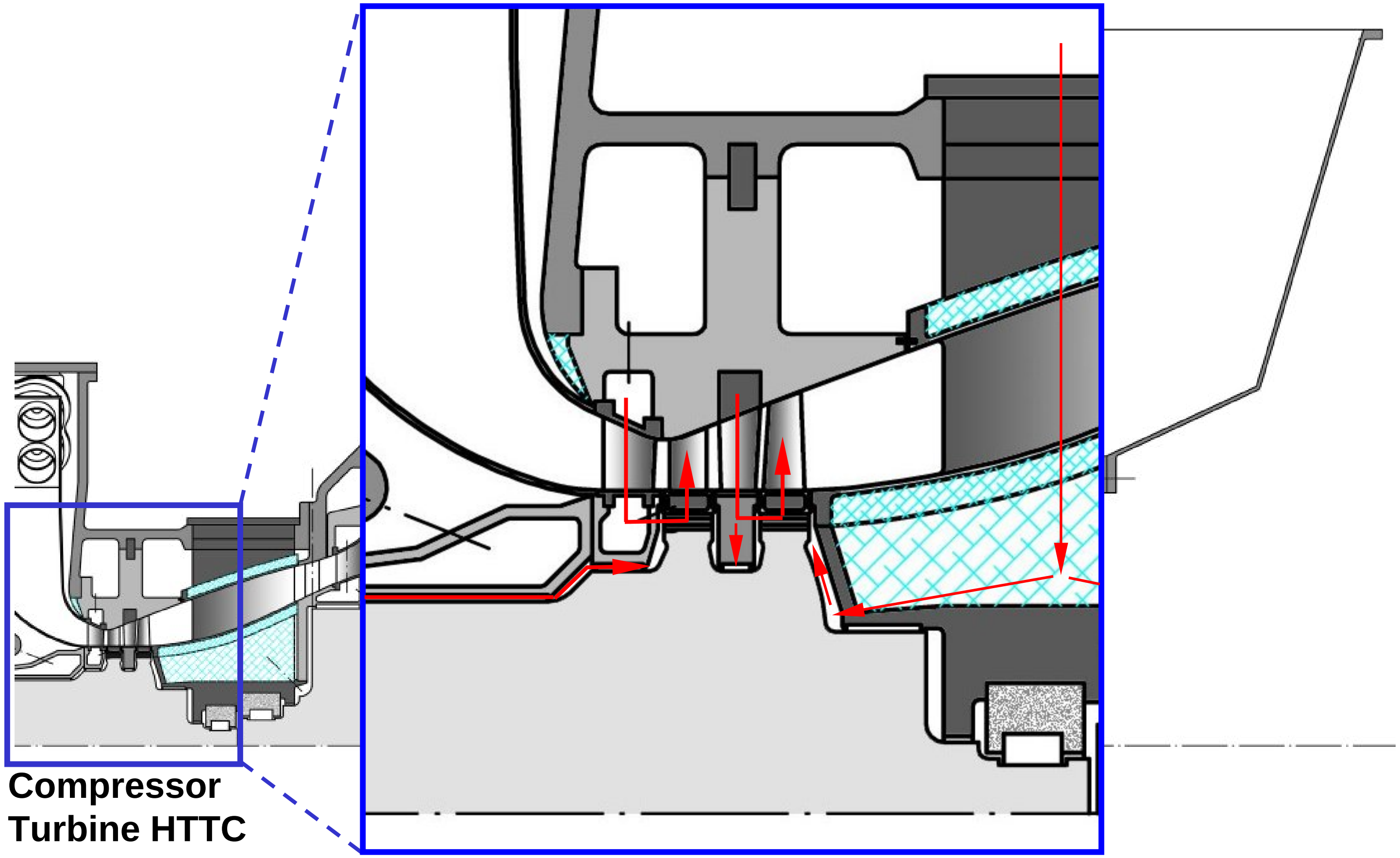




- Design as presented at ASME 2003, scaled up from 75 to 400 net power
- Stoichiometric combustion of fossil fuel and O2 at 40 bar
- Combustor exit temperature: 1400 °C
- Oxidizer is not cooling medium, thus risk of incomplete combustion. So fuel and O2 inflow have to be kept in close contact in burner vortex
- Cooling of burner by steam wrapping around burner head, limits flame temperature and prevents acoustic vibrations excitation
- Annular flame casing with 6 quadruples of burner tubes
- Cooling of annular flame cage by recompressed working fluid flow
- Tangential arrangement provides additional flow path length for better mixture and pre-swirl for first turbine stage

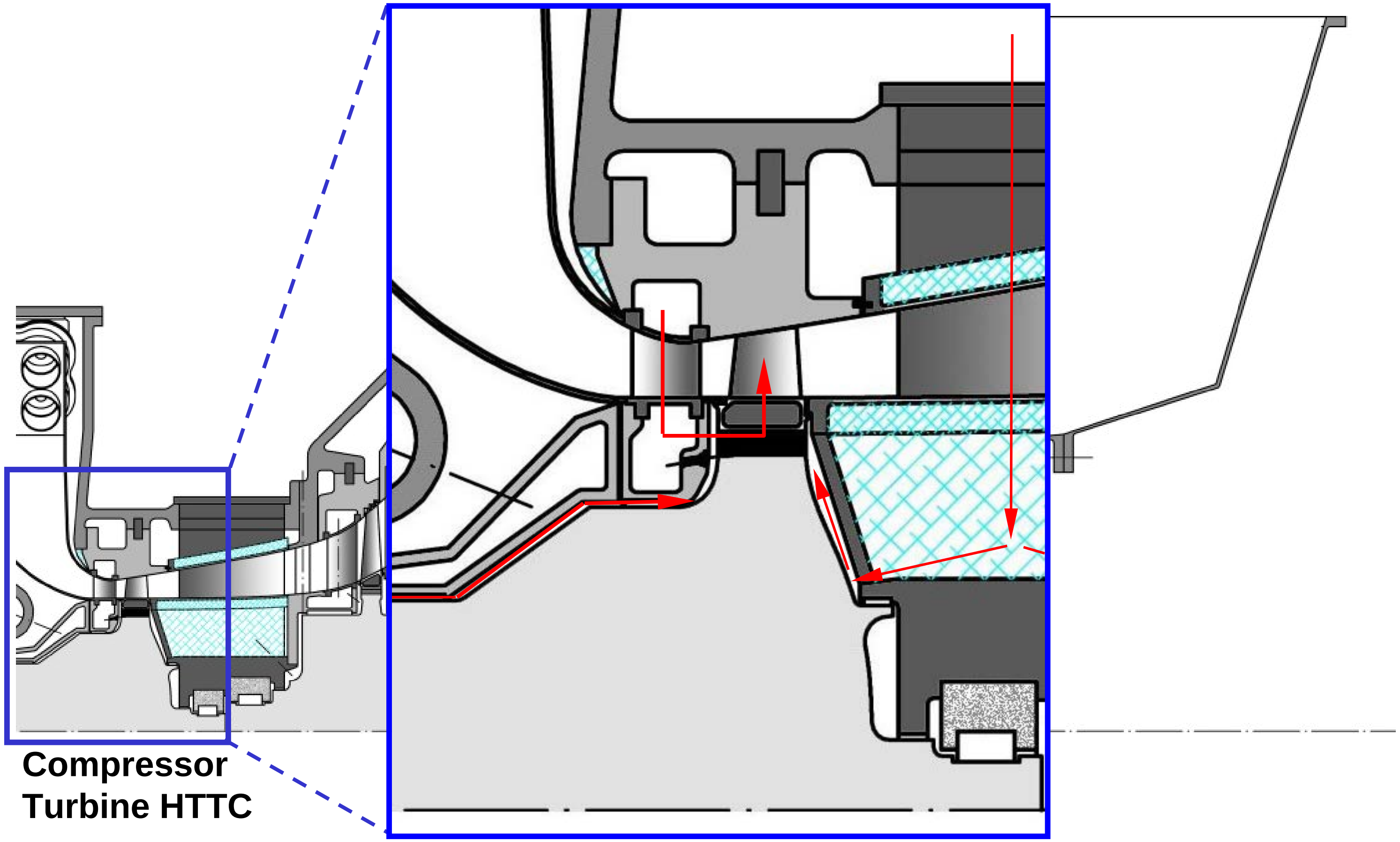
Compressor Turbine HTTC for 50 Hz

- HTTC: reaction turbine with 2 subsonic stages and blade length of 100 mm and 164 mm
- Rotor cooling steam along the drum surface
- Nozzles and blades are cooled in conventional serpentine passage design with holes



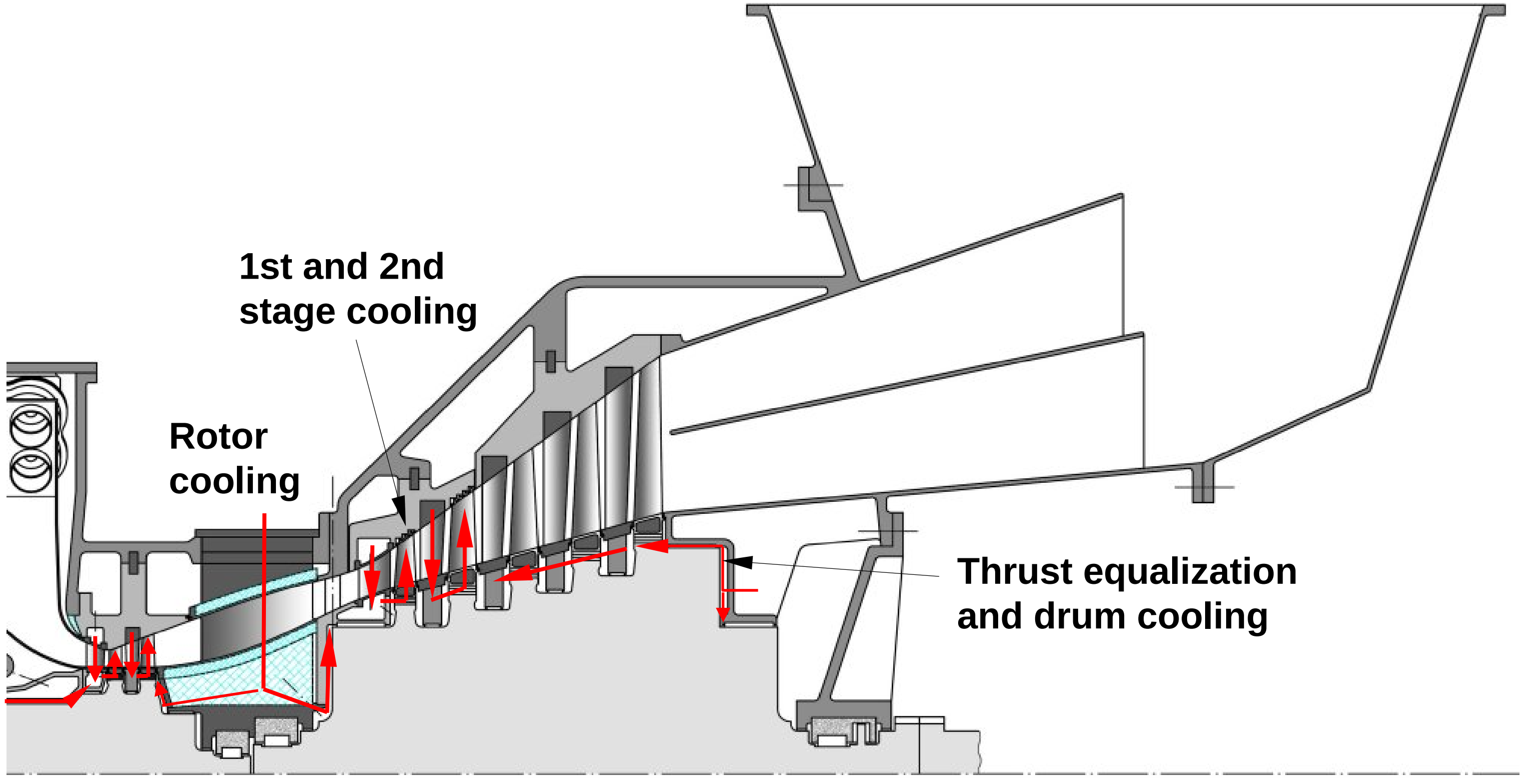
HTTC alternative design

- Alternative HTTC expansion with one transonic stage
- Blade length of 120 mm at higher radius and loading
- Application of innovative cooling design developed for transonic flows using underexpanded jets from slots (ASME 2004)



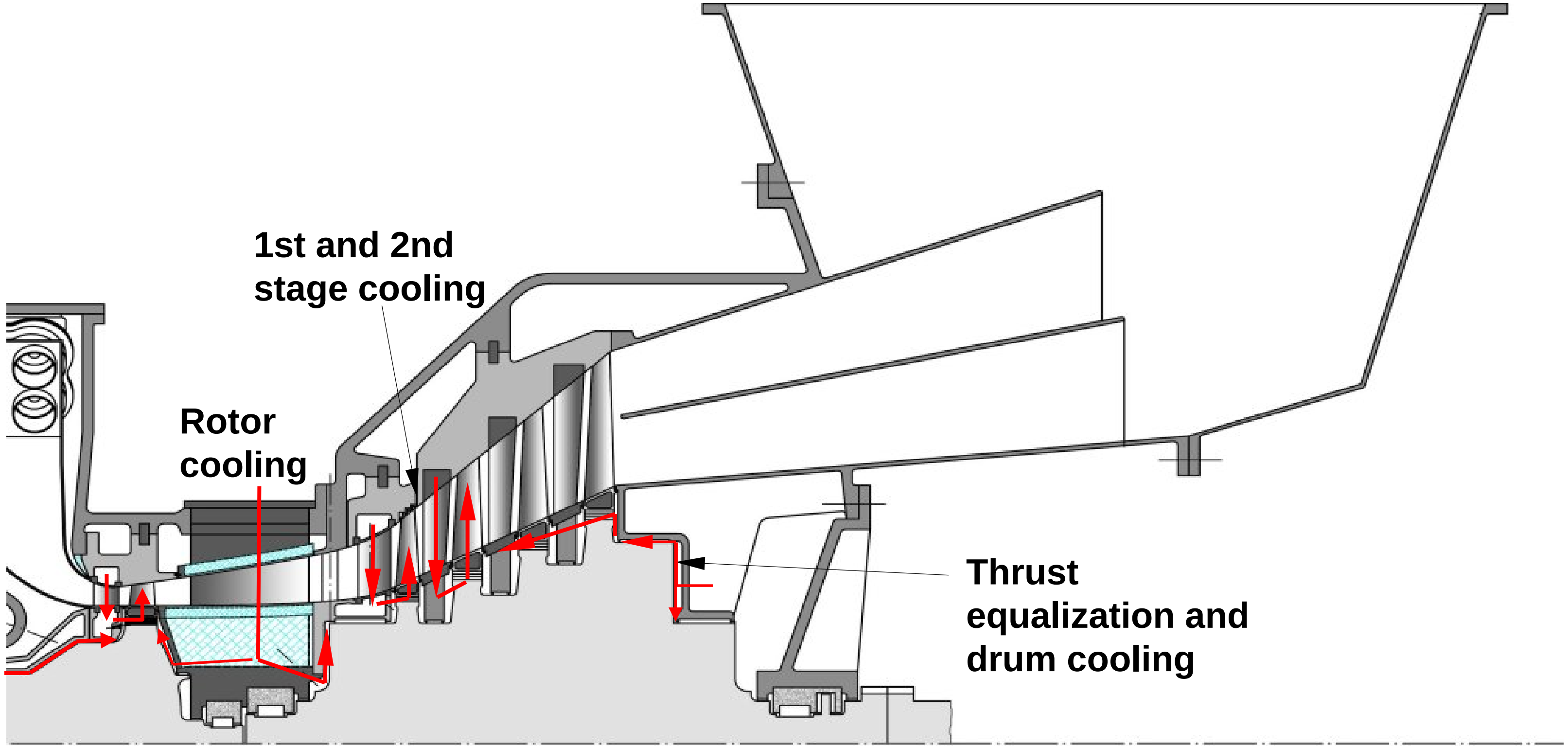
Power Turbine HTTP for 50 Hz

- 5 stages with strong change of inner radius
- Last blade length of 750 mm at 1300 mm inner radius
- Internal insulation of intermediate bearing casing, design similar to HP steam turbine presented at ASME 1988, Amsterdam
- Necessary thrust equalization and drum surface cooling on the exhaust side by steam



Power Turbine HTTP for 60 Hz

- 4 stages with strong change of inner radius
- Last blade length of 600 mm at 1300 mm inner radius
- HTTC outlet and HTTP inlet at the same radius



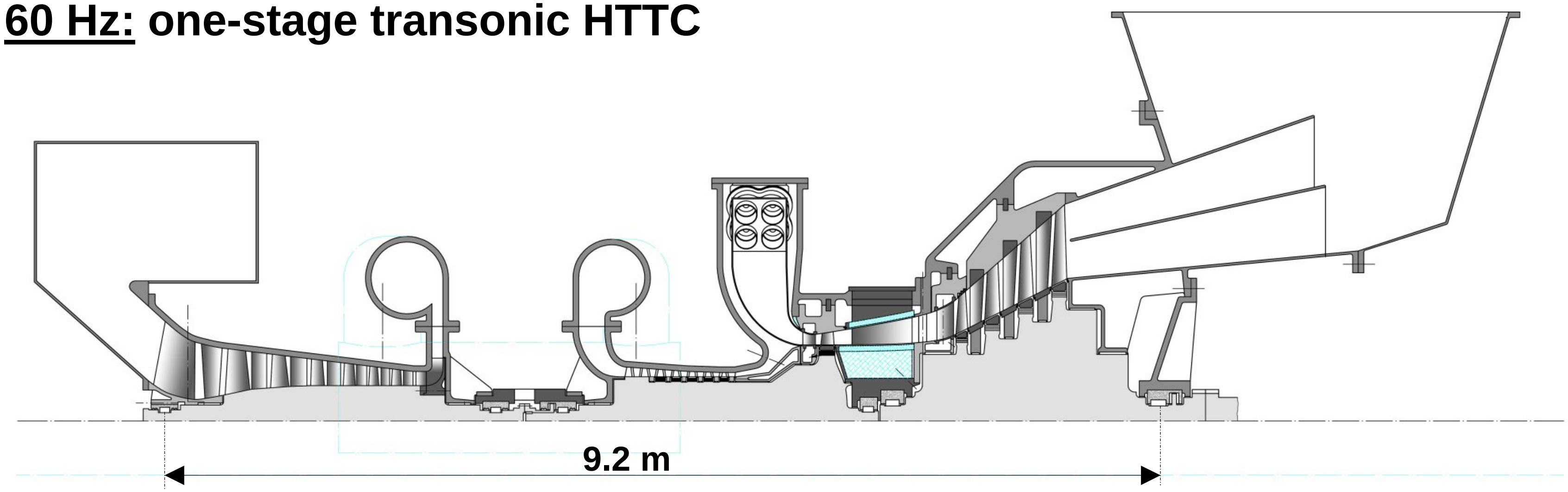
1st and 2nd stage cooling

Rotor cooling

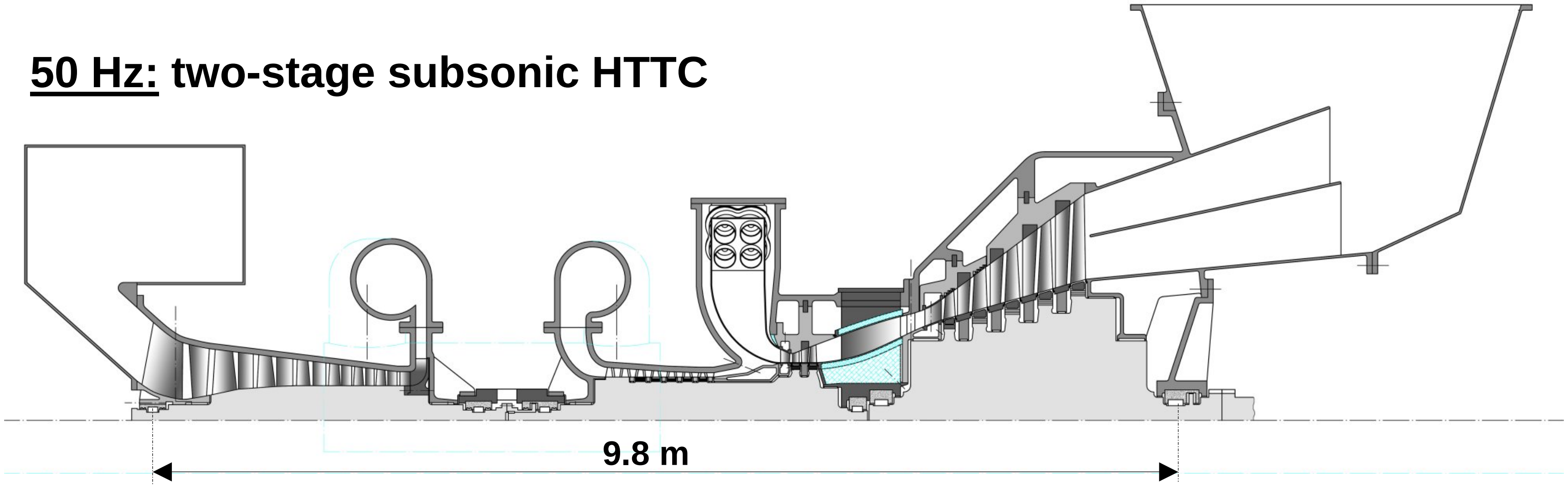
Thrust equalization and drum cooling

Comparison of turbo set 50 - 60 Hz

<u>60 Hz:</u> one-stage transonic HTTC

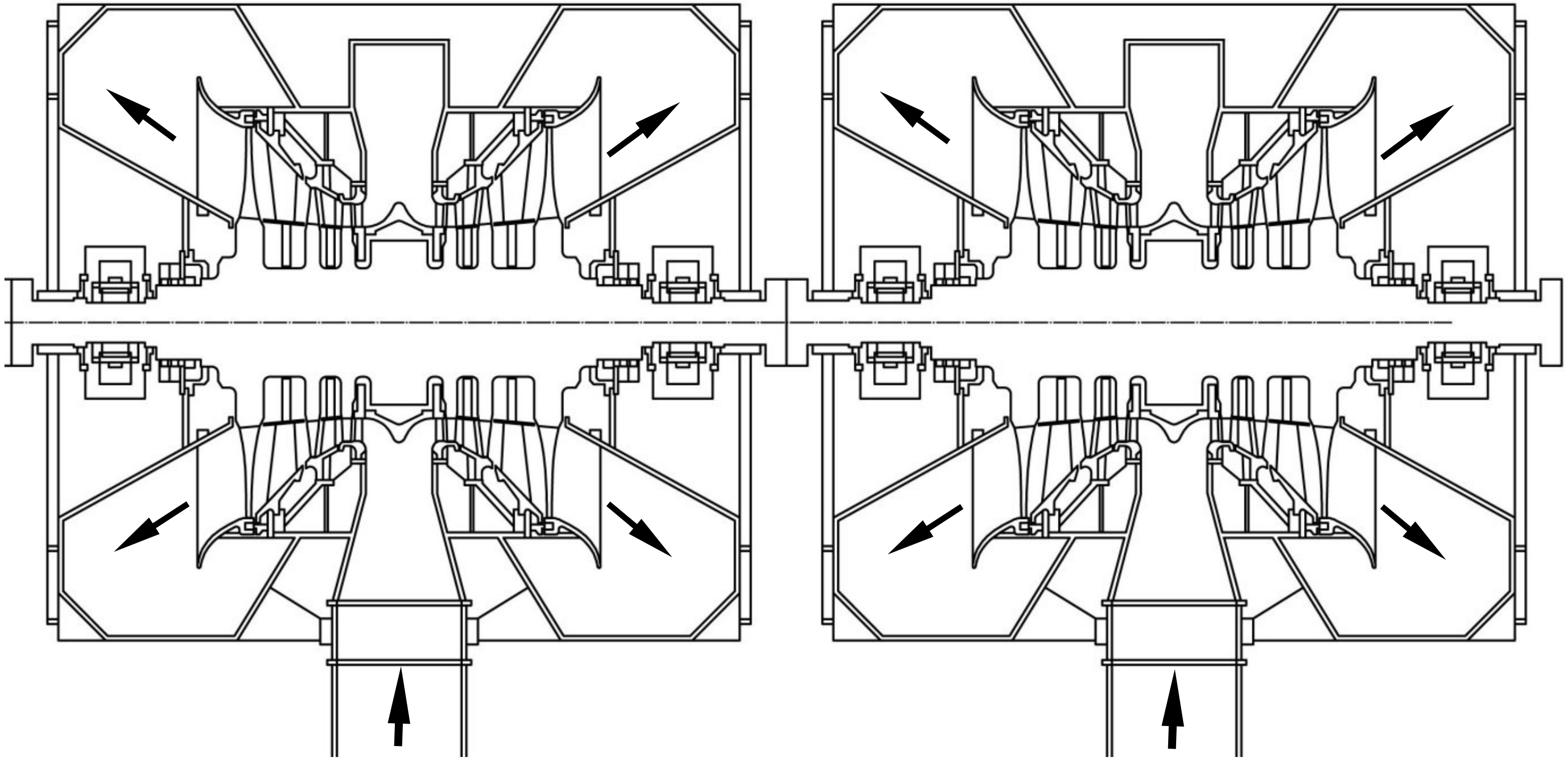


<u>50 Hz:</u> two-stage subsonic HTTC



Low Pressure Steam Turbine

- Inlet: 0.75 bar and 175°C
- Condensation pressure of 0.021 bar leads to a high volume flow
- At 50 Hz a four-flow design with three stages
- Transonic last stage with a blade length of 970 mm
- Expansion line crosses Wilson line at last stage inlet; thus formation of small droplets only in the exhaust



Economic Analysis S-GC - I

Investment costs

Component	Scale parameter		Specific costs
Reference Plant [13]			
Investment costs	Electric power	$\$/kW_{el}$	**414**
S-Graz Cycle Plant			
Investment costs	Electric power	$\$/kW_{el}$	**414**
Air separation unit [14]	O_2 mass flow	$\$/(kg\ O_2/s)$	**1 500 000**
Other costs (Piping, CO_2-Recirc.) [14]	CO_2 mass flow	$\$/(kg\ CO_2/s)$	**100 000**
CO_2-Compression system [14]	CO_2 mass flow	$\$/(kg\ CO_2/s)$	**450 000**

- **yearly operating hours: 8500 hrs/yr**
- **capital charge rate: 12%/yr**
- **natural gas is supplied at 1.3 ¢/kWh_{th}**

Comparison of Component Size

	Conventional CC Plant 400 MW	Graz Cycle Plant 400 MW
turbine of "gas turbine"/ HTT	667 MW	618 MW
compressor of "gas turbine"/ C1+C2+C3+C4	400 MW	232 MW
steam turbine/ HPT+LSPT	133 MW	120 MW
HRSG	380 MW	360 MW
Generator	400 MW	490 MW

- Turbine power of same size
- Compressor power smaller
- Generator power higher

Economical Analysis S-GC - II

COE ...

Cost of Electricity

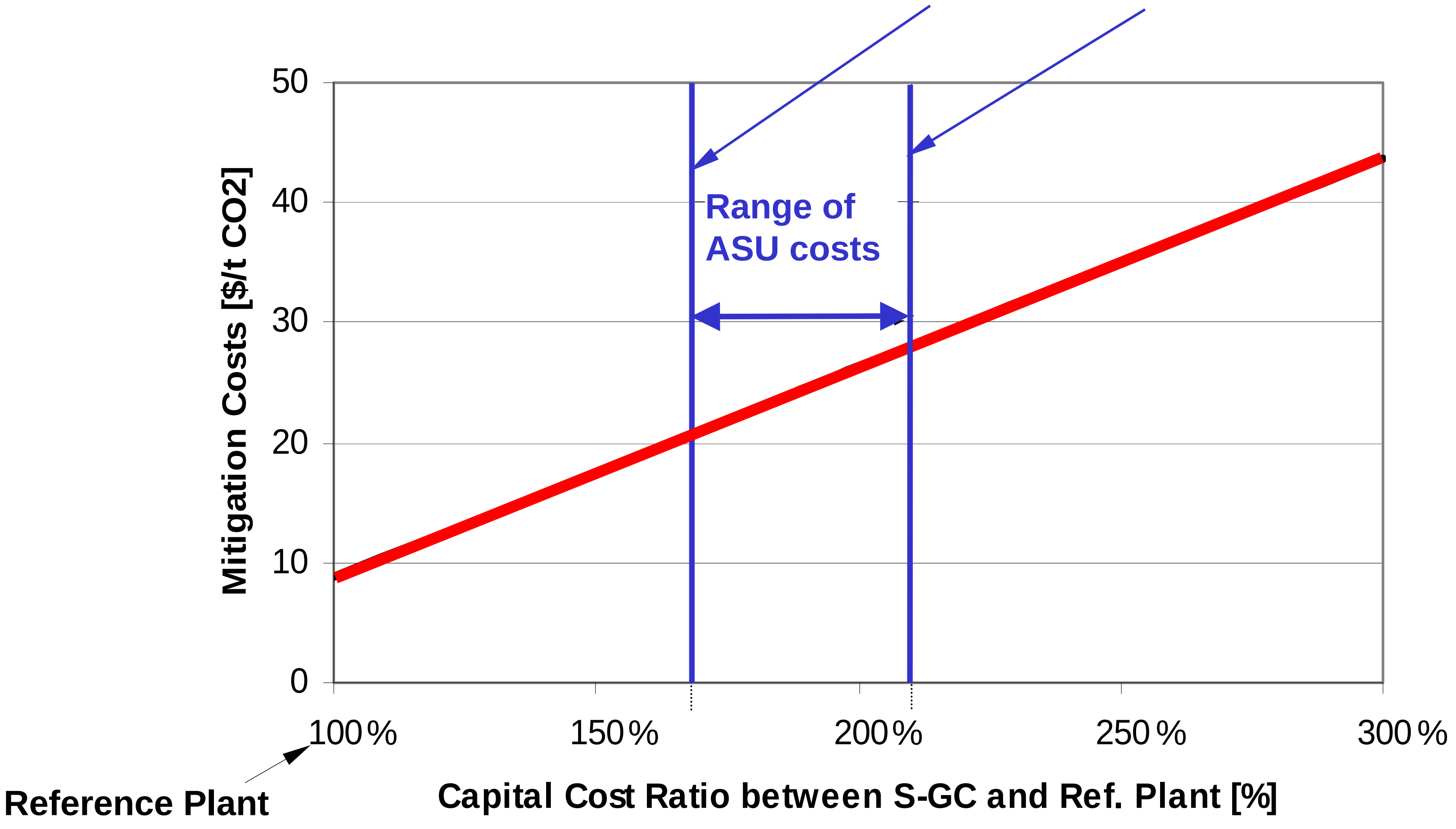
	Reference plant [23]	S-GC new version
Plant capital costs $[\$/\mathrm{kW_{el}}]$	414	414
Addit. capital costs $[\$/\mathrm{kW_{el}}]$		288
CO$_2$ emitted [kg/kWh$_{el}$]	0.342	0.0
Net plant efficiency [%]	58.0	53.1
COE for plant amort. [¢/kWh$_{el}$]	0.58	0.99
COE due to fuel [¢/kWh$_{el}$]	2.24	2.45
COE due to O&M [¢/kWh$_{el}$]	0.7	0.8
Total COE [¢/kWh$_{el}$]	3.52	4.24
Comparison		
Differential COE [¢/kWh$_{el}$]		0.72 (+ 20 %)
Mitigation costs $[\$/\mathrm{ton\ CO_2\ capt.}]$		21.0

Influence of Capital Costs S-GC

Favorable assumption of Göttlicher (VDI): 70 % additional capital costs for air supply and CO2 compression

But large uncertainty in cost estimation:

e.g.: ASU: cost estimates differ between 230 and 400 $/kW_el



Conclusions

- Graz Cylce is an oxy-fuel power cycle of highest efficiency
- Modified cycle configuration with condensation in the range of 1 bar with re-evaporation of pure steam to feed LPST results in a high net cycle efficiency above 53 %
- Output raised from industrial size of 75 MW to 400 MW net output
- A design concept for this size is presented with two shafts, a fast running compression shaft and the power shaft and LPST
- Economic comparison with reference plant shows the strong influence of capital costs on CO2 mitigation costs
- Mitigation costs vary between 20 - 30 $/ton CO2 depending on additional investment costs (ASU)
- Presentation of a design solution for an oxy-fuel CO_2 retaining gas turbine system which can by acceptance of international gas turbine industry be put into operation within a few years