How (not) to design pumps and motors?

INNAS

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Ladies and gentleman.

Today, I will tell you a story. A story about beautiful art and some wise man. A story about a labyrinth, in which you can get lost. And a story about the secret of successful creativity.

The power to create is one of the most precious gifts of mankind. It is the ability to find new ways and new solutions, often for problems, that we – ourselves– created. In order to find new solutions, creativity needs to be combined with skills, knowledge and of course talent. The combination is called craftsmanship. In the end, the quest for a designer is not to find just a random solution, which you might do with just creativity, but to find the right solution.

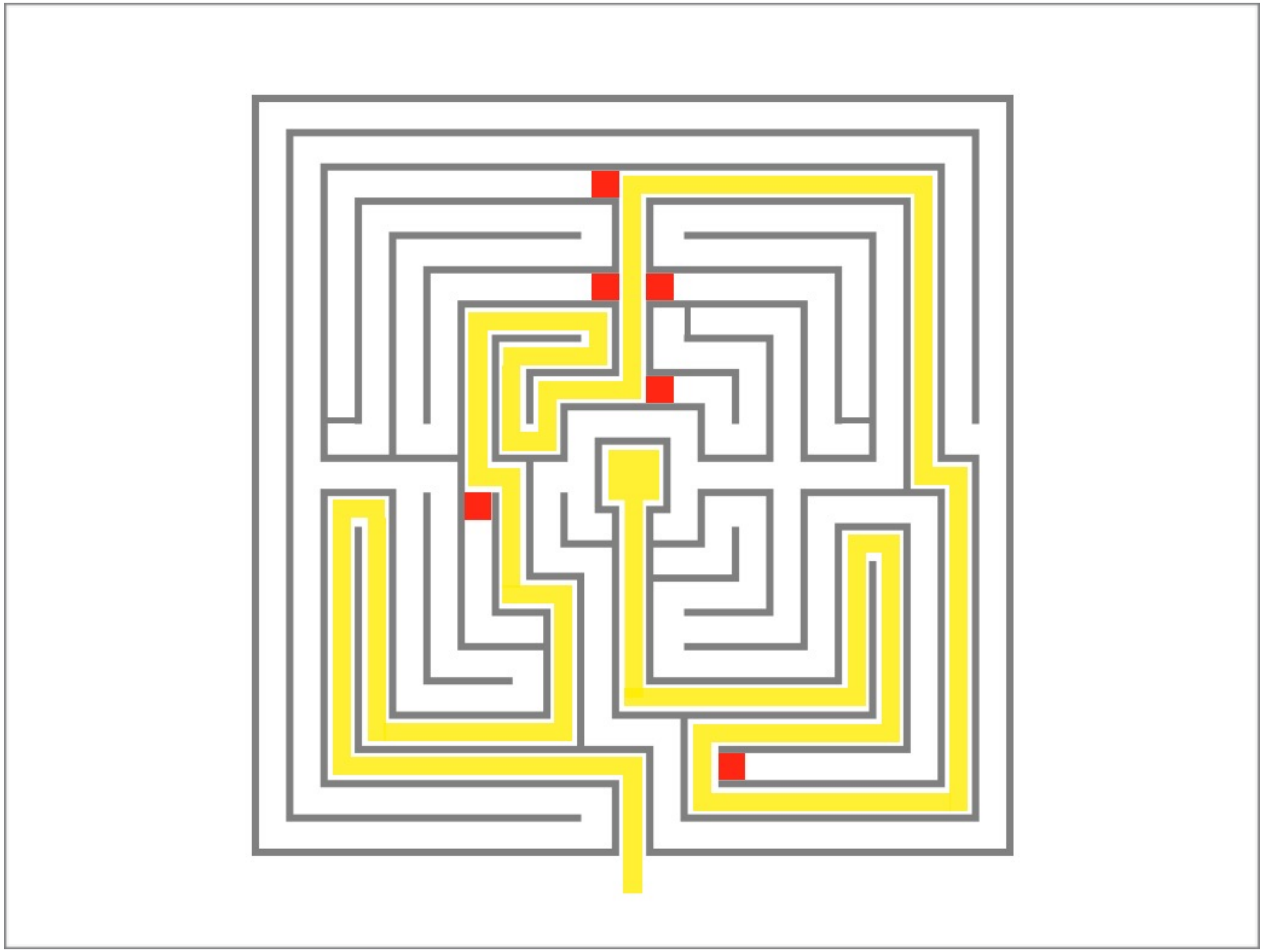
But how? How do you find the right solution, the good design, amidst thousands of wrong ideas?

Well, there is a methodology. It is called:…

Via Negativa

Designing by avoiding problems

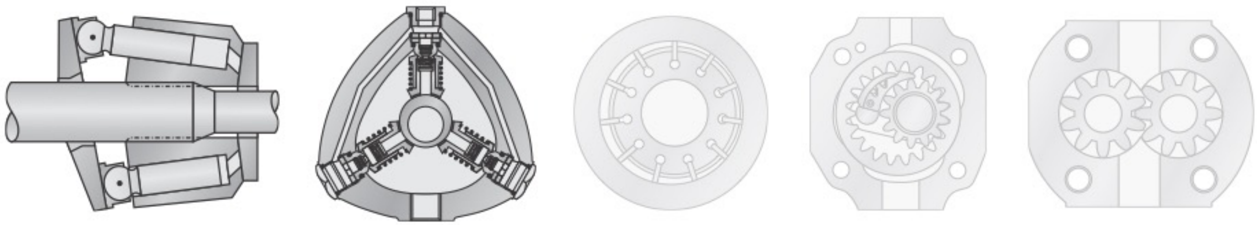
The ‘via negativa’. Design, simply by means of avoiding problems. The idea behind it is, that it is impossible, or –at least– very hard, to find something, which doesn’t exist yet. But, we do know, or at least should know, the problems and disadvantages of current designs.



The philosophy of the ‘via negativa’ can be best explained by means of a maze. If you know which turns to avoid, you will be directed automatically to the right solution: The new and better solution will present itself.

focus

- heavy duty: ≥ 350 bar
- constant & variable displacement
- efficiency



Let me show you how this works, by taking current hydrostatic machines as an example.

Heavy duty machines, to be precise, both constant and variable displacement.

Today, I will only talk about piston pump principles, and about the efficiency as a design parameter.

Our quest can therefore be defined as a search for a new, efficient, hydrostatic principle

about the origins of pumps

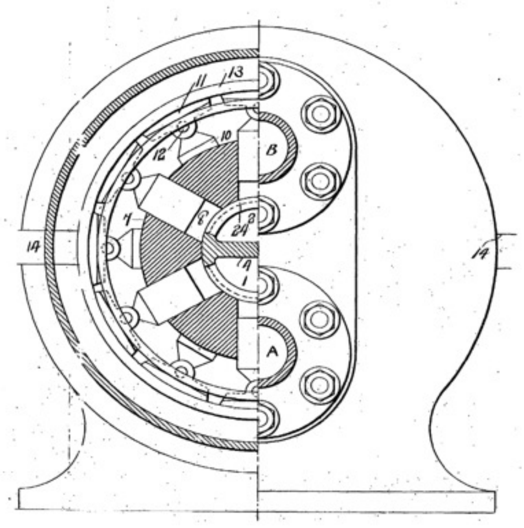
The engineers, that designed today’s pump principles, were no fools. They were as skilled and creative as today’s engineers, and maybe even more.

So, why should we start looking for a new principle? The answer is simple: they created their designs, within the constraints, requirements and knowledge of their lifetime, not of ours!

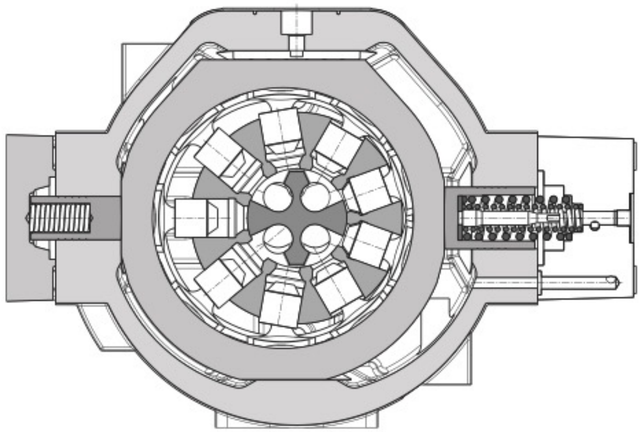
Most probably, if the same engineers would have lived today, knowing today’s production and design techniques, material properties, and market demands, they would have come up with rather different solutions and different designs.

Therefore, what are the origins, of our pump ‘species’? How old are current piston pump principles? And, who were the heroes, that designed them?

Radial piston



Hele-Shaw (1909)

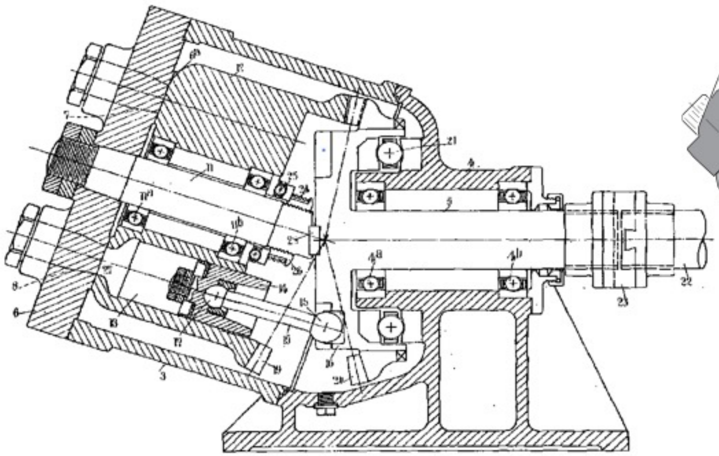


Moog (2015)

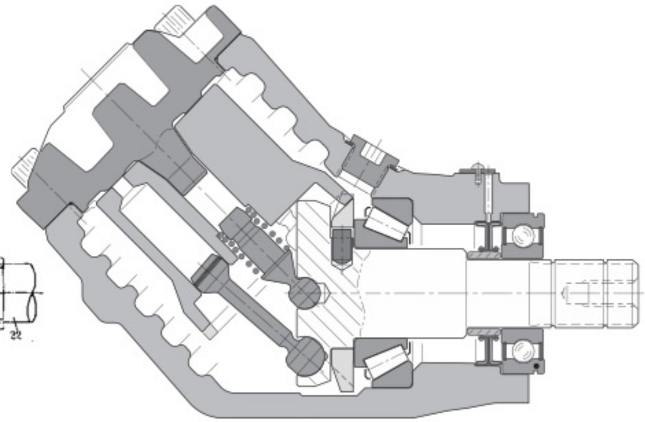
In 1909, the British engineer Henry Selby Hele-Shaw received a patent on a radial piston pump. In this design, each piston is supported by a curved slipper.

The basic design of today's radial piston pump from Moog is almost identical.

Bent axis



Clergue (1909)

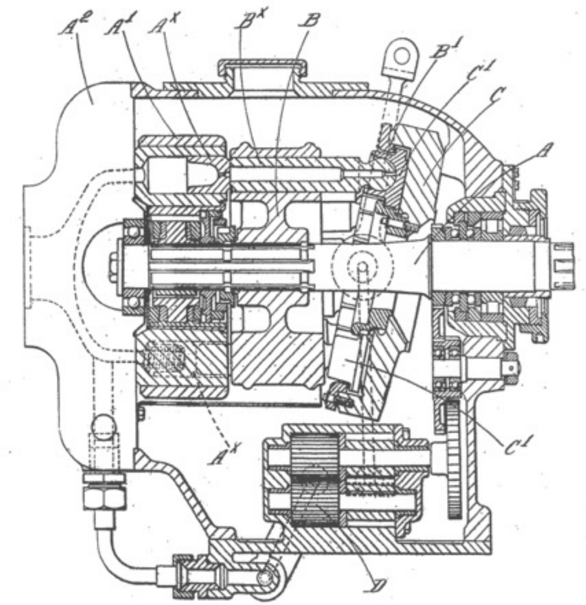


Parker F1 (2015)

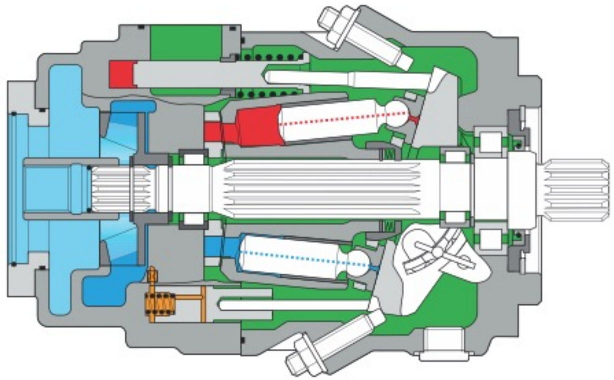
In the same year 1909, Francis Hector Clergue, from the city of Westminster, received a patent on a bent axis pump or motor.

The similarity with the modern bent axis F1 from Parker is striking.

Slipper type



Ingoldby (1923)



Bosch Rexroth (2015)

Finally, a patent from 1923. It was granted to another Englishman, Maurice Kerr Ingoldby, working for the Vickers company.

This patent can be regarded as the blue print of a modern, slipper type, swash plate pump. It even included a low pressure charge pump…

…much alike the modern slipper type pump from Bosch Rexroth.

what have we learned?

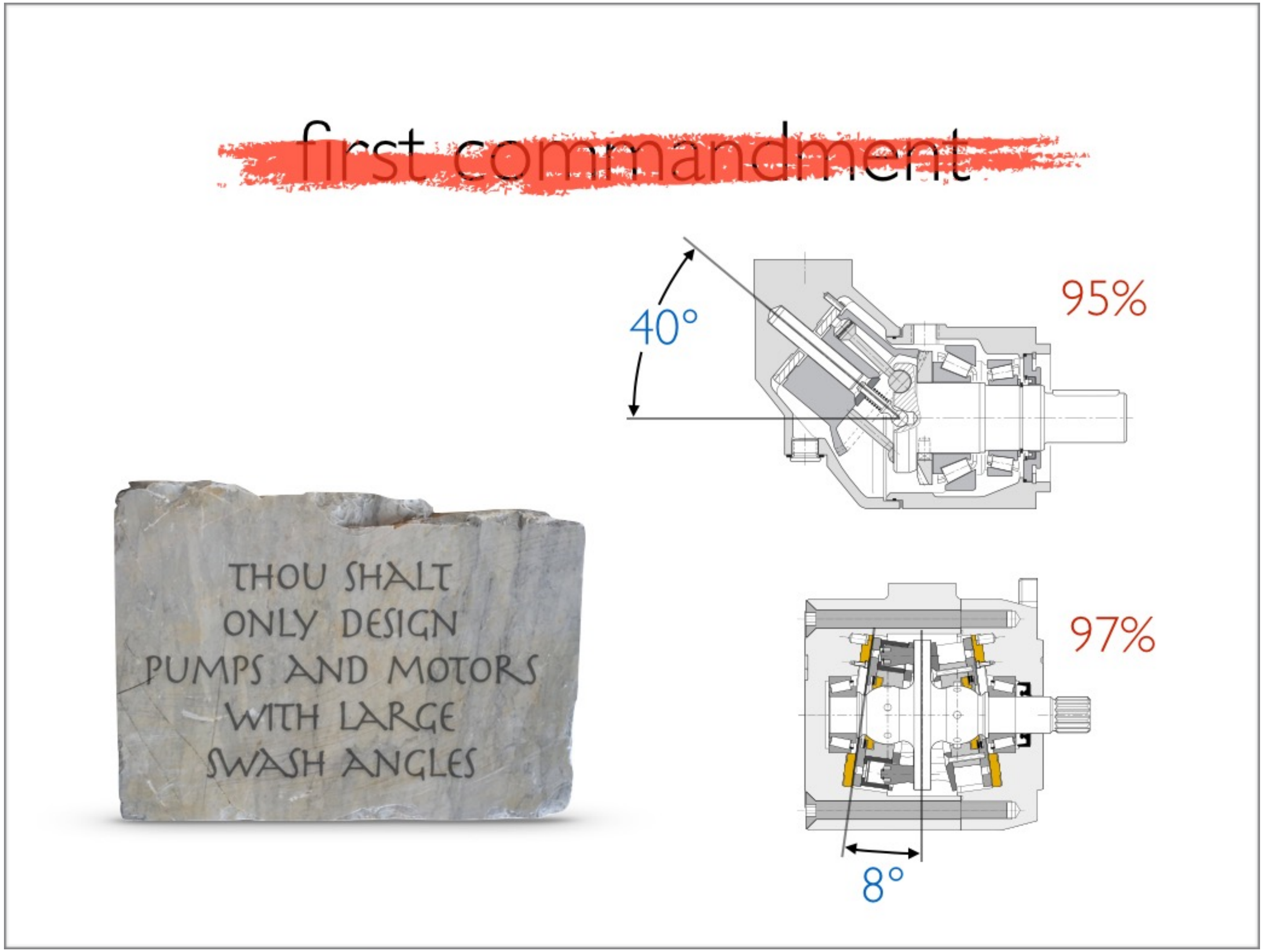
So, what have we learned about these pumps and motors since then. What progress, regarding the efficiency of pumps and motors, have we made in the past century?

first commandment

Let me start with an often heard basic rule for the design of efficient hydrostatic machines:

“Thou shalt only design pumps and motors with large swash angles!”

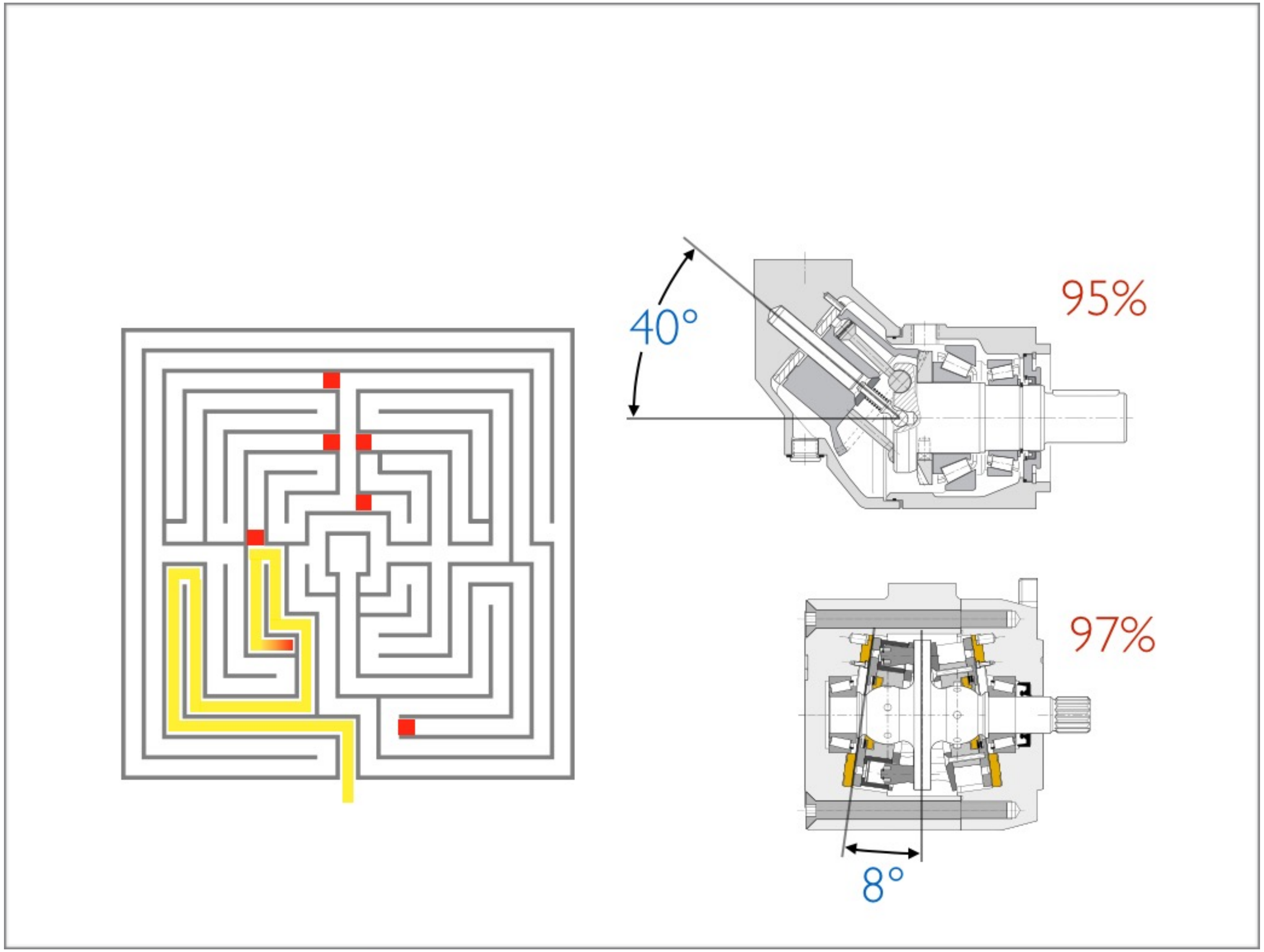
For some, this is nothing less than a commandment, carved in stone.



Only machines with a large tilt angle, they argue, like this F12 from Parker, can achieve a high efficiency.

However, our company and also others, have proven that this guideline is utterly wrong. The floating cup pump achieves efficiencies of 97%, whereas the tilt angle of the barrel is only 8°.

If we want to succeed in our search for improvements, it is important to avoid these misconceptions…



…otherwise we end up at a dead end in the labyrinth.

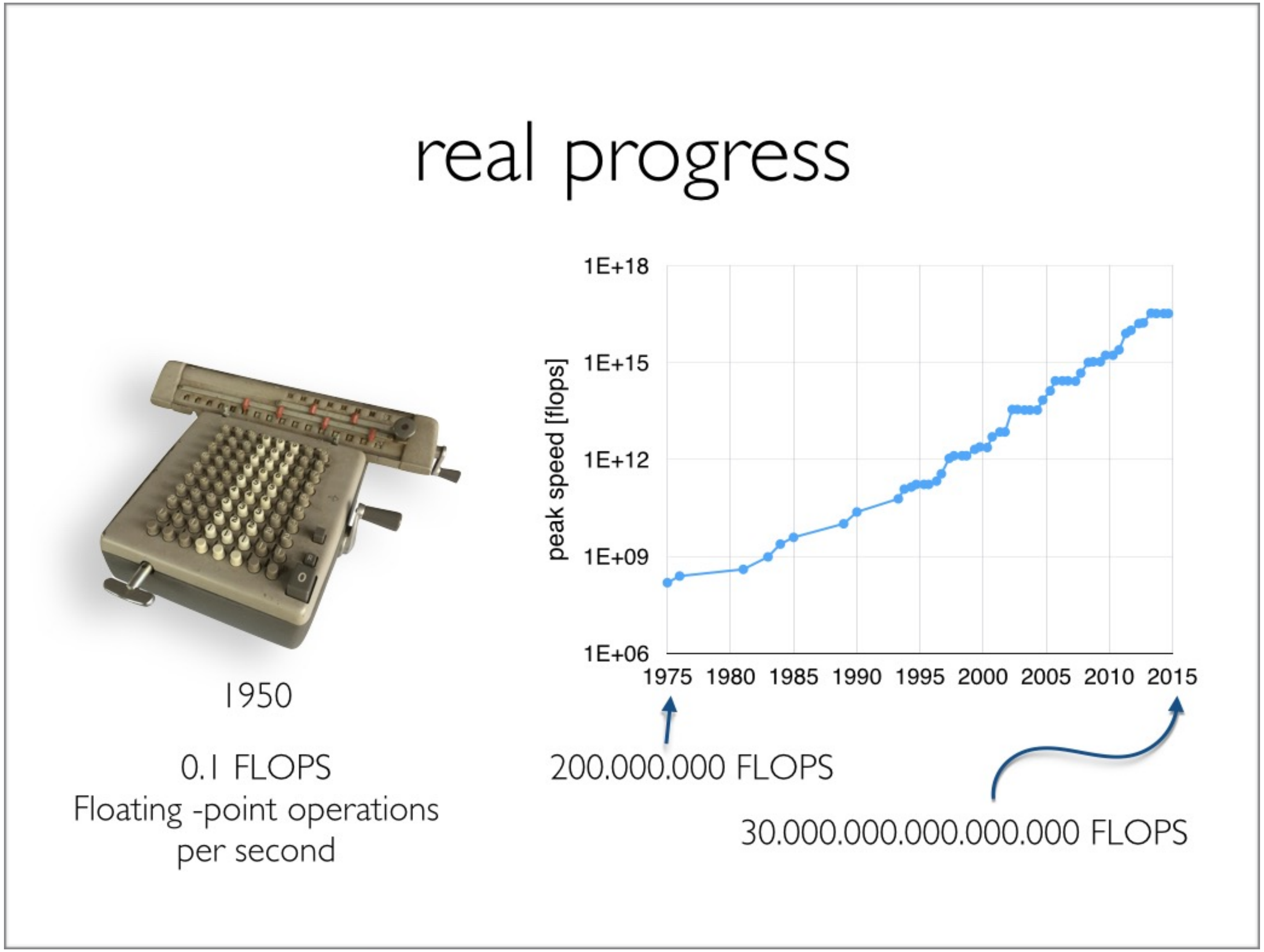
real progress

- elasto-hydrodynamic-lubrication (EHL)
- cavitation
- commutation

But, we did of course make some real progress, especially in the areas of:

- Elasto-hydrodynamic deformation and lubrication
- Cavitation
- and commutation

But, the progress was not achieved because we became more intelligent or better designers. We simply have stronger computing powers at our disposal.



This is the machine I inherited from my father. I estimate it could do about 0,1 floating point operations per second. That is 0,1 flops.
Nowadays, we have unparalleled computing powers available.

Every decade, computers have become 100 times more powerful.

In 1975, when I started my studies at the university, computers could already perform 200 megaflops.

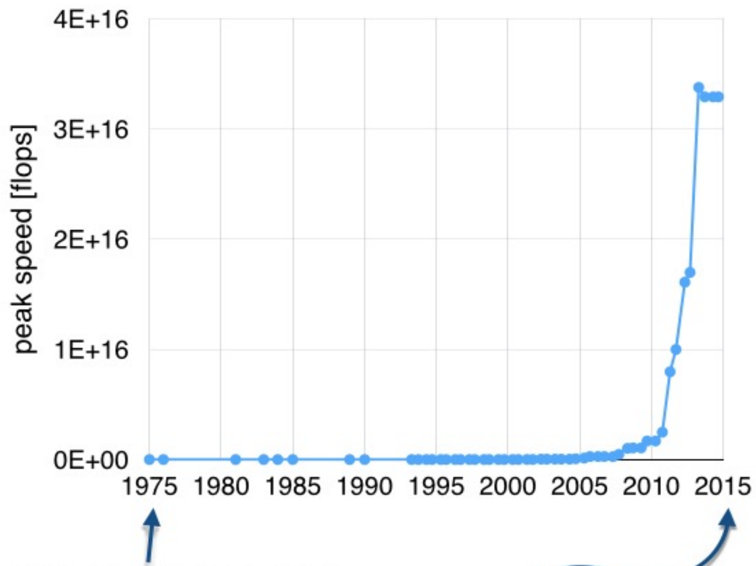
Now the strongest computer in the world can do 30 petaflops. That is an increase of a factor 150 million.
Super computers will soon have the strength of exaflops: a million, times a million, times a million calculations per second.

Mind you: the vertical axis has a logarithmic scale…

real progress

1950

0.1 FLOP
Floating -point operations
per second

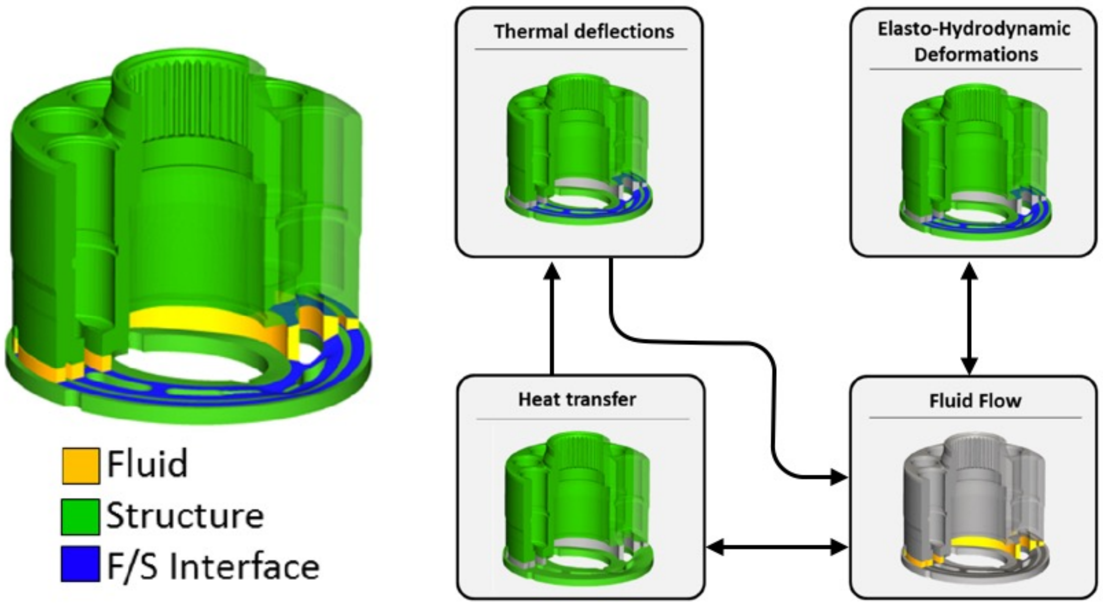


200.000.000 FLOPS

30.000.000.000.000.000 FLOPS

…This is how the graph looks like having a linear scale: a complete explosion of computational power. Extremely tempting for engineers as a weapon in their search for new and better solutions.

complex modeling



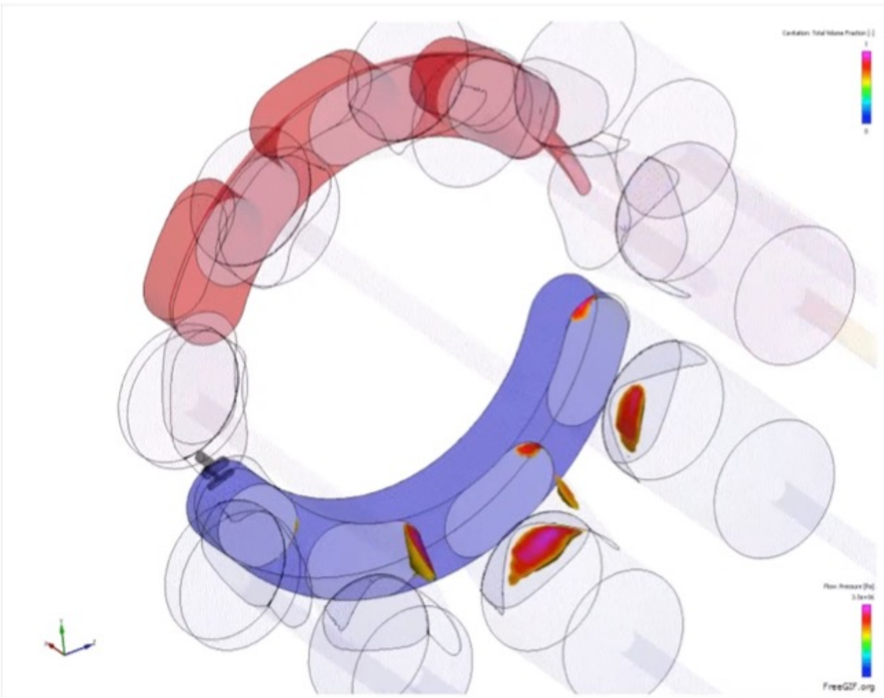
source: Purdue University (Marco Zecchi)

Let me show you a few examples of what progress we made:
The university of Purdue has managed to include thermal effects in the calculation of the bearing interfaces.

It involves a combination of a structural analysis of the mechanical deformation, a calculation of the fluid flow, a heat transfer model and a calculation of the thermal expansion and deformation.

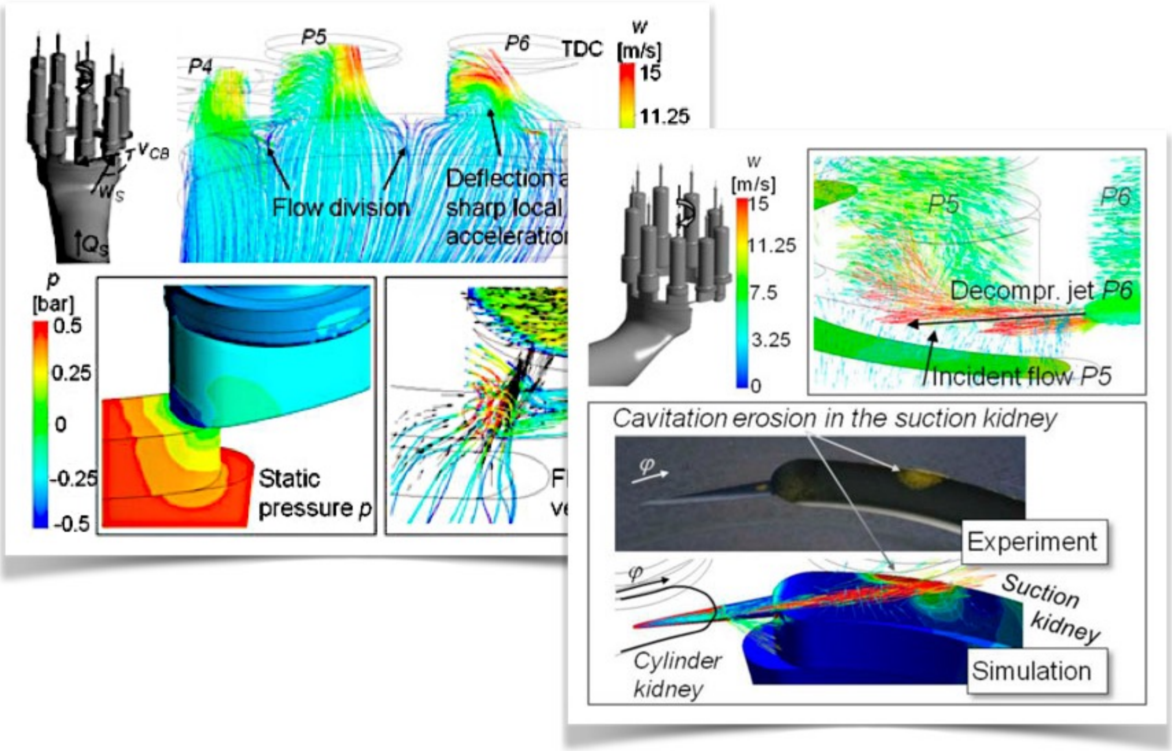
And all of these sub-models are interrelated in various ways.

cavitation modelling



source: IFAS RWTH Aachen (Christian Schleihs)

Modern computers also allows us to get a much better understanding of cavitation phenomena, like is shown here in this animation from Aachen University.



source: IFD TU Dresden (Norman Bügener, et al)

Or in these illustrations from the Technical University of Dresden.

However, this is all just knowledge. A lot of knowledge, detailed and very scientific. Good for peer reviewed papers and doctoral thesis. But, it doesn’t necessarily bring us any closer to new designs.

It seems to me, that we have forgotten that computer simulation is not a goal in itself. It is just a means, a technique to get to a better understanding.

Simulation can even become an excuse not to start designing, because there is always a deeper, more detailed and sophisticated level to dig into. Simulation makes you number-fetished and short-sighted.

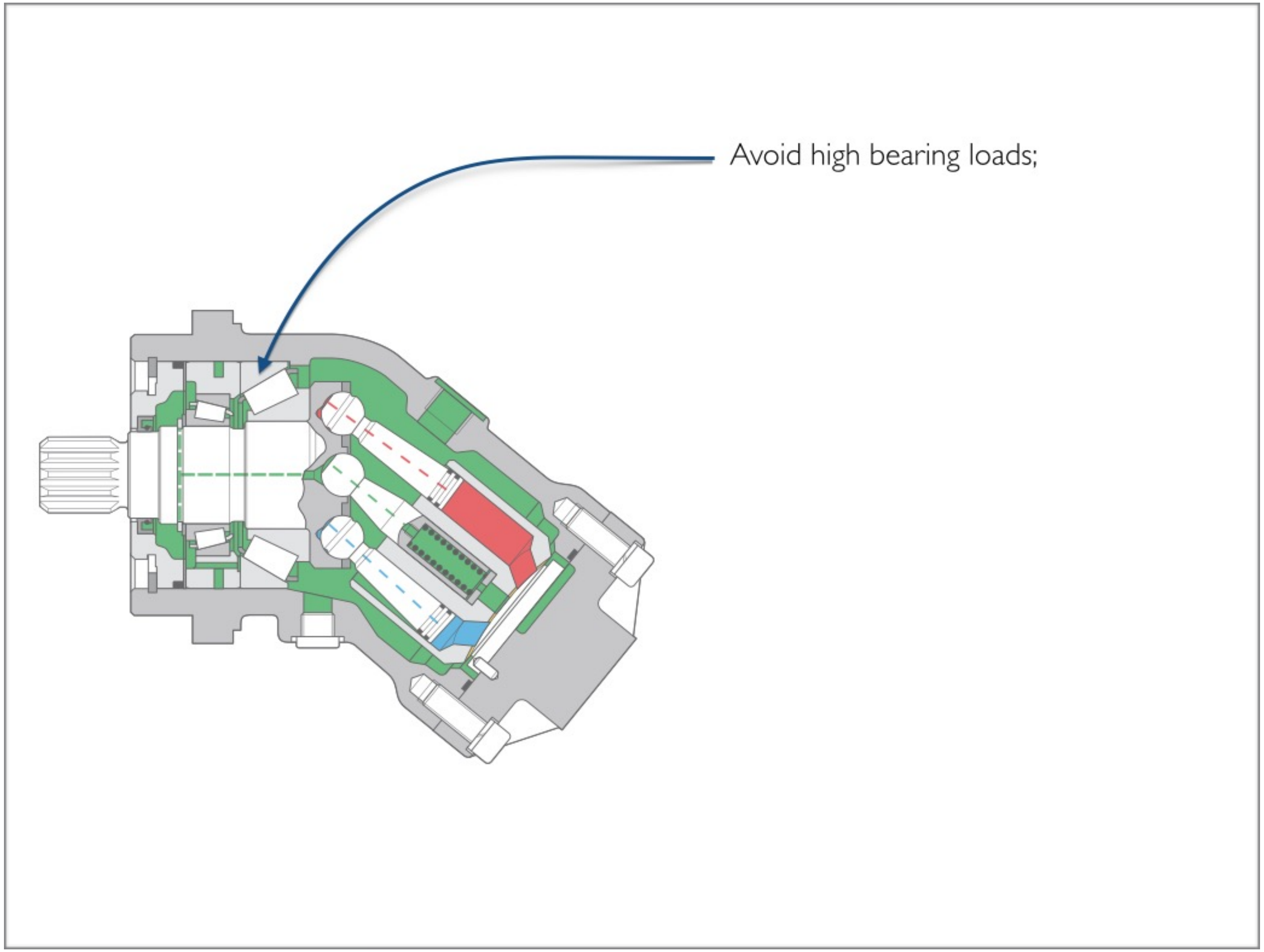
Therefore, all you number-obesed and simulation-obsessed engineers: come out of your deep and dark mines and step into the bright lights of the real world of machine design. I will give you a hand, and lead you through the labyrinth…

problems to avoid

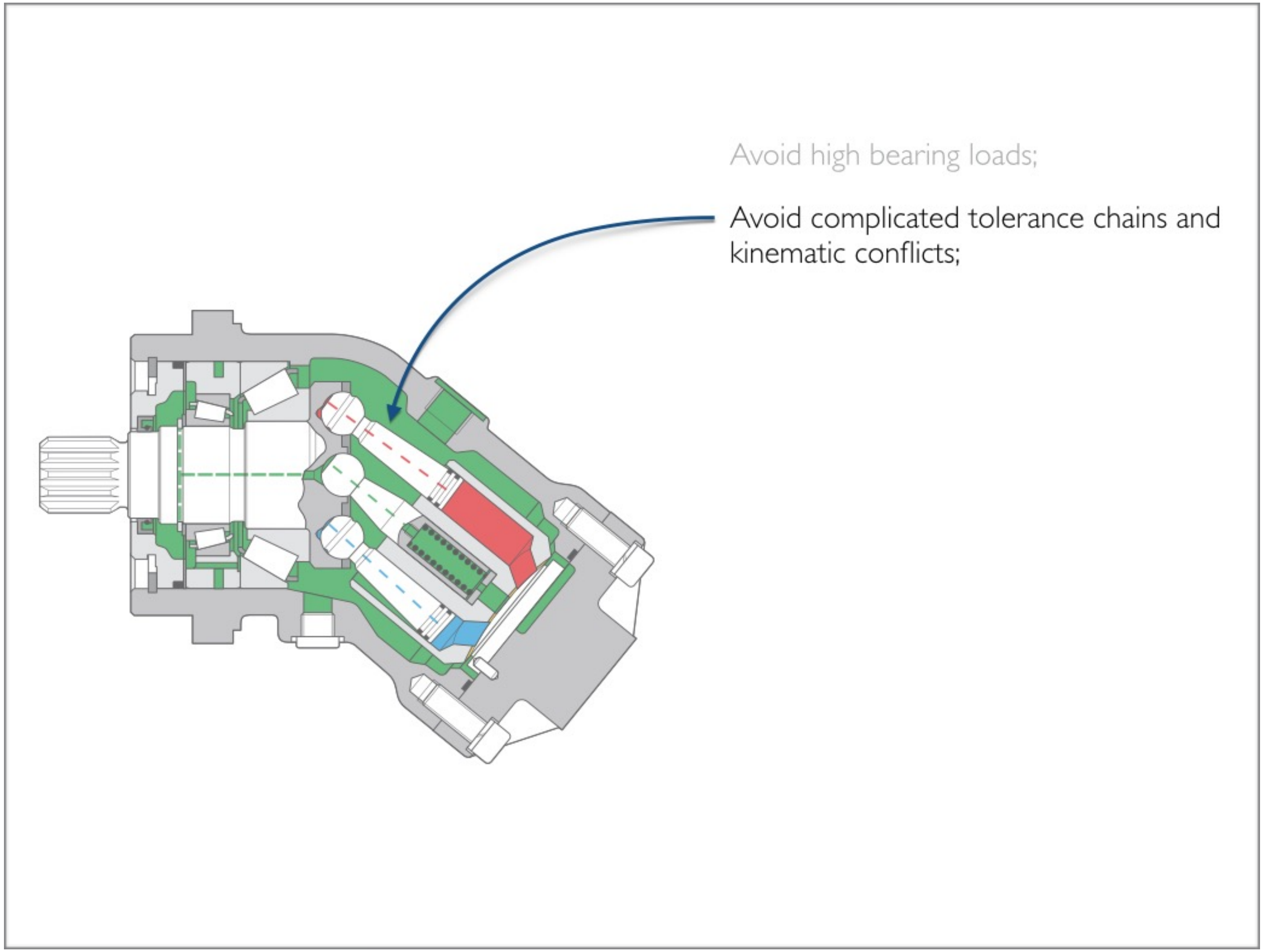
the via *negativa* in pump design

…through the maze of problems to avoid.

And these are the problems:



This is the first problem. In bent axis machines, the bearings have to take the full hydrostatic load of the rotating group. This results in friction, and also in overheating, noise issues and a reduced lifetime. Therefore: avoid high bearing loads



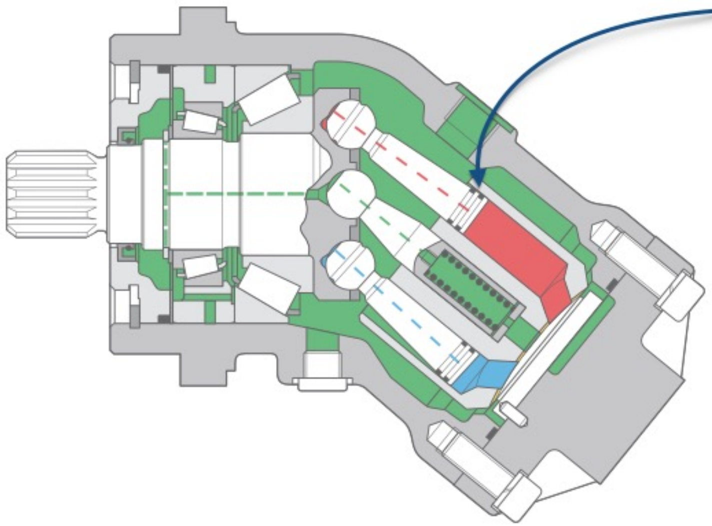
A second problem area is the tolerance chain. Especially this design, with its intriguing 'Schubladenprinzip', has a rather complicated tolerance chain, which can easily result in kinematic conflicts.

Kinematic conflicts always result in friction and wear. Avoid them.

Avoid high bearing loads;

Avoid complicated tolerance chains and kinematic conflicts;

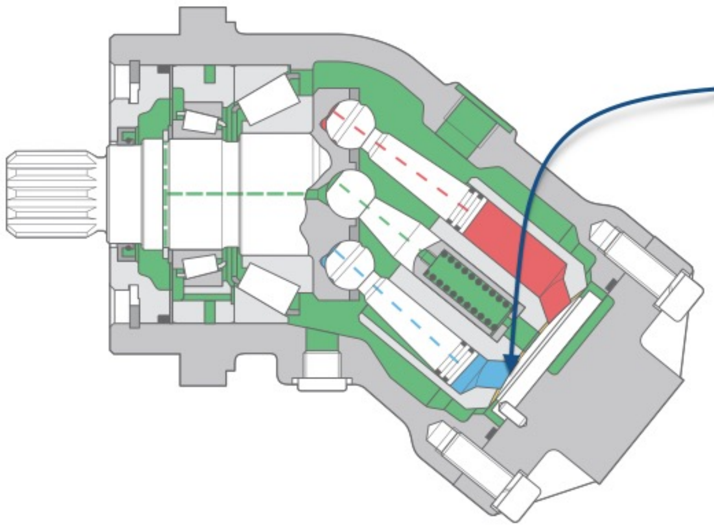
Avoid piston rings;



Bent axis machines, and also some radial piston machines, have piston rings.

Piston rings are difficult components. They are never 100% balanced and therefore create a substantial friction between the piston and the cylinder.

If possible: avoid piston rings.



Avoid high bearing loads;

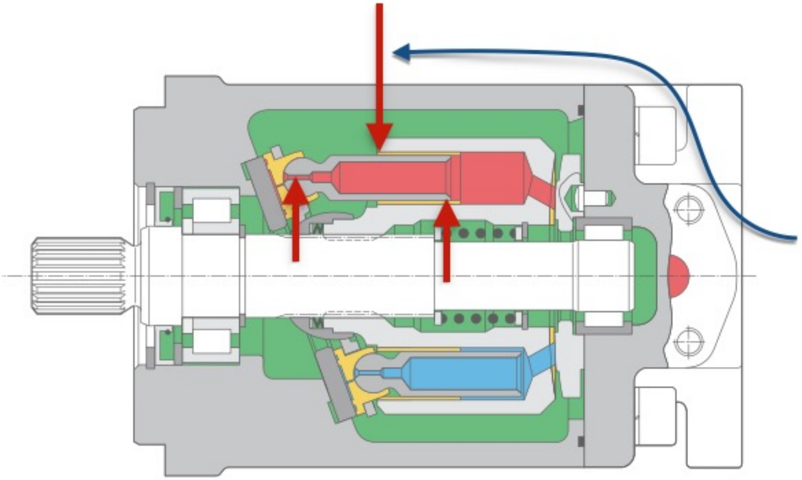
Avoid complicated tolerance chains and kinematic conflicts;

Avoid piston rings;

Reduce the risk for cavitation;

Constructions with a large tilt angle of the barrel, like this bent axis machine, suffer from small opening areas of the barrel ports and of high piston accelerations.

These machines have a high risk for cavitation. The small port openings also increase the flow resistance, and therefore create an additional pressure drop and efficiency reduction.



Avoid high bearing loads;

Avoid complicated tolerance chains and kinematic conflicts;

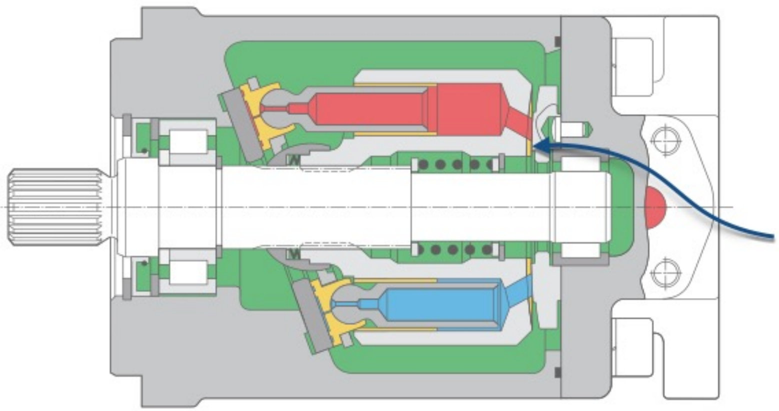
Avoid piston rings;

Reduce the risk for cavitation;

Avoid lateral loads in sliding interfaces;

In slipper type machines, one of the key problems is the high lateral load in the contact between the piston and its cylinder. The full hydrostatic power is transferred via these sliding contacts.

This is most certainly, fundamentally wrong.



Avoid high bearing loads;

Avoid complicated tolerance chains and kinematic conflicts;

Avoid piston rings;

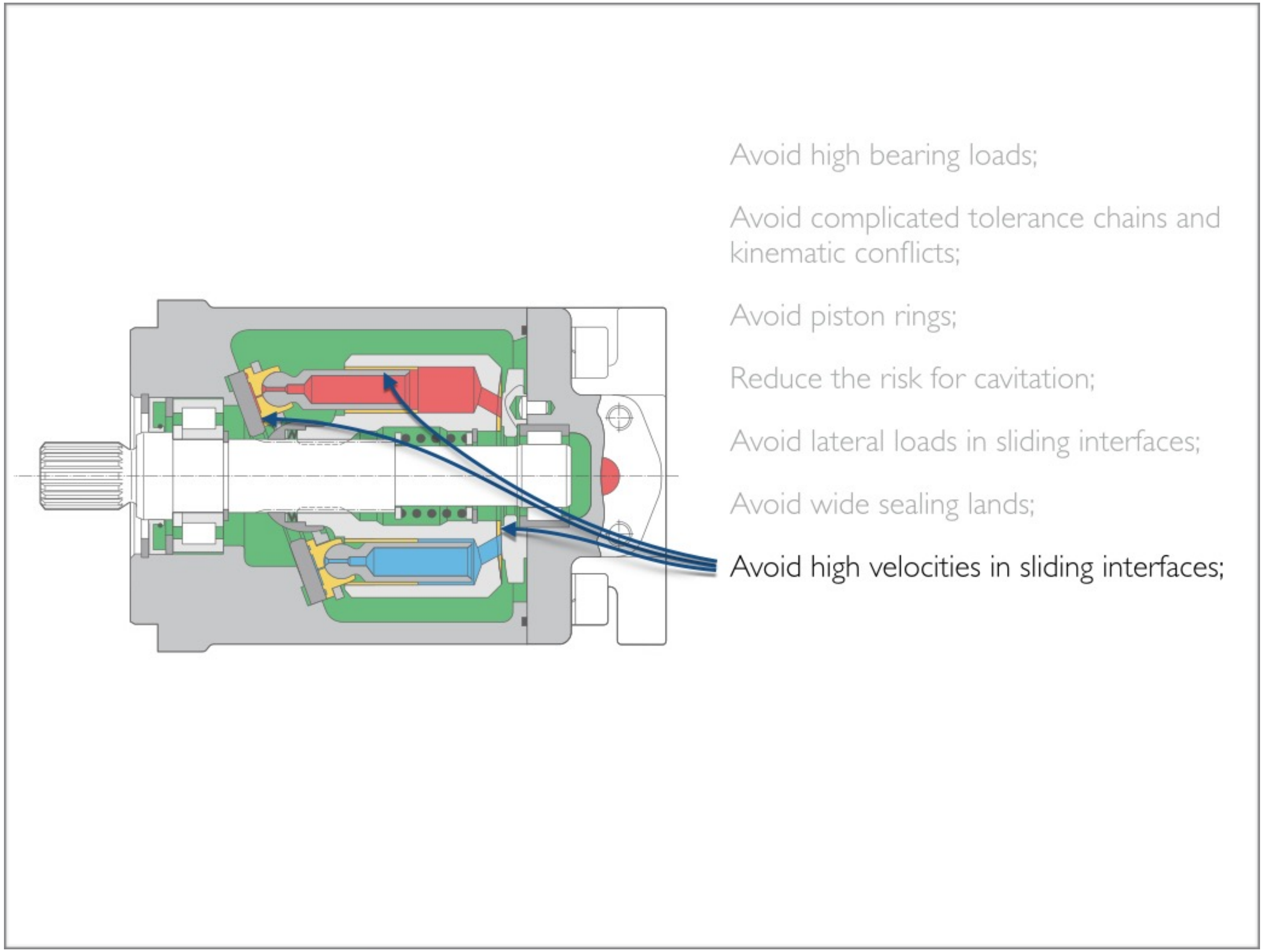
Reduce the risk for cavitation;

Avoid lateral loads in sliding interfaces;

Avoid wide sealing lands;

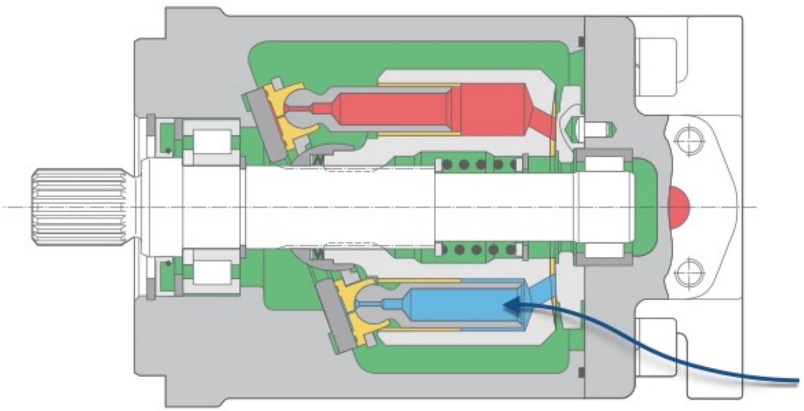
We also strongly recommend to avoid wide sealing lands. The phenomena in sealing and bearing interfaces are still not fully understood. But, it is certain that wide seal lands increase the risk of over- or under-balancing.

This is one of the most crucial points in the design of hydrostatic machines.



Piston pumps and motors are positive displacement machines. They always have sliding interfaces, and thus viscous friction. As such, viscous friction can not be avoided.

But it can be minimized, simply by reducing the velocity of the sliding interfaces. If possible, high shear velocities need to be avoided.



Avoid high bearing loads;

Avoid complicated tolerance chains and kinematic conflicts;

Avoid piston rings;

Reduce the risk for cavitation;

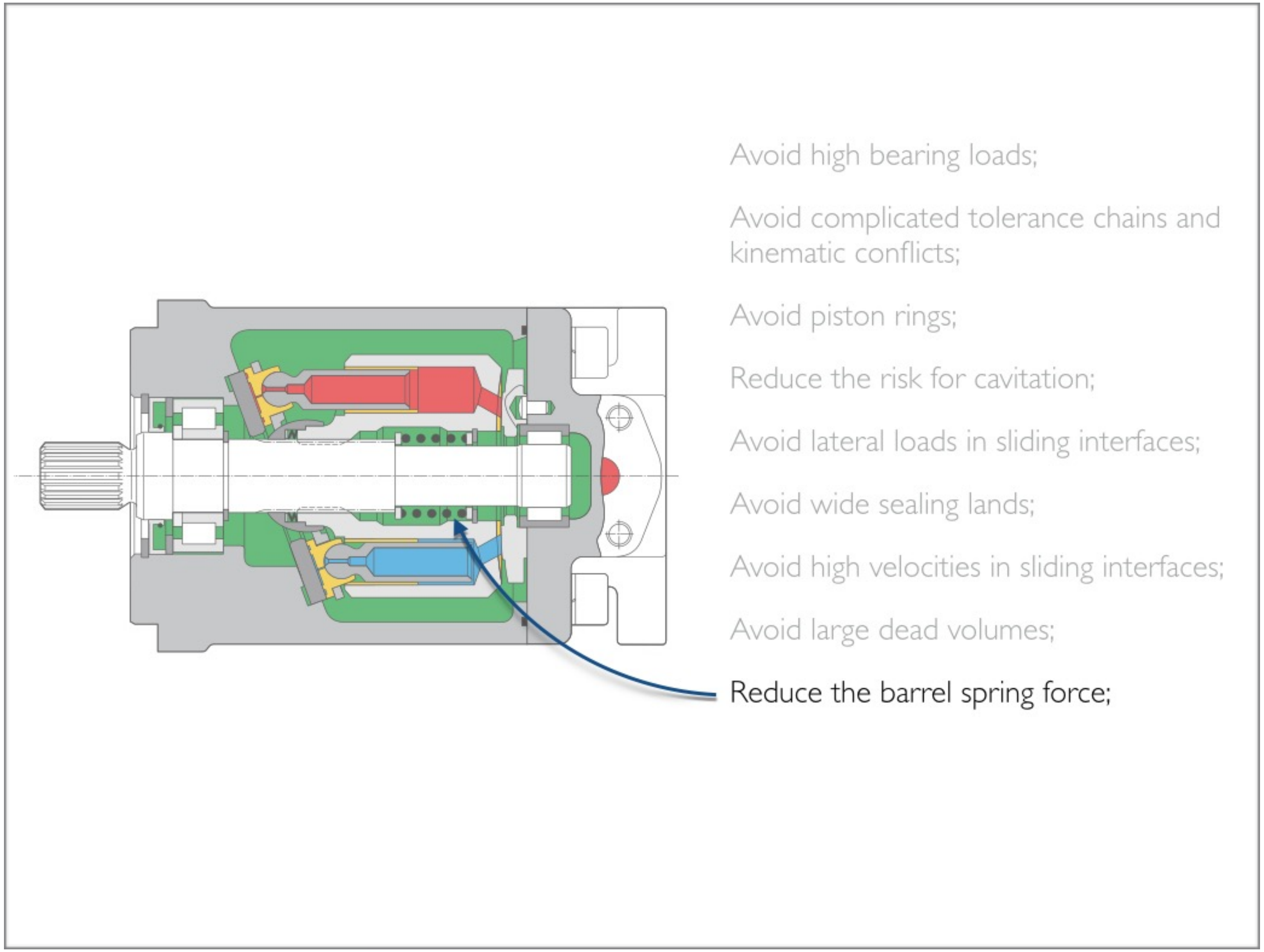
Avoid lateral loads in sliding interfaces;

Avoid wide sealing lands;

Avoid high velocities in sliding interfaces;

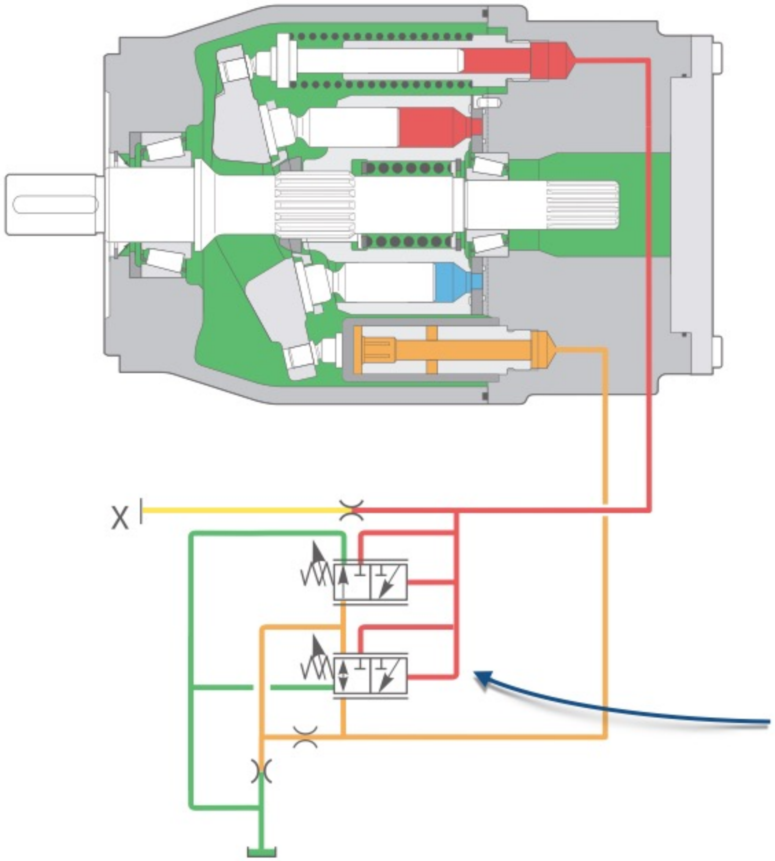
Avoid large dead volumes;

Dead volumes can also contribute to significant losses. Large dead volumes, like in this example, must be avoided. There is, however, a good reason why the pistons are made hollow. The cavity reduces the piston mass and, therefore, the centrifugal forces.…



…This again, helps to bring down the required force of the barrel spring, and thus reduces the friction between the barrel and the port plate.

Yet, despite the large dead volumes of the pistons, the centrifugal forces are still high. The tipping torque is further increased by the piston friction. Both factors require a stronger barrel spring. This clearly should be avoided in a new hydrostatic principle.



Avoid high bearing loads;

Avoid complicated tolerance chains and kinematic conflicts;

Avoid piston rings;

Reduce the risk for cavitation;

Avoid lateral loads in sliding interfaces;

Avoid wide sealing lands;

Avoid high velocities in sliding interfaces;

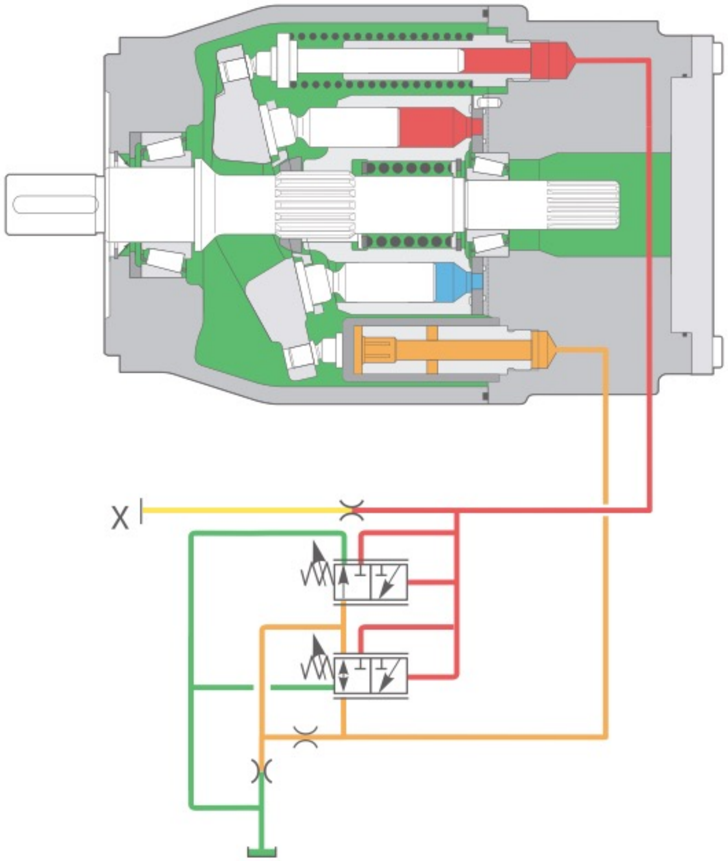
Avoid large dead volumes;

Reduce the barrel spring force;

Reduce the losses of the displacement control

Finally, in current variable displacement machines, the displacement control is extremely inefficient.

I find it hard to understand why the hydraulic industry has neglected and ignored these losses for such a long time, even up to this moment.



High bearing loads;

Complicated tolerance chains and kinematic conflicts;

Piston rings friction;

Risk for cavitation;

High lateral loads in sliding interfaces;

Wide sealing lands;

High velocities in sliding interfaces;

Large dead volumes;

Strong barrel spring force;

High losses of the displacement control

This is awfully painful, isn't it? Seeing all the things that are wrong.
It is, as if you would come to the doctor and hear that you are ill, very ill indeed, much more than you thought.

I personally don't think that these faults can be cured, simply by small design changes, like new materials or coatings, or by applying waved profiles on the pistons.

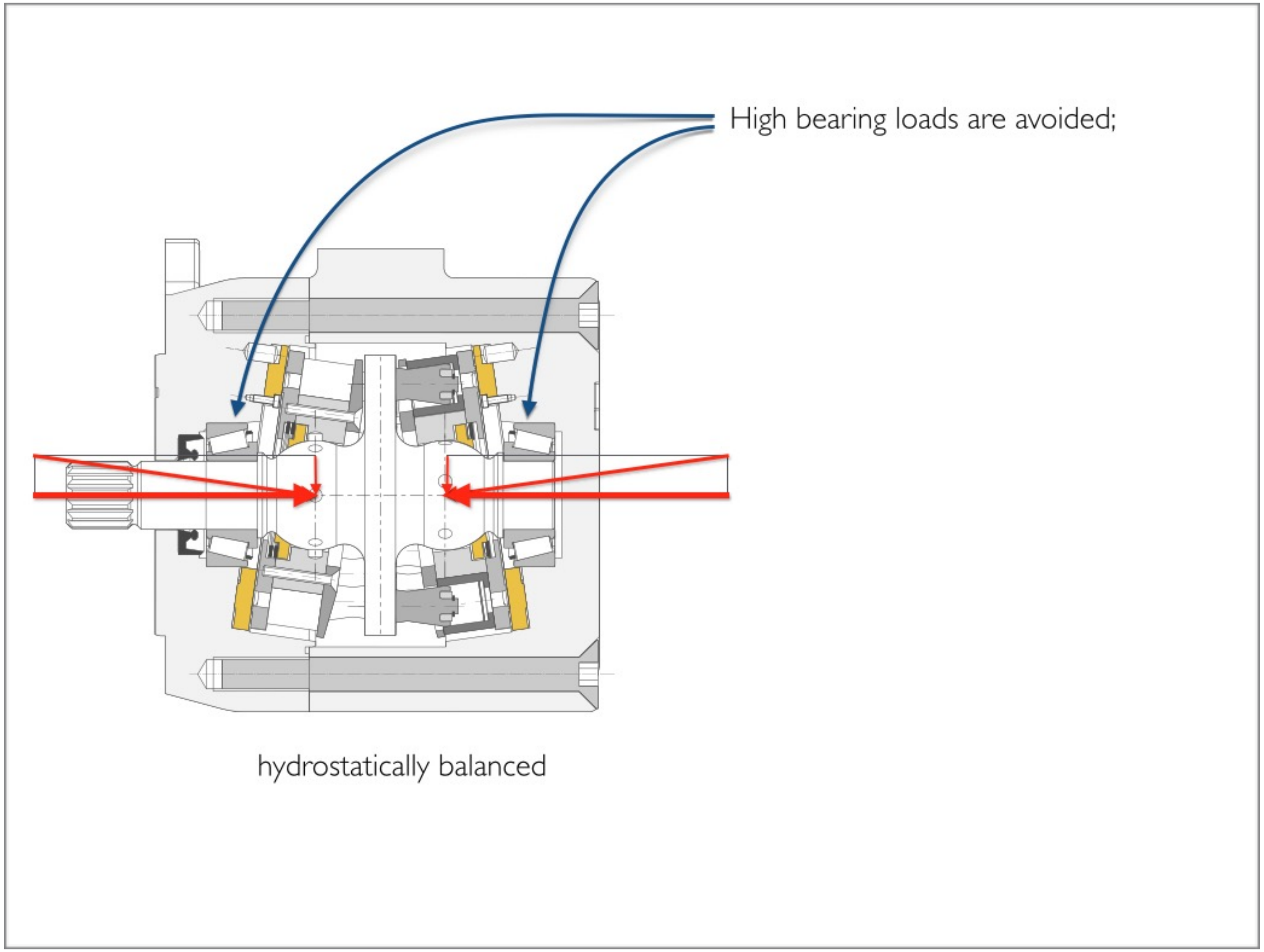
Therefore, quite a few years ago, we have already decided to leave the old pump principles, and start afresh with the design of a completely new principle:

…the floating cup principle.

It is by no means the only alternative for current piston pumps, and I strongly believe there is plenty of room for other, innovative designs.

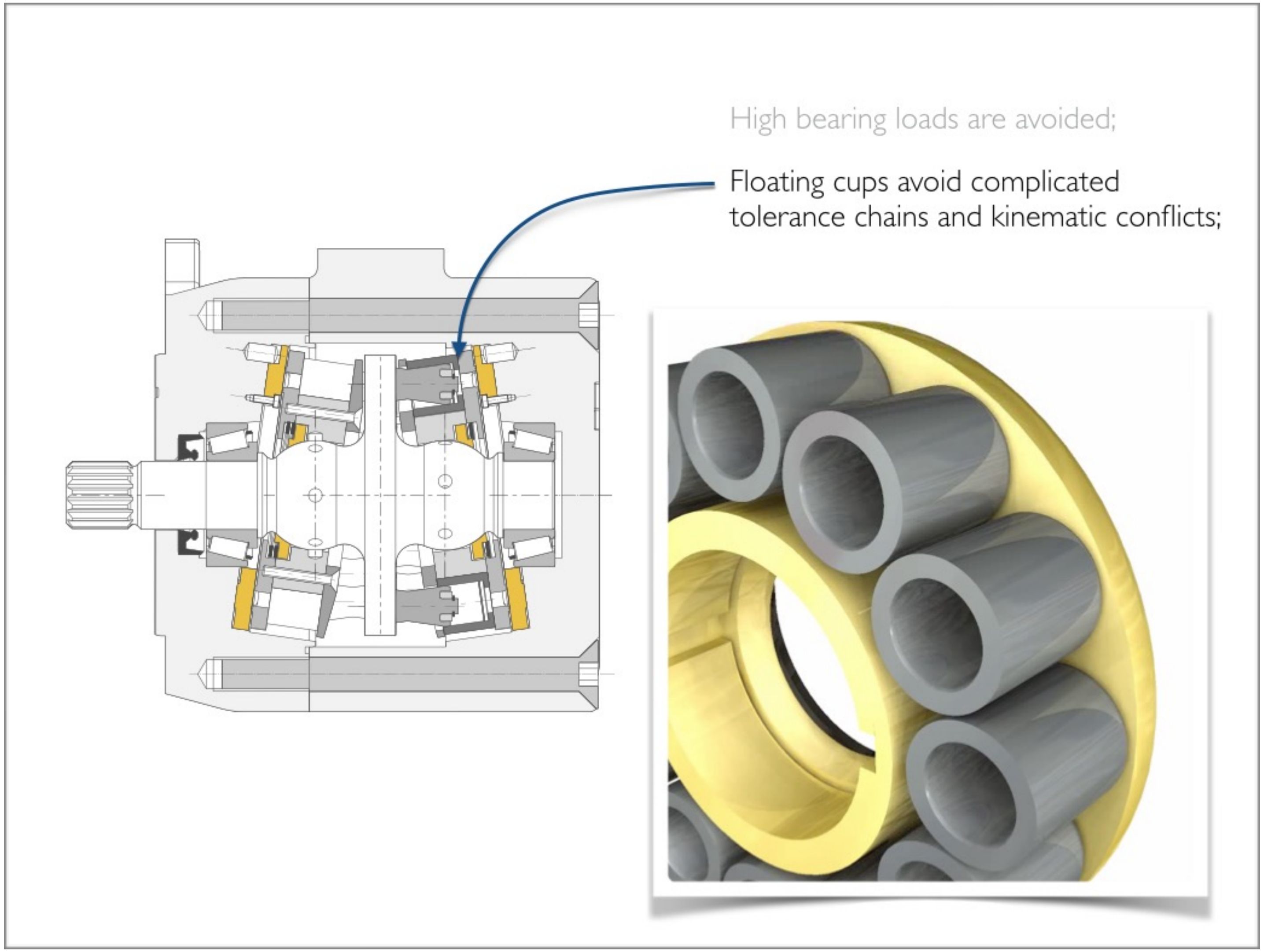
But, it is ours. And as it happens, I know a lot about it.

Let me show you how we followed the 'via negativa', and managed to avoid all wrong turns and dead ends in the maze.



First the bearing load. Floating cup machines have a mirrored construction, in which the axial loads are hydrostatically balanced.

High loads on the roller bearings, as in the bent axis machines, are avoided.



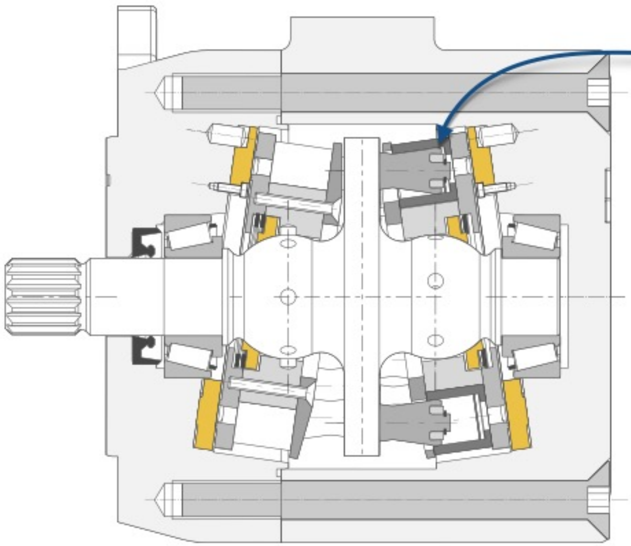
Kinematic conflicts are avoided as well. The cylinders are isolated from the barrel. They have become individual cups, as we call them, which are floating on a rotating barrel plate.

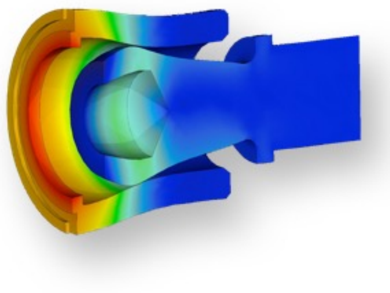
Since these cups are free to position themselves on the barrel plate, there is no tolerance chain from one piston to the other.

High bearing loads are avoided;

Floating cups avoid complicated tolerance chains and kinematic conflicts;

No piston rings;



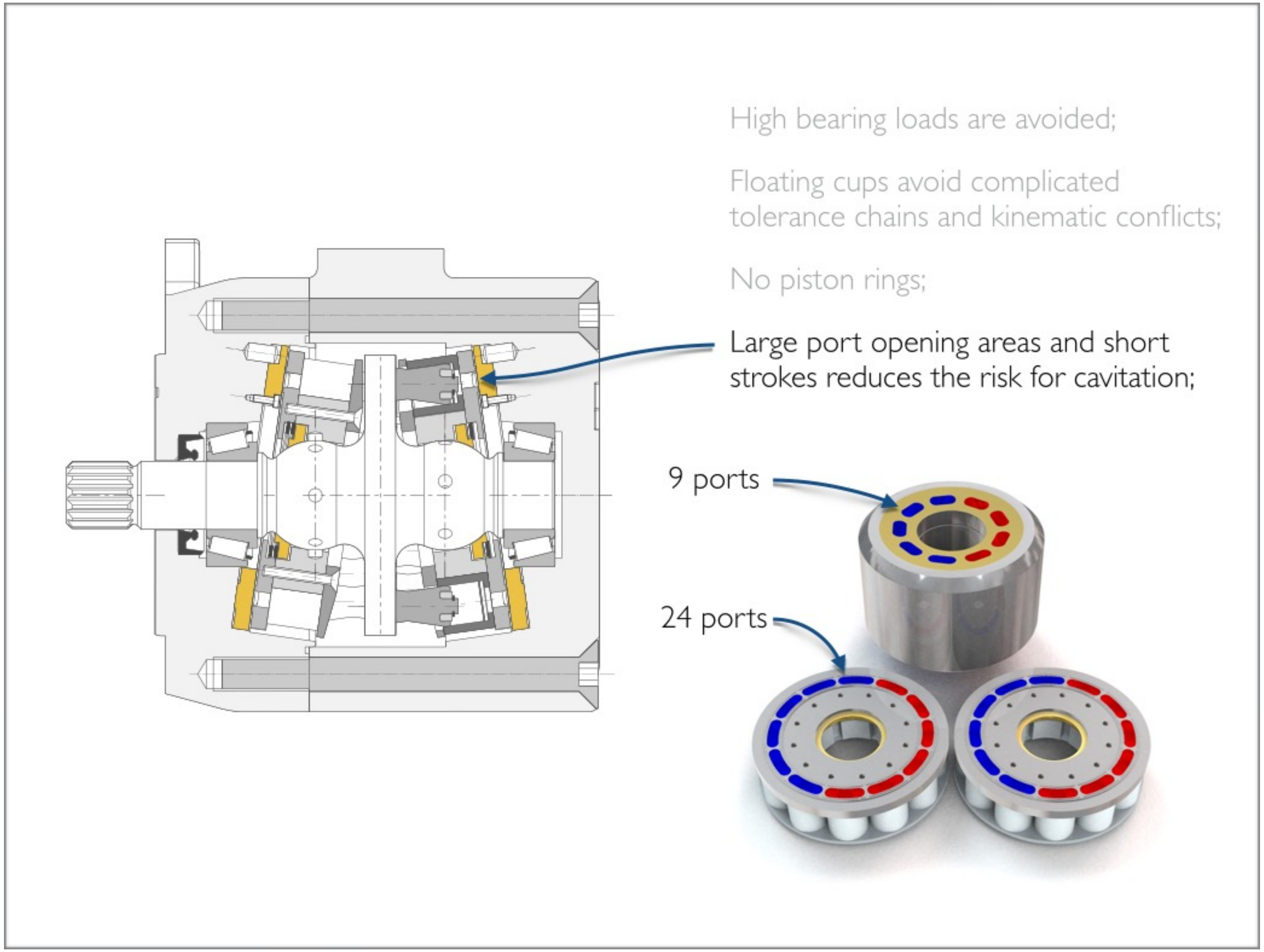


Pistons and cups expand symmetrically
No influence of neighbouring cups

Piston rings are avoided as well. This is possible because the cups expand equally in all radial directions.

By making a small cavity in the piston, the piston crown expands as well, thereby following precisely the expansion of the cup.

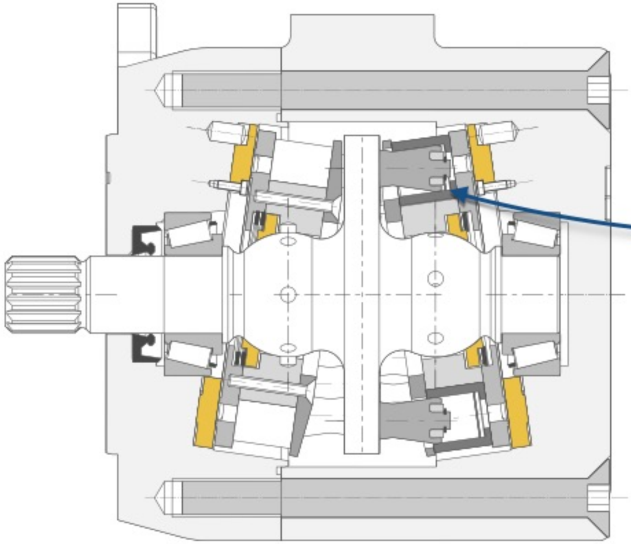
Piston rings are no longer needed.



The floating cup principle is a multi piston design, typically having 24 pistons, and therefore also 24 barrel ports. That is about three times as much as in conventional axial piston pumps.

Due to the small swash angle, the piston acceleration is also much less, which further reduces the risk for cavitation.

The large number of barrel ports also reduces the flow losses.



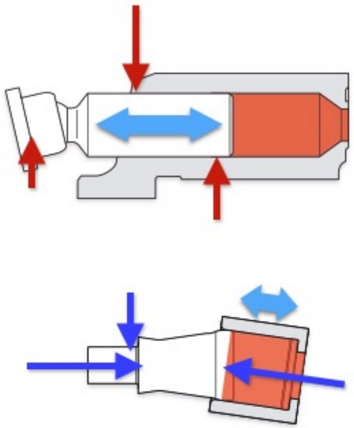
High bearing loads are avoided;

Floating cups avoid complicated tolerance chains and kinematic conflicts;

No piston rings;

Large port opening area and short stroke reduces the risk for cavitation;

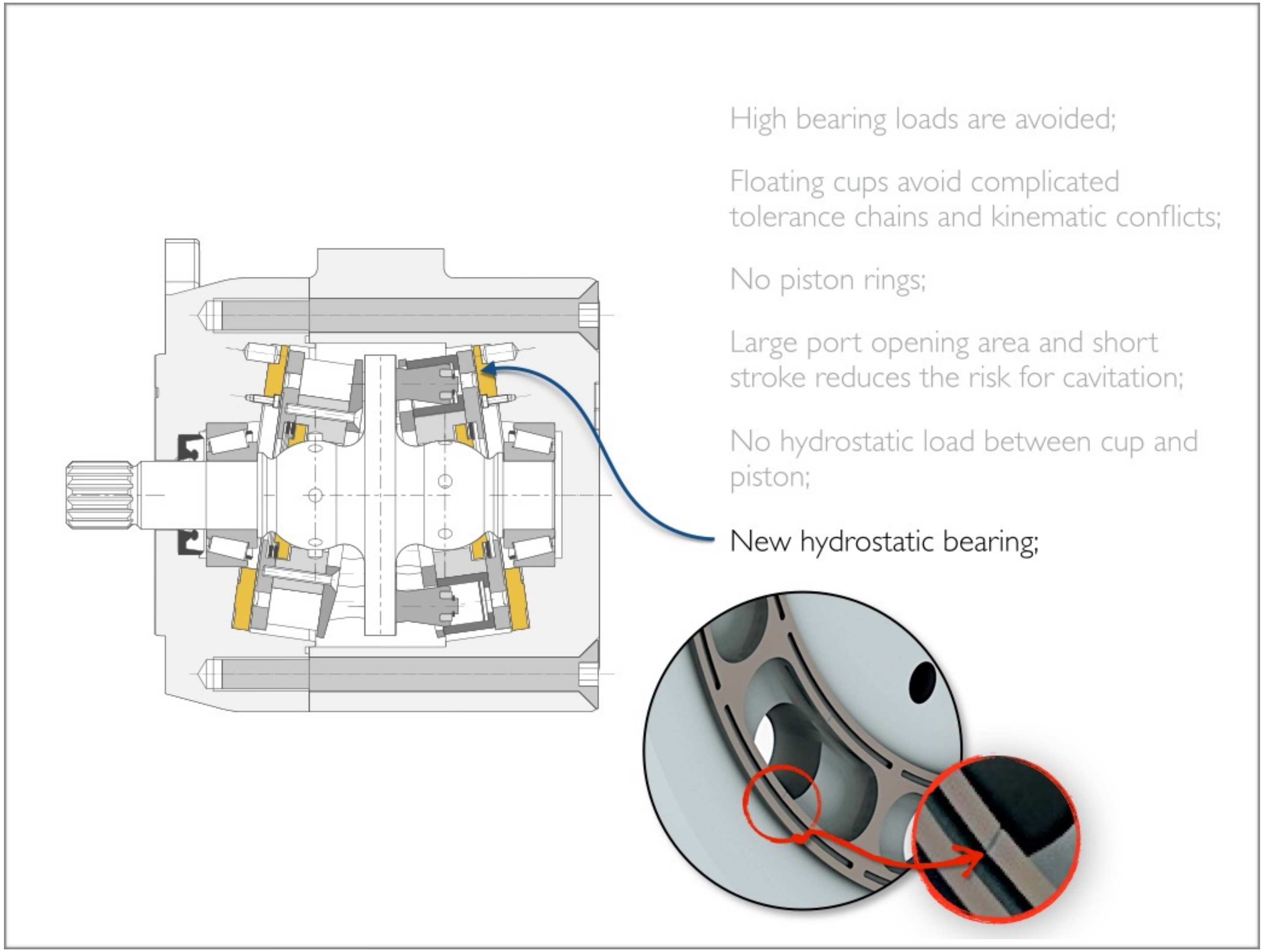
No hydrostatic load between cup and piston;



The floating cup principle completely eliminates the load between the cups and the pistons. It also eliminates high loads on all other bearing interfaces.

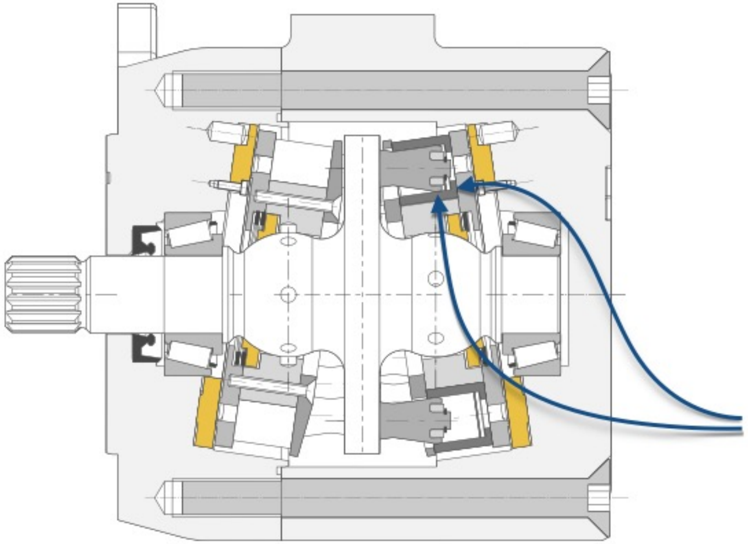
In slipper type machines, high loads are transferred in bearing interfaces. The combination of friction forces and relative movements is a main source of energy losses and wear.

In the floating cup principle, the hydrostatic forces act directly on the pistons, and from thereon on the rotor. There are no relative movements, no friction losses and wear.



In the floating cup principle, the barrel has a rather large diameter. As a result, the shear velocities in the oil film between the barrel and the port plate is rather high. That is not what we wanted. Moreover, we have not just one, but two barrels, which doubles the problem.

However, we found an escape. We designed a new hydrostatic thrust bearing and face seal. The new construction is robust, very efficient and easy to manufacture.



High bearing loads are avoided;

Floating cups avoid complicated tolerance chains and kinematic conflicts;

No piston rings;

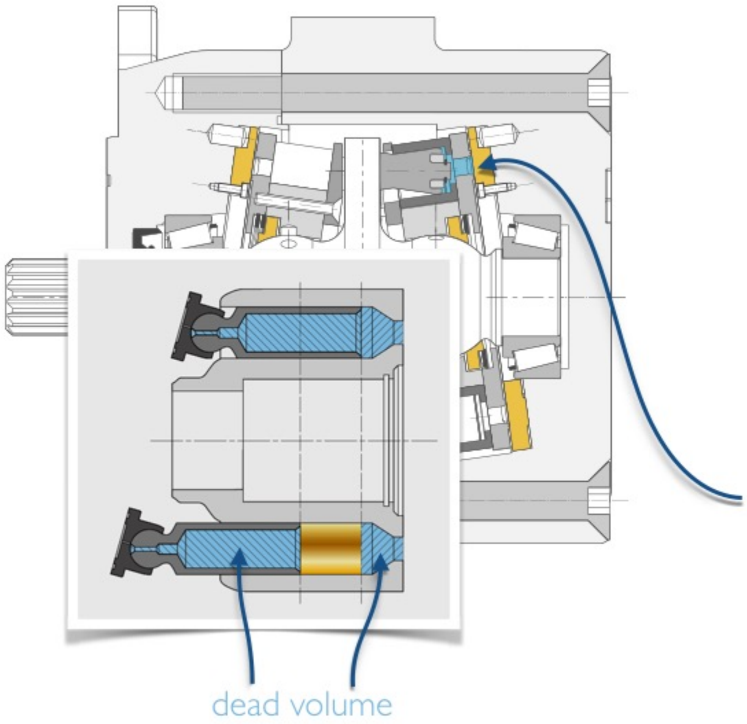
Large port opening area and short stroke reduces the risk for cavitation;

No hydrostatic load between cup and piston;

New hydrostatic bearing;

Low velocities in other sliding interfaces

In all other, remaining sliding interfaces, like, for instance, between the cups and the barrel, the shear velocities are so low that the viscous losses can be neglected.



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Large port opening area and short stroke reduces the risk for cavitation;

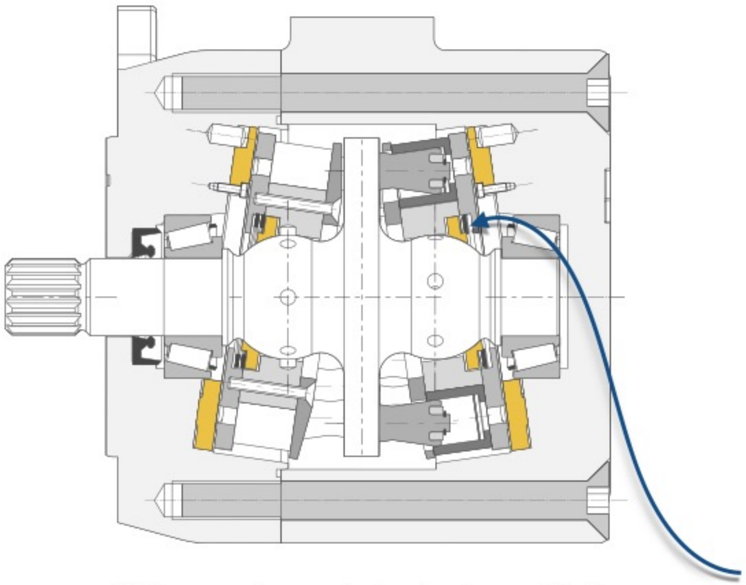
No hydrostatic load between cup and piston;

New hydrostatic bearing;

Low velocities in other sliding interfaces

minimum dead volume

We also managed to reduce the dead volume to a minimum, being much smaller than in current slipper type pumps.



light cups + small stroke + no friction
⇒ small tipping torque
⇒ light barrel spring

High bearing loads are avoided;

Floating cups avoid complicated tolerance chains and kinematic conflicts;

No piston rings;

Large port opening area and short stroke reduces the risk for cavitation;

No hydrostatic load between cup and piston;

New hydrostatic bearing;

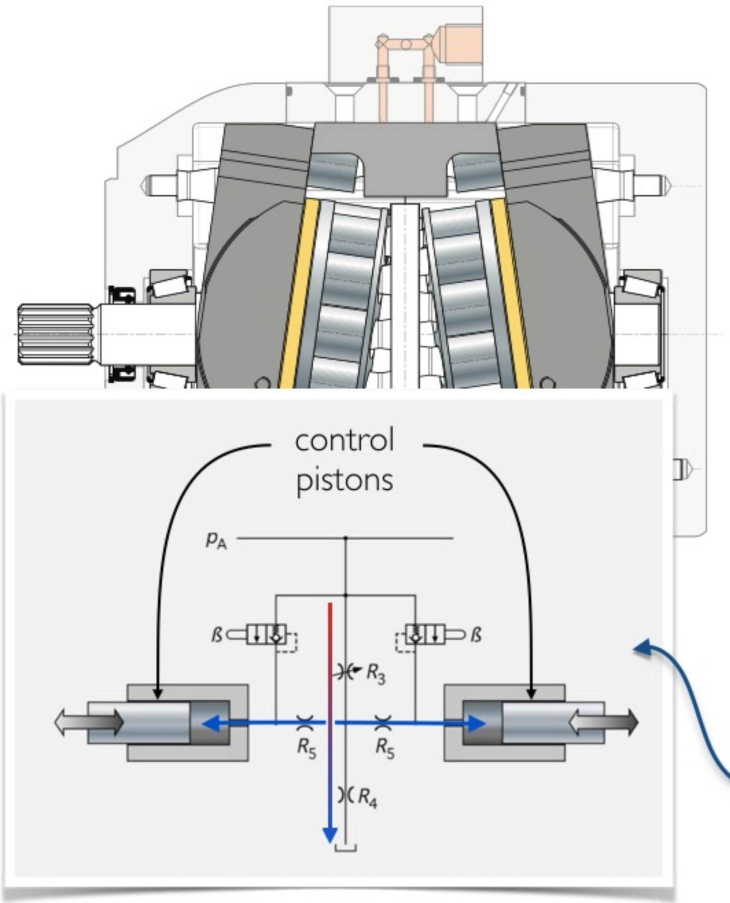
Low velocities in other sliding interfaces

minimum dead volume

minimum barrel spring force

The floating cup principle requires a very light barrel spring. Compared to other axial piston machines, the centrifugal forces, generated by the cups are very small.

Also the elimination of friction between the pistons and the cups has strongly reduced the tipping torque. As a result, the barrel spring can be extremely light.



High bearing loads are avoided;

Floating cups avoid complicated tolerance chains and kinematic conflicts;

No piston rings;

Large port opening area and short stroke reduces the risk for cavitation;

No hydrostatic load between cup and piston;

New hydrostatic bearing;

Low velocities in other sliding interfaces

minimum dead volume

minimum barrel spring force

new, efficient swash plate control and oscillation damping

The last steps on our 'via negativa' concerned the swash plate control of the variable displacement pump. We had to find, and we did find, a better, much more efficient solution.

finding the right solution

Finding the right solution, finding your way through the labyrinth.

I can't help it. It ain't easy. Life can be a hassle, and quite demanding.

Via Negativa

The Via negativa.

It was a long journey, our ‘via negativa’, which lasted for about 12 years. But it has been a rewarding and successful journey. Floating cup pumps and motors will be manufactured and sold. You can buy them around the end of this year.