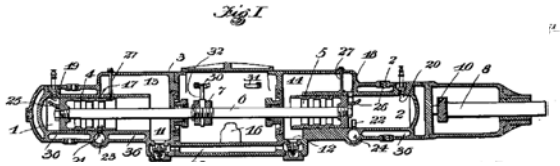
Linear Power Systems
History & applications

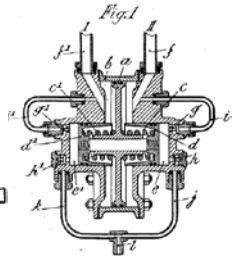
Sam Cockerill, CEO
Libertine FPE

www.libertine.co.uk

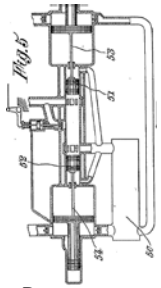
‘Free Piston Engine’ concept dates back to 1903



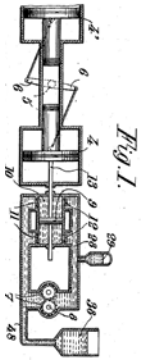
National Free Piston Engine Co. Ltd 1903



Free piston compressor 1907



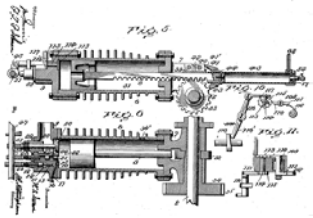
Pescara gas generator 1932



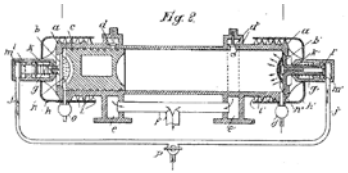
Pescara pump 1937

1807
De Rivaz engine
(Chain drive piston)

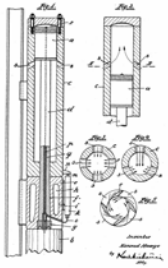
1902
Free piston explosive engine (Rack & pinion)



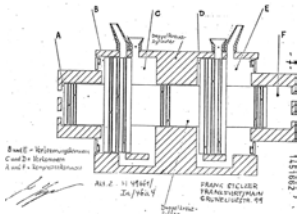
1912
Free piston gas generator



1935
Diesel Hammer



1963
Stelzer Engine

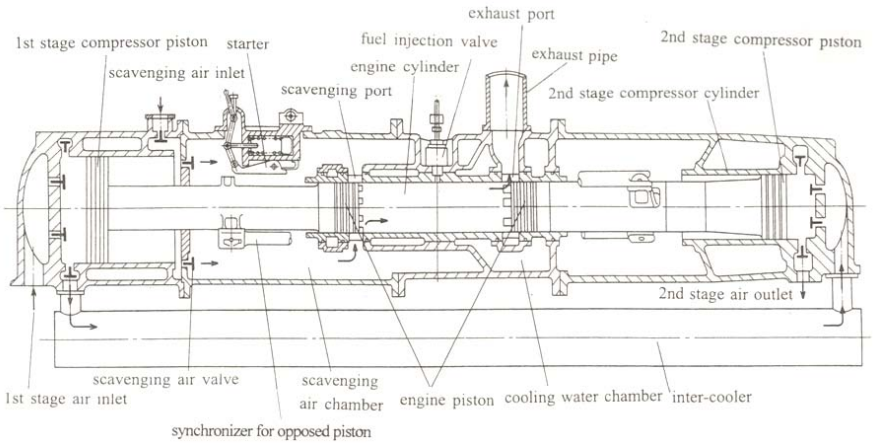


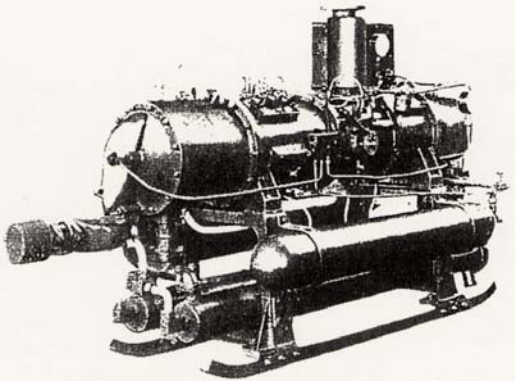
Key questions for FPE pioneers:

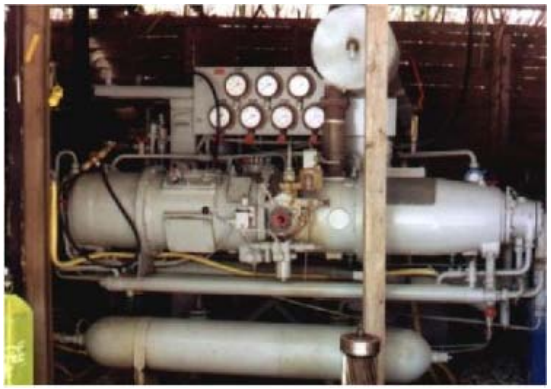
- Balanced or unbalanced?
- How to synchronise pistons?
- What to do with the power?

Compressors

Junkers air compressors used in mobile and marine applications from 1930s to 1940s



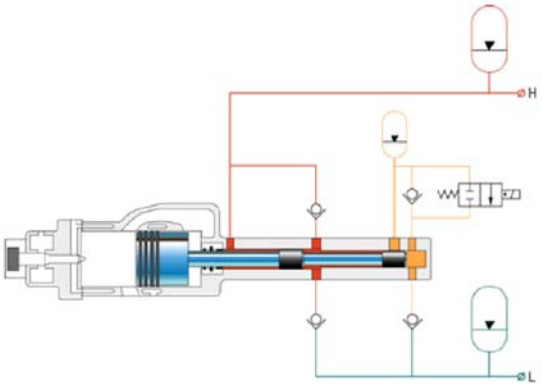




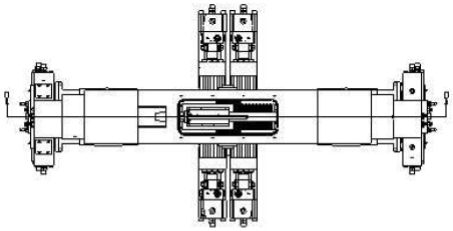
Source: http://www.jsme.or.jp/tsd/ICBTT/conference02/kohama3.html
http://www.freikolben.ch/37464/98401.html

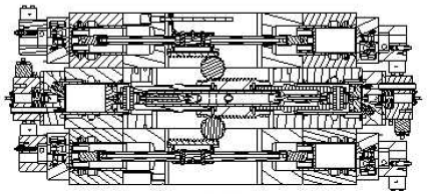
Hydraulic pumps

Innas Chiron (~2000)

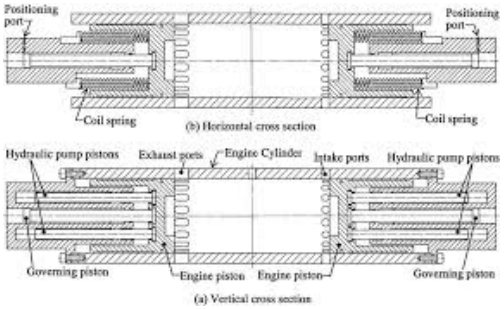


US EPA/FEV (2005)

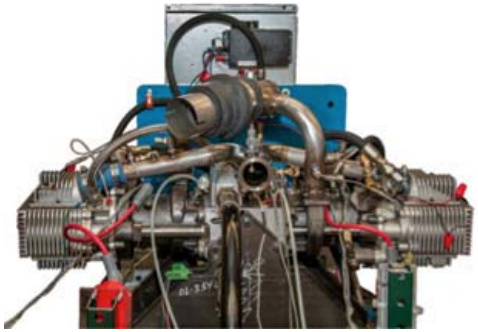


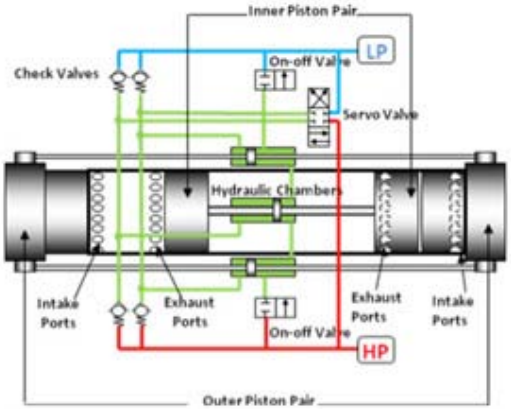


Toyohashi University (~2004)



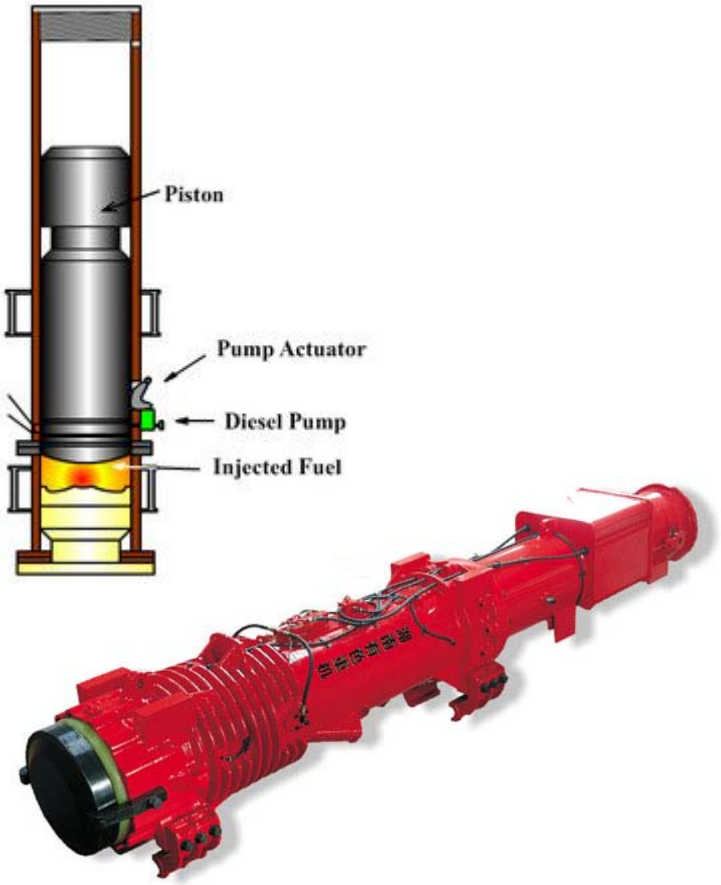
University of Minnesota (~2013)





Source: http://www.innas.com/CFPE.html
http://www.mobilehydraulictips.com/ccefp-update-hydraulics-free-piston-engines/

Diesel pile hammers



Pescara/SIGMA gas generator technology was applied in multiple applications during 1950-60s

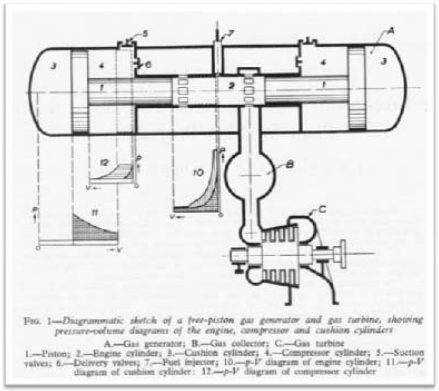
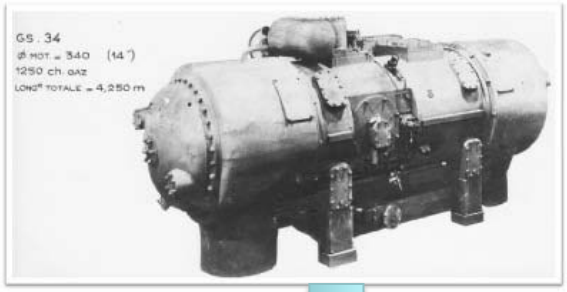


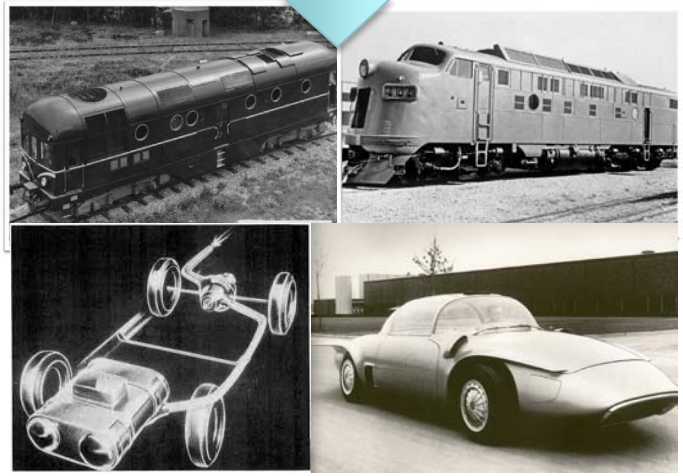
FIG. 1.—*Diagrammatic sketch of a free-piston gas generator and gas turbine, showing pressure-volume diagrams of the engine, compressor and cushion cylinders*

A.—Gas generator; B.—Gas collector; C.—Gas turbine

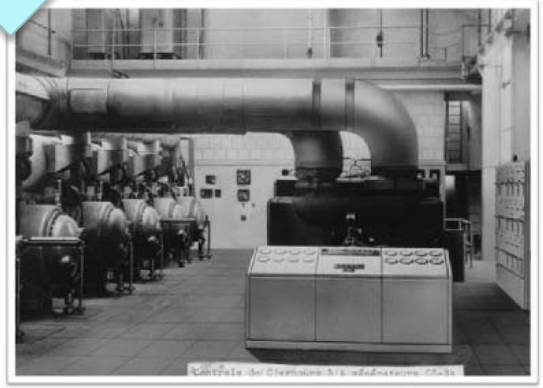
1.—Piston; 2.—Engine cylinder; 3.—Cushion cylinder; 4.—Compressor cylinder; 5.—Suction valves; 6.—Delivery valves; 7.—Fuel injector; 10.—p-V diagram of engine cylinder; 11.—p-V diagram of cushion cylinder: 12.—p-V diagram of compressor cylinder



Marine propulsion
(Minesweepers, liberty ships)



Prototype trains & cars



1-30MWe SIGMA power stations
(Reims, Corsica, Cherbourg,
New Caledonia)

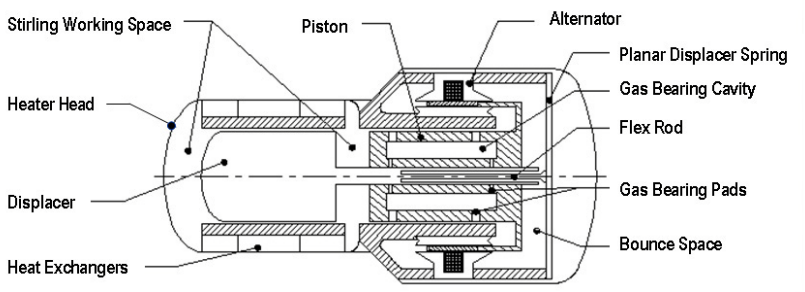
Source:
http://utahrails.net/up/fg9.php
http://www.freikolben.ch/37464/98443.html

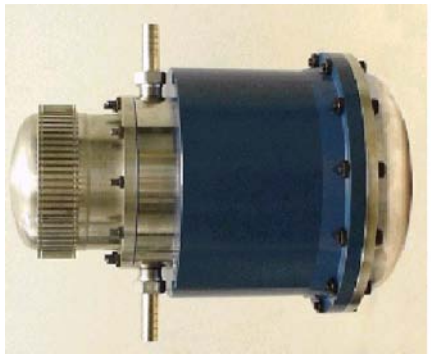
..but '*Free Piston + GT*' system efficiency was not competitive and was displaced by technology advances

Initial FPGT applications	Utility scale power gen	Marine propulsion	Train propulsion	Small scale power gen
Technology drivers	Scale economics & efficiency	Efficiency (on marine fuel)	Efficiency (on diesel fuel)	Fuel, capital and O&M cost ("LCOE")
FPGT displaced by	CCGT (Gas) Steam turbines (Coal & nuclear)	Scale CI-ICE GT	Electrification CI-ICE	Packaged CI-ICE Packaged GT

Stirling engines

Sunpower



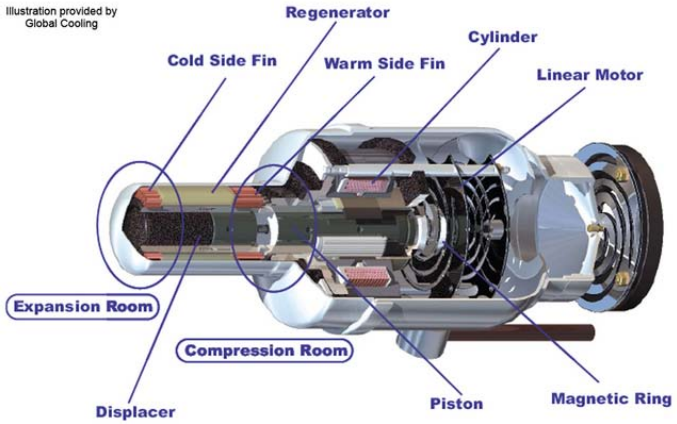


Infinia/Qnergy

Source: http://us.sunpowerinc.com/
http://www.qnergy.com/

Stirling coolers

Apex instruments
SGC-4000HG

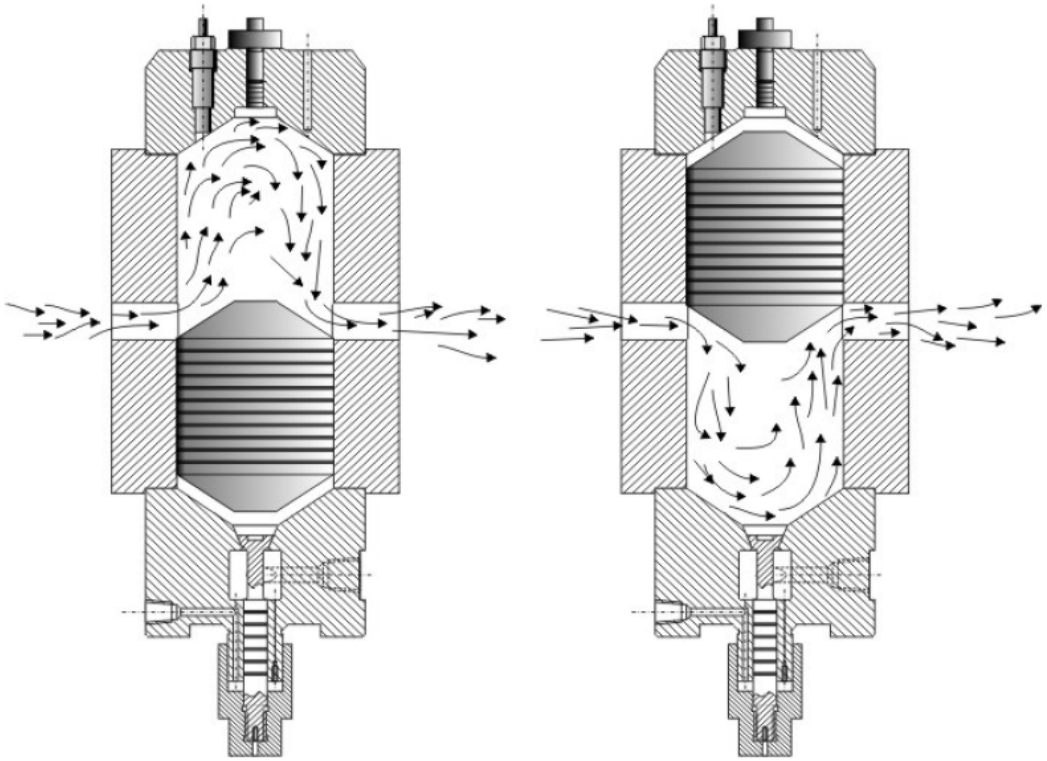


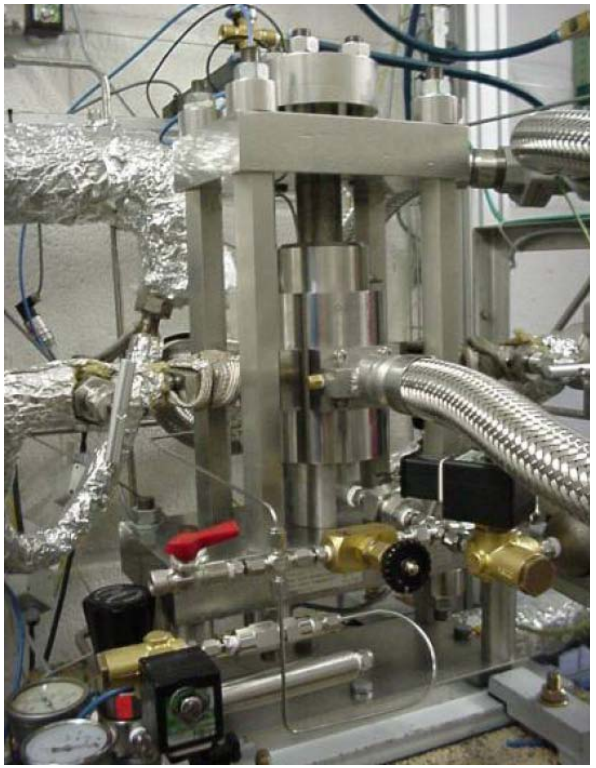
Sunpower
Cryotel range

Twinbird
SC-TC04 40W

Source: Supplier literature

Encontec free piston pulsed compression reactor





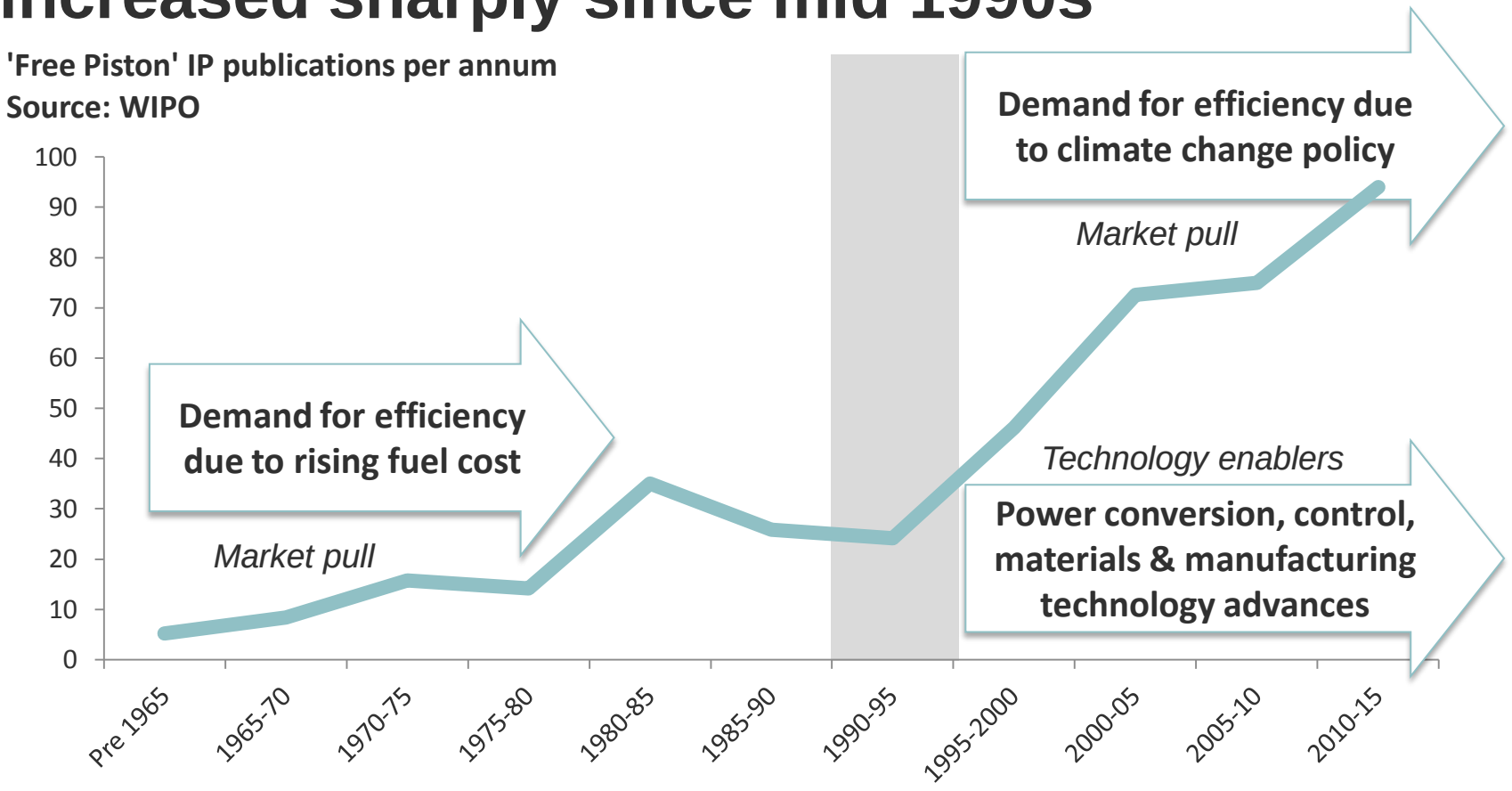
Source: http://www.encontech.nl/papers/PaperLyonWHEC16.pdf

Research & development free piston engines

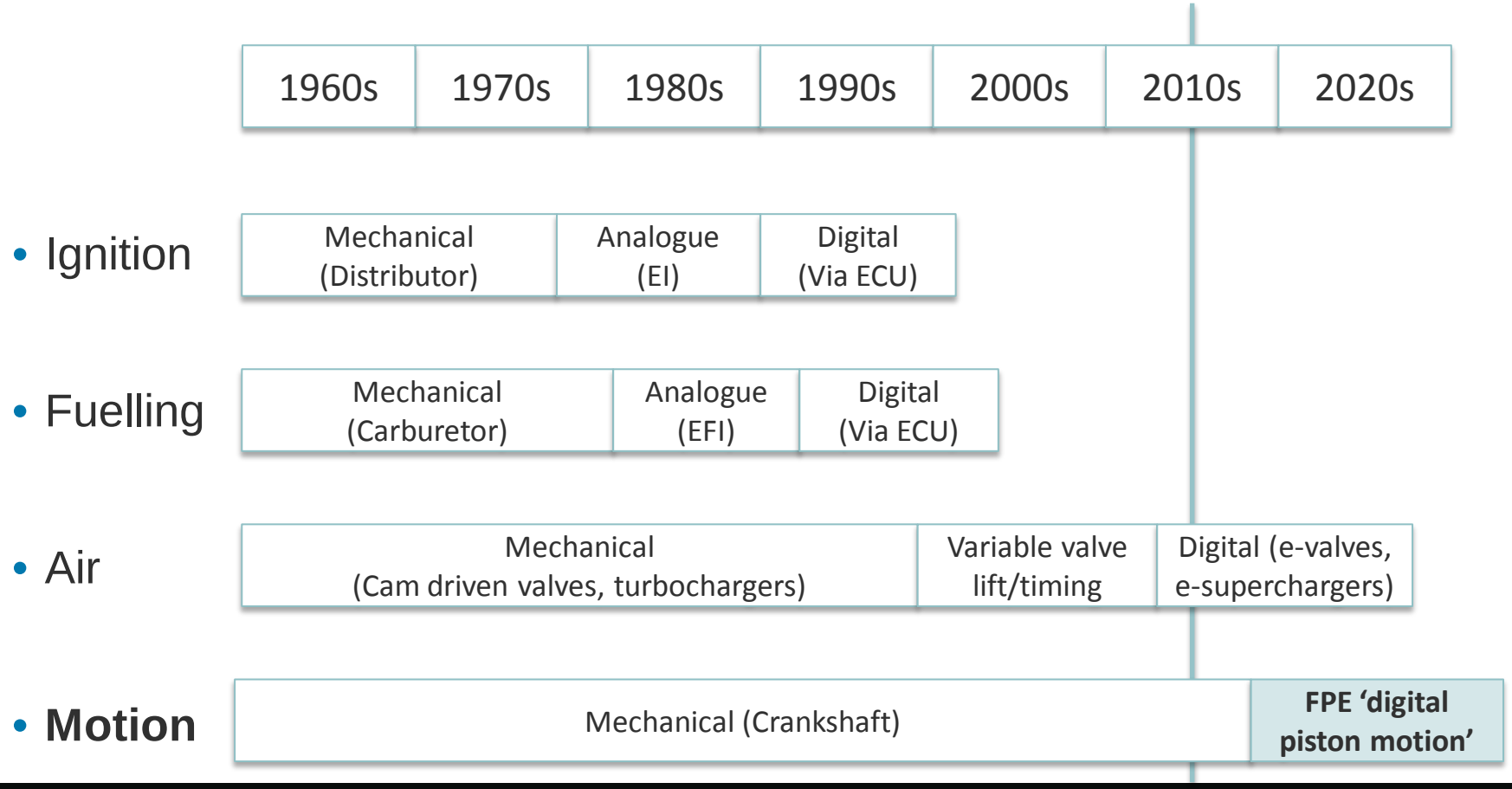
- Aerodyne Research inc.
- Czech Technical University
- General Motors/Sandia Labs
- German Aerospace Centre
- Lotus/Loughborough University
- Newcastle University
- Pempek
- PETRONAS
- Sussex University (AMOCATIC)
- Toyota Central R&D Labs
- West Virginia University Research Corporation
- Volvo/Stockholm Institute of Technology
- ..

Has anything changed?

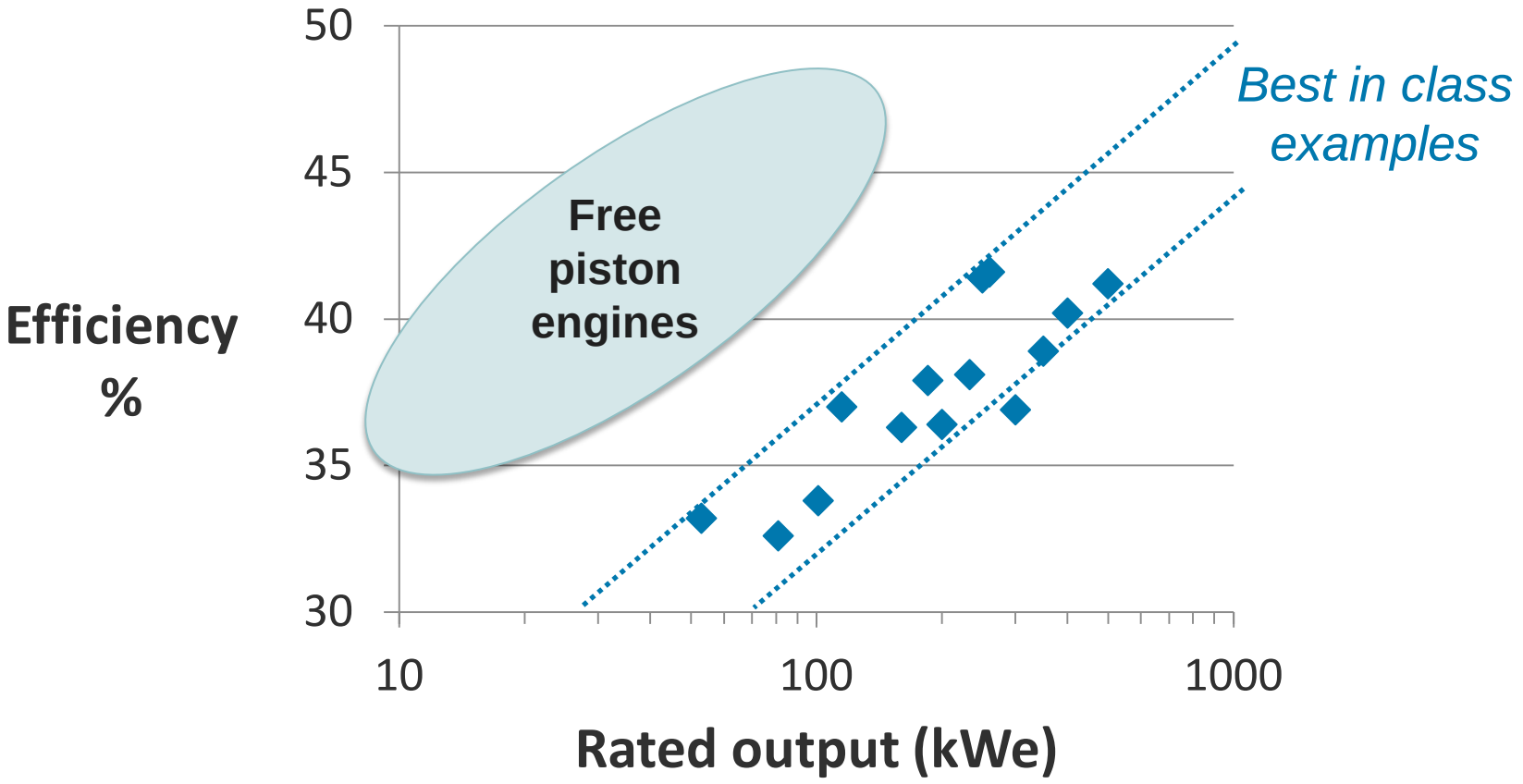
Free Piston patent publication rate has increased sharply since mid 1990s



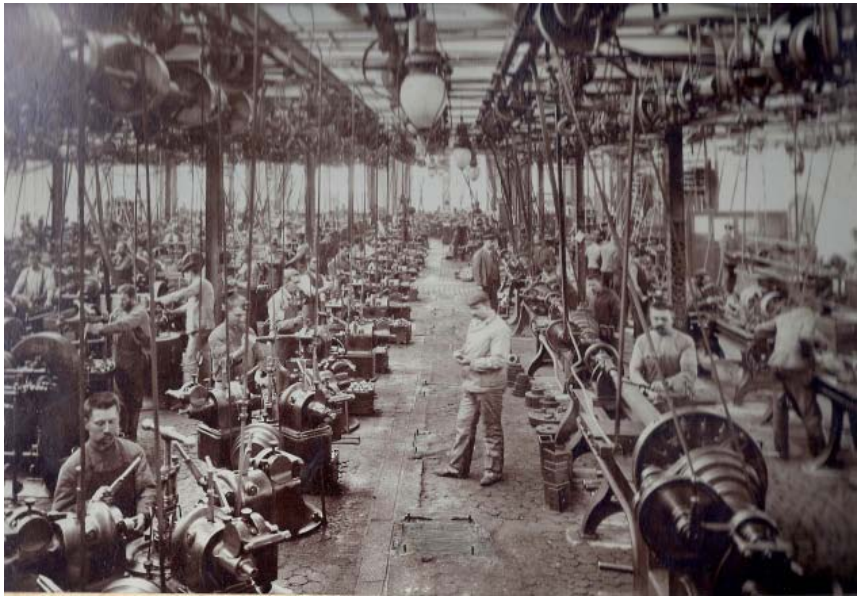
Evolution of combustion engine control



Free piston engine efficiency can deliver a third more power than today's 'best in class' generators



Mechanical transmission of power used to be the norm before electrification

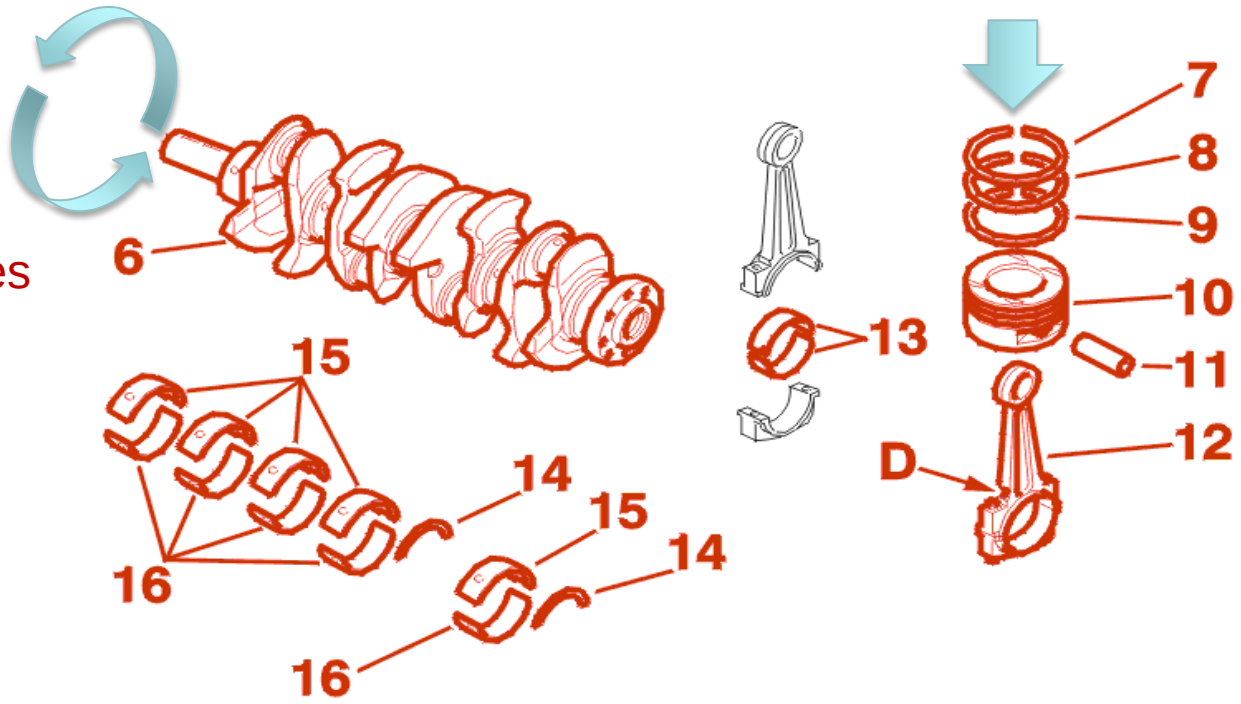


Factories with mechanical transmission equipment in Schaffhausen, ~1880

In cars, mechanical transmission of power persists despite complexity, cost & inefficiency

Input
(Combustion power)

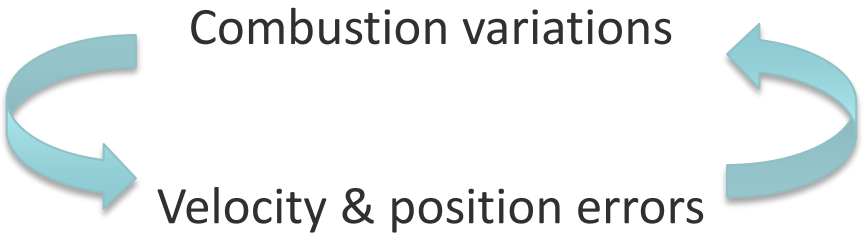
Output
(Shaft power to gearbox, auxiliaries and valvetrain)



So where are all the free piston engines?

Technical challenges have stalled mass adoption

- **Motion control**

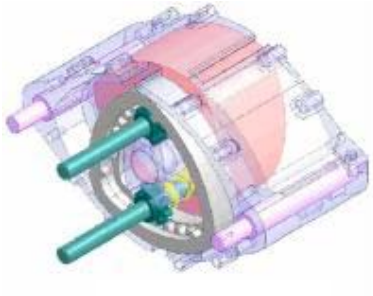


- **System losses**
  - Thermodynamics
  - Friction
  - Sealing
  - Electrical machine
  - Power conversion

- **Complexity**
  - Costly design architectures adopted to solve motion & system loss challenges

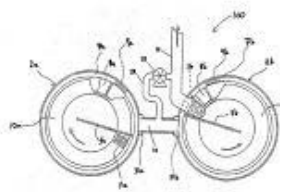
Proliferation of ‘new engine’ concepts

LiquidPiston



RadMax

Lontra



Ox2

Moller

Scuderi

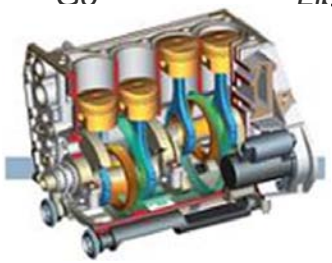
REVETEC

Star Rotor

Anyoon

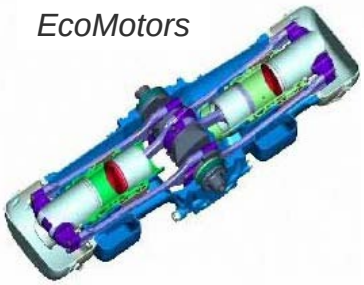
Hefley

Go



Libralato

EcoMotors



Astremo

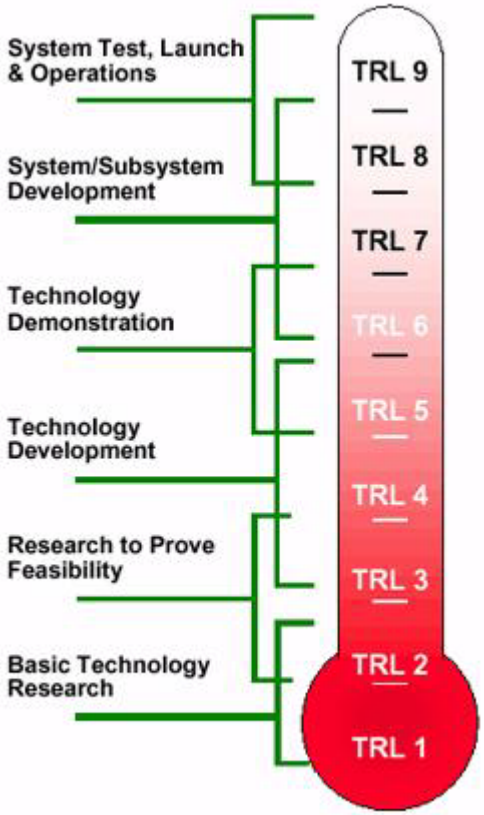
.. and many more

Car companies don’t buy new engine concepts

Pre-requisites for mass adoption

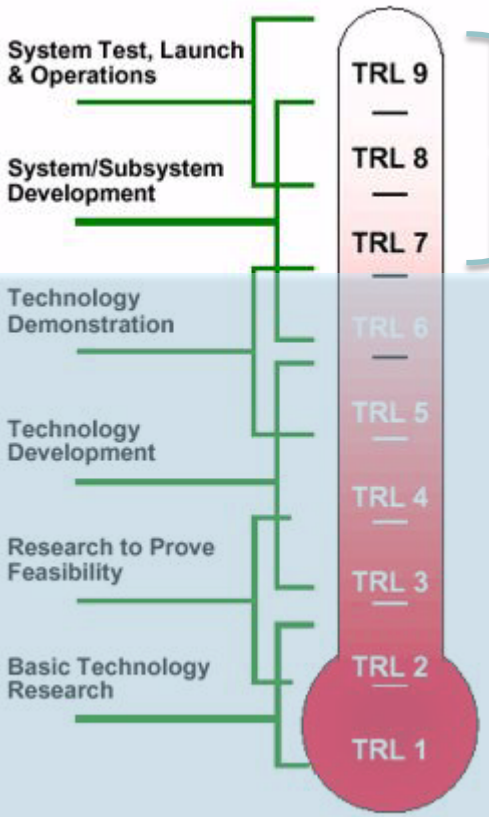
1. Technology maturity (TRL/MRL)
2. Demonstrated performance advantage
3. Cost competitive

Technology maturity



Manufacturing Readiness Level (MRL)		
Phase	MRL	State of Development
Phase 3: Production Implementation	9	Full production process qualified for full range of parts and full metrics achieved
	8	Full production process qualified for full range of parts
	7	Capability and rate confirmed
Phase 2: Pre production	6	Process optimised for production rate on production equipment
	5	Basic capability demonstrated
Phase 1: Technology assessment and proving	4	Production validated in lab environment
	3	Experimental proof of concept completed
	2	Application and validity of concept validated or demonstrated
	1	Concept proposed with scientific validation

Technology maturity



~90% of cost

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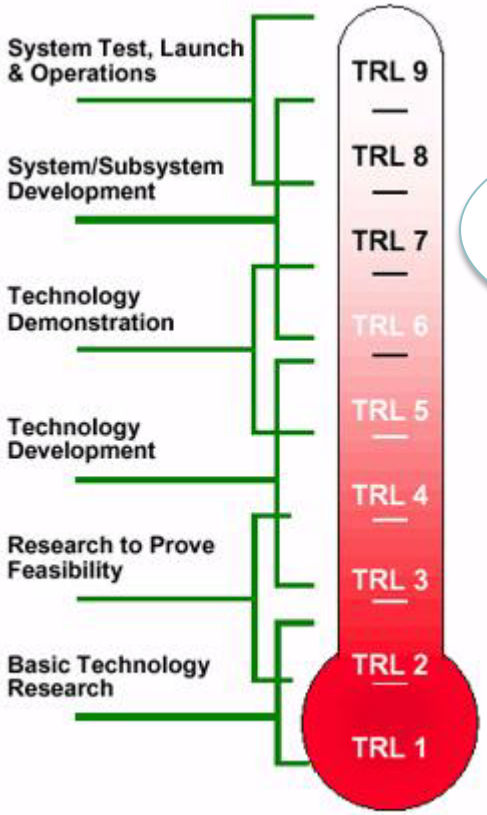
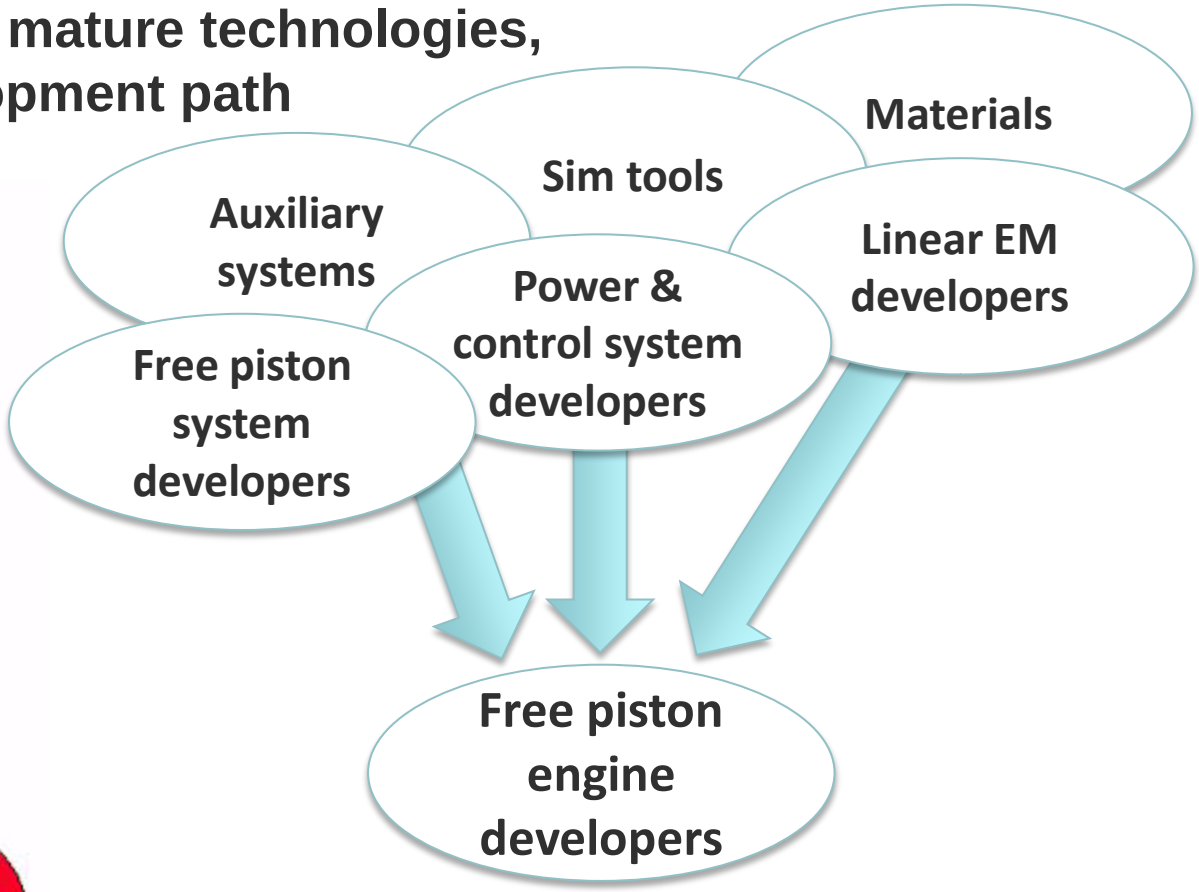
	2	Application and validity of concept validated or demonstrated
	1	Concept proposed with scientific validation

Low TRL = under-performance, low MRL = high cost

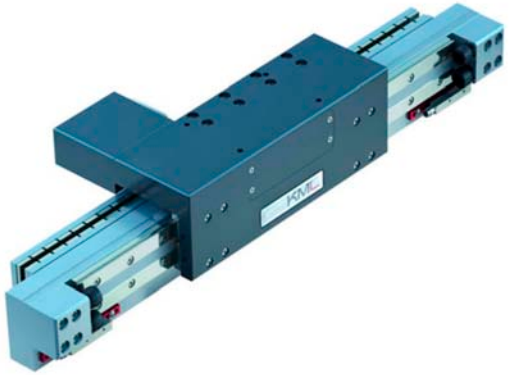
Completing the development journey pre-revenue is too expensive, so technology remains in the lab

Opportunity to buy in mature technologies, shortening the development path

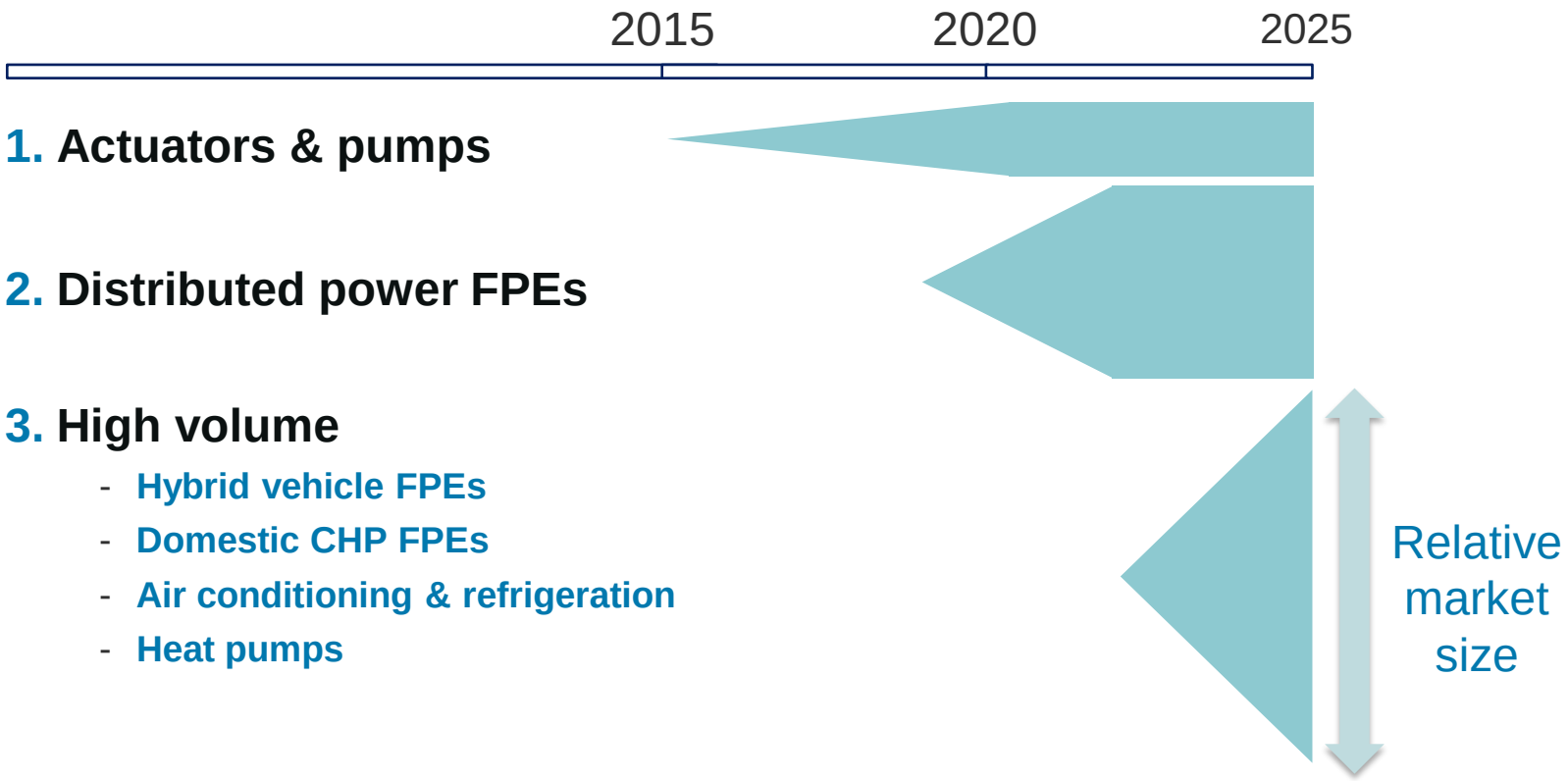




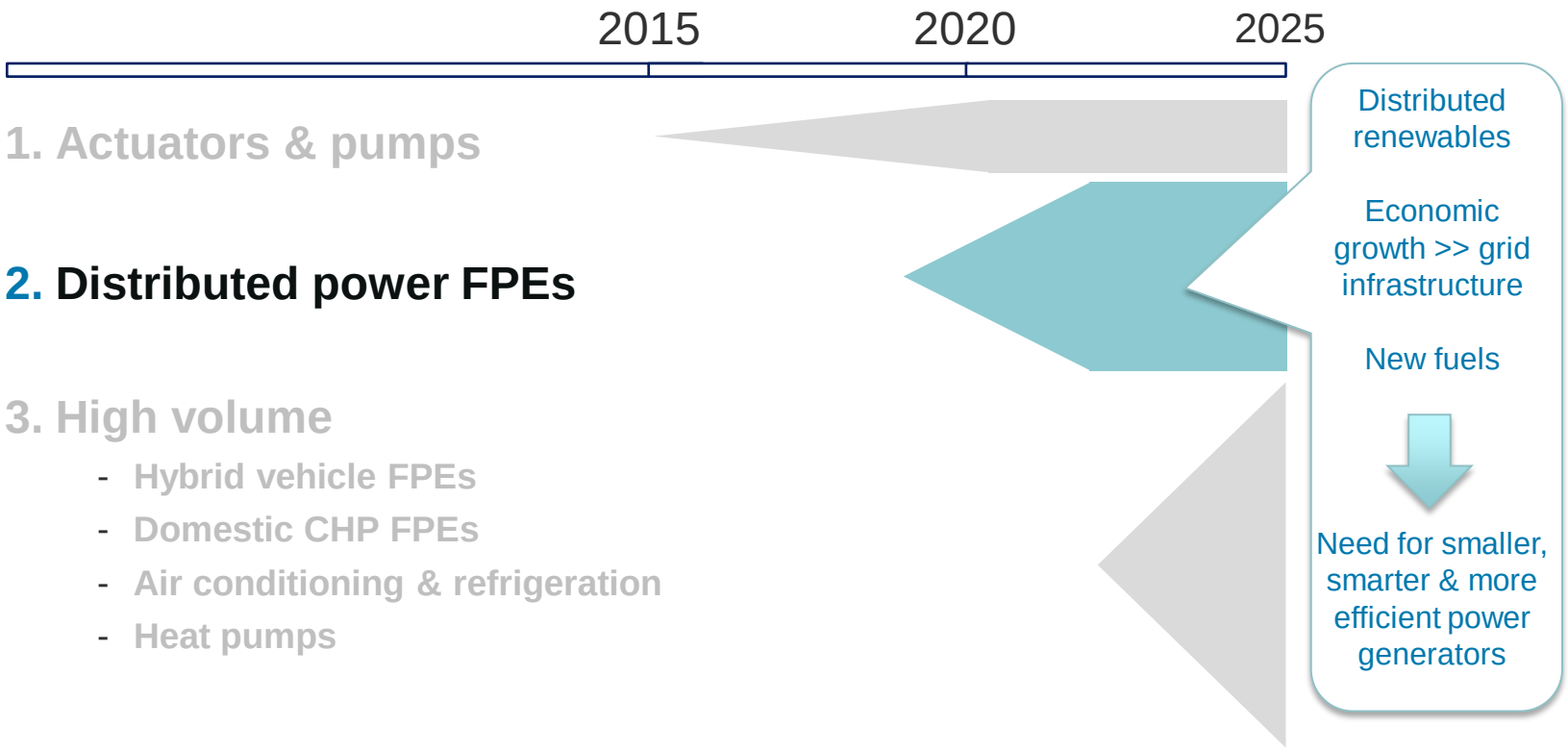
Linear e-machines technology is maturing fast



Market opportunities

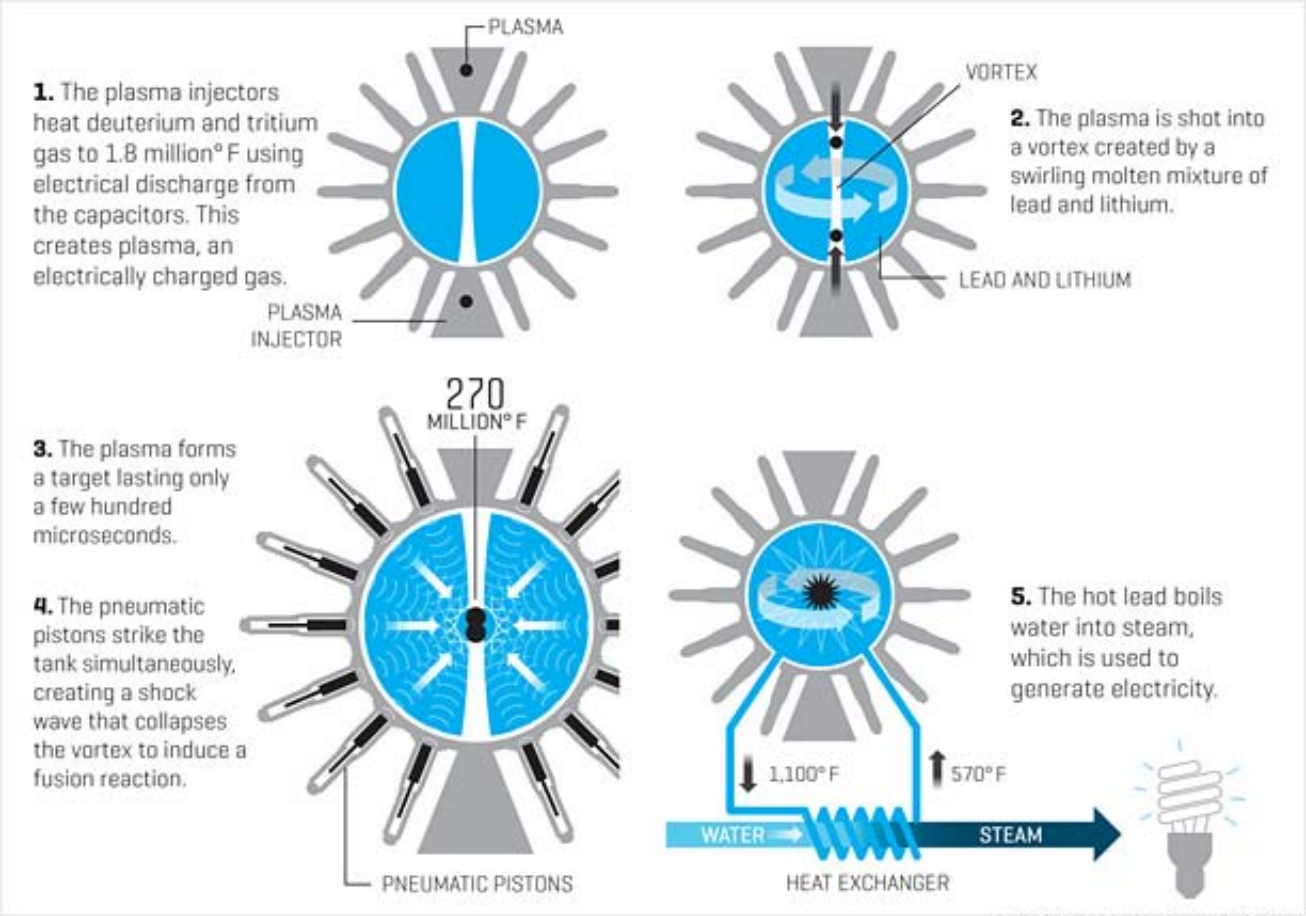


Market opportunities



Emerging market opportunities

General Fusion: The ultimate linear power system?



Linear Power Systems
Challenges & opportunities

Sam Cockerill, CEO
Libertine FPE

www.libertine.co.uk

Thank you