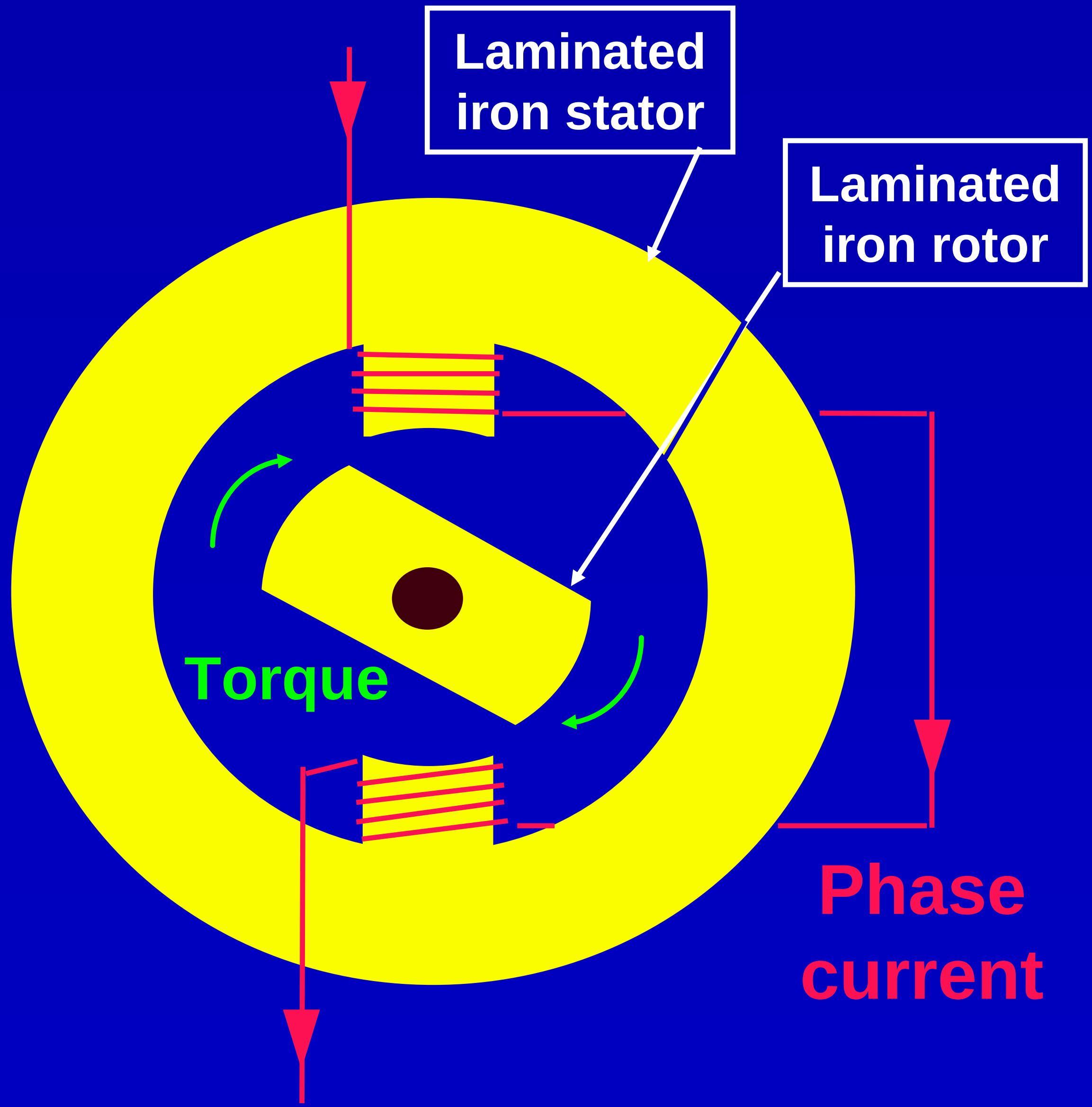
S R Drives®

an introduction to switched reluctance motors and controls

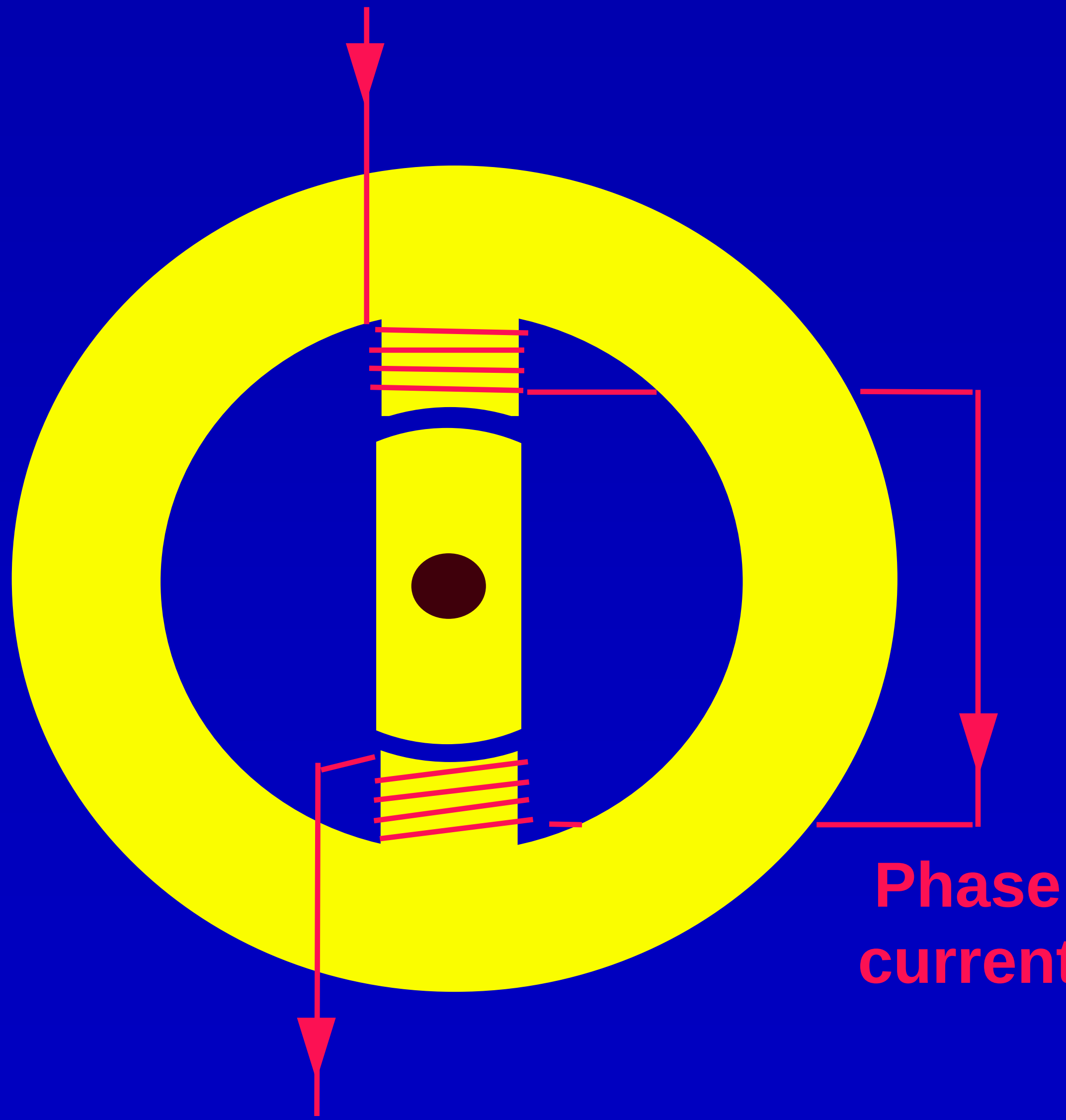
How does it work?

- Consider simple, single-phase, motor
- Phase current sets up magnetic flux in stator
- Magnetic attraction will try to turn rotor to its fully-aligned position
- Clock-wise torque will be produced (green arrows)
- This is the principle of a "variable reluctance motor"



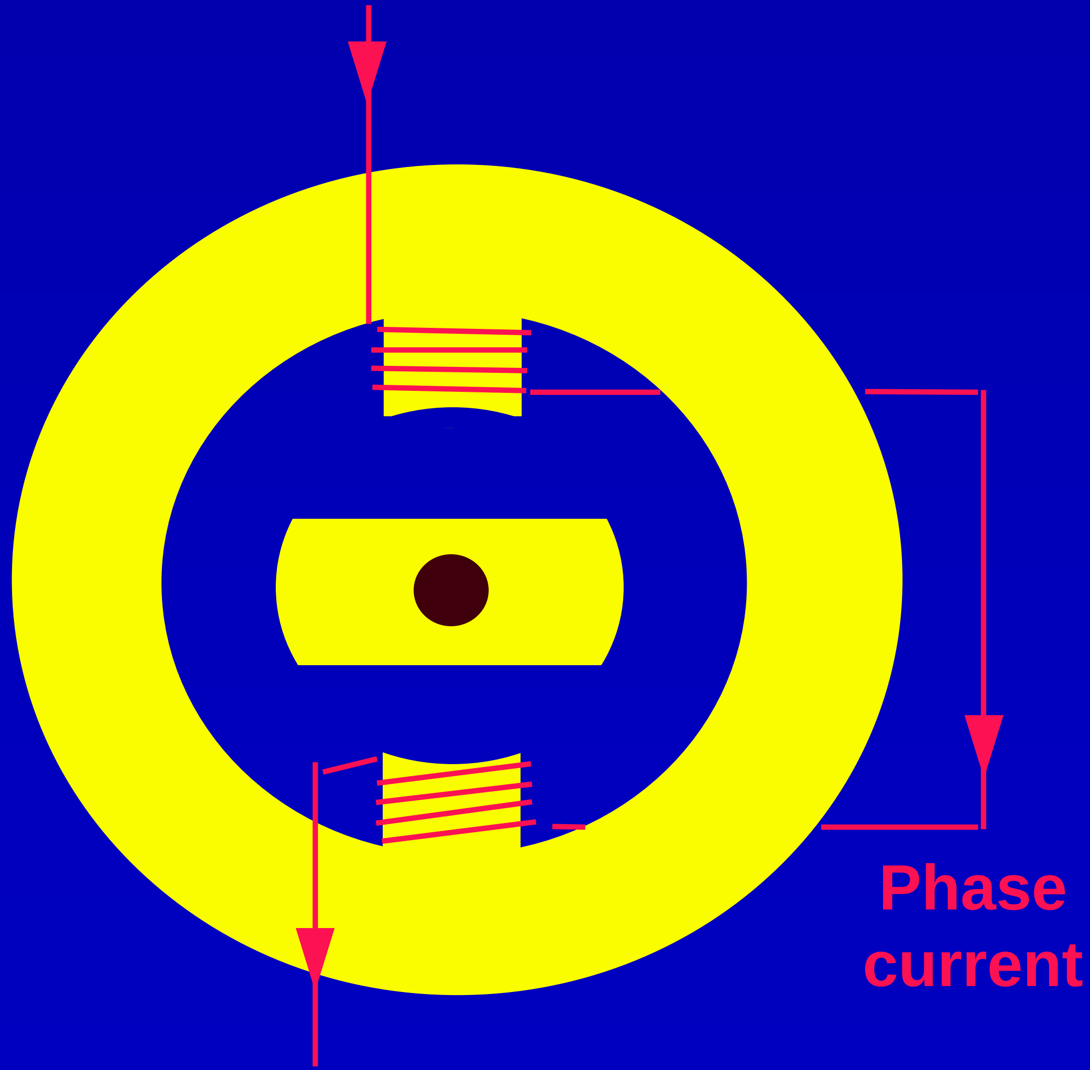
Phase torque is zero at fully aligned position

- Rotor position shown gives minimum magnetic circuit "reluctance"
- Phase inductance is at its maximum (L_{max})
- This position often called "top dead centre" (TDC)



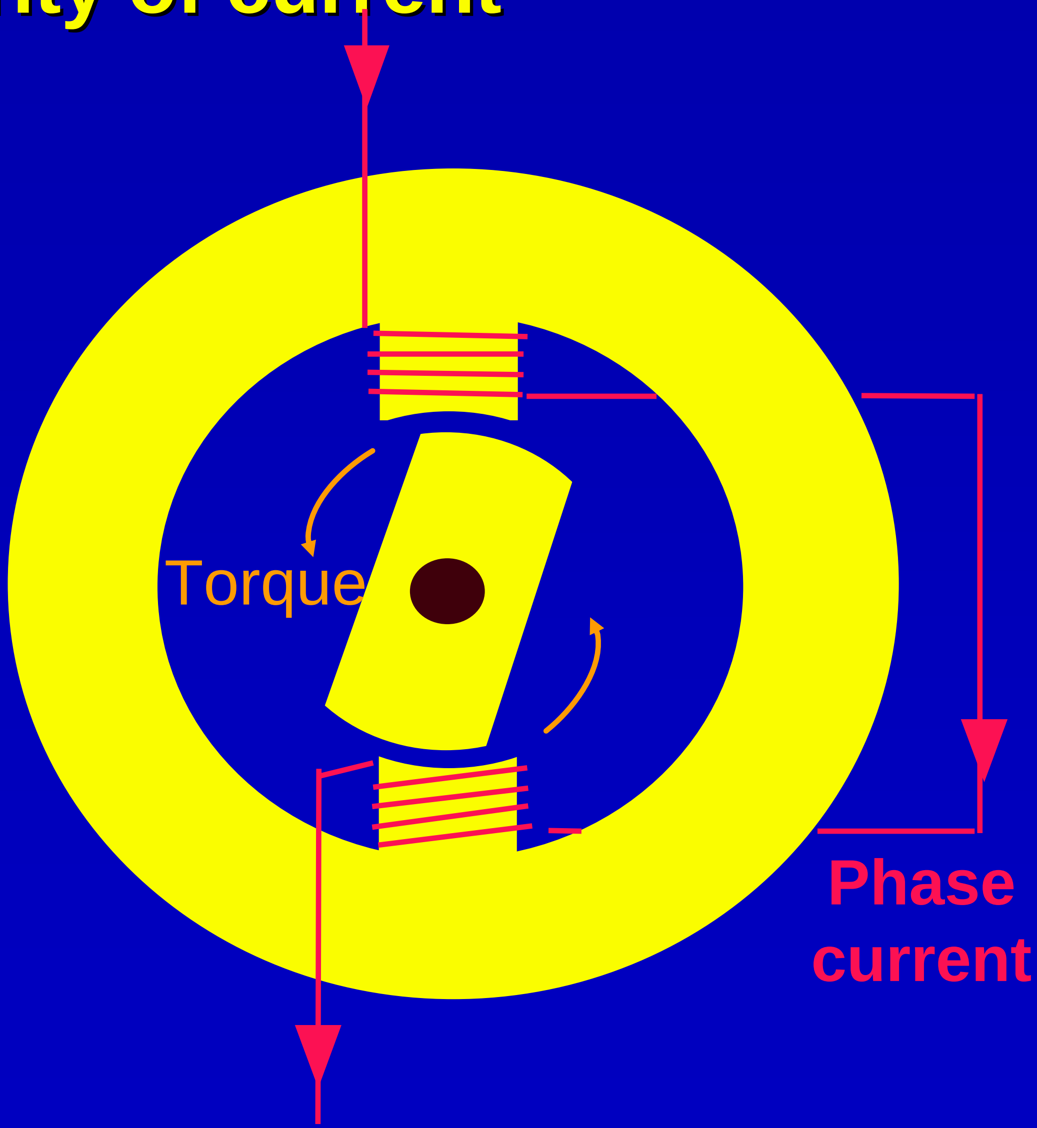
Zero torque also at fully un-aligned position

- Rotor position now yields maximum magnetic circuit reluctance
- Phase's electrical inductance will be at a minimum (L_{min})
- Position often called "bottom dead centre" (BDC)



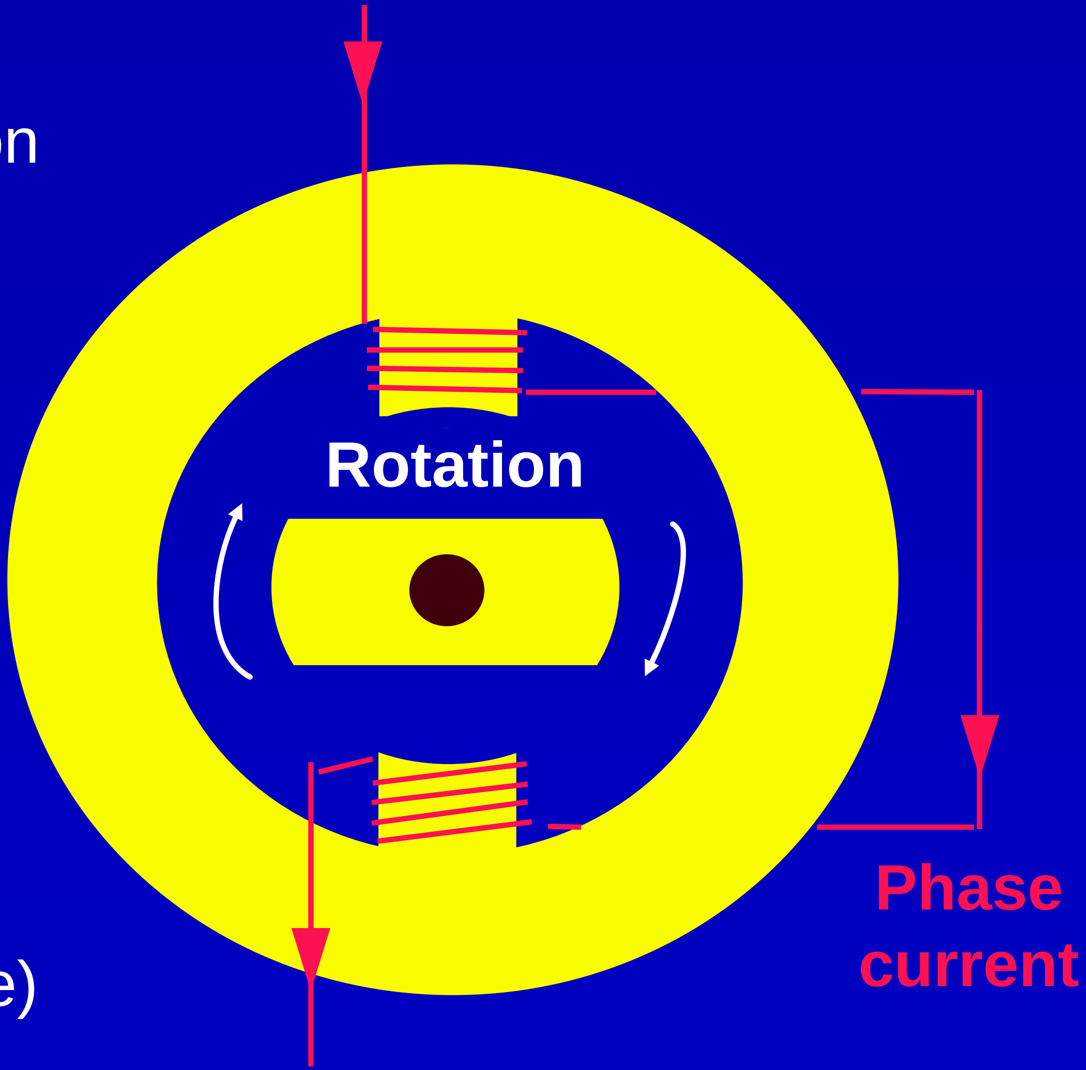
Torque can be reversed without changing polarity of current

- If phase current still flows in the interval after TDC, and before BDC is again reached, anti-clockwise torque will be produced *(orange arrows)*
- If the rotor is still rotating clockwise, this torque is BRAKING the load
- Positive or negative torque obtainable, simply by altering timing of winding excitation



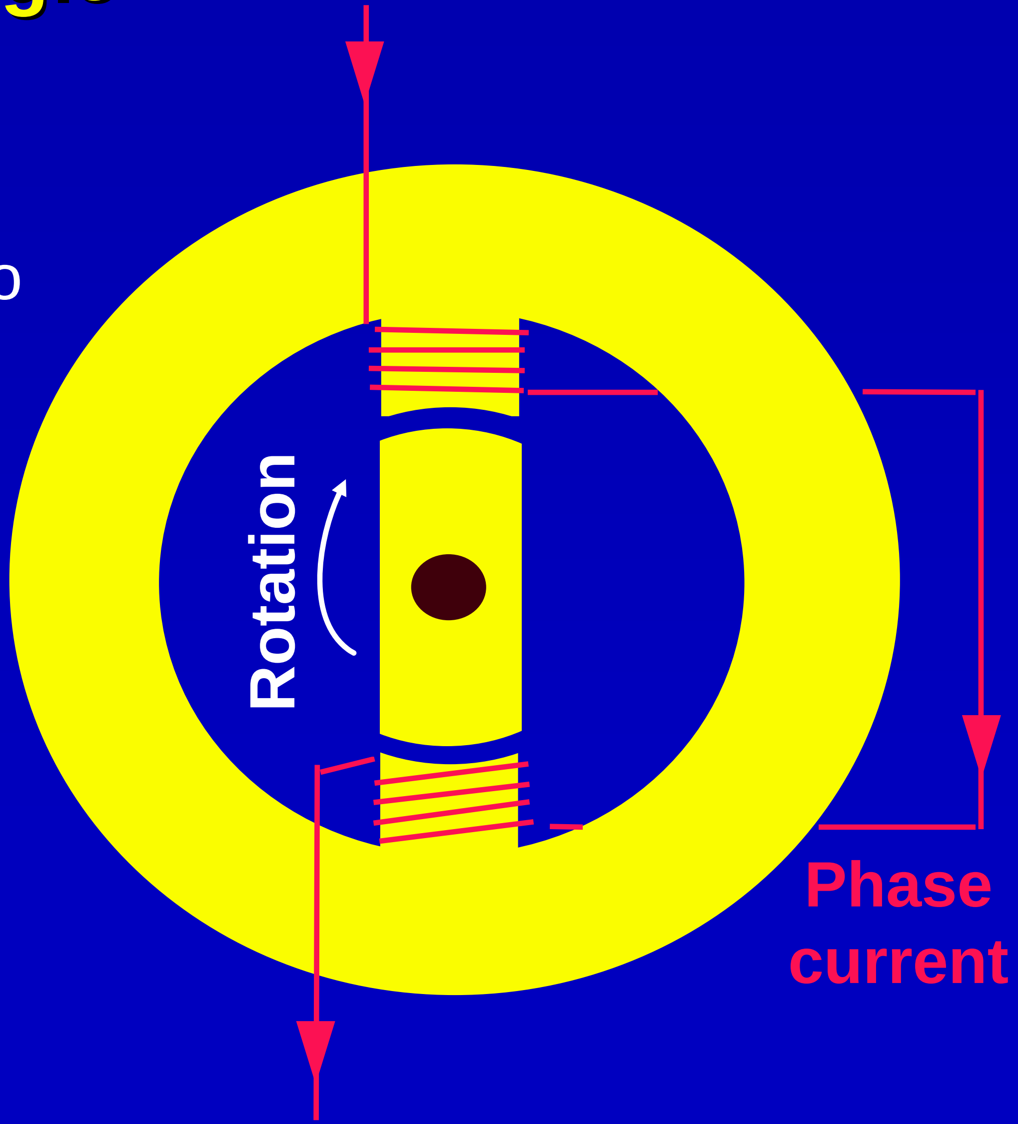
Operation as a switched reluctance motor

- Assume CLOCKWISE rotation
- Rotor is shown at BDC
- Get clockwise torque once rotor has turned past BDC
- If we switch phase on before BDC, we will get anti-clockwise torque
- So: ideally switch on at BDC – but not before! (to maximise motoring torque)



De-energising at the correct rotor angle

- When TDC is reached, the instantaneous torque falls to zero
- Get <u>anti-clockwise</u> braking torque when the rotor turns past TDC -- <u>unless we switch phase current off</u>
- (Ideally) switch off at TDC to maximise motoring torque

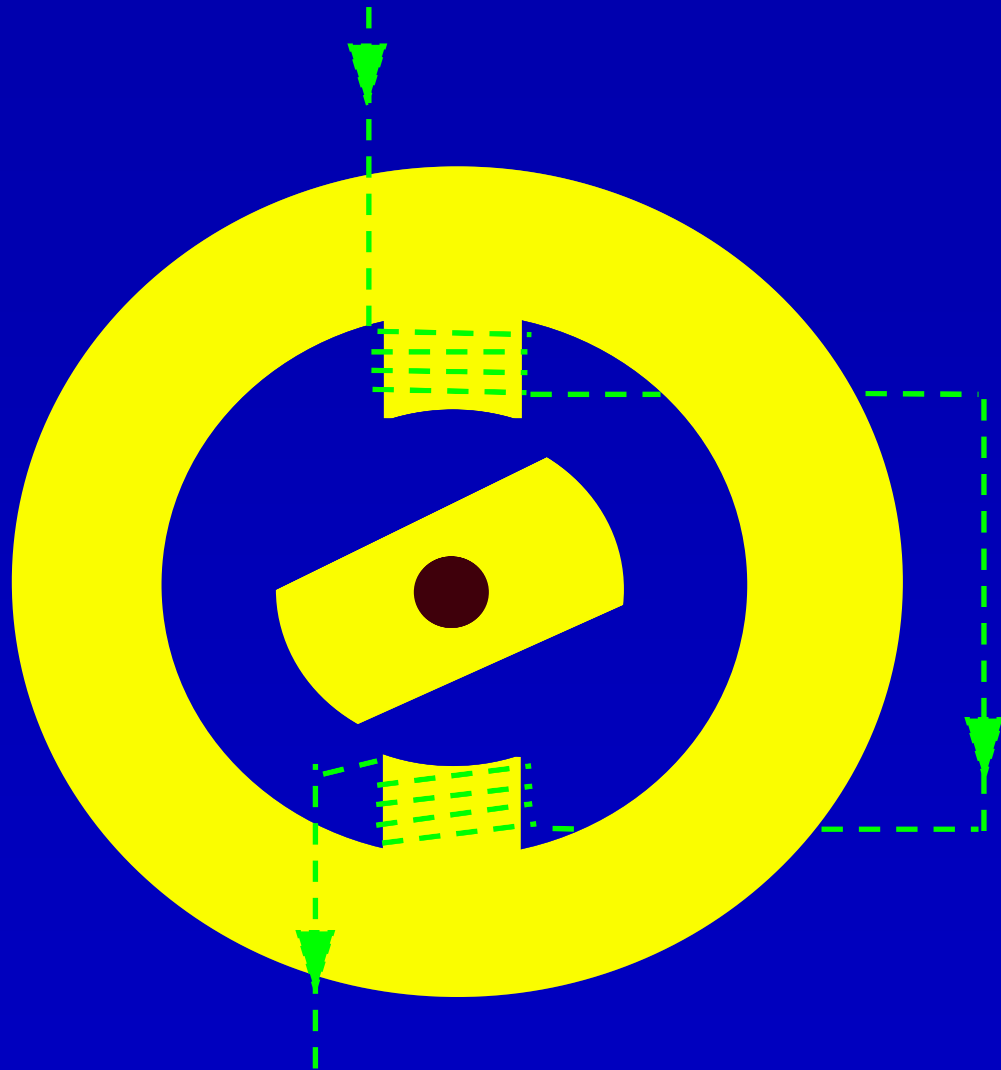


Simple animation of motoring operation follows…

– Clockwise rotation assumed
– Switch on at bottom dead centre
– Switch off at top dead centre

CW rotation

No torque

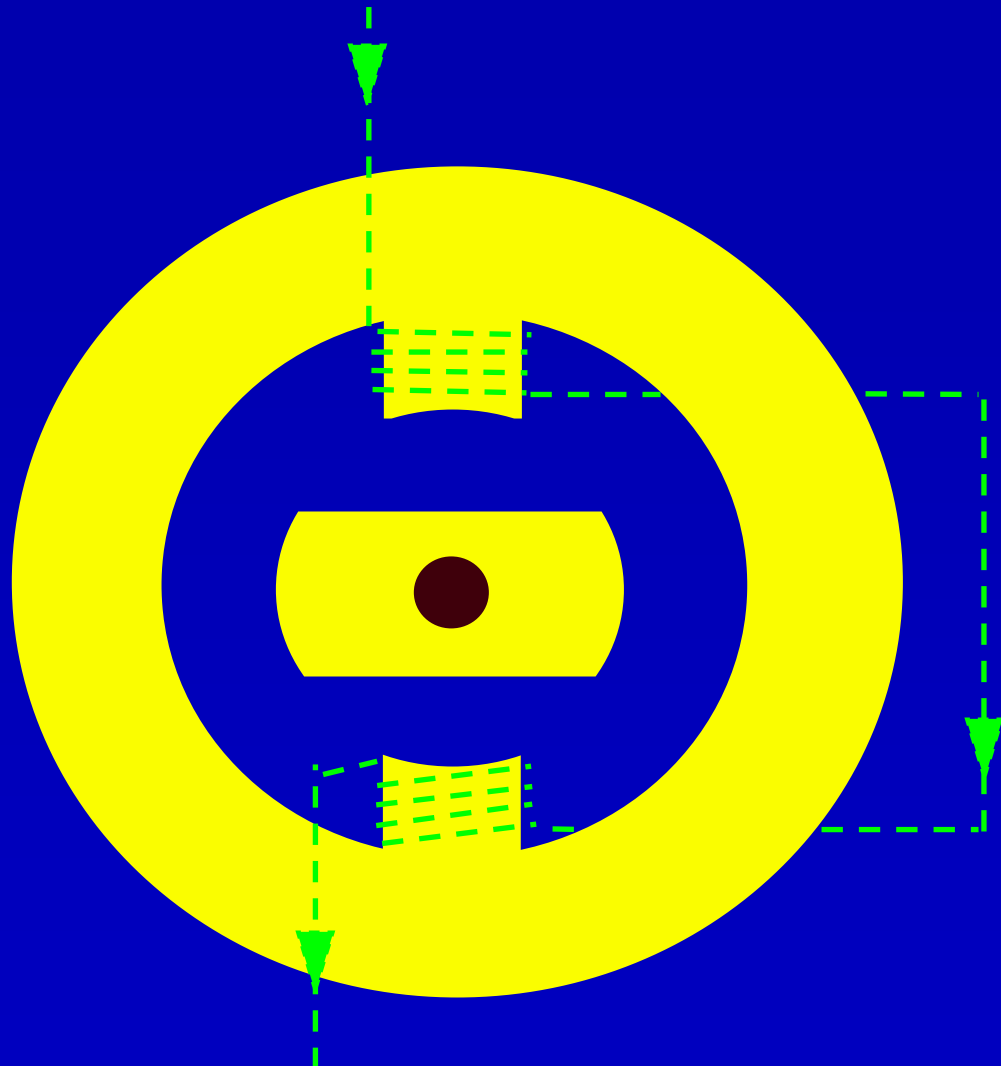


Phase current = ZERO

CW rotation

- - - - - -

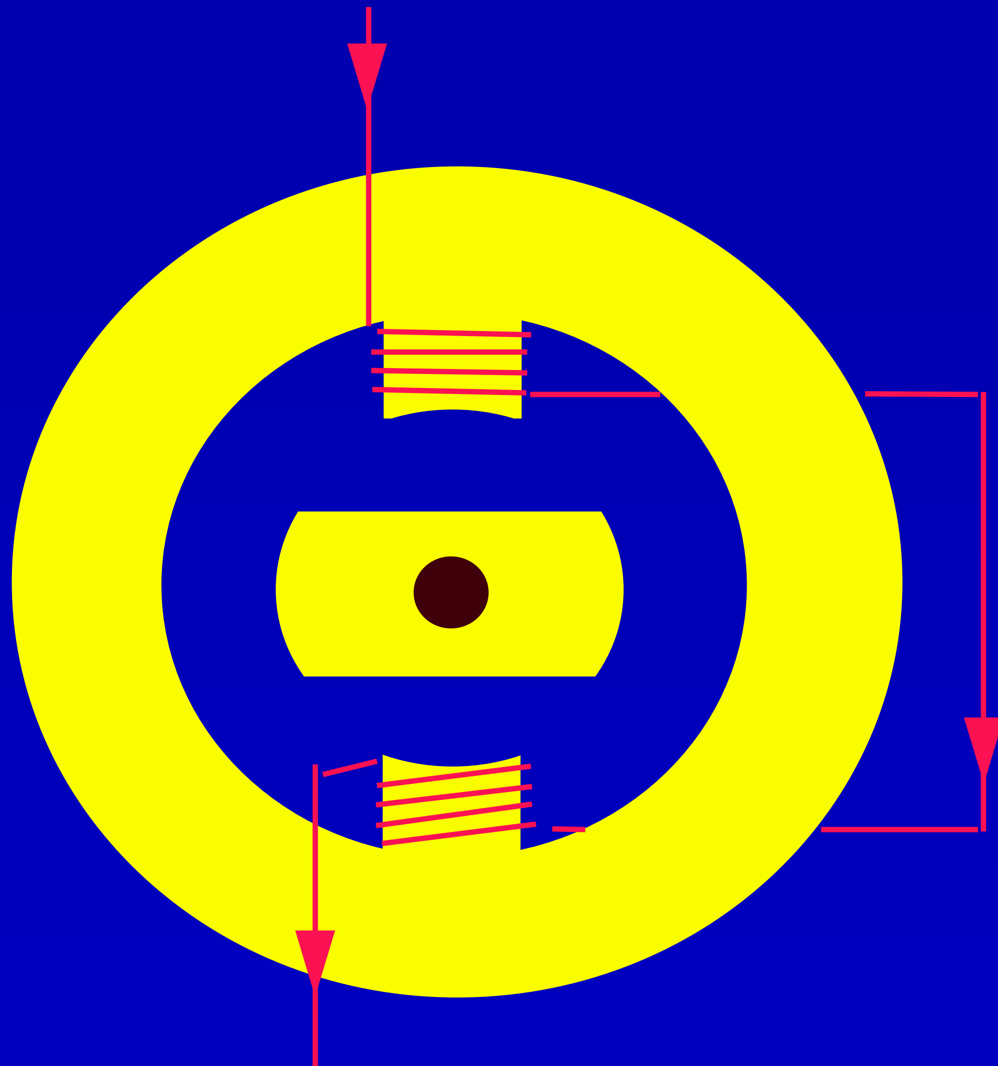
No torque



Phase current = ZERO

CW rotation

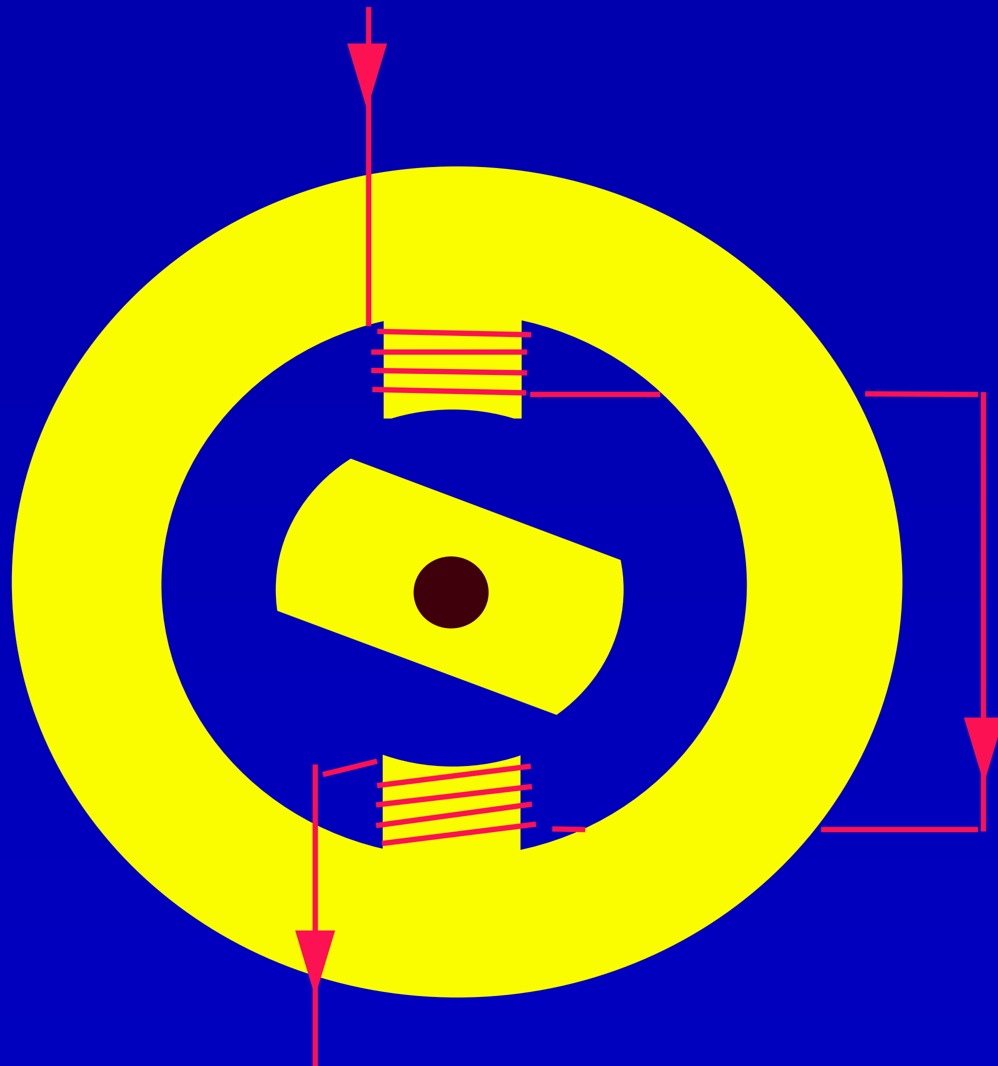
No torque



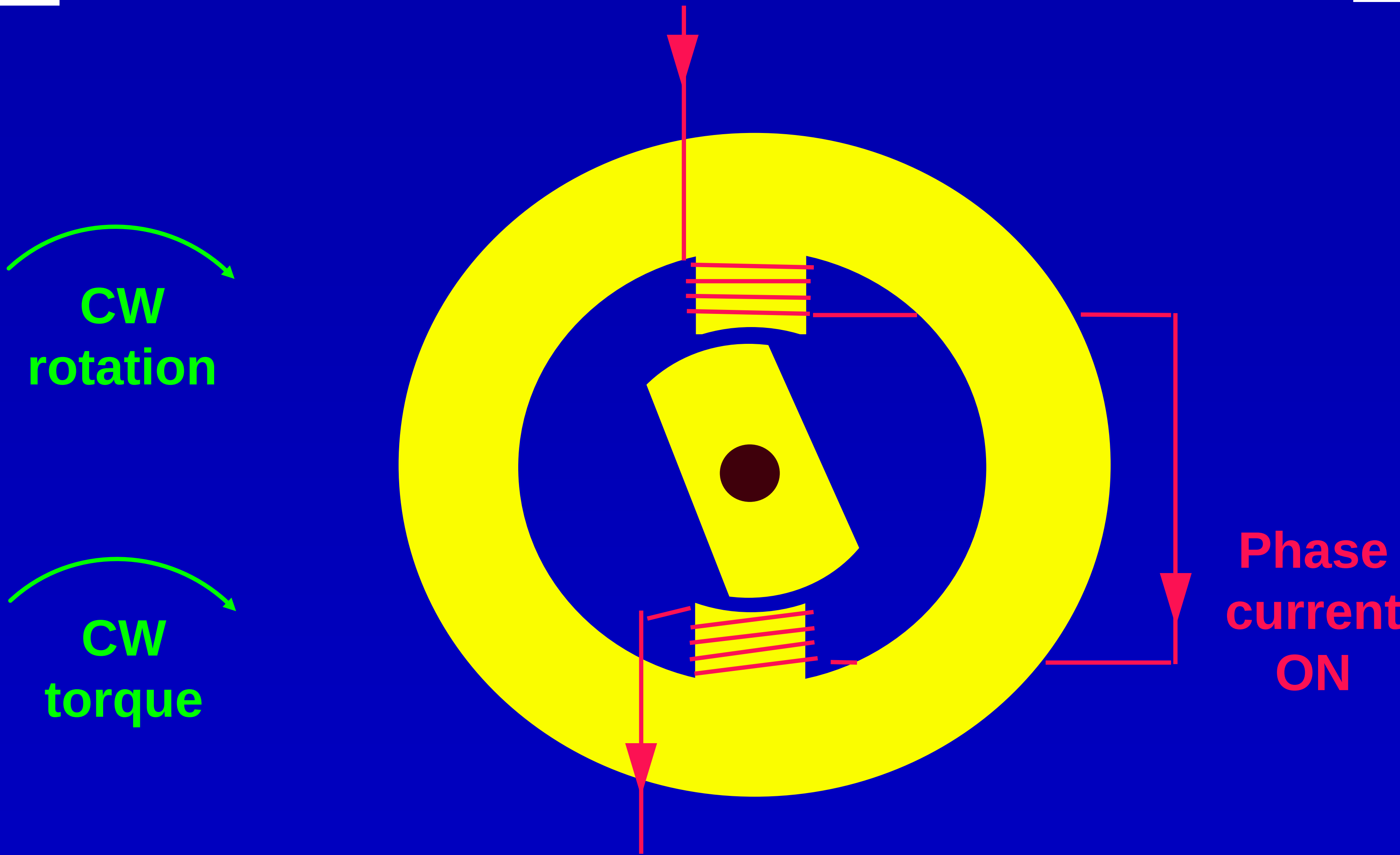
Phase current ON

CW rotation

CW torque

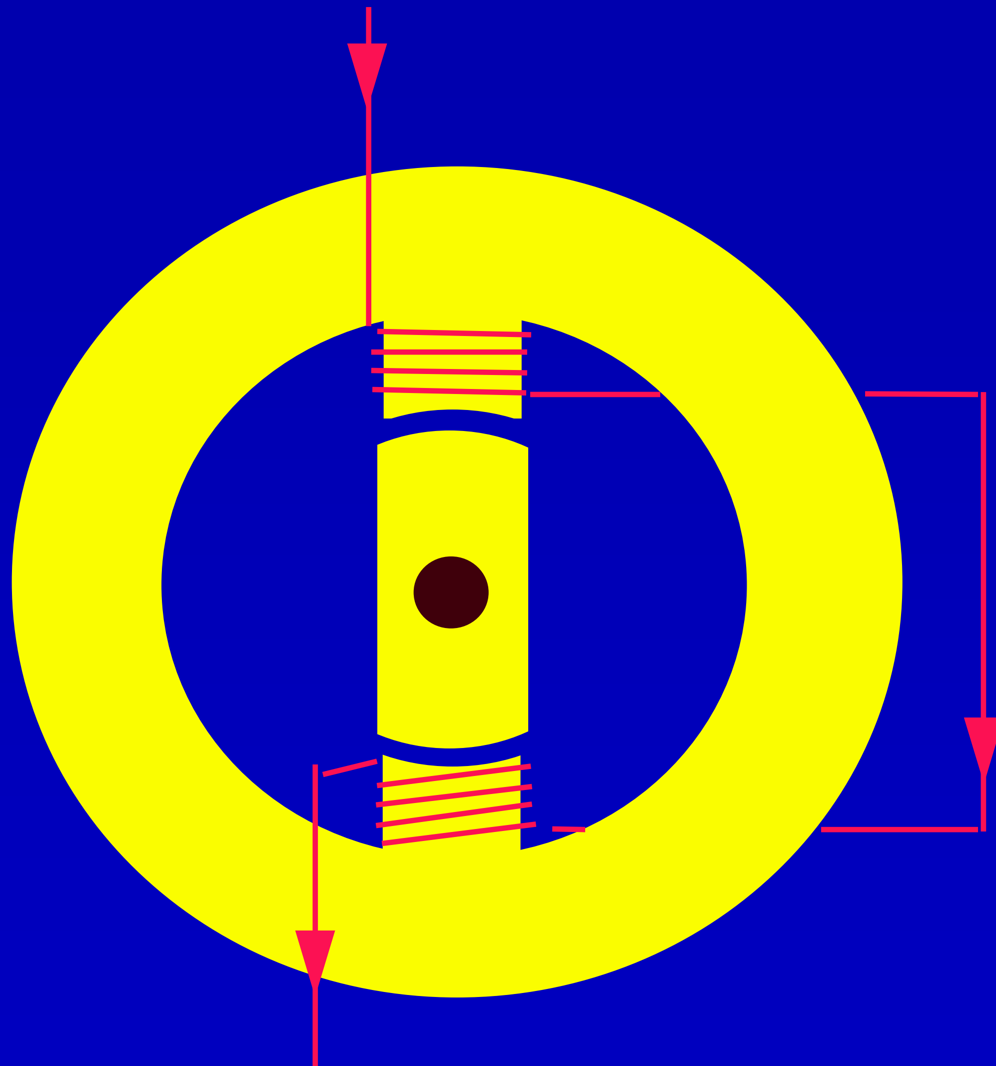


Phase current ON


CW
rotation
CW
torque
Phase
current
ON

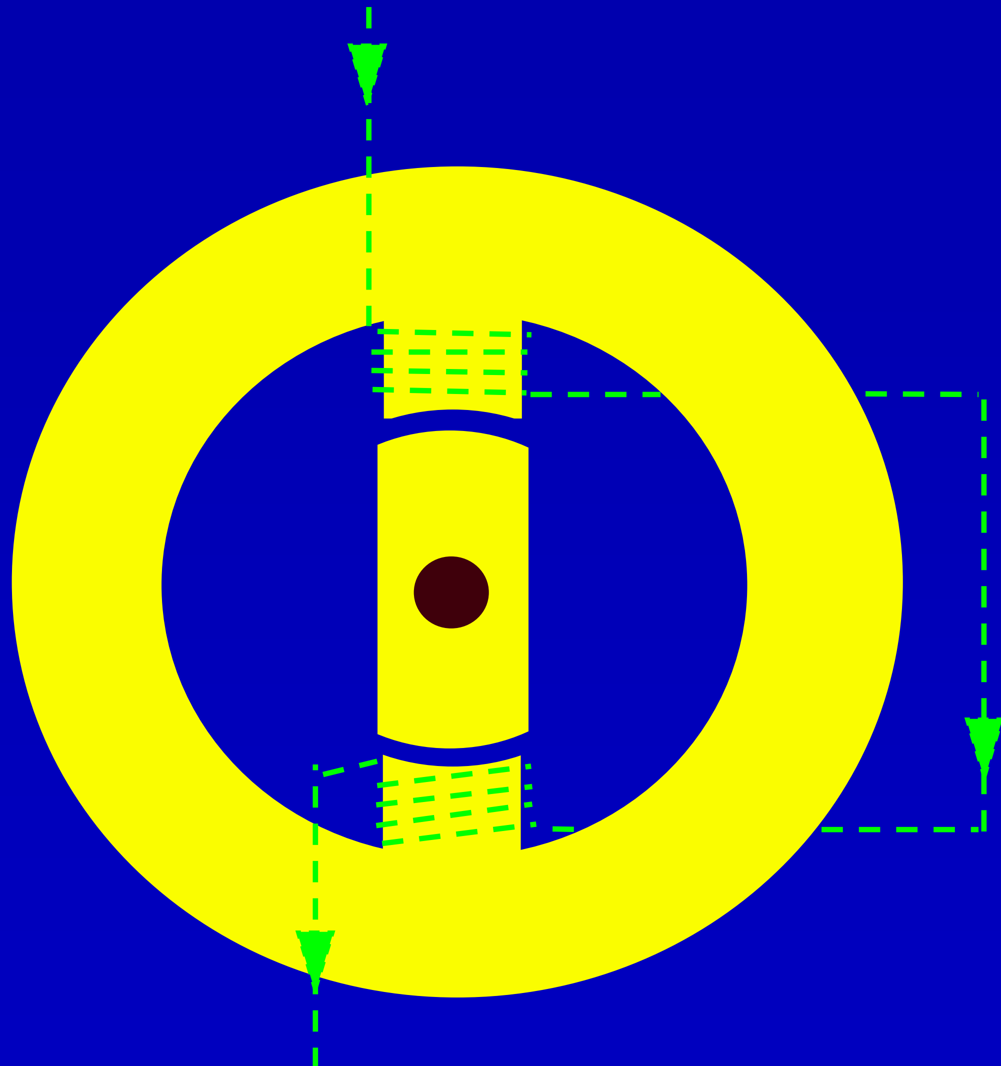
CW rotation

No torque



Phase current ON

CW rotation

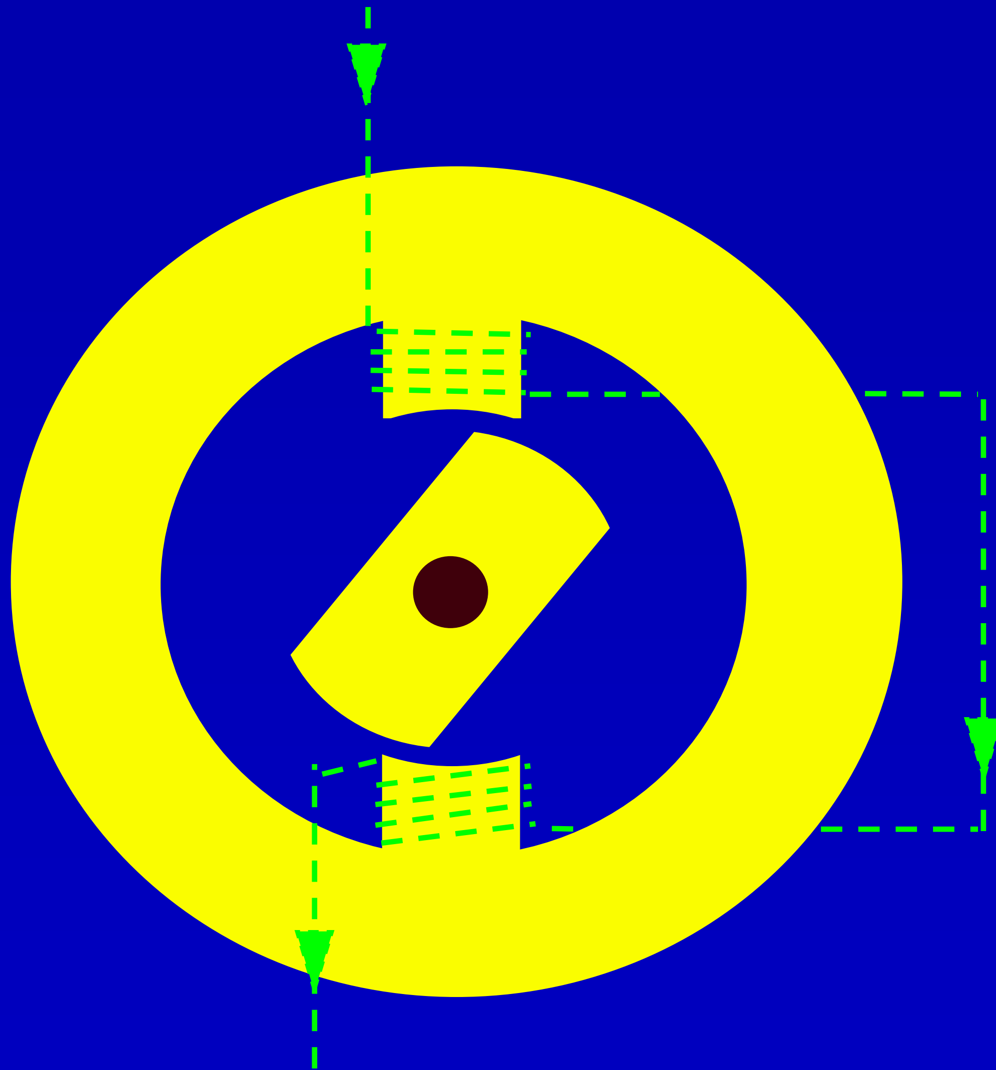


No torque

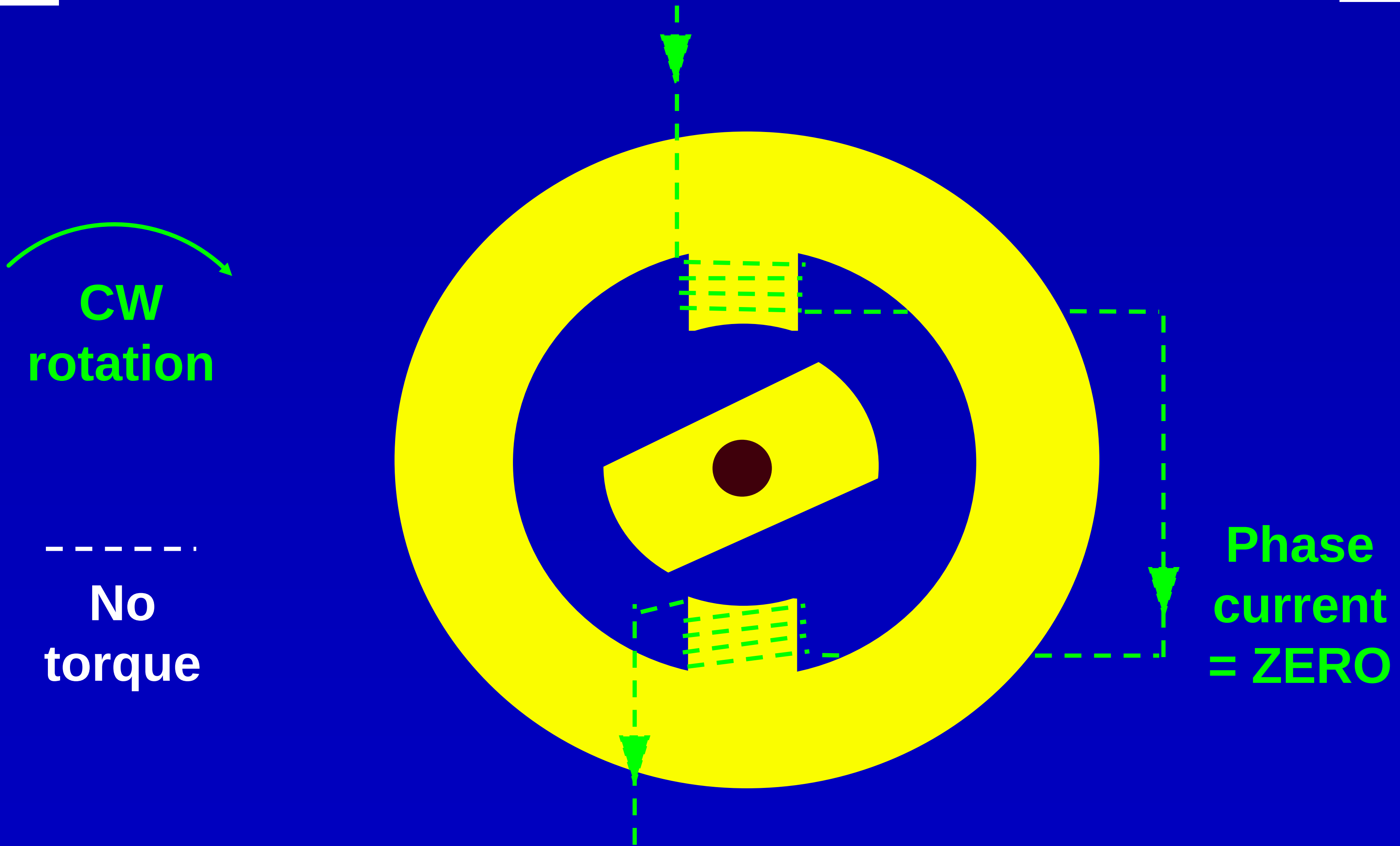
Phase current = ZERO

CW rotation

No torque



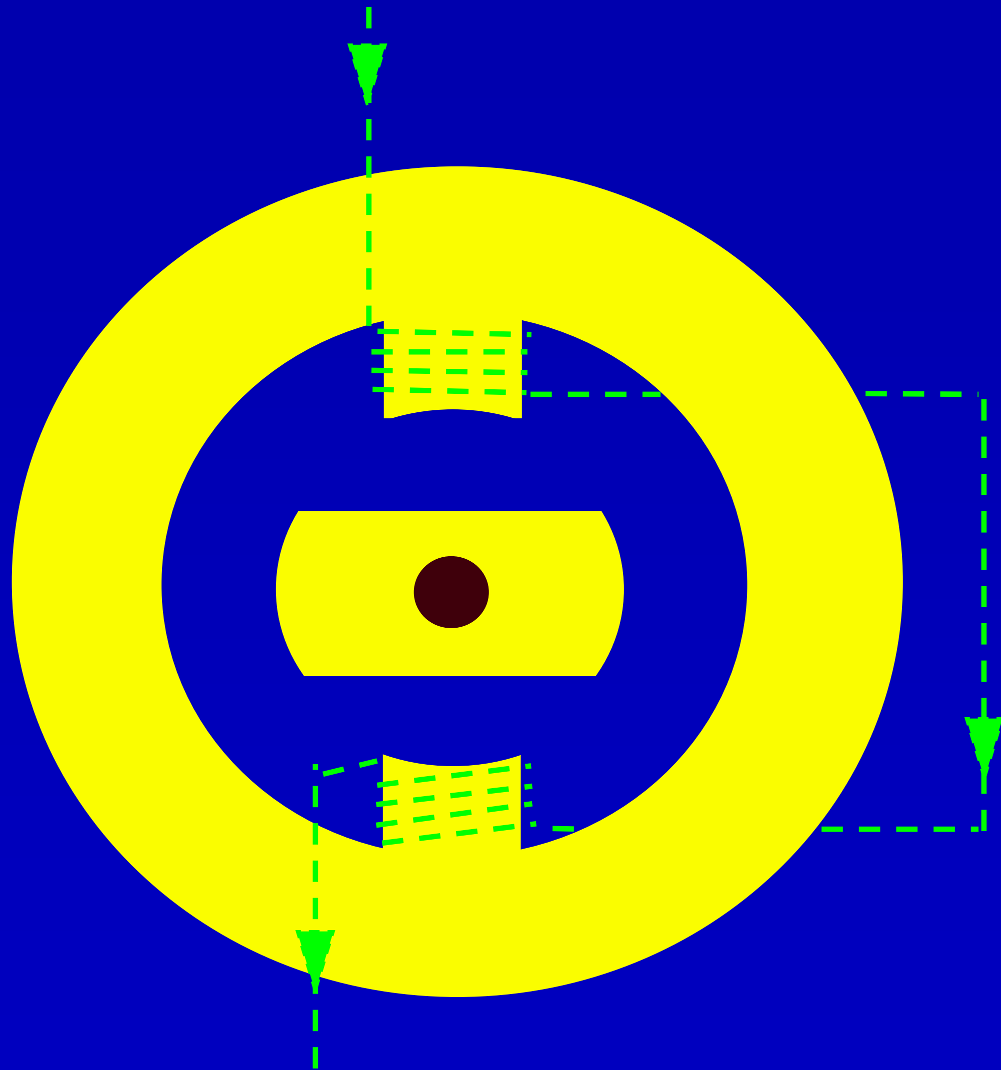
Phase current = ZERO



CW
rotation
No
torque
Phase
current
= ZERO

CW rotation

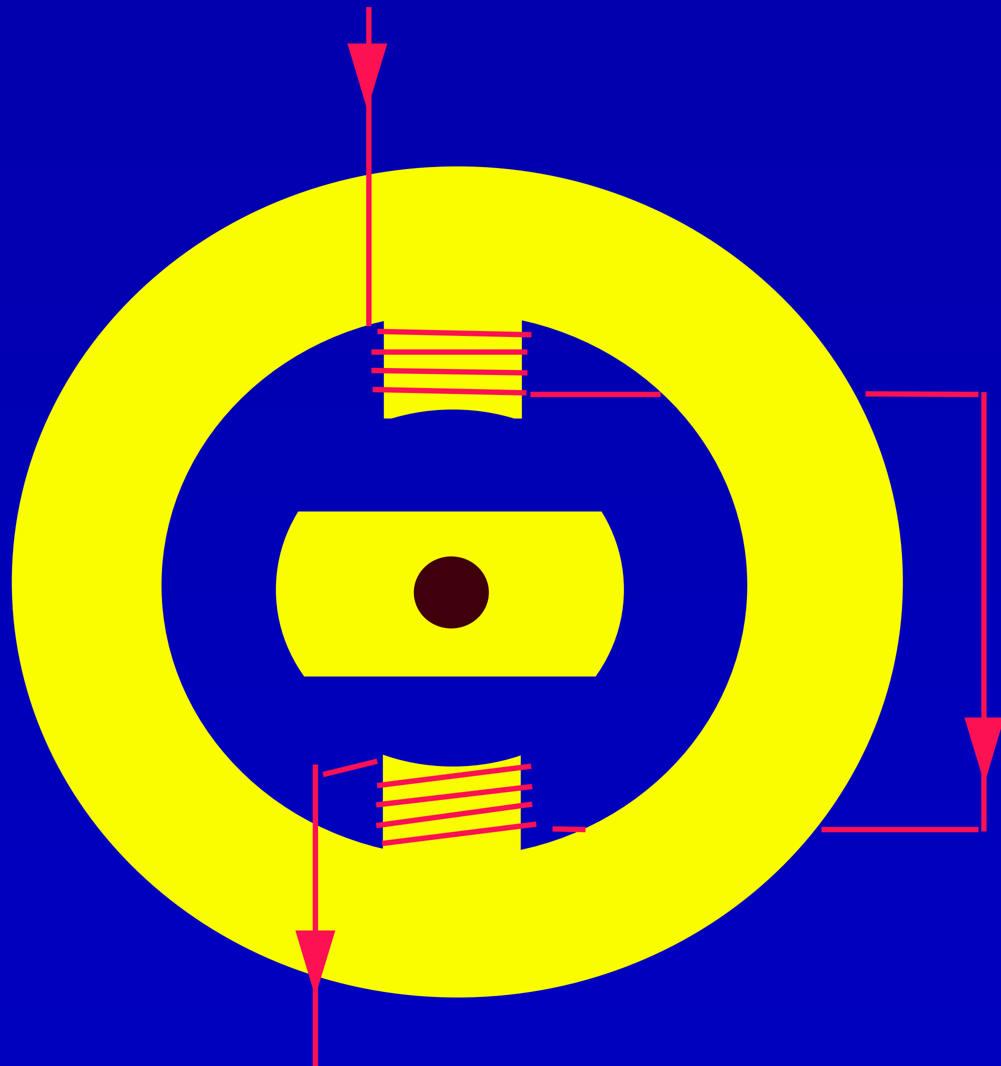
No torque



Phase current = ZERO

CW rotation

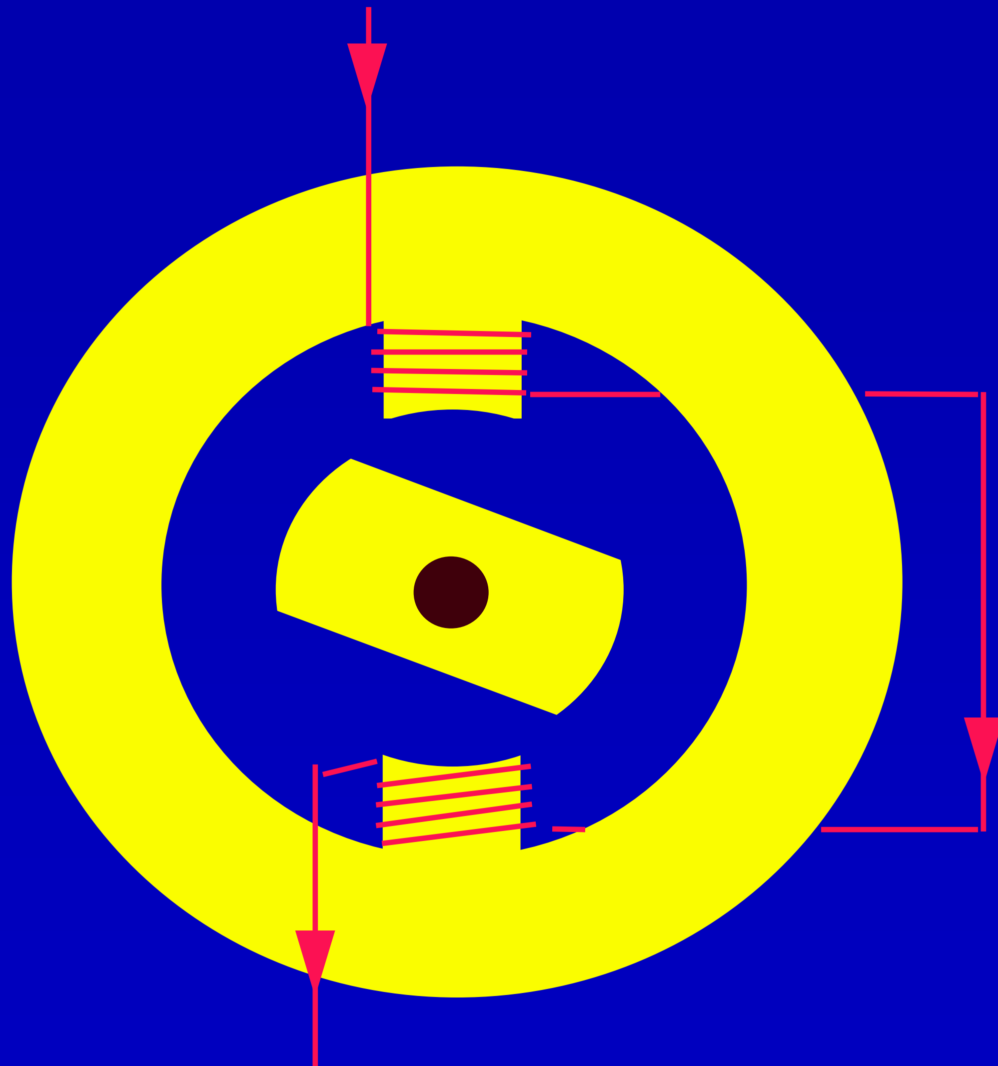
No torque



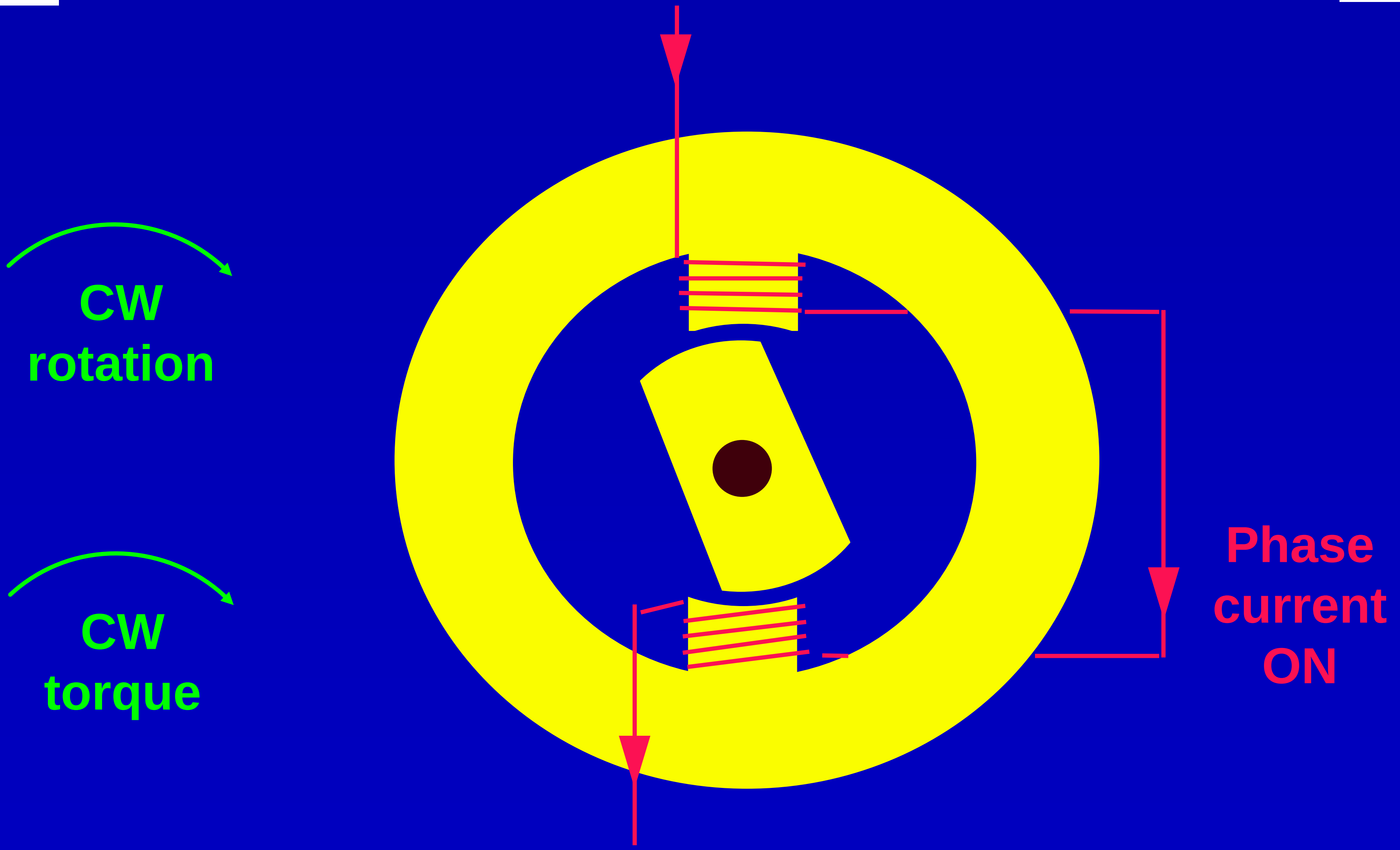
Phase current ON

CW
rotation

CW
torque

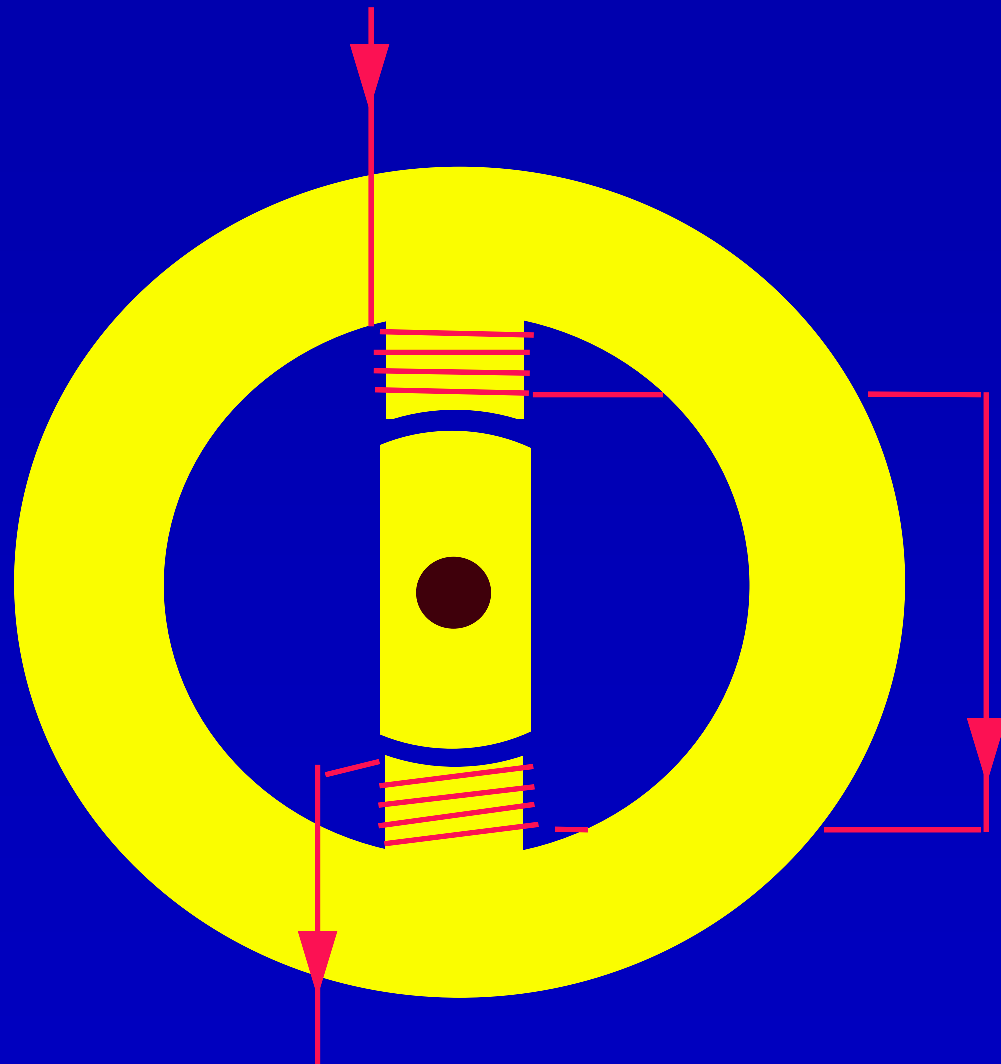


Phase
current
ON

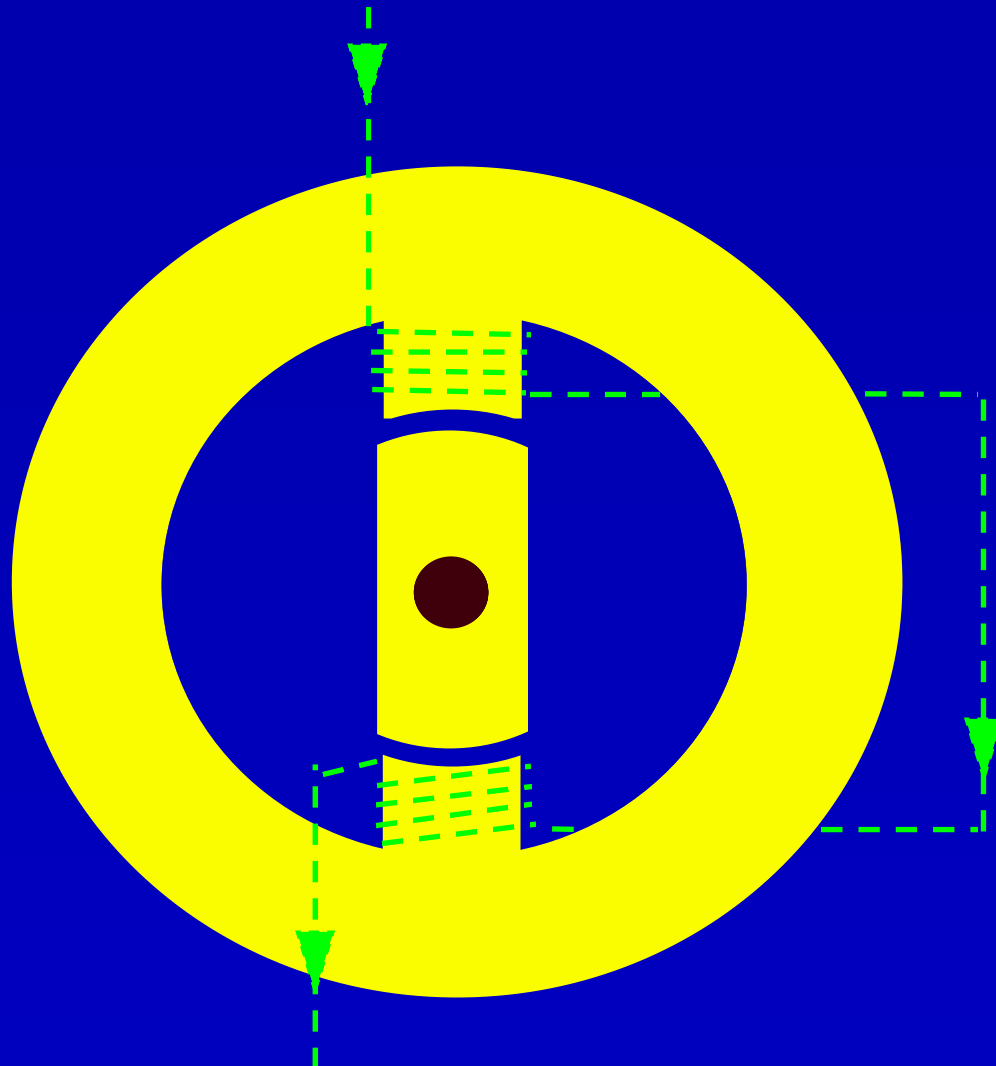

CW
rotation
CW
torque
Phase
current
ON

CW rotation

No torque



Phase current ON

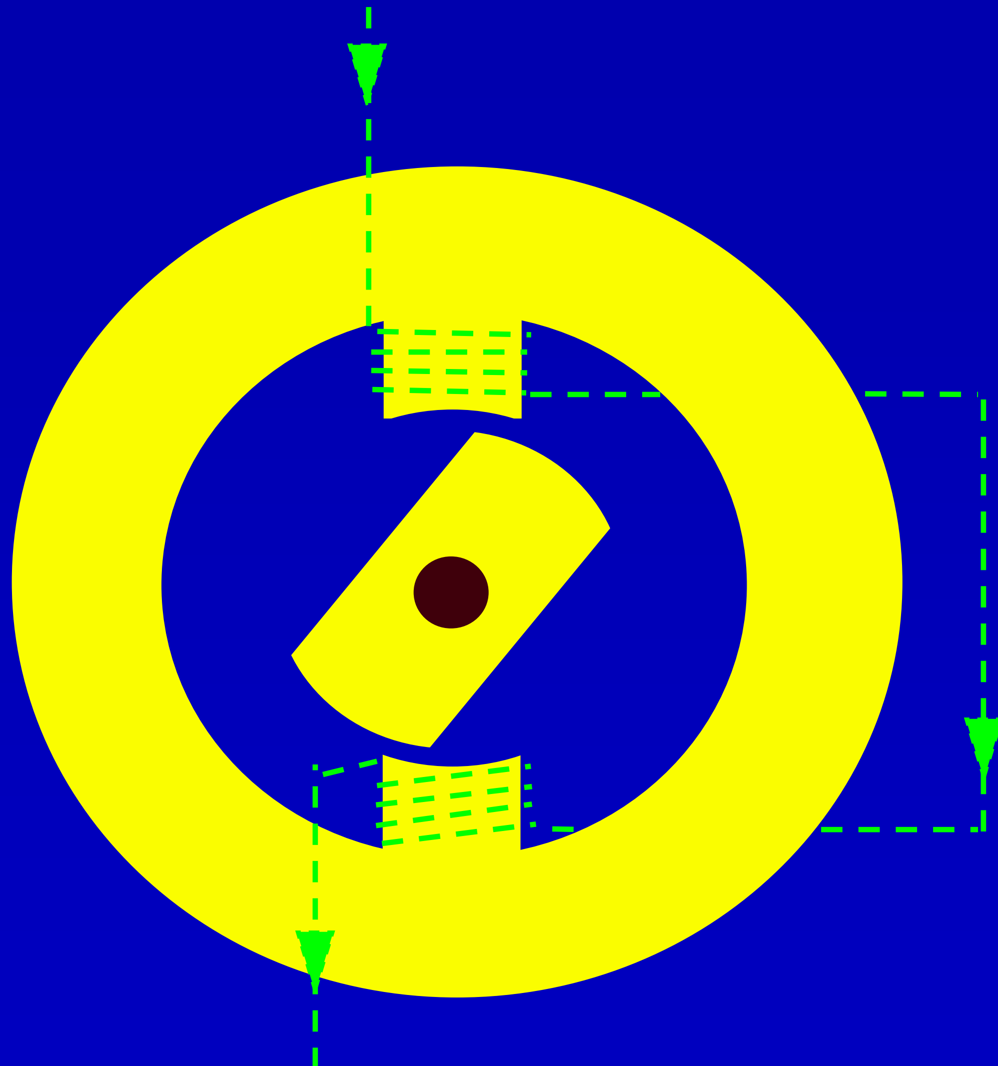


CW rotation

No torque

Phase current = ZERO

CW rotation

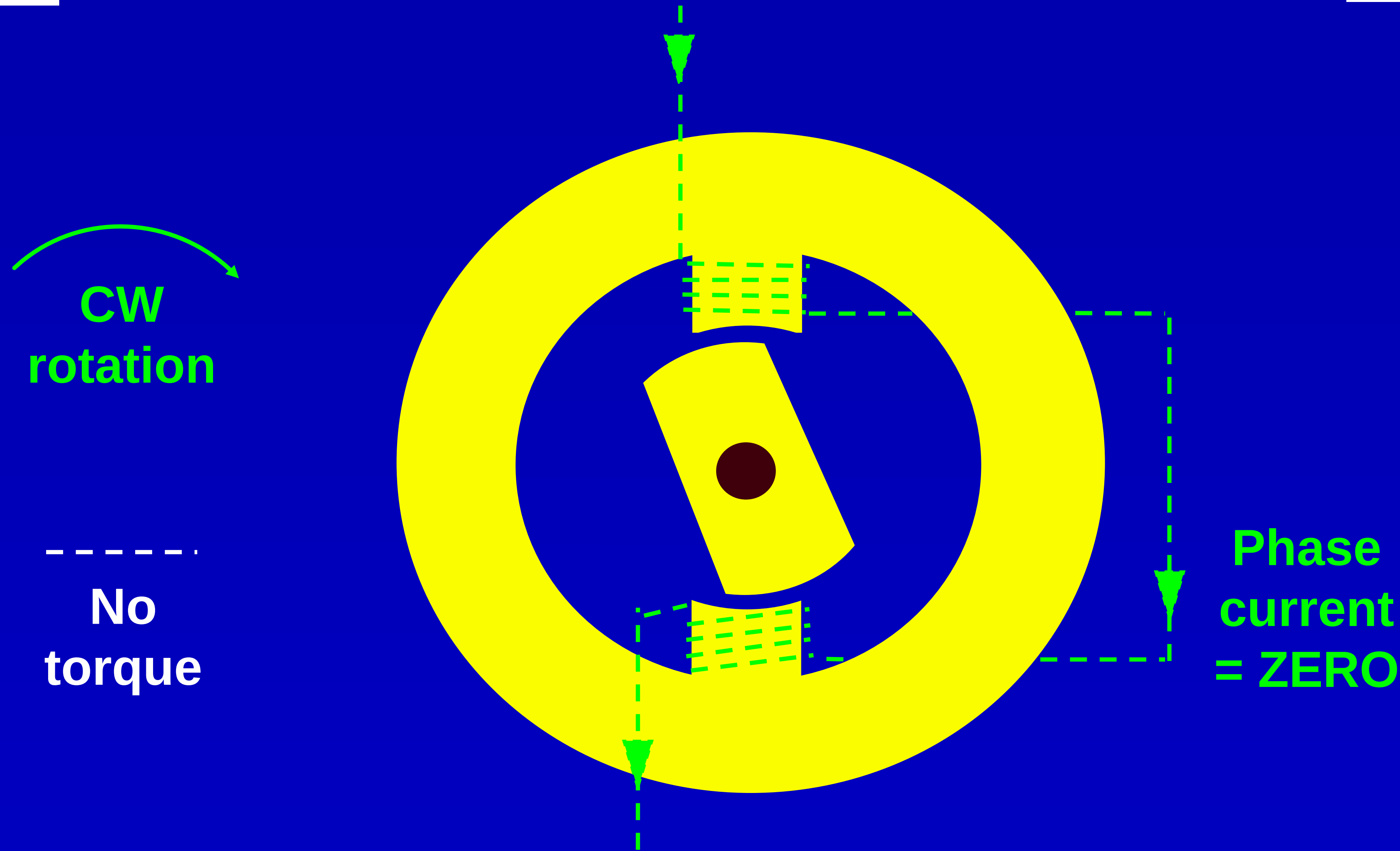


No torque

Phase current = ZERO

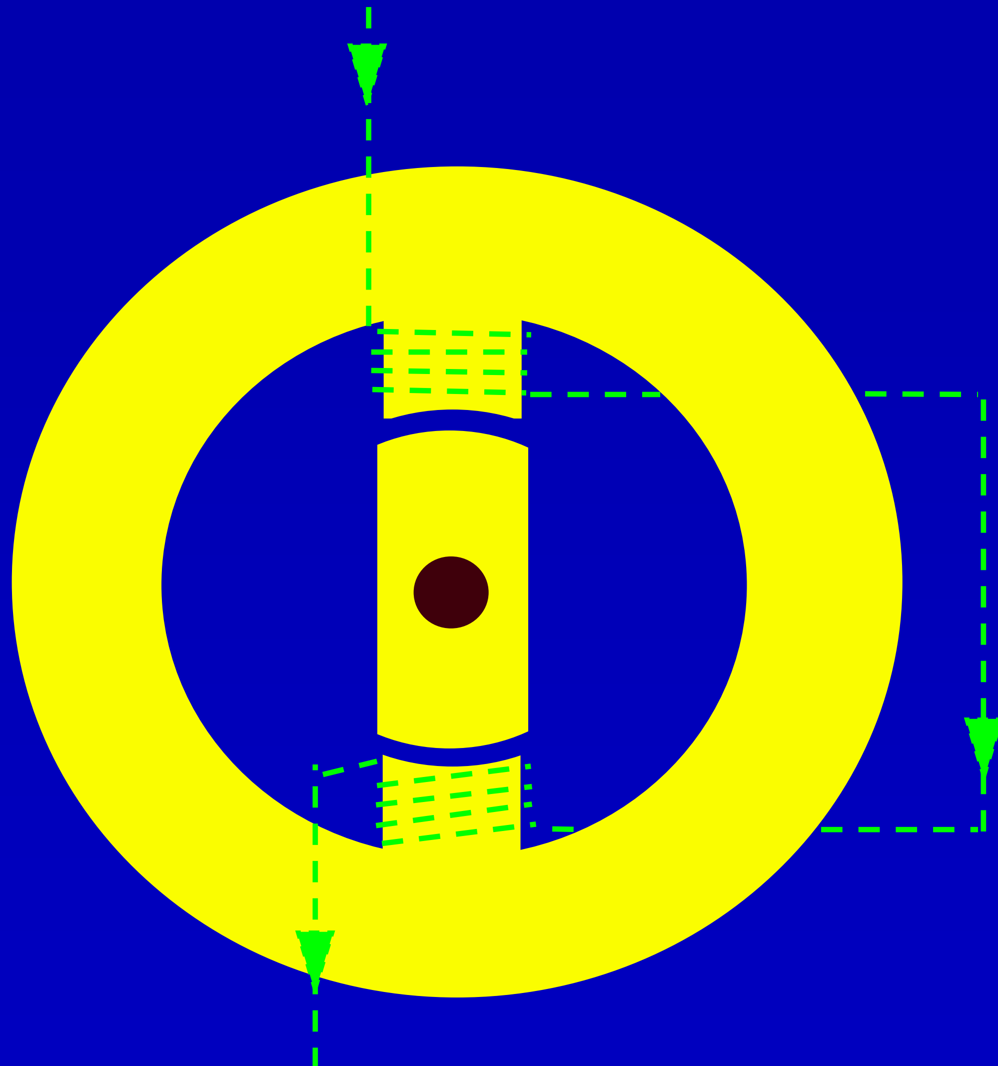
Operation as a brake or electrical generator

- Exact dual of motoring operation
- Braking torque is produced when rotor & stator poles are being “pulled apart” – i.e. when inductance is falling
- Switch phase current (and magnetic flux) ON at TDC *(ideally)*
- Switch phase current (and magnetic flux) OFF at BDC *(ideally)*



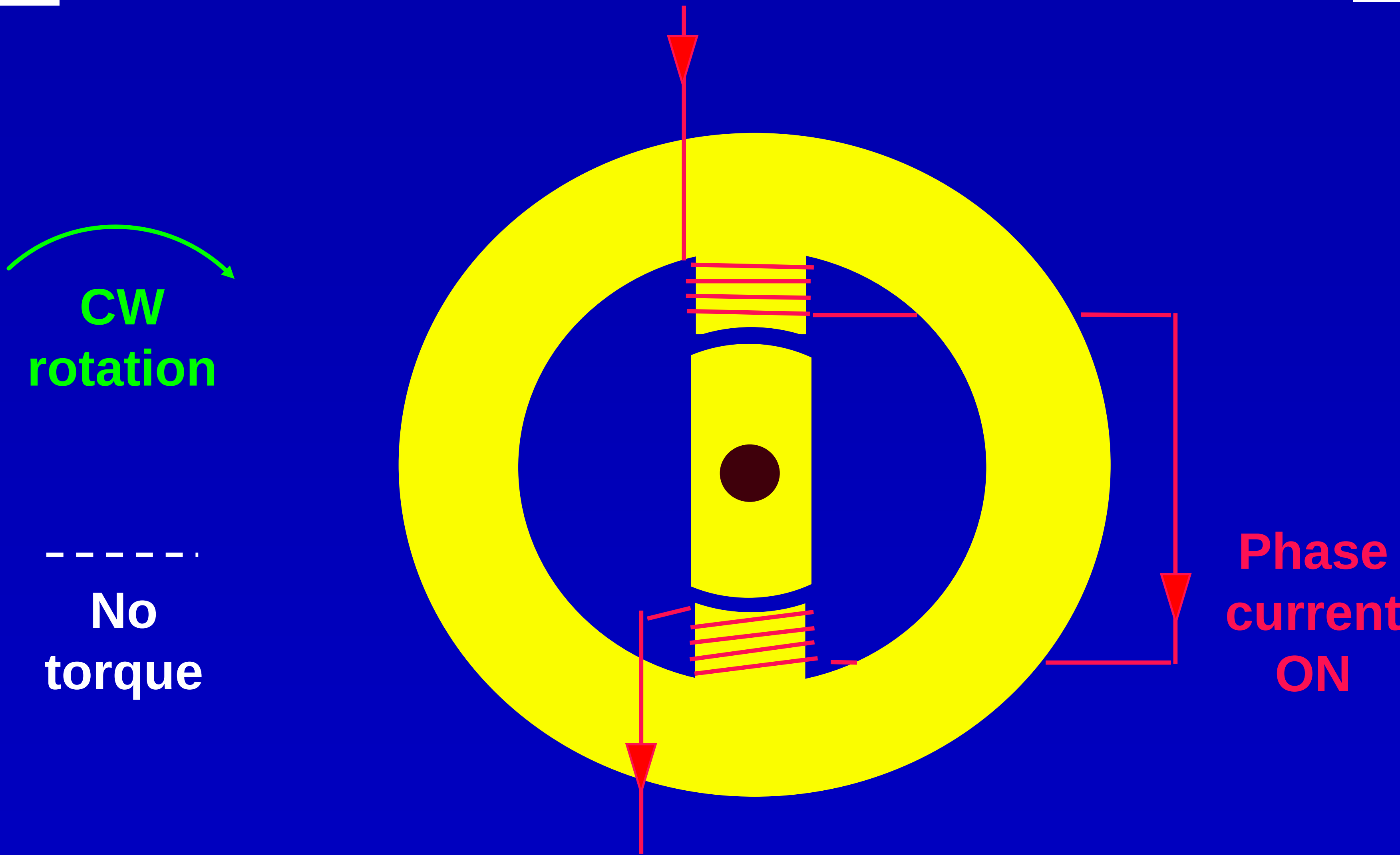
CW
rotation
No
torque
Phase
current
= ZERO

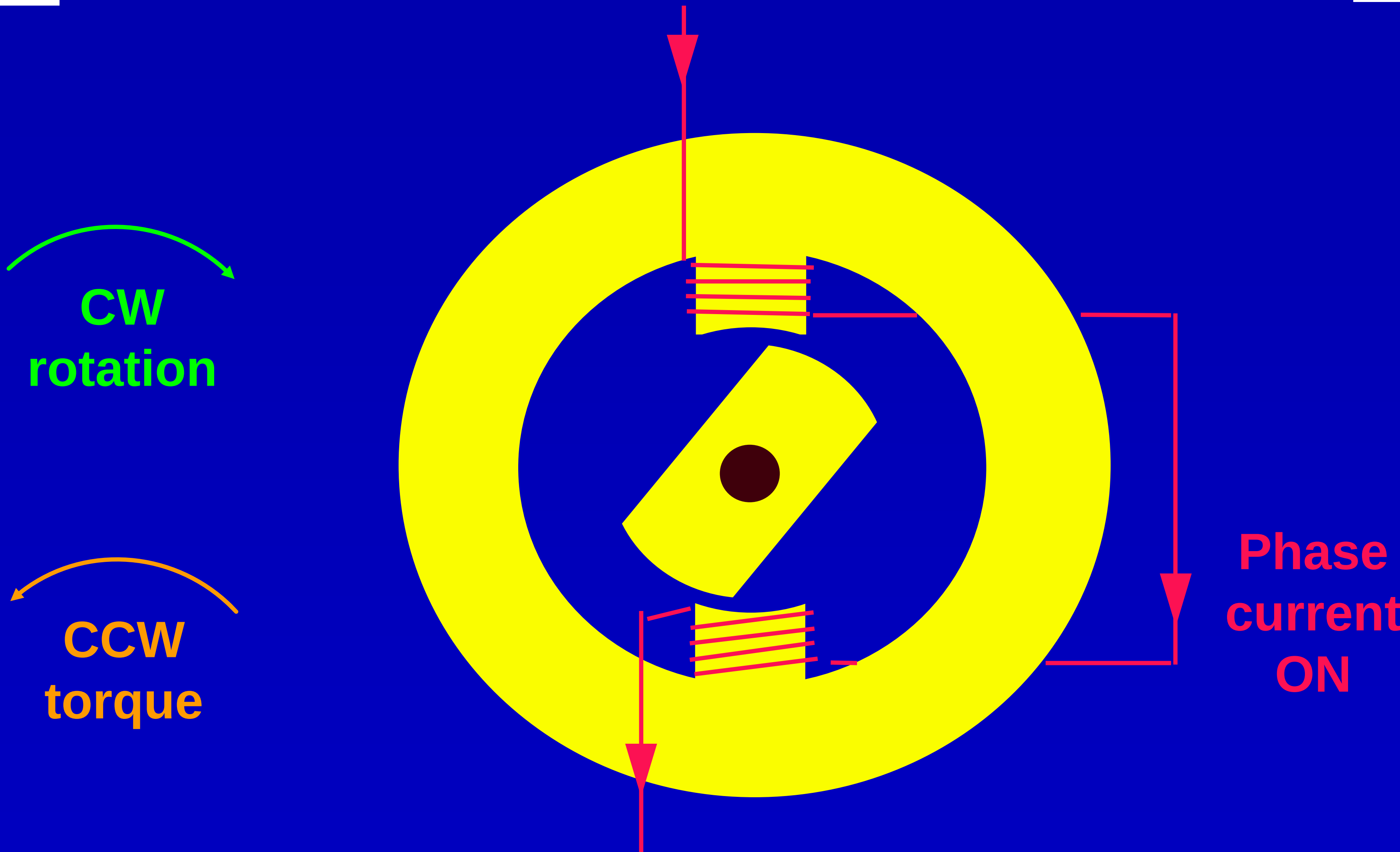
CW rotation



No torque

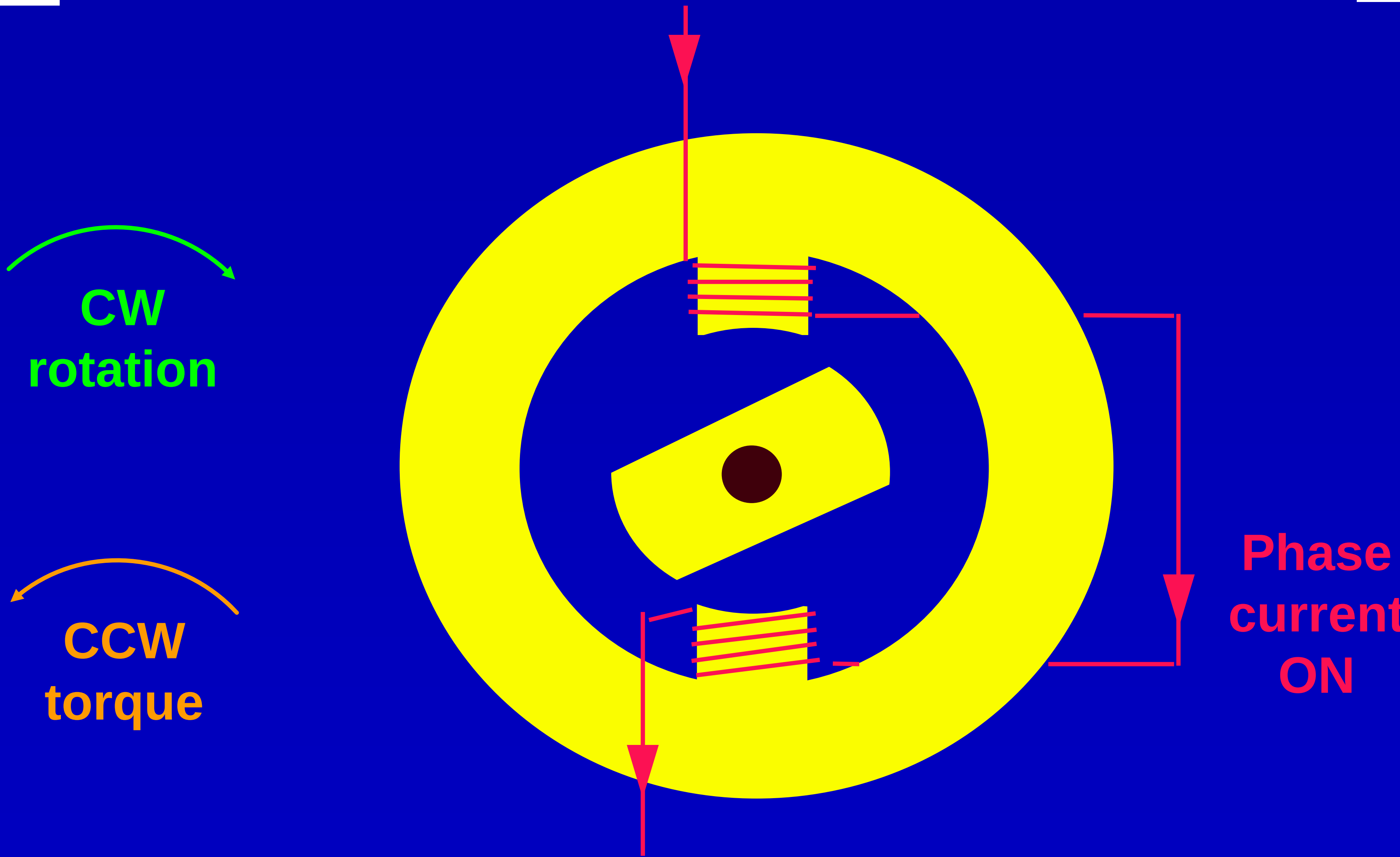
Phase current = ZERO

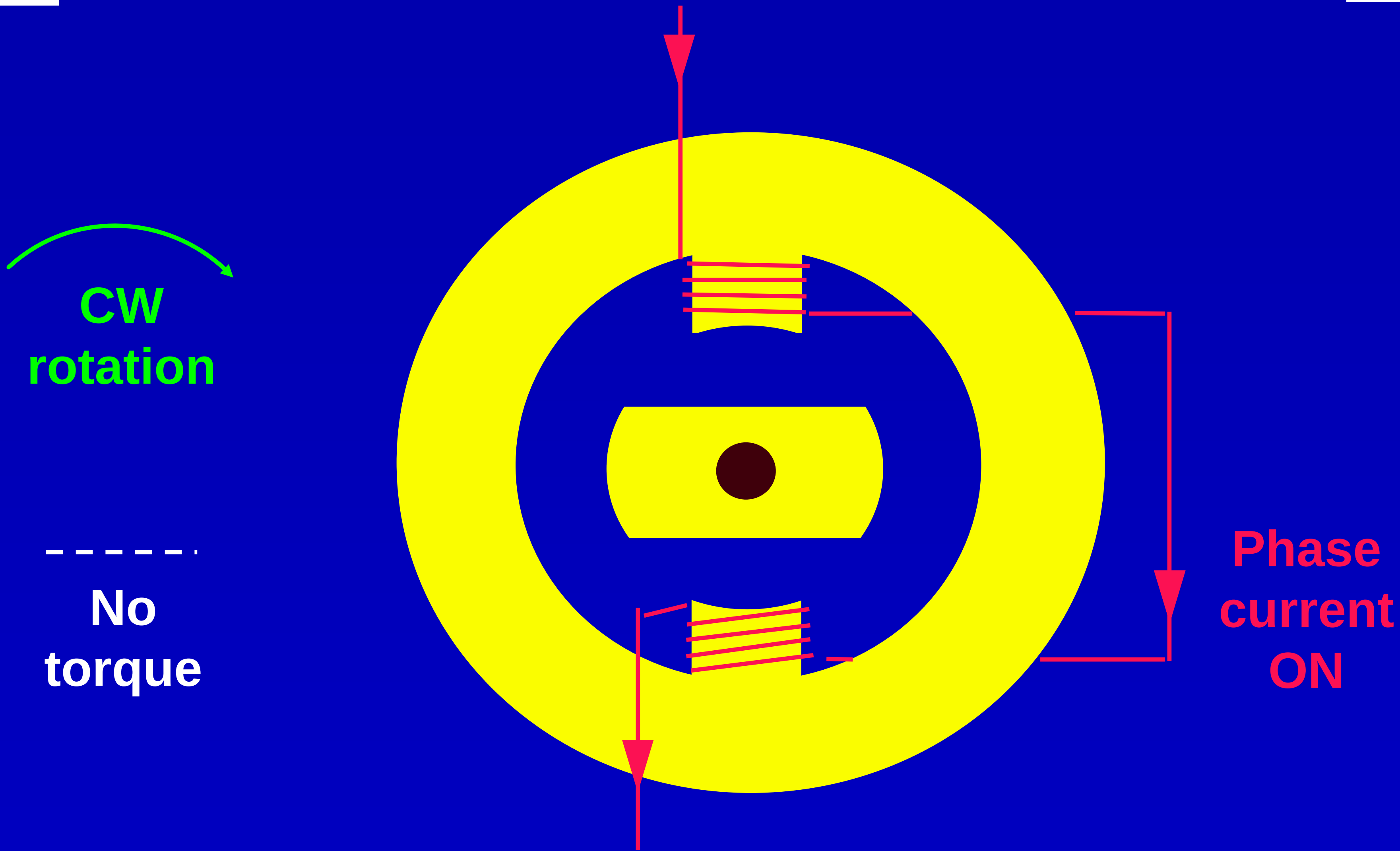

CW
rotation
No
torque
Phase
current
ON


CW
rotation
CCW
torque
Phase
current
ON

SR DRIVES

EMERSON Motor Technologies

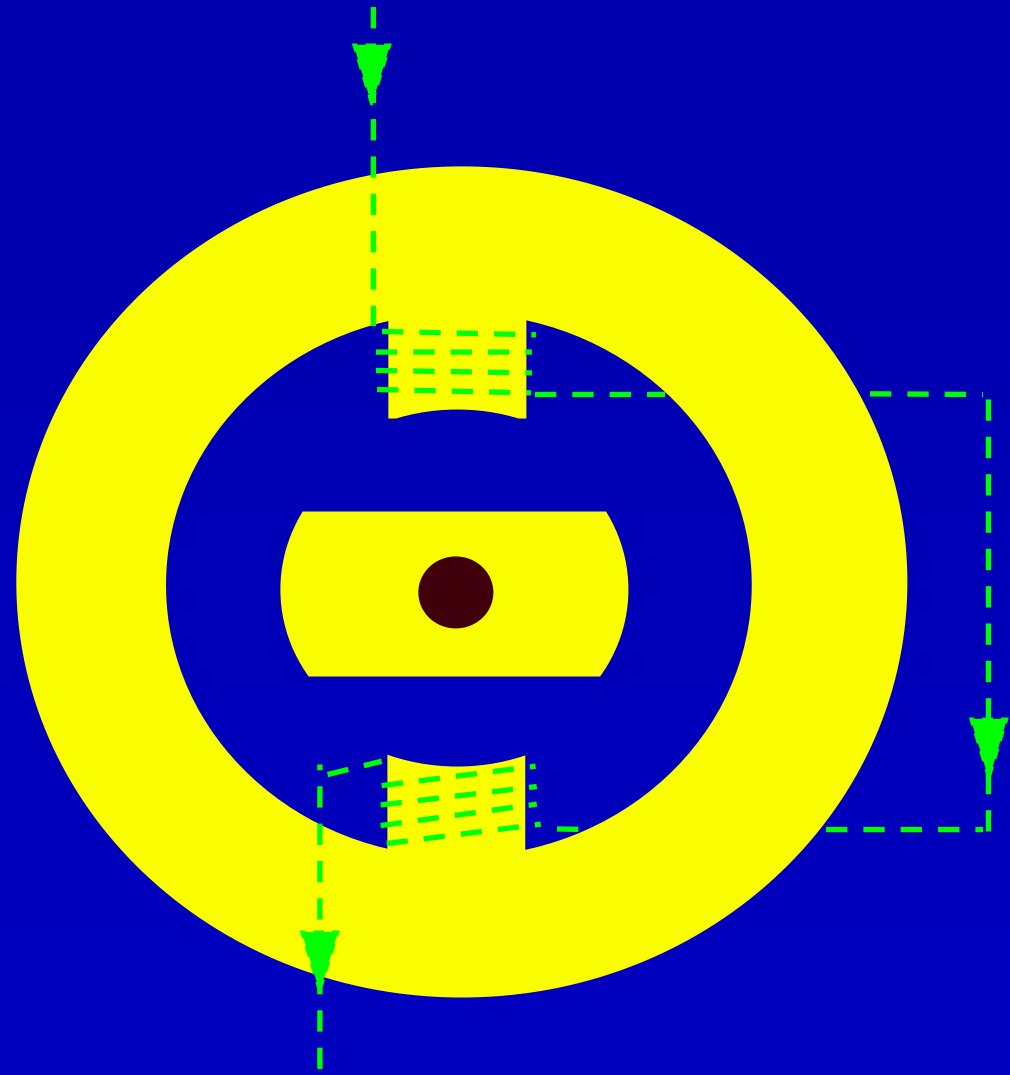




CW
rotation
No
torque
Phase
current
ON

CW rotation

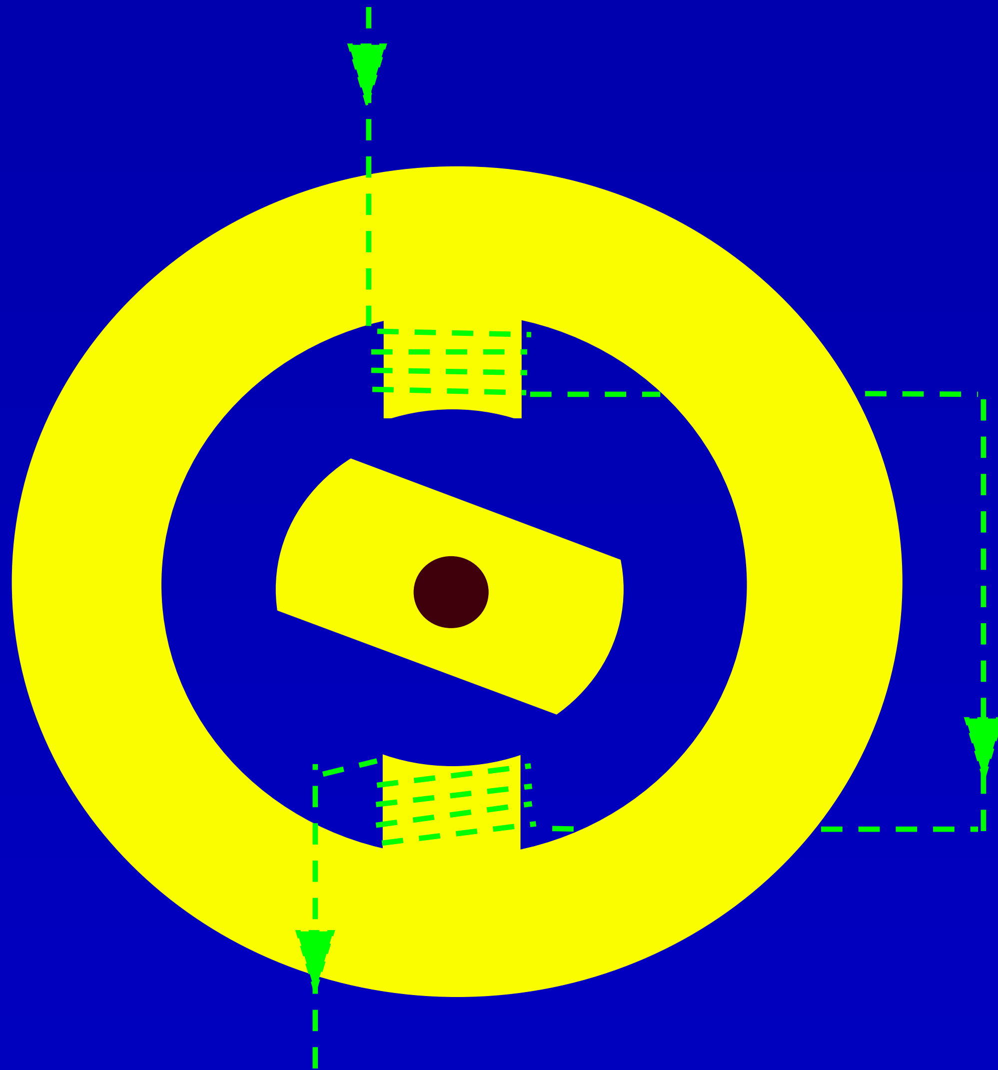
No torque



Phase current = ZERO

CW rotation

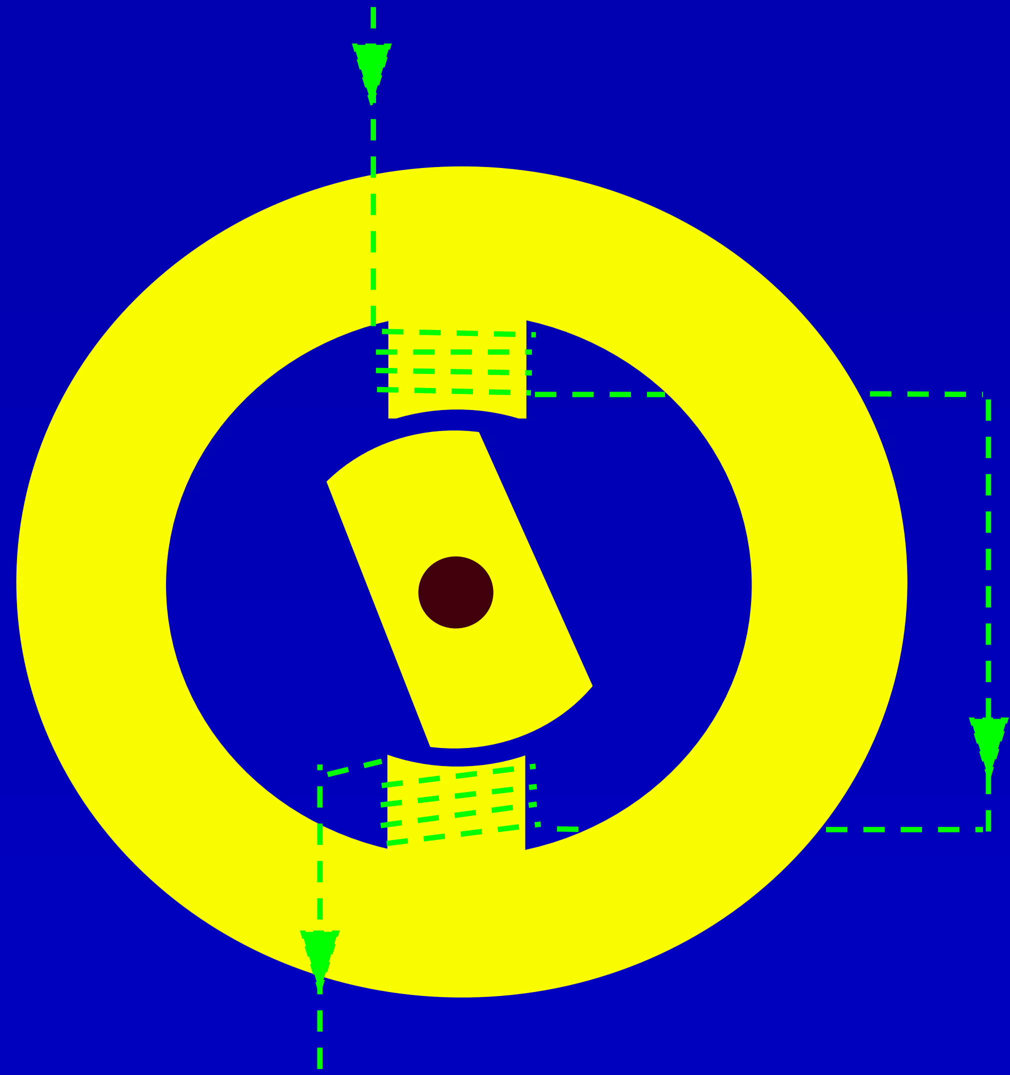
No torque



Phase current = ZERO

CW rotation

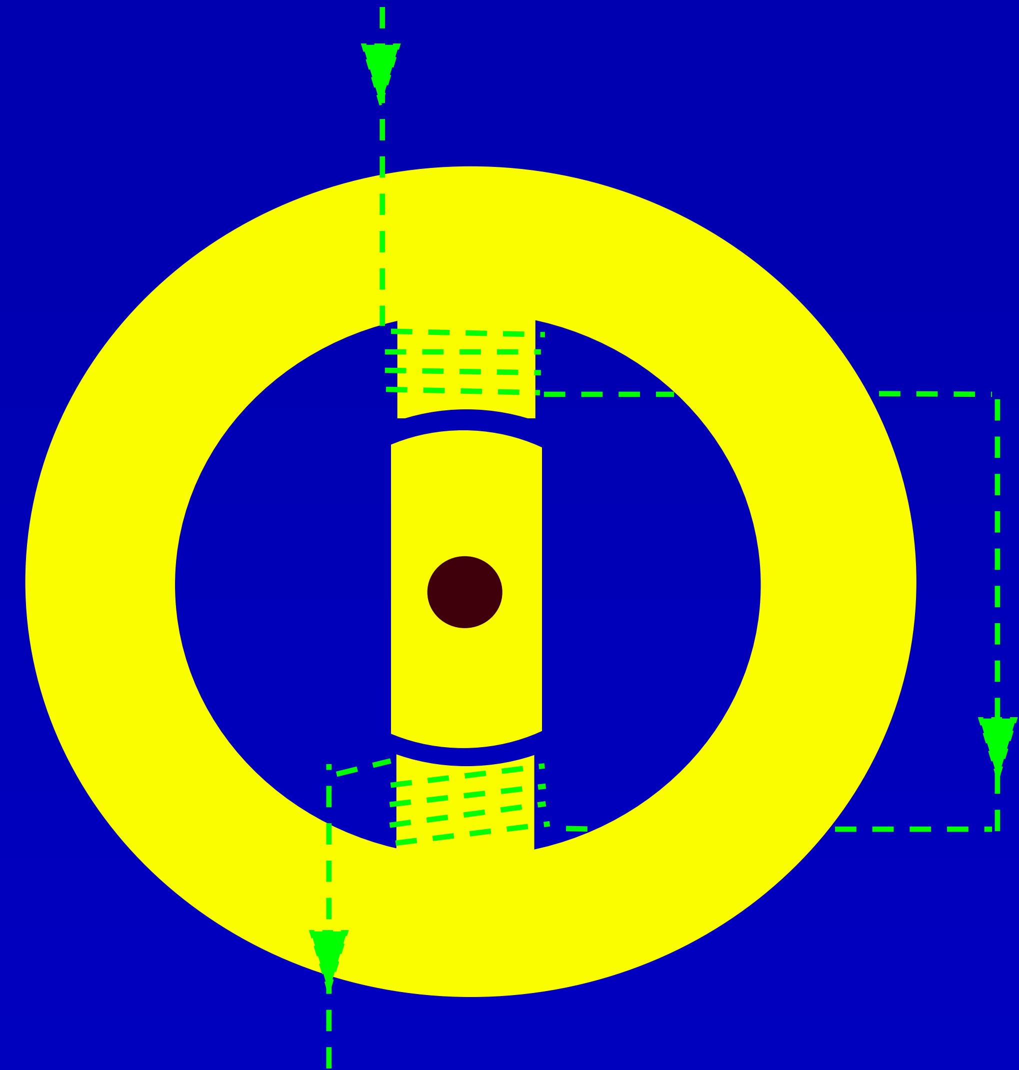
No torque



Phase current = ZERO

CW
rotation

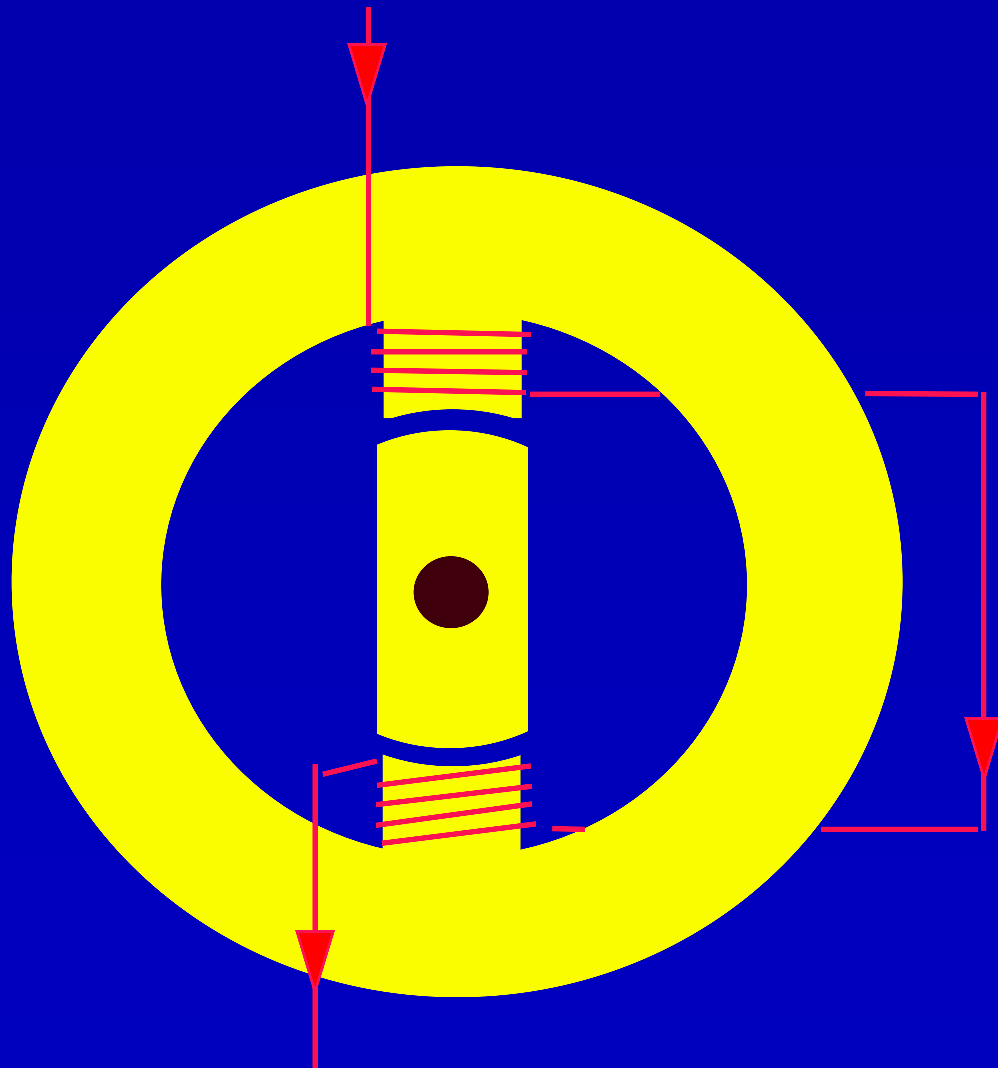
No
torque



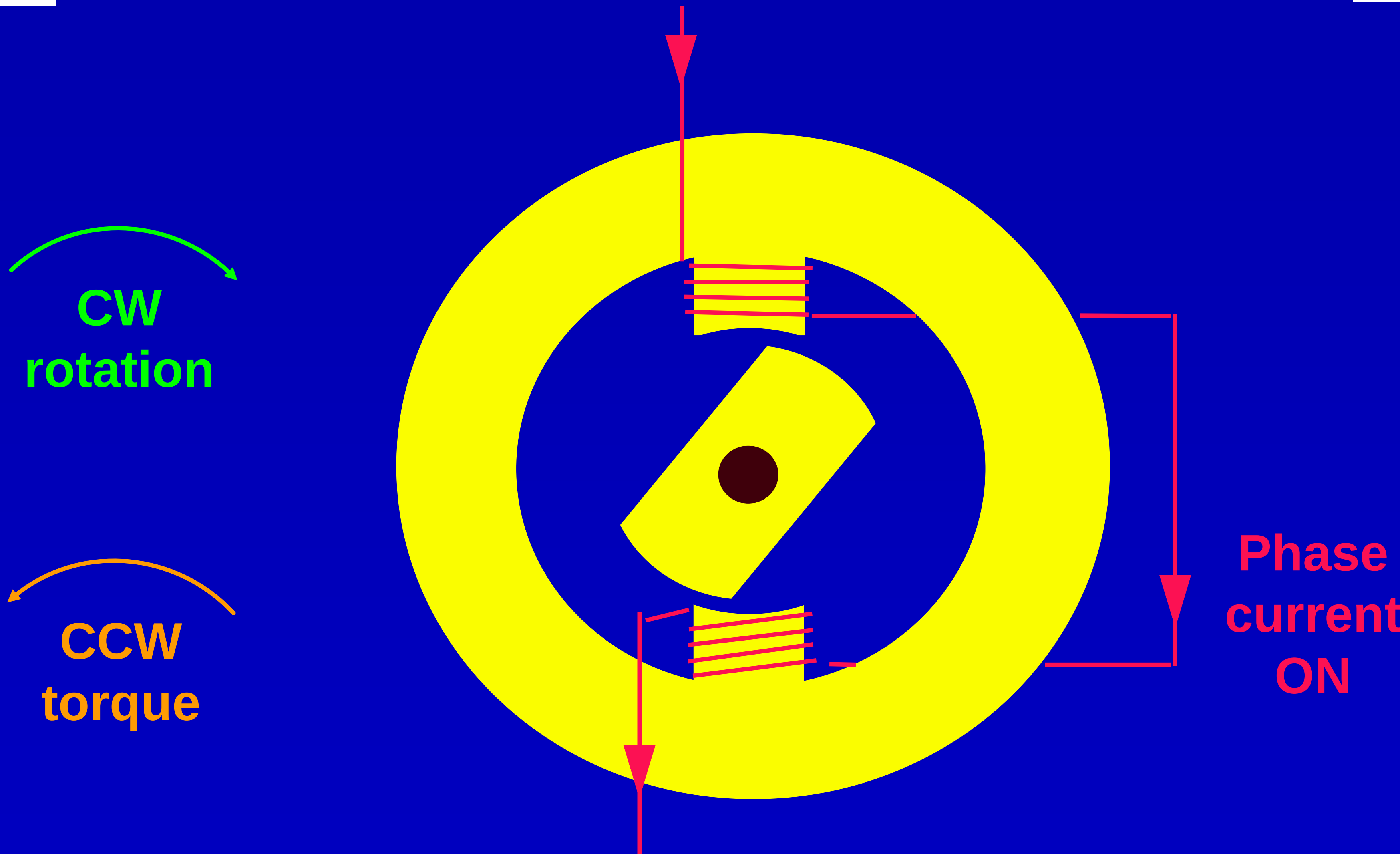
Phase
current
= ZERO

CW rotation

No torque

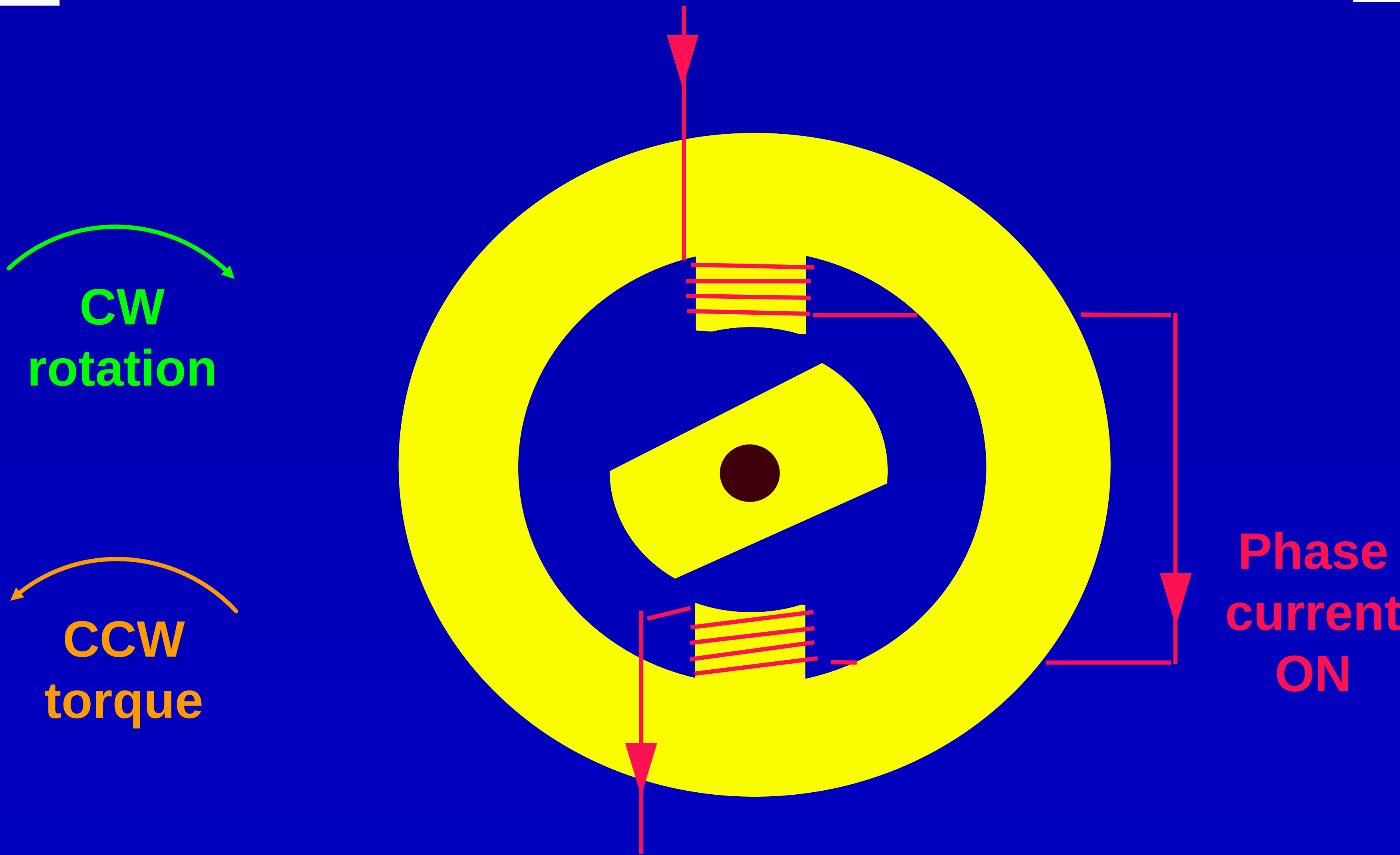


Phase current ON


CW
rotation
CCW
torque
Phase
current
ON

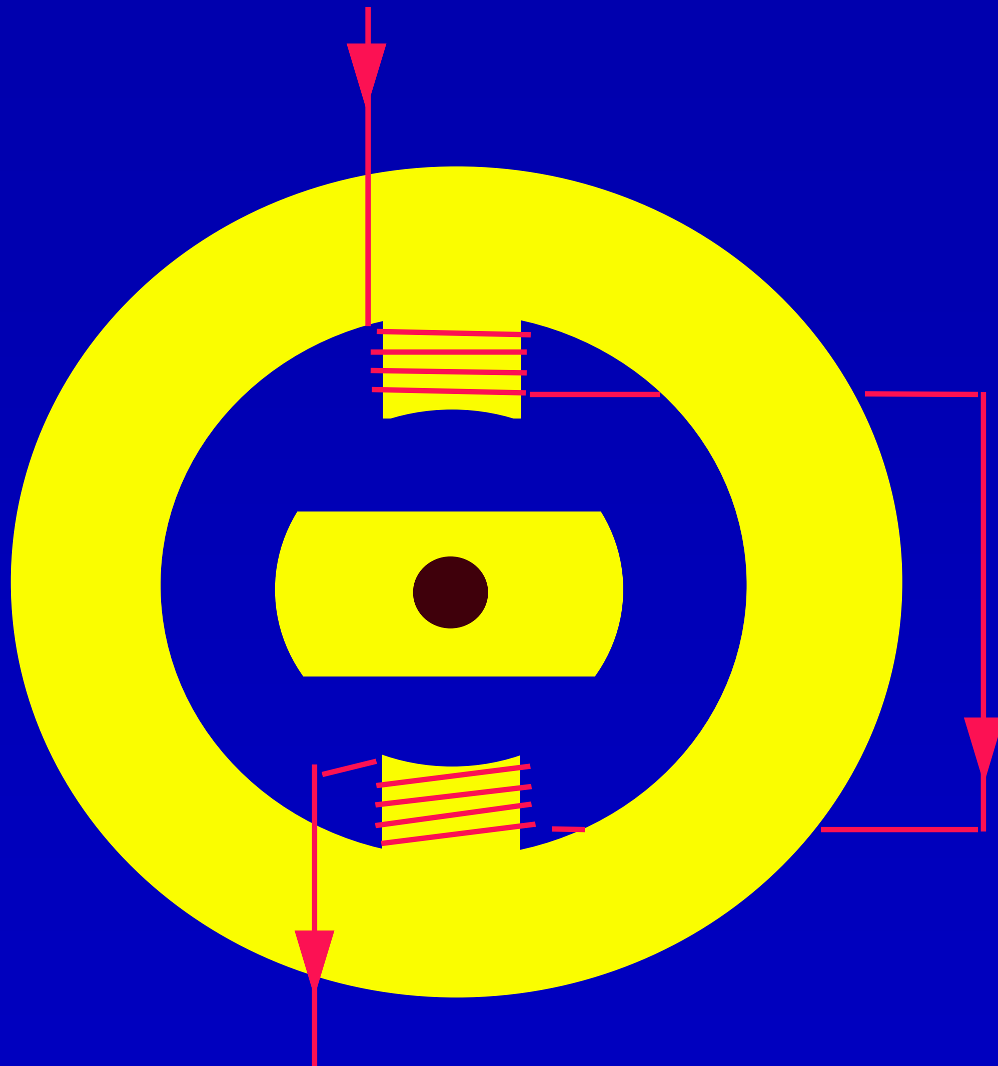
SR DRIVES

EMERSON
Motor Technologies

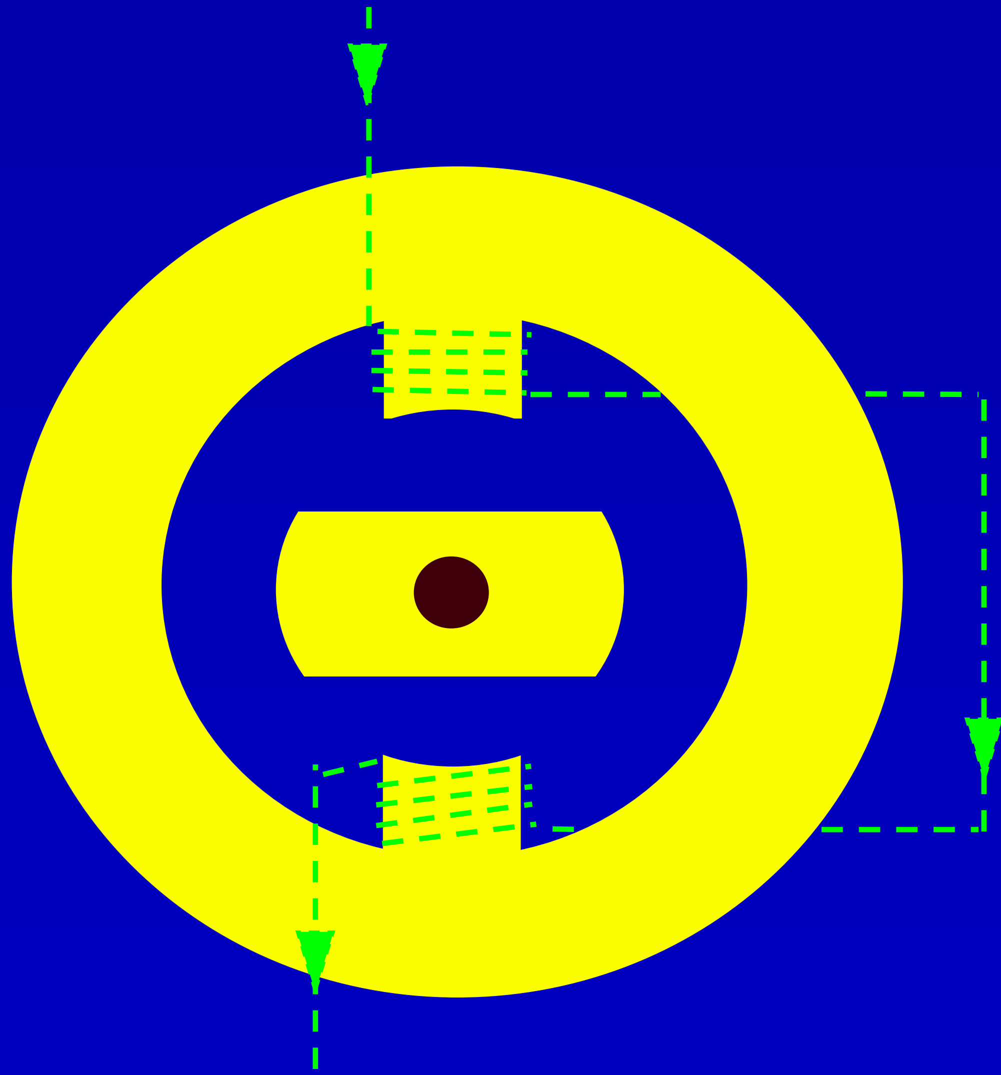


CW rotation

No torque



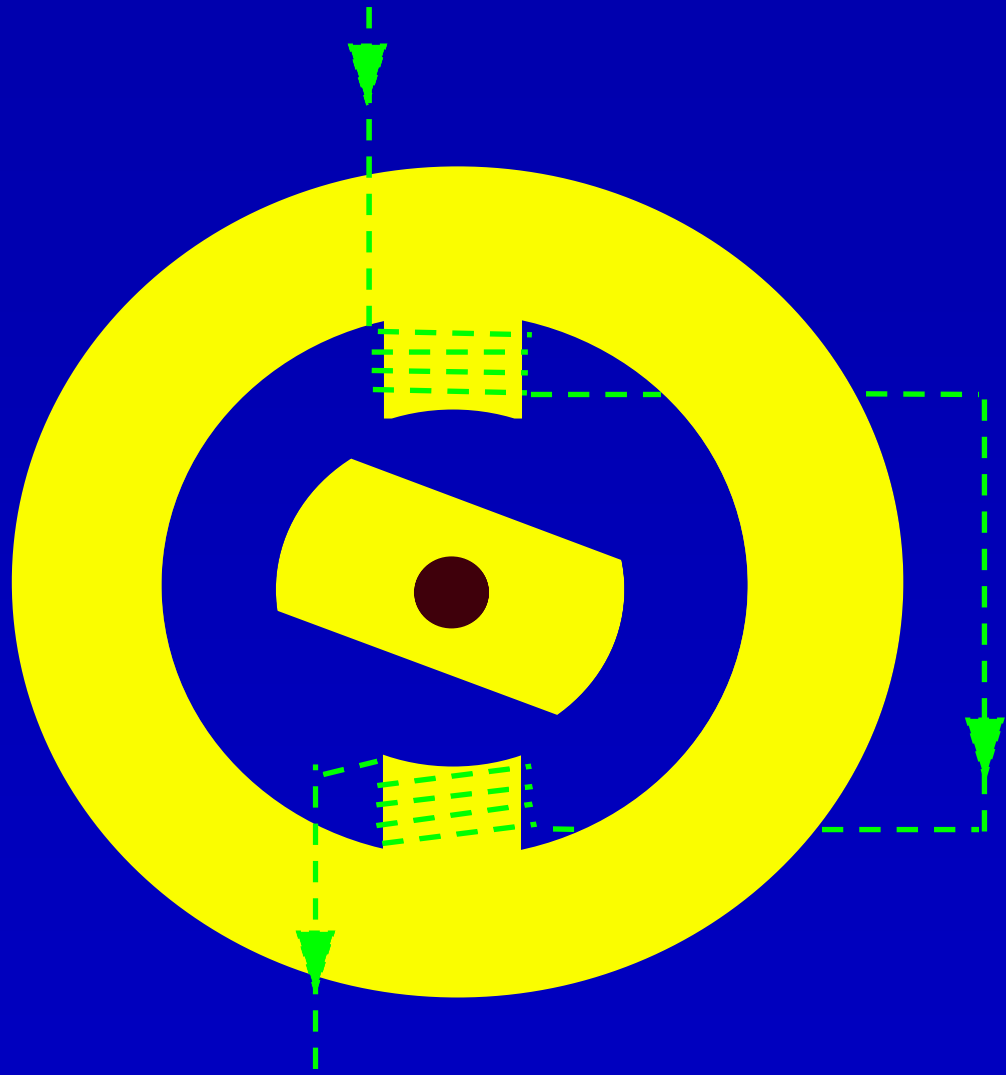
Phase current ON



CW rotation

No torque

Phase current = ZERO



CW rotation

No torque

Phase current = ZERO

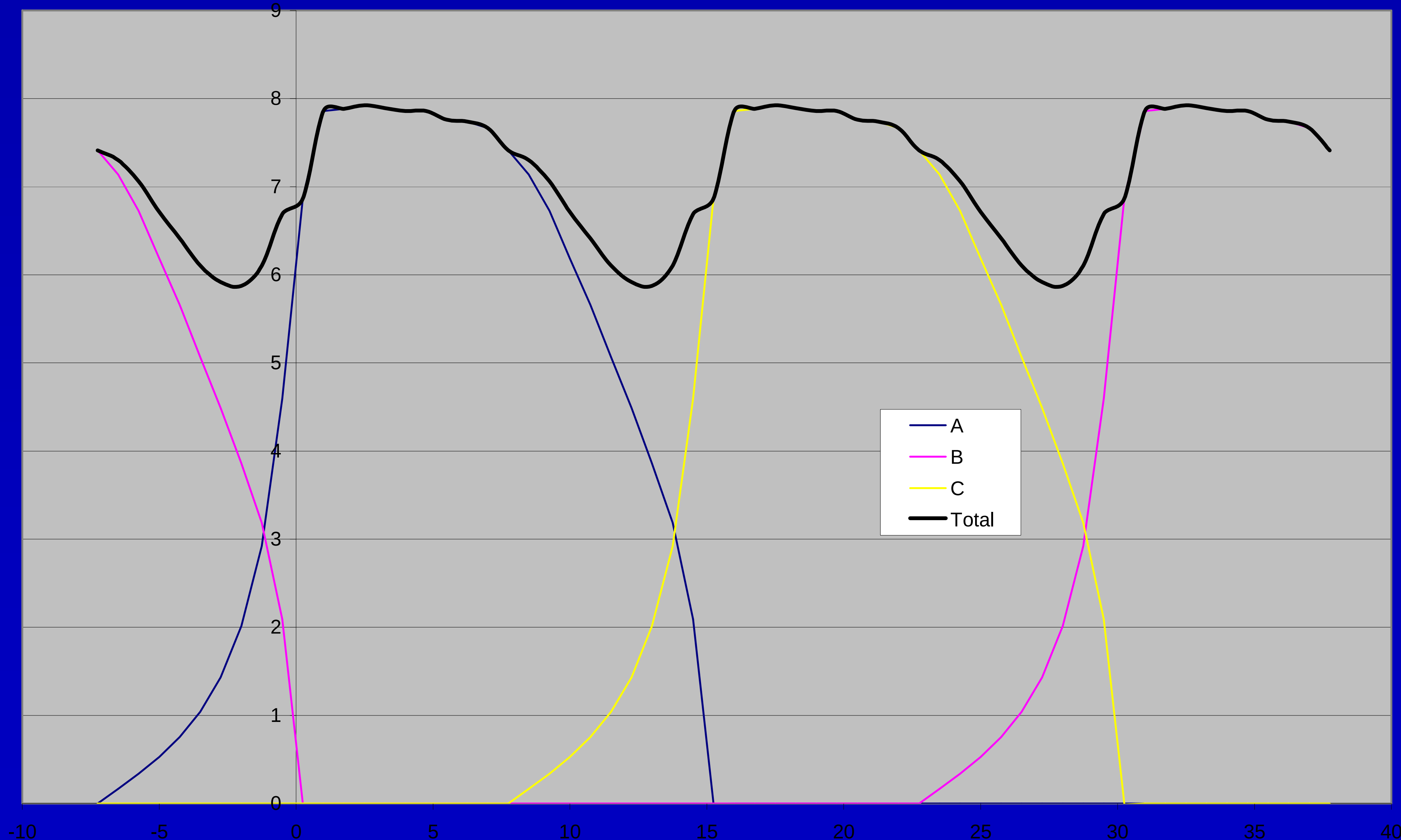
Summary so far…

- Motor is a member of the family "variable reluctance motors" (fundamental torque-producing mechanism)
- Operated by switching phases on & off with respect to rotor angle – *hence "switched" reluctance motor"!*
- Torque is produced as a result of changing phase inductance with respect to rotor angle
- Energise phases over *rising inductance* region to yield *motoring* torque
- Energise phases over *falling inductance* region to yield *braking* torque

Practical operation of "real" SR motors

- 1-phase motor discussed so far produces torque only half the time (inductance rises over half a revolution)
  - special arrangements to ensure starting (e.g. parking magnet)
  - but good for high speeds (e.g. fans, vacuum cleaners etc)
- Poly-phase motors usual for industrial applications
  - typically two, three or four phases
  - allow starting and generate smoother torque
- Phases are energised so that they overlap
  - e.g. 120 electrical degrees spacing on 3-phase motor,
    90 electrical degrees on 4-phase motor
- Discussion so far assumes phase currents can be switched on & off instantaneously
  - not true in practice
  - controller has a bit more "work" to do to allow for this....

Summation of torque in three-phase motor



Rise/fall times of current and magnetic flux are finite

- Rate of rise/fall of magnetic flux ϕ is finite, as dictated by Faraday's Law:

$$\frac{d\phi}{dt} = \frac{V}{N}$$

where V is applied voltage
N is number of turns

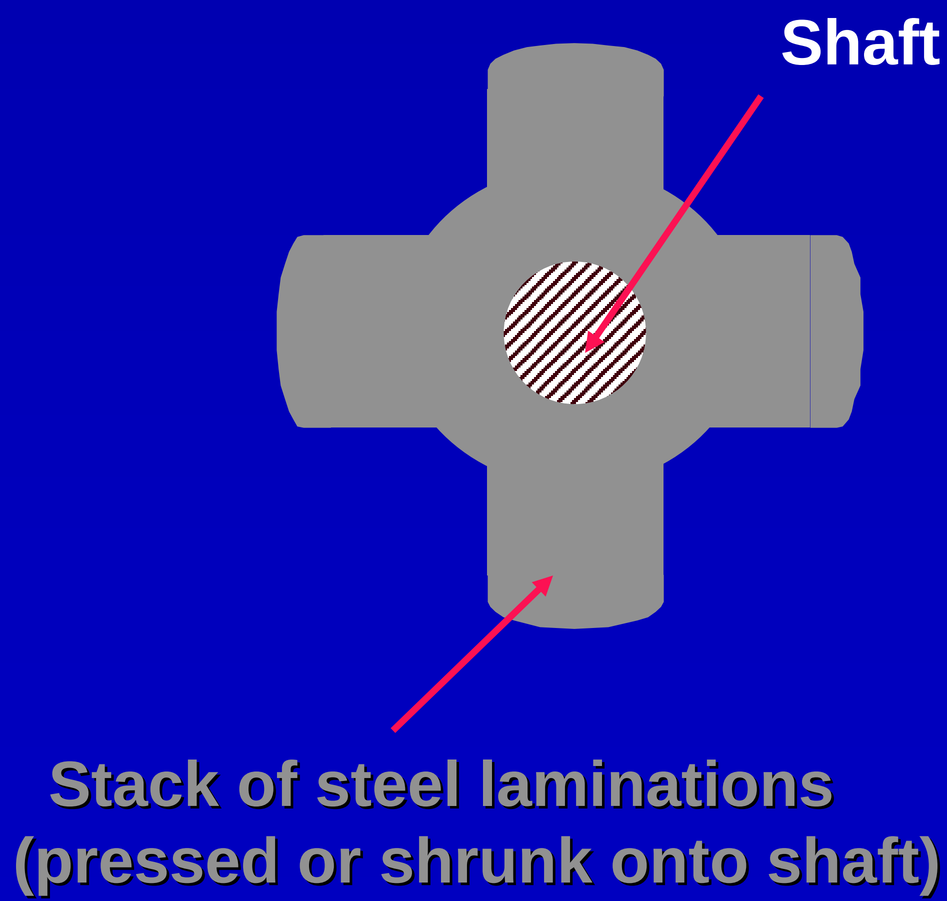
- Consider motoring operation:
  1) At BDC, there will be a delay before the current and magnetic flux reach their working values
  2) After switch off at TDC, flux and current will persist for a time
- Result would be fall in output and efficiency, because:
  1) would reduce the motoring torque component;
  2) would result in an additional braking torque component and also would prolong phase current ($\Rightarrow$ more winding heat)
- Fortunately we can avoid this through cleverer control…

How is efficiency maintained at higher speeds ?

- At low speed, rise/fall times are negligible compared with time occupied by one electrical cycle
- As speed rises, delays become significant
- Compensate for delays by changing the rotor angles at which we switch-on and switch-off the phase excitation
  - switch on earlier, get flux to working value when inductance rising
  - switch off earlier, get flux down to low value before inductance falls
- Optimise switch-on and switch-off angles for best efficiency
- Very high efficiency possible over wide range of speeds and torques
- *Analogy -- advance in internal combustion engine*

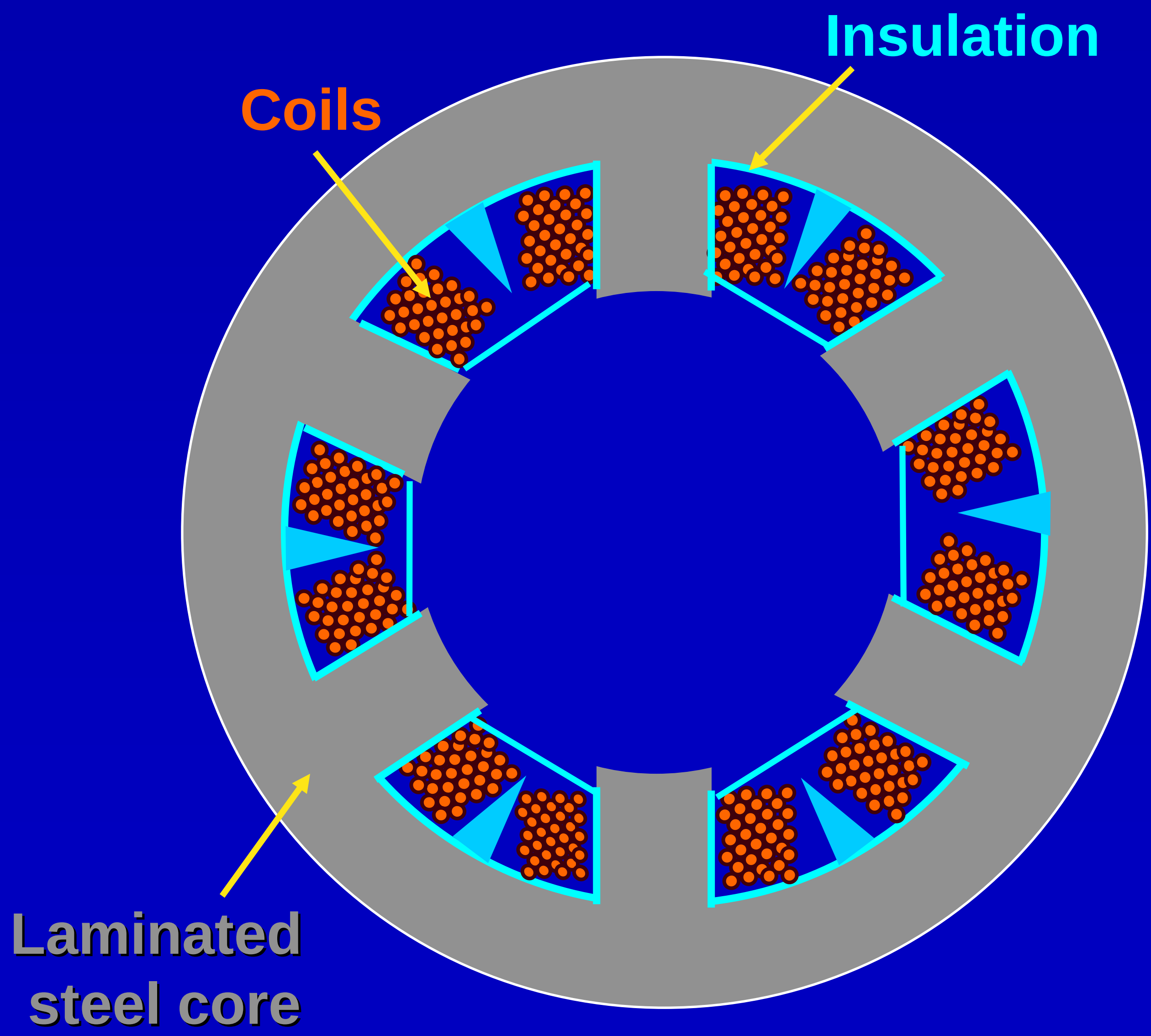
“Simplest possible rotor”

- No windings
- No commutator
- No rotor bars
- No magnets
- Minimal loss – “cool rotor”
- High speed and/or rapid acceleration no problem
- HIGHLY ROBUST



"Simple, robust stator"

- No overlap between phase windings – reduced risk of insulation failures
- Easily cooled
- Simple to wind, robust
- High dV/dt withstand
- Low capacitance to frame – reduced EMI

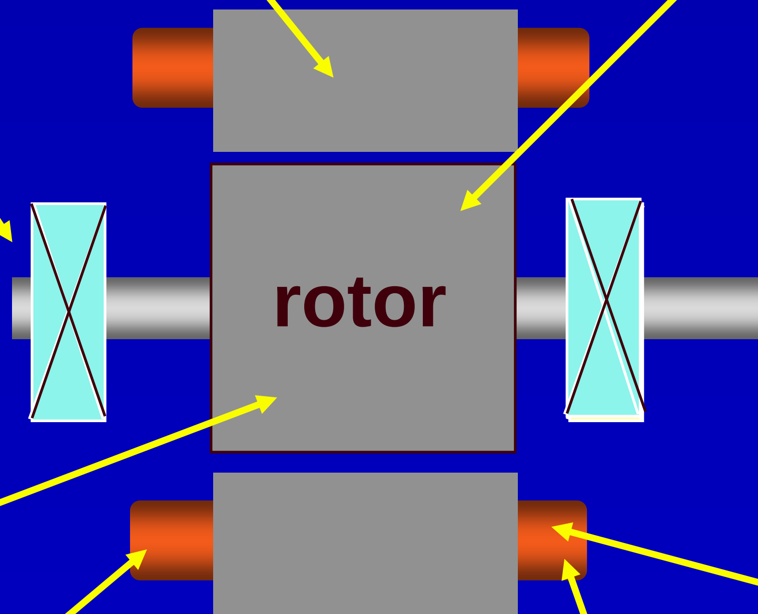


SR motor - inherent reliability

Simple thermal management

Simple rotor:
- No windings
- No conductors
- No magnets
- No commutator

Cool bearings



Mechanically Robust

Cool rotor

No phase overlaps

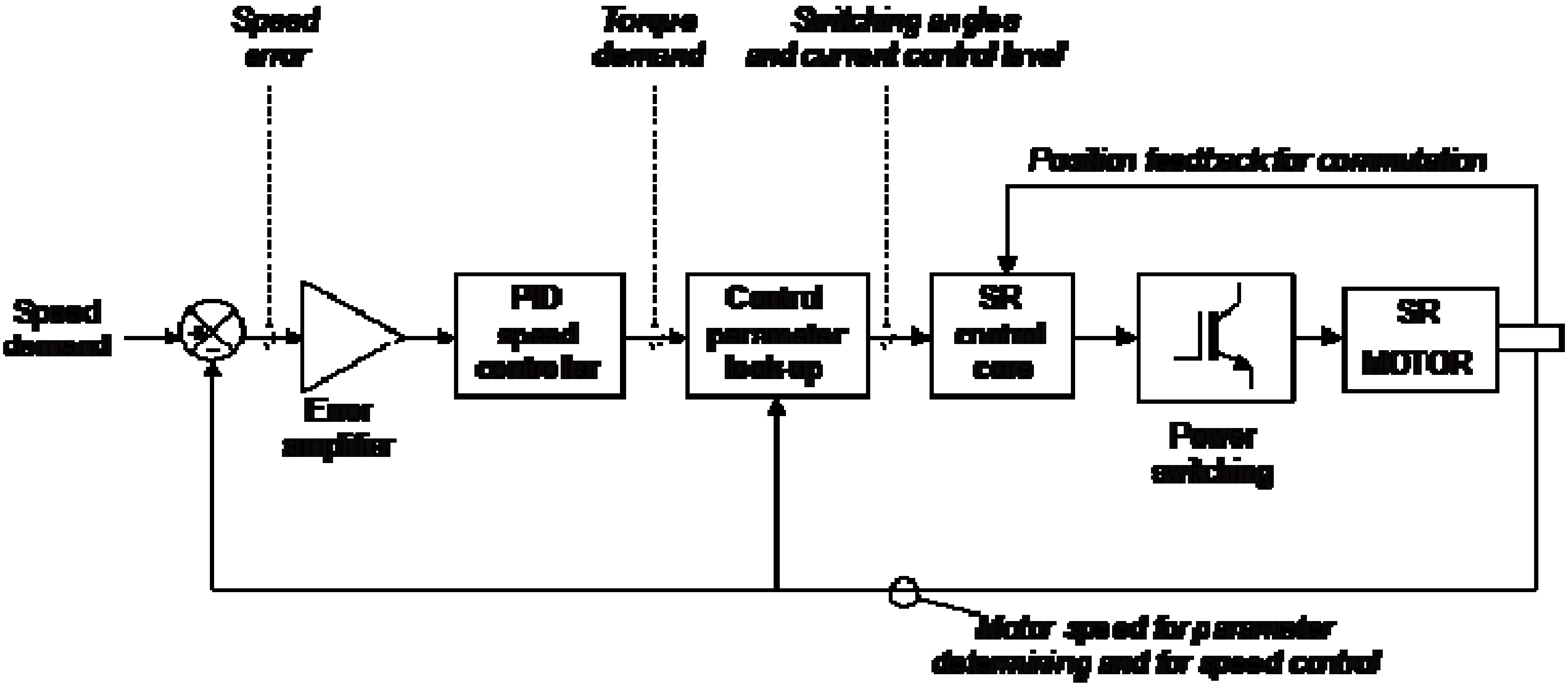
High dV/dt withstand
Lower capacitance to frame reduces RFI

Short winding overhangs
- Lower hot spots
- Less movement

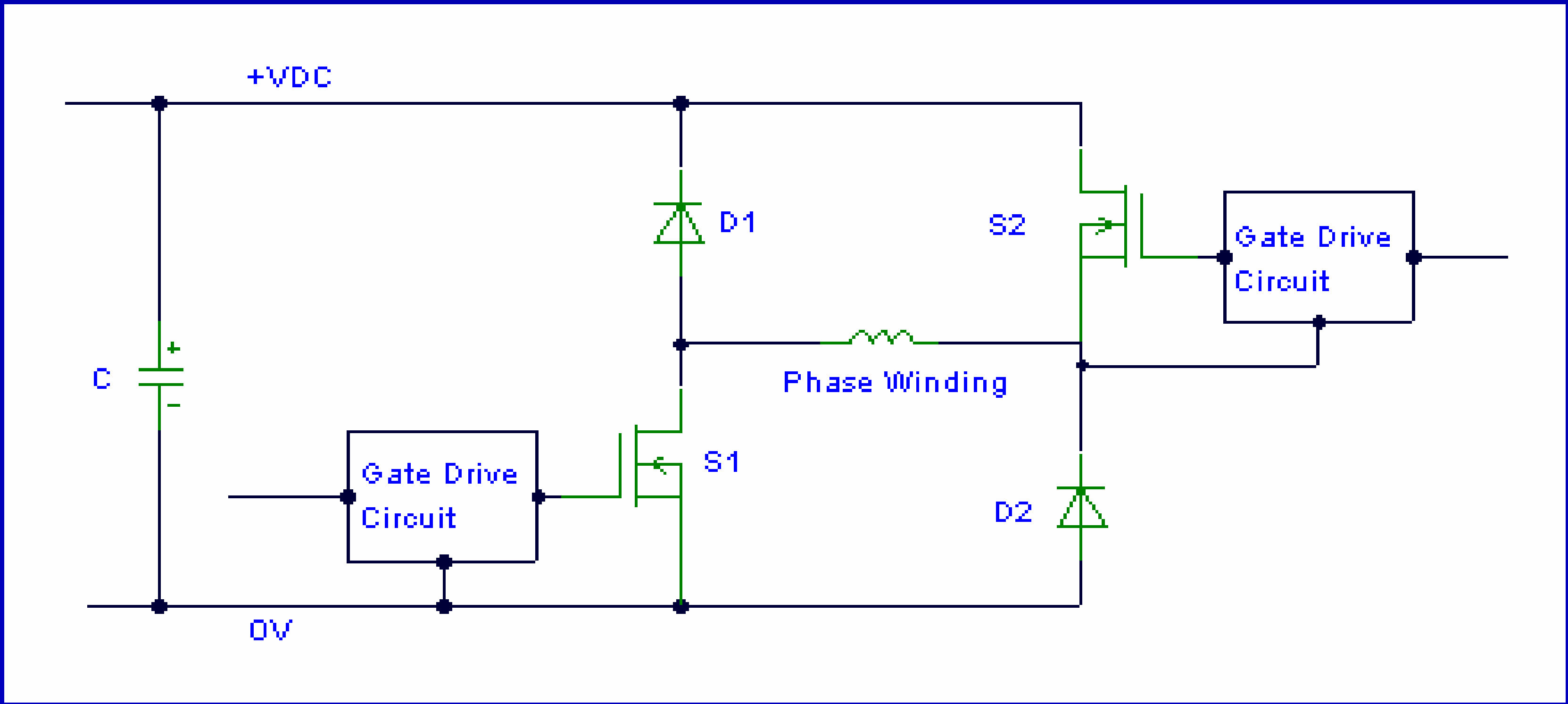
Key advantages of SR motor construction

- Brushless motor
- Simple laminated iron construction with salient poles
  - No rotor bars, no windings on rotor, no magnets
  - One simple coil per stator pole (may be pre-wound on bobbin/former)
- Ease of thermal management
  - losses concentrated in stator
  - cool rotor means improved bearing life
- High overload torques readily achieved (e.g. 1000%)
- Low rotor inertia inherent in geometry
- Short end-windings - good use of active material
  - flexible aspect ratio, high performance “pancake” motors possible

SR Drive®: typical control system architecture

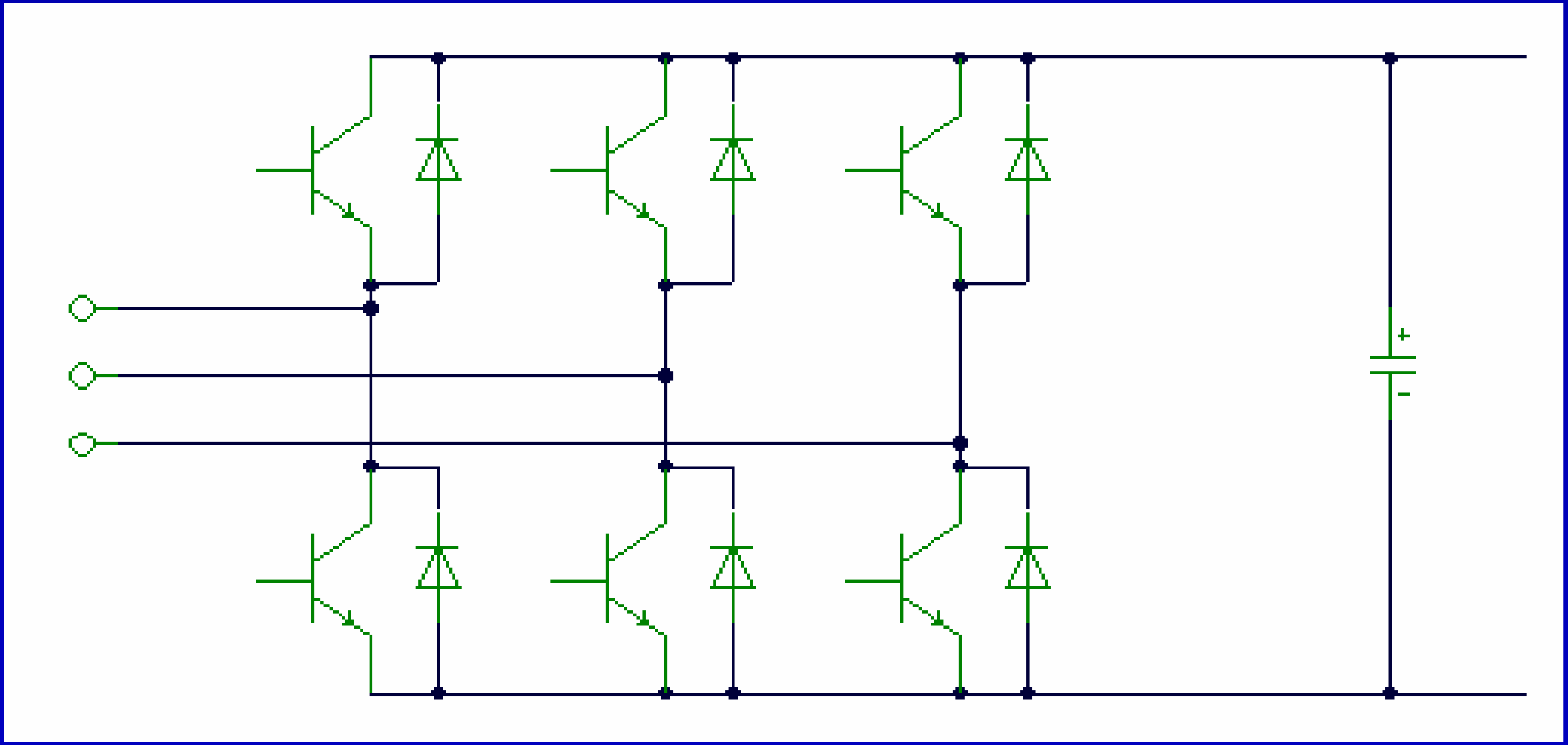


SR power converter "phase leg"



Semiconductor "switches" used, e.g. IGBT, GTO thyristor

3-phase inverter for PM and AC motors - for comparison



Note transistor switches are in series across power supply (= shoot-through possibility) and that they are in parallel with freewheel diodes (= dV/dt stress on switches)

SR power electronics advantages

- Winding in series with switches – no “shoot-though” path
  - simplifies protection, enhances reliability
- Lower power switch ratings compared with AC inverter
  - high torque/amp inherent in SR motor
  - good high speed performance without reducing motor winding turns
- Low switching frequency – not synthesizing sinusoid
  - reduced switching losses and EMC
- Unipolar currents in motor (even when regen. braking)
- Operation at “medium voltages” (e.g. 3.3kV AC) simplified by “stacking” converters (difficult in inverter)
- Switches are not subjected to reverse recovery transient voltage of freewheel diodes (unlike inverter)
  - simplifies gate drive requirements

SR controller advantages

Fault tolerant, robust

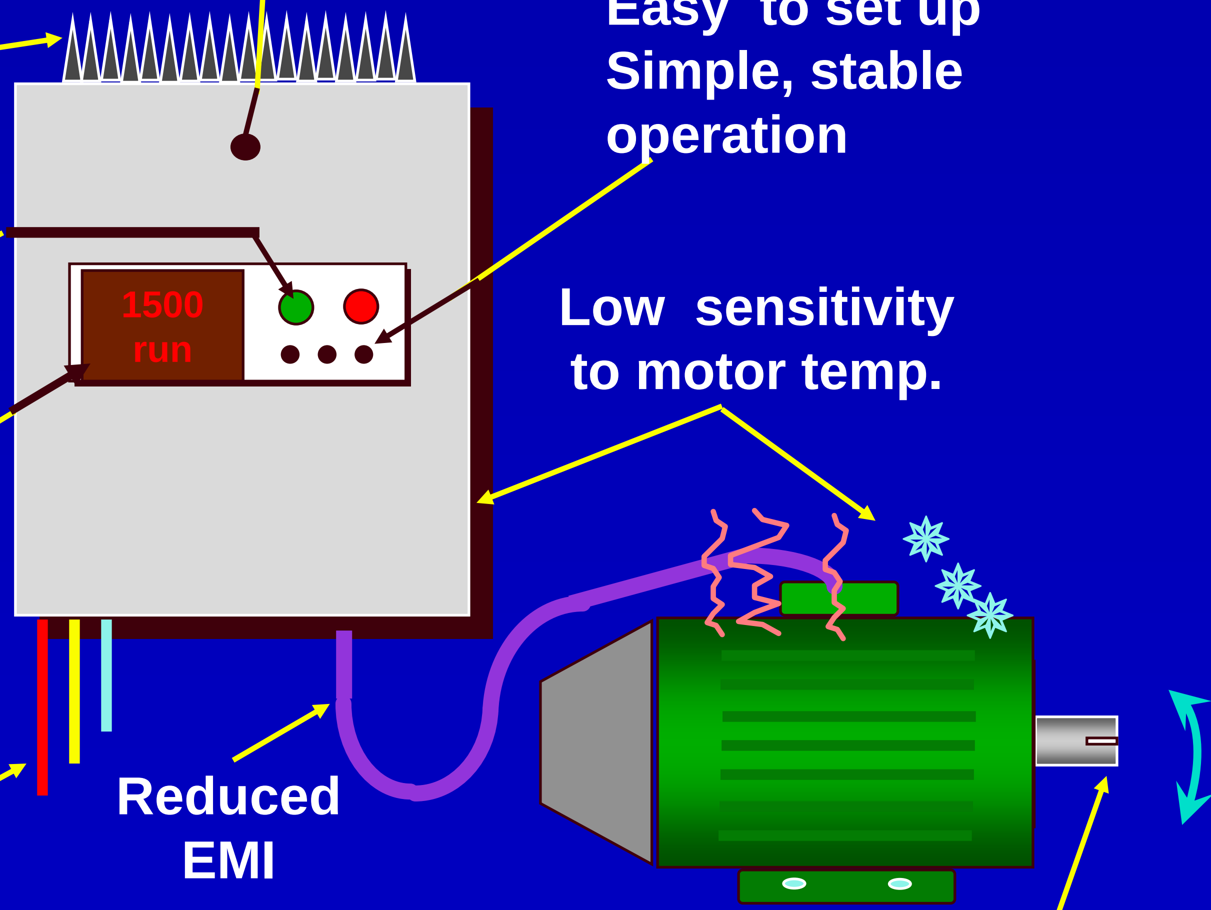
Lower heat loss
Smaller IGBT's

Easy to set up
Simple, stable
operation

Unlimited
starts/hour

Immediate
flying start

Low sensitivity
to motor temp.



Higher system efficiency
over wide range of speed
and torque

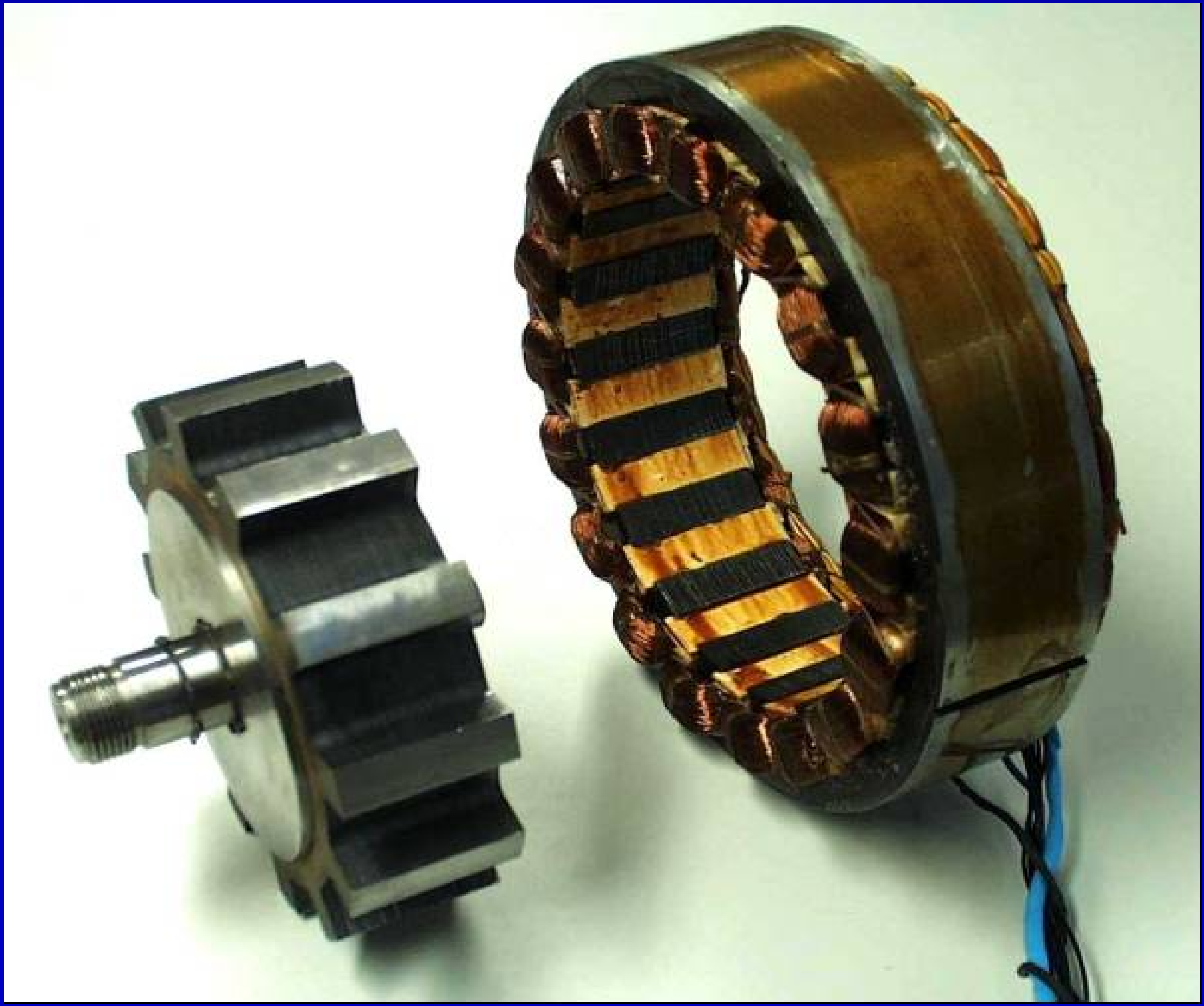
Reduced
EMI

Wide supply voltage range

High voltages possible

Stable, fast dynamics
Long stall endurance

SR Stator and Rotor

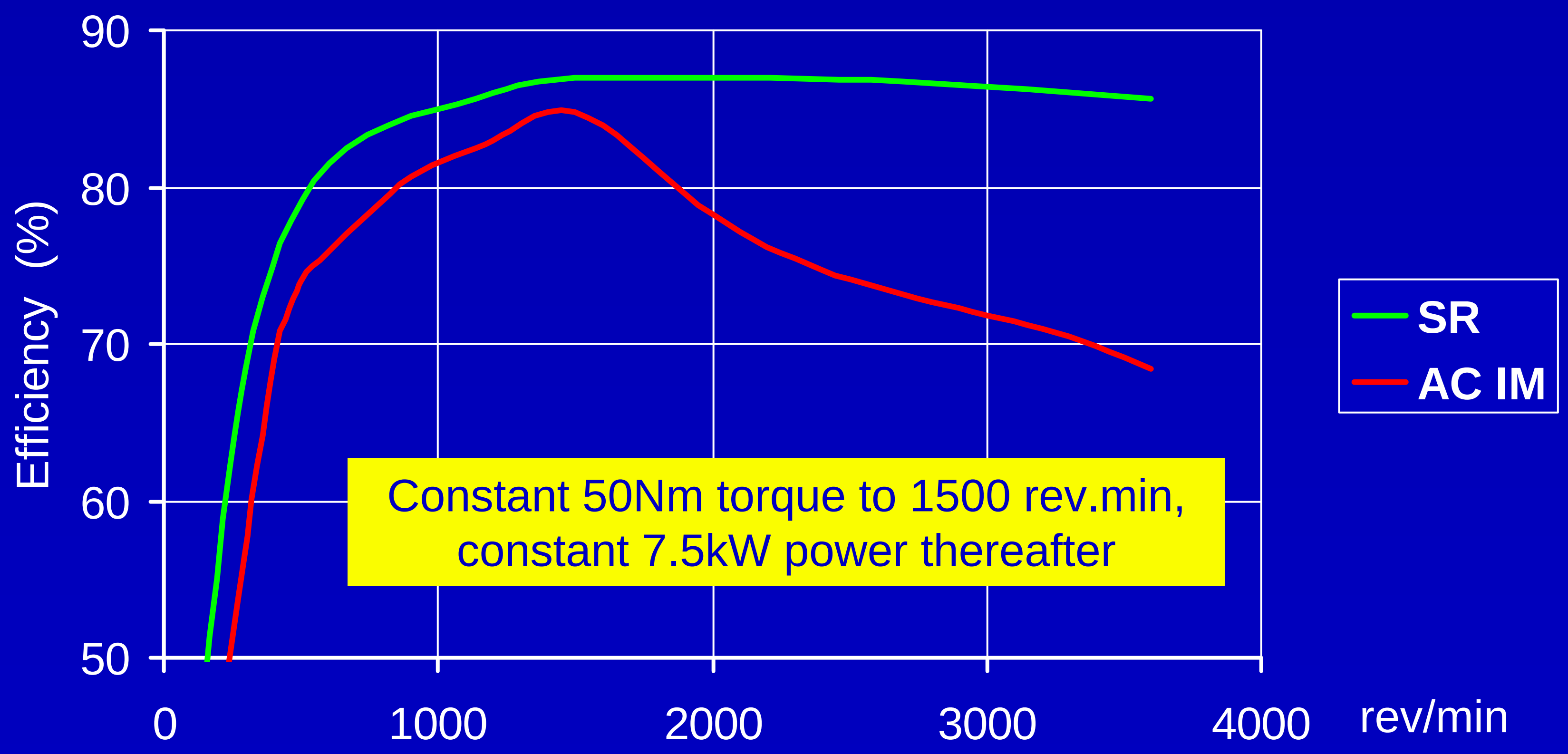


S R Drive® control system

- Direct torque control via current and commutation angles
  - Constant (controlled) torque operation possible
  - Optimised efficiency for wide range of torque & speed
  - Ability to tailor torque-speed envelope to suit application
  - Easy to use, only simple parameter set necessary (like DC drive)
  - but highly flexible, programmable control available if desired
- Sensorless control now available if appropriate
  - encoder often used (sim. to BPM & vector controlled IM)
- Robust and fault tolerant
  - rapid load changes and supply disturbances not a problem
  - fault diagnostics excellent
- Acoustic noise control possible through electronic means
  - significant IPR held here
  - also addressed through proper understanding of machine design

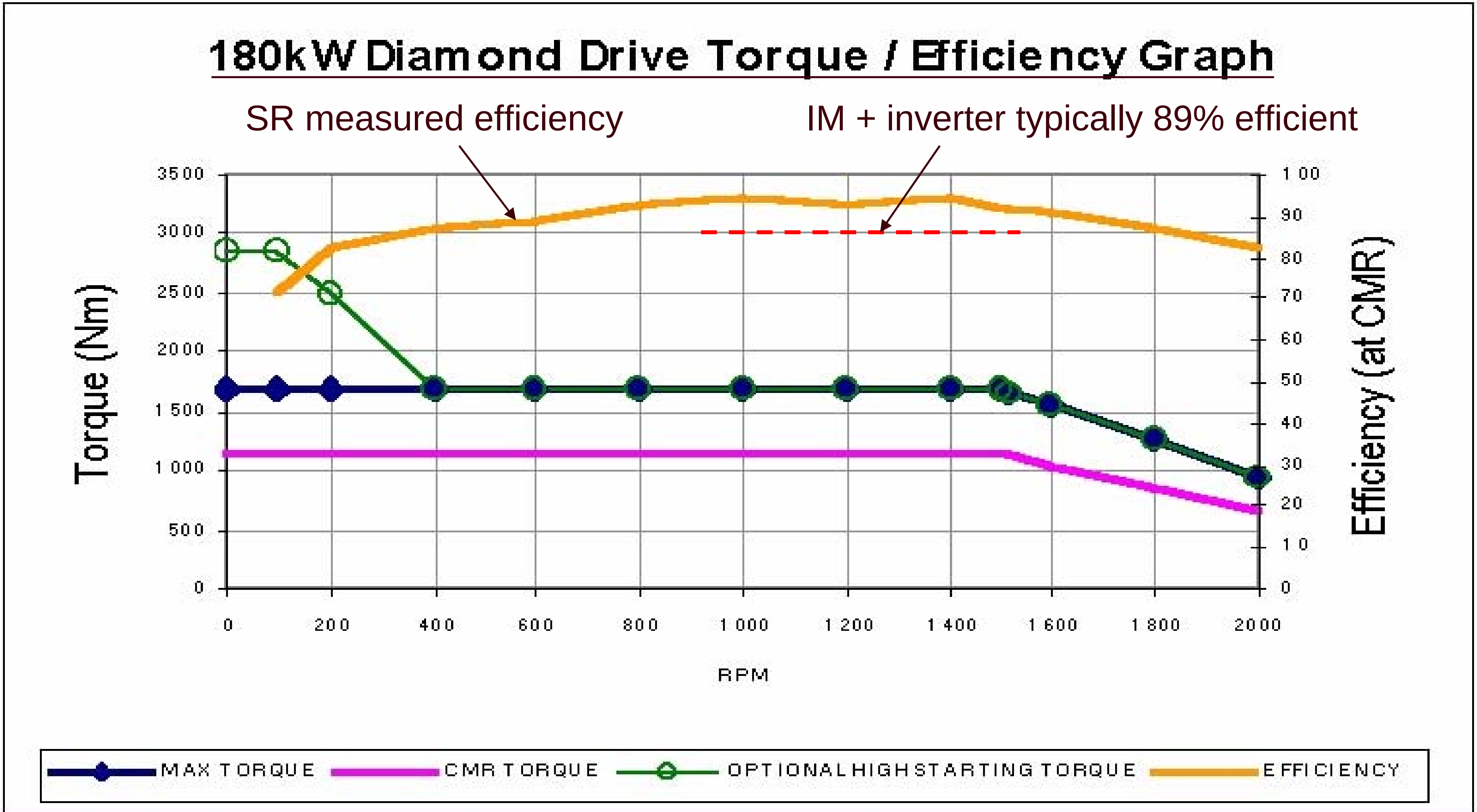
System efficiency: SR vs.vector AC motor @ 7.5kW

Same TEFC frame, IEC 132. Same switches, 50A IGBT. Full load torque



- **SR efficiency is nearly flat over most of the working range**
- **Efficiencies & “flatness” maintained for torque values down to low levels**

SRDML Diamond Drive torque and efficiency



Remarkably constant efficiency under varying load: e.g. IEC D250 motor (90kW)

Drive system comprising motor type 03-00017 operated with controller 02-00017
Measured system efficiency plotted vs. speed at 380V AC SR Drives Manufacturing Ltd