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Systems Modeling Update including Magnetic Deflection

Wayne Meier

LLNL

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General Atomics

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Outline/Topics

- **Additional sensitivities studies**
- **Preliminary look at impact of magnetic diversion**
  - **Considered economic benefit of smaller chamber in generic sense**
  - **Still need to add new model for MD Chamber (geometry scaling, collector plates, materials and costs)**
  - **Also need to add cost for magnets**
- **Effects of including direct conversion**
  - **Efficiency calculations modified to account for some fraction directly converted to stored energy needed for laser pulsed power**
  - **Determine allowable cost for DC hardware (as opposed to bottoms up cost estimate since we don’t have a detailed design)**

Cost of electricity (COE) as a figure of merit

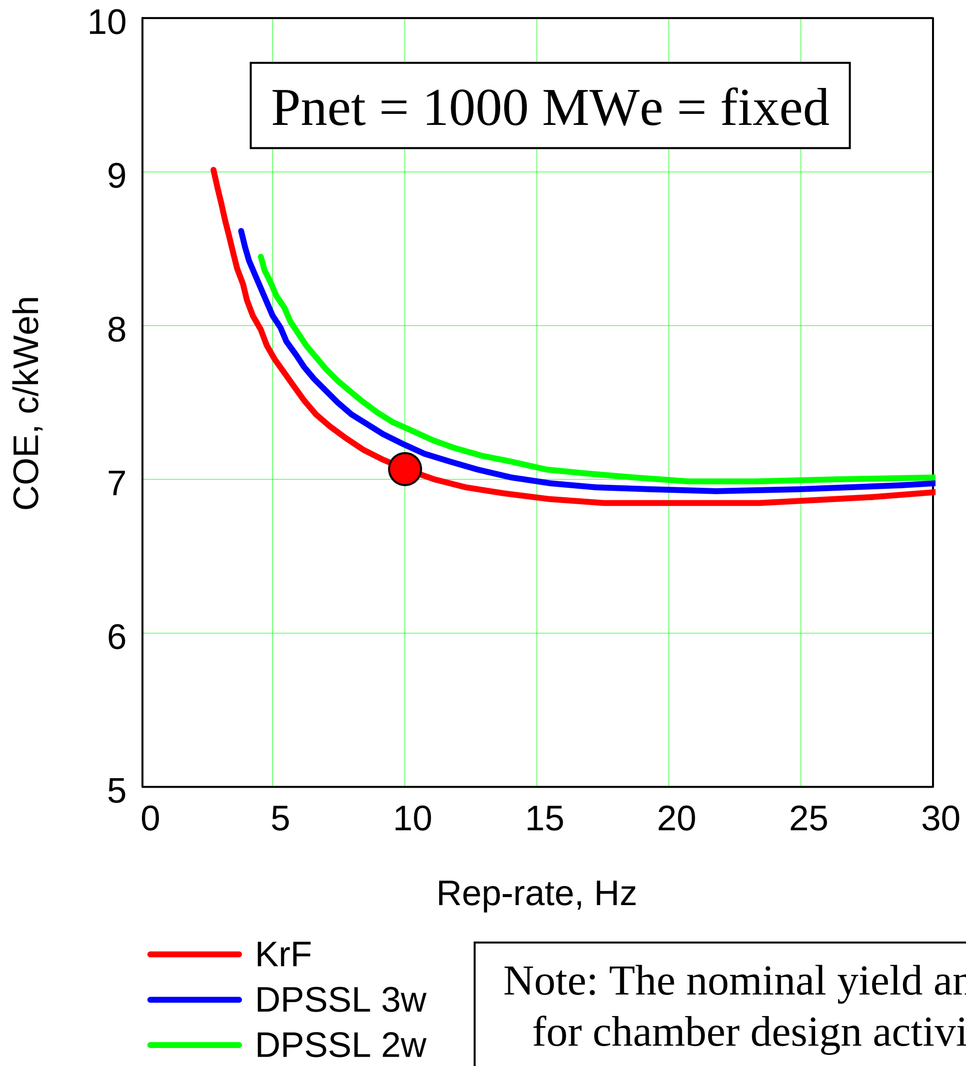
$$COE = \frac{FCR \cdot TCC + OM}{0.0876 \cdot P_n \cdot CF} + D$$

With these assumptions:
Capital charges → 1.30 ¢/kWeh per $B TCC
O&M cost → 1.34 ¢/kWeh per $100M annual

COE = Cost of electricity, ¢/kW$_e$h
FCR = Fixed charge rate, 0.0966/yr
TCC = Total capital cost, $M
OM = annual operations & maintenance costs, $M
D = decommissioning charge, 0.05 ¢/kW$_e$h)
0.0876 = (8760 h/yr) × (1000 kW/MW) × (10^{-8} $M/¢)
P_n = Net electric power, MW$_e$
CF = annual capacity factor, 0.85

Fusion plant COE is a useful figure of merit for self-consistent design trades and optimization. It is far less useful as a predictor of future reality due to large uncertainties in technologies and costing.

Where we left off (ORNL meeting) – COE versus rep-rate for different gain curves and laser eff.



For this talk we use the KrF, 10 Hz point as reference case example:

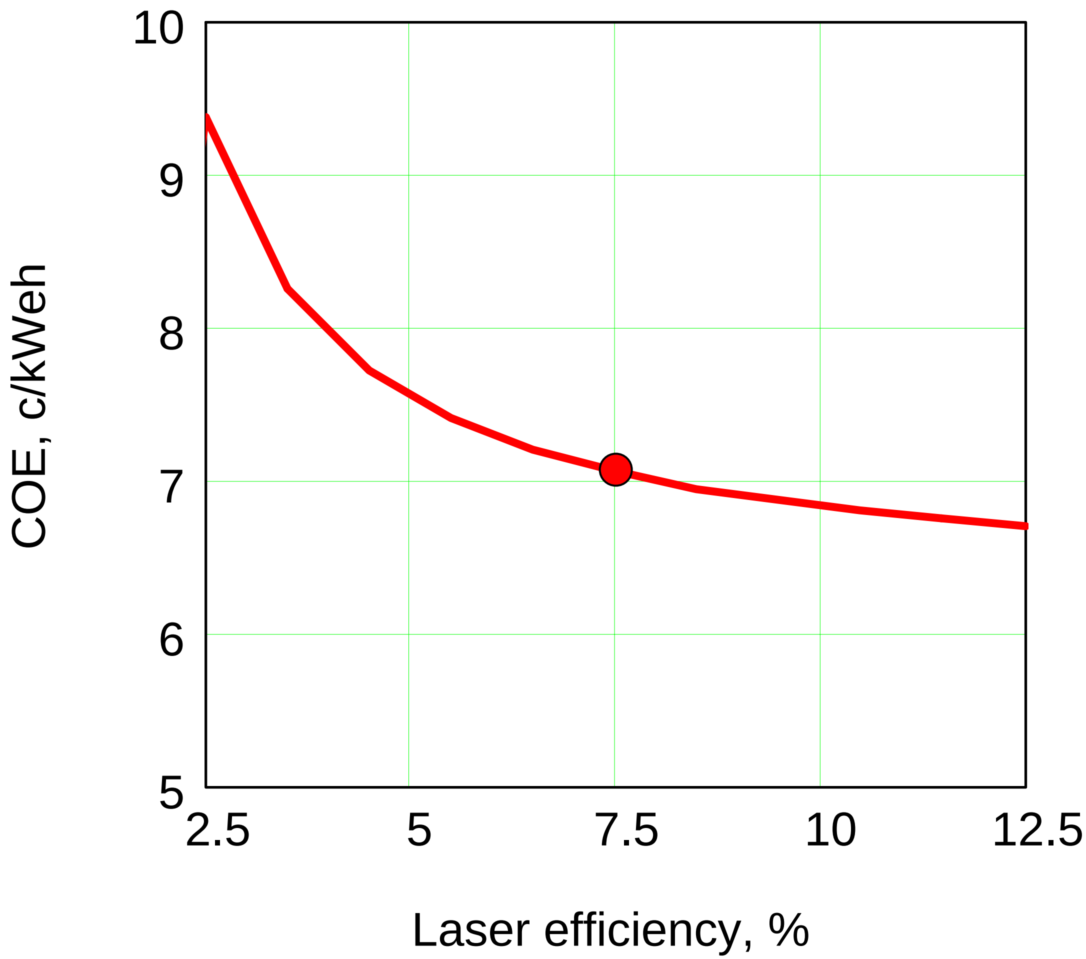
Net power = 1000 MWe
Laser Total Cap. Cost = $400/J
Laser efficiency = 7.5%
Laser energy for 10 Hz = 1.91 MJ
Target yield = 241 MJ
Chamber radius = 9.0 m
COE @ 10 Hz = 7.1 ¢/kWeh

Note: The nominal yield and rep-rate (Y = 350 MJ, RR = 5 Hz) used for chamber design activities, give Pnet = 750 MWe, E = 2.4 MJ, Rw = 10.5 m and COE = 8.9 ¢/kWeh (+25%) for KrF.

Sensitivity studies about reference case have been completed

- Laser efficiency
- Laser cost
- Target cost
- Chamber radius
- Plant efficiency

Sensitivity of COE to laser efficiency – Increases most dramatically below ~ 5%

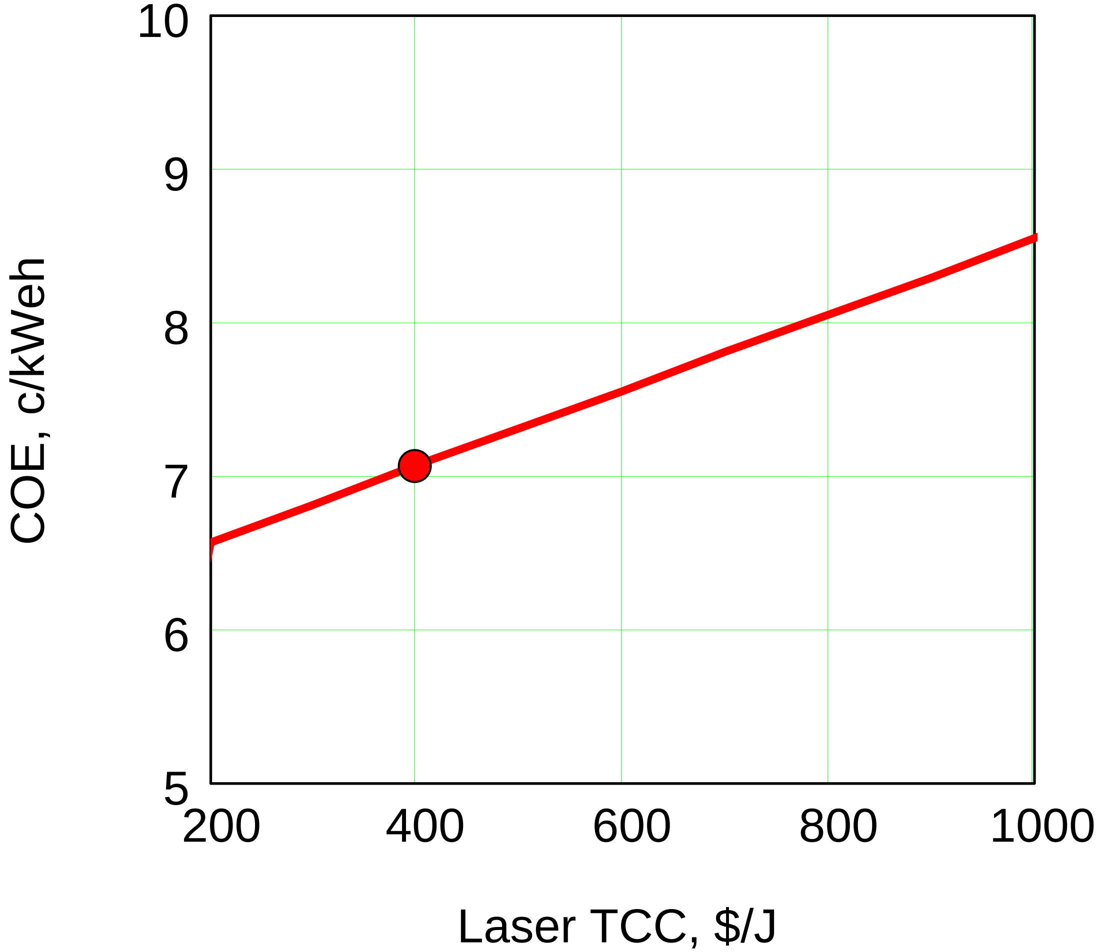


Net power = 1000 MWe
Rep-rate = 10 Hz = fixed
Laser energy and target gain vary to maintain above.*

7.5% → 5.0%, COE +7%
5.0% → 2.5%, COE +24%
7.5% → 12.5%, COE -5%

* If laser energy and target gain were fixed, Pnet would increase with conversion efficiency and comparison would be for different plant sizes. See back-up slides.

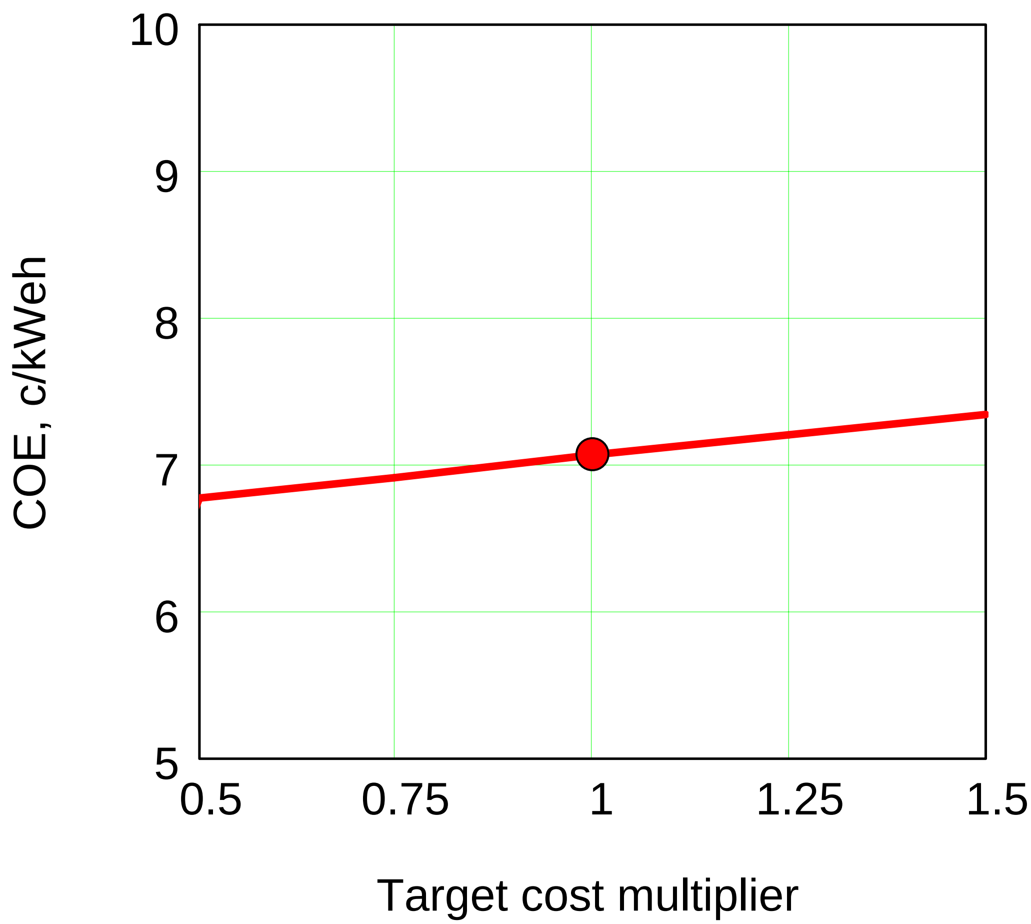
Sensitivity of COE to laser total capital cost – Increases linearly at ~0.25¢/kWeh per $100/J



Net power = 1000 MWe
Reference case parameters
except laser cost

$400/J → $800/J, COE +14%
$400/J → $200/J, COE -7%

Sensitivity of COE to target cost – Target costs have small impact on COE



Net power = 1000 MWe
Reference case parameters
except target cost

+50% target cost, COE +4%
-50% target cost, COE -4%

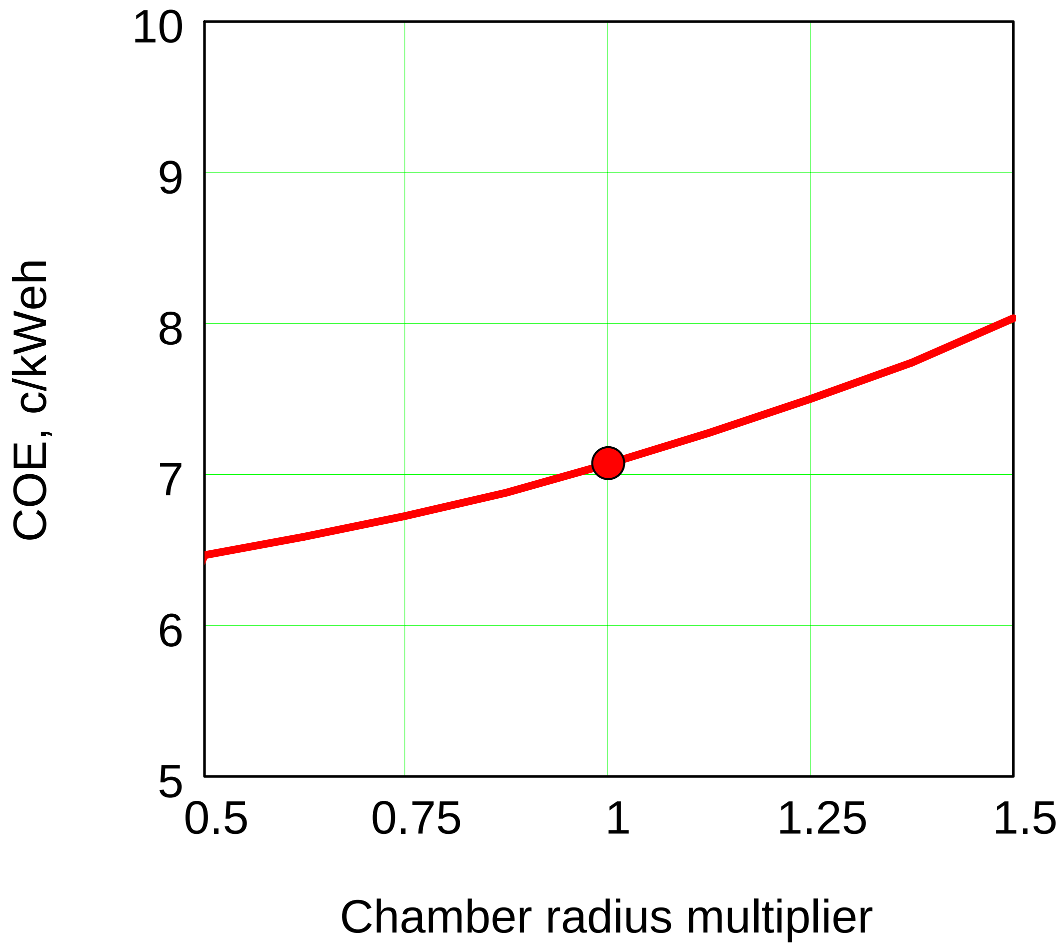
Reference case values:
Targets produced = 0.27 B/yr

TCC = $171 M
Capital charges = $16.6 M/y
= 6.2 ¢/target

O&M costs = $25.5 M/y
= 9.5 ¢/target

Total target cost = 16 ¢/target

Sensitivity of COE to chamber radius – Increases as weak power of Rc, like $Rc^{0.1 \text{ to } 0.3}$



Net power = 1000 MWe
Reference case parameters
except chamber radius

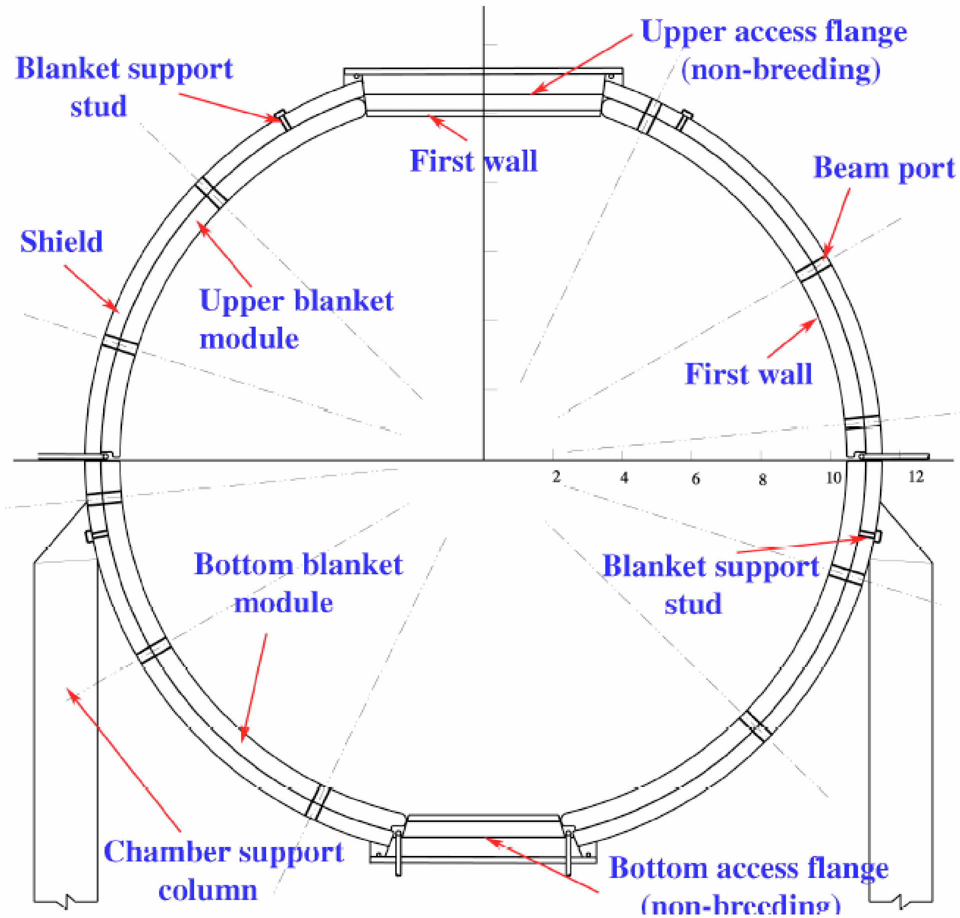
+50% Rc → COE +14%
-50% Rc → COE -9%

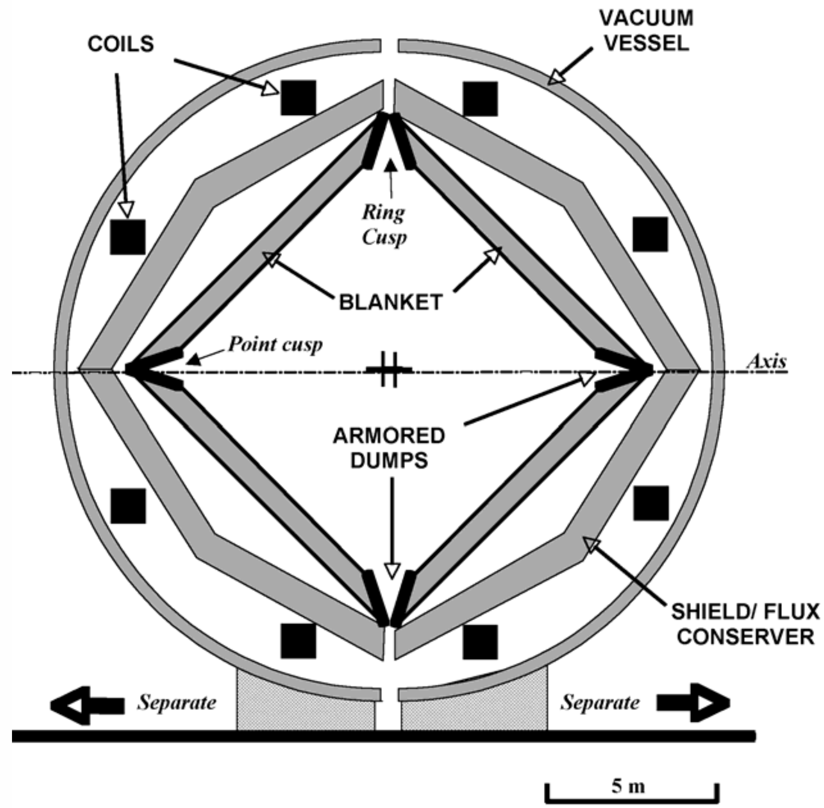
Reference case values:
Rw = 9.0 m

TCC = $245 M includes first wall, blanket, shield and Li (~ 0.3 ¢/kWeh)

Replacement cost = $40M/yr assuming 5 yr life (~ 0.5 ¢/kWeh)

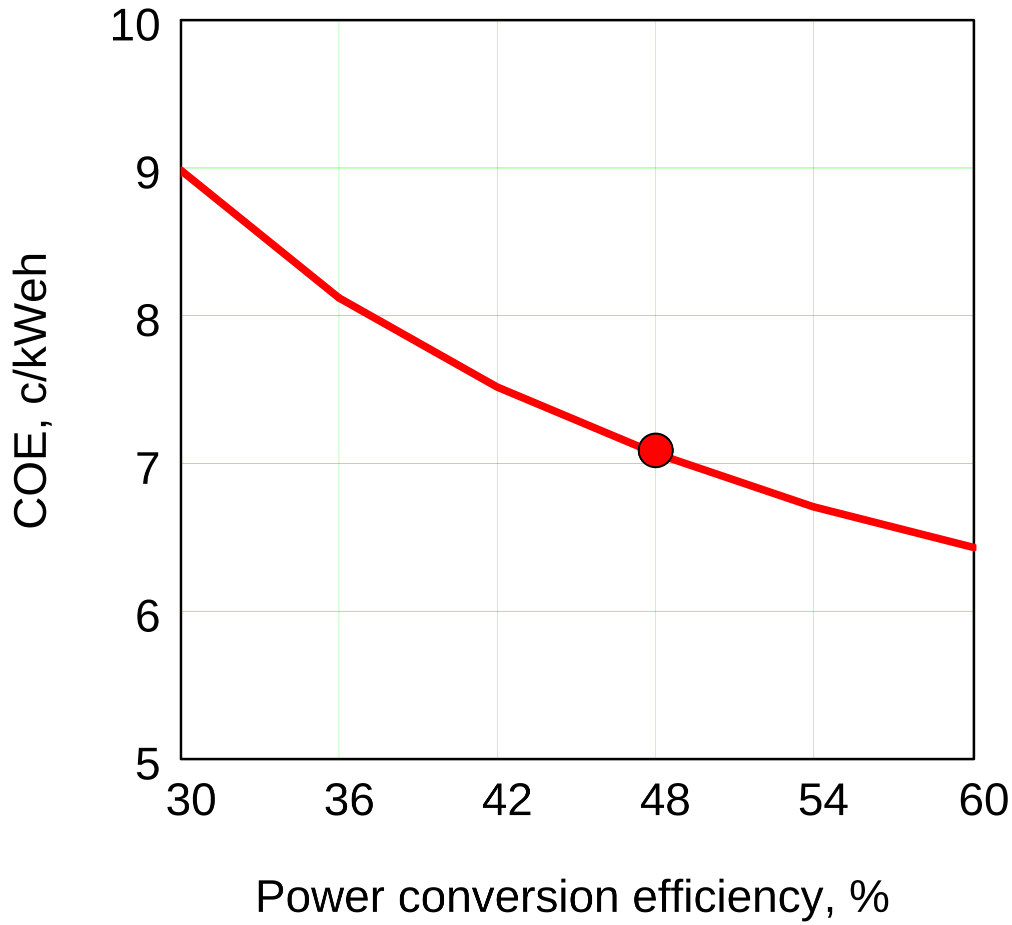
Savings for smaller, magnetic diversion chamber will be less than indicated by chamber cost scaling on previous chart





Even though magnetic diversion chamber is smaller, VV envelop is nearly as large

Sensitivity of COE to conversion efficiency (η_c) – Decreases as weak power of η_c, like $\eta_c^{-0.4 \text{ to } -0.5}$



Net power = 1000 MWe
Rep-rate = 10 Hz
Laser energy and target gain vary to maintain Pn and RR

48% → 36%, COE +15%
48% → 60%, COE -9%

What can you pay for higher efficiency? Start with basics:

Reference case power balance:

Driver energy (Ed) = 1.91 MJ

Target gain (G) = 126

Yield (Y) = 241 MJ

Rep-rate (RR) = 10 Hz

Fusion power (P_f) = 2411 MW

Overall energy mult. (M) = 1.13

Thermal power (P_t)= 2725 MWt

Conversion efficiency (η_c) = 48%

Gross electric (P_g) = 1307 MWe

Driver eff (η_d) = 7.5%

Driver power (P_d) = 255 MWe

Aux. power = $0.04 \cdot P_g$ = 52 MWe

Net electric (P_n) =1000 MWe

Net eff. (η_{net})= P_n/P_t = 36.7%

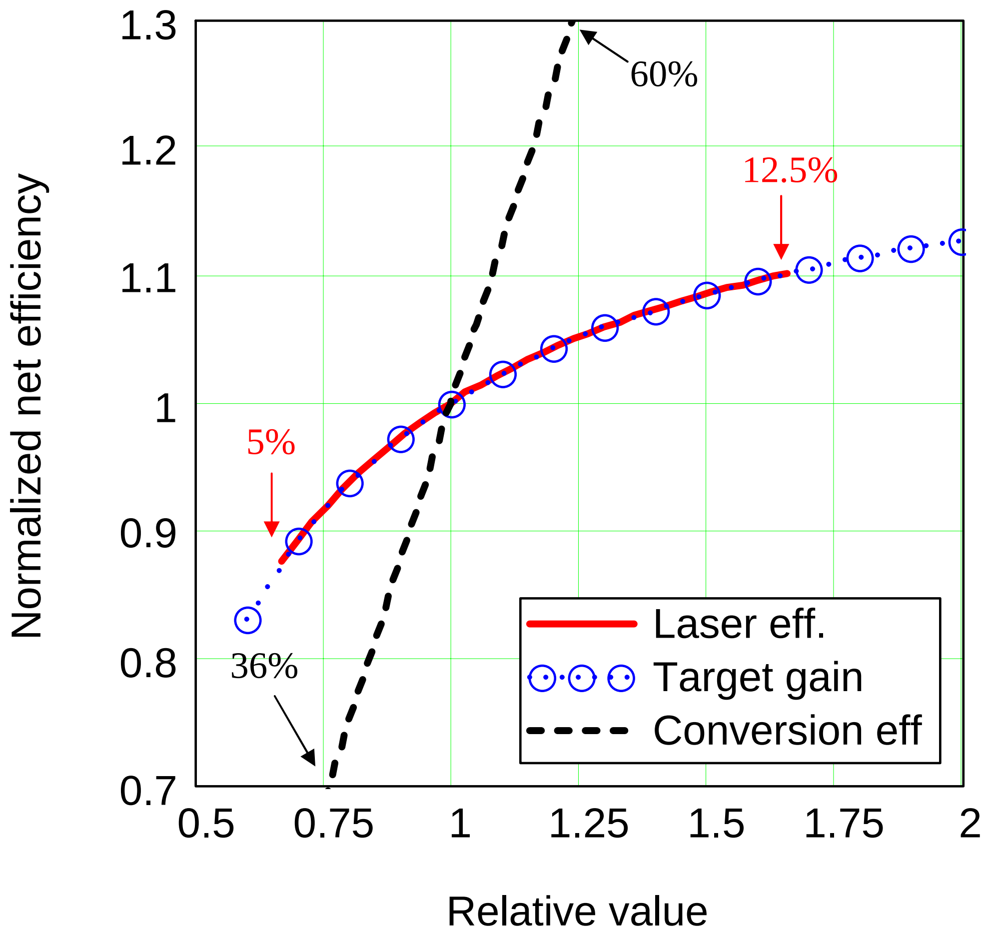
$$\eta_{net} = \eta_c \cdot \left[1 - 0.04 - \frac{1}{\eta_d \cdot G \cdot M \cdot \eta_c} \right]$$

Net efficiency improved by higher driver efficiency, higher target gain, and/or high power conversion efficiency.

To be consistent with other results, we need to compare plants with the same net power, i.e., a more efficient plant of with the same net output, not a plant with larger output due to higher efficiency.

As conversion efficiency increases, driver energy and target gain decrease to give the same net power (1000 MWe). Rep-rate is fixed at 10Hz (still below optimum).

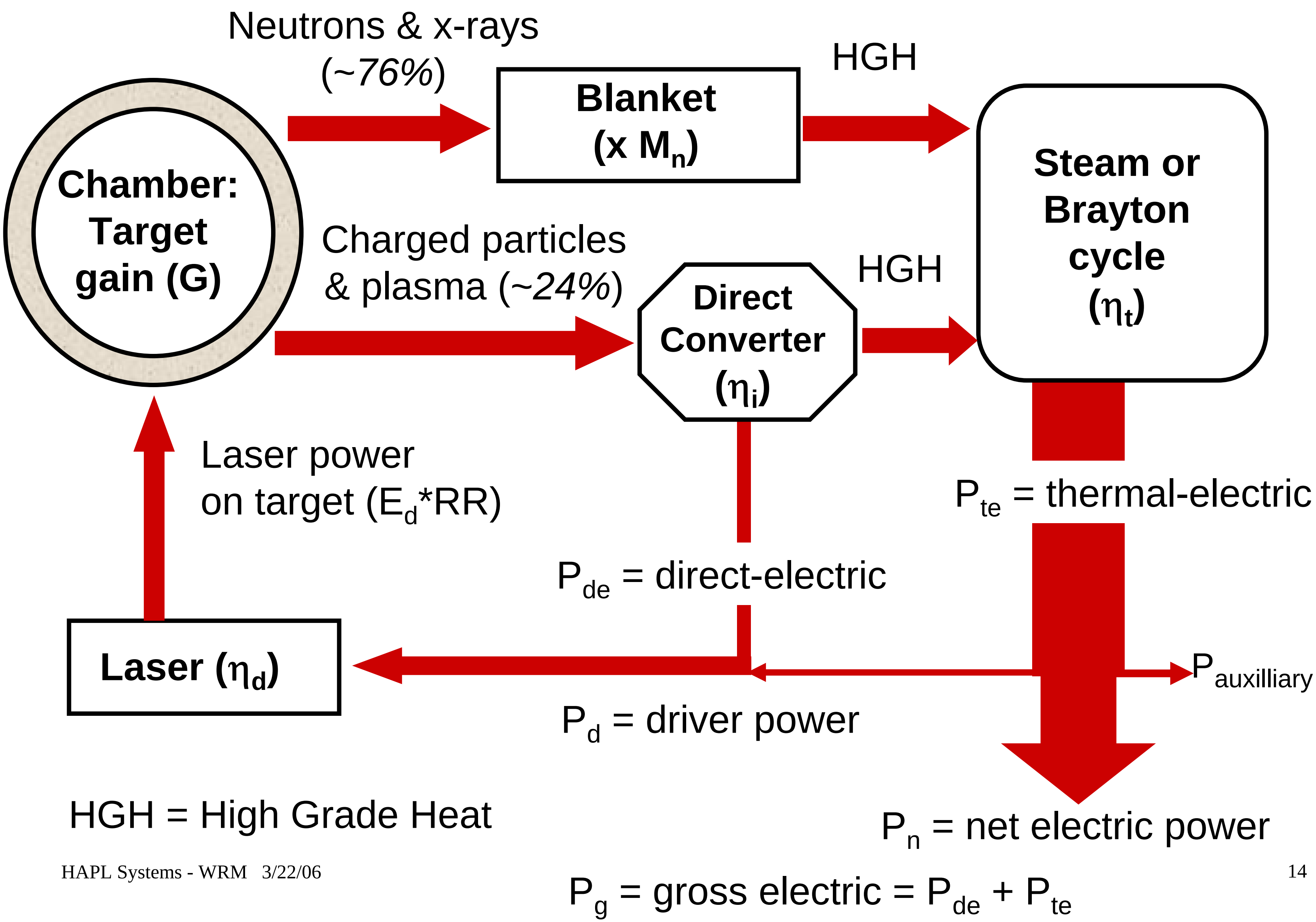
Power conversion efficiency is the dominant factor in determining net efficiency



Reference values:
Laser efficiency = 7.5%
Target Gain = 126
Conversion eff. = 48%

- Laser efficiency and target gain have same relative impact – both reduce laser recirculating power fraction.
- Changes in conversion eff. have greater impact

Power flow diagram with direct conversion



Accounting for direct conversion

Assume:

- Ion energy = 24% of yield (Perkins) = 21% of total energy when accounting for overall energy multiplication of 1.13 (Sawan)
- All ion energy available for direct conversion by magnetic pulse compression
- Ion-to-electric conversion efficiency (η_i) examined parametrically
- Residual ion energy available for conversion at same thermal conversion efficiency (η_t) as rest of blanket power
- "Electric" power from ions considered equivalent to electric from thermal cycle
- Expression for power conversion efficiency is modified as indicated below:

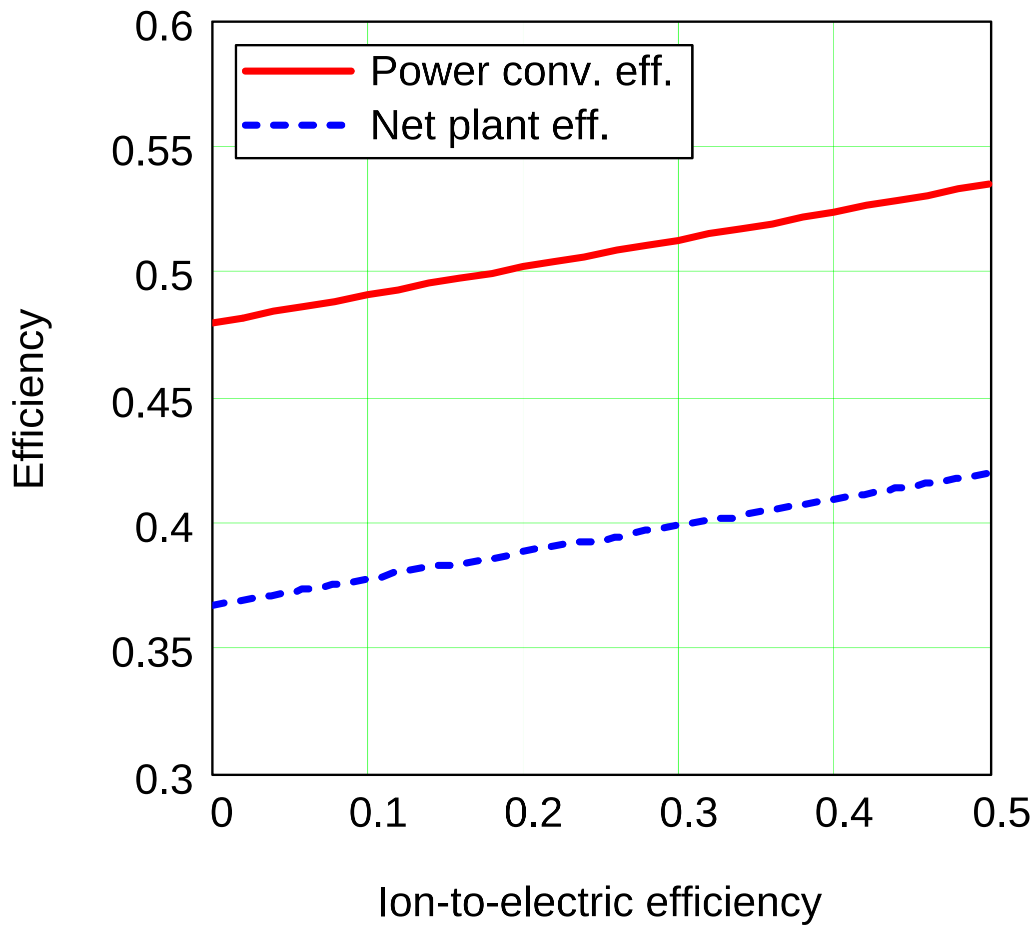
Ion-electric part

Thermal-electric part

$$\eta_c = \frac{0.24 \cdot \eta_i + \left[0.76 \cdot 1.17 \; + \; 0.24 \cdot (1 - \eta_i)\right] \cdot \eta_t}{1.13}$$

Total ion + thermal

Direct conversion of ion energy is one way to increase power conversion efficiency



Assumes:
Target gain = 126
Ion fraction of yield = 24%
Ion fraction of total = 21%
Laser eff. = 7.5%
Thermal eff. = 48%
Ion dump heat also converted at 48%

Power conversion efficiency includes both ion-to-electric and thermal-to-electric contributions

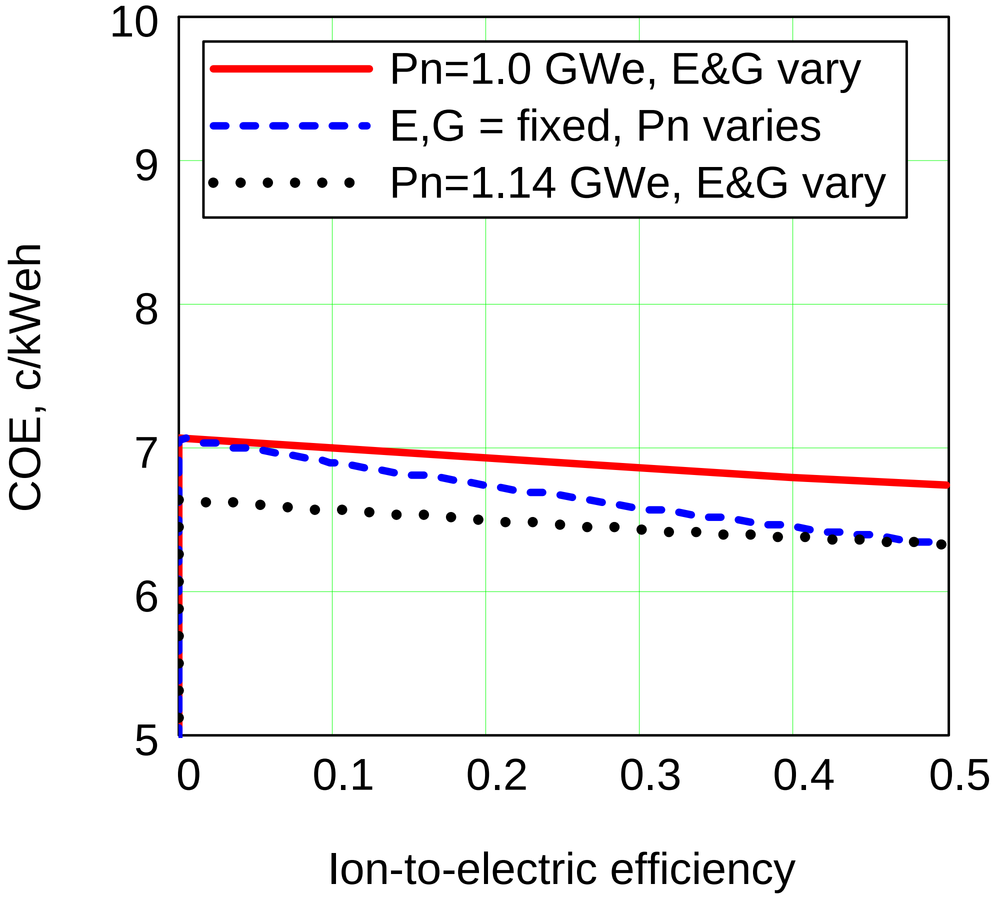
At 50% ion-to-electric:

η_c increases from 48 to 53%

η_n increases from 36.7% to 42%

Ignoring added costs, COE decreases by 5% with direct conversion of ion energy

RR = 10 Hz for all cases



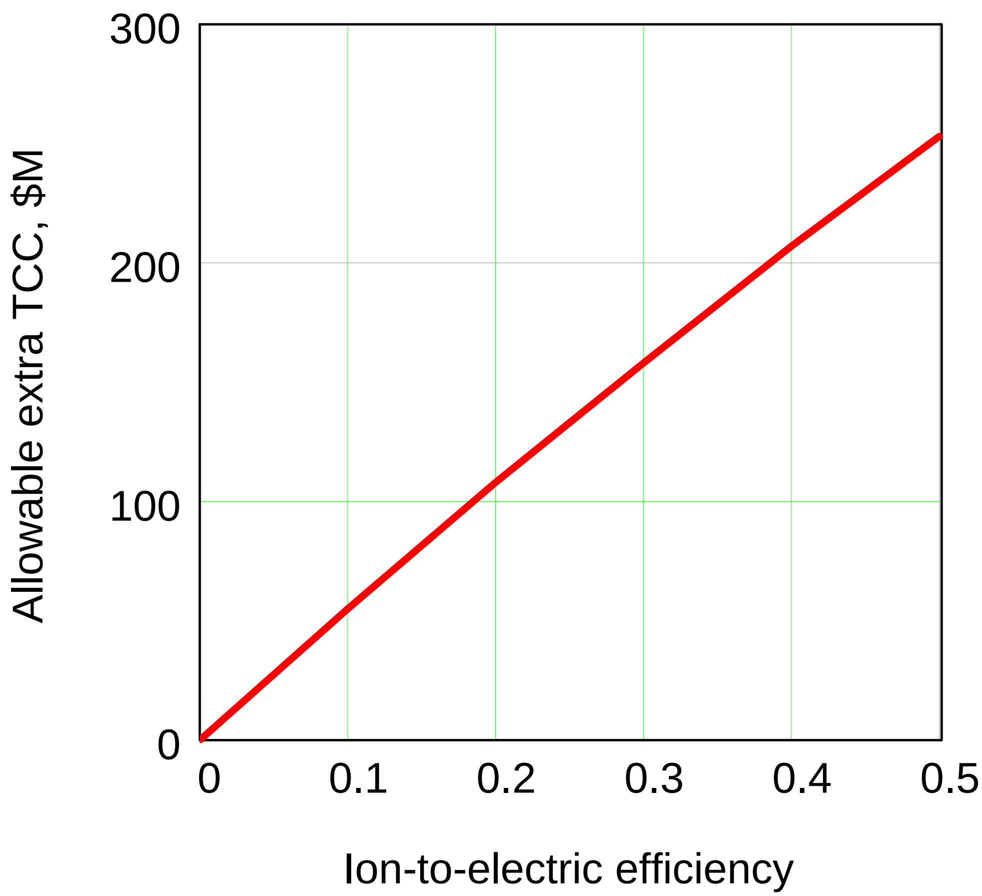
• If hold Pn and RR constant:
- COE decreases by <5% since E and G decrease to keep Pn fixed. (**red line**)

• If hold E, G and RR fixed:
- Pn increases with increasing ηi
- Pn = 1144 MWe at ηi = 50%.

- COE → -11% compared to 1000 MWe case without direct conversion (**blue dashed line**)

- But COE → only -6% compared to 1144 MWe case without direct conversion (**black dotted line at ηi=0**)

Allowed additional capital cost is with direct conversion is modest



Pnet = 1000 MWe
Allowed **direct** costs are ~2x smaller

Summary

- Additional requested sensitivity studies have been completed showing impact of cost and performance variations
  - Most effects are modest (<10-15%) over likely ranges
- Smaller chambers, as possible with magnetic diversion, are desirable; more detailed costing (including magnets, etc.) will diminish advantages
- Improving overall power conversion efficiency is more important than comparable improvements in target gain and driver efficiency
- With current targets, ion fraction of output is low, thus limiting the potential benefits of direct conversion (<5% at fixed net power, ~11% at fixed fusion power)
- Must be careful to compare apples to apples (i.e., same size plants) in evaluating the benefits of direct conversion

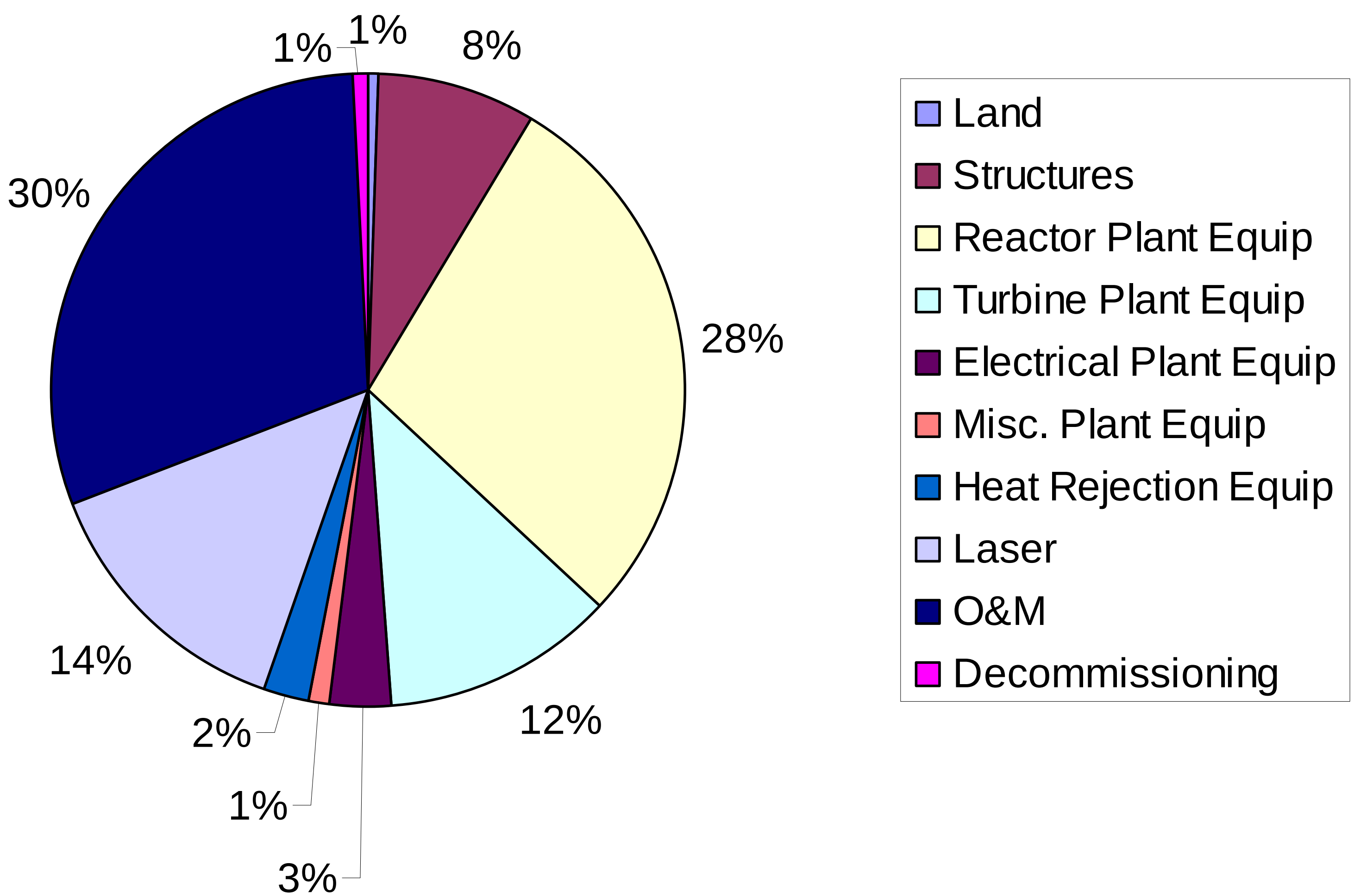
Next steps

- Add new model for MD Chamber (geometry scaling, collector plates, new materials and costs)
- Add cost for magnets
  - Scale with magnet volume
  - Examine range of unit costs ($/KA-m)
- Brayton cycle model – not sure if cost info is available, could examine parametrically
- Improved laser models, including cost of optics – Open to suggestions

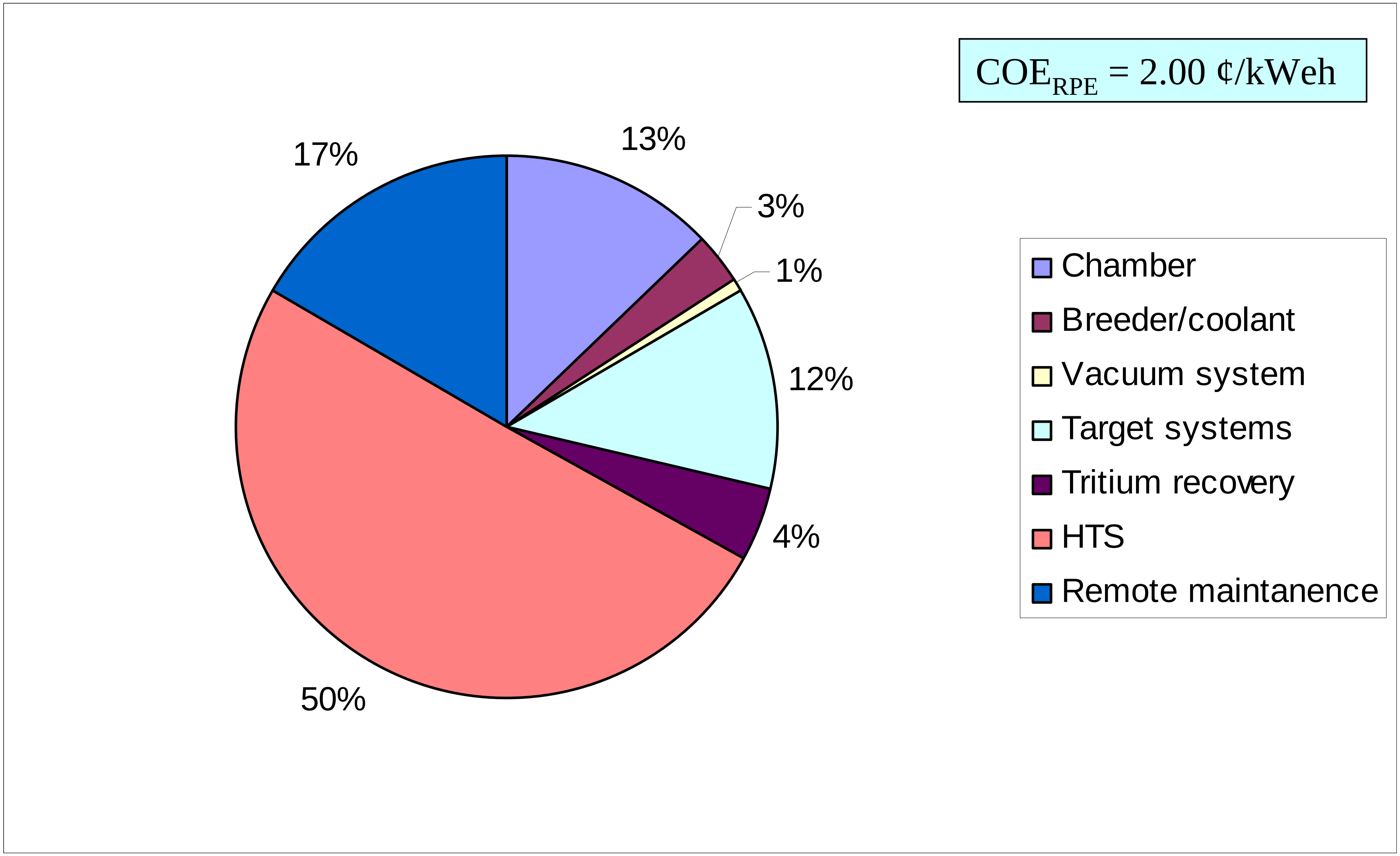
Back-ups

Contributions to COE

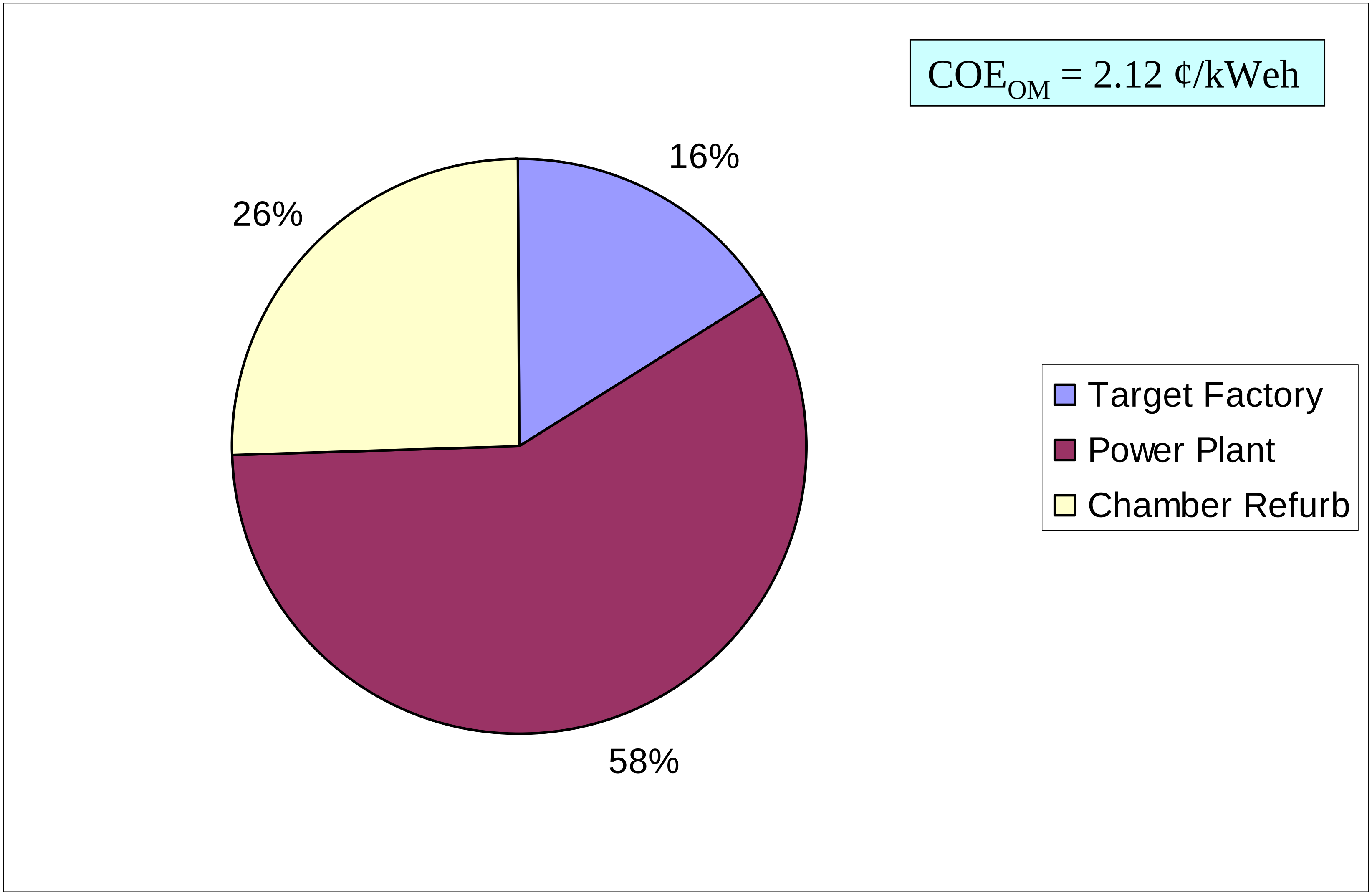
COE = 7.06 ¢/kWeh



COE from Reactor Plant Equipment

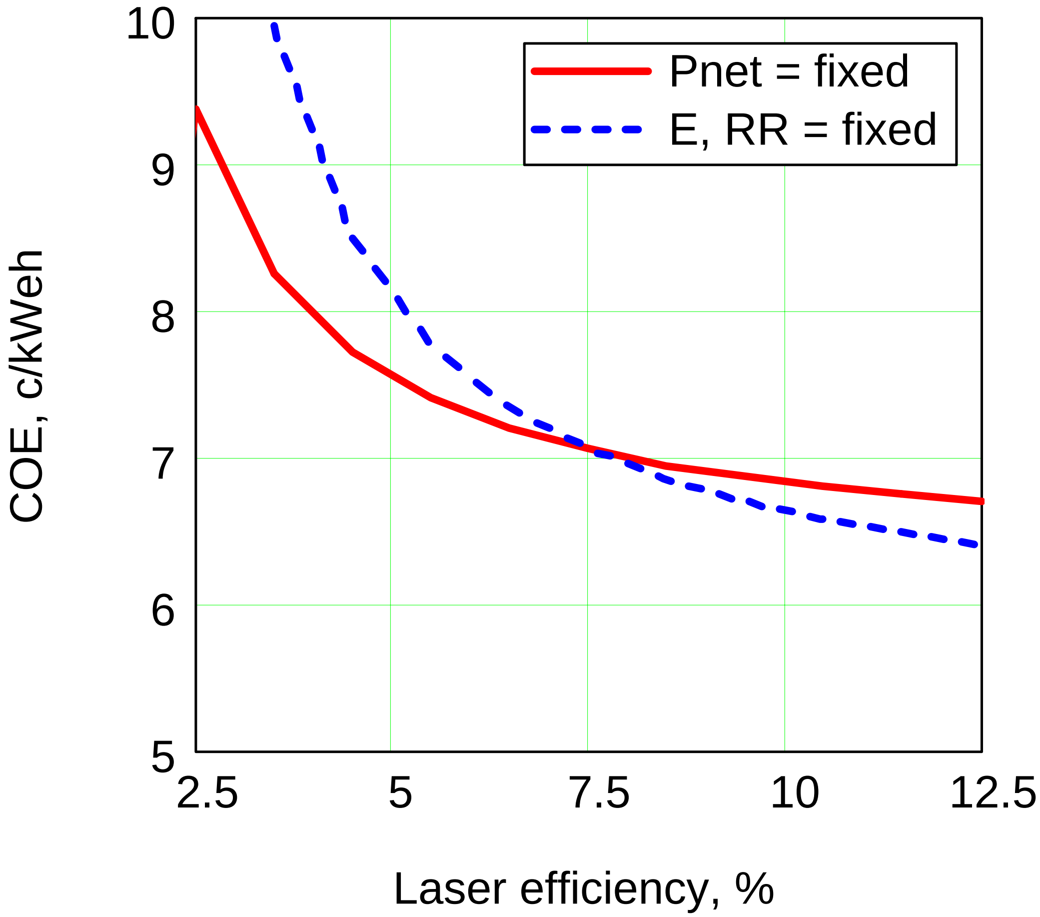


COE from O&M



Laser O&M not explicitly included

COE vs laser efficiency when net power is allowed to vary



Red curve:

Pnet = 1000 MWe = fixed

RR = 10 Hz = fixed

E and G vary

Blue curve:

E = 1.91 MJ = fixed

G = 241 MJ = fixed

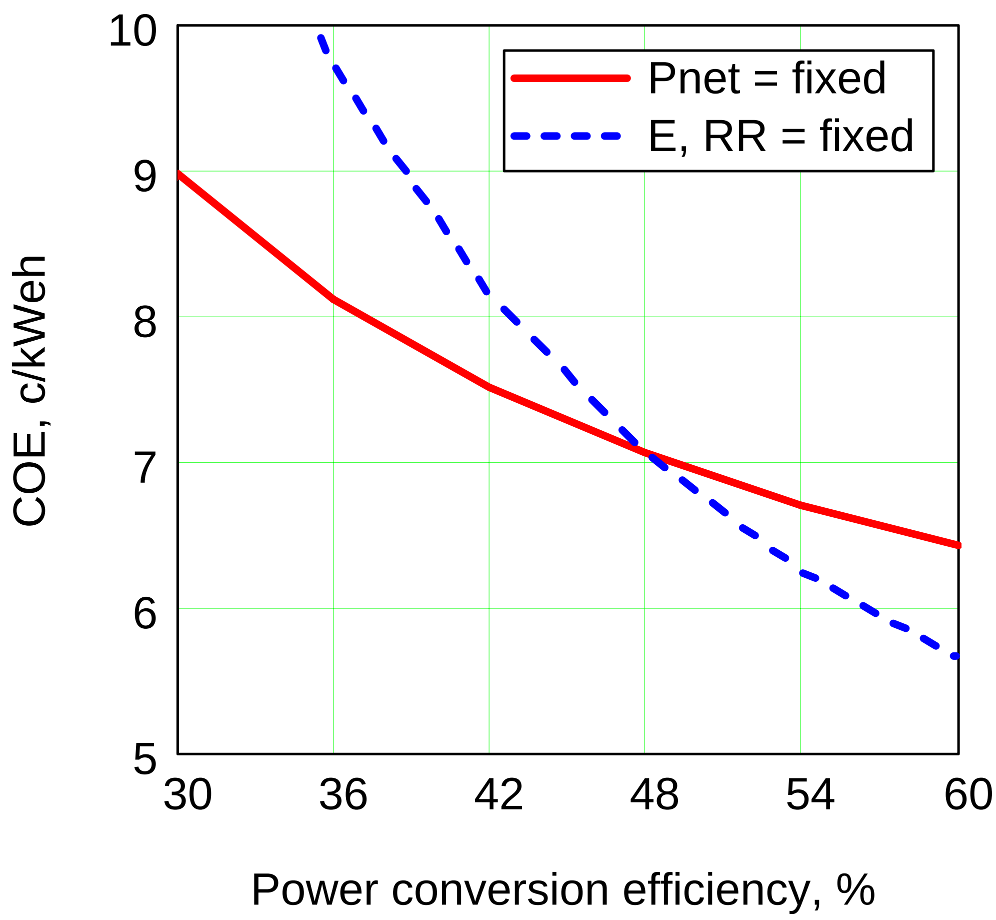
RR = 10 Hz = fixed

Pnet varies:

η_d = 2.5% → Pnet = 493 MWe

η_d = 12.5% → Pnet =1102 MWe

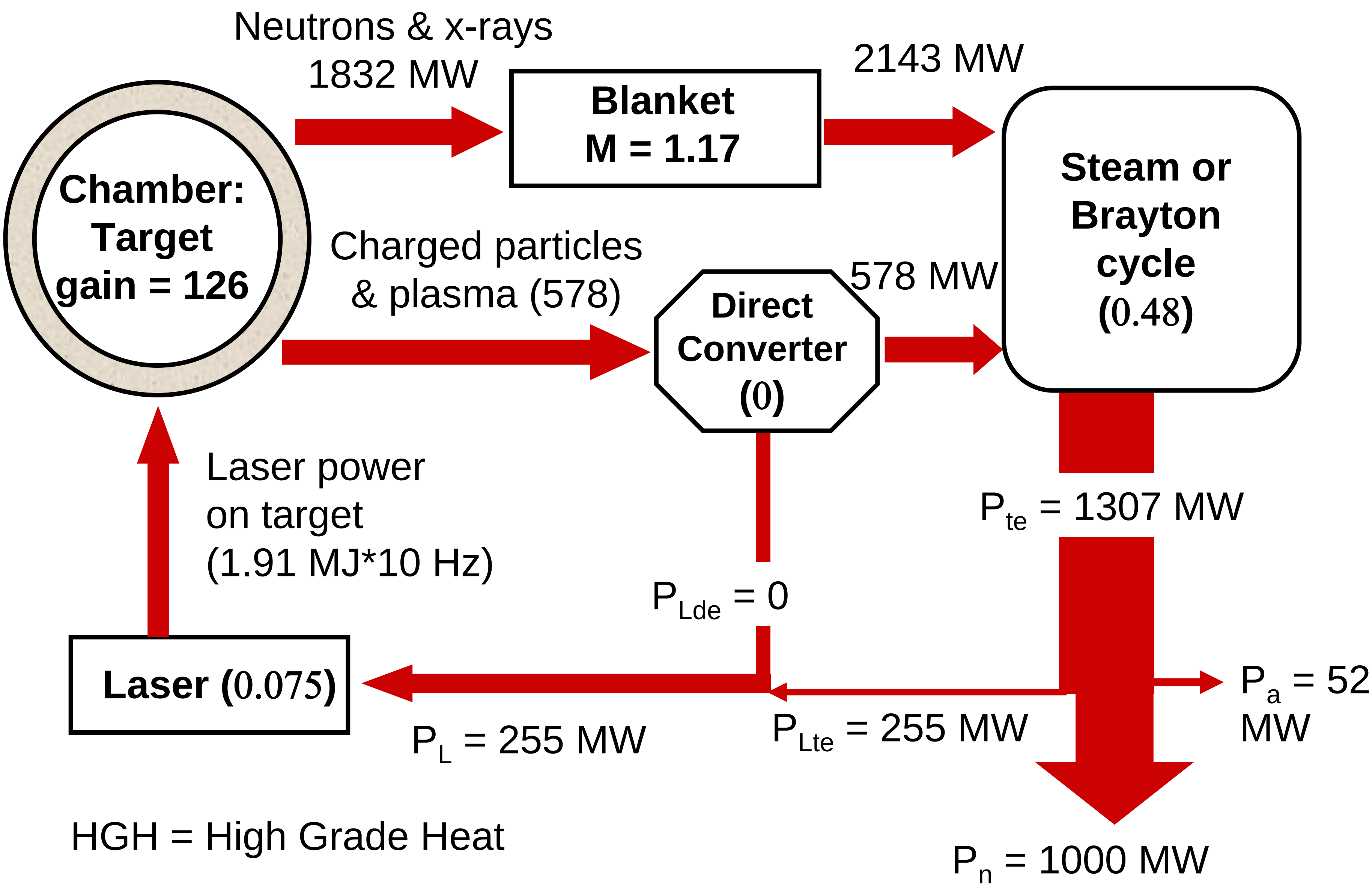
COE vs power conversion efficiency when net power is allowed to vary



Red curve:
Pnet = 1000 MWe = fixed
RR = 10 Hz = fixed
E and G vary

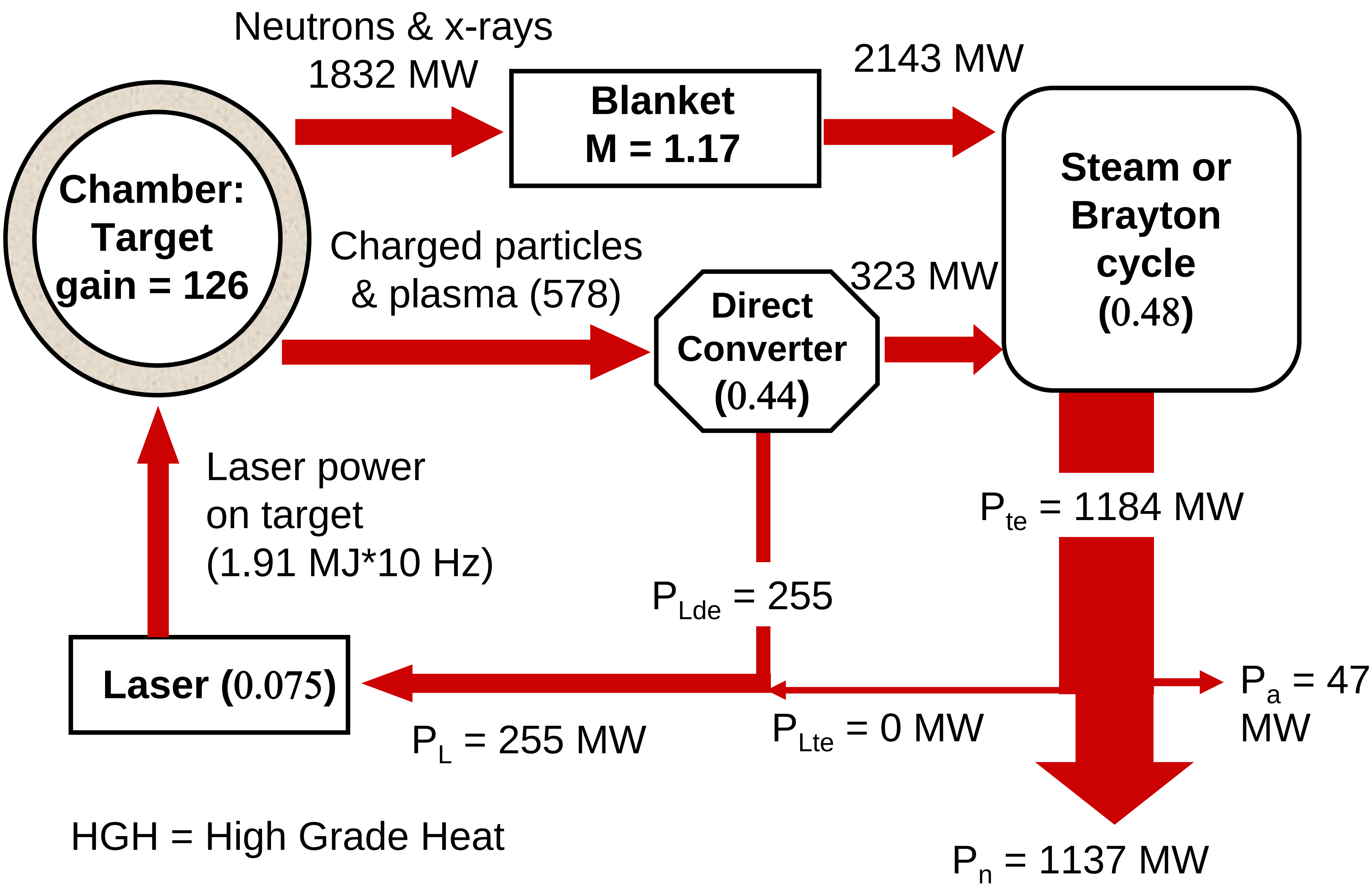
Blue curve:
E = 1.91 MJ = fixed
G = 241 MJ = fixed
RR = 10 Hz = fixed
Pnet varies:
η_c = 36% → Pnet = 686 MWe
η_c = 60% → Pnet =1313 MWe

Power flow diagram with direct conversion: Direct electric = 0



HGH = High Grade Heat

Power flow diagram with direct conversion: Direct electric = Laser power



If annual costs = constant, COE decreases by 12%

Many system trades need to be considered for magnetic diversion concept (repeat from 11/05)

- **Costs**
  - \+ **Chamber (smaller chamber → lower cost first wall and blanket)**
  - – **Magnets, cryo refrigeration system, magnet structural support and shielding**
  - – **Ion dump (ion dump "first wall", cooling, shielding)**
- **Performance**
  - \+ **Lower first wall heat flux → more options for FW coolant**
  - \+ **Possible higher operating temp → higher thermal conversion efficiency, but**

    - requires advanced materials → higher costs, longer development time?
  - \+ **Possible direct conversion of ion energy → possible higher conversion eff., but**

    - requires added equipment, cost and complexity
- **Nuclear Considerations**
  - – **Small chamber → shorter FW life for given fusion power**
  - – **Neutron leakage thru ion port → reduced TBR, shielding issues**
  - – **Need to shield cryo magnets**