TRI ALPHA ENERGY
THE POWER OF INGENUITY

pB11-reactor: trends and physics issues

S.Putvinski
For TAE team

OUTLINE

- New cross section for pB^{11}
- Optimization of plasma and device parameters
- Physics issues for reactor
  - Gas/recycling control
  - Plasma fueling
  - Ash control requirements
  - Energy conversion

TAE goal is development of pB^{11} fusion

$$^{1}H + ^{11}B = ^{4}He + ^{4}He + ^{4}He$$

- Advantages:
  - No neutrons (almost), no neutron damage of the wall
  - No Tritium breeding is required
  - Fuel is benign and widely available (^{11}B abundance 80%)
  - Low activation of plasma facing components
- Difficulties:
  - High plasma temperature is required
  - The required nτ is larger than for other fuels
  - Sensitive to He ash

pB^{11} cross section and α spectrum has a long history

Dee and Gilbert , *1936* *Proc. Roy. Soc. A, vol.* 154, *Plate* 5

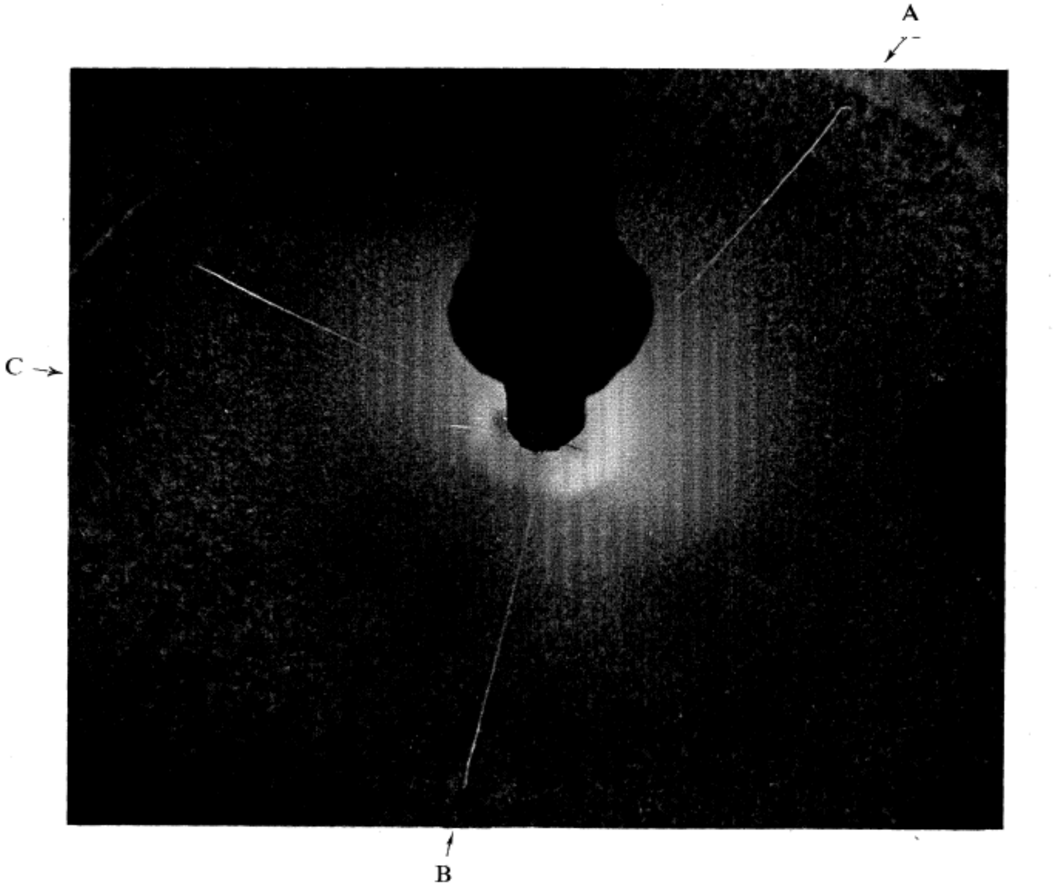
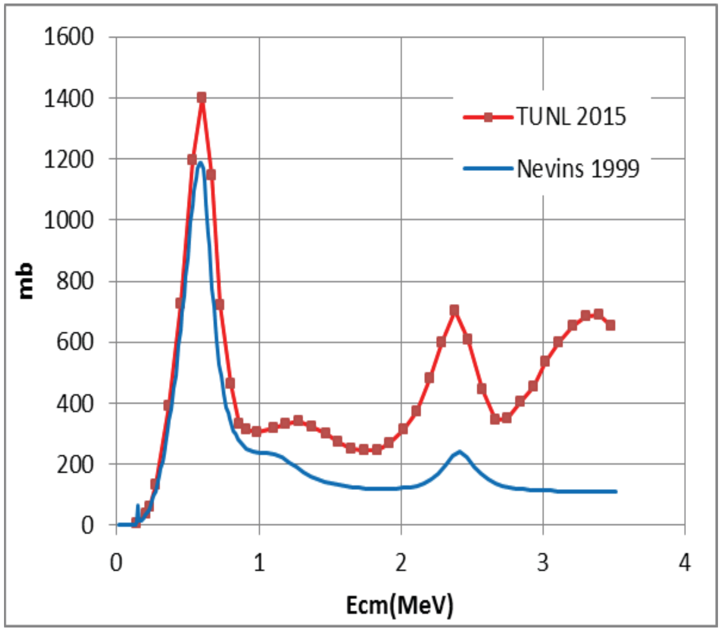


FIG. 6.

- The most cited study is: H. Becker, C. Rolfs, H. Trautvetter, Z. Phys. A 327 (1987) 341.

New pB^{11} cross sections from TUNL



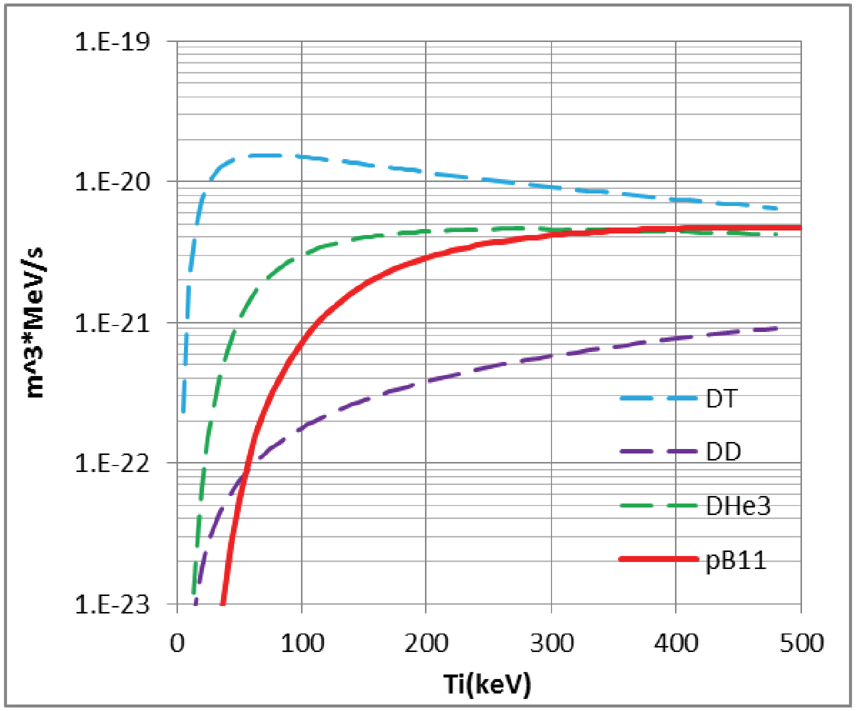
M.C.Spraker, et al. J. Fusion Energy, 2011

S.Stave, et al., Phys. Let. B, 696(2011)26

“Updated reaction rate calculations of pB11B”,
M.H. Sikora,H.R. Weller, *Duke University and TUNL,*
June, 2015

- pB^{11} cross section have been re-measured at TUNL facility (uncertainty 3.5%). It is higher than previously assumed
- α-particle spectrum is also different from widely accepted (after H. Becker, et al., Z. Phys. A 327 (1987) 341)

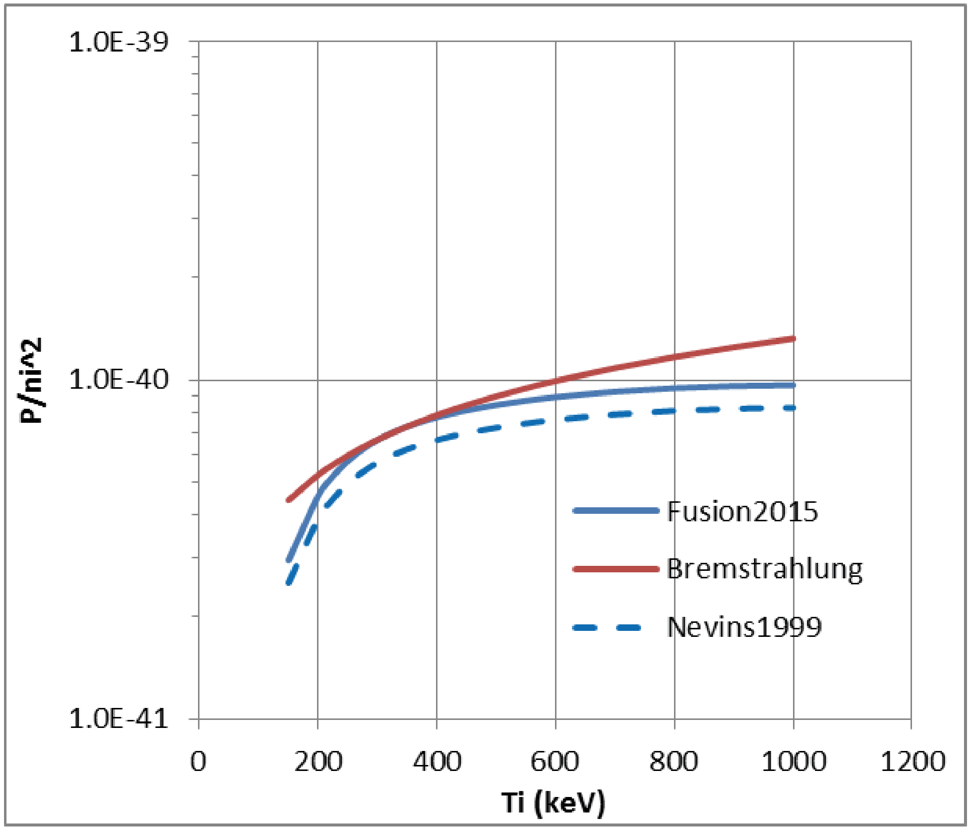
pB^{11} fuel has good reactivity



- Maximum fuel reactivity, $<\sigma v>*E_{fusion}$, of pB^{11} is high:
  - Only 3 times less than DT,
  - Comparable with DHe^3,
  - 5 time higher than DD

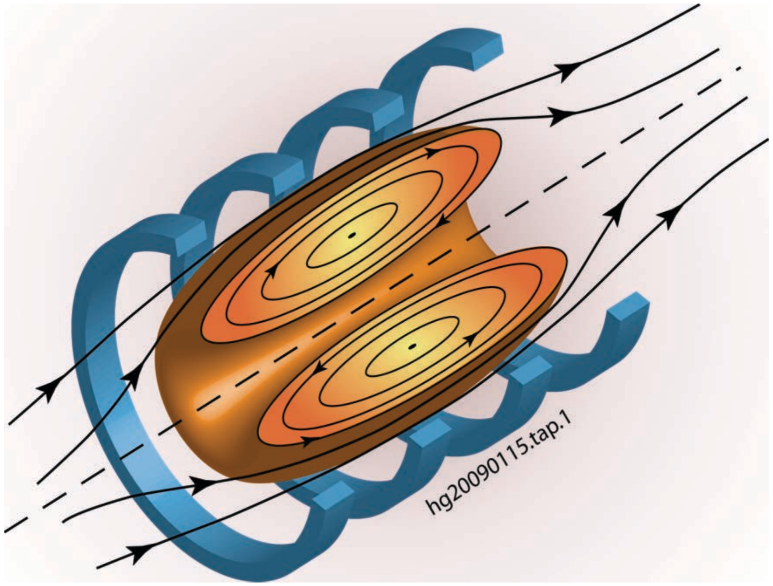
- pB11 fuel requires higher temperature to achieve high reactivity

pB11 can have higher Q than previously concluded



- Ignition of pB11 fuel is possible with new cross sections
- Optimum ion temperature is in the range 200-400 keV

Neutral Beam Driven Field Reversed Configuration



- FRC opens a unique pass to high temperature plasma
- Very low magnetic field -> low synchrotron radiation
- Confinement scaling predicts plasma confinement time increases with plasma temperature

$$n\tau \sim (rB)^{\alpha}T^{\gamma}$$

Two step optimization of design point

- Optimization of plasma parameters to estimate Q
- Optimization of device parameters

0D model

- Power balance equations for ions and electrons
- Total power balance to evaluate NB power:

$$P_{fus} + P_{NB} = P_{brem} + P_{conv}$$

- Electron power balance to evaluate T_e:

$$P_{fus,e} + P_{aux,e} + P_{ie} = P_{brem} + P_{conv,e}$$

- Convective loss: $P_{conv} = n\eta T/\tau_p$ *with* $\eta_i = 1.5$, $\eta_e = 5.5$

Fusion gain, Q

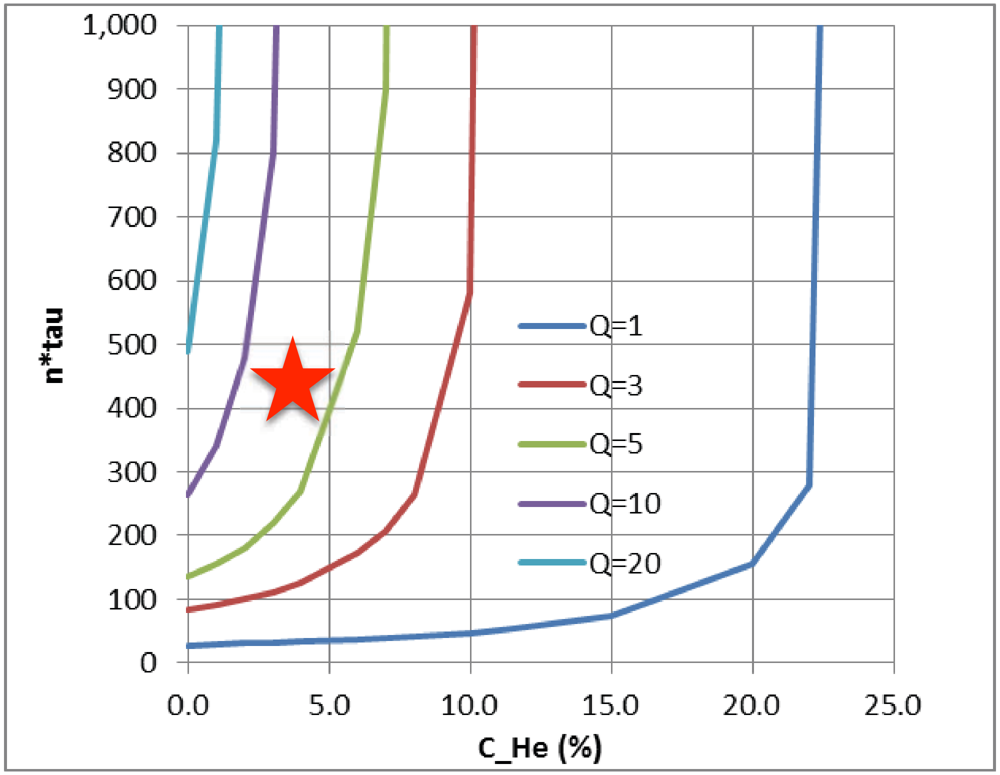
- All powers ~ n_i^2 -> density drops from balance equations

- Essential plasma parameters
  - Ion temperature, T_i
  - Boron concentration, $C_B = n_B/n_i$
  - He ash concentration, $C_{He} = n_{He}/n_i$
  - $n_i\tau_p$

- T_i and C_B are optimized to maximize $Q = P_{fus}/P_{aux}$

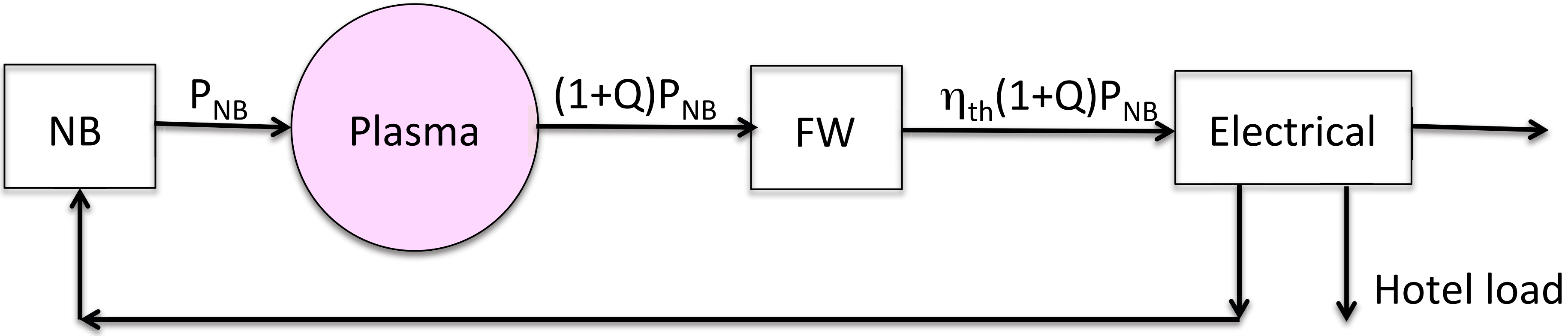
- Optimum values: T_i ~ 330 keV, C_B ~ 0.12 -0.14.

Maximum Q of pB11 fuel vs $n\tau_p$ and C_{He}



- There is lethal He concentration, C_{He}, for each Q
- Ignition is possible but requires very high $n\tau_p$

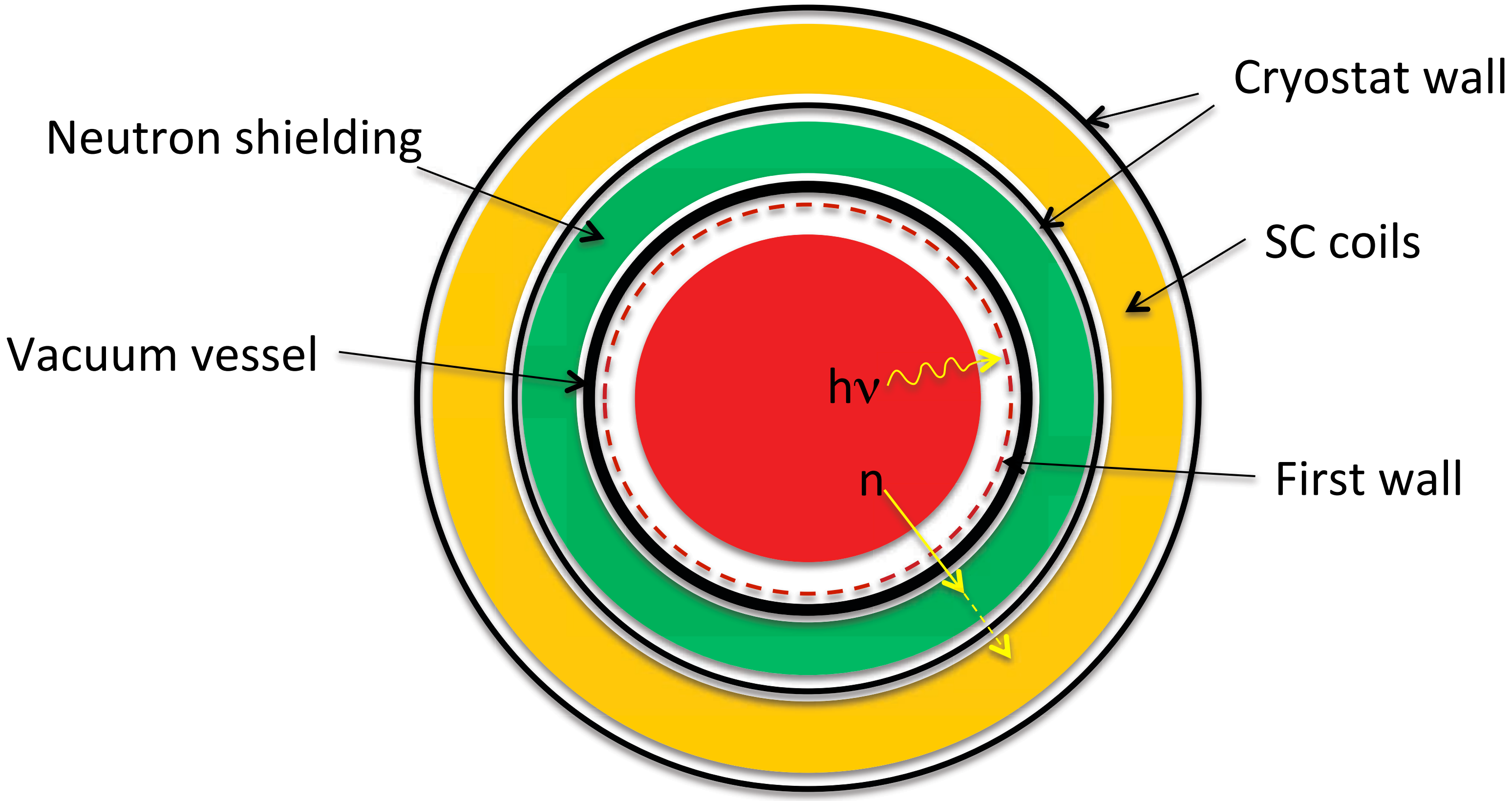
$Q = P_{fus}/P_{NB} > 3$ is required for Plasma Energy Generator (PEG)



$$P_{el} = P_{NB}\{(Q+1)\eta_{th} - 1/\eta_{NB} - \eta_{hotel}\}$$

- To get net electrical power $Q > 3$ (at $\eta_{th} = 40\%$, $\eta_{NB} = 0.7$, $\eta_{hotel} = 0.15$)

Optimization of PEG device



- 80% of fusion power in form of 100-200 keV photons from Bremstrahlung
- 0.1% of fusion power in from of 1-2 MeV neutron from secondary reaction $\alpha(B^{11},n)N^{14}$
- Constrain: Δ = shielding + other shells + gaps ~ 0.4-0.5 m

Optimization of PEG device

- At fixed temperature $n \sim B^2$ and fusion power scales as:

$$P_{fus} \sim V_{pl} n^2 \sim r_s^3 n^2 E \sim B^4 r_s^3 E$$

- Increase of magnetic field improves economics
- Field is limited by SC technology
- Plasma radius, $r_s > 2\Delta$, for efficient use of magnetic field

Stability constrain S*/E

- Traditional FRC's have density limit S*/E < 3.5

$$S^*/E \sim r_s/\rho_L E \sim r_s B/ET^{1/2} \sim n^{1/2}/E$$

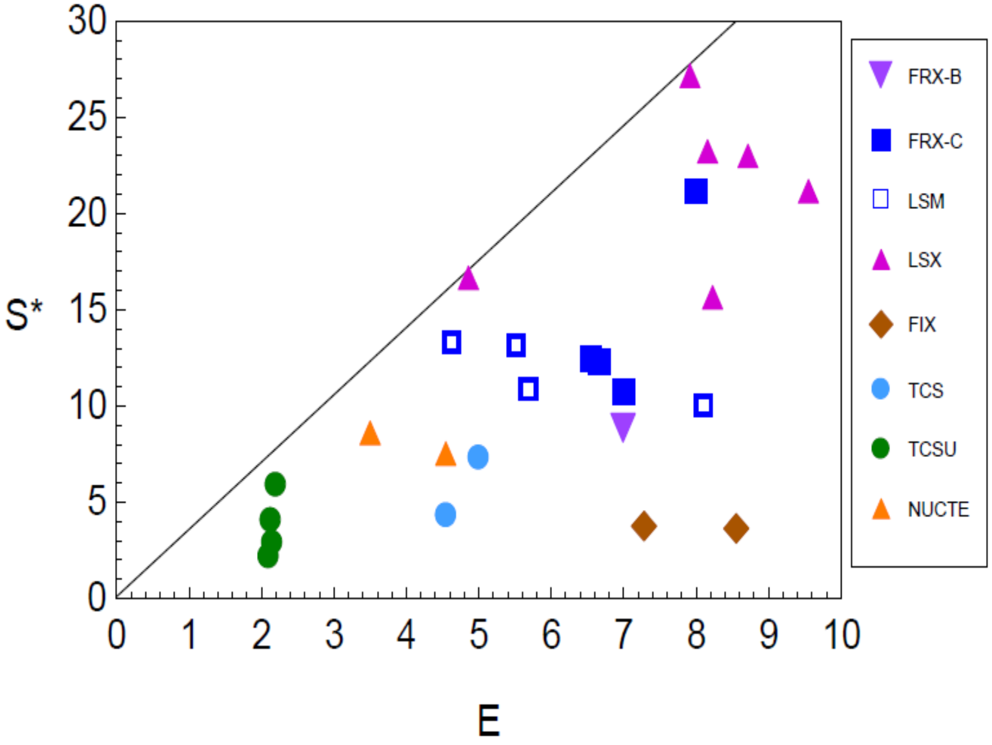
- Economics drives to higher fusion power density, $p_{fus} \sim n^2$, i.e. to density limit

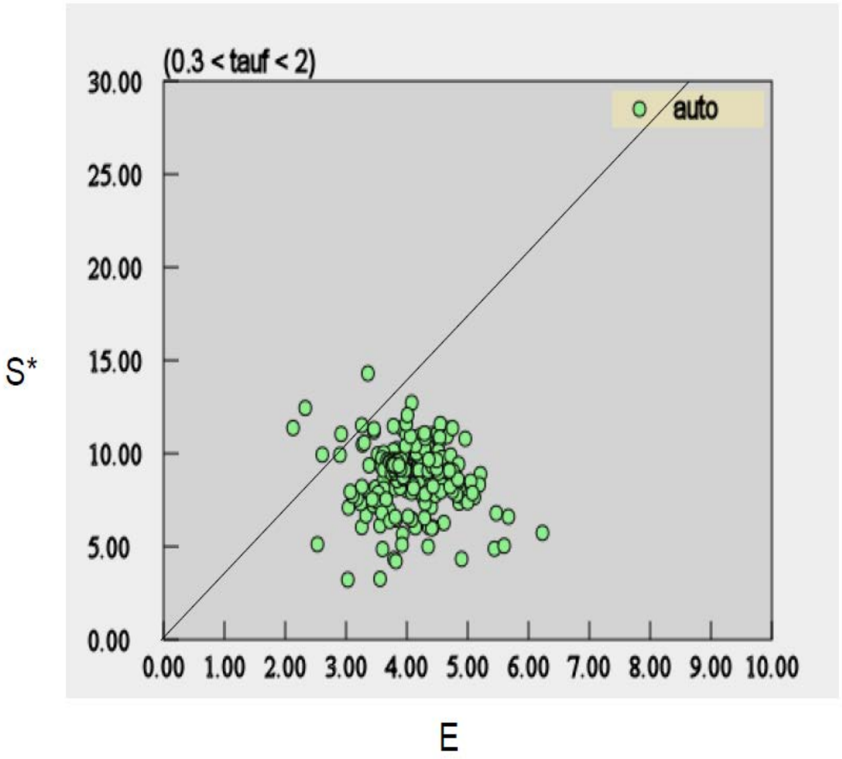
- TAE confinement scaling predicts $n\tau_p \sim rTB \sim S^*T$

- The higher S^* -> the larger $n\tau$, the larger power density -> the better economics

- Reactor shall operate close to the density limit. Plasmas with large elongation are preferable for the reactor

Plasma stability limit





- Tilt mode stability *S*/E < 3.5*
- Present database limited by *E < 10, S* < 27*
- NB driven FRC's with high pressure of beam ions are expected to be more stable.

DEMO-lite, DEMO-E, and Commercial PEG

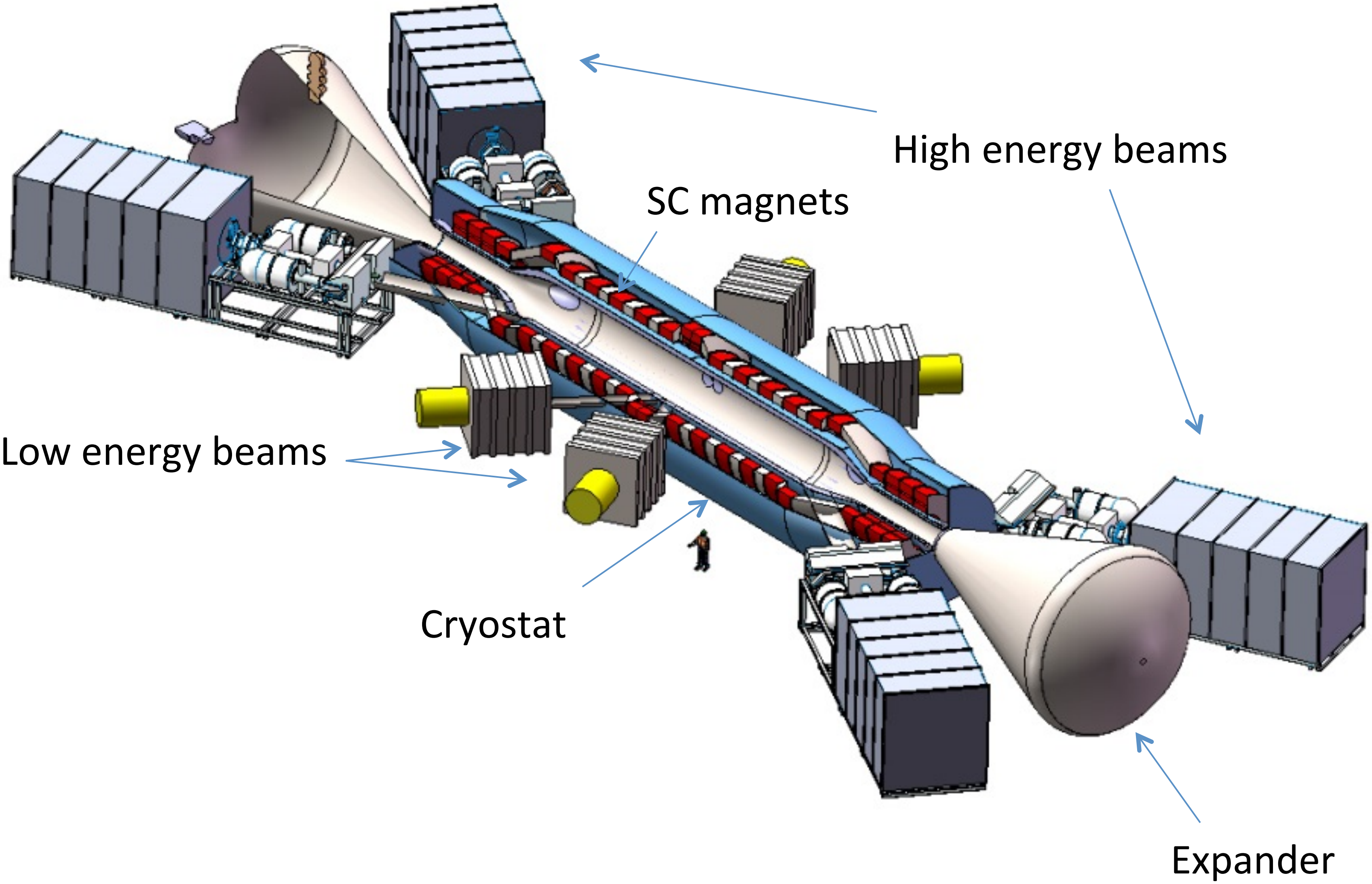
	DEMO -lite	DEMO-E	CPEG
Plasma radius, rs (m)	0.80	1.20	1.25
Magnetic field (T)	6.0	6.0	8.0
Fusion power (MW)	**40**	200	1000
Q	3	5.20	7.00
NB power in plasma (MW)	40	40	140
Net electrical power (MW)	NA	**34**	**380**
Required $n\tau_p$ (10^{21} s/m^3)	10	30	40
Confinement margin for TAE scaling*)	5.6	5.2	6.8
Ash concentration (%)	<10	4.00	3.00

*)Confinement margin = τ_p(scaling)/τ_p (required)

DEMO-lite (ITER type)

- Demonstration of Q > 1(3) with pB^{11} fuel at pulse length up to 500 s
- No electrical power production
- Does not require high efficiency of NB's
- Cold, water cooled wall
- Assumed parallel development of efficient NB's, hot wall technology, direct energy convertors, etc

DEMO-lite


High energy beams
SC magnets
Low energy beams
Cryostat
Expander

DEMO-lite plasma parameters

Q	3	1
Required $n\tau_p$ (s/m^3)	1.0E+22	4.5E+21
Ash concentration (%)	5	10
Ion density, n_i (10^20m-3)	1.42	1.44
Fusion power (MW)	45	44
Radiation power (MW)	49	49
Convective loss (MW)	12	38
Proton beam power (MW)	10.8	22.5
Boron beam power (MW)	4.3	5.8
RF power (MW)	0	15
Confinement time (s)	100	31
Confinement margin*)	5.6	18
S*/E	3	3
S*	43	43

*) Confinement margin = τ_p(scaling)/τ_p (required)

Physics issues for the reactor

- Gas/recycling control
- Plasma fueling
- Ash control requirements
- Energy conversion

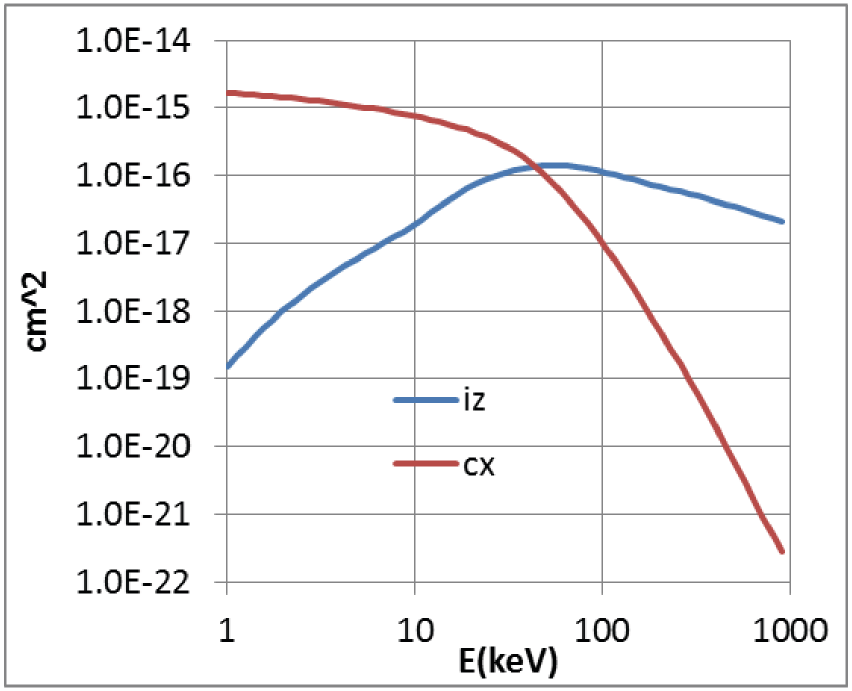
Core plasma fueling is required

- Hydrogen can be fueled solely by NBs
- Boron core fueling must to be developed. Viable candidates are
    - Injection of Compact Toroids (CT)
    - Boron ion beams (developed earlier by TAE)
    - Boron NB's - 500-700 keV to penetrate into core (based positive ion technology)
- Tests with two component plasmas at C-2W

Gas handling is much easier in FTC

- At T ~ 300 keV CX cross section is very small. No CX loss for NB or hot plasmas

- Neutral ionization length is < 1 cm. No neutral can penetrate in SOL plasma



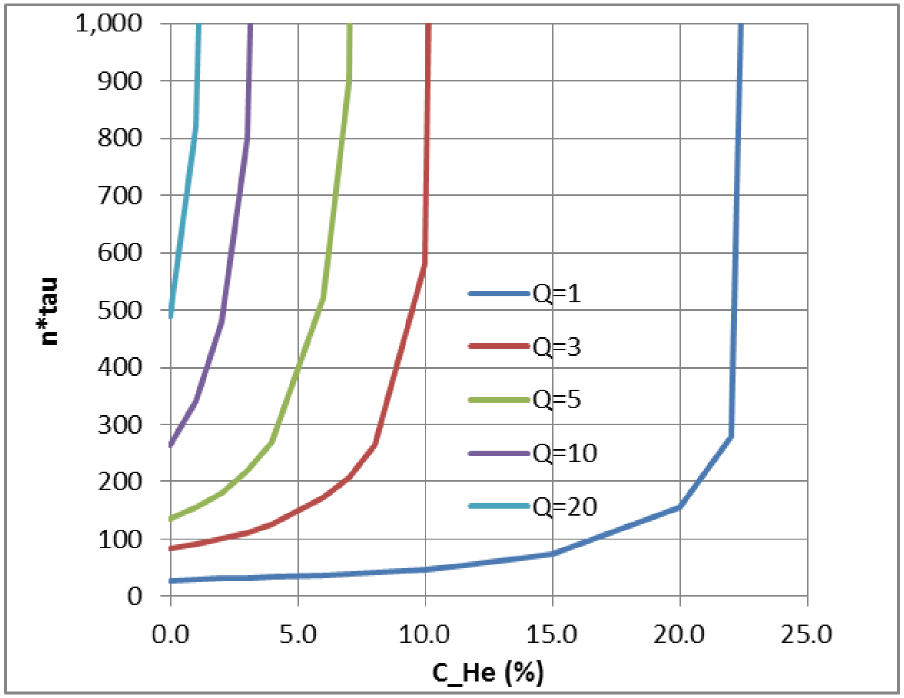
Gas handling in divertors

- Fueling and exhaust composition

	Fueling (%)	Exhaust (%)
Protons	67	29
Borons	33	5
He	0	66

- Total exhaust rate G ~ 10^{20} 1/s
- It is much easier to achieve required gas condition
  - The required pumping speed ~250 m^3/s (compare with 2000 m^3/s in C2W!)
  - Predominantly He with Hydrogen and Boron impurities

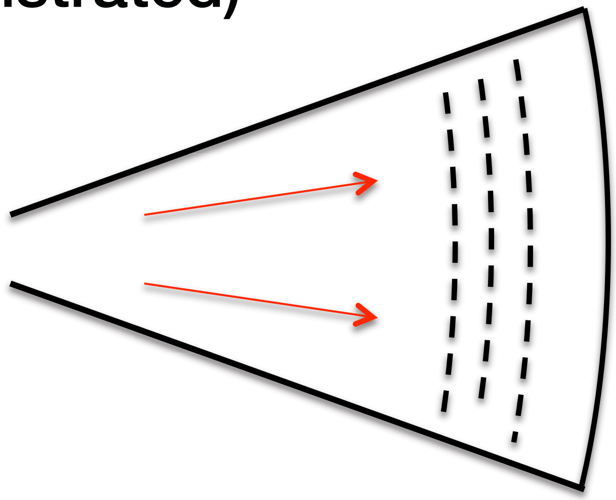
Ash control is critical for pB^{11}



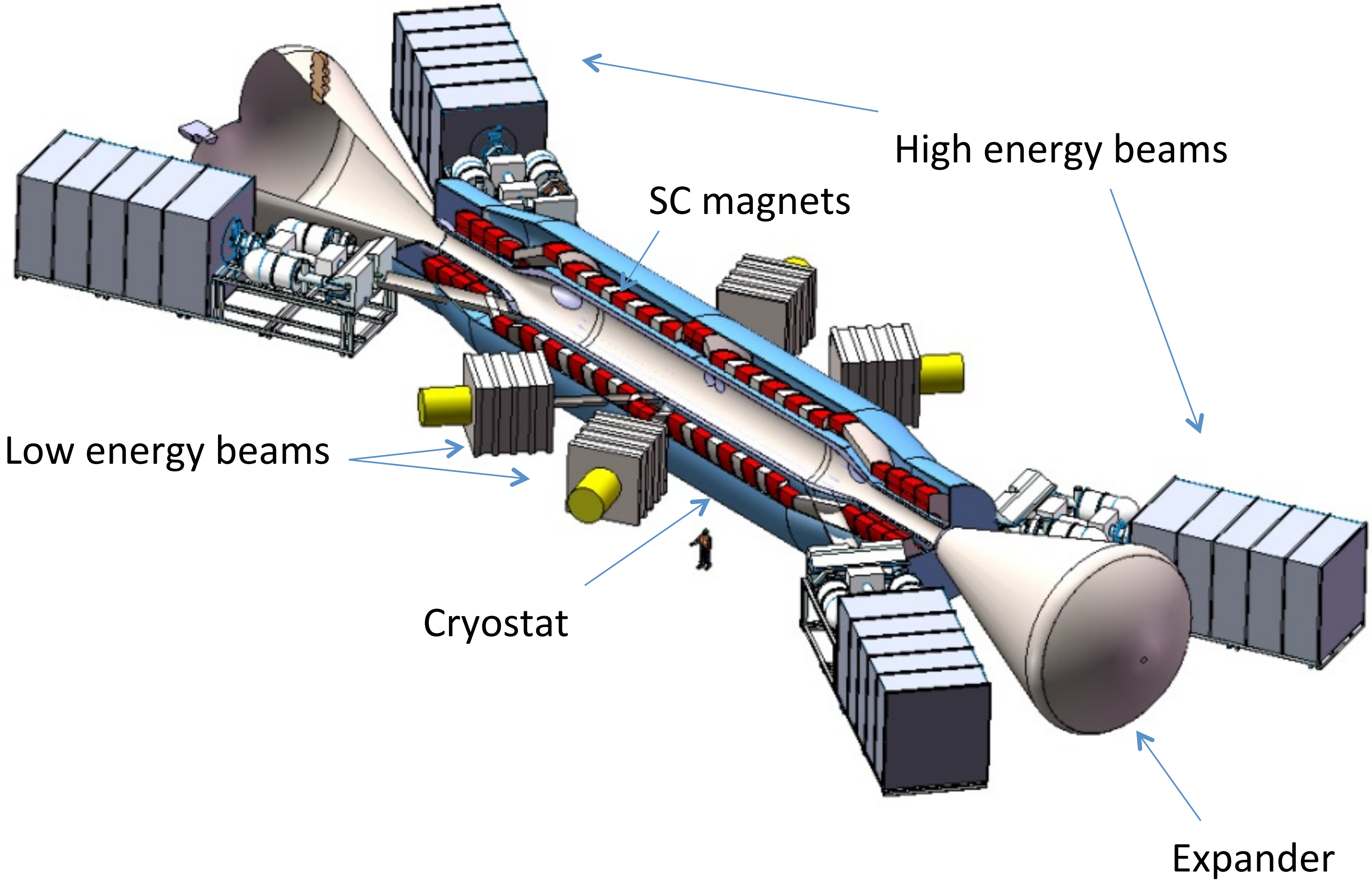
- Without ash control: C_{He} ~ *70-80%* resulting in a very low *Q*
- It takes about 100 s to build up ash
- High *Q* requires very efficient ash control
- Required ash concentration < 5%

Energy conversion

- 80% of fusion energy goes to the side wall in form of x-rays (~150keV). Converted in electricity by a thermal cycle (50% efficiency)
- Convective energy loss into expanders (20% of fusion power) can be converted electrostatically in expanders
- Ions are accelerated by *gradB* and electric potential in the convertors to $E_{||} \sim 1.2\text{-}1.5\ MeV$ with $E_{perp} < 10\ keV$
- Technology developed for mirror machines in 70th (85% efficiency demonstrated)



DEMO-lite


High energy beams
SC magnets
Low energy beams
Cryostat
Expander

Summary

- Higher Q ~ 6-8 is possible with new cross sections

- Many physics and engineering challenges to address but no stoppers

- C-2W will address some of the critical physics issues. A parallel R&D work is equally important

TRI ALPHA ENERGY
THE POWER OF INGENUITY