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Divertors of Linear Systems

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Some of Norman's contributions to fusion energy:

1960s: Test-particle approach to fluctuation theory

Plasma rotation in theta-pinches

1970s Relativistic electron beams

High-power ion beams

1980s Collective ion acceleration

Gas-puffs and wire arrays

1990s Non-thermal fusion reactors

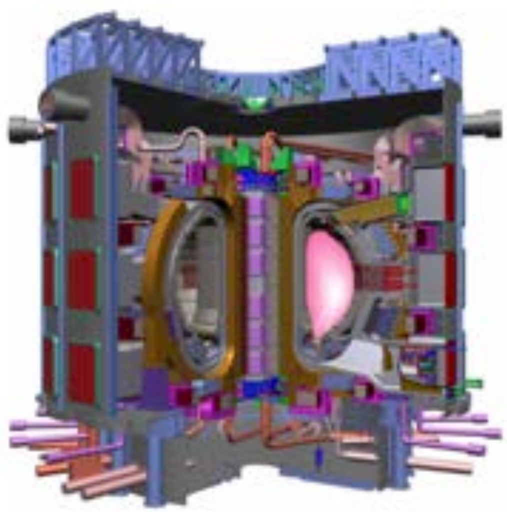
Colliding beams and alternative fusion concepts

Field-Reversed Configurations

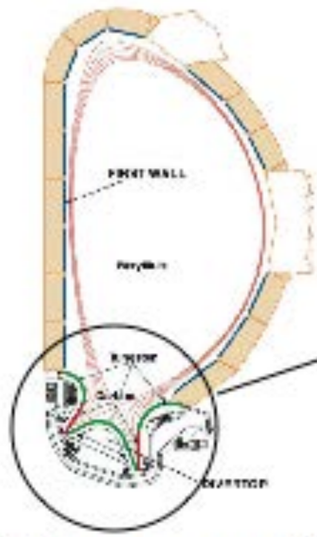
A direct continuation of this work is an FRC-based linear system that is being developed by the TAE (*Binderbauer, M. W.; Tajima, T.; Steinhauer, L. C. andTAE Team. A high performance field-reversed configuration PHYSICS OF PLASMAS Volume: 22, Article Number: 056110 , MAY 2015*)

Any (successful) fusion system needs to find solutions for the heat-exhaust problem

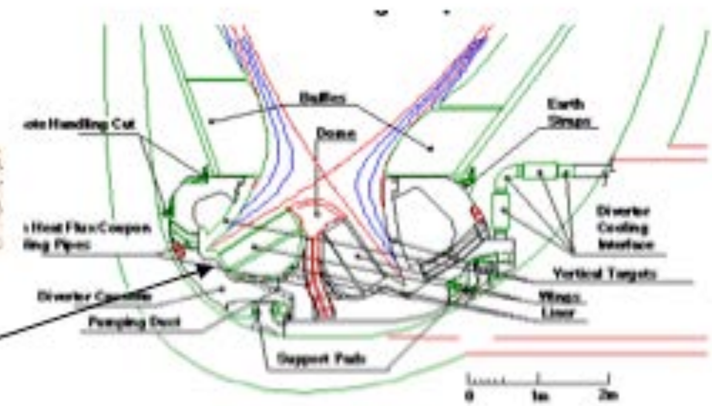
This problem is quite severe for the tokamaks



ITER (International Thermonuclear Experimental Reactor)



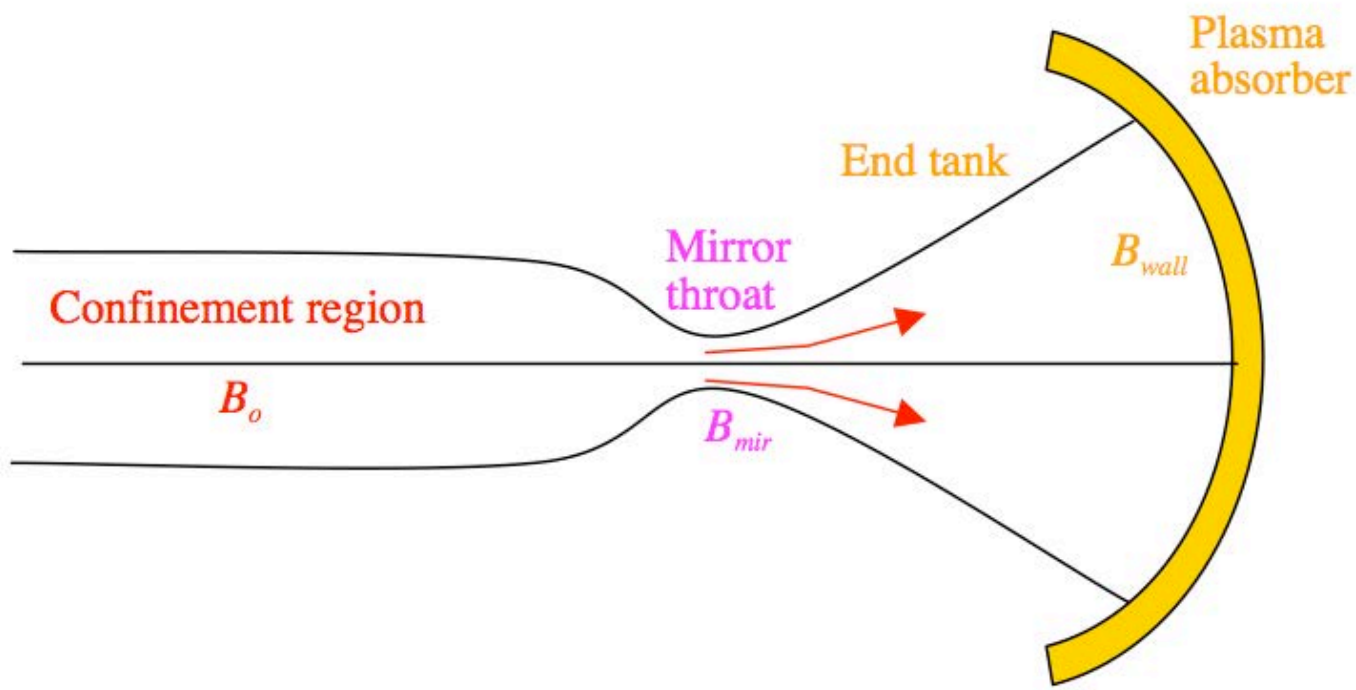
ITER cross section



Divertor detail

In various design studies, the values of the heat loads of ~ 30-60 MW/m^2 were found for future commercial reactors (energy flux at the surface of the Sun is 60 MW/m^2). The present technological limit is 5 (10) MW/m^2

This problem has a natural solution for the linear fusion systems



By using absorbers of 5 m radius, one can reduce the heat load on the end plates to a comfortable level of 1-1.5 MW/m^2
($S=\pi r^2 \sim 80\ m^2$, 100 MW per end)

An issue of too high electron heat loss along the open field lines is often mentioned as a show-stopper for the linear confinement systems

This is actually not an issue for the pulsed, high-density linear system: use large expansion tanks, so that the plasma would not reach the ends for the time sufficient for the energy release

We, however, are interested in steady or quasi-steady systems – the reason for this talk

OUTLINE

A reference case of a zero secondary emission

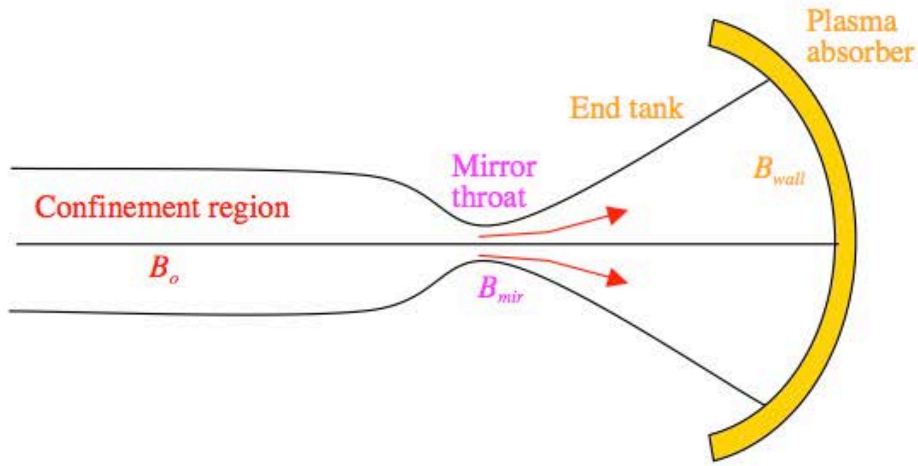
Large secondary emission

Non-negligible gas pressure in the end tanks

Summary

Zero secondary emission

A paradox: charge neutrality and current neutrality seem to be incompatible at large expansion ratios, $K \equiv B_{mir}/B_{wall} > (m_i/m_e)^{1/2}$



Charge neutrality:

$$n_i \sim n_{mir}\frac{B}{B_{mir}} = n_e \sim n_{mir}\exp\left[\frac{e(\varphi - \varphi_{mir})}{T_e}\right]$$

Current neutrality (equal number of electrons and ions leaves the mirror):

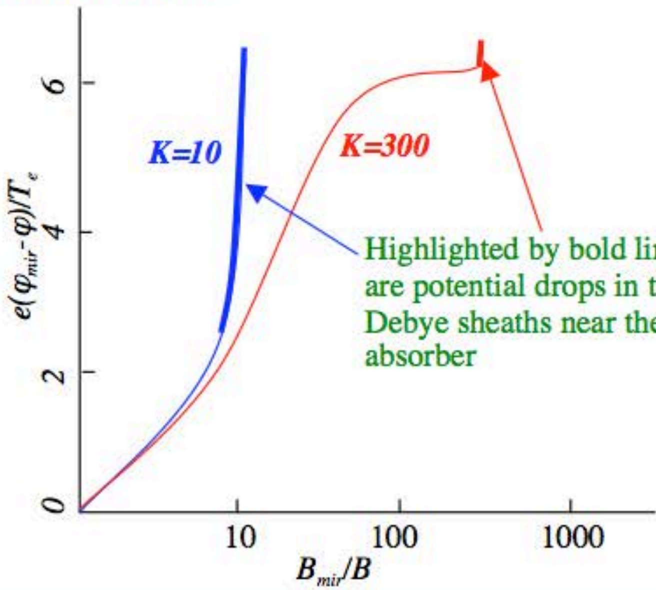
$$j^{(i)}_{mir} \sim en_{mir}v_{Ti};\quad j^{(e)}_{mir} \sim en_{mir}v_{Te}\exp\left[\frac{e(\varphi_{wall} - \varphi_{mir})}{T_e}\right]$$

By evaluating the plasma potential from the charge neutrality and plugging it into expression for j_{emir}, one finds that, at $K \equiv B_{mir}/B_{wall} >> v_{Te}/v_{Ti} \sim (m_i/m_e)^{1/2}$, $j^{(e)}_{mir}$ *becomes formally much less than* $j^{(i)}_{mir}$ which cannot be true.

Zero secondary emission

A solution to the paradox*: the electron distribution function becomes strongly different from the Maxwellian at $B_{mir}/B \gg (m_i/m_e)^{1/2}$ leading to a flattened potential distribution

Potential distribution for the absorber situated at K=10, and K=300. Note a flattening of the potential in the zone of a weak magnetic field in the second case



Comments:

The total potential drop between the wall and the mirror remains relatively constant, $\sim 6T_e/e$, independent of K

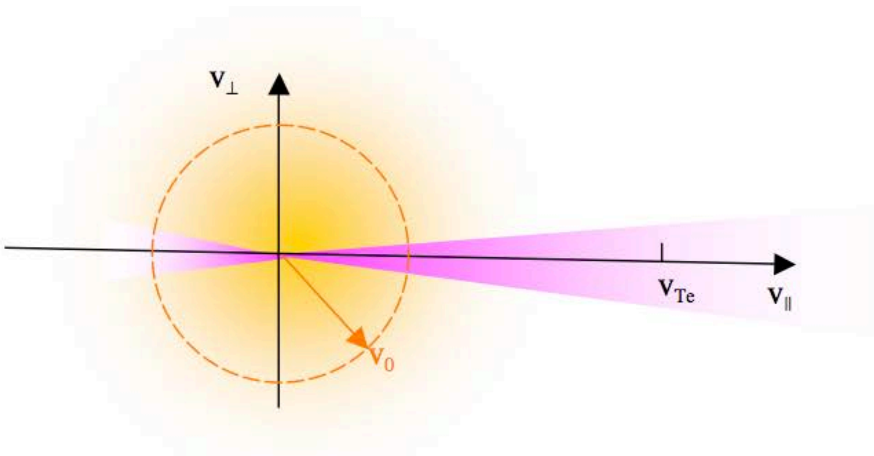
The region of the flat potential for K=300 occupies much larger section of the expander than it might seem from the figure (an effect of a logarithmic scale)

Sheath potential drop becomes small for $K \gg (m_i/m_e)^{1/2}$:

$$e\delta\varphi_{Debye}/T_e \sim (1/K)^{2/3}(m_i/m_e)^{1/3} \ll 1$$

* I.K. Konkashbaev, I.S. Landman, F.R. Ulinich. JETP, **74**, 956 (1978); V.V. Mirnov, D.D. Ryutov. "Gas Dynamic Trap," In: Summaries in Science and Technology, v.8., 1988 (in Russian).

Electron distribution function in the expander has a peculiar shape



In addition to the transiting particles (purple), originating at the mirror, there appears also a large group of trapped particles (orange), sustained by the scattering of the transiting particles; trapped particles provide the main contribution to the electron density

v_{Te} – electron thermal velocity

v_0 – characteristic velocity of electrons trapped in the end tank

$$v_0 \sim \frac{v_{Te}}{K^{1/3}} \left(\frac{m_i}{m_e} \right)^{1/6}$$

Large secondary emission

Large secondary emission may substantially increase electron heat loss

However, there are several possible lines of defense against a large secondary emission:

1. Do nothing and rely on the large mirror ratio between the wall and the mirror throat
2. Use the "Venetian blind"* type of the plasma absorber, with the material surface forming a shallow angle to the magnetic field
3. Use very long end tank, to allow for collisional and anomalous scattering of secondary electrons to occur
4. Use suppressor grids

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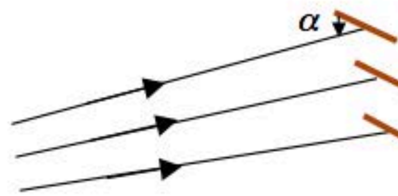
*Cf. R.W. Moir, W.L. Barr, Nuclear Fusion, **13**, 35 (1973).

Large secondary emission

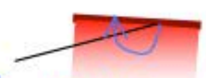
The “Venetian-blind” approach



End-wall split into a number of rings tilted with respect to the magnetic field. (Shown is a part of the end-wall.)

Potential benefits of this approach:

1. Give a strong kick to the secondary electrons in the direction normal to the magnetic field, via acceleration in the Debye sheath, and thereby increase their μ (and the μB term in the Yushmanov potential)



2. Reduce the secondary emission coefficient η (works at a very small α: then, most of the electrons return to the wall within one gyro-orbit)*

An important parameter affecting the efficiency of this approach: the ratio q of the electron Debye radius to the electron gyro-radius near the wall:

$$q = \frac{\rho_{De}}{\rho_{Le}}\Big|_{wall} = \frac{\omega_{Be}}{\omega_{pe}}\Big|_{wall}$$

*E.g., S. Mizoshita, K. Shiraishi, N. Ohno, S. Takamura, J. Nucl. Mater., **220-222**, 488 (1995), and references therein.

Large secondary emission

There is a substantial difference between GDT and "standard" mirrors with respect to the "Venetian-blind" approach

One has: n_{wall}~n_{mir}/K, $B_{wall}=B_{mir}/K=B_0R/K$, where R is the mirror ratio for the confinement region. Let us also introduce a notation $\varepsilon=n_{mir}/n_0$.

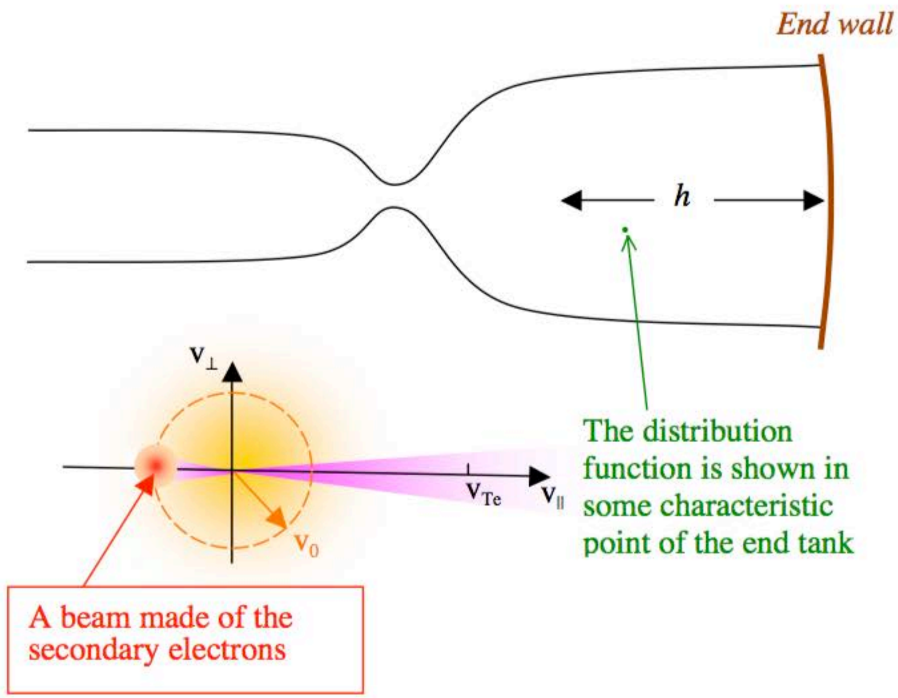
Then, $$q \approx \frac{300 B_0(G)}{\sqrt{n_0(cm^{-3})}} \times \frac{R}{\sqrt{\varepsilon K}}$$

	B_0 G	n_0, cm^{-3}	R	K	ε	q
"Standard" mirror, Q~1	$2 \cdot 10^4$	10^{14}	3	300	10^{-4}	10
GDT, Q~1	$2 \cdot 10^4$	$2 \cdot 10^{14}$	15	1000	1	0.3

The Debye sheath is shorter than the gyroradius for GDT and much longer than the gyroradius in a "standard" mirror.

Using a long end tank

Secondary electrons accelerated by the ambipolar field form a beam-type distribution



If the length *h* of a uniform magnetic field is made longer than the scattering length of the beam of the secondary electrons, they will be reflected from the region of a strong magnetic field

The scattering length for the beam of the secondary electrons:

$$\lambda \sim \frac{10 v_{Te}}{\omega_{pe}(n_0)} \left(\frac{m_i}{m_e} \right)^{2/3} \frac{K^{1/6}}{\varepsilon^{1/2}}$$

For "standard" mirrors the required *h* can be ~ 30-40 m, i.e., quite large but still compatible with the overall reactor design.

Non-negligible amount of the neutral gas

Ionization of the neutral gas in the end tank produces cold electrons and ions

These electrons can be pulled into the confinement region and cause a loss of energy ~ T_e per electron.

The number of ionizations per unit time (related to a unit cross-section in the mirror throat)

$$\dot{N} \sim \varepsilon n_{neutral} n_0 h < \sigma v >_i$$

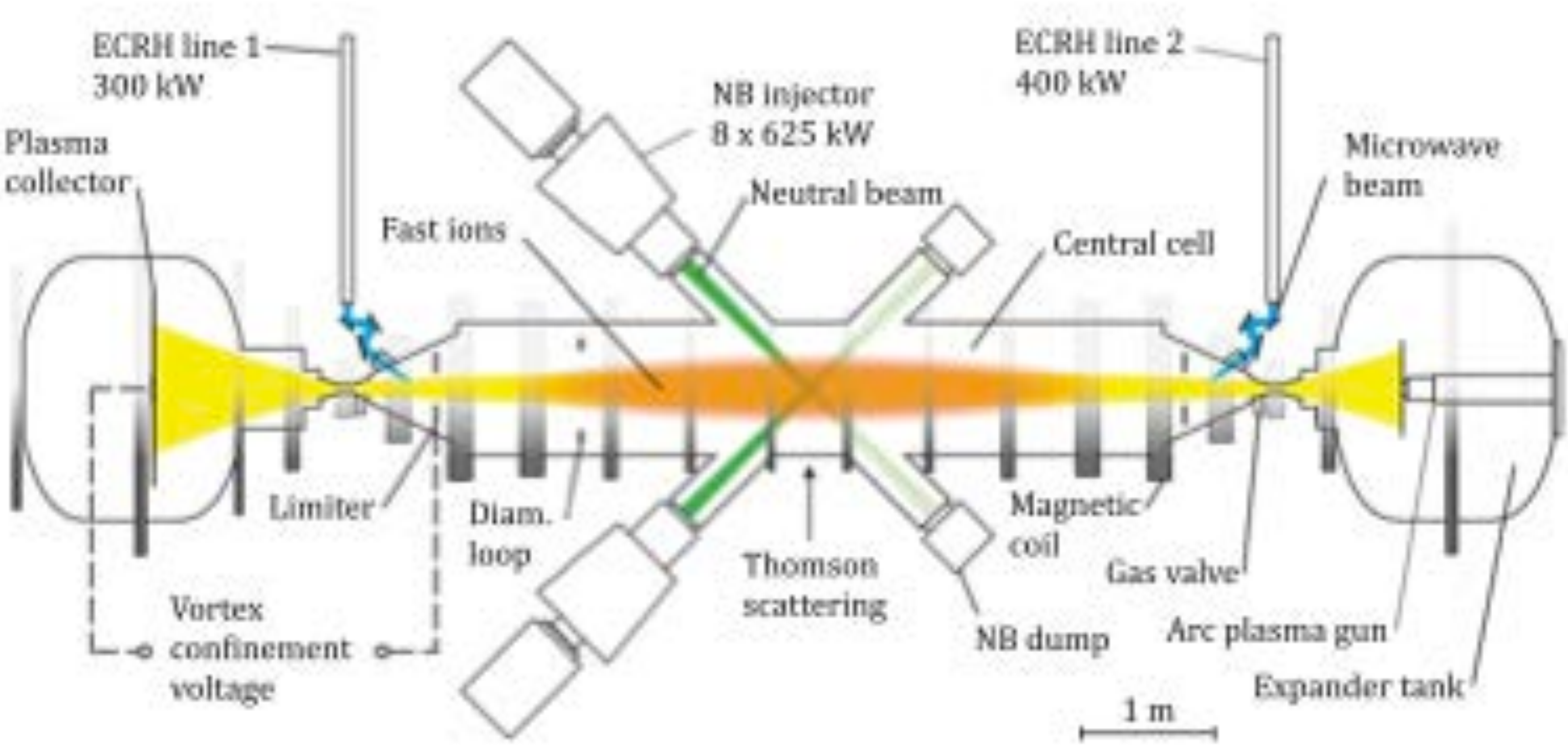
This can cause an additional energy loss ~ $T_e \dot{N}$ (per unit cross-section of the mirror throat):

Comparing this with the usual energy loss ~$(6T_e + 2T_i)\varepsilon n_0 v_{Ti}$, one finds the following constraint on the acceptable neutral density:

$$n_{neutral} << 10 \frac{v_{Ti}}{h < \sigma v >_i}$$

The resulting neutral densities are in the range of 10^{13} cm^{-3} (v_{Ti}~ 10^8 cm/s, $<\sigma v>_i$ ~10^{-8} cm/s, *h*~30 m). The pumping system must be such as to allow pumping of the gas that forms by neutralization of the plasma coming out of the mirrors and maintaining the gas density at the level determined by this inequality. May be somewhat challenging for GDT.

On the GDT facility at Novosibirsk an electron temperature of 0.9 keV is achieved, at the density 2×10^{13} cm^{-3}.



SUMMARY

The exhaust power density can be made comfortably low in linear fusion devices (including the ones with aneutronic fuel)

In the absence of the secondary emission from the end wall, parallel electron heat losses are modest and perfectly compatible with good overall energy balance

Substantial ($\eta \sim 1$) secondary emission may increase electron heat loss

However, there are several ways of reducing the detrimental effect of the secondary emission (tilting the end plates, increasing the length of the end tank, exploiting the beam-plasma instabilities, or using the suppressor grid).

Specific technique would depend on the parameters of a particular device. Constraints on the neutral gas density in the end tanks do not look insurmountable