Survey of Astrophysical Plasma Conditions for Magnetic Reconnection and a Phase Diagram

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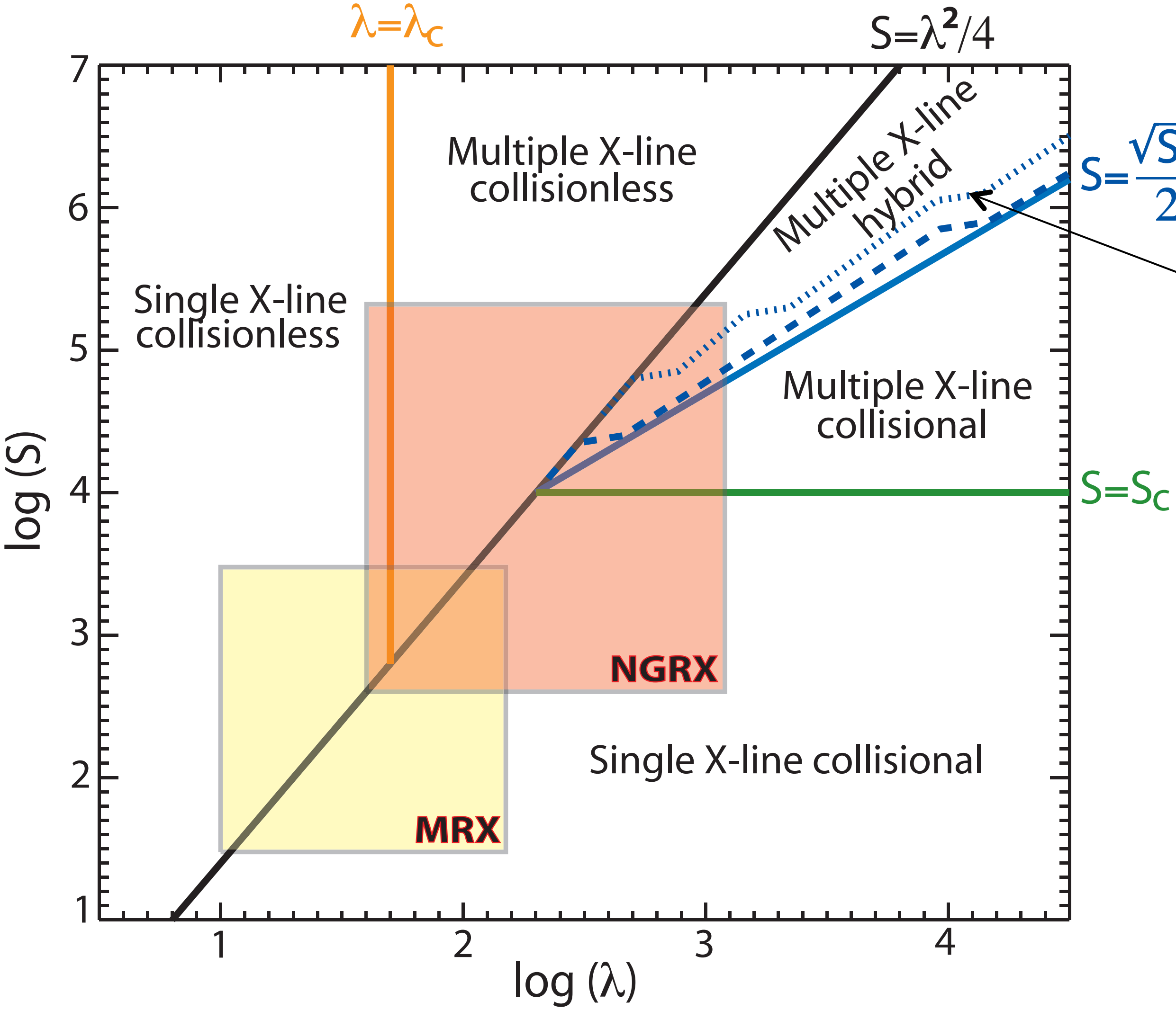
Fundamental Reconnection Problems

- **How is reconnection rate determined? (*The rate problem*)**
- **How does reconnection take place in 3D? (*The 3D problem*)**
- **How does reconnection start? (*The onset problem*)**
- **How are particles energized? (*The energy problem*)**
- **How do boundary conditions affect reconnection process? (*The boundary condition problem*)**
- **How does reconnection take place in relativistic and strongly magnetized plasmas? (*The relativity problem*)**
- **How to apply local reconnection physics to a large system? (*The scaling problem*)**

A Reconnection “Phase Diagram”

Ji & Daughton (2011)

$$S = \frac{\mu_0 L_{CS} V_A}{\eta};\ L_{CS} = \frac{L}{4} \qquad \delta_{SP} = \frac{L_{CS}}{\sqrt{S}} = \rho_s \quad \Rightarrow \quad S = \frac{\lambda^2}{4}$$



Island hierarchy truncated at N=2

$$\lambda \equiv \frac{L}{\rho_S}$$

A Hierarchy Model of Islands

- Hierarchy of islands:

$$N_1, N_2, N_3, \ldots, N_j$$

$$S_1, S_2, S_3, \ldots, S_j$$

$$\delta_1, \delta_2, \delta_3, \ldots, \delta_j$$

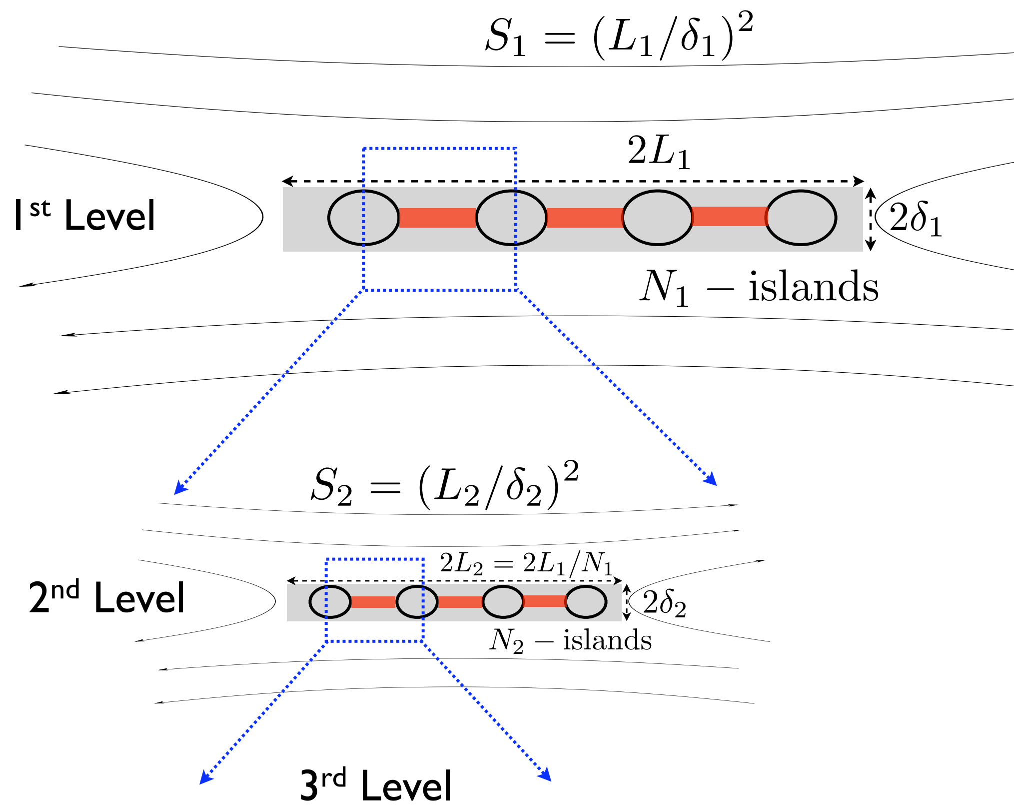
- Assume

$$N_j = \left(\frac{S_j}{S_c}\right)^{\alpha}$$

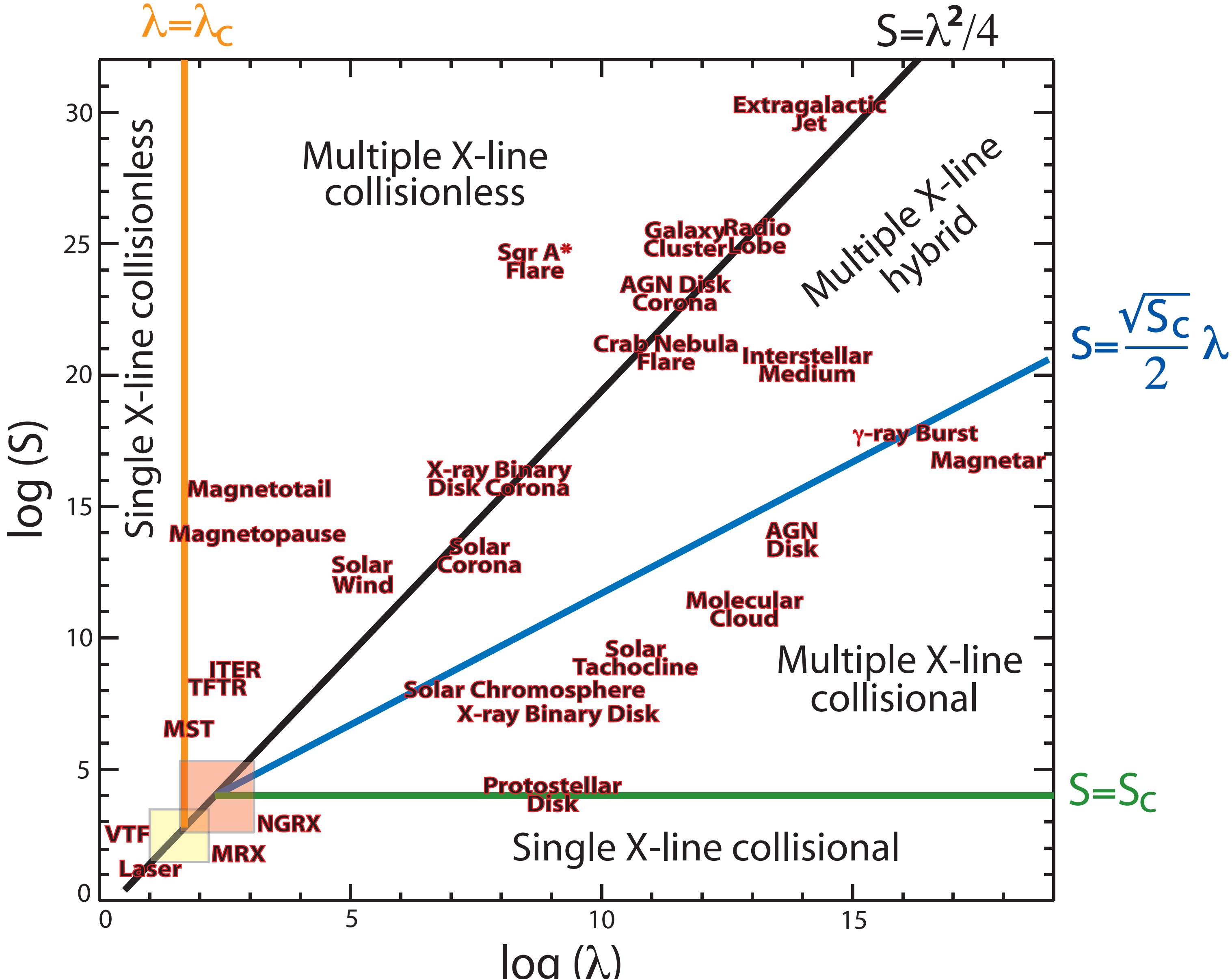
then

$$\delta_j = \frac{\delta_{j-1}}{\sqrt{N_{j-1}}} = \ldots = \frac{\delta_1}{\sqrt{N_{j-1} N_{j-2} \ldots N_1}} = \rho_s$$

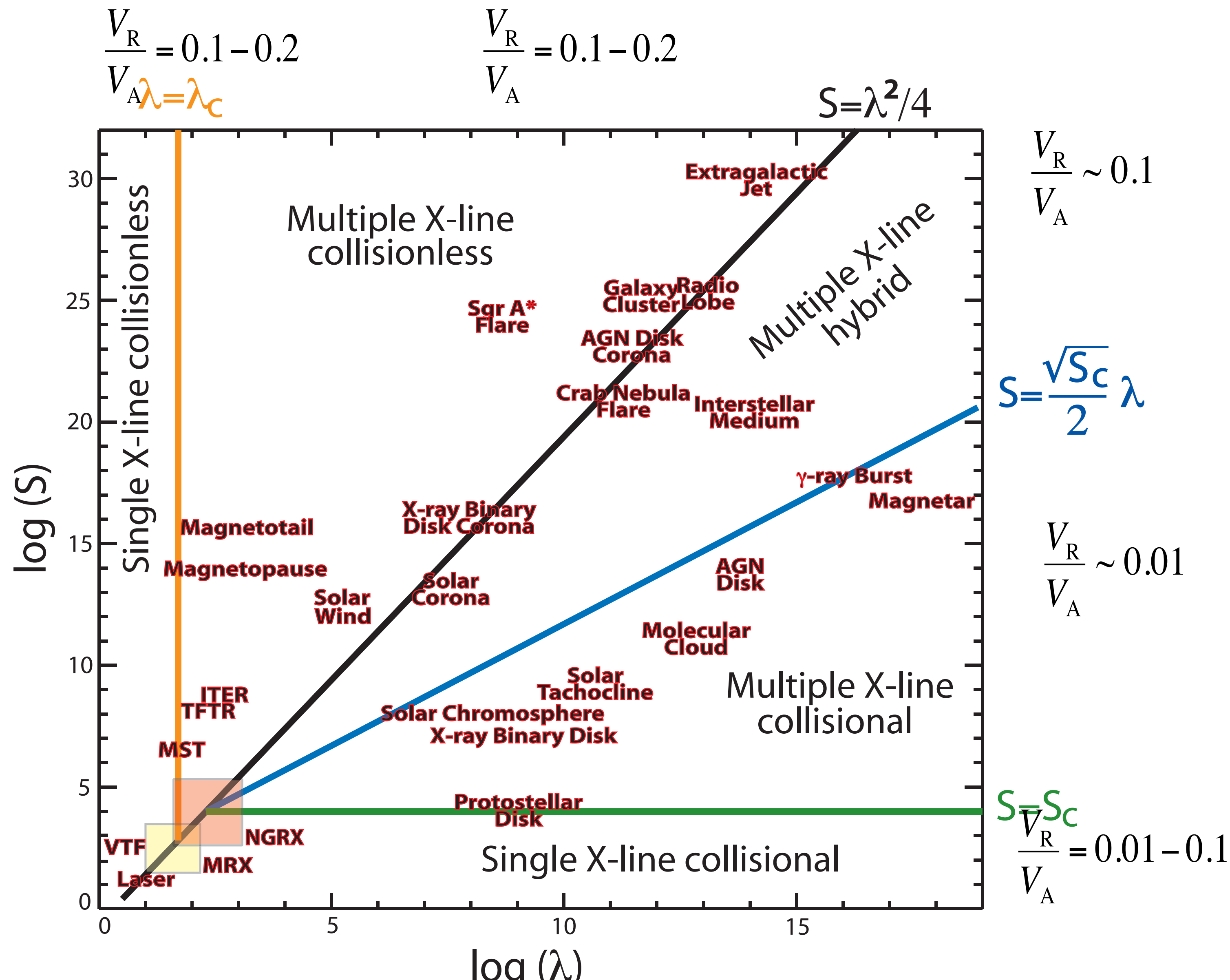
$$\Rightarrow S = \frac{\sqrt{S_c}}{2}\lambda$$



New Phases Provide Access to Astrophysical Reconnection



All Phases Are Fast – But Different Physics Which Should Lead to Different Heating/Acceleration?



Location	Plasma	Size (m)	T_e (eV)	n_e (m^{-3})	B_T (Tesla)	S	λ	Notes
Lab	MRX[75]	0.8	10	1×10^{19}	0.1	3×10^3	1.5×10^2	$\epsilon = 1/4$, $T_i = T_e/2$, $B_R = 0.3B_T$
	VTF[14]	0.4	25	1.5×10^{18}	0.044	3×10^2	4×10^0	$\epsilon = 1/4$, $T_i = 5$ eV, Ar^+
	Laser plasma[76]	2×10^{-4}	10^3	5×10^{25}	100	2×10^1	1×10^1	Al^{+13}, $B_R = B_T$
	MST[77]	1.0	1.3×10^3	9×10^{18}	0.5	3×10^6	6.2×10^1	$T_i = 350$ eV, D^+, $B_R = 0.05B_T$
	TFTR[78]	0.9	1.3×10^4	1×10^{20}	5.6	1×10^8	2.3×10^2	$T_i = 36$ keV, D^+, $B_R = 0.01B_T$
	ITER[79]	4	2×10^4	1×10^{20}	5.3	6×10^8	5×10^2	D^+, $B_R = 0.01B_T$
	NGRX[80]	1.6	25	1×10^{19}	0.5	1×10^5	1×10^3	$\epsilon = 1/4$, $T_i = T_e/2$, $B_R = 0.3B_T$
Solar system	Magnetopause[81]	6×10^7	300	1×10^7	5×10^{-8}	6×10^{13}	9×10^2	$B_R = B_T$ (p. 267)
	Magnetotail[81]	6×10^8	600	3×10^5	2×10^{-8}	4×10^{15}	1.3×10^3	$B_R = B_T$, $T_i = 4.2$ keV (p. 233)
	Solar wind[81]	2×10^{10}	10	7×10^6	7×10^{-9}	3×10^{12}	2×10^5	(p. 92)
	Solar corona[81]	1×10^7	200	1×10^{15}	2×10^{-2}	1×10^{13}	4×10^7	(p. 79)
	Solar chromosphere[82]	1×10^7	0.5	1×10^{17}	2×10^{-2}	1×10^8	3×10^8	Neutral particle effects are weak[82]
	Solar tachocline[83,84]	1×10^7	200	1×10^{29}	1	1×10^9	5×10^{10}	
Galaxy	Protostellar disks[85]	9×10^9	3×10^{-2}	6×10^8	2×10^{-5}	8×10^3	1×10^9	$L = 2h(R = 1\text{AU})$, e-n collisions included,[82] Mg^+
	X-ray binary disks[86,87]	4×10^4	75	1×10^{27}	36	3×10^7	9×10^8	$M = 10M_\odot$, $L = 2h(R = 10^2 R_S)$, $\alpha = 10^{-2}$, $\dot{M} = 10^{16} g/s$
	X-ray binary disk coronae[88]	3×10^4	5×10^5	1×10^{24}	1×10^4	1×10^{16}	9×10^7	$M = 10M_\odot$, $R = R_S$, $T_i = (m_p/m_e)T_e$, $\eta_{Compton}$ included (Ref. 88)
	Crab nebula flares[89–91]	1×10^{14}	130	10^6	10^{-7}	5×10^{20}	2×10^{11}	Pair plasma, T from ${B_R}^2/2\mu_0 = 2nT$
	Gamma ray bursts[92]	10^4	3×10^5	2×10^{35}	4×10^9	6×10^{17}	2×10^{16}	Pair plasma
	Magnetar flares[92,93]	10^4	5×10^5	10^{41}	2×10^{11}	6×10^{16}	5×10^{17}	Pair plasma, SGR 1806-20
	Sgr A* flares[94,95]	2×10^{11}	7×10^6	10^{13}	10^{-3}	2×10^{24}	5×10^8	$L = 2R = 20R_S$
	Molecular clouds[96,97]	3×10^{16}	10^{-3}	10^9	2×10^{-9}	1×10^{11}	7×10^{12}	Neutral particle effects included,[82] HCO^+
	Interstellar media[96,97]	5×10^{19}	1	10^5	5×10^{-10}	2×10^{20}	1×10^{14}	L = magnetic field scale height
Extra-galactic	AGN disks[86,87,98]	2×10^{11}	24	8×10^{23}	0.5	2×10^{13}	1×10^{14}	$M = 10^8 M_\odot$, $L = 2h(R = 10^2 R_S)$, $\alpha = 10^{-2}$, $\dot{M} = 10^{26} g/s$
	AGN disk coronae[88]	3×10^{11}	5×10^5	1×10^{17}	4	10^{23}	3×10^{11}	$M = 10^8 M_\odot$, $R = R_S$, $T_i = (m_p/m_e)T_e$, $\eta_{Compton}$ included (Ref. 88)
	Radio lobes[69]	3×10^{19}	100	1	5×10^{-10}	2×10^{25}	8×10^{12}	
	Extragalactic jets[99]	3×10^{19}	10^4	3×10^1	10^{-7}	6×10^{29}	1×10^{14}	3C 303
	Galaxy clusters[100]	6×10^{18}	5×10^3	4×10^4	2×10^{-9}	2×10^{25}	6×10^{11}	A1835

Solar Corona Example

L	1E+7 (m)
L_cs	5E+5 (m)
T	200 (eV)
N	1.0E+15 (m^-3)
B_guide	200 G
B_rec	20 G
S	1.1E+13
ϱ_s	0.28 (m)
λ	3.6E+07

$$V_R = \frac{\eta}{\mu_0 \rho_S} \sim 1 \text{ m/s} \sim 10^{-6} V_A$$

→ Field line breaking due to collisionless processes

→ Purely collisionless process or need MHD+collisionless?

Crab Nebula Flare

L	1E+14 (m)
L_cs	5E+13 (m)
T	130 (eV)
N	1.0E+6 (m^-3)
B_guide	1E-4 G
B_rec	1E-3 G
S	5E+20
ϱ_s	530 (m)
λ	2E+11

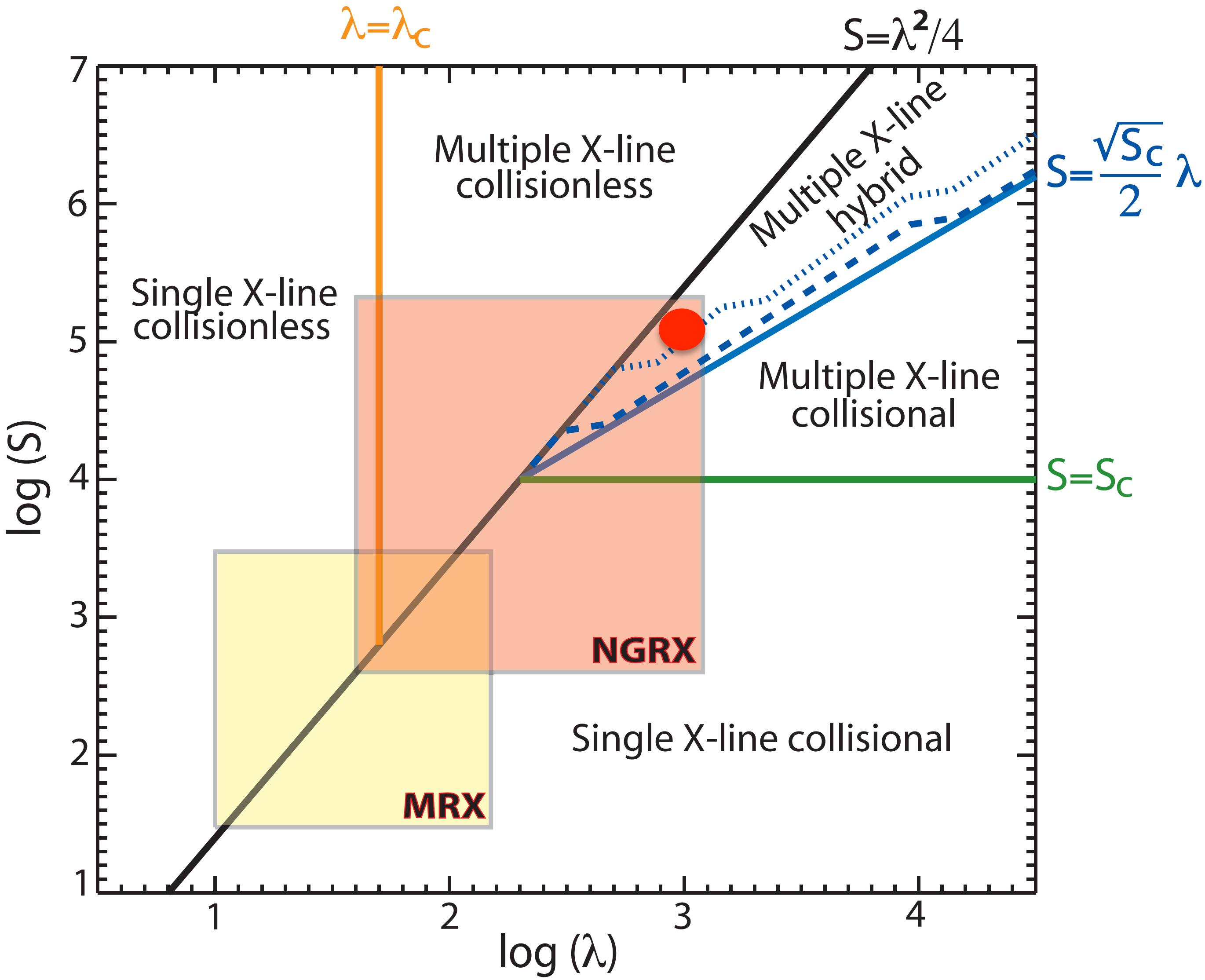
Pair plasma

Assume thermal plasma

$$2nT \sim \frac{B_{rec}}{2\mu_0}$$

→ Purely collisionless process or need MHD+collisionless?

Design Goals for MRX-U



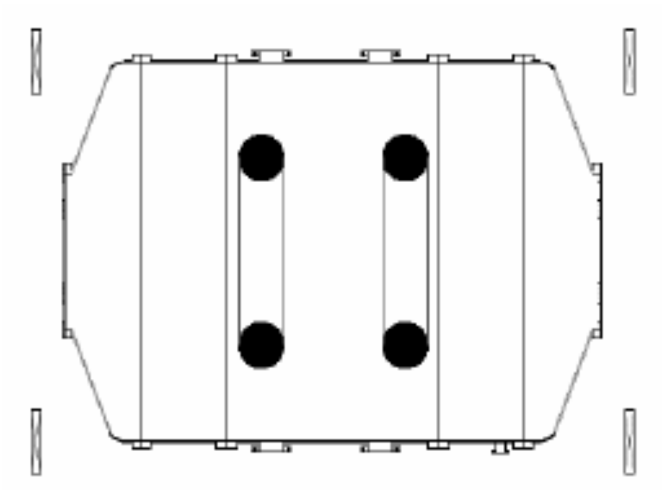
$$S = \frac{\mu_0 L_{CS} V_A}{\eta_S} = 10^5$$

$$L_{CS} = \frac{1}{4} L$$

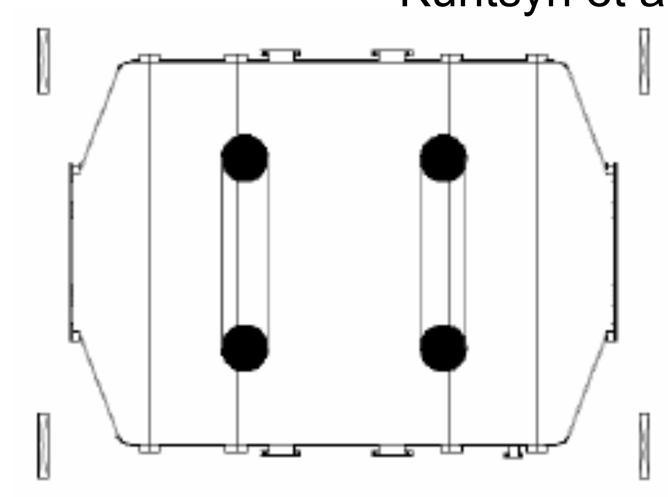
$$\lambda = \frac{L}{\rho_S} = 10^3$$

Current Sheet Length
~ System Size / 4

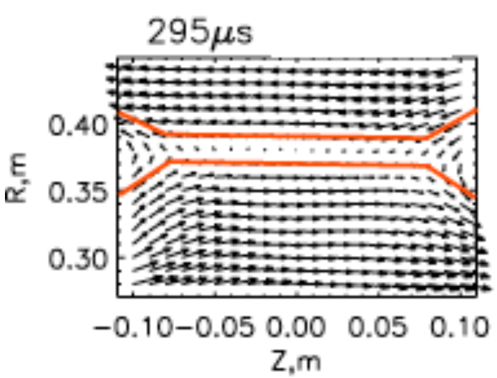
Kuritsyn et al. (2007)



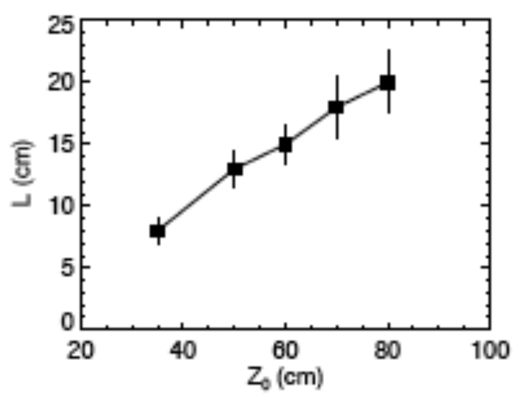
Z_0=35cm

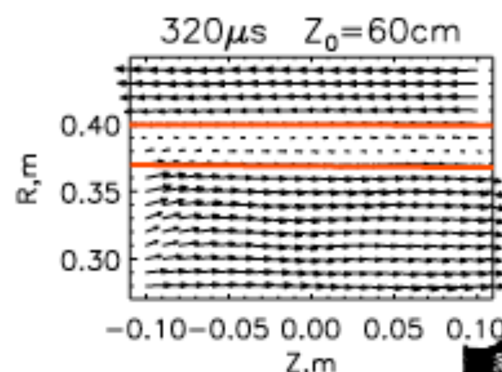


Z_0=60cm



2L=16 cm





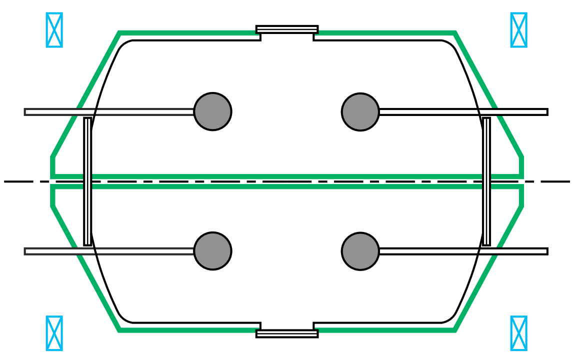
2L=30cm

$$S = 1.09\times10^{5}\left(\frac{L}{1.6m}\right)\left(\frac{B_{rec}}{0.1T}\right)\left(\frac{n}{10^{19}}\right)^{-1/2}\left(\frac{T_e}{30eV}\right)^{3/2}$$

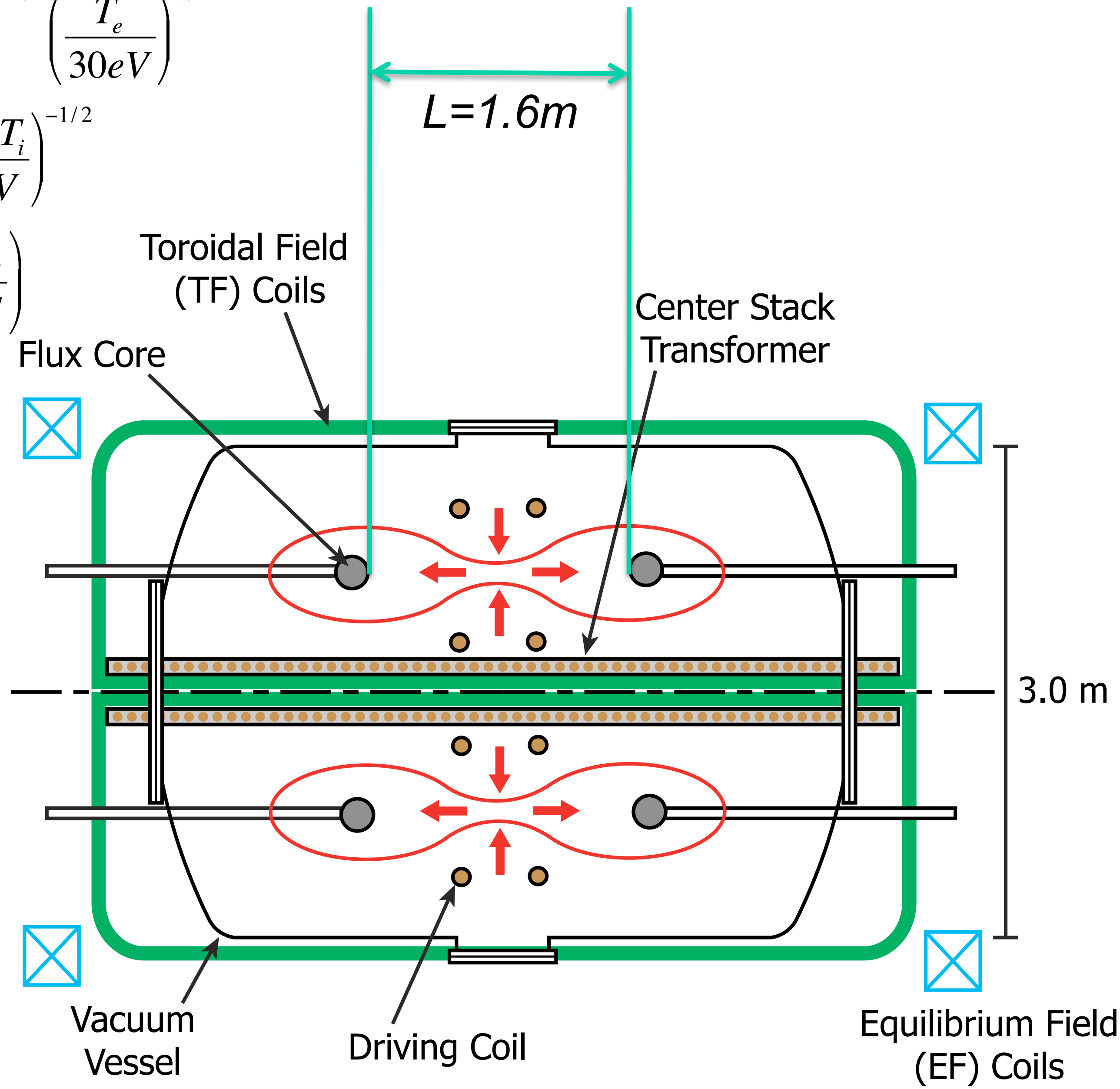
$$\lambda = 1.01\times10^{3}\left(\frac{L}{1.6m}\right)\left(\frac{B_{guide}}{0.5T}\right)\left(\frac{T_e+T_i}{60eV}\right)^{-1/2}$$

$$I_t = 1.875\,MA\cdot turn\left(\frac{R_0}{0.75m}\right)\left(\frac{B_{guide}}{0.5T}\right)$$

$$I_{CS} = 127kA\left(\frac{L}{1.6m}\right)\left(\frac{B_{rec}}{0.1T}\right)$$



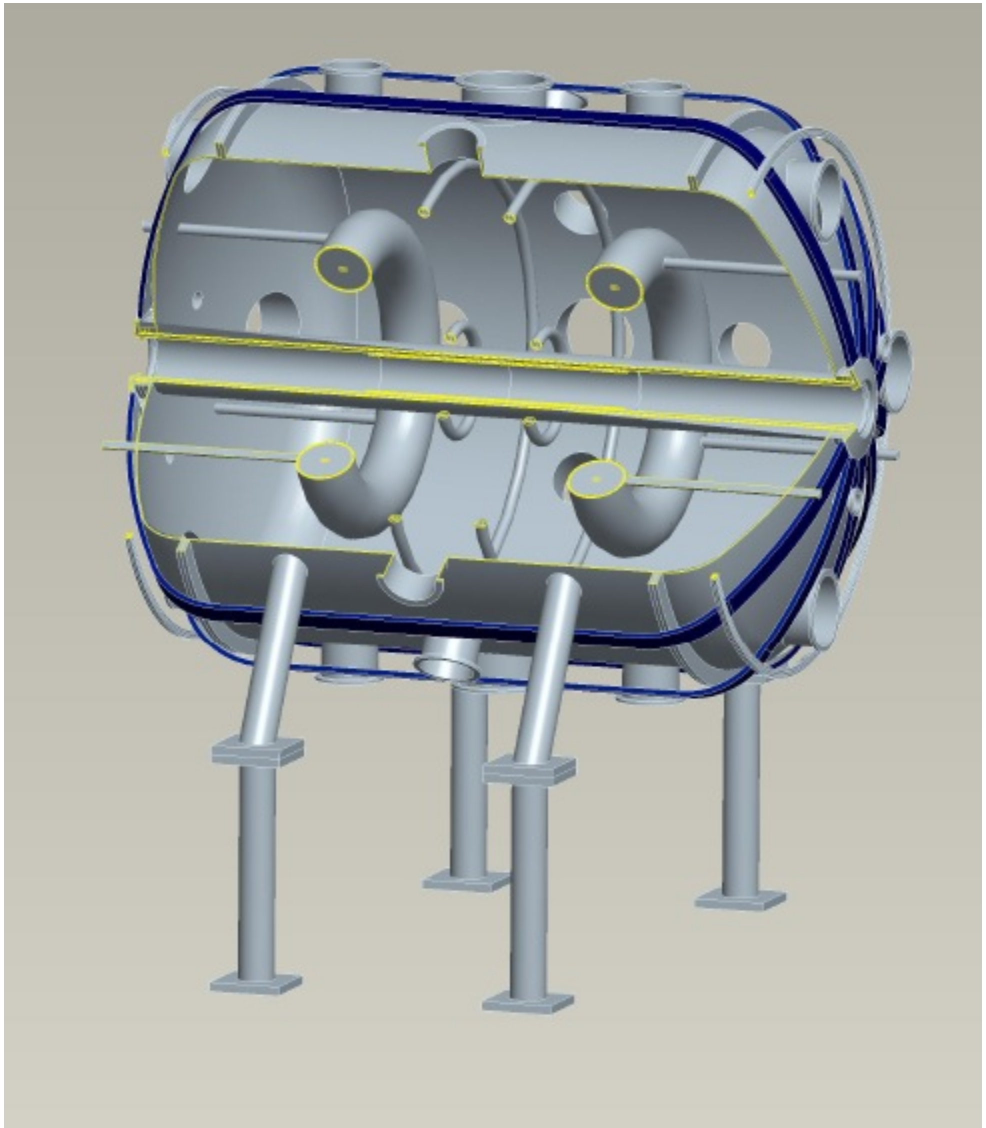
MRX



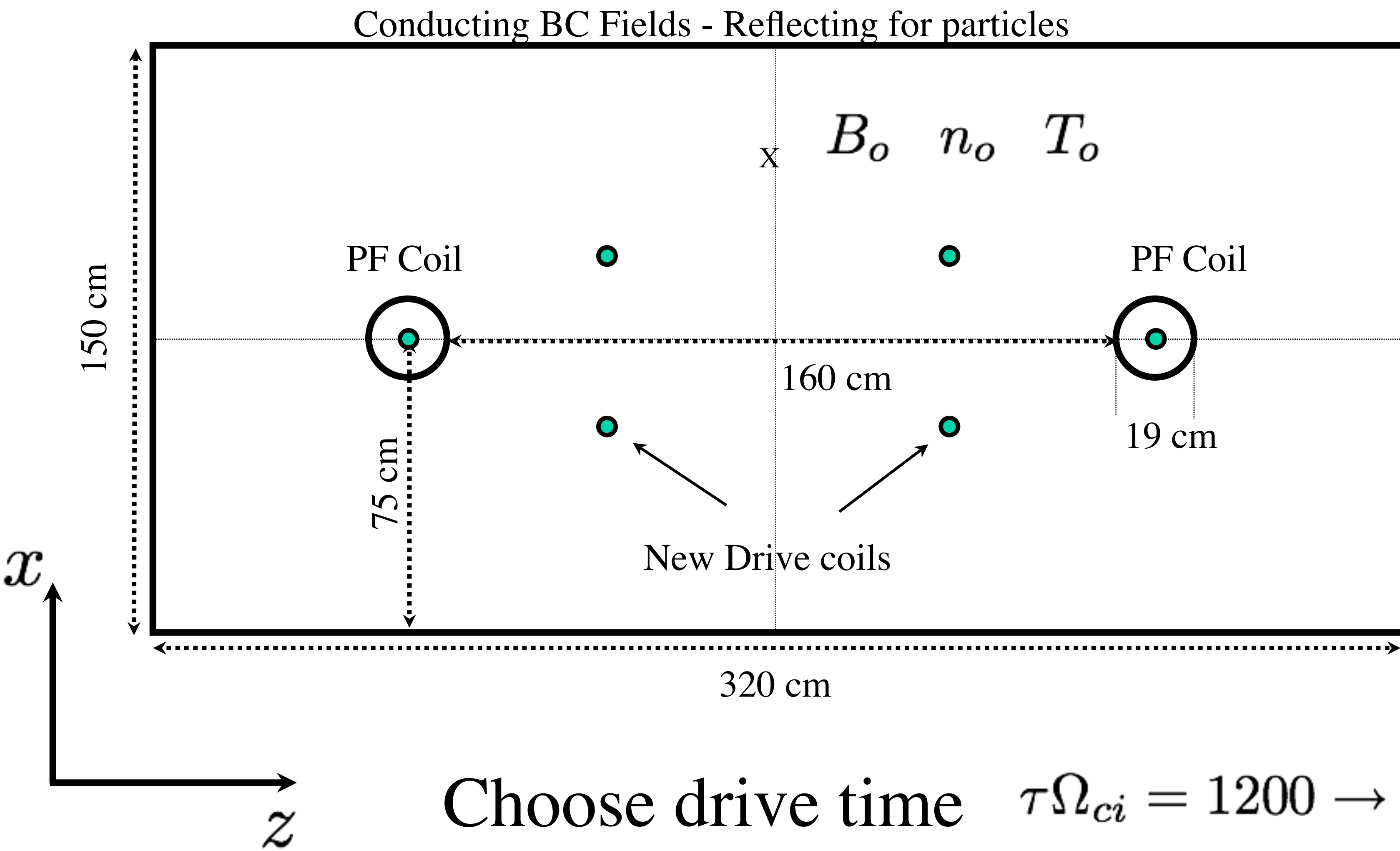
MRX-U

Conceptual Designs Are Nearly Complete

Parameters	MRX	MRX-U
Device diameter	1.5 m	3 m
Device length	2 m	4 m
Flux core diameter	0.75 m	1.5 m
Stored energy	~100 kJ	~3 MJ
Plasma heating	No	OH (~1MW)



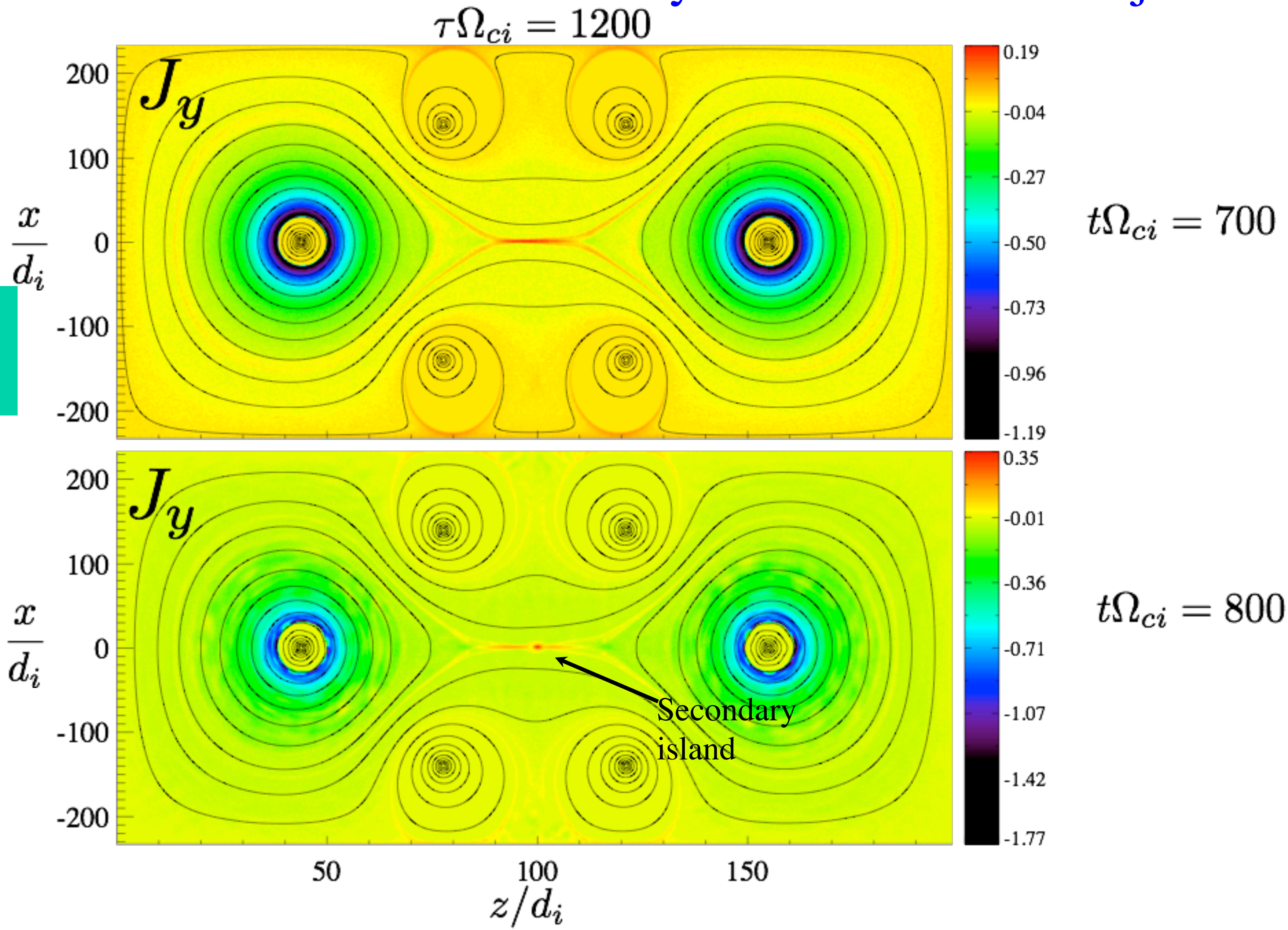
Geometry & Boundary Conditions for Fully Kinetic Simulations



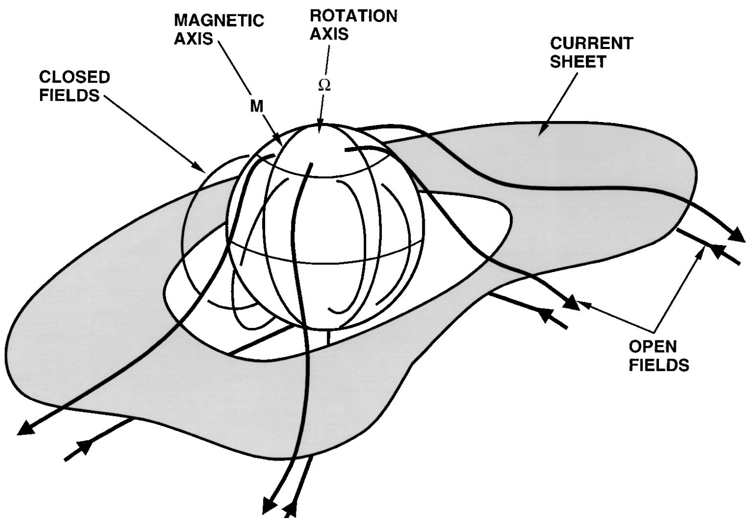
Choose drive time $\tau\Omega_{ci} = 1200 \rightarrow 2000$

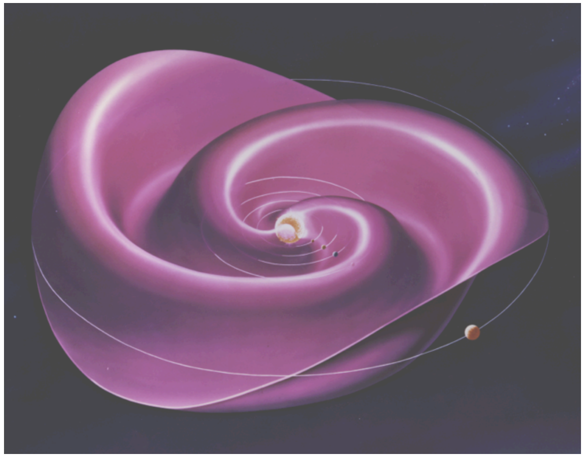
Include Fokker-Planck collision operator

Drive coils improve control over layer formation; There are sufficient time for many islands to form & eject

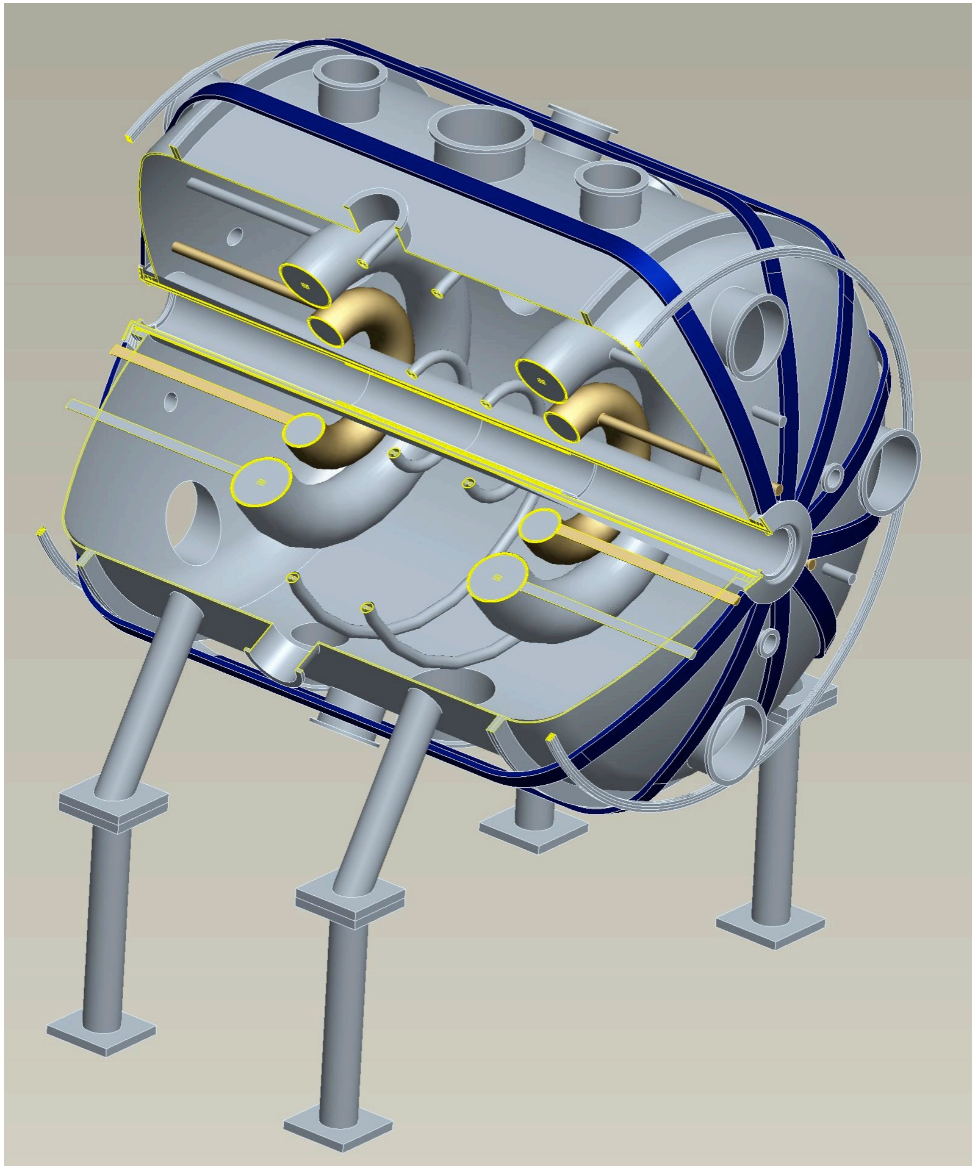


Reconnection of Sectored Magnetic Fields?





Heliospheric current sheet



Summary

- A phase diagram in term of Lundquist number (S) and effective size (λ) has been developed to summarize current understanding of magnetic reconnection involving different dynamic processes.
- A survey of plasma parameters was done for a large number of plasmas where magnetic reconnection might occur.
- MRX-U is proposed to access all reconnection phases with larger λ (~10×) and higher in S (~100×). Conceptual engineering design underway, guided by state-of-the-art numerical simulations with relevant geometry and parameters.