Complete prevention of runaway electron beam formation with a passive 3D coil in SPARC

RA Tinguely[1], VA Izzo[2], DT Garnier[1], A Sundström[3], K Särkimäki[4], O Embréus[3], T Fülöp[3], RS Granetz[1], M Greenwald[1], M Hoppe[3], I Pusztai[3], and R Sweeney[1]

[1]MIT PSFC *[2]Fiat Lux* *[3]Chalmers* *[4]IPP Garching*

Submitted to PRL

Outline

- SPARC and its runaway electron problem

- Runaway Electron Mitigation Coil (REMC)

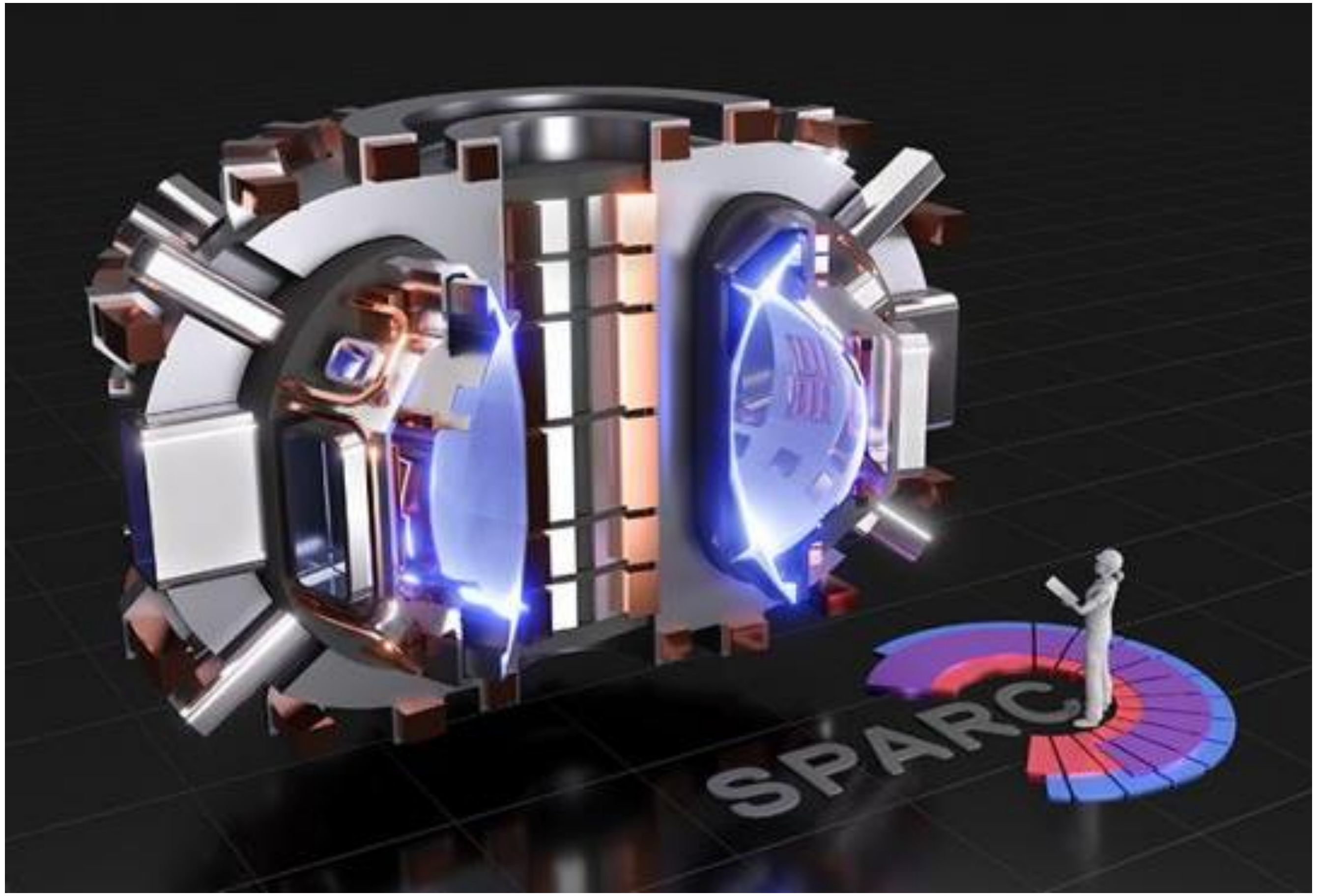
1. Model vacuum fields with COMSOL
2. Model 3D MHD with NIMROD
3. Evaluate transport with ASCOT5
4. Evolve runaways with DREAM

- Additional considerations and ongoing work

SPARC: high-field, compact, DT tokamak

full-field DT H-mode	
R_0	1.85 m
a	0.57 m
B_T	12.2 T
I_P	8.7 MA
q_{95}	3.4
κ_{95}	1.75
$\langle n_e \rangle$	3 x 10^{20} m^{-3}
$\langle T_e \rangle$	7 keV
f_G	0.37
β_N	1.0
P_{ICRF}	11.1 MW
P_{fusion}	140 MW
Q	11

Creely JPP 2021



https://www.psfc.mit.edu/sparc

SPARC: great potential for runaway electron formation

full-field **DT** H-mode	
R_0	1.85 m
a	0.57 m
B_T	12.2 T
$\boldsymbol{I_P}$	**8.7 MA**
q_{95}	3.4
κ_{95}	1.75
$\langle n_e \rangle$	3 x 10^{20} m^{-3}
$\boldsymbol{\langle T_e \rangle}$	**7 keV**
f_G	0.37
β_N	1.0
P_{ICRF}	11.1 MW
$\boldsymbol{P_{fusion}}$	**140 MW**
Q	11

Creely JPP 2021

DT → tritium beta decay*

I_P 8.7 MA → enhanced avalanching

$\langle T_e \rangle$ 7 keV → enhanced hot-tail/Dreicer generation

P_{fusion} 140 MW → inverse Compton scattering*

*Martín-Solís NF 2017

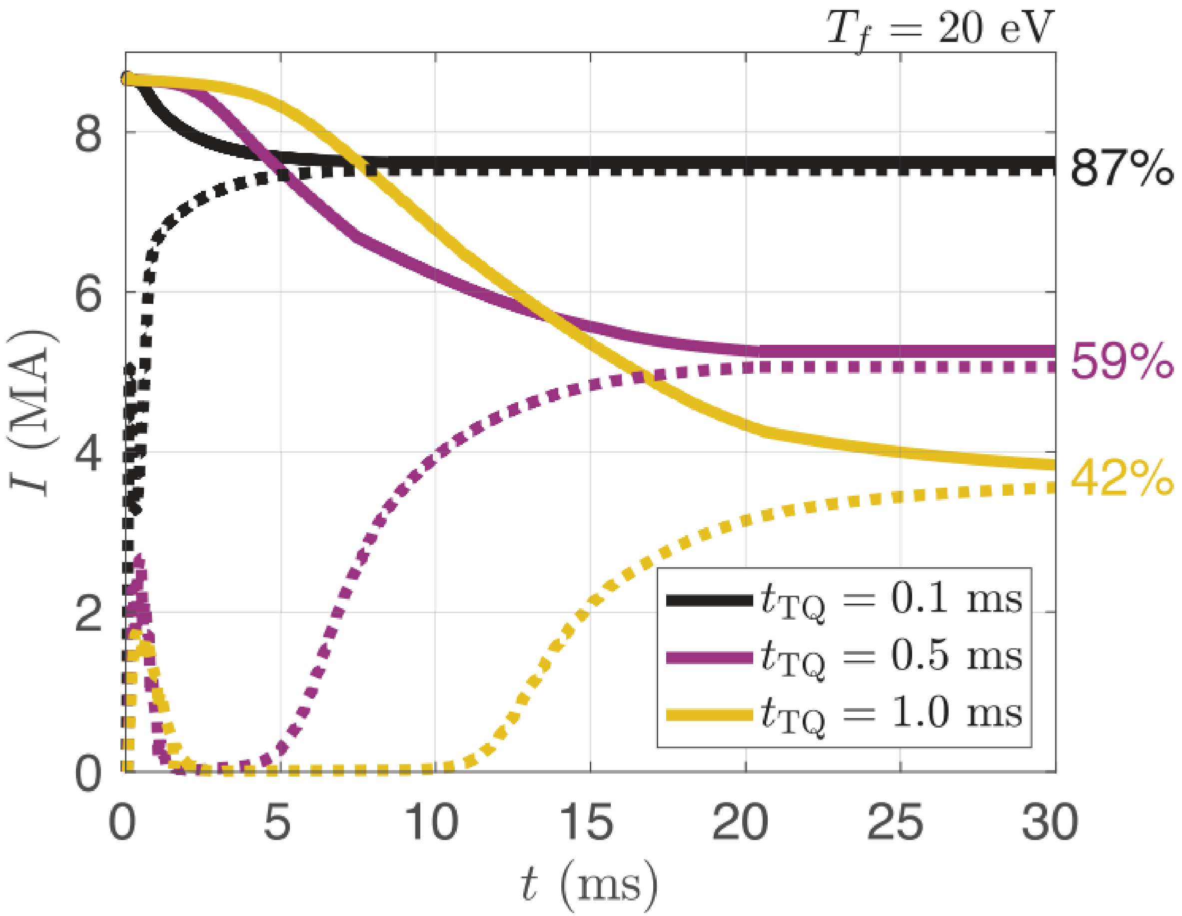
SPARC: it's not all bad though…

full-field DT H-mode		
R_0	1.85 m	
$\boldsymbol{a}$	**0.57 m**	→ fast transport time scales
$\boldsymbol{B_T}$	**12.2 T**	→ enhanced synchrotron radiation
I_P	8.7 MA	
q_{95}	3.4	
$\boldsymbol{\kappa_{95}}$	**1.75**	→ reduced E-field*
$\langle \boldsymbol{n_e} \rangle$	**3 x 10^{20} m^{-3}**	→ enhanced collisional friction
$\langle T_e \rangle$	7 keV	
f_G	0.37	
β_N	1.0	
P_{ICRF}	11.1 MW	
P_{fusion}	140 MW	
Q	11	

Creely JPP 2021

*Fülöp JPP 2020

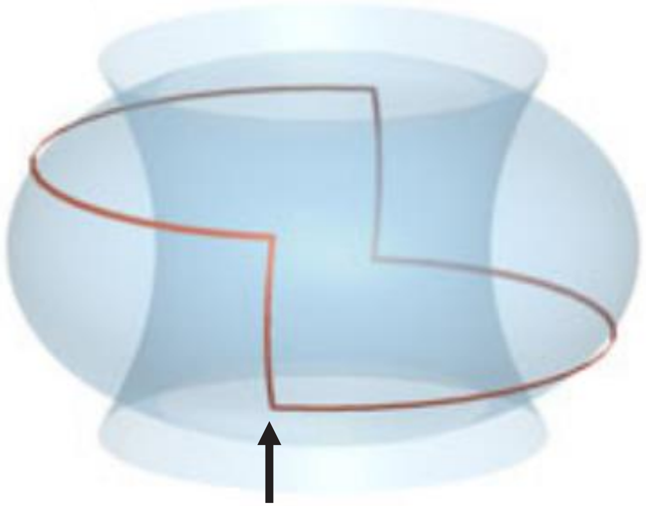
Yet GO+CODE indicates almost full current conversion ☹



Sweeney JPP 2021

Solution: *Passive* 3D RE Mitigation Coil (REMC) to deconfine REs faster than they are generated

Boozer PPCF 2011, Smith PoP 2013



(vertical legs to avoid ports)

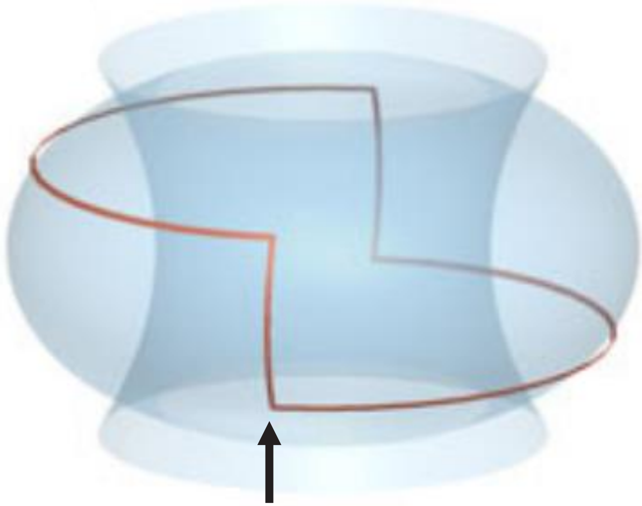
Sweeney JPP 2021

- Switch triggered by uniquely high disruption voltages
  - Probably Shockley diode/thyristor
  - (No disruption predictor required)
- Location outside the vessel for accessibility and radiation protection
- Closed circuit also under assessment
  - Close mechanical switch near I_P flat-top
  - Expect little effect from sawteeth
  - Investigating impact of ELMs, I_P ramp-up/down,…

Solution: *Passive* 3D RE Mitigation Coil (REMC) to deconfine REs faster than they are generated

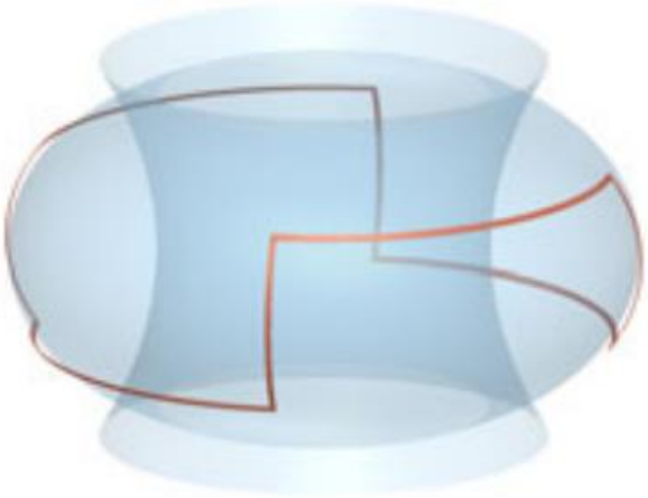
Boozer PPCF 2011, Smith PoP 2013

n = 1

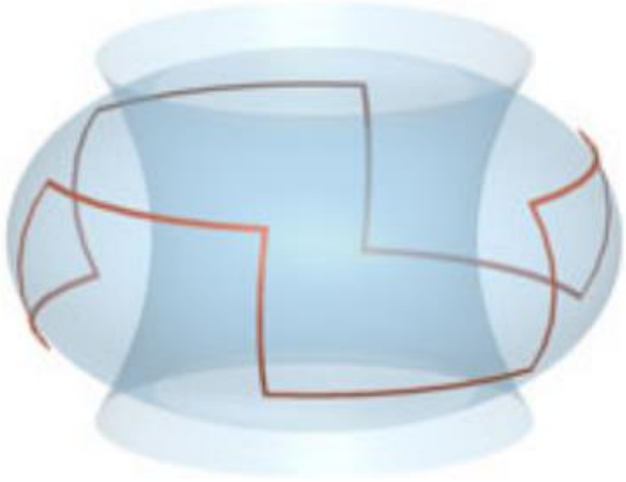


(vertical legs to avoid ports)

n = 2



n = 3

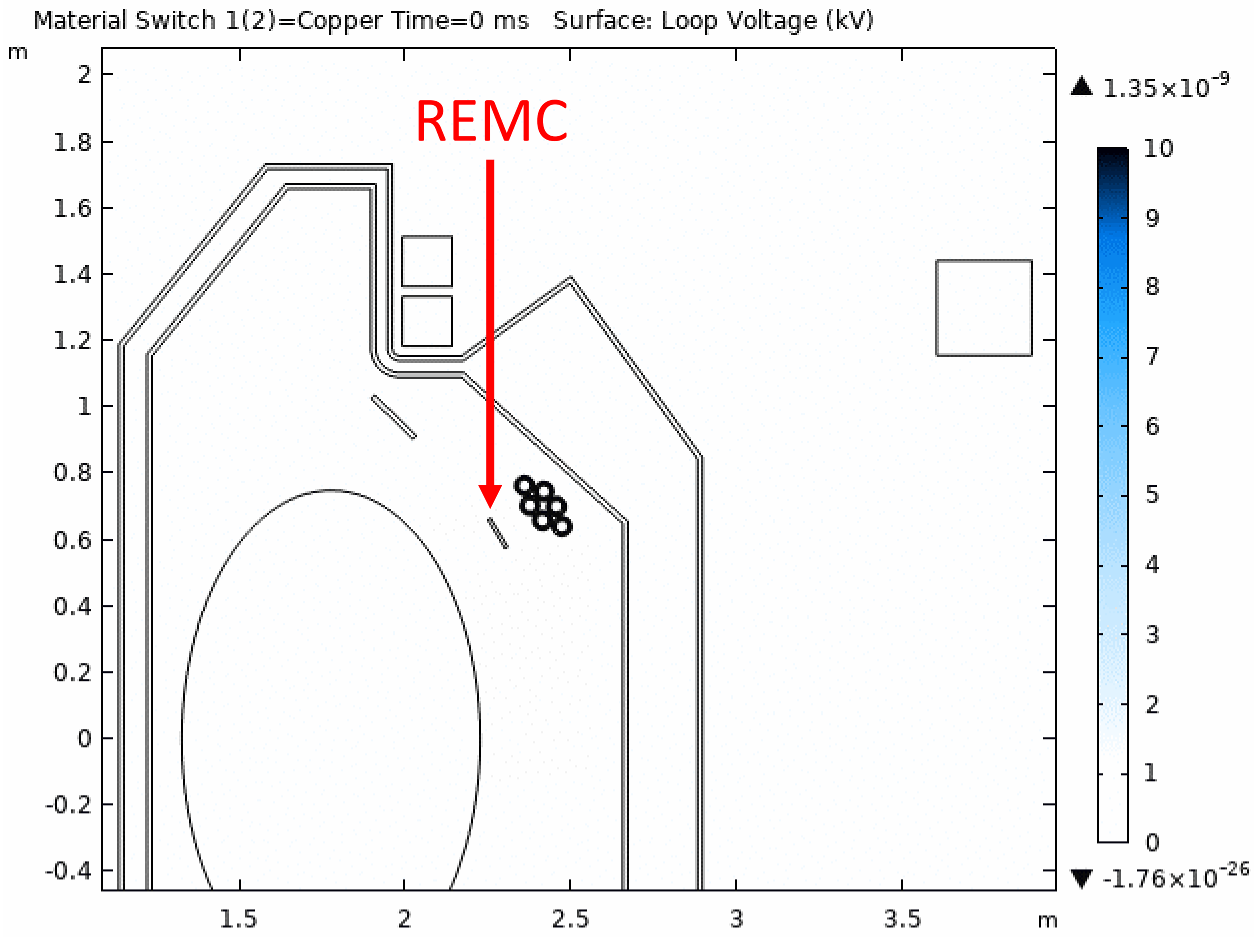


Sweeney JPP 2021

Step 1: Model vacuum fields with COMSOL (D Garnier)

- Ellipse of constant current density
- Inside realistic tokamak structure
- Simulate midplane current quench
- CQ duration ~ 3.2 ms
  (fastest expected [Sweeney JPP 2020])

→ Magnetic and electric fields throughout simulation domain

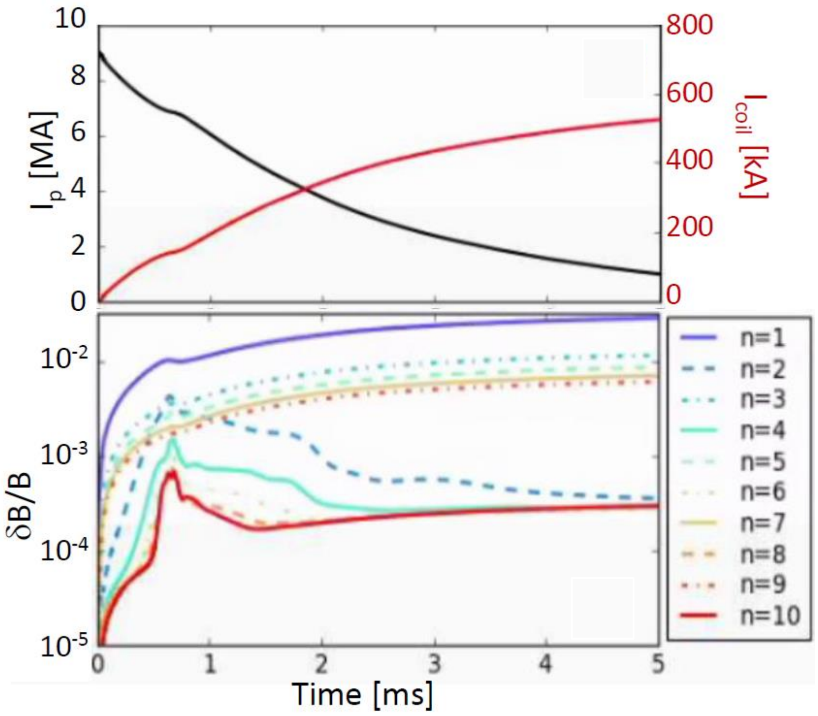


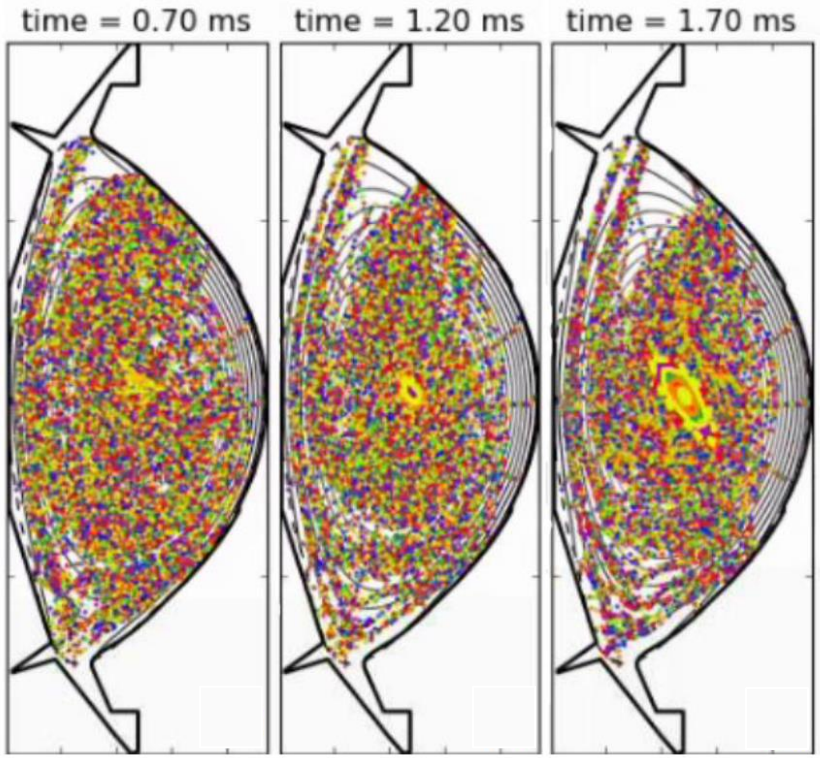
COMSOL: http://www.comsol.com/products/multiphysics/

Step 2: Model MHD with NIMROD (V Izzo)

- Use realistic plasma profiles and equilibrium
  [Rodriguez-Fernandez JPP 2021]
- Only current quench MHD (artificial thermal quench)
- B-fields from COMSOL applied at NIMROD simulation boundary
- No *a priori* t-dependence, REMC B-fields evolve with I_P

→ Fast stochasticization, but core island reforms…



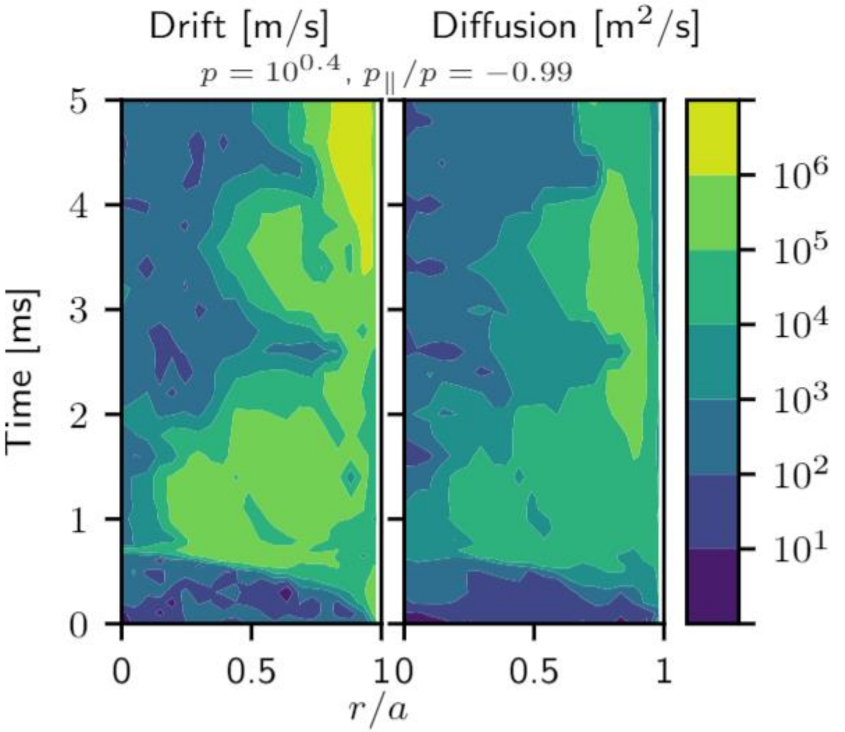


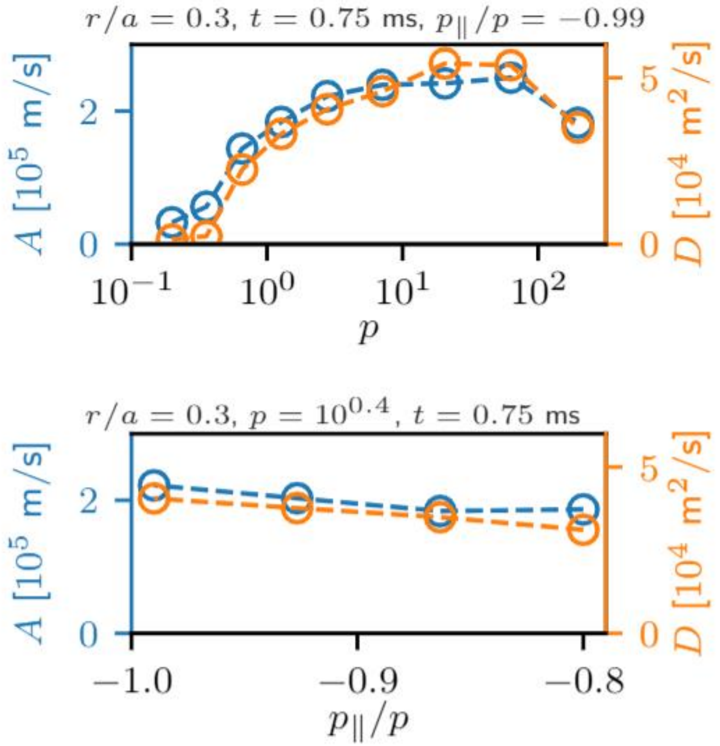
NIMROD: Sovinec JCP 2004

Step 3: Evaluate transport with ASCOT5 (K Särkimäki)

- Ensemble of markers followed in perturbed B-field at each time
- Range of momenta p/mc, pitches $p_{||}/p$, and minor radii r/a
- Calculate advection and diffusion coefficients
  [Särkimäki PPCF 2016]
- Islands *not* considered here (but will be later)

→ Fast core penetration

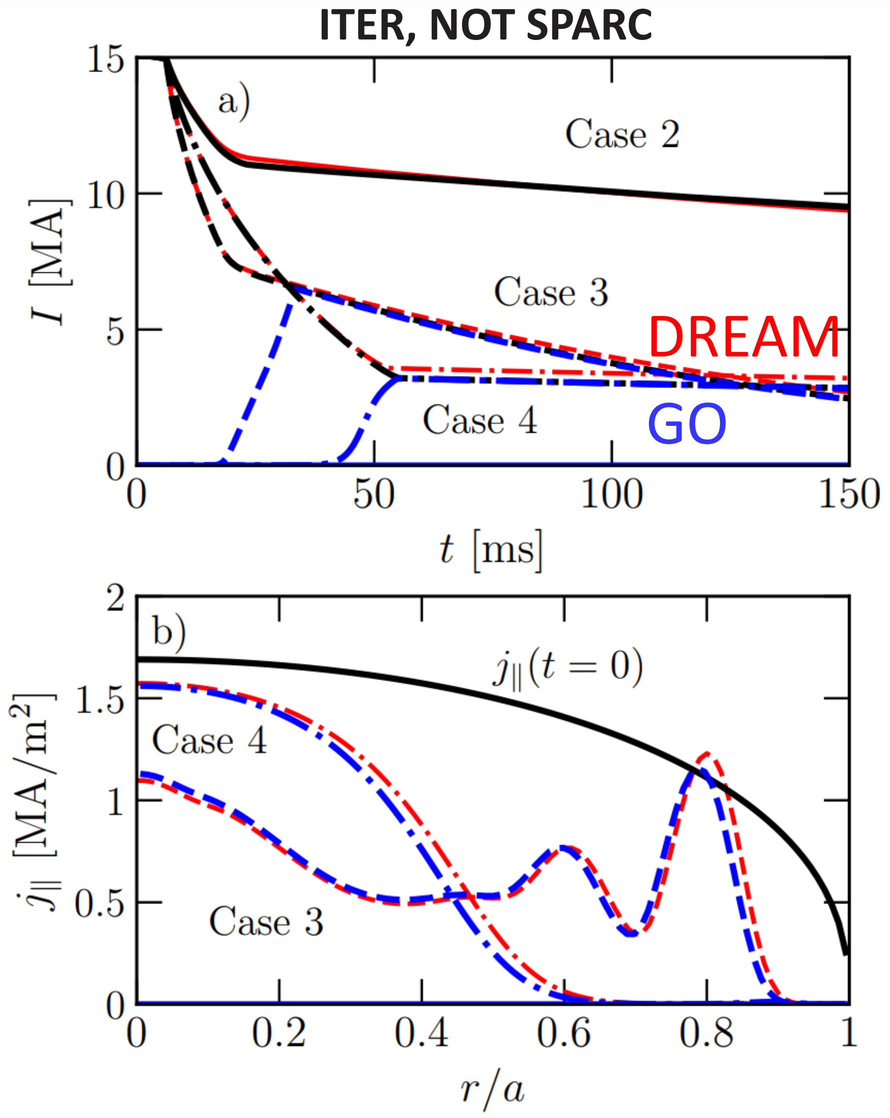




ASCOT5: Hirvijoki CPC 2014

Interlude: Introducing the code DREAM

- Evolution of electron population in
  - 1 real space dimension (r/a) and
  - 2 velocity space dimensions ($v_{\parallel}$, $v_{\perp}$)
- Computationally efficient by splitting population into thermal, hot, and relativistic (runaway) regimes
- Benchmarked with fluid code GO (ITER simulations shown)
- Validation is underway (e.g. JET [Brandström 2021 MSc Thesis])
- Generation mechanisms include
  - Hot-tail and Dreicer
  - Avalanche
  - Tritium beta-decay
  - Inverse Compton scattering
- Losses: bremsstrahlung, synchrotron radiation, transport

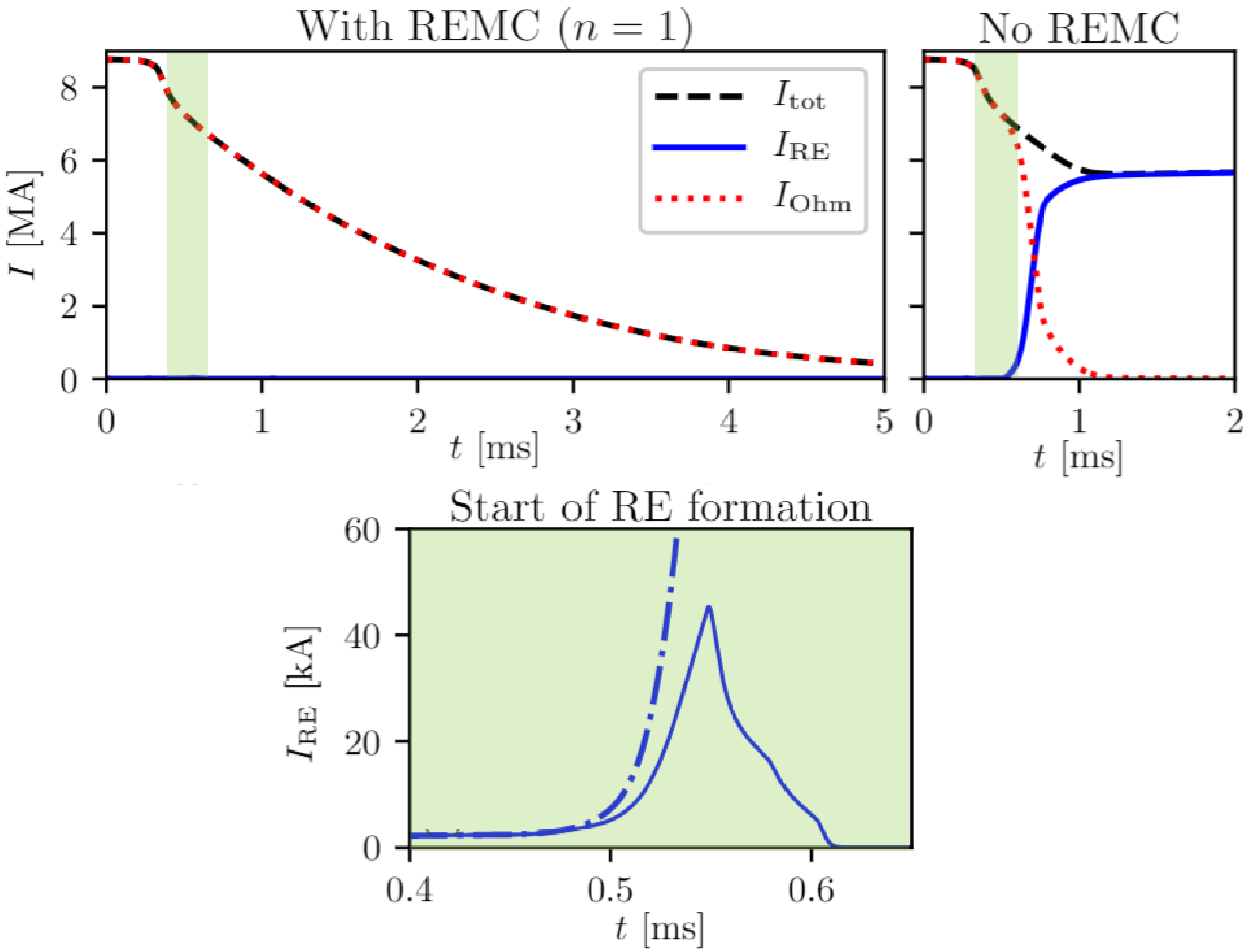


DREAM: Hoppe 2021 https://arxiv.org/abs/2103.16457

Step 4: Evolve runaways with DREAM (A Sundström)

- Use same plasma profiles and equilibrium as NIMROD
- Adjust TQ time (~0.27 ms) to best match current quench
- No *a priori* time dependence, advection, diffusion evolve with plasma current
- Dissipate same amount of magnetic energy as in COMSOL
- Use wall time of ~50 ms

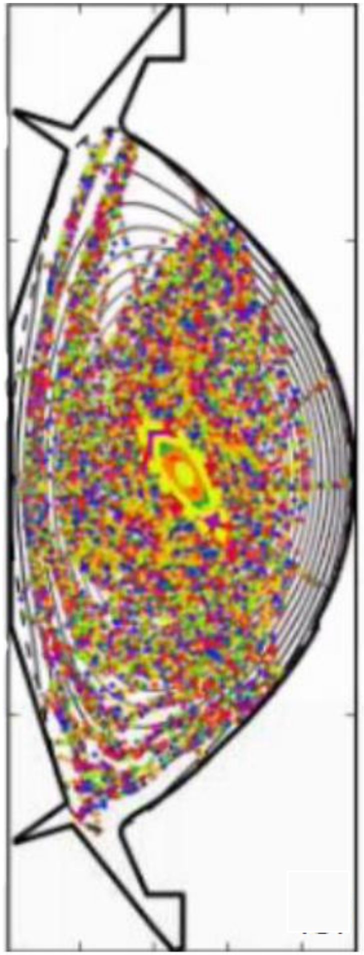
→ Transient peak of <50 kA



DREAM: Hoppe 2021 https://arxiv.org/abs/2103.16457

Additional considerations #1: Islands and other sensitivities

- 2-4 cm core islands simulated in DREAM
  - Transport coefficients set to 0 (conservatively)
  - Transient RE beams up to 2 MA can form, however…
  - Large E-fields will help REs escape the island [Guan PoP 2010]
  - Large current densities will be regulated by the kink instability ($q_0 < 1$, $\ell_i > 1.5$) [Cai and Fu NF 2015, Paz-Soldan PPCF 2019]

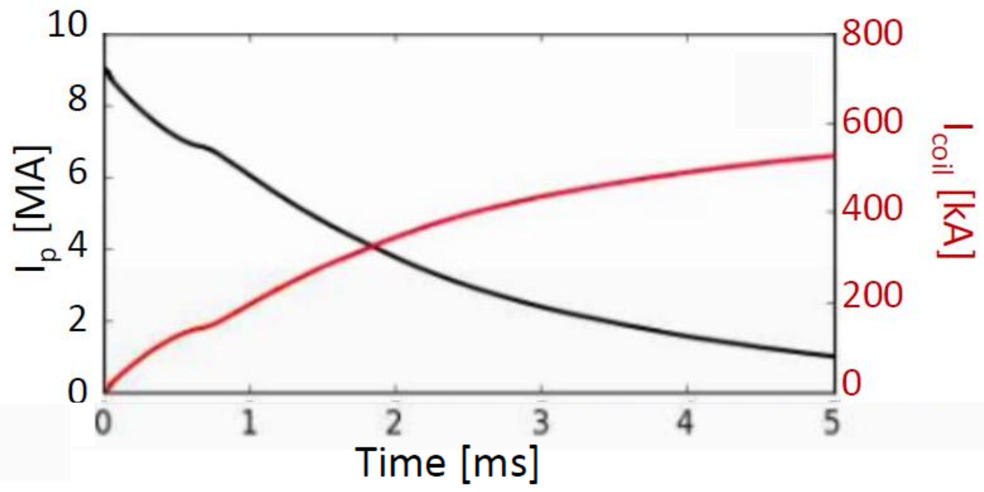


- The maximum runaway current is sensitive to…
  - Total magnetic energy available for dissipation
  - Timing and penetration "depth" of the transport
  - Thermal quench duration (although TQ transport needs dedicated modeling)
- But not as sensitive to…
  - Magnitude of transport coefficients
  - Inclusion of a resistive wall ($\tau_{CQ} \ll \tau_{wall}$)

Additional considerations #2: Engineering

- Toroidal mode number:
  - n = 2,3 designs failed as induced transport did not extend far enough into core
  - n = 1 design → sideways force <15 MN
  - Lower peak currents are under assessment
  - So are net-force-free designs

- Possible side-effects under investigation:
  - Faster CQ with enhanced losses?
  - 3D pattern of first-wall heating?
  - Kinking of the disrupting plasma?



Main takeaway: our simulations indicate that the n=1 REMC will prevent runaway plateaus in SPARC

- High currents and temperatures in SPARC → huge risk of runaways
- BUT our most-complete simulations suggest a passive 3D coil will prevent them
    1. COMSOL modeling of SPARC disruption → vacuum B-fields + magnetic energy
    2. Vacuum B-fields + NIMROD → CQ MHD during SPARC disruption + I_P decay
    3. NIMROD MHD + ASCOT5 → advection, diffusion coefficients
    4. ASCOT5 transport coefficients + DREAM → runaway electron evolution
- Checks:
    - DREAM and NIMROD produce similar current quenches
    - DREAM and COMSOL dissipate same magnetic energies
- Main result: runaway beam is prevented
    - Robust to changes in transport coefficients, thermal quench duration, resistive wall
    - Sensitive to changes in stored magnetic energy and islands

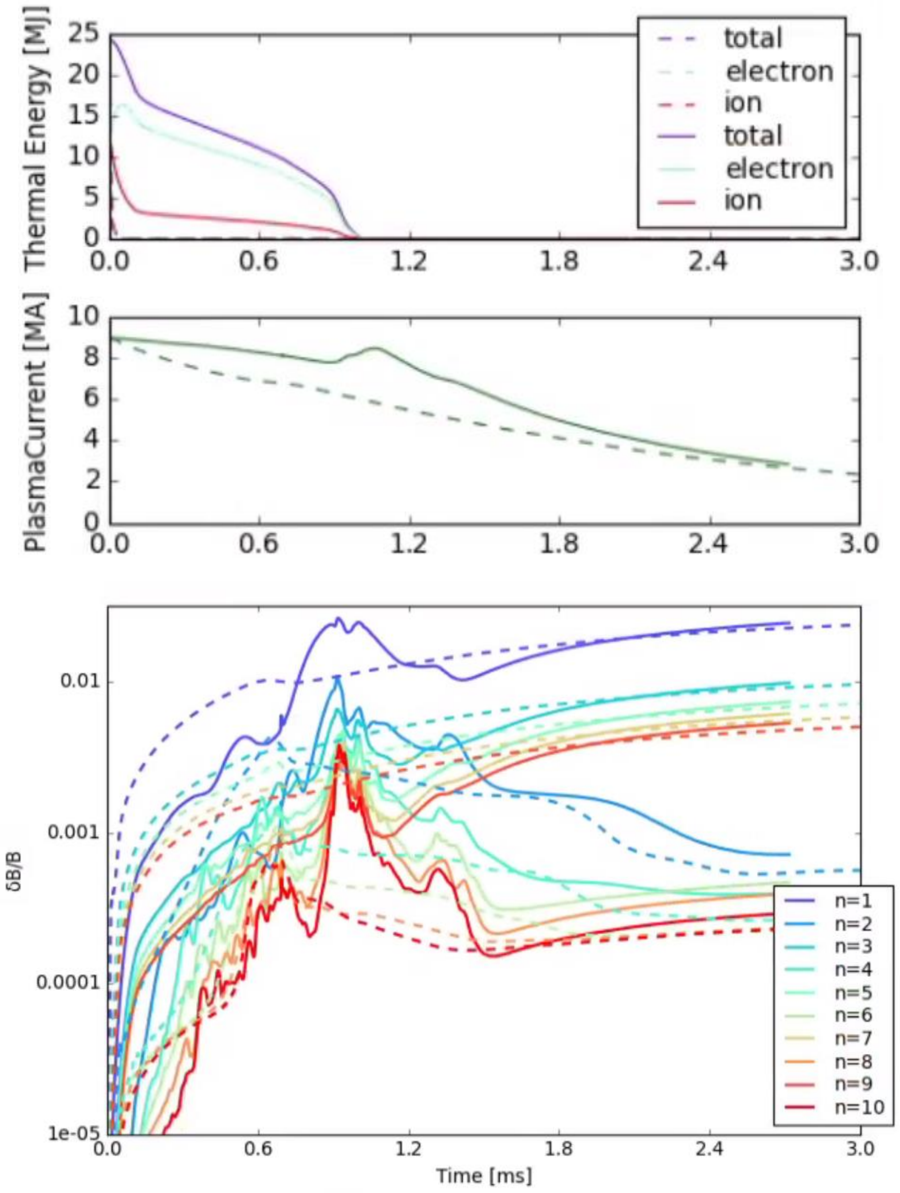
Ongoing: NIMROD simulations of TQ+CQ MHD (V Izzo)

- Dashed lines = artificial TQ + CQ MHD
- Solid lines = TQ + CQ MHD

- TQ duration <1 ms (slowest expected)
- I_P spike observed at end of TQ
- CQ duration shorter with realistic TQ

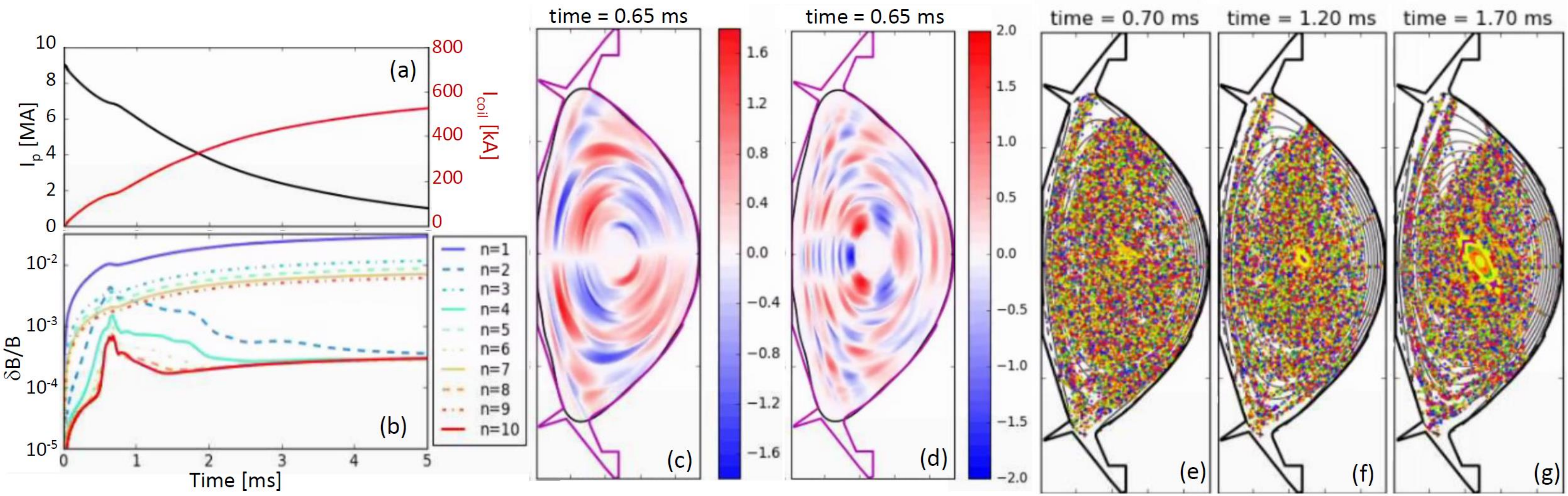
- Higher amplitudes dB/B achieved
- Similar long-time trends

→ Looks good for REMC ☺

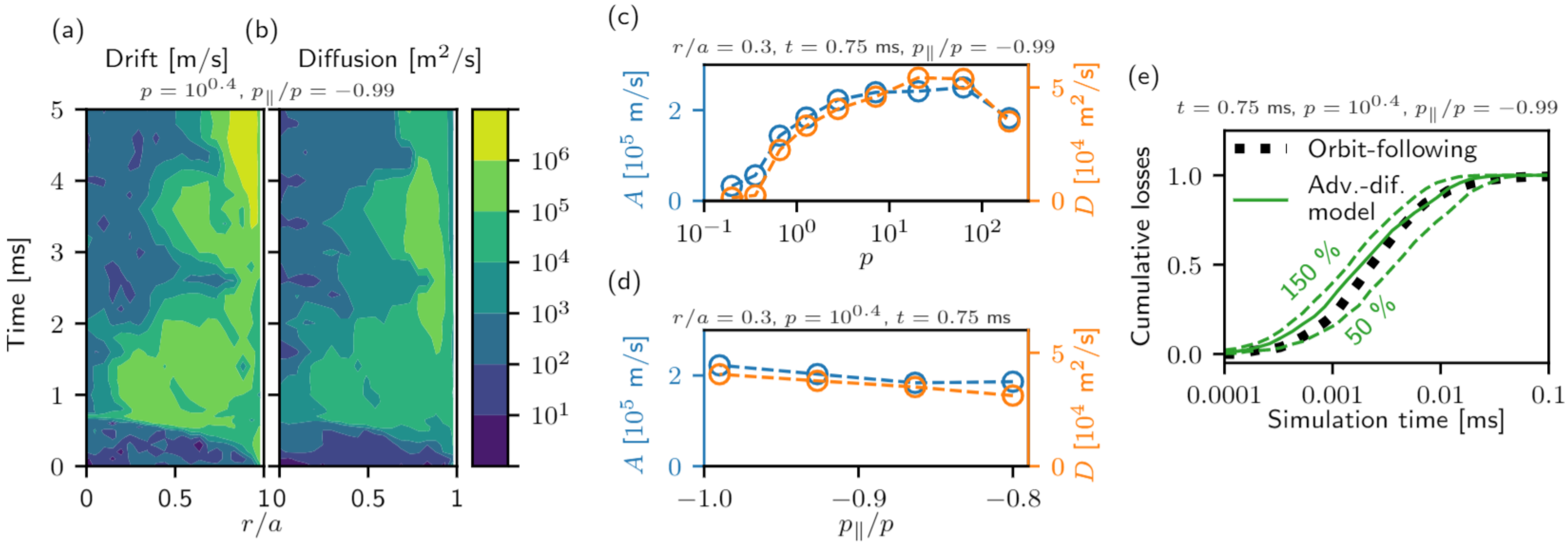


Bonus

NIMROD: CQ MHD only

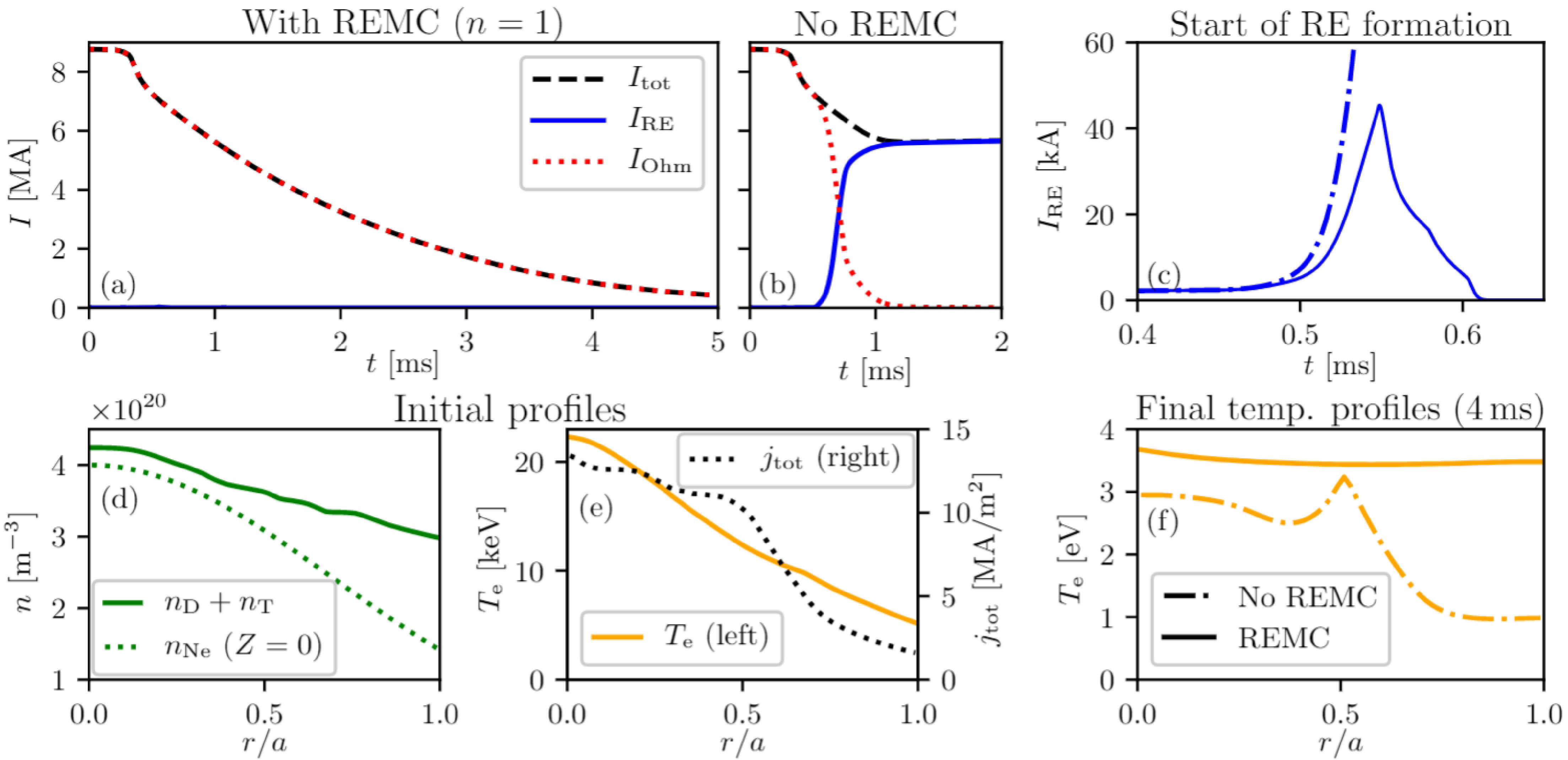


ASCOT5



(a)
(b)
Drift [m/s]
Diffusion [m²/s]
$p = 10^{0.4}$, $p_{\parallel}/p = -0.99$
Time [ms]
r/a
(c)
$r/a = 0.3$, $t = 0.75$ ms, $p_{\parallel}/p = -0.99$
A [10^5 m/s]
D [10^4 m²/s]
p
(d)
$r/a = 0.3$, $p = 10^{0.4}$, $t = 0.75$ ms
$p_{\parallel}/p$
(e)
$t = 0.75$ ms, $p = 10^{0.4}$, $p_{\parallel}/p = -0.99$
Orbit-following
Adv.-dif. model
150 %
50 %
Cumulative losses
Simulation time [ms]

DREAM



With REMC ($n = 1$)
No REMC
Start of RE formation
I [MA]
I_{tot}
I_{RE}
I_{Ohm}
(a)
(b)
(c)
t [ms]
I_{RE} [kA]
Initial profiles
Final temp. profiles (4 ms)
$\times 10^{20}$
n [m^{-3}]
(d)
$n_D + n_T$
n_{Ne} ($Z = 0$)
(e)
T_e [keV]
j_{tot} (right)
T_e (left)
j_{tot} [MA/m^2]
(f)
T_e [eV]
No REMC
REMC
r/a