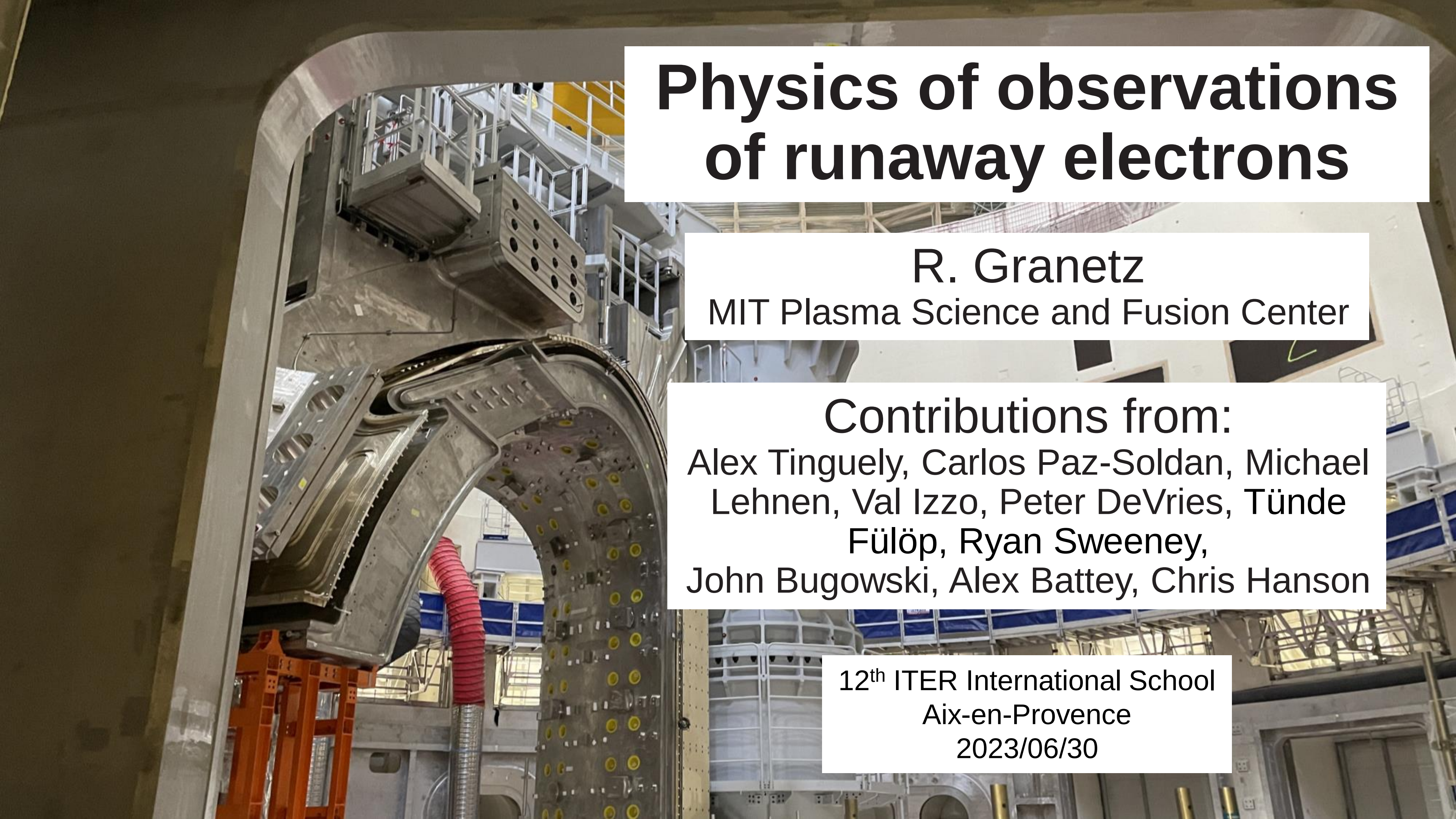


Physics of observations of runaway electrons

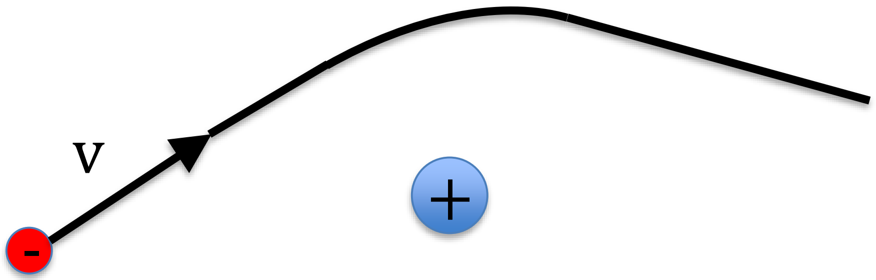
R. Granetz
MIT Plasma Science and Fusion Center

Contributions from:
Alex Tinguely, Carlos Paz-Soldan, Michael Lehnen, Val Izzo, Peter DeVries, Tünde Fülöp, Ryan Sweeney,
John Bugowski, Alex Battey, Chris Hanson

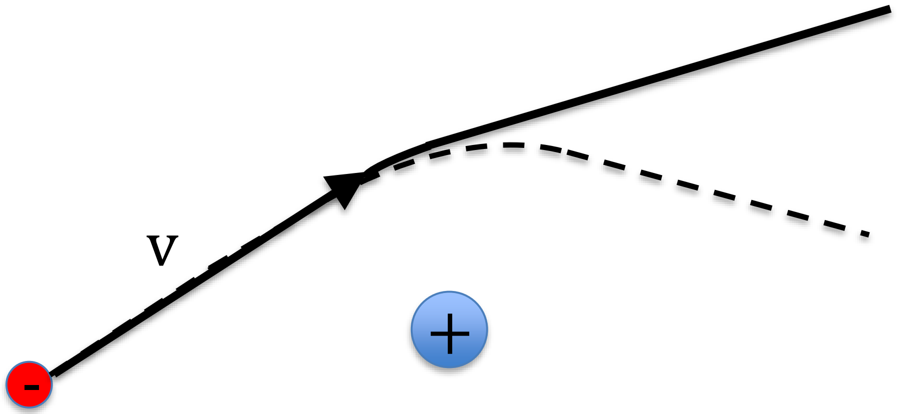
12th ITER International School
Aix-en-Provence
2023/06/30

What is the key physics that makes it possible to have runaway electrons in plasmas?

Consider a **charged** particle traveling through a **fully ionized plasma**. Particle motion is perturbed by the long-range Coulomb force



An incident particle with *higher* velocity experiences the same Coulomb force, but for a shorter time, and therefore its trajectory is perturbed *less*.



In a plasma, ***faster*** charged particles experience ***less*** perturbation of their motion than slower ones

Define ‘collision frequency’, ν [s^{-1}]

$$\frac{d\mathbf{v}}{dt} = -\nu\mathbf{v}$$

ν is a measure of how much a particle’s motion is changed by collisions

From plasma physics: $\nu = \dfrac{ne^4 \ln \Lambda}{4\pi\varepsilon_0 m^2 \mathrm{v}^3}$

$$\frac{d\mathrm{v}}{dt} = -\nu \mathrm{v}$$

$$m\frac{d\mathrm{v}}{dt} = -m\nu\mathrm{v}$$

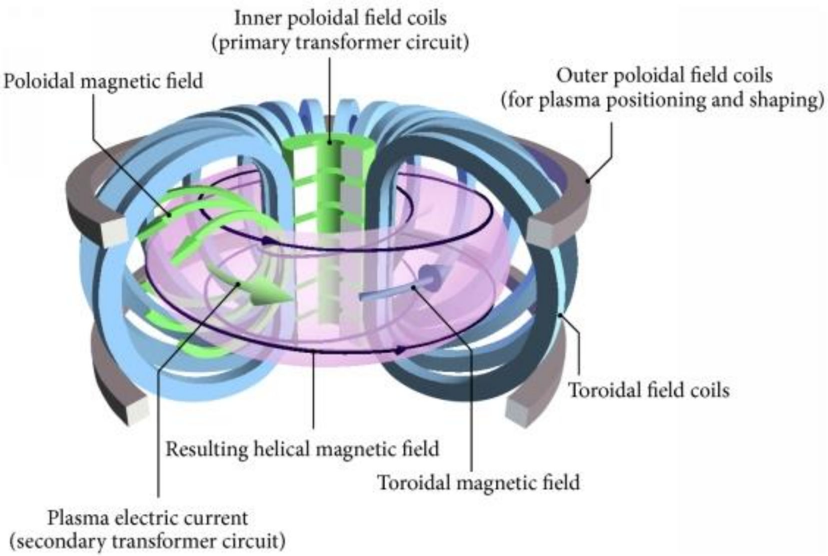
$$F_{\text{coll}} = m\frac{d\mathrm{v}}{dt} = -m\nu\mathrm{v}$$

F_{coll} is the collisional friction force

$$F_{\mathrm{coll}} = -m\nu \mathrm{v} \propto -1/\mathrm{v}^2$$

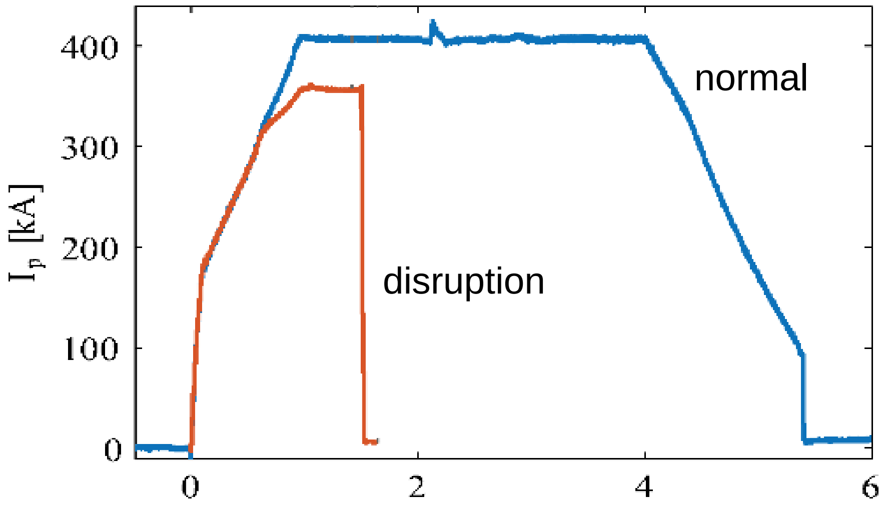
Hence, for a plasma, the tail particles in a Maxwellian distribution experience *less* collisional friction than the bulk, and therefore could *potentially* separate from the bulk distribution.

In a tokamak, a toroidal E-field is purposely applied to drive a large current in the plasma



The toroidal E-field and the $1/v^3$ dependence of ν provide the ingredients to make runaway electrons

Tokamaks are also subject to disruptions, which generate a *huge* toroidal E-field during the short time of the current quench



Primary (Dreicer) runaway generation

Now consider force on an electron with an applied electric field:

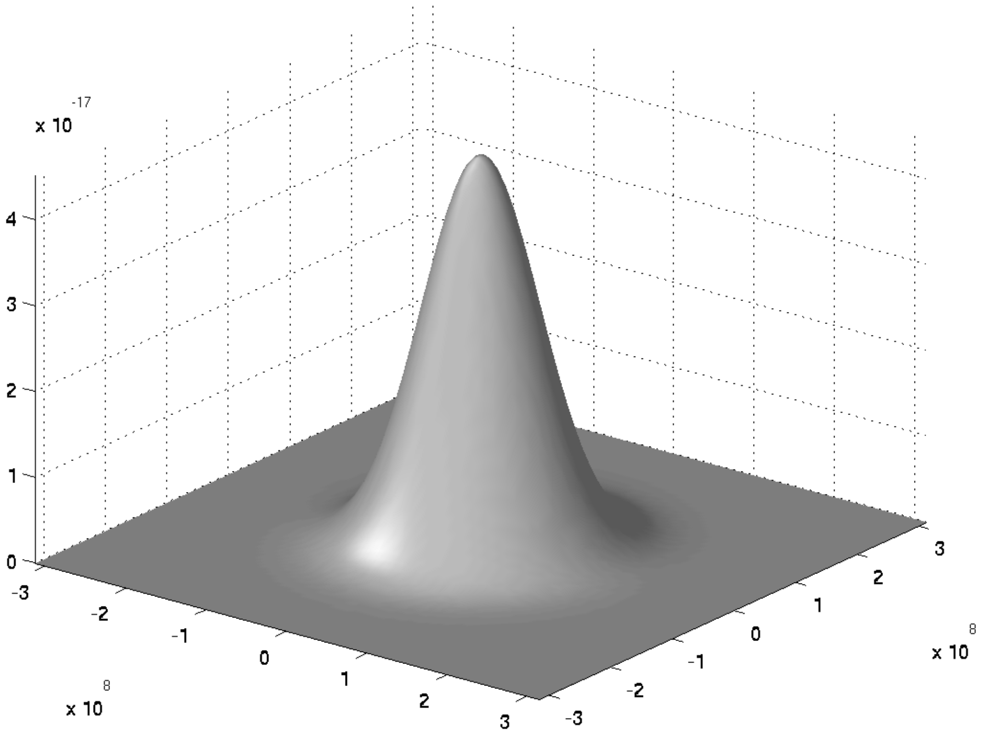
$$F = F_{\mathrm{E}} + F_{\mathrm{coll}} = -eE - m\nu \mathrm{v} \quad \text{where} \quad \nu = \frac{ne^4 \ln \Lambda}{4\pi\varepsilon_0 m^2 \mathrm{v}^3}$$

If $F_E \geq F_{coll}$ the electron will accelerate forever, i.e. run away *if there are no other energy loss mechanisms*.

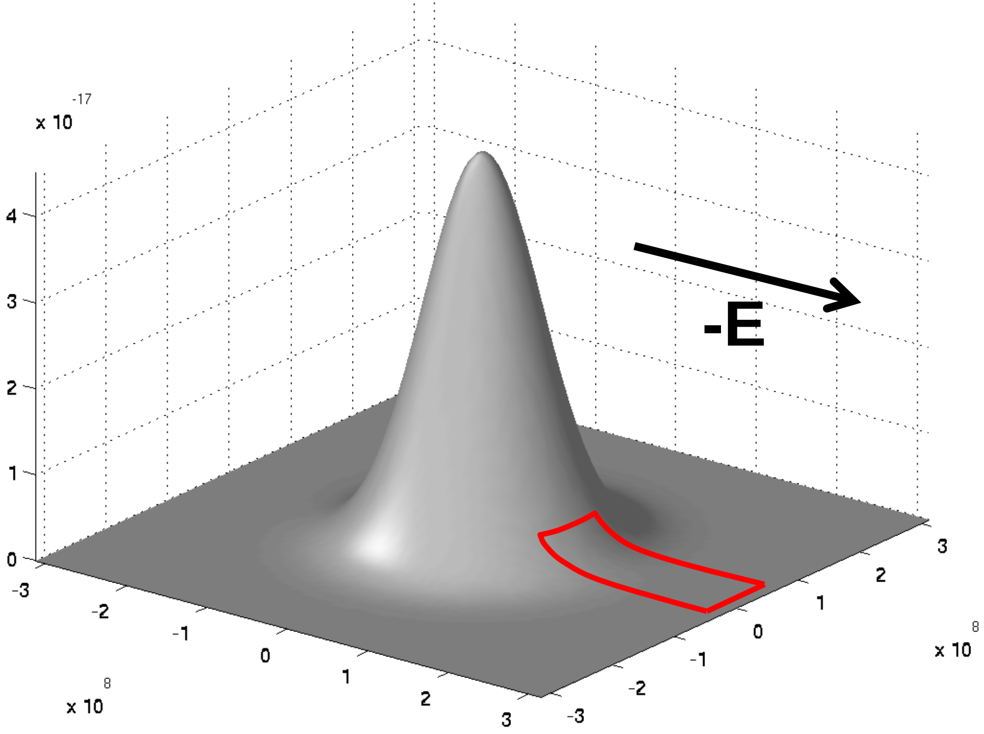
This gives a condition for runaway generation:

$$E \geq \frac{ne^3 \ln \Lambda}{4\pi\varepsilon_0 m \mathrm{v}^2}$$

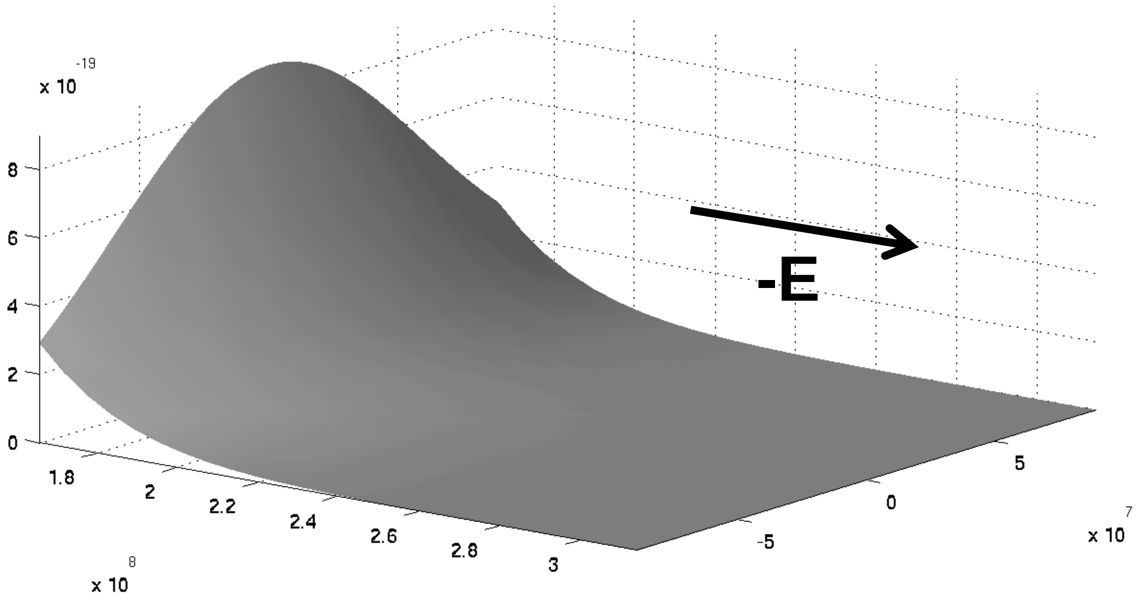
Maxwellian velocity distribution function



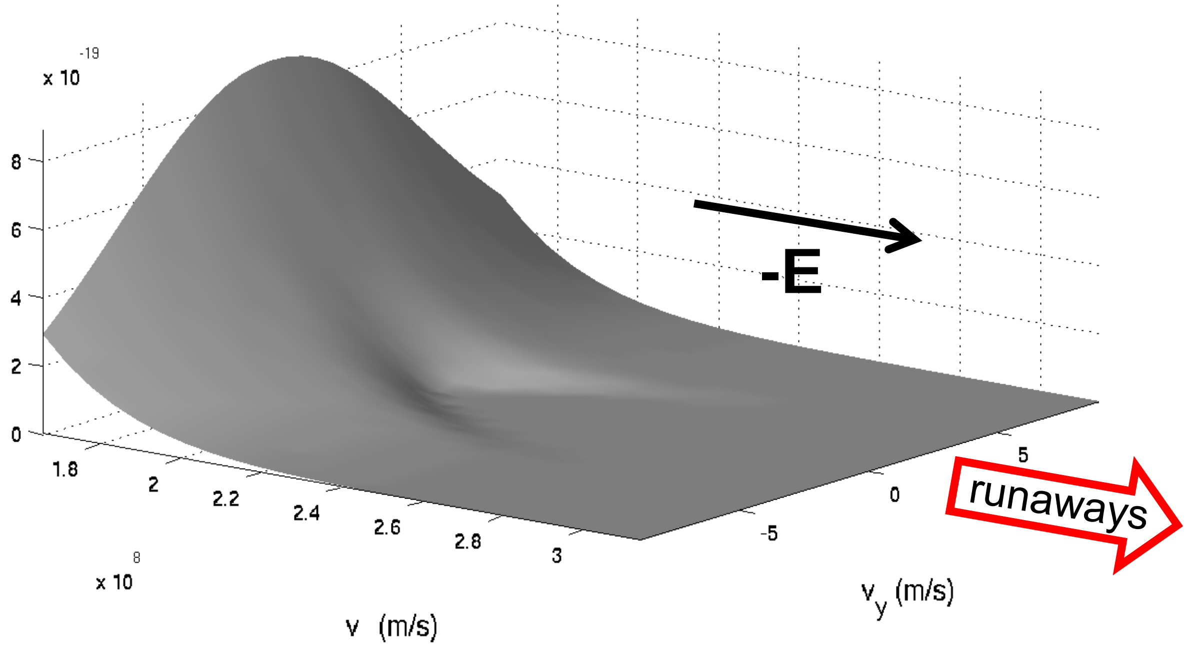
Apply E-field
($V_{loop}/2\pi R$ in tokamaks)



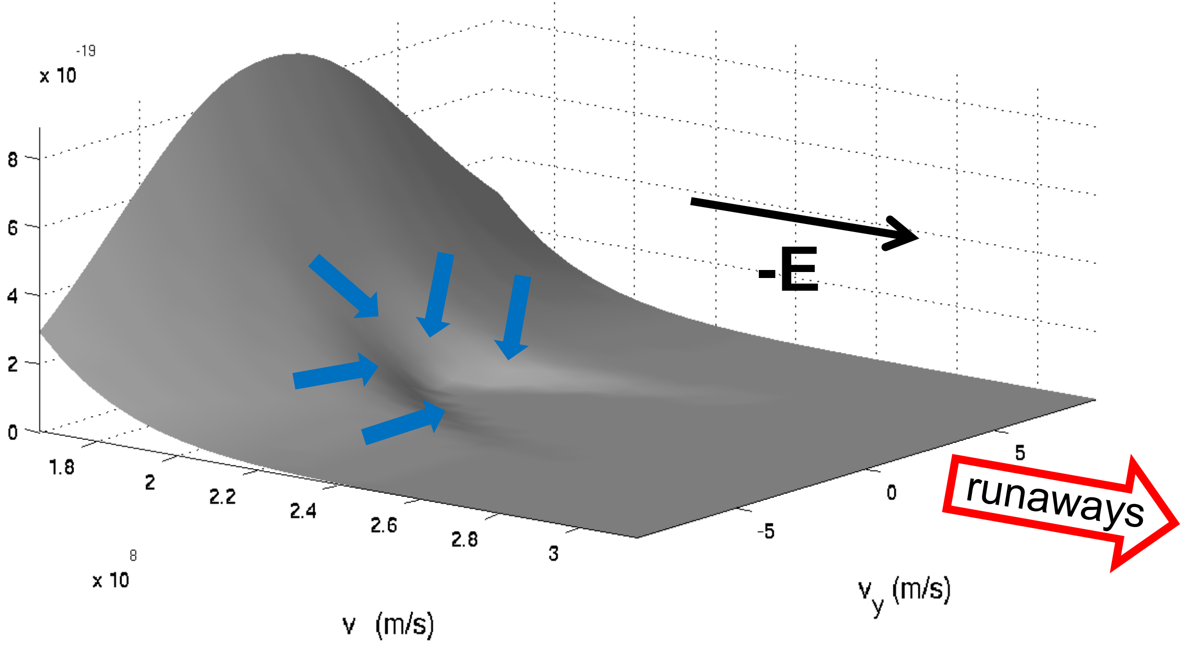
Tail region of Maxwellian velocity distribution function



Tail electrons run away due to E-field and low collisional drag



RE growth rate is set by rate that electrons continuously fill in hole in f(v)



Notes about simple Dreicer picture of primary RE generation:

- Relativistic runaways have no slowing down mechanism, and no loss mechanism. Each RE continues to gain velocity indefinitely.
- Assumption is that n_{RE} is small compared to background distribution, and therefore does not affect ‘fill-in’ rate
- This implies that:

$$\frac{dn_{RE}^{primary}}{dt} = \text{ fill−in rate } = f(n_e, T_e, Z_{eff} \text{ BUT NOT } n_{RE})$$

i.e, not exponential, but sensitive to plasma parameters

$$E \geq \frac{n_e e^3 \ln \Lambda}{4\pi\varepsilon_0 m \mathrm{v}^2}$$

However, the maximum possible electron velocity is $v = c$. The fully relativistic derivation for runaways gives:

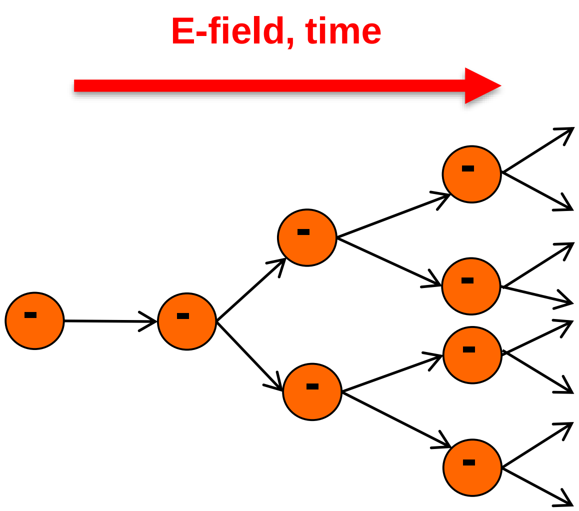
$$E_{\mathrm{crit}} = \frac{n_e e^3 \ln \Lambda}{4\pi\varepsilon_0^2 m_e c^2}$$

This E_{crit} is the absolute minimum E-field required to generate any runaways.

J.W. Connor and R.J. Hastie, Nucl.Fusion ***15*** *(1975) 415*

There is also another way to generate runaway electrons:

Avalanche process



- Requires some relativistic (~MeV) runaway electrons (REs) to already exist (i.e. a seed)
- RE collides with thermal electron
- Transfers ~ ½ initial energy (MeV)
- Now there are TWO relativistic electrons
- Those two REs each collide with thermal electrons, producing FOUR REs
- dn_{RE}/dt is exponential

$$Gain \sim e^{\frac{current\,[MA]}{0.4}} \sim \exp(37.5) \sim 2\times10^{16}\ !!!$$

more detail in Tünde Fülöp’s lecture

M.N. Rosenbluth and S.V. Putvinski, Nucl. Fusion 37 1355 (1997)

Runaways can occur during several different phases of a tokamak plasma discharge

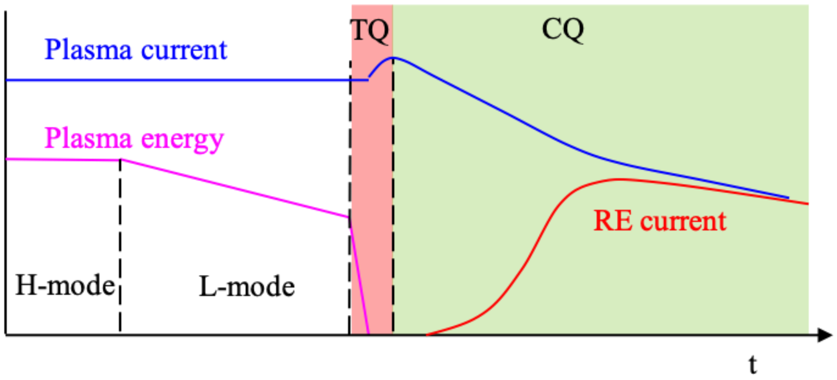
- Disruptions: HUGE loop voltage, but plasma conditions are poorly controlled, and not well diagnosed.
- Steady-state flattop: well-controlled conditions for research physics
- Plasma startup: loop voltage is higher than normal and density is low

Runaways can occur during several different phases of a tokamak plasma discharge

– Disruptions: HUGE loop voltage, but plasma conditions are poorly controlled, and not well diagnosed.

- Could cause catastrophic damage in ITER
- Elaborate disruption mitigation system (DMS) being developed based on shattered pellet injection
- Several other RE mitigation concepts being looked into

Disruption runaways in ITER



$$V_{Loop} = -L_{plasma}\frac{dI_p}{dt}$$
$$= 5\,\mu\mathrm{H} \times (15\,\mathrm{MA}/50\,\mathrm{ms})$$
$$= 1500\ \mathrm{volts}$$
$$E_{//} = V_{Loop}/2\pi R = 38\ \mathrm{V/m}$$

Modeling of ITER 15 MA disruptions leads to predictions of up to 10 MA of current carried by runaways, with 10-20 MeV energies

– Potentially very damaging to blanket and divertor modules

Runaways need to be mitigated, collisionally or otherwise

– ***Collisional-only*** mitigation requires extremely high n_e :

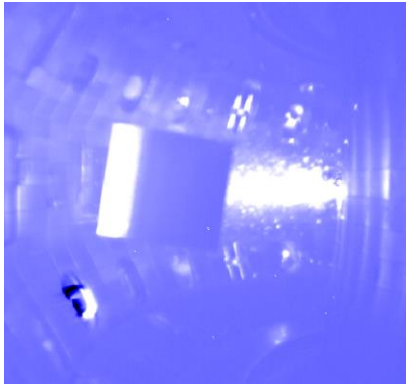
$$E_{\mathrm{crit}} = 0.08 n_e \quad \Rightarrow \quad n_e \geq \frac{38}{0.08} = 4 - 5 \times 10^{22}\mathrm{m}^{-3}$$ (Rosenbluth density)

– Serious implications for tritium-handling plant, cryopumps, etc.

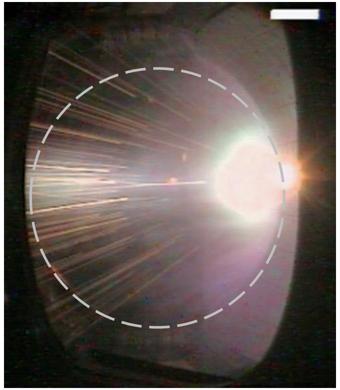
– Experiments on existing machines have difficulty reaching the Rosenbluth density

Relativistic electrons generated during disruptions can damage the tokamak wall

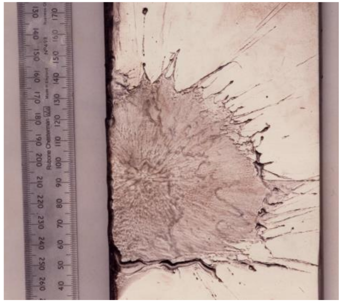
RE impact (DIII-D, USA)



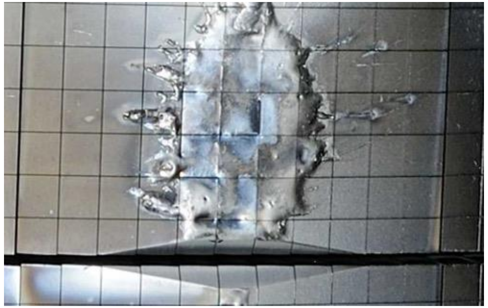
RE impact (TEXTOR, Germany)



Post-Impact on Carbon (JET, UK)

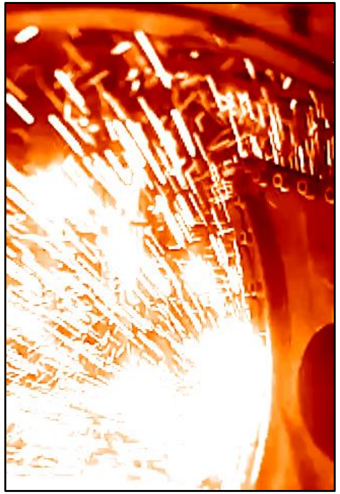


Post-Impact on Beryllium (JET, UK)



above only ~ 1% energy of a potential RE strike in ITER!

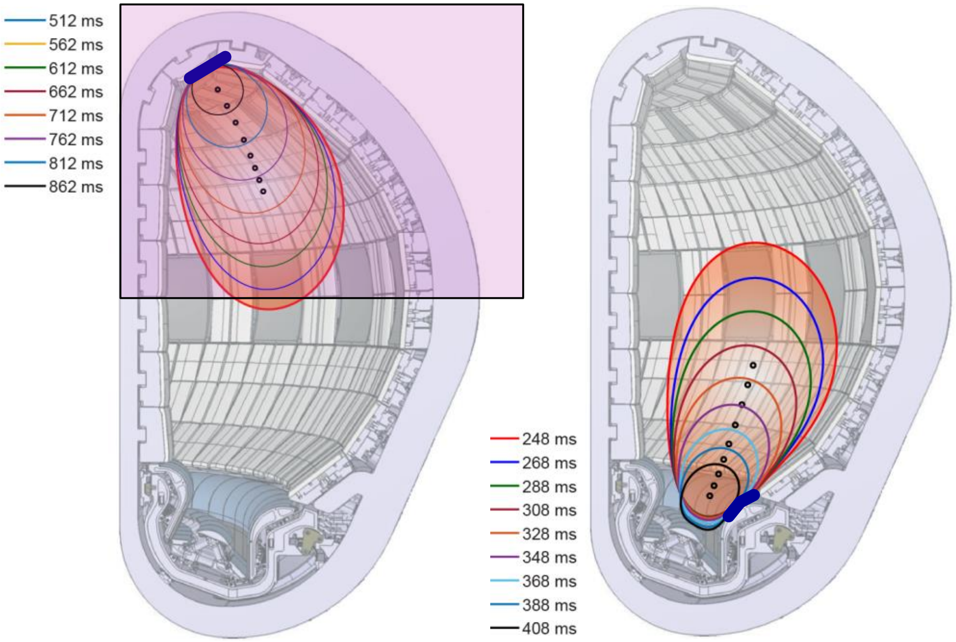
REEs impacting outboard limiter on Alcator C-Mod



Motivation

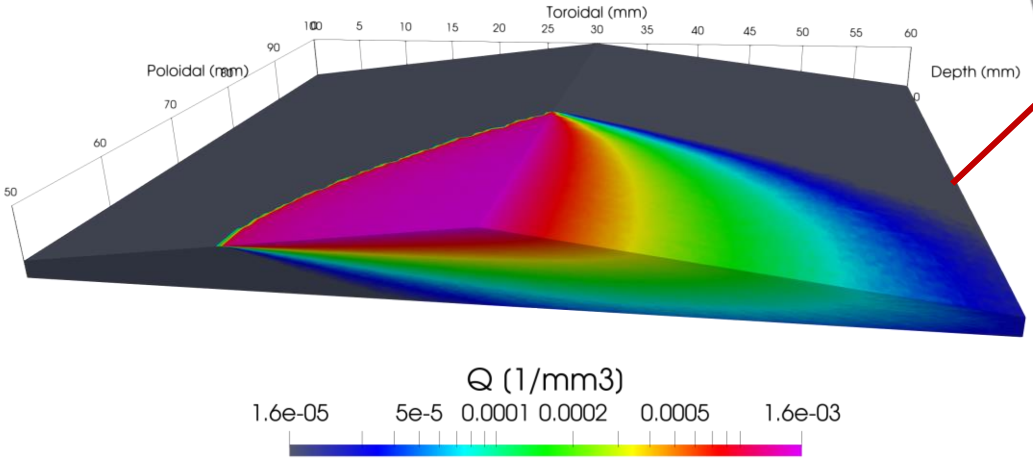
- REs carrying currents up to 10 MA with kinetic energy ~ 20 MJ could be formed during the Current Quench of plasma Disruptions in ITER (15 MeV particles).
- Up to hundreds of MJ of magnetic energy can be converted to kinetic RE energy.
- The power deposition width is expected to be extremely narrow (Larmor radius scale).
- ITER plasma facing components (PFC) are all actively water cooled → volumetric energy deposition of RE into the bulk may lead to damage of the cooling interface.

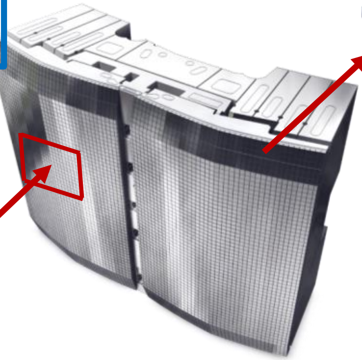
R. Pitts et al. 47th EPS Plasma Physics conference

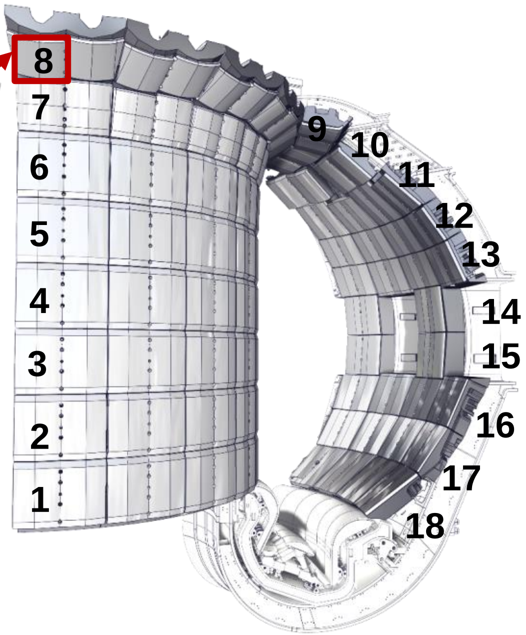


GEANT4: volumetric energy deposition (Δr_{RE} = 2 mm)

Normalized energy deposition in the cross section on one apex





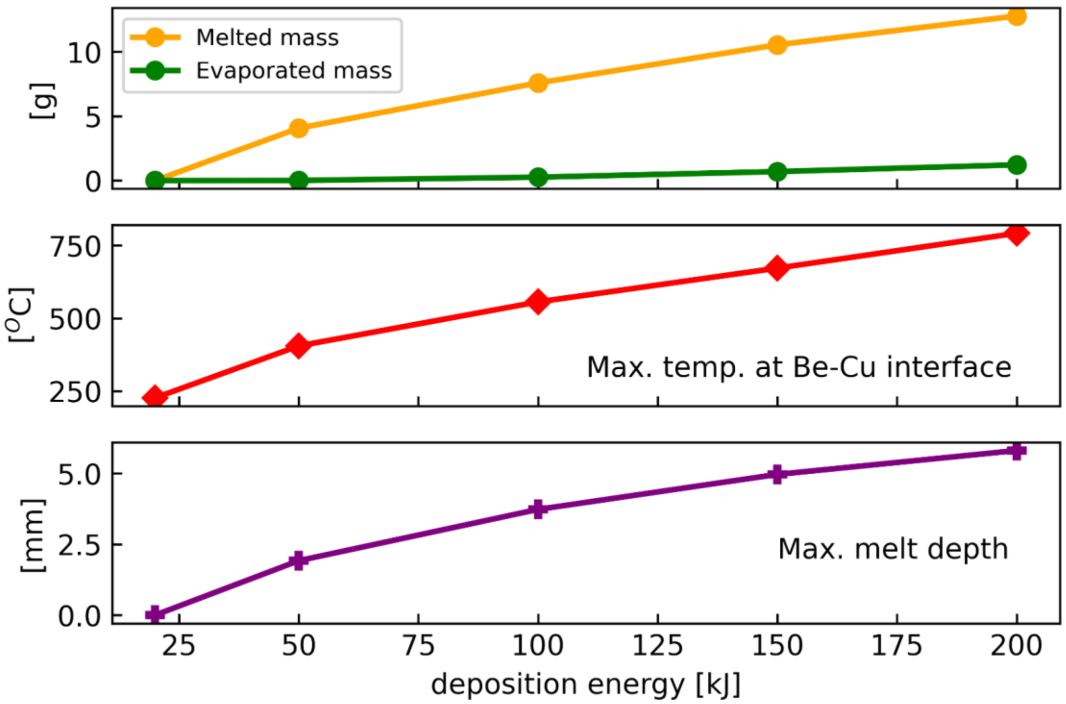


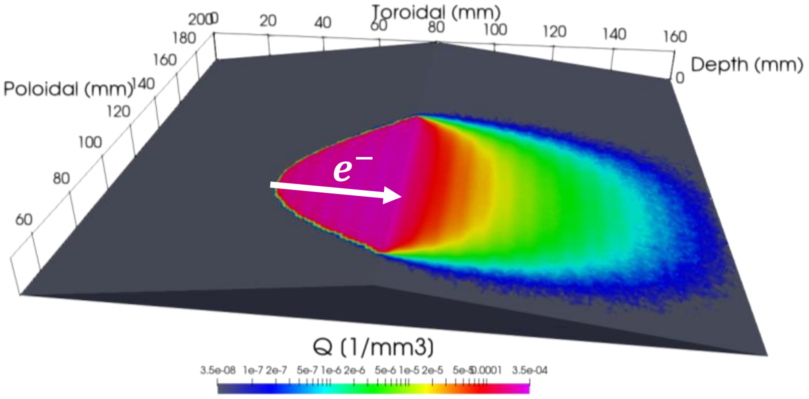
- Electrons passing through the previous Be panels are not taken into account in GEANT4 simulations.

With the beam width Δr_{RE} = 2 mm, the RE footprint area (the area where runaway electrons entering the materials) is very localized: 5 cm^2 (a few Be castellations)

One entire row of First wall panel:
18 sectors × 2 = 36 apexes

Scanning of parameters (Δr_{RE} = 4 mm, Δt = 1 ms)





- Small footprint area (14 cm^2)
- Deep melting and high $T_{interface}$ already at low E_{dep}
- Melted mass is negligible (no significant contribution to dust formation)

Note: The value of maximum melt (evaporated) mass, deposition energy shown are on one Apex.

Thresholds for melting and cooling channel integrity

Melt threshold

- ~20 kJ (deposition on one apex)
  → *RE current in the few kA range*
- ~720 kJ (uniform energy distribution over the entire row of FWP)
  → *RE current of ~360kA (Δt = 1ms) or ~490kA (Δt = 100ms)*

Threshold for cooling channel integrity ($T_{interface}$ = 800°C)

- ~200 kJ (deposition on one apex)
  → *RE current of ~100kA (Δt = 1ms) or ~260kA (Δt = 100ms)*
- ~7.2 MJ (uniform energy distribution over the entire row of FWP)
  → *RE current of ~3.6MA (Δt = 1ms) or ~1.5MA (Δt = 100ms)*

→ The uniformity of the energy deposition is critical and will depend on alignment and the nature of the MHD event causing the RE deposition

Note that the energy scales linear with I_P for the 1 ms scenario and quadratic for the 100 ms scenario.

Summary and conclusions

❖ JET validation study

- A multi-physics workflow was developed to assess the melt damage to plasma facing components (PFCs) induced by a RE beam strike. The workflow has been applied to JET.
- Modeling results are in good agreement with experimental observations if the RE deposition width is 1~2 mm.
- Already the deposition of 100 kJ during 6 ms leads to a significant melting and boiling.

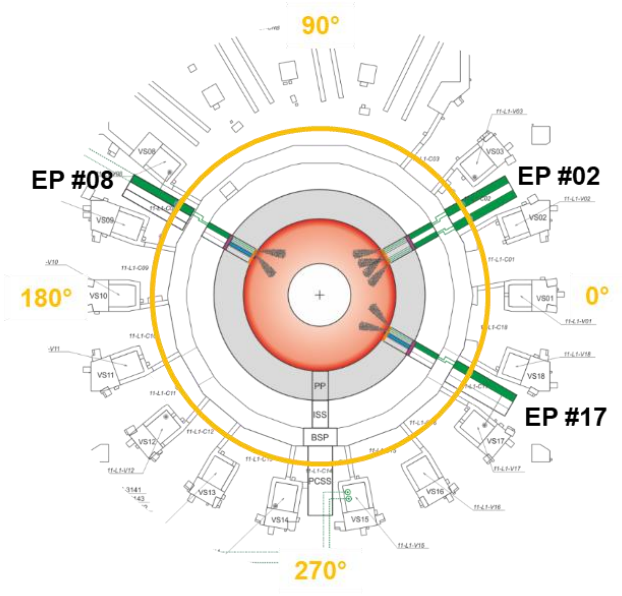
❖ ITER simulations

- Simulations for a beam width of 4 mm and deposition times of 1 and 100 ms were performed.
- Deep melting is observed at low energies due to the very localized energy deposition; e.g. 8 mm melt depth at ~400 kJ per apex
- The integrity of the cooling channels would be at risk already during a strike of RE beams of a few 100 kA in the most pessimistic scenario (energy deposition on a single apex)
- The simulation results emphasize the importance of reliable RE avoidance by the ITER Disruption Mitigation System

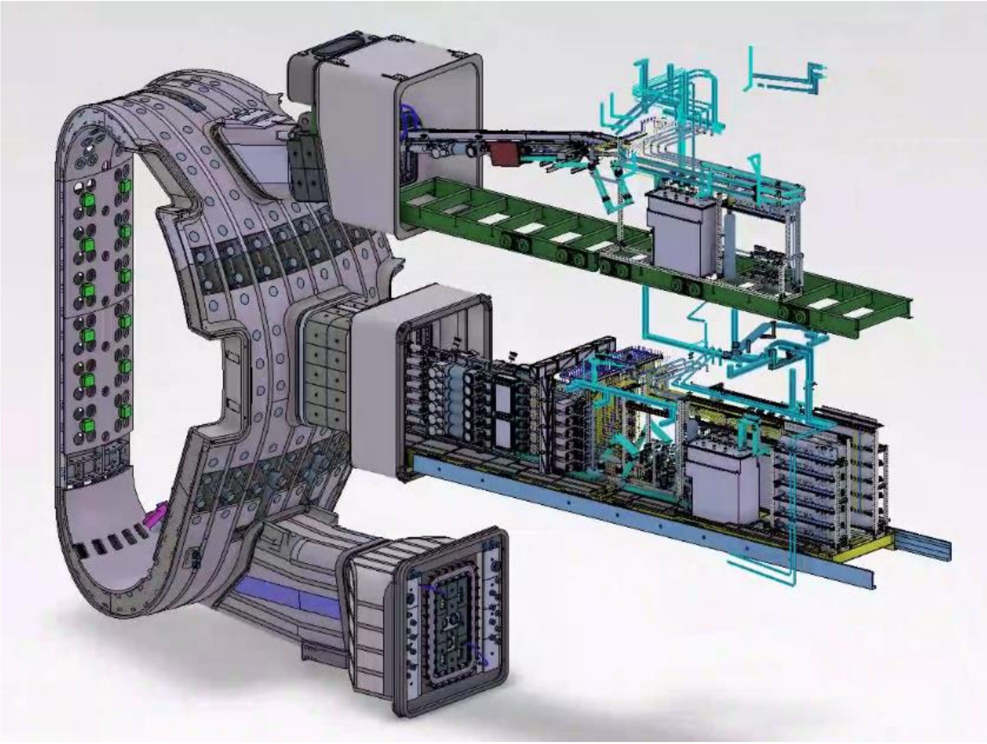
ITER's baseline strategy for RE mitigation is raising the density (collisional mitigation)

Baseline technique: Injection of frozen D2 pellets and impurity (Ne, Ar) pellets via shattered pellet injection (SPI)

Assumption (unproven): All of the injected material gets ionized and confined in the disrupting plasma, increasing n_e to the Rosenbluth density ($\sim 5 \times 10^{22}$ m^{-3})



DMS design status



DMS Final Design Review Meeting rescheduled to **March 2024**

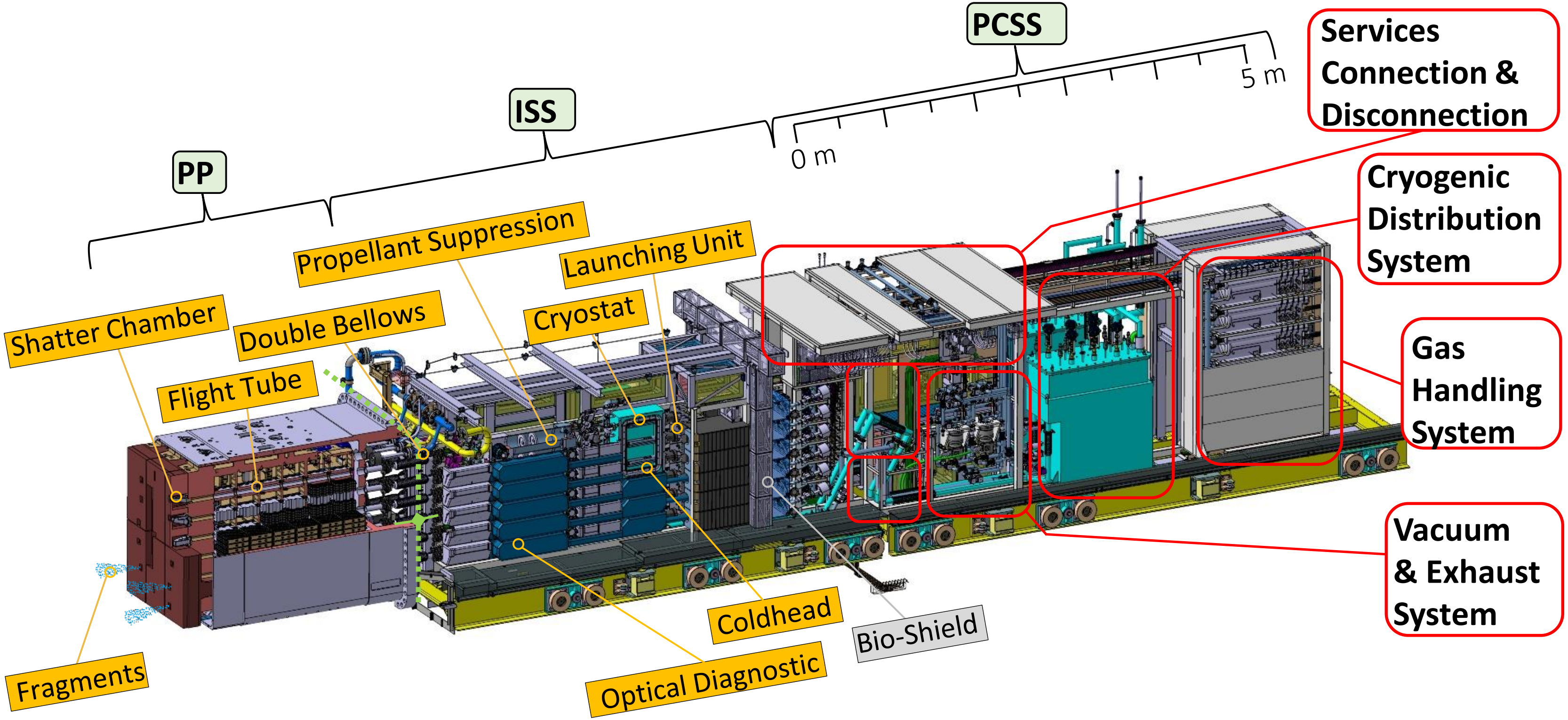
UP #02, #08, #14:
each 1 injector

EP #02:
12 injectors

EP #08, #17:
each 6 injectors

DMS design status

Present design for port plug EP#02



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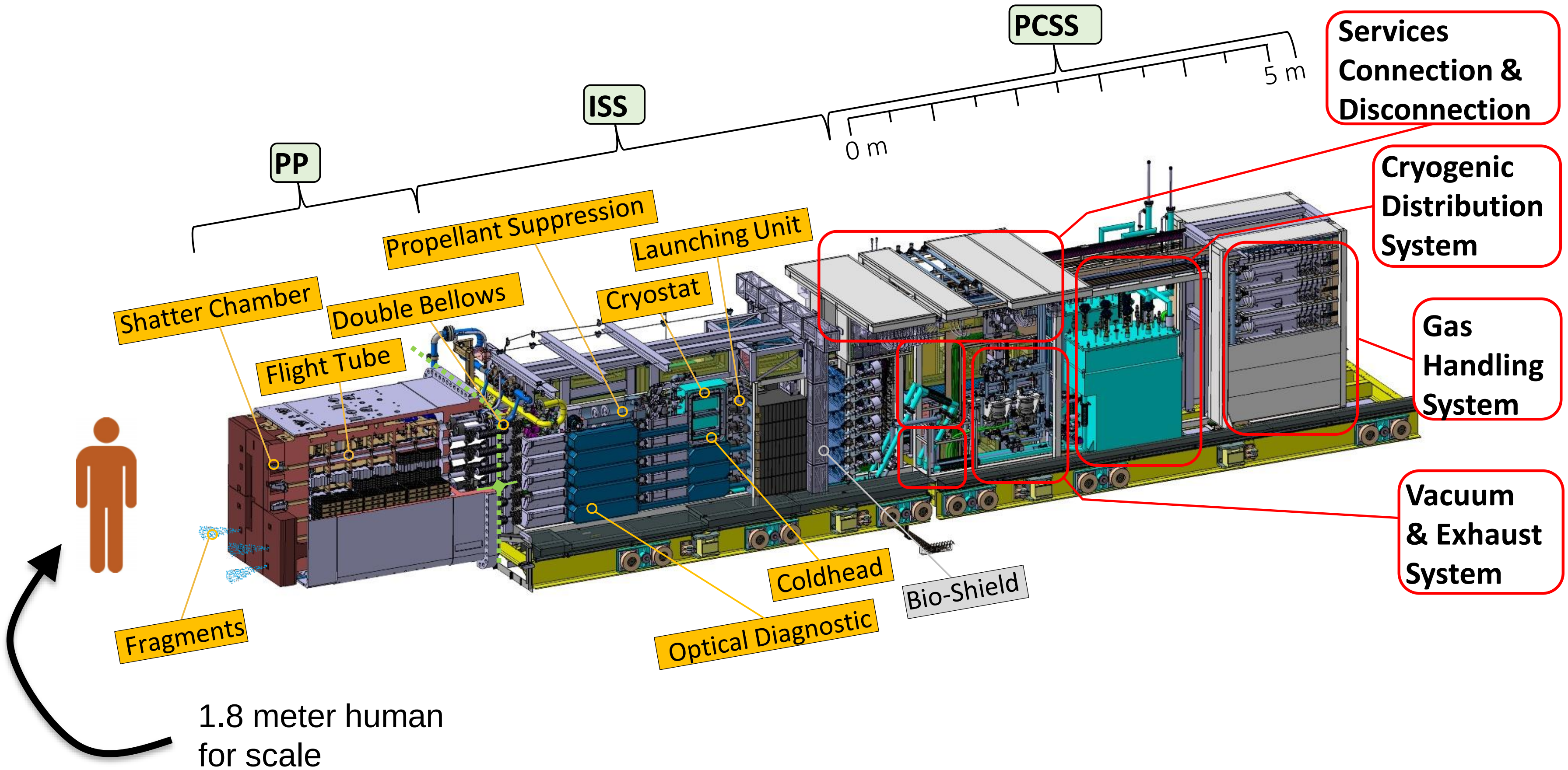
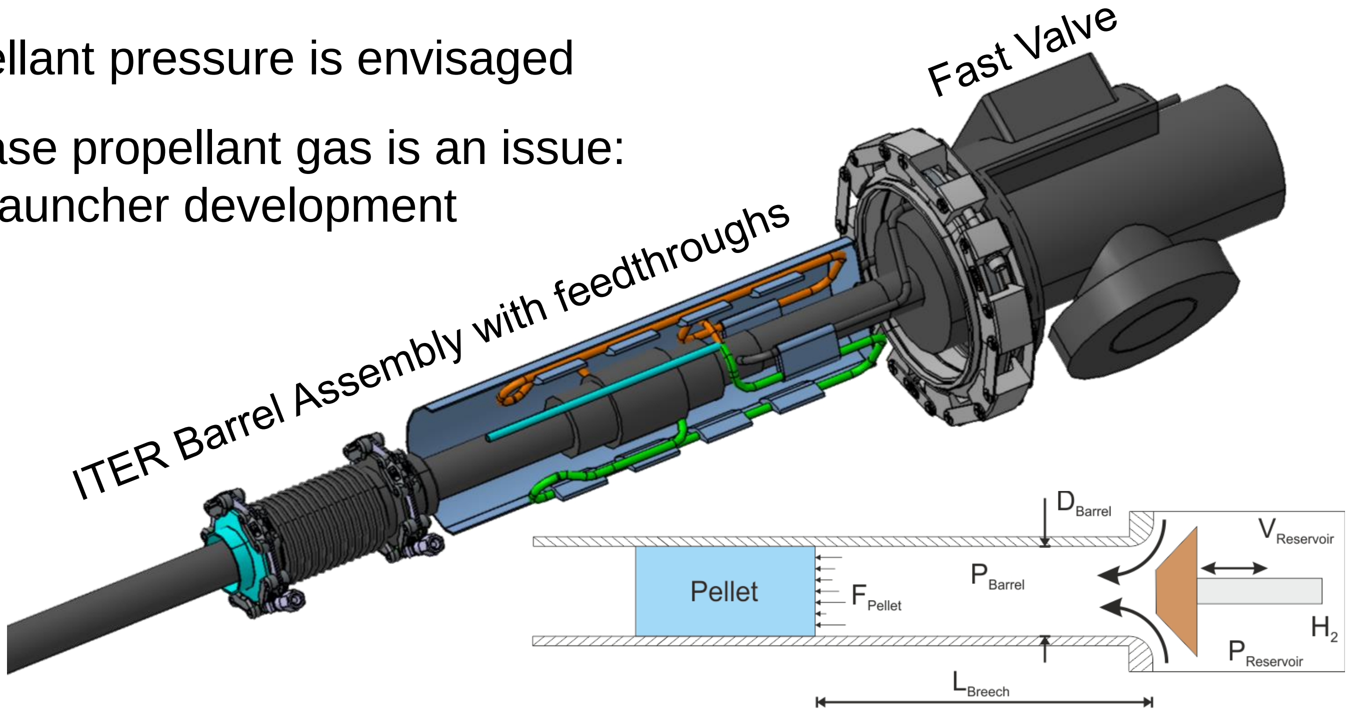


DMS design solutions – Pellet launching

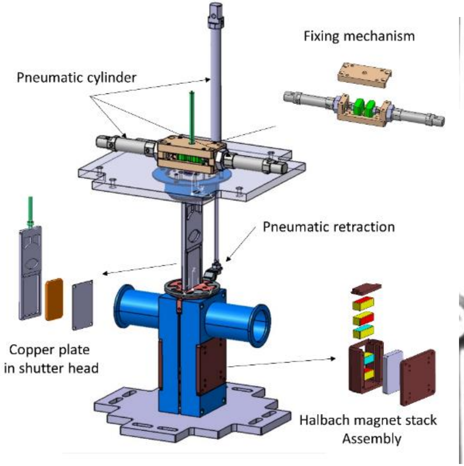
- A fast eddy-current actuated valve (aka flyerplate valve) provides the required flow and breakaway pressure
- Up to 100 bar propellant pressure is envisaged
- Risk mitigation in case propellant gas is an issue: Mechanical Pellet Launcher development started Q1/2023

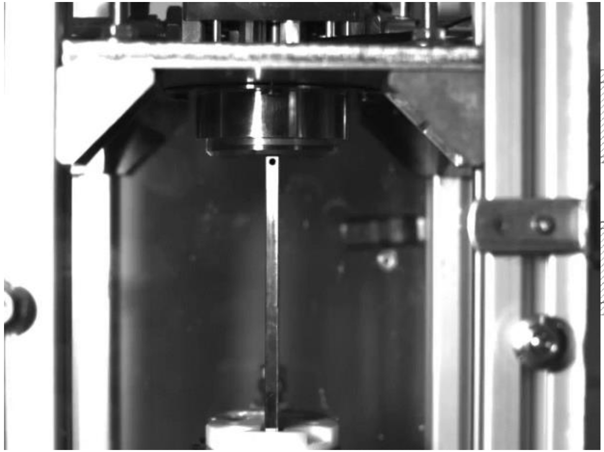


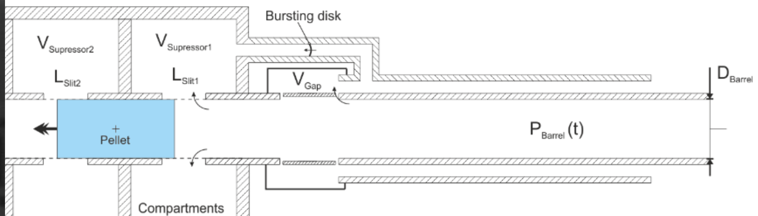
DMS design solutions – Propellant Gas

- ❑ Propellant gas entering the plasma before the fragments needs to be minimised
- ❑ Pellet rotation needs to be avoided to allow free flight

- ➢ Due to restricted space the expansion volume is small (~50 l per injector)
- ➢ Efficient pumping is not possible → the gas must be retained/suppressed
- ➢ The baseline solution utilises a suppressor volume together with a fast shutter



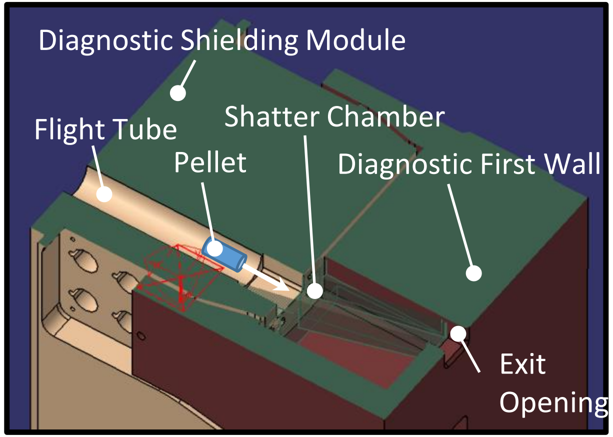




Achieved closing time < 3 ms
Target is 1 ms

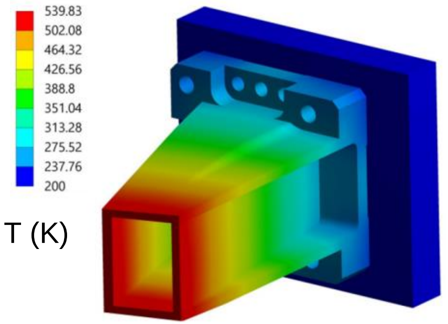
A. Zsákai et al, Centre for Energy Research

DMS design solutions – Shattering



Heat load optimization

- ➢ shape modification
- ➢ material reduction

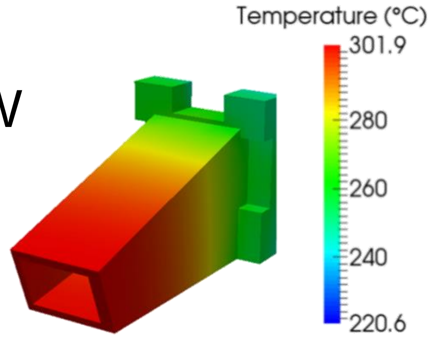


Plasma radiation

850 W/ 700 W → 550 W

Neutron heating

1950 W → 1200 W



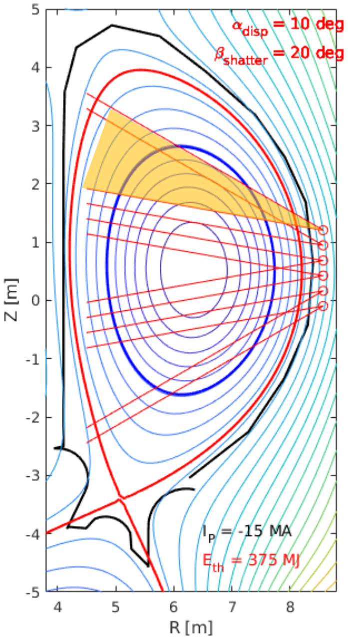
Pellet impact may affect integrity

- ➢ Modelling underway at EMI Fraunhofer
- ➢ Tests in the fundamental studies lab at CEA

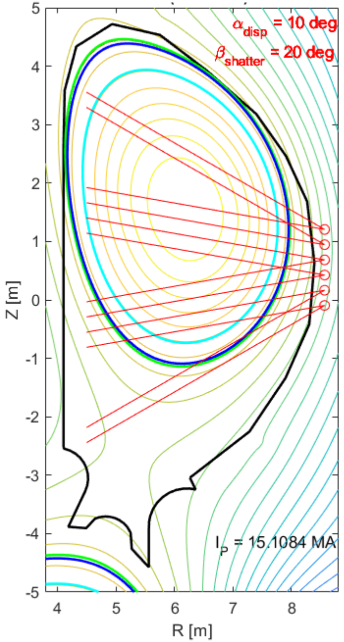
Injection directions

pre-TQ injection

Major Disruption (baseline scenario)

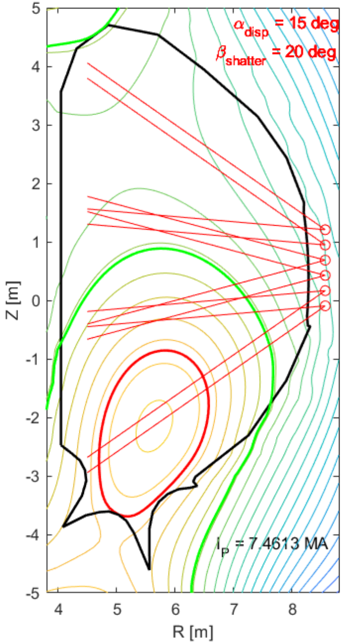


Upward VDE

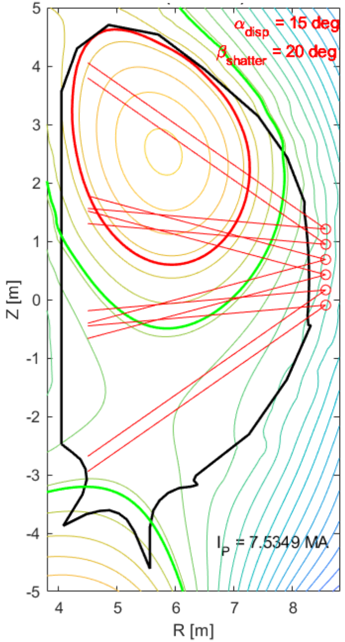


post-TQ RE mitigation

Downward VDE (t@7.5 MA)

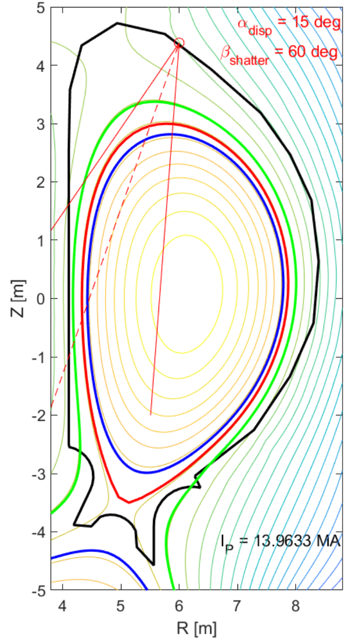


Upward VDE (t@7.5 MA)



post-TQ

Downward MD



In case SPI is not able to mitigate disruption runaways, what's the backup plan?

Experiments on several tokamaks have shown that B-field perturbations can cause REs to be deconfined.

– NOTE: the deconfined REs must be spread over a large surface area, not concentrated onto a small spot

- $\tilde{B}$ due to actively generated non-axisymmetric fields (i.e. EF correction coils, RMP coils)
- $\tilde{B}$ due to actively induced MHD instabilities
- $\tilde{B}$ due to TAE instabilities generated by fusion α's
- $\tilde{B}$ due to passively generated non-axisymmetric fields (REMC coil)

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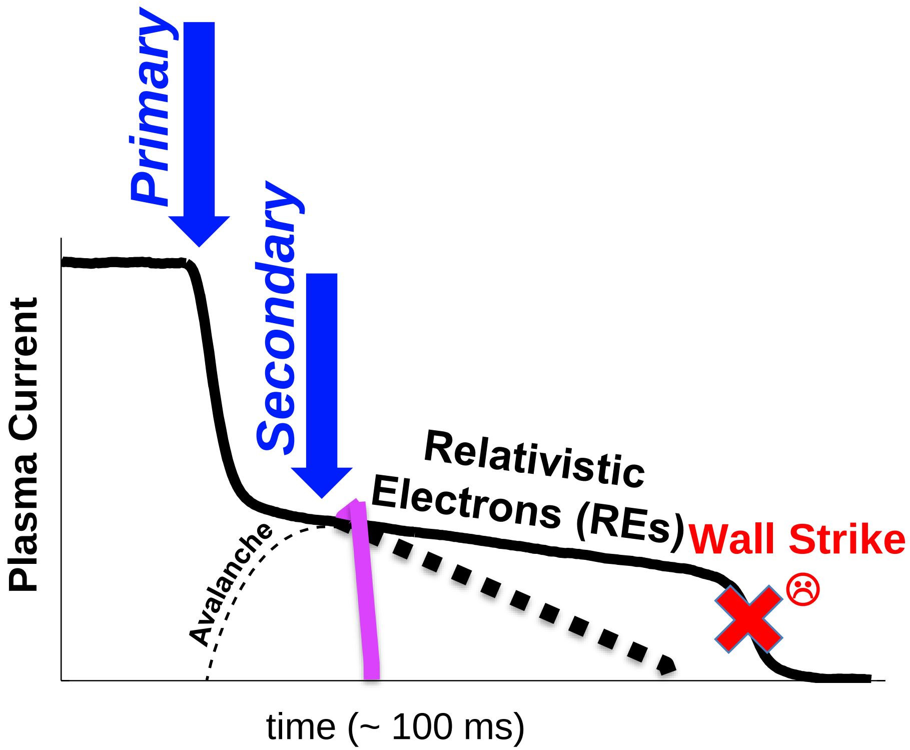
Disruption Mitigation:
Manage Fast Electrons via Secondary Injection



Secondary Injection:

Baseline Approach: *Collisional*

- **Inject as much mass as possible**
- **Dissipate energy via collisions**

Alternate Approach: 3-D Fields

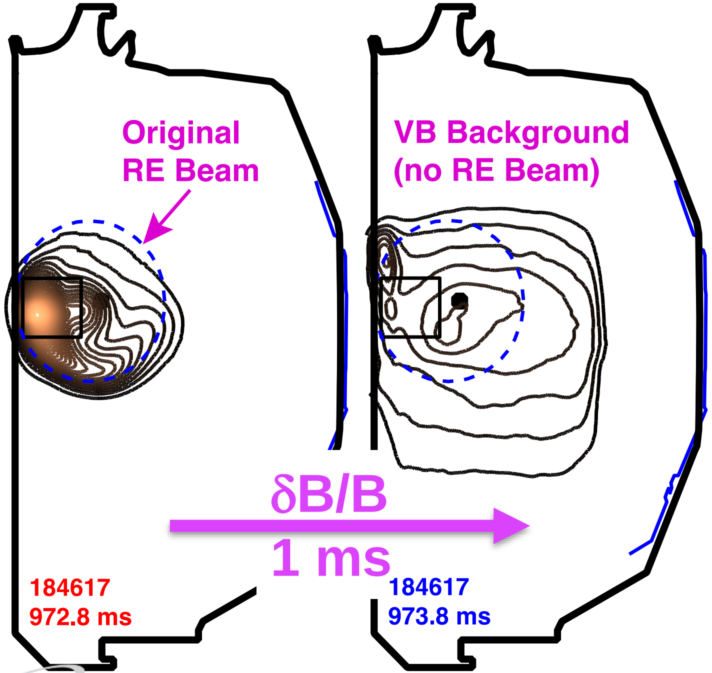
- **Injection promotes MHD activity**
- **Goal: get large-scale 3-D fields**
  - Intrinsic or extrinsic $\delta B/B$

What does a big 3-D field do to a beam of fast electrons?

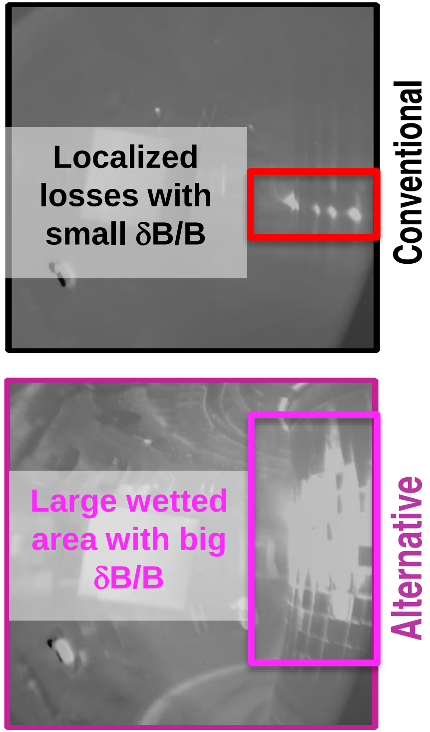
DIII-D NATIONAL FUSION FACILITY

Large-Scale 3-D Fields:
Terminates and Disperses Relativistic Electron Beam

Visible Imaging:
REs vanish in under 1 ms



Infrared Imaging:
Dispersed impact



[1]C. Paz-Soldan et al, PPCF 2019
[2]C. Reux et al, Phys. Rev. Lett 2021 & C. Paz-Soldan et al Nucl. Fusion 2021

Large-Scale 3-D Fields: Terminates and Disperses Relativistic Electron Beam

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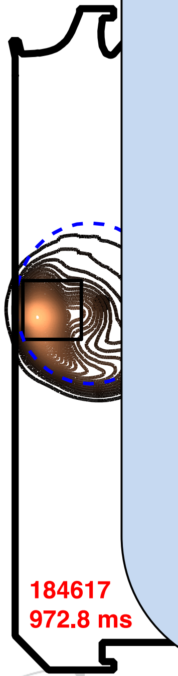
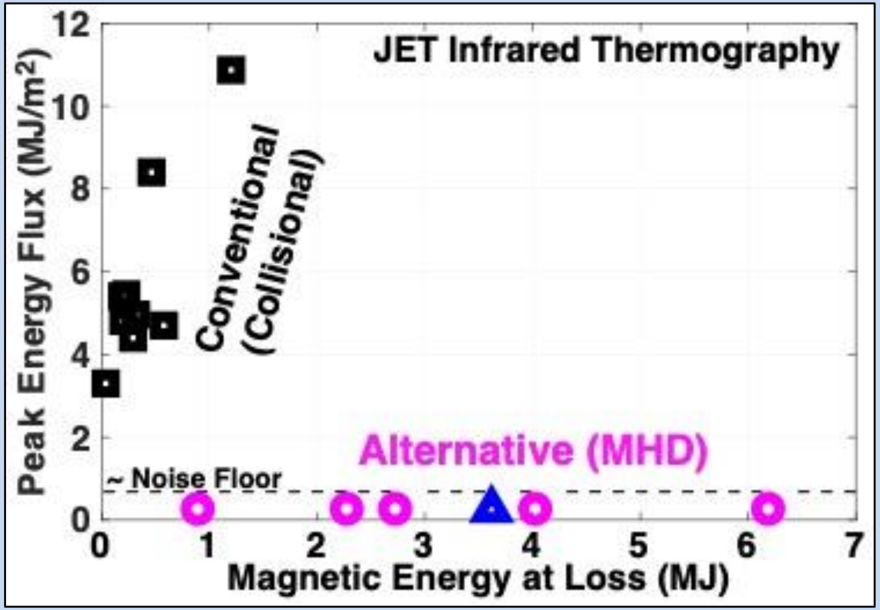
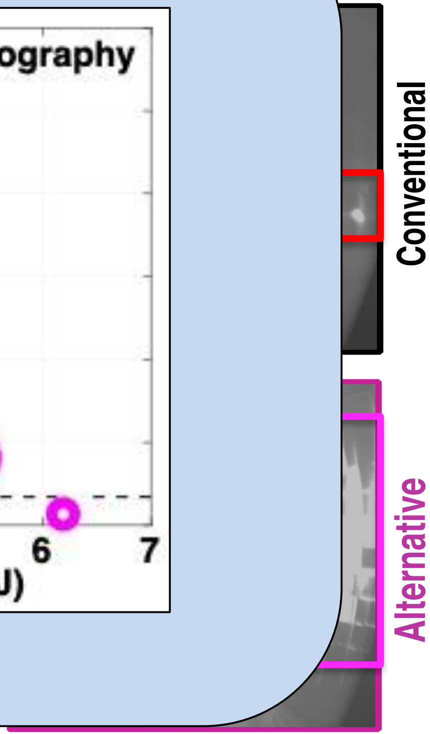


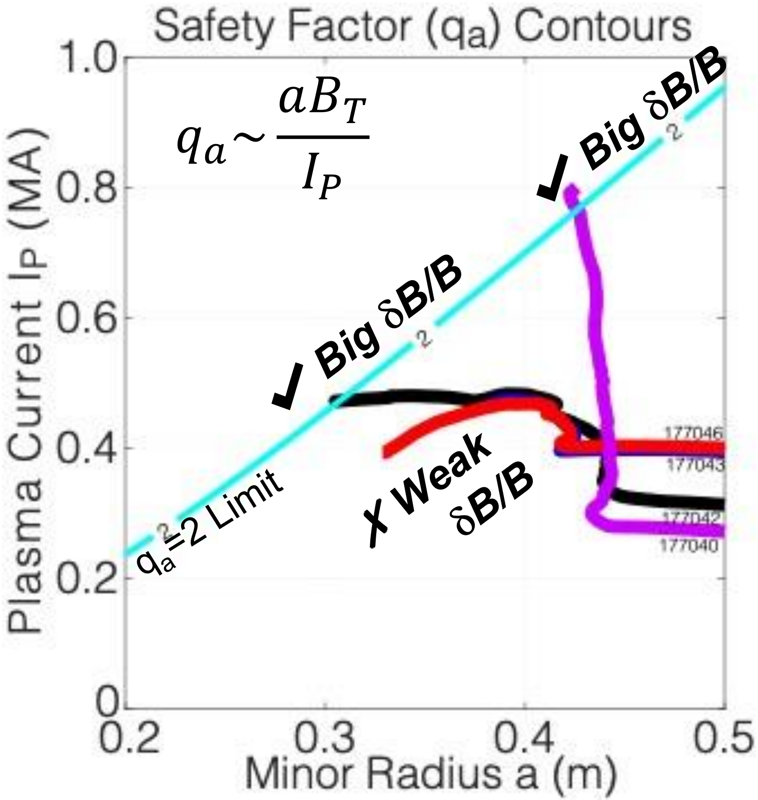




[1]C. Paz-Soldan et al, PPCF 2019
[2]C. Reux et al, Phys. Rev. Lett 2021 & C. Paz-Soldan et al Nucl. Fusion 2021

Intrinsic MHD Instability Responsible for Large-Scale δB/B

- **DIII-D data consistently finds large δB/B at external kink stability limit**
  - Boundary is more complex at JET[1]
- **Mechanical analog: twisting an elastic band until it kinks**
  - Safety factor quantifies B-field twist

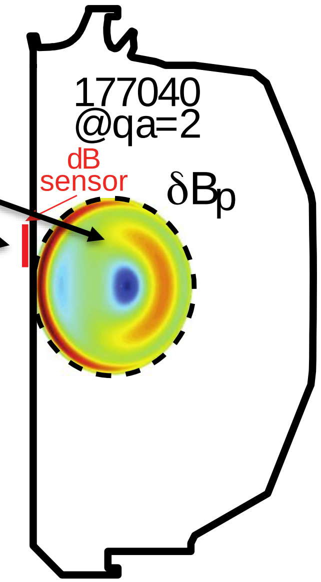


DIII-D NATIONAL FUSION FACILITY

[1]C. Reux et al, Phys. Rev. Lett 2021 & C. Paz-Soldan et al Nucl. Fusion 2021

Modeling Supports Picture of Termination and Dispersal

- **Stability model[1] identifies kink mode structure at termination**
  - Scale size to match sensor data



[1]Y. Q. Liu et al, Nucl. Fus 2019 & Phys Plasmas 2020

Modeling Supports Picture of Termination and Dispersal

- **Stability model[1] identifies kink mode structure at termination**
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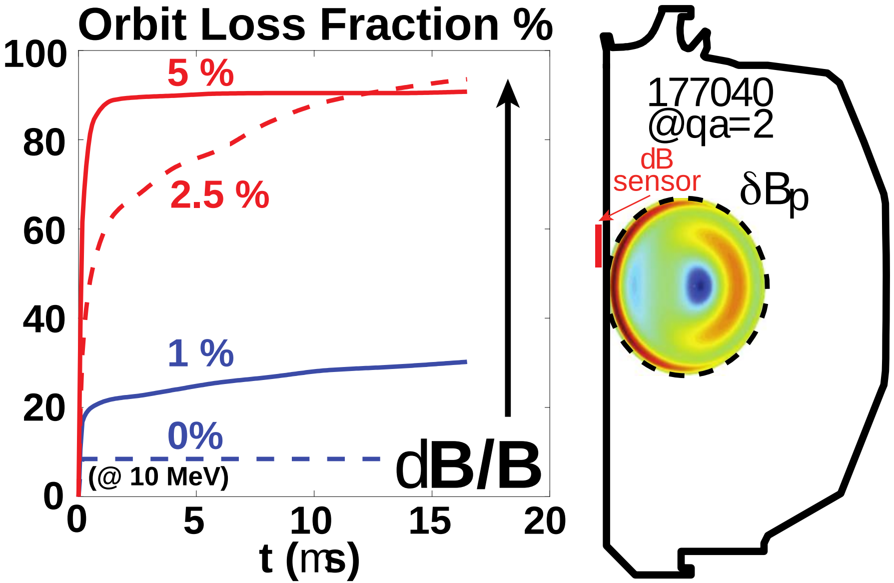
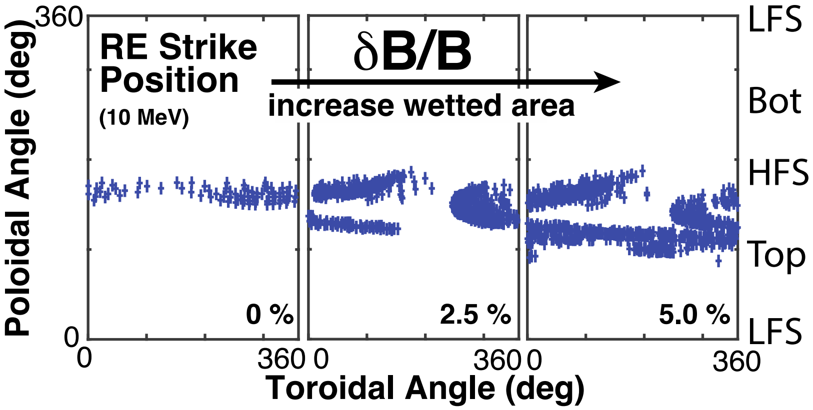
- **Near-total loss of REs predicted for experimental δB/B values**

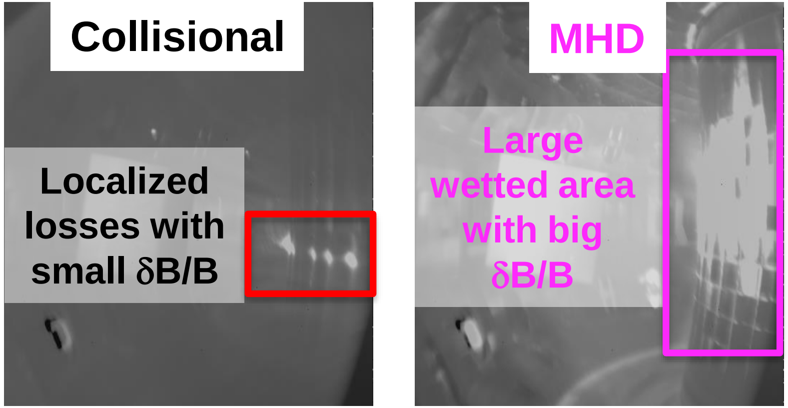


[1]Y. Q. Liu et al, Nucl. Fus 2019 & Phys Plasmas 2020

Modeling Supports Picture of Termination and Dispersal

- **Stability model[1] identifies kink mode structure at termination**
  - Scale size to match sensor data
- **Near-total loss of REs predicted for experimental δB/B values**
- **Predicted impact "wetted area" increases with δB/B values**
  - Consistent with experiment





[1]Y. Q. Liu et al, Nucl. Fus 2019 & Phys Plasmas 2020

Deploying Large-Scale 3-D Fields: Candidate Solution for Disruption-Induced Fast Electrons

- **Fast tokamak shutdowns (disruptions) a risk to reactor walls especially due to relativistic electrons**
  - Conventional approach (c. 1980s): maximize collisional dissipation
- **New pathway to address problem: large-scale 3-D fields**
- **Large $\delta B/B$ via intrinsic MHD demonstrated in present devices**
  - Robustness of access and extrapolability to ITER underway
- **Extrinsic $\delta B/B$ application via passive conductors: robust !**
  - Will be explored and qualified in upcoming projects

In case SPI is not able to mitigate disruption runaways, what's the backup plan?

Experiments on several tokamaks have shown that B-field perturbations can cause REs to be deconfined.

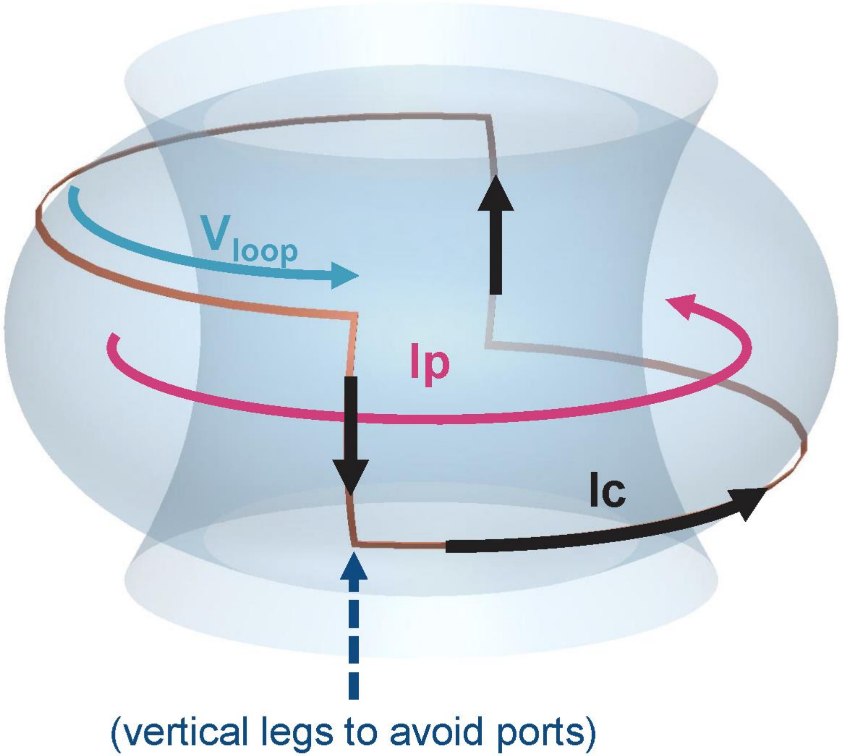
– NOTE: the deconfined REs must be spread over a large surface area, not concentrated onto a small spot

- $\tilde{B}$ due to actively generated non-axisymmetric fields (i.e. EF correction coils, RMP coils)
- $\tilde{B}$ due to actively induced MHD instabilities
- $\tilde{B}$ due to TAE instabilities generated by fusion α's
- $\tilde{B}$ due to passively generated non-axisymmetric fields (REMC coil)

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

*Boozer PPCF 2011, Smith PoP 2013

Use the high loop voltage that occurs during a disruption to induce large current in a non-axisymmetric coil, thus producing ‘error’ fields at exactly the right time to degrade RE confinement.



Sweeney JPP 2020

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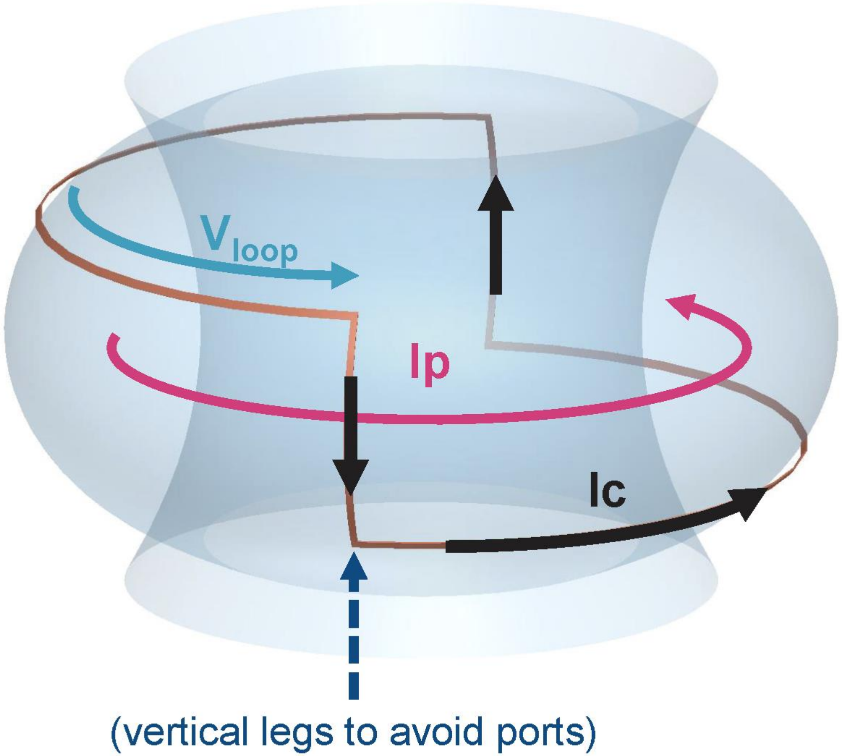

- No high-current power supply needed
- No warning time required (i.e. disruption prediction)

Sweeney JPP 2020

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

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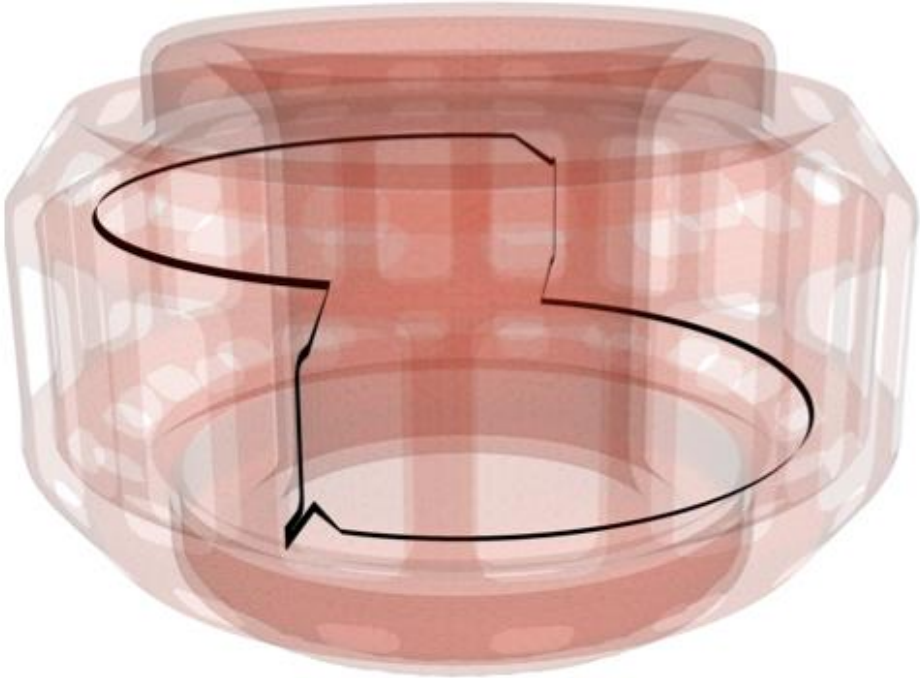


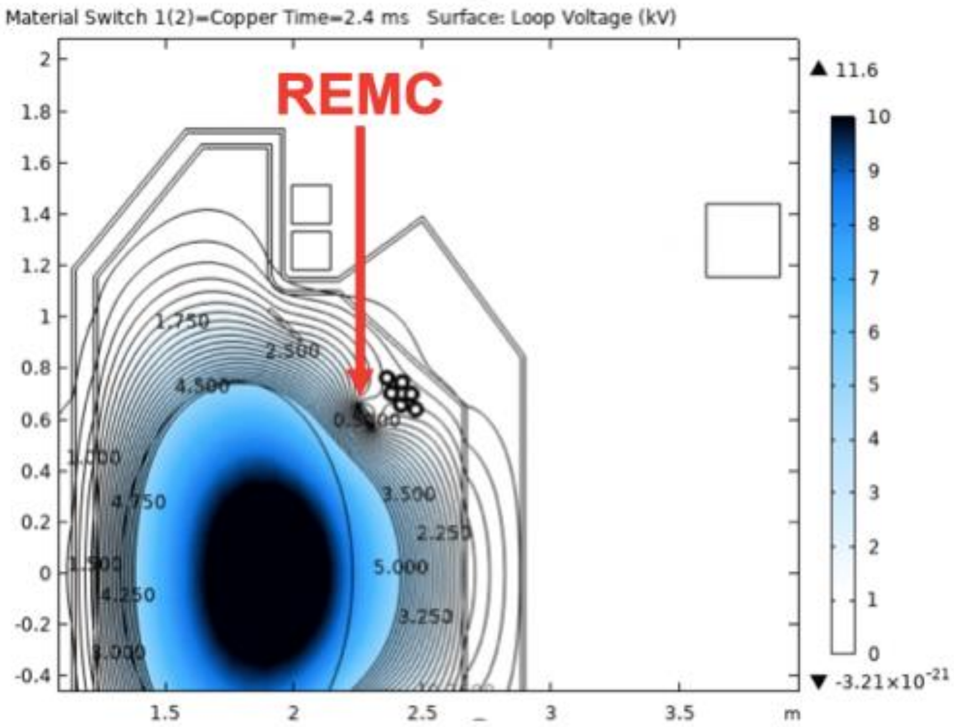
Engineering CAD

Sweeney JPP 2020

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

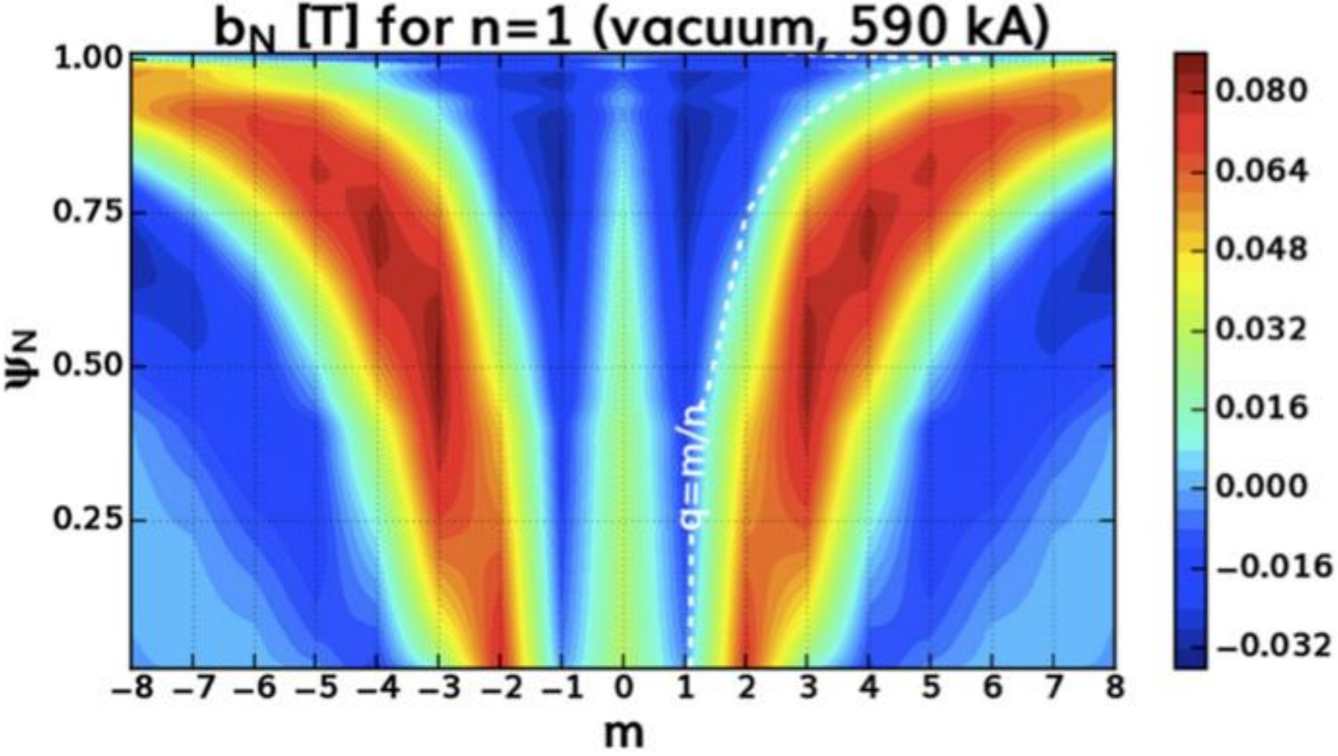
- Ellipse of constant current density
- Inside realistic tokamak structure
- Simulate midplane current quench
- Fastest expected CQ ~ 3.2 ms [Sweeney JPP 2020]

→ Magnetic and electric fields throughout simulation domain



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

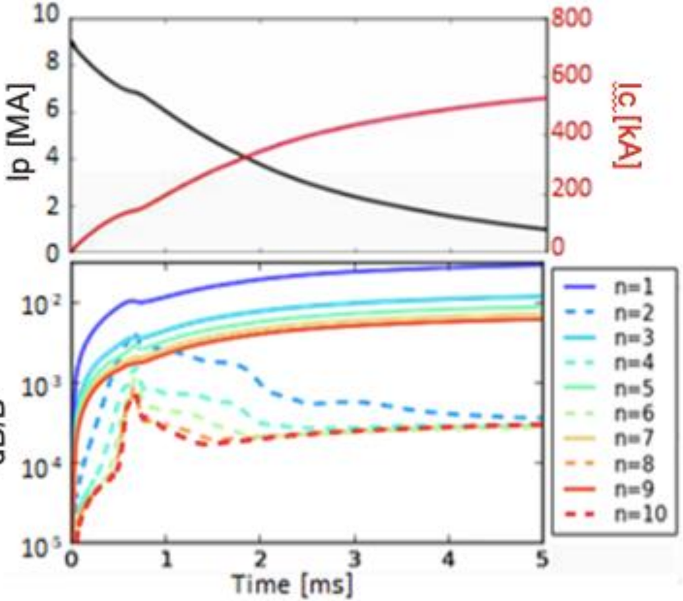
Low-|*m*| vacuum fields extend farthest into the core

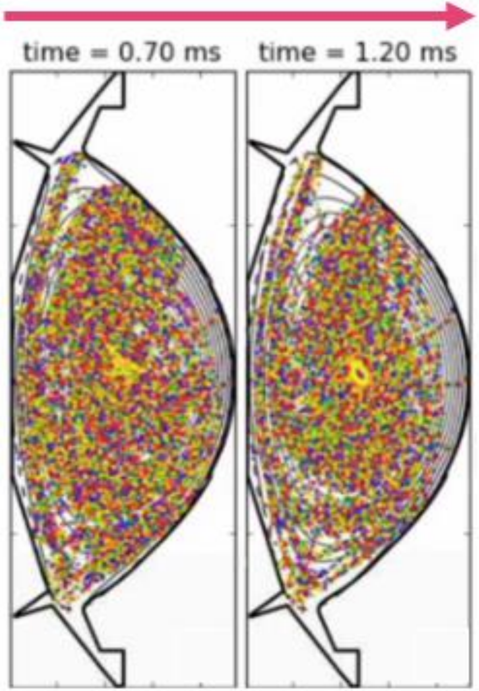


Step 2: Model MHD with NIMROD (V Izzo)

- Use realistic plasma profiles and equilibrium [Rodriguez-Fernandez JPP 2020]
- Include thermal and/or current quenches (TQ/CQ)
- B-fields from COMSOL applied at NIMROD simulation boundary
- Ideal wall approximation
- No *a priori* t-dependence, REMC B-fields evolve with I_P

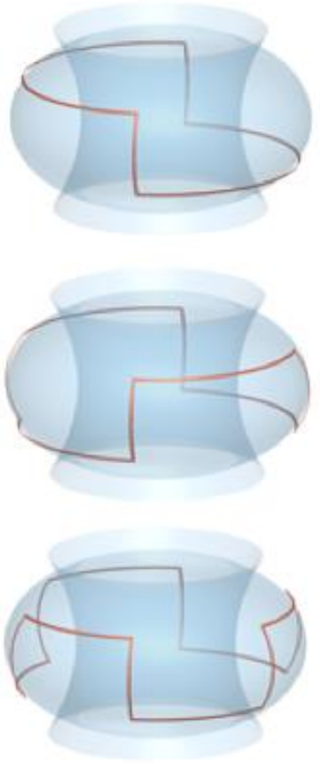
→ Fast stochasticization, but core island reforms…

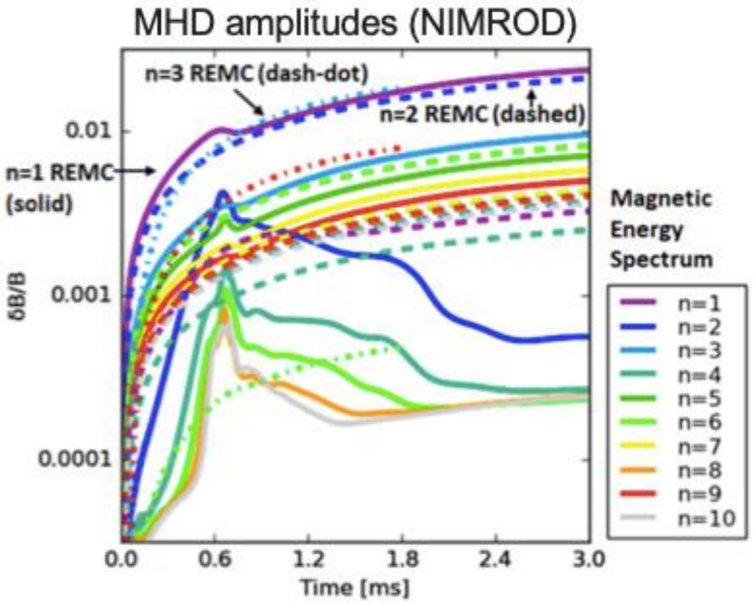


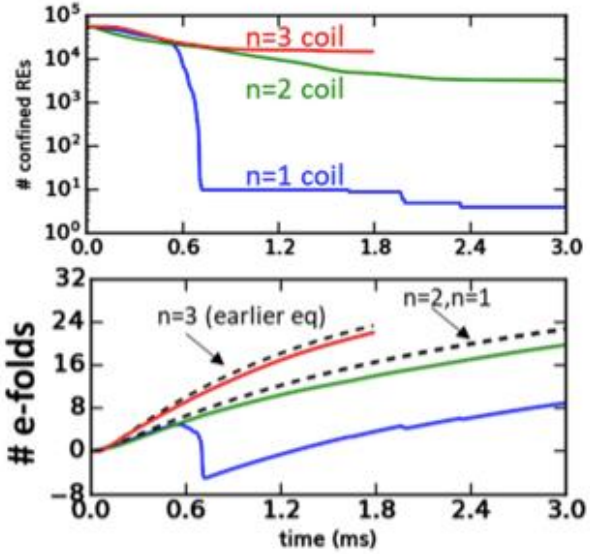


NIMROD: Sovinec JCP 2004

n = 2,3 coil geometries ineffective compared to n = 1



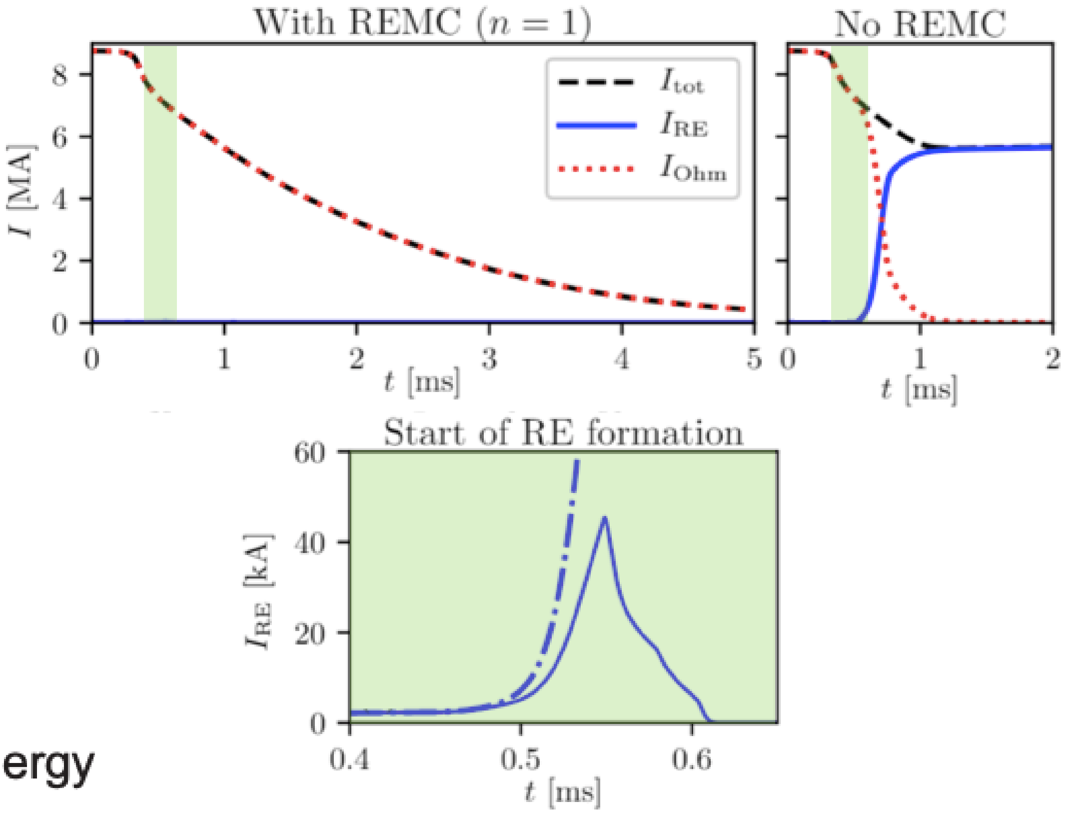




Step 4: Evolve runaways with DREAM (A Sundström, I Pusztai)

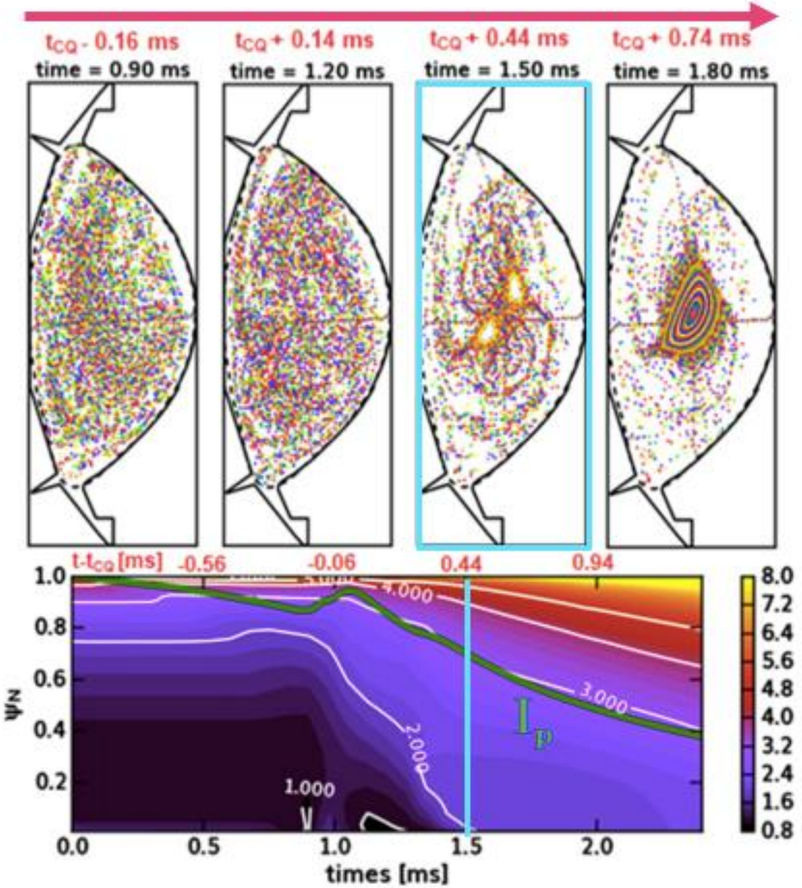
SPARC

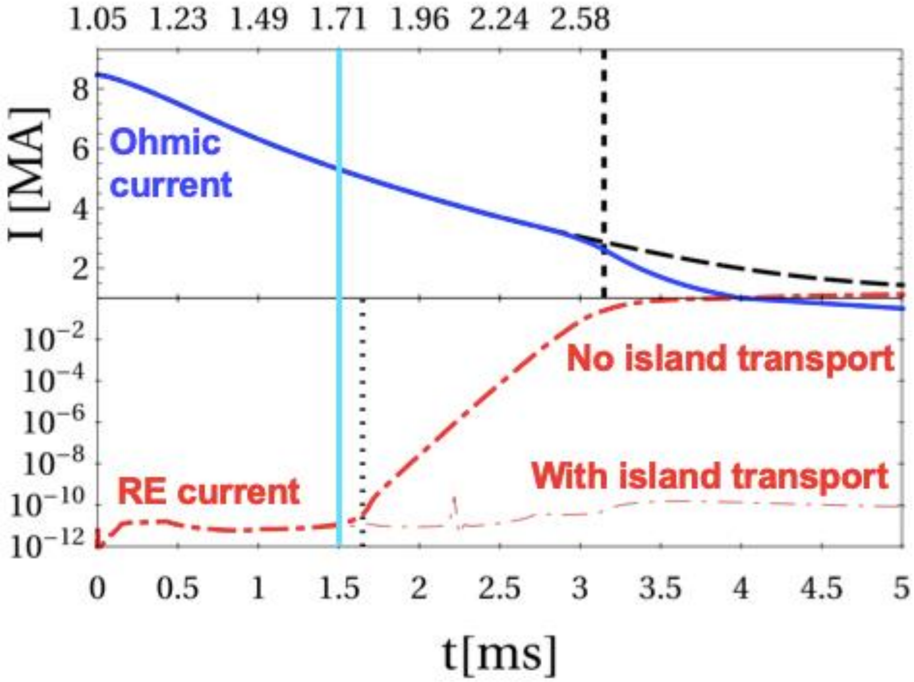
- Use same plasma profiles and equilibrium as NIMROD
- Adjust TQ time to best match current quench
- No *a priori* time dependence, advection, diffusion evolve with plasma current
- Dissipate same amount of magnetic energy as in COMSOL
- Use wall time of ~50 ms
- Note: RE current sensitive to TQ duration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



Tinguely NF 2021

TQ+CQ → early RE loss ☺ but early flux re-healing ☹



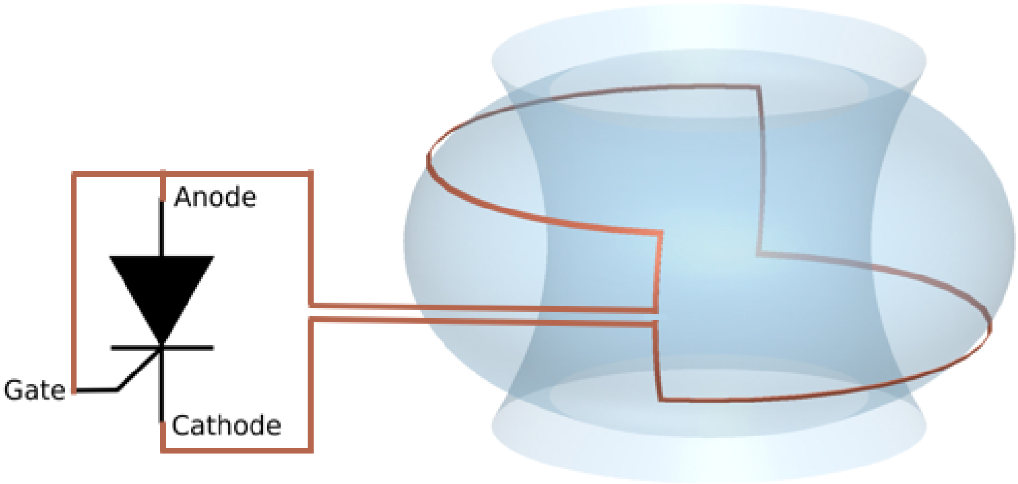


Designing a real REMC coil for SPARC presents a number of very difficult engineering challenges

- The large induced current gives rise to huge I×B forces, particularly on the vertical sections. Neutron shielding in SPARC constrains the space available for structural hardware.
- The coil must not conduct current *EXCEPT* during disruptions. (high-current threshold switching mechanism needed). Ideally the switch should be passive.
- Due to D-T neutron flux, a solid-state switch cannot be inside the vessel, therefore high-current feedthroughs and leads are required.
- The coil loop voltage is predicted to reach 2500 volts, and therefore it must be electrically insulated from its support structure, even during MGI when Paschen breakdown could be a concern

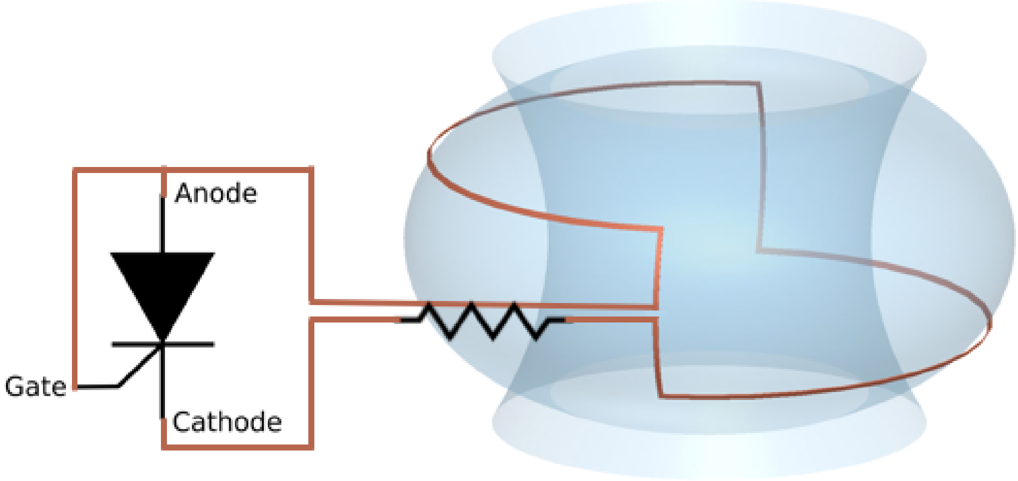
Passive, high voltage/current switch required

- Likely multiple silicon-controlled rectifiers (SCRs)
- Gate triggered by the disruption-induced voltage (~kV)
- Threshold to be set above other voltages (>100 V)
  - Ip flat-top ~ 1 V
  - Ip ramp-up/down ~ 10 V
  - ELMs ~ 10 V
- Uni-directionality allows current to flow only in the direction of Ip



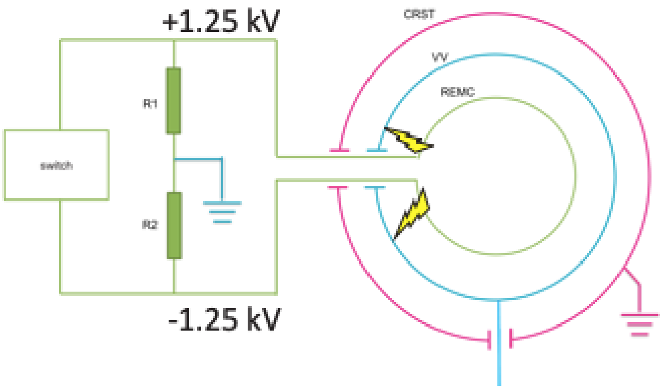
Resistors required to limit REMC current and forces
(new MIT postdoc John Boguski starting Jan 2023)

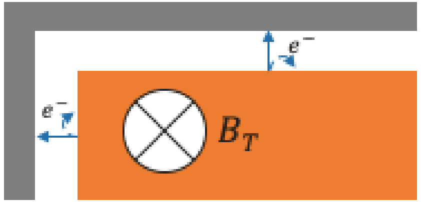
- SPARC REMC baseline design:
  - Current Ic ~ 600 kA
  - Sideways force F < 15 MN
  - **New max Ic < 350 kA**
- Self-inductance L ~ 14 uH
- Resistance ~ 0.2 mOhm
- Add ~10 mOhm → Ic < 250 kA
- Add ~100 mOhm → F < 1 MN
- Still exploring parameter space and implementation

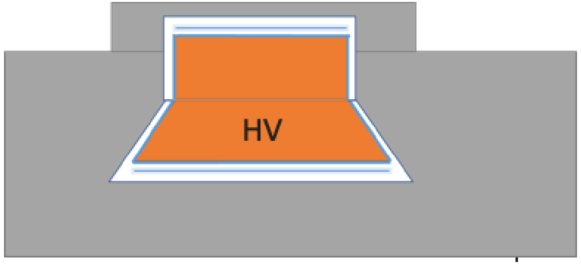


Arcing solutions

- Central grounding
  - cuts potential in half
- Magnetic field suppression of arcing
  - Get this for free, most arcing is cross-field, where the e- Larmor radius is 0.5 μm
- Insulation
  - Too risky that un-intended parallel field lines will intersect un-insulated regions of the REMC, so insulate the entire REMC.
  - Still testing optimal solution

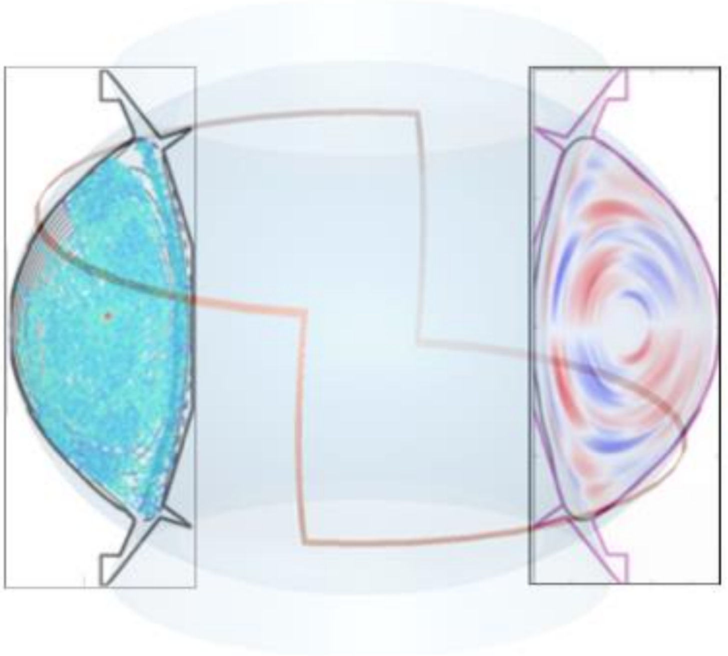






Summary

- SPARC design and construction are well underway, including a passive n = 1 REMC
- Modeling *conservatively* suggests >2x reduction in RE current, and *optimistically* full RE beam prevention
- Need to limit the maximum current to ~350 kA, so need to model this new scenario
- Passive switches, added resistors, and commissioning plans are under development



R.A. Tinguely *et al* 2022 PPCF *(under review)*
V.A. Izzo *et al* 2022 *Nucl. Fusion* **62** 096029
R.A. Tinguely *et al* 2021 *Nucl. Fusion* **61** 124003

Runaways can occur during several different phases of a tokamak plasma discharge

- Disruptions: HUGE loop voltage, but plasma conditions are poorly controlled, and not well diagnosed.

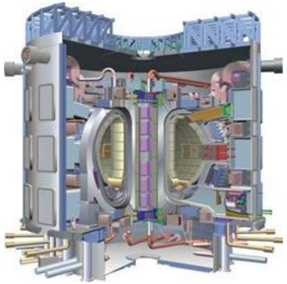
- Steady-state flattop: well-controlled conditions for research physics

- Plasma startup: loop voltage is higher than normal and density is low

Runaways can occur during several different phases of a tokamak plasma discharge

– Steady-state flattop: well-controlled conditions for research physics

  - Measure threshold E-field for runaways and compare to Connor-Hastie E_{crit}
  - Is synchrotron emission a significant energy loss mechanism?
  - Analyzing synchrotron images



An ITPA joint experiment to study threshold conditions for runaway electron generation and suppression

R. Granetz, A. DuBois, B. Esposito, J. Kim, R. Koslowski, M. Lehnen,
J. Martin-Solis ,C. Paz-Soldan, T.-N. Rhee, P. de Vries, J. Wesley, and L. Zeng

IAEA FEC 2014
St. Petersburg, Russia
2014/10/16

Motivation for ITPA joint experiment

Do we really have to get to the Rosenbluth density to quench runaway electrons in ITER?

$\Downarrow$

- Are other RE loss mechanisms, in addition to Coulomb collisional damping, important?
- If yes, is it true for tokamaks in general?

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- If yes, is it true for tokamaks in general?

$\Downarrow$

Measure threshold *E*-field in well-controlled and well-diagnosed conditions on a number of tokamaks, and compare with E_{crit}

Critical *E*-field for runaway electrons

Minimum *E*-field required to generate *and* sustain any runaways:

$$E_{\mathrm{crit}} = \frac{n_e e^3 \ln\Lambda}{4\pi\varepsilon_0^2 m_e c^2}$$

J.W. Connor and R.J. Hastie, Nucl.Fusion 15 (1975) 415

This E_{crit} criterion applies to *both* primary (Dreicer) and secondary (avalanche) mechanisms.

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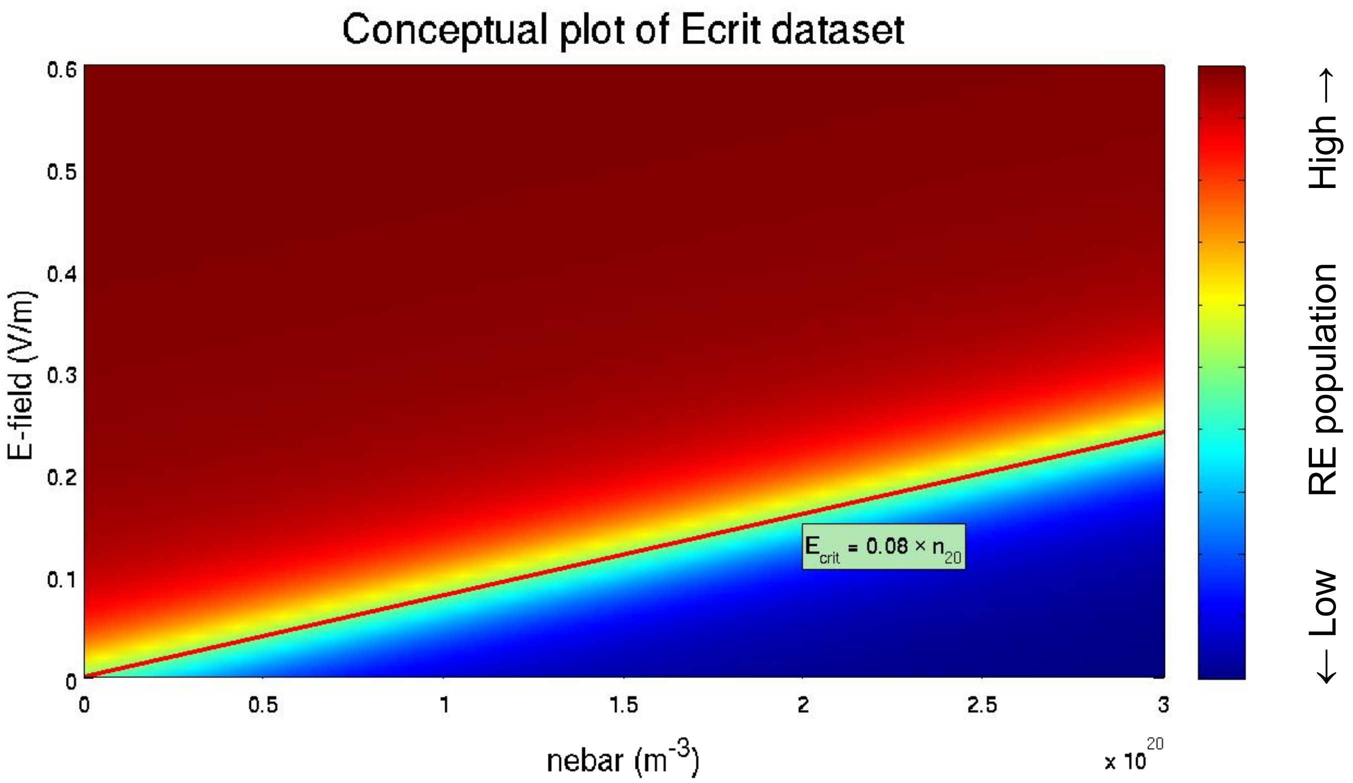
Critical *E*-field for runaway electrons

Minimum *E*-field required to generate *and* sustain any runaways:

$$E_{\text{crit}} = \frac{n_e e^3 \ln\Lambda}{4\pi\varepsilon_0^2 m_e c^2} = 0.08 n_{20} \quad (\text{for } \ln\Lambda = 15)$$

This E_{crit} criterion applies to *both* primary (Dreicer) and secondary (avalanche) mechanisms.

Parameter space: runaway population vs E-field and density



Constraints for ITPA joint experiment

- Make measurements during quiescent flattop, rather than during disruptions, because results should be more reproducible, and the loop voltage, electron density, Z_{eff}, T_e, etc. can be accurately measured.

- To minimize confusing factors, exclude discharges with LHCD or ECCD, because they can distort the electron velocity distribution

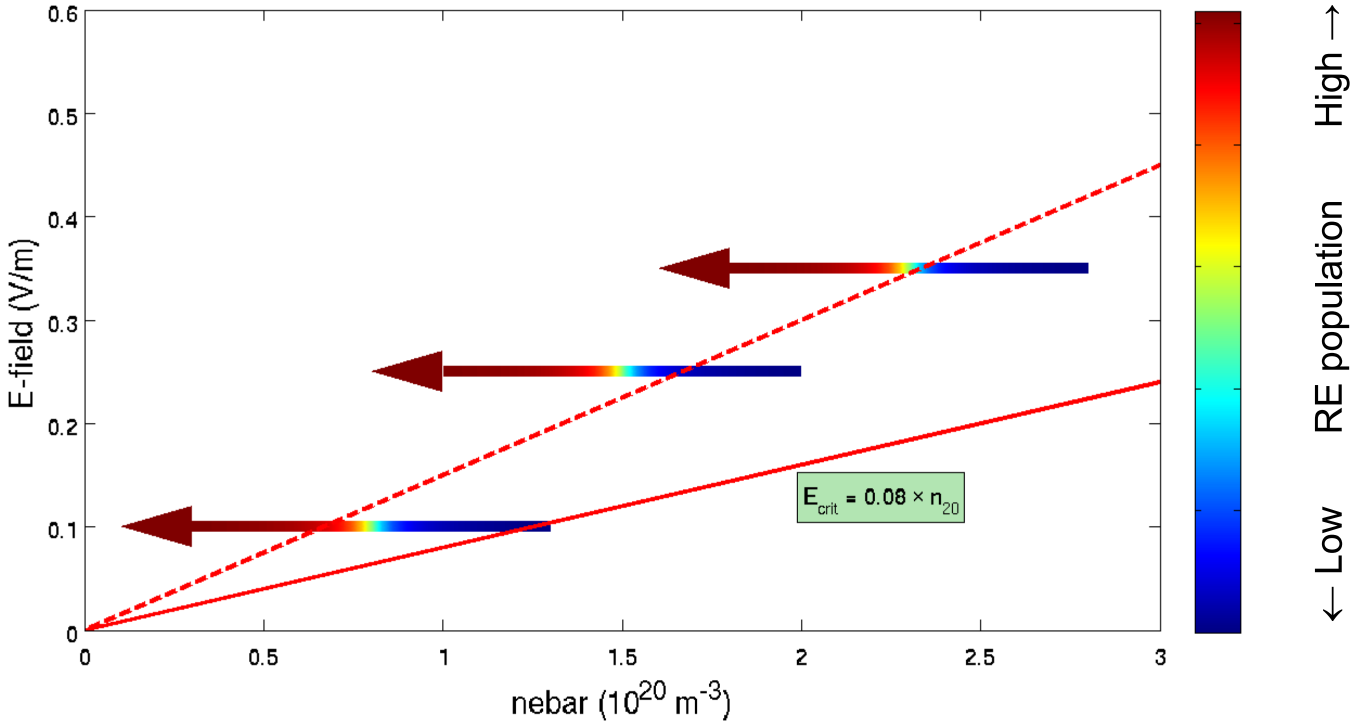
- Several different diagnostics are used for detecting runaways:
  - hard x-ray (HXR), γ-ray detectors
  - detection forward-peaked emission (IR, visible)

Participants in MDC-16:

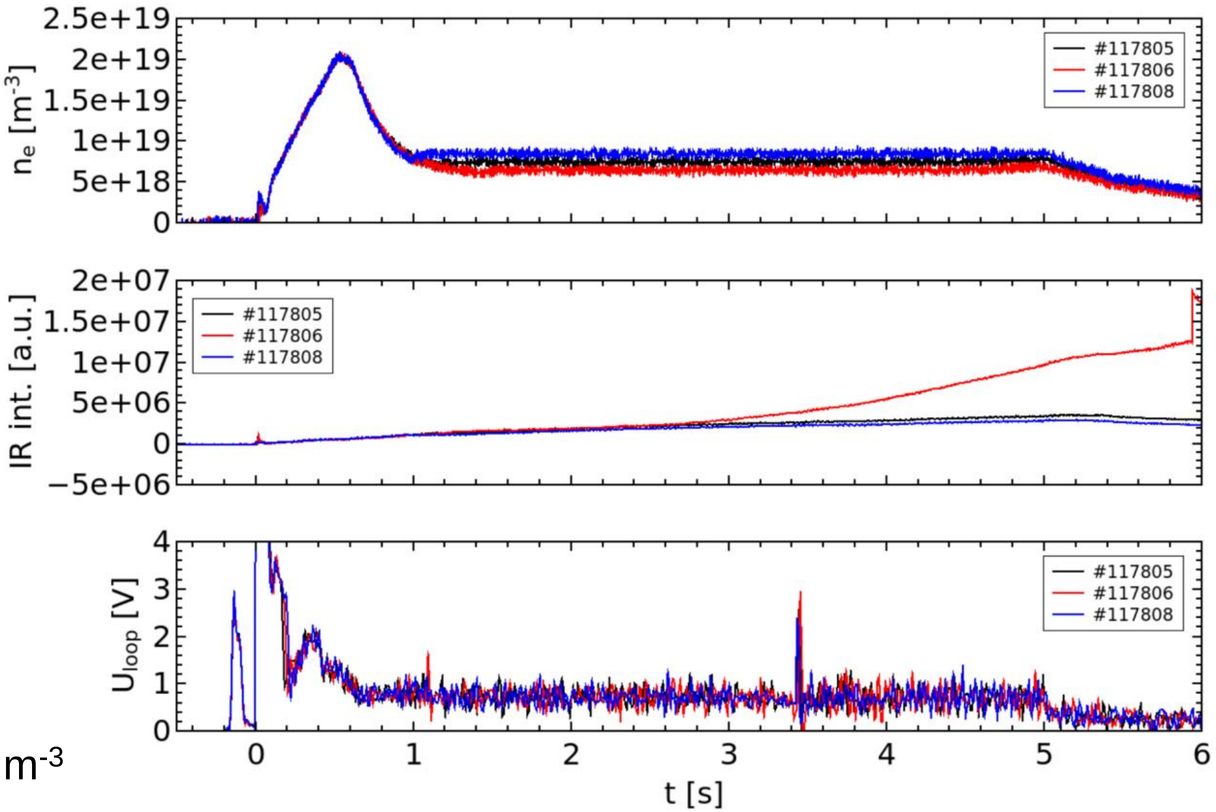
- FTU (dedicated experiments)
  - J. Martin-Solis, B. Esposito
- TEXTOR (dedicated experiments)
  - R. Koslowski, M. Lehnen
- Alcator C-Mod (data mining and dedicated experiments)
  - R. Granetz
- DIII-D (data mining and dedicated experiments)
  - J. Wesley, C. Paz-Soldan
- KSTAR (data mining)
  - T. Rhee, J.H. Kim
- JET (data mining; *not during flattop*)
  - P. deVries
- MST (dedicated experiments; RFP in tokamak mode; low T_e)
  - A. DuBois, B. Chapman

Several possible ways to measure threshold *E*-field:

(1) Determine RE onset by decreasing n_e



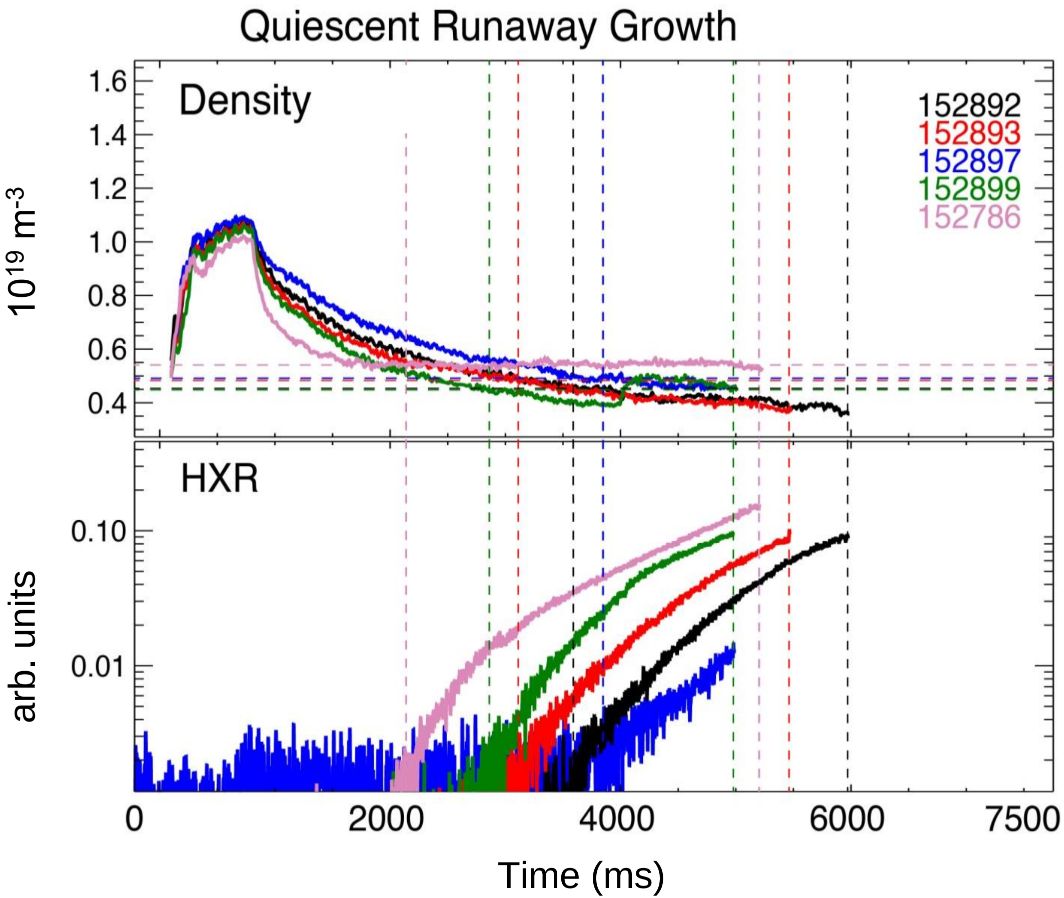
TEXTOR dedicated experiment



RE onset:

E = 0.066 V/m
n_e = 0.07 x 10^{20} m^{-3}

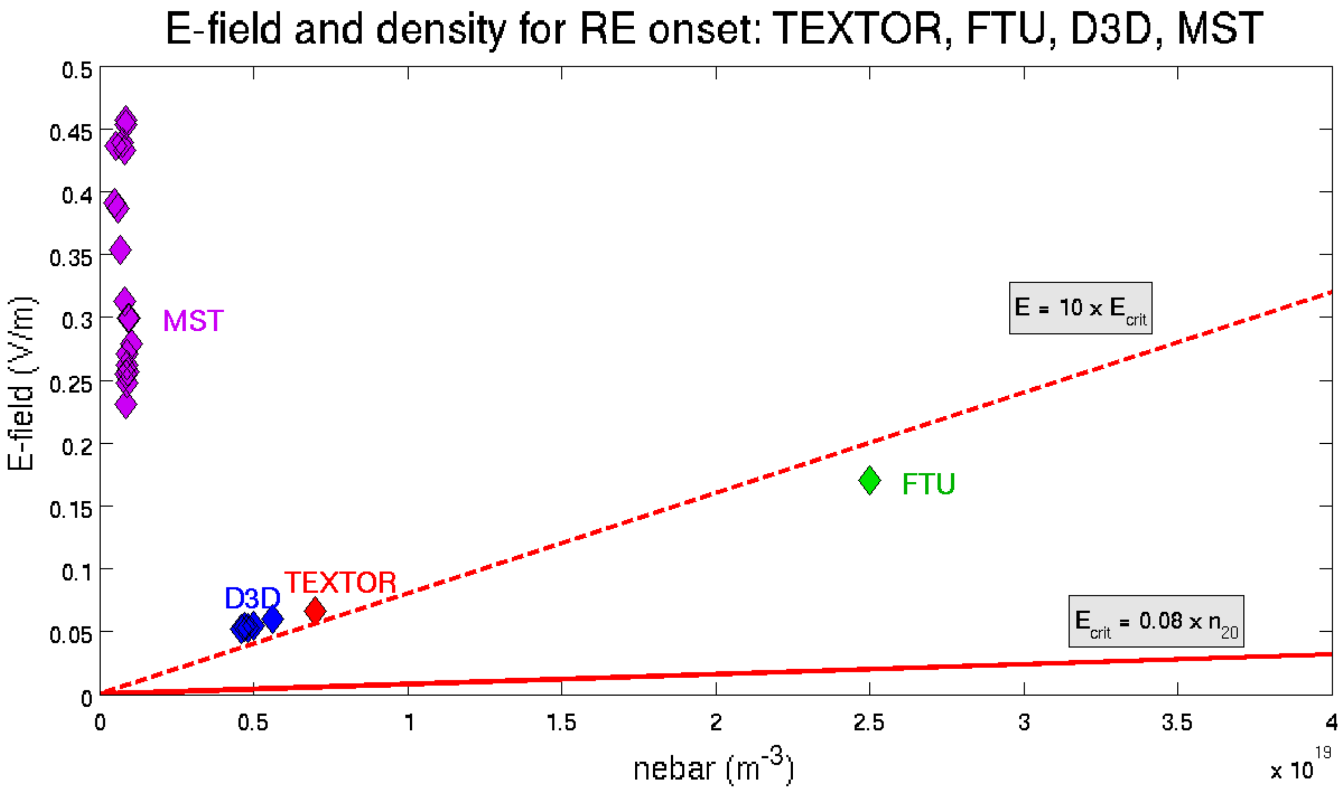
DIII-D dedicated experiments



Shot	E (V/m)	n_e (10^{20} m^{-3})
152892	0.052	0.046
152893	0.055	0.050
152897	0.053	0.048
152899	0.054	0.047
152786	0.060	0.056

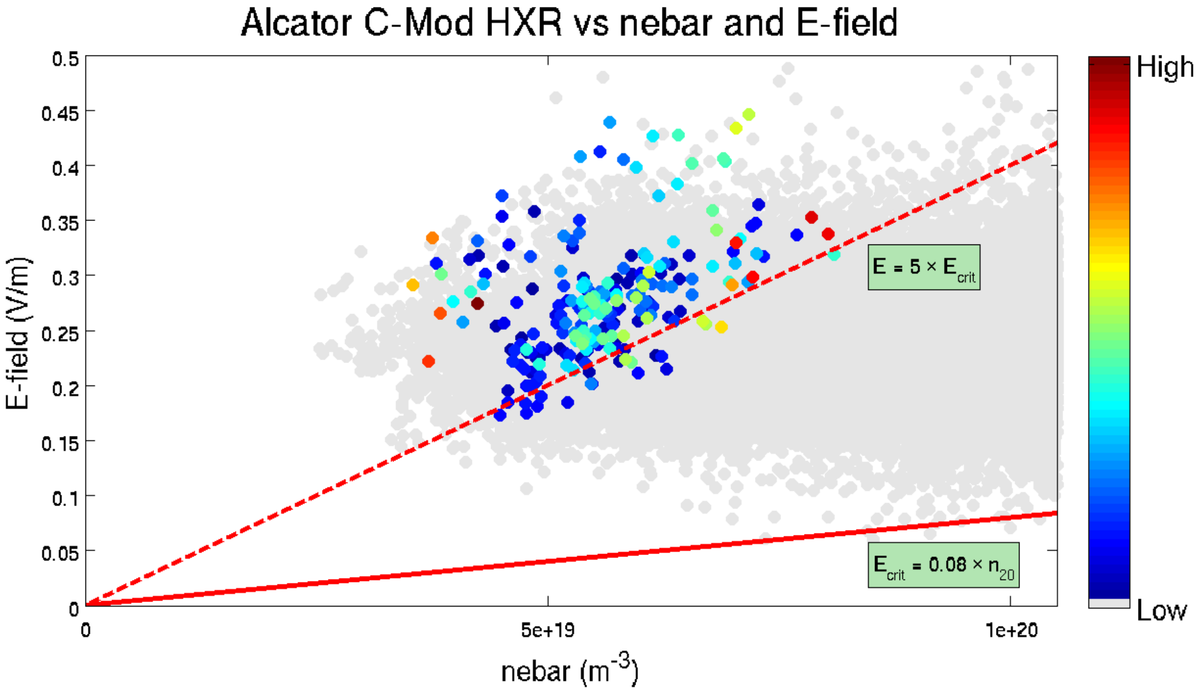
Note: intrinsic error fields must be carefully reduced to prevent locked modes at these low densities

E-field and density for RE onset

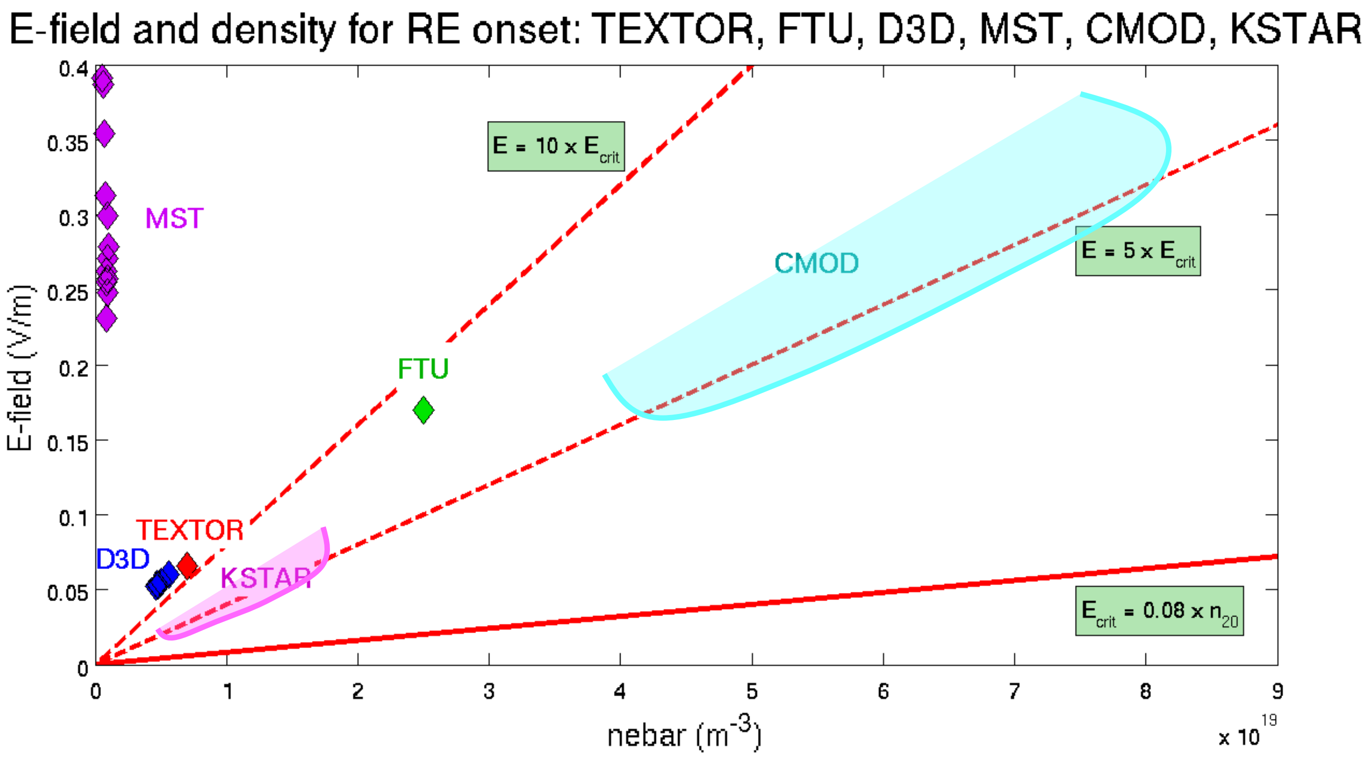


Several possible ways to measure threshold *E*-field:

(2) Assemble dataset of (*E*, *n*, RE) from previously existing data; Determine threshold boundary



Thresholds for RE onset on multiple machines



Caveats of using ‘onset’ method to determine threshold E-field

1) RE detectors (usually HXR) have finite sensitivity, i.e. a minimum detectable level of REs

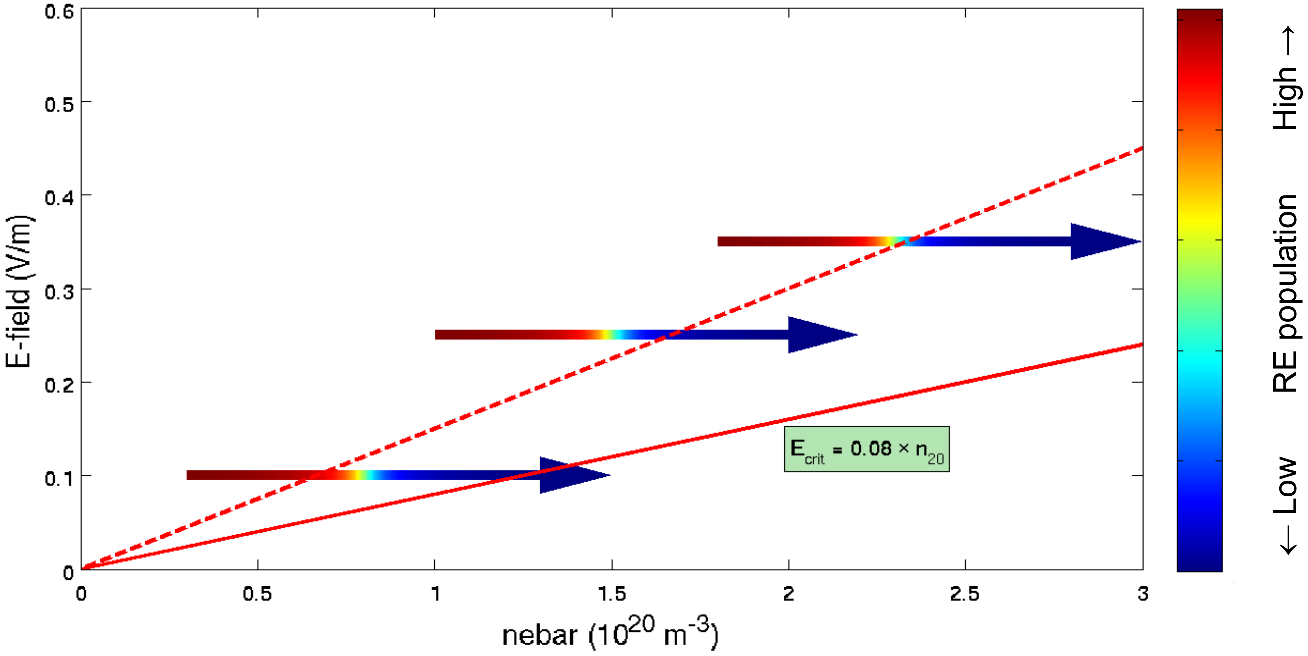
2) In a Maxwellian of a few keV and ~10^{20} electrons, with V_{loop} ~ 1 volt, the initial number of runaways is well below detectable limits

Therefore, in order to be detected, i.e. the observed “onset”, the RE population must grow to a measurable size, which takes finite time, comparable to the duration of these discharges.

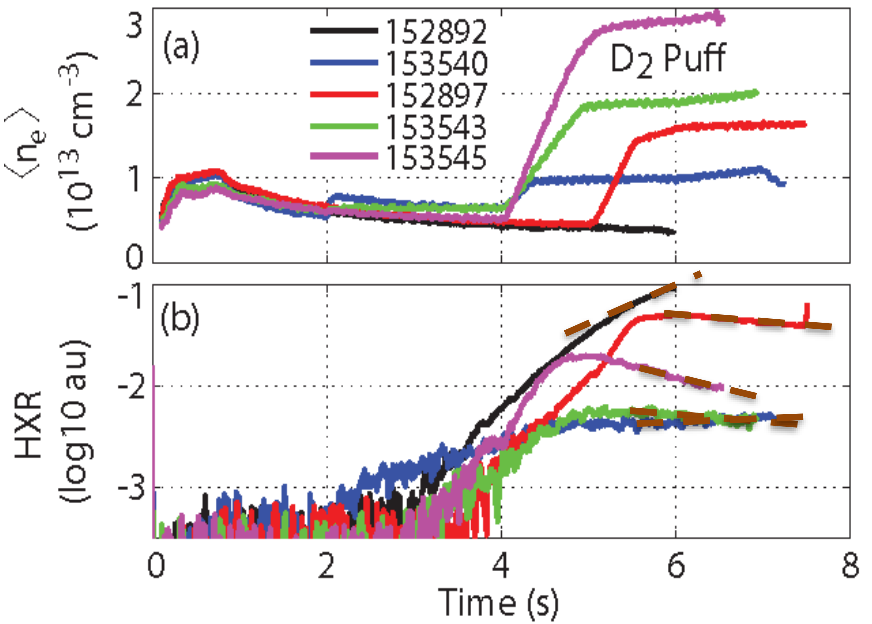
Hence, E and n_e at the time of onset detection may not be the same as E and n_e at the RE threshold

Several possible ways to measure threshold *E*-field:

(3) Start in low-density regime with RE's and *increase* n_e to find threshold for RE suppression

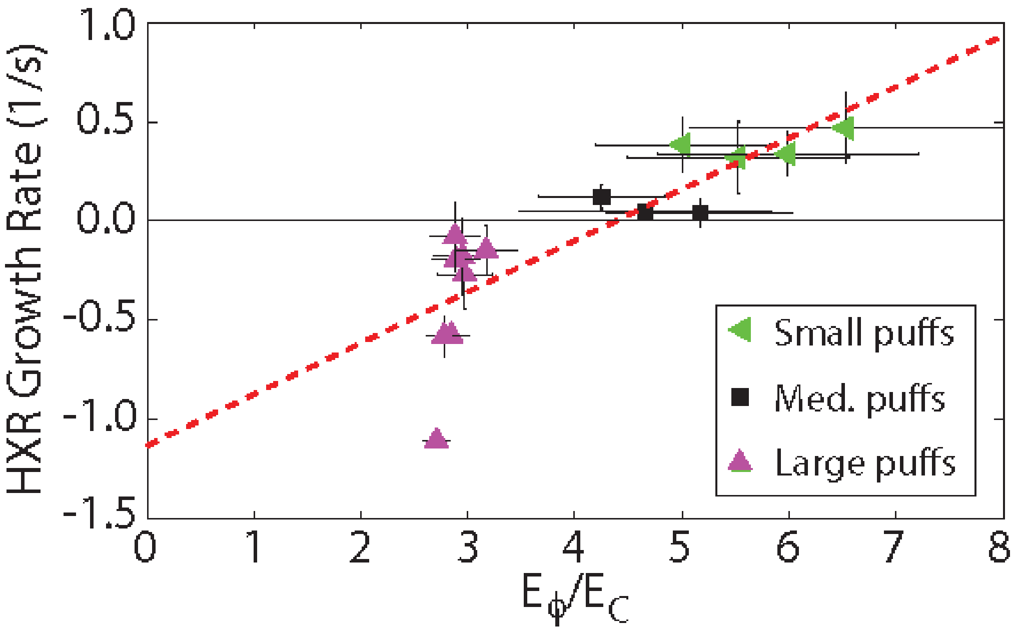


Measuring RE growth & decay rates on DIII-D



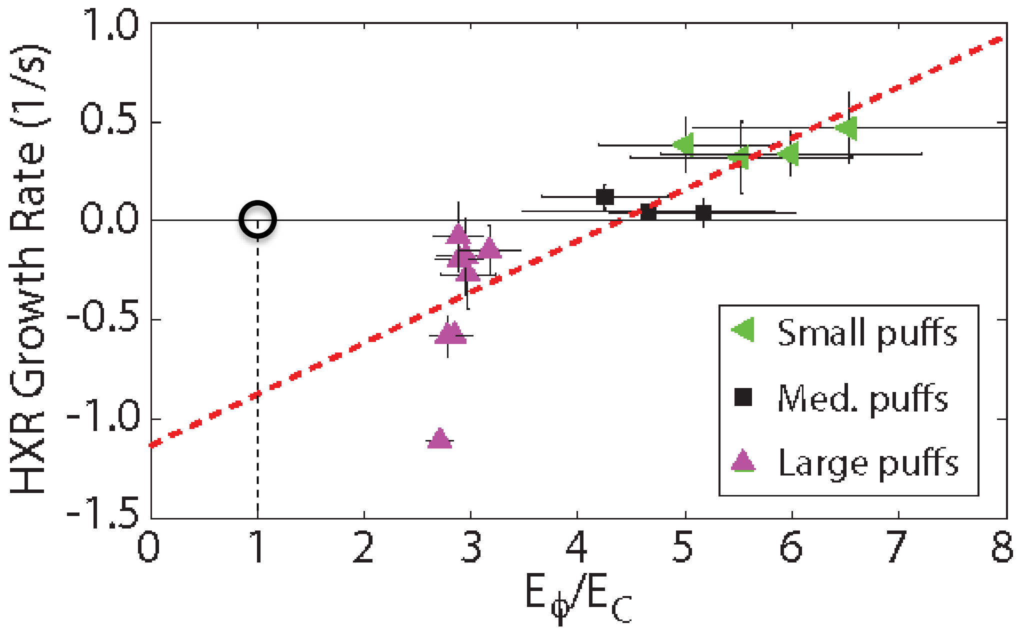
- First, get RE's by reducing density
- Then change density to new value and hold constant to reach new steady-state
- Determine growth or decay rate

Measuring RE growth & decay rates on DIII-D



- Transition from growth to decay occurs at $E/E_{crit} \sim 3 - 5$

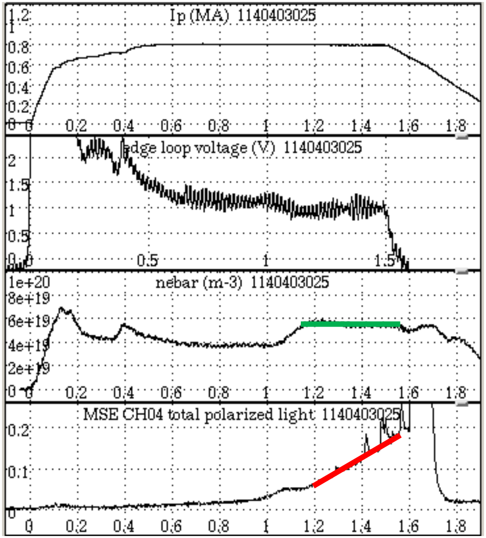
Measuring RE growth & decay rates on DIII-D



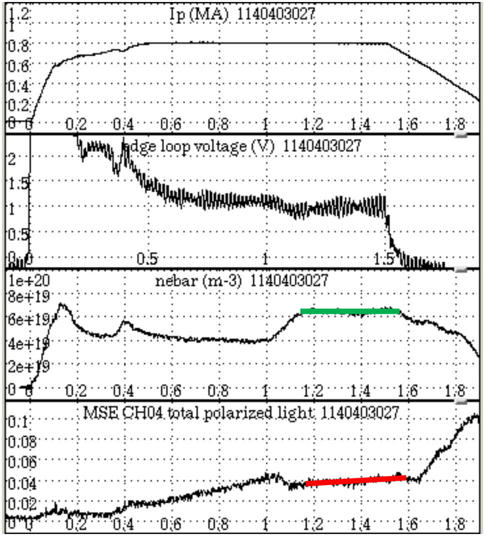
- Transition from growth to decay occurs at E/E_{crit} ~ 3 – 5
- Theory says this should occur at $E/E_{crit} = 1$

Measuring RE growth & decay rates on C-Mod

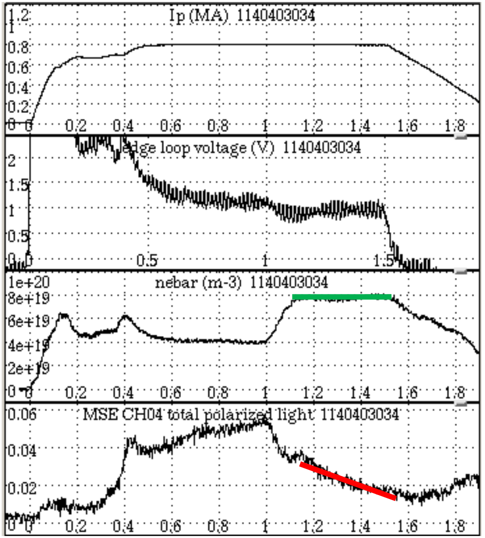
increasing RE’s



nearly steady RE’s



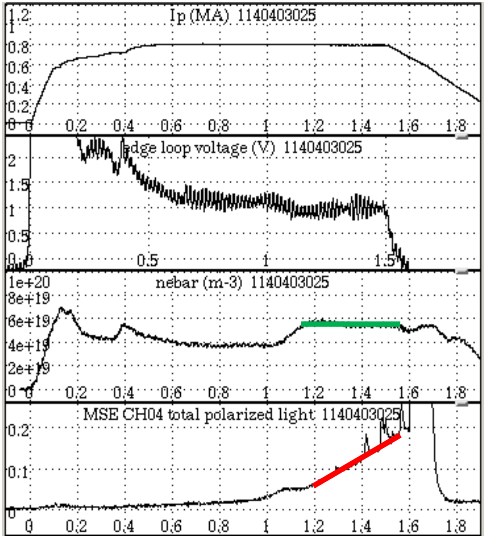
decreasing RE’s



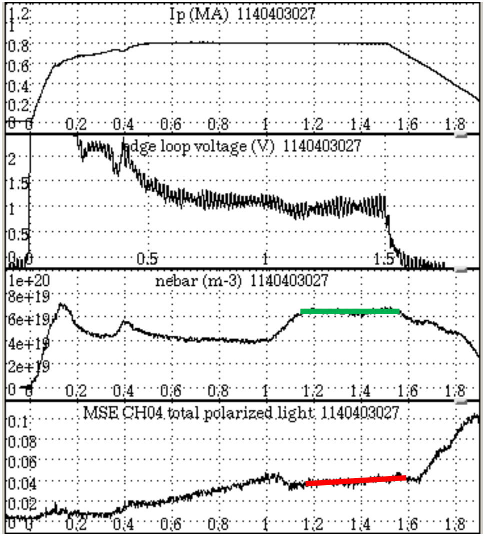
- First, get RE’s by reducing density
- Then change density to new value and hold constant to reach new steady-state
- Determine n_e, $E_{//}$, and dn_{RE}/dt for each case

Measuring RE growth & decay rates on C-Mod

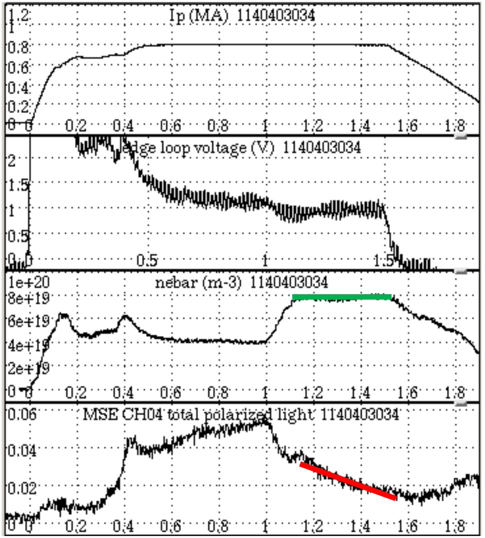
increasing RE's



nearly steady RE's

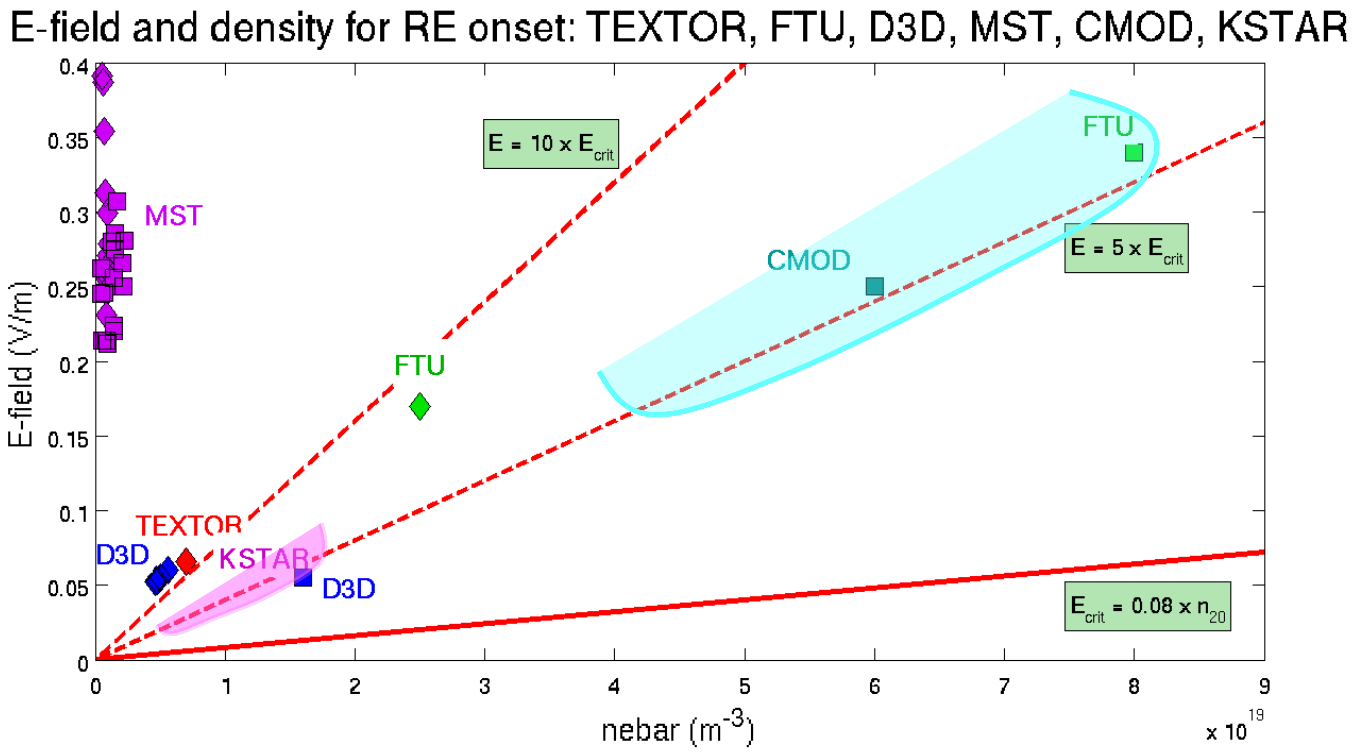


decreasing RE's



- First, get RE's by reducing density
- Then change density to new value and hold constant to reach new steady-state
- Determine n_e, $E_{//}$, and dn_{RE}/dt for each case
- Center case has n_e=0.6×10^{20} m^{-3}, $E_{//}$=0.25 V/m

Thresholds for RE onset (◆) and suppresion (■) on multiple machines



Summary: results

A study of runaway electrons under well-controlled, well-diagnosed conditions in a number of tokamaks finds that the threshold density for both onset and decay of RE signals is at least 4 – 5 times less than expected from collisional damping only.

This implies that there are other significant RE population loss mechanisms in addition to collisional damping, *even in steady-state quiescent plasmas*.

Possible RE loss mechanisms in addition to Coulomb collisional drag include:

- synchrotron emission losses from Larmor motion
- drift orbit losses
- stochastic losses due to $\tilde{B}$ (which are probably much larger during disruptions)
- scattering in velocity space due to RE instabilities

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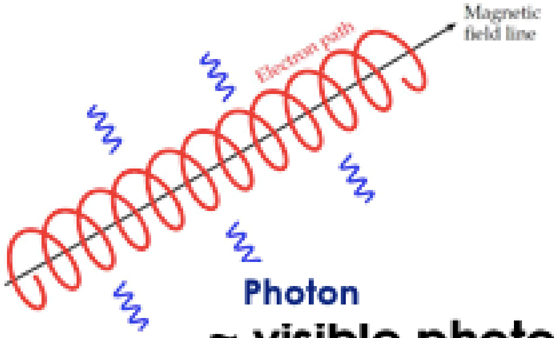
Runaway electrons generate characteristic radiations in a tokamak

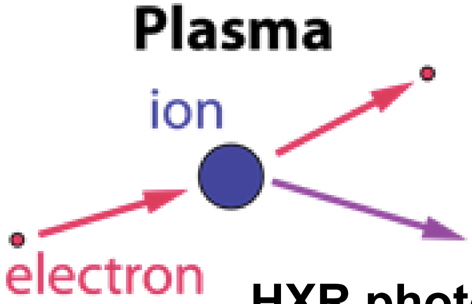
Synchrotron (acceleration radiation)

B-field required



~ visible photon (~eV)

Bremsstrahlung (braking radiation)



HXR photon (100's keV)

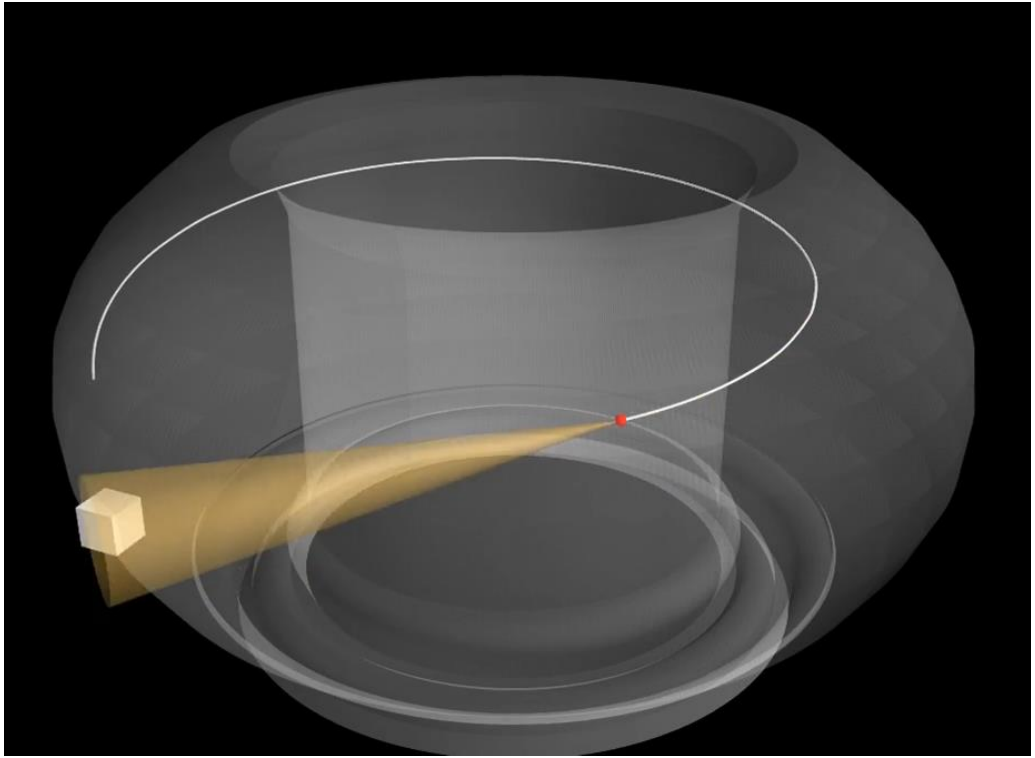
γ-rays (MeV)

How do we know that a camera looking at visible light is seeing synchrotron radiation?

Relativistic particles emit synchrotron radiation[1,2] that is forward-peaked in their direction of motion

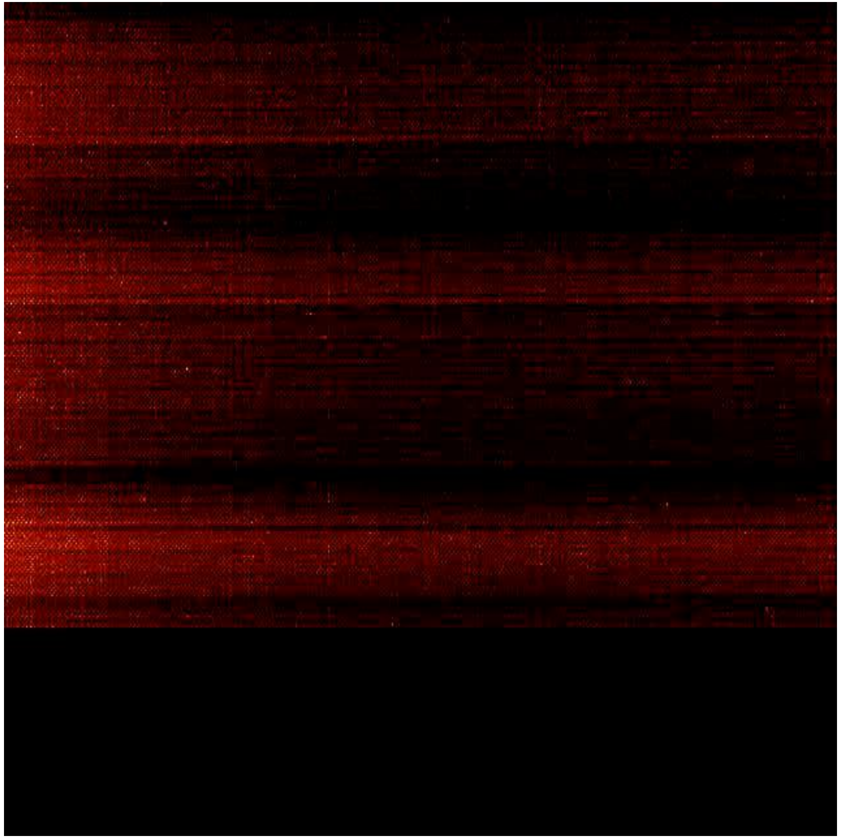
1. Schwinger 1949 *Physical Review*
2. Westfold 1959 *The Astrophysical Journal*

How do we know that a camera looking at visible light is seeing synchrotron radiation?



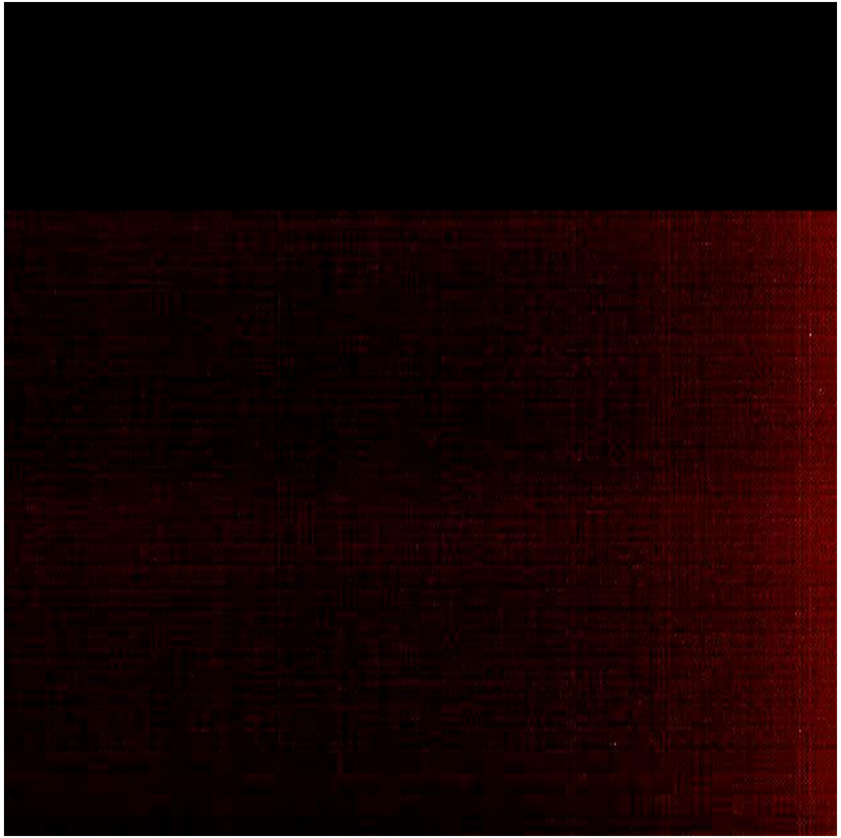
How do we know that a camera looking at visible light is seeing synchrotron radiation?

Normal plasma (no REs) has toroidally uniform emission, and no speckles



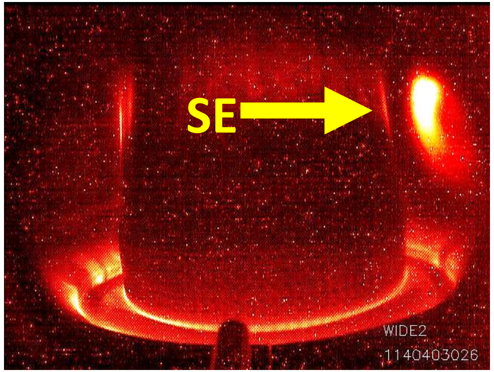
How do we know that a camera looking at visible light is seeing synchrotron radiation?

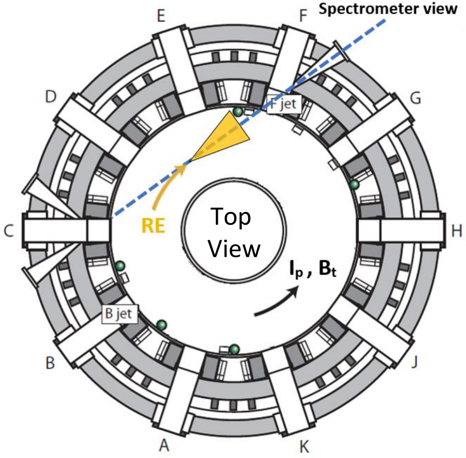
This plasma has speckles (HXR) and synchrotron emission *on the side where the current goes into the page*

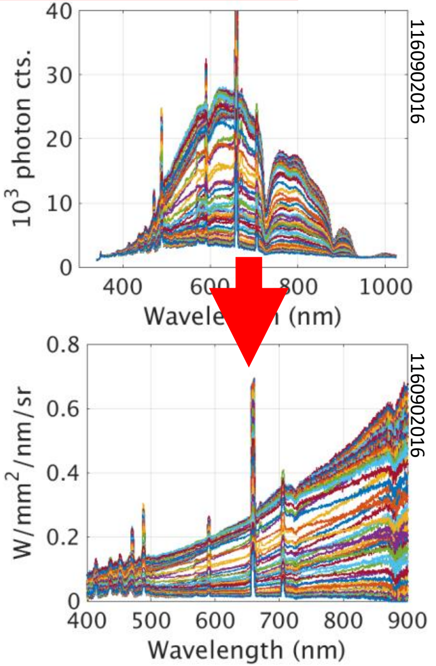


Absolutely-calibrated visible/NIR spectrometers (~300-1000 nm) measure SE on C-Mod.

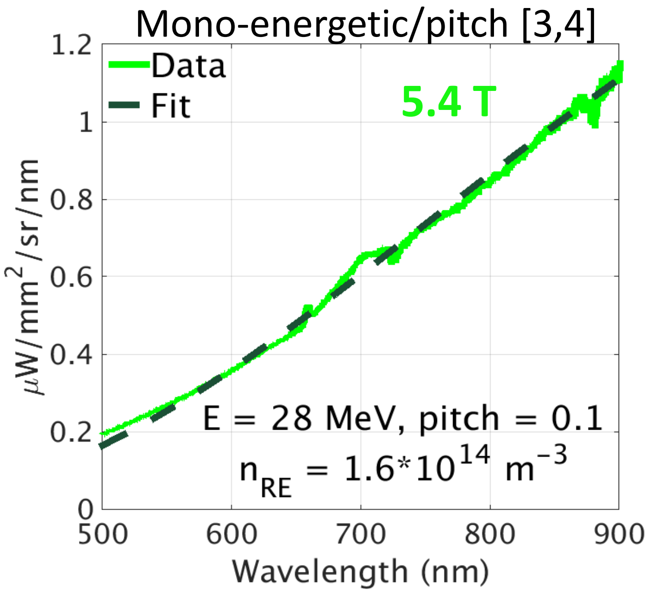
	C-Mod	ITER
B_{tor} (T)	5.4 (2 – 8)	5.3
$\bar{n}_e$ (10^{20} m^{-3})	1 (0.2 – 4)	1.0







Synchrotron spectra contains information on RE energy and pitch

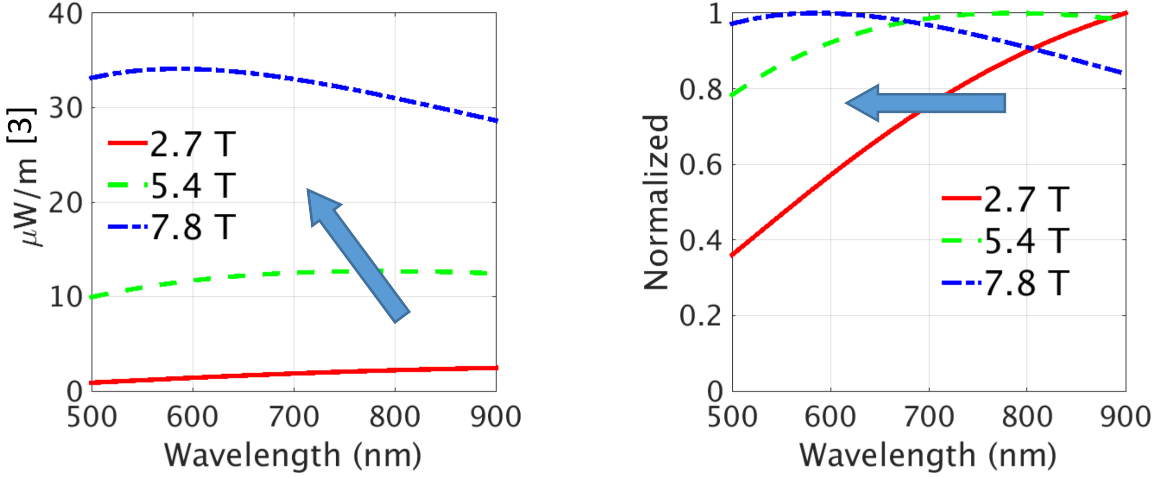


Fit Pankratov theoretical spectrum at B = 5.4 T to measured spectrum to get RE energy (assuming mono-energetic REs with pitch = 0.1)

[3] I.M. Pankratov. Plasma Phys. Reports 25, 2 (1999).
[4] J.H. Yu, et al. PoP 20, 042133 (2013).

Does synchrotron emission limit the maximum energy of REs?

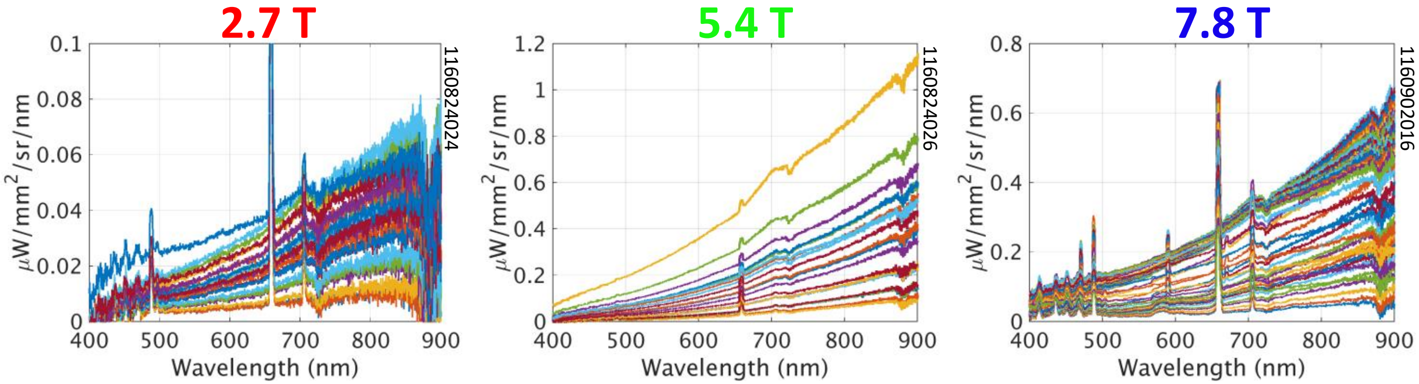
Consider an electron with energy E = 40 MeV and pitch = 0.1 in three different magnetic fields.



[3] I.M. Pankratov. Plasma Phys. Reports 25, 2 (1999).

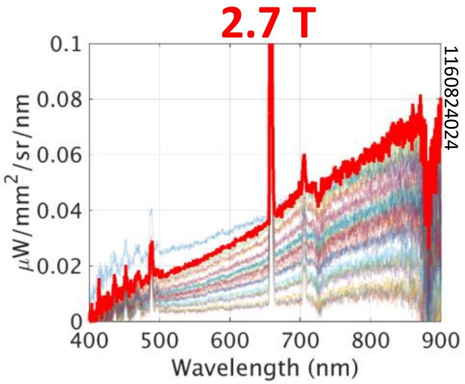
Absolutely-calibrated visible/NIR spectrometers measure synchrotron emission on C-Mod

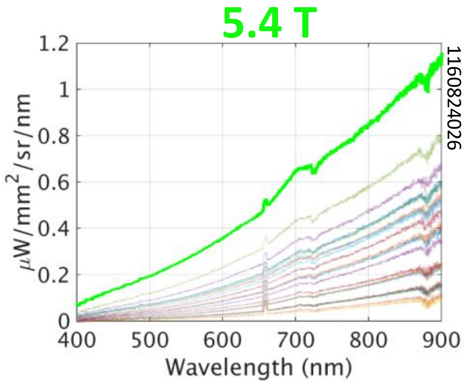
- RE densities are difficult to reproduce, so we are not interested in the absolute amplitude.
- Instead, we are interested in the spectral shape.

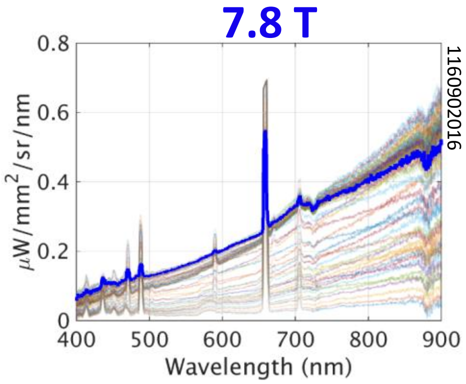


Absolutely-calibrated visible/NIR spectrometers measure synchrotron emission on C-Mod

- Select one time-slice near maximum emission during steady plasma parameters.
- Take the ratio of two spectra and normalize.





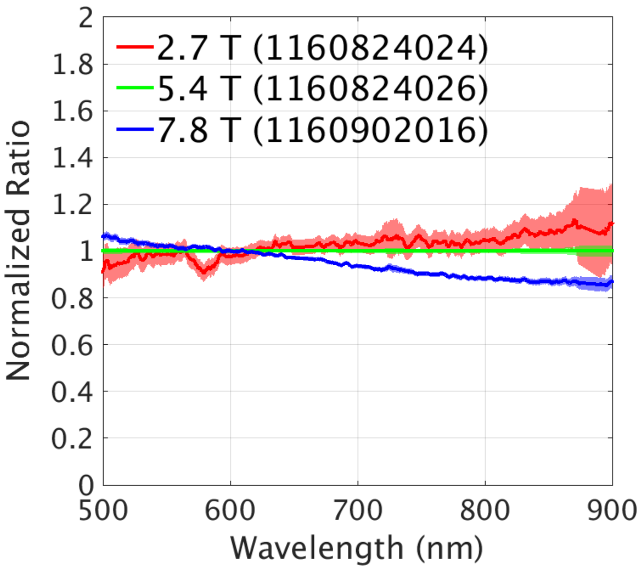


Compare synchrotron emission at three magnetic fields

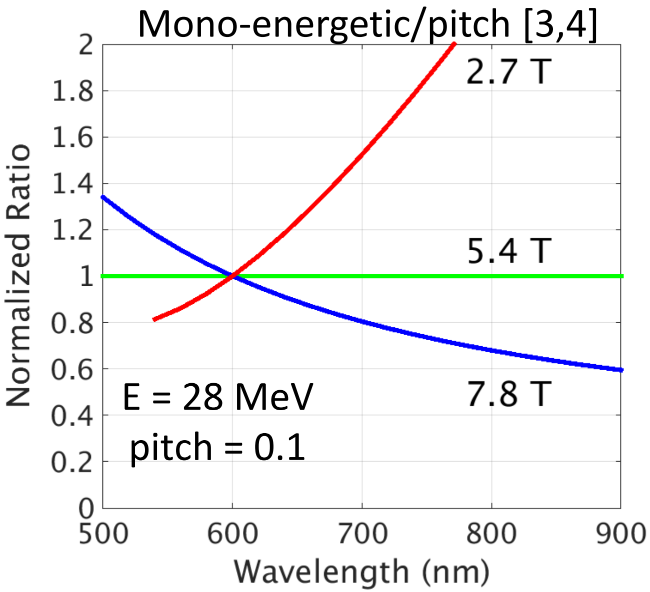
*Relative to the reference spectra

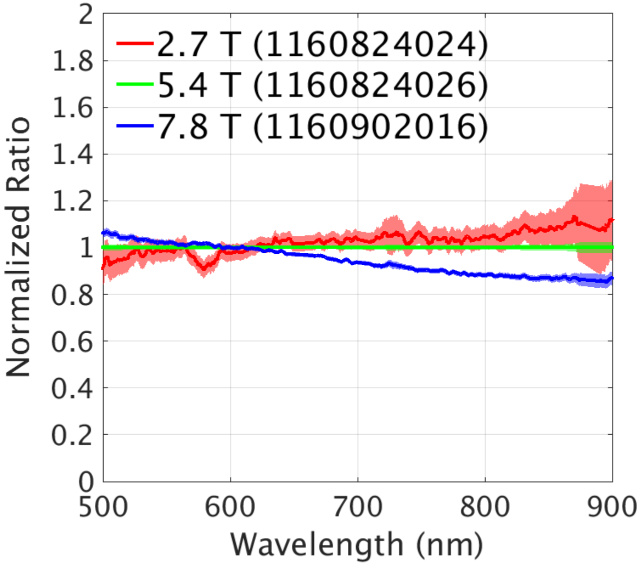
Positive slope
- More brightness at longer wavelengths
- Shifted toward the **red**

Negative slope
- More brightness at shorter wavelengths
- Shifted toward the **blue**



Compare synchrotron emission at three magnetic fields





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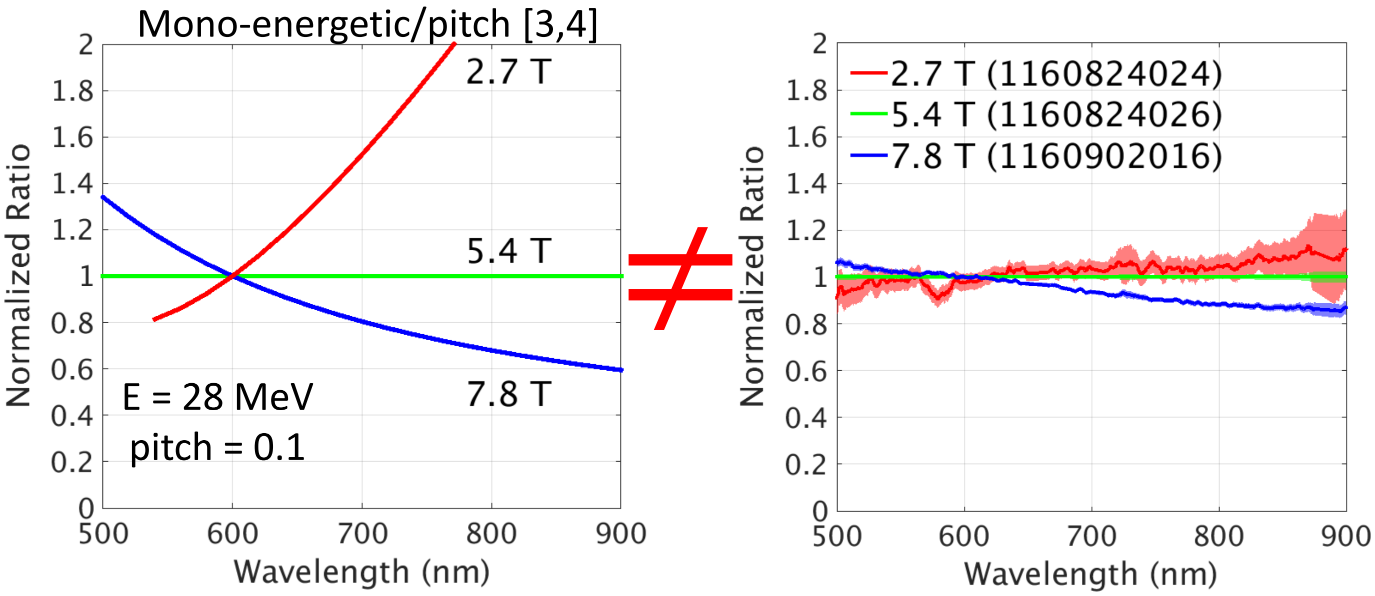
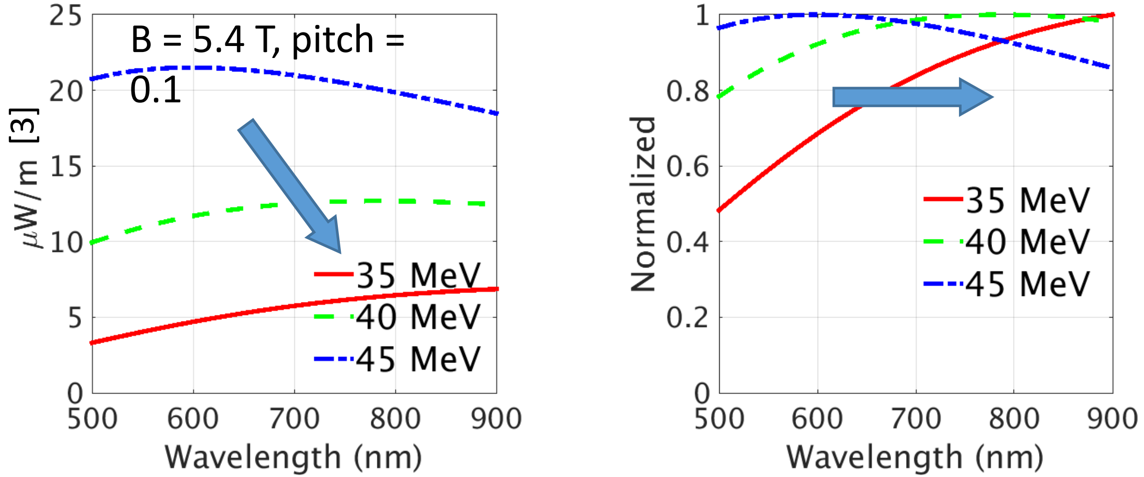


[3] I.M. Pankratov. Plasma Phys. Reports 25, 2 (1999).
[4] J.H. Yu, et al. PoP 20, 042133 (2013).

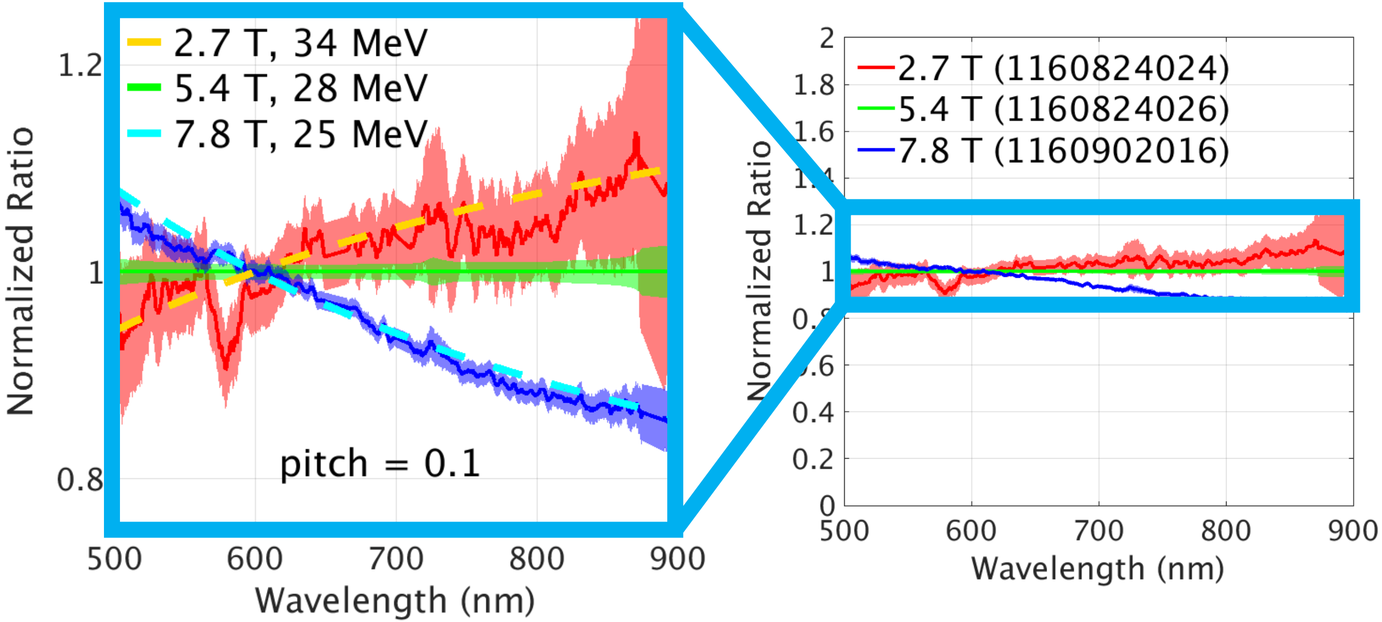
Decreasing RE **energy** decreases synchrotron emission amplitude and shifts toward the **red**



→ To keep the brightness the same, an increase in magnetic field requires a decrease in energy.

[3] I.M. Pankratov. Plasma Phys. Reports 25, 2 (1999).

Synchrotron emission limits the mono-energetic RE energy

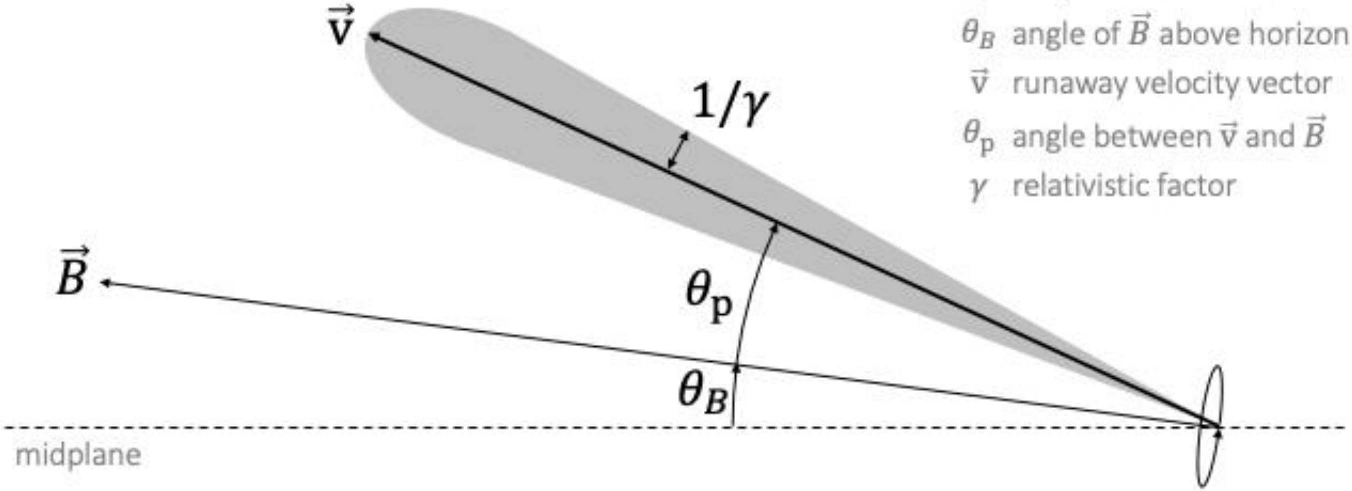


Summary of Results

- Per particle, synchrotron emission increases and shifts toward shorter wavelengths with increasing magnetic field and energy (for fixed pitch).
- Measured synchrotron brightnesses at three magnetic fields (2.7 T, 5.4 T, and 7.8 T) have similar spectral shapes.
- Assuming a mono-energetic RE beam at a fixed pitch, an increase in synchrotron emission per particle (from an increase in magnetic field) reduces the energy.

  → Synchrotron emission is limiting the energy of REs.

Relativistic particles emit **synchrotron radiation**[1,2] in their **direction of motion**

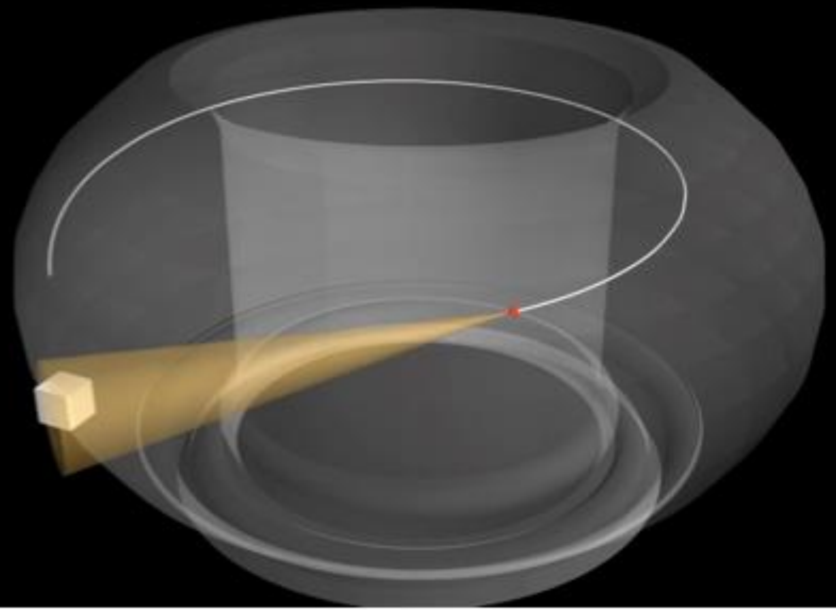


$\vec{B}$ magnetic field vector
θ_B angle of $\vec{B}$ above horizon
$\vec{v}$ runaway velocity vector
θ_p angle between $\vec{v}$ and $\vec{B}$
γ relativistic factor

Fast gyro-motion makes this look like a **cone of emission**, with opening (**pitch**) **angle** θ_p

1. Schwinger 1949 *Physical Review*
2. Westfold 1959 *The Astrophysical Journal*

Synchrotron-detecting Orbit Following Toolkit (SOFT)[1]



inputs

- magnetic geometry (EFIT[2])
- detector geometry
- phase space distribution

  $f(r, p, \theta_\mathrm{p})$ (*optional*)

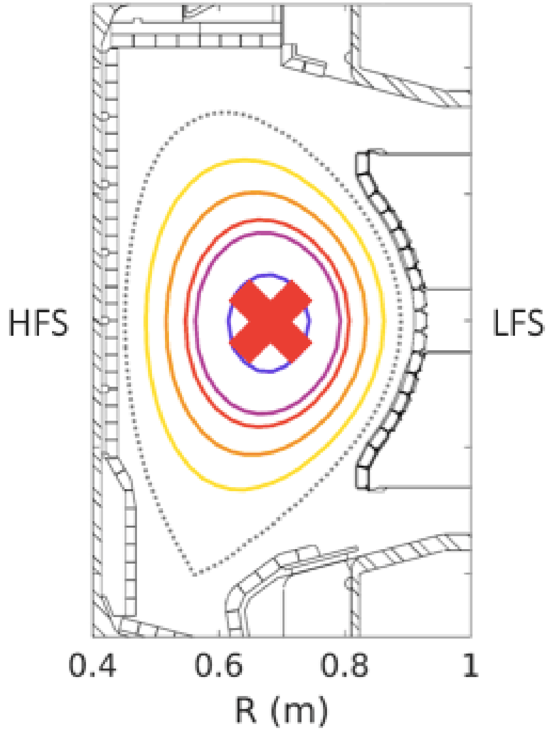
outputs

- spectra
- images
- polarization information
- Green's function

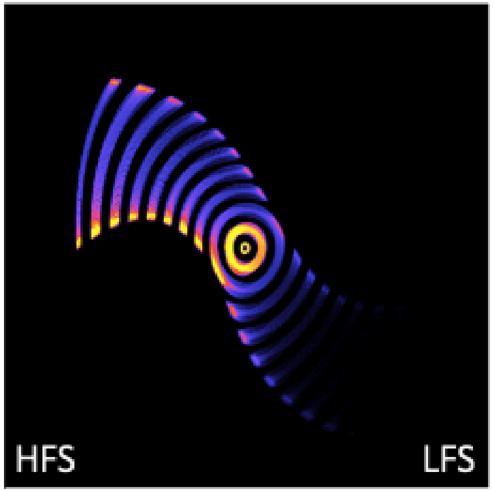
  $\hat{G}(r, p, \theta_\mathrm{p})$

1. Hoppe *et al* 2018 *Nuclear Fusion*
2. Lao *et al* 1985 *Nuclear Fusion*

Charged particles, including runaways, are confined to move on **poloidal flux surfaces**



x = camera view



SOFT image

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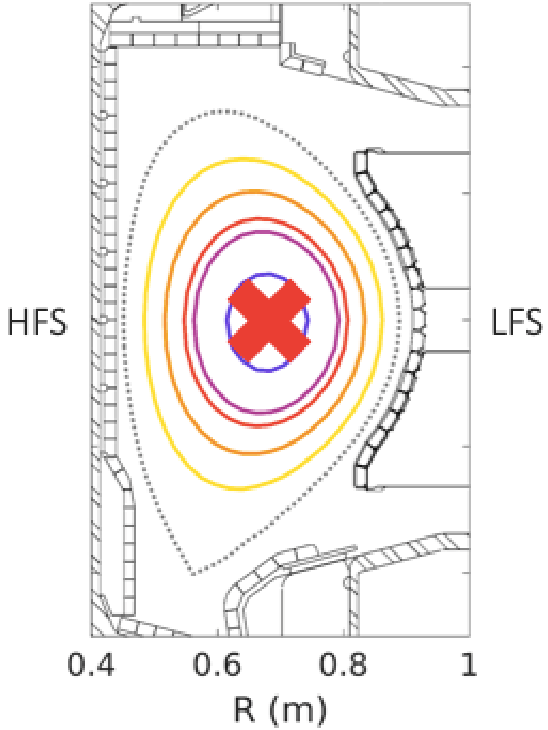

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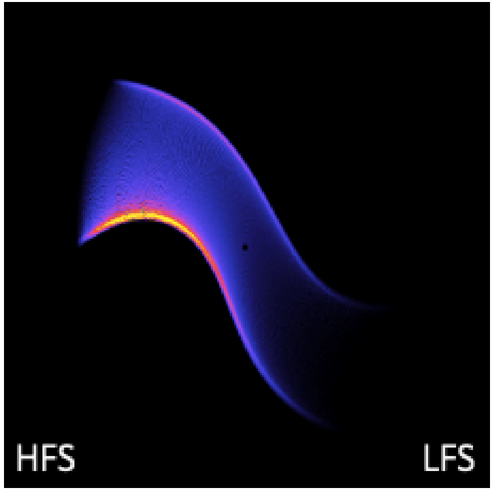
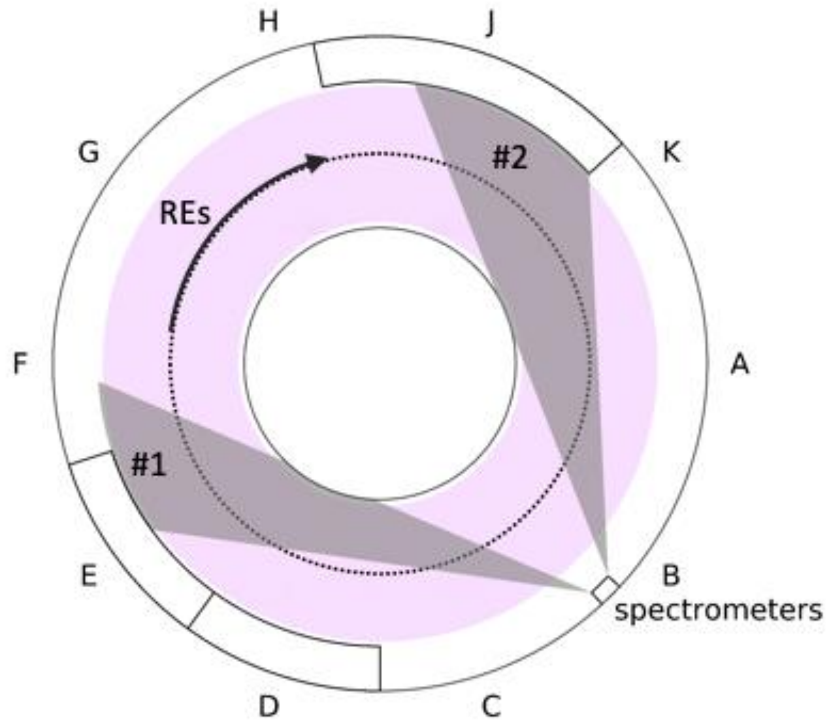
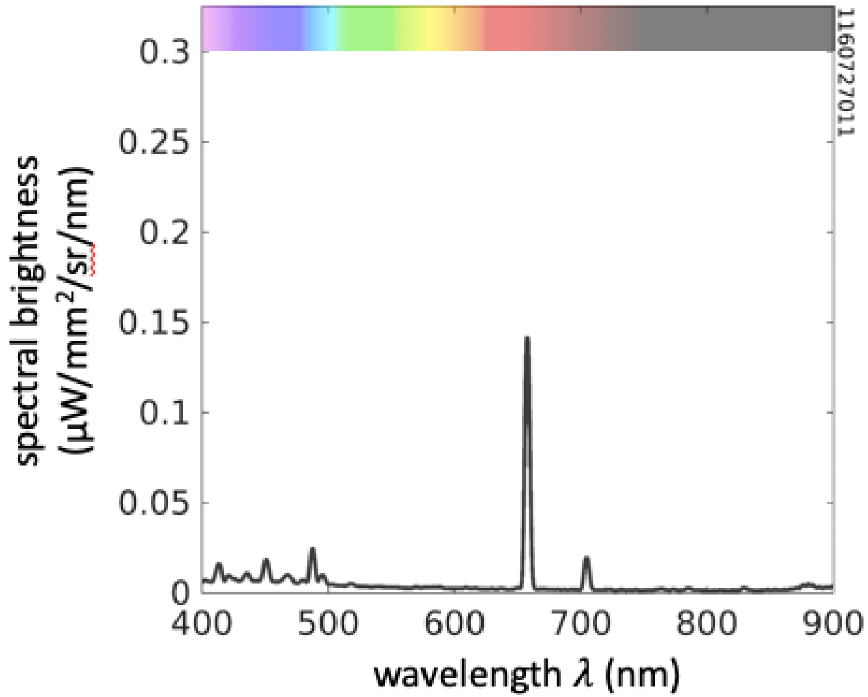


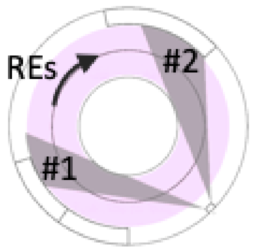
SOFT image

Two **absolutely-calibrated** visible spectrometers view **opposite** directions

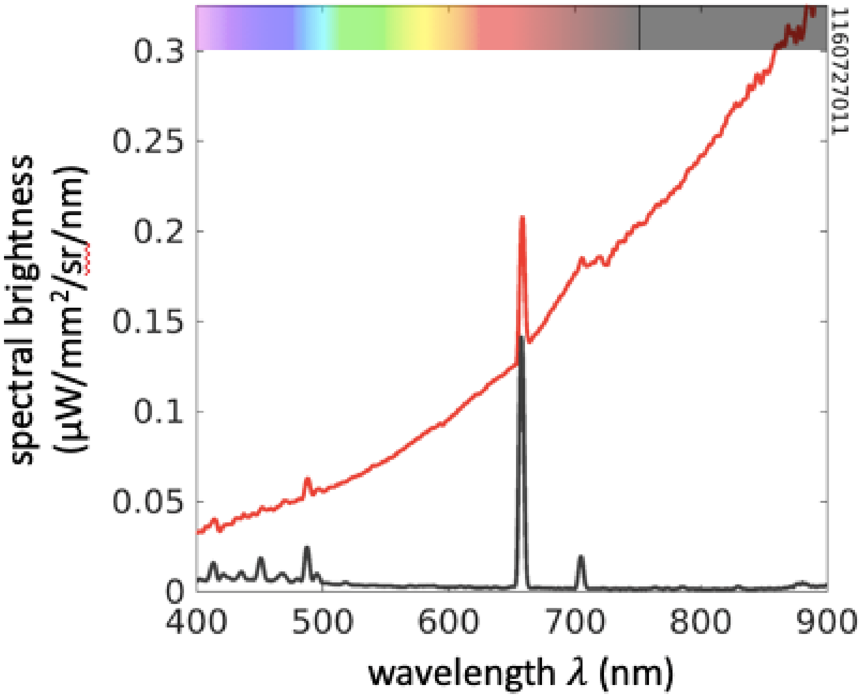


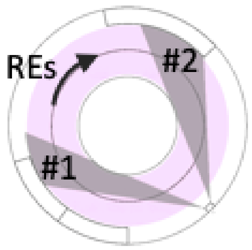
View #1: see primarily **line radiation** from atomic excitation and recombination



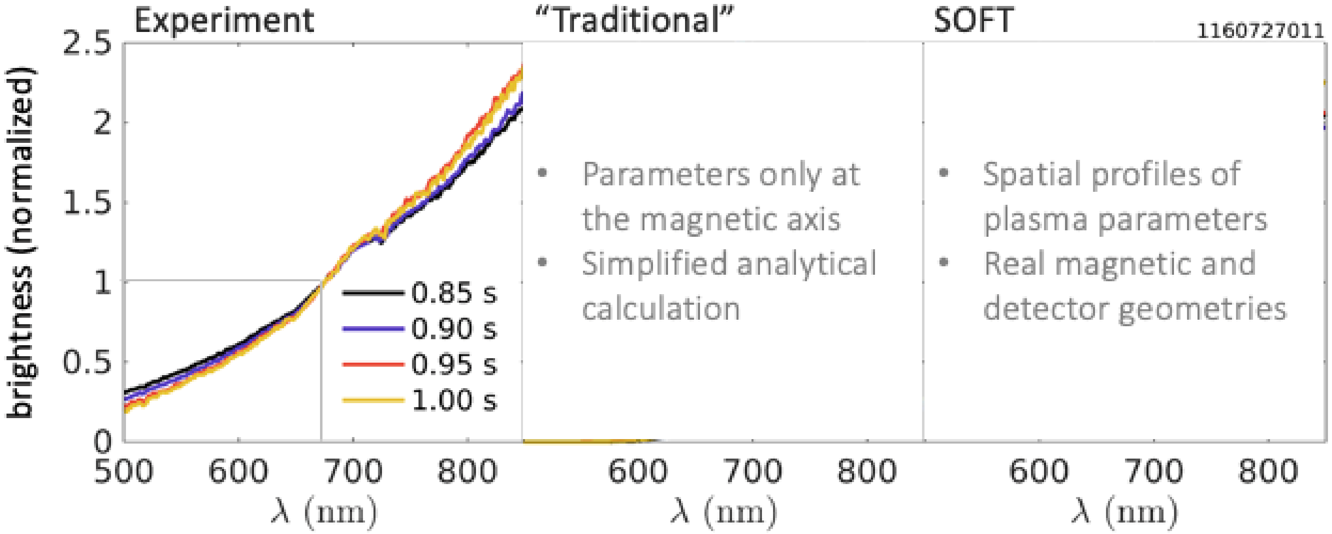


View #2: also see **continuum** spectrum in the visible range from **synchrotron emission**



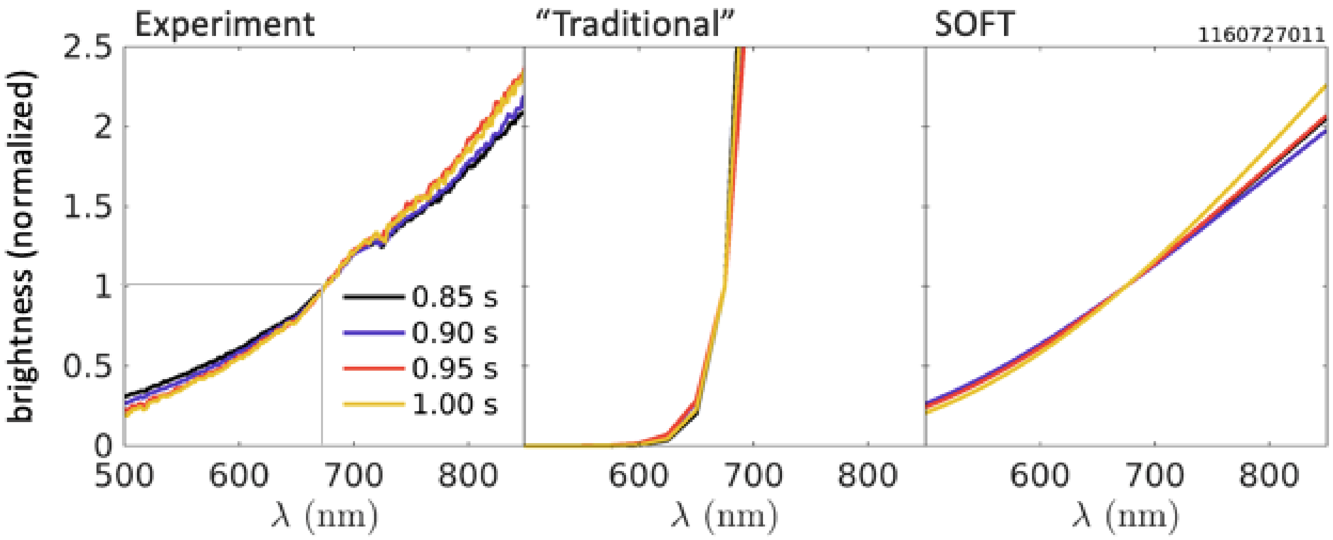


Compare synthetic spectra computed via the **"traditional"** approach[1-4] and **SOFT**



1. Jaspers *et al* 2001 *Review of Scientific Instruments*
2. Yu *et al* 2013 *Physics of Plasmas*
3. Popovic *et al* 2016 *Physics of Plasmas*
4. Esposito *et al* 2017 *Plasma Physics and Controlled Fusion*

Synthetic spectra from SOFT **match experiment** far better than the traditional[1-4] approach



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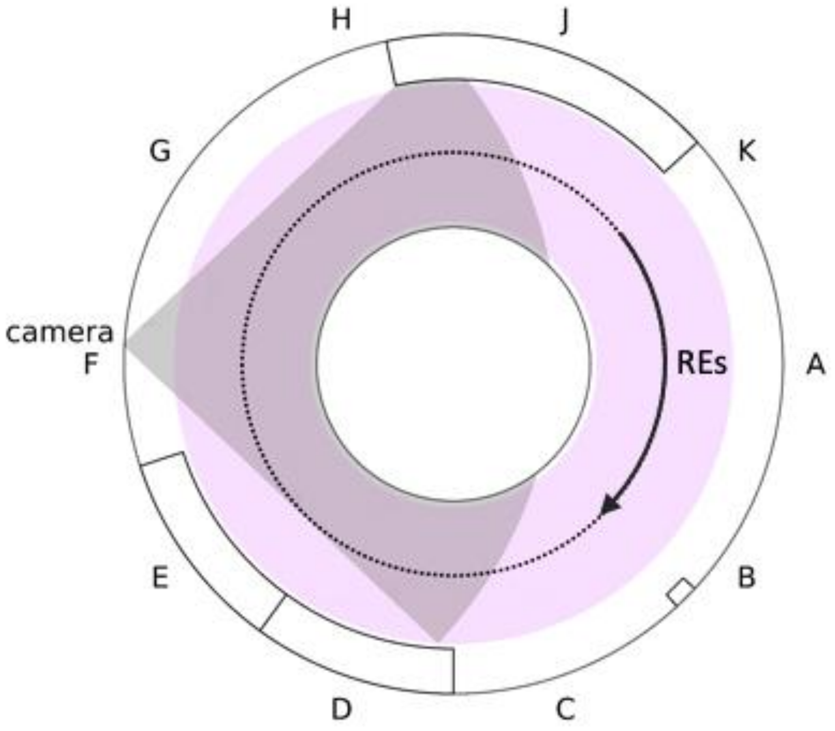
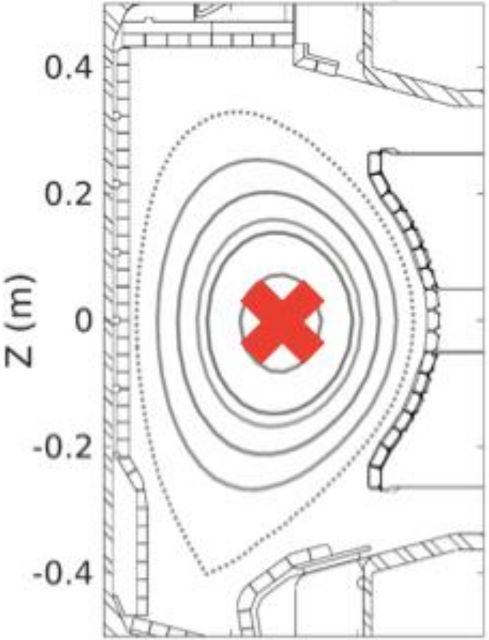
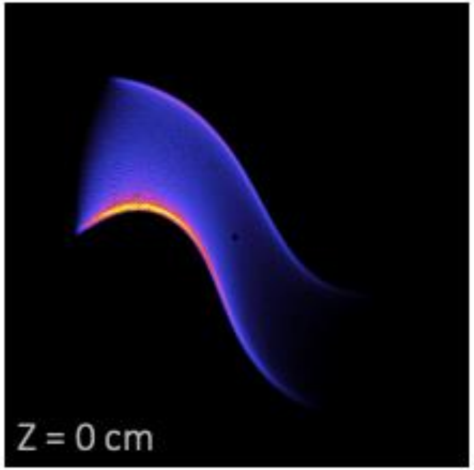
Visible/near-infrared images captured by a **wide-view** camera situated **below the midplane**



Vertically-displaced cameras see different portions of the **real space** distribution





x = camera view

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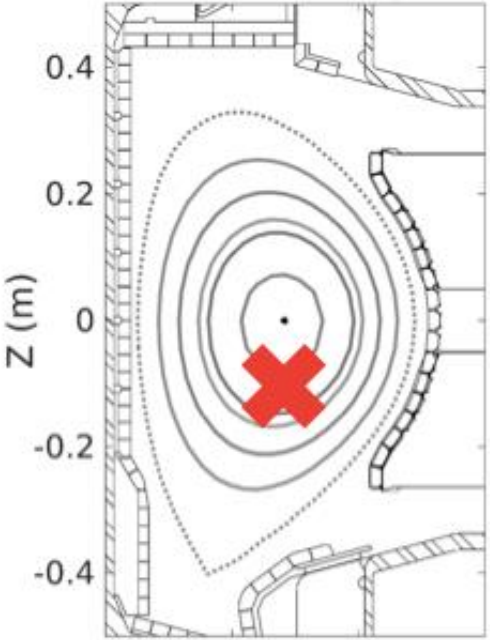

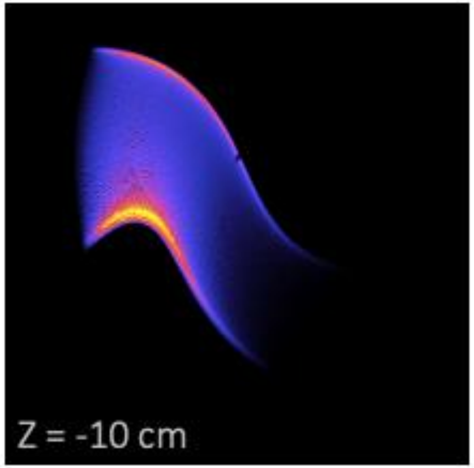

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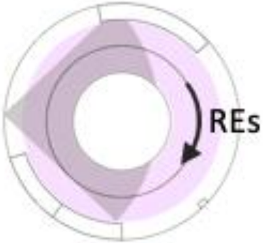
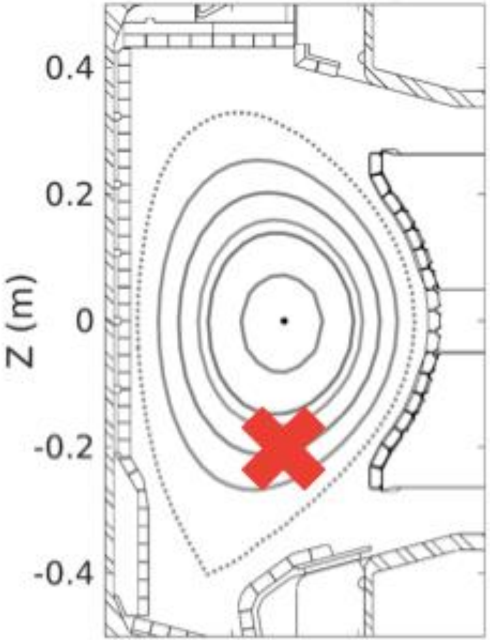
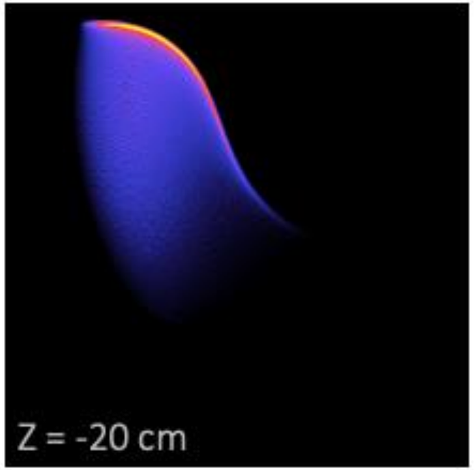
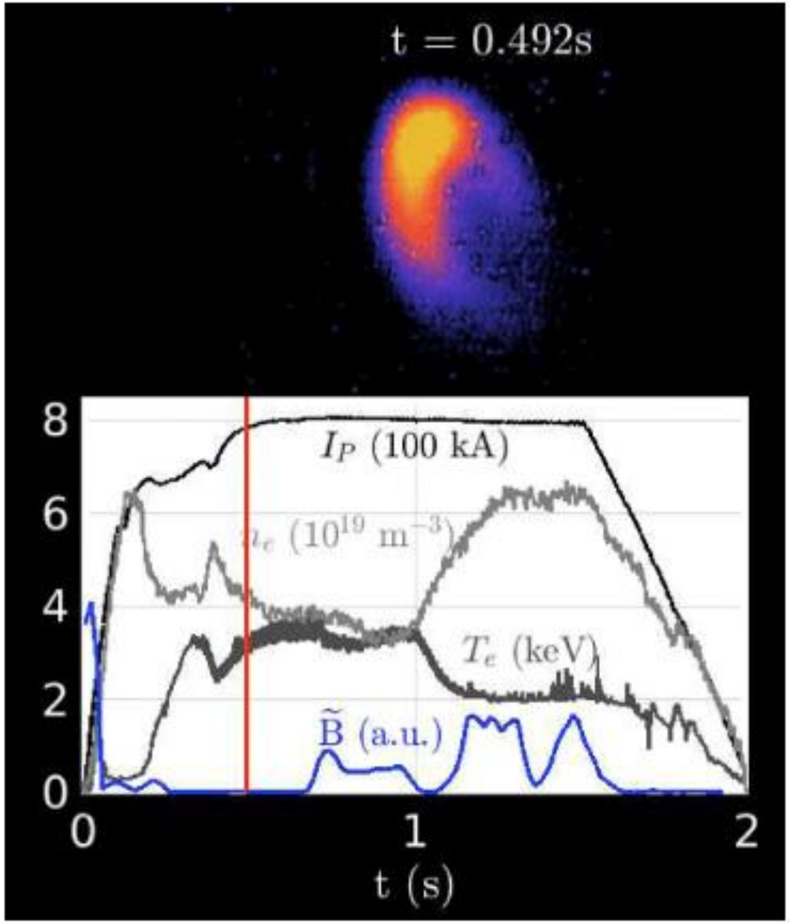
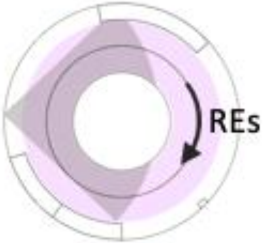






x = camera view



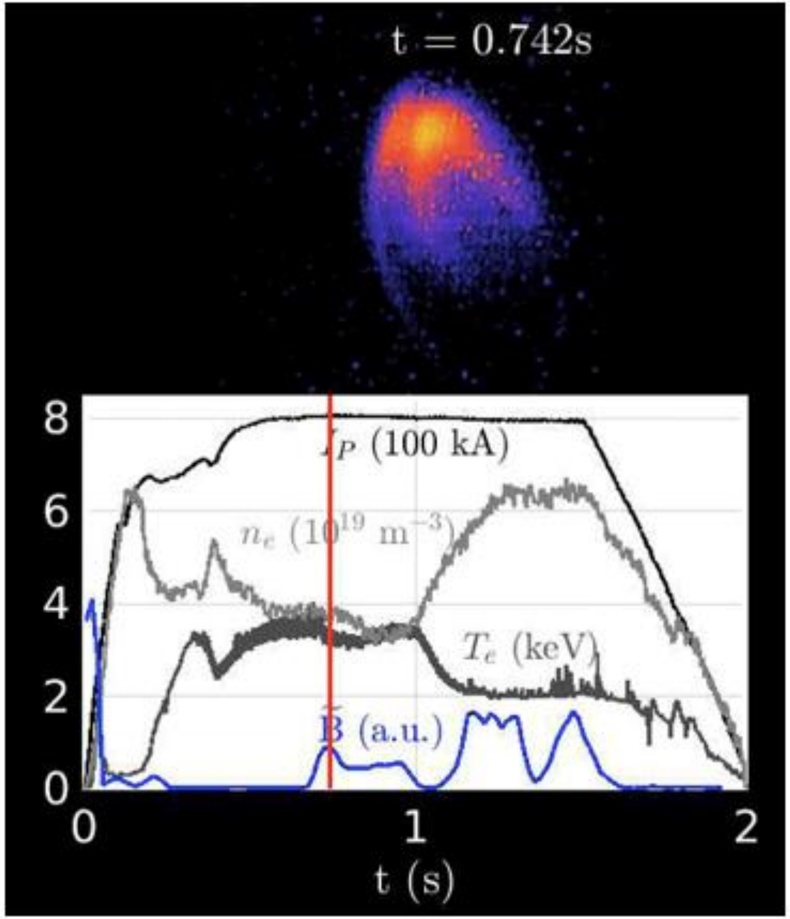


I_P plasma current

n_e plasma density

T_e plasma temperature

$\tilde{B}$ magnetic fluctuations



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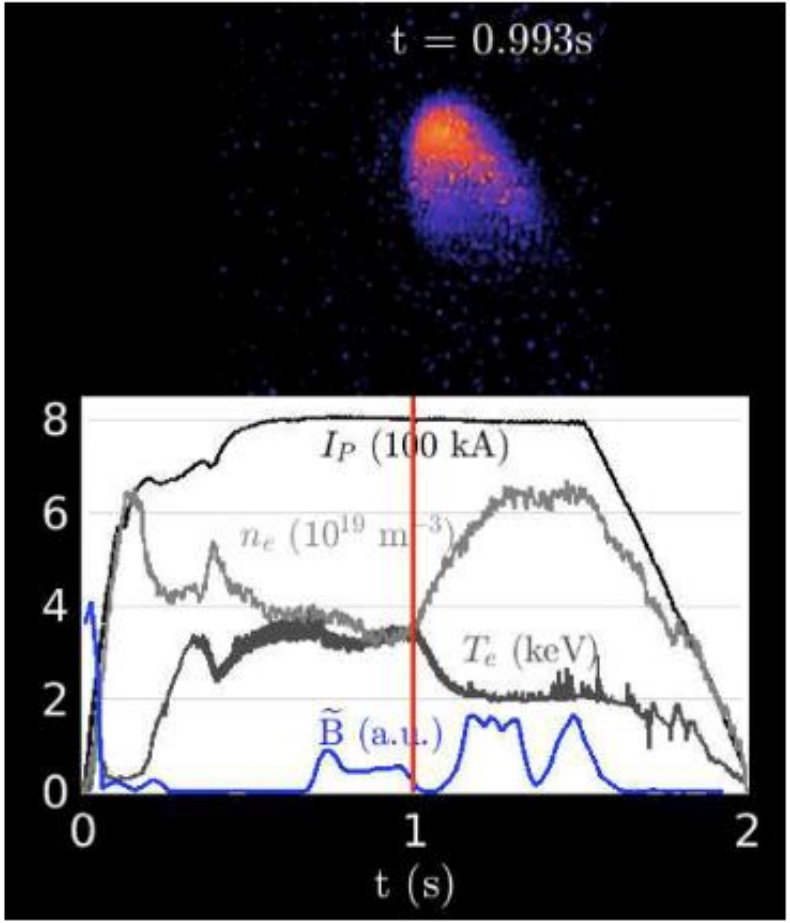

I_P plasma current

n_e plasma density

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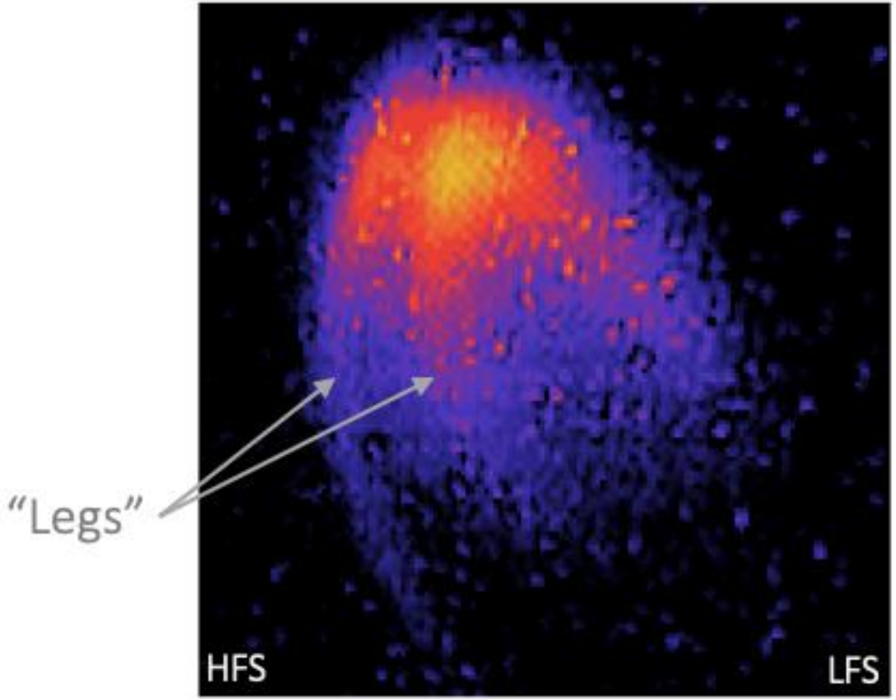
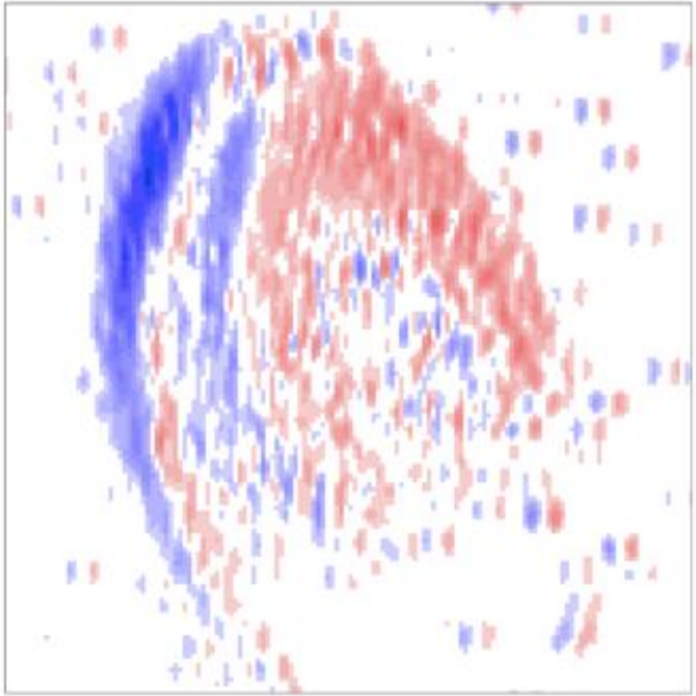
$\tilde{B}$ magnetic fluctuations

Complex **spatial structure** is observed in the **experimental** image at the onset of **magnetic fluctuations**

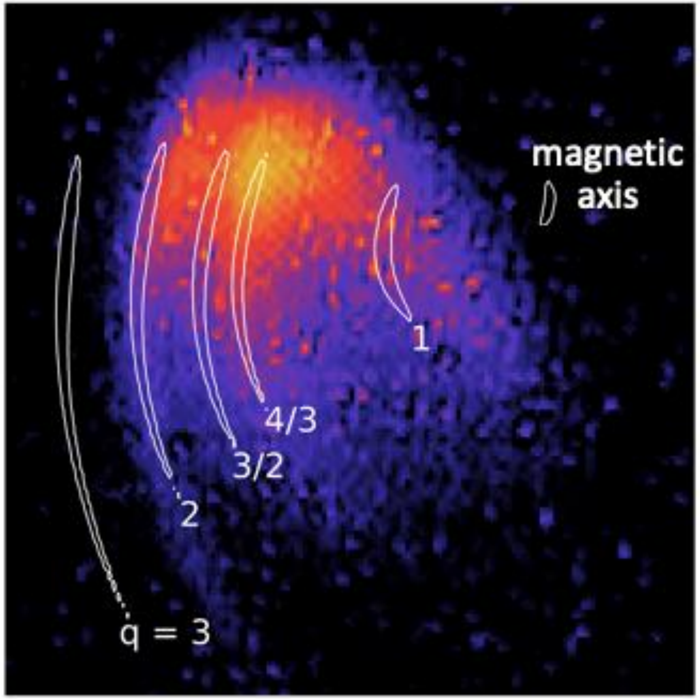


Spatial structure is seen more clearly in the **experimental** image using **edge detection**[1]



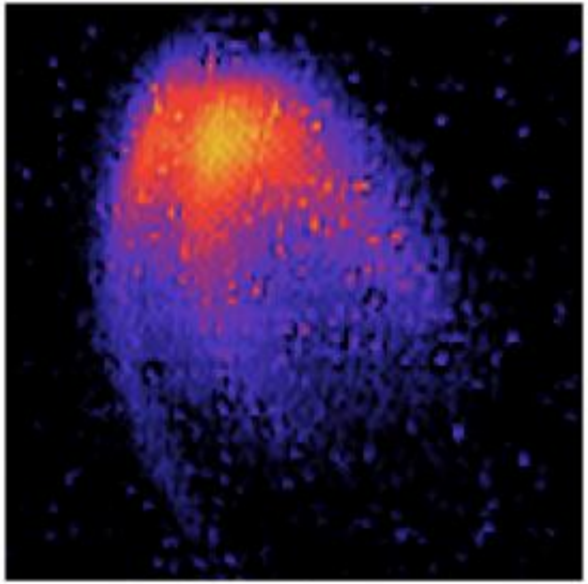
1. Sobel and Feldman 1968 Presented at *Stanford Artificial Intelligence Project*

Outer "leg" corresponds to runaway emission on the **q = 2 surface** during the growth of an **MHD instability**

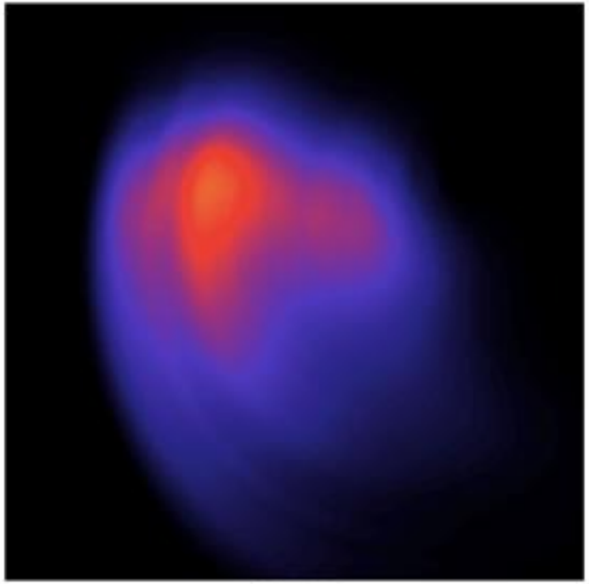


MHD = magnetohydrodynamics

Use **non-overlapping** synchrotron emission from adjacent flux surfaces to **fit** synthetic SOFT images

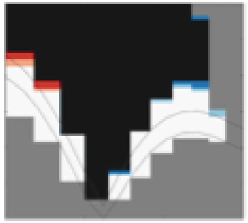


Experiment

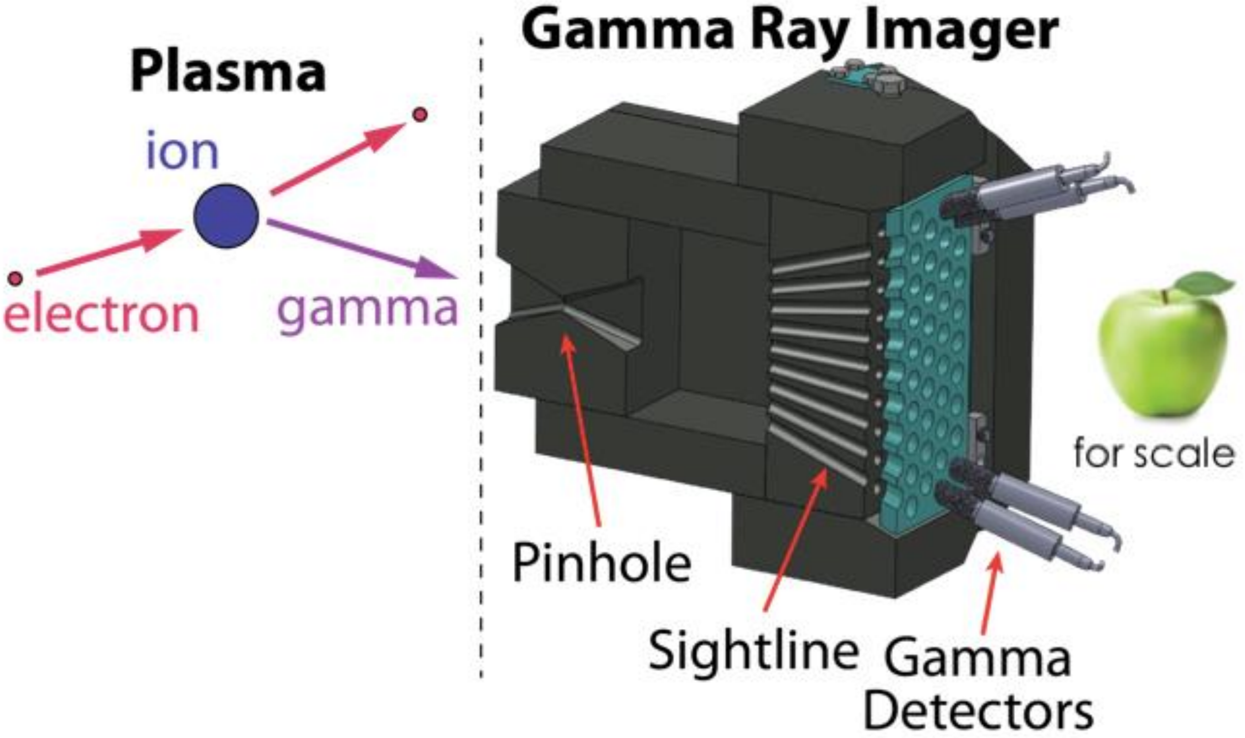


SOFT

experimental polarization of synchrotron emission

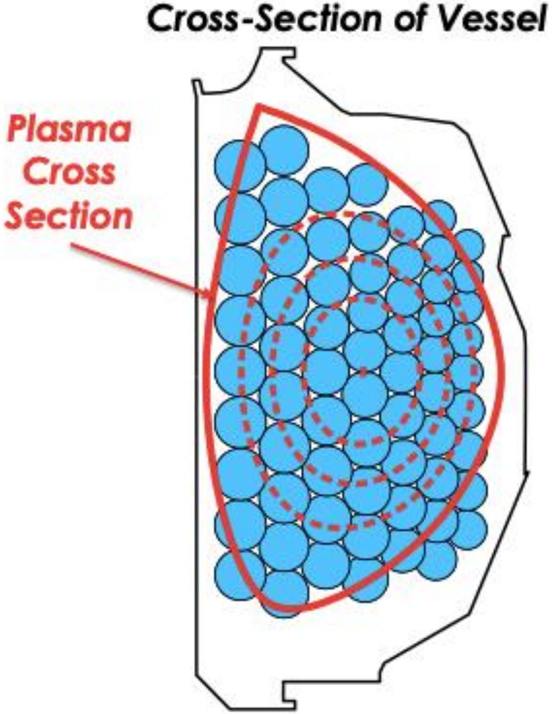


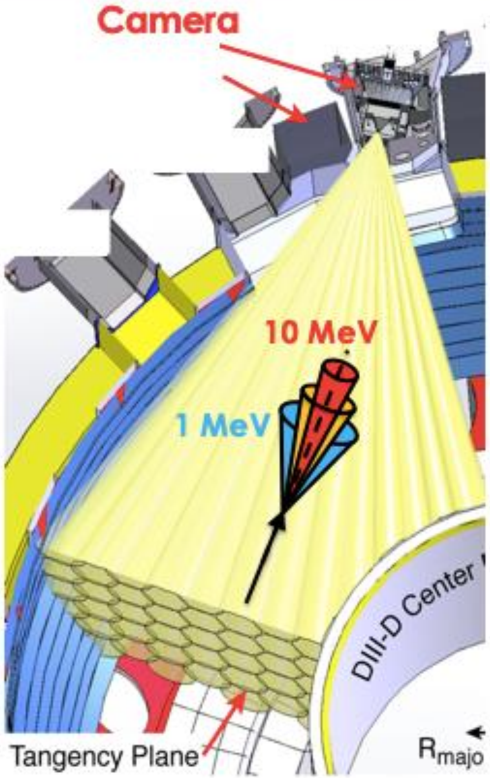
Pinhole Camera Made of Lead ("GRI") Developed to Collimate Hard X-Ray Flux from Relativistic Electrons



D. Pace et al,
Rev. Sci. Instrum. 2016

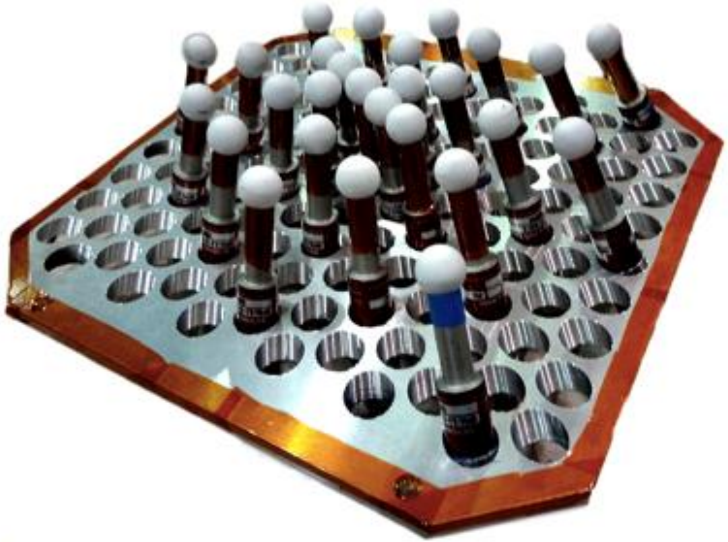
Pinhole Camera Made of Lead ("GRI") Developed to Collimate Hard X-Ray Flux from Relativistic Electrons





Each "pixel" of the camera is a scintillating crystal with an integrated photodiode detector

Integrated scintillator, photodiode, and amplifier @ each pixel



Detectors focusing on pinhole

C. Cooper et al,
Rev. Sci. Instrum. 2016

Runaways can occur during several different phases of a tokamak plasma discharge

- Disruptions: HUGE loop voltage, but plasma conditions are poorly controlled, and not well diagnosed.
- Steady-state flattop: well-controlled conditions for research physics
- Plasma startup: loop voltage is higher than normal and density is low

Runaways can occur during several different phases of a tokamak plasma discharge

– Disruptions: HUGE loop voltage, but plasma conditions are poorly controlled

- Of concern for ITER because breakdown & burnthrough must be done at very low pre-fill
- Poorly understood; Ongoing ITPA joint activity

Cross-machine comparison of runaway electron generation during tokamak start-up for extrapolation to ITER

P.C. de Vries[1], Y. Lee[2,3], Y. Gribov[1], A.B. Mineev[4,5], Y.S. Na[2,3],
R. Granetz[6], B. Stein-Lubrano[6], C. Reux[7], Ph. Moreau[7], V. Kiptily[8], B. Esposito[9],
D.J. Battaglia[10,11], J.R. Martin-Solis[12] and ITPA IOS collaborators.

Italian National Agency for New Technologies, Energy and Sustainable Economic Development

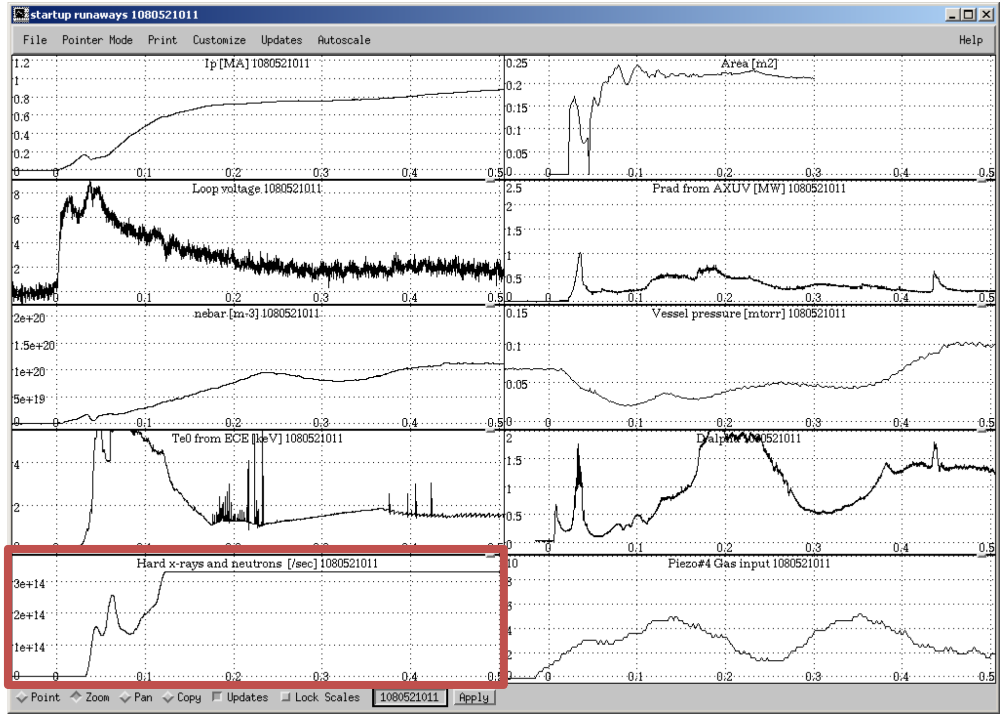
- Ohmic plasma initiation in ITER may only succeed in a narrow range around a low prefill pressure. Consequentially the density during breakdown and burn-through will be low, which is often quoted as reason for the formation of supra-thermal or runaway electron discharges. Runaway electron (RE) discharges could damage in-vessel components and should be avoided.

- In the first two decades of tokamak research, start-up RE got a great deal of attention. But this has now shifted to the, more risky, formation of RE by tokamak disruptions.

- The generation of runaway electrons during plasma initiation was simply linked to too low a prefill pressure for a given toroidal electric field. Often suggesting, that if the right prefill, breakdown or start-up sequence was applied, start-up RE could be avoided.

- This might have been true for smaller devices, for which the plasma initiation process is very short in duration, however, for larger devices, such as JET, it was shown that the whole process is significantly more complex[1].

[1] P.C. de Vries, et al., Plasma Phys. Control. Fusion 62 (2020) 125014.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nebar [m-3] 1080521011
Vessel pressure [mtorr] 1080521011
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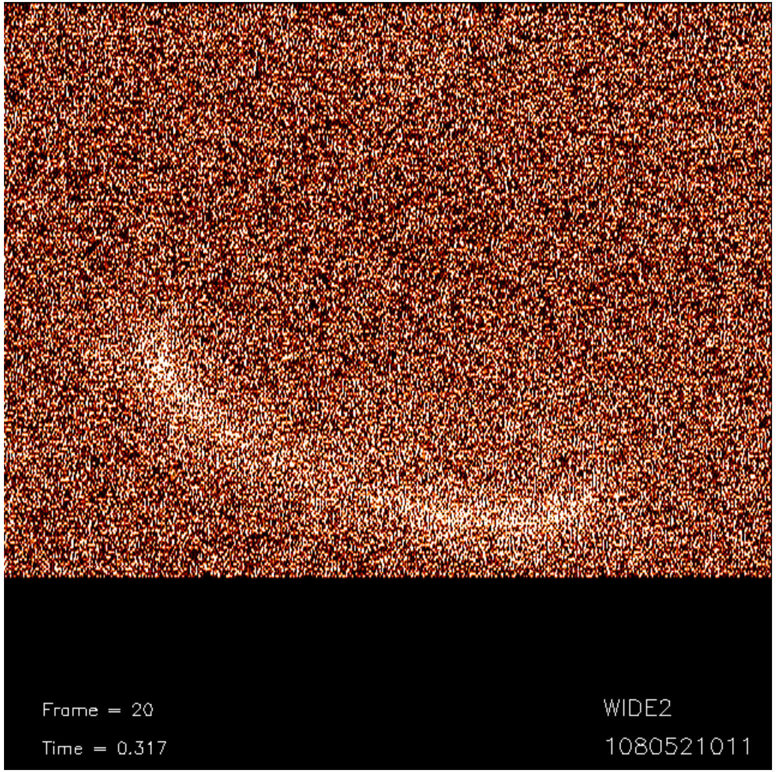
Hard x-rays and neutrons [/sec] 1080521011
Piezo#4 Gas input 1080521011
Point Zoom Pan Copy Updates Lock Scales 1080521011 Apply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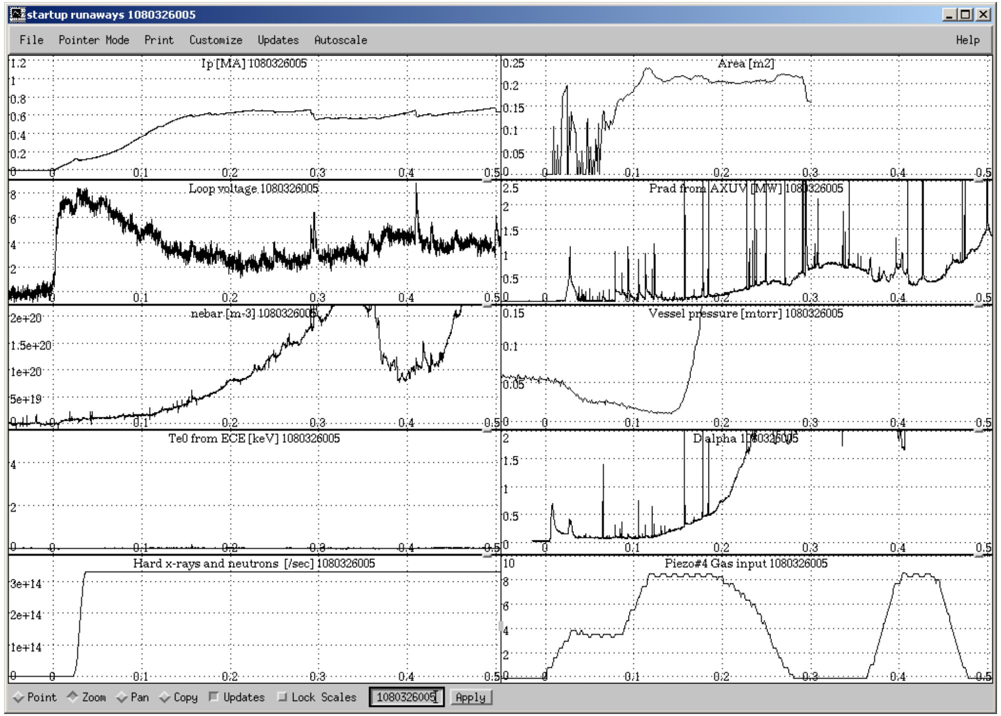
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Te0 from ECE [keV] 1080326005
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Hard x-rays and neutrons [/sec] 1080326005
Piezo#4 Gas input 1080326005
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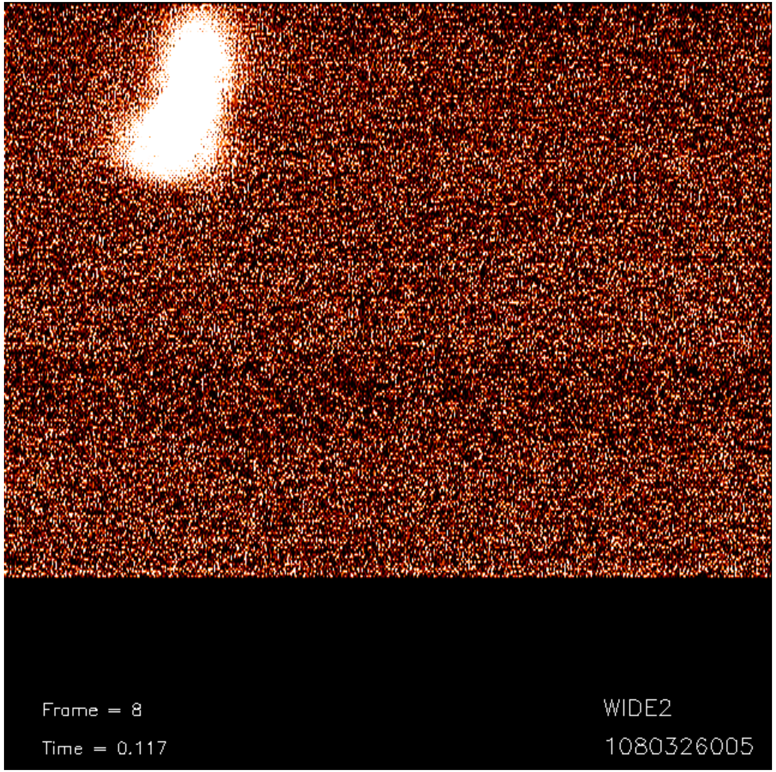
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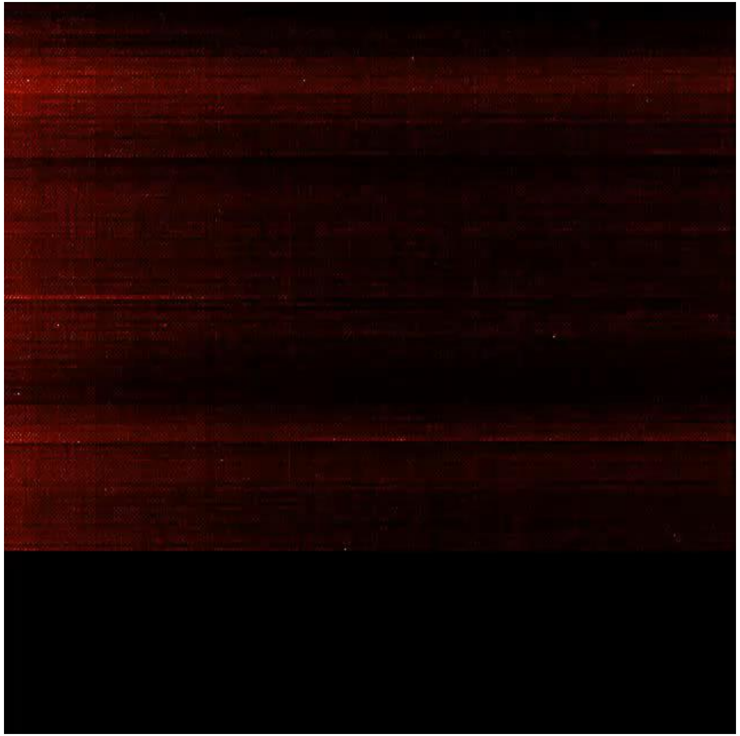
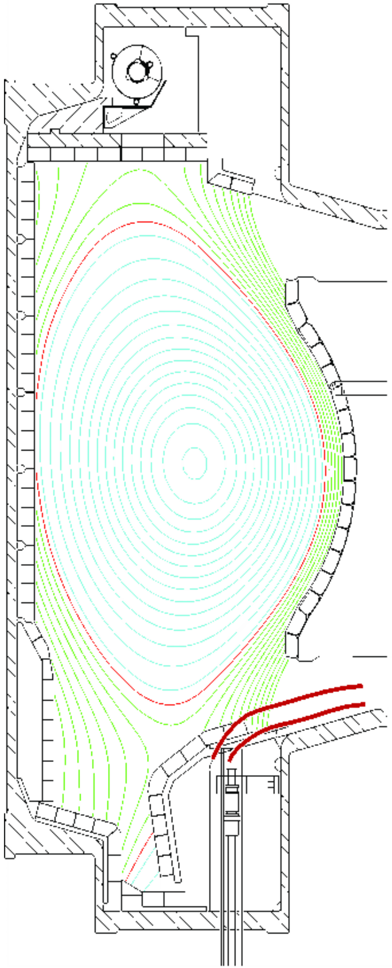
Horrendous startup REs



XTOMO signal cables go down D-bottom port

1080326005 EFIT: 0.580



Close-up of damaged XTOMO signal cables