

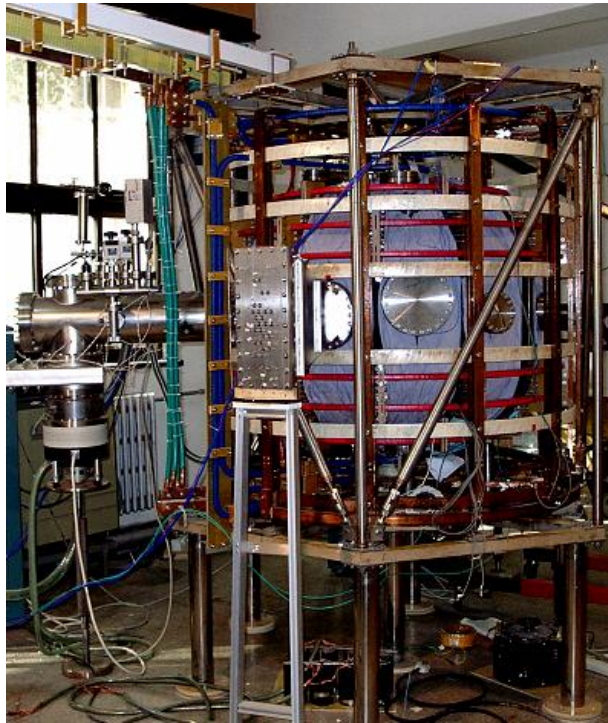
Twenty years of research on the SUNIST spherical tokamak

Tan Yi, Gao Zhe, and the SUNIST group

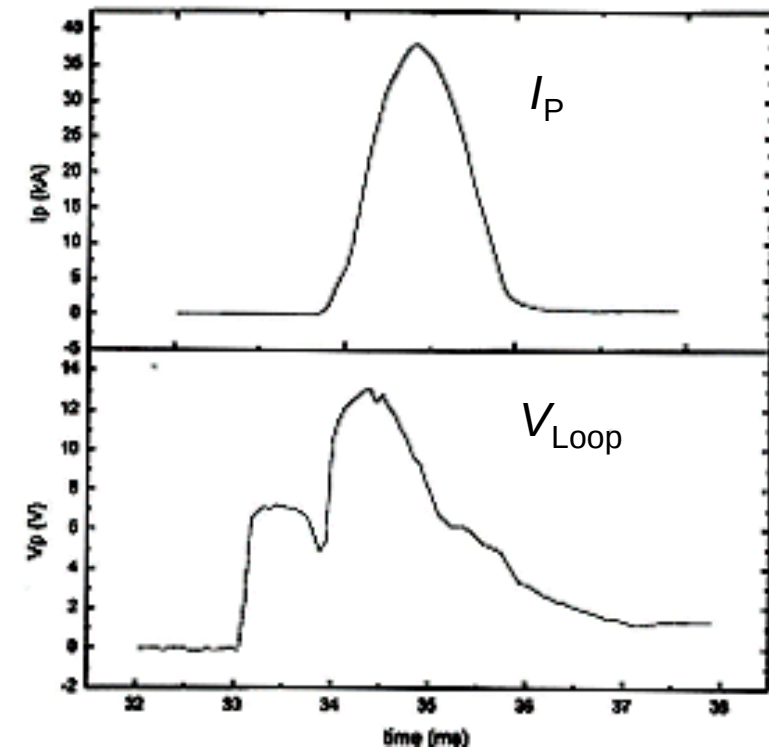
Email: tanyi@sunist.org

Nov. 4th 2002, the 1st plasma of SUNIST

- Got a plasma (40 kA / 2 ms) in the **FIRST** discharge with all fields together
- Start of the **TWENTY** years of research

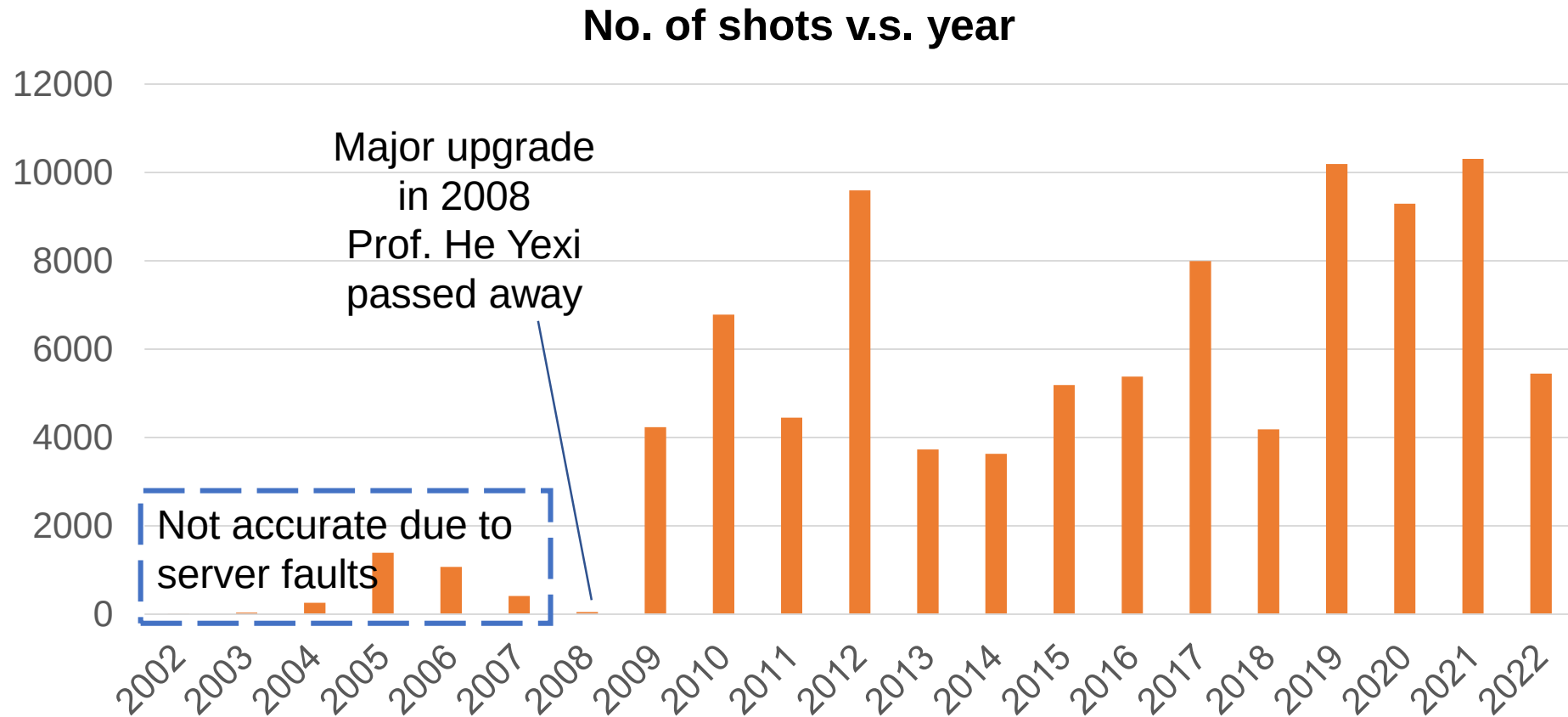


SUNIST at 2002



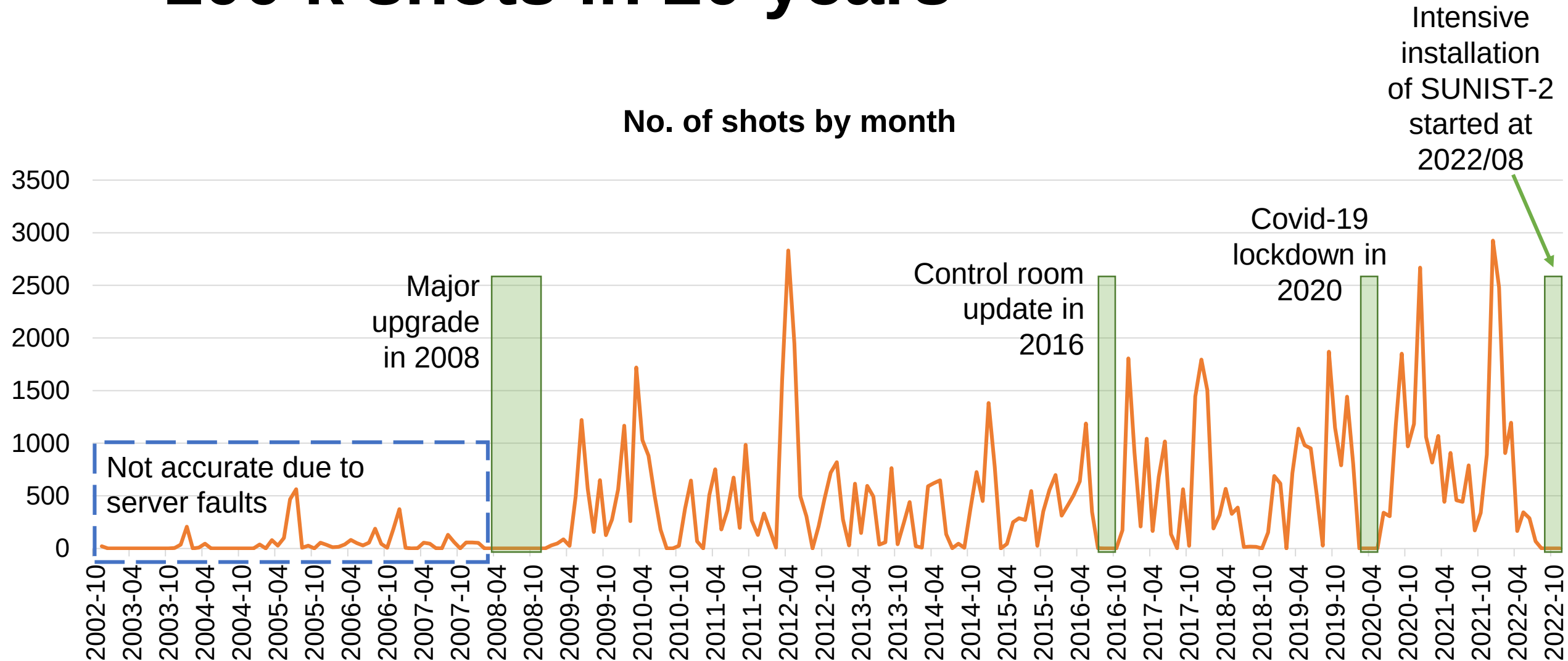
the FIRST plasma of SUNIST

~100 k shots in 20 years



~100 k shots in 20 years

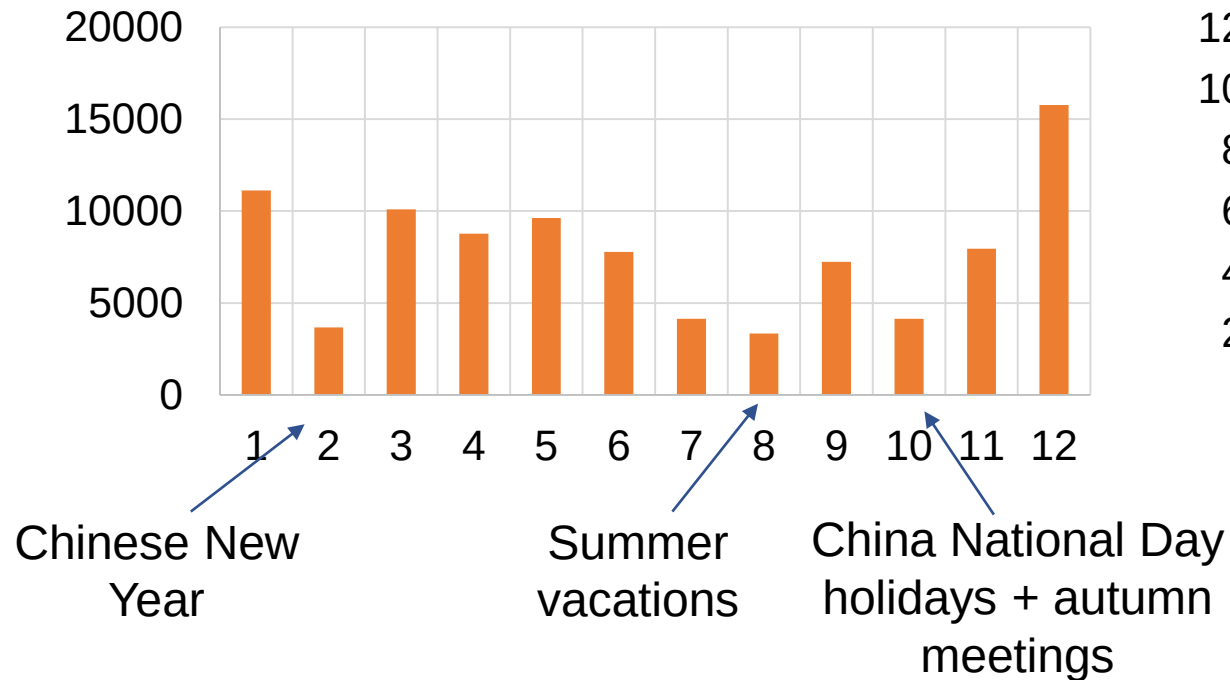
No. of shots by month



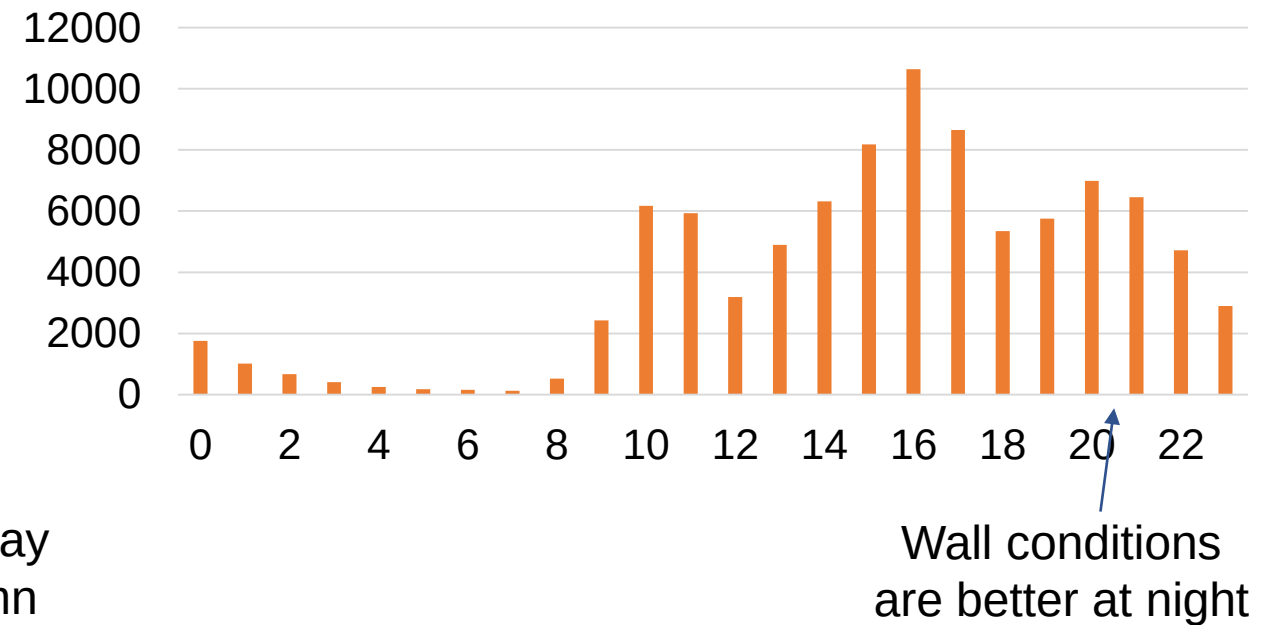
Other statistics

- Similar to normal workplaces in China
- Fast maintenance, quickly resumed to experiments, no seasonal experimental campaigns

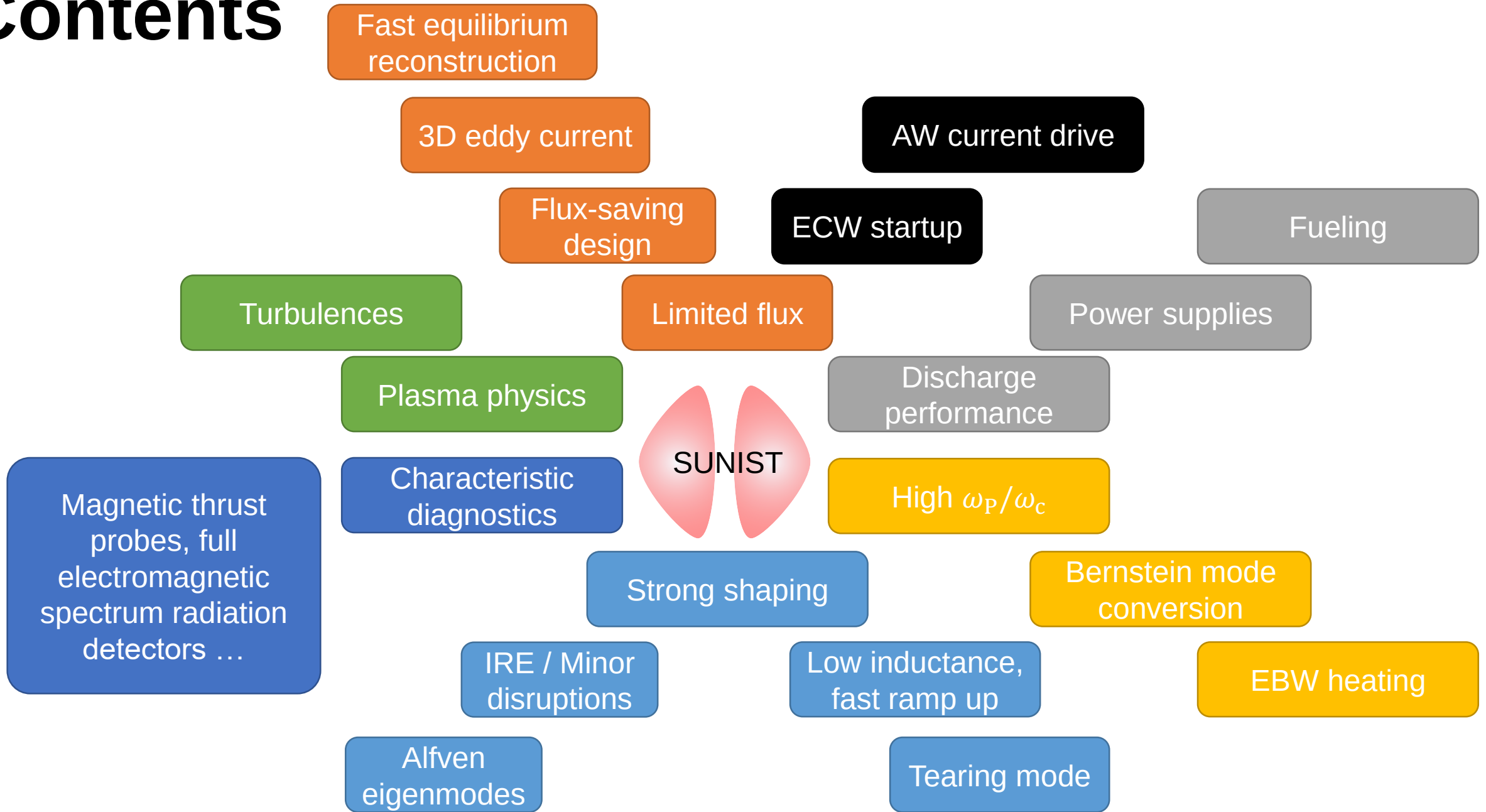
No. of shots v.s. month



No. of shots v.s. hour



Contents



Contents

Fast equilibrium
reconstruction

3D eddy current

AW current drive

Flux-saving
design

ECW startup

Fueling

Turbulences

Limited flux

Power supplies

Plasma physics

Discharge
performance

SUNIST

Characteristic
diagnostics

High ω_P/ω_C

Magnetic thrust
probes, full
electromagnetic
spectrum radiation
detectors ...

Strong shaping

Bernstein mode
conversion

IRE / Minor
disruptions

Low inductance,
fast ramp up

EBW heating

Alfven
eigenmodes

Tearing mode

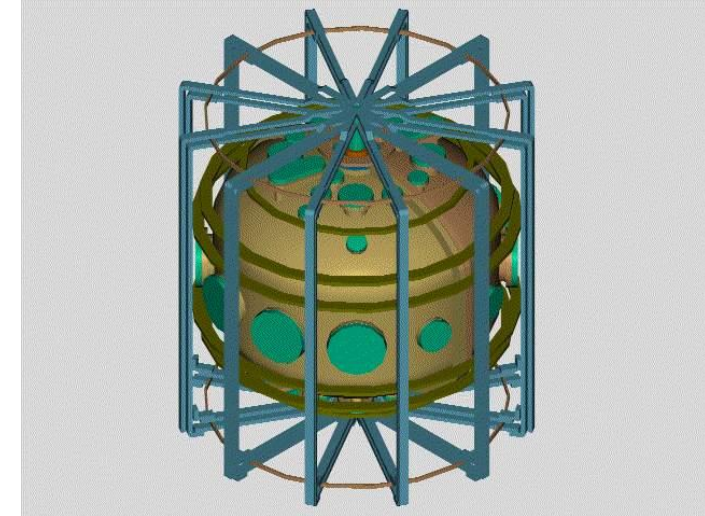
Design of SUNIST

- **Parameters**

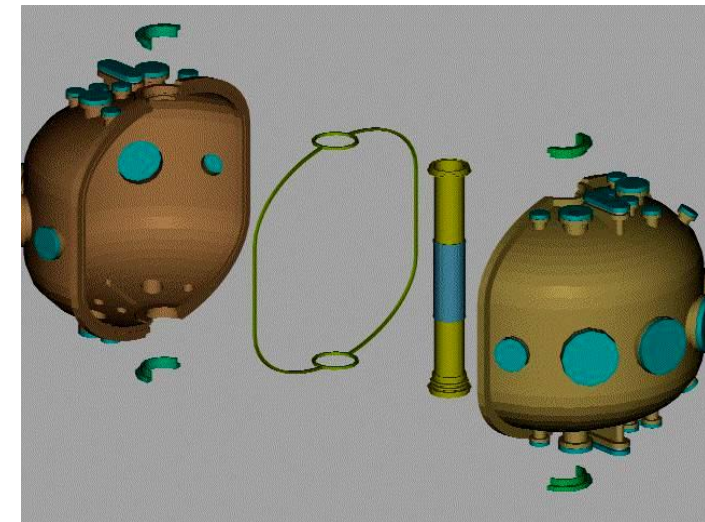
- R_0 : 0.3 m, a : 0.23 m
- A : ~ 1.3 , κ : 1.6 – 1.8
- B_{T0} : 0.15 T, I_P : 50 kA
- Ohmic flux: 60 mv.s

- **To save flux, the vacuum vessel was split by a 3D Viton seal**

- 3D seal was challenged by many colleagues
- Actual vacuum performance: overall good ($2E-5$ Pa)
- Small leak at initial seal, no leak after 2008 upgrade



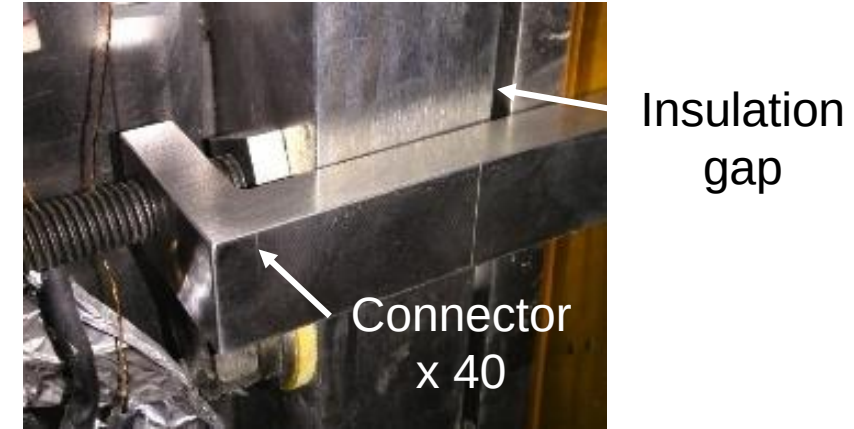
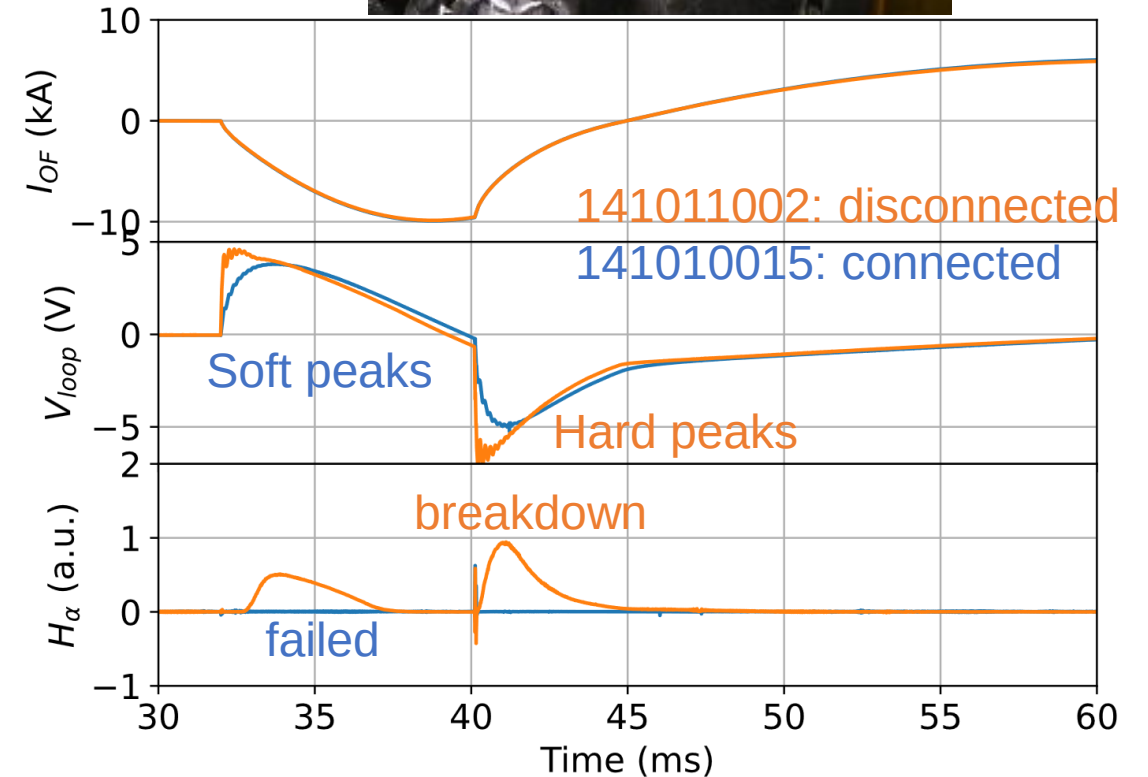
3D model of SUNIST



Split VV to save flux

Effects of the gap

- **Total flux saving**
 - Not very much
- **Loop voltage**
 - Peaks effectively maximized
 - Easy to breakdown
- **Eddy current**
 - Strange distribution



3D eddy current in VV

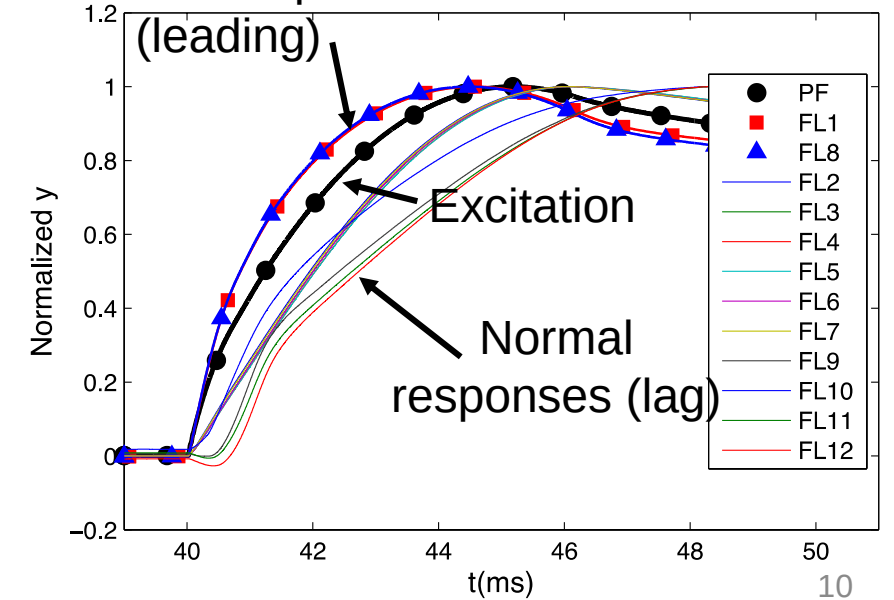
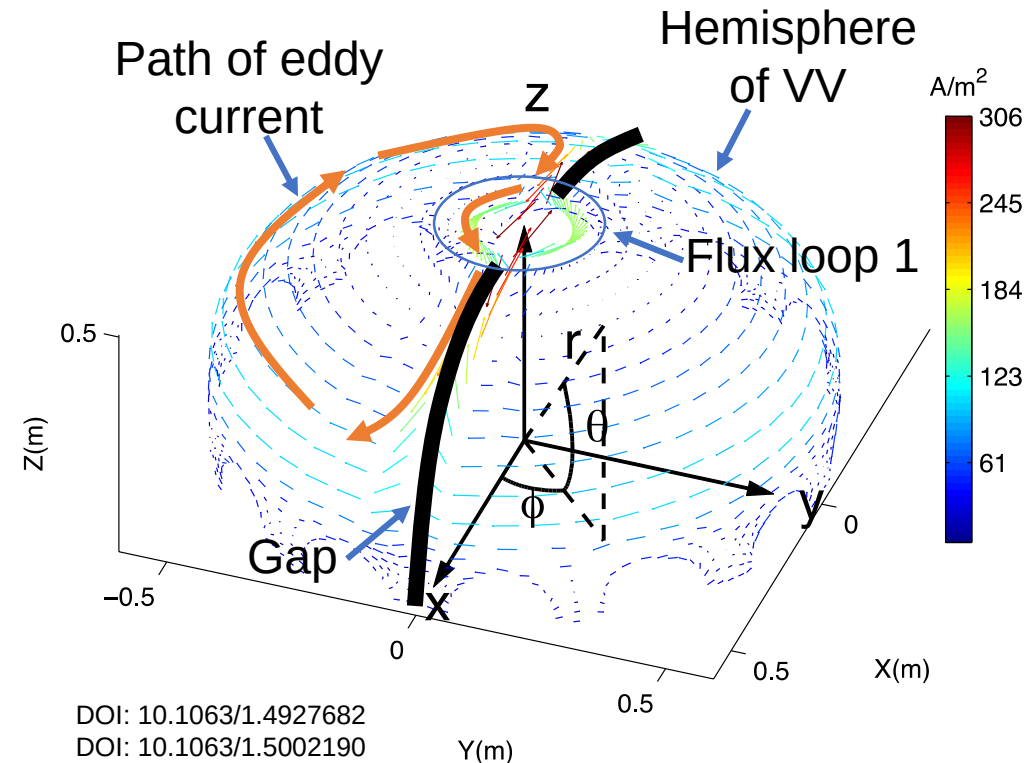
- Due to the gap, the eddy current flows in a 3D path
 - Experimentally verified by an orth-probes array



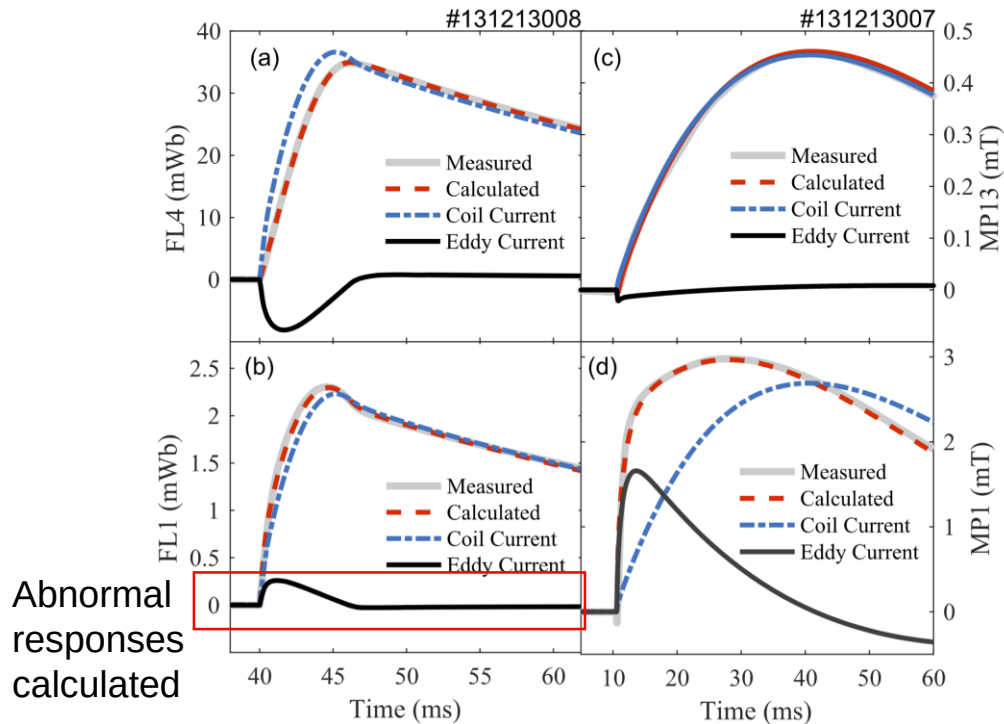
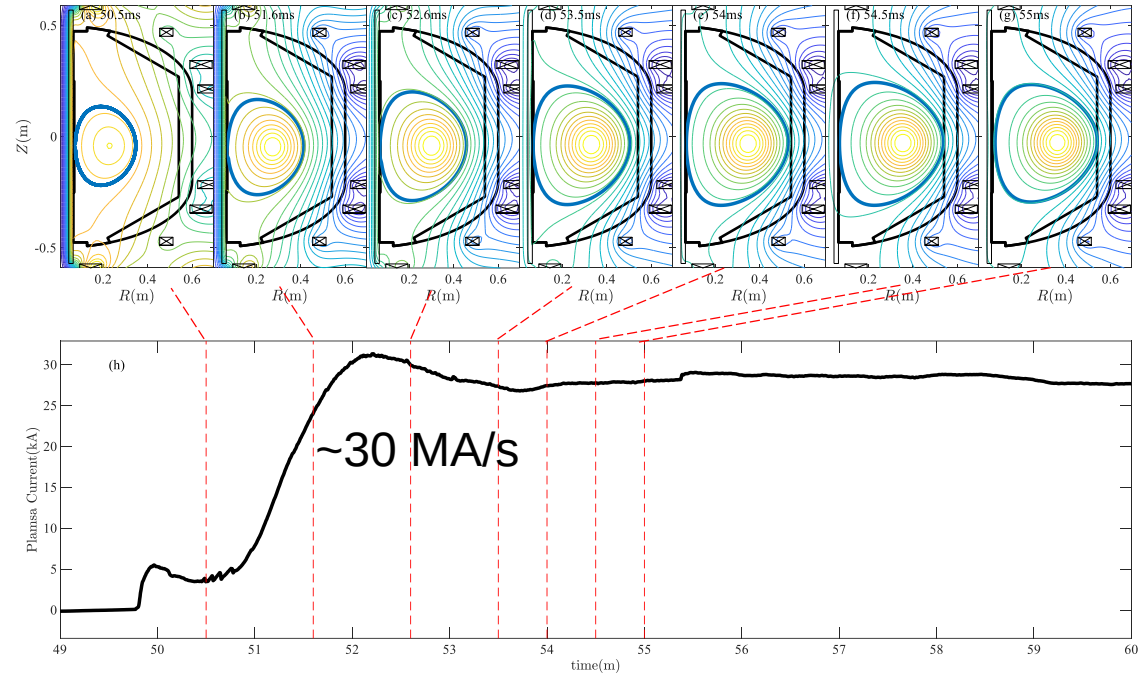
an orth-probe

The orth-probes array installed near the slit

Abnormal responses



Include 3D eddy current in equilibrium reconstruction

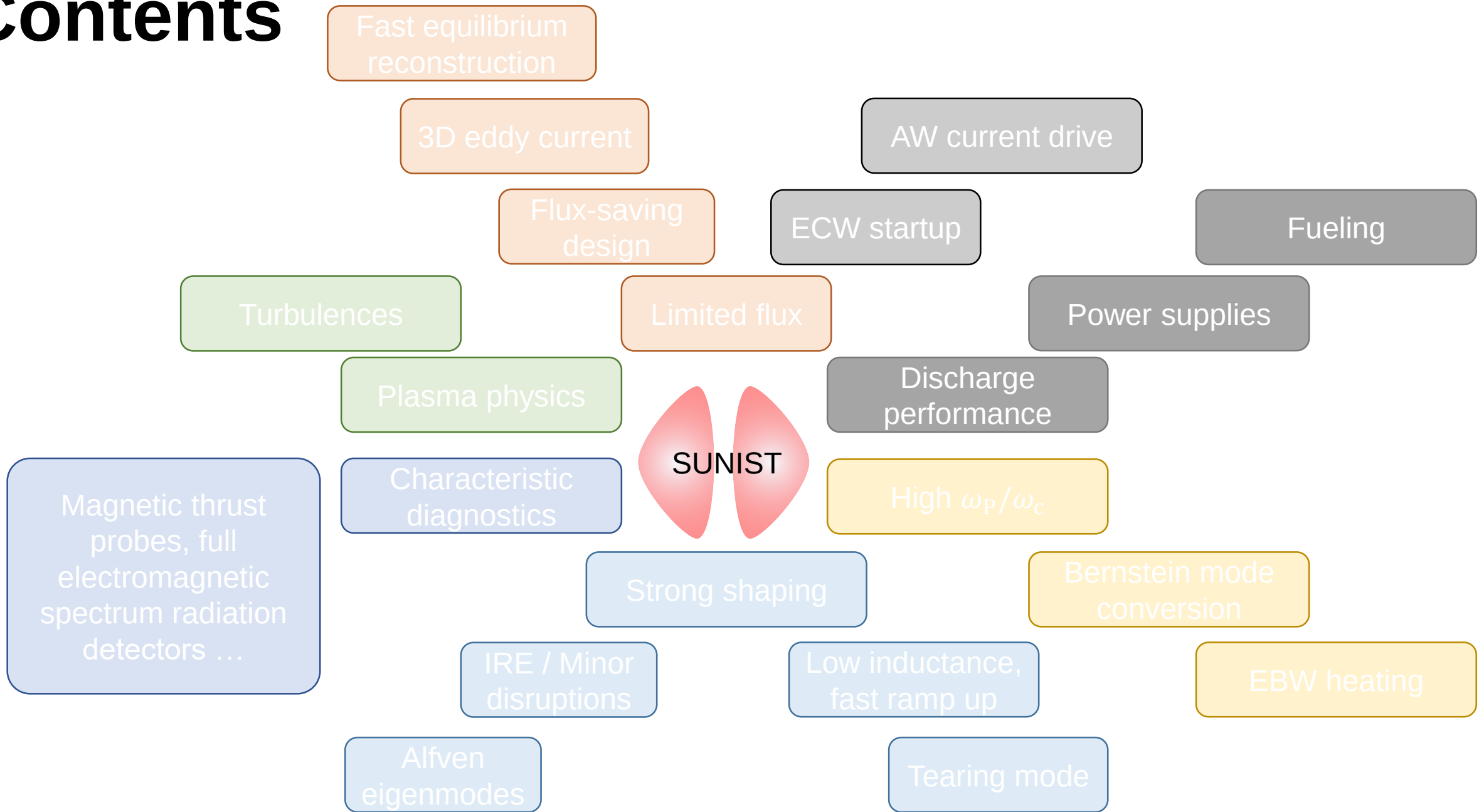


Magnetic measurements are corrected by **response functions**. Eddy current components can be accurately separated.

DOI: 10.1063/1.5002190

Magnetic surfaces are successfully reconstructed from the very beginning of discharge with **30 MA/s** ramp rate when eddy current effect is huge.

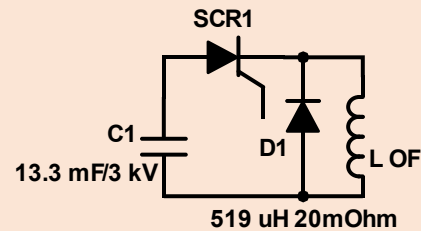
Contents



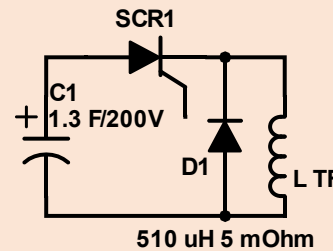
Upgrade power supplies

- All field power supplies have been upgraded >1 times

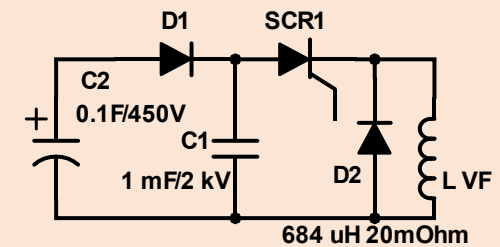
Initial



Ohmic field PS

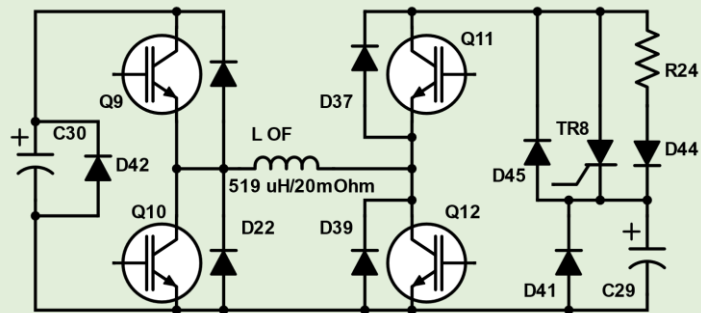


Toroidal field PS

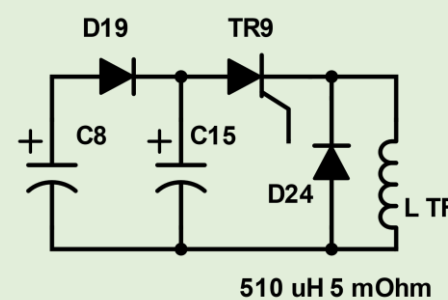


Vertical field PS

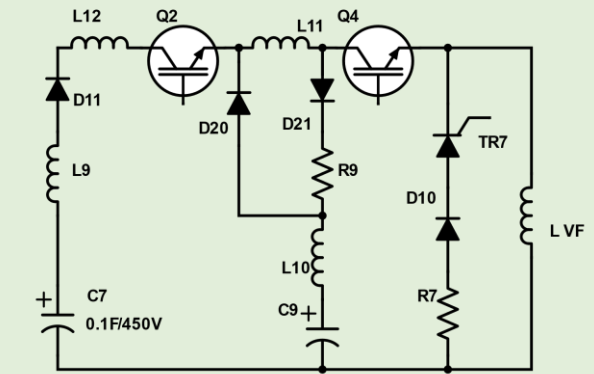
Now



Double swing, ± 10 kA



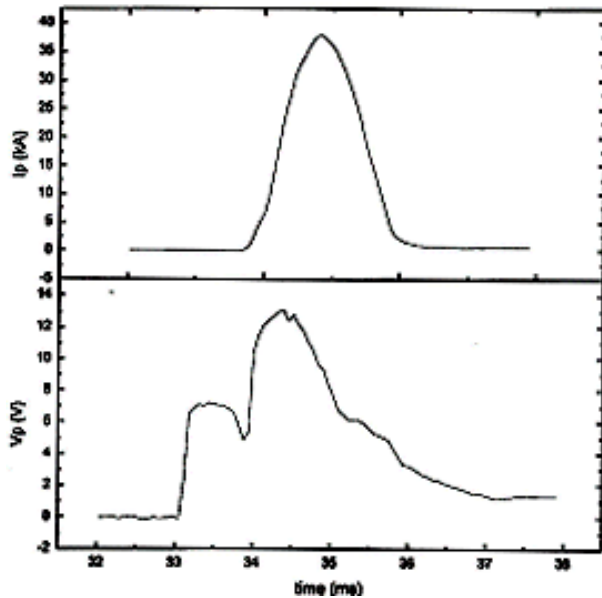
10 kA $\rightarrow$ 20 kA



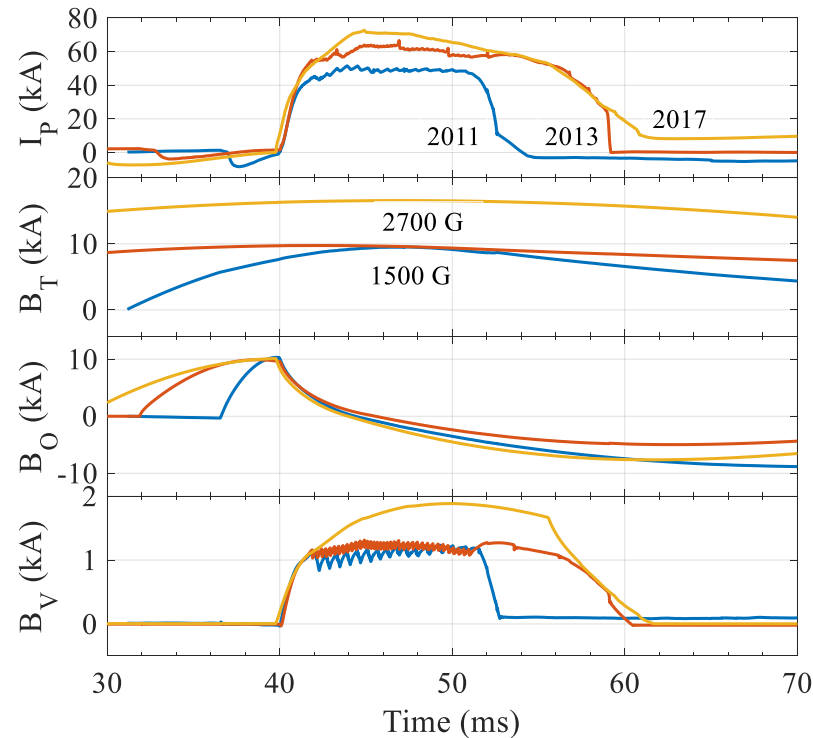
Current feedback

Discharge performance improved

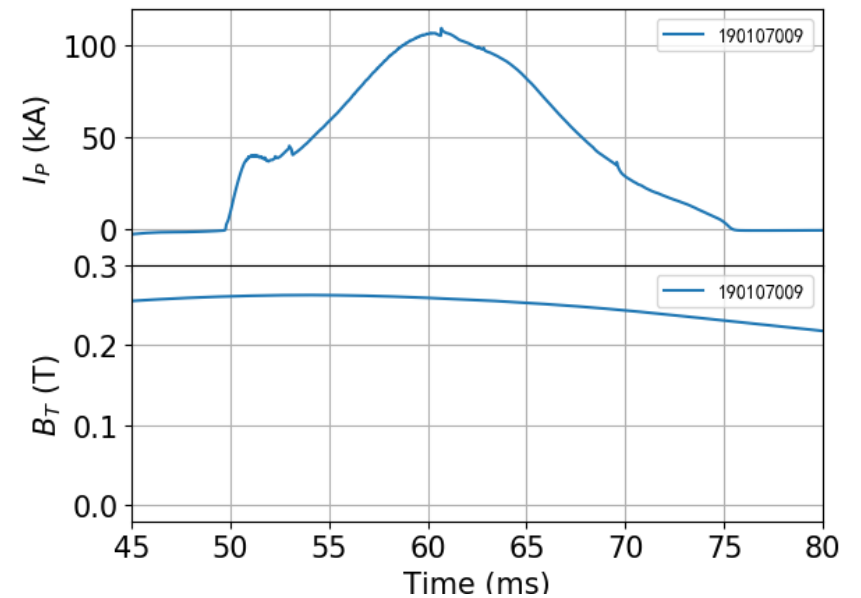
- I_p , B_T , pulse length: 2.2X, 1.8X, 2X design values



2002: 40 kA / 0.06 T, 2 ms

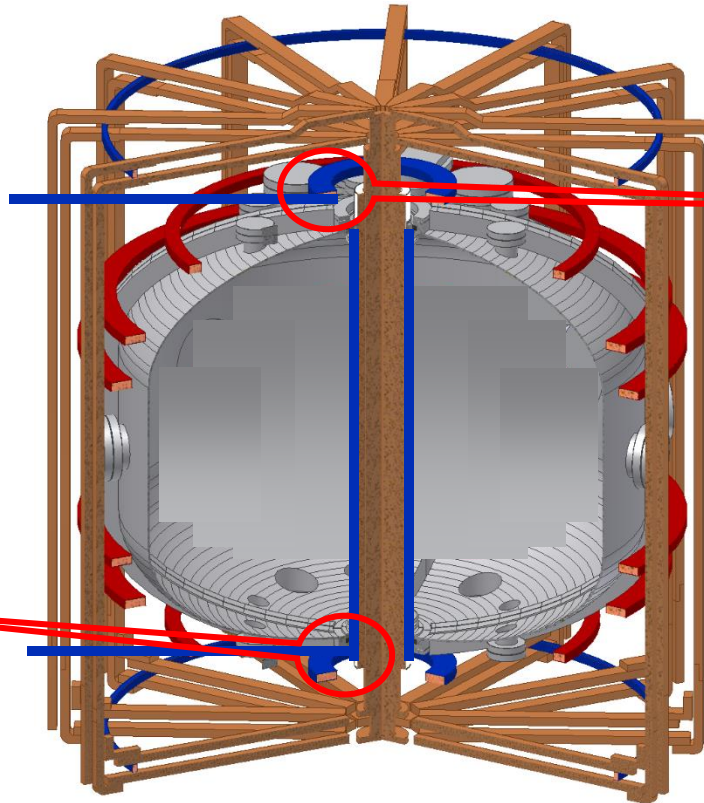


2017: 70 kA / 0.27 T, 20 ms



2019: 120 kA / 0.27 T

Two coil failures due to fatigue



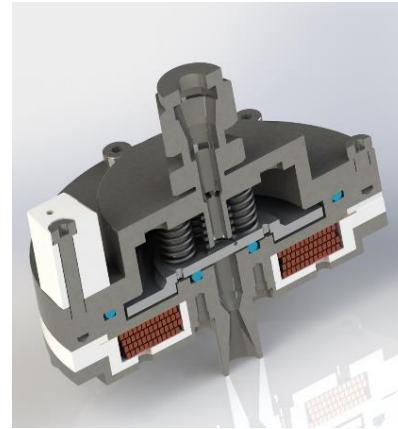
Dec. 2017, the bottom lead of CS

Sep. 2019, a lead of a top compensation coil

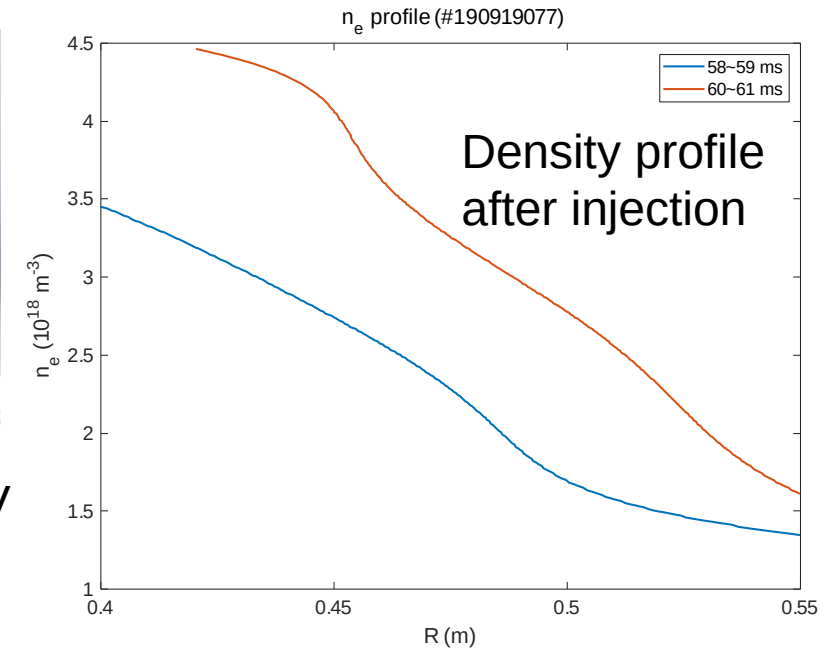
High field side SMBI supplement

Gas injected from HFS top at 1500 m/s

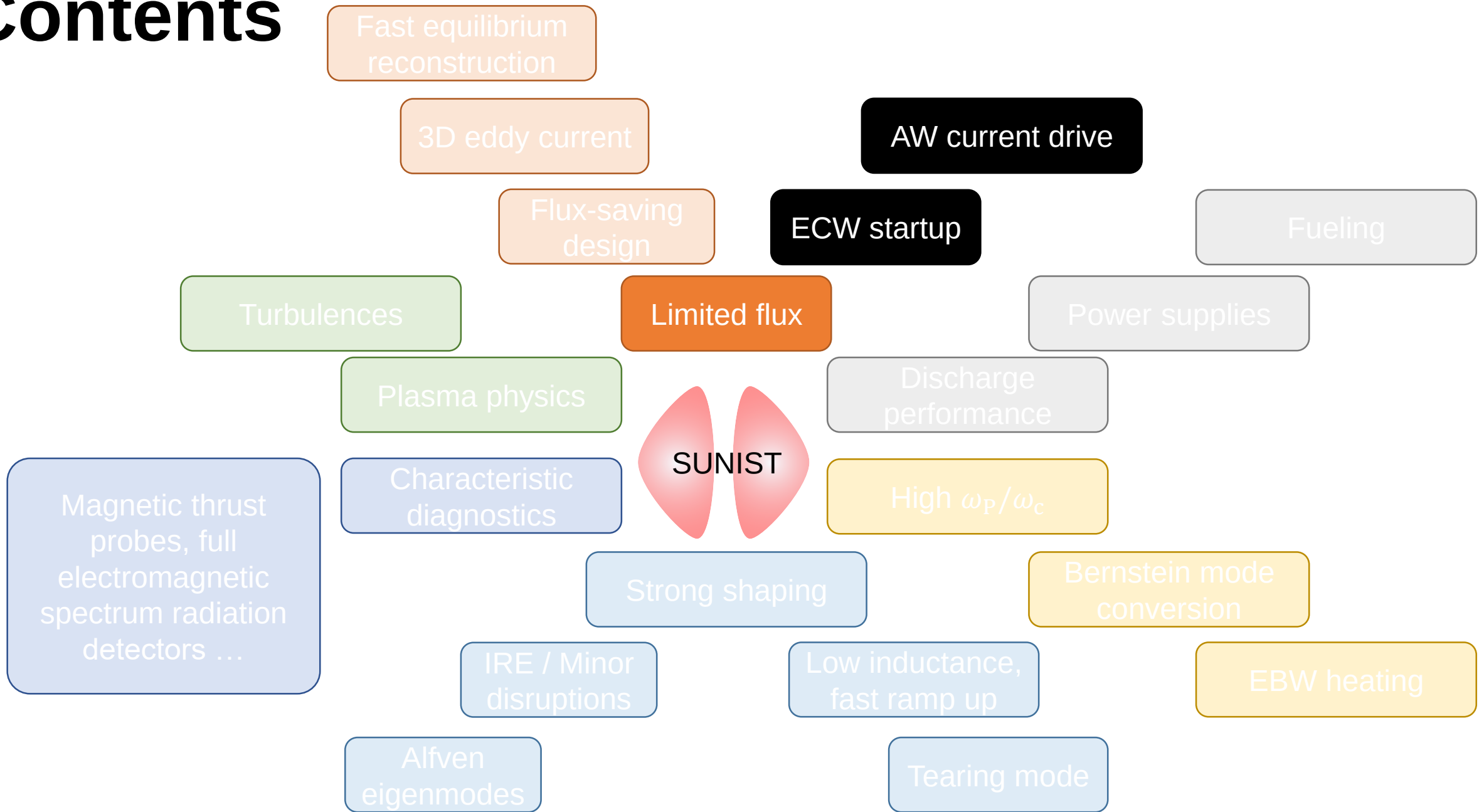
- A small vacuum proof valve with a Laval nozzle
 - Turn on time: 1 ms
 - Repeat interval: < 3 ms
 - Injection speed: 1500 m/s
 - Installed on the top of HFS
- A tiny, mid-plane HFS SMBI is being developed



The valve inside VV

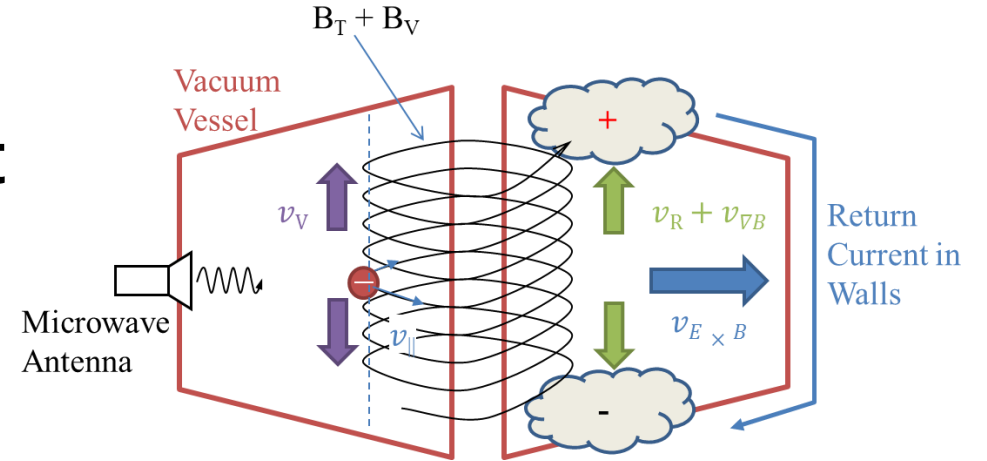
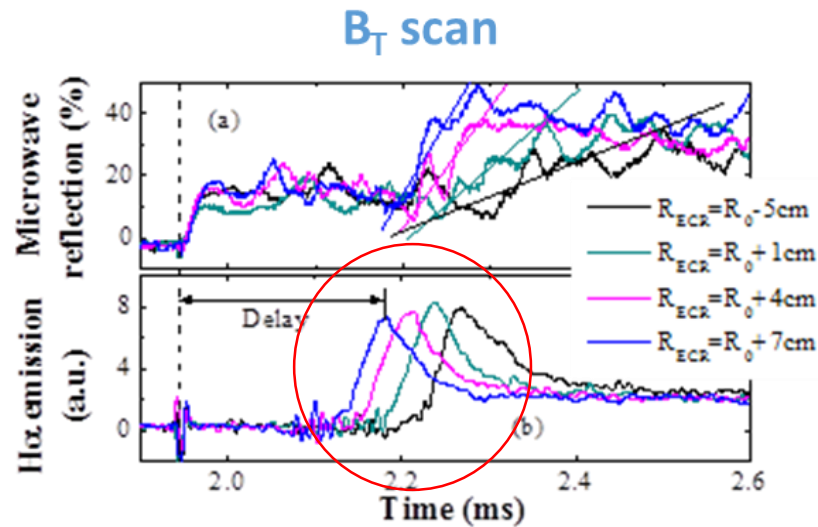
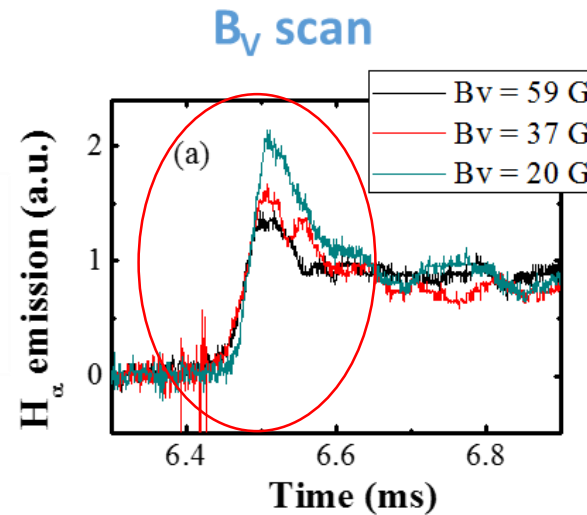
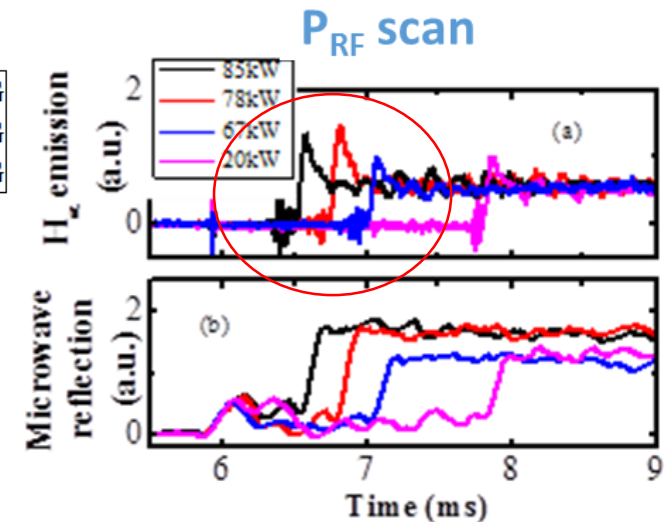


Contents



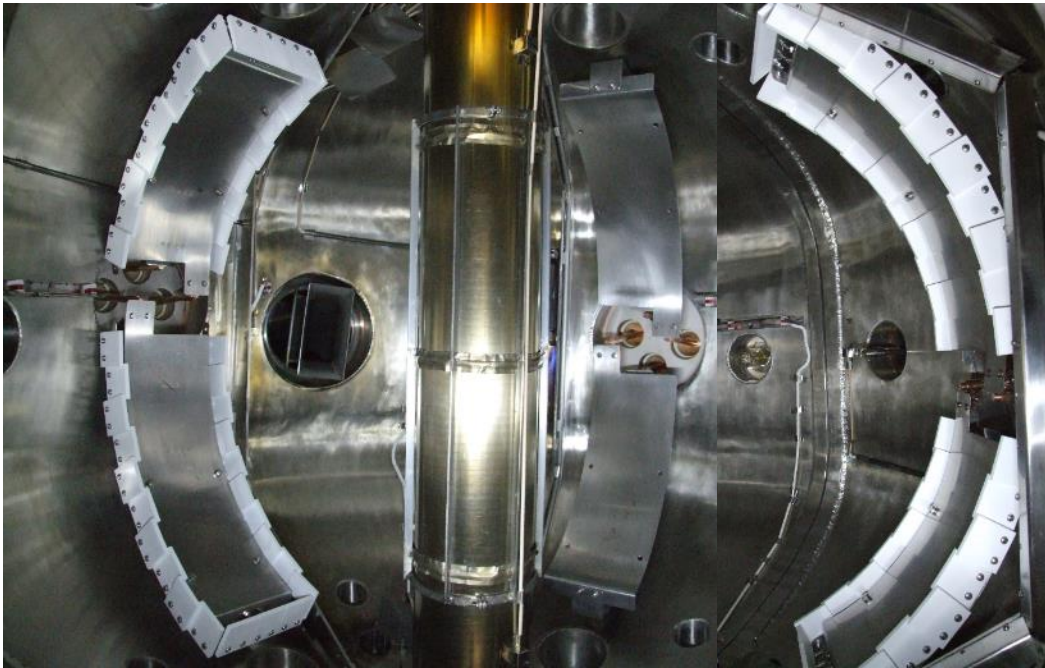
Electron cyclotron wave startup

- Due to low frequency (2.45 GHz), spikes of IP, ne are widely found at the beginning of discharges
 - Long wavelength and evanescent field caused this phenomenon



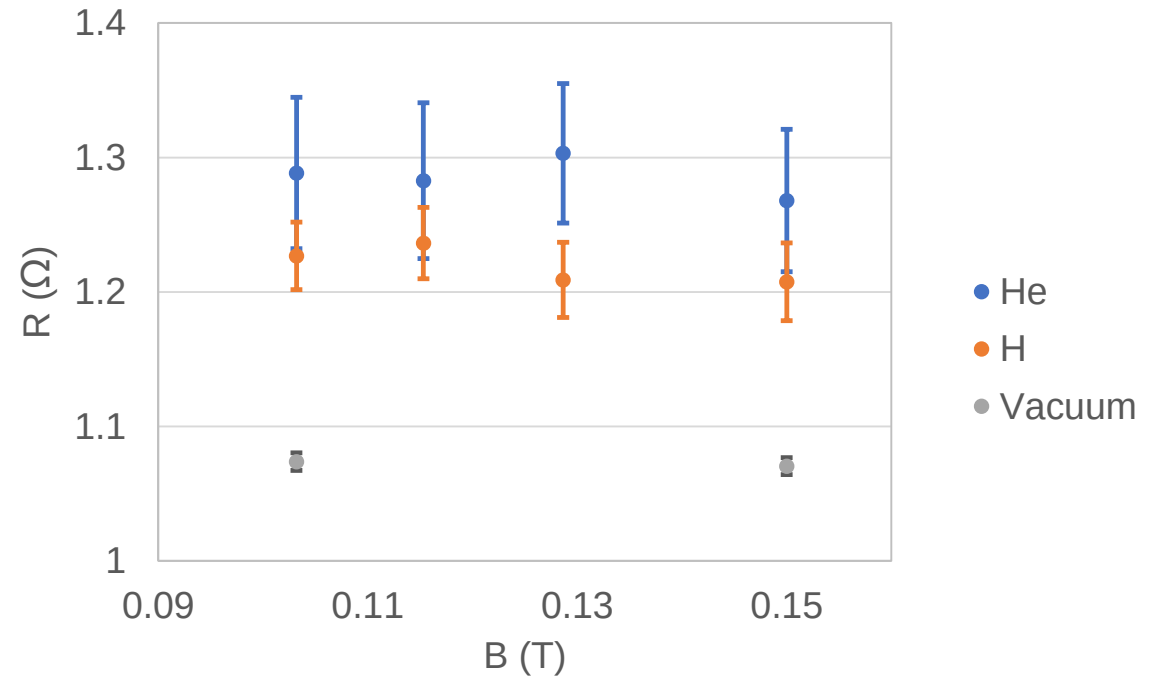
Alfven wave current drive

- 0.4 – 1 MHz, hard to couple, measured loading



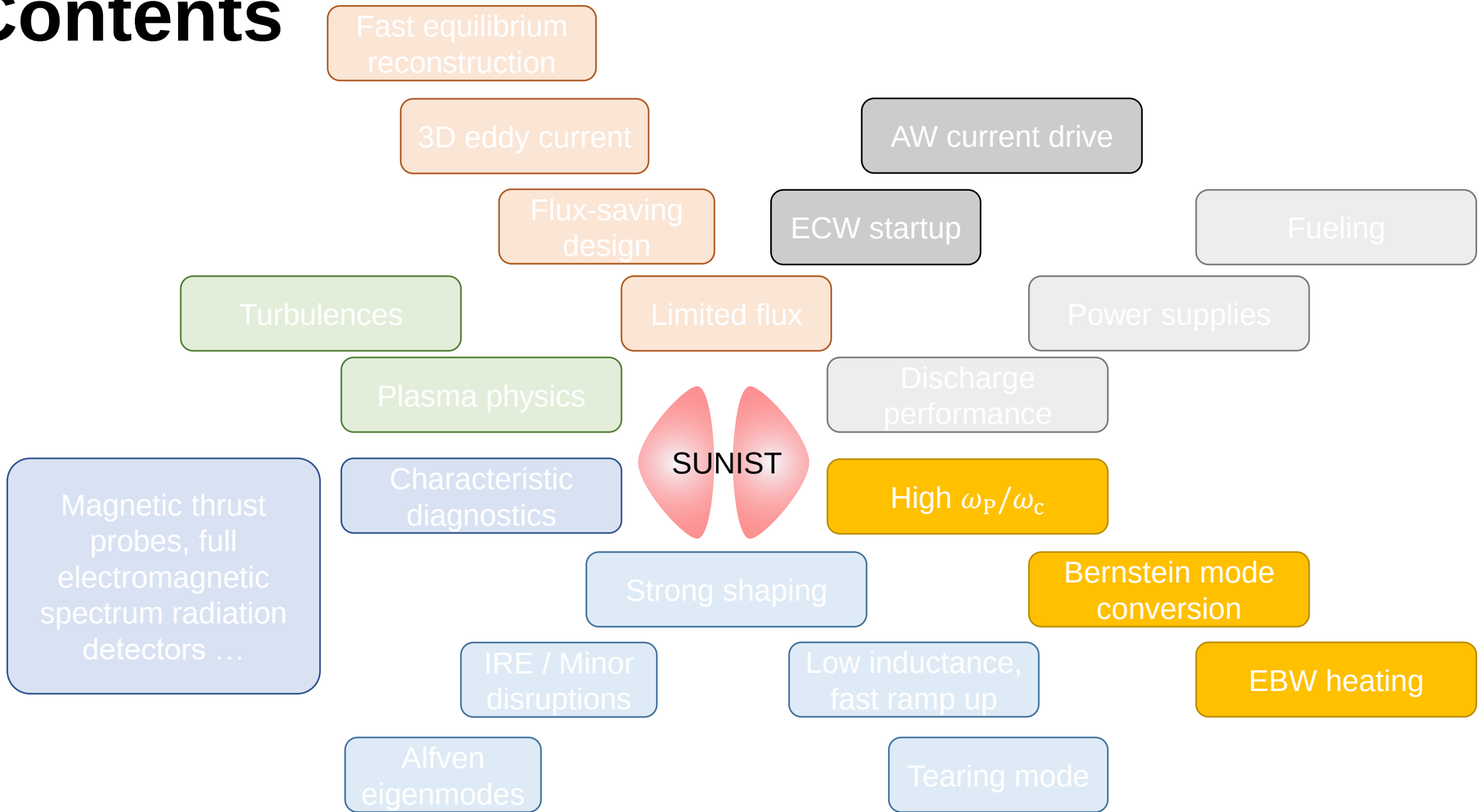
Alfven wave antennas inside VV

High quality boron nitride plates were loaned from PPPL
(by courtesy of Dr. R. Majeski, PPPL & DOE)



Loading resistance of the Alfven wave antennas

Contents



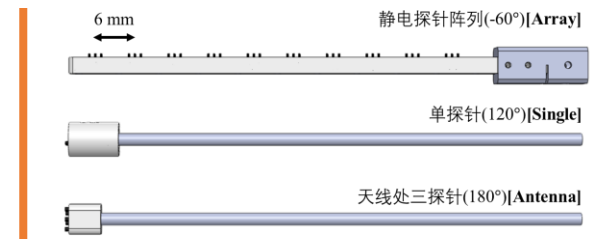
Mode conversion: XB or BX

- Ohmic plasmas of SUNIST are very over dense
 - $n_e > 5.8 \times 10^{18} \text{m}^{-3}$
 - Microwave 2.45 GHz, $n_{\text{cutoff}} \sim 7.4 \times 10^{16} \text{m}^{-3}$
- Comprehensive methods are used in EBE conversion ratio estimation: **62%** in SUNIST

Point	0	1	2	3	4	Sum
N_y	0.00	0.88	0.01	-0.88	0.01	
N_z	-0.01	0.01	-0.27	0.00	0.26	
s	37%	13%	18%	14%	19%	100%
η	222 Ω	1335 Ω	246 Ω	1279 Ω	249 Ω	
Couple	93%	69%	96%	70%	96%	
I_X	100%	100%	89%	99%	90%	
I_O	0%	0%	11%	1%	10%	
MC	92%	25%	79%	7%	80%	
Total	32%	2%	13%	1%	14%	62%

Detailed in Dr. WANG Shouzhi's talk

LP arrays



Full wave calculation

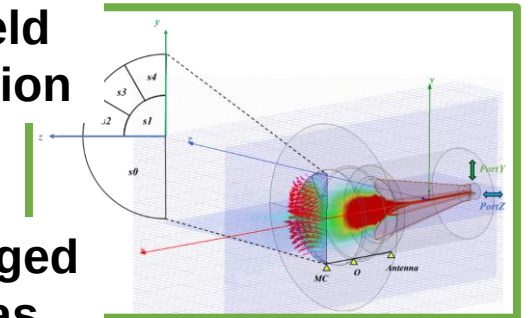
$$\partial F_k / \partial \xi = A_k \cdot F_k$$

$$\xi = k_0 x$$

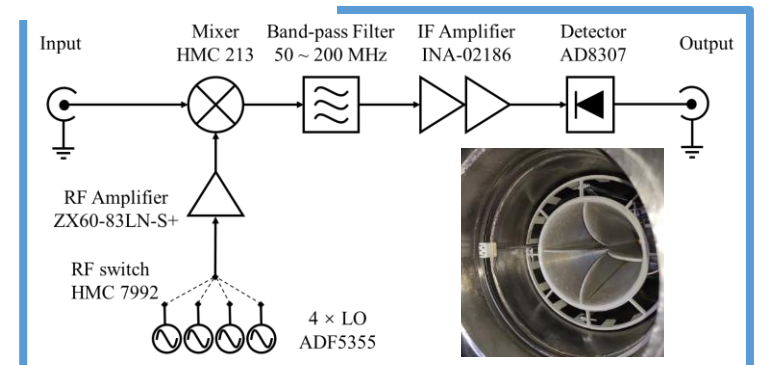
$$F_k = (E_x, E_y, E_z, i\chi E'_x, cB_z, -cB_y)^T$$

$$A = i \begin{bmatrix} 0 & 0 & 0 & -\chi^{-1} & 0 & 0 \\ N_y & 0 & 0 & 0 & 1 & 0 \\ N_z & 0 & 0 & 0 & 0 & 1 \\ \epsilon_{xx} & \epsilon_{xy} & 0 & 0 & N_y & N_z \\ -\epsilon_{xy} & \epsilon_{xx} - N_z^2 & N_y N_z & 0 & 0 & 0 \\ 0 & N_y N_z & \epsilon_{zz} - N_y^2 & 0 & 0 & 0 \end{bmatrix}$$

Near field simulation

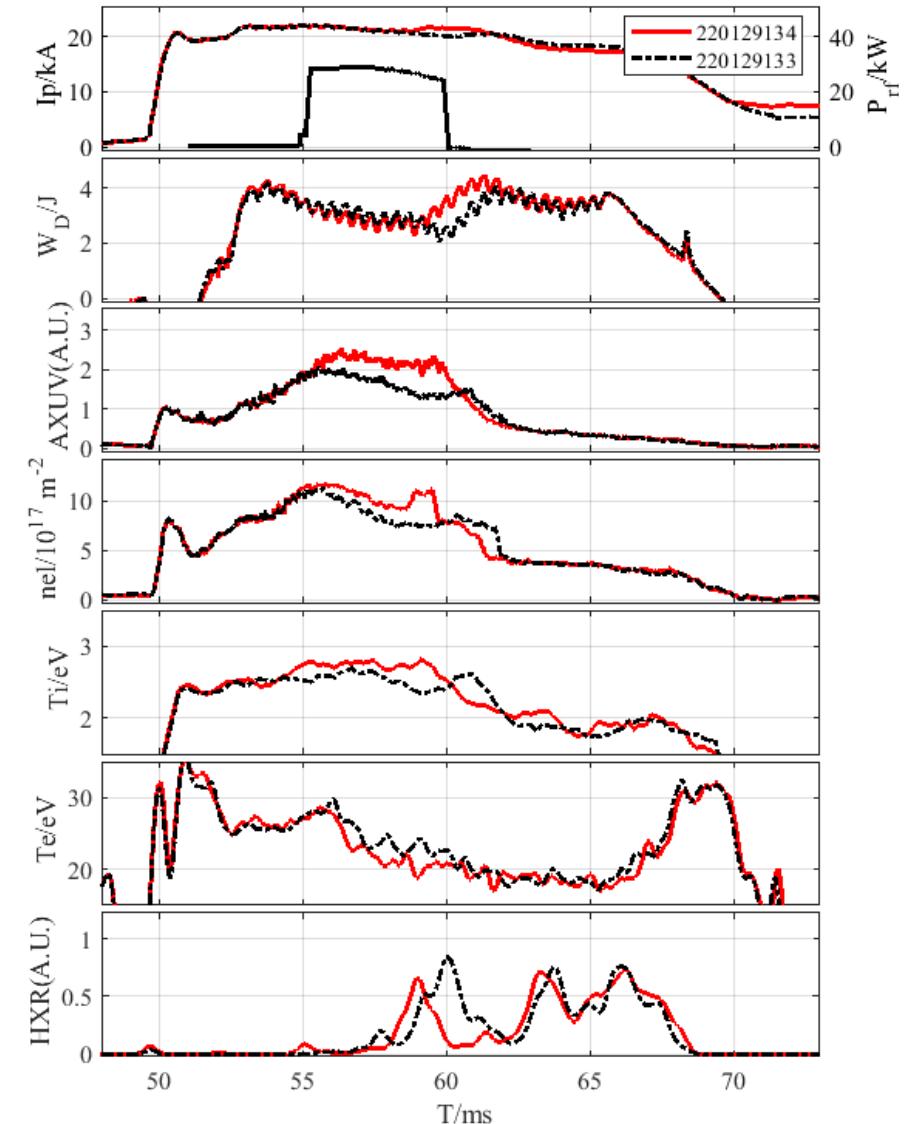


Quad ridged horn meas.

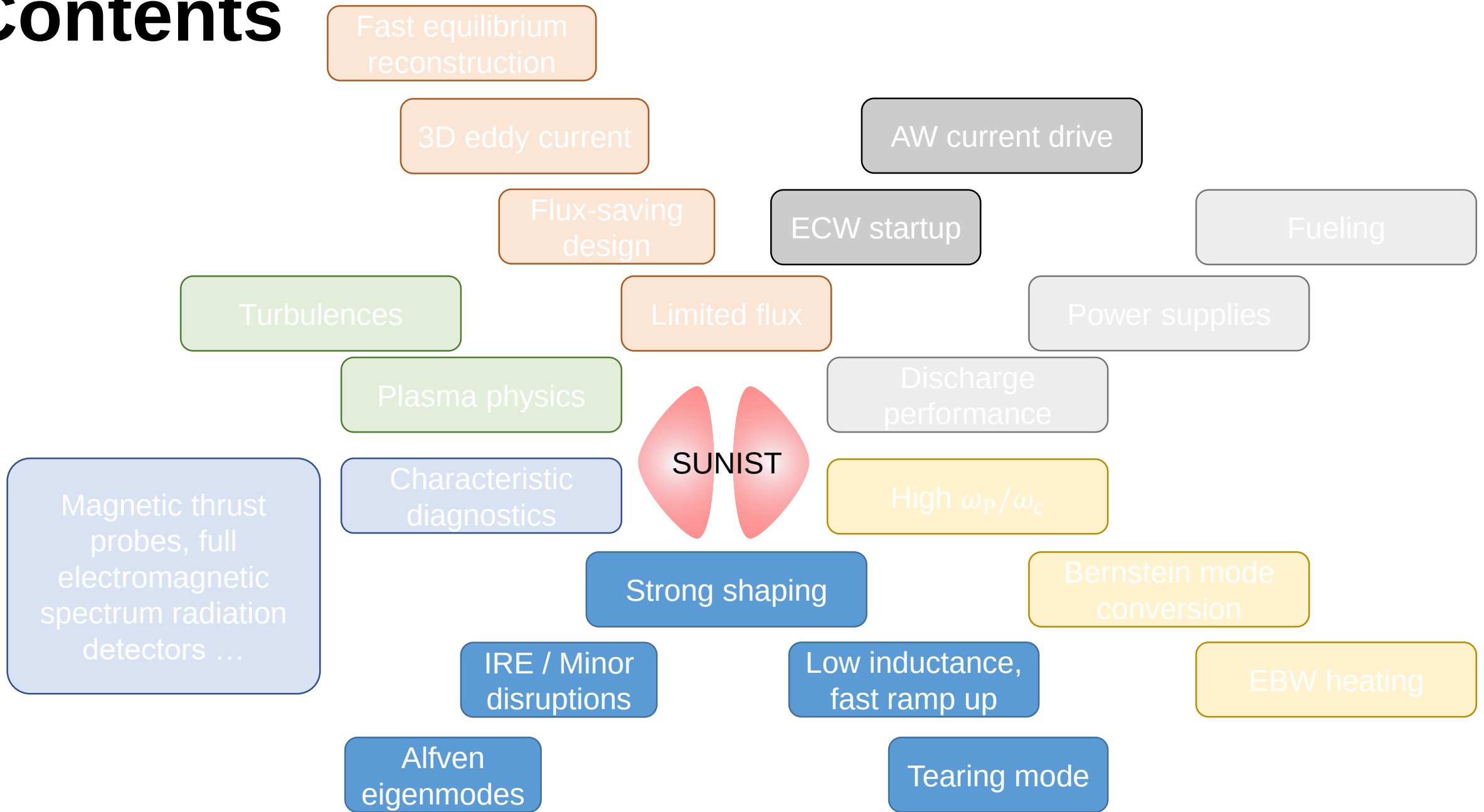


EBW heating in ohmic plasmas

- **Experimental apparatus**
 - 2.45 GHz 30 kW microwave
 - FX-B mode conversion
- **Results**
 - Parametric processes and energetic electrons absorption
 - → Wave energy mainly deposited at periphery
- **Hard to heat core plasmas**

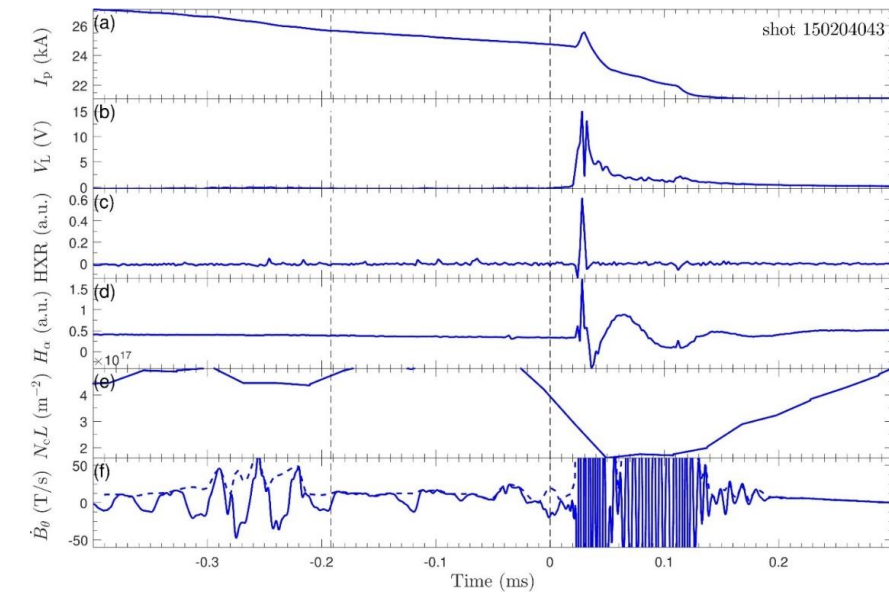


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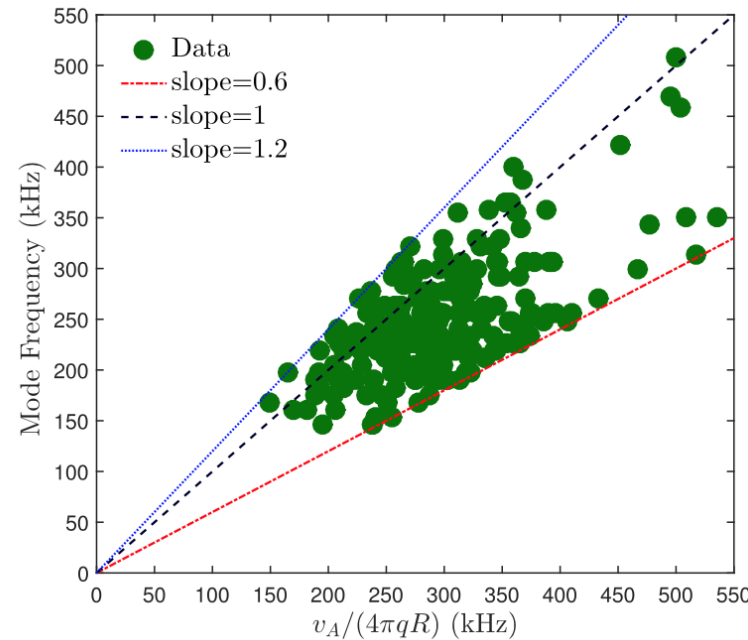


IRE (internal reconnection event) and minor disruptions

- High frequency (>200 kHz) magnetic perturbations found in both IREs and minor disruptions
- But only in minor disruptions exhibit Alfvénic properties, runaway electrons?

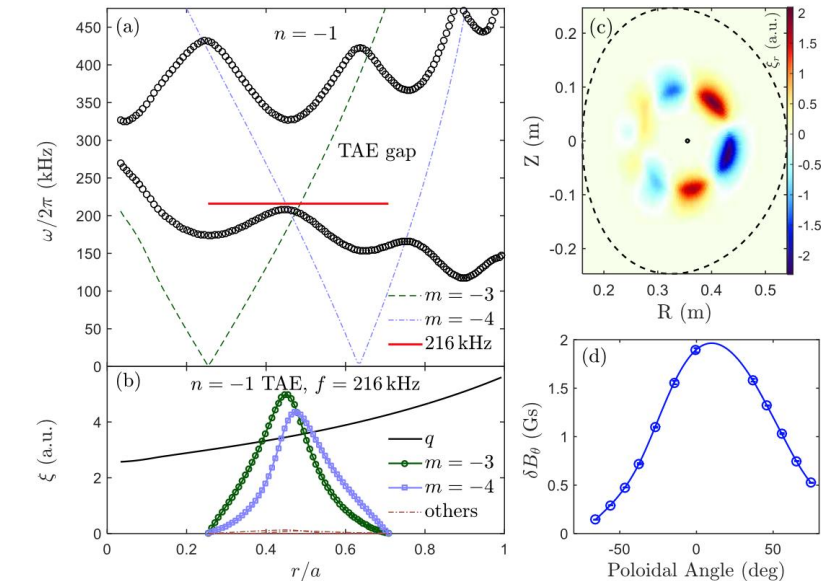


High dB often observed in minor disruptions



dB exhibits Alfvénic properties

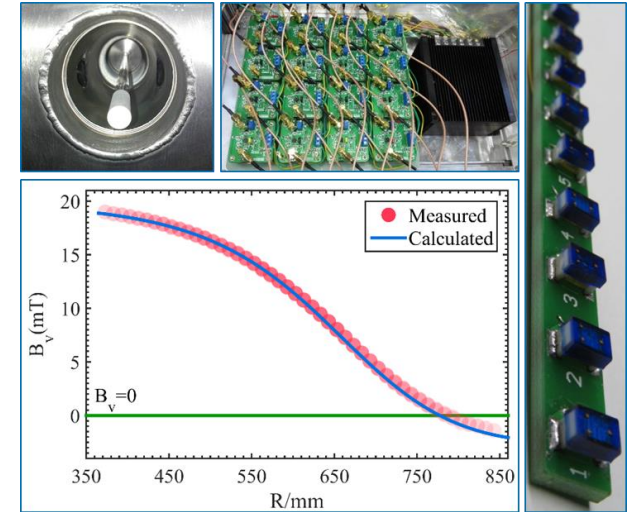
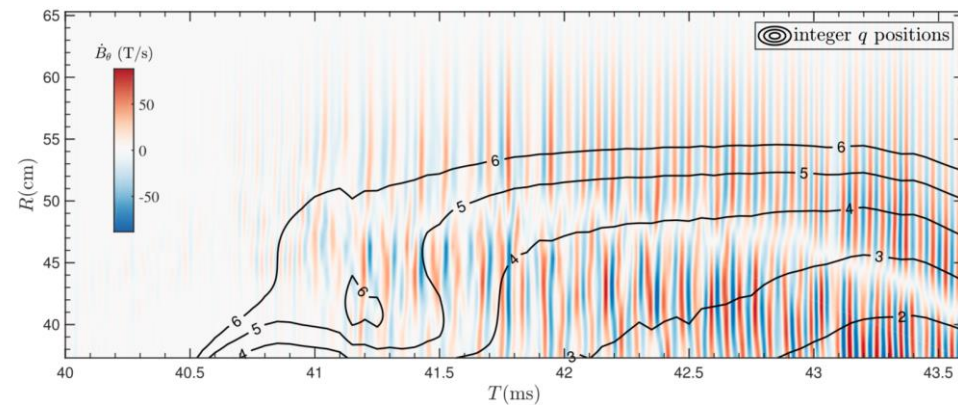
Detailed in Miss SU Pengjuan's poster



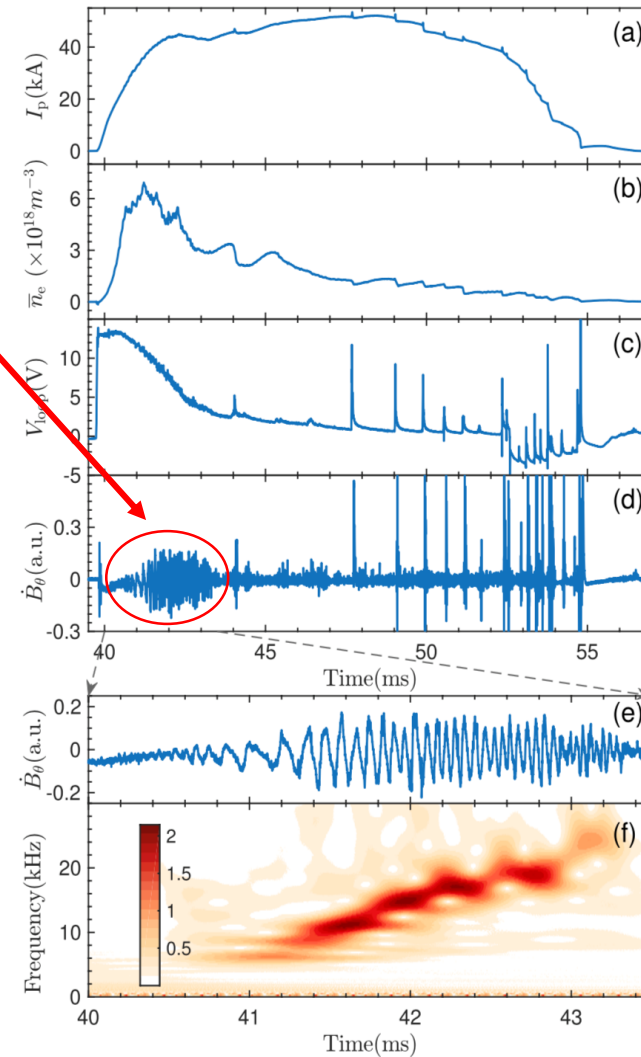
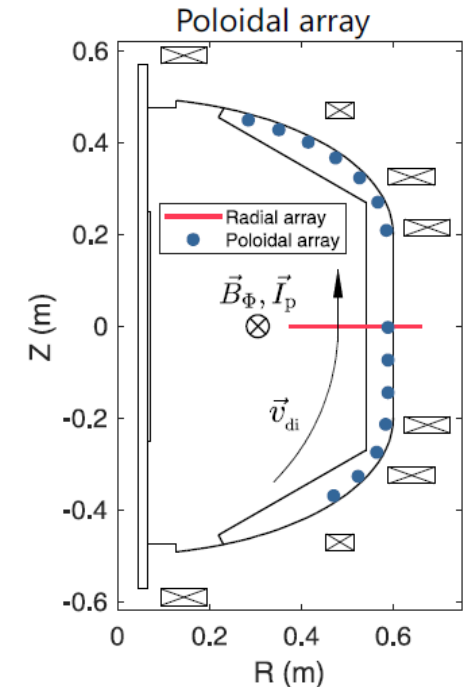
Calculations seems to be agree with experiments

Tearing modes

- Ramp up rate up to 30 MA/s
 - Tearing modes often excited
- An internal radial mag. probes array clearly measured the structure
 - Its effects on confinement studied

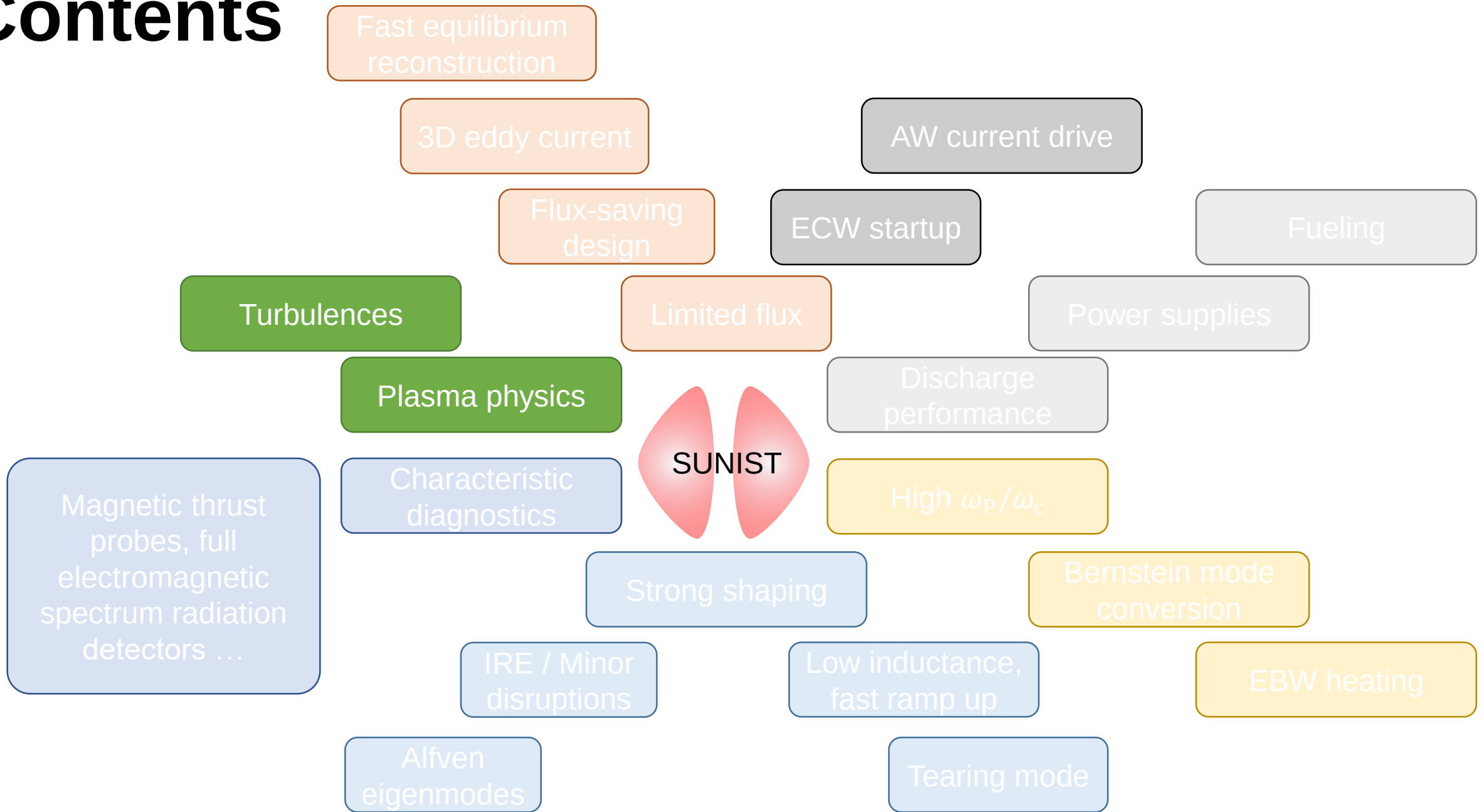


Temporal-spatial structure of the tearing mode



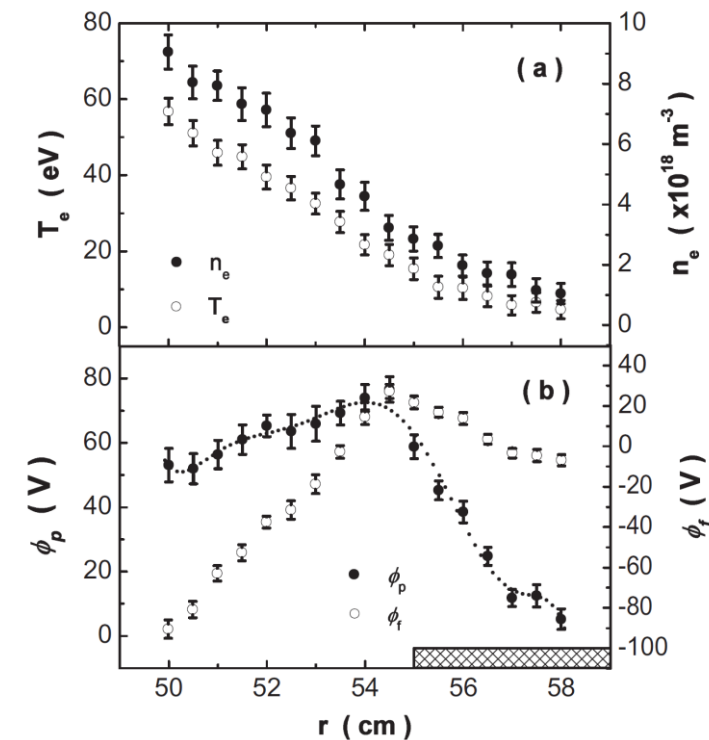
internal radial mag. probes array

Contents

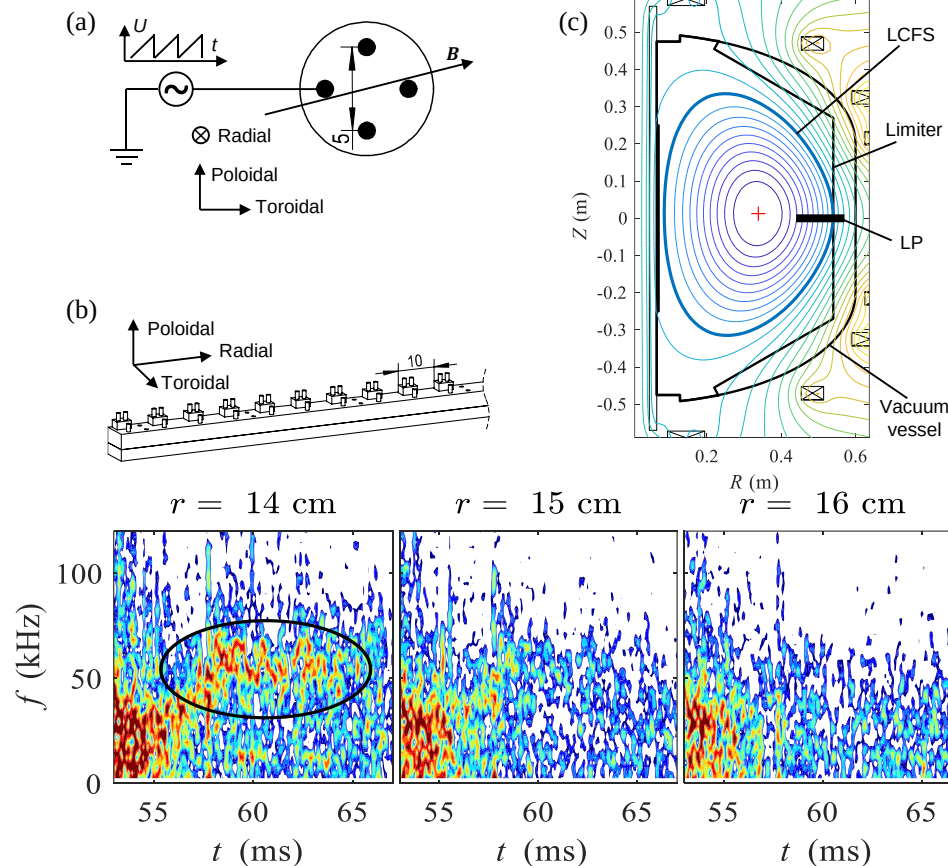


Turbulence studies

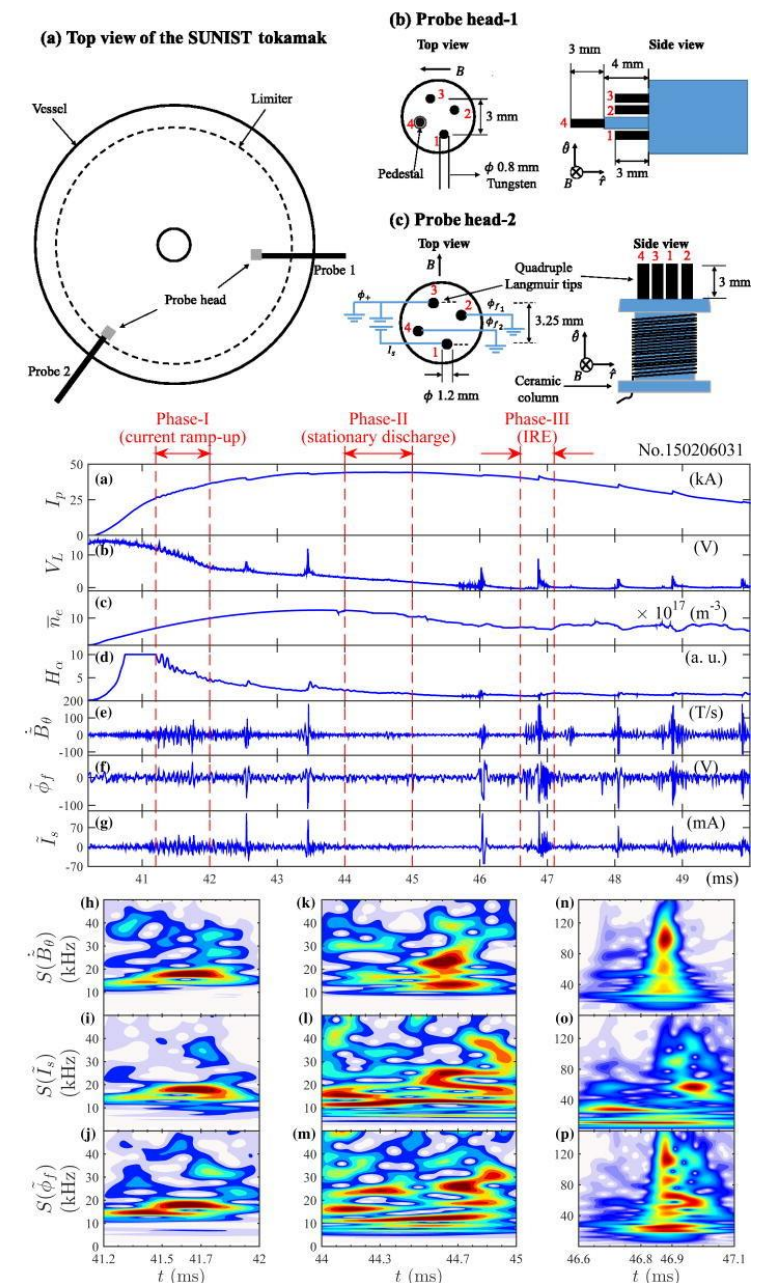
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DOI: 10.1063/1.4977450
DOI: 10.1088/2058-6272/ac85a3
DOI: 10.1088/0256-307X/34/2/025201



Edge parameters

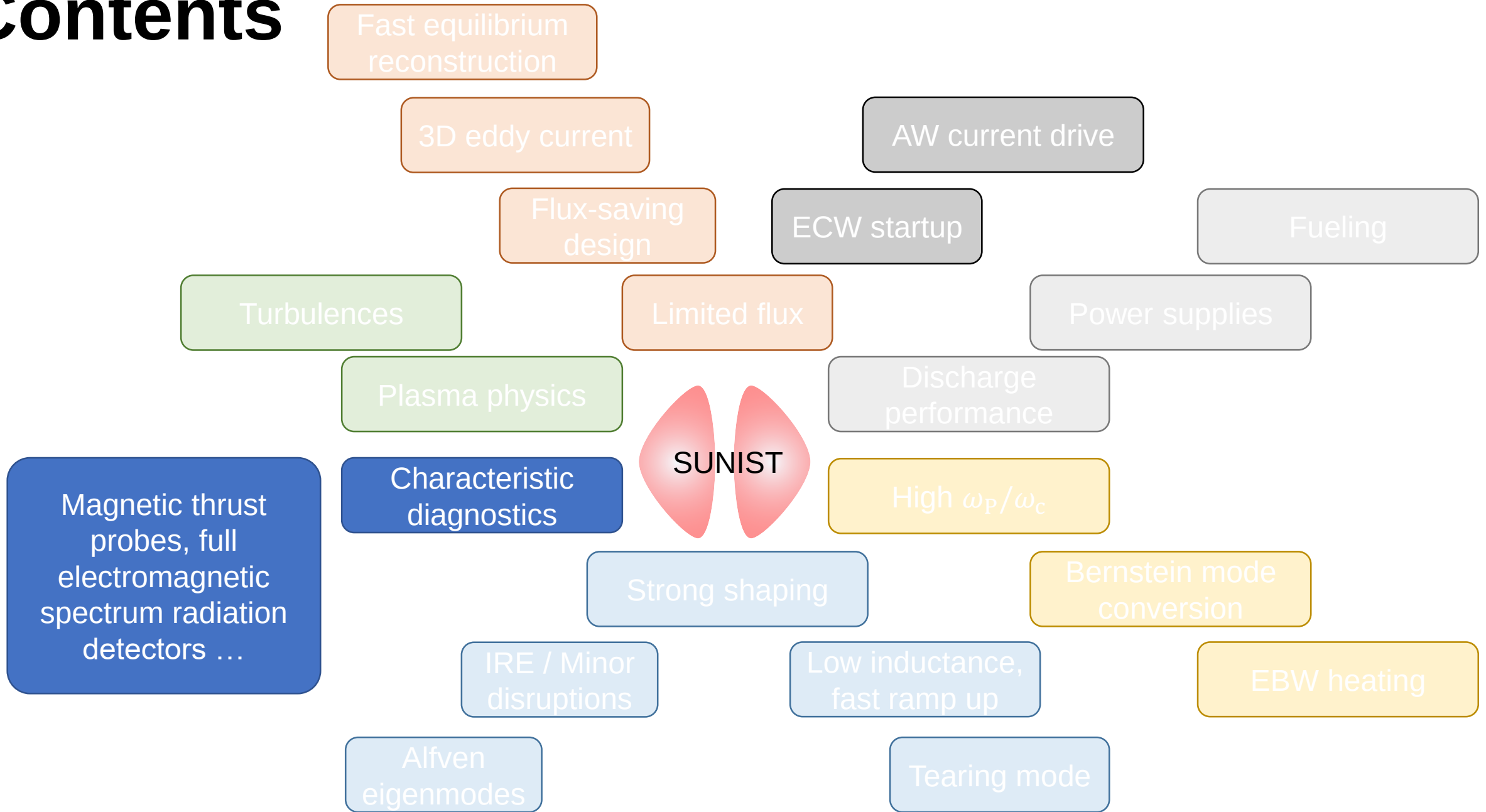


Quasi-coherent mode in core plasmas

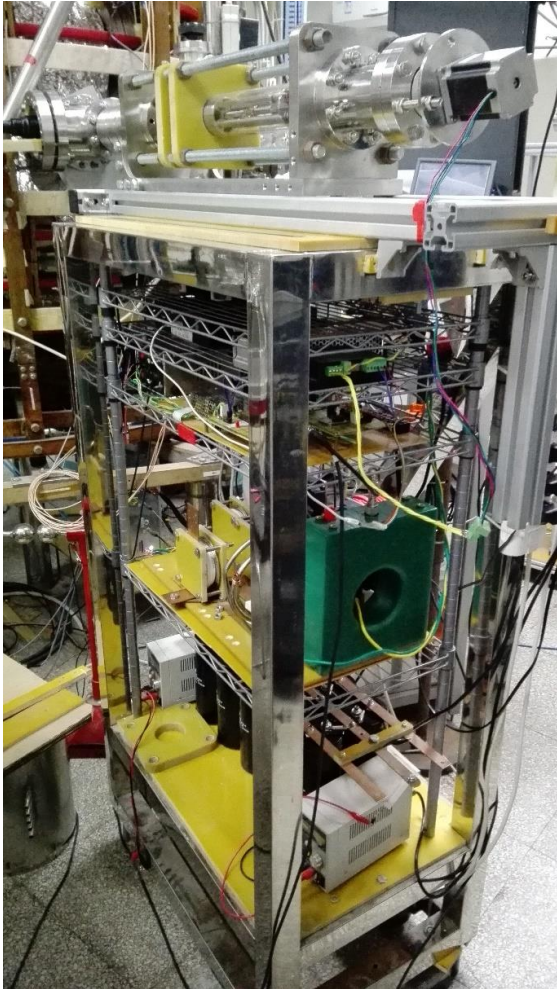


Energy transfer between dB and dI_s

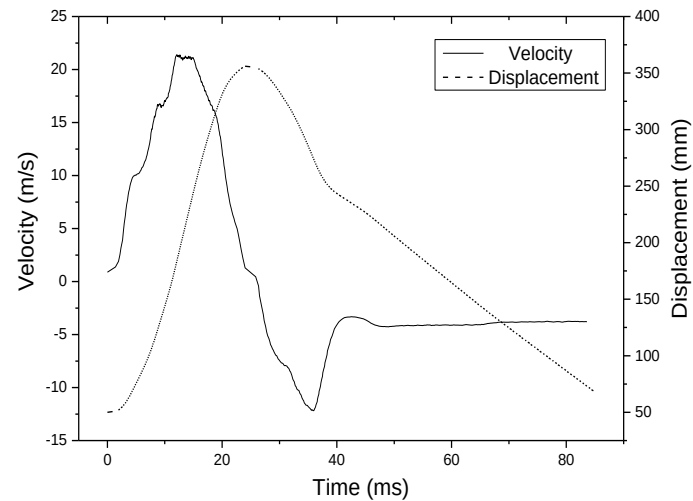
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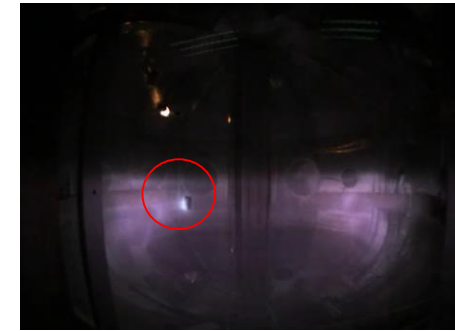
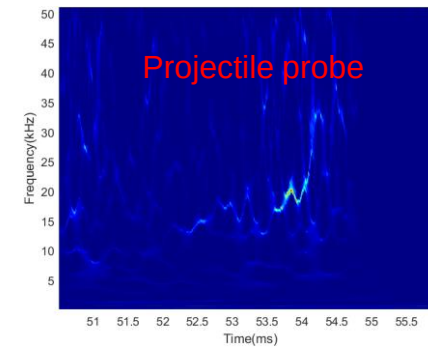
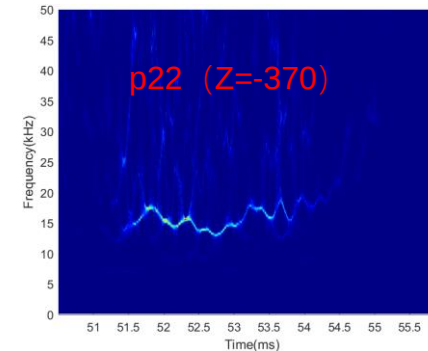
Magnetic thrust probes



- Left, horizontal, reciprocating probe up to 20 m/s
- Right, vertical, floating probe



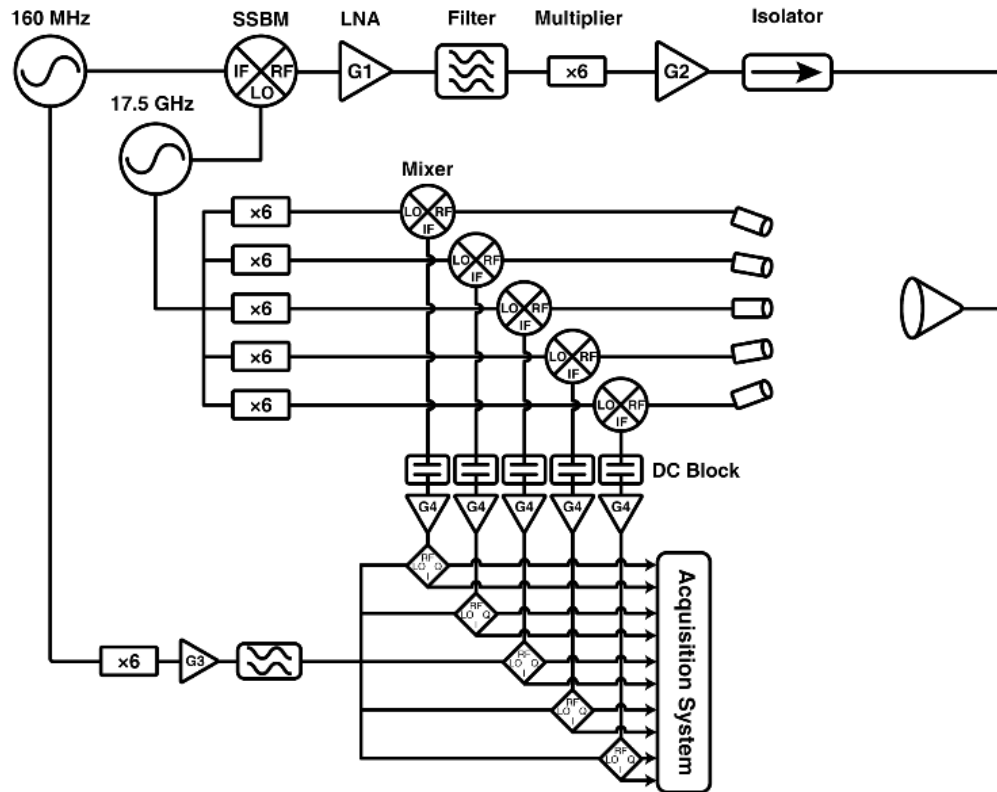
Speed and position vs time of the horizontal probe



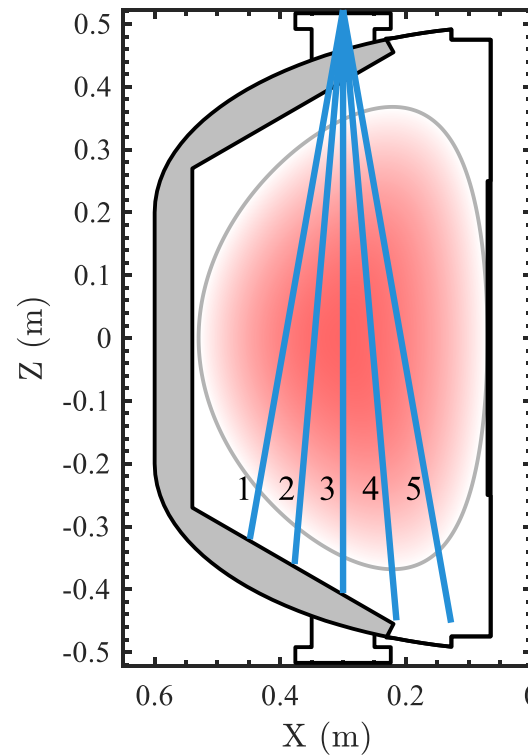
Detailed in Mr CHANG Tingzhi's poster

Very fast, very sensitive interferometers

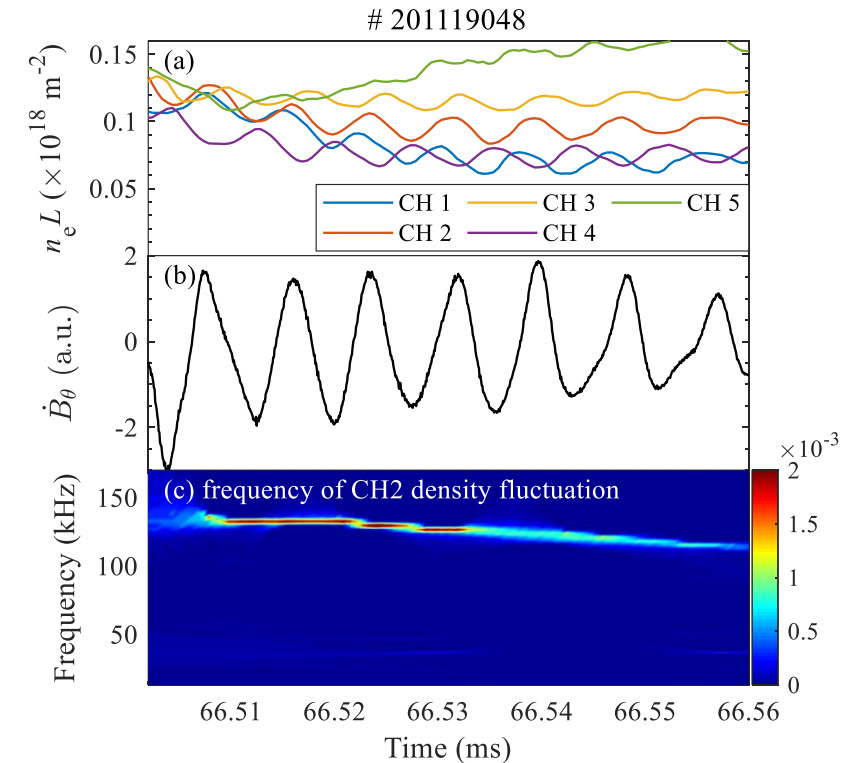
- 105 GHz, 0.5 μs , $1 \times 10^{15} \text{ m}^{-2}$ resolution



Block diagram of the five-channel interferometer system

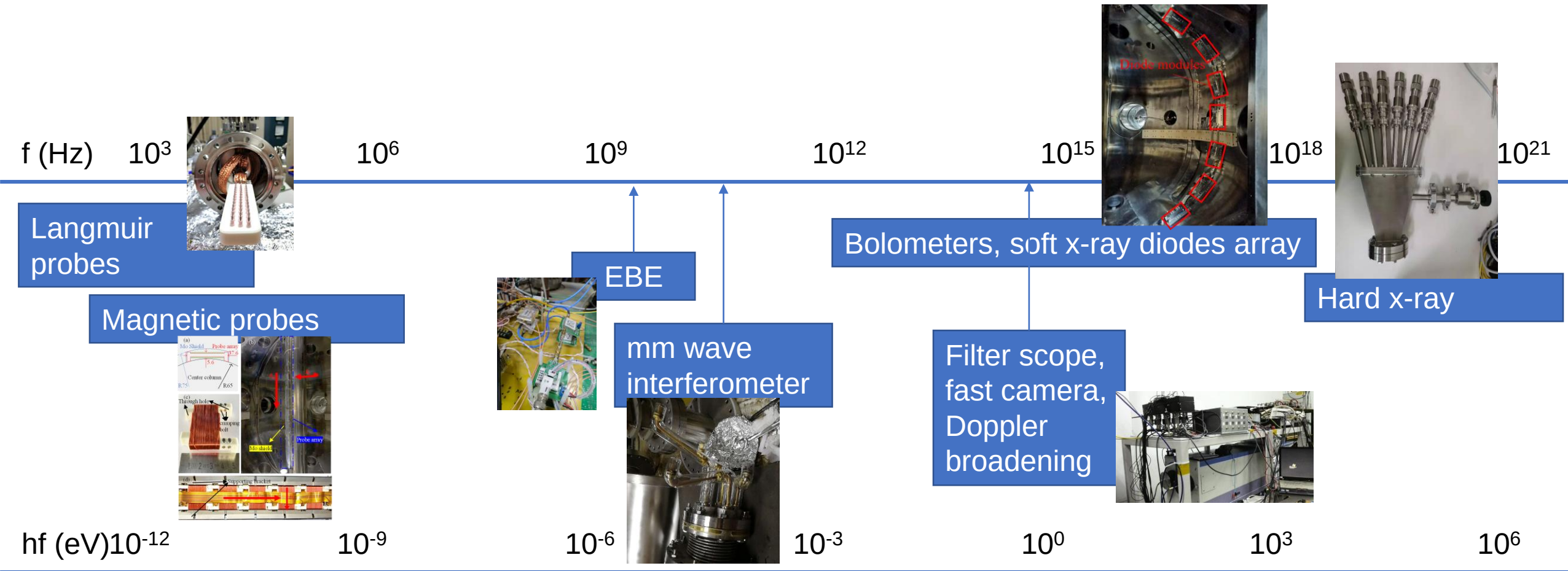


The optical paths of the five measurement chords



Density fluctuation caused by Alfvén waves can be measured

Full electromagnetic spectrum utilized



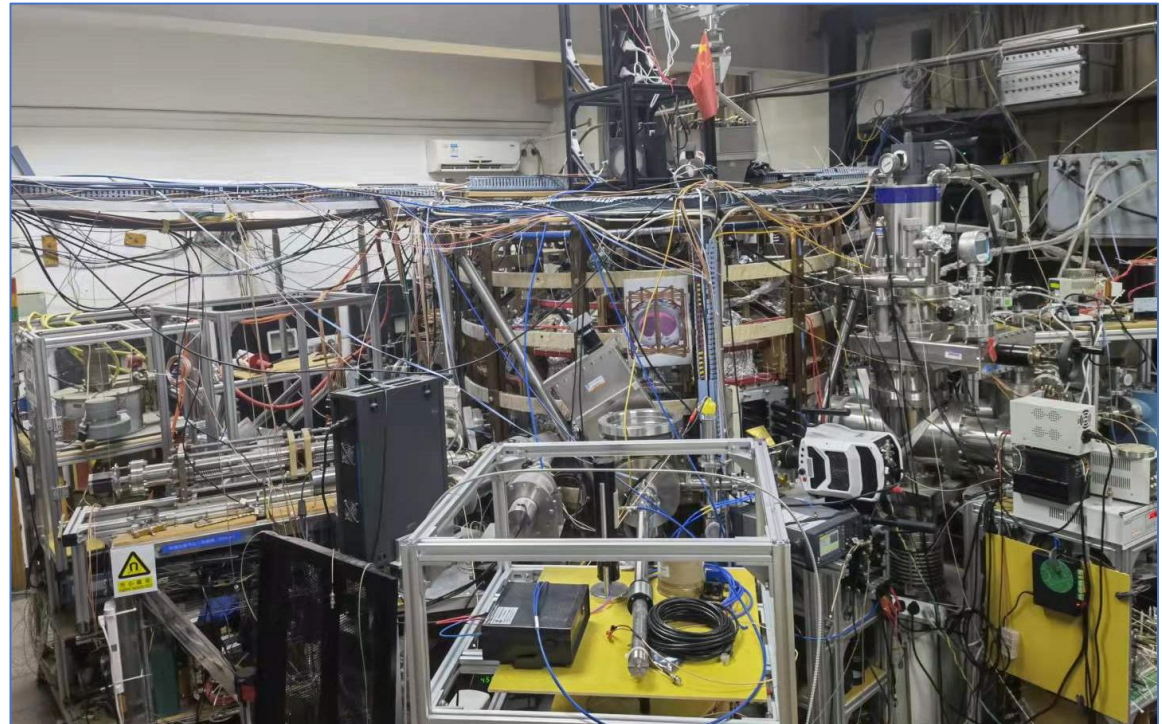
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 DOI: 10.1063/5.0043667

Future plans

- SUNIST will continue running, platform for new ideas and education



SUNIST at 2002



SUNIST at 2022

Summary

Fast equilibrium
reconstruction

3D eddy current

AW current drive

Flux-saving
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SUNIST

Characteristic
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High ω_P/ω_c

Strong shaping

Bernstein mode
conversion

Magnetic thrust
probes, full
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spectrum radiation
detectors ...

IRE / Minor
disruptions

Low inductance,
fast ramp up

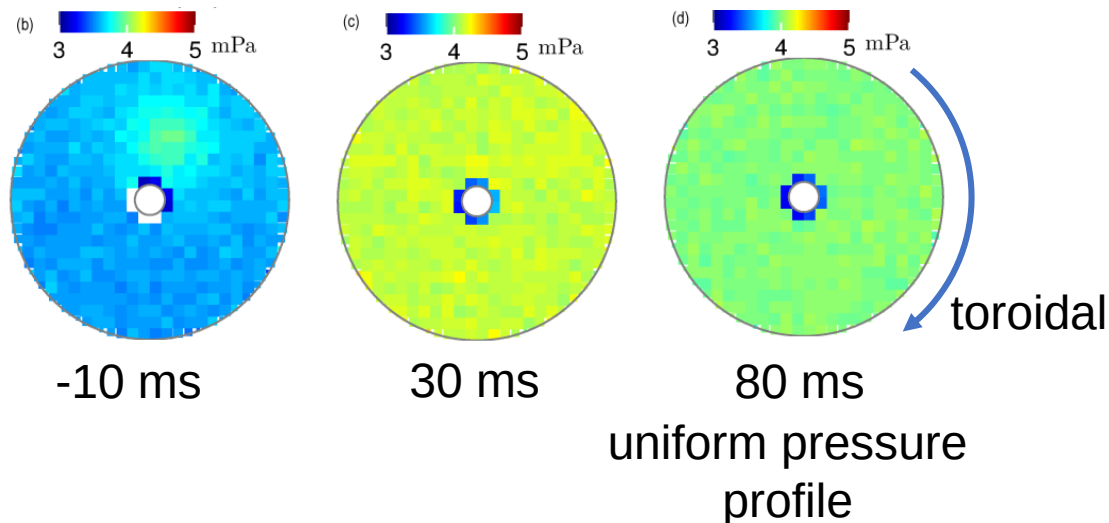
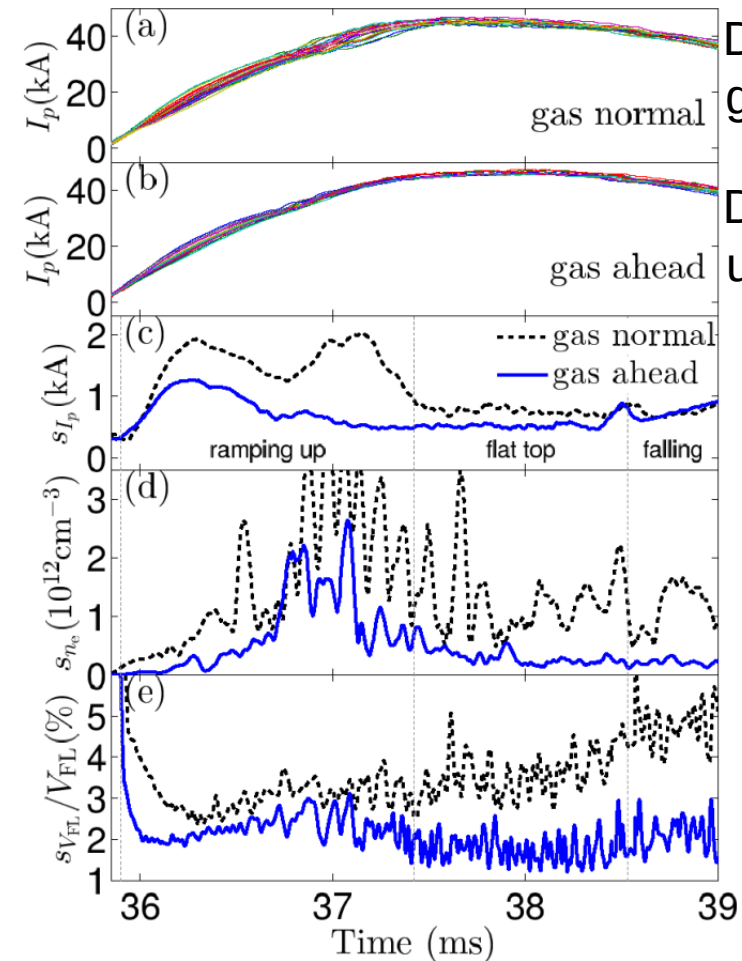
EBW heating

Alfven
eigenmodes

Tearing mode

Discharge v.s. gas puffing timing

- About 80 ms is needed to form a uniform pressure profile
 - Repeatability of discharges can be improved if discharges start at a uniform pressure profile



Discharges when gas puffing stops

Discharges when uniform pressure profile formed

Wall conditioning

- Molybdenum limiters
- Baking < 373 K
- Glow discharge: H_2 , He
- Siliconization was test several times before 2008