Ion Cyclotron Range of Frequency Power on the way to DEMO

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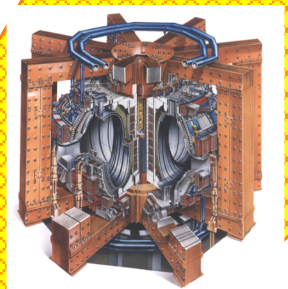
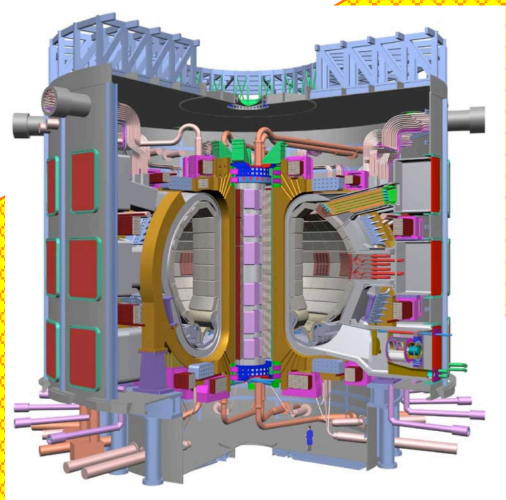
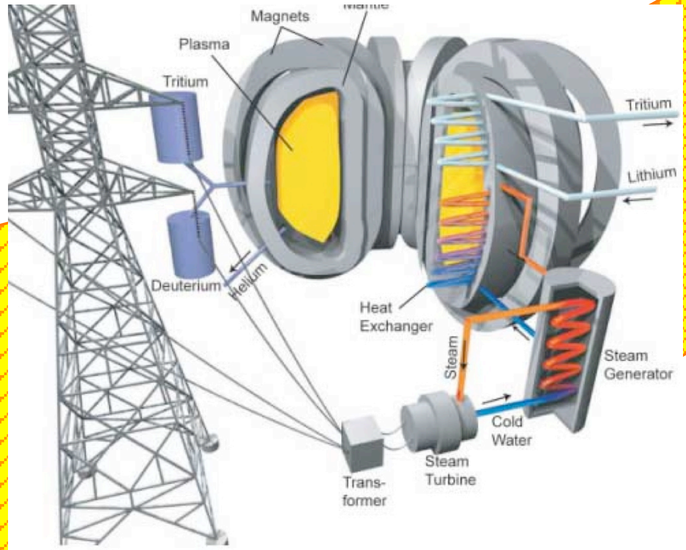
the way from present machines to ITER to DEMO

changes for
the "auxiliary" systems







Artists impression of a fusion power plant (Courtesy: EFDA)

- **use**
  - **from heating to control**
- **environment**
  - **more and more neutrons**
- **requirements**
  - **from flexibility to economics**

1.Use: from dominant heating to control

- **Present**
  - dominant heating, all the time; some current drive
  - control, mostly for experimental flexibility and demonstration purposes
    - density profile, influencing impurity accumulation
    - NTM
    - current *profile*
    - rotation
- **ITER**
  - heating to ignition, typically 100 s from 300 s
  - control, still with high flexibility
    - burn control
    - current profile control
- **DEMO**
  - heating to ignition, necessary but only a minimal fraction of the time
  - maybe *current drive*, most of the time
  - multiple control, but as simple as possible

Consequence: system must be able to do more than heating

2. Environment: more and more neutrons

- **present**
  - little or no neutrons
  - manual maintenance, partially remote
- **ITER**
  - neutrons, radiation: biological aspects, some technical aspects
  - larger dimensions → larger distances
  - remote maintenance
- **DEMO**
  - neutrons, radiation: biological + materials and waste aspects
  - *T breeding essential*
  - scheduled remote maintenance, as short as possible

Consequence: systems near machine must be simple and with small penetration through blanket

3. Requirements: from flexibility to economics

- **Present**
  - multiple systems, flexibility more important than capital cost
  - cost of operation (electricity) non-issue
  - availability (the proportion of time a system is in a functioning condition) important but not essential
  - reliability (the ability of a system or component to perform its required functions under stated conditions for a specified period of time) important but not essential

- **ITER**
  - capital cost becomes important
  - operating cost still not an important issue
  - availability and reliability important

- **DEMO**
  - capital cost important
  - operating cost essential

Consequence: system must be cheap, reliable, high efficiency

Present to ITER

- use: heating → heating + control
- environment: neutrons, some remote → full remote
- requirements: economics more important but not dominant

• changes for ITER

are mostly of a quantitative nature,

we are already close to needed parameters

with high voltage for long pulse

the main issue

Typical values for ICRF systems comparison

- **ASDEX Upgrade**

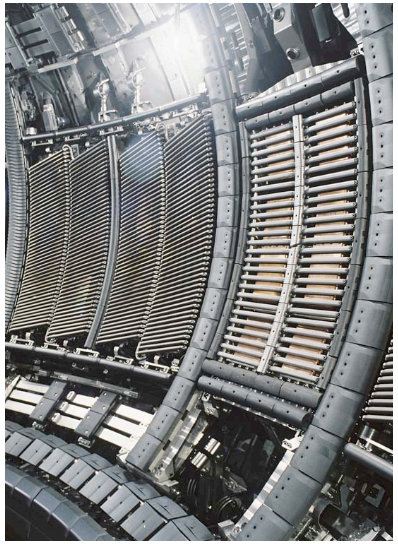
7.2 MW launched
8 MW installed
30-60 (120) MHz
10s
four 4x1 2strap antenna, 1 m^2
2 MW/m^2, 30 kV

- **JET, A2**

22 MW launched
32 MW installed
23-57 MHz
10s
four 4x1 2strap antenna, 2.9 m^2
1 MW/m^2, 30 kV

- **JET ILA**

4 MW launched
8 MW installed
30-49 (55) MHz
10s
one 2x2 2strap antenna, 0.9 m^2
8 MW/m^2 (design), 45 kV (achieved)



Generators

KSTAR, 1.9 MW, 300s

Matching

LHD, liquid stub

Antenna

JET, ILA

- **ITER**

20 MW into plasma
24 MW installed, VSWR =1.5
(35) 40-55 (65) MHz
1000s
one or two 4x2 3strap antenna, 3.85 m^2
5.2 - 2.6 MW/m^2, 40 kV

Generators

2 x 1.5 MW units, 1000s

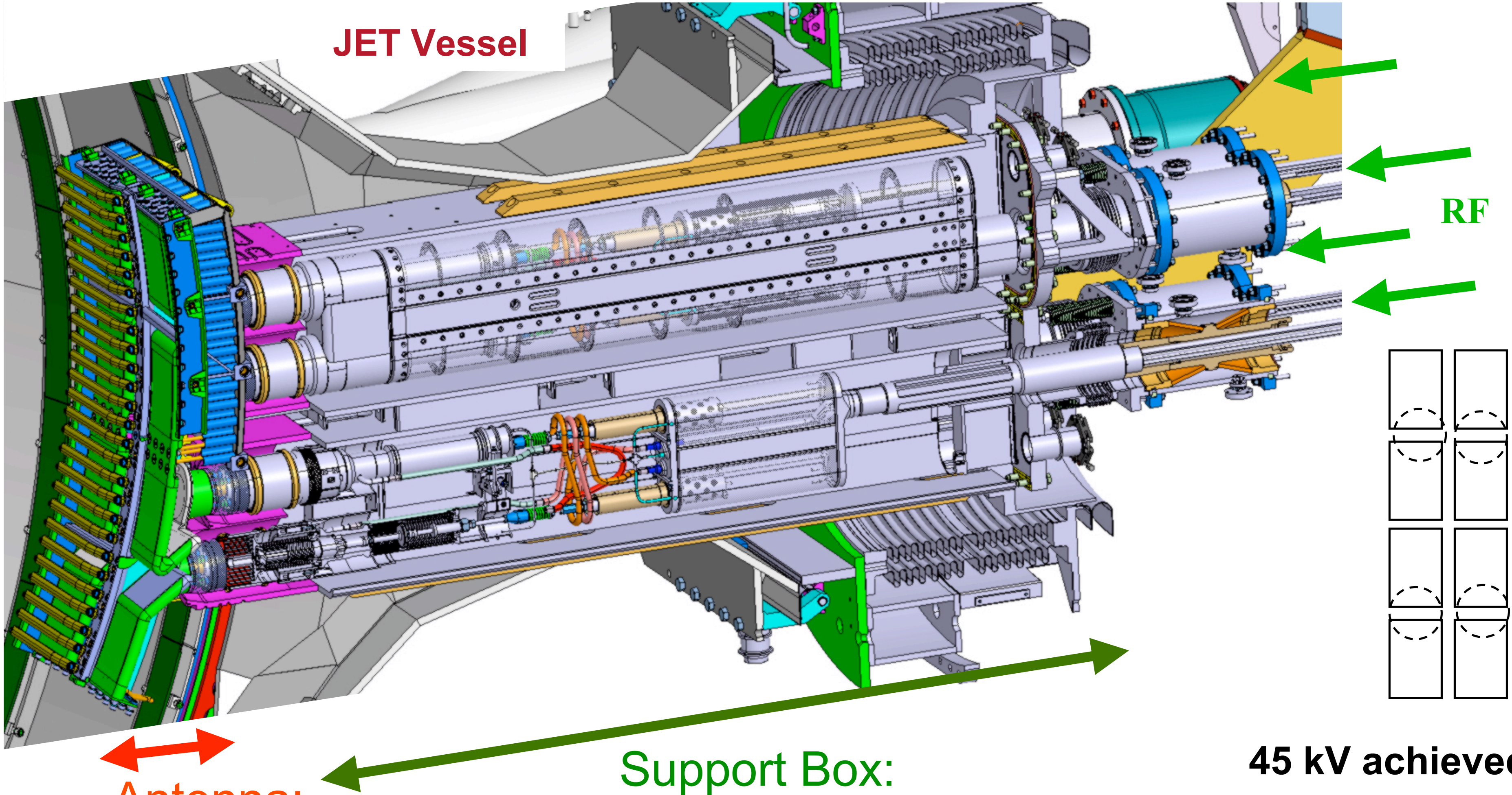
Matching

Standard components, steady state

Antenna

compact multiple straps, high voltage

JET IterLikeAntenna

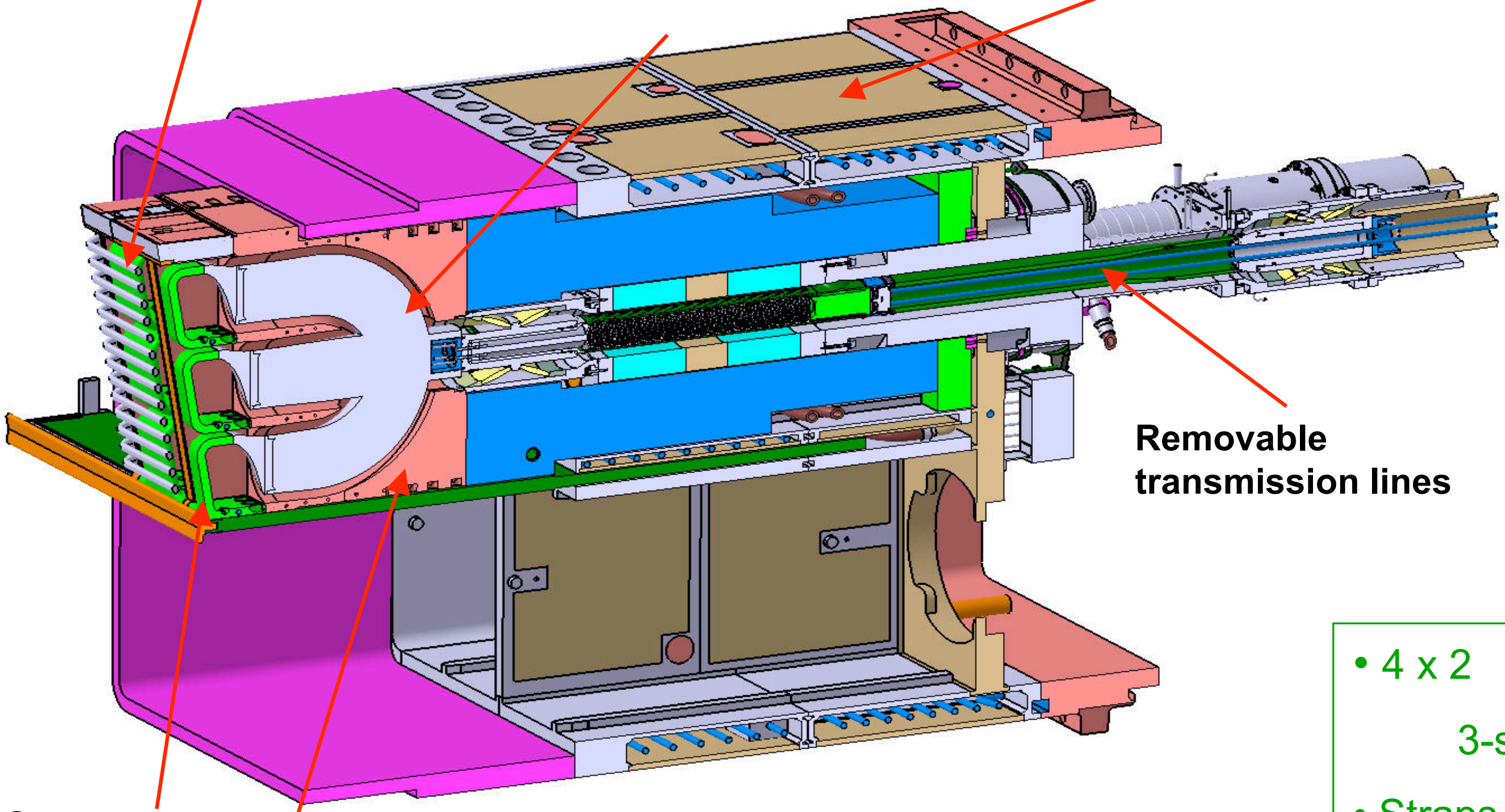


45 kV achieved

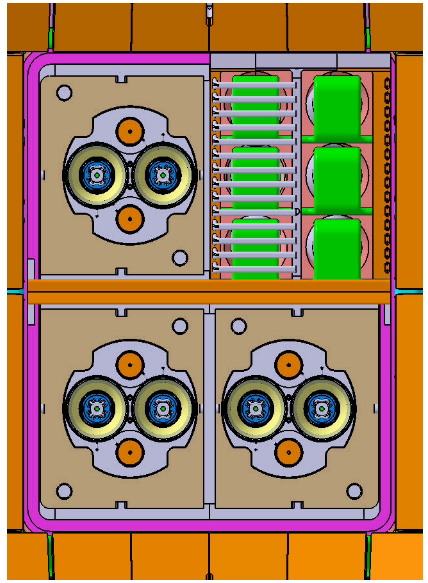
Antenna:
- Housing
- Straps
- Faraday Screen

Support Box:
- Mechanical Support
- Inner Vacuum Transmission Lines
- In-vessel Matching System

ITER ICRF Antenna Port Plug



Europe



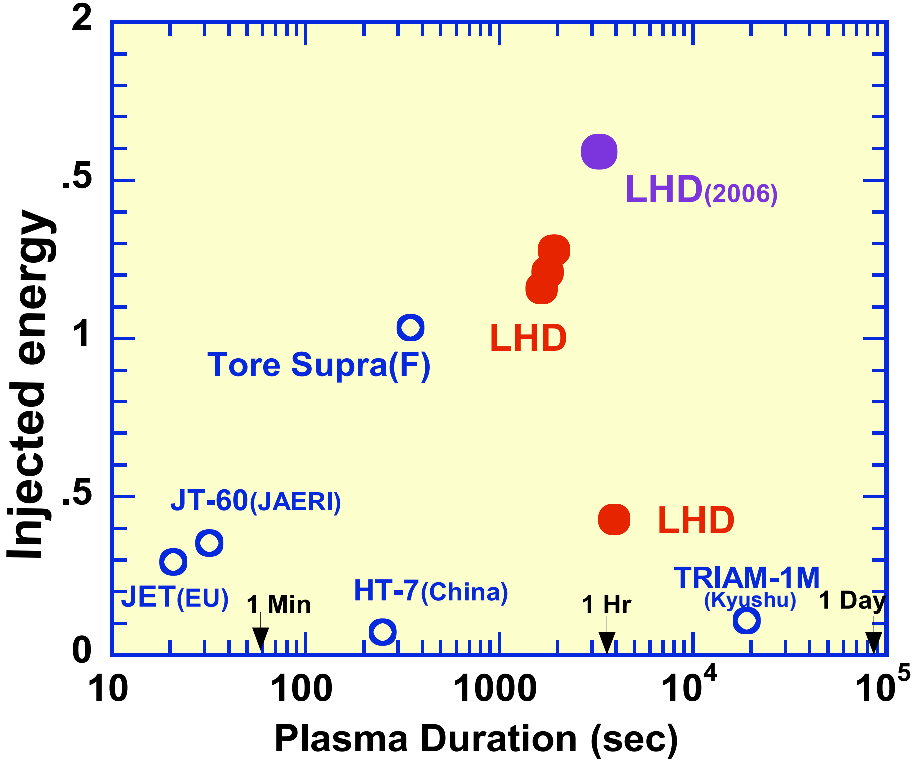
- 4 x 2

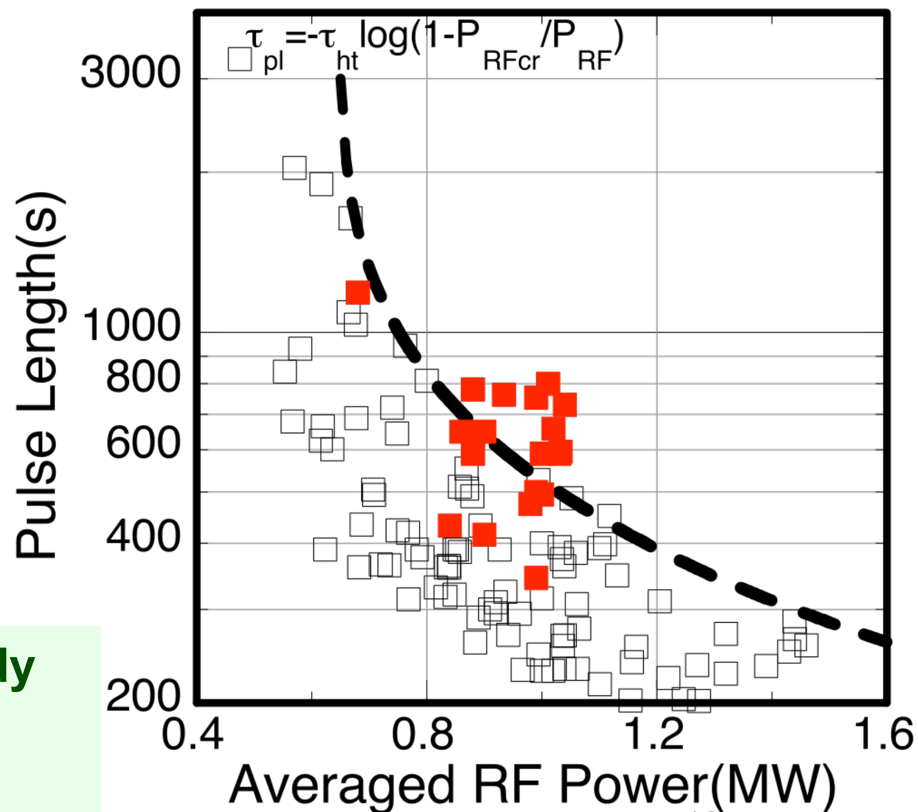
  3-strap array
- Straps grouped in triplets
- Triplets combined pairwise

A Borthwick (UKAEA)

Synergy Helical system and ICRF

LHD has demonstrated the long pulse capability of ICRF



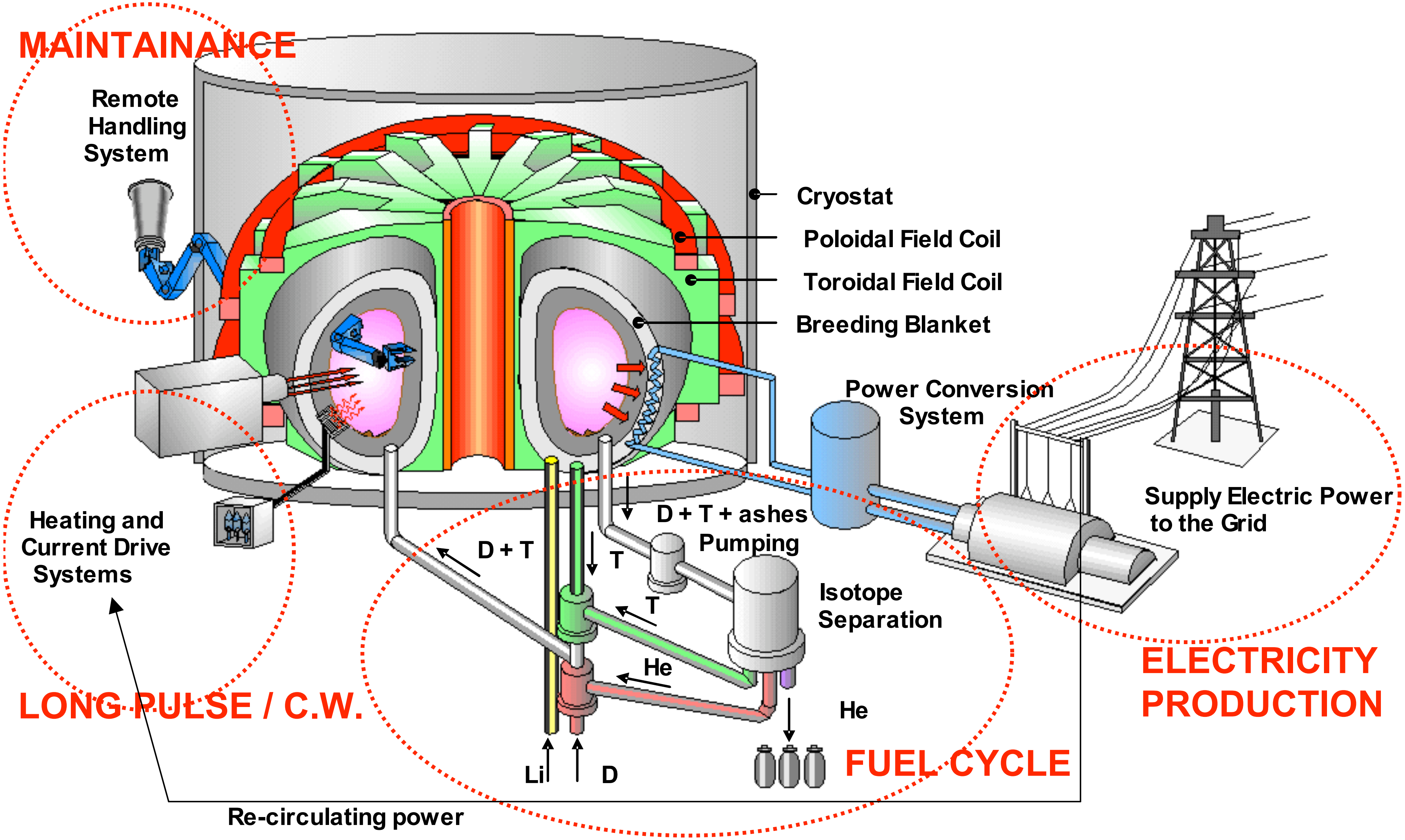


Steady state capability of helical system allows

First successful demonstration of the steady state potential of a heating method at MW level

jmn2008.20.10

DEMO



MAINTAINANCE
Remote Handling System
Cryostat
Poloidal Field Coil
Toroidal Field Coil
Breeding Blanket
Power Conversion System
Supply Electric Power to the Grid
Heating and Current Drive Systems
D + T
T
T
D + T + ashes
Pumping
Isotope Separation
He
He
Li
D
ELECTRICITY PRODUCTION
LONG PULSE / C.W.
FUEL CYCLE
Re-circulating power

ITER to DEMO

changes substantial and more of a qualitive nature

- **use: heating + control → multiple control, steady state**

- **environment: even more neutrons,**
  - materials and waste aspects → flexible in choice of material
  - T breeding essential → small penetration through blanket
  - *scheduled* remote maintenance → availability
- **requirements: economics essential**
  - capital cost
  - operating cost → availability, maintainability, efficiency

1. Use: More than heating

heating + control → multiple control, steady state

- heating to ignition only small part,
  - if steady state: minutes wrt year: 1/500 000
- burn control ✔
- sawtooth control ✔
- current profile ✔
- current drive (✔) ?

2. Environment: even more neutrons

system near machine must be simple

and with small penetration through blanket

- materials and waste aspects → flexible in choice of material ✔
- T breeding essential → small penetration through blanket ✔
  - in the limit: only TL through blanket
- *scheduled* remote maintenance → availability ✔
  - no moving parts
  - no consumables

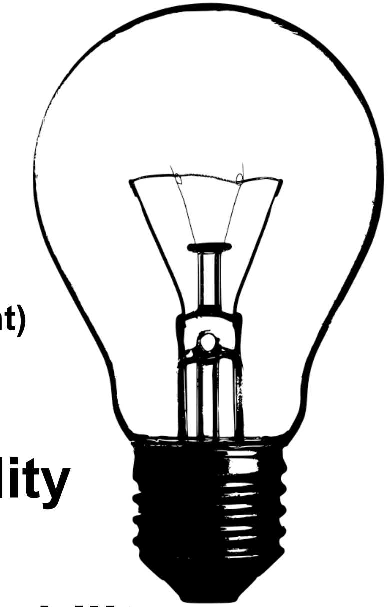
3. Requirements: economics essential

cost of electricity proportional to:
operating cost + (capital cost/payback period)/ availability

- capital cost and *availability*
  - machine cost, ….
  - cost of auxiliary system: propotional to installed power - ITER: typ. 10 %
    - cost / installed power: depends on method ✔
    - installed power inversely proportional to efficiency
      (effect on plasma) / (power to plasma) (✔, ✘)
- operating cost depends among others on
  - plug to power *efficiency* ✔
  - efficiency (effect on plasma)/ (power to plasma) (✔, ✘)

Availability

The ratio of
(a) the total time a functional unit
is capable of being used during a given interval to
(b) the length of the interval



$$A = \frac{MTBF}{MTBF + MTTR}$$

MTBF: Mean Time Between Failure (or Mean Time Between Replacement)
MTTR: Mean Time To Repair (or Mean Time To Replace)

MTBF = 1000 h = 40 days, must be high to maximise Availability

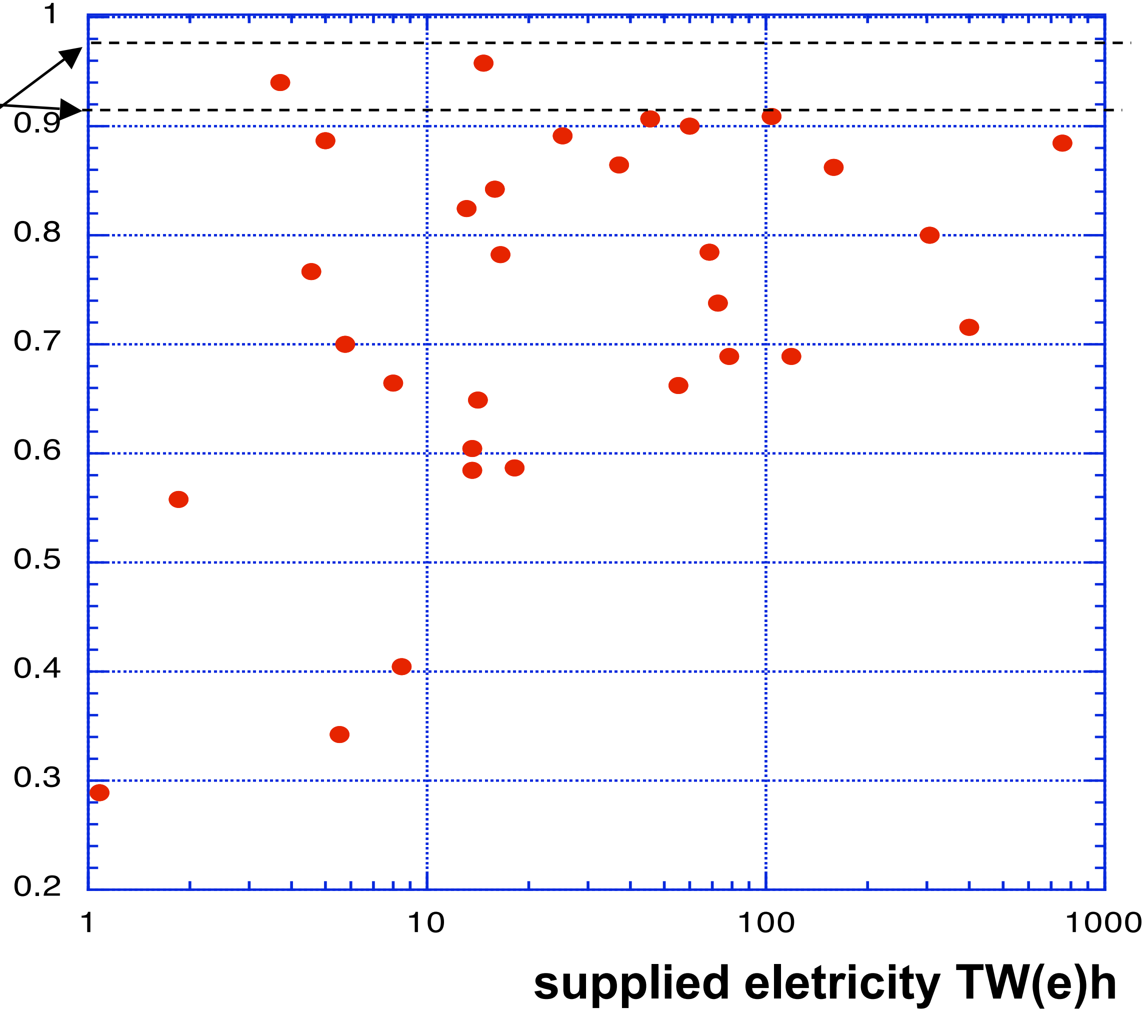
MTTR = replacement time, must be short , maximise Maintainability
- **if replacement on site available: 1 min → 0.999983 “5 nines”**
- **if replacement on site not available: 1 h → 0.999 “3 nines”**
- **if need to repair: 50 h → 0.952 “1 nine”**

Yard stick: Nuclear Power Plant

- scheduled maintance, refuelling
  - 1 month from 12 month:
    - 11/12 = 0.916
  - 1 month from 36 month:
    - 35/36 = 0.972
- increase by 6%
- historical data USA

1980	56%
1990	66%
2000	88%
2002	>90%

iaea 2000/ 32 countries



ICRF is well placed on the issues relevant for DEMO and thus a good candidate for DEMO

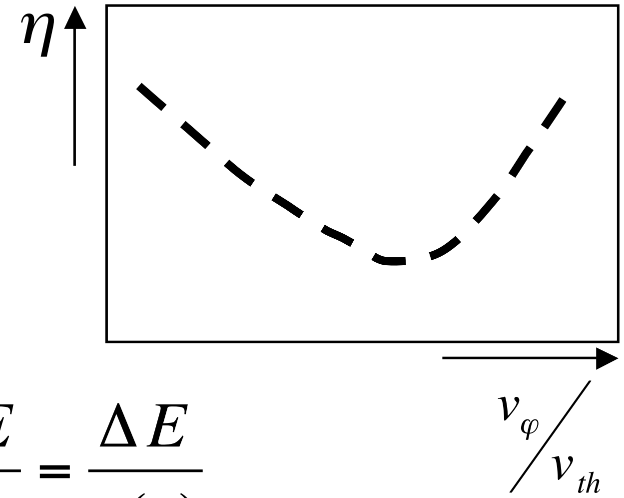
Areas where progress is needed and could be criticical:

- **-if high Z metallic wall → impurity of production**
- **-current drive**

Solutions?

Current drive efficiency

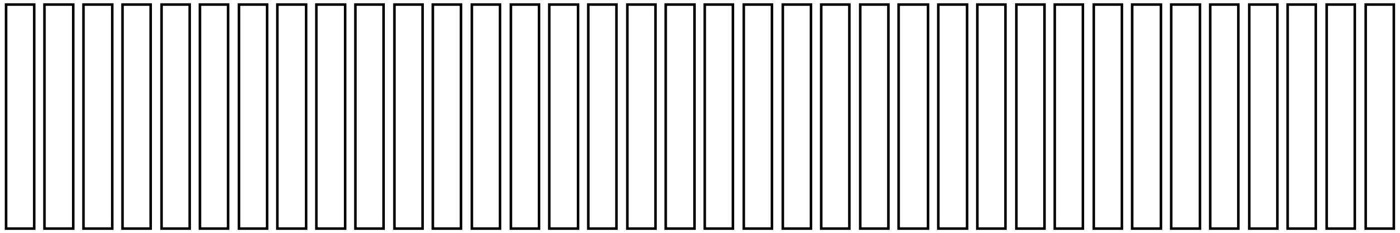
- **change in momentum** $\Delta p_{//} = m\Delta v_{//}$
- **corresponding energy** $\Delta E = m v_{//} \Delta v_{//}$
- **driven current** $\Delta J = q \Delta v_{//}$



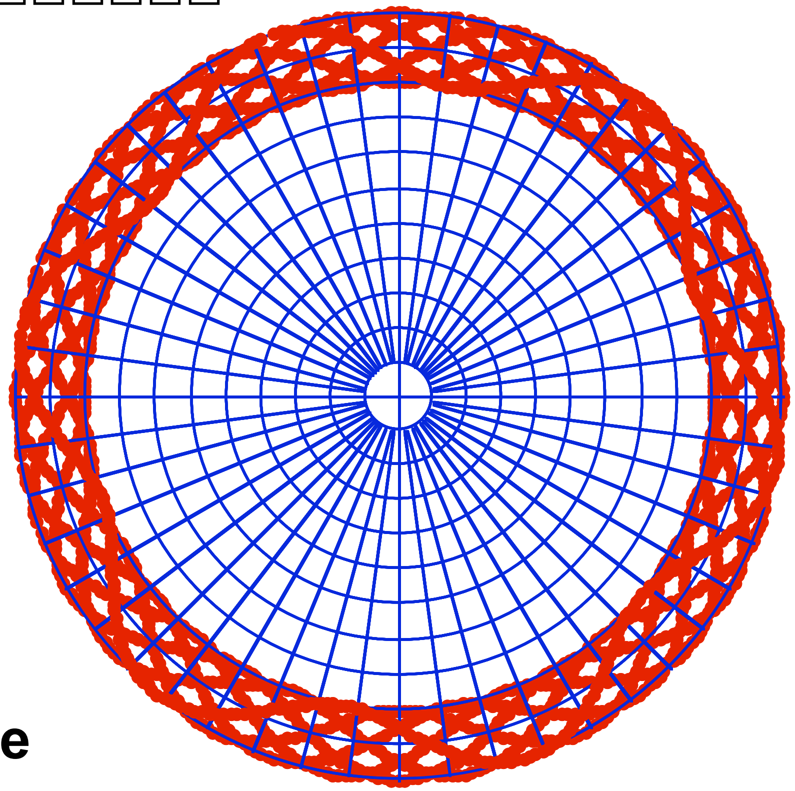
- **power needed to maintain current** $P = \dfrac{\Delta E}{\Delta t} = \dfrac{\Delta E}{\tau(v)}$
  - **efficiency** $\eta = \dfrac{\Delta J}{P} = \dfrac{q}{m v_{//}} \tau(v)$
- **limits** $\text{for } v_{//} \approx 0, v_{\perp} \approx v_{th} \rightarrow \tau(v) = \text{const} \rightarrow \eta \propto \dfrac{1}{v_{//}}$

$$\text{for } v_{//} >> v_{th} \rightarrow \tau(v) = v_{//}^3 \rightarrow \eta \propto v_{//}^2$$

Possible concept of ICRF for DEMO?



- **many antennas in the wall**
  - **low power density**
  - **low voltage**
  - **low sheat effects, no edges**
  - **low $k_{//}$ but without $k_{//}$=0**
    good coupling, good absorption
  - **penetration through the wall:**
    only the transmission line



- **rotating field → rotamak type current drive**

- **there are many advantages to a (quasi) steady state reactor**
  - **average power/maximum power**
  - **materials, …. fatigue**
- **if current needed → current drive efficiency may be a driving paramater**
- **if current drive efficiency too low: concepts that do not need steady state current drive may be favoured**
  - **helical system**
  - **steady state pulsed reactors**

Synergy Helical System and ICRF

inherently steady state

used to demonstrate
long pulse capability of

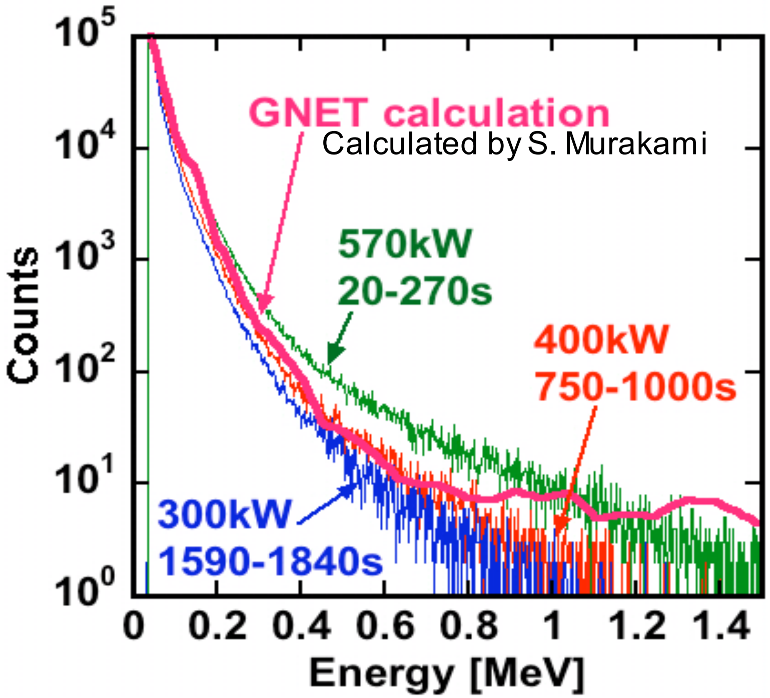
helical system

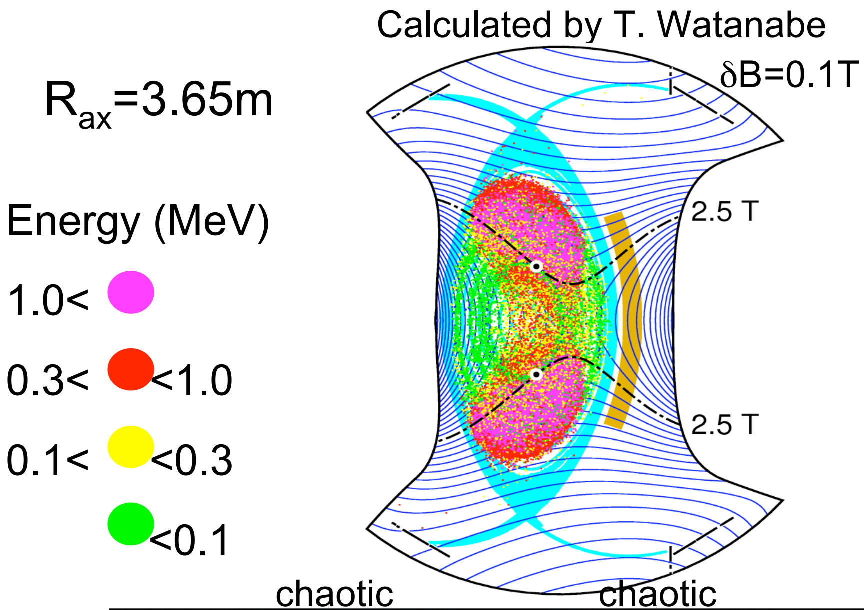
ICRF

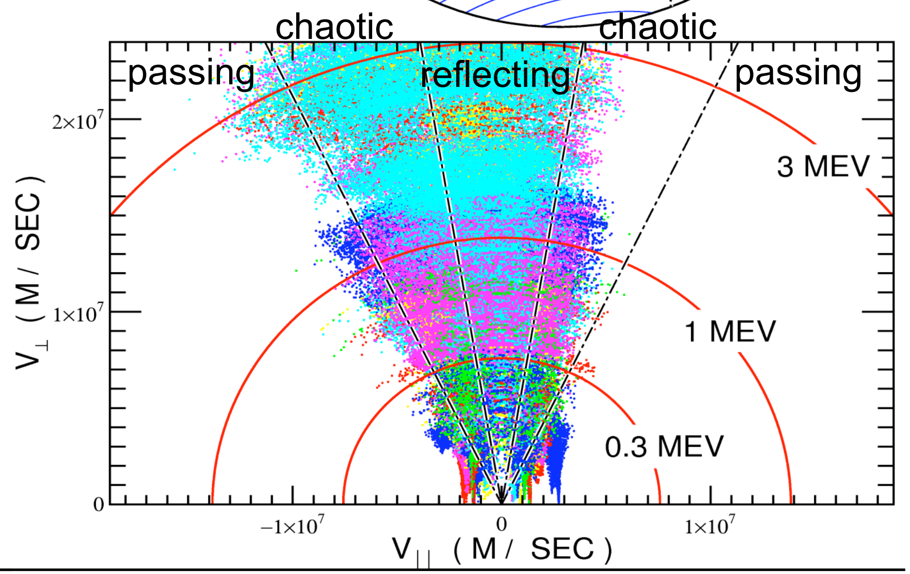
used demonstrate
confinement of fast particles

fast particles

High energy ion tail (> 1MeV) observed in LHD in steady state ICRF-heated plasma







- **theoretical calculation show that MeV class particles can be confined in LHD**
- **Confirmed by experiments with fast ICRF particles**
- **Perpendicular component measured using 6I Si-FNA (inward port)**
- **Possible by accumulation of detected particles using long pulse discharge**

ICRF on the way to DEMO

there will be substantial changes for the "auxiliary" systems in the

- use
  - from heating to control
- environment
  - more and more neutrons
- requirements
  - from flexibility to economics

from *present to ITER:* changes quantitative, and we are well on our way

e.g. helical systems have shown the steady state capability of ICRF

from ITER to DEMO: changes are substantial and more qualitative

ICRF is well placed for use in DEMO,
and even more so if bulk current drive is not an important requirement

ICRF can be used to qualify helical systems for DEMO