50 years in Fusion and the Way Forward

10^{26} \text{ watts}, 0.01 \text{ W/m}^3

5.108 \text{ watts, } 5 \times 10^5 \text{ W/m}^3
Credits

Discussions with many colleagues and direct input from:


Case for fusion

Key milestones

Lessons from the past

The way forward
Energy: a major challenge for the 21$^{\text{st}}$ century

China 2006: +105 GW, 90% coal!
More than the total French electricity per year (80 GW)

Today: >80% of primary energy comes from fossil resources
Gaz & petrol consumption exceeds new discoveries
Increasing dependance for energy (>50% for EU)
Energy = 4000 billions Euros per year

Back to coal or do better?
Moderate consumption, renewable energy, fission, fusion

Fusion presents major advantages
but requires advances in physics and technologies
Why Fusion?

• **Fuel**
  – Inexhaustible and well distributed on earth
    Deuterium: plentiful in the oceans
    Tritium: produced from Lithium

• **Safety**
  – No run away effect
  – No proliferation

• **Wastes**
  – Neutron induced activation
    (low radio toxicity < 100 years)
3 ways for fusion

### Sun
- **Confinement:**
  - Dimension: $1.3 \times 10^8$ m
  - Duration: $3 \times 10^{16}$ s
  - Pressure: $10^9$ atm
- **Ion temperature:** 100 million deg $\Leftrightarrow$ thermal energy $= 10$ keV

### Tokamak (JET / ITER)
- **Confinement:**
  - Magnetic:
    - Dimension: 10 m
    - Duration: 400 s
    - Pressure: 2 atm
  - Inertial:
    - Dimension: $10^{-2}$ m
    - Duration: $10^{-8}$ s
    - Pressure: $10^9$ atm
- **To ignite:**
  - $nT\tau \sim 10^{-3}$ m·keV·s $\sim 1$ bar·seconde

### Target compression
- **Confinement:**
  - Dimension: ?
  - Duration: ?
  - Pressure: ?
Milestones

• 1932 - 1958
  – Fusion discovered
  – Lawson criteria ➔ Confinement or compression essential

• 1958
  – Fusion declassified (also Kurtchatov at Harwell in 1955)
  – Artsimovitch, Teller ➔ international collaboration
  – Many labs created

• 1968 - 1990
  – Tokamak breakthrough; global stability

• 1990 – 2000+
  – Scaling laws
  – Fusion for real ➔ Tok: Pfus > 10MW; $310^{18}$ neutrons
    ➔ Tok + Stel: Duration $>>$ minutes
    ➔ IF: 600 times liquid, 10kev, $10^{13}$ neutrons

• 2000 to present
  – Start of a new era ➔ ITER + BA; NIF & LMJ
They discover the neutron, fission & fusion

Figure 3.6.3 Rutherford demonstrating deuterium fusion at the Royal Institution, 1934. The Metropolitan-Vickers transformer is to the extreme right of the apparatus. Reproduced by kind permission of Sir Mark Oliphant from his book Rutherford: Radiations of the Century. Reprinted by permission of Cambridge University Press.

1933: Oliphant et Rutherford fuse deuterium atoms
The stars then the criterion

$\tau \geq 1.5 \times 10^n$

J. D. Lawson 1923 – 2008

Jans Bethe 1906 - 2005
September 1958 “Atoms for Peace” (IAEA, Geneva)

Kadomtsev et al: plasma stability

111 papers: Aymar, Braguinsky, Bierman, Dreicer, Drummond, Kerst, Lehnert, Myamoto, Rosembluth, Shafranov, Thoneman etc

Just to name a few…

Spitzer: describes the Stellarator
Plasma physics is very difficult. Worldwide collaboration is needed for progress.

Fusion technology is very complex. It is almost impossible to build a fusion reactor in this century.

L.A. Artsimovich

E. Teller
Around 1958: Creation of many labs

An example:
Creutz, Bohr & Kerst in 59 at the dedication of the Jay Hopkins Lab

Strong links with universities (US, Japan, Germany, France etc.)
### In Europe after 58: the Associations

<table>
<thead>
<tr>
<th>Euratom</th>
<th>Country</th>
<th>Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>CEA</td>
<td>France</td>
<td>1958</td>
</tr>
<tr>
<td>ENEA</td>
<td>Italy</td>
<td>1960</td>
</tr>
<tr>
<td>IPP</td>
<td>Germany</td>
<td>1961</td>
</tr>
<tr>
<td>FOM</td>
<td>Netherlands</td>
<td>1962</td>
</tr>
<tr>
<td>FZJ</td>
<td>Germany</td>
<td>1962</td>
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<td>Belgian State</td>
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<td>1969</td>
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<td>Riso</td>
<td>Denmark</td>
<td>1973</td>
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<tr>
<td>UKAEA</td>
<td>United Kingdom</td>
<td>1973</td>
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<tr>
<td>VR</td>
<td>Sweden</td>
<td>1976</td>
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<tr>
<td>Conf. Suisse</td>
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<td>1979</td>
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<tr>
<td>FZK</td>
<td>Germany</td>
<td>1982</td>
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<tr>
<td>CIEMAT</td>
<td>Spain</td>
<td>1986</td>
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<th>Year</th>
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<tr>
<td>- IST</td>
<td>Portugal</td>
<td>1990</td>
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<td>TEKES</td>
<td>Finland</td>
<td>1995</td>
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<td>DCU</td>
<td>Ireland</td>
<td>1996</td>
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<td>OAW</td>
<td>Austria</td>
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<td>Greece</td>
<td>1999</td>
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<td>Czech Republic</td>
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<td>HAS</td>
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<td>MECT</td>
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<td>Univ. Latvia</td>
<td>Latvia</td>
<td>2002</td>
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<td>IPPLM</td>
<td>Poland</td>
<td>2005</td>
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<tr>
<td>MHST</td>
<td>Slovenia</td>
<td>2005</td>
</tr>
</tbody>
</table>

**Joint construction of JET**

Joint European Torus (JET) Culham, UK (1978)
## Milestones (toroidal devices)

<table>
<thead>
<tr>
<th>Period</th>
<th>Phys. concepts</th>
<th>Experimental/Technology</th>
</tr>
</thead>
<tbody>
<tr>
<td>1958 - 68</td>
<td><strong>Foundations:</strong> Spitzer (Stellarator, div), Kadmosev, Rosembluth, Sagdeev, Shafranov etc</td>
<td><strong>Mirror machines:</strong> Ioffe stabilizes interchange but micro instabilities Tokamak breakthrough (1 keV on T3)</td>
</tr>
</tbody>
</table>
| 1969 - 78  | **Heating systems:** NB, IC, EC  
**Current drive:** LH (Porkolab, Fish)  
Neo-classical theory - Bootstrap current (Galeev, Bickerton, multipole TFTR) | **TFR (2keV), PLT (9keV) confirm confinement and use heating (NB & IC)  
Conf. degrades vs P but improves with H-mode (Asdex) and pellet (Alcator C)** |
| 1979 - 88  | **Scaling laws** (Goldston)  
**Limits:** Beta (Troyon), density (Greenwald) | **Russian gyrotrons (T10)  
Divertor/H-mode phys (JFT2-a, JFT2-a)  
Construction of many tokamaks** |
| 1989 - 98  | Confinement barriers  
**Gyrokinetic scaling** (wind tunnel and later by simulation) | **D/T > 10MW in TFTR & JET (+ beryllium +Remote Handling); Divertor studies; NNBI (LHD, JAERI)** |
| 1999 - 08  | **Advanced/hybrid Tokamak** (DIII-D, JT-60, Asdex-U, etc.)  
**Simulation:** intermittency, zonal flows  
**NTM suppression:** Asdex-U, DIII-D | **1GJ on Tore Supra, 1.6GJ on LHD  
Elm mitigation (DIII-D; JET)  
Construction: ITER, EAST, KSTAR, ST1  
High density mode on LHD** |
Breakthrough in Kurtschatov (FEC 1968)

T confirmed by UK Thomson scattering team

Artsimovitch: “Fusion will be ready when society needs it.”

TFR (CEA) ~ 1971
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>External diameter</td>
<td>13.5 m</td>
</tr>
<tr>
<td>Plasma major radius</td>
<td>3.9 m</td>
</tr>
<tr>
<td>Plasma minor radius</td>
<td>0.6 m</td>
</tr>
<tr>
<td>Plasma volume</td>
<td>30 m$^3$</td>
</tr>
<tr>
<td>Magnetic field</td>
<td>3 T</td>
</tr>
<tr>
<td>Total weight</td>
<td>1500 t</td>
</tr>
</tbody>
</table>

**Large Helical Device (LHD)**

- **NBI (Co)**
- **NBI (Ctr)**
- **NBI (Perp)**
- **Local Island Divertor (LID)**
- **ECR**: 84 – 168 GHz
- **ICRF**: 25-100 MHz

**Strong programmes in Japanese universities**
Tokamak line Fusion Research in Japan (JAERI/JAEA)

- JFT-2a (DIVA)
  - First Divertor Experiments in the world (1974-1979)
  - Divertor coil
  - Shell

- JFT-2M
  - H-mode physics
  - Edge plasma control
  - AMTEX (Advanced Material Tokamak Experiment)
  - CT injection
Progress of Fusion Plasma Performance in JT-60U

- Highest DT-equivalent fusion gain of 1.25
- Highest ion temperature of 45 keV
- Development of steady-state tokamak operation scenario
- Confinement physics
- Divertor physics
- N-NB injection
Fusion for real: TFTR & JET

Rebut and the project team ~ 1976

16 MW, JET, November 1997

ITER basis

TFTR (1994)

JET (1991)

JET (1997)

Q ~ 0.65

Q ~ 0.2

(5 x 10^{18} n)
Establishing the ITER organization

Negotiations

Commissioner Potočnik: “hard winds bring strong trees”
Milestones for inertial confinement

1960  Laser innovation
      Townes, Basov, Prochorow, Maiman

1 keV and DD neutrons
  France: Limeil (Floux et al)

1972  Implosion concept
      Nuckolls

1986 10-keV temperature demo.
      Japan  1x10^{13} neutrons
      US     2x10^{13} neutrons

1989 High-density demo
      US     100-200 times liquid density
      Japan  600 times liquid density
      US     high convergence

First thermonuclear ignition (Q=10) in laboratories is expected in early 2010’s.
Compactness of Fast Ignition will accelerate inertial fusion energy.

1983-92 Concept Exploration by T. Yamanaka, Basov
1994 Concept Innovation: Tabak, PoP
2002 1-keV heating by fast ignition scheme by Japan-UK

Ongoing program:

Japan-FIREX-I
US-EP
Europe-PETAL

Proposed FIREX-II
Proposed ARC
HiPER-under design

The ongoing programs will demonstrate ignition temperature in early 2010’s, followed by ignition programs.
A trademark: international collaboration

• IAEA
  – IFRC
    • Journal Nuclear Fusion
    • FEC, technical meetings (topical), projects, education
    • Atomic & Molecular (A&M) Data for Fusion
    • Auspices for ITER
      – Conceptual design
      – EDA
      – ITER negotiations
      – Custody of ITER documents

• EURATOM-national fusion lab associations
  – All EU countries + Switzerland

• IEA
  – FPCC, since 1975, 9 implementing agreements (physics, technology, materials, safety, environmental and socio-economic aspects)
    • Staff exchange, joint experiments, hardware exchange
    • Evolving in light of recent changes
International Tokamak Physics Activity (ITPA)

• **ITER Expert Groups (1992), then ITPA (2001) by EU, Japan, Russia, US**
  – Tokamak physics – data bases – projections to ITER

• **Now under ITER IO, including all 7 ITER members**

• **Major contributor to the** ITER physics basis
  • Scaling laws
  • Validation of models and computer codes
  • Joint experiments on ITER issues

• **Published:** “Progress in the ITER physics basis”

  **18,495 downloads of chapters (as of June 08)!!**
Databases and modeling for confinement projection (from ITPA)

Dimensionless “wind tunnel” scaling:
• Fundamental basis for performance projection
• Comforted by gyrokinetic simulation

• Theory/models also used to project confinement.
Lessons from the past: physics

• **Plasma physics**
  – Linear phenomenae now well understood
  – Non-linear effects (turbulence) require more work
    • **Theory/simulation**
      – *will provide new insight*. Vortices, zonal flows etc.
      – *Predictive?*

• **Wind tunnel approach was essential ➔ scaling**
  – International collaboration ➔ data bases
  – Network of experiments ➔ size, shape, heating
    • **Strengthening required**

• **Next challenge:**
  – Physics of burning plasma
  – Physics & engineering of long pulses (Tokamak)
Lessons from the past: engineering

• Very integrated with physics
  – The machine itself is the experiment
  – “plasma engineering”; e.g. disruption forces

• Becoming predominant:
  – Supra conductors
  – Materials
  – Heat transfer
  – Safety

• Operation in CW or high duty cycle
  – The obvious next challenge for both MF and IF

→ a new era for engineering!
Lessons from the past: organisation

• **JET:**
  H. O. Wüster to US Congress: “JET could succeed because it was given the power to manage”

  **Organisation:**
  Council sets “What” (objectives & resources). JET **director** sets “How”. Council approves (or not) proposals from the director.

• **ITER** has in-kind procurement by domestic agencies
  – ATLAS in CERN also!
    ➔ It did work!
    ➔ **but central project team needs to be strong and should cross-check procurements at all time and levels**
    ➔ **the devil is in “classical details” (welds) not in high technology**
    ➔ **pulling knowledge together is beneficial**
    ➔ **Cost increase for ATLAS ~ 16% (but in time)**
Way forward (magnetic fusion)

JT60-SA
Supra conductors
SS operation

JET ~ 80 m
D/T ~ 16 MWth

+ 

many other contributing facilities via ITPA, IEA, IAEA

ITER
800 m
~ 500 MWth

Dominant self heating

DEMO
~ 1000 - 3500 m
~ 2000 - 4000 MWth

Iter Supra conductors SS operation
The way forward

**Demonstration of burning plasmas:** Q=10 (FCM, IF)

**Joules not just watts:** CW operation or duty cycle

**Technology:** Reliability, longevity (PFC & structural materials, lasers etc.)

**Fusion Safety:** Tritium confinement, inventory and cycle

**Strengthen education:** physicists and engineers in rare supply

**Are resources and time scale sufficient?:** need to scale with tasks and stake. Accelerate fusion ➔ fast track? (ITER first!)
Coming decade: The “Broader Approach”

ITER

JT60-SA

IFEREC

IFMIF-EVEDA

B.A.
Way forward  
(Coming decade)

Success in ITER is absolutely essential

• Challenges:
  – Cost ➔ ‘several key items are first of a kind’
    » Reduce risk ➔ simplify!
  – Availability of industry for construction? *(busy with fission!)*
    » Modus vivendi with industry

• Winning cards:
  – the 50 year legacy
    » A solid physics and technical basis
    » A culture and a practice of international collaboration of unprecedented size and quality

‘when there is a (good) will there is a way’
Summary

Fusion: a need for this century; present effort enough?

50y legacy: International collab. and a sound basis

Next step for MCF & IF: an exciting Q=10 milestone

Happy 50 year anniversary!