A laboratory report - Copenhagen, SCX MC32.

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PET and Cyclotron unit

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Agenda

1. Cyclotrons in Denmark.

2. The PET- and Cyclotron unit in numbers and hardware.

3. Various ongoing upgrades.

4. The musical fingerprint of isotopes.

5. Neutron activation of the cyclotron vault.

6. Ion source development.
1-A Cyclotrons in Denmark

   - One of the ”first” cyclotrons in Europe.
   - One of the longest running cyclotrons.

2. 1992-2048+, Rigshospitalet
   - Scanditronix MC32
   - The John and Birthe Meyer foundation.

3. 1994, Århus PET center.
   - GE, PETtrace

4. 2005, Rigshospitalet. (d. 17/01/2005)
   - CTI/Siemens, RDS Eclipse HP
   - The John and Birthe Meyer foundation.

5. 2005, Risø. (d. 22/01/2005)
   - GE, PETtrace
1-B Cyclotrons in Denmark

6. 2007, Odense PET center.
   • GE, PETtrace.

7. 2009, Herlev
   • IBA, Cyclone 18/9

8. 2010, Århus PET center.
   • IBA, Cyclone 18/9

9. 2011, Risø.
   • GE, ”Micro-cyclotron” PT600

10. 201?, Aalborg, Herning, …
    • ???
1-C Cyclotrons in Denmark

11. 2012, Rigshospitalet
   • Liselotte’s latest pink cyclotron

Status today (2013)
   • 9 cyclotrons in total
   • More on the way.
   • Dansk Cyklotron Klub
   • http://www.pet.rh.dk/krypton/DCK_Deltagere.htm
Agenda

1. Cyclotrons in Denmark.

2. The PET- and Cyclotron unit in numbers and hardware.
   a) Staff,
   b) Labs,
   c) Equipment,
   d) Productions,
   e) Uptime,
   f) ...

Side 6
2-A The PET and Cyclotron unit in numbers and hardware

The hospital:
- 1200 beds, 8500 employees, 700 M Euro budget, +2000 publications.

Department of Clinical Physiology, Nuclear Medicine & PET:
- “0 beds”, 120 employees, 10 M Euro budget, +100 publications,
- +40,000 patient investigations, …

PET and Cyclotron unit:
- 60-70 employee,
- 5 PET/CT,
- 1 PET/MR,
- 1 HRRT brain scanner,
- 6000-7000 PET-scans per year,
- 5 radiochemistry GMP labs,
- 14 hot cells.
- 9 chemist, 2 radio pharmacist, 4 lab. technicians for chemistry
- Marketing authorisation for two products: FDG and $^{81m}$Rb/$^{81m}$Kr
2-B The PET and Cyclotron unit in numbers and hardware

$^{[18\text{F}]}$FDG:
- 7 customers in Denmark (and 3 in Sweden)
- 16.3 % increase per year since 2006.

$^{81\text{Rb}}/^{81\text{mKr}}$ generators:
- Produced in Denmark since 1977
- 6 customers
- 15-20 generators per week
- Steady production

$^{[11\text{C}]}$-tracers:
- 27.3 % increase per year since 2006.
# Radiopharmaceuticals

<table>
<thead>
<tr>
<th>Tracers available for human use</th>
<th>Tracers expected to be available in the near future</th>
<th>New tracers available for preclinical use</th>
</tr>
</thead>
<tbody>
<tr>
<td>[(^{18}\text{F})]FDG</td>
<td>[(^{11}\text{C})]Cimbi-36</td>
<td>Apoptosis:</td>
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<tr>
<td>[(^{18}\text{F})]FLT</td>
<td>[(^{11}\text{C})]AZ10419369</td>
<td>• [(^{18}\text{F})] Annexin V</td>
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<td>[(^{18}\text{F})]FET</td>
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<td>Angiogenesis:</td>
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<tr>
<td>[(^{18}\text{F})]Altanserin</td>
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<td>• 64Cu-NODAGA-cRGDyK</td>
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<tr>
<td>[(^{11}\text{C})]PIB</td>
<td></td>
<td>• 64Cu-NODAGA-E[cRGDyK]_2</td>
</tr>
<tr>
<td>[(^{11}\text{C})]DASB</td>
<td></td>
<td>• 68Ga-NODAGA-cRGDyK</td>
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<td>[(^{11}\text{C})]Flumazenil</td>
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<td>EGFRvIII:</td>
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<td>[(^{11}\text{C})]SB207145</td>
<td></td>
<td>• [(^{18}\text{F})]FALGEA</td>
</tr>
<tr>
<td>[(^{11}\text{C})]CUMI-101</td>
<td></td>
<td>uPAR:</td>
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<tr>
<td>[(^{13}\text{N})]NH\text{\textsubscript{3}}</td>
<td></td>
<td>• Radiolabelled AE105</td>
</tr>
<tr>
<td>[(^{15}\text{O})]H\text{\textsubscript{2}}O</td>
<td></td>
<td>Brain imaging:</td>
</tr>
<tr>
<td>[(^{68}\text{Ga})]DOTATOC</td>
<td></td>
<td>• 5-HT\text{\textsubscript{7}} receptors</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Nicotinic receptors</td>
</tr>
</tbody>
</table>
The PET and Cyclotron unit in numbers and hardware

Cyclotron unit:

- Scanditronix MC32 (1992) and CTI/Siemens RDS Eclipse HP (2005)
- 2 physicist, 4 cyclotron technicians, 6 physics students (=operators),
- “No” service contracts,
- $^{18}$F, $^{11}$C, ($^{13}$N) at both cyclotrons (11 and 16 MeV)
- $^{15}$O, $^{82}$Rb/$^{82m}$Kr, $^{111m}$Cd and $^{211}$At only at MC32 (d- and α-beams and 16/32 MeV)
- $^{18}$F and $^{11}$C our major isotopes.
- Average success rate since 2006: 99.4%
Cyclotron unit:

- Average dose per employee stabilized despite of an increased production.
- Radioactive release per year has dropped despite of an increased production.
2-F Scanditronix MC32

- **Negative ions** (H⁻ and D⁻ beams).
- Magnetic field can be reversed for acceleration of **positive ions** for internal bombardments (i.e. H⁺, D⁺, He²⁺-beam).
- **Dual beam** exit possible.
- **Variable energies** 16-32 MeV and 8-16 MeV for H⁻, He²⁺ and D⁻ respectively.
- Sector focused, AVF.
- Internal ion source, **cold cathode Penning source** with two chimneys.
  - The main isochronous magnet field is approximately 1.6 T.
  - Resonance frequency 24.3 MHz.
  - Magnet 58 tons.
  - Vacuum 2x10⁻⁶ mbar (beam on) and 3x10⁻⁷ mbar (beam off).
- Total power consumption ≈ 130 kW.
2-G CTI/Siemens RDS Eclipse HP

- Negative ion (H⁻), 11 MeV.
- Penning type ion source.
- Deep valley (27:1) magnet design.
- Peak hill field, 1.9 T. Trimbars.
- Resonance frequency $f_{\text{CYK}}=18$ MHz.
- $4 \times 30$-degree dees.
- $f_{\text{RF}} = 72$ MHz
- 10 + 40 ton
- Total power consumption $\approx 25$ kW.
- **Dual beam** exit.
- 4 target per port.
- $^{18}$F, $^{11}$C, $^{13}$N, $^{15}$O, $^{64}$Cu, …?
- $^{18}$F yield, 7 Ci in 2 hours, dual beam, $2\times60 \, \mu$A.
- $^{11}$C yield, 1.8 Ci in 40 min,
Agenda

1. Cyclotrons in Denmark.

2. The PET- and Cyclotron unit in numbers and hardware.

3. Various ongoing upgrades:
   a) New $^{18}$F target “Lund/Uppsala type”
   b) S5 + CP527 $\rightarrow$ S7 + IGSS upgrade
   c) Vacuum upgrade
   d) Central region modification
   e) % RF upgrade
3a-A New $^{18}$F target “Lund/Uppsala type”

- Our SCX standard $^{18}$F targets were replaced with new IBA targets in 2003.
  a) 2.2 ml volume,
  b) Nb-target body,
  c) max. current 40 $\mu$A, max. pressure 40 bar.
  d) 16-17 MeV,
  e) saturation yields: $Y_{\text{sat}} = 8.6 \pm 0.6$ GBq/$\mu$A,
  f) 35 $\mu$A, 2h, gives 160 GBq EOB.
- Reported at the SCX Users meeting in Cologne in 2005.
3a-B New $^{18}\text{F}$ target “Lund/Uppsala type”

- The target has some **good** features
  a) consistent target yields,
  b) Niobium is an excellent target material,
  c) ...

- The target has several **bad** features
  a) a very complicated design for target, helium cooler and collimator,
  b) something like 15-20 O-rings and seals
  c) not service friendly
  d) O-rings, pipes, pressure distributor, ... becomes irradiation damaged,
  e) designed for a $<10\text{mm}$ beam diameter

- The MC32 is designed for a $20\text{mm}$ extracted beam.
- We loose typically $30\%$ beam at the collimator with the IBA target.
- This is a problem if limited by ion-source performance (see later)
- We want to replace the target with a $\varnothing=20\text{mm}$ target rather than the IBA $\varnothing=10\text{mm}$.
- Joachim Schultz suggested to try out the “Lund-design” (by Anders Sandell).
3a-C New $^{18}$F target “Lund/Uppsala type”

- In Lund one idea was to adapt the target shape to the wide MC17 beam profile.

- With 100% extraction the old 35 µA, 2h, is expected to give 50 µA on target for the same $I_{\text{arc}}$ and therefore 230 GBq EOB.

- Re-use of the original IBA target loading/unloading system. Rheodyne valve.

- Delay due to volume restriction for IBA system

- But we want to build our own loading/unloading system in the future.

- Our target uses a standard SCX He-cooling flange.

- Target was build in Uppsala. But we are making tests on doing the machining locally for the next target
3a-D New $^{18}$F target “Lund/Uppsala type”

- Groove for viton O-ring 3x29.2mm introduced. Helicoflex rings are difficult!
- High-pressure HPLC-type connectors introduced for load and unload pipes. 10-32 UNF.
- Lower leak rate obtained (Helium: 100→90 psi in 30 minutes).
3a-E New $^{18}$F target “Lund/Uppsala type”

- Niobium target body.
- Similar to the DKFZ shape. Radius=10mm, $\Delta h=3$mm.
- 7 mm deep ($R_{16\text{MeV}} = 3.3$ mm).
- Volume = 2.6 ml.

- Work in progress. Target is not fully validated yet.
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   b) S5 + CP527 → S7 + IGSS upgrade
   c) Vacuum upgrade
   d) Central region modification
   e) % RF upgrade
3b-A S5 + CP527 $\rightarrow$ S7 + IGSS upgrade

- The former SCADA system from SCX works perfect.
- Hardly any problems for the first 20 years.
- But S5 components are not produced and sold by Siemens anymore.
- Increasingly difficult to get spare parts.

- Running out of S5-135-U, CPU928 memory.
- Wish for improvements in control system and new projects.
- The CP527 GUI system is VERY difficult to code.
- Alarm handling.
- Data-logging and reports.
- Trend curves and graphical supervision/representation.
- Dynamical data exchange with other software, databases, ...
- Remote control, via internet,
- ....

- Joachim recommends me to stick to S5, but we want a replacement.
3b-B S5 + CP527 → S7 + IGSS upgrade

- First upgrade was attempted in 2000.
- Replacement of S5-135-U PLC with a S7-414 PLC.
- Replacement of CP527 based GUI with a modern IGSS32 redundant 2 server SCADA.
- Pure 1:1 translation of the code.
- Reported at the SCX/IBA meeting in Milan, November 2002.

System was never fully validated or put into operation.
- Lack of resources (re-organization of staff).
- Hardware (server failure) problems.
- Bugs in software.
- New upgrade was started in 2012.
3b-C S5 + CP527 → S7 + IGSS upgrade

• Upgrade in 3 steps:
  1. Step:
     ➢ New software company: Taangberg Pro Consult [http://www.taangberg.dk/]
     ➢ Replacement of S5-135-U PLC with S7-414-3 PN/DP PLC.
     ➢ Replacement of CP527 based GUI with only one server IGSS32 and two operator stations.
     ➢ Pure 1:1 translation of the code.
     ➢ Most of the old code-translation could be used.
     ➢ All hardware changed (out-dated).
     ➢ Bugs fixed.
     ➢ 81 kEuro (IGSS license = 24.5 kEuro!!)
3b-D S5 + CP527 → S7 + IGSS upgrade

- Easy to re-configure one operator station to a server station

TerminalNet.
Placeret i kontrolrum

Fiber

TerminalNet.
Placeret på Holgers kontor

IGSSERVER
Located in control-room

Operatørstation 1
Located in control-room

Operator station 2
Located at office

PLC for Cyclotron
3b-E S5 + CP527 → S7 + IGSS upgrade

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     ➢ 81 kEuro (IGSS license = 24.5 kEuro!!)
  2. Step:
     ➢ Replacement of all I/O modules.
     ➢ Some changes in the code for making this.
     ➢ Some new I/O (more AI).
     ➢ New 11C target control system.
     ➢ 53 kEuro.
  3. Step:
     ➢ Moving stand alone target control systems (kr, 13N, 18F) back into S7.
     ➢ New target pages.
     ➢ Improvements on alarms, logging, graphs, …
     ➢ 21 kEuro.
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   a) New $^{18}$F target “Lund/Uppsala type”
   b) S5 + CP527 $\rightarrow$ S7 + IGSS upgrade
   c) **Vacuum upgrade**
   d) Central region modification
   e) %% RF upgrade
3c-A Vacuum upgrade

• We are working on having less back streaming.

• Our CTI RDS Eclipse uses SantoVac and is anyway growing black.
• But it has no baffles.

• MC32 has baffles and is growing black too.

• Expected to affect the ion source performance.
3c-B Vacuum upgrade

• Regular service:
  a) Oil change for MP every ½ year.
  b) Full service for DP every 2 year,

• Better oil:
  a) Replacement of the Baltzer 71A mineral oil with DC 704 silicon oil. 1600 Euro.
  b) Pfeiffer+HSR/Balzers promises a **factor 10 reduction** in back streaming.
  c) I want to know more about the effect of SantoVac oil. It is also very expensive.

• Improved cooling of baffles:
  a) Present cooling water temperature: 12-14°C.
  b) Replacement with HSR *BFC 400 multi* baffles with PCF145-Z refrigerator.
  c) Both water and refrigerant (R134a) cooled.
  d) $T = -13-17^\circ C$
  e) Can be cooled with LN$_2$ too.
  f) Back streaming down by a **factor 10**.
  g) 23000 Euro
3c-C Vacuum upgrade

- Modification of central region, better pumping conductance.
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   b) S5 + CP527 $\rightarrow$ S7 + IGSS upgrade
   c) Vacuum upgrade
   d) Central region modification
   e) % RF upgrade
3d-A Central region modifications

- Precise alignment (tenth of millimeter) is essential for the beam performance.
- New and better alignment tools and procedures has been developed.
- Strong wear observed at both support plates and dee-tips
- We want to be able to do all parts our self and do modifications if needed.
- Impossible to do any development together with IBA..
- Problems in beam focusing and E- and/or B-fields.
  - Wants to be able to do field calculations!
3d-B Central region modifications

- Precise alignment (**tenth of millimeter**) is essential for the beam performance.
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   e) $\% \%$ RF upgrade
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1. Cyclotrons in Denmark.

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4. The musical fingerprint of isotopes.
4-A The musical fingerprint of isotopes.

80% of all productions is either $^{18}\text{F}$ or $^{11}\text{C}$. Is this funny? No! So let us look at the isotopes in a slightly different way.

CANBERRA Users Meeting 2012

“The Radioactive Orchestra”

http://www.nuclear.kth.se/radioactiveorchestra/

- $^{18}\text{F} + ^{11}\text{C}$ boring.
- My first nucleus I worked at: $^{169}\text{Lu}$, (DSAM)
- But what about other examples of isotopes
  - $^{175}\text{Ta}$, $^{99}\text{Tc}$
  - $^{81}\text{Rb}$, $^{81}\text{Kr}$
  - $^{62}\text{Zn}$, $^{62}\text{Cu}$

Productions in 2012

<table>
<thead>
<tr>
<th></th>
<th>18F</th>
<th>11C</th>
<th>Kr</th>
<th>13N</th>
<th>211At</th>
<th>15O</th>
<th>111Cd</th>
</tr>
</thead>
<tbody>
<tr>
<td>608</td>
<td>526</td>
<td>152</td>
<td>107</td>
<td>22</td>
<td>13</td>
<td>6</td>
<td></td>
</tr>
</tbody>
</table>
Agenda

1. Cyclotrons in Denmark.

2. The PET- and Cyclotron unit in numbers and hardware.

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5. **Neutron activation of the cyclotron vault.**
5-A Neutron activation of cyclotron vault

- De-commissioning plans for 2048
- Activation of concrete, cyclotron and other equipment.

- Both thermalized neutrons and fast/direct neutrons contribute to the activation.
5-B Neutron activation of cyclotron vault

- The first analyzed sample is from the Kr-target room, $E_p = 32$ MeV.
- Ge, $\Delta t_{acq} = 12h$. Lots of nice peaks.
5-C Neutron activation of cyclotron vault

- The first analyzed sample is from the Kr-target room, $E_p = 32$ MeV
- The abundance of Eu, Co and Cs in concrete is only a few ppm. But anyway becomes the most serious activation due to the long half lives (continuous build up for decades).
- The level is higher than the $^{40}$K background!

<table>
<thead>
<tr>
<th>Isotope</th>
<th>A [Bq/g]</th>
<th>$\Delta A$ [Bq/g]</th>
<th>$T^{1/2}$</th>
<th>Reaction</th>
</tr>
</thead>
<tbody>
<tr>
<td>152Eu</td>
<td>0.3037</td>
<td>0.0059</td>
<td>13,537 y</td>
<td>151Eu(n,\gamma)</td>
</tr>
<tr>
<td>154Eu</td>
<td>0.0355</td>
<td>0.0010</td>
<td>8,593 y</td>
<td>153Eu(n,\gamma)</td>
</tr>
<tr>
<td>60Co</td>
<td>0.1572</td>
<td>0.0061</td>
<td>5,274 y</td>
<td>59Co(n,\gamma)</td>
</tr>
<tr>
<td>134Cs</td>
<td>0.0531</td>
<td>0.0013</td>
<td>2,0648 y</td>
<td>133Cs(n,\gamma)</td>
</tr>
<tr>
<td>46Sc</td>
<td>0.0525</td>
<td>0.0020</td>
<td>83,79 d</td>
<td>45Sc(n,\gamma)</td>
</tr>
<tr>
<td>54Mn</td>
<td>0.0173</td>
<td>0.0009</td>
<td>312.5 d</td>
<td>54Fe(n,p)</td>
</tr>
<tr>
<td>56Mn</td>
<td>0.0051</td>
<td>0.0003</td>
<td>2.578 h</td>
<td>56Fe(n,p)</td>
</tr>
<tr>
<td>59Fe</td>
<td>0.0141</td>
<td>0.0005</td>
<td>44.5 d</td>
<td>59Co(n,p)</td>
</tr>
<tr>
<td>24Na</td>
<td>0.0184</td>
<td>0.0010</td>
<td>14.98 h</td>
<td>27Al(n,\alpha)</td>
</tr>
<tr>
<td>40K</td>
<td>0.0572</td>
<td>0.0032</td>
<td>1.277E+9 y</td>
<td>Background</td>
</tr>
</tbody>
</table>

The abundance of Eu, Co and Cs in concrete is only a few ppm. But anyway becomes the most serious activation due to the long half lives (continuous build up for decades). The level is higher than the $^{40}$K background!
5-D Neutron activation of cyclotron vault

- The first analyzed sample is from the Kr-target room, $E_p = 32$ MeV
- The abundance of Eu, Co and Cs in concrete is only a few ppm. But anyway becomes the most serious activation due to the long half lives (continuous build up for decades).
- The level is higher than the $^{40}\text{K}$ background.

![Activity vs Year Graph]

Non-active waste: <10 Bq/g
5-E Neutron activation of cyclotron vault

- The next samples are from the vault and shows the angular dependence.
- 5+1 concrete sample points.
# 5-E Neutron activation of cyclotron vault

- The next samples are from the vault and shows the angular dependence.

<table>
<thead>
<tr>
<th>Angle (°)</th>
<th>Eu152</th>
<th>Eu154</th>
<th>Co60</th>
<th>Cs134</th>
<th>Sc46</th>
<th>Mn54</th>
<th>Mn56</th>
<th>Fe59</th>
<th>Na24</th>
<th>K40</th>
</tr>
</thead>
<tbody>
<tr>
<td>-90</td>
<td>0.131</td>
<td>0.024</td>
<td>0.137</td>
<td>0.006</td>
<td>0.082</td>
<td>0.095</td>
<td>2.138</td>
<td>0.079</td>
<td>3.194</td>
<td>0.047</td>
</tr>
<tr>
<td>-45</td>
<td>0.213</td>
<td>0.022</td>
<td>0.166</td>
<td>0.010</td>
<td>0.092</td>
<td>0.135</td>
<td>2.317</td>
<td>0.090</td>
<td>3.759</td>
<td>0.050</td>
</tr>
<tr>
<td>0</td>
<td>0.197</td>
<td>0.024</td>
<td>0.166</td>
<td>0.010</td>
<td>0.092</td>
<td>0.135</td>
<td>2.317</td>
<td>0.090</td>
<td>3.759</td>
<td>0.050</td>
</tr>
<tr>
<td>45</td>
<td>0.125</td>
<td>0.013</td>
<td>0.110</td>
<td>0.006</td>
<td>0.054</td>
<td>0.115</td>
<td>1.883</td>
<td>0.061</td>
<td>2.890</td>
<td>0.052</td>
</tr>
<tr>
<td>90</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>180</td>
<td>0.040</td>
<td>0.006</td>
<td>0.021</td>
<td>0.003</td>
<td>0.017</td>
<td>0.000</td>
<td>0.454</td>
<td>0.007</td>
<td>1.499</td>
<td>0.048</td>
</tr>
</tbody>
</table>

- Data are not corrected for variations in solid angle.
5-F Neutron activation of cyclotron vault

- The next samples are from the vault and shows the depth dependence.

- Work in progress.
5-G Neutron activation of cyclotron vault

- To predict the future activation ($2048^+$) we
  a) Must make assumptions on the future beams/use
  b) Measure the flux of thermalized neutrons
  c) Measure the flux and energy distribution of fast/direct neutrons
- Flux and neutron energy spectrum is measured by the use of monitor-reaction-foil technique.
- Activation of metal foils with known nuclear reaction cross sections for both thermal and fast/direct neutrons are used.
- The work is ongoing, but Camilla and Esben must be ready with their bachelor project before 12/06/2012.
Agenda

1. Cyclotrons in Denmark.
2. The PET- and Cyclotron unit in numbers and hardware.
3. Various ongoing upgrades.
4. The musical fingerprint of isotopes.
5. Neutron activation of the cyclotron vault.
6. Ion source development.
6-A Ion source development

• Why my talk about ion sources?
• You all have cold cathode Penning like ion sources for positive ions and they are f.. simple to operate.
• I guess most of you do not worry about the performance.
• Typical performance for positive ion sources:
  a) ISGR: $I_{arc} : I_{beam} \approx 1 \text{ mA} : 2 \mu\text{A} \text{ or even better } (< 0.5)$.
  b) No service or 1-2 year interval.
• Negative ion sources are much more difficult.
• Acceptance criteria in 1992 for our MC32:
  a) $\text{H}^- 100\mu\text{A}, 8\text{h}$ and b) $\text{D}^- 60\mu\text{A}, 8\text{h}$
• I haven’t seen this performance during my 15 years at Rigshospitalet.
• We have tried many things.
• I have discussed and discussed with “everybody” and haven’t found any real experts.
• CAS, Specialized Course at IS experts says negative IS is impossible without Cs.
• Cesium is explosive and very difficult to handle and I have not seen any implementation in an internal PIG source.
• Negative IS development was done in the 60’ and 70’ties.
• Experts are no longer active. Read the literature.
6-B Ion source development

- $\text{ISGR} = \frac{I_{\text{arc}}}{I_{\text{beam}}} \approx 8-9$, measured at $^{18}\text{F}$ productions with 30 $\mu$A at target.
- Important to look at the ratio under the same conditions.
- Pos. IS ($< 0.5$) shown for comparison.
- Let us forget the results for 2013 for a while.
6-C Ion source development

- We need to be able to control all IS parts our self.
  - a) Except for the anode base we (PW and/or HRS) make all parts our self.
- Careful service and logging of all details.
- Precise central region alignment is essential, fractions of mm can give 1/10 beam.
  - a) New tools/procedures developed.
- \( \alpha \)-beam \((^4\text{He}^{++})\) main cause for ion service:
  - a) \( \alpha \)-chimney service for every 2-3 productions.
  - b) \( \text{H}^-\), \( \text{D}^-\) need no service except for new isolators. Cathodes can run for 1-2 year.
  - c) We are looking for better isolator material (replacement for BoronNitride)
• Is it a IS problem or something else?
• At DKFZ they run 100 µA H⁻ for \( I_{\text{arc}} \approx 600\text{-}1000 \text{ mA} \) (\( I_{\text{arc}}/I_{\text{foil}} \approx 6\text{-}10 \)).
• Our ion sources would saturate long before this power level.
• In Jan. 2012 we tested our IS at DKFZ and got 100 µA at \( I_{\text{arc}} \approx 800 \text{ mA} \).
• Conclusion: **Our IS is not bad.**
  We have to find another explanation.


6-E Ion source development

- One obvious difference between the DKFZ and Copenhagen MC32 was found in the central region.
- Modification of dummy-dee-support plates is expected to give a better vacuum.
  b) Reason for our new baffles, new oil, …
  c) The machine anyway becomes dirty in the central region. Is this a problem??
  d) In the CTI RDS Eclipse HP they have a DP directly under the IS. (ISGR≈2.2)
6-F Ion source development

- Modifications in the central region is part of the improvement seen in 2013.
  a) We are now running $I_{\text{arc}}/I_{\text{foil}} \approx 3.3-3.7$ and sometimes better.
  b) Ratio is slowly improving

![Graph showing modifications and dates]
6-G Ion source development

- A second suggestion from DKFZ was to use restrictor rings in the IS anode tube.
  a) Our understanding is that the hot plasma is moved away from the surface close to the extraction slit.
  b) The H- ionization is a multi-step reaction, where the final low-energy (surface) ionization forming H- is disturbed by the presence of a hot plasma.
  c) The hot plasma in the center is at the other hand necessary for the first reaction steps (volume ionization).
- In 2012 we tested this idea and optimized the diameter of the ring.
6-H Ion source development

- Optimizing the ring diameter.
- This work was done by a student Martin R. Henriksen, NBI, as a part of a bachelor project in physics.
- The effect drops for increasing power in plasma ($I_{\text{arc}}$).
- The restrictor rings is part of the improvement seen in 2012/2013.
6-1 Ion source development

- Optimizing the plasma distance from the extraction slit.
- The effect is dramatic.
- This also tells us that the B-field must be correct.
6-J Ion source development

- Sometimes you can save several weeks of work by spending a few hours of searching the literature.
- Conference proceedings from the 60’ and 70’ties:
  - Plasma distance = slit width. (Exactly as Martin found it)

**RECENT DEVELOPMENT OF INTERNAL H^-/D^- SOURCE FOR COMPACT CYCLOTRONS**

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**ABSTRACT**

Small internal H^-/D^- sources based on Ehler’s PIG source design have been used in recent years for a number of compact cyclotrons of various sizes needing only...
6-K Ion source development

- The typical IS performance today (05/2013):

![Graph showing the performance of different ion sources over a range of ion source currents.]

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<th>I-arc</th>
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<th>IS-4, H+</th>
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</table>
6-L Ion source development

- Comparison with other cyclotrons.
  a) CTI Eclipse performs almost a factor 2 better.
  b) PETTrace is comparable for the only example I have.
  c) MC17 is still a factor 2 better for positive ions.
6-M Ion source development

• There is still room for a lot of improvements:
• Reading the old literature gives me the impression that both negative and positive ions can be improved a lot.
Finito, basta, … a good place to stop