HDDesgin

January 4, 2025

[2]:
```
import os
import sys
import datetime
print(datetime.datetime.now().strftime('%Y-%m-%d %H:%M:%S'))

module_dir = os.path.abspath('../../pynextsw/')  # Adjust path as needed
sys.path.append(module_dir)

import time
import glob
import tables as tb
import numpy as np
import pandas as pd
import matplotlib.pyplot as plt
import matplotlib.image as mpimg

from functools import reduce
import numpy.testing as npt
from operator import itemgetter, attrgetter
%matplotlib inline
%load_ext autoreload
%autoreload 2

plt.rcParams["figure.figsize"] = 10, 8
plt.rcParams["font.size"     ] = 14
pd.options.display.float_format = '{:.2g}'.format
```

```
2025-01-03 14:03:39
The autoreload extension is already loaded. To reload it, use:
  %reload_ext autoreload
```

[3]:
```
from pynext.system_of_units import *
```

[4]:
```
import pynext.pynext_types as pn
from pynext.CylinderGeomEff import barrel_detection_efficiency
```

[42]:

```python
def set_fonts(ax, fontsize=20):
    for item in ([ax.title, ax.xaxis.label, ax.yaxis.label] +
                 ax.get_xticklabels() + ax.get_yticklabels()):
        item.set_fontsize(fontsize)

def plotxy(xx, yy, xl, yl, tit, color='r', label="", figsize=(6,4)):
    fig, axs = plt.subplots(1, 1, figsize=figsize)
    axs.plot(xx, yy, color, label=label)
    axs.legend()
    axs.grid()
    axs.set_title(tit)
    axs.set_xlabel(xl)
    axs.set_ylabel(yl)
    fig.tight_layout()
```

1 Paths to HD/BOLD Detectors

JJ, NEXT-CM, January 2025

1.1 HD Design Drivers

- **Physics**
  - Best possible energy resolution (imply best possible calibration)
  - Performance of topological signature (physics, diffusion, pitch).
- **Radiopurity**
  - Dominated by copper
  - Minimize radioactive budget inside the copper shield.
- **BOLD constrains**
  - Use of TPB disfavoured (Is there a quantitative argument?)
- **Practical**
  - Cost & Complexity
  - Expanding collaboration

1.2 Baseline HD (BHD) design

- TPB allowed.
- Operating conditions: T = 20 C, P= 15-20 bar.
- Tracking plane. Can be sparse (**STP**) o dense (**DTP**).
  - Both STP and DTP can perform the tracking function.
  - DTP can measure energy (and ideally also S1).
- Barrel Fiber Detector (**BFD**) readout by cooled SiPMs.

- BFD can measure energy and S1.

1.3 Ultra Violet HD (UVHD)

- No TPB allowed. This leads naturally to a detector based on "VUV SiPMs" (**vSiPMs**).
- The most feasible option is a detector with two DTPs (one per anode) which perform tracking, measure the energy and measure S1.

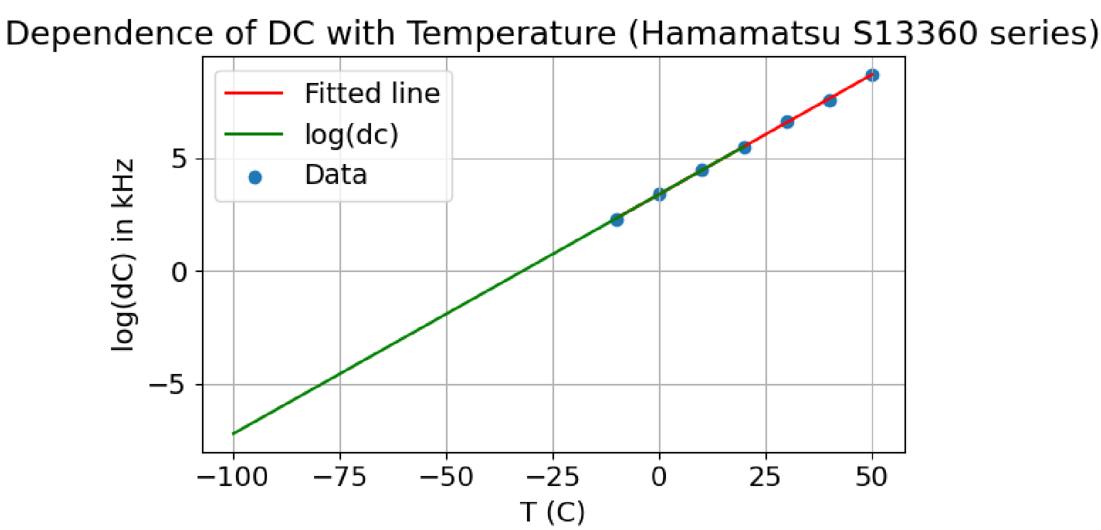
1.4 Dark Current considerations

- Let us examine first the dependence of the dark current rate (dcR) of SiPMs with temperature.
- We take as model the modern, low DC, Hamamatsu data S13360 series

[50]:
```python
xx = np.arange(-100, 20, 0.1)
yy = pn.logdc_vs_t(xx)


# Plot data and fitted line
def plot_dc():
    fig, axs = plt.subplots(1, 1, figsize=(6,4))
    axs.scatter(pn.tC, pn.ldR, label='Data')
    axs.plot(pn.tC, pn.y_fit, 'r-', label='Fitted line')
    axs.plot(xx, yy, 'g-', label='log(dc)')
    axs.legend()
    axs.grid()
    axs.set_title("Dependence of DC with Temperature (Hamamatsu S13360 series)")
    axs.set_xlabel("T (C)")
    axs.set_ylabel("log(dC) in kHz")
    fig.tight_layout()
```

[51]:
```python
plot_dc()
```



1.5 Operating temperature and pressure

- For this discussion I will assume that HD operates at P=20 bar, T= 20C. Notice that the density of the gas in this case is the same than when operating the detector at P=15 bar, T=-40C. *This is relevant, because VUVHD needs to operate with cool gas*
- At P=20 bar, T= 20C (*or at P=15 bar T=-40C*), a detector of **R= 110 cm** and **L/2 = 110 cm** (e.g, the length of one of the two symmetric TPCs) has a total mass of **1040 kg**
- With these dimensions, the area to be instrumented is **3.8 m^2** per end-cap, that is a total of **7.6 m^2** for the DSP, e.g., almost twice the area required by nEXO.

[27]:
```
Rg   = 110 * cm
zmin = -110 * cm
zmax = 110 * cm
cl = pn.Cylinder(Rg, zmin, zmax)
hdxe = pn.TpcXe(cl, "xe_2020")
print(hdxe)
print(f"area of barrel = {hdxe.cyl.area_barrel/m2:.2f} m2")
print(f"area of end-caps = {hdxe.cyl.area_endcap/m2:.2f} m2")
```

```
Configuration  = xe_2020
density (rho)  =    0.12 g/cm3
mass           = 1039.51  kg
Cylinder       =
Cylinder: radius =1100.0 mm, length = 2200.0 mm
```

```
area of barrel = 15.21 m2
area of end-caps = 3.80 m2
```

1.6 EL Parameters

- A higher pressure (density) is is enough with E/P ~1.5 to achieve an amplification gain ~1000.
- The high voltages are challenging (~**15 kV** in the gate and **75 kV** in the cathode), but can presumably be achieved, with enough R&D

[118]:
```
EP   = 1.5 * kilovolt / (cm * bar)
dV   = 0.5 * kilovolt / cm
P    =  20 * bar
d    =  5 * mm
L    = 120 * cm
Ws   =  39.2 * eV
Wi   =  21.9 * eV
hdel = pn.TpcEL(EP, dV, P, d, L, Ws, Wi)
```

[120]:

```
hdel
```

[120]:

```
E/P =    1.50 kV * cm^-1* bar^-1
dV = drift voltage =    0.50 kV * cm^-1
P  = pressure =   20.00 bar
d  = EL grid gap =    5.00 mm
L  = drift lenght =   1.20 m
Grid voltage =   15.00 kV
Cathode voltage =   75.00 kV
Yield =  9.40e+02 photons/e


Primary scintillation photons per MeV = 2.55e+04
Primary ionization electrons per MeV = 4.57e+04
EL photons per MeV                   = 4.29e+07

Primary scintillation Krypton = 1.06e+03
Primary ionization electrons Krypton = 1.89e+03
EL photons Krypton                   = 1.78e+06

Primary scintillation Qbb = 6.27e+04
Primary ionization electrons Qbb = 1.12e+05
EL photons Qbb                   = 1.06e+08
```

1.7 Cooling the SiPMs in VUVHD

- The number of SiPMs in VUVHD is 3.8×10^4 per DSP plane, assuming that the detector is fully tiled. Assuming 8 mW per channel for the readout ASIC the dissipated power is **640 W** (to compare with 100 W design specs for nEXO).
- At the same time, the SiPMs need to operate at low temperature to reduce dcR to reasonsable values. Ideally one would like to see the Krypton S1 signal for calibration purposes, in particular in the case of a DTP with filling factor substantially less than one. If this is not possible, one should see at least the signal from Na-22 sources (511 keV).

1.8 The fDTP (in VUV)

- We will consider first a DTP fully tiling up the anodes (**fDTP**), made of vSiPMs of 10×10 mm^2 at a pitch of 10 mm. The PDE corresponds to the last generation of Hamamatsu SiPMs (**PDE = 30 %**).
- The DTP has 3.8×10^4 SiPMs per Plane covering an area of 3.8×10^6 mm^2.
- **The dcR at t = -40 C is 91 counts per window of 500 ns (S1 detection window) and per DTP**. At T=-30C dcR=261 cs per plane and at T=-20 dcR=757 cs per plane.
- **Optical efficiency for S1** (both DSTP planes used to record S1)
  - Geometrical efficiency: $\epsilon_g \sim 0.15$ (neglecting reflections in the barrel, assuming VUV light)

- Grid transparency: $\epsilon_g \sim 0.9^2$
- SiPMs PDE: $\epsilon_{PDE} = 0.15$

$$\epsilon_{total} = \epsilon_g \times \epsilon_g \times \epsilon_{PDE} = 0.035$$

[29]:
```
vsipm = pn.SiPM("s10x10", 10*mm, 0.3)
vsipm
```

[29]:
```
sensor =s10x10, size = 10.0 mm, PDE = 0.3
DCR per u.a. (tC = 20C) = 2.8e+04 Hz/mm2;
DCR per u.a time window (tC = 20C, t=500 ns) = 0.014 cs/mm2;
```

[33]:
```
dtp = pn.DTP(vsipm, Rg, 1.0)
dtp
```

[33]:
```
DTP: Fill factor = 1.0
area = 3.8e+06 mm2, number of SiPMs = 3.8e+04
SiPMs:
sensor =s10x10, size = 10.0 mm, PDE = 0.3
DCR per u.a. (tC = 20C) = 2.8e+04 Hz/mm2;
DCR per u.a time window (tC = 20C, t=500 ns) = 0.014 cs/mm2;

DCR  (tC = 20C) = 1.1e+11 Hz;
DCR  time window (tC = 20C, t=500 ns) = 5.3e+04 counts;
```

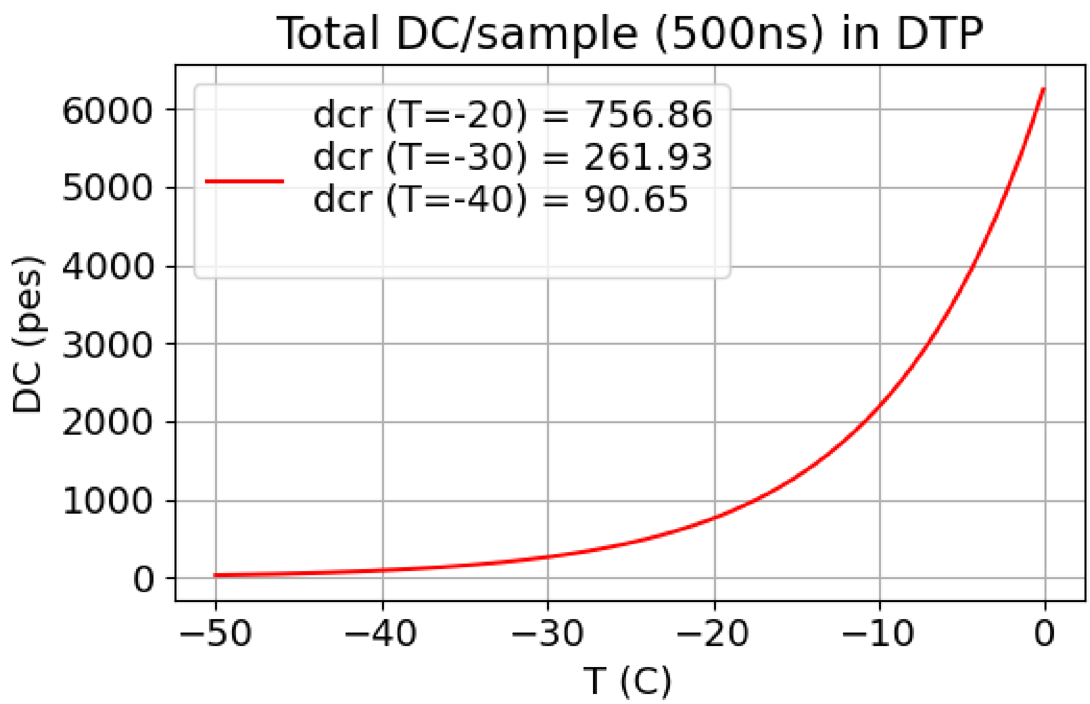
[56]:
```
Lhalf = (zmax - zmin) / 2
eff_barrel = barrel_detection_efficiency(Rg, Lhalf) # L in the equation is␣
 ↪semilength
eff_ecup = 1 - eff_barrel
print(f"eff_barrel = {eff_barrel}")
print(f"eff_endcup = {eff_ecup}")
eff_mesh = 0.9
eff_tot = eff_mesh**2*eff_ecup*vsipm.pde
print(f"Transport efficiency for the DTP = {eff_tot}")
```

```
eff_barrel = 0.8536776763694542
eff_endcup = 0.14632232363054576
Transport efficiency for the DTP = 0.03555632464222262
```

[54]:
```
tt = np.arange(-50, 0, 0.1)
dc = dtp.dcr_sipm_per_time(tt, 500*ns)
l1 = f"dcr (T=-20) = {dtp.dcr_sipm_per_time(-20, 500*ns):.2f}\n"
```

```
l2 = f"dcr (T=-30) = {dtp.dcr_sipm_per_time(-30, 500*ns):.2f}\n"
l3 = f"dcr (T=-40) = {dtp.dcr_sipm_per_time(-40, 500*ns):.2f}\n"
```

[53]:
```
plotxy(tt, dc,  "T (C)", "DC (pes)", "Total DC/sample (500ns) in DTP",
       label=l1+l2+l3)
```



[55]:
```
hdtp = pn.DTPDetector(hdel, hdxe, dtp, eff_grid=0.9, sampling=500*ns, tempC=-40)
print(hdtp)
print(f"Primary scintillation 511 keV detected = {hdtp.tpcel.
 ↪scintillation_photons(511 * keV)* hdtp.efficiency_s1:.2e}")
```

```
gas pressure   =   20.00 bar
gas density    =    0.12 g/cm3
gas mass       = 1039.51  kg

Dimensions(Cylinder)  =
Cylinder: radius =1100.0 mm, length = 2200.0 mm


Light efficiency (s1) = 3.56 %
Light efficiency (s2) = 13.50 %
SiPM PDE           = 0.30
SiPM size          = 10.00 mm
```

```
Sampling S1       = 500.00 ns

Primary scintillation Krypton          = 1.06e+03
EL photons Krypton                     = 1.78e+06
Primary scintillation Qbb              = 6.27e+04
EL photons Qbb                         = 1.06e+08

Primary scintillation Krypton detected = 3.76e+01
EL photons Krypton detected            = 2.40e+05
Primary scintillation Qbb detected     = 2.23e+03
EL photons Qbb detected                = 1.42e+07


Number of DCR photons in the detector for:
 --operating temperature (-40.00 C)
 --sampling time of 500.00
 -- nDCR = 181.30

Primary scintillation 511 keV detected = 4.64e+02
```

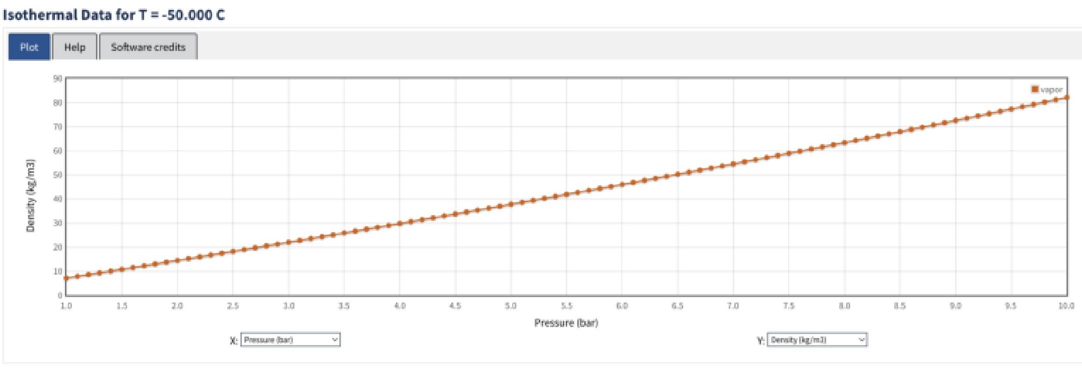
1.9 fDTP requires cold gas operation

- The S1 signal detected for krypton is ~38 pes, and for Na22 (511 keV) 464 pes
- Thus, Kr cannot be observed at -40 C, but 511 keV from Na-22 can be observed with S/N~2.5. At higher temperatures Na22 cannot be observed.
- Thus, the **minimum operating temperature for the SiPMs is -40 C**.
- With a power dissipation of 640 W and the requirement to cool uniformly ~80k SiPMs to -40 C, the most realistic option is **operation with cold gas**.

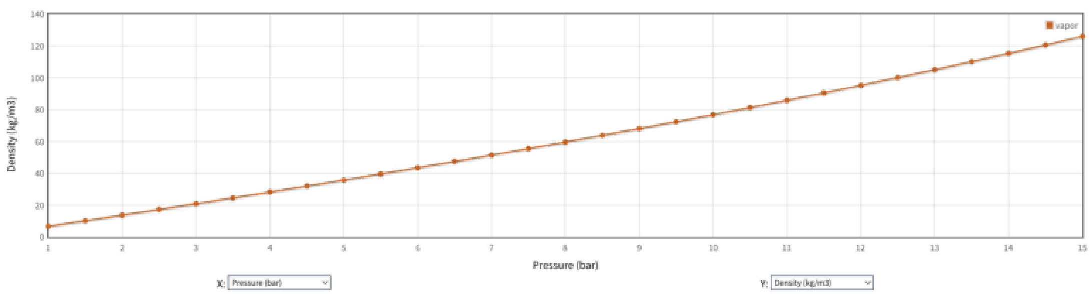
1.10 Pressure vs Density as a function of temperature

- When considering cool gas one has to take into account two factors. The curves of density versus pressure for a given temperature, and the pressure at which the gas becomes liquid for a given temperature.
- At T = -50 C, gas becomes liquid above 10 bar. At 10 bar the density is 80 kg/m3, which is equivalent to a pressure of 14 bar at T = 20C.
- At T = -40 C, gas becomes liquid above 15 bar. At 15 bar the density is 126 kg/m3 which is equivalent to a pressure of 20 bar at T=20C. The gain in mass is 60 %
- In exchange, at T = -40 C one has 12.5 % more DC than a -50. Taking into account both effects favours cooling at -40 C.

[9]:
```
img = mpimg.imread('xenon_p_vs_rho_minus_50.png')
plt.imshow(img)
plt.axis('off')  # Hide axes
plt.show()
```



[10]:
```python
img = mpimg.imread('xenon_p_vs_rho_minus_40.png')
plt.imshow(img)
plt.axis('off')  # Hide axes
plt.show()
```



[21]:
```python
u = kHz/mm2
dcm40 =pn.dc_mm2(-40) / u
dcm50 =pn.dc_mm2(-50) /u
print(f"DC/mm2 of Silicon at -40 C = {dcm40:.2g} kHz/mm2")
print(f"DC/mm2 of Silicon at -50 C = {dcm50:.2g} kHz/mm2")
print(f"DC ratio -40/-50 = {dcm40/dcm50}")
print(f"Mass ratio -40/-50 = {pn.rhoXe['xe_15m40'][1]/pn.rhoXe['xe_10m50'][1]}")
```

```
DC/mm2 of Silicon at -40 C = 0.048 kHz/mm2
DC/mm2 of Silicon at -50 C = 0.017 kHz/mm2
DC ratio -40/-50 = 2.889512931355543
Mass ratio -40/-50 = 1.5749999999999997
```

1.11 fDTP: challenge for the ASIC

- The capacitance of 10 x 10 mm^2 SiPMs is very large, making a fine sampling of the signal challenging. A realistic size for the SiPMs is 6 x 6 mm^2. This increases the number of SiPMs and the number of electronic channels by a factor 3.6.
- Notice that the cost of SiPMs is proportional to the area covered by silicon, not to the SiPM size. On the other hand, the cost of the electronics is proportional to the number of channels.

1.12 Cost of the fDTP

- Cost of the SiPMs (estimation from Hamamatsu offer) (2.96 €/mm^2). This is a total cost of **22.5 M€** for both planes.
- Cost of the electronics and DAQ (20 €/channel) (**5.5 M€**)
- To this cost one has to add the cost of DAQ, processing and storage, which is very significant, give the very high throughput.
- A realistic guess with today's prices of the cost of fDTP is ~**30 M€**.

[57]:
```
sipm_6x6_4x4 = 223 #e
sipm_6x6_4x4_units = 16
sipm_6x6_cost = sipm_6x6_4x4/sipm_6x6_4x4_units
sipm_cost_mm2 = sipm_6x6_cost/36
print(f"Hamamatsu: cost SiPMs 6x6  per channel = {sipm_6x6_cost:.2f}, per mm^2␣
↪= {sipm_cost_mm2:.2f}")

sipm_6x6_4x4 = 1705 #e
sipm_6x6_4x4_units = 16
sipm_6x6_cost = sipm_6x6_4x4/sipm_6x6_4x4_units
sipm_vuv_cost_mm2 = sipm_6x6_cost/36
print(f"Hamamatsu: cost VUV SiPMs 6x6  per channel = {sipm_6x6_cost:.2f}, per␣
↪mm^2 = {sipm_vuv_cost_mm2:.2f}")
print(f"Ratio VUV/Blue = {sipm_vuv_cost_mm2/sipm_cost_mm2}")
```

```
Hamamatsu: cost SiPMs 6x6  per channel = 13.94, per mm^2 = 0.39
Hamamatsu: cost VUV SiPMs 6x6  per channel = 106.56, per mm^2 = 2.96
Ratio VUV/Blue = 7.645739910313901
```

[110]:
```
print(f"cost of DTP silicon (2 planes) {2 * sipm_vuv_cost_mm2* hdtp.dtp.area/
↪mm2:.2e} €")
print(f"cost of DTP electronics) {2 * 20* 3.6* hdtp.dtp.n_sipm:.2e} €")
```

```
cost of DTP silicon (2 planes) 2.25e+07 €
cost of DTP electronics) 5.47e+06 €
```

1.13 pDTP (DTP with partial coverage)

- While the fDTP guarantees be best measurement of S2 (since it records most of the light with negligible cracks, thus minimizing geometrical corrections), a pDTP instrumenting only a fraction of the surface may be a more realistic option, **if the impact in the energy resolution is not too large**.

- Interestingly the pDTP has similar performance than the fDTP for observing S1. This is due to the fact that both signal and dcR decrease linearly with area.
- On the other hand, the performance concerning the measurement of S2 need to be carefully quantified.
- The cost is reduced to ~8M€ (+ 1.5 M€ for electronics).
- A realistic guess with today's prices of the cost of pDTP is ~**10 M€**.

[68]:
```
dtp2 = pn.DTP(vsipm, Rg, 0.36)
dtp2
```

[68]:
```
DTP: Fill factor = 0.36
area = 3.8e+06 mm2, number of SiPMs = 3.8e+04
SiPMs:
sensor =s10x10, size = 10.0 mm, PDE = 0.3
DCR per u.a. (tC = 20C) = 2.8e+04 Hz/mm2;
DCR per u.a time window (tC = 20C, t=500 ns) = 0.014 cs/mm2;

DCR  (tC = 20C) = 3.8e+10 Hz;
DCR  time window (tC = 20C, t=500 ns) = 1.9e+04 counts;
```

[75]:
```
hdtp2 = pn.DTPDetector(hdel, hdxe, dtp2, eff_grid=0.9, sampling=500*ns,␣
 ↪tempC=-40)
print(hdtp2)
s1511d = hdtp2.tpcel.scintillation_photons(511 * keV)* hdtp2.efficiency_s1 *0.36
print(f"Primary scintillation 511 keV detected = {s1511d:.2e}")
```

```
gas pressure   =   20.00 bar
gas density    =    0.12 g/cm3
gas mass       = 1039.51  kg

Dimensions(Cylinder)   =
Cylinder: radius =1100.0 mm, length = 2200.0 mm


Light efficiency (s1) = 3.56 %
Light efficiency (s2) = 13.50 %
SiPM PDE           = 0.30
SiPM size          = 10.00 mm
Sampling S1        = 500.00 ns

Primary scintillation Krypton           = 1.06e+03
EL photons Krypton                      = 1.78e+06
Primary scintillation Qbb               = 6.27e+04
EL photons Qbb                          = 1.06e+08
```

```
Primary scintillation Krypton detected = 1.36e+01
EL photons Krypton detected            = 8.66e+04
Primary scintillation Qbb detected     = 8.03e+02
EL photons Qbb detected                = 5.13e+06


Number of DCR photons in the detector for:
 --operating temperature (-40.00 C)
 --sampling time of 500.00
 -- nDCR = 65.27
```

```
Primary scintillation 511 keV detected = 1.67e+02
```

[60]:
```
print(f"cost of DTP silicon (2 planes, f=0.36) {2 * 0.36* sipm_vuv_cost_mm2*␣
 ↪hdtp.dtp.area/mm2:.2e} €")
print(f"cost of DTP electronics) {2 * 20* hdtp.dtp.n_sipm:.2e} €")
```

```
cost of DTP silicon (2 planes, f=0.36) 8.10e+06 €
cost of DTP electronics) 1.52e+06 €
```

1.14 DTP Requirements and implications for the ASIC and DAQ

- The following discussion applies for a fDTP (with SiPMs of 10 x 10 mm^2) or a pDTP (with SiPMs of 6 x 6 mm^2), with the caveats discussed above.
- the DTP must be able to sbserve S1 from Na-22 onwards. This requires extracting the full waveform (without ZS) from each one of the ~80K SiPMs.
- it needs to eeasure energy with excelent resolution from S2. This requires spe calibration, as well as Kr calibration. A potential (but solvable) handicap is that the DTP cannot observe S1 from Krypton.

- While observing spe is a must, S2 should not saturate the SiPMs.

1.15 Measuring S1

- The pes/SiPM in the DTP is $\sim 4 \times 10^{-3}$. This means that most SiPMs will measure only noise, and those who have a signal will have a single pe. These cannot be distinguished from DC counts (zero in most SiPMs) until the full waveforms from all the SiPMs are added. **Given the sparse signal, ZS appears unfeasible**.
- Each event will take 11.7 GB, posing significant challenges to DAQ and storage

[78]:
```
nel511 = hdtp2.tpcel.scintillation_photons(511 * keV)* hdtp2.efficiency_s1 *0.36
nS1_511PerSiPM = nel511/dtp2.n_sipm
ndcrPerSiPM = 2*dtp2.dcr_sipm_per_time(-40, 500*ns)/dtp2.n_sipm
print(f"pes/SiPM for 511 keV S1 = {nS1_511PerSiPM:.2e}")
print(f"dcr/SiPM for 511 keV S1 = {ndcrPerSiPM:.2e}")
```

```
pes/SiPM for 511 keV S1 = 4.39e-03
dcr/SiPM for 511 keV S1 = 1.72e-03
```

[83]:
```
data = 2400 * 64 * 2 * dtp2.n_sipm/1e+9
print(f"Data throughput = {data:.1f} GB")
```

```
Data throughput = 11.7 GB
```

1.16 Dinamic range

1.17 Interlude: S2 in SiPMs.

For a pointlike, isotropic source of N photons at distance r from a detector of area A (normal to the radial line), the **number of detected photons** is

$$N_{\text{hits}} = N \frac{A}{4\pi r^2}.$$

[84]:
```
def nhits(N, A, r):
    return N * A /(4 * np.pi * r**2)
def adcrange(nbits):
    return 2**nbits -1

def maxpes(nbits, adctopes):
    return adcrange(nbits)/adctopes
```

1.18 Dynamic range

- Kr is a point-like signal. After diffusion and passing through the grid, the signal is distributed in around 10 mus. Assuming we read each 0.5 mus, the signal per sample is $8.7 \times 10^4/20 = 4350$ pes. Of these about 124 pes are detected by the SiPM receiving the maximum signal (here I am assuming 6 x 6 mm^2, the situation is worse for 10 x 10 mm^2). -If we want a dynamic range from 1 pes (needed for S1) and 124 pes (needed for S2 Kr), we need a 12 bit ADC (with a maximum of 15 ADC counts per pes).
- On the other hand, the blobs of a double electron have tipically 300 keV of energy, or 6 times the energy of the krypton. **This will saturate even a 13 bits ADC.**

[114]:
```
nkR = 8.7e+4/20
nhkr = nhits(nkR, 36, 10)
print(f"pes in SiPM for kR = {nhkr:.1f}")
print(f"pes in SiPM for Qbb blob = {6*nhkr:.1f}")
print(f"maxpes for 12 bit ADC = {maxpes(12, 15):.1f}")
print(f"maxpes for 13 bit ADC = {maxpes(13, 15):.1f}")
```

```
pes in SiPM for kR = 124.6
pes in SiPM for Qbb blob = 747.7
maxpes for 12 bit ADC = 273.0
maxpes for 13 bit ADC = 546.1
```

1.19 Summary: VUV HD

- The design constrain of not using TPB yields to a detector with two DTPs instrumented with SiPMs.
- The ideal scheme to measure S2 is a fully tiled DTP (as proposed by nEXO) which, however appears extremely challenging in terms of cost, power dissipation, ASIC impedance (due to the very high capacitance), dynamic range and throughput.
- Some of these challenges are mitigated by considering smaller SiPMs (e.g., 6x6 mm^2), but the impact on energy resolution need to be evaluated. The cost is reduced by 1/3 (~10 M€). The problem of throughput and dynamic range still reamins.
- Operation of the DTP requires cold gas, given the large power dissipation needed and the requirement of cooling the SiPMs to -40 C.
- Krypton S1 cannot be observed. Observation of 511 keV gammas from Na-22 is feasible but not trivial.

1.20 Veto on TPB and HD/BOLD

- The veto on TPB is a (**debatable**) requirement for NEXT-BOLD. To my knowledge the effect on TPB on Ba2+ tagging has not been fully quantified.
- I see no strong arguments to veto TPB in the case of NEXT-HD. On the contrary, as shown below, allowing TPB simplifies detector design and makes it very affordable.
- The performance of HD in the search for $\beta\beta0\nu$ will depend on achieving the best possible energy resolution and topological signal, as well as reducing at maximum the radioactive budget. None of this requirements are affected by using or not TPB.
- However, if we need to veto TPB for BOLD, a future detector based on pDTPs, although challenging and "expensive", appears feasible, provide we can quantify good performance for S2 measurement with a pDTP.

1.21 HD Baseline

- The simplest configuration would be to use a Sparse Tracking Plane (STP) similar to those already in operation in previous NEXT detectors and a Barrel of optical fibers (BFD).

1.22 The BFD

- Made of WLSF of 1 mm, coated with TP, readout by SiPMs.
- Detector has ~7000 fibers readout by ~70 bSiPMs of 10 x 10 mm^2 (or 195 SiPMs of 10 x 10 mm^2).
- Enough light to detect Krypton and small dcR (can operate at -20C and still see the Krypton)
- Total cost ~**100 k€**

[101]:
```python
tpb = pn.WLS("TBP", 0.65)
print(tpb)
fwls = pn.FiberWLS(d = 1*mm, wls = tpb, qfib = 0.85, qptfe=0.98, ncore = 1.6,
    nclad1 = 1.49, nclad2 = 1.42, latt = 3.5*m)
print(f"fibers: {fwls}")
# for DC calculation consider that each fiber of 1 mm diameter need 1 mm2 of
    silicon to be read. Thus, one can count
```

```
# 1 sipm per fiber. In a real detector, one will use larger SiPMs to bundle␣
 ↪many fibers.
s1mm = pn.SiPM(name='s1mm', xsize=1*mm, PDE = 0.5)
print(s1mm)
```

```
WLS(name='TBP', qeff=0.65)
fibers:
        diameter =1.0 mm, Q = 0.85, PTFE refl = 0.98
        ncore = 1.6, nclad1 =1.49, nclad2 =1.42
        Absoprtion prob at 450 nm      = 0.6692690255200586
        Trapping efficieny             = 0.05843750000000007
        Fiber coated with WLS          = TBP
        WLS QE                         = 0.65




        sensor =s1mm, size = 1.0 mm, PDE = 0.5
        DCR per u.a. (tC = 20C) = 2.8e+04 Hz/mm2;
        DCR per u.a time window (tC = 20C, t=500 ns) = 0.014 cs/mm2;
```

[102]:
```
fdHD = pn.FiberDetector(hdel, hdxe, fwls, s1mm, eff_t=0.85, sampling= 500 * ns,␣
 ↪tempC=-20)
fdHD
```

[102]:
```
         gas pressure   =   20.00 bar
         gas density    =    0.12 g/cm3
         gas mass       = 1039.51  kg

         Dimensions(Cylinder)  =
         Cylinder: radius =1100.0 mm, length = 2200.0 mm


         Fibers efficiency = 2.36 %
         of which: Transport = 3.23 % & attenuation = 73.03 %
         Total detection efficiency = 1.18 %
         SiPM PDE           = 0.50
         SiPM size          = 1.00 mm
         fiber size         = 1.00 mm
         Sampling S1        = 500.00 ns
         number of fibers   = 6912

         Primary scintillation Krypton          = 1.06e+03
         EL photons Krypton                     = 1.78e+06
         Primary scintillation Qbb              = 6.27e+04
         EL photons Qbb                         = 1.06e+08
```

```
Primary scintillation Krypton detected = 1.25e+01
EL photons Krypton detected            = 2.10e+04
Primary scintillation Qbb detected     = 7.39e+02
EL photons Qbb detected                = 1.24e+06

Primary scintillation Krypton det/fiber = 1.81e-03
EL photons Krypton det/fiber            = 3.04e+00
Primary scintillation Qbb det/fiber     = 1.07e-01
EL photons Qbb det/fiber                = 1.80e+02

Number of DCR photons in the detector for:
 --operating temperature (-20.00 C)
 --sampling time of 500.00
 -- nDCR = 1.38
```

1.23 The STP

- blue SiPM of 1x1 mm^2, thus cost of SiPMs reduced by factor 7 (blue to VUV) x 36 (area of silicon) = 252
- Area per SiPM is 36 times smaller than in DTP. Can observe spe, not saturating S2 with 10 bit ADC. ASIC much simplified.
- Does not need to measure S1, thus ZS is possible. Throughput reduced by a large factor (~**90 %**).
- Small SiPMs, small capacitance, 10 bit ADC: Much reduced cost of electronics, simplicity and less power dissipation.
- No cooling complications
- Cost ~**1M€** (leading cost now is electronics).

[116]:
```
nkR = 8.7e+4/20
nhkr = nhits(nkR, 1, 10)
print(f"pes in SiPM for kR = {nhkr:.1f}")
print(f"pes in SiPM for Qbb blob = {6*nhkr:.1f}")
print(f"maxpes for 10 bit ADC = {maxpes(10, 15):.1f}")
```

```
pes in SiPM for kR = 3.5
pes in SiPM for Qbb blob = 20.8
maxpes for 10 bit ADC = 68.2
```

[107]:
```
print(f"cost of STP silicon (2 planes, f=0.1) {2 * 0.01* sipm_cost_mm2* hdtp.
 ↪dtp.area/mm2:.2e} €")
print(f"cost of DTP electronics) {2 * 10* hdtp.dtp.n_sipm:.2e} €")
```

```
cost of STP silicon (2 planes, f=0.1) 2.94e+04 €
cost of DTP electronics) 7.60e+05 €
```

1.24 But a pDTP may be a better option for HD baseline

- Since S1 will be measured by the BFD, the pDTP does not need to measure it. Thus, cooling the SiPMs is not necessary and ZS becomes feasible. This reduces the cost and complexity of the system, and makes credible to build one in the "short" term.

- The problem of dynamic range remains, though. We need spe for calibration and we cannot afford saturation of S2. This may be solved by using dual channel ADCs.
- The cost is 2 x STP, still affordable. A fDTP with SiPMs of 6x6 mm^2 would cost ~**2 M€**.

[117]:
```
print(f"cost of DTP silicon (2 planes, f=0.36) {2 * 0.36* sipm_cost_mm2* hdtp.
    ↪dtp.area/mm2:.2e} €")
print(f"cost of DTP electronics) {2 * 10* hdtp.dtp.n_sipm:.2e} €")
```

```
cost of DTP silicon (2 planes, f=0.36) 1.06e+06 €
cost of DTP electronics) 7.60e+05 €
```

1.25 What would be the added value of DTP?

- Same performance in the tracking function than STP (determined by pitch, ~10 mm)
- Provides an additional measurement of the energy, with different corrections (systematics) than BFD.
- If energy resolution with a pDTP is at least as good as that achieved by the BFD, then the physics argument is compelling. Energy resolution is one parameter where we have marging for improvements.

1.26 Summary

- The "no TPB" restriction imposes very hard requirements on our detector and increase the cost of the system by a very large factor. While this requirements may be necessary for BOLD (to be demonstrated) it is not needed for HD.
- HD Baseline seems sound enough for a detector whose physics goals are to achieve a sensitivity of 10^{27} y in $\beta\beta0\nu$. HDB may operate with a STP or a DTP. Energy resolution is a compelling argument to build a DTP for HD baseline.
- Preparing a future DPT (vuv) for BOLD is another crucial argument. Showing excellent energy resolution with a pDTP in HD, will support extending the design to the more challenging and expensive case of VUV.

1.27 A path forward towards HD : HD-DEMO

- HD-DEMO can test the performance of BFD, STP and DTP. The prototype is large enough to provide a good measurement of energy and tracking in the double escape peak of Tl, as well as a full energy calibration, from Kr to Tl.
- HD-DEMO is being prepared to operate with a STP and standard (NEXT-White) electronics. The first phase of HD-DEMO operation (~2025-2026) would asess the performance of the simplest configuration.
- During HD-Demo phase I, we should build a DTP with the goal of operating it in 2027.Operation of the DTP in HD-DEMO would permit us to assess its merits concerning enery resolution.

1.28 A path forward towards HD : N100-U2

- We are currently considering N100-U1. This is “upgrade 1” with respect to NEXT-10 and will implement a BFD and new electronics. The current plan is to leave NEXT-100 STP. The time scale to prepare U1 is 3 years (during this time we will operate NEXT-100). Then one could operate U1 for 1-2 years.
- Why not build N100-U2? The “upgrade 2” (get the pun? You too!) would add a pDTP to U1 including the ASIC and the construction time scale could be 4-5 years.
- U2 would offer a great opportunity for new collaborators to join the DTP effort.
- Given that the cathode is free, we could consider the possibility to add a camera to test CRAB reconstruction of tracks at large scale.

1.29 Time line

- 2025-2027: Operate NEXT-100. Build and operate HD-DEMO.
- 2028-2029: Build and operate U1.
- 2030-2031: Build and operate U2.
- 2032-2033: Build HD. Xenon from KamLAND-Zen may be available around this date.

1.30 HD White paper.

- We should produce a document that acts both as a roadmap and as an advertising brochure for potential collaborators.
- We could write a White Paper in late 2025 or 2026 describing a path to HD, including NEXT-100 operation, HD-DEMO and N100-U2. The White paper could also describe a path to BOLD (starting from HD operation with pDTP).