A Lifetime Calculator at ALBA

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Abstract

The lifetime calculator is a tool that calculates the lifetime from the machine model as a function of different parameters like RF voltage, coupling, etc. It allows the continuous comparison of this calculated lifetime with the measured one from the current decay and has a simulator environment to predict the lifetime for different machine conditions. The report describes both the calculation method, and also its integration in the control system.

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Abstract

The lifetime calculator is a tool that calculates the lifetime from the machine model as a function of different parameters like RF voltage, coupling, etc. It allows the continuous comparison of this calculated lifetime with the measured one from the current decay and has a simulator environment to predict the lifetime for different machine conditions. The report describes both the calculation method, and also its integration in the control system.

1 Introduction

Lifetime is a very sensitive parameter in an electron Storage Ring, which is usually measured from the beam current decay. The comparison between the calculated and measured lifetime values is an interesting way to diagnose anomalies in the Storage Ring, and detect possible changes in the machine conditions.

The main goals of this project are:

- to provide a sensitive diagnostic of the machine general behavior

- to provide a lifetime simulator to calculate a lifetime under user defined conditions

Lifetime studies performed at ALBA allowed to develop a real-time tool to estimate the expected lifetime from machine parameters like beam current, coupling, RF voltage, pressure, etc.

This report shows the characterization of the storage ring lifetime, and the integration of a new operation tool in the accelerator control system.

The beam dynamics group has defined the calculation method and the Operations section, supported by controls, has developed the Dynamic Device Server (DynamicDS) and the Graphical User Interface completely integrated in the Tango control system of the machine.

2 Calculation Method

The lifetime in a storage ring tells how long will the particle beam survive.

This time depends on the particle loss rate α:

$$\alpha = \frac{1}{\tau} = -\frac{1}{N}\frac{dN}{dt} , \tag{1}$$

where τ is the lifetime and N the number of electrons inside the ring.

As a first approximation, we assume the particle loss rate to be constant under certain conditions, and the number of particles inside the ring can be expressed as

$$N_t = N_0 \, e^{-\frac{t}{\tau}} . \tag{2}$$

Since the current of a storage ring is

$$I_{sr} = \frac{N}{T_{rev}} = N f_{rev} , \tag{3}$$

we can also express the current at time t as

$$I_t = I_0 \, e^{-\frac{t}{\tau}} . \tag{4}$$

Therefore, we can define the total lifetime of a storage ring as the time needed to reduce the initial current by a factor e.

There are three different effects that contribute to the total lifetime of a storage ring:

- Touschek lifetime: electron-electron scattering inside the beam

- Gas lifetime: electron collissions with the residual gas molecules

- Quantum lifetime: quantum fluctuations as result of radiation

At electron storage rings the quantum lifetime can be neglected and so we express the total lifetime as:

$$\frac{1}{\tau_{total}} \approx \frac{1}{\tau_{touschek}} + \frac{1}{\tau_{gas}} . \tag{5}$$

In normal operation the lifetime is dominated by the Touschek component ($\tau_{Touschek}$) but there is also a significant effect of the gas lifetime (τ_{gas}).

Next, we explain the calculation of $\tau_{Touschek}$ and τ_{gas}, for which we will use the parameters shown in Tab. 1.

Table 1: Constant values and units used for lifetime calculations

Parameter	Value
Electron radius (r_e)	$2.818 \cdot 10^{-15}$ m
Boltzman constant (k_B)	$1.381 \cdot 10^{-16}$ pbar $\cdot$ m$^3 \cdot$ K^{-1}
Speed of light (c)	299792458 m $\cdot$ s^{-1}
Vertical beta function at scraper $(\beta_{y,e})$	7.5 m
Harmonic number (h)	448
Ver aperture (A)	$4.75 \cdot 10^{-3}$ m
Hor aperture Septum	$16 \cdot 10^{-3}$ m
Lorentz factor (γ)	5832
Nominal Energy (E_0)	2980 MeV
Residual gas atomic number (Z)	7
Temperature (T)	296 K

We use the atomic number of the nitrogen $(Z = 7)$ because the residual gas of the storage ring is mainly made of CO and H_2 (not contributing, due to the low Z), and CO has the same number of protons than N_2 [1].

2.1 Gas Lifetime

The following equations show how to calculate the gas lifetime:

$$\frac{1}{\tau_{\text{gas}}} \approx \frac{1}{\tau_{\text{ee}}} + \frac{1}{\tau_{\text{ei}}} + \frac{1}{\tau_{\text{ne}}} + \frac{1}{\tau_{\text{ni}}} \tag{6}$$

$$\frac{1}{\tau_{\text{ee}}} \equiv \frac{1}{\tau_{\text{electron−elast}}} \approx \frac{2\pi r_e^2 cPZ}{k_B T\gamma} \frac{1}{\delta_{\text{acc}}} \cdot 3600 \cdot 2 \tag{7}$$

$$\frac{1}{\tau_{\text{ei}}} \equiv \frac{1}{\tau_{\text{electron−inelast}}} \approx \frac{4r_e^2 cPZ}{137k_B T} \frac{4}{3} \ln\left(\frac{2.5\gamma}{\delta_{\text{acc}}} - 1.4\right)\left[\ln\left(\frac{1}{\delta_{\text{acc}}}\right) - \frac{5}{8}\right] \cdot 3600 \cdot 2 \tag{8}$$

$$\frac{1}{\tau_{\text{ne}}} \equiv \frac{1}{\tau_{\text{nuclei−elastic}}} \approx \frac{2\pi r_e^2 cZ^2}{k_B T\gamma^2} \frac{\langle P_i \cdot \beta_{y_i}\rangle}{A^2} \cdot 3600 \cdot 2 \tag{9}$$

$$\frac{1}{\tau_{\text{ni}}} \equiv \frac{1}{\tau_{\text{nuclei−inelast}}} \approx \frac{4r_e^2 cPZ^2}{137k_B T} \frac{4}{3} \ln\left(\frac{183}{Z^{1/3}}\right)\left[\ln\left(\frac{1}{\delta_{\text{acc}}}\right) - \frac{5}{8}\right] \cdot 3600 \cdot 2 \tag{10}$$

All the parameters of the previous formulae are constant values (defined in Tab. 1) except:

- P: Average Pressure of the storage ring obtained from the Cold Cathode Gauges (CCG) readings

- $\langle P_i \cdot \beta_{y_i}\rangle$: Average value of the products of local pressure times local vertical beta function along the Storage Ring

3

- δ_{acc} : Energy Acceptance as a function of coupling and RF voltage (see the next subsection for details)

These parameters are continuosulsy measured in the machine.

2.2 Touschek Lifetime and Energy Acceptance

The Touschek lifetime quantifies the particle losses due to the intra-beam electron scattering inside inside each bunch.

A simplified formula for the Touschek lifetime is (Eq. 6 in [1]):

$$\frac{1}{\tau_{\text{Touschek}}} = \frac{r_e^2 c n_e D(\zeta)}{8\pi\gamma^2(\sigma_x\sigma_y\sigma_s)\delta_{\text{acc}}^3} \tag{11}$$

where n_e is the number of electrons in a bunch, σ_x, σ_y and σ_s are the RMS average beam sizes (transversal and longitudinal),

$$D(\zeta) \approx \sqrt{\zeta}(-\ln(1.78\zeta - 1.5)) \text{ and} \tag{12}$$

$$\zeta = \left(\frac{\delta_{\text{acc}}\beta_x}{\gamma\sigma_x}\right)^2. \tag{13}$$

But in this case, our colleagues from beam dynamics group have calculated the Touschek lifetime using the Piwinski formula from an internal NSLS-II report (Eq. 6 in [2]), which will be skipped here for brevity.

The Piwinski formula is solved by calculating the local energy acceptance, δ_{acc}, along the ring. This is carried out by particle tracking using the Matlab Accelerator Toolbox [3].

Since this is a heavy computational process (and we wanted to have a continuous calculation of the lifetime integrated in the ALBA control System), the beam dynamics group calculated the Piwinski Touschek factor Ts and the energy acceptance for each combination of RF voltage and coupling at the nominal limiting apertures (see Tab. 1). This way, we obtained two 2D grids (see Fig. 1) which allow to calculate Ts and the δ_{acc} as a function of the RF voltage and coupling every 3s by linear interpolation.

Finally, the Touschek lifetime is obtained by dividing Ts by the storage ring current, assuming the operation of the machine with the nominal filling pattern:

$$\tau_{\text{touschek}} \approx \frac{Ts}{I_{\text{SR}}}. \tag{14}$$

2.3 Correction Coefficients

It is known that the pressure measured at CCG must be somehow corrected because it is not the real pressure seen by the electron beam. The same happens with the total RF voltage.

For that reason, we performed some systematic measurements scanning RF voltage and coupling to try to fit these correction coefficients with a model, from where the values in Tab. 2 are obtained.
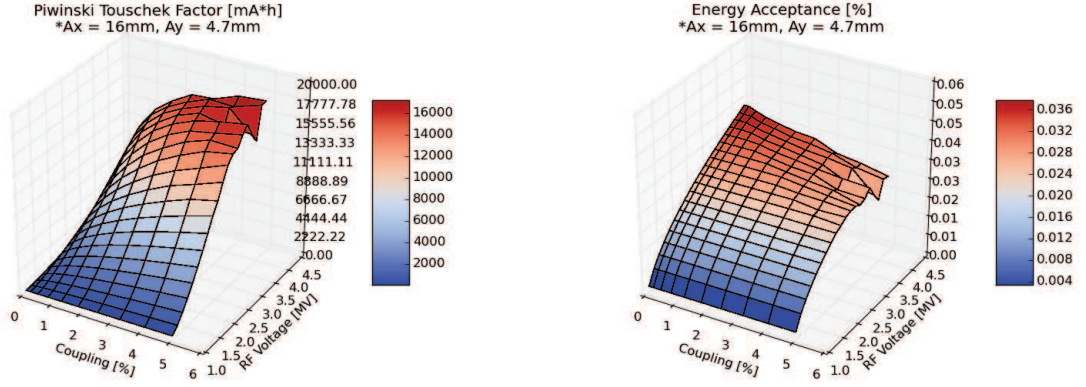
Figure 1: **Left:** Touschek Factors Grid 2D. **Right:** Energy Accpetance Grid 2D.

Table 2: Correction coefficients for pressure and RF voltage

Parameter	Value
Pressure	-17%
Total V_{RF}	-2.4%

2.4 Practical issues

2.4.1 Position of the Scrapers

In all the calculations, the horizontal and vertical limiting apertures of the ALBA Storage Ring are assumed to be the nominal ones for user operation, i.e., 16mm for the horizontal plane (septum in normal operation) and 4.75mm for the vertical (vertical scraper). Thus, the calculated lifetimes are not reliable if any of the following conditions is fulfilled:

- any of the horizontal scraper jaws position is below 16mm

- any of the vertical scraper jaws is out of its nominal position

An example of this deviation is shown in Fig. 5 during the 3rd scan.

2.4.2 Measured Beam Size Sensitivity

The machine coupling, K, is needed to calculate the energy acceptance and the Touschek lifetime. It is obtained from the pinhole image beam size as

$$K = \frac{\epsilon_y}{\epsilon_x}, \tag{15}$$

5

where ϵ_x is the horizontal emittance

$$\epsilon_x = \frac{\sigma_x^2 - (D_x\sigma_\delta)^2}{\beta_x}\,,\tag{16}$$

σ_δ is the energy spread and ϵ_y the vertical emittance

$$\epsilon_y = \frac{\sigma_y^2}{\beta_y}\,.\tag{17}$$

To have accurate beam size measurements through the pinhole it is very important to control both the filter thickness and the image quality.

It is also important to consider that any phenomena which affects the measured beam size but not the charge density inside each single bunch, such as multibunch instabilities, will cause wrong lifetime calculations. This is because we calculate the Touschek factor considering the coupling as an indicator of the charge density inside each bunch. But we measure the beam size with large exposure times at pinhole position (300ms), thus we are integrating light coming from all the bunches along 300 kturns. Therefore, if there are vertical multibunch instabilities our measured vertical beam size will be larger than the size of the individual bunches, and so the Tosuchek effect will be undererestimated because the system will assume less charge density than the real one.

This is an example of the possible applications of this simulator: if an instability occurs, the measured and calculated lifetimes will differ.

2.4.3 Filling Pattern

As mentioned above, the Touschek effect has to do with the intra-bunch electron scattering, i.e., on the charge density inside the bunch. But we do not measure the bunch population, but only the integrated beam current, to calculate the Touschek lifetime (see Subsection 2.2). This means that a certain filling pattern has been assumed for the calculation of the Ts 2D grid, which is the nominal one for normal operation (10 trains of 32 homogeneous bunches).

Thus, the lifetime will not be correctly calculated if the filling pattern of the machine is not the nominal one.

2.4.4 Signal Filtering

- **RF voltage**
  It is obtained as the sum of each cavity voltage. But, as the signals of the measured voltages at some cavities are sometimes noisy, we take the settings of the LLRF control loops instead. Moreover, in order to filter out the non-working cavities, we check the forward power in the waveguides and assign 0V if it is below 5kW.

  This solution introduce deviations in the calculated lifetimes during the switching on and off transients of the RF cavities, but it is the best option to avoid constant glitches on the calculated lifetimes. An example of these deviations can be seen in Fig. 5 before the first scan.

- **CCG**
  To filter bad readings of any CCG, we assign the storage ring average pressure to those sensors with values under 10^{-11} mbar.

- **Beam size**
  It has been programmed to assign 0 to all the calculated lifetimes, emittances and coupling if the gaussian fit of the pinhole image does not converge, to avoid providing meaningless lifetime values if the pinhole image is not correct (e.g, because the Storage Ring current is too low or the image ROI is not the proper one).

3 Control System Integration

3.1 Overview

The calculations detailed in the previous section have been integrated in the ALBA control system through a dedicated DynamicDS: sr/di/calc.

These parameters are seen by the user as regular Tango attributes, and so they can be archived and accessed from all the standard taurus widgets and tango applications (taurustrend, taurusform, taurusplot, etc.).

The following new attributes have been created and are acquired continuously: EnergyAcceptance, Coupling, EmittanceX, EmittanceY, TotalVoltage, ApertureH, ApretureY, CalcTouschekLifetime, CalcGasLifetime, CalcLifeTime, CalcProduct, CalcLifetimeError...

Currently, the attributes included in the ALBA archiving system (both Time Data Base and Historic Data Base) are: CalcLifeTime, CalcProduct, CalcGasLifeTime, CalcTouschekLifetime, TotalVoltage and Coupling.

3.2 DynamicDS

The DynamicDS are powerful tools which allow the users to create and configure Dynamic Attributes *on their own* without the know-how required to program a regular Device Server (DS) from scratch. They are a class from the Fandango module. For more information, see [4, 5, 6].

All the Dynamic Attributes (which can be constants or variables) must use Tango types and can take their values from other attributes from other DS processed by mathematical operations and Python coding. They can be created and edited using Jive, as a Property of the DynamicDS. Nevertheless it is better to create a file and use the Property "Load-FromFile" to write the filename with the absolute path. In our case, the source code of the sr/di/calc Dynamic Attributes is in the following file:

```
/control/user-scripts/composers/sr_di_calc.py
```

Moreover, all the sr/di/calc Dynamic Attributes have been configured to give Warnings, Description, Units and Format. All these detalis can be checked using Jive.

3.3 Extra Modules: User Defined Libraries

Since the lifetime calculations need the Scipy 2D interpolators and access to data files to update the machine functions and other parameters, a new feature was added by our controls group to the DynamicDS called Extra Modules.

This is a way to use python scripts (which are executed in the CompactPCI where the DynamicDS is running) every time the Device Server is started. And also the objects and funcions programmed there can be imported to the Dynamic Attributes environment to be used inside the DynamicDS. They are like user libraries for *usual* programmers.

For the sr/di/calc these scripts are in a subdirectory of the ALBA PYTHONPATH: `/control/user-packages/malvarez`

This *user library* does the following tasks:

- reads three different data files and write all the relevant values into Dynamic Attributes

  - `/data/MML/Release/measdata/ALBA/StorageRing/LOCO/BendTwiss.out`
    for the machine functions from last LOCO analysis

  - `/data/Diagnostics/ubaldo/pinhole/results.dat`
    for the SR Energy spread from the last execution of acdiEmittance.py script

  - `/data/MML/Release/machine/ALBA/CommonApplications/Pressure_beta.h5`
    for the β_y local values at ccg positions

- creates the interpolator objects that are used by the DynamicDS to obtain the values of the energy accpetance and Touschek factor continuously.

4 User Interface

Taking advantadge of the integration in the ALBA control system, a *user friendly* GUI has been built using Taurus GUI application.

The main features of the Lifetime GUI are:

- provide a calculated lifetime, which can be compared with the measured lifetime

- provide a simulator to predict the lifetime if the machine parameters change

The GUI can be launched from all the Control Room machines by typing `$ acopLifeTime` in a Linux console.

Three different Perspectives have been set in the *Factory Settings* version:

1. **Life Time Calculator**
   Fig. 2 shows the standard perspective for operation. It provides the main machine parameters, the different lifetime components calculated by the sr/di/calc DS and the measured lifetime at DCCT.
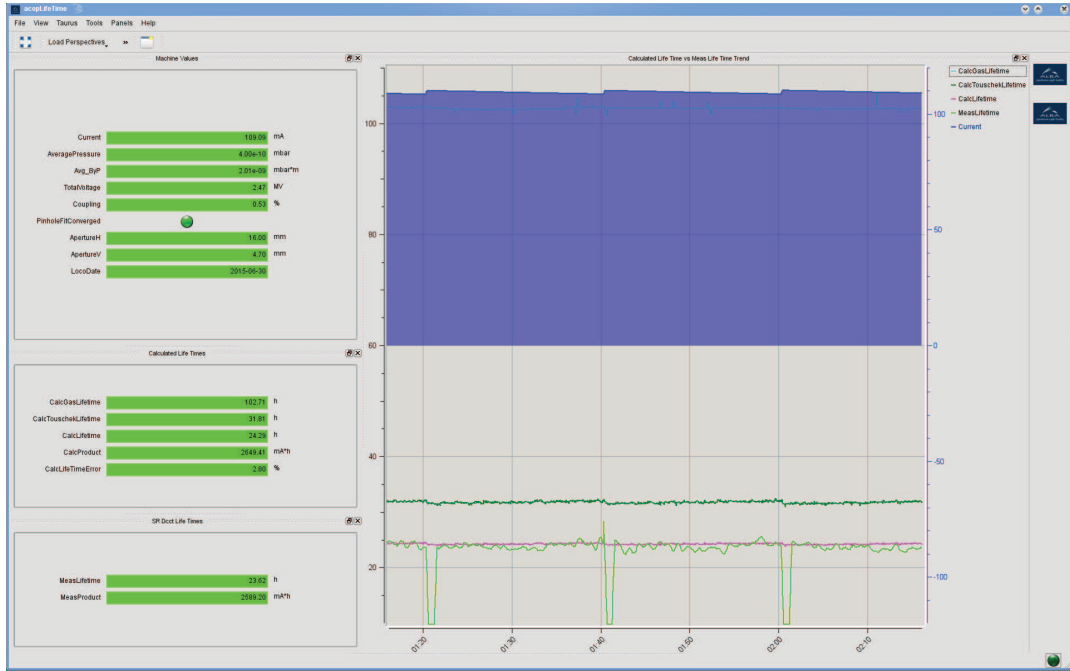
Figure 2: Snapshot of the Life Time Calculator Perspective.

2. **Life Time Simulator**

Fig. 3 shows the simulator environment which allows to predict the lifetime for different conditions of the machine.

The parameters which can be defined by the user are: current, average pressure, RF voltage and coupling.

For each parameter there are 3 fields:

- UserDefValue

- SetMachineValue: True = Takes the measured value // False = Takes the UserDefValue

- SimulatorValue: Value used by the simulator to calculate the theoretical lifetimes. It can be used as a readback to confirm that the change of the SetMachineValue has been applied.

3. **Expert View**

Fig. 4 shows the expert perspective, that has additional information which can be useful to diagnose problems related with the sr/di/calc DS or understand possible deviations of the calculations.
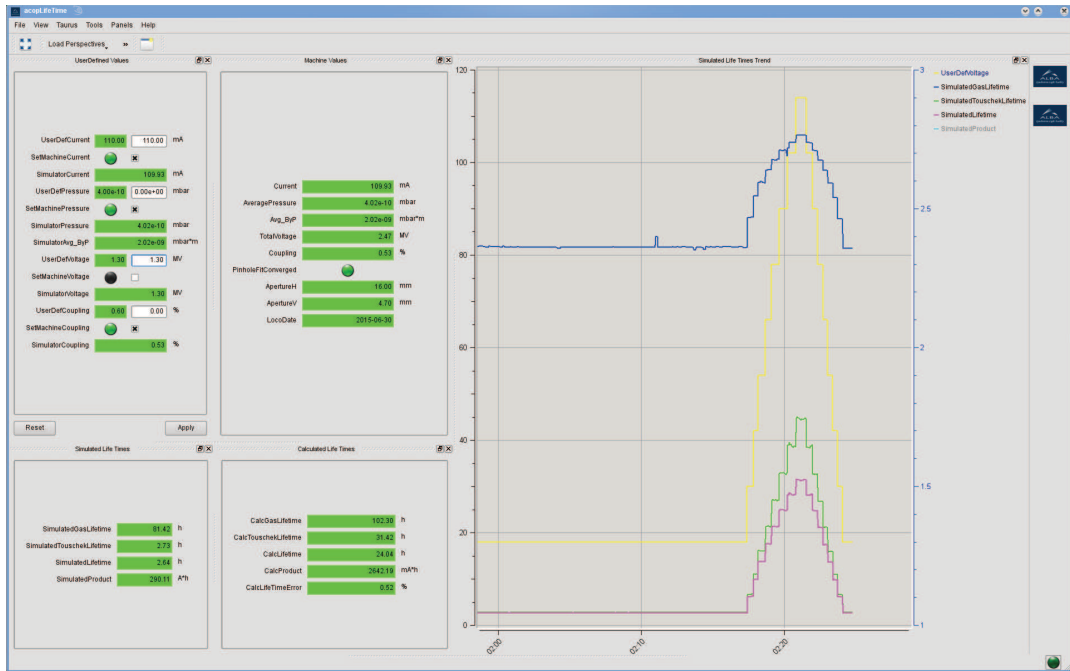
9

Figure 3: Snapshot of the Life Time Simulator Perspective with a UserDef RF Voltage Scan.

Figure 4: Snapshot of the Expert View Perspective.

5 System Test

Once the *user libraries* and the Dynamic Attributes were programmed, the new DS was tested during dedicated beam time. For that we performed scans of coupling and voltage to confirm the agreement between the lifetime calculated by the sr/di/calc and the measured one from the DCCT signal.

The results (Fig. 5) show that the calculated lifetime follows the measured lifetime throughout the first and second scan, performed in the same conditions, i.e., with the nominal scrapers and 5 of the 6 RF cavities ON.

During the third scan there is no agreement between the calculated and the measured values. That is because the horizontal scraper was closed (out of the nominal value) to lower the noise in the measured lifetime signal (the larger the current slope, the lower the measurement noise). See Subsection 2.2 for details.

At the beginning of the plot, there is a little step down in the calculated lifetime and RF voltage traces. This is related with the switching off transient of an RF cavity (in this case, it was SR-10A) due to the signal processing method used to get the total RF voltage. See Subsubsection 2.4.4 for details.
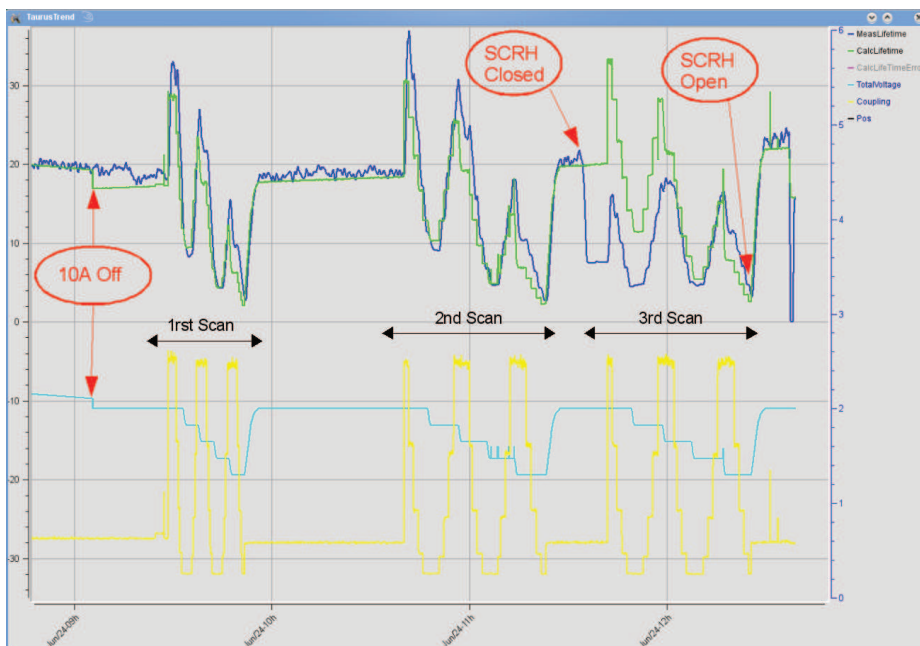

Figure 5: Evolution of the measured lifetime (blue trace) and calculated lifetime (green) during three V_{RF} (light blue) and coupling (yellow) scans.

Finally, in order to make it easier to track the agreement between the calculated and measured lifetime, we created an attribute (CalcLifeTimeError) which shows the relative error of the calculated lifetime

$$\text{CalcLifeTimeError } [\%] = \frac{\text{CalcLifeTime - MeasLifeTime}}{\text{MeasLifeTime}} \cdot 100 \tag{18}$$

11

6 Summary

- The DynamicDS for lifetime calculation and simulation is already comissioned and working properly.

- In operation mode, we have a CalcLifeTimeError below 5% (wrt the measured lifetime).

- We can detect deviations of the nominal parameters of the SR by observing changes on the theoretical lifetime calculation.

- We can estimate the theoretical lifetime in different conditions by setting user defined values for certain parameters.

- The main attributes are archived both at TDB and HDB.

- We have room for improvement by implementing 4D grids for Touschek factors and energy acceptance, including vertical and horizontal limiting apertures.

7 Acknowledgements

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