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Optimization of Neutrino Rates from the EURISOL Beta-beam Acclerator Complex

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Abstract

The beta beam concept for the production of intense (anti-)neutrino beams is now well established. A baseline design has recently been published for a beta-beam facility at CERN. It has the virtue of respecting the known limitations of the CERN PS and SPS synchrotrons, but falls short of delivering the requested annual rate of neutrinos. We report on a first analysis to increase the rate using the baseline ions of 6He and 18 Ne. A powerful method to understand the functional dependence of the many parameters that influence the figure of merit for a given facility is available with modern analytical calculation software. The method requires that a symbolic analytical description is produced of the full accelerator chain. Such a description has been made using Mathematica for the proposed beta beam facility at CERN. The direct access from Mathematica to an ORACLE database for reading basic design parameters and re-injecting derived parameters for completion of the parameter list is both convenient and efficient.

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Optimization of Neutrino Rates from the EURISOL Beta-beam Accelerator Complex

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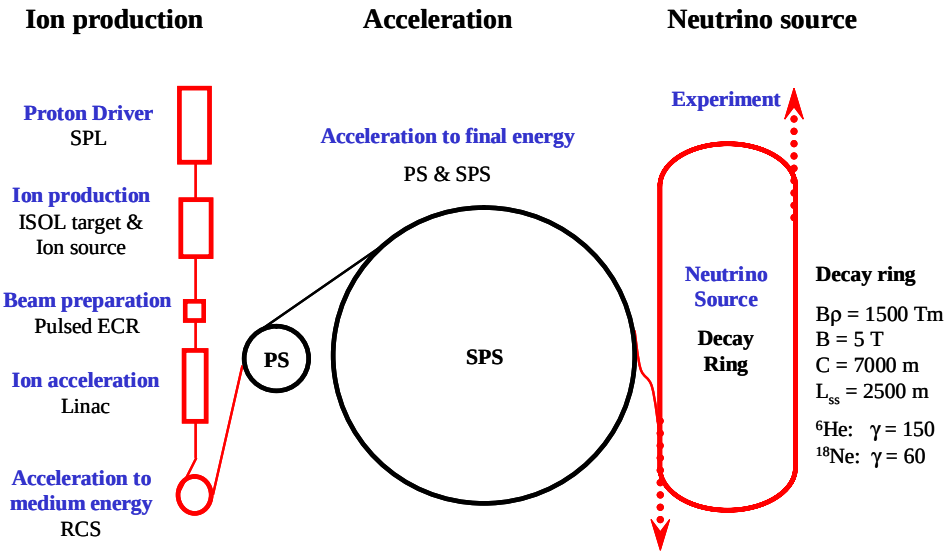
The beta beam concept for the production of intense (anti-)neutrino beams is now well established. A baseline design has recently been published for a beta-beam facility at CERN. It has the virtue of respecting the known limitations of the CERN PS and SPS synchrotrons, but falls short of delivering the requested annual rate of neutrinos. We report on a first analysis to increase the rate using the baseline ions of 6He and 18 Ne. A powerful method to understand the functional dependence of the many parameters that influence the figure of merit for a given facility is available with modern analytical calculation software. The method requires that a symbolic analytical description is produced of the full accelerator chain. Such a description has been made using Mathematica for the proposed beta beam facility at CERN. The direct access from Mathematica to an ORACLE database for reading basic design parameters and re-injecting derived parameters for completion of the parameter list is both convenient and efficient.

■ Introduction

A powerful method to understand the functional dependence of the many parameters influencing the figure of merit for a certain facility is available with modern analytical calculation software. The method requires that a symbolic analytical description is produced of the full accelerator chain and such a description has been done for the proposed EURISOL beta-beam facility at CERN using Mathematica [3–5]. Each process in each machine requires the solution of a set of differential equations to produce the resultant beam intensity given the intial one. The complete chain of accelerators is modelled simply by evaluating all such steps in the correct order. Care has been taken to express all inter-related parameters using delayed assignments. This permits dynamic scoping using the mechanism of Mathematica blocks. Thus, for example, results can be visualized as two-dimensional plots of the figure of merit as a function any of the machine parameters open to optimization. However, it is important to note that while such plots will help to identify the right parameter space for a requested machine design, they do not themselves guarantee that a realizable technical solution can be found. The work presented here has been done respecting the constraint of using the existing CERN accelerators, PS and SPS and accelerating the baseline ions of 6He and 18Ne. In addition, the current decay ring design [6] is used even though it has been assumed that the Lorenz gamma of the stored ions can be changed without major changes to the lattice of the decay ring. For the stacking we have assumed that 15 6He bunches and 20 18Ne bunches can be merged in the decay ring without major losses. The situation is slightly better for 18Ne, which due to a more advantageous charge-to-mass ratio, will see an almost three times larger longitudinal acceptance of the decay ring. Theoretically this would permit up to 45 merges for 18Ne, but known limits in low level RF beam control precision restricts it to a maximum of 20 merges. All parameters for the EURISOL DS baseline of May 2005 are documented in the appendixes of [4,5].

Below we can see the machines involved in the beta beam production from the proton driver (here a superconducting linear proton accelerator), accelerating protons for radiactive ion production on a target, to the final decay ring. The ions decaying on the straight sections produce (anti-)neutrinos useful for the experiments.



■ Annual Neutrino Production Rates

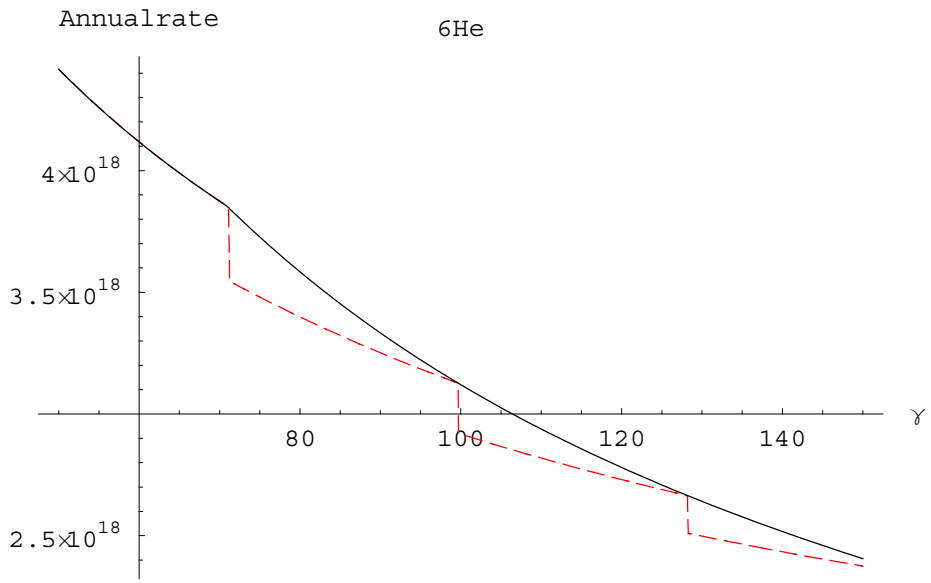
The figure of merit for the beta-beam is the rate (R) of (anti-)neutrinos at the end of one of the straight sections in the decay ring over a given period and it can be expressed as,

$$R = \frac{I_{in} \times f}{T_{rep}} \times \left(1 - 2^{-\frac{mr \times T_{rep}}{\gamma_{top} t_{half}}}\right) \times T_{run}$$

where the mr is the number of merges that can be done in the decay ring without major losses from the merging process itself, T_{rep} is the repetition period for the fills in the decay ring, γ_{top} the gamma factor of the decay ring, t_{half} the half life at rest for the ions, I_{in} the total number of ions injected into the decay ring for each fill, f the fraction of the decay ring length for the straight section generating the neutrino beam and T_{run} the length in seconds of the run. The first term gives the rate per chosen period for the ideal decay ring in which an endless number of merges can be accepted, the second term gives the limit set by the restriction on maximum number of merges that can be accepted due to longitudinal emittance limitations and the third term is by convention chosen as the length of a “snow mass year” [7] which is used as an international standard to calculate running time of high energy physics experiments and it is 10^7 seconds long.

■ Gamma Dependence of the CERN Baseline

The gamma dependence of the rate is mainly due to the gamma dependence of the acceleration time in the SPS, the lifetime of the ions in the decay ring and of the available longitudinal acceptance in the decay ring. The acceleration time in the SPS has a minimum length depending on hardware limitations and also increases in steps of 1.2 seconds due to the basic timing period of the CERN accelerator complex. For a given radiofrequency (RF) voltage, the longitudinal acceptance will to first order scale as the square root of gamma. Below we see the dependence of 6He. The maximum gamma that can be reached with the CERN SPS for 6He is 150 and for 18Ne 250. Below we see the annual rate of anti-neutrinos from 6He as a function of gamma . The red dashed line shows the annual rate with the given source rate respecting a basic period of 1.2 seconds of the CERN accelerator complex. The solid line shows the same dependence but with a "smooth" choice of acceleration time for PS and SPS.



■ Simulating Beam Losses in *Mathematica*

One of the major issues of the accelerator chain of the beta-beam concept are beam losses caused by particle decay. The beta-decay of unstable isotopes changes the charge-to-mass ratio leading to beam loss due to the changed magnetic forces. Based on beta-beam cycle optimized for the neutrino rate [4,5] one can calculate the energy loss in the various machines of the accelerator chain. The parent particle population N(t) as a function of time during accumulation, acceleration and storage decreases like

$$\frac{d}{dt} N(t) = \frac{\ln(2)}{t_{1/2}\,\gamma(t)} \times N(t) \qquad (1)$$

where $t_{1/2}$ is the half-live of the isotope at rest and $\gamma(t)$ the usual relativistic parameter. The daugther particles with the changed charge-to-mass ratio are lost more or less equally distributed over the circumference of the machine. There is a certain dependence on the accelerator lattice, which is neglected here. The energy of

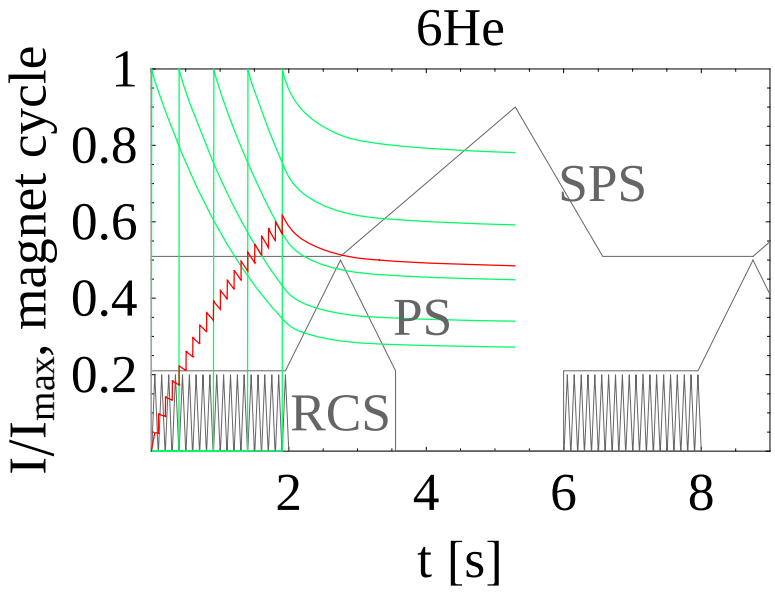
the particles lost from the beam will be deposited in the vicinity of the beam line, mainly in magnetic elements and shielding. The lost energy is calculated as

$$E_{loss/cycle} = \int_0^{t_{cycle}} \frac{dN}{dt} \times T(t)\, dt \qquad (2)$$

where T is the kinetic energy and t_{cycle} is the cycle time of the Beta-beam complex. A representativenumber, which can be compared with other accelerator cases, is the time-averaged power loss per unit circumference of the machine:

$$P_{loss/l} = \frac{E_{loss/cycle}}{t_{cycle} \times circumference_{machine}} \qquad (3)$$

The acceleration cycle for the Beta-beam baseline accelerator complex [5] is shown below for 6He. For illustration purposes the single bunch intensities (green) are indicated for the 1st, 5th, 10th, 15th and 20th bunch.



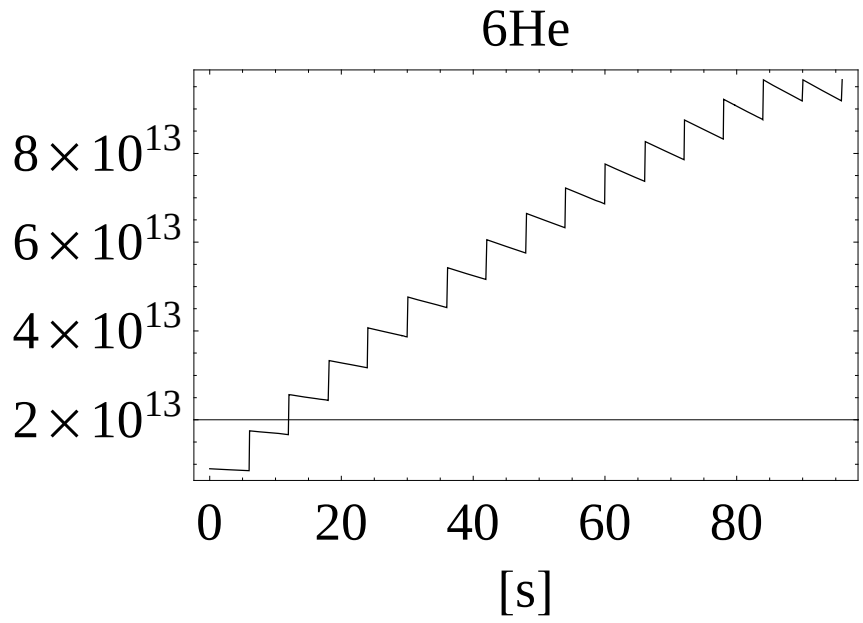
Different accelerator machines are used sequentially to accelerate the isotopes to the top energy, where they are injected in to the decay ring. The RCS is operated at 10 Hz. 20 RCS bunches are accumulated at injection energy in the PS over 1.9 seconds. The beam is then accelerated in PS and SPS to $\gamma = 100$. The magnet cycles of the RCS, PS and SPS are superimposed. The black, solid line indicates the repetition of post acceleration at 10 Hz, followed by the acceleration of the accumulated bunches through the PS and the SPS. 20 new bunches are sent from the SPS to the decay ring every 6 seconds in the 6He case. During the long accumulation in the PS at low gamma and the following acceleration at low gamma, the intensity of the bunches decreases remarkably. E.g., the first bunch injected into the PS has a remaining intensity at the end of the PS accumulation of about 35% for 6He. The bunches injected later remain with accordingly higher intensity at the end of PS accumulation. This is illustrated with green lines showing single bunch intensities. All intensities are normalized to the equivalent maximum intensity, which occurs at the individual injection from the RCS. The total intensity is indicated by the red line, normalized to the total number of ions injected into the RCS. The highest values of the time averaged power loss are estimated to 3 W/m, which occur in the PS machine and are comparable to the ones of existing high intensity operation

scenarios like CNGS[8], which is to start in May 2006.

Below is shown, as an example, the last step of the chain, the calculation of the intensity of accumulated 6He ions in the decay ring. Epern is the ion rest mass and topTpern is the ion top energy.

```
decayringaccumulation := (ClearAll[n];
  gamma[t_] := 1 + topTpern / Epern;
  decayrate[t_] := Log[2] n[t] / (gamma[t] thalf);
  eqns = {D[n[t], t] == -decayrate[t], n[0] == nout6};
  nsinglebatch[t_] = n[t] /. DSolve[eqns, n[t], t] // First;
  n[t_] = Sum[UnitStep[t - t0]
     UnitStep[t0 + mergesratio * spsrepetitiontime - t] *
     nsinglebatch[t - t0], {t0, 0, t, spsrepetitiontime}];
  nout7 = n[(mergesratio - 1) spsrepetitiontime])
fullchain := (spsout; decayringaccumulation)
 (* spsout is the accumulated intensity
   from the preceding step, the SPS ring *)


fullchain
Plot[n[t], {t, 0, (mergesratio + 1) spsrepetitiontime + 10^-4},
  PlotLabel → name,
  FrameLabel → {"[s]", None}, PlotRange → All];
```



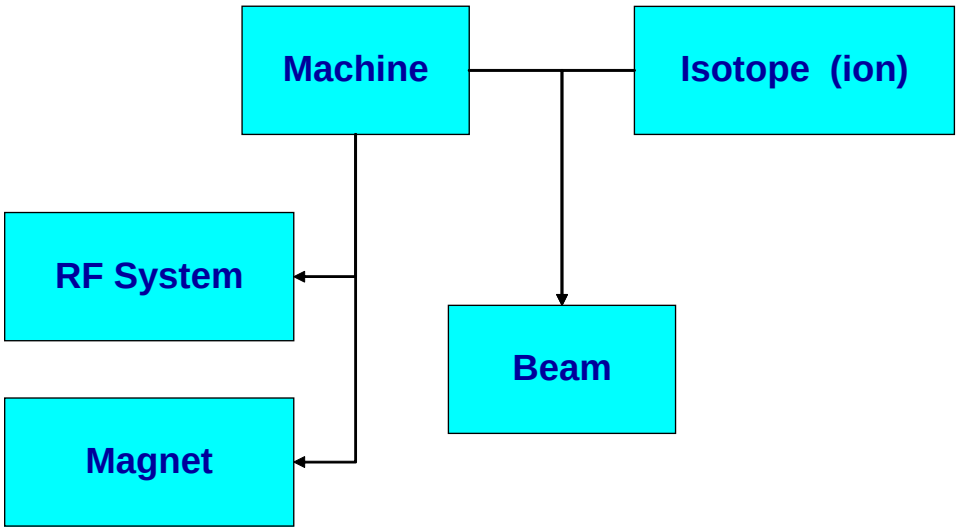
The intensities in the different machines, from the target to the decay ring are calculated using *Mathematica*. Basic design data is stored in a database and can be accessed after data base connection and reading in of baseline data from the data base and used in the calculations.

■ Baseline Parameters Database

□ Database Design

To develop a new project invloving many people and many institutes demands the use of similar standards and the same basic parameters and units troughout the community. Information accessible on the Web is not enough. The need is not only a common source but also versioning of the base-line parameter set and a possibility for users to read and make updates of the parameter lists from *Mathematica*. Our approach to these reqirements is to define a database for parameter storage. On top of this database is built a package in *Mathematica* that permits easy access to the parameters in the database. Users can develop their applications in *Mathematica* accessing directly the parameters, using their specific identifiers.

We have designed a generic database able to store the description of any system with objects having a tree or a network structure. This design meets the requirements for the storage for the parameters of a system in evolution (storing the system metadata together with the parameters, extensibility, versioning, and logging the changes). To simplify the design the allowed type of the network was limited by the condition that each node may have only one or two parents. This is enough for the project (see the system schema on the figure below; arrows represent the one-to-many relationship, the beam object has two parents: machine and ion).



Each object can have variable list of parameters defined. The number of parameters defined for an object type is not limited. The *values* of a given parameter are scalar and can have various sources:

- Given value. The value has to be inserted manually, and for each value the exact source (published document, presentation, web site etc.) must be specified. All sources are registered in the detailed *Data Sources list.*
- Automated input from *Mathematica* (for the parameters derived from other parameters with complex calculations).
- Calculated on the fly upon parameter access (the formulae are defined and stored in the database along with the parameter definition).

The type of the source for parameter values and unit for the numeric values are defined (fixed) in the parameter definition. The value itself can be either numeric or alpha-numeric. The transparent access to the parameter values is obtained through

the stored database procedures, which encapsulate the optional parameter calculation and, if required, translate the parameter value into the number format, HTML or *Mathematica* strings.

□ Working with the Database in *Mathematica*

This loads the package *DatabaseLink*

```
Needs["DatabaseLink`"]
```

Open the database connection (specific database access parameters may be added inside the square brackets or the user can select a named connection using the Connection Tool):

```
conn = OpenSQLConnection[];
```

The following command uses an Oracle specific stored database package to add the application information to the current database session:

```
SQLExecute[conn,
  "call dbms_application_info.set_client_info('
    Mathematica: beta beam parameters calculation')"];
```

This defines a function to retrieve a numeric parameter value from the database. BB.PVALUE is a custom PL/SQL package function stored in the database, which performs the work to search for the parameter named **par** for the component **object**:

```
GetParameterValue[object_String, par_String] :=
 First[First[
   SQLExecute[conn,
    "select BB.PVALUE(`1`,`2`) from dual", {object, par}]]]
```

An example:

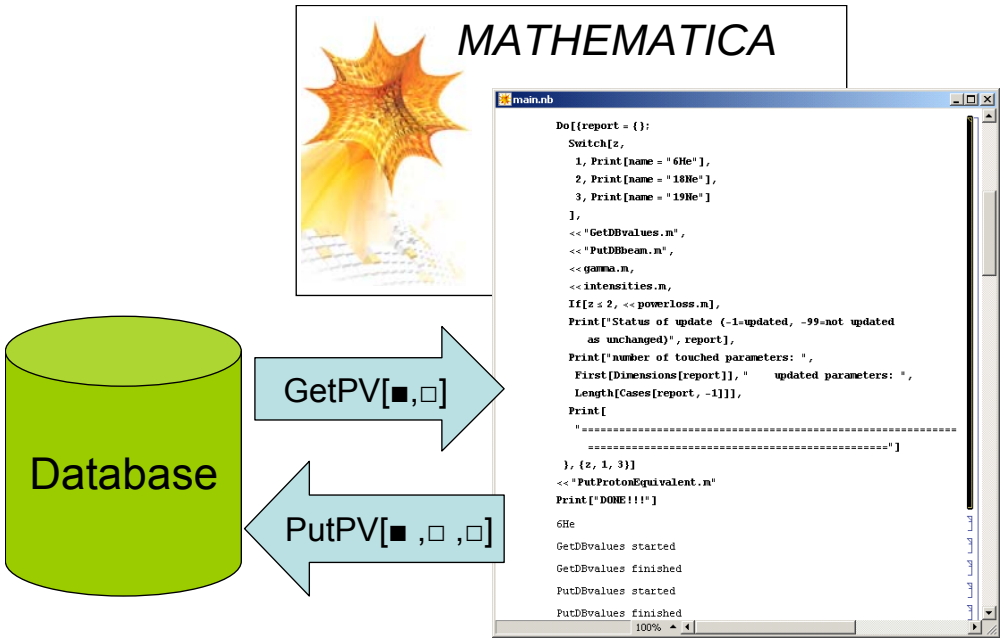
```
GetParameterValue["6He", "ion_thalf"]
```

```
0.81
```

The compexity of the functions is encapsulated in a package. A set of functions was defined to retrive, to change and to delete the parameter values: `GetPV[□,□]`, `PutPV[□,□,□]` and `DelPV[□,□]`. The two last functions are used only by the person in charge of maintaining the parameter list and requires the connection to an Oracle account having specific rights on the parameter database.

□ Setting Up the Derived Parameter Values in *Mathematica*

The updates of the parameters are made by the responsible for the contents of the parameter database. The two functions `GetPV[□,□]` and `PutPV[□,□,□]` are used for this purpose, illustrated in the following way:



After opening the connection and the calculation of the derived parameters in *Mathematica* is made using the data retrieved from the database with the function `GetPV`. The derived parameters are then stored in the database with the function `PutPV`. The typical derived parameters update session looks as follows:

```
Do[{report = {};
  Switch[z,
   1, Print[name = "6He"],
   2, Print[name = "18Ne"],
   3, Print[name = "19Ne"]
  ],
  << "GetDBvalues.m",
  << "PutDBbeam.m",
  << gamma.m,
  << intensities.m,
  If[z ≤ 2, << powerloss.m],
  Print["Status of update (-1=updated,
     -99=not updated as unchanged)", report],
  Print["number of touched parameters: ",
   First[Dimensions[report]], "    updated parameters: ",
   Length[Cases[report, -1]]],
  Print[
   "==========
     ==========
     "]
 }, {z, 1, 3}]
<< "PutProtonEquivalent.m"
Print["DONE!!!"]
```

□ Using WebServices

Along with the Beta Beam Base-line parameters web site we provide a web service deployed as JWS in the Apache Axis application within CERN central J2EE service. With the use of the Web service the database connection is not needed:

```
Needs["WebServices`"]
WebServices`InstallService[
  "http://beta-beam-parameters-ws.web.cern.ch/beta-
    beam-parameters-ws/getParameterValue.jws?wsdl"];
GetPV[id_String, par_String] :=
  If[NumericQ[ToExpression[getString[id, par]]],
   ToExpression[getString[id, par]], getString[id, par]];
```

We have encountered a problem in receiving of the numeric parameter values as XML xsd:double numbers. Large scale numbers are not considered safe in the SOAP envelope (InvokeServiceOperation::insecure). It was decided to pass all parameter values as strings (all parameters values are stored in the database as strings) and process them as shown above.

```
{GetPV["6He", "ion_target_prod_rate"],
 GetPV["6He", "ion_target_method"]}
```

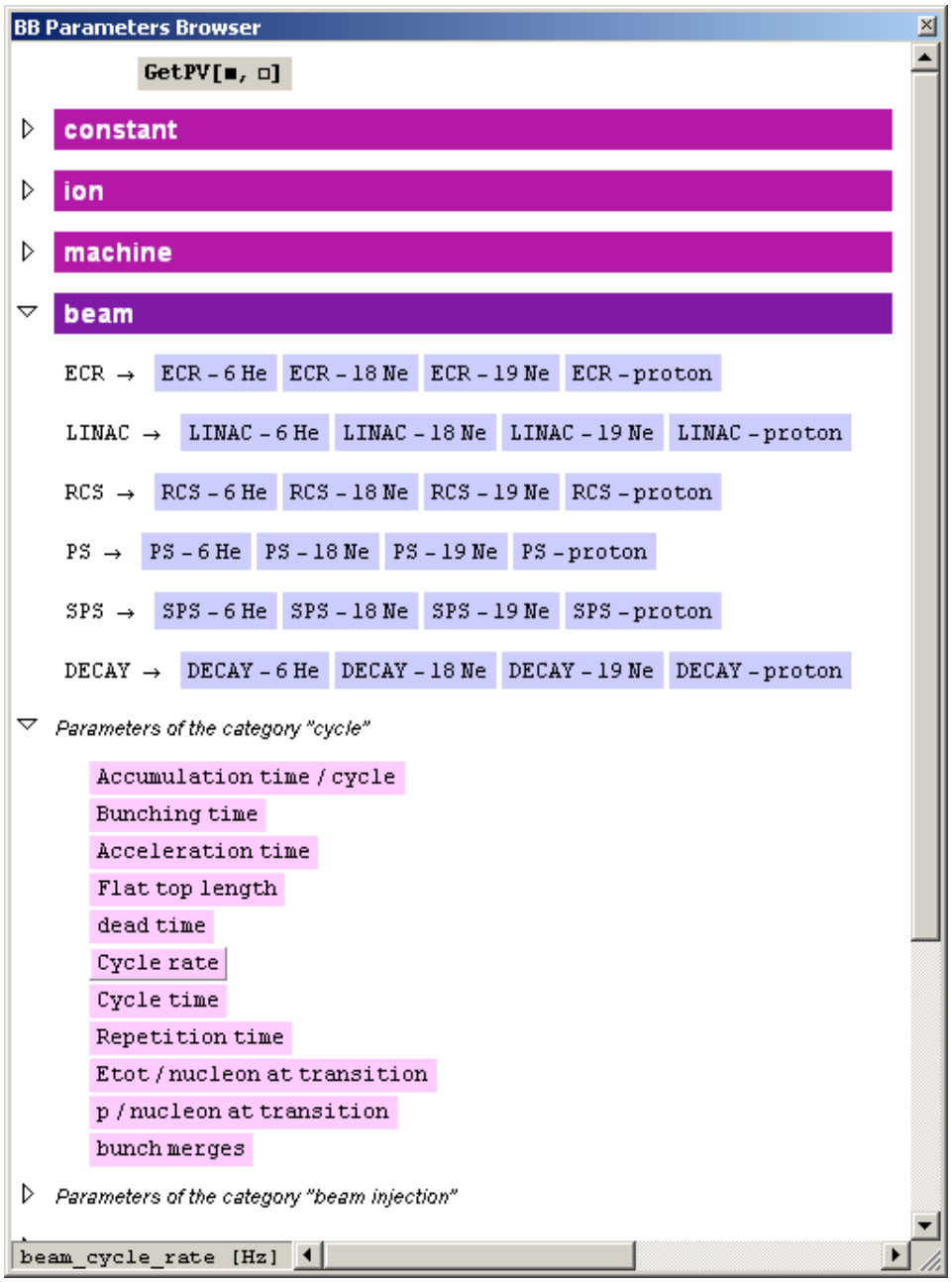
$\{4.97107 \times 10^{13}, \text{converter}\}$

□ Parameter Browser Palette

To ease the input of the object and parameter identifiers we have created a special palette where the objects and parameters can be searched by their common names. The palette notebook itself is generated in *Mathematica*; the current definitions of the objects and parameters are selected from the database and transformed into the button boxes.

```
<< "BBObjectBrowserMakerINIT.m"
```

```
NotebookObject[ <<BB Parameters Browser>> ]
```



When a user clicks on the object (blue) or parameter (rose) buttons, their identifiers are pasted into the user's active notebook. The `GetPV` function template button is also provided. When the user inserts the object identifier (for the first placeholder), the second placeholder is selected automatically. When the user points on a button, the value going to be pasted and the unit for the parameter (if it is the button for a parameter) is displayed in the status bar.

■ Conclusion

The database for the EURISOL beta beam parameters is now in operation. The possibility to easily integrate user applications in *Mathematica* with the parameter database either via the DatabaseLink or via the WebServices is a great help to have coherent information in all the different *Mathematica* applications used for otimally designing the beta beam complex to have a maximum number of useful decays in the decay ring. The data base design tools and the access tools in *Mathematica* may now be applied directly to other tasks of which some Large Hadron Collider upgrade applications and EURISOL applications are envisaged.

■ References

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