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Overview of the CASTLE circuit simulator*

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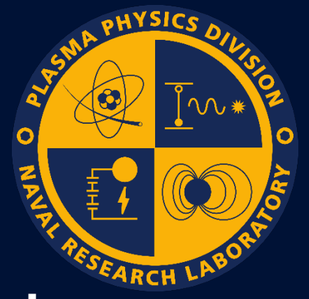

ABSTRACT

CASTLE (Circuit Analysis and Simulation with Transmission-Line Emphasis) is a PC based code for simulating nonlinear analog circuits, designed primarily for Pulsed Power. CASTLE is an MNA (Modified Nodal Analysis) code that does transient analysis in a way that is very similar to SPICE and its derivatives. One key difference is that CASTLE has a fixed time step while SPICE has a variable time step. There are two main reasons for the fixed time step. One is exact reproduction of the output of our transmission line code, Bertha. This is very important of benchmarking with and transfer of specialized physics based models of Pulsed Power diodes. The second reason is to avoid the too-small-time-step failures that SPICE often has with Pulsed Power circuits. The CASTLE simulator has the ability to speed simulation using a unique matrix reduction technique. CASTLE uses the self-isolating property of transmission lines, in a similar way as transmission-line codes, to turn one large matrix into several smaller ones. This can lead to dramatic speed advantages for very large circuits, compared to SPICE. CASTLE has recently added an MPI (Message-Passing Interface) mode to further speed simulation. Also, there is now a dll version (for both Windows and Linux) of CASTLE that allows it to be run from the command line or other programs such as Python or C++. CASTLE includes a schematic entry GUI with sufficient quality for presentation or publication. This generates a SPICE compatible netlist that is used by the simulator.

CASTLE (Circuit Analysis and Simulation with **Transmission-Line Emphasis**)

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- CASTLE, at its core, is a Modified Nodal Analysis (MNA) type of circuit simulator, like the famous SPICE (Simulation Program with Integrated Circuit Emphasis)
- CASTLE source code is maintained by NRL, Code 6770 (allen@nrl.navy.mil)
- **CASTLE was designed with Pulsed Power circuits in mind**, hence it has several features that make it better than SPICE derivatives for this application:
  - Fixed time step: Never fails like SPICE with time step too small error
  - Easy to connect transmission-line (TL) elements: No ground is required for simple TL connections
  - Advanced TL elements: Special elements like transmission-line transformers utilize transmission-line circuit code techniques to offer time step resolution for impedance transitions and any resistances.
  - Easy to add custom elements: Relatively easy to add custom elements, such as Railgun, Pinched-Beam Diode, Rod-Pinch Diode, etc.
  - Gives identical results as Transmission-Line circuit codes: This is extremely helpful transitioning old but well tested circuits and models from TL codes to CASTLE.
  - Free from convergence failures: Another common failure mode in SPICE is largely avoided in CASTLE (The semiconductor diode model is the only model that may fail to converge in rare circumstances).

CASTLE can be > **150X faster than LTSpice** for very large simulations

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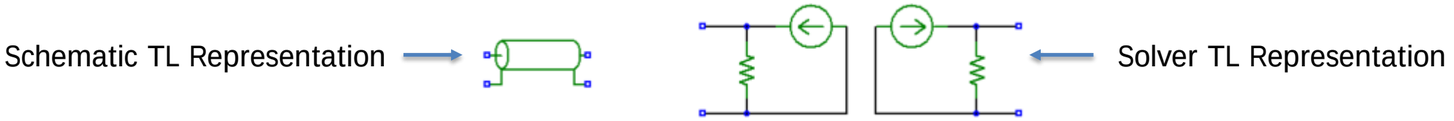
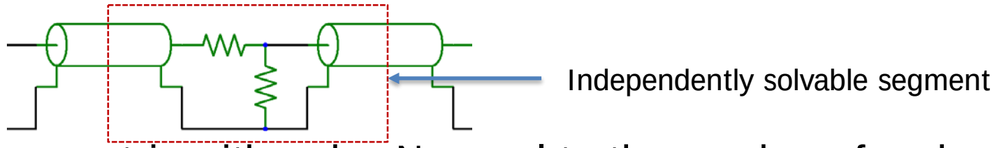
- CASTLE has not yet been optimized for speed, however there are two features that can make it much faster than LTSpice for very large simulations: Automatic Matrix Subdivision and a new MPI (Message-Passing Interface) mode.
- **Automatic Matrix Subdivision**
  - CASTLE uses the self-isolating property of transmission lines (TLs) to automatically subdivide the circuit into smaller, independently solvable segments
  - The two ends of a TL are not connected in the internal representation



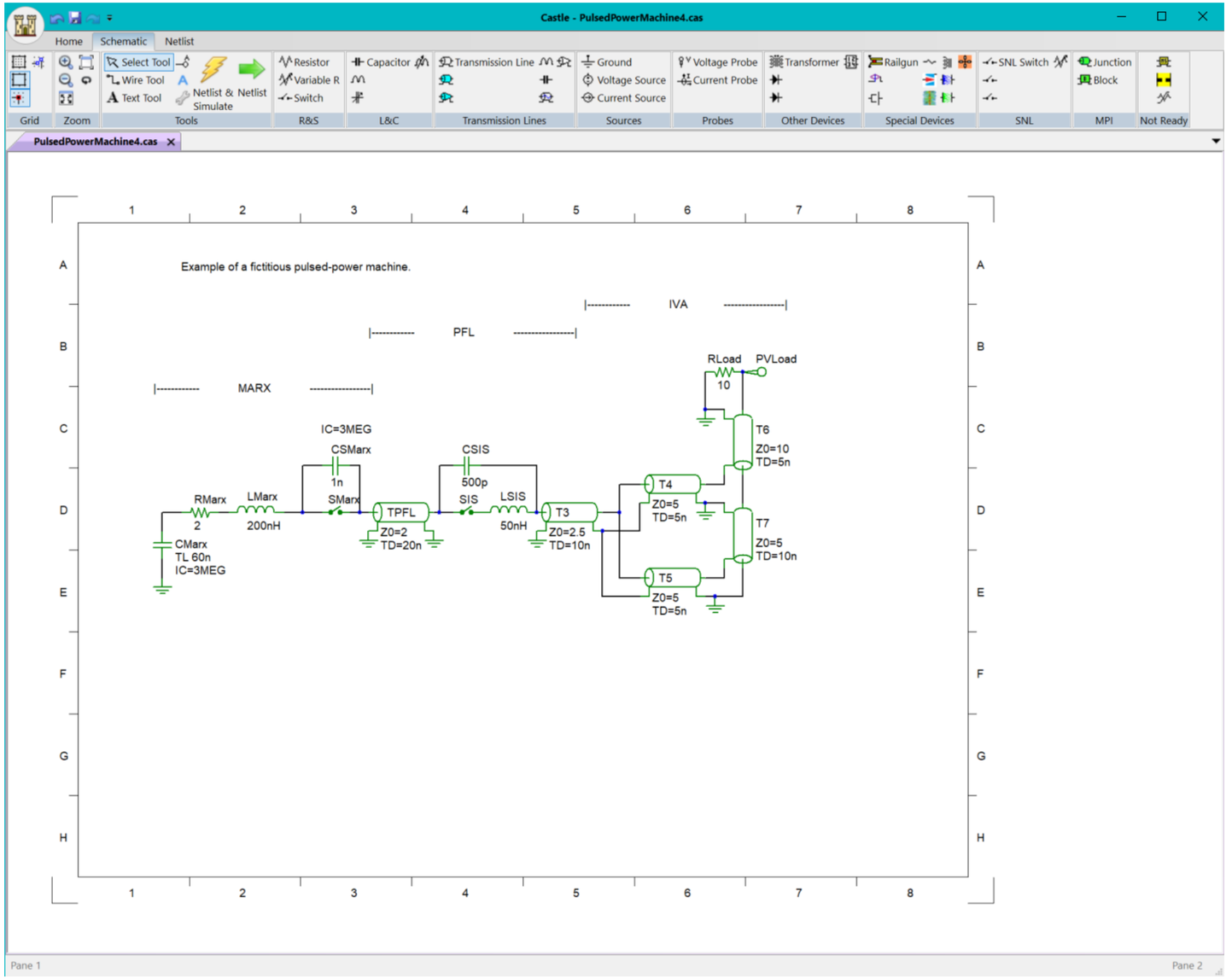
  - Any section of the circuit that is encapsulated by TLs can be solved independently



  - MNA codes need to invert a square matrix with order, N, equal to the number of nodes plus voltage sources in the circuit
  - Because the time needed to invert the matrix scales with N^X, where X ranges from ~2 (optimized solver) to 3 (basic solver), enormous speed advantages are realized in large circuits
- **MPI Mode**
  - CASTLE can now do multi-process simulations using MPI
  - Speed can be increased up to a factor equal to the number of cores in the computer

The Windows version of CASTLE includes a **GUI for Schematic Entry**

- The CASTLE Graphical User Interface (GUI) has many of the features common to circuit simulation programs
  - Optional grid
  - Zooming
  - Text Labels
  - Parameter evaluation
  - Subcircuits
  - Copy and Paste to PowerPoint
  - Several sheet sizes
- The GUI generates a netlist that is the input to the CASTLE circuit simulator



CASTLE has several **unique circuit elements** for Pulsed Power applications

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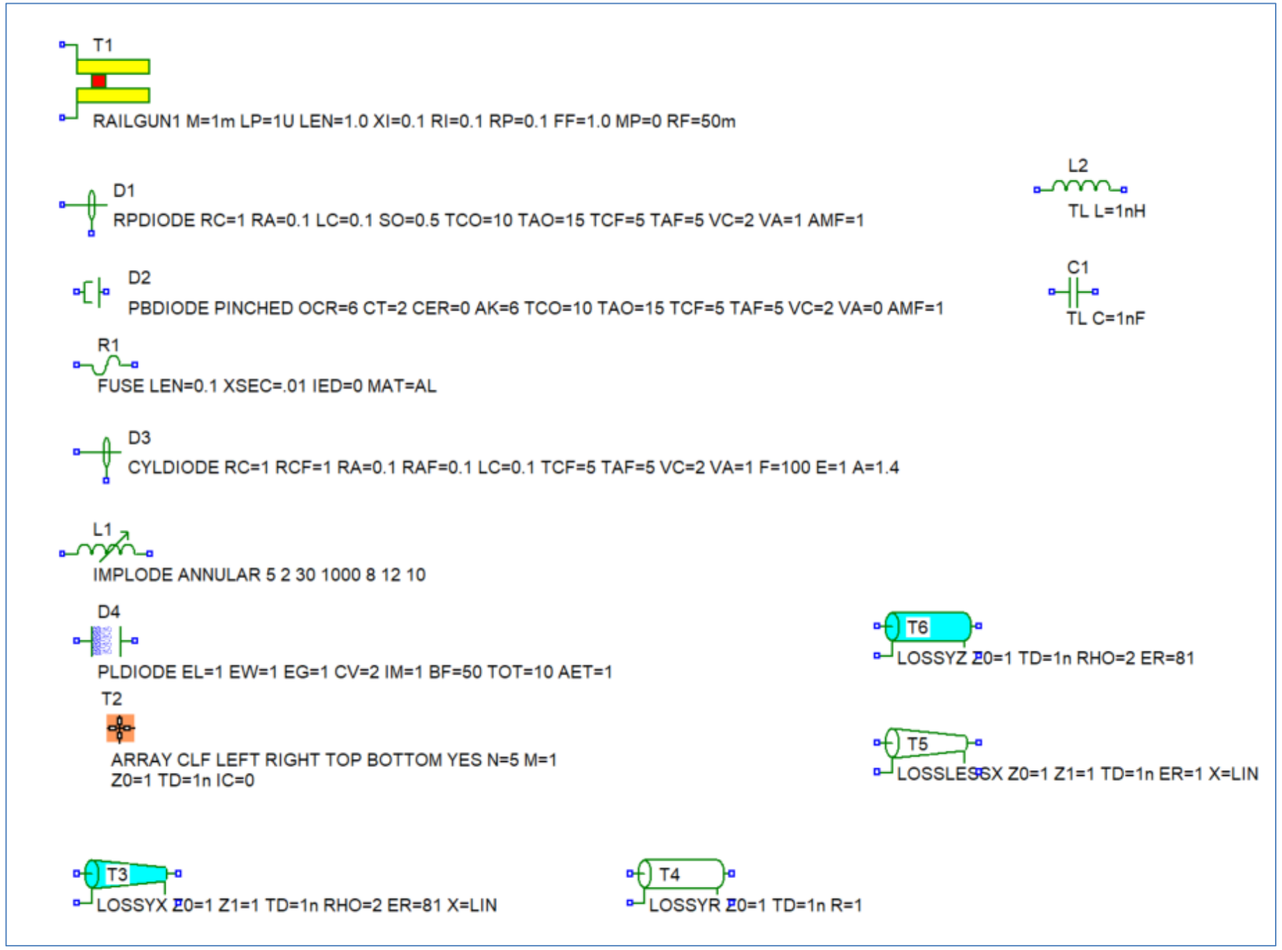
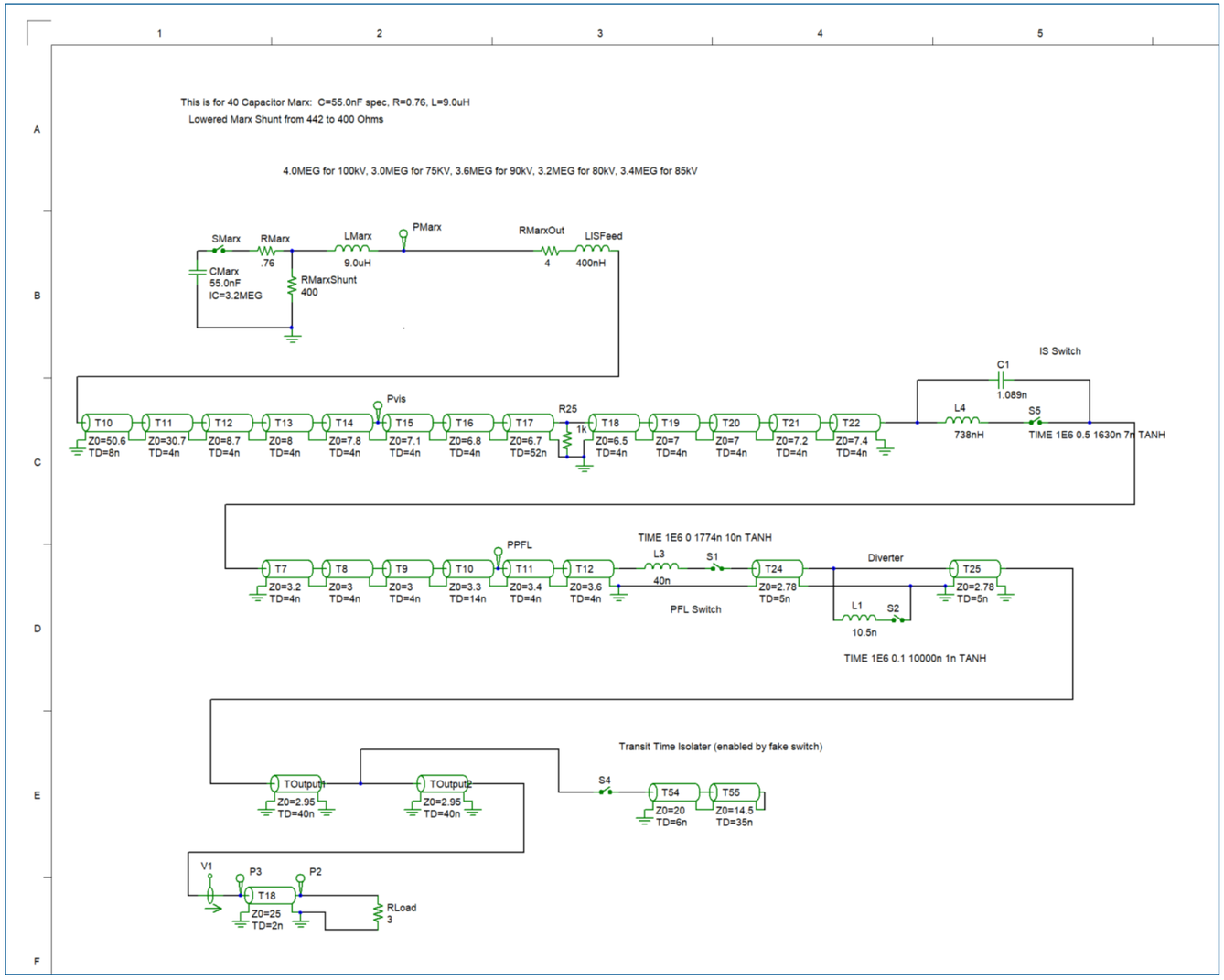
- Example Pulsed Power physics based models include Rod-Pinch Diode, Railgun, Pinched-Beam Diode, Exploding Fuse, Cylindrical Diode, Imploding Load, Planar Diode
  - Many of these were easily ported from out transmission line circuit code, Bertha
  - Comparison with Bertha output was used to verify the implementation in CASTLE
- Special TL based elements include a TL Capacitor, a TL Inductor, a Lossy TL, a Lossy TL Transformer, a Resistive TL, a Lossless TL Transformer, and a new TL Array
- CASTLE can now also include Bertha circuits
  - Additionally, Bertha can include CASTLE circuits



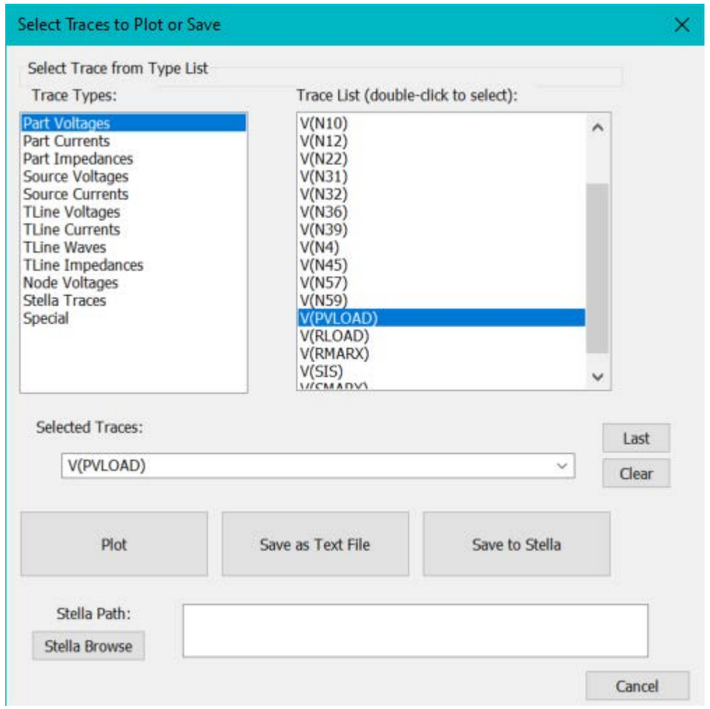
Example: The **Gamble II Circuit Model**

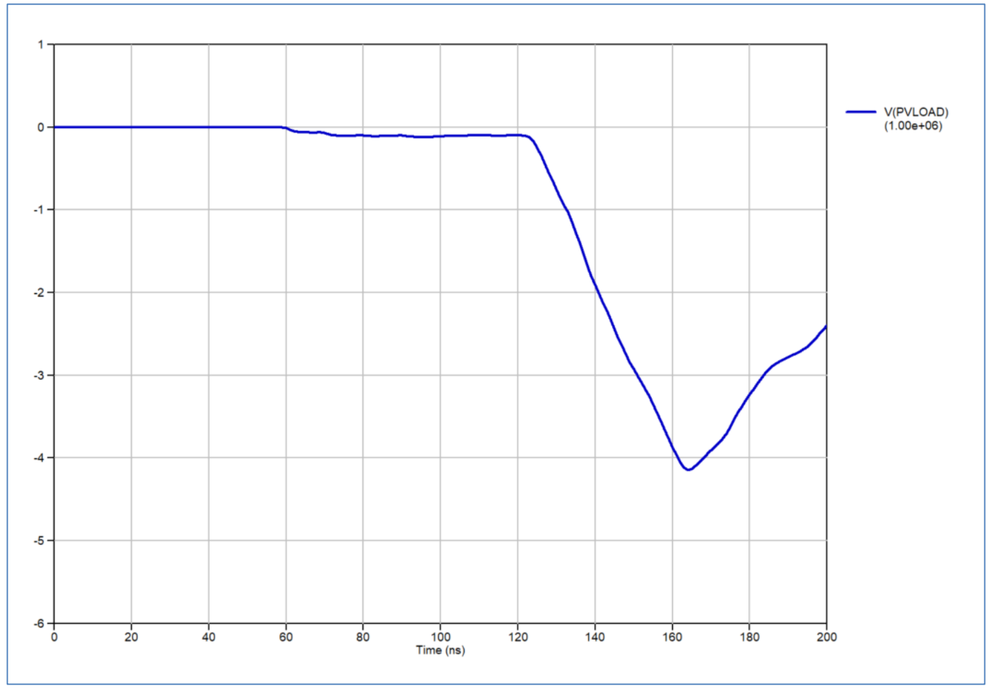
- The Gamble II circuit model is a good example of how CASTLE improved our circuit simulation capabilities
  - The Gamble II circuit diagram was originally a TL code text file
  - A graphical schematic was created from the TL code text and then verified to give identical results in CASTLE
  - Modifications to the model to include a new Marx and a constant, 3 Ω, output line were easily made in CASTLE



CASTLE includes a graphical output **trace plotter and text file output**

- After simulation, all traces are available for plotting and/or saving as a text file
  - CASTLE's plotting capabilities are currently very rudimentary
- Unique to CASTLE are TL wave outputs, including waves coming in and out of both ends
- Can also output directly to NRL's data capture and analysis software, Stella
  - Stella makes it easy to manipulate traces and can produce much better plots
- Controls such as .plot can automate data plotting and output file saving





CASTLE is relatively **easily coupled to other codes**, such as Chicago, for simultaneous simulations

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- CASTLE has been **coupled to the Chicago PIC code** (Voss Scientific)
  - **Aided by the fixed time step** that both codes employ
  - Allows simulations to be driven easily by complicated circuits by adding only a few lines to the input deck
  - Would be easy to replicate for other PIC (particle-in-cell) codes

- Coupling is enabled by an alternate, granular interface that allows passing of waves back and forth along stub transmission lines
  - CASTLE can be called by any code that supports transmission-line boundaries
  - CASTLE can call any code that provides this interface

- CASTLE has been coupled to our older, pure-TL code Bertha
  - CASTLE circuits can have Bertha sub-circuits and vice-versa
  - Example: a very large, almost-purely-TL circuit in Bertha can use CASTLE to handle more-complicated components
  - It would be straightforward to couple with other codes, (e.g. TLCode at L-3 Harris)

There are now **several ways to run CASTLE** simulations in latest versions

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- In CASTLE version 4, using the Windows GUI, castle.exe, was the only way to run simulations.
- With CASTLE version 5, a **new castle.dll file** was made available for running simulation in new ways
  - Can now run CASTLE netlists from Python, Matlab, and regular C++ codes
    - Have demonstrated automated circuit parameter optimization
  - Can also run CASTLE simulations from the Windows command line, allowing batch processing
  - Stella has now integrated CASTLE support so CASTLE netlists can be run from Stella macros
- The very latest, CASTLE version 6, includes a **new Linux .so file version** that can allow running of simulations on Linux machines
  - This will allow running of **CASTLE simulations on HPC**
  - When combined with MPI, should result in extremely fast simulations of large circuits

Summary

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- CASTLE is an MNA circuit simulator, **similar to SPICE, but with a fixed time step** that avoids simulations errors that are common with Pulsed Power circuits and also allows direct validation with transmission-line circuit codes
- CASTLE includes a unique matrix subdivision algorithm and also an MPI mode that allows very large simulations to run **> 150X faster than LTSpice**, for example
- CASTLE includes a **GUI for schematic entry** with publication quality views
- CASTLE has several unique circuit elements for **Pulsed Power physics based diode models** and also some special transmission line elements
- We were able to convert the **Gamble II circuit model** directly from TL code to CASTLE, verify it gave identical results, and now more easily update it.
- CASTLE **can plot output traces** directly, or one can save to Stella or text file
- The latest versions of CASTLE include a **.dll file** that allows CASTLE simulations to be run from **Python, Matlab, command line**, or just about any program allowing for automated parameter optimization.
- CASTLE is relatively **easily coupled to other codes** that employ a fixed time step, such as the PIC code, Chicago
- The very latest version of CASTLE includes a .so file that allows simulations to be run on **Linux**