



ARIES Systems Code Development & Results

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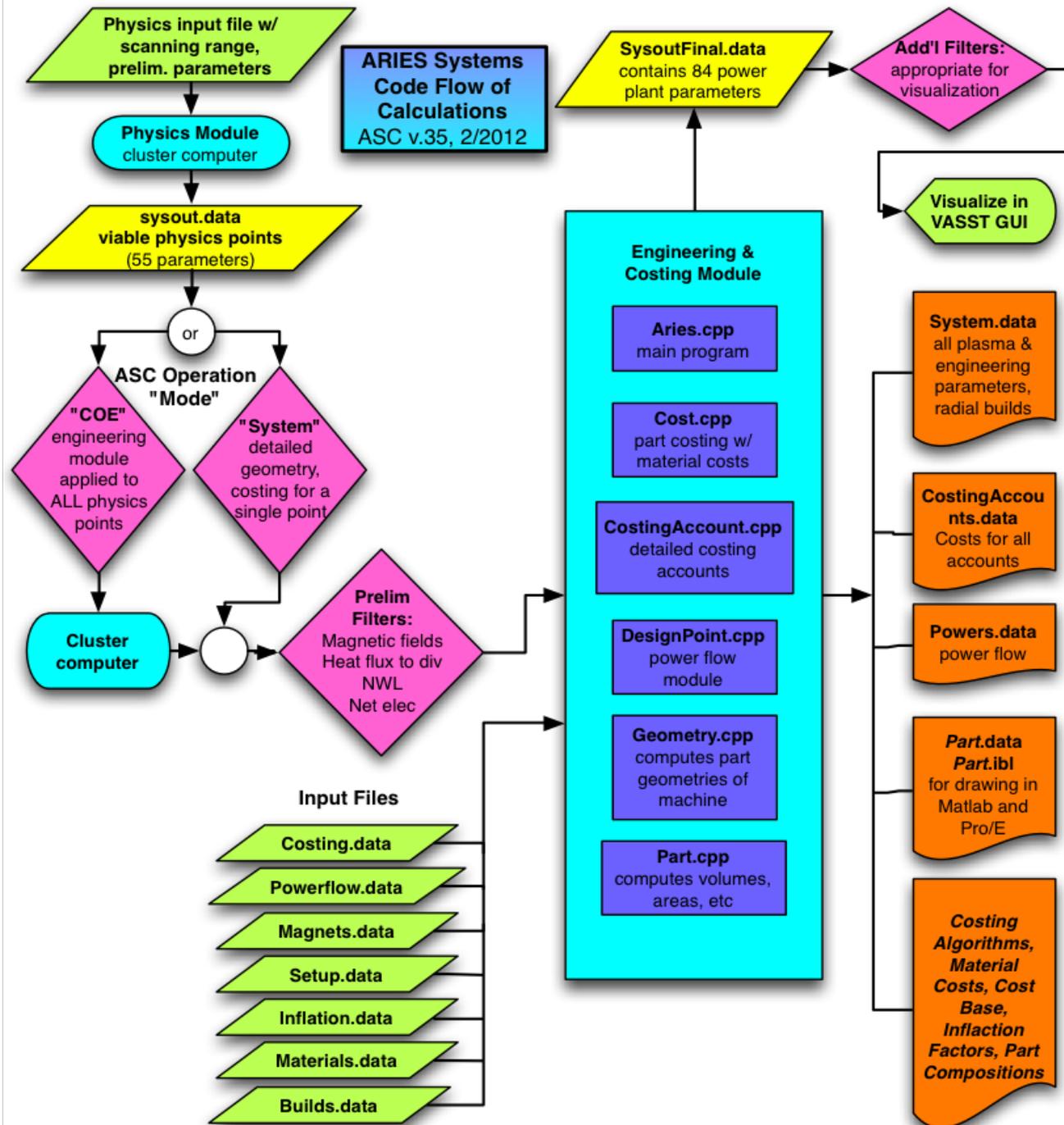
Outline of Progress

1. Improving and substantiating the ARIES Systems Code (ASC)
2. Documentation and ASC homepage
3. Strawmen points issued
4. VASST GUI for visualizing data

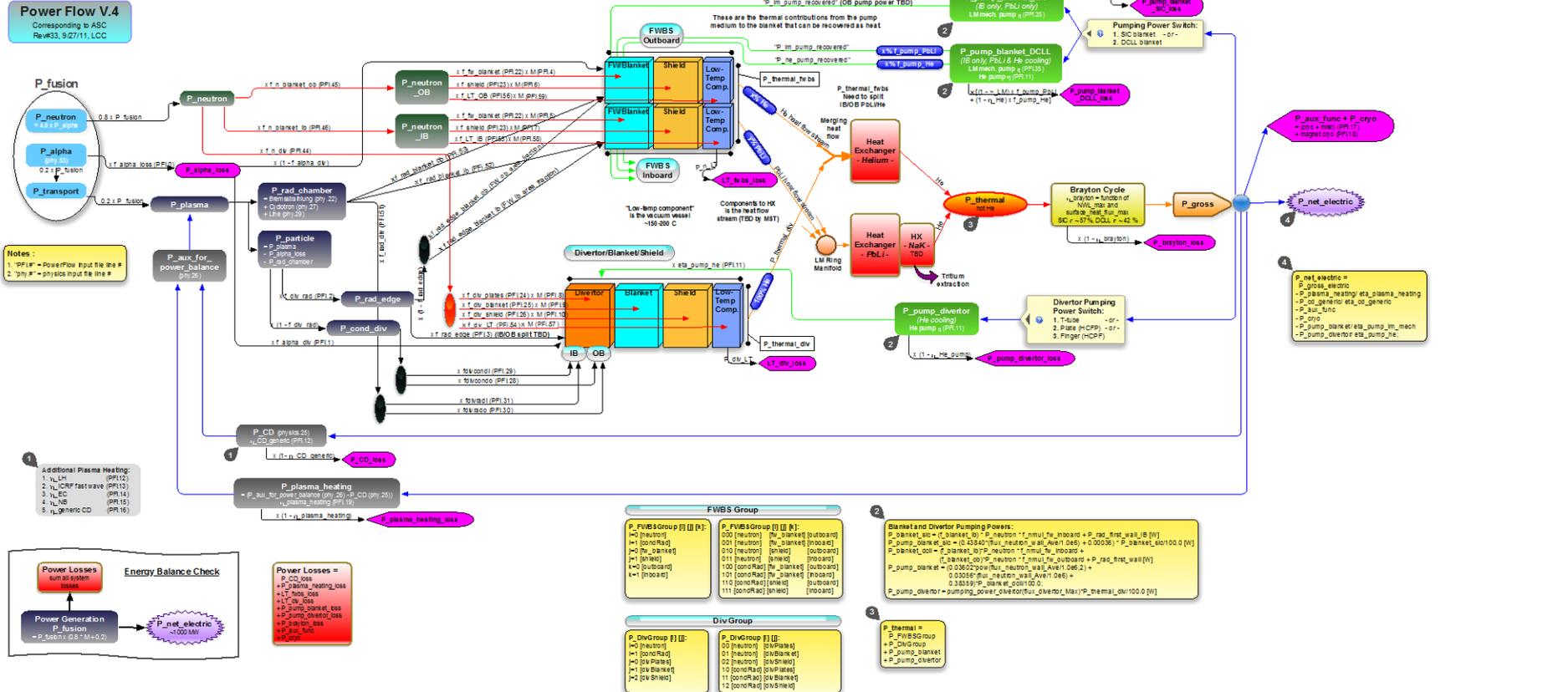
ASC Flow of Calculations

(medium detail)

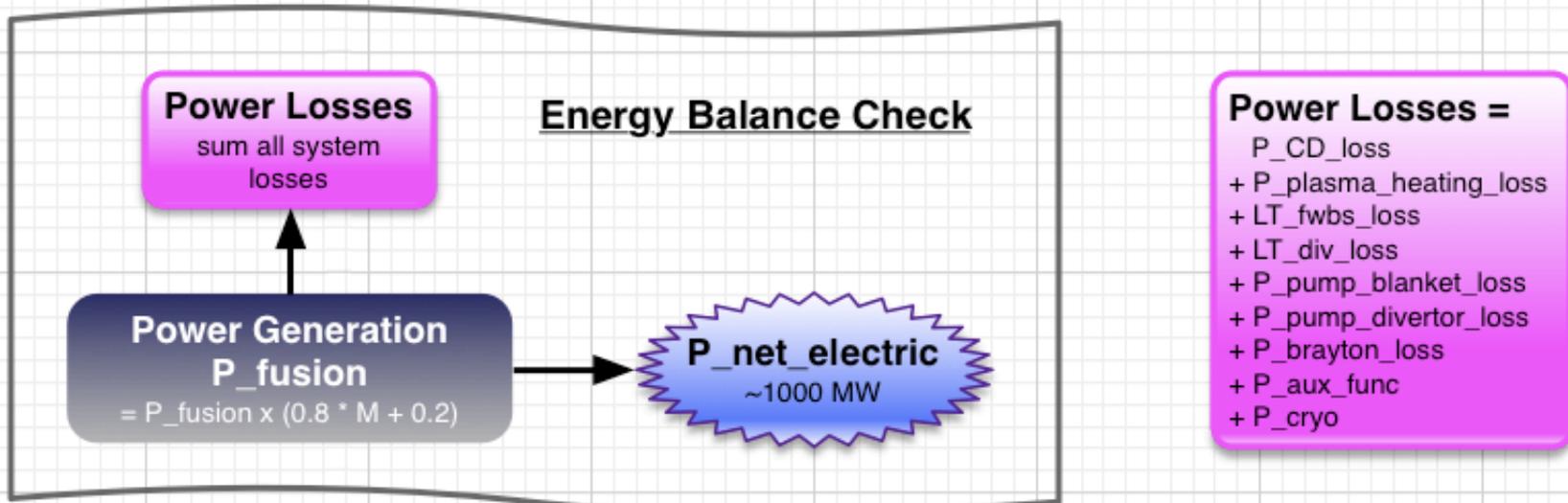
- Systems code consists of modular building blocks
- Two modes of operation
- Adjustable input files



Power Flow Diagram Ensures Power Accountability



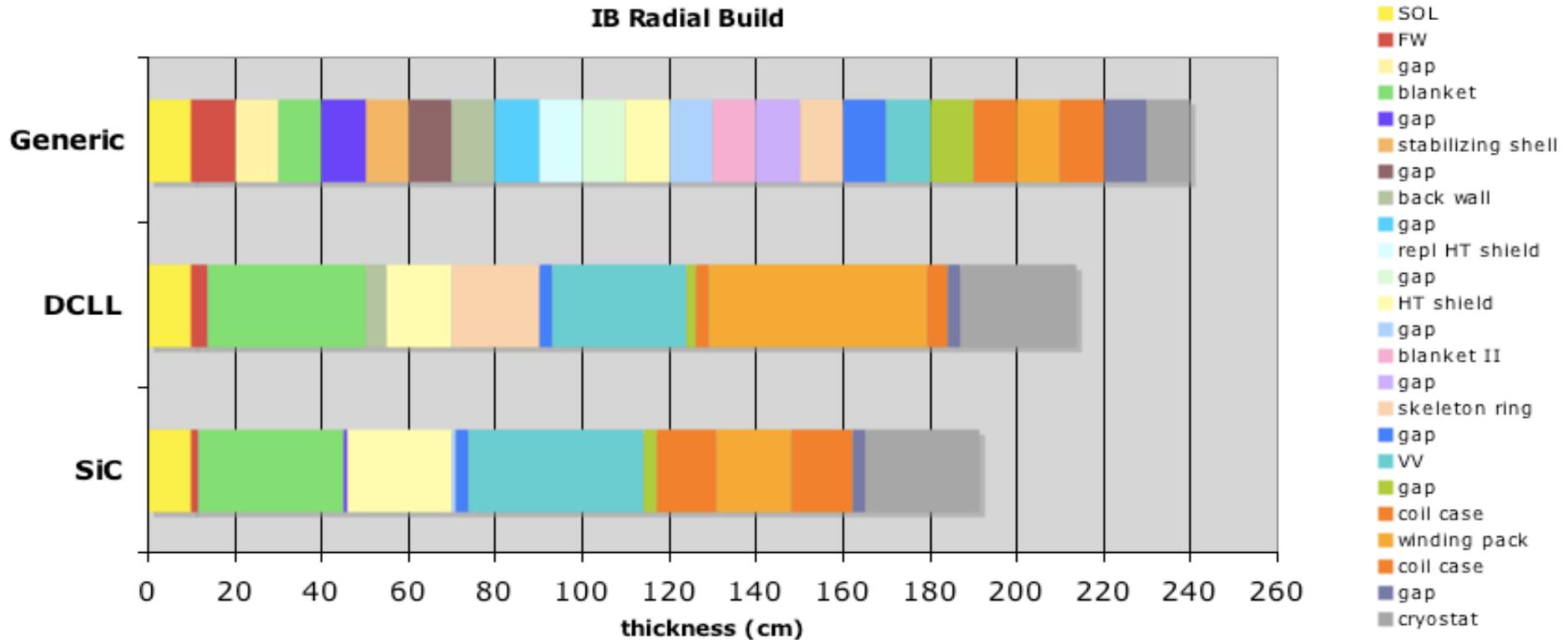
✓ Power Balance Verified ✓



	DCLL TEST CASE		ACT-Ib point	
Power Balance Check:			Power Balance Check:	
Power Generation [MW]:	3412.8		Power Generation [MW]:	1951.02
P_losses [MW]:			P_losses [MW]:	
P_plasma_heating_loss [MW]:	0.371163		P_plasma_heating_loss [MW]:	24.1256
P_cd_loss [MW]:	96.89		P_cd_loss [MW]:	26.9
P_brayton_loss [MW]:	2053.04		P_brayton_loss [MW]:	864.052
P_pump_blanket_loss [MW]:	1.81491		P_pump_blanket_loss [MW]:	0.640638
P_pump_divertor_loss [MW]	10.6583		P_pump_divertor_loss [MW]	1.91271
P_aux_func+P_cryo [MW]:	65		P_aux_func+P_cryo [MW]:	65
Sum of P_losses [MW]:	2227.78		Sum of P_losses [MW]:	982.631
Net Electrical Power [MW]:	1185.02		Net Electrical Power [MW]:	968.389
Leftover [MW]:	-4.55E-13	✓	Leftover [MW]:	1.14E-13

Generic radial build implemented

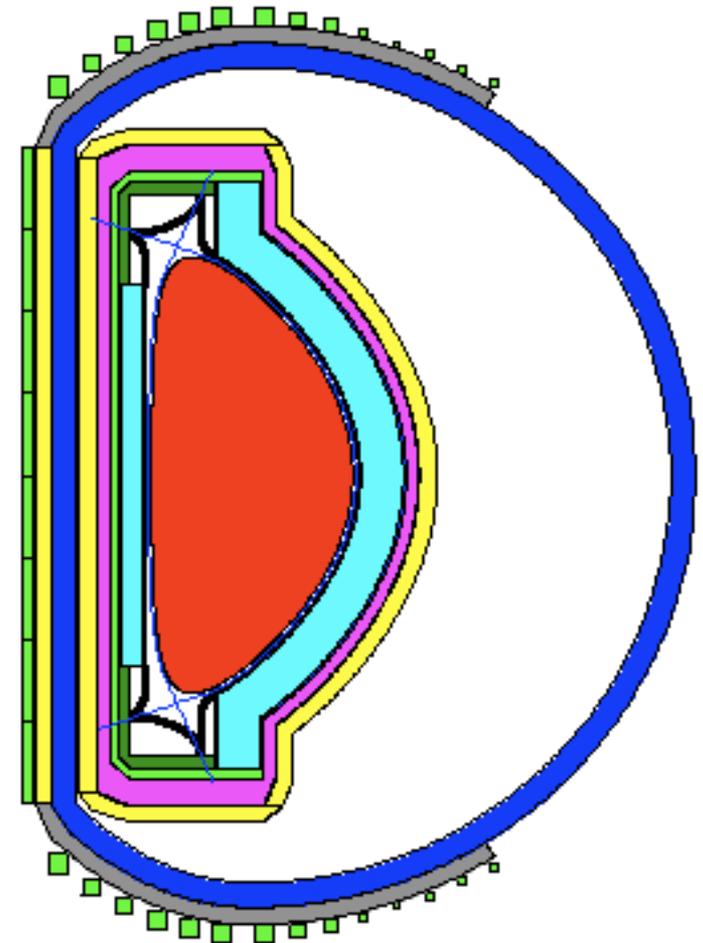
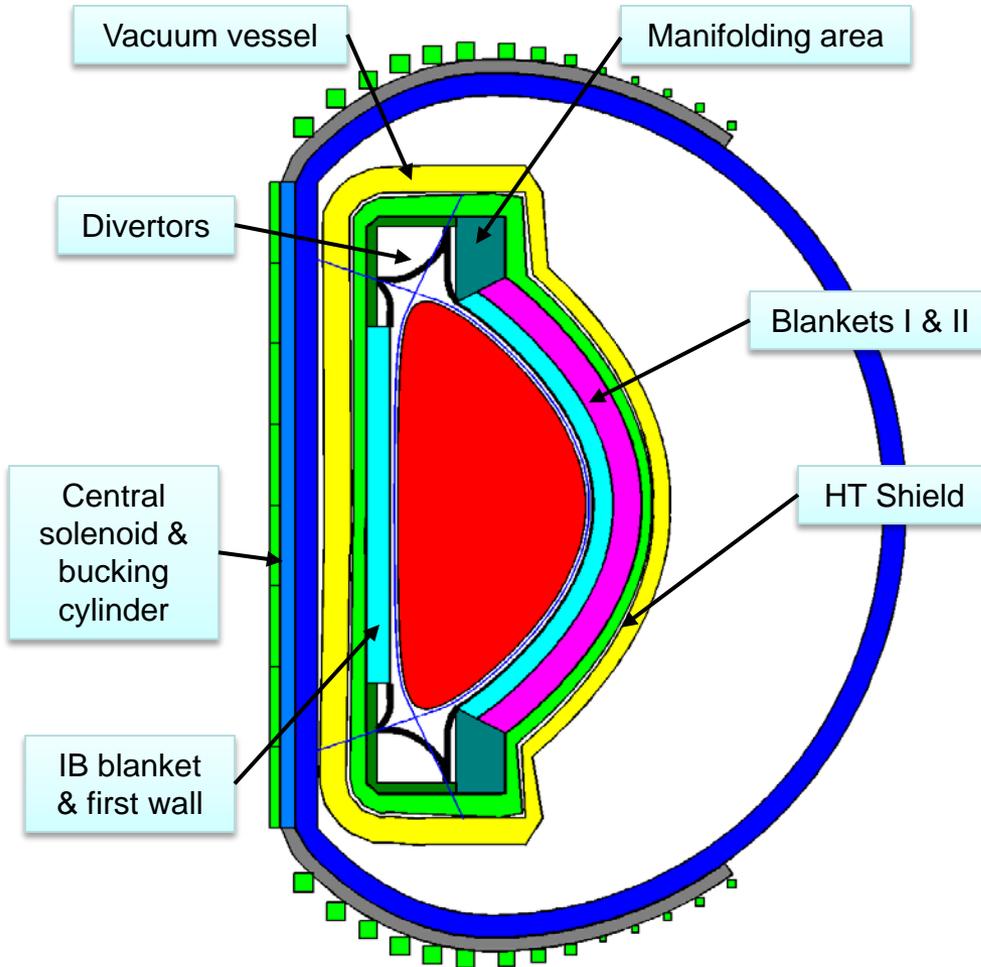
- Generic radial build allows true modularity of blankets to add components as required.
- Items not in use are given a thickness = 0.



ASC Constructs Radial Builds for Both Blankets

ACT-SA (c) SCLL

DCLL test case



All-encompassing ASC Homepage

1. History

2. Documentation

- Modifications
- Equations
- Code Modules
- Input & outputs
- Examples
- Flow of calculations
- Power flow diagram
- Reference documents
- Old documentation

3. Strawmen Points

4. VASST

<http://aries.ucsd.edu/carlson/aries/>



ARIES Systems Code Homepage

The Aries Systems Code (ASC) is a critical tool used in the process of identifying an attractive operating regime for a potential fusion power plant. The code integrates the most up-to-date physics from the fusion community, as well as sound engineering and costing models and algorithms to create a self-consistent and balanced power plant design. In the current pathways study (2010 – 2012), the code is being used for parametric evaluations in support of the major goals of the program as to asses areas of advanced physics and technology as well as conventional regimes. The systems code can determine which parameters, such as cost of electricity (COE), are sensitive to certain criteria or limitations placed on the design, and use a visualization tool to enhance and support the iterative design process.

Updated:	11/2011 by L. Carlson
Current Systems Code Version:	ASC v.34
History:	In ~2010, L. Carlson took over operation and maintenance of the systems code from Z. Dragojlovic. Since then, the ASC has undergone many revisions, updates and error corrections, which have been mainly documented in Aries Pathways project meetings. These can be found grouped together or in the Aries meeting archives .
Documentation:	Documents in support of the different systems code modules.
Strawmen Points:	The current study is tentatively named <i>Advanced and Conventional Tokamaks</i> or (ACT). Four combinations of advanced and conventional physics and technology create four corners that define the tokamak parameter space. The detailed parameters and specifications of various strawmen points can be found on this page.
VASST:	The Visual Aries Systems Scanning Tool (VASST) is a visualization and filtering tool written in Matlab. The tool takes the database of viable tokamak power plants from the systems code and is able to visualize a multitude of plots that are of interest to the user.

All modifications are listed to archive changes

○ **Modifications:**

- Subversion SVN version control
- SVN history log
- Modifications sheet (ASC_mods.xlsx)

Version	Date	Notes documented on SVN history file (author = lcarlson)
y.23	2011-01-10	Imported 14 core ASC files from Z.D., only SiC module files for now.
y.24	2011-01-10	Working on proper plasma surface area.
y.25	2011-01-10	End of the day backup, working on plasma surface areas and getting P_pump_blanket working again.
y.26	2011-01-24	LCC - multiple details before Aries Meeting on Jan 26, 2011. Notable work on restricting range of values for blanket and divertor pumping powers given from tables. Also trying to implement thermal recovery from MHD pumps. Corrected f_{geo_div} with the correct 10% ratio from Laila. See detailed comments within the code. Also work on the correct plasma surface area. Also trying to understand power balance and power flow - what is needed to inputs and what are the outputs.
y.27	2011-02-08	20110208 LCC: Many error corrections and modifications from the Jan 2011 meeting. Recommendations from Laila from her presentation. Also work on PF coils costing and volumes, cryostat (not complete), NWL corrected ~2.8-3.0 MW/m ² , SOL = 10cm, more to come. See ASC Legend 18.xls for complete listing of mods.
y.28	2011-02-11	20110211 LCC: backup right after sending Laila her Jan 2011 Aries presentation back after addressing many issues she raised. Some work on He costing in accounts 27.2 and 27.4, structural support volume added to CA.cpp account 22.5 and costed, this also required modification to the CA.h file, also corrected costing for 21.2 and 21.7 since AT volume correction factor needed "0" at the end of the numbers.
y.29	2011-03-04	2011-03-04 LCC: Major changes throughout all files. Comments from Laila E and Les W taken into account after Interim Printout from Feb 2011. See doc files "Laila validation re interim strawmen.doc" and "Validation of 2 11 ASC Strawmen (2 23 11).doc"
y.30	2011-03-09	2011-03-09 LCC: Committing the final version to SVN before running scans on the cluster to find new, revised strawmen #3. This incorporates the many comments from Les and Laila, finished up from the last rev #. About 95% of their comments have been implements, but there are a few that need lots of time to fix, e.g. breaking up HT shield into components behind the divertor. For references, see their comments listed in last rev #, plus ASC Legend 18.xls.
y.31	2011-04-15	2011-04-15 LCC: Lots of changes after the April 2011 strawmen have been issued, ACT-I, II. Have focused mainly on generalizing the code in anticipation to converting it to the DCLL blanket module. Right now, the two blankets are two entirely separate codes and all the work up until now has been on the SiC code. Focused on taking the data from inside the code and making it part of the input files. E.g. all the material properties are now one input file rather than part of Part.cpp. Also did inflation factors and CD costs and frequency and efficiencies. Also implemented a "tab;" after all the output files. This expedites the conversion so a webpage since they can be imported into excel and delimited by the colon and line right up into columns. For more details see ASC Legend 23.xls and ASC mods after modification #34 when the revision was locked at 30.



All equations are listed, explained and referenced

○ Equations:

- Volume calculations
- Blanket, divertor pumping powers
- First wall and divertor heat flux
- Power summation
- Gross cycle efficiency
- Current drive
- Part construction, references and constraints

Part or calculation

A. Plasma Surface Area

Ref. docs, where this
resides in the code, notes

Reference: C. Kessel 5/2011 "Plasma Contour2 – Kessel plasma geometry discretized formulas.pdf"
Code Modules: *Geometry.cpp* "1/2 Plasma Geometry – at plasma surface" & "2/2 Plasma Geometry – w attached."
Notes: Calculates the surface area of the plasma. The average neutron wall flux uses this by dividing neutron power by the plasma surface area.

Equations, notes,
assumptions

C. Discretized equations:

These take into account all the plasma factors that affect its size. This is the most accurate formula currently used in the code. To take advantage of symmetry, the contour shape is multiplied by two.

- $R = R_o + a \cos(\vartheta + \sin^{-1}(\delta) \sin(\vartheta))$
- $Z = a \kappa \sin(\vartheta + \zeta_o \sin(2\vartheta))$ for $\vartheta < \pi/2$
- $Z = a \kappa \sin(\vartheta + \zeta_i \sin(2\vartheta))$ for $\vartheta \geq \pi/2$

Defined variables and
explanations

- R_o = plasma major radius
- a = plasma minor radius (add SOL thickness here to find surface area incl. SOL)
- κ = plasma elongation
- δ = plasma triangularity
- ζ_o = plasma squareness on outboard side (~0)
- ζ_i = plasma squareness on inboard side (~0)
- ϑ = poloidal angle

- **Code Modules (C++):**

- Physics, Aries, Cost, Costing Accounts, Design Point, Geometry, Part.cpp

Code module →

- Date of documentation
- ASC version (SVN #)
- Module name
- History of the module
- Notes on module and its purpose
- Reference docs (viewable on ASC Documentation page)

Costing Accounts Module Equations

Revision: 10/2011 by L. Carlson

Code Version: ASC v.34

Code Modules: *CostingAccount.cpp*, *CostingAccount.h*

History: Z. Dragojlovic received from L. Waganer 12/2009. Since then we have made a few modifications, mainly related to replaceable algorithms.

Module note: This module applies detailed and intricate costing algorithms. The CostingAccounts.cpp module creates an output file and lists the results. Calculating the costs. There are no numbers in this file, only the code. The output file is the best way to stay up to date on the current algorithms, which are slightly dependent on the blanket in use.

Reference: *Complete costing account documentation by L. Waganer 10/11-25-10.doc*
MOST RECENT costing accounts and algorithms in spreadsheet "Algorithm Comparison (RevD.120910).xls"

Input files are more easily modified

○ Input files:

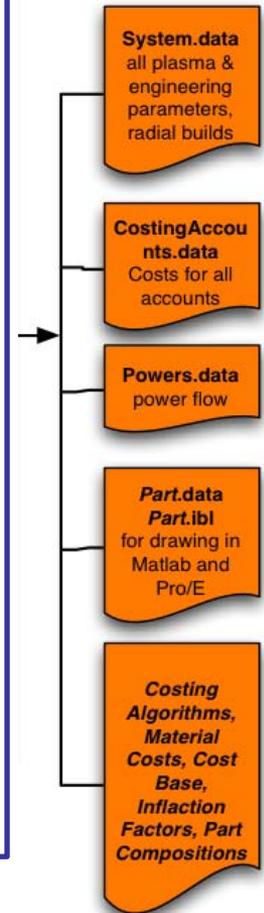
- Raw data file from physics module
- Setup files – choose divertor, blanket, scanning mode
- Runaries script – designates points to scan
- Radial build input file – IB, OB, vertical
- Materials – name, purpose, density, cost, cost basis year
- Inflation factors
- Costing parameters
- Magnets – TF and PF coil parameters
- Power flow – neutron multiplication factors, efficiencies, power flow fractions

```
PbLi
Li17Pb83_liquid_90%Li6_enrichment_650C
liquid_breeder_coolant
8897
9.06
2011

RAFS
FS_RA_large_complex_structure_(composite)
vacuum_vessel_complete_structure_&_cryostat_structure
9500
44.78
2011
```

```
*****
*** SiC BUILD, AT-like ***
*****
INBOARD Radial Build *
plasma inward to R=0 *
00) SOL *
1.000E-01 *
01) FW *
1.400E-02 *
02) Blanket *
3.360E-01 *
03) Gap *
0 *
04) Stabilizing shell *
4.000E-02 *
05) Gap *
0 *
06) Back wall IB *
0 *
07) Gap *
1.000E-02 *
08) HT Shield *
2.000E-01 *
09) Gap *
0 *
10) Skeleton ring *
0 *
11) Gap *
0 *
12) Manifolds *
0 *
13) Gap *
3.000E-02 *
14) Vacuum vessel *
3.300E-01 *
15) Gap *
0 *
```

- **Output files:**
 - Raw data output file
 - Part files for CAD drawings
 - Costing accounts and algorithms
 - System engineering summary
 - Powers and heat fluxes summary
 - Inflation factors, material properties, part compositions printouts
- **Flow of calculations diagram** – flow of the code structure
- **Power flow diagram** – complete listing of all power fractions, power flow, generated, lost and recovered heat.
- **Reference documents** – spreadsheets, papers, journal articles, etc. from contributing team members to reference equations, assumptions and hard numbers in the systems code.
- **Old reference documents** – for archival purposes.



ARIES ACT Strawmen Designs

- **Two blanket designs:** *advanced SCLL technology and conventional DCLL*
- **Two physics regimes:** *advanced (β_N 0.04-0.06) and conventional physics ($\beta_N \sim 0.03$)*
=> 4-corners scanning approach to cover parameter space

Name	Blanket	Physics	Strawman Point
ACT-SA	SCLL (SiC self-cooled PbLi)	Advanced	Issued April 2011
ACT-SA (b)	SCLL	Advanced	Re-run June 2011
ACT-SA (c)	SCLL	Advanced	Re-ran Jan 2012
ACT-SC	SCLL	Conventional	Issued April 2011
ACT-DA	DCLL (dual-coolant PbLi)	Advanced	Forthcoming
ACT-DC	DCLL	Conventional	Forthcoming

All formally-issued strawmen available online:
<http://aries.ucsd.edu/carlson/aries/>

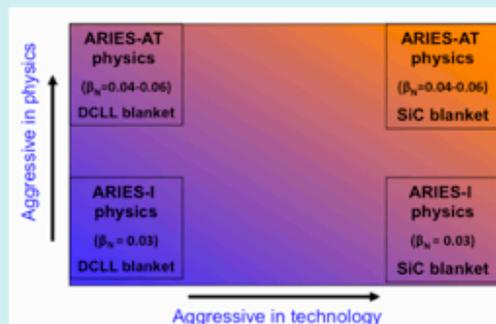
Strawmen Points Page

- Version
- History/overview
- Four-corners approach
- Strawmen issued
 - Name
 - Date
 - Blanket
 - Physics
 - ASC version
 - Notes
- Filtering sequences



Revision:	1/2012 by L. Carlson
Code Version:	ASC v.34
History:	Strawmen points have been issued in the past by R. Miller for ARIES-AT. The full output of the final strawman point that became ARIES-AT is printed here .

Four-corners Approach: Four combinations of advanced and conventional physics and technology create four corners that define the tokamak parameter space. Our interest lies in defining the corners and exploring the viable operating points in between to better analyze tradeoffs and relationships between parameters.



Strawman Name	Issued	Blanket	Physics	ASC Version	Notes:
ACT-SA (a) (ACT-Ia)	4/8/2011	SCLL*	Advanced*	v.30	Initial
ACT-SA (b) (ACT-Ib)	6/8/2011	SCLL	Advanced	v.32	To update Ia
ACT-SA (c) (ACT-Ic)	1/5/2012	SCLL	Advanced	v.34	To update Ib
ACT-SC (ACT-II)	4/8/2011	SCLL	Conventional	v.30	Initial
ACT-DA (ACT-III)	TBA	DCLL**	Advanced		
<i>Preliminary</i>					
ACT-DC (ACT-IV)	TBA	DCLL	Conventional**		

* SCLL – self-cooled lead-lithium. Advanced physics – betaN ~ 4.0 – 6.0
 ** DCLL – dual-coolant lead-lithium. Conventional physics – betaN ~ 3.0

Filtering Sequence: Finding a single strawman point to issue from thousands to tens of thousands of possible points is difficult to do. To select the strawmen point we have employed the VASST visualization GUI to help filter out points

Easier-to-read part printouts combine all part parameters

Part Name	Material Name	Volume Frac	Density Frac	Material Density [kg/m3]	Cost/Unit Mass [\$/kg]	Cost Basis Year	Volume of Part [m3]	Surface Area [m2]	Liquid Metal Mass [kg]	Mass of Part [kg]	Cost of Part [M\$]
Plasma AT							400.65	502.27			
FirstWallInboard	SiC-comp	0.73	0.95	3200	602.66	2011	1.8753	132.63	4.5049	260.1	2.2174
	PbLi	0.27	0	8897	9.06	2011					
FirstWallOutboard	SiC-comp	0.73	0.95	3200	602.66	2011	5.9729	372.21	14.348	828.4	7.0625
	PbLi	0.27	0	8897	9.06	2011					
FW Sums							7.8482				
BlanketInboard	SiC-comp	0.17	0.95	3200	602.66	2011	43.047	134.7	317.88	1390	11.853
	PbLi	0.83	0	8897	9.06	2011					
BlanketOutboard	SiC-comp	0.17	0.95	3200	602.66	2011	109.54	390.81	808.88	3538	30.162
	PbLi	0.83	0	8897	9.06	2011					
BlanketII	SiC-comp	0.2	0.95	3200	602.66	2011	166.34	418.06	1139.5	12340	64.45
	PbLi	0.77	0	8897	9.06	2011					
	W	0.03	1	19300	124.08	2011					
Blankets Sums							318.92				
HTShieldInboard	SiC-comp	0.15	0.95	3200	602.66	2011	50.703	102	45.111	21806	19.578
	PbLi	0.1	0	8897	9.06	2011					
	W	0.05	1	19300	124.08	2011					
	B-FS	0.7	1	7800	7.73	2011					
HTShieldOutboard	SiC-comp	0.15	0.95	3200	602.66	2011	84.292	284.13	74.995	33222	23.85
	PbLi	0.1	0	8897	9.06	2011					
	B-FS	0.75	1	7800	7.73	2011					
RepHTShieldTop	SiC-comp	0.15	0.95	3200	602.66	2011					
	PbLi	0.1	0	8897	9.06	2011					
	B-FS	0.75	1	7800	7.73	2011					

Some example scanning parameters

	Range	Resolution
R (m)	4.0 - 8.25	0.25
B_T (T)	4.5 - 8.5	0.25
BetaN	0.025 - 0.06	0.005
Q gain	15 - 40	5
n/n_{Gr}	0.7 - 1.3	0.1
P_{aux}	5 - 40	5
...		

Preliminary filtering:

1. $P_{nelec} = 1000 \text{ MW} \pm 25 \text{ MW}$
2. Divertor (in/outboard) limit $< 15 \text{ MW/m}^2$
3. $B_{Tmax} = 6 - 18 \text{ T}$

**System scans done
on cluster computer
with 100's nodes**

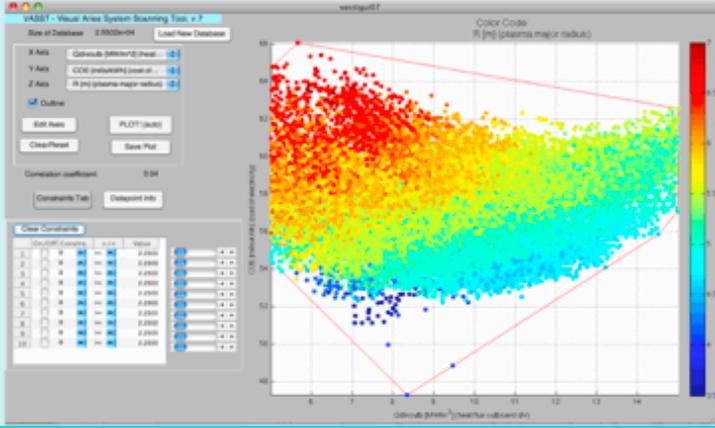
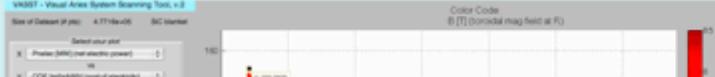
**Large system scans can
produce $10^6 - 10^8$ points**

VASST Webpage

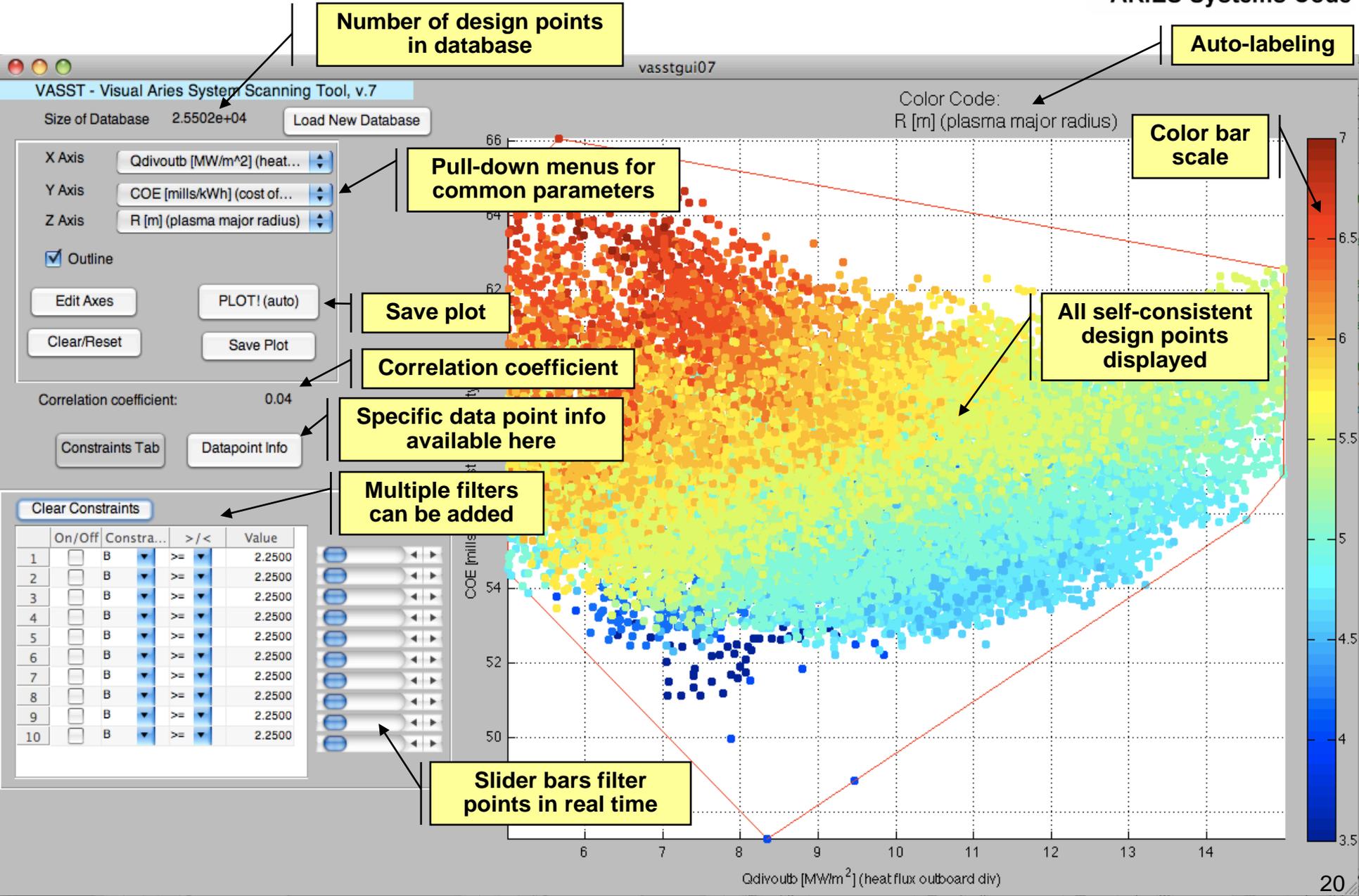
- VASST Version
- Overview
- Filtering sequences
- Samples
- Screenshots



Visual Aries Systems Scanning Tool (VASST) Documentation

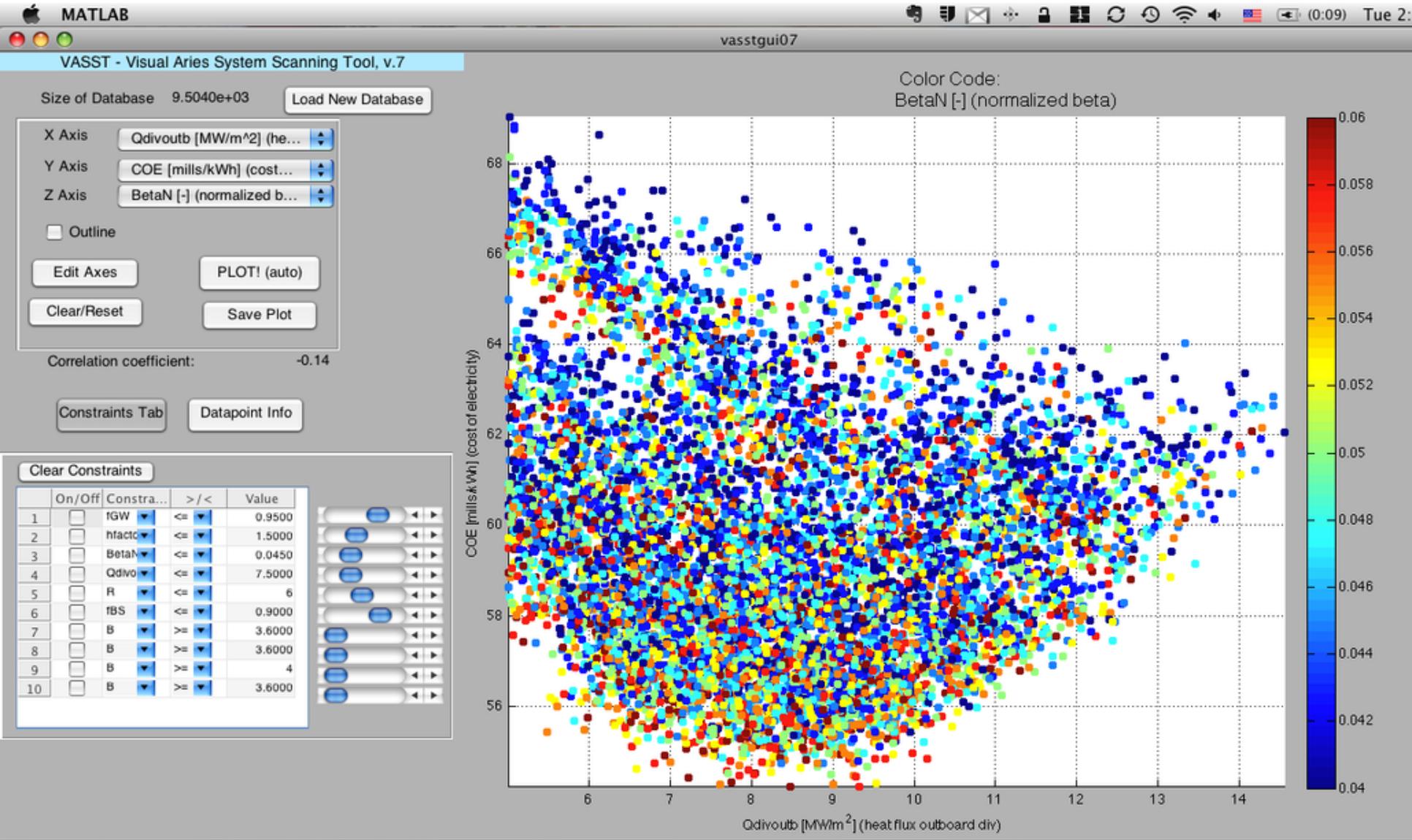
Revision:	11/2011 by L. Carlson
VASST Version:	VASST v.7 (vasstgui07.m)
Overview:	<p>This graphical user interface tool, build in Matlab, was designed to be able to more clearly visualize the enormous database of possible tokamak points that the systems code produces. The tool seeks to make an easy to use and intuitive user interface in which the user can plot and explore different parameters of the systems code output file. VASST allows the user to plot two parameters against each other and plots another parameter as a colored overlay on the points.</p> <p>See How to run the VASST GUI for details on running the code. (v.3 6/2011)</p>
Filtering Sequence:	<p>Filtering sequence example of SCLL points.</p> <p>Filtering sequence example #2 of 20,000 DCLL points showing GUI constraints tab as they are applied.</p> <p>Filtering sequence example #3 of 9,500 SCLL points showing GUI constraints tab as they are applied, used to find ACT-SA (c) point.</p>
Screen Shots:	 <p>The screenshot shows the VASST GUI interface. On the left, there are control panels for 'Size of Database' (23920404), 'X Axis' (Ohmicub (MMA) / (ohmicub outward dir)), 'Y Axis' (CGC (radial) / (ohmicub outward dir)), and 'Z Axis' (R (plasma major radius)). There are buttons for 'Plot', 'Clear/Reset', and 'Save Plot'. Below these is a 'Constraints Tab' with a table of constraints. The main plot area shows a scatter plot of points colored by R (plasma major radius), with a color bar on the right ranging from 0 to 15. The plot is bounded by a red triangle.</p>
	 <p>This is a partial screenshot of the VASST GUI, showing the 'Size of Database' (41718404) and 'Color Code' (R (plasma major radius)).</p>

VASST - Visual ARIES Systems Scanning Tool v.7



VASST Filtering Sequence

- Used to help find ACT-SA strawmen points



Summary

- ✓ ASC continues improvements and is ready to be run
- ✓ All-encompassing documentation of systems code and
ASC Homepage
- ✓ Preliminary strawmen for ARIES Physics & Technology
Assessment issued
- ✓ VASST visualization tool provides visual interaction with
systems code database