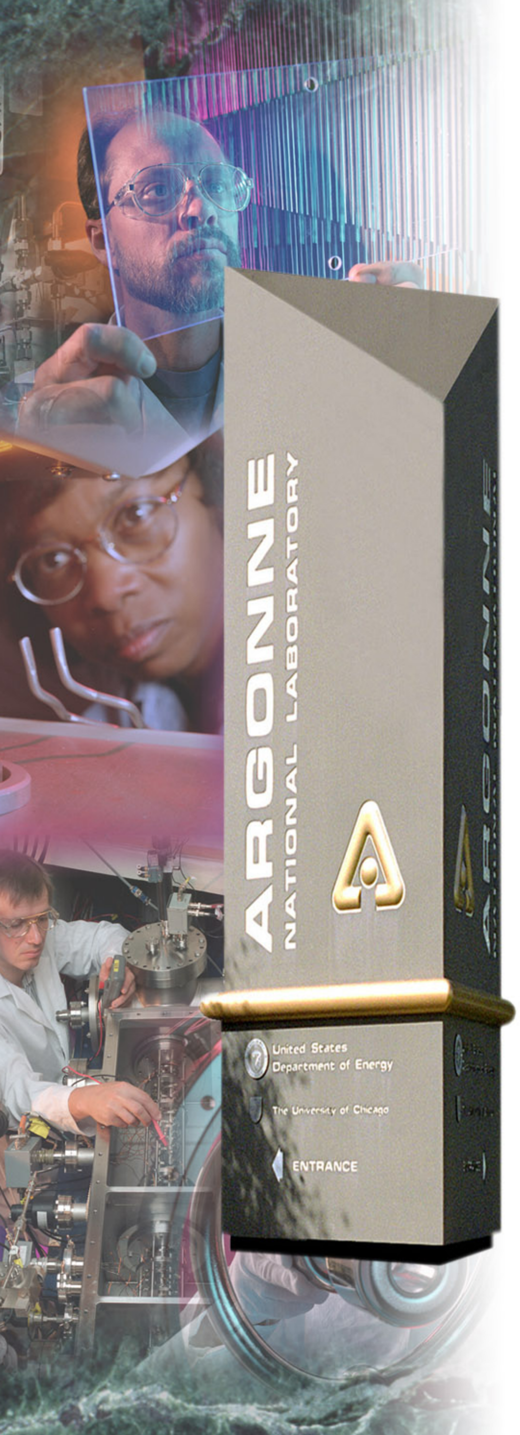

High-Brightness Injector Modeling

Presented at the 2004 Advanced Accelerator Concepts workshop

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Office of Science
U.S. Department of Energy

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Some Basic Questions

- **What does “High-Brightness” mean?**
- **What’s an injector?**
- **What do I mean by “modeling?”**
- **What is this talk *not* about?**
  - Detailed description of individual codes
  - Comparison between different “injector” codes
  - Not here to castigate nor advocate a particular code, code suite, or code writer; *every* injector code has bad points, most have good points too.

What is brightness? What's High-Brightness?

- **One canonical definition:** $$B_n = \frac{2I}{\pi^2 \varepsilon_{n,x} \varepsilon_{n,y}}$$

- **Another definition:** $$\rho = \left[\alpha \cdot \frac{I}{\sigma_x^2}\right]^{1/3} \propto \left[\frac{I}{\varepsilon_n}\right]^{1/3}$$

- **The actual characteristics of a beam, relative to those which are of interest for the task we wish to perform with the beam**

- **In useful terms, brightness is situational.**

What's an injector? Why single it out?

- **Broadly: an accelerator which provides beam to another accelerator.**
  - Plasma channel
  - DC or RF gun, perhaps including a booster tank
  - Linac (including source)
  - Linac + damping ring
- **For this talk: kinetic energies from 0 $\rightarrow$ ~30 MeV (for electrons)**

- **Why single it out?**
  - Transition to relativistic motion; allowed approximations change
  - Beam quality doesn't get any better than it is here (generally)
  - Keystone component: Replacing the injector can upgrade the facility performance as a whole

What is modeling?

$$\frac{d\vec{p}}{dt} = q \cdot \left(\vec{E} + \frac{d\vec{r}}{dt} \times \vec{B} \right)$$

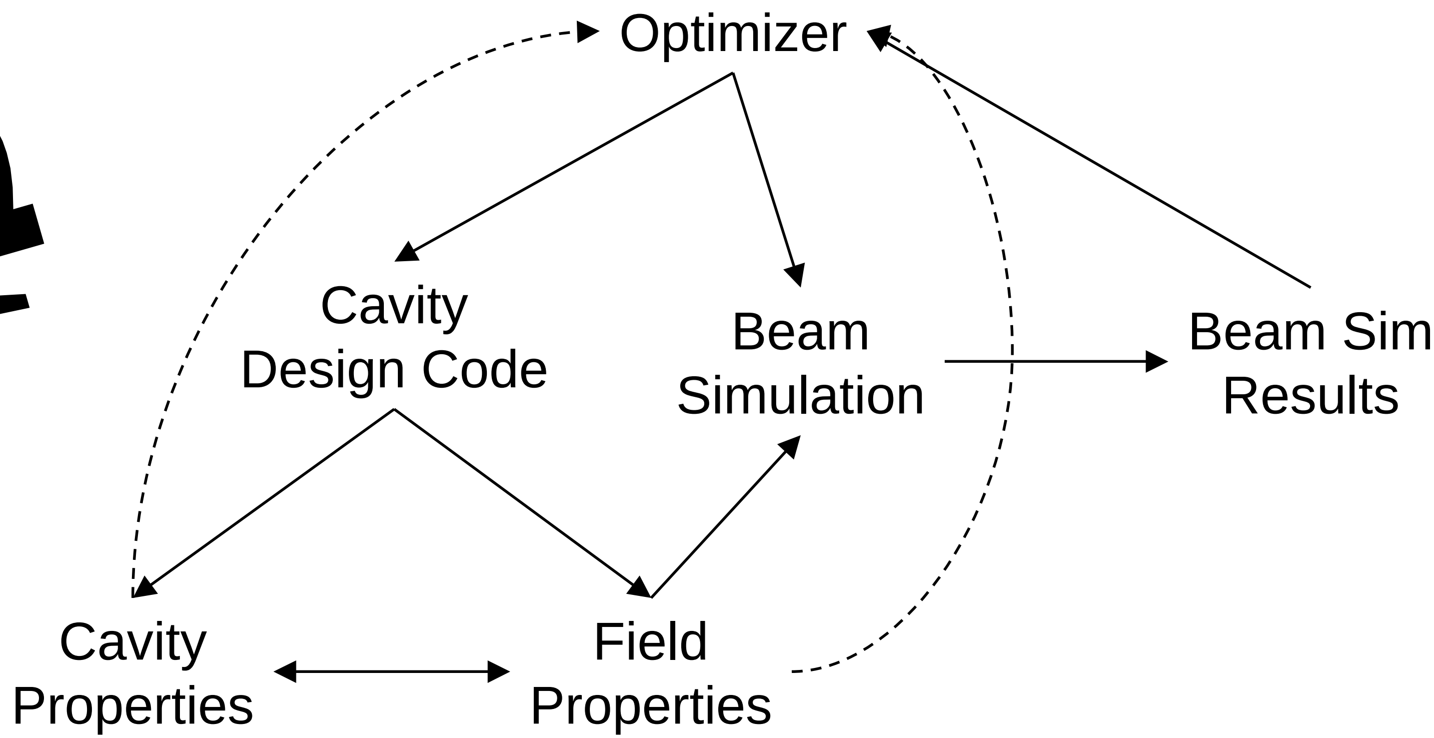
$$\frac{d\vec{r}}{dt} = \frac{c\,\vec{p}}{\sqrt{m^2c^2 + \vec{p} \cdot \vec{p}}}$$

$$\vec{E} = \vec{E}(\vec{r}, t)$$

$$\vec{B} = \vec{B}(\vec{r}, t)$$

(The solution is left as an exercise to the modeler.)

Generic Modeling Process



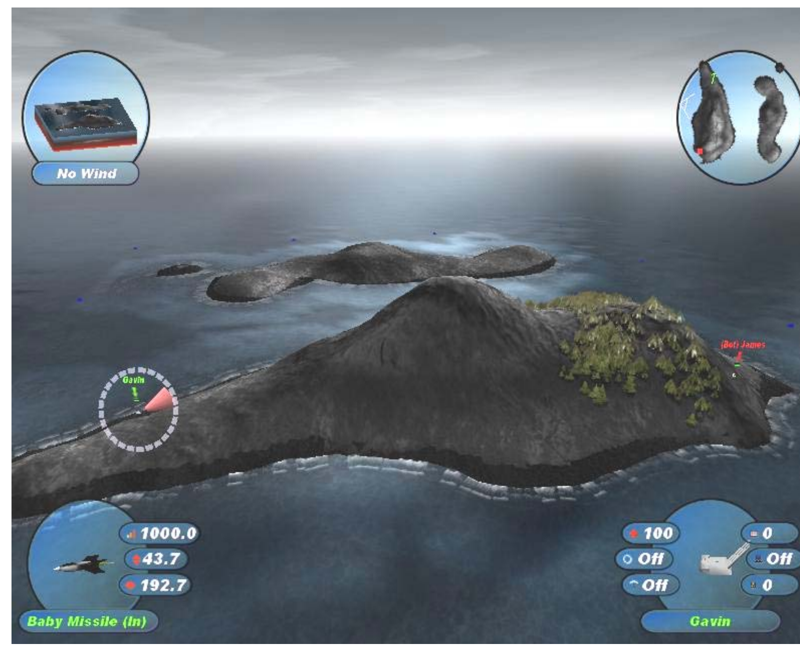
Each link:

- adds computation expense
- must be validated for correct operation with *all* previously applied links
- *should* increase self-consistency and validity of the answer

What is the intent of modeling?

- **Determine the behavior of a corresponding physical system**
  - What kind, and level, of detail determined by the goals for the injector
  - What level of physical abstraction is acceptable?
  - Increasingly, more than “beamware” is needed

Courtesy Steffen Kopf , “Artillery Duel”



Courtesy Gavin Camp, “Scorched Earth 3D”

What are some trends?

- **Lower emittance (tranverse & longitudinal both)**
  - Particle emission models become far more important
  - Fine-structure intrabeam interactions become far more important
  - Beam-edge details become more important
  - Short-range wakefield details become more important
  - Need to handle disparate spatial scales in general
- **Higher average power**
  - Beam halo modeling becomes far more important
  - Impedance modeling becomes far more important
  - Cavity modeling becomes far more important
- **Unique design configurations require new sim. capabilities**
  - BNL diamond-pass cathode
  - SRF photoinjectors
  - LANL Cs-regeneration cathode
  - UMd photo-thermionic cathodes
  - APS planar focusing cathode

Directions for Injector Development

- “Big Iron” accelerators
  - Linear colliders
  - Next-generation x-ray light sources
- “Desktop” accelerators
  - Electron microscopy
  - Electron beam lithography
  - Small laboratory experiments
- “Mini-Me” accelerators
  - Radioisotope generation
  - High-power free-electron lasers
  - Slow positron production
  - Pulse radiography

Courtesy SLAC/LCLS

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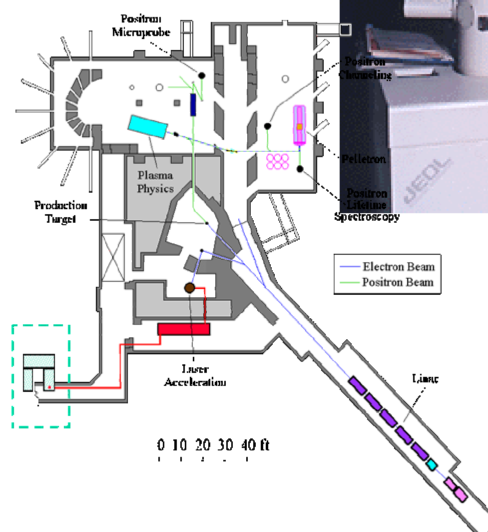


Courtesy LLNL

Directions of exploration...

Some different requirements

- **“Big Iron”**
  - lower emittance (10x)
  - higher peak currents (5x)
  - emittance aspect ratio control
- **“Desktop”**
  - ultra-low emittance (10^3x)
  - very low energy spreads (10^{-5})
- **“Mini-Me”**
  - (usually) modest beam quality (e.g. we can sometimes get there today)
  - high average power (e.g. 1 MW from the gun for FEL)
  - at least quasi-CW operation
  - beam halo is a critical issue

Some common themes

- Higher performance levels than are routinely achieved today are demanded
- With few exceptions, the injector is a quasi-standalone component
- Injector reliability is key to the uptime of the entire facility
- Backup injector capability would be a large benefit
- “Beyond the beam physics” issues are very important

What do we need to get started?

- What are we modeling, overall? Gun? Gun + linac? Etc.
- What is the particle source to be modeled? Cathode type?
- Is the gun a DC, RF or hybrid gun?
- What is the operational parameter space for our new source?
- How many spatial dimensions are required?
- What physical effects will we need to incorporate?
- How do we determine the applied fields? Model the cavities?
- What type of beam model are we assuming? Particle-based? Fluid-based?
- What type of space-charge model are we going to use? Lorentz-transformed pseudo-PIC code? Point-to-point? Ring-to-ring? True PIC code? A hybrid? Vlasov equations?
- What interactions with the environment (e.g. cavity wakes) do we deem important? Which of those do we include?
- Do we care about jitter? If so, which parameters? How do we model that?
- Is this a scenario under which we care about particle-field-particle effects (e.g. CSR, FEL interaction)? How is *that* approached?
- How will we know if the simulation results are valid or not?
- …

What is to be modeled?

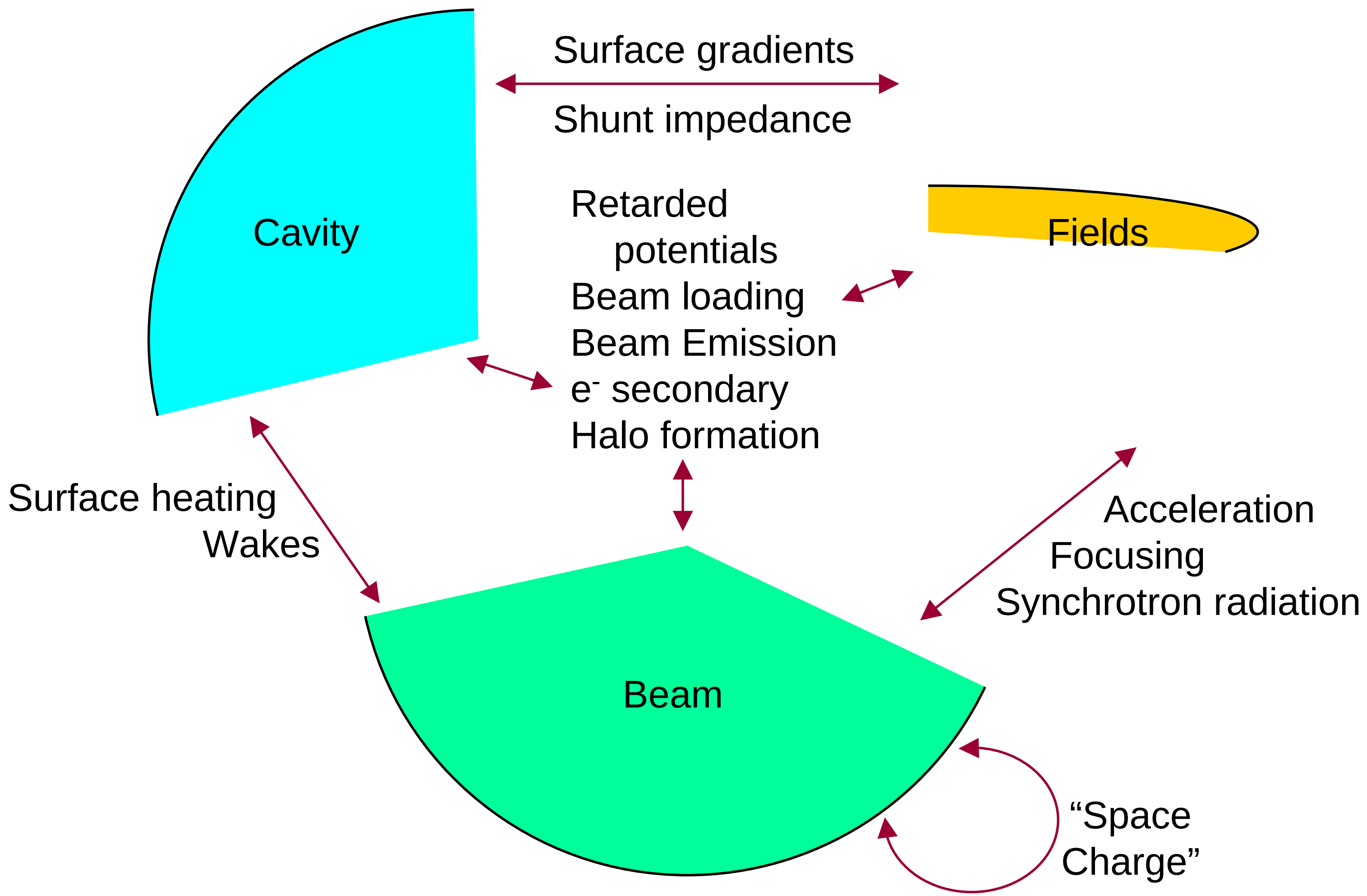
"Just the Physics"

- **Beam ↔ beam interactions**
  - "space charge"
  - Bunch-bunch interactions
- **Beam emission / generation process**
- **Beam ↔ field interactions**
  - Acceleration
  - Focusing
  - Synchrotron radiation, CSR
- **Beam ↔ cavity interactions**
  - Wakefields
  - Surface heating
- **Cavity ↔ field interactions**
- **Multiple interactions**
  - Retarded potentials
  - Beam loading
  - e^- secondary formation
  - Beam emission

"Other Stuff"

- **Long-timescale effects**
- **Cavity / power source interactions**
- **Beam loss**
- **Jitter**
- **Component reliability & lifetime**
- **Etc...**

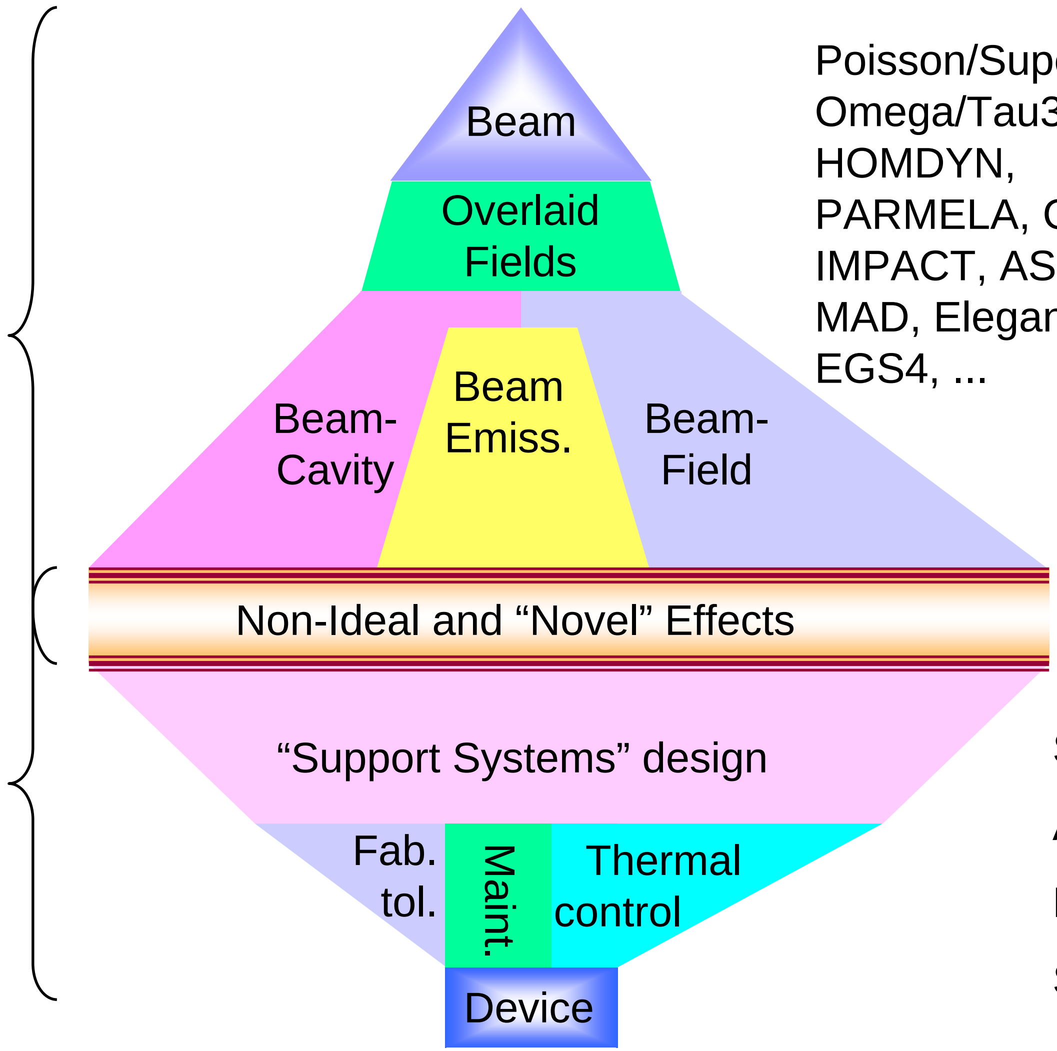
What is being modeled?



Alternate view of the modeling process:

“Physics” Codes

“Engineering” Codes



Poisson/Superfish, MAFIA, HFSS,
Omega/Tau3P,
HOMDYN,
PARMELA, GPT, spiffe, Tredi,
IMPACT, ASTRA,
MAD, Elegant, Trace-3D, traffic4,
EGS4, ...

SPICE

ANSYS

Pro/E, AutoCAD,

SolidWorks,

...

Just a reminder...

The “physics stuff” allows you to postulate a new beam source, and perhaps build & test it on a small scale.

However....

The “other stuff” is what you need to build and use it successfully, be it a small lab or a national facility!

The easier the interface, the better the chances of getting it right!

For future codes:

- **The algorithms need to be known and the implementation well-documented.**
- **There should be means for (helping to) validate results; these should be well-documented also. This includes documenting known problem areas with the algorithms, as well as post-change validation testing.**
- **Some features that would be nice:**
  - The ability to add new interactions, fields, particle emission models, etc., without dramatic changes to the core code. (Murphy's Law in context.)
  - General usability improvements
  - True multiphysics

Two Forward-Looking Codes Codes

- **General Particle Tracer – GPT**
  - Commercial code, copyright Pulsar Physics (Netherlands)
  - Beam physics code
  - Does not include PIC capabilities, so no intrinsic beam-element interaction

- **Finite-Element Modeler – FEMlab**
  - Commercial code, copyright COMSOL, Inc.
  - “Device Engineering” code ... sort of.
  - 1 – 3D models, MATLAB interface avail.
  - Does not include beam physics (yet) or system-level design

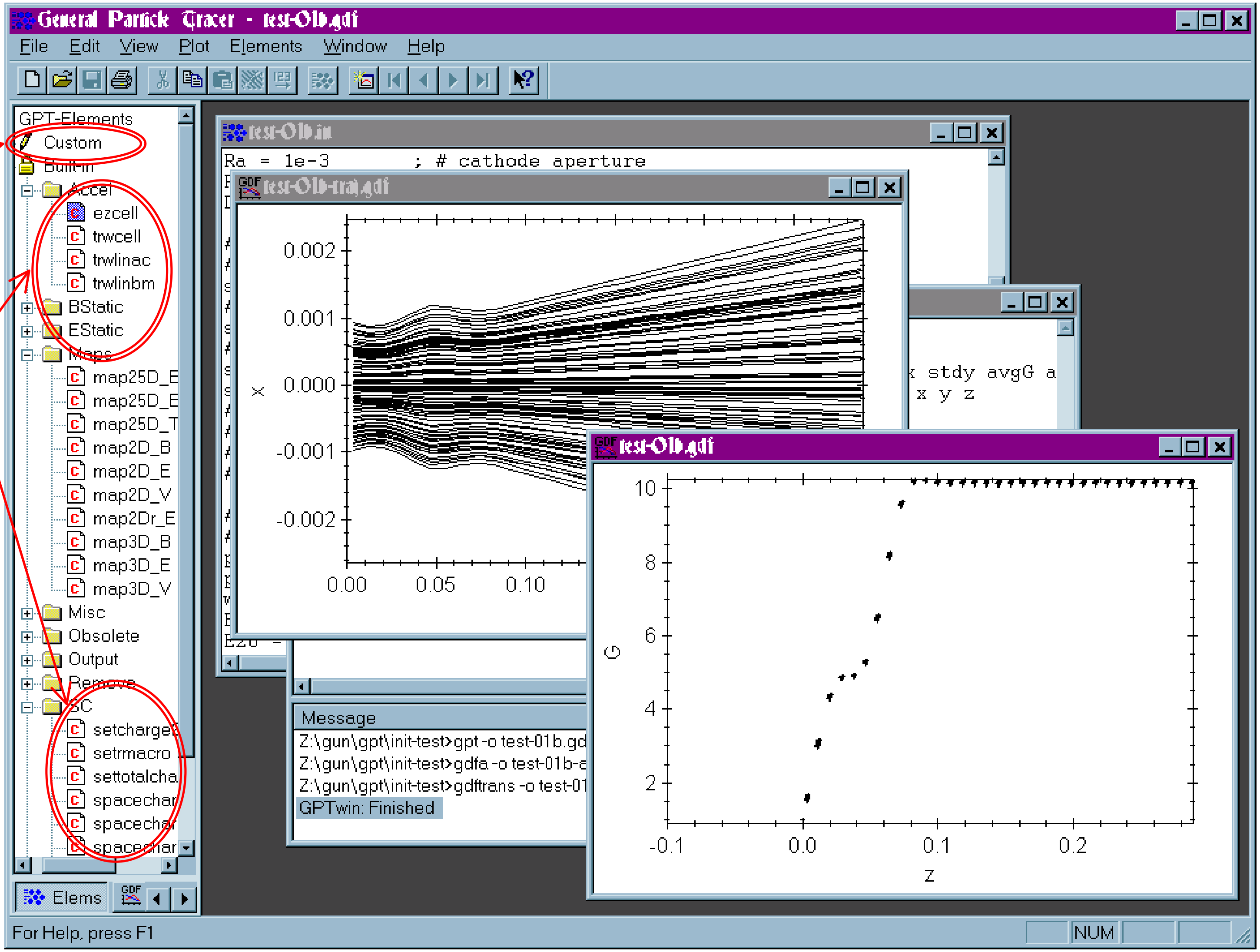
Beam Physics – GPT (General Particle Tracer)

User-defined elements treated the same as built-in elements

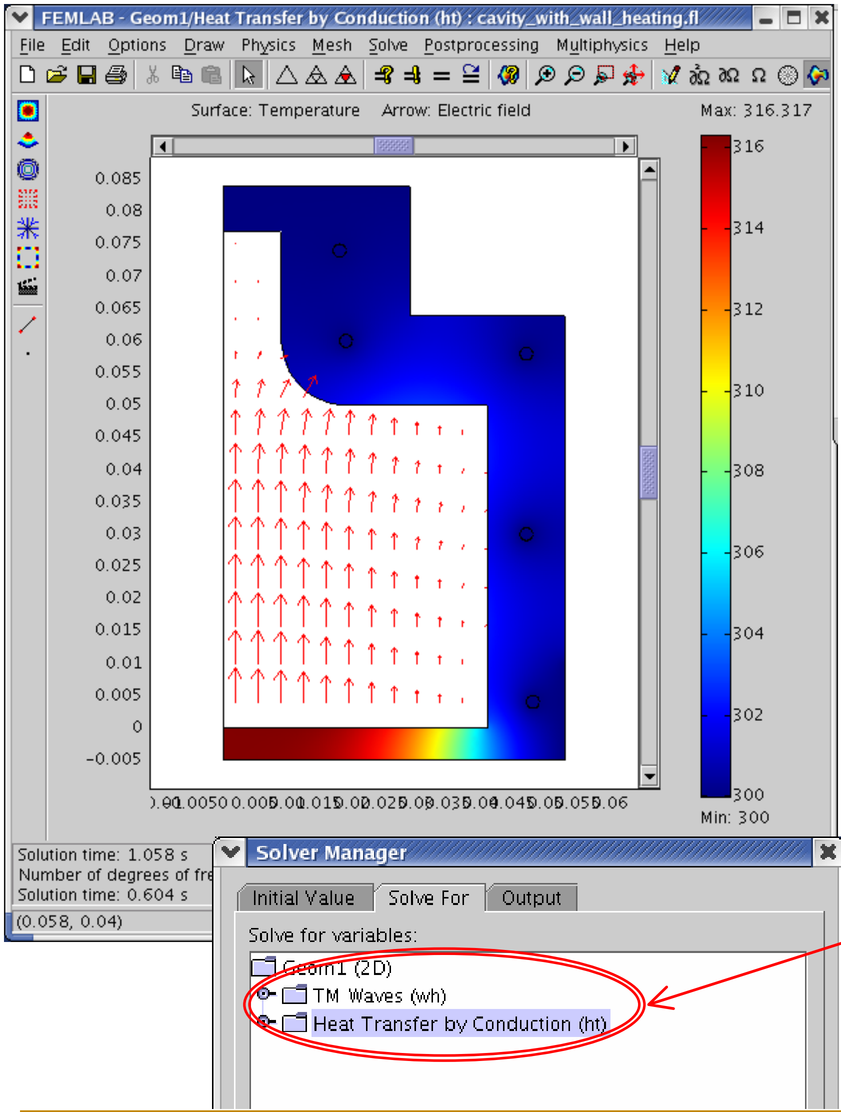
Source code provided for all elements and interactions

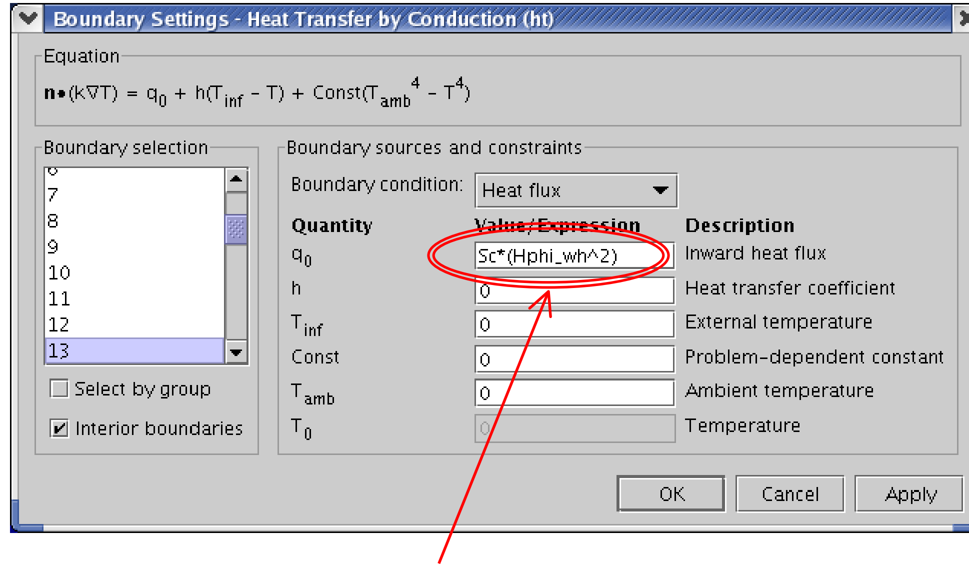
Can be run in batch mode

GPT is a commercial code; copyright Pulsar Physics



FEMlab – Finite-Element Modeling Software





Analytic expressions for coupling: here, heating at Cu/vac. boundary via H

Time-dependent fluid flow already built-in...

Built-in “multiphysics” modes ... but can define one’s own equation system

Common themes:

- Good balance between oversimplification and single-career codes
- Extensibility is built into the programs from the start
- Some built-in tools to assist with validity and input checking
- Ability to run in a user-interface mode, or in a “batch” environment suitable for automated execution (with some digging)

Where do we go from here?

- ***Detailed*** **photoemission process**
- **Beam-bunch microinstabilities, longitudinal space-charge instabilities**
- **Evolution of ultra-low emittance beams**
- **Head-tail effects; energy spread effects**
- **Self-field images from cavity / injector surfaces**
- **Resolving beam, field, edge effects in extreme geometries (e.g. needle-type cathodes)**

- **Improved interaction between beam physics, cavity design, and cavity modeling codes, as well as core code improvements.**
- **Inclusion of other physics effects, for “total gun” modeling**

Acknowledgements

- ANL Theory Institute on Production of Bright Electron Beams: "Towards Advanced Electron Beam Brightness Enhancement and Conditioning" (http://www.aps.anl.gov/techpub/lsnotes/lsnotesTOC.html)
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- Pulsar Physics (GPT)
- COMSOL, Inc. (FEMlab)

Murphy's Law in Context:

- **Any really new idea is bound to break at least one simulation code. Why? Because it'd be a feature of some code, somewhere, if someone thought of it already.**