Klystron simulations: Review/comparison of existing tools

27/1/15

Dr Chris Lingwood

With thanks to:
C. Marelli, I. Syratchev, A. Baikov, I. Guzilov, F. Peauger, Q. Vuillemin, B. Delana, P. Ferguson, M. Read

Introduction

- Choice of code depends on what you want to achieve
  - Design codes (quick, various assumptions)
  - Detailed evaluation codes (slow, detailed simulation)
- Many approaches
  - Design
    - Analytical Small Signal
    - Disk/Ring
    - Discrete Model
    - Reduced PIC
  - Detailed
    - Full PIC
- Many codes!

Codes (14)

In no particular order:

Disk/Ring
- AJDisk
- Klys4.5
- Dev5

Discrete Model
- Klypwin
- Tesla

Reduced PIC
- Klys2d
- KLSC
- FCI

PIC
- VSim
- WARP
- MAFIA
- CST PS
- GdfidL
- Magic

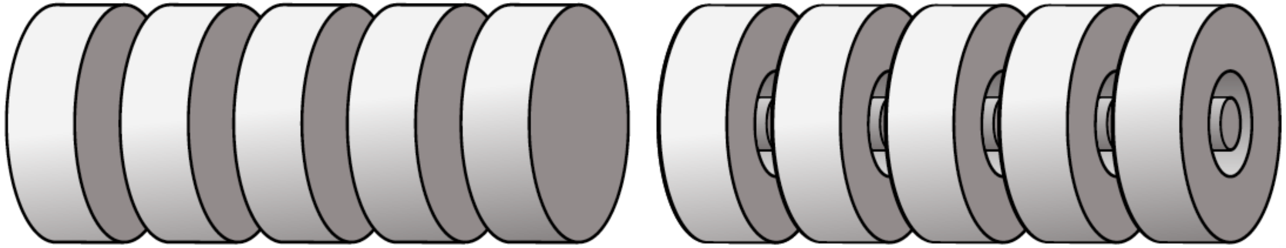
Analytical Small Signal

- Solution of space charge waves on a beam
- Directly obtain solution
- Make assumptions of linearity which are very wrong indeed for large signal

- **Very fast way of getting the wrong answer**

Disk/Ring Models

- Model the beam as a series of disks or rings
- Port approximation of cavities
- Solve the cavity fields iteratively with the beam
- Quite fast
- Non-linear



(a) Disks (b) Rings

Space Charge - Green's functions approach

- Charge is represented as a delta disk
  - Integrate Greens function over two delta function disks to calculate the force between them

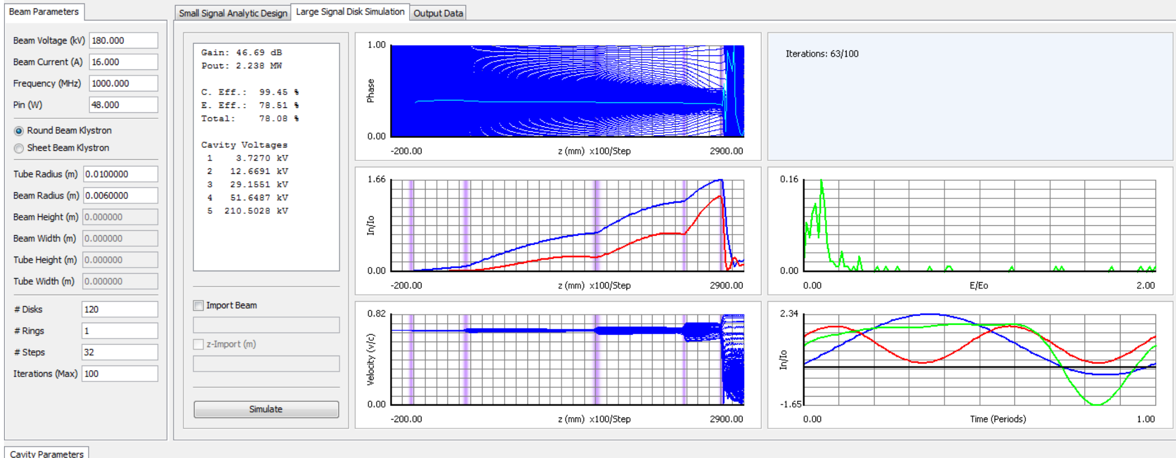
- In a close encounter (overtake) between disks the space charge forces
  - become infinite (just large for a truncated series)
  - don't take into account the reduction in force as disks "merge"
- Charge to charge solution for forces (calculations escalate (very) quickly) limits resolution

AJDisk - SLAC

Lancaster University

- Basic Green's function approach (doesn't solve overlap issues)
  – The higher the efficiency the more overlap…
- No radial movement, no focussing
- Field profile Gaussian in z, radially constant
- Multiple output gap but no coupled cavities

- **Freely available**

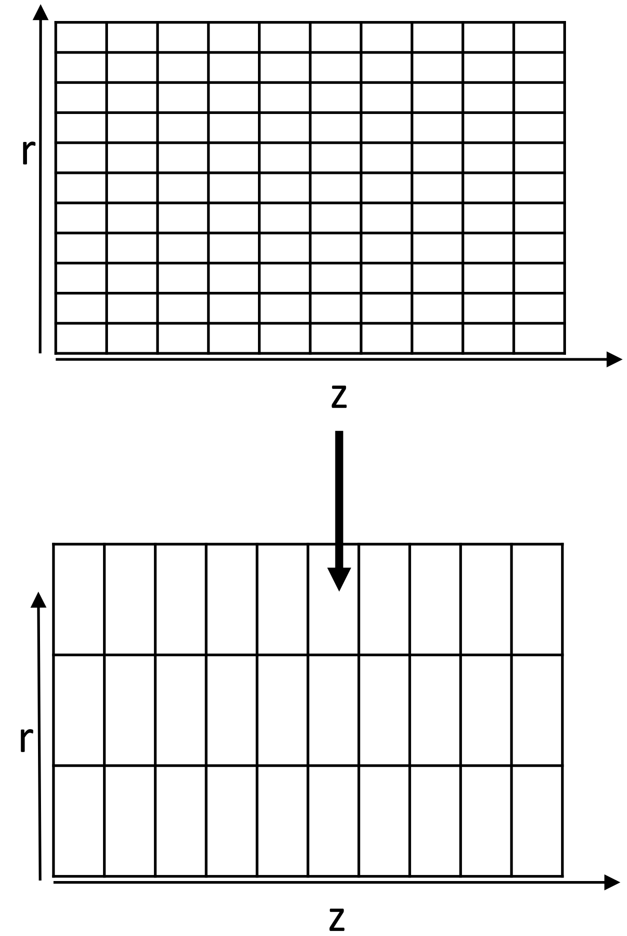


Cavity ID, Unused	R/Q (ohms)	M or SF7 Grid File, z(m)	Qe	Qo	f (MHz)	z (m)	d (m), Unused	Harmonic
1	182.000	0.9230	334.000	10000.000	1000.000	-0.02000	0.0000000	1
2	117.000	0.8910	95000.000	10000.000	1006.000	0.46000	0.0000000	1
3	102.000	0.8100	95000.000	10000.000	1016.000	1.61000	0.0000000	1
4	158.000	0.9520	95000.000	10000.000	1030.000	2.38000	0.0000000	1
5	180.000	0.9320	55.000	10000.000	1000.000	2.71000	0.0000000	1

Space Charge - Hockney Method

- Deposit charges on a mesh
- Fourier analysis in z and cyclically reduce in r down to 3 steps
- Apply more boundary conditions and solve to get potential matrix

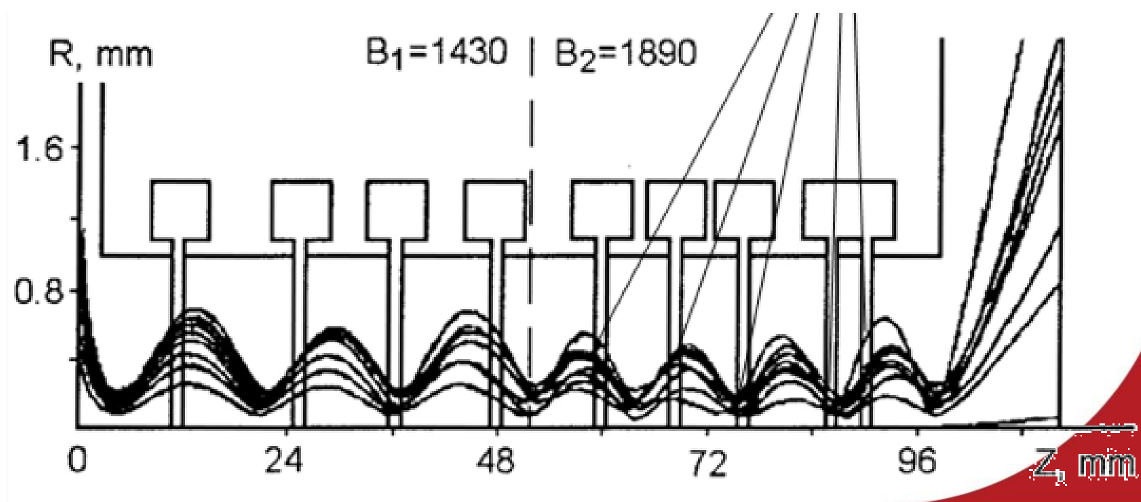
- Faster than greens function approaches (not charge to charge)
- Based on Fourier analysis has no issue with close encounter problem



Klys4.5

thanks to I Guzilov

- Hockney Method for space charge
- Radial movement, PPM or Solenoid Focusing
- Numerical solution of real cavity fields
- Double gap cavities
- Single and multibeam
- Input and output ladder-type filters



Dev5.1

thanks to I. Guzilov

- Hockney method for space charge
- Cavity model extends to swift calculation of coupled cavities using 6-Pole method
  - CCTWT + Klystrons + Hybrids
- Radial Movement - PWM or Solenoid
- Electrostatic approximation for longitudinal field profile
- Input output ladder filters

Disk Model Comparison

	1	2	3	4	5	Efficiency
AJDisk	0.021389	0.070556	0.167222	0.288333	1.17	**78.26**
Dev5.1						**65.16**
Dev5.1 (retune)	0,02012	0,06843	0,16382	0,2966	1,14869	**76.41**
Klys4.5	0.02010	0.06728	0.13366	0.21853	1.05347	**65.08**
Klys4.5 (retune)	0.02010	0.06728	0.16469	0,29652	1.14389	**76.74**

Cavity voltage normalised to beam voltage

Retuning is cheating

Discrete Model

- Other ways of modelling space charge fields (breaking down into sums of harmonics)
- Fewer larger steps (in z rather than t)
- Quicker

TESLA – NRL
thanks to M. Read

- Based on the telegraphers equations
  - Space charge field in beampipe represented by modes in local cross section
- Use a slow timescale (of charge density change) approximation (update time scale is fill time not high frequency period)
- Radial Movement - PWM or Solenoid
- Single and Multiple beam
- Cavity Fields flat, Guassian or arbitrary

- Pretty well tested

Klypwin

A. Baikov

Lancaster University

- Discrete-analytic model of a beam
  - Derived using Frozen Beam Approximation from a general solution for small signal. Assumes:
    - Steps in z are small
    - bunching rate is slow (compared to beam velocity)
  - Models potential field as sum of harmonics
  - Predicts time of arrival for each particle (iterated individually)
- Quite new

Discrete Models Comparison

	1	2	3	4	5	Efficiency
AJDisk	0.021389	0.070556	0.167222	0.288333	1.17	**78.26**
Klypwin						**77.53**
TESLA	0.025922	0.080511	0.13365	0.271067	1.094506	**71**

Cavity voltage normalised to beam voltage

Reduced PIC

- PIC model for beam
  - Rather than point to point space charge models deposits charge onto a mesh to resolve the forces
  - More efficient and allows…
- Higher resolution on beam
- 2.5D
- Normally approximated cavities for efficiency (port approximation)

- No monotron or other HOM based issues
- Steady state

Klys2D – Thales

thanks to Q. Vuillemin

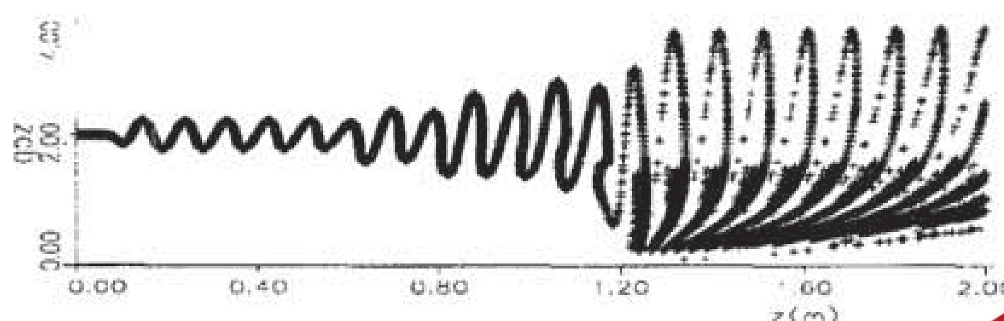
- Radial movement, Solenoid and PPM focussing
- Well benchmarked
- Quite quick

- Bouncing electrons in output gap observed for Chiara’s klystron

KLSC – CCR

thanks to P. Ferguson

- Cavities solved by iterating to find self consistent cavity field
  - Different methods for input and gain cavities for stability
  - Gain cavities prone to voltage magnitude errors
- Uses SUPERFISH cavity fields
- Supports coupled output cavities



FCI - Japan

- A bit of an oddity
- PIC, but ring based
- Cavity voltages found in two ways:
  - Small signal regime – calculated directly for steady state (input – idlers) – observed idlers can be wrong with simple iterative solution (for speed!)
  - Large signal (non linear) iterated

Reduced PIC Comparison

	1	2	3	4	5	**Efficiency**
AJDisk	0.021389	0.070556	0.167222	0.288333	1.17	**78.26**
Klys2D	0.0202	0.0741	0.1790	0.3158	1.1261	**72.00**
FCI						**?**
KLSC						**75**

PIC Codes

- Deposit charges onto a grid
- Normal FDTD Yee algorithm using currents
- Fully self consistent
- High beam resolution
- Information may go backwards
- Full geometry of tube
  - Full cavity model with high order modes
- WILLFULLY transient
- Can be used for prediction of monotron, multipactor, instabilities…
- SLOW

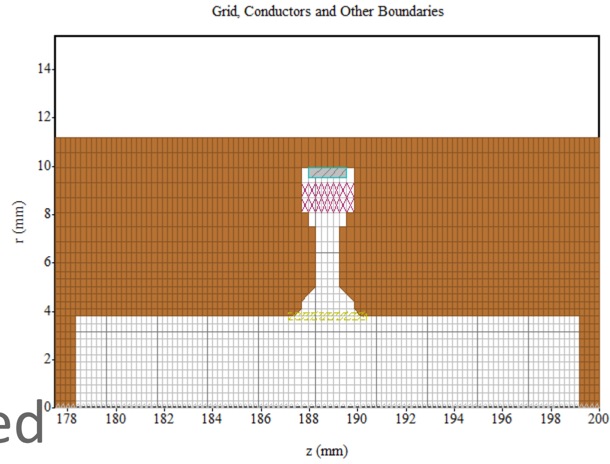
Variations in approach

- Cavity losses (Q is important!)
- External coupling
- Cut cells (PBA, deymittra…) or square mesh
- 2D or 3D (often both)

MAGIC

thanks to B. Delana, F Peauger

- Standard, well tested, **trusted**, in some ways dated/basic
  - GPU+cutcells imminent (trust?)
- Surface losses calculated
- Waveguide ports for inputs and outputs
- Square mesh
- Confidence in precise cavity geometry limited
  - Useful retuning tools to get right interaction
- Arbitrary Magnetic Field
- Relatively easy to get started with examples
- Is parallel, but anecdotally doesn't scale very far
- Pretty good in 2D



MAFIA -> CST PS

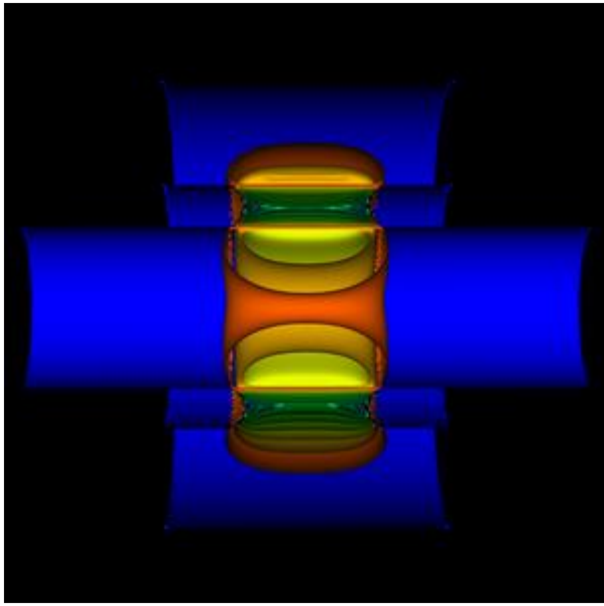
- Mafia -> CST PS (loss of 2D)

- PBA (cut cells)
- External coupling
  - Discrete ports (apply a voltage across a gap)
  - Waveguide port
- Wall losses calculated
- GPU capability
- Good scaling (improving)
- Very easy to setup
- Good secondary emission model

- Having some numerical issues

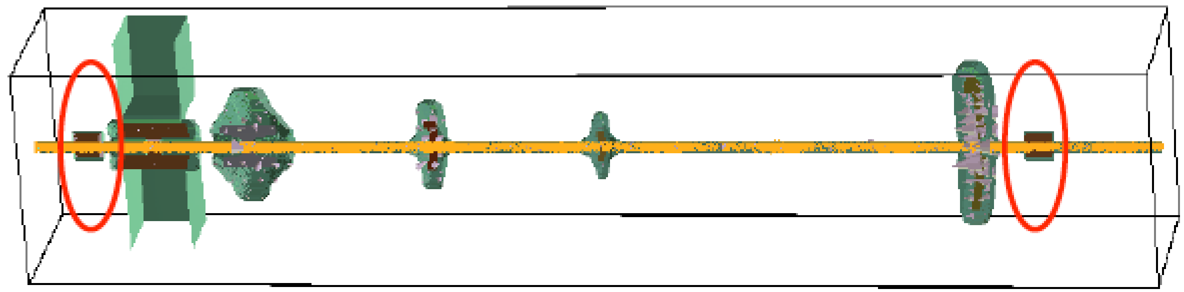
VSim (TechX)

- Demonstrated scaling to 100s cores on clusters
  - huge meshes, lots of particles
- Physical wall losses can be calculated
  - Also dummy loads for speed
- Waveguide port-like coupling
- Very flexible (almost arbitrary algorithms)
- Fiddly to setup
- Potential for very high resolution
- Lancaster has good experience of complex multipactor sims



GdfidL

thanks to C. Marrelli, R. Wegner



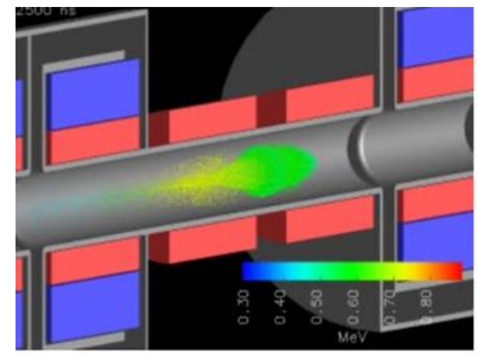
- No surface losses
- Cavity tuners
  - Change magnetic permeability for frequency
  - Change magnetic conductivity for losses
- Similar technique used to add losses for beam pipe
- Waveguide ports
- Scaling was an issue (could be resolved)
- Not great voltage agreement with AJDisk for 4th-5th cavities (different tube)
- Output cavity not attempted yet

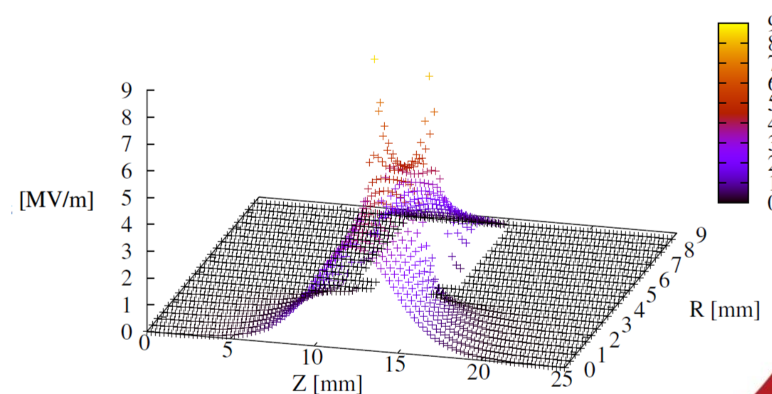
WARP (Klystron Module 2D)

thanks to B. Delana, F Peauger

- Reads AJDisk file
- Input is field map based on Superfish simulations, scaled to correct power level
- Calculates cavity losses
- Further development required:
  - monitoring of the current
  - output power calculation

- Not ready yet





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KLSC						**75**

No results from PIC simulations yet

Conclusion

- Our codes are not in good agreement!
- AJDisk is used too often because it's available rather than necessarily right, good or clever.
  - Potential for increased errors at high efficiency.
- Perhaps telling there are no results for full PIC codes yet.
  - Interesting to see if they will agree

Disk Codes

	AJDisk	Klys4.5	Dev5.1
License	Free	Restricted	Restricted
OS	Win	Win	Win
Parallel	No	No	No
Simulation 2D/3D	1.5D	2.5D	2.5D
GUI	Yes	Yes	Yes
RAM	Minimal	Minimal	Minimal
Availability	Free!	I. Guzilov	I. Guzilov

Discrete Equations

	Klypwin	Tesla
License	Restricted	Restricted
Parallel	No	No (Yes for MBK)
Simulation 2D/3D	1.5D	2.5D
GUI	Yes	Yes
RAM	Minimal	Minimal
Availability	A. Baikov	US

Reduced PIC

	Klys2D	KLSC	FCI
License	Restricted	Restricted	Restricted
Open Source	No	No	No
Parallel	No	?	No
Simulation 2D/3D	2.5D	2.5D	2.5D
GUI	Yes	?	?
RAM	Small	Small	Small
Availability	Thales	CCR	?

PIC

	CST PS	VSim	WARP	MAGIC
License	Licensed	Licensed	Free (klystron module?), Open Source	Licensed
Parallel	GPU, Multi-thread	Designed for clusters (MPI)	Yes (openMP, MPI)	Yes (licenced)
Simulation 2D/3D	3D	2D/3D	2D/3D	Yes (but separate licenses)
GUI	Yes	Yes (text)	Ish (text)	Yes (text)
RAM	Lots	Lots	Lots	Lots
Availability	Lancs, ESS, others	Lancs (256 core)	CEA	CEA, Lancs

References

- Large-Signal Klystron Simulations using KLSC, B. Carlsten
- Klystron simulation and design using the Field Charge Interaction (FCI) code, T. Shintake
- Validation of klystron development code-KLYS 4.5, A. Malykhin
- The Space-Charge Potential In A Cylindrical Tunnel, J.R.M Vaughan
- Synthesis of six-pole network simulating of coupled cavity chain characteristics in two passbands, A. V Konnov
- Simulation of Microwave Devices With External Cavities Using MAGY, A, Vlasov
- TESLA: Large Signal Simulation Code for Klystrons A. Vlasov
- CODE TESLA FOR MODELING AND DESIGN OF HIGH-POWER HIGH-EFFICIENCY KLYSTRONS, I.A. Chernyavskiy
- Model of electron beam transformation in a narrow tube, A. Baikov
- Frequency-domain code Dev.5.0 for analysis of coupled–cavity traveling wave tubes, klystrons and their hybrids, A Konnov
- Simulation of Conditions for the Maximal Efficiency of Decimeter Wave Klystrons, A. Baikov