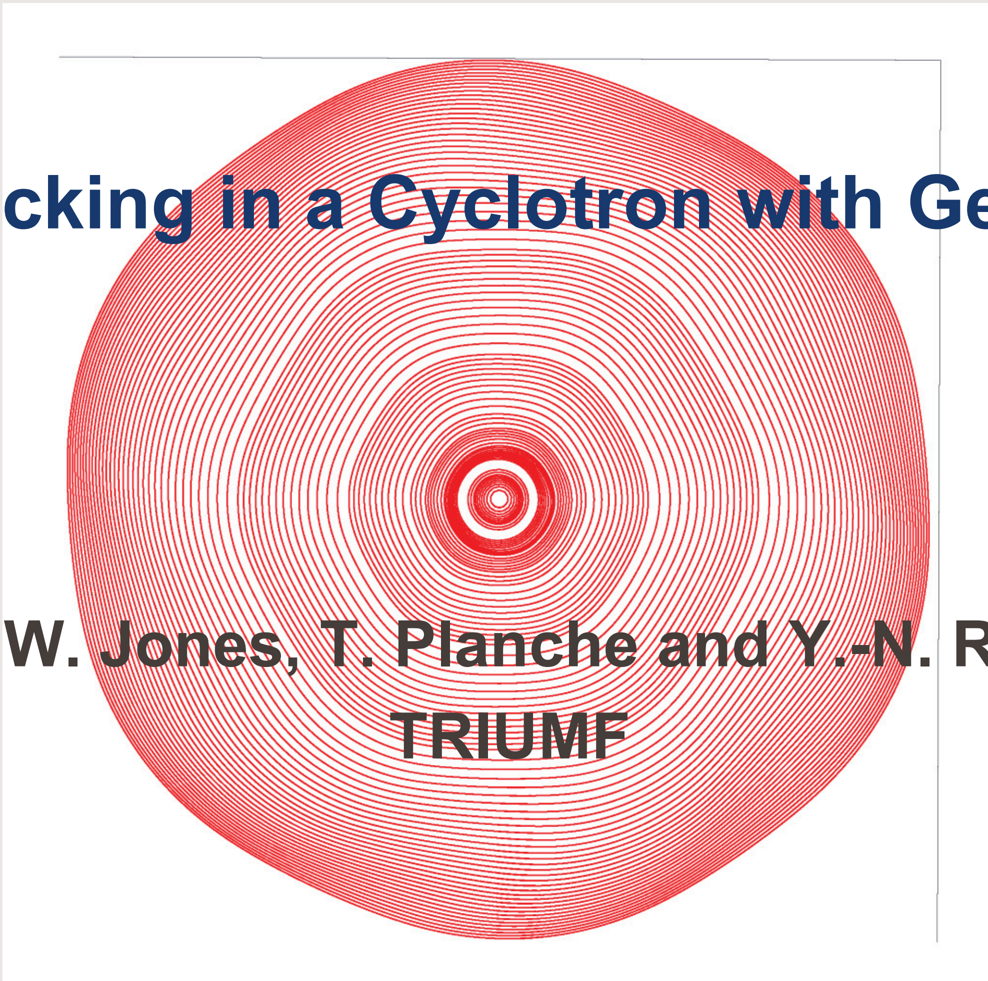
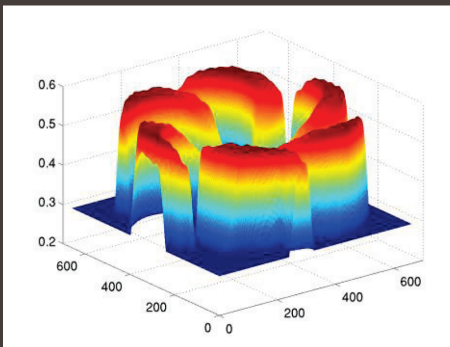
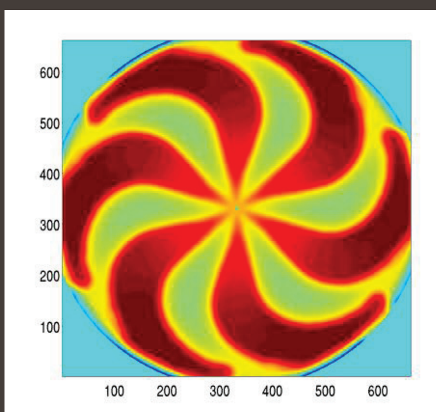
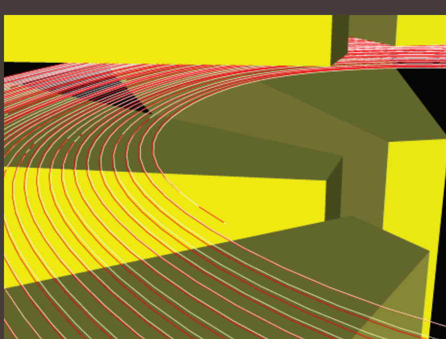
Tracking in a Cyclotron with Geant4



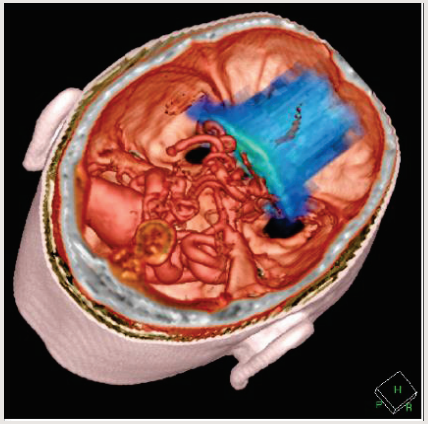
F.W. Jones, T. Planche and Y.-N. Rao
TRIUMF

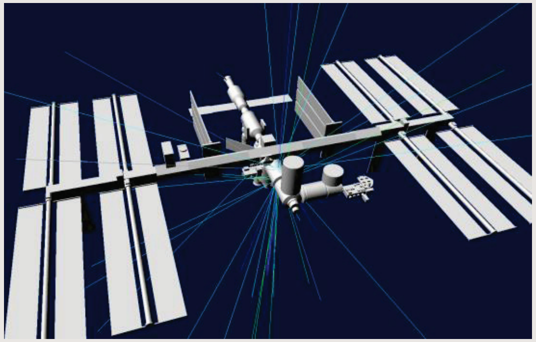


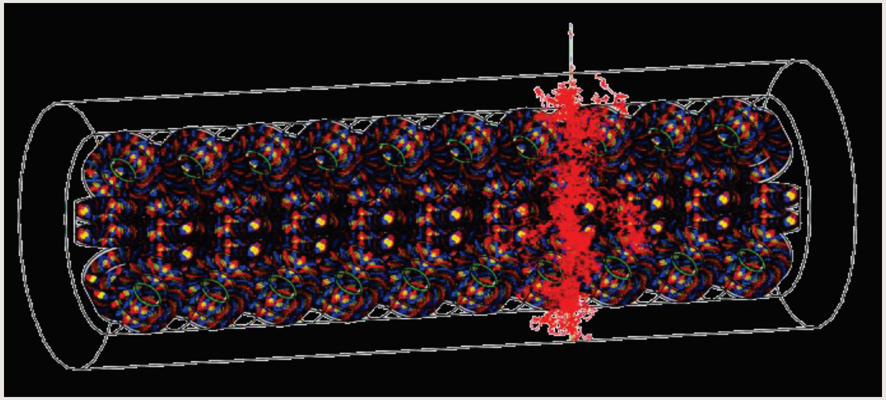


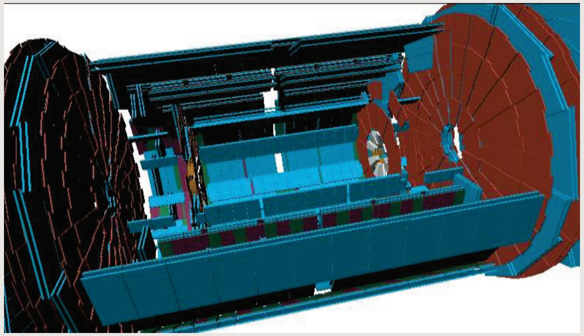


- Geant4 collaboration and software
- A world-wide software collaboration: (~100 members, 47 institutions) and a software toolkit for building simulations.
  - The kernel: particle tracking in a 3D geometry with electric and magnetic fields.
  - The rest: many physics processes (models), detector response, biasing, scoring, visualization.
  - Modern object-oriented (C++) software architecture and development process.
  - Large user community, with some users developing specialized turnkey applications: e.g. for space, medical, and accelerator physics.







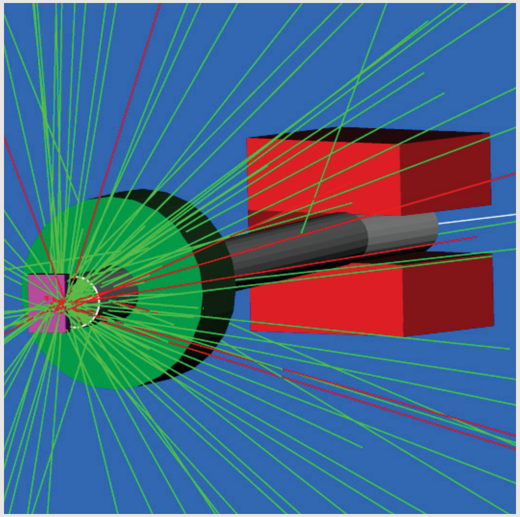


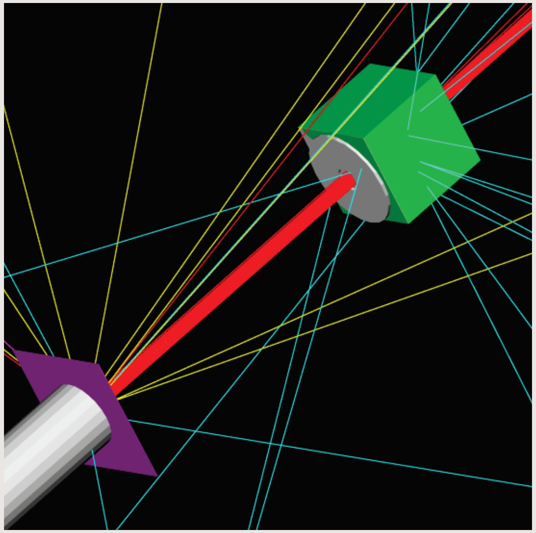
G4Beamline

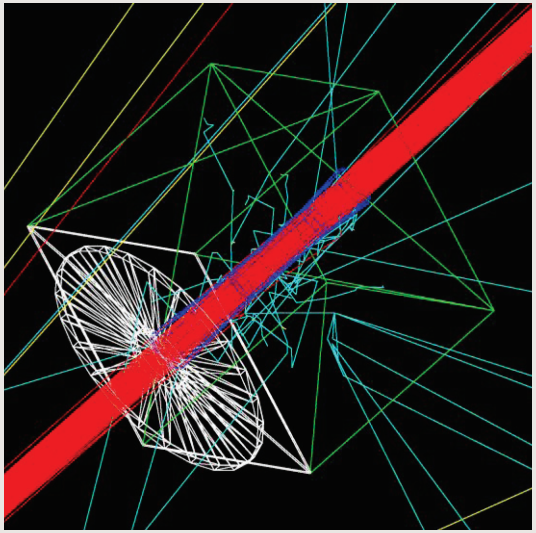
- A Geant4-based application
- Free and open-source: www.muonsinc.com

Muons, Inc.
Innovation in Research

- Contains a wide range of beam line components with detailed specification via named element parameters, and flexible specification of fields and field maps.
- User defines the beam, machine components, layout, fields, output options via a text file. Input scripting language is similar to MAD and is a good fit to most beam physics application needs.







Cyclotron Simulation Model

- Magnetic field preparation
  - Field data stored as Fourier harmonics tabulated as a function of radius. Original survey data taken at 3” and 1° intervals, together with trim coil contributions.
  - Reconstructed on 3D Cartesian grid (0.5”) by Fourier series evaluation and first-order expansion off the midplane.
  - Due to a limitation in G4Beamline’s beam input format, all tests were done using protons instead of H^-.
  - To preserve isochronism it is sufficient to scale the entire field by the ratio of masses m_p/m_{H-}.

Simulation Model - 2

- Dee gap field
  - Field region is defined in G4Beamline to be 9" wide (approximate width of the flat-top field region for 6" physical gap)
  - Simplification: uniform peak field $\times \cos 2\pi f t$
  - Frequency 23.05508 MHz, period 43.37439 ns, 5^{th} harmonic.
  - Peak RF voltage 188 kV – max. energy gain 376 keV/turn
  - Geant4 adaptively samples the field based on the particle position and time coordinates.
  - Energy gain is slightly underestimated (~1%) due to neglect of the fringe field regions.

G4Beamline input

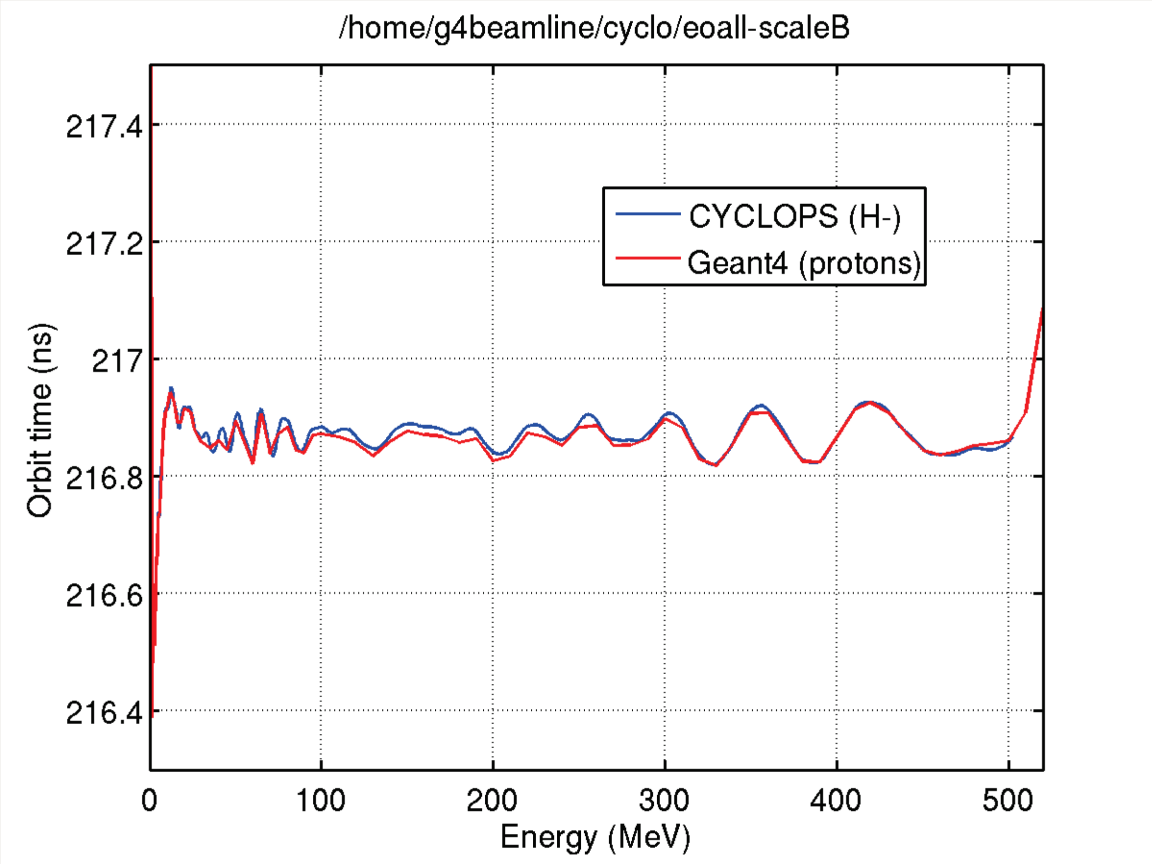
```
*   G4Beamline: TRIUMF Cyclotron
*   Magnetic field from policyinita6.dat, EOs from cycdata581.dat, with RF
    acceleration
physics QGSP_BIC doStochastics=0
beam ascii filename=fort.81 nEvents=$nEvents
trackcuts kineticEnergyMax=502.757831
param worldMaterial=Vacuum

fieldmap TRICYCLO filename=policyinita6-scaleB.blfieldmap current=1

param pi=acos(-1) INCH=25.4
param tau=0.2*216.872
fieldexpr RFGAP Ex=0.188/(9*0.0254) time=cos(2*$pi*t/$tau) factorE=1.0 \
          length=660*$INCH width=9*25.4 height=200 period=$tau

place TRICYCLO rename=TRICYCLO. z=0 rotation=X-90
place RFGAP rename=RFGAP. z=0 rotation=Y-90

zntuple format=asciiExtended z=0 coordinates=global require=x>0
```

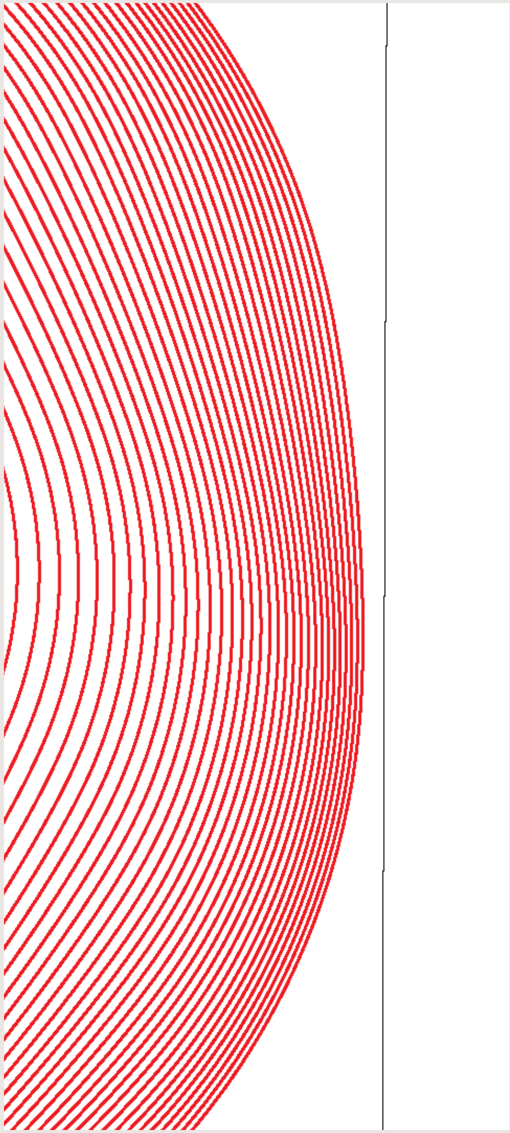
fort.81:

```
#BLTrackfile created by GENRAYS
#x y z Px Py Pz t PDGid EvNum TrkId Parent weight
#mm mm mm MeV/c MeV/c MeV/c ns - - - - -
1066.86255  0.  0.  1.74445093  0.  96.9777298 -1.2 2212 1 1 0 1
```

Equilibrium orbits and isochronism

- Geant4 tracking of CYCLOPS equilibrium orbits starting at 0^{o} azimuth.
  - Closure of Orbits
  - Isochronism





Differences in the codes

	CYCLOPS & GOBLIN	G4Beamline + Geant4
Field map	2D polar	3D cartesian
Mesh spacing	Radial: 3” Azimuthal: 1°	0.5”
Interpolation	R: 4-point Lagrange θ: none* Z: none (calculated from 2nd order expansion)	8-point linear from 3D mesh
Integration	4th order Runge-Kutta	4th order Runge-Kutta
Step size	2° azimuthal intervals*	Adaptive to error requirements
RF gap	Energy kick at gap center with correction terms (GOBLIN)	Tracking through finite gap with time-dependent electric field

Stability of orbits

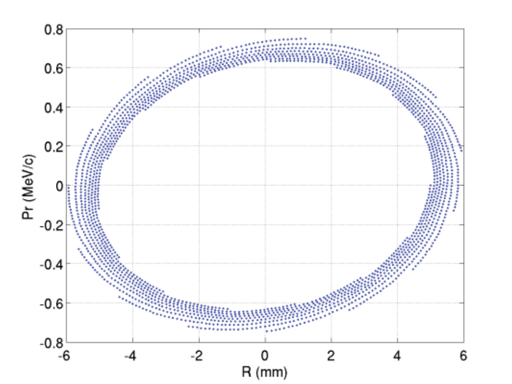
Equilibrium orbits are very stable …

Equilibrium orbit deviations in mm

Energy (MeV)	Difference from CYCLOPS E.O.	After 1000 turns	After 10000 turns	After 50000 turns
5	0.9688	-0.1068	-0.5011	-1.8025
20	1.0985	-0.0653	-0.2859	-1.1428
100	2.0026	-0.0612	-0.1339	-0.5755
200	2.6716	-0.0171	-0.0572	-0.1997
500	1.9482	0.0060	0.0062	-0.0038

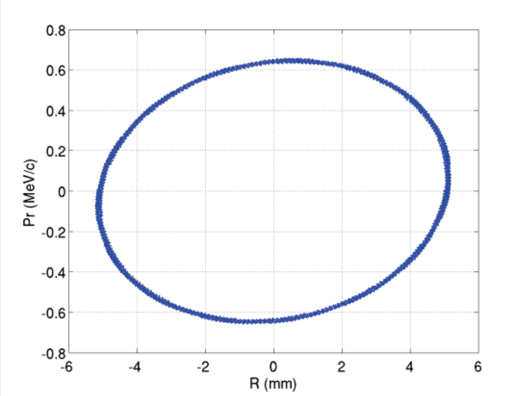
… but horizontal phase space is not well conserved in tracking 5mm from the E.O. for 2000 turns. (Vertical is much better)

0.5” mesh: emittance changes up to ±50%



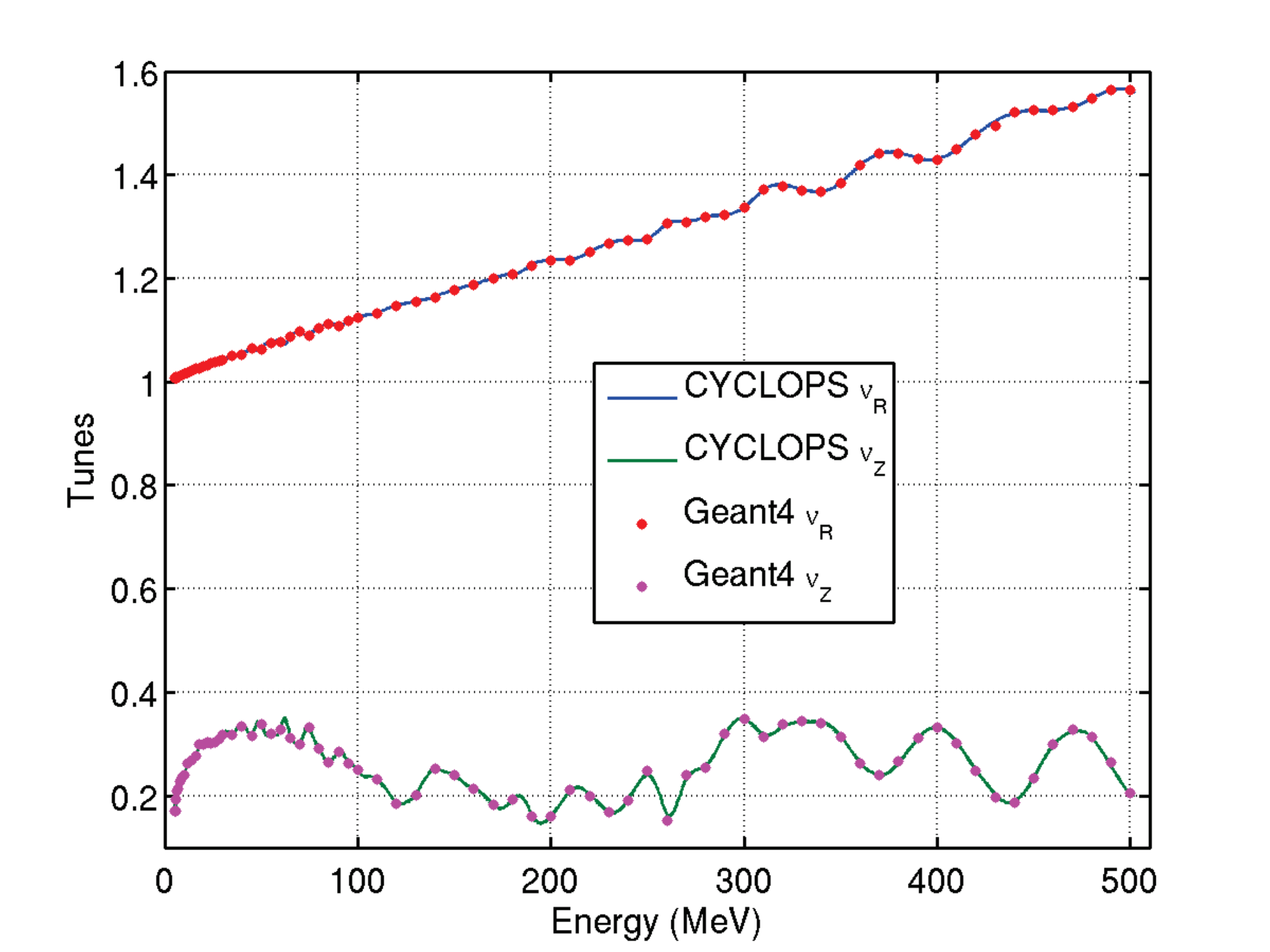
110 MeV, 0.5” mesh

0.25” mesh: emittance change reduced to ±7%



110 MeV, 0.25” mesh

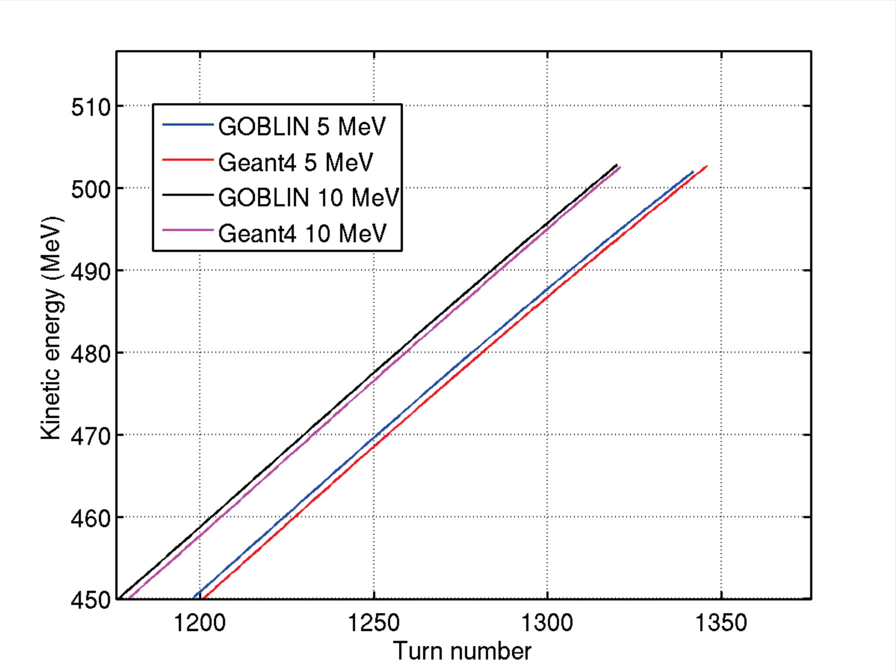
Tune measurements



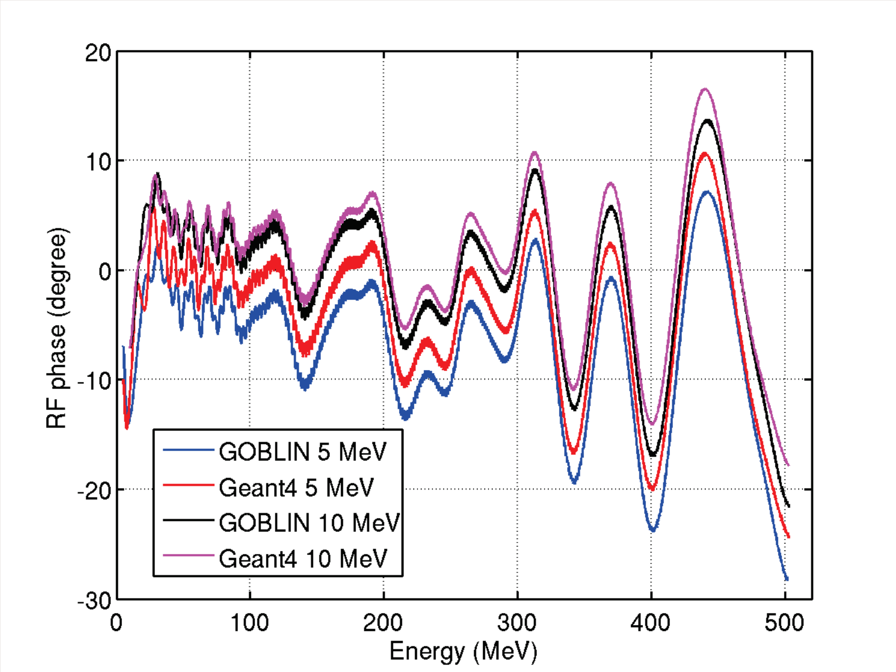
Tunes in Geant4 determined by 1000-turn tracking near (5mm) to equilibrium orbits, FFT of R and Z data sampled once per turn.

Accelerated orbits

- Acceleration test → 500 MeV
  - Launch on 5 & 10 MeV equilibrium orbits
  - Initial rf phase of -7° from GOBLIN reference runs
  - Small adjustment (10^{-5}) to rf frequency for comparable phase tracking.
  - Tuning of Vrf for comparable energy gain per turn.
  - Finite-gap effect: occupies 25°+25° of azimuth at 5 MeV.

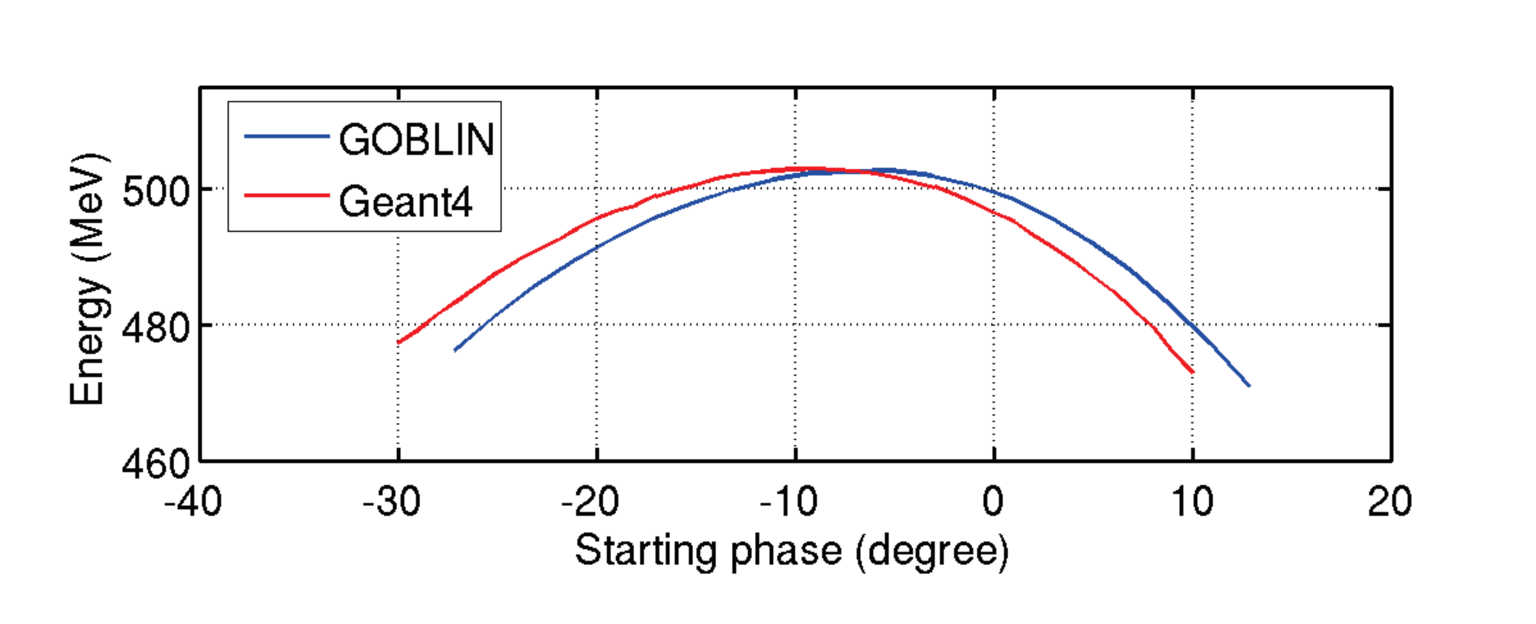


Detail at end of acceleration



Phase history

Acceleration vs starting rf phase



Phase scan:

- Launch particles on 10 MeV equilibrium orbit at 1-degree intervals
- Stop after 1320 turns and record final energy.
- Phase sensitivity has the same profile, with optimal phase shifted by 2-3°

Conclusions

- Geant4 is not a cyclotron code by design, but it is sufficiently accurate and versatile to produce results that compare well with the CYCLOPS and GOBLIN codes, using the same magnetic field data.
- Isochronism, repeatable equilibrium orbits, tunes, and acceleration have been demonstrated and are in accord with the cyclotron codes.
- Limitations
  - Multiparticle longer-term (~1000 turns) tracking is a problem: further adaptations (field mesh, interpolation, integrator) would be required for better performance and emittance conservation.
- Potential applications
  - Applications should focus on unique Geant4/G4Beamline abilities.
  - Overlapping/superimposed and orientable fields: finite rf gap, electric focusing of gap, extraction elements, etc.
  - Interactions in matter: extraction foils, probes, loss processes (+decays)
  - 3D geometry: automatic and accurate detection of particle losses
  - Interactive visualization: indispensable for checking/adjusting the model.