Full longitudinal polarization for multiple halls

or

A Wien for each beam

Jay Benesch

Outline

- Present injector
- Idea and scheduling issue
- Present Wien
- New Wien model
- New Wien with focusing solenoids
- Triple Wien
- OPERA constraints
- Future work?
- Conclusion

What does the injector contain?

(in order)

1. 130 keV gun (200 keV 2015)
2. vertical Wien filter (90 degrees precession)
3. two spin flipper solenoids for left/right flip with vertical Wien
4. prebuncher to reduce longitudinal spread in bunch due to space charge effects
5. aperture 1 of two, defining transverse bunch extent
6. horizontal Wien, setting final precession angle for all 3 halls, one optimally or a compromise except at two-hall "magic" energies. All focusing solenoids thereafter are counter-wound for zero net precession.
7. aperture 2 of two, finishing transverse bunch definition.
8. chopper, allowing different currents for three halls – the only place in the injector where the three beams are separated, at 120^{o} intervals on a 30mm diameter circle. Holes 24^{o} by 6mm
9. Buncher cavity, again reducing bunch length
10. Capture cavity, accelerating to 500 keV kinetic energy (incorporate in (12) in 2015)
11. apertures 3 and 4, transverse beam cleanup, usually no intercepted current
12. two-cavity cryomodule, accelerating to 6.3 MeV/c momentum (change in 2015)

Idea

- The injector group within Accelerator Operations is working on a new front end with 200 keV gun and a new cryo-unit incorporating the capture.
- Reza Kazimi and I were chatting about it, discussing the problems caused by the pre-buncher between the two Wiens. Reza asked if one could build a minature Wien and install three in the chopper region.   I decided to investigate.
- Current density required appeared too high, ~2000 A/cm^2, for conventional conductor – until the YR melted. That runs at 3700 A/cm^2 at 6 GeV, so it's possible.

Scheduling Issue Example

- Single horizontal Wien can be set to maximize polarization to one (parity) experiment or maximize the sum of P or $\mathbf{P^2}$.
- For example, Qweak energy was reduced 2 MeV in October 2011 to improve the polarization for hall A on passes 2-5. With C at $P^2=1$ Hall B has $P^2=1$ on passes 2 and 4 and $P^2=0$ on passes 3 and 5. HD-Ice wanted polarization on pass 3 as well, but ….

Hall A Pass	P^2 549 MeV/linac	P^2 548 MeV/linac
2	.870	.884
3	.869	.902
4	.909	.957
5	.969	1.00

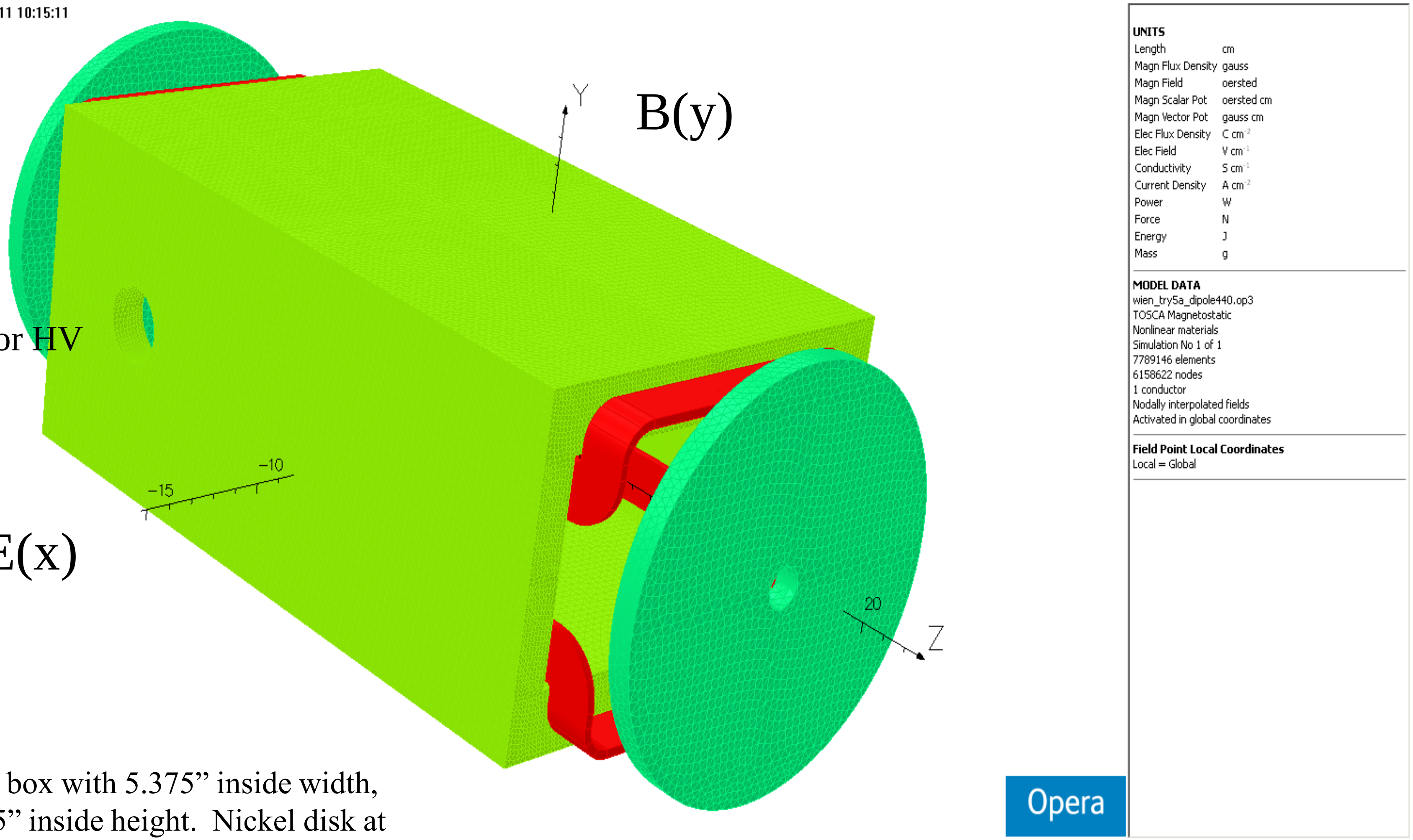
Wien equations

$$\text{precession} = \frac{Ze\left(1 - \frac{g-2}{2}\right)}{mc\beta\gamma^2} \int B_\perp ds$$

Wien condition

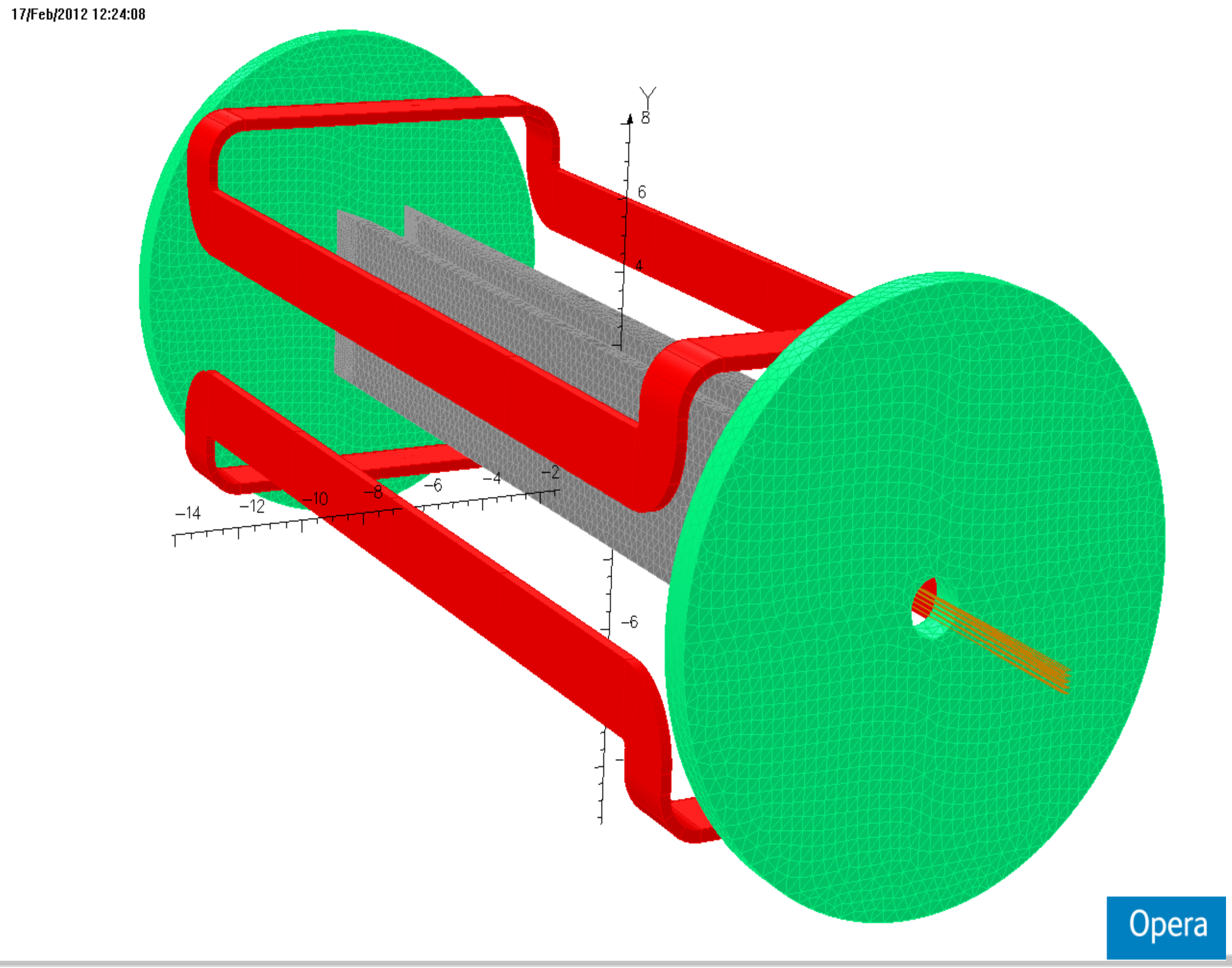
$$\frac{E \times v}{c^2} = \frac{1-\gamma^2}{\gamma^2} B_\perp$$

Present Wien

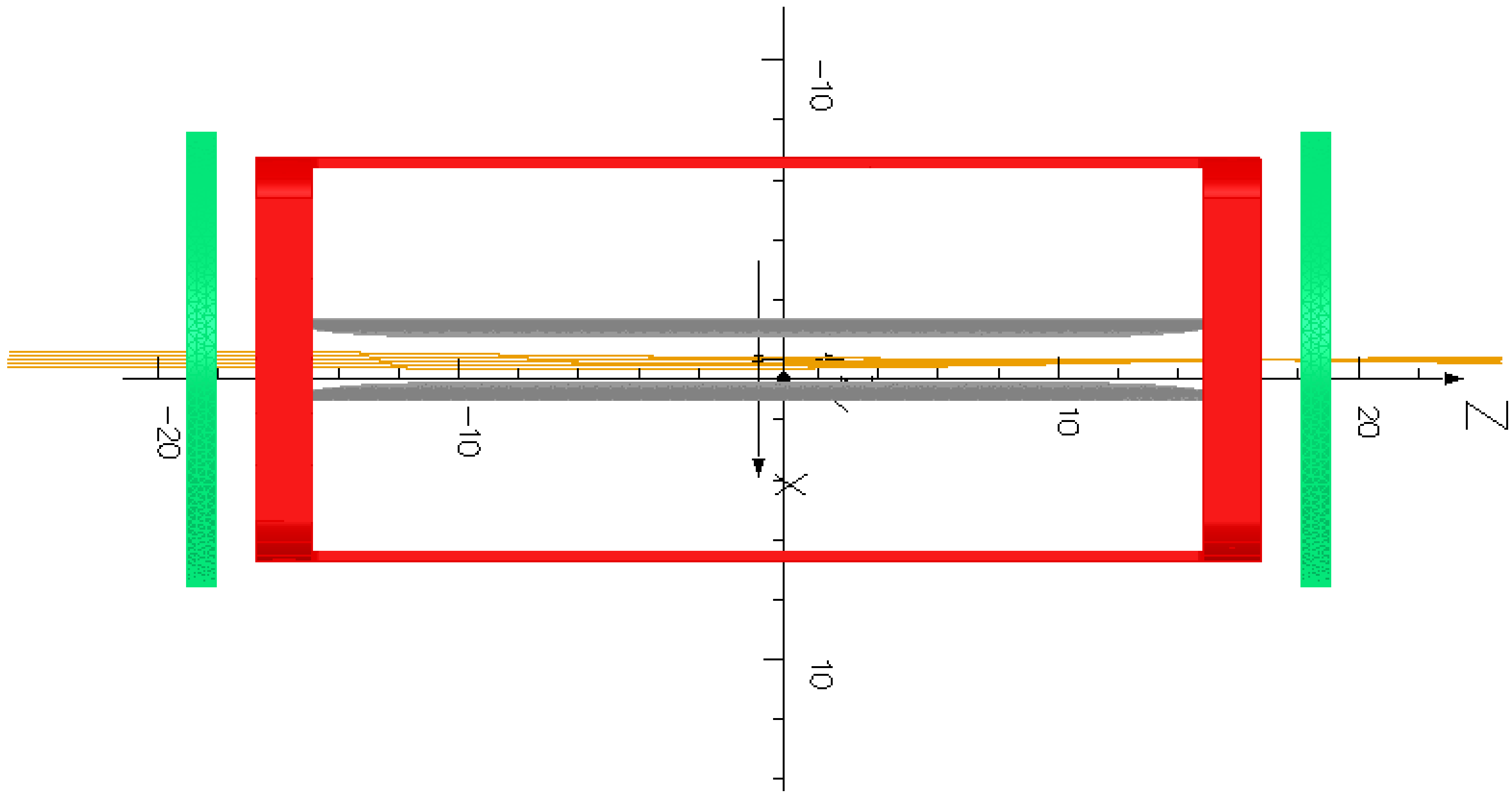


Steel box with 5.375” inside width, 3.125” inside height. Nickel disk at each end to reduce field Z extent.

Present Wien Internals

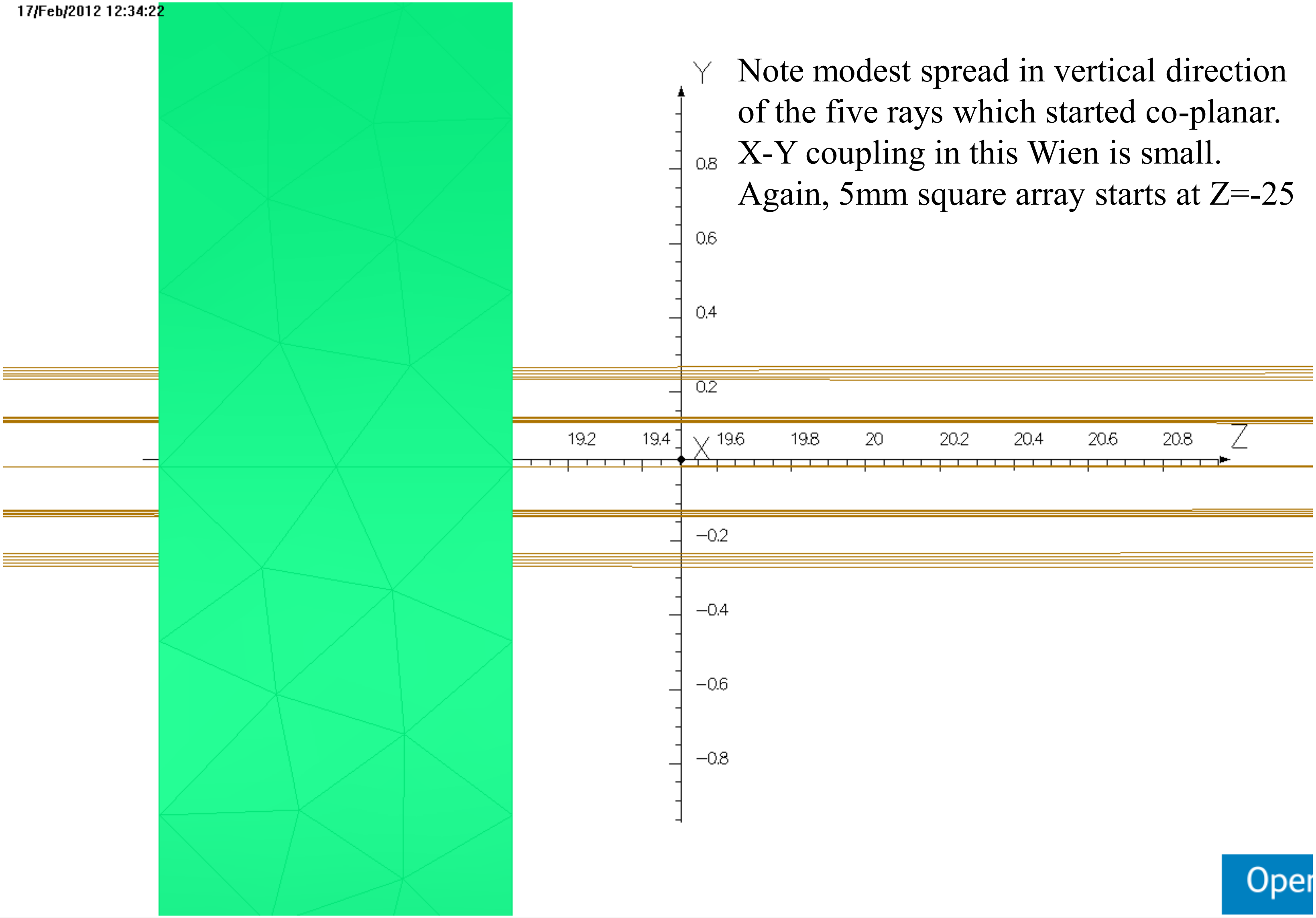


Present Wien Top View



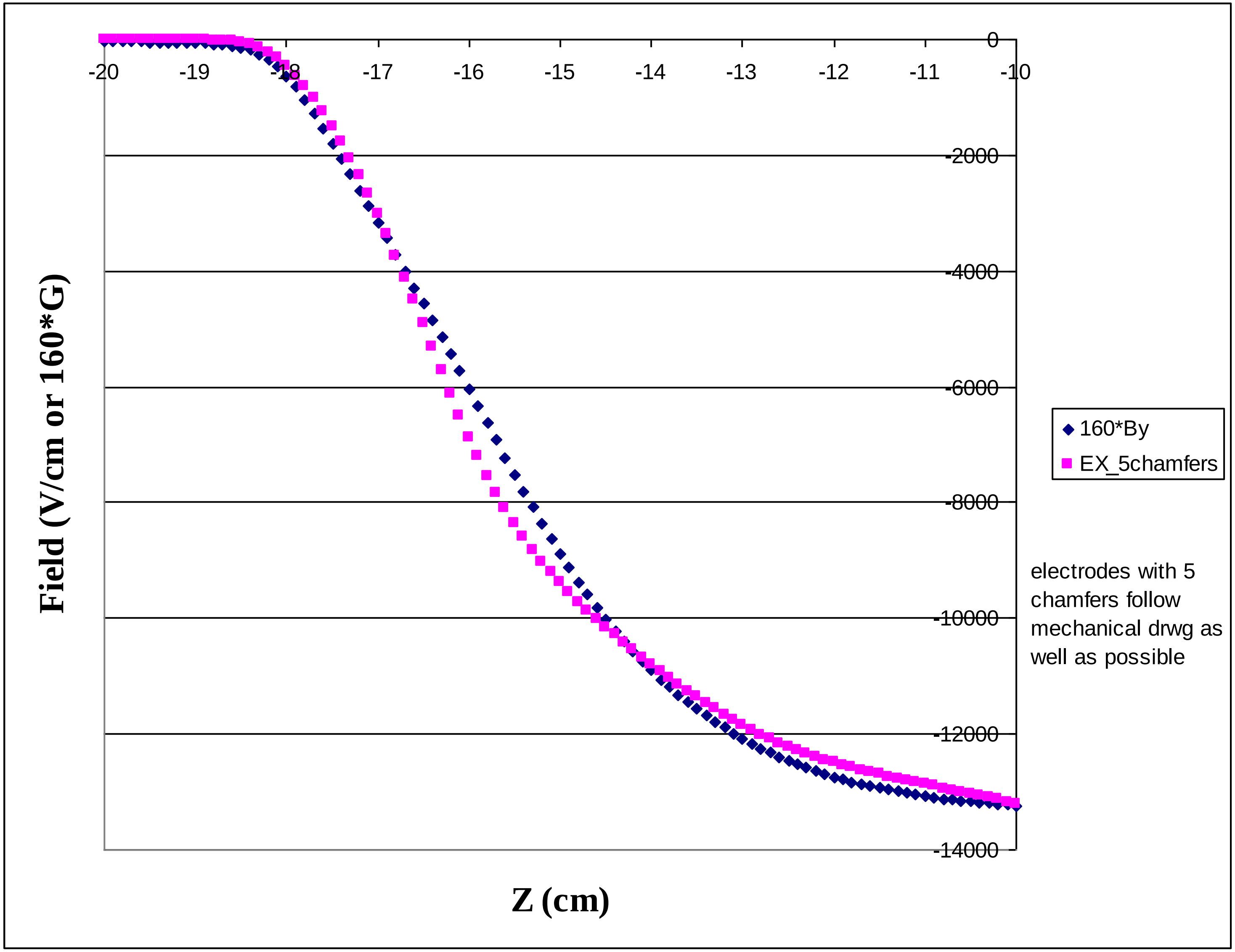
5mm square array of 200 keV particles enter at left.   BdL 3600 G-cm, electrode voltage +- 18.2kV. Note horizontal focusing.

Present Wien: Side view at exit

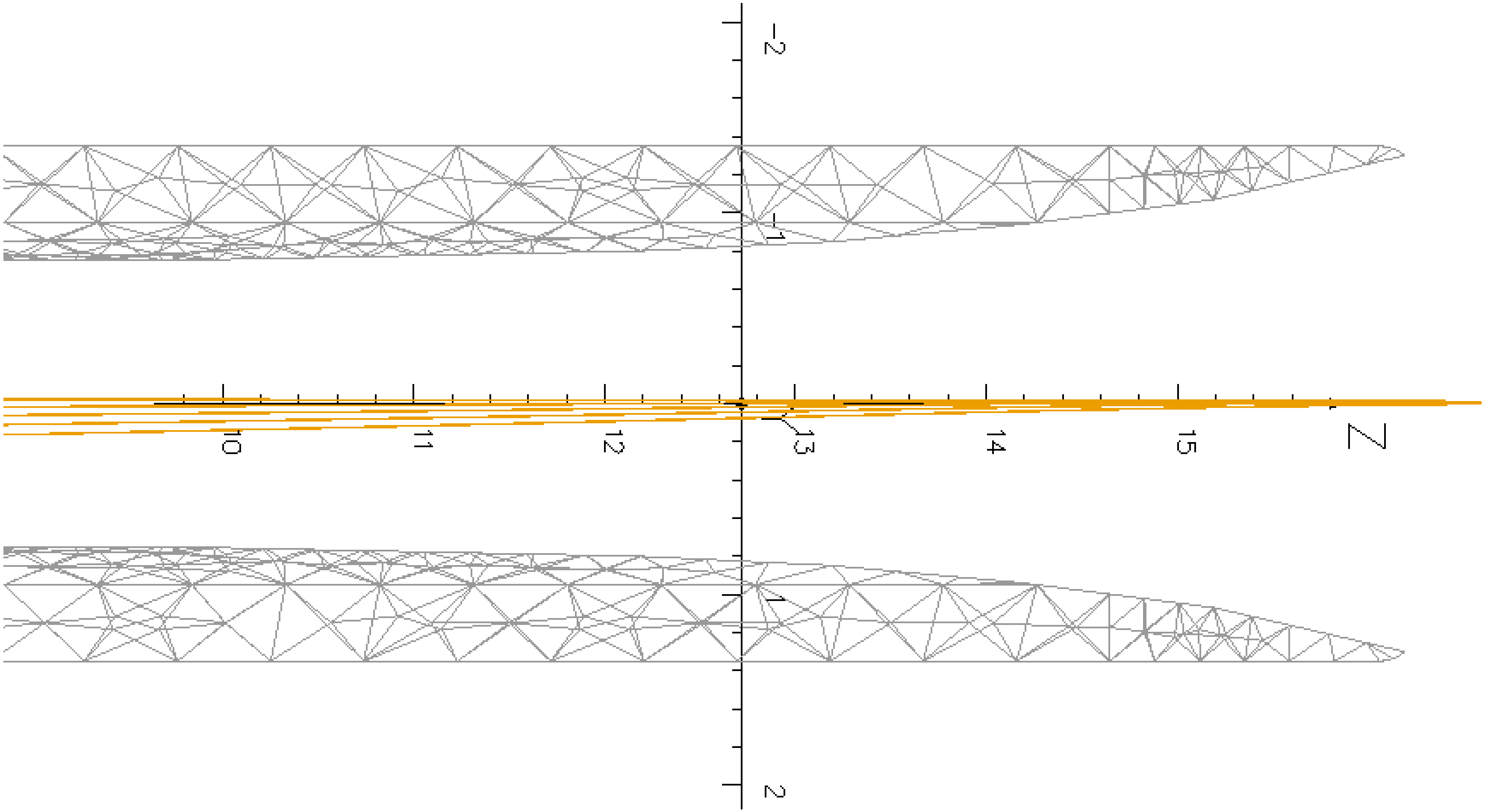


Note modest spread in vertical direction of the five rays which started co-planar. X-Y coupling in this Wien is small.
Again, 5mm square array starts at Z=-25

Field fall-off at end of present Wien



Electrode taper in model



Field integral comments

- B is determined by precession desired. 90^o here.
- E is determined by need for straight orbit on axis.
- 100 keV: BdL= 2097 G-cm, E=-11.2 kV/cm
- 200 keV: BdL= 3600 G-cm, E=-24.3 kV/cm =-2.43 MV/m
- electrodes are 1.5cm apart, so latter equals +-18.2 kV

Things to check for present Wiens

- Power supplies +-15 kV now. 20 kV needed for 200 keV.
- Cables and connectors 20 kV capable?
- 20A magnet supply needed? Double up wires down to tunnel?

Chopping system

- Symmetric pair of transverse 499 MHz cavities and solenoids put the three bunches at 120^{o} intervals on a 30 mm diameter circle.
- Moving slits may then independently reduce the current for each hall.
- Master slit has 24^{o} apertures, +-3mm radially about 30mm circle
- 24^{o} of 30mm circle is 6.3mm = width of beam between the slits and the de-chopping half of the system.
- Anything within the chopping system **must have at least this aperture and have "unity" transfer matrix**. -1 preferred and currently implemented.
- RF power adequate for 200 keV per R. Kazimi

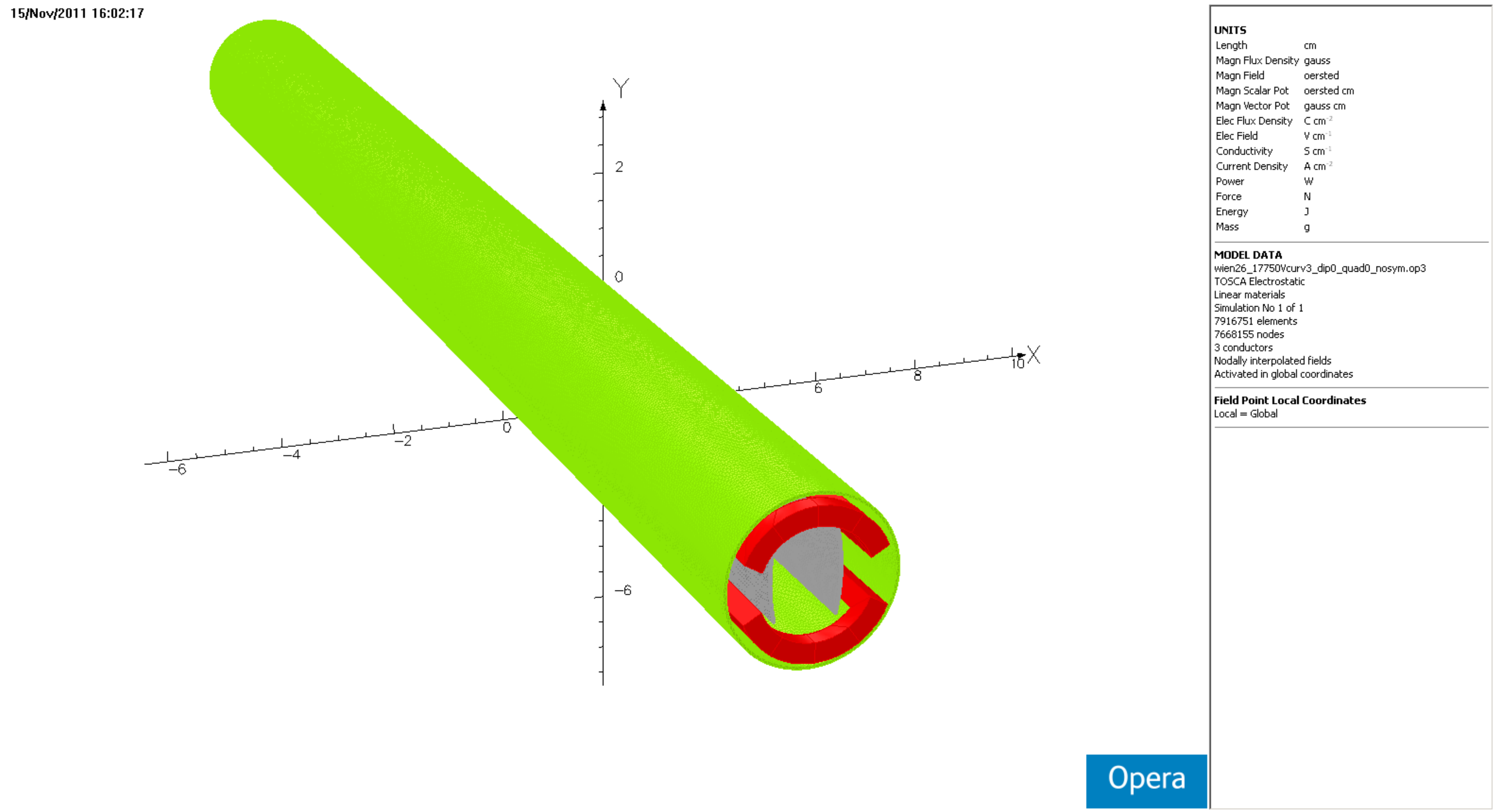
Aperture choice for new Wien

- I assume in what follows that a parallel beam fills the A and C chopping apertures and fills half the B angle extent. Full 6mm radial extent in three beams.
- Less than 1% of the 180 μA Qweak beam at 130 keV is intercepted by the "master slit".
- If the chopper slits were 20^{o} by +-2.5mm radially the Wien design task would be much easier. The Operations Injector Group would have a more difficult design task.

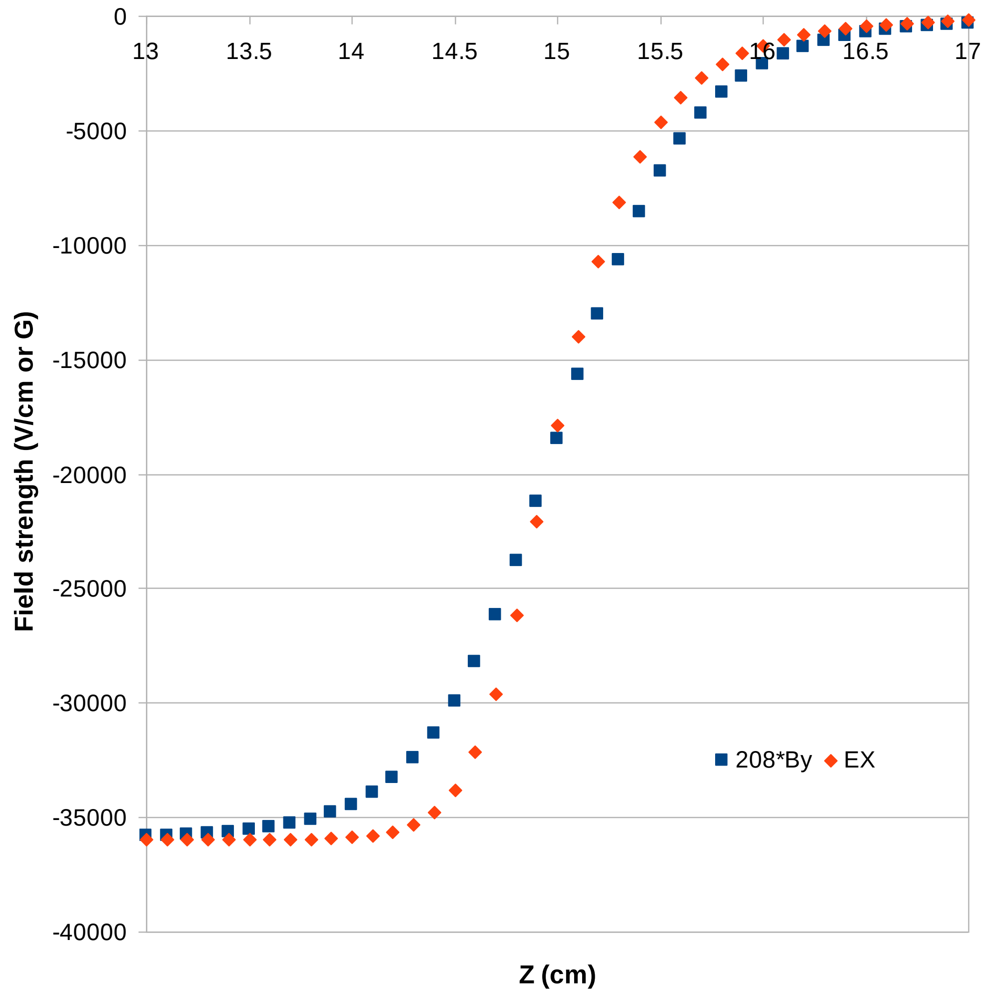
Basics of new Wiens

- Three osculating 26mm circles have their centers on a 30mm circle.
- There's a stock metric steel tube size 26mm OD, 1mm wall – perfect for shielding one Wien from the next.
- E-field limit suggested 4 MV/m
- 200 keV beam, 90 degree precession capability needed
- For those values and sharp edged fields 30 cm long, BdL=3600 G-cm and E=2.5 MV/m.
- Since E field and B field don't fall off the same way in Z, the electrode length has to be adjusted to minimize steering.

single Wien model



End fields



Electrode length was adjusted to match magnetic field fall-off.

Magnetic shield length was varied in a failed attempt to adjust the B field end profile.

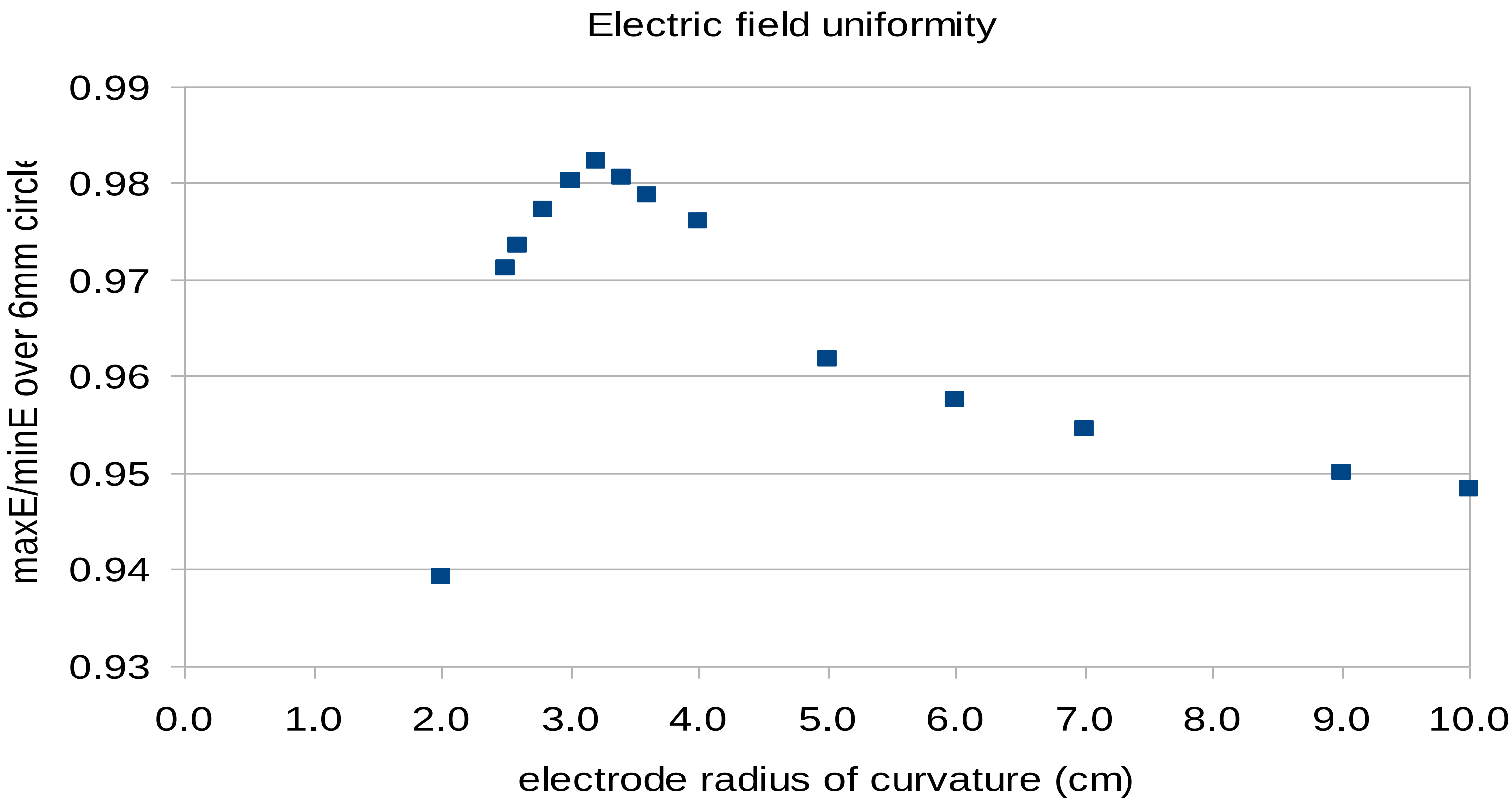
Final electrode 14.8 cm half-length.

Final steel tube 15cm half-length.

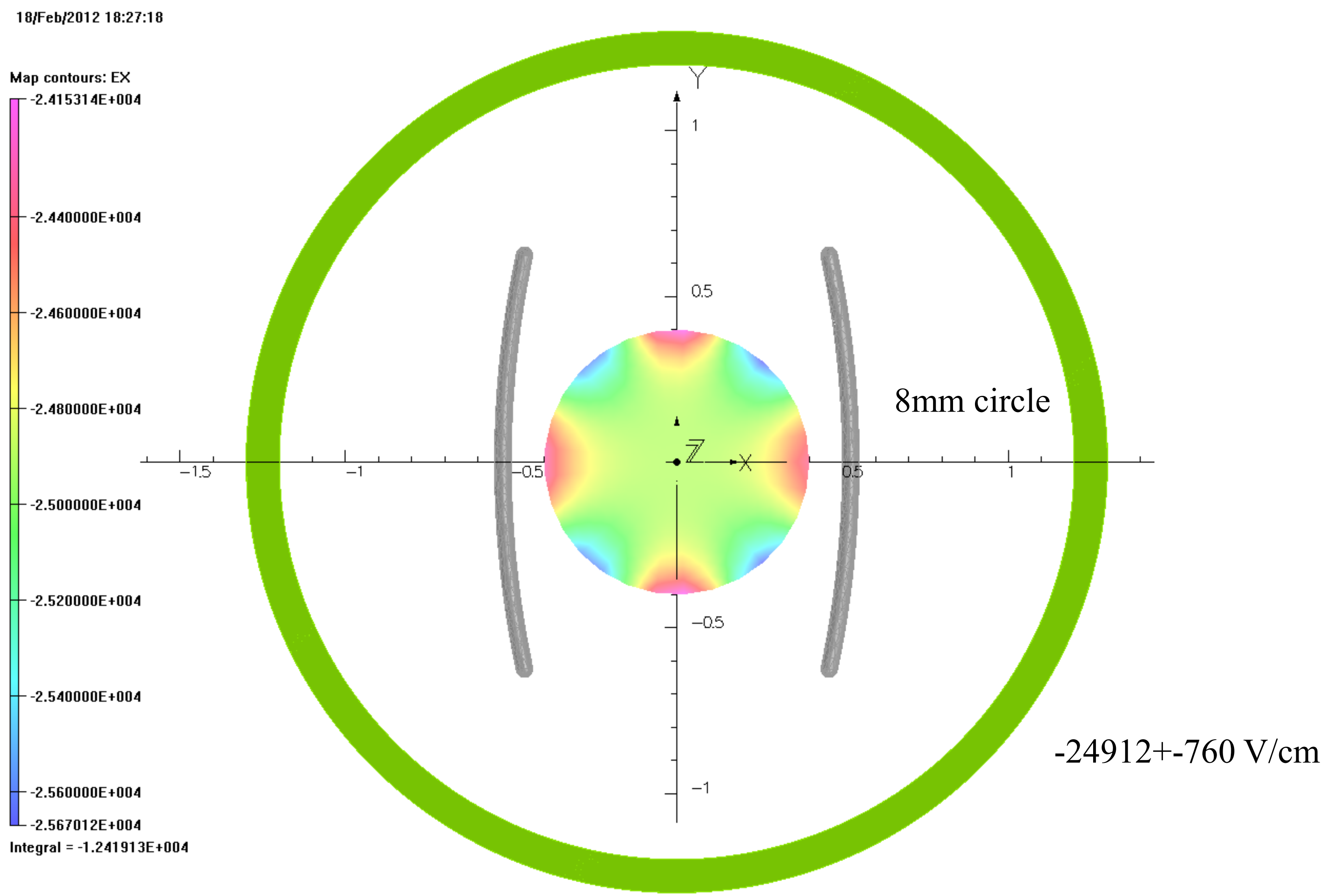
x axis cm from center
y axis V/cm or 208*G

Electrode curvature

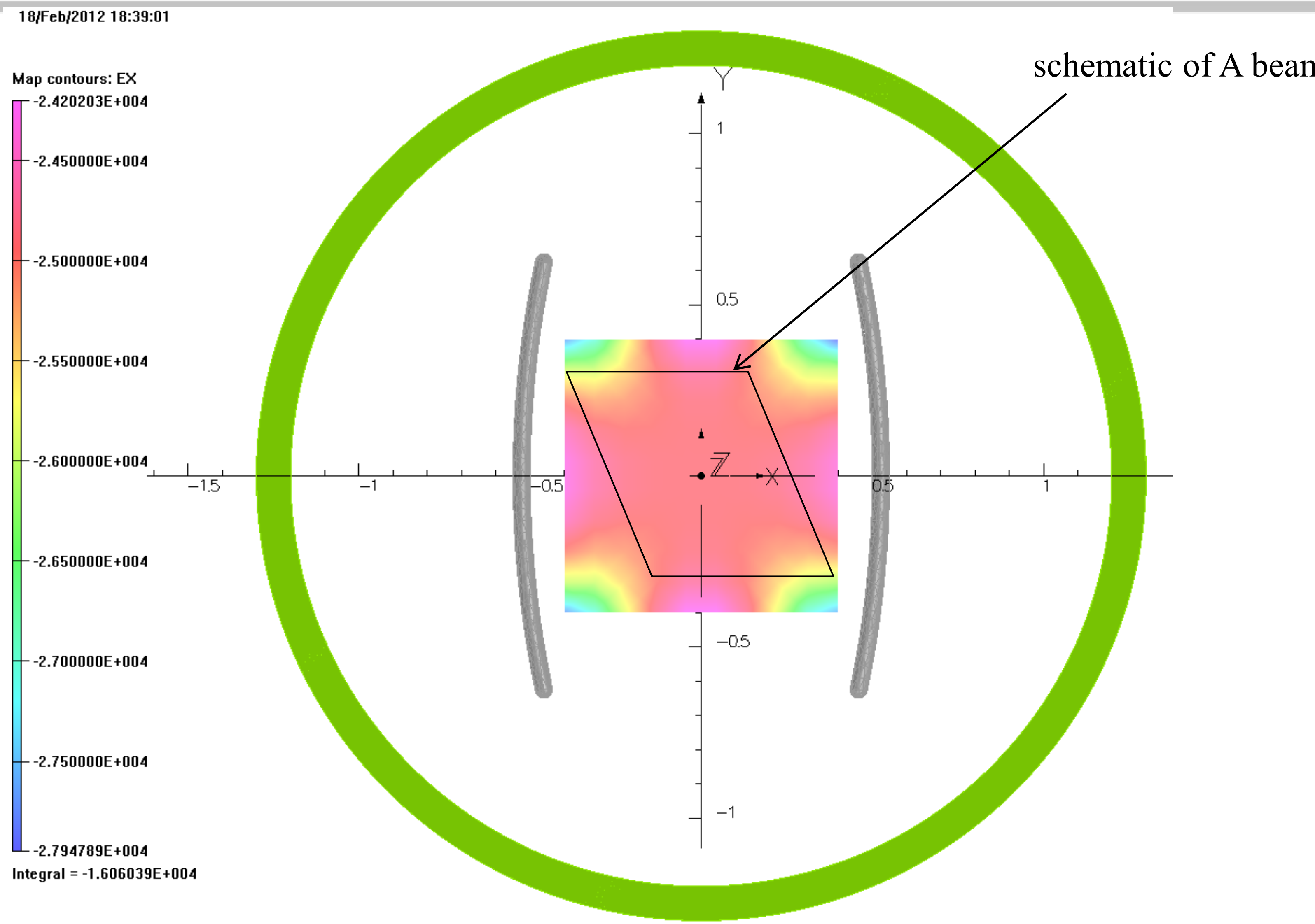
I explored electrodes as arcs of circles, keeping 1cm spacing on mid-plane.   3.05 cm chosen



E field in midplane of Wien

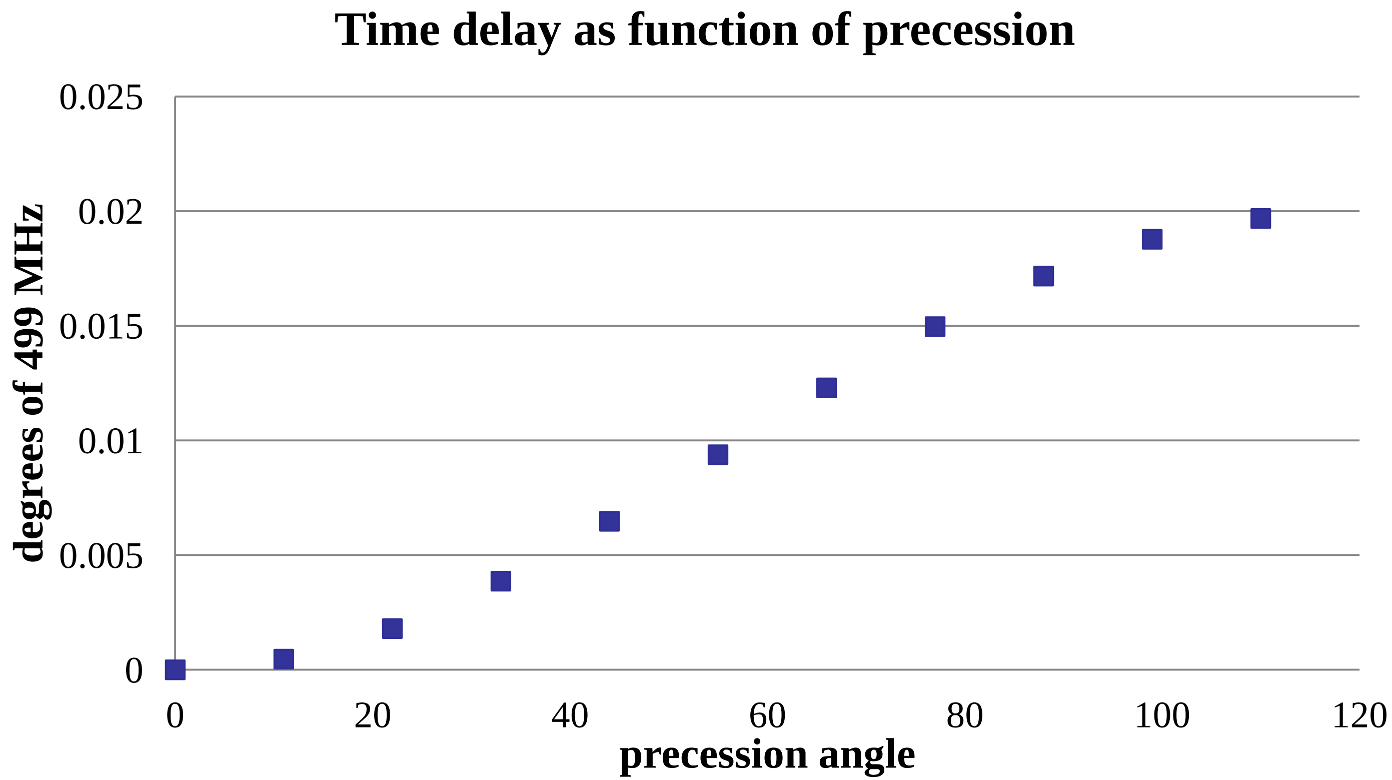


E field in midplane of Wien



Time delay as a function of precession

- J. Grames sees degree phase delays in the present Wien at 130keV at large angles. The new model doesn't show a problem at 200keV. I haven't checked the model of the old Wien.



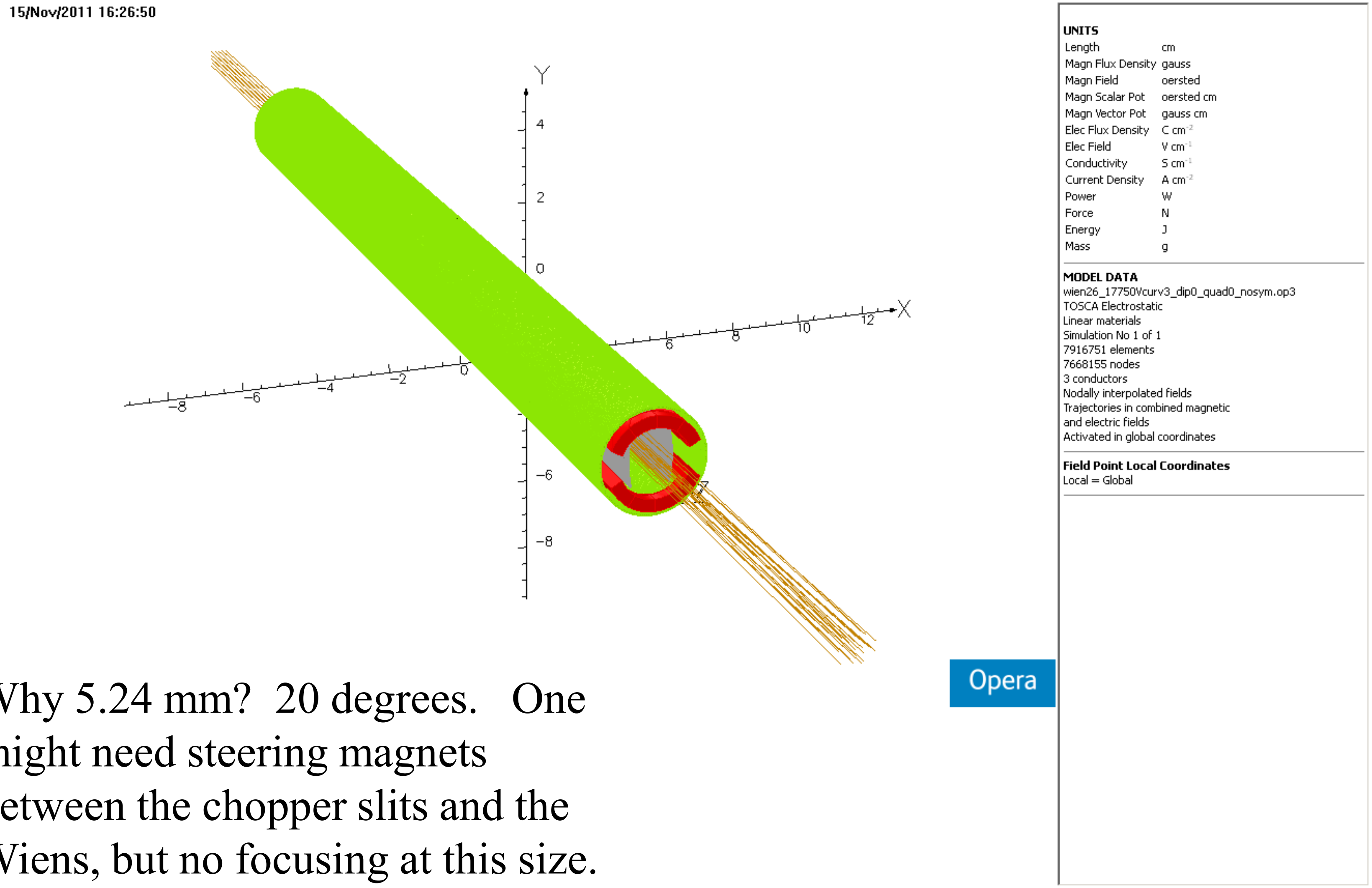
conductor choice

- Some gap between the OD of the conductor and the steel desired to reduce field distortion. 0.5mm final choice.
- The smaller the angle subtended by the dipole conductor, the better the field. I tried 15^o, 12^o and **10^o** .
- For this round of modeling, I used a square "helical end" coil built into Tosca, 3mm square, 15cm half-length.
- Hollow conductor may be fabricated in **10^o** wedge, 7.445 mm^2 , or 1/8" diameter refrigeration tubing used, 5.776mm^2 of copper. Use tubing – cheaper and less chance of water leaks into vacuum.

field quality from these choices

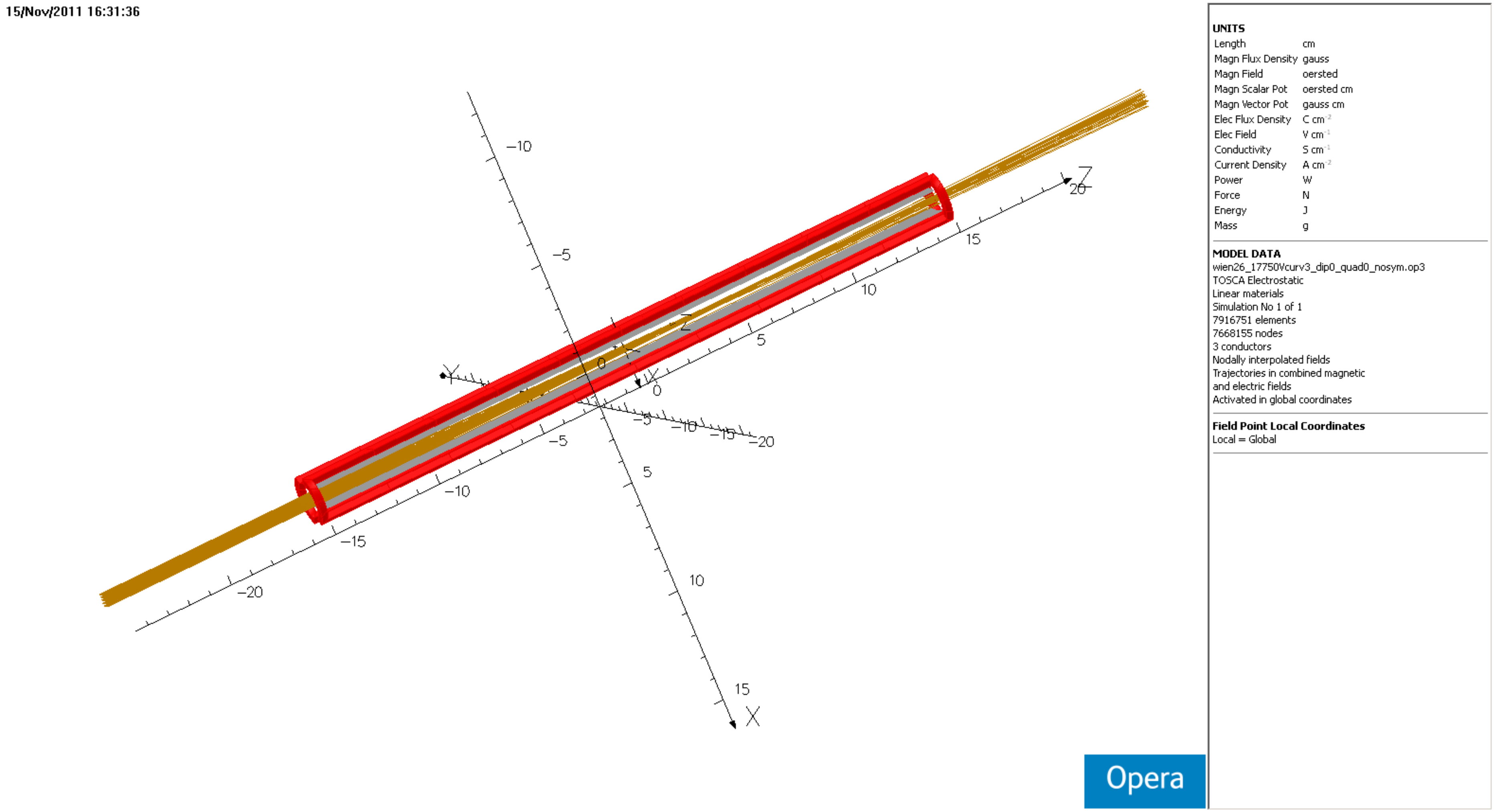
- Magnetic dipole field +/- 0.6% over 6mm diameter circle
- Electric field +/- 0.9% over 6mm circle
- Power supplies must be stable to better than 0.05% to avoid beam steering.
- Scaling up the design doesn't help because the 24^{o} of chopping circle scales too.

5.24 mm square array through Wien



Why 5.24 mm? 20 degrees. One might need steering magnets between the chopper slits and the Wiens, but no focusing at this size.

view showing horizontal focusing

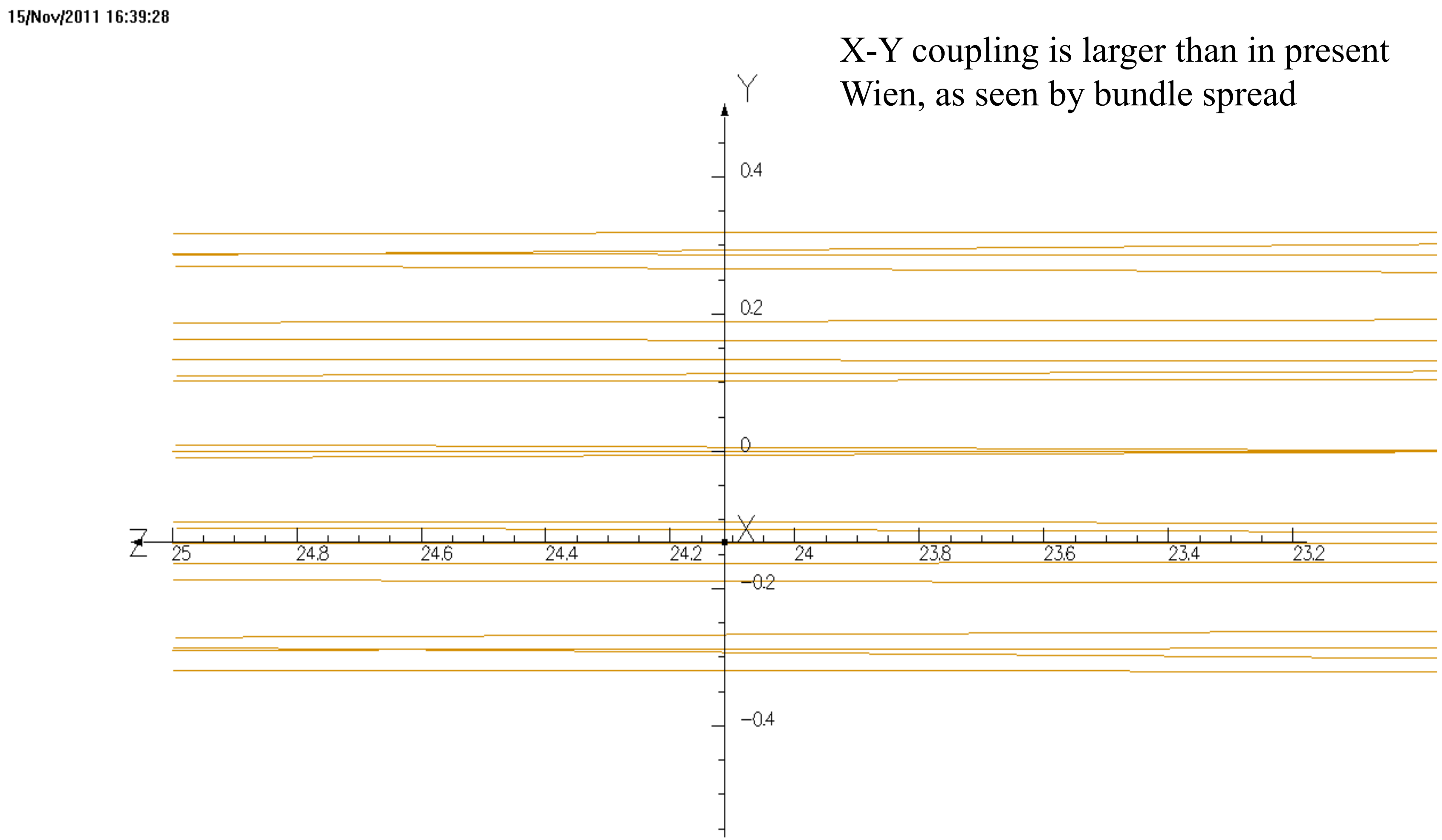


A full length quad doesn't help

- A full length quad was added to the model in an attempt to counteract the horizontal focusing.
- Vertical focusing was so great as to preclude its use.
- Since it complicated the assembly and was no use, delete.
- Next two slides show the beam divergence in the XZ and YZ planes 10cm beyond the steel tube.
- Conclusion: focusing elements are needed fore and aft to allow full chopped beam through the filter.

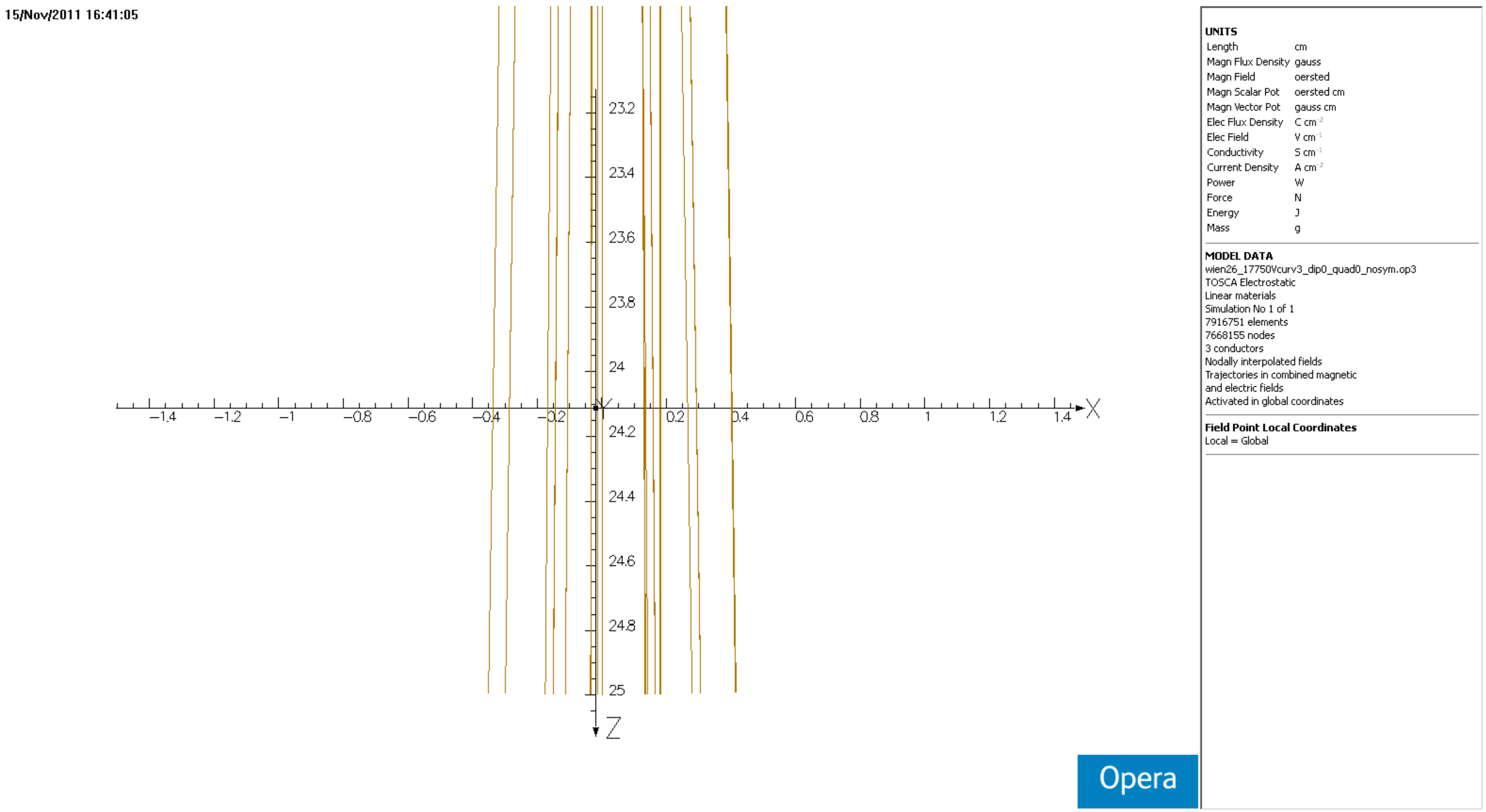
- To date, counter-wound solenoids have been used in the models. Quadrupoles will likely be required for engineering reasons.

YZ projection 10cm downstream

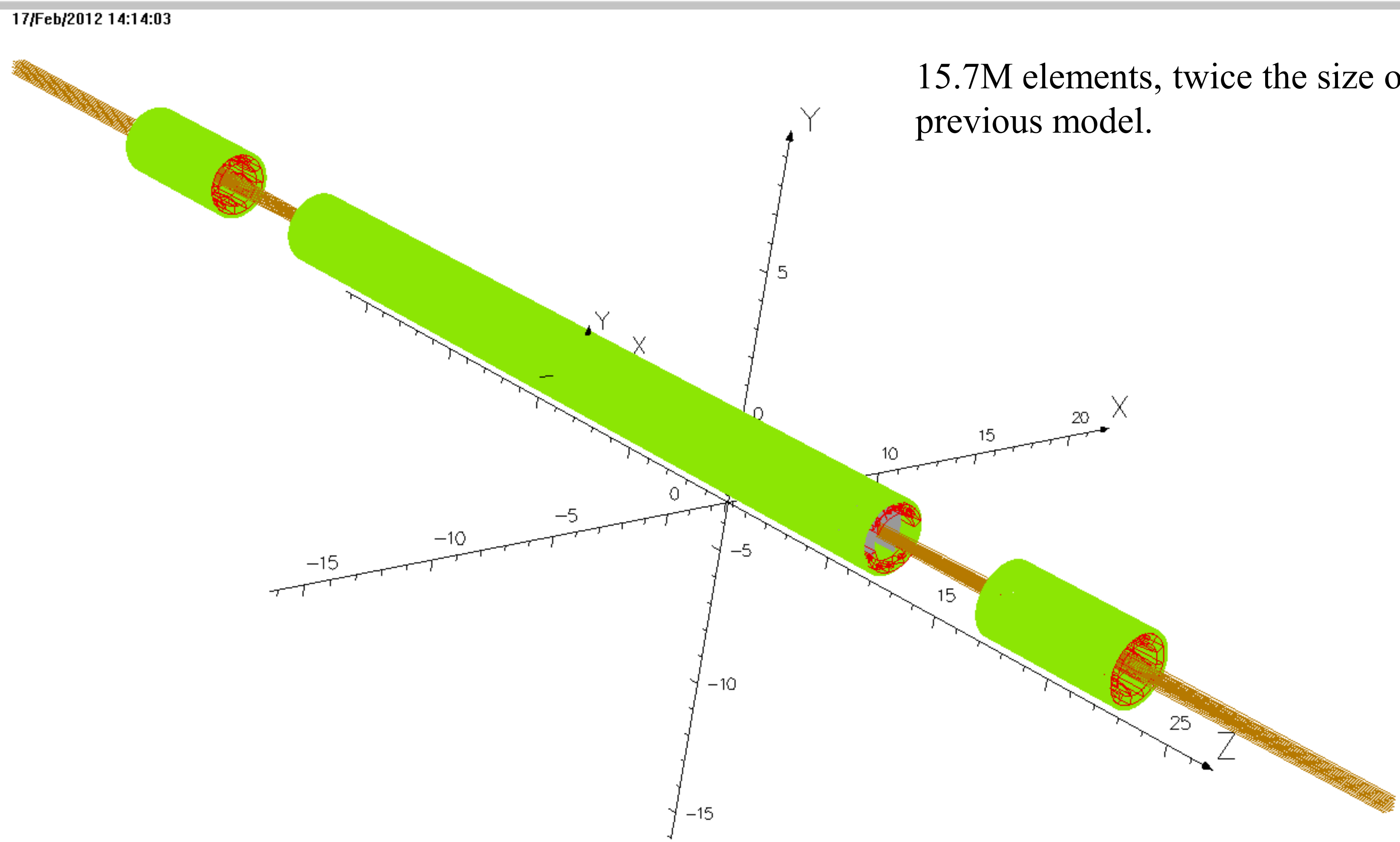


X-Y coupling is larger than in present Wien, as seen by bundle spread

XZ projection 10cm downstream



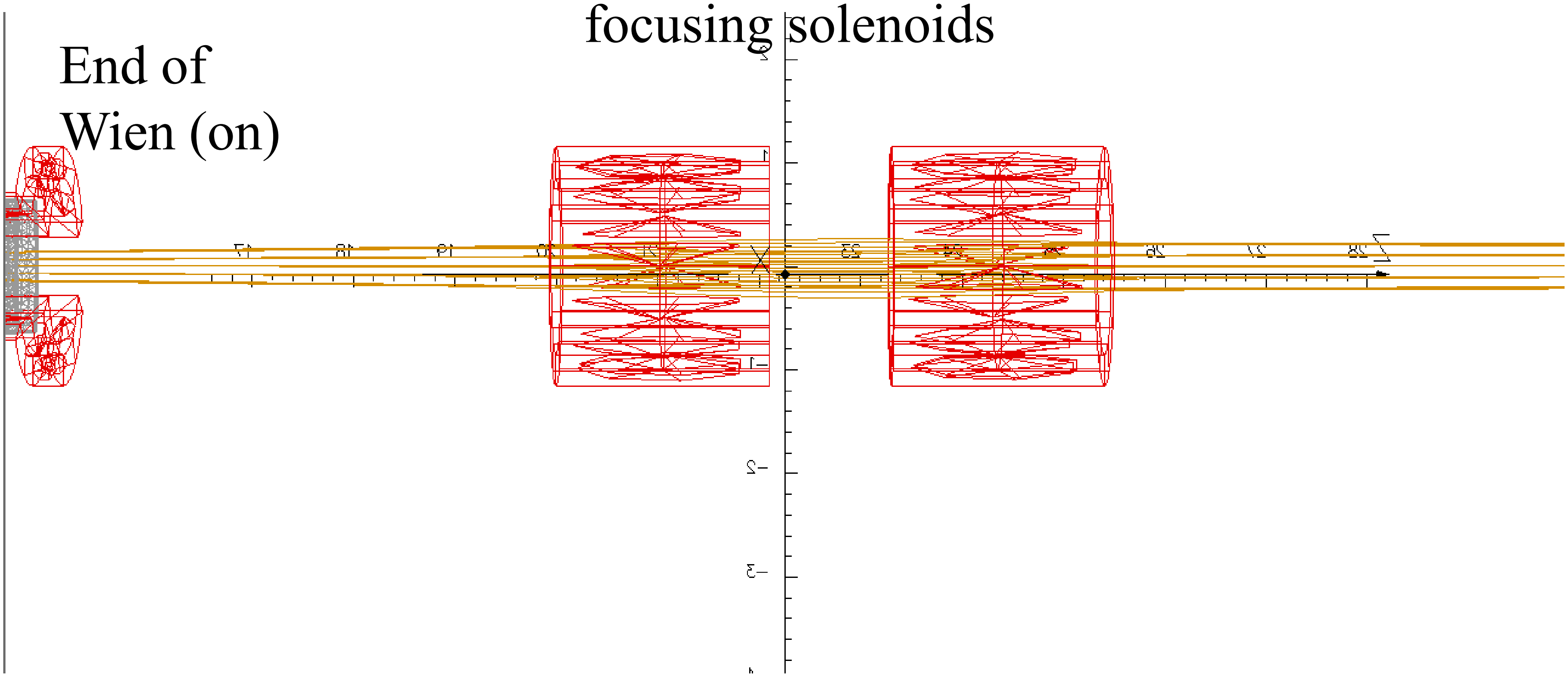
Single Wien with solenoids



15.7M elements, twice the size of previous model.

Opera

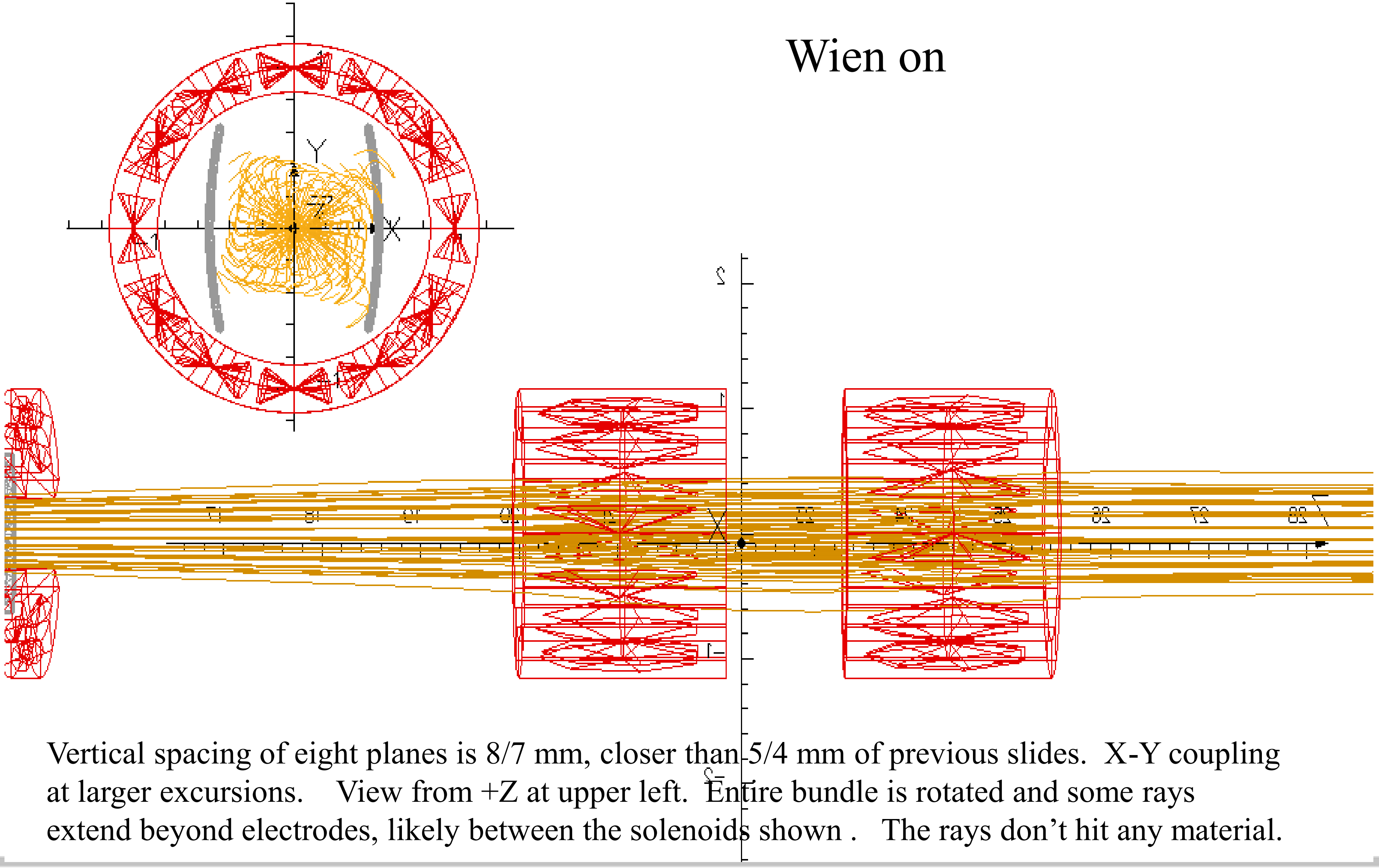
5mm bundle with focusing



Exit of Wien at left with vertical divergence due to focusing by counterwound solenoids upstream of Wien. 5mm bundle is nicely preserved. However …

8mm bundle with same focusing

Wien on

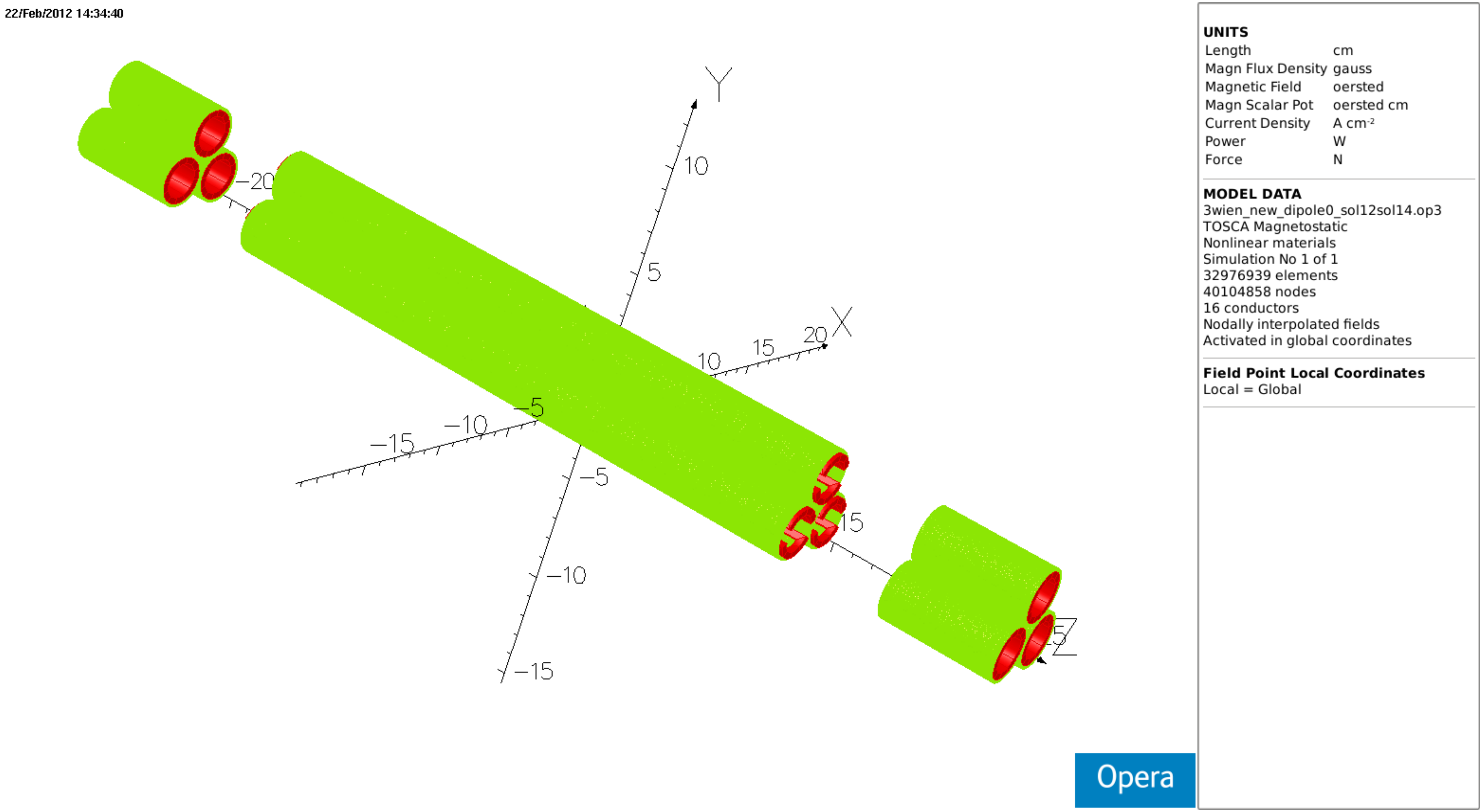


Vertical spacing of eight planes is 8/7 mm, closer than 5/4 mm of previous slides. X-Y coupling at larger excursions. View from +Z at upper left. Entire bundle is rotated and some rays extend beyond electrodes, likely between the solenoids shown . The rays don't hit any material.

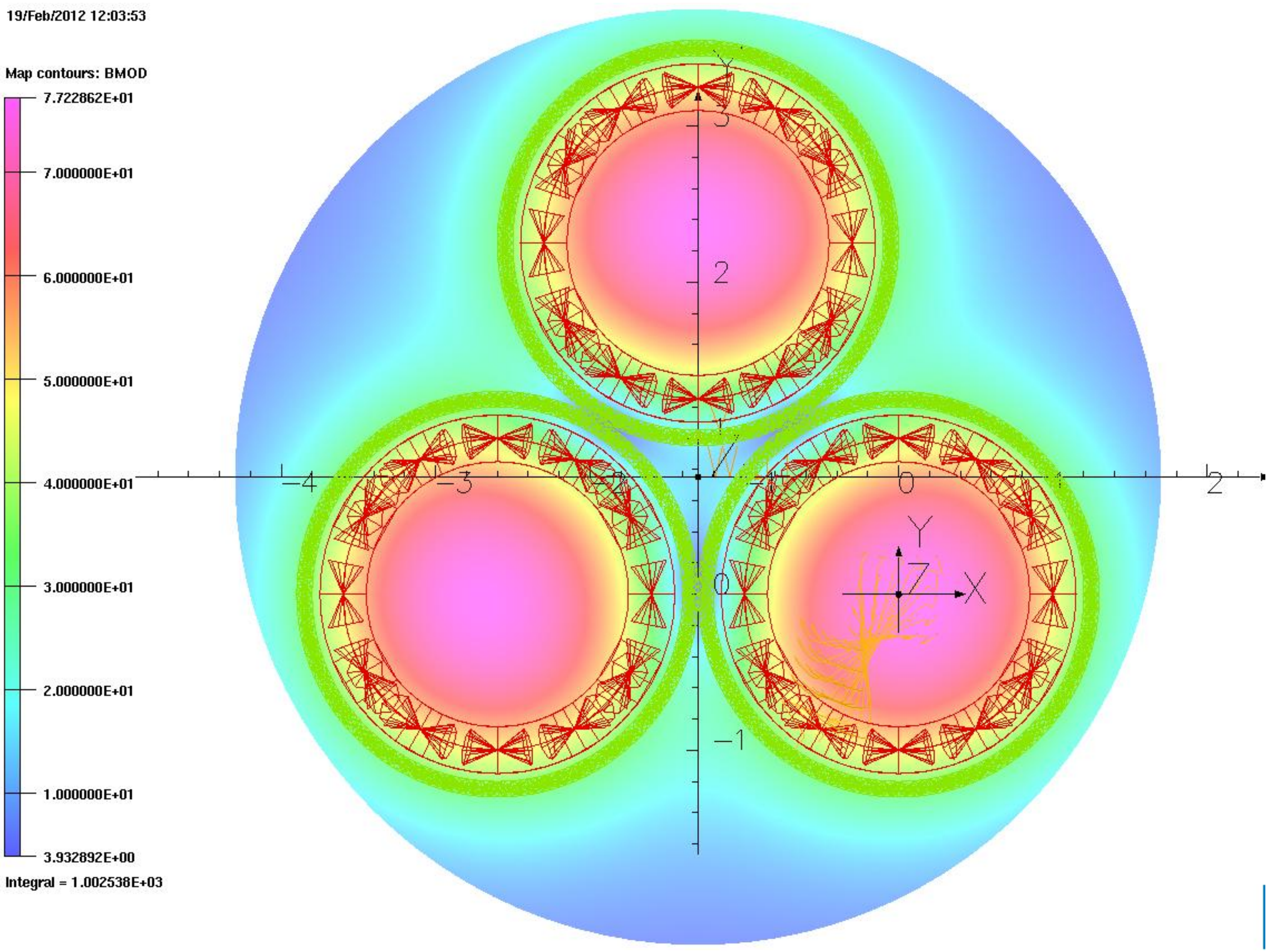
Is the magnetic shield adequate?

- Model was copied twice with offsets to create a larger model with three Wiens on 30mm diameter chopping circle.
- E and B fields are identical in the three Wiens. Current in B dipole is 0.39% higher than A/C to get same BdL.
- Square bundles of 200 keV "particles" were propagated through the model and its parts to answer the question.

Three Wien filters on 30mm circle

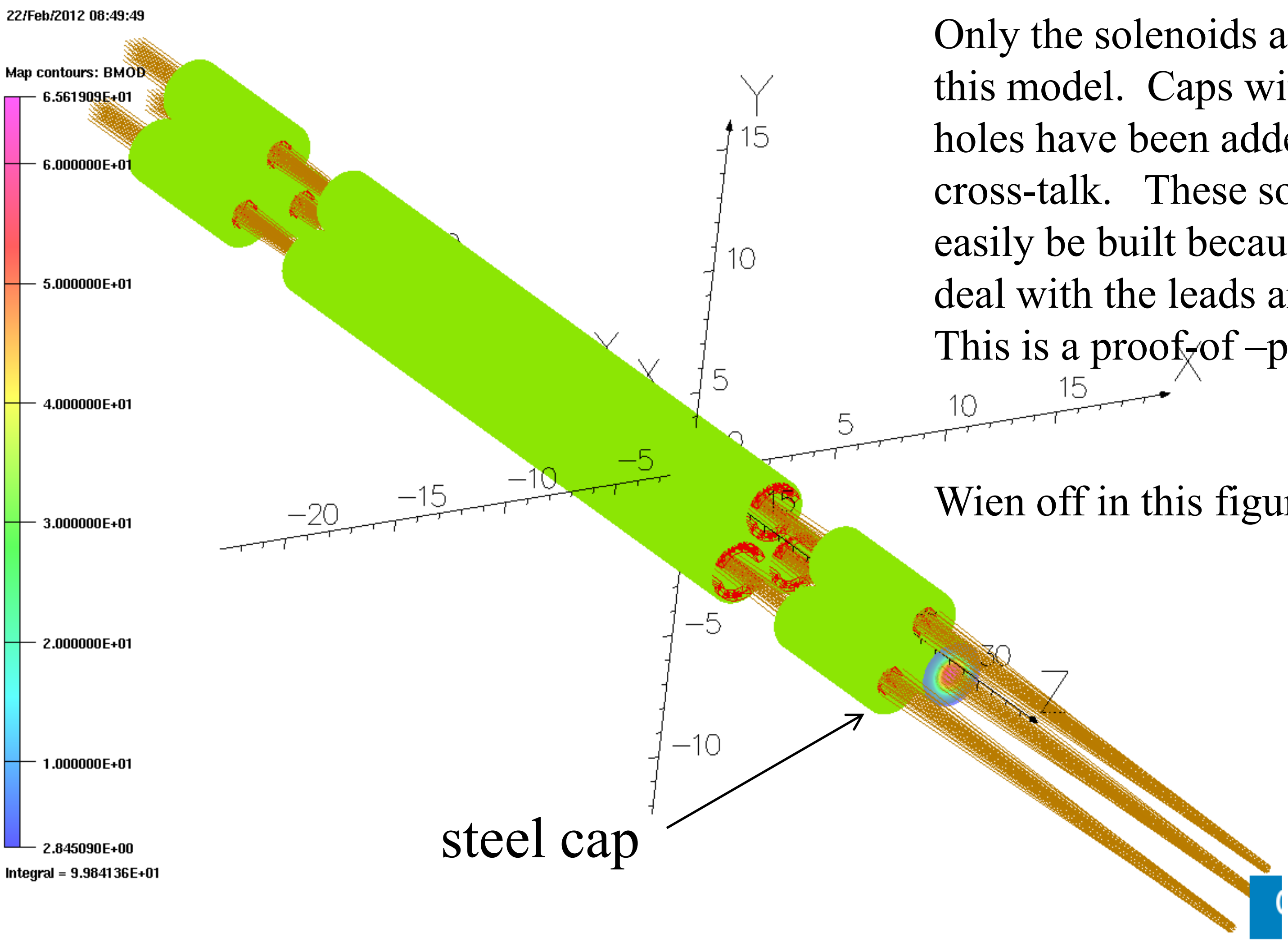


Three Wiens Z+ end view



Field 6mm downstream of solenoids. Fields are not symmetric about center of each Wien so beams don't propagate properly. More shielding is needed.

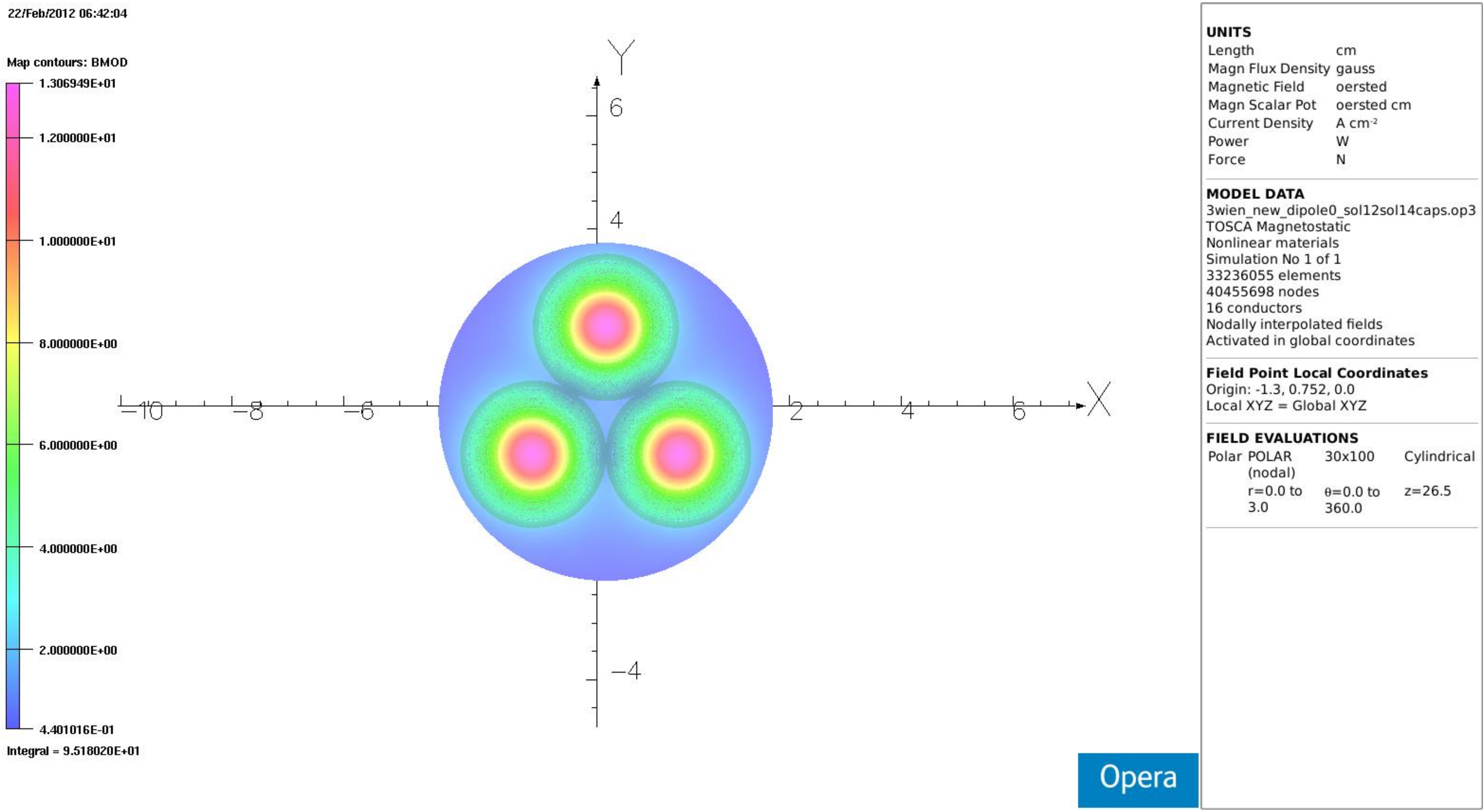
Caps added to solenoids



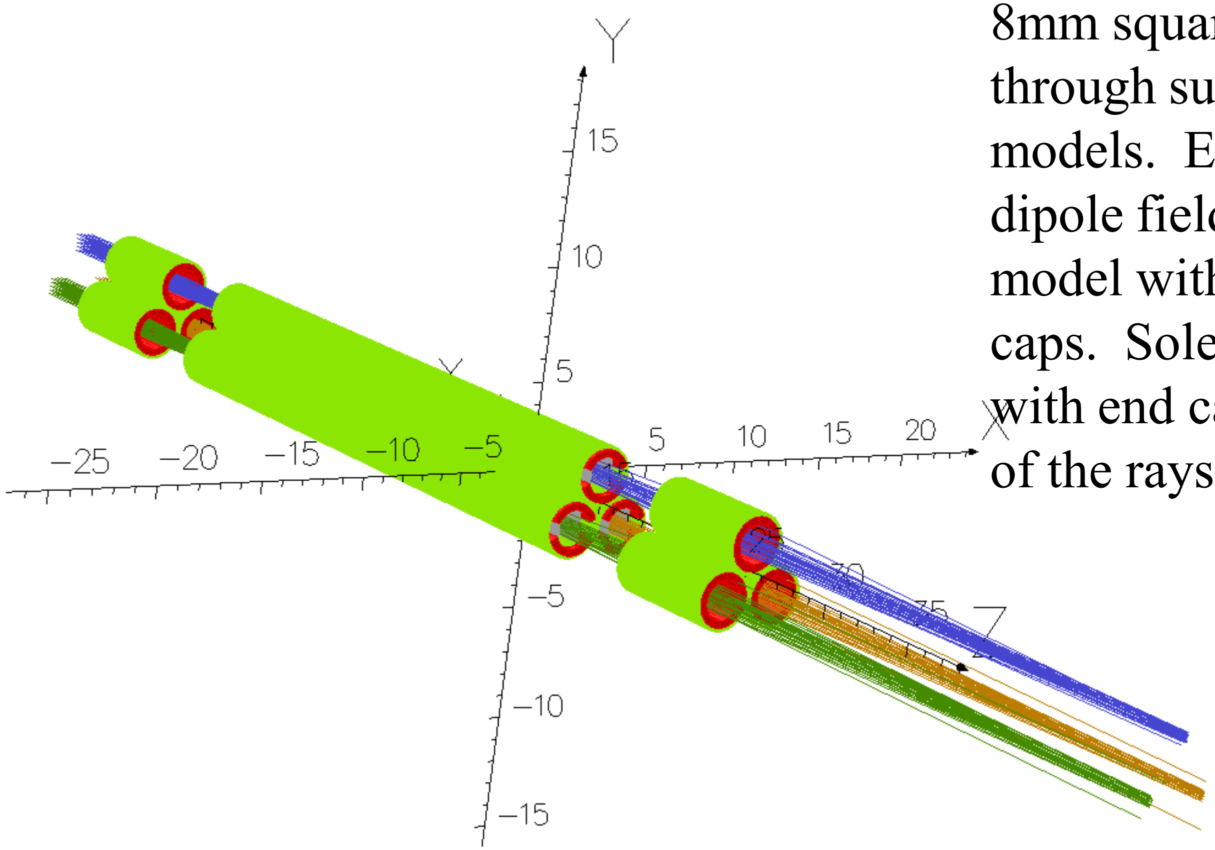
Only the solenoids are turned on in this model. Caps with 0.65cm radius holes have been added to reduce cross-talk. These solenoids can't easily be built because it's difficult to deal with the leads and get pure Bz. This is a proof-of –principle model.

Wien off in this figure.

Cross-talk eliminated with steel end caps



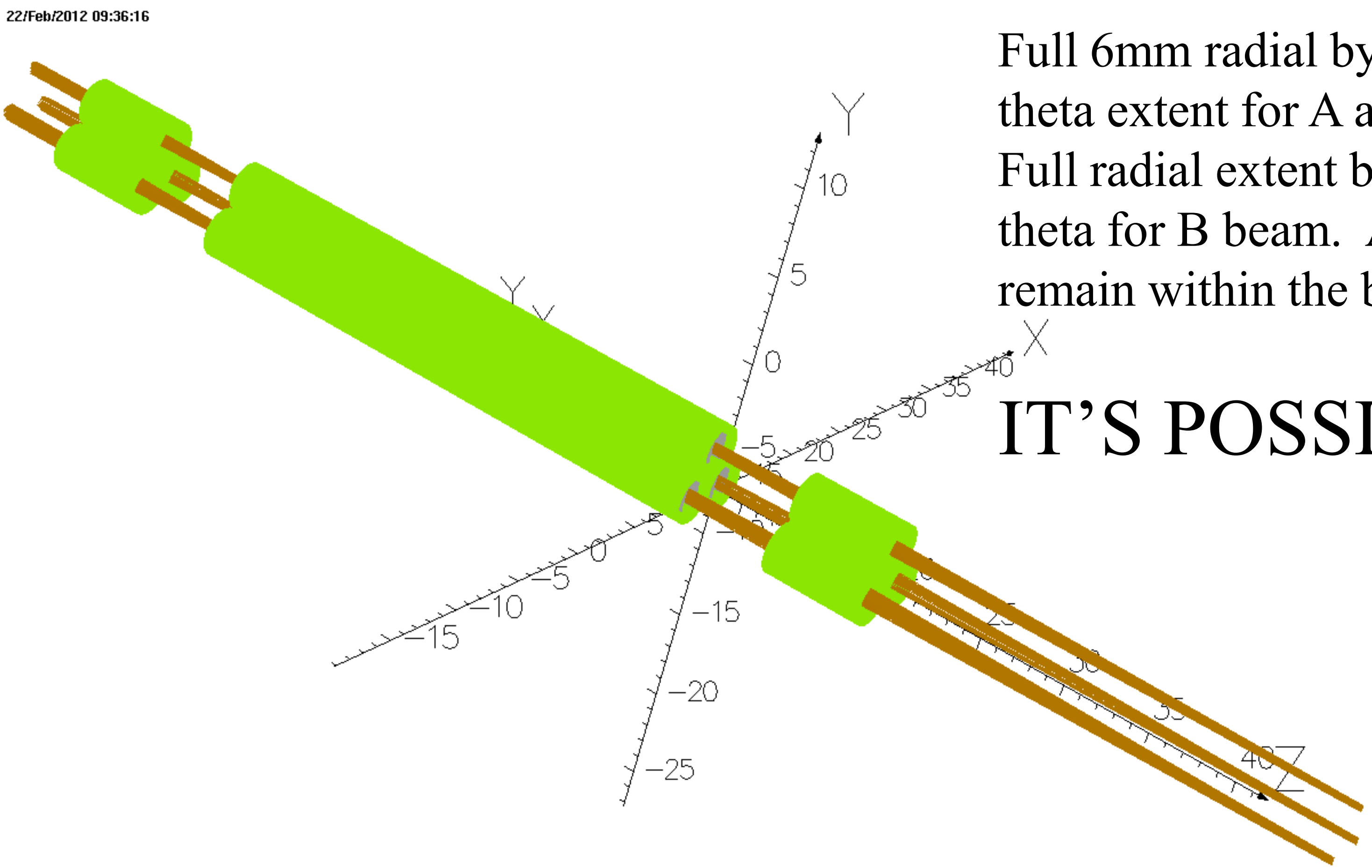
Full model with Wien on



8mm square arrays propagated through summed fields of models. Electrostatic and dipole fields calculated on model without solenoid end caps. Solenoid fields calculated with end caps. Note that some of the rays escape the bunch.

Ope

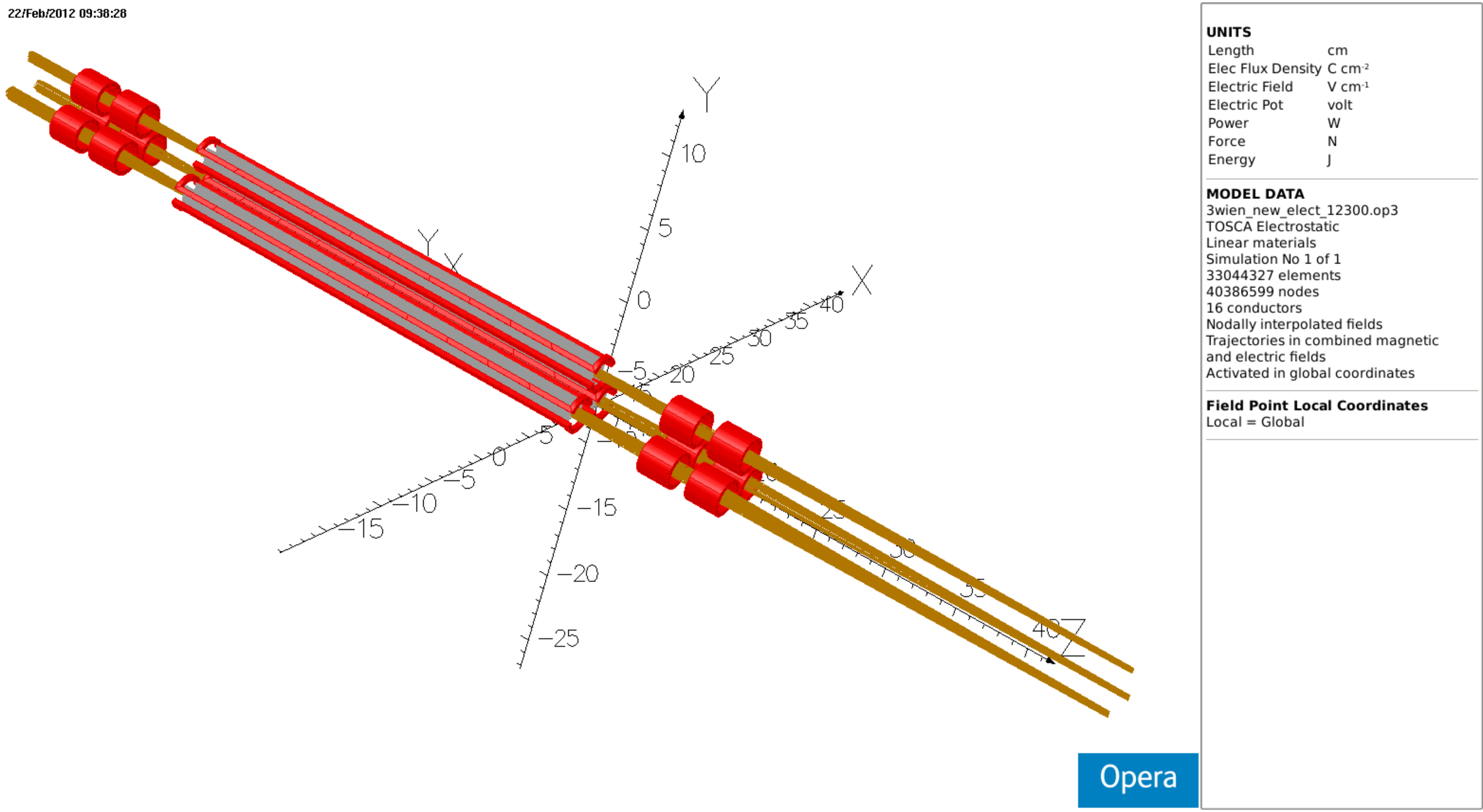
Chopped beam through the model



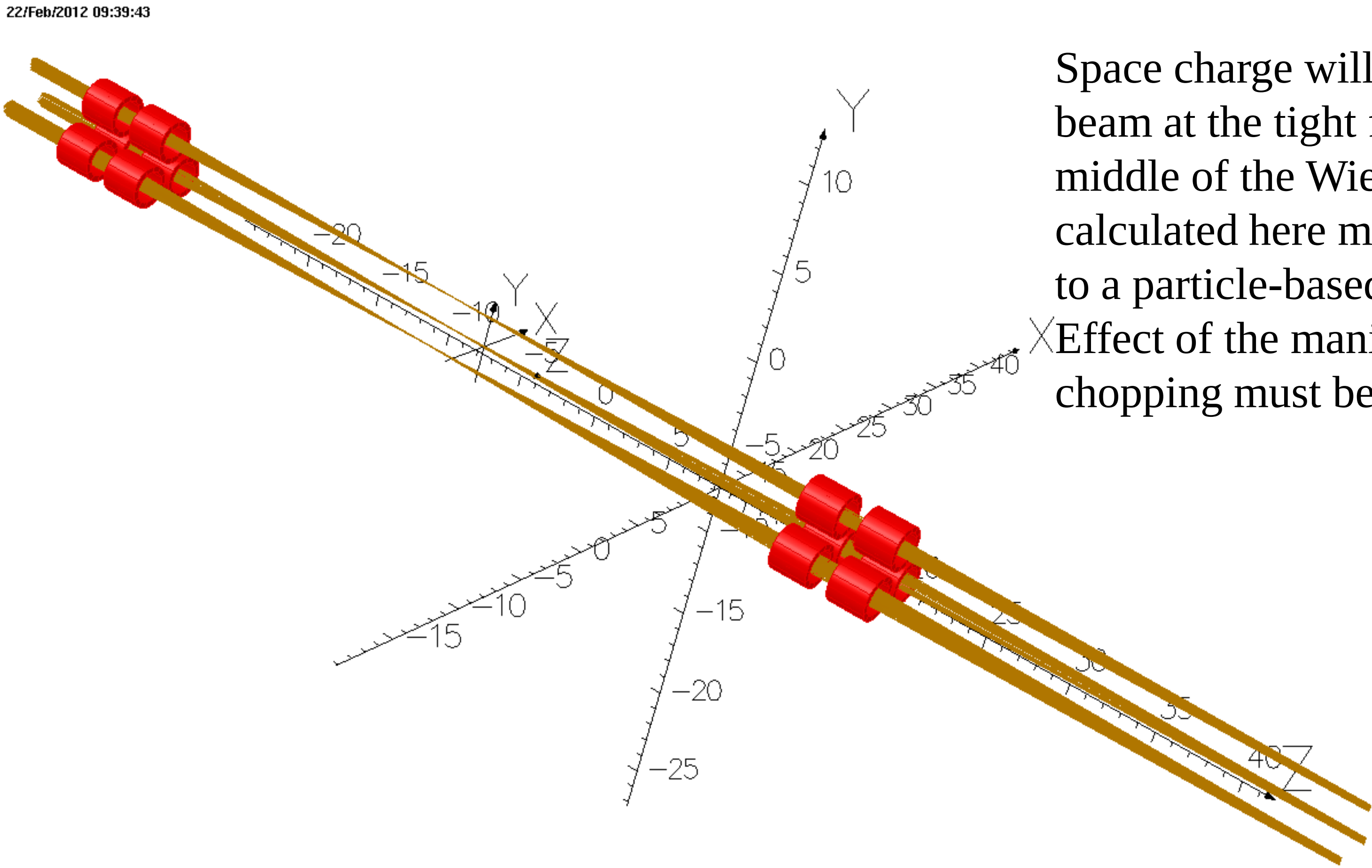
Full 6mm radial by 24 degree theta extent for A and C beams. Full radial extent by 12 degree theta for B beam. All the rays remain within the bunches.

IT'S POSSIBLE!

Chopped beam view 2



Chopped beam view 3



Space charge will blow up the beam at the tight focus in the middle of the Wien. Fields calculated here must be transferred to a particle-based simulation code. Effect of the manipulations on de-chopping must be modeled too.

Ope

Conclusions on 3 wien model

- Magnetic shielding is sufficient on the Wien proper
- Magnetic shielding was insufficient on the focusing elements fore and aft. Two options will be explored:
  - steel caps on tubes, 0.65cm radius holes
    - They work; engineering very difficult with return current and leads
  - investigate change to quadrupole arrays with steel tubes like those around the Wiens proper, no end caps
- Exploring the options on focusing elements will take some months due to computer hardware constraints.
- Unity transfer matrix must be achieved, including nulling x-y coupling.

Modeling constraints in OPERA

1. Entire model must reside in RAM
2. single-threaded with some use of SIMD instructions in Intel CPUs
3. single-Wien model with solenoids occupies 6GB first iteration, 1GB for each additional, takes ~20 hrs for first and 5 hrs for subsequent
4. triple Wien occupies 16.7GB first iteration, 3GB for each additional, so three iterations max in my 24GB machine of 2010 vintage. 62 hours for first, 12 for second/third
5. replacing the entrance and exit solenoid pairs with quad triplets expands the model 50%, too much for my workstation, so I'll have to coarsen it.
6. maximum problem size OPERA will run takes ~60GB RAM
7. Jlab has four OPERA 3D network licenses
8. ME has two unused individual OPERA licenses, one of which they will allow to be converted to network for $5900 (first year) and $1180/year thereafter by another Division
9. I have about 4TB of solved models, half backed up by sneaker-net. 620GB on the Wiens

Possible FY12 Milestones and Resources

- **Management decision on further work**. If yes:
- Modeling of the 200 keV injector sufficient to determine if smaller bunch extent (20^{o} by 5mm) is feasible.
- Model focusing and steering arrays
- Begin modeling of proposed chopper region including RF. Can unity transfer matrix be achieved?
- Machine wooden dowels and form refrigeration tubing into a dipole for feasibility tests.
- 1 FTE mostly modeling (includes me)
- ~$40K burdened for the fifth license and an OPERA compute server for use by me and Physics

Possible FY13 Milestones and Resources

- Complete 200 keV injector modeling
- Design and fabricate single Wien assembly including focusing and steering elements as needed
- Test single Wien in EGG test stand
- Decide whether to proceed to triple-wien project based on EGG tests and models.
- 3 FTE: modeling, engineering, design, assembly, test
- $100K: materials, machining, power supplies
- WAG: Full installation (FY 14-16) might be $300K + 10 FTE-years, labor mostly for radical re-arrangement of injector. Significant labor savings if combined with planned 2015 injector upgrade.

WAG Discussion

- Capture is 40cm long. In the very optimistic scenario, smaller bunch at 200 keV allows only the triple Wien to be installed by adding this 40cm to the chopping region, displacing the girder downstream of the chopper 40cm.
- In the optimistic scenario, only the triple Wien and downstream corrector/focusing array will be required in the chopper region, ~80cm total. Capture plus ~40cm shift in quarter cryo needed.
- In the pessimistic scenario, about 1.4m needed in the chopper region for focusing and steering, precession, diagnostics, focusing and steering. Capture plus 1m shift in quarter cryo and compress 6 MeV lattice.
- Existing horizontal Wien is between A1 and A2 and their spacing can't be compressed, so there's no real estate gained by removing it. Leave it in for back-up.

Conclusion

The physics and scheduling benefit of the proposed device merits funding through experimental testing in the Injector Test Facility. The injector test facility is crucial for bumpless integration into the injector. After such testing incorporation in the 2015 injector AIP project or making it a separate AIP proposal would be debated.

Can I coarsen the model?

The discretisation is inadequate to model the coil field.
If you are not interested in the local values of the field
increase the value of #MAXEDGEHDLPTS (current value is 32,
minimum value 8, maximum value 1024, a power of 2).
If you want good local values of fields, improve the mesh at
the following locations ...
... at -2.034969652,0.5932691501,-17.90397636 (cm), Error 2.377E-03%
... at -2.120387067,0.6651094925,-17.92213716 (cm), Error 3.288E-03%
... at -2.091743085,0.6425010534,-17.92364535 (cm), Error 2.49E-03 %
... at -2.061793882,0.6186492849,-17.91912528 (cm), Error 3.618E-03%
... at -1.827145311,-0.274035773,-17.7994915 (cm), Error 3.422E-03%
... at -1.781289417,0.0324909175,-17.66482969 (cm), Error 3.814E-03%
... at -1.962044227,0.5151815544,-17.87561671 (cm), Error 1.551E-03%
... at -1.902698577,0.4300843549,-17.85722873 (cm), Error 2.399E-03%
... at -1.884628211,0.4008031438,-17.85226522 (cm), Error 3.58E-03 %
... at -1.869043299,0.3699945223,-17.84801607 (cm), Error 3.007E-03%
... at -1.782625648,0.0655654358,-17.58918861 (cm), Error 2.3E-03 %

This continues for ~450 pages. The model is already coarser than VF defaults suggest. I'm using 1mm maximum extent elements in sources and the volume occupied by the beam. 0.5mm around the dipole coil ends.