Constant-Tune Cyclotrons

FFA Workshop 2023

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TRIUMF

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- How to design a practical cyclotron magnet “orbits first”
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Introduction – Isochronous condition

Isochronous condition:

$$\mathcal{R} = \beta \mathcal{R}_\infty$$

where $\mathcal{R}$ is the circumference of the closed orbit divided by 2π, and $\mathcal{R}_\infty$ is a constant.

The integral of the relative error can never exceed the ratio between a quarter of the rf period and the total time of flight from injection: on the order of 10^{-4} or less, for most cyclotrons. Stray away from this strict condition, and no more beam will come out of the machine.

Introduction – Isochronous field distribution

There is no analytical solution* for an isochronous $B(r, \theta)$. Producing an isochronous field distributions is the job of the magnet designer: iterative process that takes many iterations, and on the order of days.

*Except for the case $B(r)$, which is out of question: unstable vertical motion.

Introduction – Isochronous field distribution

For lack of an analytical formula, there is a way to generate a perfectly isochronous (and Maxwellian) field distribution in a split second using a trick I presented at the cyclotron conference in 2019 [Planche, 2019].

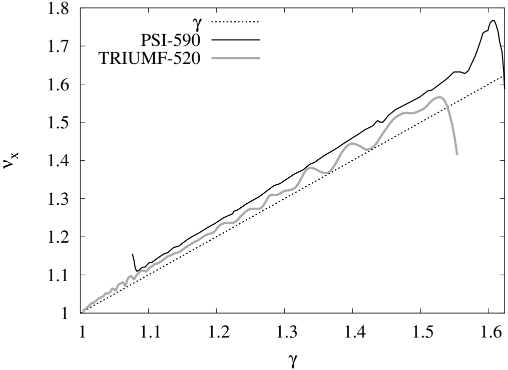
The trick, in a nutshell, is to start from the geometry of a set of **closed orbits** to derive the **tunes** and the **field** distribution.

closed orbits $\rightarrow$ **tunes** $\rightarrow$ **field**

which is circular permutation of the more conventional order in which things are normally done. The work I am presenting here is depends heavily on this trick.

Introduction – $\nu_x \approx \gamma$?

The two “most-relivistic” cyclotrons ever built:

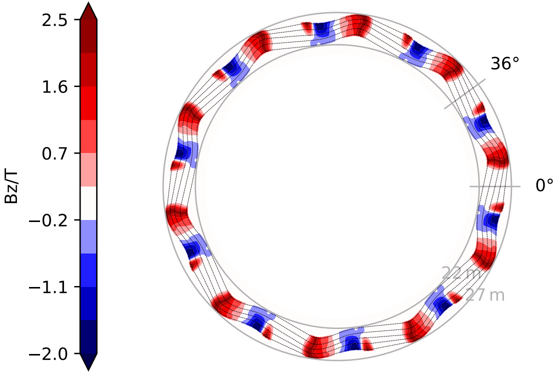


In a cyclotron, does ν_x necessarily follows γ?

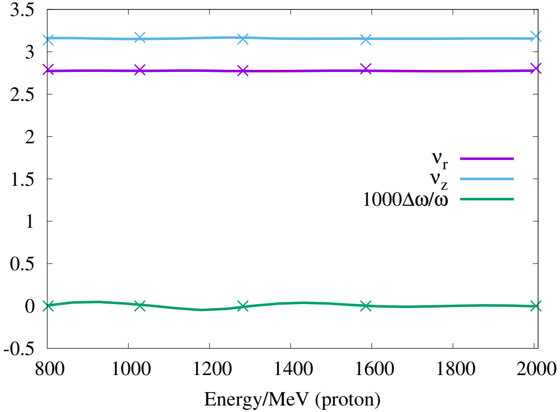
Are higher-energy cyclotrons doomed to cross many resonances?

Introduction – constant-tune cyclotrons

I have shown last year that there exists isochronous fixed field distributions (consistent with Maxwell's equations) that produce constant vertical and horizontal tunes. I had for instance shown the example of a 2 GeV proton cyclotron:

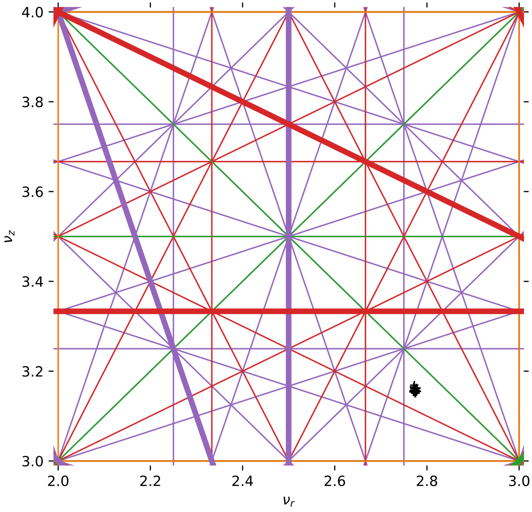


Introduction – constant-tune 2 GeV cyclotron

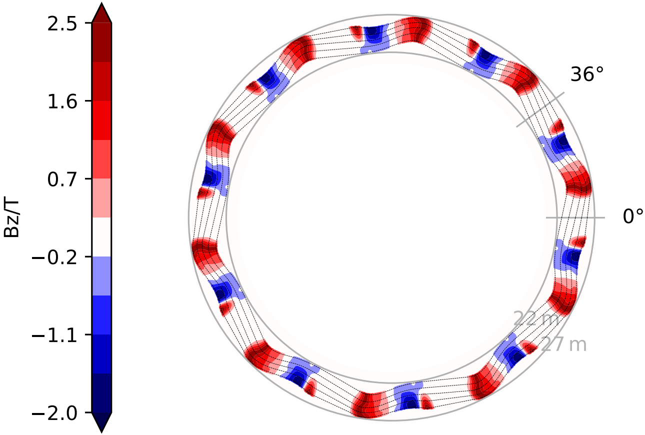


Solid lines: tracking result using `CYCLOPS` [Gordon, 1984].
Crosses: from the geometry of the closed orbits using `from_orbit`.

Introduction – constant-tune 2 GeV cyclotron

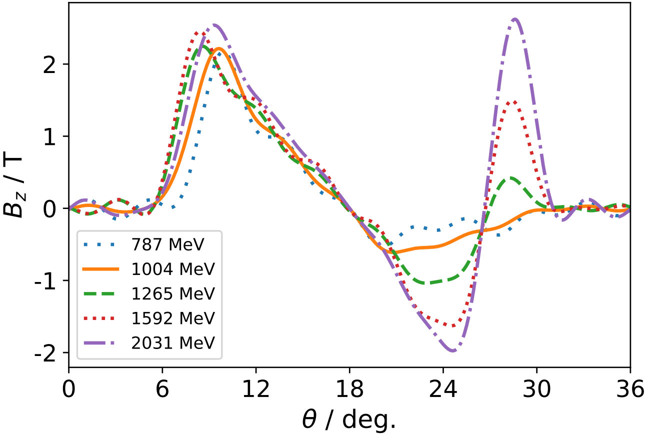


Introduction – constant-tune 2 GeV cyclotron



$r(a, \theta)$ is parametrized so as to have drift sections between sectors.

Introduction – constant-tune 2 GeV cyclotron



Magnetic field plotted along 5 closed orbits.

Introduction. . . finally getting to the point

All this work has been written up in an article that is part is part of a recent ICFA special issue on cyclotrons [Planche, 2023], if you are interested.

The question that remains is: **how can one use this technique in practice to design accelerator magnets?**

How to couple `from_orbit` with `OPERA-3D`

I needed to start from less arbitrary, more practical orbits.

Process:

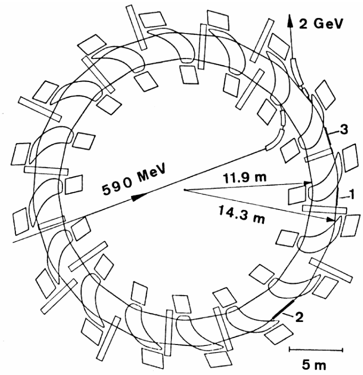
1. Get a field map from some initial 3-D magnet model (`OPERA-3D`).
2. Track particles to find the corresponding closed orbits (`CYCLOPS`).
3. Use `from_orbit` to figure out what transformation (shift, scale) need to be applied to these obits to achieve the desired tunes.
4. Applying the same transformations to the magnet geometry.
5. Iterate.

metaOPERA

I went on a bit of wild-goose chase to automate fully the construction and post-processing of OPERA-3D model. The result is a python library developed in collaboration with Shinji's group (ISIS Neutron and Muon Source) and my post-doc Huiwen, **see Ta-Jen's talk on Thursday.**

Proof-of-principle 3D magnet design

I chose to design a magnet for W. Joho 2 GeV cyclotron proposal: ASTOR [Joho, 1983].



and to start with designing so that only ν_y is constant at first.

Proof-of-principle 3D magnet design

For each iteration:

- I run `OPERA-3D`, and get a field map.
- With this field, I run `CYCLOPS` [Gordon, 1984] to get a set of closed orbits.
- With these orbits, I run `from_orbit` and shift every orbit azimuthaly until I get a constant vertical tune.
- I extract a new magnetic field profile, and a new spiral angle profile, and adjust the magnet gap height and spiral shape accordingly.

Proof-of-principle 3D magnet design

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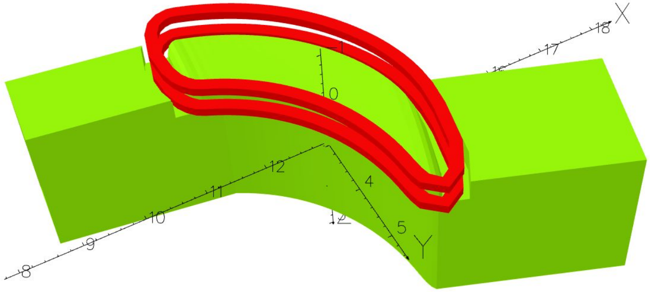
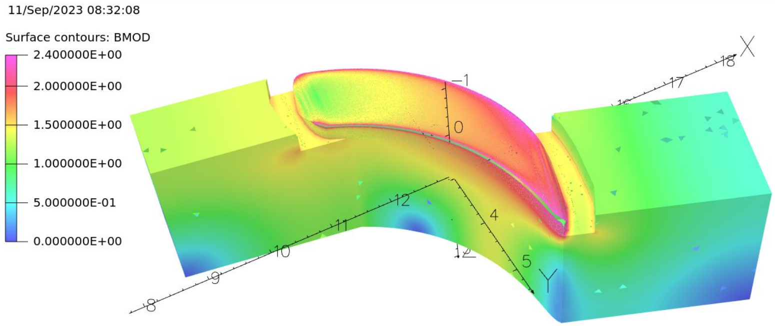
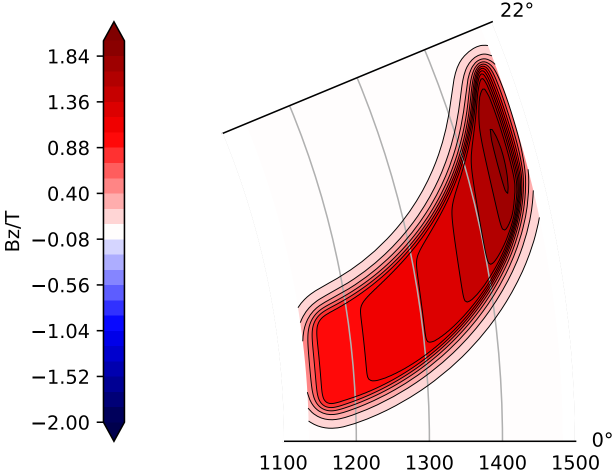


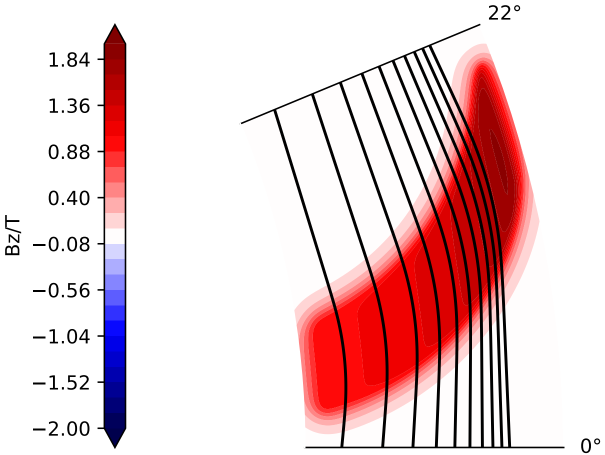
Proof-of-principle 3D magnet design



Proof-of-principle 3D magnet design



Proof-of-principle 3D magnet design



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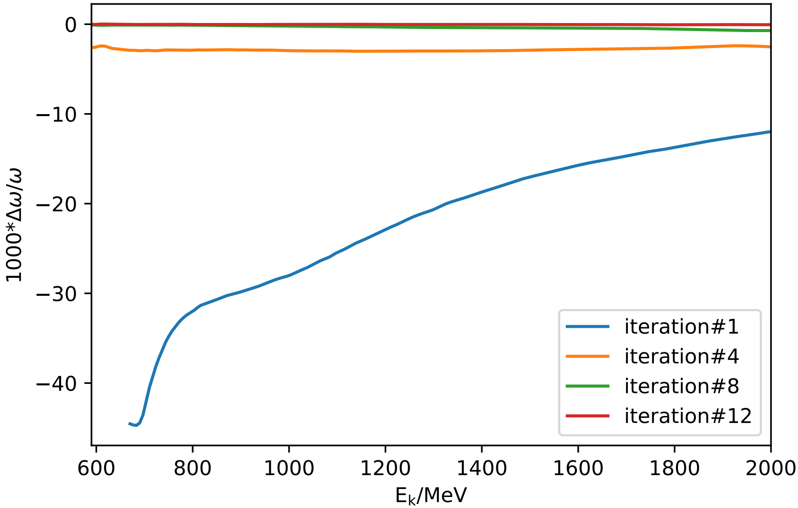

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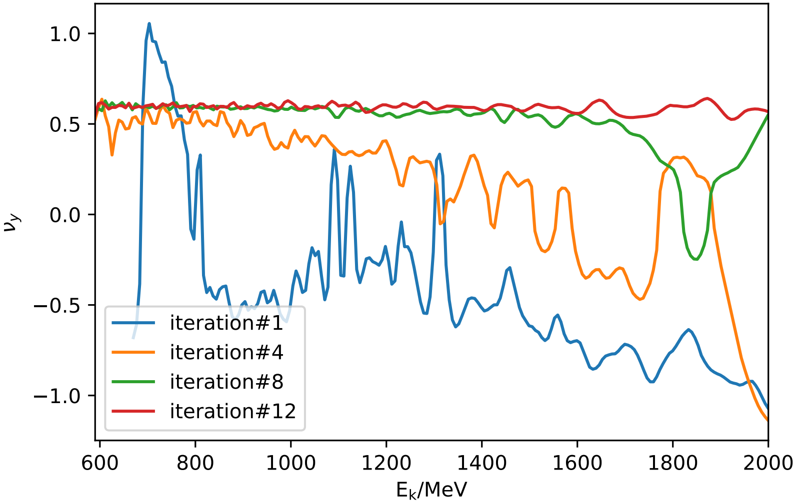
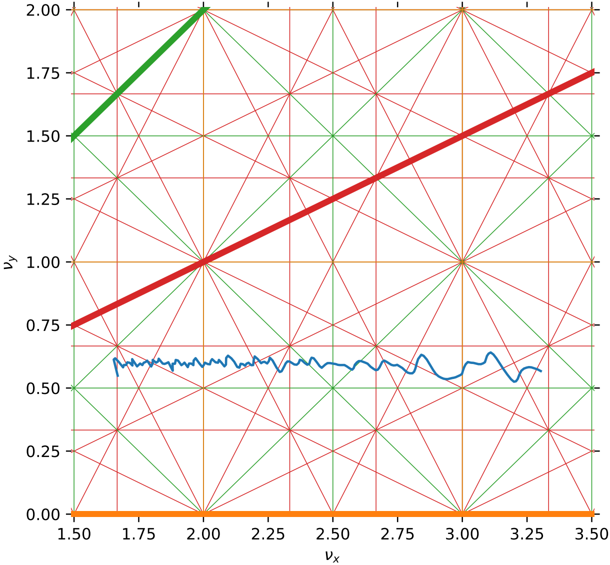


Proof-of-principle 3D magnet design



Future work

Next step is to design for both ν_x and ν_y constant at the same time.
This will require a reversed bend.

Conclusion

`from_orbit` can be coupled with a 3-dimensional finite element code like `OPERA-3D` to design fixed-field accelerator magnets.

It allows the design to converge extremely rapidly. I am using it to design cyclotron magnets, but the technique can be applied to design any FFA magnet (not VFFA though).

Thank you

Thank you for your attention

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