FFAG’23 WORKSHOP

Jefferson National Laboratory
September 10-15, 2023

FFAG CLASS

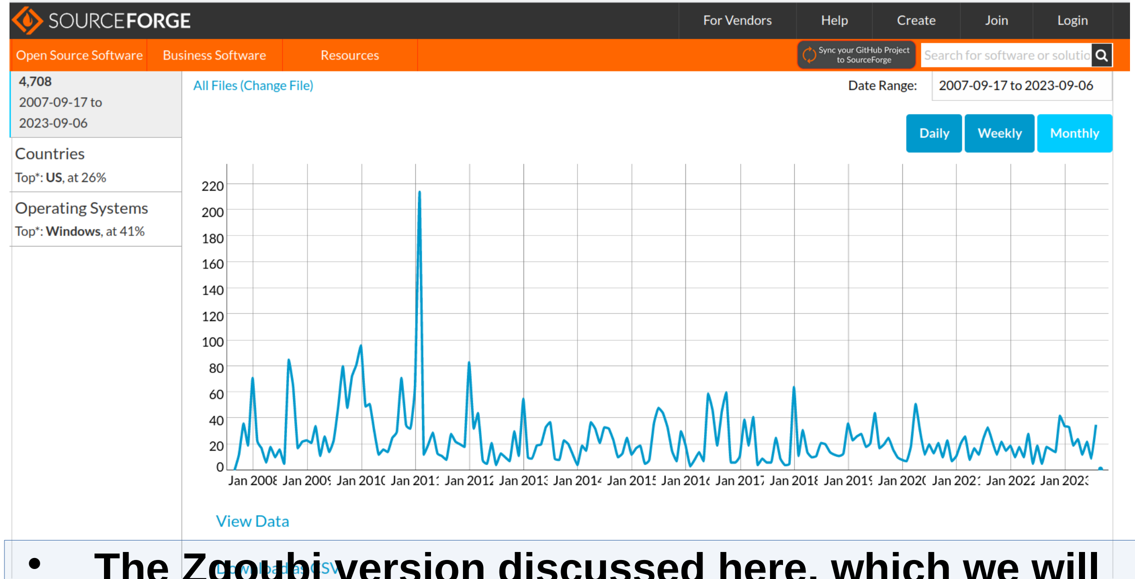
Sept. 10

AN INTRODUCTION TO ZGOUBI

François MÉOT
Brookhaven National Laboratory
Collider-Accelerator Department

Zgoubi is present in many labs, worldwide.
Codes spreading around is most natural as we know.
In the early days, 1972 at Saclay, that meant CERN, GANIL, CEA, JINR/Dubna and several other Nuclear Physics collaborations

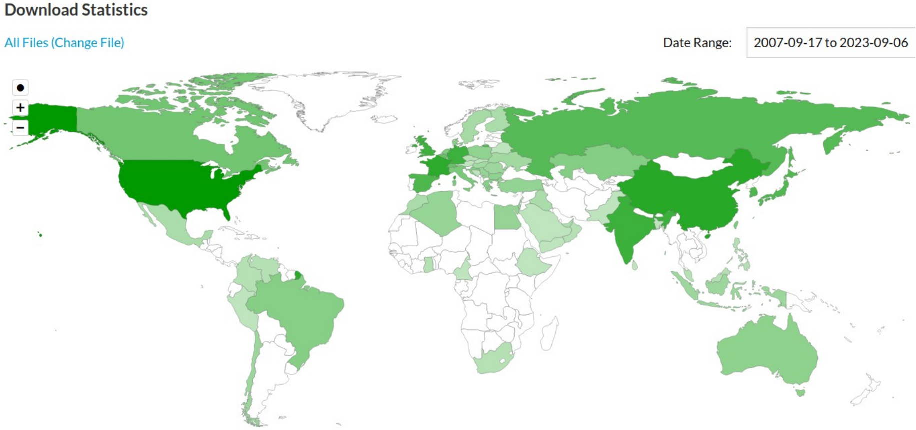
Keeps spreading over the years:



- **The Zgoubi version discussed here, which we will use during the workshop, is that made available on sourceforge in 2007, and maintained there:**

https://sourceforge.net/p/zgoubi/code/HEAD/tree/trunk/

~5,000 downloads so far, from 68 countries



From USA, China ...

... to Peru, Bangladesh

	Country	Android	Linux	Macintosh	Unknown	Windows	Total
1.	United States	0%	17%	12%	17%	20%	973
2.	China	0%	15%	6%	3%	53%	423
3.	France	0%	11%	11%	6%	12%	365
4.	India	0%	10%	0%	58%	23%	248
5.	Germany	0%	9%	2%	47%	24%	246
6.	United Kingdom	0%	25%	14%	1%	27%	240
65.	Sri Lanka	0%	0%	0%	0%	100%	1
66.	Cameroon	0%	0%	0%	0%	100%	1
67.	Peru	0%	0%	0%	0%	100%	1
68.	Bangladesh	0%	0%	0%	0%	100%	1
							4,708

- Zgoubi writing commenced in 1972:
by Jean-Claude Faivre & Denis Garreta
DPHN-HE, CEA Saclay

It was written to design and operate the SPES2 spectrometer at SATURNE experimental areas, solving

$$m\frac{d\vec{v}}{dt} = q\,\vec{v}\times\vec{b}$$

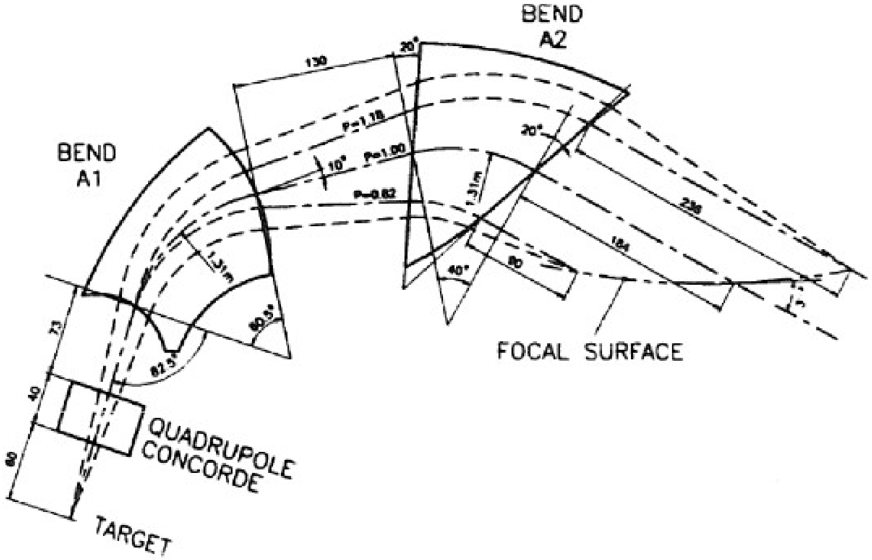


Figure 48: SPES 2 Layout.

- The integrator is still there, unchanged, a Taylor series method, Zgoubi's specificity :

$$\vec{R}(M_1) \approx \vec{R}(M_0) + \vec{u}(M_0)\,\Delta s + \vec{u}\,'(M_0)\,\frac{\Delta s^2}{2!} + ... + \vec{u}\,'''''(M_0)\,\frac{\Delta s^6}{6!}$$

$$\vec{u}(M_1) \approx \vec{u}(M_0) + \vec{u}\,'(M_0)\,\Delta s + \vec{u}\,''(M_0)\,\frac{\Delta s^2}{2!} + ... + \vec{u}\,''''(M_0)\,\frac{\Delta s^5}{5!}$$

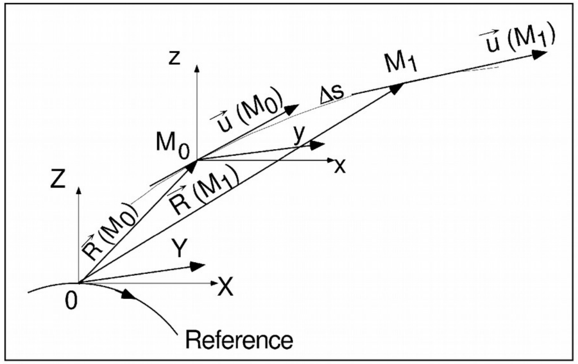


Figure 2: Position and velocity of a particle in the reference frame.

All the optical elements developed then at Saclay and Labs around are still there, still operational, half a century later

They reflect the history of the code and of the nuclear physics equipments, moving around:

PS170 - CERN PS exp^{al} areas
SPEG - GANIL, Caen, early 1980s
SPES2 - back and forth Saclay ↔ CERN
SPES3 - CEA Saclay
VENUS - CERN PS exp^{al} areas
and others

Glossary of Keywords, Part A

Available keywords and where they are to be found in Part A.

AGSMM	AGS main magnet	97
AGSQUAD	AGS quadrupole	98
AIMANT	Generation of dipole mid-plane 2-D map, polar frame	99
AUTOREF	Transport beam into a new reference frame	104
BEAMBEAM	Beam-beam lens	105
BEND	Bending magnet, Cartesian frame	106
POLARMES	2-D polar mesh magnetic field map	151
PS170	Simulation of a round shape dipole magnet	152
QUADISEX	Sharp edge magnetic multipoles	153
QUADRUPO	Quadrupole magnet	154
REBELOTE	'Do it again'	80
RESET	Reset counters and flags	83
SCALING	Power supplies and R.F. function generator	84
SEPARA	Wien Filter - analytical simulation	156
SEXQUAD	Sharp edge magnetic multipole	153
VENUS	Simulation of a rectangular shape dipole magnet	167
WIENFILT	Wien filter	168
YMY	Reverse signs of Y and Z reference axes	169

Two important remarks here, regarding the "philosophy" of code developments in zgoubi:

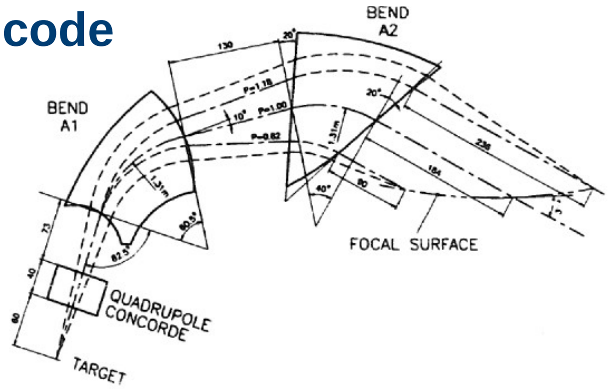


Figure 48: SPES 2 Layout.

(i) ***AIMANT*** was the first semi-analytical dipole model in Zgoubi – for SPES2.
A powerful magnet modeling tool, which yielded the fancy ***DIPOLE-M*** and ***DIPOLE[S]***, the ***FFAG*** series: radial, spiral, vertical

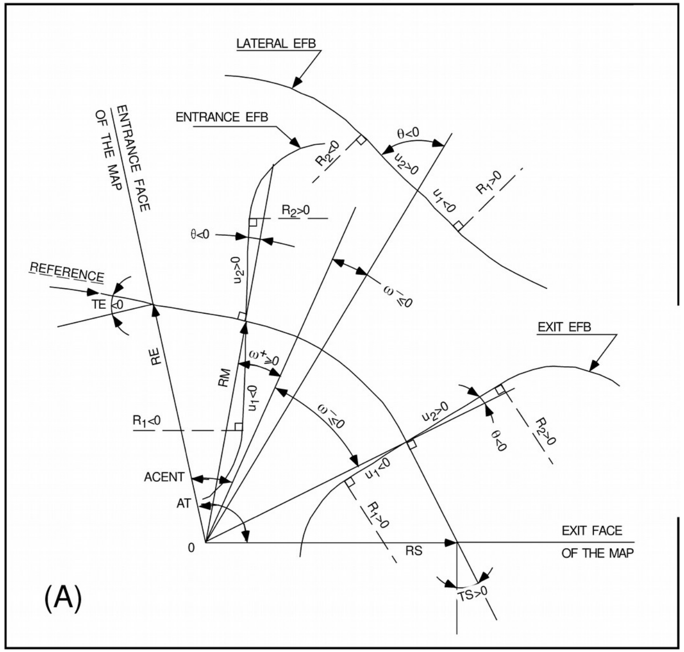
Because a prime objective of Zgoubi in the 1970s was the parameterization of spectrometers using measured field maps, ***AIMANT*** was designed to first generate a field map, through which Zgoubi would then track particles

This emphasizes that Zgoubi was designed to be skillful at handling field maps – a paramount component in trajectory accuracy.

(ii) Zgoubi resilience:

These 3 SPES2 measured field maps still exist (concord.map, a1.map, a2.map), they run quite well with the very zgoubi.dat files from those early days:

https://sourceforge.net/p/zgoubi/code/HEAD/tree/branches/exemples/spectrometers/ spes2_spectrometer/



This is a general feature of the code: its developments are, and have always been, carried out to ensure compatibility with past input files.

Further spectrometer tooling developments included various Monte Carlo procedures:

MCOBJET: generation of many sorts of initial object distributions **(we'll be using it a lot)**

OBJETA: Monte Carlo object from a decay reaction $M_1 + M_2 \rightarrow M_3 + M_4$

MCDESINT: 3-body in-flight decay. First developed for Saclay SPES3 spectrometer, early 1980s, intensively used for the Neutrino Factory design in early 2000s

In-flight decay of muons ...

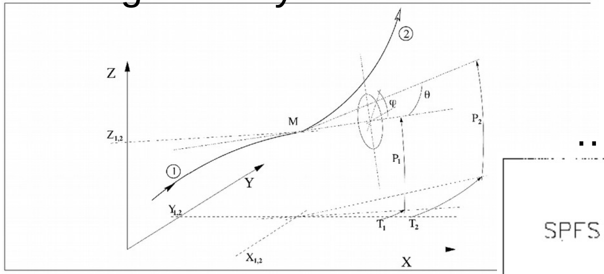
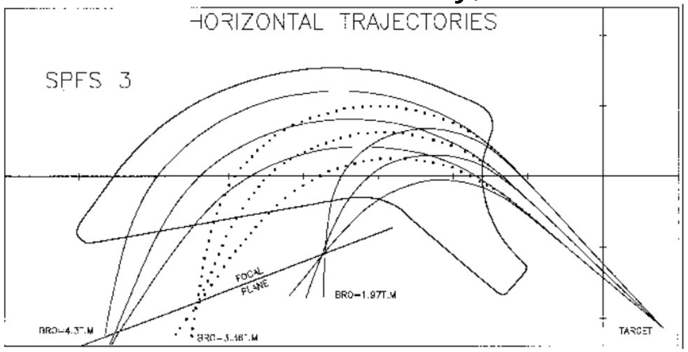


Figure 8: At position $M(X_1, Y_1, Z_1)$, particle 1 decays into 2 and 3 ; **zgoubi** then pro
with the computation of the trajectory of 2, while 3 is discarded.
θ and ϕ are the scattering angles of particle 2 relative to the direction
incoming particle 1 ; they transform to T_2 and P_2 in **zgoubi** frame.

... in SPES3 at Saclay, 1970s



Neutrino Factory
muon bunch,
Early 2000s

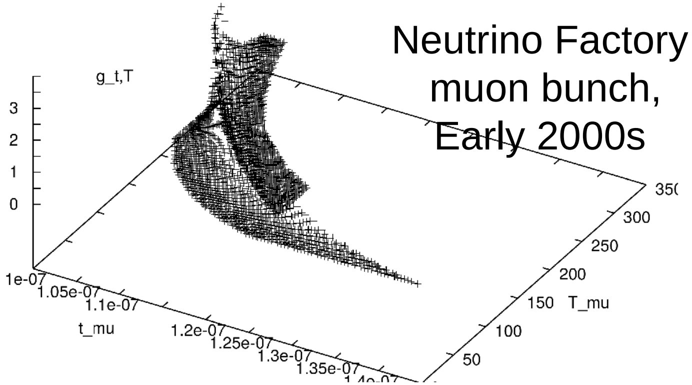
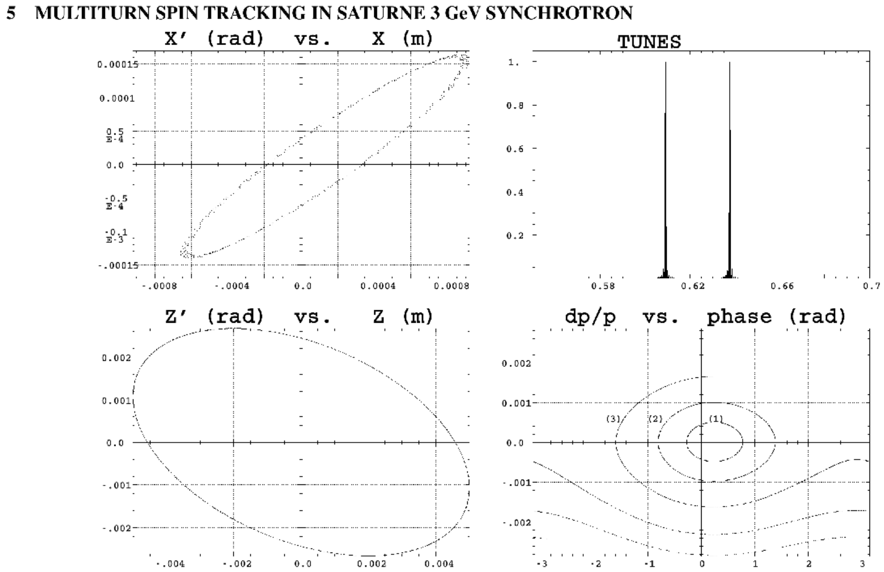


Figure 5: Muon density (in arbitrary units) at $s = 30$ m, in a time-Kinetic energy fr

Time-energy muon bunch "banana",
from $\pi \rightarrow \mu + \nu$,
at the Neutrino Factory front-end

Zgoubi's reach has been extended out of the spectrometers world in the mid-1980s.



- **The spin ODE**

$$\frac{d\vec{S}}{dt} = \frac{q}{m}\vec{S}\times\vec{\omega}$$

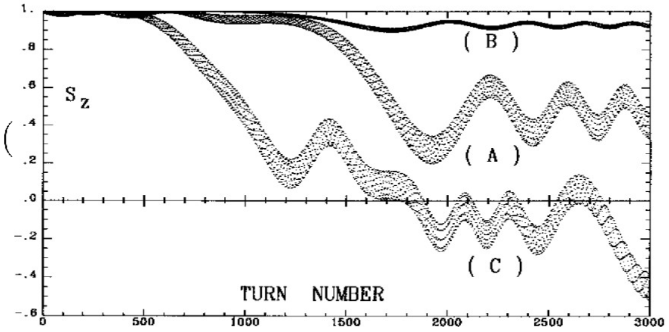
$$\vec{\omega} = (1+\gamma G)\vec{b} + G(1-\gamma)\vec{b}_{/\!/} + \gamma\left(G + \frac{1}{1+\gamma}\right)\frac{\vec{e}\times\vec{v}}{c^2}$$

was introduced in mid-1980s.

That was to study the use of a partial Siberian snake in SATURNE (following developments at the AGS)

- This involved the critical step toward multi-turn tracking… successful thanks to the accuracy of the integrator,

$$\vec{S}(M_1) \approx \vec{S}(M_0) + \frac{d\vec{S}}{ds}(M_0)\,\Delta s + \frac{d^2\vec{S}}{ds^2}(M_0)\frac{\Delta s^2}{2} + \frac{d^3\vec{S}}{ds^3}(M_0)\frac{\Delta s^3}{3!} + \frac{d^4\vec{S}}{ds^4}(M_0)\frac{\Delta s^4}{4!} + \frac{d^5\vec{S}}{ds^5}($$



Crossing $G\gamma=7-\nu_Z$ in 3000 turns

- It also meant introducing in Zgoubi a complete basic panoply of circular accelerator equipment… a never ending job!

- **The electrification of Zgoubi goes back to ~1992, so solving**

$$\frac{d(m\vec{v})}{dt} = q\left(\vec{e} + \vec{v} \times \vec{b}\right)$$

- This required 2 additional Taylor series:

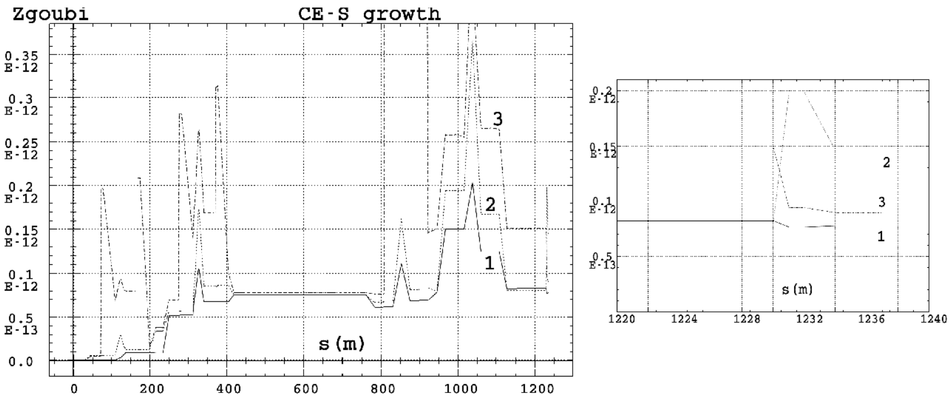
  - Rigidity: $(B\rho)(M_1) \approx (B\rho)(M_0) + (B\rho)'(M_0)\Delta s + \ldots + (B\rho)'''''(M_0)\frac{\Delta s^5}{5!}$

  - Time: $T(M_1) \approx T(M_0) + T'(M_0)\,\Delta s + T''(M_0)\,\frac{\Delta s^2}{2} + \;\ldots\; + T'''''(M_0)\,\frac{\Delta s^5}{5!}$

Synchrotron radiation energy loss was introduced in the late 1990s for TESLA Test Facility design studies at Saclay (the EU version of the next linear collider)

EXAMPLE 1 : Emittance increase in the e^+e^- linear collider beam delivery system

• **Evolution of the concentration ellipse ($\mathcal{S}_x(s) - \mathcal{S}_x(s=0)$) along TESLA-BDS,**
$2\ 10^4$ **particles ray-traced.**



- solid line : zero initial emittances, sextupoles off ;
- dashed line : initial emittances $\epsilon_x = 10^{-11}$, $\epsilon_z = 10^{-14}$ m.rad, sextupoles off ;
- dotted line : initial emittances $\epsilon_x = 10^{-11}$, $\epsilon_z = 10^{-14}$ m.rad, sextupoles are excited.

Note : strong overshoots in the $s \approx 850$ m region, in the low-β quad and final focus region (zoomed on the right) are due to chromatic distortion of the concentration ellipse.

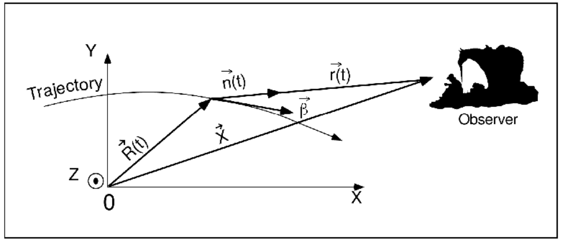
There is much more, regarding

- SR in rings

- spin diffusion

SR Poynting: a different topic in terms of SR - Zgoubi (actually zpop) has it installed

Spectral-angular radiation density



• The ray-tracing provides the necessary ingredients to compute the radiated electric field

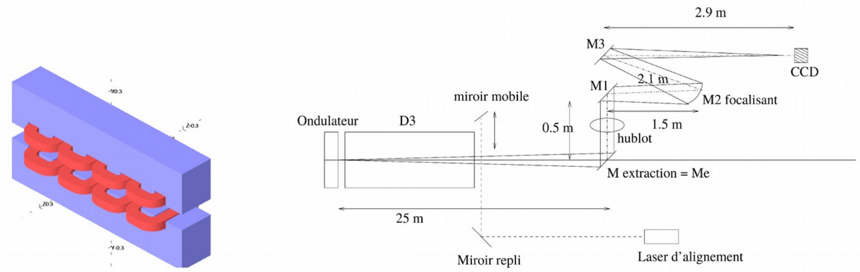
$$\vec{\mathcal{E}}(\vec{n},\tau) = \frac{q}{4\pi\varepsilon_0 c}\,\frac{\vec{n}(t)\times\left[\left(\vec{n}(t)-\vec{\beta}(t)\right)\times d\vec{\beta}/dt\right]}{r(t)\left(1-\vec{n}(t)\cdot\vec{\beta}(t)\right)^3}, \qquad \mathcal{B} = \vec{n}\times\frac{\vec{\mathcal{E}}}{c}$$

• The electric field of the radiation is then Fourier transformed, yielding the spectral angular energy density

$$\frac{\partial^3 W}{\partial\phi\,\partial\psi\,\partial\omega} = 2r^2\left|FT_\omega\left(\vec{\mathcal{E}}(\tau)\right)\right|^2/\mu_0 c$$

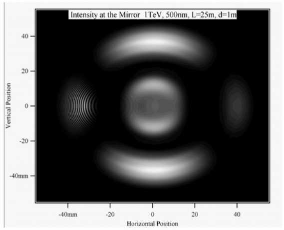
Proton beam profile from SR, at LHC.
the only way to see the beam at injection, today

• The Undulator setup at IR4 was designed using Zgoubi, cross-checks used SRW (ESRF).



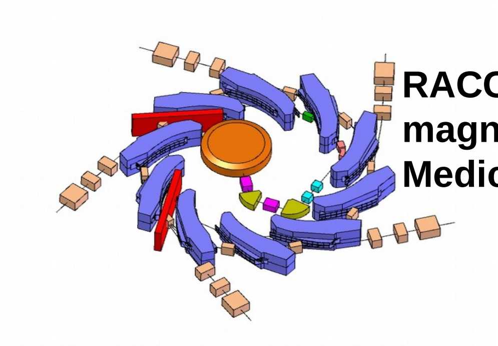
LHC undulator upstream of a long dipole, and the optical system, drawn on that of LEP.

Intensity emitted (horizontal component) by 1 TeV protons, λ = 500 nm, with a distance d = 1 m between the two sources, simulated with Zgoubi (left) and with SRW (right).



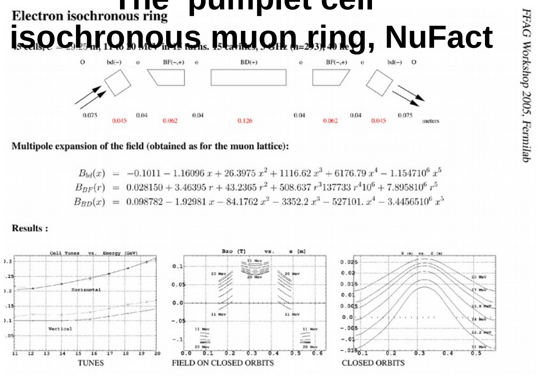
• **Details in** [L. Ponce et al., *"LHC proton beam diagnostics using synchrotron radiation"*, Yellow Report CERN-2004-007.]

And on top of all that: the FFAG zoology, all simulated in Zgoubi - just an excerpt, there is much more, cf. FFAG workshops, and *https://sourceforge.net/p/zgoubi/code/HEAD/tree/branches/exemples/*



RACCAM, spiral magnet prototyping. Medical 5-beam FFAG

The 'pumplet cell' isochronous muon ring, NuFact

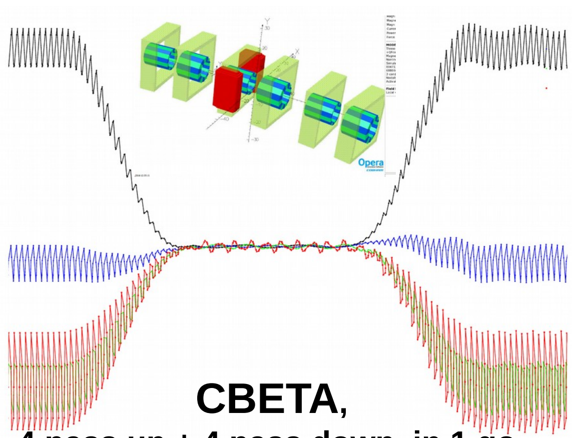


Electron isochronous ring

Multipole expansion of the field (obtained as for the muon lattice):

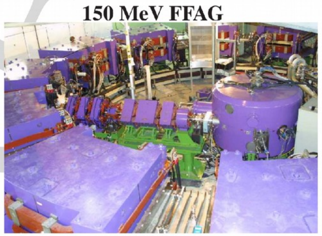
$$B_{bd}(x) = -0.1011 - 1.16096\,x + 26.3975\,x^2 + 1116.62\,x^3 + 6176.79\,x^4 - 1.154710^6\,x^5$$
$$B_{BF}(r) = 0.028150 + 3.46395\,r + 43.2365\,r^2 + 508.637\,r^3 137733\,r^4 10^6 + 7.895810^6\,r^5$$
$$B_{BD}(x) = 0.098782 - 1.92981\,x - 84.1762\,x^2 - 3352.2\,x^3 - 527101.\,x^4 - 3.4456510^6\,x^5$$

Results :

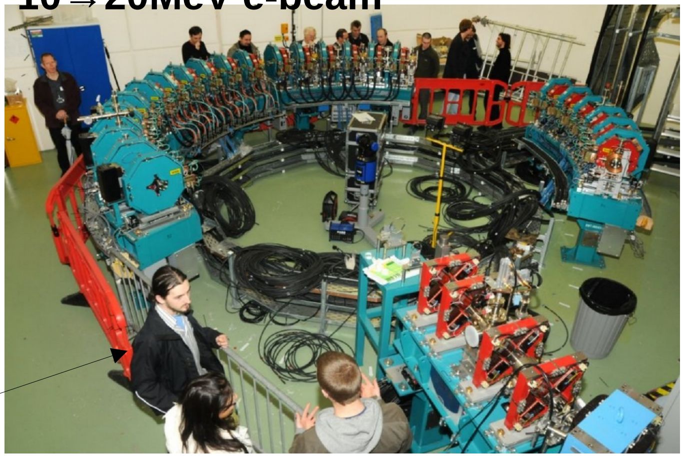


CBETA,
4 pass up + 4 pass down, in 1 go.
Using OPERA field maps, exclusively

KEK and KUNST radial scaling FFAGs

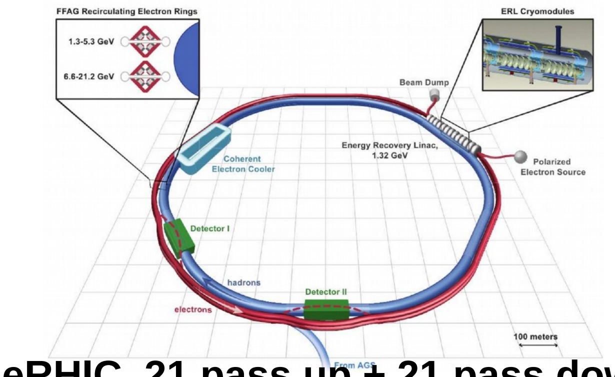


EMMA, Daresbury
10 → 20MeV e-beam



btw … Sam, the author of pyZgoubi

$$5.3 \xrightarrow{up} 21.164 \xrightarrow{down} 5.3\,\mathrm{GeV}$$

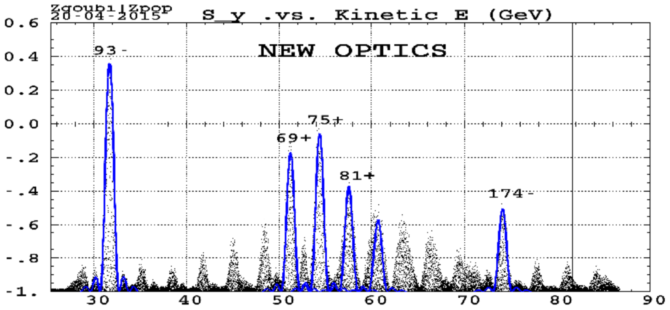


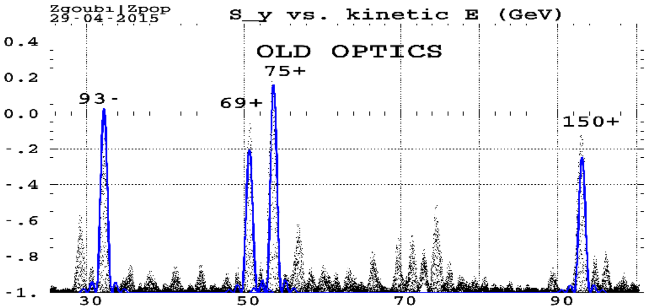
eRHIC, 21 pass up + 21 pass down …
full 6D bunch+spin tracking in 1 go

“Don’t be afraid of long-term tracking in rings - accuracy-wise”

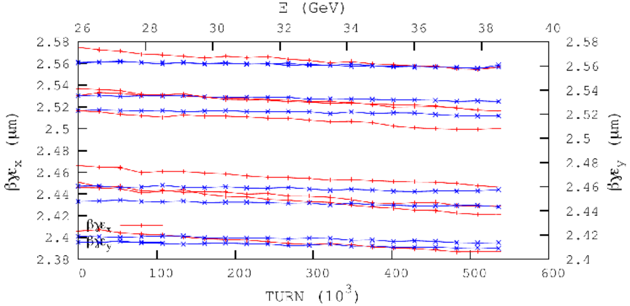
- **A recent example : comparison of polarization transport over the acceleration ramp in the 100 GeV×100 GeV pp runs, 3 million turns at a rate of $\dot{\gamma} = 2$:**
  - **- new, ’Run 15’ optics**
  - **- ’Run 13’ and earlier optics**

8 particles on 10 rms invariants are plotted.
Envelopes (blue) are from theory [SYL].

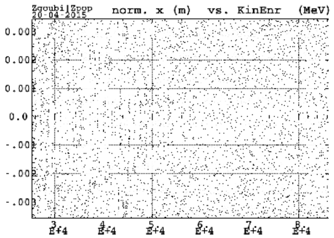


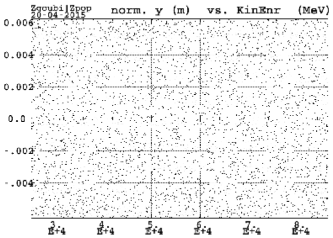


Normalized invariants over 500,000 turns :



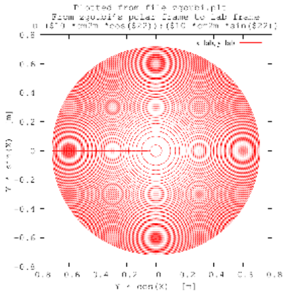
$x \times \sqrt{(p/p_0)}$ *and* $y \times \sqrt{(p/p_0)}$
over 3 million turns :



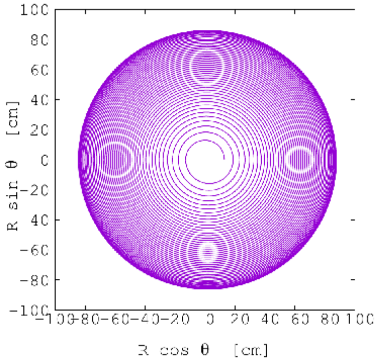


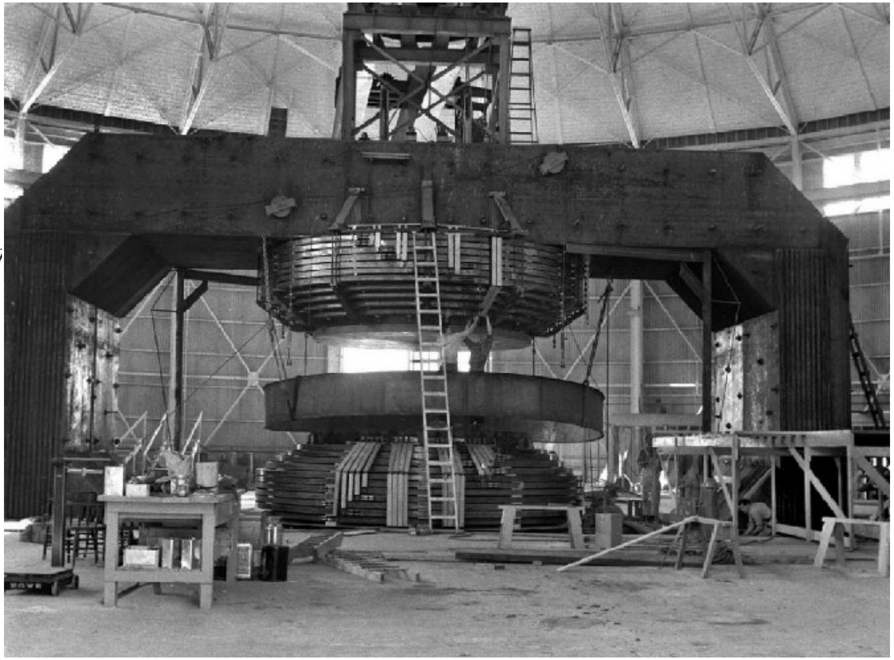
Let's move toward the conclusion...
All in all, Zgoubi ends up being as good at reproducing the "cyclotron equation"...

- **Find the orbits in a classical cyclotron** $(B = B_0(R/R_O)k,\ -1 < k < 0)$, **make sure circles do tightly close**



- **Double-Dee acceleration to 10 MeV in 50 turns:**





◇ **184 inch cyclotron at Berkeley, 100MeV/u ions (1940s)**

◇ **Successfully assessed (Veksler's, McMillan's), "phase stability", when operated as a "synchro-cyclotron" (200 MeV d)**

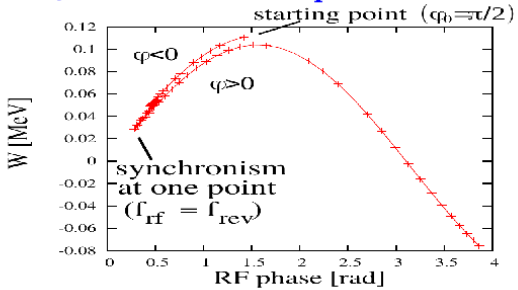
- **And, test the cyclotron equation (the equation that tells that protons cannot be accelerated to more than** $\sqrt{M \times eV_{RF}} \sim$ **20 MeV - requires 400 kV between Dees):**

$$[\cos\phi](W) = \cos\phi_0 + \pi\left[1 - \frac{\omega_{RF}}{\omega_{rev_0}}\left(1 + \frac{W}{2m_0c^2}\right)\right]\frac{W}{q\hat{V}}$$

Phase shift accumulates, turn by turn:

$$\Delta\phi_{RF} = \pi\left(\frac{\omega_{RF}}{\omega_{rev}} - 1\right)$$

eventually leading to limited energy range / deceleration / etc.



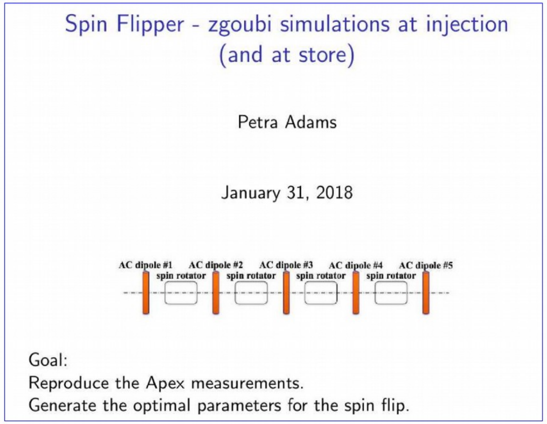
… as it is at tracking spin over 100s of thousands of turns in a big collider.

This is also what this FFAG'23 school is about:

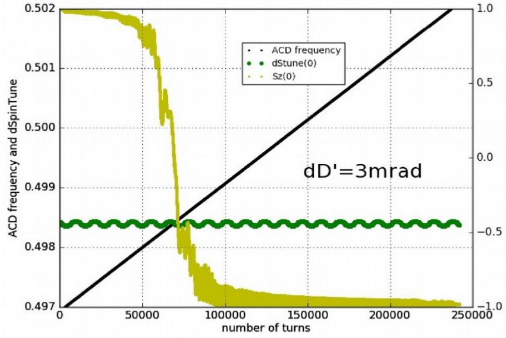
showing Zgoubi's reach in the matter of accelerator and particle dynamics simulations

4.3 RHIC spin flipper

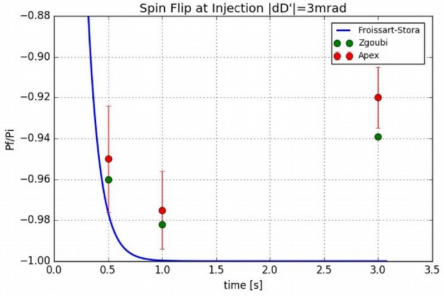
- **An AC-dipole + DC-rotator assembly excites a single, isolated resonance, at $Q_s = Q_{osc}$.**



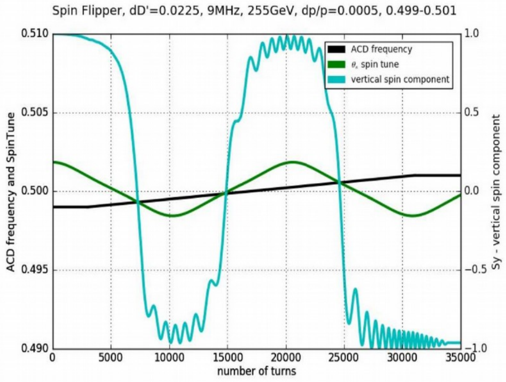
Spin flip by Q_{osc} sweep through $Q_s \approx 1/2$ (a matter of a few 10,000 turns)



Injection : optimum at 1 sec. sweep;
boundary on the left : crossing is too fast
(*spins can't follow flip of stable spin direction*),
boundary on the right : multiple crossing



Multiple crossing

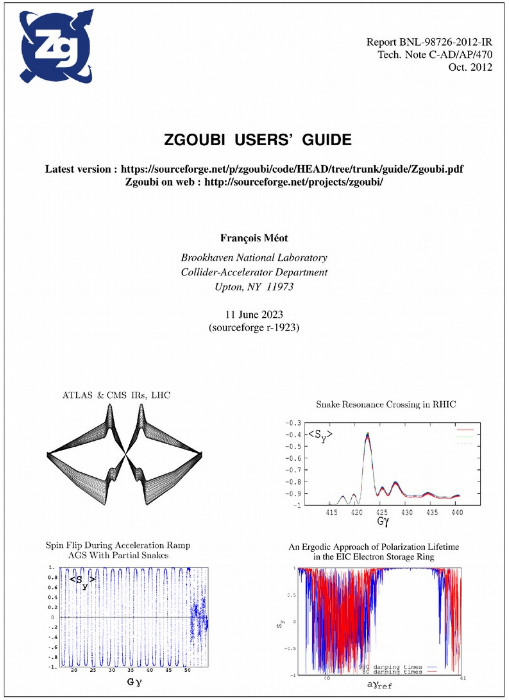


Information sources regarding developments / use / simulations over the years:

https://www.osti.gov/

http://www.jacow.org/Main/Proceedings

Lookup “zgoubi” there



Report BNL-98726-2012-IR
Tech. Note C-AD/AP/470
Oct. 2012

ZGOUBI USERS’ GUIDE

Latest version : https://sourceforge.net/p/zgoubi/code/HEAD/tree/trunk/guide/Zgoubi.pdf
Zgoubi on web : http://sourceforge.net/projects/zgoubi/

François Méot

Brookhaven National Laboratory
Collider-Accelerator Department
Upton, NY 11973

11 June 2023
(sourceforge r-1923)

Zgoubi Users’ Guide:

An unescapable tool for this -brief- school

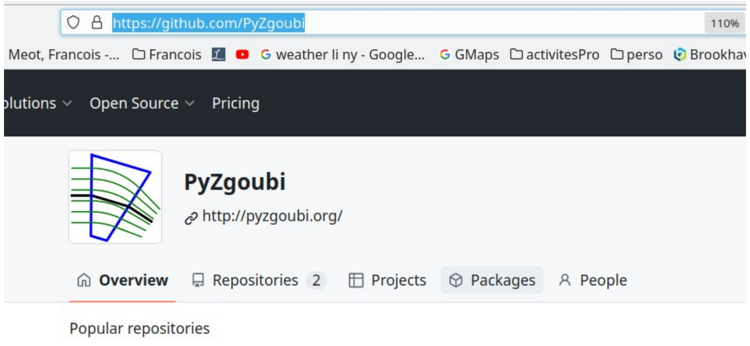
https://sourceforge.net/p/zgoubi/code/HEAD/tree/trunk/guide/Zgoubi.pdf

You’d like an interface?

https://github.com/PyZgoubi

Python interface

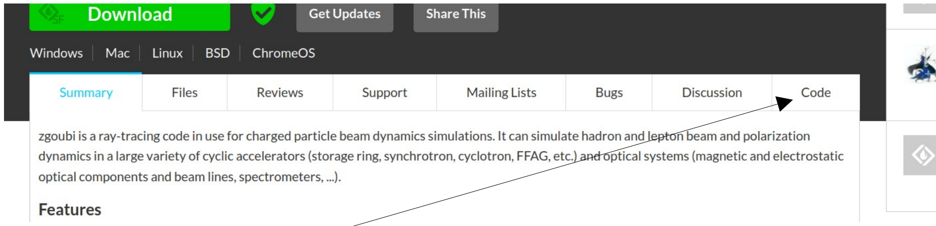
See with David Kelliher – he is in this workshop



https://ulb-metronu.github.io/zgoubidoo/

Python 3 interface

APPENDIX: Installing zgoubi

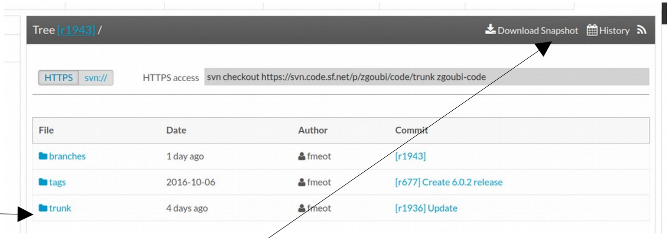


A – Download zgoubi package from sourceforge:

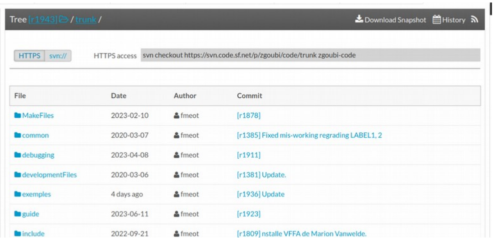
1/ on any browser: lookup 'sourceforge zgoubi'

2/ Once in sourceforge, zgoubi site,

- on the bar to the right: click on 'Code'. That takes you here:



- there, click on 'trunk',
that takes you here:



That's the download you want!   Click on Download Snapshot.

Be patient, you're downloading zgoubi package which includes 100sMBs of examples, from LHC to light sources, to FFAGs and cyclotrons, that takes some time (the code itself is peanuts, ~1MB)
That will get you   zgoubi-code.zip

(%)

3/ Unzip zgoubi-code-r1805-trunk.zip.

In order to ease communication and file exchanges during the class, you're encouraged to unzip in a dedicated folder, with name

'zgoubi'

You'll then be facing that zgoubi-code folder content:

```
12:09_fmeot:/home1/meot/zgoubi/SVN/zgoubi-code$ ls
1_WARNING  common   debugging          exemples  include  Makefile   marionVanwelde  publications  tests  toolbox  zpop
AUTHORS    COPYING  developmentFiles   guide     INSTALL  MakeFiles  modules         README        TODO   zgoubi
12:09_fmeot:/home1/meot/zgoubi/SVN/zgoubi-code$
```

4/ Making zgoubi executable:

In that [path2]/zgoubi-code/ folder, just 'make'

(this is a short for 'make -f Makefile, it assumes Makefile is present here).

This requires gfortran. If you have some other Fortran compiler then substitute in Makefile. Otherwise download one on internet.

You're done. zgoubi exec is ./zgoubi/zgoubi

Its full address, when used from an arbitrary folder, is [pathTo]/zgoubi-code/zgoubi/zgoubi **(%)**

B - Testing your install

That's just a matter of trying an example:

Go in

/zgoubi-code/exemples/FFAG/KEK150MeV/analyticalModel/matrix

In there, execute

[pathTo]/zgoubi-code/zgoubi/zgoubi -in SFFAGCell_MATRIX.dat

That will run the example, results of the execution are (always!) found in the listing zgoubi.res.

Try the following:

diff zgoubi.res SFFAGCell_MATRIX.res

If no major difference (may be just the date!), then your install is ok, you're done, it works.

BTW: in passing, you may want to go through zgoubi.res, find the transport matrix at the bottom, and figure out (using Zgoubi Users' Guide and its INDEX) what zgoubi did from top of file down to **'END'**