Potential and Issues for Future Accelerators and Ultimate Colliders

Including a few things from the "F3iA 2016" meeting in Germany

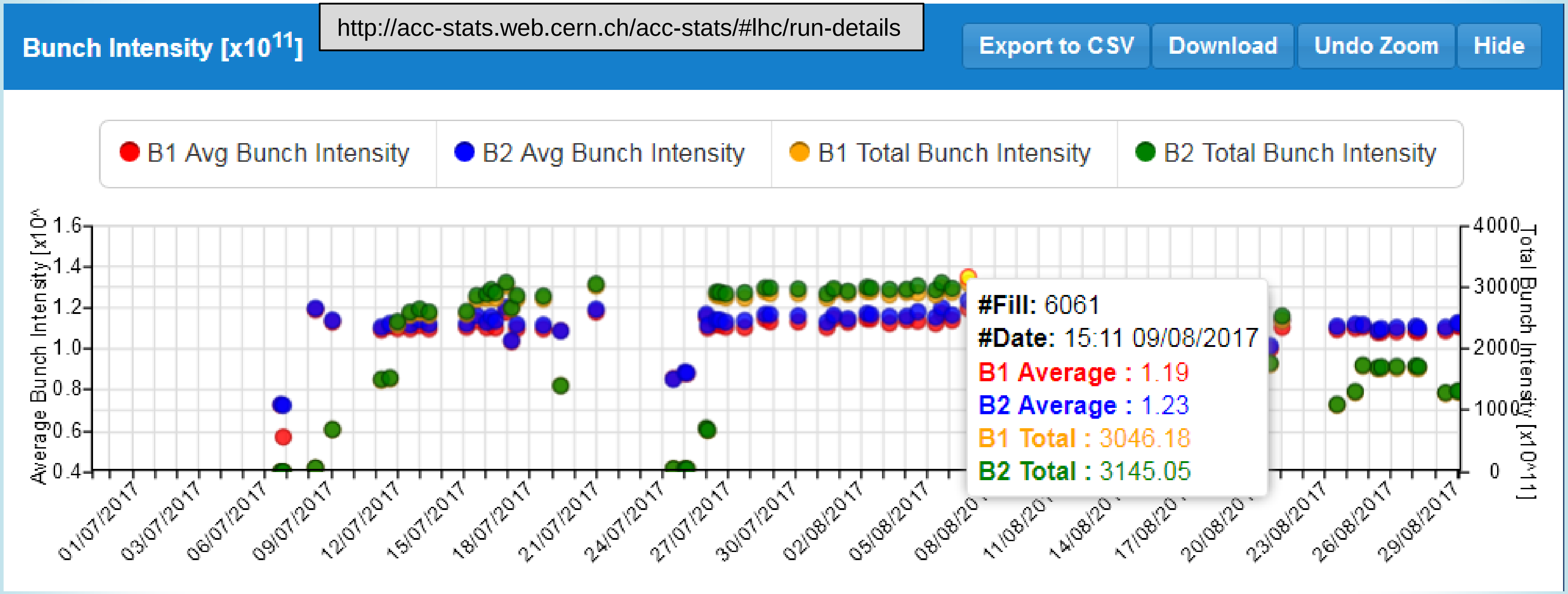
(look it up for others' perspectives)

https://indico.desy.de/indico/event/15657/

Energy Frontier

- What if there is no easy new physics and a large "energy desert" to cross?
- Let's examine an extreme example and see what could be different about energy frontier machines in the far future that are capable of discovering new physics
  - Context for the F3iA meeting was "accelerators in the 2nd half of the 21st century"
  - What I describe here could be even further out

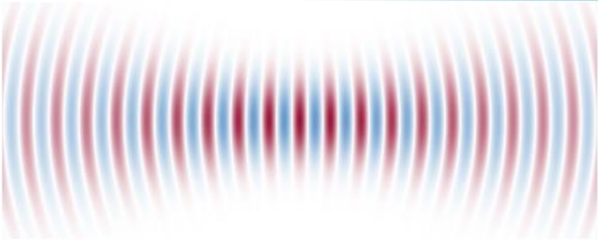
The Case for Optimism



- 2 * 3.1e14 * 6500 GeV = 645 MJ = 0.33 E_{Planck}
- Total energy is OK but in too many particles
  - – Maybe we should try 1 particle per beam?

Single-Particle Accelerators

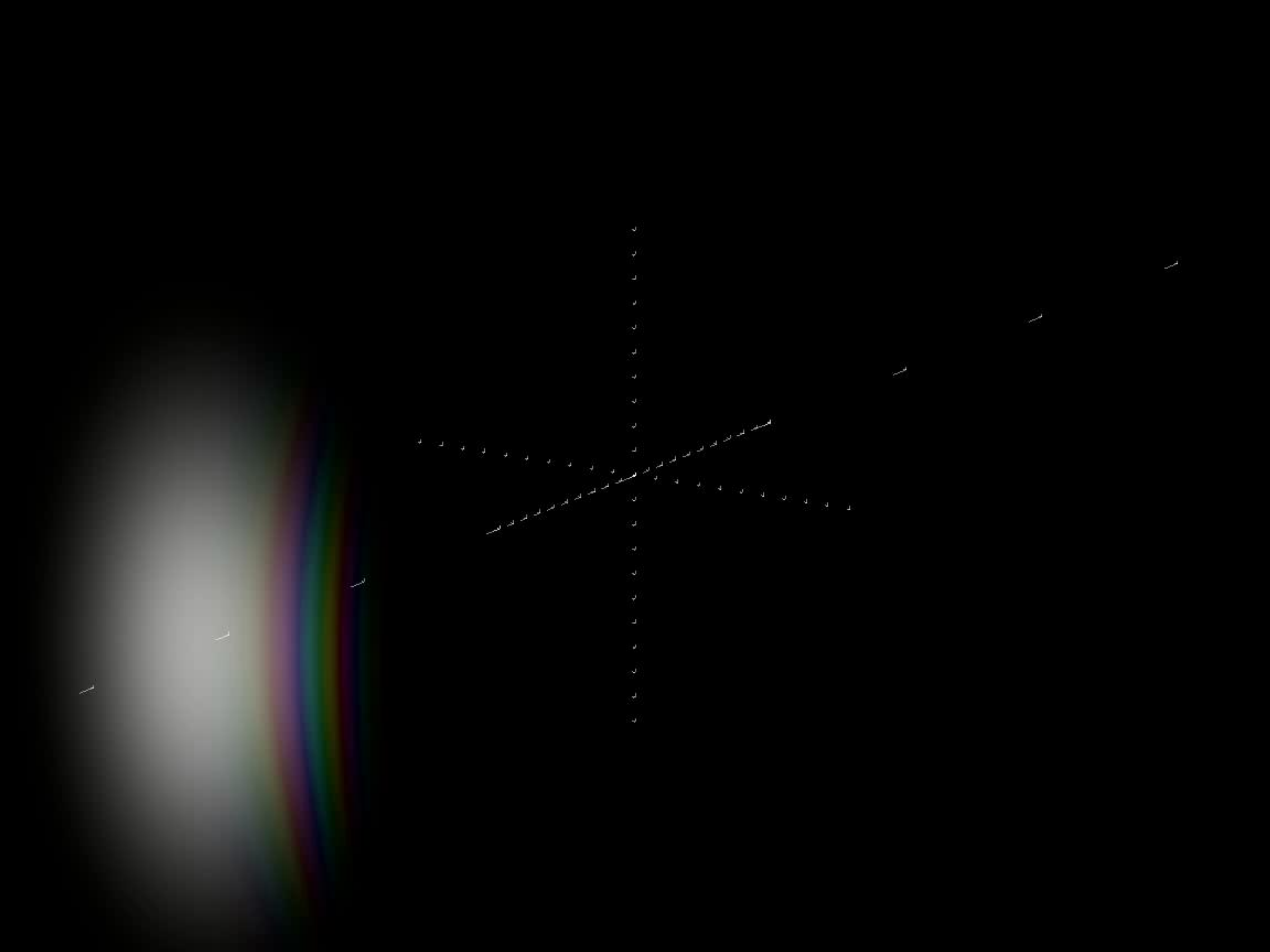
- Wavefunction propagates through lattice
  - Can still form optical foci like with laser photons
  - Minimum emittance $\varepsilon_{N,rms}=\hbar/2mc$ set by uncertainty principle



- Need emerging ultra-cold and precision alignment technology
  - Unfamiliar areas for us!

Collaboration with:
Atomic physics
Quantum computing
Ultra-cold physics
Metrology
Gravitational wave detection

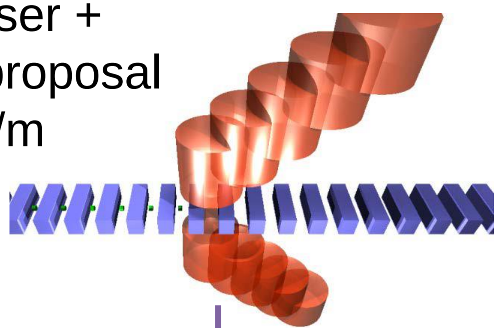
Experiment example:
Put single particles with quantum behaviour (e.g. from "double slit") through accelerator-type optics and final focus



Gradients in a 2×10km-long Facility

A. Pukhov *et al.*, Eur. Phys. J. ST 223, 1197–1206 (2014)

Fibre laser +
dielectric proposal
2 TV/m



Energy
1 TeV

Cosmic ray
3×10^8 TeV

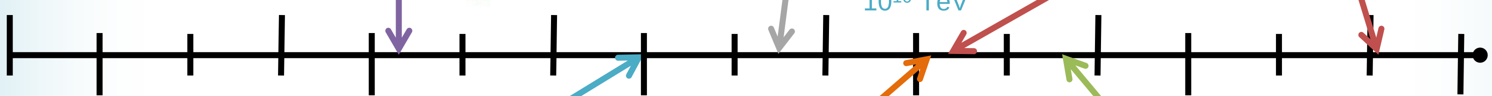
E.R. Caianiello, Lett. Nuovo Cimento 41, 370 (1984)
G. Papini, arXiv:quant-ph/0407115 (2004)

Quantum maximum acceleration
$a_{max}=2mc^3/\hbar \rightarrow G_{max}= 2m^2c^3/\hbar q$

e μ

10^{16} TeV

10^{10} TeV



E_{Planck}

1 GV/m

1 TV/m

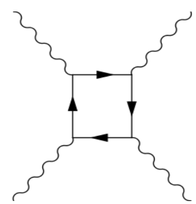
100 MV/m
Gradient

10^{24} V/m

10^{15} V/m
ELI-NP laser,
Romania

1.3×10^{18} V/m
Schwinger limit

5×10^{19} V/m
Achieved (briefly)



At ~10^{18} V/m gradient, would need ~10 million km to get to the Planck energy. Or can we do something about that? In 10km.

On a Diffuse Reflection of the α-Particles.
By H. Geiger, Ph.D., John Harling Fellow, and E. Marsden, Hatfield Scholar, University of Manchester.
(Communicated by Prof. E. Rutherford, F.R.S. Received May 19,—Read June 17, 1909.)

Shortcut to Planck scale: Black Hole

M.W. Choptuik and F. Pretorius, Phys. Rev. Lett. 104, 111101 (2010)

- Black holes can form from k.e. in collisions
  - Schwarzschild radius scales linearly with mass
  - Instead of putting 1 E_{Planck} in 1 L_{planck} …

    $r_s = 2GM/c^2$
  - Put 10^6 E_{Planck} in 10^6 L_{planck}
- Need a diffraction-limited focus of 10^{12} particles at 10^{10} TeV (instead of 2 at 10^{16} TeV)
  - Energy requirement goes up by 10^6 to 893 GW.h
    - Large but not a show-stopper in the long run

If we don't make a black hole (e.g. in the case of Einstein-Cartan theory), that's OK, we've still probed new physics

Black Hole Factory Parameter Table

Parameter	Bosons e.g. photons (overlapping)	Fermions or non-overlapping bosons
Energy	10^{10} TeV	10^{12} TeV
Length	10 km	1000 km (space)
Gradient	10^{18} V/m	10^{18} V/m
Number of particles	10^{12}	10^{12}
Total energy per pulse	3.22×10^{15} J = 893 GW.h	3.22×10^{17} J=89.3 TW.h
Repetition period	14 days	14 days
Average power	2.66 GW	266 GW
$\sigma_x^* = \sigma_y^* = \sigma_z^*$	1.97×10^{-29} m	1.97×10^{-27} m (beam)
$\sigma_\theta^* = \sigma_E^*/E$	0.5 rad = 50%	0.5 rad = 50%
Black hole radius = $2.14\sigma_x^*$	4.22×10^{-29} m	4.22×10^{-27} m
Black hole mass	28.4 grams	2.84 kg
Black hole lifetime	1.10×10^{-22} s (evaporation)	1.10×10^{-16} s

Deepest mine=4km, allows +/-226km laterally within Earth

worse

$107M per shot at US avg. electricity price

worse

By far the hardest parameters are the alignment & emittance

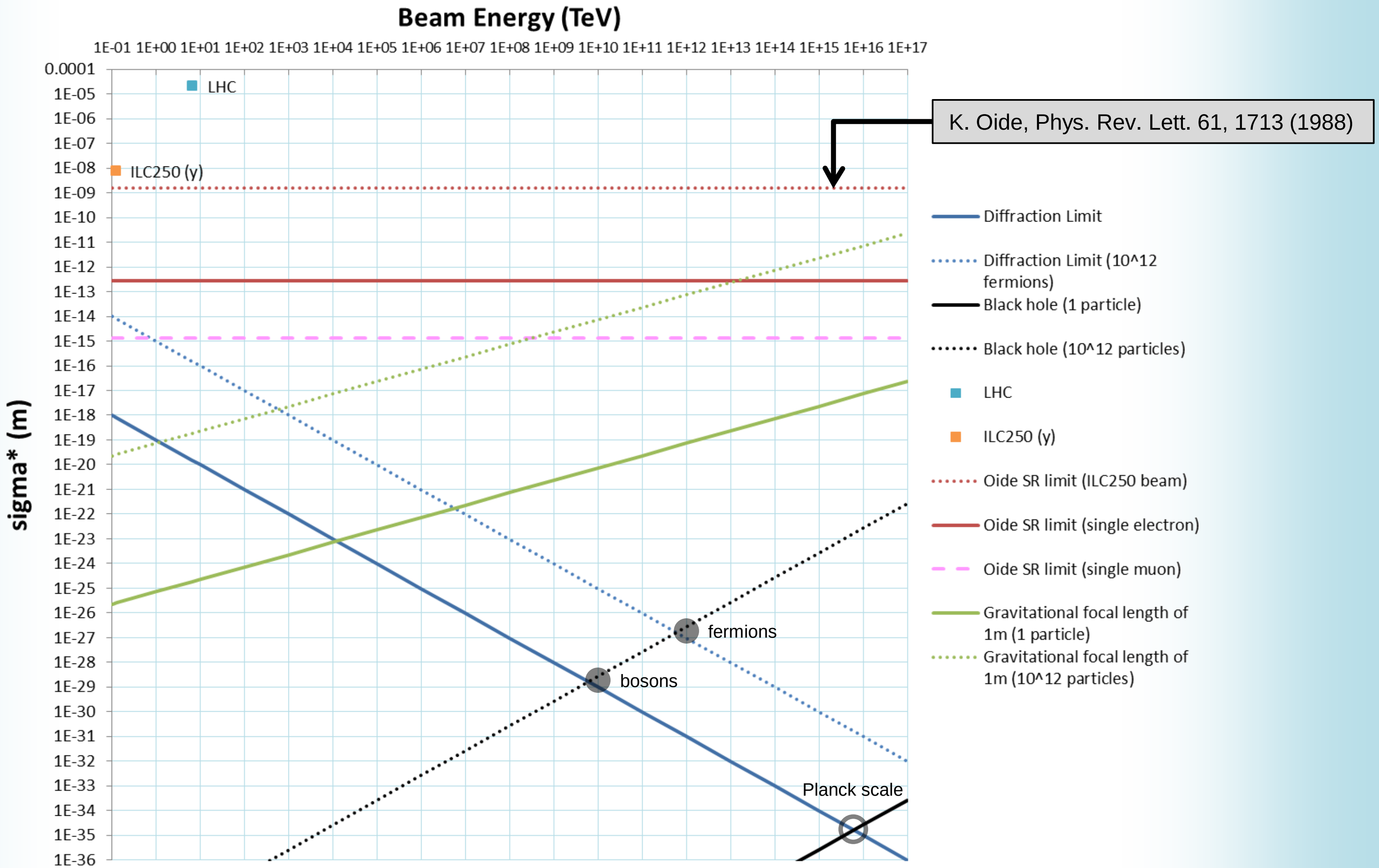
6D phase space N times larger, $N^{1/3}$ each plane

S.W. Hawking, Nature 248, 30 (1974)
D.N. Page, Phys. Rev. D 13, 198–206 (1976)

Compare at 100km Length

Parameter	Bosons e.g. photons (overlapping)	Fermions or non-overlapping bosons
Energy	10^{11} TeV	10^{11} TeV
Length	100 km	100 km
Gradient	10^{18} V/m	10^{18} V/m
Number of particles	10^{10} better	10^{15} way worse
Total energy per pulse	3.22×10^{14} J = 89.3 GW.h	3.22×10^{19} J = 8.93 PW.h
Repetition period	14 days $10.7M per shot at US avg. electricity price	14 days
Average power	266 MW better	26.6 TW way worse
$\sigma_x^* = \sigma_y^* = \sigma_z^*$	1.97×10^{-30} m	1.97×10^{-25} m (beam)
$\sigma_\theta^* = \sigma_E^*/E$	0.5 rad = 50%	0.5 rad = 50%
Black hole radius = $2.14\sigma_x^*$	4.22×10^{-30} m	4.22×10^{-25} m
Black hole mass	2.84 grams	284 kg
Black hole lifetime	1.10×10^{-25} s	1.10×10^{-10} s

Energy vs. Focus Size



Limit? Emittance Growth from SR

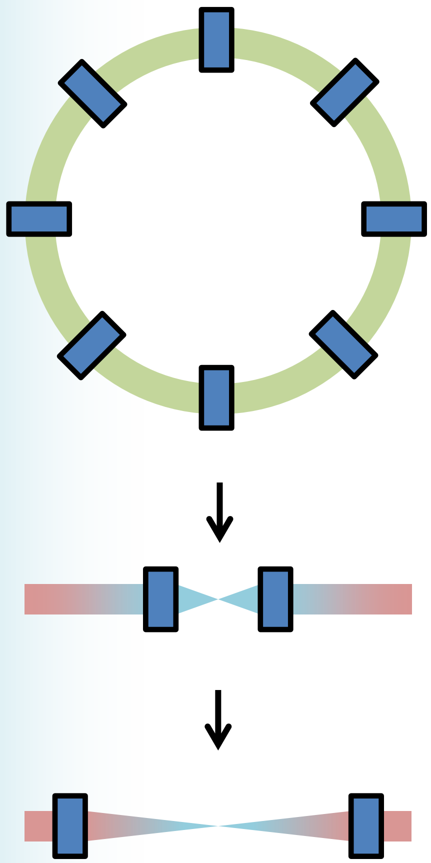
- Oide's bound depends only on ε_N

K. Oide, Phys. Rev. Lett. 61, 1713 (1988)

$$\sigma^*_{y\,\mathrm{min}} = \left(\frac{7}{5}\right)^{1/2} \left[\frac{275}{3\sqrt{6\pi}} r_e \lambda\!\!\!^{-}_e F(\sqrt{K}L, \sqrt{K}l^*)\right]^{1/7} (\epsilon_{Ny})^{5/7}$$

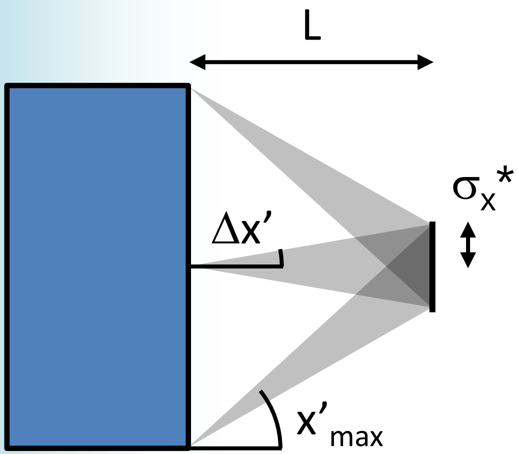
- The final focus magnets themselves cause synchrotron radiation emission and scattering
- Exceptions to the assumptions of this formula:
  - (A) Bending happens at lower energy than focus
  - (B) Quantum effects (coherence, entanglement)
  - (C) Non-electromagnetic focussing

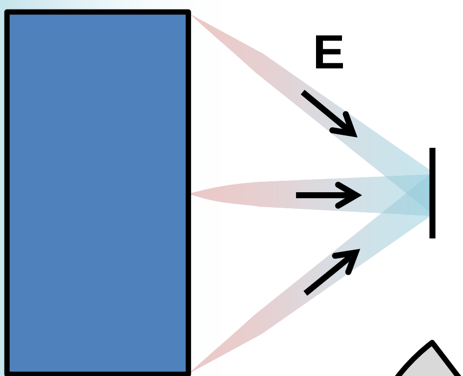
(A) Even Linearer Colliders



- Rings bend 360 degrees per turn up to highest energy
- Linear colliders bend by ~mrad at highest energy
- Bend at lowest energy and then accelerate afterwards?

(A) Beyond the Lower Bound

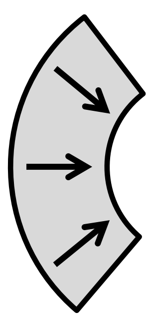




- Consider the optimised focus
- Bend in magnet is x'_{max}
- Now add **E**-field parallel to trajectories, reduces $\Delta x'$
- Bend in **E**-field only $\Delta x' = \sigma_x^*/L$
  - Can make this arbitrarily small, so not a significant source of SR

Experiment:
Can we break K. Oide's lower bound on focus size in the lab?

Pillbox cavity with spherical ends

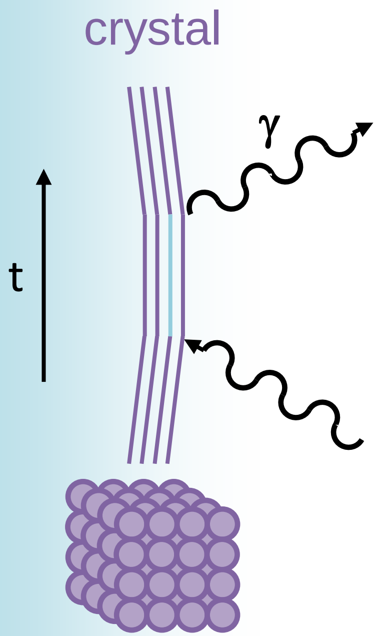


(B) The Problem in Quantum Terms

- Is there an initial state that…
  - Forms a black hole on a reasonable time-scale
  - No high energy particles, total size R<10km, total mass-energy and density ~= everyday objects?
- Answer: yes
  - Construction: take the state just before Planck black hole formation and track backwards in time using CPT theorem, particles hit walls, produce showers, eventually a few MJ-GJ of energy absorbed; result: warm concrete walls
- This state is entangled in a very particular way
  - Also applies to Mössbauer accelerators

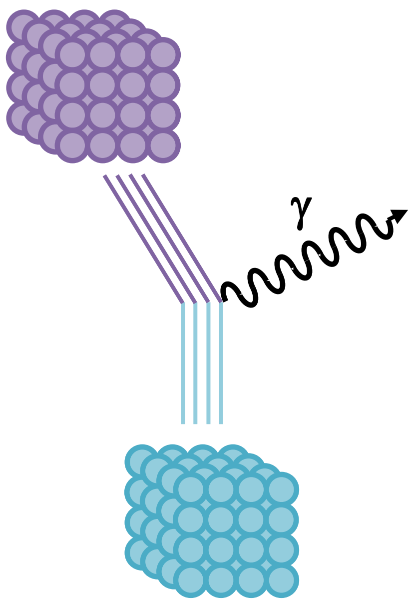
(B) Mössbauer Accelerator

R.L. Mössbauer, Z. Physik 151, 124 (1958)
P.P. Craig *et al.*, Phys. Rev. Lett. 3, 221–223 (1959)



Mössbauer effect: Gamma ray from nuclear excitation recoils against the entire mass of the crystal, giving very low energy spread

A.-S. Müller, talk at F3iA 2016 meeting



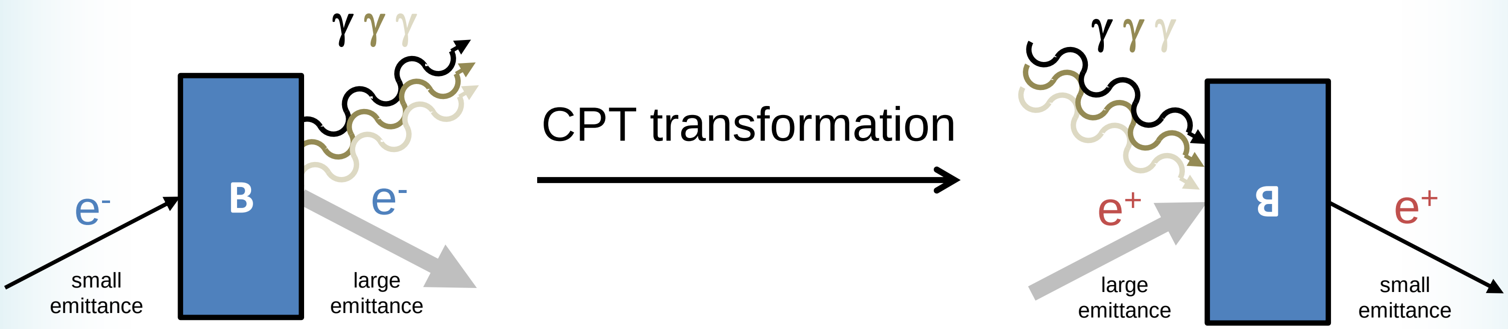
If many nuclei are excited, could the entire energy be transferred to a single emitted particle, since the crystal is acting coherently?

E.g. ^{191}Ir* emits 129keV gamma rays, a macroscopic crystal of 9.5×10^{22} iridium atoms (30 grams) could emit E_{Planck}

F. Vagizov *et al.*, "Coherent control of the waveforms of recoilless γ-ray photons", Nature 508, 80–83 (2014)

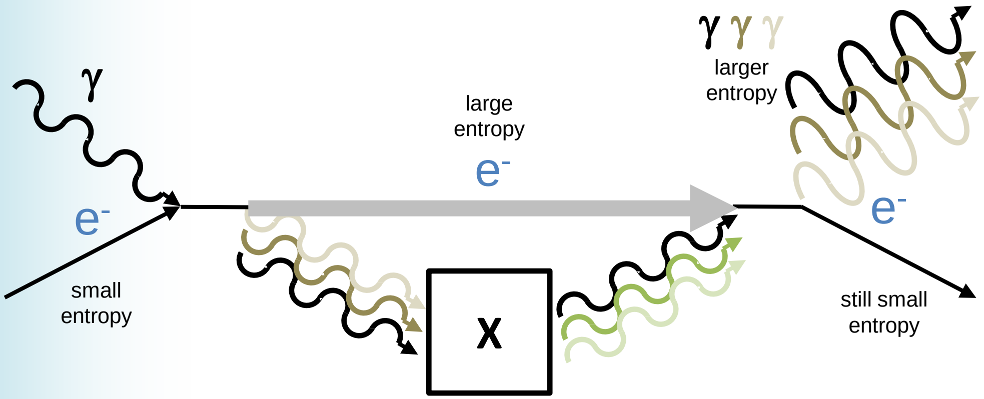
← Another useful application: modulating the wavefunction of a single gamma photon using the Doppler shift

(B) Time Reversal of SR Emission



There are some quantum scenarios where emittance growth from SR can be stopped or even reversed. Below is a generic “cooling” system.

Experiment:
Can we make the photon state in the diagram above? NB: it’s probably entangled with the input positron



Simulation/experiment:
Does such a process X exist and it be realised?

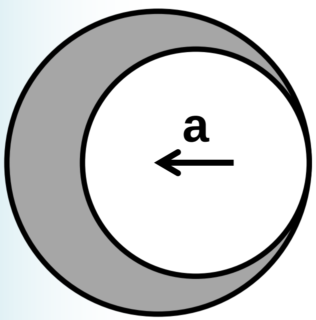
(B) Unused Degrees of Freedom

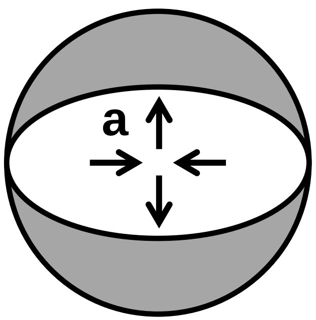
- Non-thermal distributions of particles
- Control of particle wavefunctions
  - Beam particle(s)
  - Accelerating photons (RF/laser)
- Entanglement
  - Between beam particles
  - Between beam and RF/laser
  - Between RF/laser and itself

As experimenters, we make **both** the beam and the accelerating photons, so no reason why this is not allowed

(C) Gravitational Final Focus

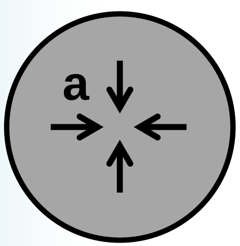
- If you can make a black hole, you can make a gravitational lens at lower densities
  - Use it to help reduce opening angle of final focus





2D, completely-linear gravitational dipole and quadrupole, based on subtracting two K-V distributions of mass

No synchrotron radiation emitted because gravity redefines what a "straight line" is



Linear "monopole" focussing lens also possible but the beams would collide! A shame because two interpenetrating KV beams would self-focus analogous to high intensity e-p IRs

(C) Simplified Calculation

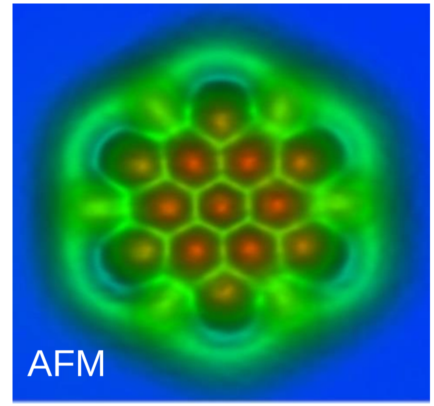
- Assume you only have σ_θ*=0.5/N rad (N× low)
  - So can only make σ_x* N× that needed for BH
- Deflection from lensing $\theta = 2r_s/r = 2/N$ rad
  - So need at least 0.5/(2/N) = N/4 times the mass
- Extra mass required scales up as inverse of originally achievable σ_θ*
  - Particles forming lenses do not create black hole
    - So candidates for energy recovery

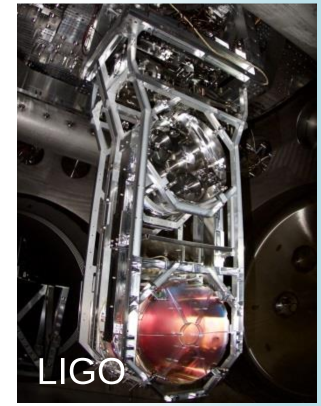
Nucleus-Level Alignment?

Nearer-term experiments

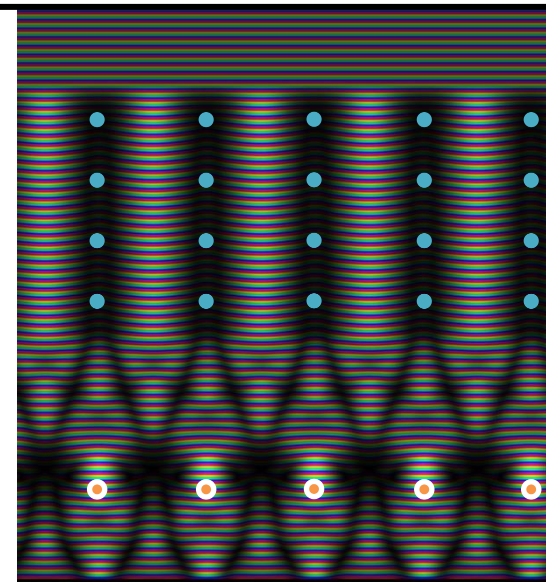
Collaboration with:
Nanotechnology, fusion(?)

- Can we demonstrate changing a nuclear reaction rate by a spatial/positioning effect?
  - AFM tip ≤ 5×10^{-11} m
  - LIGO mirrors ~10^{-16} m
    - Measurement ~10^{-18} m
- Or could use crystal channelling alignment





XY Scanner	Single module flexure XY-scanner with closed-loop control
	50 µm × 50 µm (optional 10 µm × 10 µm or 100 µm × 100 µm)
	Resolution : 0.05 nm
Park NX10	**Position detector noise** : < 0.25 nm (bandwidth: 1 kHz)
	Out-of-plane motion : < 2 nm (over 40 µm scan)



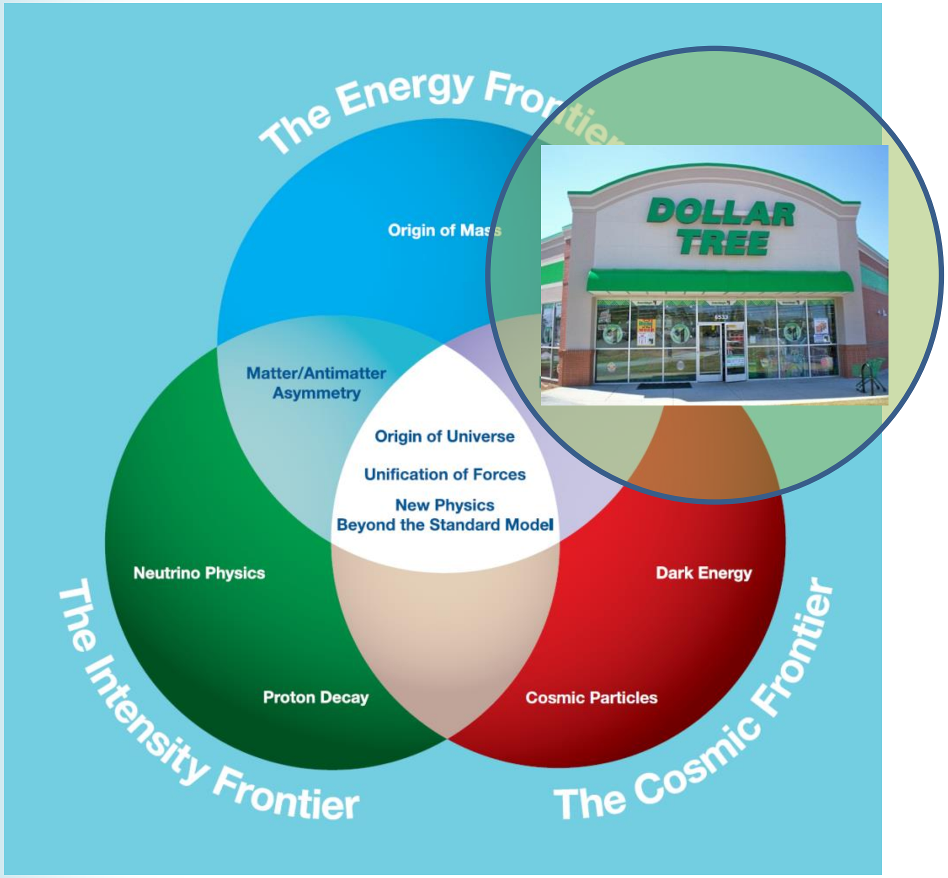
Summary: Single-Particle Collider

- Currently, we collide a billion+ particle bunch and get ~10 events per crossing
  - Somehow a $>10^8$ factor in efficiency has been lost
  - Various factors to blame: with 20th century technology this was the only way to get it to work
    - And it's still hard
    - But big reward
      - e.g. LC power limit

Experiment:
Apparatus to collide particles individually, then gradually increase accelerating voltage

- There is no intra-beam scattering if you only have one particle per bunch

Cheapness Frontier



Mass-produced parts
- Benefit from other industries

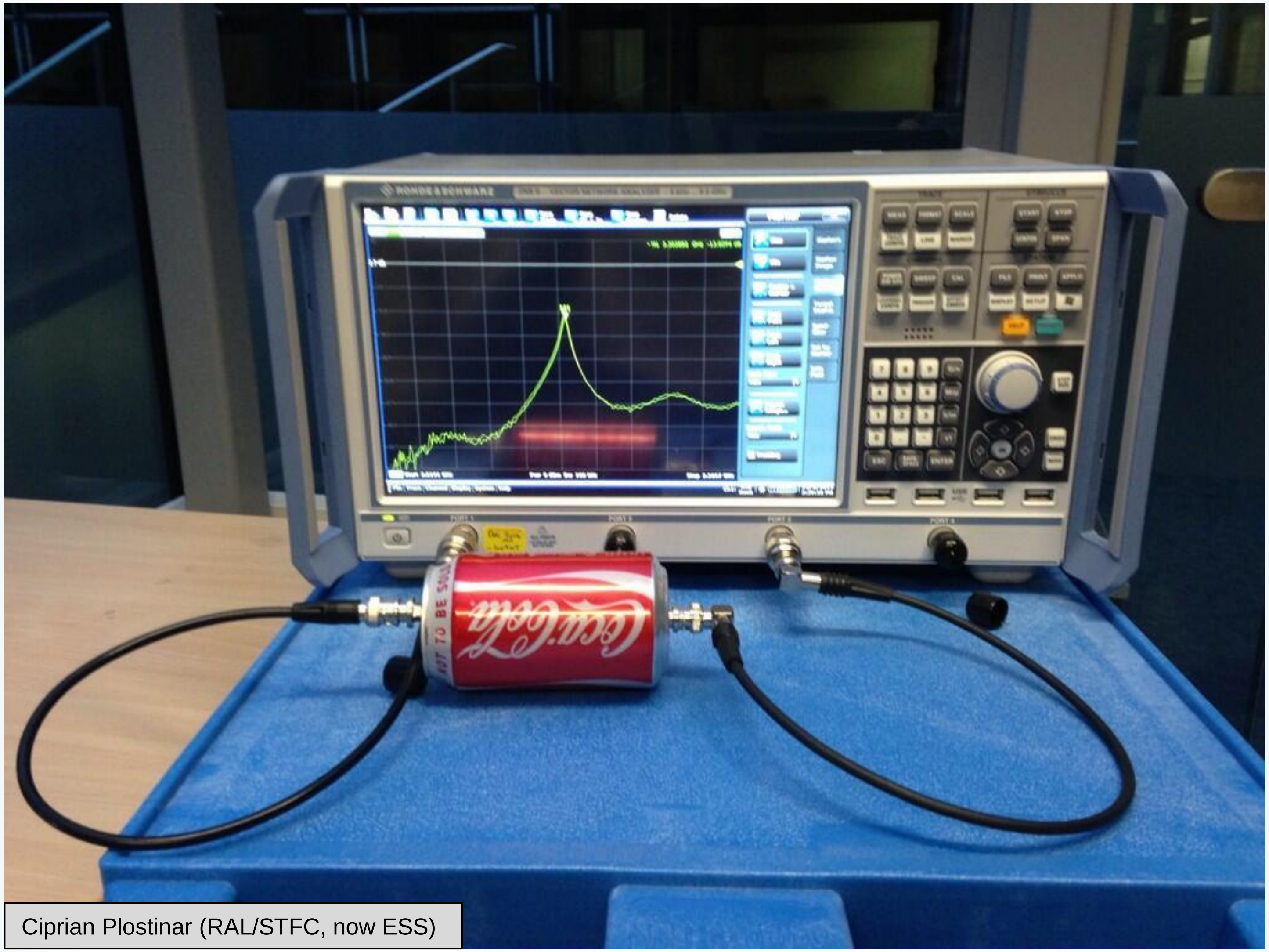
Don't over-spec
- Evade precision requirements by staging and feedback

Automation
- Manpower will be the most expensive item in the future
- 3D printing, robotics
- AI / automated design

Recycling
- Energy recovery, multi-pass

- Why? Since accelerators are already at the limits of government research budgets

f = 3.3 GHz, Q = 50



Ciprian Plostinar (RAL/STFC, now ESS)

f = 150-165 MHz, Q = 9700

GERALD DAVID OBE FREng
AERIAL FACILITIES LTD

DESIGN AND TECHNOLOGY

The beer barrel as a VHF cavity *resonator*

In the 1970s, use of mobile radio frequencies was expanding dramatically and existing antennas were becoming heavily overloaded. The engineering solution devised by Gerald David was to introduce multiple transmitter combiners onto a single antenna using band-pass filters. The use of a beer barrel in this context shows how existing structures can be adapted to new uses at a fraction of the cost of purposely designed components.

G. David, Ingenia Magazine 18, 21–25 (2004)

The unloaded Q_0 obtained in practice at 150 MHz exceeded 9000 and in very carefully prepared cavities figures up to 9700 could be obtained.

we did not come across any significant problems due to the casting or welding so the quality of the conductivity was of the highest order. The other great advantage of this device was the price which, in the raw form, was £47 per barrel when ordered in quantities of 100.

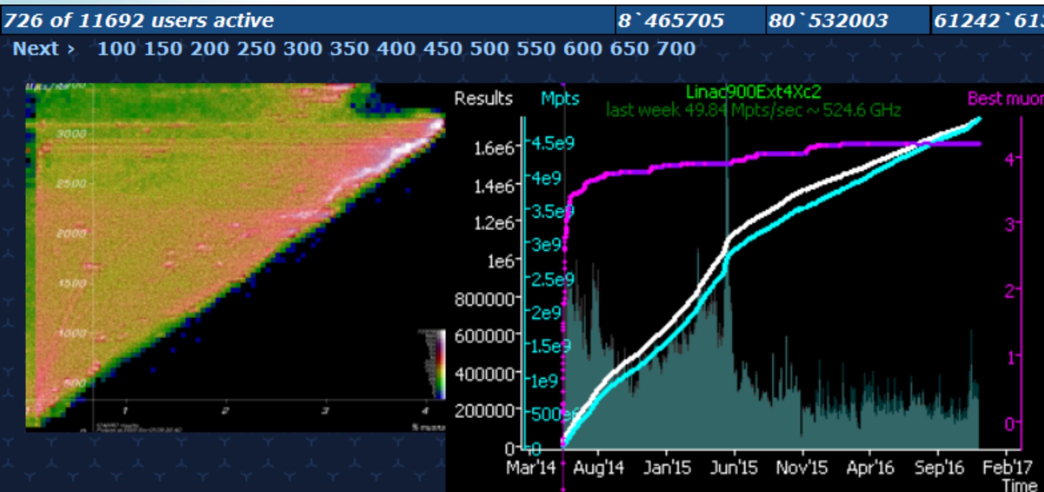
Multi-Channel Power Supply

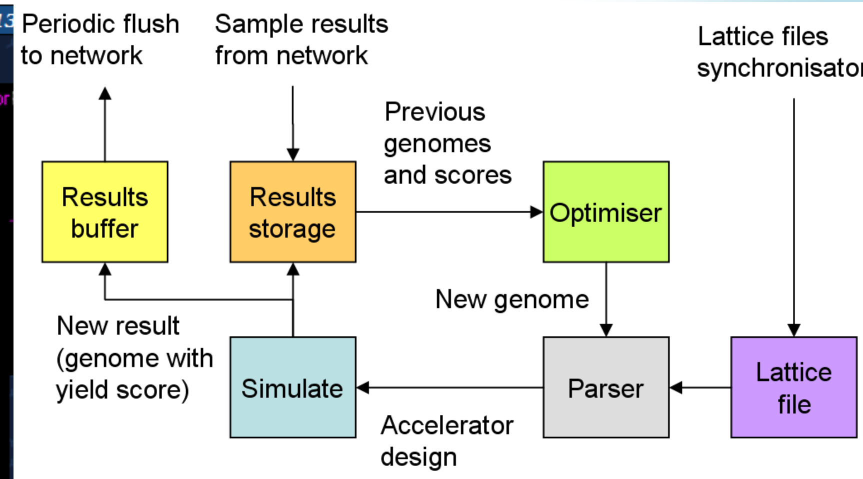
- Generic rack power supply
  - >$1000 for one channel
- My monitor
  - $699 for 11M channels
    - 2560*1440*3
  - $0.000063 per channel

- Factor of $>10^7$ is available if all you want is a large number of independent outputs
  - Via mass production, lithography industry etc.

Automated Design: Muon1

Optimisation of design space with 100s of parameters using a genetic algorithm and distributed computing. The same optimiser designed the ATF fixed-field line.





Linac900Ext4Xc2 *Tab-separated stats list [updated 2016-Dec-01; 15:08 UTC]*

Show users active in last **day**, **week**, **month**, **quarter**, **year**, or **ever**.

#	Username	v4.4 results	Mpts	Best muon percentage	Hours since last active
1.	[OCAU] badger	67211	186`105231.1 (3.86%)	4.183458	0
2.	[DPC] White Panther	71611	32`970995.6 (0.684%)	4.183205	5
3.	CloverField	1603	4`163566.4 (0.0864%)	4.182676	14
4.	[Crunchers Inc]cswchan	18465	51`769559.1 (1.07%)	4.181424	1d 5
5.	Boots[OCAU]	26166	69`329152.3 (1.44%)	4.180717	11
6.	Mumps [MM] 22343 (Boinc Wrapper)	8052	28`699688.7 (0.596%)	4.180638	1w 6d 14
8.	[ARS]GOD	80909	225`686874.8 (4.68%)	4.180474	2w 6d 10
11.	[TA]Silverthorne	44006	120`478849.9 (2.50%)	4.176259	7
14.	[TA]JonB	30116	81`240721.7 (1.69%)	4.174589	1d 12
16.	AETiglathPZ [US-Distributed]	25511	67`472784.3 (1.40%)	4.173764	1w 3d 21
660 of 4423 users active		*1`742214*	*4818`448939.7 (7.87%)*	*4.183458*	*0*

Next › 50 100 150 200 250 300 350 400 450 500 550 600 650

S.J. Brooks, "Muon capture schemes for the neutrino factory", DPhil. University of Oxford (2010)

Designs lattice starting from almost nothing: labour-saving!

Magnet with 3D Printed Parts

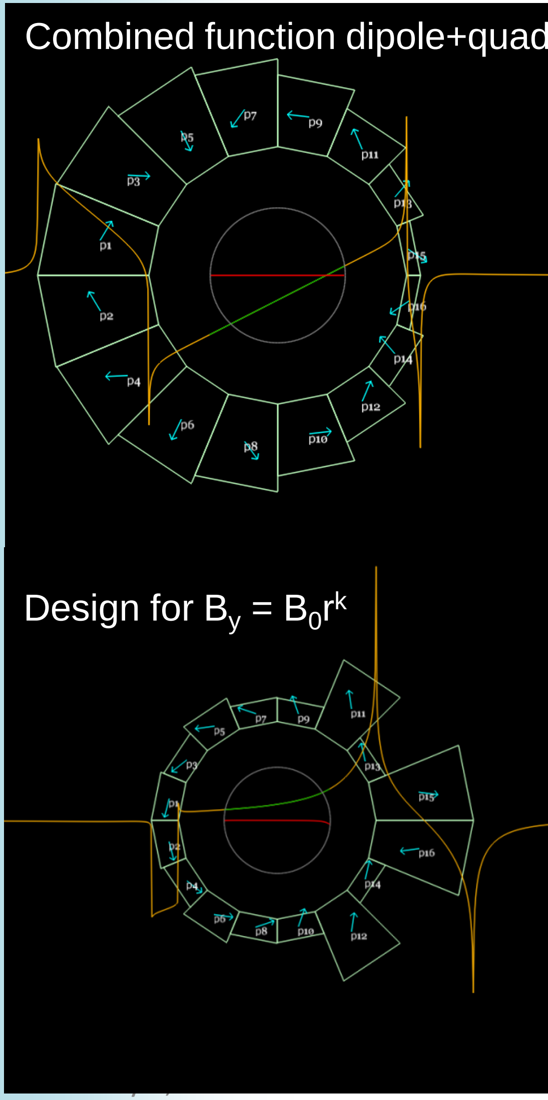
S.J. Brooks *et al.*, "Production of Low Cost, High Field Quality Halbach Magnets", Proc. IPAC 2017

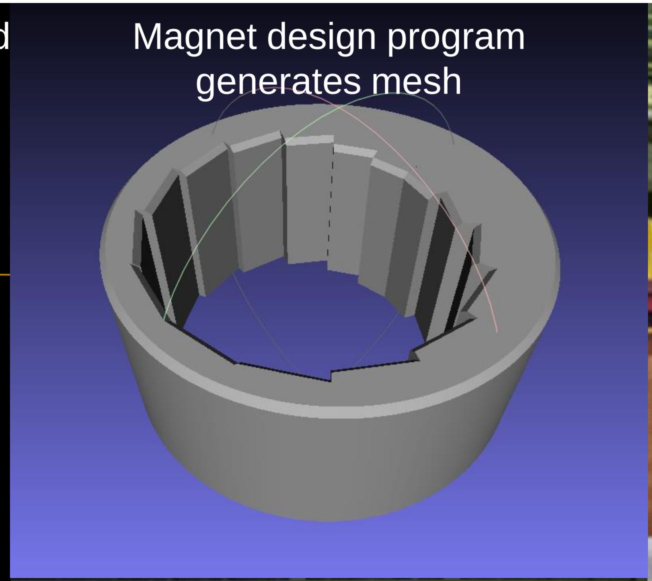
- Split accuracy task into two stages

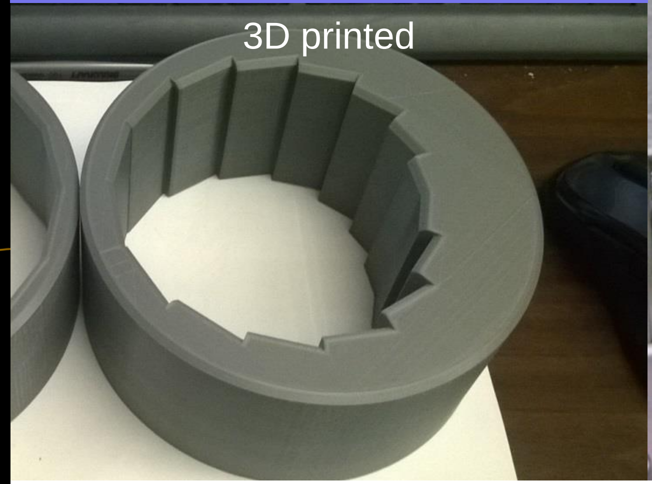
Halbach quadrupole using NdFeB, 23.6 T/m, R=34.7mm bore (0.82T max), 10^{-4} errors at R=10mm

Material cost: $1100. No alignment better than 0.25mm required anywhere. Assembled with mallet.

Custom and Cheap – is it possible?

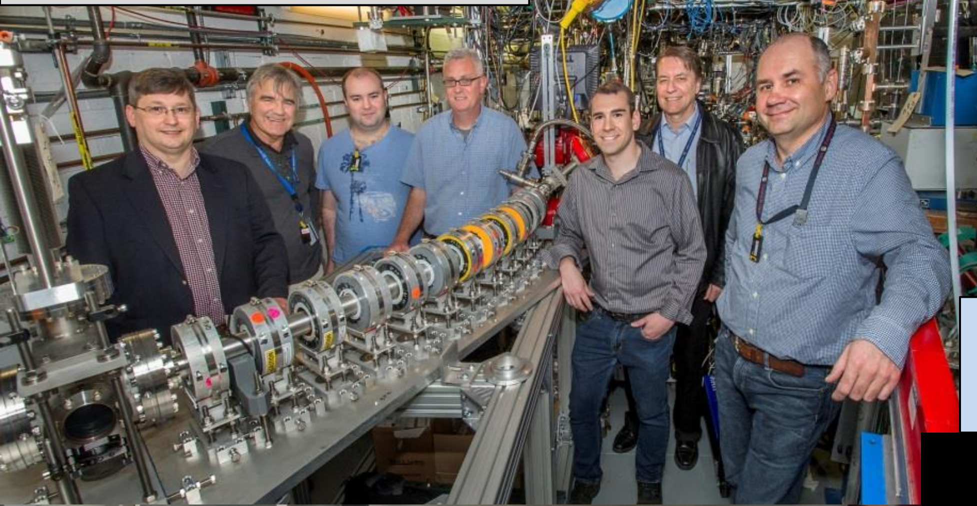


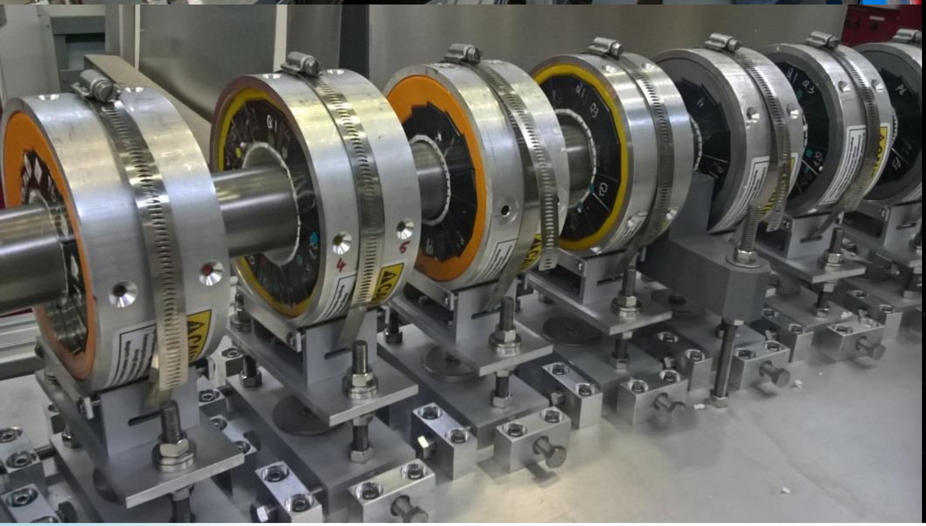


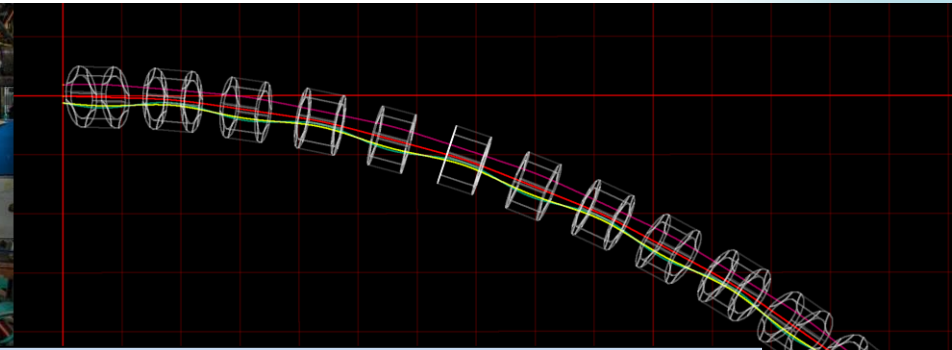


ATF1 Fixed-Field Arc Test (AE79)

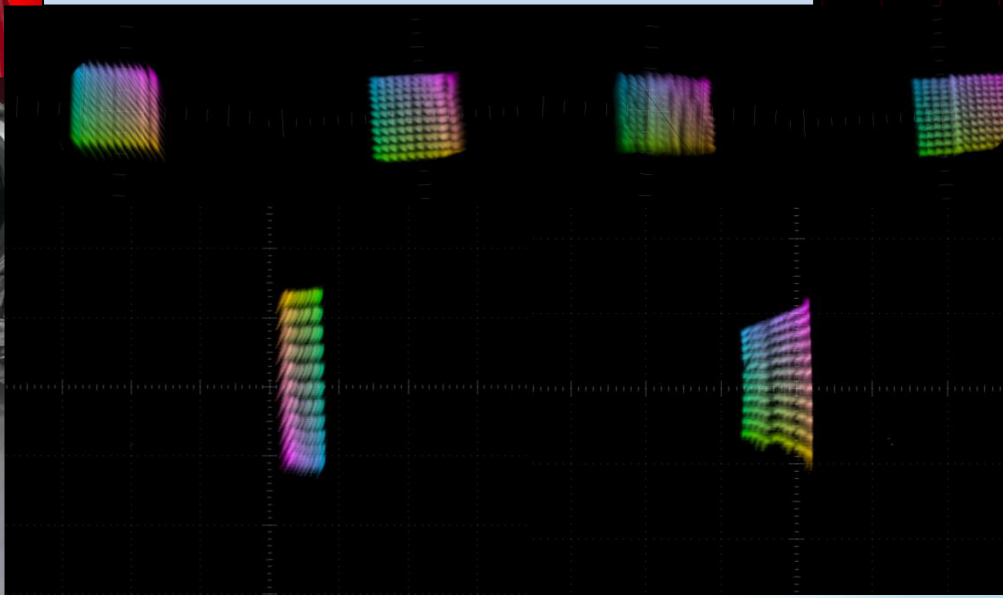
S.J. Brooks, talk at FFAG 2017 workshop







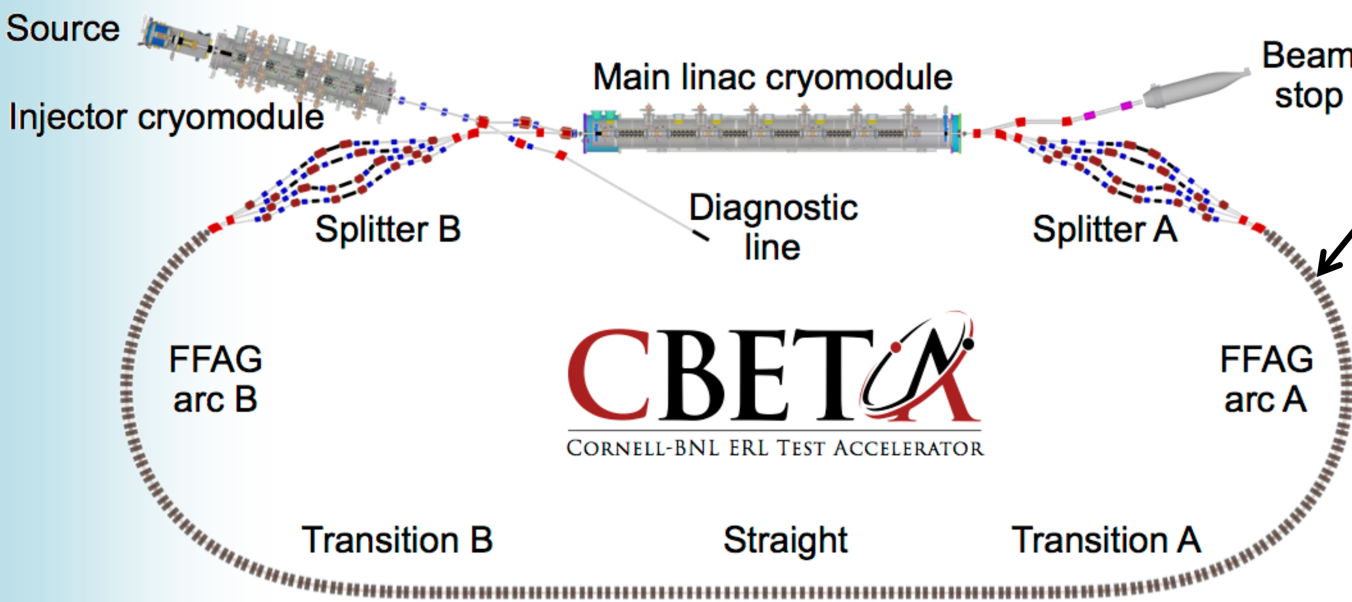
- No power required for magnets
- 3.8× energy range in one line



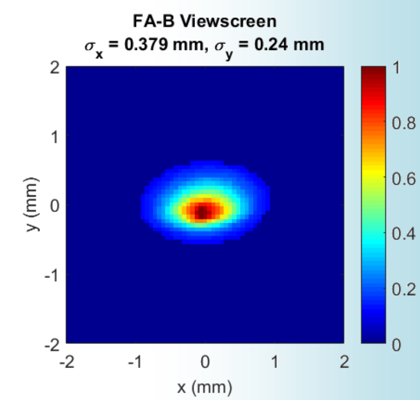
G.H. Hoffstaetter *et al.*, "CBETA Design Report, Cornell-BNL ERL Test Accelerator", arXiv:1706.04245

Also several papers at this conference: TUYGBE2, TUPMF023, TUPMF024, TUPMF066, WEPMF038, THPAF021, THPAF022, THPAF023

Re-use/Recycle: CBETA ERL



First beam to here, April 18th

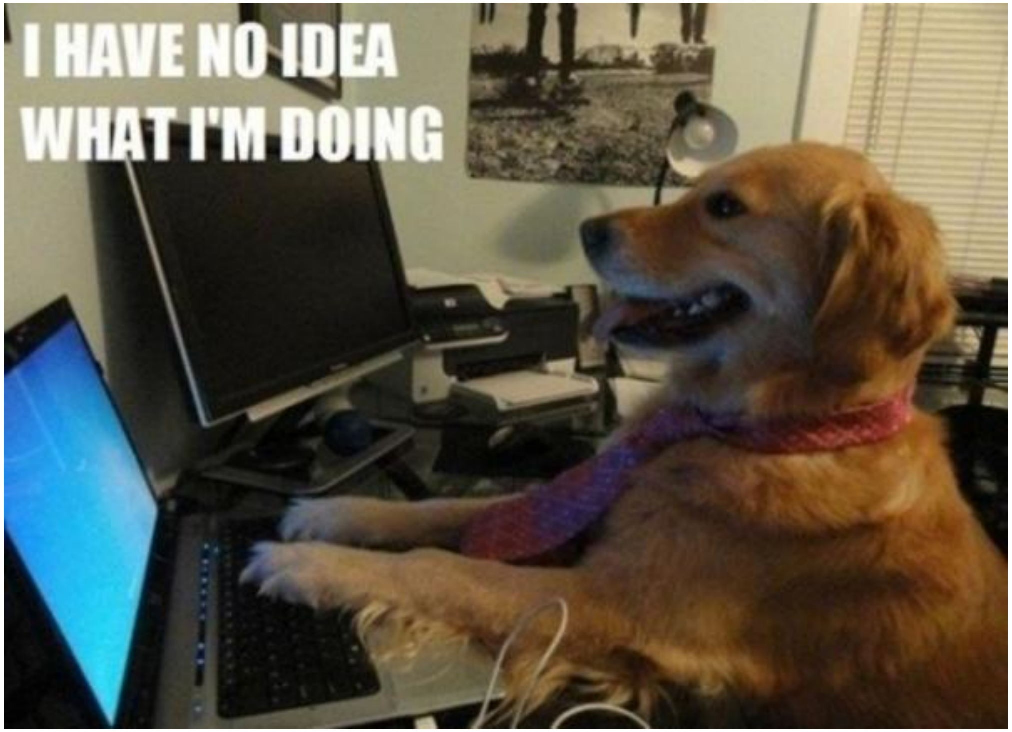


- Superconducting linac module
  - With energy recovery (150MeV*40mA = 6MW power in beam, 45kW of actual RF amplifiers)
  - 36MeV energy gain module used 4 times (more energy per hardware)
- Permanent magnet recirculating lines (low/zero power)
  - Used multiple times in fixed-field optics (4 energies in one line, CW)

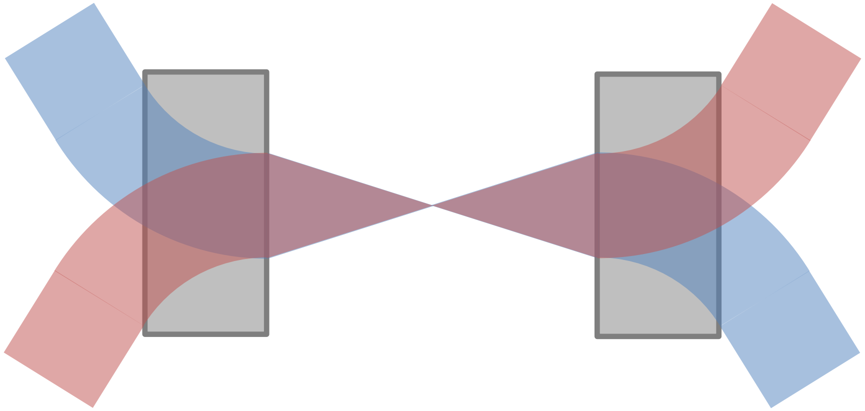
BACKUP

Warning

- Lots of this talk is speculative



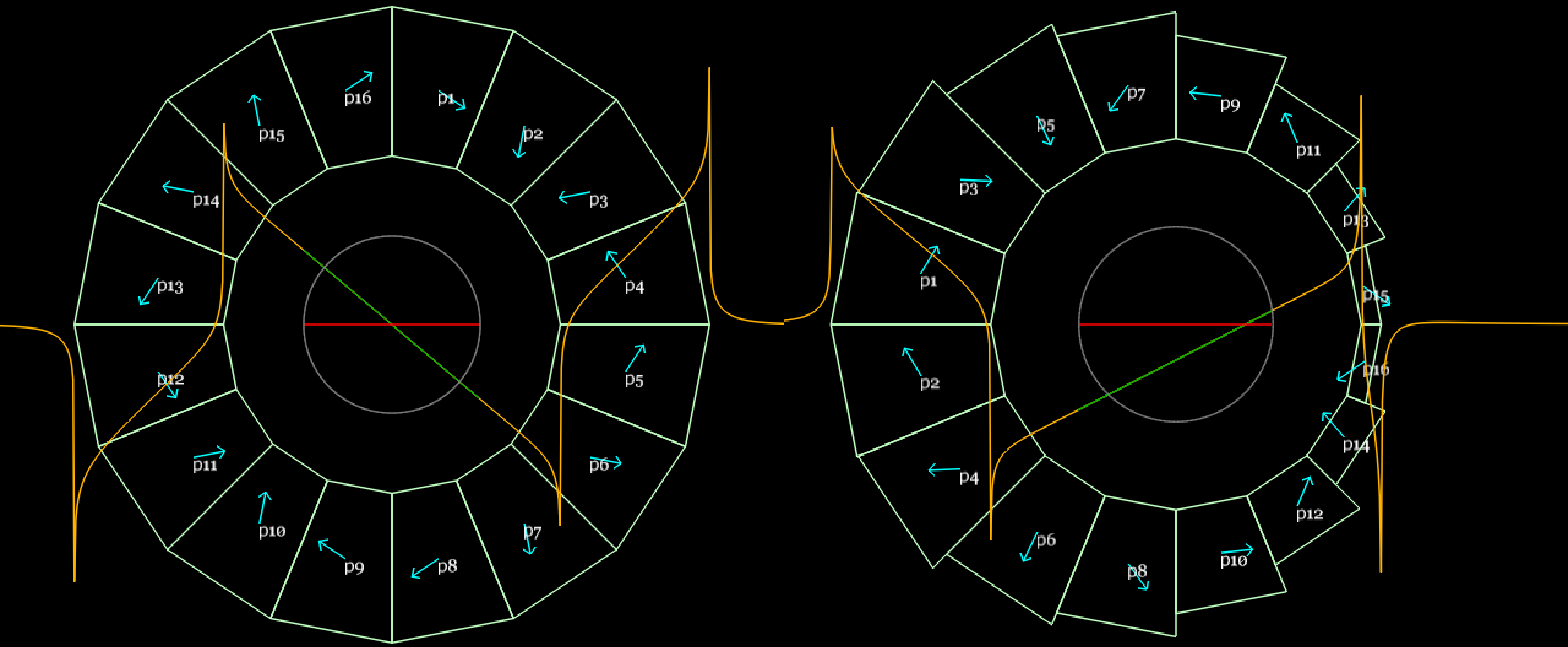
Neutralised Focus: Solution in Search of a Problem



- No good for beam-beam limit
  - Instability governed by dForce/dx not size of Force
- Probably no good for fusion (ICF)
  - Requires awkward energy recovery system
- Maybe can make dense/degenerate matter?

Generalised Halbach design

My current sheet approximation code (PM2D) is good enough



Material grade: N35SH from AllStar Magnetics, B_r(eff.)=1.194T

Best so far: QF3

Table 1: Field harmonics from ERHIC-PMQ_0503_0004_001 at R=10mm. The nominal magnet length is 57.4412mm and the average field corresponds to 23.6386 T/m.

Field harmonic	Normal units	Skew units
Dipole	0.00	-0.00
Quadrupole	10000.00	0.00
Sextupole	-0.18	-0.94
Octupole	0.34	0.17
Decapole	-0.65	0.09
Dodecapole	-0.05	0.02
14-pole	-0.02	-0.01
16-pole	-0.00	0.00
18-pole	0.00	0.00
20-pole	-0.00	-0.00
22-pole	-0.00	-0.00
24-pole	-0.00	0.00
26-pole	0.00	-0.00
28-pole	0.00	-0.00
30-pole	-0.00	-0.00

Cost and Labour per Magnet

- Permanent magnet wedges (AllStar N35SH)
  - $1052.67 per QF magnet (16 wedges)
  - $758.00 per BD magnet (16 wedges)
- Labour ~8h per magnet: 3h measurement, 2h shimming, 2h assembly, 1h 3D printer setup
- Required infrastructure
  - 3D printer ($2-3k), used Ultimaker 2 Extended+
  - Rotating coil (~$50k)

Benefits

- No power consumption
  - No power supply, no copper wires or windings
- Any field shape you like within strength limits
- No "cross-talk" between iron surfaces in compact lattices
- Can be assembled with mallet
- 1e-4 accuracy is possible after shimming
- Seems cheap, at least for short magnet length