Storage Ring Resonant Nuclear Transmutation

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2 Storage ring nuclear transmutation as nuclear power source

- The eventual goal is to produce electrical power using deuteron and helion (He3 nuclei) beams for the process

$$d, h \rightarrow p + \alpha$$

.

- An early step to be taken in a (slightly modified) existing COSY ring, could use simultaneous proton and deuteron beams converting into helions:

$$p, d \rightarrow h + \gamma$$

- Since this process is not very exothermic it cannot be expected to contribute to the war against global warming.
- Nevertheless, it will be astonishing to observe and measure in detail any nuclear transmutation occurring at room temperature.

3 Storage ring nuclear transmutation as nuclear power source (continued)

- This can be a small (second or third) step taken toward eventual room temperature conversion,

$$d + h \rightarrow p + \alpha$$

which, like (current favorite) deuteron, triton conversion

$$d + t \rightarrow n + \alpha,$$

is strongly exothermic,
- but produces neutrons that will inevitably ruin, by radiation damage, whatever equipment is being used to heat the target material from room temperature to the tens of KeV temperature needed to ignite termonuclear transmutation.

4 Superimposed electric and magnetic storage ring bending

- As Koop first suggested, in the context of EDM measurement,
- it is possible, with superimposed electric and magnetic bending, for beams of two different particle types to circulate simultaneously
- This opens the possibility of "rear-end" collisions occurring while a fast bunch is passing through a slow bunch.
- Bunches of the same beam type can also circulate simultaneously if they have different momenta.
- This opens the possibility of "rear-end" elastic scattering; for example p, p.
- But, at low CM energy, the relative velocity of fast and slow bunches may be inconveniently small, making the collision rate small.

5 Electric insertions for COSY

- Kirill Grigoryev and others have built a sophisticated device capable of inserting vertical electric bending within magnets in COSY.
- Not yet tested in COSY, it is expected to succeed.
- Still needed will be for every bending magnet in COSY to have such an electric field insertion—not cheap, except relative to everything else in the nuclear power world, and certainly to the German GSI, FAIR project.

6 Superimposed magnetic and electric bending in COSY

- With primary beam protons and secondary beam deuterons, judicious RF control will bunch the beam into (let's say one) "slow" and one "fast" bunch.
- Eventually the fast bunch will "lap" the slow bunch, causing p,d "rear end" collisions periodically.
- This is essential!—the storage rinig configuration causes the center of mass (CM) to be in a moving frame, in which the particle kinetic energies are in the range roughly, from 100 KeV to 1 MeV, while their laboratory energies are in the range roughly, from 10 MeV to hundreds of MeV.
- The center of mass will be traveling at roughly the velocity at which deuterons have 50 MeV energy in the laboratory.
- The center of mass energy (where their momenta are equal and opposite) is (roughly) 1 MeV , which is above the Coulomb barrier for d+d nuclear interaction, and the threshold for

$$p + d \rightarrow h$$

7 Kirill Grigoryev electrostatic deflector

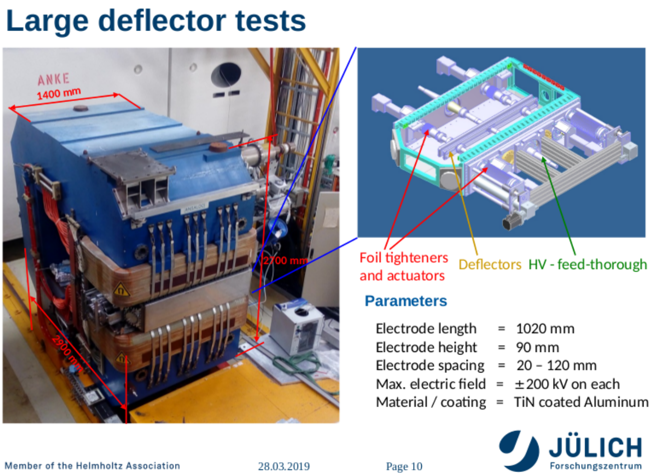
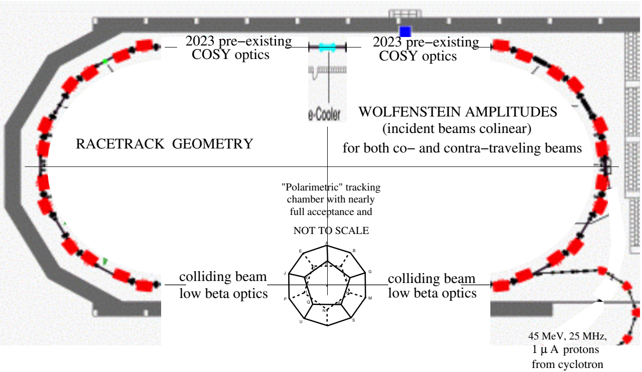


Figure 1 : Kirill Grigoryev electrostatic deflector presentation.

8 COSY proposed resonant transmutation, $p, d \rightarrow h, \gamma$



- COSY, as modified for resonant nuclear transmutation of protons and deuterons into helions
- Stripper foil polarized deuteron beam injection from cyclotron,
- Proton injection method is yet to be determined
- Except electric bending inserts, all elements are unchanged in their current locations—including electron cooling

9 Carbon foil, full aperture stopping-proton tracker/polarimeter

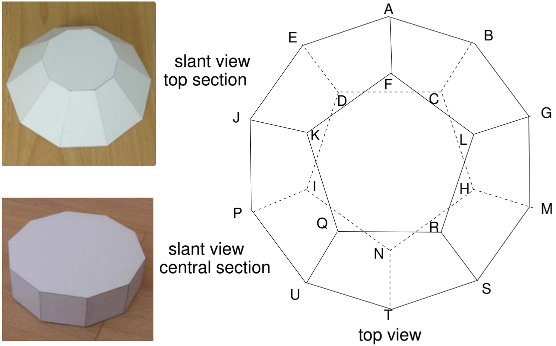


Figure 2 : On the right is an artist's conception top view of an almost full-acceptance tracking/stopping/polarimeter at the storage ring intersection point IP. Their dodecahedral faces subtend roughly equal solid angles. The figures shown on the left are slant views of horizontal slices. To accommodate passage of the colliding beams there is little useful particle detection in the up-down central section.

10 COSY resonant transmutation, $p, d \rightarrow h, \gamma$

bm	m1	G1	q1	beta1	Qs1	KE1	E0	B0	m2	G2	q2	beta2	KE2	bratio	Qs2	bm
1	GeV					MeV	MV/m	mT	GeV				MeV			2
p	0.9383	1.7928	1	0.2032	-3.354e+00	20	6.82	-15.86	1.875	-0.1430	1	-0.2470	60.0112	-1.2157	-6.750e-01	d
p	0.9383	1.7928	1	0.2032	-3.354e+00	20	6.82	-15.86	1.875	-0.1430	1	0.15807	23.8820	0.7777	-1.483e+00	d

bm	beta1	Qs1	KE1	E0	B0	beta2	Qs2	KE2	beta*	gamma*	M*	Q12	7*bratio	bm
1			MeV	MV/m	mT			MeV			GeV	KeV		2
p	0.2032	-3.35	20	6.82251	-15.863	-0.2471	-0.675	60.011	-0.09796	1.0048	2.87998	66092.6	-5.75808	d
p	0.2032	-3.35	20	6.82251	-15.863	0.1581	-1.483	23.882	0.17322	1.0153	2.81457	681.95	9.00002	d

Table 1 : Kinematic parameters for (primary, forward going) proton beam 1 and (secondary) beam 2. The lower block extends the upper block, with some parameters repeated.

- With beta2 being positive in the lower row, this case has co-traveling beams, as needed for resonant nuclear transmutation, with 20 MeV protons, 23.882 MeV deuterons, and Q12=681.95 KeV, well above the Coulomb barrier.
- The entry in the lower right corner shows bratio=9/7; the proton beam makes 9 turns for every 7 deuteron turns.

11 Derbenev geometry and T-violation signature

- Unlike fixed target experiments, rather than being colinear, in Derbenov geometry incident beams collide at right angles.
- All initial and final state laboratory proton energies being equal produces a huge statistical polarimetric advantage.
- *Persuasive visual evidence of T-violation will be provided by unexpected correlation between the p-carbon scattering directions of final state protons.*

12 COSY reconfiguration with T-violation plus nuclear transmutation capability

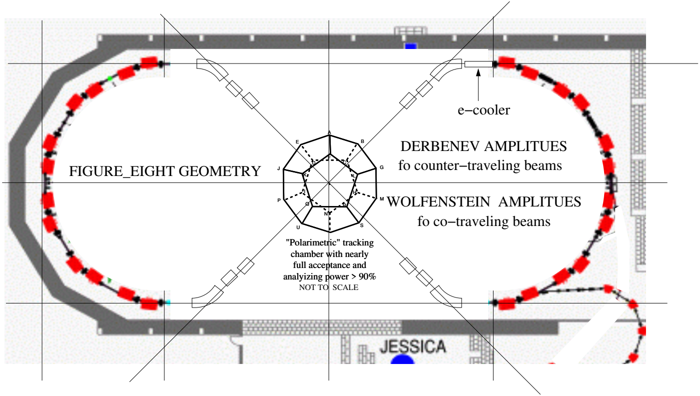


Figure 3 : COSY reconfiguration into DERBENEV geometry

- Realistic design requirements may require the crossover lines to be not quite orthogonal.
- Detailed design of crossover lines may include extraction of final state particles, to take advantage of their significant collimation in the laboratory frame.

13 COSY resonant transmutation, $h, d \rightarrow p, \alpha$

bm 1	beta1	Qs1	KE1 MeV	E0 MV/m	cB0 mT	beta2	Qs 2	KE2 MeV	beta*	gamma*	M* GeV	Q12 KeV	7*bratio	bm 2
h	0.1769	-0.665	45	4.643	-3.308	0.1547	-1.09	22.86	0.1680	1.014	4.684	292.18	8.00287	d
h	0.1788	-0.666	46	4.749	-3.364	0.1564	-1.09	23.37	0.1698	1.014	4.684	298.53	8.00219	d
h	0.1807	-0.666	47	4.855	-3.419	0.1581	-1.09	23.88	0.1716	1.015	4.684	304.87	8.00151	d
h	0.1826	-0.666	48	4.961	-3.475	0.1597	-1.09	24.39	0.1734	1.015	4.684	311.21	8.00083	d
h	0.1844	-0.666	49	5.067	-3.530	0.1613	-1.09	24.90	0.1751	1.015	4.684	317.54	8.00015	d
h	0.1862	-0.666	50	5.173	-3.586	0.1630	-1.09	25.41	0.1769	1.016	4.684	323.87	7.99947	d
h	0.1880	-0.667	51	5.279	-3.641	0.1645	-1.09	25.92	0.1786	1.016	4.684	330.19	7.99879	d
h	0.1898	-0.667	52	5.386	-3.697	0.1661	-1.09	26.42	0.1803	1.016	4.684	336.50	7.99811	d
h	0.1916	-0.667	53	5.492	-3.753	0.1677	-1.09	26.93	0.1820	1.016	4.684	342.81	7.99744	d

Table 2 : Kinematic parameters for fine-grain scan.

- The *h* beam spin tune Qs1 is no longer constrained to vanish; rather it is tuned to Qs1=-0.666 by adjusting the E/M field ratio to produce perfect 7/8 velocity ratio, for KE1=49.2 MeV helion energy and 25.0 MeV deuteron energy.
- Notice, in paricular, the approximate match of Q12=317 KeV, with the Coulomb barrier height, $V_{d,3He} = 313.1\,\mathrm{KeV}$
- This matches the available kinetic energy to the CM kinetic energy required to surmount the repulsive Coulomb barrier.

14 Practicality of industrial scale electrical power generation using storage rings?

- Nobody knows.
- But, a "euro**news**" article read on Nov 26, 2022, estalishes a scale.
- "The kind of work it [CERN] carries out requires a lot of power. CERN uses an average of 1.3 terawatt hours of electricity per year, roughly equivalent to a town of 230,000 inhabitants. The Large Hadron Collider alone accounts for about half its consumption."
- "CERN particle accelerator complex will shut down on November 28, two weeks earlier than originally planned. After this winter break, CERN use of the LHC will further be reduced by 20 per cent in 2023."
- On this scale, storage ring electrical power generation with 500% efficiency could eventually amortize the construction cost?

15 Possible first step at Cornell-BNL ERL Test Accelerator CBETA

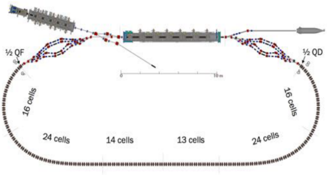


Figure 4 : Lattice layout for the Cornell-BNL ERL Test Accelerator CBETA.

bm	beta1	Qs1	KE1	E0	B0	beta2	Qs2	KE2	beta*	gamma*	M*	Q12*	bm
1			MeV	MV/m	mT			MeV			GeV	KeV	2
e	1.0000	0.305	134.0	3.598	18.819	1.00	0.206	90.82	0.99999	216.905	0.00104	19.19	*e*

Table 3 : Kinetic parameters for two positron (or electron) beams in CBETA. CM variables are marked with *; M* being rest energy, Q12* available energy.

- Conversations with Stephen Brooks suggest that current injection components (indicated at the top of the figure) would require significant rebuilding to allow conversion of CBETA into a storage ring with long beam survival.
- However, the possibility of demonstrating dual beam storage ring capability with minimal power consumption could begin to demonstrate the practicality of electrical power production using storage rings.

16 Extra slides

Thanks for your attention

17 Cross section: $d + h \to p + \alpha$

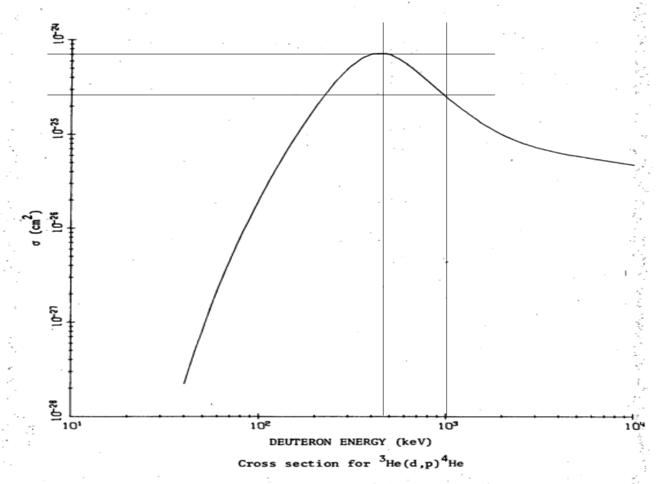


Figure 5 : Cross section: $d + h \to p + \alpha$

18 T-reversal symmetry of elastic p, p scattering

- In a Derbenev-style figure-8 storage ring, independently polarized, diametrically opposite bunches of the same beam collide at the crossing point.
- All 4 particle energies, initial and final state, are the same.
- This makes it practical to investigate spin dependence and time reversal T-symmetry of "elastic" pp scattering with unprecedented sensitivity.
- Recognizing that the proton is anomalous, e.g. anomalous MDM, "elastic" scattering may be accompanied by T-violating spin rearrangement with undetectably small energy excitation.
- It seems likely, after elastic scattering, that the final proton states are "entangled".
- For example, the horizontal orientation state of each individual proton may be random, but the other may necessarily be opposite.

19 T-reversal symmetry of elastic p, p scattering (continued)

- Operating above the 69.5 MeV laboratory energy at which proton-carbon scattering asymmetry analyzing power exceeds 99% to roughly 400 MeV (the pion production threshold), both scattered protons come to rest in graphite polarimeter chambers providing nearly full directional coverage.
- Both initial proton polarization states are pure and both final state proton polarizations are measured with nearly ideal analyzing power.

- The presence or absence of T-violation in nuclear forces is thought to bear significantly on important cosmological issues, especially missing mass, dark energy, and the matter, anti-matter imbalance.
- The possible existence of a semi-strong, T-violating, nuclear force with coupling strength compatable to the electromagnetic interaction was proposed independently by Lee and Wolfenstein, by Prentki and Veltman, and by Okun in 1965.
- Of the uncertain properties of nuclear physics, none is more fundamental, nor less well understood, than the nucleon-nucleon interaction.

21 Theory—conjectural

- Current-day nucleon-nucleon theory is “spin-inert”; usually neither spin flips, but if one spin flips, so does the other.
- The electromagnetic-nuclear interaction is not at all “inert”; especially as regards anomalous MDM. .
- A “toy” theoretical model (“gedanken experiment”) incorporating the anomalous proton MDM predicts strong T-violation, in a “nuclear-electric married particle”, such as the proton.
- The Derbenov collider configuration promises unambiguous detection of this effect.

22 T-reversal investigation with figure-8 storage ring configuration

- Spin dependence is most easily detectable at low proton energy.
- Rearrangement of existing COSY components into a "FIGURE-8" storage ring allows diametrically opposite polarized proton bunches in a single stored beam to collide.
- "Spin transparency" in figure-8 geometry is used to enable Fourier enhancement of T-violation sensitivity.
- The required COSY lab rearrangement is also compatable with PTR, a prototype EDM measurement ring capable of measuring the deuteron anomalous EDM using easily achievable, superimposed electric and magnetic bending.