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**High Field Synchrocyclotron Extraction Proof of  
Principle Demonstration with a Small Compensated  
Axial Bump.**

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TO: PROJECT FILES

SUBJECT: High Field Synchrocyclotron Extraction Proof of Principle Demonstration with a Small Compensated Axial Bump

Peeler-Regenerator or Regenerator-only extractions systems for synchrocyclotrons exhibited intrinsically low extraction efficiency of 5-10% typically. The relative contributions of miss-matched phase space distribution, energy spread and field imperfections to this low extraction efficiency are largely un-quantified for all operated synchrocyclotrons. The addition of supplementary elements- electrostatic deflectors or “C” electrodes, for example, did result in some synchrocyclotrons achieving extraction efficiencies above 50%. However space constraints, electric field strength limitations in the high B field environment, and clinical application RAM requirements considerations effectively preclude these as options as being consistent with the configuration of the compact 9T synchrocyclotron.

It was demonstrated for superconducting synchrocyclotrons at 5.5T [Wu, 1990] that an important contributing factor to low extraction efficiency could be the limitation imposed by the need to minimize axial losses resulting from reduced axial phase space stability in the presence of the strong regenerator field. We see no reason why this was not also a feature of operating synchrocyclotrons, particularly given the standard use of ‘unhooded’ ion sources, in which the physical constraints in the center would set a phase space envelope certain to exceed feasible extraction acceptance- either radial or axial.

Finally, we observed earlier here, in code benchmark studies of synchronous variable frequency acceleration for the high field synchrocyclotron, that we could ‘freeze’ the radial precession with a small  $\sim 0.1$ - $0.3$ T perturbation of the axial field, and that this ‘freezing’ was neither an artifact of either the computational algorithm nor a problem with the computational precision of high numbers of orbits (thousands).

Freezing of the radial precession with a small axial field perturbation, coupled with the designed low energy gain per turn in the 9T synchrocyclotron(dee voltage/power issues), affords an opportunity to develop an alternative method for extraction from a high field synchrocyclotron, based on a small (for synchrocyclotrons!) ‘precessional bump’ which is consistent with field strength limitations, extraction aperture constraints and possibly easier control of the axial betatron oscillations. While the effort in this direction is far from complete, it is now possible to demonstrate that this small precessional bump *in principle* can result in sufficient orbit separation for the extraction of protons at 250 MeV from a 9T superconducting synchrocyclotron.

**Table 1: Basic input parameters (base + bump2 B fields)**

Input parameters	Physical meaning	Typical value	File	
pi	circle constant	3.14159274101257	defpara.cmn	
np	number of proton	1		
nxdata1	base B x grid number	101		
nydata1	base B y grid number	73		
nzdata1	base B z grid number	21		
nxdata2	bump B x grid number	21		
nydata2	bump B y grid number	31		
nzdata2	bump B z grid number	21		
xbumpc	center of x bump	0.3		
xbumpa	amplitude of x bump	0.1		
ybumpc	center of y bump	2.05		
ybumpa	amplitude of y bump	0.5236		
c	speed of light	2.99793e8 m/s		
q	charge of proton	1.602176e-19 C		
m <sub>0</sub>	static mass of proton	1.6726e-27 kg		
r0	initial radius of proton	272 mm		Input_k250.f
phi0	initial angle of proton	pi radian		
dphi0	proton phase error	-47deg.		
z0	initial z of proton	0 mm		
B (Br, Bz)	B value at grid Interpolated from data file Base field: 4mu-a-r15z20-basic Bump field: field-2bump3-ass-patch-bump.table & field-2bump3-ass-patch-basic.table			
alpha	electrode open angle	5°		
ag	gap of Dees	2 mm		
Vd	voltage amplitude	10kV		
Cf	Freq reduction factor	0.9997		
nj	number of turn per freq step	20		
Nturntotal	total turn for simulation	3000		
ndiv	time division per turn	36000		
rlimit	maximum field radius	0.5 m		
nstore	data storage step	1,000		

Figure 1. Proton radius gain over approximately 1200 turns, from a start at a radius where the bump influence is minimal (272 mm). The onset of large radial oscillations at 298 mm is seen. The calculation extends beyond a turn number at which ions would extract in practice.

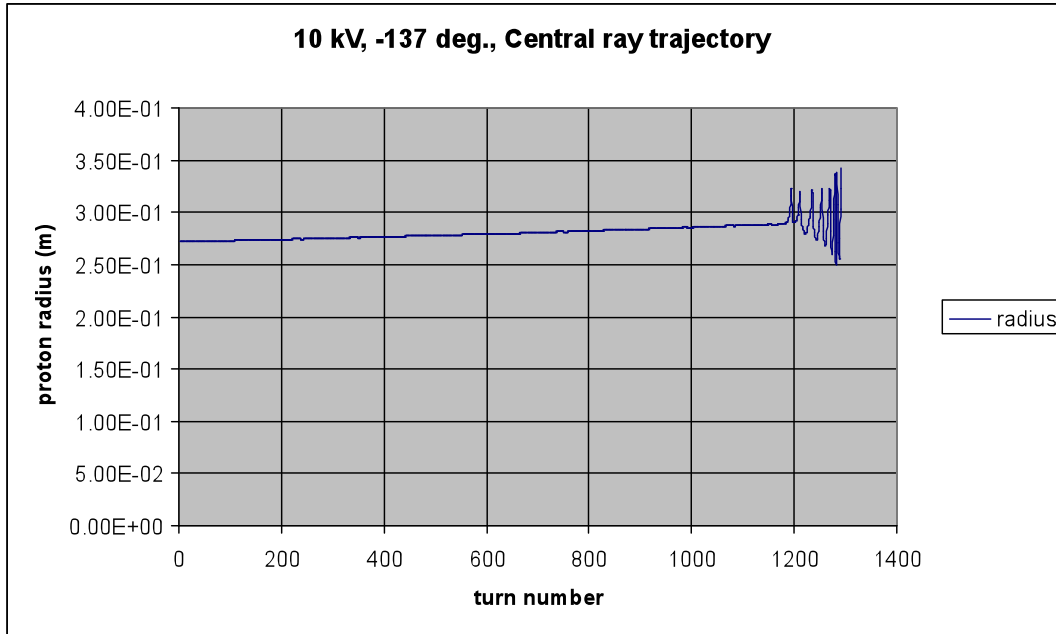
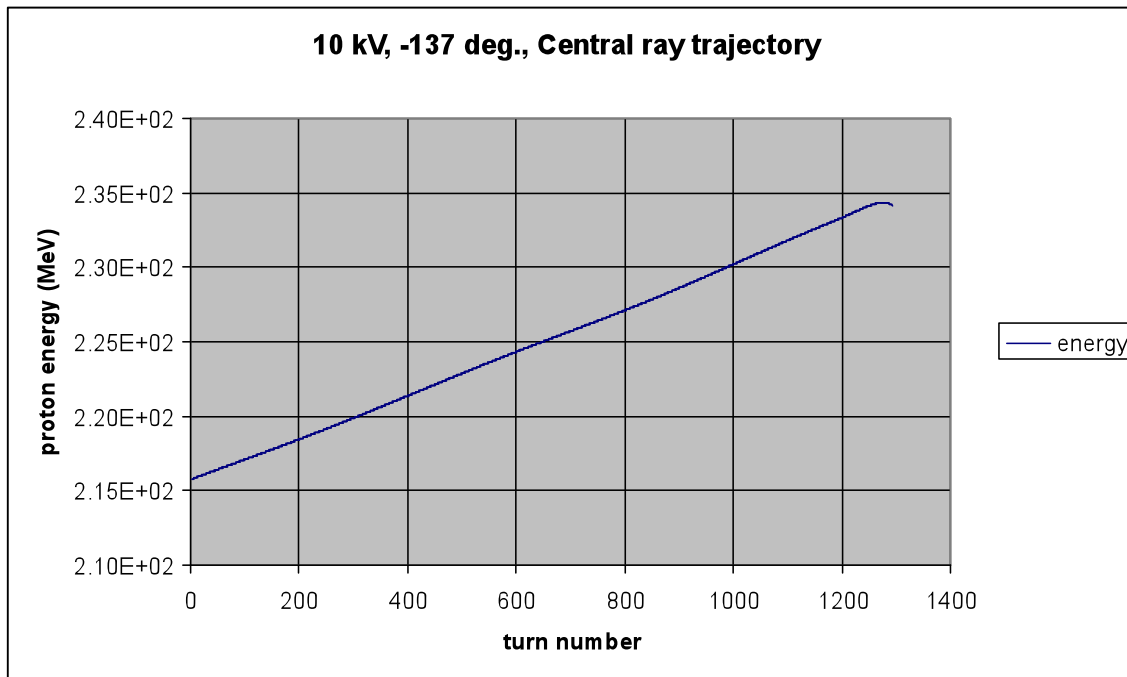
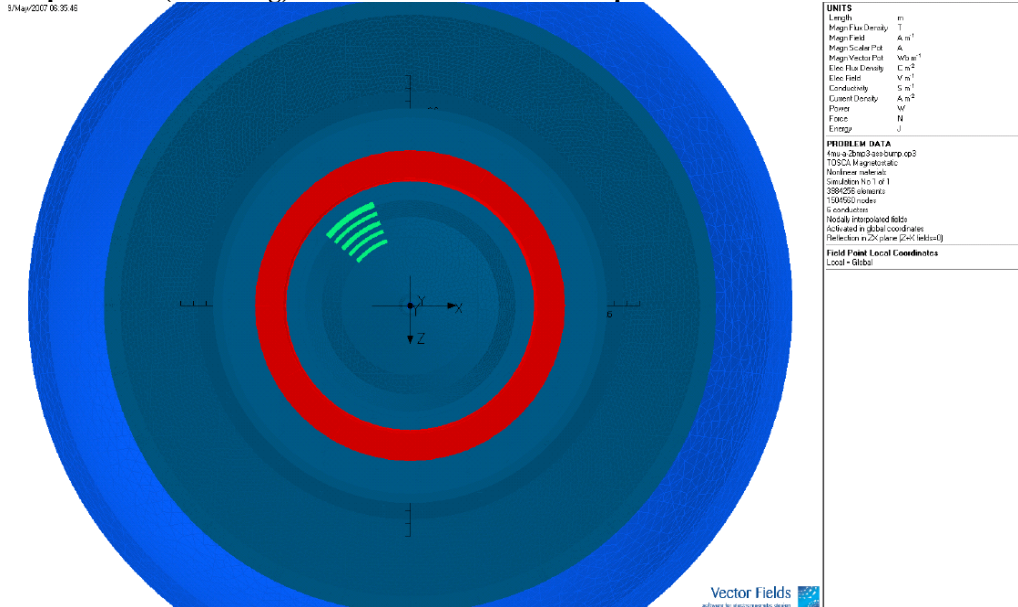


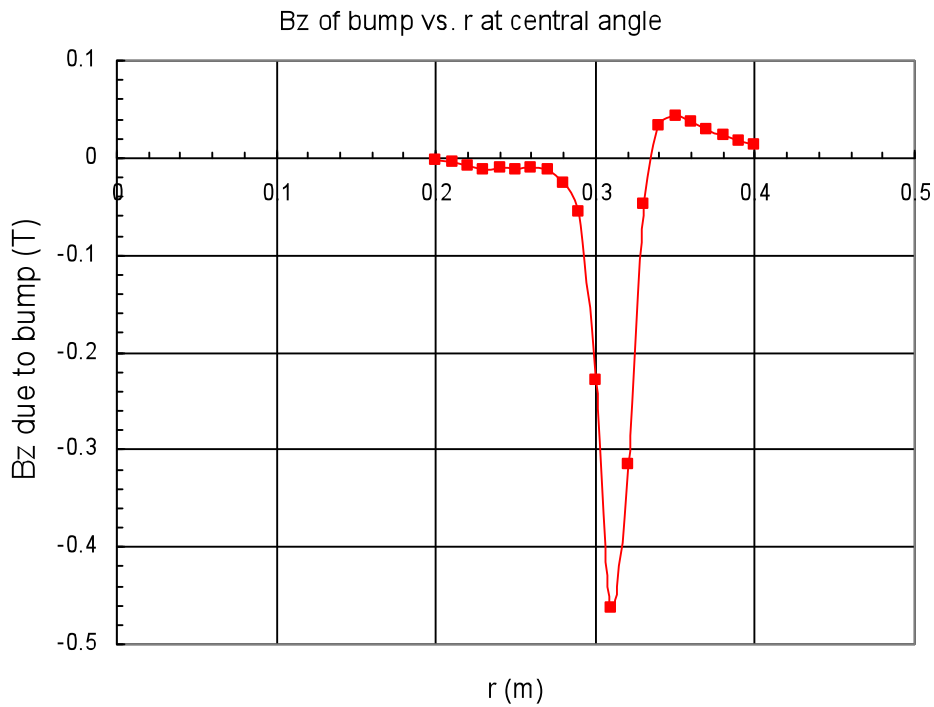
Figure 2. The final extraction energy is only 234 MeV. The bump has been set too far inward. More calculations such as these are required to determine the integral effect of the precessional to permit correct radial positioning of the bump relative to the base synchrocyclotron field to reach 250 MeV.



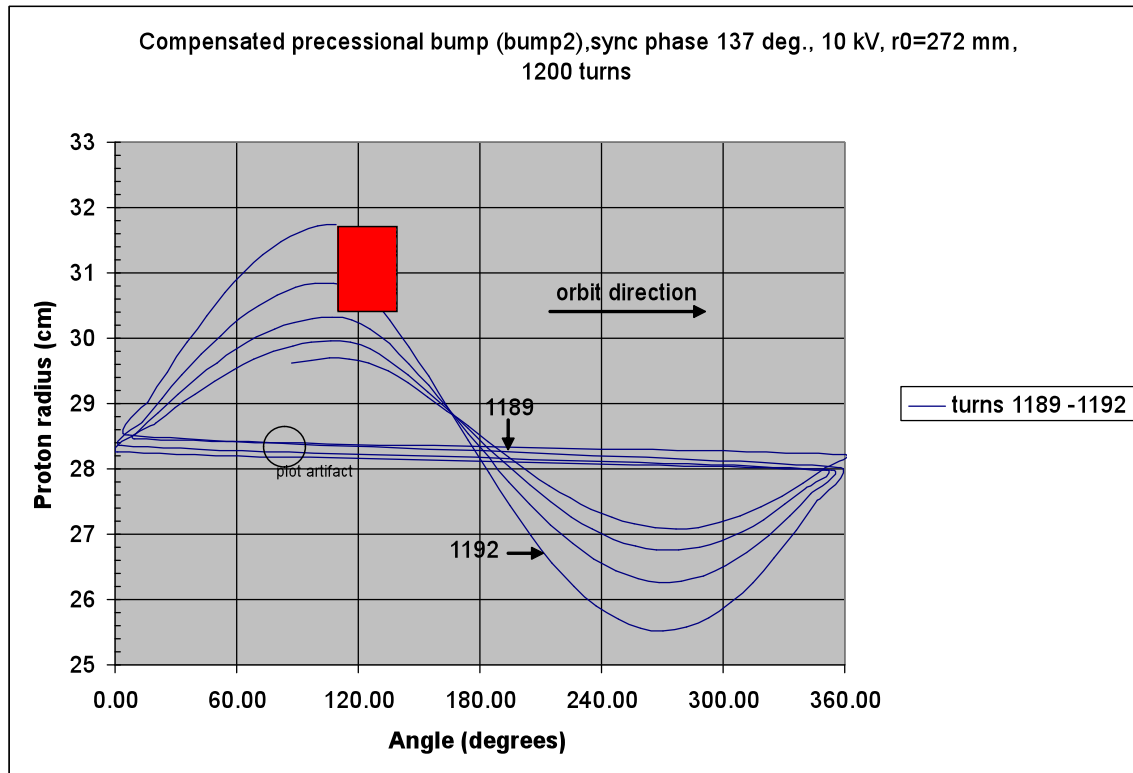
**Figure 3. Plan view of the pole (grey-blue), coil (red), return yoke (blue) and precessional bump (yellow). This image is derived from the corresponding VF model field. The set of smaller field compensation (flattening) elements inward of the bump are visible.**



**Figure 4. the central value of this bump is plotted versus radius. A radius of .272 m (216 MeV) was chosen for the proton acceleration calculation, based upon the still relatively low value of the bump field there. The inward radial flattening field by the compensation elements is clearly evident.**



**Figure 5.** The very first radial oscillation induced by the precessional bump, starting at 298mm (orbit 1189) is sufficient to reach about 1 cm of turn separation 4 turns later. (As in the case of the regenerator, the build up of the radial growth is exponential.) This should provide ample clearance to introduce a magnet channel to begin the redirection of the beam from the machine, as a 7 mm thick septum or less is anticipated. Compare this plot with the completely equivalent Figure 3-6 in Wu 1990. The red box in the figure shows the radial and azimuthal extent of the dominant element of the precessional bump. 4 complete orbits are plotted. [The return lines between orbits, also spanning 360 degrees, are an artifact of the orbit unfolding in the plot, and should be ignored.]



Given the nominal 10 micron separation of turns at high energy in this 9T synchrocyclotron, the above demonstration of the development of adequate turn separation, for a small but feasible bump (it has an engineering design), is seen as the fundamental proof of principle. In addition, observe that it is only about 5% of the axial field level at large radius (.45T/8.4T). For a weak focusing machine, this is almost nothing. It is hoped that this will aid the overall extraction efficiency development in general by minimizing the synchrotron oscillation shifts and overall phase space distortions, and in particular minimize axial losses from resonance coupling.

A number of obvious adjustments are required (energy, bump angle relative to dee for channel entrance space, etc.), and a number of analyses remain. This memo is intended as a back note on this step only. A supporting ‘small perturbation’ analytic treatment for this precessional effect has been developed and will be reported when time permits.

Reference:

XiaoYu, Wu. 1990. Conceptual Design and Orbit Dynamics in a 250 MeV Superconducting Synchocyclotron [dissertation]. [East Lansing (MI)]: Michigan State University. pg 1-29.