Future Directions for Accelerator R&D at Fermilab Workshop
May 11-13, 2009 – Lake Geneva, WI

ALTERNATIVE CONCEPTS FOR A HIGH-POWER PROTON DRIVER*

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Two alternative concepts are discussed:

-- multi-cavity proton cyclotron [1]; and

-- two-beam detuned-cavity proton accelerator [2].

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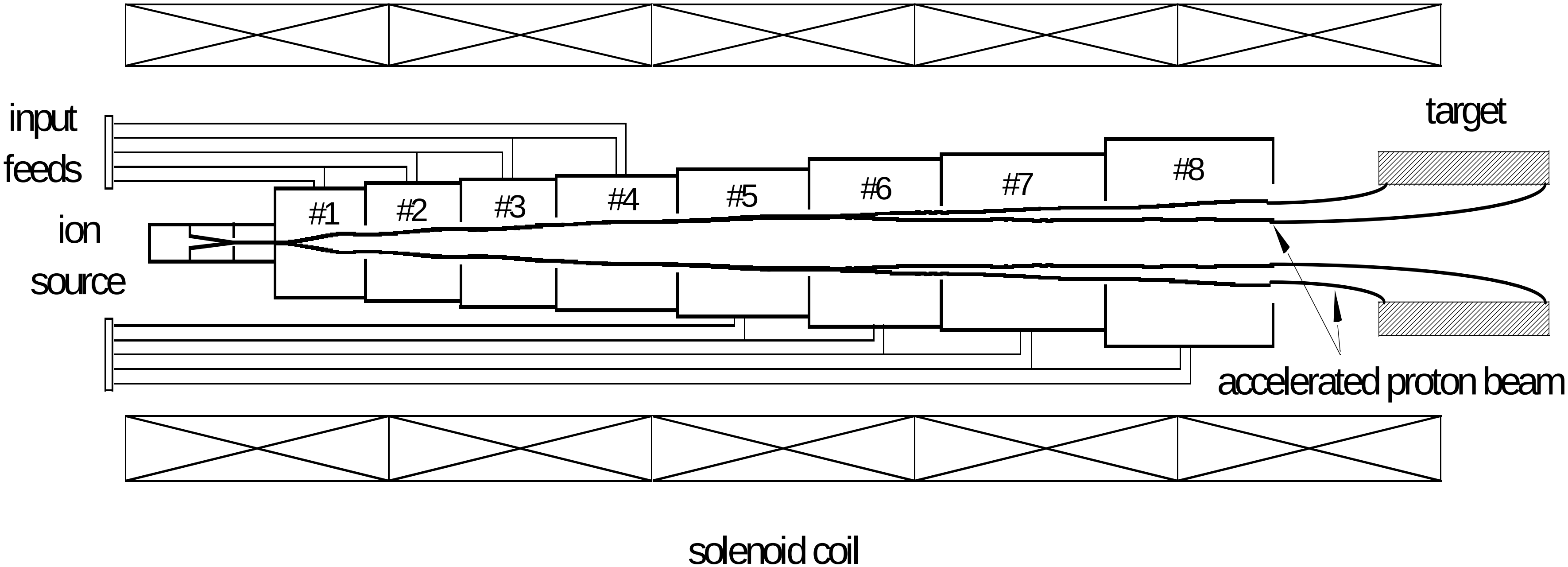
[2] collaborators: S.Yu. Kazakov, Y. Jiang.

*Work supported by US DoE, OHEP and ONP.

Multi-cavity proton cyclotron*



*J. L. Hirshfield, C. Wang, and V. P. Yakovlev, "Multicavity proton cyclotron accelerator," *Phys. Rev. STAB* **5**, 081301 (2002).

VIRTUES AND BLEMISHES FOR MULTI-CAVITY PROTON CYCLOTRON

Virtues:

- high effective acceleration gradient (> 40 MV/m);
- high average current (>100 mA);
- low surface electric fields in the cavities (< 6 MV/m);
- low rms energy spread possible for the accelerated beam (< 0.1%);
- large apertures in the cavities, to guard against beam interception and HOM wake fields;
- beam is self-scanning;
- absence of any need for additional focusing magnets; and
- use of room-temperature RF cavities.

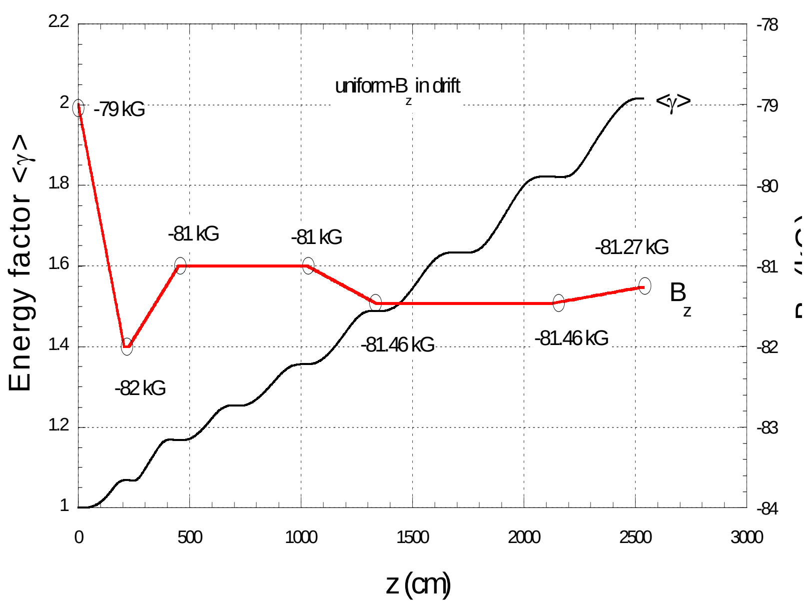
Blemishes:

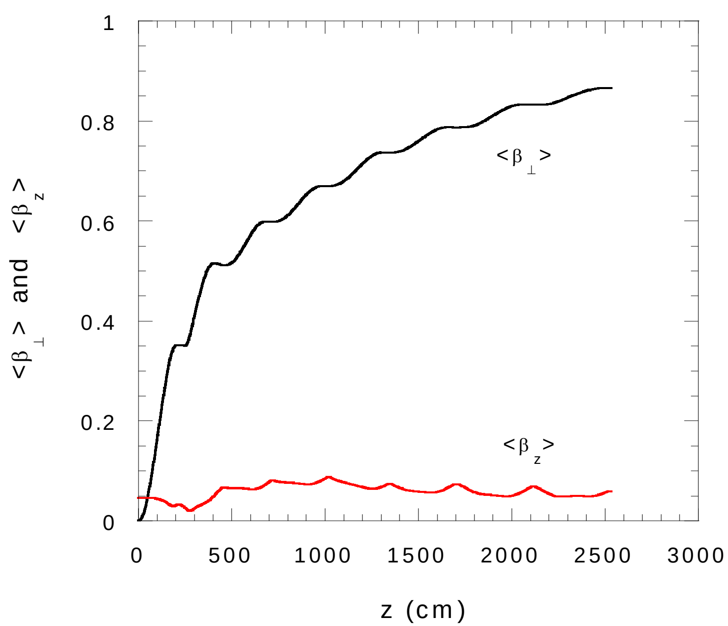
- need for a <u>really</u> big magnet (e.g., 8T, 4-m diam x 25 m long);
- lowered efficiency due to room-temperature wall losses;
- challenging beam transport system needed, from accel to reactor.

Multi-cavity proton cyclotron: How does it maintain phase synchronism?

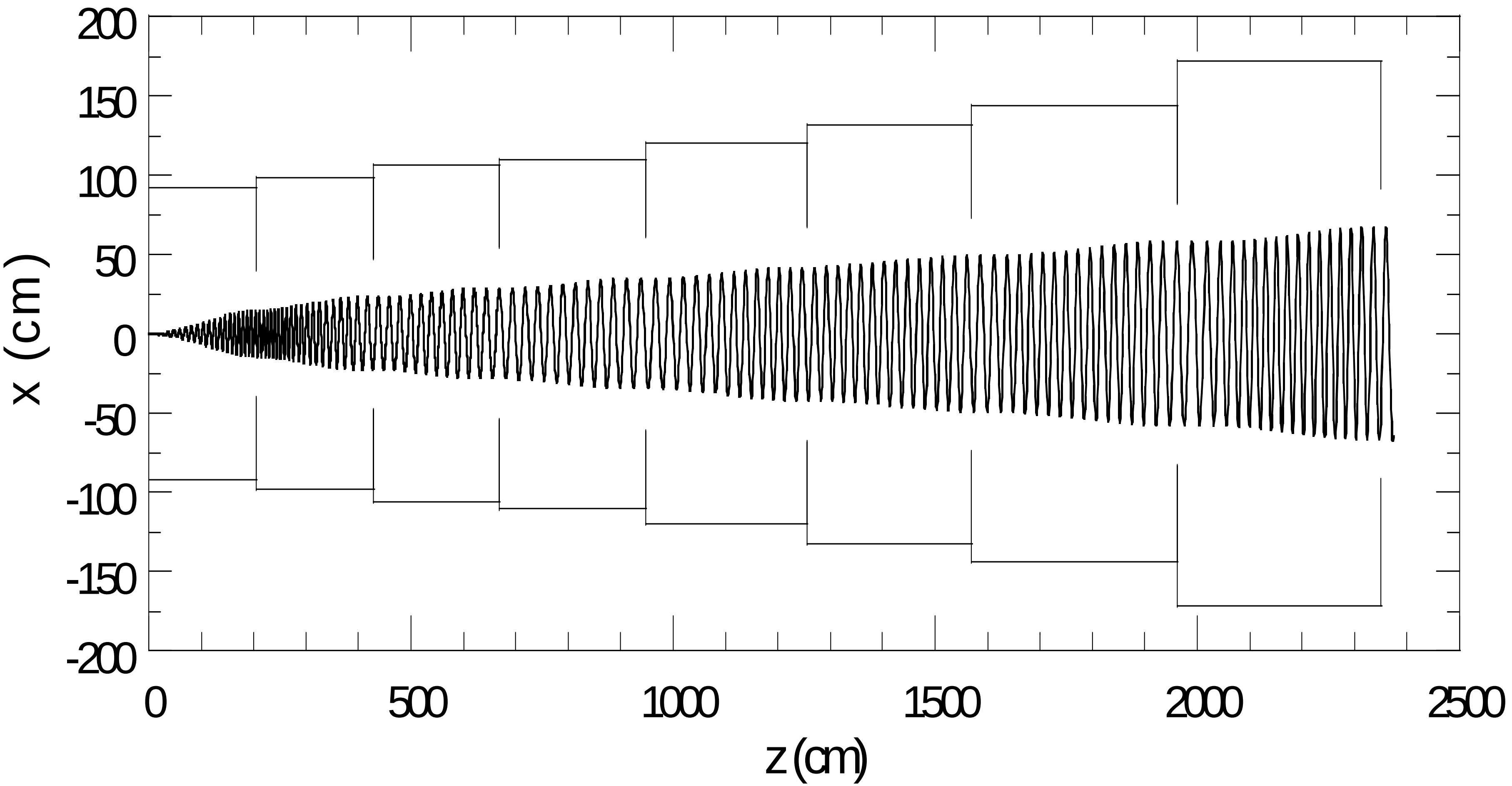
- Cavity resonance frequencies decrease in sequence by Δf;
- Protons are injected at a intervals $\Delta T = 1/(\Delta f)$;
- RF sources for each cavity are phase-locked to the Δf master clock;
- RF phases in each cavity are fixed to optimize acceleration.

At left is shown proton acceleration to 1 GeV in L = 25 m, and B-field.
At right are shown transverse and axial momenta.





Approximate scale for eight-cavity 1-GeV multi-cavity proton cyclotron

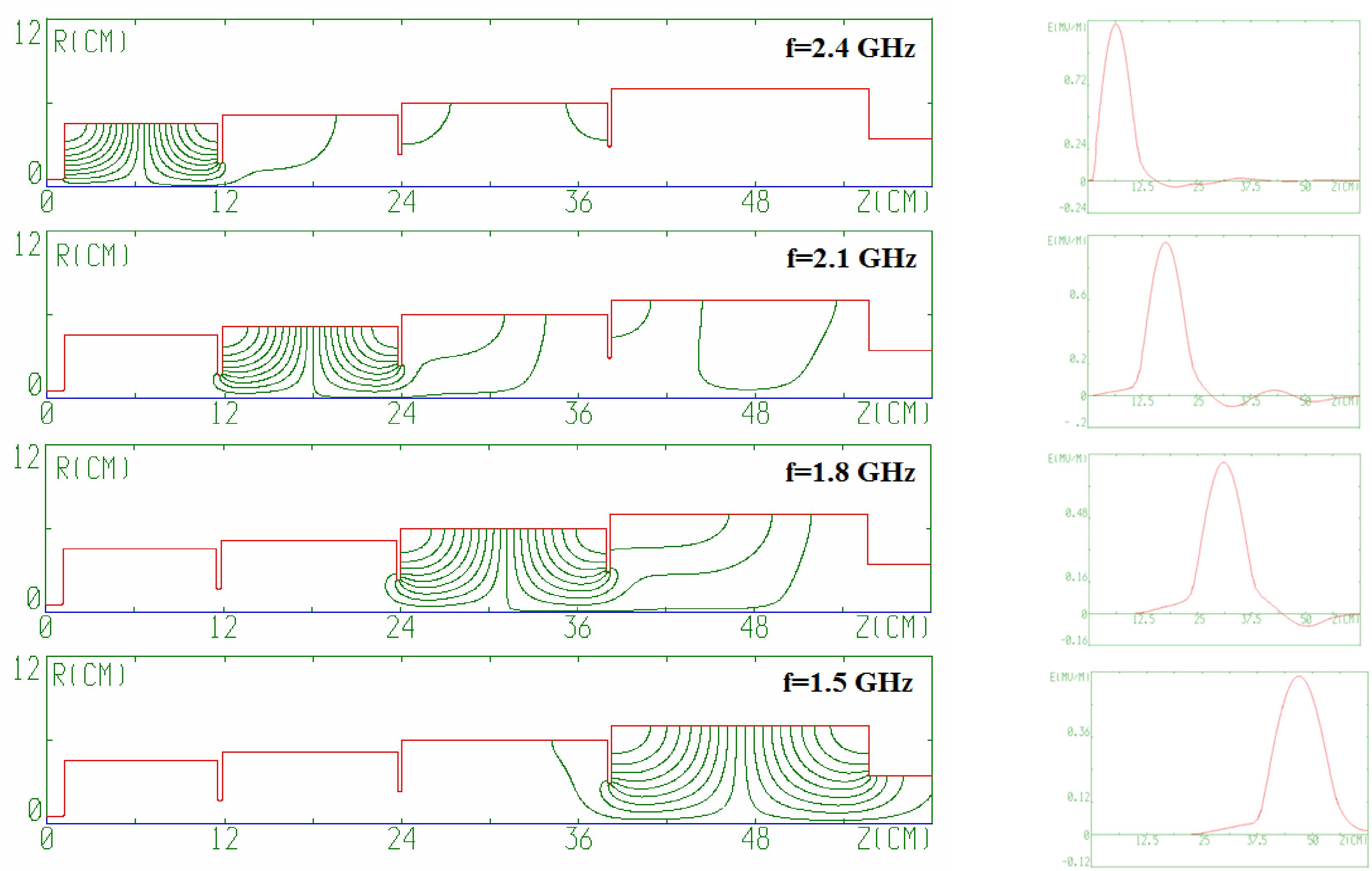


PARAMETERS FOR 8-CAVITY PROTON CYCLOTRON

final beam power = 116 MW, duty = 13.3%, eff. = 66.7%,
wall loading < 50 W/sq.cm., 20-cm tunnels between cavities

cavity resonance freq	cavity radius & length (m)	RF power (MW)	RF relative phase	cavity loaded Q	max surface E-field	energy gain (MeV)
120	0.92/2.06	18.0	0	6.25 e4	7.2	63.6
112	0.98/2.23	15.0	1.40π	2.68 e4	4.0	92.9
104	1.06/2.39	15.5	1.45π	4.36 e4	4.8	80.9
96	1.10/2.81	18.5	1.85π	4.39 e4	4.9	96.1
88	1.20/3.07	24.0	0.50π	4.41 e4	5.1	124.3
80	1.32/3.38	23.0	1.70π	3.67 e4	4.1	135.3
72	1.44/3.92	30.0	0.15π	3.65 e4	4.2	177.0
64	1.72/3.89	30.0	0.55π	3.85 e4	3.9	182.7
total	L = 25.2 m	174.0				952.7

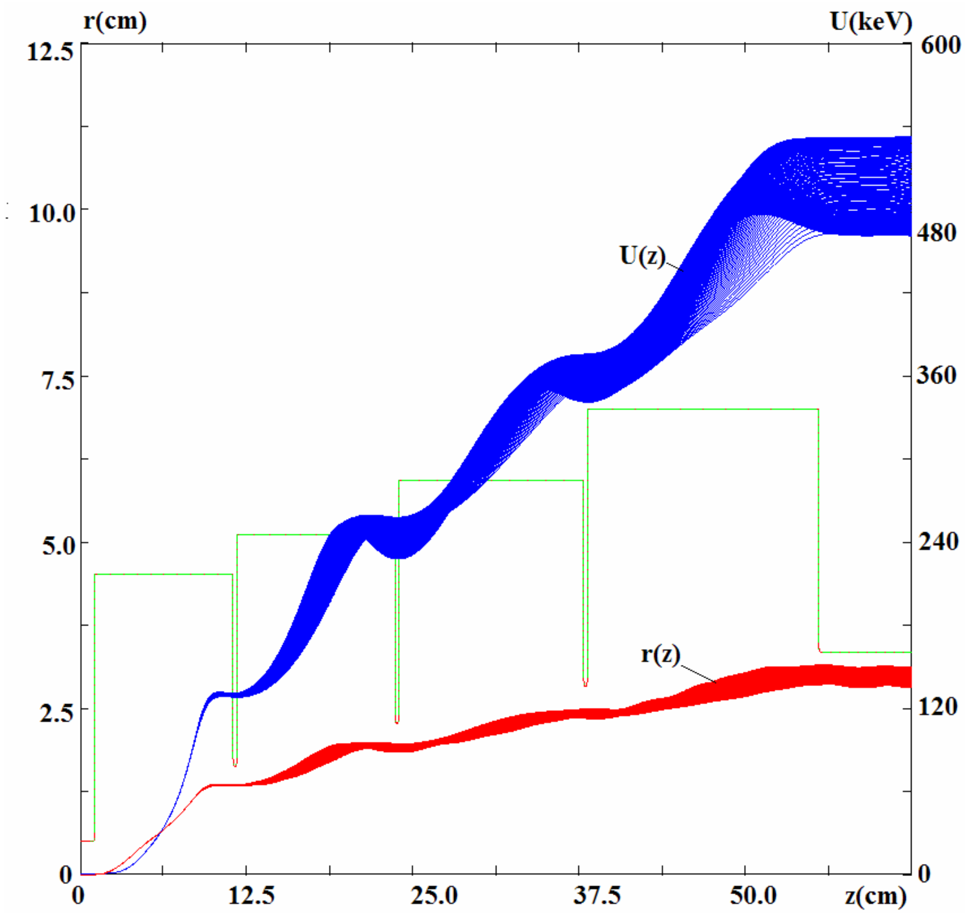
A four-cavity electron counterpart multi-cavity cyclotron is to be built and tested.



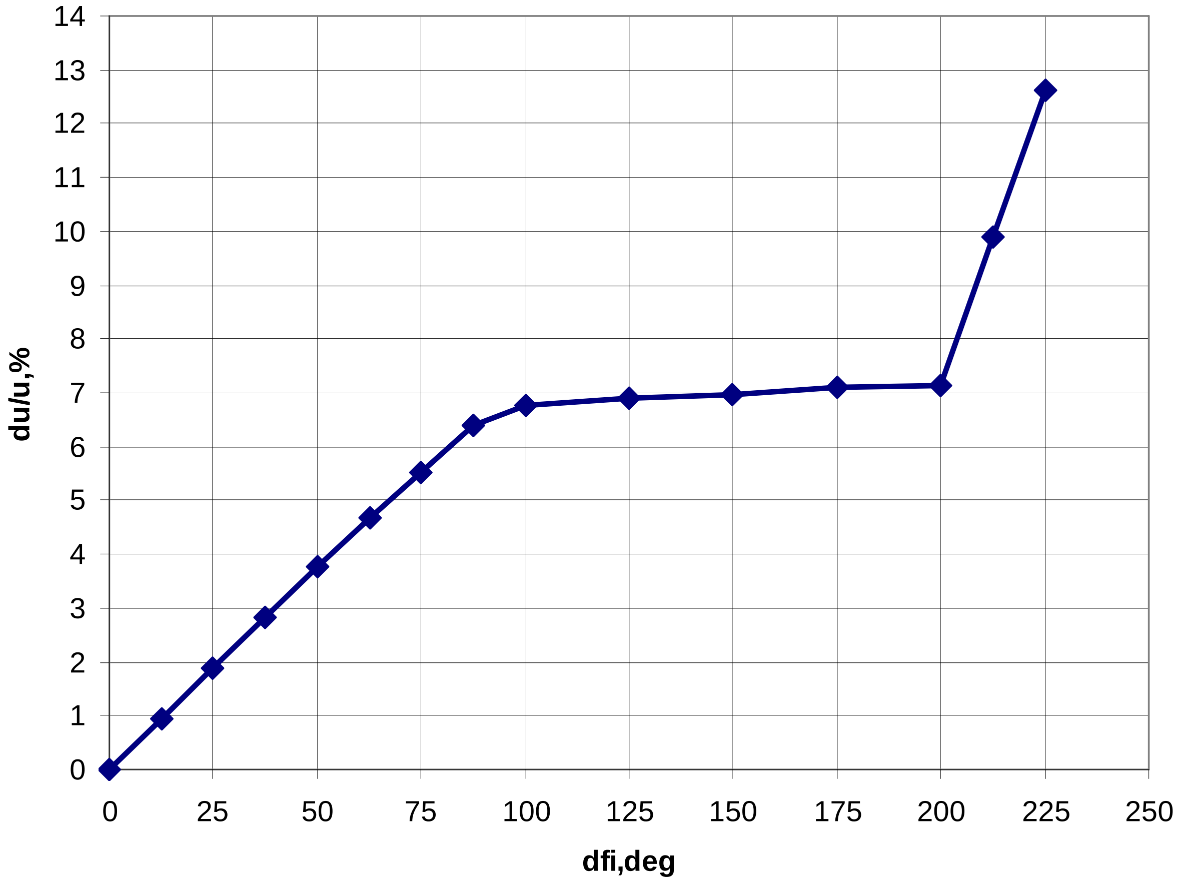
Cavity parameters

TE_{111} cavity	*freq.* GHz	*R* mm	*L* mm	*a* mm	*Q*	*P* *Watts*	ΔU keV
#1	2.4	45.37	104	16.3	24,300	207	119
#2	2.1	51.21	119	22.8	26,000	420	123
#3	1.8	59.24	139	28.4	28,500	367	105
#4	1.5	70.05	174	33.6	30,800	426	147

Particle radii (red) and energies (blue) along the 4-cavity cyclotron *for 200° injection window!!*

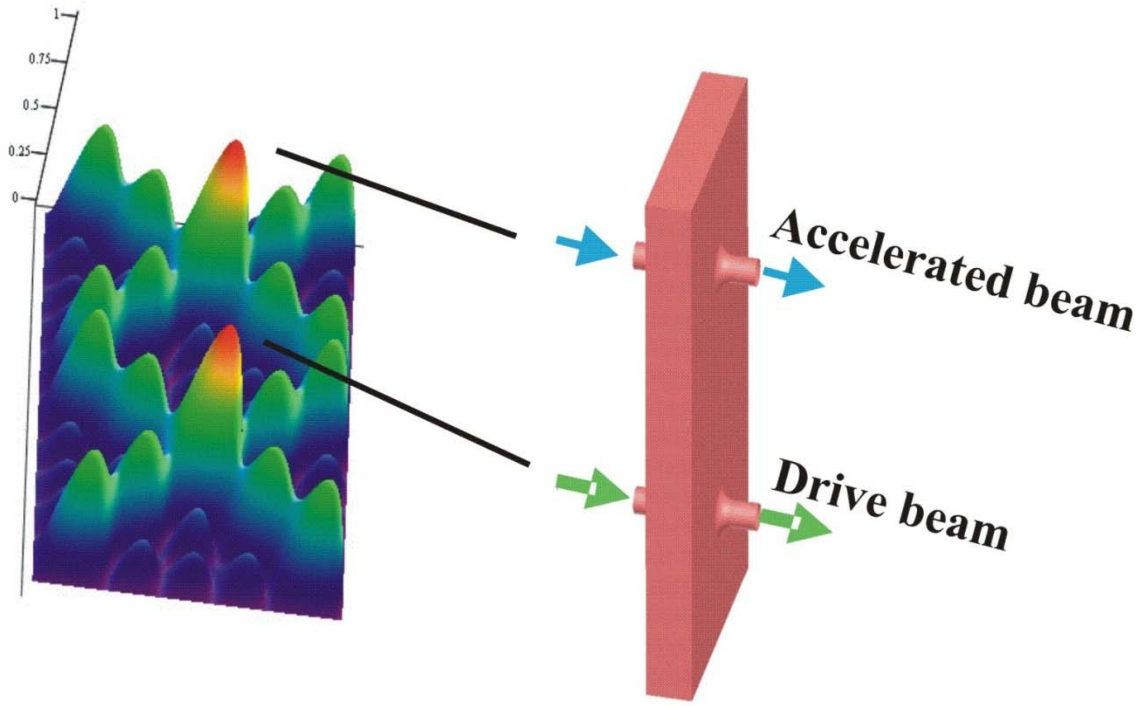


Final energy spread $(U_{max} - U_{min})/2U_{av}$ versus initial injection phase window width



TWO-BEAM ACCELERATION IN A TWO-BOX CAVITY

TM_{nno} modes of a square box have eigenfrequencies nf_1, and two boxes can be joined that share this property. Thus, a train of short bunches at f_1 can excite several harmonically-related modes.

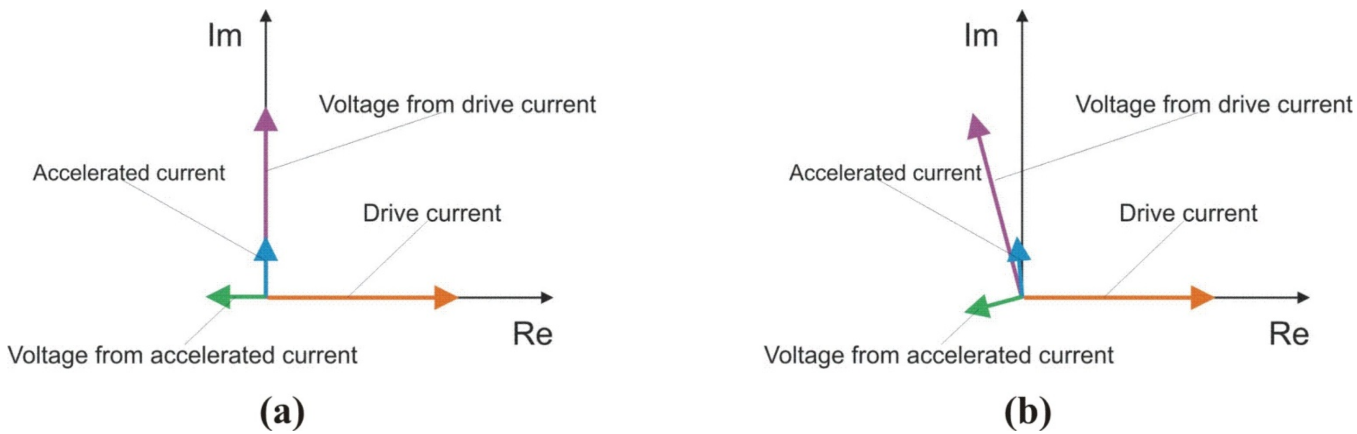


But for this case, the transformer ratio $T = 1$, so this is evidently not useful as an e-e two-beam accelerator.

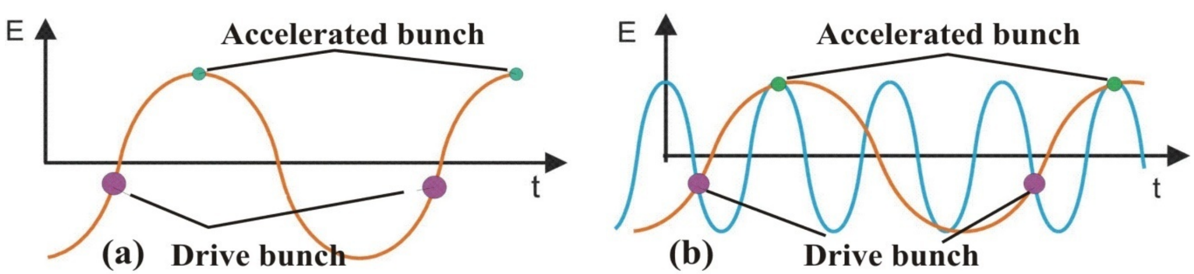
DETUNING ALLOWS T>>1

no wall losses

with wall losses

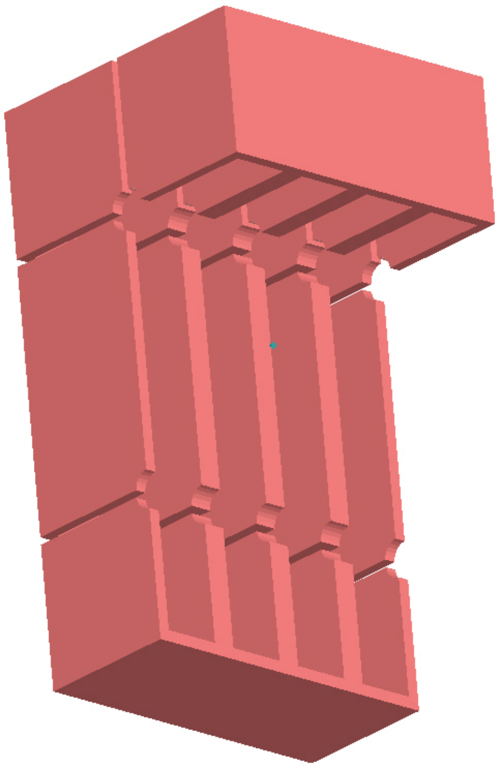


$$T = \eta \frac{I_d}{I_a} = \frac{2Q\dfrac{\Delta\omega}{\omega}\sin\varphi - \alpha - \cos\varphi}{2\alpha Q\dfrac{\Delta\omega}{\omega}\sin\varphi + 1 + \alpha\cos\varphi}$$



TWO-BOX CAVITY MODEL

Assembly of six precision-machined blocks can constitute a cascade of two-box cavities, with slots to suppress/damp undesired modes, and for pumping.



BUT PARALLEL BEAMS ARE NOT EFFECTIVE FOR ACCELERATING PARTICLES (IONS) WITH LOW-β.

HOWEVER ALTERNATE DETUNING (+,-,+,-, etc.) CAN ALLOW EFFECTIVE ACCELERATION

Synchronous normalized velocity β_{sync}, with alternate cavity detuning, is:

$$\beta_{sync} = \frac{v_{sync}}{c} = \frac{\beta}{1 \pm \frac{\varphi}{\pi} \frac{\lambda}{\Lambda}}$$

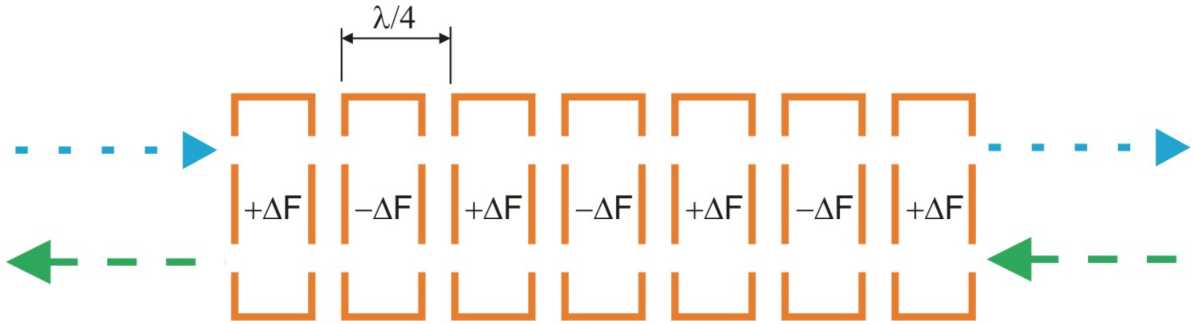
where β is drive-beam speed (~1), φ is detuning, λ is wavelength, and Λ is cell length (gap + wall). (+) sign in denominator is for parallel beams, and (-) sign is for anti-parallel beams. Low negative β_{sync} can be achieved for anti-parallel beams and small gaps with $\varphi \sim \pi/2$.

ALTERNATE DETUNED CASCADE OF CAVITIES AS AN ACCELERATOR STRUCTURE

Amplitude of lowest-order backward travelling synchronous *E*-field:

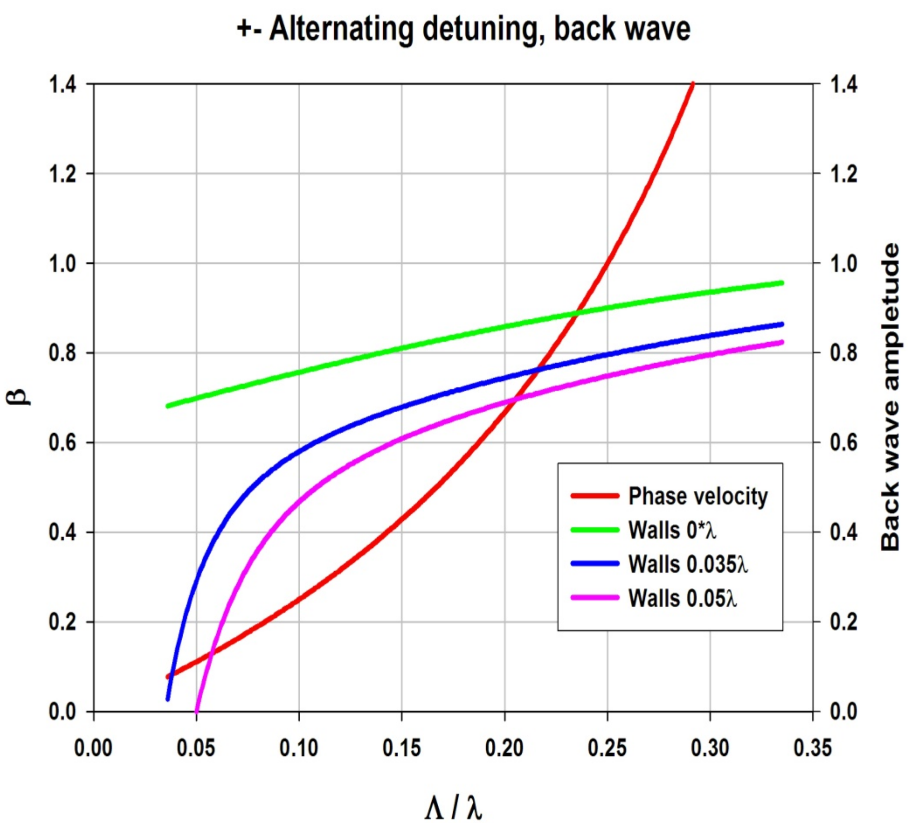
$$\frac{E_1}{E_o} = \frac{2\beta\lambda}{\pi(2\Lambda - \beta\lambda)} \sin\left[\pi G\left(\frac{1}{\beta\lambda} - \frac{1}{2\Lambda}\right)\right] = \frac{G}{\Lambda}\frac{\sin\Theta}{\Theta}$$

where $\Theta = \pi G / \lambda\beta_{sync}$, with G = gap width. When $\Lambda = \lambda/4$, $\beta_{sync} = -\beta$, and when $\Lambda < \lambda/4$, $\beta_{sync} < -\text{mag}(\beta)$.

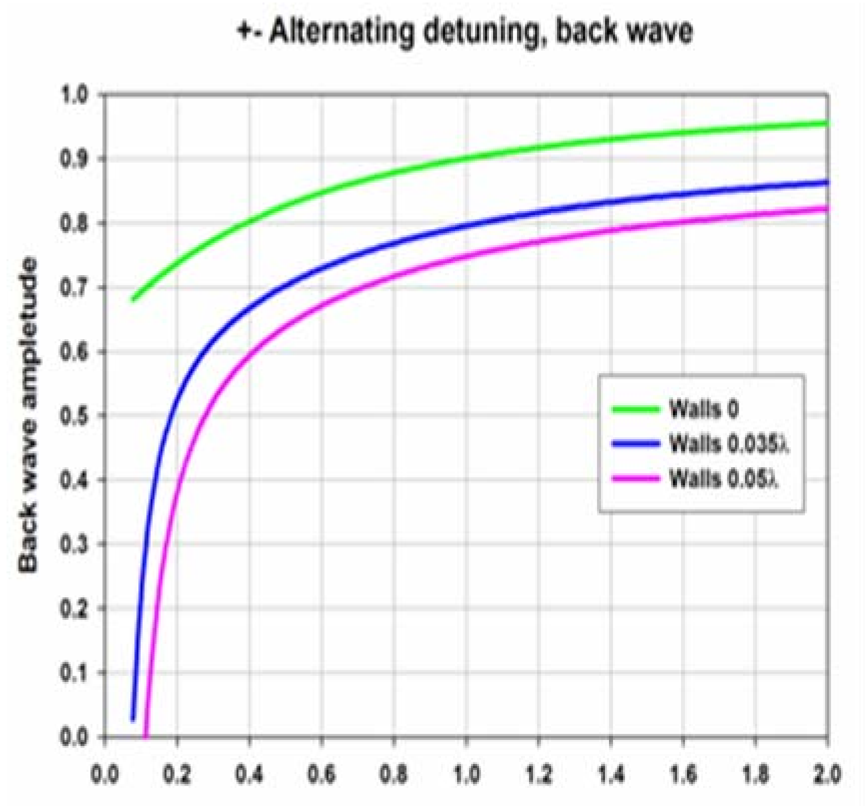


SYNCHRONOUS SPEED – β_{sync} & AMPLITUDE

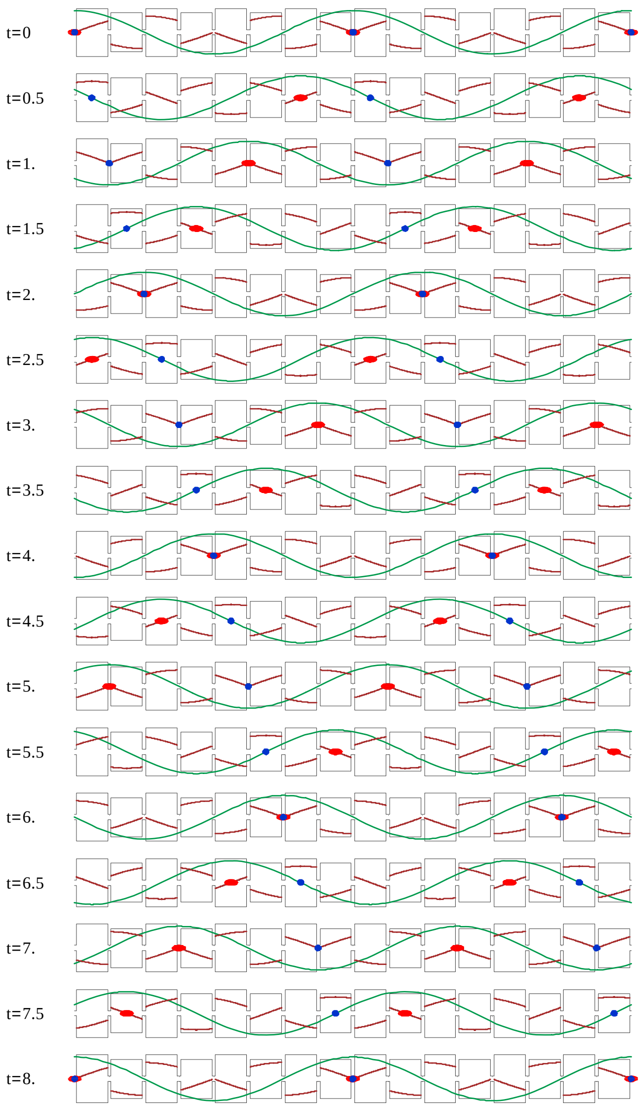
β_{sync} versus cavity width Λ/λ



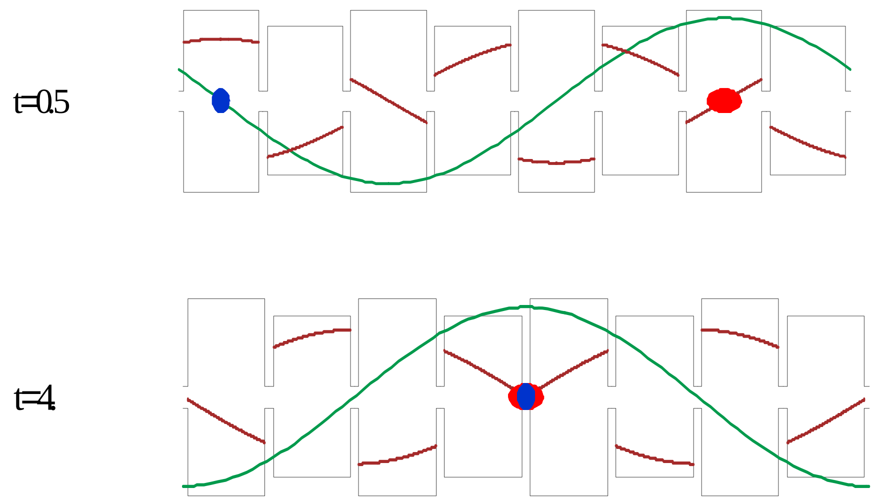
amplitude versus β_{sync}



Snapshots of E_z field amplitude as time develops; red dots are drive bunches moving left with $\beta = 1$; blue dots are test bunches moving right with $\beta = 1/3$.



Note that field reaches max just as test bunch gets to cavity center, and that field passes zero just as drive bunch reaches cavity center. Also note bunches passing through one another.

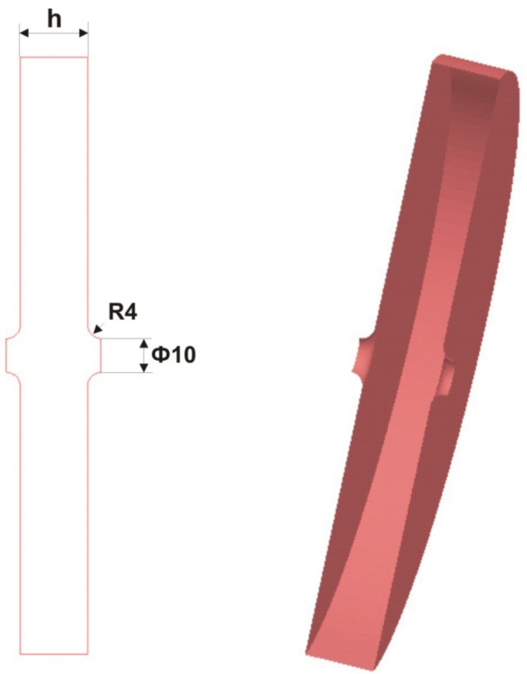


Tentative parameters for a 1-GeV, 10 MW (average) proton driver, with active length 27 m. (1.3 GHz)

interaction efficiency	50%		70%	
proton beam current	1.2 A pulsed		2.8 A pulsed	
duty factor	0.0083		0.0036	
average wall dissipation	22 W/cm2		10 W/cm2	
transformer ratio	5:1	10:1	5:1	10:1
e-beam drive energy	210 MeV	110 MeV	210 MeV	110 MeV
e-beam pulse current	12 A	24 A	20 A	40 A
e-beam pulse power	2.52 GW	2.64 GW	4.2 GW	4.4 GW
electron charge/bunch	9.23 nC	15.4 nC	18.5 nC	30.8 nC

PRELIMINARY EFFICIENCY RESULTS FROM SELF-CONSISTENT CALCULATION

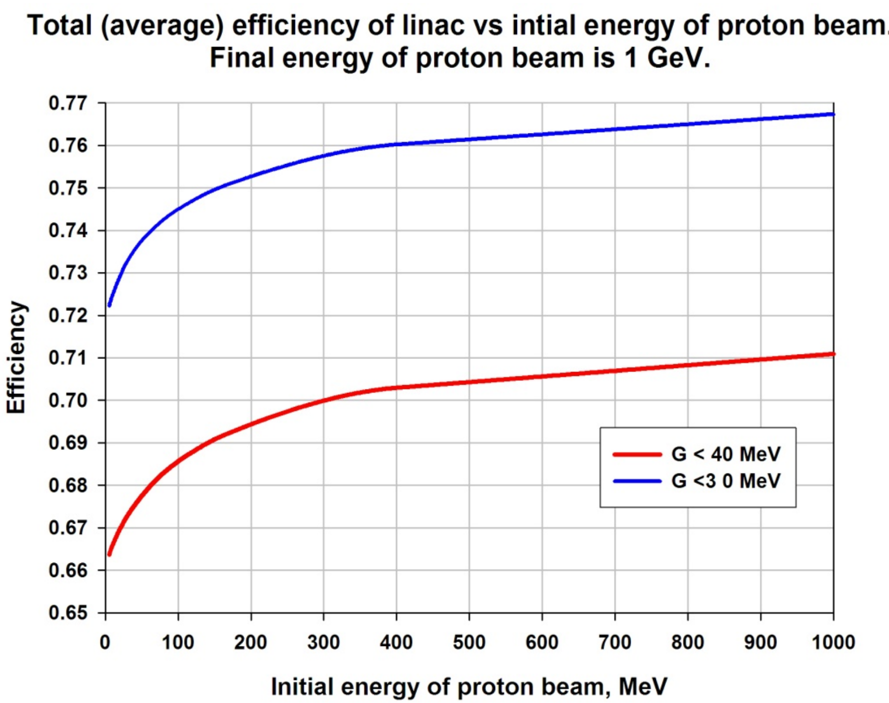
model of cavity



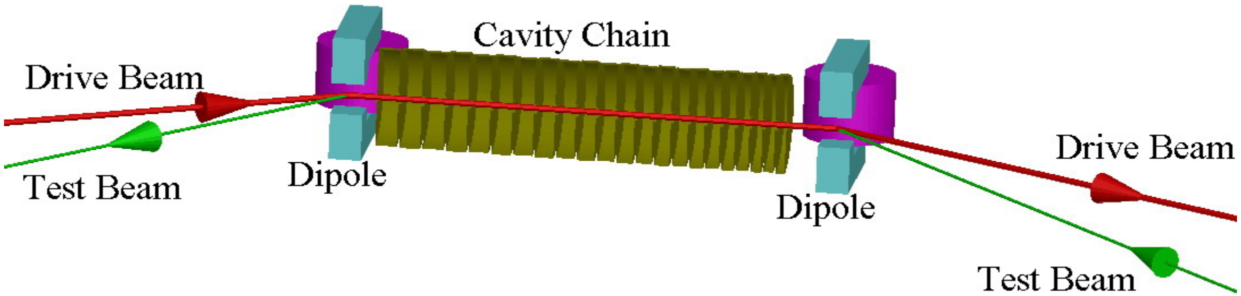
(β = 0) 0 < h < 49.7mm (β = 1)

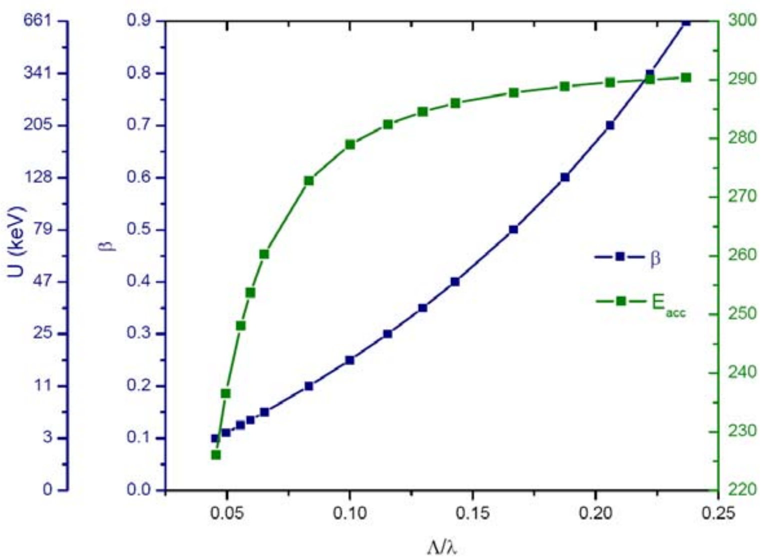
f = 1.3GHz*(1+χ)   χ – detunung

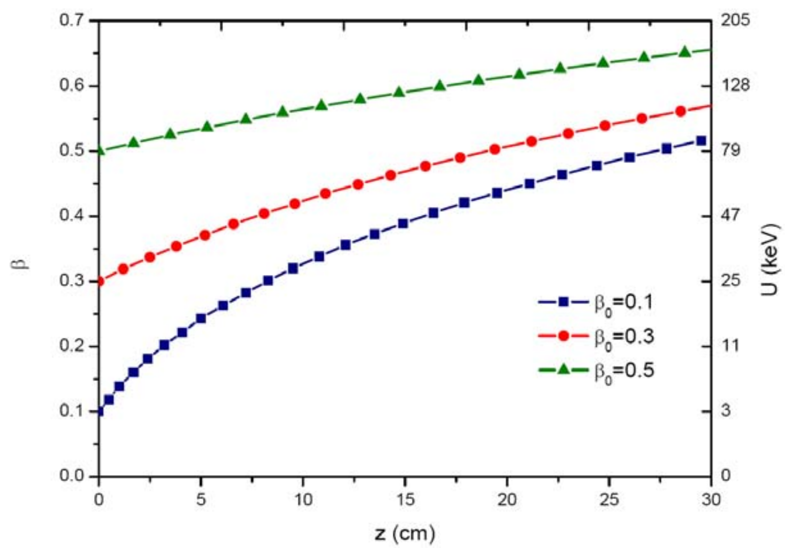
efficiency for 1 GeV beam



An electron counterpart accelerator can be built, using an available 6-MeV S-band RF gun (thermionic cathode).







Values in graphs are based on 0.1 nC/bunch from the Yale S-band RF gun.

COMMENTS

- Two room-temperature proton accelerator concepts have been described that may hold promise for production of a high-power beam for ADS.

  multi-cavity cyclotron:

  moderate eff. – increase # of cavities, injection window?

  large magnet – increase B to reduce coil diam and length?

  not a candidate for SCRF.

  detuned cavity structure:

  electron/proton mutual focusing?

  possible SCRF design?

  much more work to do.....

In either case, for ADS, waste heat may be combined with reactor heat to improve system efficiency.

- The indulgence of the audience is appreciated.