Status Report – RF Linac Group

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RF Linac Group Activities

- Look at, but did not pursue 100 Mhz DT linac and single-bunch pulsed drift tube device.
- Instead, went for a solution capable of higher current made possible by very high field superconducting solenoids
  - Still need parallel beamlets to deliver 1 microcoulomb
  - Developed three scenarios differing in energy ramper
  - Alternate solution with a single beam and stacker ring
- Took a look at ultimate charge density for linac bunch

Charge Density

- Looked at several approaches
  - Maschke formulas (several of them, all different scalings, reflecting different relationships between implicit variables).
  - Experience with multiparticle simulations
- All give charge densities in the range of a few times 10^{10} /cm^3 for linacs in the frequency range looked at here.
  - Formulas and simulations were in pretty good agreement
- Ion source turned out to be the current limit in our case, for a useable emittance.

Basic Parameters

_ 1 microcoulomb of Ne+1, compressed to 1 nsec

_ Based on the debunched linac energy spread, compression of 200 feasible

_ 5 amps at 200 nsec gives required charge

_ 300 mA/beam gives about 16 parallel beams

_ 60% capture in linac requires 500 mA/beam from the ion source

_ 50 Mhz selected for RF, optimum not searched

Linac Lattice

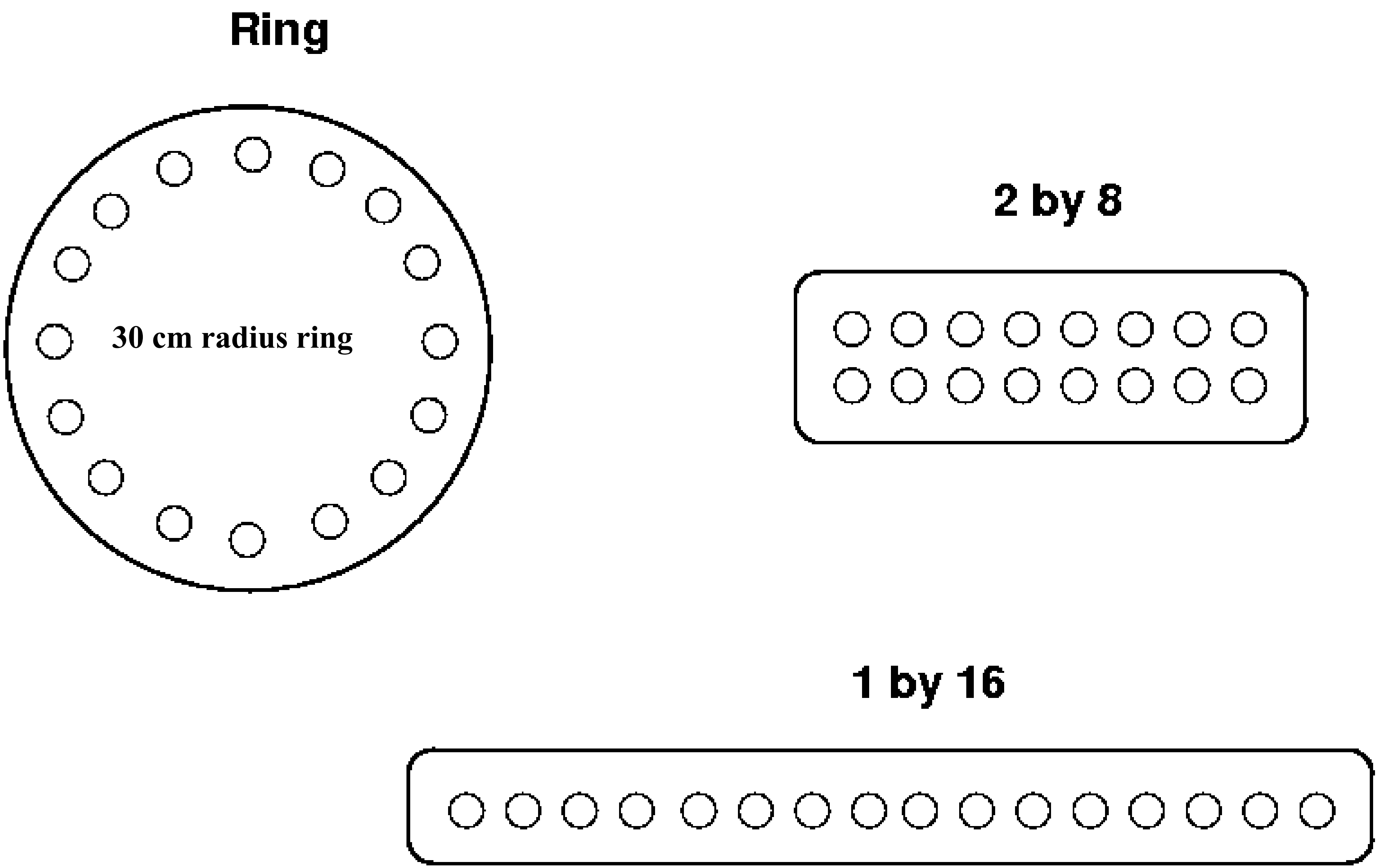
- Linac based on 50 Mhz modules with 2-3 gaps and no focusing, based on a TE mode structure (Interdigital H-mode cavity with drift tubes)
  - 1 or 16 parallel beam channels, various distribution
  - 25 cm long, 1-1.5 MV energy gain per cavity
- Between linac sections sits a 15 T SC solenoid
  - 1.5-2 cm bore radius, 5.5 cm overall radius
  - 15 cm long
  - Dimensions derived from existing designs

Ion Source and Number of Beams

- 1 microcoulomb, 200 nsec, 60% bunching efficiency requires 500 mA in 16 beamlets
- Each of 16 sources is a 7-hole multiaperture extraction geometry with a 100 kV voltage across a 7.1 mm gap.
- Sources spaced 12 cm apart
- Emittance of each source 0.09 pi mm-mrad
  - 1 times rms normalized
- Rest of 2 MV injector made up in column with parallel beams

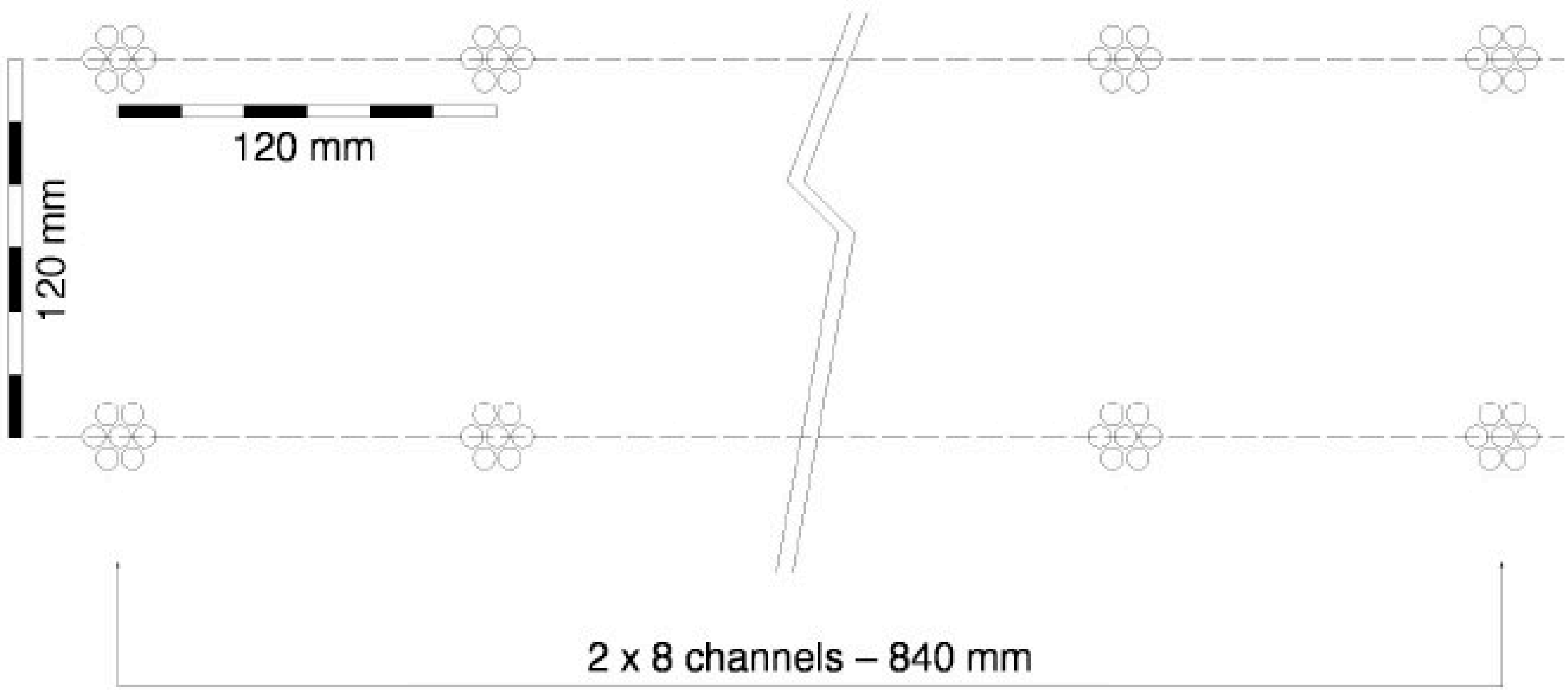
Configurations of 16 beams

Spacing between centers is 11-12 cm

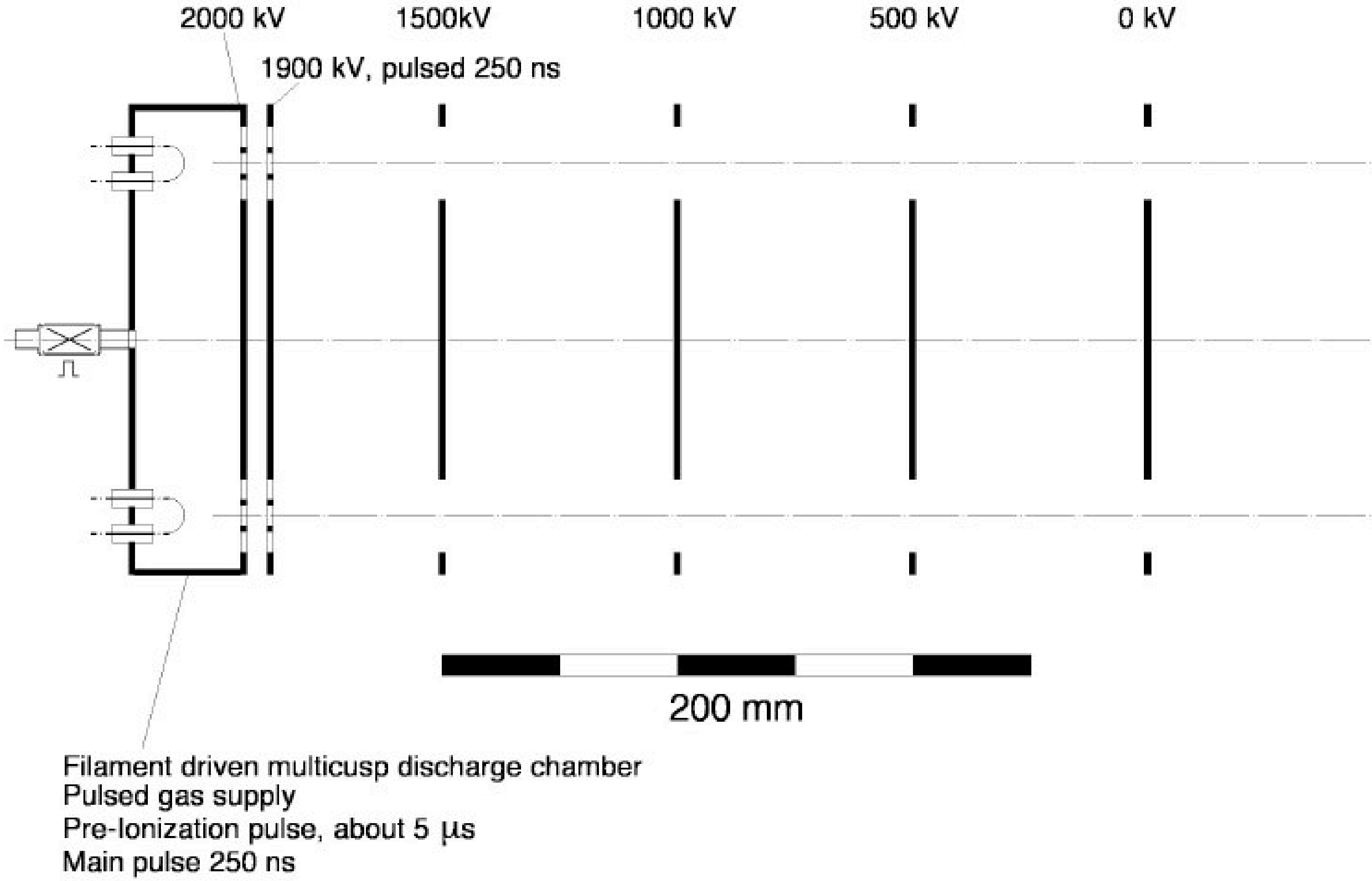


Worksheet based on experimental measurements

Ion Extraction Worksheet					*RK: 041028*			
HEDP workshop, very short extraction pulse (2x less gap assumed)								
					Bold: Result of calculation		given	
Single Aperture								
					Reduced gap		x/x'	
Current	Voltage	Aspect Ratio	Charge State	Atomic Weight	d min	R	Eps n rms	j
[mA]	[kV]			[amu]	[mm]	[mm]	[pi mm mrad]	[mA/cm^2]
74.54	100	0.5	1	20	7.1	3.54	0.014	47.5
Multi-Aperture								
	100		1	20		14.14	0.087	
Channel Values								
Current								
[mA]		# of holes						
521.75		7						
Multi-Channel, round								
	2000		1	20		452.5	8.26	
Global Values				*Minimum*				
Current			Circumfer.	*Lg. Radius*				
[mA]		# of channels	[mm]	[mm]				
8348		16	452.5	72.01				



Beam Channel Pattern for RF Linac Scenario

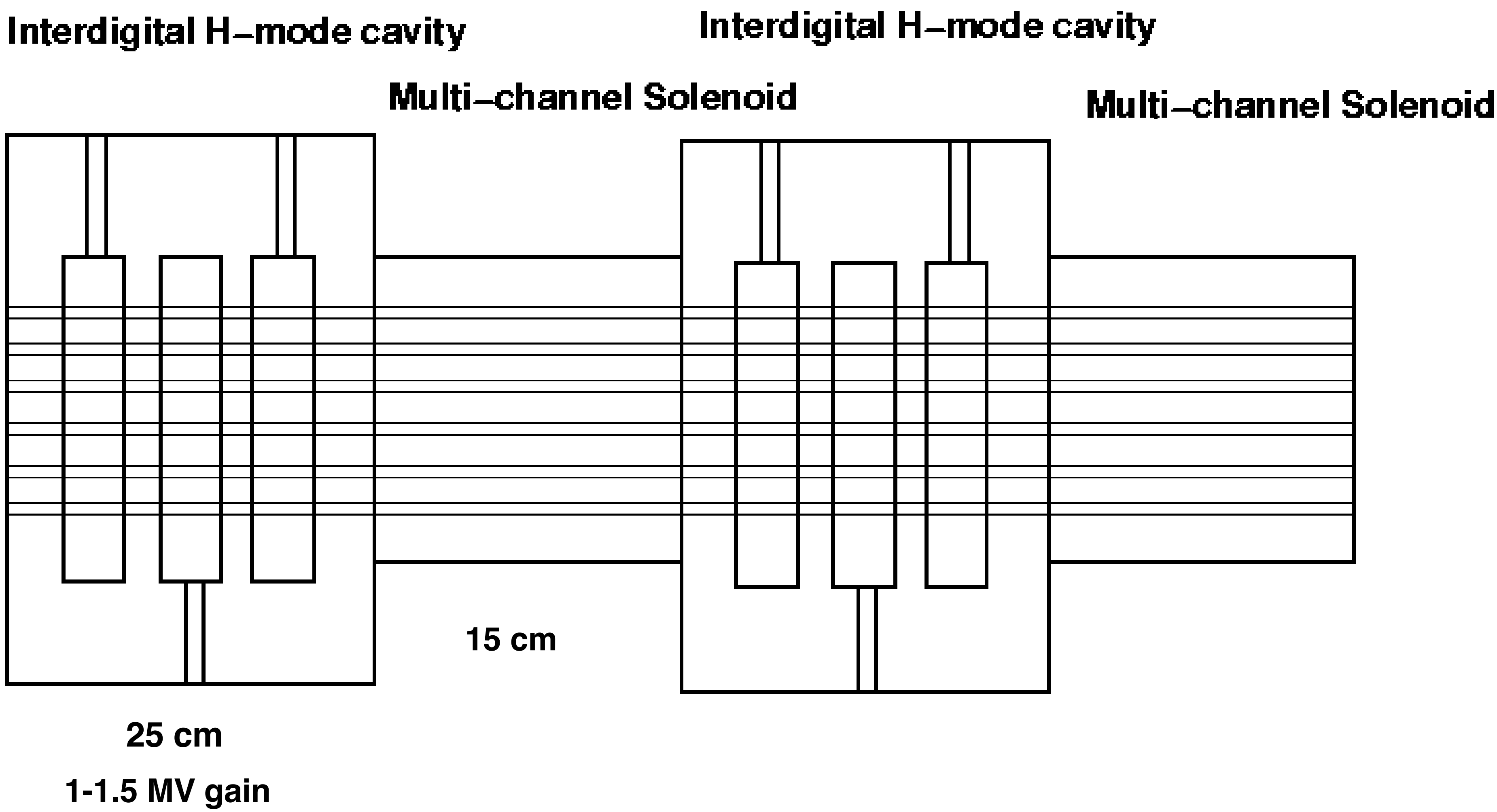


Ion Source, Extraction, and Injection Column
112 Beamlets, total, in 2x8 channels

Buncher and Linac

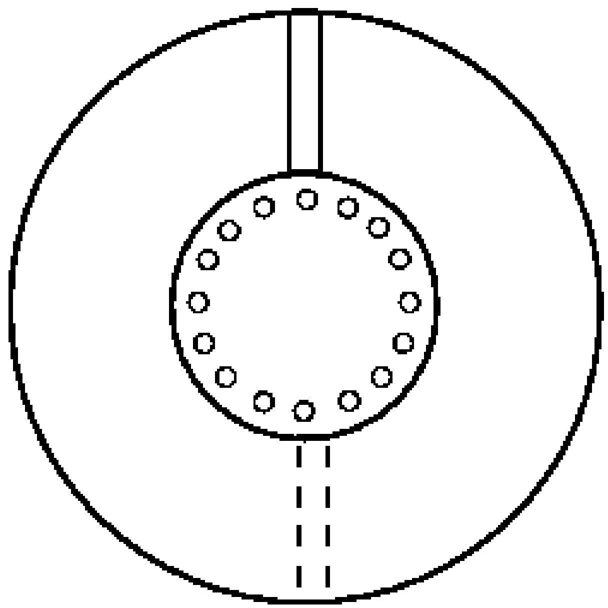
- Kick buncher (not designed, but using same cavity design as linac) with 60% capture into linac
- Linac a lattice of 50 Mhz cavities and solenoids
  - 25 cm long cavities, 1-1.5 MV energy gain
  - 15 cm long, 15 T SC solenoid, based on commercially available devices, closed-packed in array with cold bore.
- Short linac sections, coupled with energy tilt cavity or core allows *continuous output energy variation*

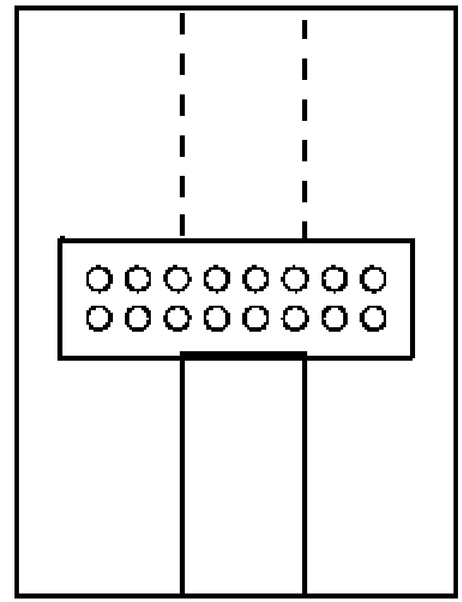
Linac lattice



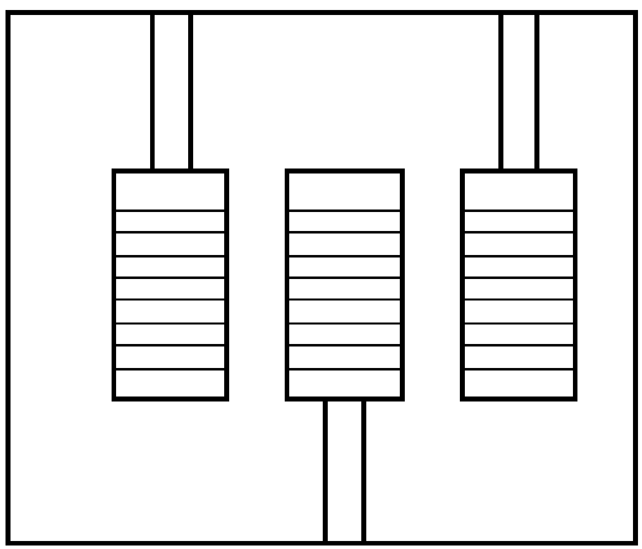
Interdigital H–mode resonator configurations

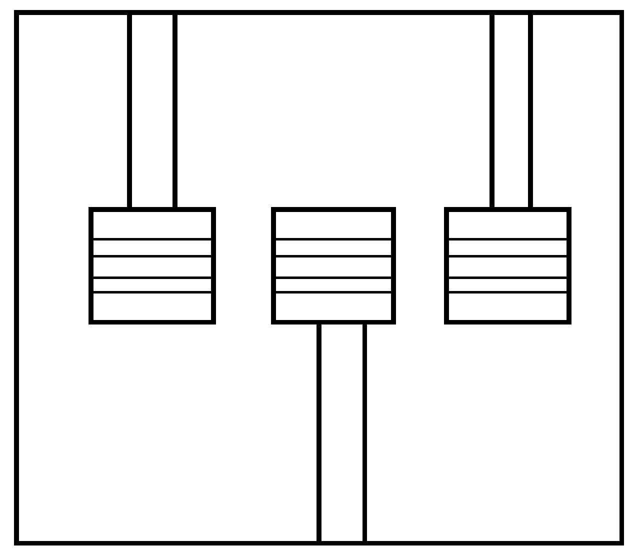
Ring Beam





Planar Beam





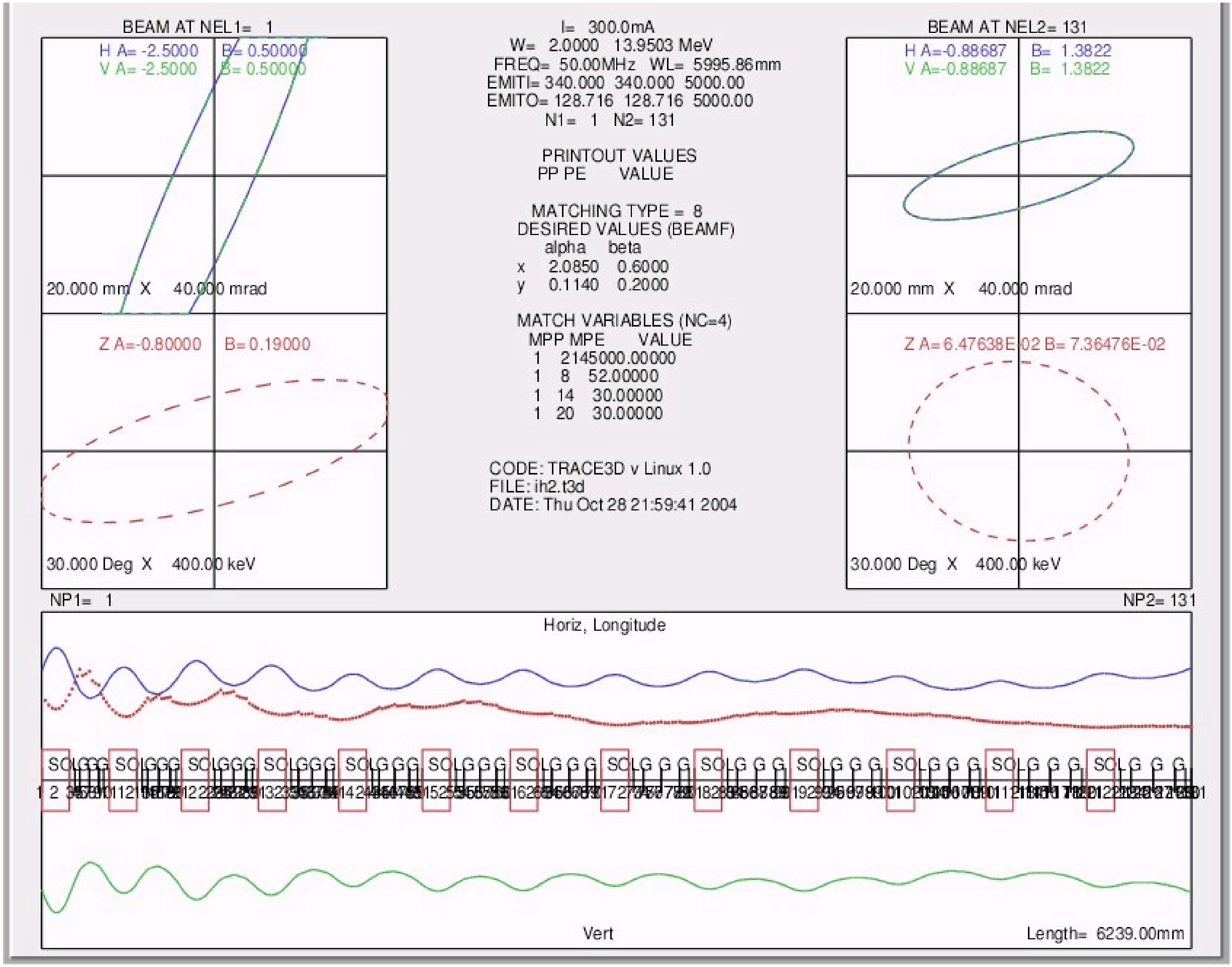
Neon^{+1} Beam at Linac Exit

- 20 MeV (1 MeV/amu), beta = 0.046
  - Phase width ~ 20 degrees
  - Energy spread ~ +/-0.6%
- Transverse emittance growth a factor of 3
  - Estimated from DTL studies, may be less
  - 3 pi mm-mrad, 1 times rms, normalized
  - Lower input emittance does not significantly improve output emittance
- Beam simulated with Trace-3D to check matching and current dependence
  - No emittance growth, loss mechanism

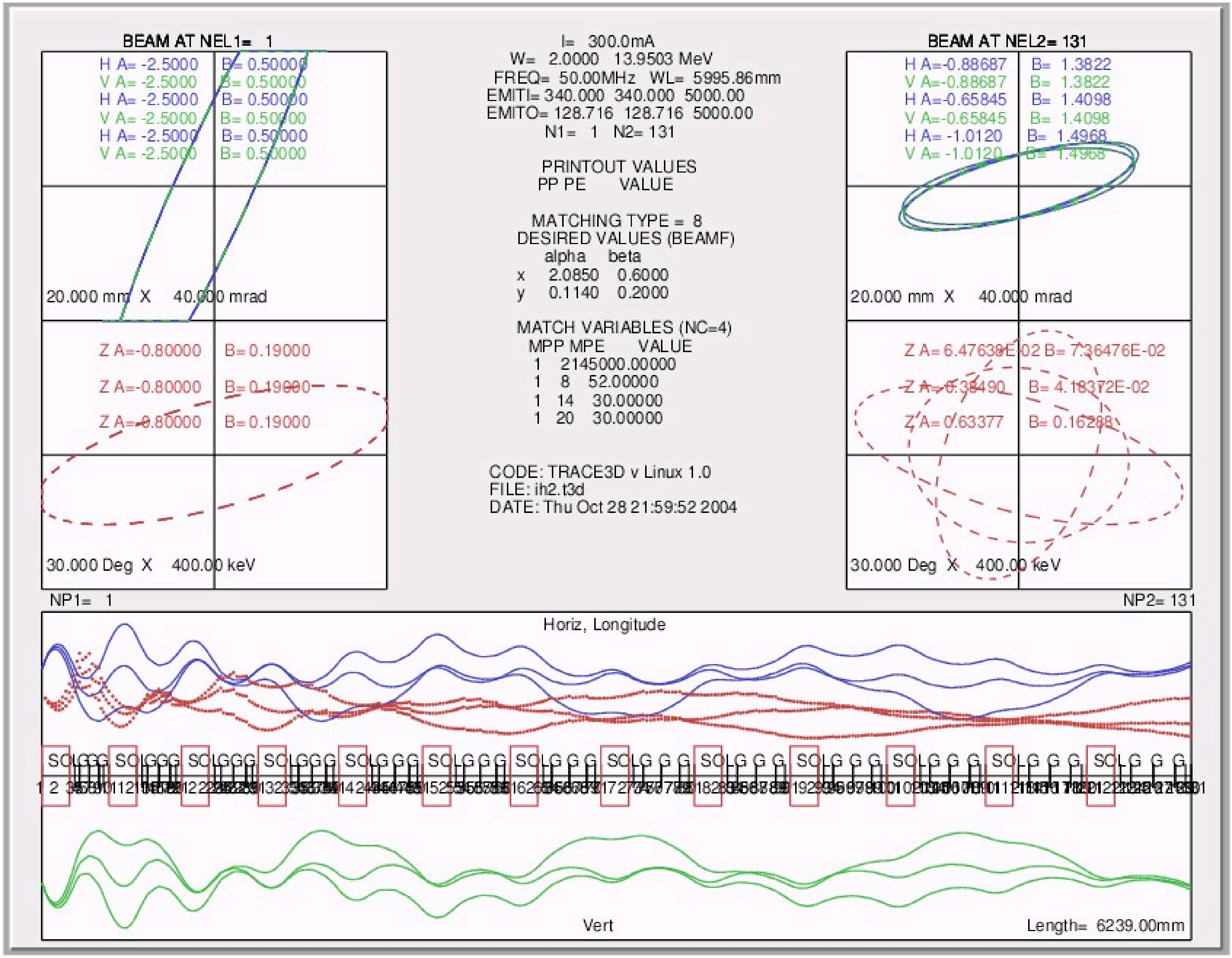
TRACE 3D simulations of the Linac

Beam	Ne^{1+}
Input energy	2 MeV, 0.1 MeV/u
Output energy	20 MeV, 1 MeV/u
Current	300 mA
Frequency	50 MHz
Length	8.6 m
Number of resonators	17
Voltage per gap	400-500 kV
Field in the solenoids	15 Tesla
Eff. Length of the solenoids	15 cm

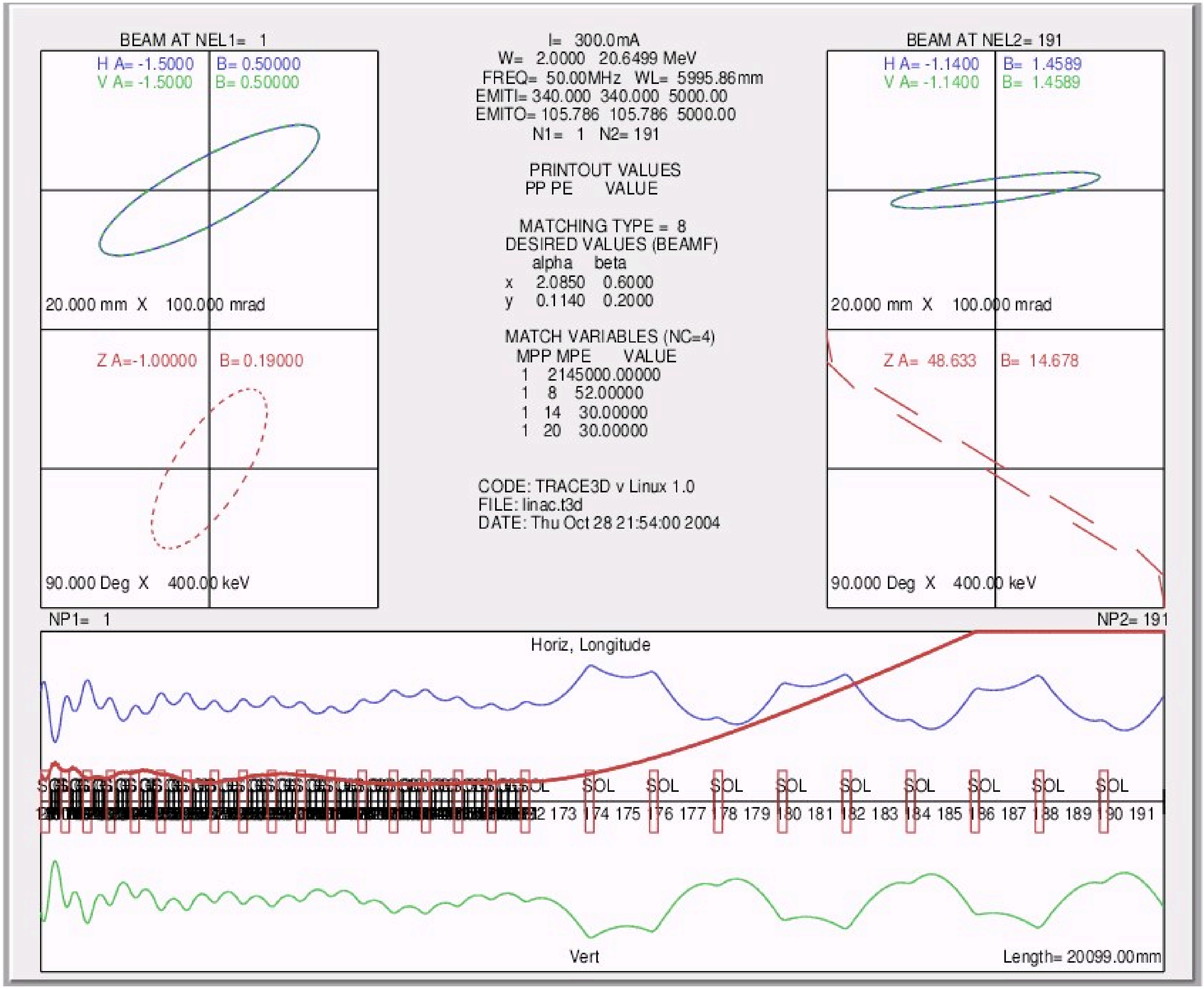
Trace-3D simulation with -40 degree stable phase, 300 mA current through first 14 MeV of linac. Note smooth beam envelope and phase envelope (red).



Same parameters: current values 0, 300 and 600 mA



Full linac to 20 MeV, followed by focused drift, showing beam debunching.



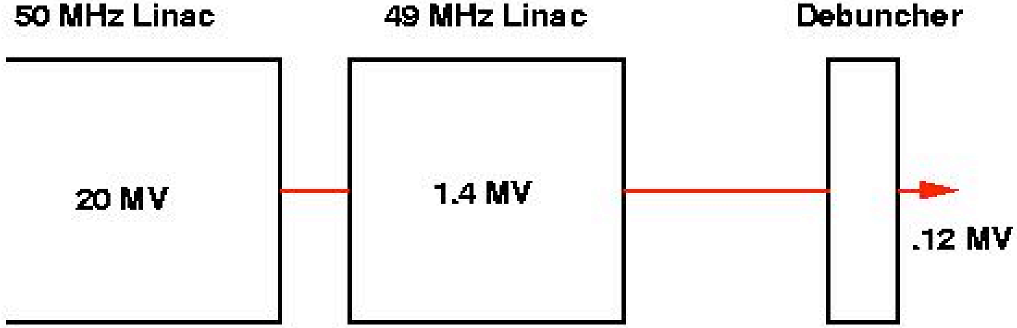
Beam Manipulation at Linac Exit

- Reduce energy spread and introduce correlated energy tilt for ballastic compression
- Three methods:
  - Tilt with frequency-offset cavity, immediately debunch to reduce energy spread to +/-0.2%
  - Debunch, then since bunch structure is too long, tilt with a 1 Mhz sawtooth cavity
  - Debunch, and follow with an induction linac core
- Debunching voltage 0.12 kV, tilt voltage 1.4 MV
  - Debuncher with small harmonic component reduces energy spread by factor of ~3.

Linac debuncher/energy tilt cavity for 4 configurations

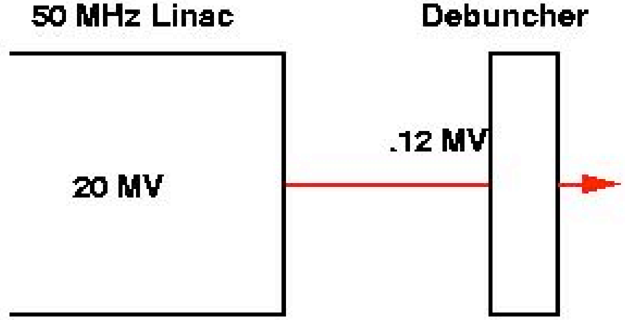
Introduce tilt first, then debunch

Linac – Tilt Linac – Debuncher



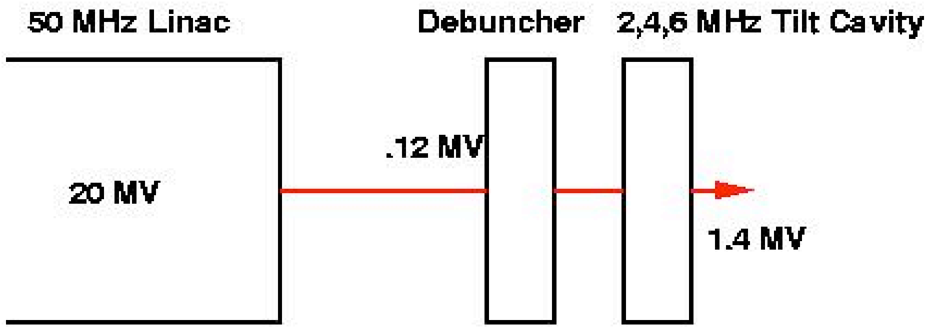
For loading ring: debunch only

Linac – Debuncher – Stacking Ring



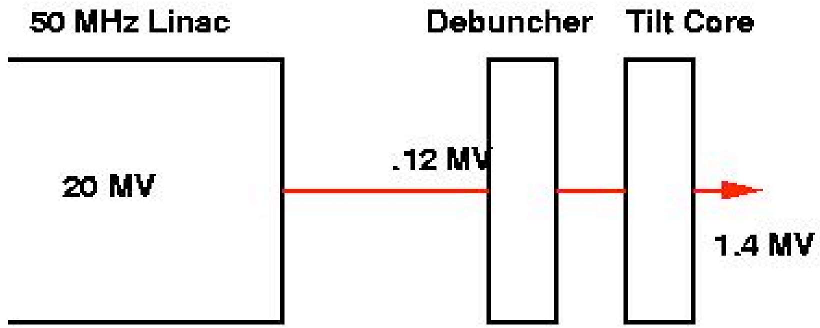
Debunch, then tilt with sawtooth

Linac – Debuncher – Tilt Cavity

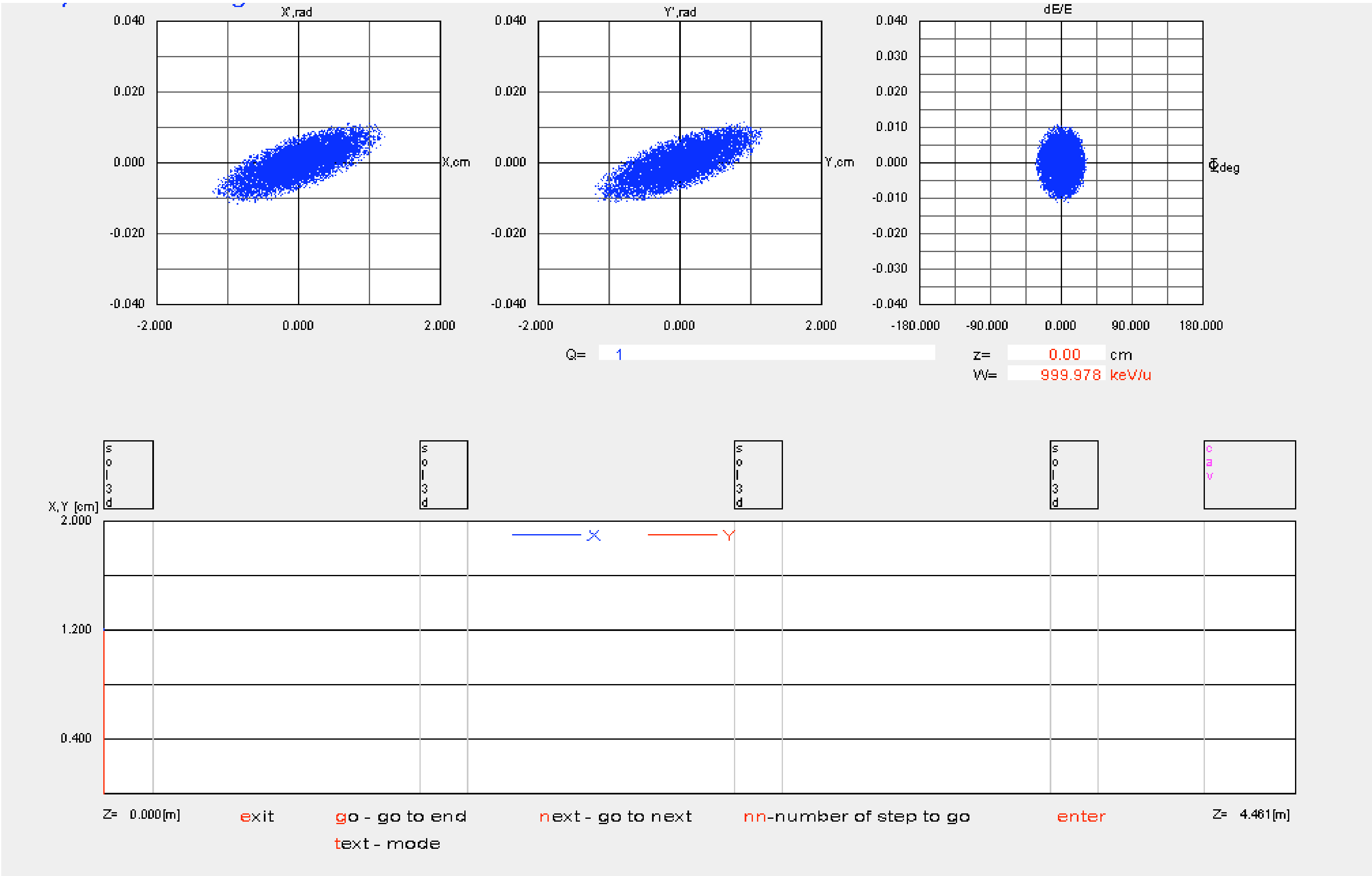


Debunch, then tilt core

Linac – Debuncher – Tilt Core

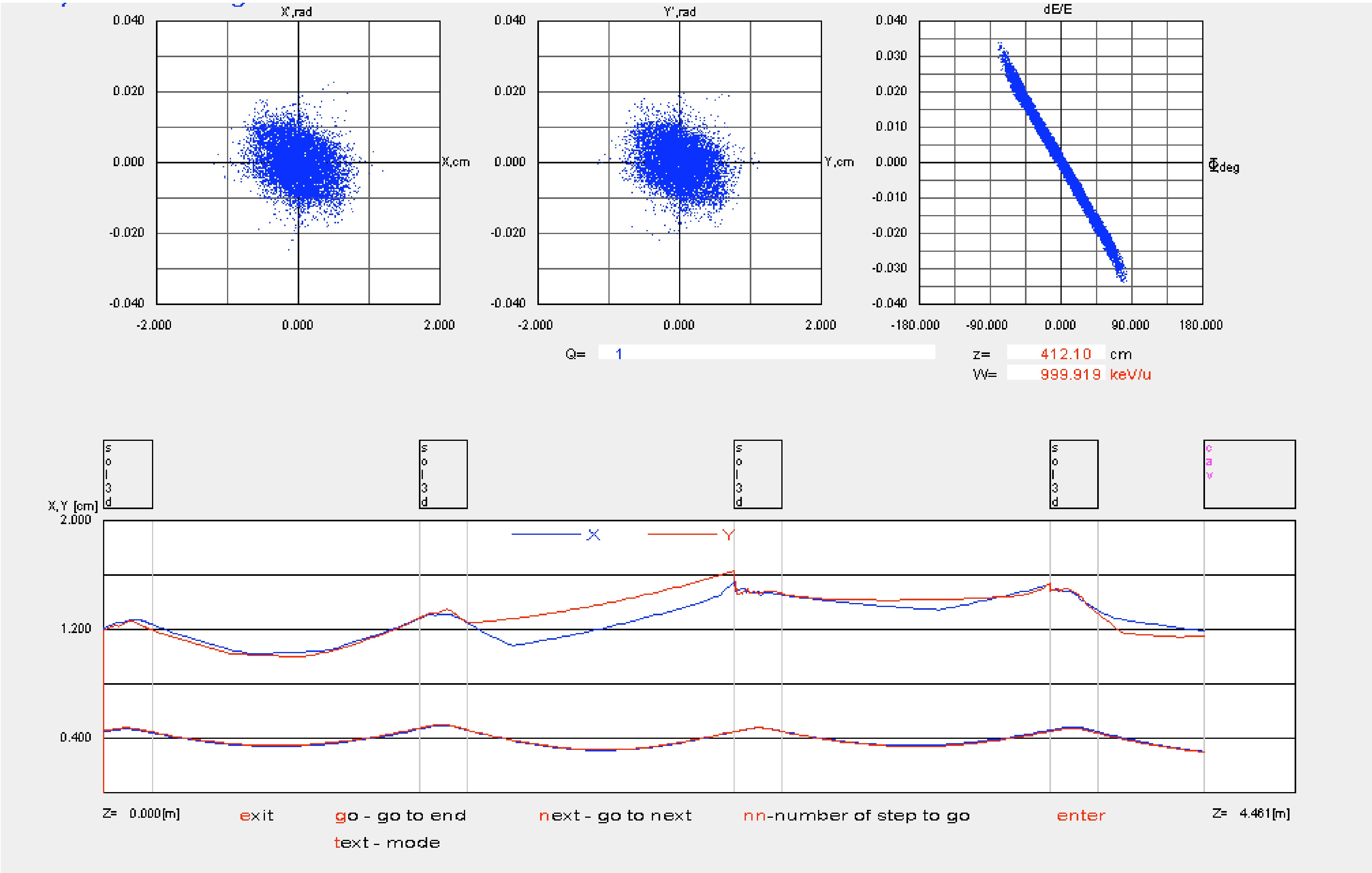


Beam simulation in the debuncher

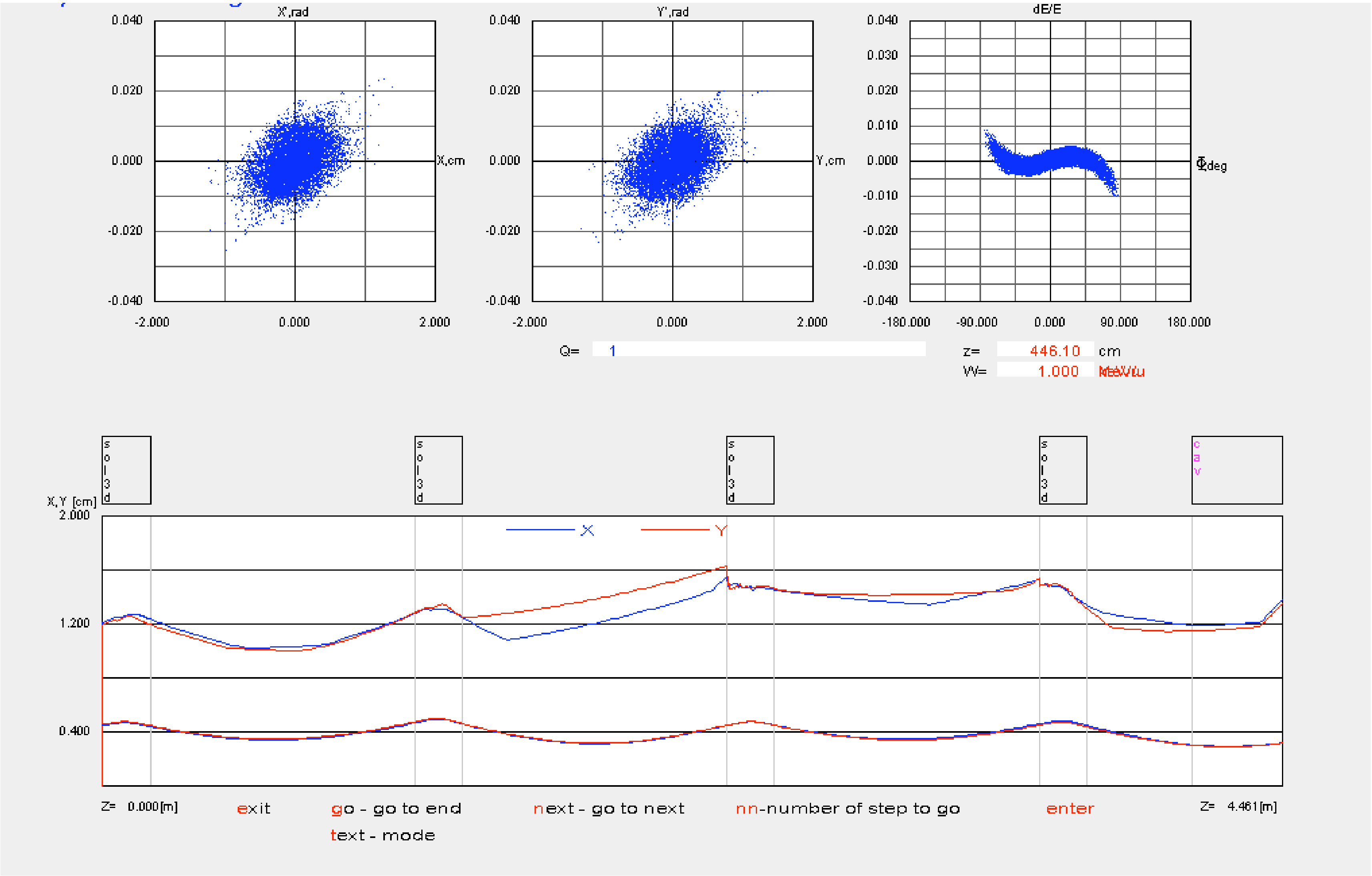


Exit of the Linac, 20 MeV Ne^{1+} , 1 MeV/u, 300 mA

Beam propagated 4.4 meters, Space charge has increased energy spread significantly



Non-linear effect can be cancelled by applying second harmonic



Tilt with Off-Frequency Cavity

- Macropulse length is 200 nsec (10 bunches)
- +/- 1.4 MV modulation over 200 nsec
- A cavity 1 Mhz off has a 1 microsecond beat frequency with the 50 Mhz bunch structure
- 200 nsec is 20% or 72 degrees of the 1 Mhz beat
- The middle +/-36 degrees (58% amplitude) of peak voltage of 49/51 Mhz cavity modulates the beam energy over the 200 nsec

Transport to Target

- Beam emerges from debuncher/tilt cavity as 16 parallel beams in a ring or linear array
  - For stacking ring, only one beam is used
- Overall emittance is large, but beams can be merged, converging to a single point at target
- Final-Focus group suggested a targeting method developed in the ICF program.
  - Ed or Simon will explain

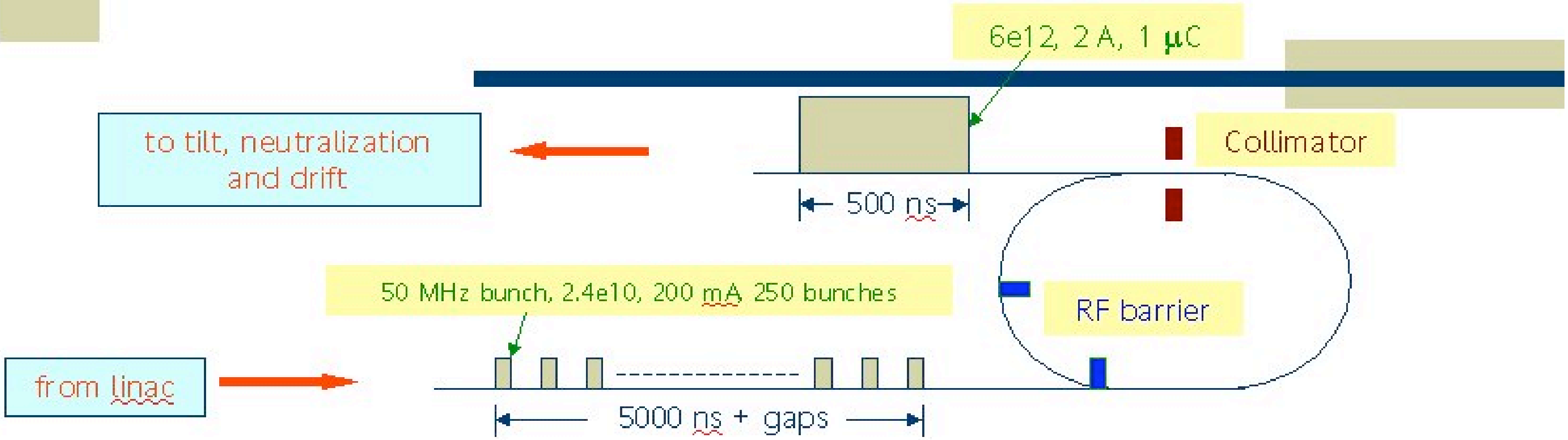
Stacking Ring Alternative (Chou)

- Instead of 16 parallel beams compressed by a factor of 200, betatron stack one beam in ring, 500 nsec for 10 turns and extract
- Apply voltage tilt after fast extraction for ballistic compression
- Transverse emittance at least sqrt(10) larger than linac beam
- Only modest vacuum required, 10^{-7} Torr
- Tune shift about 1 unit
- Few microsecond store before extraction

Observations

- Observation 1:
  - Goal: To create an extremely intense short bunch at low duty factor
  - 20 MeV, 1 μC, 1 Hz: beam power = 20 W
  - Beam loss is non-issue
  - This is very different from those high power (~ MW) hadron accelerators like SNS, PSR, ISIS, J-PARC, GSI, RIA, etc.
- Observation 2:
  - Limited budget
  - Hardware needs to be as simple and realistic as possible

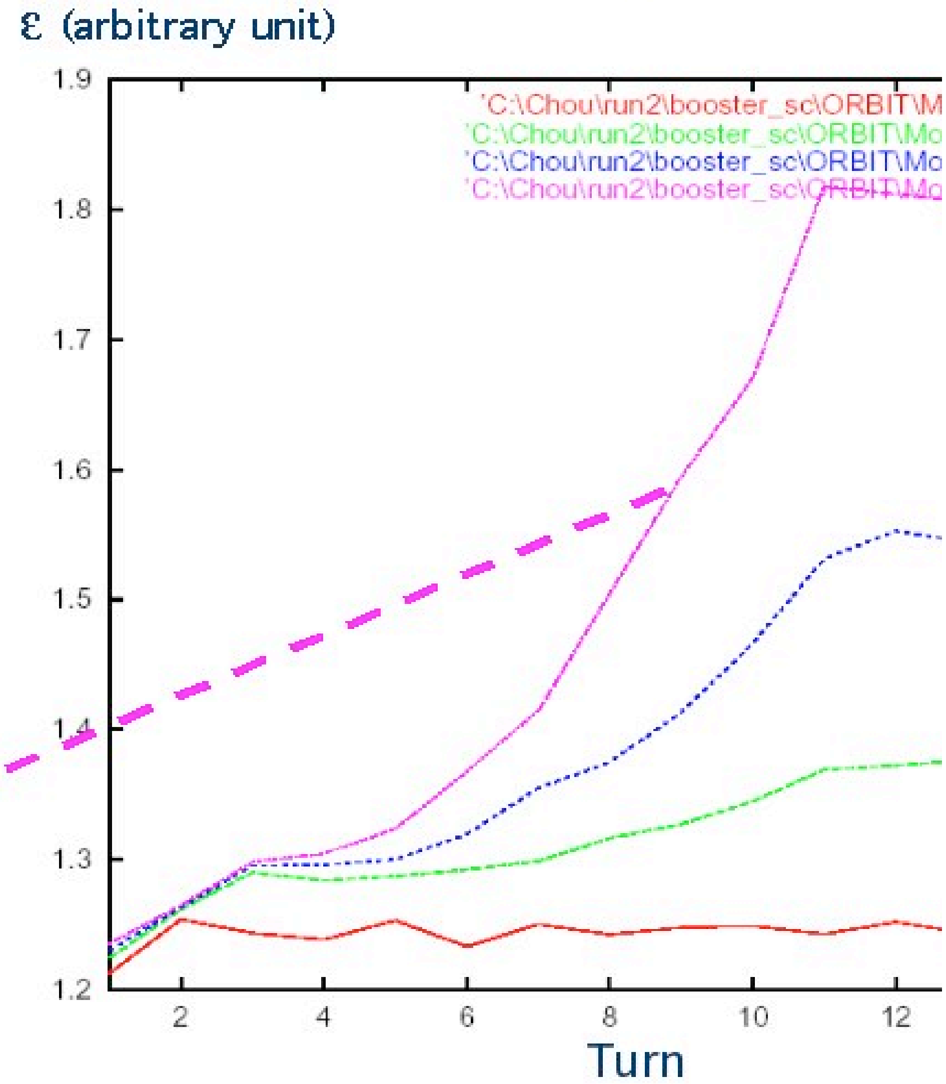
Ring Compressor for Transverse Stacking



- Ne^{+} 20 MeV, β = 0.045, A = 20.17, Bρ = 2.84 T-m
  - Warm combined function magnet: B = 1.9 T, ρ = 1.5 m, L(mag) = 9.4 m, C = 12 m
  - SC magnet: B = 4 T, ρ = 0.7 m, L(mag) = 4.5 m, C = 7.5 m
- 10-turn stacking
  - Injected linac beam width: 5000 ns, or 67.5 m
  - Extracted beam width: 500 ns, or 6.75 m
- Transverse phase space painting during 10-turn injection (similar to CERN PSB)
- RF barrier to preserve extraction gap
- Space charge induced resonances may not have time to cause damage (similar to non-scaling FFAG)
- IBS may not have time to cause dilution
- Beam halo scraping by physical aperture is ok (or use collimator for localizing loss)
- Beam parameters similar to that of existing proton linacs and rings
  - Injected 50 MHz bunch: 2.4e10 (200 mA), 1π mm-mrad
  - Beam in the ring: 6e12 (2 A)
  - Extracted beam: 2 A × 500 ns = 1 μC
- Drift compression 250-500:1

Questions and Answers

- Vacuum requirement:
  10^{-7} torr (Sessler/Yu; GSI SR reaches 10^{-11} torr)
- Outgassing from lost ions:
  Collimator to control ion loss
- Energy tilt for longitudinal compression:
  Downstream induction linac to obtain $\Delta E/E = \pm 14\%$
- Space charge – Laslett tune shift:
  - HEDP/Fermilab Booster = 3.7
  - Emittance growth simulation for tune shift ratio = 3.2 ($\Delta\varepsilon/\varepsilon \sim 50\%$ in 10 turns)



Analysis and Discussion

- Fairly conservative design
  - Ion source parameters from known sources
  - 400 kV gap voltage demonstrated in similar geometries
  - 15 T supercon solenoids based on available units
- Continuously variable output energy
- Linac beam parameters based on simulations with benchmarked codes.
- Solenoids offer wide momentum aperture and are relatively space charge independent.
- Relatively smaller sensitivity to offset errors
- No obvious show-stoppers

Problem Areas

- Cavities have large gap capacitance
  - Lowers shunt impedance, may have voltage variation amongst the gaps
  - But, provides more stored energy in cavity
    - About 10% of stored energy removed by beam pulse
- High system complexity with many components

Areas for Further Study

- Physics
  - Beam-cavity interaction and stored energy
  - Beam dynamics in linac and compression region
  - Ultimate charge density
  - Error and parameter studies
- Engineering
  - Multiple beam, low-frequency cavity, field uniformity
  - High-field supercon solenoids
- Costs
  - Not considered here