Report from working group 3: multi-gap pulsed power

Presented by Alex Friedman

Workshop on Accelerator Driven High Energy Density Physics

Friday, 2004-10-29

Participants

- Dick Briggs (co-chair)
- Alex Friedman (co-chair)
- Roger Bangerter
- Andy Faltens
- George Caporaso
- Enrique Henestroza
- Craig Olson
- Santiago Bernal
- Steve Lund
- Christine Celata
- Scott Nelson
- Grant Logan
- Peter Seidl
- Lou Reginato
- Will Waldron
- Joe Kwan
- Frank Bieniosek
- Yu-Jiuan Chen
- Ned Birdsall
- Shmuel Eylon
- Bill Herrmannsfeldt
- Igor Kaganovich
- Prabir Roy
- Tim Renk

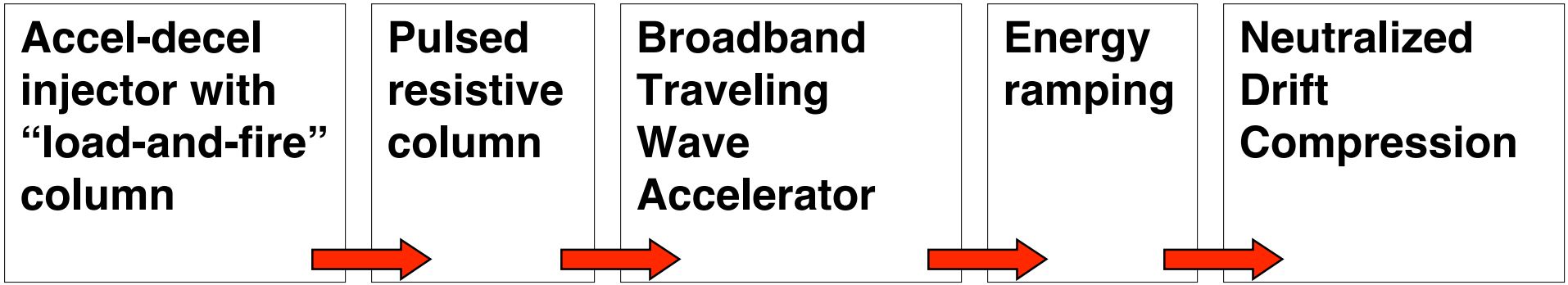
(not all, at all times)

Outline

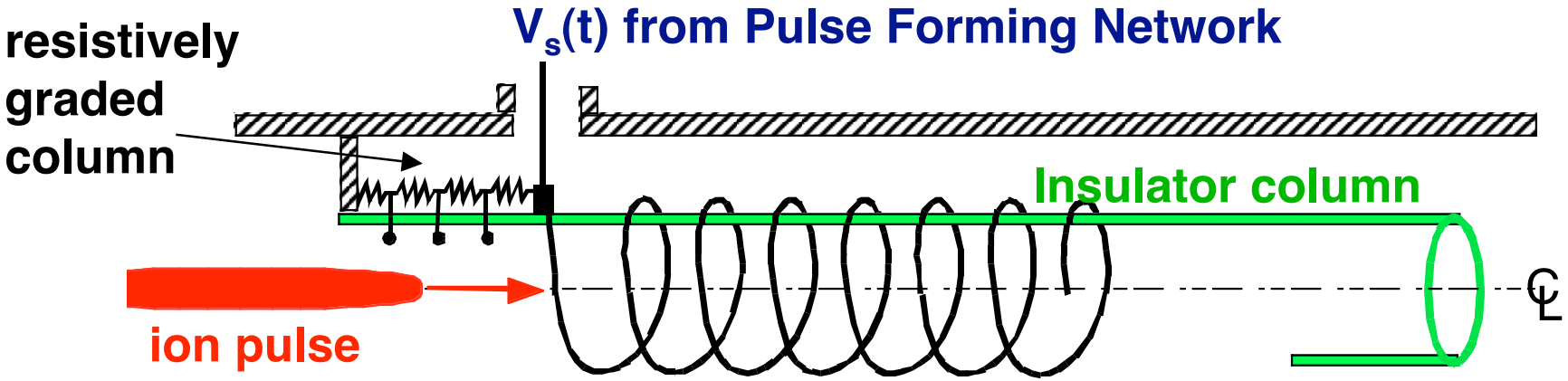
- In this summary - approaches worked on during the WS:
  - Broadband Traveling Wave Accelerator (BB-TWA)
  - Multi-beam Drift Tube Linac (DTL)

- In report - other approaches identified:
  - Multi-pulse induction
  - High-gradient induction
  - Single-gap diode
  - Ionization Front Accelerator

Concept for a Broadband Traveling Wave Accelerator



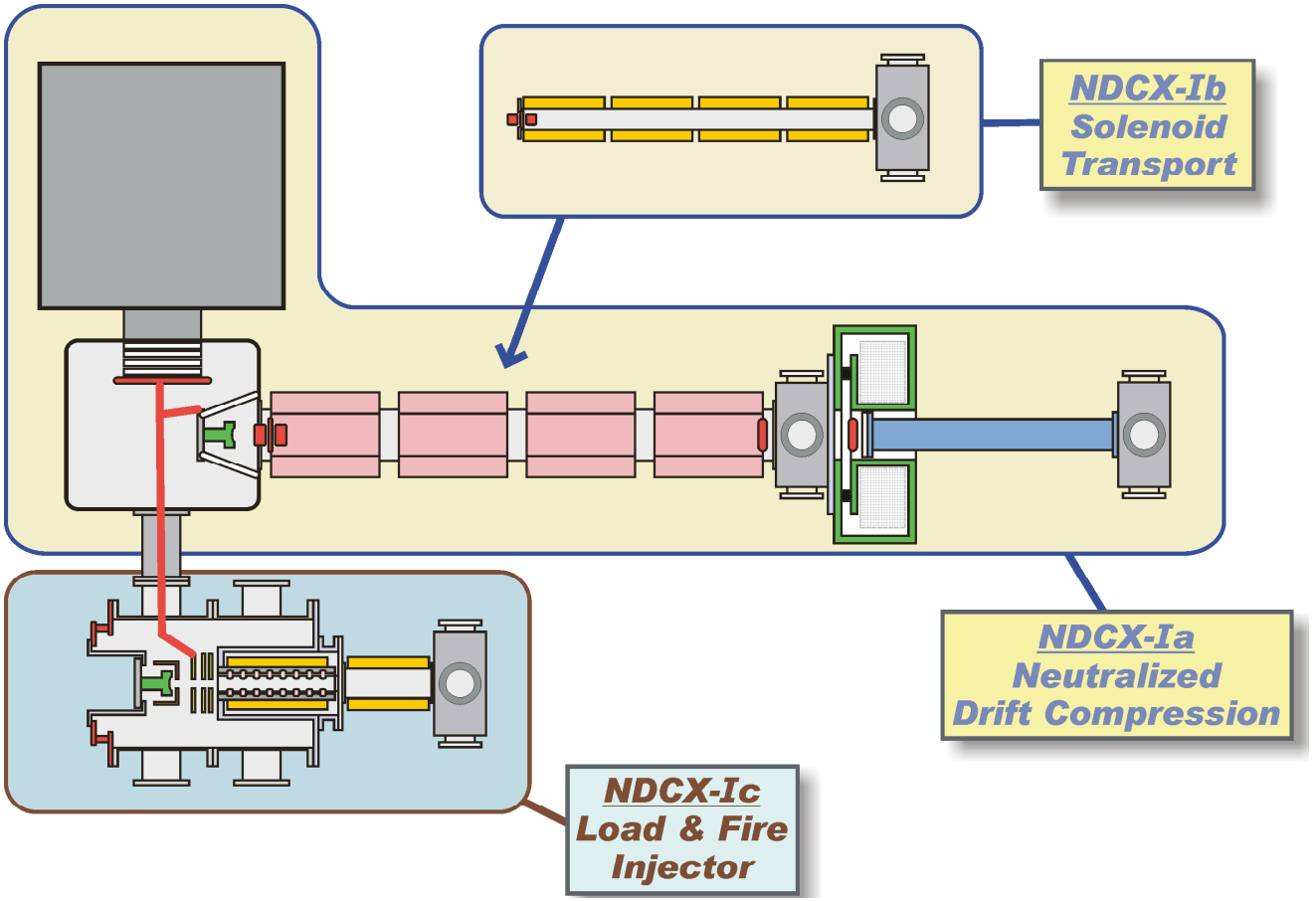
- Traveling Wave Accelerator is based on slow-wave structures (helices)
- Beam "surfs" on traveling pulse of E_z (moving at ~ 0.01 c in first stage)
- *One possible configuration:*

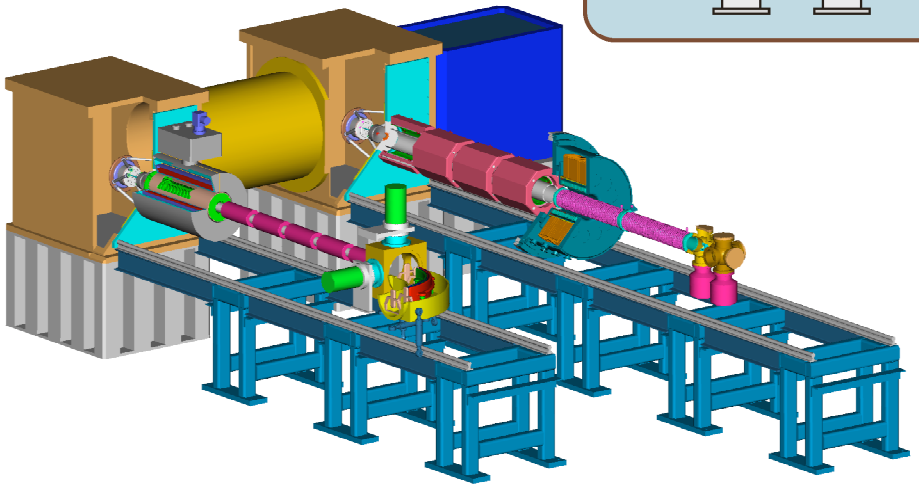


Broadband Traveling Wave Accelerator can build on NDCX sequence

- NDCX-1 experimental program (beginning ~ now) will explore key elements
  - Neutralized drift compression
  - Solenoid transport
  - Accel-decel
  - Load-and-fire
- NDCX-2 (2009 timeframe) is evolving
  - Had notionally been induction-based, He^+
  - Opportunity for BB-TWA as cheaper alternative
- "Reference design" HEDP/WDM user facility originally worked out for Ne^+ but could be Na^+ or K^+

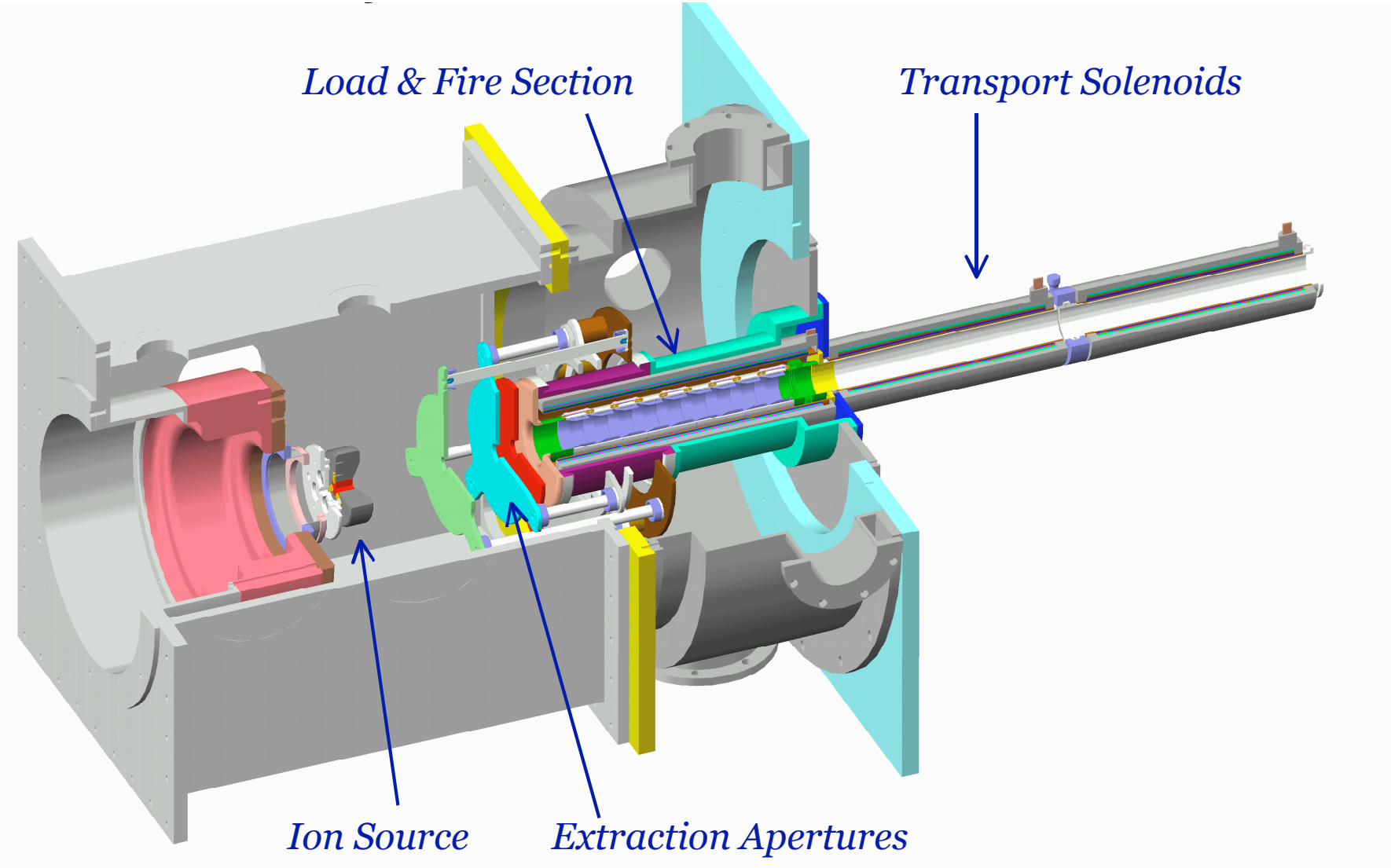
NDCX-1 has 3 stages over next ~2 years



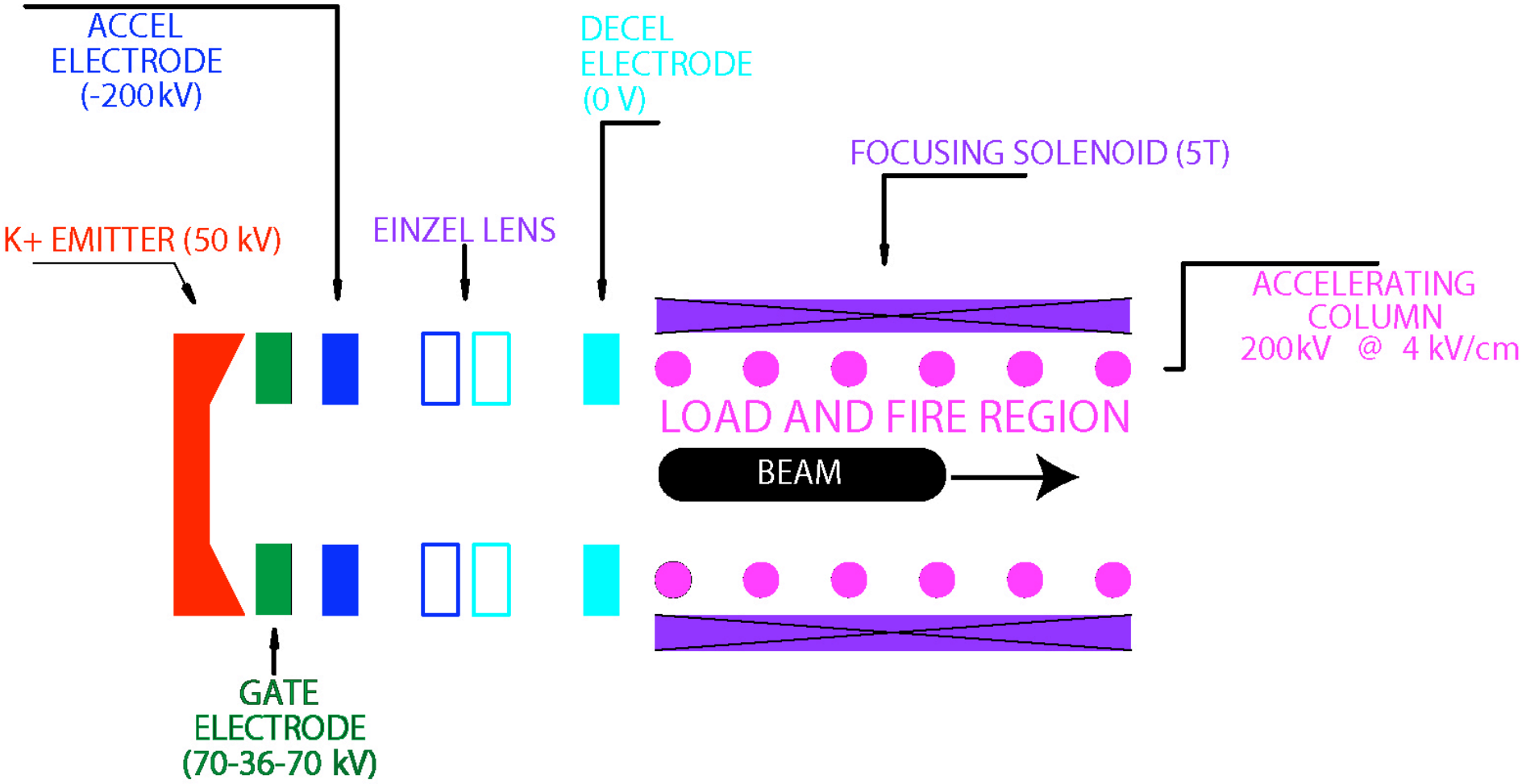


1a - Neut. Drift Compr.; starting ~ now
1b - solenoid transport; start June 05
1c - accel-decel / load & fire; start Oct. 05

Short Pulse Injector (Accel - Decel / Load & Fire)



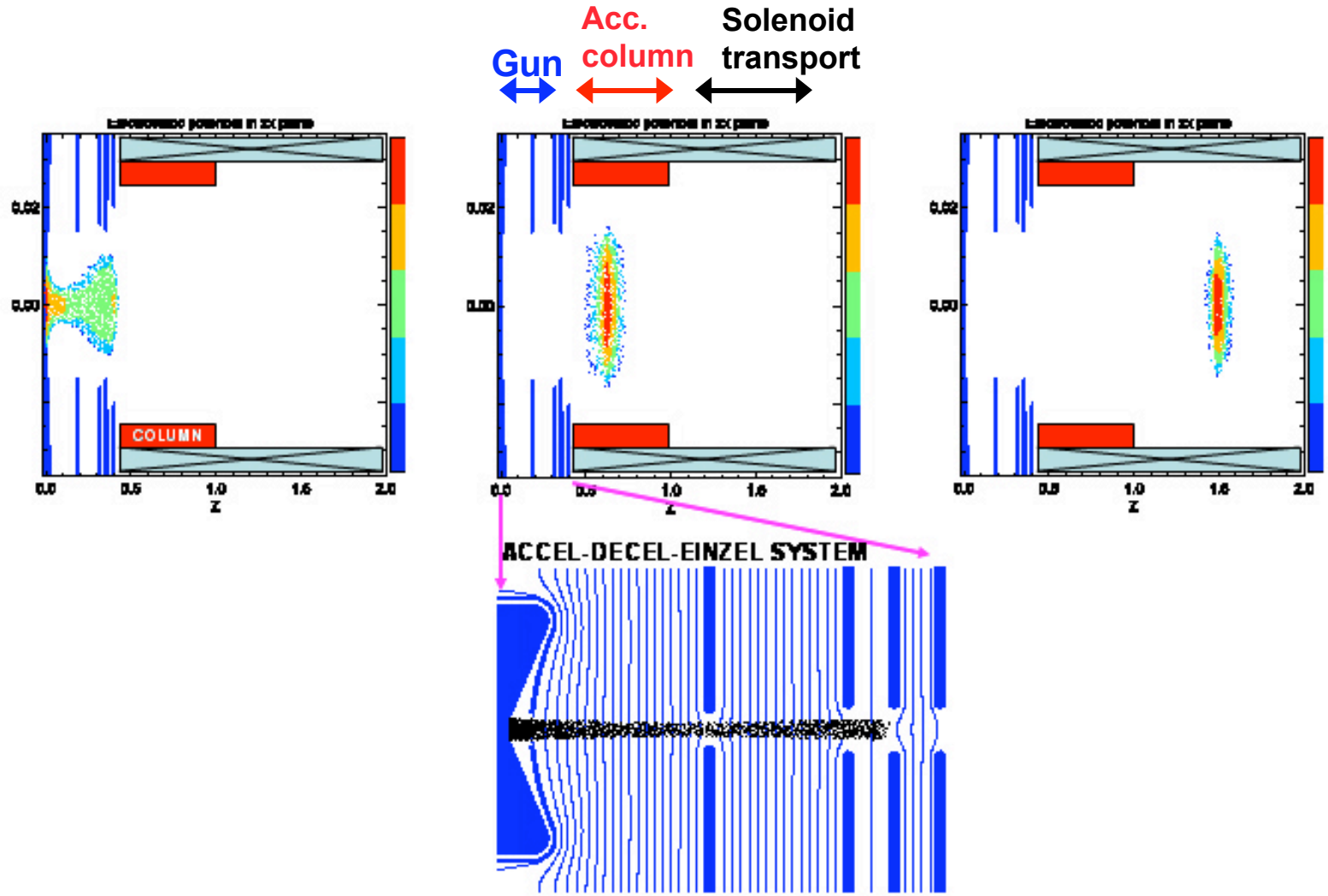
Schematic of an Accel - Decel / Load & Fire System



Informal goals for NDCX-1c: first test of Accel-Decel / Load & Fire

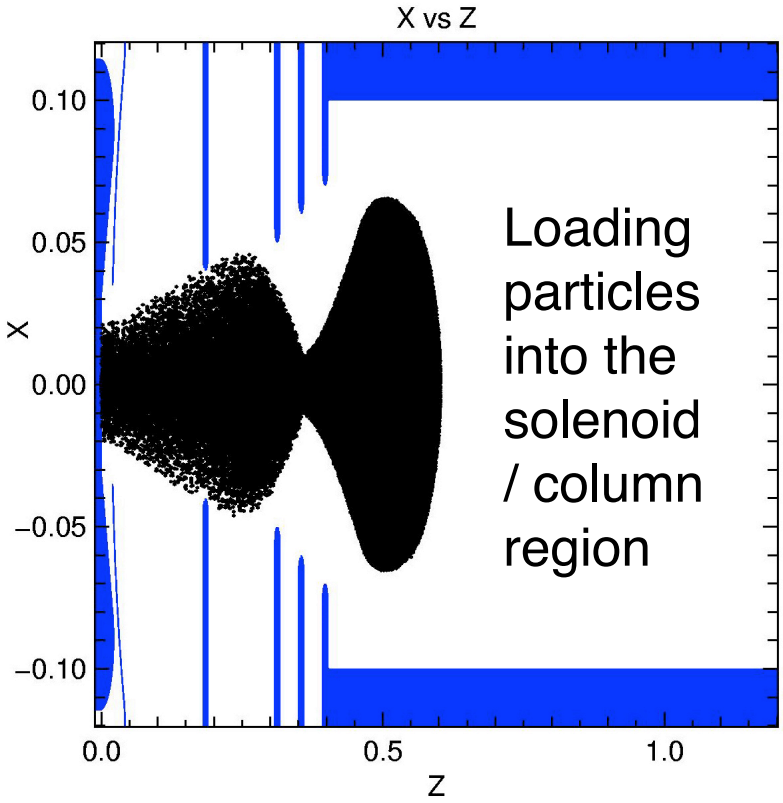
- Q = 0.05
- 140 mA peak
- Beam energy after accel-decel 50 kV
- K^+, λ = 1/4 μC/m
- τ_{pulse} = 1/2 - 1 μs --> q_{tot} = 0.05 - 0.1 μC
- Resistive column 50 cm (5 T solenoid 60 cm)
  - imparts (mostly) tilt; 200 kV version:
  - Option 1: 180 keV head, 250 keV tail (1/2 μs , beam= 25 cm)
  - Option 2: 50 keV head, 250 keV tail (1 μs , beam=50 cm)

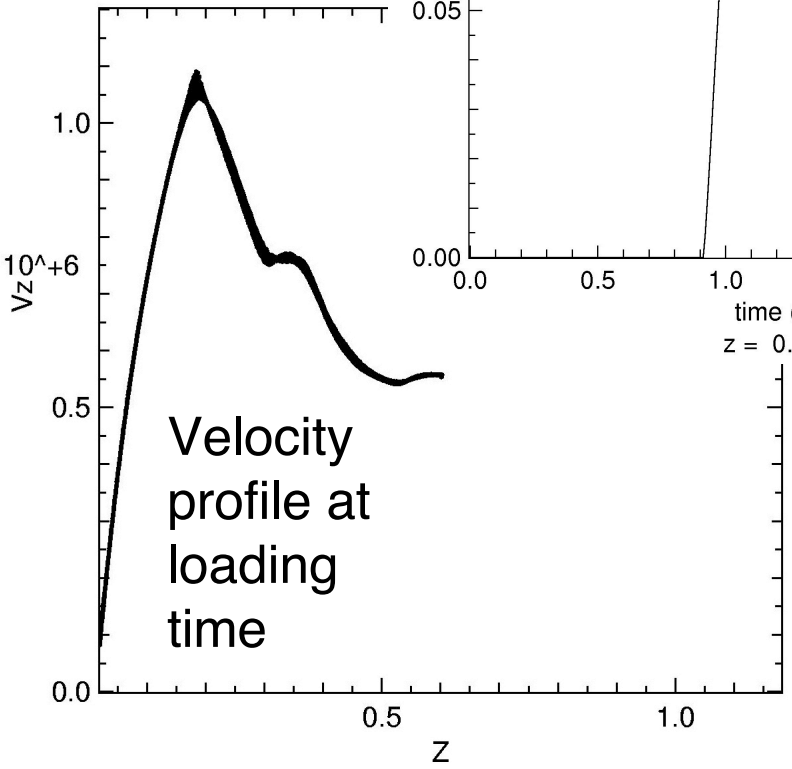
WARP3D simulation of NDCX-1c

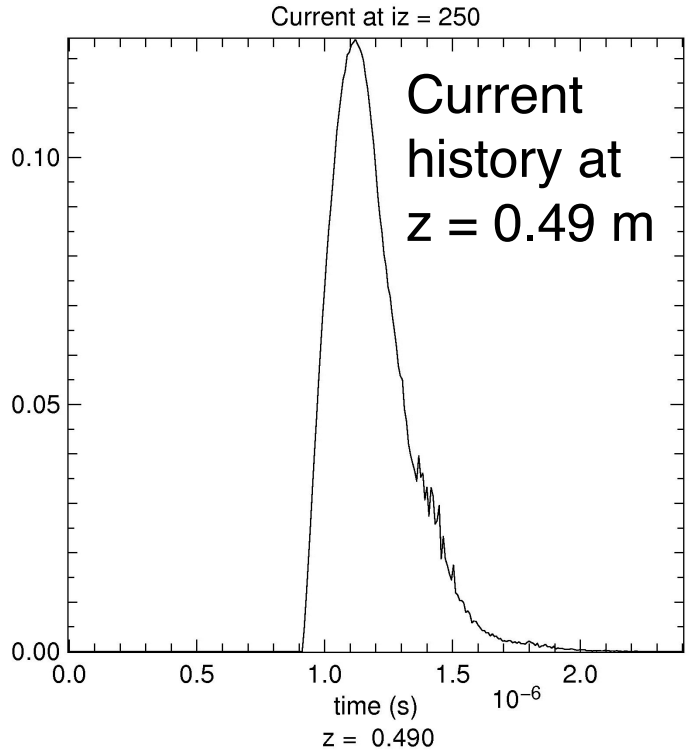


NDCX-1c for Q ~ 0.05 simulated via WARPrz shows benign behavior of beam head and z-v_z phase space

500 ns, 140 mA peak, 50 keV k^+, 0.05 μC







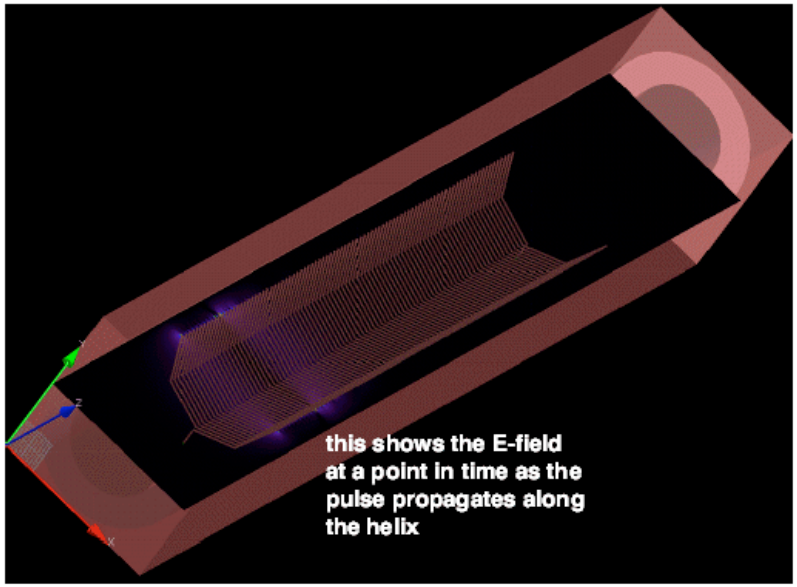
Success on NDCX-1 and on BB-TWA tests would offer new NDCX-2 opportunity

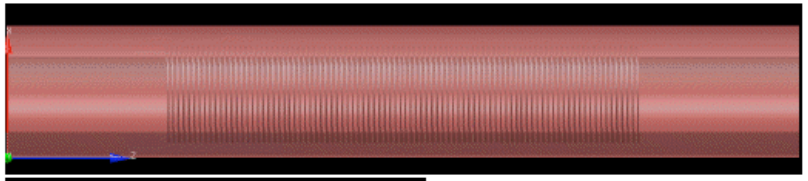
- Adds TWA to NDCX-1 (still uses K^+, not He^+)
- 20 MeV < Bragg peak (~ 50 MeV), but deposition only down ~ 10-15%
- ~ 8 meters long, < $2M for 5 T solenoid system
- R_{beam} = 2 cm, a_{helix} = 4 cm, b_{wall} = 10 cm
- +/- 450 kV drive (not all usable for beam)
- Beam 15-20 cm
- Voltage ramps over 30 cm --> acceleration at 3 MV/m

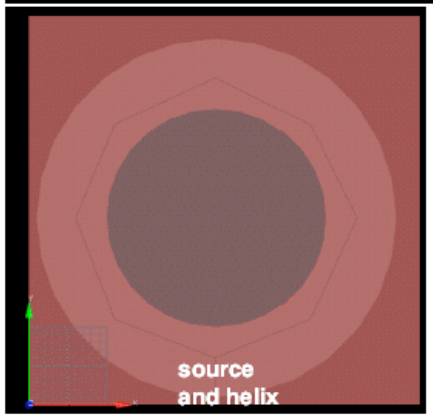
- ~3 segments of helix, each w/ tapered line tracking ~2x gain in velocity
- Voltage waveform can impart tilt in helix (in addition to any added by resistive line)
- Longitudinal blow-up controlled by "tilt" and "inertia" (rapid accel)
- Target heating to ~ 1eV if focus to r_{spot} < ~ 1 mm

3D FDTD EM simulations show traveling wave characteristics

Helix Geometry







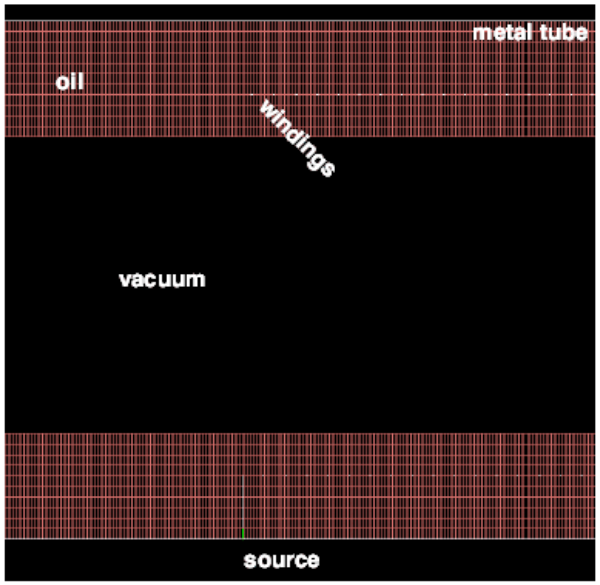
The geometry is composed of box, a round outer metal shell, and a very thin plastic beam tube.

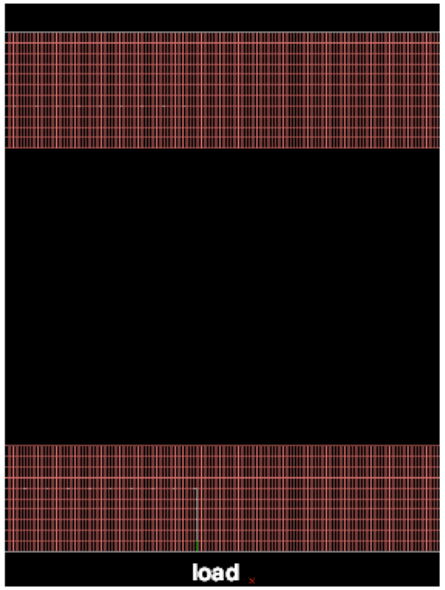
The region between the box and the beam tube is oil filled. There is a helical winding around the beam tube with a=15mm (inner radius) and b=22mm (outer radius). The structure is 300mm long.

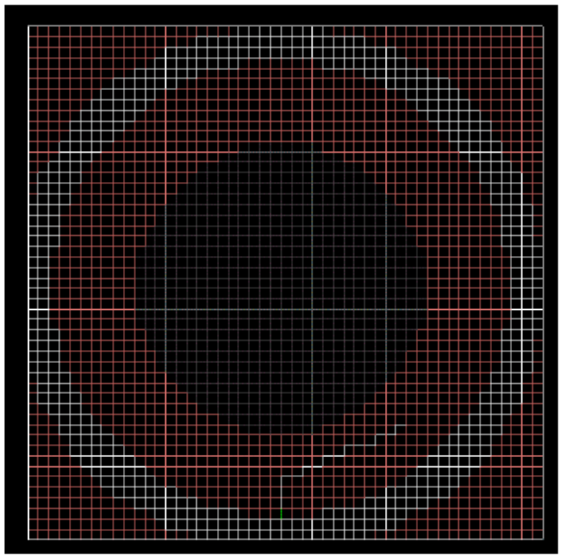
The input and output to the beam tube are open ended.

The drive is fed by a sawtooth source, dV/dt = 38ns pulse. There is a matched load at the other end.

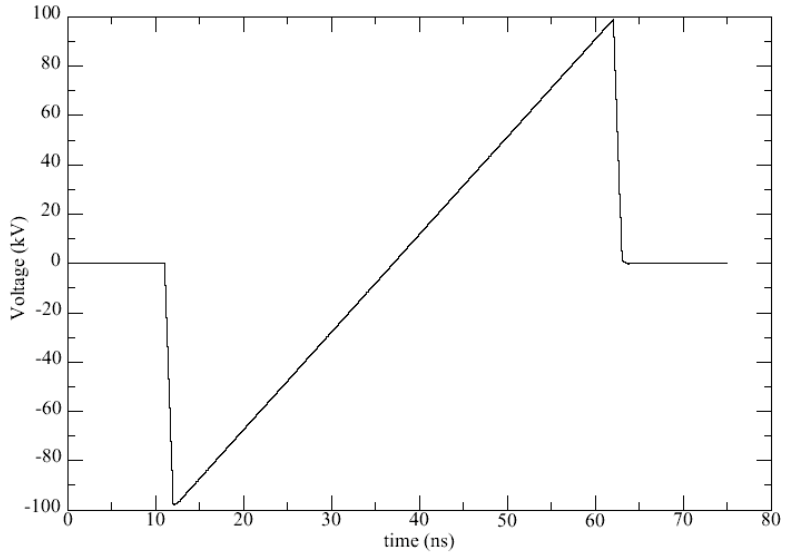
The helical winding stops 2 pipe diameters before the boundary.



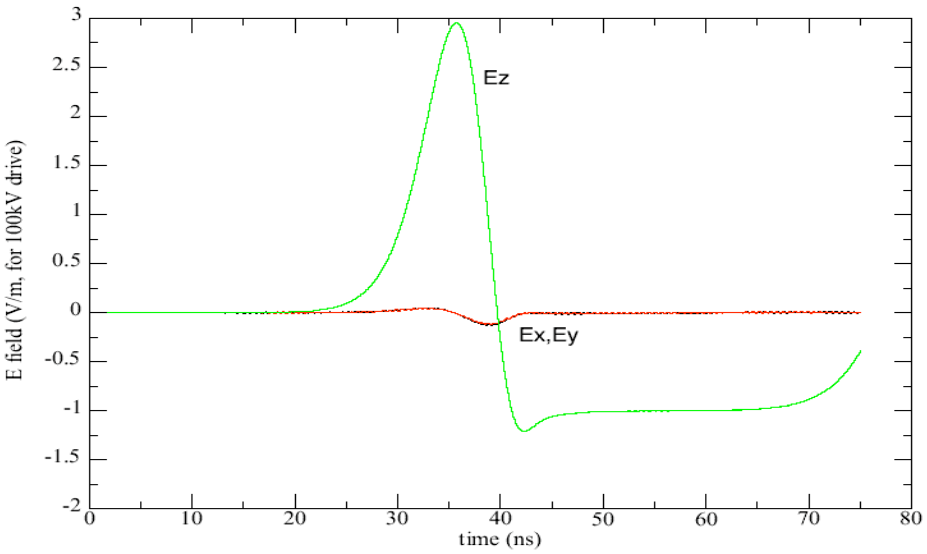


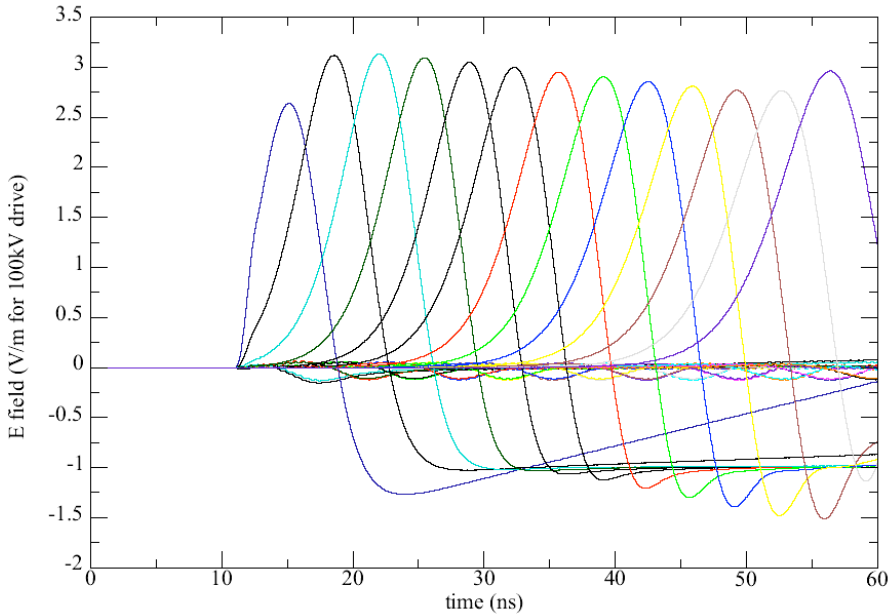


Source voltage



Ex,Ey,Ez at z=z_middle





Helix pulse-line reference parameters for HEDP

- Total charge 1 μC, 20 MeV Ne^+ beam
- Parabolic profile bunch with length constant at 30 cm, peak line charge = 5 μC/m

  Beam radius 3 cm in 9 T solenoid
- Helix radius 6 cm, peak radial voltage +/- 750 KeV,

  peak radial stress 125 KV/cm in 30 cm diameter bore tube
- Peak axial space charge field +/- 0.8 MeV/m,

  acceleration gradient 5 MeV/m = vacuum stress along insulator column

- Options for injector / front end:
  - Accel-decel + resistive-column load-and-fire
  - Accel-decel to modest λ + BB-TWA for early bunching
  - Magnetically insulated diode at high gradient

Several compression / focusing options can be considered for BB-TWA

- Final tilt is imposed by last helix segment; 30-cm pulse implies a short neutralized drift compression section (few m)
- Q at output ~ 2×10^{-3} @ 20 MeV
- Some options:

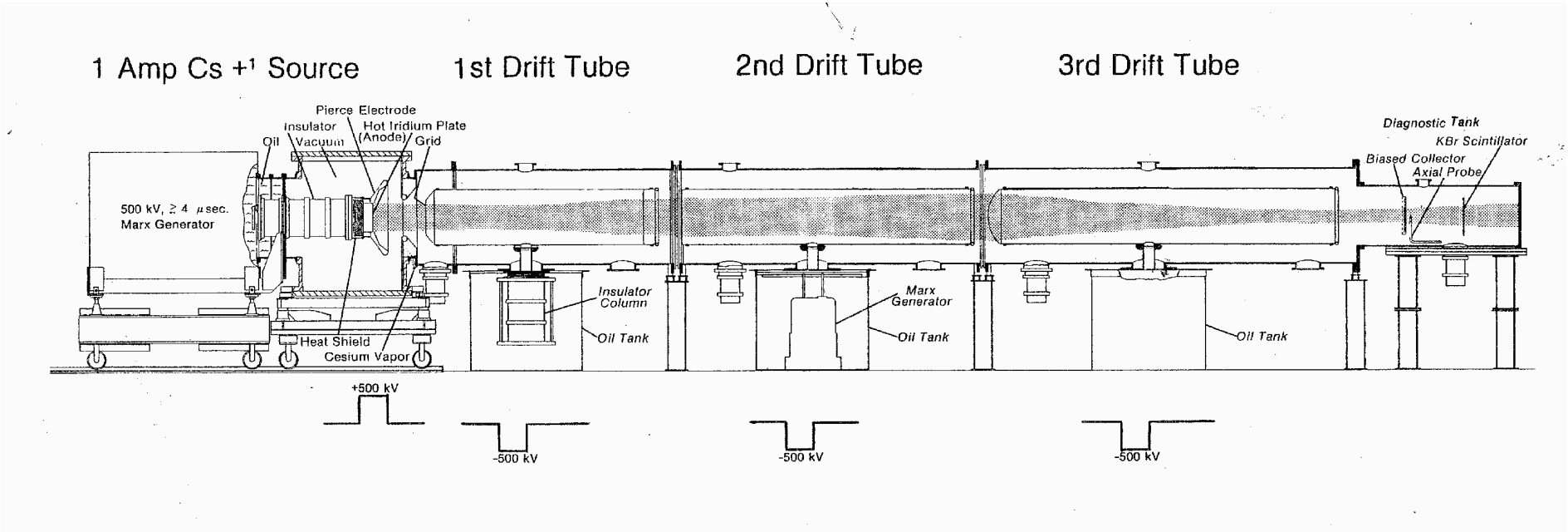
Helix -> Strong Sol's -> Dipole -> Strip to +7 -> 1 T NDC -> 15 T Sol -> Tgt
(match from ~ 3 cm to ~ 1 cm radius for NDC)

Helix -> Dipole -> Opt. Strip -> Graded Sol NDC -> 15 T Sol -> Tgt
(beam radius reduced gradually during NDC, no match section)

Helix -> Graded Sol -> 15 T Sol -> Tgt
(plasma builds up along line, gradually)

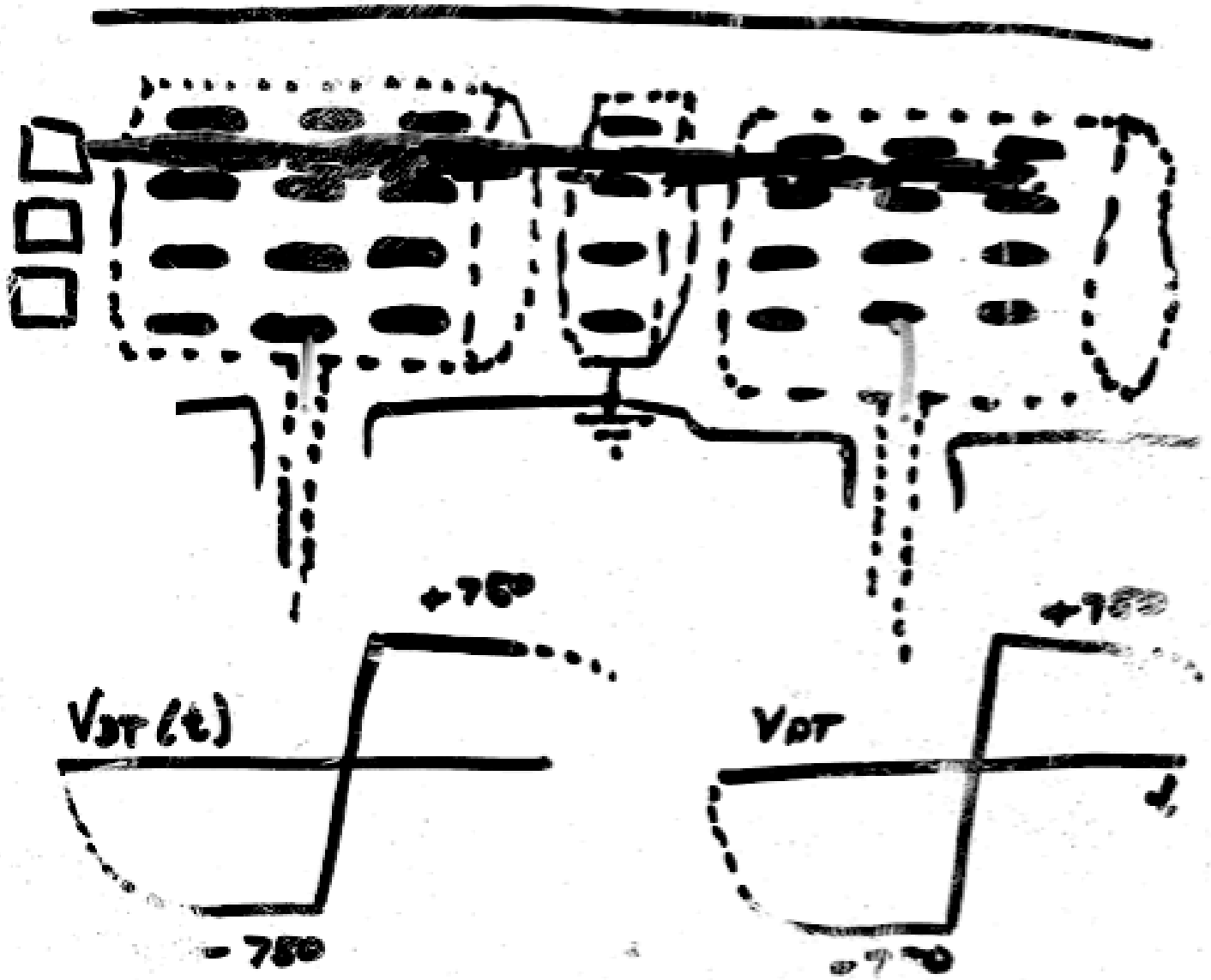
The pulsed DTL concept is similar to the 2 MeV Cs+ injector built many years ago

Line charge densities of 0.5-1 μC/m were accelerated to 2 MeV



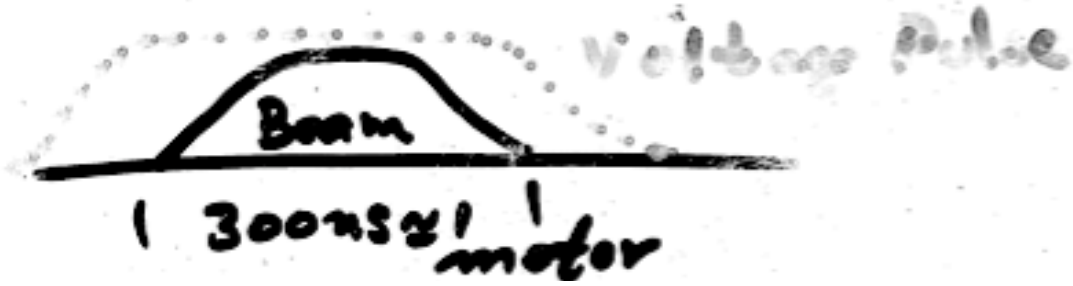
Pulsed Drift Tube Linac with internal electric quadrupoles

Compact sources at +750 kV (J. Kwan)

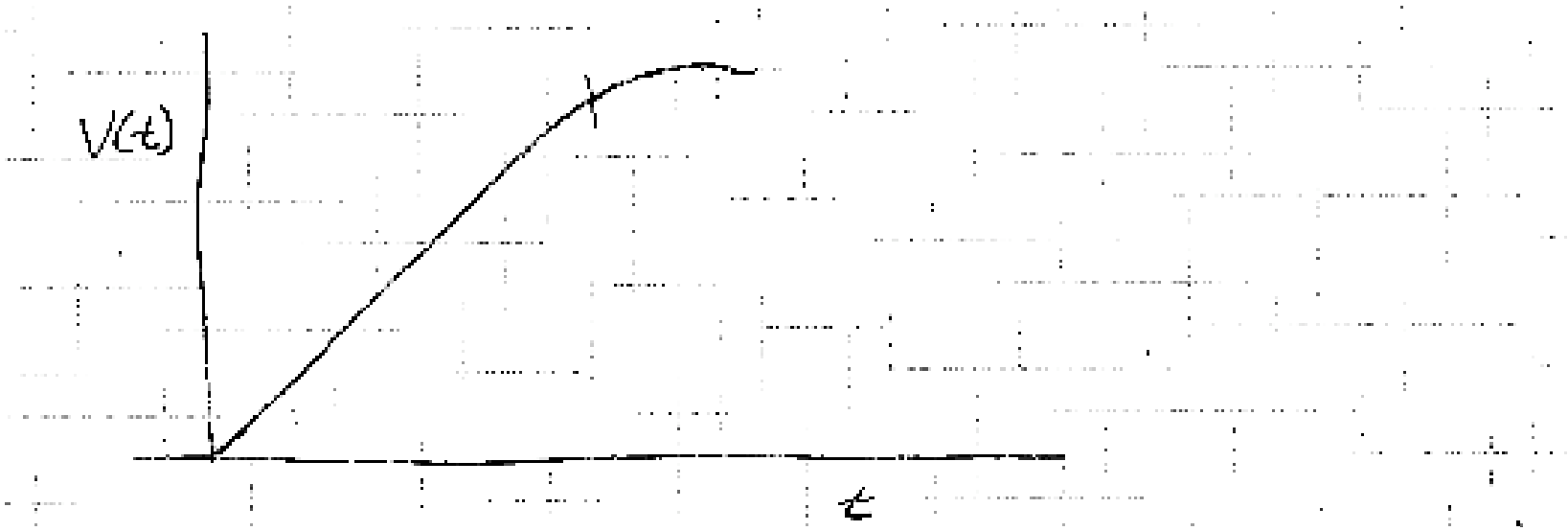


Same type of transport as HCX

- $L_{half\text{-}period} \sim 50$ cm
- $L_{electrodes} \sim 30$ cm
- $\lambda \sim 1/4\ \mu C/m$
- Beam size ~ 1 cm x 1.5 cm (beam area ~ 5 $cm^{2)}$
- $I_{beam} \sim 1$ A
- $J_{source} \sim 100$ mA / cm^2
- 100 ns good beam
  100-200 ns beam head
  100-200 ns beam tail
- Drift tube switching time 100-200 ns
  Drift tube 1-2 m long



Focusing: put energy tilt on last drift tube



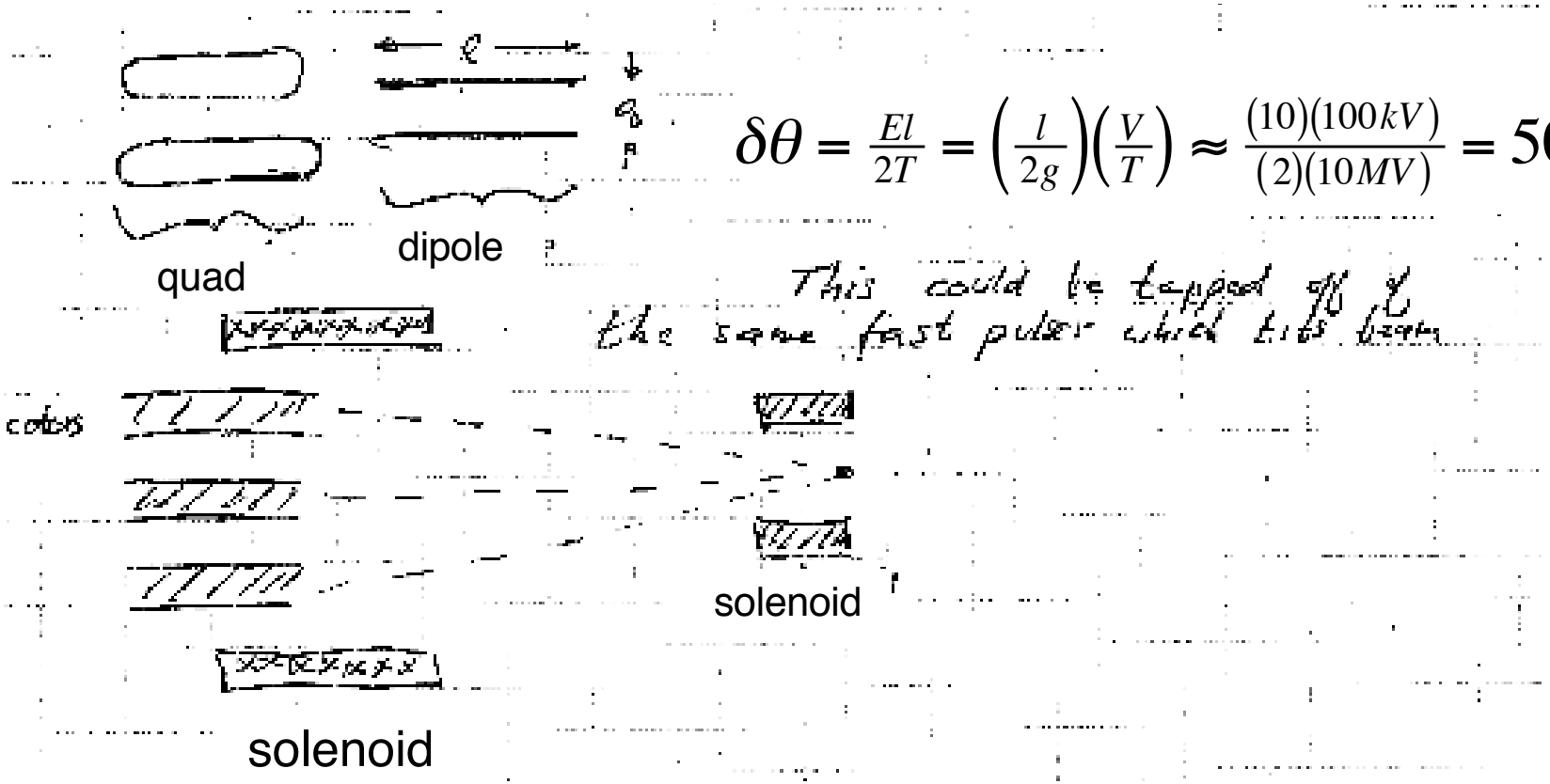
For constant bunch length, T_p has decreased as $1/E^{1/2}$.

$T_p \approx 30$ ns, e.g. Sharpening Gap on output

$\Delta V/V \approx$ (1 MeV)/(10 MeV), $\Delta v/v \approx 1/20$

$\Rightarrow$Longitudinal focus in 20 bunch lengths, or 6 meters.

Bigger tilt ⇒ greater chromatic aberration.
Compensate this with a pulsed HV deflector



$$\delta\theta = \frac{El}{2T} = \left(\frac{l}{2g}\right)\left(\frac{V}{T}\right) \approx \frac{(10)(100kV)}{(2)(10MV)} = 50mr$$

Phase space budget must be carefully monitored

- **LSP "driver case" simulations show 20 MeV energy spread acceptance in compression and focusing, so, at 5 ns pulse length, longitudinal admittance is 0.1 eV-s**

  Source temperature ~ 1 eV (typical), when boosted to lab frame and multiplied by 20 microsec pulse length, gives emittance ~ 0.1 eV-s, so on the edge

- **Parameters okay but not "fat" for our HEDP case based on this one consideration. Waveform errors of ~ 1% can be significant**

So how did we do? (relative to the goals we set for ourselves)

- List of promising approaches - yes
- Select examples for more detailed consideration - chose 2
- Develop straw-man designs for entry level and user facility
  - yes for BB-TWA, somewhat for DTL
- Develop interface requirements: - yes (injector, compression / focus)
- Identify scientific / technical challenges - yes (not fully presented in this summary)
- Develop modest-cost development paths - yes (TWA had head start)
- Consider contributions to IFE and other apps - yes (not fully presented in this summary)
- Outline report - similar to structure of these slides; appendices to cover material presented by group members during discussions
- Make writing assignments - yes

This has been most interesting and useful; thanks to all who participated!

Schedule - Tuesday and Wednesday

Tuesday

4:30-5:30 Develop group goals and agenda

Wednesday

9:00-9:30 George Caporaso – High-gradient induction

9:30-10:30 Free-think

10:30-11:00 --coffee—

11:00-11:45 Craig Olson – IFA (joint with experiments group)

11:45-12:45 –lunch--

12:45-1:15 Condensation into categories (subgroups)

Short talks:

1:15-1:40 Enrique Henestroza – Accel/decel, load and fire

1:40-2:00 Alex Friedman – BB-TWA circuit modeling & kinematics

2:15-3:00 Grant Logan – multipulse

3:00-3:15 Roger Bangerter – longitudinal emittance constraints

3:15-3:30 Develop status report & list of intergroup issues

3:30-4:00 --coffee / intergroup discussions--

Schedule - Thursday

Short talks with discussion:

- 9:00-9:45 Steve Lund – transitions
- 9:45-10:30 Scott Nelson – 3D FDTD EM modeling of helix
- 10:30-11:20 Andy Faltens – multibeam

11:20-12:15 Subgroups meet

12:30-2:00 Working lunch w/ focusing group in 71B

2:00-3:15 Subgroups meet

3:15-4:00 Subgroups report / discussion

4:00-5:30 Writing assignments and prep of final talk

Subgroups

1: Accel-decel / load-and-fire / broad-band TWA (helix)

- Alex Friedman (chair), Dick Briggs, George Caporaso, Enrique Henestroza, Ned Birdsall, Will Waldron, Yu-Jiuan Chen

2: DTL / pulsed resistive column / pulsed elongated ESQ injector

- Andy Faltens (Chair), Peter Seidl, Steve Lund

CROSS-CUT: multi-pulse and multi-beam

- Roger Bangerter (chair), Grant Logan, Frank Bieniosek

OTHER CONCEPTS (for report; not discussed in subgroups):

- Induction (Grant Logan)
- High-gradient induction (George Caporaso)
- IFA (Craig)
- Single-gap (Craig)