Project X

Linac Design – Chopper Ideas

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Introduction to the CW Linac Beam

- The 1 mA CW Project X ICD-2 CW Linac is to simultaneously serve multiple customers in the initial implementation: the RCS and three 2 GeV areas including a μ-to-e experiment, a rare kaon decay experiment, and a third experiment yet to be specified.
- Beam switching at 2 GeV is accomplished by a pulsed kicker to send 4.3 msec bunch trains to the RCS on selected 10 Hz cycles and an RF separator to deflect bunches at up to the full 325 MHz bunch frequency to one of the three 2 GeV experimental facilities.
- The nominal ICD-2 ion source provides 5-10 mA H^- beam current to meet the peak bunch intensity requirements of experiments, yet the linac current must average just 1 ma for any time interval greater than a few microseconds (beam current modulation frequencies are to be well outside the bandwidth of the accelerating cavities)
- The linac beam is CW only in the sense of the average accelerated current; the fine time structure required is complex and dynamic.

Chopper Requirements for CW Linac

- A chopping system at the front-end of the linac must:
  - Eliminate 80-90% (or 'kick-in' 10-20%) of the beam from a 5-10 ma DC ion source
  - Create a 50.3 MHz structure on each 4.3 msec segment of beam destined for the RCS while maintaining 1 mA average current
  - Create bunch patterns for the 2 GeV experimental facilities appropriately synchronized with the RF separator
    - 325/2 MHz bunches (at zero-crossings of the separator), on for ~100 nsec and off for ~900 nsec at ~continuous 1 MHz rate, for the μ-to-e experiment
    - 325/4n MHz bunches for the kaon experiment and, at opposite phase of the separator, 325/4m MHz bunches for the third experiment where integers n and m will not be static
  - Ramp up beam current in a controlled manner as the 'CW' linac transitions between off and on states
  - Maintain 1 mA average linac beam current as individual customers' beam power requirements change and downtimes occur
- Essentially a dynamically programmable chopper able to select any individual 325 MHz beam bunch is foreseen

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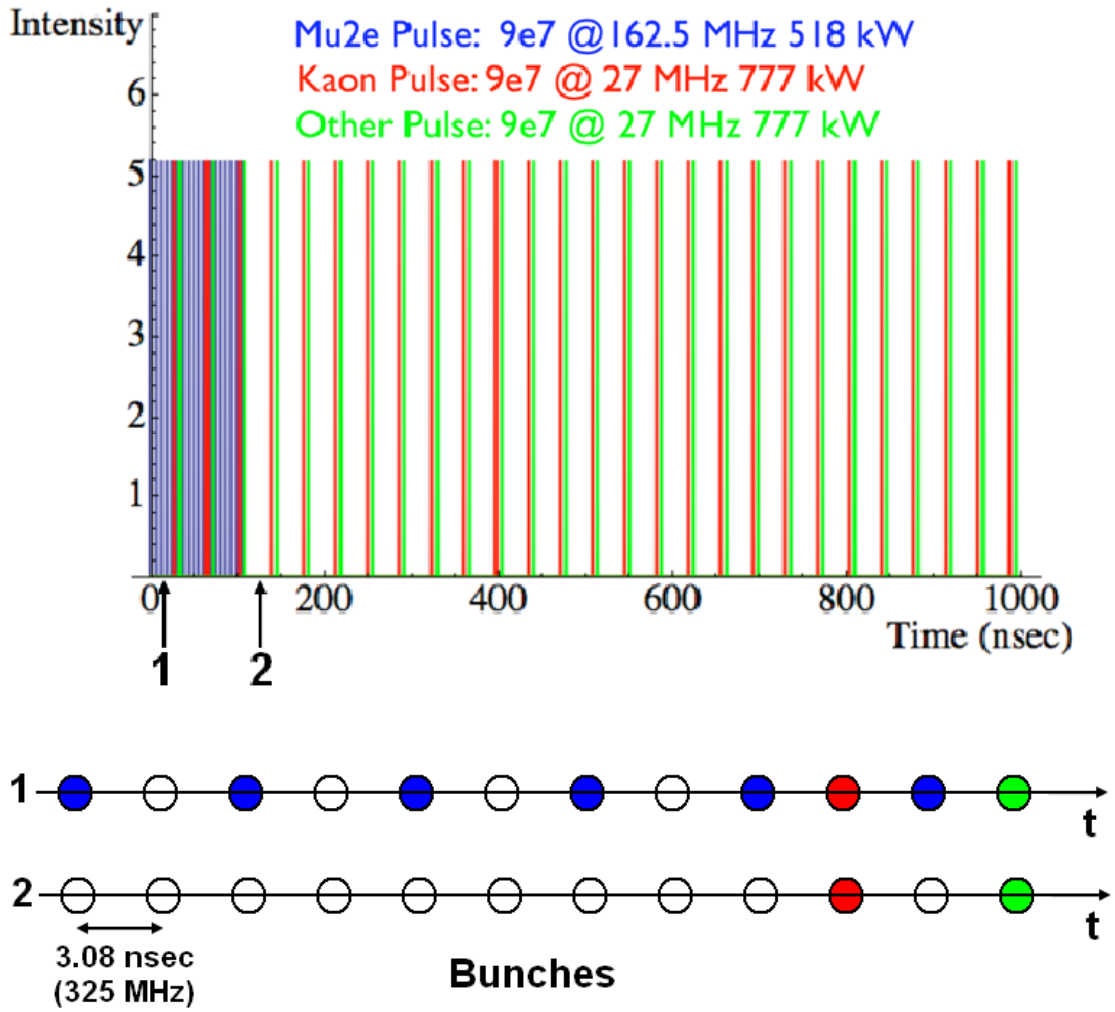
Chopping Example



Example 1 µsec period for linac (without RCS beam):

- **Blue pulses for the muon conversion experiment**
- **Red for rare kaon decay experiments, and**
- **Green for other experiments**
- **In this example the H- ion source delivers about 5 mA DC.**
- **Chopping reduces the average current to 1 mA.**

General Considerations

- The chopper system must be capable to operate at 325 MHz pulse frequency and 80-90% average duty cycle
- Chopping must be complete, >99% extinction ratio
- Discarded beam power to be absorbed will be large
  - 270 watts (90% of 10 mA) at 30 keV (pre-RFQ)
  - 22.5 kW at 2.5 MeV (post-RFQ)
- Un-chopped bunches must be minimally impacted by chopper (spec needed) to prevent emittance growth and subsequent uncontrolled beam loss
- Necessary longitudinal real estate necessary for chopper, either pre- or post-RFQ, will be obtained only with a carefully integrated optics design approach including re-bunching cavities if post-RFQ
- Pulsed power supply design will be formidable, as any approach will require a fast, high-power pulsed supply running at a high duty cycle
- The beam line chopper element will need to tolerate high peak and average power

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Existing/Proposed Choppers*

	CERN-SPL	LANL-SNS	RAL/ESS	FNAL HINS	Project X ICD-2
Beam Energy	3 MeV	2.5 MeV	2.5 MeV	2.5 MeV	2.5 MeV
Electrode Length	2 X 40 cm	35 cm	34 cm	50 cm	50 cm
Electrode Gap	20 mm	18 mm	14 mm	16 mm	16 mm
Deflection Angle	5.3 mRad	18 mRad	16 mRad	24 mRad	24 mRad
Electrode Voltage	±0.5 kV	±2.35 kV	±2.2kV	±2.4kV	±2.4kV
Pulse Rise Time	< 2ns	10 ns	2 ns	< 2ns	~1 ns
Pulse Duration	min 8ns	300 ns	12 ns	< 5.5 ns	~1 ns
Pulse Rep Rate	44MHz	1 MHz	2.4 MHz	53 MHz	325 MHz
Bunch Frequency	352 MHz	402.5 MHz	280 MHz	325 MHz	325 MHz
Burst Duration	0.6 ms	945 ns	1.5 ms	3ms, 1ms	Continuous
Burst Rep Rate	50 Hz	60 Hz	25 Hz	2.5, 10 Hz	Continuous
Duty Cycle	3 %	5.7 %	3.7 %	1 %	100 %
Chop Description	3/8 bunches	On 300,off 645 ns		1 or 2/6 bunches	Arbitrary pattern

Three green circles and the only listed chopper to actually have been applied operationally and that with unsatisfactory results

Green circles indicate relatively 'easy' specs compared to other choppers in the list
Red circles indicate relatively challenging specs compared to other choppers in the list

* Table courtesy of Robyn Madrak; ICD-2 column, Duty Cycle row, and highlights added by speaker

Beam Physics Considerations

- Beam optics design must be fully integrated with chopper system design to alleviate requirements as much as possible on technical systems that will be extremely challenging in the best of situations
  - Arrange transverse and longitudinal focusing elements to provide as generous slot lengths as possible for chopper
  - Optimize beam transverse dimensions for whatever technical solution is applied
    - Minimize aperture requirements in electromagnetic deflector
    - Ribbon beam to optimize interaction region for laser or e-beam neutralizing based chopper?
  - Maximize 'lever arm' for any deflection scheme
  - Maximize effective beam spot size on the absorber

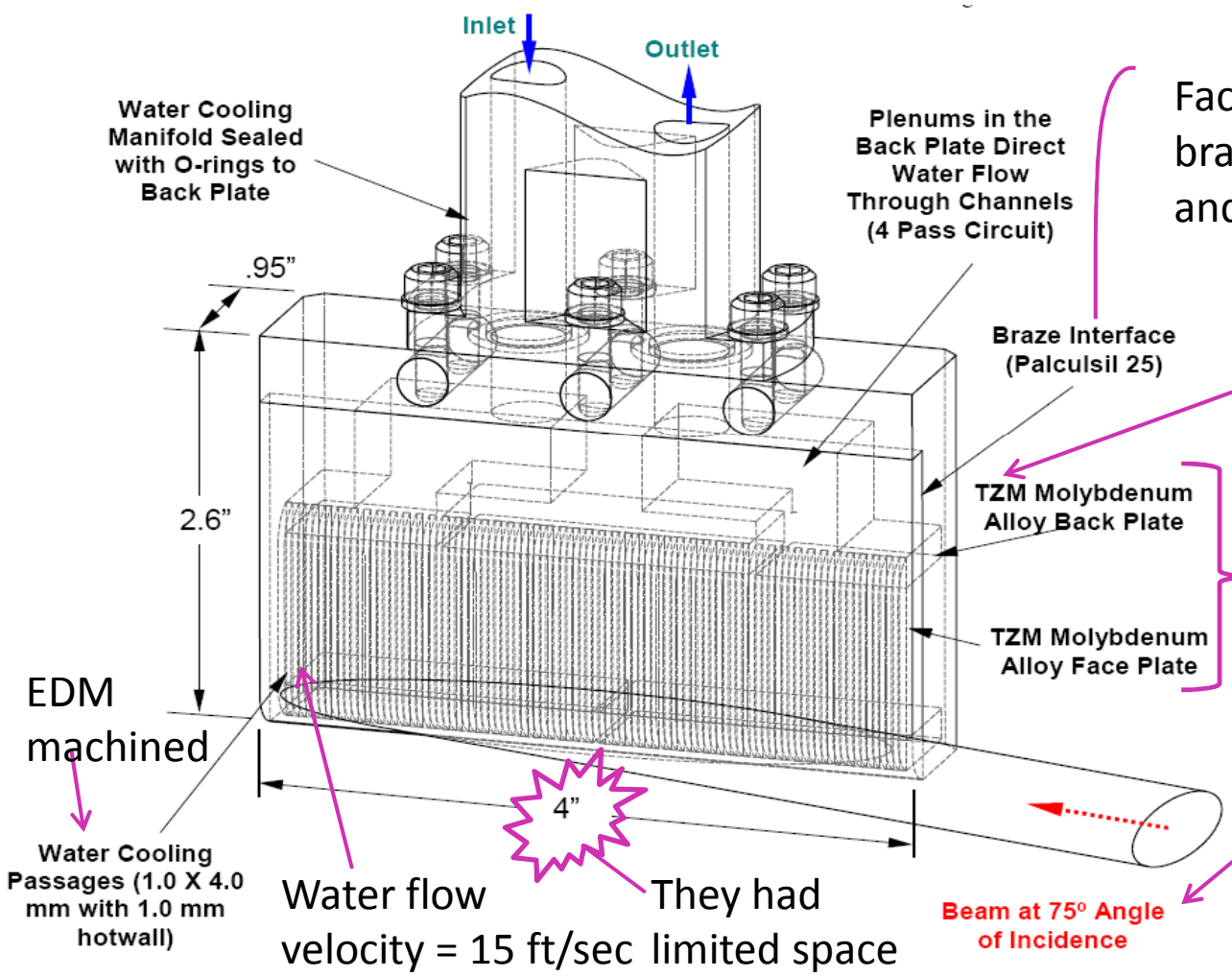
Chopping Before and After RFQ

- Pre-RFQ chopping
  - + Lower beam energy means lower chopped beam power to absorb and dissipate
  - – Beam line real estate is at a premium due to the need to deal with significant transverse space charge forces
  - – Achieving fast rise-times with very low velocity beams is fundamentally problematic
  - – Space charge forces dilute any sharp edges impressed on the longitudinal charge distribution until longitudinal focusing is applied
  - – Pre-chopping will likely be feasible only for chopping out long segments of beam (several tens of nanoseconds or longer)
- Post-RFQ Chopping
  - + Beam is bunched and longitudinal focusing is required in any case, establishing a well-defined time structure
  - – Higher beam energy means much higher chopped beam power to absorb and dissipate
  - – Beam line real estate remains at a premium due to the need here to deal with both transverse and longitudinal space charge forces
  - – Even with pre-chopping, post-chopping will be necessary to produce the high frequency components of the chopping pattern, i.e. to isolate individual bunches
  - – Rise time and fall time requirements of a post-chopper are not eased by pre-chopping
  - – The degree of relief provided by pre-chopping in terms of switching frequency and average power for the post-chopper depends on the specific chopping pattern and the effective bandwidth achievable in the pre-chopper

Thermal and Mechanical Considerations

- The chopper device and beam absorber must be as physically compact as possible and integrated into what will be less-than-generous slot lengths constrained by other beam physics requirements
- The beam absorber must absorb and dissipate the average chopped beam power, up to kilowatts
- More significantly absorber design must contend with the dominating fact that the proton range at these low energies is measured in microns and all the energy is deposited in a very thin surface layer. THIS IS A BIG DEAL…
- The effective beam spot size on the absorber must be maximized
- At 2.5 MeV materials must be selected to minimize neutron production and residual radiation in absorber

SNS MEBT Chopped Beam Absorber



Faceplate (channels) brazed to backplate and cut by wire EDM

Mo-0.5Ti-0.1Zr

no Cu or alloys; Cu65 neutron Prod thresh= 2.1 MeV

EDM machined

Water flow velocity = 15 ft/sec

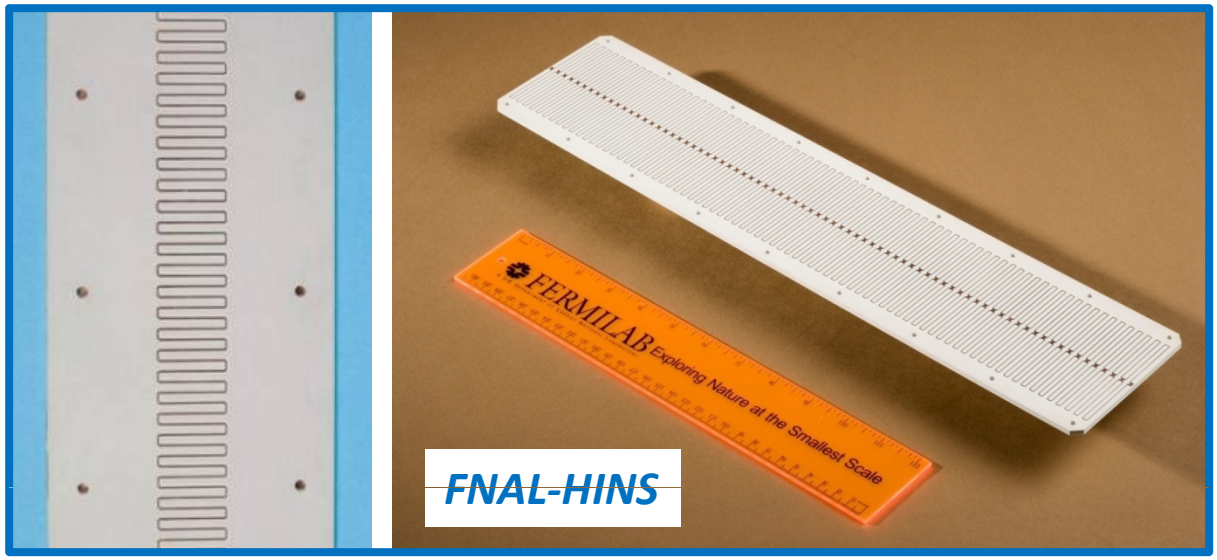
They had limited space

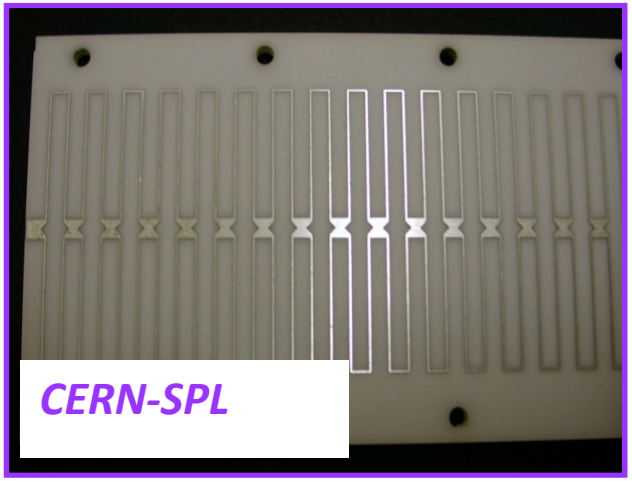
Decreases instantaneous heat flux

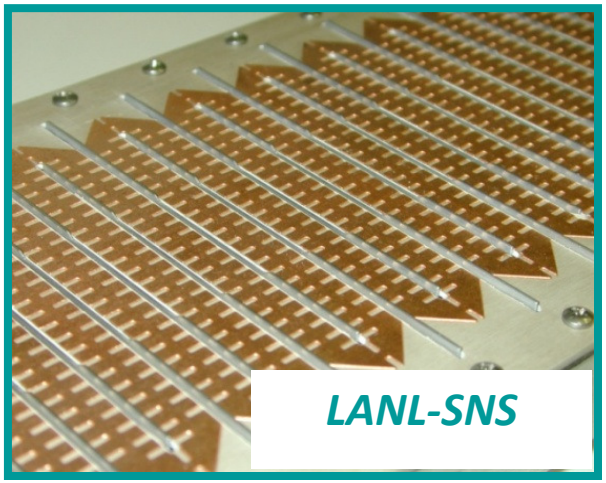
Conventional Chopper Ideas

- Segmented Einsel lens deflector ala SNS LEBT 'kicker'
  - Offers advantages and disadvantages of pre-RFQ chopping
  - Technical challenges
    - Pulsed power supply design
    - Pulse transmission line design
  - Offers possibility of dumping some chopped beam power onto RFQ vanes with resulting issues of RFQ de-tuning and possible damage
- 'Slow wave' electric deflector structure ala SNS, ESS, Linac 4 and HINS
  - Post-RFQ chopper
  - Technical challenges
    - Structure mechanical and electromagnetic design
    - Pulsed power supply design
    - Power dissipation in slow wave structure and terminating loads
- Series mini-kicker design
  - Technical challenges
    - Same as 'slow wave' chopper except complicated with multiple albeit lower voltage pulsers

Example "Slow Wave" Kicker Structures







Other Chopper Ideas

- Fast ion source modulation
  - Pre-RFQ chopper advantages and disadvantages
  - Technical questions
    - Is there a working example of controlled ion source beam current modulation on tens-of-nanoseconds time scale?
    - What effective bandwidth can be achieved?
  - Still requires fast pulsed high duty factor power supply
- Segmented RFQ buncher and RFQ accelerator sections with chopper in-between
  - This might ease kicker voltage rise time spec for the bunched beam to 3 nsec
- Superconducting transverse deflector cavity(s)
  - Resonant device is not compatible with aperiodic bunch patterns required

More Ideas

- H^- neutralization by laser
  - Laser energy of order 5 mJ (depending on spot size) per pulse is required to neutralize ~99% of the ~1.9e8 H^- in a single 2.5 MeV bunch
  - At 325 MHz pulse rate, this corresponds to >1.6 MW average laser power!
  - A mirror arrangement with multiple reflections to match beta=0.073 of the beam could reduce required photon power by a factor of 10-20 --> a mere 160 kW.
  - Firing the laser across a flat ribbon beam could reduce required power another factor (of 2?)
  - Practically realizable average power from a laser is presently a few kW
  - This concept requires more than an order of magnitude refinement to be considered possible
- H^- neutralization by electron beam
  - Cross-section of e^- on H^- is being investigated
  - Pulser to generate electron beam will no be insignificant

Pulsed Power Supply Considerations

- Nearly all conceived chopper designs require a fast, high frequency, high power pulsed power supply
  - There are real technical limitations (e.g. next slide) that might be avoided by keeping specified requirements as relaxed as possible
    - Rise time
    - Voltage
    - Pulse frequency
    - Pulse length
    - Effective duty cycle
- Need to investigate how much pulser spec can really be relaxed by 'kicking-in' rather than 'chopping out' the beam
- Reliability of a '(beyond)state-of-the-art' pulsed power supply might be an issue
- This will be a costly item

Electrical Power Switching Technology Limitation Example

- Comparison of technologies - typical specs for pulsers based on avalanche transistors and FETs

- Avalanche Transistors
  - Rise Time - Down to 100ps.
  - Voltage - Up to 6kV per module.
  - Pulse Length - Into 50 ohms, 15ns is a typical maximum but 20ns can be achieved subject to other pulser parameters, notably voltage. Capacitive loads may be pulsed for times up to several µs.
  - Repetition Rates - 1kHz with a sufficiently large power supply. Special units to 10kHz at lower voltages (~1kV).
  - Fidelity - Significant perturbations to ideal waveforms.

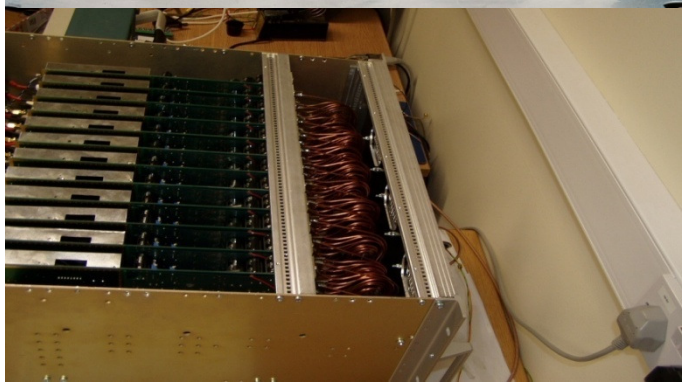
- Field Effect Transistors (FETs)
  - Rise Time - Down to a few ns.
  - Voltage - Up to 10kV per module.
  - Pulse Length - Maximum pulse lengths into 50 ohms are set by power considerations. Long pulses into capacitive loads can also be achieved.
  - Repetition Rates - Several kHz with a sufficiently large power supply. Special units to 100kHz. Low voltage units (less than 1kV) to several MHz.
  - Fidelity - Reasonable fidelity for times long compared with the rise time.

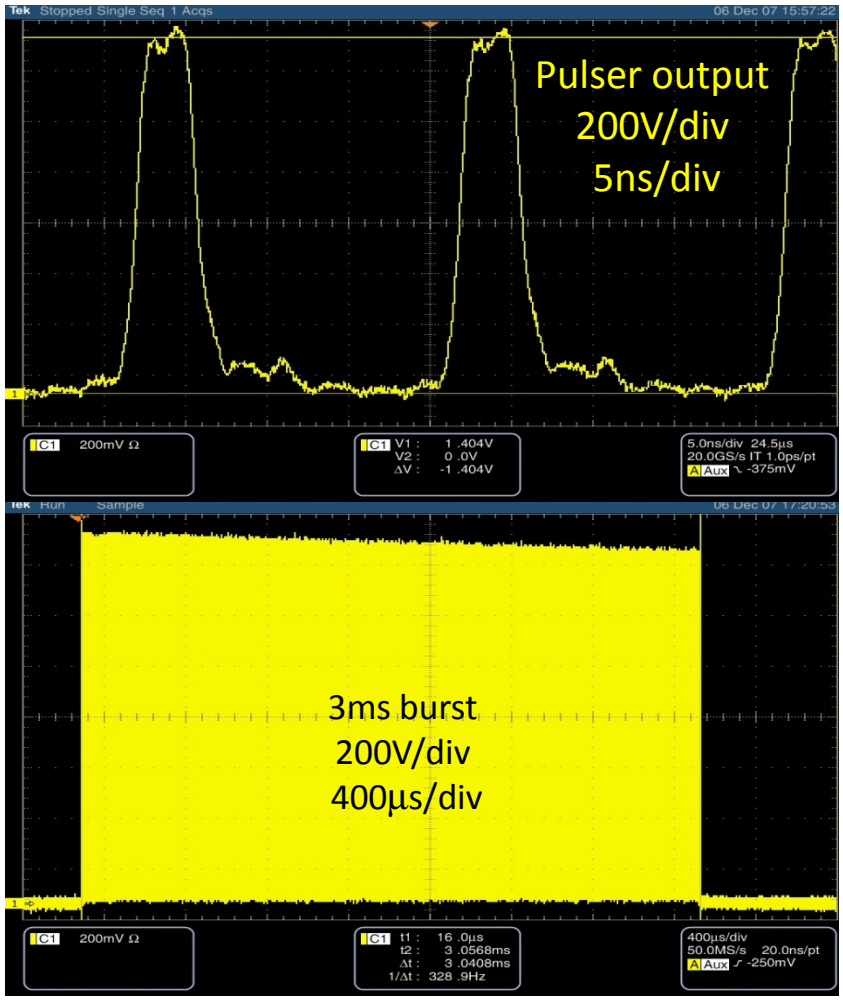
- These are far from what is required for this chopper!

Information from Kentech Instruments Ltd. website

Kentech Pulser Technology at Fermilab

- 1.2 KV unit rated for 1% duty factor – 210K$





Conclusion

- Beam chopping performance is critical to successful operation of the present CW Project X ICD-2 concept
- Design of an acceptable chopping system with requirements as currently understood is extremely challenging, pushing the limits of current technologies
- An approach that fully integrates beam physics, mechanical, and electrical design considerations from the start is necessary if a realizable solution is to be found
- Basing the success of the entire project on a system pushing the limits, as does this, is a risky proposition until a technically feasible design is outlined
- Chopper system investigations must be high priority R&D
- All ideas from collaborators are welcomed