Status of the warm front end of PIP-II Injector Test

Alexander "Sasha" Shemyakin for PIP2IT team

APT seminar

18 April 2017

Posters at IPAC'17

- Immediate reason: two posters at IPAC'17
  - Status of the warm front end of PIP-II Injector Test
    - A. Shemyakin, M. Alvarez, R. Andrews, C. Baffes, J.-P. Carneiro, A. Chen, P. Derwent, J. Edelen, D. Frolov, B. Hanna, L. Prost, A. Saini, G. Saewert, V. Scarpine, V.L.S. Sista, J. Steimel, D. Sun, A. Warner
  - Characterization of the beam from the RFQ of the PIP-II Injector Test
    - A. Shemyakin, J.-P. Carneiro, B. Hanna, L. Prost, A. Saini, V. Scarpine, V.L.S. Sista, J. Steimel

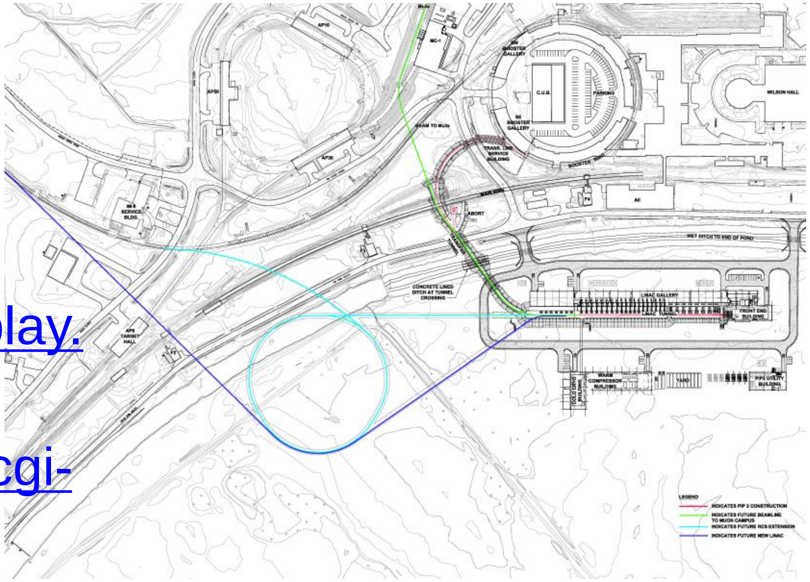
- This talk's scope is a bit larger

Outline

- PIP-II and PIP2IT
- Warm front end sections
  - LEBT
    - Partially un-neutralized scheme
  - RFQ
  - Characterization of the beam coming out of the RFQ
  - MEBT scheme
    - Scraping system
  - First version of the full – length MEBT
- Plans

Proton Improvement Plan – II (PIP-II)

- Upgrades for Fermilab Accelerator Complex
  - 800 MeV, 2 mA CW-compatible H^- Superconducting Linac and beam line to Booster
  - Upgrades to Booster, MI, and RR
  - The immediate goal is to provide >1 MW to LBNF/DUNE
- Platform for future upgrades
  - PIP-III: Higher MI power; multiple experiments
- See details at P2MAC 2017
  - https://indico.fnal.gov/conferenceDisplay.py?confId=13692
  - And CDR: http://pip2-docdb.fnal.gov/cgi-bin/ShowDocument?docid=113

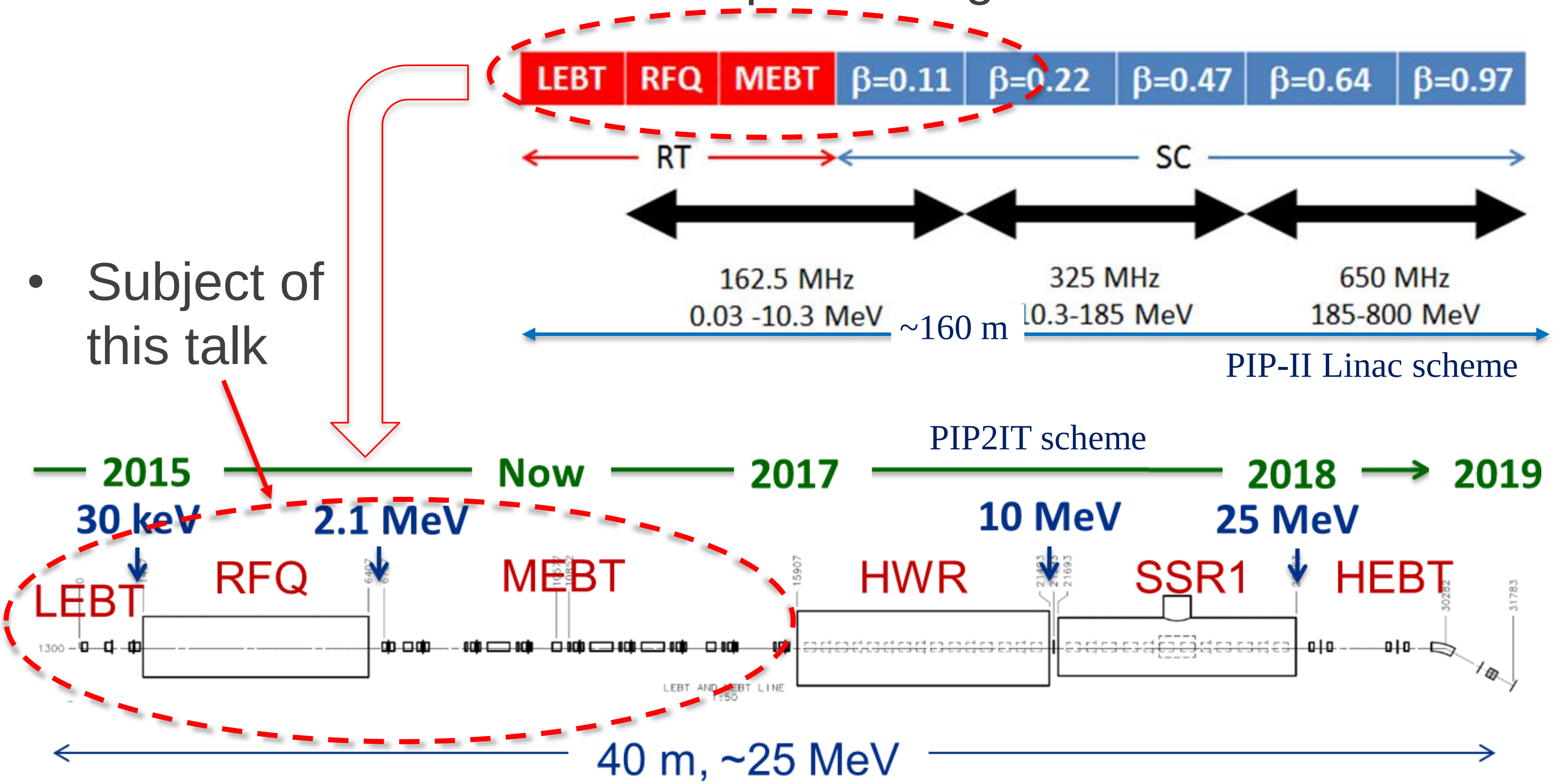


Layout of PIP-II and its possible future upgrades

CDR = PIP-II Conceptual Design report
CW = Continuous Wave

PIP-II Injector Test (PIP2IT)

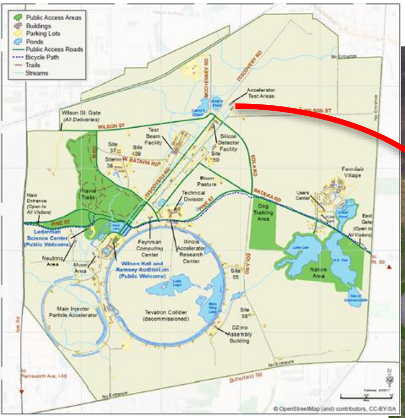
- PIP2IT: a test accelerator representing the PIP-II front end
- Subject of this talk



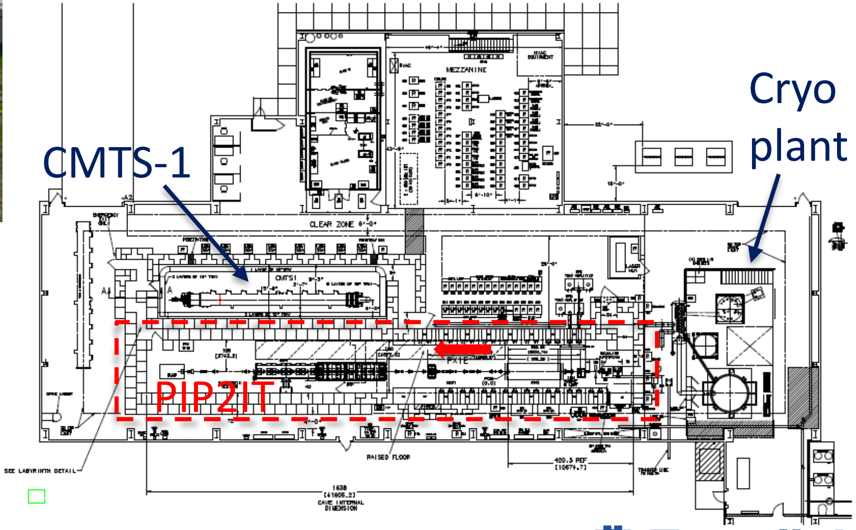
LEBT = Low Energy Beam Transport; RFQ= Radio Frequency Quadrupole; MEBT= Medium Energy Beam Transport; HWR = Half-Wave Resonator; SSR1=Single Spoke Resonator; HEBT = High Energy Beam Transport

PIP2IT location

- Coexisting with CMTS-1 in CMTF building
  - Space eventually will be used for testing PI-II cryomodules when PIP2IT parts will be moved to PIP-II front end



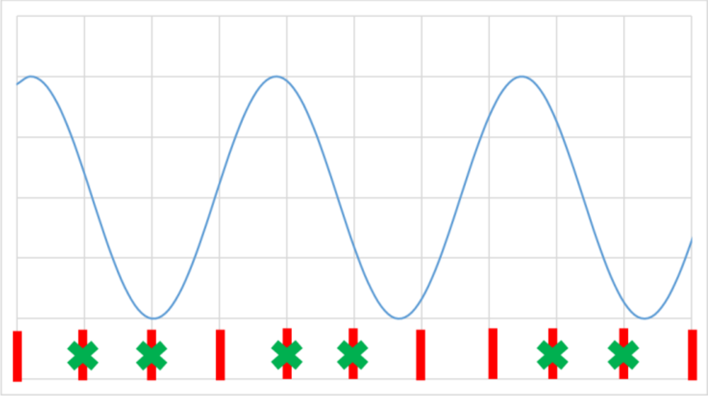
CMTF floor plan with a full-size PIP2IT cave. Arrow shows beam direction.



CMTF = Cryo Module Test Facility
CMTS1 = Cryo Module Test Stand #1

Reflection of PIP-II features in PIP2IT

- PIP-II: CW – compatible; initially pulse mode 20Hz x 0.55 ms
  - PIP2IT: acceleration in SRF from low energy (2.1 MeV); all elements are CW-compatible
  - Needs to work in a wide range of duty factors
- PIP-II: might be a workhorse for a half of century
  - Solutions that are more likely to be reliable are highly preferable
- PIP-II: longitudinal painting in Booster; multiple users in future
  - PIP2IT: bunch-by-bunch selection by MEBT chopping system

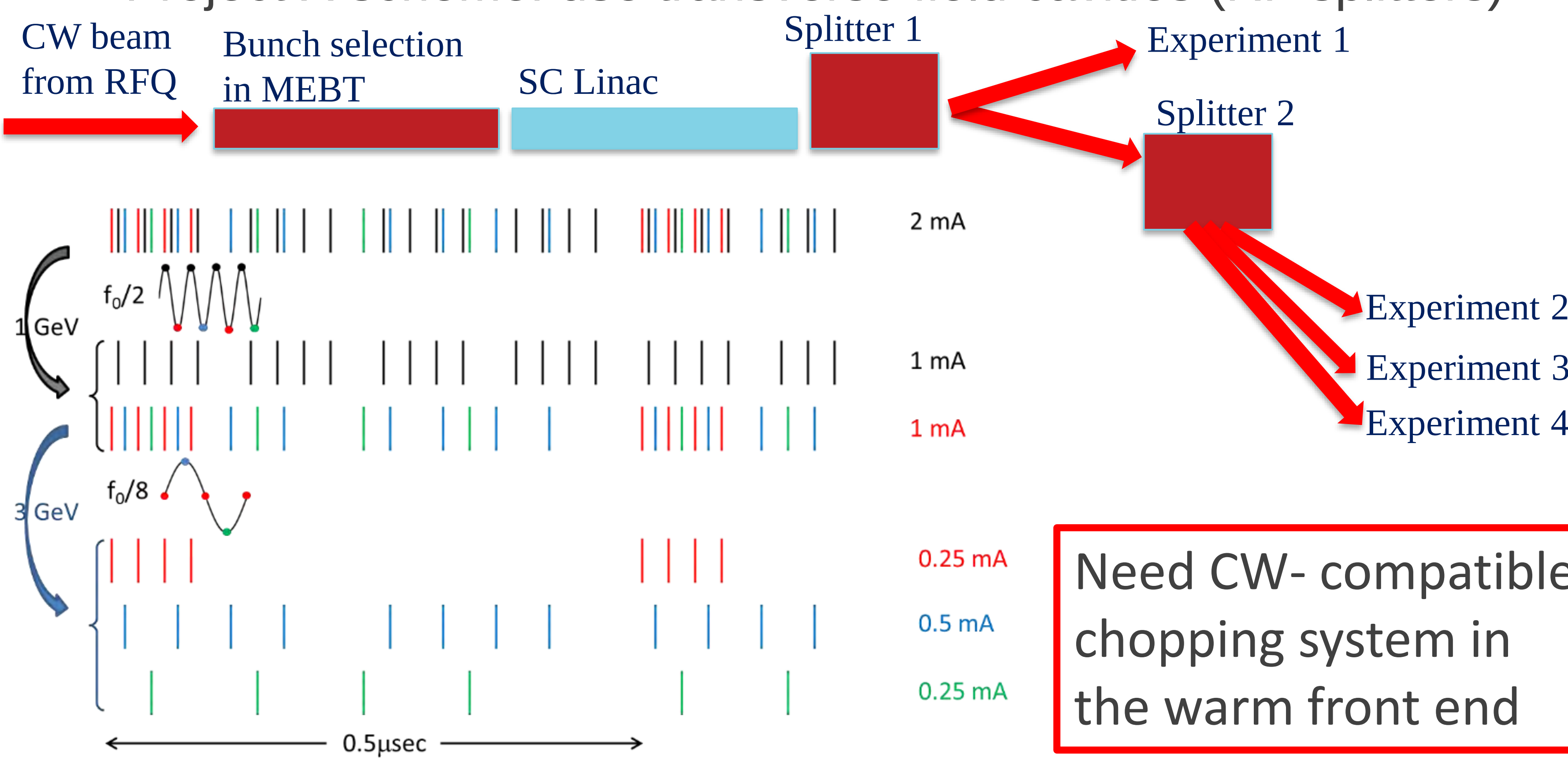


Booster RF frequency at injection: 44.7 MHz

Bunch repetition rate of the CW beam coming out of RFQ: 162.5 MHz

PIP-II bunch structure and the MEBT chopper

- Possible future use: distribution of quasi-CW beam between different users with different time structure requirements
  - Project X scheme: use transverse field cavities (RF splitters)



Need CW- compatible chopping system in the warm front end

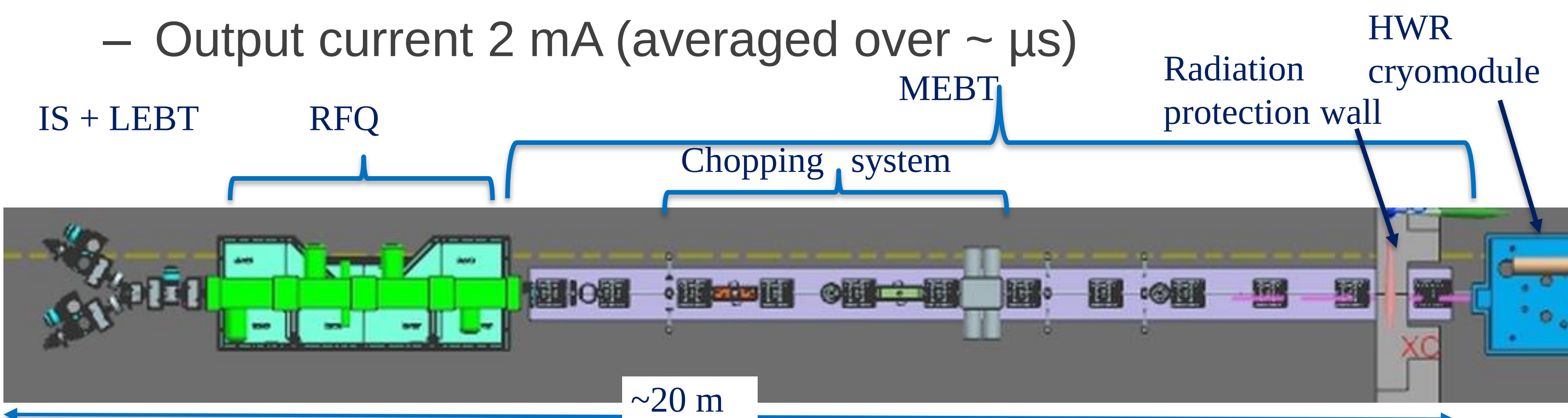
Front end output parameters

- Front end needs to supply programmable bunch sequence

Parameter	Unit	CDR	CW
Energy	MeV	2.1	
Beam current from RFQ, nominal/max	mA	5/10	
Beam current (averaged over ~ μs)	mA	2	
Typical H^- bunch population		$2 \cdot 10^8$	
Transverse emittance, rms normalized	μm	≤ 0.23	
Bunch longitudinal emittance, rms normalized	μm (eV·μs)	≤ 0.31 (≤ 1)	
Pulse frequency	Hz	20	CW
Pulse length (operation)	ms	0.55	CW
Pulse length (tuning)	μs	10	

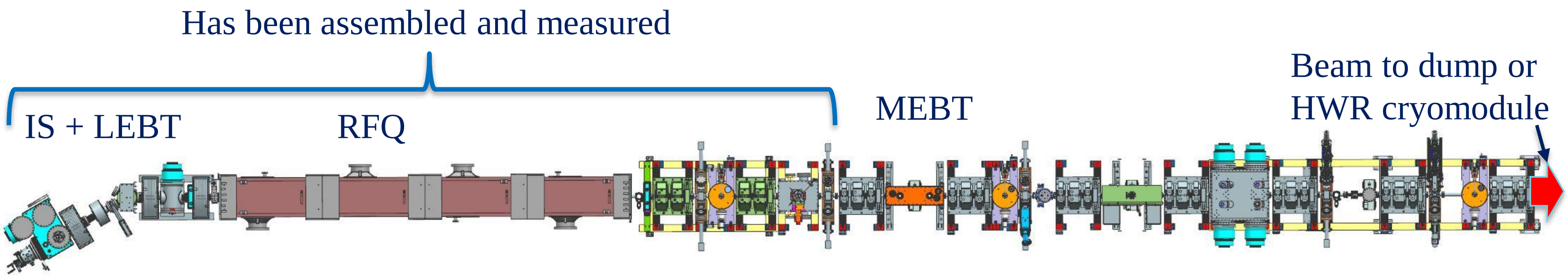
PIP-II warm front end

- IS+LEBT: 2 ion sources and Low Energy Beam Transport with a switching magnet
  - 30 keV, ≤10 mA, from 5 μs (up to 60 Hz) to DC
- RFQ: Radio Frequency Quadrupole accelerator (162.5 MHz)
  - 2.1 MeV, ≤10 mA, RF either pulsed up to 5 ms, 20 Hz, or CW
- MEBT: Medium Energy Beam Transport
  - Chopping system defines the length and most of features
  - Output current 2 mA (averaged over ~ μs)



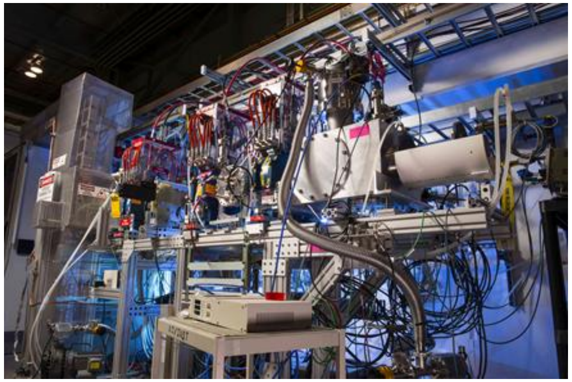
PIP2IT warm front end

- In its final configuration, “almost” the PIP-II front end.
- Differences: only one ion source; shorter MEBT
    - Not ideal protection of SRF from vacuum failures, no radiation wall, but all other features are in place
- Strategy
    - The main near goal is “CDR” parameters (20 Hz x 0.55 ms)
    - Try to push toward CW where it is possible
    - All elements that may go to PIP-II are designed CW-compatible

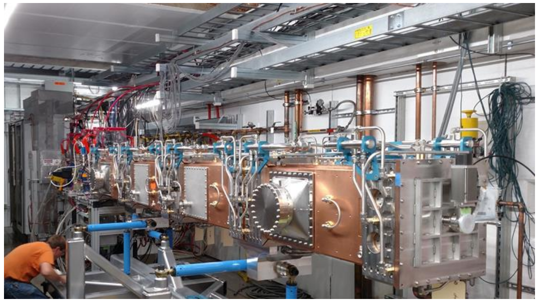


Stages

- Several stages, in pace with equipment delivery and budget
  - Ion Source + LEBT in several versions
    - Settings for optimum injection into RFQ
    - Scheme with an un-neutralized section
  - RFQ + 2-doublets MEBT: characterization of beam from RFQ

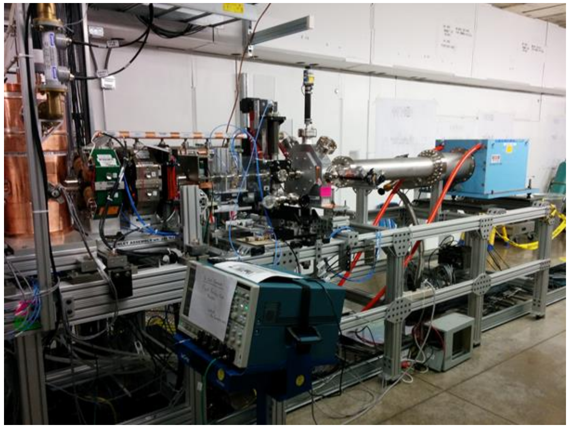


LEBT, 2015



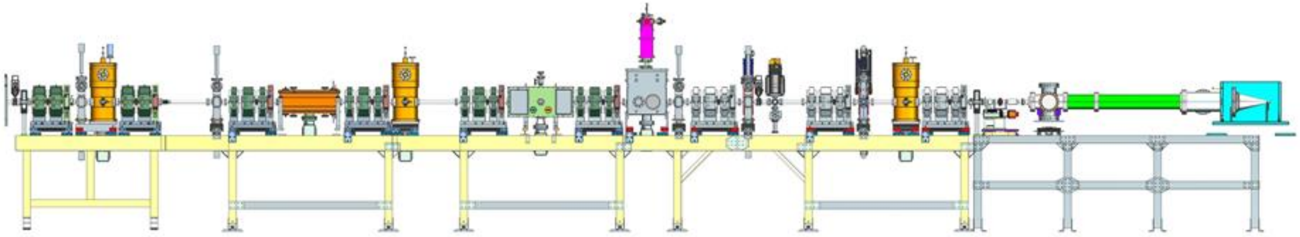
RFQ, 2016

Short MEBT, now

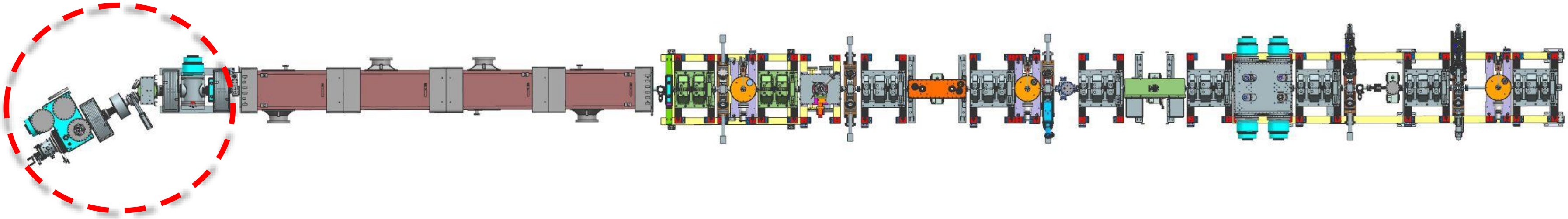


- Next: full-length MEBT

Coming in summer 2017



Ion source and LEBT



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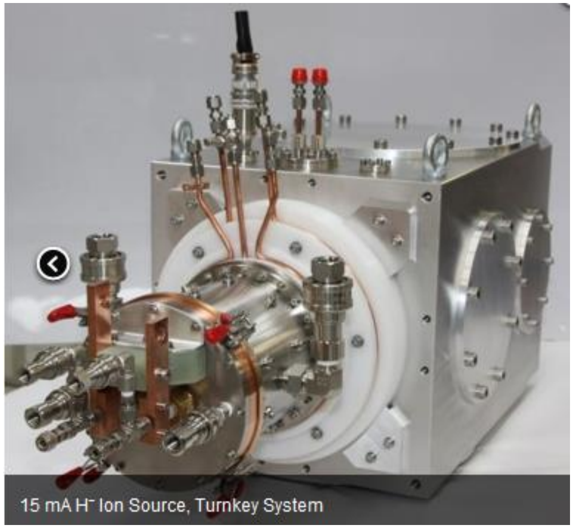
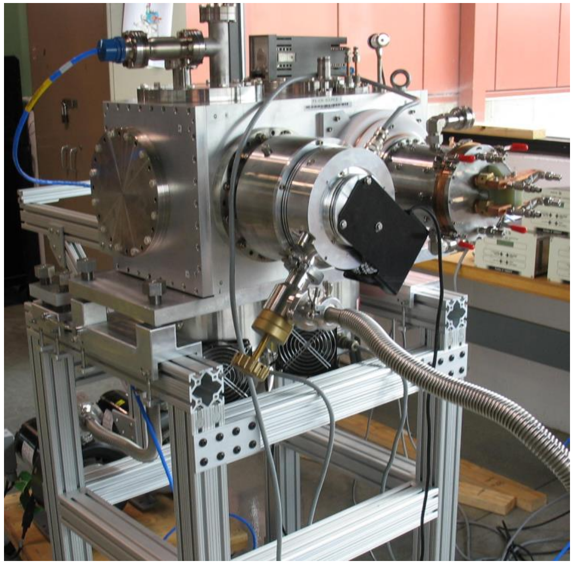
Ion source

- 15 mA DC, 30 keV H- ion source from D-Pace (Canada)
  - TRIUMF-licensed Volume Cusp, filament Ion Source
  - Maintenance is defined by filament life time, 300 – 700 hours
- Added a modulator to its extraction electrode to pulse beam
  - 5 µs – 16 ms, up to 60 Hz (G. Saewert)



From http://www.d-pace.com

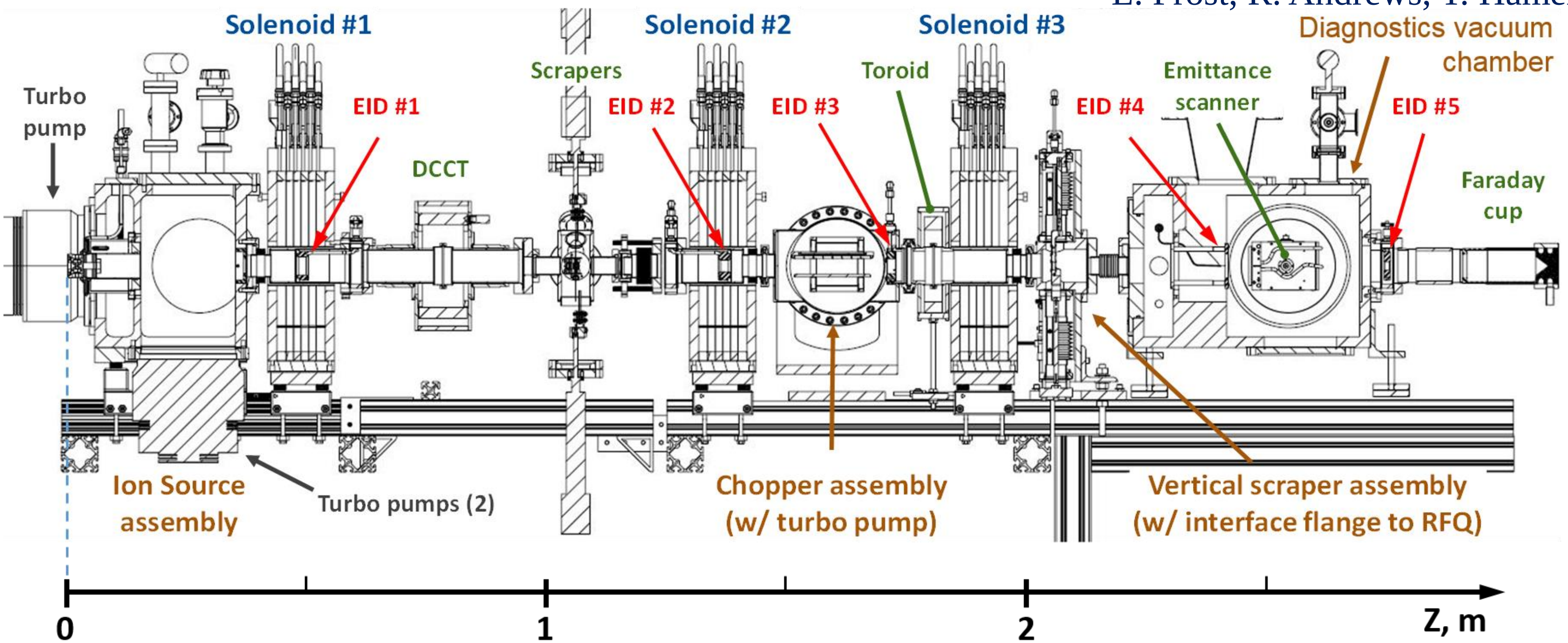


Ion source assembled at CMTF

Low Energy Beam Transport (LEBT)

- LEBT configuration where beam prepared for injection into RFQ was characterized
  - Later emittance scanner was moved to the ion source

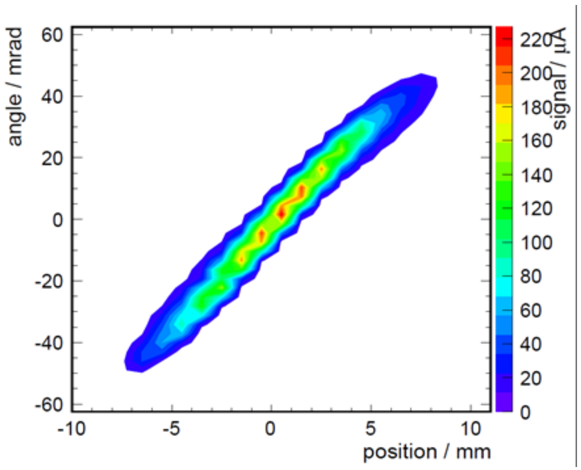
L. Prost, R. Andrews, T. Hamerla

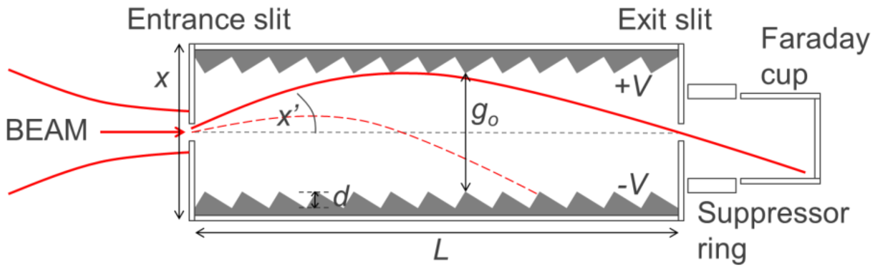


EID = Electrically Isolated Diaphragm; DCCT = DC current transformer;
Toroid = AC Current Transformer or Rogowski Coil

LEBT emittance scanner

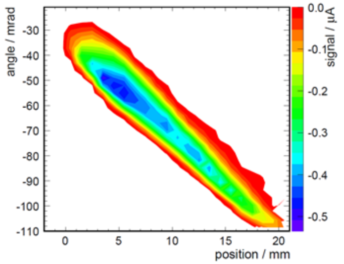
- Allison–type emittance scanner (in collaboration with SNS)
  - Previous LBNL/SNS design modified for DC operation
  - Water- cooled front slit
  - Each point of 2D phase is defined by
    - Intensity: current of a beamlet cut out by two slits
    - Position: changed by a stepper motor
    - Angle: voltage between deflecting plates





LEBT emittance scanner.
V. Scarpine, M. Alvarez

Example of the phase space portrait recorded at the end of LEBT. 5 mA. ε_x= 0.14 µm (n, rms). 1% cut.



Proton signal for the same distribution (~0.5% total).

Images are from R. D'Arcy et al., NIM-A815 (2016)

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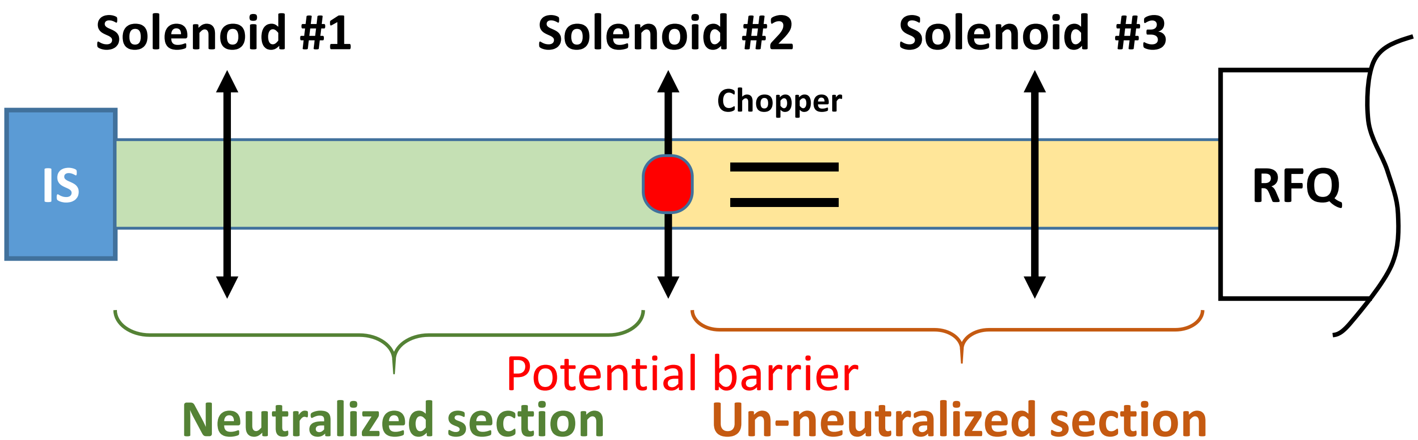
LEBT transport scheme

- Realized a scheme combining a good vacuum in RFQ and constant beam parameters through the pulse, and a low emittance growth

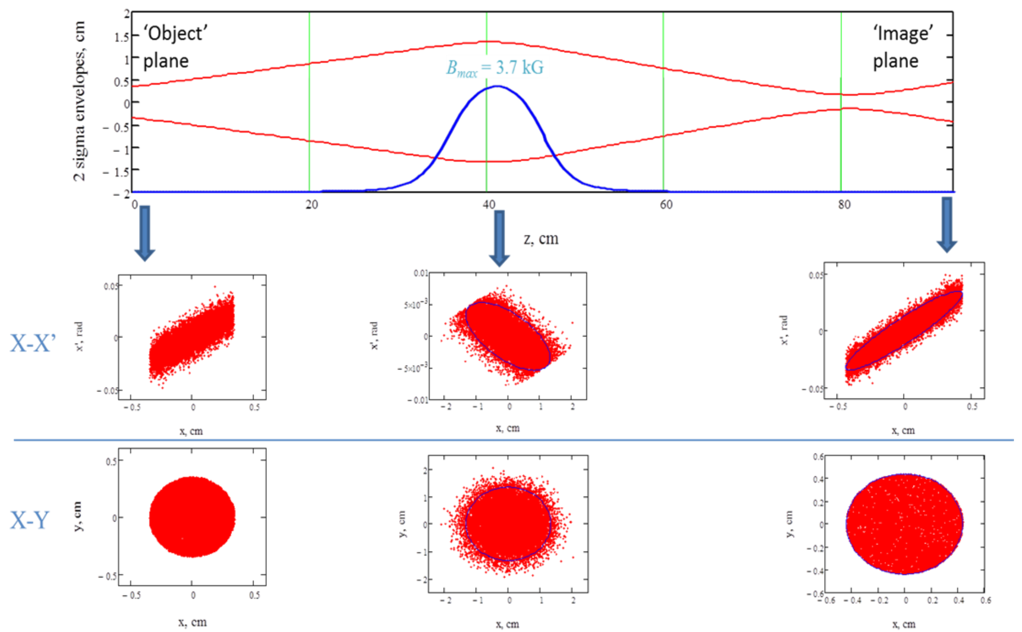


- High vacuum pressure
  - Gas load from ion source
- Neutralizing particles confined by potential barrier

- Low vacuum pressure
  - Limits rate of production of neutralizing particles
- Clearing electric field
  - Sweeps neutralizing particles out of the beam path

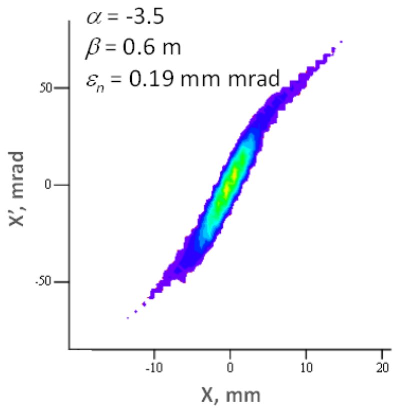
Recipe for a low emittance growth transport

- Create in the ion source a distribution close to Uniform in space and Gaussian in velocities (UG)
  - Scrape non-linear edges
- Propagate the beam fully neutralized and focus as desired
- Interrupt neutralization near the image plane
  - Beam spacial distribution is again uniform there
- Transport the beam un-neutralized through the chopper into RFQ, keeping the distances short

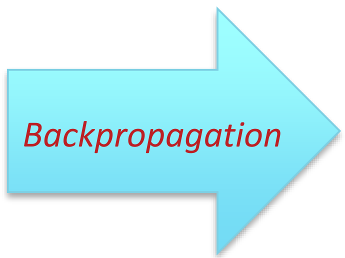


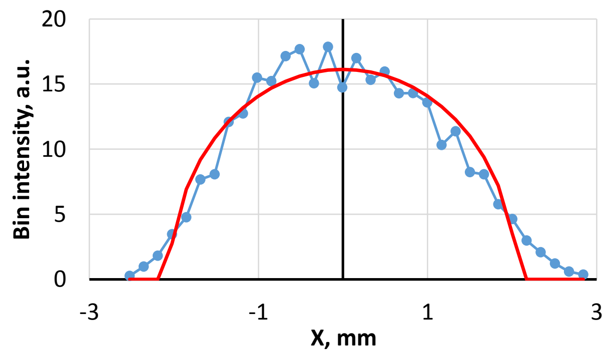
Measurements vs. Simulations

- Measurements (L. Prost, J.-P. Carneiro, B. Hanna, R. D'Arcy)
  - Beam distribution at the ion source exit (emittance scanner)
  - Profiles with scrapers between solenoid 1 and 2
  - Beam distribution at the LEBT exit (emittance scanner)
- Simulations
  - MathCad program initially written by V. Lebedev (L. Prost)
  - TRAC/TraceWin (J.-P. Carneiro)



Phase space distribution at the exit of the ion source at 5 mA

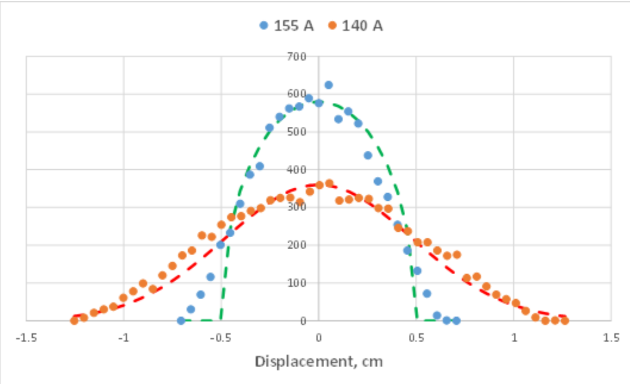




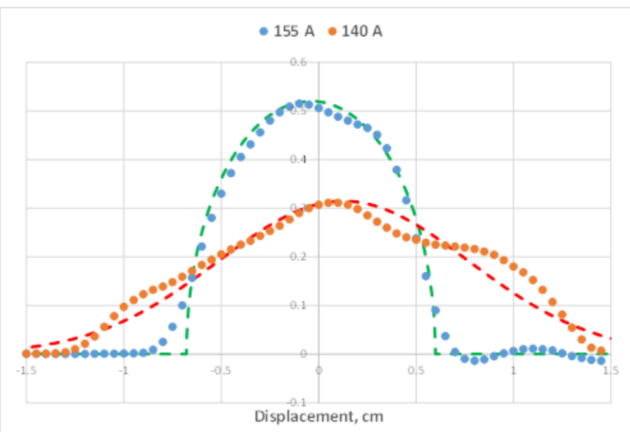
Before scraping of tales, ~20% of initial intensity

1D current density distribution from a back propagated phase portrait (blue circles) and a uniform distribution fit (red)

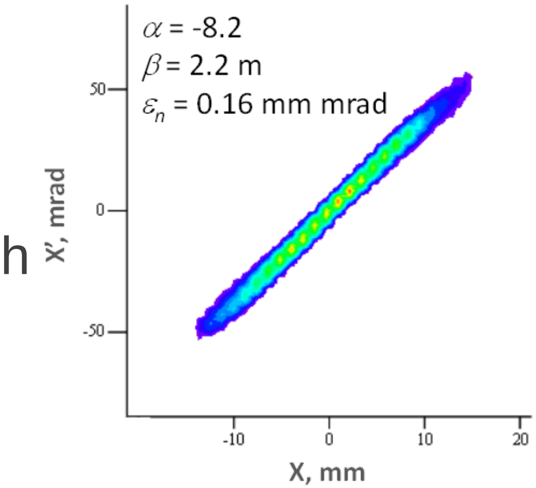
Measurements and simulations for two tunes



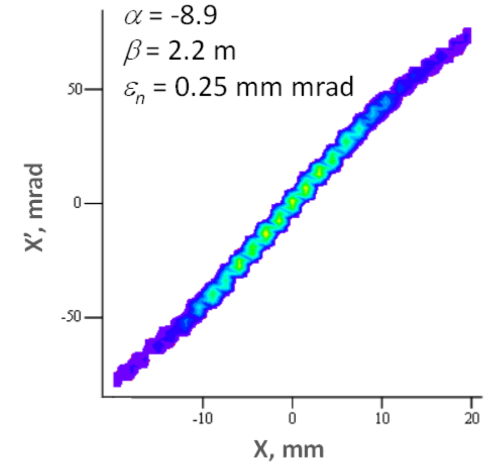
Simulations ↑ and measurements ↓ with scrapers at two different currents of Solenoid#1. 5 mA

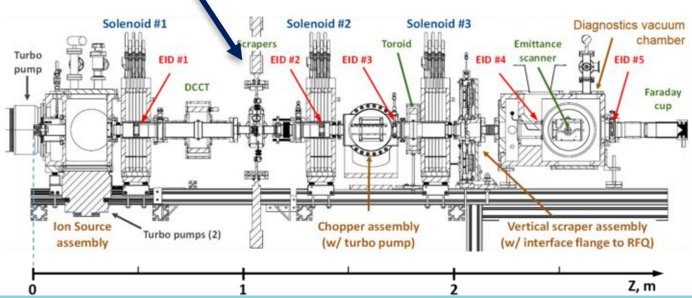


- The scheme works!
  - Combination of
    - Chopping
    - Low emittance growth
    - Good vacuum
      - <2·10^{-7} Torr at RFQ entrance



Emittance measured at the end of LEBT at the tune corresponding to Uniform (top) and Gaussian (bottom) shape at the point of neutralization interruption. 5 mA





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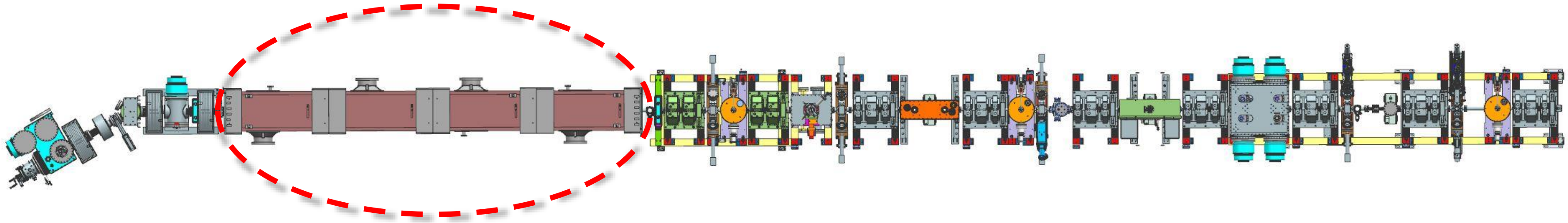
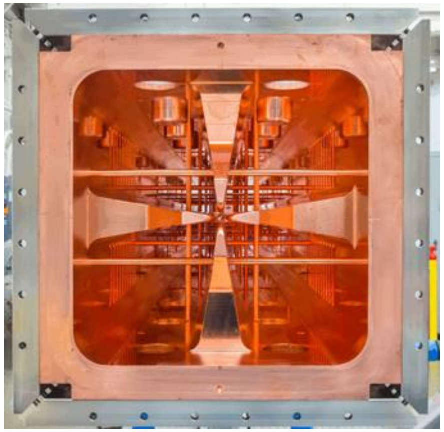
RFQ



Radio Frequency Quadrupole accelerator (RFQ)

- 2.1 MeV, 162.5 MHz CW RFQ (J. Steimel)
  - 4-vane, 4-module copper structure
  - Designed and built by LBNL
    - Detailed RF (G. Romanov) and beam simulations
    - Output $\varepsilon_\perp < 0.2\ \mu$m, $\varepsilon_L < 0.28\ \mu$m (up to 10 mA)
  - 32 pi-mode rods to suppress dipole modes
  - 80 fixed slug tuners for frequency adjustment and local field perturbation corrections
  - Nominal inter-vane voltage 60 kV
  - Nominal power 100 kW



RFQ installed at PIP2IT

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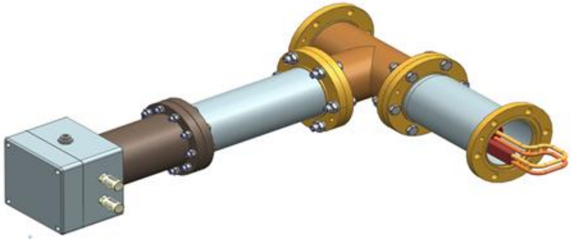
RFQ power

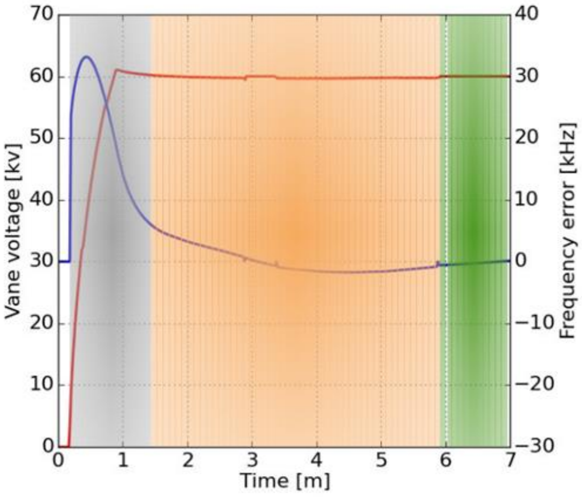
- Two 75-kW input couplers (S. Kazakov, O. Pronitchev)
  - Forced-air cooled antenna
  - DC bias to reduce multipacting
  - Work reliably in pulse mode
  - Two coupler vacuum windows developed leaks after operating in CW for several hundred hours
    - Presently work in pulsed mode only; modifications in works



- Two CW 75-kW, 162.5-MHz solid-state power amplifiers from SigmaPhi, France (R. Pasquinelli, D. Peterson)
  - Each with a 75-kW circulator
  - After initial failures of individual components, worked for >300 hours in CW
    - Intermittent problem with communication

Resonant frequency control

- Resonant frequency is controlled by adjusting ΔT between the vanes and RFQ walls water circuits (B. Chase's group)
  - Adaptive control system designed to regulate the steady state temperature of the RFQ cooling system to better than 0.1°C
  - Automated start and recovery after RF trips
    - In CW, typical cold start time for CW ~40 min, and typical recovery is from seconds to < 10 min
- Frequency in middle of regulation range is found to be low by 50 kHz
  - Will be corrected by re-machining tuners



Example of RFQ trip recovery (courtesy of J. Edelen)
Vane voltage: red, Frequency error: blue.
Grey: RFQ ramp, LLRF is in SEL. Orange: Resonance control bringing RFQ to frequency, LLRF is in SEL.
Green: RFQ is in GDR and LLRF feedback is active.
SEL=Self-Excited Loop; GDR=Generator Driven resonance

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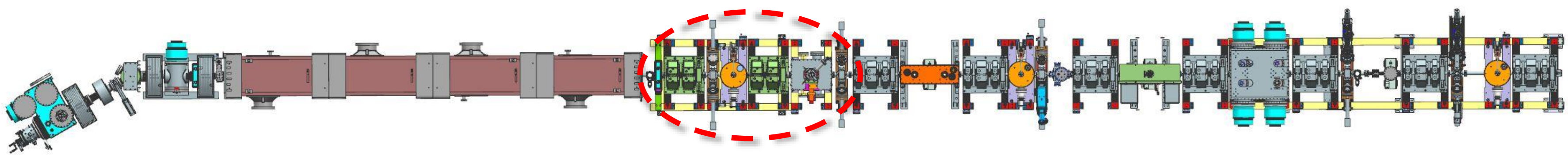
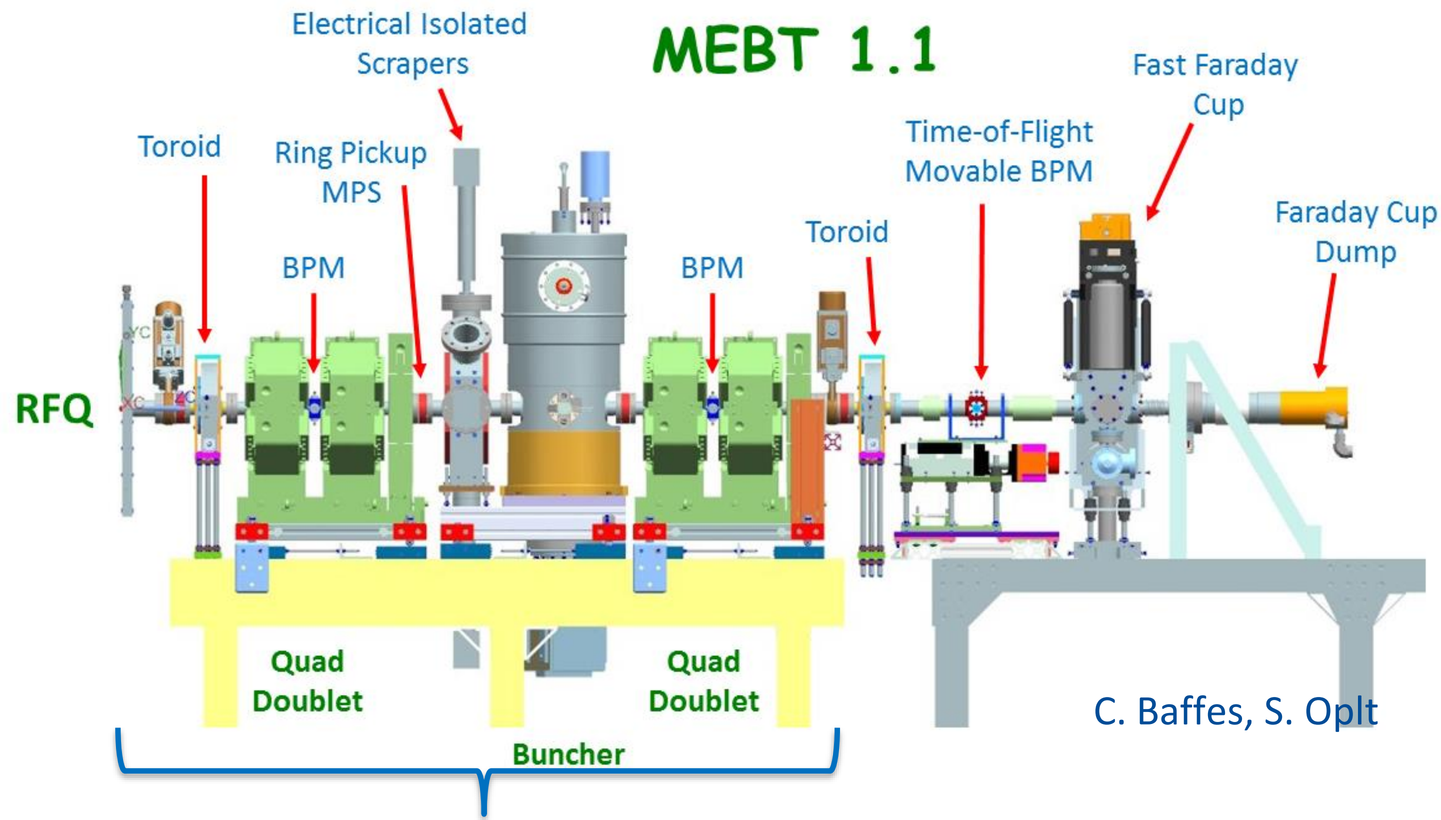
Short Medium Energy Beam Transport line (MEBT-1)

- A beam line (“MEBT-1”) was assembled to characterize the beam from RFQ
  - Several configurations different mainly in diagnostics
  - 2.1 MeV, up to 10 mA (nominal 5 mA)



MEBT-1.1 configuration

- Focusing
  - Two quadrupole doublets delivered by BARC, India
  - Bunching cavity (HiTech Inc)



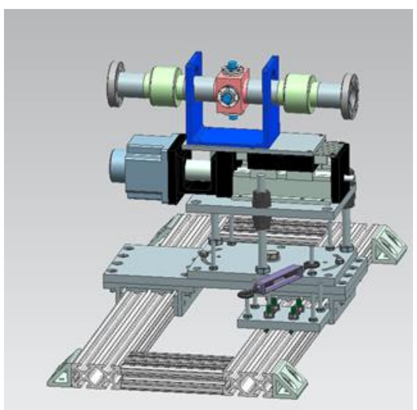
BARC= Bhabha Atomic Research Centre, Mumbai; MPS = Machine Protection System; BPM = Beam Position Monitor (capacitive pickup)

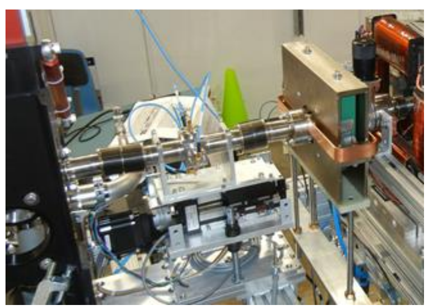
Portion of the final MEBT; stayed the same in all configurations

Beam measurements: transmission; energy

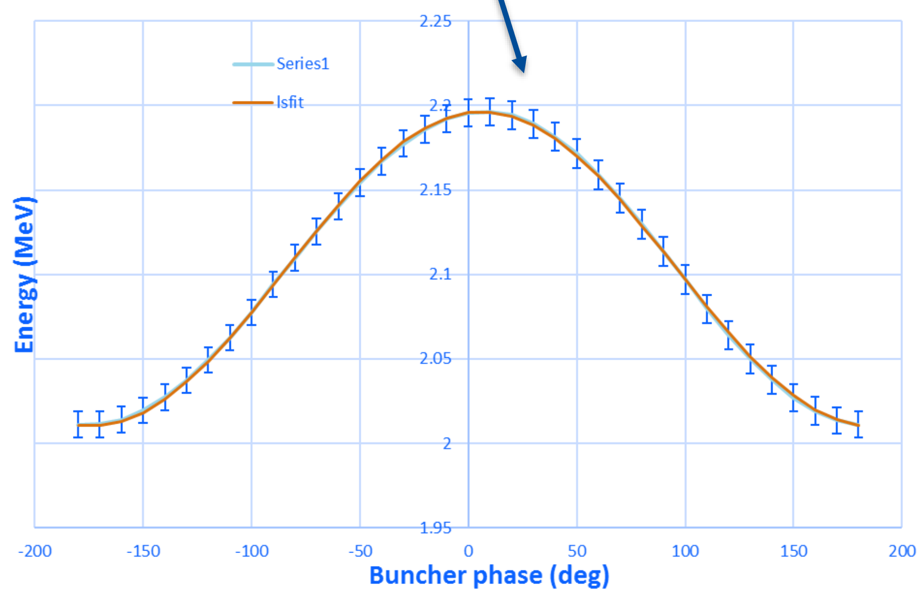
- RFQ transmission: 98% ±2% (at 5 mA; the best result)
  - Toroids at the entrance and exit of the RFQ
- Energy: Time-of-Flight (“movable BPM”, idea from SNS)
  - Phase from a capacitive pickup is recorded vs its position
  - Energy is plotted vs phase of the bunching cavity
  - 2.11 MeV ±0.3%

V.L.S. Sista





M. Alvarez,
V. Scarpine



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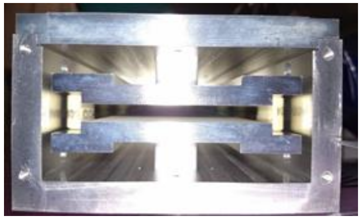
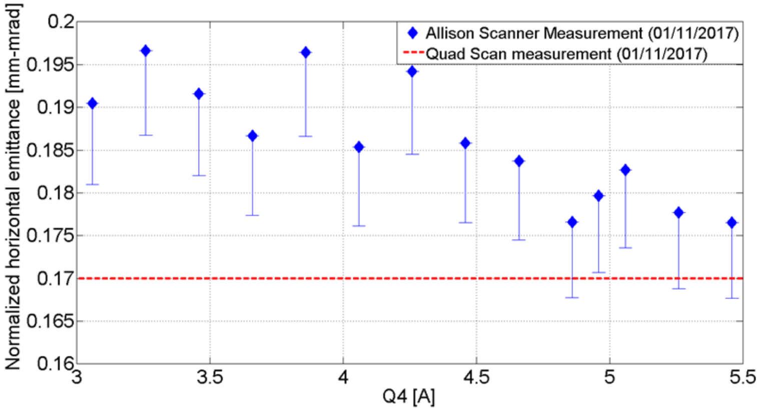
Beam measurements: transverse emittance

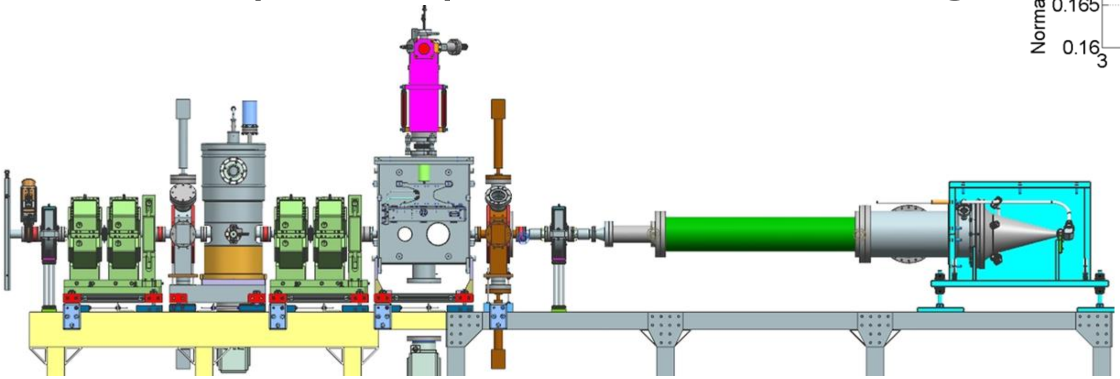


V. Scarpine, M. Alvarez

- MEBT emittance scanner (in MEBT-1.3)
  - Allison-type emittance scanner similar to LEBT's
    - Common electronics and software
    - Angular range: ±12 mrad;
    - Careful position (± 0.018 mm) and angular calibration (<1%)
- $\varepsilon_{n,\, rms} \le 0.2$ µm (1 – 5 mA)
  - Agrees with quad scans
    - Using scrapers
  - Requires optimum LEBT tuning



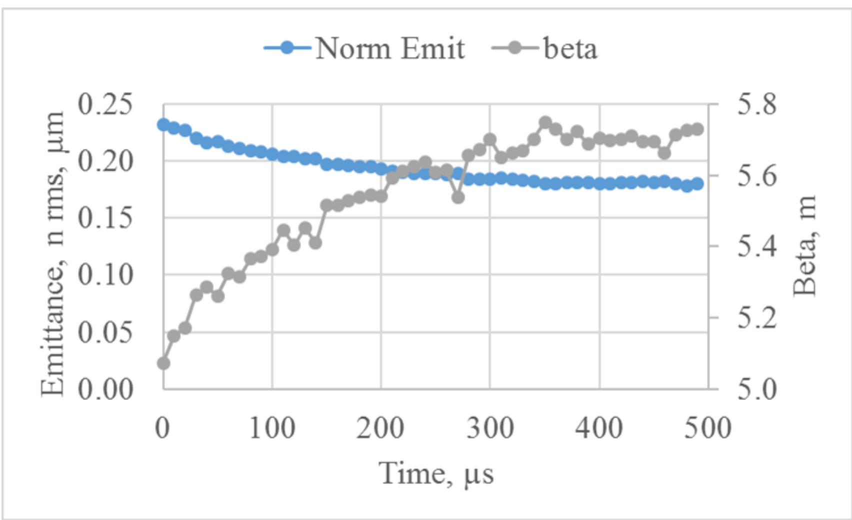
J.-P. Carneiro



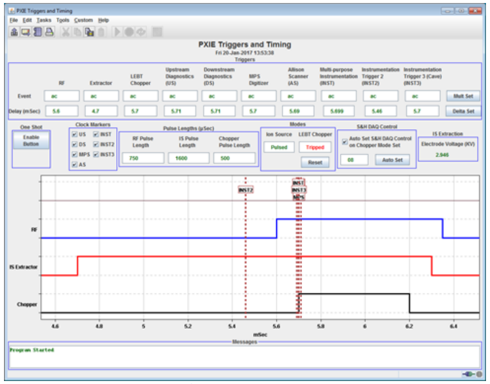
MEBT-1.3. C. Baffes, S. Oplt
Present position of the emittance scanner is horizontal (shown vertical for presentation purpose).

Parameters variation during the pulse

- Emittance scanner allows measuring beam parameters in “time bins” down to 1 μs
- Beam parameters were found varying through a 0.5 ms pulse
  - ~10% variations in emittance and Twiss functions
  - Likely several effects, e.g. not waiting enough (1 ms) for neutralization upstream of the chopper to reach a steady state
    - Will address to use 10 μs pulses for all tuning



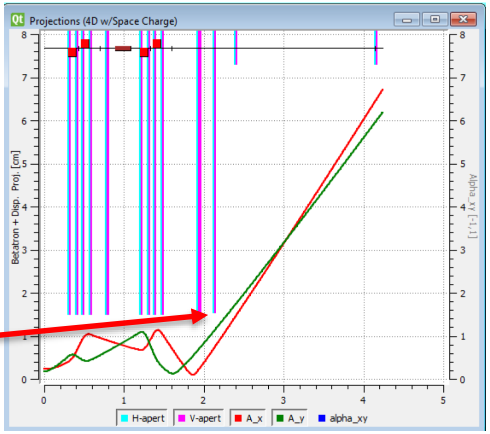
Variations through the 0.5 ms pulse as measured by MEBT Allison scanner. Time bin is 10 μs. 5 mA.

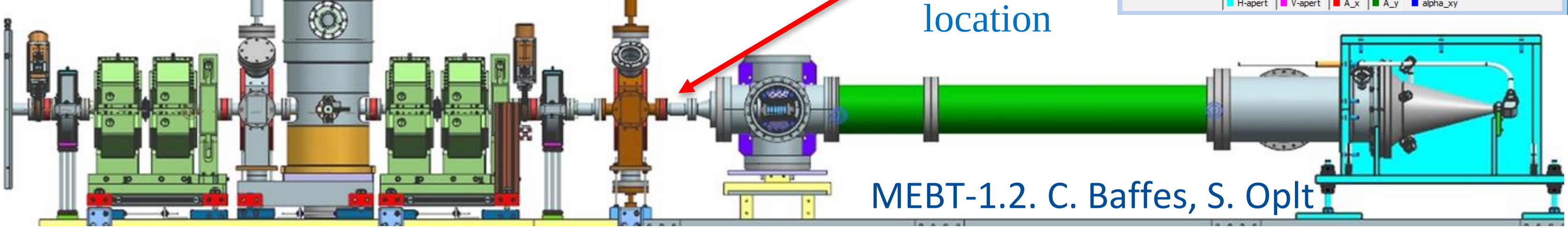


Timing diagram (W. Marsh’s program). Pulse injected into RFQ is chopped at 1 ms from start of the ion source modulator pulse.

High-power operation

- Operation at duty factors closer to CW
  - Beam needs to be over-focused to increase its size in dump but still pass the minimum aperture
- Max power 5 kW (8 ms x 60 Hz x 5 mA x 2.1 MeV) ~ hours
  - 12 hr run at 2.5 kW and 24 hr run at 0.5 kW (average power)
- Tuning at high power ended up by drilling a hole in bellows
  - Then, RFQ coupler failure did not allow operation at > 0.5 kW





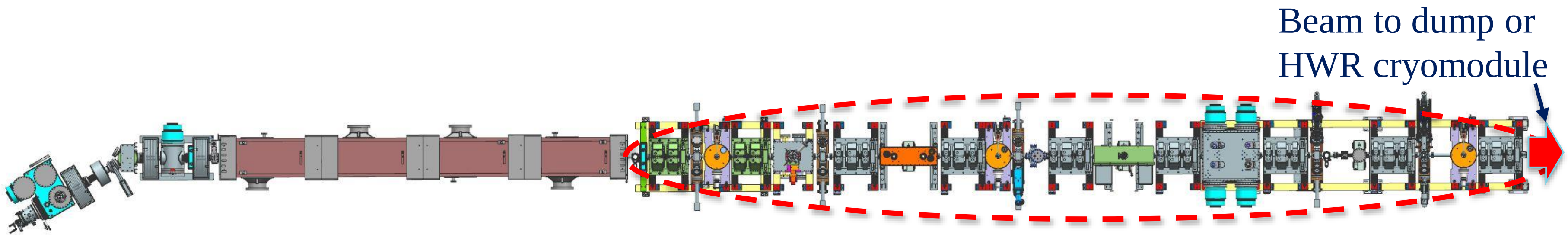
Fermilab

Present status

- Finishing the run after installation of the LEBT bend
  - Effects of the bend on beam properties in MEBT is below measurement errors (e.g. changes in emittance ≤5%)
  - Measurements of longitudinal bunch properties with Fast Faraday Cup (design of D. Sun, B. Hartsell)
  - Further development of the Machine Protection System (MPS)
    - A. Warner, R. Neswold, J.-Yu. Wu, Instrumentation department
  - Continue optics measurements
- Preparing components for "MEBT-3"
  - Full – length MEBT with some temporary elements
- Designing the "final"(for PIP2IT) MEBT (next slides)
  - MEBT absorber, differential pumping, clean sections …
- Looking for a solution for the RFQ couplers

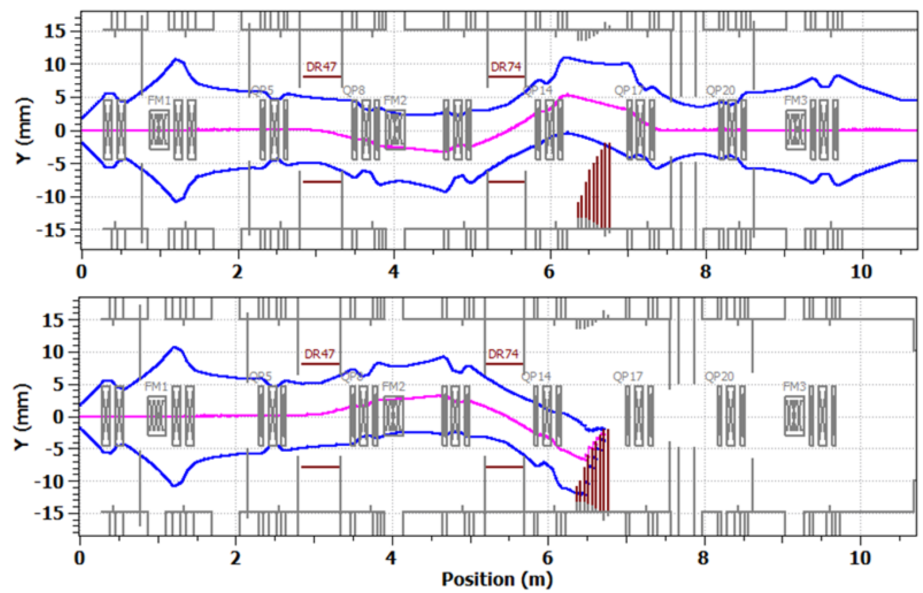
"Final" PIP2IT MEBT

- "Final" PIP2IT MEBT is the Medium Energy Beam Transport line that is planned to be assembled before passing the beam through cryomodules



MEBT optics

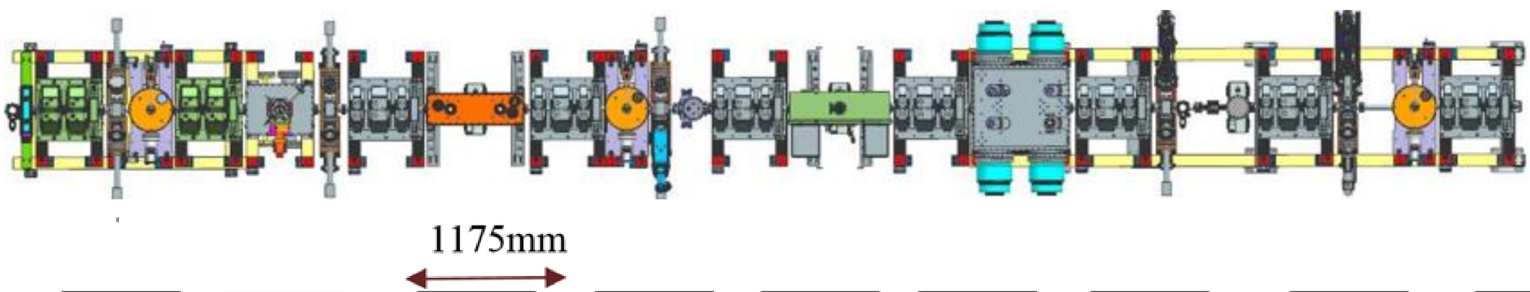
- Transverse focusing: quadrupoles in 2 doublets and 7 triplets
  - Spaces between doublets or triplets are referred as “sections”
- Longitudinal focusing: 3 bunching cavities
- Chopping system: 2 kickers and a beam absorber
  - Kickers are separated by 180º of phase advance; work in sync
- Differential pumping section downstream of absorber
  - to decrease the H_2 flux into the HWR cryomodule
- Smooth optics to avoid emittance growth



3σ envelopes of passed (top) and removed (bottom) bunches simulated with TraceWin. A. Saini.

PIP2IT MEBT sections

- Spaces between doublets or triplets are referred as "sections"
- The length of regular sections is determined by space required by kickers and absorber (650 mm flange-to-flange)

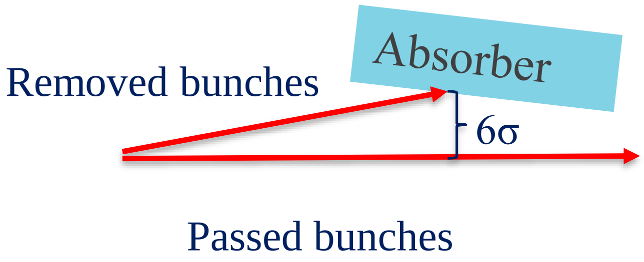


	#0	#1	#2	#3	#4	#5	#6	#7	#8	
Slow valve, toroid	Ring pickup, scrapers RF, wire scanner	Emittance monitor, scraper, wire scanner	Kicker	RF, laser wire test station	Kicker	Absorber	Diffential pumping, scrapers, slow valve, ring pickup, wire scan.	Scrapers, RF, extinction monitor, wire scanner	Fast valve, DCCT, toroid, laser wire	Slow valve

Sections are colored according to their main function

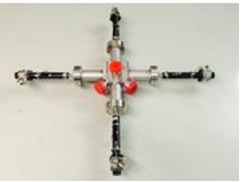
Chopping system

- Chopping system directs unneeded bunches to absorber
  - Bunches marked for removal and passing needs to be separated at the absorber by 6σ.
- Kickers
  - Travelling-wave kickers
    - optimized for v/c=0.0668±0.5%
  - Voltage at each kicker plate changes by 500V between passing and removing states
  - Notes about status follow
- Absorber
  - Rated to 21 kW CW, maximum beam power
    - Beam comes at 29 mrad to decrease power density to <17 W/mm^2
    - Issues: heat management; high power of reflected particles

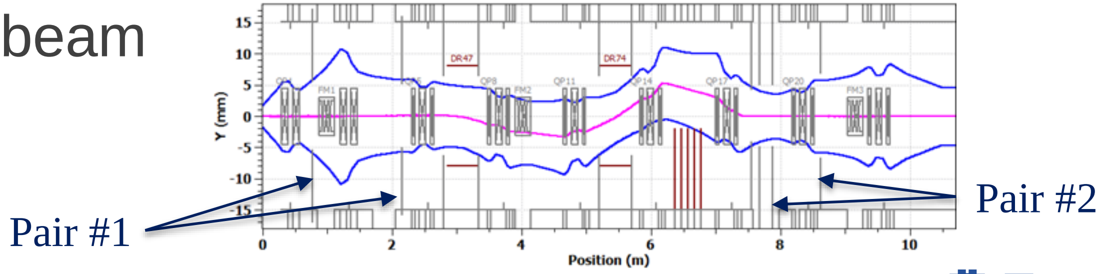


Scraping system

- A system 16 scrapers is envisioned in MEBT
  - 4 assemblies with 4 plates in each (Up, Down, Left, Right)
    - Electrically isolated, radiation-cooled movable TZM plates
  - Two pairs of assemblies: after the RFQ (#1) and downstream of the absorber (#2); ~90º phase advance in the pairs

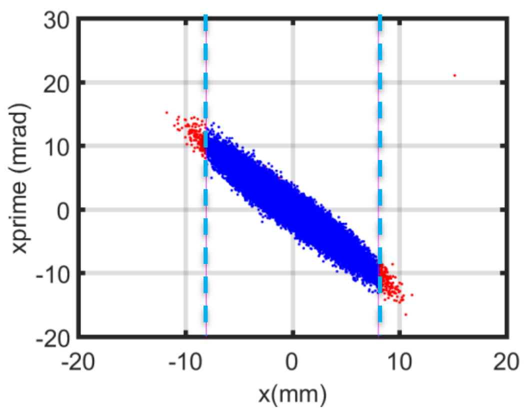


- Functions
  - Protections from erroneous changes in beam envelope and position: passive (intercepting) and active (signal to MPS)
  - Scraping of transverse tails, mainly in #1 (both pulsed and CW)
  - Beam size measurements in short – pulse mode
  - Forming a pencil beam for tuning

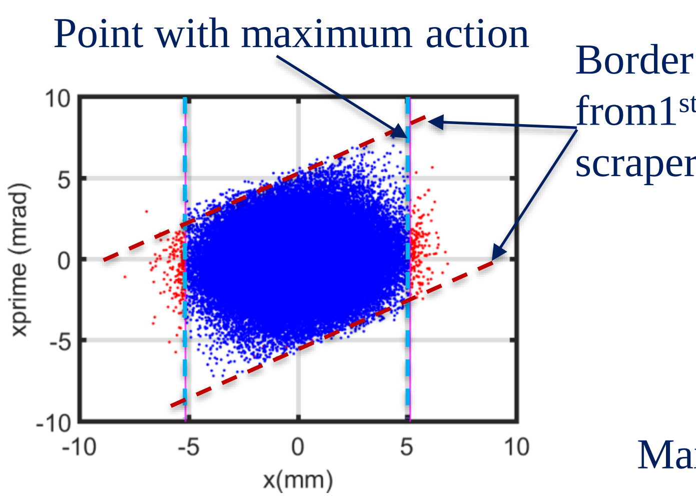


Optimal scraping

- Criterion to optimize positions of scrapers:
  - Minimum action for the given loss at scrapers
- Optimum phase advance between scrapers is 90º
  - For ~9ε_{rms}, need to scrape ~1% with scrapers separated ~90º

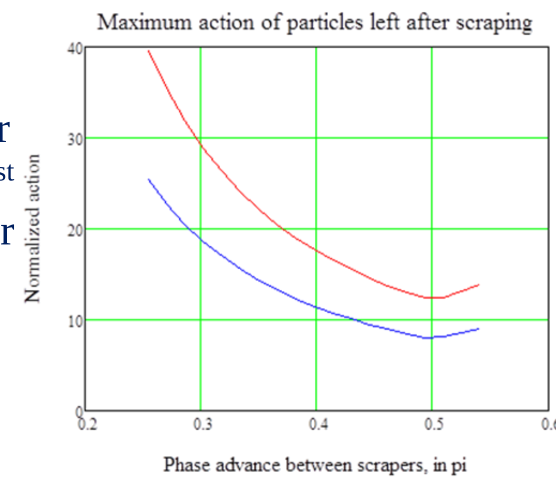


Scraping in 1st scraper



Scraping in 2nd scraper

Scraping with 2 scrapers with phase advance between scrapers of 58.7º. Simulation with TraceWin. A. Saini.



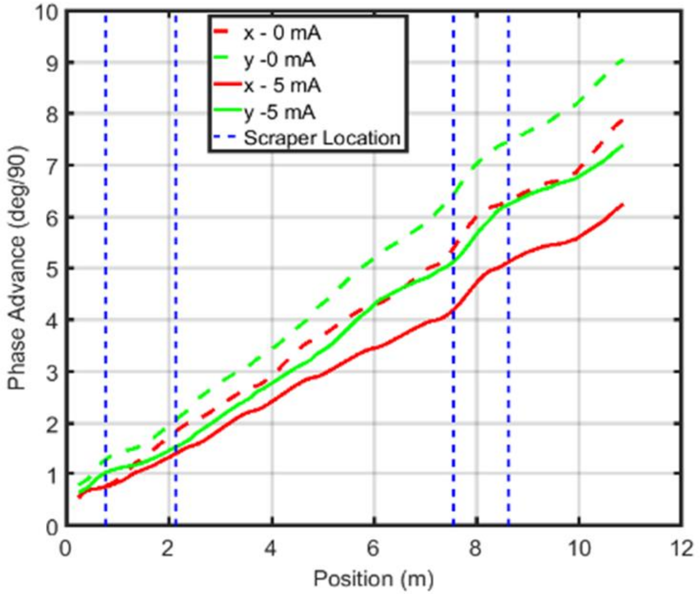
Maximum action normalized by ε_{rms} vs phase advance between two scrapers for beam scraping of 1% (blue) and 0.1% (red).

Optics with scraping system

- Optimum positions to protect from errors in envelope and trajectory are different due to space charge
  - Result is a compromise between them as well as with mechanical limitations

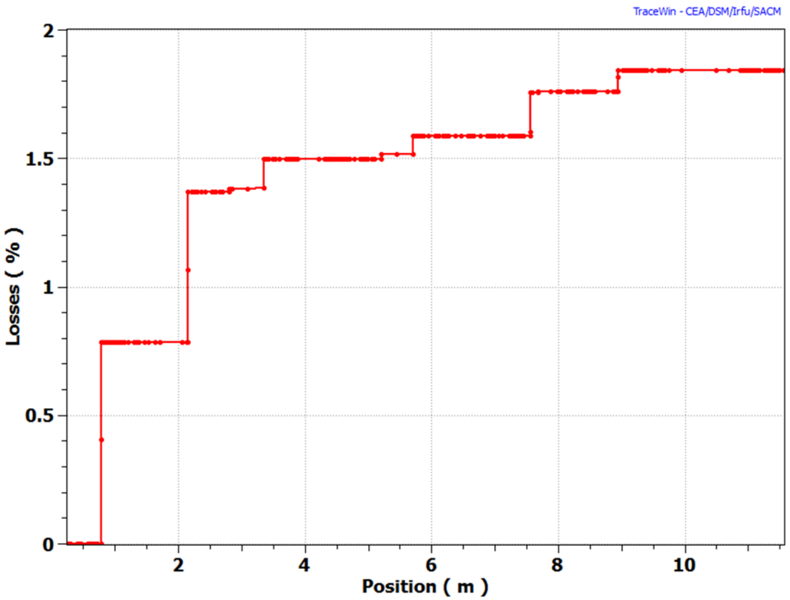
		Scraper 1-2	Scraper 3-4
0 mA	x	95.7º	83.5º
	y	69.8º	92.4º
5 mA	x	58.7º	83.4º
	y	45.1º	100º

Phase advance between scrapers. A. Saini.



Phase advance along MEBT. Simulation with TraceWin by A. Saini. Vertical lines show location of scrapers.

Scraper system in operation

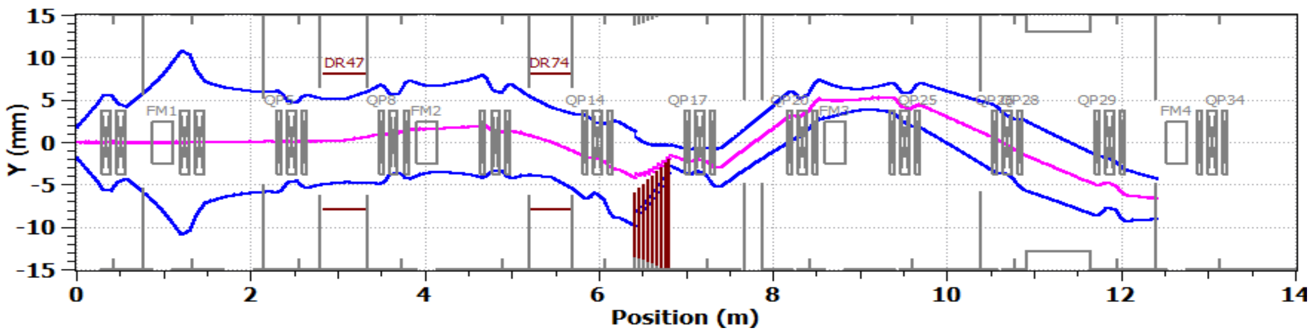


Integrated loss of passing bunches in PIP2IT MEBT

- SRF should be protected from trajectory and envelope jumps upstream of 2nd pair of scrapers

Scraper 1	Scraper 2	Scraper 3	Scarper 4
0.8 %	0.6%	0.16 %	0.08 %

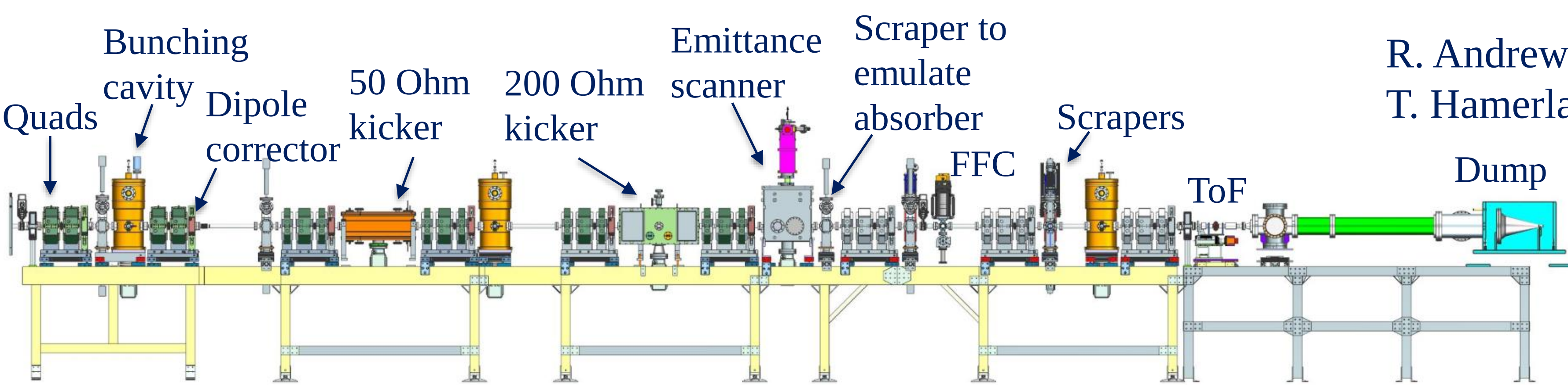
Nominal loss at individual scrapers



3σ Y beam envelope with voltages on all kicker plates equal to half of the nominal value required for chopping bunches out. A. Saini.

MEBT-3

- Full – length MEBT with some temporary elements
  - Final quads and bunching cavities
  - Most of scrapers installed
  - Prototype kickers; no absorber
  - Prototype diagnostics
- The main goal is to test kickers
  - Deflection amplitude and survival

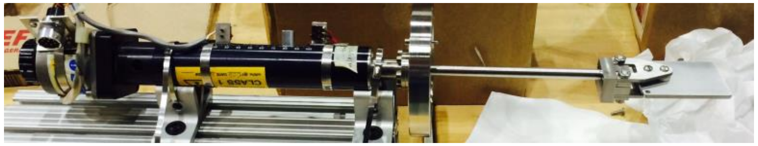


R. Andrews,
T. Hamerla

Status of elements (in addition to MEBT-1)

Quads at TD. Photo courtesy of S. Stoynev

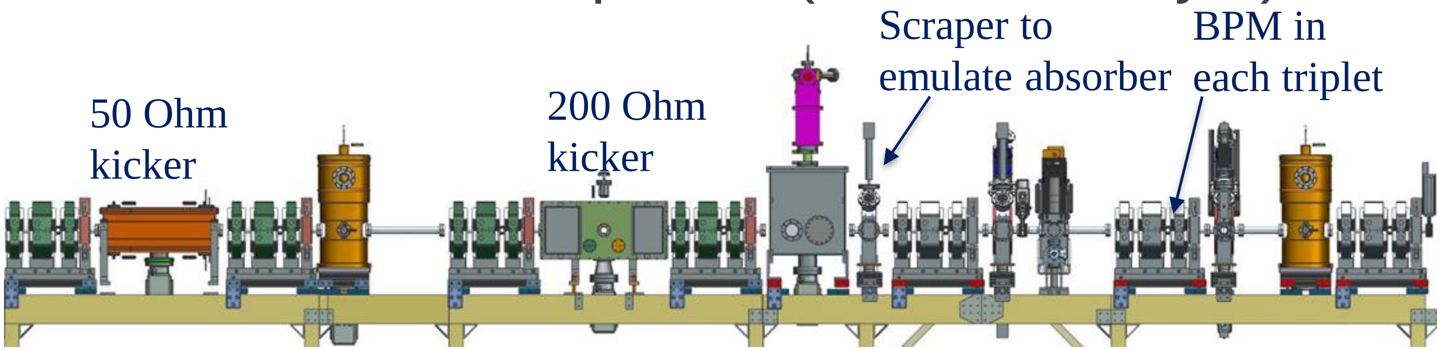
- Magnets are produced by BARC, India
  - Quads for 4 triplets are at TD, for 3 more are measured at BARC
  - All dipole correctors are at Fermilab
  - Have all power supplies installed
- 3 more bunching cavities have been made
  - One is ready; 2 are leaking
  - Have five 3-kW, 162.5 MHz RF amplifiers
    - Two circulators are on hand; 3 more are coming in May
- BPM pickups are ready for installation inside triplets
- Scrapers are being procured
- Girders are ready
- Absorber is at the stage of conceptual design



K. Kendziora, C. Baffes

Kickers

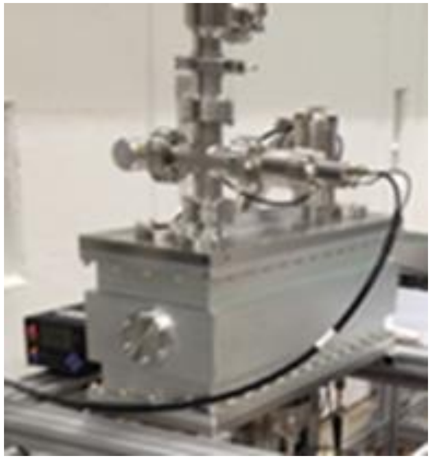
- Two kicker prototypes are ready to be installed
  – Referred by their impedance, 50 Ohm and 200 Ohm
  – Both were power tested and RF measured
- Questions for tests with beam (need to chose the version)
  – Survival in real beam environment
  – Actual deflection efficiency
    - Measured by BPMs + fast scopes and by scrapers
- Will pass a long-pulse beam through and will measure deflection with short pulses (no absorber yet)



50 Ohm kicker prototype

- Electrodes connected by cables in vacuum (D. Sun, A. Chen)
- In the final MEBT, would be powered by commercial wide-band amplifiers (not procured)
  - Low-power version was successfully tested on load in 2012 to demonstrate correction of signal distortion
- In MEBT-3 tests, will be powered by two narrowband RF amplifiers at 81.25 MHz, kicking out every other bunch

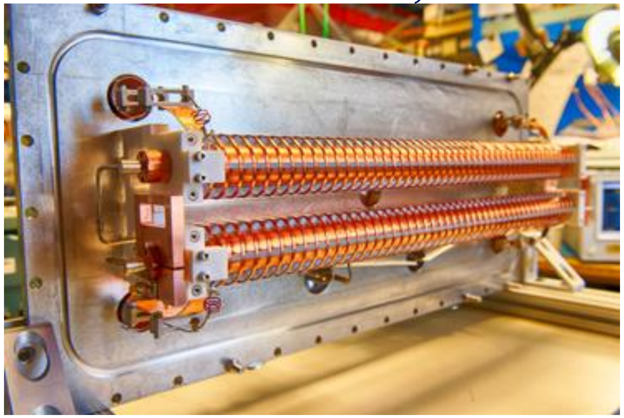
D. Sun, A. Chen

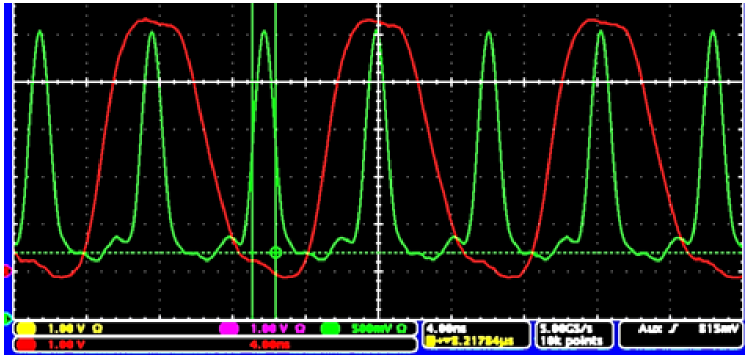


200 Ohm kicker prototype

- Two helixes with welded electrodes
- High impedance allows an in-house made fast switch (G. Saewert, D. Frolov)
  - A prototype switch demonstrated parameters close to needed for CDR scenario
- In MEBT-3 tests, the kicker will be driven by two such switches
  - Capable to generate arbitrary pulse pattern
  - Chopper program module is prepared by B. Chase's group

G. Saewert, A. Chen





Red: scope trace of signal passed through the helix. It corresponds to removing every other bunch. Amplitude 600 V; time scale: 4 ns/div. Green trace mimics 162.5 MHz bunches. G. Saewert, D. Frolov.

Plans

- April 2017 – run in the present configuration
- May- July 2017 – shutdown to install MEBT-3
- July – December 2017 – MEBT-3 run
- 2018 – shutdown to install cryo distribution system and both cryomodules (HWR and SSR1)
  - At the same time, install “final MEBT” and a simple HEBT
- 2019-2020 – work toward CDR parameters
  - MEBT: final parameters; bunch-by-bunch chopping
  - Try regimes closer to CW where it comes with minor expenses
- ~2023 – move into PIP-II enclosure all PIP2IT elements that meet PIP-II requirements

Summary

- PIP2IT closely replicates the PIP-II front end as it is envisioned in CDR
- The initial part of the warm front end was assembled and commissioned
  - LEBT combining a low emittance growth, chopping and good vacuum
  - RFQ in pulsed and CW modes
    - Need to address couplers and frequency shift
  - First section of MEBT and some of MEBT diagnostics
  - Beam accelerated in RFQ is partly characterized
- Full – length MEBT is prepared for installation