Overview and Future Demands of Fast Choppers

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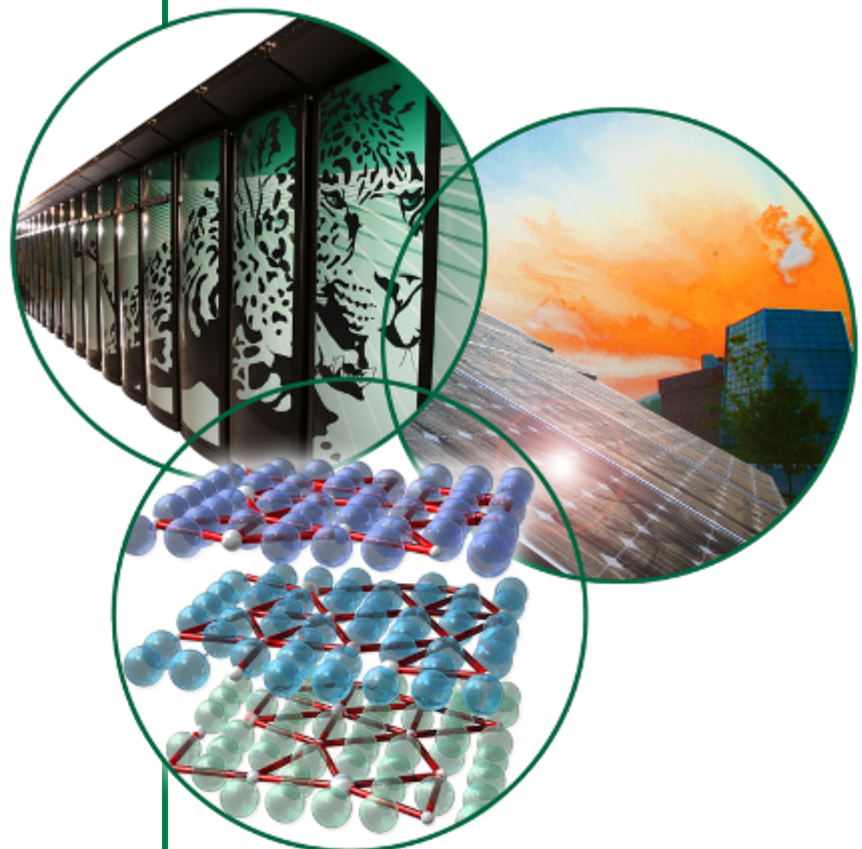
Spallation Neutron Source, Oak Ridge



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Outline

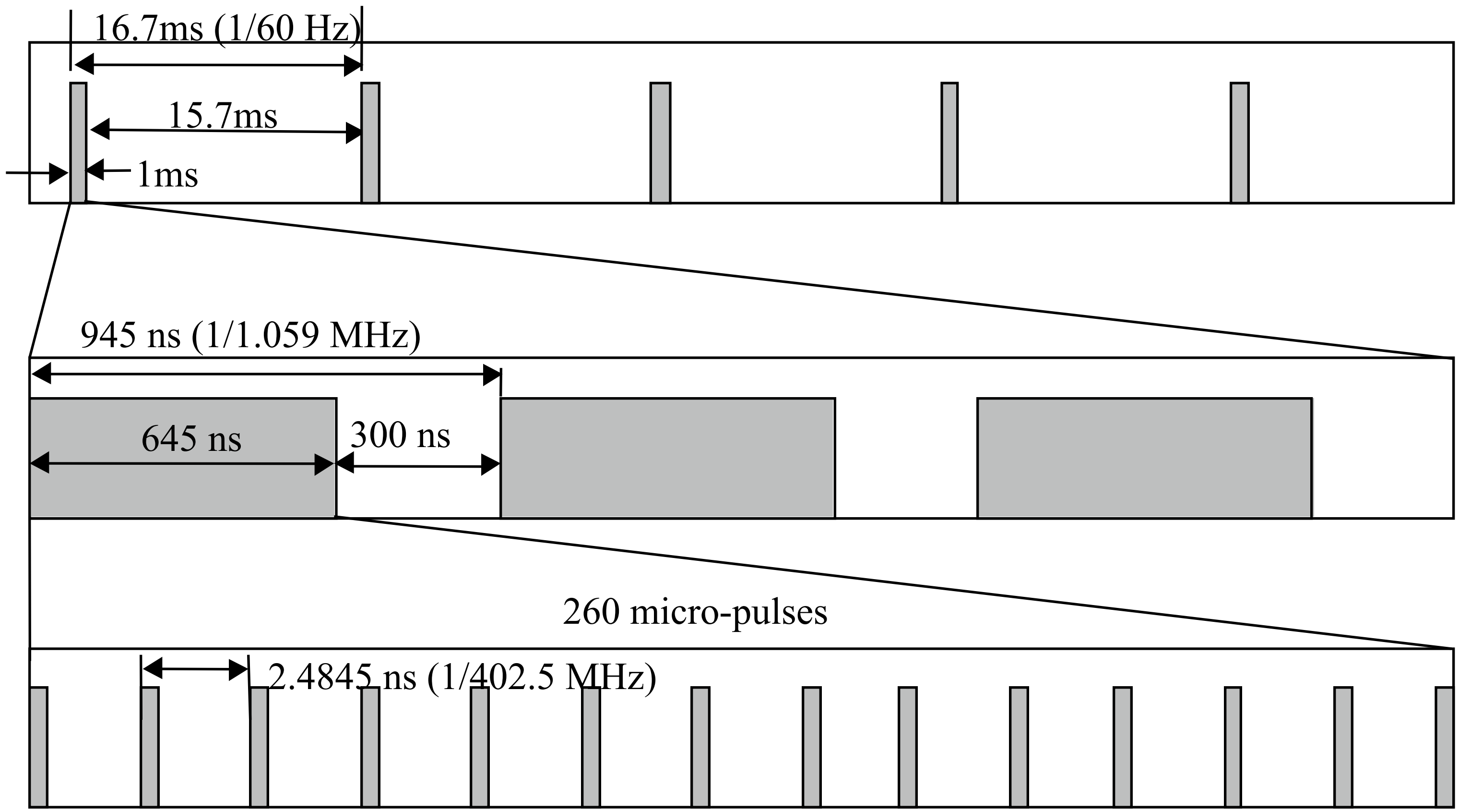
- Chopper requirements for current and emerging projects
- Introduction and basic concepts
  - Chopper line layouts
  - Chopper kicker structures
- Examples of designs for current and future linacs:
  - Operational: SNS, JPARC
  - Approaching commissioning: Linac4-SPL (CERN)
  - Future: Project-X (Fermilab)
- **Drivers for fast choppers**
- Summary

Chopper is a device for creating time structure in the beam by removing parts of the beam

Macro-pulse
Structure
(made by the
Ion Source)

Mini-pulse
Structure
(made by the
choppers)

Micro-pulse
structure
(made by the
RFQ)

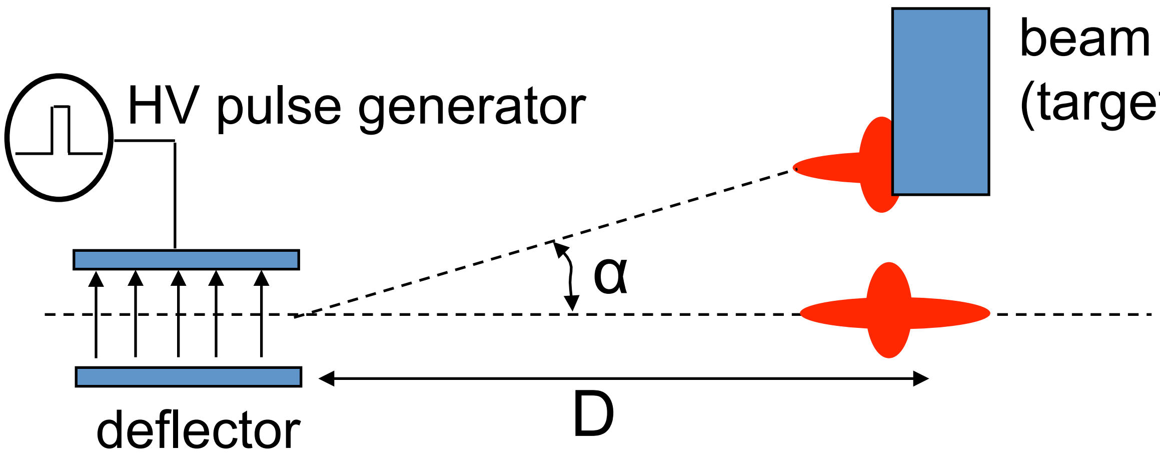


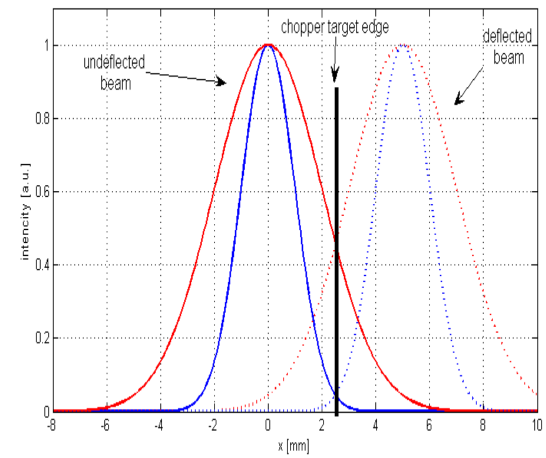
SNS temporal beam structure

Chopper requirements

	SNS	J-PARC	Linac-4 /SPL	Project-X
Bunch frequency, separation	402.5 MHz 2.5 ns	324 MHz 3.1 ns	352.2 MHz 2.8 ns	162 MHz 6.2 ns
Rise time	(2),[10], <15 ns	10 ns	2 ns	2 ns
Chopping frequency	1 MHz	1.2 MHz	1 MHz / 44Mhz	162 MHz
Mini – pulse length	650 ns	455 ns	30 – 1700 ns /8-1700 ns	6.2 ns
Macro-pulse length, repetition rate	1 ms, 60Hz	0.5 ms, 25Hz	.6 ms, 1Hz / 50Hz	CW
Average beam power on chopper target	~ 100 W with pre-chopper (1200W)	~ 100 W with pre-chopper (800W)	~40 W (2000)	> 20kW

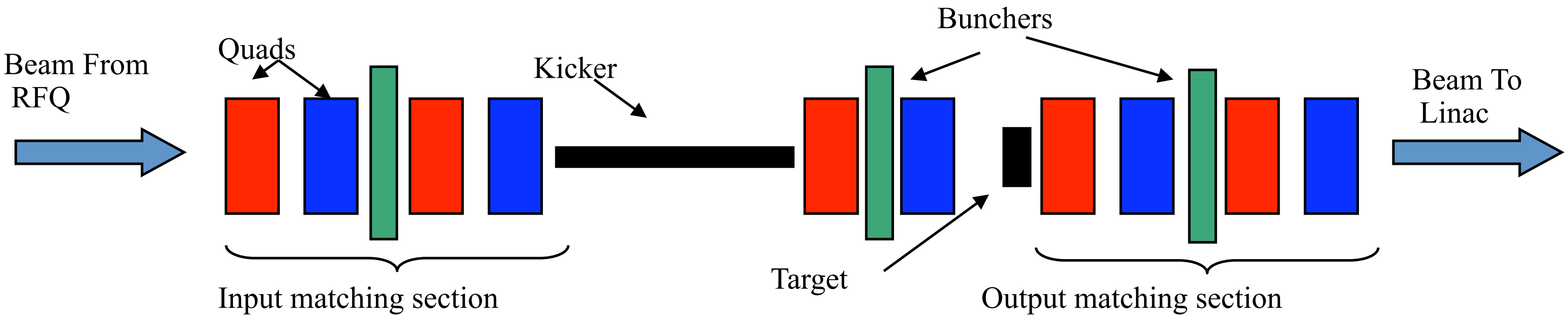
Kicker/target chopper





- **This simple configuration is not practical for high current ion machines**
- **Strong external focusing is required to counteract transverse and longitudinal beam space charge forces**
- **Long drifts cause significant deterioration of beam quality (emittance increase)**

Medium Energy Chopper Line



- Typically, MEBT
  - is located between RFQ and LINAC
  - 2 – 5 MeV ion beam energy
  - 3 – 6 m long
  - Often, whole purpose of MEBT existing is to provide chopping

Chopper efficiency

Displacement ***d*** of bunch center position on the target due to angular kick ***α*** :

$$d = r_{12} \cdot \alpha = \sqrt{\beta_1 \beta_2} \sin(\Psi_{12}) \cdot \alpha$$

Chopper efficiency ***R*** is defined by bunch center displacement ***d*** and bunch transverse size ***σ₂*** :

$$R = d / \sigma_2$$

Bunch transverse size at target $\boldsymbol{\sigma_2}$ can be calculated from beam emittance ε and β-function at the target β_2^*:

$$\sigma_2 = \sqrt{\beta_2^* \varepsilon}$$

, which gives

$$R = \sqrt{\frac{\beta_1}{\varepsilon}} \sin(\Psi_{12}) \cdot \alpha$$

Deflector of length ***L***, gap ***Δ*** and voltage ***V*** provides angular kick of :

$$\alpha = k_1 \frac{V \cdot L}{\Delta}$$

Deflector gap ***Δ*** is limited by beam transverse size σ_1 inside the deflector:

$$\Delta = k_2 \sigma = k_2 \sqrt{\beta_1^* \varepsilon}$$

, which finally gives

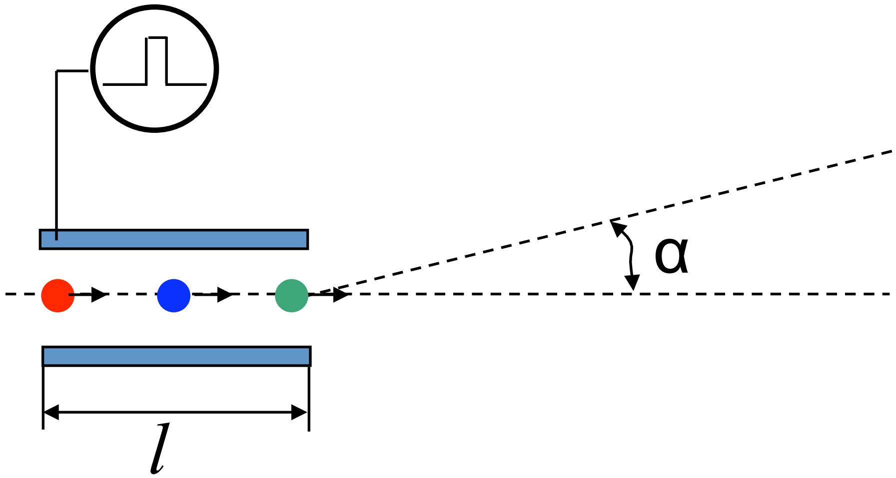
$$R = \frac{k_1}{k_2} \cdot \sin(\Psi_{12}) \cdot \frac{V \cdot L}{\varepsilon}$$

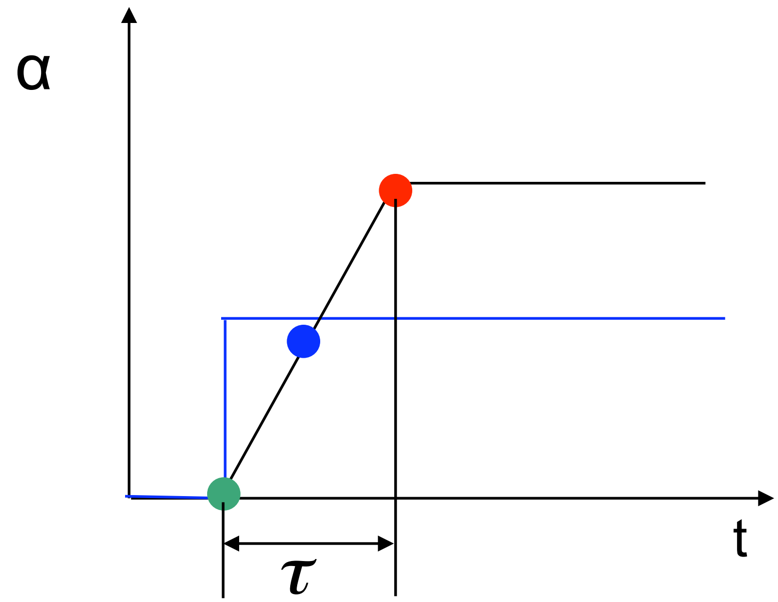
Maximizing chopper efficiency

$$R \propto \sin(\Psi_{12}) \cdot \frac{V \cdot L}{\varepsilon}$$

- Beam transport line parameters: ***$\sin(\Psi_{12}) \leq 1$***
- Deflector voltage **V** is limited by available high speed driver
- Deflector length is limited by
  - Allowable drift length, dictated by beam dynamics
  - Change of betatron phase ***Ψ_{12}*** along the deflector
- Kicker plates can be distributed along transport line as long as phase advance is close to 90° +k*180° for each plate

Traveling wave kicker rise time

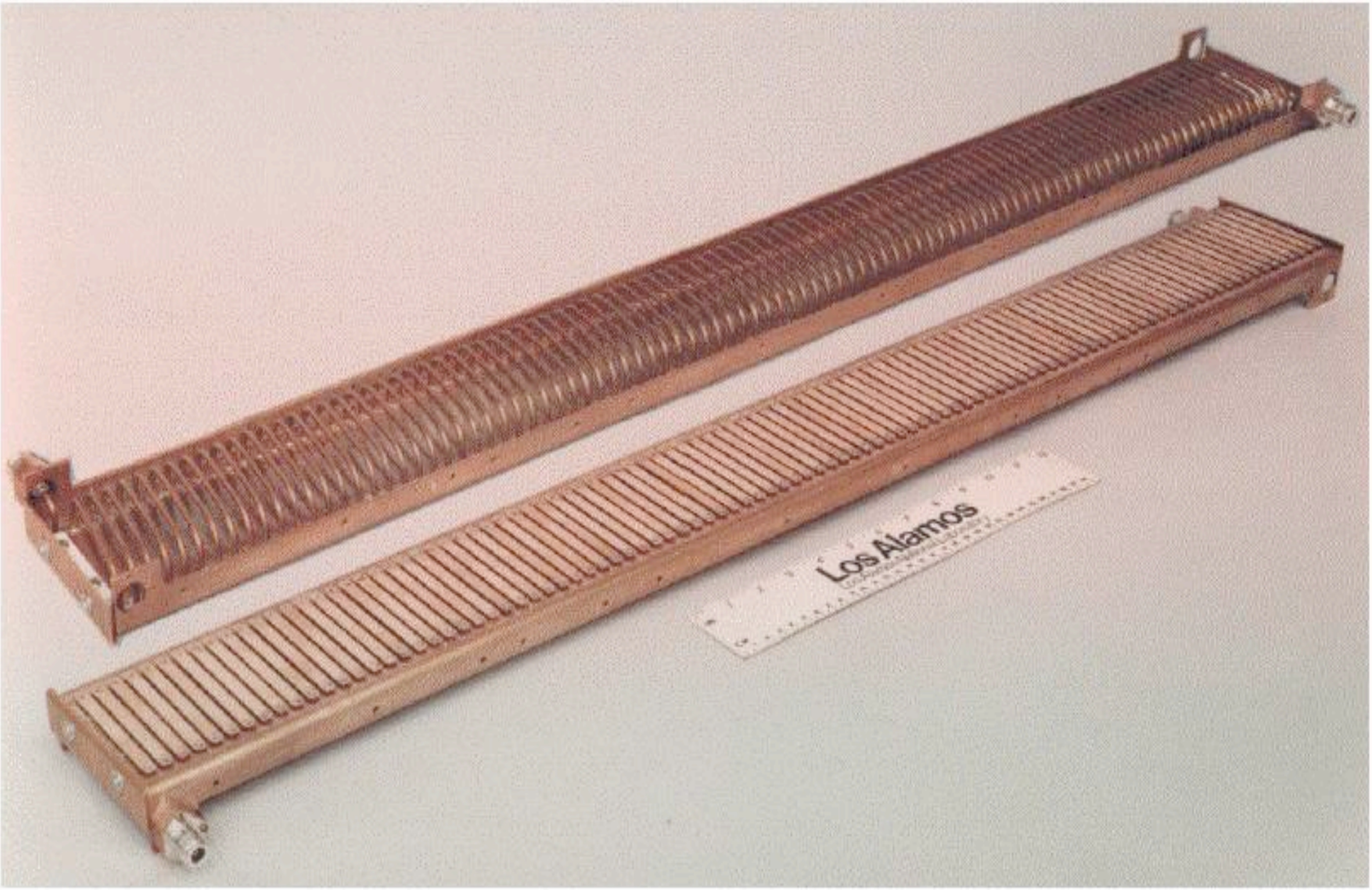




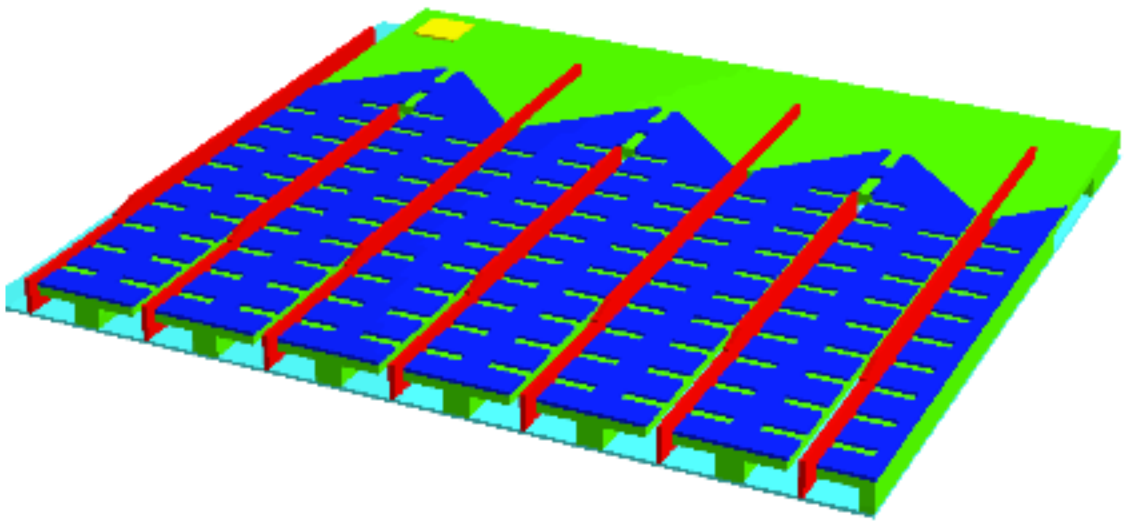
$$\tau = \frac{L}{\beta_p c} \cdot \left(1 \pm \frac{\beta_p}{\beta_w}\right)$$

$\tau = 0$ in “slow wave” structure, when $\beta_p = \beta_w$

LANCE chopper structure: an example of slow wave transmission line



Meander line problems



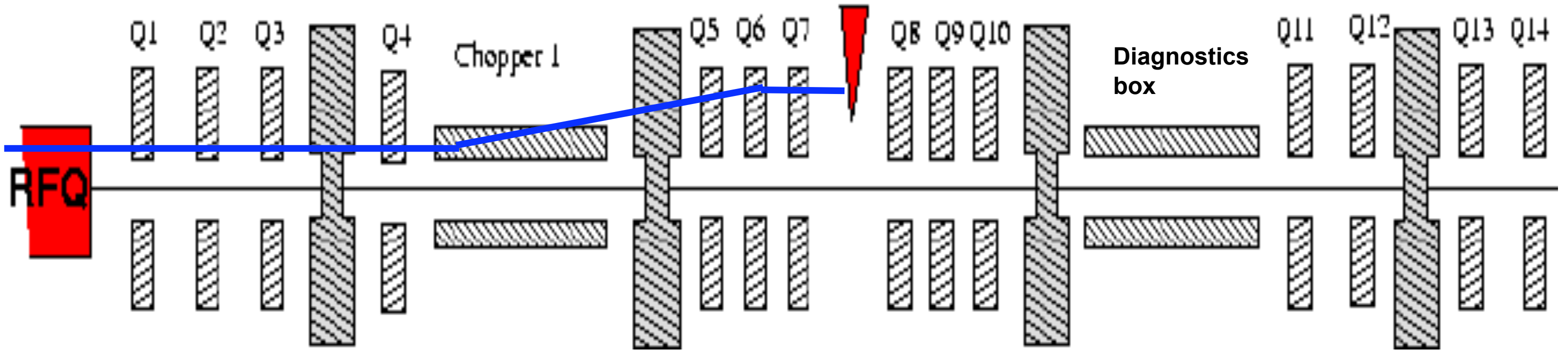
Coupling between adjacent folds cause dispersion, which limits bandwidth and/or maximum structure length. Typical max length is~.5m

Increasing distance between folds to control dispersion reduces overall efficiency (coverage factor). Typical coverage factor ~ 0.6 – 0.8

Examples of fast choppers

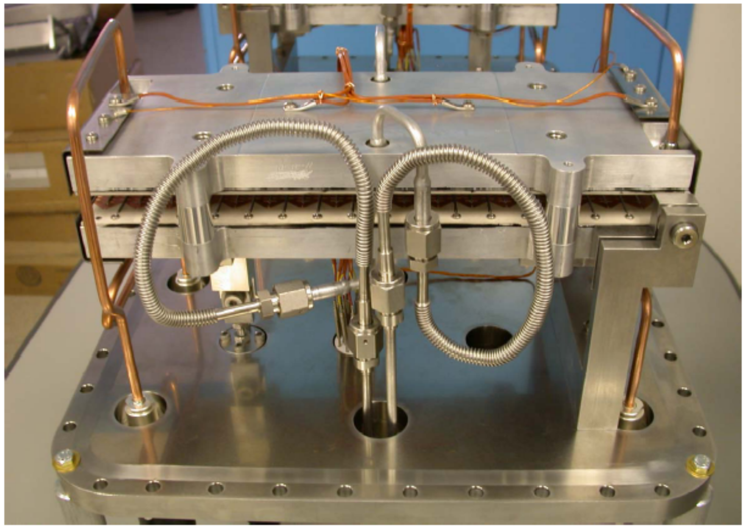
- Spallation Neutron Source (Oak Ridge, USA)
- J-PARC (Japan)
- Linac-4 (CERN)
- Project-X (Fermilab)

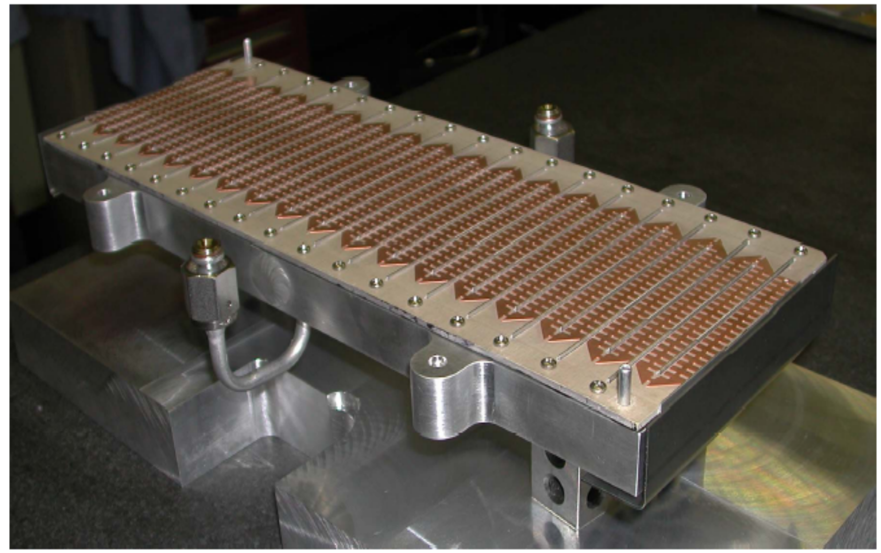
SNS MEBT chopper

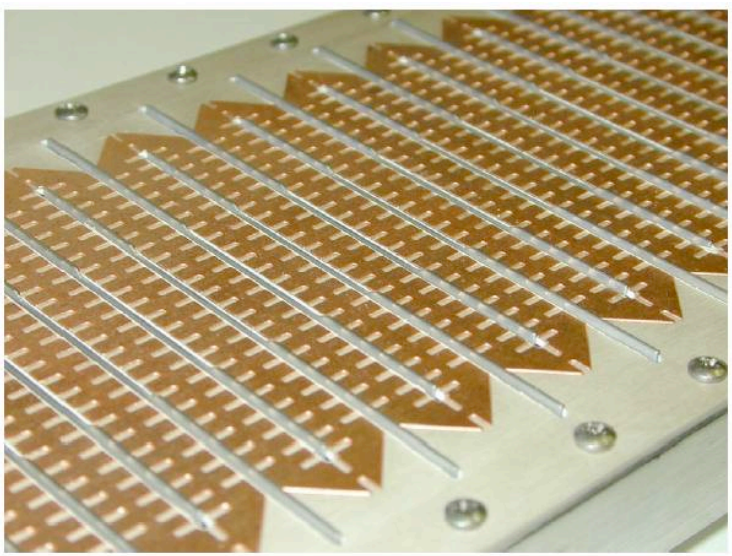


Ion energy		2.5 MeV
β = v/c		.073
Max Voltage		± 2.25 kV
gap		18 mm
deflector length		~370 mm
Max deflection		18 mrad
Power supply rise time (commercial device)		~10 ns

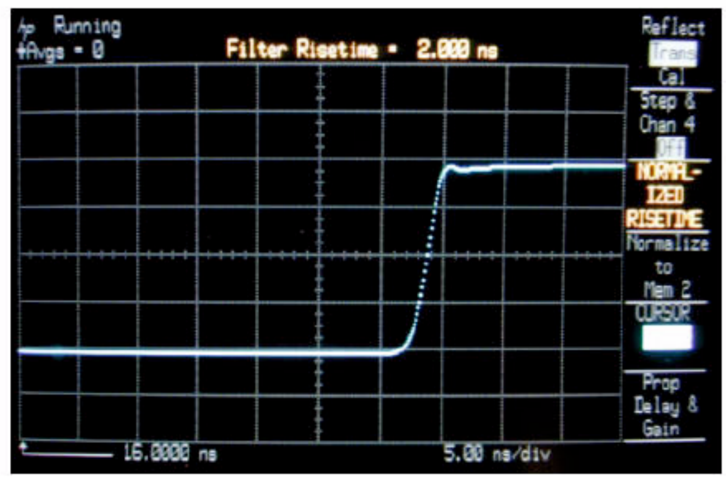
Original design – meander line on a dielectric substrate



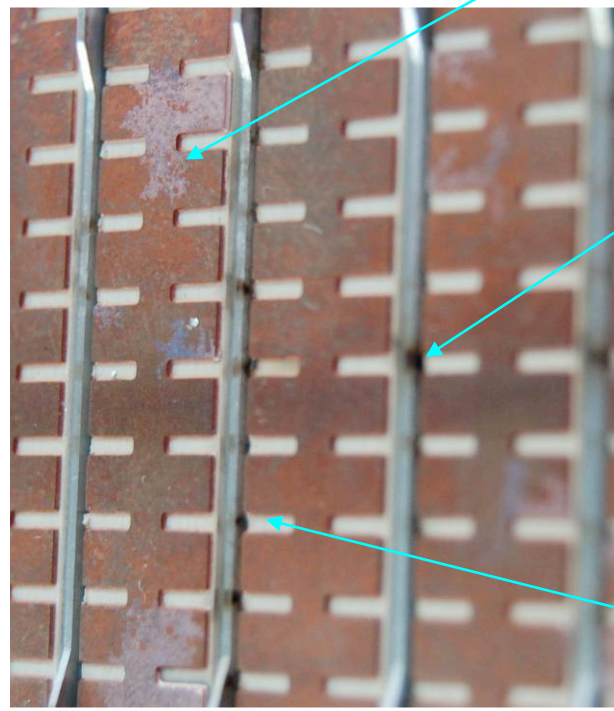




Input
2 ns



Did not survive high power beam operation

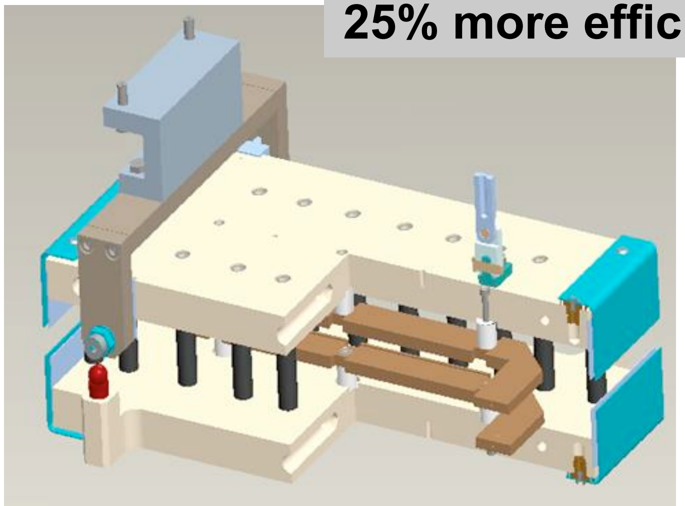


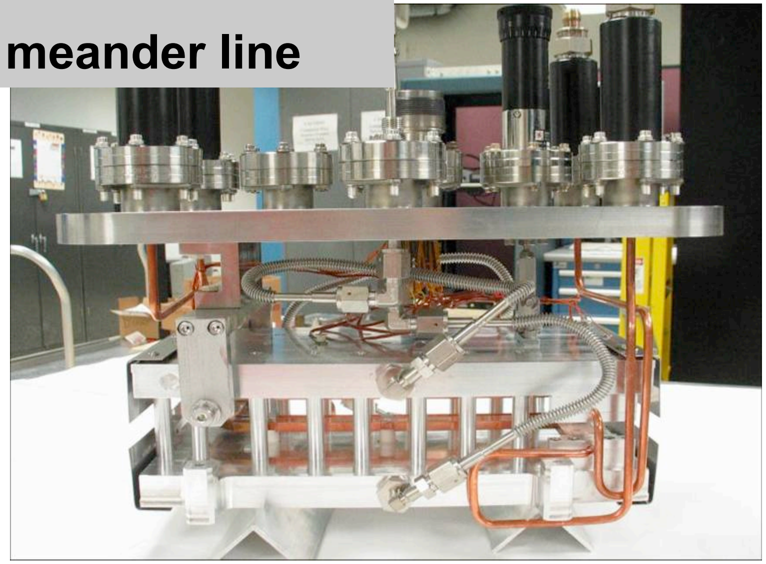
Small <u>uncontrolled beam spills</u>
caused copper trace overheat and delaminating from substrate
due to <u>poor heat conductance</u> of the dielectric

New SNS chopper design

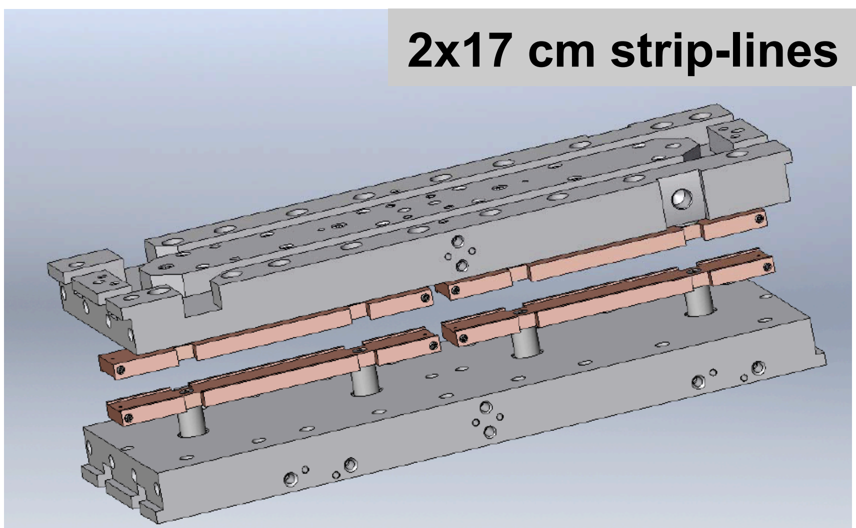
35 cm strip-line : 17 ns transient

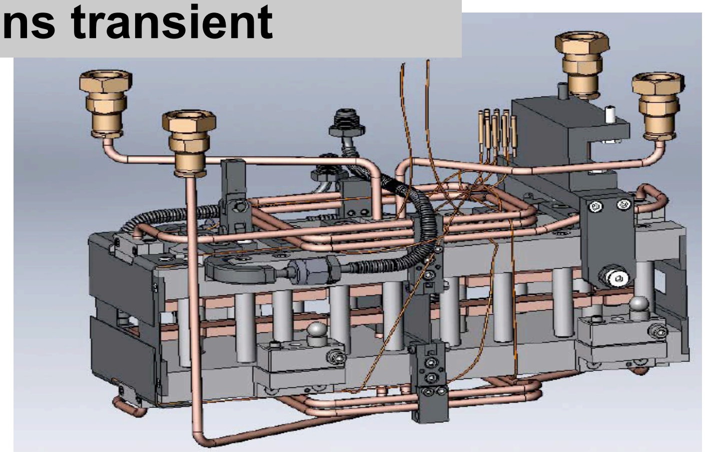
25% more efficient than meander line





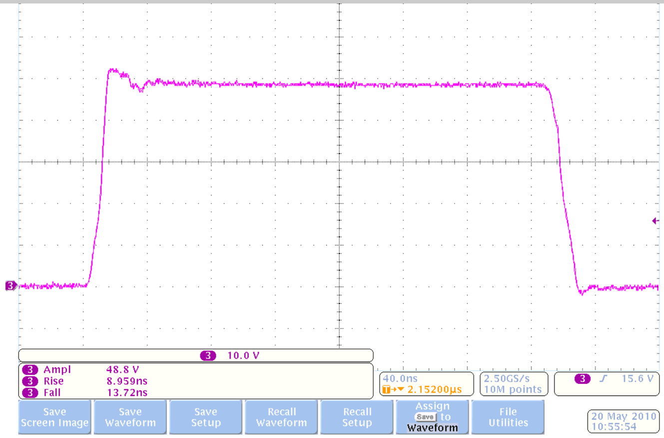
2x17 cm strip-lines : 8 ns transient

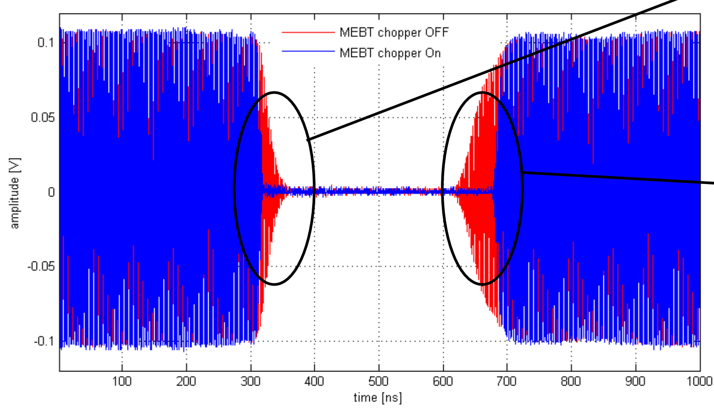




SNS chopper performance (1MW operation)

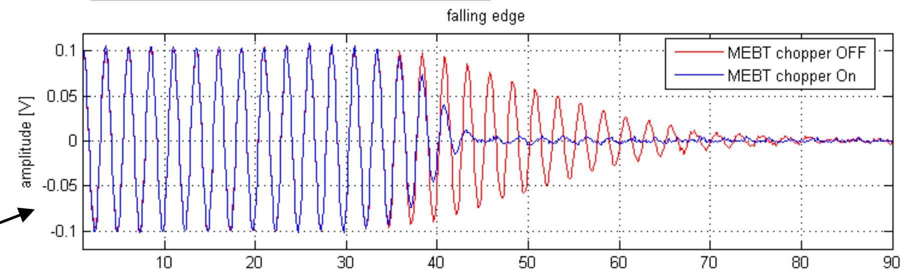
High voltage pulse: ~9ns rise time, ~14ns fall time

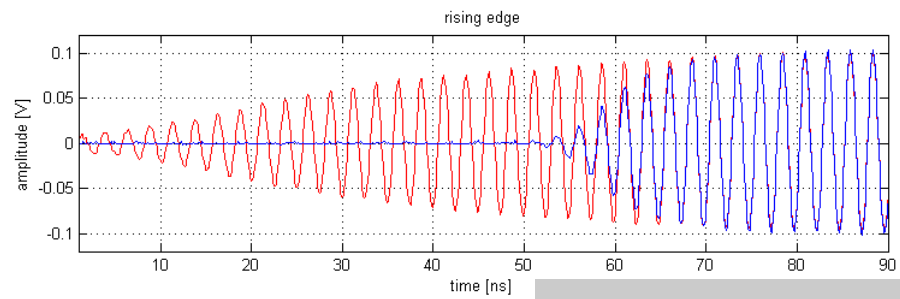




Beam current: pre-chopper only is in red, pre-chopper and MEBT chopper is in blue

~ 10 ns fall time





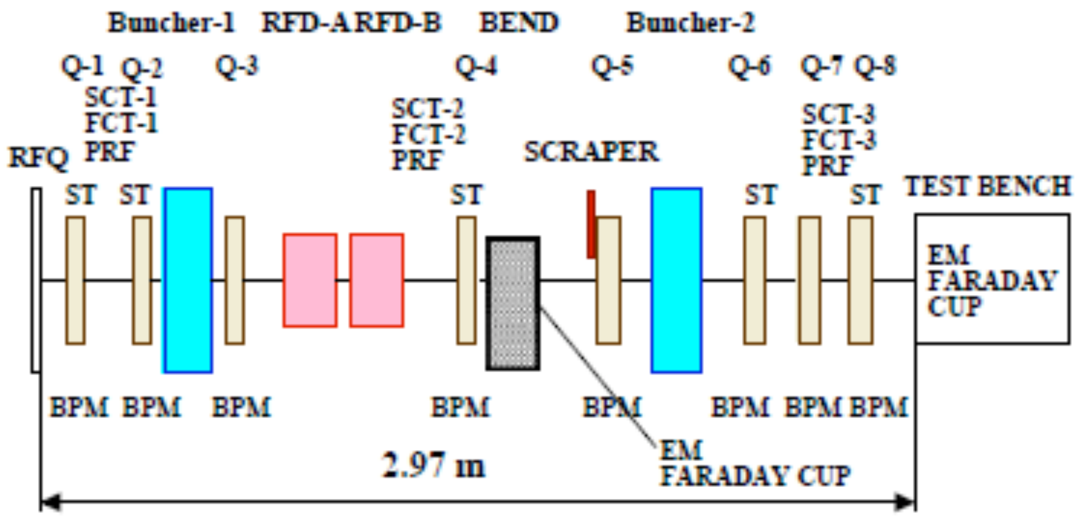
~ 15 ns fall time

Measured extinction ratio is < 10^{-4}

Examples of fast choppers

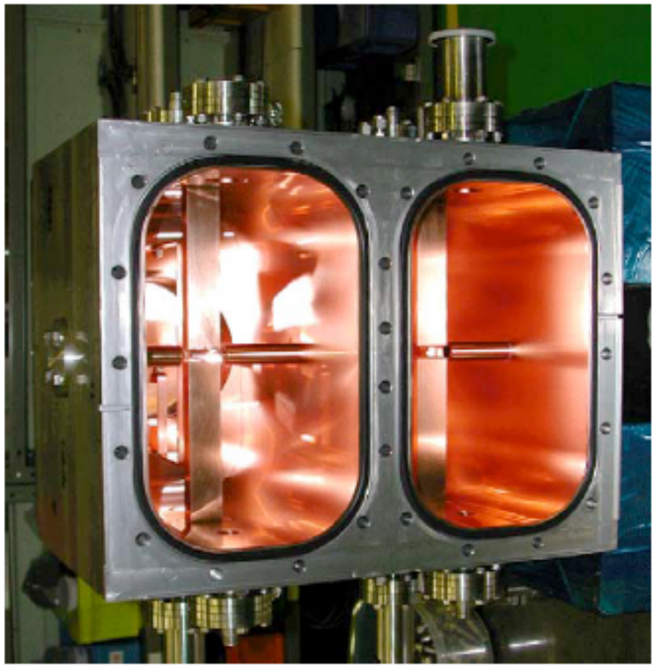
- Spallation Neutron Source (Oak Ridge, USA)
- J-PARC (Japan)
- Linac-4 (CERN)
- Project-X (Fermilab)

J-PARC MEBT chopper



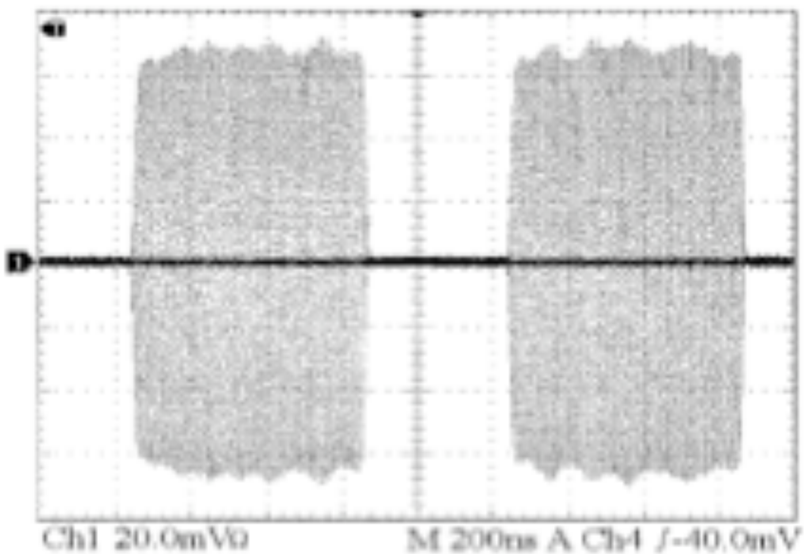
Ion energy		3 MeV
β = v/c		.08
deflector type		RF cavity
aperture		10 mm
deflector length		2x170 mm
Max field		1.6 MV/m
Gap length		20mm

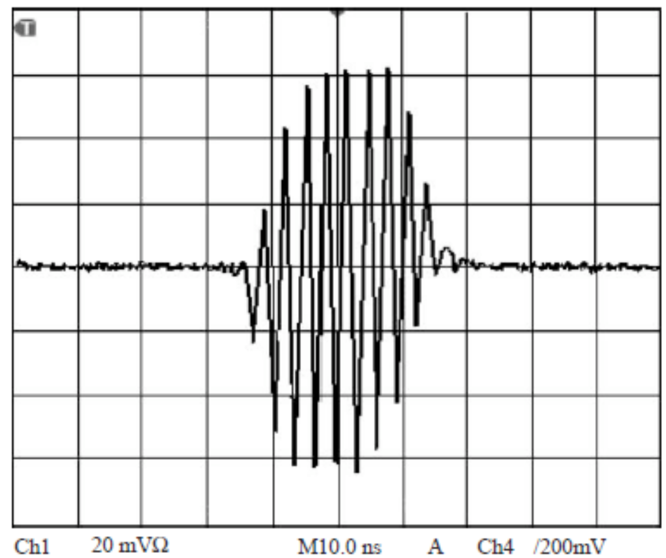
J-PARC RF deflector



frequency		324 MHz
Q		~10
Cavity rise time		10ns
Power amplifier		Solid state, 36kW
Amplifier rise time		15ns
Max field		1.6MV/m
Gap length		20mm

J-PARC MEBT chopper performance





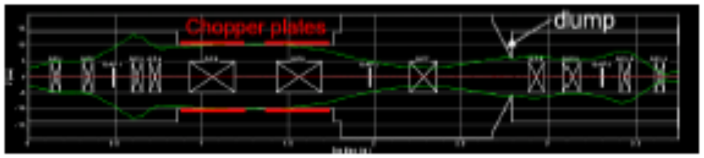
Shortest rise time: 10ns

Off/On ratio : ~1e-7

Examples of fast choppers

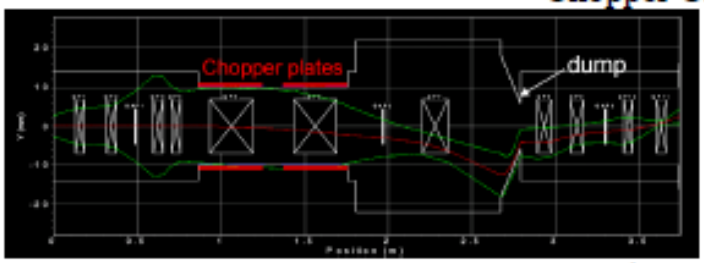
- Spallation Neutron Source (Oak Ridge, USA)
- J-PARC (Japan)
- Linac-4 (SPL), CERN
- Project-X (Fermilab)

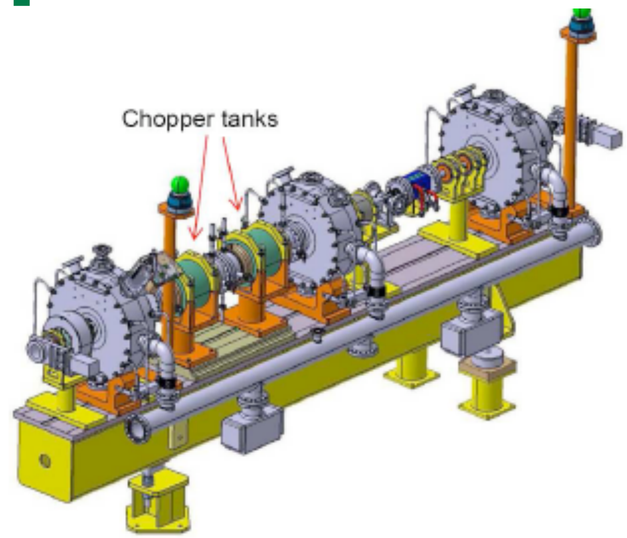
Linac-4 (SPL) MEBT chopper



Chopper OFF

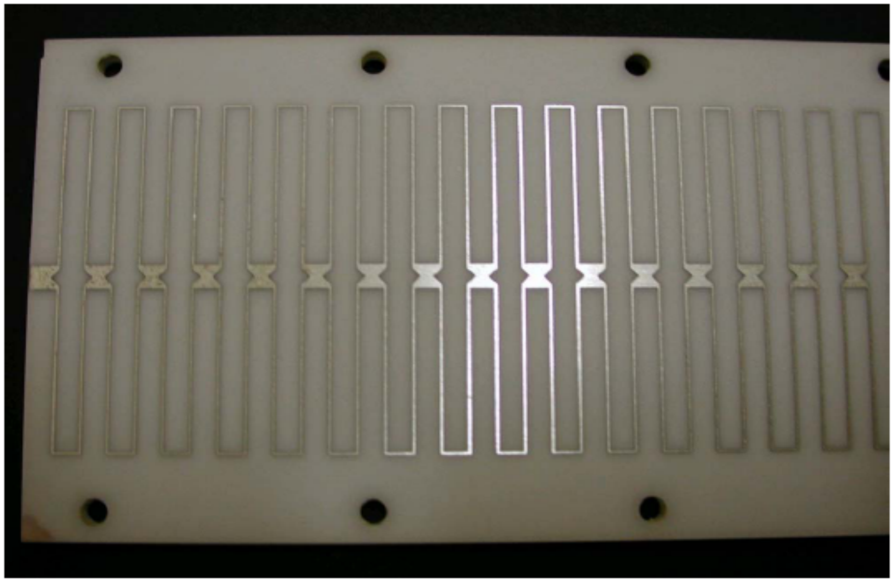
Chopper ON



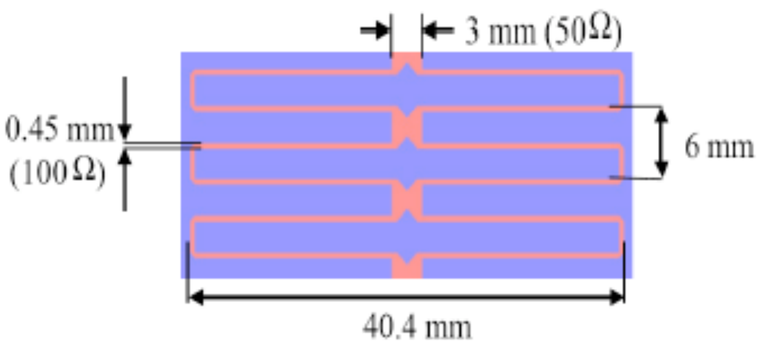


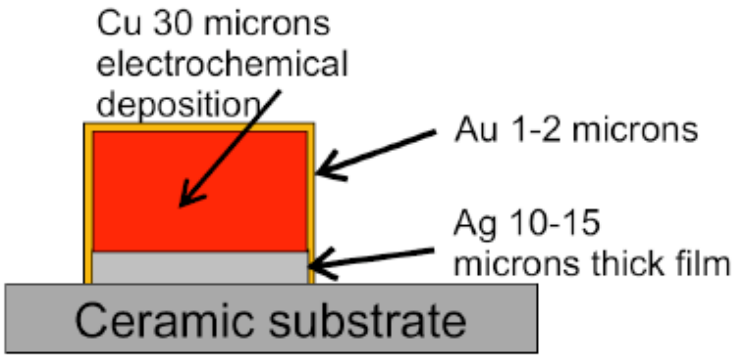
Ion energy		3 MeV
β = v/c		.08
Max Voltage		± 600 V
gap		20 mm
deflector length		2x400 mm
Max deflection		6 mrad
Power supply rise time		~2 ns

Linac-4 (SPL) double meander kicker

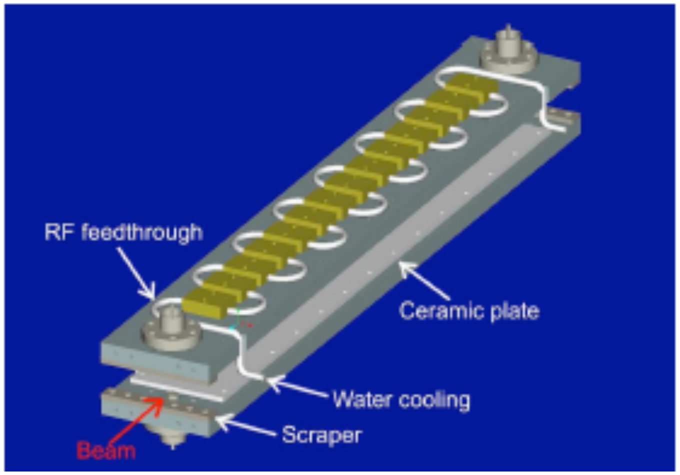


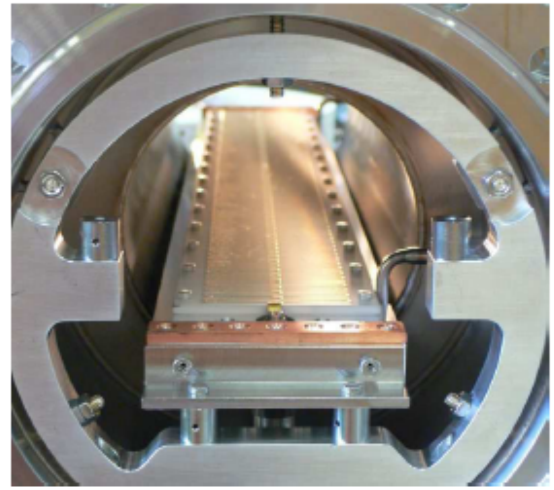
Coverage factor ~ .78

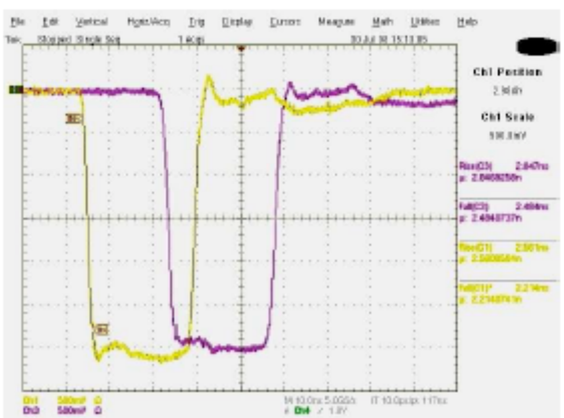




Linac-4 (SPL) double meander kicker







Measured structure rise time ~1ns

Examples of fast choppers

- Spallation Neutron Source (Oak Ridge, USA)
- J-PARC (Japan)
- Linac-4 (CERN)
- Project-X (Fermilab)

Project-X MEBT chopper plans

- Fast, high frequency, high duty factor driver is major challenge
  - 300V driver
- Low voltage driver requires long kicker
  - 4m total length
- Beam dynamics does not allow so long drifts
  - Separate to four 1m long kickers
  - (2k+1)*90° betatron phase advance between each plate and target
  - 10m long MEBT
- Kicker type: short strip-lines connected by delay lines

High voltage drivers

- High voltage driver is the major technological challenge
- Solid state devices exclusively
- Multiple transistors in series and parallel (5-100s)
  - Various combining schemes
  - FID (Fast Ionization Dynistor) is exception
- Commercial and In-house solutions

Summary

- Choppers with 10 ns rise time, 1MHz chopping rate and ~10% duty factor are in operation and reliable
- Choppers with 2 ns rise time, 10s MHz chopping frequency and ~10% duty factor is the next step. Solutions are proposed.
  - CERN chopper will be a good test
- Chopper with 2 ns rise time ,100s MHz chopping frequency , CW is demand of near future
  - High voltage driver is the major challenge
  - Solutions for chopper line, kicker are available

Thank you for attention