# Technical Challenges in Multi-MW Proton Linacs

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- Beam loss and IB stripping
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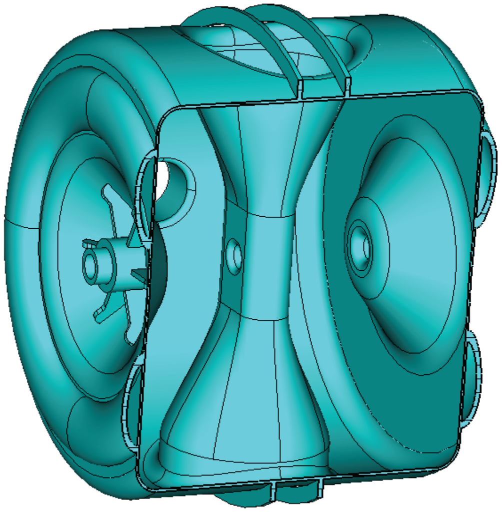
# Introduction

- Applications of MW proton linacs
  - Spallation Neutron sources
    - SNS (Oakridge, USA): 1 MW, 0.9 GeV, 38 mA with 58%DF, 0.85 ms@60 Hz
    - ESS – (Lund, Sweden): **5 MW**, 2.5 GeV, 50 mA, 2.86 ms @ 14 Hz
    - CSNS (China): 0.1 MW, 81 MeV $H^-$ DTL + 1.6 GeV RCS
  - ADS – Accelerator driven systems
    - MYRRA (Belgium): 2.4 MW, 0.6 GeV, 4 mA, CW
    - Indian ADS: **30 MW**, 1 GeV, 30 mA
    - China ADS: P>>1 MW, 1.5 GeV SC linac  
      to support operation of **1 GW reactor**
  - Physics intensity frontier
    - SPL (CERN): **4 MW**, 5 GeV, 40 mA, 0.4 ms with 100%DF, 0.4 ms@50 Hz
    - Project X (Fermilab, USA) – **3 MW**, 3 GeV, 1 mA*, CW + 8 GeV pulsed linac  
      * Bunch population corresponds to 10 mA @ 325 MHz
    - Main Injector(Fermilab) – 120 GeV, 320 kW ->700 kW (2013) ->2 MW (Pr.X)
    - JPARK (KEK, Japan), 3 GeV RCS + 50 GeV synchrotron
    - PSI cyclotron (PSI, Switzerland): 1.2 MW, 0.59 GeV, 2 mA
  - Nuclear Physics
    - FRIB – 0.4 MW, >0.2 GeV/u , 0.65 mA el. current of multi-charged ions

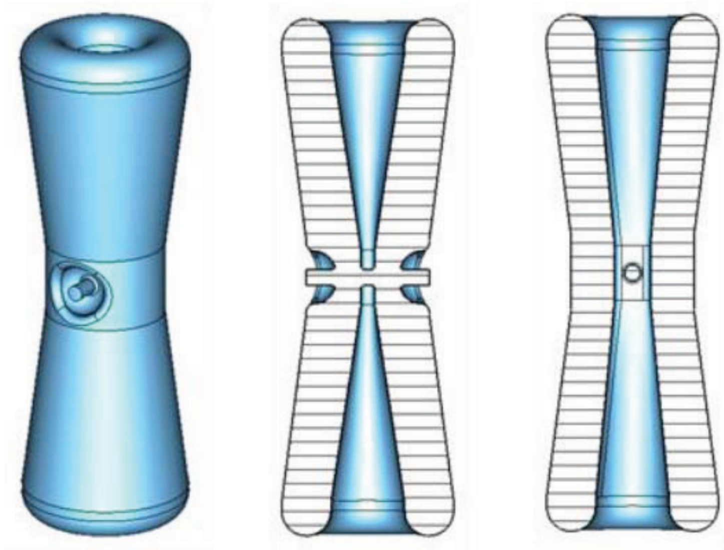
# Introduction (continue)

## Recent SRF technology development

- High beta cavities (elliptic)
  - ♦ CEBAF (1996) : Recirculating electron linac, 1 MW, 1 GeV
    - 5 MV/m (1996) - > 7.5 MV/m (~2000) -> 15 MV/m (2014?)
  - ♦ SNS (2007): Pulsed proton linac
    - 13 MV/m
  - ♦ ILC
    - pulsed: >30 MeV/m (breakdown limited)
    - CW: > 17 MeV/m (cryo-limited)



- Low beta cavities (quarter-wave, half-wave, spoke cavities)
  - ♦ Development was happening in parallel with elliptic cavities
  - ♦ ATLAS in ANL (1978)

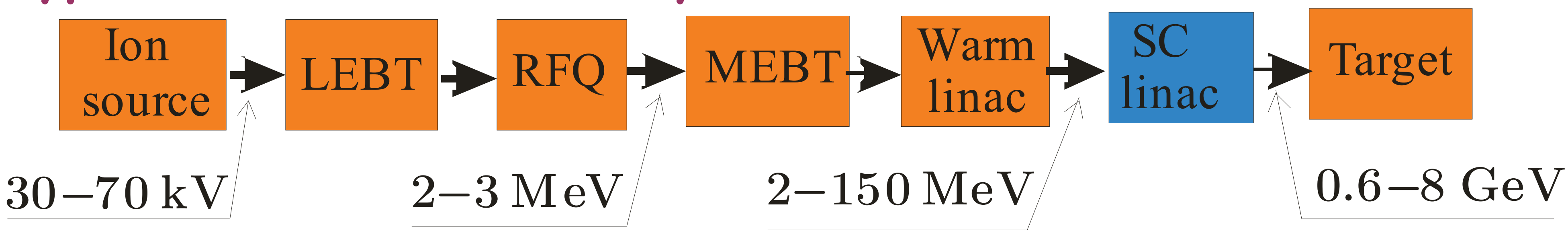


# Introduction (continue)

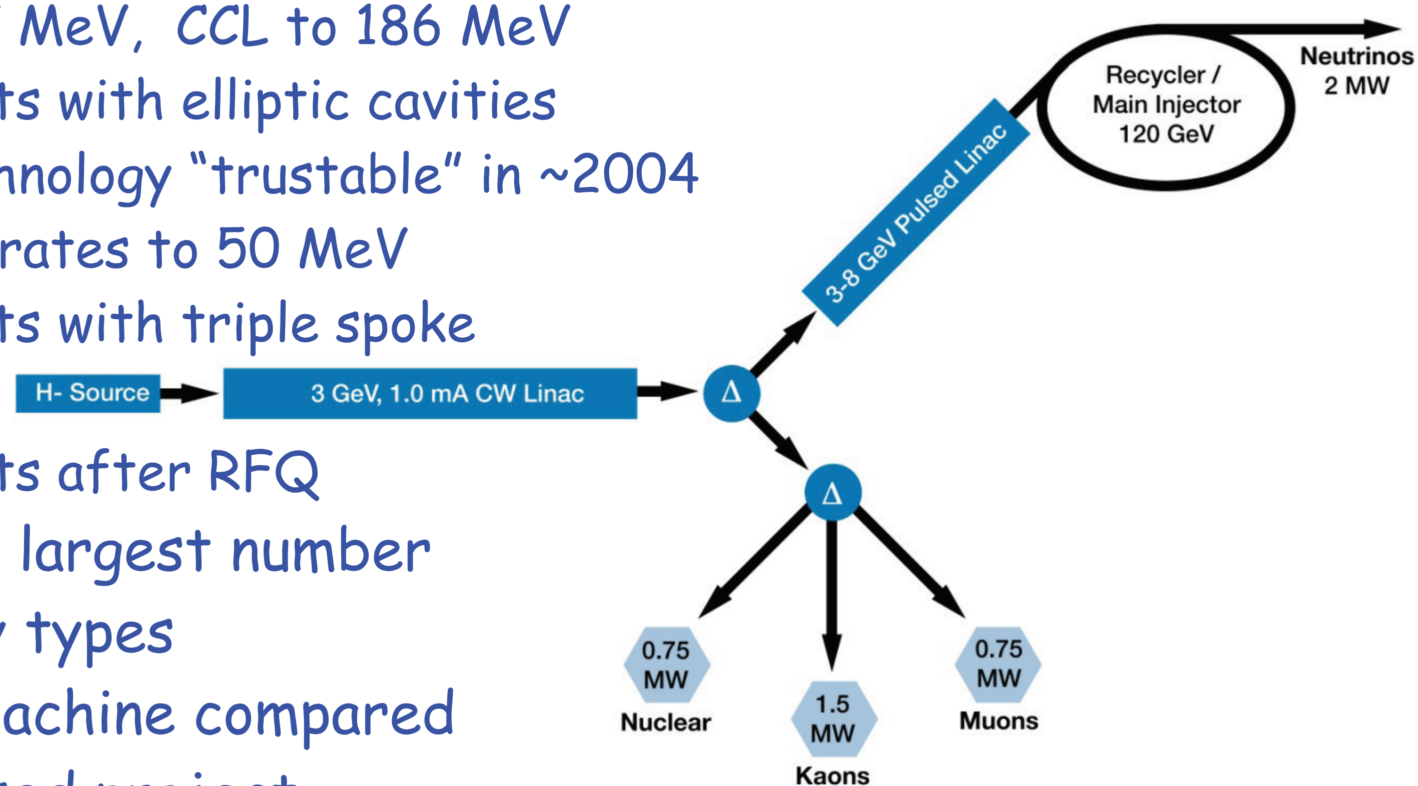
- Machine types
  - Cyclotrons: ~1 MW
  - Synchrotrons
    - high energy: 0.3 MW -> ~2 MW
    - low energy RCS: 0.3 kW -> 1 MW ?
  - Linacs
    - 1 MW -> 10-20 MW? (CW, 1-2 GeV)
    - No obvious insurmountable engineering limitations which are presently feasible
- SC linacs look as the most promising technology for multi-MW proton accelerators
  - Only SC linacs can deliver multi-MW power efficiently for CW moderate energy machines (1 – 10 GeV)
- SC linac based accelerators are the main focus of this presentation

# Introduction (continue)

## Typical SC Proton Linac Layout

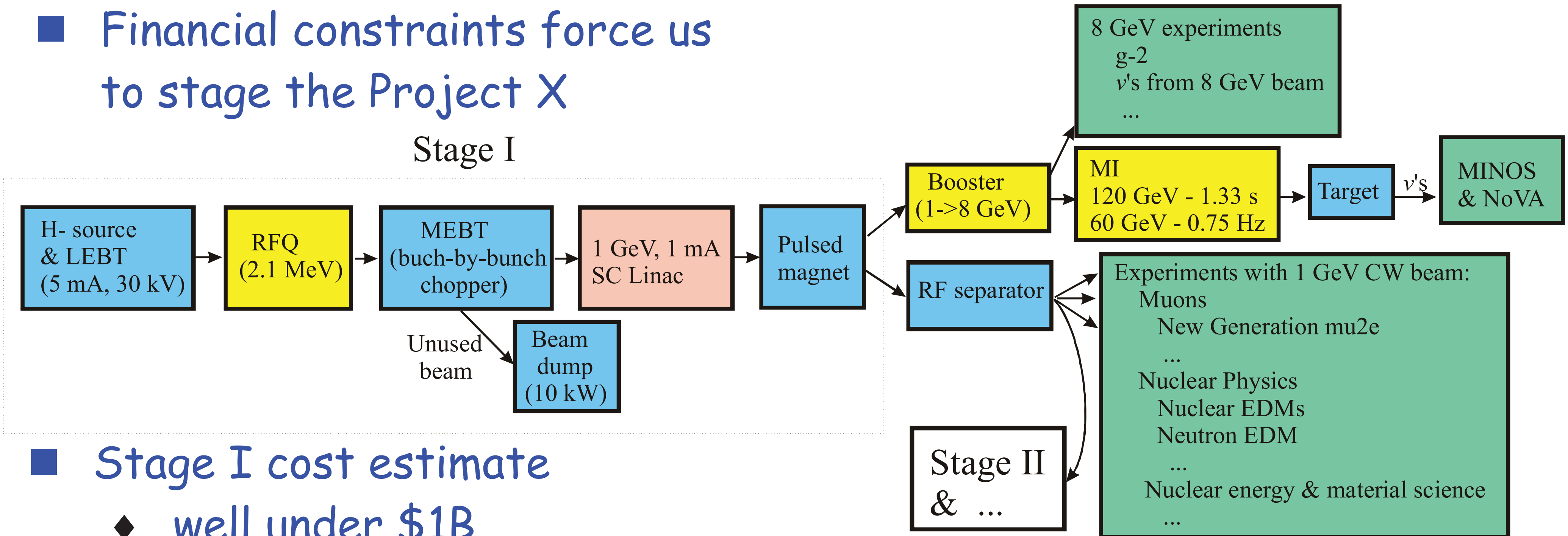



- Length of warm linac is decreasing with development of SC technology
  - SNS: DTL to 87 MeV, CCL to 186 MeV
    - SC part starts with elliptic cavities
      The only technology "trustable" in ~2004
  - ESS: DTL accelerates to 50 MeV
    - SC part starts with triple spoke
  - Project X linac
    - SC part starts after RFQ
- Project X linac has largest number of different cavity types
  - Most diverse machine compared to other proposed project

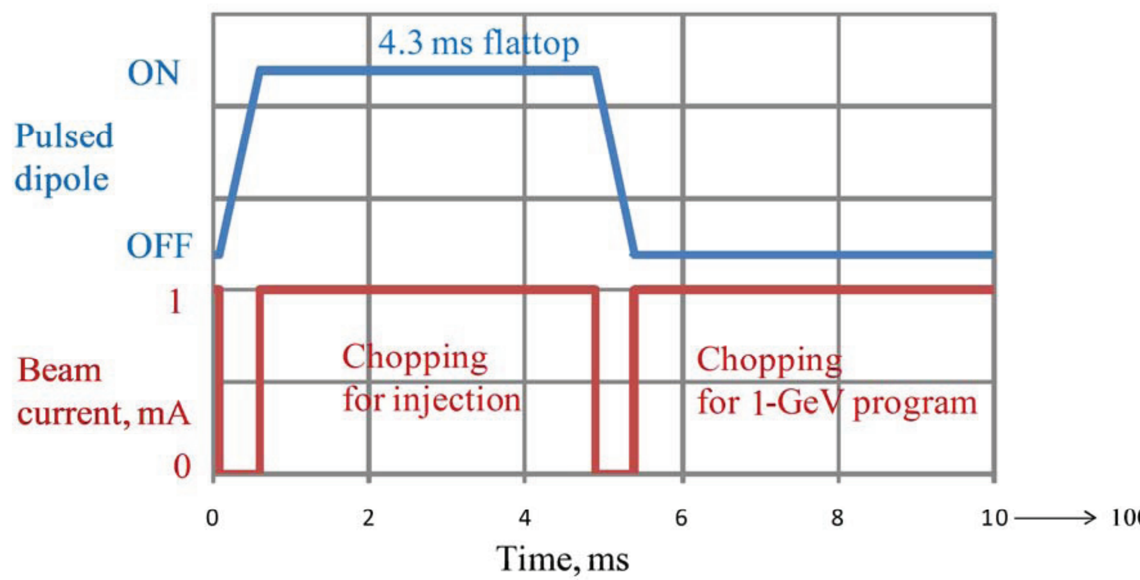


# Project X Staging

- Financial constraints force us to stage the Project X

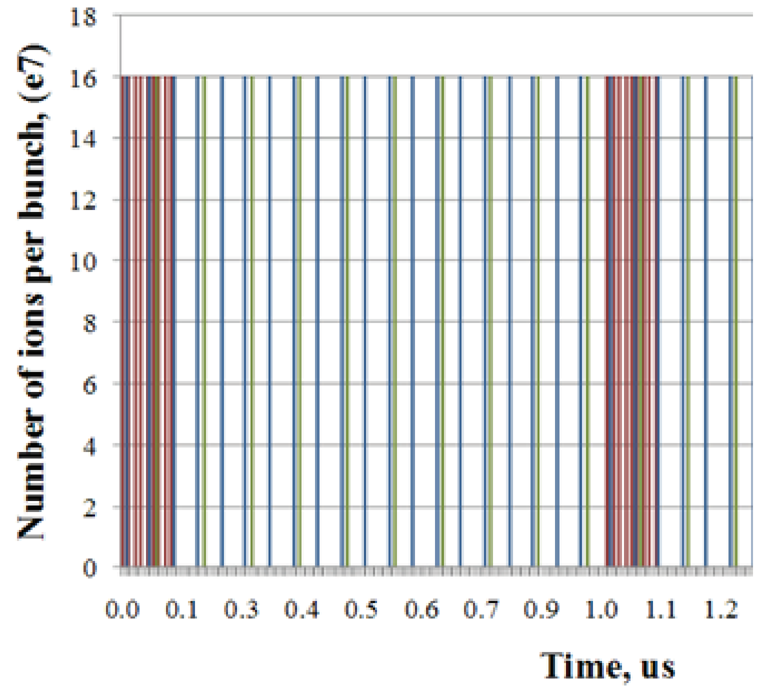


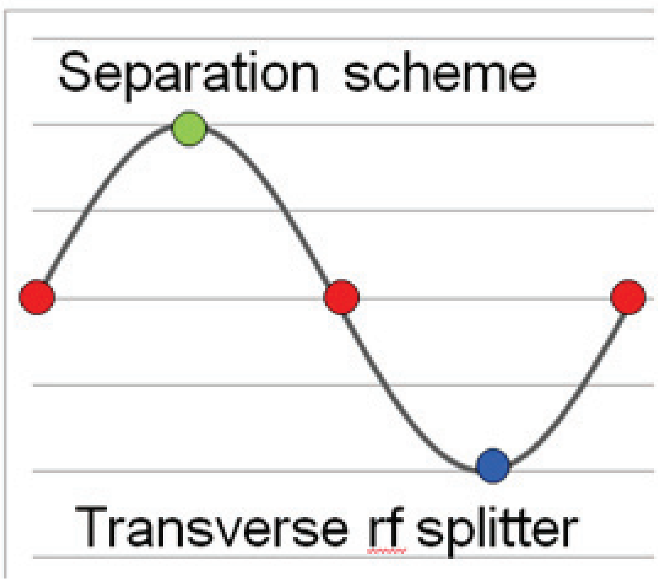

- Stage I cost estimate
  - well under $1B
- Active discussion of Project X physics program is going
- 2 mA in SC linac can significantly strengthen the program (2 MW @ 1 GeV)
  - ~$30M price increase

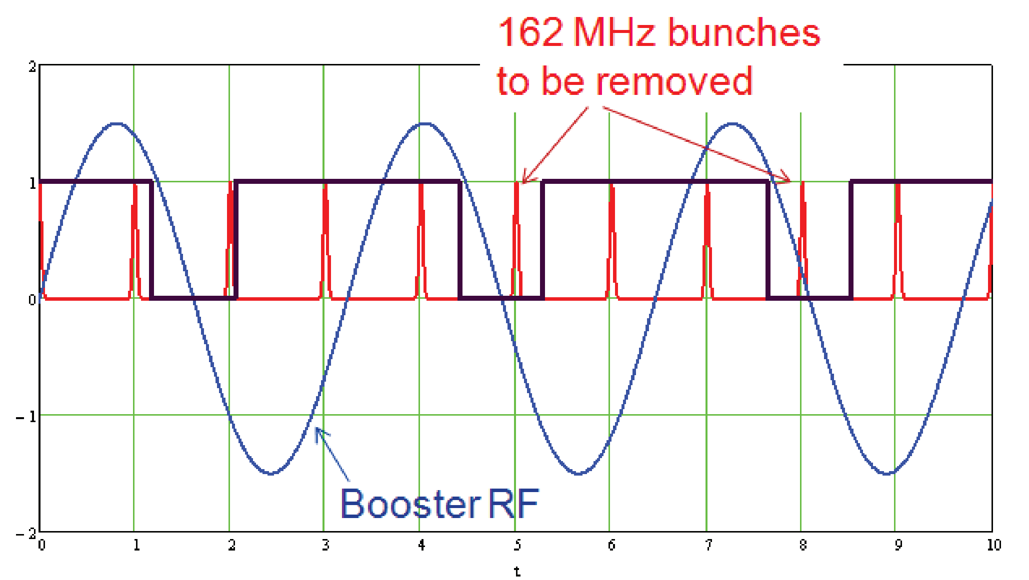


# Project X Chopping and Splitting

- Bunch sequence for each experiment is controlled by bunch-by-bunch chopper
  - Undesired bunches are removed from uniform RFQ bunch stream for each experiment independently
- RF separation is simular to CEBAF



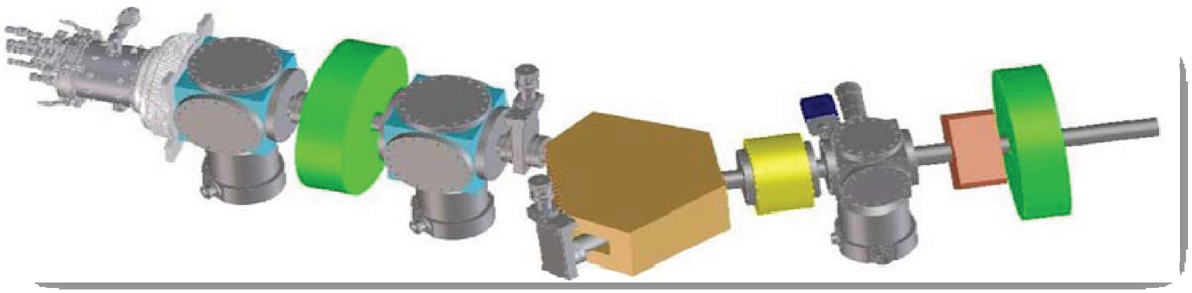




- Ring injection: bunches coming to the RF bucket boundary are prevented from injection to the ring

# *Ion Source*

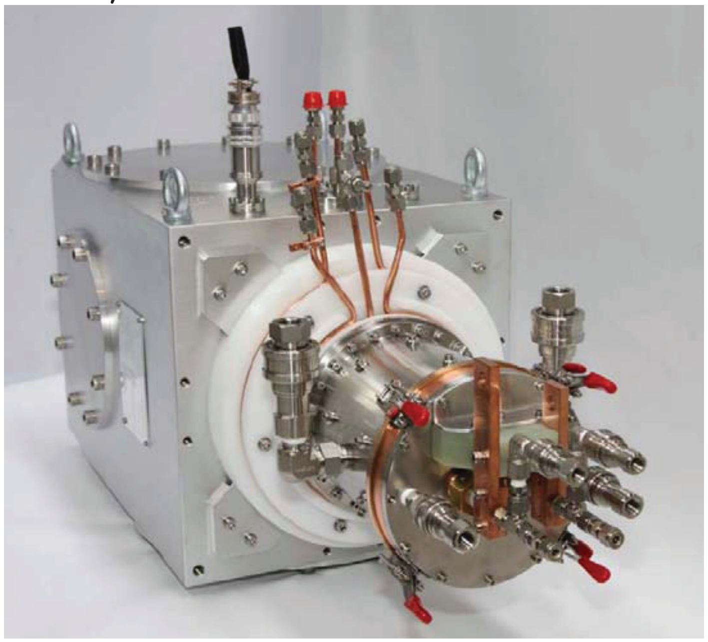
- Machine performance is usually not limited by ion source current or its phase density
  - Even in the case of H- ion source
- Beam brightness: $I_{beam}/\varepsilon_{norm,rms}$
  - $H^-$ - ~100 mA/mm mrad
    - TRIUMF: DC, 10 mA, 0.12 mm mrad
    - SNS: Pulsed: 0.9 ms, 50 Hz
      38 mA, 0.3 mm mrad
  - Protons ~400 mA/mm mrad
    - ESS: Pulsed: 2.9 ms, 14 Hz
      90 mA, 0.2 mm mrad
- Ion source lifetime is an issue – 350 hours at 15 mA for TRIUMF IS
  - Operation with 2 ion sources: operating source and hot spare



Volume-cusp $H^-$ ion source developed by TRIUMF

Beam current – CW to 15mA

$\varepsilon_{norm,\ rms}$ < 0.25 mm-mrad



http://www.dehnel.com/

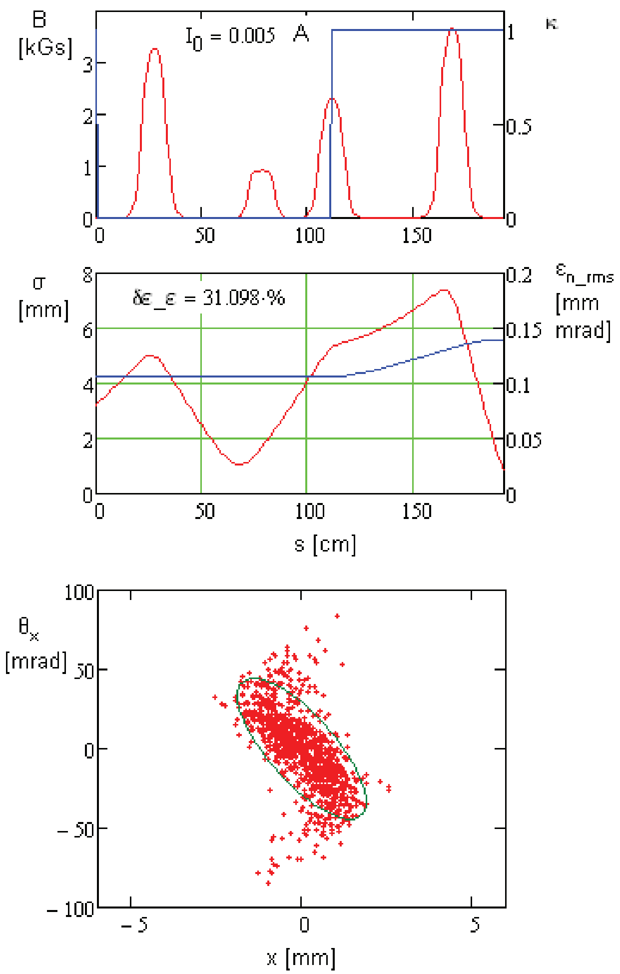
# Low Energy Beam Transport – LEBT

- Assignments
  - Beam transport from ion source to RFQ
  - Match the ion source phase space to RFQ
  - Differential pumping to reduce gas flux from ion source to RFQ
- Length ranges from 20 cm (SNS) to about 2 m (Project X and ESS)
  - Larger length - more effective differential pumping
    + Space for LEBT beam chopper for beam current control
- Beam energy ranges from 30 to 80 kV.
  - Perveance for most machines ~ 60-120 $\mu A/kV^{3/2}$
- Two lenses - to have enough freedom for beam envelope matching
  - Electrostatic einzel lenses (like in SNS, work on magnetic LEBT)
  - Axially-symmetric magnetic lenses (ESS, Project X)
  - Quads do not make " compact" focusing and normally are not used
- The beam space charge introduces non-linear focusing which results in an emittance growth
  - Effect is scaled with dimensionless parameter:
  - For a two-lens transport and $\kappa_{SC} \approx 100$ the space charge increases the beam emittance by ≈ 30%.

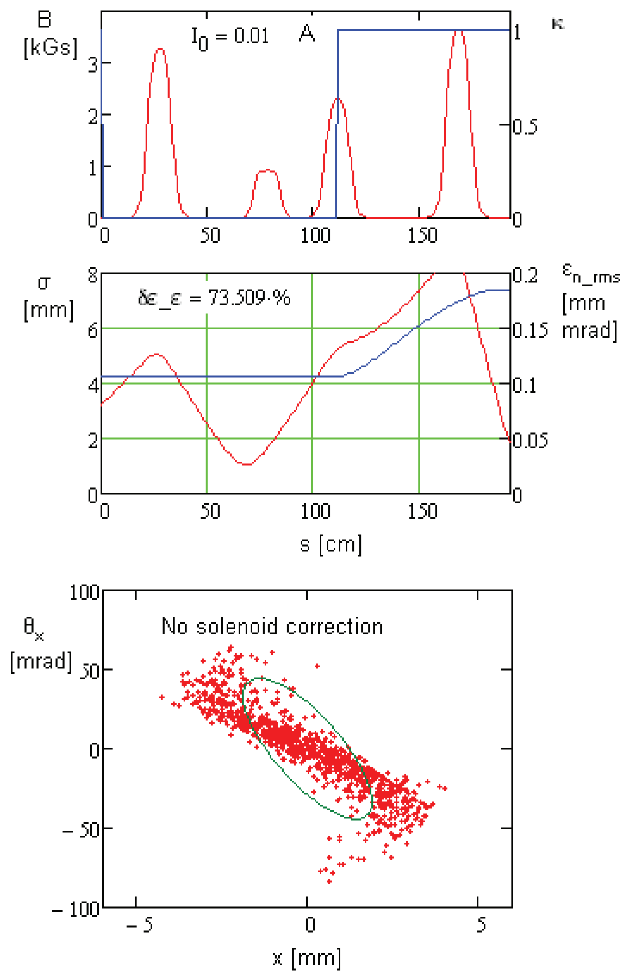
$$\kappa_{SC} = \frac{Z_0 I_b L}{4\pi U \varepsilon_n}$$

# LEBT Simulations for Project X

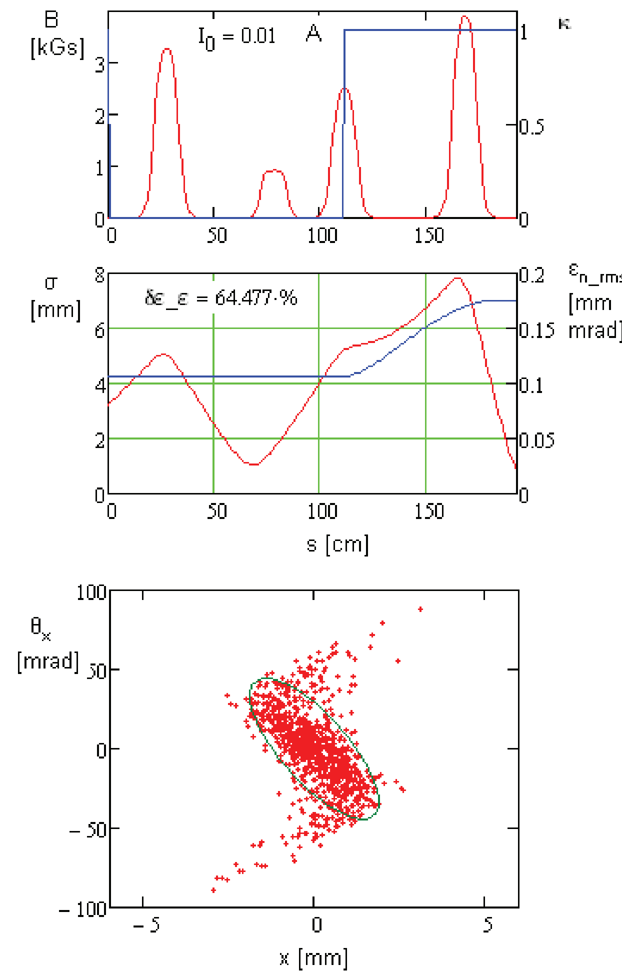
- Optics with 3 solenoids
- Partially compensated beam transport for LEBT beam chopping
- Solenoid strength depends on beam current




*5 mA optics (5 mA beam)*




*5 mA optics (10 mA beam)*




*10 mA optics (10 mA beam)*

***30 keV, 0.11 mm mrad***

# Radio Frequency Quadrupole Accelerator – RFQ

- Frequency is usually set by frequency of downstream accelerators
- For most projects it is 352.2 or 325 MHz
  - Good frequencies for further acceleration.
    - 352.2 is bound to the LEP RF frequency
      $\Rightarrow$ existing CERN infrastructure
    - 325 MHz is bound to the $4^{th}$ subharmonic of ILC frequency
      $\Rightarrow$ use of ILC cavity design for acceleration at high energy
- Blistering and sputtering result in a degradation of RFQ parameters in a long run the beam loss
  - Effect grows proportionally to the beam current loss.
  - Design of a high power RFQ has to be aimed to minimize the beam loss to the RFQ vanes.
  - It is more important for low energy particles which produce more spattering and blistering than high energy particles.

# Project X RFQ

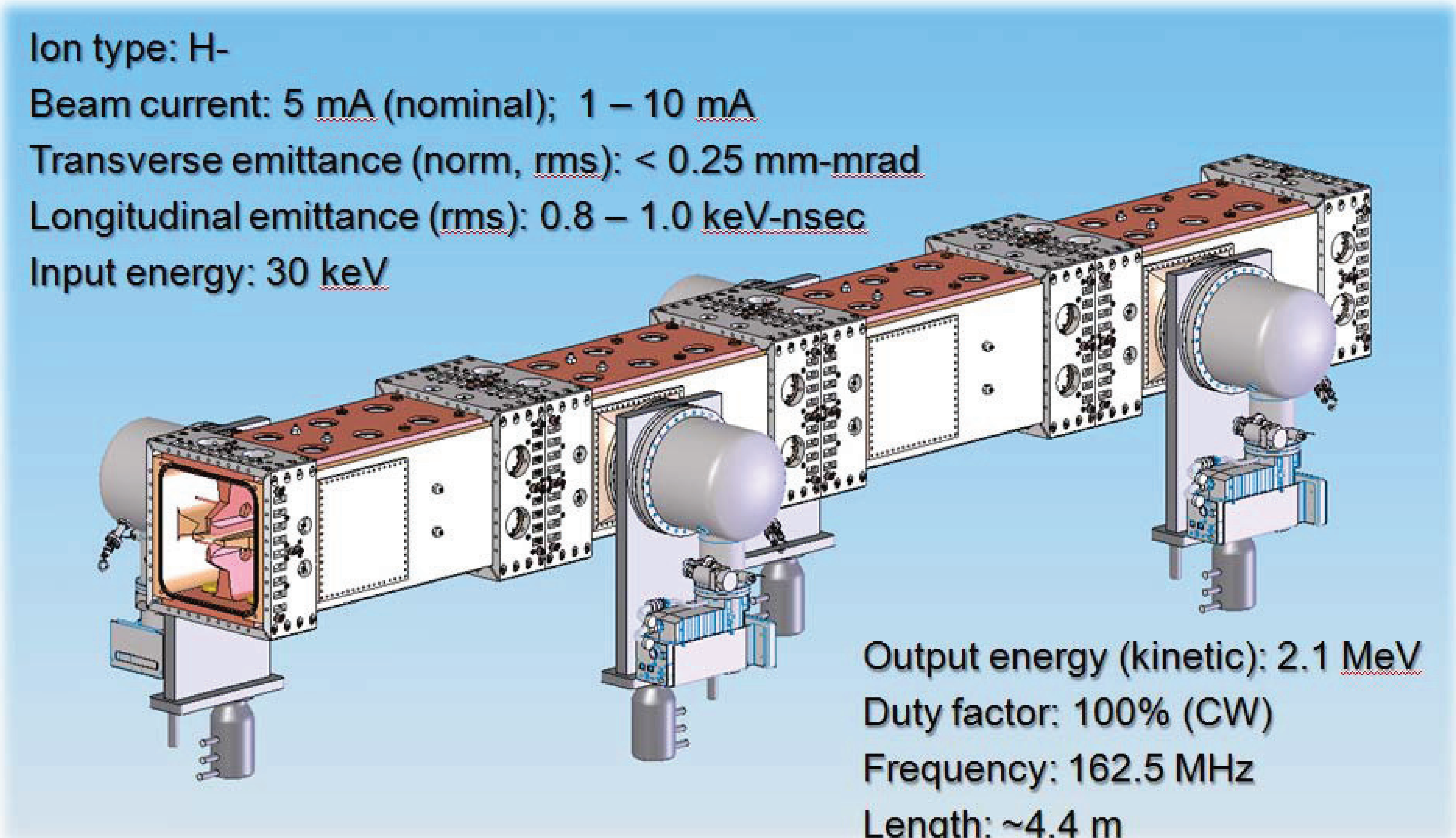
- Frequency choice of 162.5 MHz is caused by a requirement of bunch-by-bunch chopping
  - It looks feasible at 162.5 MHz but hardly possible at 325 MHz
  - Higher frequency RFQ has shorter length (due to faster bunching) and larger power density but other parameters are not much different.

Comparison of Project X RFQs operating at different frequencies, J. Staples

| | Type 1 | Type 2 | |
|---|---|---|---|
| Frequency | 162.5 | 325 | MHz |
| Injection Energy | 35 | 30 | keV |
| Output energy | 2.5 | | MeV |
| Beam current | 10 | | mA |
| Length | 385 | 287 | |
| Vane-to-vane voltage | 98.8 | 64.2 | kV |
| Peak E-field | 20.7 | 27.6 | MV/m |
| E-field/Kilpatrick | 1.52 | 1.55 | |
| Cavity power | 155 | 149 | kW |
| Max. wall power density | 2.1 | 5.2 | $W/cm^2$ |
| Transmission | 94 | 90 | % |

- Later in the design process the output RFQ energy was reduced to 2.1 MeV to avoid radioactive activation in the RFQ and MEBT.

# Project X RFQ




- *Last stages of design*
- *Operational in 2014-15*

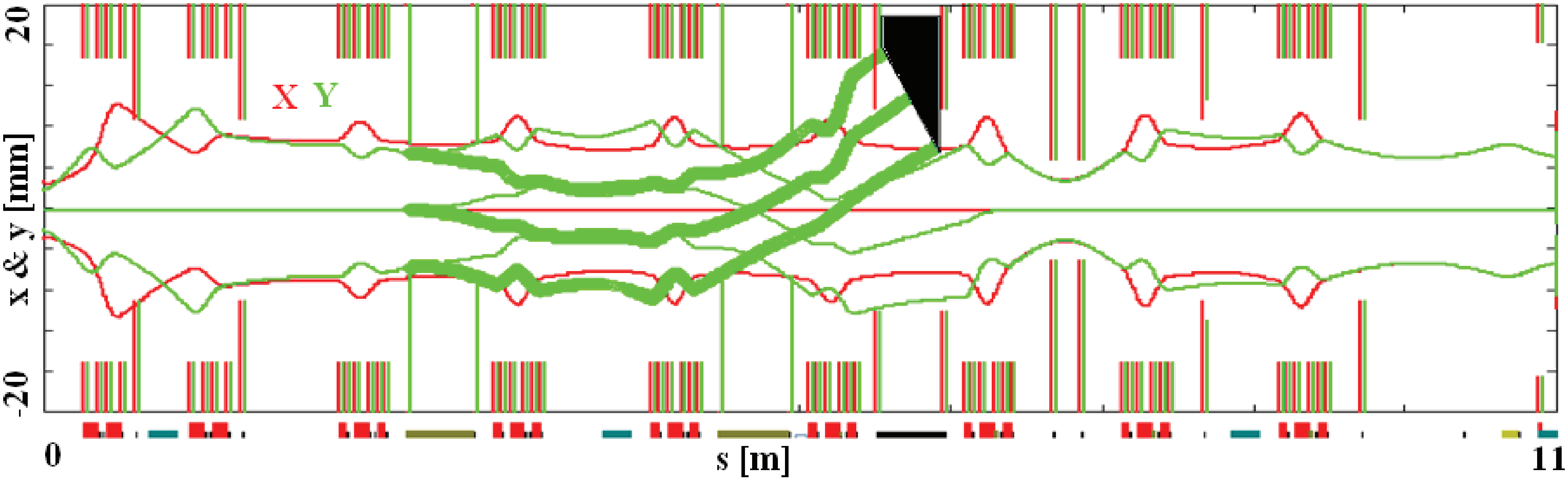
# Medium Energy Beam Transport - MEBT

- Assignments
  - Match the bunch envelopes from RFQ to downstream accelerator.
  - In addition to 2 ⊥ planes the longitudinal plane has to be matched
    - ≥2 RF cavities
  - Instrumentation and hardware
    - to characterize the RFQ beam
    - to assist in the envelope matching
    - to scrape the transverse beam halo
- Space charge effects are still strong (relative to LEBT)
  - Higher energy helps
  - bunching makes it worse
  - However some period lengthening is possible
    - quadrupoles can be use
- Scraping of RFQ longitudinal tails is a problem.
  - If present they can be lost in further acceleration
  - Need to be avoided in a MW scale machine
    - Special attention to the longitudinal tails in RFQ design

$$\kappa_{SC} = \frac{Z_0 I_b L}{4\pi U \varepsilon_n \kappa_b}$$

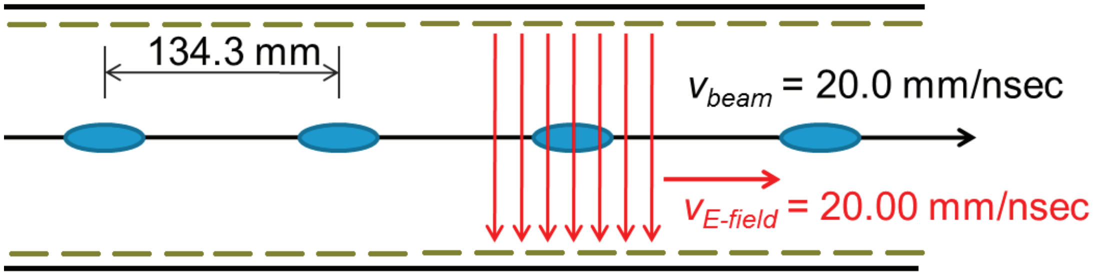
# Project X MEBT

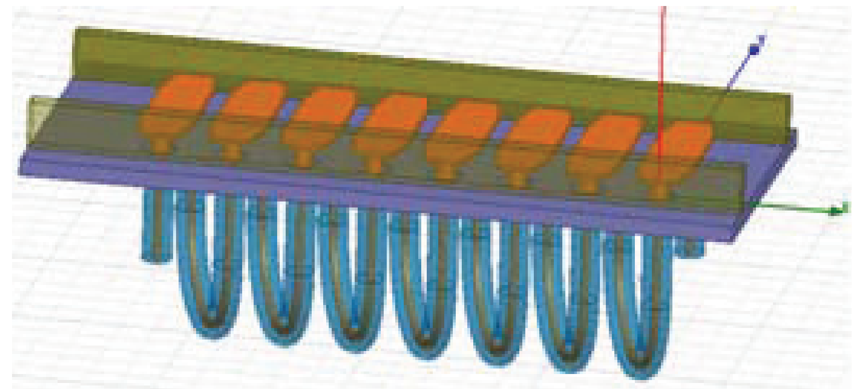
- Due to bunch-by-bunch chopping Project X has long & complex MEBT



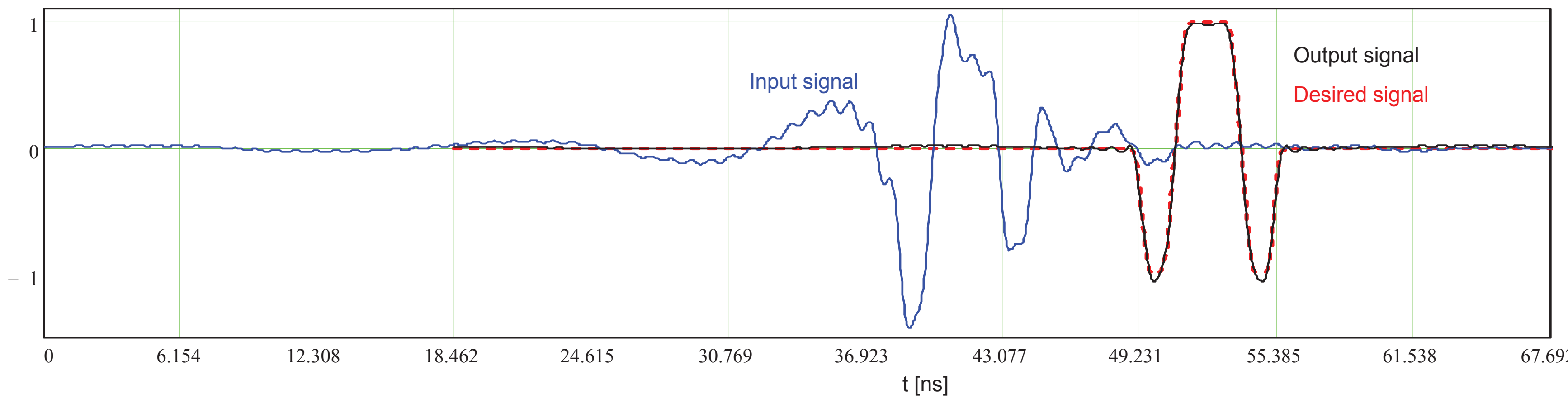

- Triplet focusing with ~90 deg. phase advance per cell
  - minimizes beam sizes and creates "smooth" focusing
    - $\Rightarrow$ small emittance growth
- Three RF cavities: 162 MHz, 100 kV (amplitude)
- Two kickers to obtain acceptable voltage (power)
  - Kickers are separated by 180 deg in betatron phase
- Incoming $H^-$ beam brings large volume of $H_2$ : 5 mA = $4.4 \cdot 10^{-4}$ $l \cdot torr/s$
  - Differential pumping (Ø10 mm)
    - to reduce gas flux from absorber to SC cavities

# MEBT Bunch-by-Bunch Kicker



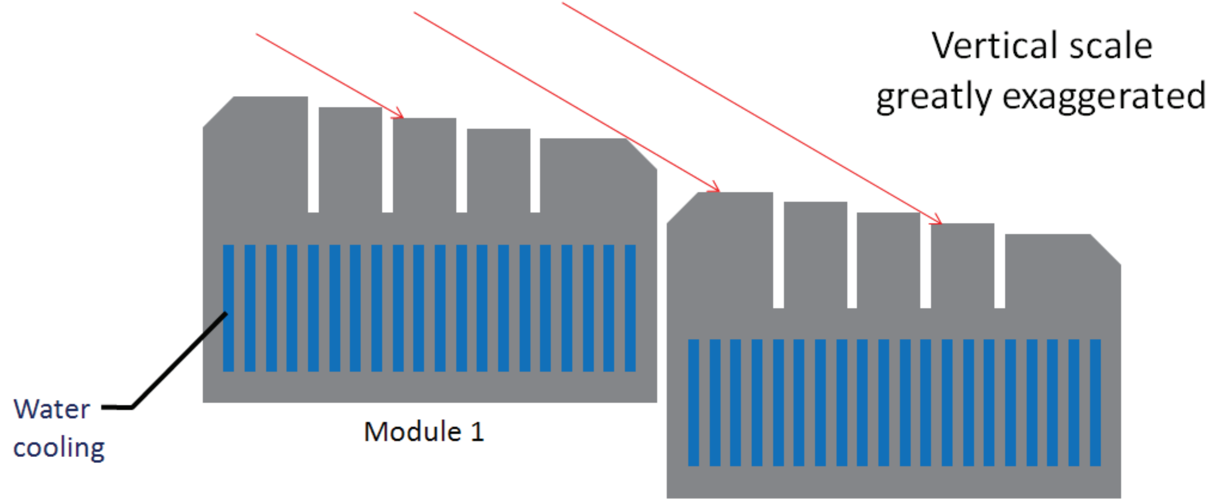
- Kicker: 16 mm gap, 500 mm length, 13 mm aperture restriction (protect.)
  - Improved version of Los-Alamos kicker
- Driven differentially by 2 power amplifiers with ±250 V (1 kW)
- Pulse pre-distortion  allows forming nearly perfect pulses with commercial amplifier (1 kW, 50 – 1000 MHz, ~±300 V)

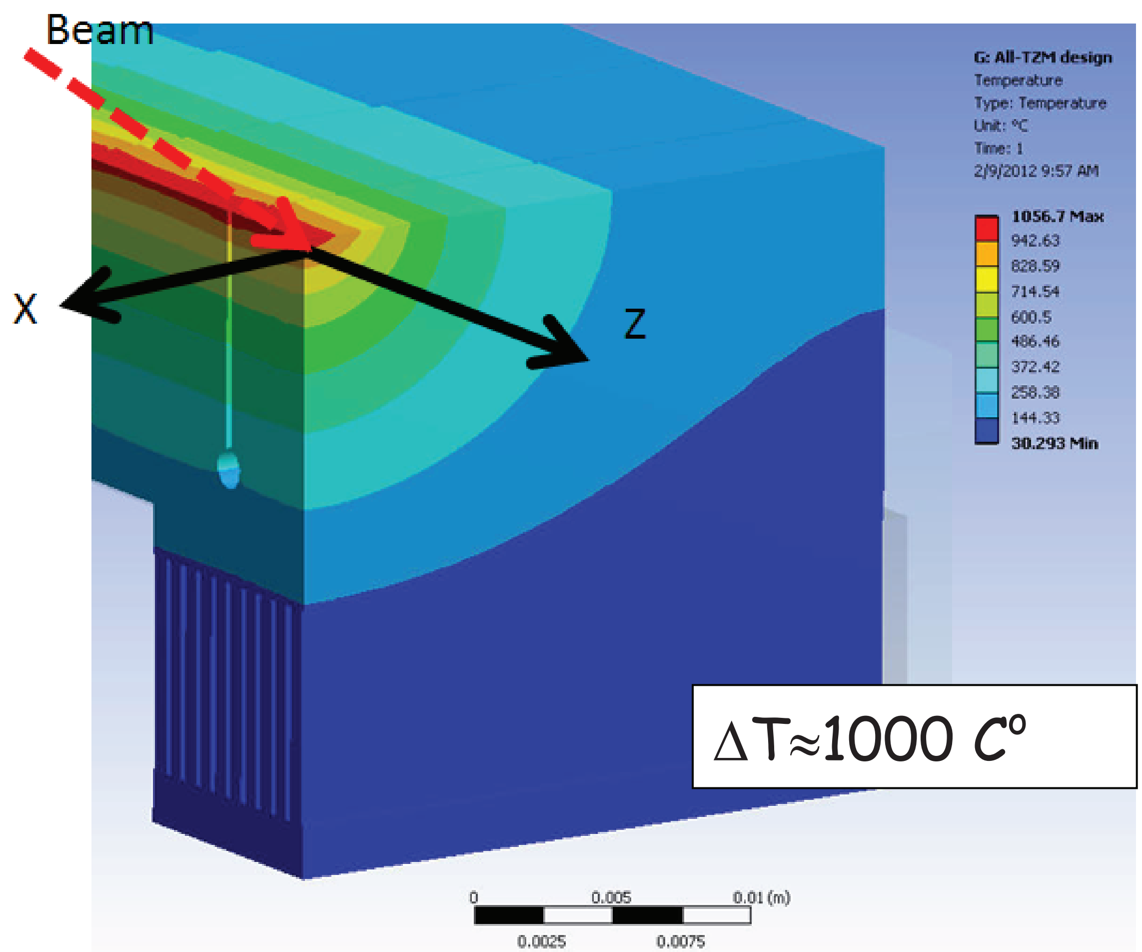



- Kicker design is in the final stage
  - Test of fully engeneered prototype is expected at the beginning of 2013

# MEBT Beam Dump

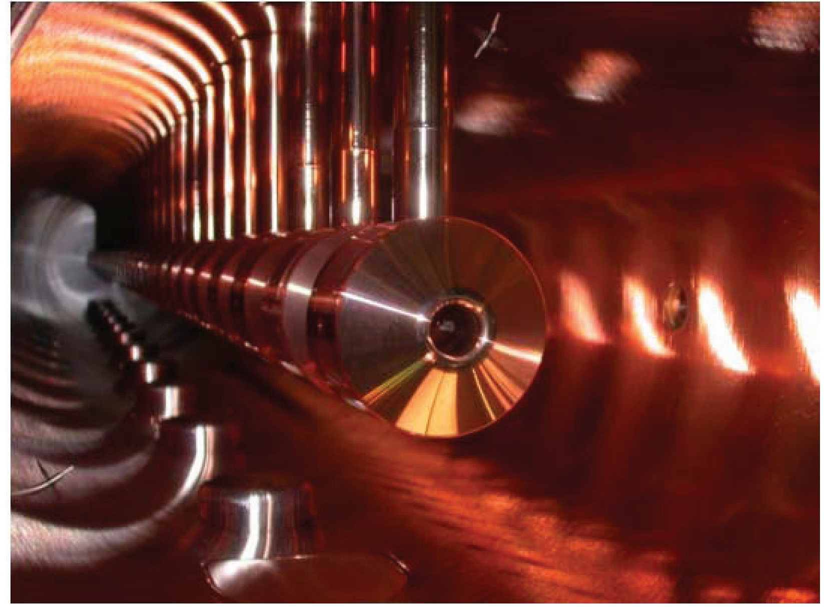
- 21 kW in $\sigma_x \approx \sigma_y \approx 2$ mm
- High power density in the beam, ~80 kW/cm$^2$
  - 29 mrad grazing angle $\Rightarrow$ 2.2 kW/cm$^2$
  - micro-channel cooling
  - 650 mm available length
- Spattering and blistering
  - ~0.2 mm/year
  - Molybdenum (TZM) alloy has high endurance to blistering and good relationship between thermal expansion, Young's modules and yield stress
- ~25% beam power is reflected due to multiple scattering, $\sigma_\theta$~100 mrad

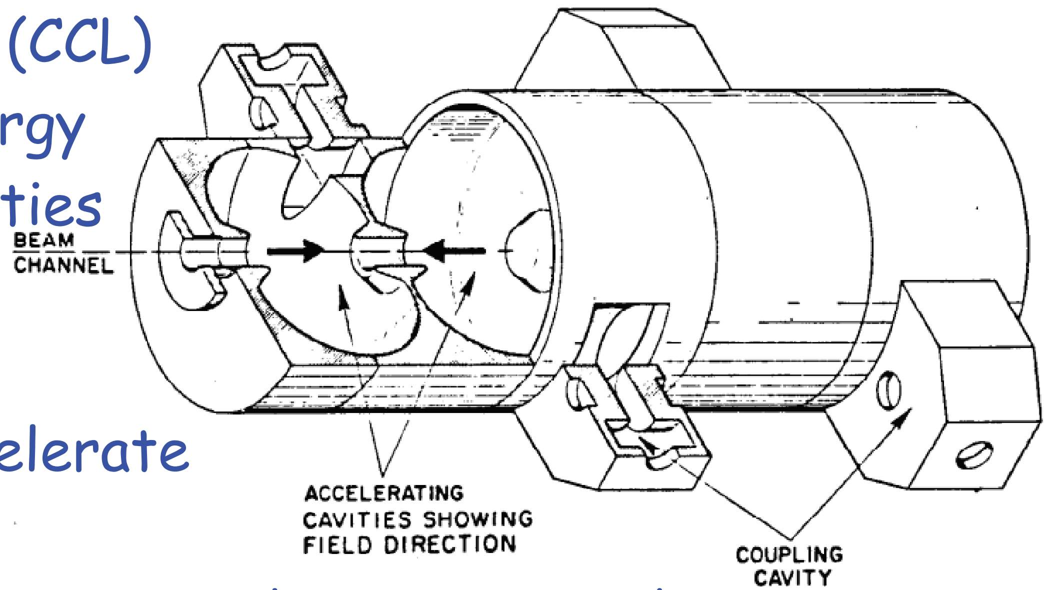


# Warm Linac

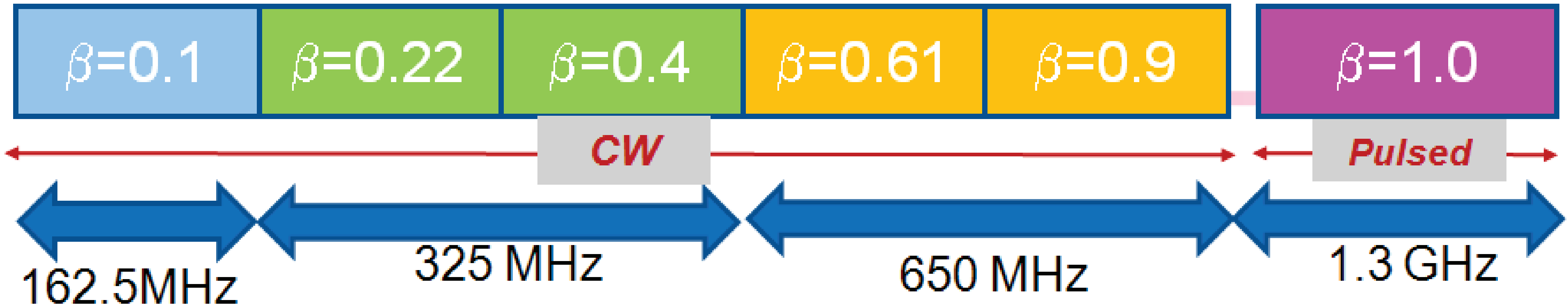
- Usage of SC acceleration at low energy does not bring significant advantages for pulsed machines
  → pulsed machines normally use normal conducting accelerating sections between RFQ and SC part of the linac
  - SNS warm part consists of
    - Drift Tube Linac (DTL) with 87 MeV output energy
    - and Coupled-Cavity Linac (CCL) with 186 MeV output energy
- Recent developments in SC cavities reduced the energy where the SC section can start
  - ESS plans to use DTL to accelerate the beam to 50 MeV
  - Project X will be a CW accelerator and its superconducting part starts immediately after MEBT at 2.1 MeV





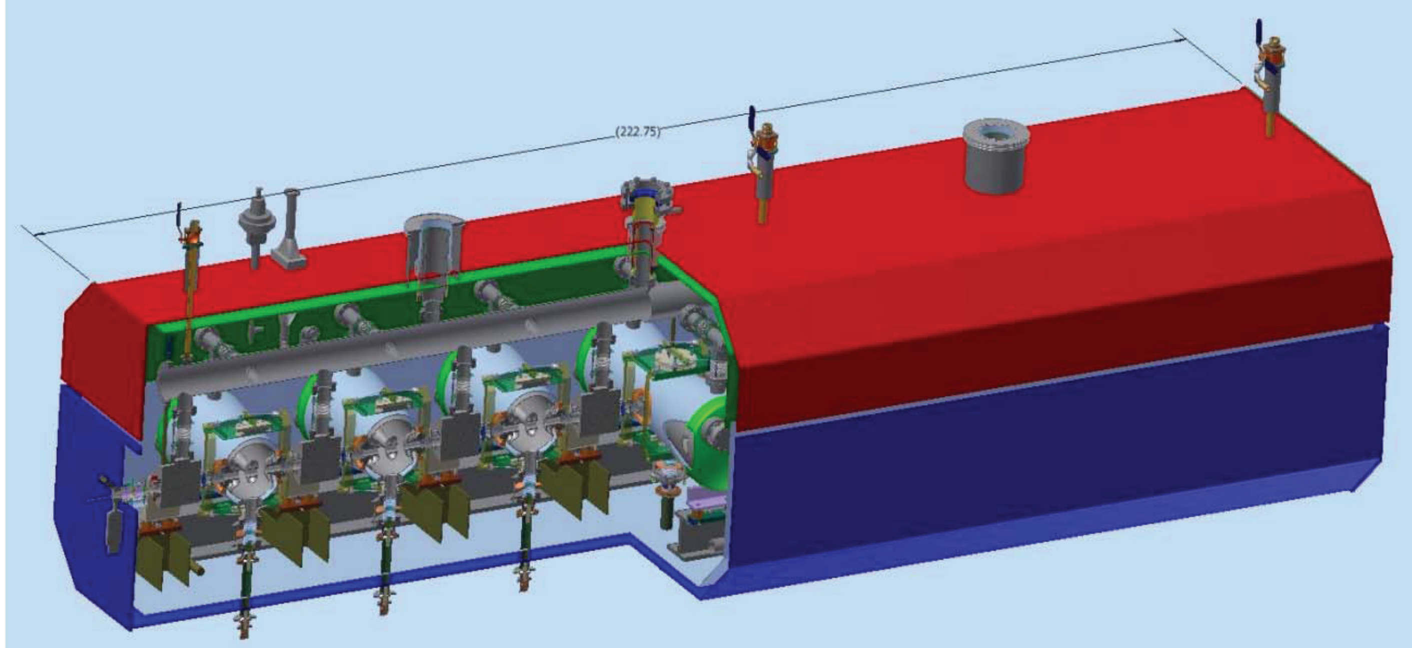
# Project X SRF Linac Technology Map

- 5 types of SC cavities are required for Stage I

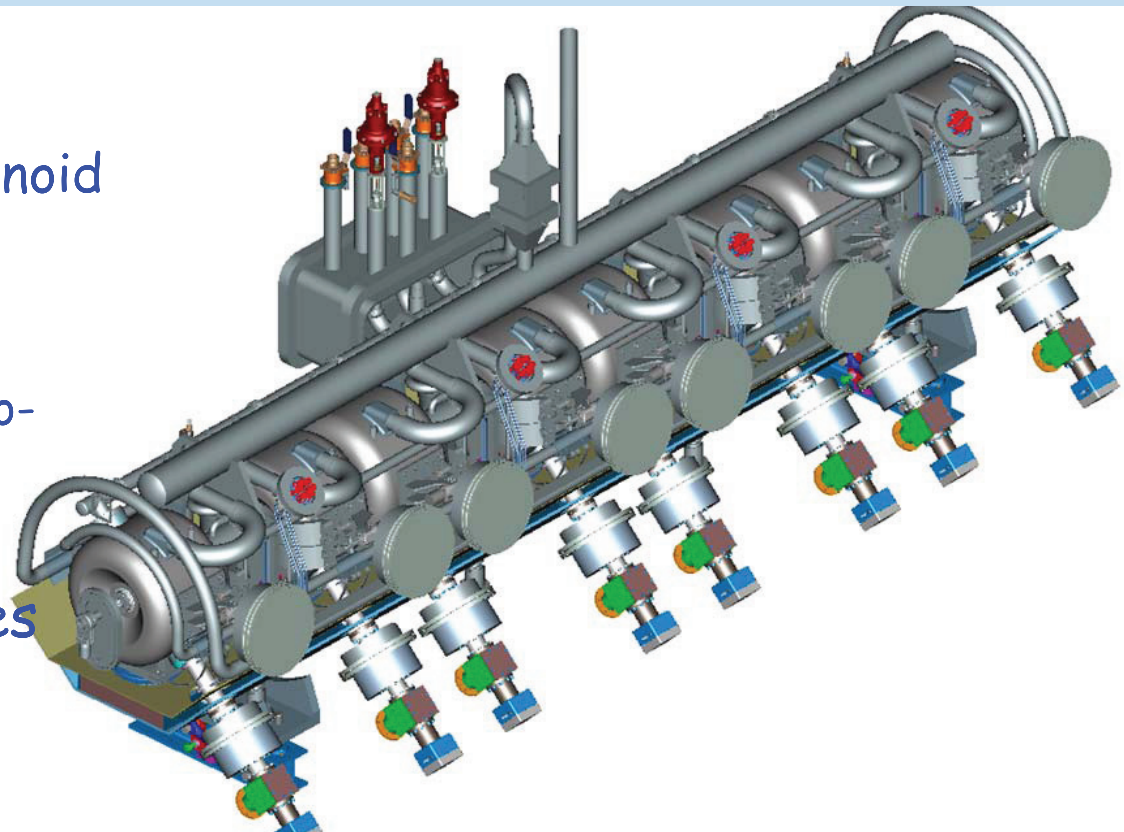



| Section | Freq | Energy (MeV) | Cav/mag/CM | Type |
|---|---|---|---|---|
| HWR ($\beta_G$=0.1) | 162.5 | 2.1-11 | 8 /8/1 | HWR, solenoid |
| SSR1 ($\beta_G$=0.22) | 325 | 11-38 | 16/8/ 2 | SSR, solenoid |
| SSR2 ($\beta_G$=0.47) | 325 | 38-177 | 36/20/4 | SSR, solenoid |
| LB 650($\beta_G$=0.61) | 650 | 177-467 | 30 /10/5 | 5-cell elliptical, doublet |
| HB 650($\beta_G$=0.9) | 650 | 467-2000 | 96/12/12 | 5-cell elliptical, doublet |
| ILC-CW($\beta_G$=1.0) | 1300 | 2000-3000 | 72/9/9 | 9-cell elliptical, quad |
| ILC-pulsed($\beta_G$=1.0) | 1300 | 3000-8000 | 224 /28 /28 | 9-cell elliptical, quad |

# HW and SSR1 cryomodules are in the advanced design stage



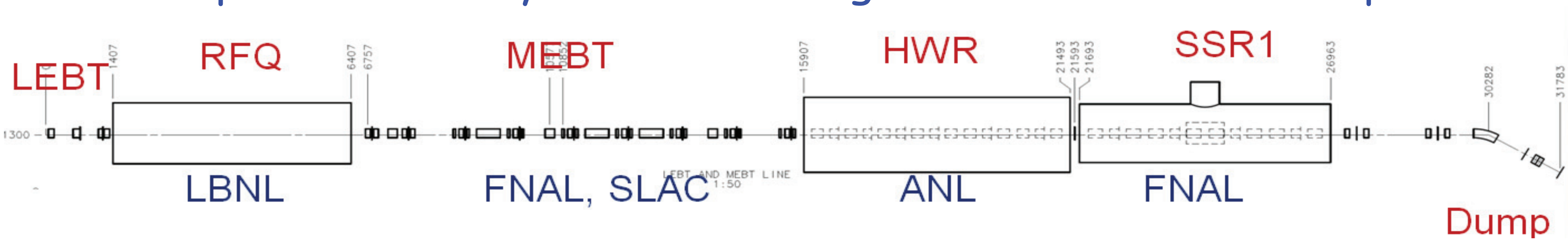

- 2 SSR1 cavities are tested good in VT
- Design features
  - Solenoid with active shielding
  - button BPM is bolted to solenoid
  - SSR1 cryo-vessel design suppresses df/dP
    - Mechanical tuner with piezo-tuner for microphonics control

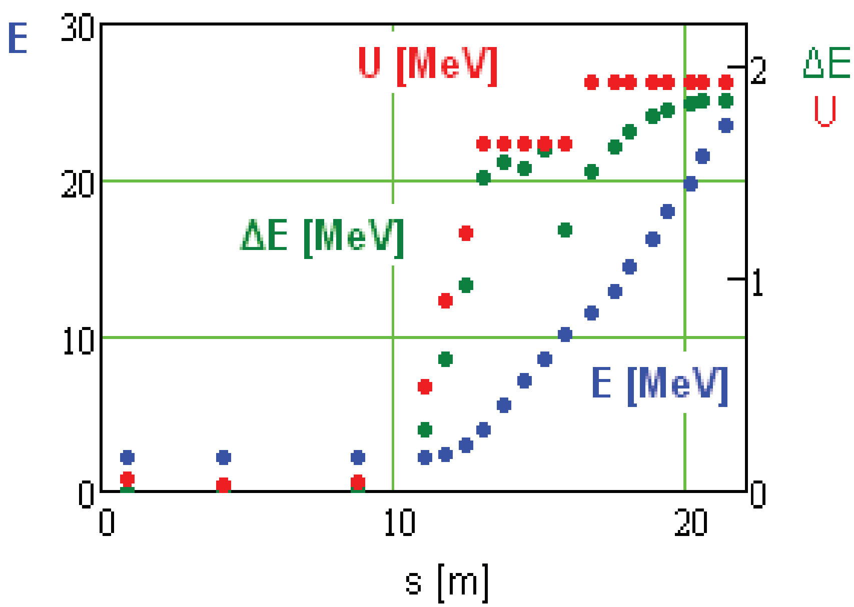


- Couplers for both cryomodules are designed and their tests should proceed soon
- More details see in R. Kephart presentation in WG-C

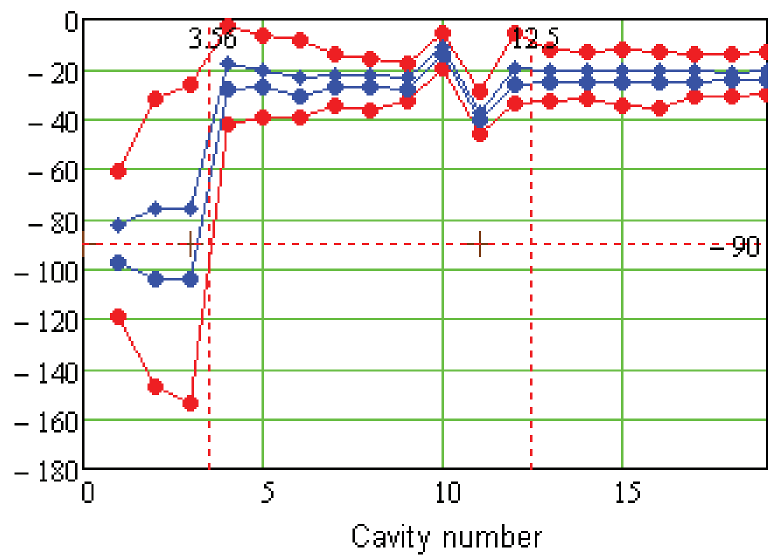
# PXIE – Project X Injector Experiment

- Test of most critical Project X technologies
- Warm part + 2 SC cryomodules + diagnostic line & beam dump




Acceleration in SC Cryomodules



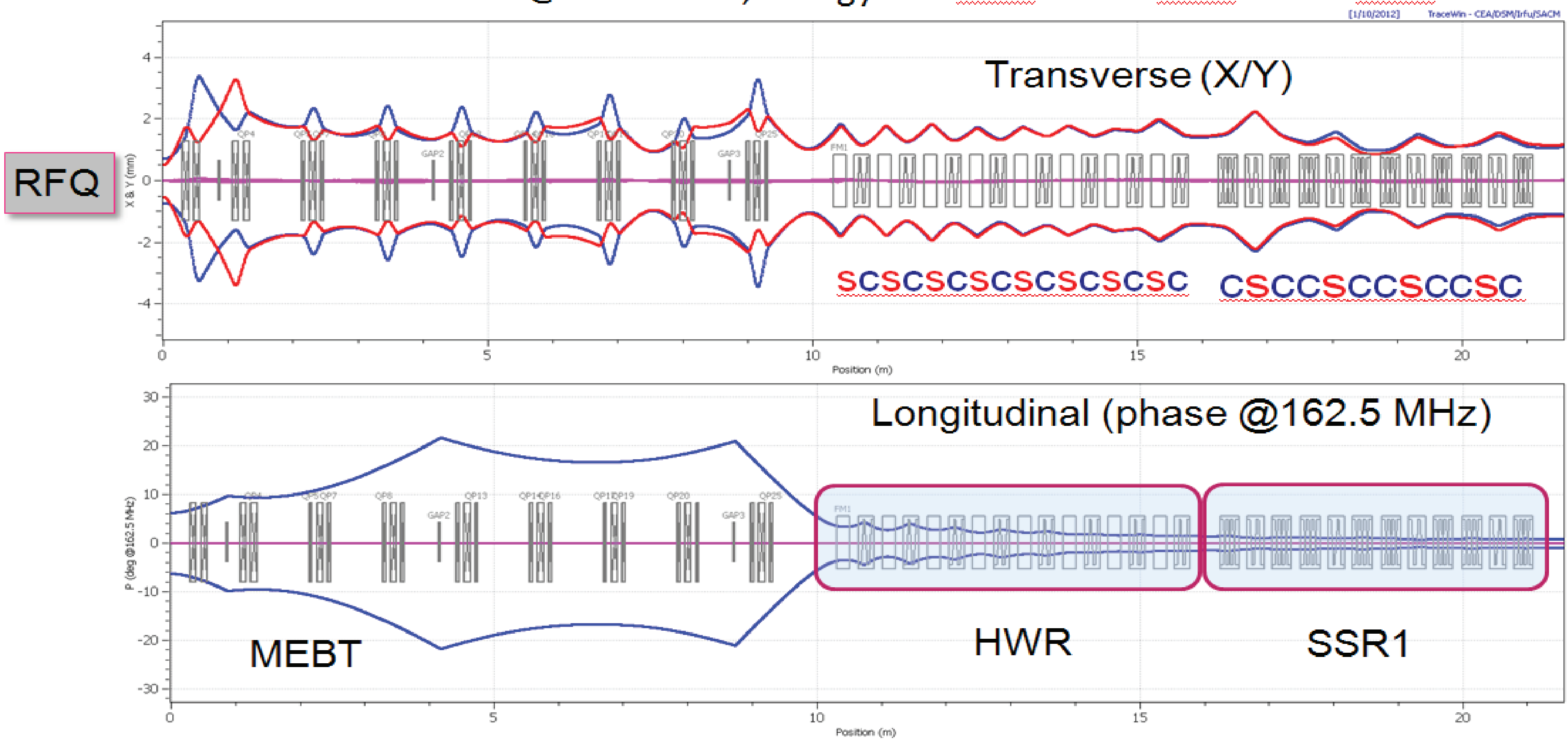

1σ and 4σ bunch ends relative to the accelerating phase [deg]

- Accel. gradient of first 3 SC cavities is reduced due to L. overfocusing
- Design intent for operating voltages are: 1.7 MV – HW & 2 MV SSR1
- Reliable operation requires RF volt. & phase to be within 1% & ~0.5°

# SC Linac Beam Dynamics

- Strong space charge effects in Project X SC linac
- Bunch population corresponds to 10 mA beam current at 325 MHz
  - 80% bunches are chopped out & RFQ at half frequency (162.5 MHz)
  - Nearly the same beam brightness as at the SNS

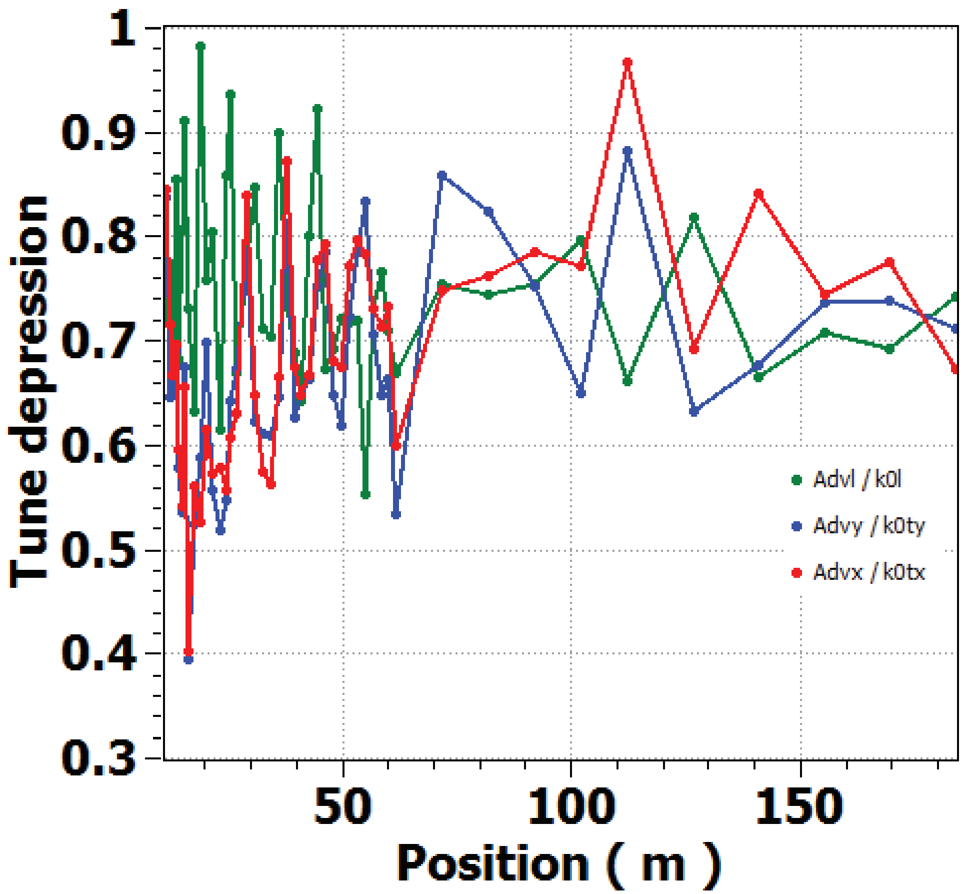
Current 5 mA@162.5 MHz; Energy: 2.1 MeV – 10.8 MeV – 22.1 MeV

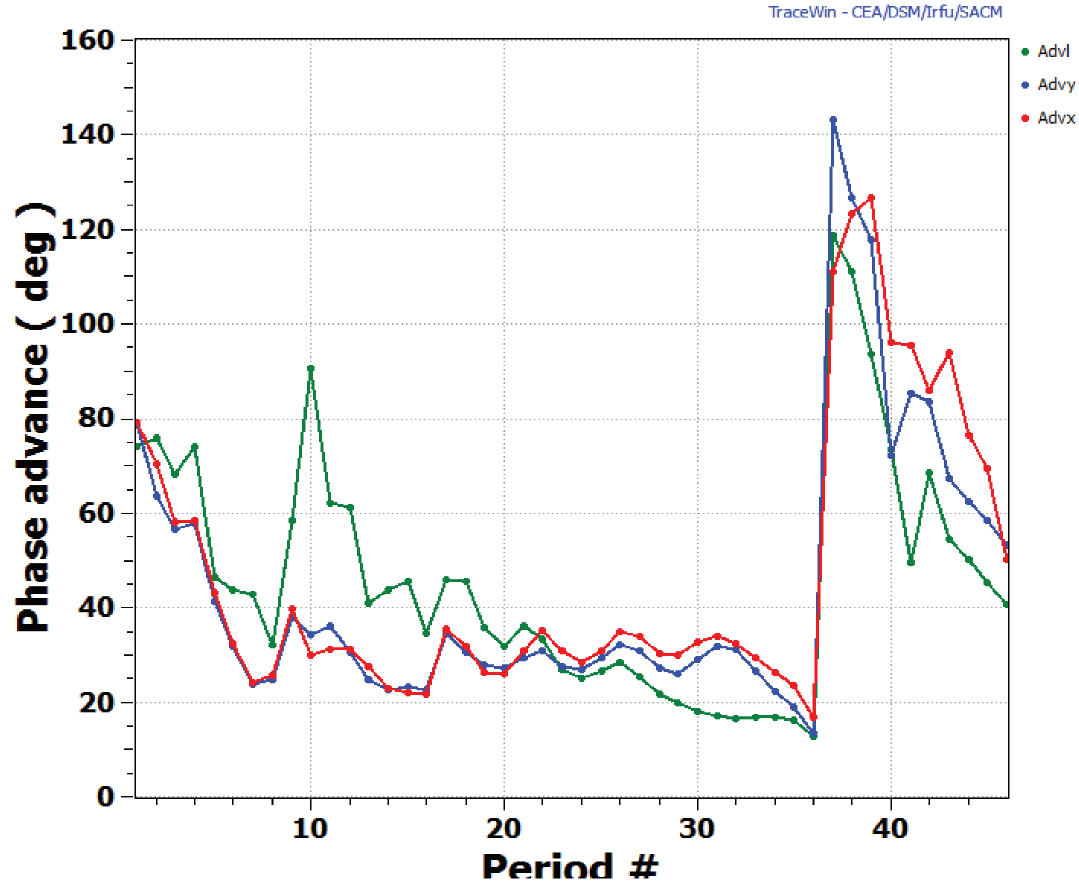



- SC – CS transition between cryomodules
- Moderate emittance growth – 40% - transverse; 60% - longitudinal

# Phase Advance per Cell

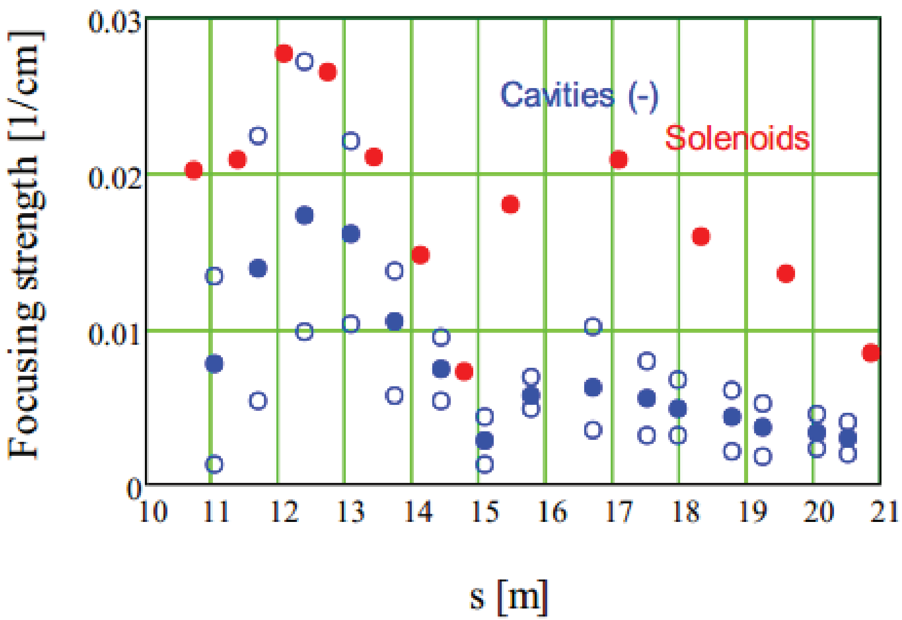
- Long. phase is larger than the transverse ones for first 22 periods (middle of of SSR2)
- Phase advancece per meter are reduced adiabatically

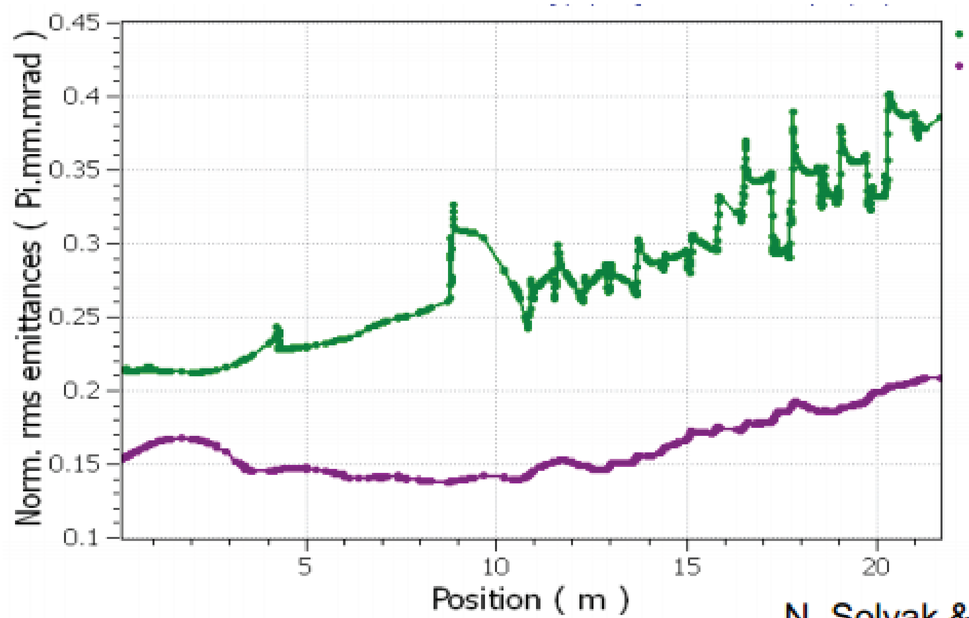



- Tune depression stays nearly the same due to reduction of focusing strength with acceleration
- No significant emittance growth after the second cryomodule
  - Due to adiabaticity in longitudinal motion (small phase per cavity)

# Focusing and beam transport in SC cryomodules




N. Solyak & B. Shteynas

- Defocusing in SC cavities is RF phase dependent
  - That sets minimum focusing strength of the SC solenoids
- Transverse and longitudinal focusing are adjusted to compensate space charge effects.
  - Space charge does not produce harmful effects and does not produce noticeable beam loss
  - However growth of longitudinal emittance is not negligible

■ Beam loss estimate in the first two cryomodules: P ≤ 10 W

♦ Compare to 50 W due to e.-m. loss (25 W/cryomodule @ 2 K°)

# Beam Loss

- Intrabeam striping is the major mechanism of beam loss for H- beam
  - It makes ~0.1-0.2 W/m beam loss in SNS
- High sensitivity of beam loss to the longitudinal optics (cavity phases)
  - RFQ non-Gaussian tails look as major offender
    - In simulations they are well visible beyond 3$\sigma$
  - Scraping of long tails does not look practical
  - One has to pay attention to the RFQ tails at design stage
- For well tuned machine the beam loss for proton beam is much smaller than for $H^-$

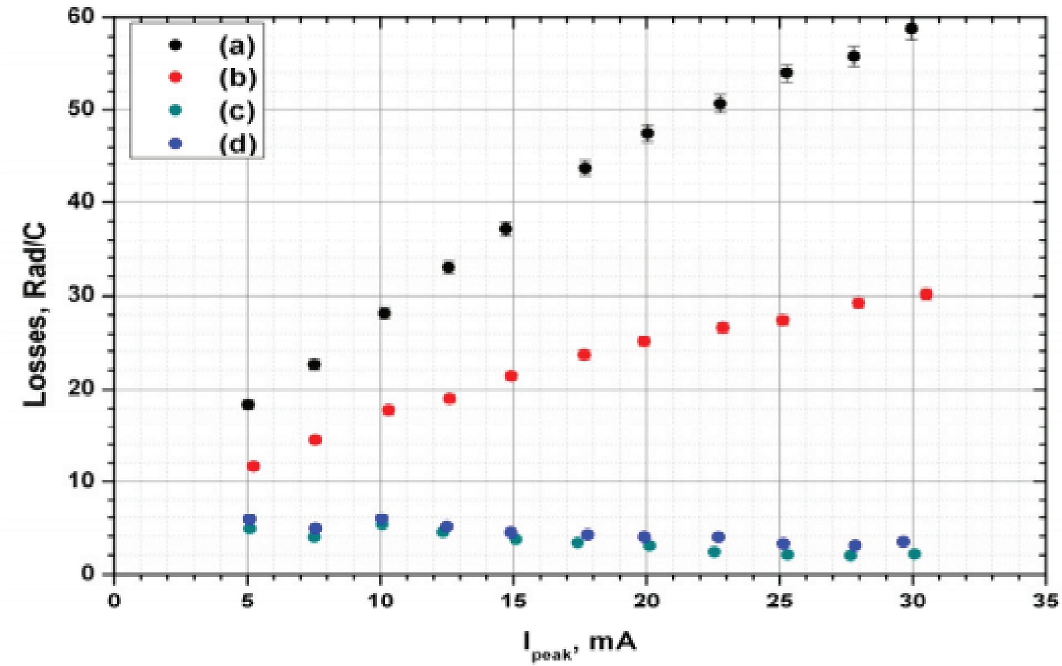



Figure 5: The normalized BLM signals vs. peak current for different beams and optics: (a) and (b) $H^-$ beam for the design and production SCL optics respectively; (c) and (d) proton beam for the design and production SCL optics respectively.

# Conclusions

- SC linacs look as a great technology for the multi-MW proton accelerators
- Recent improvements in surface treatment greatly improved Q values for SC cavities and push operating gradient beyond 20 MV/m
  - At 1.3 GHz the Q-value of $7.5 \times 10^{10}$ at 2 K and at a 20 MV/m were achieved (A. Romanenko, A. Grassellino, 2012, Fermilab)
- There are no insurmountable physics or engineering problems to be overcame
  - Making cavities still require extensive R&D
  - Getting experience in the SRF design and development is irreplaceable for any organization making and/or developing SRF cavities
- These SRF developments will affect many fields
  - HEP, Nuclear energy, solid state and nuclear physics, chemistry, biology …