# Project X ICD-1 and ICD-2 Overview

Sergei Nagaitsev (FNAL)

Sep 11 2009

# Project X: the promise

1. Neutrino program with Main Injector: 2 MW at 60-120 GeV

2. Concurrent with 1: 100s of kW's of beam for muon and kaon rare decay experiments

3. An upgrade path to 4 MW for a muon collider or/and neutrino factory

# Project X: the issues

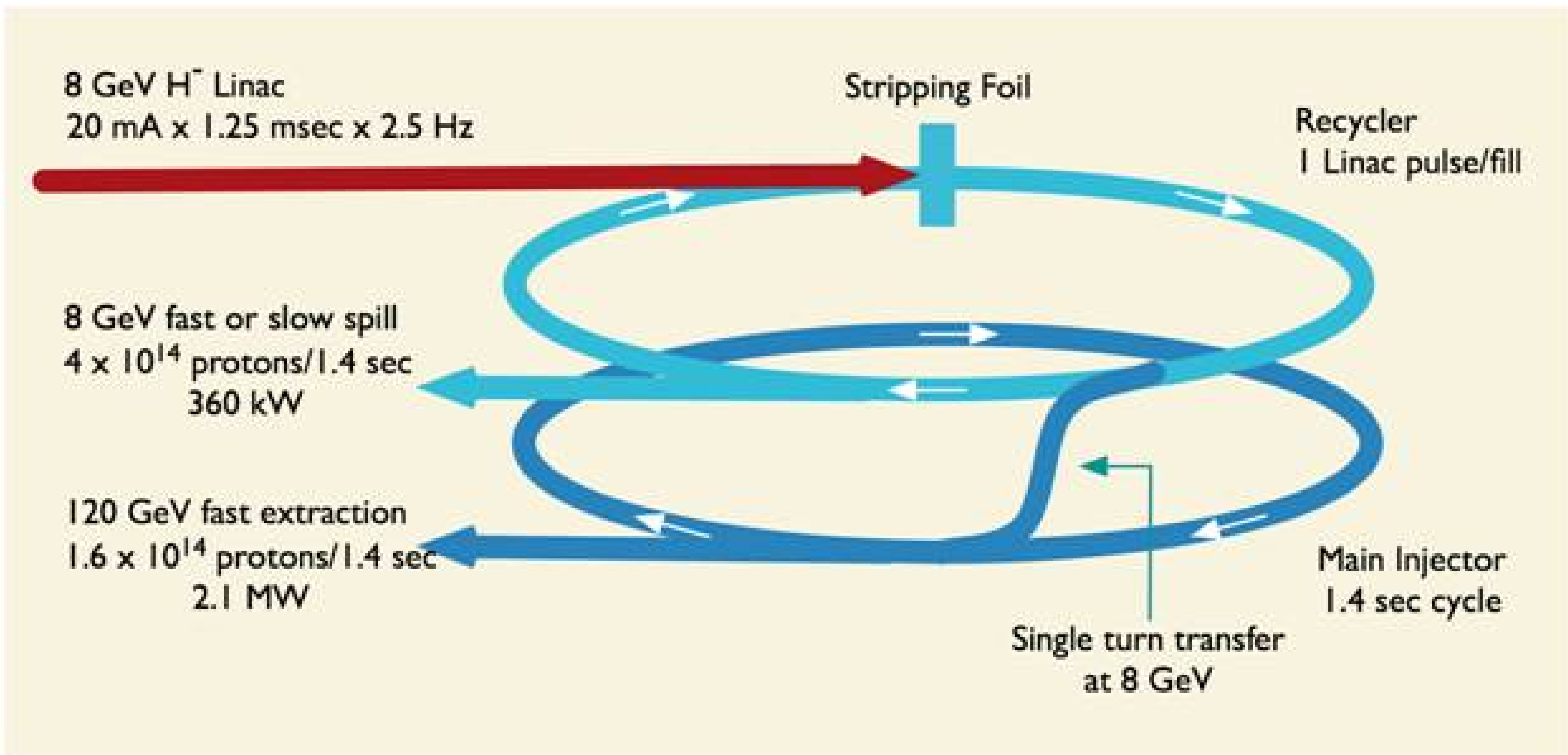
- The 3 missions require high beam power (MW's)
  - Compare to:
  - Present Booster (8 GeV) at 15 Hz: 75 kW max
  - soon, MI with Nova upgrades: 750 kW at 120 GeV
- They also require a different bunch formatting
  - Neutrinos: single turn extraction (many bunches) from MI
  - Rare decays: high-duty factor stream of short bunches. Variable format, good beam extinction between bunches.
  - MC/NF: Single bunch (2ns) on target at 10-100 Hz.

  - These bunch formatting schemes have little in common.

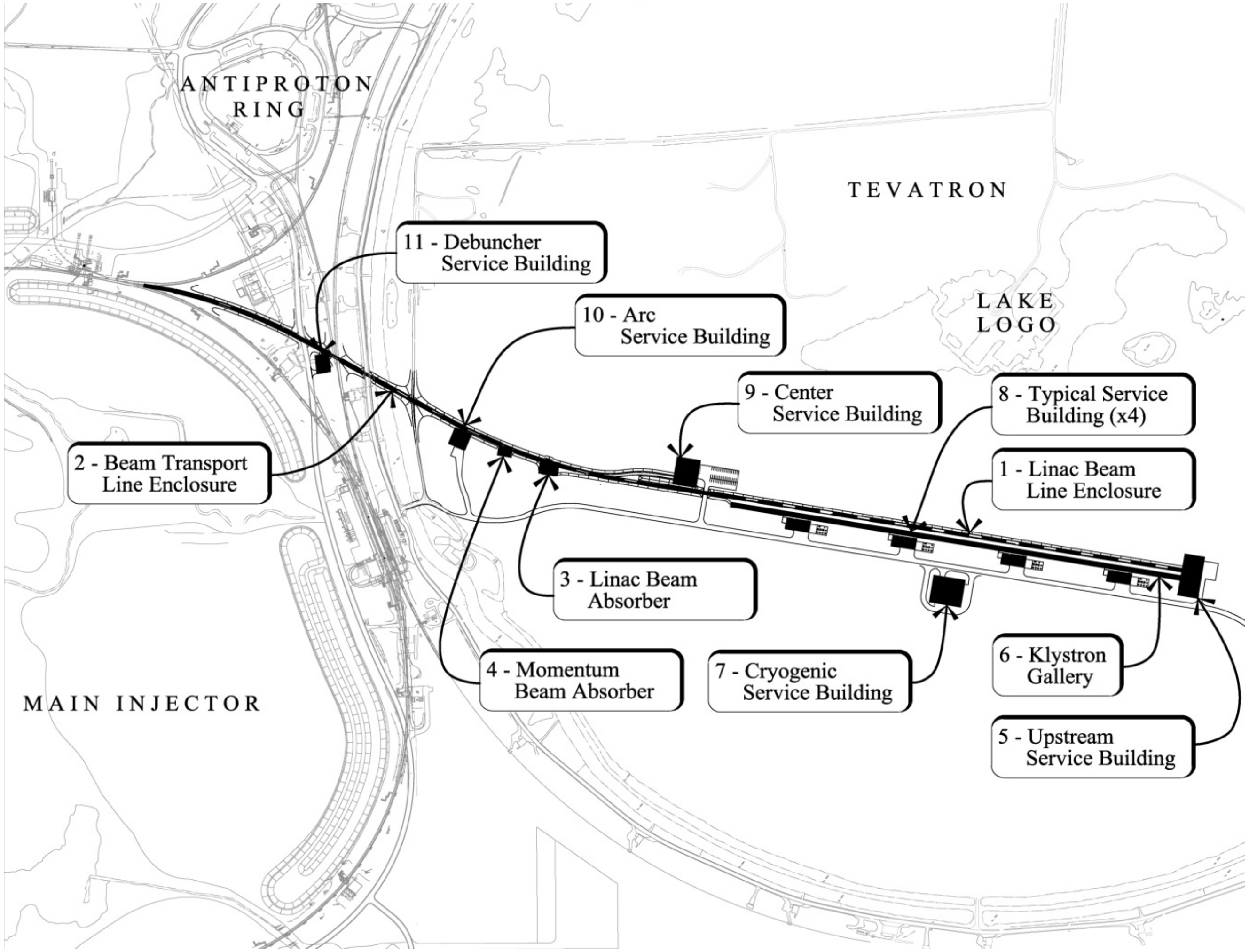
| | Train Frequency | Pulse Width (nanoseconds) | Inter-Pulse Extinction |
|---|---|---|---|
| Kaon experiments | 20-30 MHz | 0.1-0.2 | $10^{-3}$ |
| Muon conversion experiment | 0.5-1.0 MHz | 50 | $10^{-9}$ |

# Project X ICD1

Started with a 5-Hz Linac rep rate or 1 MW beam at 8 GeV
ICD1 cost estimate was made for 1 MW beam



# ICD1 siting


ANTIPROTON RING
TEVATRON
LAKE LOGO
MAIN INJECTOR
11 - Debuncher Service Building
10 - Arc Service Building
9 - Center Service Building
8 - Typical Service Building (x4)
1 - Linac Beam Line Enclosure
2 - Beam Transport Line Enclosure
3 - Linac Beam Absorber
4 - Momentum Beam Absorber
7 - Cryogenic Service Building
6 - Klystron Gallery
5 - Upstream Service Building

# ICD-1 Linac concept

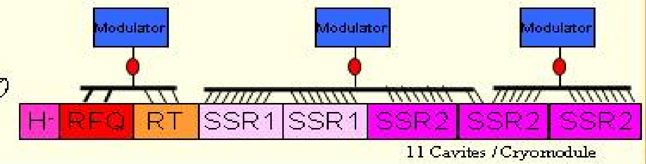
**_Project X_**
**500 kW 8GeV Linac**

31 Klystrons (2 types)
445 SC Cavities
58 Cryomodules

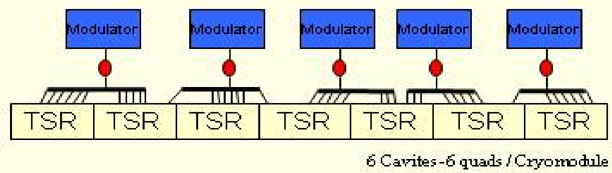
## Front End Linac

325 MHz 0-10 MeV
*1 Klystron (JPARC 2.5 MW)*
*RFQ + 18 RT Cavities*

325 MHz 10-120 MeV
*2 Klystrons (JPARC 2.5 MW)*
*51 Single Spoke Resonators*
*5 Cryomodules*




325 MHz 0.12-0.42 GeV
*5 Klystrons (JPARC 2.5 MW)*
*42 Triple Spoke Resonators*
*7 Cryomodules*



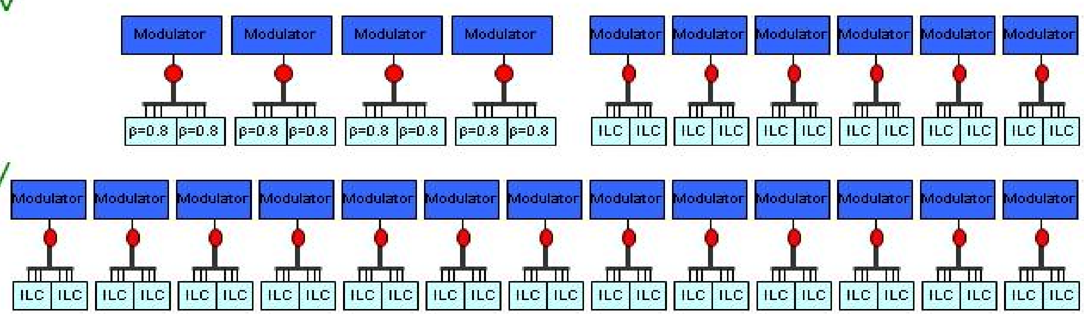

2.5 MW JPARC Klystron

Multi-Cavity Fanout
Phase and Amplitude Control

## 1300 MHz LINAC

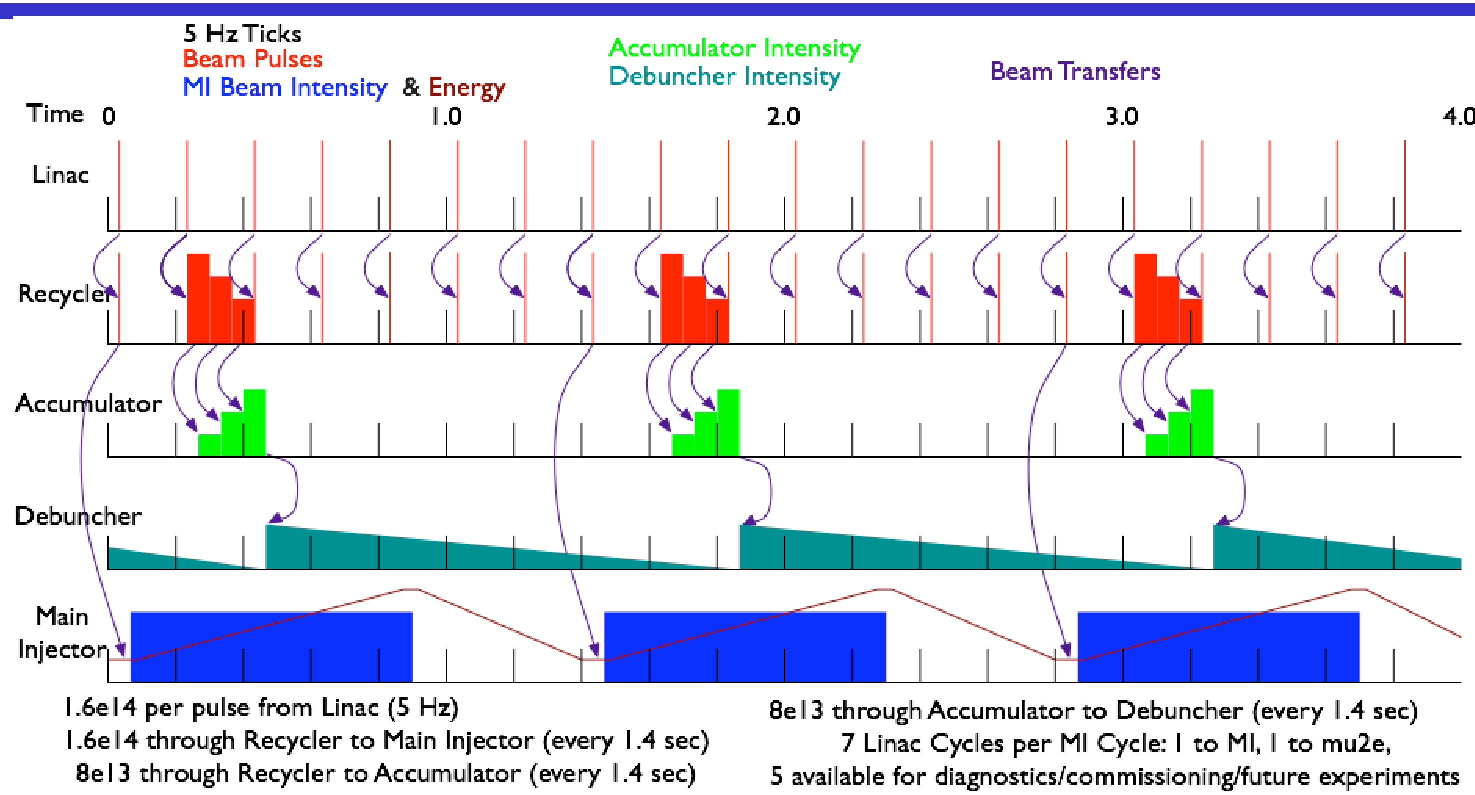
1300 MHz 0.42-1.3 GeV
*4 Klystrons (ILC 10 MW MBK)*
*56 Squeezed Cavities ( β=0.81)*
*8 Cryomodules*

1300 MHz 1.3-8.0 GeV
*19 Klystrons (ILC 10 MW MBK)*
*296 ILC-identical Cavities*
*38 ILC-like Cryomodules*




Most (~ 7/8) of LINAC is built of ILC-like CM but ~ 25MV/m gradient

# Initial 5 Hz scenario – does not work.




1. Five out of seven linac pulses are unused.
2. 8e13 every 1.4 sec to Mu2e does not work – (1) high tune shift in Debuncher, (2) long emittance too high (150 eV-s)
3. Incorrect linac chopping pattern to extract 3 batches from Recycler
4. Note: Mu2e beam power in this scenario is 75 kW

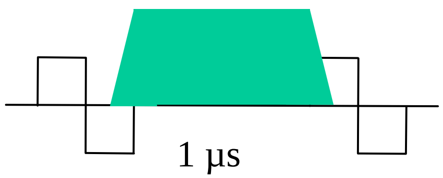
# ICD-1 design criteria

- MI: 2 MW at 60-120 GeV.
  - Single linac pulse injection at 8GeV: 1.6e14 protons every 0.8-1.4 seconds.
  - Recycler used to inject H-, hold beam, and extract (single turn).
- Debuncher: 150 kW slow-extracted beam for Mu2e at 8 GeV
  - Mu2e present design is for 25 kW beam
  - Twice the existing Booster power after Nova upgrades.
  - Kaon program not supported
- MC/NF: 4 MW could be achieved by increasing the linac rep rate to 20 Hz
  - Additional rings are required for accumulation and rebunching

# ICD-1 bunch formats

- MI/RR for neutrinos
  - paint beam transversely (KV) and longit. to keep the space charge tune shift <0.1.
  - 53 and 106 MHz rf systems in both the MI and RR
- MI/RR for Mu2e (working back from Debuncher):
  - Recycler is filled with 7 barrier-bucket bunches (1-μs long), long. emitt. 10 eV-s, 0.6-μs gaps, 1.2e13 ppb

7 bunches:




  - Bunches are then transferred to the Accumulator (at ~15 Hz rate) for bunch rotation (10 ms) and then to the Debuncher for slow extraction

# Mu2e beam requirements

- Working back from the Debuncher:
  - Single bunch: 25ns rms bunch length (100ns, FW)

Number of protons: $N := 1.2 \cdot 10^{13}$

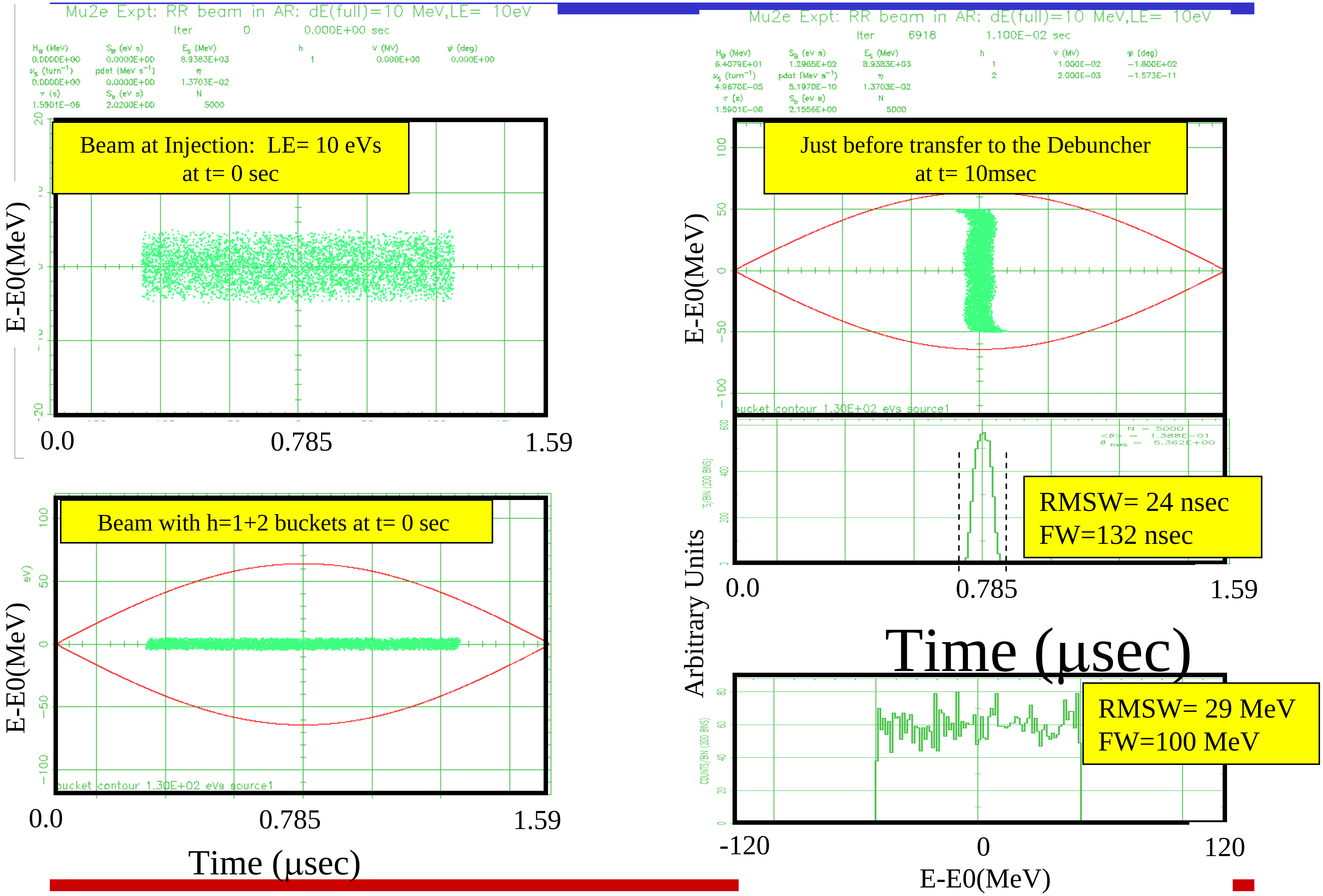
Proton DC beam current: $I_p := N \cdot e \cdot f$ $\quad I_p = 1.133\,A$

Normalized 95% emittance: $\varepsilon_n := 50 \cdot \mu m$ assume gaussian distribution

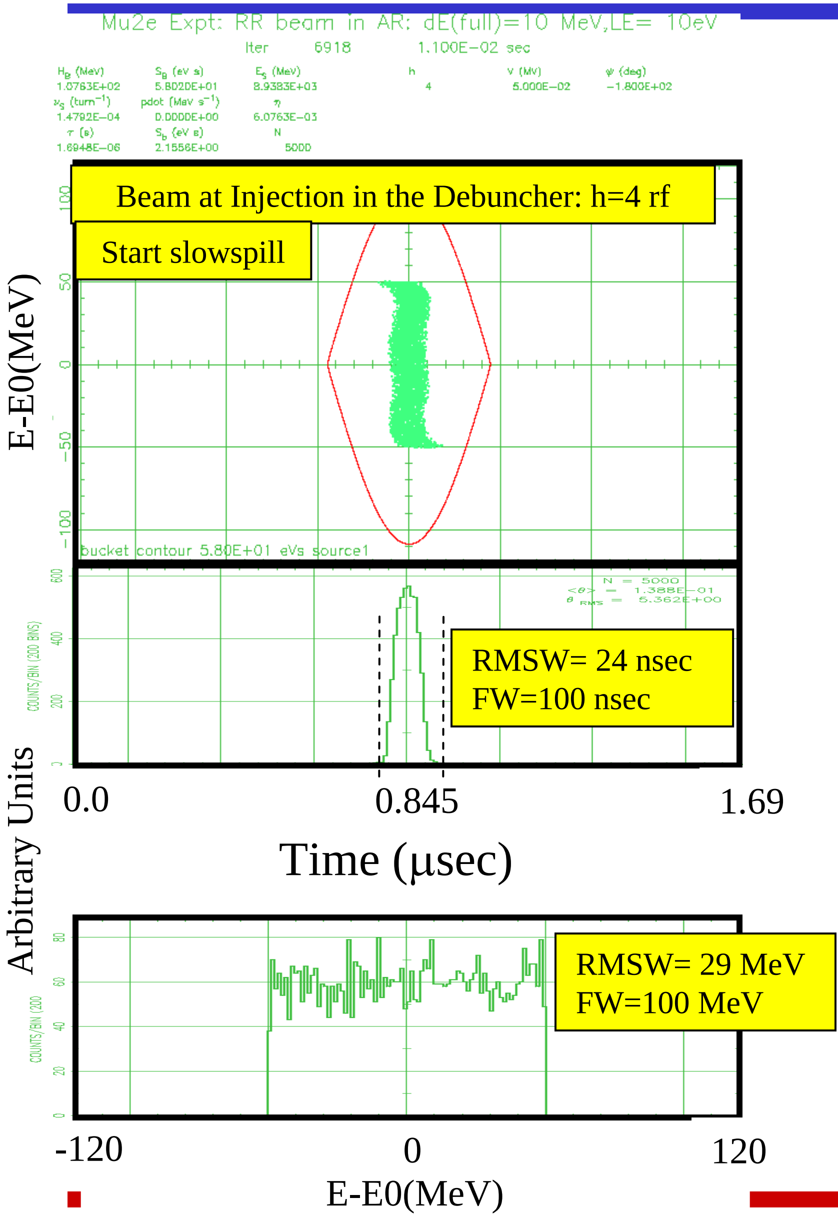
$$\Delta\nu := -\frac{3 \cdot N \cdot r_p}{2 \cdot \pi \cdot \beta \cdot \gamma^2 \cdot \varepsilon_n \cdot B} \qquad \Delta\nu = -0.053$$

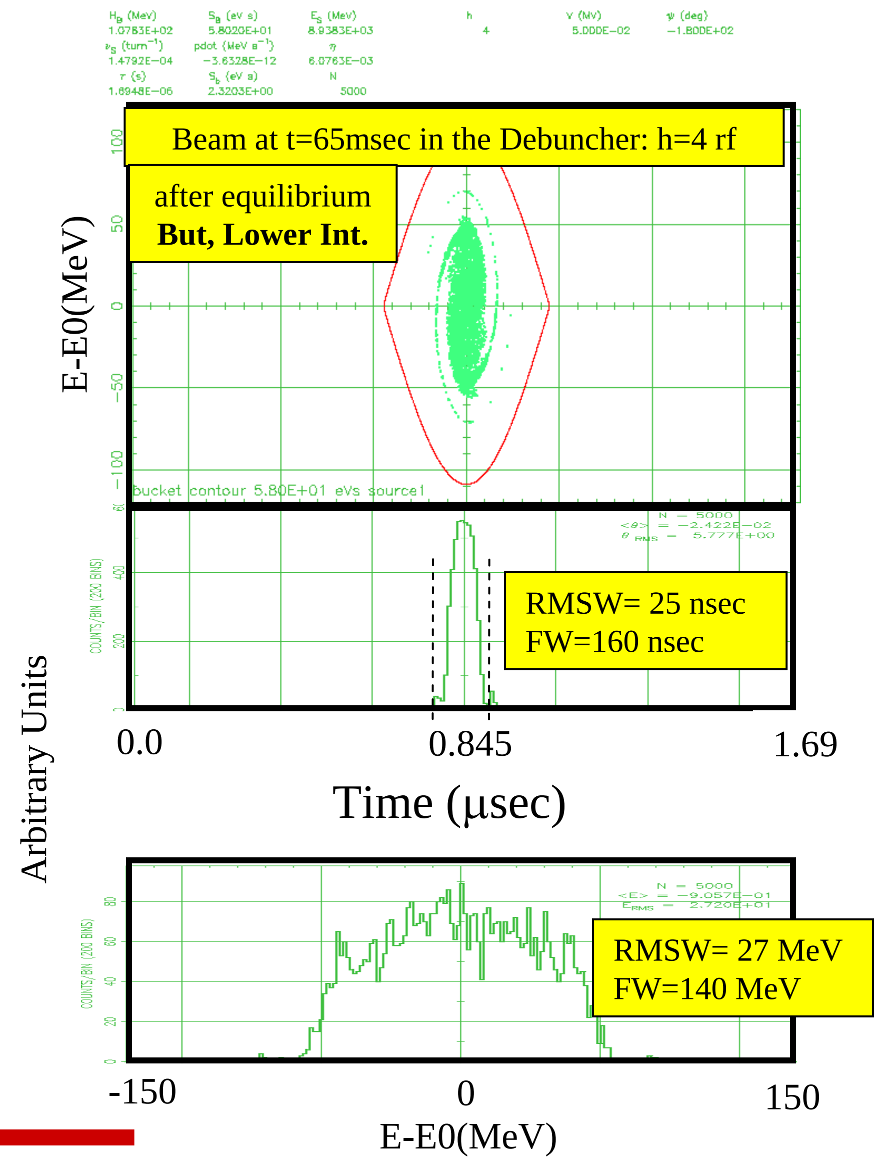
  - To fit into Debuncher momentum aperture (±2%) the bunch momentum spread must be < 150 MeV (95%)
    - ~15-20 eV-s long. emitt (95%)

# Simulations: Beam in the Accumulator

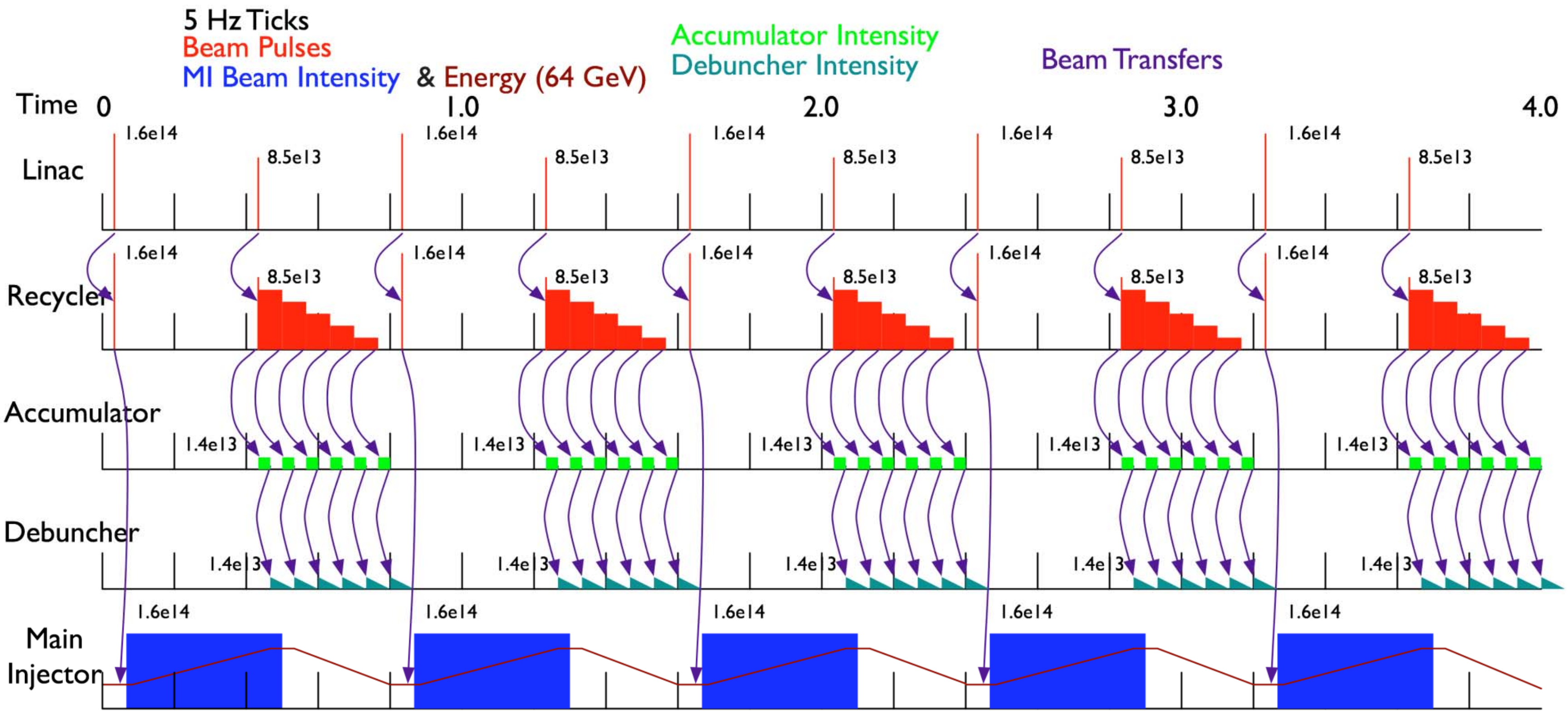


# Simulations: Beam in the Debuncher



# ICD-1 scenario (MI@60 GeV)

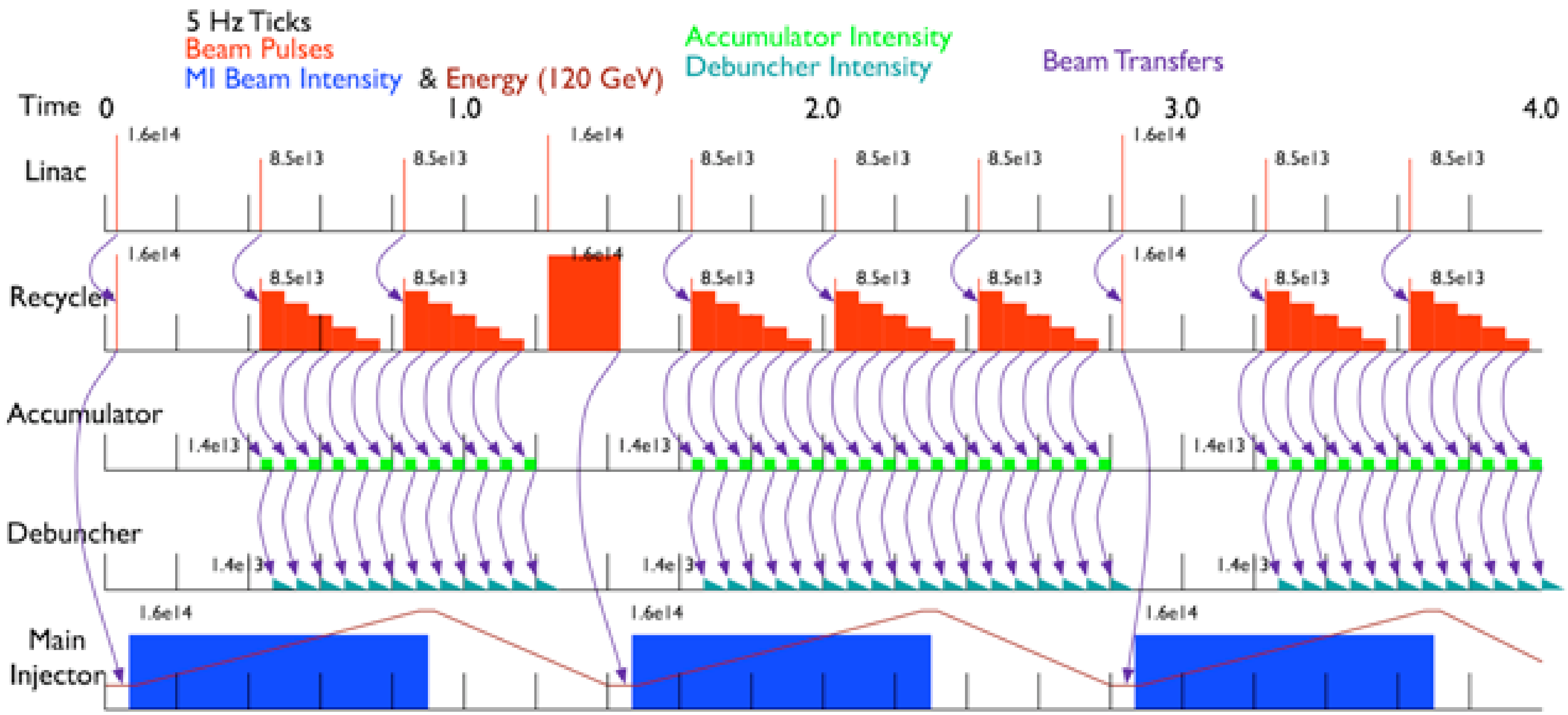



1.6e14 per pulse from Linac (2.5 Hz)
1.6e14 through Recycler to Main Injector (every 0.8 sec)
1.4e13 through Recycler to Accumulator (every 67 msec)

1.4e13 through Accumulator to Debuncher (every 67 msec)
2 Linac Cycles per MI Cycle: 1 to MI, 1 to mu2e,
2.12MW for neutrino, 136 kW to mu2e

Assumes 15 Hz transfers to Accumulator
Could use 17.5 Hz transfers (7 instead of 6 every 0.4 seconds)
159 kW to mu2e

# ICD-1 scenario (MI@120 GeV)




1.6e14 per pulse from Linac (2.5 Hz)
1.6e14 through Recycler to Main Injector (every 1.4 sec)
1.4e13 through Recycler to Accumulator (every 67 msec)

1.4e13 through Accumulator to Debuncher (every 67 msec)
3.5 Linac Cycles per MI Cycle: 1 to MI, 2.5 to mu2e,
2.13MW for neutrino, 194 kW to mu2e

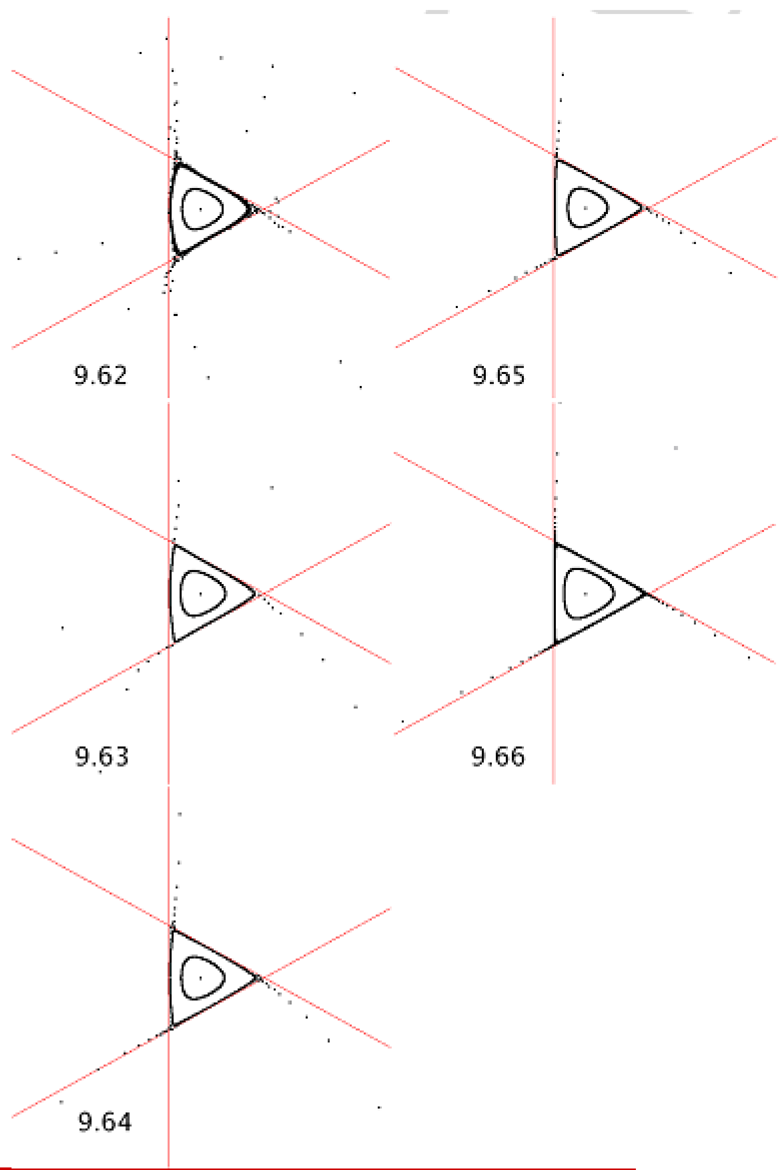
Assumes 15 Hz transfers to Accumulator
Could use 17.5 Hz transfers (7 instead of 6 every 0.4 seconds)
225 kW to mu2e

# Slow extraction experience

- Many labs have done it: FNAL (MR, Tevatron and MI), BNL (AGS), CERN (PS), etc
  - all unbunched beam (?)
- AGS at 25 GeV extracted 70 kW of unbunched beam with 2% losses (1.4 kW) – perhaps one of the best SE examples.

# Slow extraction issues (for Mu2e)

- The beam is highly bunched:
  - Space charge related betatron tune shift and spread
  - Momentum spread leads to betatron tune spread due to chromaticity
- It appears that the total tune shift/spread budget is limited to 0.05
- AGS at 25 GeV, $7\times10^{13}$ protons
  - Tune shift $\Delta\nu \approx 0$ (very small)



# Space charge tune shift

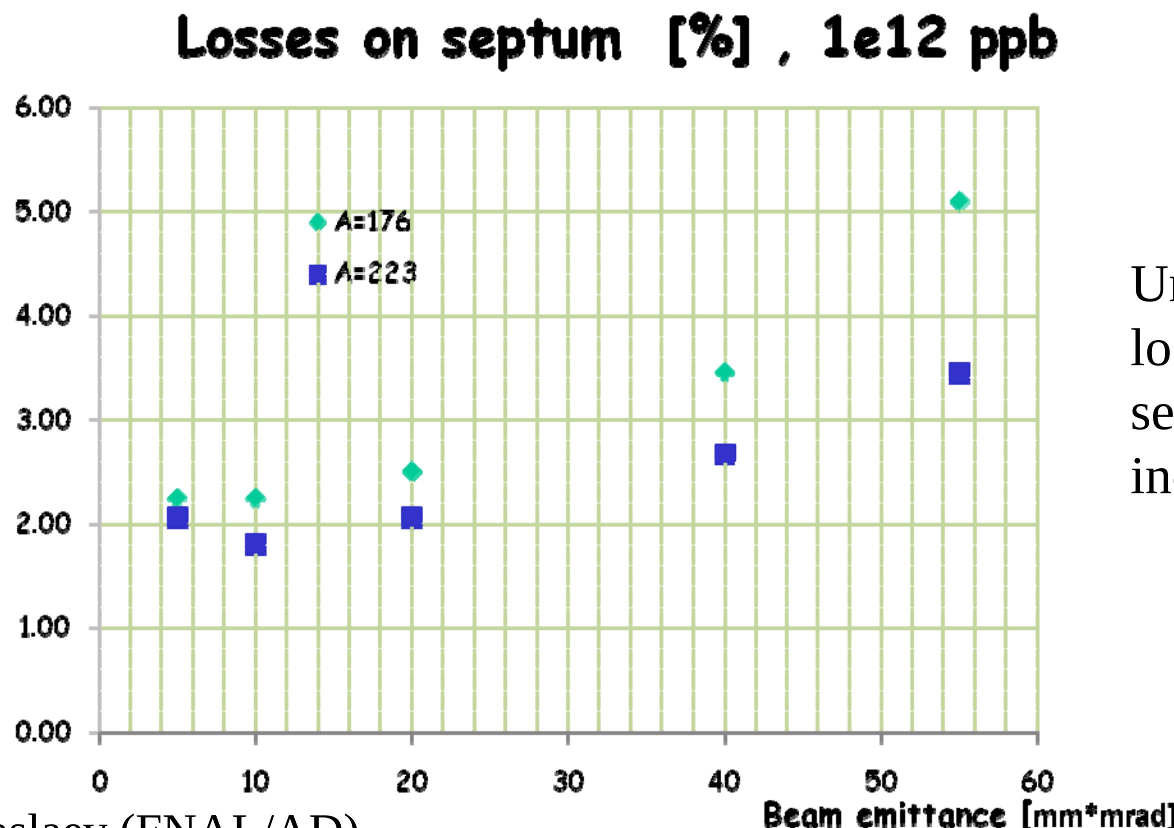
$$\Delta\nu = -\frac{3Nr_p}{2\pi\beta\gamma^2 B\varepsilon_n}$$

- Perhaps one can reduce the tune shift by increasing the beam emittance, $\varepsilon_N$?
- …Not really! The losses increase because beam gets bigger and closer to the aperture limit (septum).

(see next page)

# Simulation of 3rd order resonant SE (code Orbit)

- Two different septum locations (in units of mm-mrad)
- Debuncher acceptance is 350 mm-mrad
- Baseline emittance: 25 mm-mrad




Uncontrolled losses (not on septum) also increase to ~1%

Courtesy V. Nagaslaev (FNAL/AD)

# Is 500kW SE beam possible from the Debuncher?

- Short answer: unlikely…
- What is 500-kW in terms of beam?
  - $2.6\times10^{13}$ ppb at 15 Hz. Very large tune shift!
  - $1.3\times10^{13}$ ppb at 30 Hz. Tune shift <0.05 possible for emittance greater than 50 mm-mrad. This leads to a 5% (at least) beam loss or 25 kW!
  - $6.5\times10^{12}$ ppb at 60 Hz (16 ms spill). Relative time for manipulations may be too long, losses too high.

# What is the limit?

- Debuncher extraction cycle at 30 Hz, 6e12 ppb, and 100% duty factor – 230 kW max with 2-3% losses.
- With a realistic duty factor (75%) the beam power limit is about 150 kW.
- Other issues with SE:
  - Uses three rings to prepare beam – potential conflicts with other programs.
  - No flexibility for multiple users or other bunch formats.

# ICD2

- This forced us to look at how to avoid slow extraction of high power beams
- Found a solution: CEBAF
- Slow extraction avoided by a bunch-by-bunch rf splitter with a cw beam

Table 1: 12 GeV CEBAF Upgrade key parameters

| | |
|---|---|
| Energy to Halls D /A,B,C | 12 GeV / 11 GeV |
| Number of passes for Halls D / A,B,C | 5.5 (add a tenth arc) / 5 |
| Duty Factor | CW |
| Max. Current to Halls A,C / B,D | 85 µA / 5 µA |
| New Cryomodules | 10 (5 per linac) |
| Central Helium Liquefier Upgrade | 9 kW (~2x present capacity) |

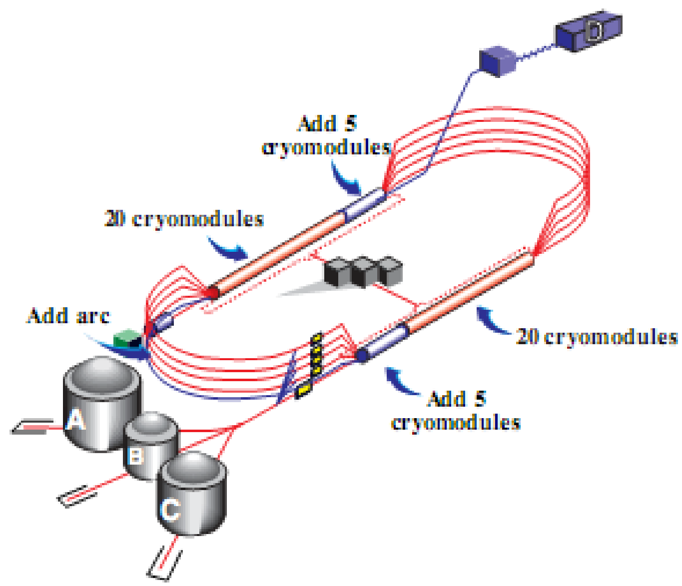
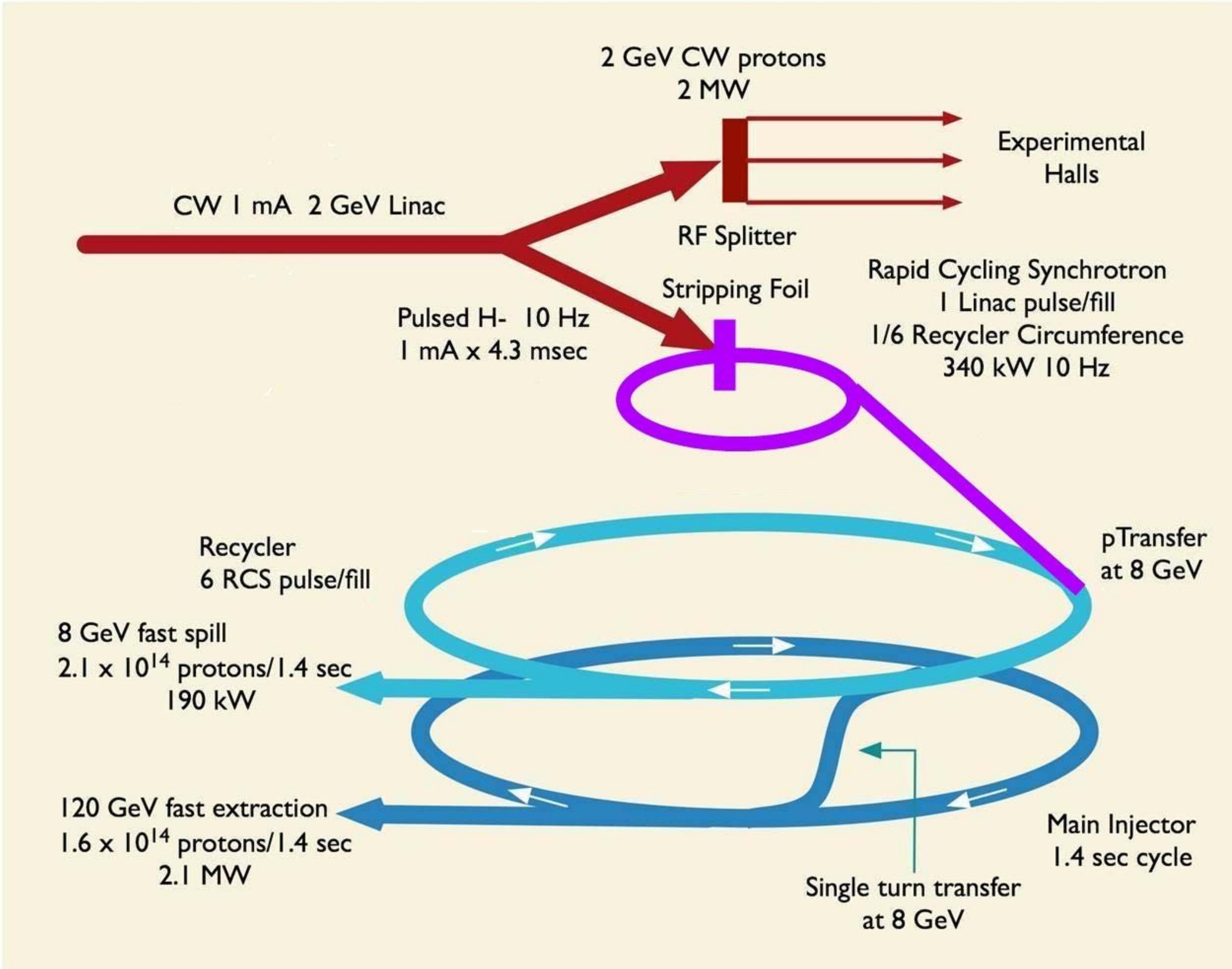
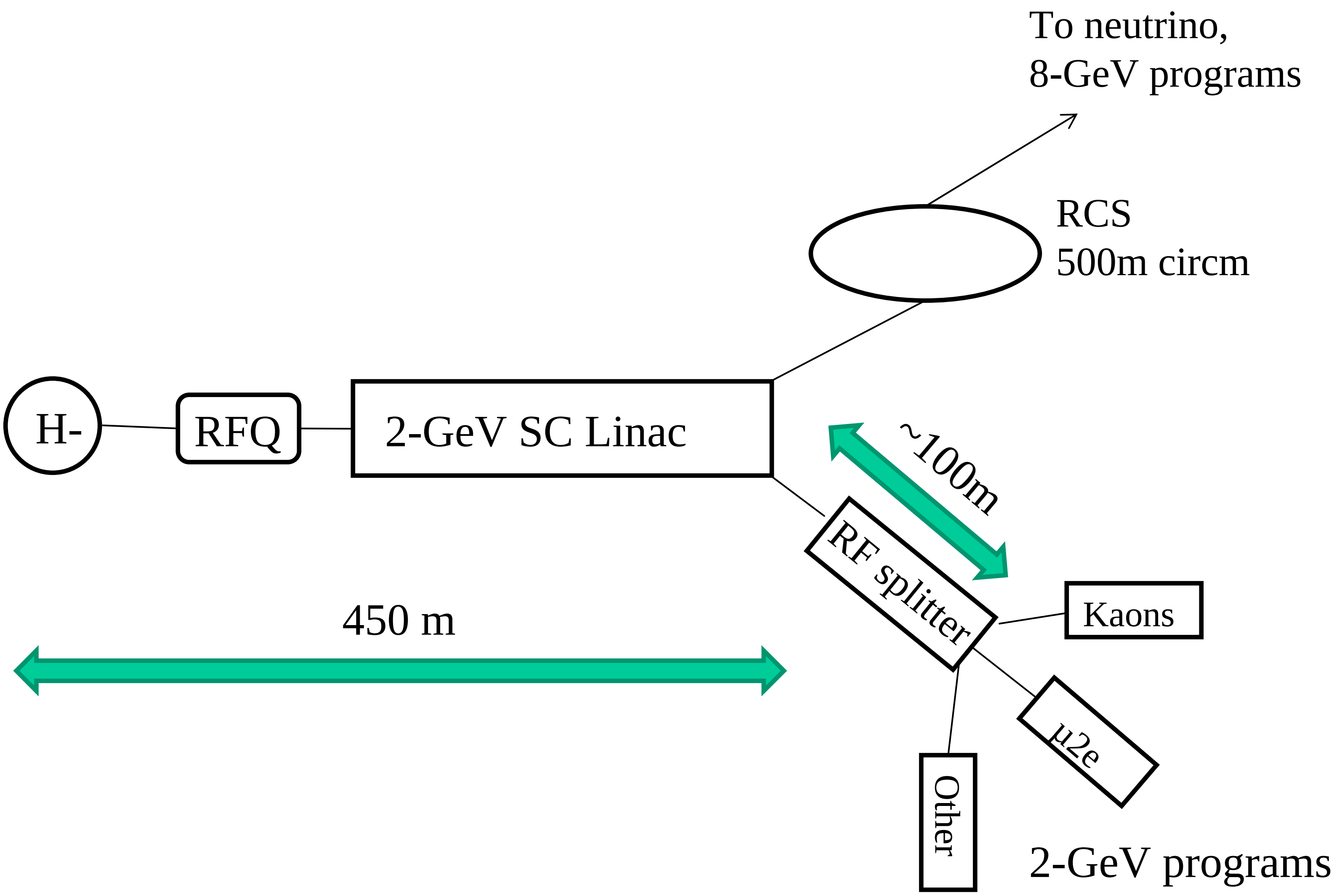



Figure 1: Schematic illustration of the CEBAF 12 GeV Upgrade.

# ICD2 schematic



# ICD2 schematic



# 2 GeV, 1 mA cw

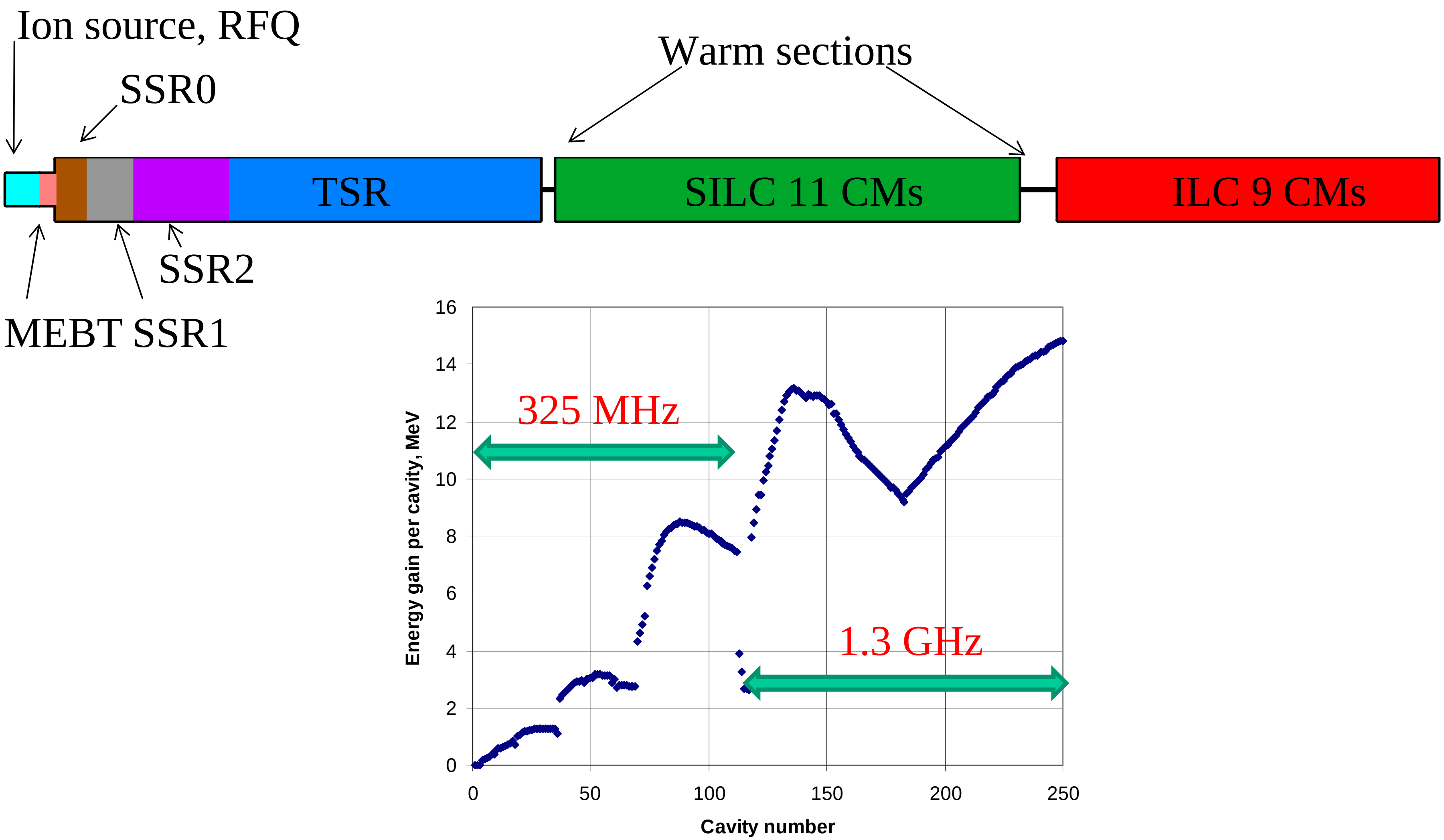
2.1 GeV Tp

- 1 mA is needed for the stripping injection into the RCS;

- 2 GeV, 10 psec bunches are needed for Kaons;

# ICD2 siting proposal

# 2-GeV CW linac schematic ~440m length



# Ion source

- DC 10 mA H-, 30 keV
- Emittance: 0.25 mm-mrad (norm, rms)
- commercially available from D-Pace, Inc:
  - **Model IS·10mA·30keV·H¯**
  - The **TRIUMF Type DC Volume-Cusp H¯ Ion Source**, Model IS·10mA·30keV·H¯ produces stable and reproducible H¯ ion beams with low emittance and high brightness.

# RFQ

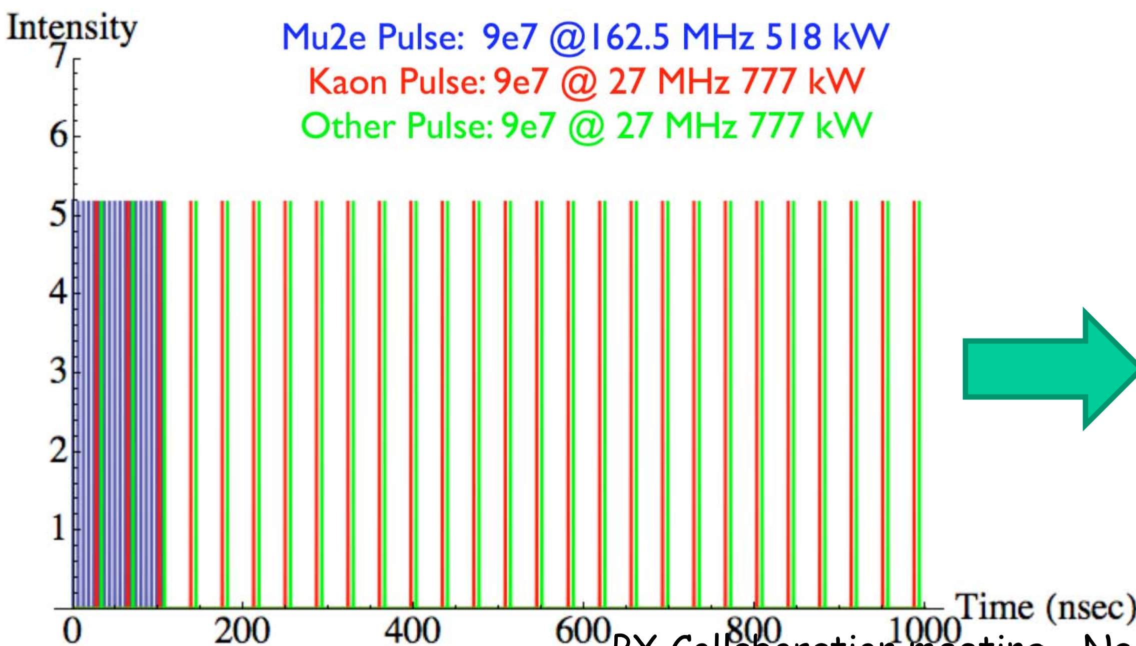
- room temperature, 325 MHz, 2.5 MeV
- 10 mA max. current
- Examples of CW RFQs:
  - LEDA (LANL): 100 mA, 6.7 MeV, 350 MHz
  - IUCF: 6mA, 750 keV, 213 MHz (in operation since 2003)
- Possible alternative: 162.5 MHz

# MEBT

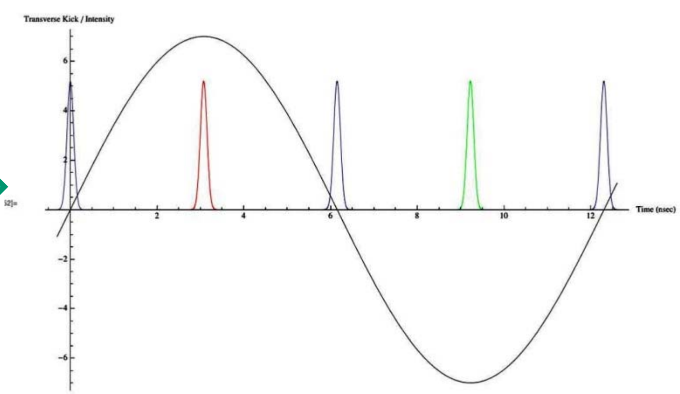
- Chopper is the key element of the project.
- Must be able to remove up to 90% of beam: 10 mA -> 1 mA (ave)
  - Remove individual bunches at 325 MHz

# Flexible bunch formats

- Variable H- ion source provides current 1 to 10 mA DC
- Variable bunch formats:
  1. Ion source at 1 mA, no beam chopping: $1.9 \times 10^7$ protons per bunch at 325 MHz rate
  2. Ion source at 10 mA, 90% beam chopping: $1.9 \times 10^8$ protons per bunch at 32.5 MHz rate (1 mA ave current)
  3. Bunch-by-bunch chopping example (ion source at 4.7 mA), chopping and rf splitting for 3 experiments

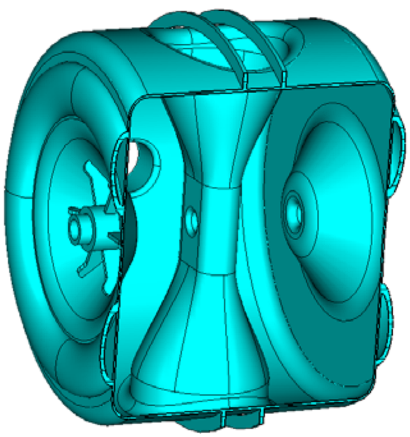


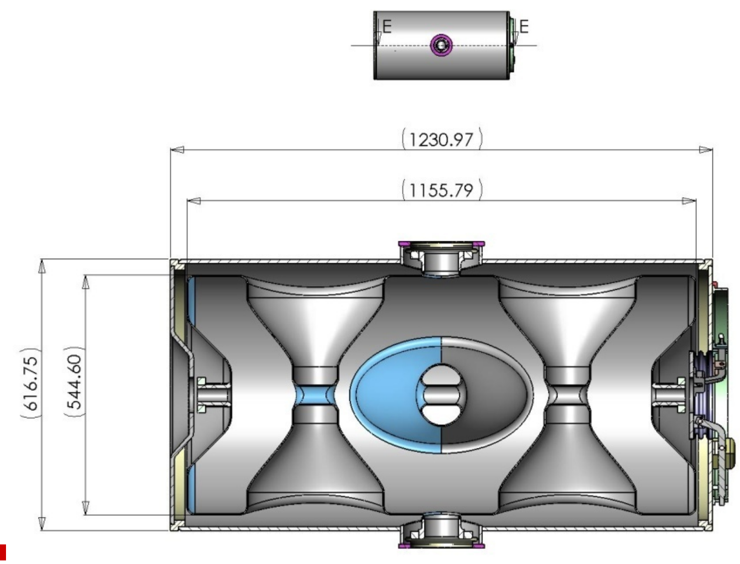

Transverse kick at rf splitter
(406 MHz, similar to crab cavity)



# SSR and TSR sections (325 MHz)

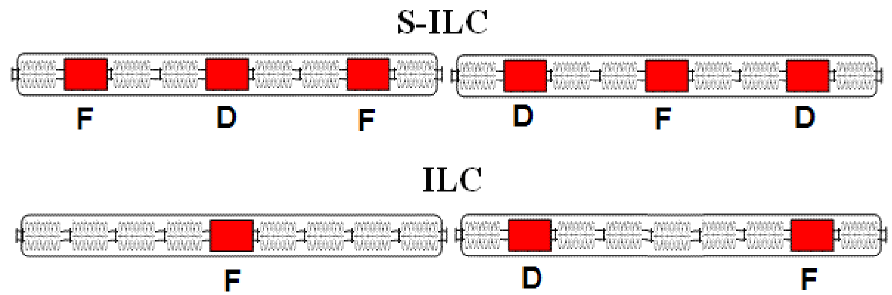
- 2.5 – 466 MeV
- 3 types of single-spoke (SSR)
- 1 type of triple-spoke (TSR)
- Possibly operating at 2K to reduce microphonics



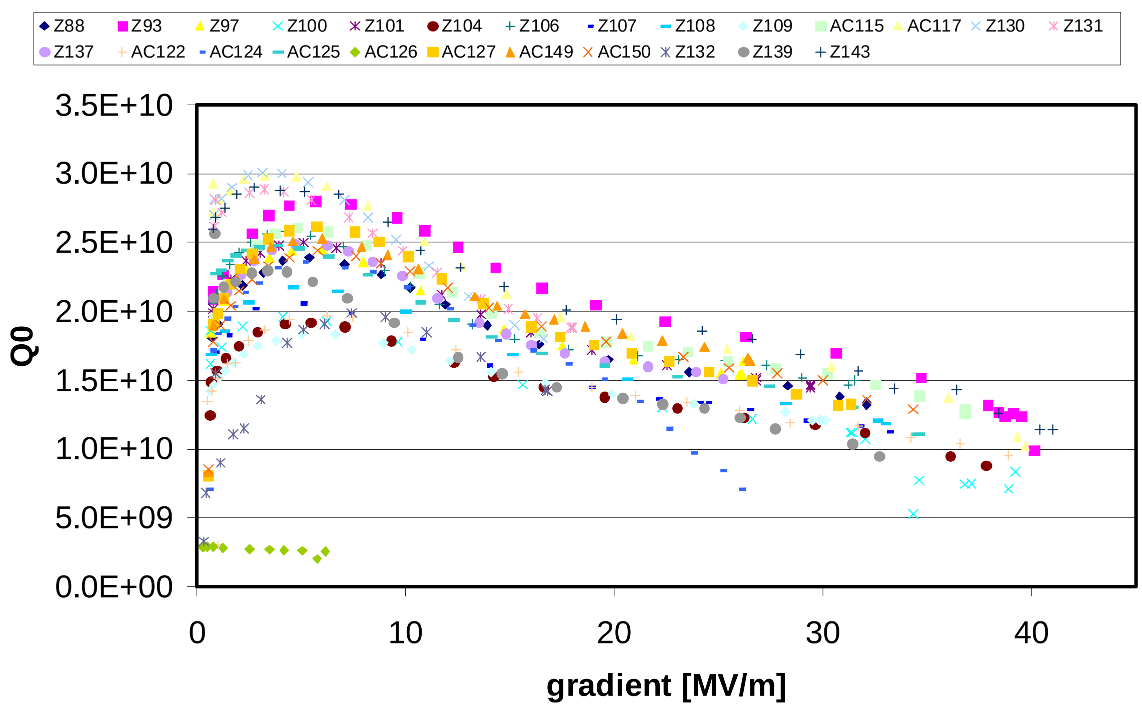


# SILC and ILC sections (1.3 GHz)

- 466 MeV to 2 GeV
- 18 MV/m, Q=1.5e10 (at 2K)




**DESY data (last test) - status March 2009**




Coupler requirements: 16 kW ave

# Rapid Cycling Synchrotron

| | |
|---|---|
| Energy, min/max, GeV | 2/8 |
| Repetition rate, Hz | 10 |
| Circumference, m (MI/6) | 553.2 |
| Tunes, $\nu_x/\nu_y$ | 18.42 / 18.44 |
| Transition energy, GeV | 13.36 |
| Number of particles | $2.6 \times 10^{13}$ |
| Beam current at injection, A | 2.2 |
| Transverse 95% normalized emittance, mm mrad | 25 |
| Space charge tune shift, inj. | 0.06 |
| Norm. acceptance at injection, mm mrad | 40 |
| Harmonic number for main RF system, *h* | 98 |
| Harmonic number for 2-nd harmonic RF system, | 196 |
| RF bucket size at injection, eV s | 0.38 |
| Injection time for 1 mA linac current, ms | 4.3 |
| Required correction of linac energy (kinetic) during injection | 1.2% |
| Total beam power required from linac, kW | 90 |
| Total beam power delivered by RCS, kW | 340 |

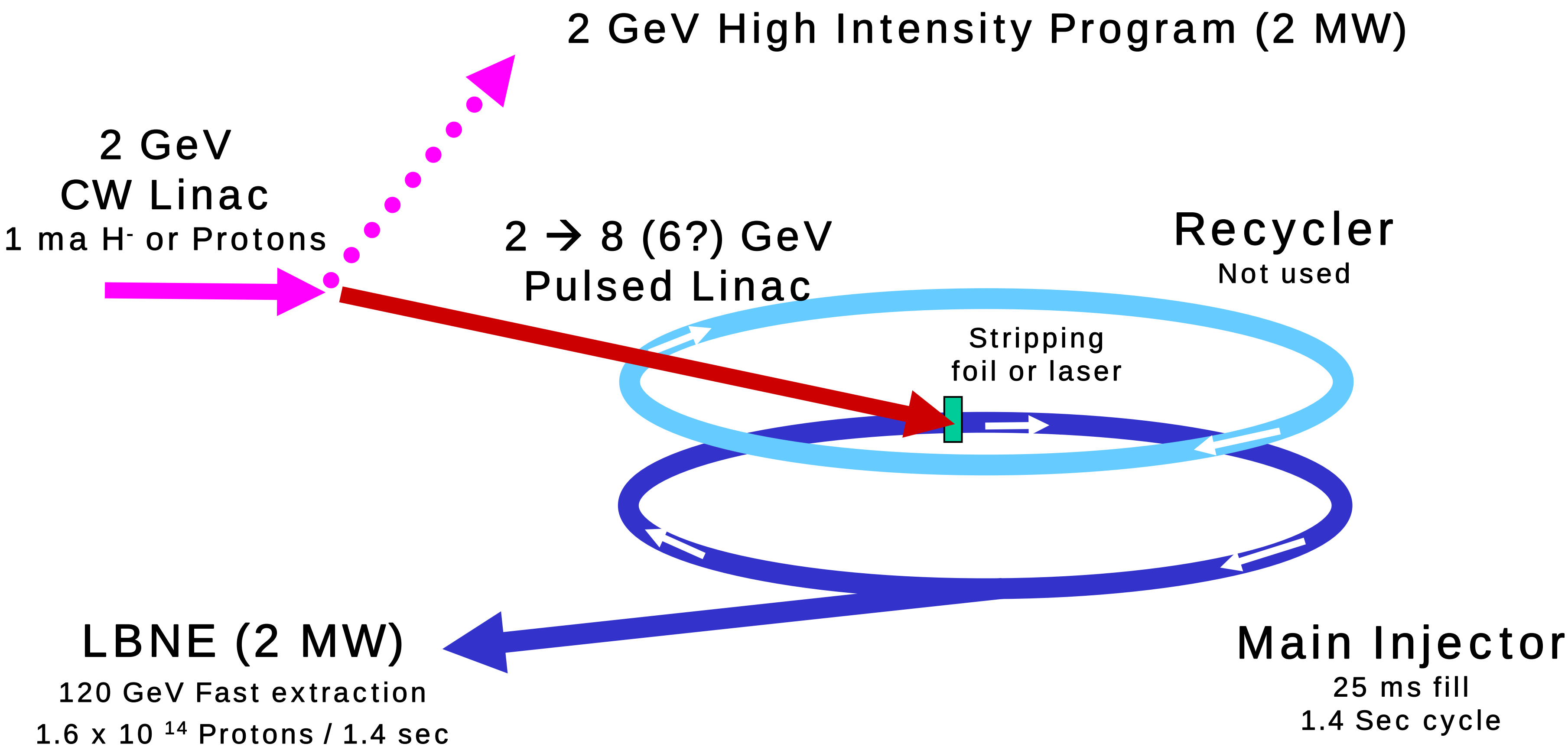
# Summary for ICD-1

- Excellent fit for the MI/RR neutrino program
- Not ideal for the rare decay program
  - Mu2e limited to 150 kW
  - Kaons are not supported
  - Single-turn extraction from RR possible
- A path to 2 MW is well understood; 4 MW possible with R&D
- Critical R&D items:
  - Linac RF system with fast phase shifters; high peak power 500 kW per cavity;
  - Stripping injection at 8 GeV

# Summary of ICD-2

- Good fit for the MI/RR neutrino program
- Excellent fit for the rare decay program
  - supports a variety of bunch formats up to 2 MW beam power
- Although the beam power is 2 MW, ICD-2 is not ideal for the MC/NF because the energy is too low.
  - Possible path to 4 MW is to add 2 -> 8 GeV pulsed linac operating at 20 Hz with 25 ms pulses (1 mA)
- Critical R&D items:
  - CW chopper;
  - Stripping injection;
  - Possibly, preservation of KV distribution from RCS to RR to MI

# ICD-X???



2 GeV High Intensity Program (2 MW)
2 GeV
CW Linac
1 ma H- or Protons
2 → 8 (6?) GeV
Pulsed Linac
Recycler
Not used
Stripping
foil or laser
LBNE (2 MW)
120 GeV Fast extraction
1.6 x 10 14 Protons / 1.4 sec
Main Injector
25 ms fill
1.4 Sec cycle