Project X ICD2 Briefing

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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. A self-consistent upgrade path to muon collider or/and neutrino factory

- Project X documents can be found at: http://projectx.fnal.gov/

Project X: the issues

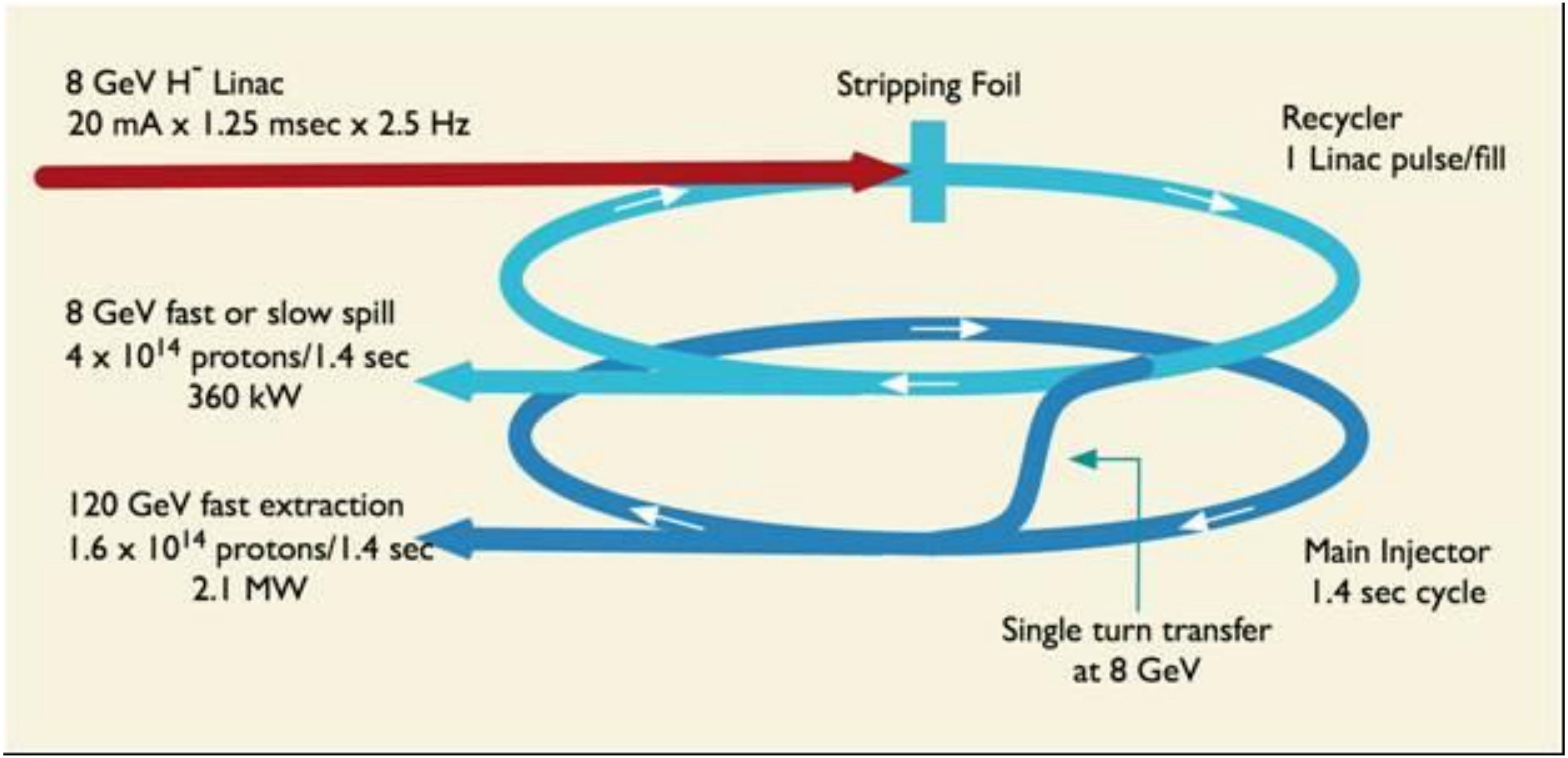
- The 3 missions require high beam power (MW's)
  - Compare to:
  - Present Booster (8 GeV) at 15 Hz: 75 kW max
  - soon, MI with Nova upgrades: 750 kW at 120 GeV
- They also require a different bunch formatting
  - Neutrinos: single turn extraction (many bunches) from MI
  - Rare decays: high-duty factor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

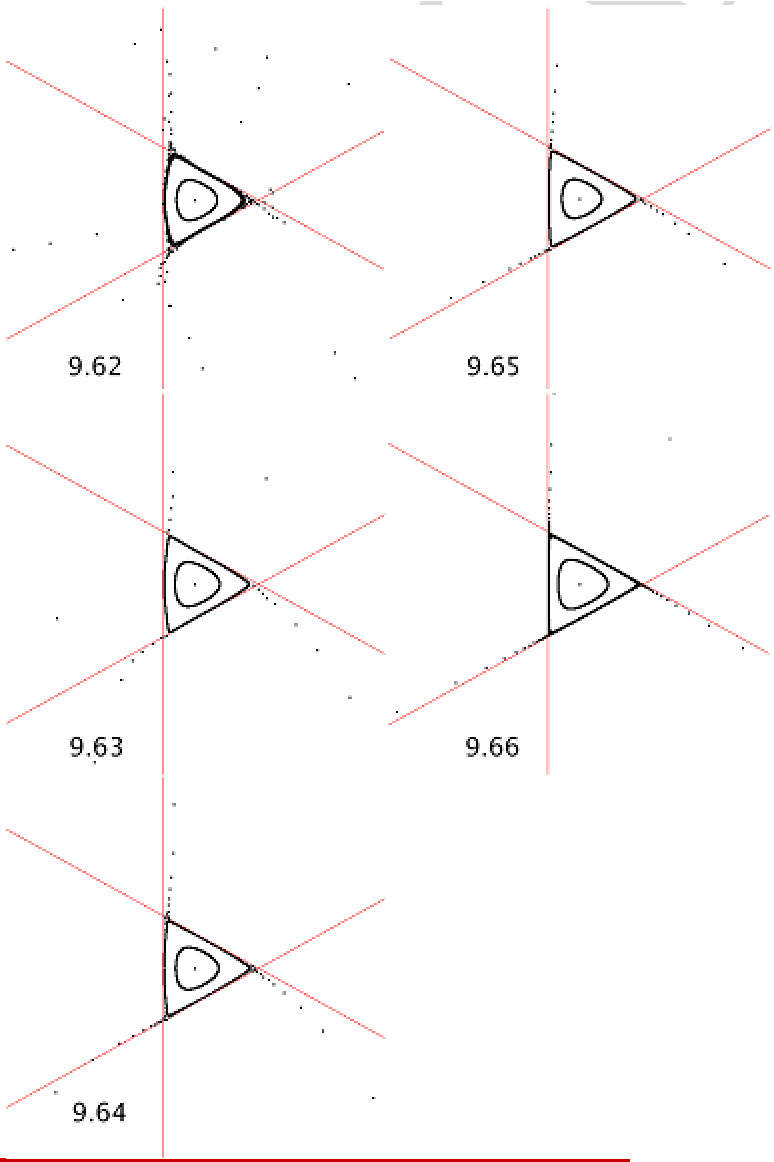


Slow extraction experience

- 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.

Mu2e specific issues

- 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, 7×10^{13} protons
  - Tune shift $\Delta\nu \approx 0$ (very small)
- Recall Mu2e baseline scenario:
  - 3 Booster batches, 1.2×10^{13} p/bunch
  - 30 ns rms bunch length
  - Tune shift $\Delta\nu \approx 0.08$



Space charge tune shift

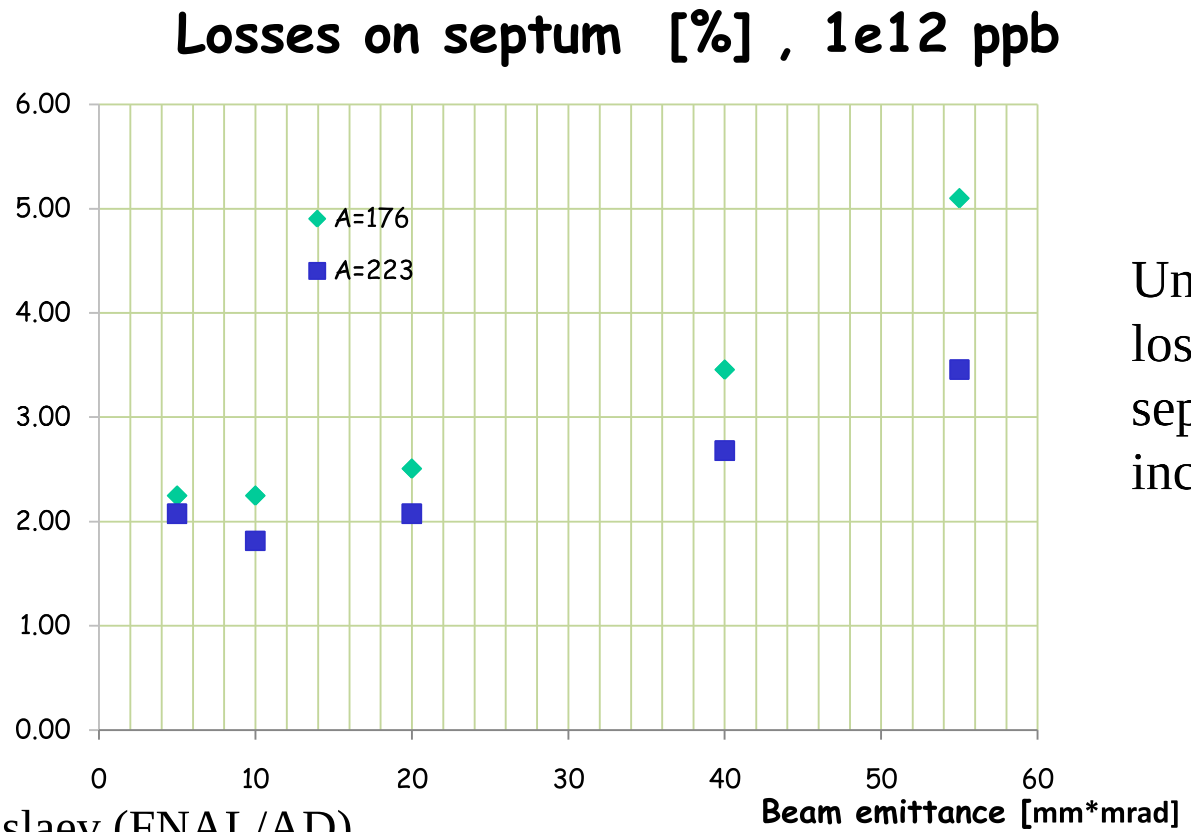
$$\Delta \nu = -\frac{3Nr_p}{2\pi\beta\gamma^2 B\varepsilon_n}$$

- Tune spread and tune shift are comparable.
- Perhaps one can reduce the tune shift by increasing the beam emittance, ε_N?
- …Not really! The losses increase because beam gets bigger and closer to the aperture limit.

(see next page)

Simulation of 3rd order resonant SE

- 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?
  - 2.6×10^{13} ppb at 15 Hz. Very large tune shift!
  - 1.3×10^{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!
  - 6.5×10^{12} ppb at 60 Hz (16 ms spill). Relative time for manipulations may be too long, losses too high.

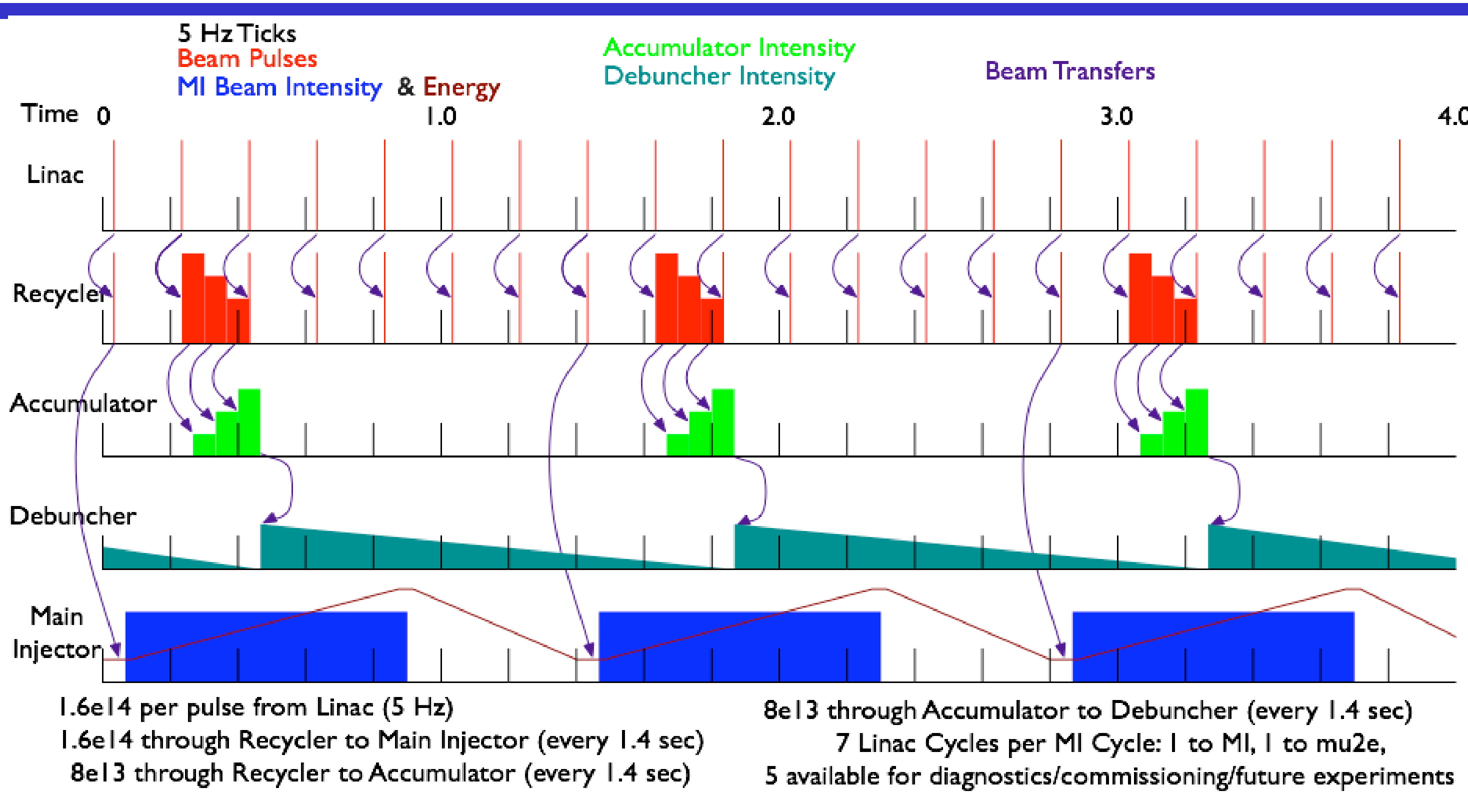
Project X ICD1

- Project X Initial Configuration Design can be found at: http://projectx.fnal.gov/

- Latest version: 1.1 (Mar 15, 2009)

- Reviews:
  - Feb 2009: Fermilab Accelerator Advisory Committee
  - Mar 16 2009: Directors cost review

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

Evolved Mu2e scenario with ICD1

- This scenario was worked out before the loss simulations…
- Spill parameters
  - 15 Hz spill cycle
  - Beam quality important (work back from the Debuncher)
  - 1.2e13 max per slow-spill cycle in the Debuncher
    - to keep tune shift <0.05 transv emittance (95%) should be 50 mm-mrad
  - Bunching pattern important (see following slides)

Mu2e beam requirements

- Working back from the Debuncher:
  - Single bunch: 25ns rms bunch length (100-160ns, FW)

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

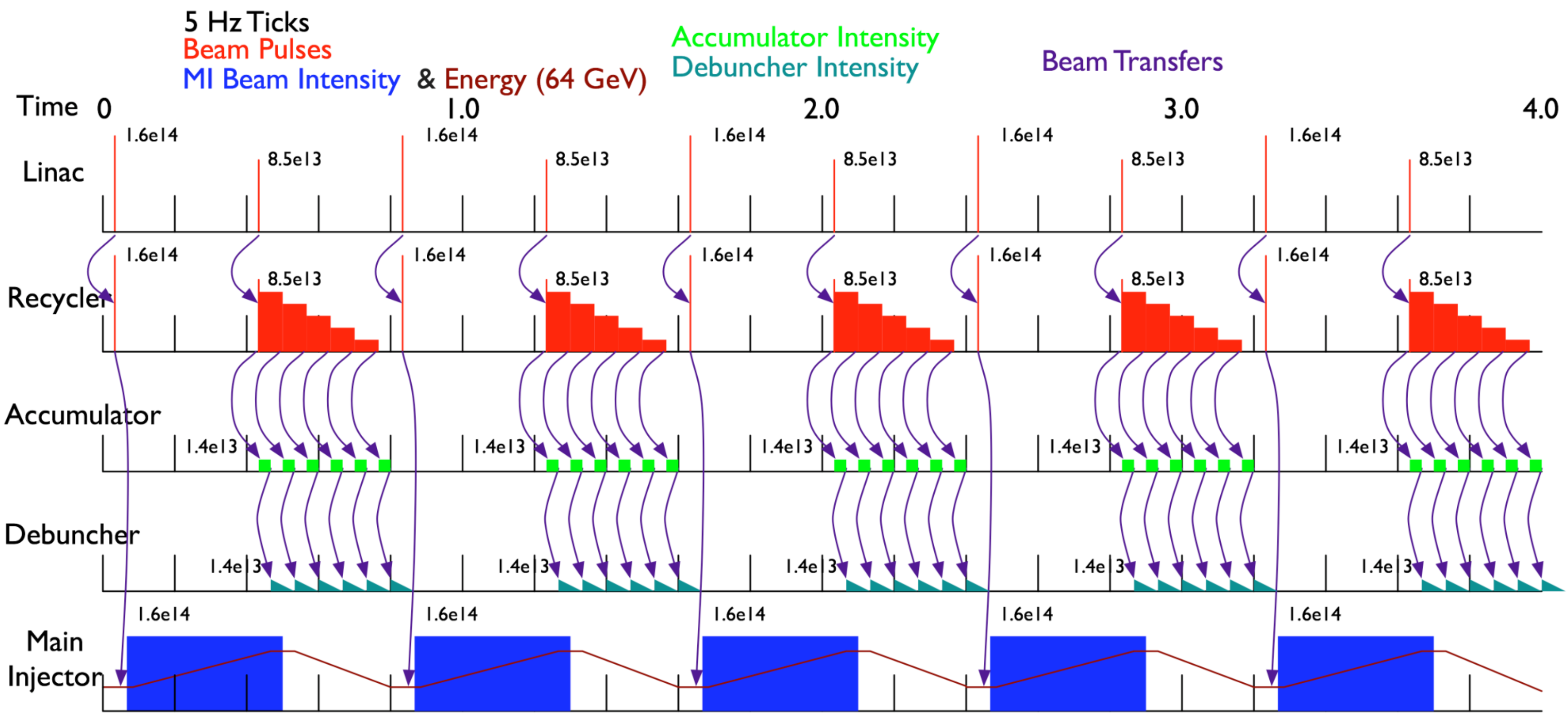
Proton DC beam current: $I_p := N \cdot e \cdot f$ $\quad I_p = 1.133\,A$

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

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

  - To fit into Debuncher momentum aperture (±2%) the bunch momentum spread must be < 150 MeV (95%)
    - ~15-20 eV-s long. emitt (95%)
  - Must use Accumulator to prepare the bunch every 50 ms

New proposed 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

What is the limit?

- It appears that even the 150 kW scenario of SE from the Debuncher will have unacceptable losses of at least 5% (7.5 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)

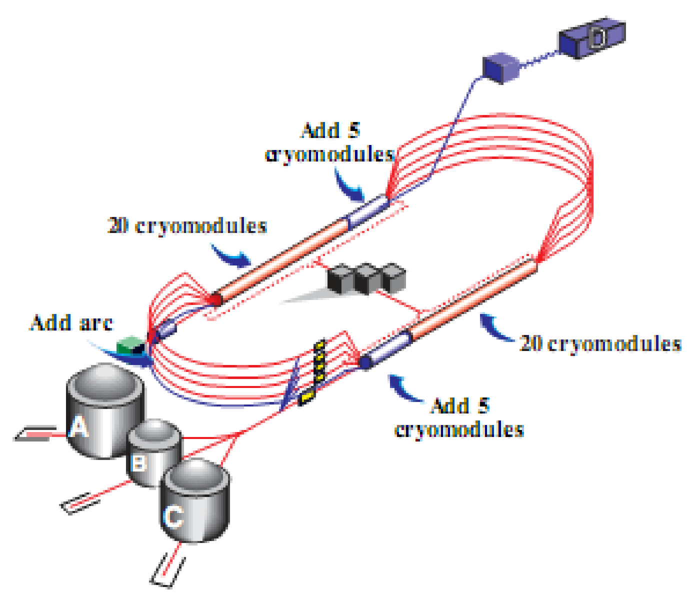
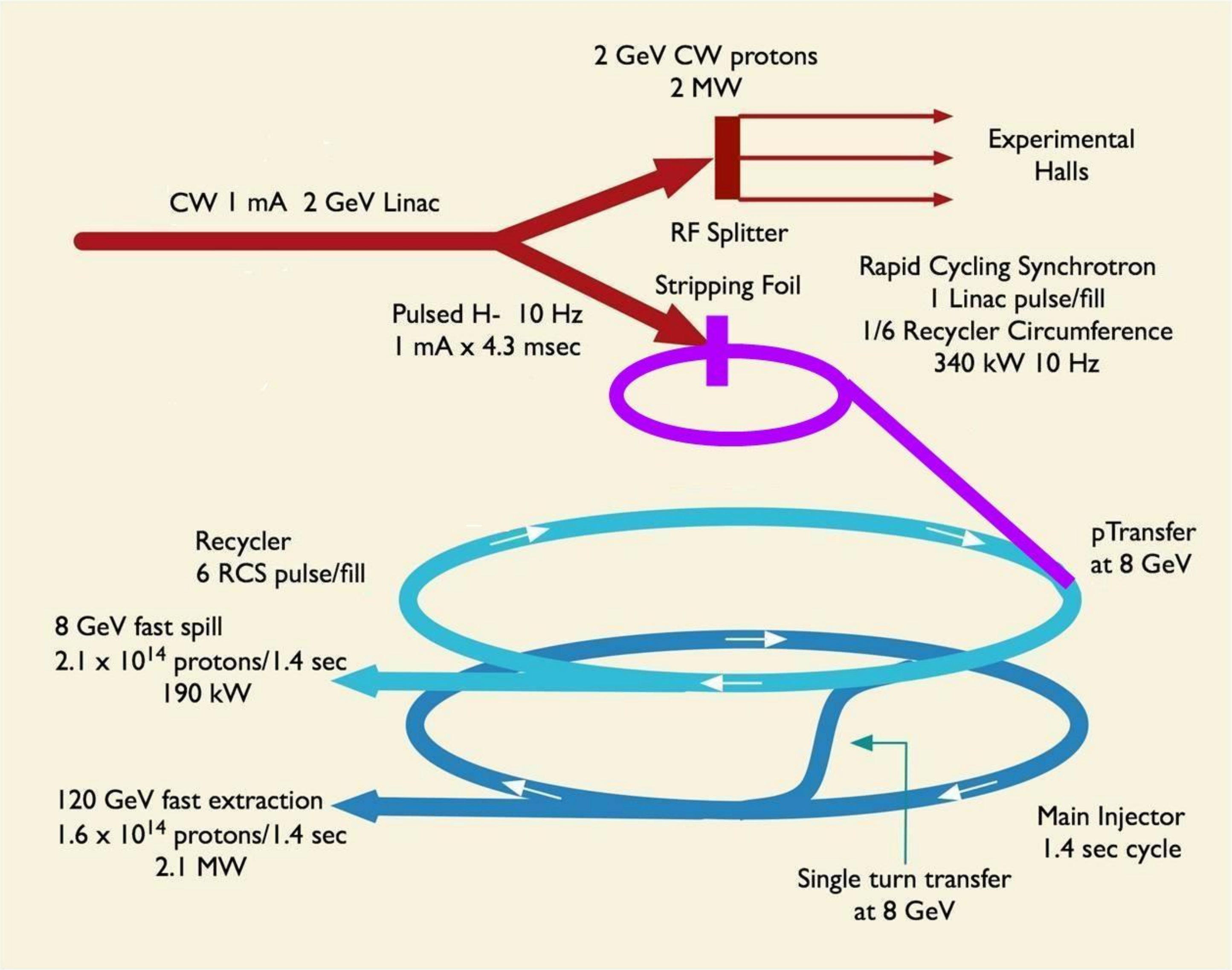
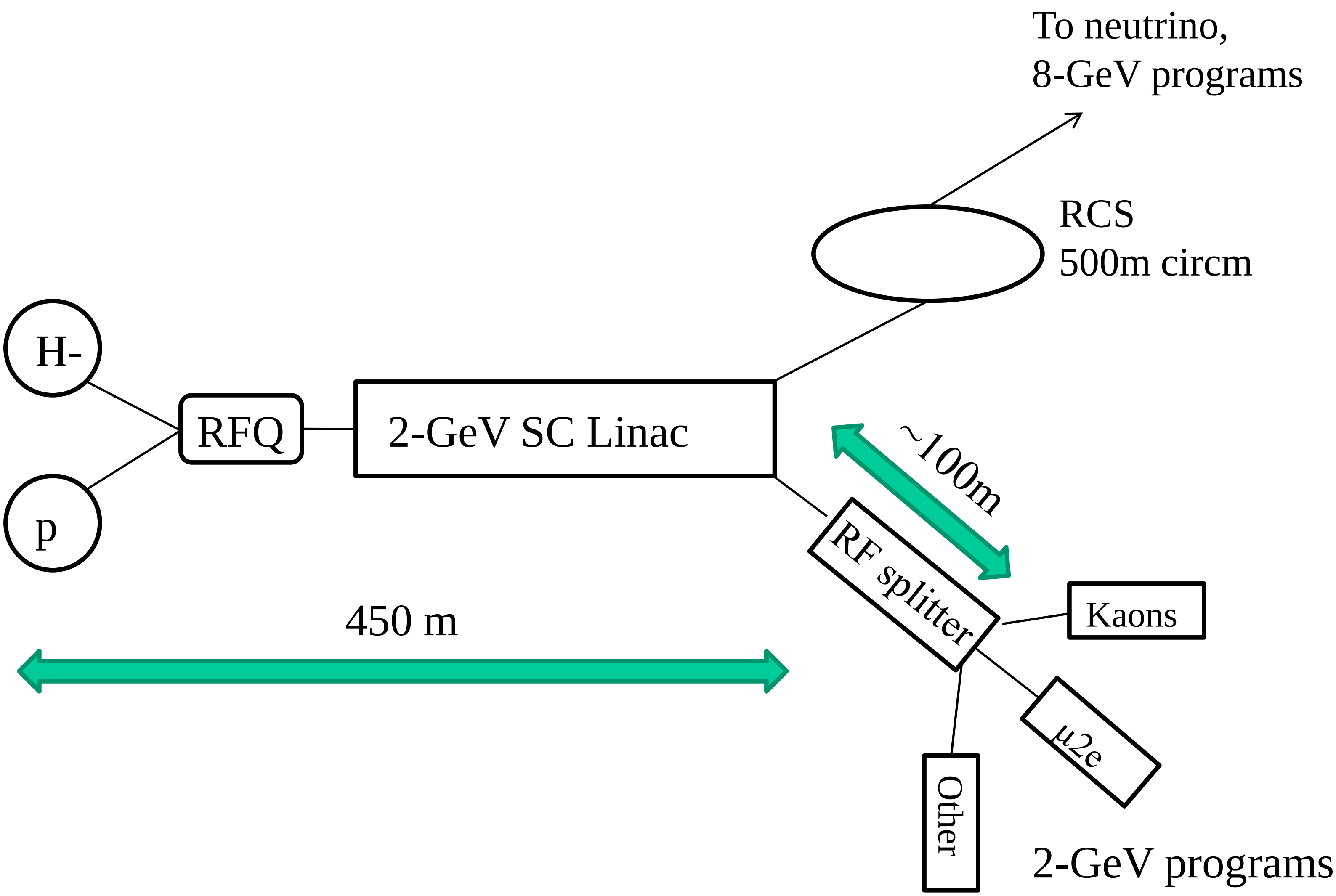


Figure 1: Schematic illustration of the CEBAF 12 GeV Upgrade.

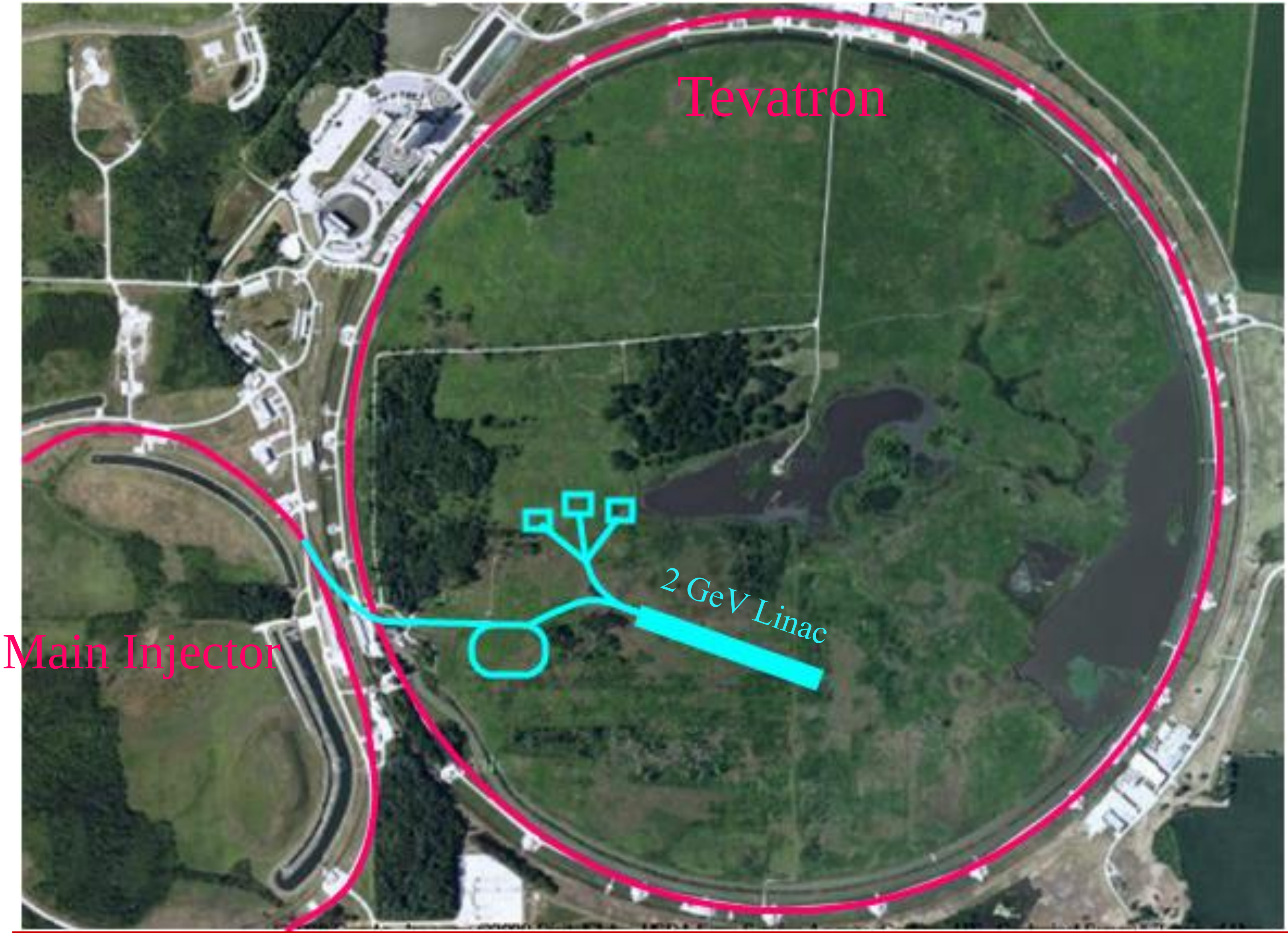
ICD2 schematic



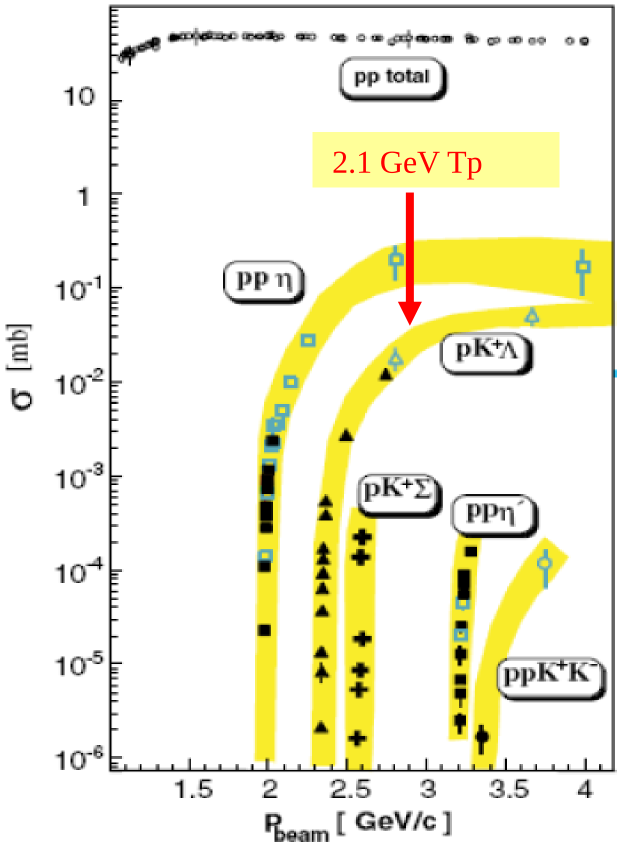
ICD2 schematic



ICD2 siting proposal

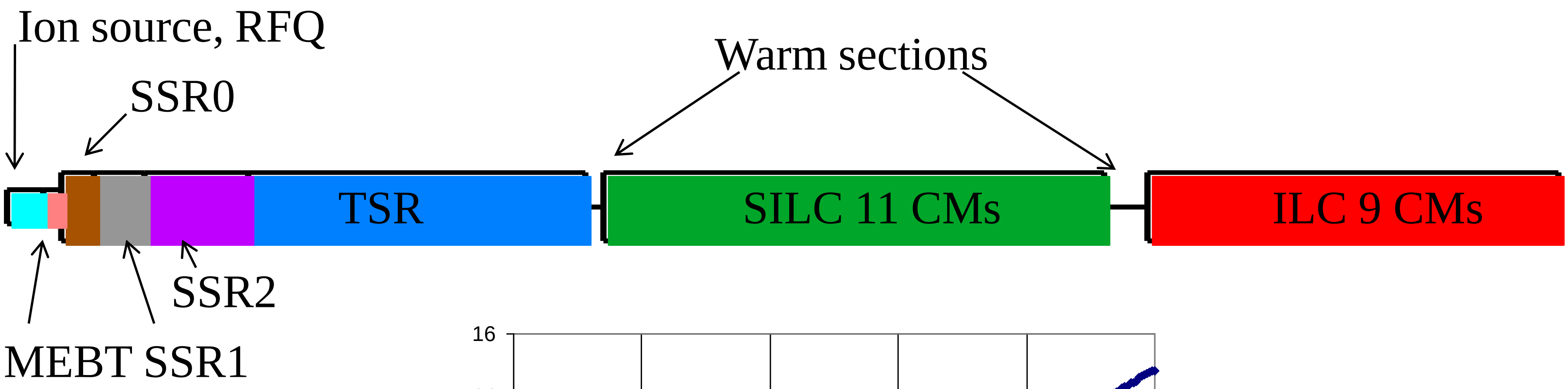


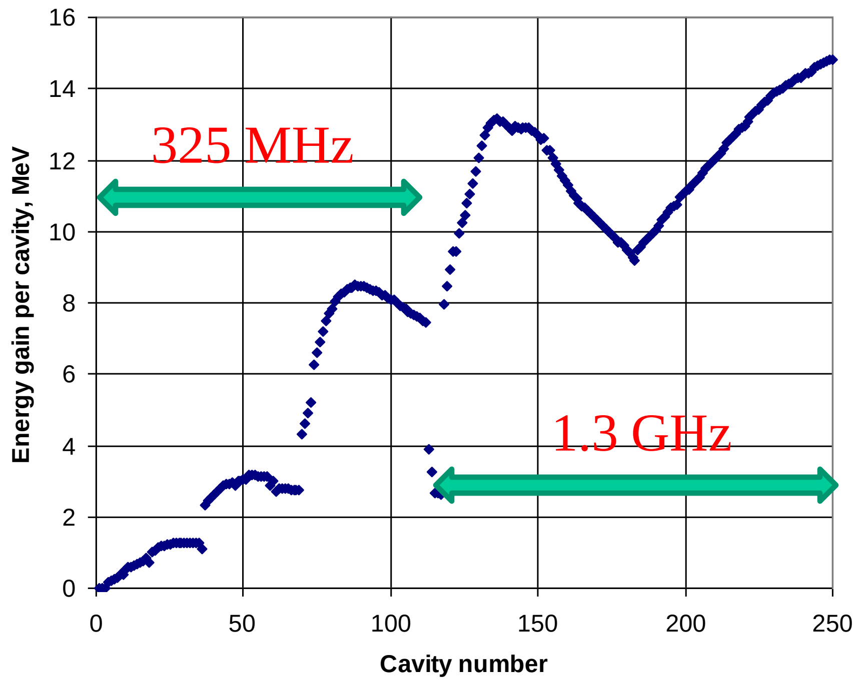
2 GeV, 1 mA cw



- 1 mA is needed for the stripping injection into the RCS;
- 2 GeV, 10 psec bunches are needed for Kaons;

2-GeV CW linac schematic
~440m length (to scale)





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

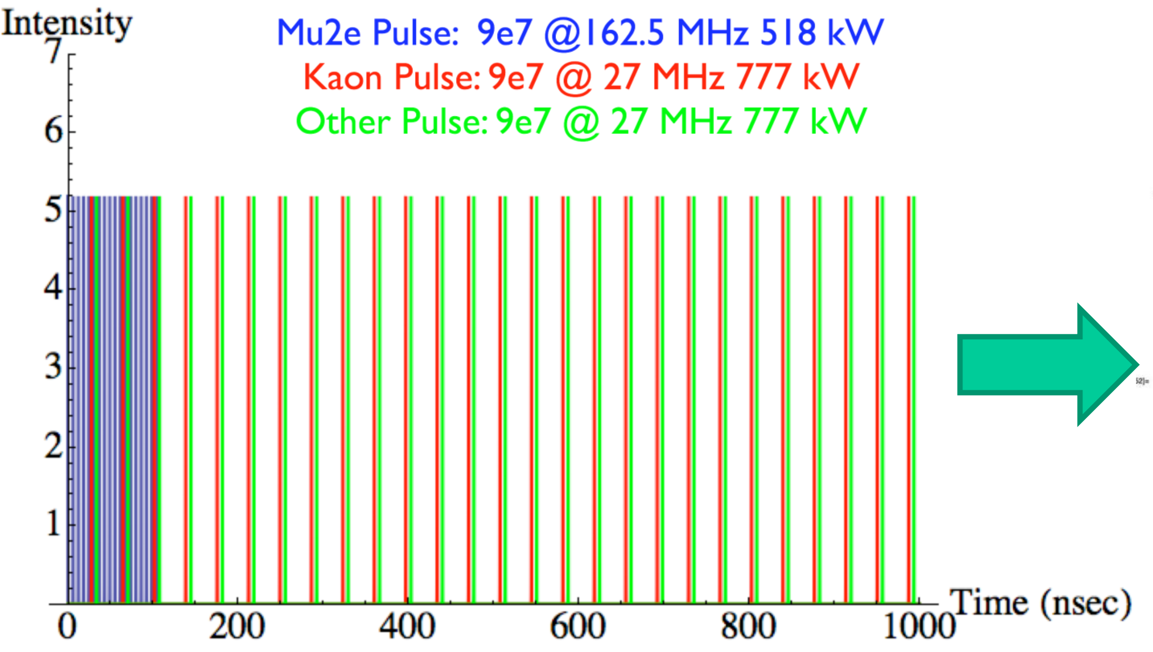
- room temperature, 325 MHz, 2.5 MeV
- 10 mA max. current
- Examples of CW RFQs:
  - LEDA (LANL): 100 mA, 6.7 MeV, 350 MHz
  - IUCF: 6mA, 750 keV, 213 MHz (in operation since 2003)
- Possible alternative: 162.5 MHz

MEBT

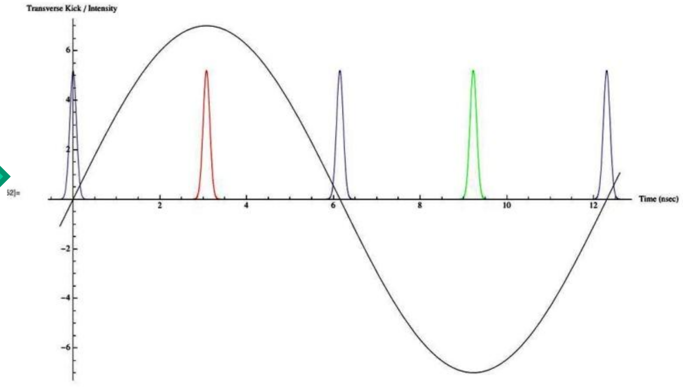
- Chopper is the key element of the project.
- Must be able to remove up to 90% of beam: 10 mA -> 1 mA (ave)
  - Remove individual bunches at 325 MHz

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: 1.9×10^7 protons per bunch at 325 MHz rate
  2. Ion source at 10 mA, 90% beam chopping: 1.9×10^8 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

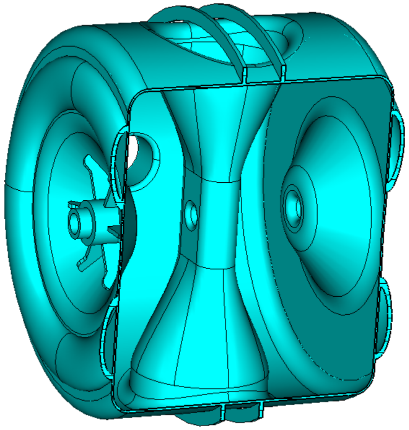


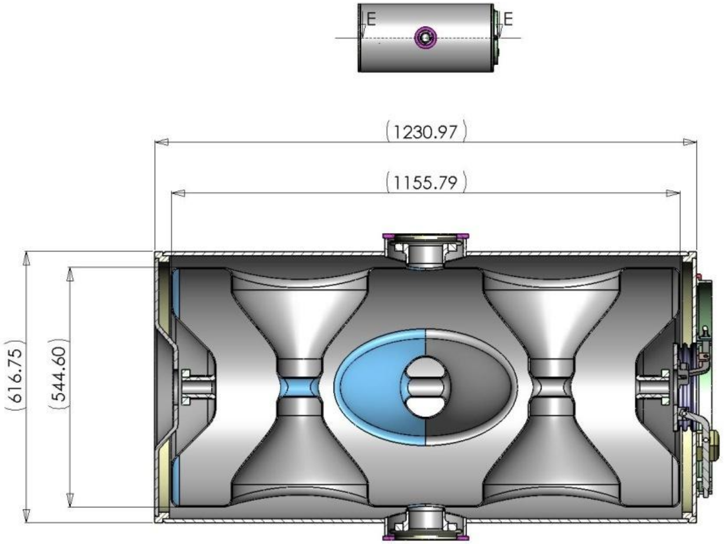
Transverse kick at rf splitter (406 MHz, similar to crab cavity)



SSR and TSR sections (325 MHz)

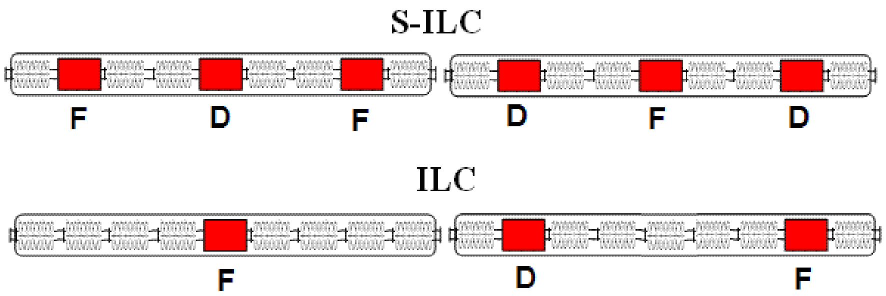
- 2.5 – 466 MeV
- 3 types of single-spoke (SSR)
- 1 type of triple-spoke (TSR)
- Possibly operating at 2K to reduce microphonics



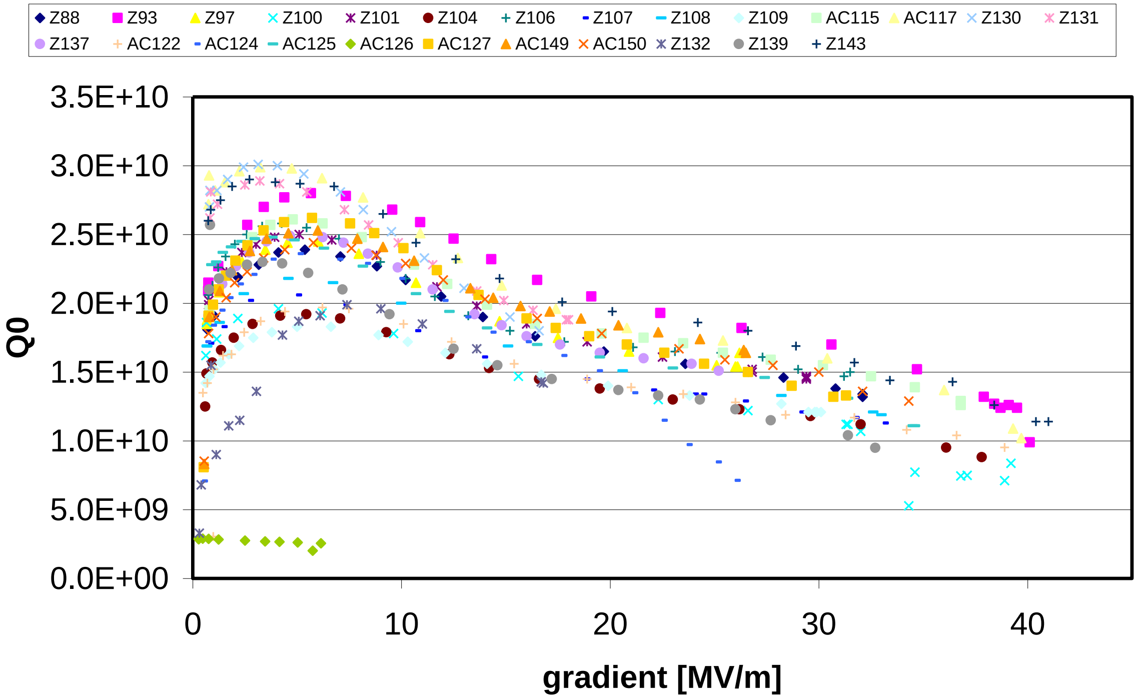


SILC and ILC sections (1.3 GHz)

- 466 MeV to 2 GeV
- 16 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, ν_x/ν_y	18.42 / 18.44
Transition energy, GeV	13.36
Number of particles	2.6×10^{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

What about that ICD-2 beam power??

- 2GeV x 1 mA = 2 MW of beam power.
- 5% of Linac timeline required to drive the 2 MW LBNE program.
- x10 beam power of the ICD-1 rare-decay program, x7 goal of JPARC.
- 1.2×10^{23} protons per year, a *mole* of protons in five years.

This is the intensity frontier!

Summary

- A new concept for Project X beam delivery has emerged.
  - Not another rendition of AGS or JPARC
  - Avoids complications of slow extraction

- Variable chopper + Super Conducting CW linac + an rf splitter → totally new approach to the rare decay programs.