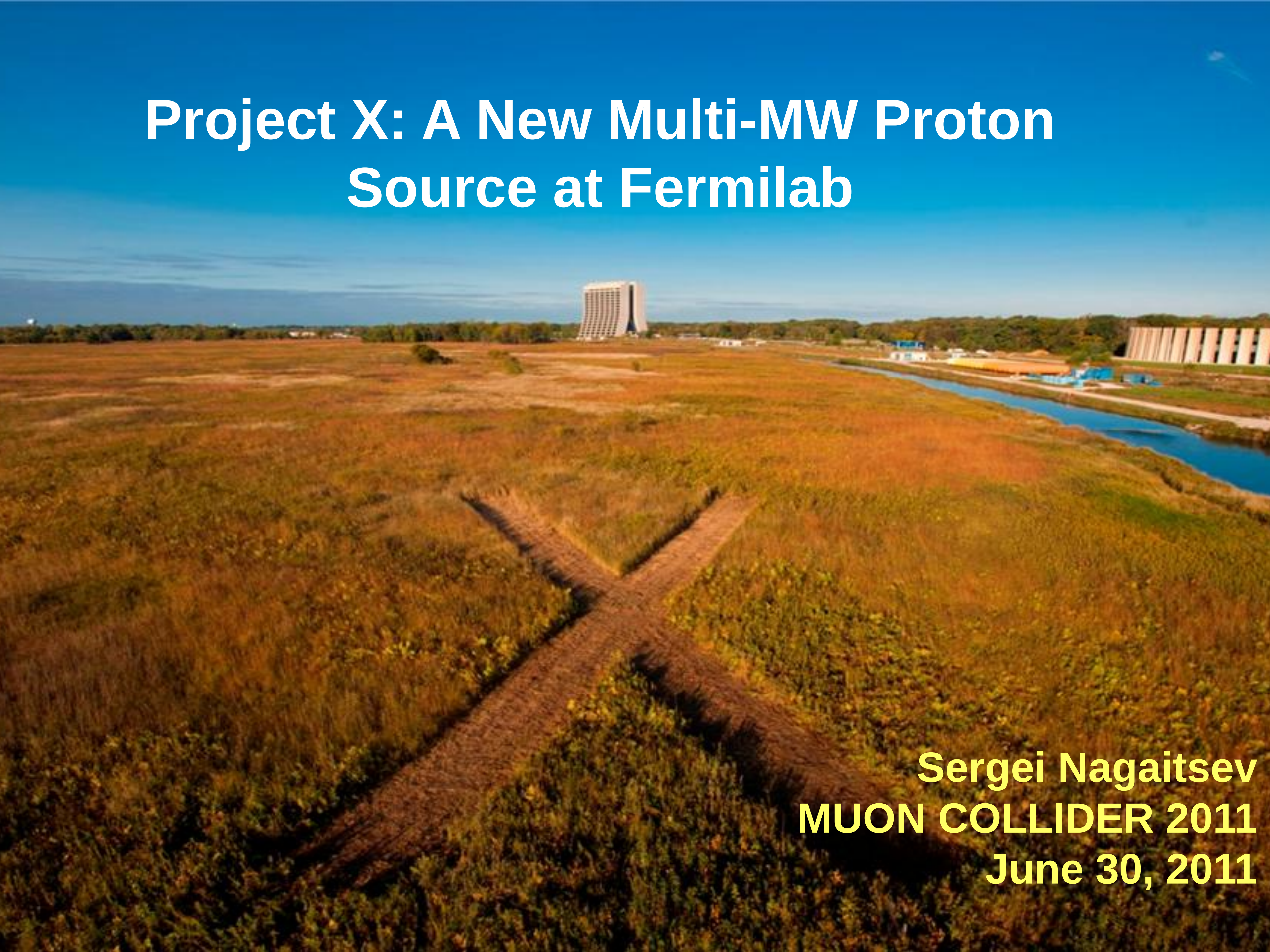
Project X: A New Multi-MW Proton Source at Fermilab



Sergei Nagaitsev

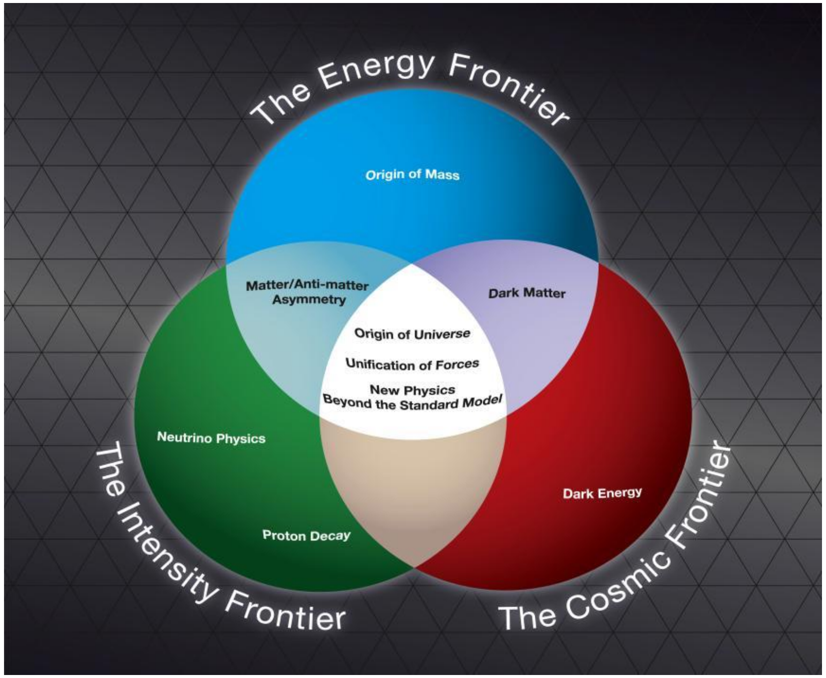
MUON COLLIDER 2011

June 30, 2011

Fermilab Long Range Plan

Fermilab is the sole remaining U.S. laboratory providing facilities in support of accelerator-based Elementary Particle Physics. Fermilab is fully aligned with the strategy for U.S. EPP developed by HEPAP/P5.

⇒ ***The Fermilab strategy is to mount a world-leading program at the <u>intensity frontier</u>, while using this program as a bridge to an <u>energy frontier</u> facility beyond LHC in the longer term.***

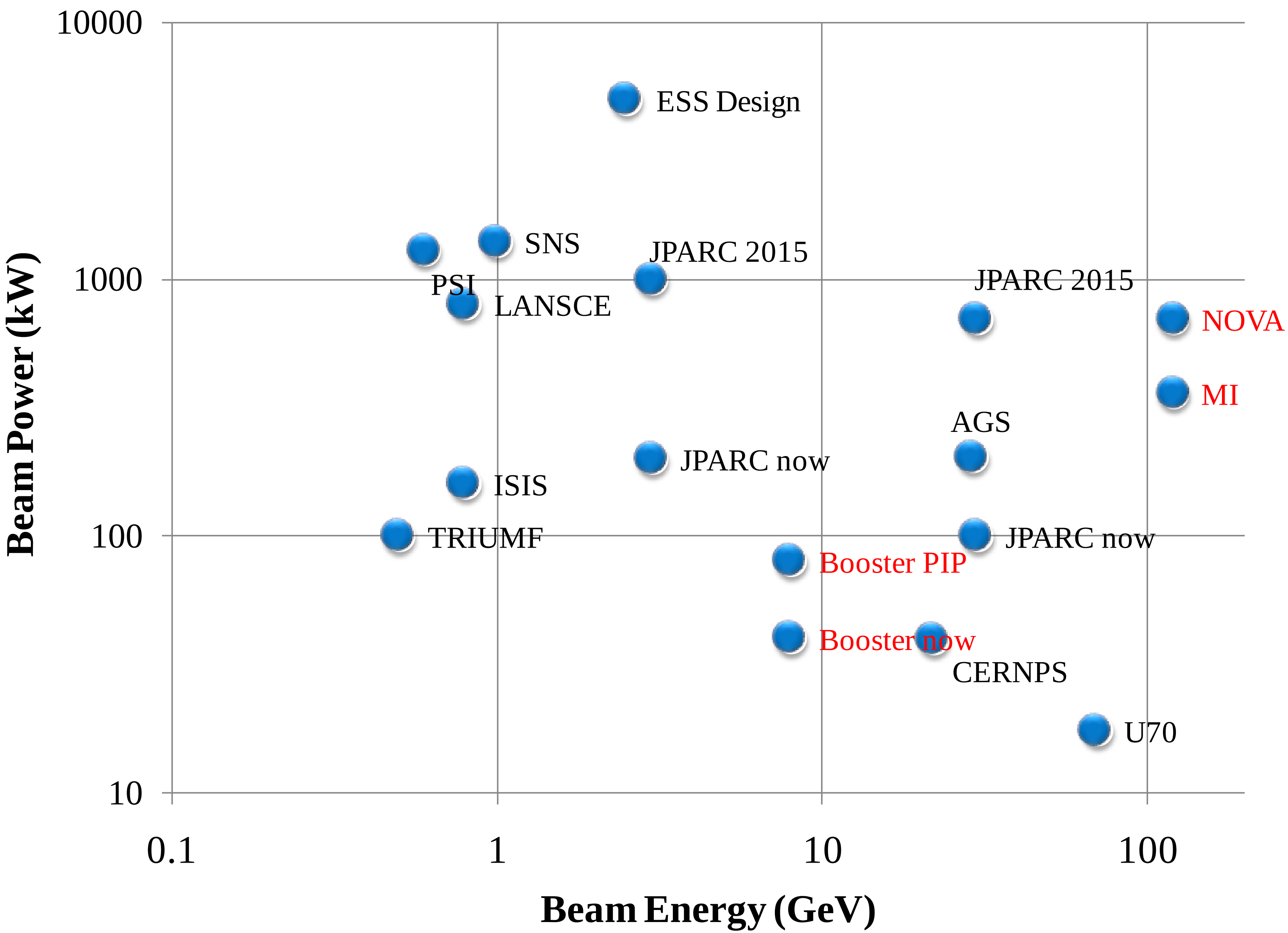


Project X is the key element of this strategy.

Metrics to Measure Proton Accelerator Capabilities for Intensity Frontier

1. Average beam power on target
   - By far, the most important metric
2. Beam energy on target
   - Muons: ~0.8 GeV – 15 GeV
   - Kaons: ≥ 3 GeV
   - Neutrinos: ≥ few GeV
   - Nuclear: 1-2 GeV
3. Bunch format (or bunch timing)
   - Small duty-factor for neutrinos (minimize background)
   - Special formats for NF/MC
   - CW for all others
     - Bunch spacing depends on decay time

This science has attracted competition: The proton source landscape this decade...

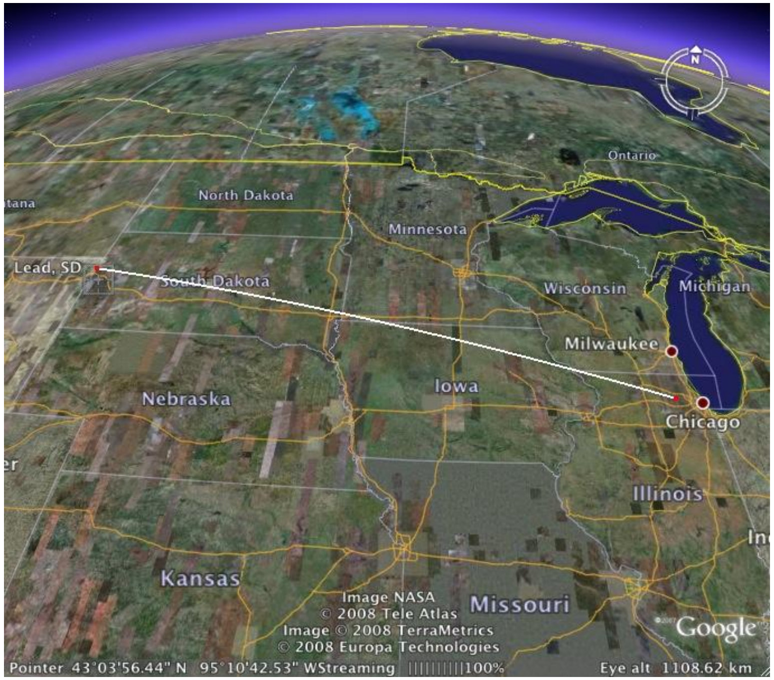


From Proton Driver to Project X

- Fermilab has recognized the need for a new proton source more than 10 year ago.
  - Has been part of Fermilab strategy
  - Present missions are largely based on a HEPAP/P5 report (May, 2008)
- Configurations varied from a synchrotron to an SCRF linac.
  - Present (reference design) configuration has been “frozen” since mid. 2010.

Project X Mission Goals

- A neutrino beam for long baseline neutrino oscillation experiments
  - 2 MW proton source at 60-120 GeV



- High intensity, low energy protons for kaon and muon based precision experiments
  - Operations simultaneous with the neutrino program
- A path toward a muon source for possible future Neutrino Factory and/or a Muon Collider
  - Requires ~4 MW at ~5-15 GeV .
- Possible missions beyond HEP
  - Standard Model Tests with nuclei and energy applications

Project X research program

- ***Kaon, muon, nuclei & neutron precision experiments***

These could include world leading experiments searching for muon-to-electron conversion, nuclear and neutron electron dipole moments (edms), and world-leading precision measurements of ultra-rare kaon decays.

- ***Neutrino oscillation experiments***

A high-power proton source with proton energies between 8 and 120 GeV would produce intense neutrino beams directed toward near detectors on the Fermilab site and massive detectors at distant underground laboratories.

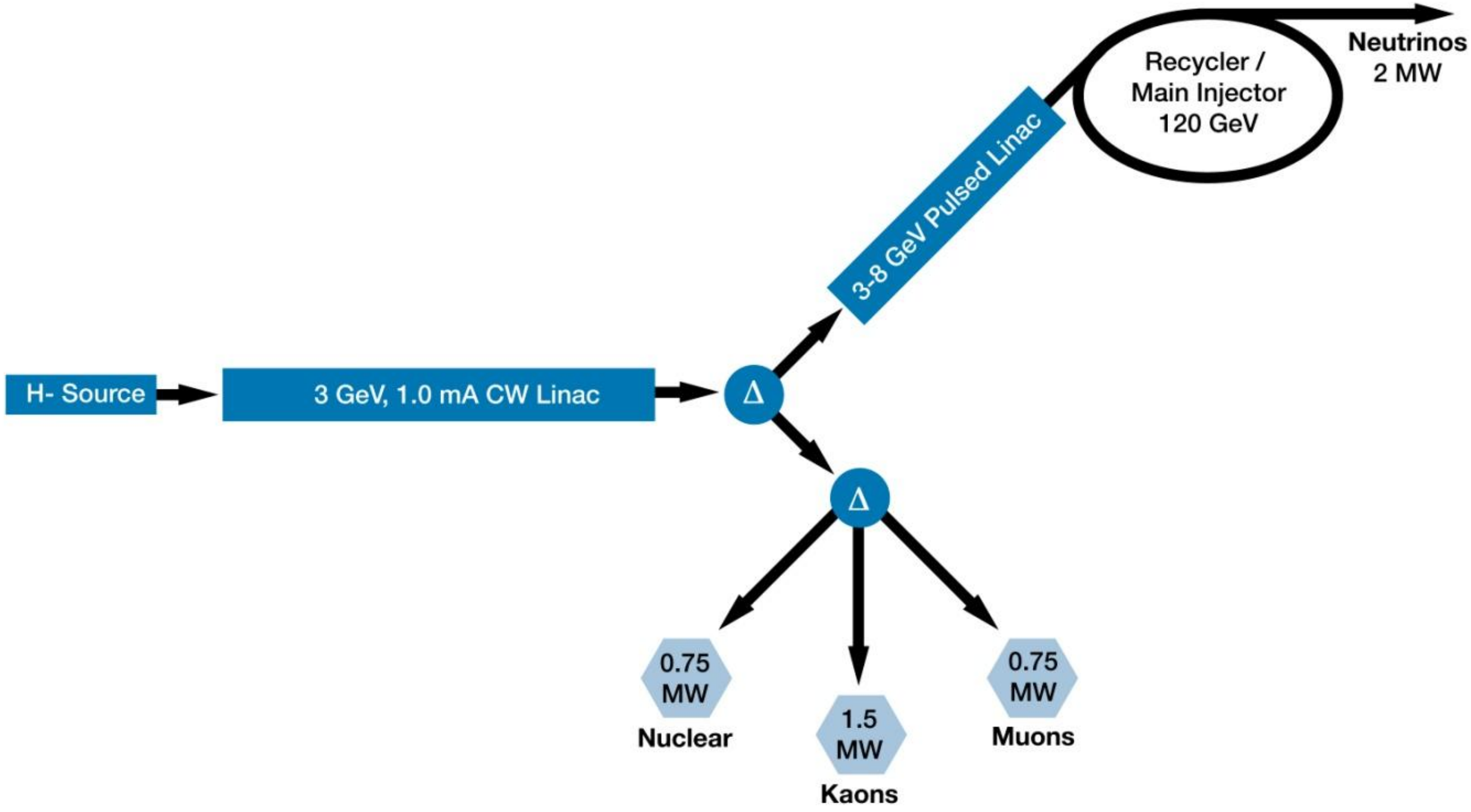
- ***Platform for evolution to a Neutrino Factory and Muon Collider***

Neutrino Factory and Muon-Collider concepts depend critically on developing high intensity proton source technologies.

- ***Nuclear Energy Applications***

Accelerator, spallation, target and transmutation technology demonstration which could investigate and develop accelerator technologies important to the design of future nuclear waste transmutation systems and future thorium fuel-cycle power systems.

Reference Design



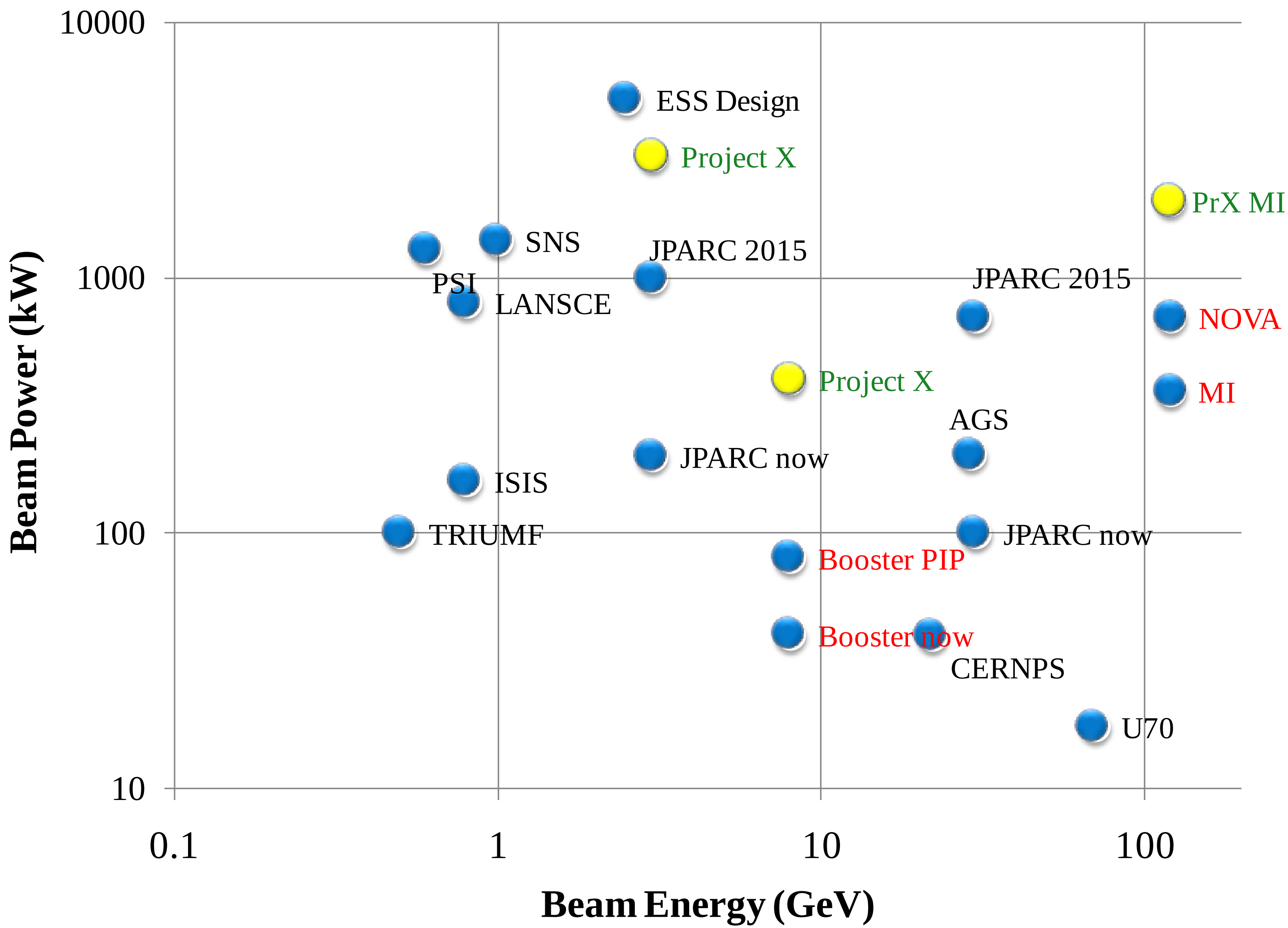
Reference Design Capabilities

- 3 GeV CW superconducting H- linac with 1 mA average beam current.
  - Flexible provision for variable beam structures to multiple users
    - CW at time scales >1 μsec, 15% DF at <1 μsec
  - Supports rare processes programs at 3 GeV
  - Provision for 1 GeV extraction for nuclear energy program
- 3-8 GeV pulsed linac capable of delivering 300 kW at 8 GeV
  - Supports the neutrino program
  - Establishes a path toward a muon based facility
- Upgrades to the Recycler and Main Injector to provide ≥ 2 MW to the neutrino production target at 60-120 GeV.
- Day one experiment to be incorporated utilizing the CW linac

$\Rightarrow$ Utilization of a CW linac creates a facility that is unique in the world, with performance that cannot be matched in a synchrotron-based facility.

Project X

Project X vs. other facilities



CW linac and RF splitter

- Very powerful combination to support several experiments concurrently.
- CEBAF uses this technology with electrons.
- Project X would add a bunch-by-bunch chopper to this scheme
  - Enhancement: supports variable bunch patterns

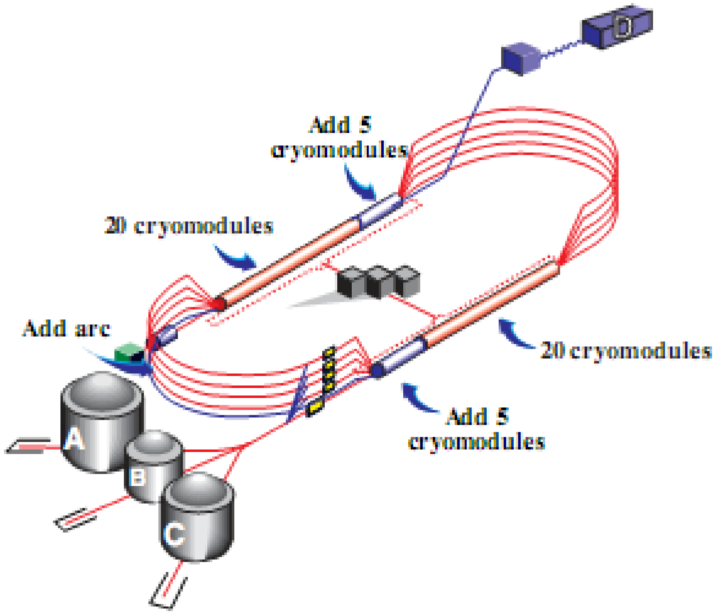
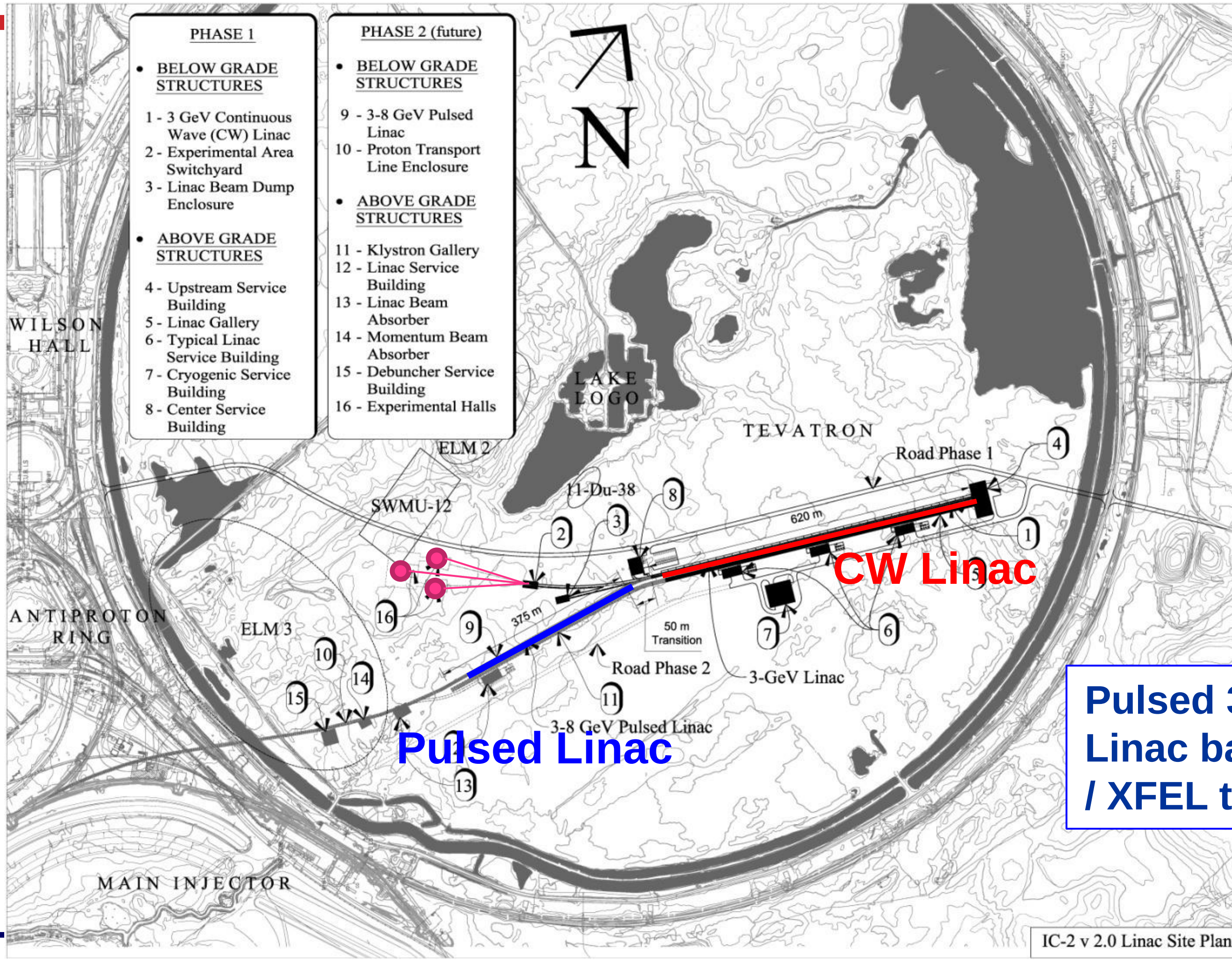


Figure 1: Schematic illustration of the CEBAF 12 GeV Upgrade.

Reference Design

Provisional Siting

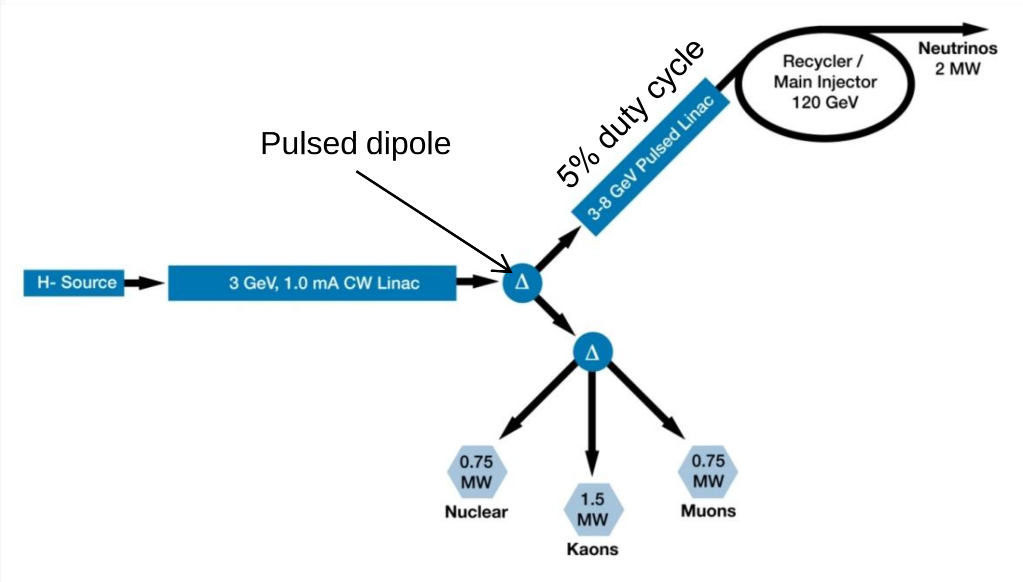


Pulsed 3-8 GeV Linac based on ILC / XFEL technology

3-GeV Research Campus at end of CW Linac

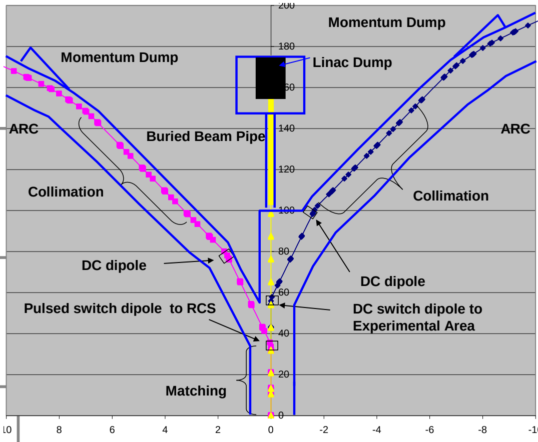
Reference design: scope

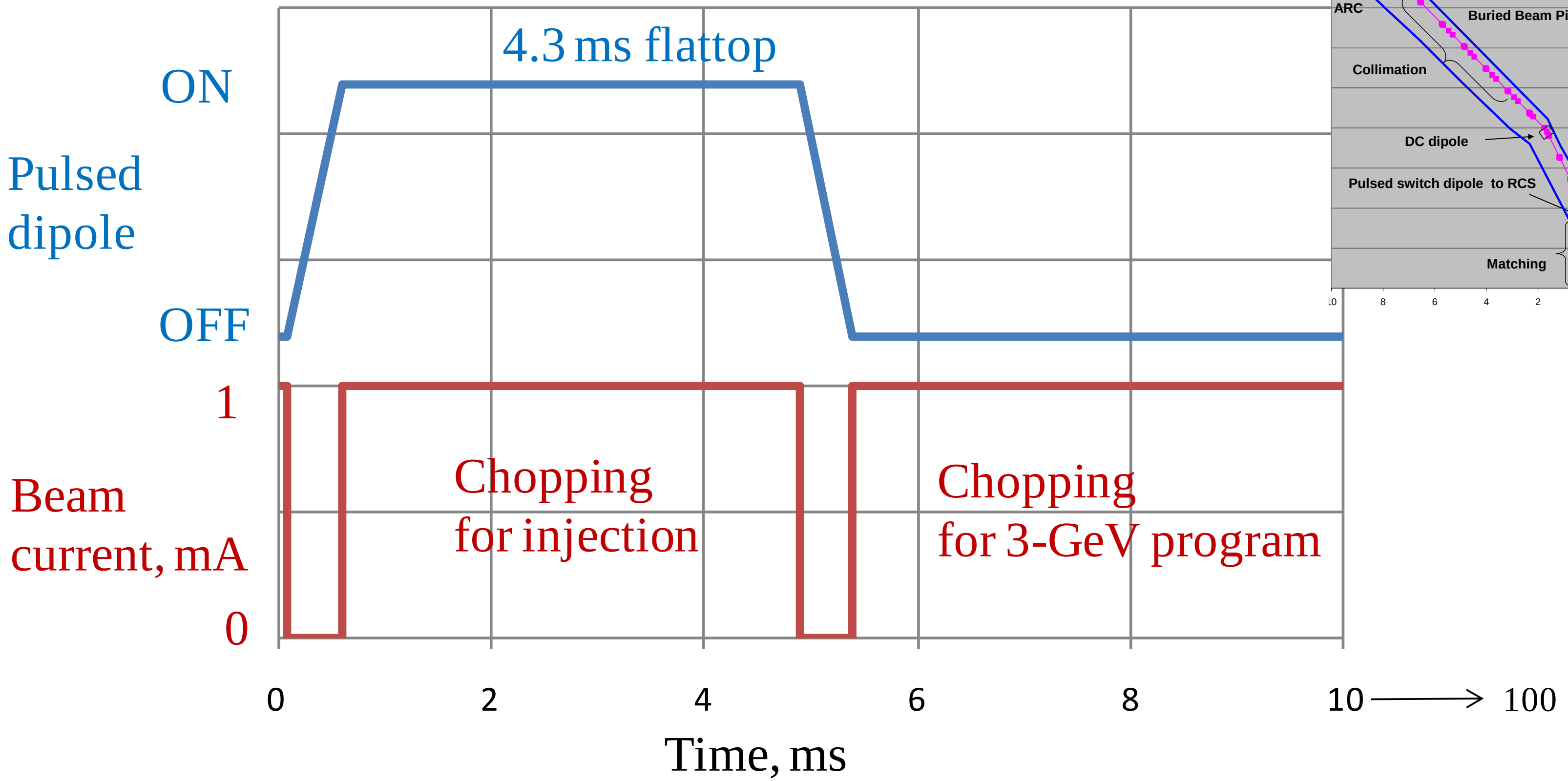
- Warm cw front end 162.5 MHz, 5 mA (H- ion source, RFQ, MEBT, chopper)
- 3-GeV cw SCRF linac (325, 650 MHz), 1-mA ave. beam current
- Transverse beam splitter for 3-GeV experiments
- 3-8 GeV: pulsed linac (5% duty cycle), 1.3 GHz
- Recycler and MI upgrades
- Various beam transport lines



Linac beam current

- Linac beam current has a periodic time structure (at 10 Hz) with two major components.



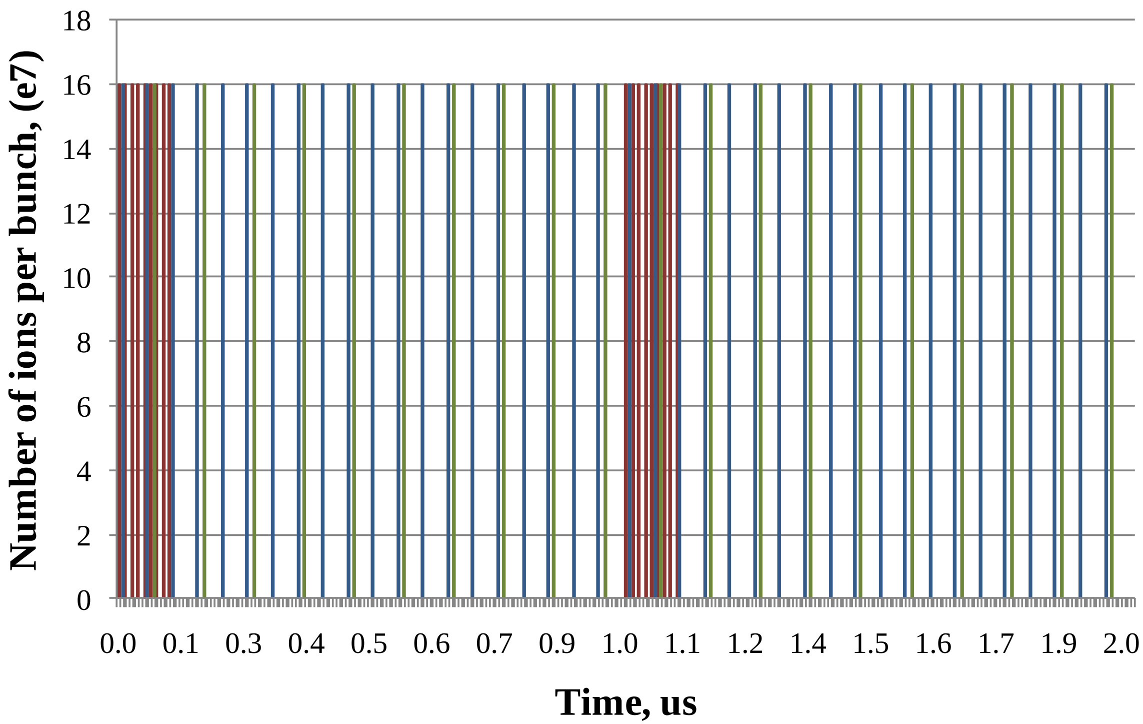


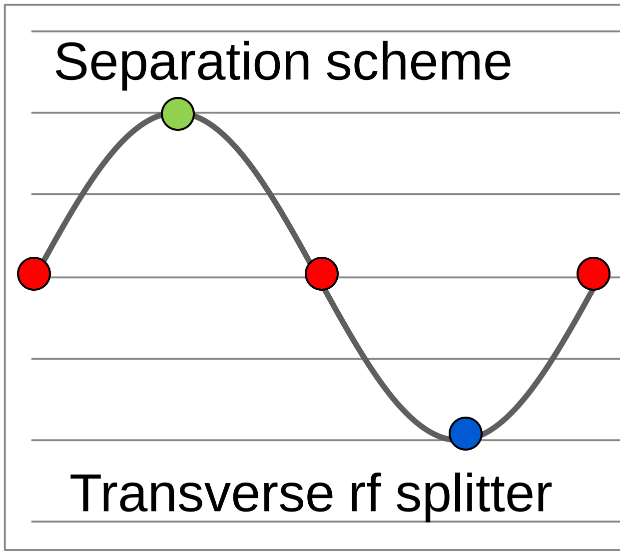
Chopping and splitting for 3-GeV experiments

1 μsec period at 3 GeV

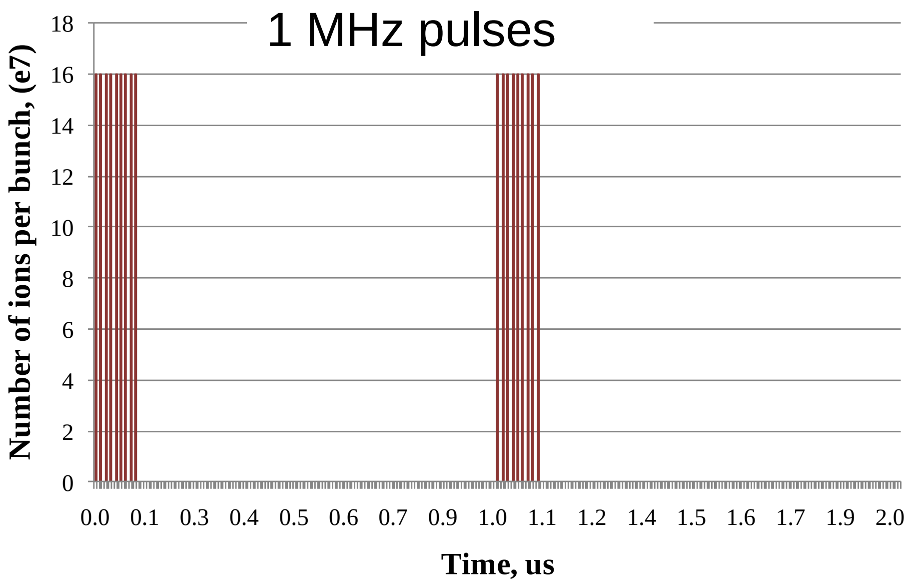
Muon pulses (16e7) 81.25 MHz, 100 nsec at 1 MHz	700 kW
Kaon pulses (16e7) 20.3 MHz	1540 kW
Nuclear pulses (16e7) 10.15 MHz	770 kW

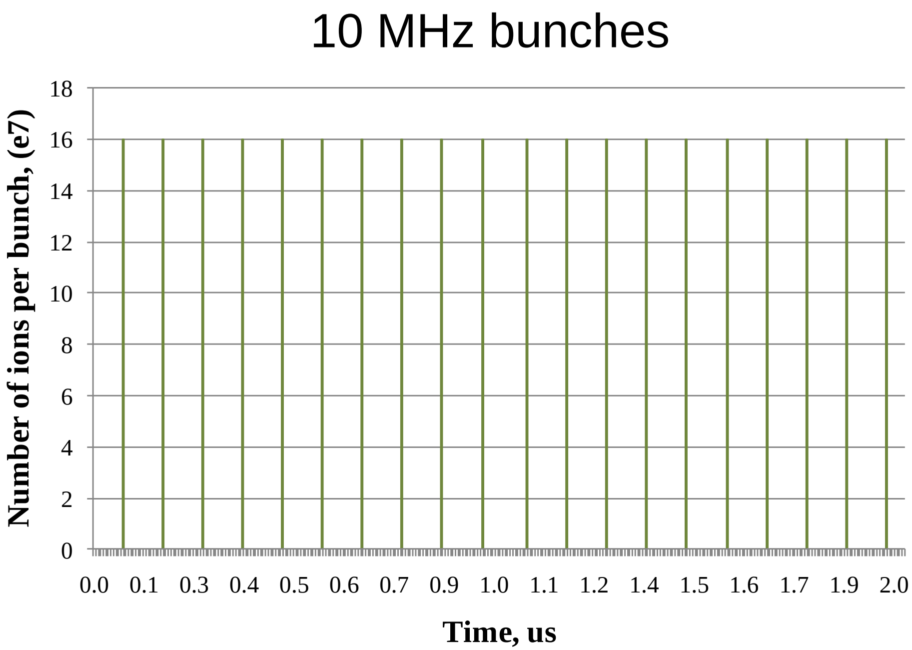
Ion source and RFQ operate at 4.2 mA
75% of bunches are chopped at 2.5 MeV after RFQ

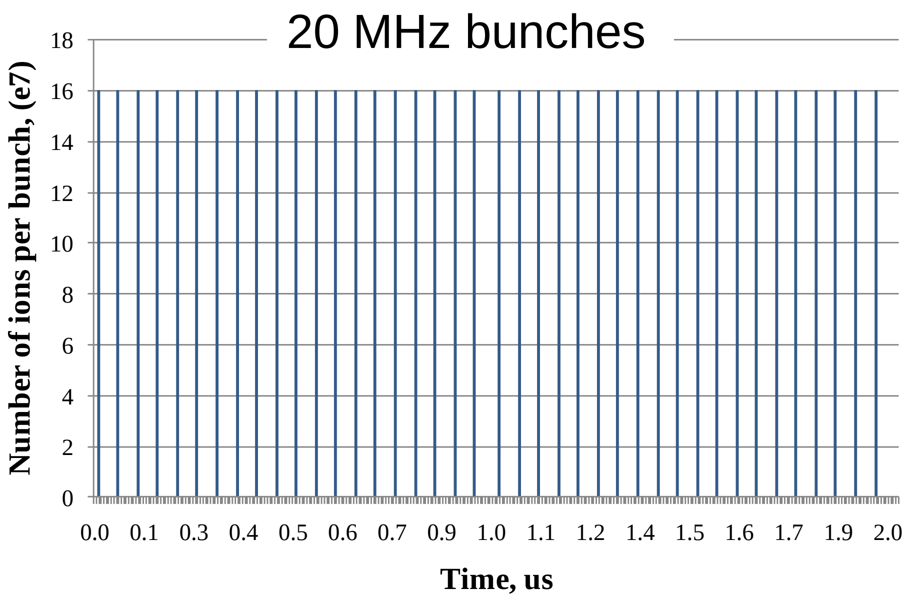




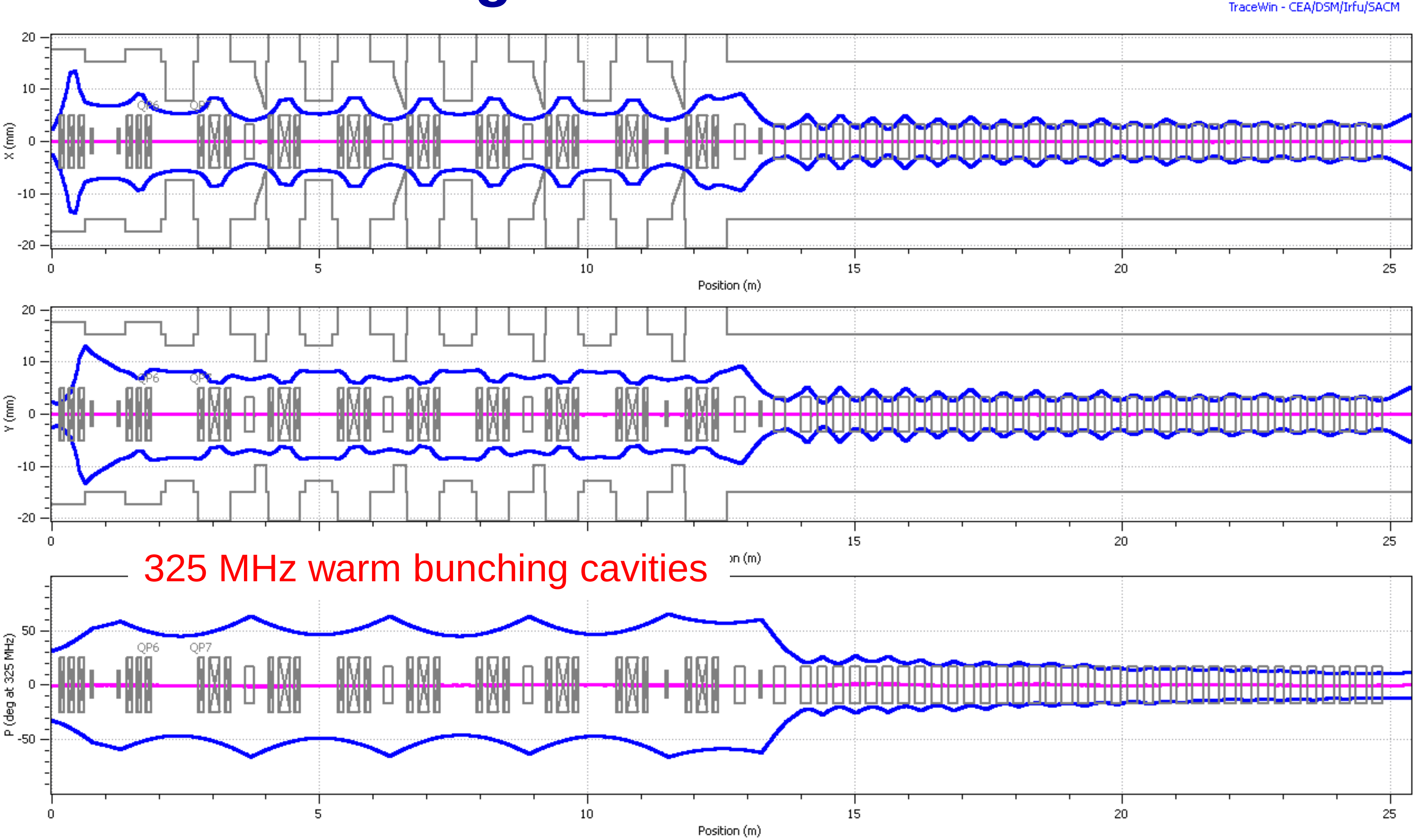
Beam after splitter





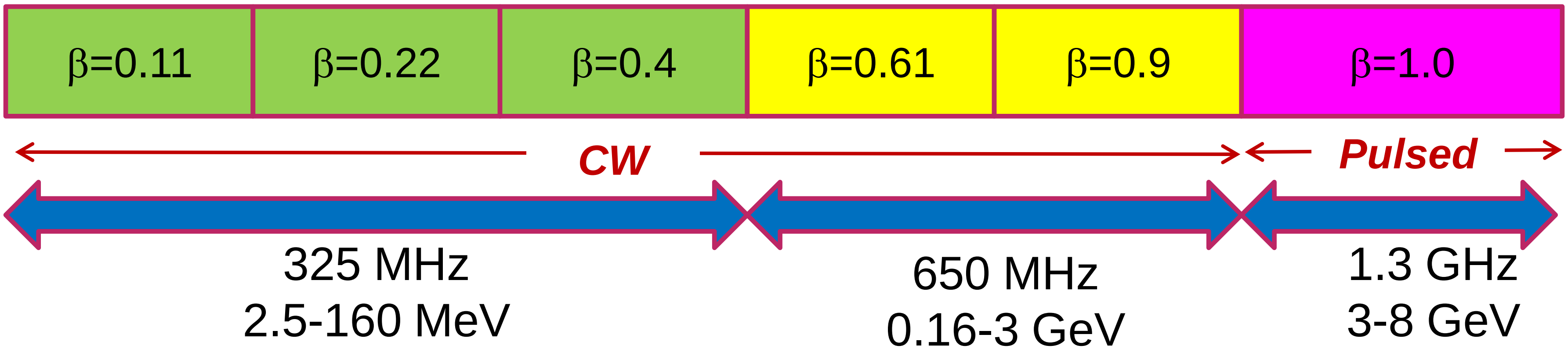


MEBT design: 5 mA at 162.5 MHz beam



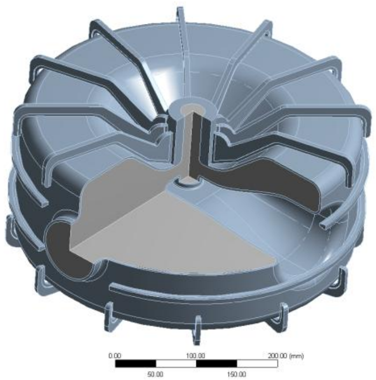
$\varepsilon_{\perp}=0.25\ \pi\cdot\mu m$; $\varepsilon_{z,n}=0.3\ \pi\cdot\mu m$

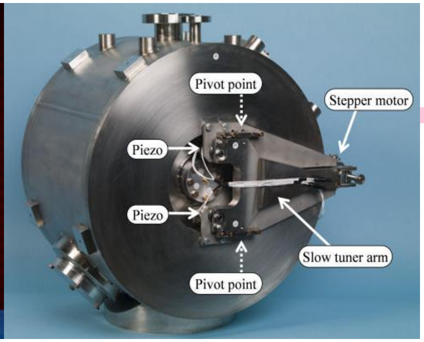
SRF Linac
Technology Map

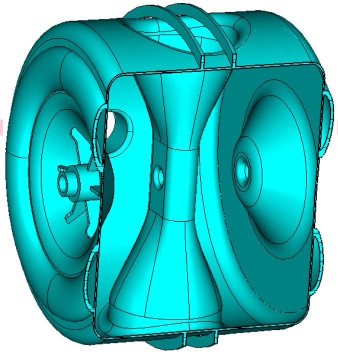


Section	Freq	Energy (MeV)	Cav/mag/CM	Type
SSR0 (β_G=0.11)	325	2.5-10	18 /18/1	SSR, solenoid
SSR1 (β_G=0.22)	325	10-42	20/20/ 2	SSR, solenoid
SSR2 (β_G=0.4)	325	42-160	40/20/4	SSR, solenoid
LB 650 (β_G=0.61)	650	160-460	36 /24/6	5-cell elliptical, doublet
HB 650 (β_G=0.9)	650	460-3000	160/40/20	5-cell elliptical, doublet
ILC 1.3 (β_G=1.0)	1300	3000-8000	224 /28 /28	9-cell elliptical, quad

325 MHz spoke cavity families







SSR0 – design, prototyping

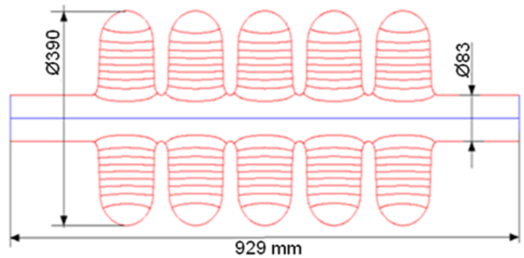
SSR1 – prototyping, testing

SSR2 - design

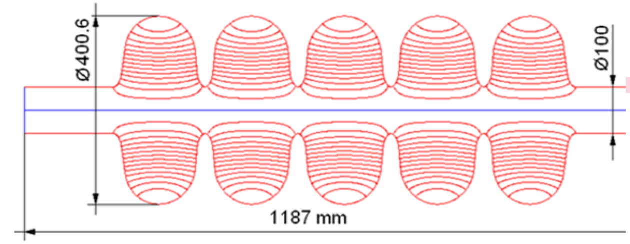
Parameters of the single-spoke cavities

cavity type	β_G	Freq MHz	$U_{acc,\,max}$ MeV	E_{max} MV/m	B_{max} mT	R/Q, Ω	G, Ω	*$Q_{0,2K}$ $\times 10^9$	$P_{max,2K}$ W
SSR0	β=0.114	325	0.6	32	39	108	50	6.5	0.5
SSR1	β=0.215	325	1.47	28	43	242	84	11.0	0.8
SSR2	β=0.42	325	3.34	32	60	292	109	13.0	2.9

650 MHz cavities



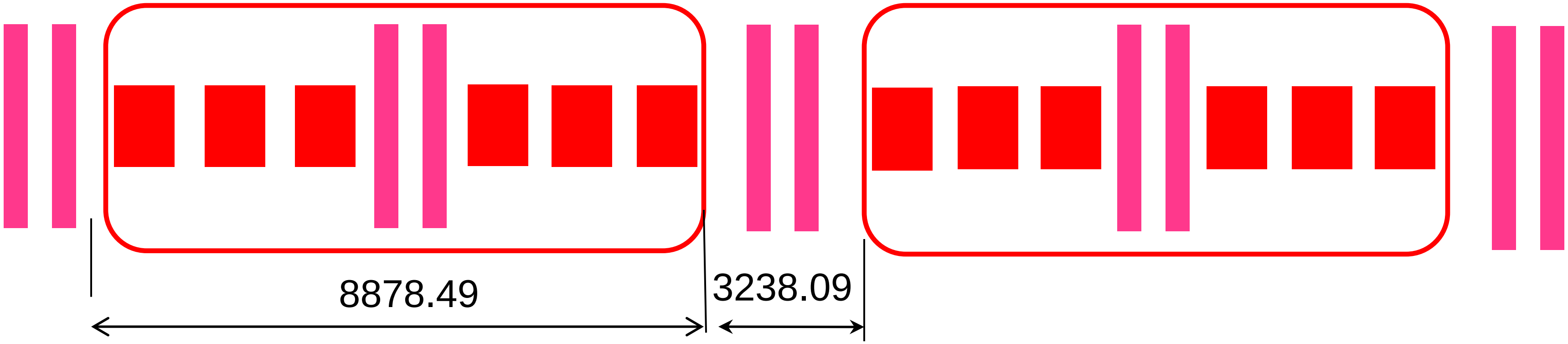
650 MHz: β=0.61



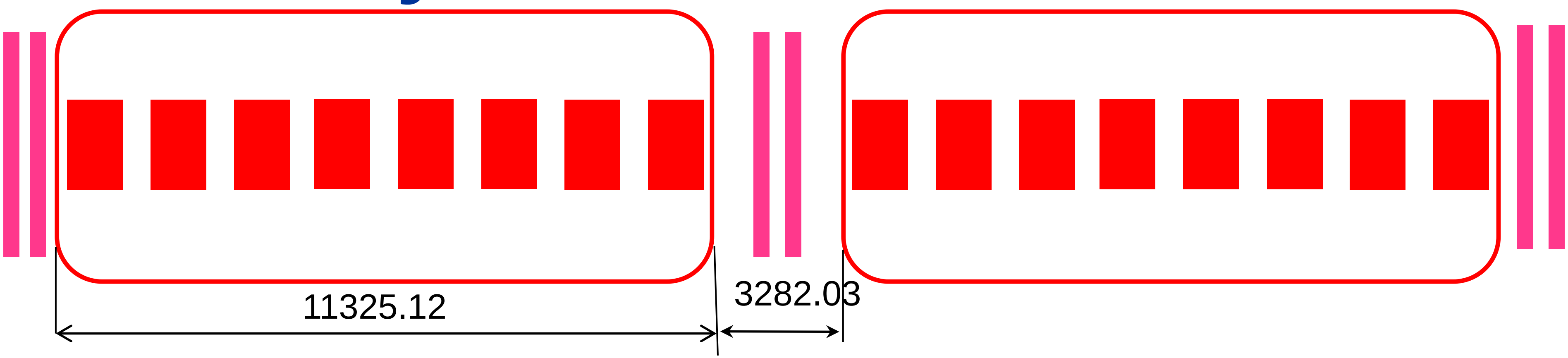
650 MHz: β=0.9

Parameter		LE650	HE650	
β_geom		0.61	0.9	
R/Q	Ohm	378	638	
G-factor, Ohm		191	255	
Max. Gain/cavity (on crest)	MeV	11.7	19.3	
Acc. Gradient	MV/m	16.6	18.7	
Max surf. electric field	MV/m	37.5	37.3	
Max surf. magnetic field,	mT	70	70	
Q_0 @ 2° K	$\times 10^{10}$	1.5	2.0	
P_{2K} max	[W]	24	29	

LE Cryomodules

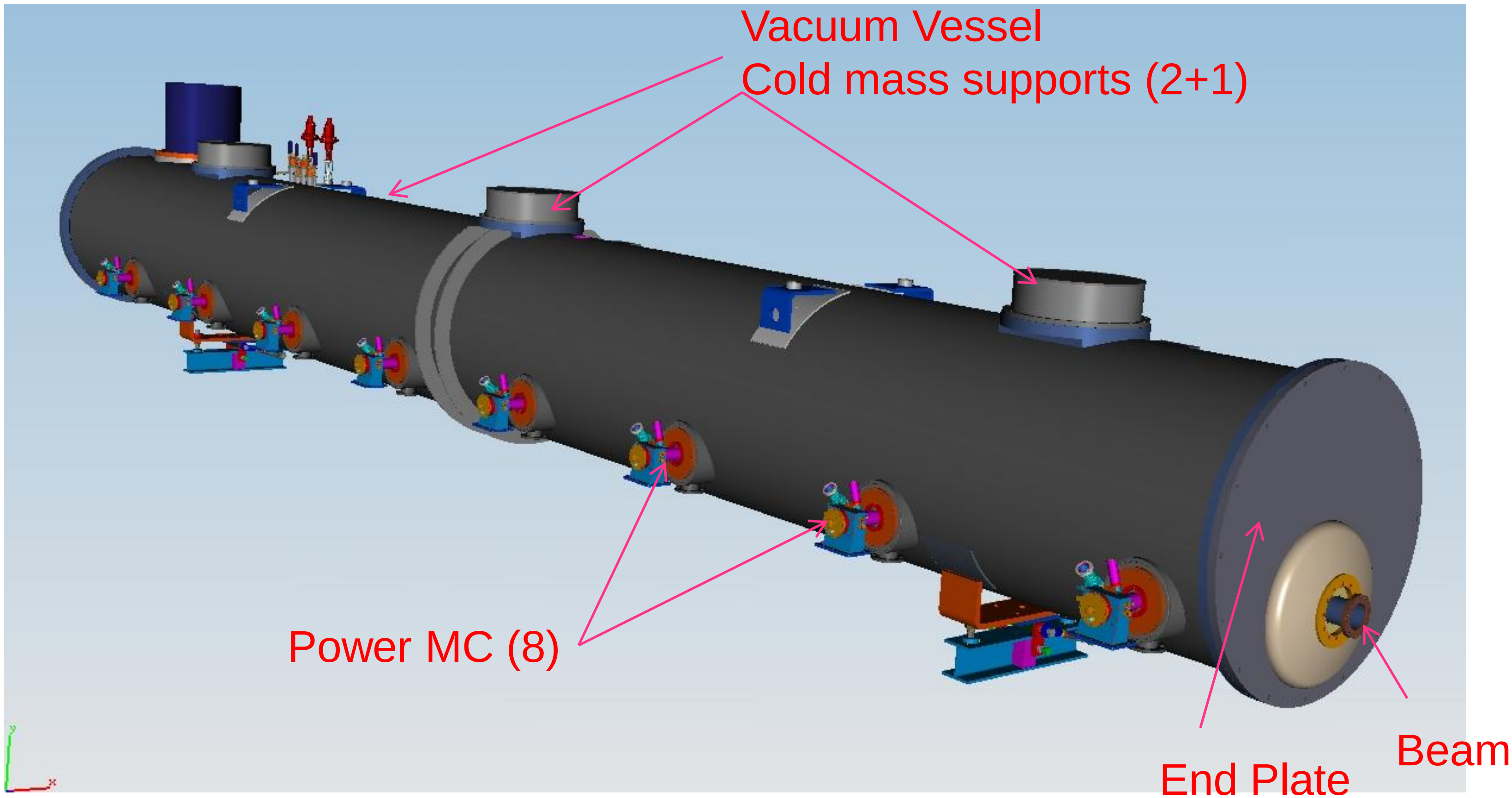


HE Cryomodules

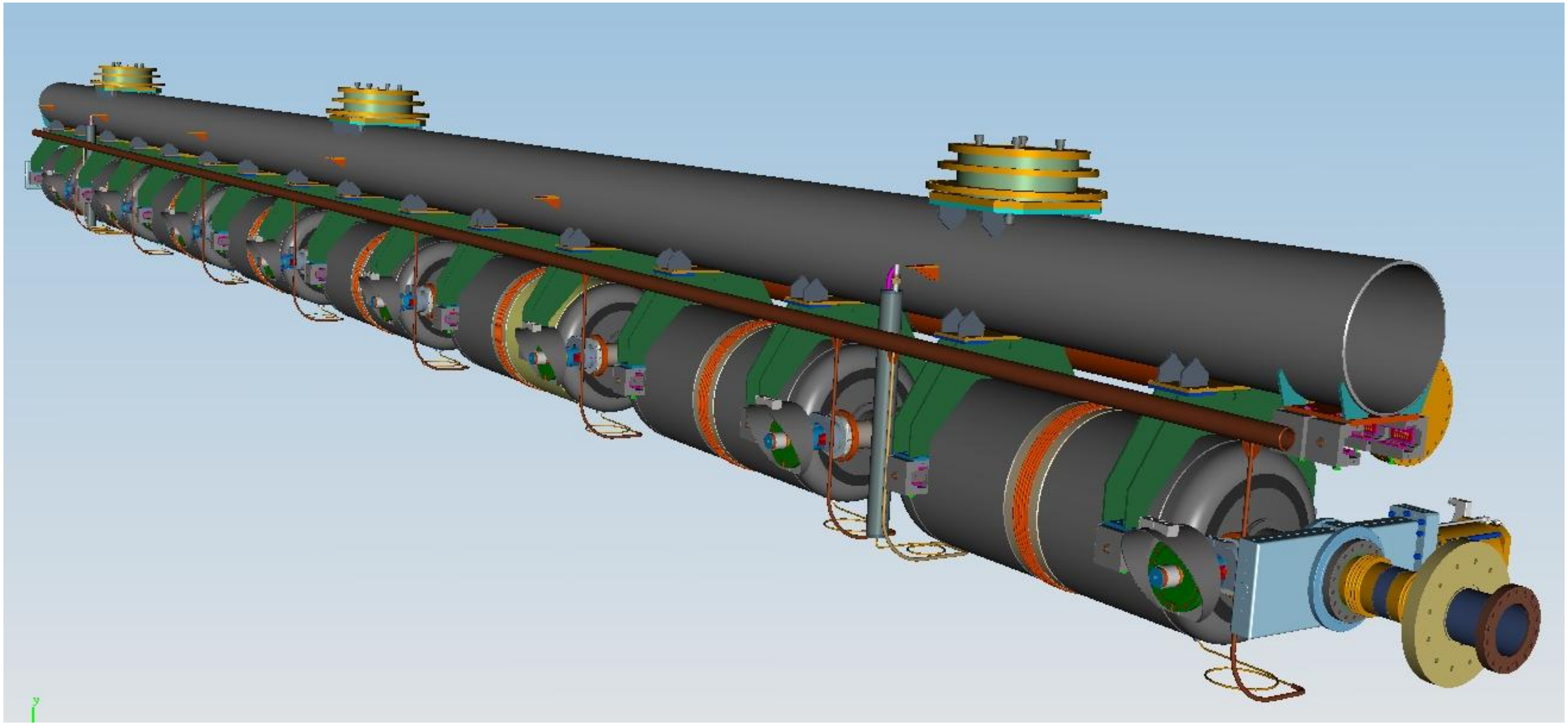


CMs lengths are shown from the first cavity iris to the last cavity iris.

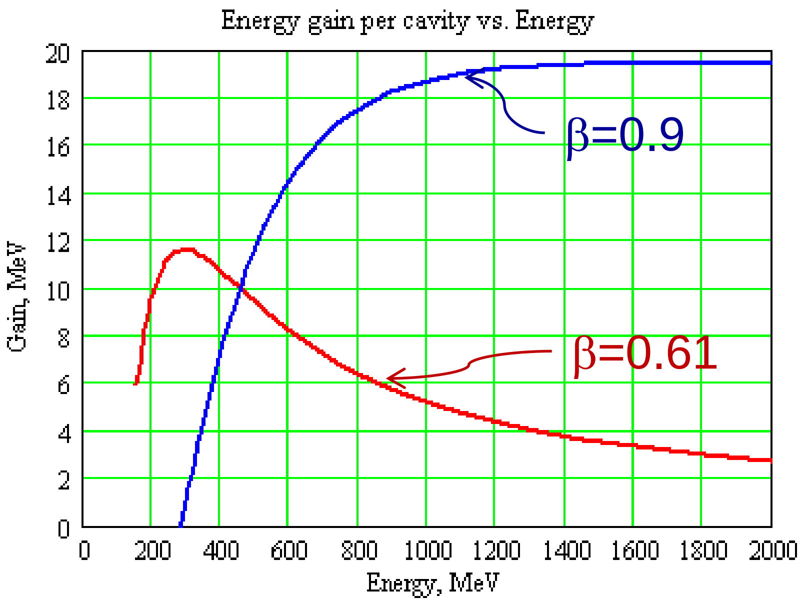
650 MHz Cryomodule (Tesla Style-Stand Alone, 250 W @ 2K)

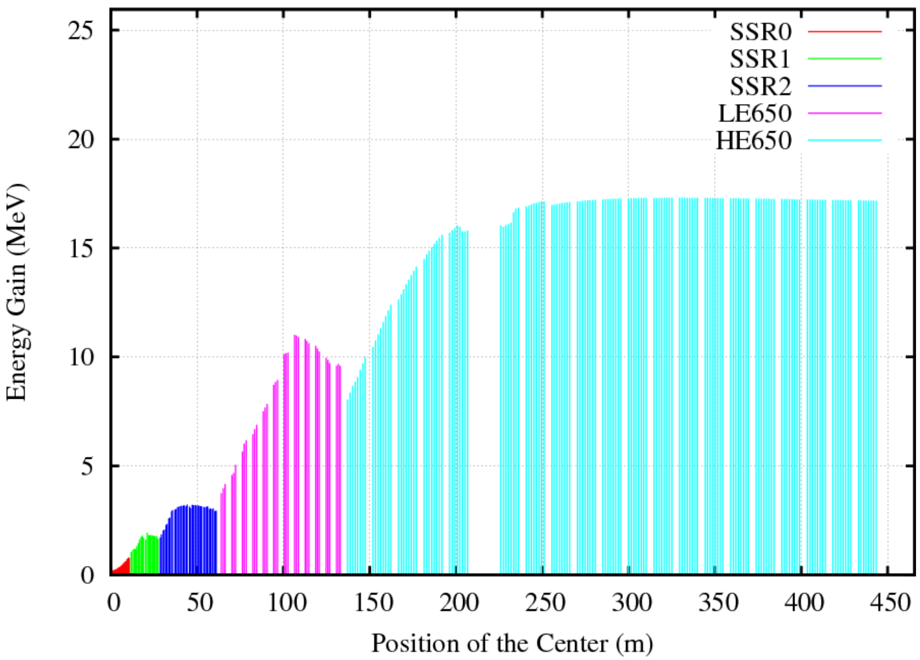


Cavity string & 300mm pipe



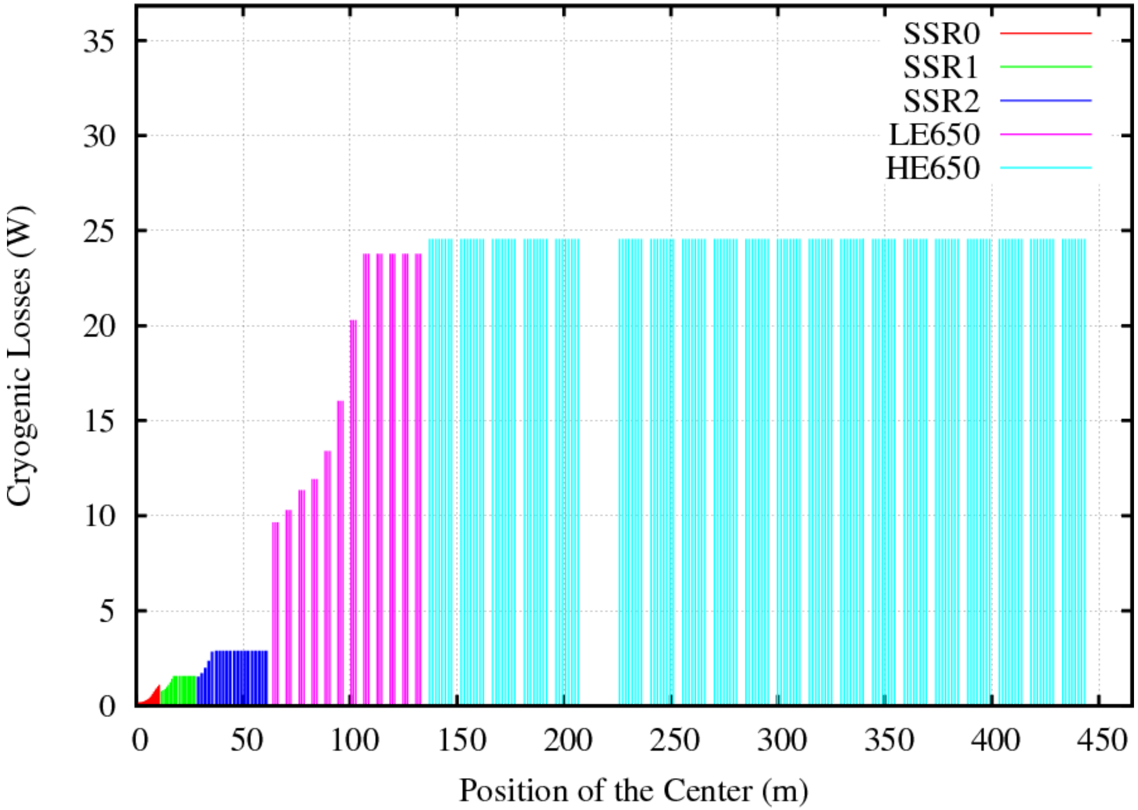
3 GeV CW Linac
Energy Gain per Cavity





- Based on 5-cell 650 MHz cavity
  - Crossover point ~450 - 500 MeV
- Single cavity per power source
  - Solid State, IOT

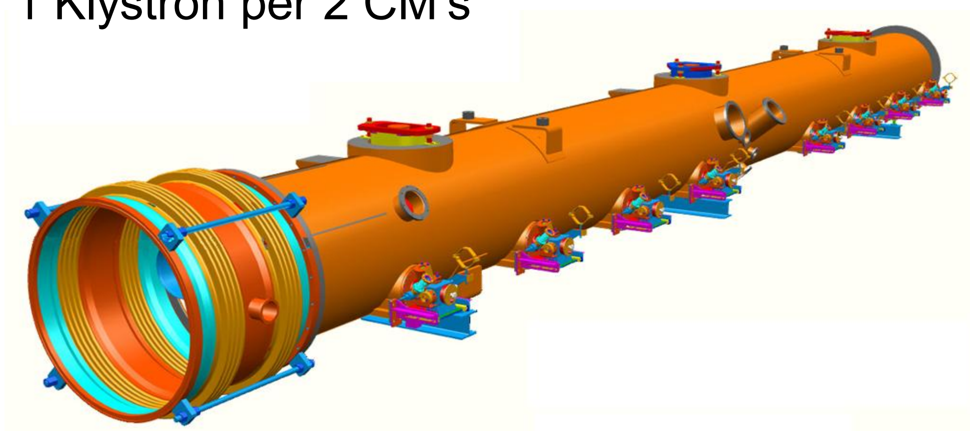
3 GeV CW Linac
Cryogenic Losses per Cavity



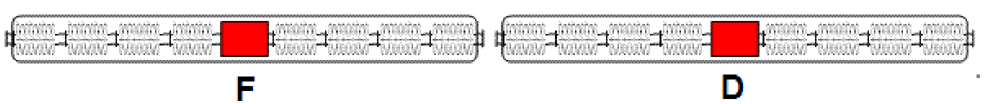
- ~42 kW cryogenic power at 4.5 K equivalent

3 – 8 GeV acceleration

- Pulsed linac based on the ILC technology
  - 1.3 GHz, 25 MV/m gradient, ≤5% duty cycle
  - considering 1-30 ms pulse length
  - ~250 cavities (28 ILC-type cryomodules) needed.
  - Simple FODO lattice
  - 1 Klystron per 2 CM's



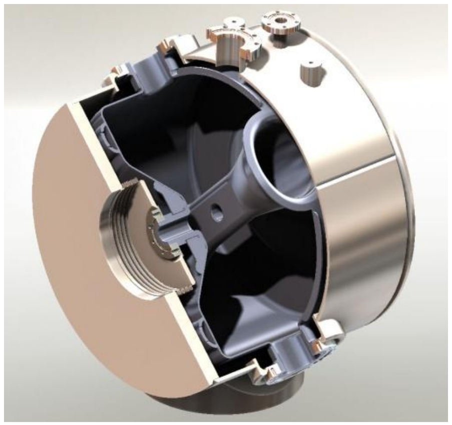
ILC

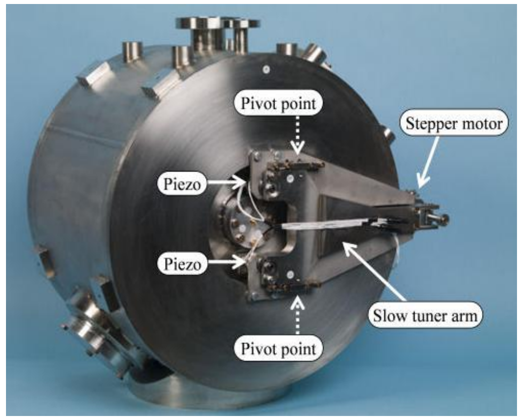


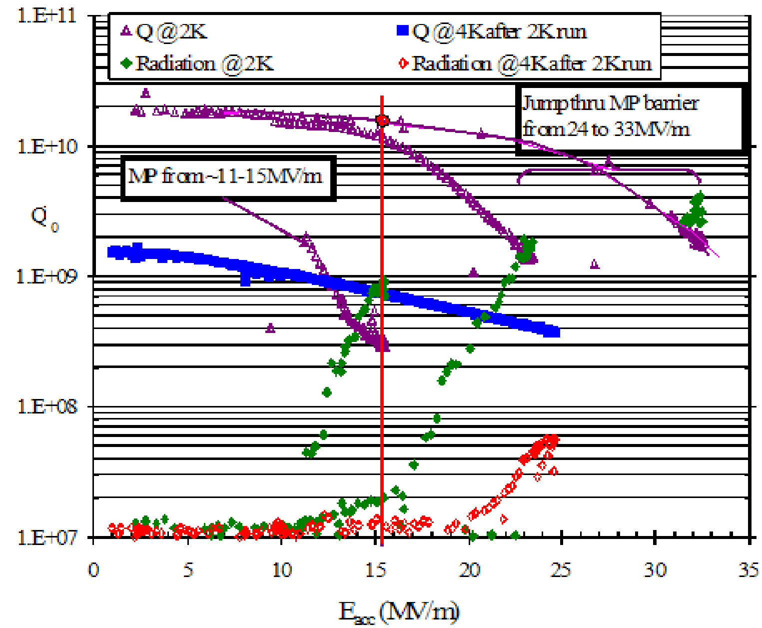
SRF Development Status

- 1300 MHz
  - 88 nine-cell cavities ordered
  - ~ 44 received (16 from U.S. industry, AES)
  - ~ 30 processed and tested, 8 dressed
  - 1 CM built (DESY kit) + second under construction (U.S. procured)
    - CM1 is now cold and about to initiate rf testing
- 650 MHz
  - MOU signed with Jlab for 2 single cell β =0.6 cavities
  - Order for six β = 0.9 single cell cavities in industry
- 325 MHz
  - 2 SSR1 β =0.22 cavities (Roark, Zannon) both VTS tested
  - 1 SSR1 dressed and under test at STF
  - 2 SSR1 being fabricated in India
  - 10 SSR1 ordered from Industry (Roark)
- Design work started on 325 and 650 MHz CM

SRF Development
325 MHz







- SSR1 (β=0.22) cavity under development
  - Two prototypes assembled and tested
  - Both meet Project X specification at 2 K
- Preliminary designs for SSR0 and SSR2

Proposed power upgrade for Project X linac

- To attain 4 MW at 8 GeV we propose:
  - to increase the beam current during the injection pulse to 5 mA (10 mA peak);
  - to increase the rep. rate to 15 Hz;
  - to increase the beam pulse length to 6.7 ms (10% duty cycle).

Collaboration

- A multi-institutional collaboration has been established to execute the Project X RD&D Program.
  - Organized as a "national project with international participation"
    - Fermilab as lead laboratory
    - International participation via in-kind contributions, established through bi-lateral MOUs.
  - Collaboration MOUs for the RD&D phase outlines basic goals, and the means of organizing and executing the work. Signatories:

ANL	ILC/ART	RRCAT/Indore
BARC/Mumbai	IUAC/Delhi	SLAC
BNL	LBNL	TJNAF
Cornell	ORNL/SNS	VECC/Kolkata
Fermilab	MSU	

- It would be natural for collaborators to continue their areas of responsibility into the construction phase.

R&D Program

- The primary elements of the R&D program include:
  - Development of a wide-band chopper
    - Capable of removing bunches in arbitrary patterns at a 162.5 MHz bunch rate
  - Development of an H- injection system
    - Require between 4.4 – 26 msec injection period, depending on pulsed linac operating scenario
  - Superconducting rf development
    - Includes six different cavity types at three different frequencies
    - Emphasis is on Q_0, rather than high gradient
      - Typically 1.5E10, 15 MV/m (CW)
      - 1.0E10, 25 MV/m (pulsed)
    - Includes development of qualified partners
- Goal is to complete R&D phase by 2015

Summary

- Project X is central to Fermilab’s strategy for development of the accelerator complex over the coming decade
  - World leading programs in neutrinos and rare processes;
  - Potential applications beyond elementary particle physics;
  - Technology aligned with ILC, Muon Collider, and Nuclear Energy
- Project X design concept is well developed and well aligned with the requirements of the physics program:
  - 3 GeV CW linac operating at 1 mA: 3 MW beam power
  - 3-8 GeV pulsed linac injecting into the Recycler/Main Injector complex
- A plausible upgrade path to 4 MW at 8 GeV for Project X exists.
- Project X could be constructed over the period ~2016 – 2020