Project X Upgrade Options
for 4 MW at 8 GeV

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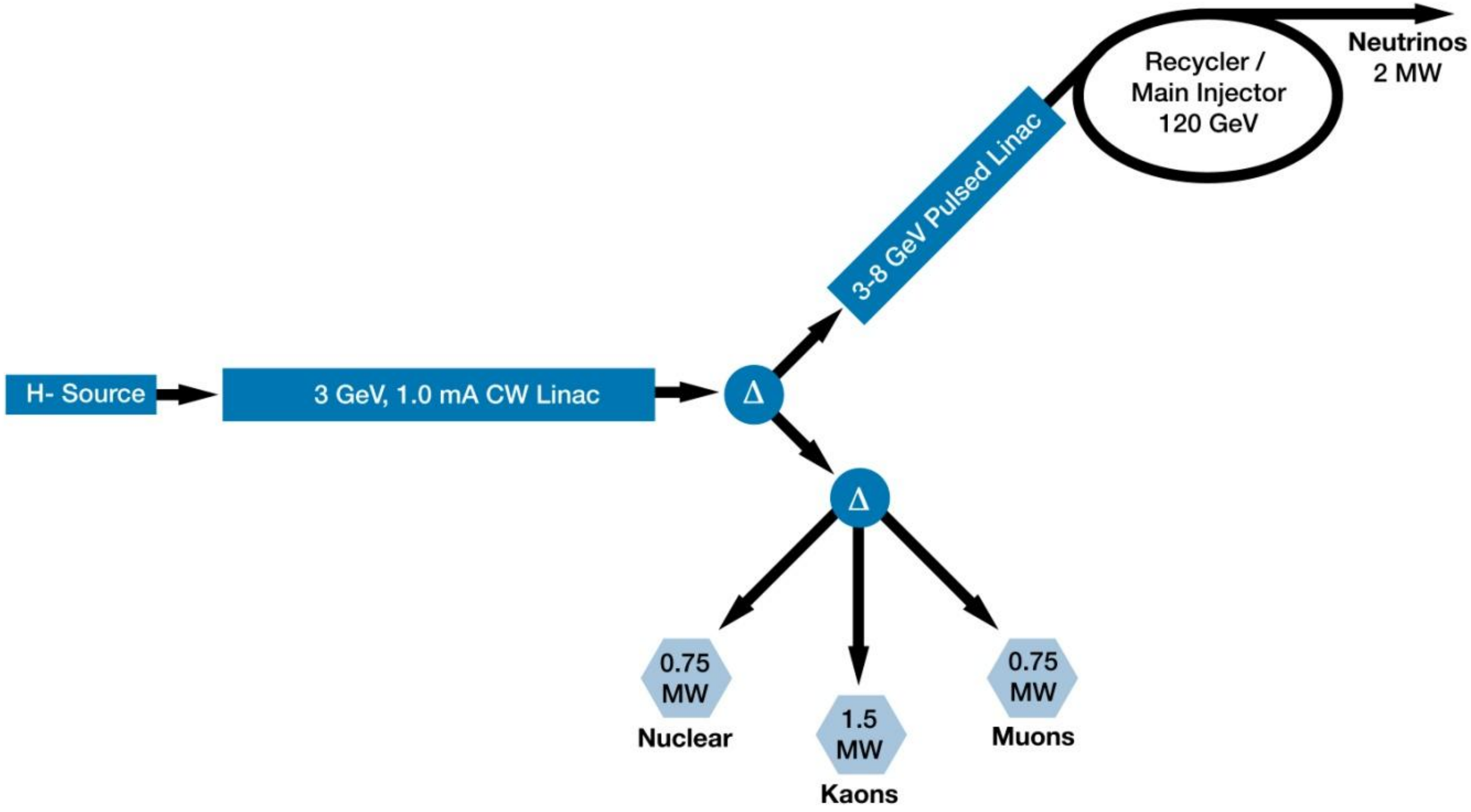
June 28, 2011

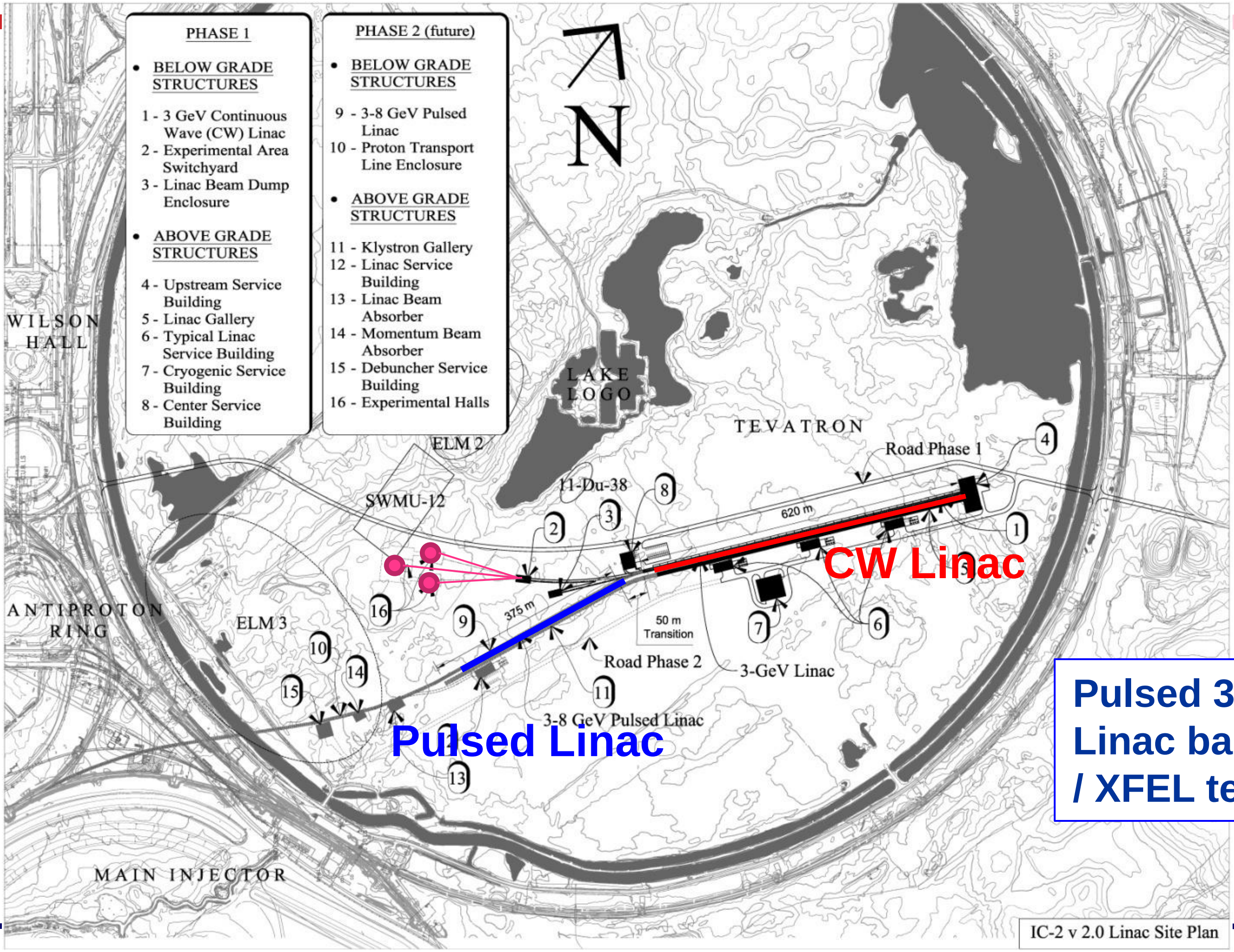
Reference Design



Reference Design Capabilities

- 3 GeV CW superconducting H- linac with 1 mA average beam current.
  - 3 MW beam power at 3 GeV
  - 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 340 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.

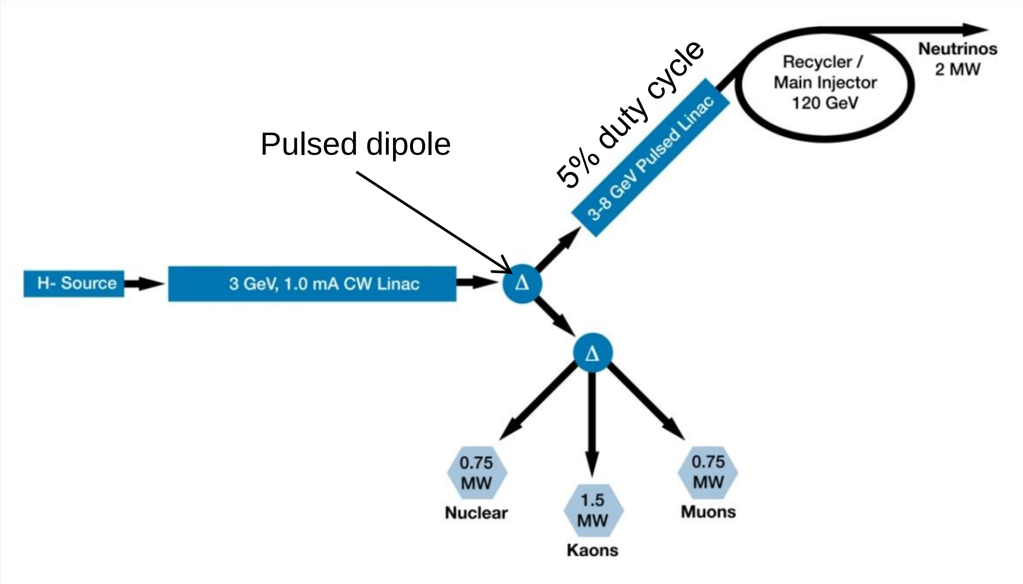
Reference Design
Provisional Siting



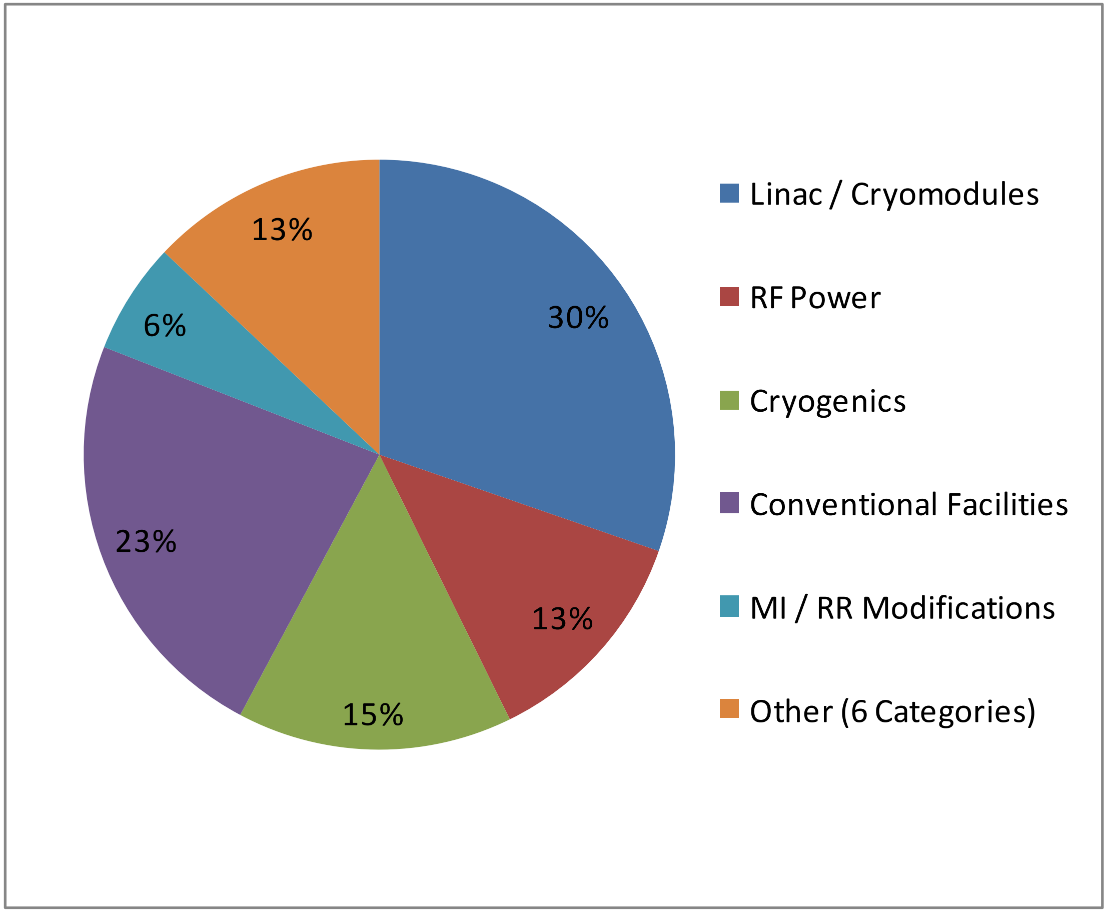
Pulsed 3-8 GeV Linac based on ILC / XFEL technology

Reference design: accelerator 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

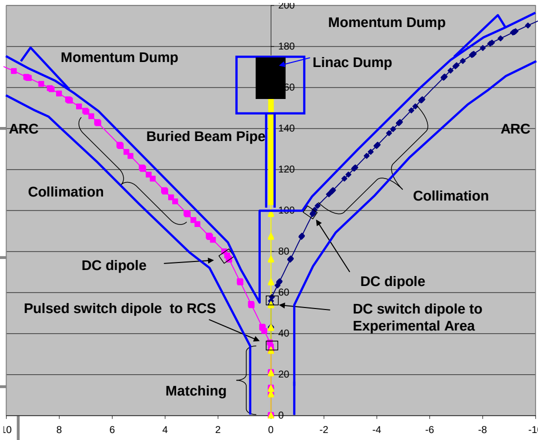


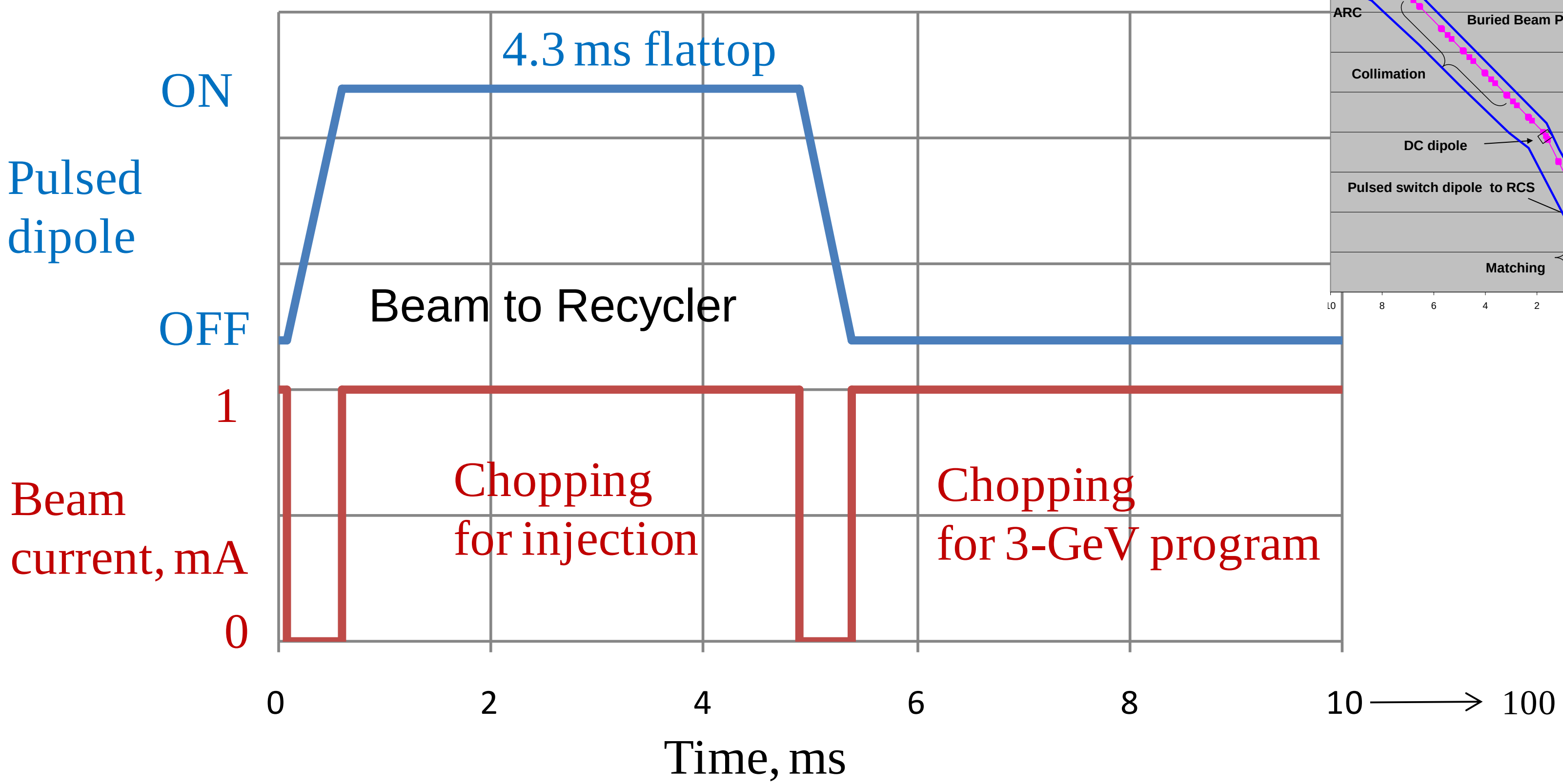
Reference design: cost distribution



Linac beam current

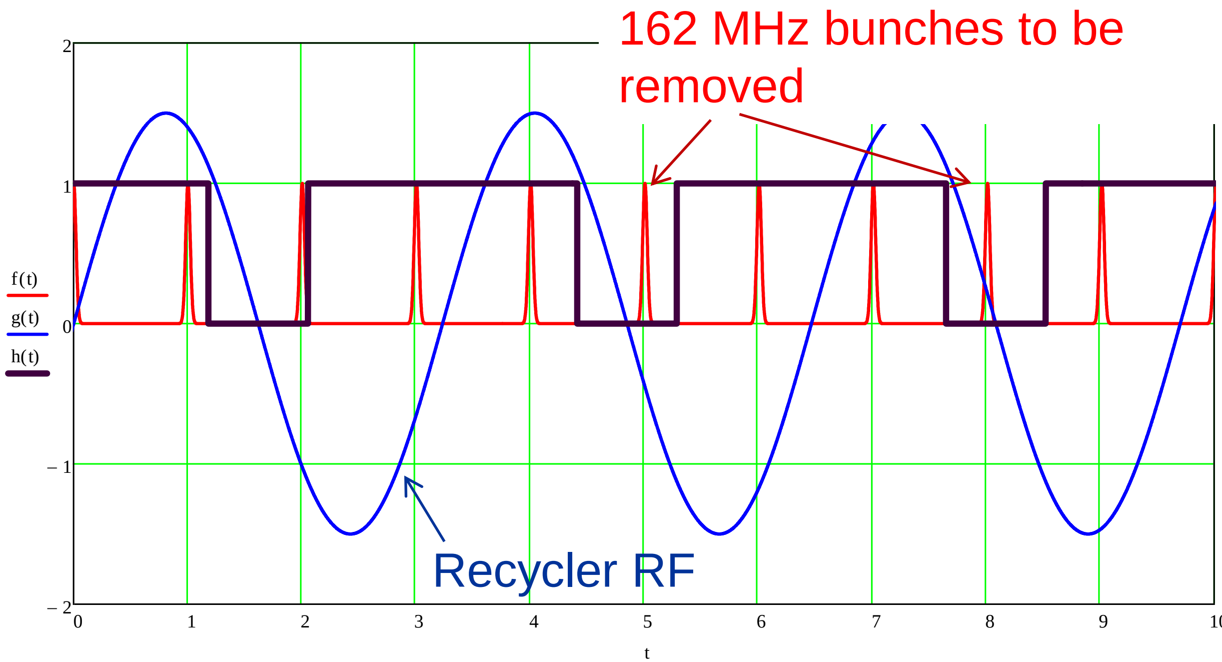
- Linac beam current has a periodic time structure (at 10 Hz) with two major components.



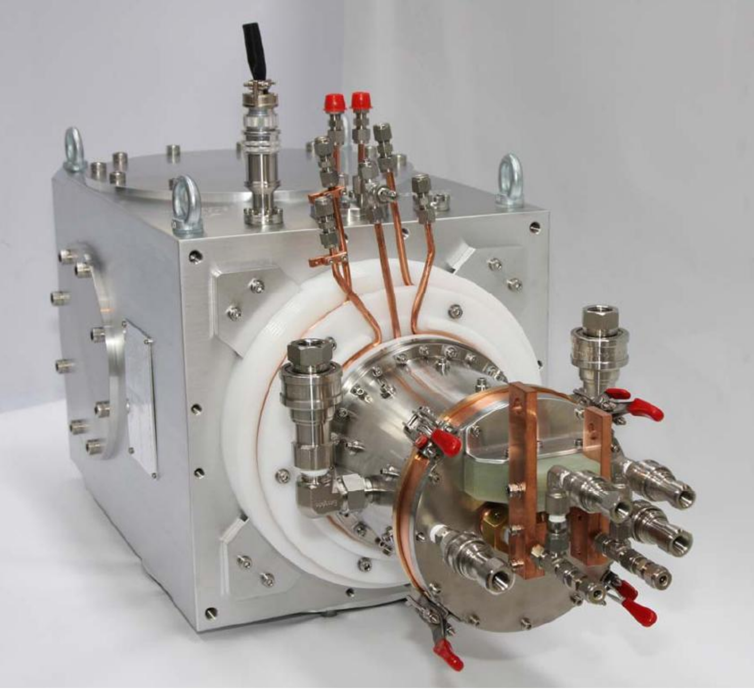


Chopping for injection

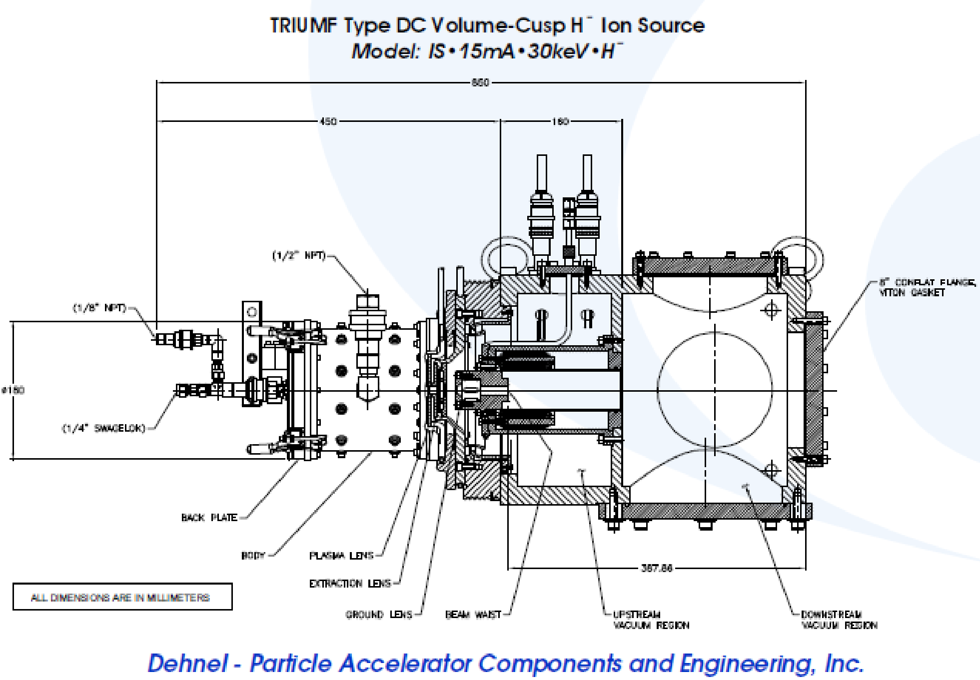
- RF frequency at injection into the Recycler : ~50 MHz
- Chopper needs to provide a kicker gap (~200 ns per 11 µs) and needs to remove bunches that fall into “wrong” phase of ring rf voltage.
  - 50% of bunches are removed (ion source at 2 mA)
  - 80% of bunches are removed (ion source at 5 mA)



Ion source: TRIUMF-type H- DC ion source



Delivered to LBNL: June 2011



Model: IS•15mA•30keV•H^- SPECIFICATIONS

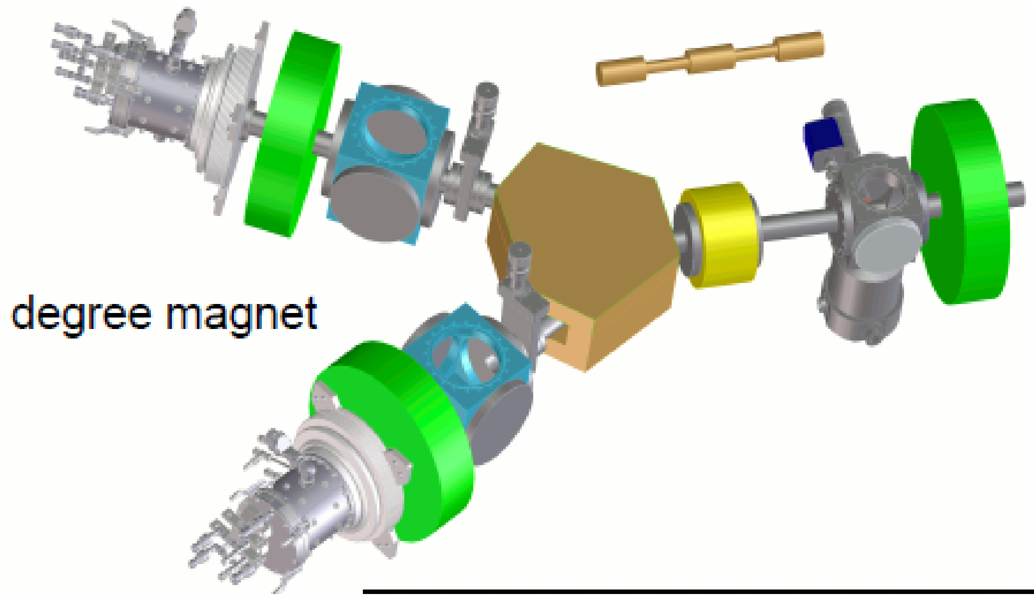
Ion Source Specifications

Particle Type:	H^-
Beam Current:	0 to 15 mA
Beam Kinetic Energy:	20 to 30 keV
Normalized 4rms Emittance:	<1 mm×mrad
Beam Purity:	>98%
Filament Lifetime:	>350 hours at peak current
Beam Current Stability:	±3% over 24 hours

Proposed LEBT configuration

Two ion sources, selected by a 20 degree magnet

Solenoid focusing
after the ion source
in front of the RFQ



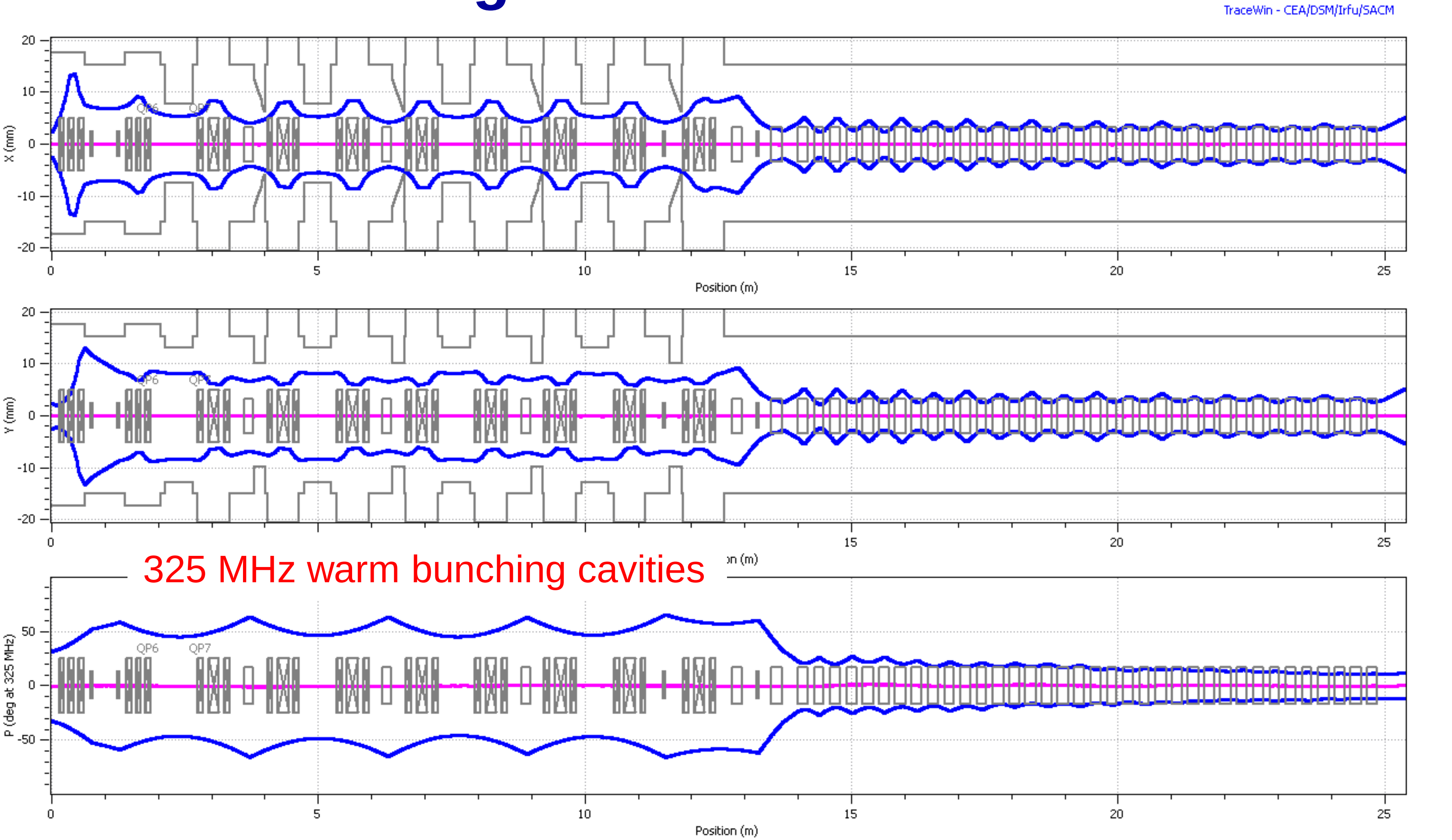
- LEBT will have a chopper to provide gaps of >100 ns

RFQ (162.5 MHz)

Input energy	30 keV
Output energy	2.1 MeV
Vane-vane voltage	58 kV
Length	446 cm
S'Fish power/cm	120 watts
Total Power	<100 kW
Wall Power Density	0.6 w/cm^2

I (mA)	ex	ey	ez	keV-nsec	transm	Data Set
0	0.01178	0.01173	0.04047	1.27	98.9	30.05
1	0.01205	0.01260	0.03129	0.98	97.8	30.01
2	0.01305	0.01297	0.02549	0.80	96.4	30.05
3	0.01275	0.10264	0.02051	0.64	95.8	30.05
4	0.01192	0.10224	0.01939	0.61	95.5	30.05
5	0.01115	0.01190	0.01989	0.62	95.5	30.05
7	0.01166	0.01179	0.02404	0.75	95.5	30.05
10	0.01859	0.01806	0.02883	0.90	95.3	30.10

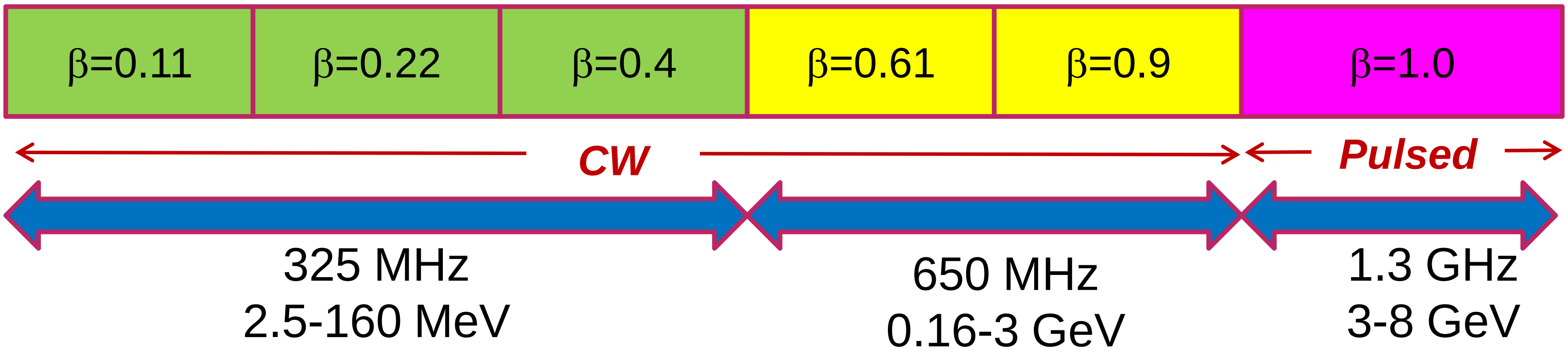
MEBT design: 5 mA at 162.5 MHz beam



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

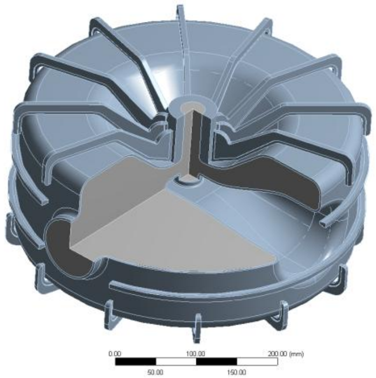
Project X

SRF Linac
Technology Map

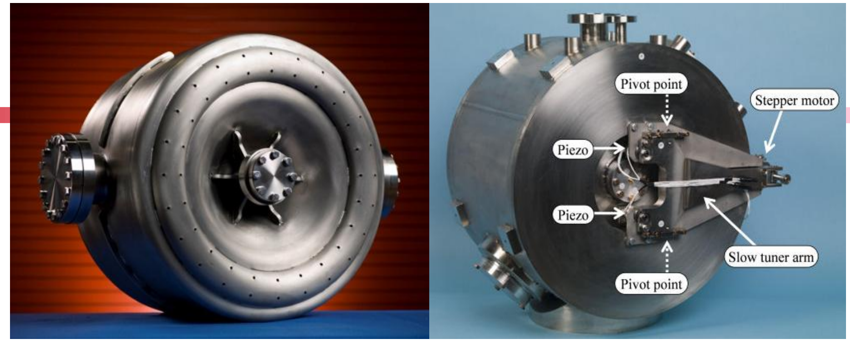


Section	Freq	Energy (MeV)	Cav/mag/CM	Type
SSR0 (β_G=0.11)	325	2.5-10	18 /18/1	SSR, solenoid
SSR1 (β_G=0.22)	325	10-42	20/20/ 2	SSR, solenoid
SSR2 (β_G=0.4)	325	42-160	40/20/4	SSR, solenoid
LB 650 (β_G=0.61)	650	160-460	36 /24/6	5-cell elliptical, doublet
HB 650 (β_G=0.9)	650	460-3000	160/40/20	5-cell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

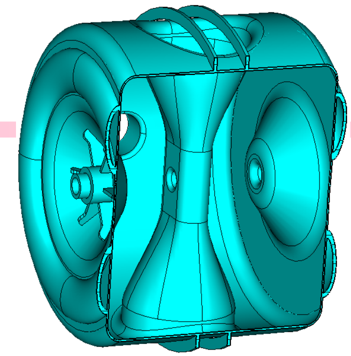
325 MHz spoke cavity families



SSR0 – design, prototyping



SSR1 – prototyping, testing

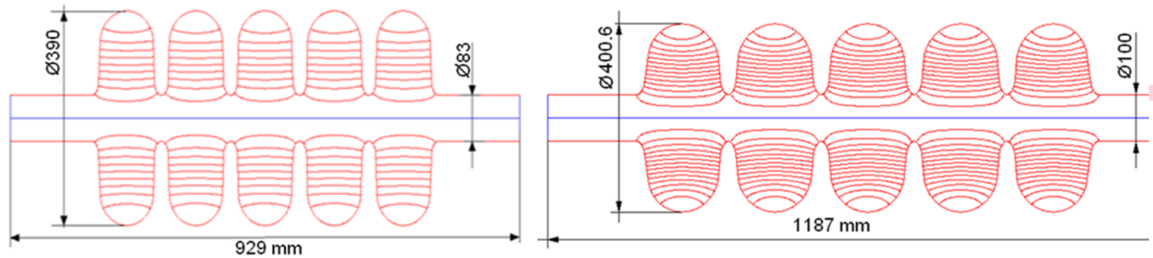


SSR2 - design

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

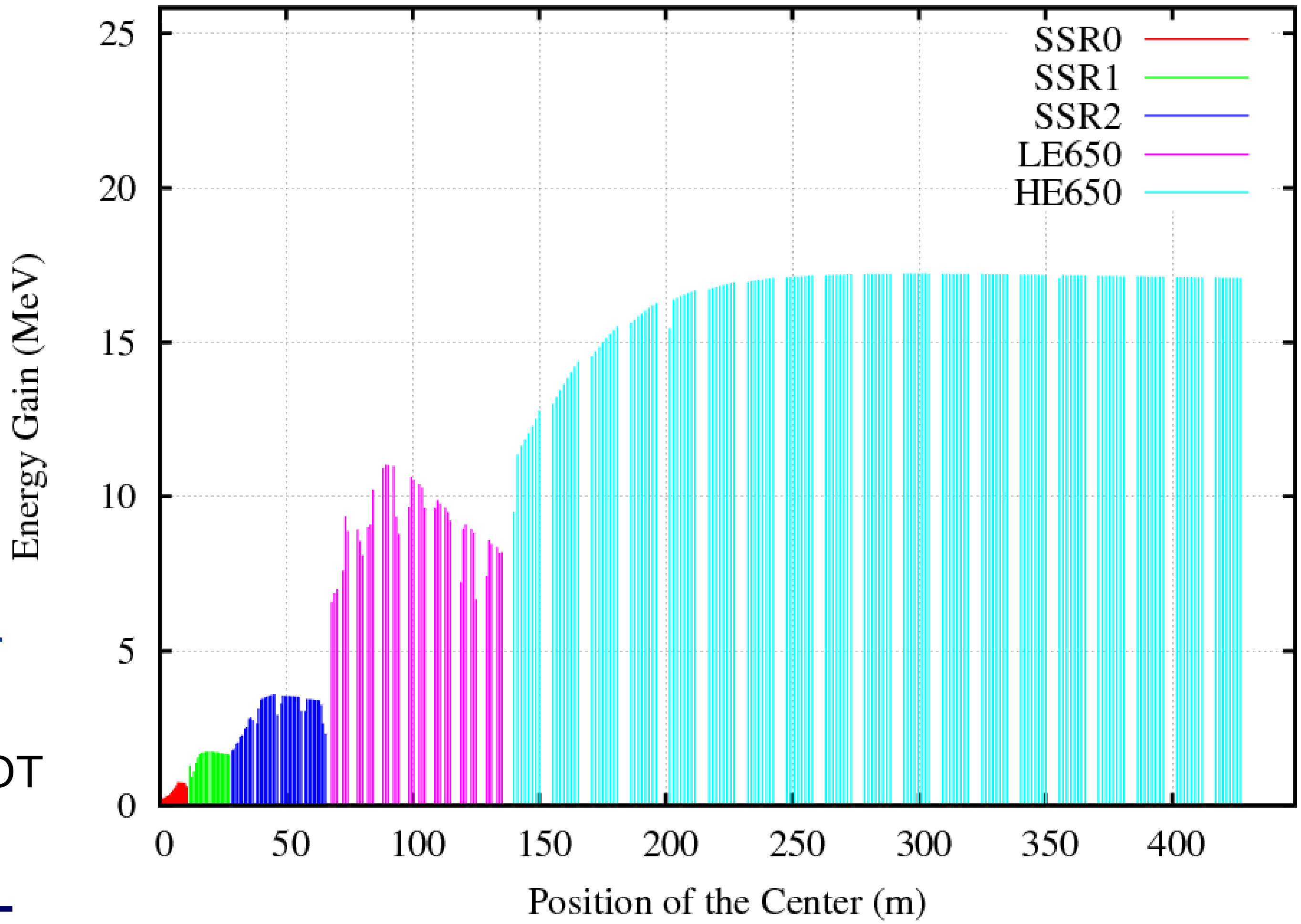


650 MHz: β=0.61

650 MHz: β=0.9

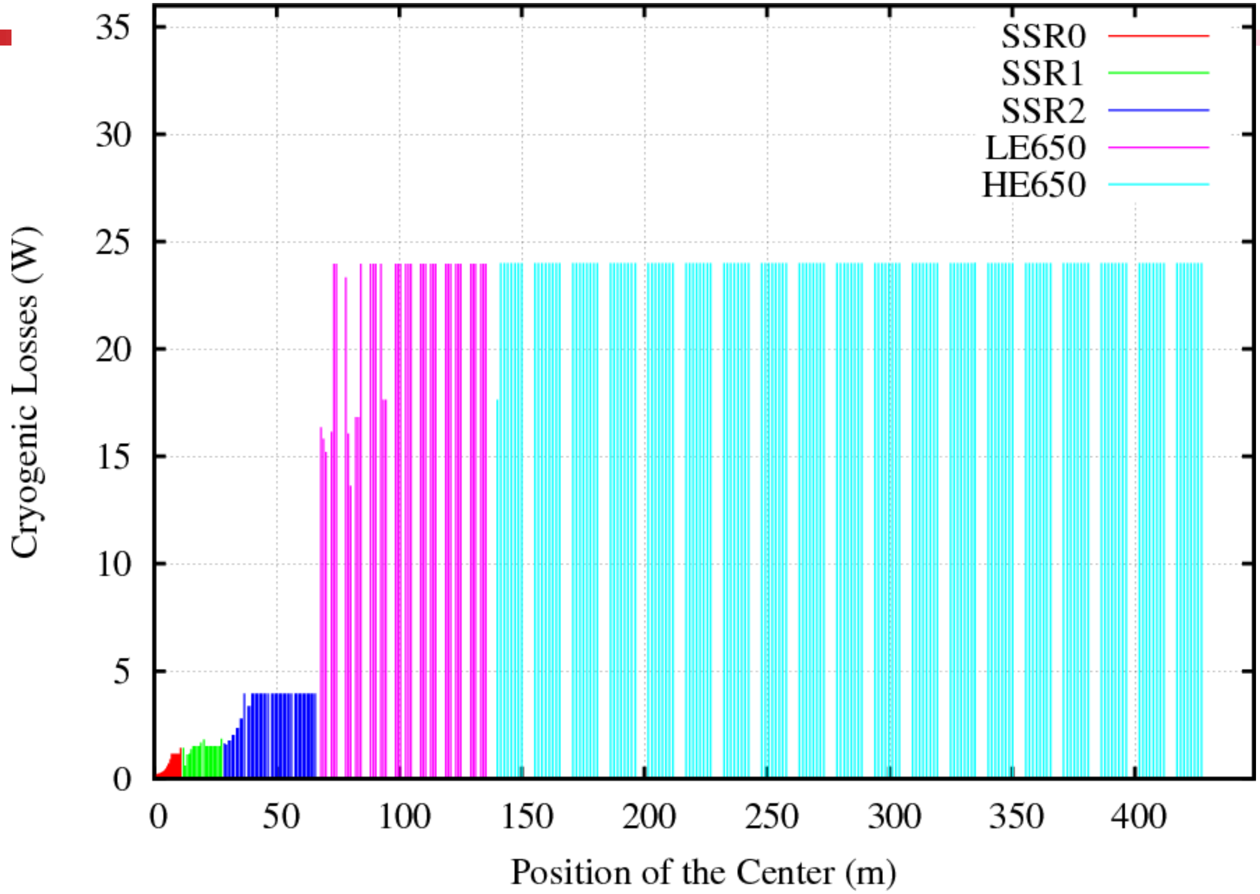
Parameter		LE650	HE650	
β_geom		0.61	0.9	
R/Q	Ohm	378	638	
G-factor, Ohm		191	255	
Max. Gain/cavity (on crest)	MeV	11.7	19.3	
Acc. Gradient	MV/m	16.6	18.7	
Max surf. electric field	MV/m	37.5	37.3	
Max surf. magnetic field,	mT	70	70	
Q_0 @ 2° K	$\times 10^{10}$	1.5	2.0	
P_{2K} max	[W]	24	29	

Energy Gain per Cavity



- Single cavity per power source
  - Solid State, IOT

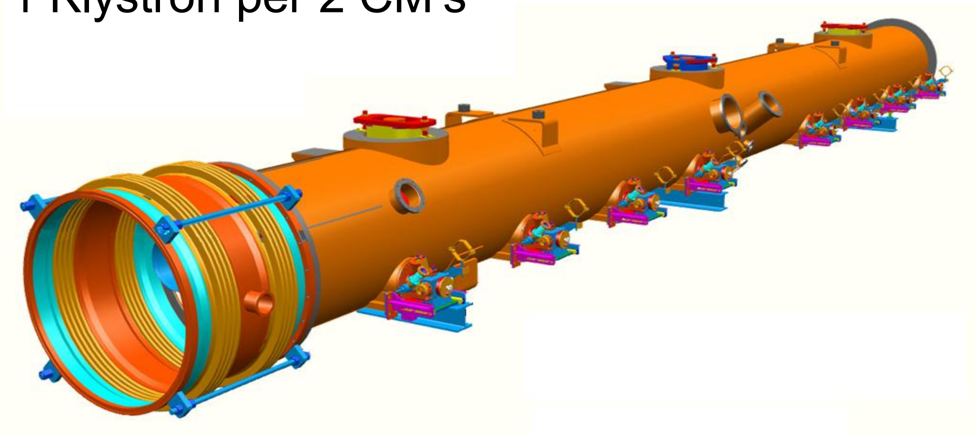
3 GeV CW Linac
Cryogenic Losses per Cavity

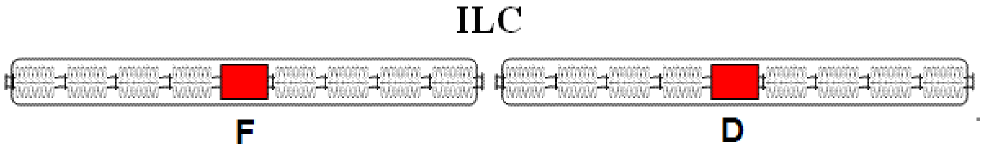


- ~42 kW cryogenic power at 4.5 K equivalent

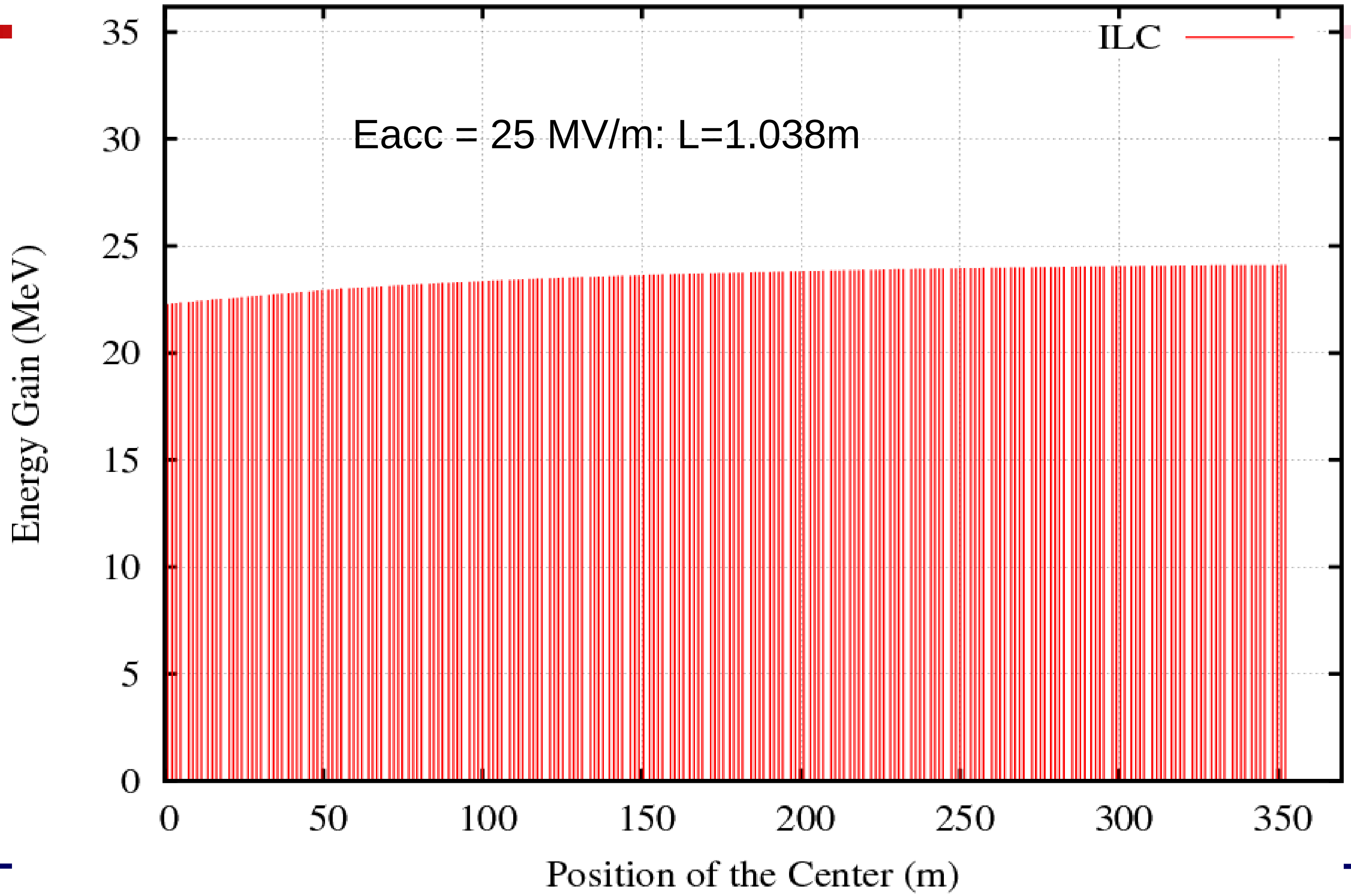
3 – 8 GeV acceleration

- Pulsed linac based on the ILC technology
  - 1.3 GHz, 25 MV/m gradient, ≤5% duty cycle
  - considering 8-30 ms pulse length
  - ~250 cavities (28 ILC-type cryomodules) needed.
  - Simple FODO lattice
  - 1 Klystron per 2 CM's





Cavity Energy Gain



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).

Impact of upgrade on linac subsystems

- Front End: no impact (it is already being designed for 10 mA ave.)
- CW linac: the impact depends principally on the demand for beam power at 3 GeV.
  - Worst-case scenario: 10% duty cycle – 5 mA for MC/NF and 90% duty cycle – 1 mA
- Pulsed linac: the impact is well understood
  - More rf power (because of higher current);
  - Upgrade power couplers (because of higher current);
  - More cryo capacity (because of a longer pulse);
- Conventional facilities
  - more water cooling;
  - more room for Klystrons;
  - the impact is not fully understood yet.

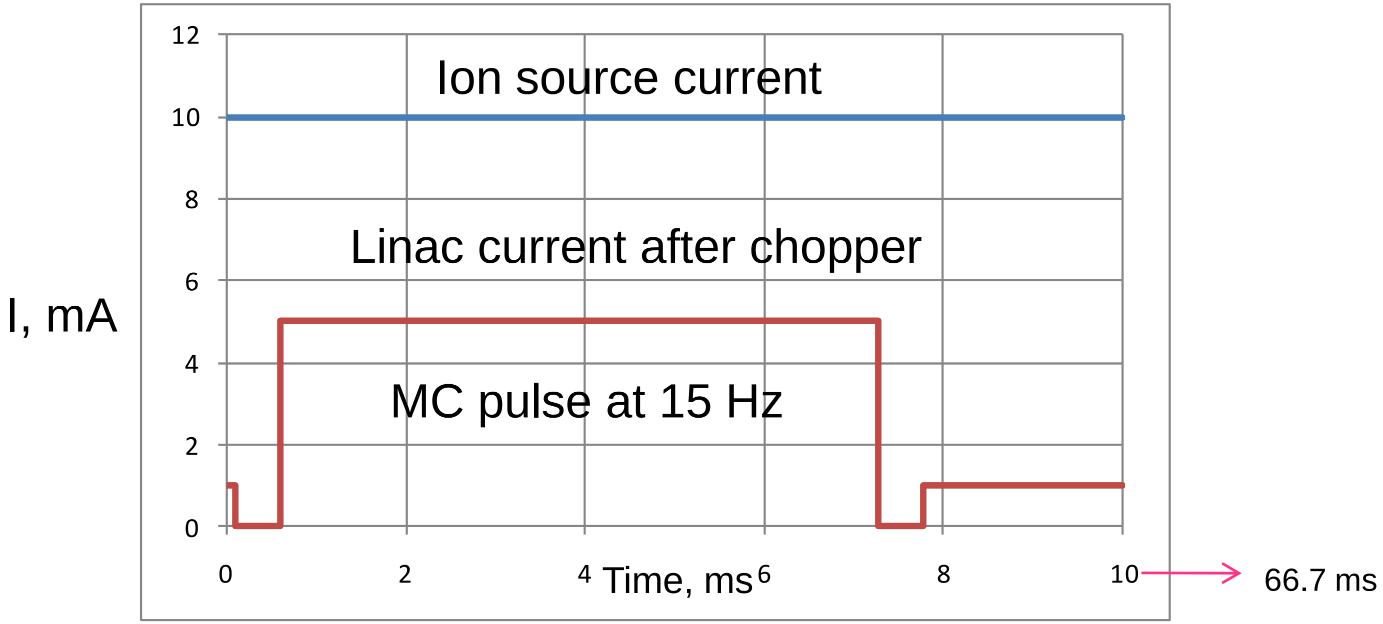
Pulsed linac (1.3 GHz)

	Reference Design Report (RDR)	Upgrade for Muon Collider
Rep rate, [Hz]	10	15
RF period, [msec]	100	67
Duty cycle, [%]	4.3	10
Fill time ,[msec]	3.0	1
Beam pulse, [msec]	4.3	6.7
Beam current, [mA]	1	5
4.5 K Equivalent heat load, [kW]	8	13
Normalized cryo plant cost, [-]	1	1.3

Linac parameters	
Eacc, [MV/m]	25
Q_0, [-]	1.50E+10
Beam Energy, [GeV]	8
Number of Cavities	224
Number of Cryomodules	28

- Average rf coupler power:
  - RDR: 2 kW
  - Upgrade: 15 kW
- Pulsed rf power:
  - Upgrade: 125 kW per cavity (~7.5 ms at 15 Hz)
    - such Klystrons exist (e.g. Philips YK1240)

CW Linac

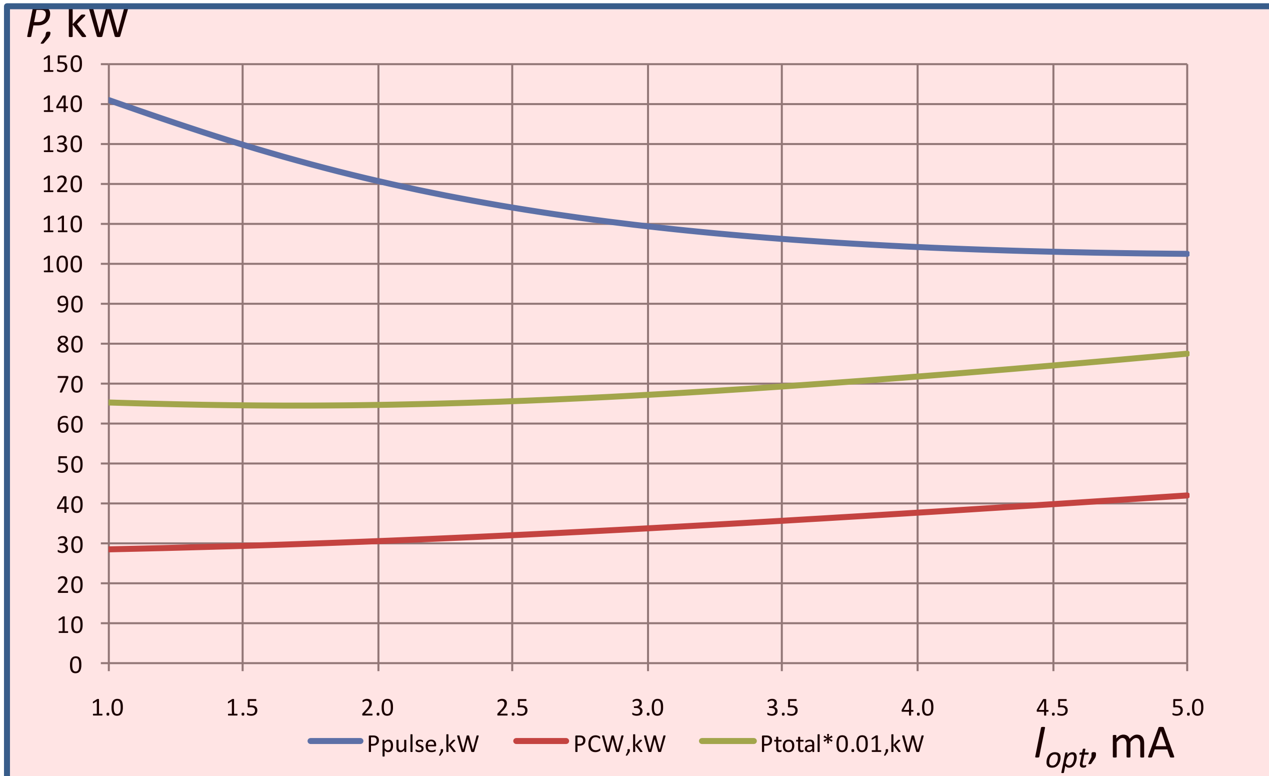


- With present technology: rf power to beam power is not 100% efficient. Some power will be reflected and transferred to heat.
- Cryogenic power remains the same in RDR

RF power requirements at 650 MHz

f= 650 MHz;
δf=18 Hz -microphonics;
(r/Q) = 640 Ohms;
I_{CW} = 1 mA –DC current;
I_{pulse}=5 mA –pulse current
φ=-10° -synch. phase;
V=17.5 MeV –gain/cavity;
=7.3 msec –pulse width;
f_{rep}=15 Hz;
N=160 – number of cavities
16% overhead for control and losses in the line

Q_{load}(1mA)=1.5e7
Q_{load}(2mA)=1.1e7
P_{CW}(1mA)=28 kW
P_{CW}(2mA)=30 kW



I_{opt} is the current which corresponds to the optimal coupling.

$$P_{total} = N(P_{CW}(1 - f_{rep}\tau) + P_{pulse} f_{rep}\tau)$$

Summary

- A plausible upgrade path to 4 MW at 8 GeV for Project X exists and includes:
  - increasing the beam current during the injection pulse to 5 mA (10 mA peak);
  - increasing the rep. rate to 15 Hz;
  - increasing the beam pulse length to 6.7 ms (10% duty cycle).
- Such an upgrade would reuse > 75% of RDR cost.