Project X and its RF system

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May 06, CWRF2010

Project X: What is it?

Multi-MW Proton Source under development at Fermilab

- **Enables a broad suite of rare decay experiments**
- **Enables Long Baseline Neutrino Experiment (LBNE)**
- **Stepping stone to an eventual Neutrino Factory or Muon Collider**

Current situation:

Project X is currently in the R&D phase awaiting CD-0 approval
- DOE is funding a vigorous R&D program, emphasis on SRF

Several possible "Initial Configurations" of the machine were examined

All versions provide 2 MW of beam power to LBNE

ICD-1 was based on a pulsed 8 GeV 20 ma ILC-like H- linac
- Excellent choice for the neutrino mission
- Problematic for the study of rare processes

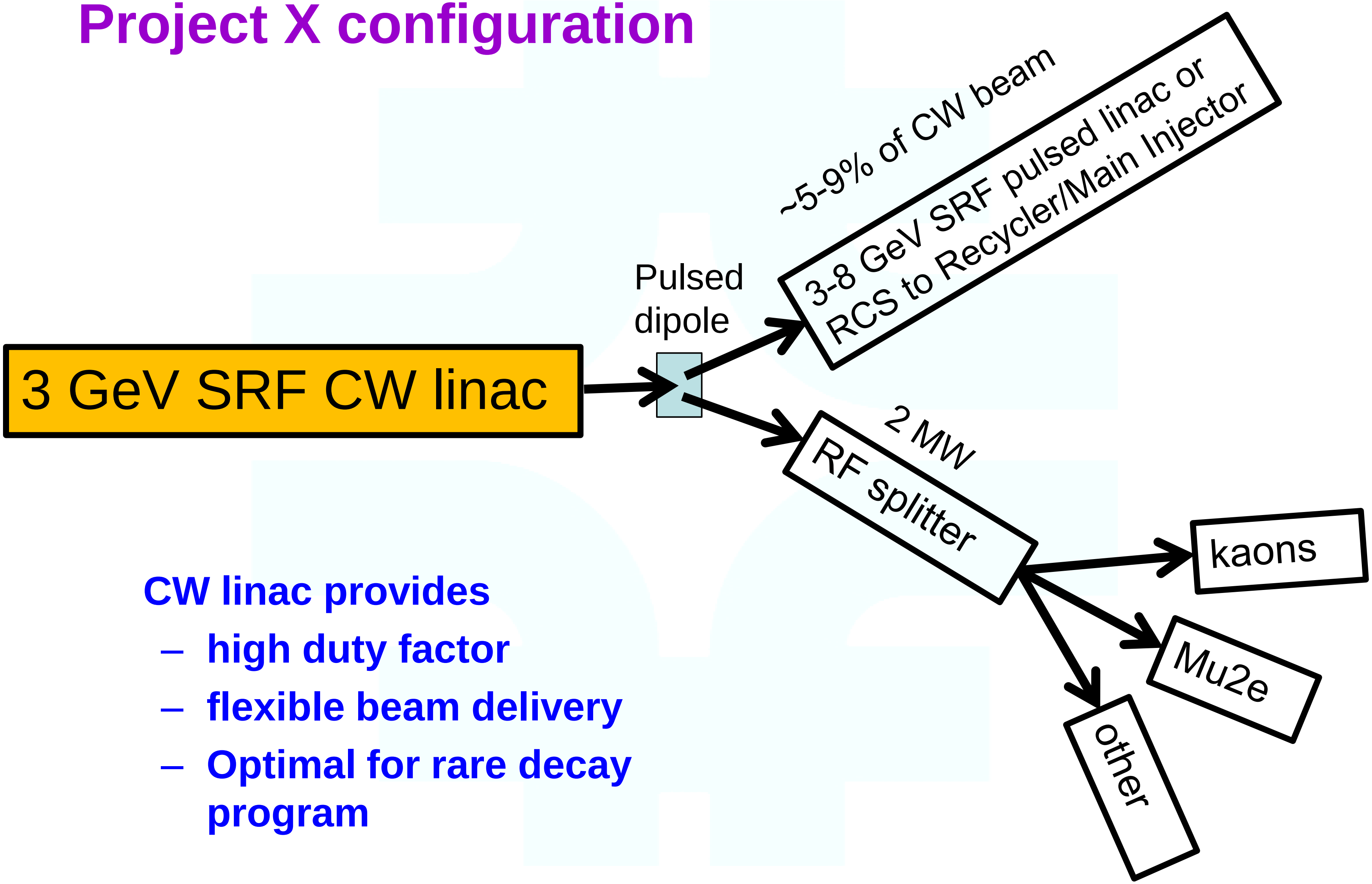
ICD-2 employs a 3 GeV 1 ma CW linac that accelerates H- or protons
- Provides an additional 2-3 MW to the high intensity program
  - High duty factor & flexible beam manipulation via RF separators
- 3-8 GeV = <u>either</u> a pulsed linac or a rapid cycling synchrotron.

ICD-2 is currently the focus of our R&D efforts

Optimum energies and beam structure required for various proposed rare decay programs

	Proton Energy (kinetic)	Beam Power	Beam Timing
Rare Muon decays	2 – 3 GeV	> 500 kW	1 kHz – 160 MHz
Precision K^0 studies	2.6 – 3 GeV	> 200 kW	20 – 160 MHz (< 50 psec pings)
Rare Kaon decays	2.6 – 4 GeV	> 500 kW	20 – 160 MHz (< 50 psec pings)
(g-2) measurement	8 GeV	20 – 50 kW	30 - 100 Hz
Neutron and exotic nuclei EDMs	1.5 – 2.5 GeV	> 500 kW	> 100 Hz

Project X configuration



CW linac provides

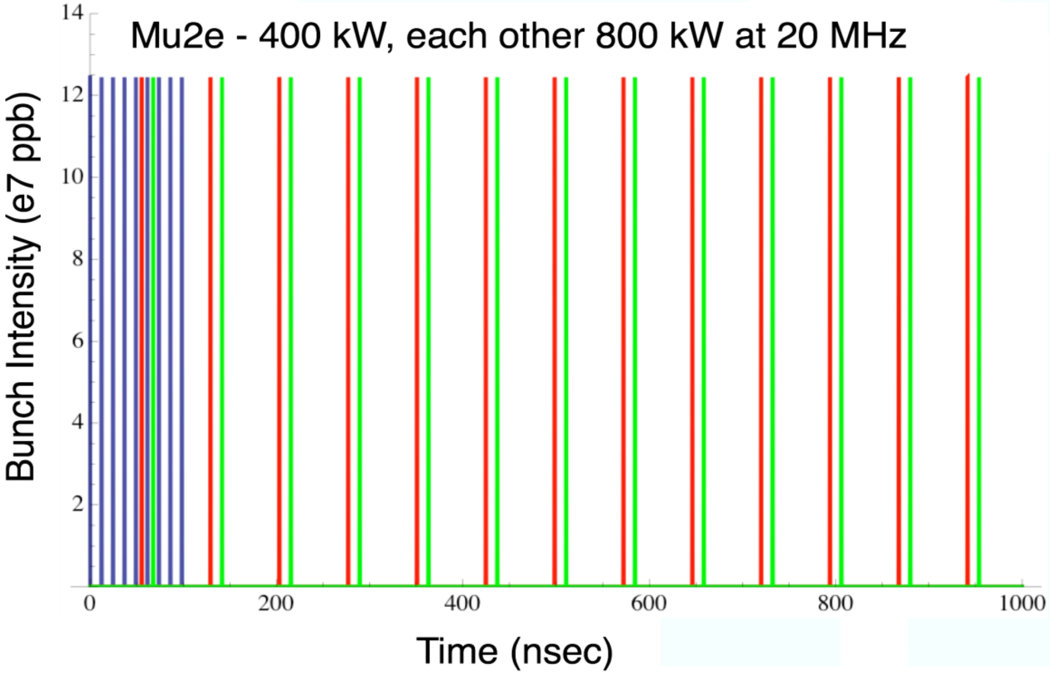
- **high duty factor**
- **flexible beam delivery**
- **Optimal for rare decay program**

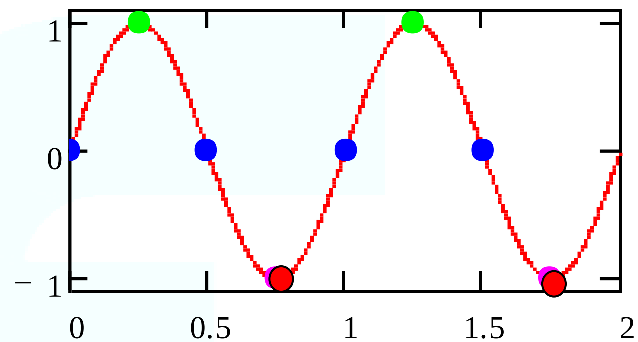
SRF CW Linac: high duty factor
RF separator: Flexible Beam Delivery

High bandwidth chopper ➔ select which RF cycle to fill with beam

<u>1 msec period at 3 GeV</u>

mu2e pulse (9e7) 162.5 MHz, 100 nsec	400 kW
Kaon pulse (9e7) 27 MHz	800 kW
Other pulse (9e7) 27 MHz	800 kW

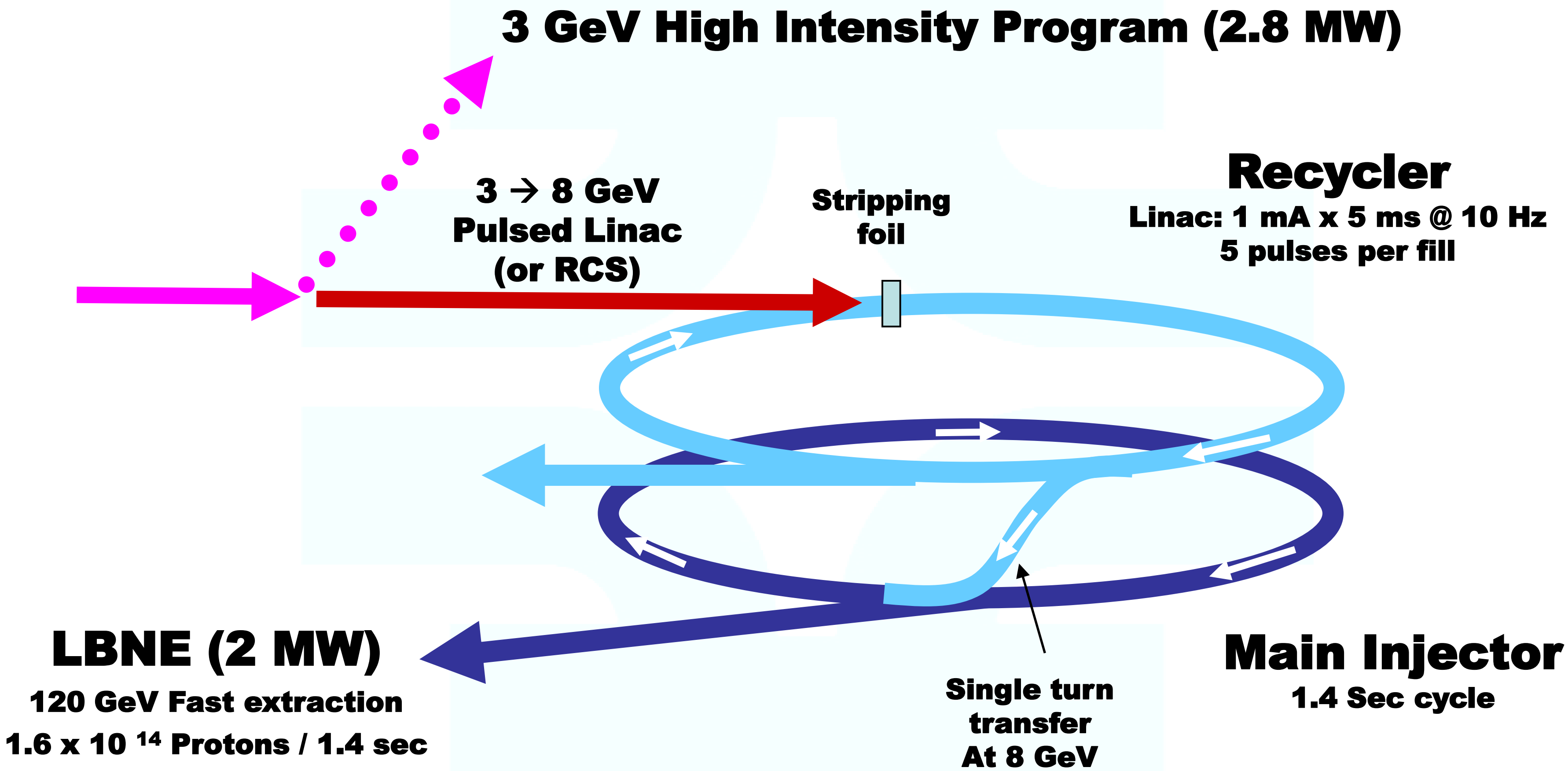




RF Separation Scheme

(The beam time structure does not reflect LBNE needs)

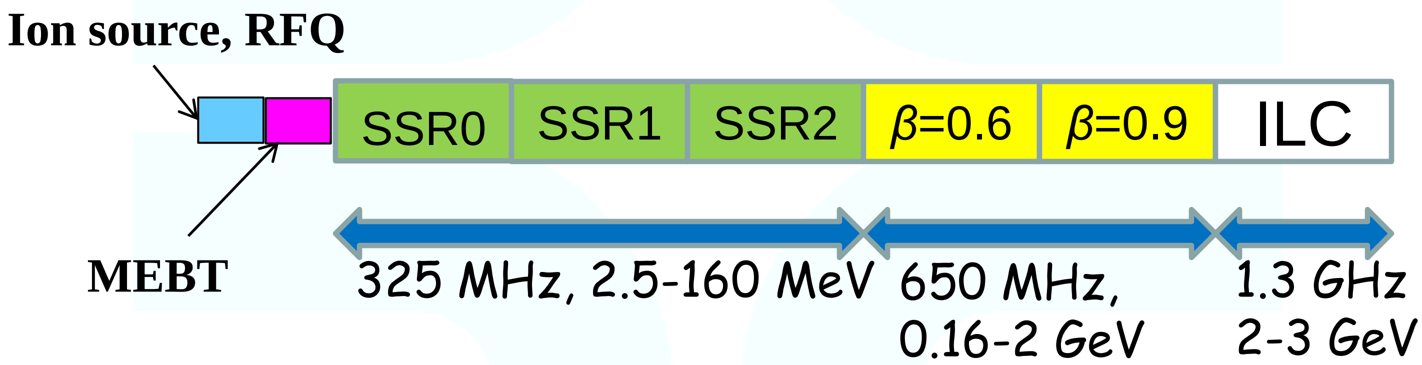
Project X configuration (cont.)



3-8 GeV linac would be 1300 MHz pulsed ➔ retains synergy with ILC R&D but long pulse R&D needed

3 GeV CW Linac

- **Design based on 3 families of 325 MHz Single Spoke resonators, two families of 650 MHz elliptical cavities, then 1300 MHz ILC cavities**



Note: 650 MHz, b=0.9, 5-cell cavities are same physical length as 1300 MHz, b=1.0, 9-cell cavities

Linac conceptual design

- **H^- -source: 10 mA CW**
- **RFQ: CW**
  - 325 MHz (also looking at 162.5 MHz),
  - ~ 2.5 MeV output energy
  - ~ round beam at the exit
- **MEBT**
  - Use RT buncher cavities, P ~ 5kW each
  - Triplet optics (keep round beam)
  - High bandwidth chopper **(chopped to 1 mA average)**
- **Low-energy SRF 325 MHZ linac (2.5-160 MeV)**
  - 3 families of single-spoke cavities *(β=0.12, β=0.22, β=0.4)*
  - Solenoidal focusing (SC) (doublet or triplet is also possible)
  - Separate cryomodules with warm inter-connects

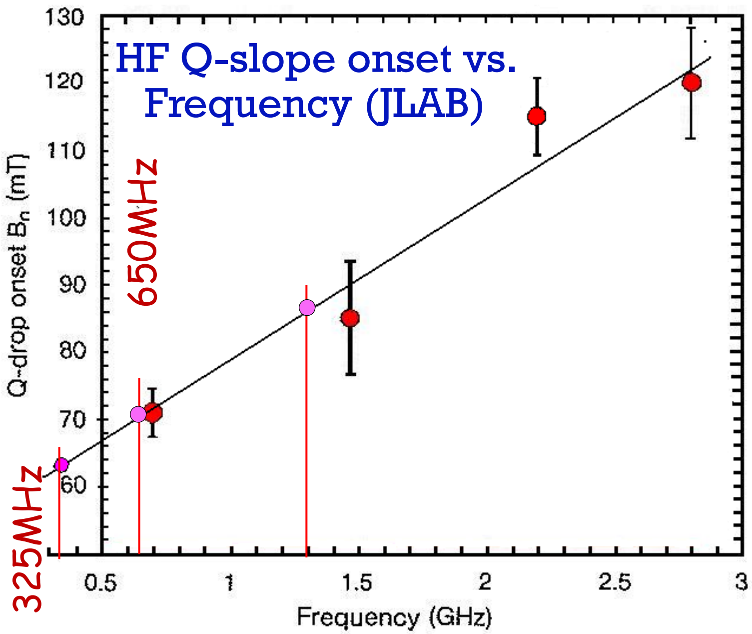
Linac conceptual design (cont.)

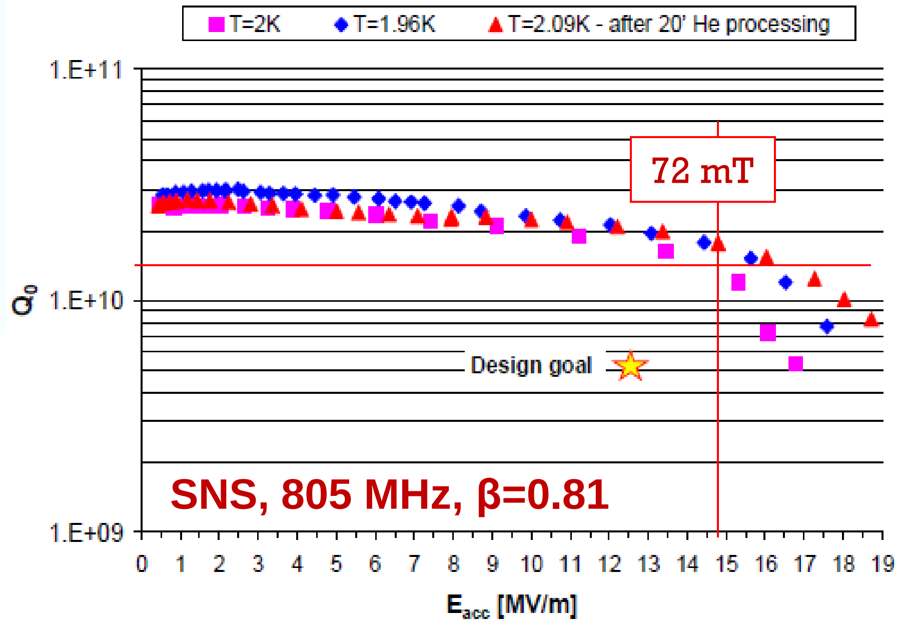
- **2 families of 650 MHz cavities to cover 160 MeV - 2 GeV**
  - **Low-**β (LB) : β=0.61
  - **High-**β (HB): β=0.9 both elliptical cavities
  - Modified ILC Type-4 (2/5/8) cryomodules in cryostrings

- **ILC cavities (1.3 GHz) above 2 GeV)**
  - ILC type-4 (2/5/8) cryomodules in Cryo-strings
  - Baseline = β=1.0 ILC cavities

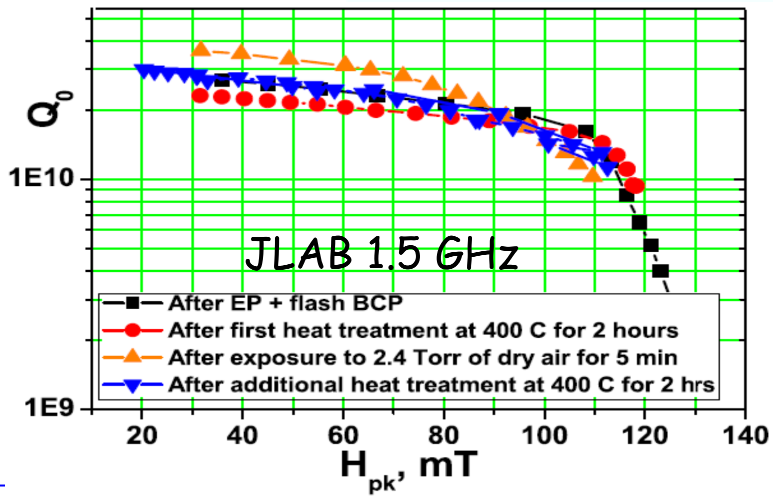
- **Local RF power distribution: One CW RF source per cavity**
  - Solid state amplifier at 325MHz and 650 MHz (?)
  - IOT 650 MHz and 1300 MHz

Choice of SC cavity gradient





Design: E_{acc} = 15.6 MV/m; Q_o ~$1.7\cdot10^{10}$ @ 2.1 K



CW Project X assumptions:

- 325 MHz: B_{pk} < 60mT
- 650 MHz: B_{pk} < 72mT
- 1300 MHz: B_{pk} < 72mT

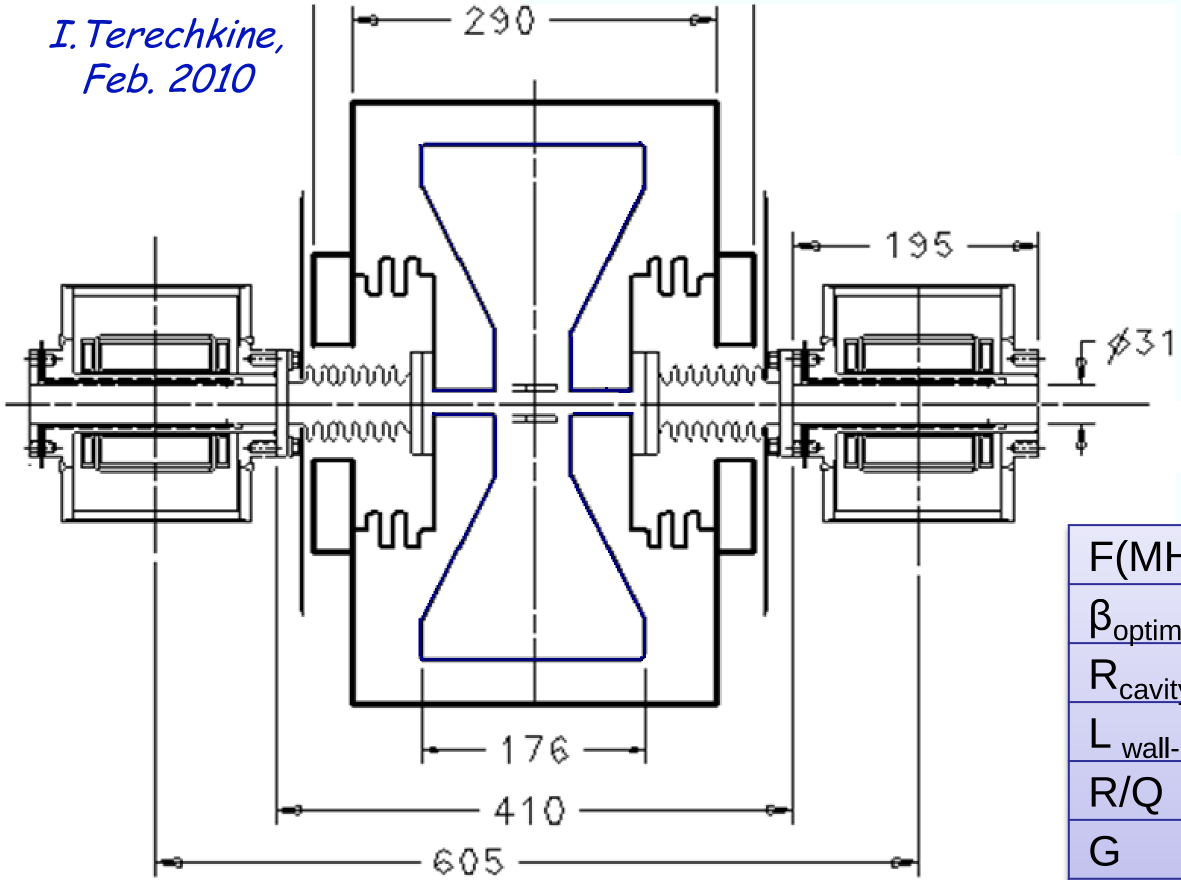
Summary of 3 GeV CW linac cavities

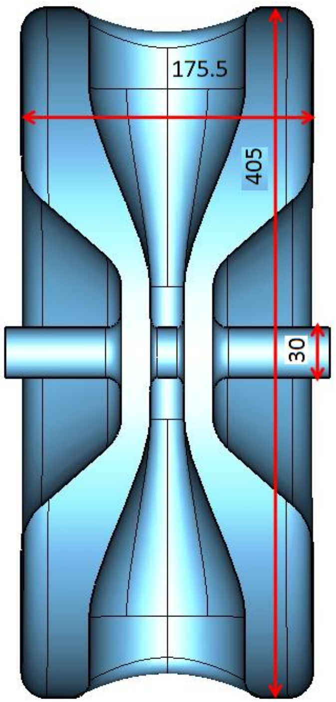
Section	Energy range MeV	β	Number of cavities	Type of cavities	Maximal power per cavity*, kW
SSR0 (β_G=0.12)	2.5-10	0.073-0.146	26	Single spoke cavity.	0.5
SSR1 (β_G=0.22)	10-32	0.146-0.261	18	Single spoke cavity.	1.5
SSR2 (β_G=0.4)	32-160	0.261-0.52	44	Single spoke cavity.	3.2
650 MHz (β_G=0.61)	160 - 500	0.52-0.758	42	Elliptic cavity	11.5
650 MHz (β_G=0.9)	50 - 2000	0.758-0.95	96	Elliptic cavity	18.5
1300 MHz (β_G=1)	2000-3000	0.95- 0.97	64	Elliptic cavity	16

***Without overhead**

SSR0 Section

I. Terechkine, Feb. 2010

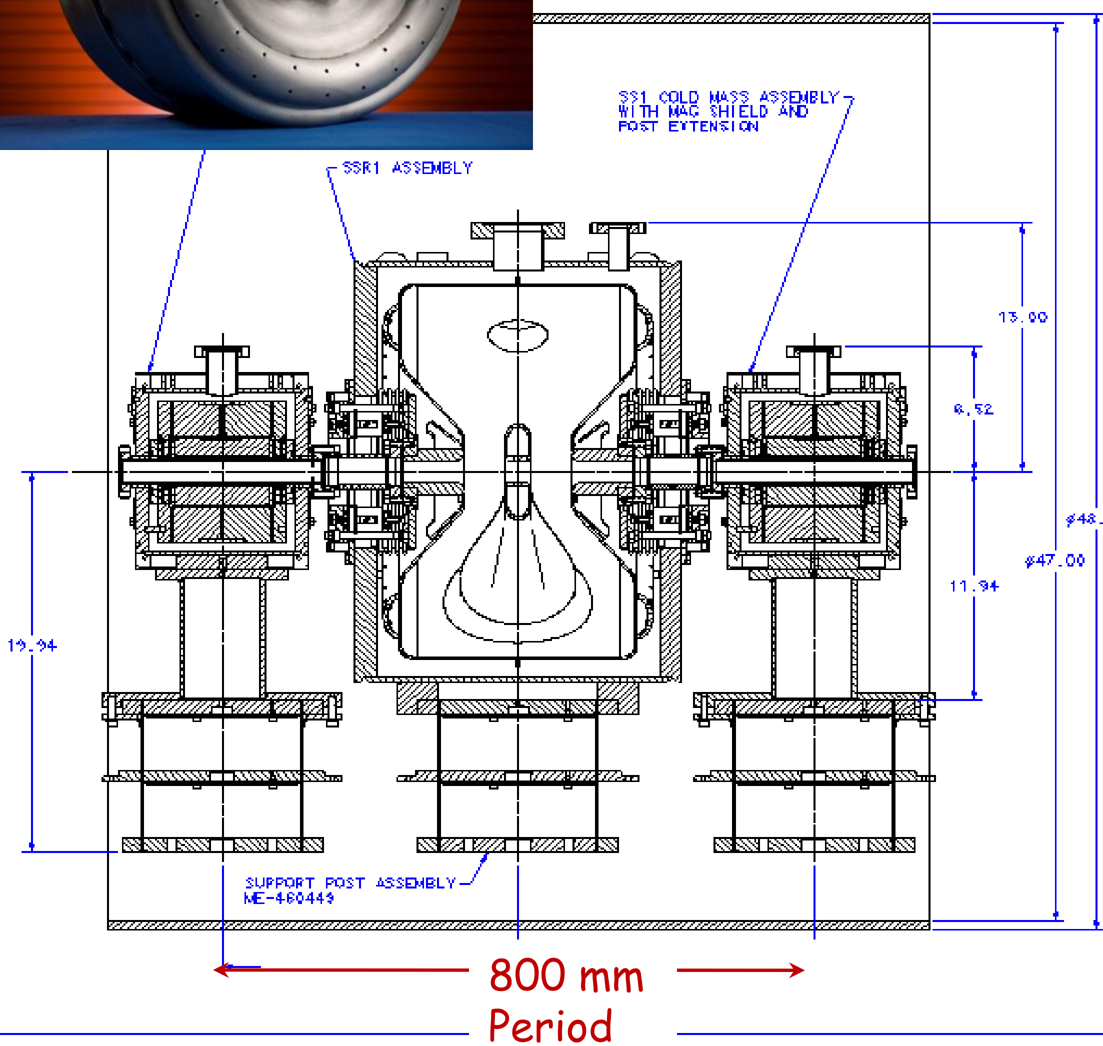




F(MHz)	325	MHz
$\beta_{optimal}$	0.117	
R_{cavity}	204.3	mm
$L_{wall-to-wall}$	175.5	mm
R/Q	110	Ω
G	52	Ω
E_{max}/E_{acc}	5.97	
H_{max}/E_{acc})	6.89	mT/(MV/m)
$D_{eff}=(2\beta_{opt}\lambda/2)$	108	mm

- **Minimize period (~610 mm)**
- **Solenoid with BPM and under design**

SSR1 Section



Cavity

- F = 325 MHz
- β = 0.22
- Design complete

Cavity status

- 2 prototypes tested (30MV/m)
- 1st SSR1 dressed
- 10 in production Roark
- 2 in production in India

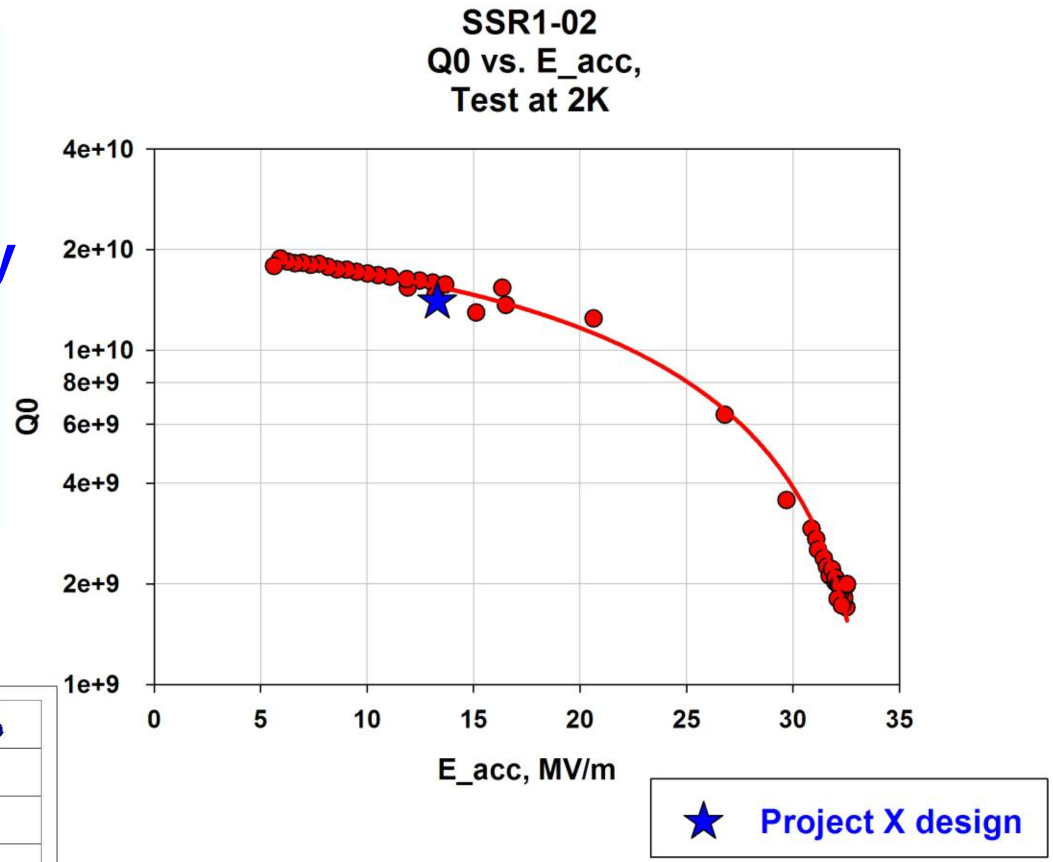
Solenoid status

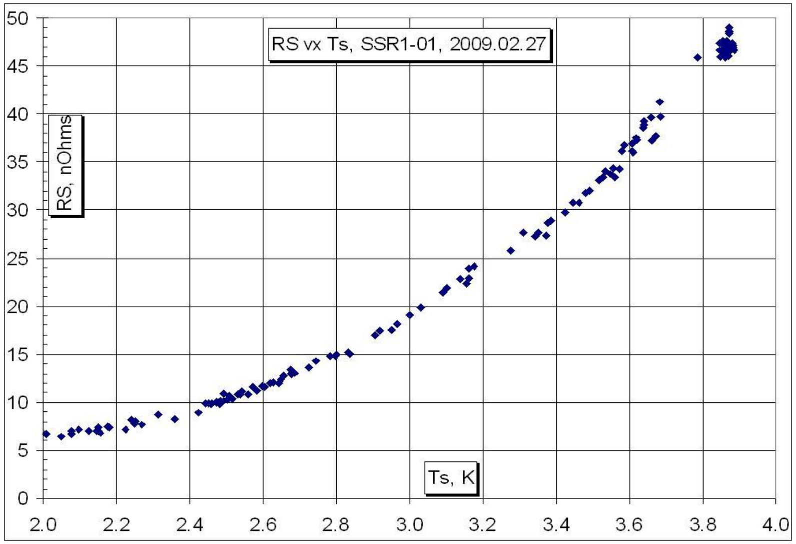
- Prototypes in production

Cryomodule

- Design of spoke resonator cryomodule is starting

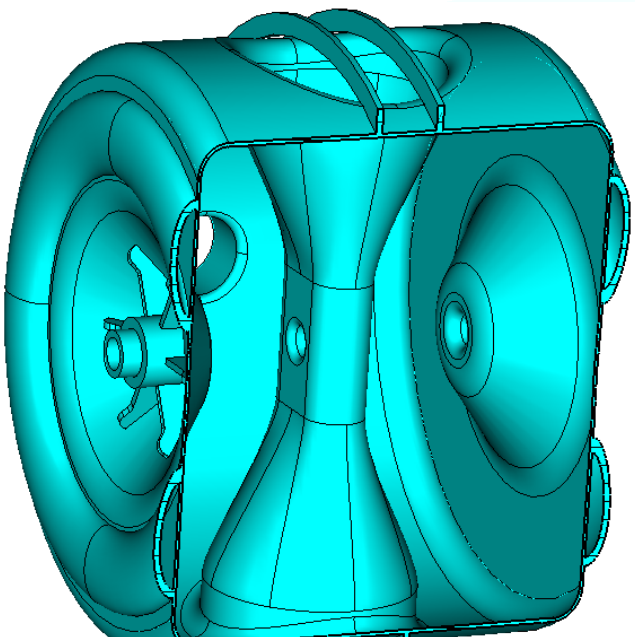
Test results of SSR1 cavity





SSR2 Cavity

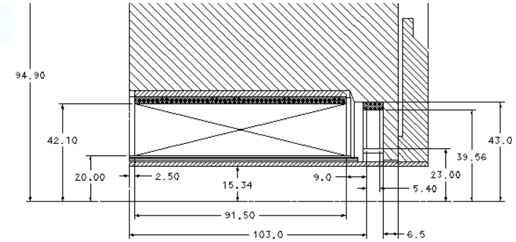
RF design – In Progress
- Mech. Design: to be completed.



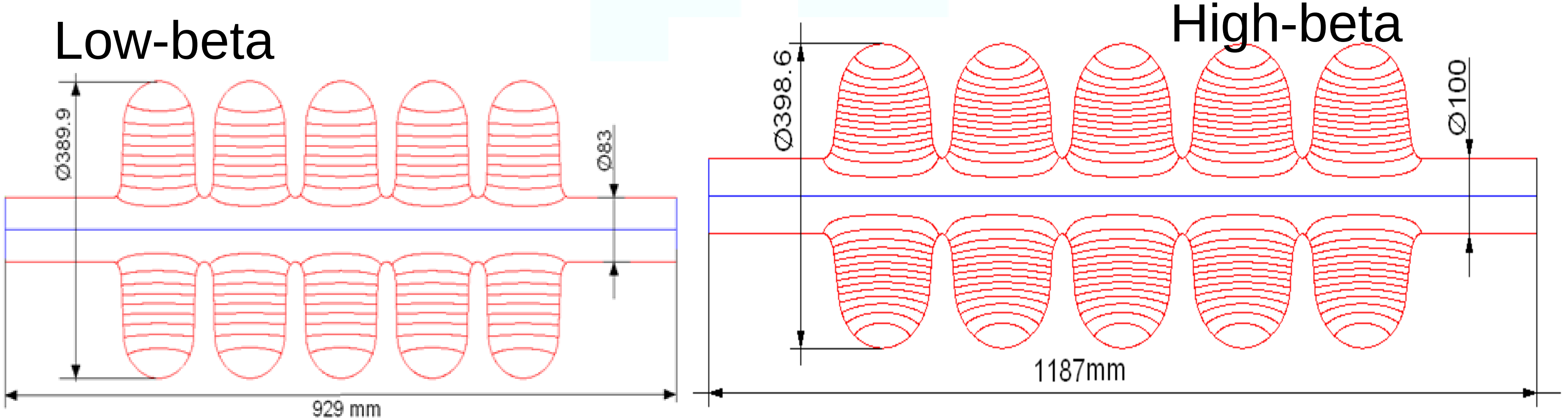
Operating frequency	325	MHz
β_G	0.4	
Cavity Length from wall to wall	406	mm
Dressed cavity length	~530	mm
Cavity diameter	556.2	mm
R/Q	322	Ω
G-factor	112	Ω
Max. gain per cavity (φ-0)	3.16	MeV
Max. surface electric field	33	MV/m
Max.surface magnetic field	54	mT

<u>Solenoid:</u>
- Design completed
- Prototype ready for test (w/o vessel)

<u>Period</u>
- 1300 mm
- 2 cavities and solenoid/corrector



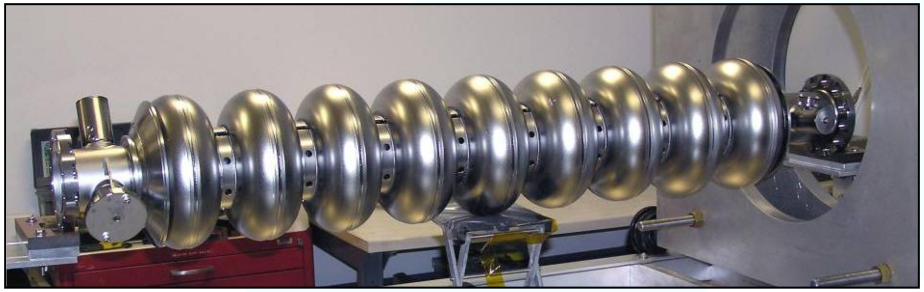
650 MHz, 5-cell cavities



β_G	0.61	0.9	
Length (from iris to iris)	705	1038	mm
Aperture	83	100	mm
Cavity diameter	389.9	400.6	mm
R/Q, Ohm	378	638	Ω
G - factor	191	255	Ω
Max. gain per cavity (φ-0)	12.0	19.9	MeV
Gradient	17.1	19.2	MV/m
Max surface electric field	38.6	38.4	MV/m
Max surf electric field	72	72	mT

Both dissipate P~ 26-29W @ 2 K

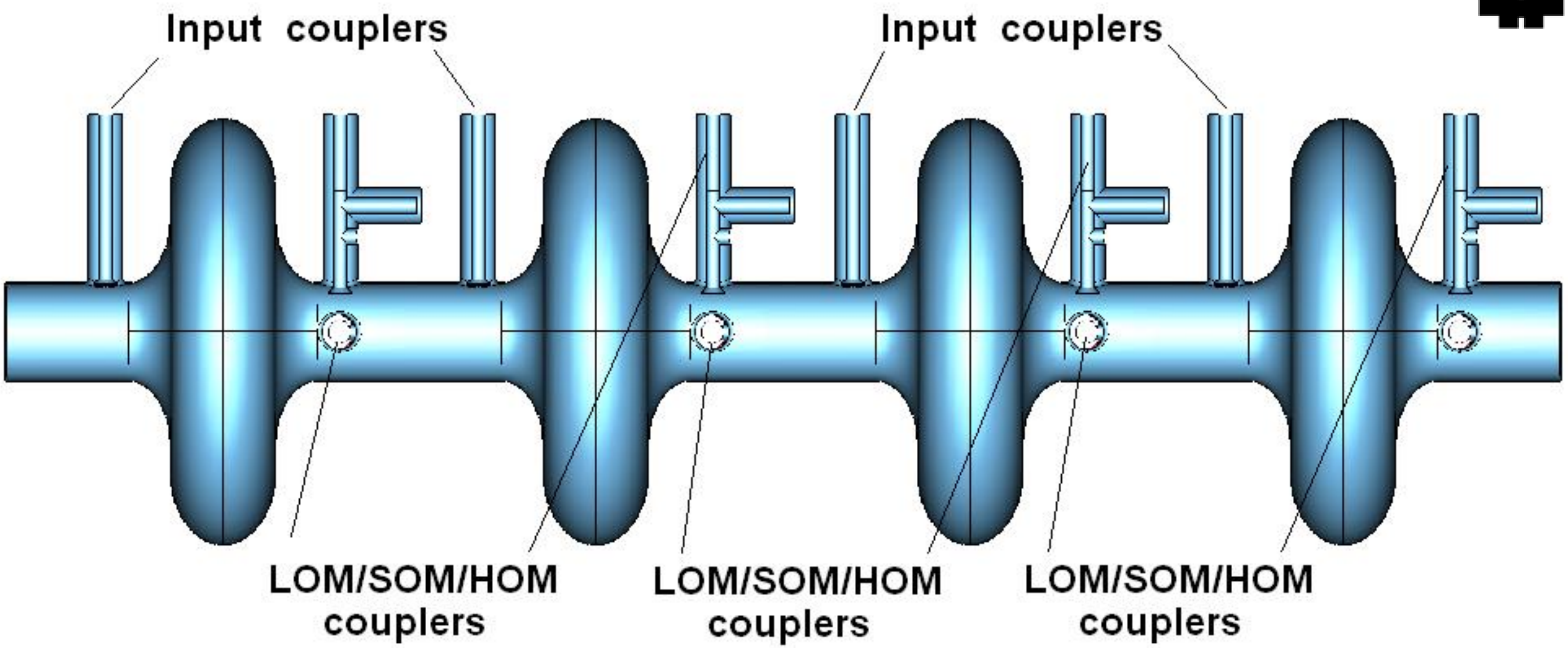
1300 MHz CW cavities



cavity type	Freq. MHz	L_{eff} mm	E_{acc} MV/m	E_{max} MV/m	B_{max} [mT]	R/Q Ω	G Ω	$Q_{0,2K}$ $\times 10^9$	P_{2K} [W]
ILC, 9-cell, β=1	1300	1038	16.9	34	72	1036	270	15.0	19.0

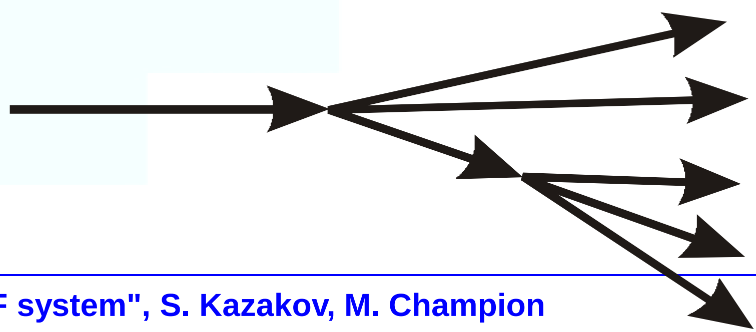
- **Our current Plan:**
  - **2 GeV → 3 GeV PX employs standard ILC cavities and CM**
  - **but, new coupler for CW operation**
  - **Separate RF source per cavity (IOT)**

Cavities of RF separator



Four cavities provide 15MeV kick

Additional RF separators allow simultaneous operation for more than 3 users



Summary of Cavity Parameters

Low energy SC Linac (2.5 – 160 MeV)

cavity type	F req 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=0.117	325	0.78	53	59.5	120	57	9.5	0.77
SSR1, β=0.22	325	1.53	34.4	50.8	242	84	14.0	0.94
SSR2, β=0.4	325	3.16	33	54	322	112	18.0	2.07

High energy SC Linac (160 – 3000 MeV)

cavity type	Freq. MHz	L_{eff} mm	E_{acc} MV/m	E_{max} MV/m	B_{max} [mT]	R/Q Ω	G Ω	$Q_{0,2K}$ $\times 10^9$	P_{2K} [W]
LB650, 5-cell, β=0.61	650	705	17.1	38.6	72	378	191	20-22	26-29
HB650, 5-cell, β=0.9	650	1038	19.2	38.4	72	638	255	20-22	26-29
ILC, 9-cell, β=1	1300	1038	16.9	34	72	1036	270	15.0	19.0

- **Average current is only 1mA -> loaded Q of cavities is high.**
  - **It intensifies problems with microphonics**
  - **But requirements for HOM dumping are decreasing**

Cavity Type	Frequency MHz	Q_{load}	Bandwidth Hz	
SSR0	325	$6.5 \cdot 10^6$	50	**New piezo-tuner**
SSR1	325	$6.5 \cdot 10^6$	50	
SSR2	325	$1 \cdot 10^7$	33	
Low-β	650	$3.3 \cdot 10^7$	20	**New piezo-tuner**
High-β	650	$3.4 \cdot 10^7$	19	
ILC	1300	$1.7 \cdot 10^7$	76	**Piezo-tuner exists**

RF couplers, requirements and constraints.

Couplers have to allow assemble and to seal cavities in clean room. Sealed cavity is to be installed in cryomodule.

1.3 GHz coupler has to match existing ILC-type cavity and cryomodule.

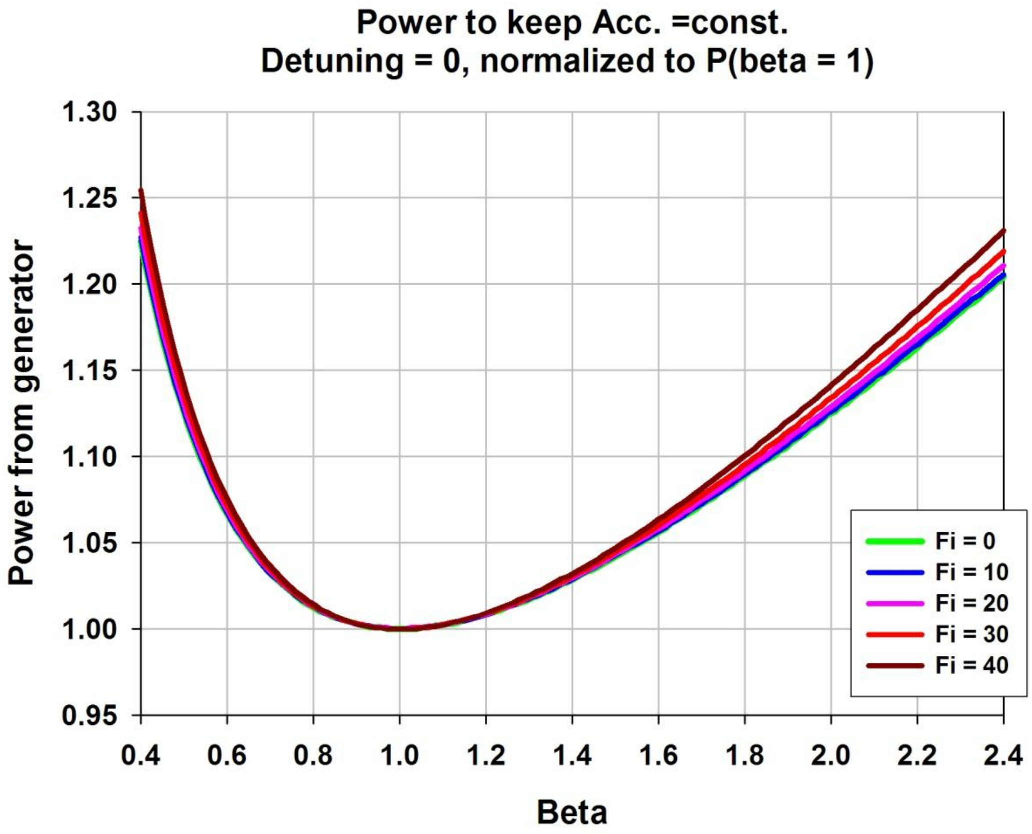
325MHz coupler has to match existing SSR1 cavity

We need to feed 6 different cavities at three different frequencies. Nevertheless, couplers components have to be universal as much as possible.

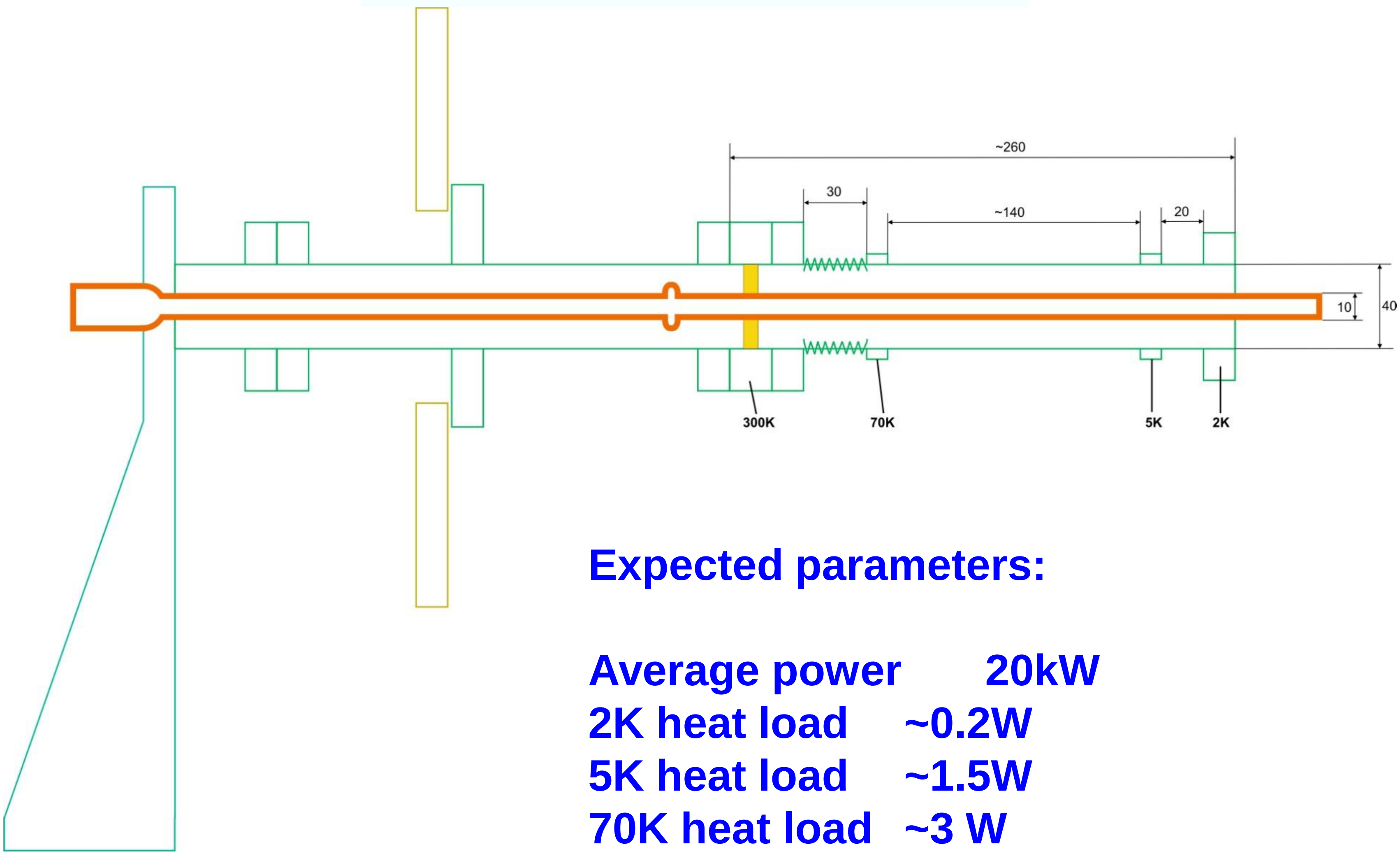
Simple, reliable, cheap.

Not adjustable with one warm flat coaxial window configuration was chosen.

Error in coupling within 0.6 – 1.6 (optimal is 1.0) requires only 6% additional power – not sensitive.



Possible configuration of 1.3 GHz coupler. Coupler has the same connections as TTF-III coupler.

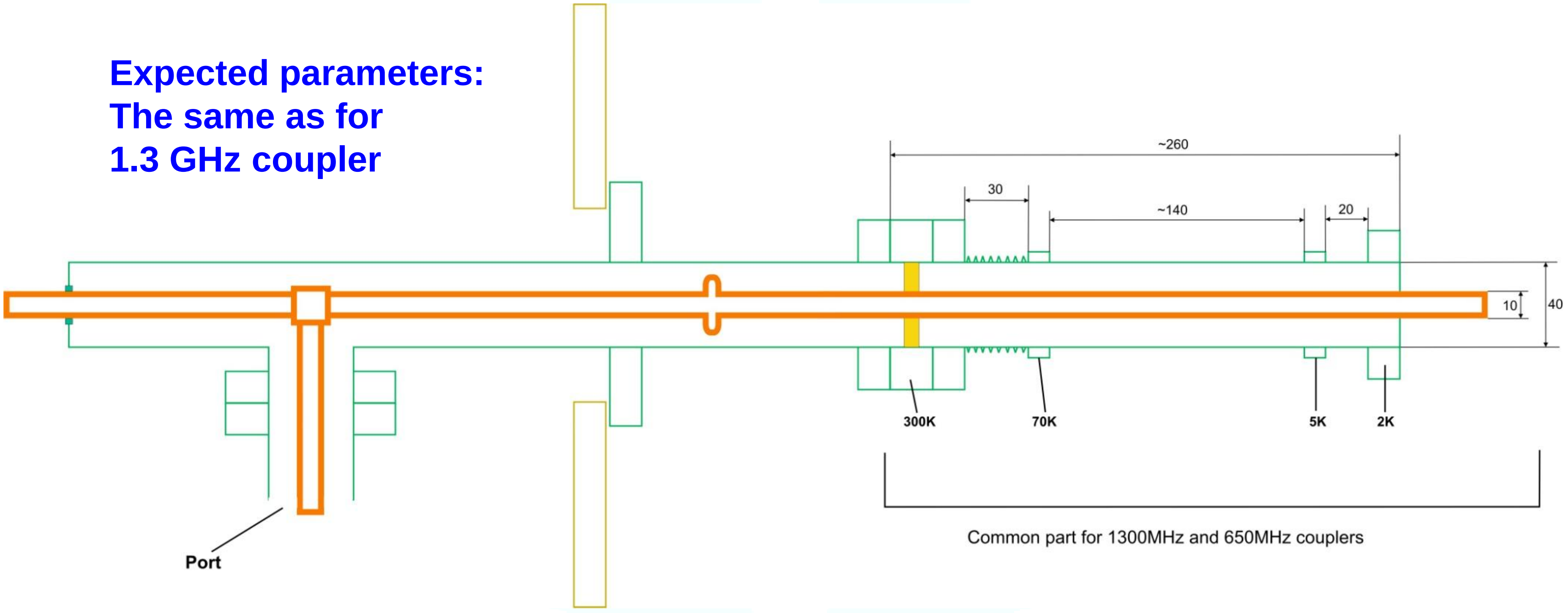


Expected parameters:

Average power 20kW
2K heat load ~0.2W
5K heat load ~1.5W
70K heat load ~3 W

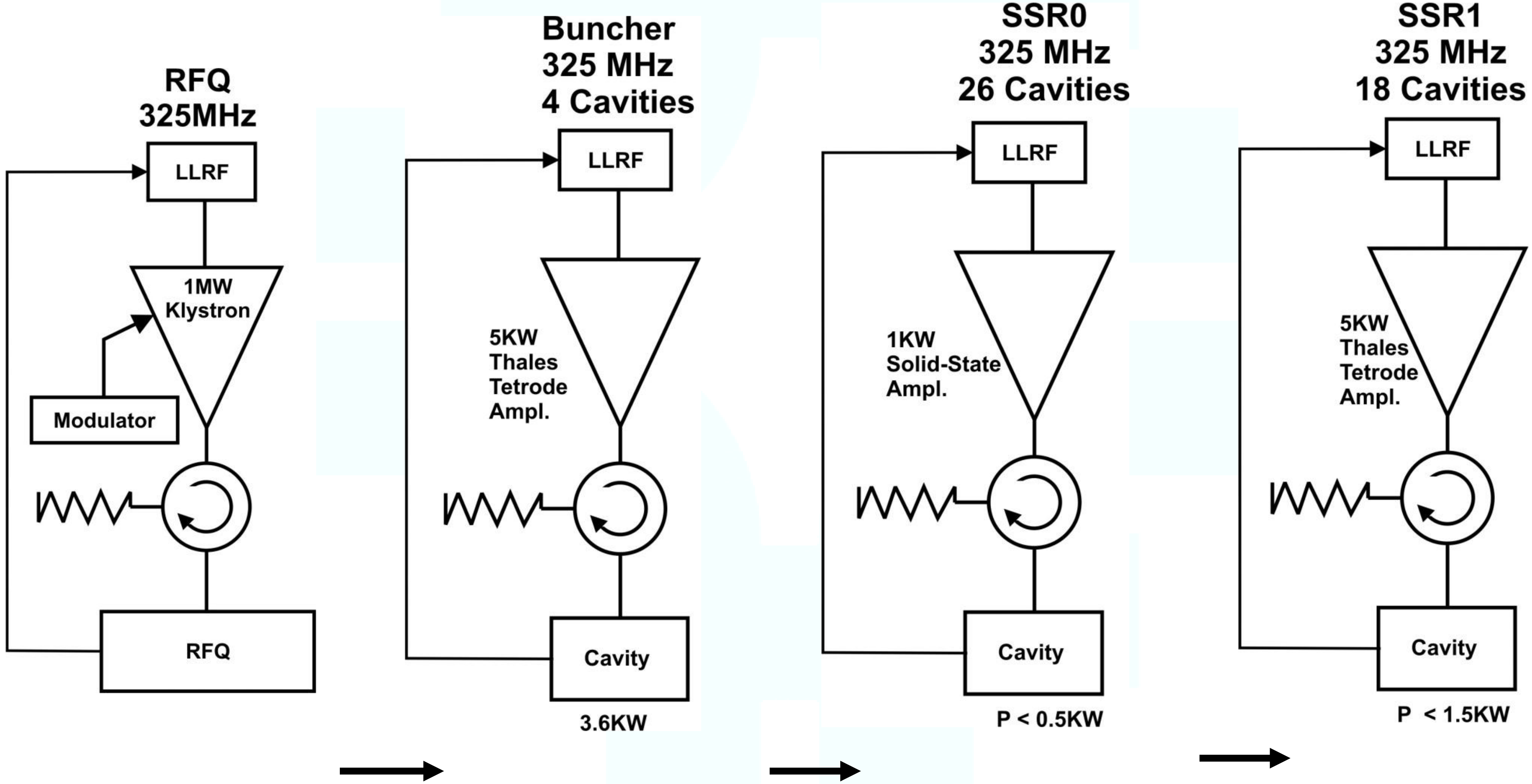
Possible configuration of 650 MHz coupler

Expected parameters:
The same as for
1.3 GHz coupler

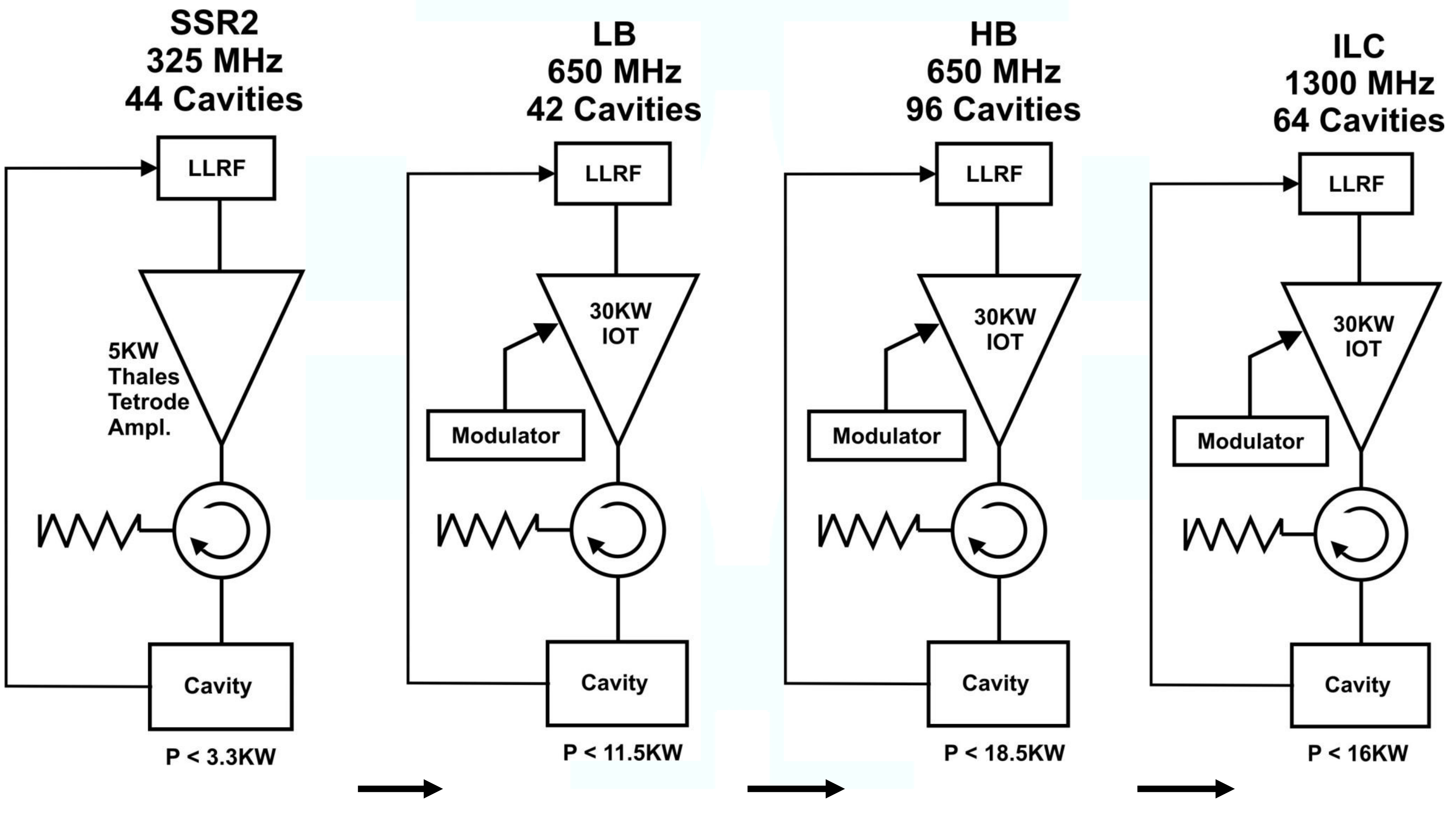


Single-window, not adjustable coupler with outer diameter 76 mm (to fit existing SSR1 cavity) is supposed to use for 325 MHz cavity. All cavities (SSR0, SSR1, SSR2) will employ the same coupler. Conceptual design is not done yet.

Block-diagram of 3GeV Linac RF system, one cavity – one RF source



Block-diagram of 3GeV Linac RF system (cont.)



1300 MHz 3-8 GeV Pulsed linac

- Current plan (still evolving):
  - Use standard ILC cavities and Cryomodules
  - Operate with large Klystrons and distributed RF like ILC
  - 5 ms 1 mA beam pulses at 10 Hz (to fill recycler)
  - Operate at ~ 25 MV/M gradient
- A 3-8 GeV linac requires
  - 200 ILC β=1, 9 cell cavities in 25 Type IV cryomodules
- A Rapid Cycling Synchrotron is still an alternative

PX R&D Plan

- **Goals:**
  - Complete baseline design, cost and schedule estimates in 2012
  - Technical component and infrastructure development
- **Linac (325 MHz)**
  - Spoke cavity development (all three betas), test dressed cavities
  - Design and construction of a prototype cryomodule
- **Linac (650 MHz)**
  - Cavity & Cryomodule design and test.
- **Linac (1.3 GHz)**
  - Cavity & CM development coordinated with ILC
  - ILC cryomodules operated CW at 17 MV/M
  - 25 MV/m gradient with good yield operated pulsed with 5 mS @ 10 Hz