Magnetron option for a pulse linac of the Project X

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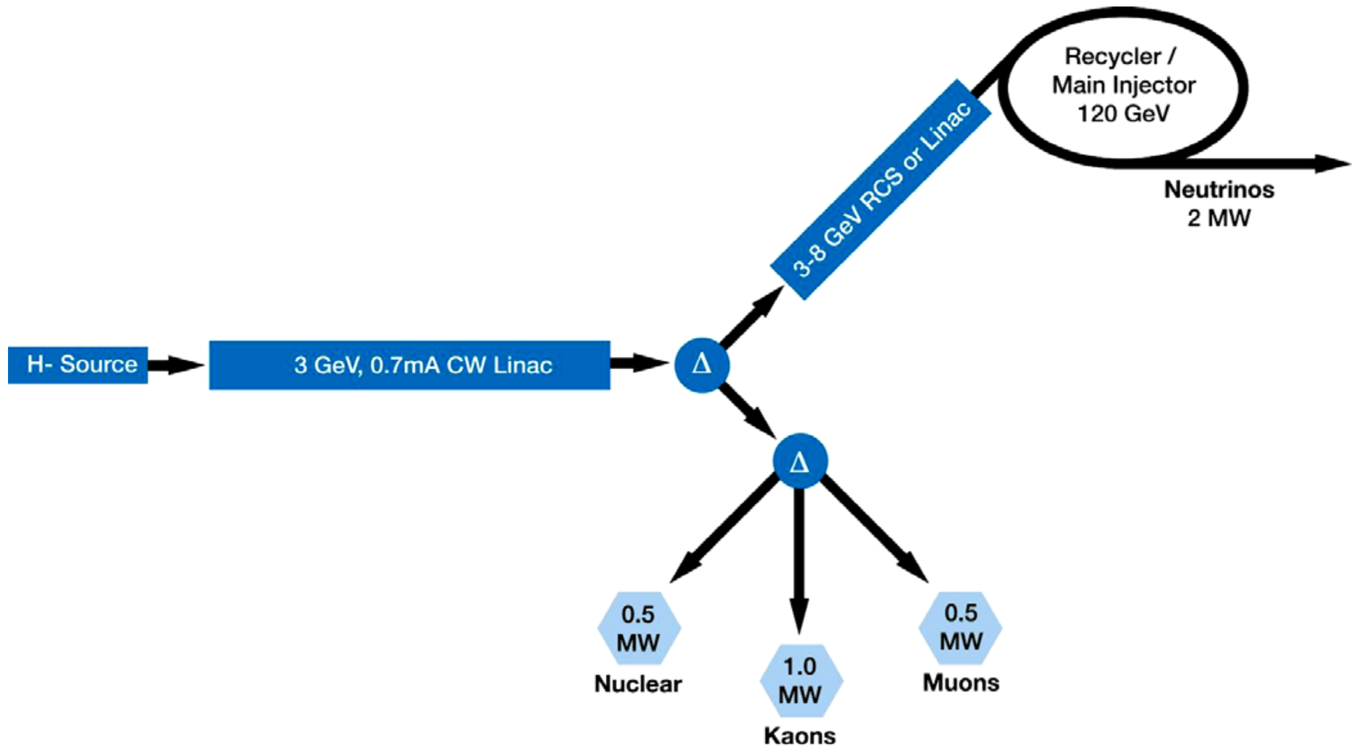


Concept of the Project X multi-experiment accelerator facility

- **The Project X provides high-intensity 3 GeV the proton CW beam for rare processes experiments and for nuclear physics experiments related to ADS program.**
- **The Project X should also provide a neutrino beam for long baseline neutrino oscillation experiments. The neutrino beam requires 2 MW proton beam at the energy of 60-120 GeV, that will be produced by the FNAL Main Injector.**
- **Injection to the Recycler/Main Injector takes place at 8 GeV. The stripping foil heating problem demands the following parameters of the RF feeding system of the pulse linac:**

3-8 GeV pulse linac parameters

As it determined with a stripping foil

Energy increment:	25 MeV/cavity
Accelerated current:	1 mA
Cavity filling time:	~3 ms
Beam pulse duration:	4.3 ms
Repetition rate:	10 Hz
External Q-factor:	10^7
Resonance frequency:	1.3 GHz
Cavity bandwidth:	130 Hz
P_C:	30 kW
P_C Overhead:	16%
$P_{C\ TOTAL}$:	35 kW
$P_{C\ AVER.}$:	2.6 kW

High-power Klystron option of RF source

Concept: L-band klystron feeds 2 cryo-modules with 16 Superconducting Cavities (SC)

Klystron pulse power (including losses) : 600 kW
Klystron average power: 40 kW
Pulse duration: 7.3 ms
Repetition rate: 10 Hz
Number of klystrons for the pulse linac: 25

Klystrons developed to drive SC

Type	VKP-7952A	VKP-7957A	
Frequency, MHz	700	499.76	
Voltage, kV	92	76	63
Beam current, A	16.8	17.7	17
Output power, kW	1020	822	608
Efficiency, %	66	61	57
Gain, dB	43	40.7	42.3

VKP-7952A klystron lay-out

Issues of the high-power klystron RF option

Feeding of a number of cavities from one RF source allows control of the vector sum of the cavity voltage only. This is very serious issue for weakly relativistic beam because of:

- **Cavity parameters spread;**
- **Errors in the power distribution system;**
- **Microphonics, which is a problem for a narrow-band cavity.**

In this case it may be a problem to provide acceptable amplitude and phase stability of RF field in a separate cavity.

The problems results in unacceptable emittance growth in the linac.

- **Moreover, the klystron is not developed yet.**

The best solution is:

System of individual RF sources for each cavity allowing independent rapid control of the cavity voltage and phase at price comparable to klystron RF system

Cost estimate for the klystron option of RF source

- **Since the klystron is not developed yet all systems used for the klystron option has to be developed and included in cost**

Klystron (Including development):	$ 0.5 M
Modulator (Including development):	$ 0.5 M
Modulator Pulse transformer (in oil):	$ 0.15 M
Ferrite circulator (including matched loads):	$ 0.04 M
Klystron filament stabilizer; Interlock system:	$ 0.1 M
Solid State RF driver:	$ 0.02 M
Klystron solenoid +PS (Includ. development):	$ 0.2 M
Cost estimate for 13 transmitters:	$ 18.5 M
RF distribution system:	$ 0.5 M
Total cost estimate:	**$ 19.0 M**

*IOT option of RF source**

Efficiency of ~ 60% and would take advantage of TV transmitters for lower frequency systems

For 1.3 GHz only ‘recently’ developed, little reliability data (short cathode-grid spacing), low gain, 2x higher voltage modulator than klystron and needs more system development (drive power 500W)

1300 MHz IOT manufacturers: CPI (30 kW), E2V (16 kW –no longer in catalog), Thales (16 kW) and recently Mitsubishi (built 30 kW prototype for KEK ERL program)

Costs for tube~ 100 k$/CPI 30 kW IOT

Station cost range from 400 –900 k$ is based on quotes from Bruker, ETM, DTI and Continental for small quantities.

*** S. Chu, http://projectx-docdb.fnal.gov/cgi-bin/RetrieveFile?docid=663&version=1&filename=1300MHZ.pdf**

*CW high-perveance low-voltage klystron and SSA options of RF source**

Klystron efficiency is ~60% and gain is ~40 dB
Klystron manufacturers: CPI sells a ‘reliable’ 11 kW tube and has a design for a 30 kW, 19 kV tube (would build one for 440 k$) and Toshiba is developing a 25 kW tube (probably for KEK)
For JLab 12 GeV accelerator upgrade: 1.5 GHz, 13 kW CW klystrons were developed
The 13 kW klystron station could cost of ~ $ 100 k for a large number of them.

A CW 40 kW low- voltage klystron is not developed yet

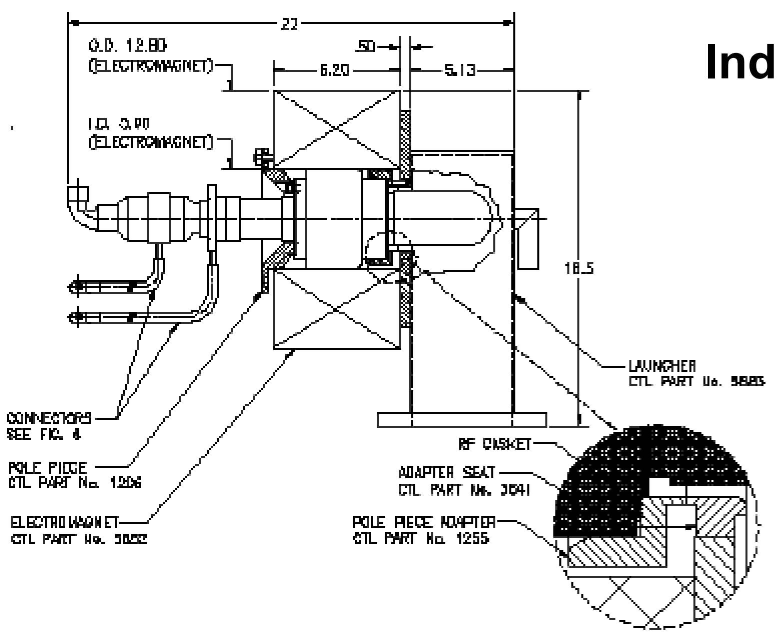
SSA advantages: Low-voltage PS
Disadvantages:
Very high cost (~ $ 500 k or more/30 kW station) and low efficiency (~ 30 % for 1.3 GHz) for now

***Ibid**

Magnetron option of RF source

Concept: L-band multi-stage phase-locked magnetron generator feeds individual SC

Magnetron pulse power (including losses) :	≈40 kW
Magnetron average power:	2.6 kW
Pulse duration:	7.3 ms
Repetition rate:	10 Hz
Number of magnetron generators for the linac:	200



Industrial CW Magnetrons (915 MHz and 896 MHz)

Model Number	U_C, kV	I, A	Po, kW
CWM-50L	15	4.0	50
CWM-75L	17	5.0	75
L10016-1	15	4.0	50
L10016-1R	15	4.0	50

The magnetrons efficiency is 83-88%

Magnetron works as a forced oscillator, but NOT as an amplifier!

- ►**Thus, magnetron output power does not depend on the amplitude of the frequency/phase locking signal.**
- ►**Variation of the frequency/phase locked magnetron voltage and current in some range does not affect the magnetron frequency/phase stability.**
- ►**Driving signal with amplitude much more than first harmonic noise amplitude is enough for frequency/phase locking. Usually it's from -8 to -20 dB in power scale.**

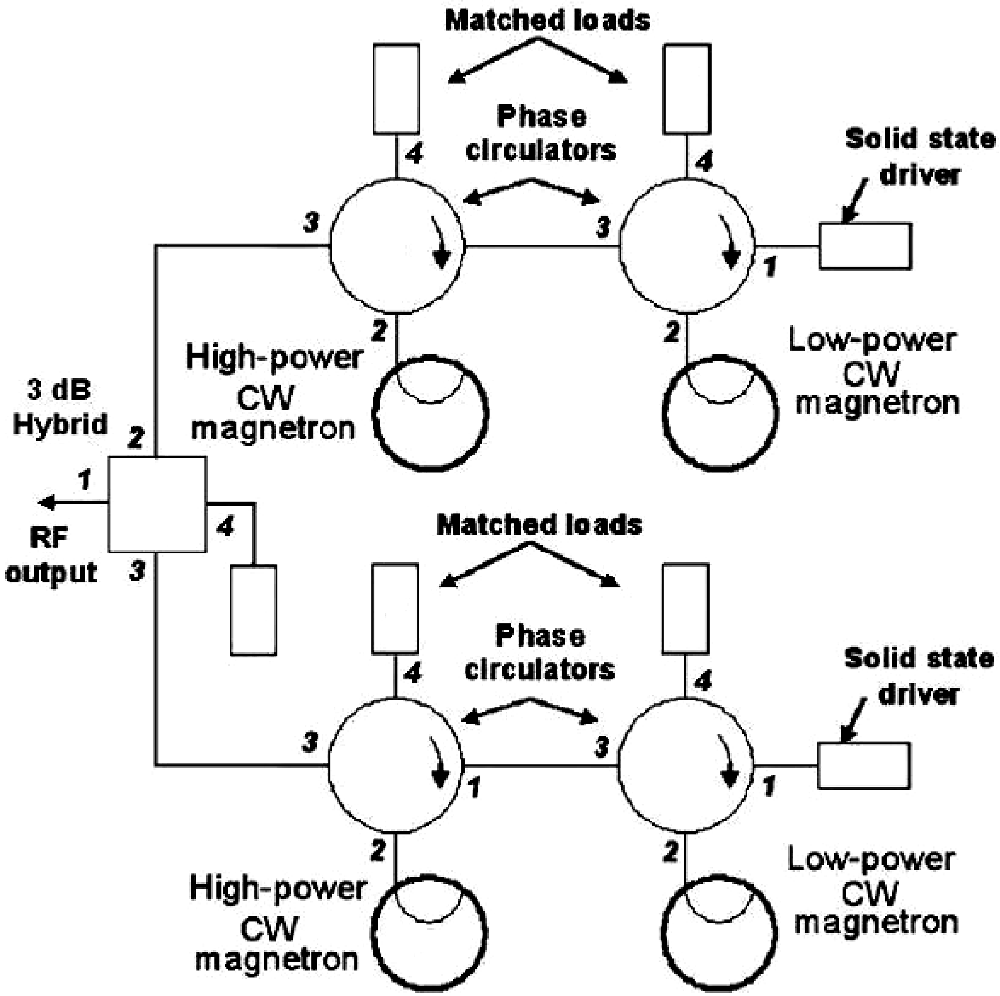
The forced oscillator model was checked in simulations and measurements; both are in an excellent agreement.

- ►**Multi-stage magnetron scheme is available.**

Linac with SC solution:

Two independently phase-controlled multi-stage frequency/phase-locked CW magnetron generators + 3 dB hybrid. That allows a rapid and deep independent control of power and phase of the magnetron generator.

Frequency/phase locked two-stage magnetron generator for a deep and rapid control of power and phase



The scheme allows 100% control of amplitude and phase in each SC cavity at high efficiency of the RF source

Cost estimate for magnetron option of RF source

High power magnetron:	$ 9.5 k
Low power magnetron:	$ 1.5 k
Four ferrite circulators (with matched loads):	$ 50 k
Two Solid State RF drivers:	$ 40 k
3 dB hybrid:	$ 5 k
Power supply for a generator:	$ 50 k
Cost estimate for one transmitter:	$ 167 k
Cost estimate for 200 transmitters:	$ 33.4 M
Total cost estimate:	**$ 33.4 M**

Note that magnetron price itself is insignificant in the estimate; it's easily replaceable device. So, utilization of number of magnetrons in the complex can't make problems in operation and maintenance.

Conclusion

Proposed concept of a frequency/phase locked magnetron RF source with following features:

- ►**Provides independent feeding of a separate SC with a rapid, independent and deep control of amplitude and phase in each cavity**
- ►**Had a cost estimate comparable or less than klystron or IOT-based RF systems**
- ►**For considered linac the magnetrons regimes are so light, that one can expect comparable life time for the magnetron RF sources and klystron those**
- ►**The concept opens a way to realize the ADS project at acceleration of many tens mA beams basing on already developed high-power CW magnetrons**
- ►**Recent experiments demonstrate phase stability of the phase-locked magnetrons better than 1 degree [1, 2]**

[1] G.M. Kazakevich, et al., Nucl. Instr. and Meth. A (2011), doi:10.1016/j.nima.2011.04.030

[2] A.C. Dexter et al., PRST-AB 14, 032001 (2011)

Thank you!