Short Pulse X-ray (SPX) at the Advanced Photon Source

A. Nassiri

Advanced Photon Source

ICFA Beam Dynamics Mini-Workshop on Deflecting/Crabbing Cavity Applications in Accelerators

The Cockcroft Institute, Daresbury, UK

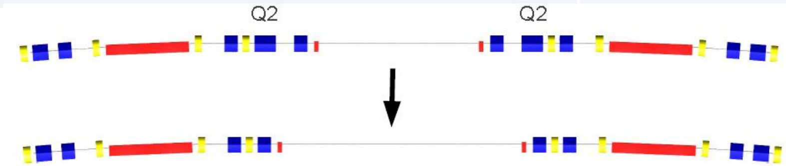
September 2010

Outline

- APS Upgrade
- SPX scheme using deflecting cavities
- Technical systems
- R&D
- Summary

- The APS Upgrade (APS-U) project at Argonne National Laboratory (ANL) will provide high-energy, high-average-brilliance, short-pulse, penetrating hard x-rays in the range above 25 keV with:
  - Nanoscale focal spots reaching < 5 nm above 25 keV;
  - Time resolution down to 1ps;
  - New or improved x-ray beamlines;
  - The technical capabilities required to fully exploit these upgraded technical components

	Present	Upgrade
Electron energy (GeV)	7	7
Stored current (mA)	100	150 ~200 mA
Effective emittance (nm)	3.15	≤ 3.5
Vertical emittance (pm)	35	10 ~50
Top-up interval	≥ 60 s	≥ 30 s
Fill patterns	24&324 bunch Hybrid mode	24&324 bunch Hybrid mode
Operational single bunch limit (mA)	16	16
Straight section length (m)	4.8	4.8 ~7.7

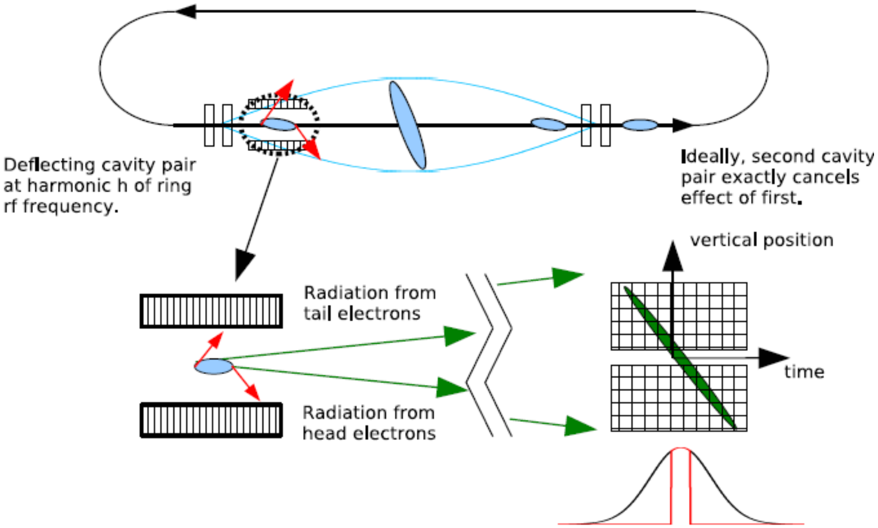


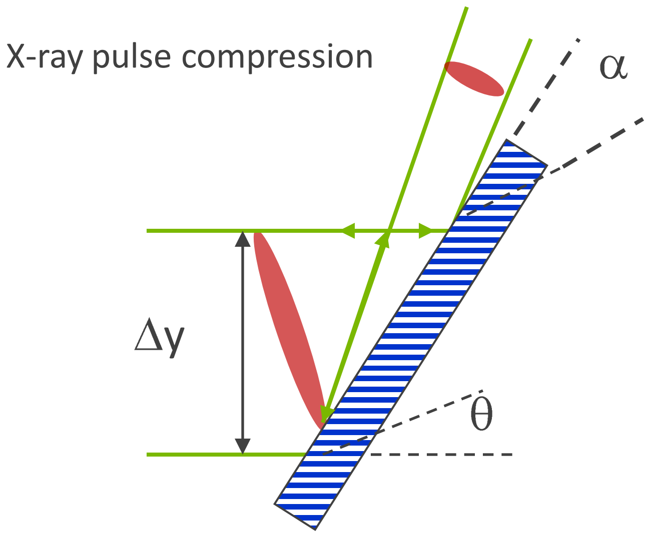
Scientific Goal:

Generate short x-ray pulses using crab-cavity-based method.

Technical Goal:

Conduct R&D to demonstrate proof of concept which will lead to design and implement of a fully integrated SRF deflecting cavities system for the APS storage ring.



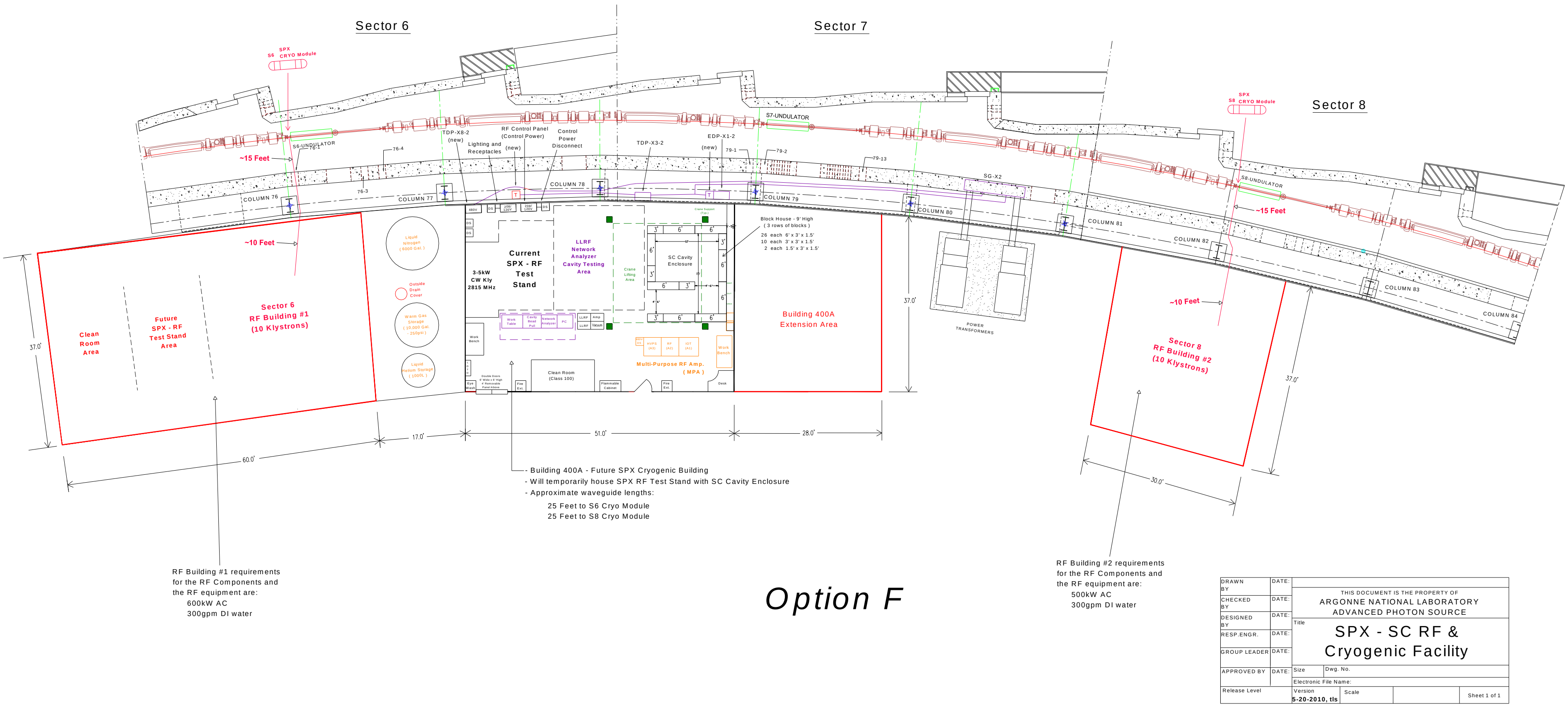


†A. Zholents, P. Heimann, M. Zolotorev, J. Byrd, NIM A 425, 385, (1999).

SPX Performance Parameters

	Peak Value	Requirement
Current	202 mA	
Energy	7 GeV	
Rf frequency	2815.44 MHz	
RF voltage	2/4 MV	
Number of cavities	8/16	
CM voltage ampl variation	< 1%	Keep intensity and pulse length variation under 1%
CM phase variation	<7 deg	Keep intensity variation under 1%
Voltage ampl mismatch error between cavities	<0.5%	Keep emittance variation under 10% of nominal 35 pm
Voltage phase mismatch error between cavities	< 0.03 deg	Keep beam motion under 10% of beam size/divergence
$R_s\ f_{HOM}$ for one monopole HOM	0.5 MΩ-GHz	
R_s for one monopole at 2 GHz	0.25 MΩ	
R_t for one x-plane HOM	1.5 MΩ/m	
R_t for one y-plane HOM	4.5 MΩ/m	
Cavity electric center alignment within cryomodule	~ ± 0.3 mm	
Cavity tilt inside cryomodule	~ ± 5 mrad	Increase horizontal emittance by 5%
Max beam emittance, ε_x (unperturbed), ε_y (unperturbed) , ε_y (w/ cavities)	2.7 nm-rad, 35 pm-rad, 50 pm-rad	

SPX Layout

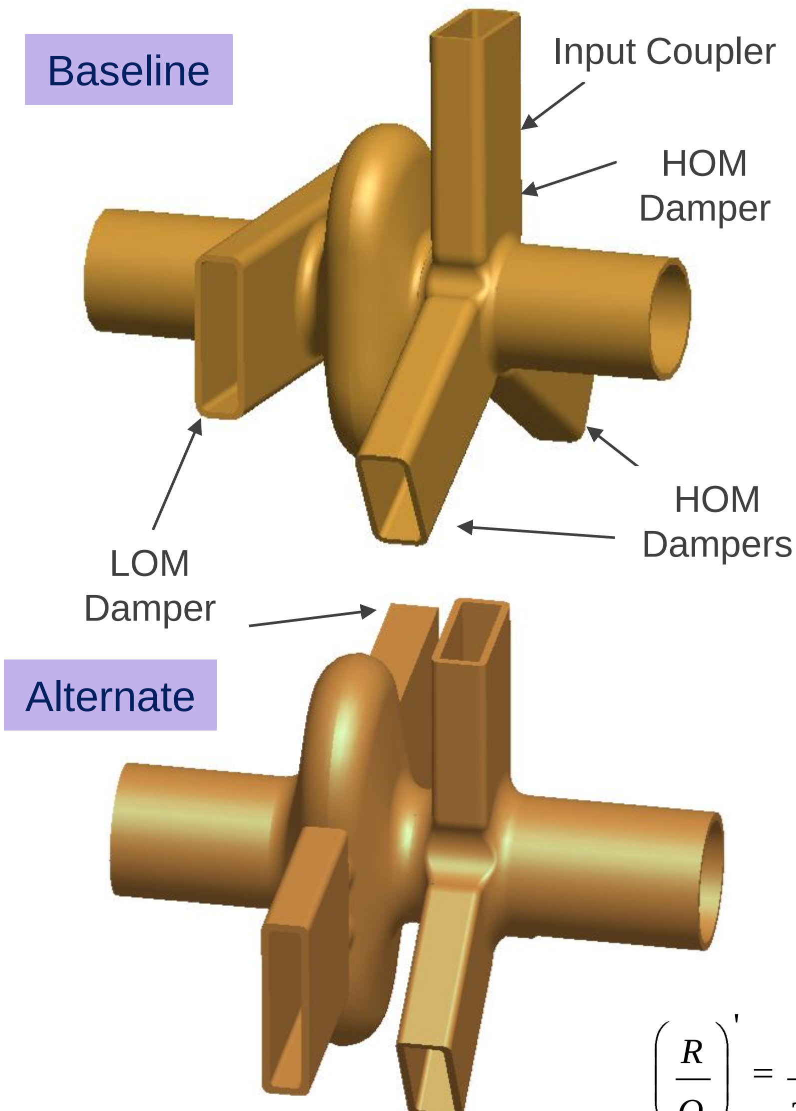


Sector 6
Sector 7
Sector 8
SPX
S6 CRYO Module
S8 CRYO Module
S6-UNDULATOR
S7-UNDULATOR
S8-UNDULATOR
~15 Feet
~10 Feet
COLUMN 76
COLUMN 77
COLUMN 78
COLUMN 79
COLUMN 80
COLUMN 81
COLUMN 82
COLUMN 83
COLUMN 84
TDP-X8-2
(new)
RF Control Panel
(Control Power)
Lighting and
Receptacles
Control
Power
Disconnect
TDP-X3-2
EDP-X1-2
(new)
SG-X2
Clean
Room
Area
Future
SPX - RF
Test Stand
Area
Sector 6
RF Building #1
(10 Klystrons)
Current
SPX - RF
Test
Stand
3-5kW
CW Kly
2815 MHz
LLRF
Network
Analyzer
Cavity Testing
Area
SC Cavity
Enclosure
Block House - 9' High
(3 rows of blocks)
26 each 6' x 3' x 1.5'
10 each 3' x 3' x 1.5'
2 each 1.5' x 3' x 1.5'
Building 400A
Extension Area
Multi-Purpose RF Amp.
(MPA)
Clean Room
(Class 100)
POWER
TRANSFORMERS
Sector 8
RF Building #2
(10 Klystrons)
37.0'
60.0'
17.0'
51.0'
28.0'
30.0'
- Building 400A - Future SPX Cryogenic Building
- Will temporarily house SPX RF Test Stand with SC Cavity Enclosure
- Approximate waveguide lengths:
25 Feet to S6 Cryo Module
25 Feet to S8 Cryo Module
RF Building #1 requirements
for the RF Components and
the RF equipment are:
600kW AC
300gpm DI water
RF Building #2 requirements
for the RF Components and
the RF equipment are:
500kW AC
300gpm DI water
Option F
DRAWN BY
CHECKED BY
DESIGNED BY
RESP.ENGR.
GROUP LEADER
APPROVED BY
DATE:
THIS DOCUMENT IS THE PROPERTY OF
ARGONNE NATIONAL LABORATORY
ADVANCED PHOTON SOURCE
Title
SPX - SC RF &
Cryogenic Facility
Size
Dwg. No.
Electronic File Name:
Release Level
Version
5-20-2010, tls
Scale
Sheet 1 of 1

Technical Systems

- Cavities
- Cryomodule
- Cryogenics
- Low-level RF
- High-power RF and waveguide distribution
- Beam diagnostics
- Timing and synchronization
- Controls/Interlocks/ Machine Protection System

Single-Cell SC Cavity



$$\left(\frac{R}{Q}\right)' = \frac{V^2\big|_{r=r_0}}{2\omega U (k r_0)^2}$$

Frequency	2815	MHz
Q_U	~10^9	
V_t	0.5	MV
Energy	0.39	J
$k_{\|\|}$	0.615	V/pC
(R/Q)'	17.8	Ohm
E_{peak} / V_t	83	1/m
B_{peak} / V_t	182	mT / MV
P_{loss}	7	W
I_{beam}	200	mA
Cavity Iris Rad	25	mm
Cavity Beam Pipe Rad	26	mm
Cavity Active Gap	53.24	mm
Q_{ext}	~ 10^6	
Cells / Cavity	1	
No. Cavity	4 * 2	

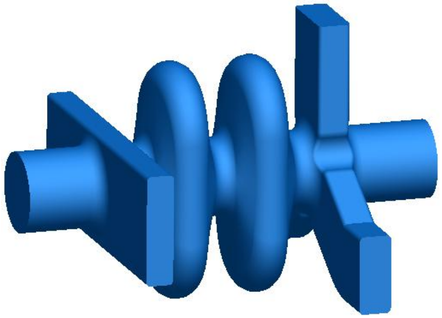
Parameters for the Baseline Cavity

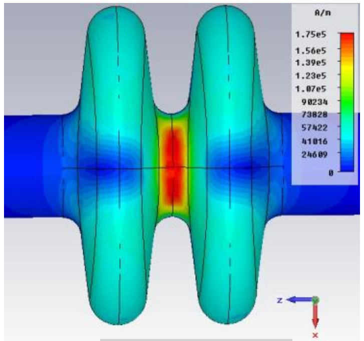
Details in Haipeng Wang's talk on Friday

2-cell Cavity Design Concepts

- 2-cell TM_{110} cavity operating in the pi-mode suffers from magnetic field enhancement on the iris. Results in little net defelcting voltage improvement.
- 2-cell TM_{110} cavity operating in the 0-mode is difficult to damp SPM pi-mode due to limited coupling to dampers.
- 2-1/2 cell Cavity
  - Center cell is used to couple the SPM into vertical damping waveguide.
  - 2 pi / 3 mode is not damped in the center cell and is utilized as the operating mode.
  - Difficult to manufacture and process center-cell geometry.

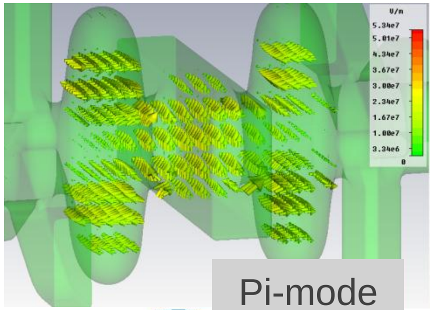
Pi-mode cavity



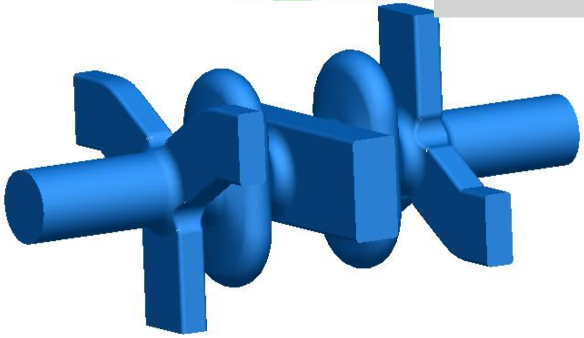


Pi-mode

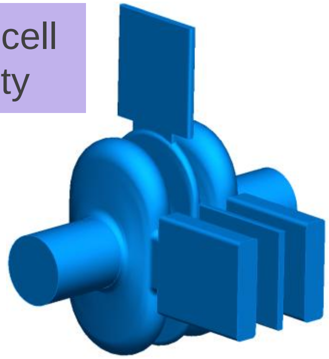
0-mode cavity

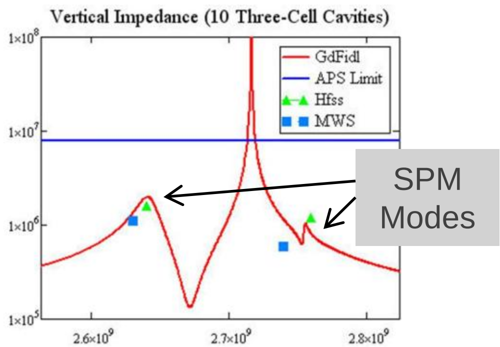


Pi-mode



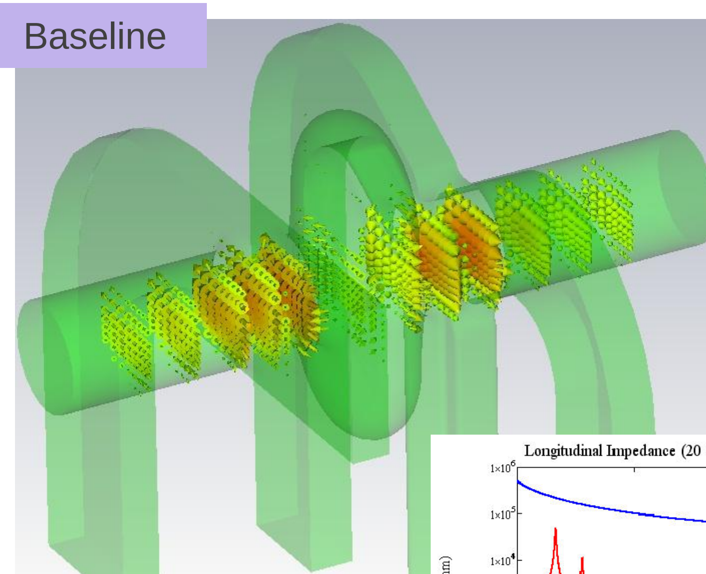
2-1/2 cell cavity

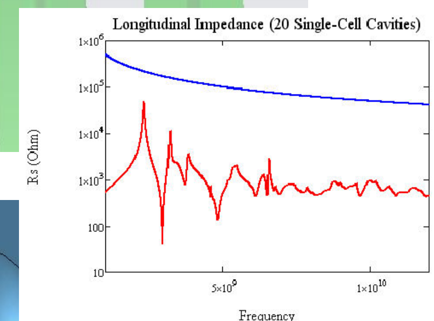




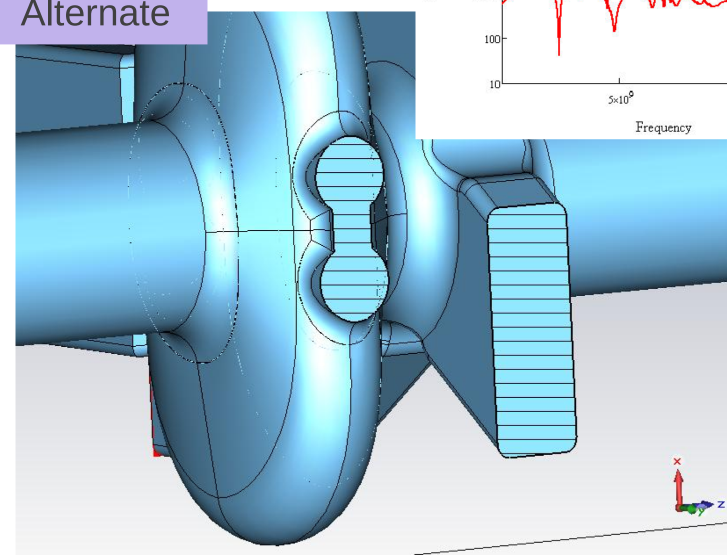
- Alternate Cavity Benefits
  - Larger stability margin for 200 mA beam current.
  - Single excited LOM plus two LOM waveguides produce less rf loading of dampers (assuming dual LOM waveguides are used)
  - More compact
- Alternate Cavity Disadvantages
  - Additional waveguide penetration for second LOM waveguide, if needed.
  - Unproven design features
    - Magnetic field enhancement? Numerical results show adequate damping without enhancement
    - Multipacting enhancement? Experimental and numerical results do not show a problem
  - More complex helium vessel

Baseline





Alternate



Details in Haipeng Wang's talk on Friday

Main Parameters

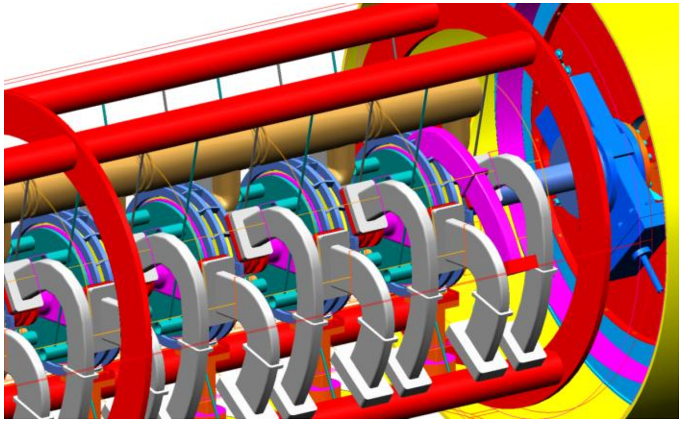
Preliminary Estimate of 2K Losses

2K Cryogenic Losses	
Static / Dynamic Losses due to Waveguides / Tuners per Cavity	2.4 W
Wall Losses per Cavity @ $Q_u=10^9$	7.0 W
Static Heat Load due to Cryo Losses e.g., Beampipe Transitions / Supports	2.0 W
Total Heat Load (8 cavities) @ $Q_u=10^9$	79 W

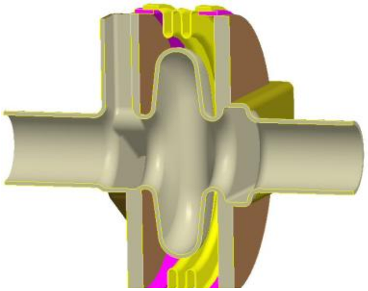
Estimated System Parameters

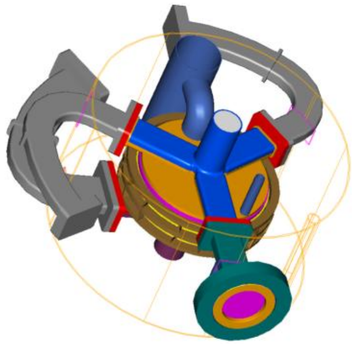
System Parameters	
Slow Tuner Range	+/-200kHz
Number of Cavities per Cryomodule	4 (8)
Total Number of Cryomodules	2
Cavity Offset Alignment Tolerance	0.3 mm
Beam Offset Tolerance	0.05 mm
Klystron Power per Cavity	5 kW

- Helium vessel plates are integral with cavity end groups and utilize existing Nb material during construction.
- Thermal properties of ‘uncooled’ outer portion of end groups must be analyzed.
- Each helium vessel is fed individually by supply lines and a gas return pipe.

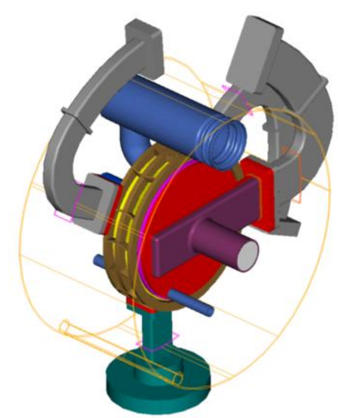


Helium vessel cut-away

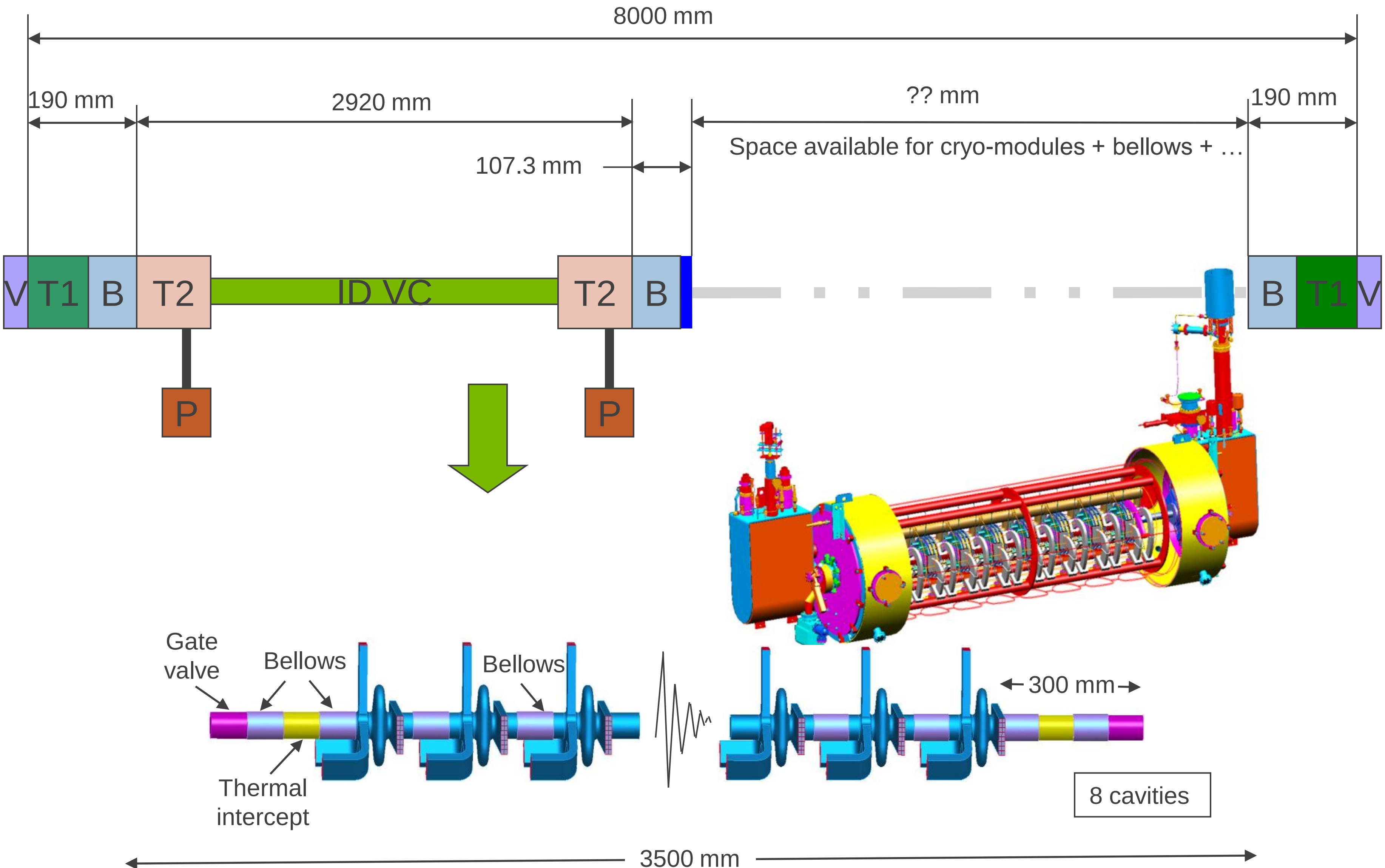




Helium vessel with waveguides and blade-tuner rings



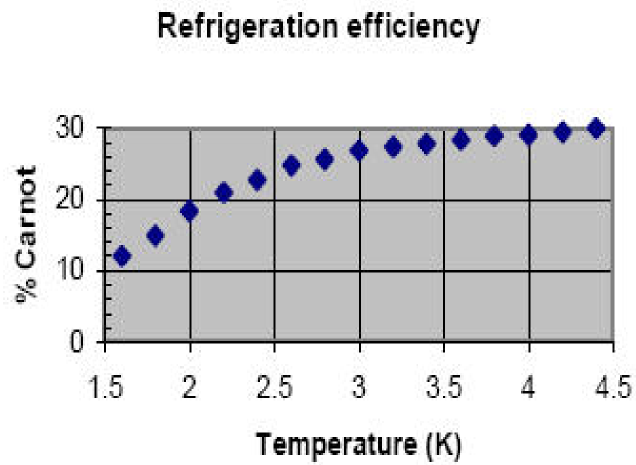
Deflecting Cavity Cryomodule Insertion



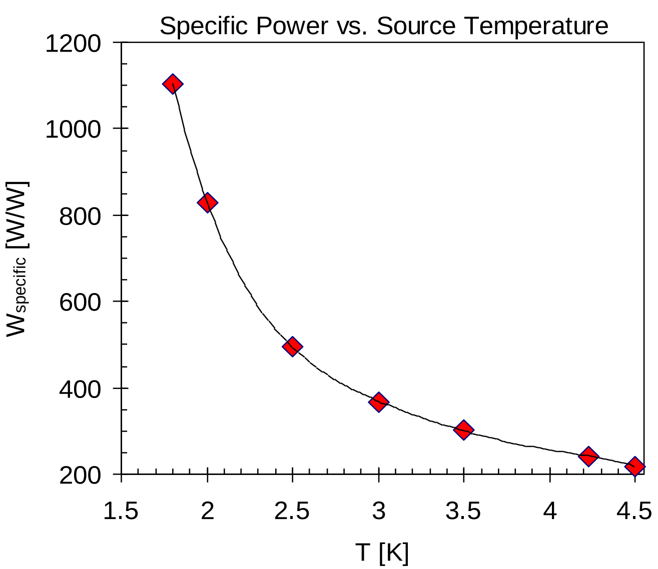
Courtesy: L. Morrison

Refrigeration

- Refrigeration @4.3K:
  - COP_{INV} = 70 W/W
  - Carnot efficiency = 30%
  - Input power required = 230 W per watt at 4.3K
- Refrigeration @2K:
  - COP_{INV} = 150 W/W
  - Carnot efficiency = 18%
  - Input power required = 830 W per watt at 2K

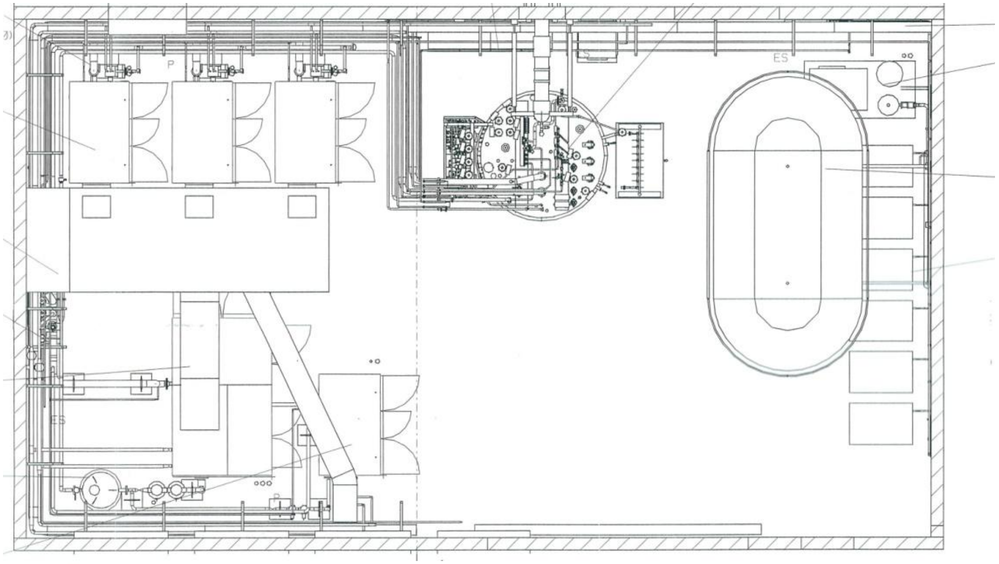


Schneider, Kneisel, Rode, "Gradient Optimization for SC CW Accelerators," PAC2003



ELBE Cryoplant
FZ-Rossendorf

- Cryoplant hall: 17m x 10m
- 220W @ 1.8K + 200W @ 80K, upgradeable to 380W with more comp & LN2 precooling
- 417kW at full load (220W)



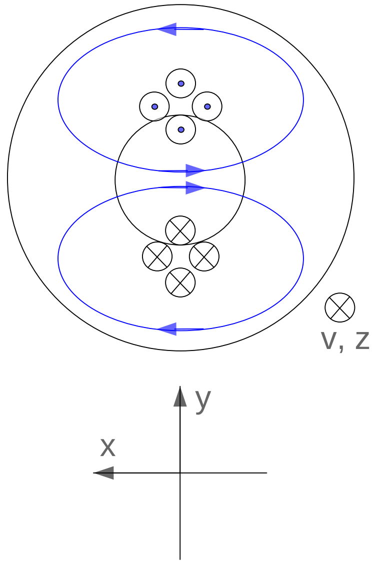
Cryoplant Costs

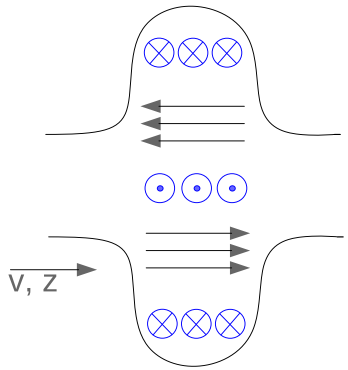
- Requirements are calculated using
  - 312W for Q=1E9
  - 200W for Q=3E9
  - 161W for Q=1E10
  - 152W for Q=2E10
  - Same Qs, but ½ voltage
- Equivalent load includes **300W** for 5-8K intercepts and distribution sys. losses and **200W** equivalent for 40-80K shield load. This extra load is a fixed value and assumed to be independent of the 2K load.
- For cryoplants of this type, 1.8K operation adds 33% to plant size compared to 2.0K operation.

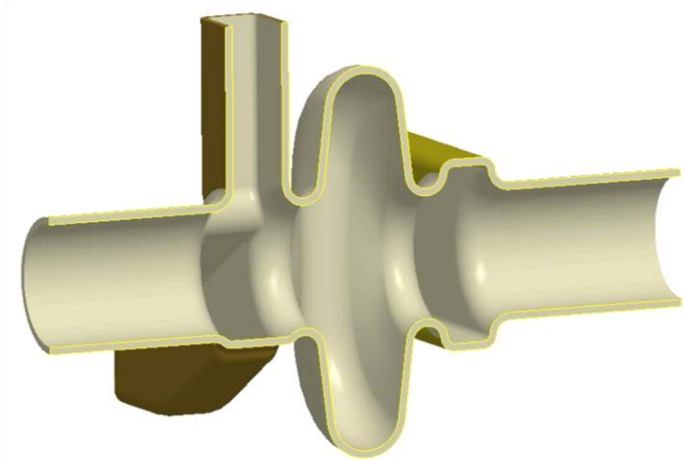
Load [W] @ operating temp	Equivalent load @ 4.5K [W]	Cost scaled from FNAL* [M$]	Compressor power for 2.0K operation [kW]
270 (FNAL reference)	1230	8.0	295
312 (4MV @ Q=1E9)	1242	8.1	298
200 (4MV @ Q=3E9)	940	6.6	226
160.8 (4MV @ Q=1E10)	834	6.1	200
152.4 (4MV @ Q=2E10)	811	6.0	195
156 (2MV @ Q=1E9)	821	6.0	197
100 (2MV @ Q=3E9)	670	5.2	161
80.4 (2MV @ Q=1E10)	617	4.9	148
76.2 (2MV @ Q=2E10)	606	4.9	145

*Fermilab is buying a new cryoplant for ILC string tests. Design capacity is 270W@2K + 300W@5-8K + 4500W@40-80K (= 1230W equivalent at 4.5K). Costs scale with the 0.7 power of plant capacity (per Byrns & Green, *"An update on estimating the cost of cryogenic refrigeration,"* 1998).

Beam loading





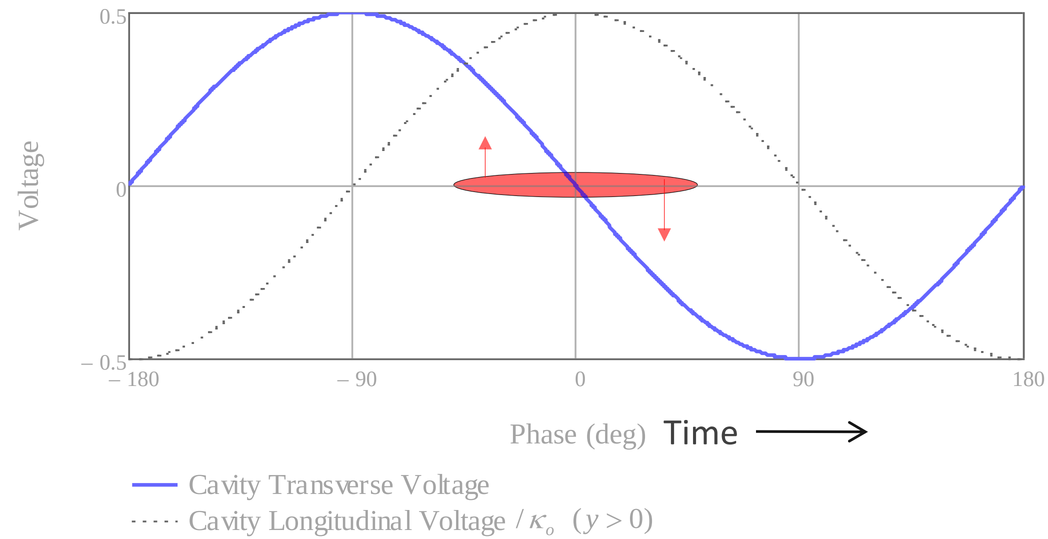


Magnetic Field

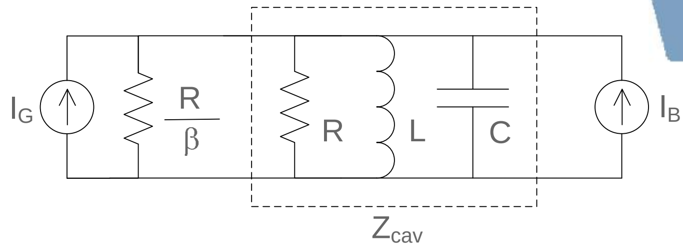
Electric Field

$$V_z(y) = V_m \cdot y$$ Longitudinal voltage

$$V_t = j\frac{V_m}{\kappa_o}$$ Vertical deflecting voltage

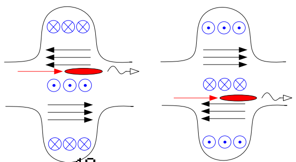


Beam loading

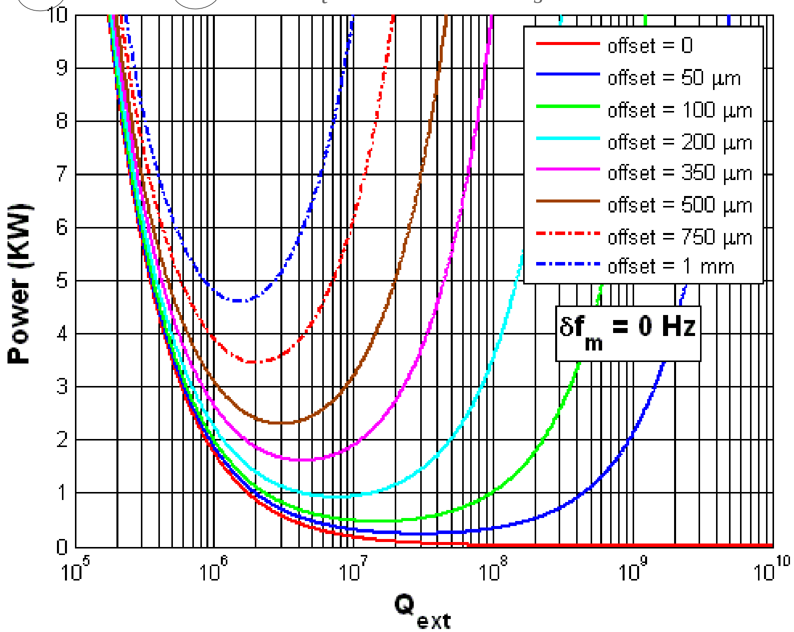


RF Generator power

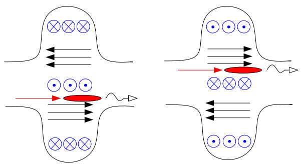
$$P_g^+ = \frac{V_t^2}{8\beta\left(R/Q\right)Q_o}\cdot\left[\left(\beta+1+\frac{P_B}{P_{cav}}\right)^2+\left(2Q_o\frac{\Delta f+\delta f_m}{f_r}+\frac{P_B}{P_{cav}}\tan\phi_s\right)^2\right]$$

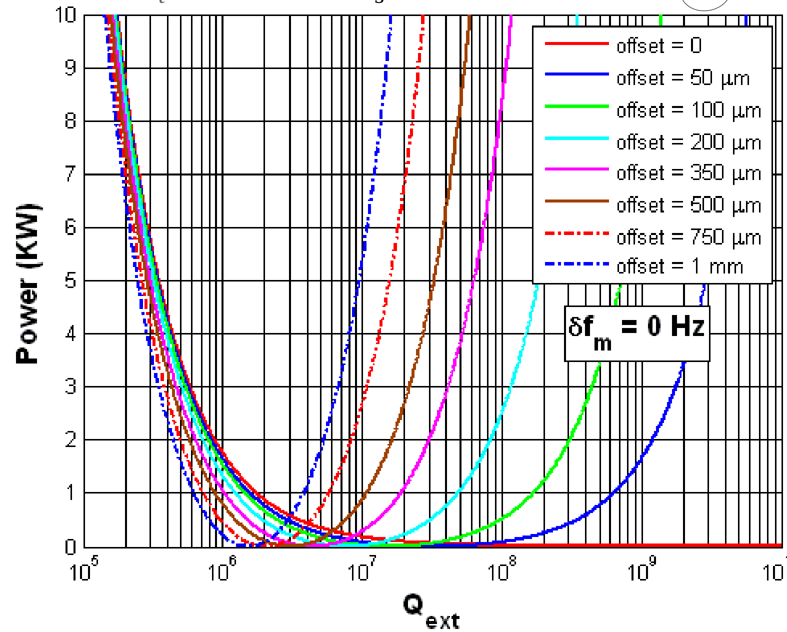


$V_t \cdot y > 0 \quad \phi_s = 0$ No Tilt

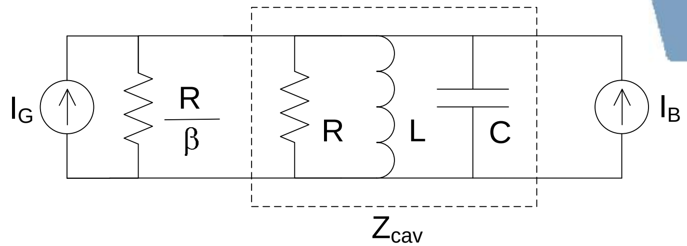


$V_t \cdot y < 0 \quad \phi_s = 0$ No Tilt





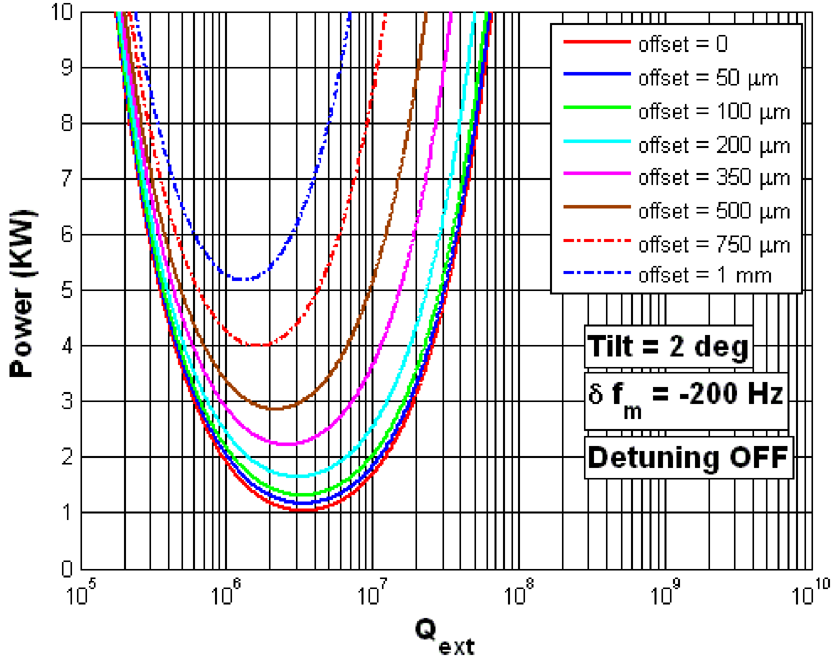
Beam loading



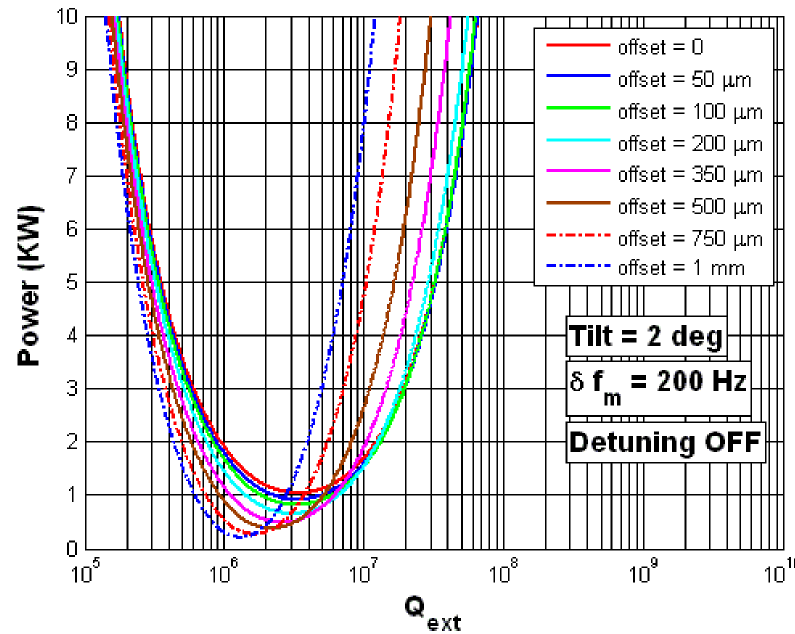
RF Generator power

$$P_g^{+} = \frac{V_t^{2}}{8\beta (R/Q) Q_o} \cdot \left[\left(\beta + 1 + \frac{P_B}{P_{cav}}\right)^{2} + \left(2Q_o \frac{\Delta f + \delta f_m}{f_r} + \frac{P_B}{P_{cav}} \tan \phi_s \right)^{2} \right]$$

$V_t \cdot y > 0$ Tilted Beam No Detuning



$V_t \cdot y < 0$ Tilted Beam No Detuning



Beam loading

- Beam Loading is offset and tilt dependent

- Unless the operating parameter space is constrained…
  - required generator dynamic range is nearly infinite and >180deg control range is needed
  - wide range in optimal loaded Q (~ 1 decade for examples shown)

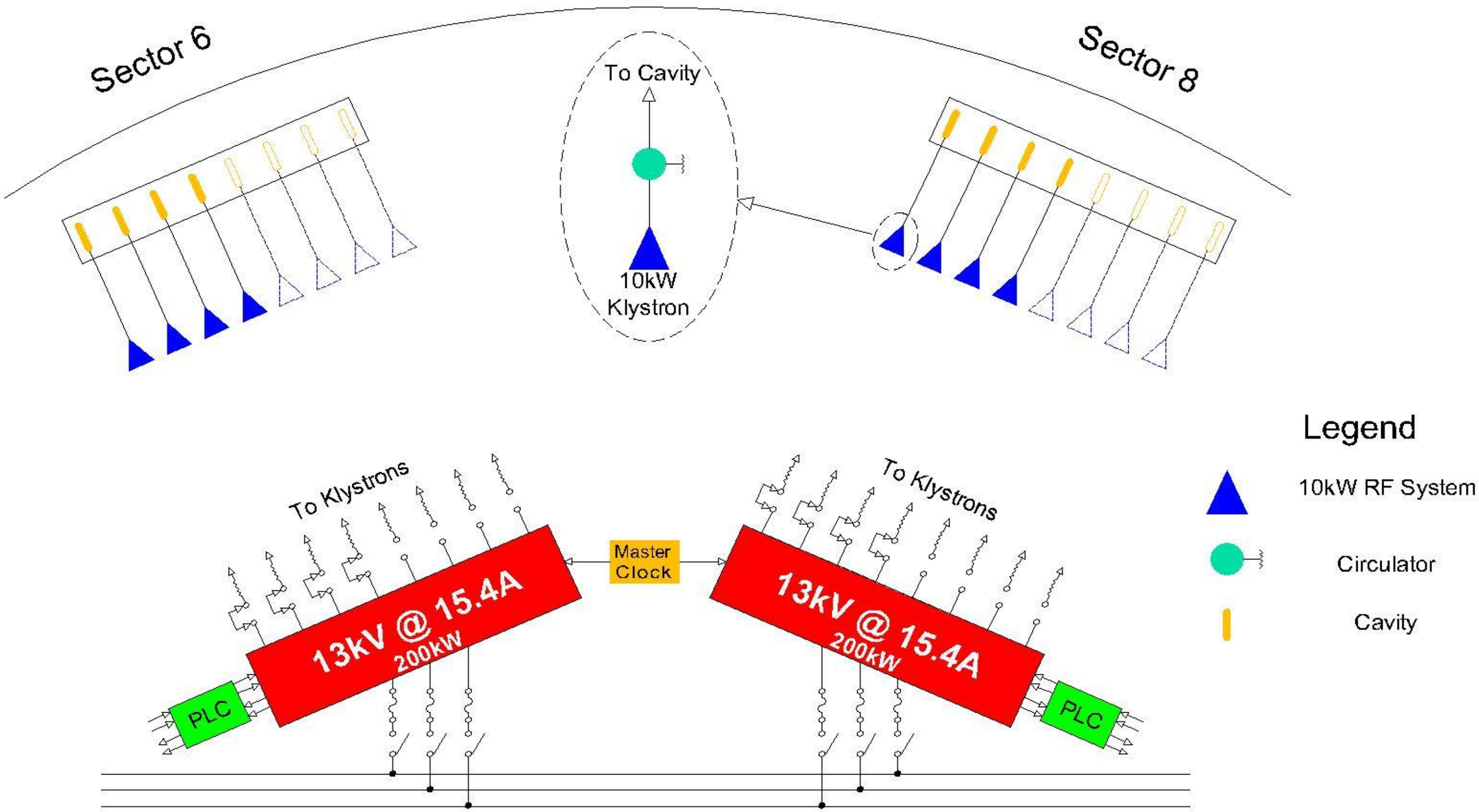
- cavity-to-cavity **electrical** center alignment is important

- Loaded Q not only influences power requirements, but also influences specification on Machine Protection System against uncontrolled beam offset

- Need to consider longitudinal Robinson stability conditions for offset beam

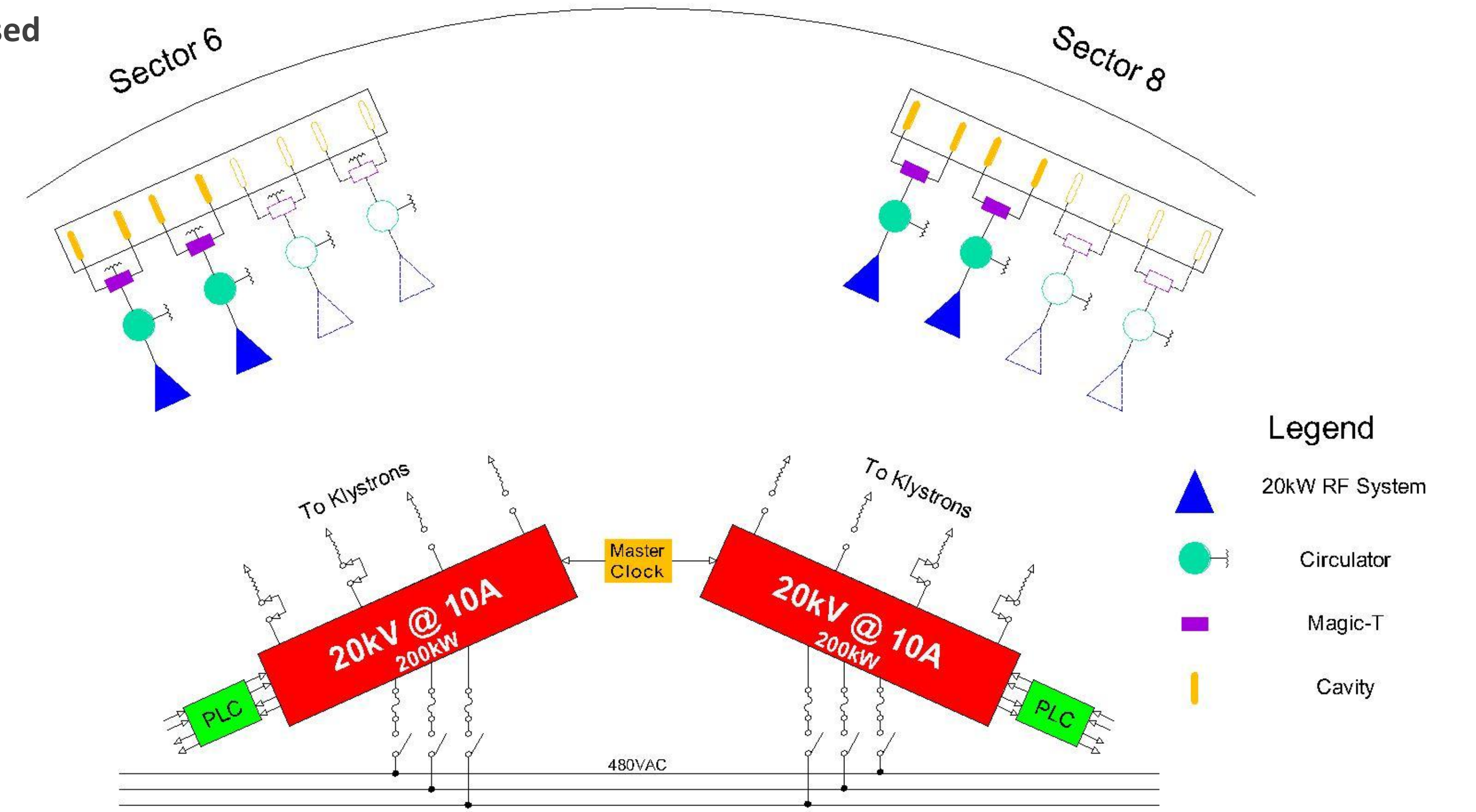
Baseline HLRF System Design

- **10kW klystron amplifiers, one per cavity**
- **Common HVPS per sector**
- **Master HVPS switching clock to correlate noise**



Alternate HLRF System Design

- 20kW klystron amplifiers, each driving two cavities
- Magic-Tee hybrid used to split power
- Common HVPS per sector



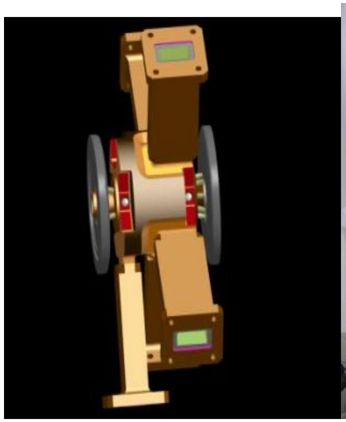
Diagnostics

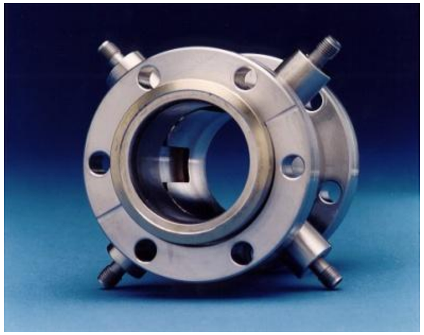
Diagnostics to implement with source development:

- RF BPM upgrade is crucial in maintaining / controlling electron beam trajectory during SPX operation.
- RF phase detector measures bunch arrival time.
- RF tilt monitor measures the chirp/tilt inside and outside of the SPX.
- Optical diagnostics measures x-ray beam vertical profile, extracting information of electron phase, tilt angle and other information about the transverse deflection cavity operations.

Diagnostics to monitor residual effects

- Sensitive rf tilt monitors and synchronized x-ray photon measurements outside of the SPX will be used to minimize the impact of SPX on other users around the ring.





Requirements

- Master Oscillator
  - 351.9 MHz and 2815 MHz
- Crab cavity LLRF
  - 2815 MHz phase reference
  - Calibration reference
  - Local oscillator
  - ADC clock
- Phase reference for beamline lasers (laser-pump/x-ray probe)

- Timing/Reference for Diagnostics
  - Within SPX Zone
    - Beam arrival time monitor
    - Six BPMs
    - Two RF beam tilt monitors
    - X-ray based tilt monitor
  - Outside SPX Zone
    - Two RF beam tilt monitors
    - X-ray based tilt monitor
    - Synchronous detection of residual effects

Beamline lasers

- High-peak power Ti-Sapphire
  - Pulse duration: 50 fs
  - Repetition rate: 1-270 kHz
- High power, sub-cycle TH source
  - Pulse duration: <1 ps
  - Repetition rate: 1- 270 kHz

- UV to mid-IR source
  - Pulse duration: <100 fs
  - Repetition rate: 1-270 kHz
- High repetition-rate fiber laser system
  - Pulse duration: <200 fs
  - Repetition rate: 6.5 MHz

- Cavity phase
  - <7 deg common mode
    - ~7 ps @2815 MHz
    - Keep intensity variation <1%
  - ± 0.03 deg uncorrelated (~30fs @2815MHz
    - Drift >100 Hz
      - Below 100 Hz corrected by orbit feedback system
    - Orbit motion <10% of beam size

- Beamline timing (Yuelin LI)
  - 100-200 fs stability (fraction of x-ray pulse width)
- S35 beamline timing (Bingxin Yang)
  - Same as common mode (~7 picoseconds)

Problem

- One meter of cable with
  - 7 ppm/degC
  - v/c=67%
- Results in ~50 fs/deg C

LBNL Femtosecond-Phase Stabilization System

- Uses frequency offset in the optical domain
  - Optical frequency is offset by an RF frequency (110 MHz)
  - Offers a large leverage over stabilization in the RF domain
    - Six-order-of-magnitude

- The frequency offset process is equivalent to a heterodyning process
  - Heterodyne (mix) original optical frequency with the offset optical frequency
  - Changes in the optical phase translate to identical changes in the 110 MHz beat signal
  - One degree of phase change in the 1530 nm optical domain translates to 1 degree of phase change in RF domain ~21 attoseconds

LBNL Results

- 2.2 km fiber
  - 19.4 fs rms @2850 MHz (60 hours)
- 200 m fiber
  - 8.4 fs rms @2850 MHz (20 hours)

- Complete and test baseline and alternative cavities as a high priority (gradient, Q, Lorentz detuning, pressure sensitivity, HOM Q's)
- Develop tuner concepts for each option
- Develop cryomodule concept for either option
- Develop better options for mechanical alignment or cold adjustability
- Develop low-impedance cold bellows
- Evaluate HOM power above cut-off and where it goes
- Determine cavity to cavity isolation spec for LLRF control
- Evaluate multi-pole components for operating mode and coupling terms in transverse wakes from perturbations in symmetry
- Quantify Operating mode leakage into LOM waveguide (fabrication tolerance)
- Quantify effect of reflections from real loads & windows on achievable Q's
- Perform on-line test of realistic slice as early as possible to allow time for corrections (need to develop temporary cryo, controls & test plans)
- Make normal conducting high Q cavity and develop LLRF system
- Obtain Berkley system for 100fsec Synch
- Link cavity and pump laser through ~100m fiber
- Measure present laser jitter
- Add beam phase lock loop to Main Storage Ring RF with Beam Arrival Time
- Cavity Tilt Monitor

- Continuing collaboration with JLab on baseline and alternative cavities design and cryomodule
- Alternative cavity design provides more margin to instability threshold
  - Being investigated in parallel to baseline cavity
  - Encouraging initial results from prototype
- Will down select in R&D phase
- Design of damper and tuner will commence soon
- Design modifications for improved cavity-to-cavity alignment or adjustments will be investigated
- In the process of establishing a formal collaboration with LBNL on LLRF controller and timing/synchronization system
- We believe, overall technical solution looks feasible but challenging in key parameters.
  - Phase stability
  - HOM damping
  - Alignment
  - Impact on the APS storage ring reliability
- We have started a comprehensive R&D program to address these challenges in the next three years.