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SPX: Short-Pulse X-Ray Generation Using RF Deflecting Cavities

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Advanced Photon Source

ESRF, Spring8, APS Three-Way Meeting (3WM08)

U.S. Department of Energy

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SPring-8

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Outline

- Existing and Future Sources
- Rf crabbing concept
- Beam emittance growth
- X-ray performance
- Technology options and challenges
- Summary

Existing and Future Sources

- Table-top plasma sources
  - **Short pulse 300 fs - 10 ps**
  - **Divergent radiation - low flux**
  - **Low rep-rate (10- 1kHz)**
  - **Not tunable (target dependent)**
- Storage Rings
  - **~100-ps duration pulse**
  - **Spontaneous x-ray radiation**
  - **High average brightness at high repetition rate**
- Laser Slicing (ALS, SLS, BESSY)
  - **Short pulse 100 -300 fs**
  - **Rep-rate kHz**
  - **Low flux 105 ph/s @ 0.1%bw**
  - **Not effective at high-energy sources**
- Linacs (LCLS/XFEL)
  - **Short pulse 100 fs**
  - **Fully coherent**
  - **Extremely high brilliance**
  - **Low rep-rate (100 Hz)**
  - **Limited tunability**

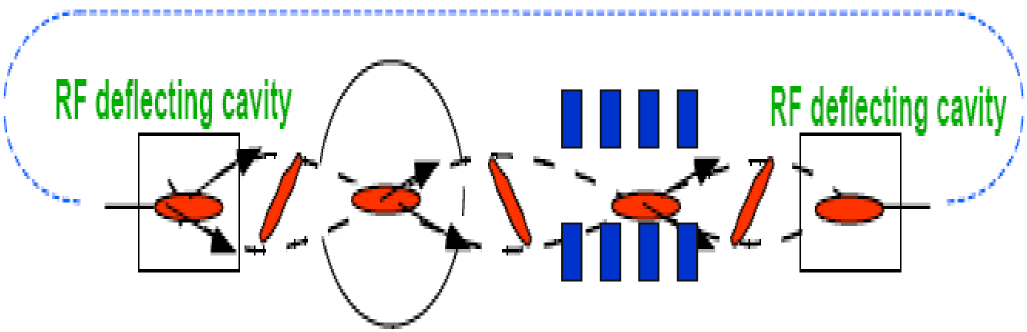
What is important to the users?

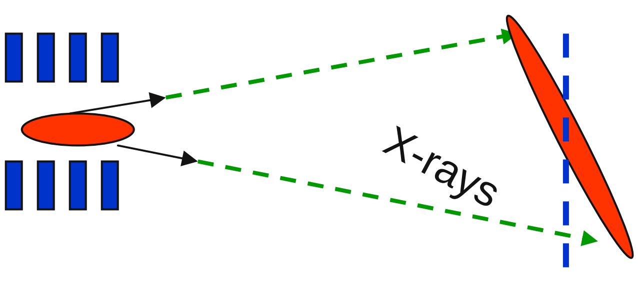
- Peak brightness isn't everything
- What is important is a combination of:
  - Short pulse (1ps or below)
  - Tunability
  - Repetition rate (1 kHz to CW)
  - Accessibility
  - Average number of photons
  - Focusibility

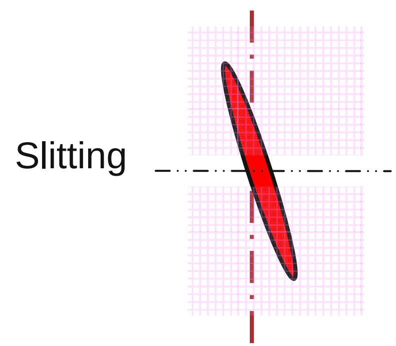
Flexible source will enable new physics

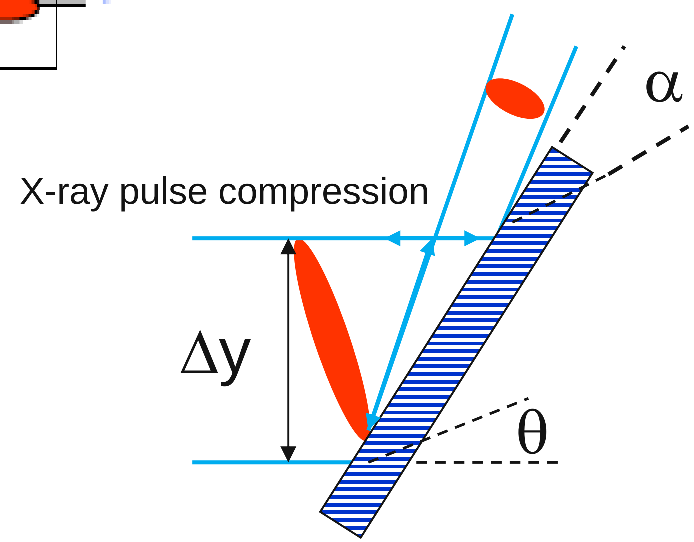
Concept

- Use transverse-deflecting rf cavities to impose a correlation (“chirp” between the longitudinal position of a particle within the bunch and the vertical momentum.
- The second cavity is placed at a vertical betatron phase advance of $n\pi$ downstream of the first cavity, so as to cancel the chirp.
- With an undulator or bending magnet placed between the cavities, the emitted photons will have a strong correlation among time and vertical slope.
- This can be used for either pulse slicing or pulse compression.





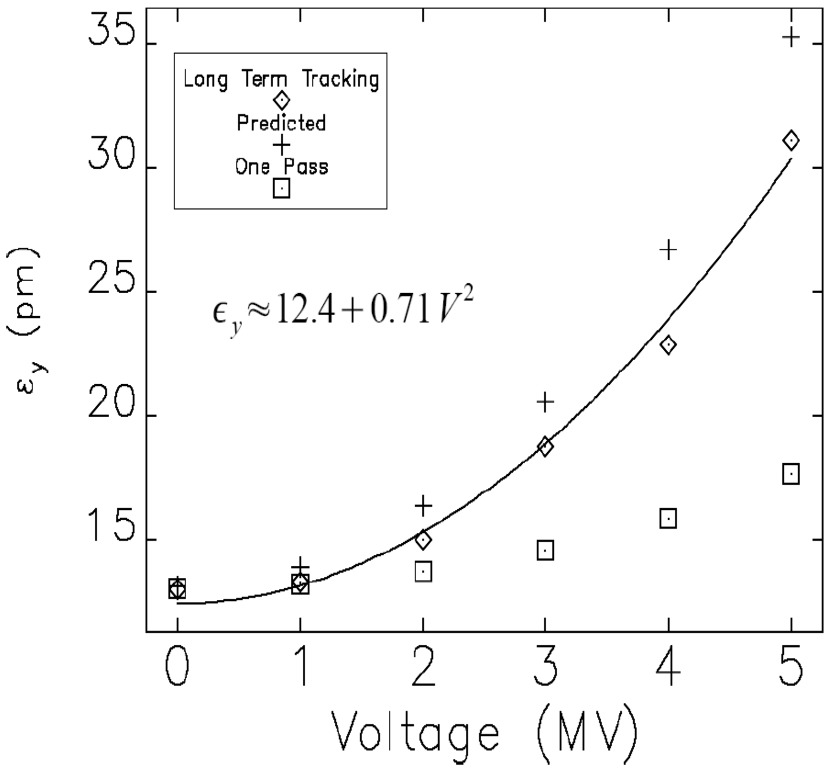




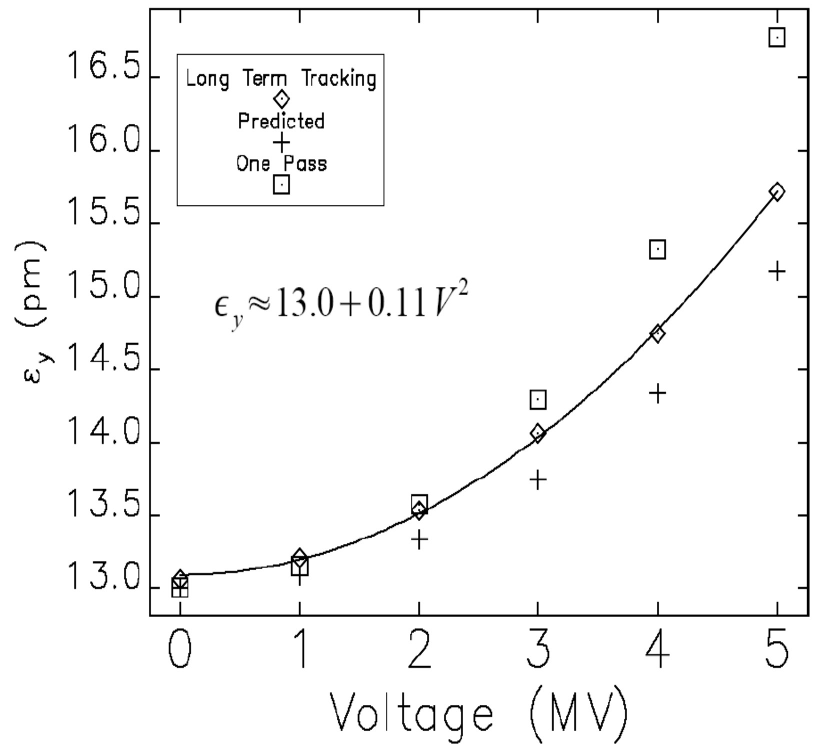
A. Zholents, P. Heimann, M. Zolotorev, J. Byrd, NIM A 425(1999), 385

Emittance growth vs. deflecting voltage

Target Bunch Emittance Growth for 1 kHz Pulse Rate



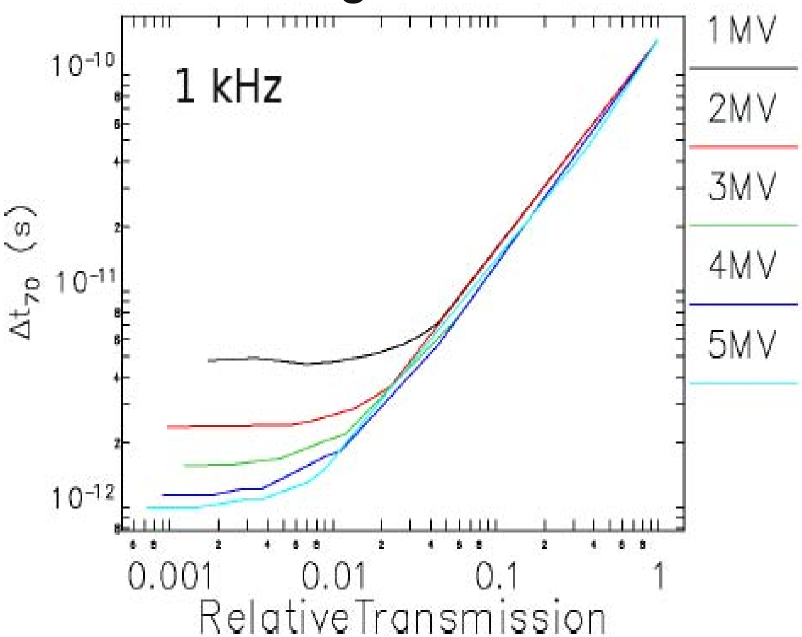
Results for 120 Hz Pulse Rate

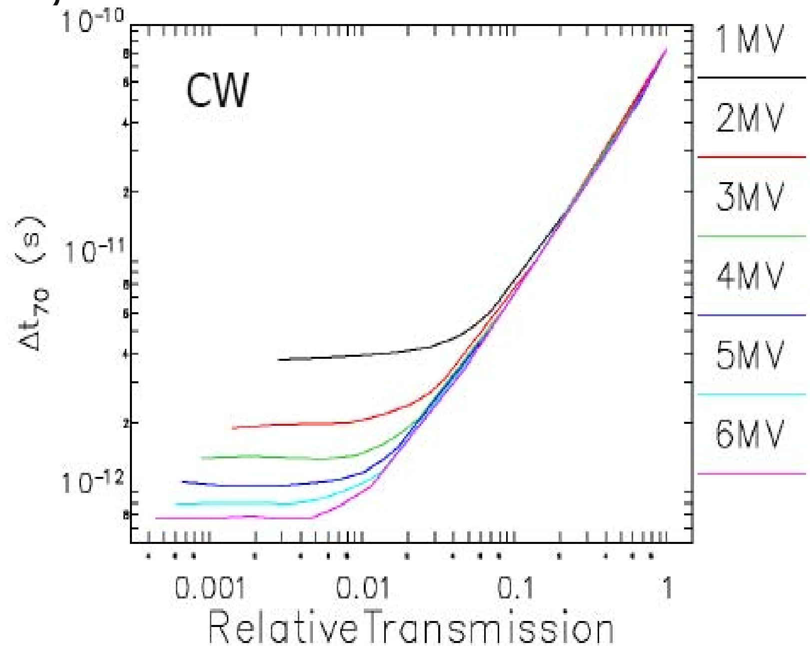


Plots courtesy M. Borland

Performance

- **Two slits at 26.5 m**
  - Vertical slit is varied from ±100 mm to ±0.01 mm
  - Fixed horizontal slit ±0.25 mm (E. Dufrense)
- **Results are very similar up to 4 MV**
  - Curves flatten out for ~1% transmission
  - Vertical slit is ~±0.1 mm at this point
- **CW has an edge due to shorter bunch, smaller emittance**





Slide courtesy M. Borland

Summary of Tolerances

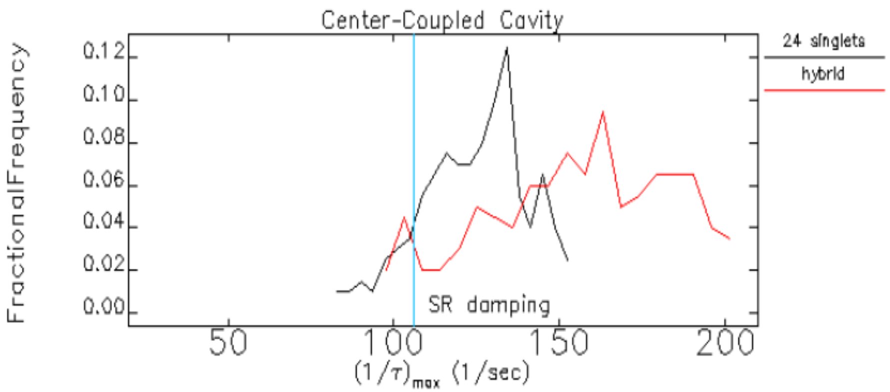
Quantity	Driving Requirement	120 Hz Tolerance	1 kHz Tolerance
Common-mode voltage	Keep intensity and bunch length variation under 1%	±1%	±1%
Differential voltage	Keep emittance variation under 10% of nominal 25 pm	±0.29%	±0.13%
Common-mode phase relative to bunch arrival	Constraint intensity variation to 1%	±10 deg	±10 deg
Differential phase	Keep emittance variation under 10% of nominal 25 pm	±0.16 deg	±0.05 deg
Rotational alignment	Emittance control	~1 mrad	~1 mrad
Net residual voltage	Emittance control (weak bunches)	26 kV	13 kV

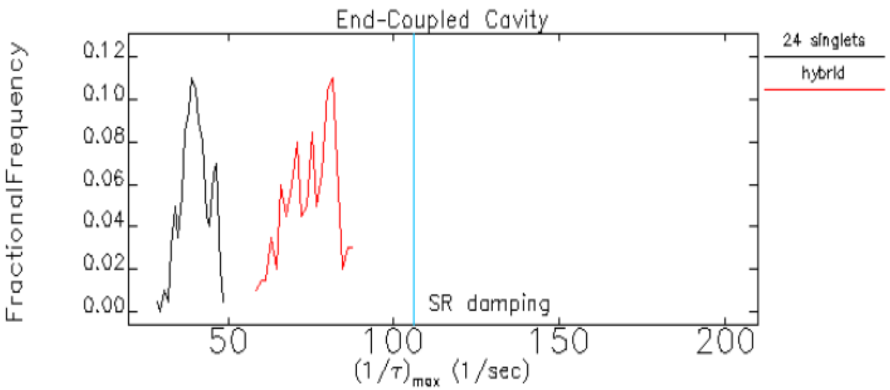
- Differential errors are assumed to be "static"
- CM errors may be dynamic, but conservatively evaluated as static
- Temperature control should be AGARA. We'll have to manage temperature-related drifts with phase shifters and attenuators.
- Tolerance on timing signal from crab cavity to users: ±0.9 deg

Slide courtesy M. Borland

Beam stability Analysis - HOM/LOM

- For three-cell cavities with coupler at end cell using 3D model for R, Q, and R/Q values
- Qs of longitudinal and horizontal planes are very low (20 – 200)
- Worst vertical plane HOM has a Q of 4100
- Horizontal and vertical planes are stable with synchrotron radiation
  - No need for coherent damping



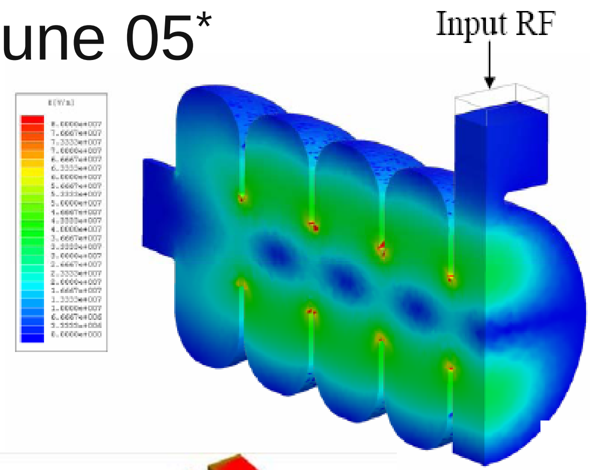


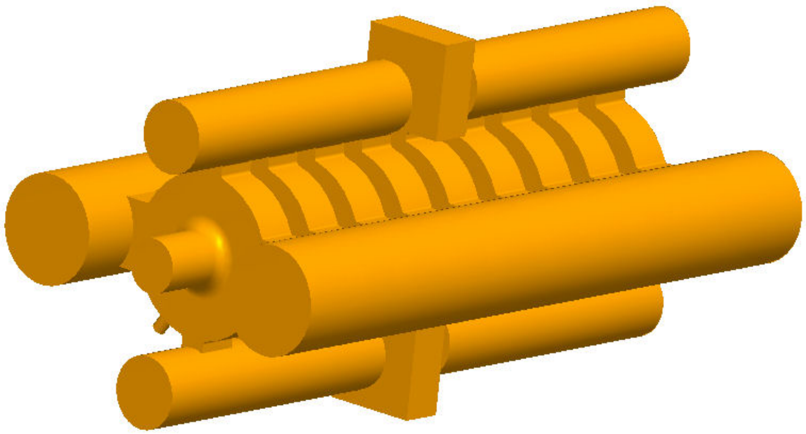
Plane	Growth Rate	Damping Rate		Comment
		Synchrotron Radiation	Coherent	
Longitudinal	60 s^{-1}	208 s^{-1}	Not applicable	Stable
Horizontal	5 s^{-1}	104 s^{-1}	>600 s^{-1}	See above
Vertical	80 s^{-1}	104 s^{-1}	>600 s^{-1}	See above

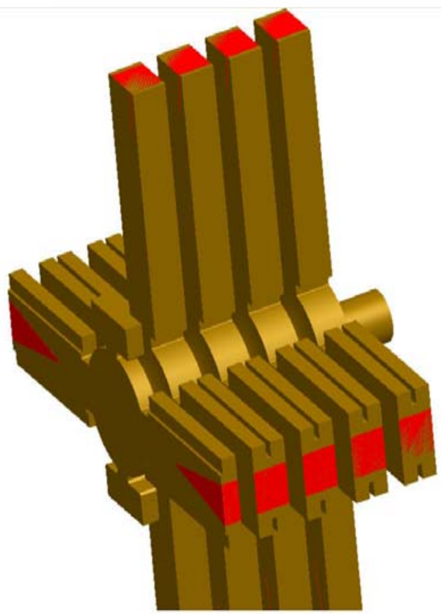
Slide courtesy L. Emery

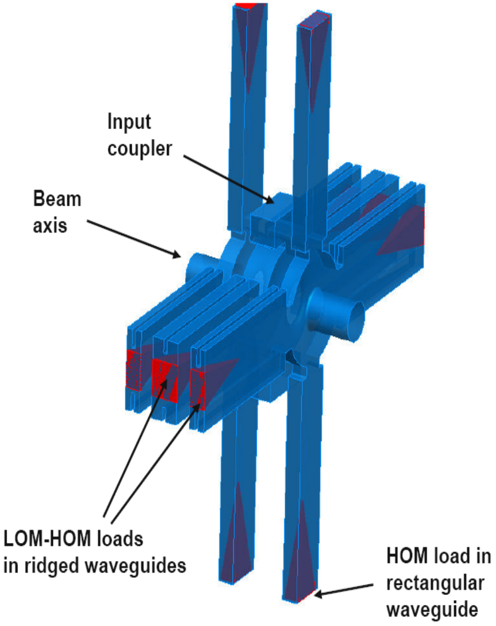
Cavity Design Evolution

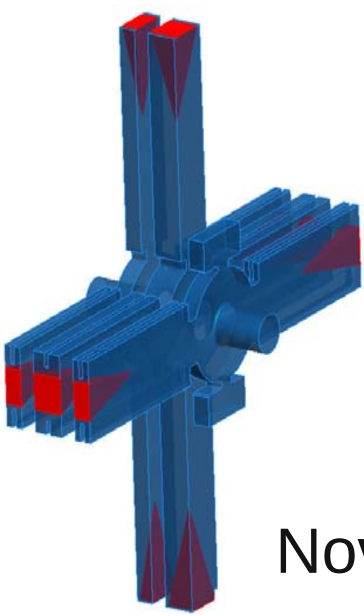
June 05*











Nov 07**

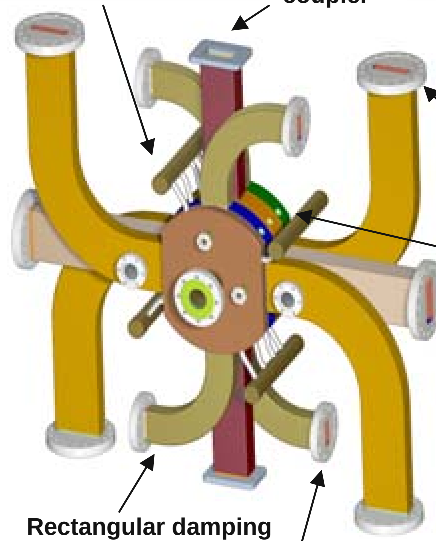
* V. Dolgashev, SLAC

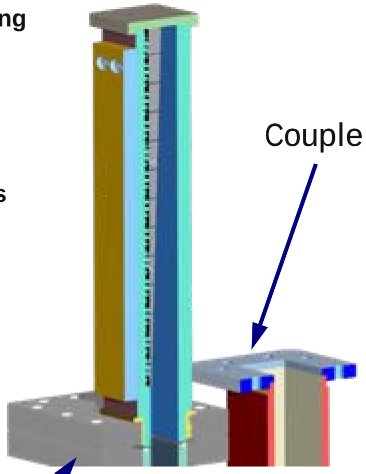
** V. Dolgashev, SLAC, G. Waldschmidt, A. Nassiri

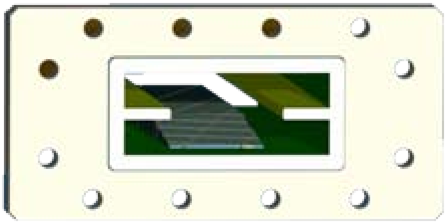
APS Short Pulse X-Ray Normal-Conducting Cavity Design*

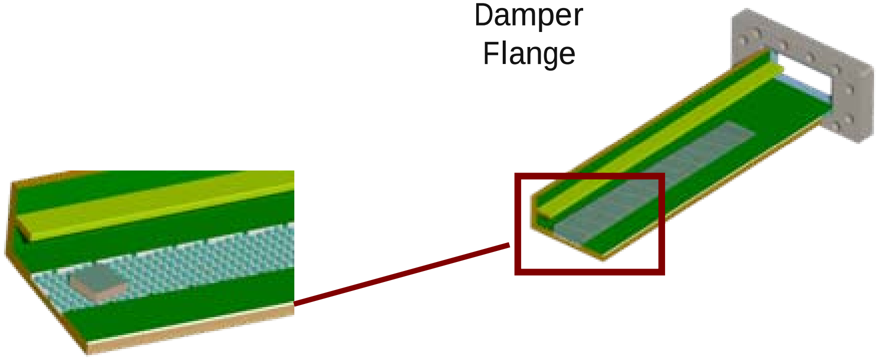
Frequency	2.815 GHz
Deflecting Voltage	2 MV
Peak Power	2.8 MW
Working mode Q_o	12000
R_t / Q	117
Iris radius	22 mm
Phase advance	π
Structure length w/o beam pipes	11.17 cm
Duty Factor	0.147%
Pulse Rate	1.0 kHz
Kick / (Power) $^{1/2}$	1.19 MV/MW$^{1/2}$
Beam Current	100 mA

Normal-conducting 3-cell cavity with damping waveguide and dual input couplers





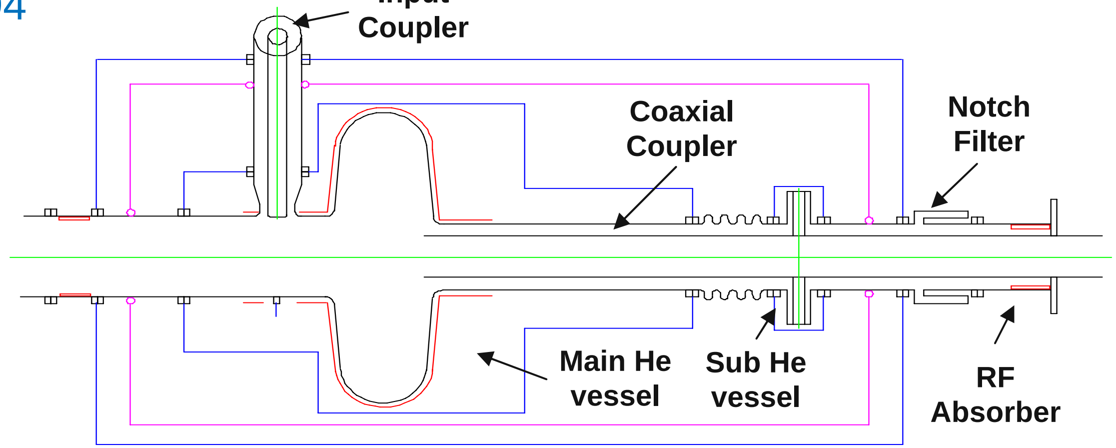




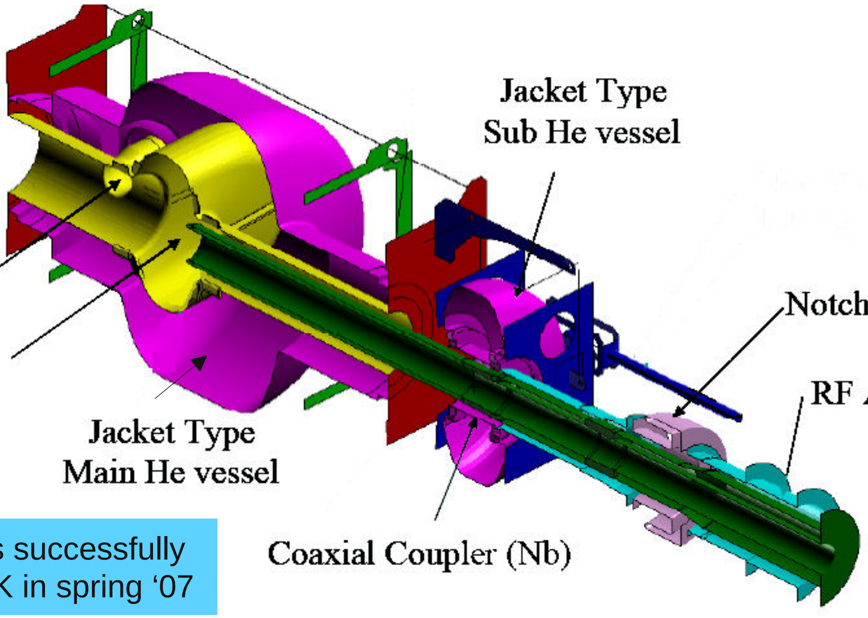
*I In collaboration with V. Dolgashev (SLAC)

KEK Single-Cell 500 MHz Crab Cavity*

1/3-scale prototyping started in 1994



Frequency (MHz)	501.7
Deflecting Voltage	1.44 / 1.41 MV
G	220
R / Q (Ω)	46.7
Min beam radius	10.0 cm
E_{sp}/V_{defl} (1/m)	14.4
B_{sp}/V_{defl} (mT/MV)	41.5

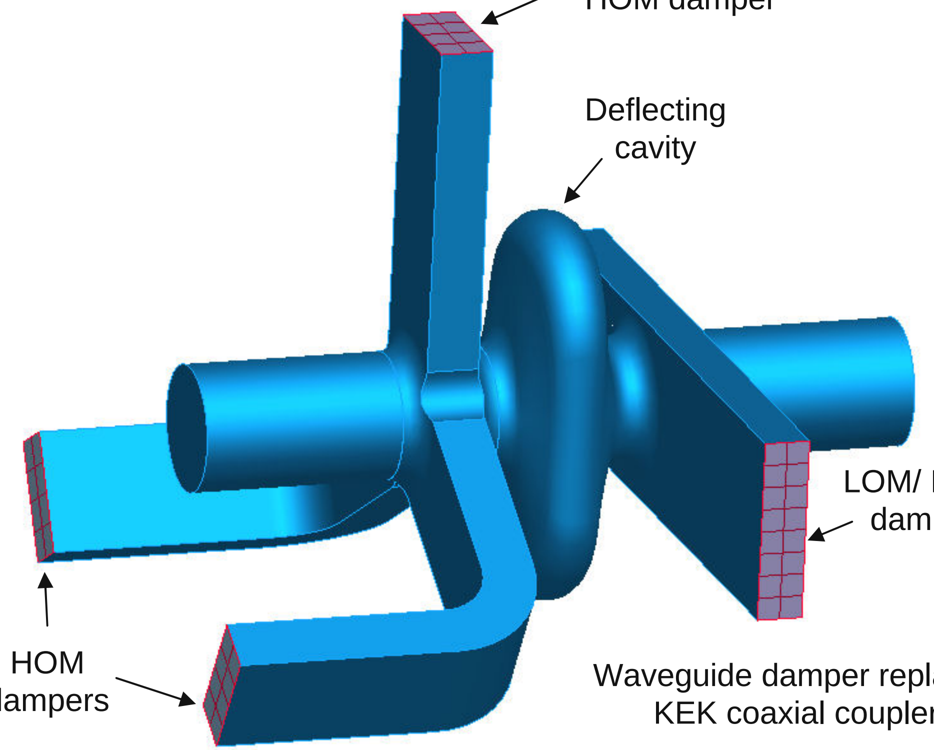


Crab cavity was successfully operated at KEK in spring '07

* K. Hosoyama, KEK

APS 2.8 GHz Superconducting Single-Cell Deflecting Cavity[1]

Frequency (GHz)	2.815
Deflecting Voltage	4 MV * 2
Qo (2K)	$3.8 * 10^9$
G	235
R_T / Q (Ω/m)	37.2
Beam radius	2.5 cm
No. Cavities	12 * 2
Operation	CW
Beam Current (mA)	100
E_{sp}/V_{defl} (1/m)	83.5
B_{sp}/V_{defl} (mT/MV)	244.1

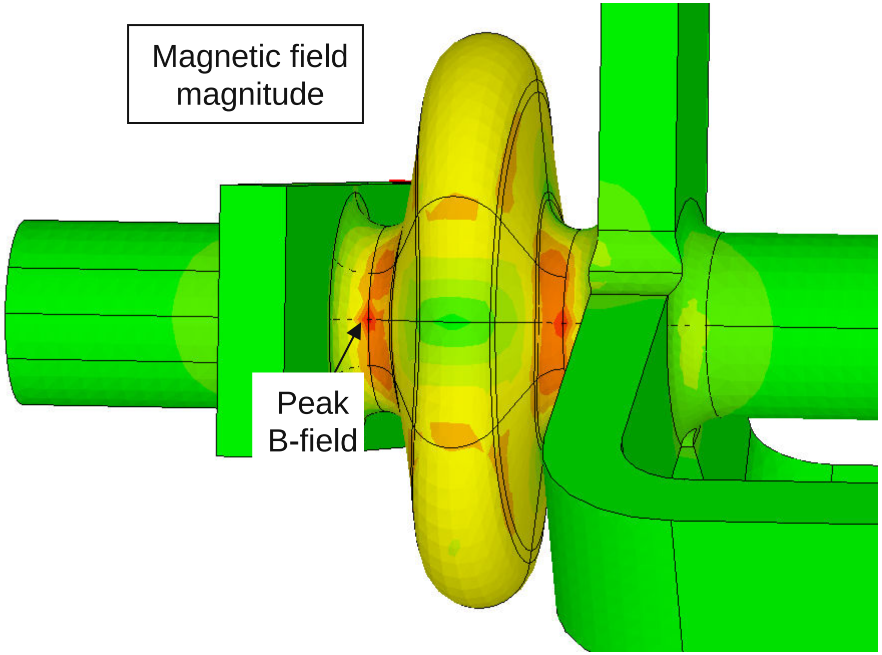


Compact single-cell cavity / damper assembly

[1] In collaboration with JLab and LBL

Deflecting Mode

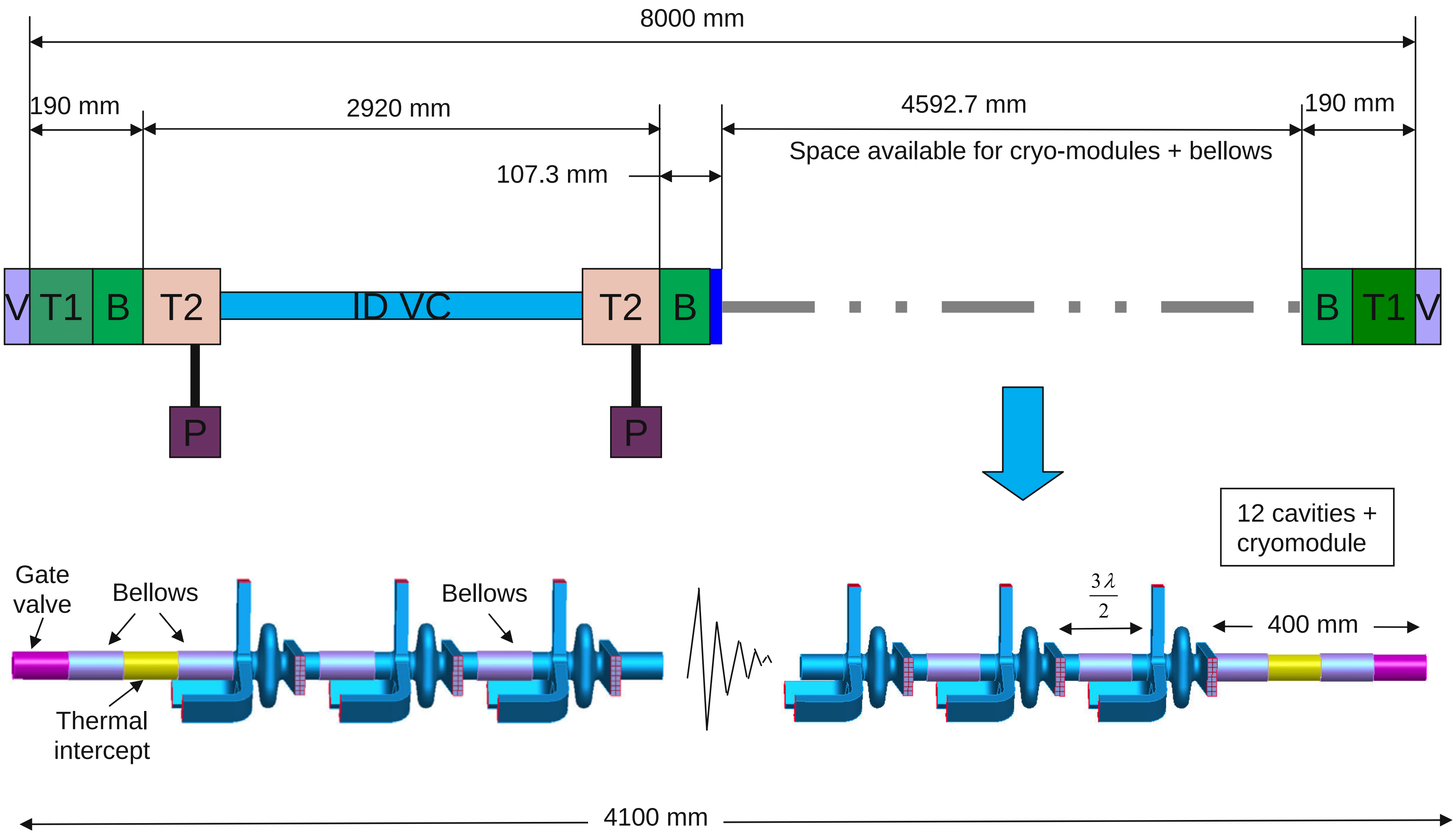
- Dampers create a 37% increase in peak magnetic field
- Strong damping requirements for APS necessitate damper proximity to cavity
- Total number of cavities is determined such that peak magnetic field is < 100 mT
- 12 mm clearance between cavity and dampers (on either side) for tuning plates.
- An elliptical beam pipe was investigated for reducing peak magnetic field, but little improvement was found in the ratio mT/MV.



	Peak mt/MV	Rt/Q	G
1-cell	178.8	36.3	239
1-cell w/ LOM	244.1	37.2	235

Deflecting mode parameters with and without dampers

Deflecting Cavity Layout - Schematic



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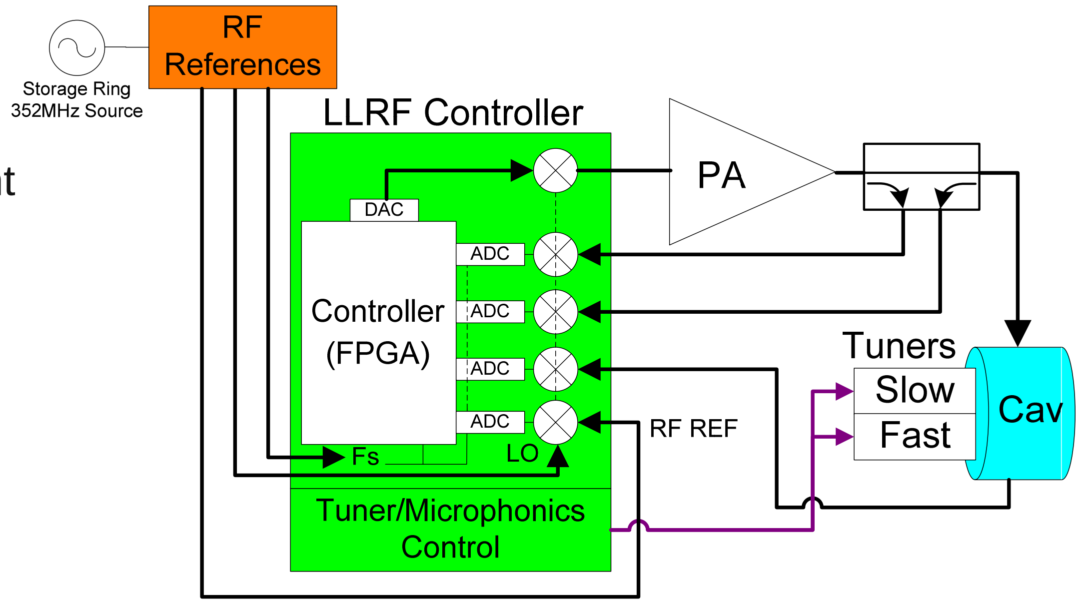
CW SRF - RF Control Challenges

- Differential Phase Error Specification: ±0.04 deg
- Differential Voltage Error Spec: ±0.29 %
- Architecture Tradeoffs:
  - Single Drive Amplifier: Correlated errors cancel, but need individual I/Q modulators
  - Individual Drive Amplifiers: Provides individual low level control, but residual phase noise is uncorrelated.
- Self-Excited Loop & Tuner Control Algorithms for fast recovery from quench/trips in presence of large static Lorentz detuning (JLab has made excellent progress in this area)
- Microphonics Mitigation
- Calibration Algorithms (cancel kick, reduce drift)
- Phase stable reference & cable plant
- Low noise down-conversion



Slide courtesy T. Berenc

Summary

- Short X-ray pulse generation at the synchrotron light sources will open up new frontiers in time domain science using X-ray techniques to study structural dynamics included but not limited to:
  - Condensed Matter, Chemical and Biological, Gas Phase Dynamics
- Both normal conducting room-temperature and SRF option are feasible but SRF offers significant advantages
  - Is not limited to SR bunch trains fill patterns
  - Higher flux and higher repetition rates up to CW
- It is complimentary to LCLS with the added advantage of energy tunability which is a unique feature in comparison to XFEL sources
  - Provides spectral coverage and resolution that is necessary in detecting electronic and nuclear geometry on ps-time scale
- Light source-based short x-ray pulse generation via Zholents' scheme has the capability of accommodating multiple users
- ANL-APS is taking a lead to develop an SRF deflecting system generating ps-type x-ray pulses.
- We invite and welcome collaborators to join us.