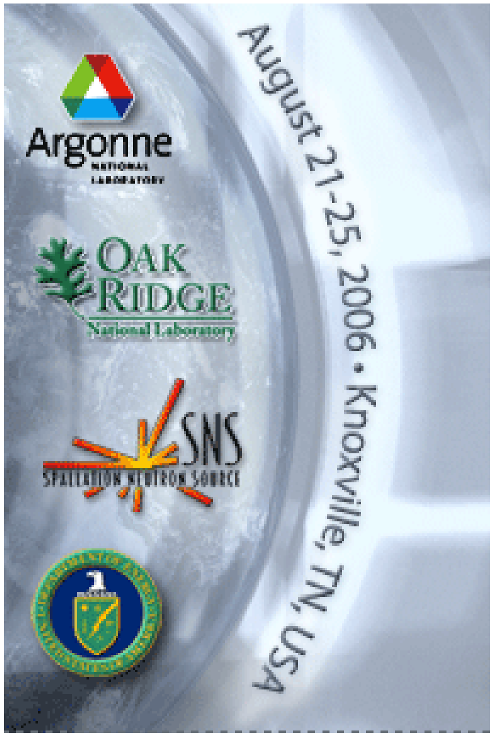
Highlight of LINAC 2006 Conference

Gianluigi Ciovati

CASA/SRF Institute Seminar

09/14/2006



http://www.sns.gov/linac06/

- 46 invited talks/5 days
- 68 posters mainly on beam dynamics, Linac designs, commissioning
- 92 posters mainly on Linac technologies (Diagnostic, cavities, sources)
- 93 posters mainly on RF systems and controls

Outline

- Linacs commissioning
  - SNS, J-PARC, ISAC-II
- Future accelerators
  - ILC, 100 kW FEL, Plasma-wake
- Components
  - SRF cavities
  - Photoinjectors
  - Cryomodules for ERLs

Acknowledgements

Thanks to S. Henderson, D. Nguyen, P. Piot, I. Campisi for providing me material for this talk

MO100 – Particle physics and the responsible use of public resources (H. Shapiro)

- High energy physics US budget: M$ 800, stagnant over past 10 years
- EPP2010: National Academy of Sciences committee for 15 years implementation plan for particle physics
- Status of US program:
  - Significant risk of losing substantial resources
  - Major experiments near the end

- ILC
  - Wait for a cost estimate
  - Wait for results from LHC
  - US is no credible bid to host ILC now
- International optimization of experimental facilities
- High energy physics is at a crossroad and the committee thinks US should play a major role in this field in the future
- FermiLab will become the only major US lab for particle physics

LINACs Commissioning

MO101 – Commissioning and initial operating experience with the SNS 1 GeV Linac (S. Henderson)

First Beam on Target, First Neutrons and Technical Project Completion Goals Met April 28, 2006

- Beam and Neutronics Project Completion goals were met
  - 10^{13} protons delivered to the target
- Formal Project Completion in June 2006

Saturday News Sentinel

Spallation celebration

OAK RIDGE NATIONAL LABORATORY

Lab scientists, engineers, instrument specialists and others gather moments before the first neutrons were produced Friday at the $1.4 billion Spallation Neutron Source. The facility will allow cutting-edge studies of materials.

Neutron source's test drive paves the way for research

One of several diagnostic screens shows the successful delivery of protons to a mercury target, producing neutrons for scientific research of materials.

OAK RIDGE — They're finally making neutrons at the nation's premier science research project.

A proton pulse hit the target at 2:04 p.m. Friday and released trillions of neutrons at the Spallation Neutron Source facility.

"There was a loud cheer, and everyone clapped," said Thom Mason, project director. "There was a lot of relief and elation.

"There are a lot of happy people."

Mason described Friday's event as a "key technical milestone for completing the project."

"We're now officially a neutron source," he said.

Ninety minutes after the initial proton pulse hit the mercury target and released the trillions of neutrons Friday afternoon, researchers revved up the pulse's intensity, Mason said.

A beam with a 10 trillion proton pulse then hit the target to release neutrons, he said. A phosphorescent screen on the target showed the beam profile.

"It made a nice, pretty picture," he said.

That stepped-up proton pulse is the level of intensity needed for a host of scientific experiments planned at the Spallation Neutron Source, Mason said.

Even when it is running at just 20 percent of its maximum capacity the facility will still be the most powerful source of neutrons in the world.

Scientists plan to use the $1.4 billion SNS to perform cutting-edge studies on various materials.

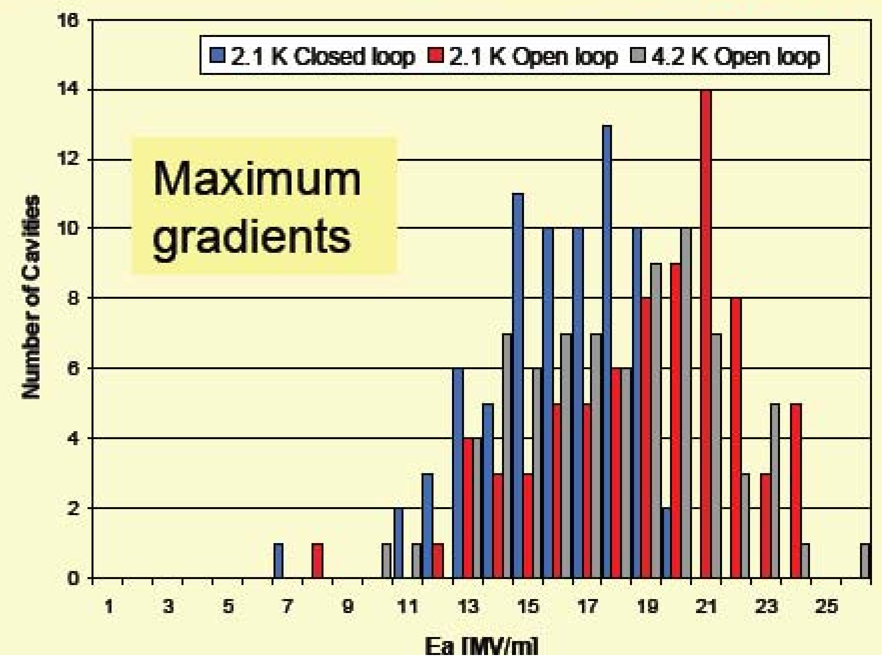
"We're now officially a neutron source."

Thom Mason, Spallation Neutron Source project director

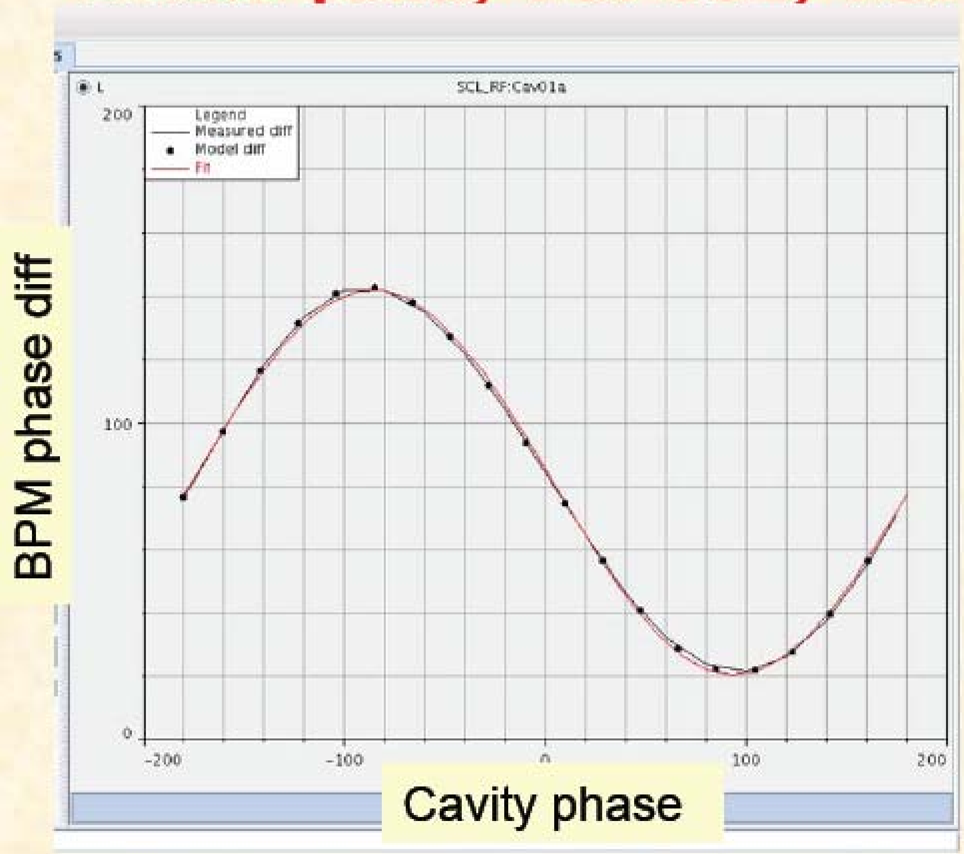
See **NEUTRONS** on A8

Superconducting Linac

- **SCL accelerates beam from 186 to 1000 MeV**
- **Cryomodules Designed and built by Jefferson Laboratory**
- **SCL consists of 81 independently-powered cavities in 23 cryomodules**
- **Two cavities geometries, (β_g=0.61, 0.81) are used to cover broad range in particle velocities**
- **E_{acc} specification = 10.2 MV/m (med-beta) and 15.6 MV/m (hi-beta)**
- **He plant supports operation at 2.1K**
- **Most operation has been at 4.2 K**
- **Operational gradients are maintained at 80% of maximum fields**



Superconducting Linac Tuneup by Phase Scan *(Chu, TUP032, TUP084; Jeon TUP071)*

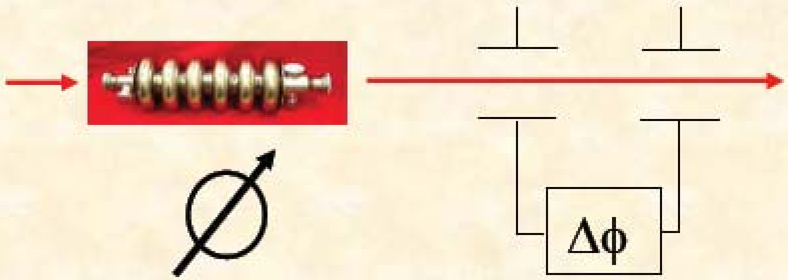


SCL phase scan for first cavity

Solid = measured BPM phase diff

Dot = simulated BPM phase diff

Red = cosine fit



- **Fit varies input energy, cavity voltage and phase offset in the simulation to match measured BPM phase differences**
- **Relies on absolute BPM phase calibration**
- **With a short, low intensity beam, results are insensitive to detuning cavities intermediate to measurement BPMs**

Linac RMS Transverse Emittance

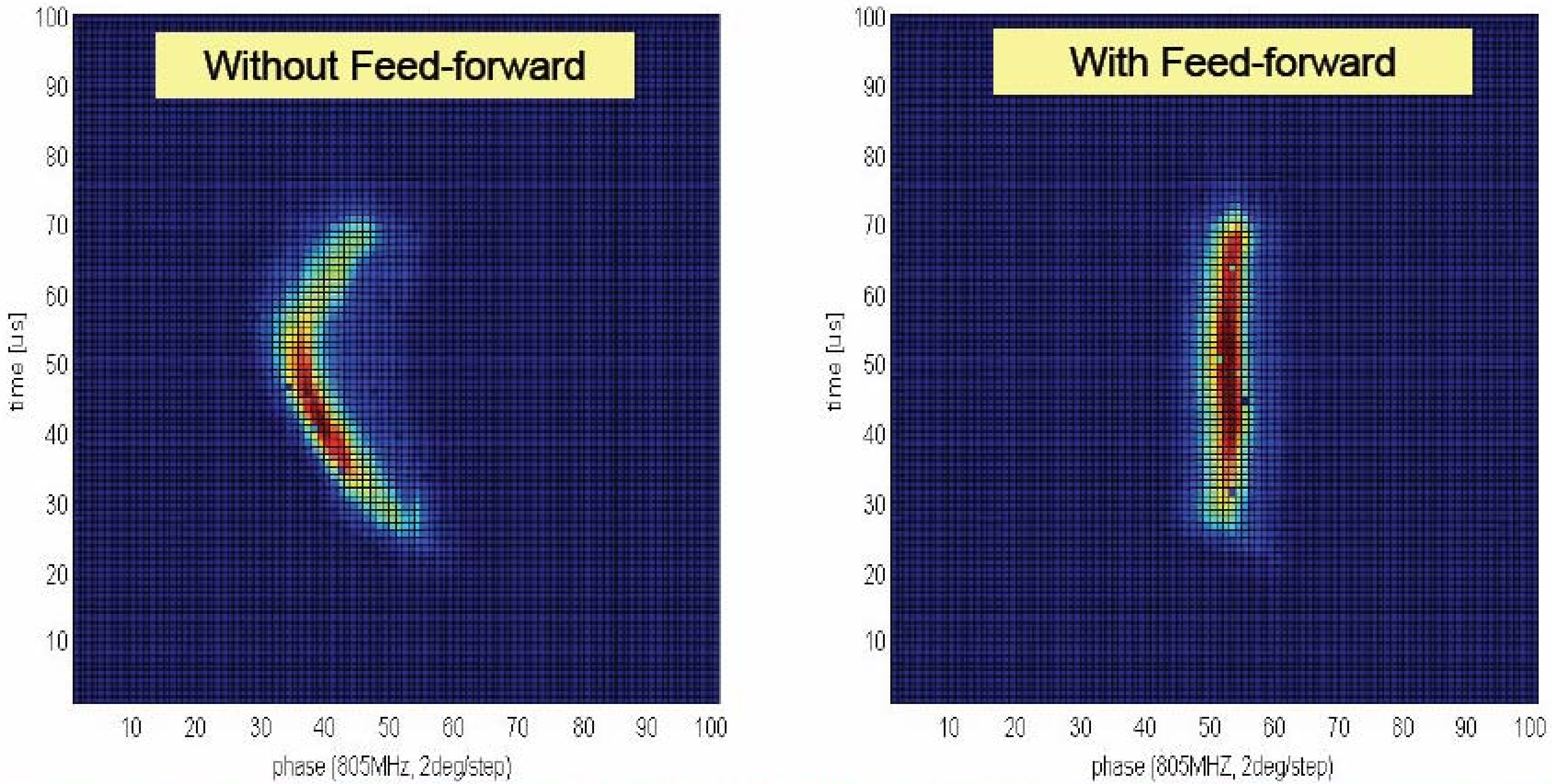
(J. Galambos, V. Danilov, D. Jeon)

	Measured ε (H, V) norm. π-mm-mrad	Parameter List ε (H, V) norm. π-mm-mrad	Notes
MEBT Entrance	0.22, 0.25	0.21	RFQ Exit Twiss study
CCL Entrance	0.22, 0.25	0.33	Matching 7 CCL profile sets
SCL Entrance	0.27, 0.35	0.41	Matching 3 SCL profile sets
Linac Dump	0.26, 0.27	0.41	1 wire, vary quads

- Measured RMS emittance is within specification

Low-level RF Adaptive Feedforward
(Ma, THP005)

- **Beam turn-on transient gives RF phase and amplitude variation during the pulse, beyond bandwidth of feedback**
- **LLRF Feedforward algorithms are used in operation (Champion, Kasemir, Ma, Crofford)**
- **Plots below show longitudinal distribution during a 50 μsec linac beam pulse**
- **LLRF system routinely gives better than 1%/1 degree amplitude/phase stability**
- **RMS energy jitter is 0.35 MeV, extrema are +/- 1.3 MeV; meets specificaton of +/- 1.5 MeV**



Summary of Beam Parameters Achieved in Commissioning

Parameter	Baseline/ Design	Achieved	Units
Linac Transverse Output Emittance	0.4	0.3 (H), 0.3 (V)	π mm-mrad (rms,norm)
CCL1 bunch length	3	4	degrees rms
Linac Peak Current	38	> 38	mA
Linac Output Energy	1000	952	MeV
Linac Average Current	1.6	1.05 (DTL1 run) 0.004 (SCL)	mA
Linac H-/pulse	$1.6x10^{14}$	$1.0x10^{14}$	Ions/pulse
Linac Pulse length/Rep-rate/Duty Factor	1.0/60/6.0	1.0/60/3.8 (DTL1 run) .050/1/.005 (CCL run) 0.85/0.2/0.017 (SCL)	msec/Hz/%
Protons/pulse on Target	$1.5x10^{14}$	$5x10^{13}$	Protons/pulse

Superconducting Linac Operations

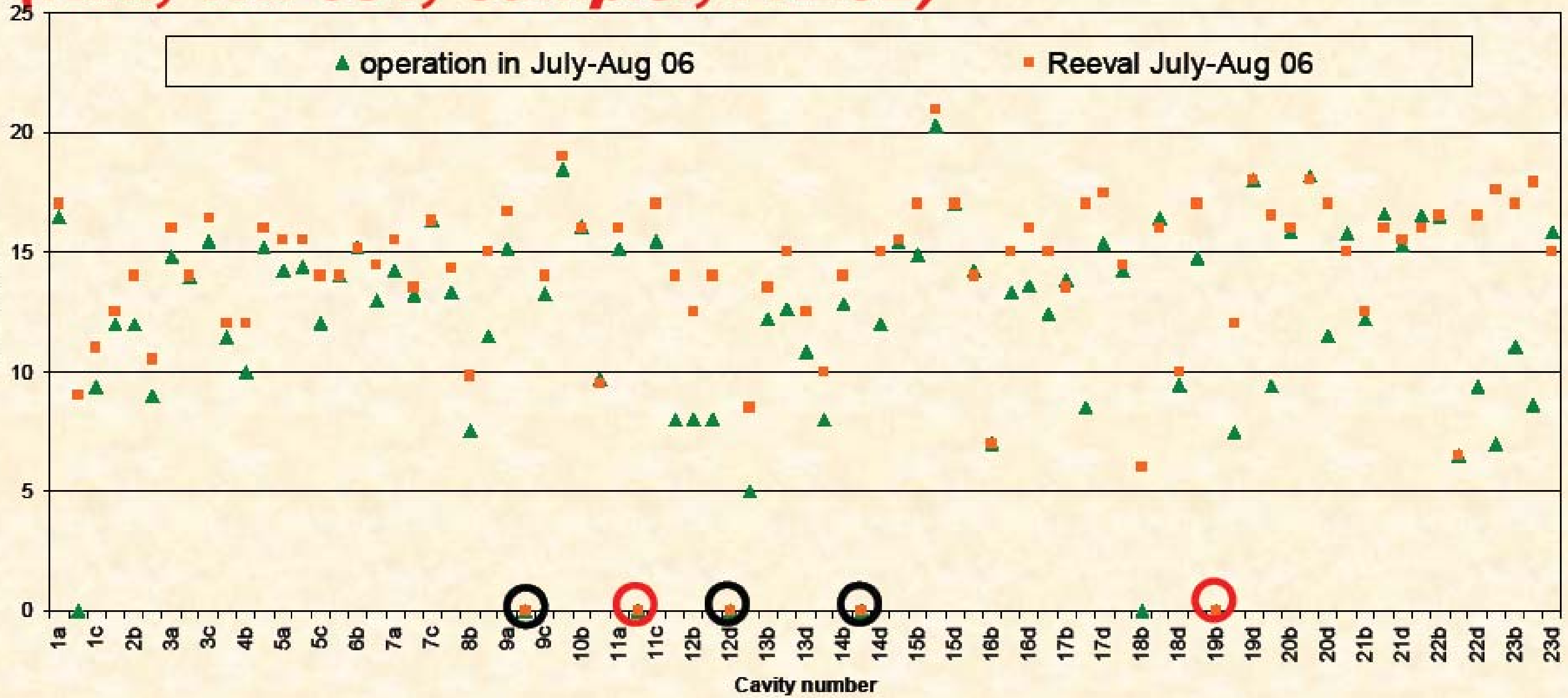
- **Beam Energy**
  - Have operated with ouput energies of 952, 930, 880, 860, 850, 550 MeV.
  - Routine operation has been near 850 MeV
- **Tuneup:**
  - It is faster to establish 81 phase/amplitude setpoints in SCL than for the 10 normal conducting setpoints
- **Flexibility**
  - One of the main benefits of a superconducting linac for proton beams is operational flexibility
  - We have taken advantage of the flexibility of individually powered superconducting cavities to “tune around” cavities with reduced gradients, etc.
  - Have operated with as many as 20 cavities turned off in initial tuneup.

SCL Operational Issues

- HOM couplers
  - 2 cavities are not in service
  - About 10 cavities show abnormal fundamental frequency signals through HOM couplers due mainly to electron activity coupler
  - These cavities are running at reduced gradients and/or lower rep. rate pending further investigation
- Cold Cathode Gauge
  - CCG's are installed to protect the FPC windows as an interlock
  - Many cavities had vacuum trips and were thought to have conditioning problems, which led us to lower gradients
  - We found that some CCG's are sleeping and waking up with sudden bursts/spasms that are making vacuum trips
  - After managing/conditioning CCG's to have proper vacuum reading, cavity operation is unimpeded
  - Currently investigating alternative vacuum interlock strategies

SCL Operations: Cavity Gradients

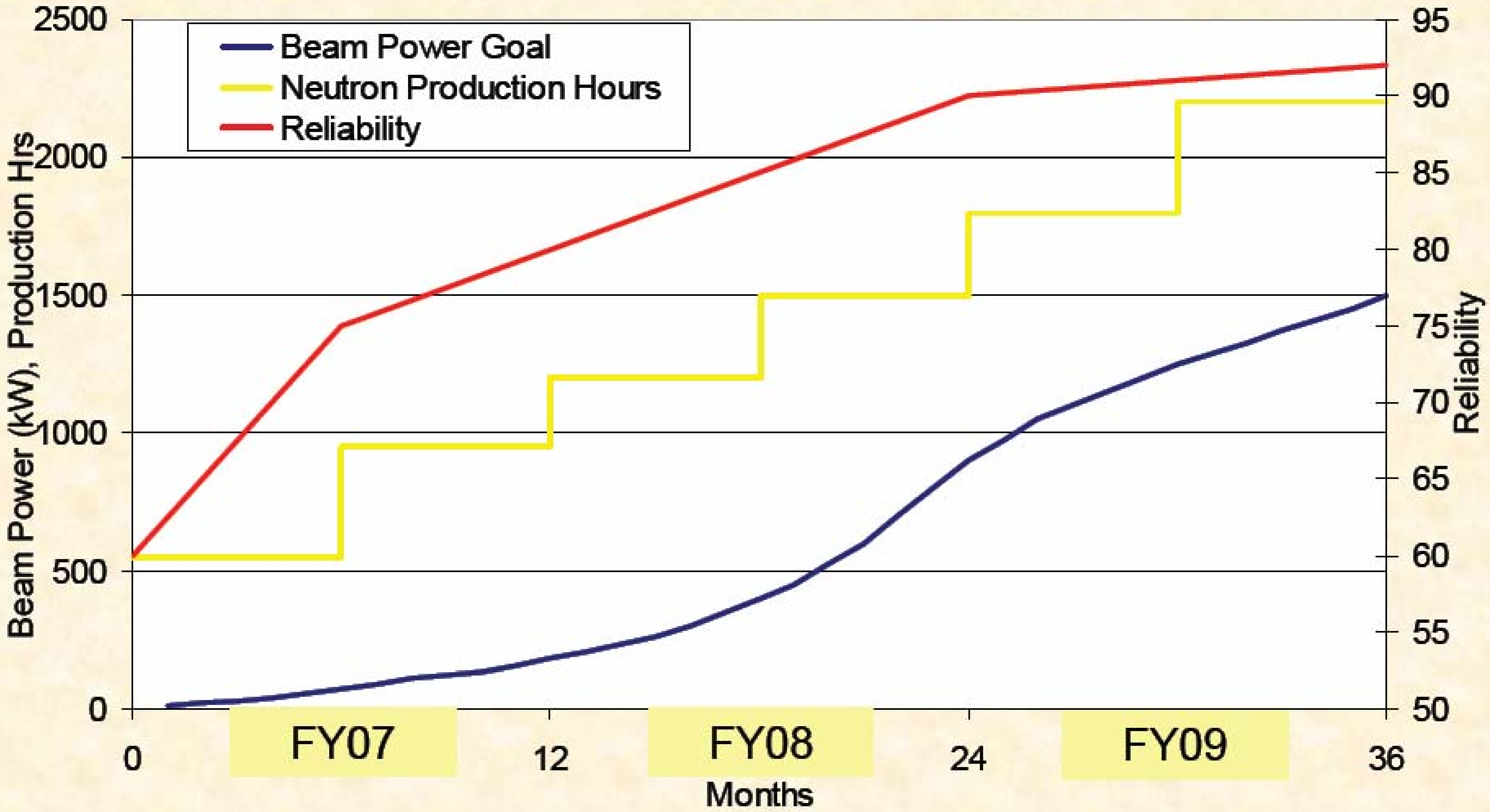
(Kim, THP081; Campisi, FR202)



Large fundamental frequency coupling through HOM coupler

Tuners out of range; two will be reset in September maintenance period

Outlook: Performance Goals



- **SNS Beam Power Upgrade Project will increase linac output energy to 1.3 GeV and provide 3 MW beam power**

Summary

- Completed 7 beam commissioning runs, amounting to more than 1 year of dedicated beam commissioning and operating time
- Achieved beam and neutron project completion requirements within project schedule and within budget
- Major beam quality goals have been met
- Flexibility afforded by a superconducting linac is essential
- We are beginning to ramp up the beam power of the SNS accelerator complex, with a goal of 100 kW on target by April 2007

MO102 – Commissioning of the J-PARC Linac (Y. Yamazaki)

- J-PARC: Japan Proton Accelerator Research Complex
  - Joint KEK/JAEA (Japan Atomic Energy Agency)
  - Multi-purpose facility: material science, nuclear/particle physics, radioactive waste transmutation

- 400 MeV nc Linac
- 600 MeV sc Linac
- 3 GeV synchrotron ring (333 μA, 1 MW)
- 50 GeV synchrotron ring (15 μA, 0.75 MW)

- Linac beam commissioning: 12/06
- Experiments will start in 2008

TH103 – Initial commissioning results from the ISAC-II SC Linac (R. Laxdal)

- 20 Nb QWR cavities: E_{acc} = 7.2 MV/m (E_p=36 MV/m, 20% higher than design goal)
- Cleaning technology developed for elliptical cavities kept improving the achievable E_p over the years for QWR also
- Successful commissioning also from beam dynamics standpoint

Future accelerators

MO202 – Energy doubling in a plasma wakefield accelerator (R. Ischebeck)

Plasma Waves (have a longitudinal E-component)

- Plasma wavelength:

$$\lambda_p \approx \sqrt{\frac{10^{15}\mathrm{cm}^{-3}}{n_p}} \quad \mathrm{mm}$$

- Wave breaking field: maximum field achievable in a plasma, occurring when the electron density becomes singular
- As calculated from non-relativistic one-dimensional theory:

$$E_0 = \frac{4\pi\,\varepsilon_0\,c\,m_e}{e}\,\omega_p$$

or, as a function of the plasma density

$$E_0 \approx \sqrt{\frac{n_p}{\mathrm{cm}^{-3}}} \quad \frac{\mathrm{V}}{\mathrm{cm}}$$

- In our case, $n_p \approx 10^{17}\,\mathrm{cm}^{-3} \quad \Longrightarrow \quad E_0 \approx 30\,\mathrm{GV/m}$

Scaling Laws (Linear Theory)

- Electric field at a distance ζ behind the bunch

$$\vec{E} = \frac{eN_b}{2\pi\varepsilon_0} k_p^2 \mathrm{e}^{-\frac{k_p^2\sigma_z^2}{2}} \sin(k_p\zeta) \qquad \text{where} \qquad k_p = \sqrt{n_p e^2/(4\pi\varepsilon_0^2 m_e c^2)}$$

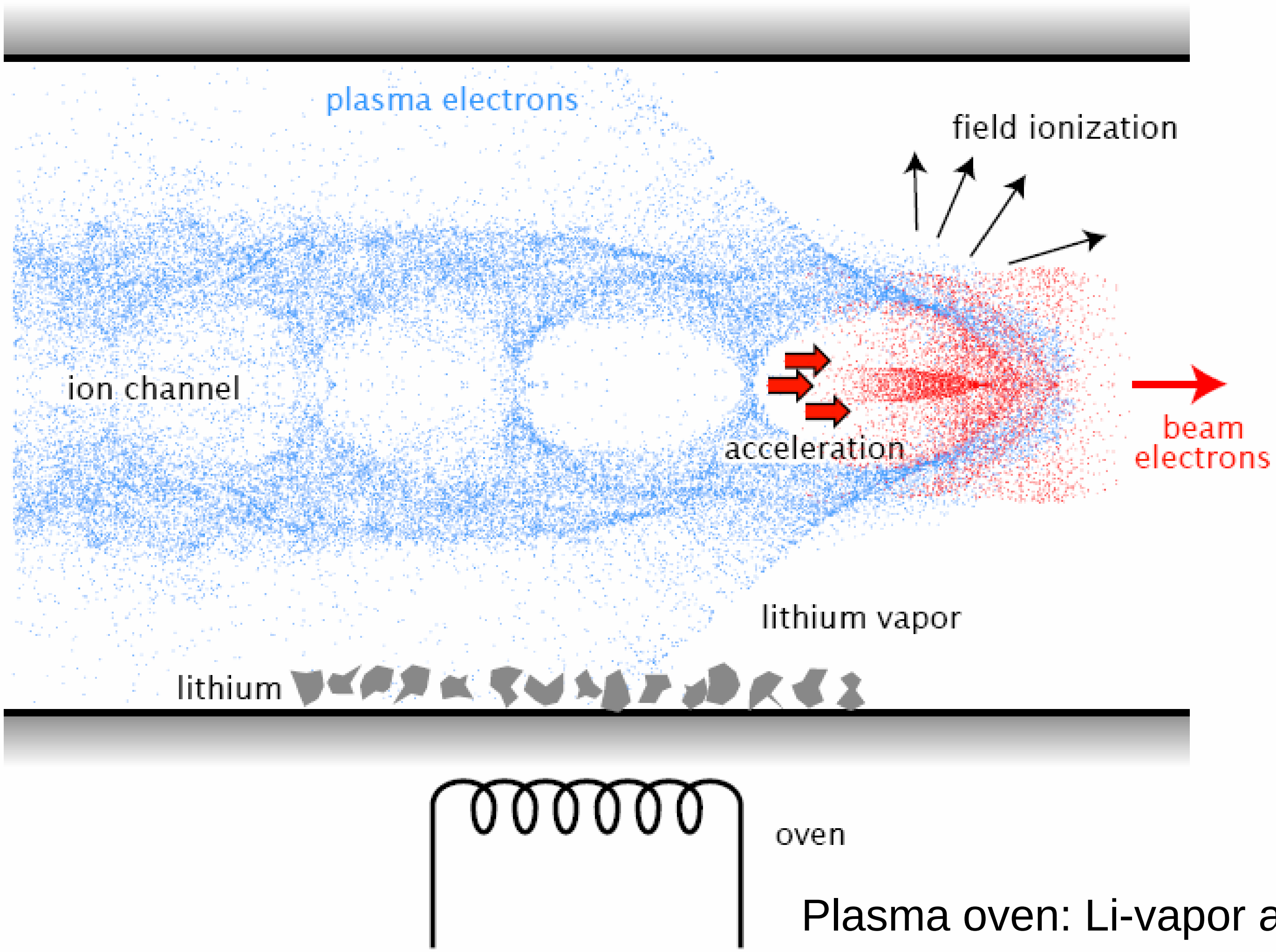
- Match bunch length to the plasma wavelength
(maximize the longitudinal electric field for a given bunch length)

$$k_p = \frac{\sqrt{2}}{\sigma_z} \quad \Leftrightarrow \quad n_p = \frac{m_e c^2}{2\pi e^2 \sigma_z}$$

$$\Longrightarrow \quad \vec{E} = \frac{eN_b}{\pi\varepsilon_0\sigma_z^2}\mathrm{e}^{-1}\sin(k_p\zeta)$$

$$\text{or} \quad \vec{E}_{\mathrm{max}} \approx 100 \left(\frac{N_b}{2\cdot 10^{10}}\right)\left(\frac{20\mu\mathrm{m}}{\sigma_z}\right)^2 \frac{\mathrm{GV}}{\mathrm{m}}$$

Plasma acceleration



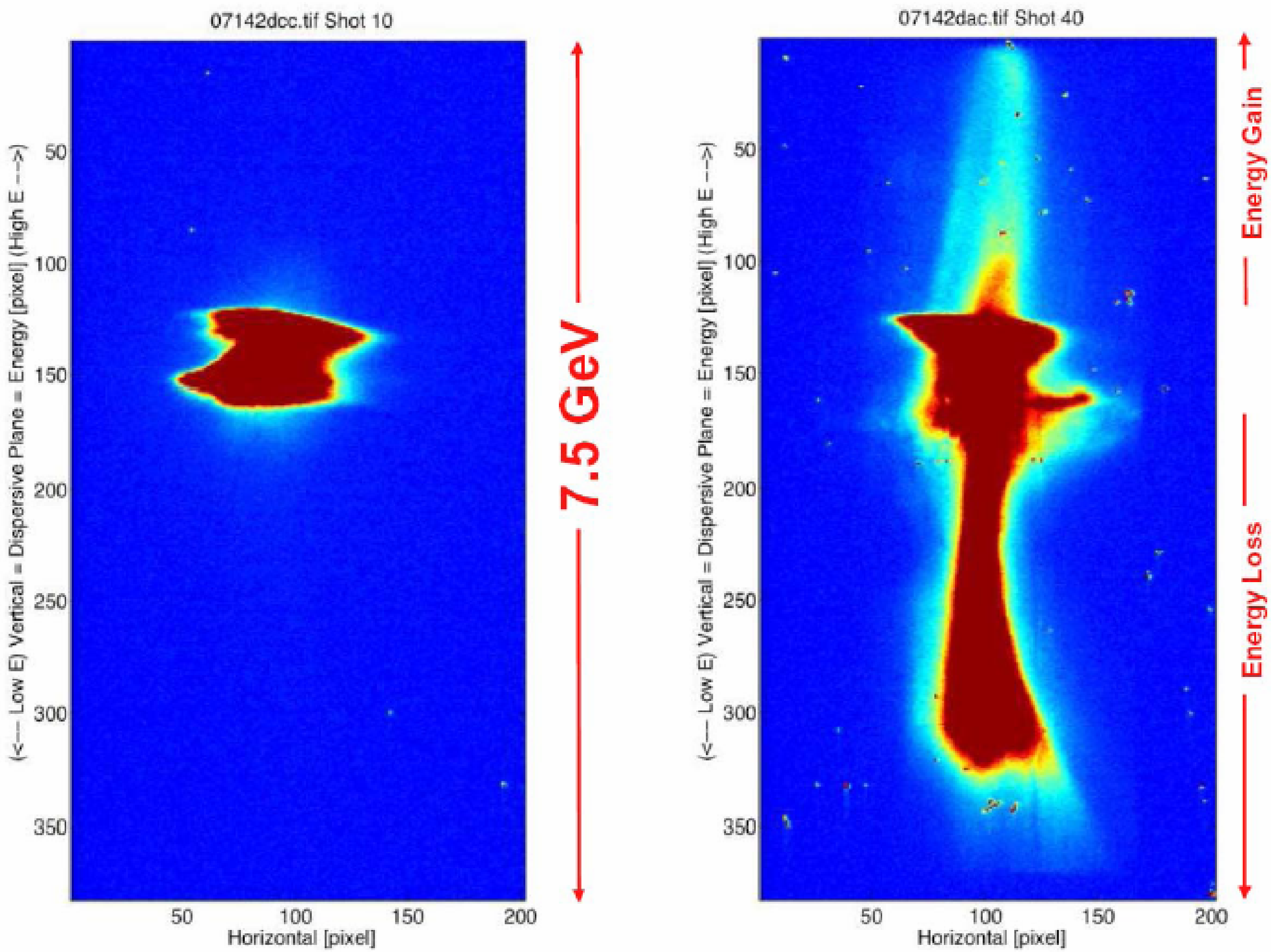
Plasma oven: Li-vapor at 1000 °C

- Drive the plasma wake with
  - Electrons
  - Photons

➡ use 40 GeV beam from SLAC Linac

- Longer plasma length gives higher energy beam
- E167:
  - Plasma length = 30.5 cm, peak beam energy = 42 GeV
  - **Plasma length = 82 cm, peak beam energy = 85 GeV**

Plasma Acceleration (E-164X)



MO204 – Status of Berlin X-FEL, Pohang X-FEL and Trieste X-FEL (W. Anders)

- BESSY X-FEL will have 3 FEL lines in the range 1.3 – 54 nm. New machine, CW, based on SC Linac. TDR completed.

- Fermi at Elettra and PAL are pulsed, NC and upgrades of existing linacs

TU101 – International Linear Collider R&D at Fermilab

- FNAL, CERN, DESY, KEK possible sites. Bid to host: 2007-2009
- Build one ILC cryomodule by FY 07
- Build and test 60 cavities (AES and ACCEL) by end FY 07 with help from Cornell and JLab

TU102 – Technologies toward a 100 kW Free Electron Laser (D. C. Nguyen)

Technologies toward a 100-kW Free-Electron Laser

Dinh C. Nguyen

LINAC06

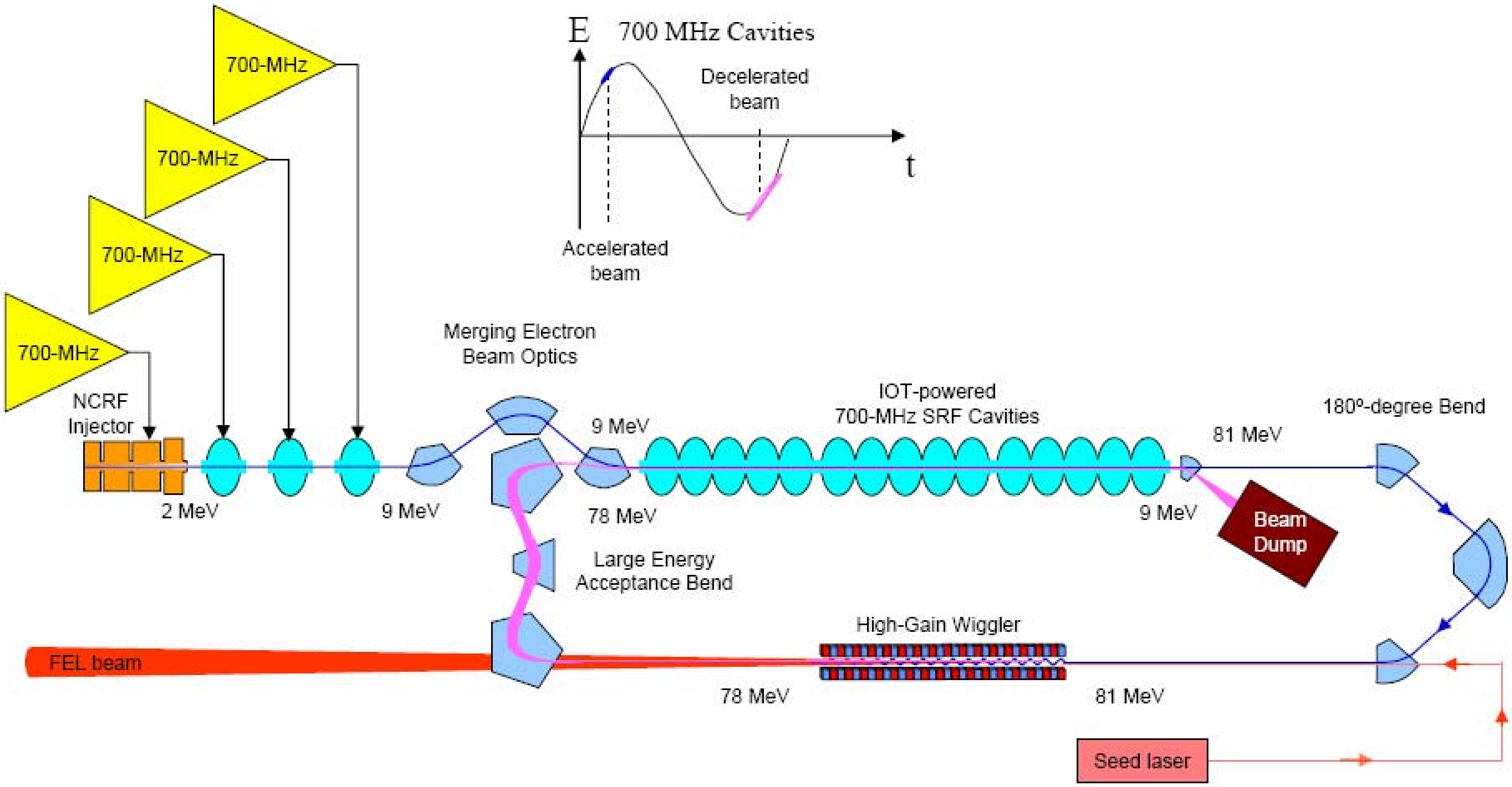
Knoxville, TN
August 21-25, 2006

Representative Parameters for a 100-kW FEL

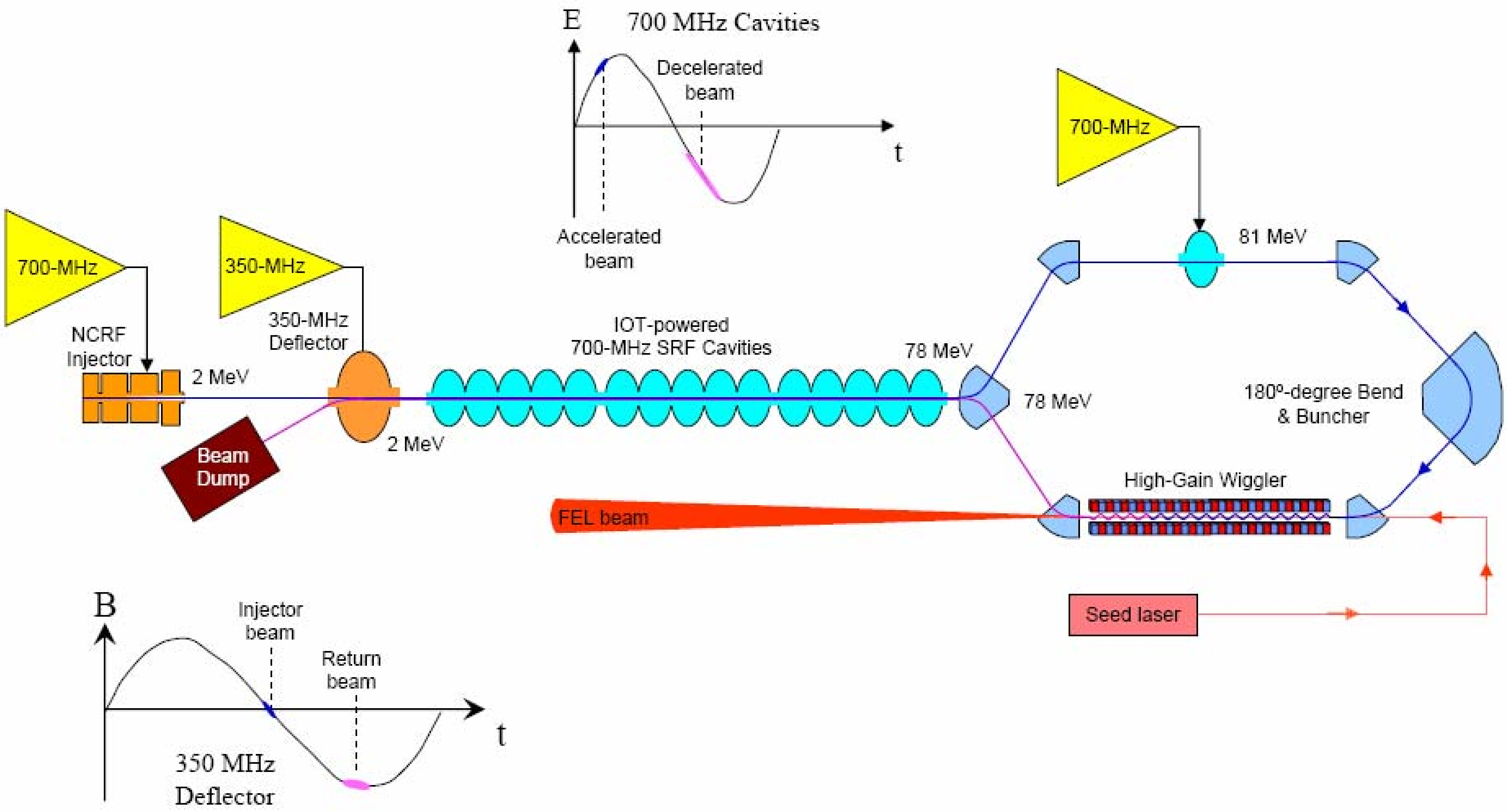
FEL Parameters	Symbols	Values
Beam energy	E_b	80.8 MeV
Bunch charge	Q	1 nC
Bunch length (FWHM)	τ_{FWHM}	1 ps
Peak current	I_{peak}	1 kA
Average current	I_{ave}	35 mA
Normalized rms emittance	ε_n	10 mm-mrad
Energy spread	$\Delta\gamma/\gamma$	0.25%
Wiggler period	λ_w	2.18 cm
Initial wiggler parameter	K_{rms}	1.187
Wiggler length	L_w	4 m
Wavelength	λ	1.052 µ
FEL peak power	P_{peak}	3.6 GW
FEL average power	P_{ave}	125 kW
FEL extraction efficiency	η_{FEL}	4.5 %

Los Alamos

Co-Propagating-Beam, Same-Cell Energy Recovery FEL



Counter-Propagating-Beam, Same-Cell Energy Recovery

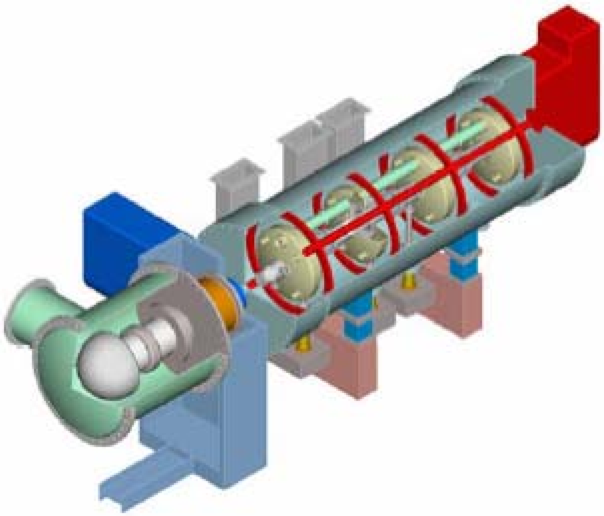


Advanced Technologies for the 100-kW FEL

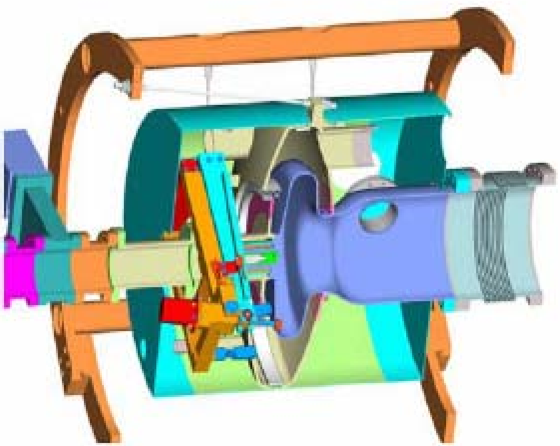
- High-gain Amplifiers driven by High-current Electron Beams
  - Regenerative Amplifier FEL
  - Scalloped Electron Beam FEL
- High-average-current Electron Injectors
  - DC Gun + SRF Booster
  - Normal-Conducting RF Photoinjector
  - Superconducting RF Photoinjector
- High-average-current SRF Cavities with Energy Recovery
  - Spoke Resonators
- Beam-Breakup Suppression
- Tapered Wigglers

High-average-current Electron Injectors

- **DC Gun + SRF Booster**
  - Injector for the Jefferson Lab 10-kW FEL
  - Demonstrated I_{ave} = 10 mA
  - Goal: I_{ave}= 100 mA



- **Normal-Conducting RF (NCRF) Photoinjector**
  - Boeing injector achieved 130 mA at 25% duty
  - New LANL/AES injector is in fabrication (next slide)
  - Goal: I_{ave} = 0.5 A
- **SRF Photoinjector**
  - Being developed at BNL/AES and FZR (Rossendorf)
  - Demonstrated I_{ave} ~ 1 mA (Rossendorf)
  - Goal: I_{ave} = 0.5 A



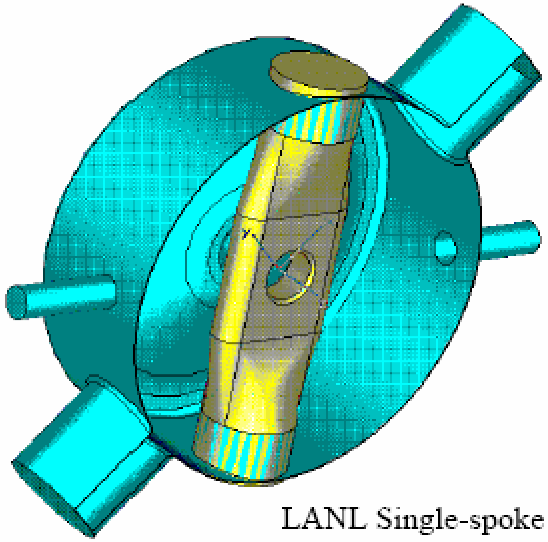
Reference: H. Bluem et al., *Proceedings of the SPIE* V.5534 (2004) 132

Los Alamos NATIONAL LABORATORY

Spoke resonators can potentially have high BBU limits

Spoke Resonator Advantages

- Half diameter of elliptical cavity at same frequency
- Rigid mechanical structures that can resist vibration
- Strong cell-to-cell coupling (no trapped modes)
- Few cells (2-3) per cavity → Simple HOM spectrum
- HOM couplers can be mounted on the side of the cavity → HOM damping does not increase length.
- Potentially high BBU limits.

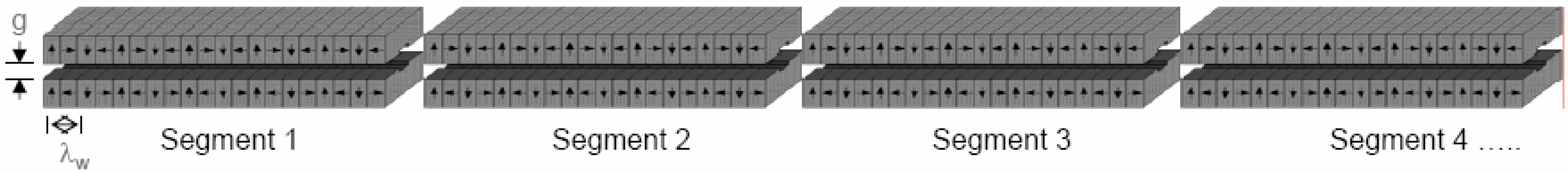


LANL Single-spoke cavity

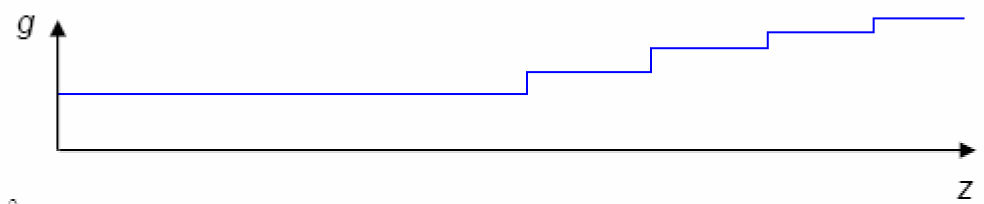
BUT

- Small beam apertures
  - Wakefields
  - Halo intercept
- No $\beta=1$ cavity designs

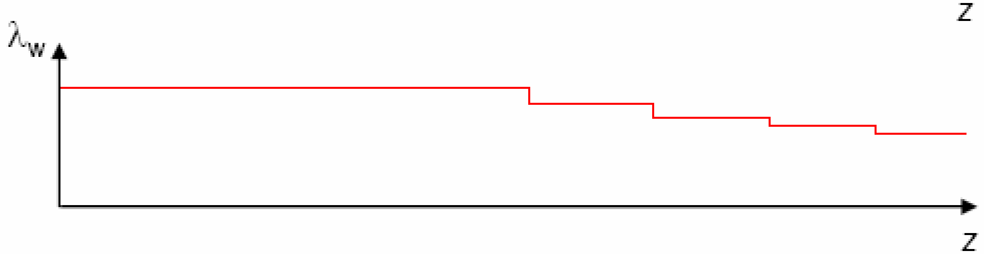
Stair-step Tapered Wiggler for High Extraction Efficiency



- Stair-step wigglers can be tapered in gap or period or both.
  - Taper in gap

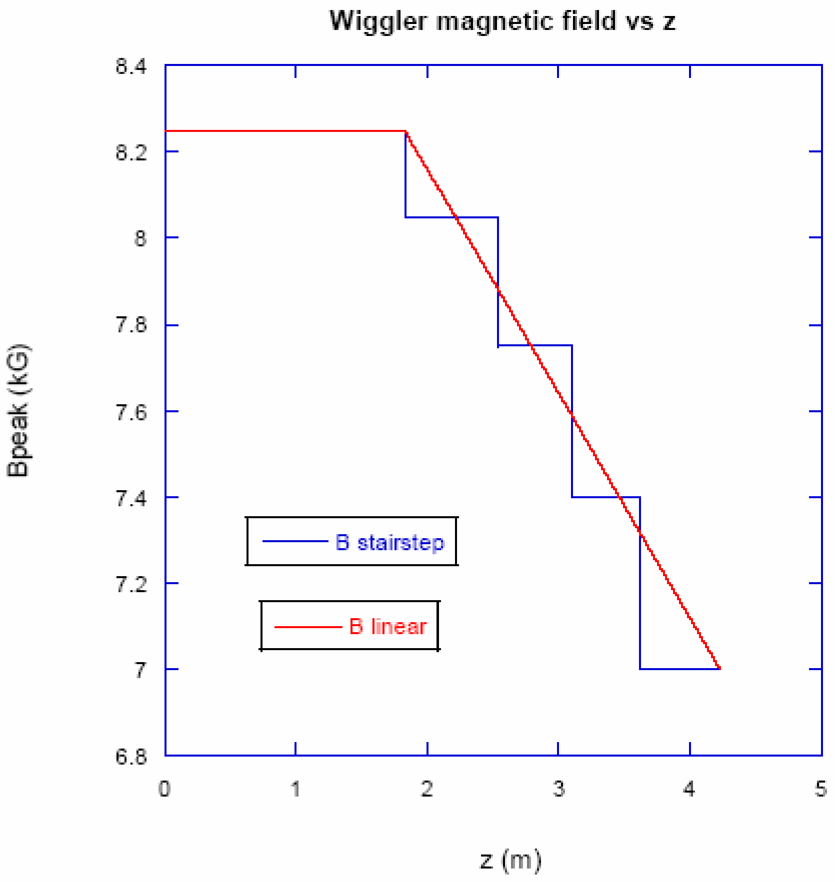


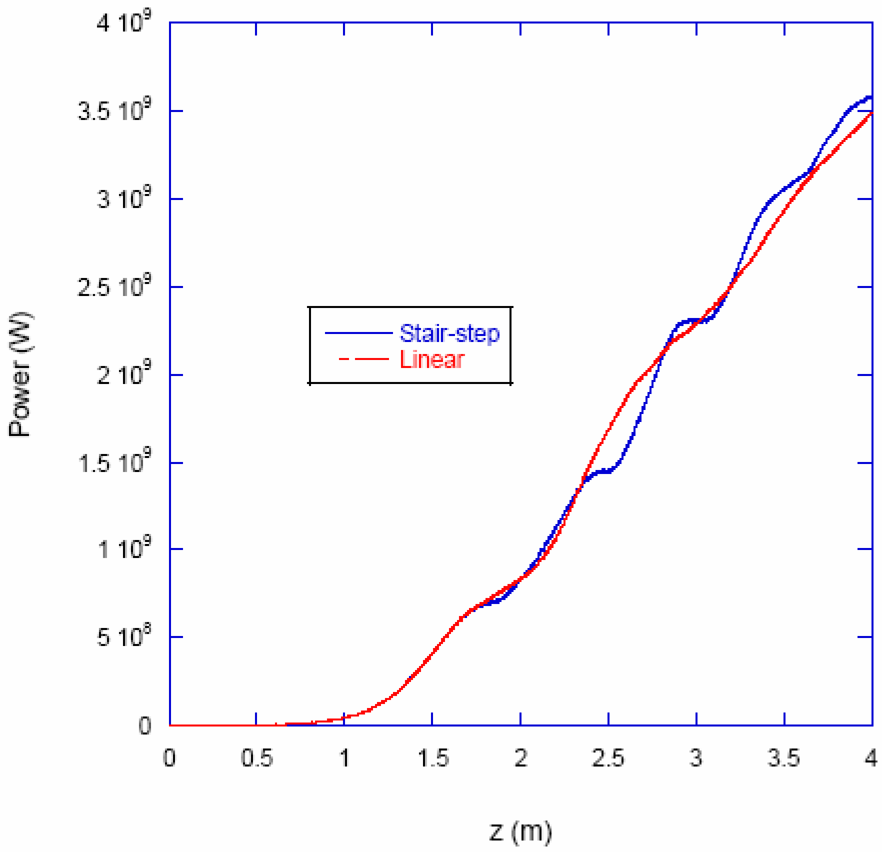
  - Taper in period



- Each segment's gap can be independently adjusted while in operation.
- A stair-step tapered wiggler is easier to build and optimize than a continuous one.

Comparison between Stair-step and Linear Tapers





Stair-step and linear tapers produce approximately equal peak power (3.5 GW) at the same taper rates.

FR204 – Science case for Energy Recovery Linac X-Ray Sources (S. Gruner)

- Need an X-ray source:
  - High brightness and flux
  - Fast x-ray pulse
  - Small x-ray source size for nanoprobes
- Therefore:
  - High current
  - Low emittance and bunch length
- ->ERL (5GeV, 100 mA)

- Applications:
  - High-pressure science study (x-ray scan of a small sample while being deformed by huge pressures)
  - Differential-aperture x-ray microscopy (analyze crystallographic properties down to sub-micron size)
  - Biological and polymer science (folding and unfolding of proteins, go to μs resolution)
  - X-ray diffraction from protein microcrystal
  - Dynamics of hydration (fs time-scale)

Components

WE104 – Cryomodules for Energy-Recovery Linacs (M. Liepe)

- Reduction of microphonics because of high Q_L
- High gradient CW operation: dynamic heat load dominates
  - Heat transfer to LHe
  - Mass transport of He gas
  - HOM losses
- Cost-optimized cavity gradient: 15-20 MV/m

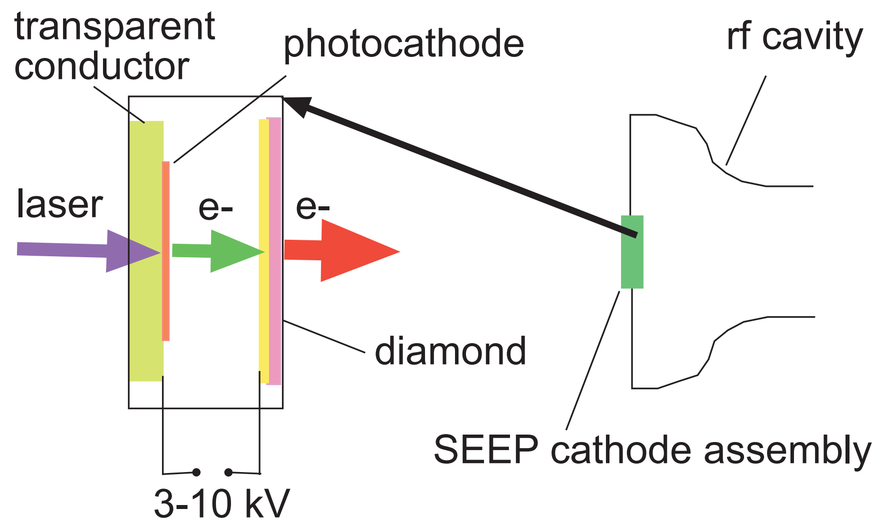
TH102 – Cryomodule test facilities and multicell cavity performance for the ILC (H. Hayano)

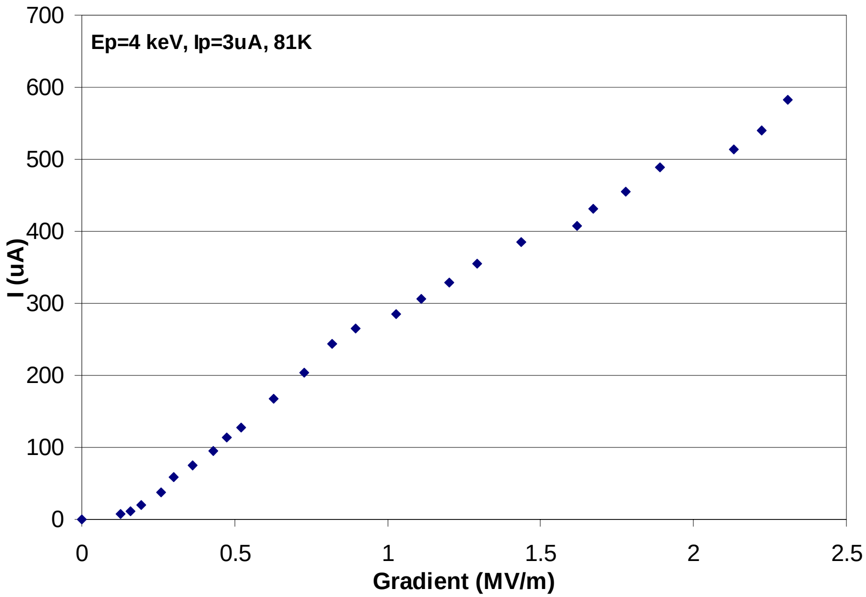
- R&D programs:
  - S0 task: achieve ILC baseline: 35 MV/m $1*10^{10}$ on 120 cavities in 3 years with 80% yield in first test, reprocess the rest to get 95%
  - S1 task: get 31.5 MV/m in 3 cryomodules

TH301 – Photoinjectors R&D for future light sources and linear colliders (P. Piot)

• Secondary Enhanced Emission Photocathodes

- **A photocathode ⇨ prim. e**
- **prim. e- are accelerated,**
- **hit a thin Diamond film**
  ⇨ secondary e-



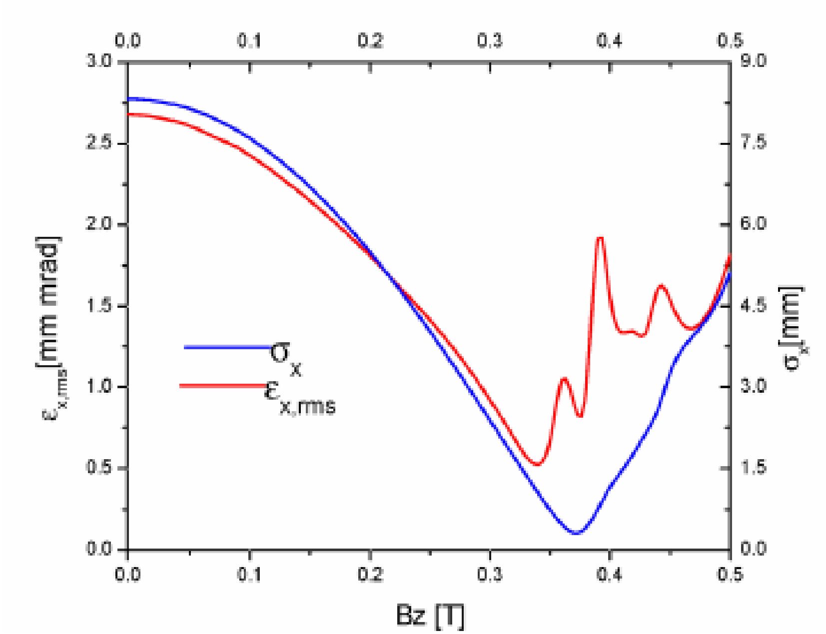


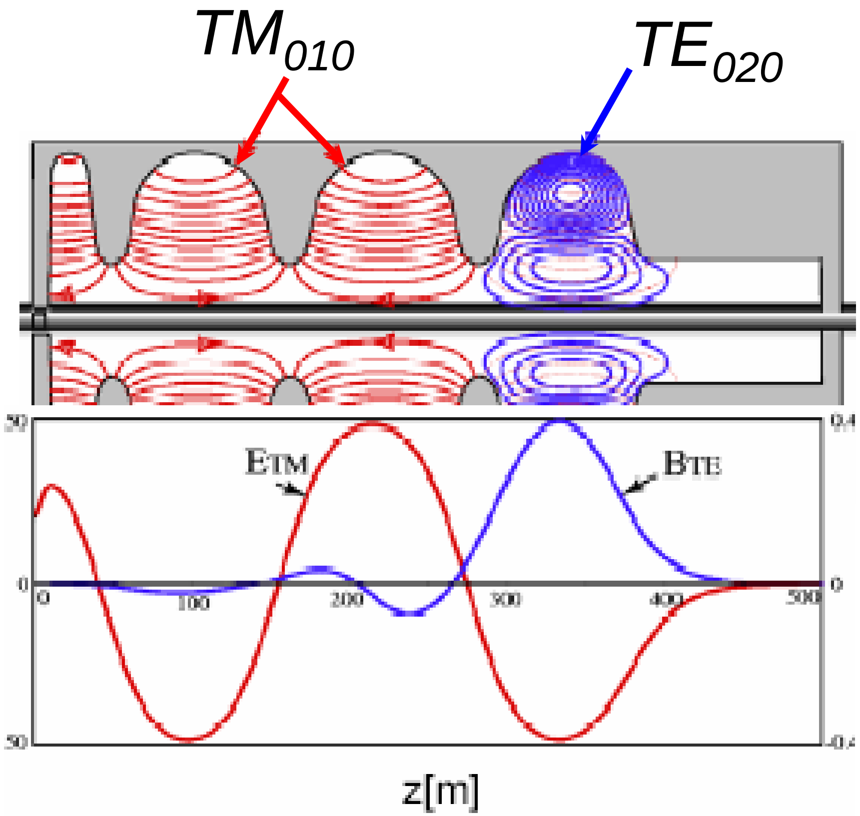
- **Production of second. e- experimentally verified,**

- **Capsulated assembly prototype being made.**

SCRF guns

- **SCRF gun operated at Rosendorf (1/2-cell) with conic back plate**
- **New gun: 3+1/2 cell +TE mode ⇨ beam size control**





- **Can also use B-field (Ferrario)**
- **Recessed photocathode (BNL)**

- Improvement of modeling (both analytical and numerical) important aspect of photoinjectors R&D
    - VORPAL fully self-consistent code (TechX) is being applied to rf-guns

- Photoinjectors-produced beams have generally very low 6D phase space and techniques to repartition the emittances in 2D sub-space are being explored for improving performance of single-pass FELs

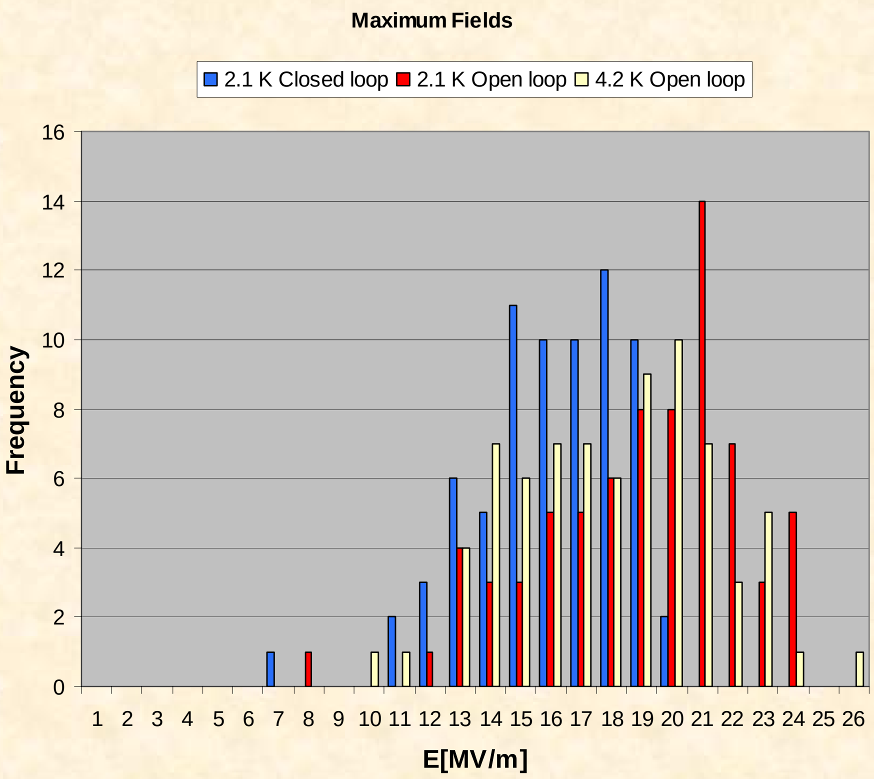
FR202 – 2K or not 2K (I. Campisi)

SNS tests: Limits at 2.1 K vs. 4.2 K

2.1K Closed Loop
16.6 MV/m

2.1K Open Loop
18.5 MV/m

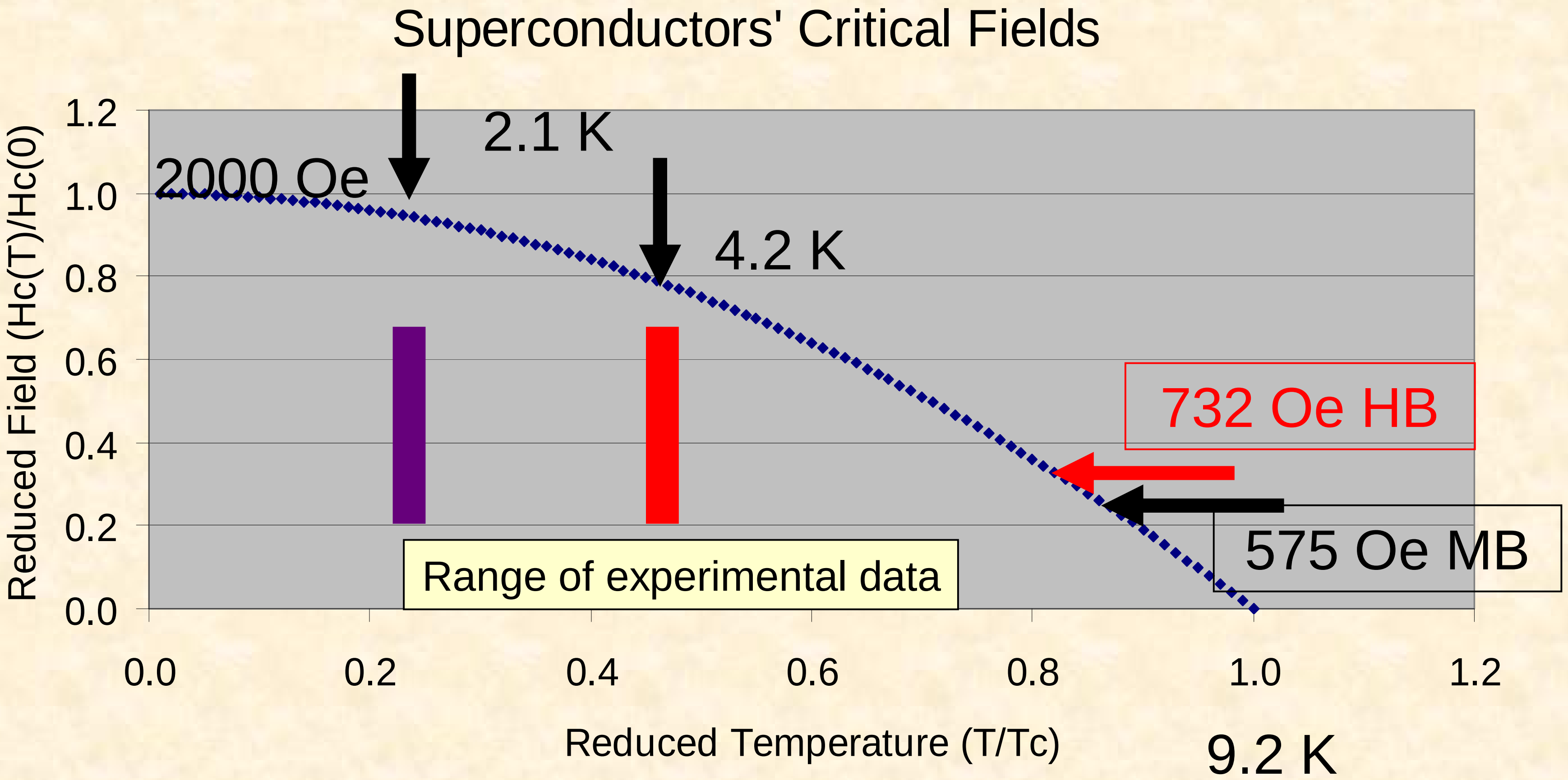
4.2K 17.6 MV/m



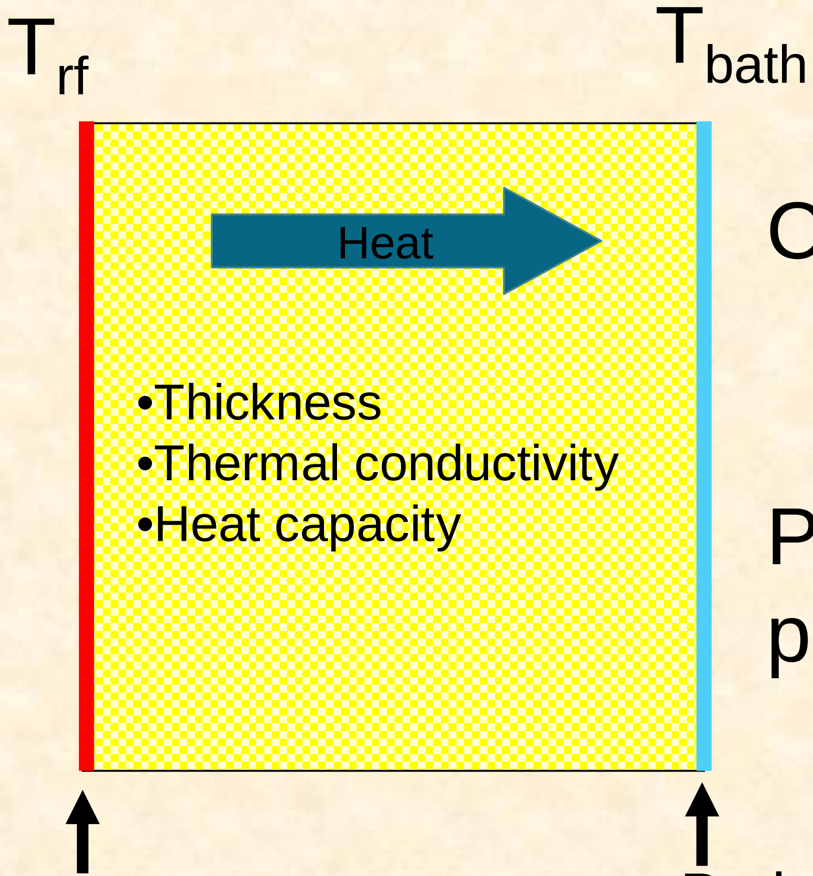
Summer 2005

Most limits due to either FE or controls optimization

Magnetic field levels: Experimental data



Heat transfer



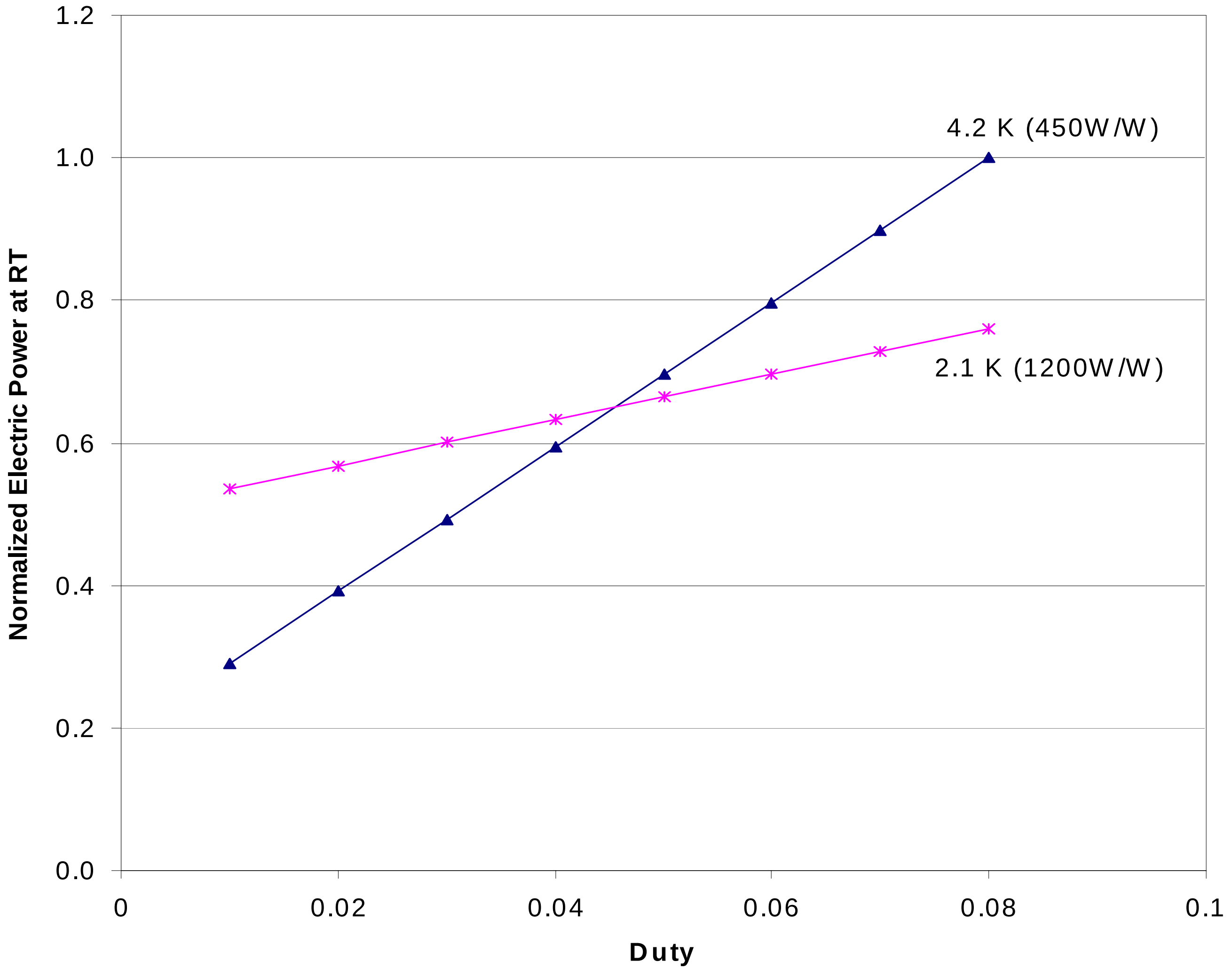
CW: equilibrium

Pulse: pulse to pulse stability

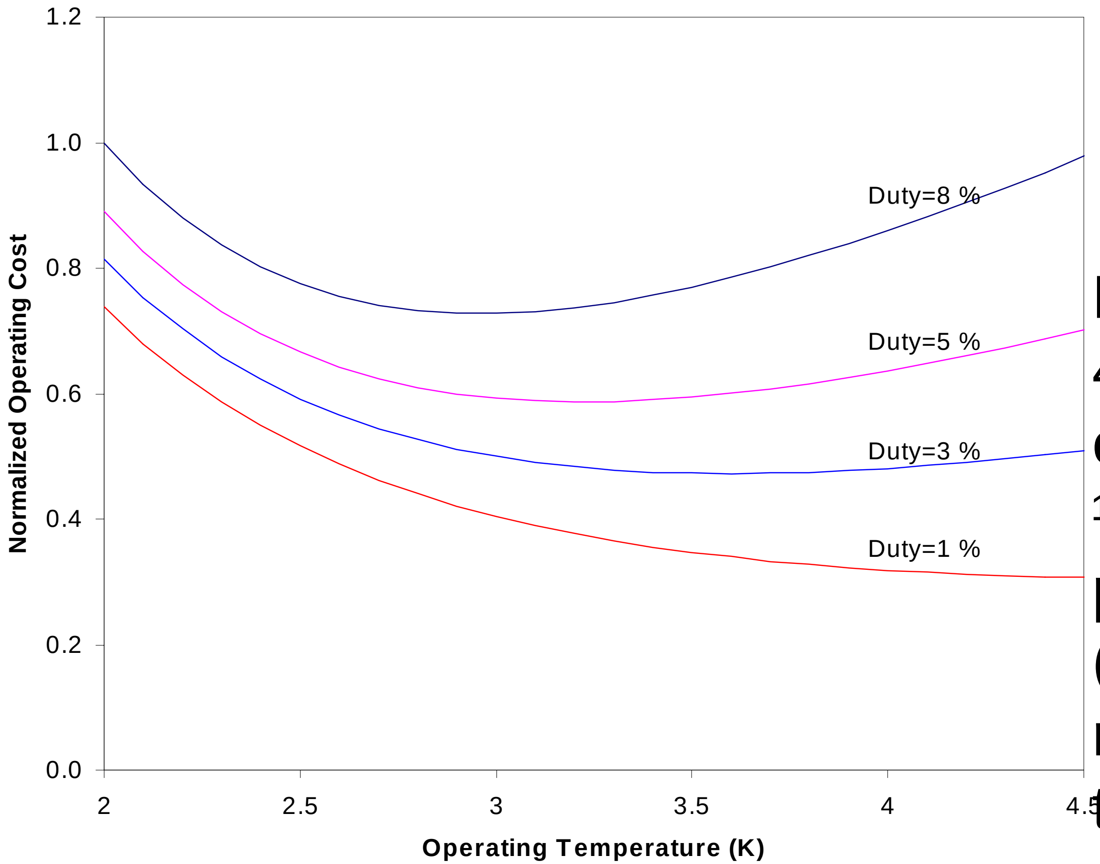
- RF losses
- Critical field

- Bath temperature
- Boiling limits

SNS-specific power demands



SNS Temperature optimization



For SNS, operation at 4.2 K is overall more economical up to about ½ of the design beam power
(if achieved by reducing repetition rate to 30 Hz)

Ability to deliver beam at reduced power if 2K plant should be unavailable

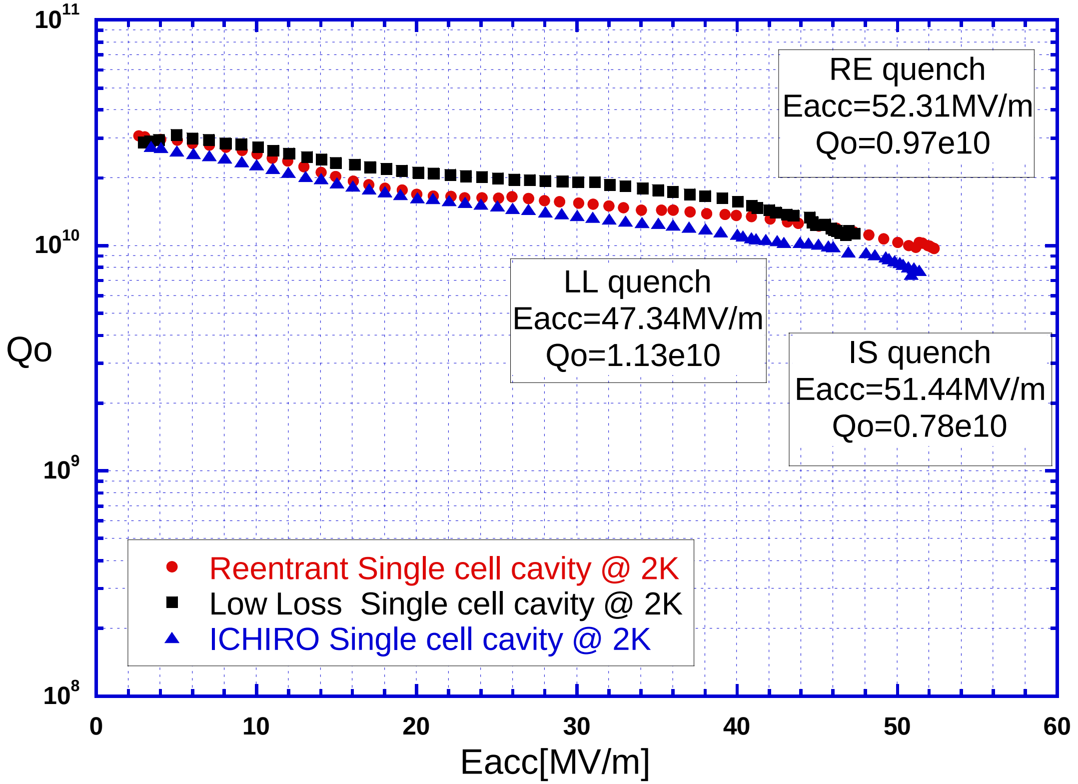
What application of pulsed RF can benefit from running above λ?

- **Relatively "small", low frequency, pulsed accelerators with reasonable cryogenic margin**
- **Cost of sub-atmospheric plants vs. 4.2 K plants**
- **Pulsed RF is not very efficient cryogenically**
- **Field emission loading best handled at higher temperatures**

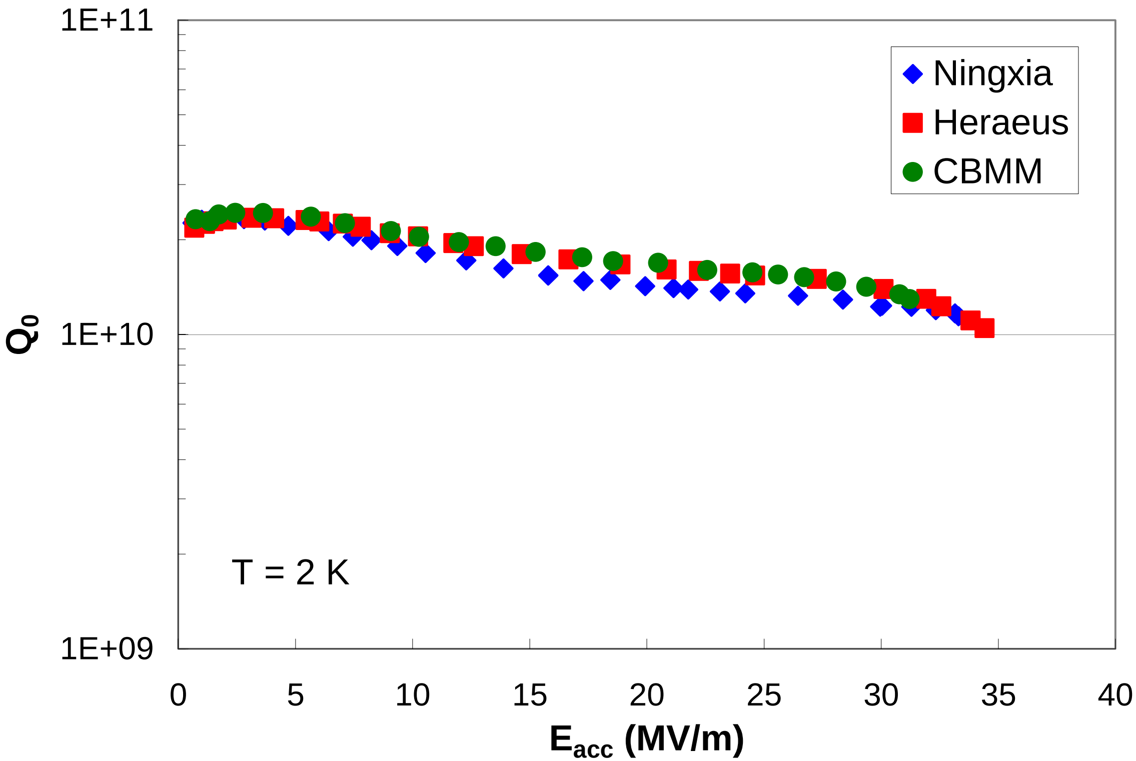
More details in Kim and Campisi, submitted to PRST AB

FR104 – Recent developments in SRF cavity science and performance (G. Ciovati)

- KEK tests of new-shape single cells achieved B_c of Nb



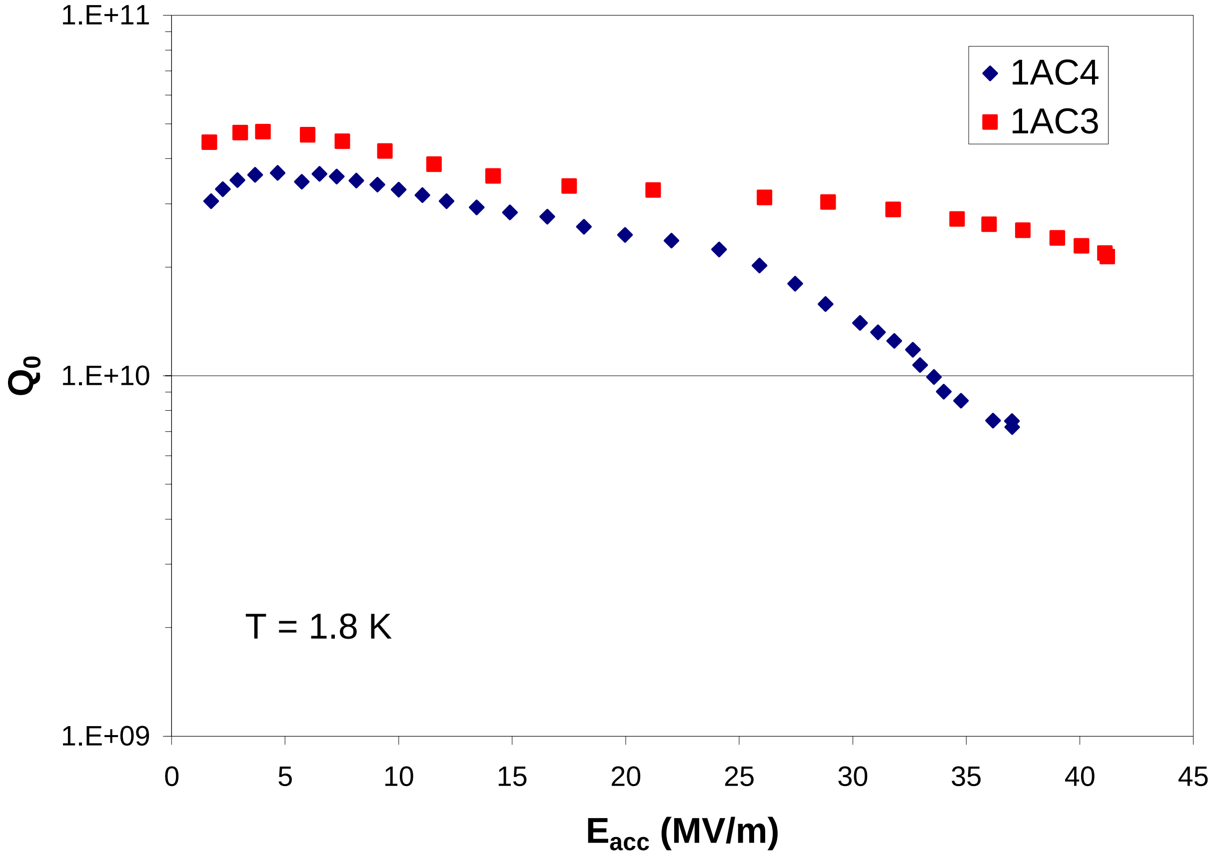
E_{acc} = 30-35 MV/m is routinely achieved in large-grain single-cell cavities treated by post-purification + BCP + 120 °C bake



P. Kneisel, EPAC'06, Edinburgh, June 2006, WEXPA01

- Large grain Nb treated by BCP is a competitive option to achieve ILC-type gradients

RF test results at 2 K for TESLA shape large-grain single-cell cavities at DESY



D. Reschke et al., this conference, TUP026

Treated by EP + 120 °C bake

- The procedures currently used to treat multi-cell SRF cavities are not suitable for a mass-production of 20,000 cavities for ILC

⇨ Procedures need to be streamlined

⇨ R&D is in progress in:

- high-pressure rinse
- electron-beam welds
- baking
- electropolishing

THP093 – Polyhedral cavity structure for linear colliders (P. McIntyre, N. Pogue, A. Sattarov)

- Make cavity with polyhedral cross-section rather then circular

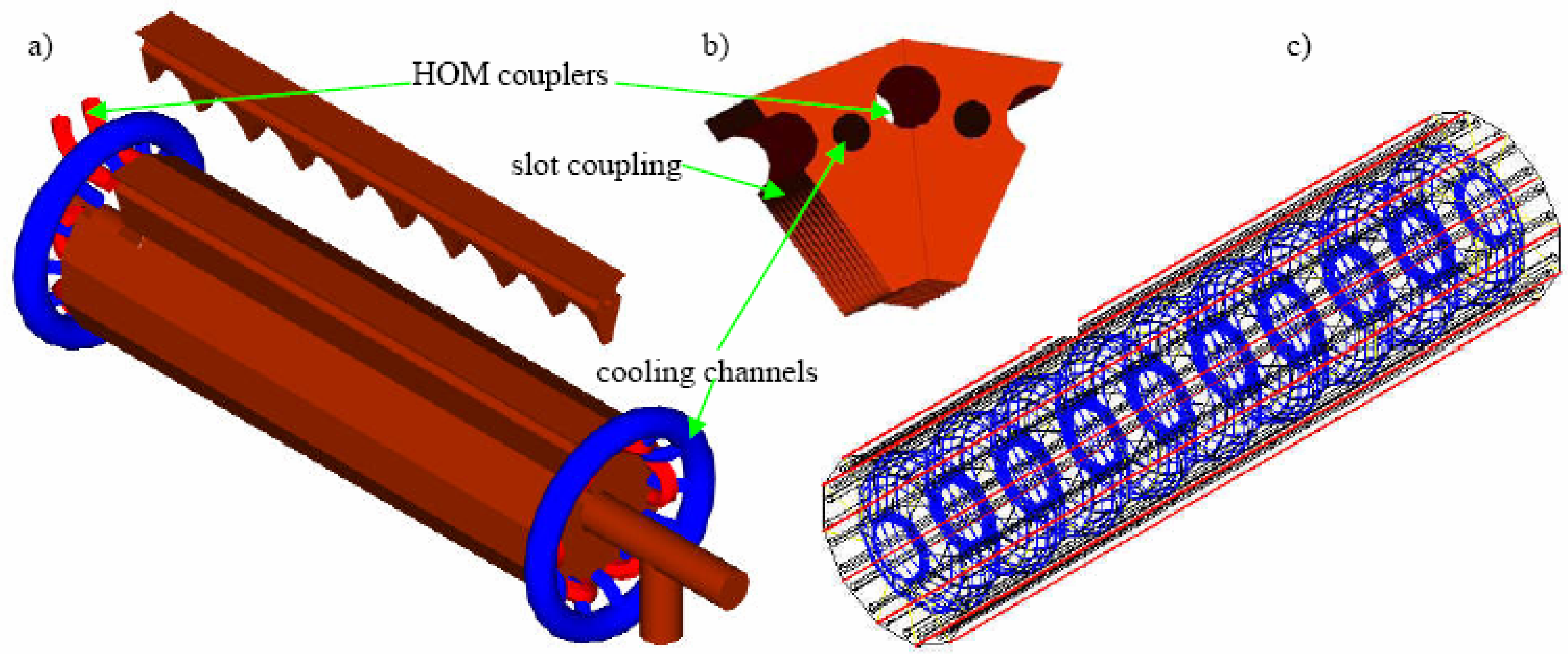


Figure 3. Assembly of 12 segments to make a polyhedral cavity module. a) polyhedral assembly, one segment withdrawn; b) detail of slot-coupled HOM waveguide and cooling channels; c) wire-frame showing interior cavity surface.

- Segments made of bulk Nb on Cu
- Claims:
  - Rigid structure: no Lorentz detuning
  - Deflecting HOMs have azimuthal currents: can be damped through coupling slots between segments
  - Closed-circuit cooling channels for refrigeration
  - TM_{010} mode has NO azimuthal currents (23% lower Q than standard Nb cavity)
  - Direct access to the Nb for surface preparation

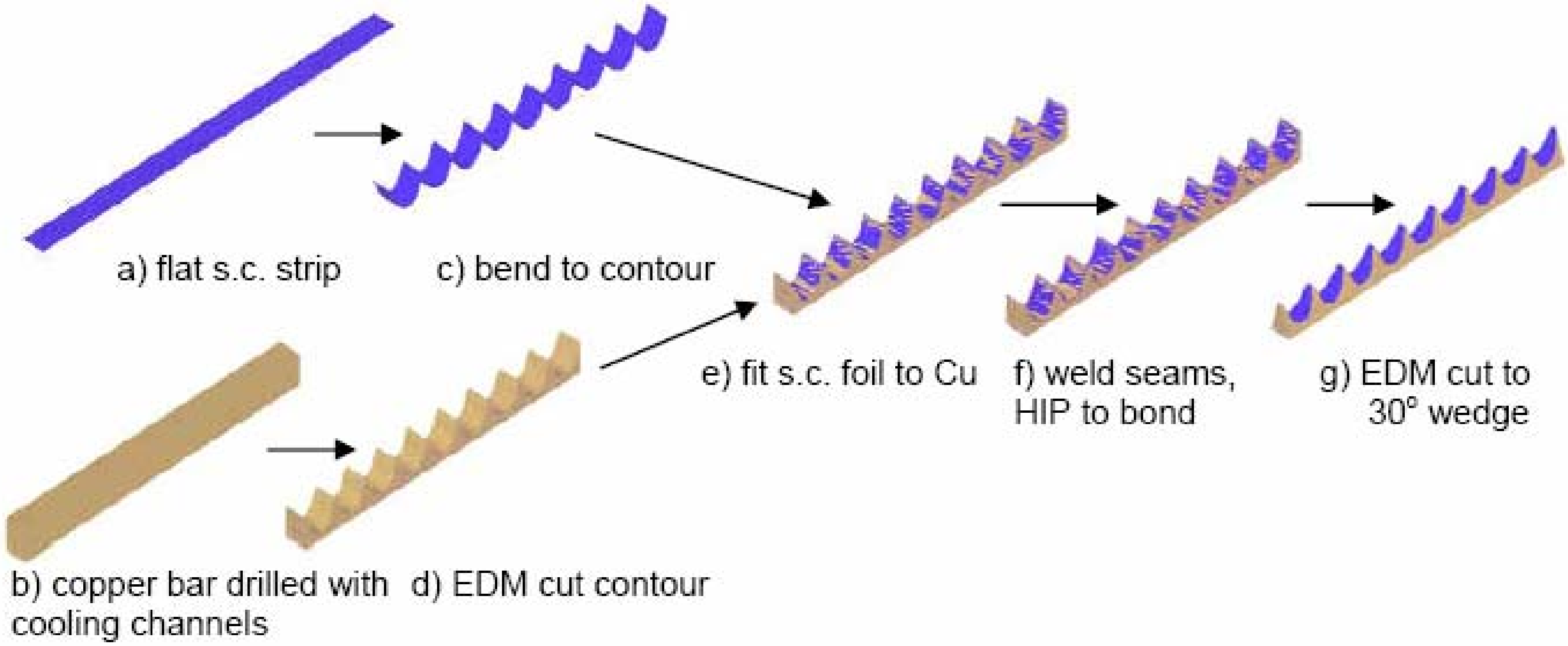


Figure 2. Fabrication sequence for constructing each wedge segment of a polyhedral cavity module.

Thank you!