Progress in Advanced Accelerator Technology

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Acknowledgements

This talk is a summary of contributions of the following colleagues from 18 institutions:

- **CERN**: T. Kehrer, J-P Delahaye, P. Lebrun, R. Garoby, G. Geshonke, W. Wuensch, A. Devred
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- **SLAC**: R. Siemann
- **Fermilab**: I. Kourbanis, S. Nagaitsev, V. Kashikhin
- **KEK**: S-I. Kurokawa, K. Takayama
- **BNL**: T. Roser, M. Harrison
- **LBL**: S. Gourlay
- **ANL**: W. Gai, M. Kelly
- **ORNL**: S. Henderson
- **Jlab**: L. Merminga, S. Chattopadhyay
- **Cornell Univ**: H. Padamsee
- **Univ. of Southern California**: T. Katsouleas
- **GSI**: G. Moritz
- **LNF-INFN**: C. Biscari
- **IHEP/China**: J-Q. Wang
- **KERI**: H. Suk
- **KAERI**: B-H. Choi
- **Muon Inc**: R. Johnson

Outline

- **Hadron Accelerators**
  - High field superconducting magnet
  - Fast pulsed superconducting magnet
  - Superconducting rf ($\beta < 1$)
  - Electron cooling
  - Slip stacking
  - Barrier rf stacking
  - Polarization
  - Induction synchrotron
  - High power liquid target

- **Lepton Accelerators**
  - Superconducting rf ($\beta = 1$)
  - Normal conducting high frequency high gradient rf
  - Pressured rf cavity
  - Energy Recovering Linac (ERL)
  - Wakefield acceleration
  - Plasma acceleration
  - Terahertz coherent synchrotron radiation
  - New ideas

ICFA Beam Dynamics Newsletter

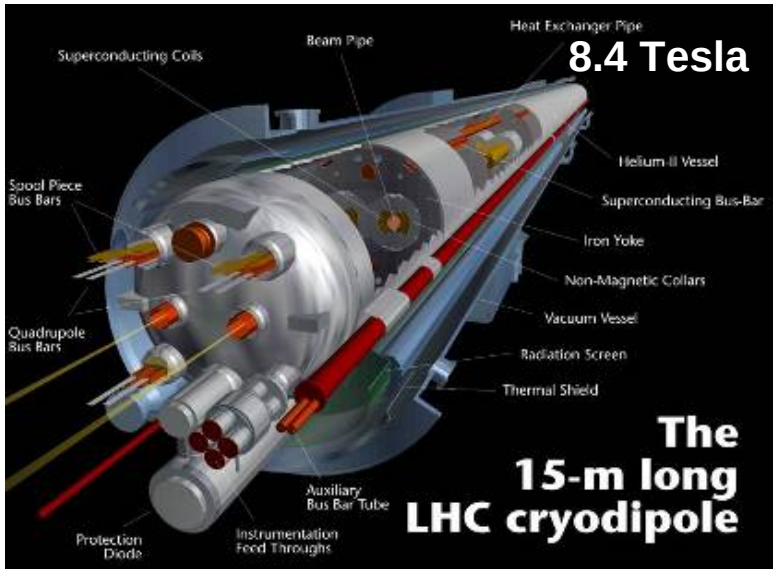
http://www-bd.fnal.gov/icfabd/news.html

Introduction

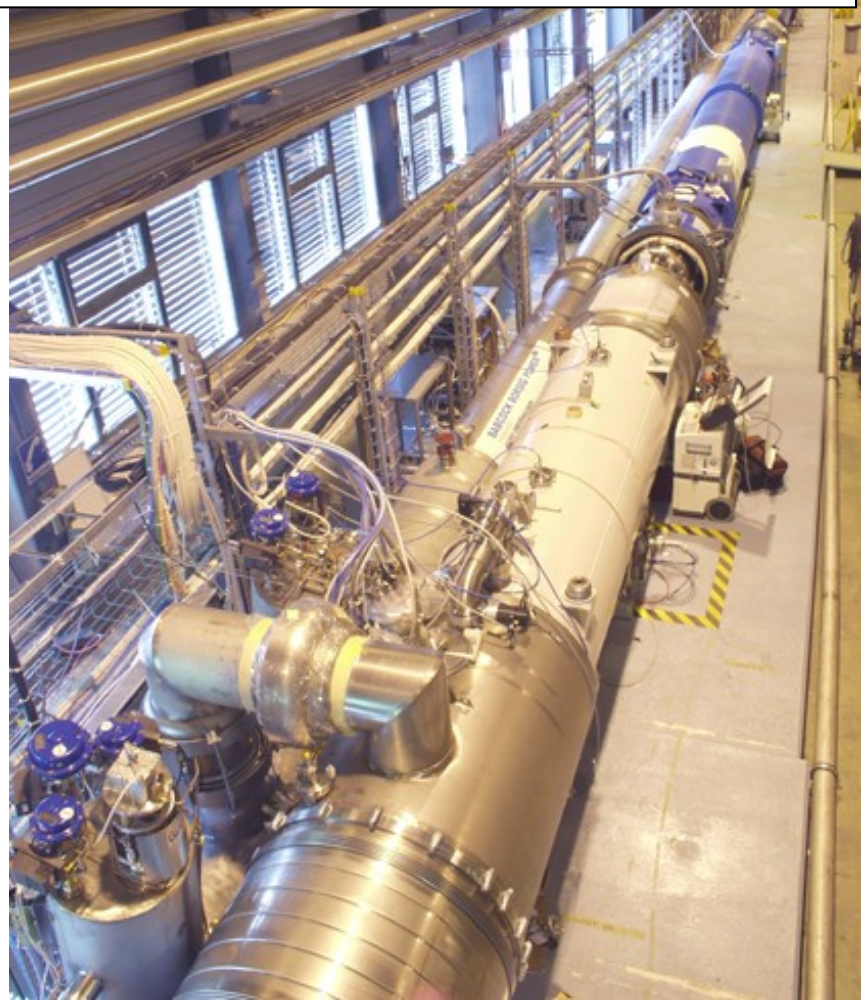
- **High beam energy**
  - Hadron accelerators – Circular:
    - Energy limited by magnetic field: $E \sim B\rho$
    - **High field magnet is the key**: Tevatron: 4.4 T, LHC: 8.4 T, VLHC: 15 T
  - Lepton accelerators – Circular:
    - Energy limited by synchrotron radiation: $P \sim \gamma^4 / \rho$
    - LEP already reached the limit ~ 100 GeV
  - Lepton accelerators – Linear: $E \sim GL$
    - **High gradient RF is the key**
    - New acceleration technologies
- **High beam power**
  - Hadrons – High average power (high intensity, long pulse)
  - Leptons – High peak power (high intensity, short bunch)
- **High beam brightness**
  - Hadrons (also muons): Cooling
  - Electrons: Damping + Emittance preservation (ILC is an extreme example)

Hadron Machines

LHC SC Magnets (P. Lebrun)



First full LHC cell (~ 120 m long) :
6 dipoles + 4 quadrupoles;
successful tests at nominal current (12 kA)



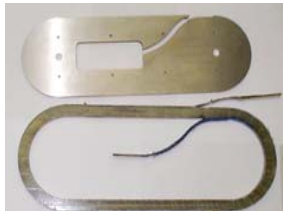
High Field SC Magnet R&D in U.S. (S. Gourlay)

Berkeley Lab

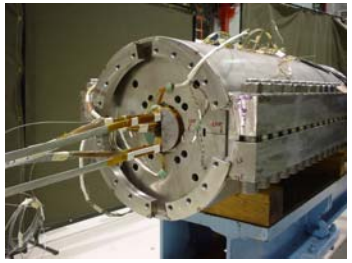
Nb_3Sn 16 T Dipole

BROOKHAVEN NATIONAL LABORATORY

Nb_3Sn and HTS Racetrack Coils



BNL



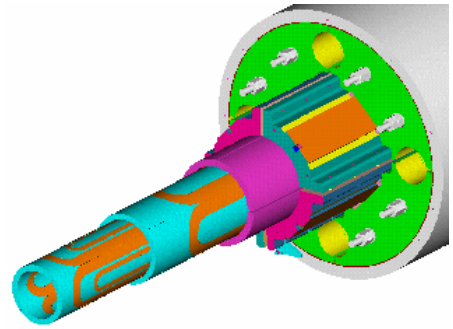
Nb_3Sn 10 T Dipole

FNAL

In Progress . . .

LHC Accelerator Research Program
Berkeley Lab, Brookhaven and Fermilab

LARP



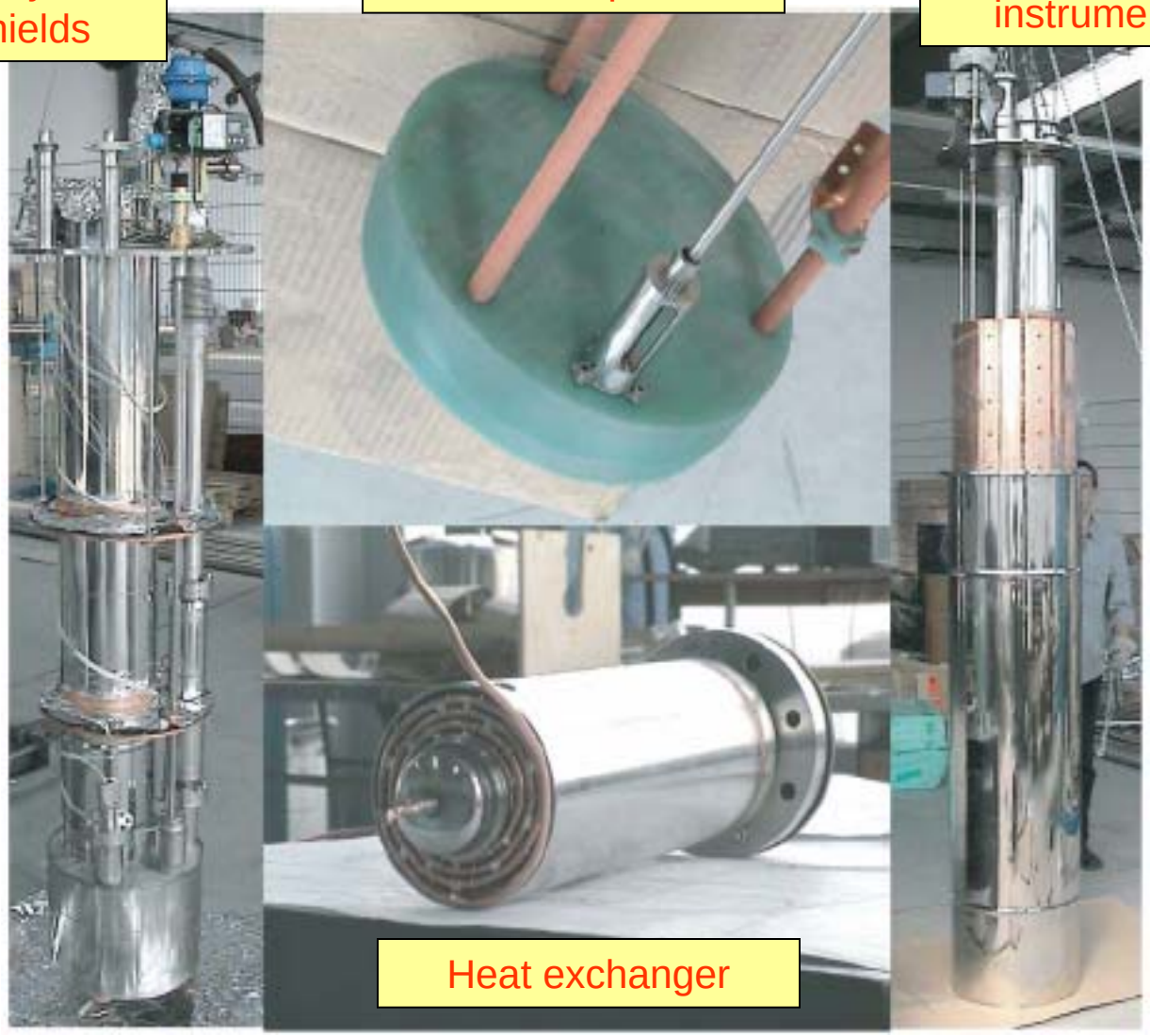
Large bore,
High gradient
Nb_3Sn quads

Next European Dipole (NED) (A. Devred)

Final assembly with thermal shields

Lambda plate

Inner assembly with instrumentation

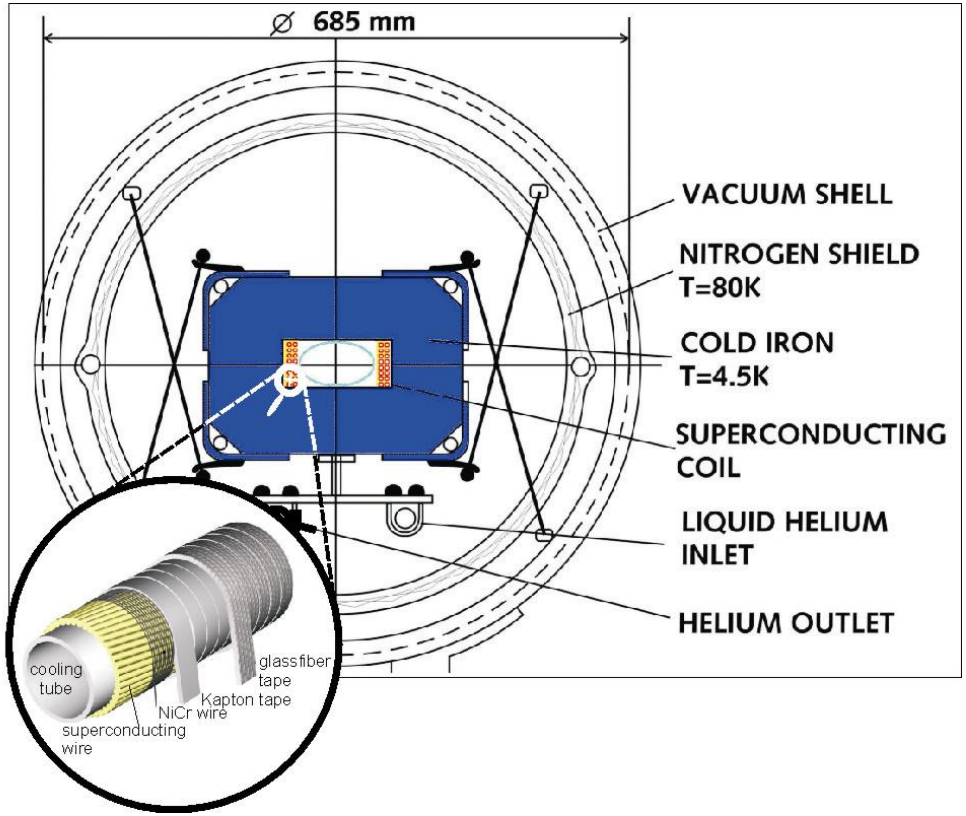


Heat exchanger

GSI-FAIR Fast-Pulsed SC Magnets (G. Moritz)

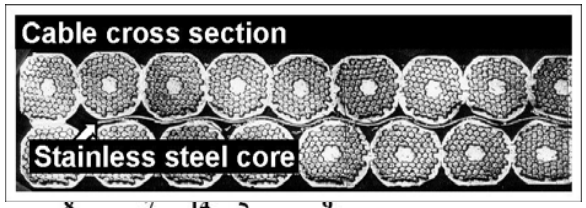
SIS 100 dipole (2T, 4T/s) (Nuclotron-type)

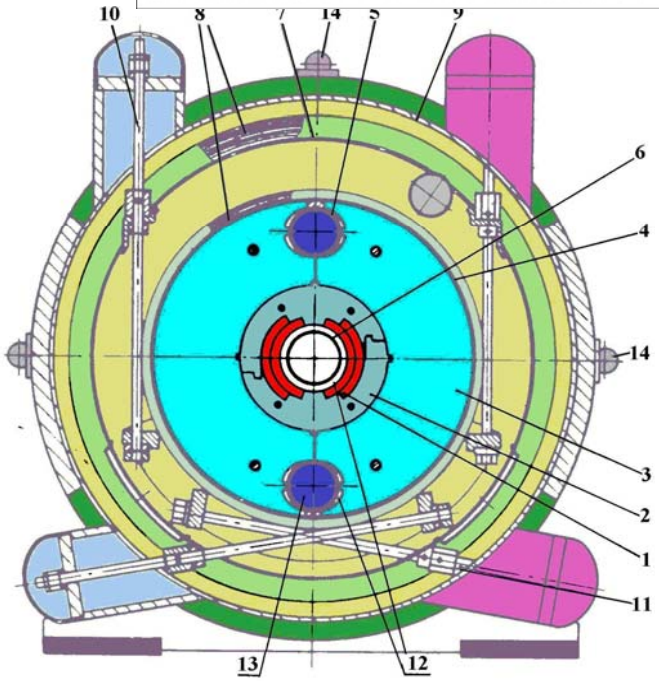
- iron-dominated, cold iron
- cooling: indirect, forced-flow (two-phase) He
- NbTi superconductor



SIS 300 dipole (6T, 1T/s)

- cos theta, two-layer coil
- cooling: supercritical He
- Rutherford-cable with core





Fast-Pulsed SC Magnets (V. Kashikhin)

Main Issue:

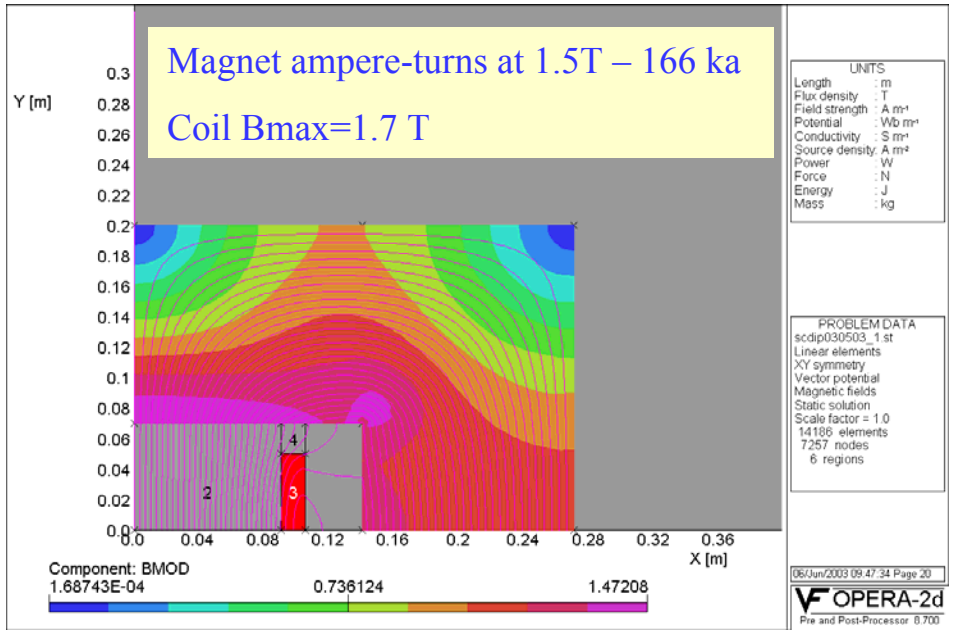
Superconducting cable and winding with low eddy current losses

Magnet Parameters:

Magnetic field	**1.5 – 3.0 T**
Frequency	**15 Hz**
Air gap	**100 – 150 mm**
Length	**5.72m – 2.86 m**
Superconductor	**NbTi/CuNi or HTS**
Iron/air core	**room temperature**
Cooling	**LHe forced flow**

Superconductor AC losses < 3.3 kW/m^3 at 15 Hz and 0.5 mm dia.
Losses for 1.5 T magnet 1.2 W/m for NbTi/CuNi superconductor with 0.16 um filaments

Hysteresis losses can be effectively reduced by decreasing a filament size up to ~ 0.2 um



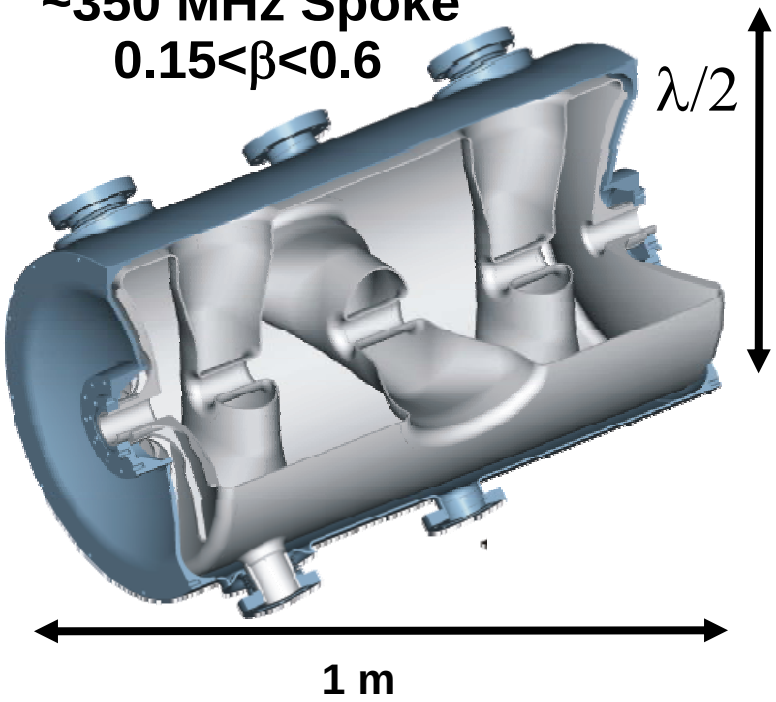
Eddy current losses effectively reduced by using high resistive CuNi matrix and small twist pitch 1.5mm for sub-wire and 6-8mm in 0.5mm wire.

Careful optimization needed between SC cable, cooling pipes/channels and construction elements to reduce heat load up to reasonable value

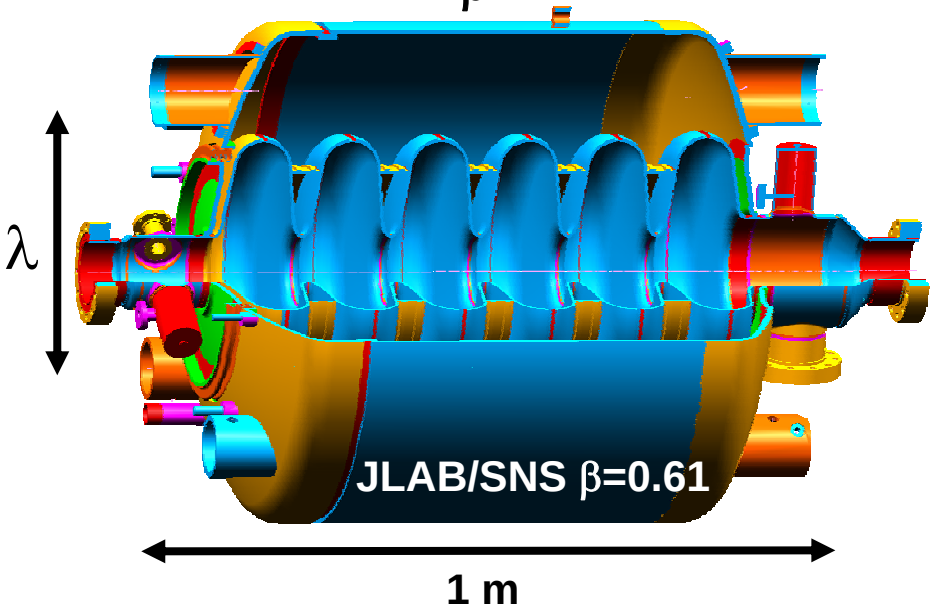
Superconducting RF for $\beta < 1$

Two Technologies: Spoke *vs.* Elliptical-Cell Cavities

~350 MHz Spoke
$0.15<\beta<0.6$



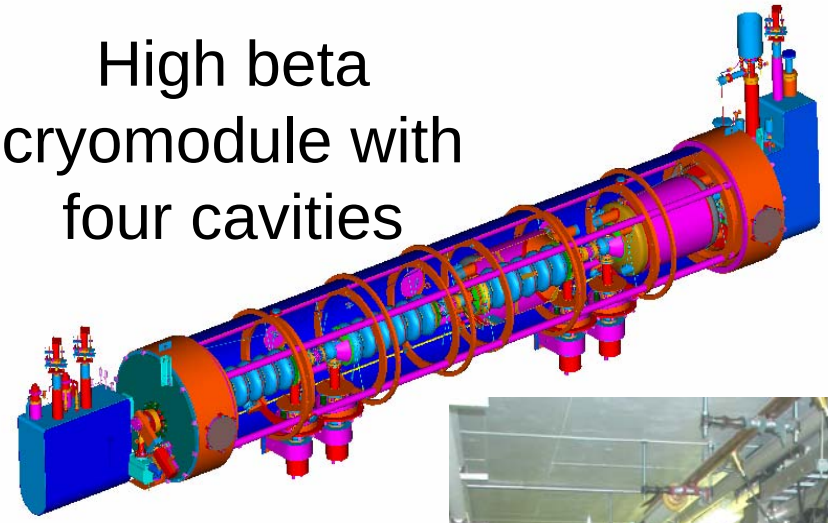
~700-800 MHz Elliptical
$0.6<\beta<1.0$



SC Elliptical-Cell Cavities at SNS (S. Henderson)

High beta (.81) niobium cavity developed at JLab

High beta cryomodule with four cavities



77 of the 81 superconducting cavities at SNS have been commissioned. Cavities have been run with and without beam both at 4.2 K and 2.1 K, demonstrating that pulsed systems give operational flexibility. Most cavities exceed the design gradients (10.1 MV/m for medium (.61) beta and 15.6 MV/m for high beta)
Final H^- beam energies in excess of **910 MeV have been reached** with 72 cavities online.

Cryomodules installed in the SNS linac tunnel

Single-Spoke Cavities (M. Kelly)

Low-Beta~0.1

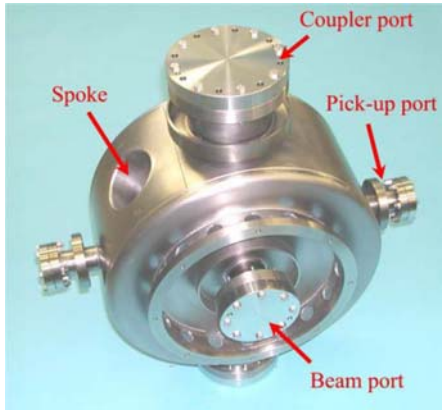
1st SC spoke 1991 (funded through SDI)

850 MHz β=0.28 ANL

340 MHz β=0.29 ANL

High-Beta~1.0

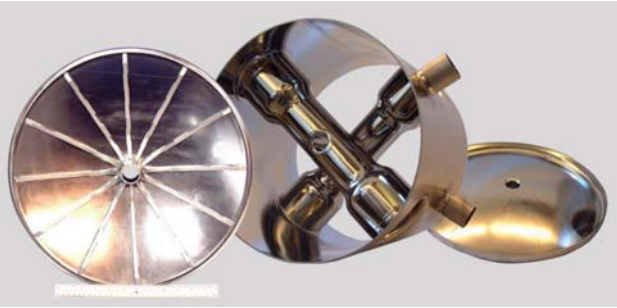
352 MHz β=0.15 IPN Orsay



350 MHz β=0.175 LANL

352 MHz β=0.35 IPN Orsay

Multi-Spoke Cavities (M. Kelly)



345 MHz β=0.40 ANL

760 MHz β=0.2 Juelich

345 MHz β=0.50 ANL

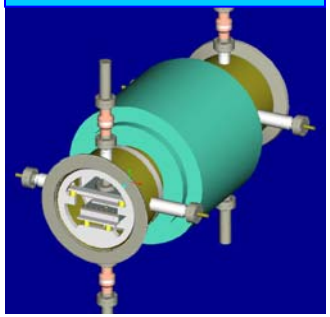
345 MHz β=0.63 ANL

CERN High Performance Proton Front End (R. Garoby)

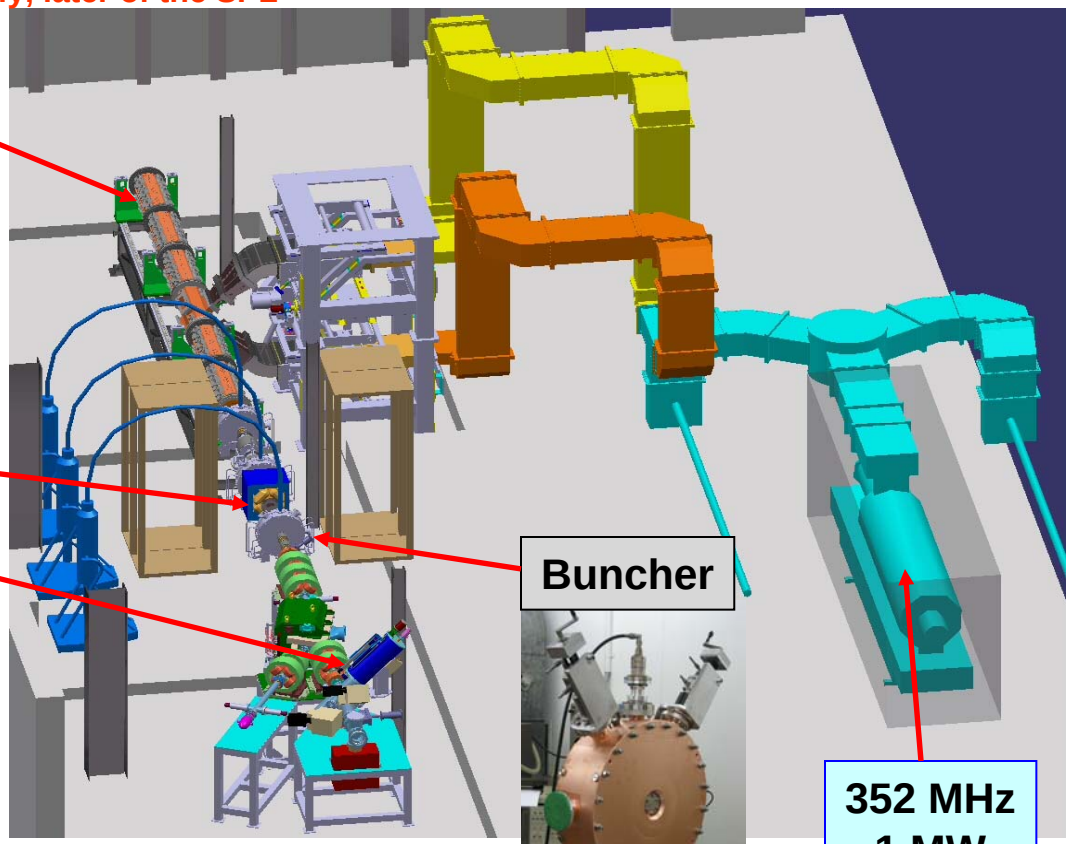
- In construction. To be operational in 2007.
- RFQ designed by CEA+CNRS (France) / brazed at CERN; 3 MeV chopping line from CERN.
- First use: characterization of high brightness beam (halo) & demonstration of chopper operation,
- Final use: front-end of Linac4 and, possibly, later of the SPL

IPHI RFQ
(2nd module before brazing)

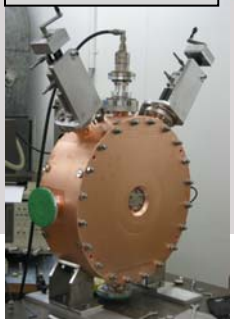
Chopper



Bunch Shape & Halo Monitor

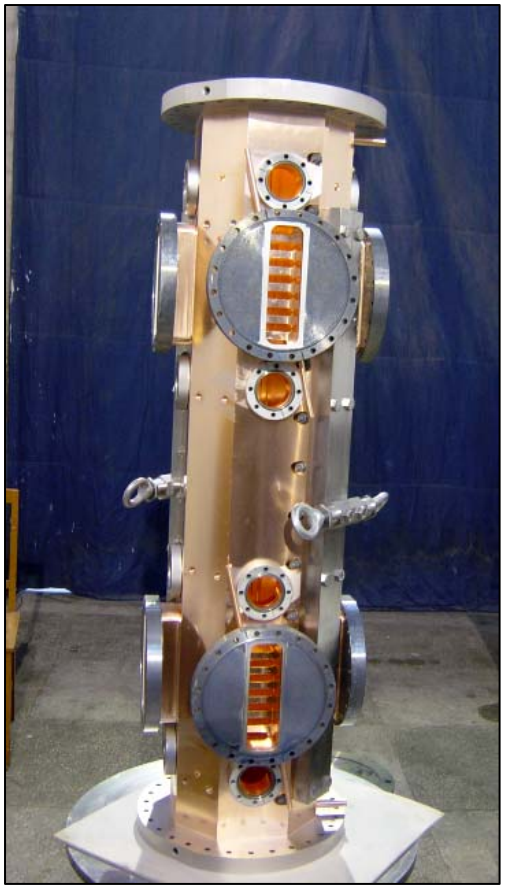


Buncher



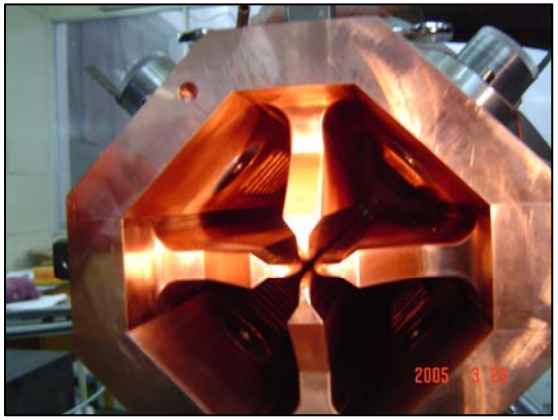
352 MHz 1 MW klystron

Beijing Spallation Neutron Source RFQ (J-Q. Wang)



Braze test of a full size module

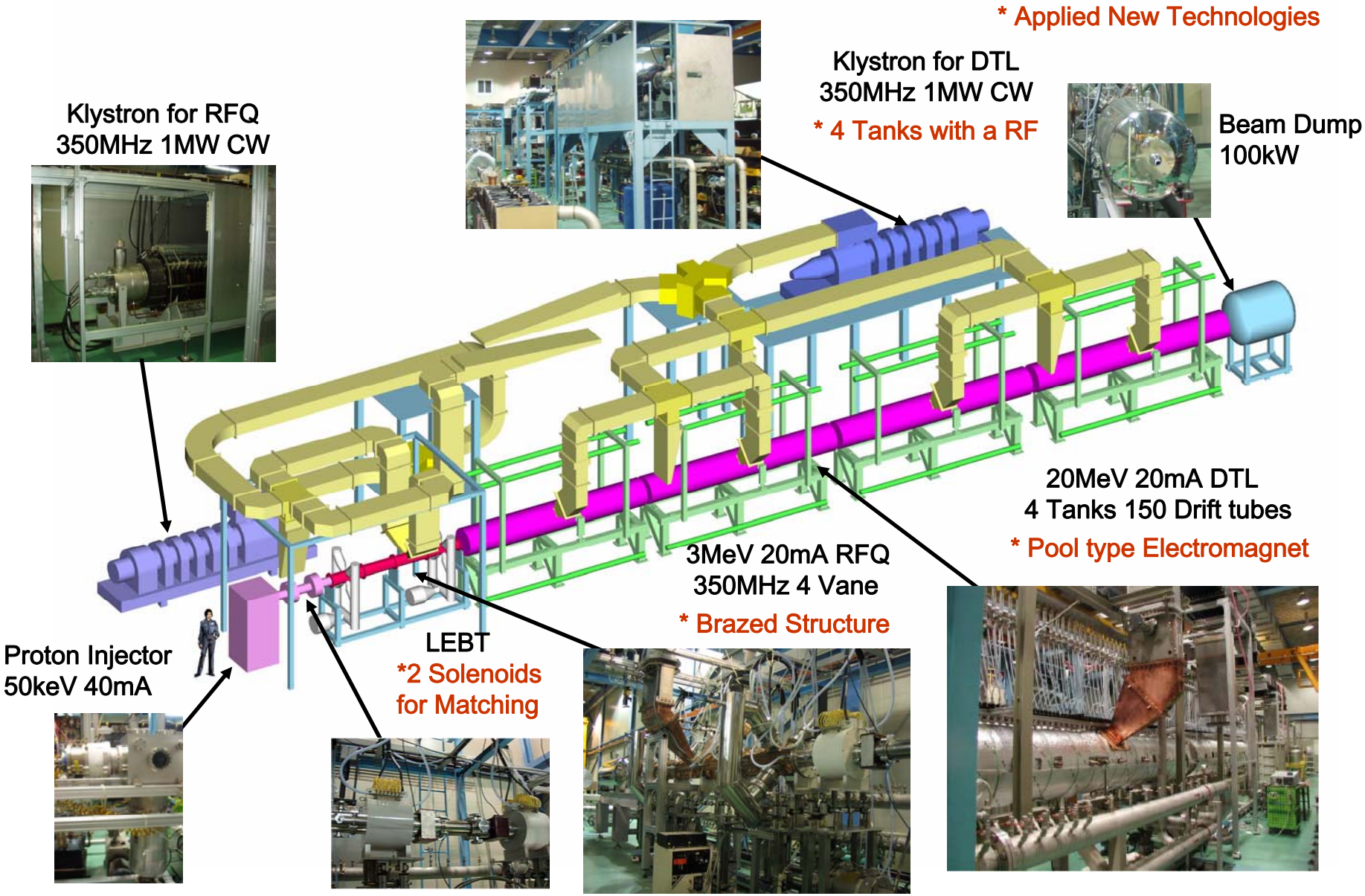
The vane after fine machining and on the CMM



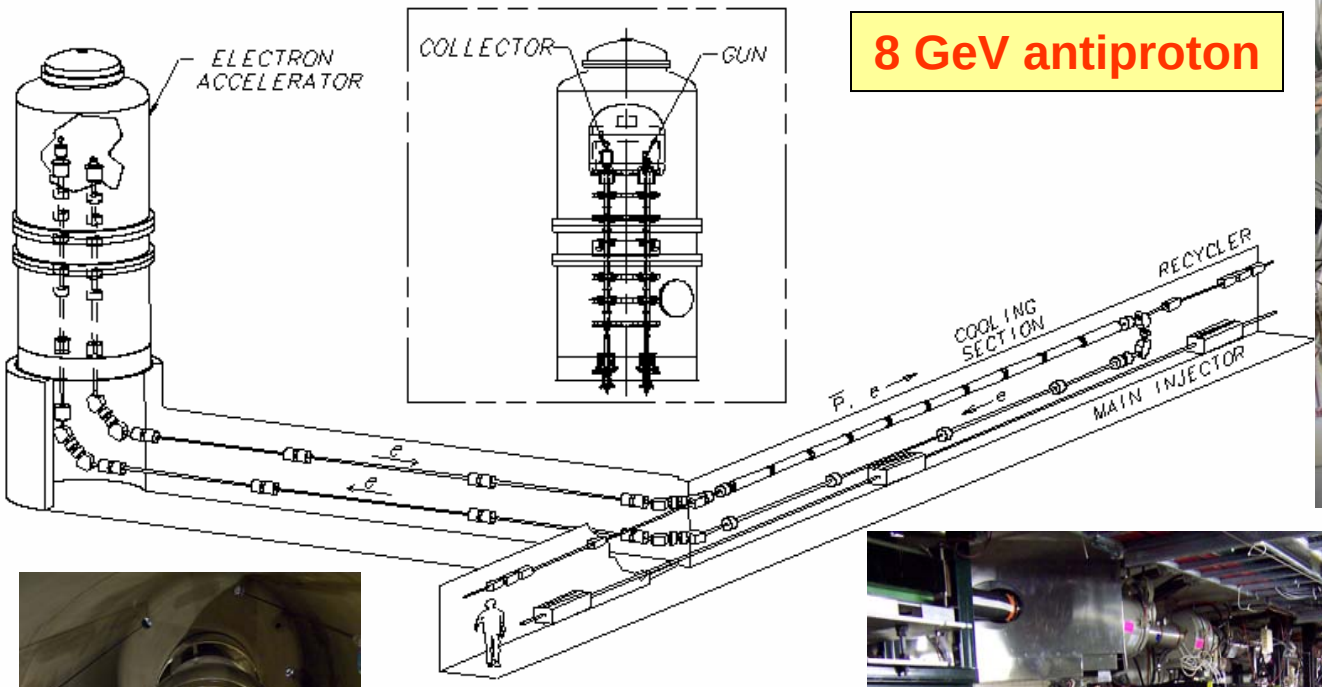
Assembled RFQ

RF measurement

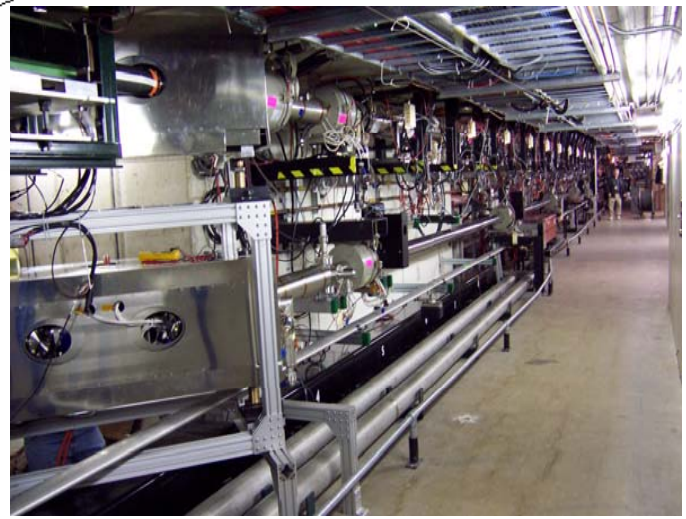
Korea PEFP Proton Linac Front End (B-H. Choi)



Electron Cooling at Fermilab (S. Nagaitsev)

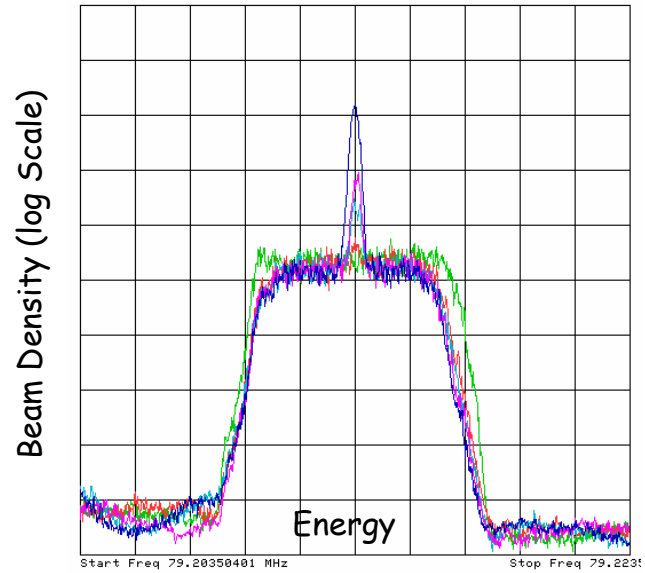


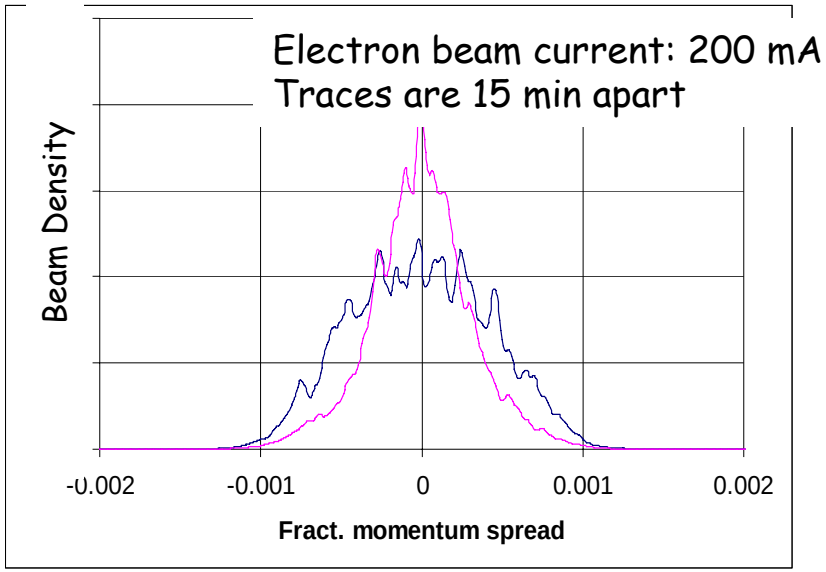
8 GeV antiproton



Electron Cooling (cont…)

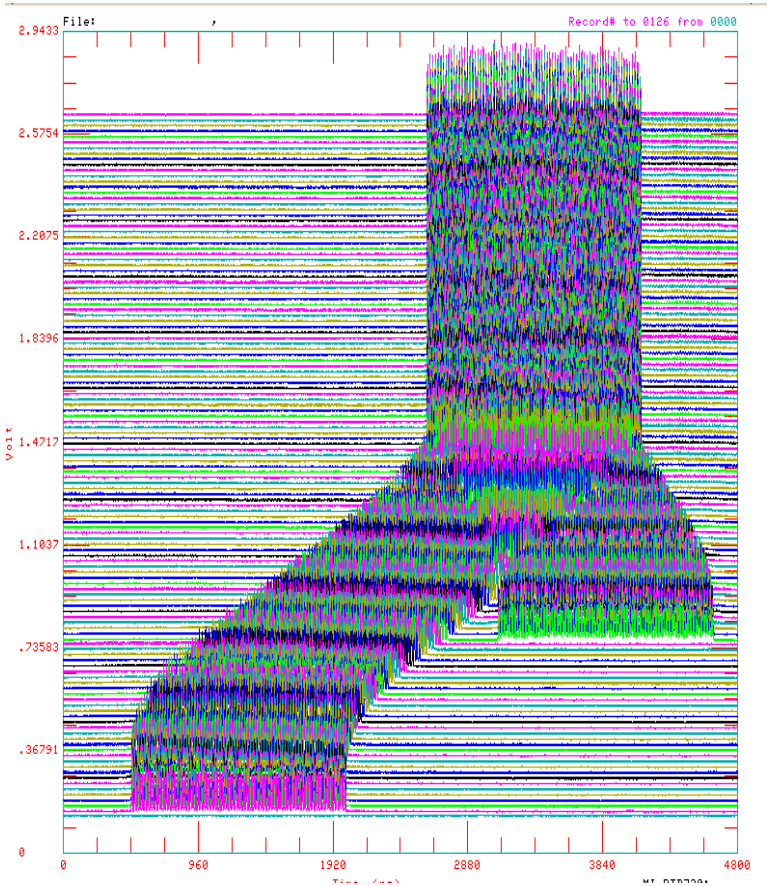
- Electron cooling commisioning
  - Electron cooling was demonstrated in July 2005 two months ahead of schedule.
  - By the end of August 2005, electron cooling was being used on every Tevatron shot
- Electron cooling rates
  - Drag rate: 20 MeV/hr for particles at 4 MeV
  - Cooling rate: 25 hr^{-1} for small amplitude particle
  - Can presently support final design goal of rapid transfers (30eV-sec every hour)
  - Have achieved 500 mA of electron beam which is the final design goal.



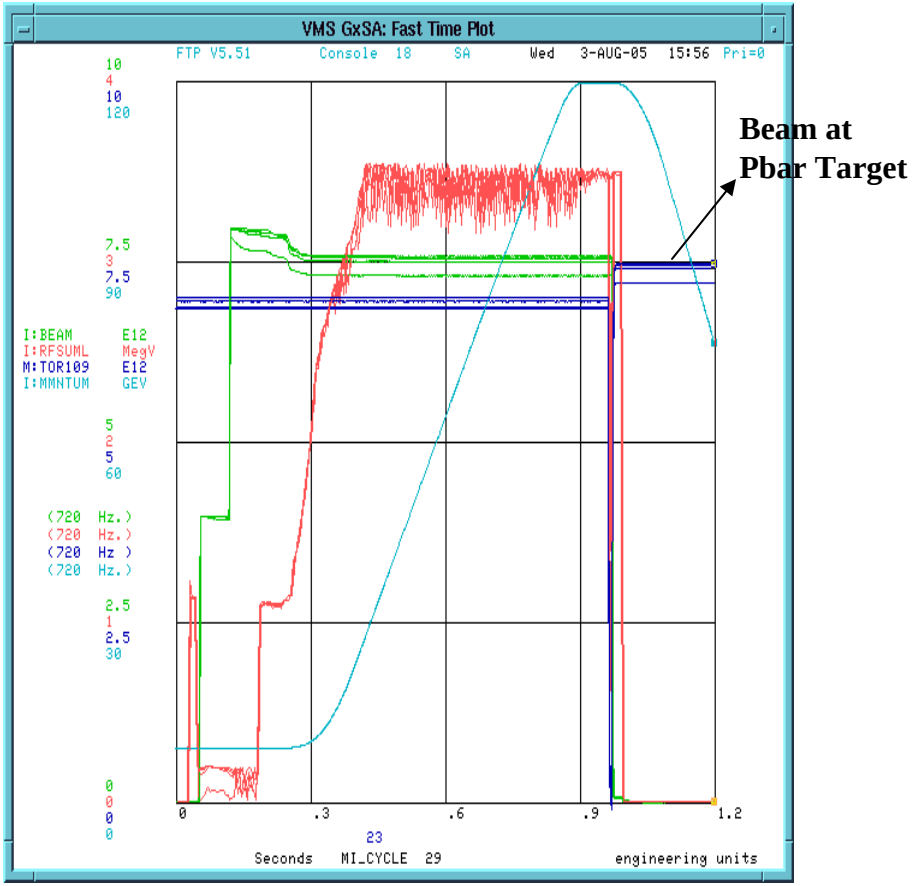


Slip Stacking at Fermilab (I. Kourbanis, K. Koba)

Stacking: To combine two bunches into one to double beam intensity

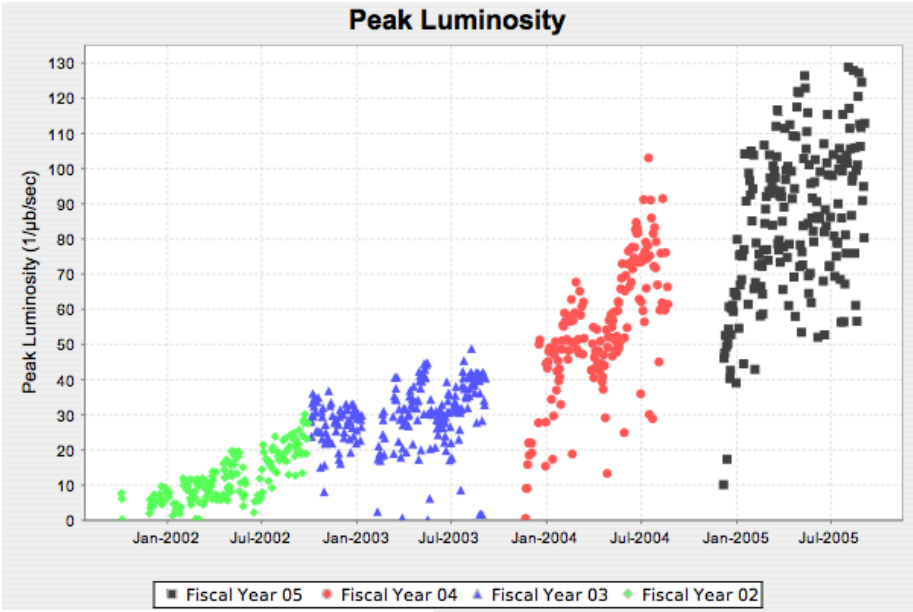


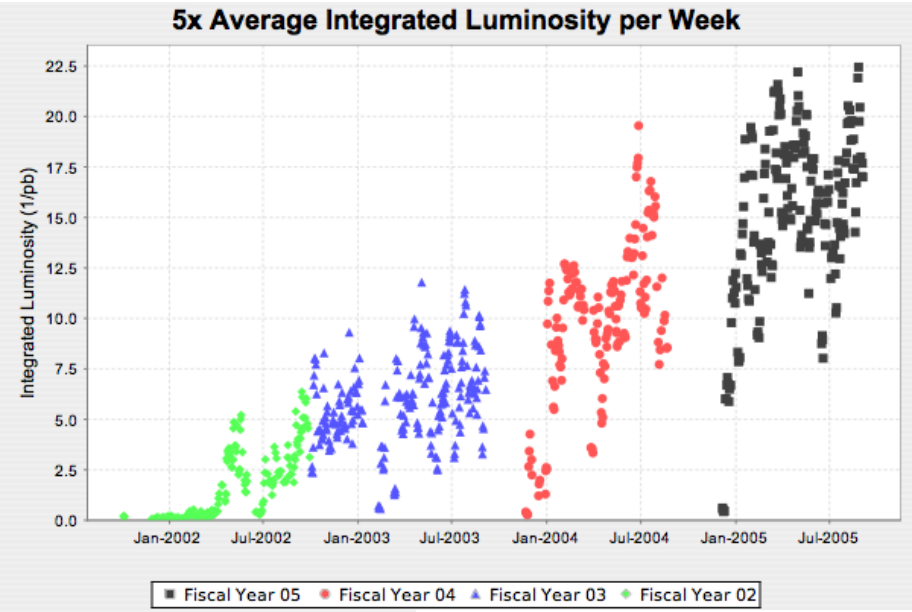
Mountain Range Picture

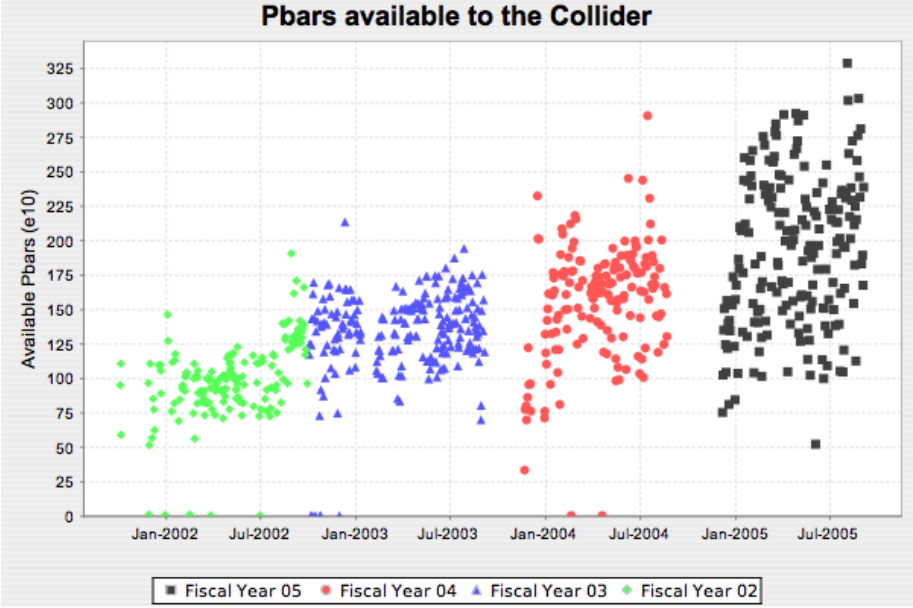


Beam Intensities (Efficiency ≥ 95%)

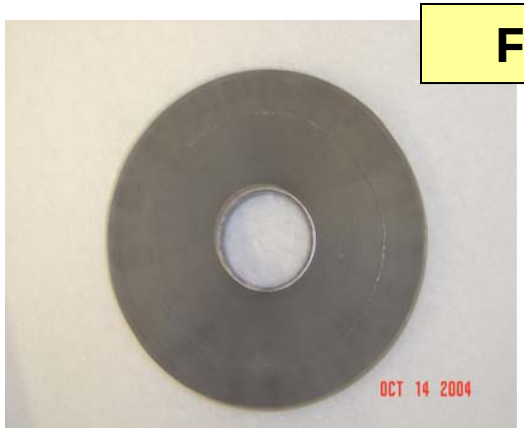
Tevatron Luminosity Evolution





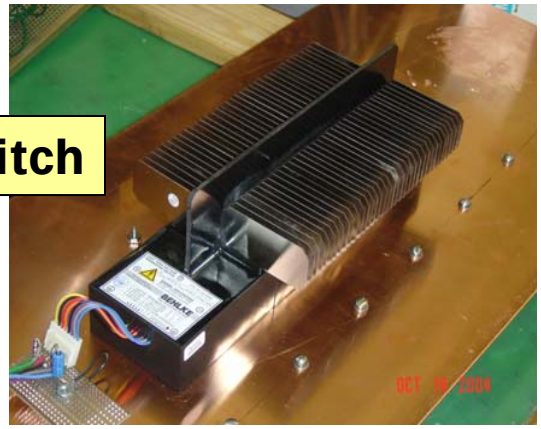


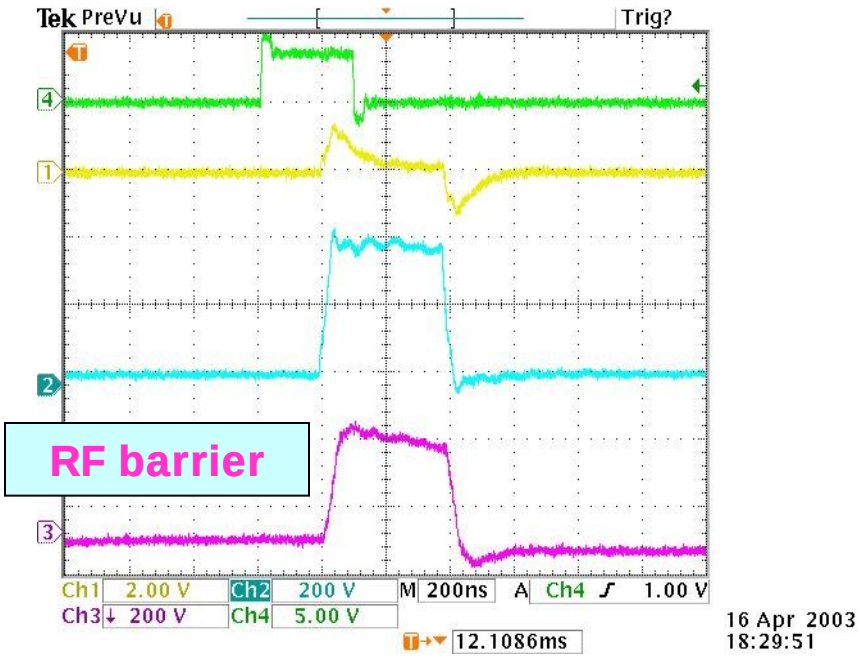
Barrier RF Stacking at Fermilab (W. Chou, D. Wildman)



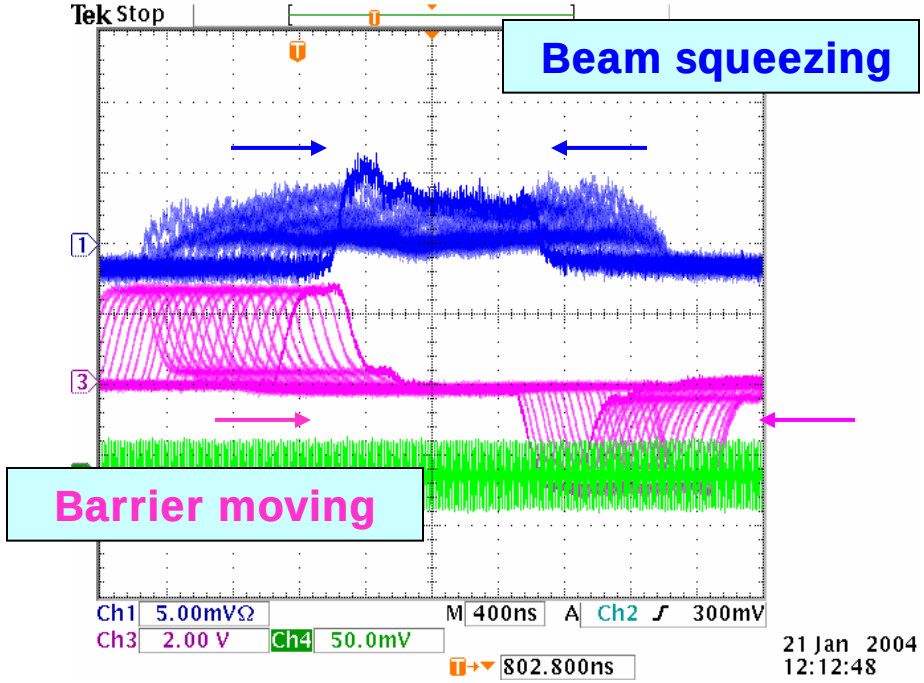
Finemet core

High voltage fast switch





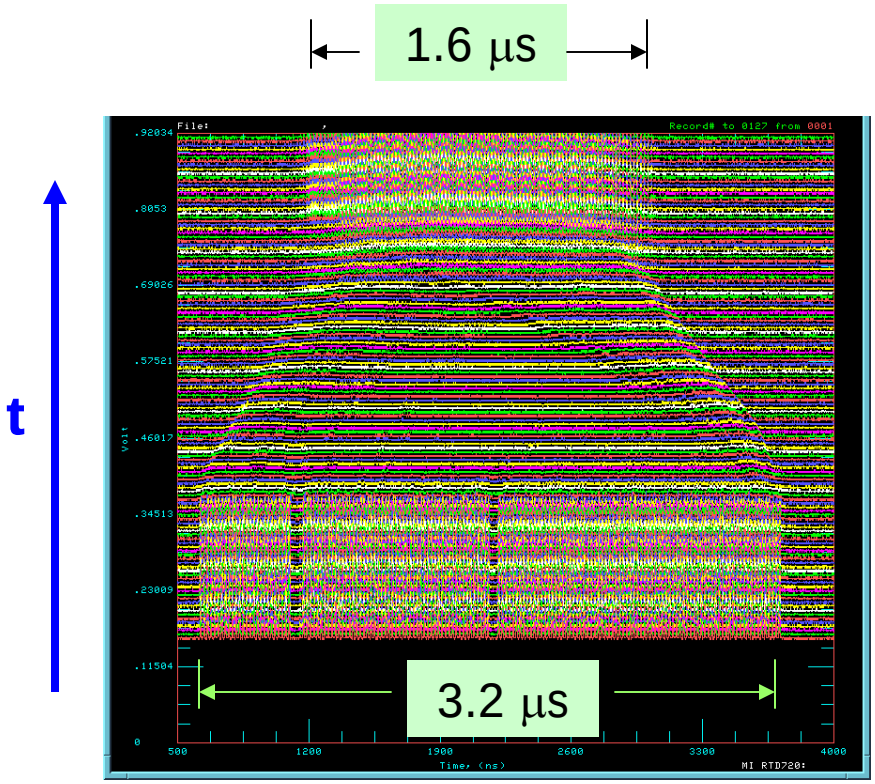
RF barrier



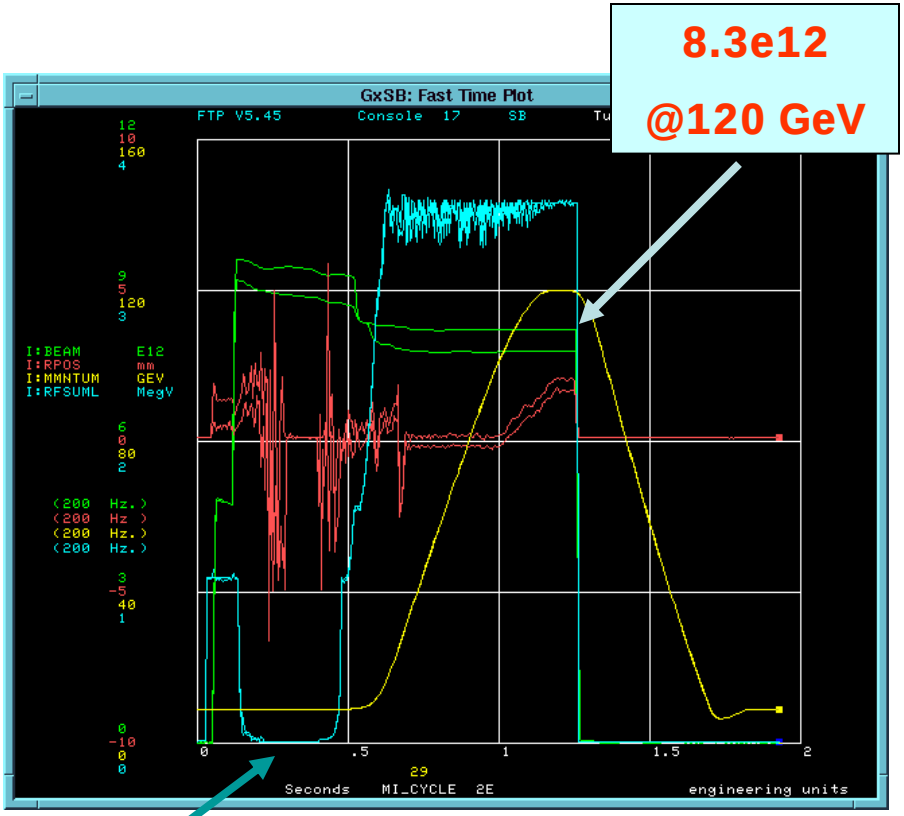
Beam squeezing

Barrier moving

Barrier RF Stacking (cont…)



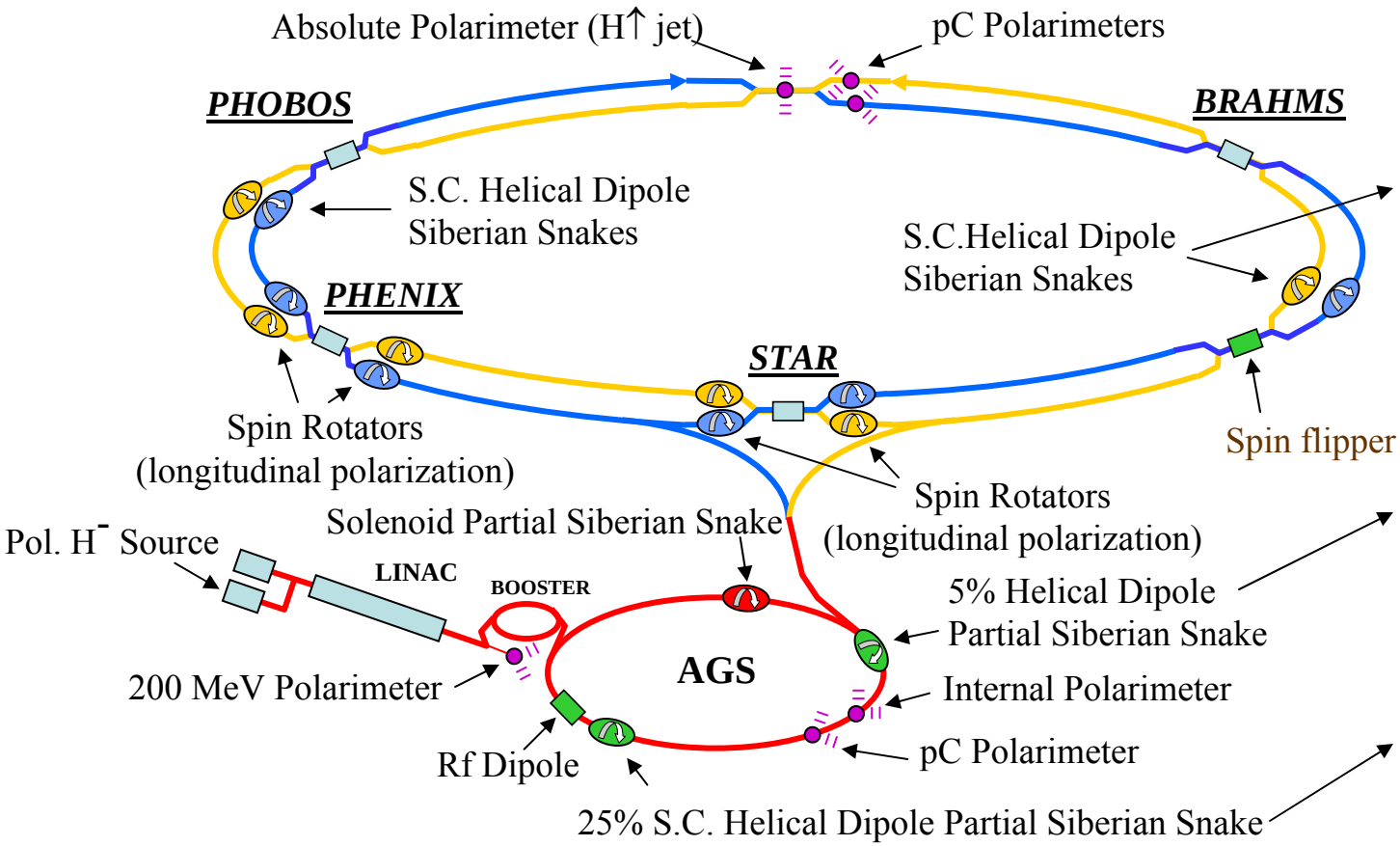
Mountain view

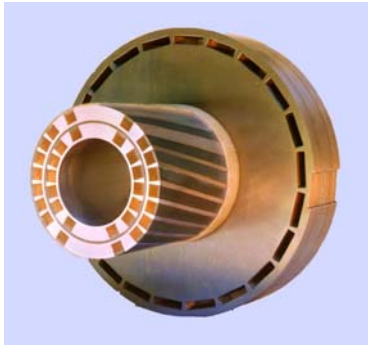


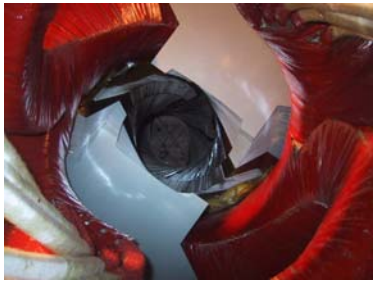
8.3e12 @120 GeV

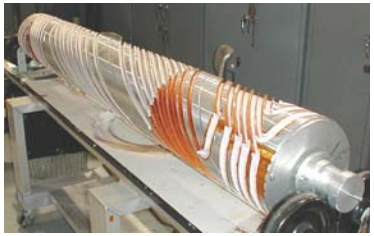
Squeezing

RHIC – First Polarized p-p Collider (T. Roser)



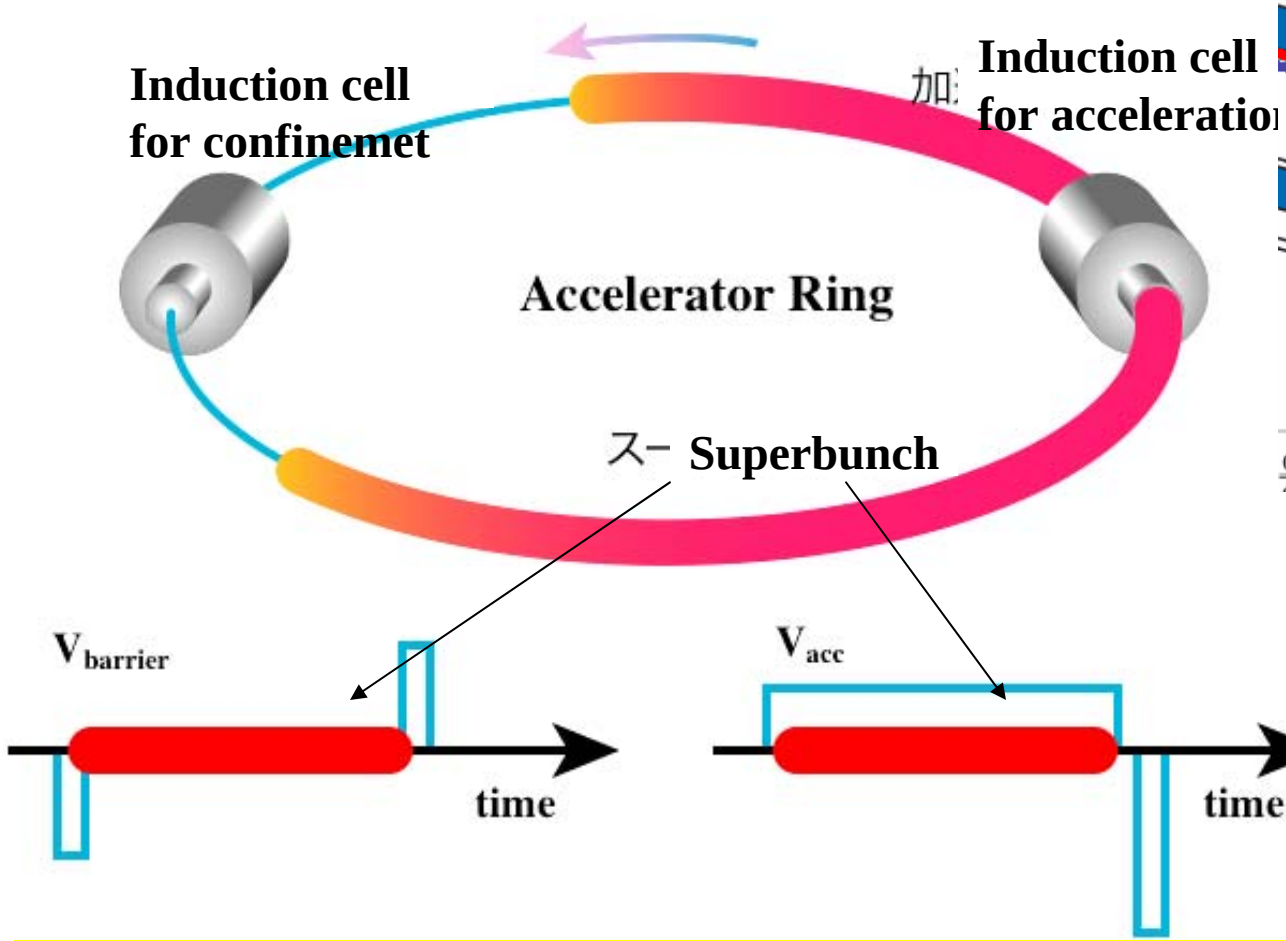


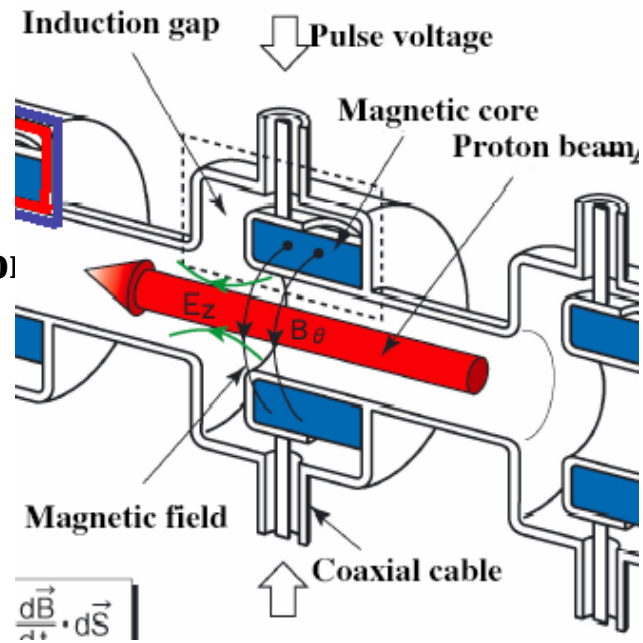




Without Siberian snakes: $\nu_{sp} = G\gamma = 1.79$ E/m → ~1000 depolarizing resonances
With Siberian snakes (local 180° spin rotators): $\nu_{sp} = ½$ → no first order resonances
Achieved ~ 50% proton polarization and 1×10^{31} cm^{-2} s^{-1} at sqrt(s) = 200 GeV

KEK Induction Synchrotron (K. Takayama)

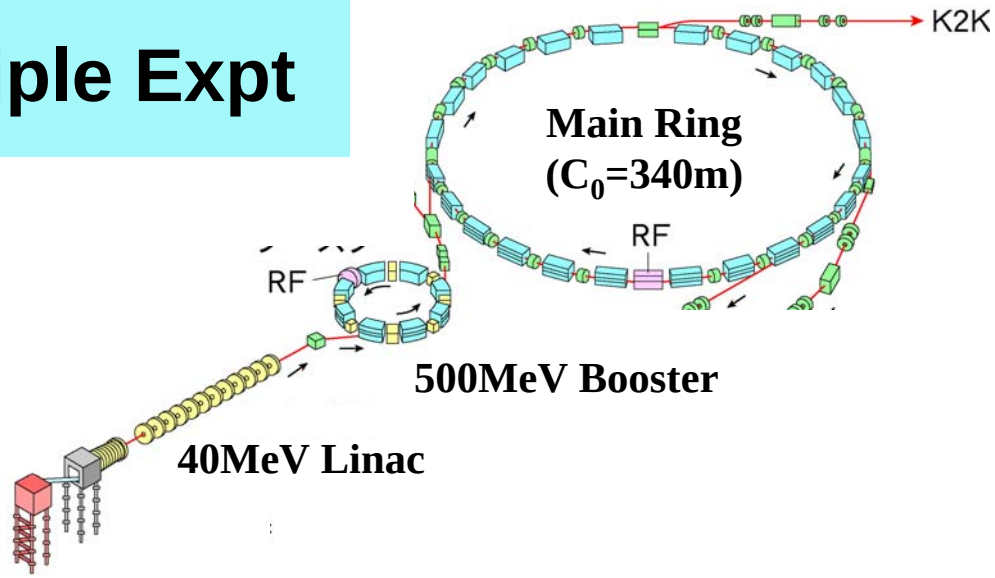




Principle for Acceleration
(Faraday's induction law)

K.Takayama and J.Kishiro, "Induction Synchrotron", *Nucl. Inst. Meth.* A451, 304(2000)

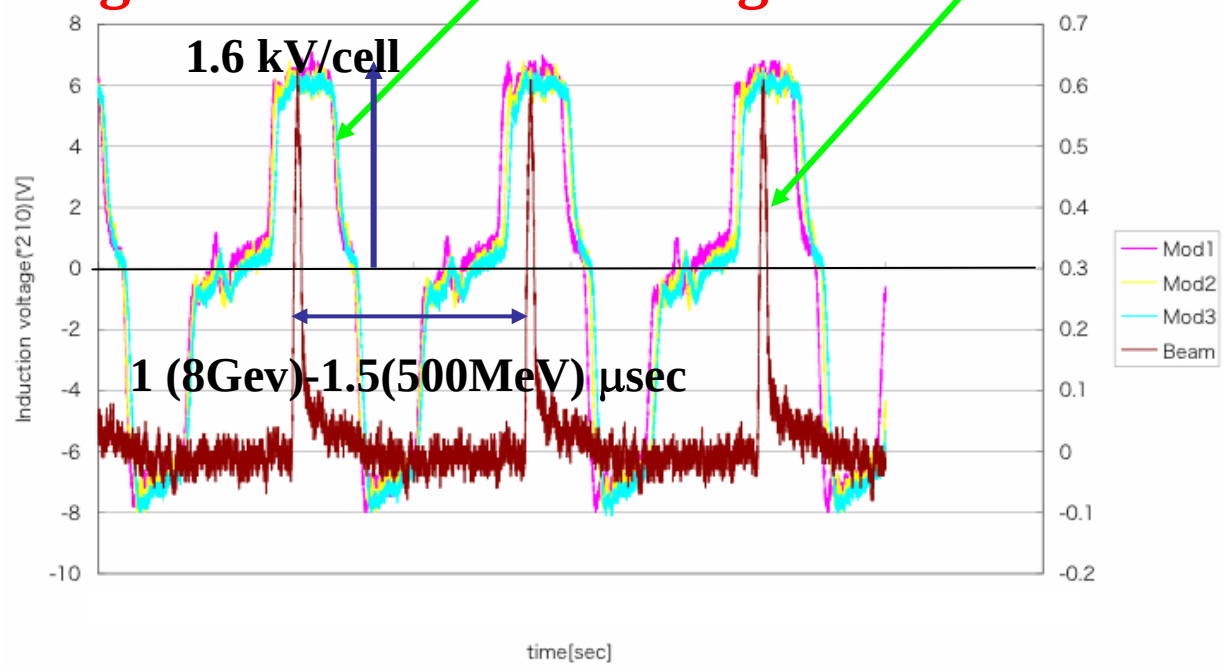
KEK-PS Proof of Principle Expt



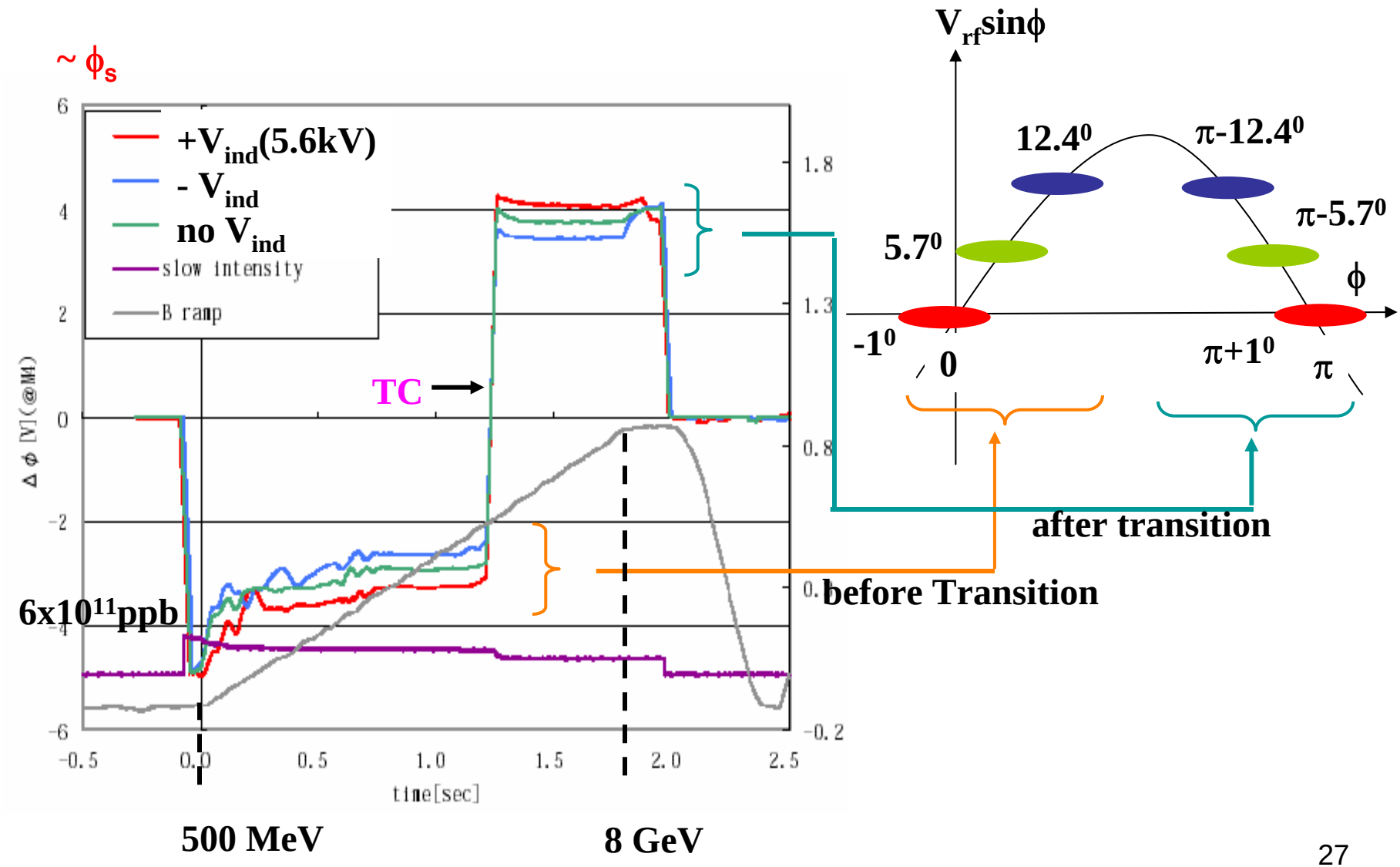
Machine/beam parameters:

- E=500MeV -> 8GeV
- h=9
- γ_t=6.6
- V_{rf}=48kV
- V_{acc}=4.8kV
- N/bunch=6x10^{11}

Monitored signals of induction voltage and an RF bunch signal



KEK-PS Proof of Principle Expt (cont…)



K.Takayama *et al.*, *Phys. Rev. Lett.* 94, 144801 (2005).

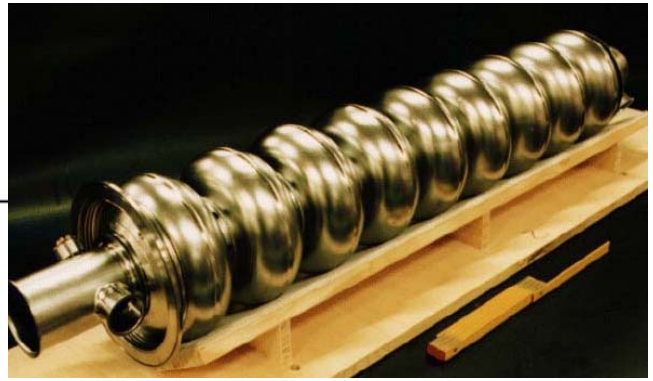
High Power Mercury Target at SNS (S. Henderson)

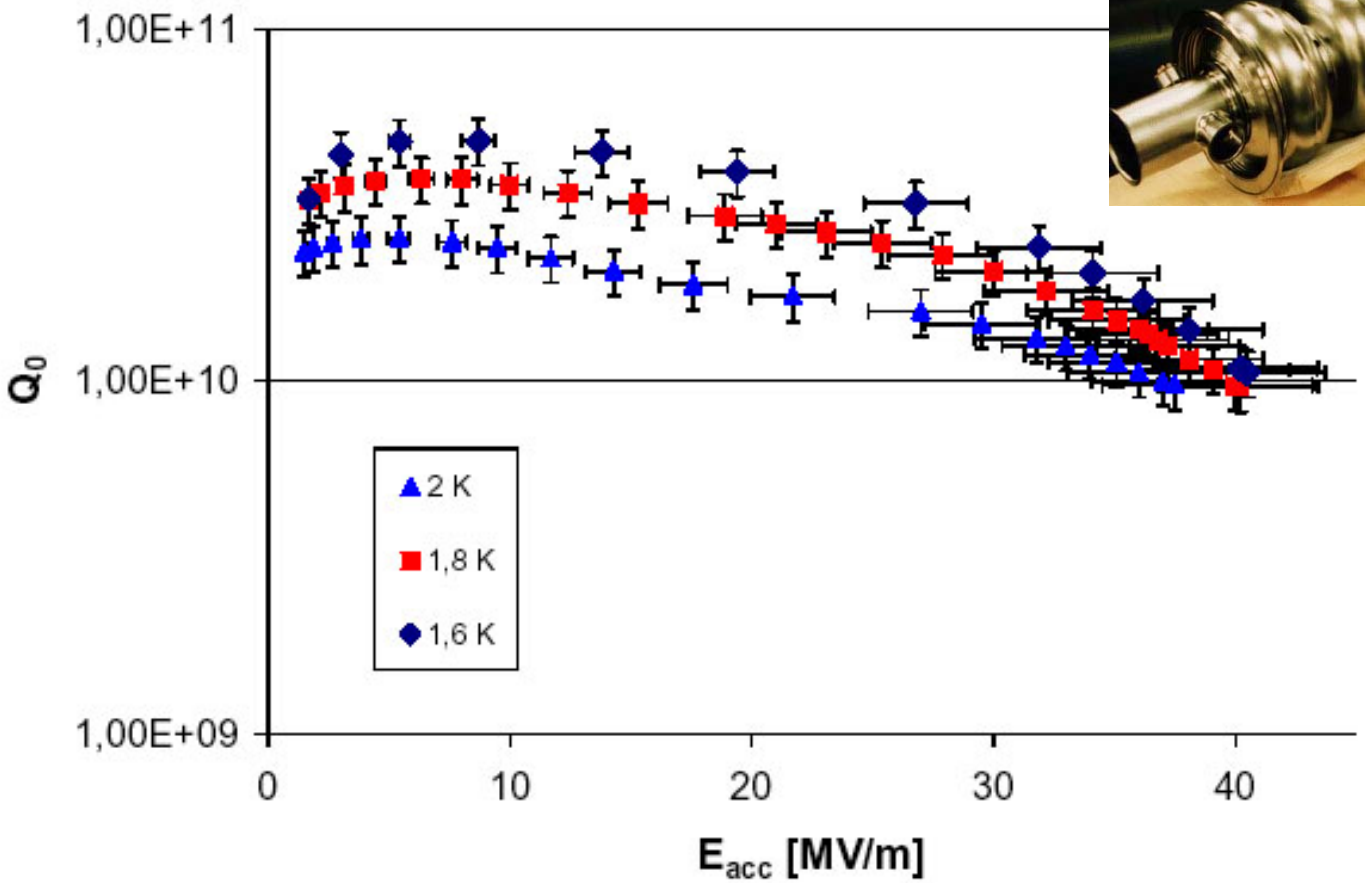
- Performing R&D with goal of > **2 MW operation of liquid Mercury target**
- R&D focuses on mitigation of cavitation induced pitting
- Conducted in-beam testing at LANSCE/WNR in June 2005
  - Bubble mitigation of pitting damage
    - First test with bubble injection and flowing mercury
  - Beam intensity – damage correlation
    - Verify fourth power dependence for beam intensity on target
  - JAERI team measured significant reduction in high-frequency (cavitation intensity) acoustic energy with flowing Hg and further reduction with bubbles
  - Waiting for specimens to cool before conducting pitting damage inspection

Lepton Machines

High G High Q Superconducting RF (H. Padamsee)

Best Cavities Tested at DESY, 35 - 40 MV/m

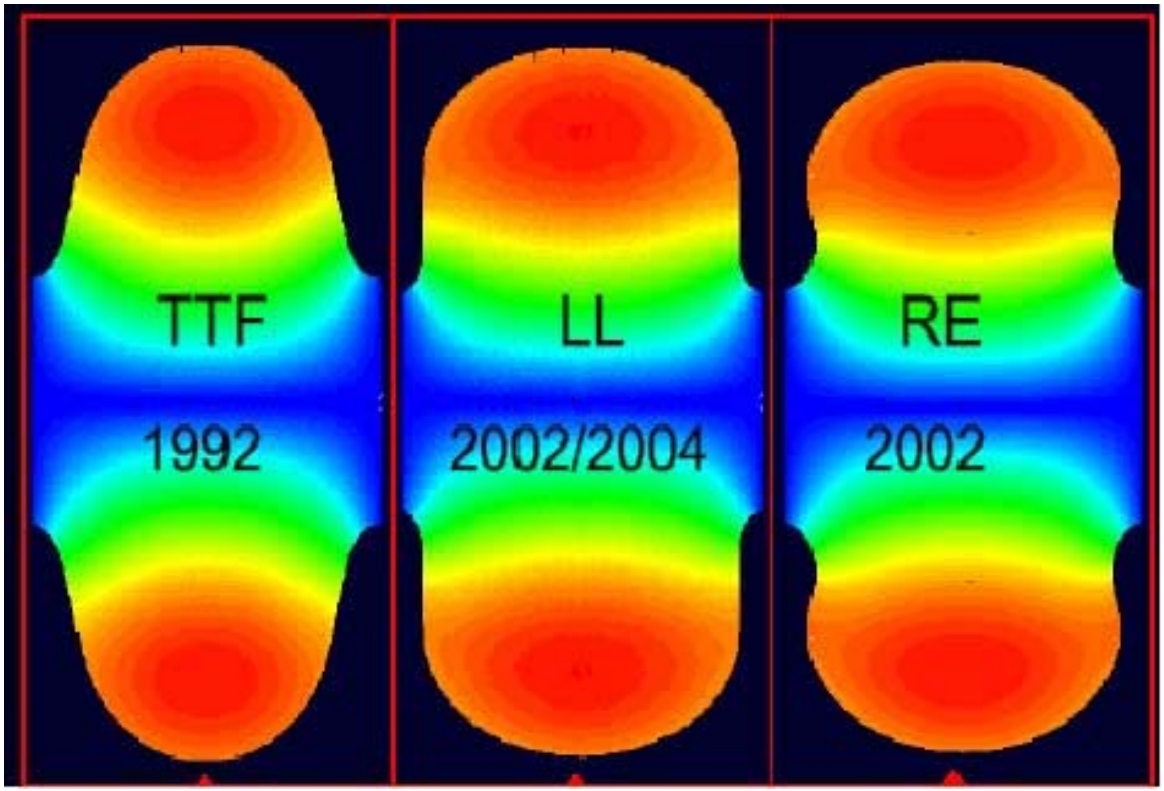




High G High Q Superconducting RF (cont…)

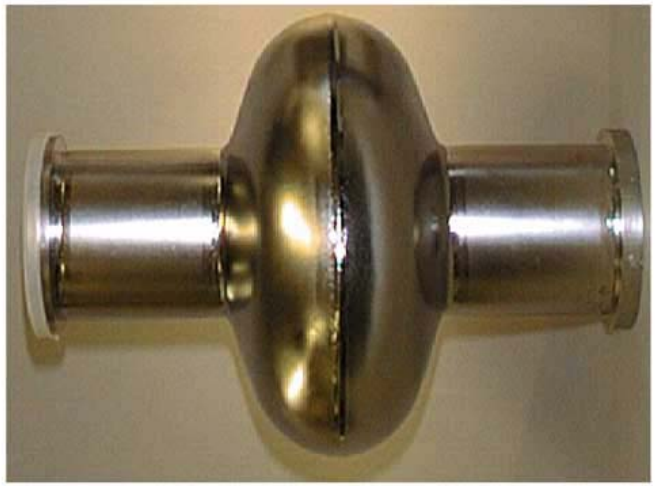
Alternative shape under development

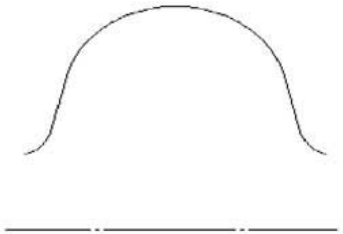
TESLA Low-Loss Re-Entrant



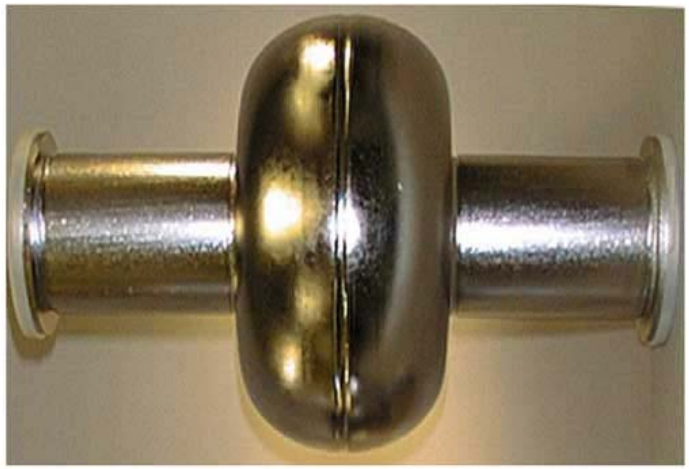
High G High Q Superconducting RF (cont…)

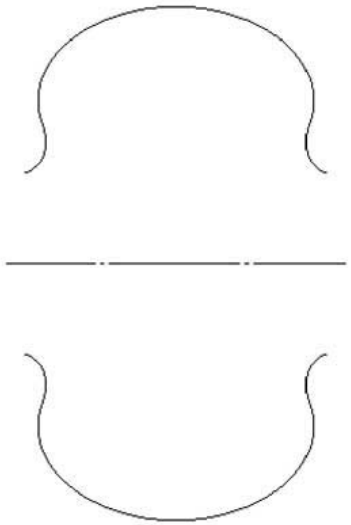
New shape developed at Cornell





TESLA Shape

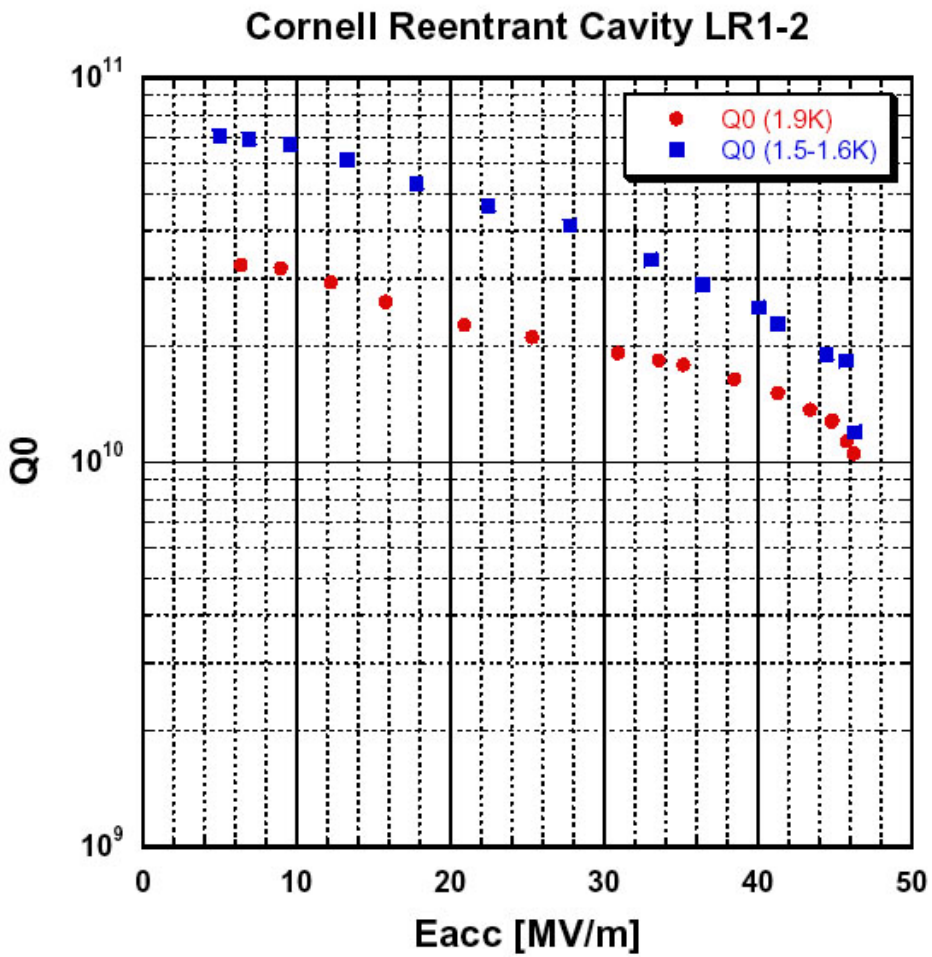




Re-entrant shape

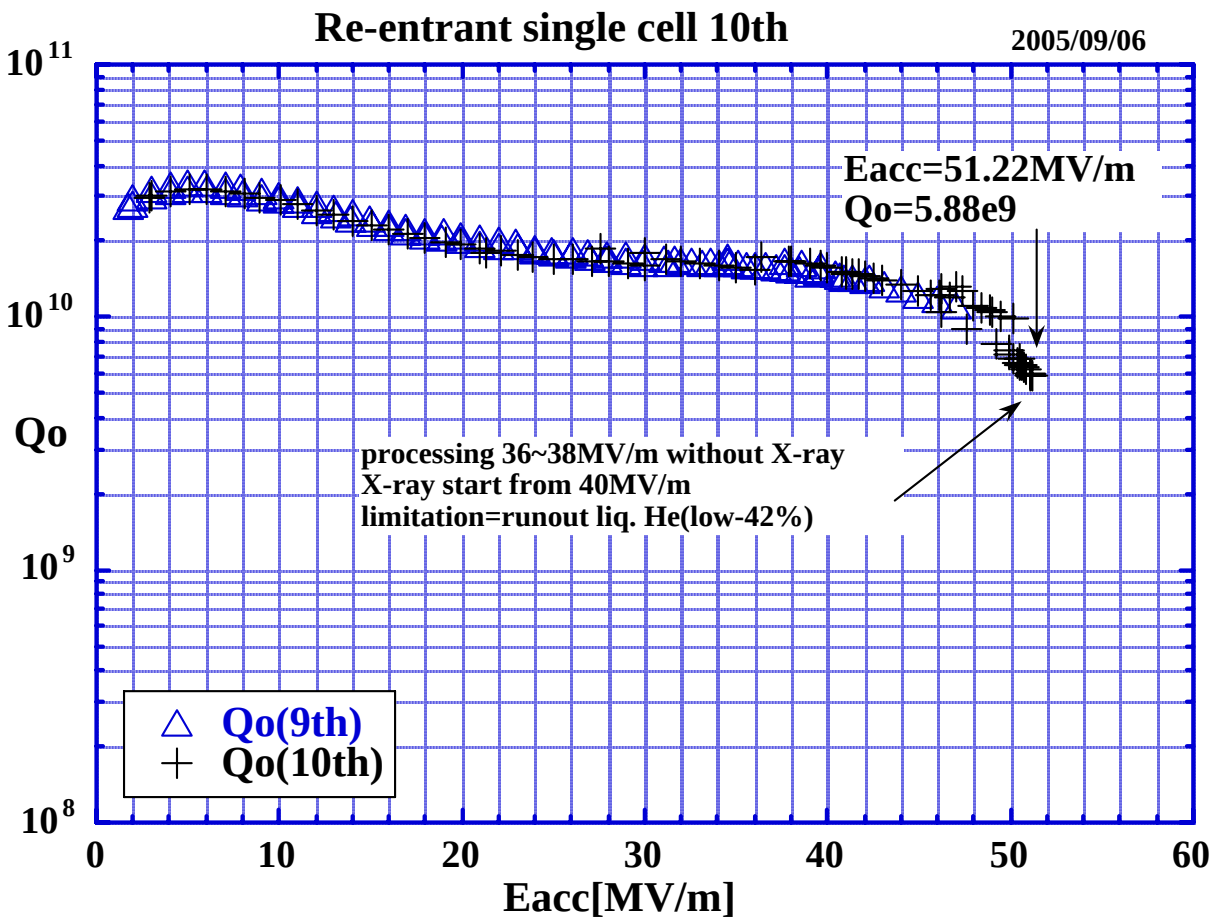
High G High Q Superconducting RF (cont…)

May 2005 – 1st Re-entrant cavity, 47 MV/m, 1.3 GHz, World Record!



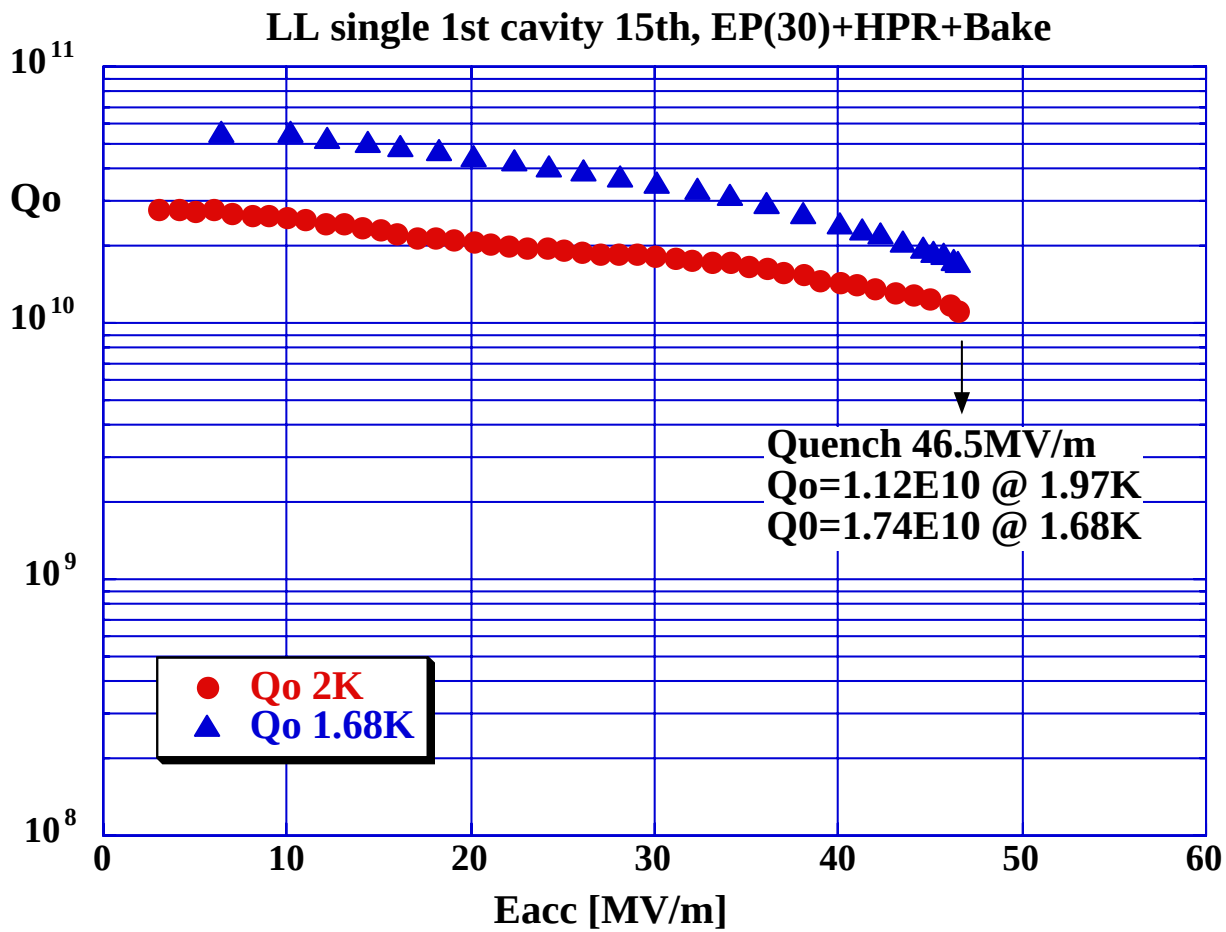
High G High Q Superconducting RF (cont…)

Sept 2005 – 2nd Re-entrant cavity fabricated at Cornell and sent to KEK, 51 MV/m!



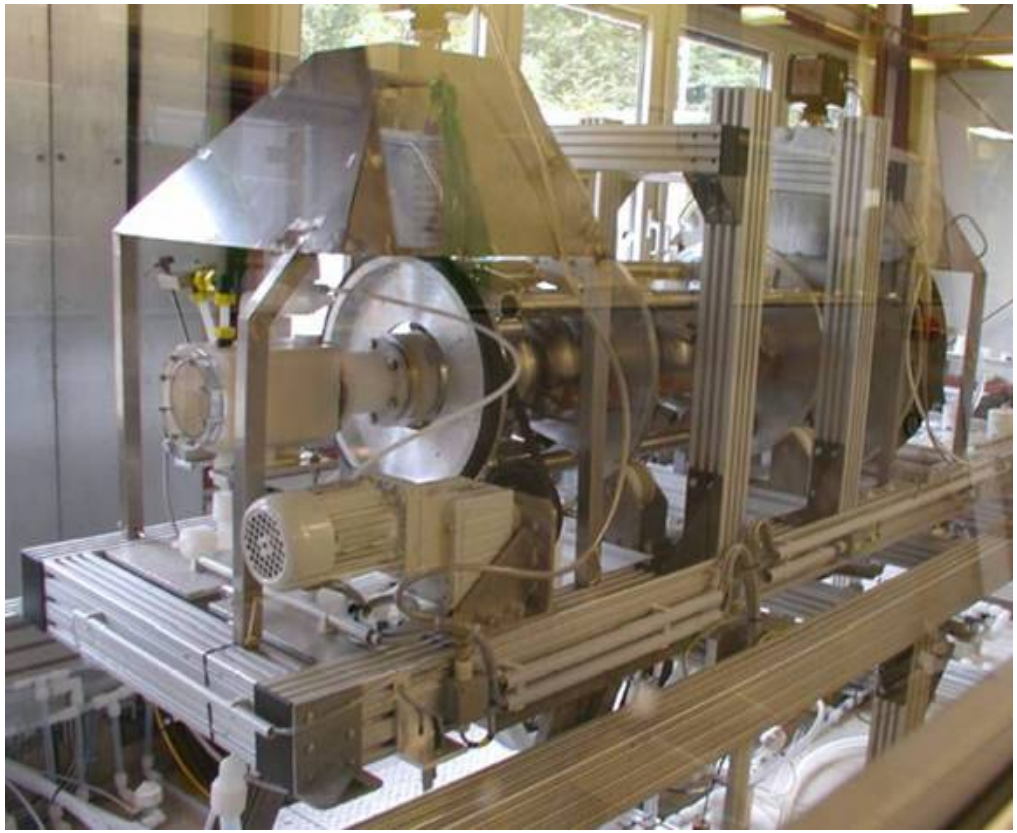
High G High Q Superconducting RF (cont…)

Low-Loss cavity developed by KEK-Jlab, 46.5 MV/m, 1.3 GHz

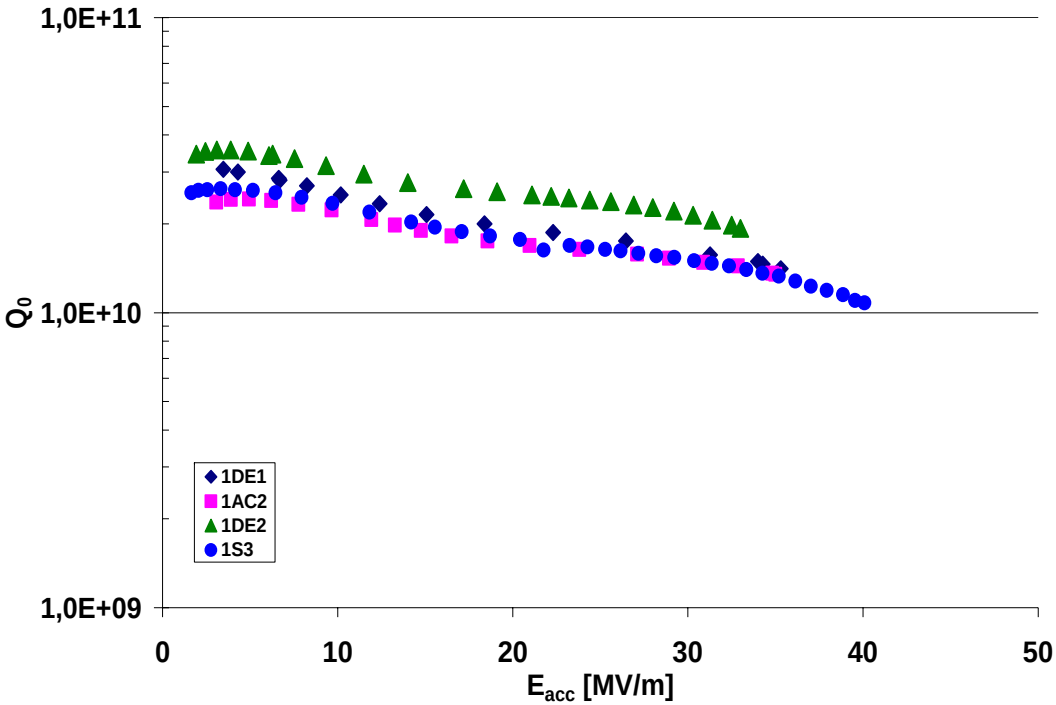


Electropolishing at DESY (D. Trines)

- First 9-cell cavities were successfully treated.
- Facility runs continuously
- Next steps: improved quality control to achieve more reproducible performance



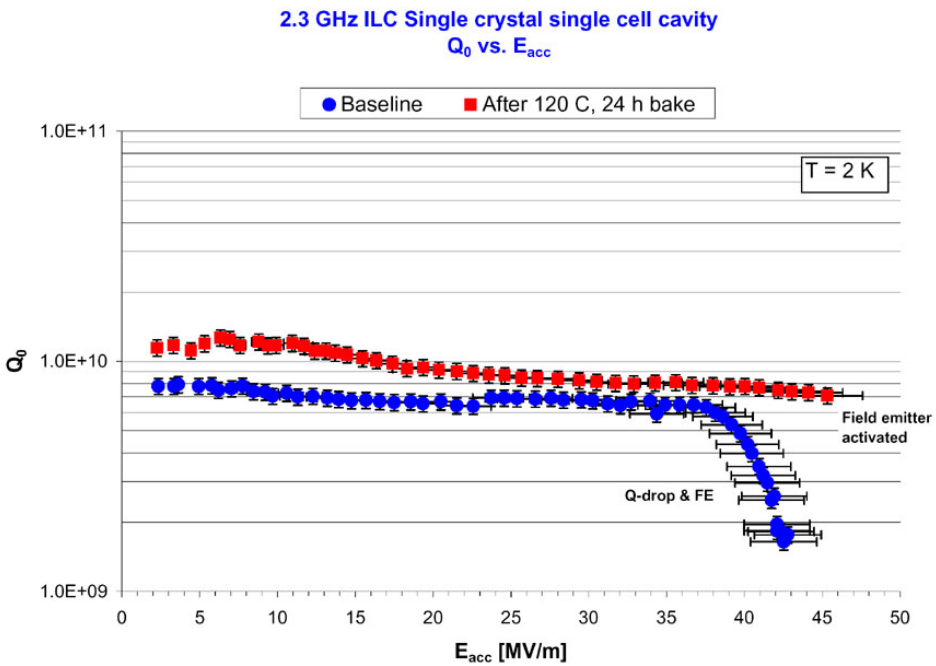
Electropolishing at Industry (Henkel Co., Germany)



- Electropolishing at Henkel company can produce very high gradient (up to 40 MV/m), high Q_0 cavities
- Improved quality control measures at DESY and Henkel
  - Electrolyte-Management
  - Improved parameter-control
- Further cavities will be treated
- 1.3 GHz three-cell cavities can also be treated

Jlab Single Crystal SC Cavity (S. Chattopadhyay)

Nb Discs



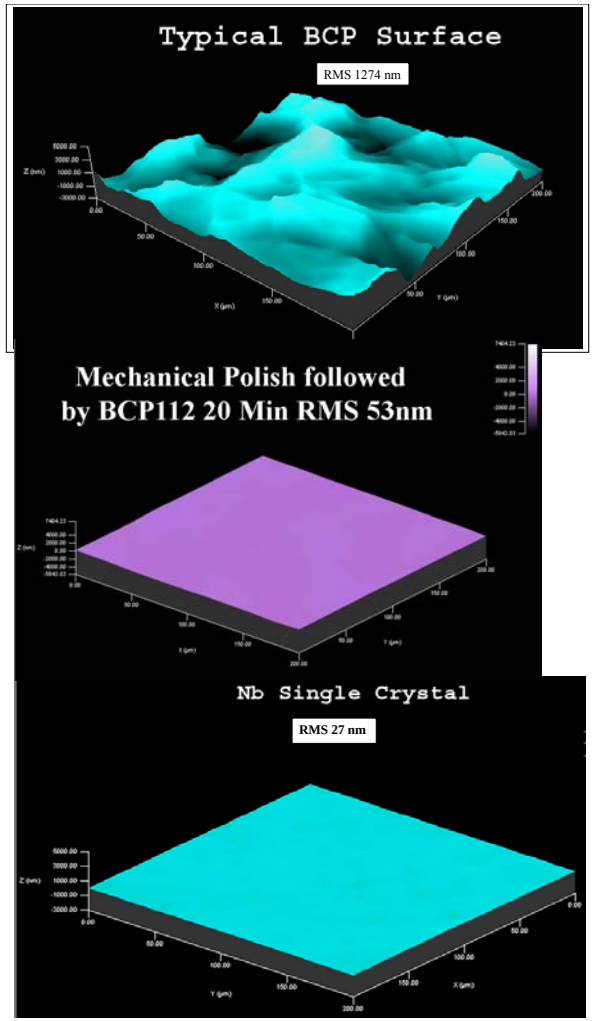
Low-Loss cavity, 45 MV/m, 2.3GHz

E_{peak}/E_{acc} = 2.072

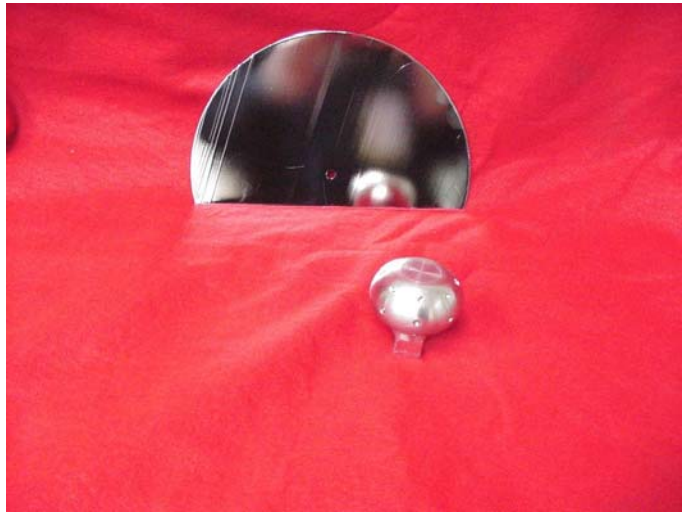
H_{peak}/E_{acc} = 3.56 mT/MV/m

Surface Roughness Improvement (S. Chattopadhyay)

BCP provides very smooth surfaces as measured by A.Wu, Jlab

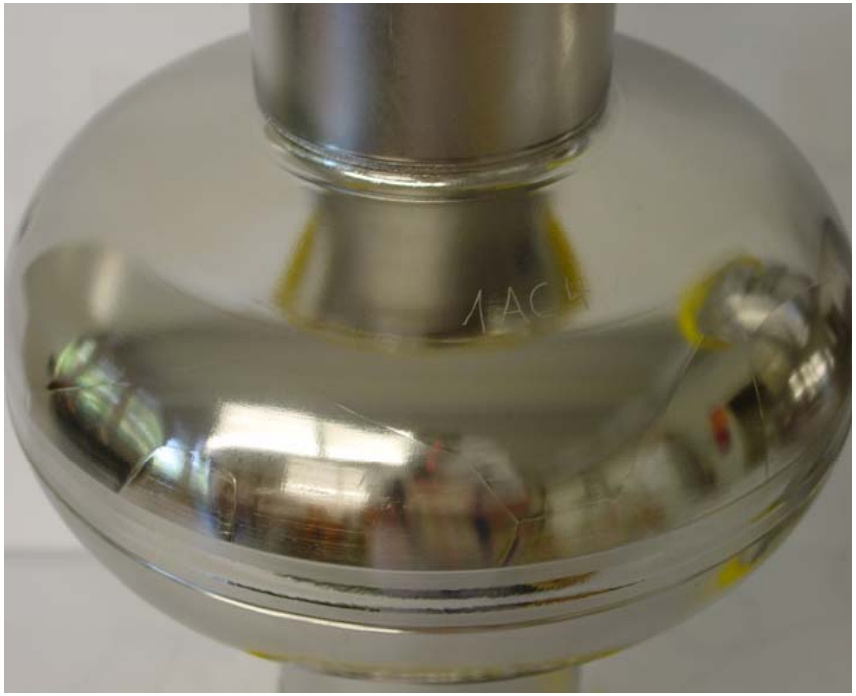


RMS: 1274 nm fine grain bcp
251 nm fine grain ep
53 nm after ~ 35 micron, single Crys
27 nm after ~ 80 micron,single Crys
(bcp: buffered chemical polishing)
(ep: electro-polishing)



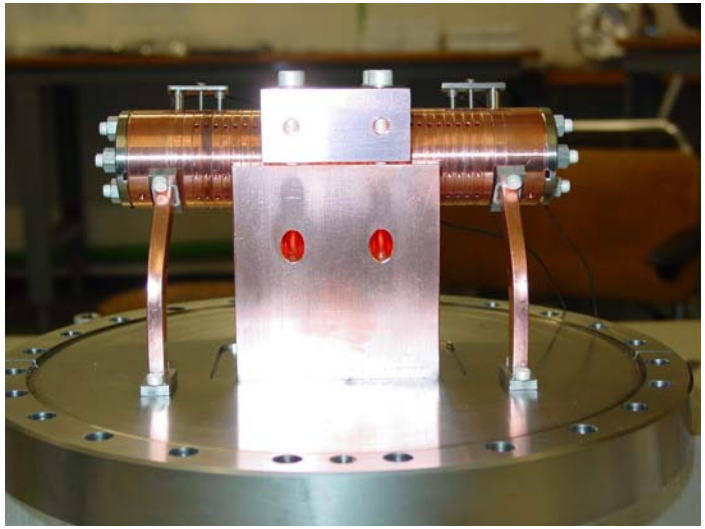
DESY Large Grain SC Cavity 1.3 GHz (D. Trines)

- Follows the development at JLab (Kneisel, Rao et.al)
  - Potential cost savings in cavity fabrication
- Of great interest also for the XFEL project

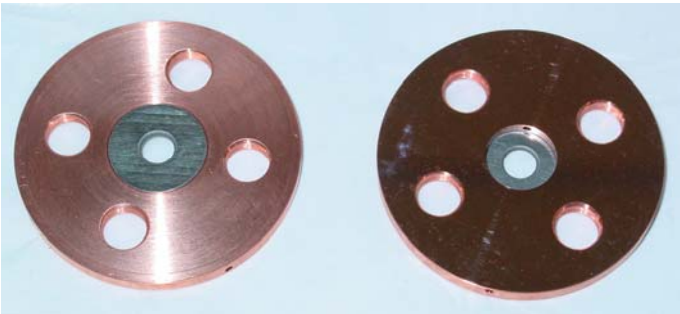


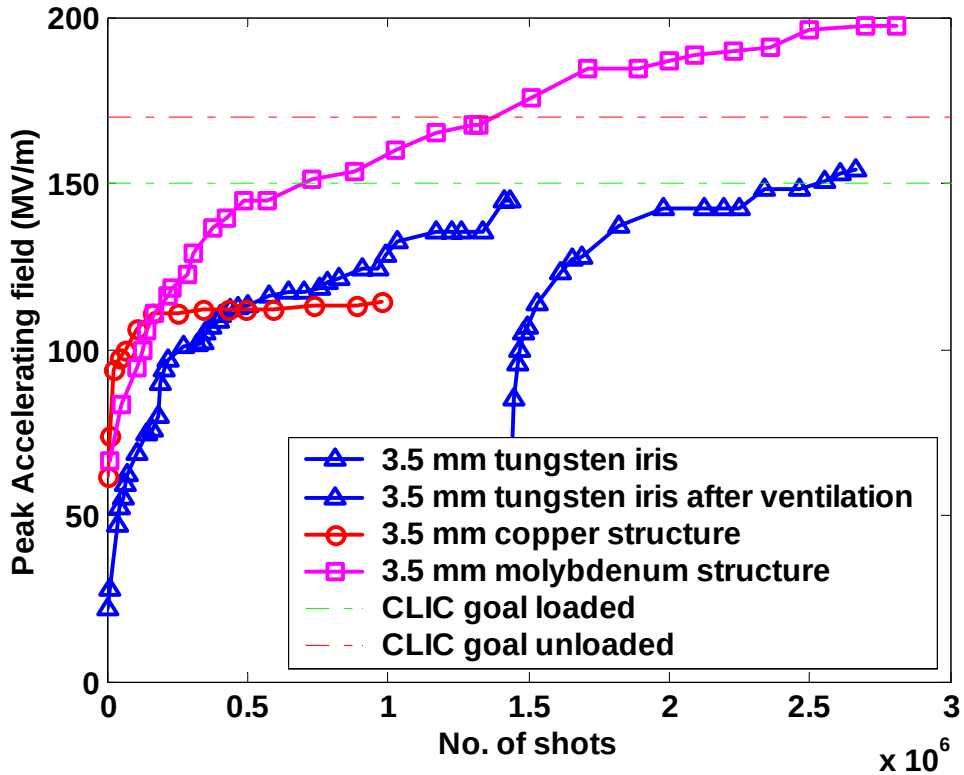
CERN CLIC CTF2 (G. Geshonke, W. Wuensch)

High gradient tests of new structures with molybdenum irises reached **190 MV/m** peak accelerating gradient without any damage well above the nominal CLIC accelerating field of 150 MV/m but with RF pulse length of 16 ns only (nominal 100 ns)



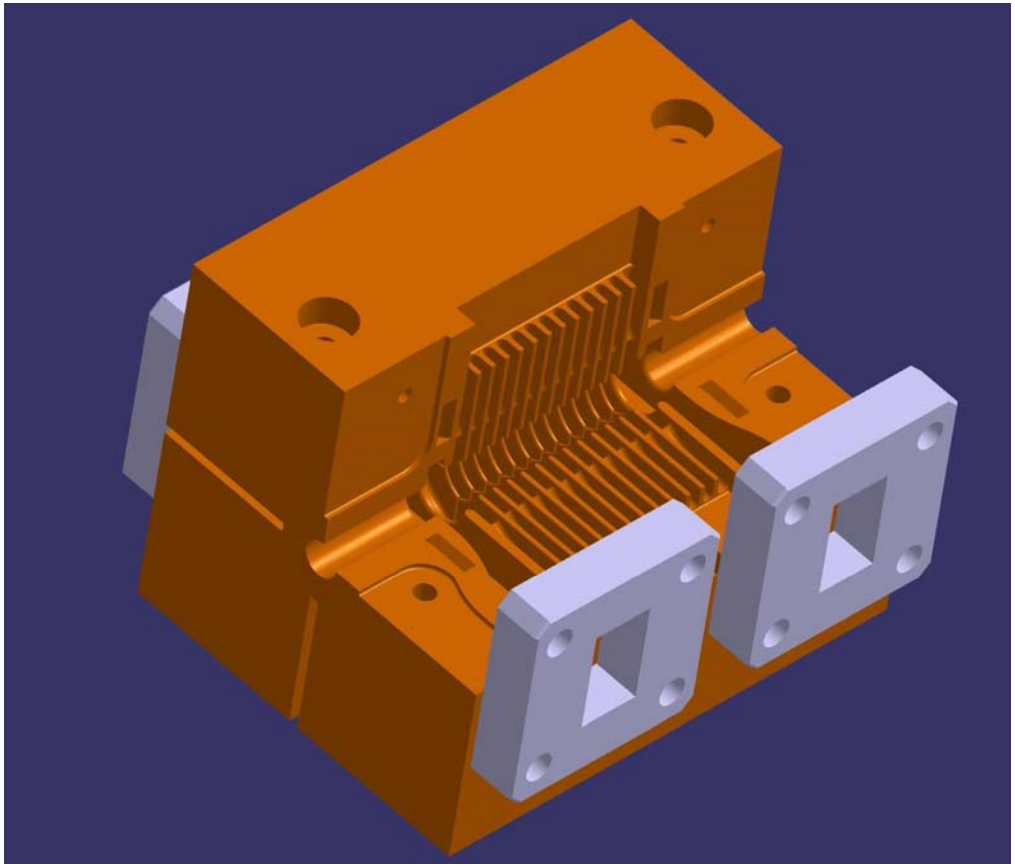
30 cell clamped tungsten-iris structure



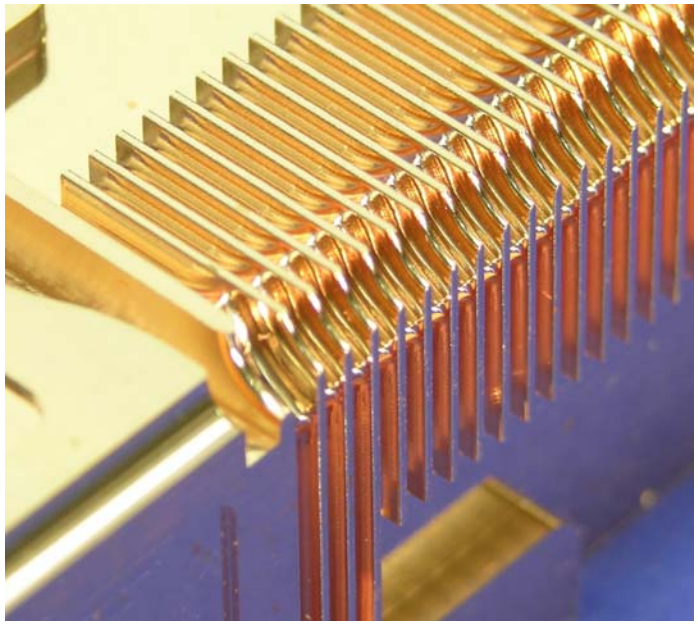


A world record !!!

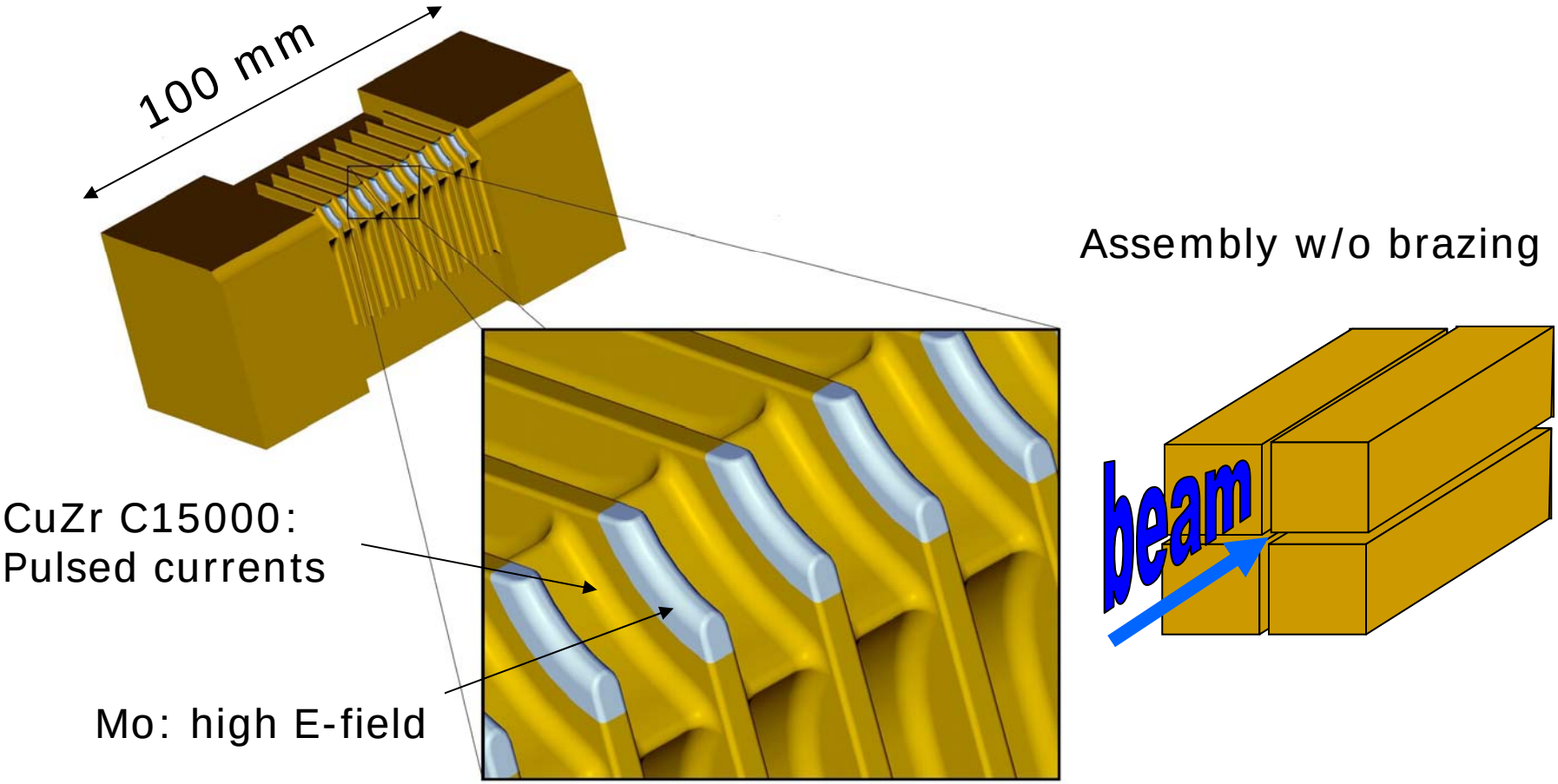
CLIC Hybrid Damped Structure (HDS)



30 GHz, phase advance per cell: 70°,
Cell length: 1.94 mm,
Smallest iris diameter: 3 mm,
accelerating gradient 150 MV/m,
Max surface field 380 MV/m,
max. ΔT 56 K,
Optimized for Mo iris, CuZr cavities

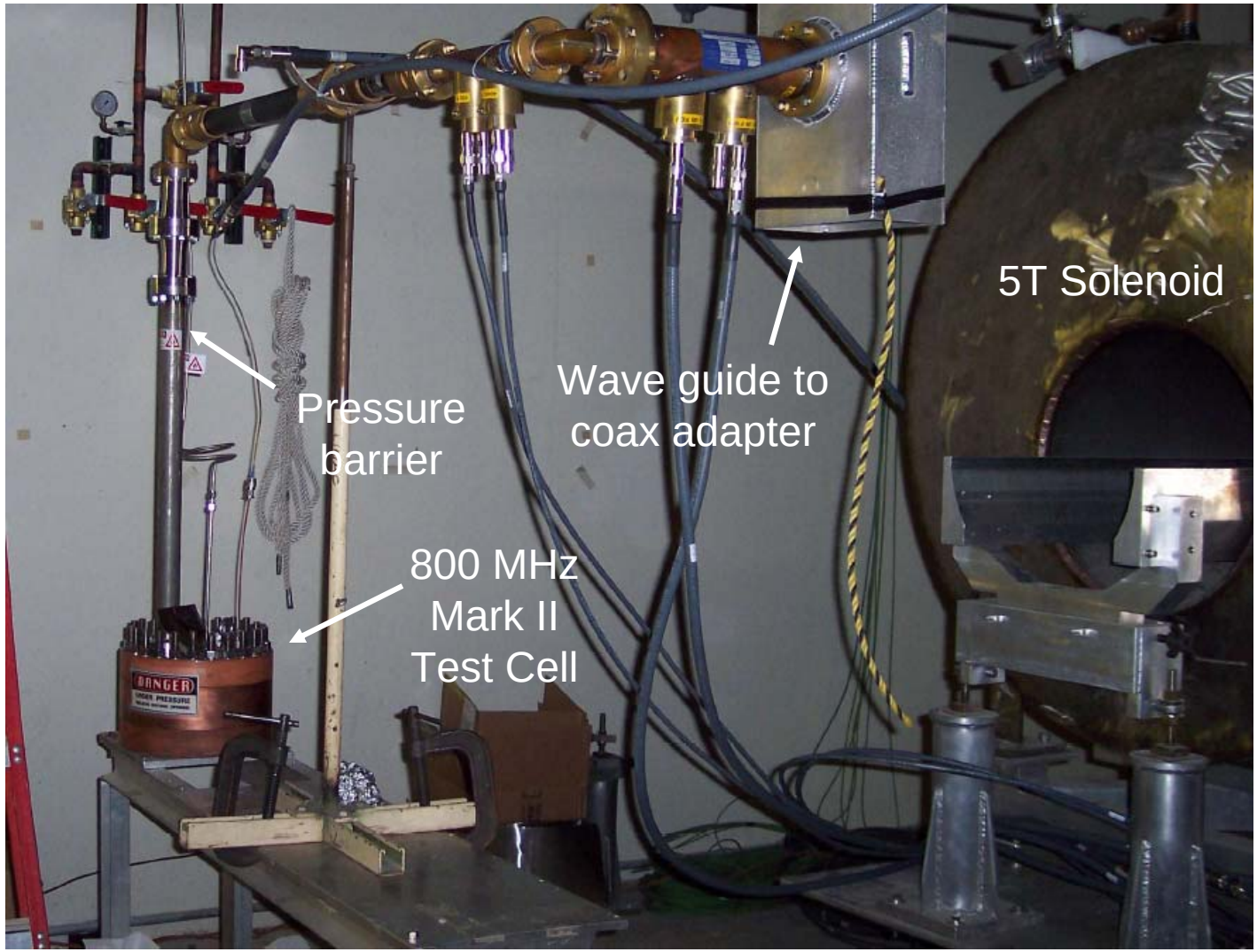


CLIC Hybrid Damped Structure (cont…)

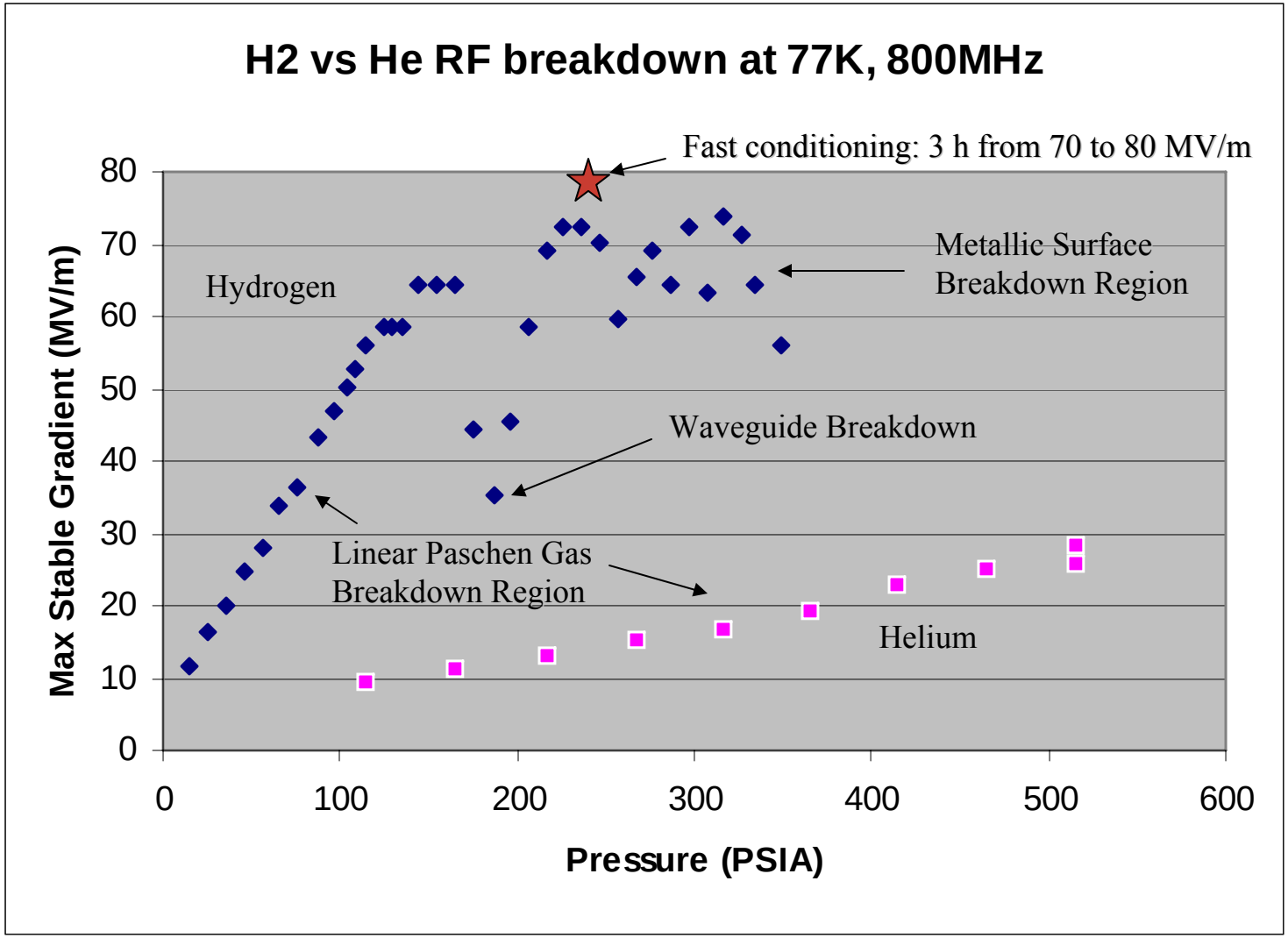


Aim: +/- 1µm accuracy, 0.05µm Ra close to the beam region

Pressured RF Cavity Test for μ–Cool (R. Johnson)

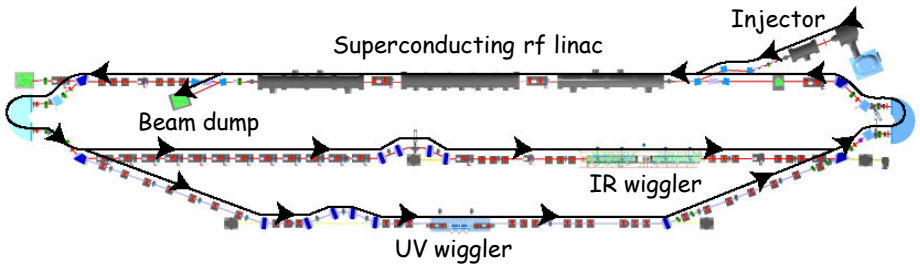


Pressured RF Cavity Test for μ–Cool (cont…)

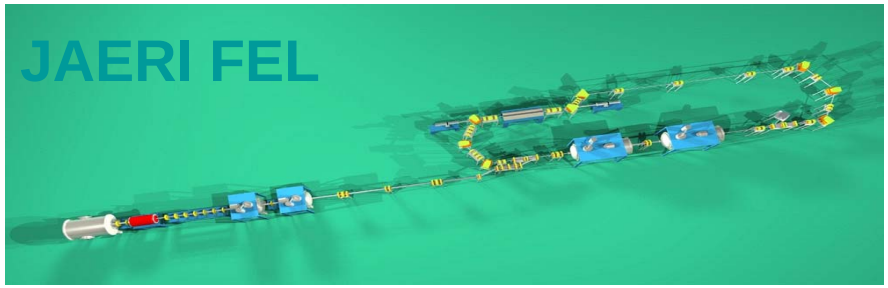


Energy Recovering Linac (ERL) FEL (L. Merminga)

JLab 10kW IR FEL and 1 kW UV FEL



Electron Beam Parameters	IR	UV
Energy (MeV)	80-200	200
Accelerator frequency (MHz)	1500	1500
Charge per bunch (pC)	135	135
Average current (mA)	10	5
Peak Current (A)	270	270
Beam Power (kW)	2000	1000
Energy Spread (%)	0.50	0.13
Normalized emittance (mm-mrad)	<30	<11
Induced energy spread (full)	10%	5%

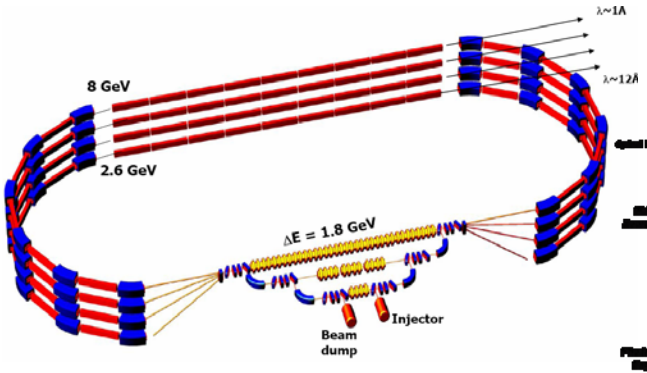


Electron Beam Parameters	Achieved	Goal
Energy (MeV)	17	16.4
Accelerator frequency (MHz)	500	500
Charge per bunch (pC)	500	500
Average current (mA)	5	40
Peak Current (A)	33	83
Beam Power (kW)	85	656
Energy Spread (%)	~0.5	~0.5
Normalized emittance (mm-mrad)	~40	~40

BINP Recuperator FEL - NC RF

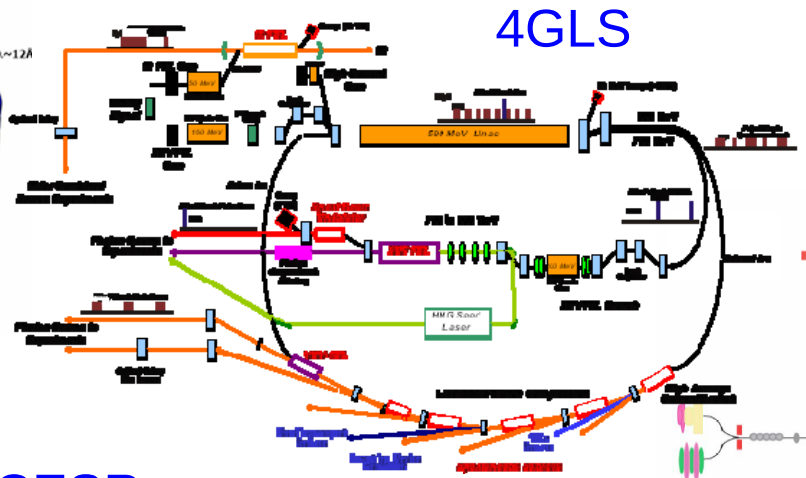
Electron Beam Parameters	IR
Energy (MeV)	12
Accelerator frequency (MHz)	180
Charge per bunch (pC)	900
Average current (mA)	20
Peak Current (A)	10
Beam Power (kW)	240
Energy Spread (%)	0.2
Normalized emittance (mm-mrad)	20

ERL Light Source



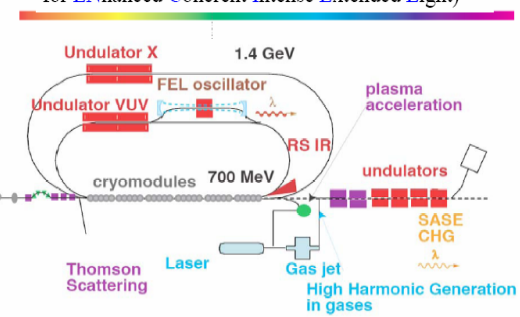
BINP MARS

4GLS

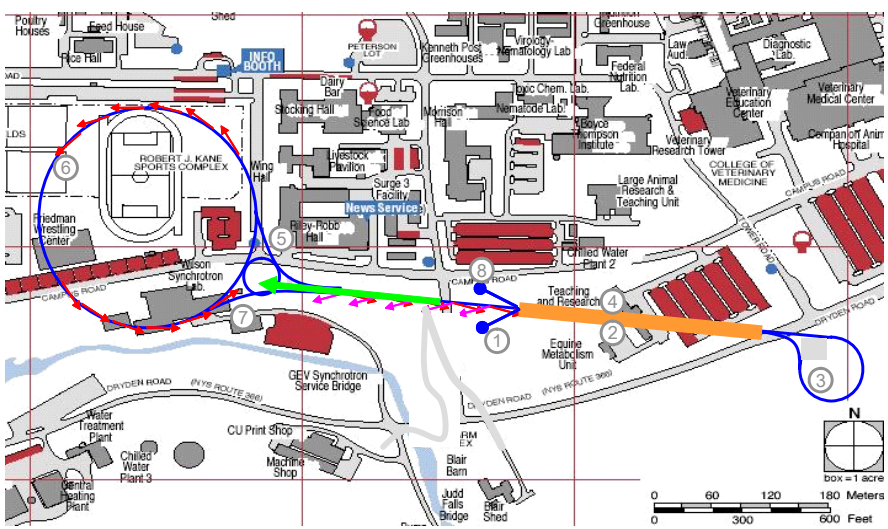


ARC-EN-CIEL

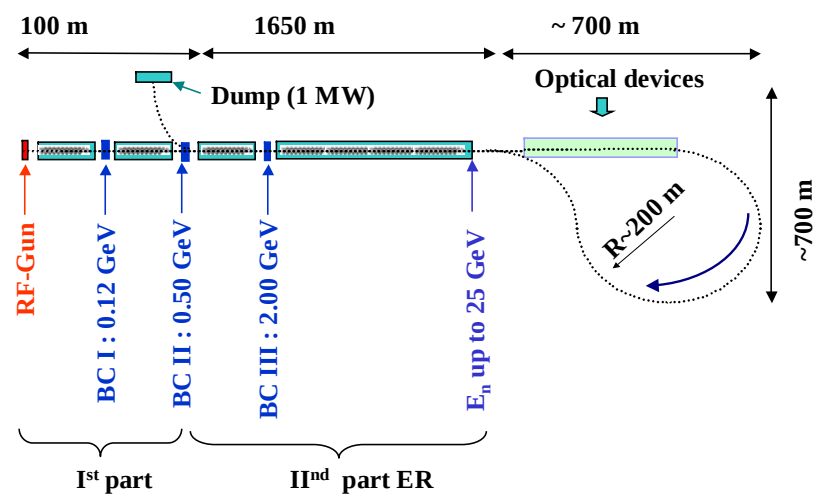
(ARC-EN-CIEL: Accelerator-Radiation Complex for ENhanced Coherent Intense Extended Light)



ERL@CESR

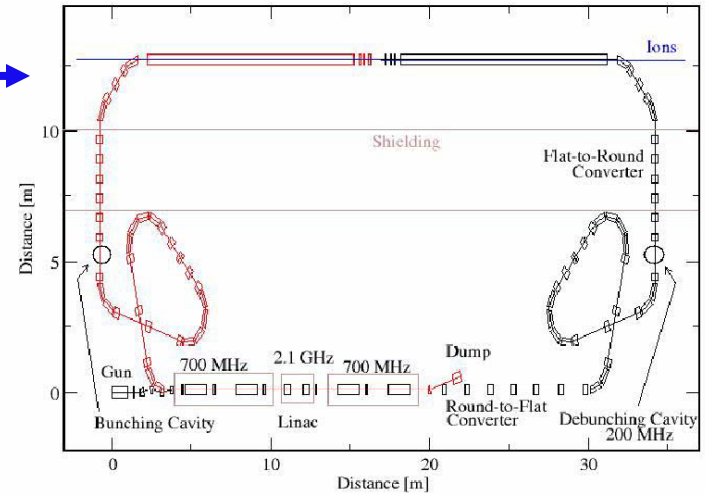


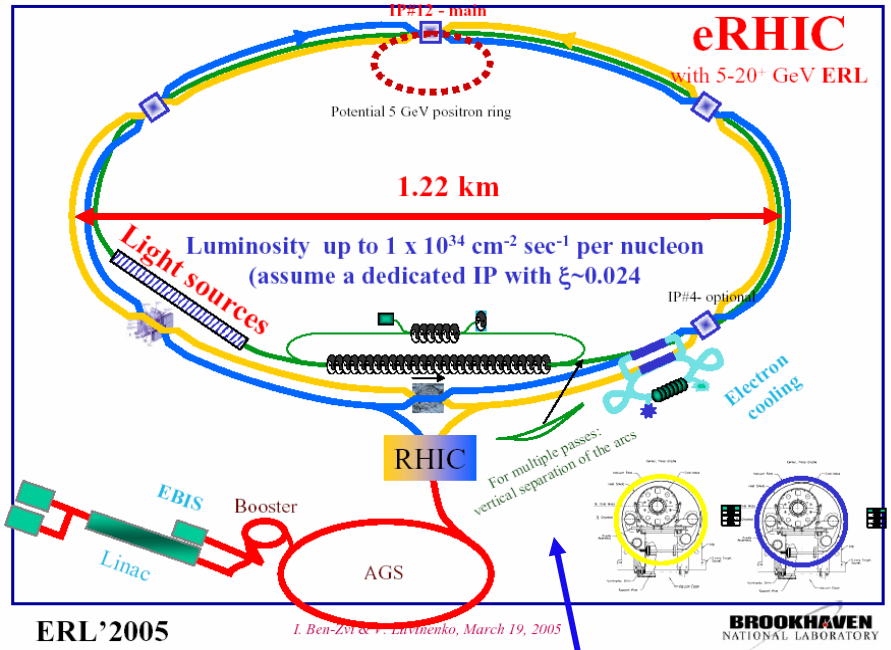
XFEL ERL



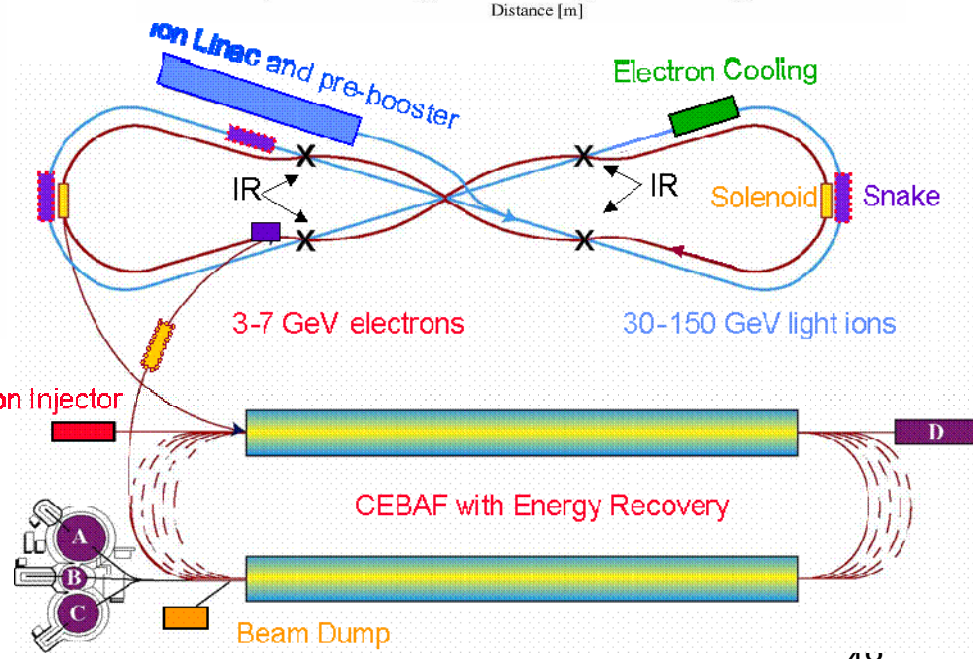
ERL for e-Cool

RHIC electron cooler based on a 200 mA, 55 MeV ERL





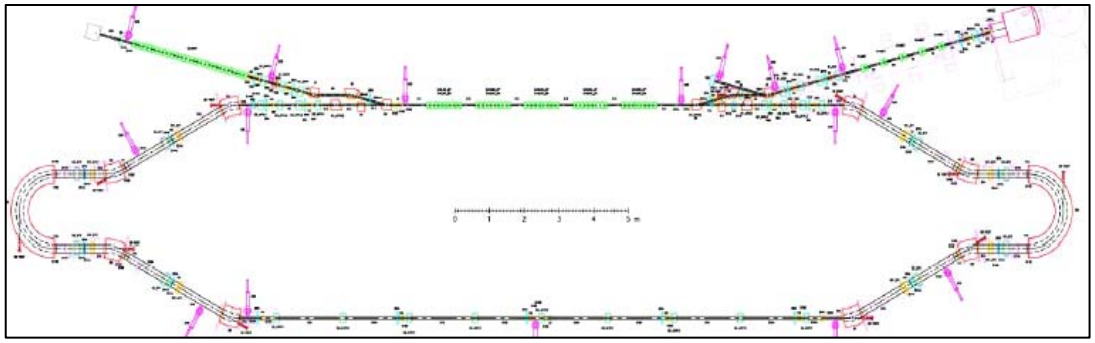
eRHIC: Electron-Ion Collider based on RHIC



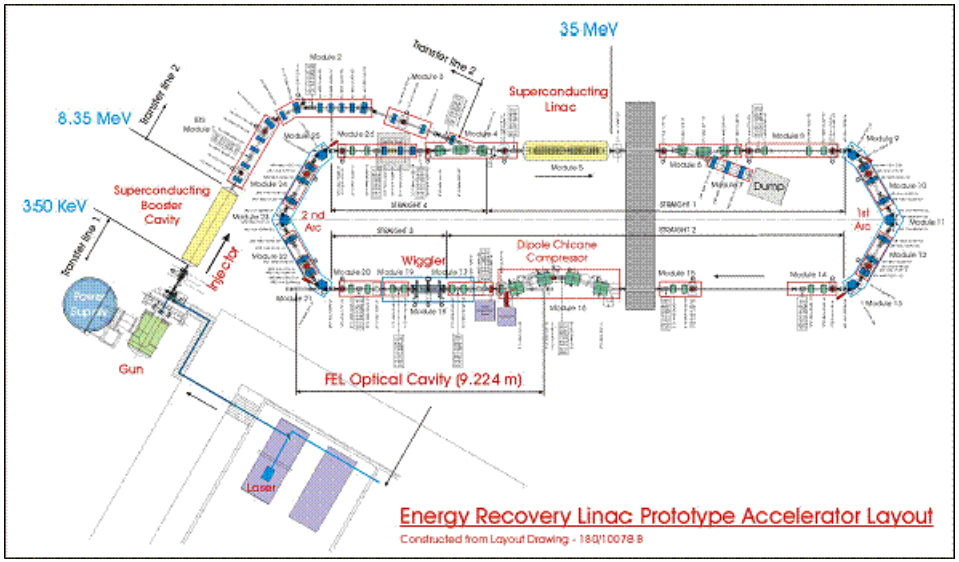
Electron – Light Ion Collider based at CEBAF

Proposed ERL Test Facilities

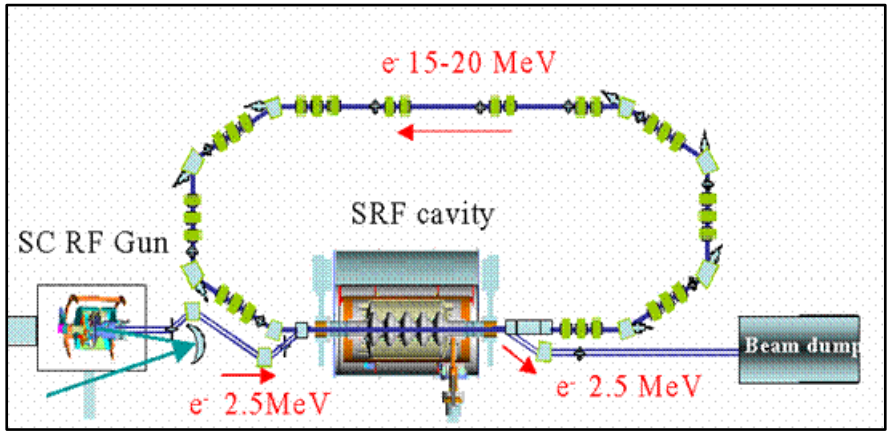
Cornell ERL Prototype



Daresbury ERL Prototype

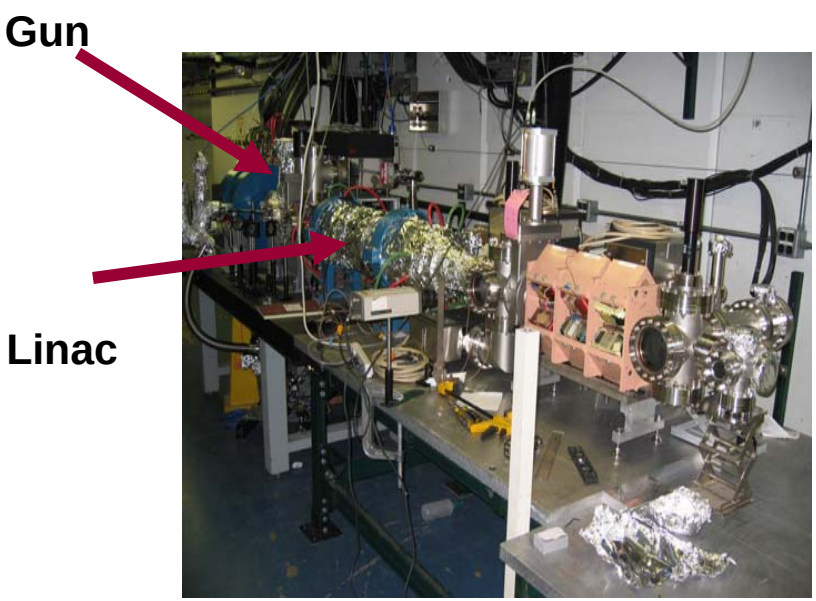


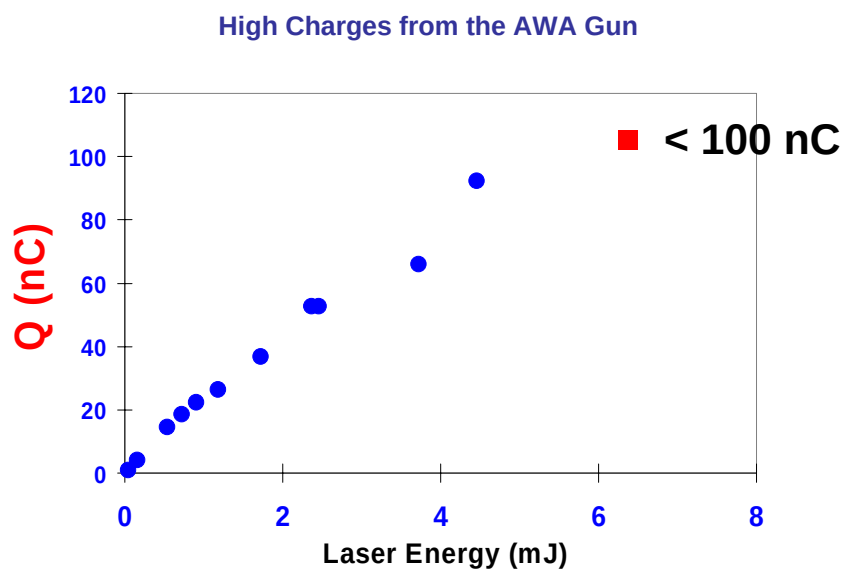
BNL R&D ERL



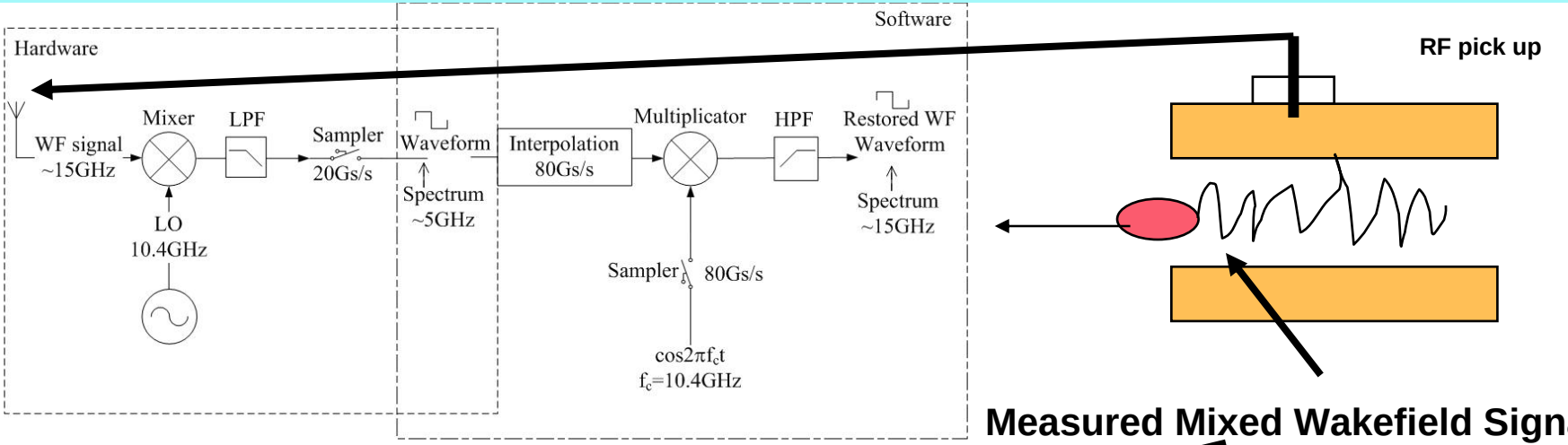
ANL Wakefield Accelerator (AWA) (W. Gai)

- RF photocathode gun based electron accelerator that generates high charge electron beam for wakefield accelerations and high power RF generations.
- Proof of principle experiments on collinear dielectric wakefield structures, two beam acceleration and plasma wakefield acceleration in non-linear regime.
- Beam with charge of 1 – 100 nC, 5 ps pulse length and energy of ~ 15 MeV. High gradient wakefield experiments underway.

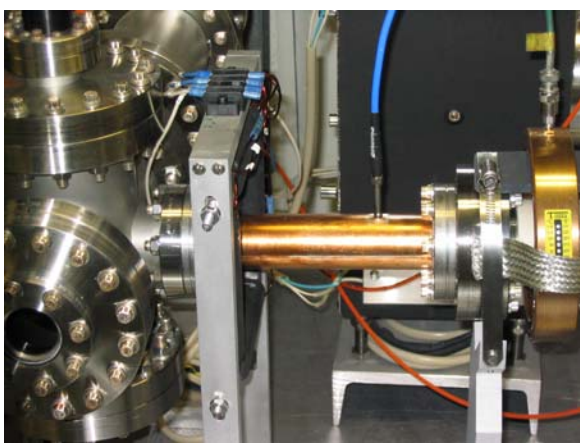


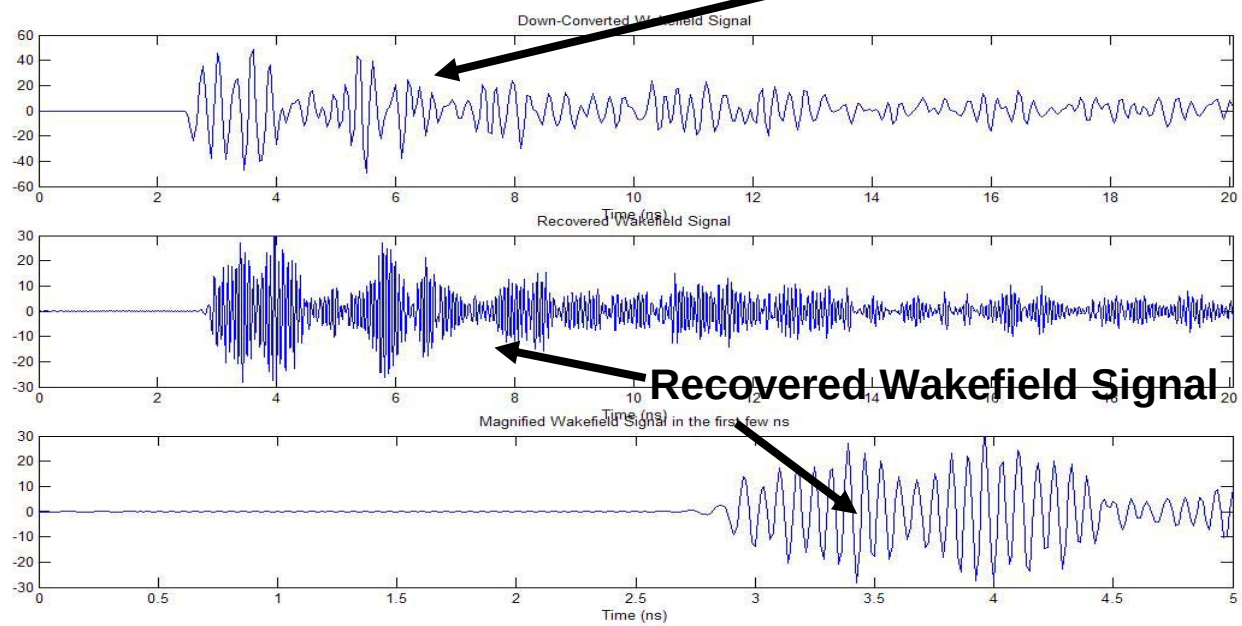


Direct Wakefield Measurement (W. Gai)



Measured Mixed Wakefield Signal



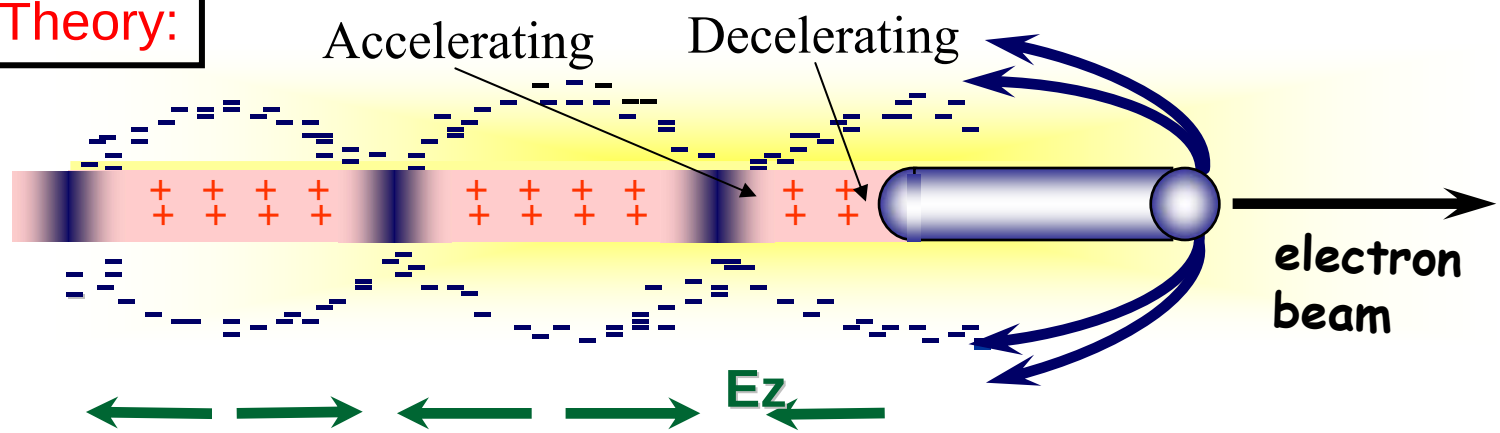


Recovered Wakefield Signal

SLAC Plasma Wakefield Acceleration (R. Siemann)

- Looking at issues associated with applying the large focusing (MT/m) and accelerating (GeV/m) gradients in plasmas to high energy physics and colliders
- Built on E-157 & E-162 which observed a wide range of phenomena with both electron and positron drive beams: focusing, acceleration/de-acceleration, X-ray emission, refraction, tests for hose instability…

Linear PWFA Theory:



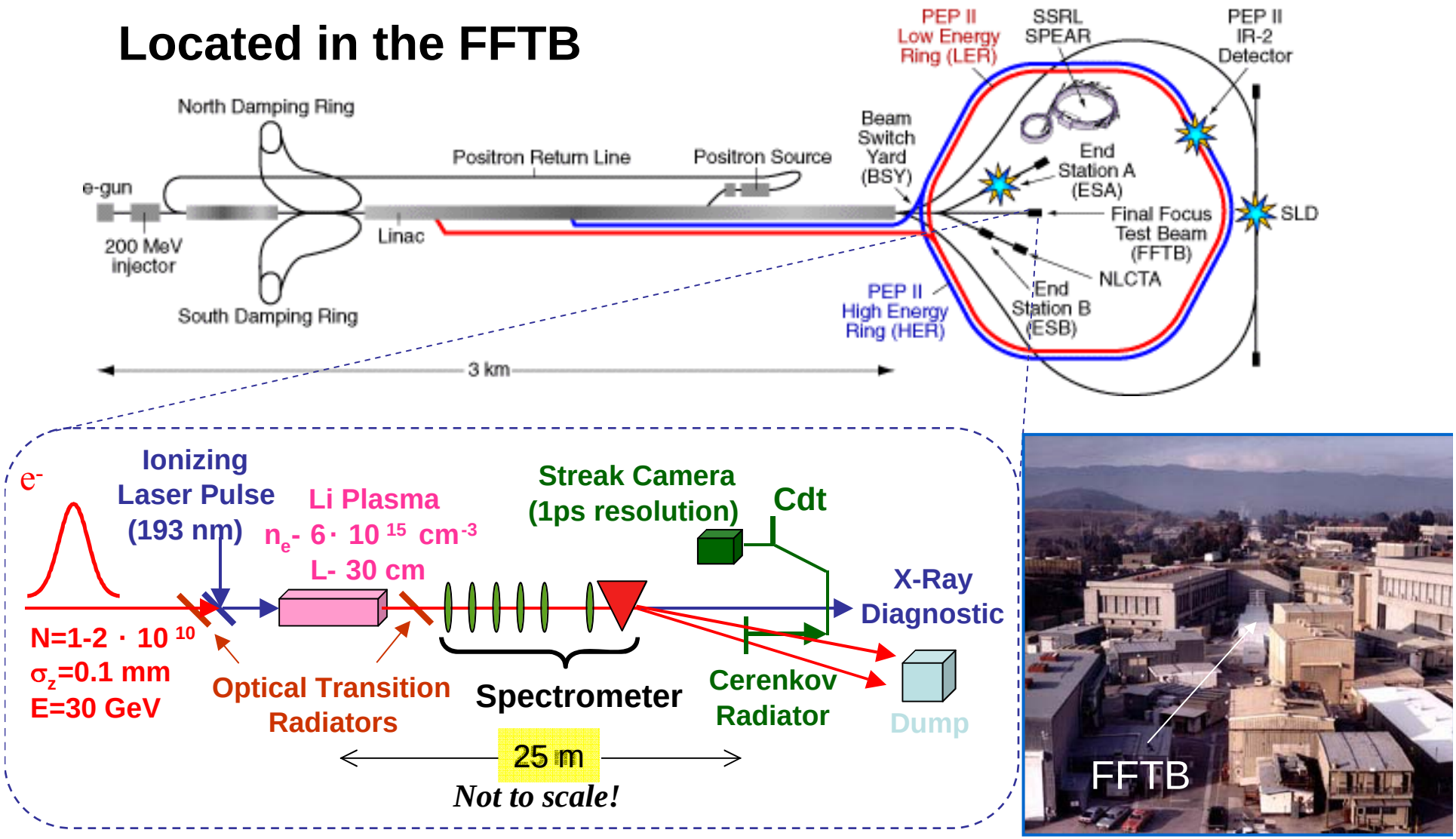
- $E_{z,linear} \propto \frac{N}{\sigma_z^2}$ ➡ Short bunch!
- For $k_p \sigma_r << 1$ and $k_p \sigma_z \cong \sqrt{2}$ or $n_p \propto \frac{1}{\sigma_z^2}$

E_z: accelerating field
N: # e⁻/bunch
σ_z: gaussian bunch length
k_p: plasma wave number
n_p: plasma density
n_b: beam density

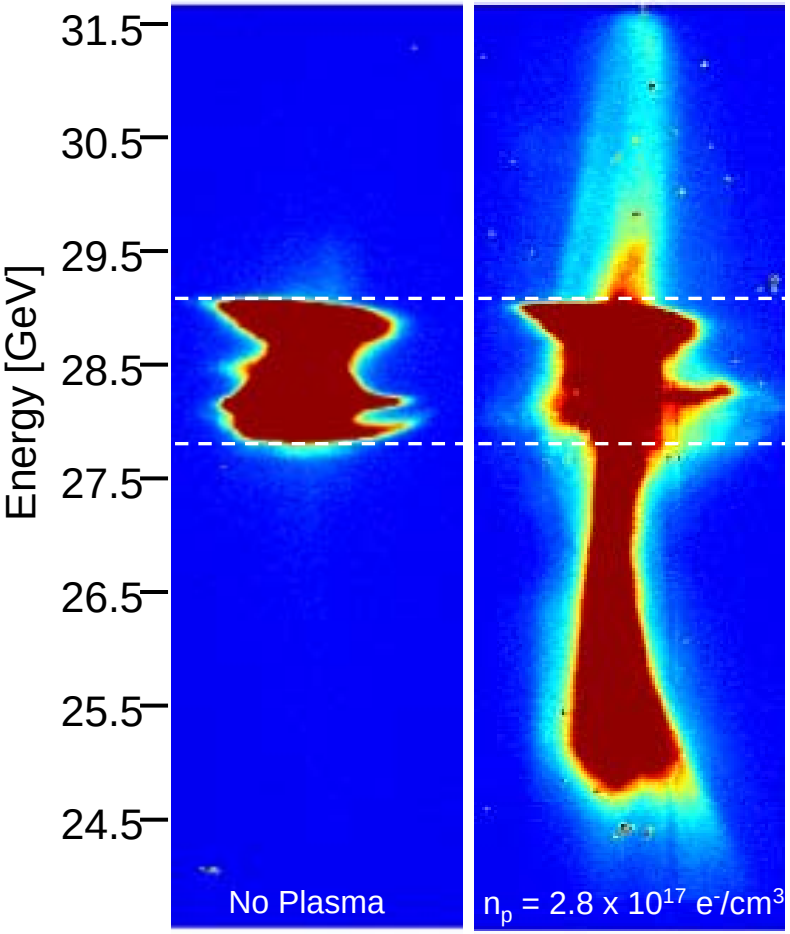
- A single bunch from the linac drives a large amplitude plasma wave which focus and accelerates particles
- For a single bunch the plasma works as an energy transformer and transfers energy from the head to the tail

PWFA Experiment E-164X (T. Katsouleas)

Located in the FFTB



E-164X: Accelerating Gradient > 27 GeV/m! (Sustained Over 10cm & Repeatable)



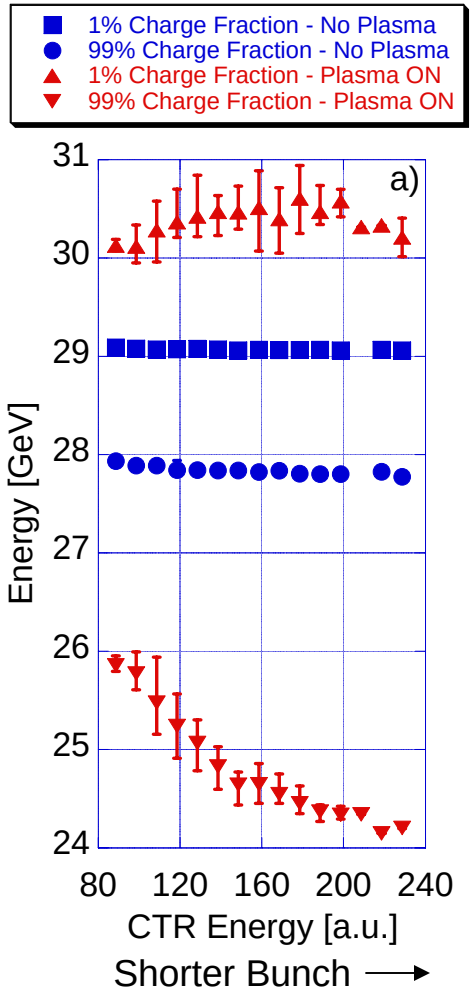
⇦ **Electrons have gained > 2.7 GeV over maximum incoming energy in 10cm**

⇦ **Confirmation of predicted dramatic increase in gradient with move to short bunches**

⇦ **First time a PWFA has gained more than 1 GeV**

⇦ **Two orders of magnitude larger than previous beam-driven results**

⇨ **Analysis of 200 sequential events shows for a fixed plasma density and a single bunch the maximum acceleration is bunch length dependent**



- Acceleration is limited by acceptance of FFTB dumpline!
- For the future want two bunches: one to drive the wake and one to sample it…

SLAC Inverse FEL Acceleration (R. Siemann)

60 MeV single bunch electron beam & Ti:Sapphire laser system
Experimental program: γe^- interactions with different accelerator structures

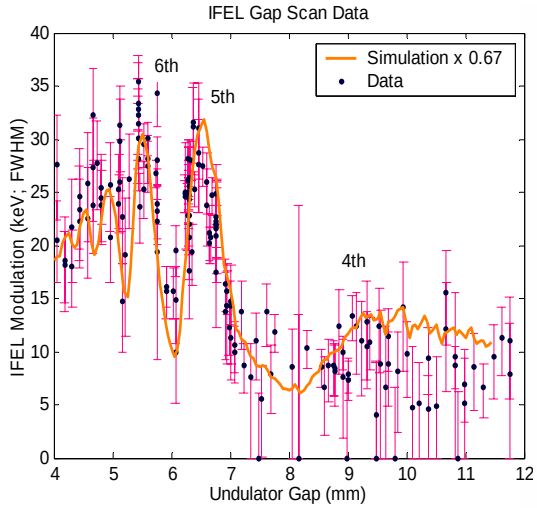
Status

- Commissioning: Summer 2005
- Accelerator design: ongoing
- First laser acceleration data: Late 2005
- Important components have been demonstrated

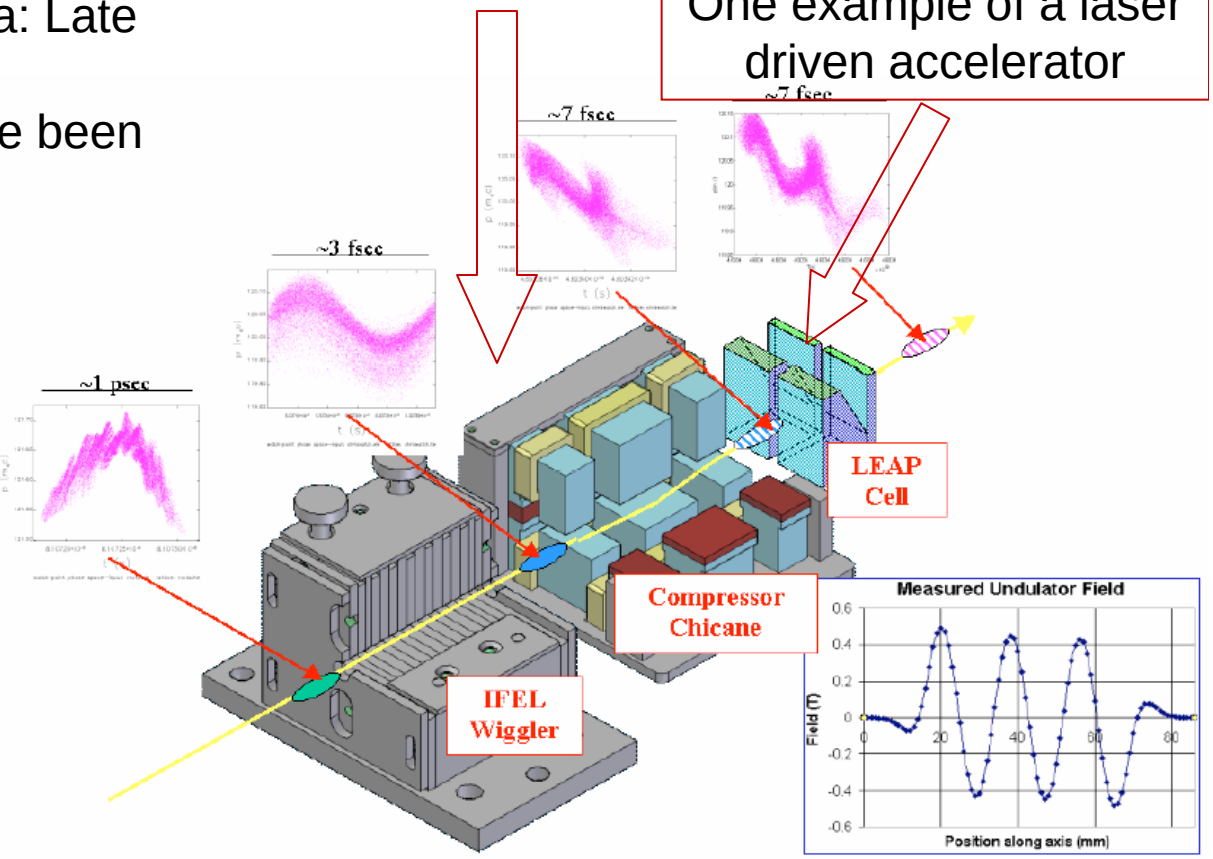
Inverse Free Electron Laser and chicane to produce bunches at λ = 800 nm

One example of a laser driven accelerator

Measured IFEL interaction

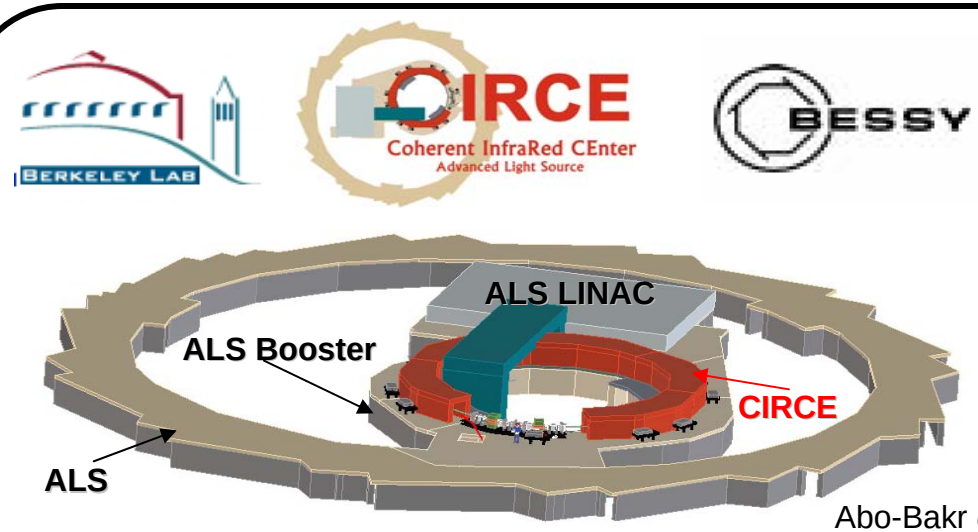


C. M. S. Sears *et al*, submitted to PRL

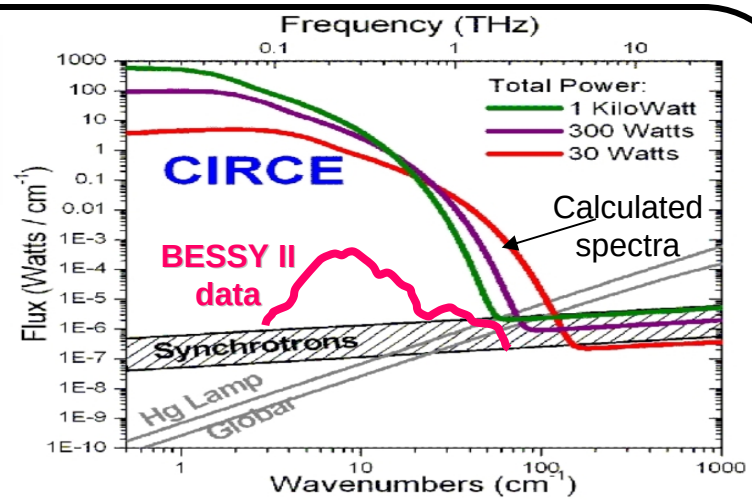


Terahertz Coherent Synchrotron Radiation (C. Biscari)

- Most synchrotron radiation is incoherent, power $\propto N$
- But when bunch length is short (~ radiation wavelength) and shielding cut off wavelength large, there will be broadband coherent synchrotron radiation (CSR) in the low frequency range (terahertz, or infrared), power $\propto N^2$
- First it was a villain (causing instability), now a hero



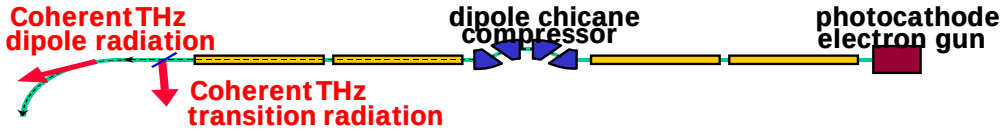
Courtesy of F. Sannibale



Abo-Bakr *et al.*, PRL **88**, 254801 (2002) & PRL **90**, 094801 (2003)
Sannibale, *et al.*,PRL. **93**, 094801 (2004)

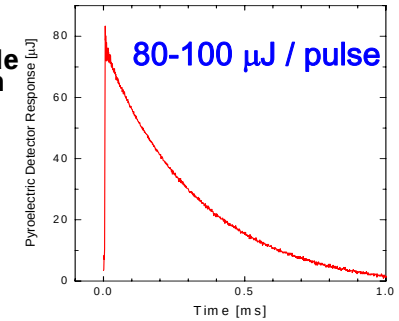
Terahertz Coherent Synchrotron Radiation (cont…)

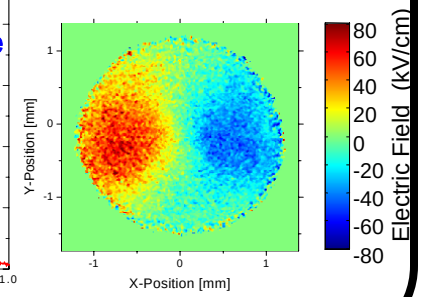
The BNL Source Development Laboratory



BROOKHAVEN NATIONAL LABORATORY

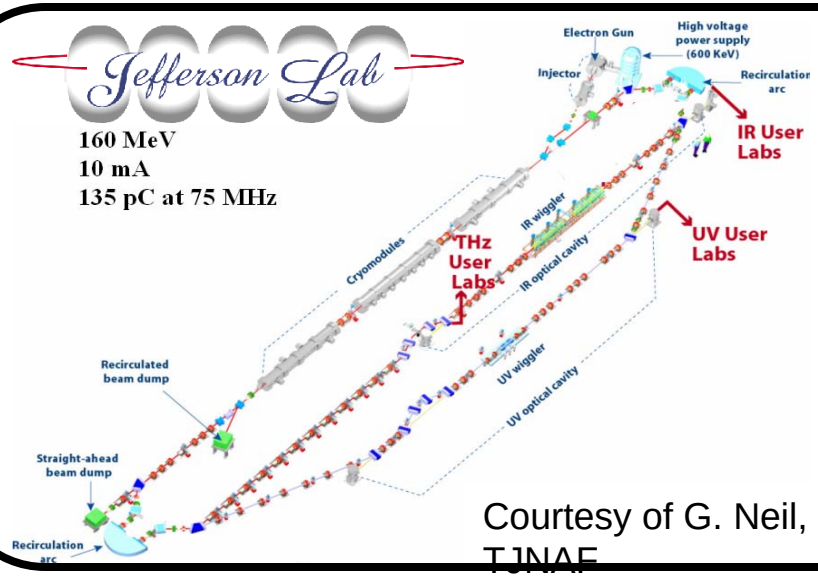
Courtesy of X.J. Wang



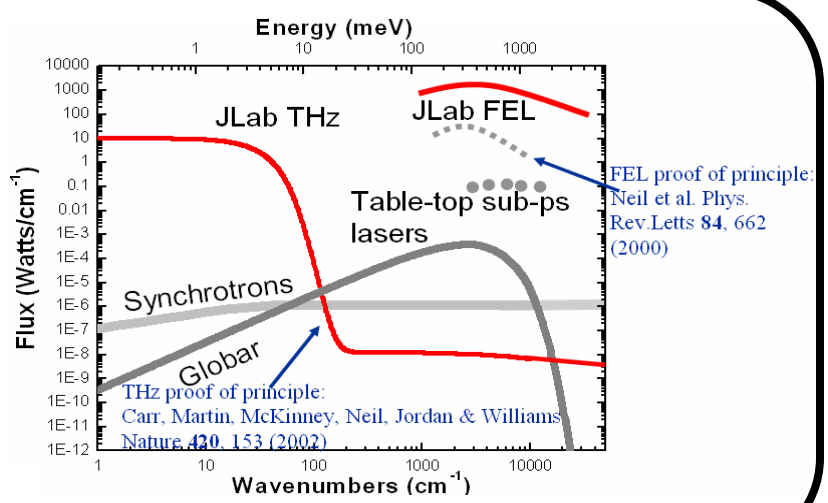


Jefferson Lab

160 MeV
10 mA
135 pC at 75 MHz



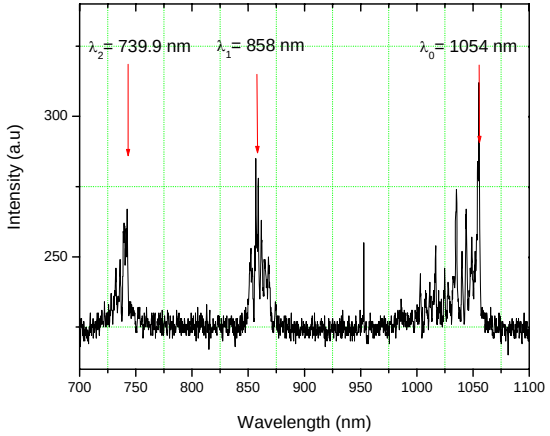
Courtesy of G. Neil, TJNAF



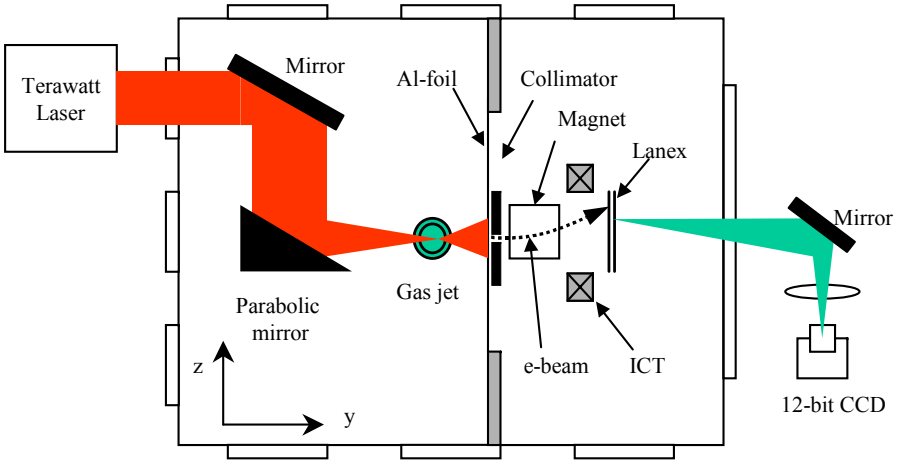
KERI Self-Modulated Laser Wakefield Acceleration (H. Suk)

2 TW Nd:glass/Ti:sapphire Laser System

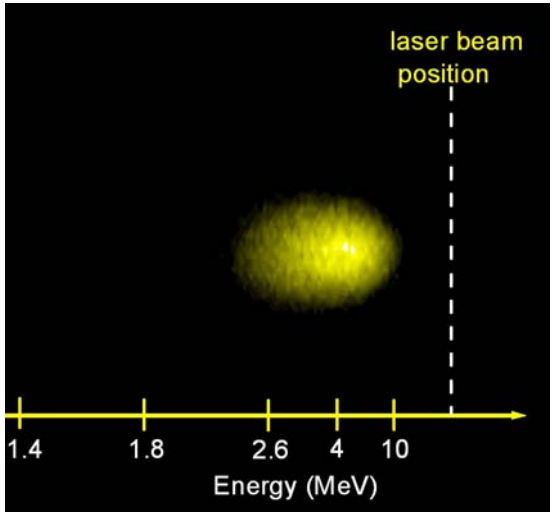
Spectrum of forward Raman scattered light



Experimental Setup



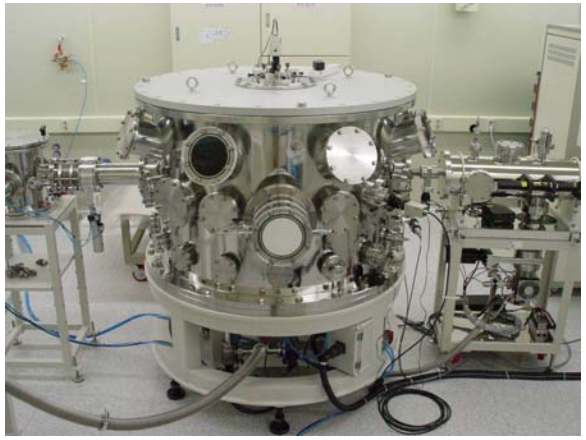
Quasi-monoenergetic electron beam generation



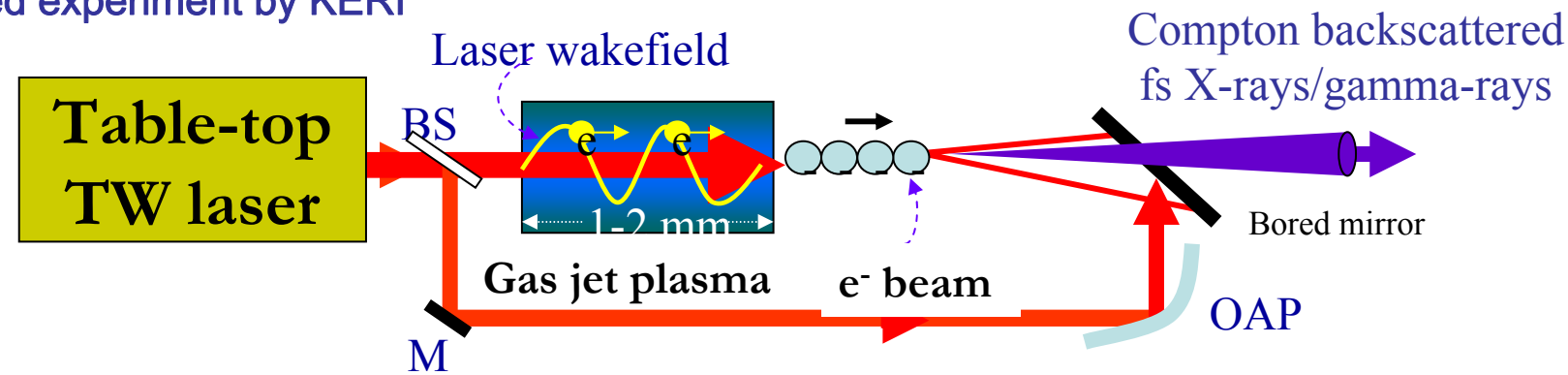
KERI-GIST X-ray / Gamma-ray Source (H. Suk)

100 TW Ti:sapphire Laser System at GIST

Target Chamber



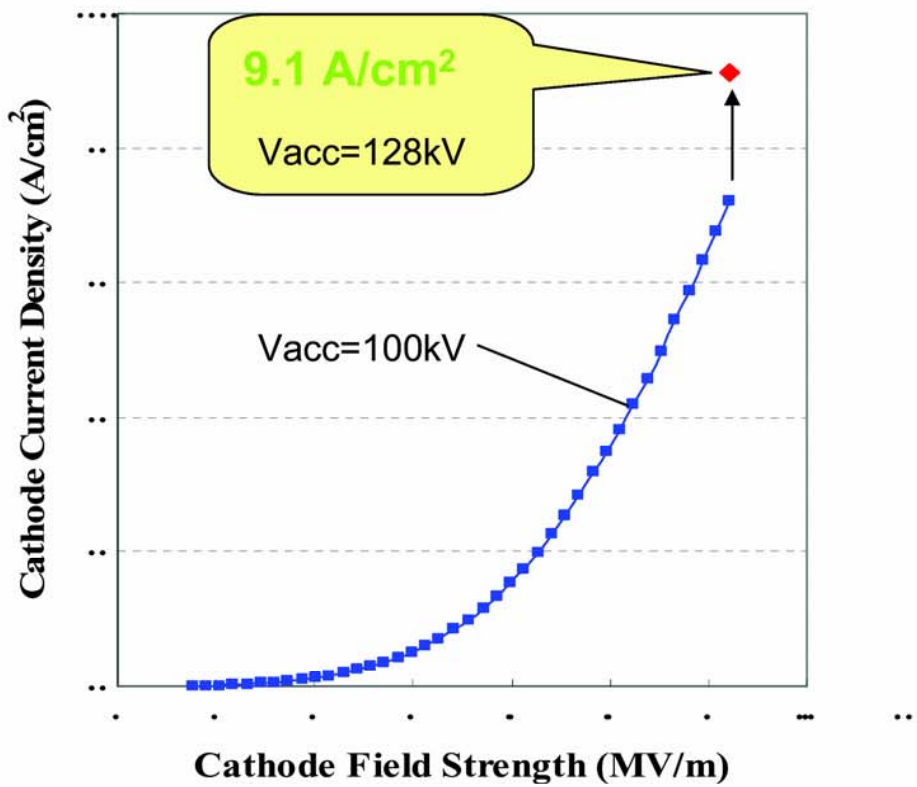
Proposed experiment by KERI



New, simple, compact, tunable fs X-ray/gamma-ray source

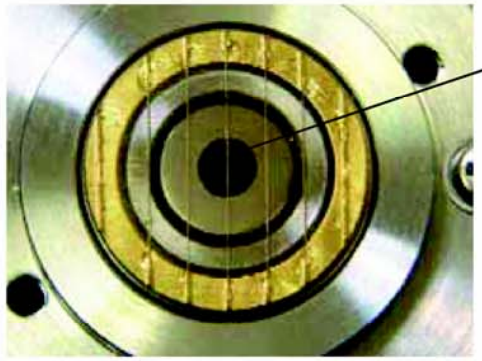
N. Hafz et al., IEEE Trans. Plasma Sci. 31, 1388 (2003).

KEK Carbon Nano-tube Electron Gun (S-I. Kurokawa)

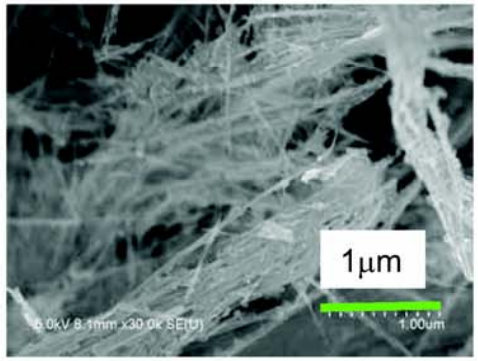


I-E characteristics of CNT-gun

Measured condition
Pulse width = 8 ns, Repetition = 50 pps, Pressure • 2• 10^{-6} Pa



Grid-cathode assembly

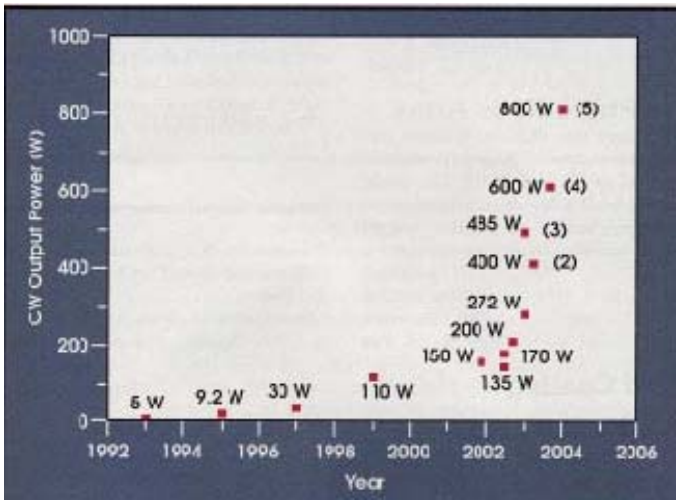


SEM figure of CNT-cathode

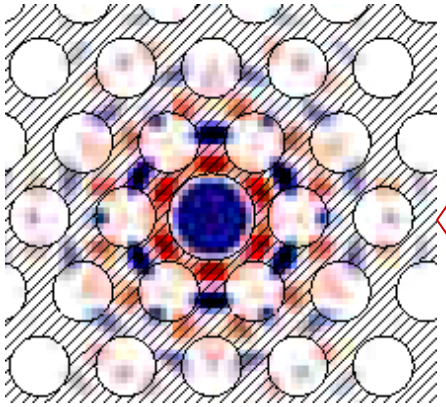
Photonic Band Gap Fiber Accelerator (R. Siemann)

Motivation For This Research
Exploring the potential of the photonics revolution for particle acceleration

Exponential growth in laser power (produced with high efficiency)



J. Limpert *et al*, "Scaling Single-Mode Photonic Crystal Fiber Lasers to Kilowatts" , Photonics Spectra, May 2004

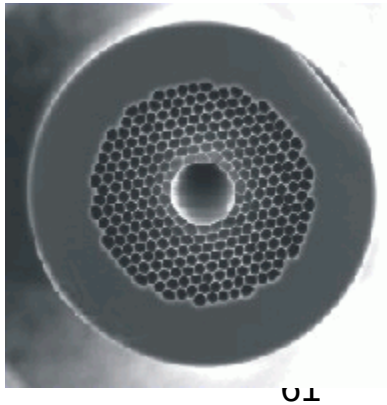


X. Lin, Phys. Rev. ST-AB, **4**, 051301 (2001).

Photonic crystal fiber structures

False color map of accelerating field in an accelerating mode

Commercially available photonic crystal fiber



Crystal Fibre A/S

Summary

- Since last ICFA Seminar, advanced accelerator technology has made significant progress in the past three years.
- This is a very dynamic field with enormous talents.
- Established technologies (e.g., high field SC magnet, high gradient SC rf) are progressing steadily. New technologies are coming up and making breakthroughs.
- We have to keep investing in this crucial field in order for the machines to meet the growing needs of physics.
- Advanced accelerator technology is no longer the territory for large laboratories only. We are pleased to see rapid growth in this field in countries like China, Korea, India, Oman and South Africa.
- ICFA Seminar provides a great forum for us to get together and learn from each other.
- Many thanks to Kyungpook National University for organizing this event.