highlights from RPIA 2006

workshop themes
selected slides

http://conference.kek.jp/rpia2006/

workshop themes

review talks

accelerator complex

- linac/injector, beam conditioning, hybrid accelerator

key items

- magnetic materials, switching elements (Thyratron, IGBT, MOSFET, SIThy, SiC-MOSFET), switching power supply/pulse modulator, induction accelerating cell (field calculation, cooling, impedance), beam monitoring & orbit control

beam dynamics

other applications of rapid switching devices

applications of induction accelerators and superbunches

working groups: (1) KEK as testbed for induction-based fast bunch rotation in HEDP, (2) comparison of ion sources and injectors, **(3) assessment of the wire lens@LHC from the current pulse power technology point of view,** (4) comparison of different barrier rf systems, (5) For HEDP compare KEK-PS and LBNL-NCDX2

Review Talks

Status of **KEK Induction Synchrotron** Project (Takayama, KEK)
RHIC Upgrades with Superbunches (Fischer, BNL)
High-Energy-Density Physics Researches based on Induction Accelerator and Pulse Power Technology (Horioka, TIT)
Overview of Recent progress in the **Heavy Ion Fusion** Science at Virtual National Laboratory (Barnard, LLNL)
RIKEN RI Beam Factory Project (Yano, RIKEN)
Status of the **DARHT 2nd Axis** at Los Alamos Laboratory (Nath, LANL)
Possible Uses of Rapid Switches and Induction RF for an **LHC Upgrade** (Zimmermann, CERN)
Bunch Compression and Stretching using **Barrier RF System at FNAL** (Bhart, FNAL)

Other Talks of Interest

Researchers on Multi-pulse Generation at IFP (**Zhang**, IFP)

Possibility of **Laser Ablation Plasma as a High-Flux Ion Source** for Induction Accelerators (Nakajima, TIT)

Physics Designs of a **High-Gradient Dielectric Wall Induction Linear Accelerator** for Radiography (Chen Yu-Jiuan,LLNL)

Pulse Line Ion Accelerator (Briggs, SAIC)

Inductive load broadband rf system and its application in **FNAL Main Injector** (Chou,Fermilab and Tagaki,KEK)

High Gradient Induction Cells Based on Advanced Insulators & Dielectrics (Caporaso, LLNL)

FAIR RF Systems based on Magnetic Alloys (Huelsmann, GSI)

Development of the **ILC kicker** (Naito, KEK)

Solid-State Inductive Adders for Fast Kicker (Cook, LLNL)

Key features of **All-ion Accelerators** (Takayama, KEK)

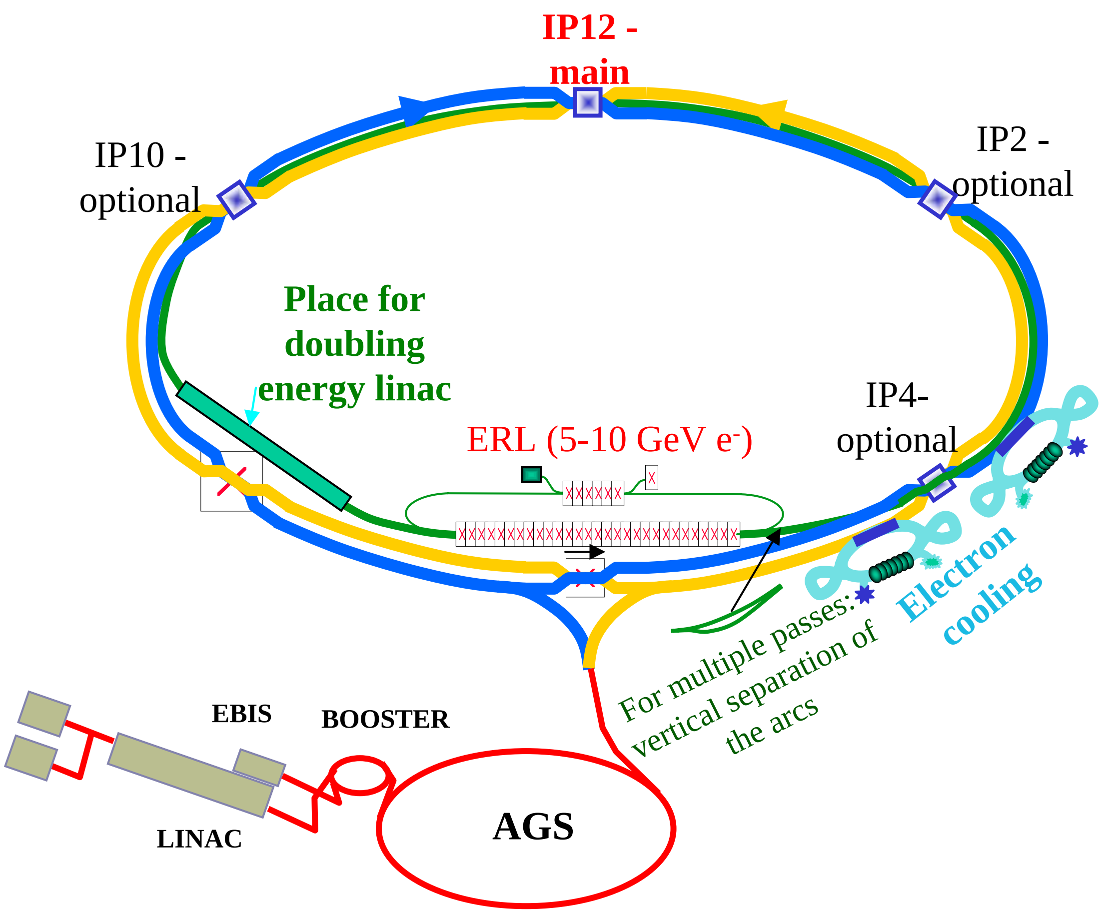
Possible **Applications of Induction Synchrotrons** (Oguri, TIT)

U. Dorda, H. Qin, Shimosaki, K. Torikai, FZ (on **CLIC**),…

RHIC upgrades – eRHIC ≥ 2014

eRHIC linac (ERL)-ring design

(also pursue ring-ring design)



Courtesy V. Ptitsyn

Main design parameters:

- center-of-mass energy
  30-100GeV/n
- e-p luminosity
  10^{32}-10^{34}cm^{-2}s^{-1}
- e-Au luminosity
  10^{32}-10^{34}cm^{-2}s^{-1}
- longitudinally polarized
  electrons, protons, and possibly light ions

Wolfram Fischer

Superbunches in RHIC

Possible application for superbunches in RHIC

Wolfram Fischer

- Transition crossing
  → limited by instabilities
- Heavy ion luminosity
  → limited by burn-off with e-cooling
- Polarized proton luminosity
  → limited by beam-beam and IBS

Assume in the following that superbunches can be made at store, filling half the circumference.

[The following scenarios are wildly optimistic.]

Transition crossing in RHIC

Focusing-free transition crossing (FFTC) in RHIC:

- Ramp-down normal rf voltage to avoid bunch shortening
- Accelerate through transition with induction cell

→ Need 48kV/turn at normal dB/dt (can be slowed down)

→ Induction acceleration ±10s around transition,
would also require barrier buckets,
(can avoid barrier buckets for ±125ms)
[calculations by J. Wei, BNL]

→ **Would allow to double the bunch intensity**

K. Takayama, J. Wei, Y. Shimosaki, and K. Torikai, “Focusing-free transition crossing in the RHIC using induction acceleration”, PAC05.

Wolfram Fischer

Hadron colliders at burn-off limit

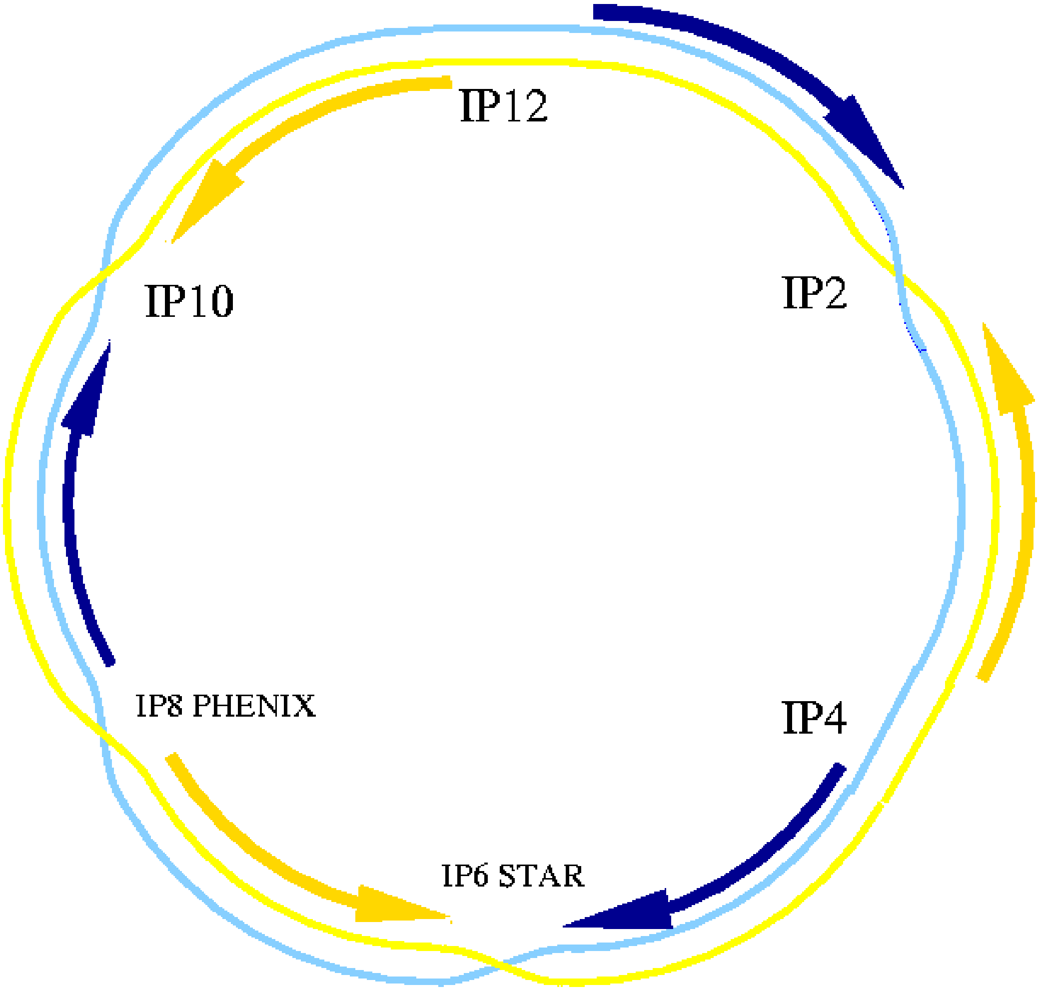
Luminosity increase at the burn-off limit

1. Increase bunch intensity N_b and emittance ε_n at the same rate (N_b/ε_n=const)
   → $L \sim N_b$
   → maintains beam-beam parameter ξ/IP
   → limited by beam size in final focus triplet

2. Increase number of bunches N
   → $L \sim N$
   → $N \to \infty$ = superbunches
   → limited by e-cloud (benign for superbunches), stored energy, …

Wolfram Fischer

RHIC heavy-ion luminosity with 3 superbunches



- 2 IRs uncrossed (for e-cooling & eRHIC)
- 3 superbunches/ring (~1μs abort gap)
- half circumference filled with beam

Wolfram Fischer

RHIC heavy-ion luminosity with 3 superbunches (II)

Wolfram Fischer

Heavy ions are burn-off limited, not beam-beam limited.

		RHIC II	SuperRHIC	comment
Energy	GeV/n	100	100	
Number of bunches N	…	111	3	6-fold symmetry
Bunch intensity N_b	10^9	1.0	800	same peak current (limit at γ_t-crossing)
Bunch length l_b	m	0.3	600	rms (RHIC II), full (SuperRHIC)
Average beam current I_b	A	0.11	2.4	
Full crossing angle α	mrad	0.0	0.5	possible with existing correctors
Peak luminosity $\mathcal{L}$/IP	10^{26} cm^{-2}s^{-1}	80	1200	
Average luminosity $\mathcal{L}$/IP	**10^{26} cm^{-2}s^{-1}**	**70**	**1100**	requires major e-cooling upgrade
Number of IPs n_{IP}	…	2	2	
Lifetime τ	h	5	5	

×16

Experiments need to be sold on superbunches.
Timing system different from existing one (large investment).

Hadron colliders at beam-beam limit

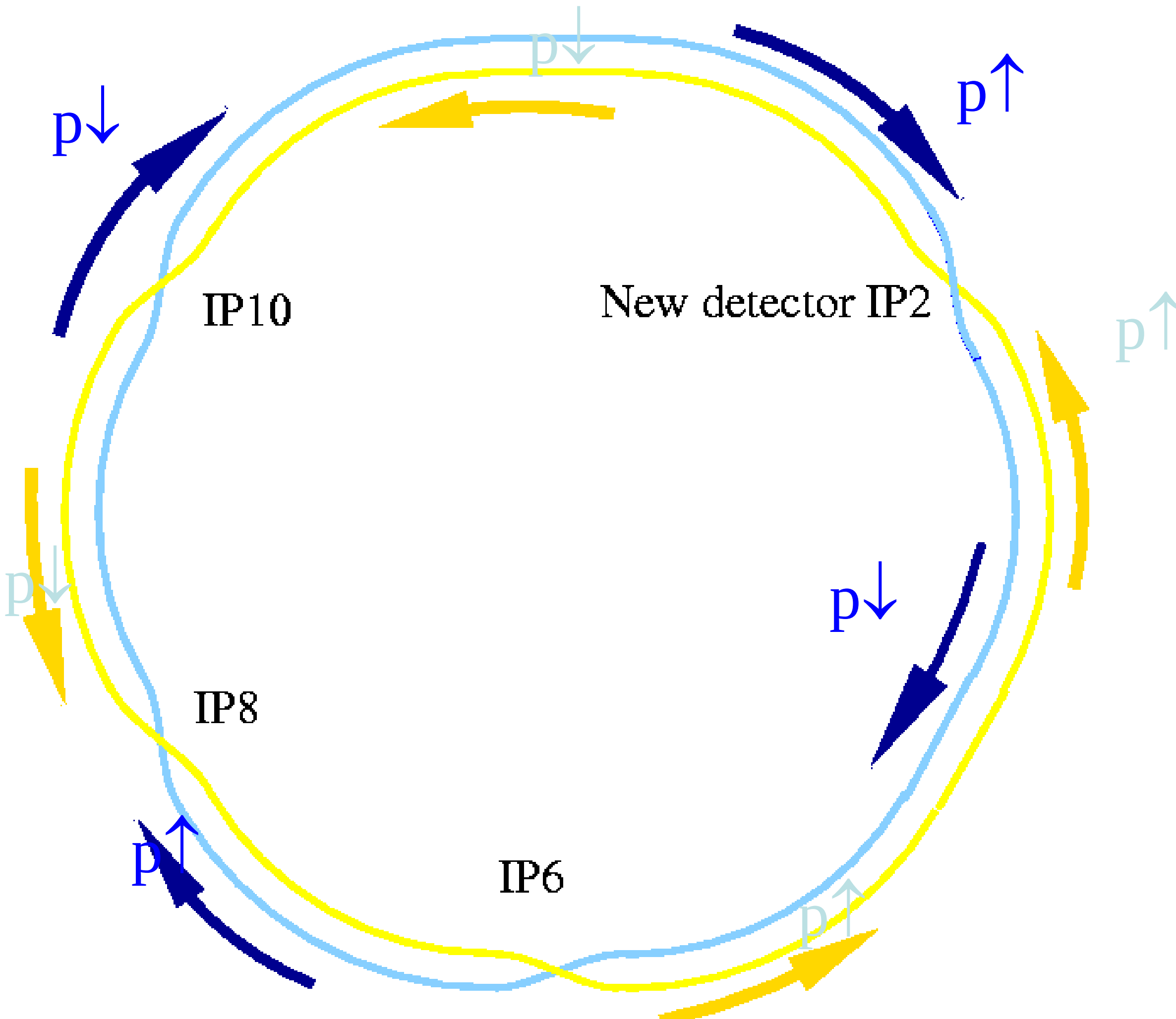
Luminosity increase at the beam-beam limit
(same strategy as for the burn-off limit)

1. Increase bunch intensity N_b and emittance ε_n at the same rate (N_b/ε_n=const)
   $\rightarrow L \sim N_b$
   $\rightarrow$ maintains beam-beam parameter ξ/IP
   $\rightarrow$ limited by beam size in final focus triplet

2. Increase number of bunches N
   $\rightarrow L \sim N$
   $\rightarrow N \rightarrow \infty$ = superbunches
   $\rightarrow$ limited by e-cloud (benign for superbunches), stored energy, …

Wolfram Fischer

RHIC polarized proton luminosity with 4 superbunches



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- 2 IRs uncrossed (for e-cooling & eRHIC)
- 1 dedicated new detector
- 4 superbunches/ring for spin patterns (~1µs abort gap)
- half circumference filled with beam

Polarized proton luminosity with 4 superbunches (II)

Requires beam-beam compensation

		RHIC II	SuperRHIC		comment
Energy	GeV/n	250	250	250	
Number of bunches N	…	111	4	4	for all spin combination
Bunch intensity N_b	10^{11}	2.0	1500	3000	limited by $\Delta Q_{bb,tot}$
Bunch length l_b	m	0.15	480	480	rms (RHIC II), full (SuperRHIC)
Average beam current I_b	A	0.28	7.5	15	
Full crossing angle α	mrad	0.0	0.5	0.5	possible with existing correctors
Beam-beam parameter ξ/IP	…	0.012	0.012	0.025	limited by $\Delta Q_{bb,tot}$
Peak luminosity $\mathcal{L}$/IP	10^{34} cm^{-2}s^{-1}	0.07	2.2	8.85	
Average luminosity $\mathcal{L}$/IP	**10^{34} cm^{-2}s^{-1}**	**0.05**	**1.6**	**6.3**	requires major cooling upgrade
Number of IPs n_{IP}	…	2	2	2	
Luminosity lifetime $\tau_{\mathcal{L}}$	h	3	3	3	dominated by beam-beam, IBS

Very challenging

[needs doubling of proven $\Delta Q_{bb,tot}$ & cooling at store]

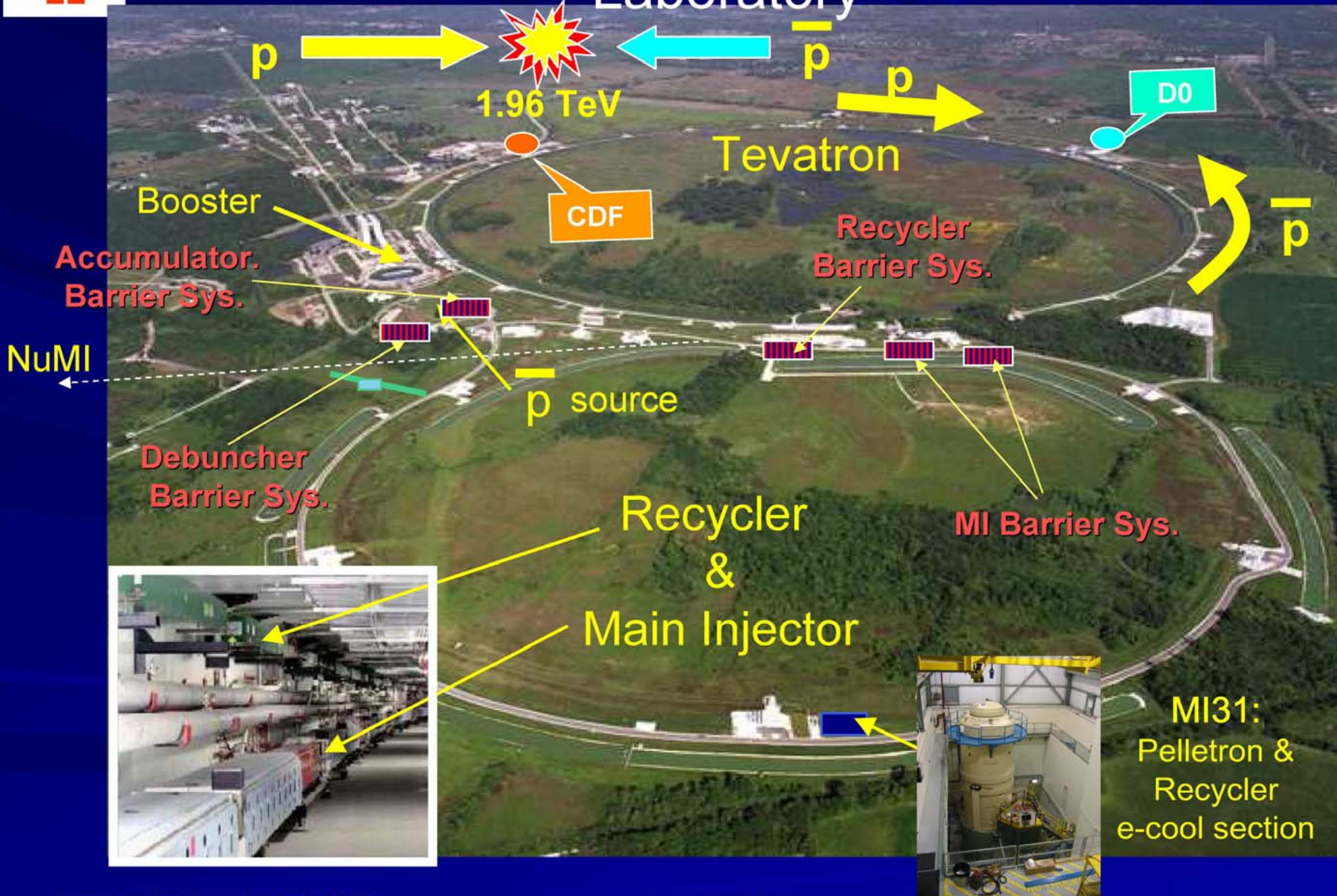
9× LHC design luminosity

130× RHIC II luminosity (pre-cooled p-beams)

10,000× current luminosity

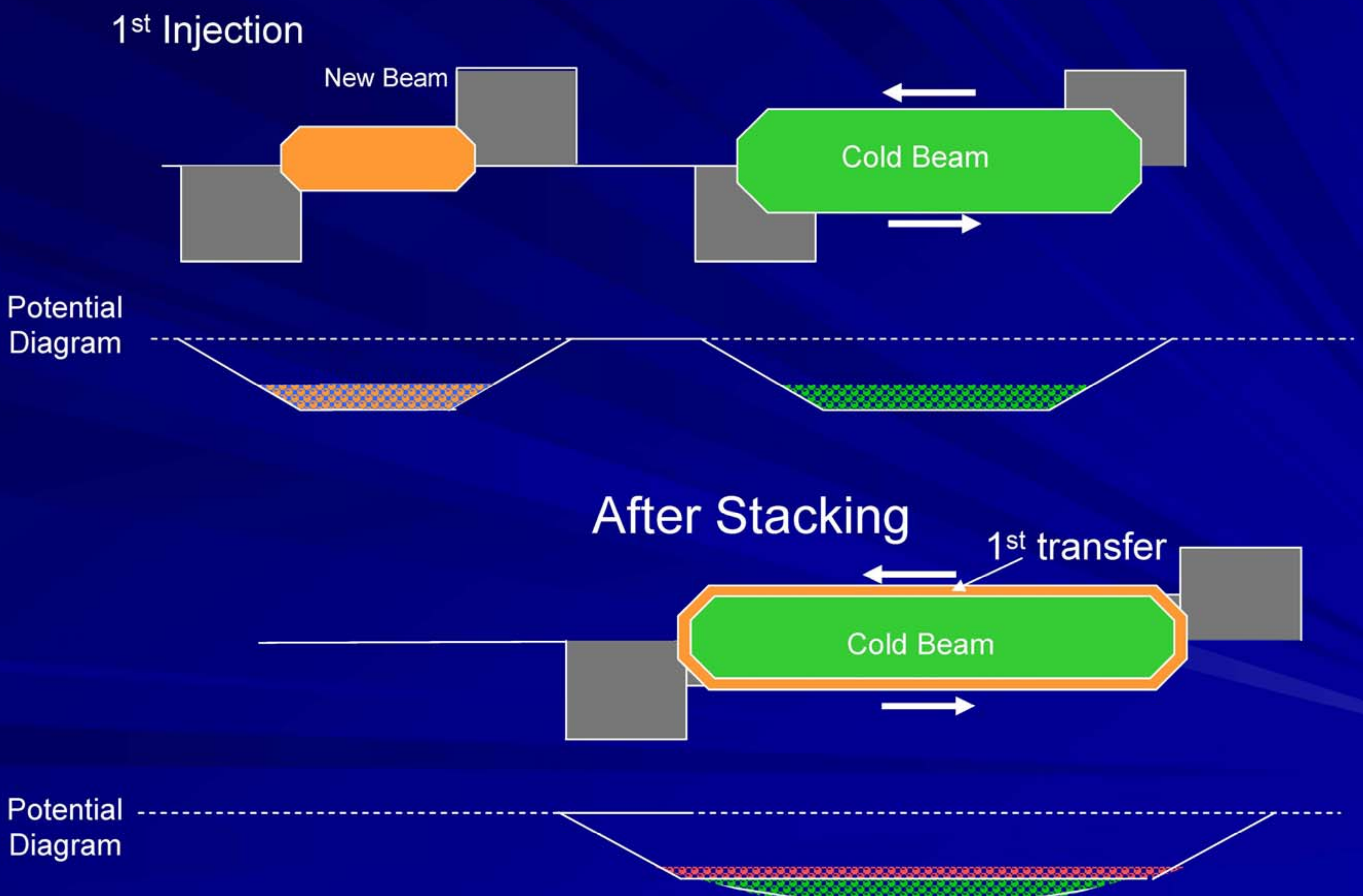
Wolfram Fischer

FERMILAB, the World's Pre-eminent HEP Laboratory



Longitudinal Phase-space Coating

C. M. Bhat, Beams-doc-2057-v1 (Dec. 2005)



Bright Proton Bunches for Tevatron to increase ppbar Luminosity (future)

Current Proton Bunch Coalescing Scheme in the Main Injector

8GeV 53MHz Beam

↓

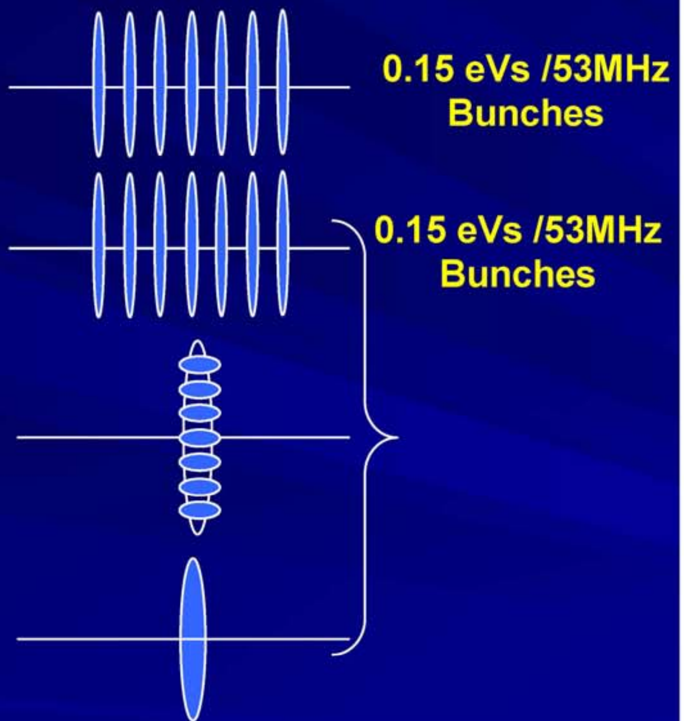
150GeV (BC) 53MHz bunches

↓

150 GeV (AC) 53MHz bunches

↓

150 GeV Bunch to Tevatron

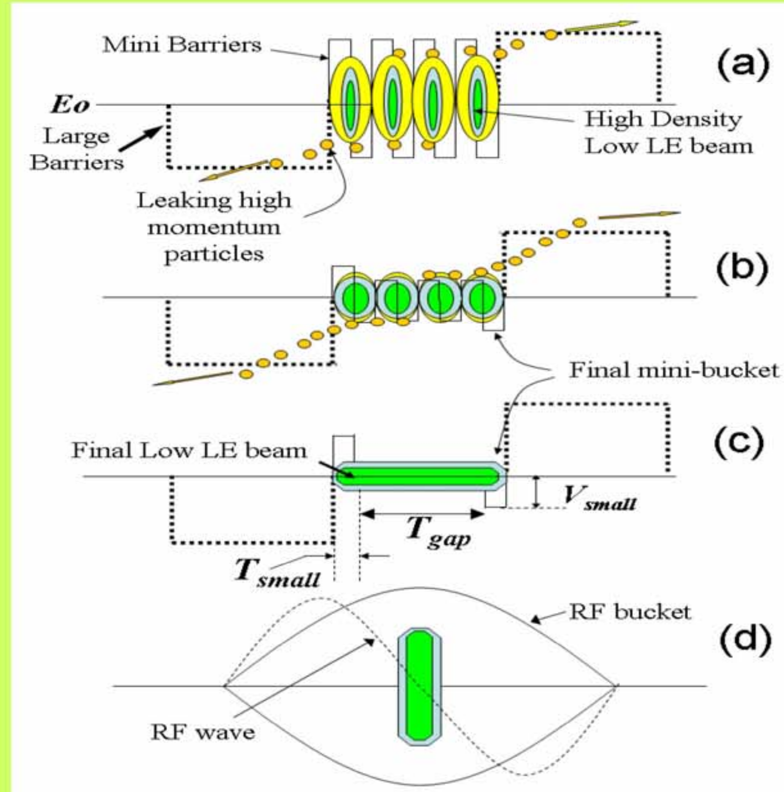


~2.8E11p/bunch, LE ~ 3 eVs
Trans. emit.~16-20pi from MI

Beam in the Tevatron at collision
~2.4E11p/bunch, LE ~ 4 eVs
Trans. emit.~16-20pi

Proposed Barrier Proton Coalescing

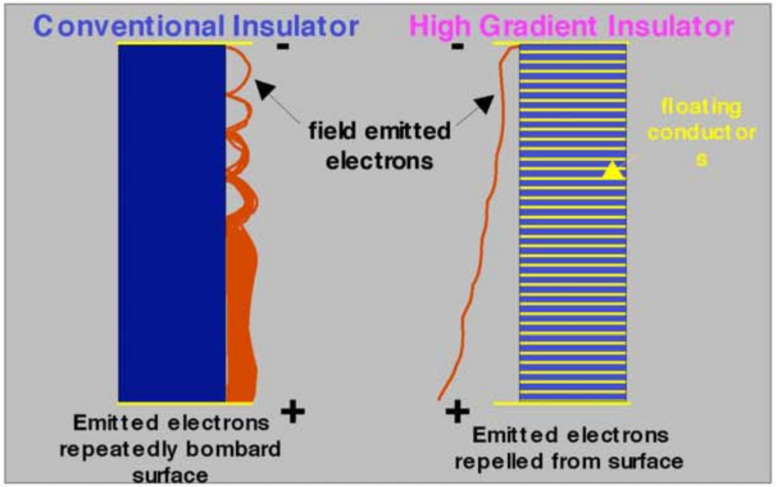
C.M. Bhat, PAC05, p 1745

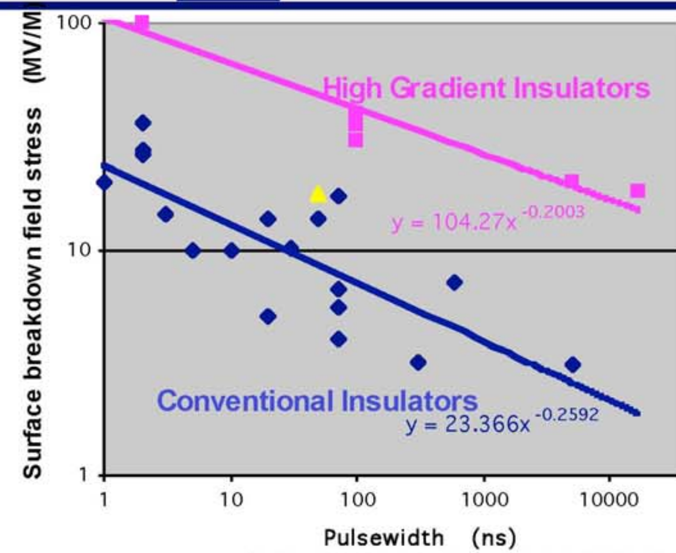


~3-4E11p/bunch
LE ~ 1.5-2 eVs
Trans. emit.~10-14pi

High gradient insulators (HGIs) perform 2 - 5 x better than conventional insulators

Beam Research Program
Lawrence Livermore National Laboratory

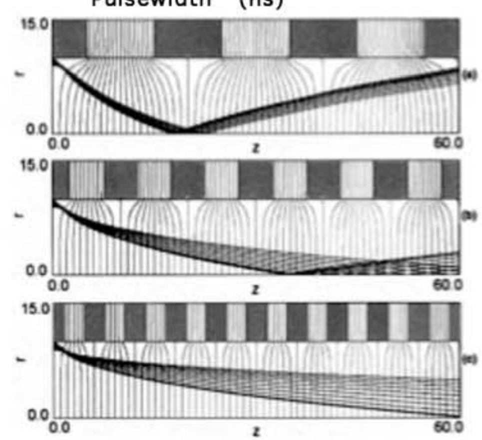




Closely spaced conductors inhibit the breakdown process

HGI structure forms a periodic electrostatic focusing system for low energy electrons

Leopold, et. al., IEEE Trans. Diel. and Elec. Ins. 12, (3) pg. 530 (2005)

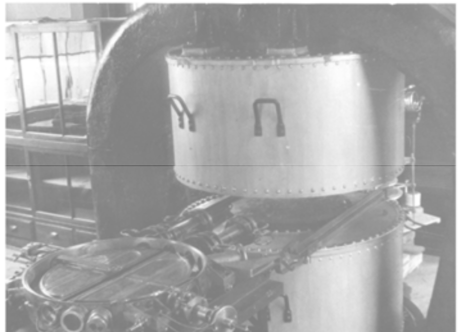


George Caporaso

RIKEN's Old Cyclotrons (1937 ~ 1990)

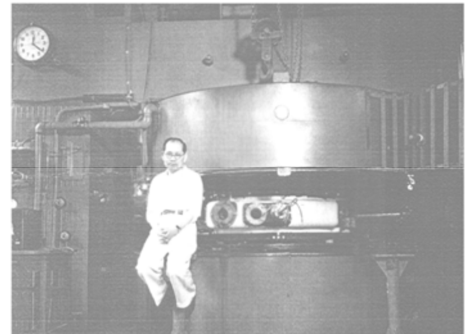
Multi-disciplinary Utilization

50th Anniversary of RI production (1990)



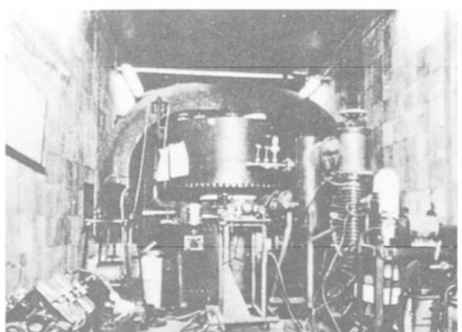
昭和12年(1937) Nishina (Tokyo Bay)

第１号サイクロトロン
磁極直径65cm
わが国最初のサイクロトロン
1st cyclotron
Magnet diameter 65cm
The first cyclotron in Japan



昭和19年(1944) Nishina (Tokyo Bay)

第２号60インチサイクロトロン
磁極直径150cm
2nd 60inch cyclotron
Magnet diameter 150cm



昭和27年（1952） Sagane (Old RIKEN)

第３号サイクロトロン
磁極直径65cm
3rd cyclotron
Magnet diameter 65cm

昭和41年(1966) Kumagai

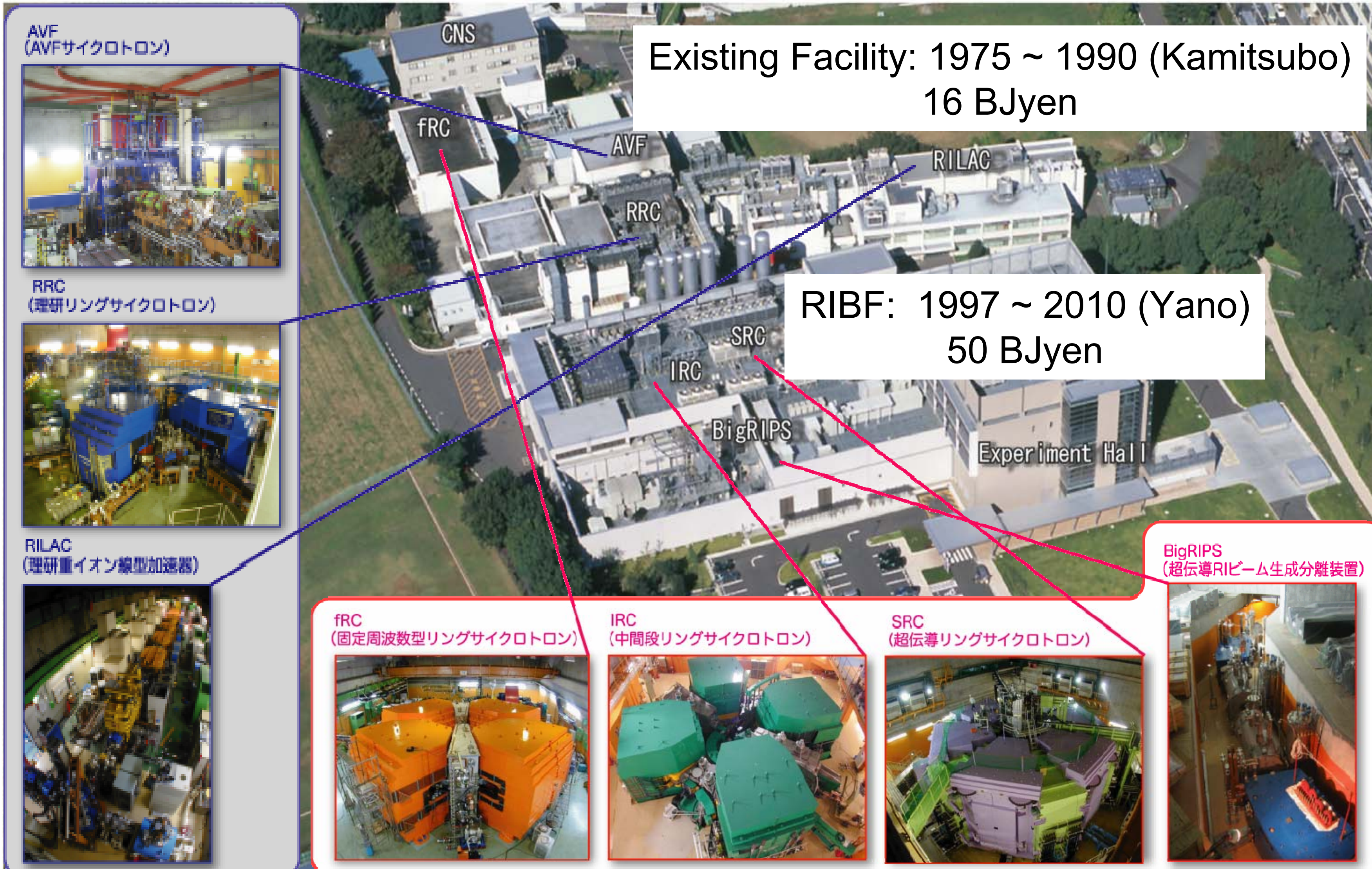
第４号160cmサイクロトロン
磁極直径210cm
わが国初の重イオン加速器
4th 160cm cyclotron
Magnet diameter 210cm

The Japan first Heavy Ion Accelerator (1967 ~ 1990)

Yasushige Yano

Nishina Center for Accelerator-based Science

since April 2006



Yasushige Yano

一家に1枚周期表

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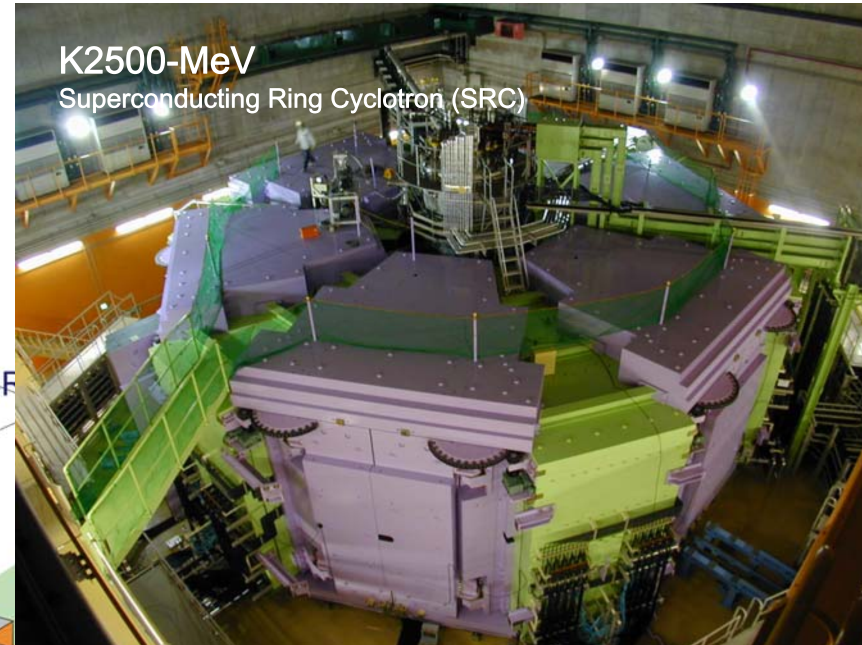
●イラストレーター：山崎 猛

Yasushige Yano

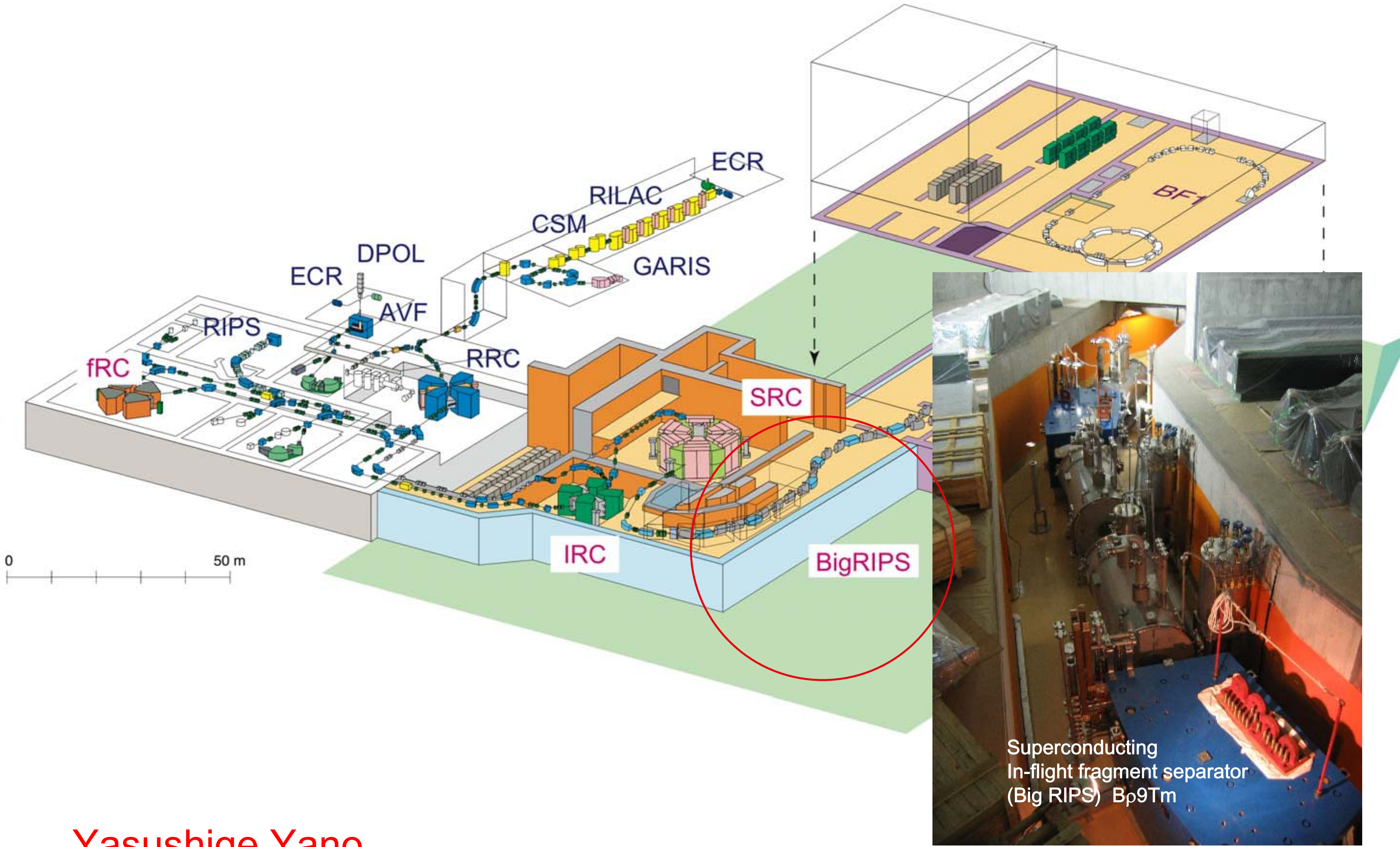
Yasushige Yano

Layout of RIBF Cyclotrons

PHASE I
350 MeV/u: All Ions



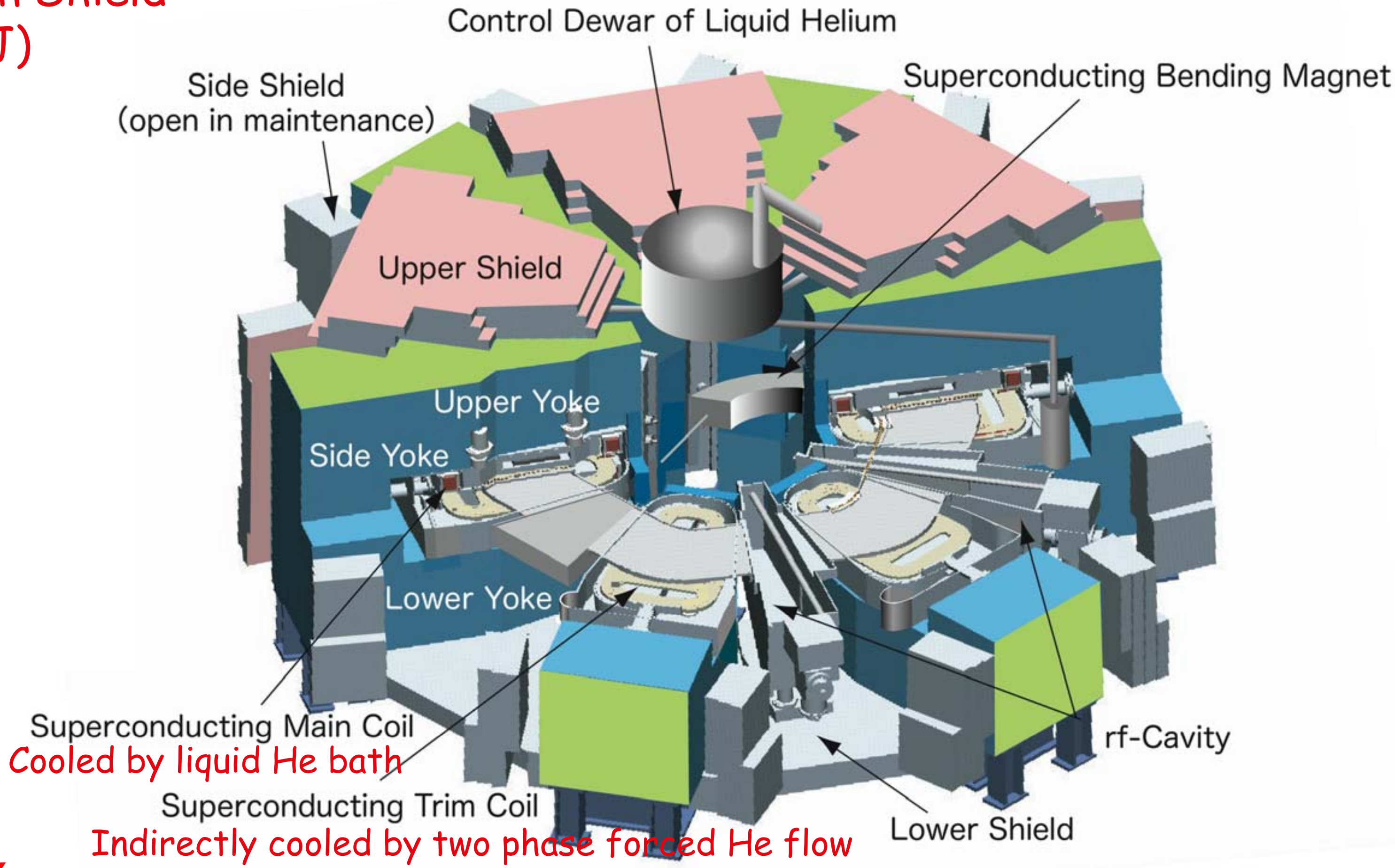
Layout of RIBF RI beam separator



Yasushige Yano

Superconducting Ring Cyclotron (SRC) (world first)

K = 2,500 MeV
Self Magnetic Shield
Self Radiation Shield
3.8T (240 MJ)
18-38 MHz
8,300 tons

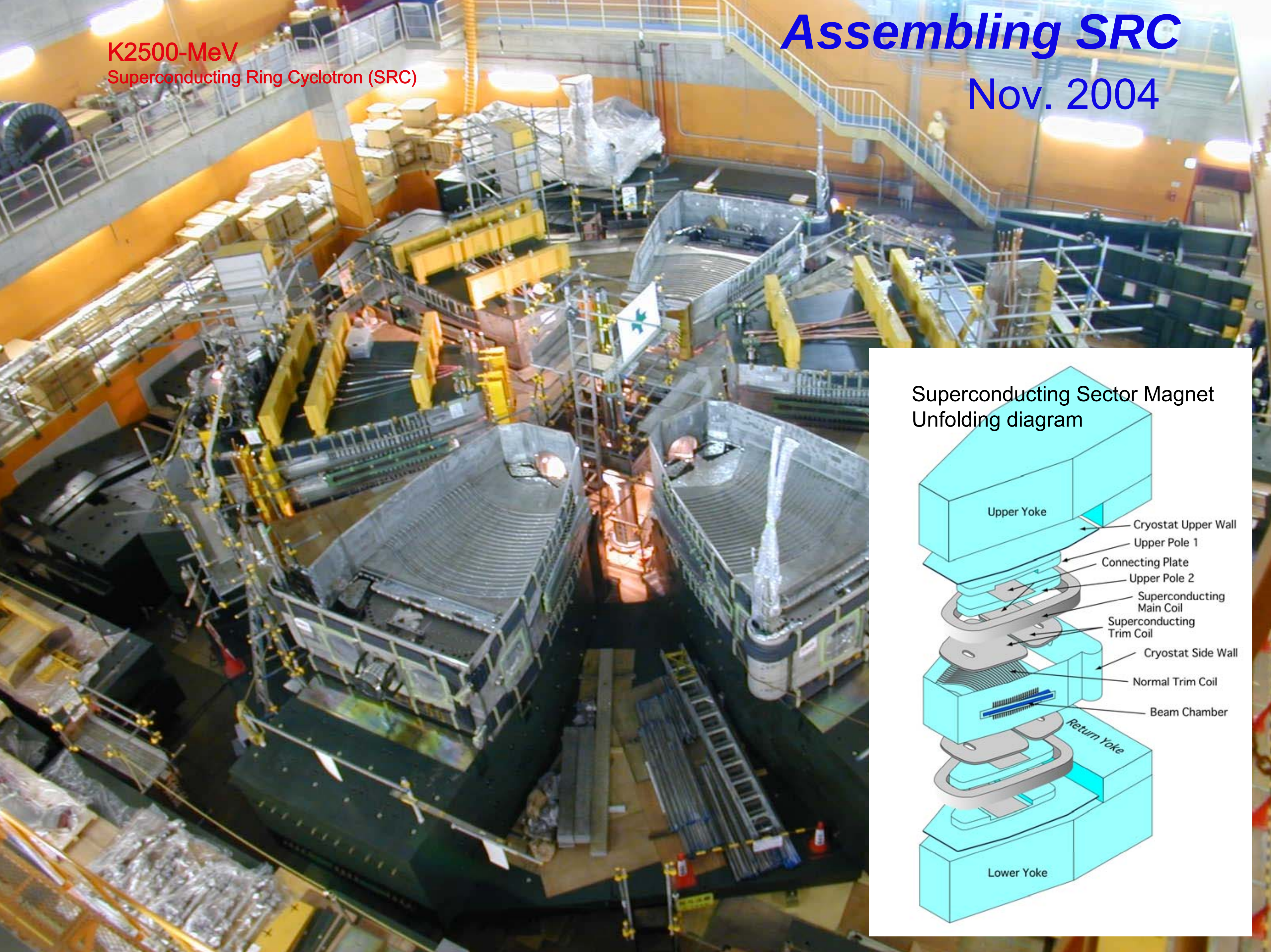


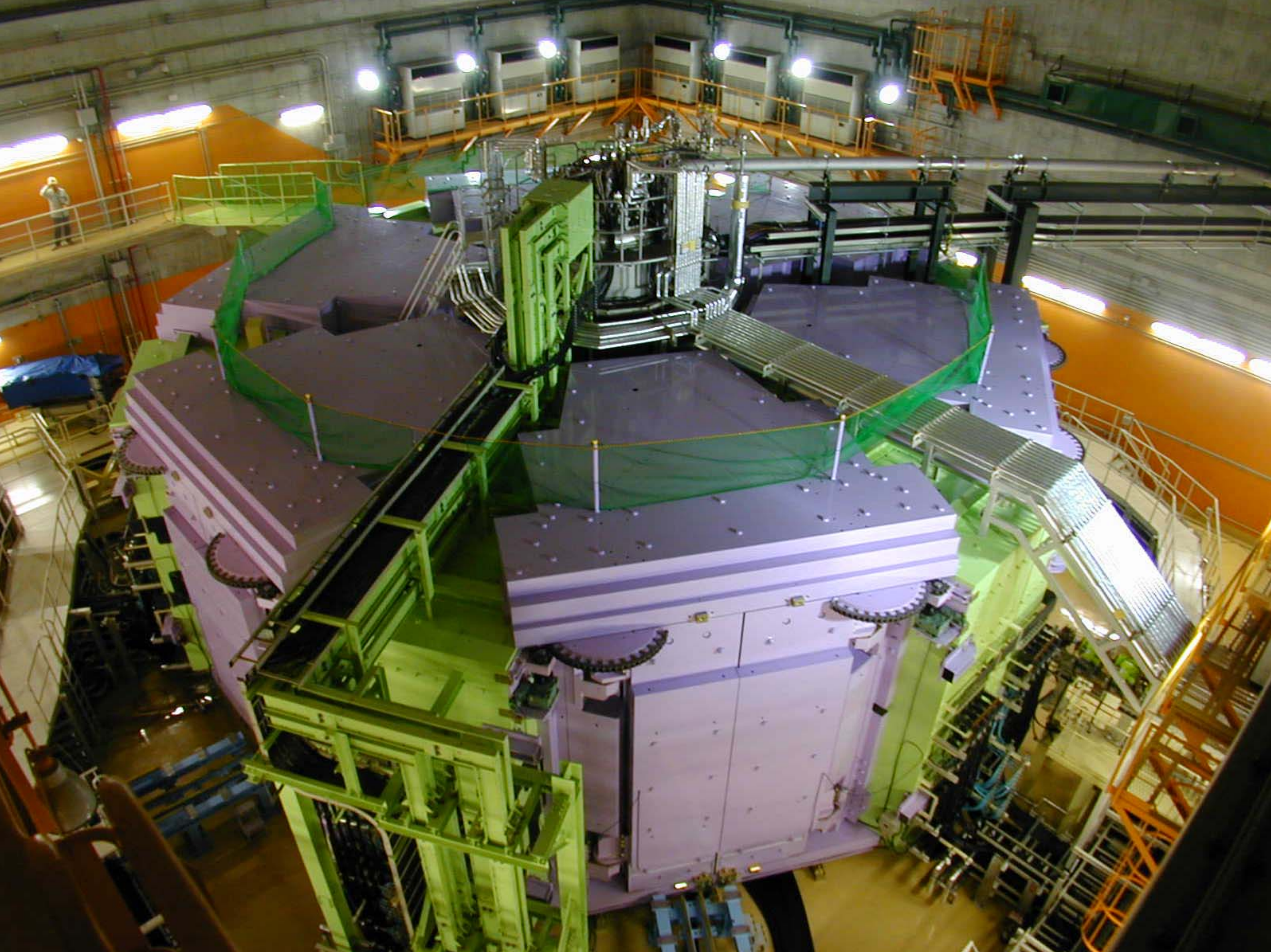
Yasushige Yano

Assembling SRC

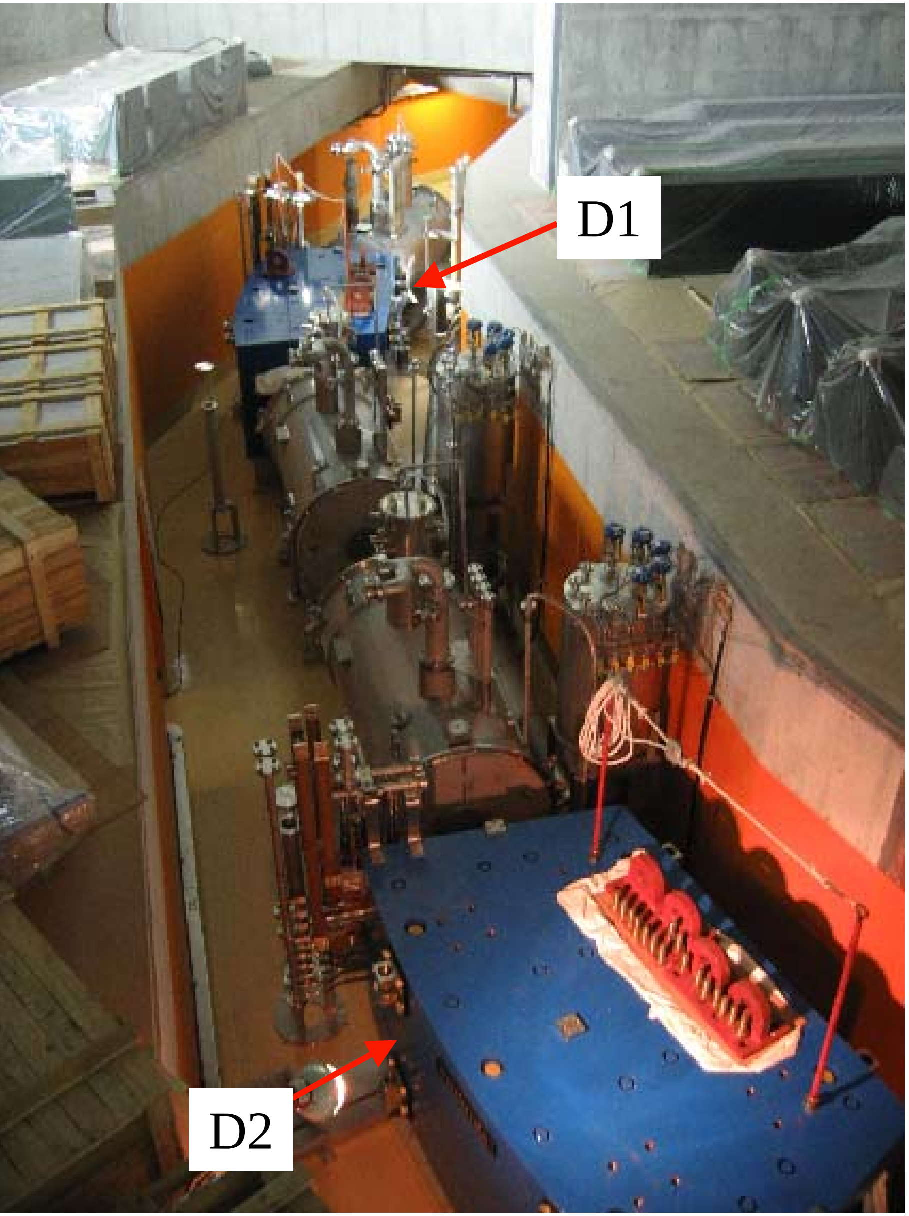
Nov. 2004

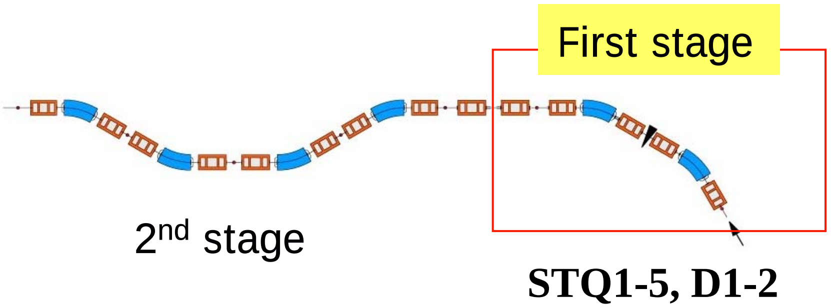
K2500-MeV
Superconducting Ring Cyclotron (SRC)

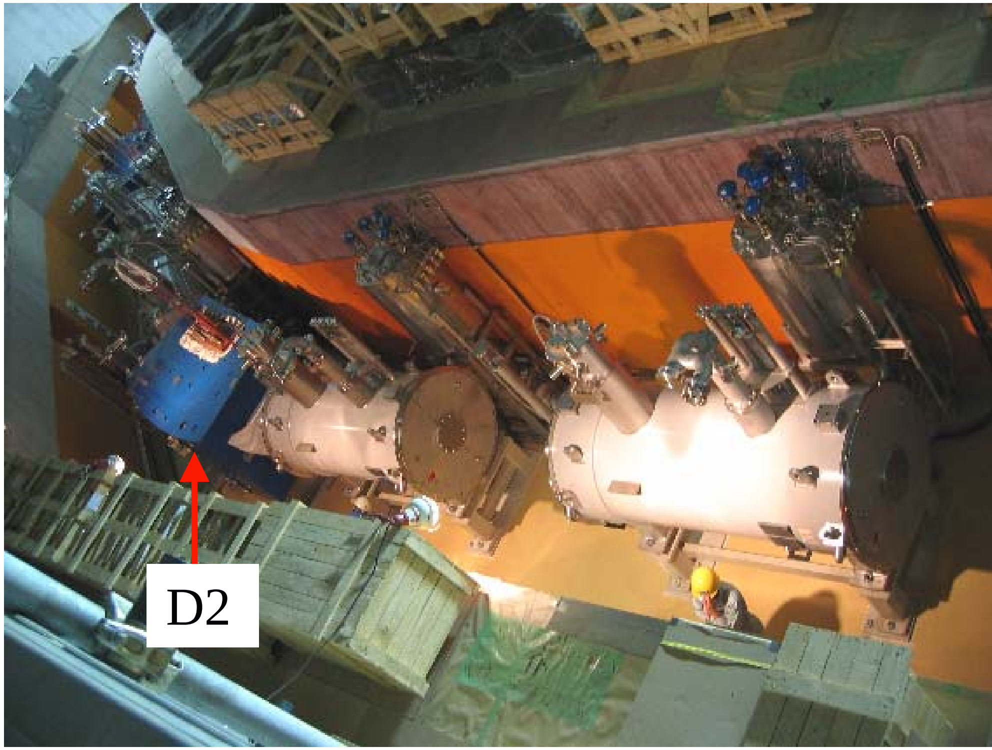




BigRIPS first stage





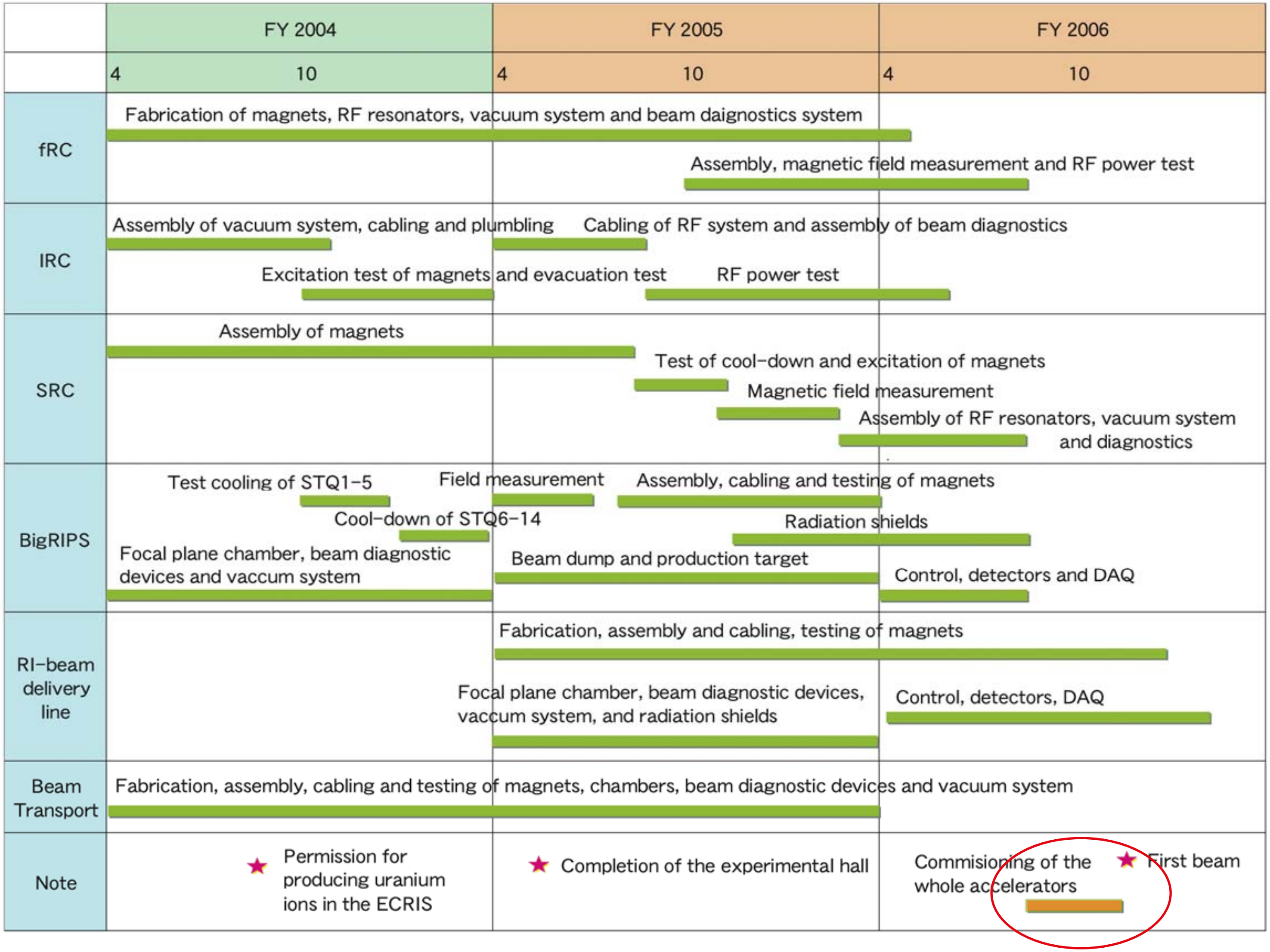


Yasushige Yano


5000 tons concrete shielding is mounted here
above the 1st stage of the BigRIPS

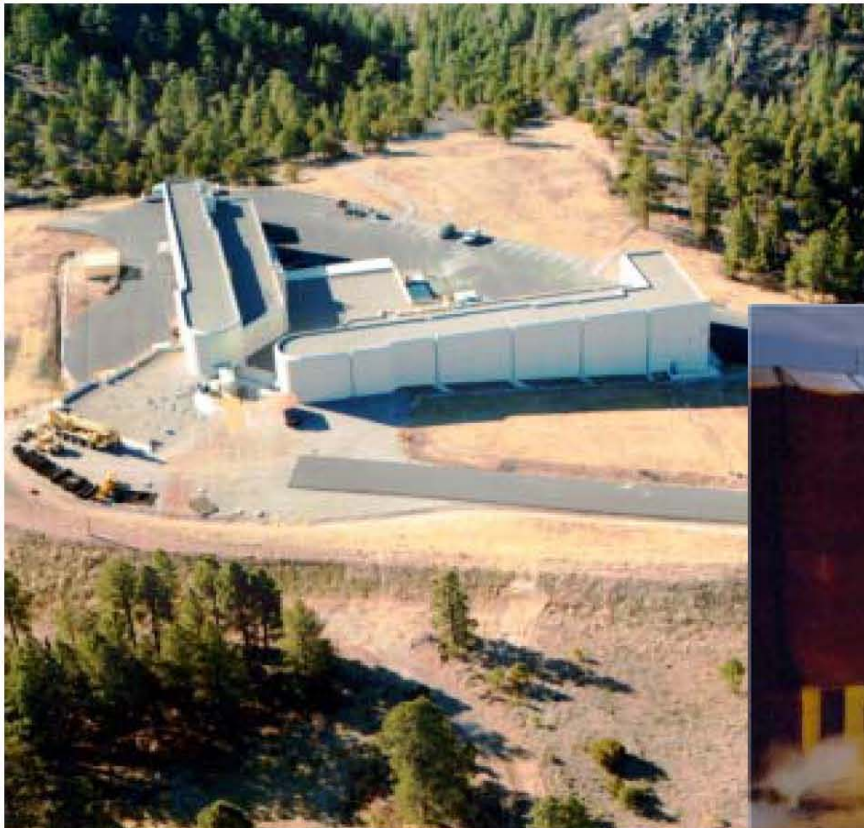
Construction Schedule

Yasushige Yano



The first beam is scheduled for at 15:34 on Dec.16 in 2006

The Dual Axis Radiographic Hydro Test Facility is located at the Los Alamos National Laboratory

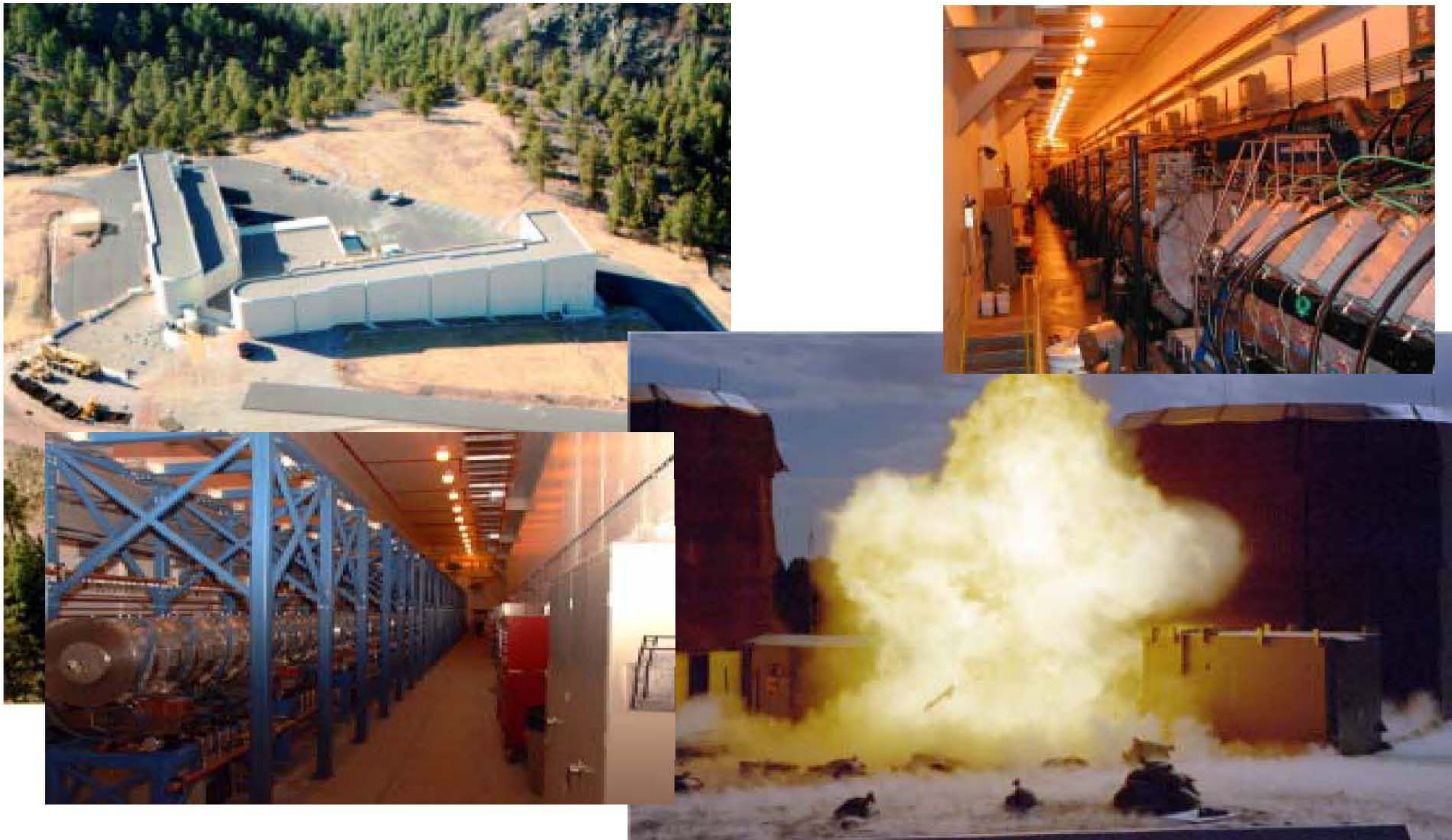


DARHT was conceived in the early 80's as a critical tool for nuclear stockpile stewardship

DARHT consists of two induction linear accelerators oriented orthogonal to each other.

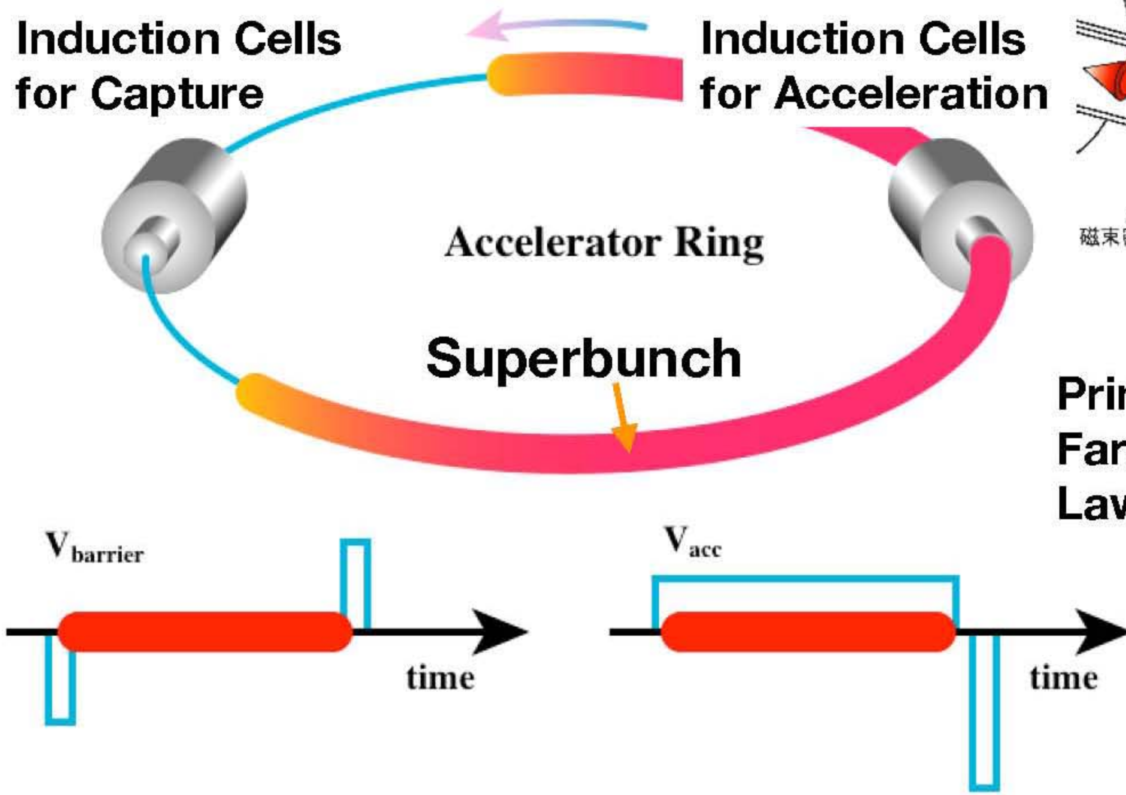
Subrata Nath

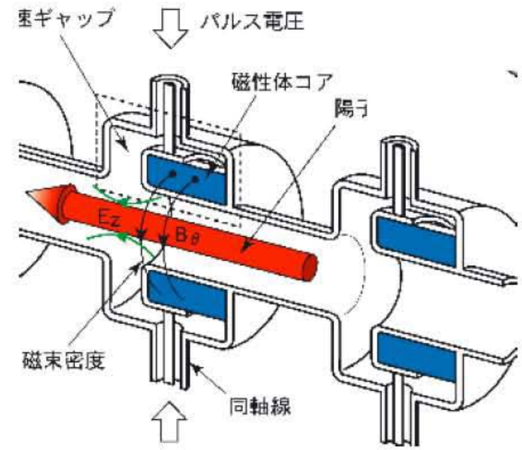
The DARHT Facility will deliver dual-axis, multi-pulse radiography by mid 2008



Subrata Nath

Schematic View of Induction Synchrotron





Principle:
Faraday's Induction Law

Ken Takayama

Revolution frequency and Switching frequency

revolution frequency:

$$f = c\beta / C_0$$

$$f = \frac{c}{C_0}\sqrt{\frac{D}{1+D}}$$

$$D \equiv (\beta\gamma)^2 = \left[\left(\frac{Z}{A}\right)\left(\frac{e\rho}{mc}\right)\right]^2 B^2(t)$$

$$\beta\gamma = \left(\frac{Z}{A}\right)\left(\frac{e\rho}{mc}\right) B$$

kinetic energy as a function of the revolution frequency:

$$T = Mc^2(\gamma - 1) = A \cdot mc^2\left(\frac{1}{\sqrt{1-\beta^2}} - 1\right) = A \cdot mc^2\left(\frac{1}{\sqrt{1-\left(\frac{f \cdot C_0}{c}\right)^2}} - 1\right)$$

Defect of the induction acceleration driven by the switching power supply:

Induction step voltage can't follow $V_{acc}(t)$.
It must be constant, V_0, from a technical reason that it is difficult to change an output voltage of the DC power supply within tens of mseconds.

Counter measure: intermittent switching
instantaneously averaged switching frequency $g(t)$

ΔE: energy gain per short time-period Δt
$g(t)=(V_{acc}(t)/V_0)f(t)$

$$\Delta E = \int_t^{t+\Delta t} eV_{acc}(t')f(t')dt' = eV_0 \int_t^{t+\Delta t} g(t')dt'$$

Control of the gate pulse density
(Patent 2005-196223)

Ken Takayama

Transverse Focusing in the AIA

Equation of motion in the transverse direction:

$$A \cdot m \cdot \frac{d}{dt}\left(\gamma \cdot v_\perp\right) = Z \cdot e \cdot v_\parallel \cdot B' x$$

with $B' \equiv \dfrac{\partial B_y}{\partial x}$

$$\gamma \cdot c\beta_\parallel \cdot \frac{d}{ds}\left(\frac{dx}{ds}\right) = \frac{Z}{A}\left(\frac{e}{m}\right) \cdot B' \cdot x \;\Rightarrow\; \frac{d^2 x}{ds^2} + K(s)x = 0$$

$$K(s) = \left(\frac{Z}{A}\right) \cdot \frac{(e/m)}{c\beta\gamma} \cdot \frac{\partial B_y}{\partial x}$$

$$K(s) = \frac{\partial B_y / \partial x}{B\rho}$$

Betatron frequency doesn't depend on ion species and its charge state.

Easy accelerator tuning for any ions

common
COD
Betatron tune
Injection/extraction orbit

gate timing is determined from the circulating bunch signal.

Interesting option

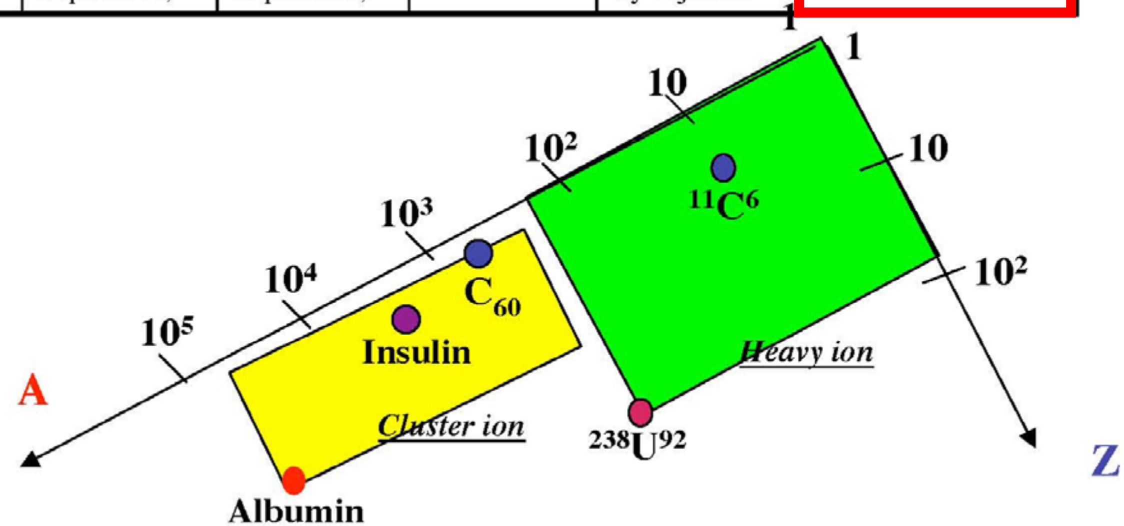
Simultaneous acceleration of different ion species with different (*Z*/*A*) in the same ring

gate triggers are generated every ion species.

Ken Takayama

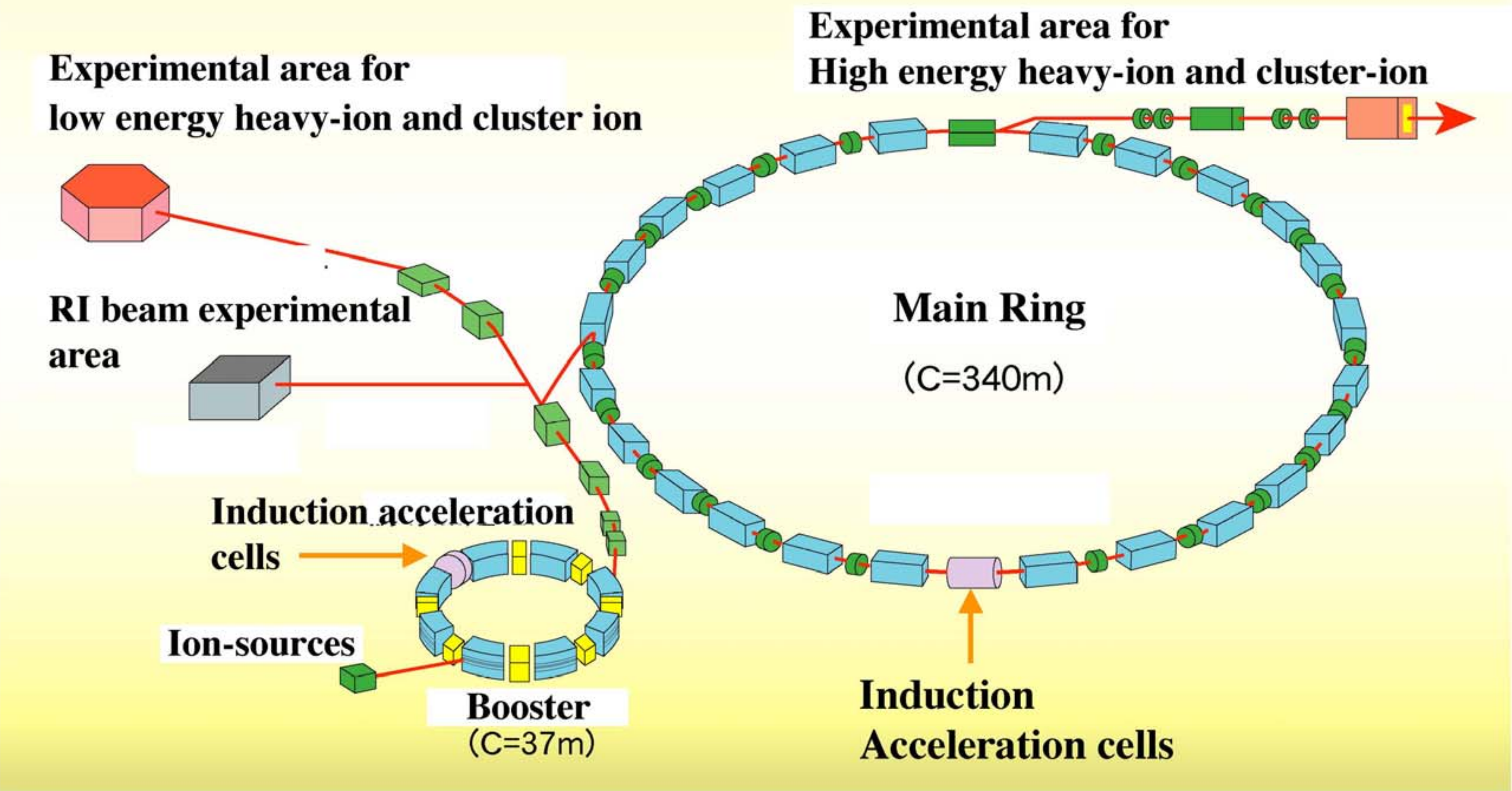
Comparison between various accelerators

Energy E/au	Static Accelerator	RFQ+DTL	Induction Linac	Cyclotron	RF Synchrotron	All-ion accelerator (Ind. Synchrotron)
Low < MeV	No limit	Limited Z/A	No limit	limited Z/A charge state	limited Z/A	No limit
Medium < GeV	*NA*	Limited Z/A (expensive)	No limit (expensive)	limited Z/A charge state	limited Z/A	No limit
High >> GeV	*NA*	Limited Z/A (too expensive)	No limit (too expensive)	*NA*	No limit but limited by Injector	No limit



Ken Takayama

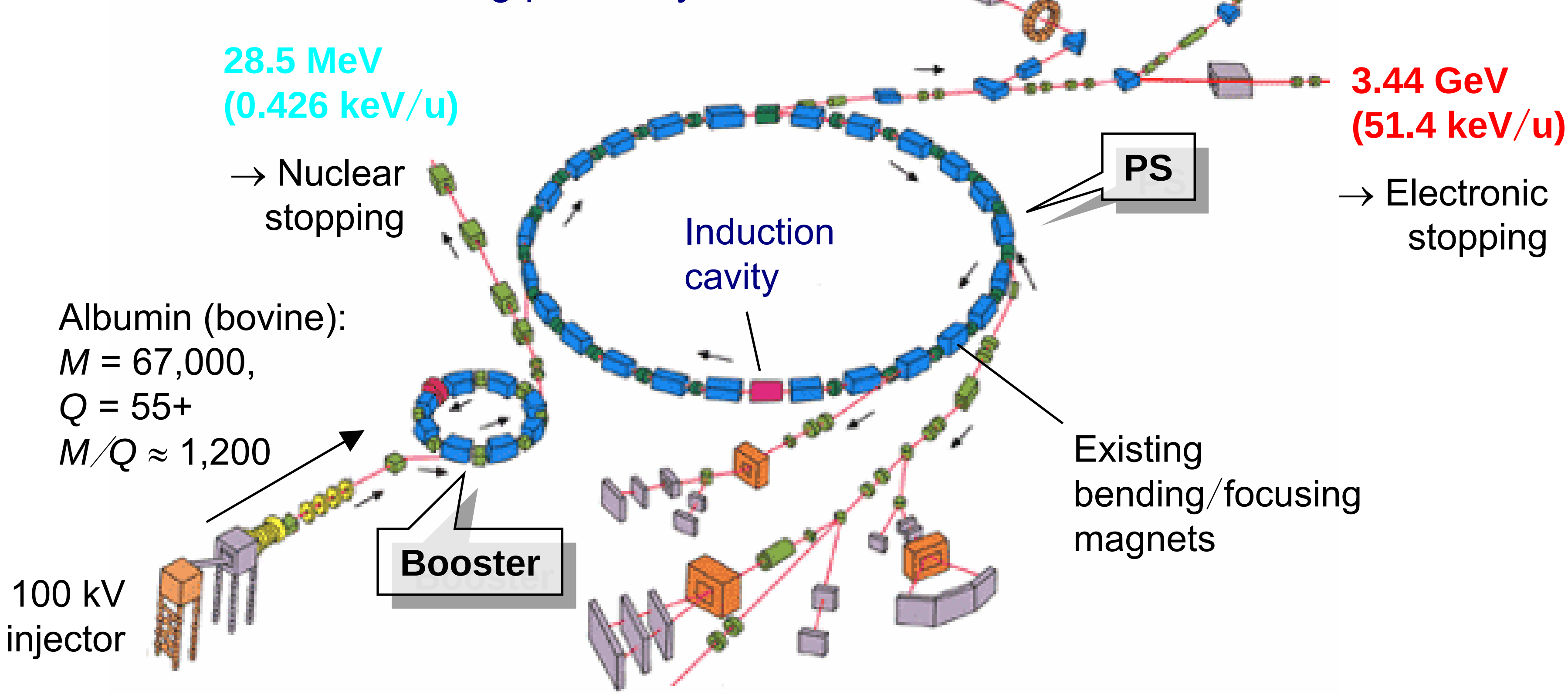
All-ion Accelerator Complex



Ken Takayama

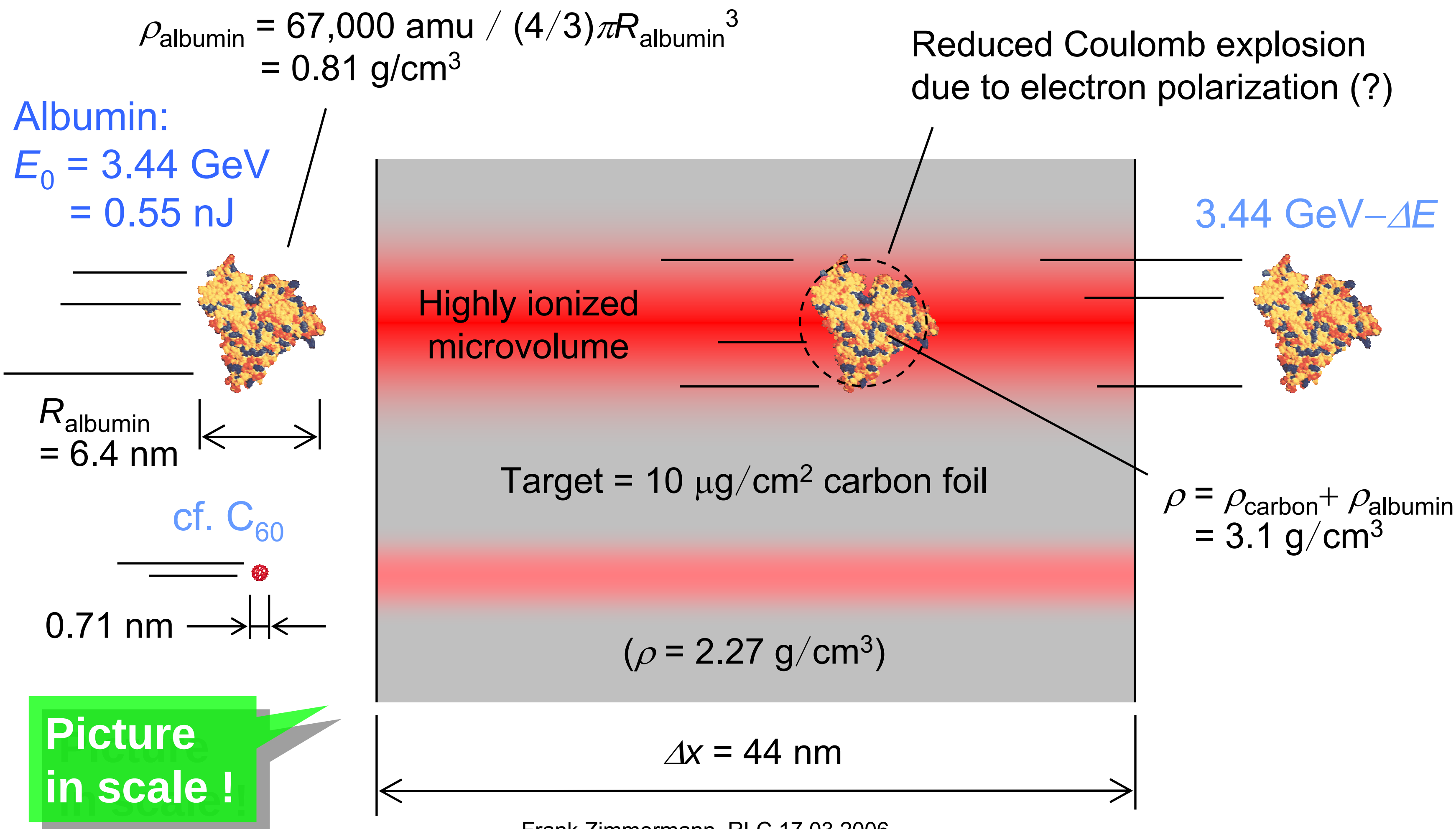
"All-Ion Accelerator" (AIA) is one of the possible ways to obtain GeV-biological macromolecular ion beams.

- Conventional RF accelerators → not available (no synchronization)
  - Induction linacs → very long (≈ 500 m ?), expensive (≈ $\$10^8$?)
- Acceleration by induction synchrotron:
  - Modification of existing proton synchrotrons



Measurement of energy loss of GeV macromolecular ions in a thin foil will be the first beam experiment.

- "Nano-joule, nano particle" irradiation experiment:



The size of the heated volume is large enough to be a "plasma", not simply an electron-ion mixture.

- Basic parameters for the heated microvolume:
  - Plasma frequency ω_{pe} (temporal neutrality):

$$\omega_{pe} = \sqrt{\frac{e^2 n_e}{\varepsilon_0 m_e}} = 3.4 \times 10^{16}\ \mathrm{s}^{-1} \qquad \therefore \frac{2\pi}{\omega_{pe}} = 0.19\ \mathrm{fs} << \tau_p$$

  - Debye shielding length λ_D (spatial neutrality):

$$\lambda_D \approx \sqrt{\frac{\varepsilon_0 k T_e}{e^2 n_e}} = 0.099\ \mathrm{nm} << r^*$$

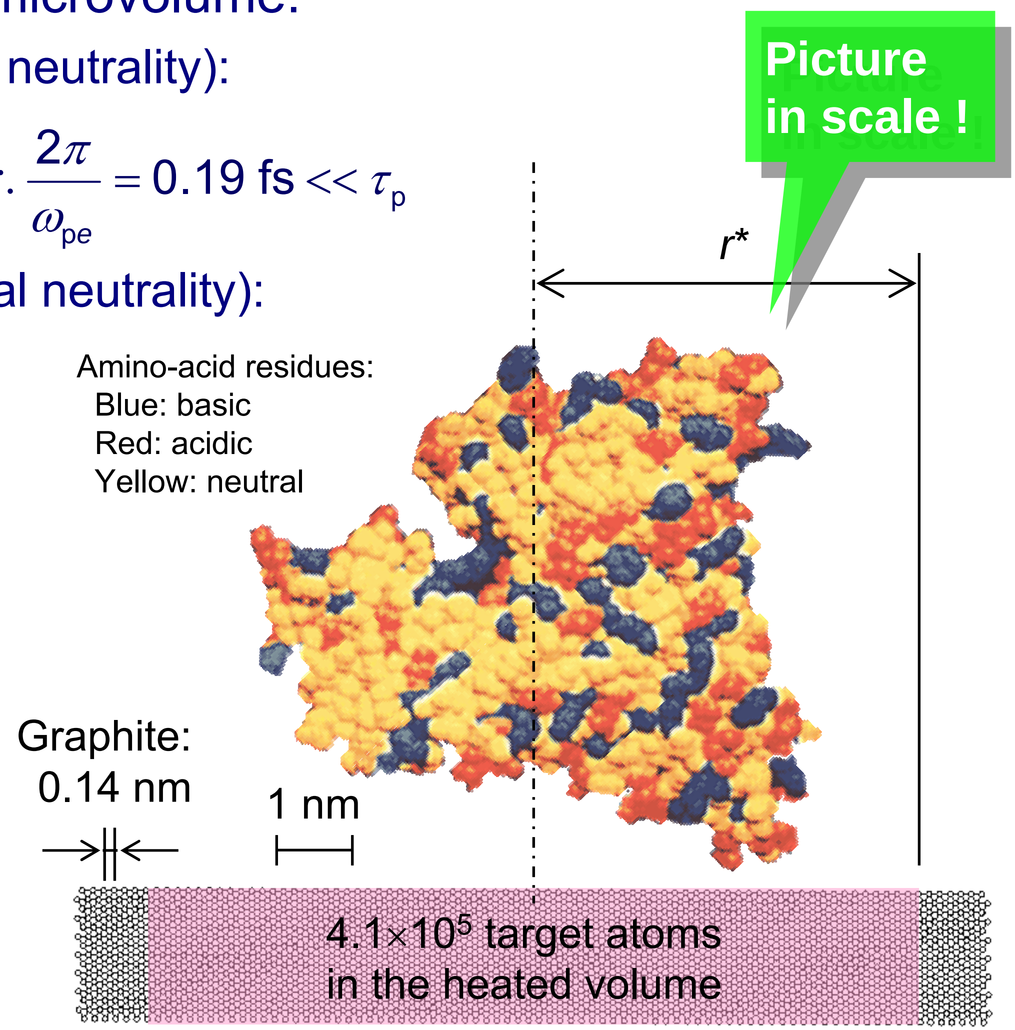
  - "Debye number" N_D:

$$N_D = \left(\frac{4}{3}\pi \lambda_D{}^3\right) n_e = 1.5$$

  - Plasma coupling parameter:

$$\Gamma = \frac{e^2}{4\pi\varepsilon_0 (3/4\pi n_e)^{1/3} k T_e} = 0.26 > 0$$

$\therefore$ Non-ideal plasma



Conclusions: The KEK-AIA facility will be a unique and useful tool for high energy-density sciences.

- GeV-TeV biological macromolecules → a novel energy driver
- KEK-AIA ("All-Ion Accelerator") as a macromolecular ion beam facility:

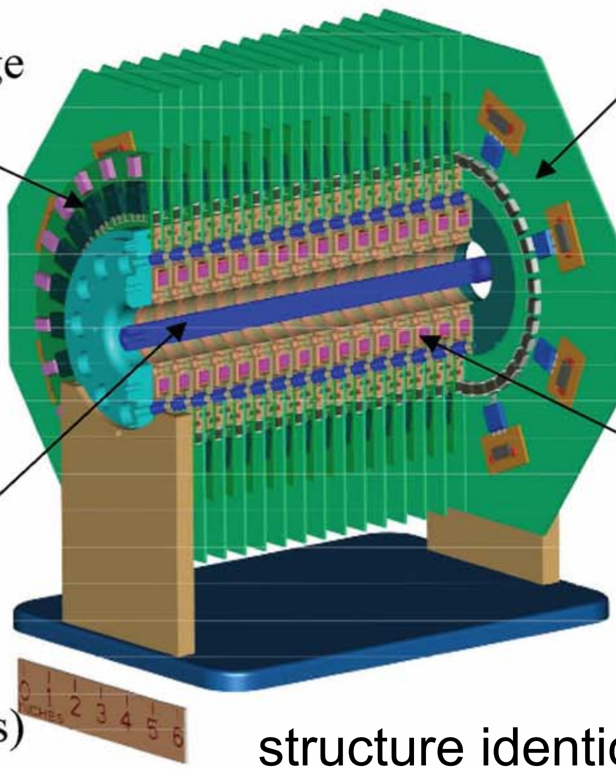
(Very rough, typical value)

Macromolecular/cluster beam facility	Projectile	Energy	Intensity	Vacuum
MP tandem (Orsay)	C_{60}, Au_n etc.	< 100 keV/u	< 10^6 ions/cm^2/s	≈ 10^{-7} Torr
600 kV Cockcroft-Walton (BNL)	Biological macro-molecules $M <\approx 10^5$	< 1 keV/u	?	≈ 10^{-7} Torr
ELISA (Aarhus)		< 100 eV/u	< 10 nA	≈ 10^{-11} Torr
ESRING (KEK)			≈ 100 nA	
DESIREE (Stockholm)			?	5×10^{-12} Torr
AIA = Booster + PS (KEK)		< 100 keV/u	?	**≈ 10^{-8} Torr**

- Preliminary experiments using MeV (↔ keV/u) beams from "Booster":
  - Realistic vacuum requirement: e.g. for Insulin (M = 5,800, 2R = 2.7 nm),
    - $q = 5+ \to E = 3.3$ MeV (0.57 keV/u)
    - $\sigma_{loss} \approx 5.7\times10^{-14}$ cm^2 → $p_{RG} \approx 9\times10^{-10}$ Torr ≈ 10^{-9} Torr
  - Nuclear stopping regime → Industrial applications (?)

Fast Pulser for ILC Kicker,
burst rate 3 MHz, 15000 pps, <3 ns rise time

Adder Conceptual Layout

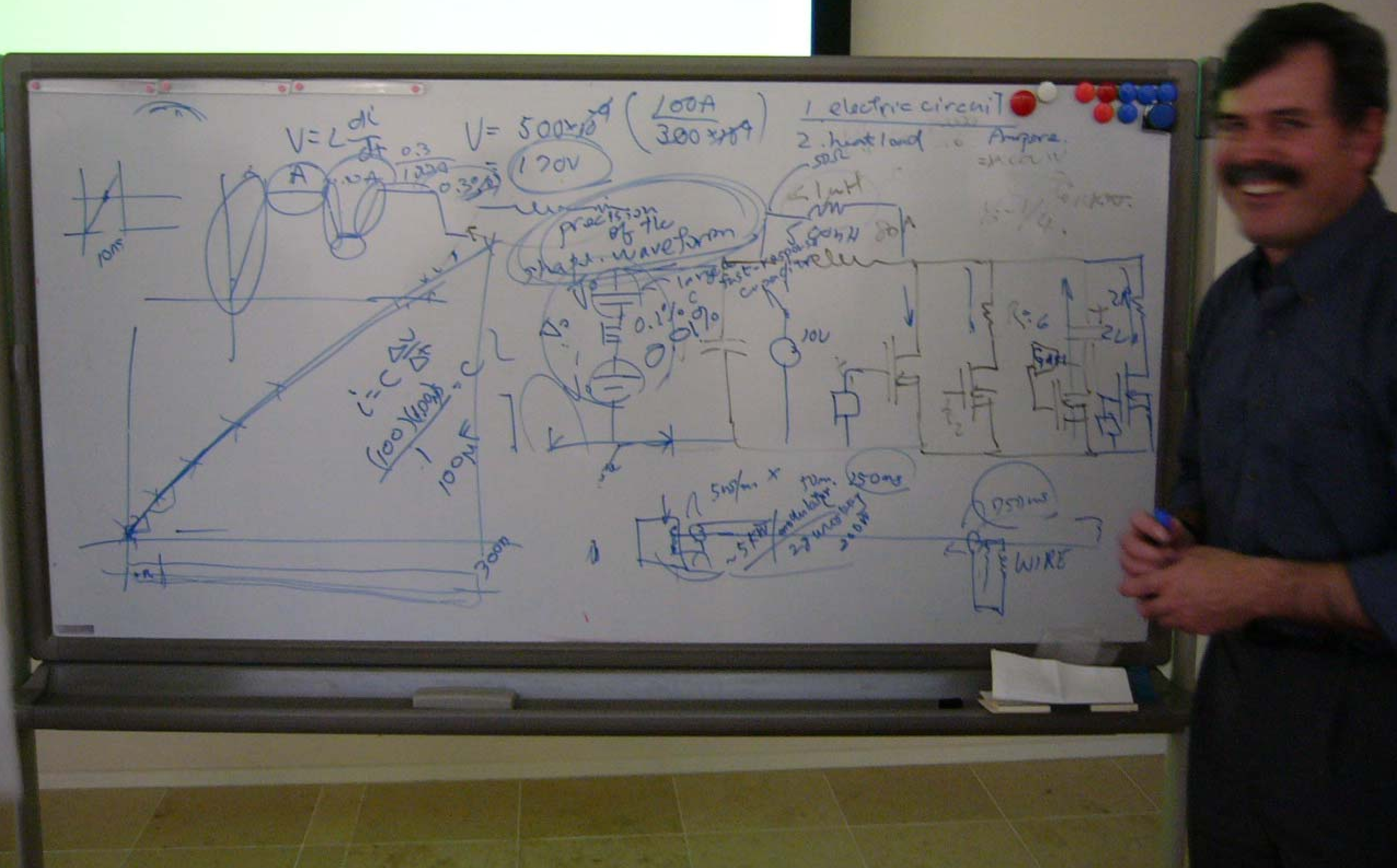


structure identical to induction accelerator
many drive circuits & transformers

Ed Cook

WG3 – “LHC Wire Lens”

Ed Cook
& draft circuit



summary of WG3 discussion

- developed circuit diagram of switching device
- 4 MOSFET switches, 2 or 3 power supplies with 10^{-4} stability, 2 resistors, 1 or 2 capacitors, arbitrary waveform generator w multiple outputs
- rather low cost
- timing jitter may or may not be a problem
- radiation hardness to be checked
- transmission line effect (impedance, reflection, etc.) to be addressed
- plan to build prototype(s) at CERN; beam test at RHIC in 2008
- alternative wide-band rf approach implies much more heating and parallel/serial MOSFETs
- check jitter of RHIC & LHC timing systems