Analysis of Induction Linac Concept for High Gradient p+ Driver

Anatoly Krasnykh
(Klystron Dept. of SLAC)
for
A Muon Collider Design Workshop

Outline

- Introduction. Items for Consideration
- Accelerating Gradient in Induction Linacs
- Analyze Ways How to Increase Gradient
- High Gradient (HG) of Solid State Approaches
- SLIM©: SLAC Induction Module (or Method)
- Conclusion

Preliminary Remarks

- There are many publications where specific problems and recent achievement for the induction linac are discussed (see for example, the presented talks on the International Workshop titled as "Recent Progress in Induction Accelerators for Future Beam Inertial Fusion and Hadron Colliders", KEK, 2002
- Because LIA technology has been one subject of my earlier professional field of activity, I continuing to review publications and the progress in the USA, France, Japan, Korea, China, Russia, and another countries
- Research reproducing LIA technology has not produced a significant increase in accelerating gradient. Is there a technology limitation?
- The presentation will focus on the aspects of induction linac technology which are not covered adequately. A breakthrough is likely

Items for Consideration

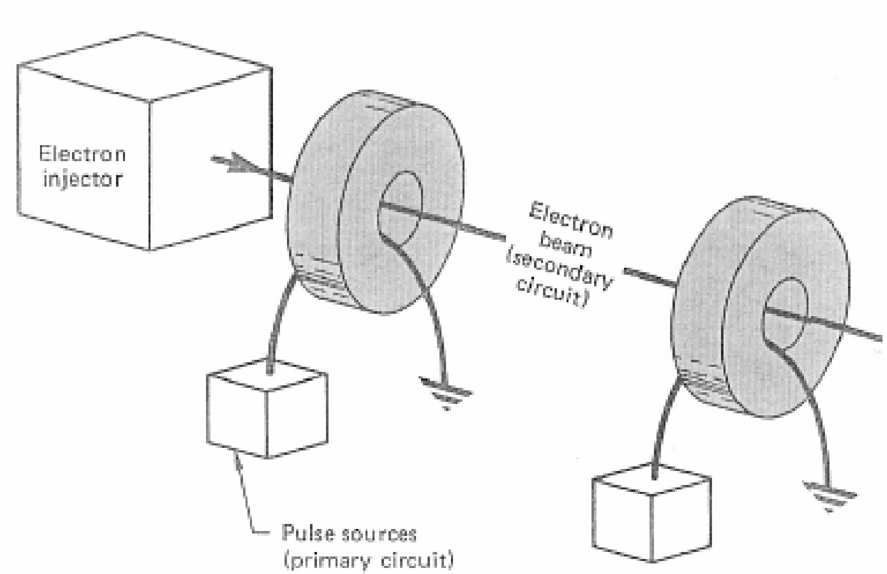
- Can an induction linac approach compete with the classical RF technologies?
- An accelerating gradient of existing induction linacs is weaker than classical rf-linacs. Why is this? Can the induction linacs possesses the accelerating gradient similar to rf-linac gradients?
- A typical pulse width for an induction system is several tenth of nanoseconds (let's say 30-100 nsec). Can the induction system deals with 10 times shorter pulses?
- Results of pioneer R&D's that were devoted to the HG induction linac concept and the present solid state coreless concepts (SLIM©)

Linear Induction Linacs

Accelerator	*Laboratory*	*Year*	*Current (kA)*	*Energy (MeV)*	*Pulse (ns)*	*Purpose*
Astron-I	LLNL (US)	1963	0.35	4	250	Fusion
Astron-II	LLNL (US)	1968	0.85	6	300	Fusion
ERA	LBL (US)	1970	0.9	4	60	Fusion
NBS	NBS (US)	1975	1.0	0.8	2000	Development
LIU -10	VNIIEF (RU)	1977	50	14	20	Effects
ETA	LLNL (US)	1978	10	5	50	Development
FXR	LLNL (US)	1982	3	18	65	**Radiography**
ETA II	LLNL (US)	1983	2	6	70	Development
ATA	LLNL (US)	1984	10	45	80	Propagation
RADLAC-II	SNLA (US)	1985	20	20	20	Propagation
LIU-30	VNIIEF (RU)	1989	100	40	20	Effects
DARHT-I	LANL (US)	1999	1.7	20.0	60	**Radiography**
AIRIX	PEM (FR)	1999	1.9	19.2	60	**Radiography**
DARHT-II	LANL (US)	2003	2	18.4	2000	**Radiography**

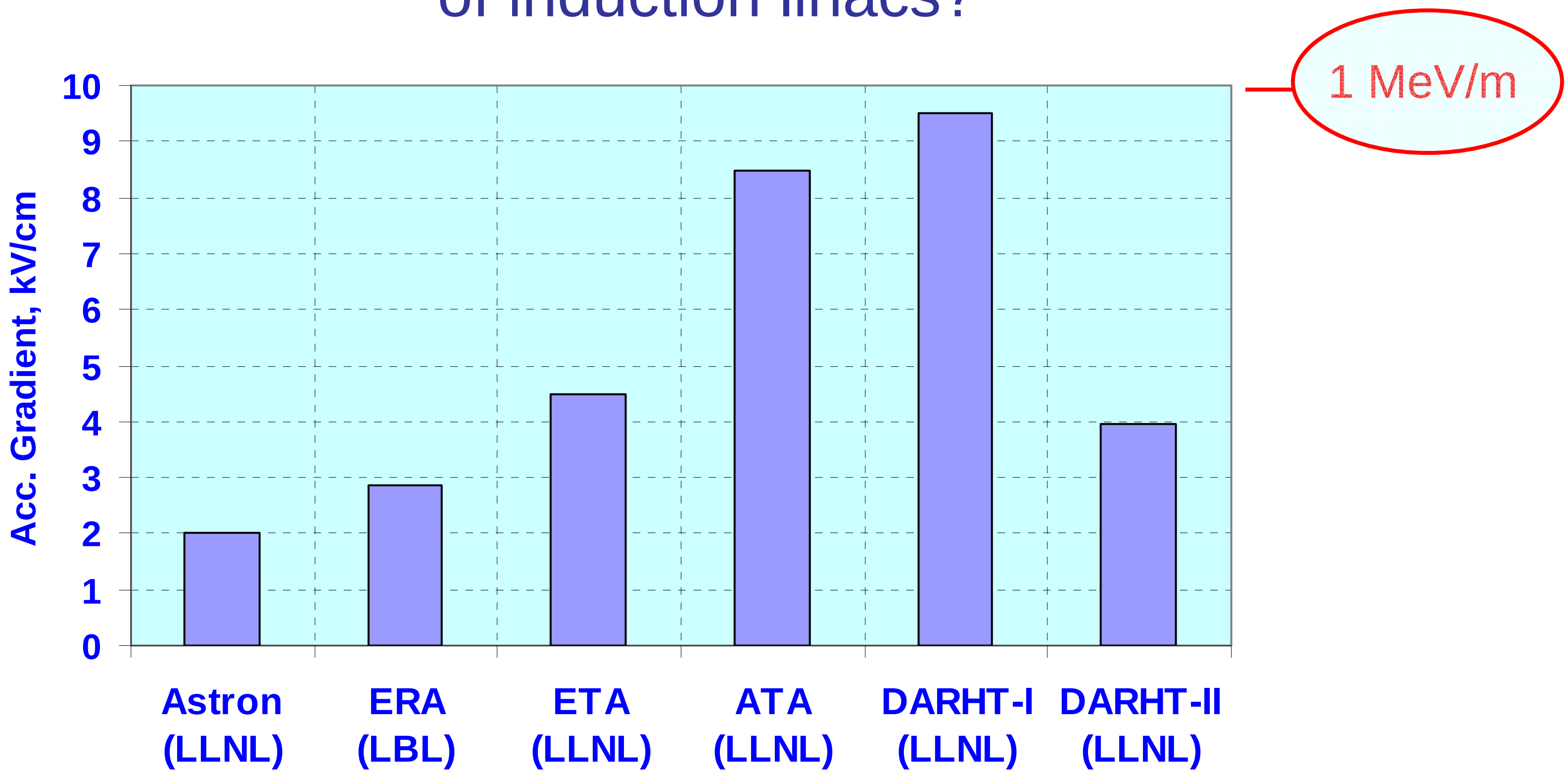
Compliment to C. Ekdahl (IEEE, Plasma Science, IEEE Transactions, V. 30, 2002, p. 254)

Classical Induction Linac Topology



- Array of Pulsers
- Array of Ferromagnetic Cores
- Cores with One Primary Turn
- Beam is as secondary circuit in 1:1 x-fmr

What is a typical accelerating gradient of induction linacs?

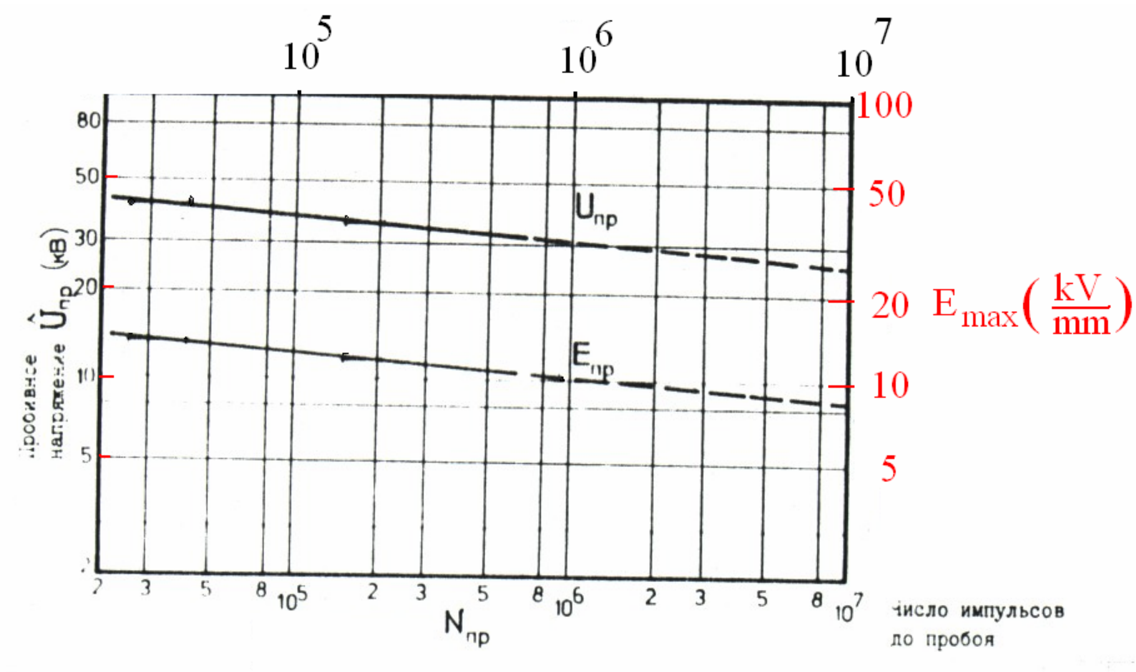


The machines were build in the period 1963-2003 (i.e. the 40 years progress)

Machines in other countries (France, Russia, China, etc.) have similar accelerating gradient

May be a Problem with a Ferromagnetic Media?

- How good are these media? Ferrites was a significant concern.



"Кривая жизни" для ферритов 600НН.

JINR preprint 9-12448, 1979

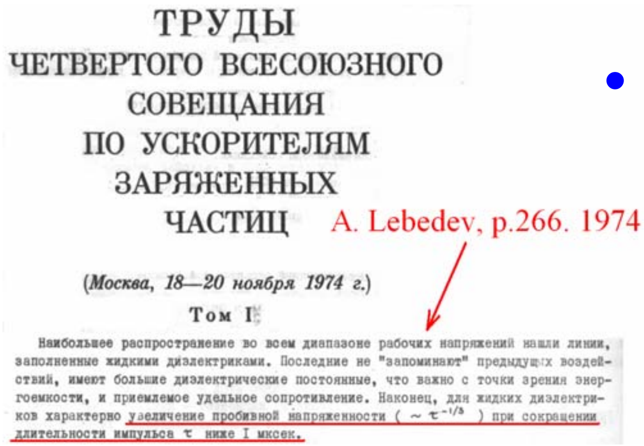
Our study showed that Ni-Zn ferrites are not so bad:

~ 50 kV/cm, (i.e. 5 MeV/m) may hold off for a number of pulses ~ 10^8 if the pulse width is 30-100 nsec

However the acceleration gradient is 5-6 time less than gradient of rf-structures

There are two natural ways →

- a reduction of the pulse width
- a reduction of the section length



ТРУДЫ
ЧЕТВЕРТОГО ВСЕСОЮЗНОГО
СОВЕЩАНИЯ
ПО УСКОРИТЕЛЯМ
ЗАРЯЖЕННЫХ
ЧАСТИЦ

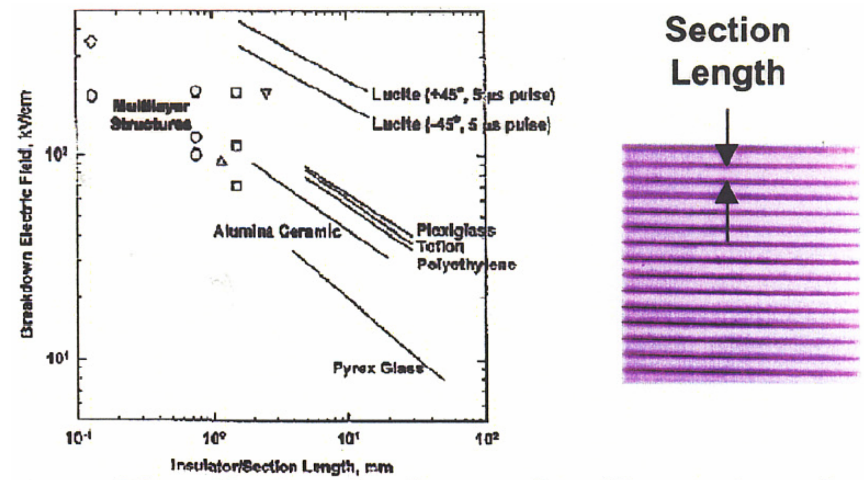
(Москва, 18—20 ноября 1974 г.)

Том I

Наибольшее распространение во всем диапазоне рабочих напряжений нашли линии, заполненные жидкими диэлектриками. Последние не "запоминают" предыдущих воздействий, имеют большие диэлектрические постоянные, что важно с точки зрения энергоемкости, и приемлемое удельное сопротивление. Наконец, для жидких диэлектриков характерно увеличение пробивной напряженности ($\sim \tau^{-1/3}$) при сокращении длительности импульса τ ниже I мксек.

A. Lebedev, p.266. 1974

$$E_{gain} \propto \frac{1}{\sqrt[3]{\frac{t_{1u\,sec}}{t_p}}}$$

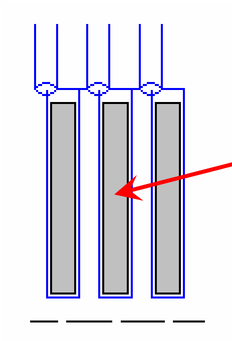


The effect scales inversely with spacing of the conductive planes

We could expect to get an increasing of 5-10 times when the pulse duration is several nsec and thin section length are used.

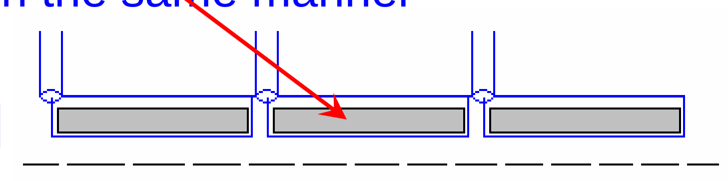
Problem: high electric field in ferrite, a micro field enhancement in the non-uniform media (ferro-seeds), solid state ionization in ferromagnetic material, magnetic properties with ionization, local thermal shocks, etc.

Can the classical induction system deal with pulse widths in the nsec range?



There is the same V*sec integral

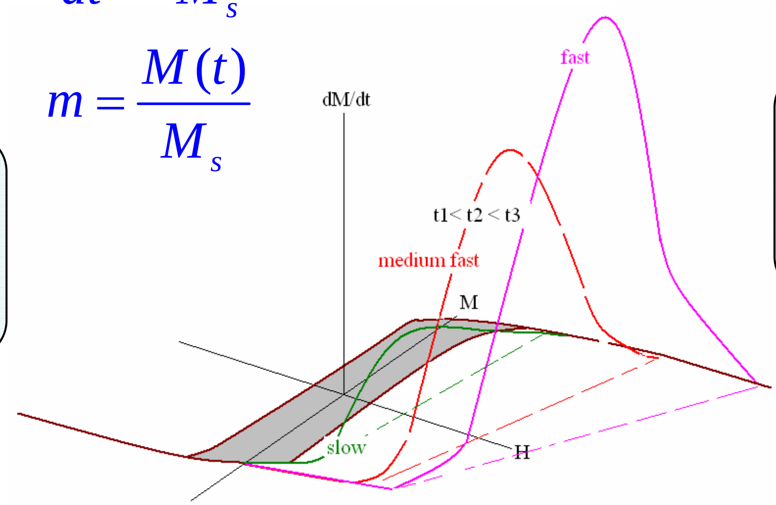
but the core does not react in the same manner



$$\frac{dm}{dt} = \frac{\lambda}{M_s} \cdot H(t) \cdot [1 - m(t)^2]$$

$$m = \frac{M(t)}{M_s}$$

Slow rise/fall times but acc gradient is high

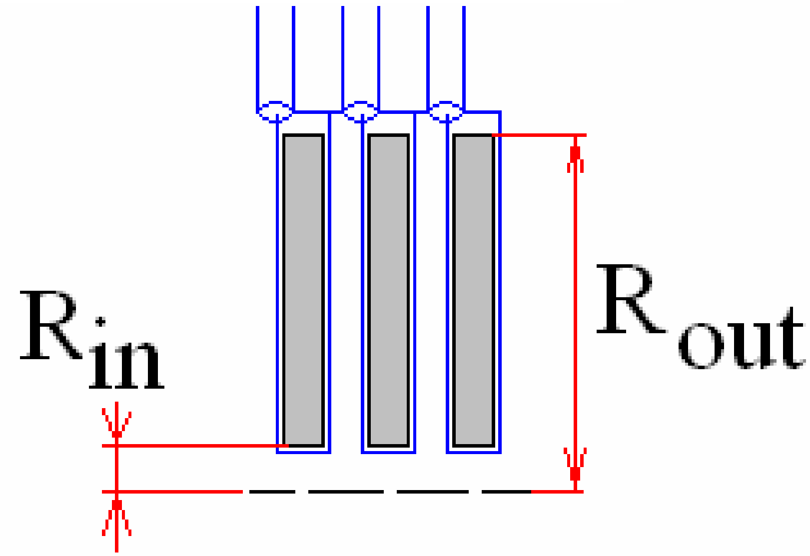


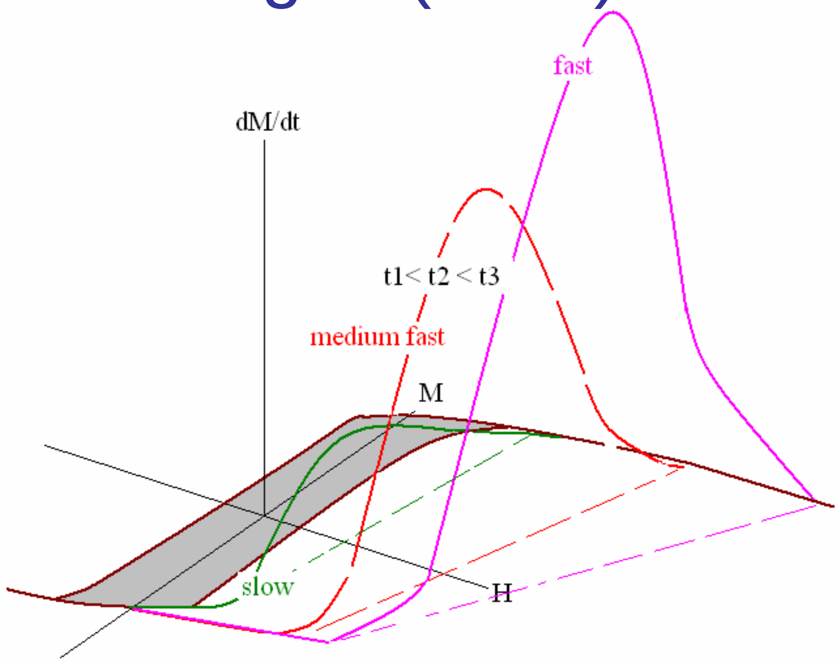
Fast rise/fall times but acc gradient is low

Physics of Fast Dynamic Magnetization

For more engineering aspects, see "Performances of Induction System for Nanosecond Mode Operation", SLAC-PUB-11853 (here the core area and the mean magnetic path length are bounded to transmit the nsec range power)

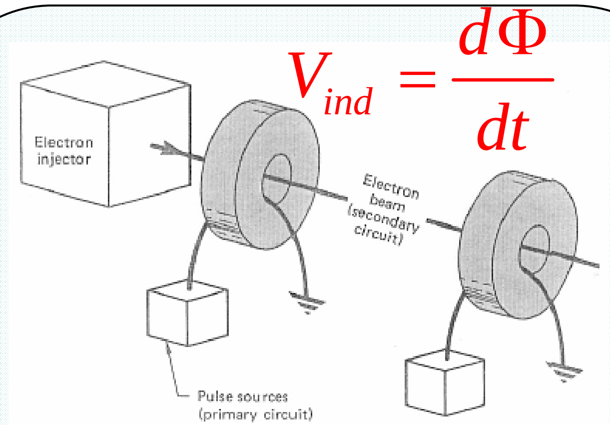
Can the classical induction system deal with pulse widths in the nsec range? (cont.)



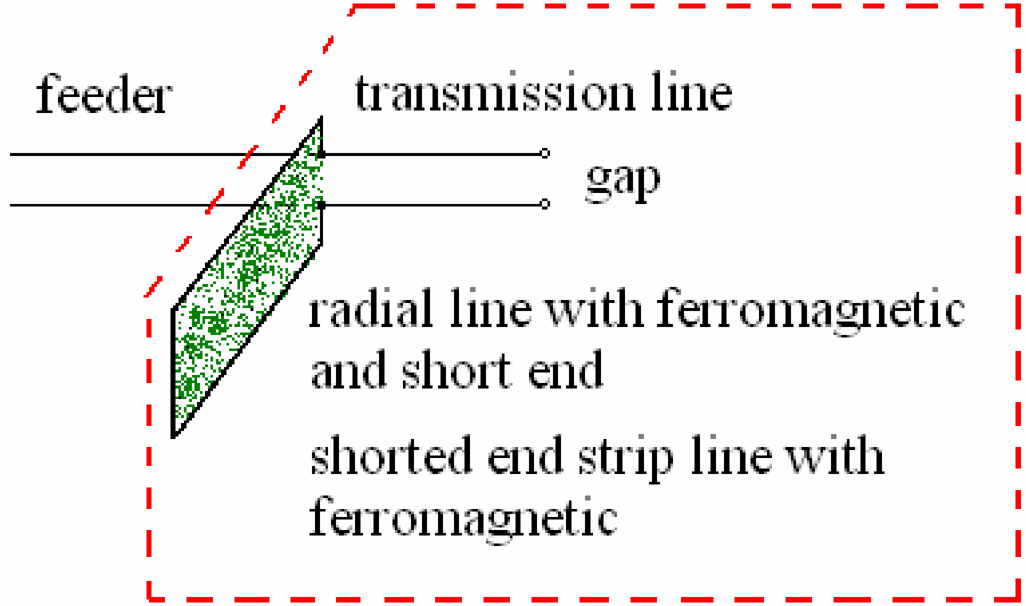


The induction system that has a large core ratio Rout/Rin, will not work effectively in nsec range. The stored energy goes to the core instead of to the beam.

Transmission Line Approach for Induction System

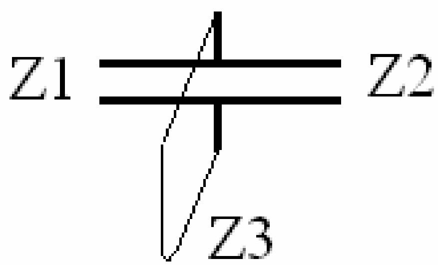


A classical approach of a working principle for the induction system does not allow us to make a leap forward on the gradient improvement



One Cell of Induction System

The transmission line approach helps to understand the role of components of individual cells (there is a contrasting view of the energy transfer from the source to the beam)



Z3>>Z1, Z2 ***see the permeability role***

Z3<<Z1, Z2

What deductions can be made?

The highest gradient for a classical induction linac concept is ~1 MeV/m

An electric field hold off in Ni-Zn ferrites is ~5 MV/m (reliably in the ten's nsec range)

A reduction of the pulse width does not lead to the HG for a classical induction system

The natural way to resolve the conflict is a coreless induction linac concept

A Coreless Induction Concept

- A. Pavlovskii, et al. (the Arzamas-16 team) Sov. At. Eng. **28**, 549 (1970)

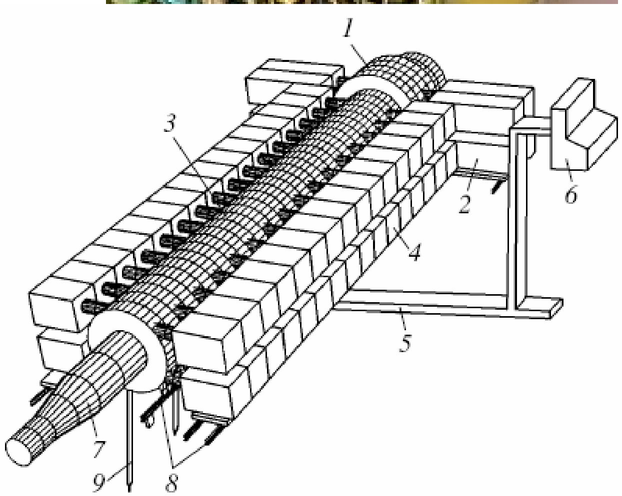
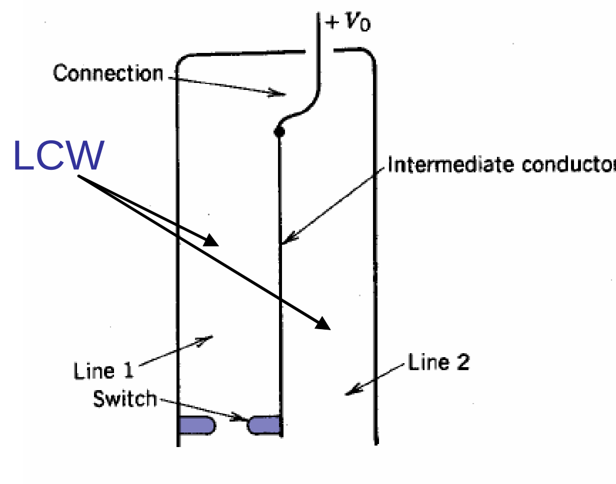
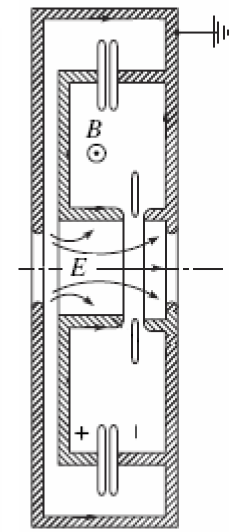


Fig. 1. Design of the LIA-30 acceleration system and arrangement of 72 SPGs: (*1*, *3*) injecting and accelerating units of the inductors, respectively; (*2*, *4*) SPGs for injecting and accelerating units; (*5*) signal-cable housing; (*6*) computerized system; (*7*) beam-extraction device; (*8*) rails for the transport of the modules; and (*9*) deep ground electrodes of the structural-grounding circuit.





LIA-30 was one of the most powerful induction linac:

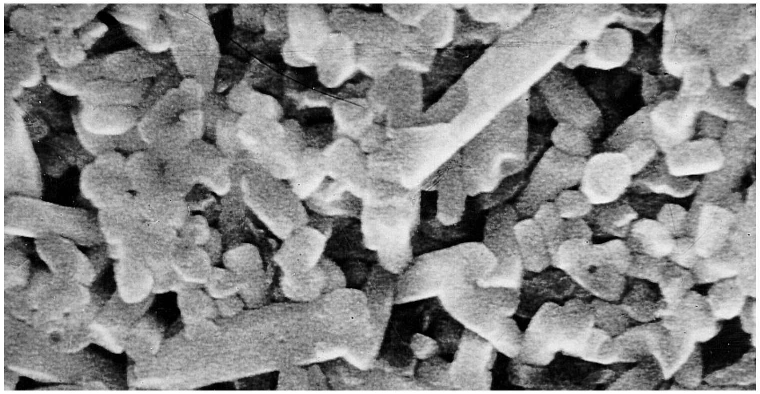
40MeV, 25 nsec, and up to 100 kA

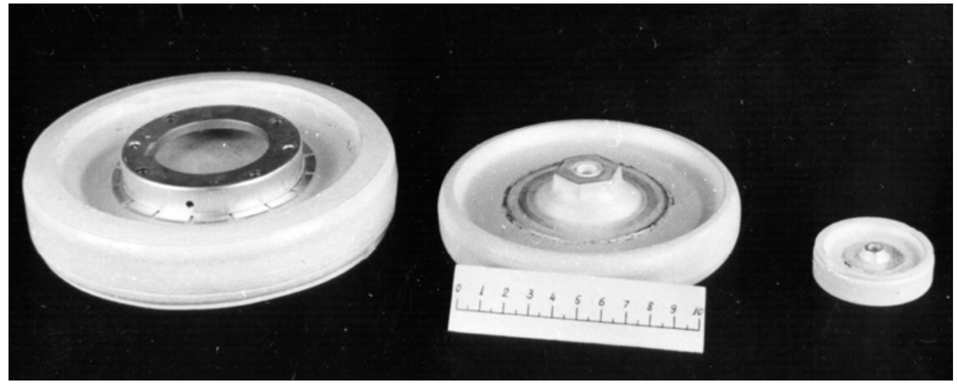
(Pulse dose is 100 Gr at the distance 1m)

Acc gradient is 10 kV/cm

Used links: http://en.vniief.ru/

Sicond©: A Potential Cell Filler





Tungsten-Bronze Crystal in glass (Sicond)
Magnification: 10,000
The typical crystal sizes is ~ 100-200 nm
(almost Nanotechnology in the middle of 70's !!!)
The crystals are surrounded by a good dielectric (glass)

The range of energy density of these capacitors is 27-60 kJ/cubic meter (up to 60 mJ/cm^3 for the DC mode operation !)

See the English presentation of Sicond© dielectric and capacitors here:

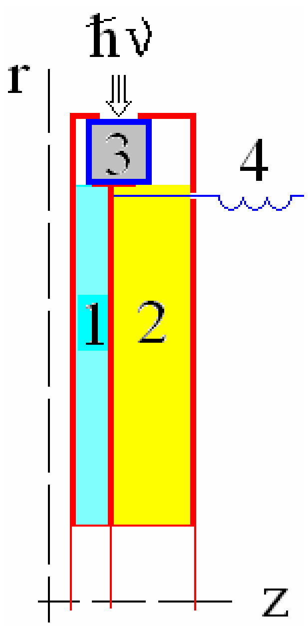
High dielectric constant materials for pulsed energy storage capacitors
Koontz, R.; Blokhina, G.; Gold, S.; Krasnykh, A.;
Electrical Insulation and Dielectric Phenomena, 1998. Annual Report. Conference on
Volume 1 , 25-28 Oct. 1998 Page(s):23 - 26 vol. 1

Our Results of Early R&D for a Solid State Coreless HG Induction Linac

In 1980's it was proposed and studied:

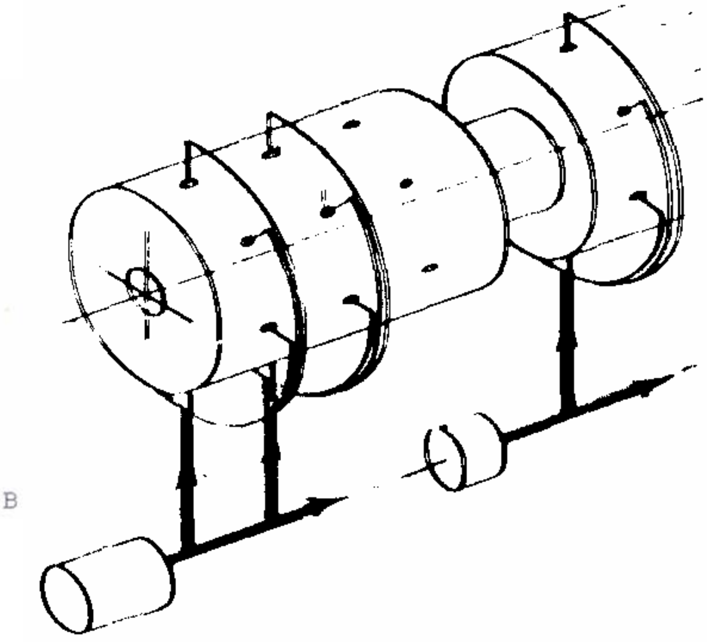
- HG solid state induction linac concepts
- A coreless induction cell with solid state dielectrics and open IR ends (DWA)
- Solid state switch driven by the pulse photon flux in HG induction cell
- HG cell with a ferromagnetic switch
- A Solid State Switch based on DSRD Mode for HG Linac Concept (NLC-like, but without rf-system)

Results of Pioneering R&D for the Solid State Coreless HG Induction Linac (cont.)



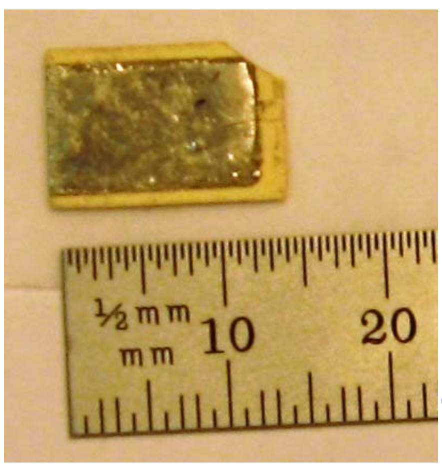
10 nsec Sicond© stripline

(Slide-rule is for a scaling)



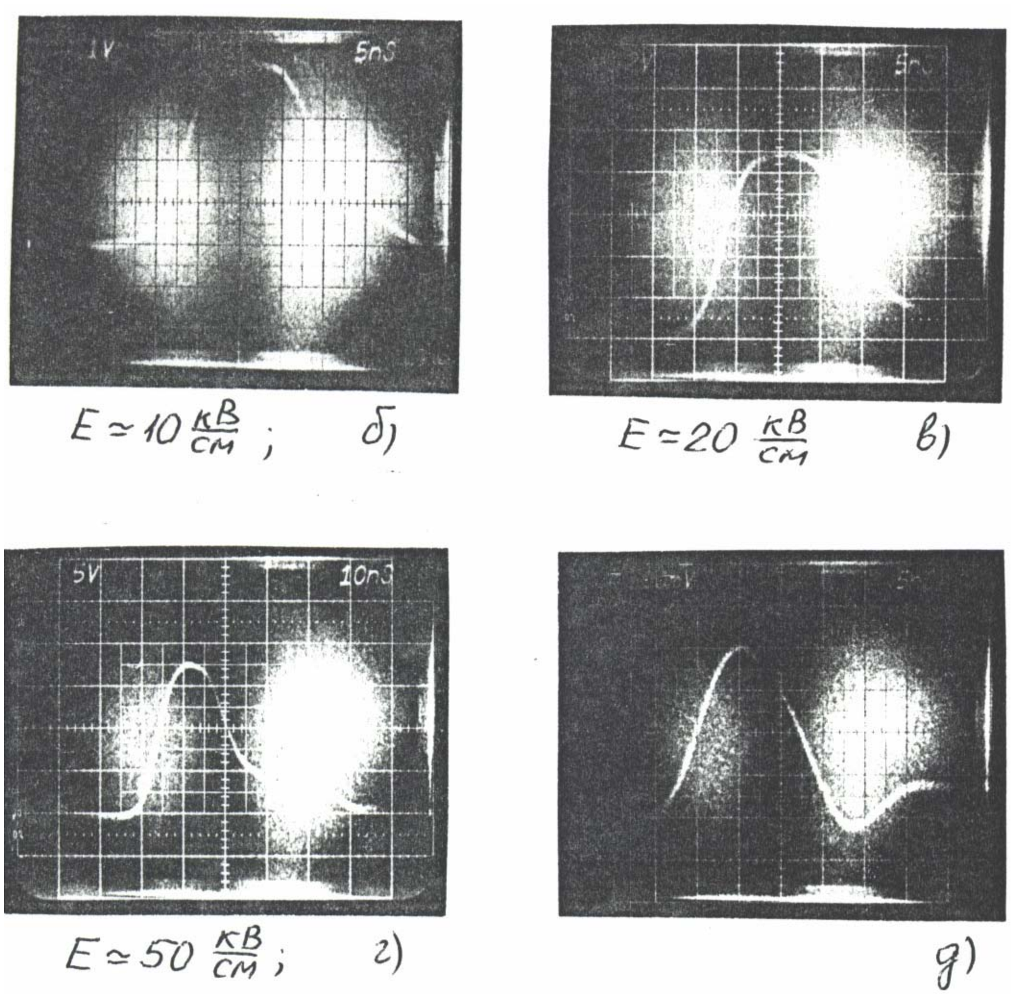
Solid State ON Switch driven by Pulse Photon Flux in HG Concept

The cell thickness is ~1.6 mm.



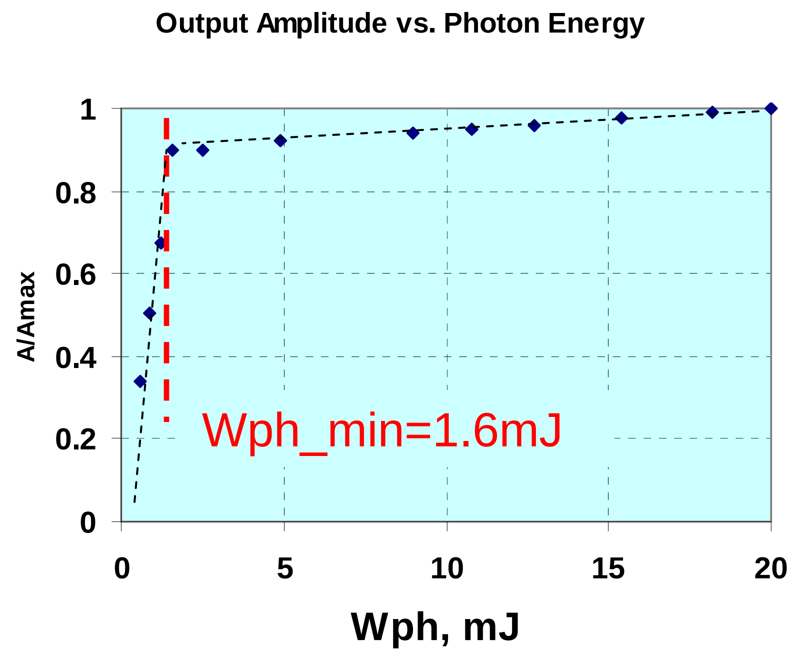
Cells with a tiny section length are a prototype for the SLIM©

Results of Early R&D for the Solid State Coreless HG Induction Linac (cont.)



Cell Impedance is ~ 2.5 Ohm
R_load ~ 3 Ohm

Nd:YAG 1064nm Laser,
Wph=20 mJ, t_p=10 nsec



5 MeV/m was shown, **see Proc. on Collective Methods of Acceleration, Dubna, 1982**

What would be the major parameters for the induction concept based on 80's results?

Parameters of p+ Driver

W=6 GeV, Ib=2kA, tp=3nsec, Rep Rate=60 PPS

Induction System & Silicon Switch

Vcell=10kV, Ccell=600pF, Ncell=600,000, Wind=36kJ

Gradient= 5MeV/m (if a charging supply is used in the DC mode)

Length=1.2 km, Vol_diel=0.9m^3 (Mass ~ 2.5 T, i.e. 5,400lb), ~1.1M$

Asw=4 m^2 (~10 kg), jsw=30 kA/cm^2, dVsw/Vcell=0.1

Laser System (based on Nd:YAG pulsed laser)

Wph=150J (photon-to-carrier efficiency ~0.1),

wph=0.2J (typical parameter), N_ampl ~ 700

This system is expensive and it is not efficient

An Induction Cell with a Ferromagnetic Switch

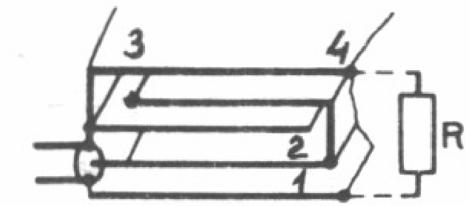


Рис.5

5nsec/div

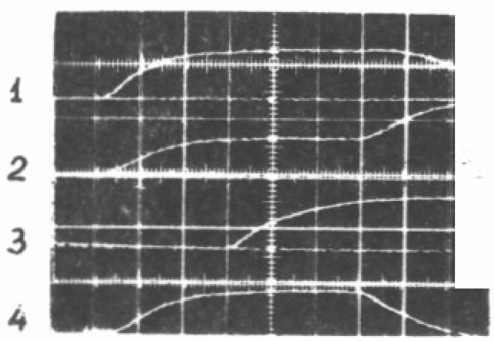
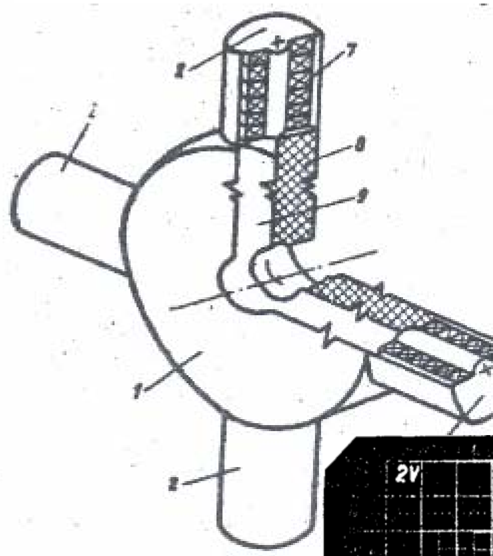
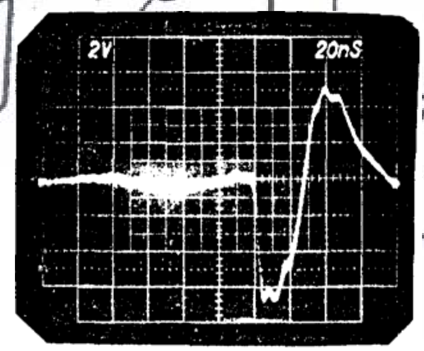
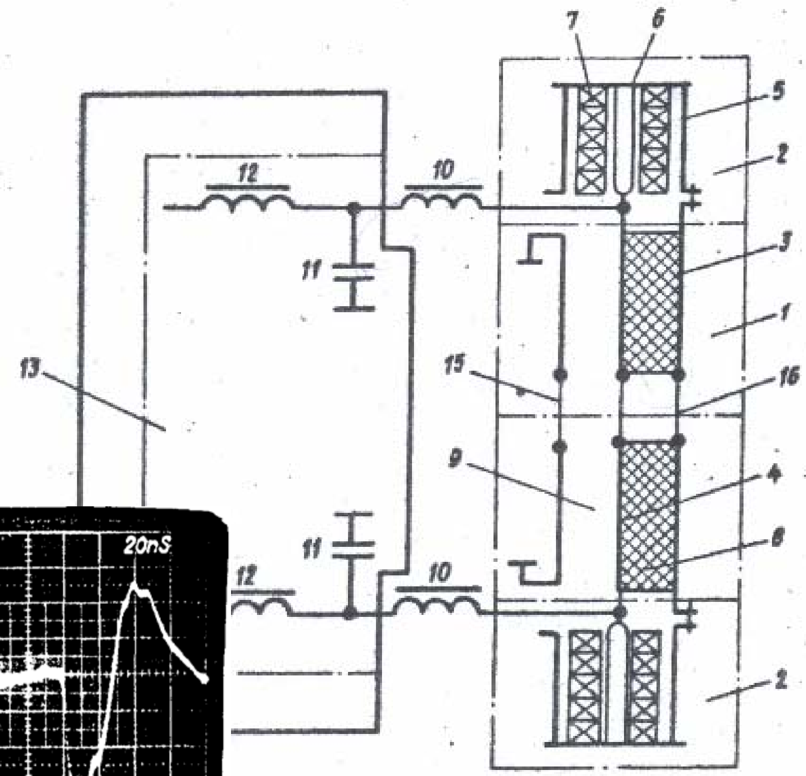


Рис.6



Фиг.1





Фиг.2

See:

- **Proc. on Collective Methods of Acceleration, Dubna, 1982**
- **SU patent #1263189, H 05h 9/00, filed January 1985**

The rebirth of DW cell was in USA by B. Carder in 1997, patent # 5,757,146

see also G. Caporaso application US2007/0145916 filed Oct. 24, 2006

Ferromagnetic as a Switch

Analyze of Physical Limitations

$$t_{sw} \approx \frac{1}{I_{ferr}}$$

• Switch needs a high current. More current will be produced by a higher voltage

• High electric fields may produce the ionization in ferromagnetic media. Plasma formation and breakdown are a killer of shock wave formation and a switch performance

• E_ferrite ~ 10 kV/cm, (for long life time: E ~ 5 kV/cm is acting electric field) → gives the rise/fall times ~1 nsec

• A ferromagnetic switch is better than the switch based on a laser system. However the concept involves magnetic compression stages. The compression rate decreases vs. pulse width reduction (see JINR preprint P9-83-193, 1983)

An Induction Cell driven by the DSRD-principle

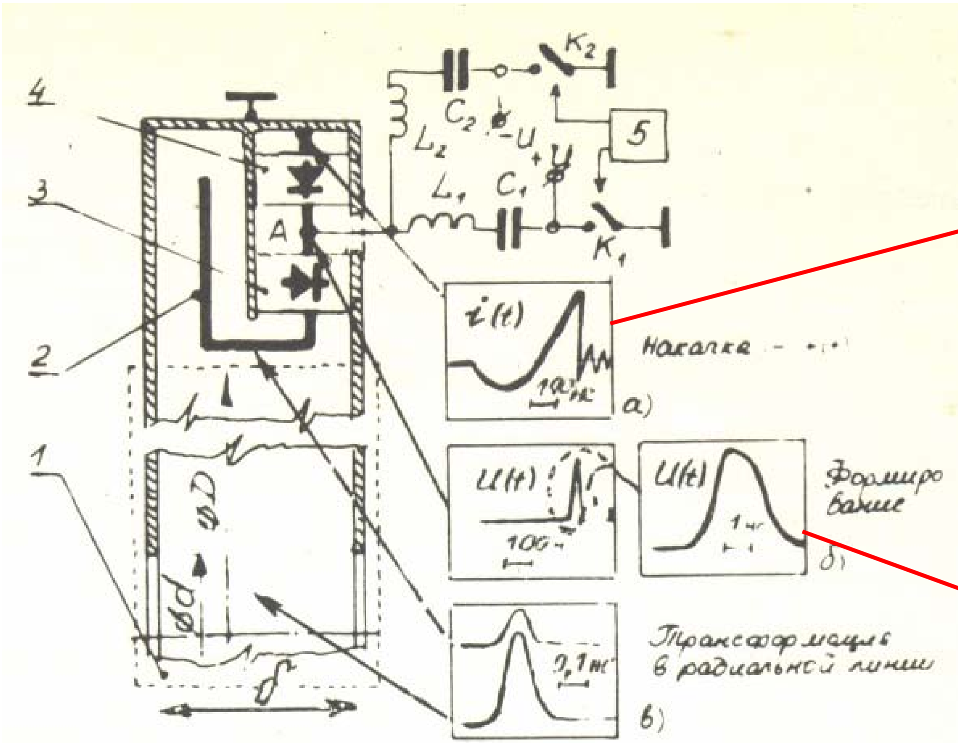


Рис.I.

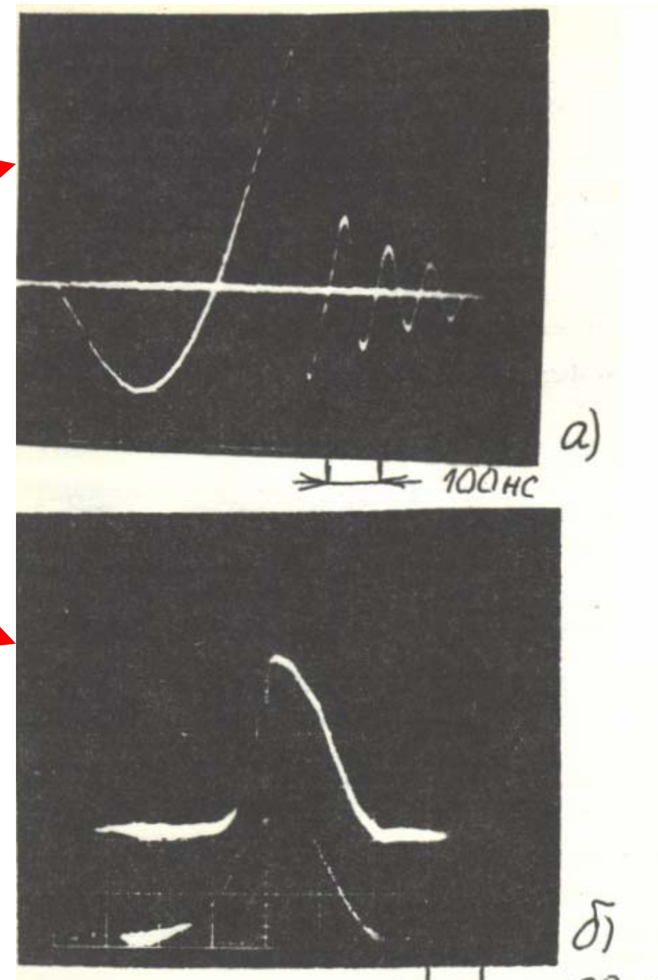


Рис.2.

Pulse transformation in the radial line that
is imposed in the inductor

see 11nd All Union Conference on Charged Particle Accelerators, Dubna, 1988

Plasma Opening Switch Mode as a Prototype Mode for the DSRD-Principle

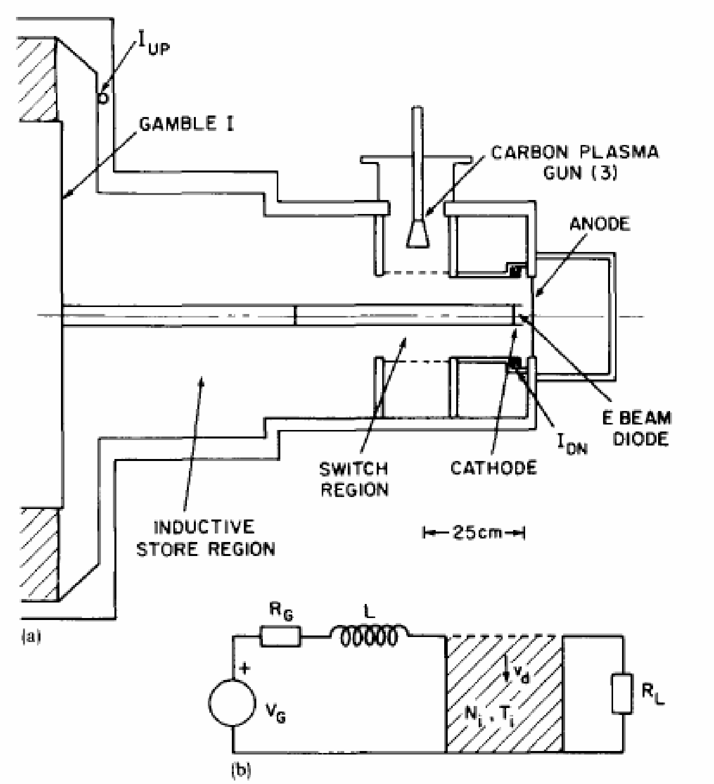


FIG. 1. (a) Schematic of the Gamble I plasma opening switch experiment (b) Circuit diagram of the experiment. V_{oc} is the open circuit voltage wave form, R_G the 2-Ω accelerator impedance, L_S the inductor, and R_L the loac impedance.

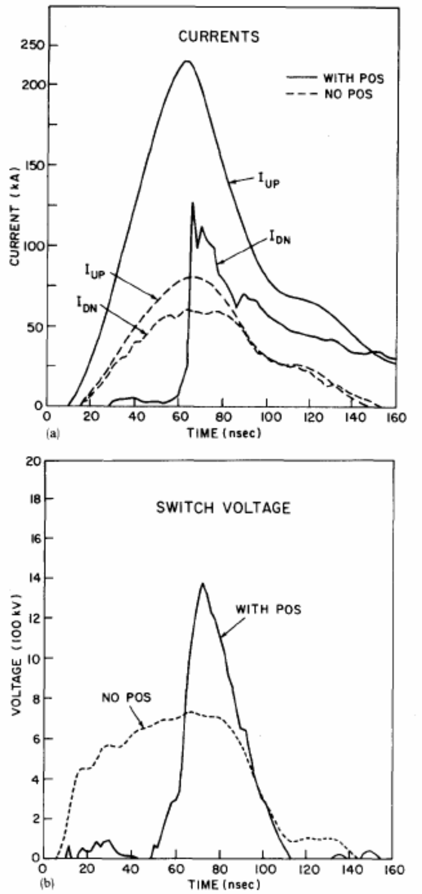


FIG. 2. (a) Currents upstream I_{UP} and downstream I_{DN} of the switch region, with and without the plasma opening switch. (b) Voltages across the switch for the two cases.

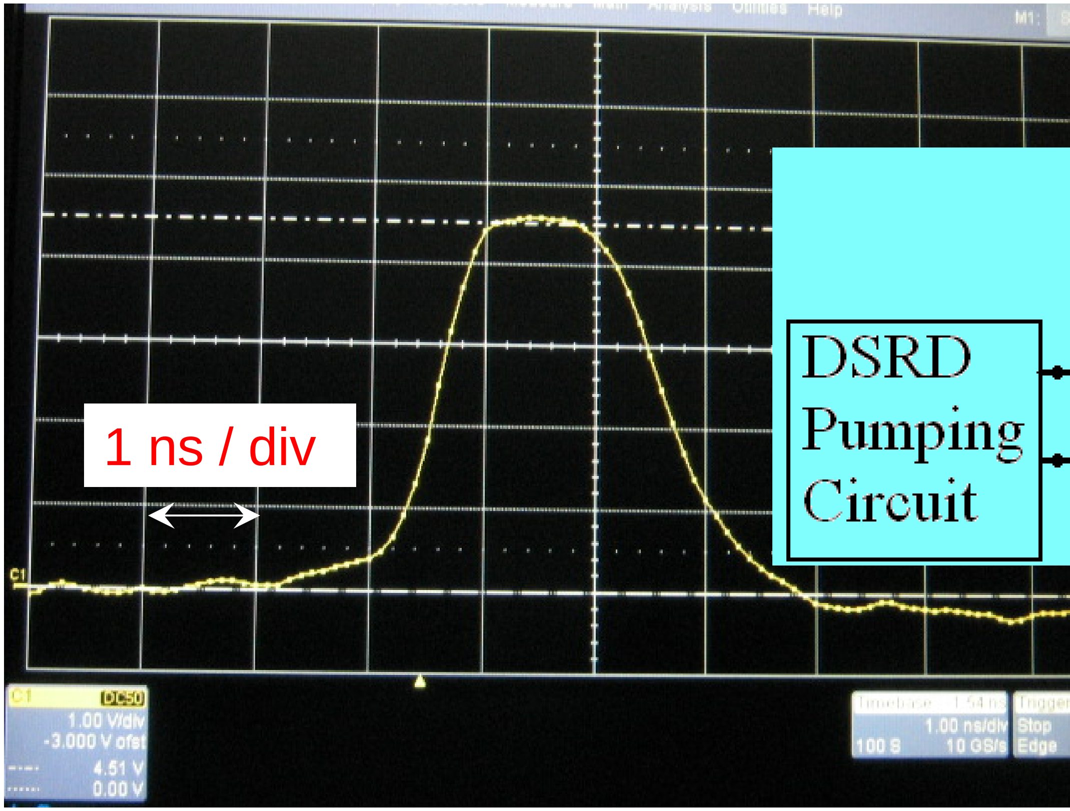
The similar effects may take place in solid state semiconductors

Drift Step Recovery Device (DSRD)

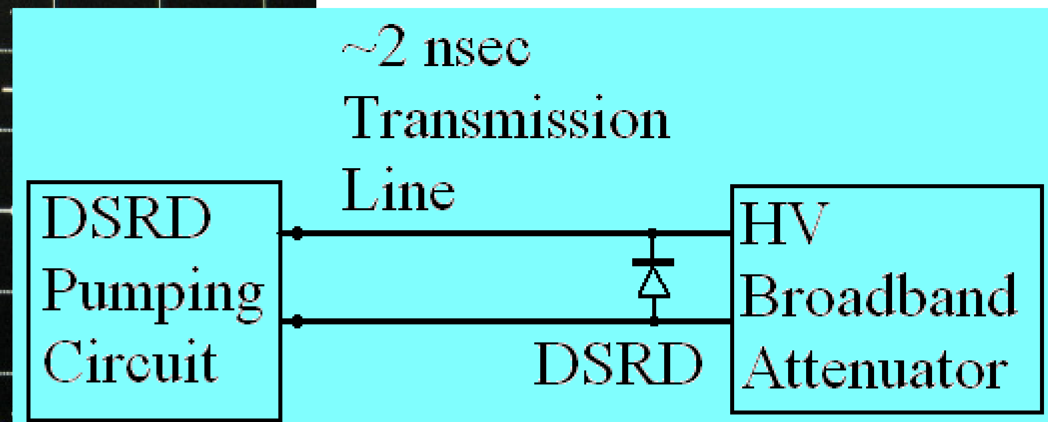
A. Kardo-Sysoev et. all (in 80’s)

Courtesy from P. Miller, Phys. Rev Letters, v. 35, 1975

Performance of DSRD at Matched Load



Simplified Diagram for the DSRD Test at SLAC



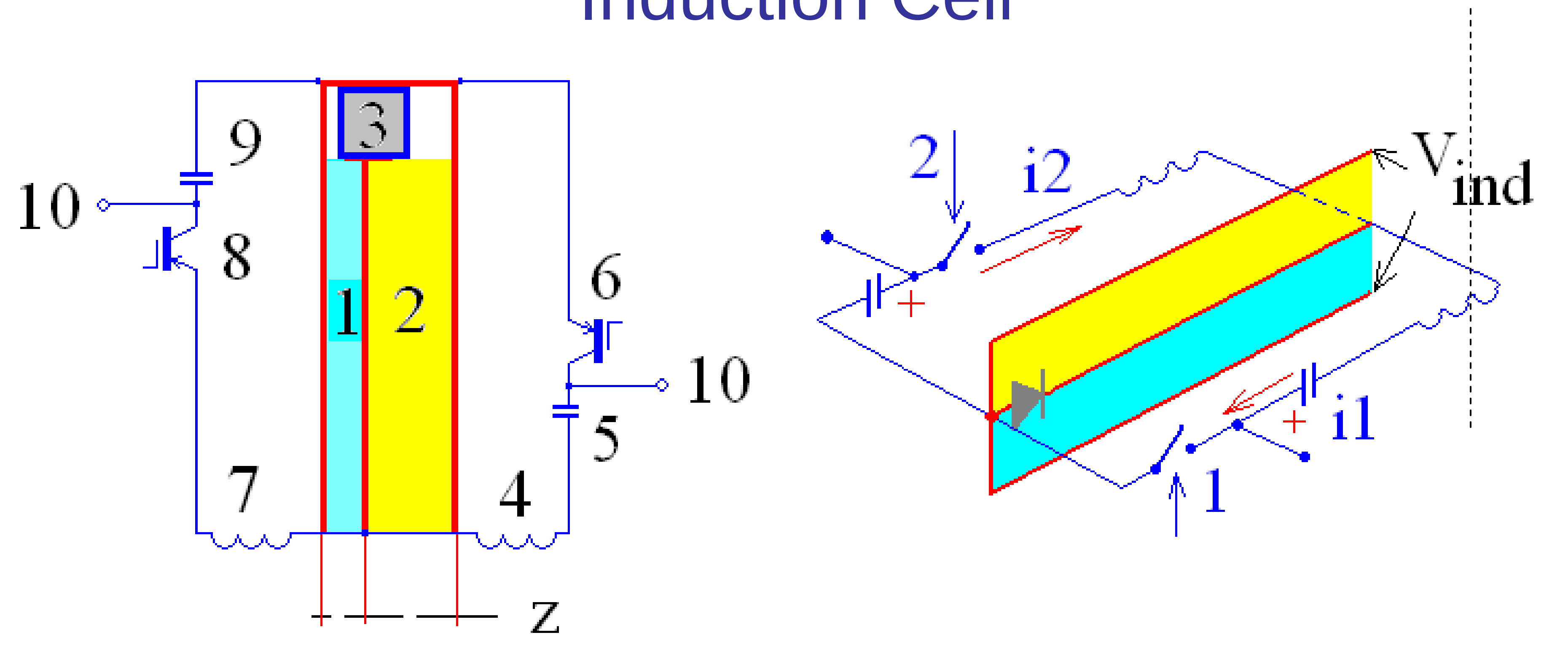
A_out = 4.5 x 600 = 2,700 V

(LeCroy oscilloscope @ 10GS/sec)

Work was performed in the frame of ILC DR Kicker R&D

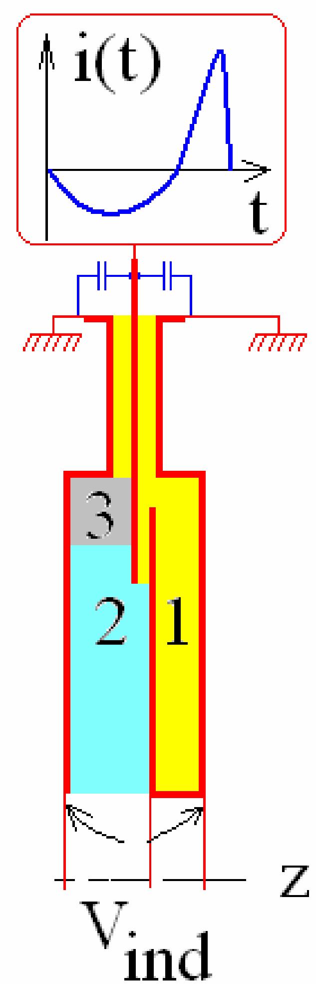
See presentation on ILCDR06 (Sept. 2006, Cornell University)

SLIM©: Feasible Topology for HG Coreless Induction Cell



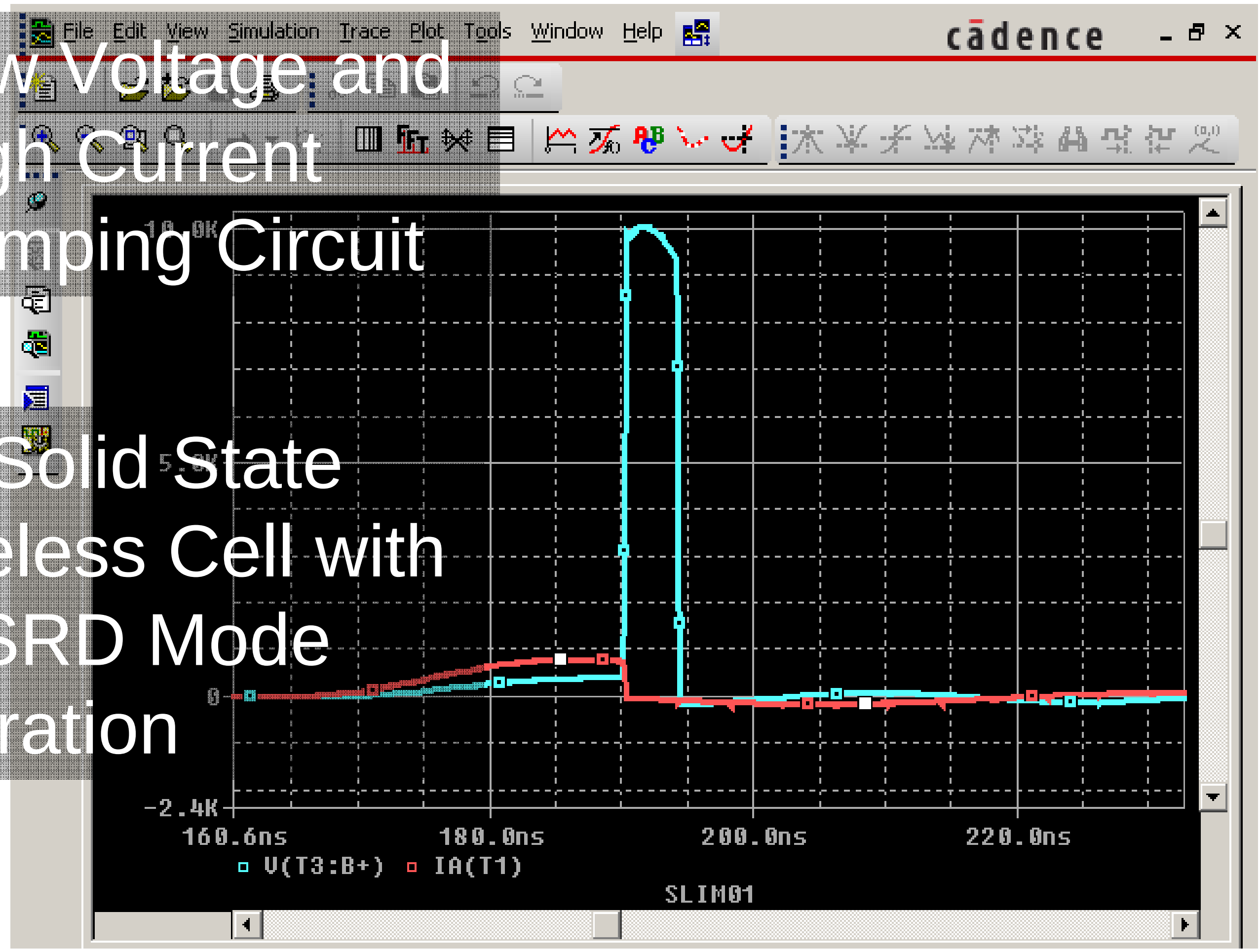
Thin in z direction cell with a DSRD Mode Operation and the open IR ends

SLIM©: Feasible Topology for HG Solid State Coreless Cell



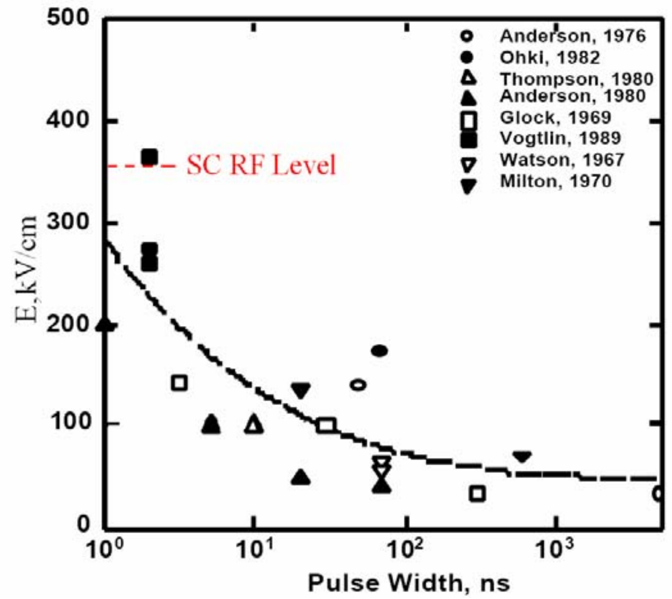
Low Voltage and High Current Pumping Circuit

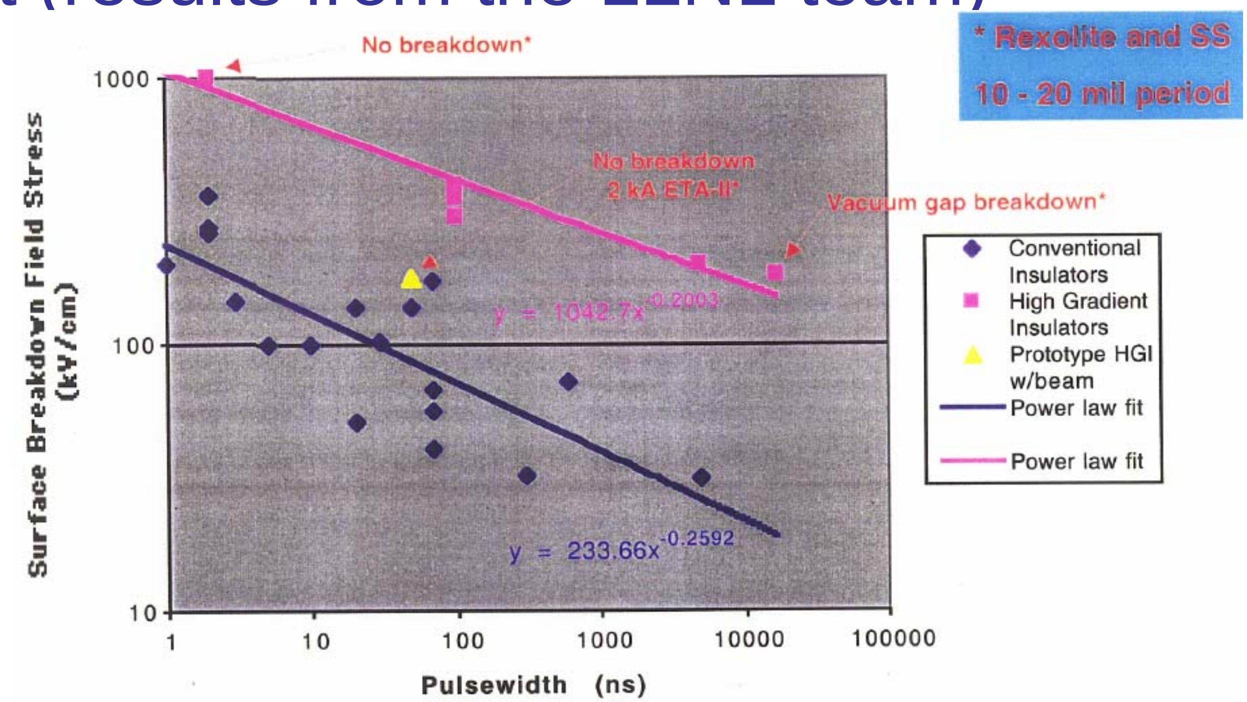
HG Solid State Coreless Cell with a DSRD Mode Operation



A tiny cell with the open and short IR end

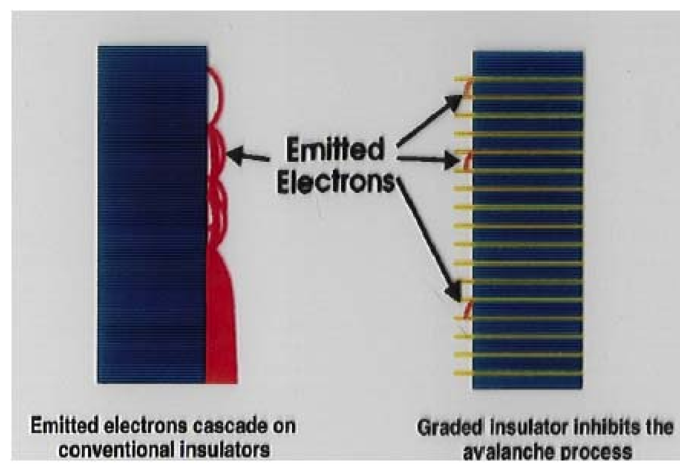
A Progress in the HG Vacuum-to-Media Interface Development (results from the LLNL team)



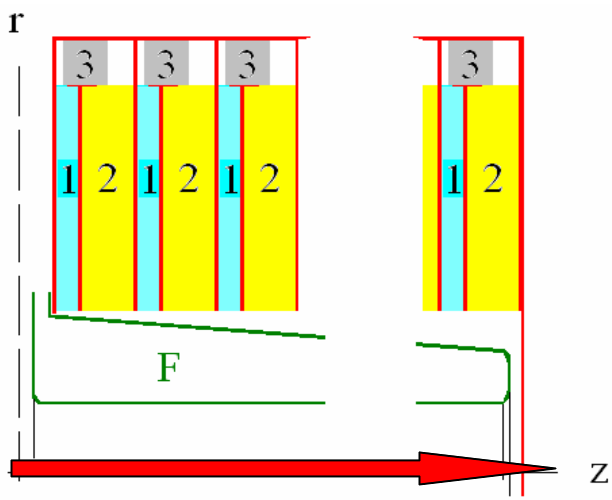


Pulsed surface breakdown electric field as a function of pulse width for single substrate, straight wall insulators

(Compliment to G. Caporaso et. al, **UCRL-JC-127274)**



SLIM©: Feasible Topology for HG Coreless Induction Module



Induction system is not conflict with the SC Foc. System

The induction system is a storage energy element

The storage energy is practically delivered to the beam during interval of several nsec, i.e. the concept has high efficiency

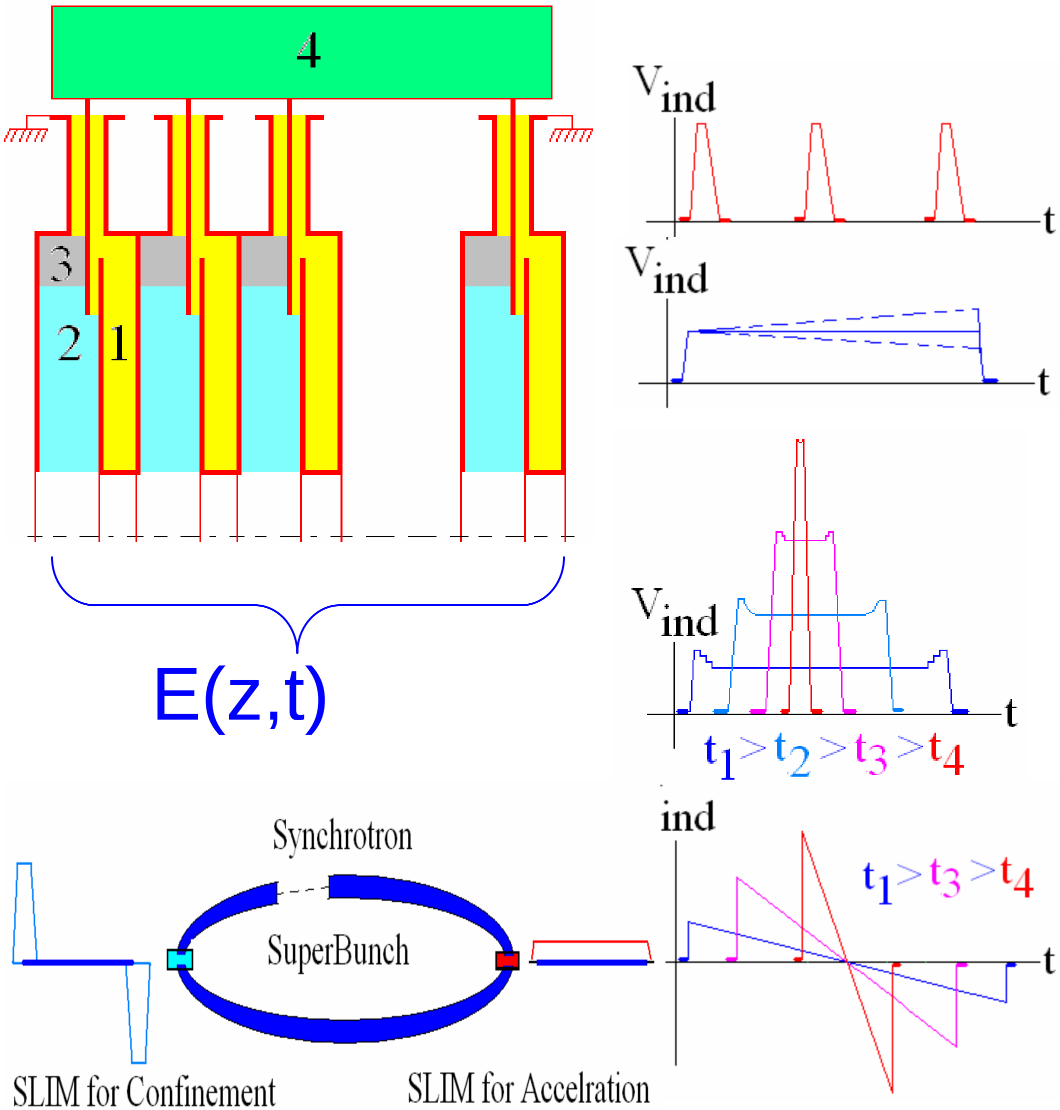
The nsec mode operation may run with a high gradient that is comparable with the rf-linac gradient (~30 MeV/m@ 5 nsec FWHM)

DSRD solid state switches are controlled precisely (jitter ~30 psec) by the electrical trigger

High rep. rate (up to several MHz) is possible

The full size proposed SLIM© did not implement. The first Western DSRD samples will be available from VMI (Visalia, CA) in the beginning of 2008.

Some Important Features for the SLIM©



HG Mode Operation with High Rep. Rate (synchronization all DSRDs as one switch)

Possible Fast Control of the Spatial E(z,t) Distribution along Induction System

Acc. Structure with Q=1 (Broadband Impedance) and Alternating Gradient in the MHz range is feasible

Evaluation of the major parameters for p+ driver based on the SLIM© concept?

Parameters of p+ Driver

W=6 GeV, Ib=2kA, tp=3nsec, Rep Rate=60 PPS

Induction System & Silicon Switch (as it shown before)

Vcell=10kV, Ccell=600pF, Ncell=600,000, Wind=36kJ

Gradient= 20-30MeV/m is feasible

Length= 200-300m, Vol_diel=0.9m^3 (Mass ~ 2.5 T, i.e. 5,400lb), ~1.1M$

Asw=4 m^2 (~10 kg), jsw=30 kA/cm^2, dVsw/Vcell=0.1

Other Programs Based on Induction Linac Topology

Summary of applications for induction accelerators

Application/ Architechture	Voltage	Beam Current	Pulse length	Rep. rate	Issues/comments
Hadron collider/ p^+ ind. synchrotron	31 TeV; 3 MeV/turn	25 A	500 ns	100 kHz CW	feasibility study going on; require upgrade of most existing detector components for higher L. competitor: low harmonic rf
RK Two Beam Acc for Linear Colliders/e^- ind. linac	10 MeV, 0.3 MeV/m	1 kA	50 - 200 ns	180 Hz	fundamental aspect has been demonstrated; no current funding
Neutrino factory;μ-collider / μ –ind. linac	200 MeV 2 MeV/m		100 ns	4 pulse @ 3 MHz; 15 Hz avg.	feasibility study going on; competition with low freq rf device; can survive rad. env.;
Heavy Ion Fusion/ HI^+ ind. linac	4 GeV 1.5 MeV/m	0.2 - 10 kA	20 μs - 10 ns	~6 Hz	Significant program ongoing

Summary of applications for induction accel's-cont'd

Application/ Architechture	Voltage	Beam Current	Pulse length	Rep. rate	Issues/comments
Spallation n-source/ p^+ ind. linac	1 GeV	60 - 100 A	1600 - 160 ns	50 Hz	Will be easier to sell if induction technology more widespread
Radiography/ e^- ind. linac	18.4 MeV	2-4 kA	~50 ns	~2 MHz bursts of 4 pulses	DARHT-II built and undergoing testing. Ion-hose, beam-target interactions AHF to use protons/synch.
Sub-critical reactor/ ind. FFAG; H- driver for spallation n-source; Accel. Trans. Waste (H- ind. FFAG)	~ 1 GeV 1-3 GeV	30 mA 10 mA (avg)	~few 100 ns	1 kHz CW	May combine rf + ind.(Ind barrier only); cost/MW beam power is low rel. to rf linac; early design, at idea stage
Driver for Microwave source FEL's, BWO	~few MeV	~kA	~few 100 ns	~kHz	Very attractive match

See, for example
http://nonneutral.pppl.gov/HIF04/US-Japan/02.Barnard.pdf

i.e.
- fusion field,
- synchrotron with induction cell (superbunch, barrier bucket, Fixed-Field Alternating-Gradient)
- high-gradient accelerator (TBA-like)
- spallation neutron and neutrino factory projects
- induction-linac-driven free electron lasers, relativistic rf-sources
- etc.

The SLIM© can be well suited for these programs!

Conclusion

An induction linac cell for a high gradient is discussed. The proposed solid state coreless approach for the induction linac topology (SLIM©) is based on nanosecond mode operation. This mode may have an accelerating gradient comparable with gradients of rf- accelerator structures. The discussed induction system has the high electric efficiency. The key elements are a solid state semiconductor switch and a high electric density dielectric with a thin section length. The energy in the induction system is storied in the magnetic field. The nanosecond current break-up produces the high voltage. The induced voltage is used for acceleration. This manner of an operation allows the use of low voltage elements in the booster part and achieves a high accelerating gradient. The proposed topology was tested in proof of principle experiments.

Acknowledgements

I would like to thank

- DoE as a sponsor
- A. Kardo-Sysoev (Ioffe PTI of RAS)
- Ron Akre and Glenn Scheitrum (SLAC)
- Yuri Alexahin (FNAL)
- You for your attention