

Oxford, Space Charge 2026, Sept. 29 – Oct. 26

A Historical View on Research in Space Charge for Particle Accelerators

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- **MURA** (Midwestern Universities Research Association) – **an early cradle of accelerator physics *)**
- **Political circumstances** 1950s /1960s
- **HIF** (Heavy Ion Inertial Fusion) driven by ion linear accelerators from 1975 – 98 / **exploring limits by coherent space charge instabilities.**
- From 2000 onwards **High Intensity Linacs** like **SNS/US, J-PARC/Japan, ESS/EU, CSNS/China, ADS /China** and others are dealing with „**real world**“ linac space charge challenges

Acknowledgments:

**) Francis Cole „Oh Camelot!“ (MURA)*

Images: Lawrence Jones (U Michigan)

The 1940's – a beginning

- In 1941 Donald Kerst (University of Illinois) started **first discussion of space-charge effects** in accelerators + **detuning** of transverse oscillations (*Phys. Rev.*)
- He also built a **betatron** (*Nature*, 1946)
- In 1949 Greek engineer **Nicholas Christofilos** patented “**alternating gradient (strong) focusing**” – at first ignored
- In 1953 meeting (BNL) about the “newly” **re-invented** “Strong Focusing” from 1952 **Courant and Snyder paper** (Courant afterwards published “credit”)



Donald Kerst (1989)



Nicholas Christofilos

The MURA era

An accelerator think tank - born from US-rivalries in 1950's

- **Big lab competition** – Fermilab (Tevatron), Argonne (ZGS), Brookhaven (AGS) and Berkeley (Bevatron)
- A „brain drain“ fear in the US-**Midwest / Chicago area: 1953** number of physicists met -> **MURA** was born
- lasted “only” **10 years**

MURA alumni in 1989:

L-R back: Don Swenson, E. Rowe, D. Young, **Keith Symon**, H.R. Crane, C. Pruett, and **Francis Cole**;

L-R front: **Fred Mills**, **Andy Sessler**, L. Jones, **Earnest Courant**, **Donald Kerst**, and W. Wallenmeyer.



The Michigan study group

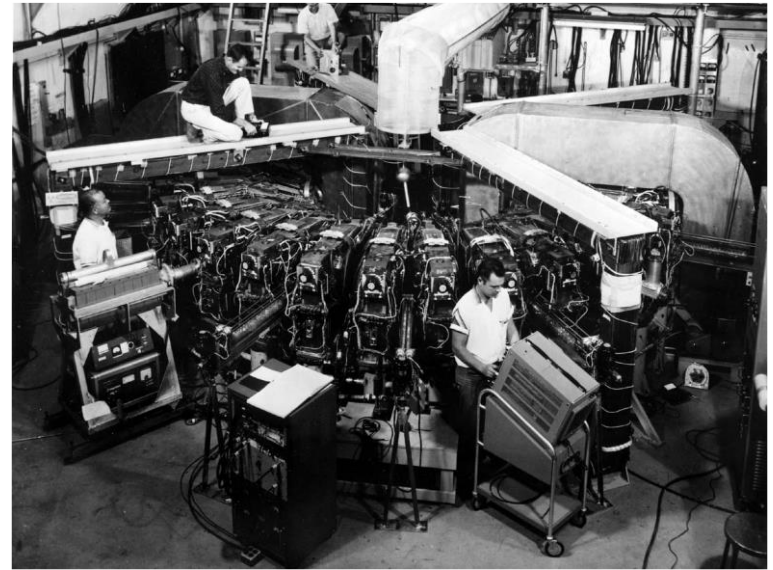
Initiated in 1954



Michigan study group; **L. Jackson Laslett**, Dick Crane, **Donald Kerst**, Kent Terwilliger, Keith Symon, & Larry (Lawrence Jones)

Some highlights

- Several smaller **electron FFA(G)s** were built – and great hopes established. In 1960 a **50 MeV electron FFA** was built in Madison for **space charge studies** & rf issues etc.
- **1956: Storage ring** invention by D. Lichtenberg et al. from MURA group – advantages over FFA:
 - have long straights for detectors
 - dc magnets less complex/cheaper
- **1959: Negative mass instability** discovered + Landau damping by C. Nielsen, A. Sessler & K. Symon



Madison: FFA 50 MeV electrons

Prominent visitors to MURA



1958 visit to MURA lab; L-R: Bob Haxby, Ragner Rollefson, Harrison Randall, **Subramanyan Chandrasekhar**, **Niels Bohr**, Charles Pruett, and Larry Jones 6

The Sputnik Crisis

a political & cultural shock of the 1957

- **October 4, 1957:** The Soviet Sputnik 1, the world's first artificial satellite
- Triggered the Cold War **Space Race** between **superpowers** in research – also accelerators – to catch up (Linacs, cyclotrons and synchrotrons already existed)
- AEC wanted a **12 GeV p accelerator** very quickly at Argonne to compete with a Soviet **10-GeV p accelerator at Dubna**
- **Competition** put pressure on **US** and **MURA**

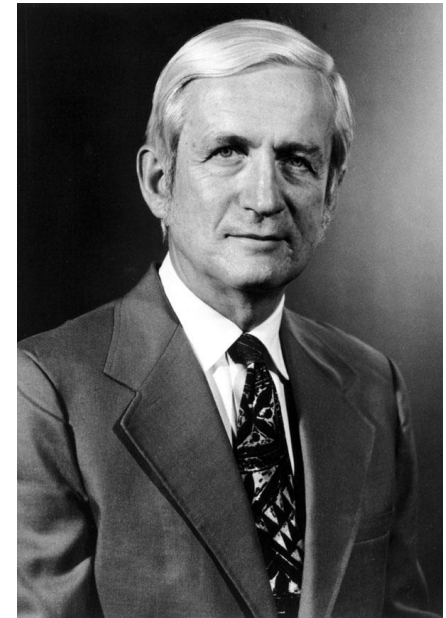


Further politics: The Ramsey Panel

The beginning of the „end“ of MURA and its big FFAG plans

- 1962, Ramsey Panel: Supported the **Berkeley 200 GeV proposal as 1st priority** + later a 1000 GeV for BNL - and supported a high intensity **MURA 12.5 GeV FFAG** only as 2nd priority.
- The MURA university presidents: **political effort to try to save MURA** - visited **President Johnson** in the White House in 1964.
- Considerable **criticism of MURA** by Berkeley & BNL of political action to **introduce politics into physics**.
- **Mura was over**

Not really: **Revival much later on** (see, for example, *“Scaling FFAG Accelerators ...”*, Shinji Machida, *Phys. Rev. Lett.* 119, 2017)



Norman Ramsey, Nobel Laureate of 1989

A glimpse on Laslett's further work in this period

- On **Space Charge**: In 1963, detailed calculation of space-charge effects & presence of conducting walls and dc magnets. The name "**Laslett tune shifts**" appeared
- On "**chaos**" (1957): The Runge-Kutta method in use for orbit studies didn't conserve phase space exactly → roundoff and truncation errors
- → Symon and Laslett developed a **symplectic algebraic transformation**
- -> In a MURA report of 1957: Laslett demonstrated a real physical basis to chaos

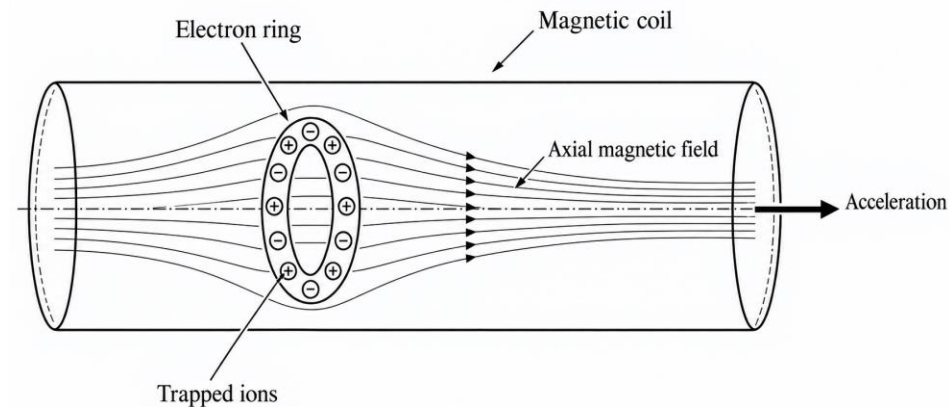
A switch: „Atoms for Peace“ / energy problem a parallel development of relevance

- **1958 in Geneva:** 2nd UN-conference on Peaceful Uses of Atomic Energy **lifted Cold War military secrecy** around thermonuclear fusion. Soviet Lev Artsimovich (**inventor of Tokamak**): most important is “... **the further development of the international cooperation**”
- **1975:** Al Maschke, BNL: **Proton/ion accelerators** a new path to drive inertial fusion – instead of a laser
- Maschke later: „board was immediately wiped off and **meeting declared as “classified”** “



Berkeley group - after 1963

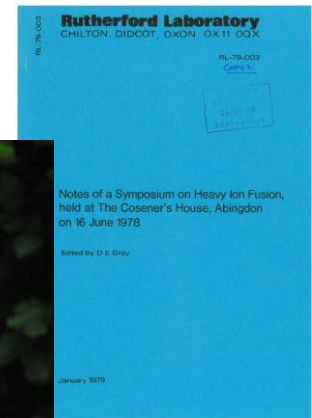
- Several MURA people had gone to LBNL and/or LLNL after 1963
- Worked first on the „**Electron Ring Accelerator**“(ERA) **collective acceleration** (plasma ring) project – a forerunner to **two-beam accelerators**, invented by Academician Veksler / SU
- **LBNL was leading in the West** - against Dubna/SU. Martin Reiser at U Maryland; Germany started an ERA project at **IPP Munich** - my **first job** in accelerator theory!
- Most people gave up after a decade -frustrated by **unexpected resonances and instabilities**
- 1975: after Maschke's proposal the **LBNL group switched to HIF**, hoping for more political support



International Meeting: Heavy Ion Fusion“ HIF

Sparks jumped over to many Labs

- 1976: LBNL organized **1st HIF workshop at Claremont/Berkeley**
- **wide participation** from many US-labs & universities as well as from Canada, CERN, GSI, RAL, Saclay, Japan ...
- In summer 1978 **John Lawson** (**1957: Lawson criterion** for fusion burn) in a meeting at **Cosener's House, Abingdon**: „Problems in HIF“ (RAL-report)

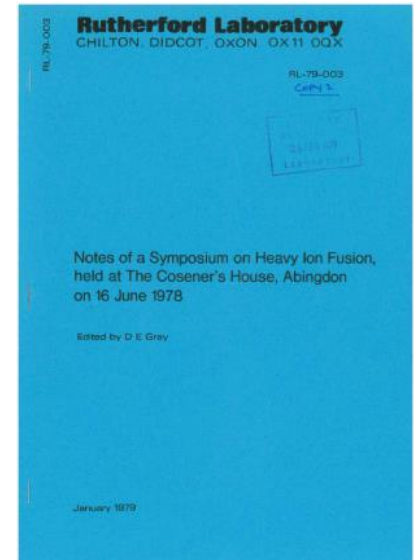


John Lawson

David Gray, RAL, in 1978: “This symposium on heavy ion fusion was held to **inform the relevant university departments** and other interested organisations of the developments and prospects in this field, and to encourage them to take up problems relevant to their own research fields.”

John Lawson, 1978: “It is now possible to see the broad outline of a concept involving heavy ion accelerators, target, reactive vessel and steam plant ... to identify problems which it would be profitable to study in the UK at the present time ...”

He listed many issues, from **charge exchange of the ions** in storage rings to transport problems in the **reactor chamber** etc.



Berkeley group HIF project

- → Single bunch **induction linear accelerator** – to handle extreme transverse space charge tune depression - Fusion required: highest intensity **and** brilliance of beam – accelerator seemed **superior** to laser (that time)
- Laslett and others were uncertain about **beam instabilities** at such high space charge level
- My chance: in 1977/78 got invited to take part in their analytical theory - **using Vlasov's equation** (my PHD background); hardly used in accelerator work – different from **plasma physics**
 - **practically no PIC codes** in accelerator community

Initially: it was „all theory only“ 0

Solving linearized Vlasov's equation (collisionless Liouville equation) in 2d for a round beam in a periodic lattice **was new!**

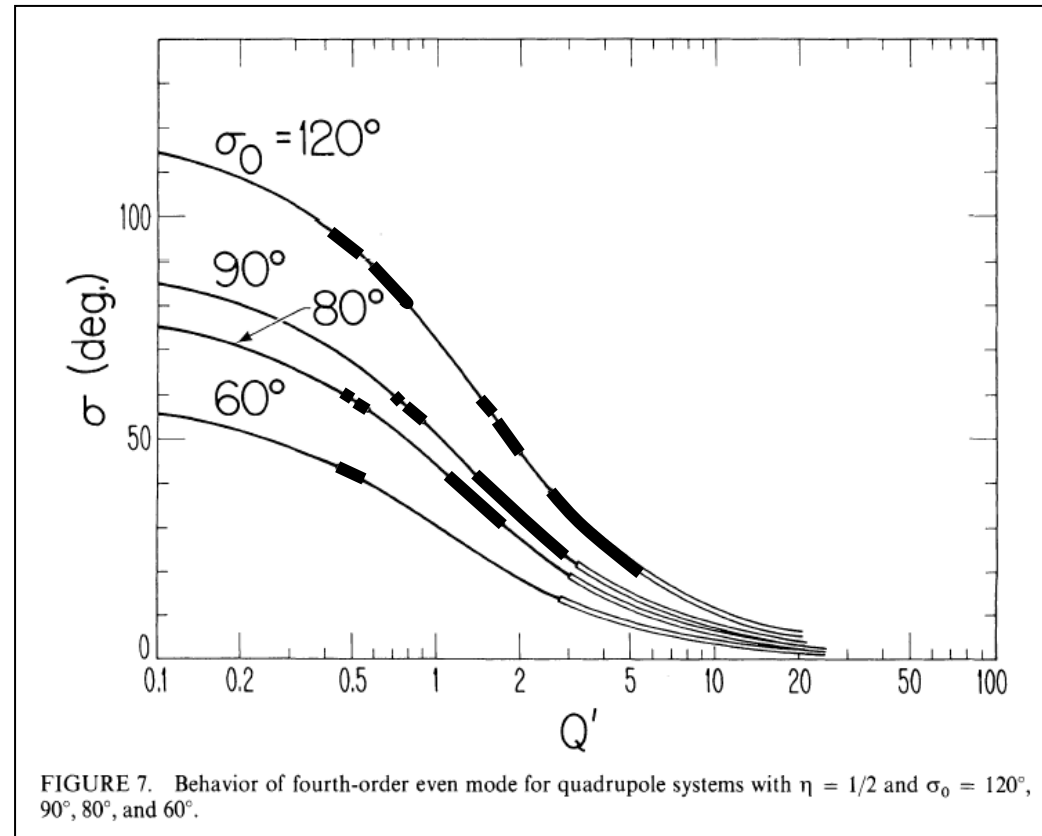
$$(f = f_0 + \mathbf{f}_1)$$


$$\begin{aligned} \frac{Df_1}{Ds} &\equiv \left\{ \frac{\partial}{\partial s} + \frac{1}{\beta_x} \left[p_x \frac{\partial}{\partial x} - x \frac{\partial}{\partial p_x} \right] + \frac{1}{\beta_y} \left[p_y \frac{\partial}{\partial y} - y \frac{\partial}{\partial p_y} \right] \right\} f_1 \\ &= \frac{2N}{\pi^2 \epsilon} \left[p_x \frac{\partial V_0}{\partial x} + p_y \frac{\partial V_0}{\partial y} \right] \cdot \delta' (x^2 + p_x^2 + y^2 + p_y^2 - 1), \end{aligned}$$

Initially: it was „all theory only“

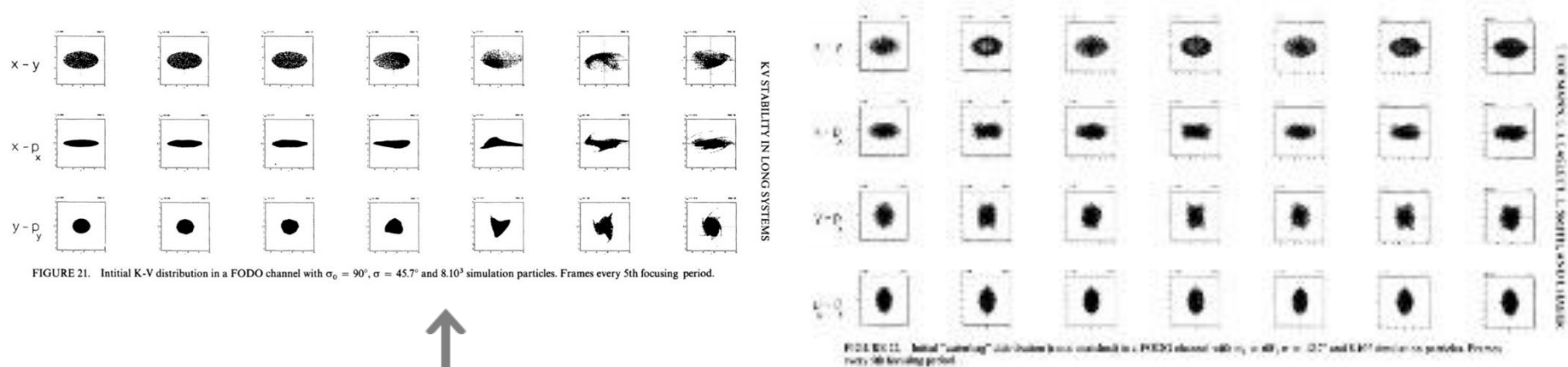


- Found „**Parametric Instabilities**“ in each order
 - growing from noise -
 - example 4th order „octupolar“ mode
 - >
- LBNL **leadership** advised: we cannot publish this pessimistic result - **work harder** and **study non-KV!**



Computer simulation „saved us“

- Our tool was one of the **first accelerator PIC simulations**



The KV beam grew in 4d

- 4d-Waterbag was ok! Absent in Gaussian, („**Landau damping**“) and **we could publish – in 1983!** Monotonically decreasing initial distribution functions provided enough Landau damping

I. Hofmann, L.J. Laslett, L. Smith and I. Haber, Stability of the K-V distribution in long periodic transport systems, Part. Accel. 13, p. 145, 1983

What happened next with HIF?

- Berkeley project **slowly declined** in late 1990's
 - Complexity of design
 - Livermore laser advanced more and more
- **1991 C. Rubbia/CERN**, : Let's go the European way!
- He argued: Accelerator much cheaper, higher rep rate & efficiency & reliability
- HIDIF - **Heavy Ion Driven Inertial Fusion** - was born -> 1995- 98
 - People from 9 countries involved, including labs CERN, GSI, KfK, RAL, ENEA-Frascati, ITEP Moscow, Orsay-France and others
 - Coordinators: Günther Plass/CERN and Ingo Hofmann/GSI

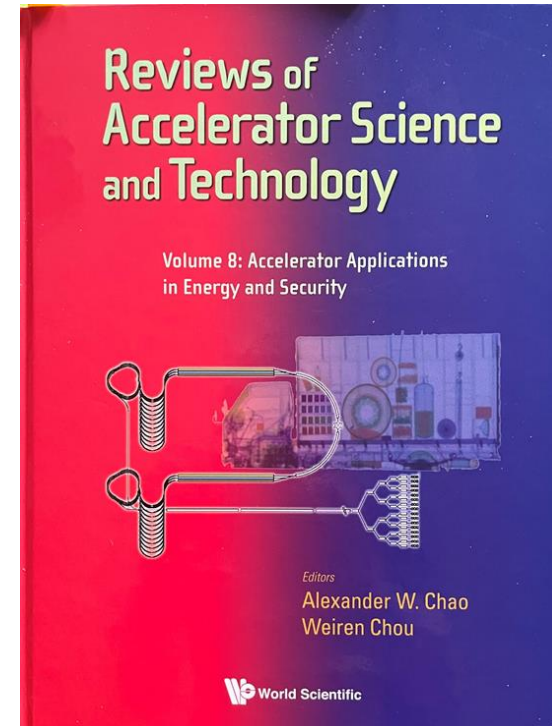
CERN „European initiative“ – began in 1991 and ended in 1998



Carlo Rubbia

Varenna, Italy, 1991, all-European start in HIF

Review of HIF in 2015 volume



Final (internal) conclusion:
cost > 10x higher than Rubbia
believed in beginning -> **end**

HIF served as a kind of **Start-up** preparing for
next generation **high-intensity** projects

High intensity linac and ring projects for p/ion (Spallation Neutron Sources ...

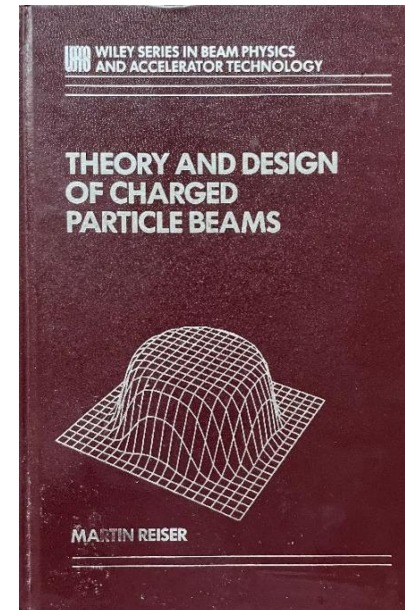
- 1998: Shelter Island Workshop
- 1999: BNL Workshop
- → preparing for SNS in theory and practice
(construction started end of 1999!)

Among them was the „**equipartitioning**“ question in
linacs - defended in **Martin Reiser's book** on beam dynamics

Thermodynamic thinking: intense linac bunches **naturally go into a state of equipartition** - „equal temperatures“ - due to **collisional effects** → energy transfer from **hotter“ direction to „colder“ one.**

But rate was too small!

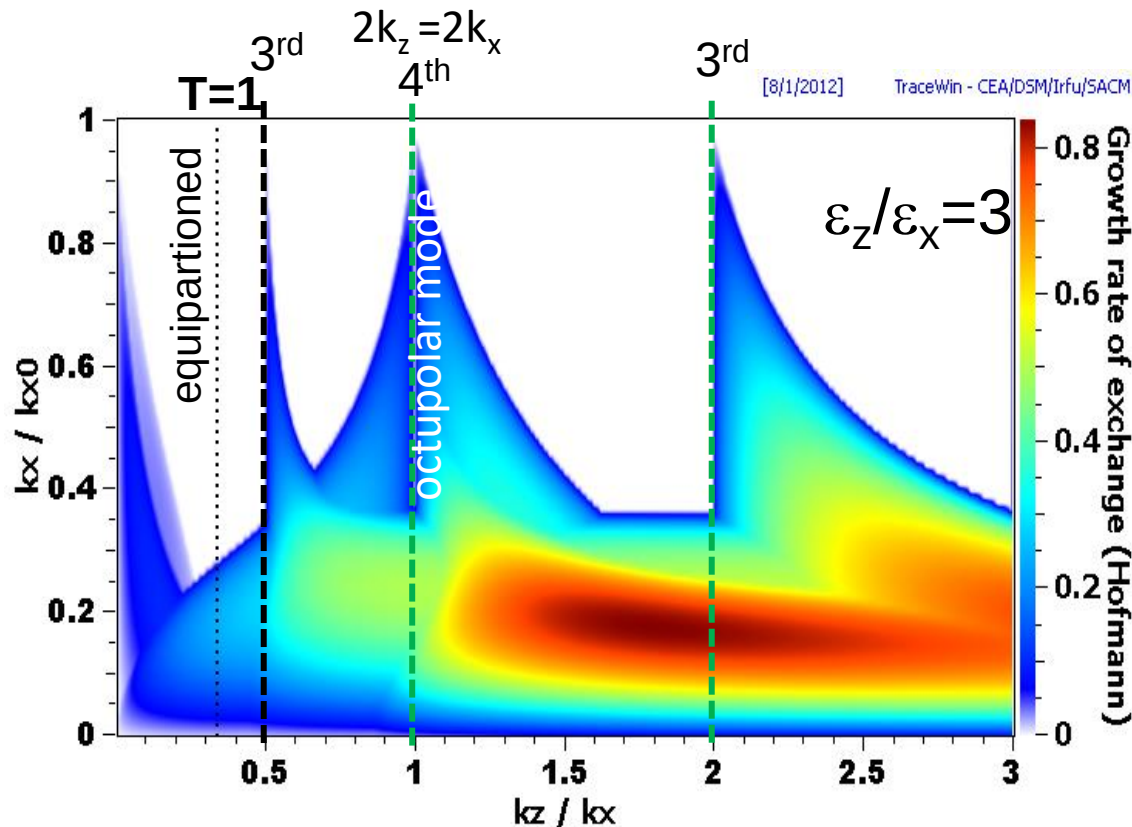
- → **Anisotropy discussion** started: resonant coherent space charge instabilities „only“ explanation for transverse emittance growth



Anisotropy - between x,y and z (linacs) - driven parametric instabilities

Anisotropy parameter $T = E_z / E_x = \varepsilon_z k_z / \varepsilon_x k_x$ with $T=1$ equipartition
„Stability Charts“: calculated **analytically** from **Vlasov equation** - **effort far above our 1983 paper**

I. Hofmann: Stability of anisotropic beams with space charge, Phys. Rev. E 57, 1998

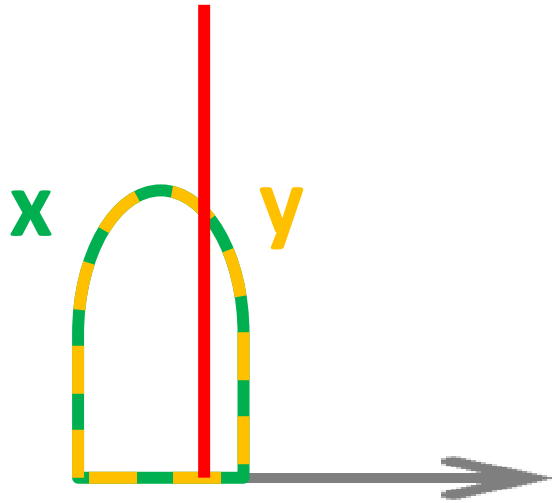


Automatic plots on TRACEWIN (Saclay group) allowed visualizing **coherent mode stopbands** on k_z / k_x plane

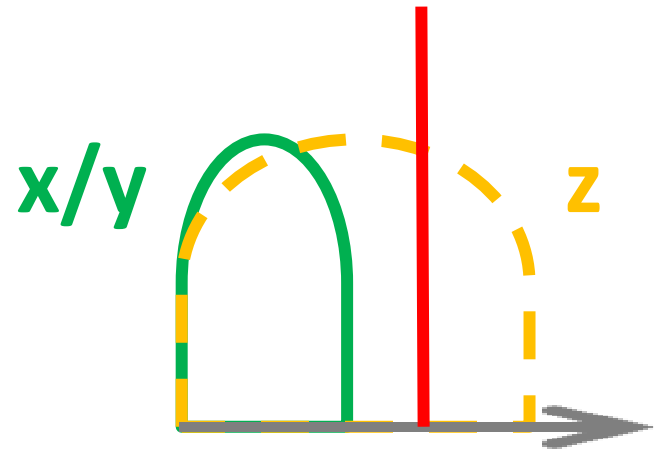
Note: Also **incoherent resonances** driven by **space charge** possible in these bands

Hofmann, Oeftiger, Boine-Frankenheim, PRAB 24(2021)

Landau damping in anisotropic beams



isotropic

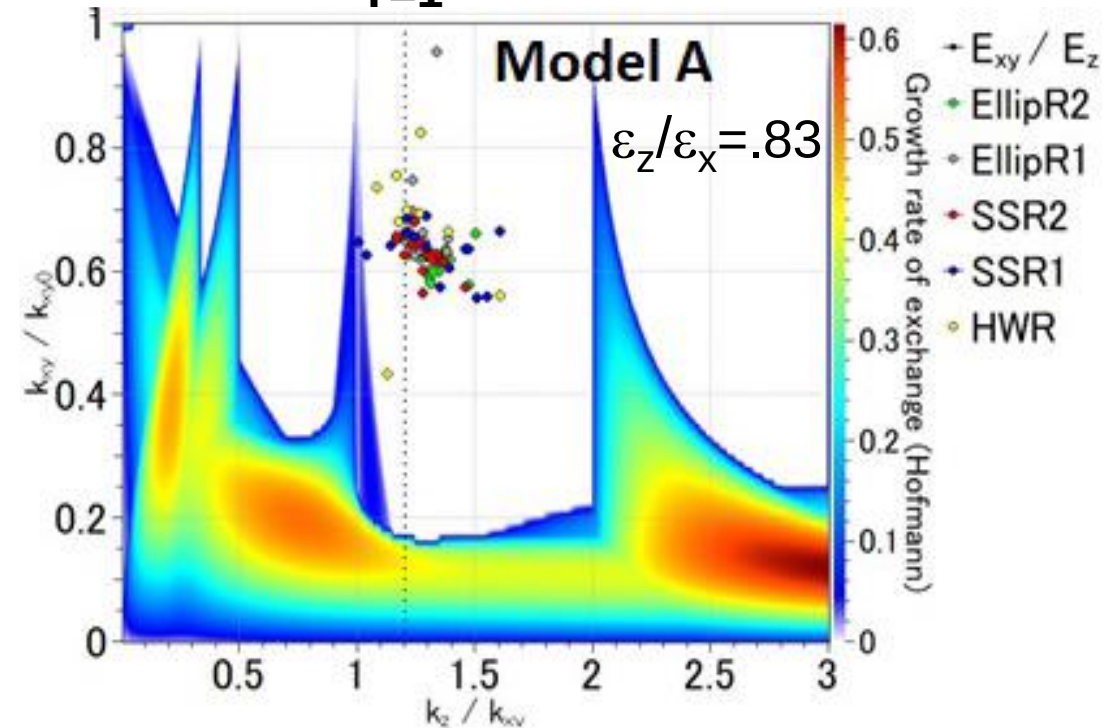


anisotropic

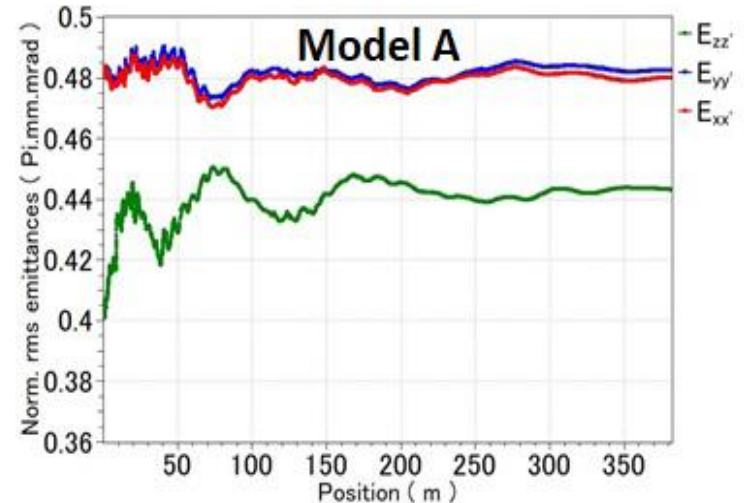
JAEA – ADS: Accelerator Driven Subcritical System

s.c . CW proton linac of 30 MW & subcritical nuclear reactor

T=1



A nearly equipartitioned design - no risk



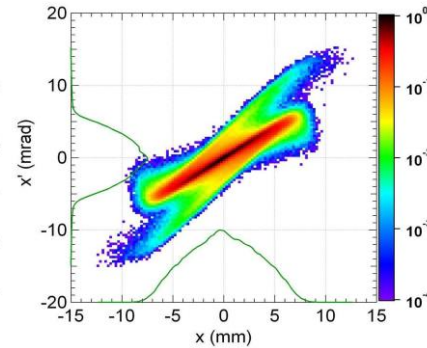
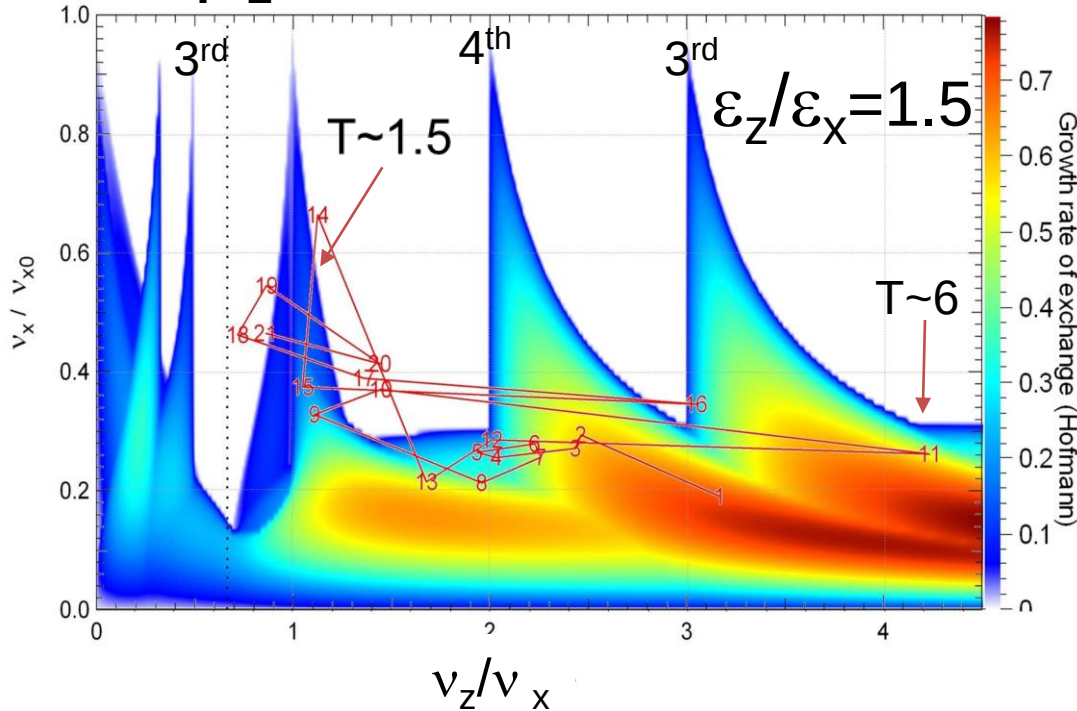
C. Plostinar et al. , Proc. IPAC'13, Shanghai, China

IFMIF-EVEDA

s.c .Fusion Material Irradiation Facility (F/J)

W. Simeoni et al, IPAC'11, San Sebastian, Spain

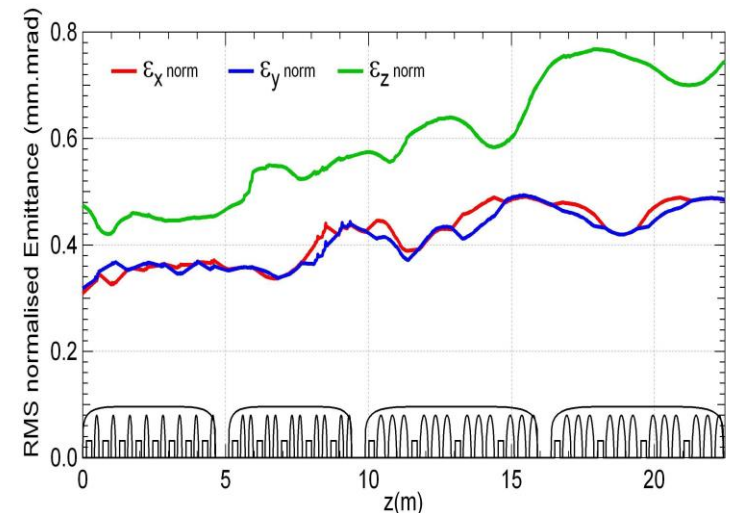
T=1



↓ “Realistic” x - x' -initial distribution as input – not Gaussian or WB
What is a realistic distribution?

Anisotropy effect: combined response of **parametric** instability and **single-particle** resonances

→ **Landau damping** may be ineffective here due to **3d z- x/y anisotropy**
- specific to **linear accelerators**, where it is sometimes overlooked!



Concluding Remarks

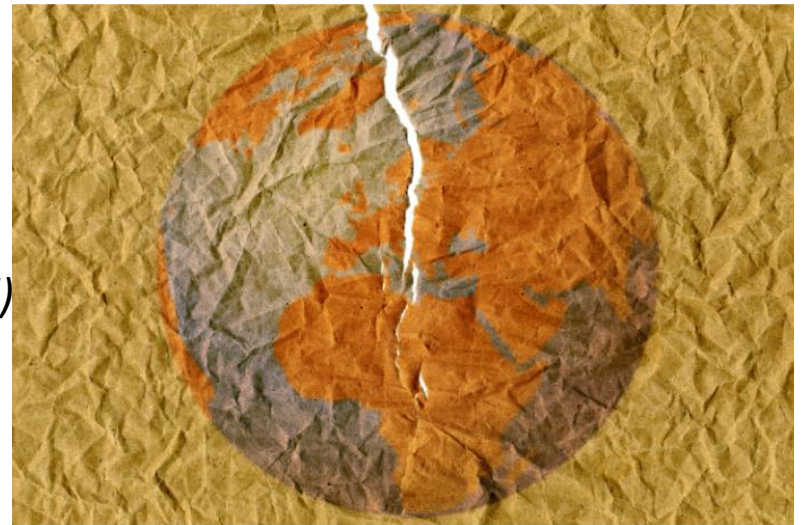
- **Progress** in accelerator science is built on about 70 to 80 years of history – also **on politics** – after the Cold War **now between the two big Supers.**

APS Journal Jan/Feb 2026:

The fight to keep science global

(Robbert Dijkgraaf, mathematical physicist and president-elect of the International Science Council)

- ✓ ““Frontier research infrastructures, such as the **next generation of particle accelerators**, space telescopes, or gravitational wave detectors ... all demand **world-scale** laboratories.”
- ✓ “Some nations are trying to shut the doors of international collaboration”
- ✓ “**Scientists can keep them open.**”



Picture from Article

- **Let us continue to keep the doors open!**

Backups

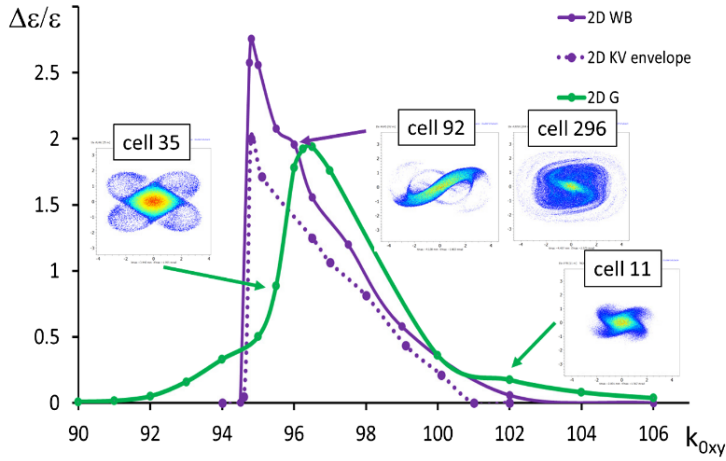


FIG. 1. Rms emittance growth versus k_{0xy} for the stopband above 90° for 2D waterbag and Gaussian distributions after 300 FODO cells. Inserts showing $x - x'$ phase space at different k_{0xy}

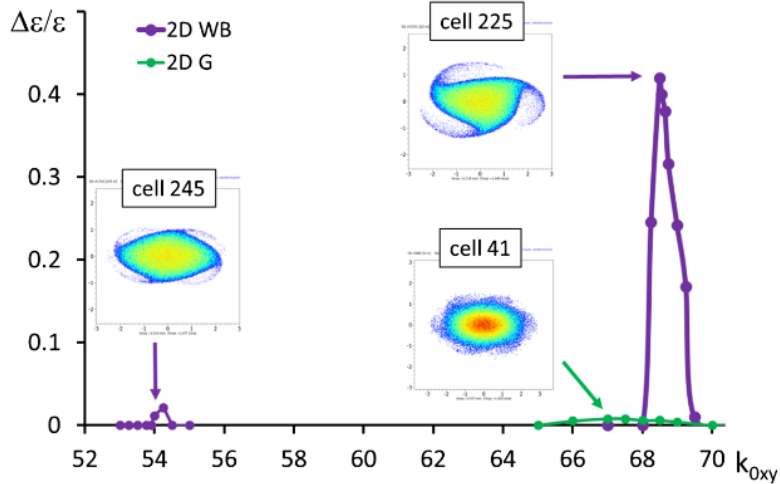


FIG. 2. Rms emittance growth versus k_{0xy} for the stopbands above 60° and 45° for 2D waterbag and Gaussian distributions after 300 FODO cells. Inserts showing $x - x'$ phase space at different k_{0xy} and cells.

growth of only 2% for the waterbag and no detectable growth for the Gaussian case.

B. Landau damping of parametric resonances

All in all, in 2D we find parametric resonances of second, third, and fourth order to exist in the waterbag distribution, but only the second order mode in the Gaussian case. We explain this by Landau damping using the tune spectra extracted from self-consistent TRACEWIN simulations. In Fig. 3 the working point $k_{0xy} = 90^\circ$ is chosen to obtain resonance-free spectra $f_0(k_{xy})$ representative for an initial beam situation at arbitrary k_{0xy} . Particle trajectories over 2^{14} elements (1820 cells with 9 elements per cell) are evaluated for this purpose. The coherent shifts following Eq. (3) (divided by m) are determined here from the peaks of

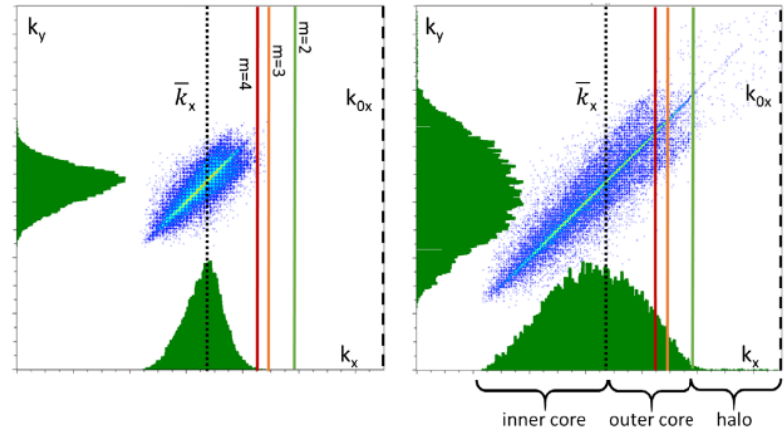


FIG. 3. Spectral distributions $f_0(k_{xy})$ (as unnormalized intensity (per bin of k_{xy})) for 2D waterbag (lhs) and Gaussian (rhs) distributions generated for a fixed k_{0xy} . Also shown are locations of $\bar{k}_x$ and of the $m = 2, 3, 4$ coherent mode lines (i.e., mode frequencies divided by m).

From our PRAB 2017

out at later times). Note that the initial distribution has strictly uniform transverse density profiles with no space charge “pseudo-octupole” content, except on the noise level. Thus, this growth can be attributed only to an **integer** ($n = 2$) **parametric resonance** $\varphi = 4k_{0;x;y} - \Delta k_{4;coh} = 360^\circ$, which drives its amplitude to a finite level until saturation.

The existence of this mode is in agreement with the linearized theory stopband prediction at 90° of Fig. 3.

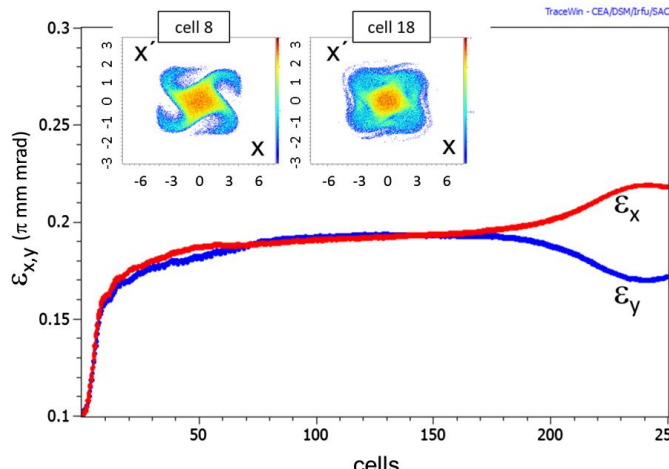
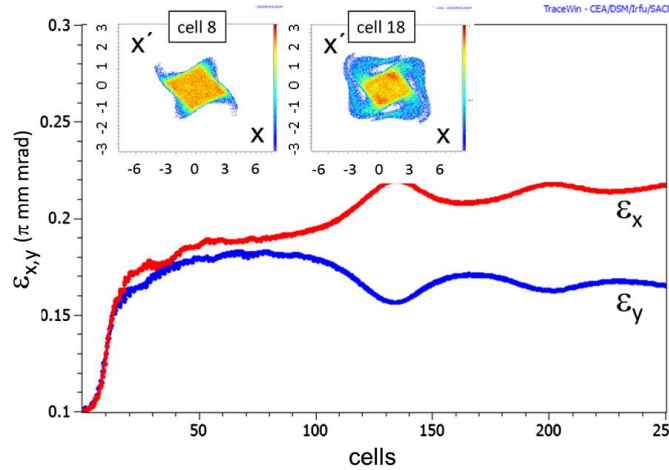
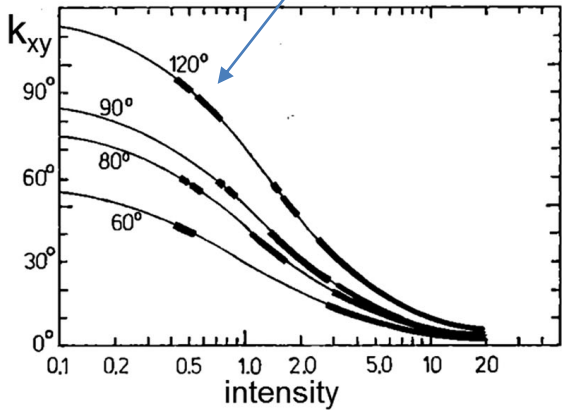
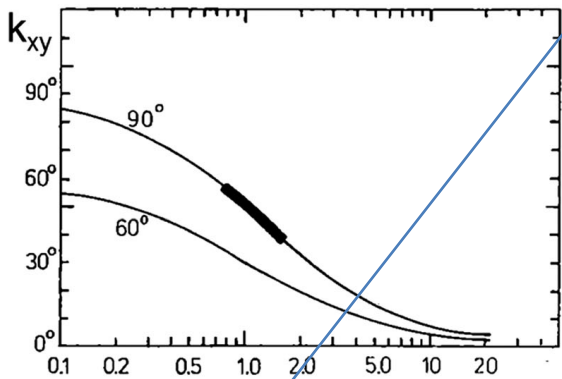
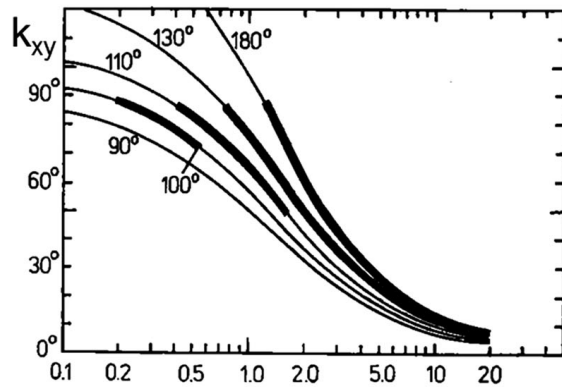
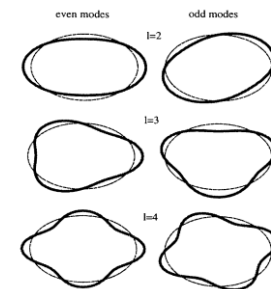
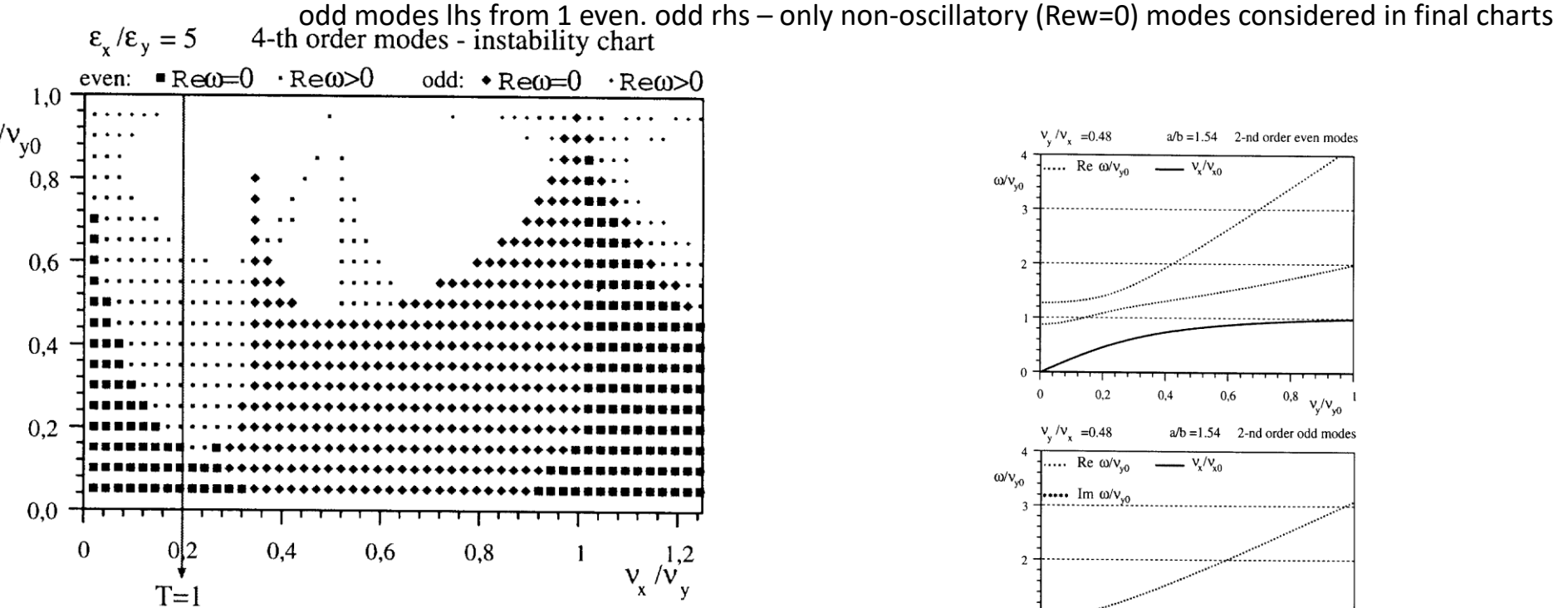


FIG. 4. rms emittances versus cell number for $k_{0;x;y} = 120^\circ$, $k_{x;y} = 80^\circ$ (inserts showing phase space plots at indicated cells) for KV beam (top graph) and for waterbag distribution beam

(bottom graph).
(even or odd modes – laslett graph shows only 4th even?)



from my 1998 paper (constant focusing!):



odd mode instability require very strong tune depression in y in this example (in sea)

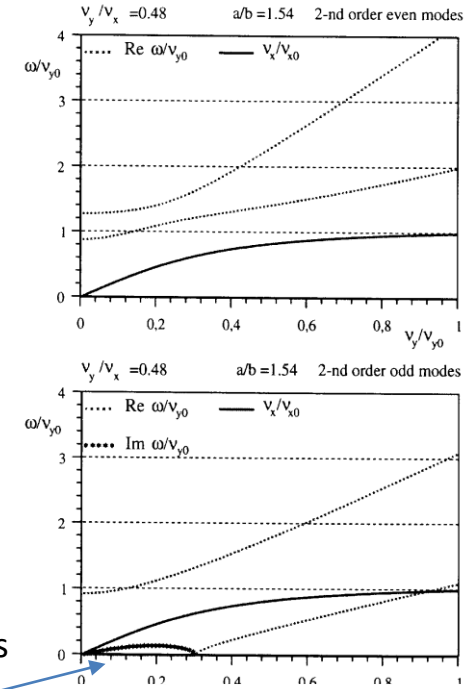


FIG. 3. Examples of coherent frequencies for second order even and odd modes of anisotropic beam ($T = 10.5$)

The solutions for the even mode are always stable, which is not necessarily true for the odd modes. We find that the low-frequency branch leads to imaginary ω if (assuming $\eta > 1$) the conditions are satisfied :

$$\alpha < 1, \quad 1 < \alpha_0 < \sqrt{\eta} \quad (34)$$

This means that the beam is unstable if for an external focusing stronger in the y -direction space charge leads to a stronger x -focusing. This tilting instability between x and y obviously requires a sufficiently large anisotropy.

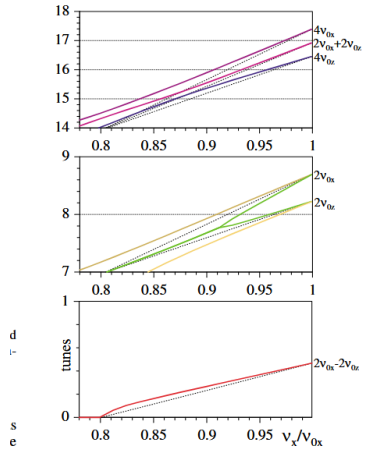


FIG. 2. (Color) Analytic results for fourth order even mode frequencies with $\epsilon_z/\epsilon_x = 2$ and machine tunes $\nu_{0z} = 4.115$, $\nu_{0x} = 4.35$.

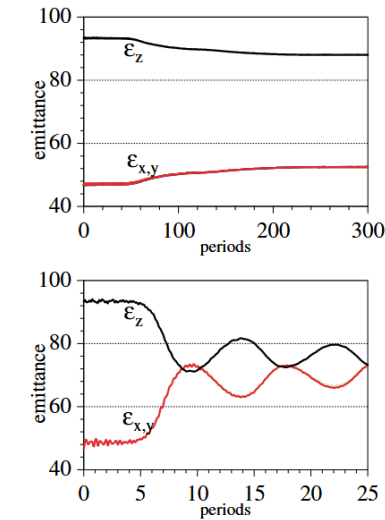


FIG. 13. (Color) rms emittances (arbitrary units) for $\epsilon_z/\epsilon_x = 2$ (WB) and fixed $\nu_{0z}/\nu_{0x} = 1.5$, both cases inside the resonance band of third order. Top panel: $\nu_z/\nu_x = 2.04$ ($T = 4.1 \rightarrow 2.6$); bottom panel: $\nu_z/\nu_x = 2.94$ ($T = 5.9 \rightarrow 1.6$). Units on the abscissa are transverse single-particle periods without space charge.

ES IN TWO AND THREE ... 024202 (2003)

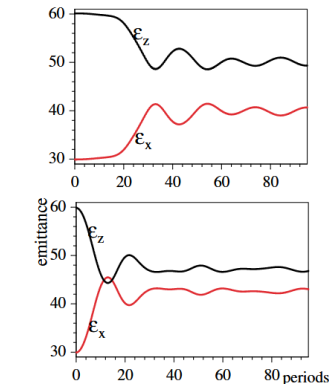


FIG. 7. (Color) Evolution of rms emittances (arbitrary units) for $\nu_z/\nu_x = 1.04$, $\nu_z/\nu_{0x} = 0.8$, and $\epsilon_z/\epsilon_x = 2$ with initial KV (top panel) and WB (bottom panel). Units on the abscissa are betatron periods in x in the absence of space charge.

Space charge resonances in two and three dimensional anisotropic beams

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GSI, 64291 Darmstadt, Germany

J. Qiang and R. D. Ryne
LBL, Berkeley, California 94720
(Received 9 October 2002; published 28 February 2003)

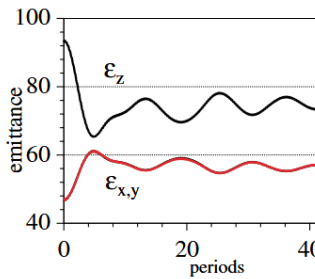


FIG. 14. (Color) Symmetric focusing $\nu_{0z}/\nu_{0x} = 1$, $\nu_z/\nu_x = 1.16$ ($\nu_z/\nu_{0x} = 0.68$) (WB: with $T:2.3 \rightarrow 1.3$).

from the beam using the MICROMAP code [28]. We have carried out simulations with initial KV as well as rms matched WB distributions for the same parameter range as in Fig. 4. The WB initial distributions, contrary to KV beams, cannot be generated in a self-consistent way in the case of anisotropy. We fill a 4D hyperellipsoid uniformly and carry out rms matching, which leaves an inevitable initial density mismatch containing fourth, sixth, and higher order modes. This density mismatch

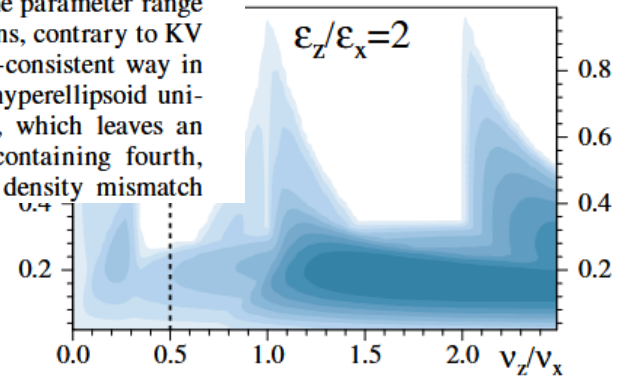


FIG. 11. (Color) Stability charts with analytically calculated stop bands (nonoscillatory modes) for arbitrary ν_z/ν_{0x} (ordinate), tune ratios ν_z/ν_x (abscissa), and emittance ratios 0.6, 1.2, and 2. Growth rates (grey scales in equidistant steps) in units of zero space charge betatron tune (in x). Dashed lines indicate equipartition tune ratios.

- [23] R.L. Gluckstern, in *Proceedings of the Linac Conference, 1970* (Fermilab, Batavia, IL, 1970), p. 811.
- [24] I. Hofmann, *Part. Accel.* **10**, 253 (1980).
- [25] I. Hofmann, *Phys. Fluids* **23**, 296 (1980).

Concluding Remarks

- **Progress** in accelerator science is built on quite on about 70 to 80 years of history
- **New ideas** have been stimulating and driving progress – many never got realized
- **Analytical efforts** are history – computer simulation and AI make the game now!
- Mind the **gap between idealized** simulation and data from **realistic input** or even measurements (example Landau damping ...)
-

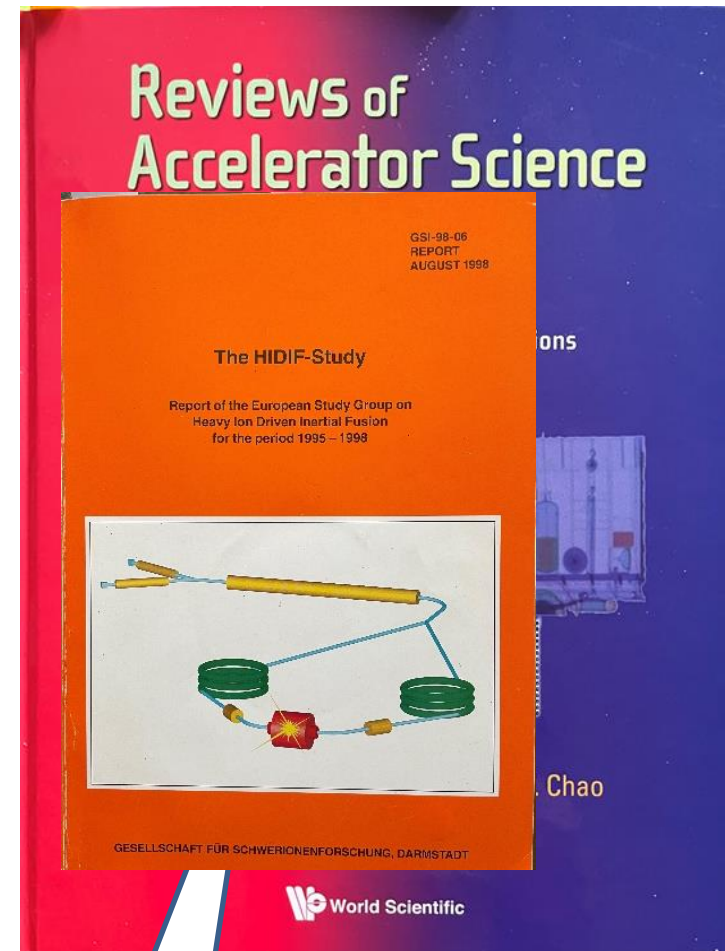
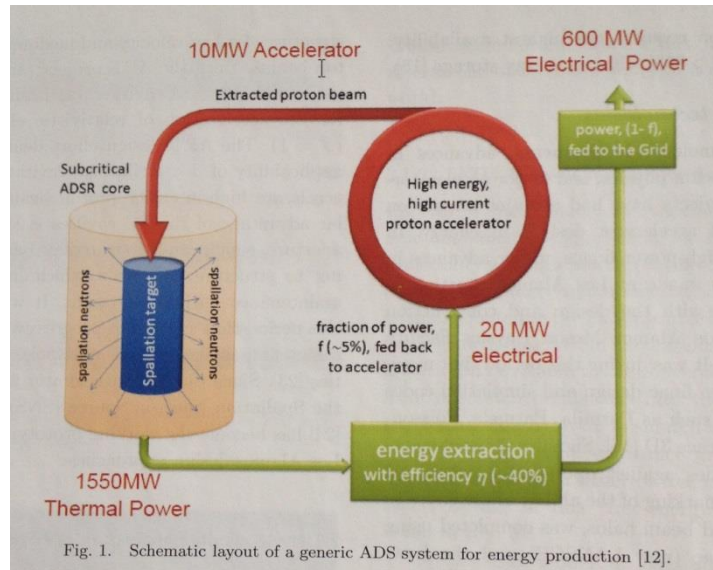
continued ...

“Accelerator Applications in Energy “

2015 Review:

Accelerator Driven Systems
are at **power frontier:**

Nuclear waste transmutation, Subcritical reactors,
Others:



HIDIF driver